Top Precision Measurements

Christian Schwanenberger

DESY

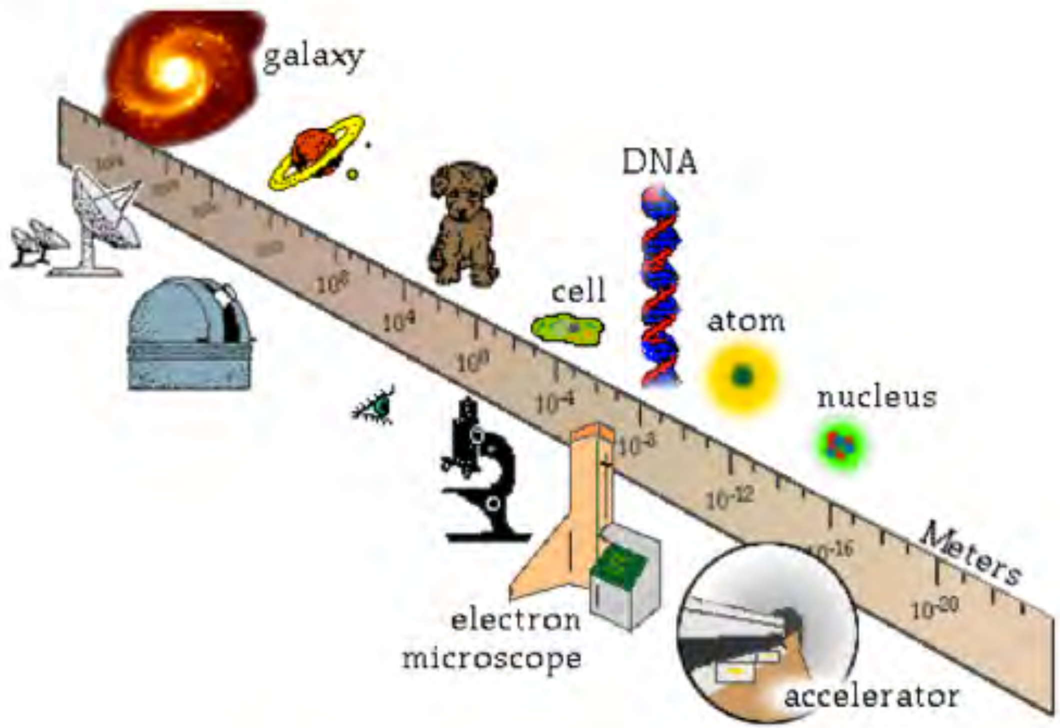
Seminar im Graduiertenkolleg

"Mass and Symmetries after the Discovery of the Higgs Particle at the LHC"

Freiburg, 28 October, 2015

Objective of Elementary Particle Physics

"So that I may perceive whatever holds the world together in its inmost folds."

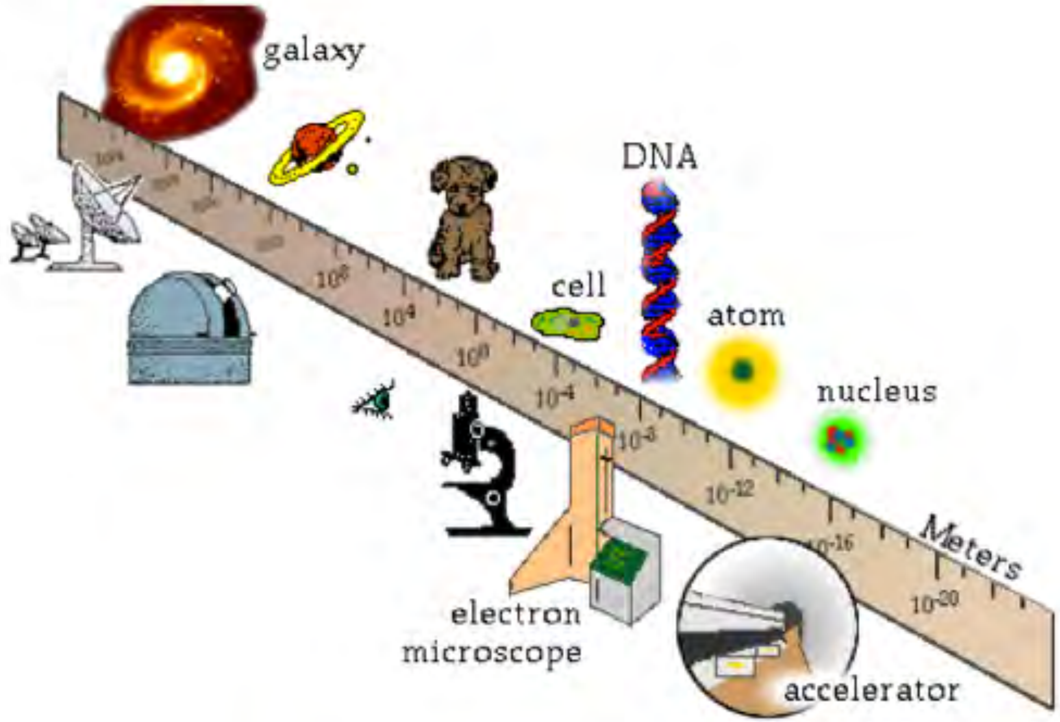


➔ **from the smallest dimensions in microcosm to the largest dimensions in the Universe**

Objective of Elementary Particle Physics

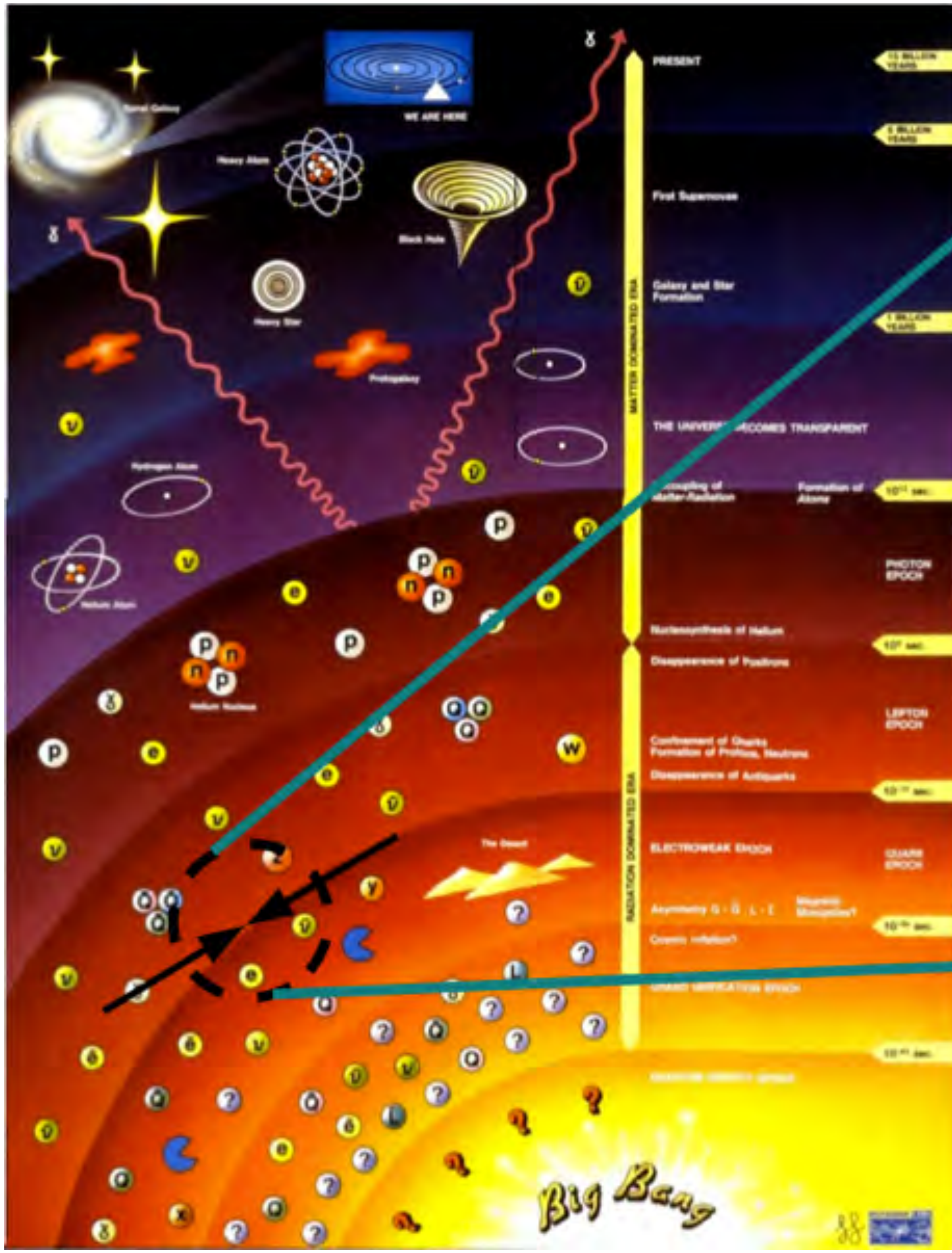
"Dass ich erkenne, was die Welt
im Innersten zusammenhält."

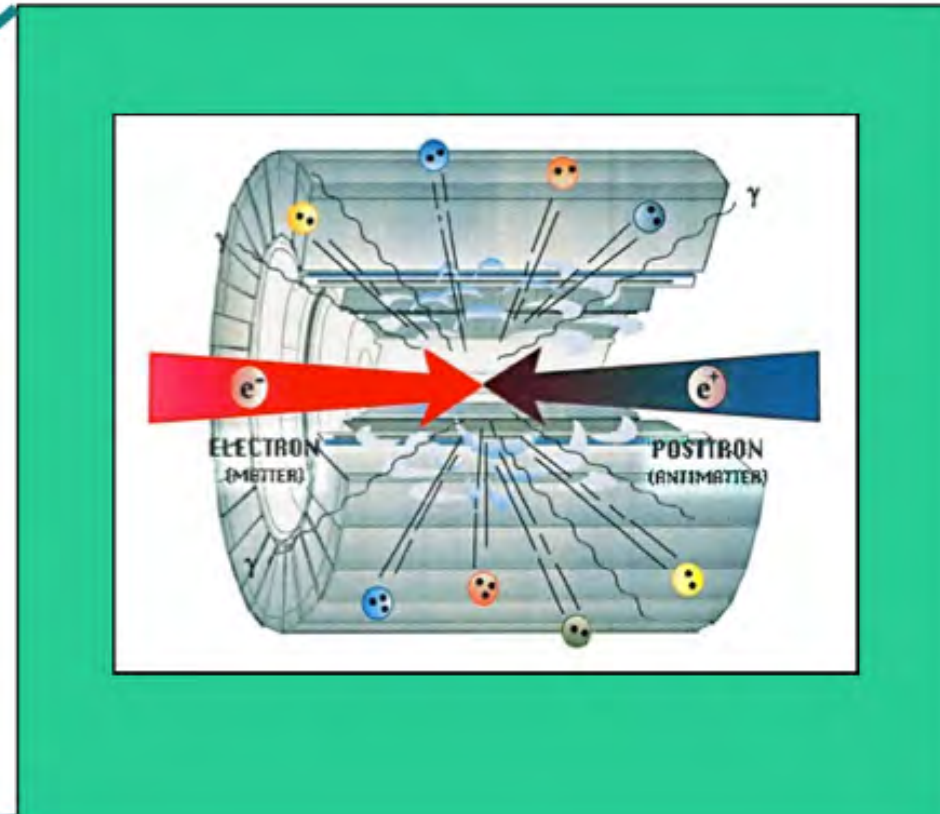
Goethe, Faust



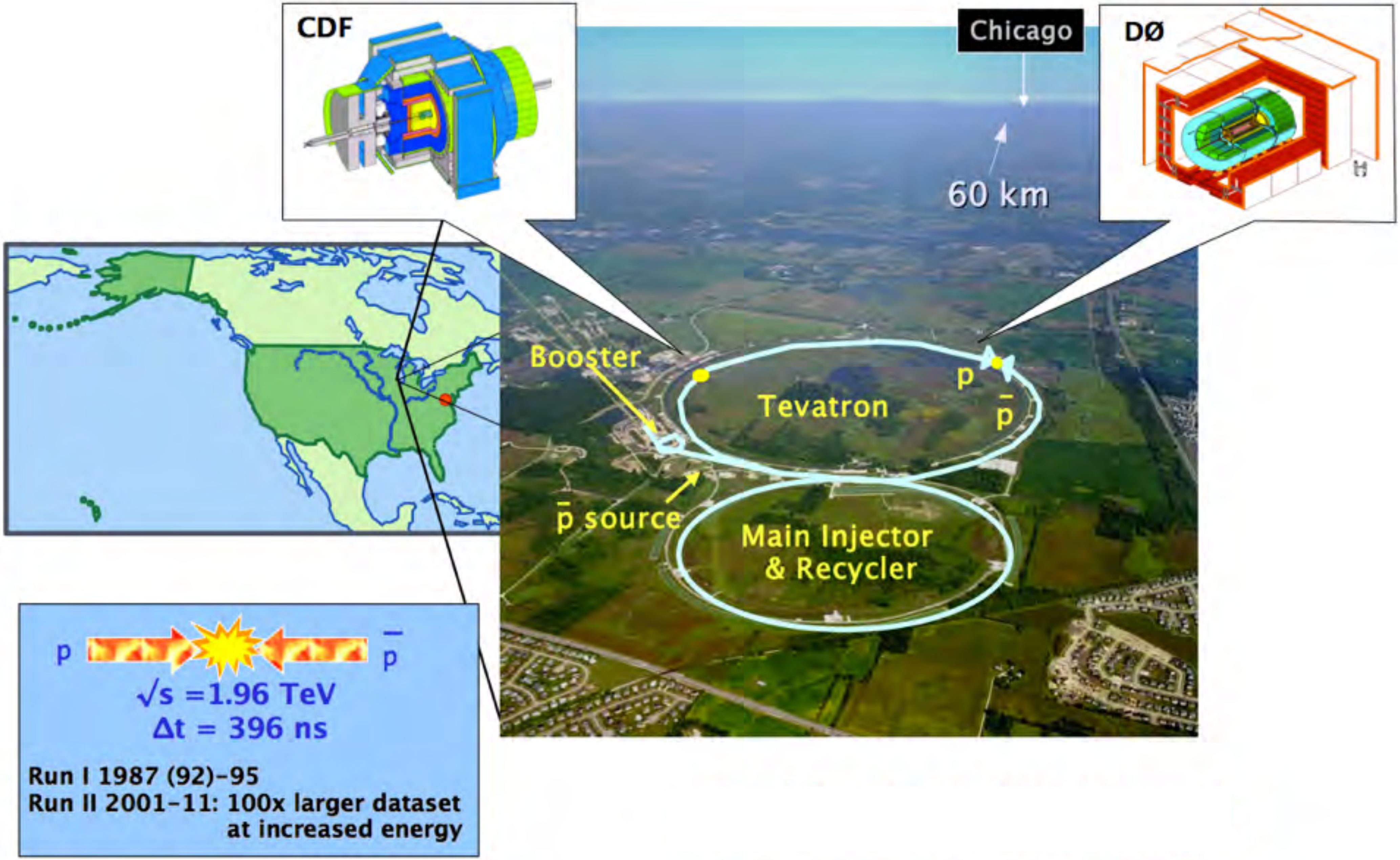
➔ **from the smallest dimensions in microcosm to the largest dimensions in the Universe**

Big Bang in the Lab?





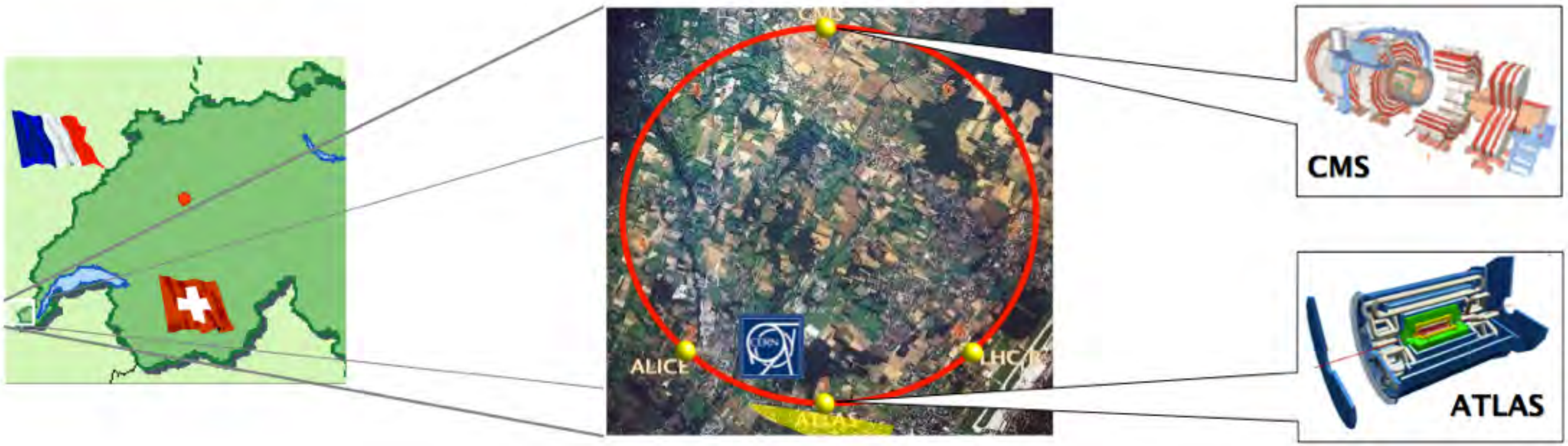
The Tevatron $p\bar{p}$ Collider at Fermilab



30 September 2011

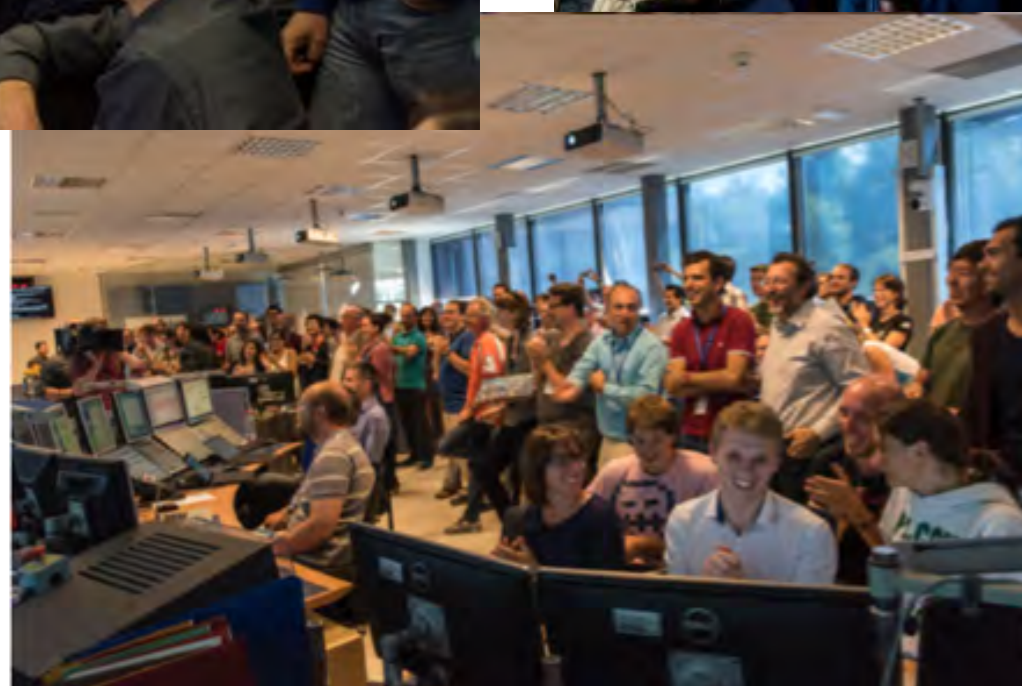
Tevatron complex shut down after 26 years of successful operation.

The LHC pp Collider at CERN

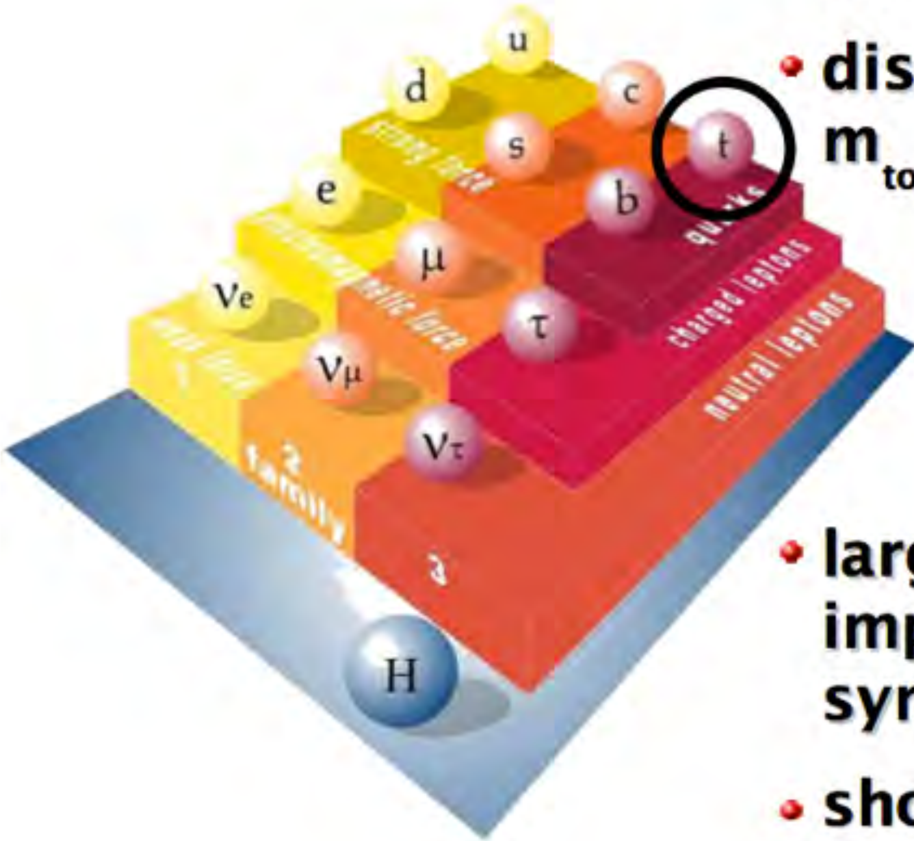


	$\sqrt{s}$ [TeV]	years	Ldt (rec.)
pp	7	2010-11	5.1 fb-1
pp	8	2012	21.3 fb-1
Pb+Pb	2.76	2010-11	160 µb-1
Pb+p	5	2013	30 nb-1

June 3rd, 2015: First Collisions @ 13 TeV



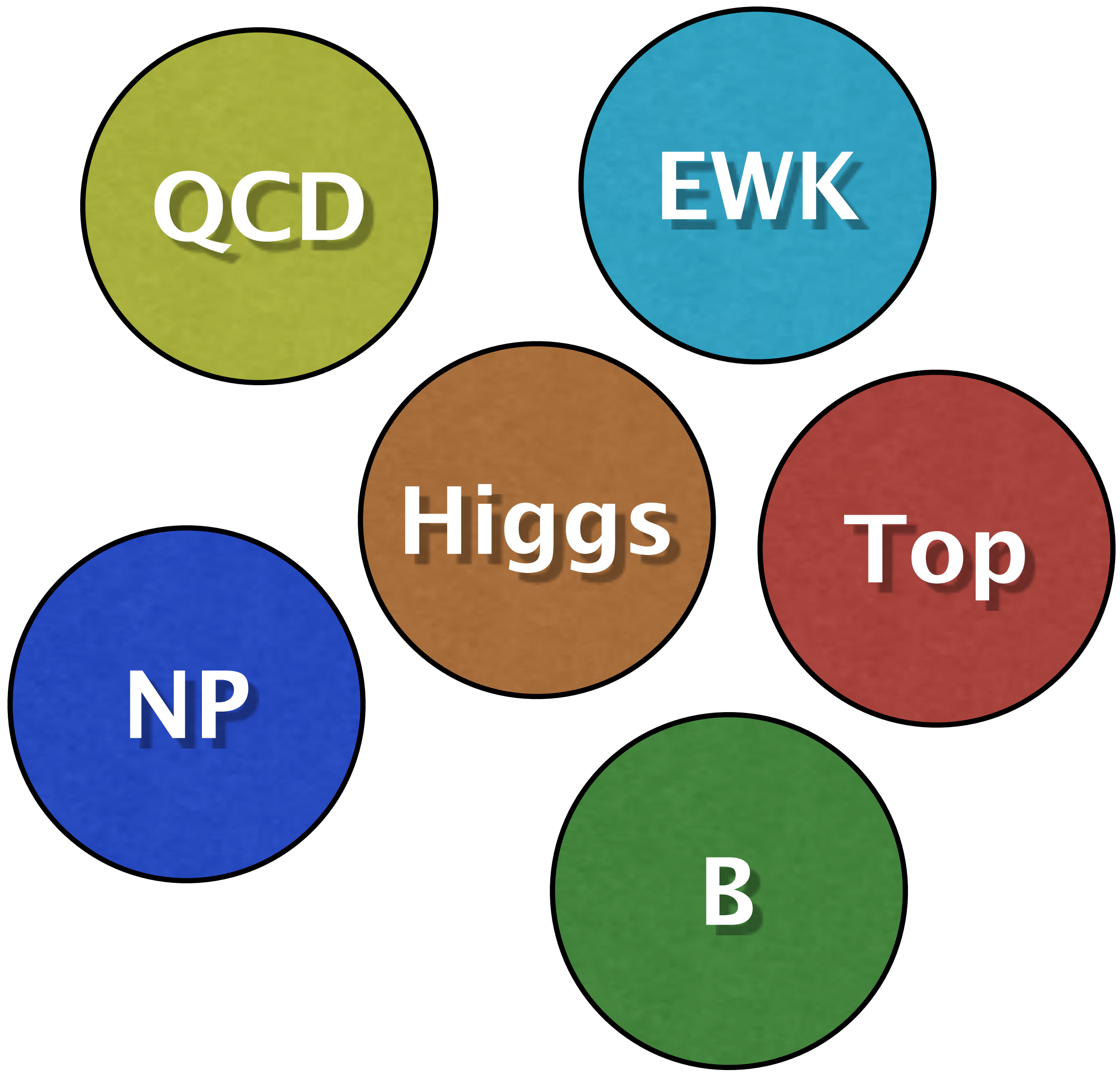
The Top Quark



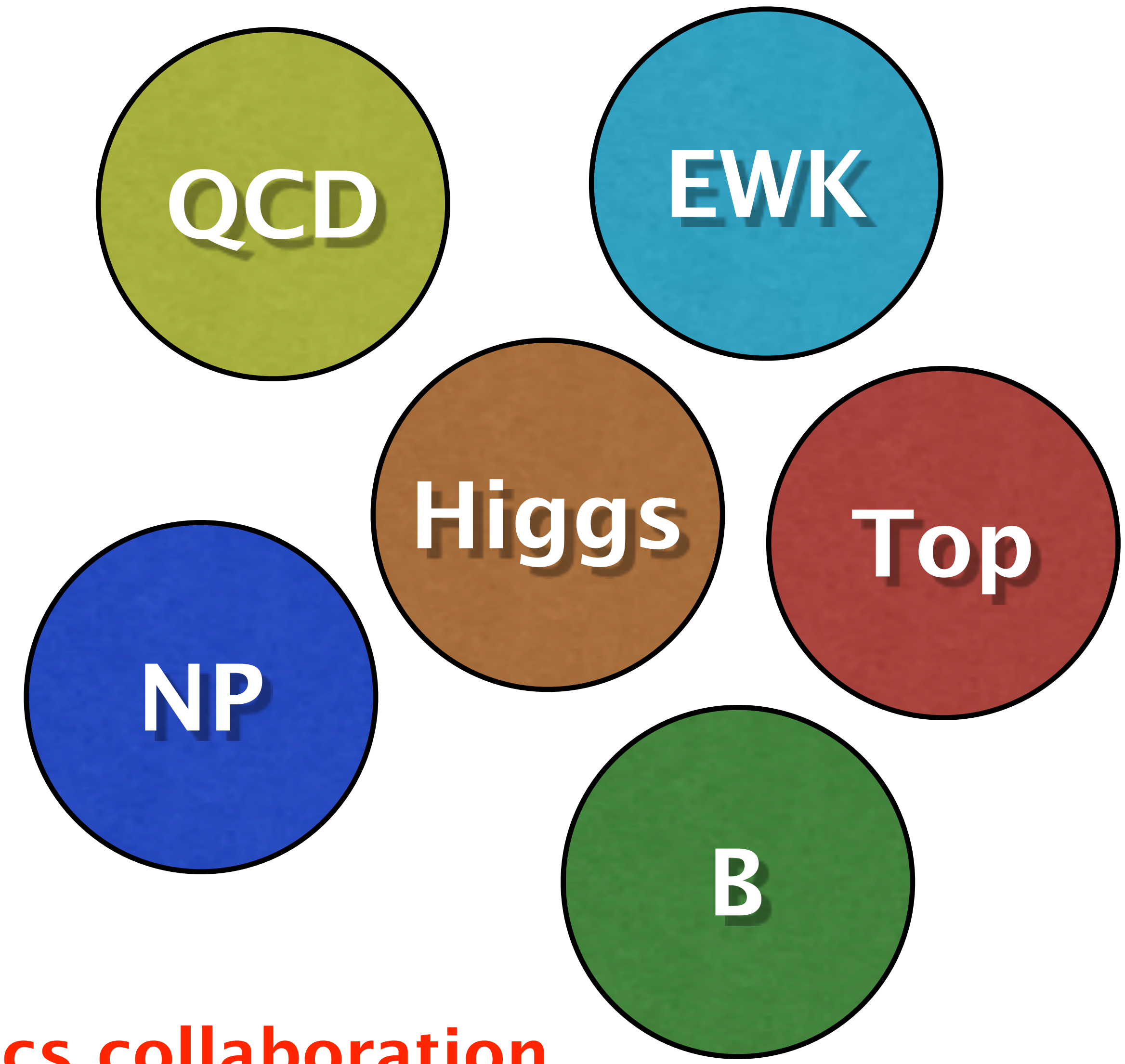
- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold nucleus
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}\mathrm{s} \ll \Lambda^{-1}_{QCD}$: decays before fragmenting
→ observe "naked" quark

Is the top quark the particle as predicted by the SM?

Physics Groups: DØ Collaboration



Physics Groups: DØ Collaboration



→ top physics collaboration

Physics Groups: DØ Collaboration

→ top physics collaboration

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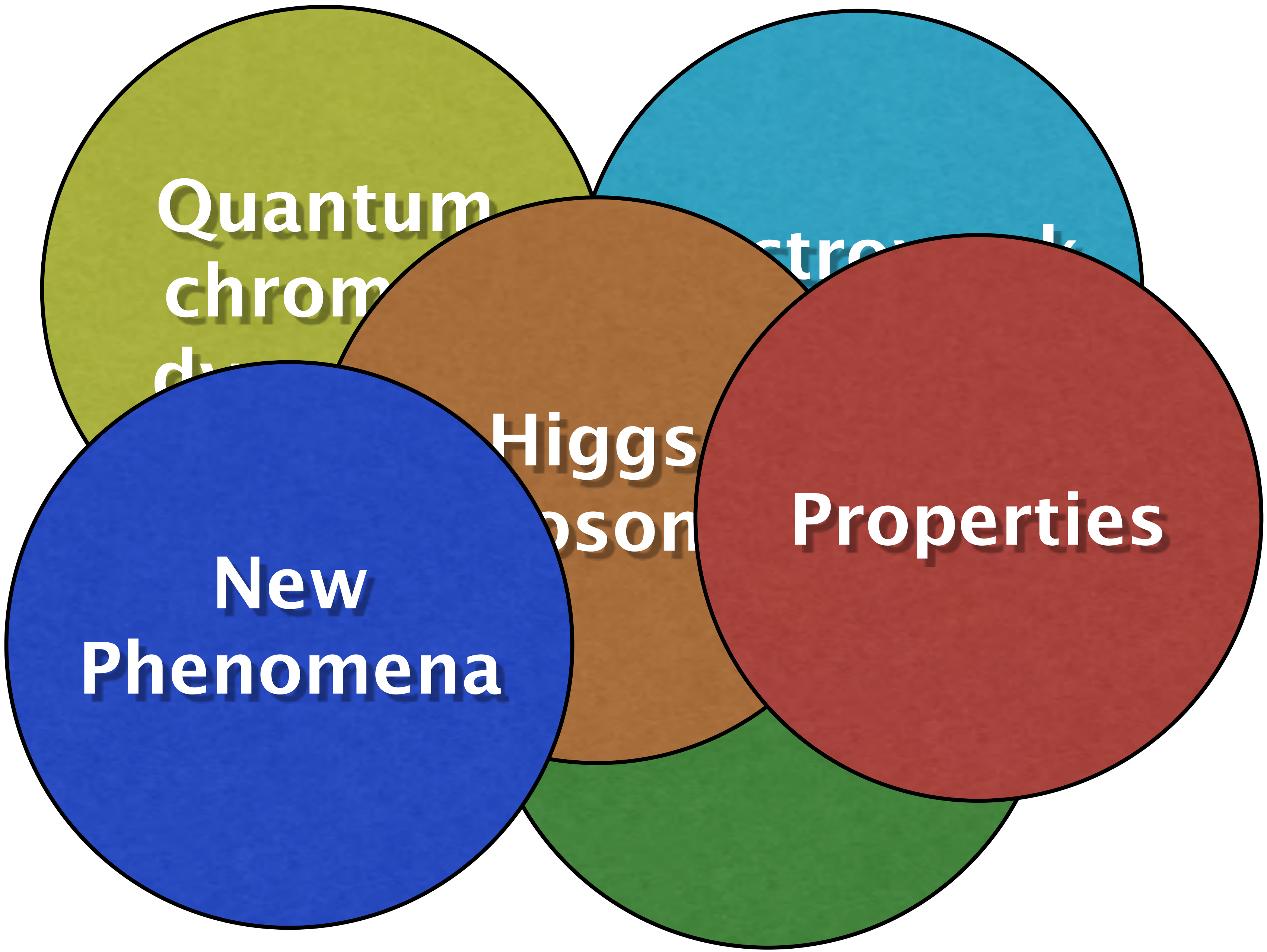
Physics Groups: DØ Collaboration



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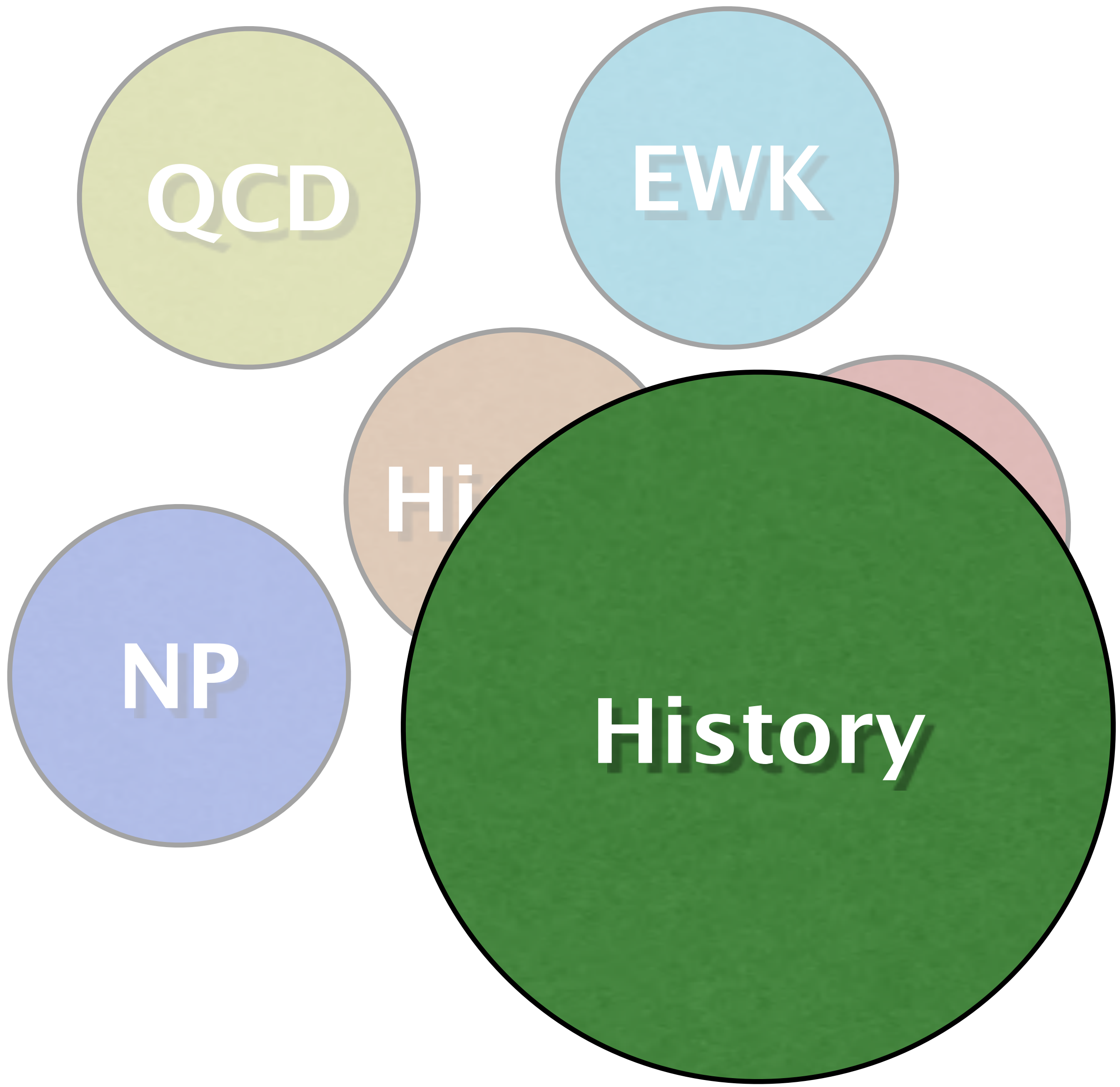
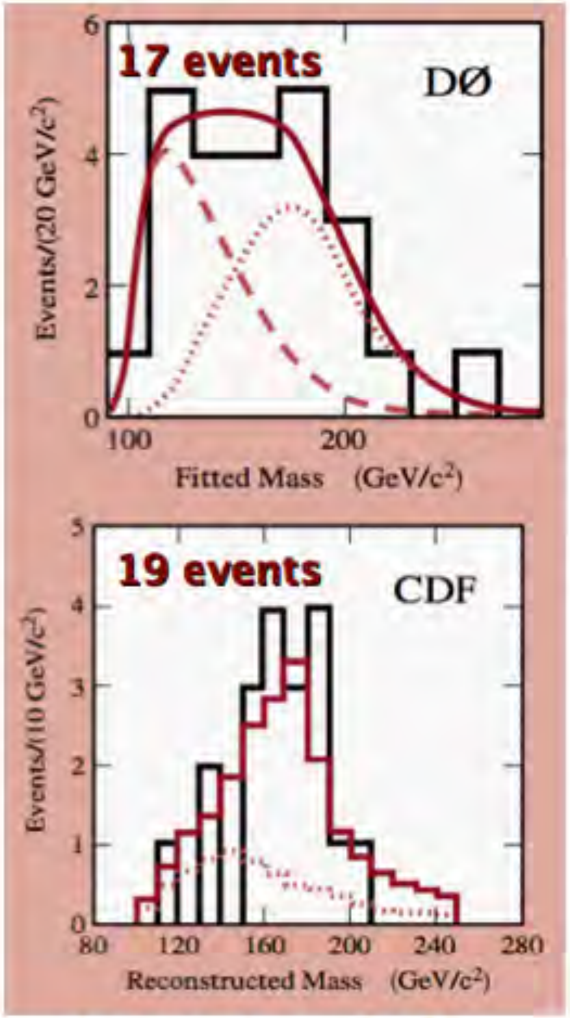


The Top Quark

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

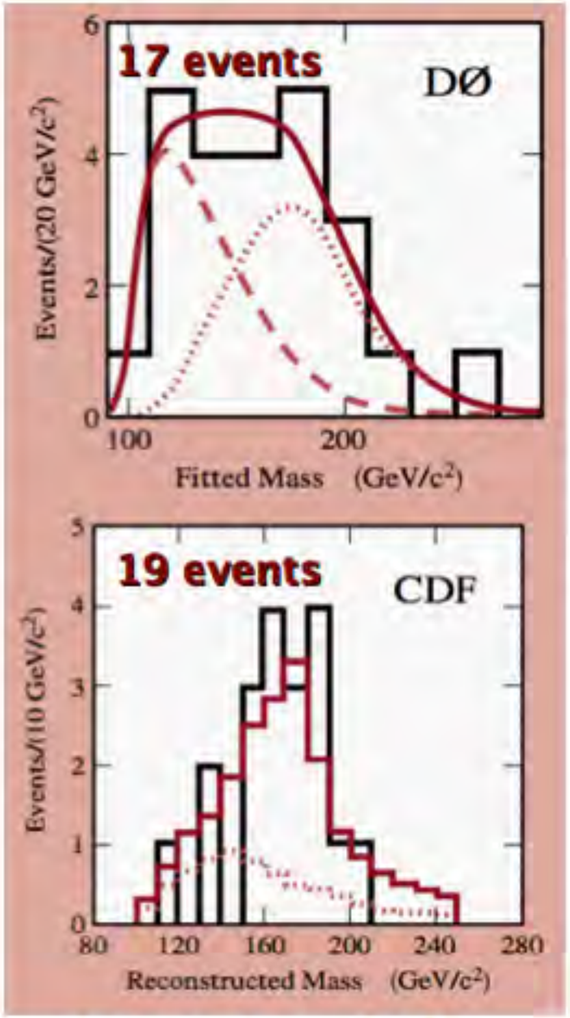


1995, CDF and DØ experiments, Fermilab

March 2nd, 1995:
First announcement of Top Discovery
in public seminar at Fermilab

The Top Quark

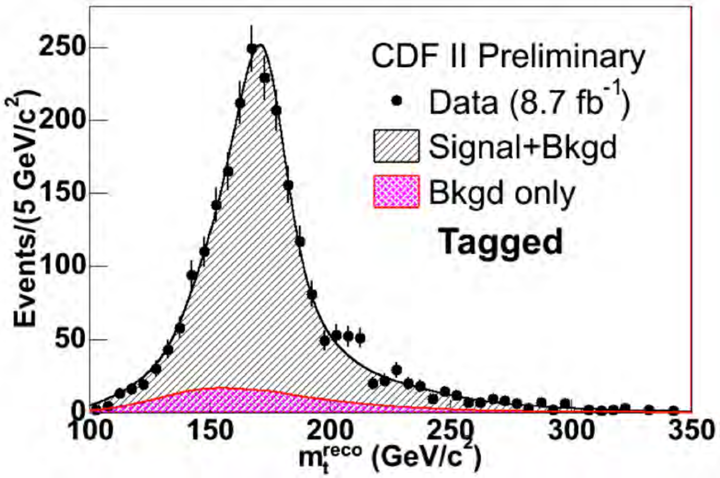
discovery PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

today

1000s of events



The Top Quark

discovery PRL 74, 2632 (1995)
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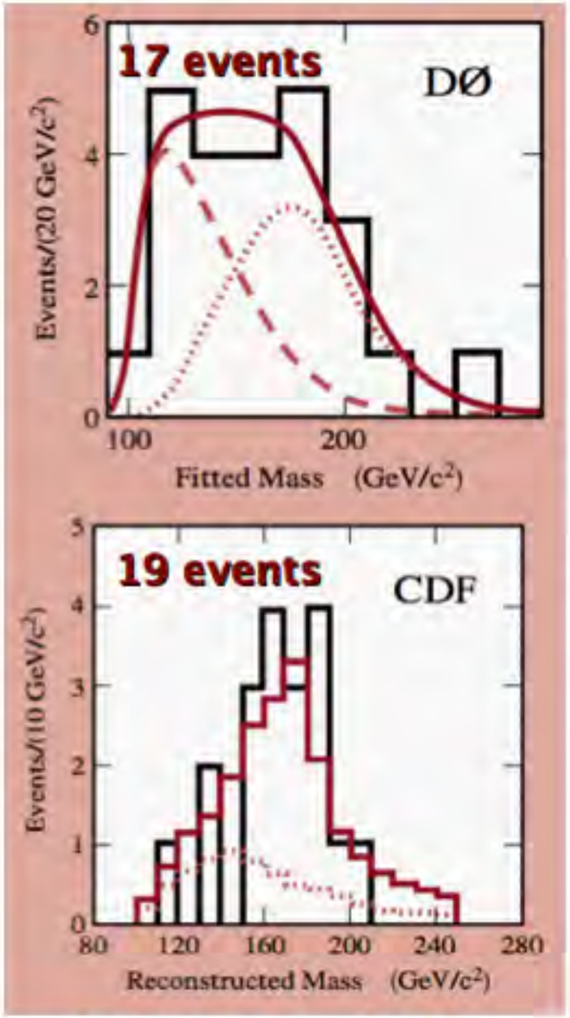

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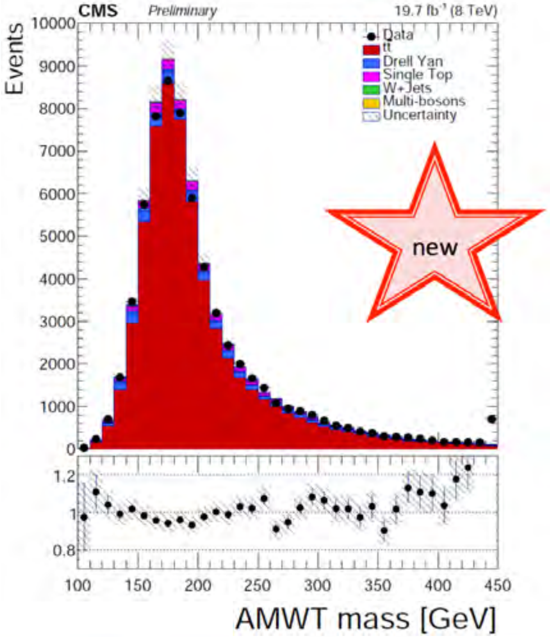
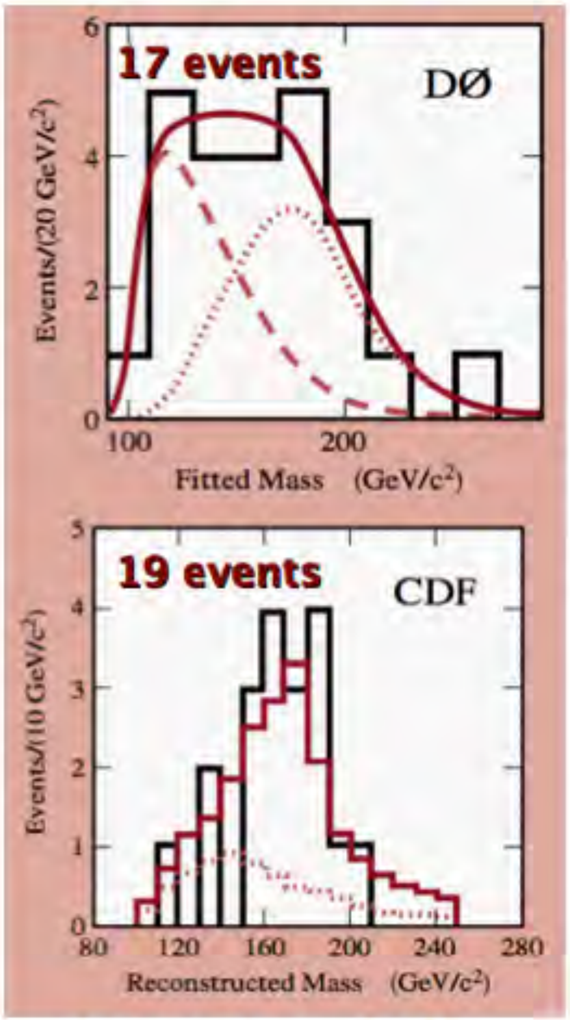


LHC: top quark factory

The Top Quark

discovery

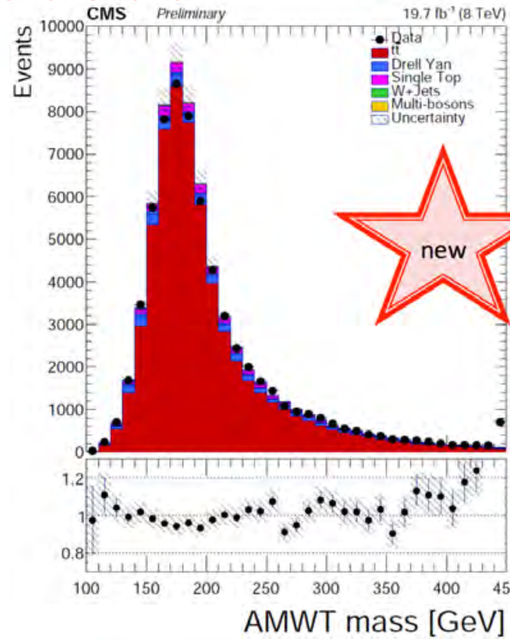
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

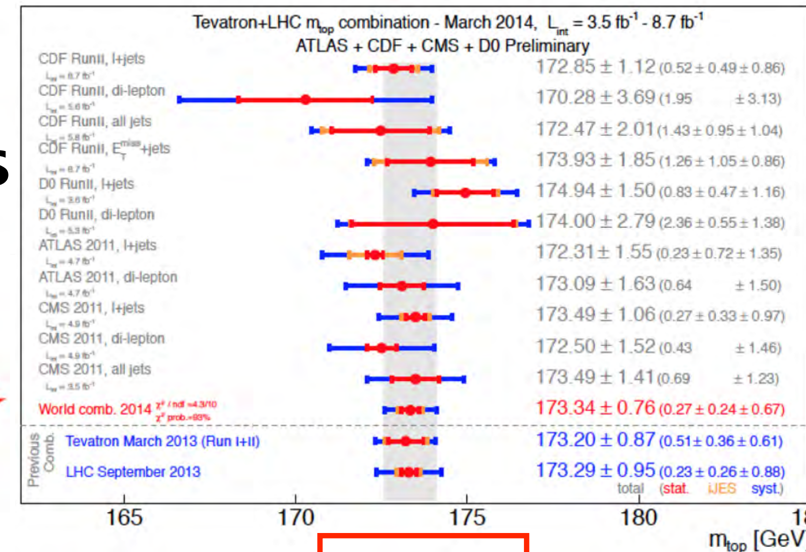
today

100000s of events



LHC: top quark factory

precision

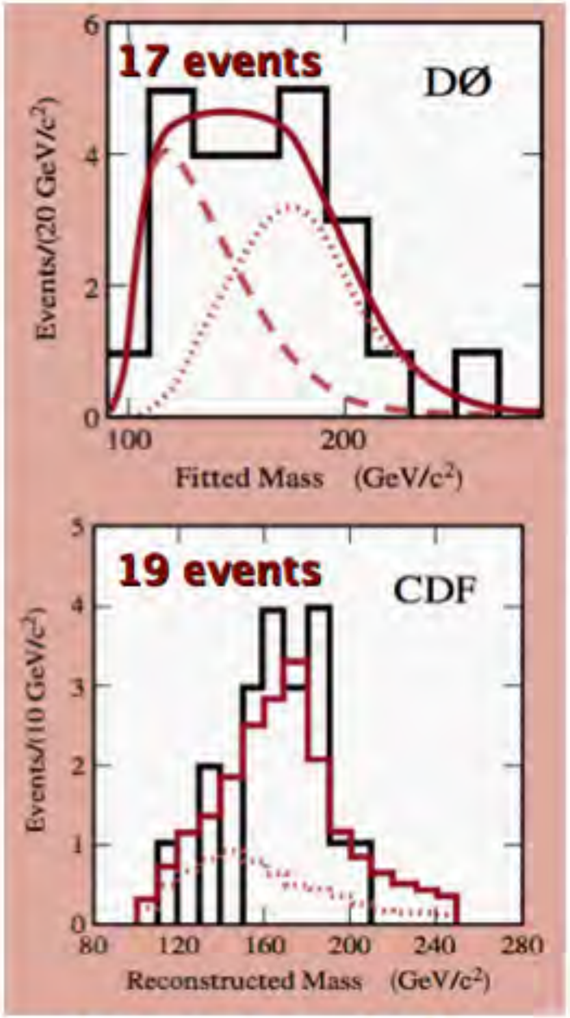


±0.44%

The Top Quark

discovery

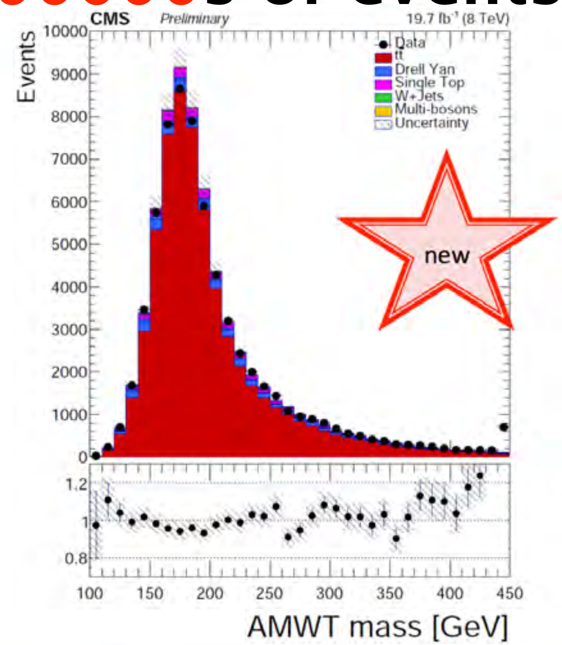
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

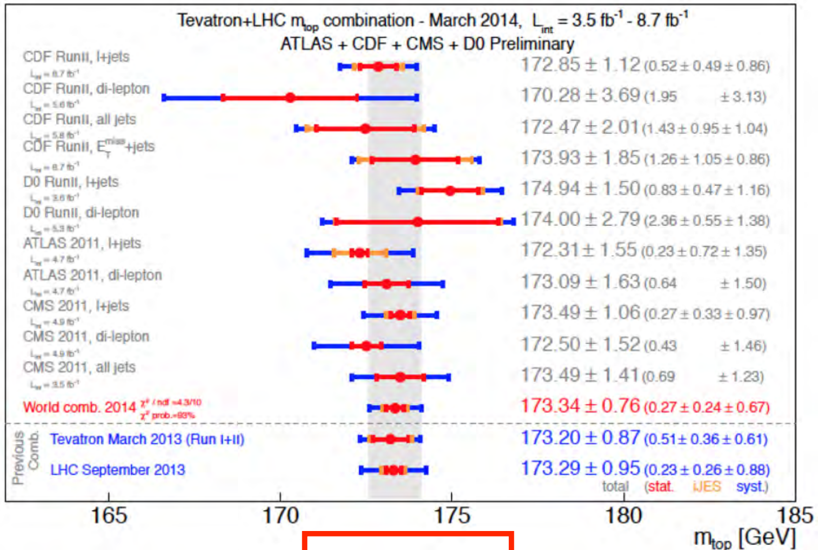
today

100000s of events



LHC: top quark factory

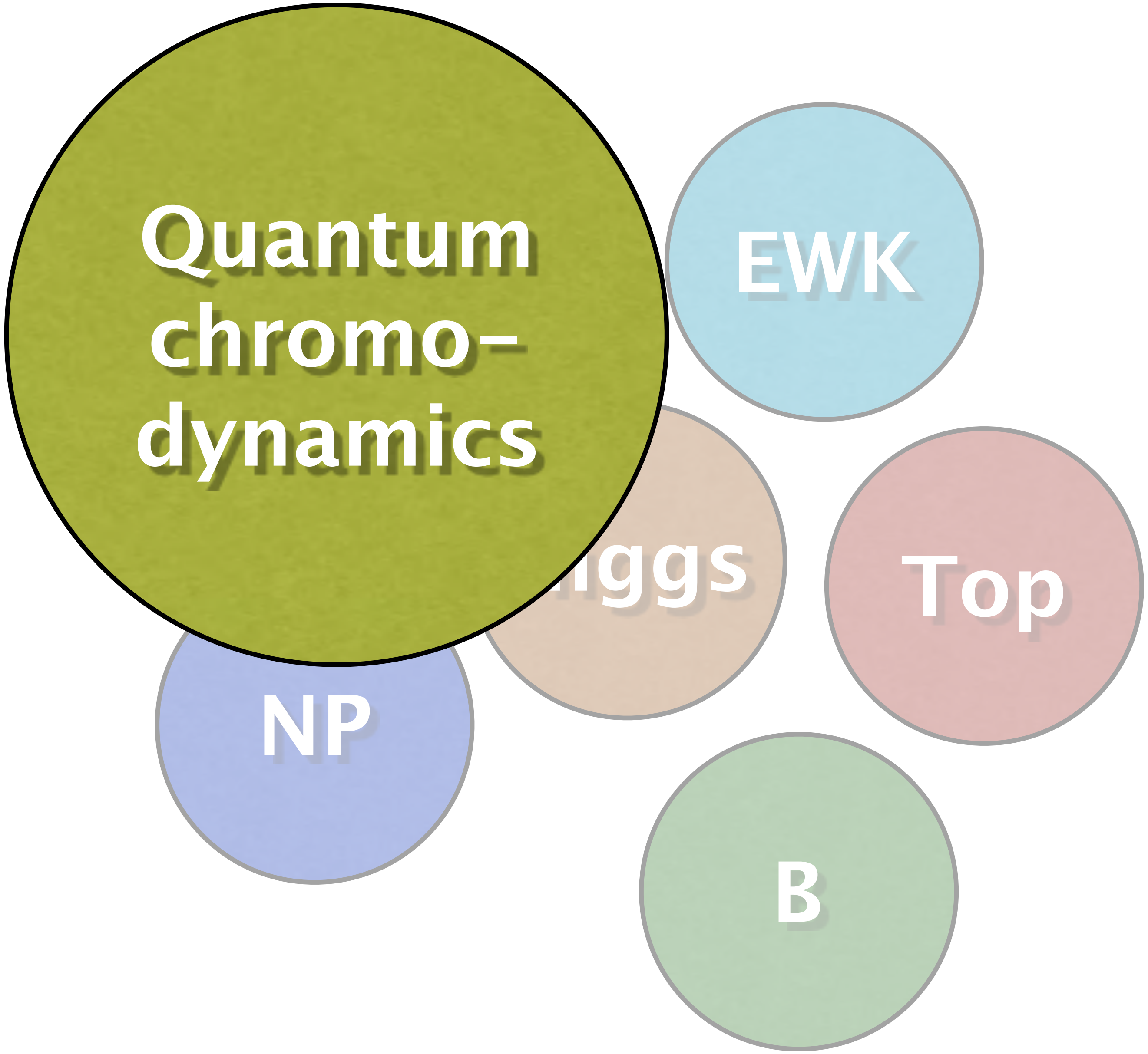
precision



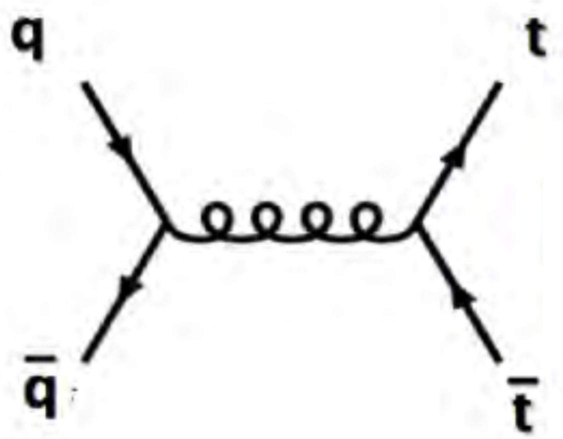
±0.44%

searches

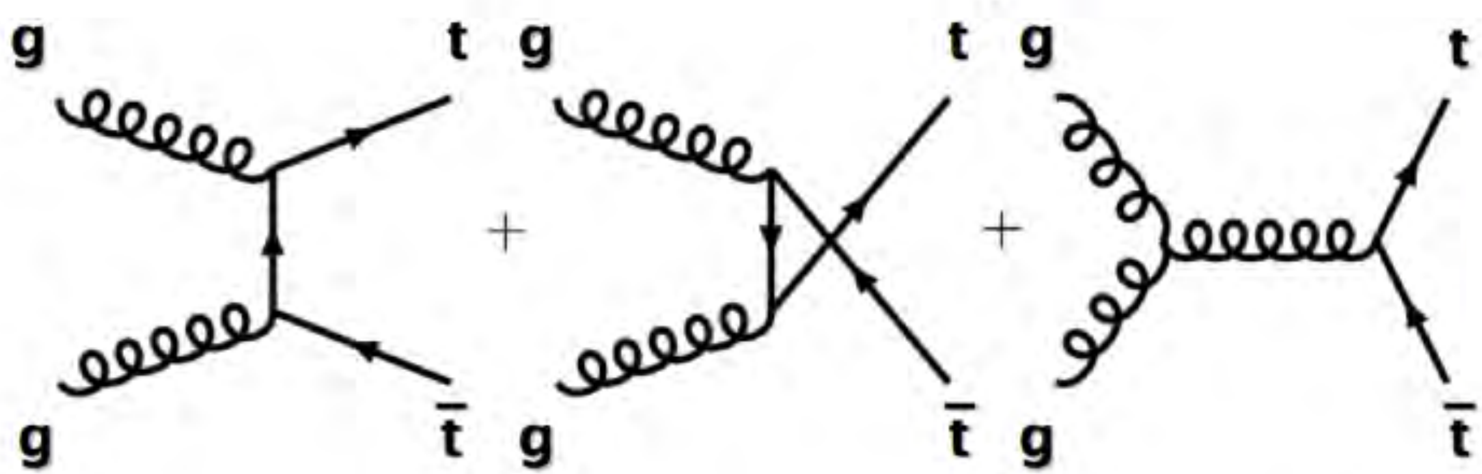
Top Quark Physics Topics



Top Quark Pair Production



Tevatron
(~85%)



LHC
(~87%)
(8 TeV)

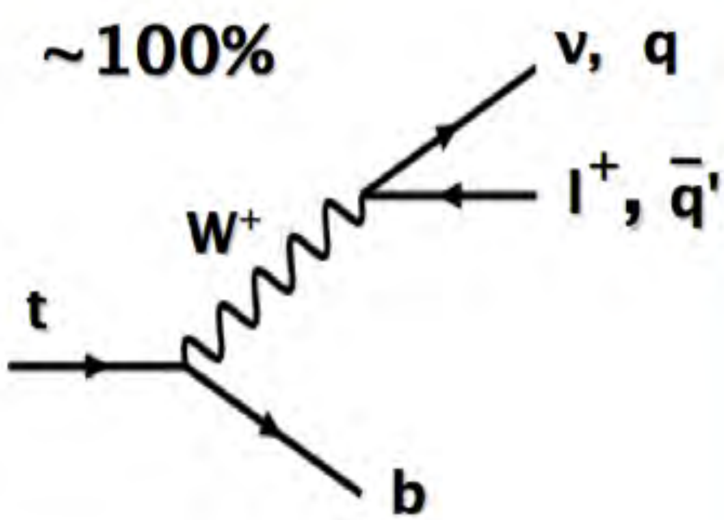
Top Quark Pair Signatures

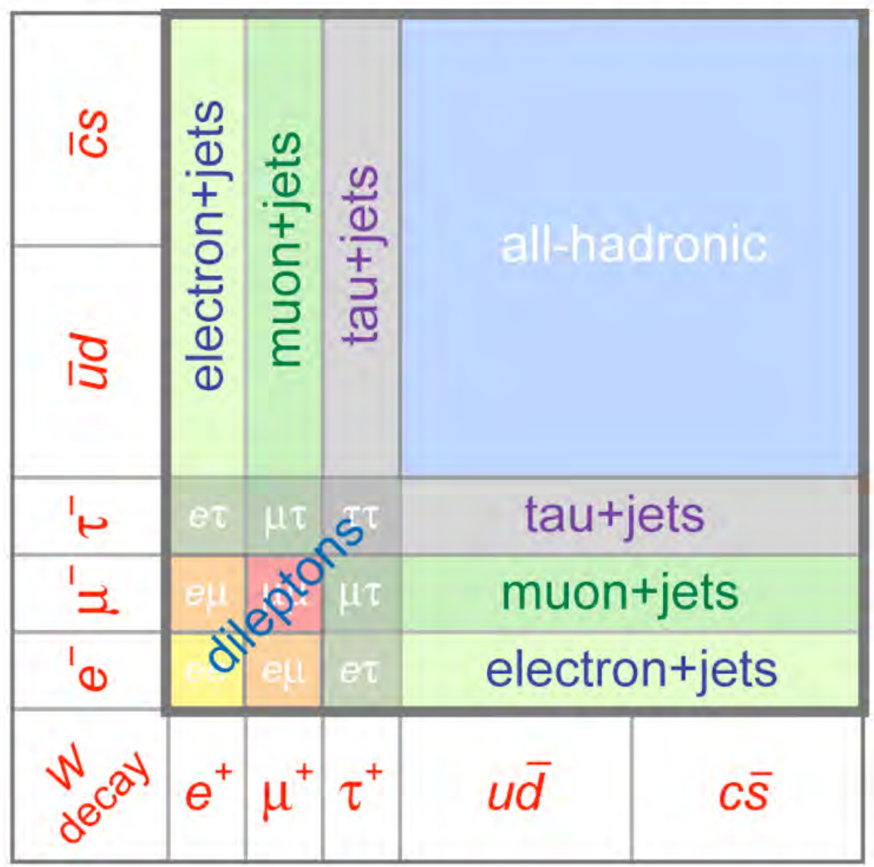
τ's 14%

Top Pair Decay Channels

alljets 46%

top decay:



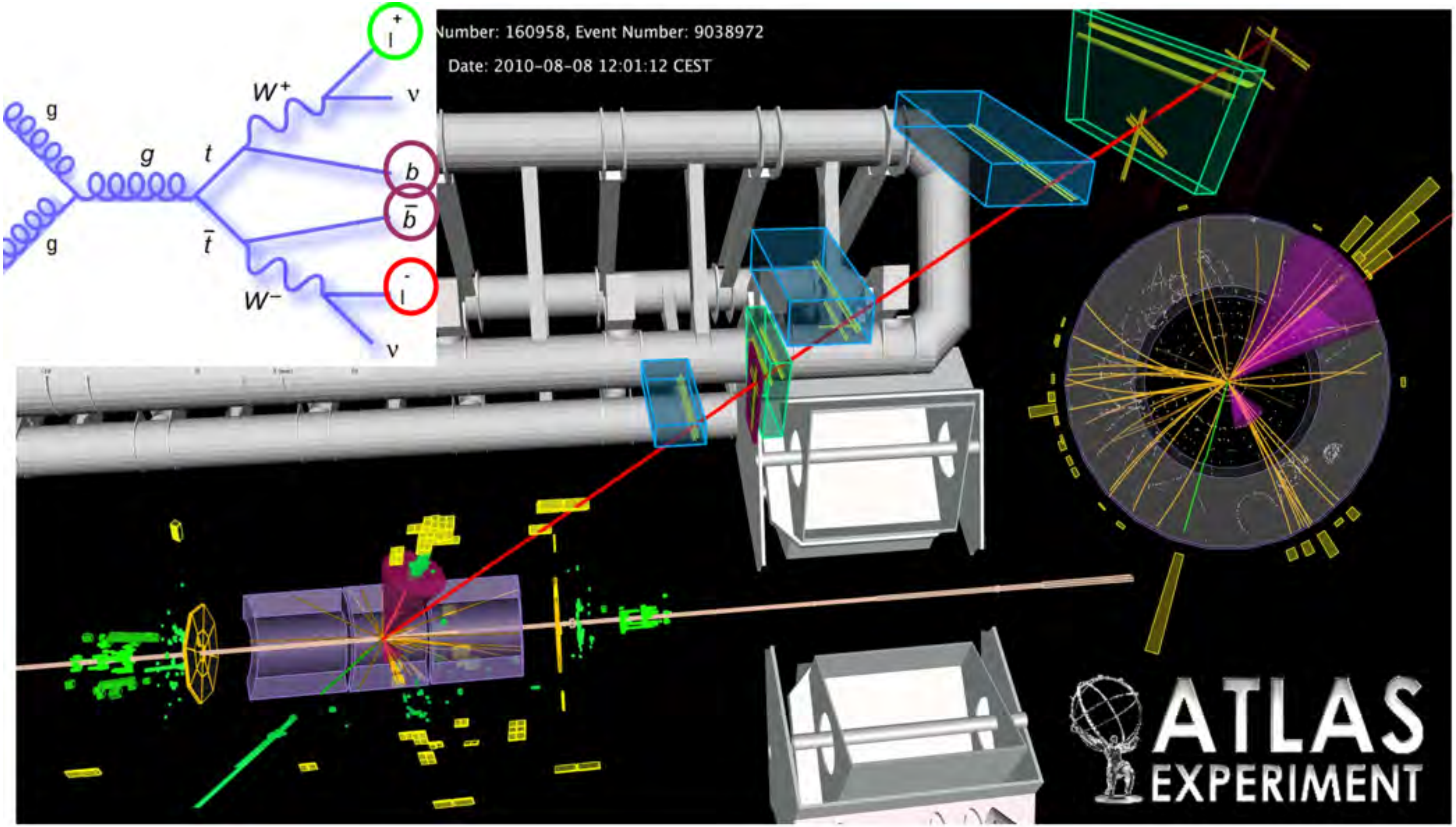


- high p_T leptons, missing E_T
- jets
- b-jets

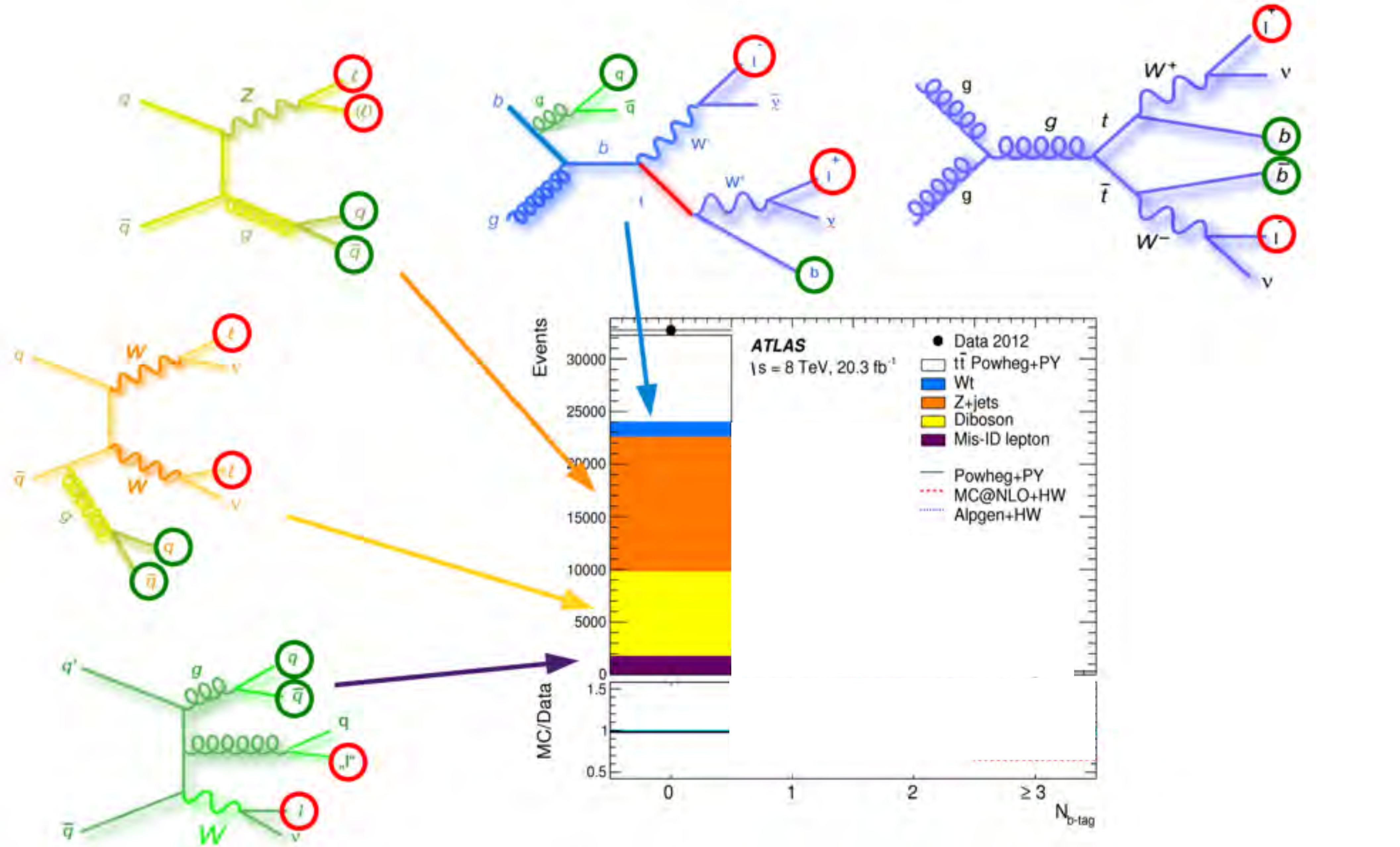
dilepton (e/μ) 6%

e/μ+jets 34%

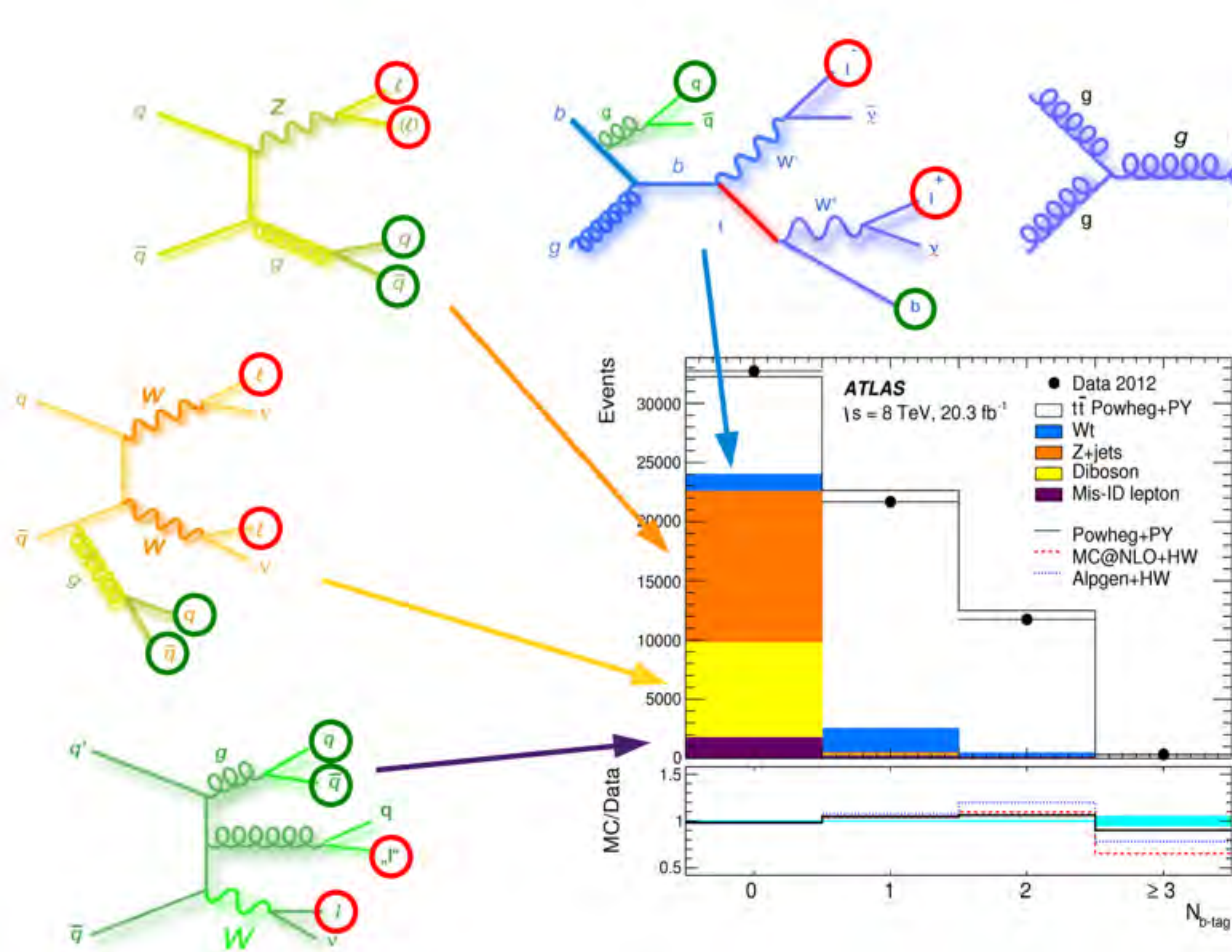
Dilepton Event

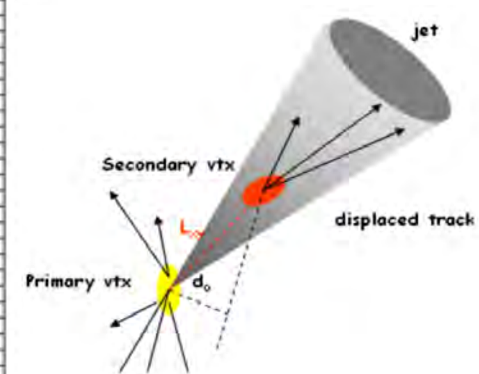


Dilepton Signatures



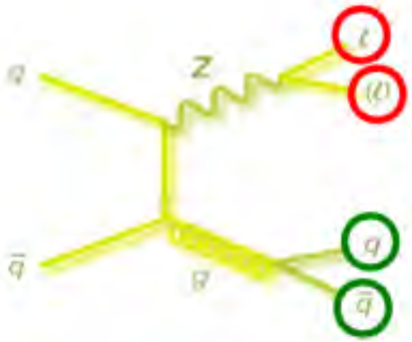
Dilepton Signatures

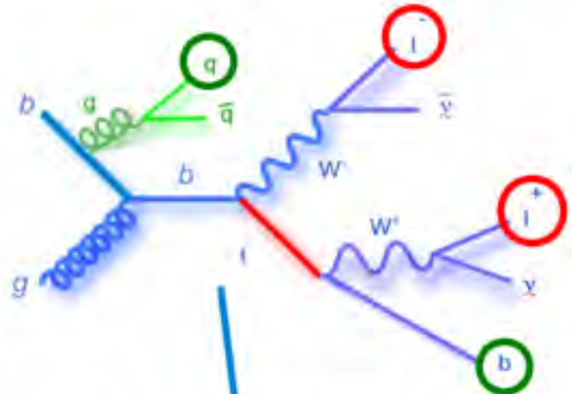


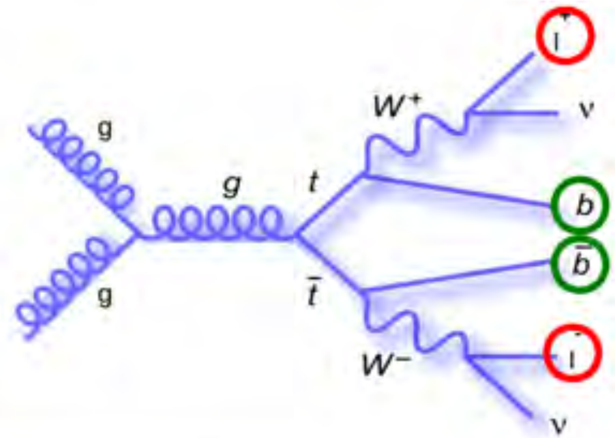


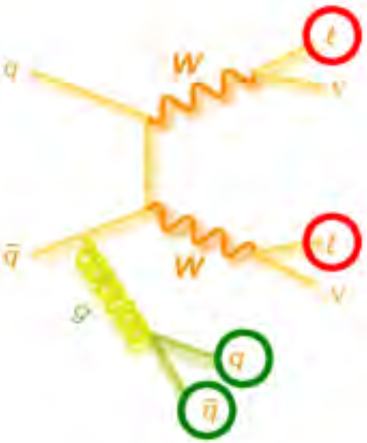
very powerful!

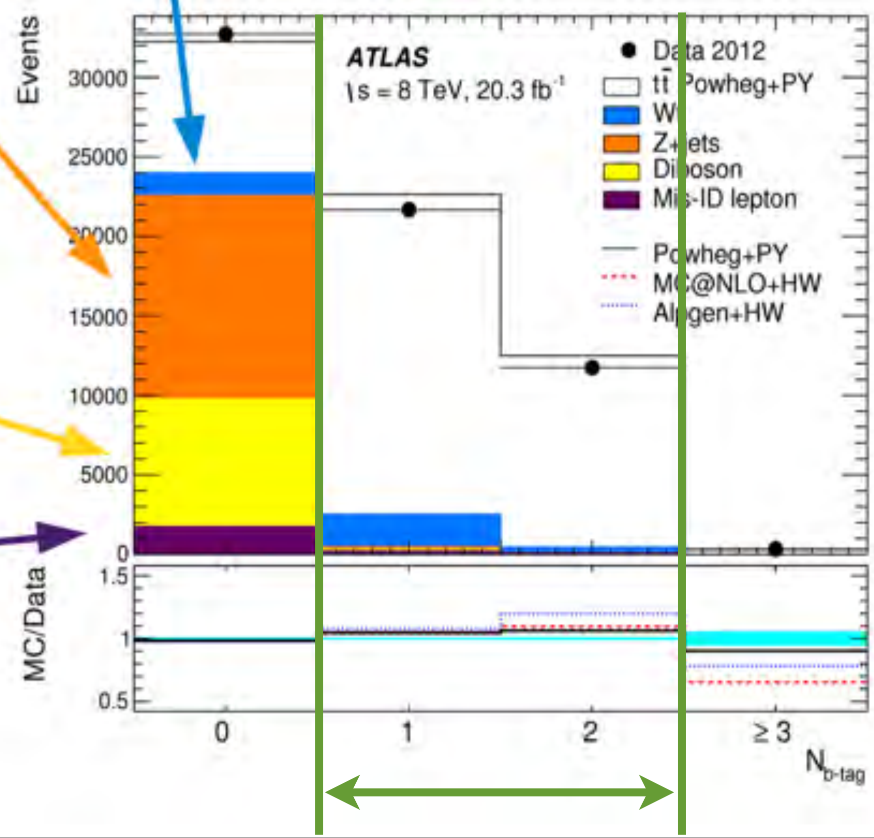
Dilepton Signatures with b-tagging

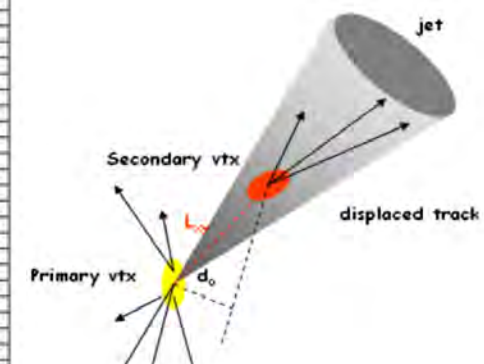












very powerful!

Dilepton cross section

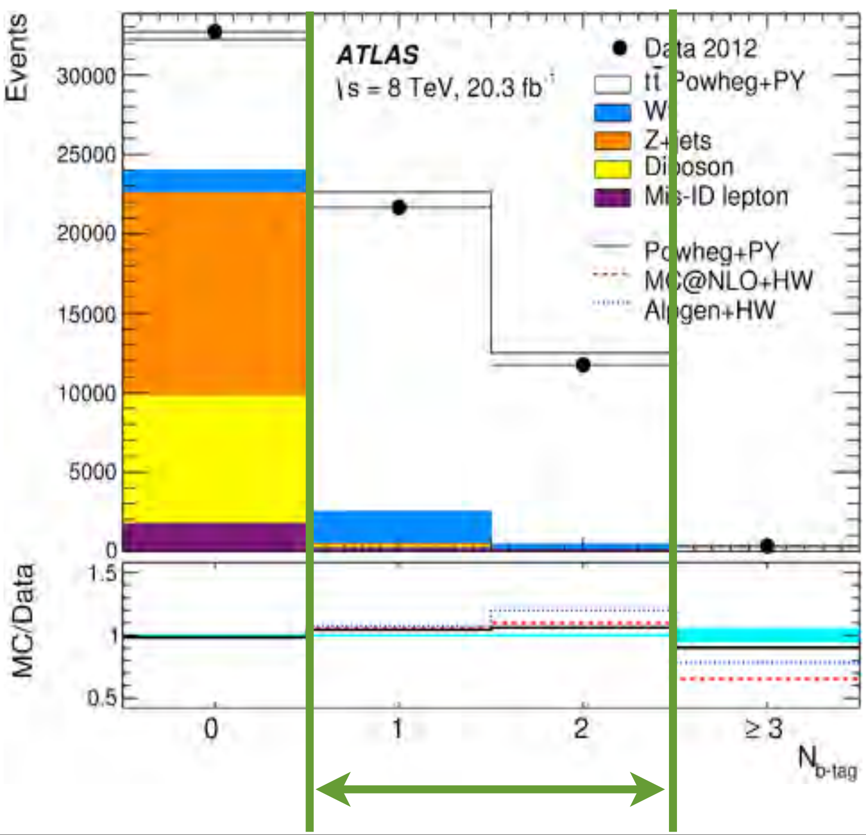
$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\mathrm{pb}\;(\sqrt{s} = 7\,\mathrm{TeV})$$ ±3.9%

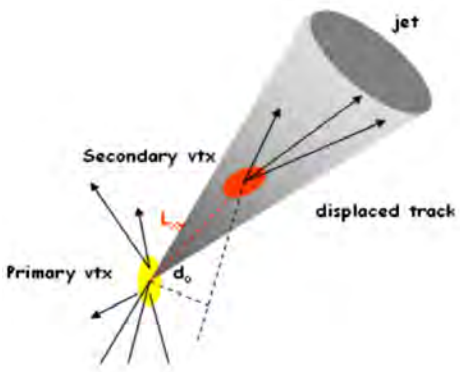
$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\mathrm{pb}\;(\sqrt{s} = 8\,\mathrm{TeV})$$ ±4.3%

(stat) (syst) (lumi) (beam)

Eur. Phys. J. C74 3109 (2014)

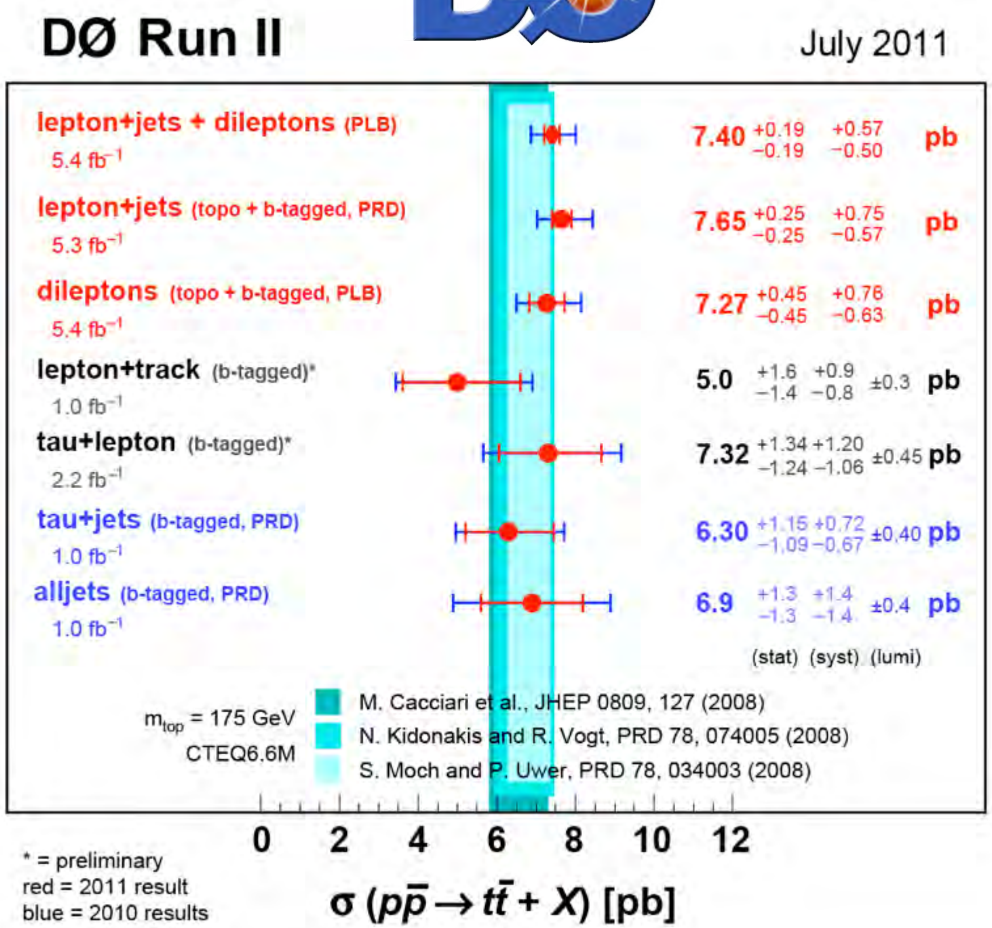
basically background free: just counting…

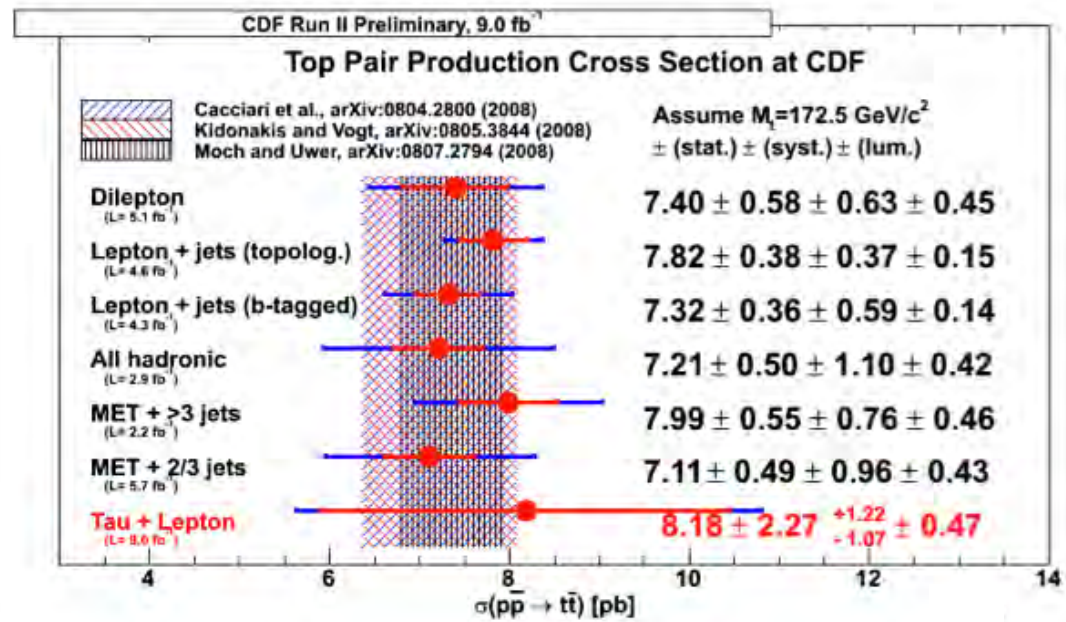




very powerful!

Top Pair Production Cross Section

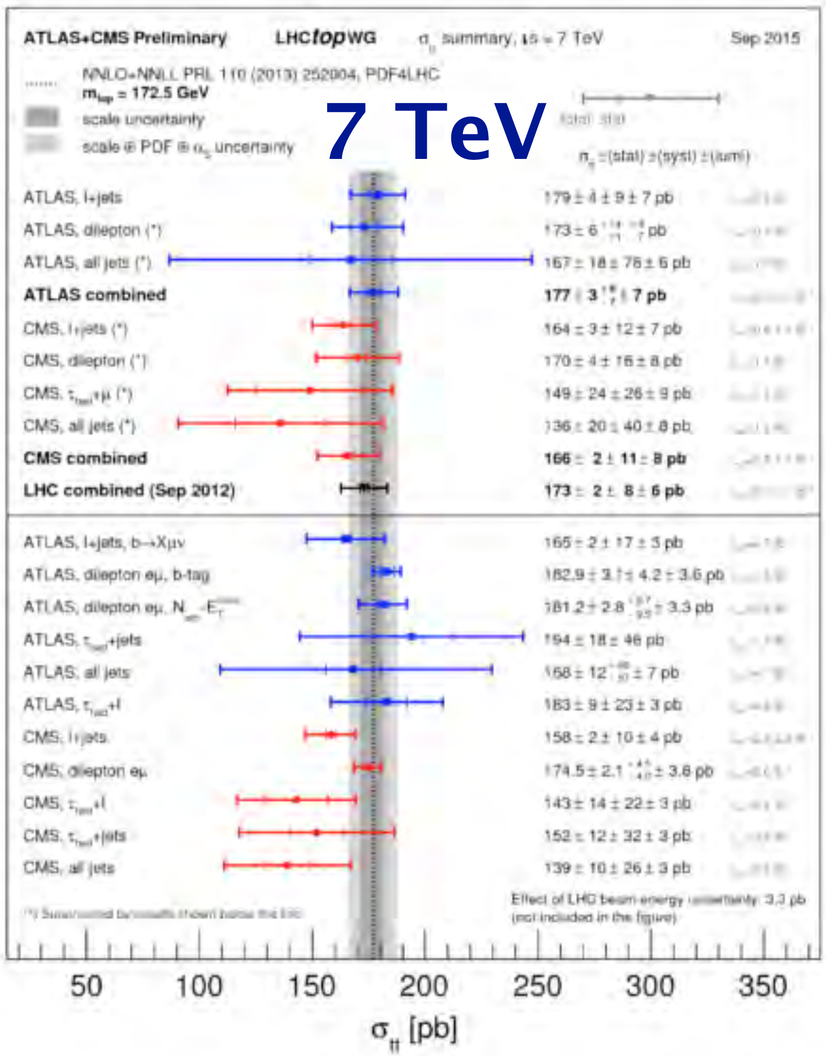


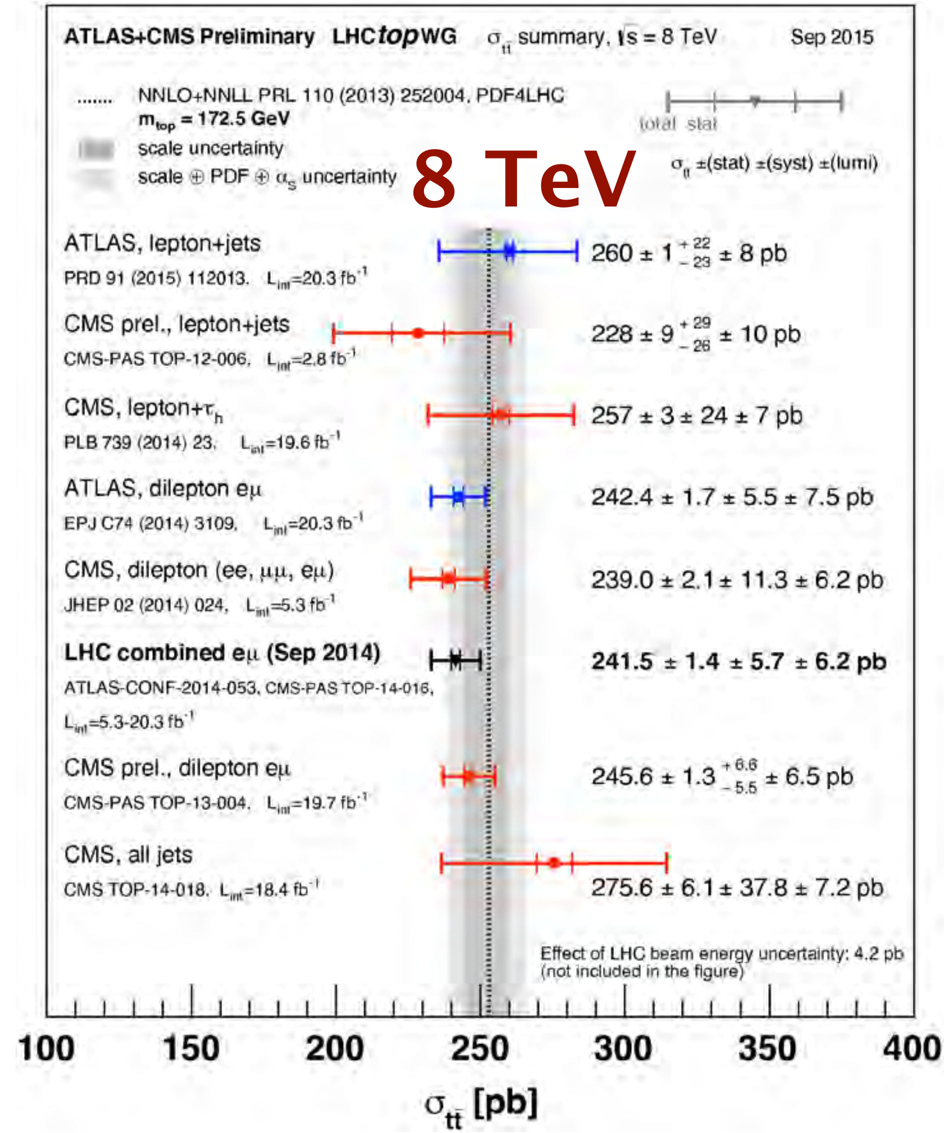


all channels measured except for $\tau_{had}\ \tau_{had}$

→ **good agreement with each other**

Top pair production cross section

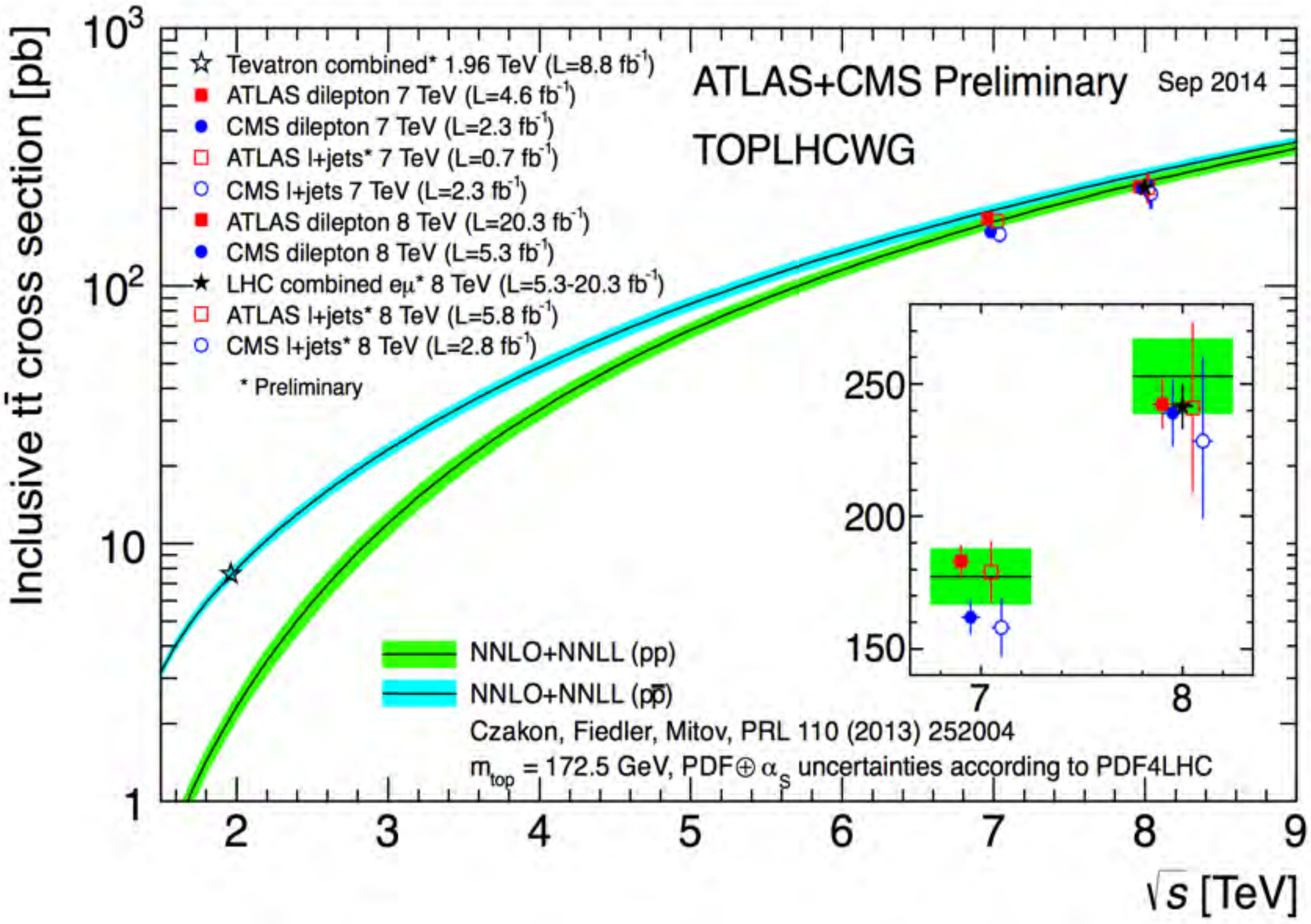




→ (all) channels measured to look for the unexpected

→ no new physics

Top pair production at hadron colliders



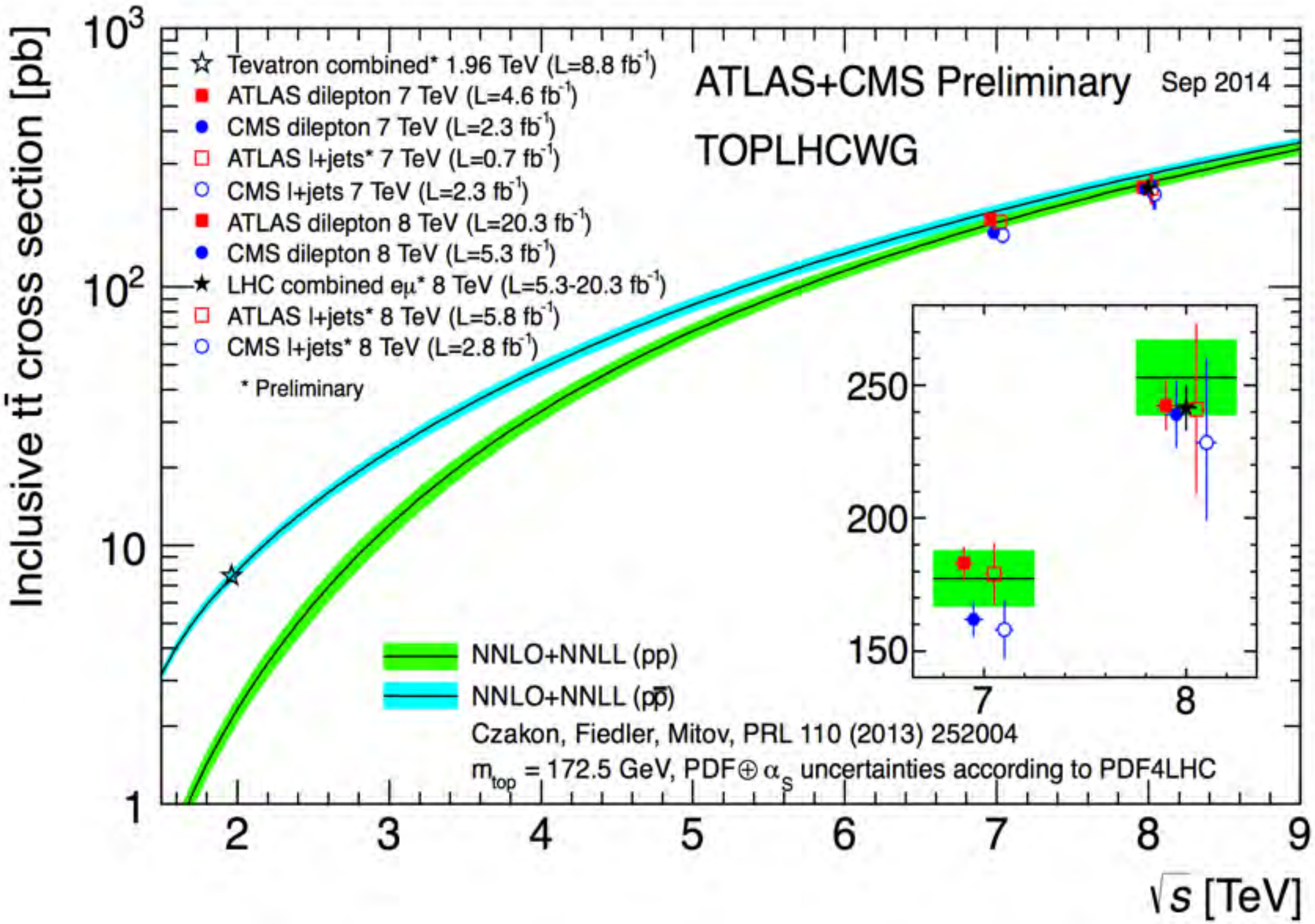
±5.7% (theo)

±3.9% (eμ)

→ experiments challenge theory again

Top pair production at hadron colliders

eager to put
a point here



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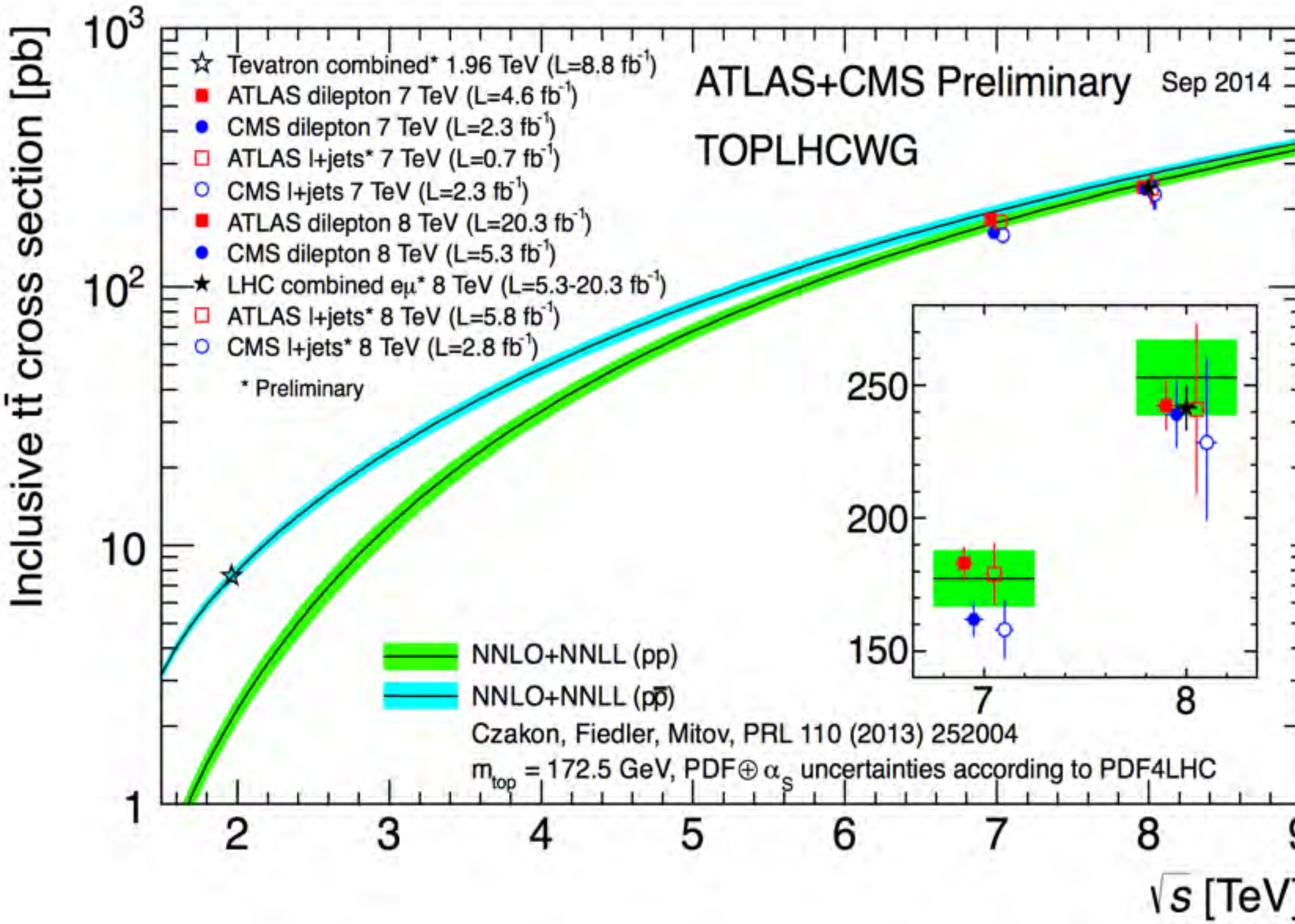
Top pair production at hadron colliders



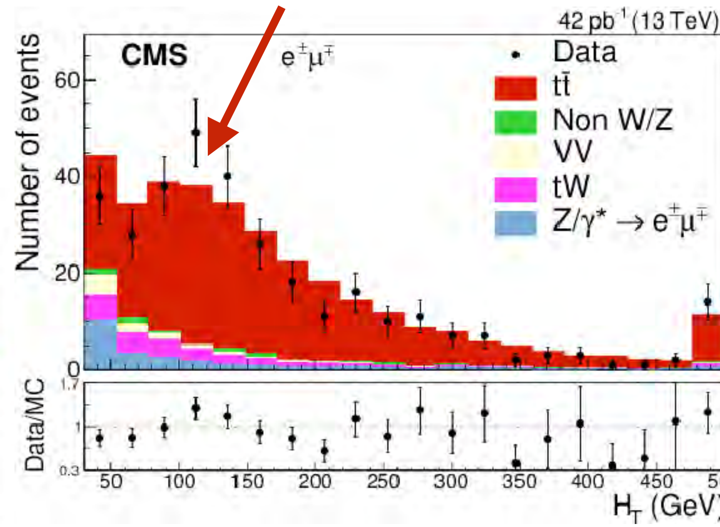
boldly go where no man has gone before

→ experiments challenge theory again

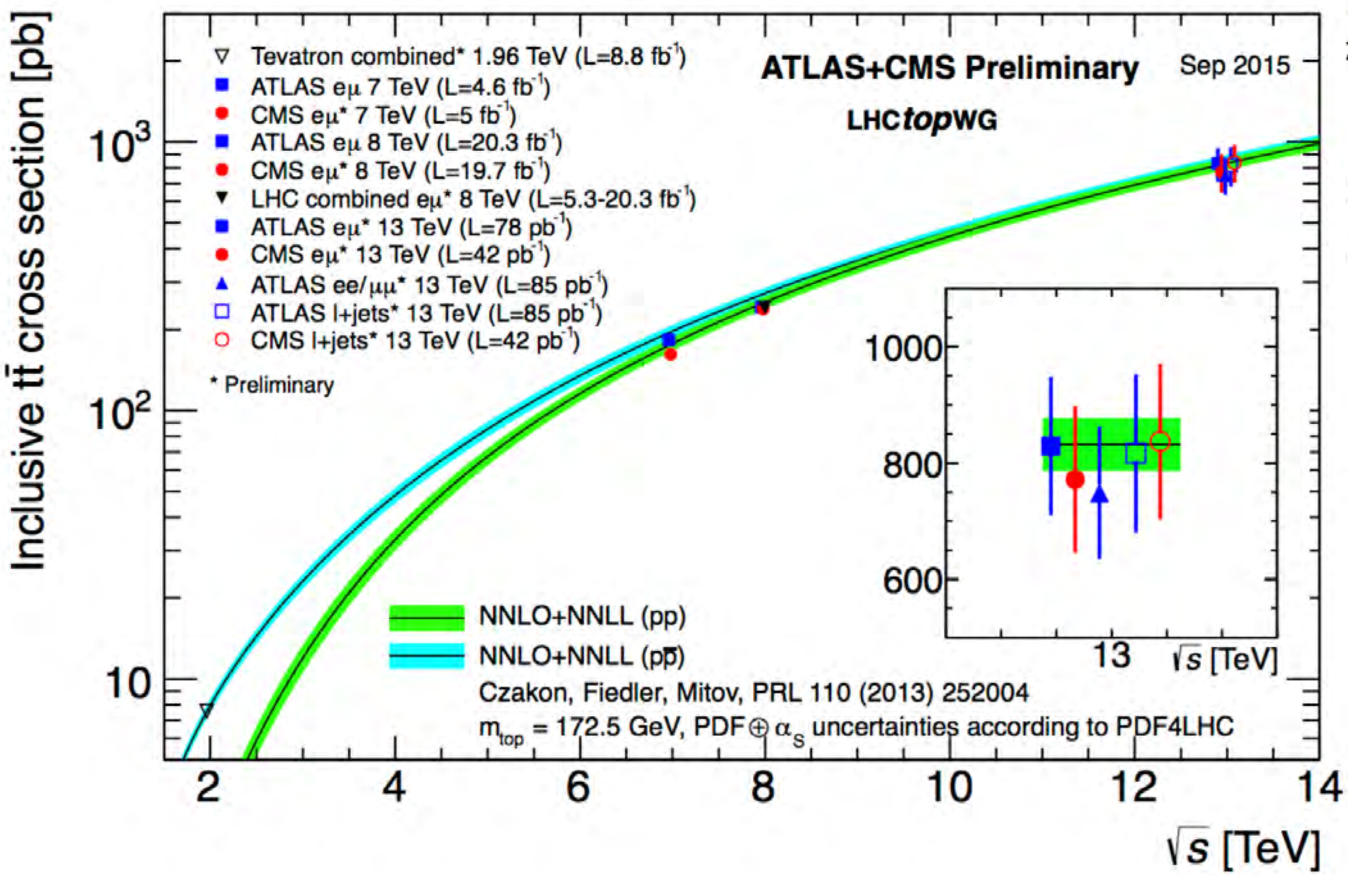
Top pair production at 13 TeV

first look at the new world energy frontier

"top quark peak"



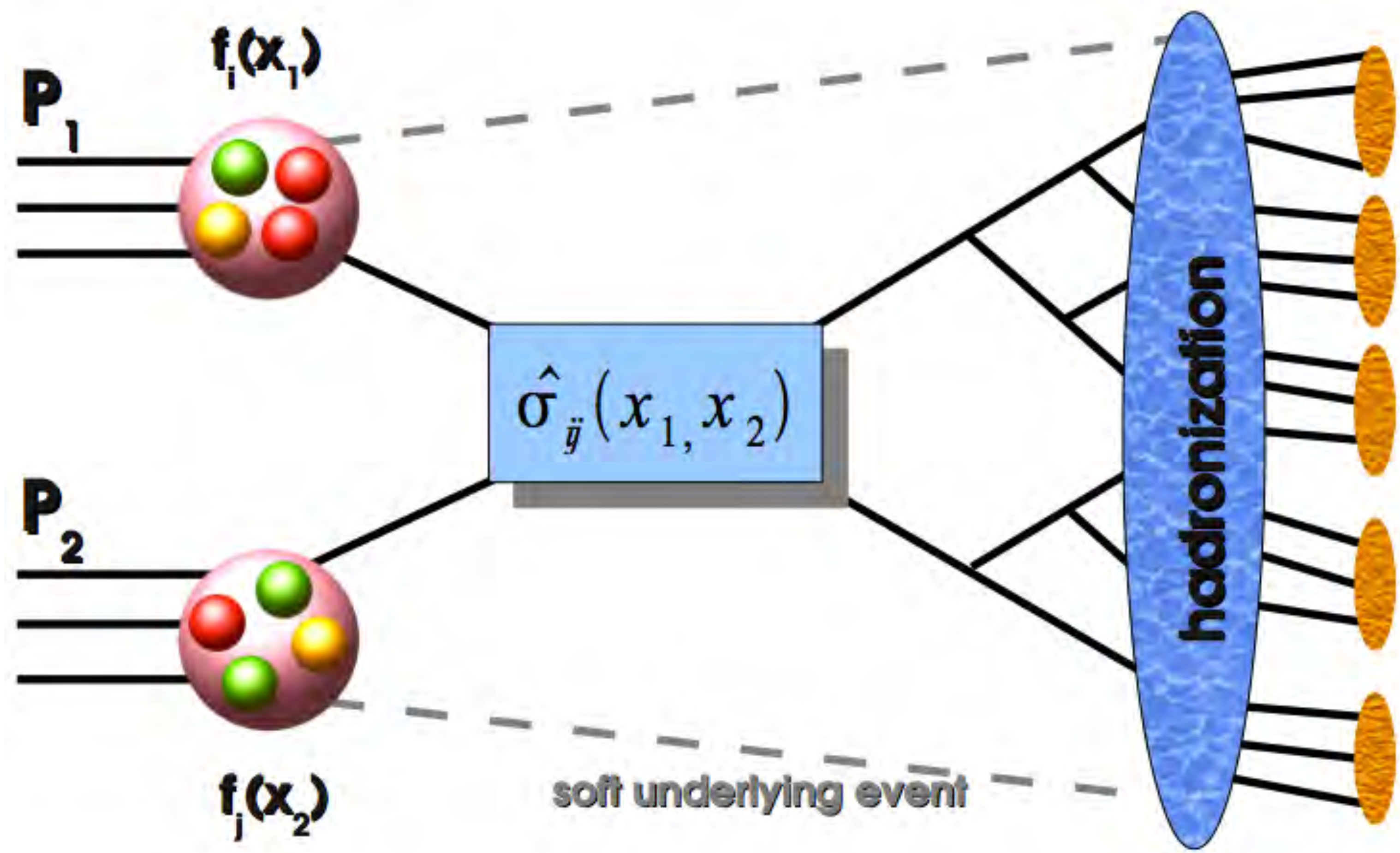
sum of scalar p_T of all jets



→ agreement with SM prediction

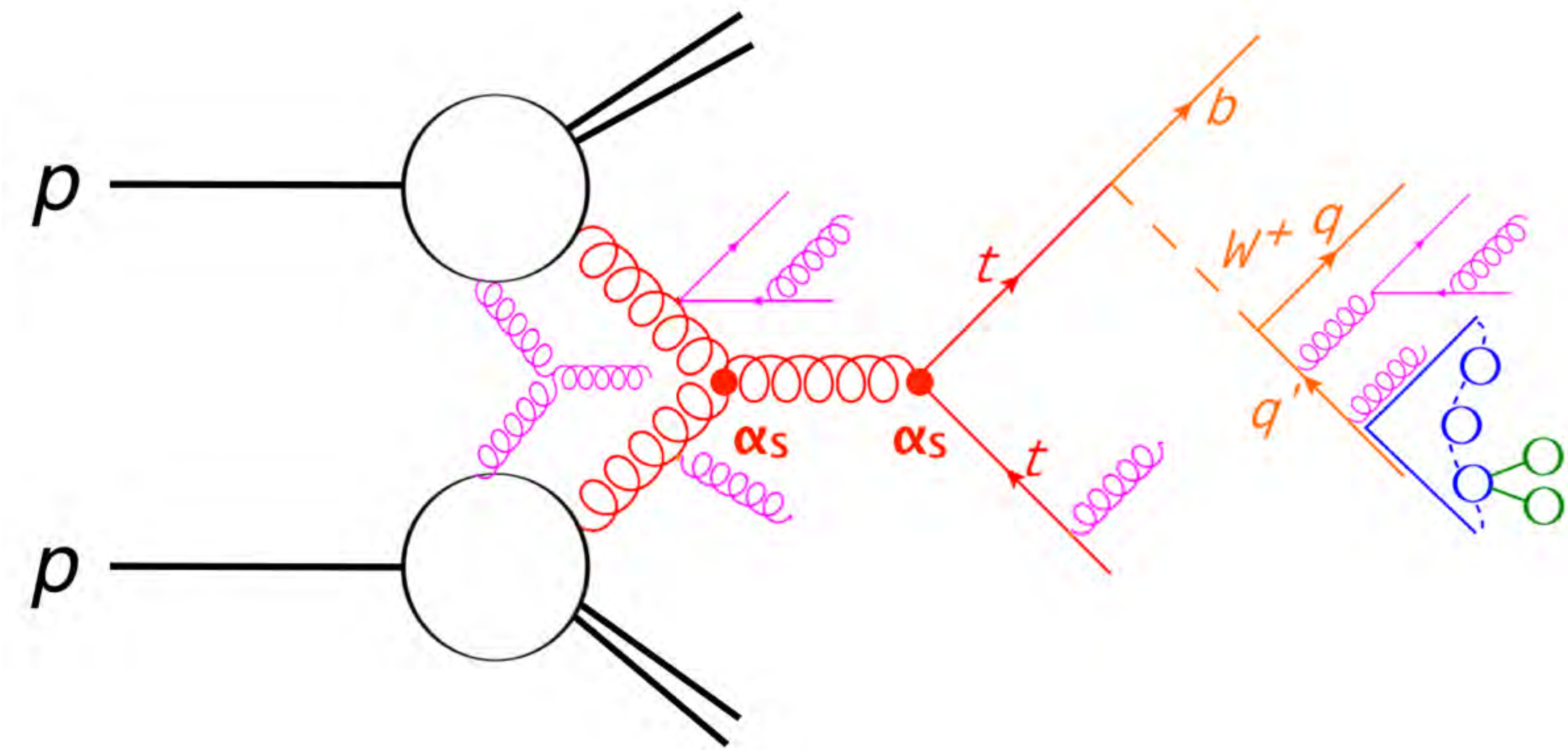
Differential Cross Sections

important tests of higher order QCD calculations:
requires "unfolding" to particle level



“Revolution” in Phenomenology

- **LO QCD+parton shower generators**
  Pythia, Herwig, ...



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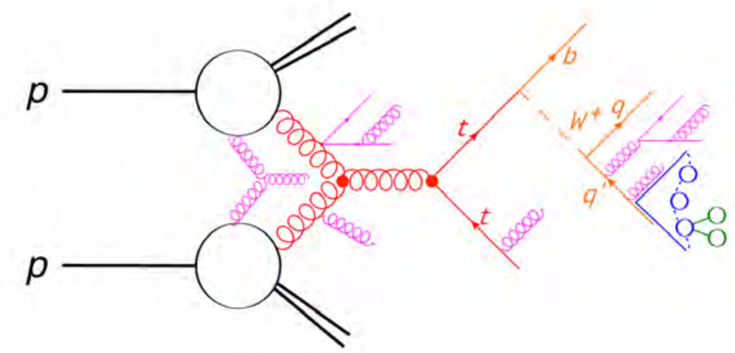
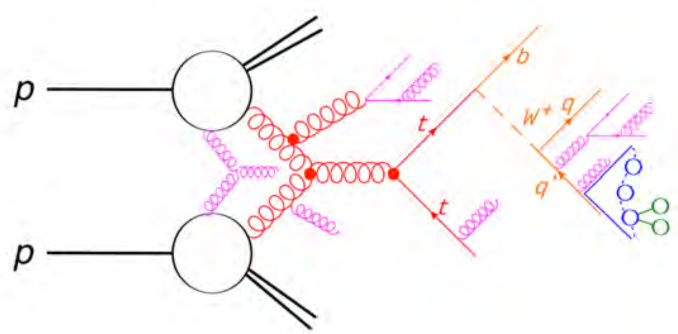
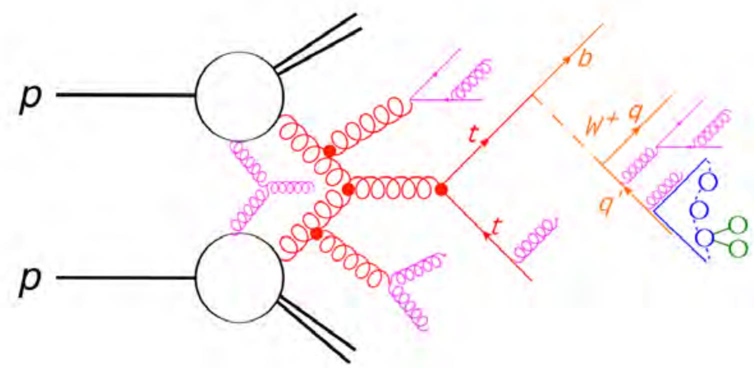
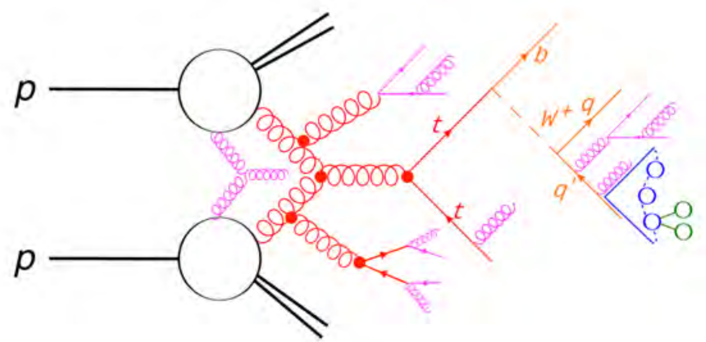


- **LO multileg generators matched with parton shower**
  Alpgen+Pythia, Alpgen+Herwig, ...







...

“Revolution” in Phenomenology

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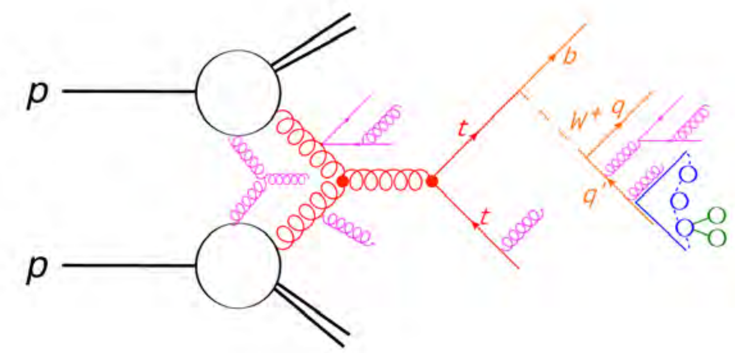

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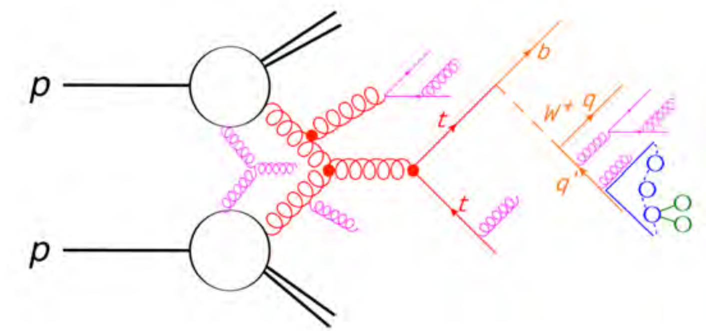
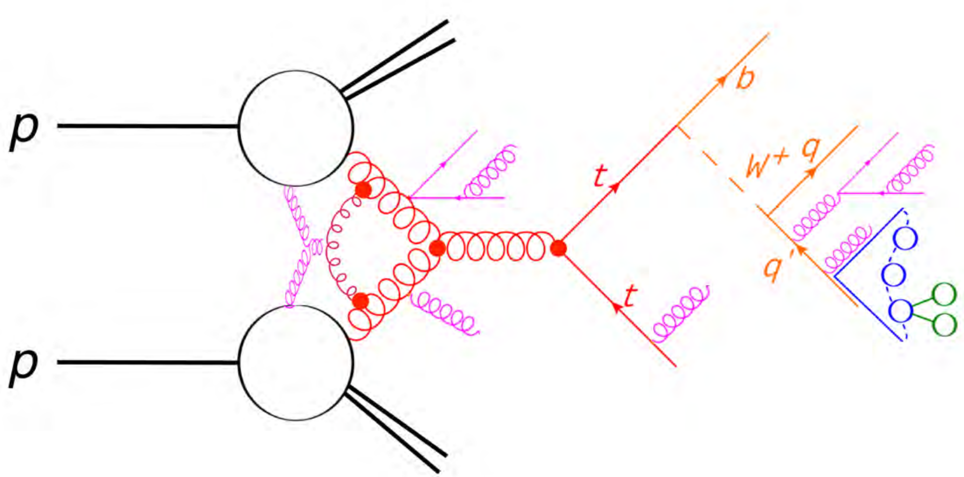


- **NLO+parton shower generators**
  Powheg+Pythia, MC@NLO+Herwig, ...



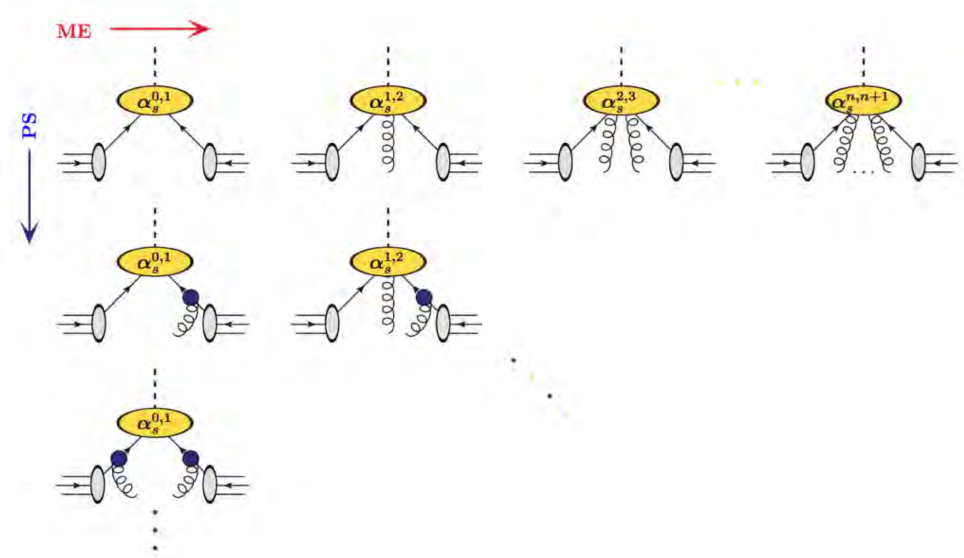
"Revolution" in Phenomenology

- **LO QCD+parton shower generators**
  Pythia, Herwig, ...

- **LO multileg generators matched with parton shower**
  Alpgen+Pythia, Alpgen+Herwig, ...

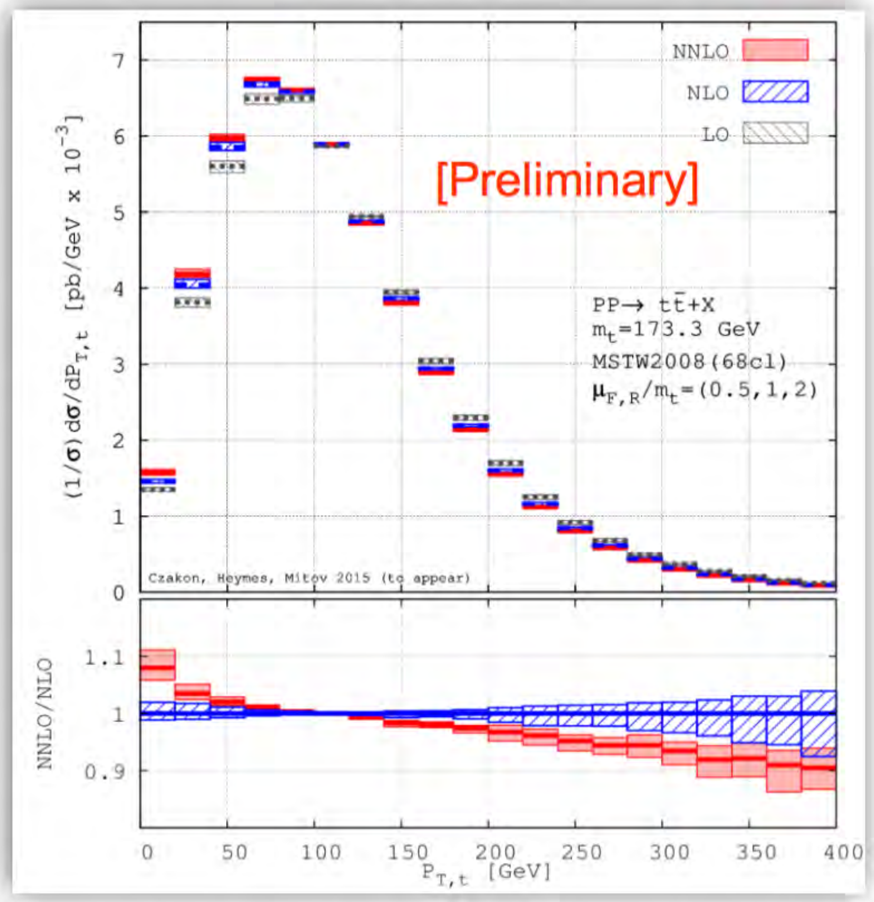
- **NLO+parton shower generators**
  Powheg+Pythia, MC@NLO+Herwig, ...

- **NLO+LO multileg generators matched with parton showers**

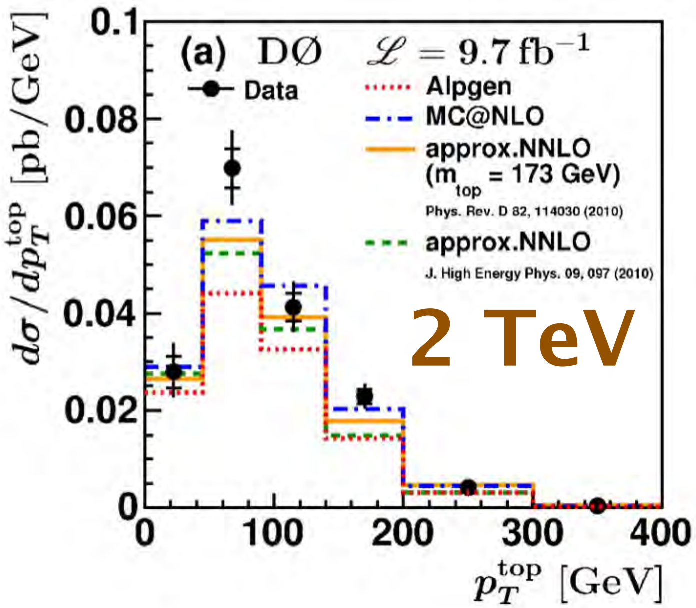


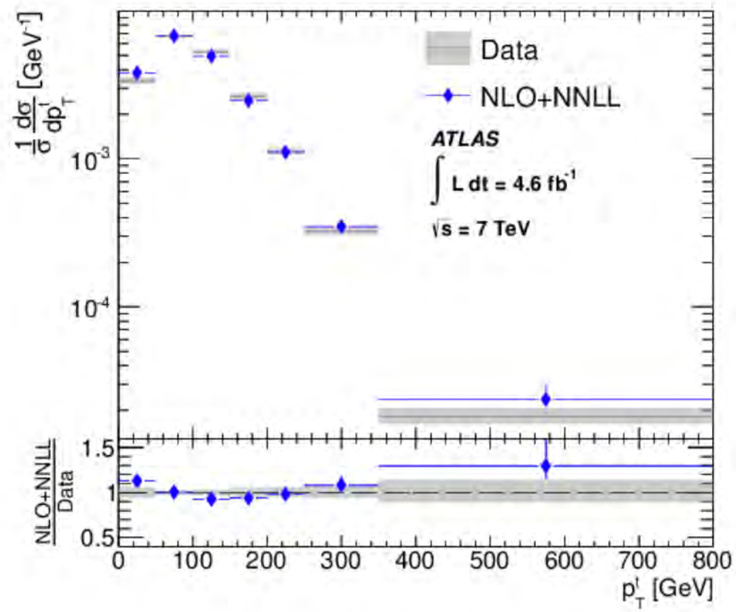
“Revolution” in Phenomenology

- LO QCD+parton shower generators
  Pythia, Herwig, ...
- LO multileg generators matched with parton shower
  Alpgen+Pythia, Alpgen+Herwig, ...
- NLO+parton shower generators
  Powheg+Pythia, MC@NLO+Herwig, ...
- NLO+LO multileg generators matched with parton showers
- NNLO QCD calculations

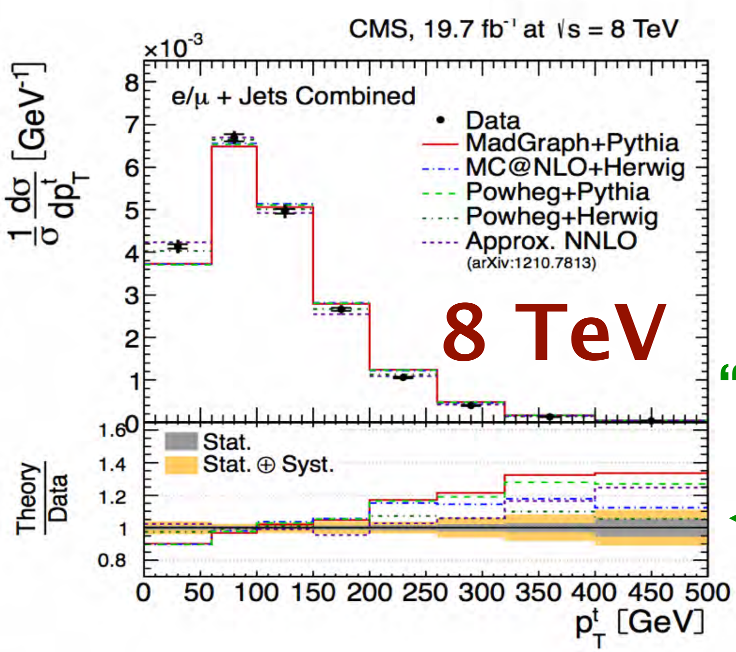


Differential, unfolded: top p_T



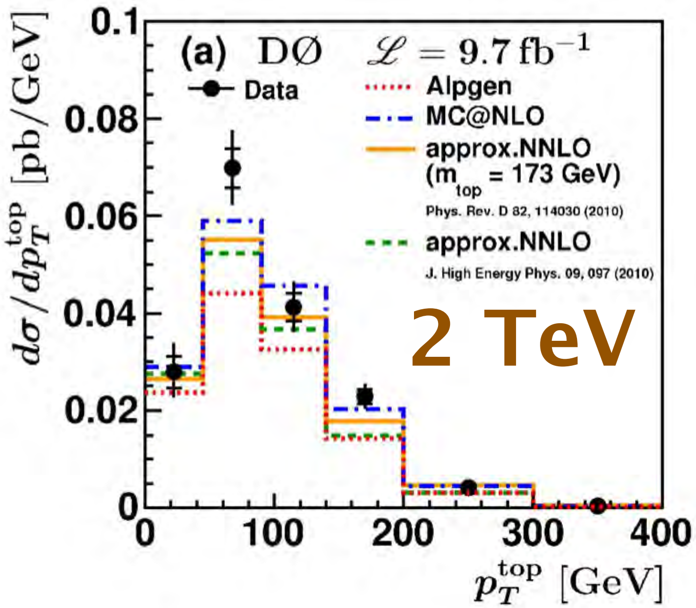


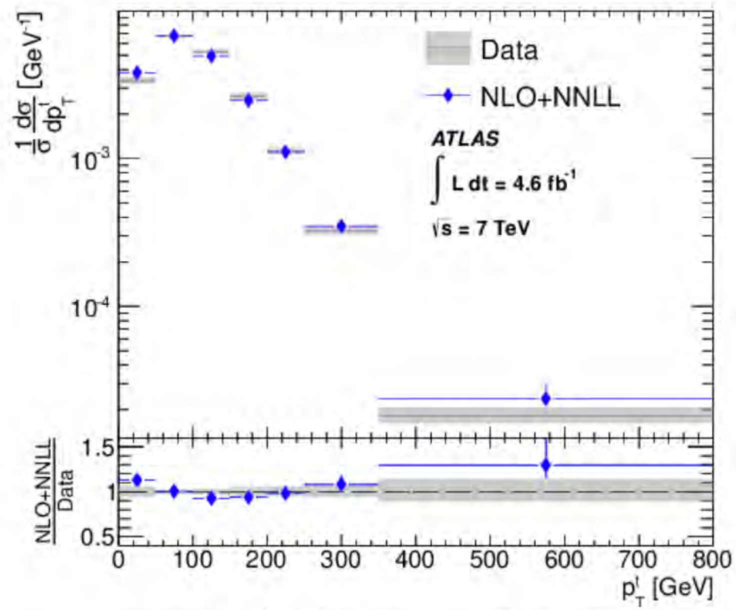
7 TeV



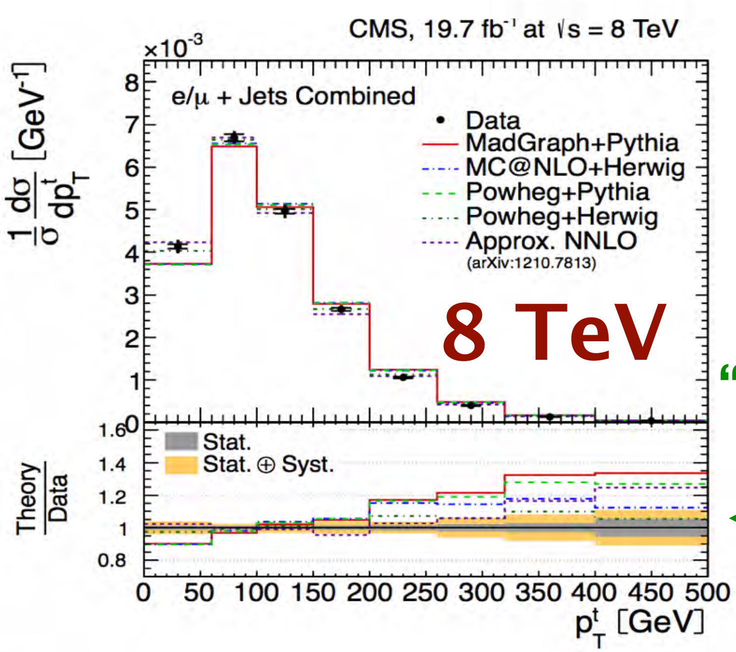
Herwig “reshuffling” helps

Differential, unfolded: top p_T

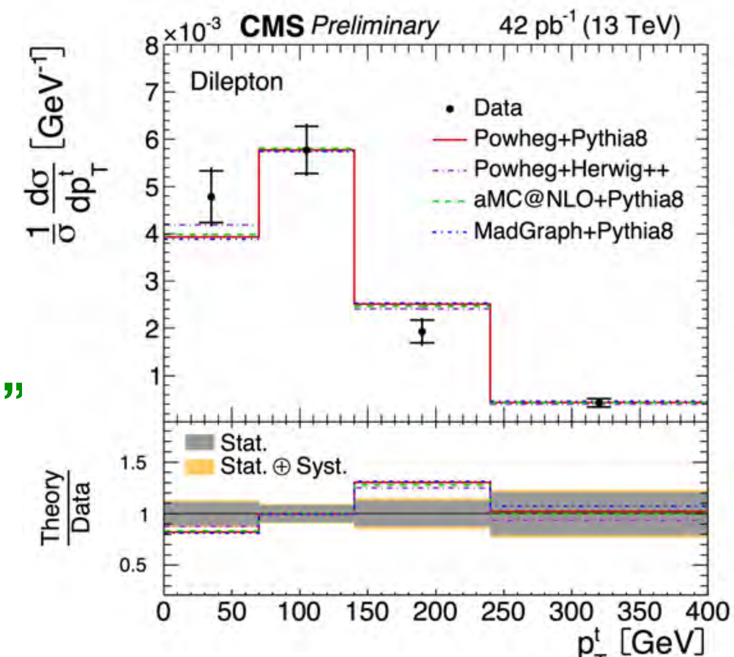




7 TeV



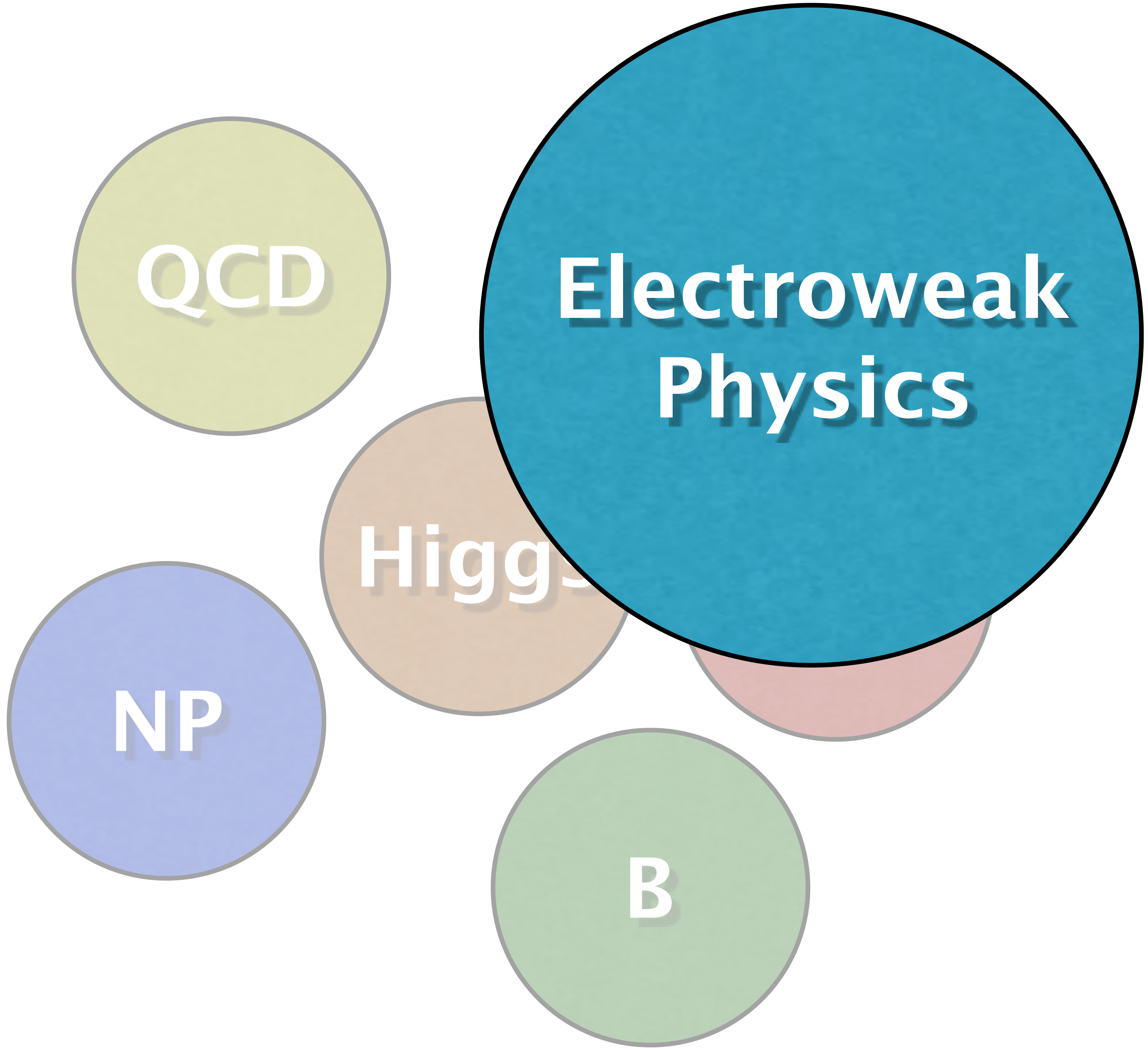
Herwig "reshuffling" helps



13 TeV

looks good…

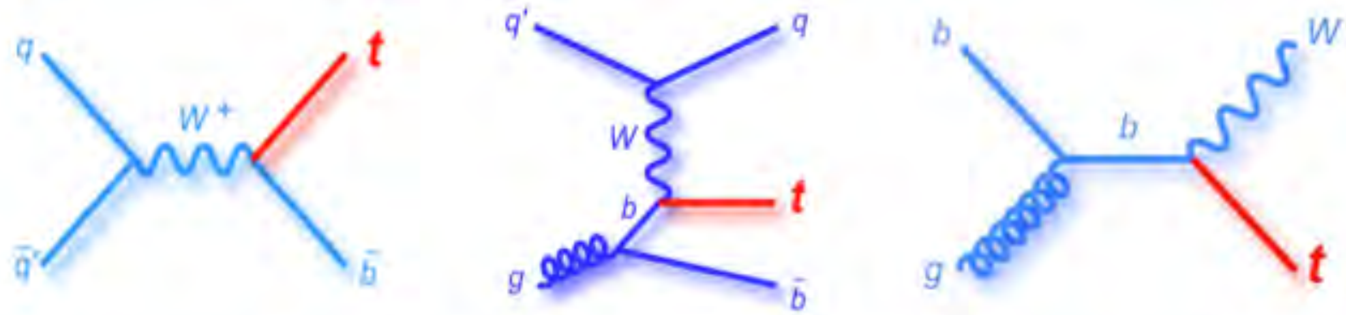
Top Quark Physics Topics

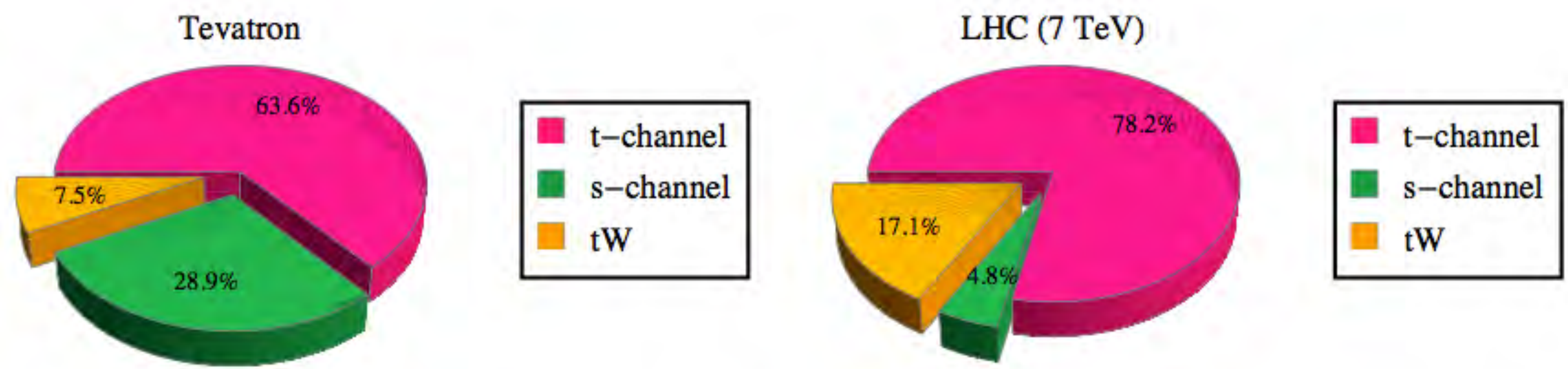


Single Top Quark Production

direct measurement of $|V_{tb}|$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$





⇒ **important to measure all channels separately to search for new physics**

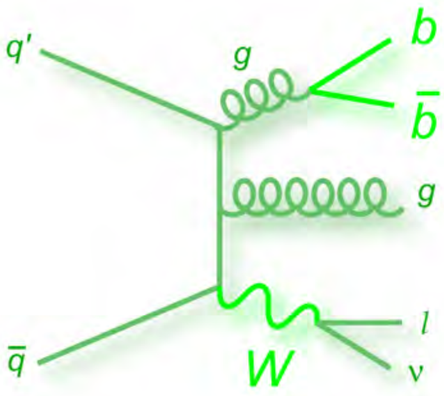
BUT: do not separate Wt in higher orders –an unphysical question!

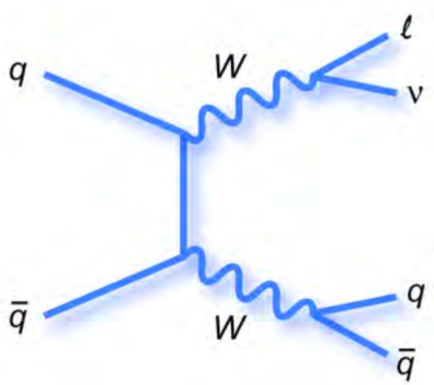
Single Top Quark Observation

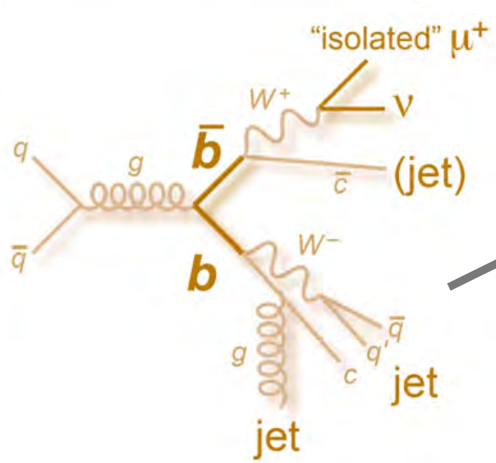
2009

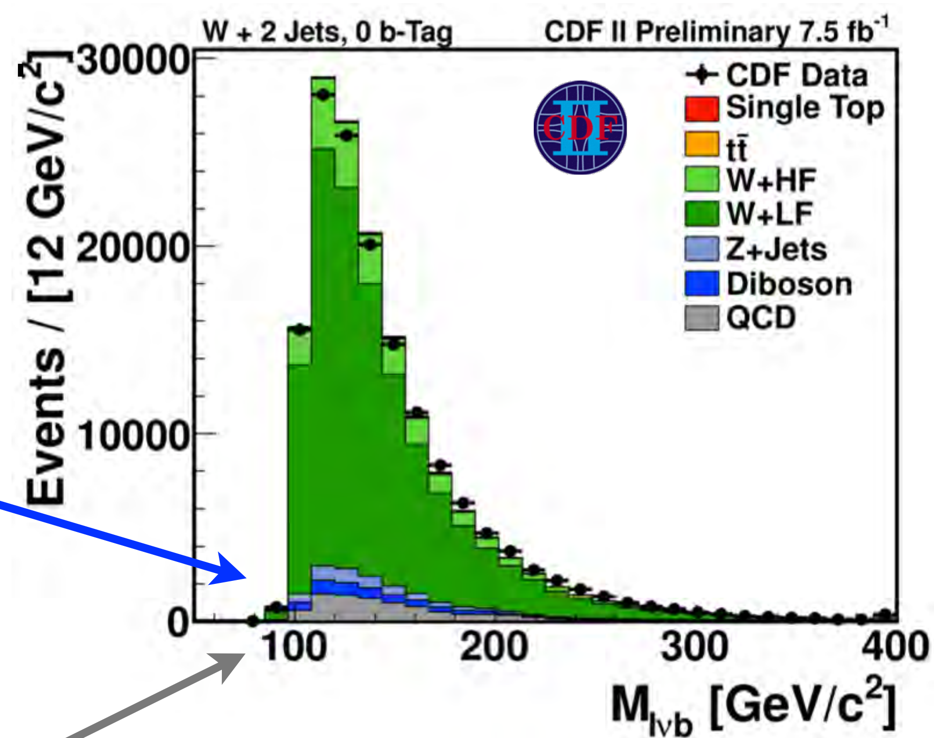
- **Multivariate analyses techniques are essential!**

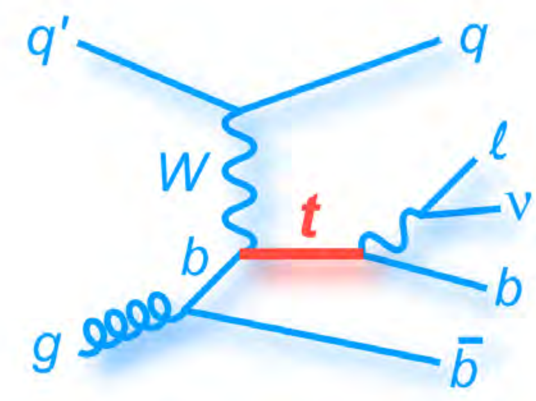
Single Top Quark Yields: pretag

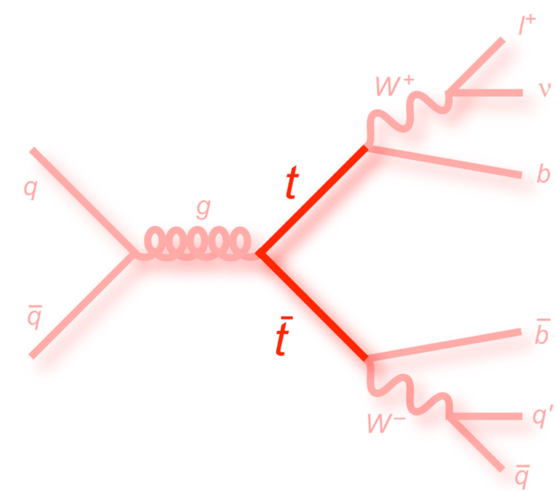






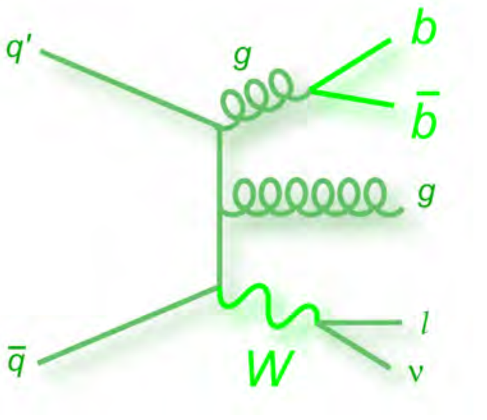


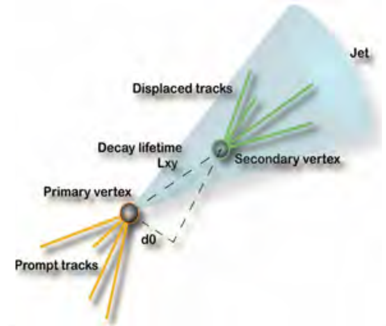


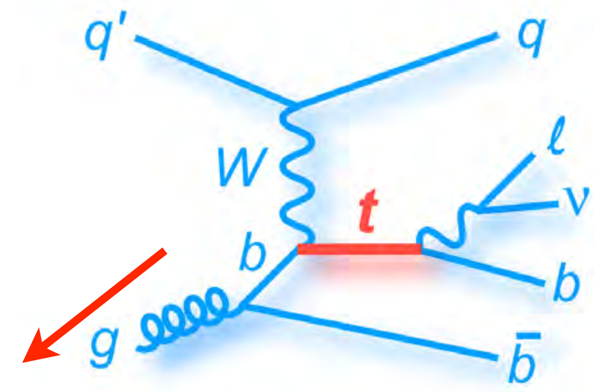


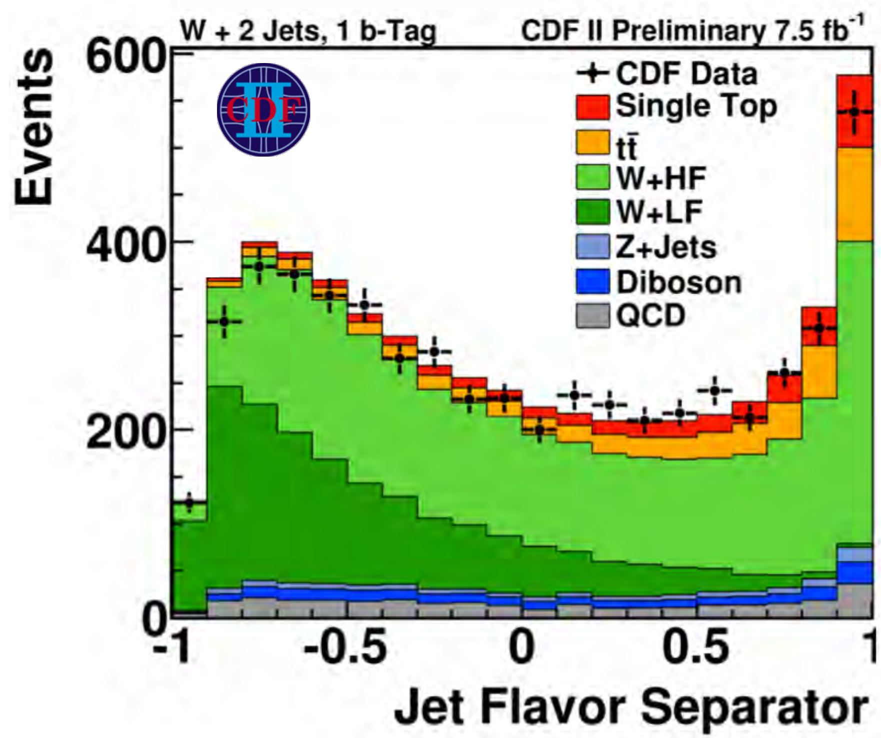
- **best s/b: ~1/200 before b-tagging**

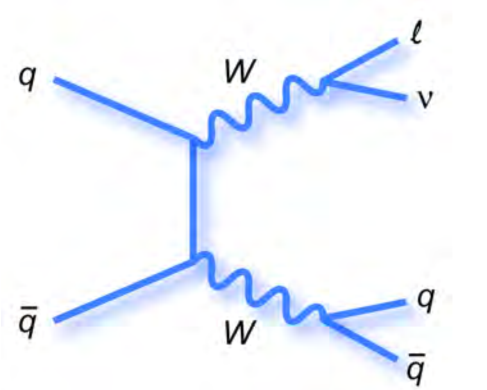
Single Top Quark Yields: b-tagged

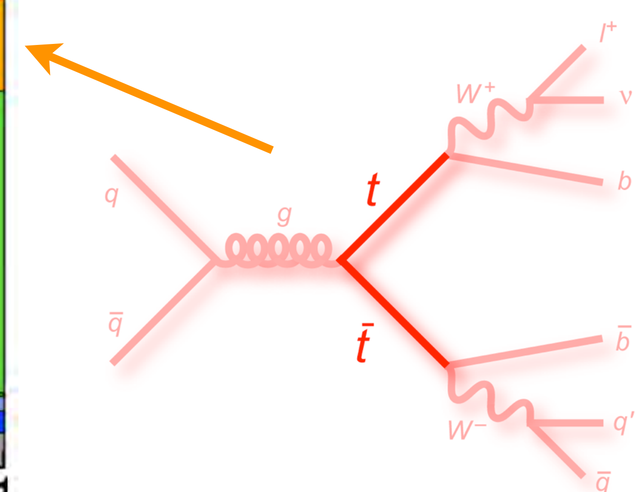


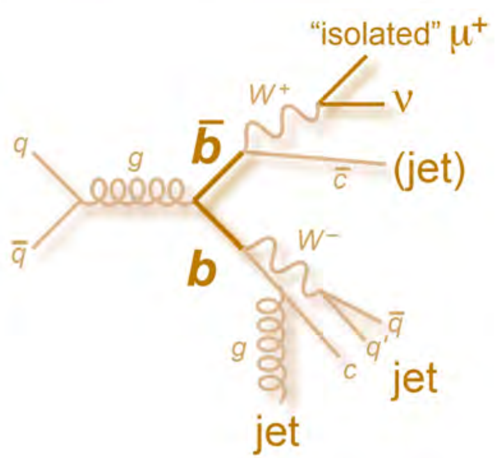






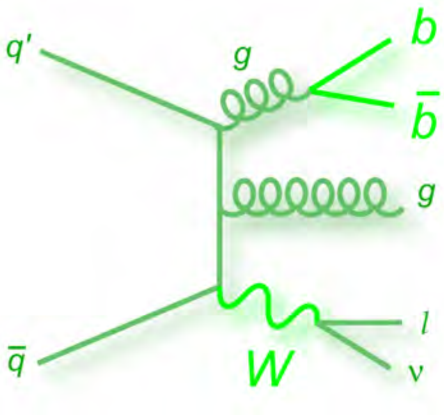




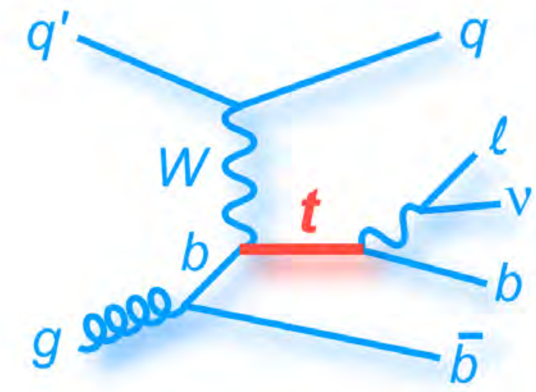


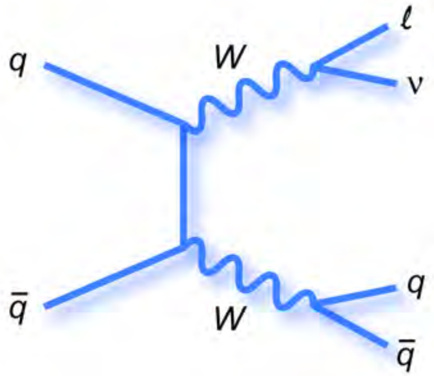
- best s/b: ~1/200 before b-tagging
- best s/b: ~1/10 after b-tagging

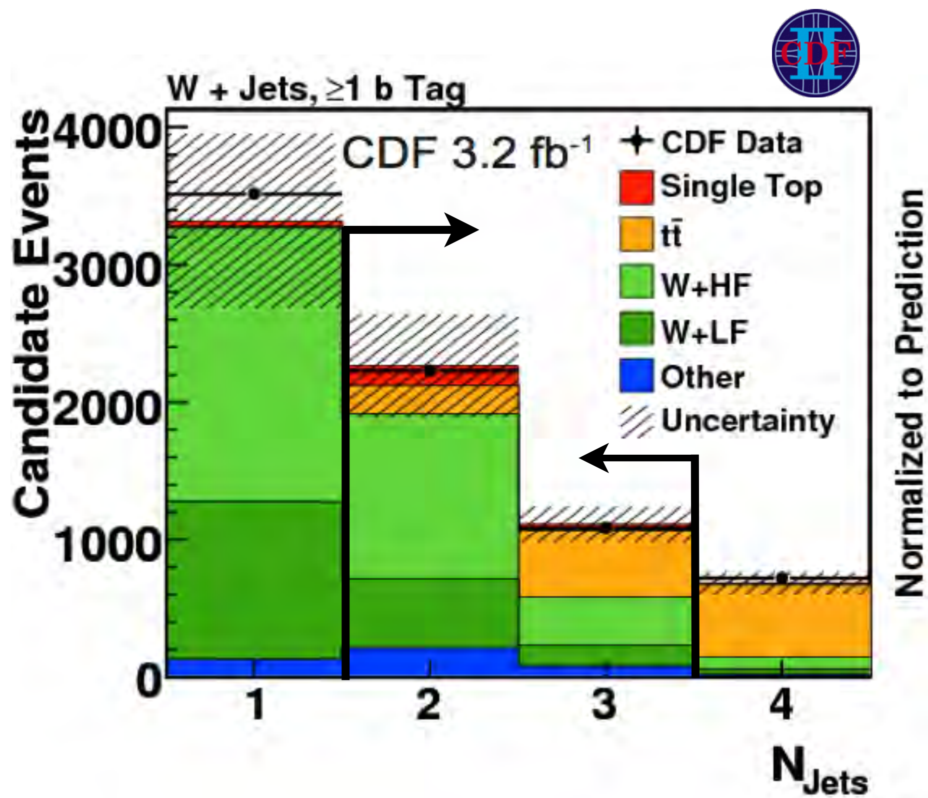
Single Top Quark Yields: b-

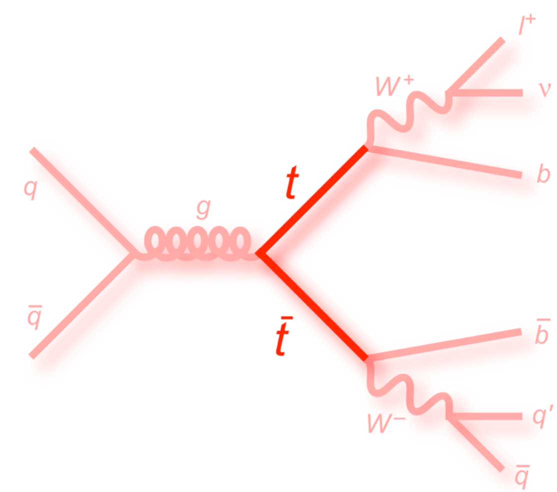


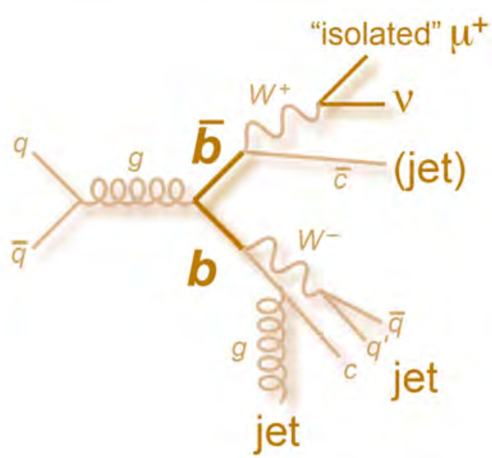
- number of jets and number of b tags to define samples







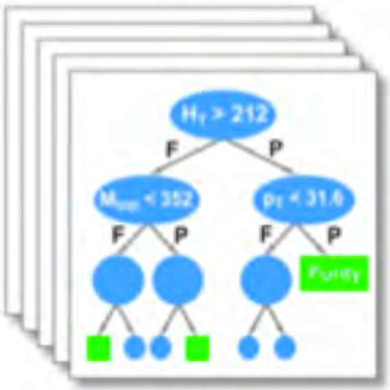




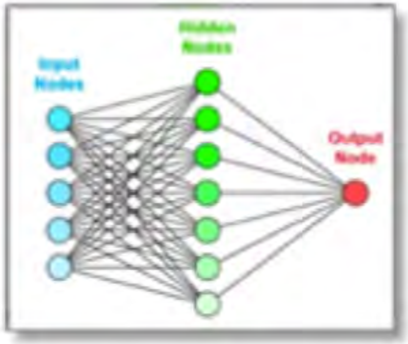
- best s/b: ~1/200 before b-tagging
- best s/b: ~1/10 after b-tagging

Multivariate Analyses

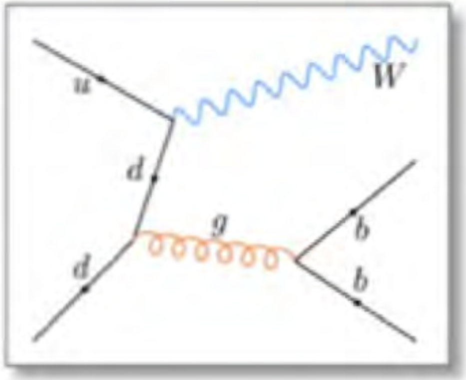
Boosted Decision Trees



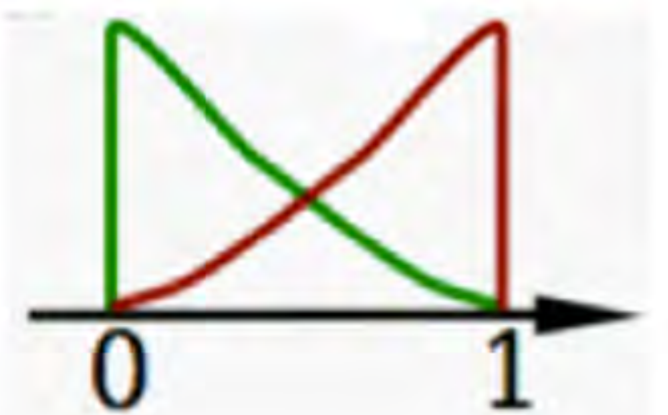
Neural Networks



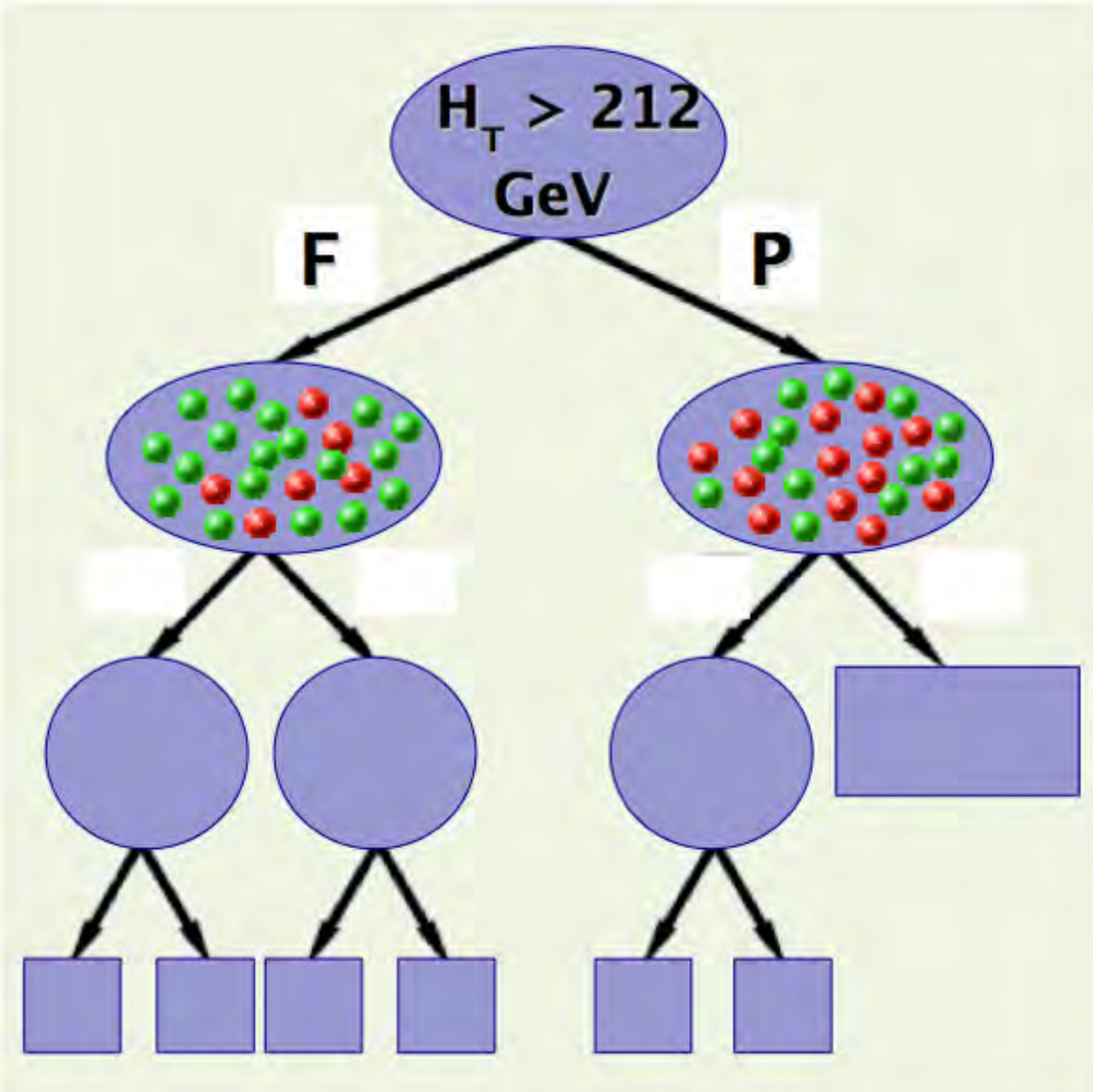
Matrix Elements



background **signal**

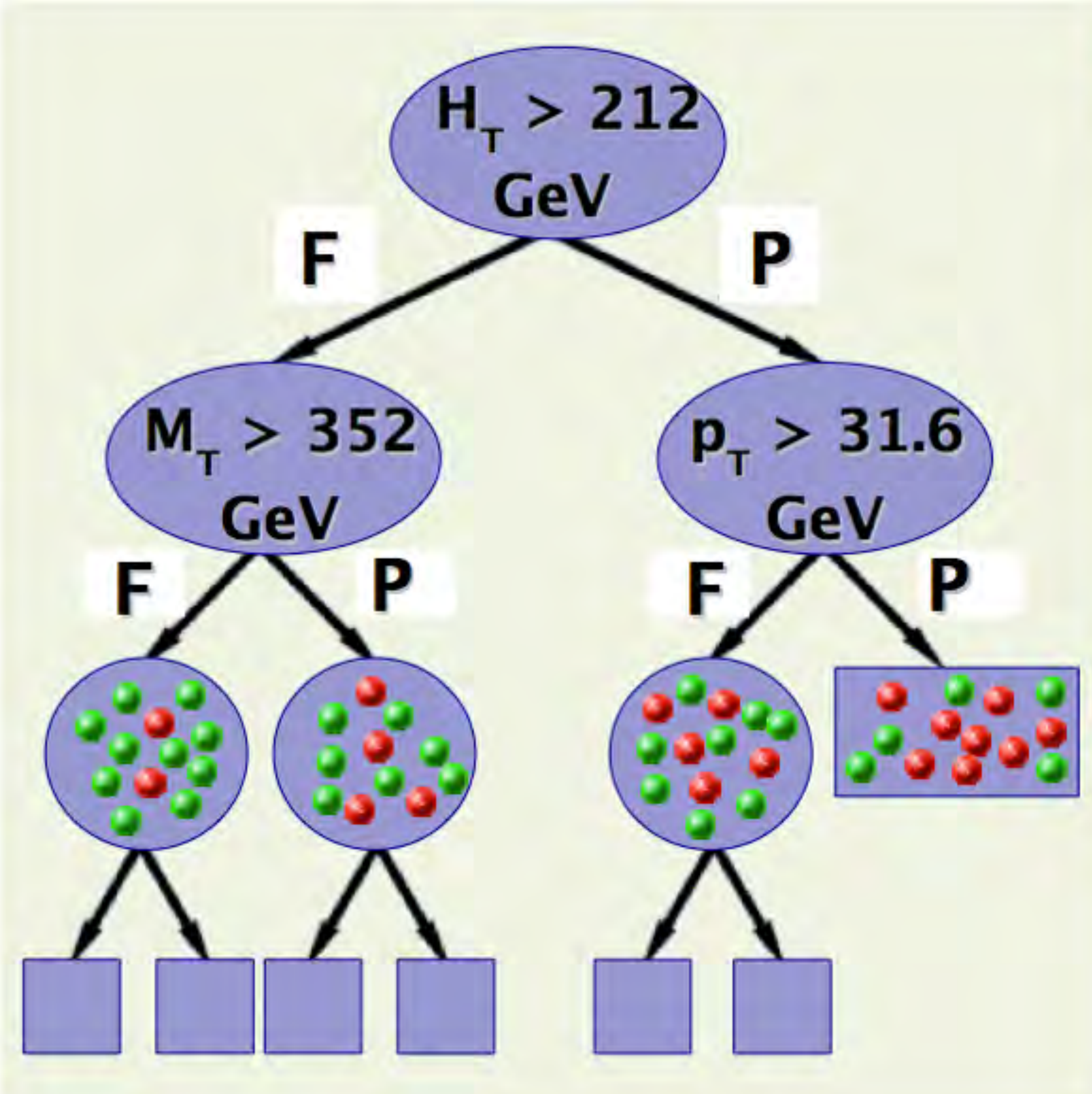


Boosted Decision Trees



- **IDEA: recover events that fail criteria in cut-based analyses**

Boosted Decision Trees



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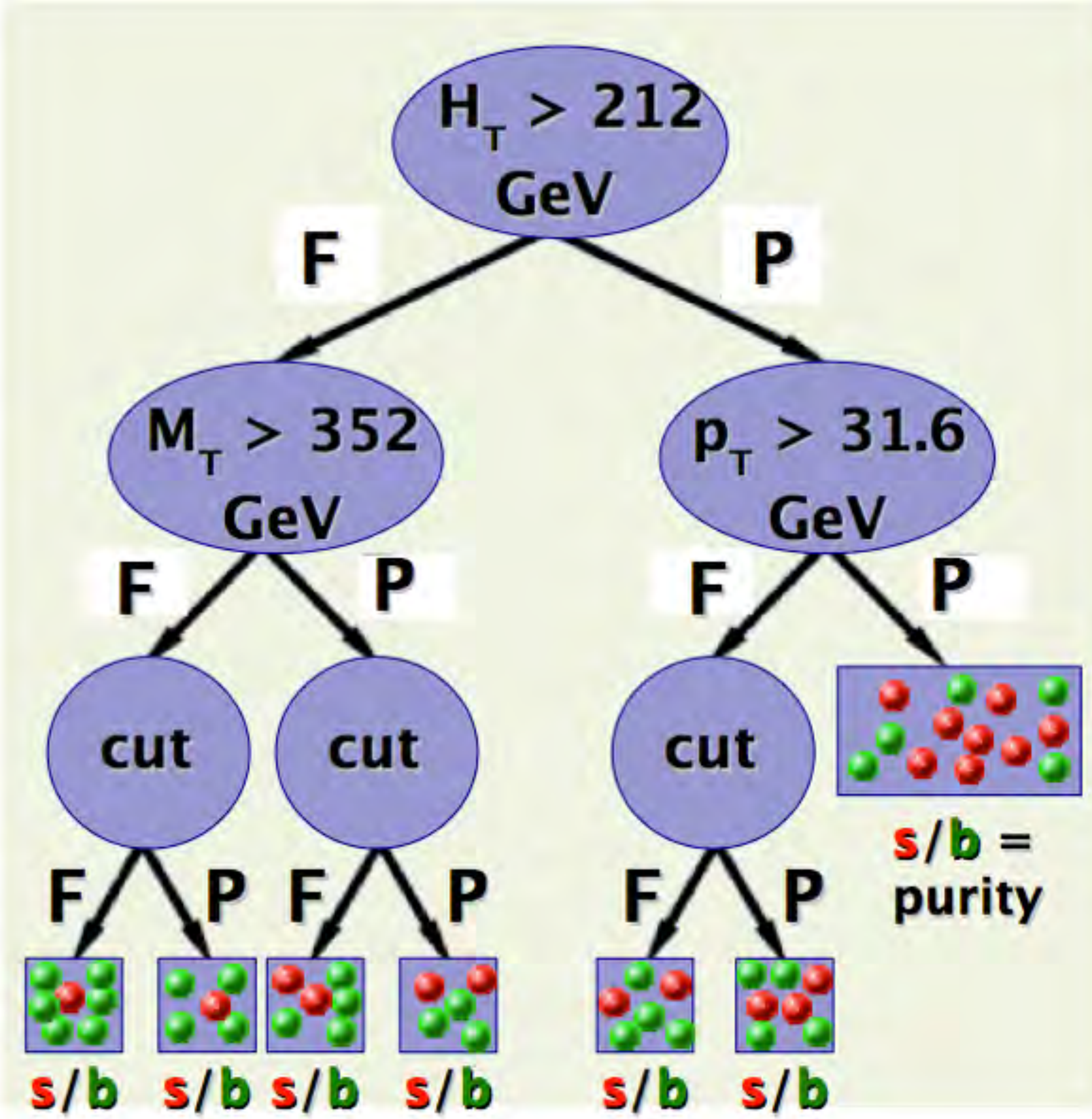
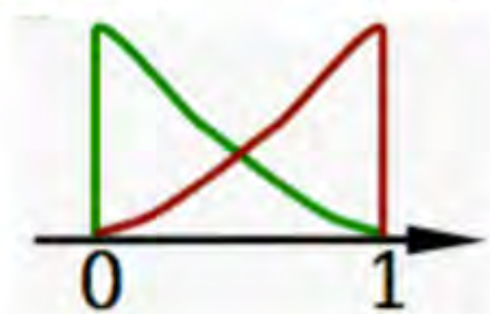
Boosted Decision Trees



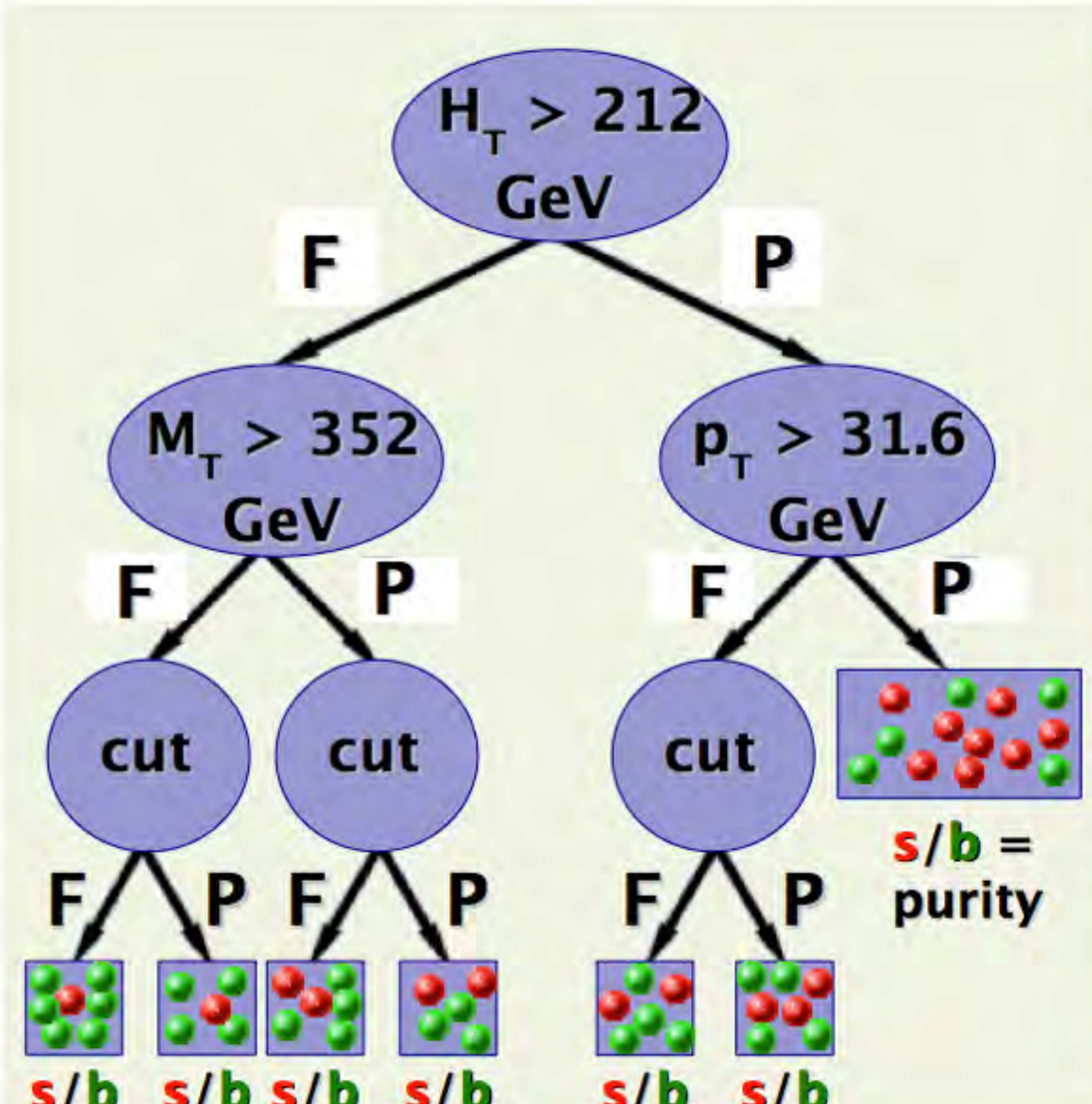
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background **signal**



Boosted Decision Trees

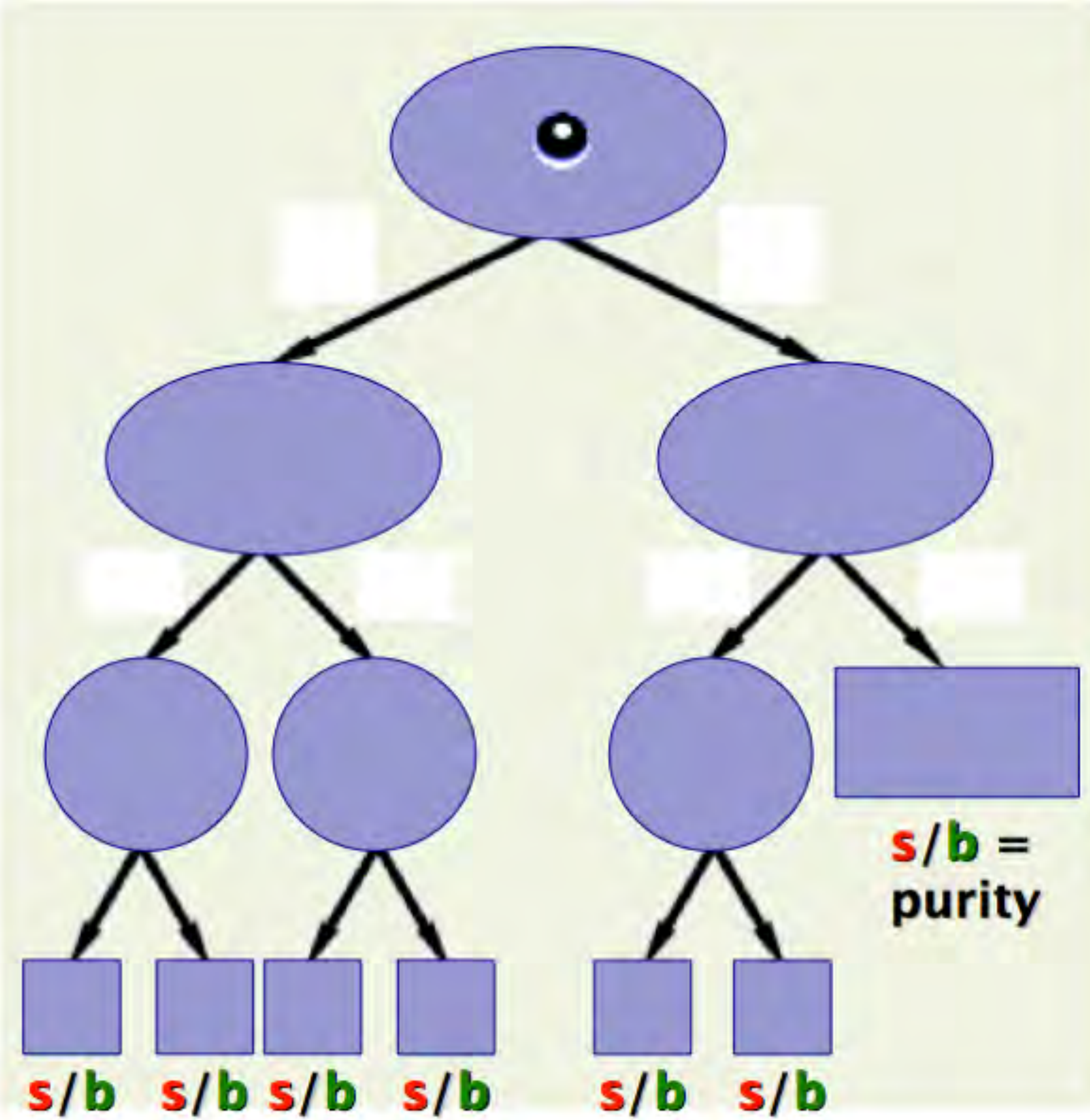


- **IDEA: recover events that fail criteria in cut-based analyses**

boosting:

- train tree: T_k
- derive weight: α_k
- retrain tree: T_{k+1} to minimize error
- average: $T = \Sigma\, \alpha_i\, T_i$

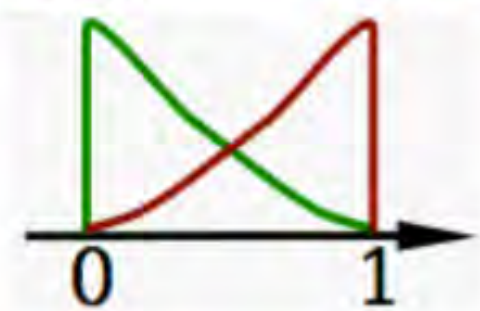
Boosted Decision Trees



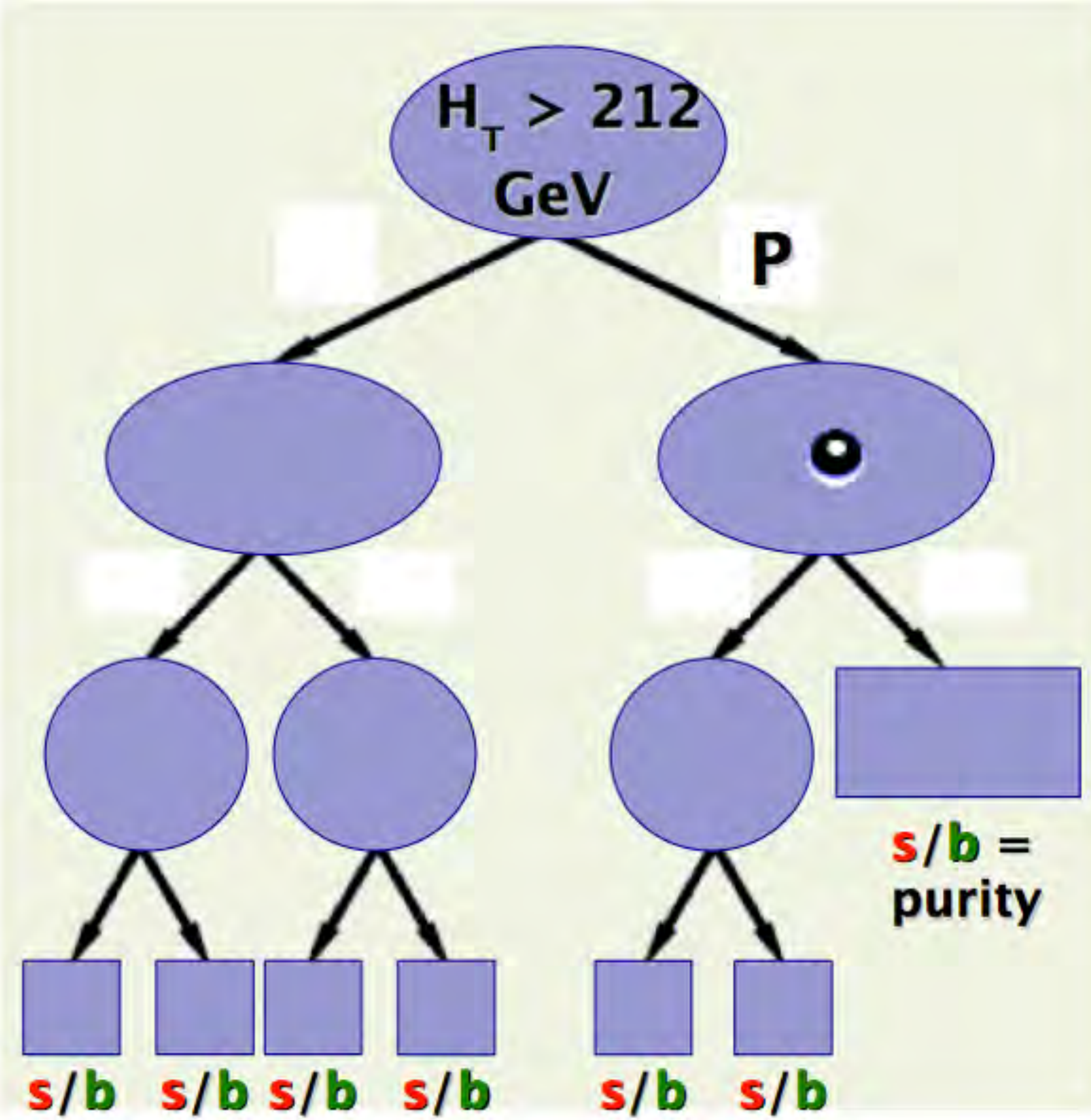
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result:
  weight for every event**

background **signal**



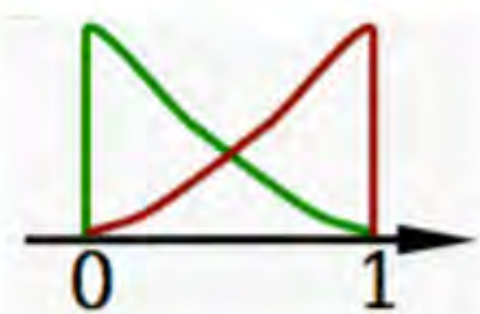
Boosted Decision Trees



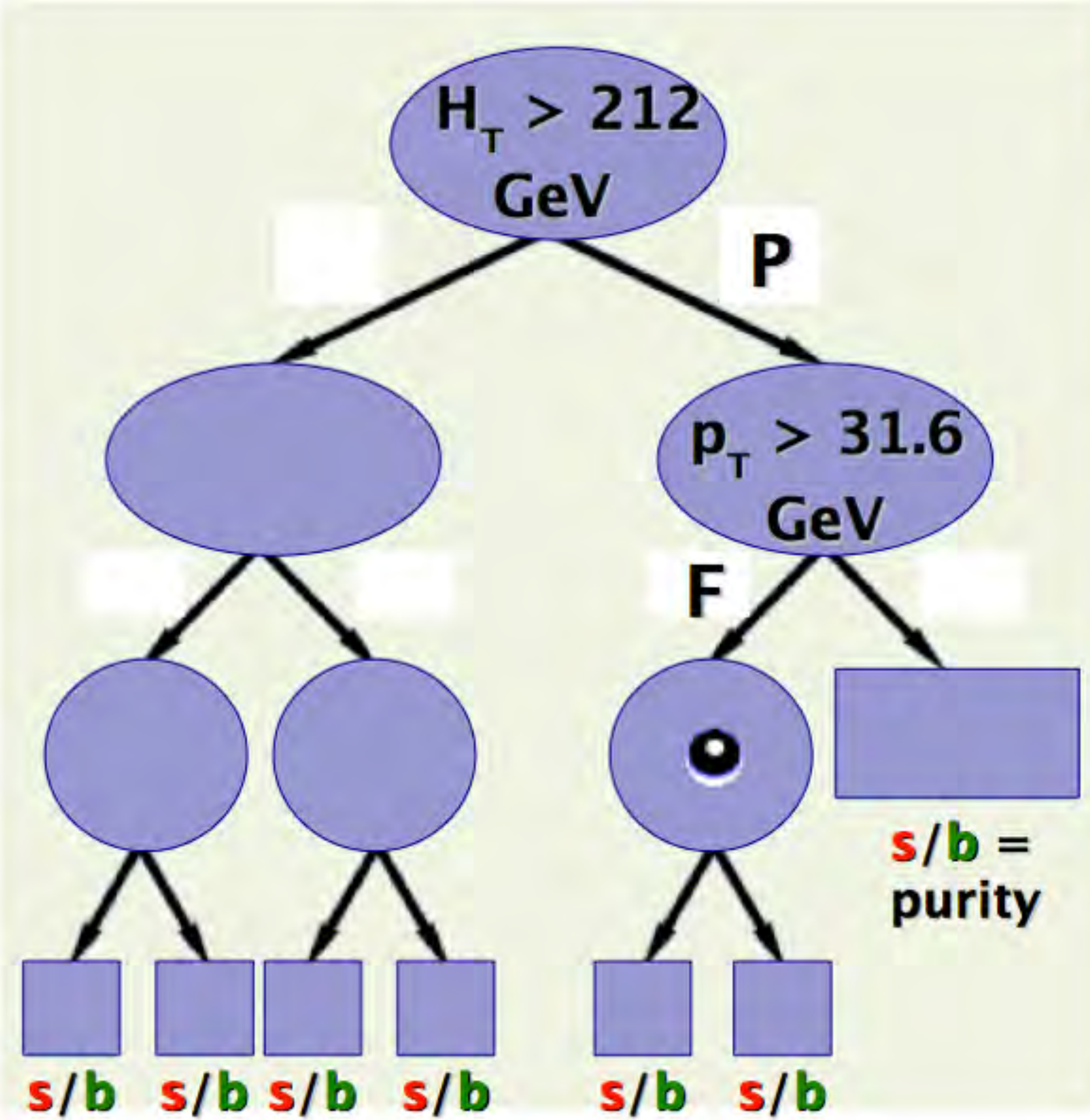
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background **signal**

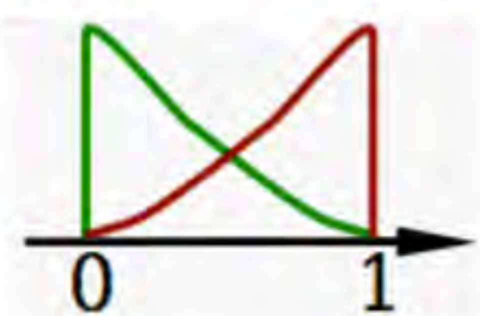


Boosted Decision Trees

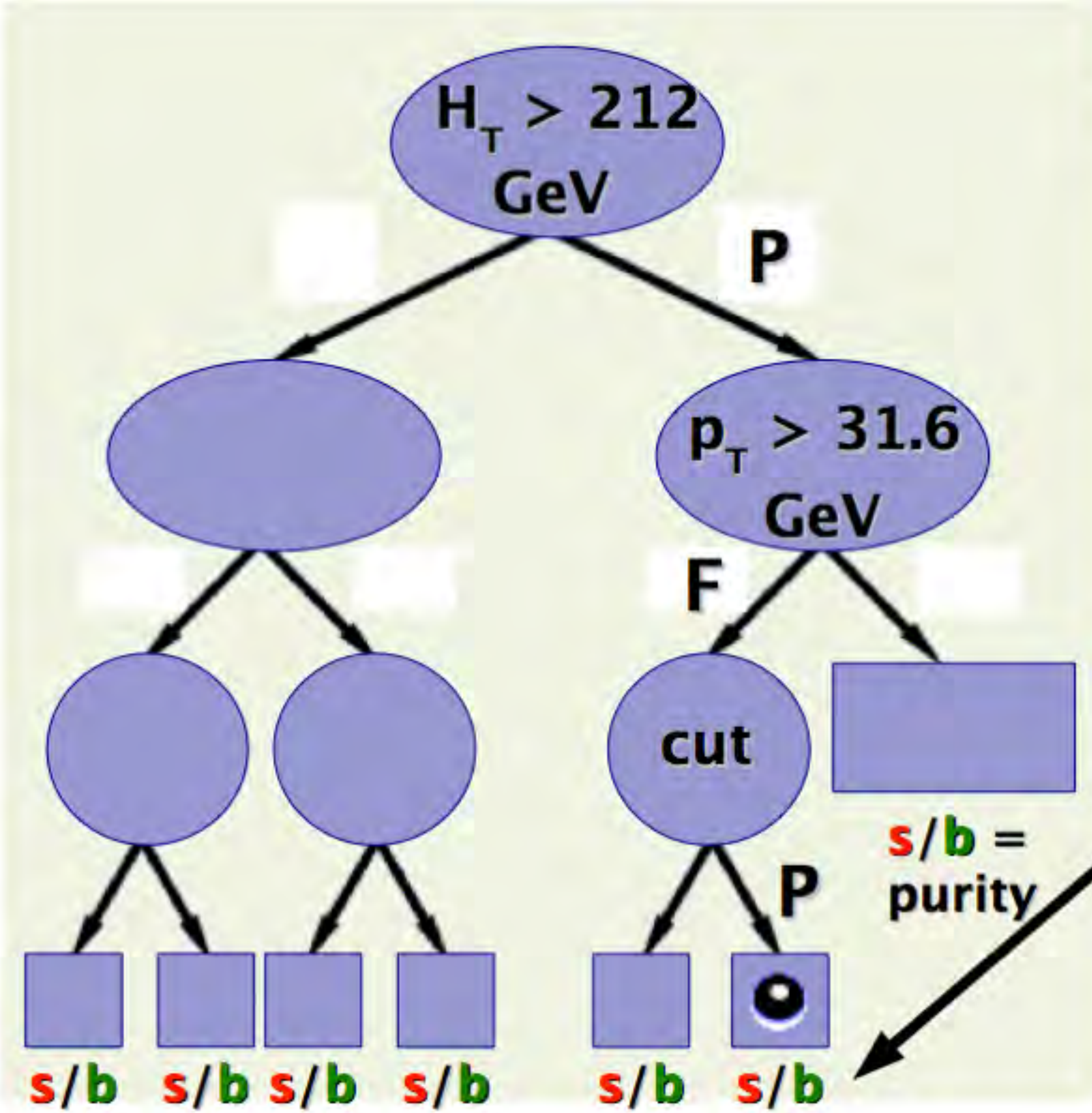


- **IDEA: recover events that fail criteria in cut-based analyses**
- **result: weight for every event**

background **signal**

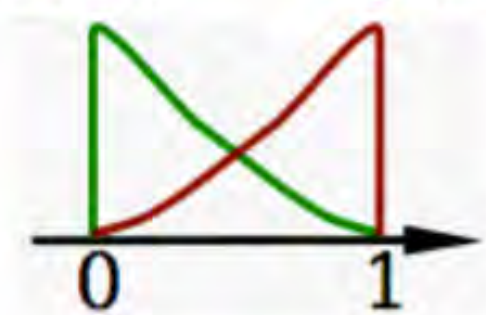


Boosted Decision Trees



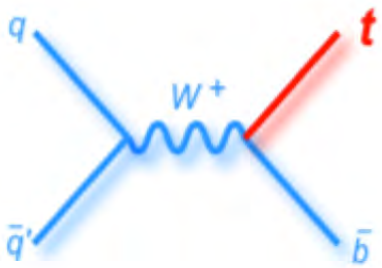
- **IDEA: recover events that fail criteria in cut-based analyses**
- **result: weight for every event**

background **signal**

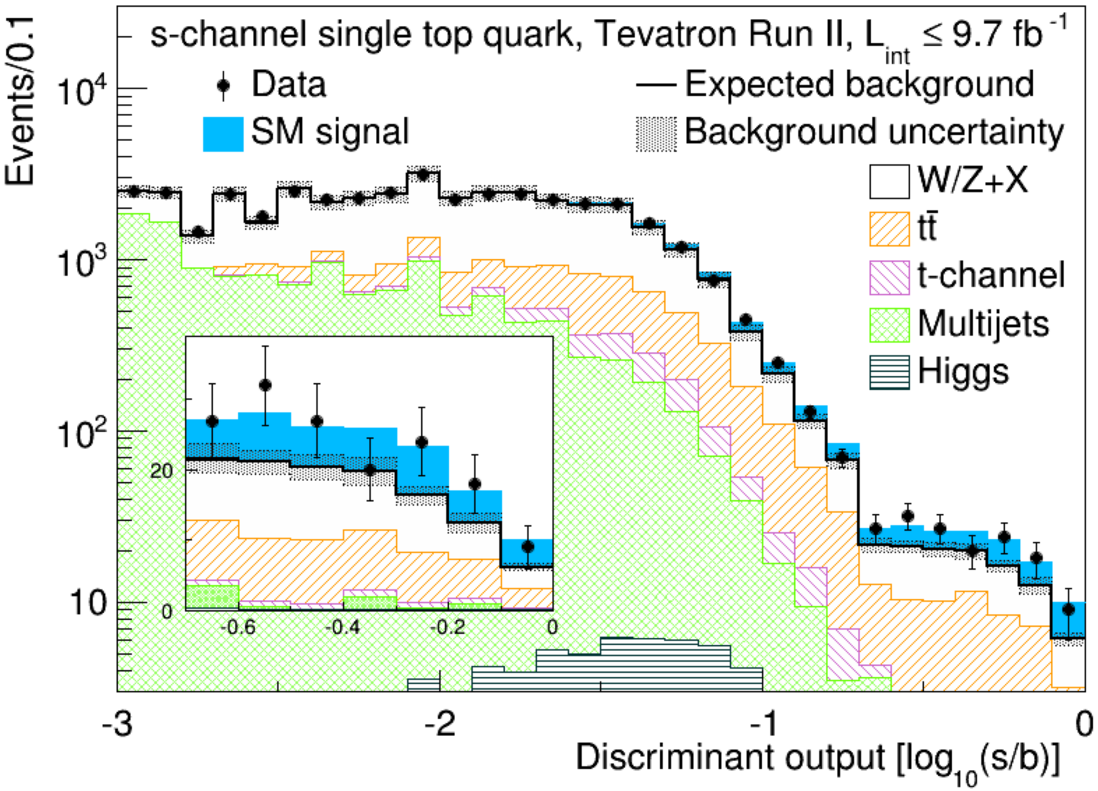


s-channel Production

Phys. Rev. Lett. 112, 231803 (2014)



- Tevatron: combine individual discriminants including all correlations

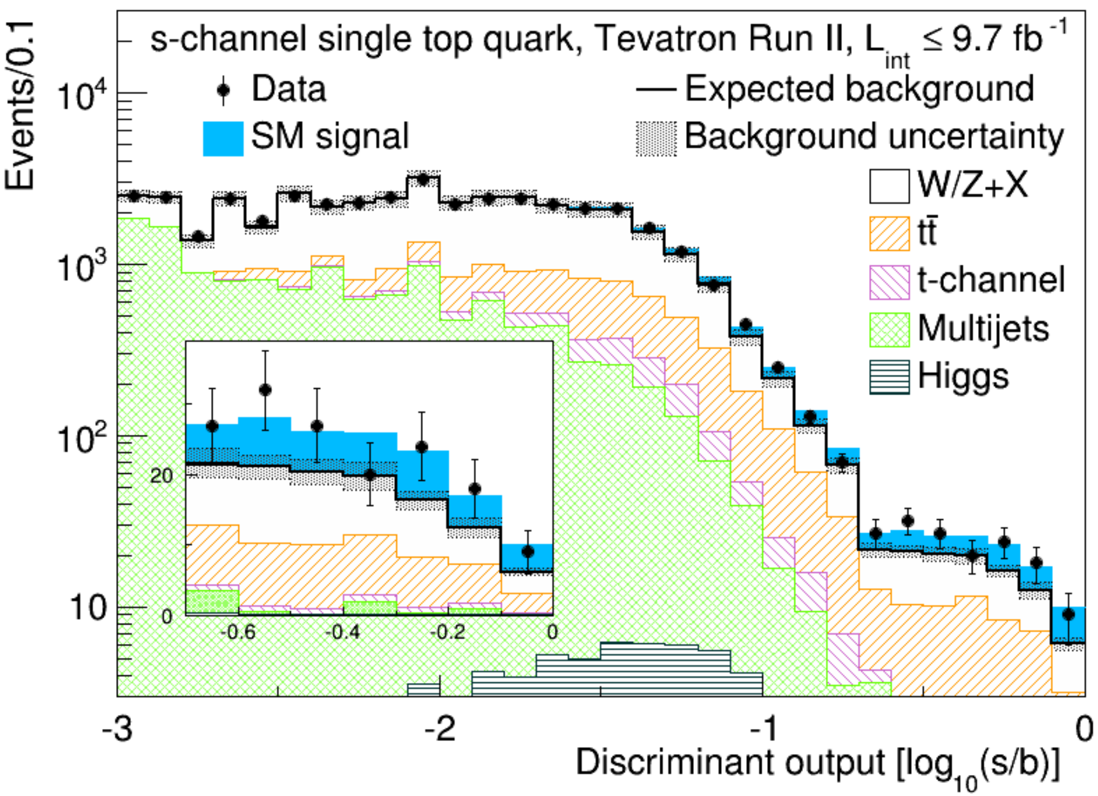


→ observation: 6.3 s.d.

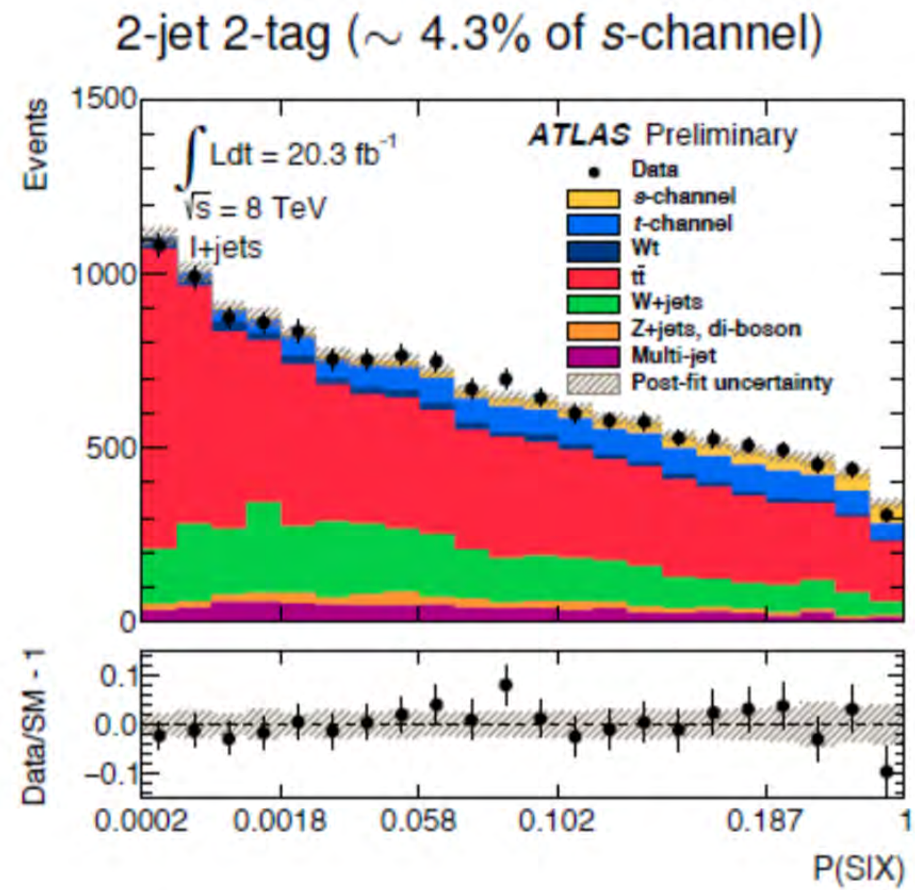
s-channel Production

Phys. Rev. Lett. 112, 231803 (2014)

- Tevatron: combine individual discriminants including all correlations



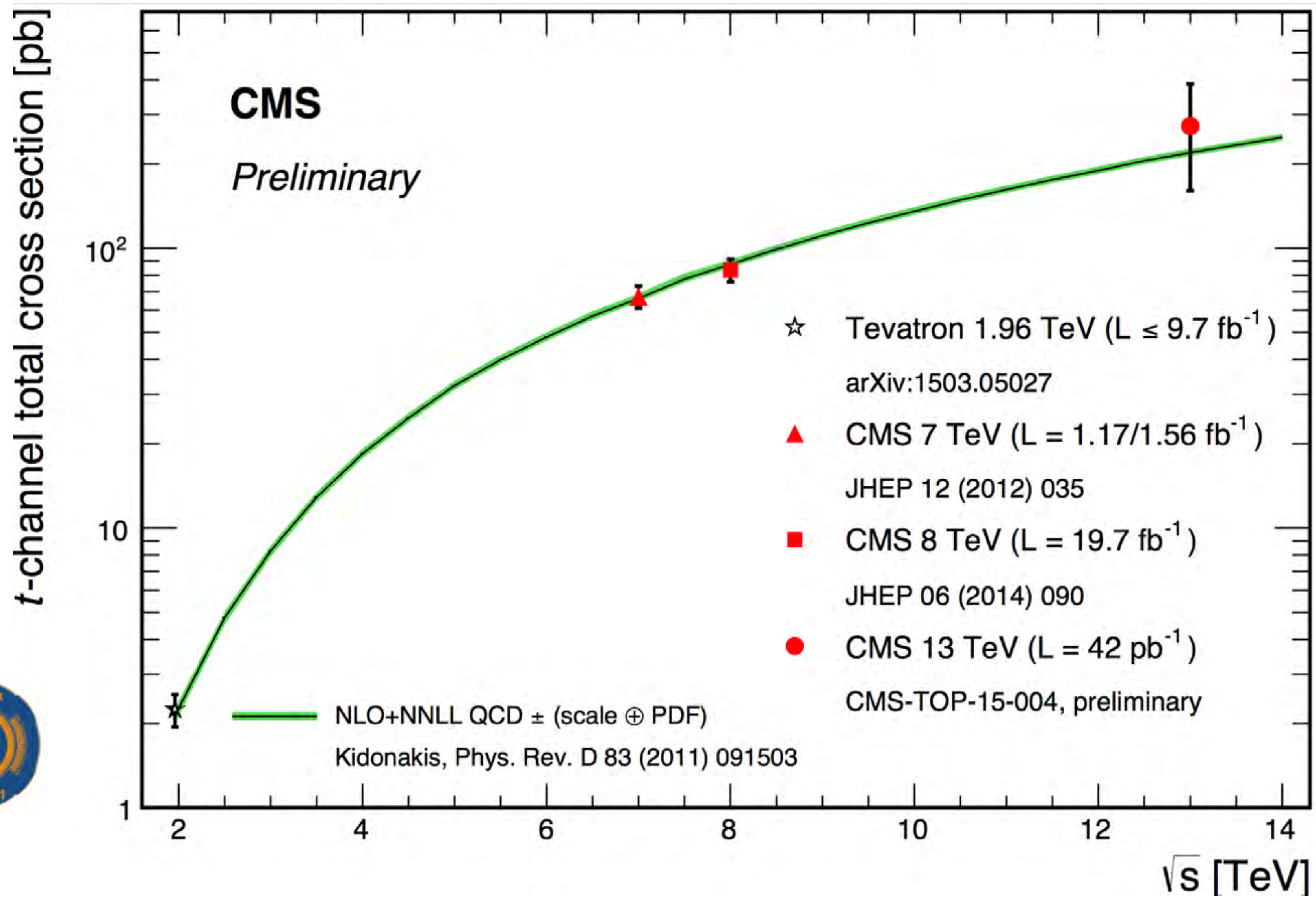
- ATLAS: matrix element method



→ observation: 6.3 s.d.

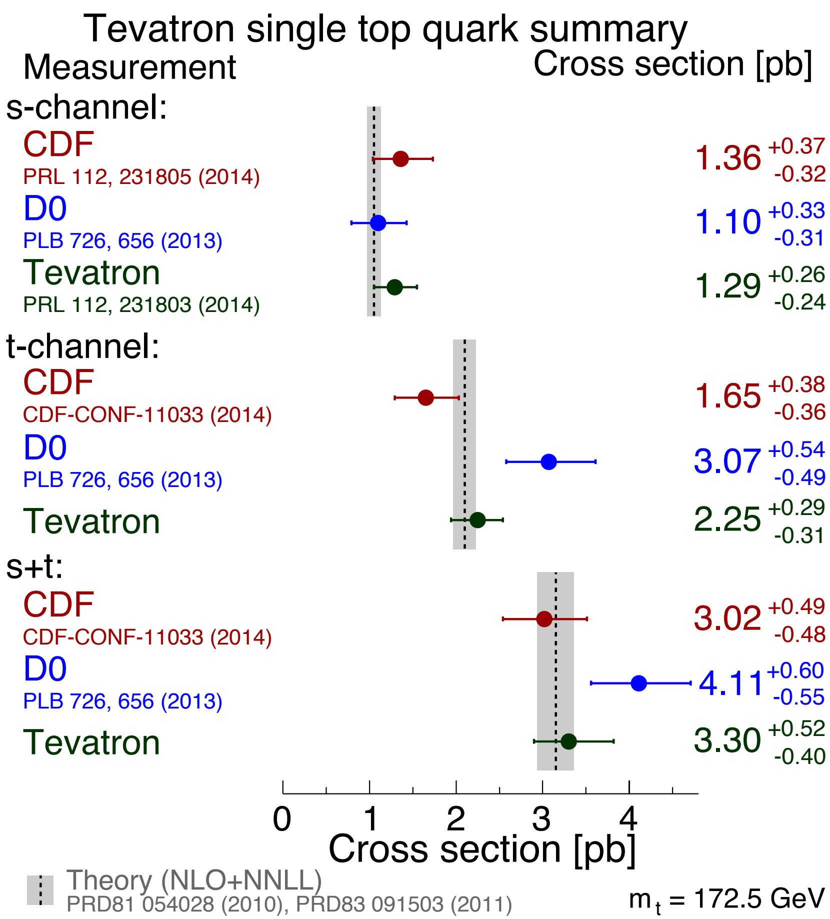
→ evidence: 3.2 s.d.

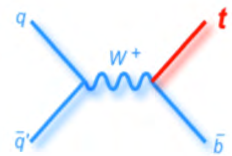
Single top t-channel cross section



→ agreement with SM predictions!

Single channel cross sections



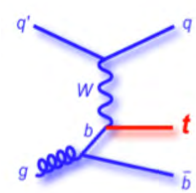


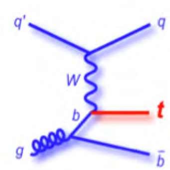
→ **observation**

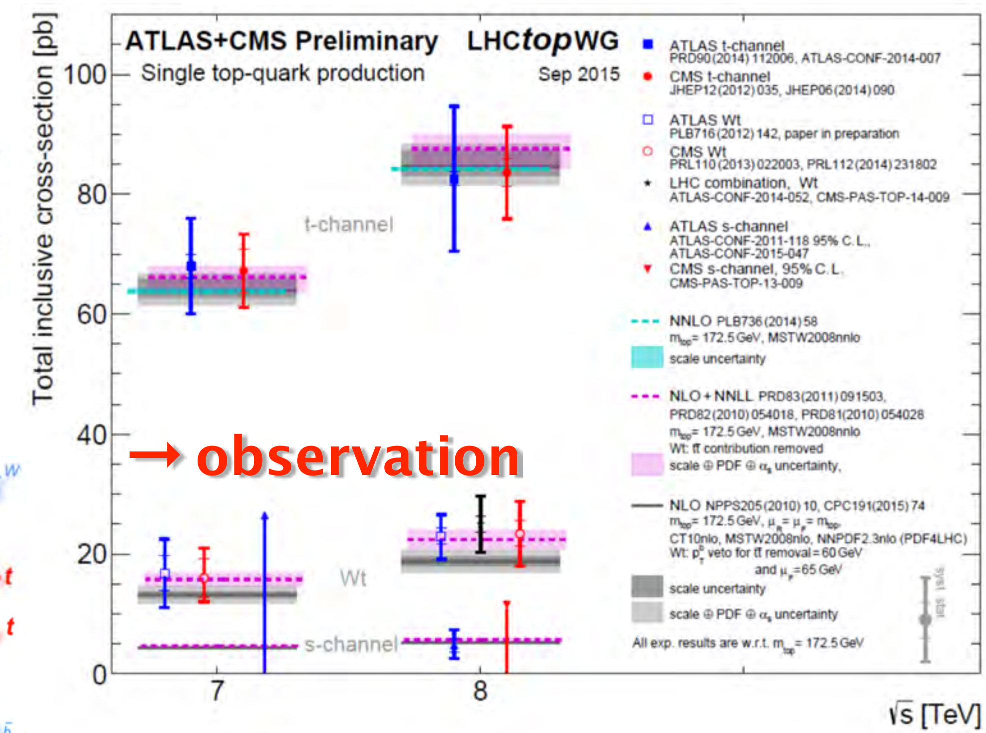
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{tb}| = 0.998 \pm 0.041$ $\pm 4.1\%$

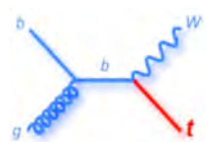
$|V_{tb}| > 0.92$ @ 95%CL

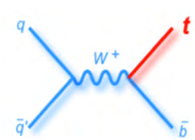






→ **observation**

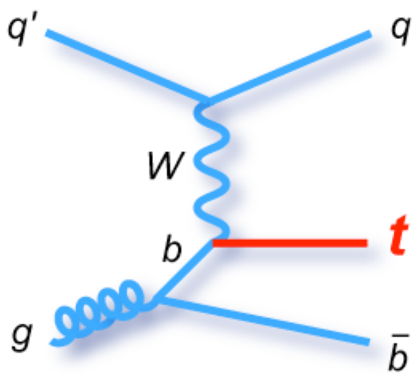




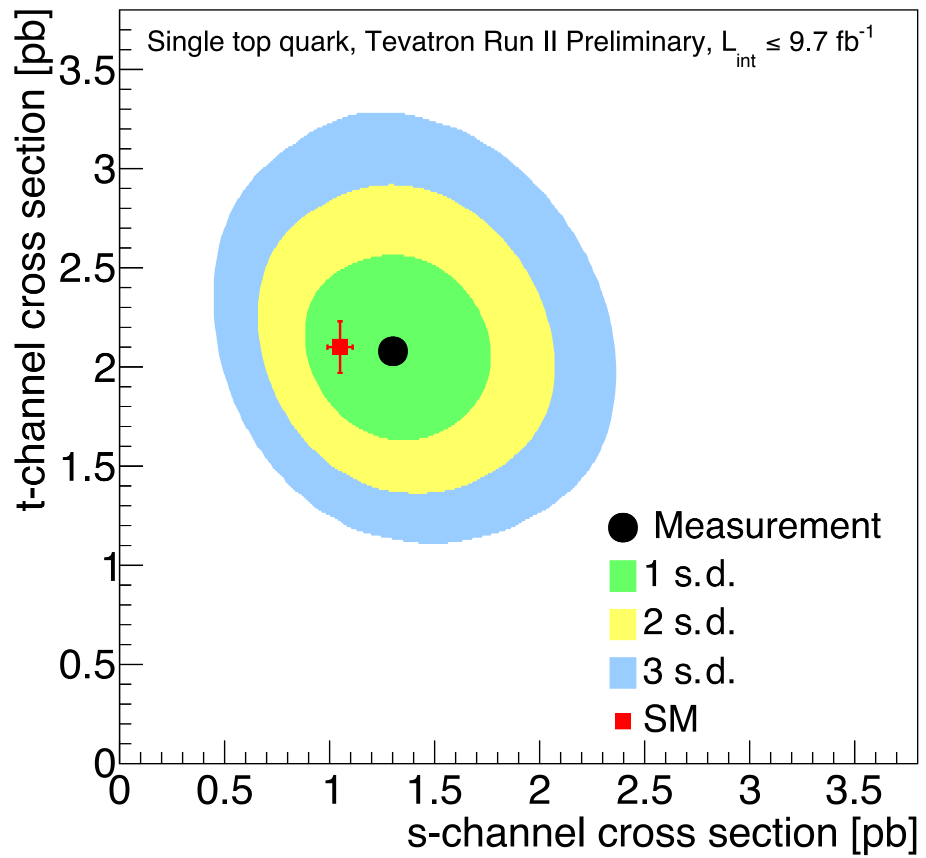
this is the final word from the Tevatron!

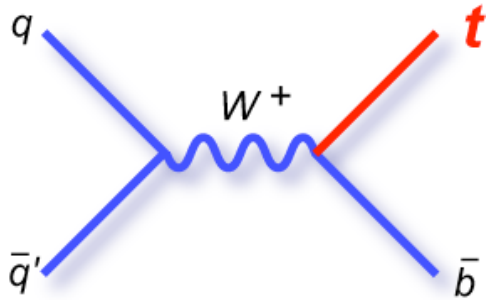
→ **all production modes observed!**

Single Top s- vs. t-channel



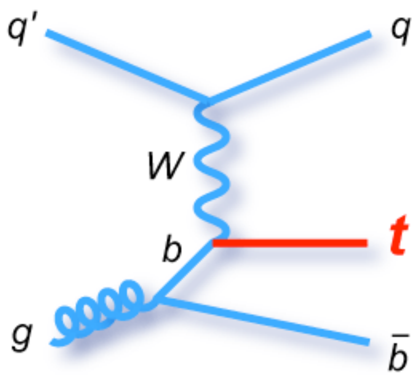
arXiv:1503.05027 [hep-ex]

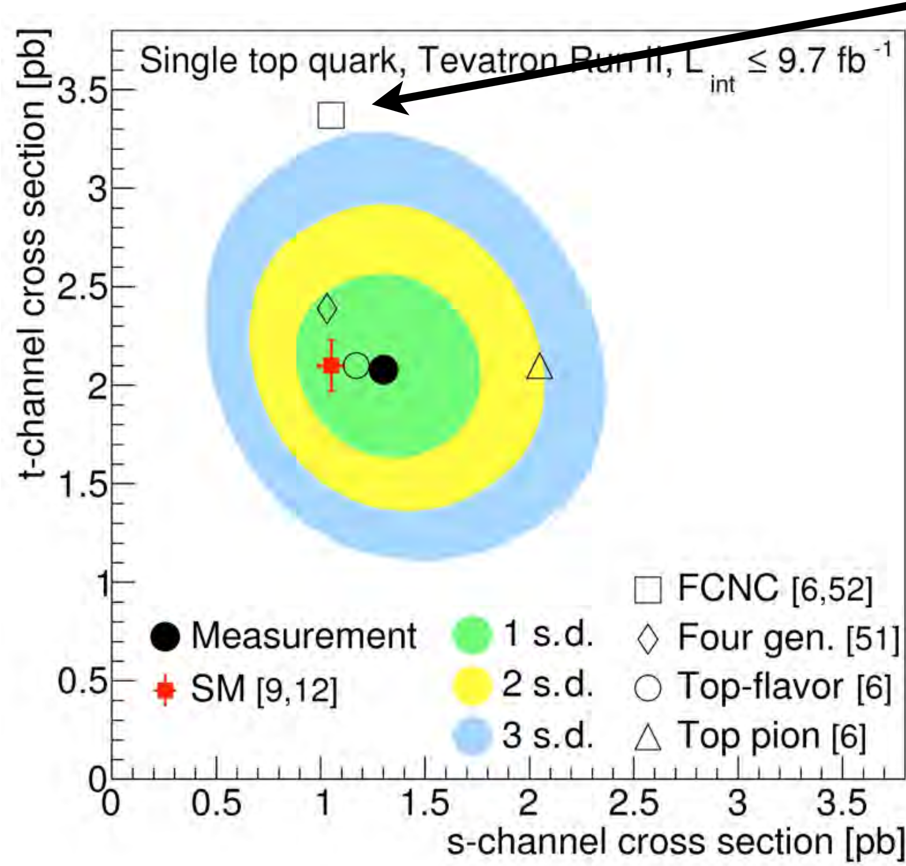


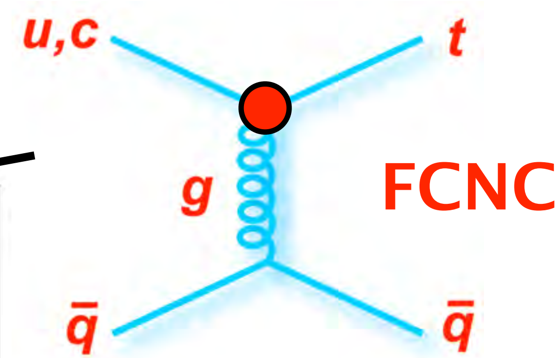


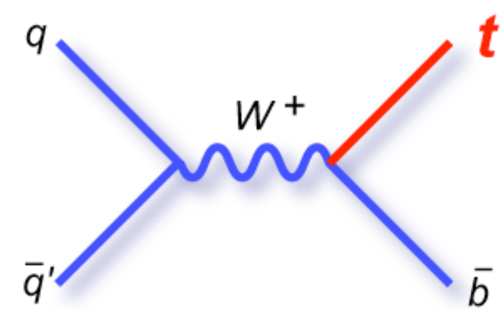
→ observed!

Single Top s- vs. t-channel



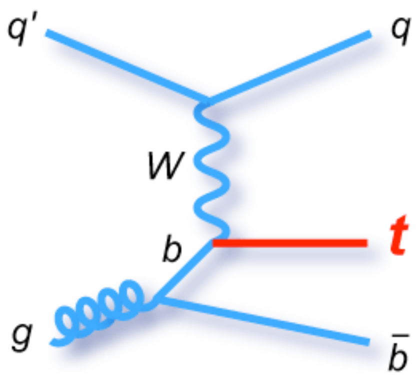


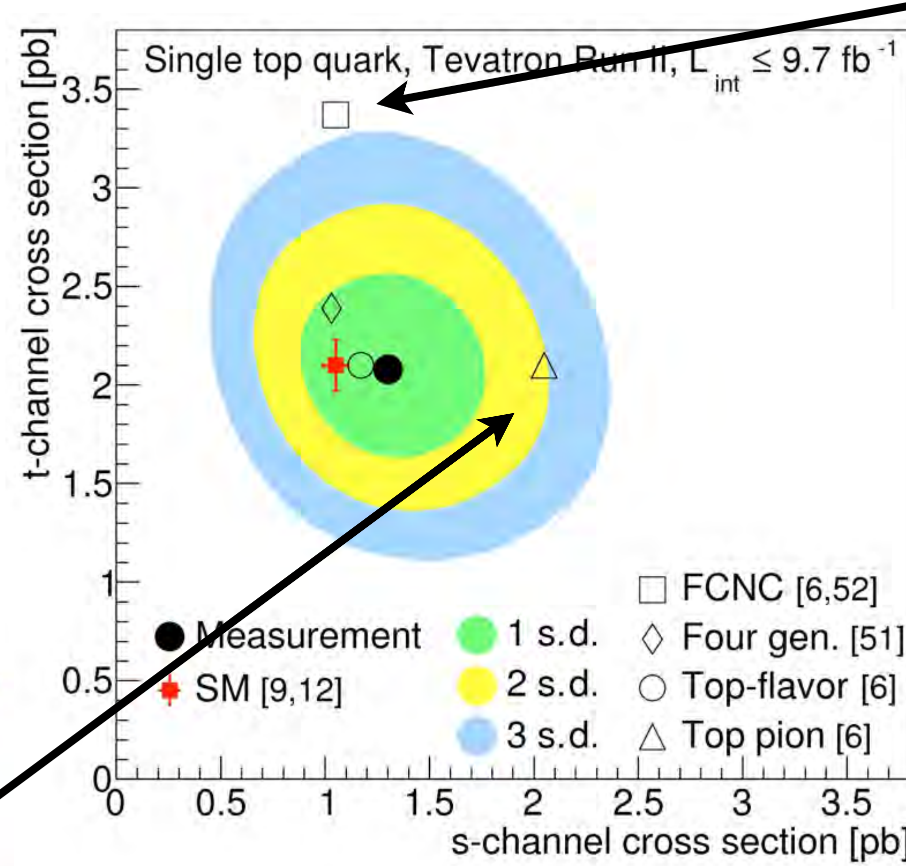


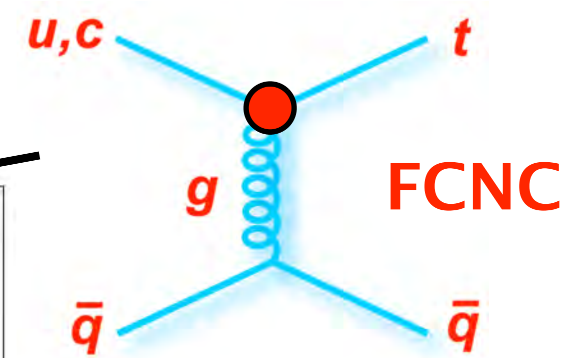


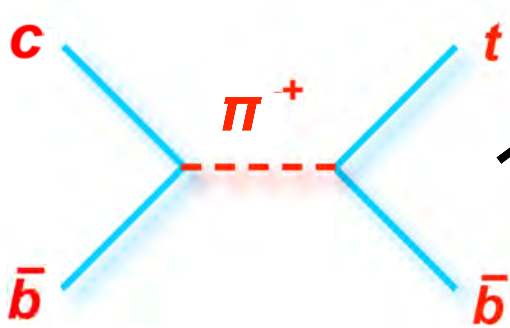
→ observed!

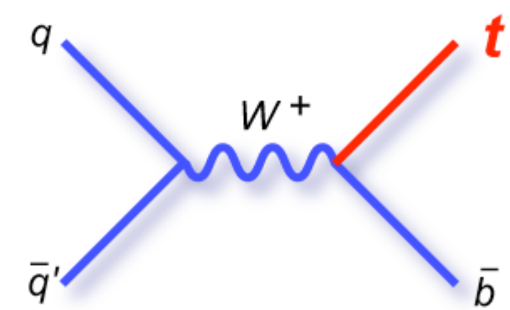
Single Top s- vs. t-channel







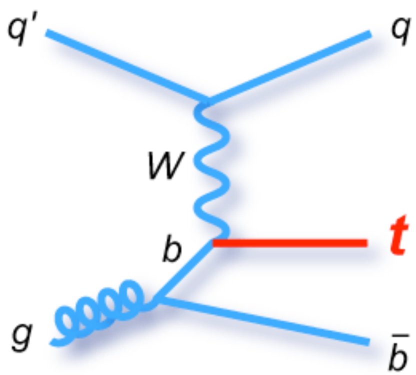


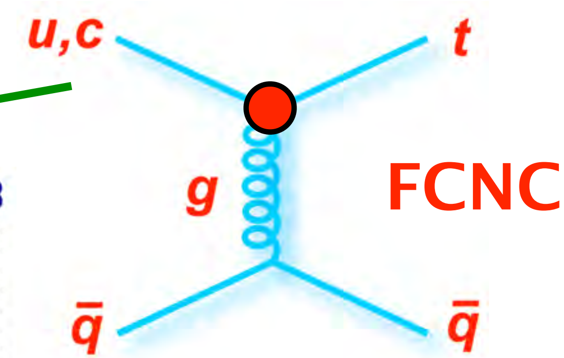


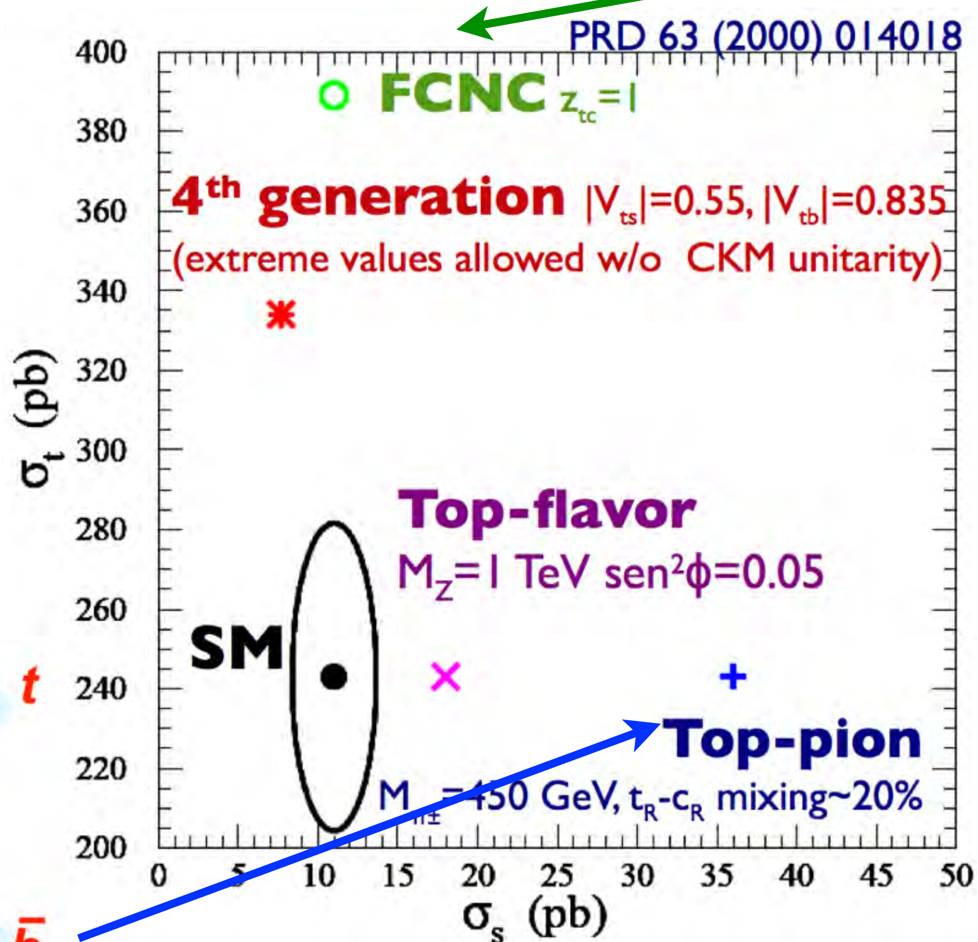
→ **observed!**

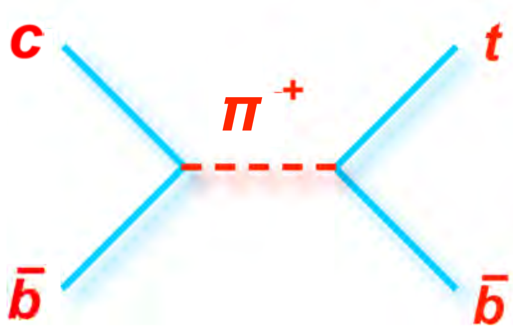
⇒ **important to study production channels separately**

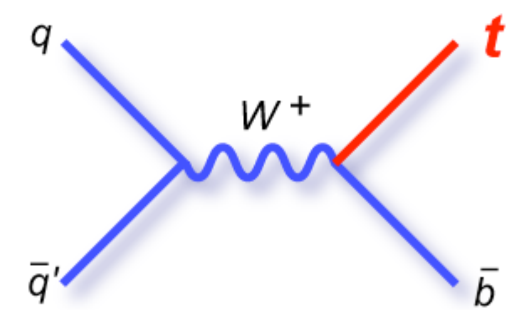
Single Top s- vs. t-channel: Run-II











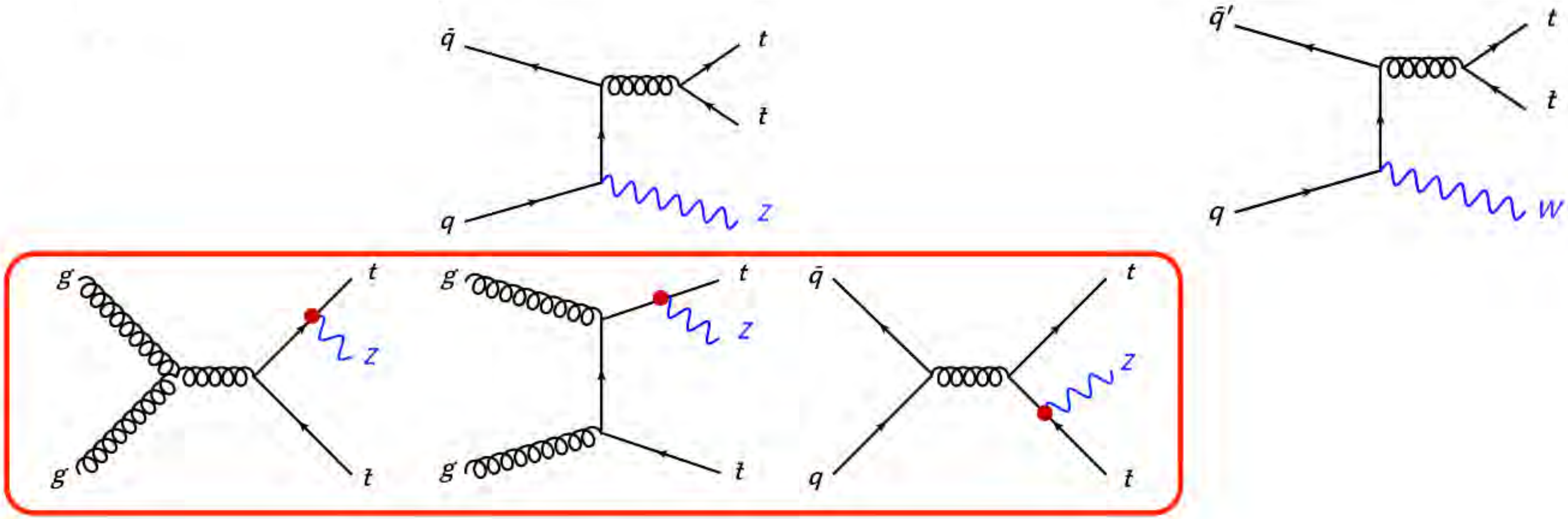
→ observed!

⇒ important to study production channels separately

$t\bar{t}Z$ and $t\bar{t}W$ Production

ISR

FSR

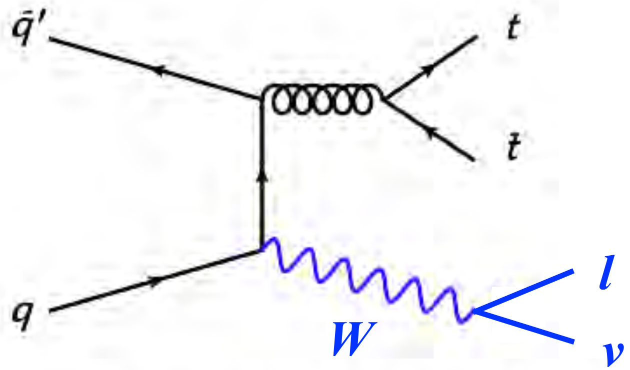


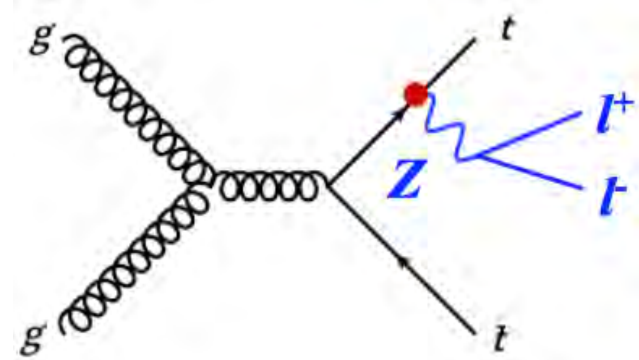
$$-i \frac{e}{\sin\vartheta_W \cos\vartheta_W}(T_3 - \sin^2\vartheta_W Q_t)\gamma^\mu$$

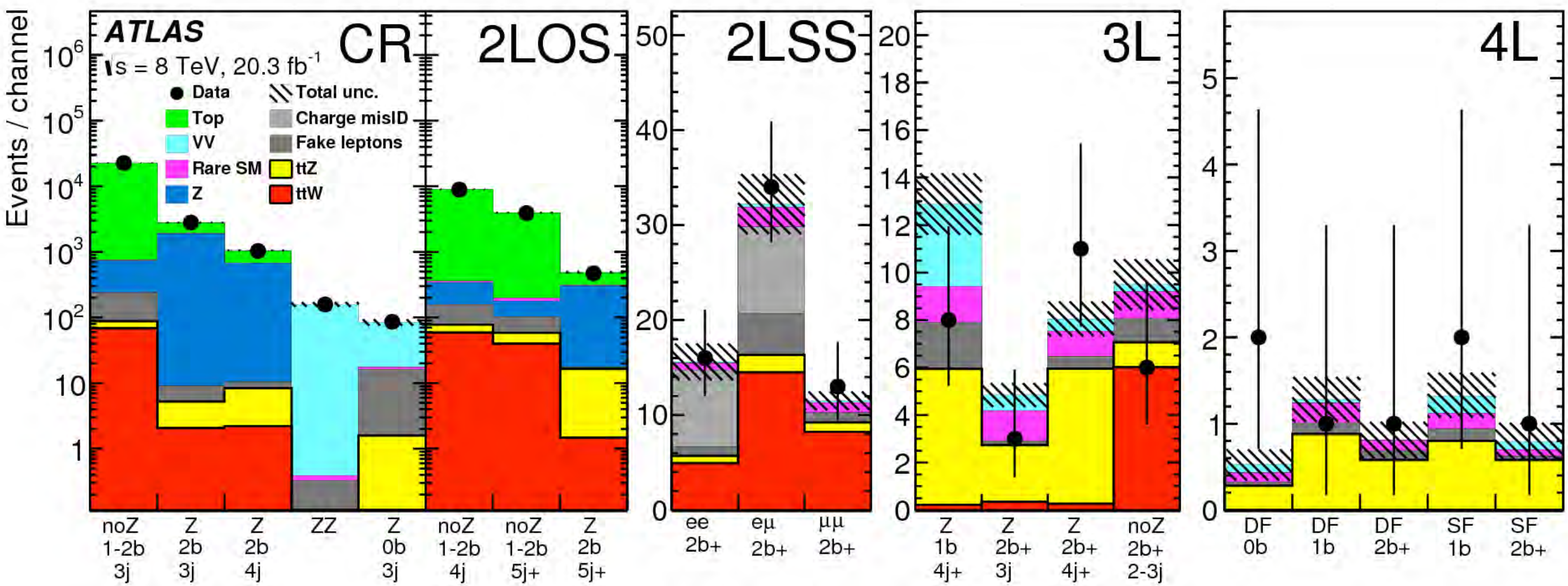
- measure 3rd component of weak isospin
- search for anomalous couplings in $t\bar{t}Z$ vertex (basically unexplored)

  → both processes are important backgrounds to searches (e.g. $t\bar{t}H$ in multilepton events)

Search for ttZ and ttW

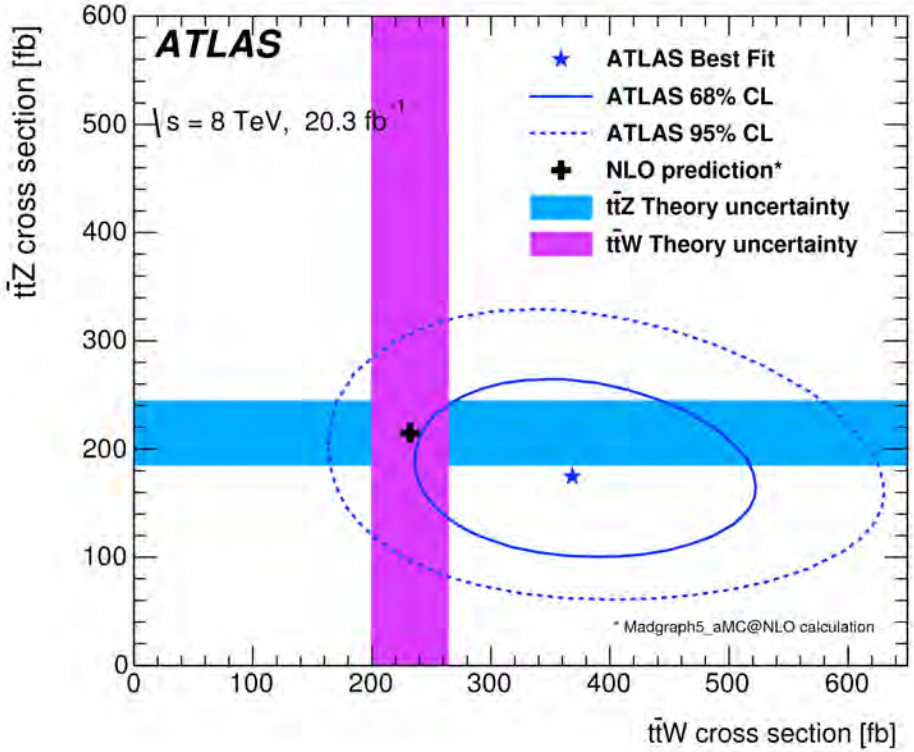


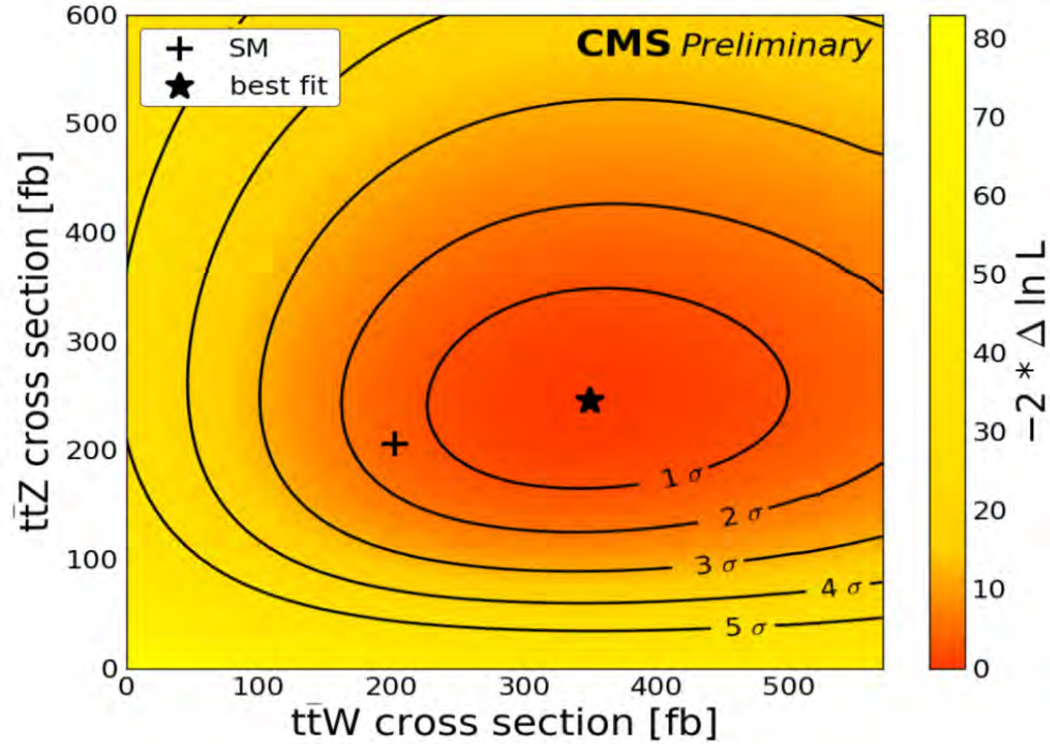




ttW ← → ttZ

Observation of ttV production



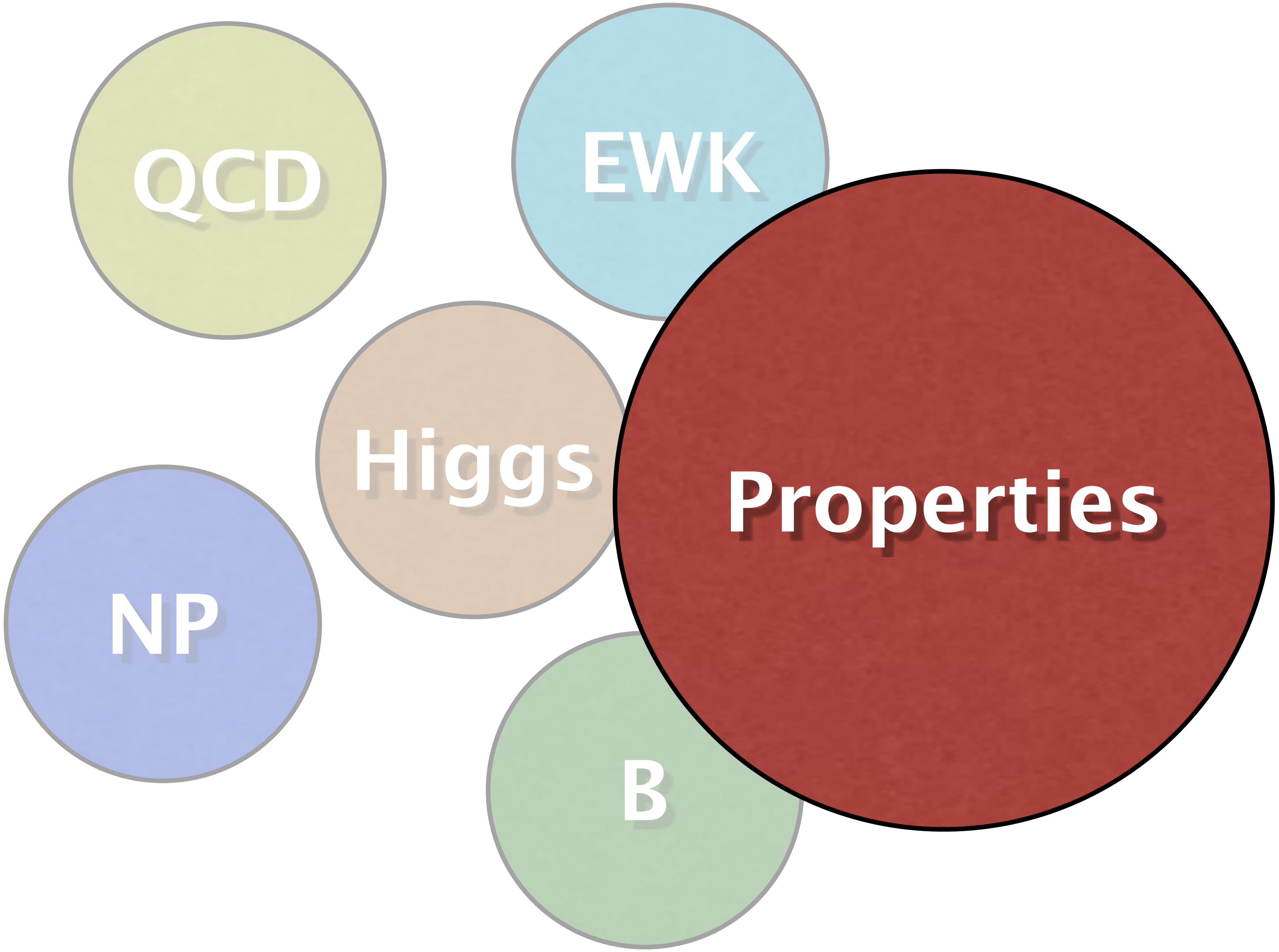


ttW:	3.2 σ (exp)	5.0 σ (obs)
ttZ:	4.5 σ (exp)	4.2 σ (obs)

ttW:	3.8 σ (exp)	4.8 σ (obs)
ttZ:	5.7 σ (exp)	6.4 σ (obs)

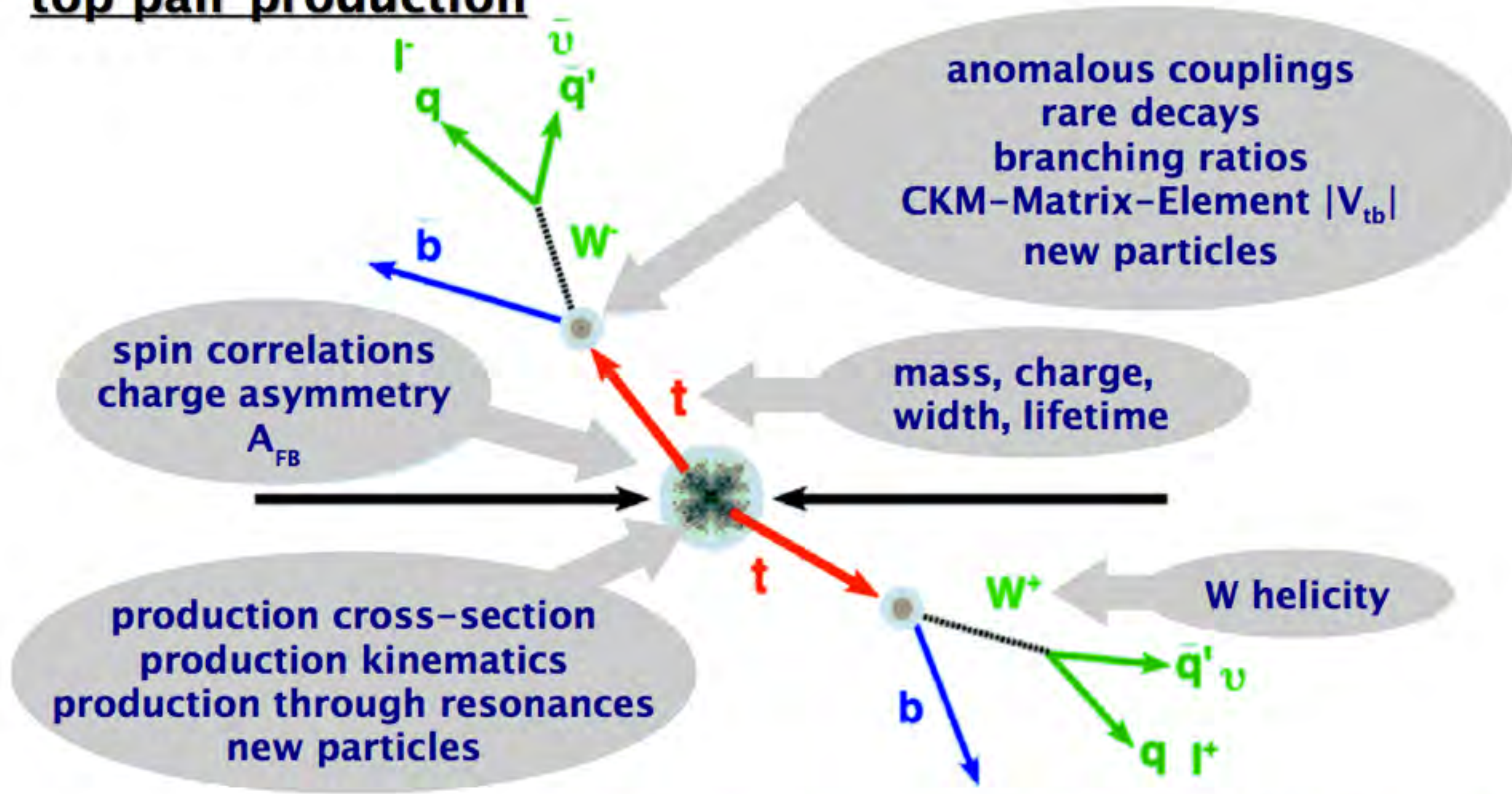
→ in agreement with the SM prediction
(ttγ also in agreement with SM prediction)

Top Quark Physics Topics



Top Quark Analyses

top pair production

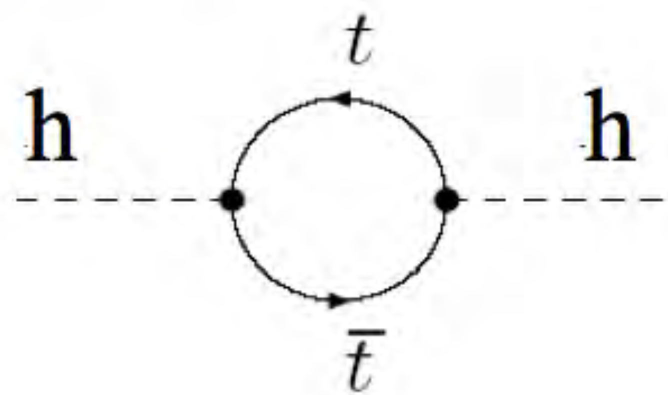


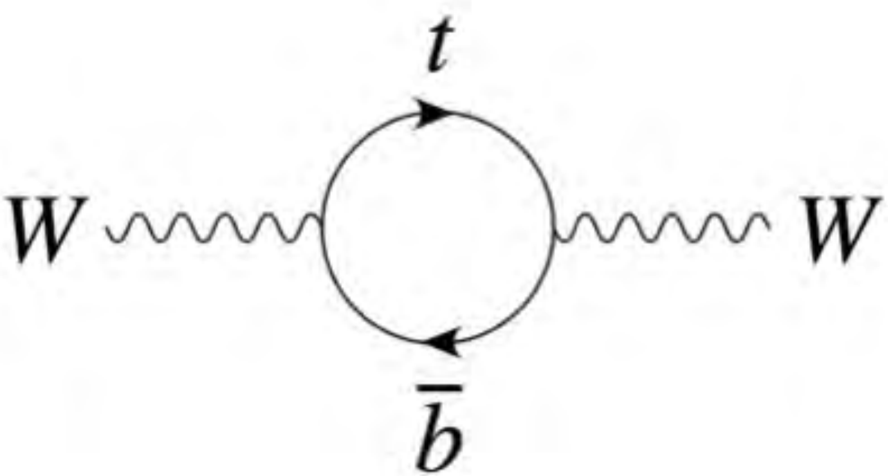
single top production cross sections, CKM matrix element $|V_{tb}|$, polarisation, SM and anomalous couplings, searches, …

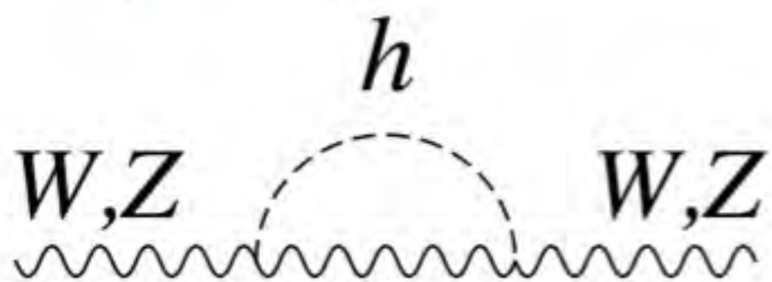
other production modes tt+jets, ttbb, ttZ, ttW, ttH and their couplings

The Top Quark Mass

- free parameter in the Standard Model
- check the **self-consistency of the Standard Model** in combination with W mass measurement
- prediction on **Higgs mass**

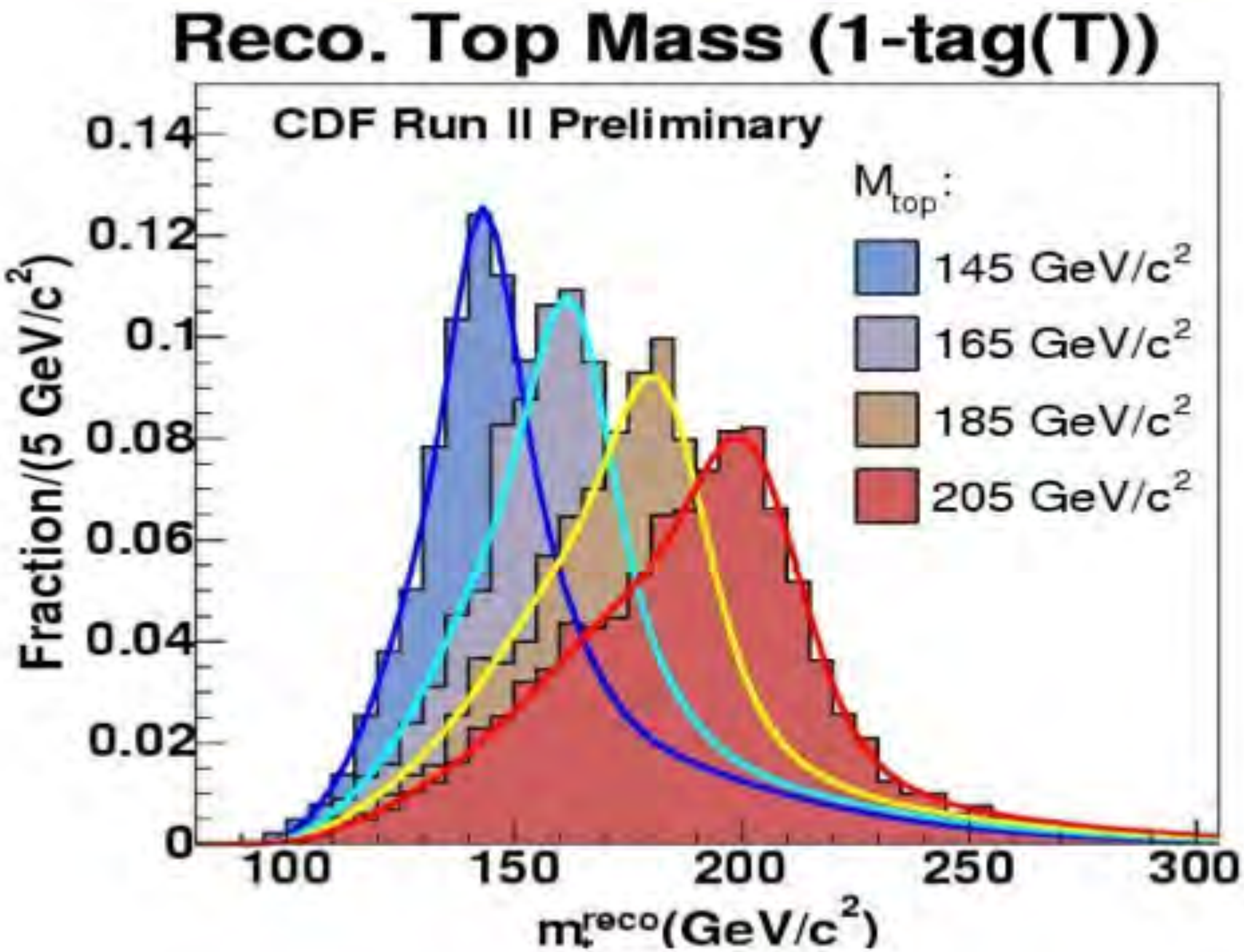






Extraction Techniques: Templates

- use variables strongly correlated with m_{top}
- compare data to MC with different m_{top} hypotheses



Extraction Techniques: Templates

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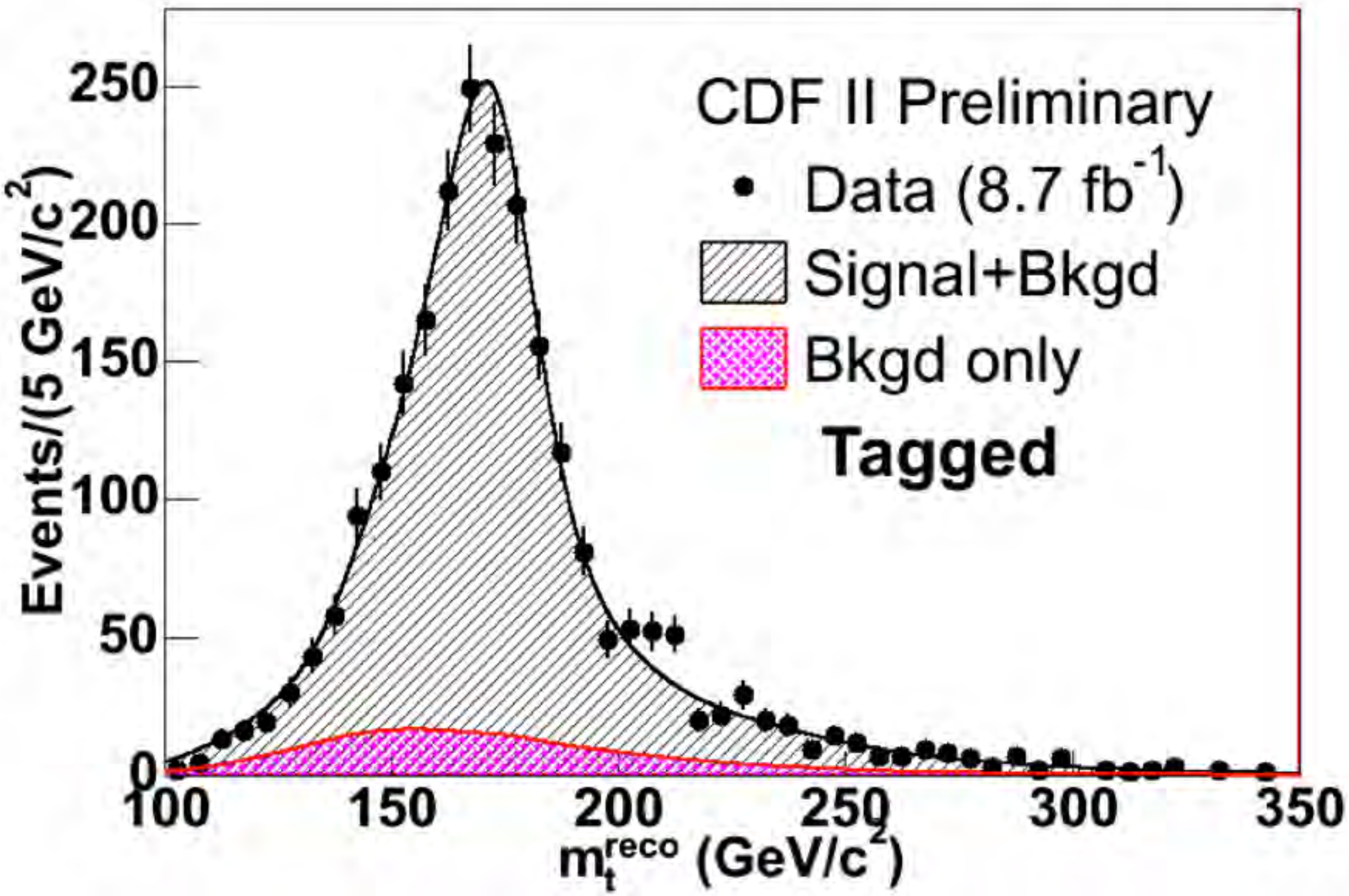

Extraction Techniques: Templates

- use variables strongly correlated with m_{top}
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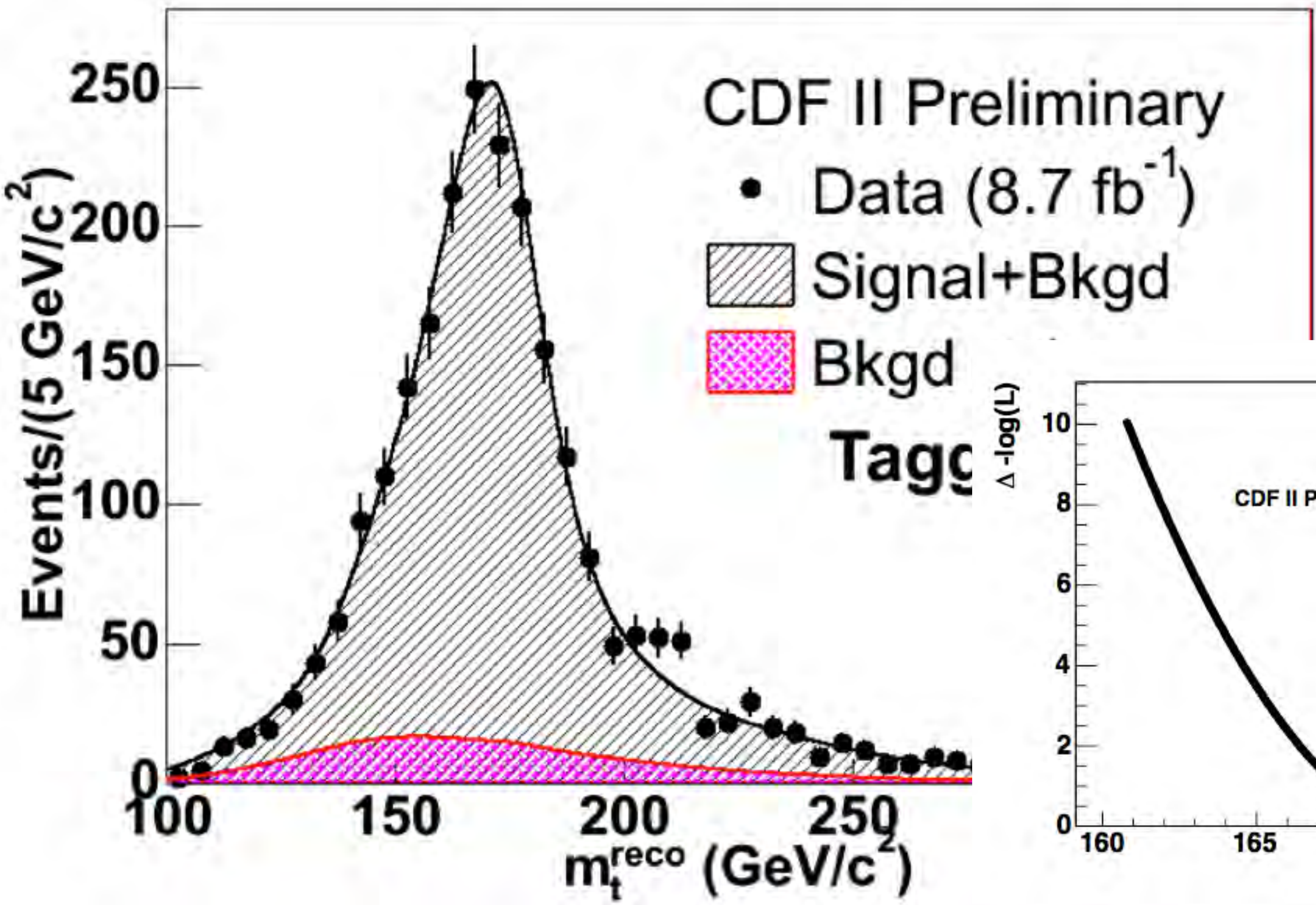
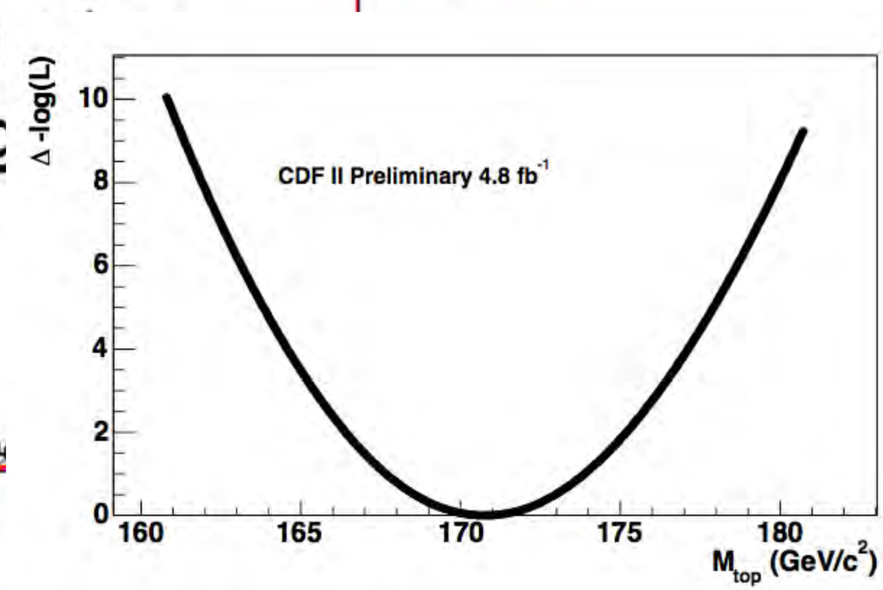
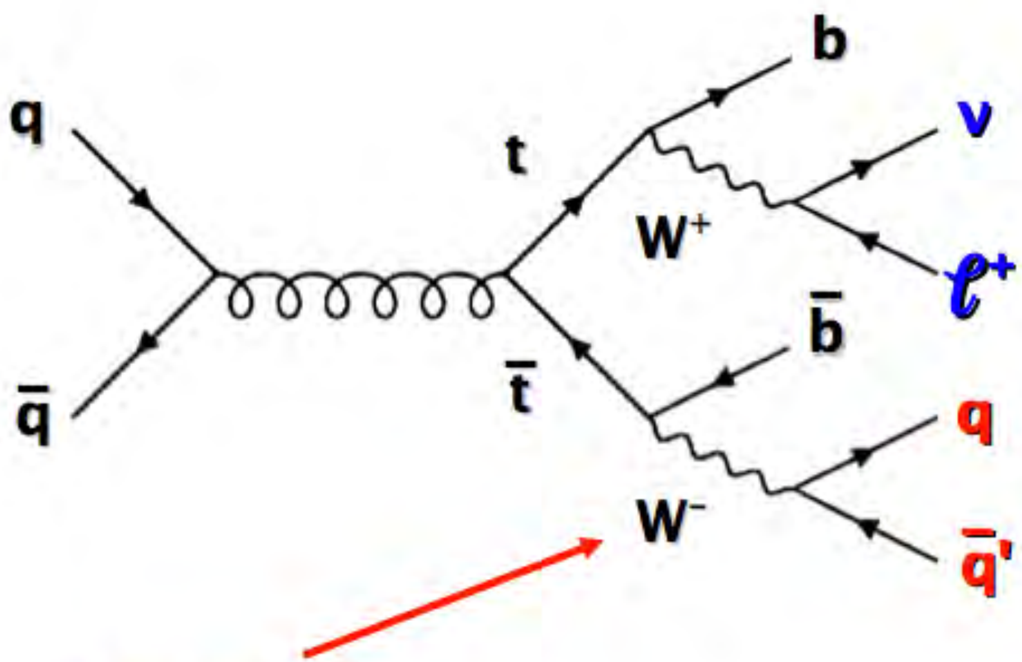




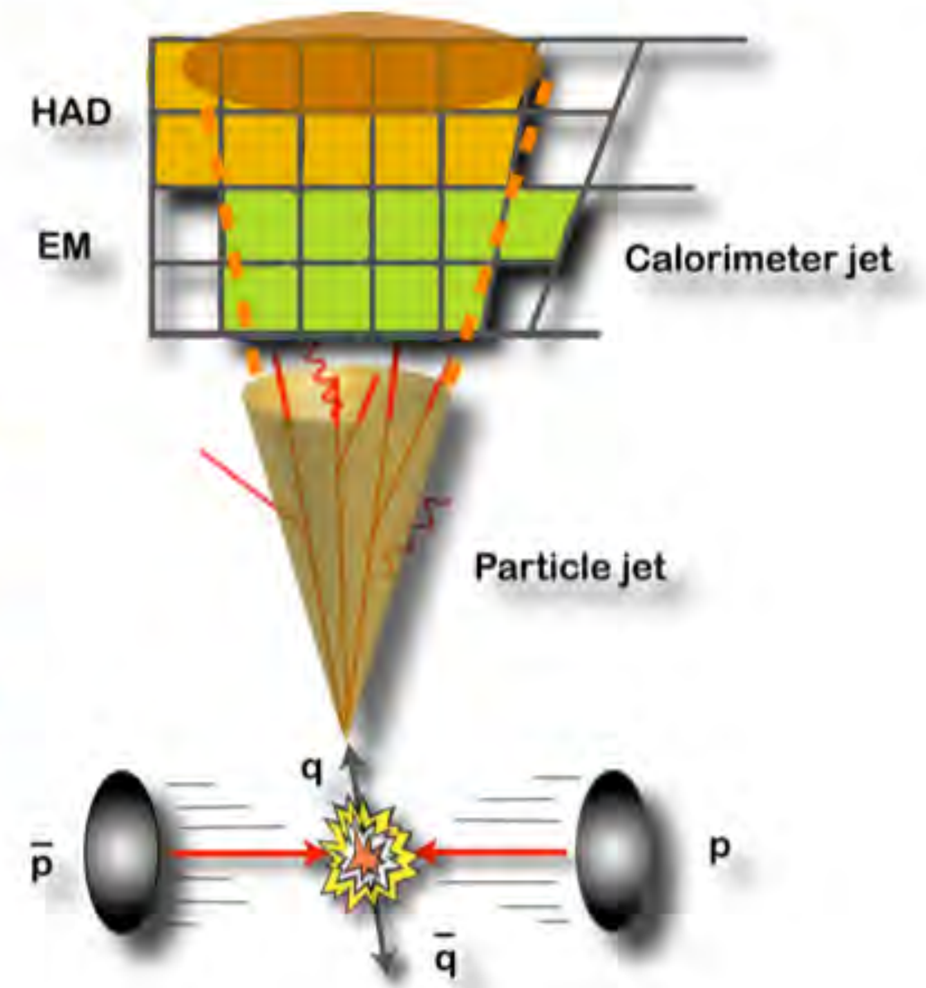
JES calibration



W mass constrains jet energy scale

jet energy scale:

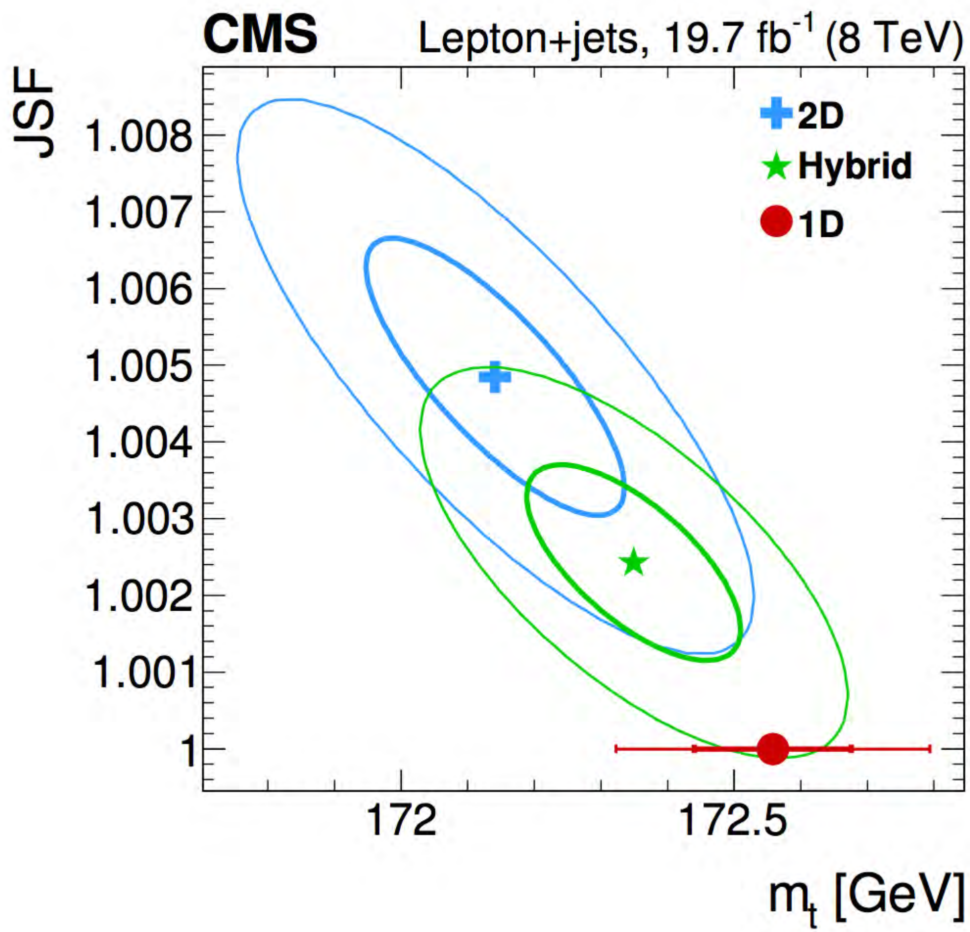
translate jet into parton energy



Result in l+jets Channel

jet energy scale:

translate jet into parton energy



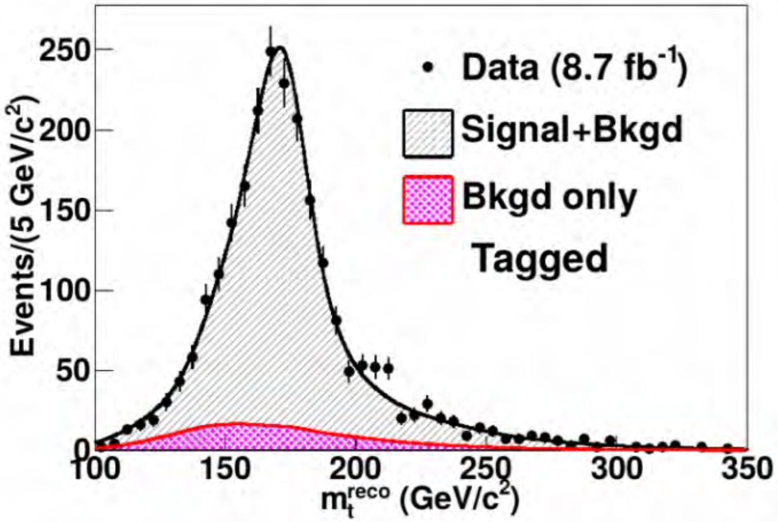
maximum likelihood fit to data

$$m_t^{\mathrm{hyb}} = 172.35 \pm 0.16\,(\mathrm{stat{+}JSF}) \pm 0.48\,(\mathrm{syst})\ \mathrm{GeV}$$

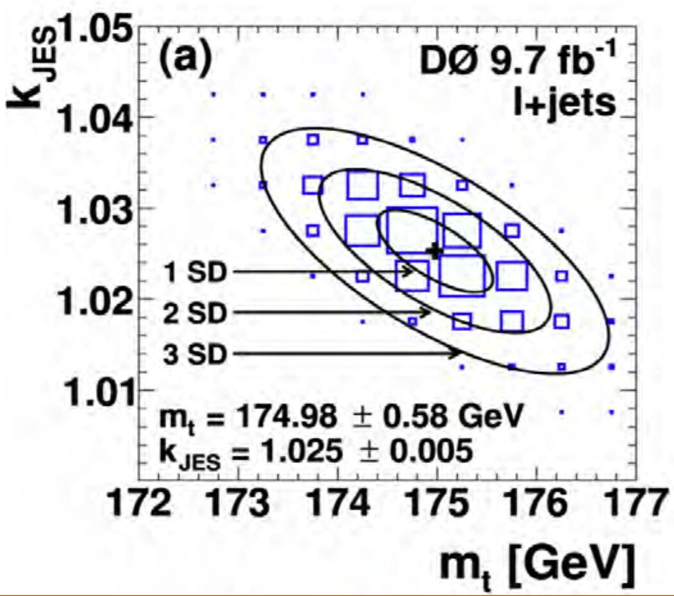
±0.29%

most precise single measurement

Top mass at the Tevatron



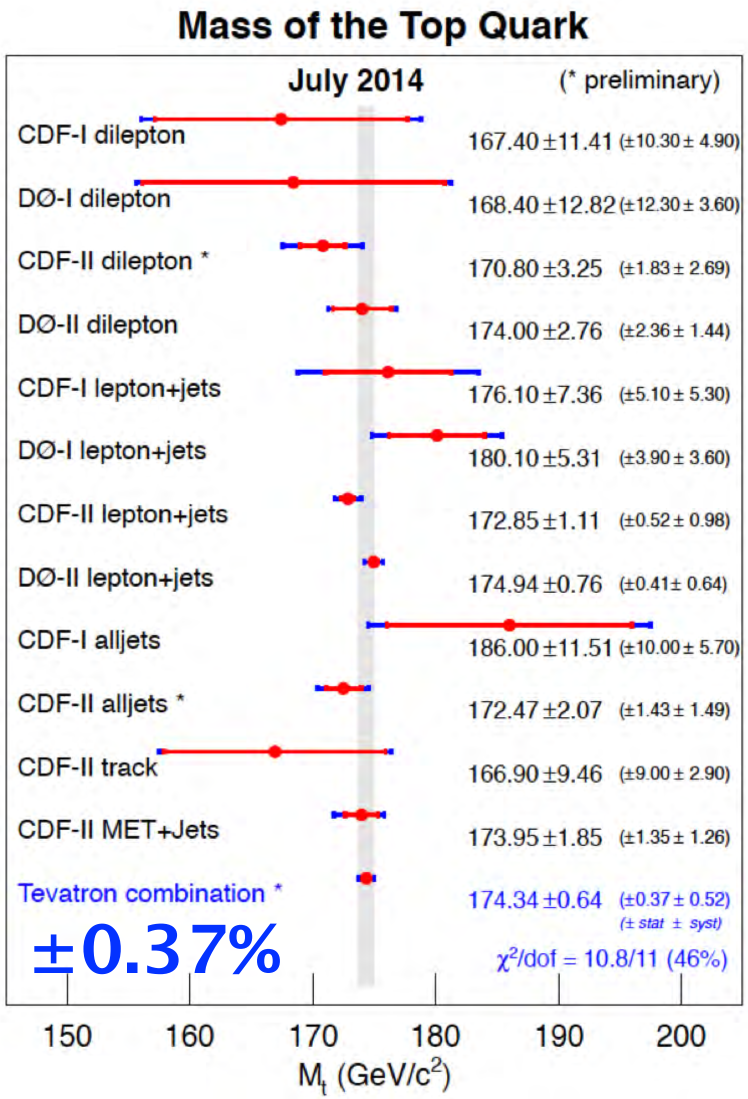
$m_t = 172.85 \pm 0.71$ (stat.) ± 0.85 (syst) GeV



$m_t = 174.98 \pm 0.58$ (stat.) ± 0.49 (syst) GeV

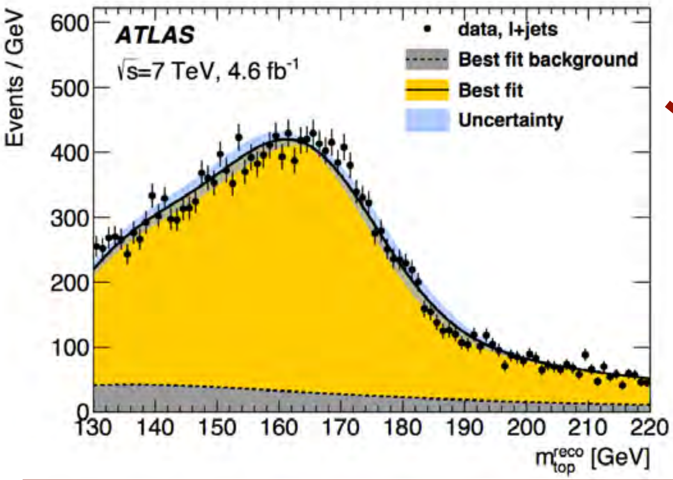
±0.63%

±0.43%



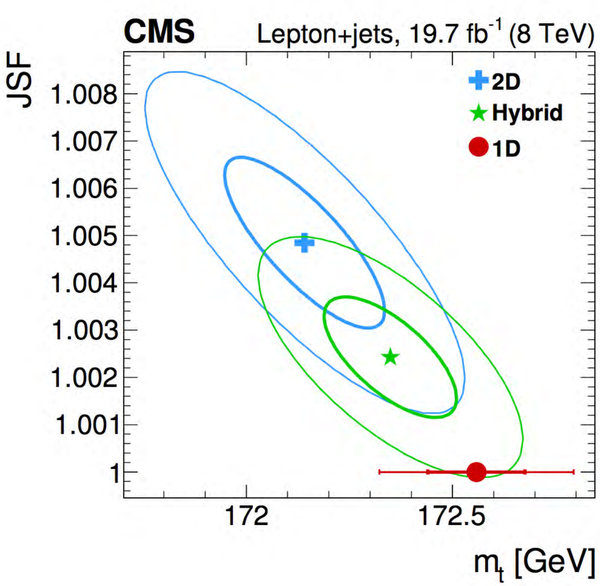
good agreement between all channels...

Top mass at the LHC



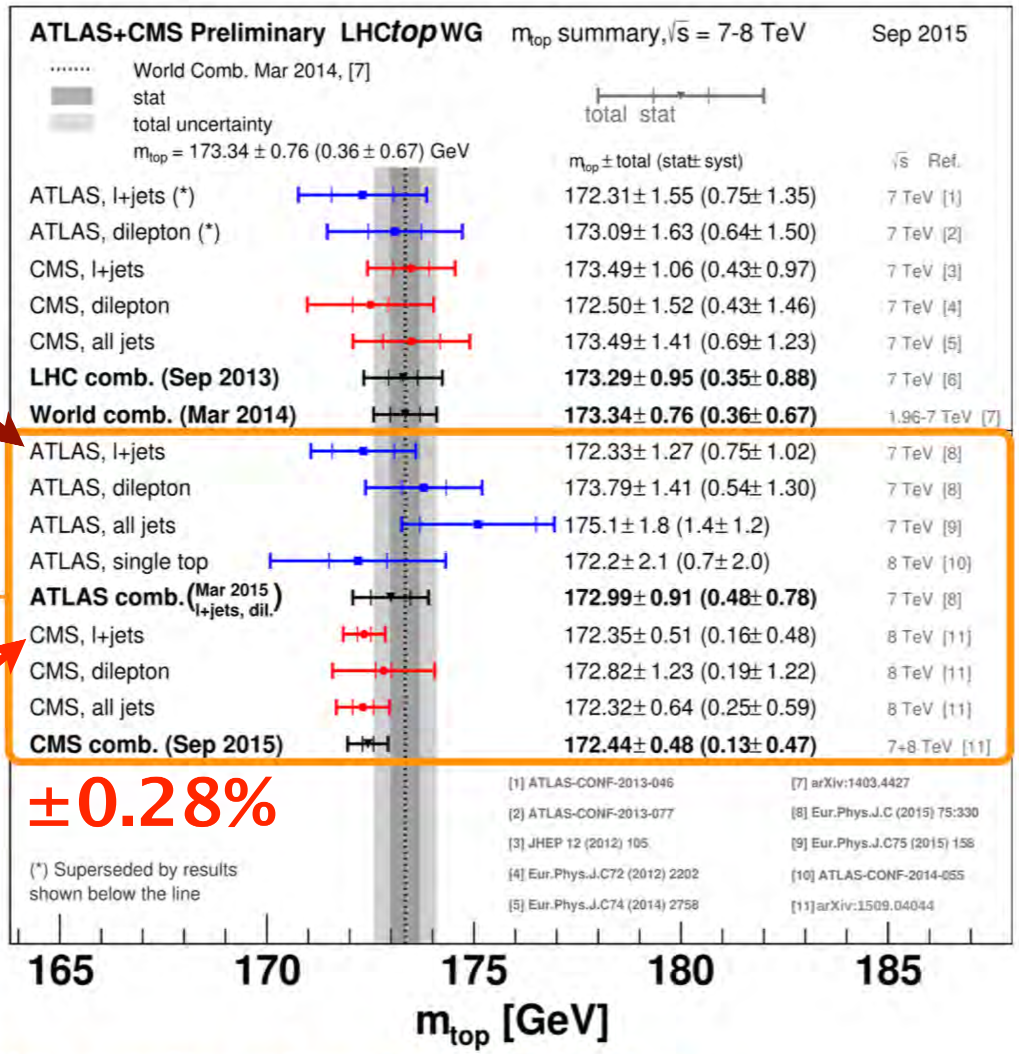
±0.73%

$$m_{\mathrm{top}}^{\ell+\mathrm{jets}} = 172.33 \pm 0.75\,(\mathrm{stat}+\mathrm{JSF}+\mathrm{bJSF}) \pm 1.02\,(\mathrm{syst})\ \mathrm{GeV}$$



±0.29%

$$m_{\mathrm{t}}^{\mathrm{hyb}} = 172.35 \pm 0.16\,(\mathrm{stat{+}JSF}) \pm 0.48\,(\mathrm{syst})\ \mathrm{GeV}$$

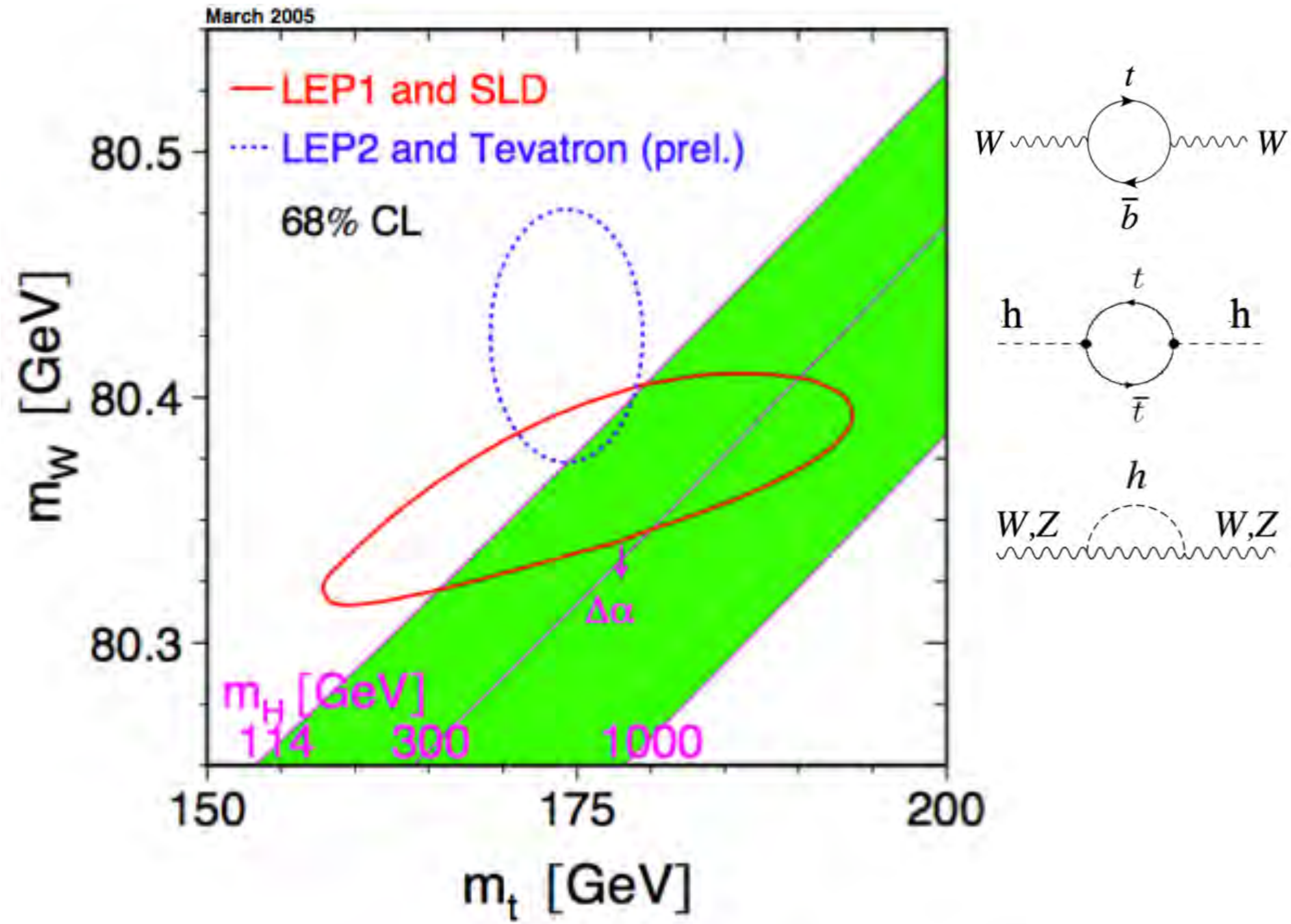


±0.28%

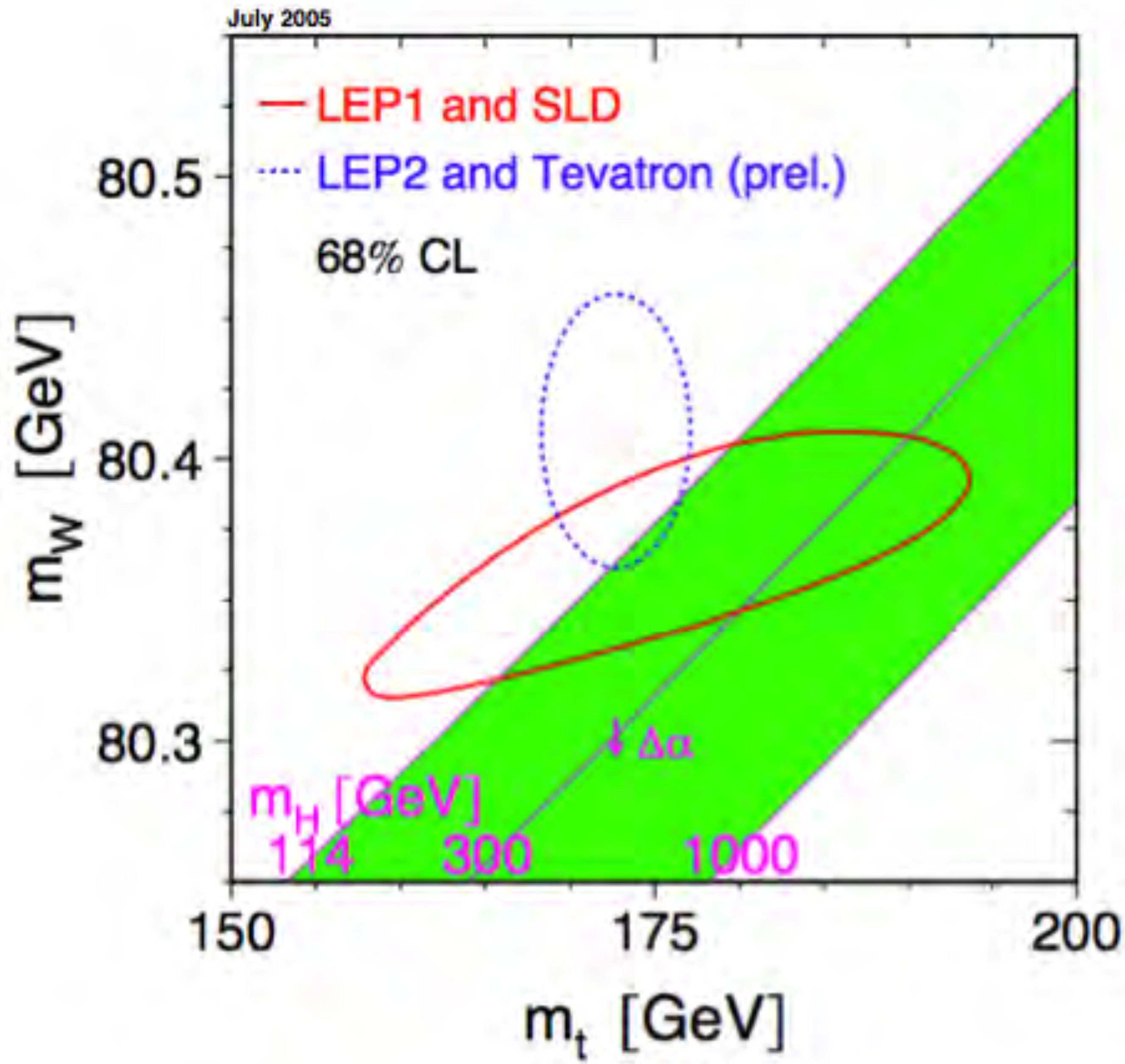
New results waiting for combination!
(in addition to latest results from Tevatron)

→ jet energy scale is crucial

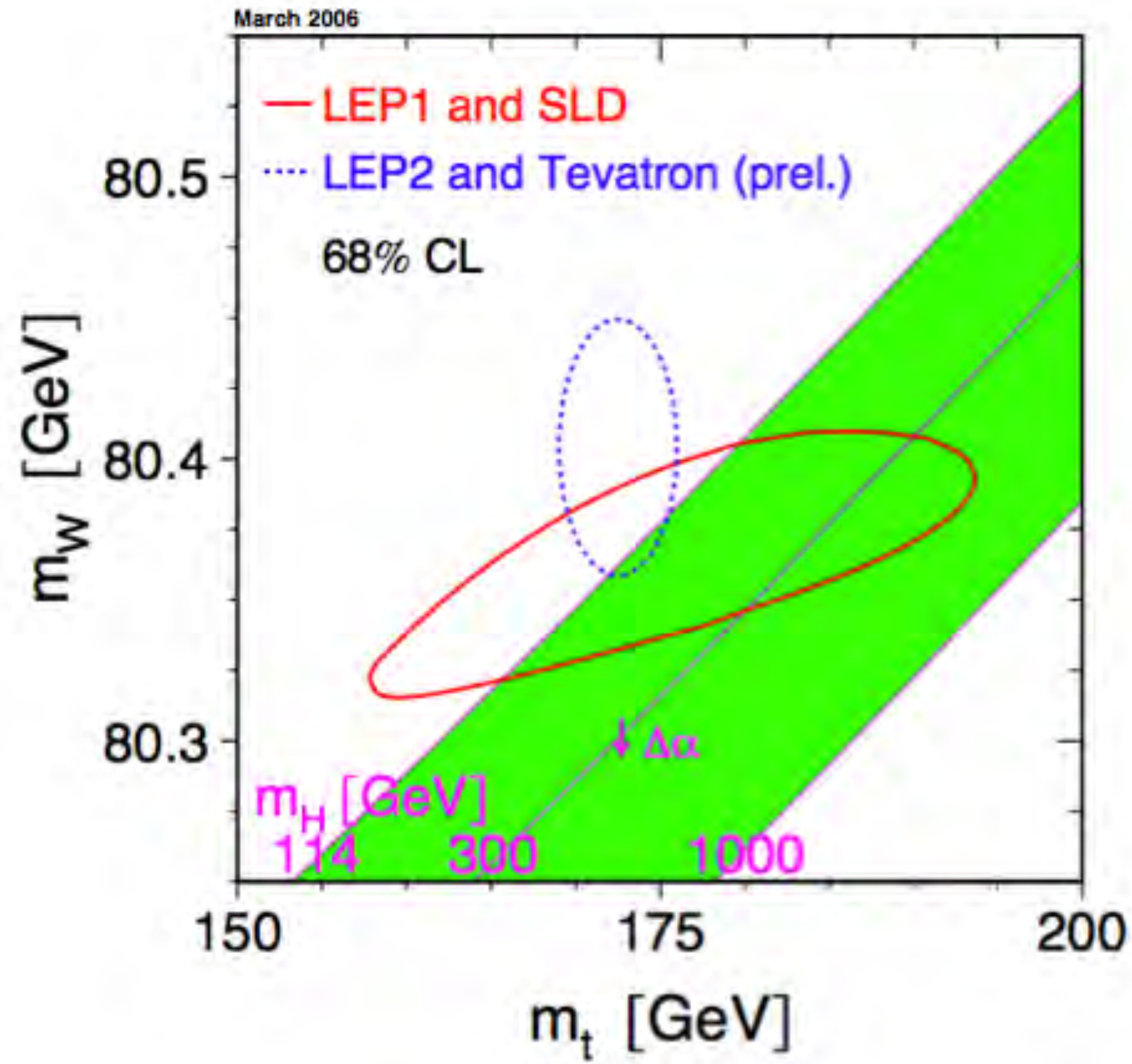
History m_{top} vs. M_W



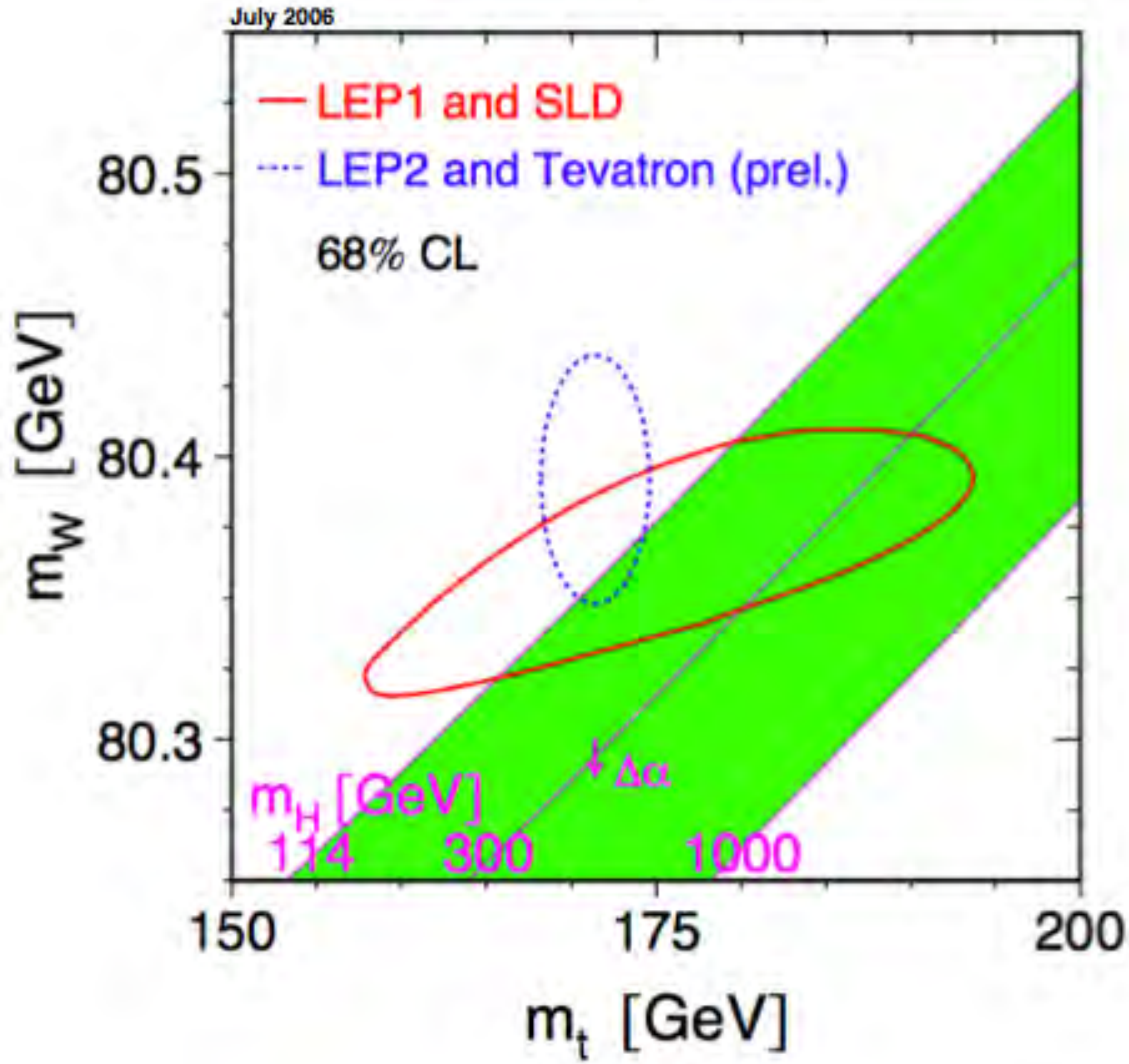
History m_{top} vs. M_W



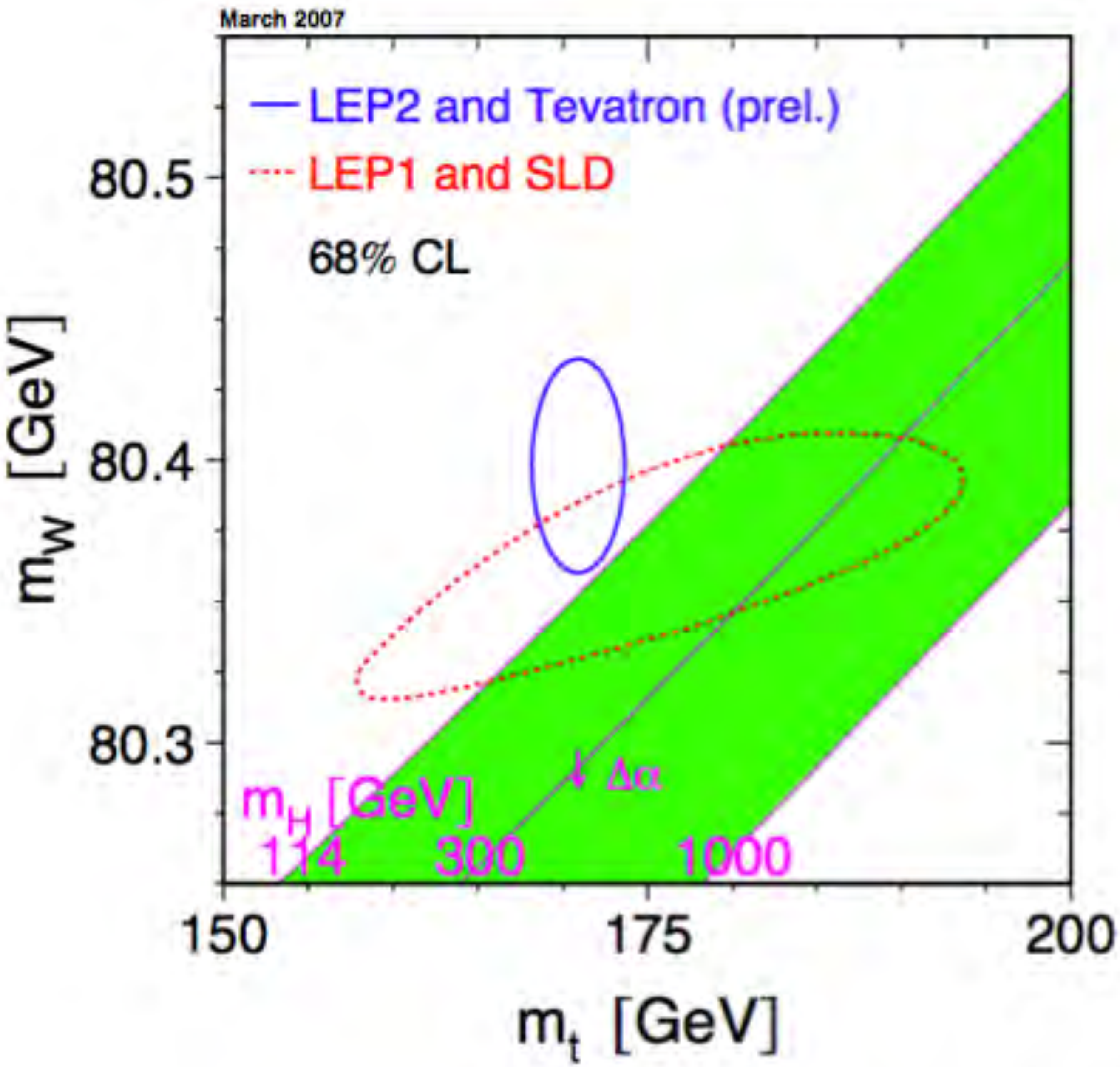
History m_{top} vs. M_W



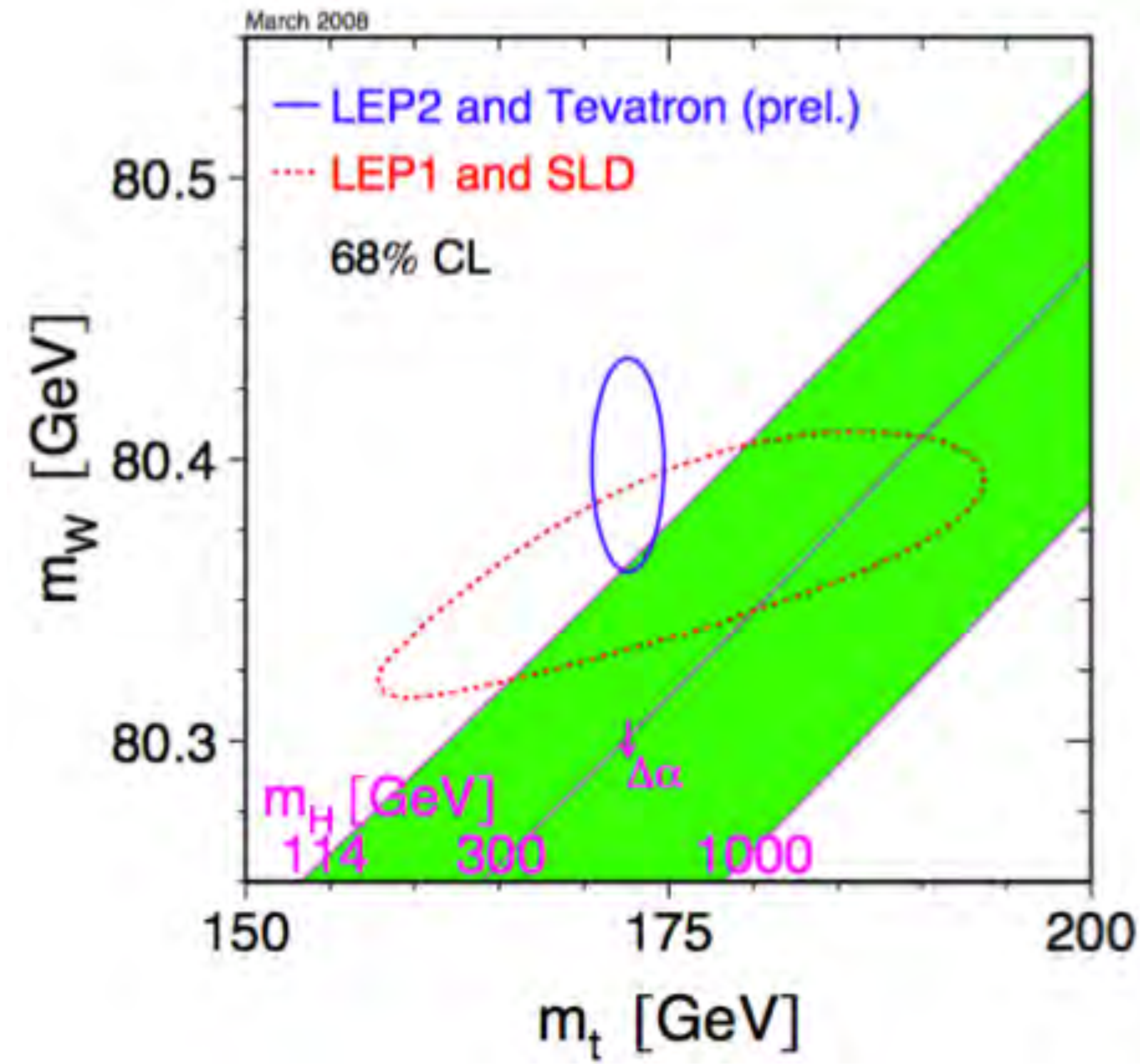
History m_{top} vs. M_W



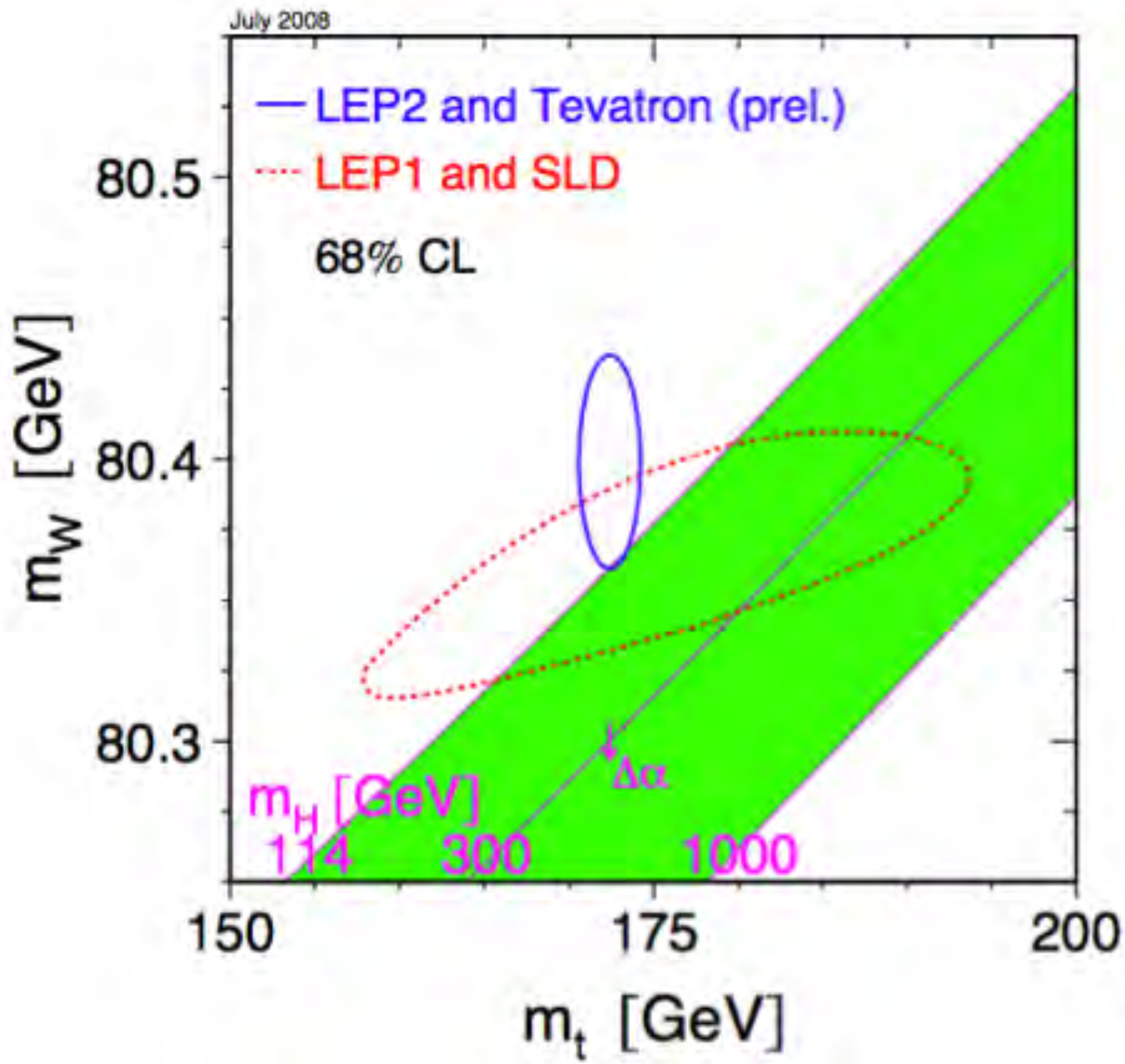
History m_{top} vs. M_W



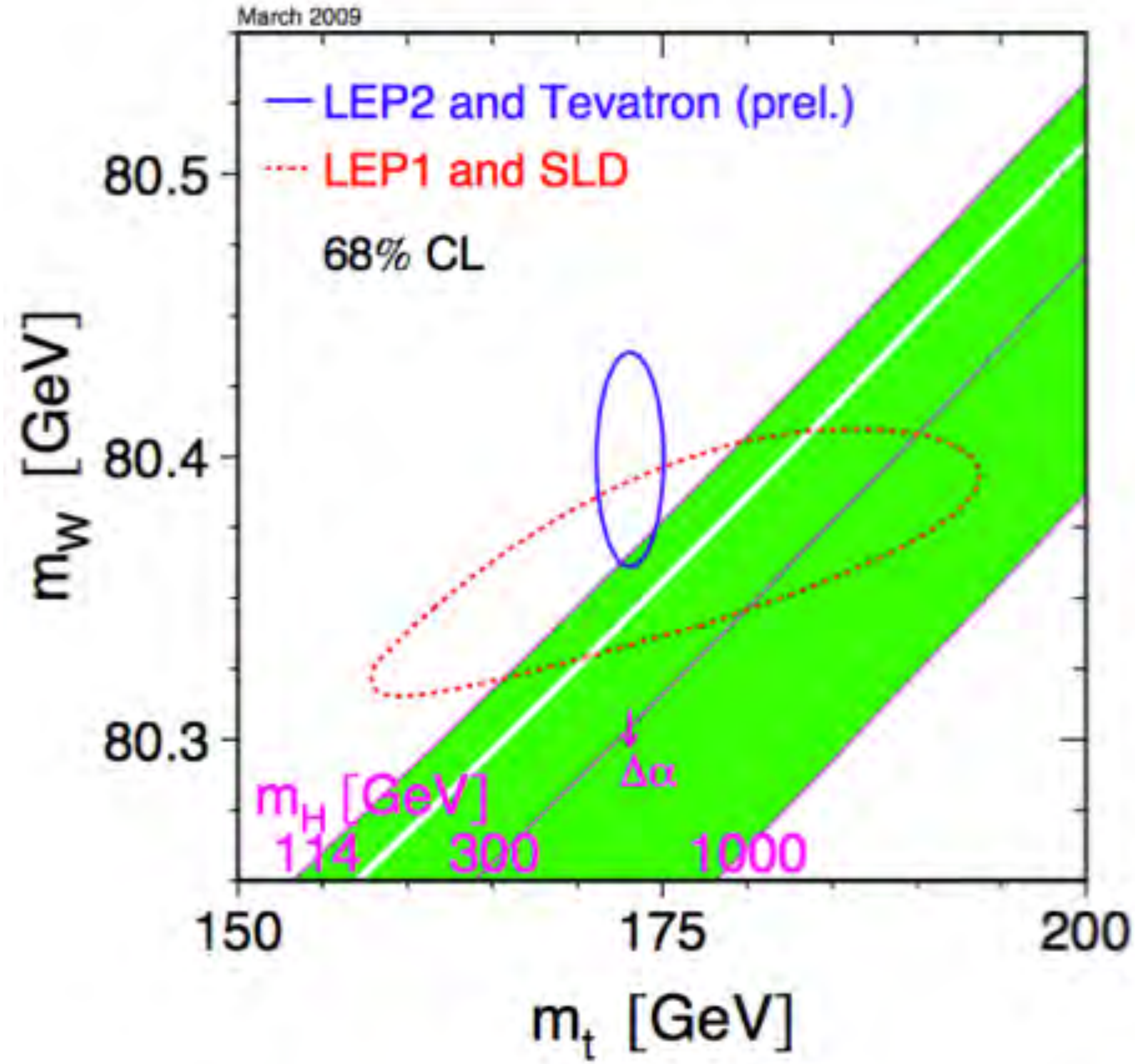
History m_{top} vs. M_W



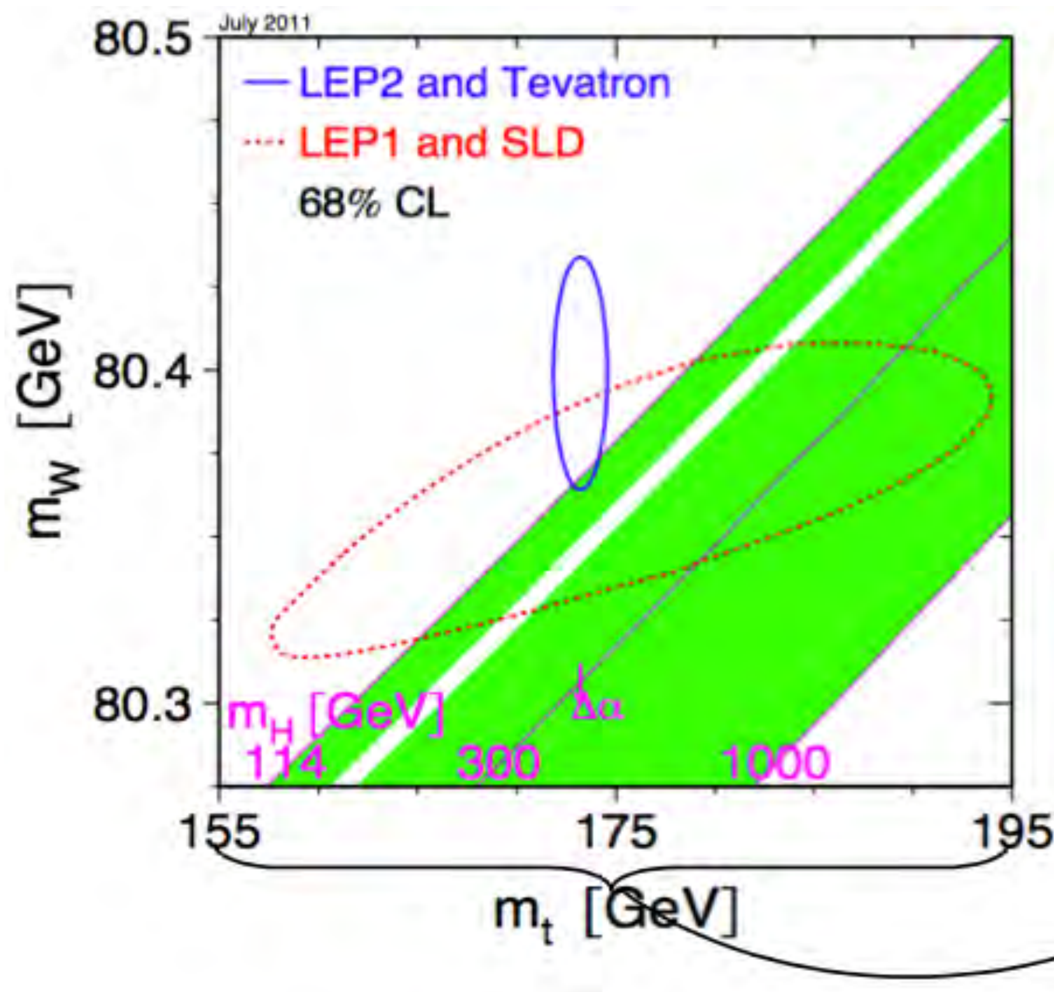
History m_{top} vs. M_W



History m_{top} vs. M_W

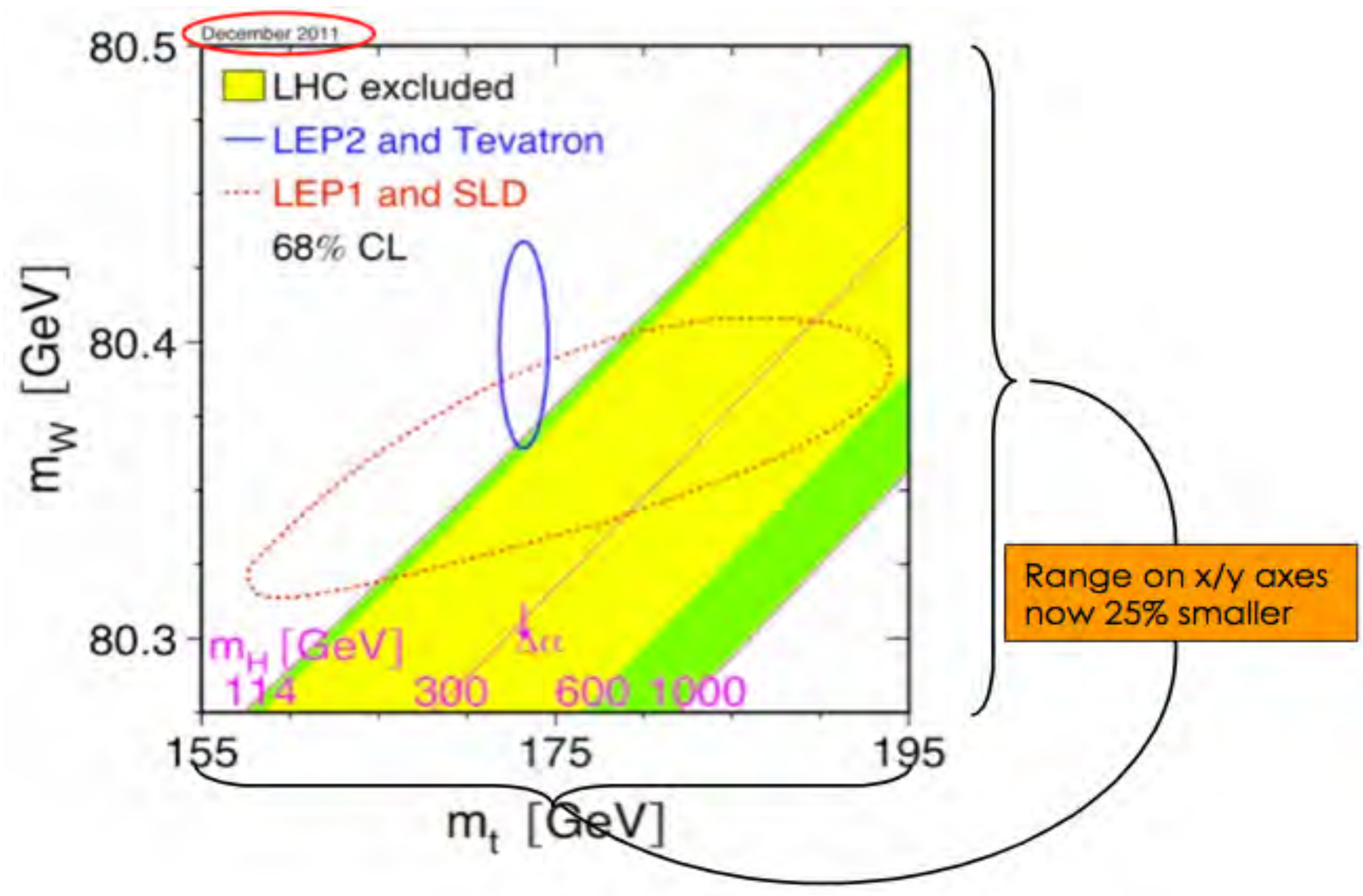


History m_{top} vs. M_W

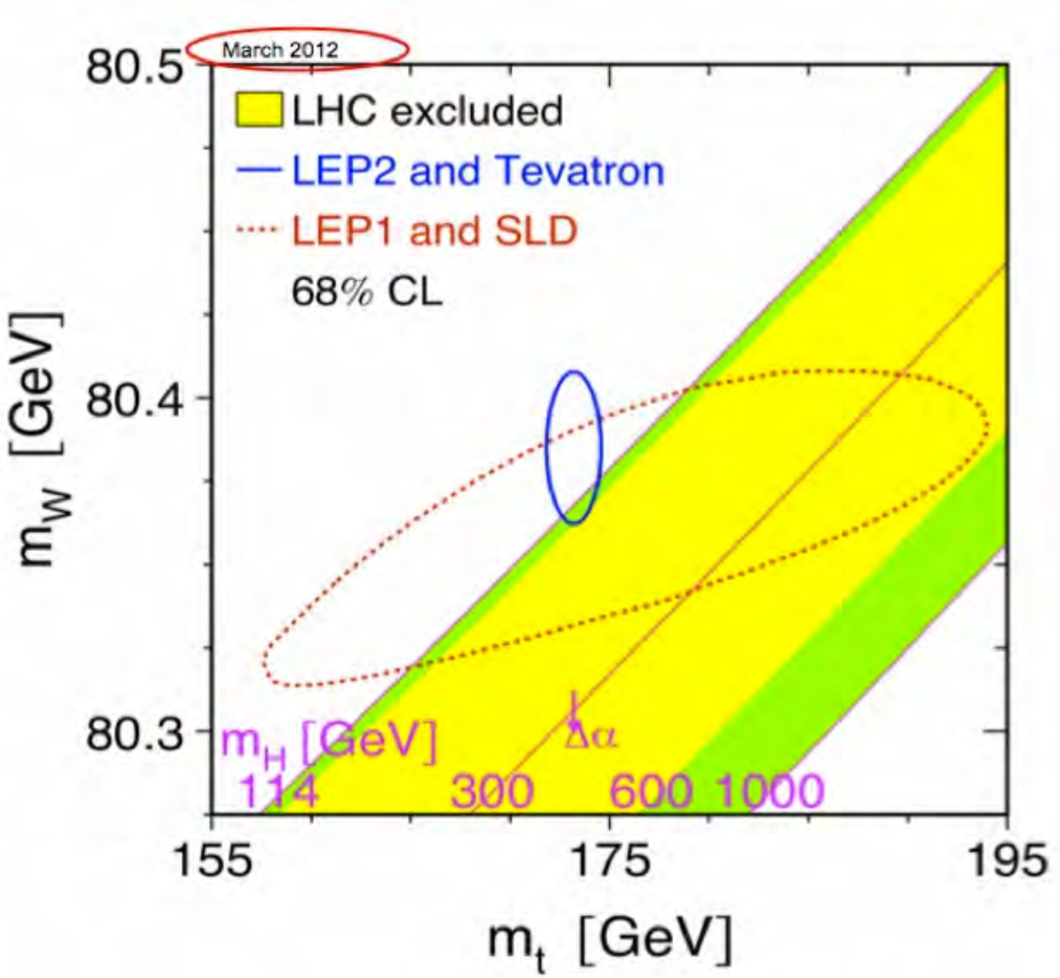


Range on x/y axes now 25% smaller

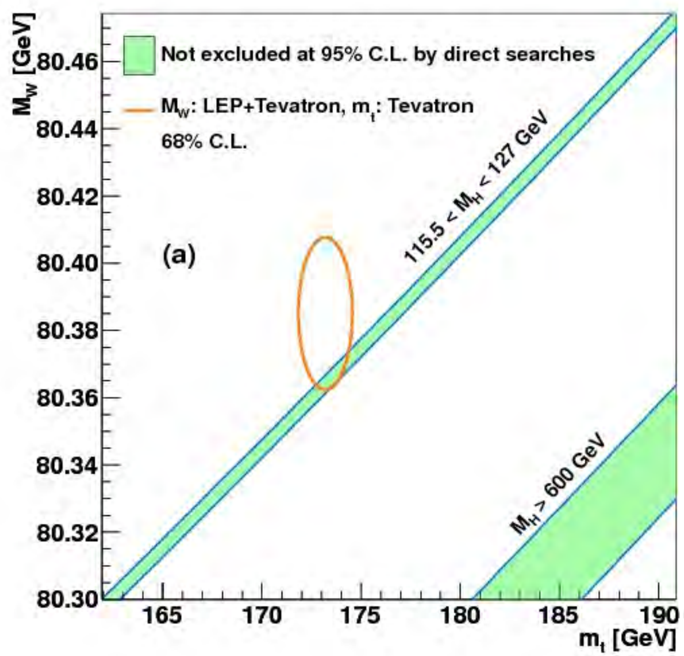
History m_{top} vs. M_W



History m_{top} vs. M_W

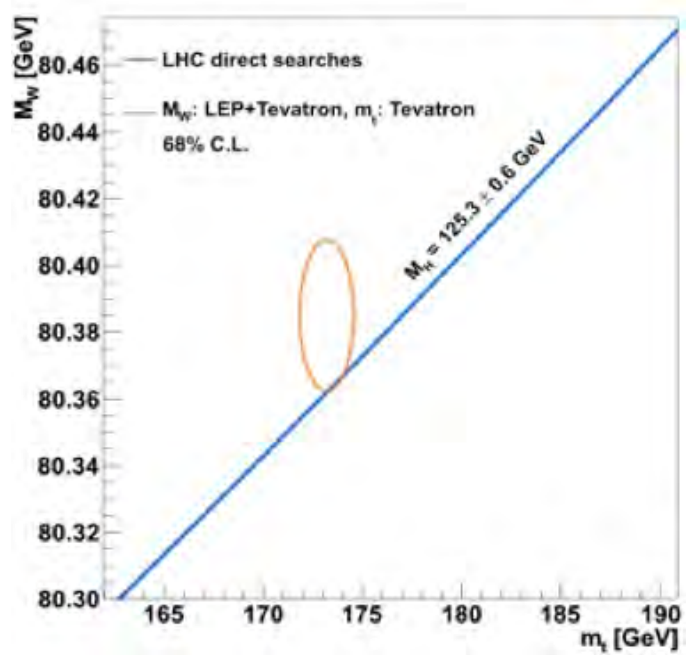


History m_{top} vs. M_W



History m_{top} vs. M_W

July 2012

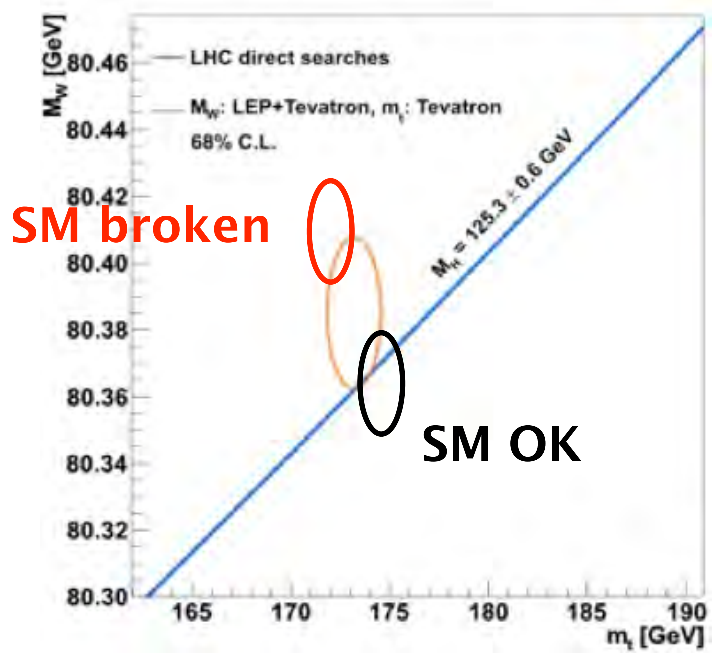


→ Standard Model is self-consistent

History m_{top} vs. M_W

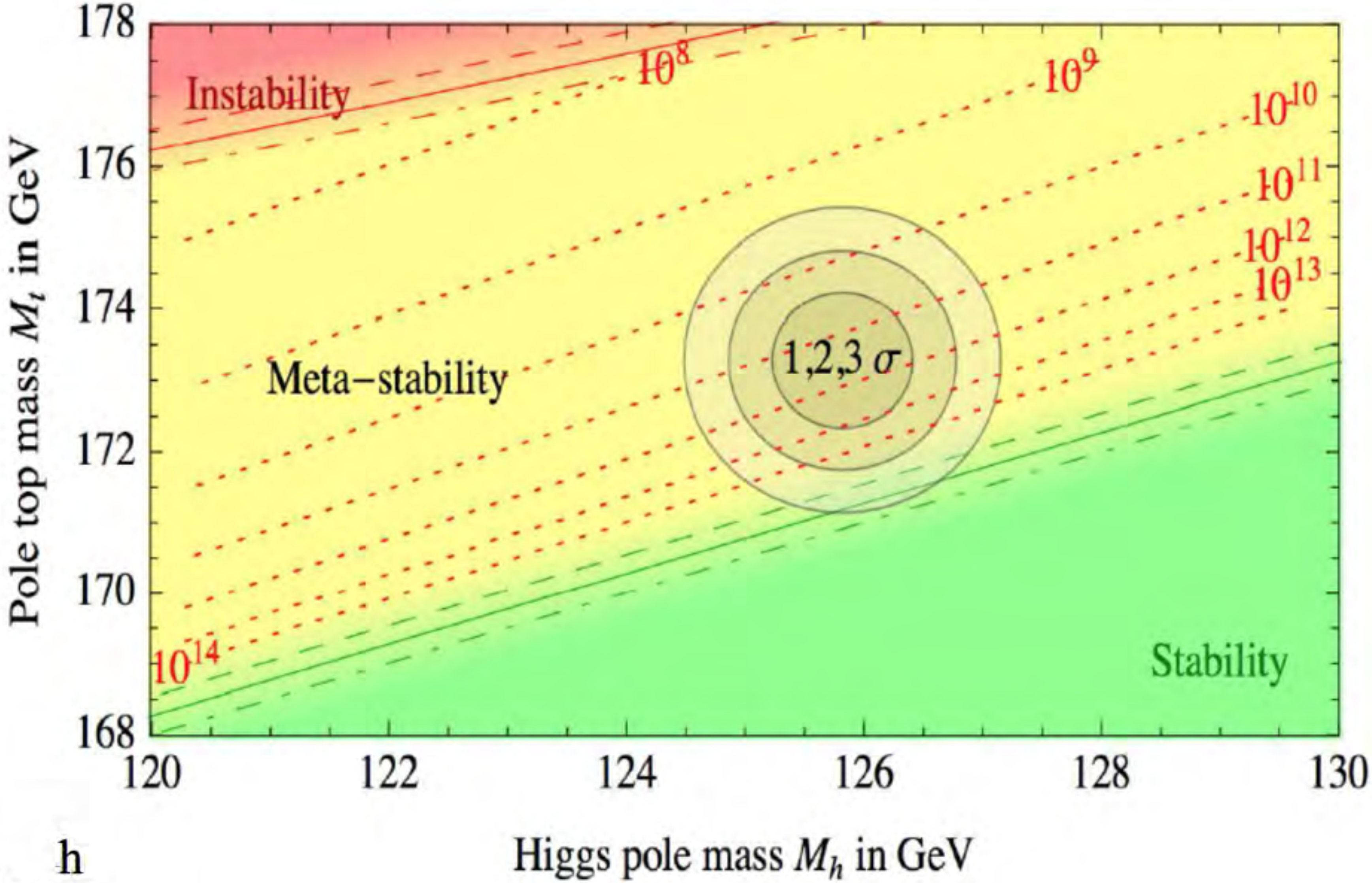
July 2012

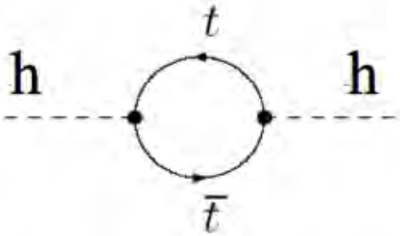
future:
$\Delta(m_W)$=6 MeV



improved W mass measurement is critical

Today: m_{top} vs. M_H





check the "fate of the Universe"

What mass do we measure?

$$\mathcal{L} = \ldots - \bar{\psi} M \psi \left(1 + \frac{H}{v}\right) \ldots$$

m_{top}

- LO QCD: free parameter
- NLO QCD: dependent on the renormalisation scale M

"Bare" parameters of QCD:

$$g_s, m_u, m_d, m_s, m_c, m_b, m_t$$

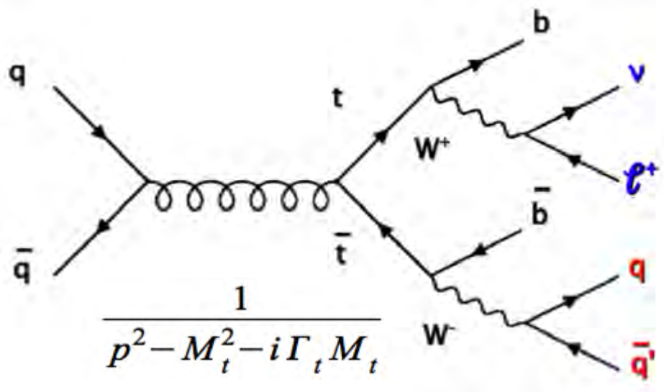
Renormalised parameters of QCD:

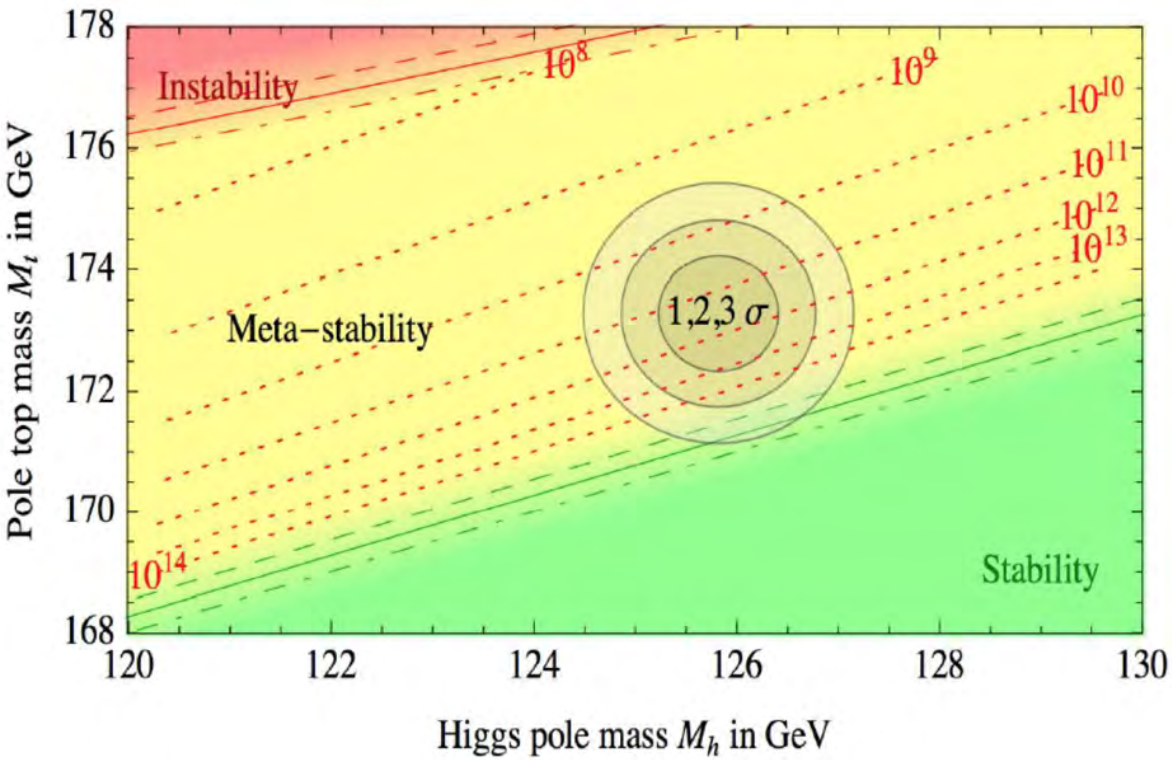
$$g_s(M), m_u(M), m_d(M), m_s(M), m_c(M), m_b(M), m_t(M)$$

the concept of quark mass is convention-dependent!

What mass do we need?

- we measure the MC mass
- we need the pole mass





- we need to calculate:

Scheme-dependent

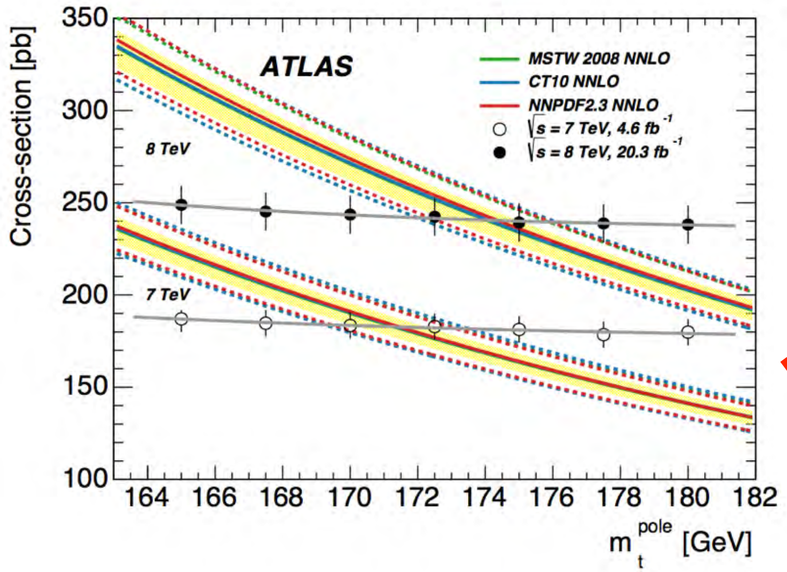
$$m_t^{\mathrm{MC}} = m_t^{\mathrm{quark}} + \Delta$$

~ O(1 GeV)

e.g. pole mass

- every MC generator mass can can correspond to different pole mass

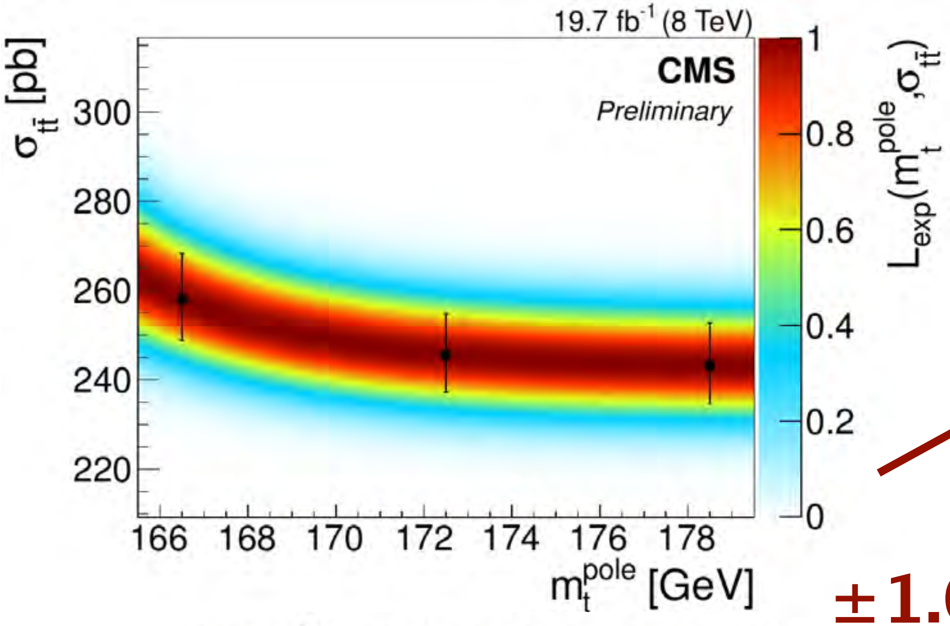
Top Quark Pole Mass



$m_t^{\mathrm{pole}} = 172.9^{+2.5}_{-2.6}\,\mathrm{GeV}\ (\sqrt{s} = 7/8\,\mathrm{TeV})$

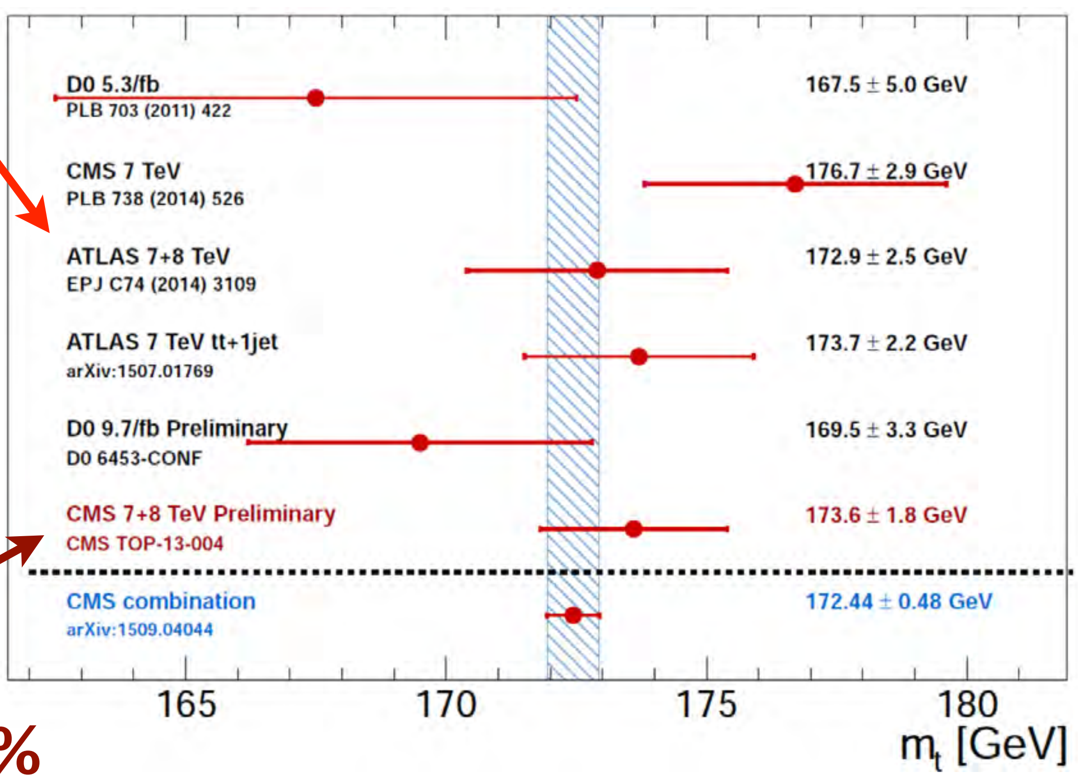
→ pole mass unambiguously!

±1.4%

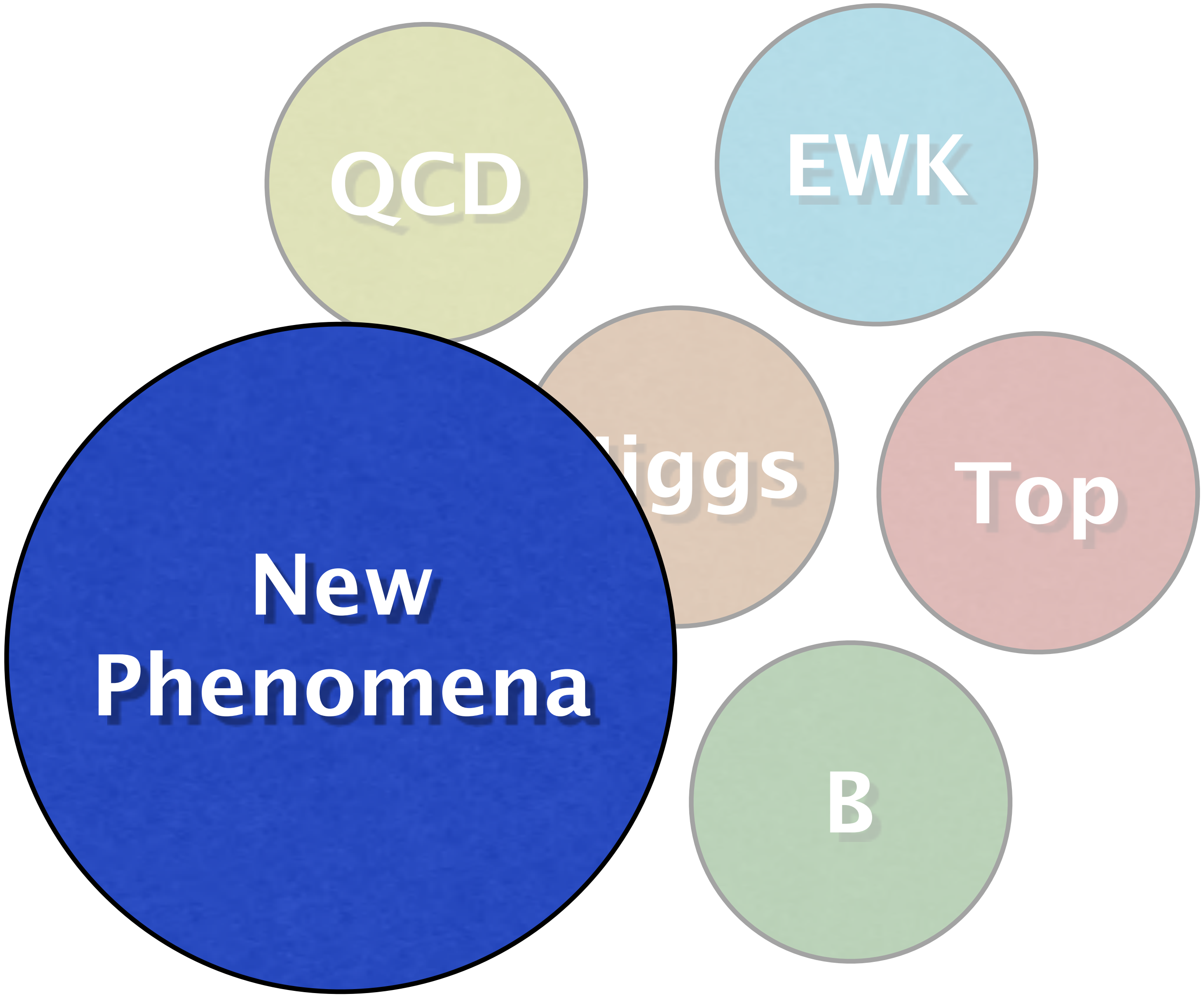


$M_t^{\mathrm{pole}} = 173.6 \pm 1.8$ GeV

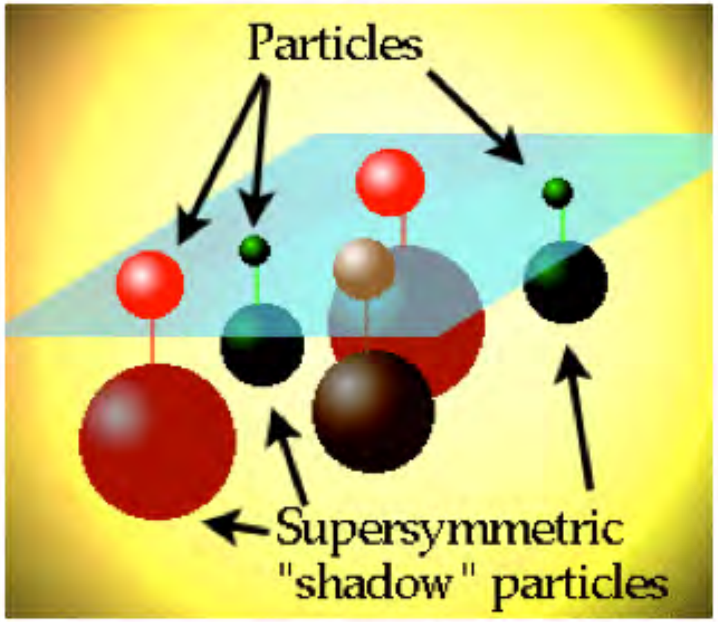
±1.0%



Top Quark Physics Topics



Supersymmetry

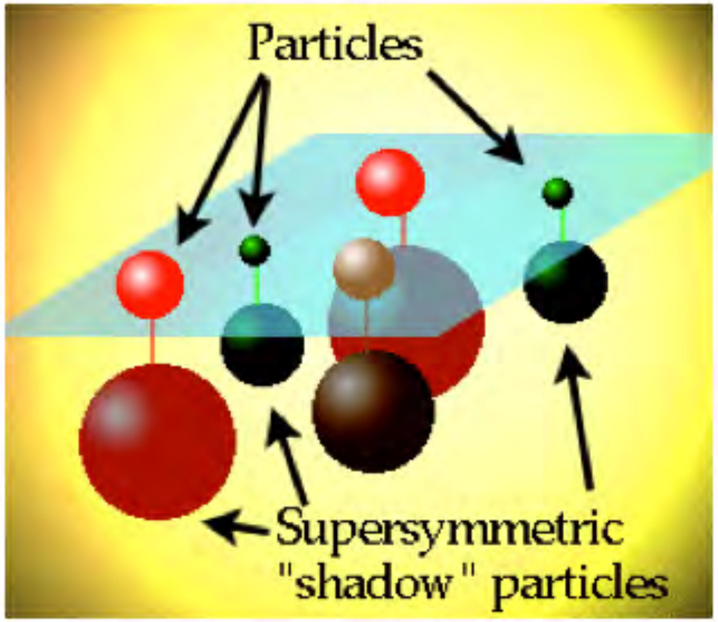


Name	Spin	Superpartner	Spin
Electron	1/2	Selectron	0
Muon	1/2	Smuon	0
Tau	1/2	Stau	0
Neutrino	1/2	Sneutrino	0
Quark	1/2	Squark	0

Name	Spin	Superpartner	Spin
Graviton	2	Gravitino	3/2
Photon	1	Photino	1/2
Gluon	1	Gluino	1/2
$W^{+,-}$	1	$\text{Wino}^{+,-}$	1/2
Z^0	1	Zino	1/2
Higgs	0	Higgsino	1/2

remedies shortcomings of SM:
e.g. dark matter candidate

Supersymmetry



Name	Spin	Superpartner	Spin
Electron	1/2	Selectron	0
Muon	1/2	Smuon	0
Tau	1/2	Stau	0
Neutrino	1/2	Sneutrino	0
Quark	1/2	Squark	0

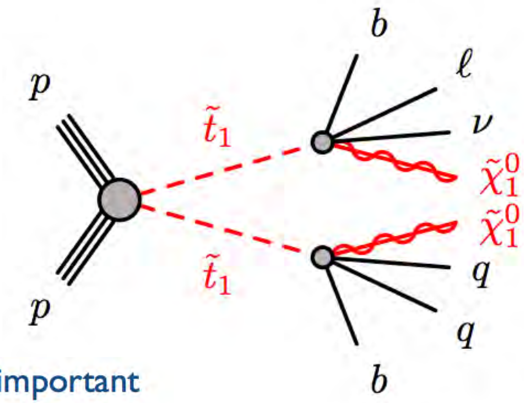
$\tilde{t}$

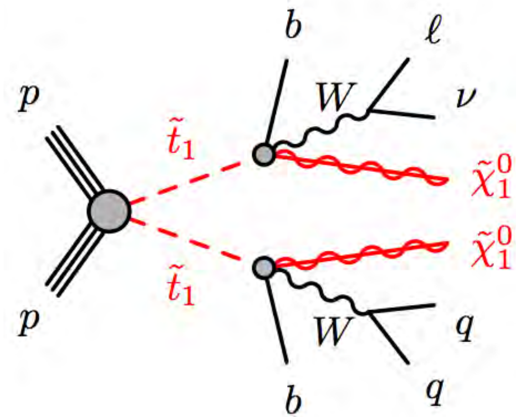
Name	Spin	Superpartner	Spin
Graviton	2	Gravitino	3/2
Photon	1	Photino	1/2
Gluon	1	Gluino	1/2
$W^{+,-}$	1	$\text{Wino}^{+,-}$	1/2
Z^0	1	Zino	1/2
Higgs	0	Higgsino	1/2

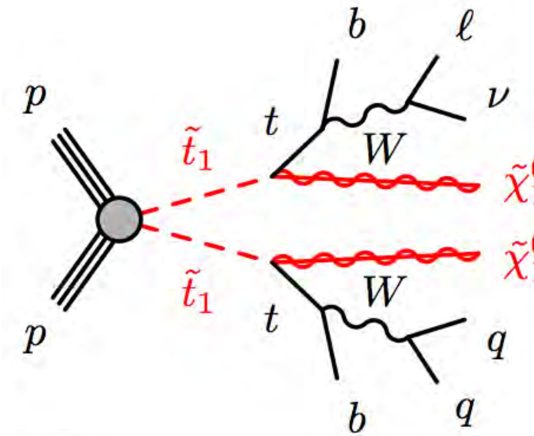
$\tilde{\chi}^0$

remedies shortcomings of SM:
e.g. dark matter candidate

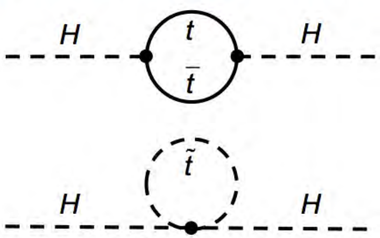
Direct stop searches



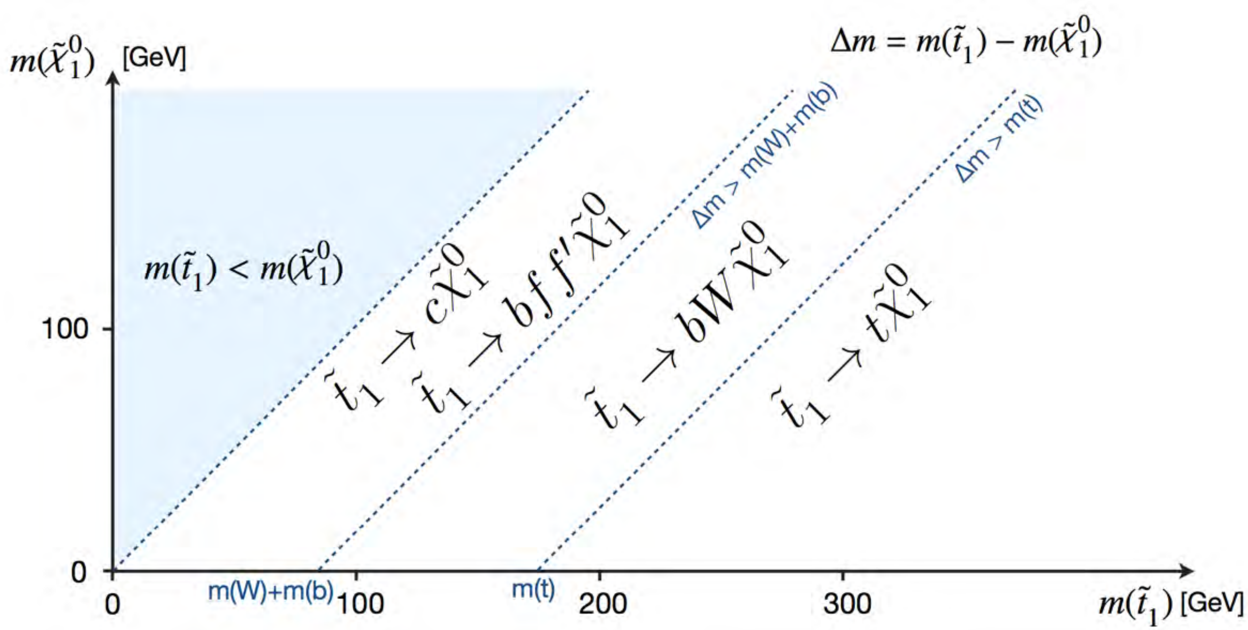




Recall: **Top loop** is the most important contribution in Higgs virtual corrections:

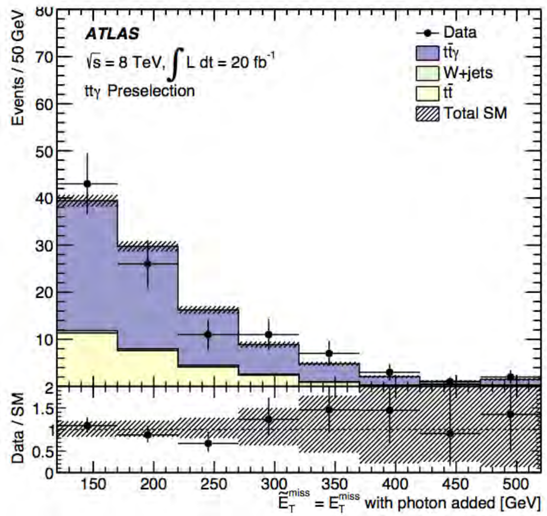


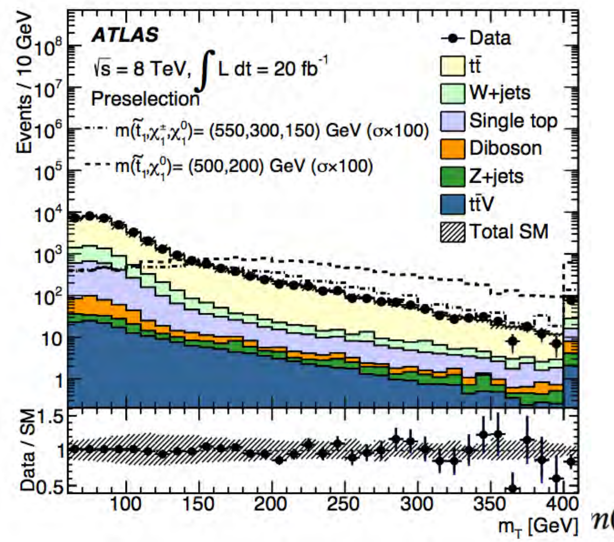
small stop mass is natural

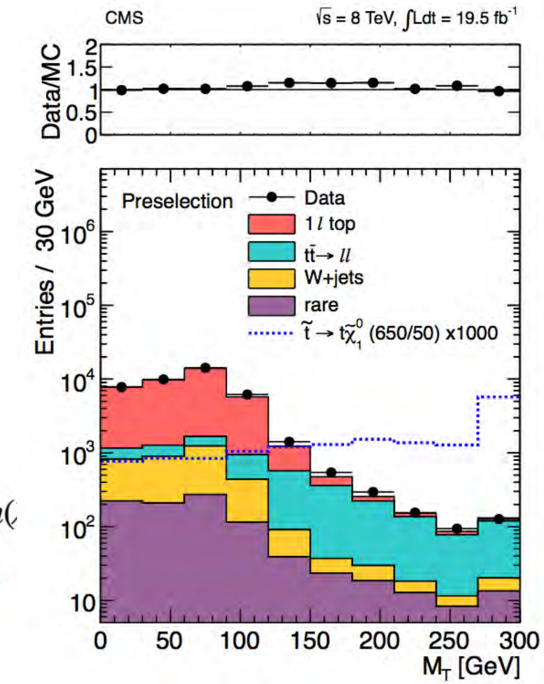


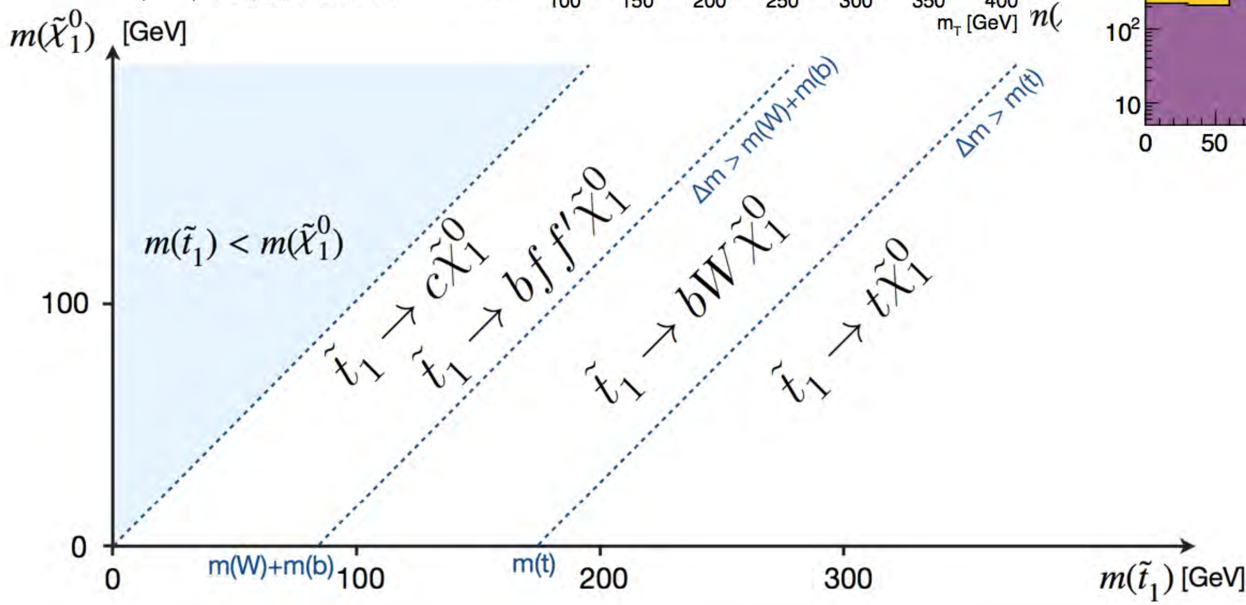
we check every little corner...

Direct stop searches



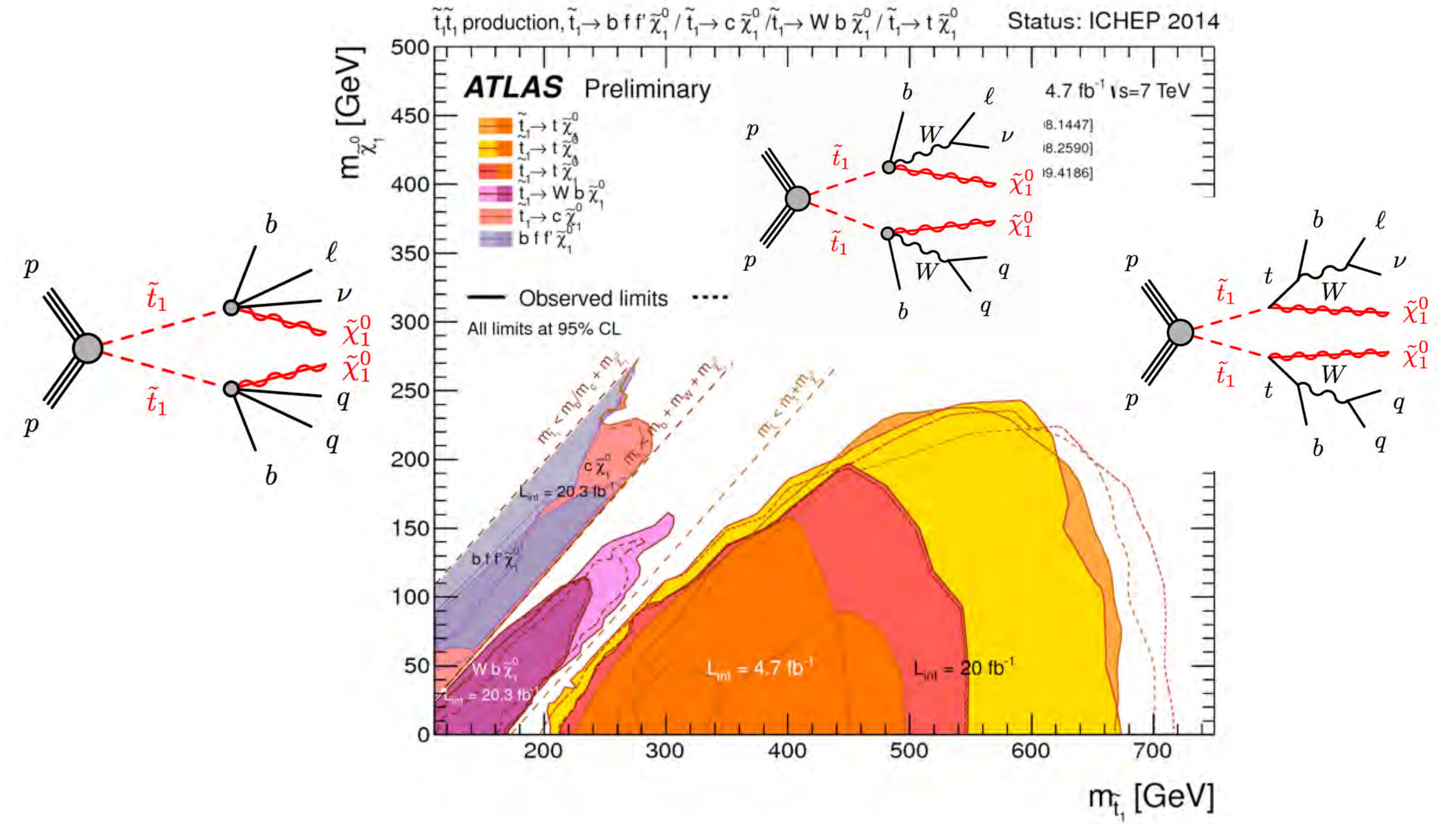






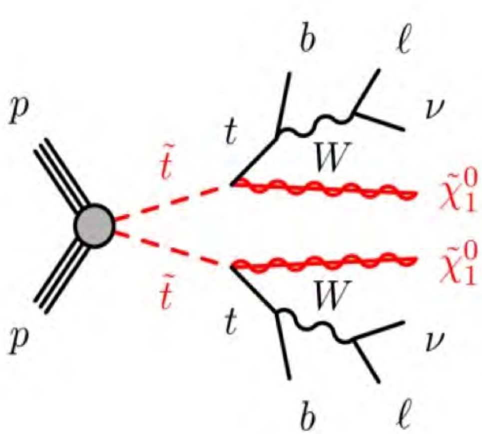
we check every little corner...

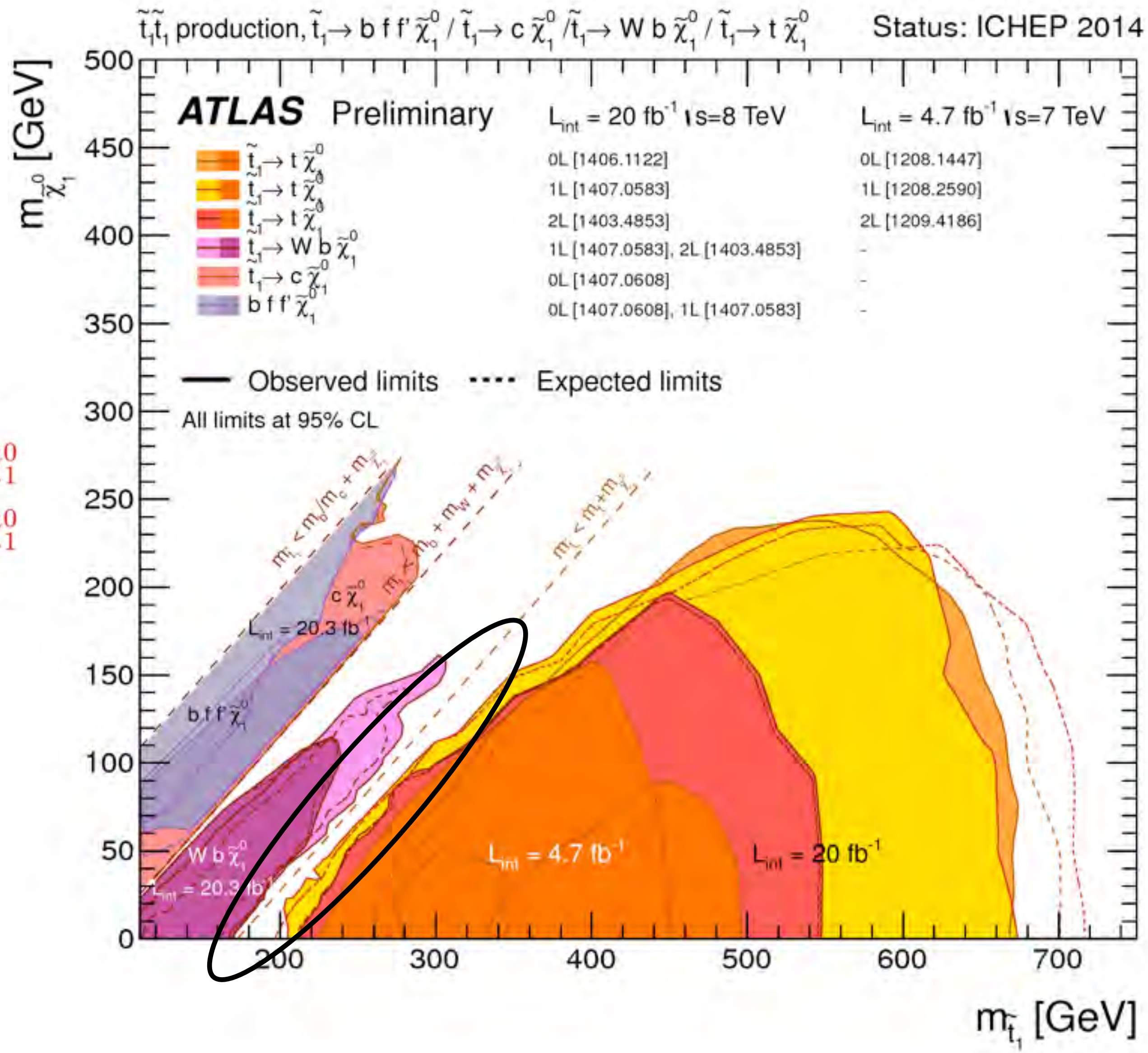
Direct stop searches



we check every little corner...

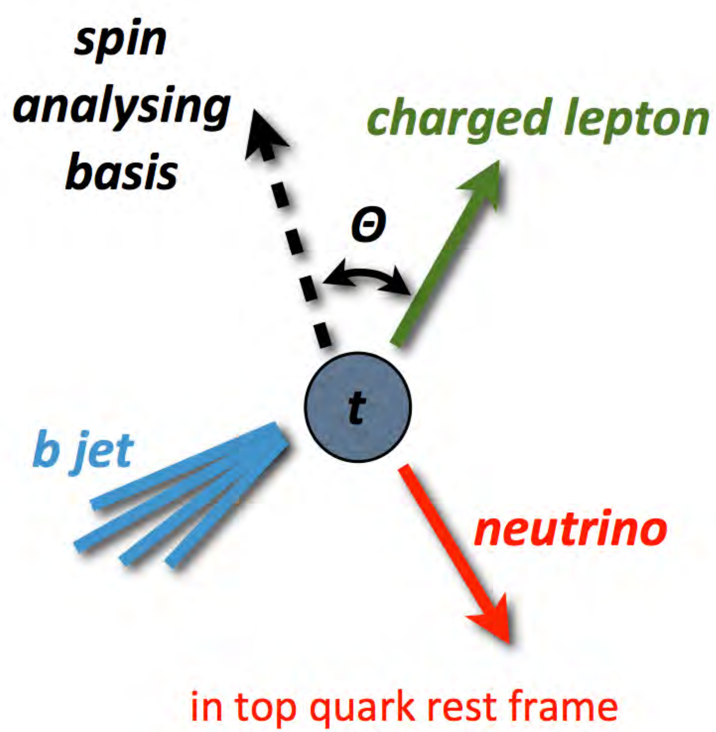
"Stealth" Stop Quarks





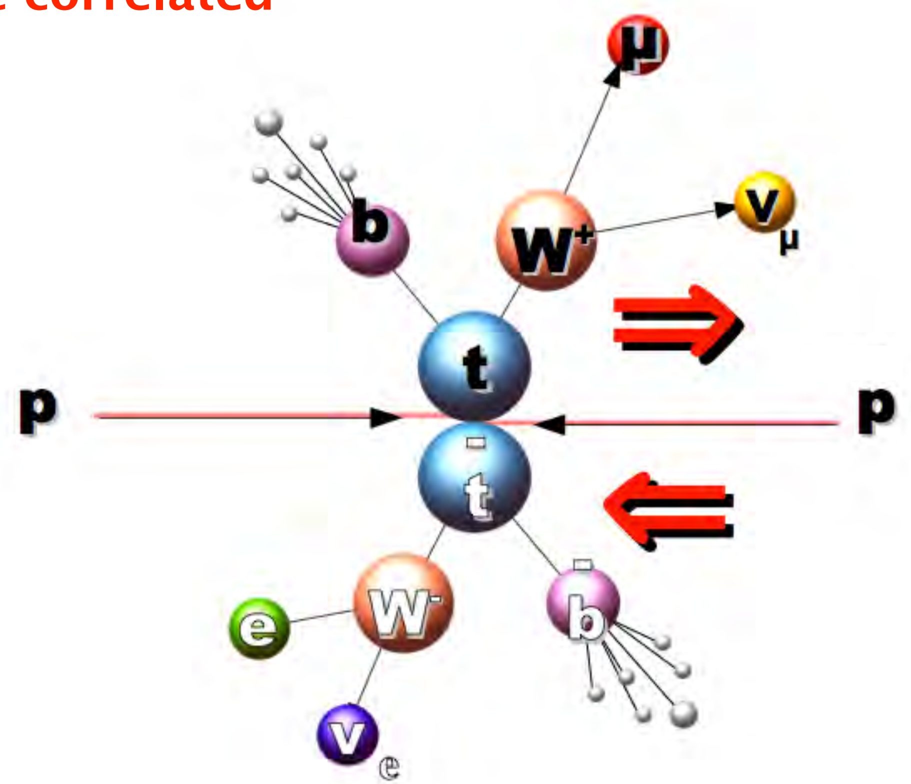
we check every little corner...

Top Pair Spin Correlation



- top quark: discovered in 1995 by CDF&DØ
- does the top quark have spin 1/2?
- top quark pair production: top quarks are not polarised, but spin of top and anti-top quarks are correlated

$$\boxed{A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}}$$

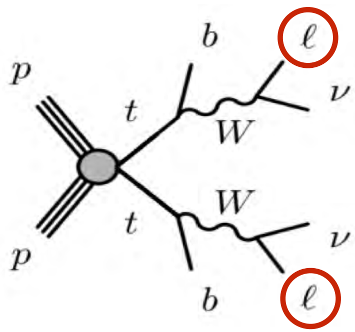


- measure $t\bar{t}$ spin correlation: consistent with SM prediction for a spin 1/2 particle?

Spin Correlation at the LHC

arXiv:1412.4742

- first measurement of spin correlation between top and anti-top quark in dilepton final states at the LHC at 8 TeV
- azimuthal angle between charged leptons in laboratory frame: sensitive and simple!

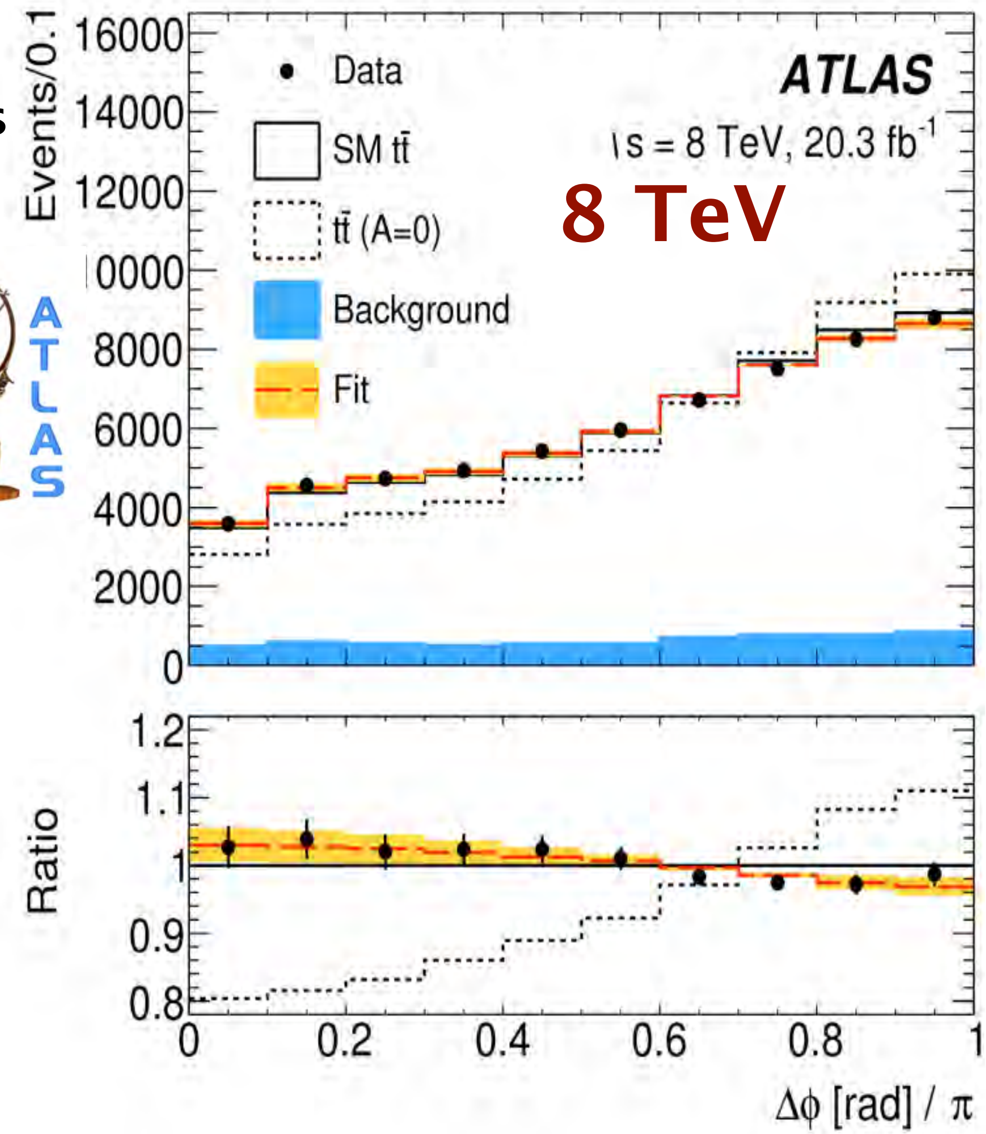


ATLAS

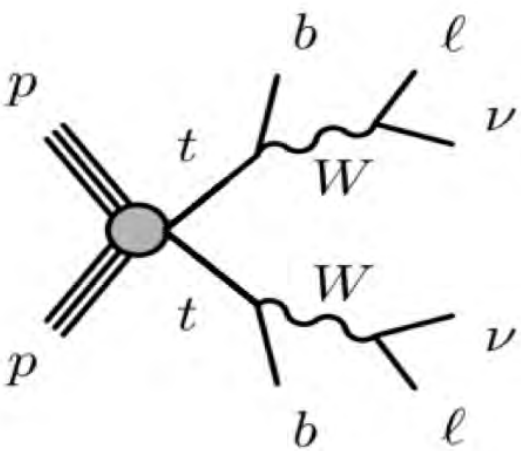
$\boxed{A_{\text{helicity}} = 0.38 \pm 0.04}$ ±12%

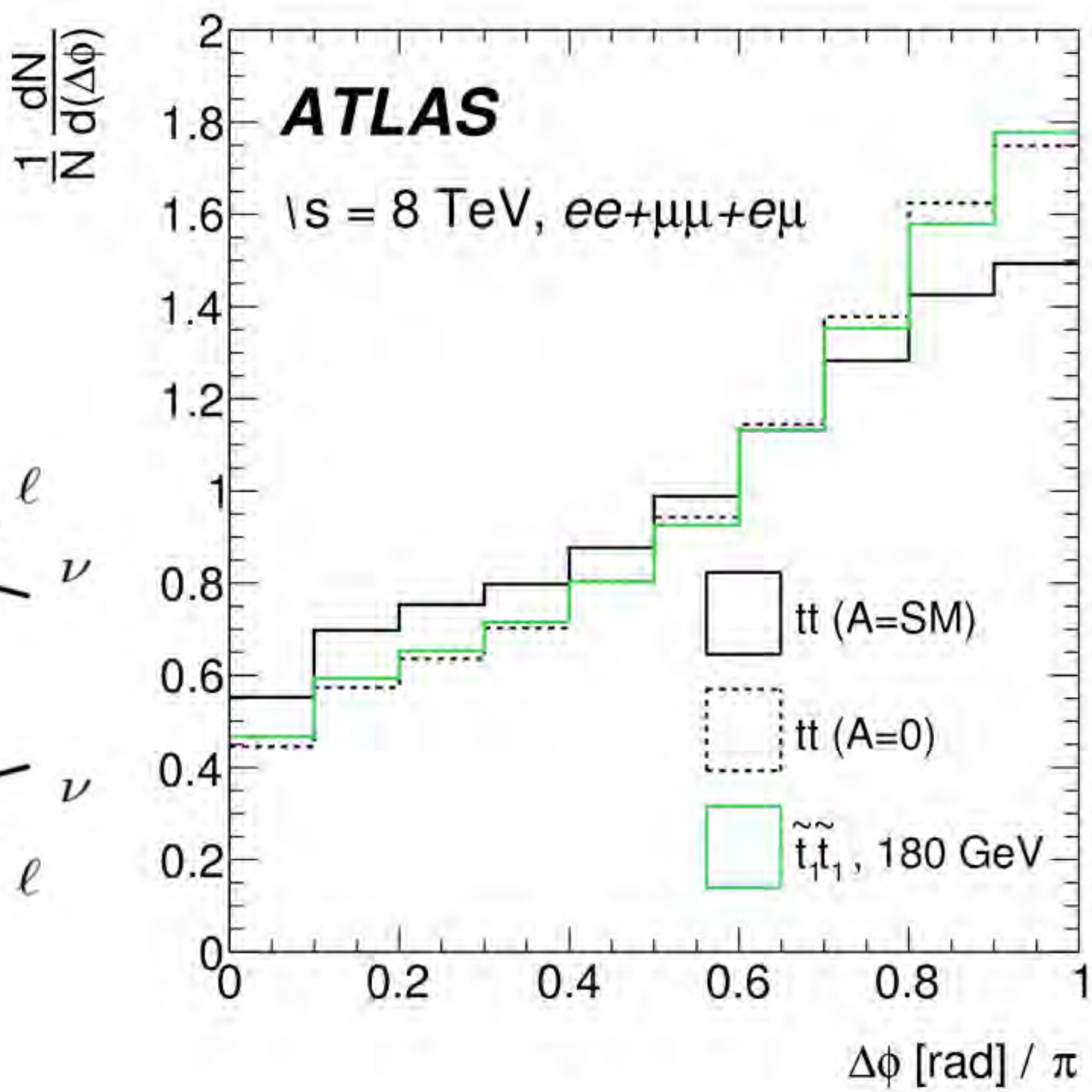
(=0.32 in NLO QCD)

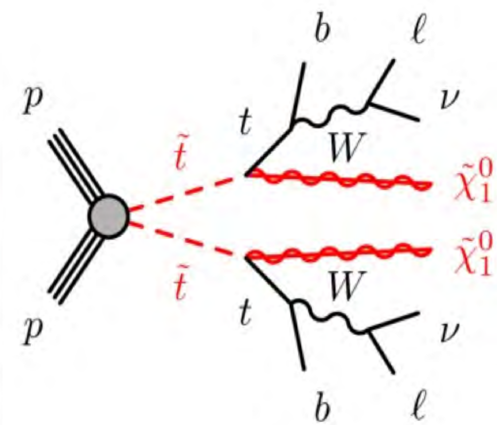
→ correlation agrees with SM spin 1/2 hypothesis



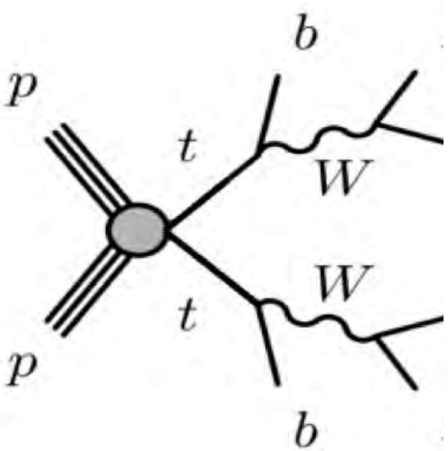
Spin correlations for “Stealth” Stop

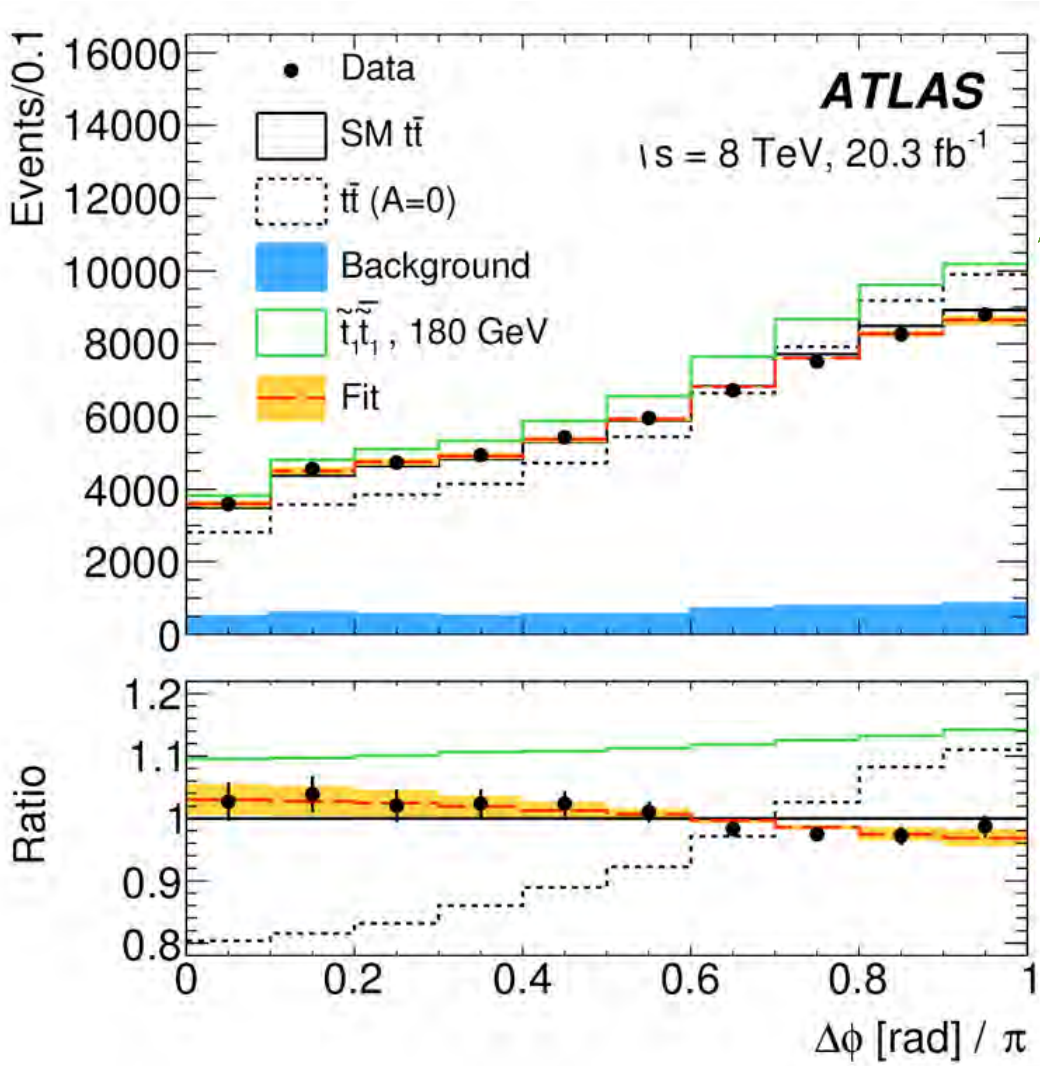


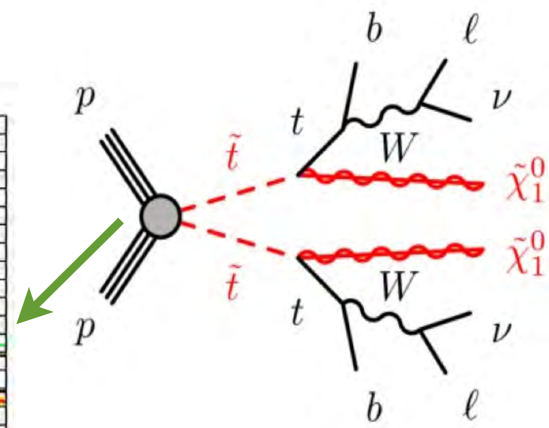




Spin correlations for "Stealth" Stop

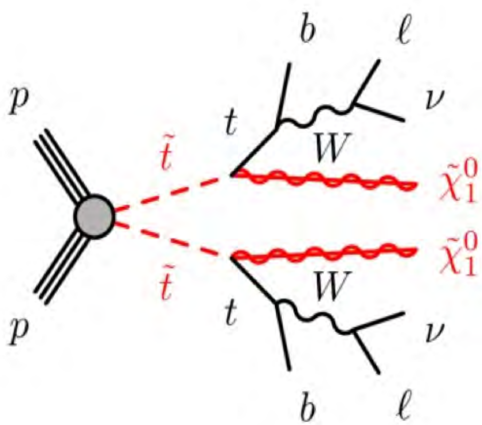


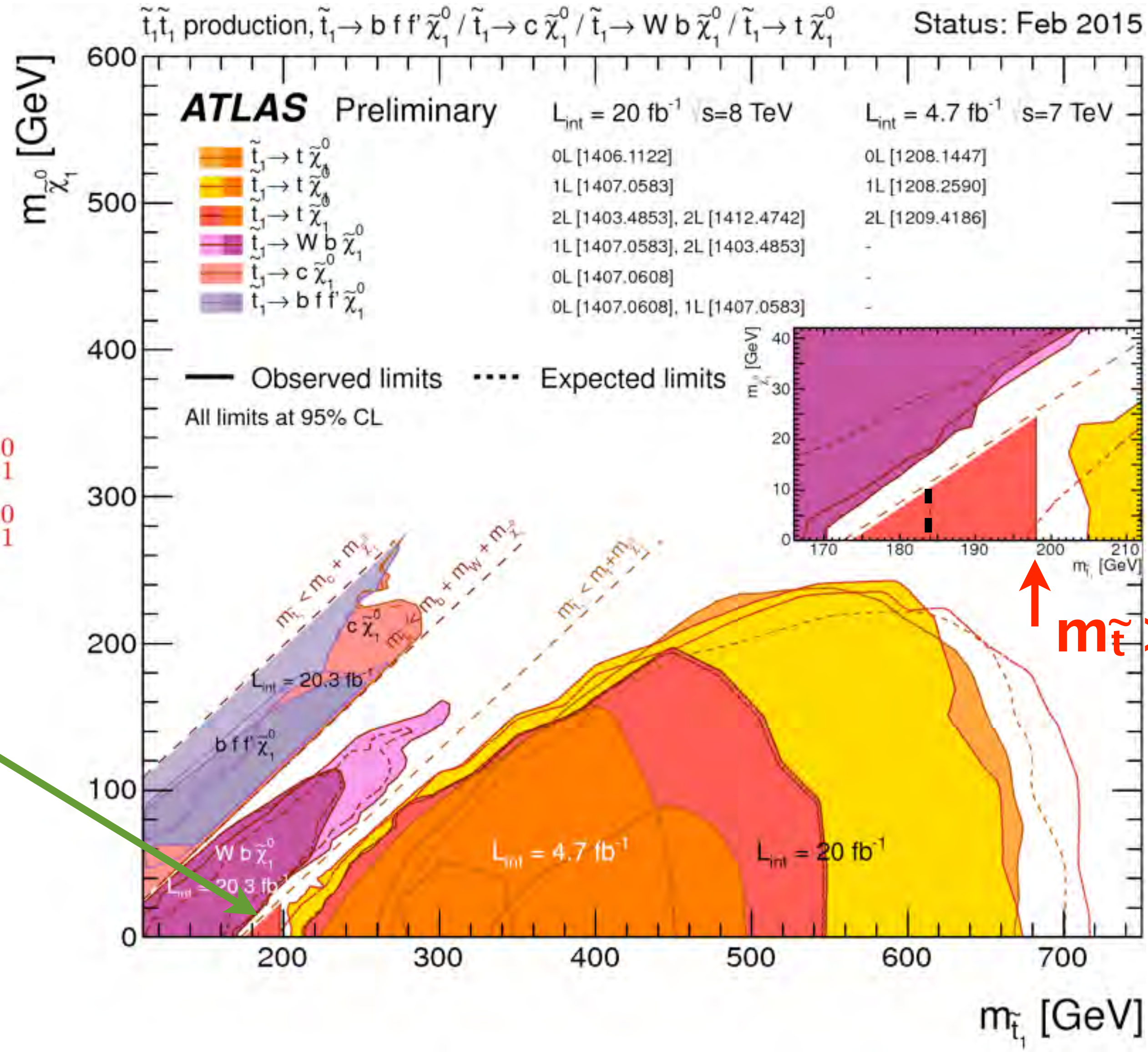




→ **no hint of stop quarks**

Direct stop searches

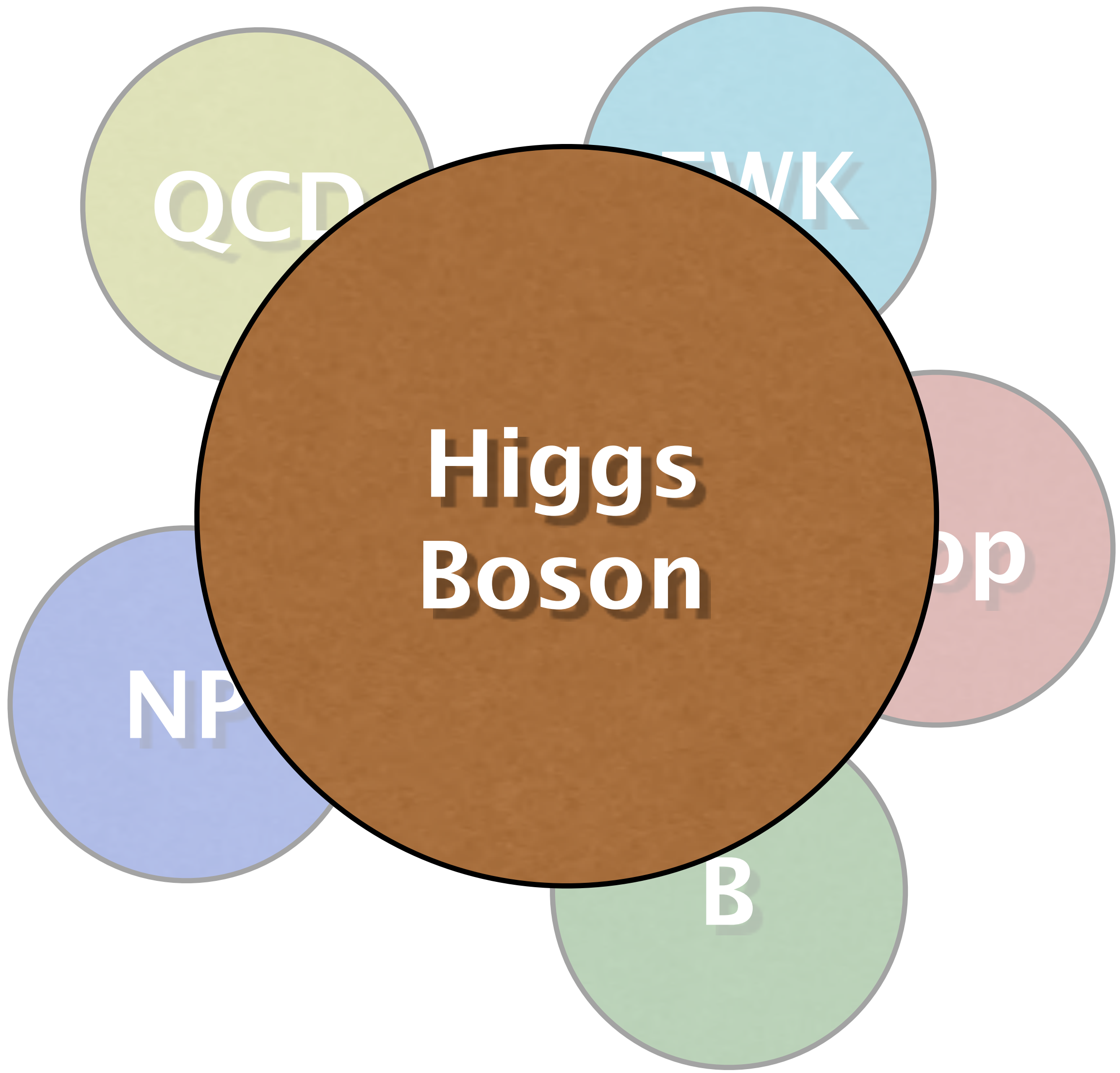




$m_{\tilde{t}} > 198$ GeV

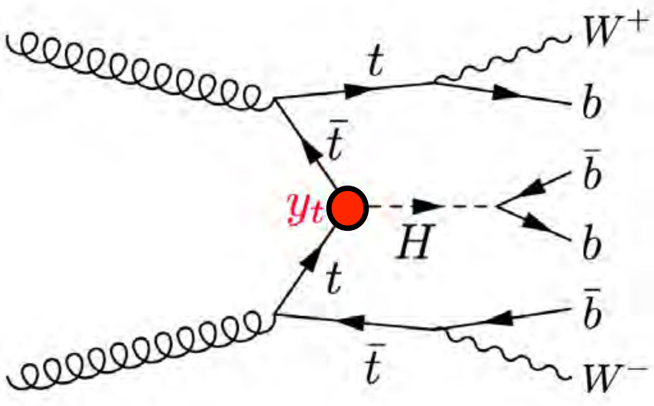
→ **using a “standard candle” for complementary exclusion**

Top Quark Physics Topics

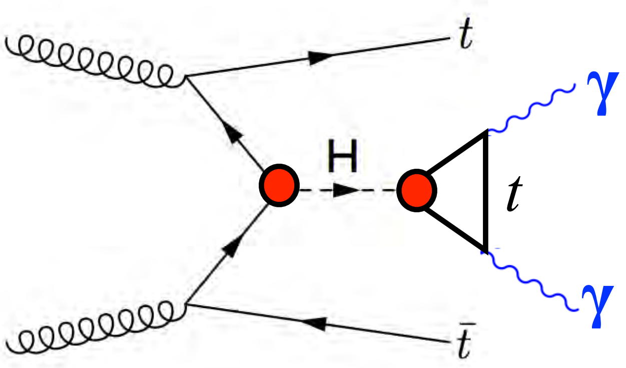


Search for ttH production

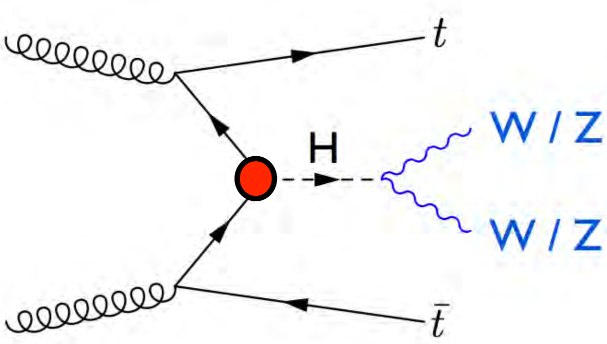
H→bb



H→γγ



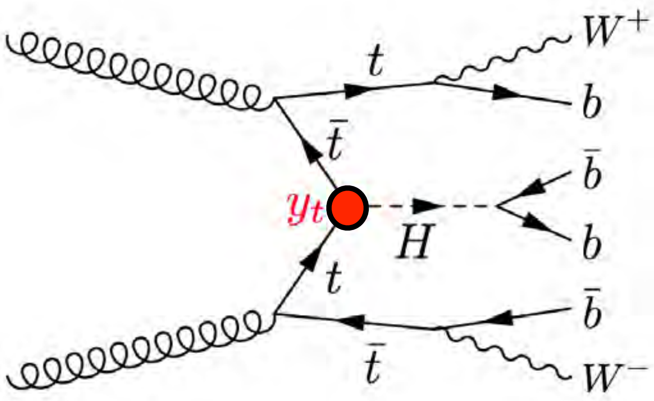
H→WW, ZZ



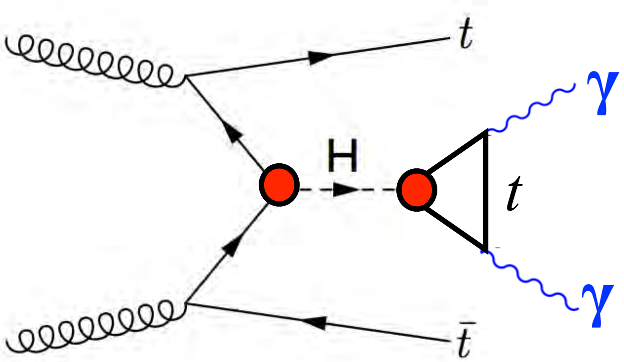
multi-leptons

Search for ttH production

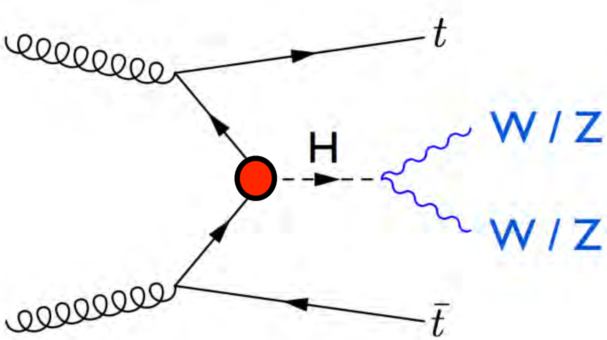
H→bb



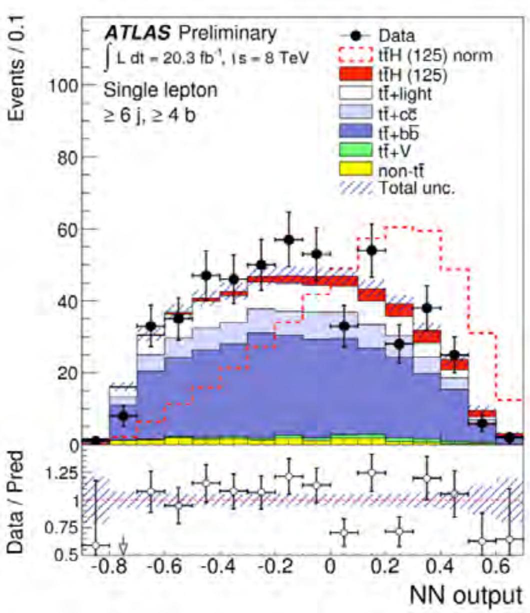
H→γγ



H→WW, ZZ

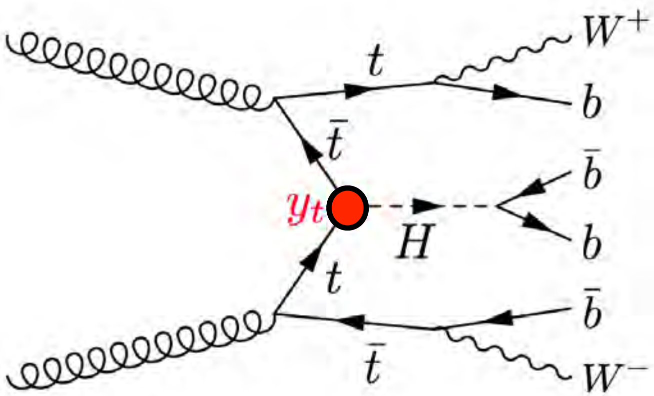


multi-leptons

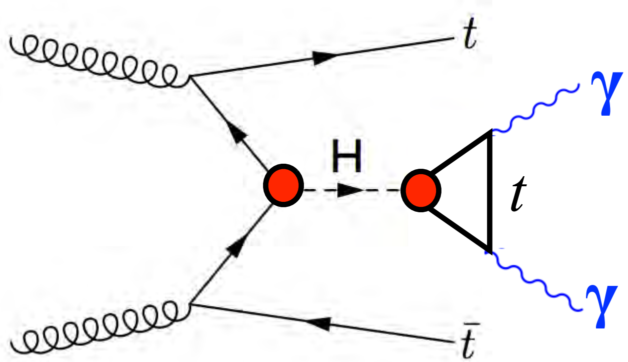


Search for ttH production

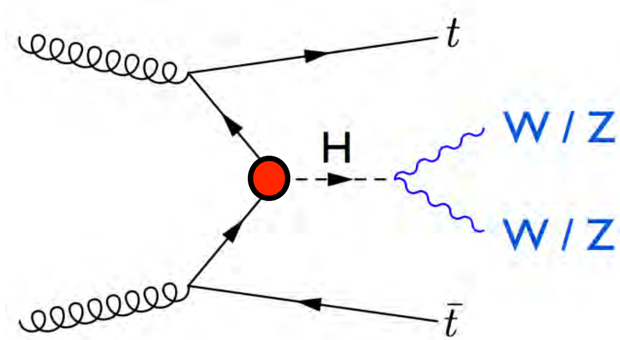
H→bb



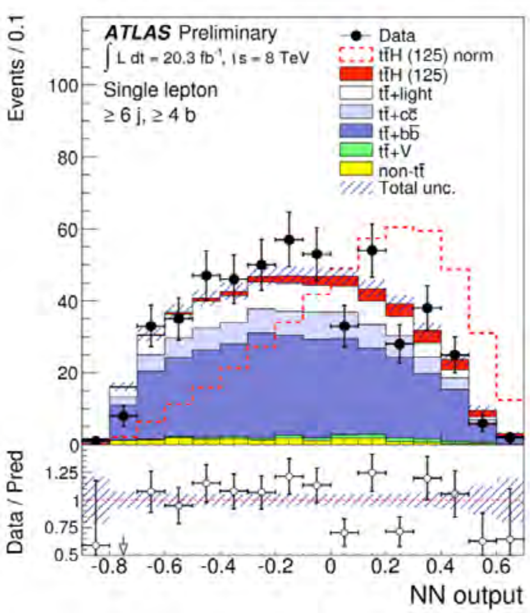
H→γγ

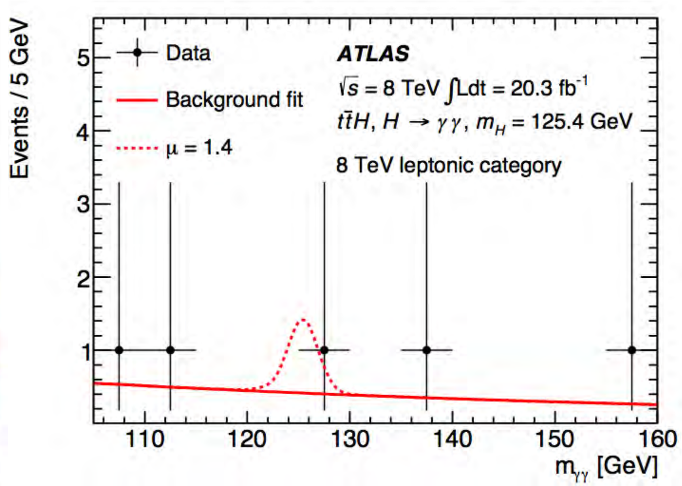


H→WW, ZZ



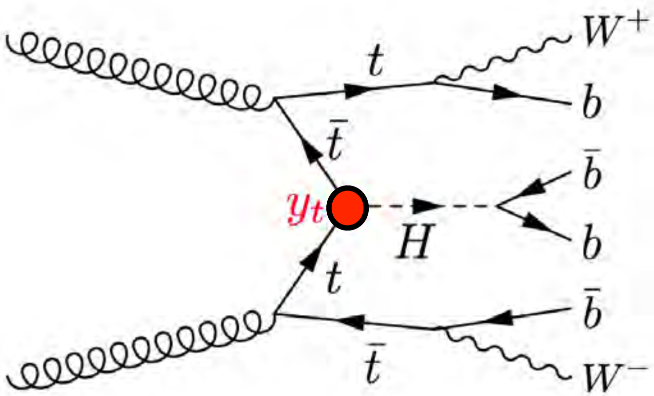
multi-leptons



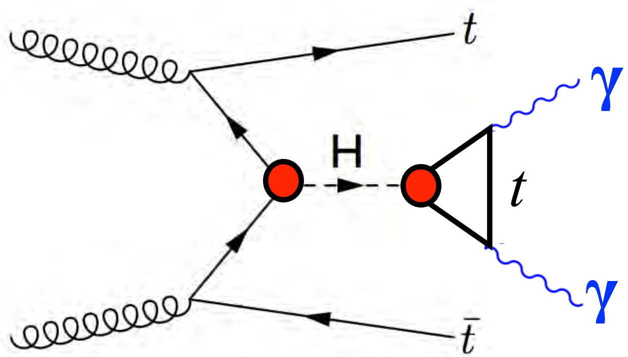


Search for ttH production

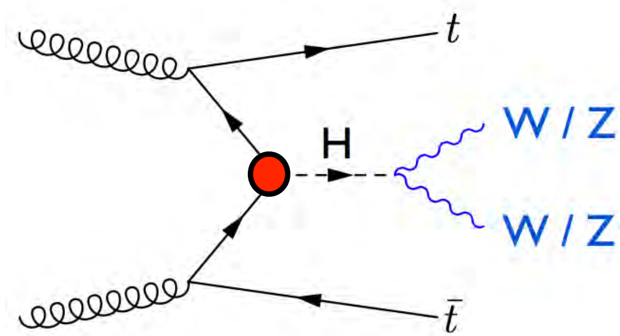
H→bb



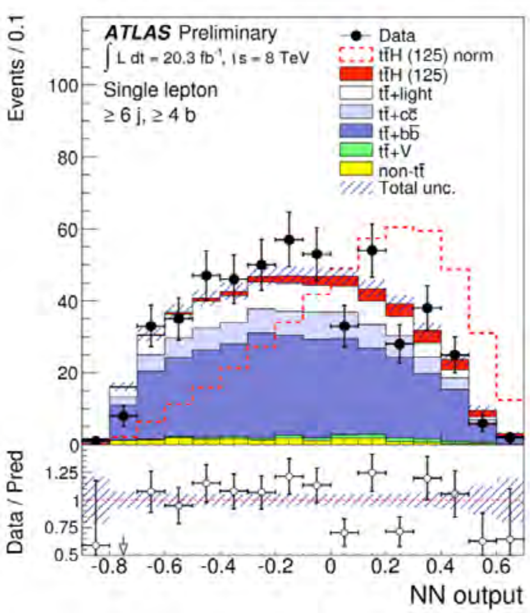
H→γγ

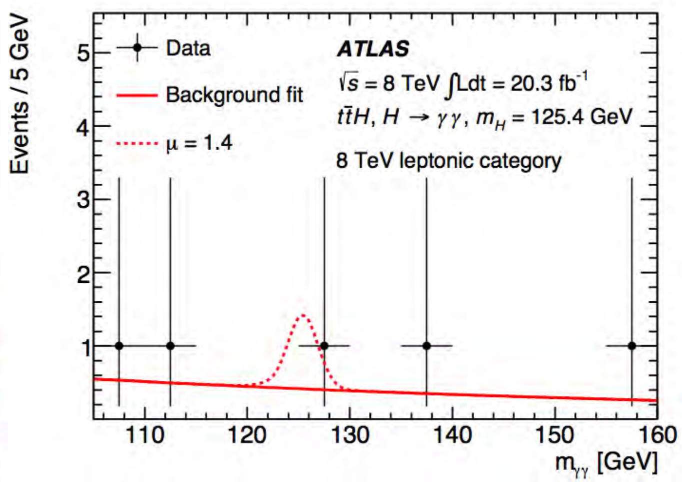


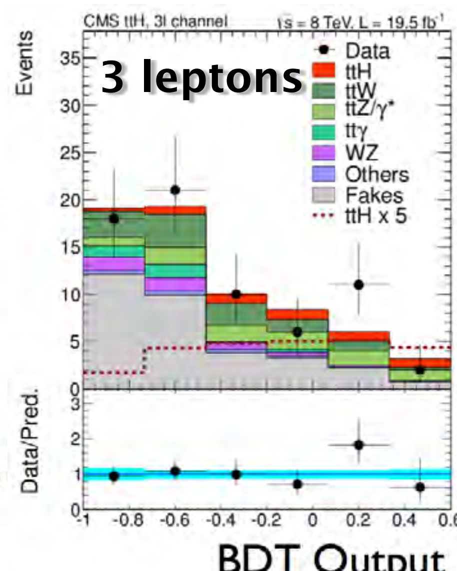
H→WW, ZZ

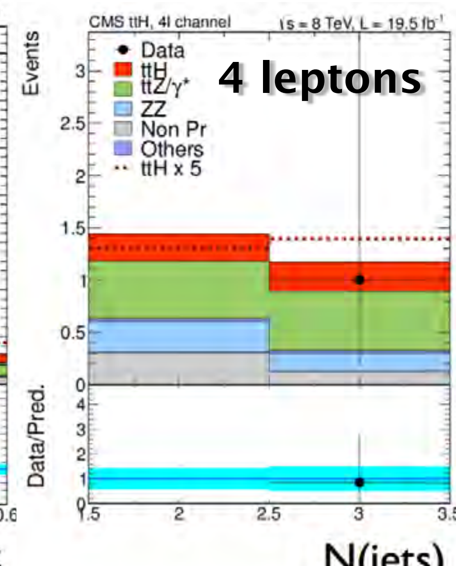


multi-leptons

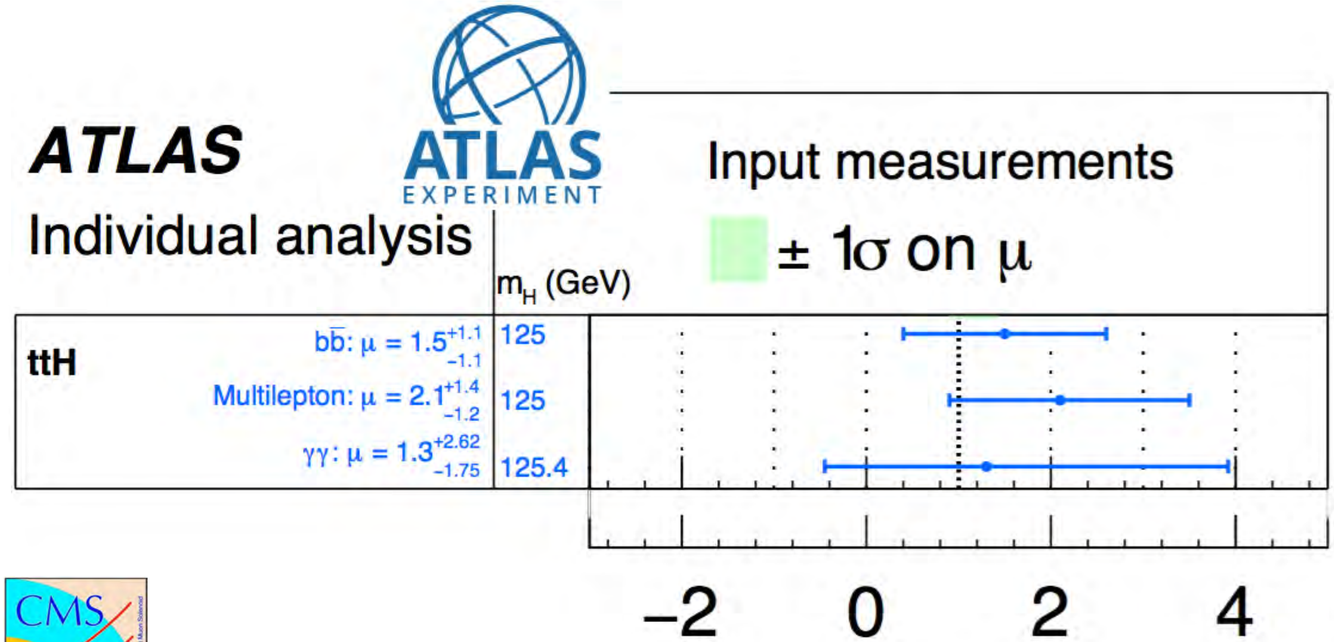






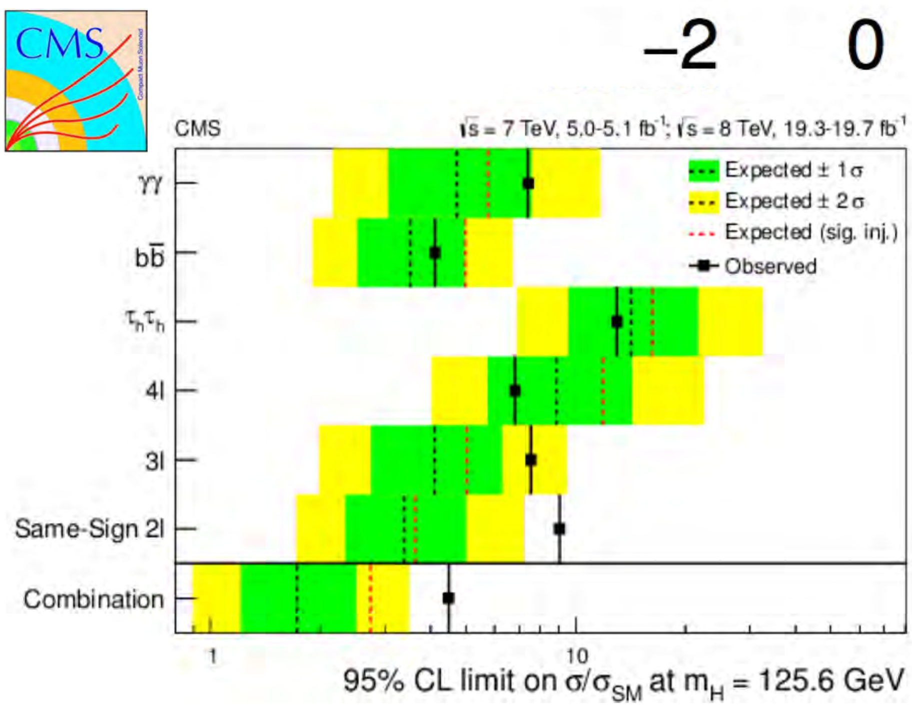


Results in ttH



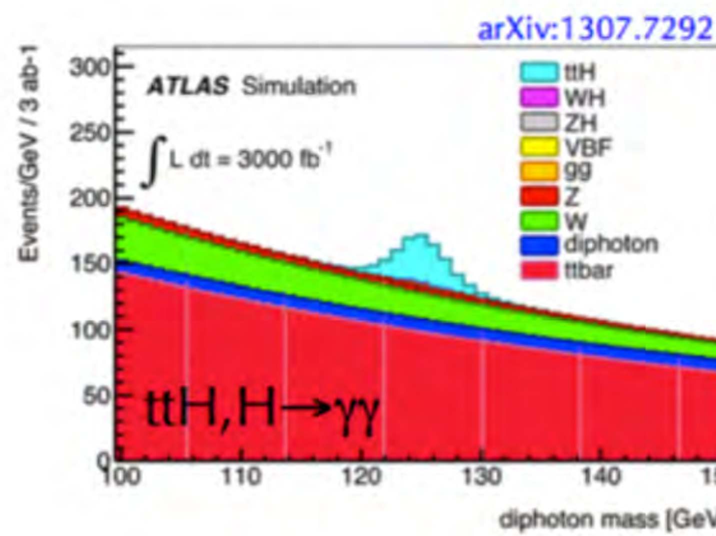
3.2σ (1.4σ exp)

σ/σSM



4.5σ (1.7σ exp)

limit on σ/σSM



→ observation in Run-II
→ measurement of top-Yukawa coupling

Summary

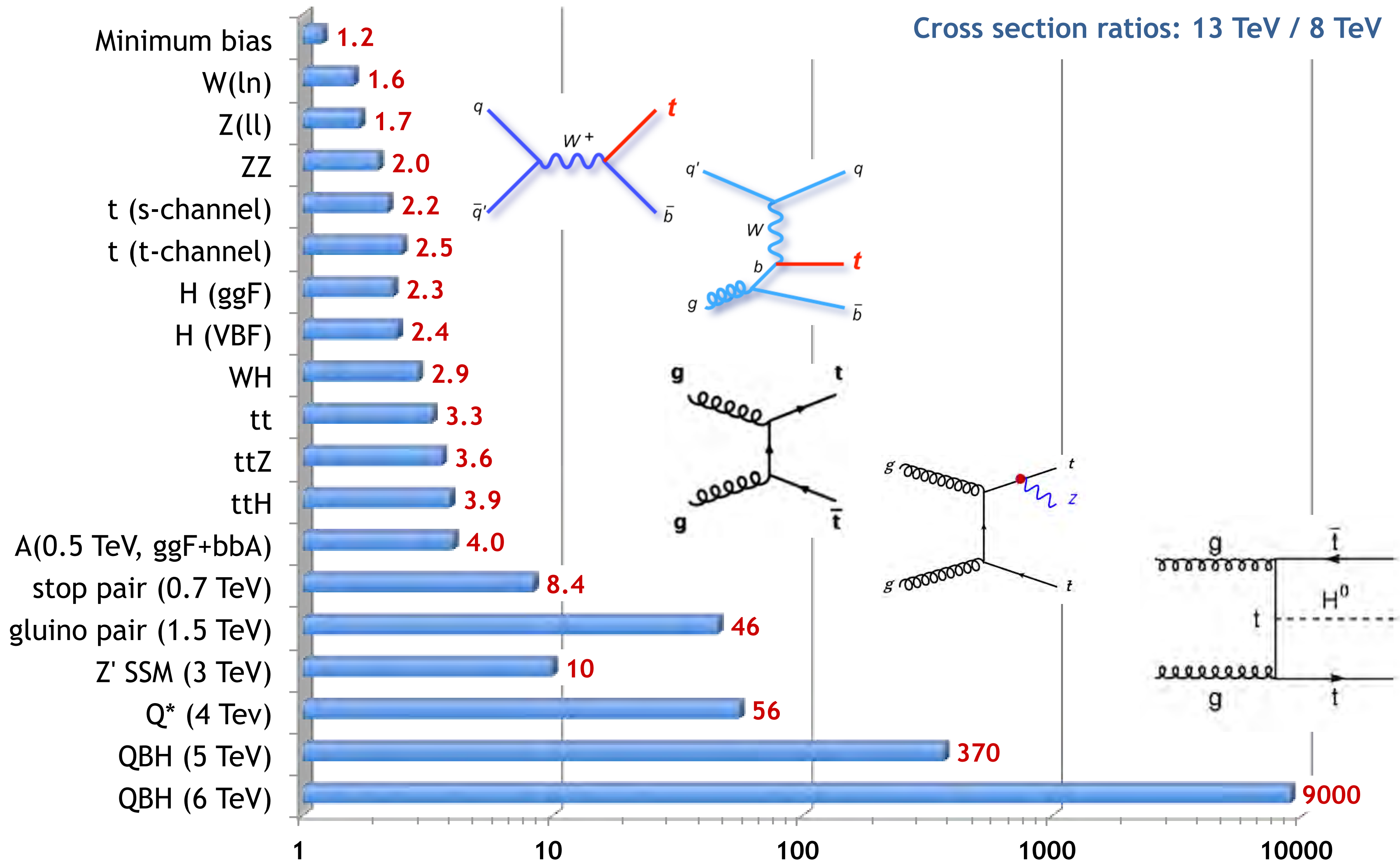
- very rich and diverse field of research!
- first results at 13 TeV!
- high precision: cross sections, mass, couplings, ...
- high precision tools: NLO+multileg MC, NNLO calculations, ...
- huge development of tools: top-tagging, combinations, b-JES, ...
- measure unfolded and fiducial!
- new processes: s-channel single top, Wt, ttγ, ttZ, ttW, ttH
- many properties, also from single top
- top mass gets more and more precise(?)
- sensitive direct searches and by precision measurements

→ observe more SM processes in Run-II, many high precision property/cross section measurements to come, many mass discussion, new physics?!?

Summary

"It is much too early to expect any discovery, we will have to be patient"
CERN DG

Cross Sections: 13 TeV/8 TeV



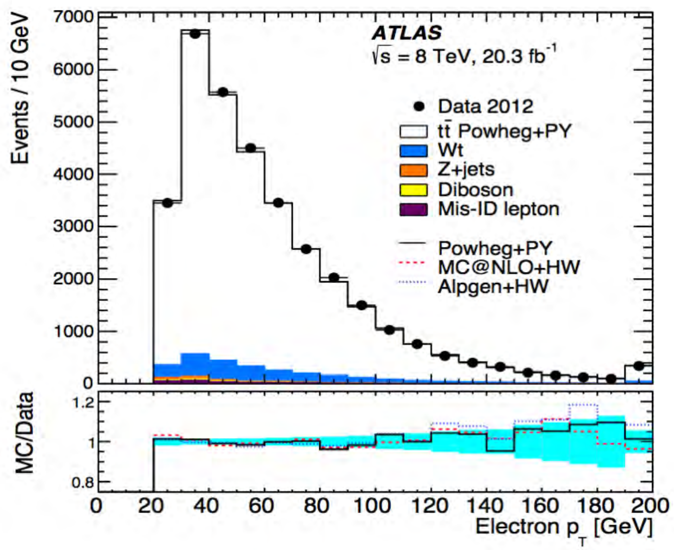
→ excellent prospects for top physics

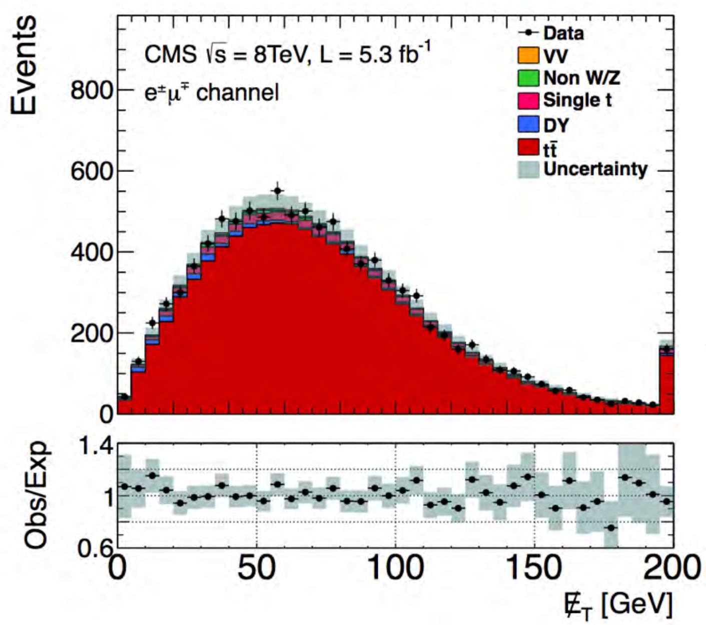
Summary

let's smash the SM in Run-2!

Backup

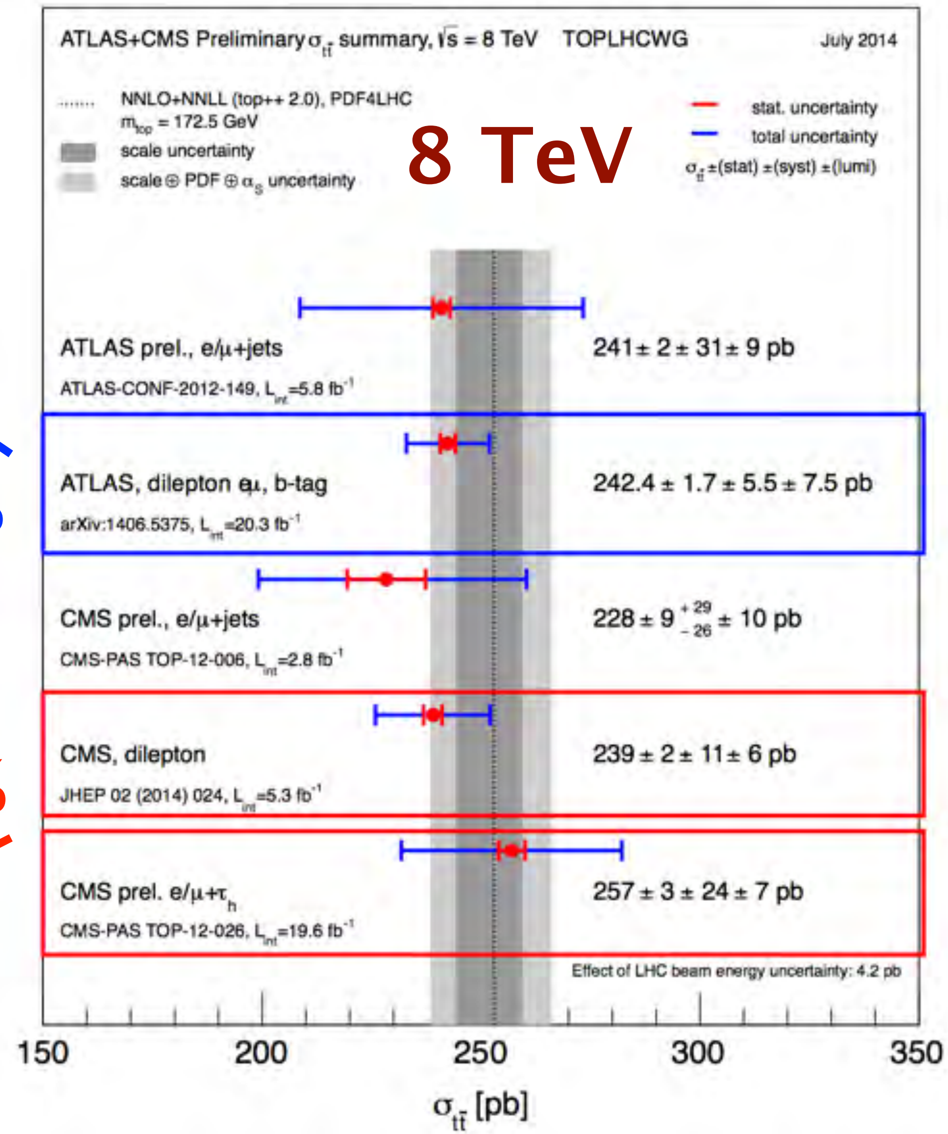
Top pair production cross section





±3.9%

±5.7%

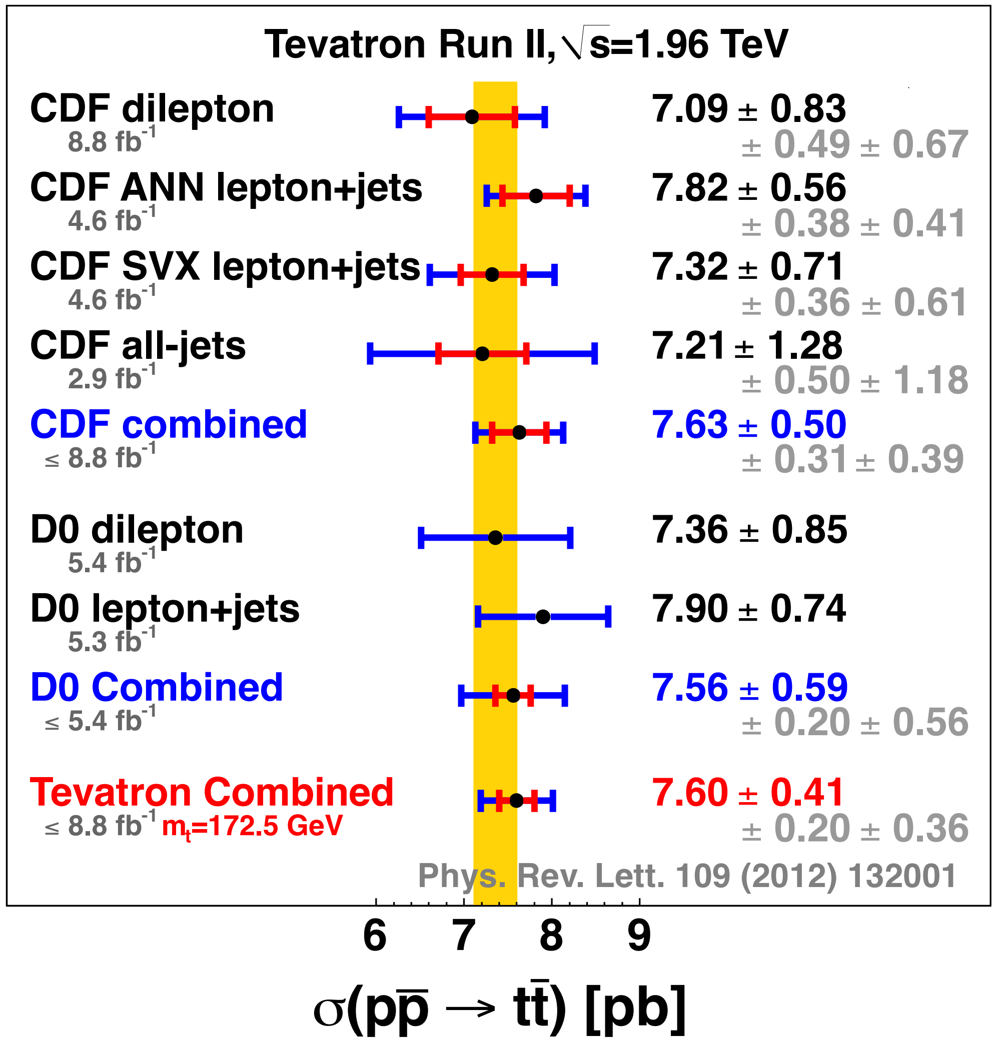


8 TeV

J. Brochero

Top Pair Production Cross Section

NNLO+NNLL

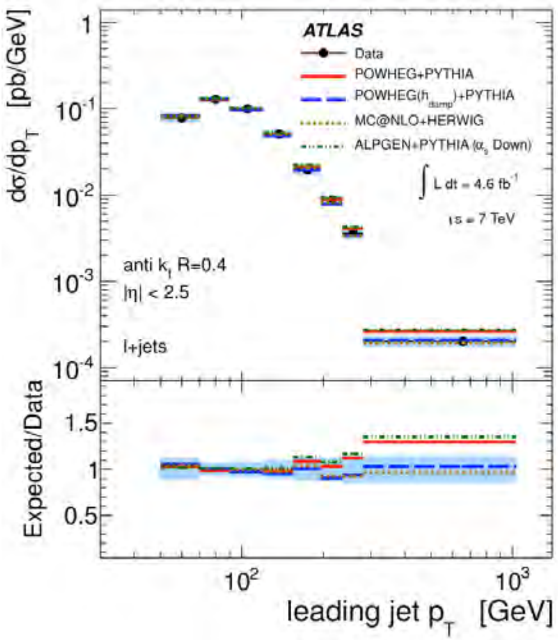


Y. Peters

±5.4%

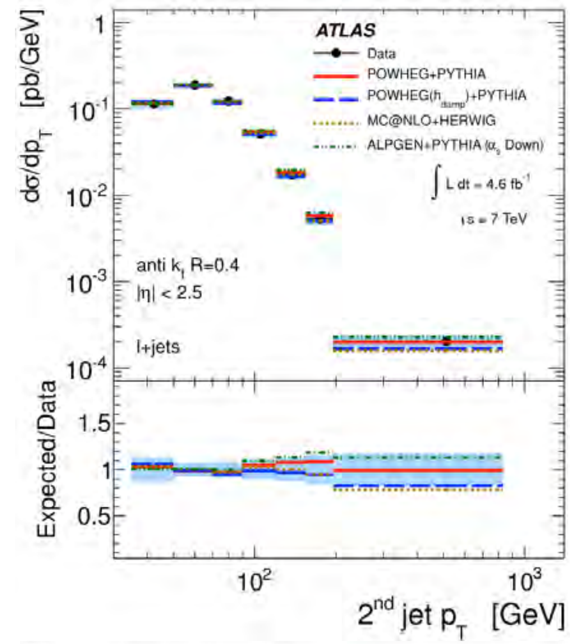
→ good agreement with NNLO+NNLL

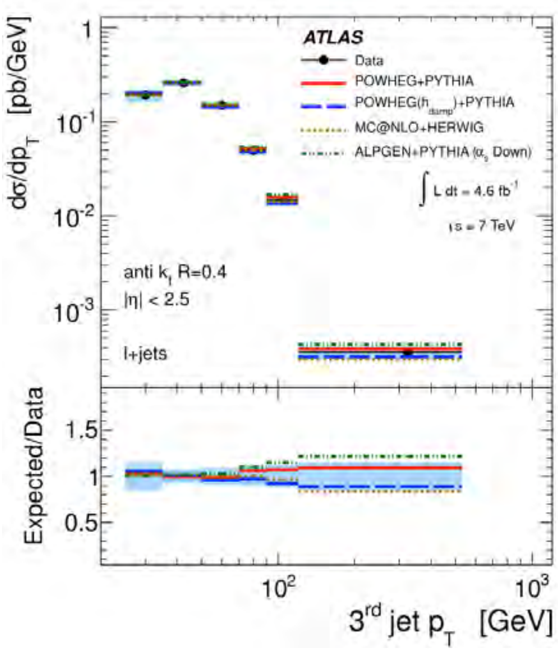
Differential (l+jets): jet p_T

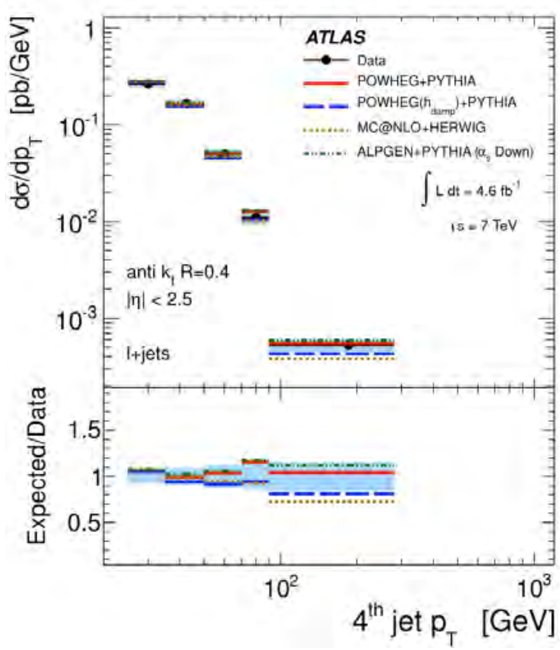


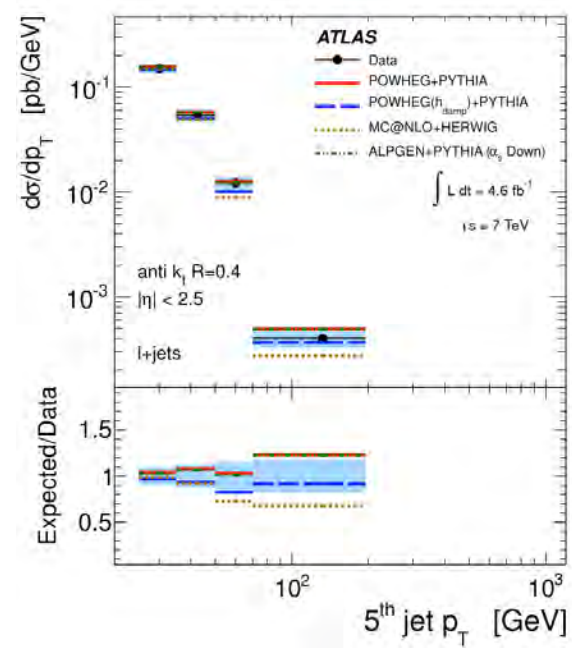
→ **NLO MCs are needed!**

Alpgen+Pythia and Powheg+Pythia disfavoured

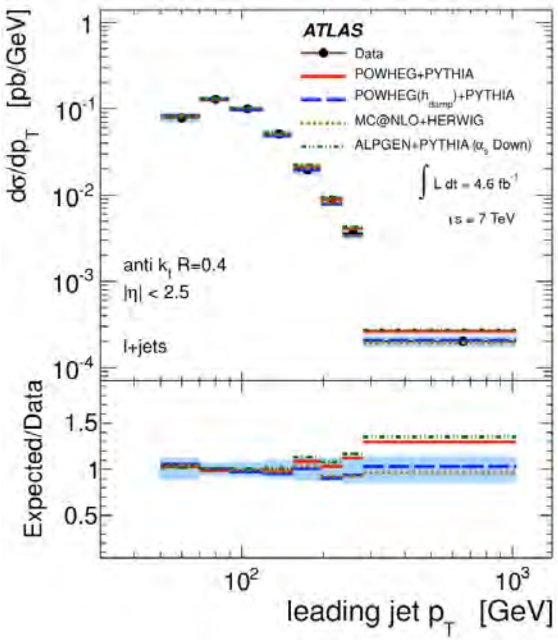




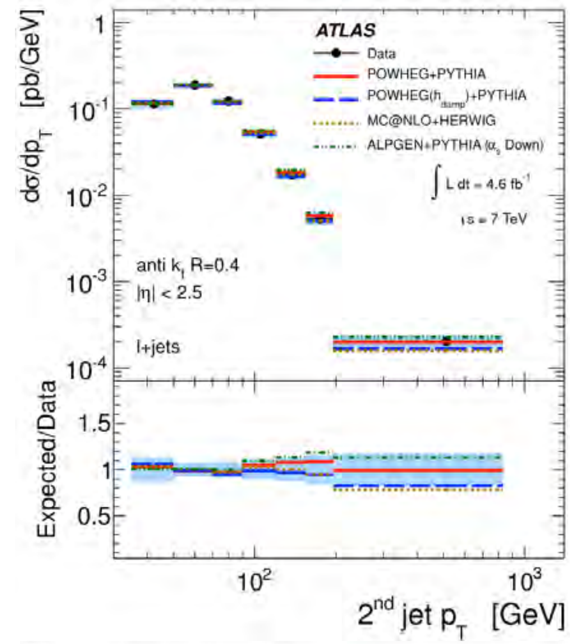




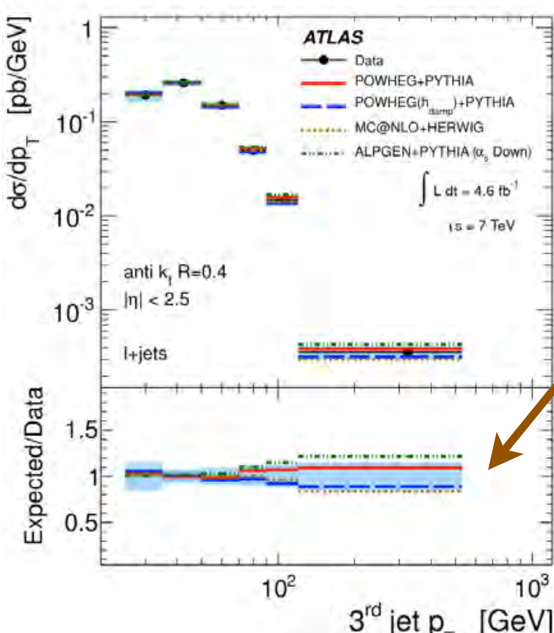
Differential (l+jets): jet p_T

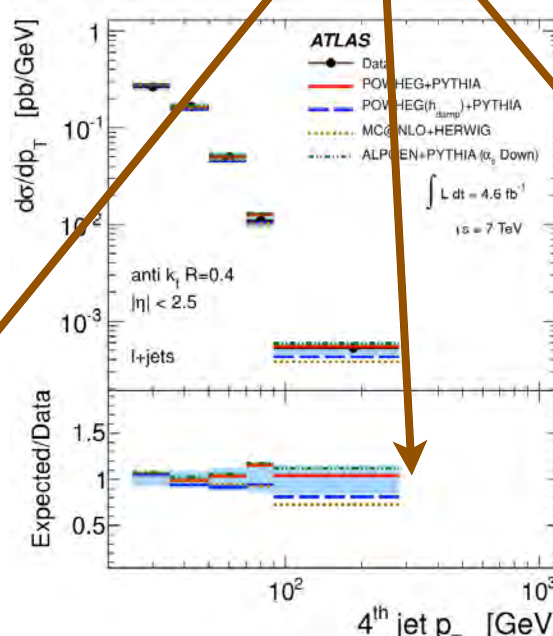


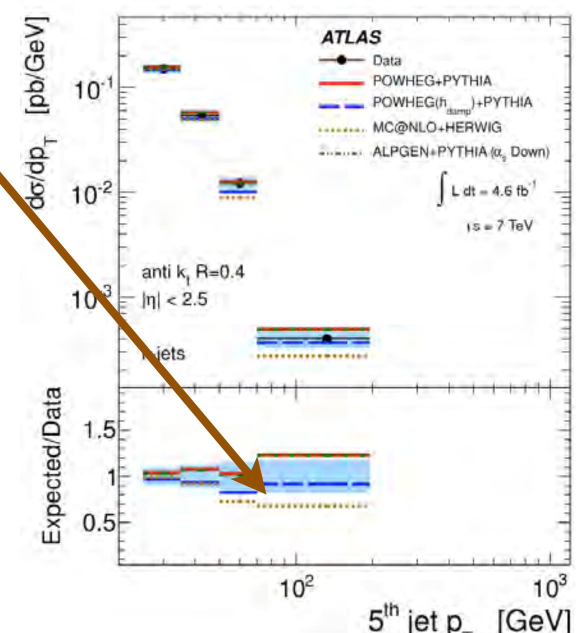
→ **multileg MEs are needed!**



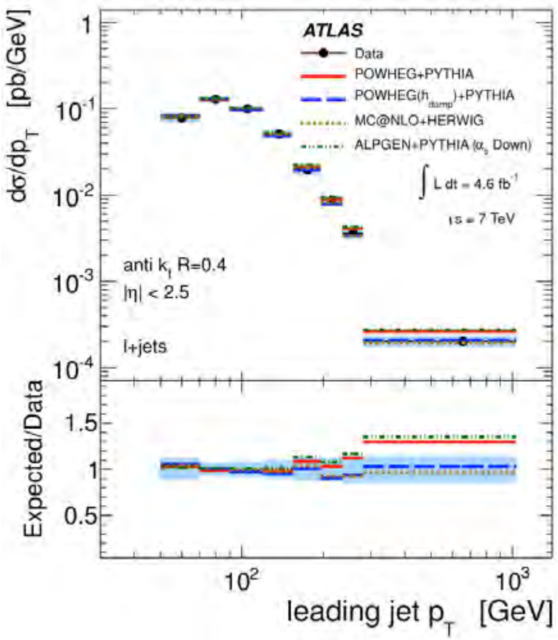
MC@NLO+Herwig too soft







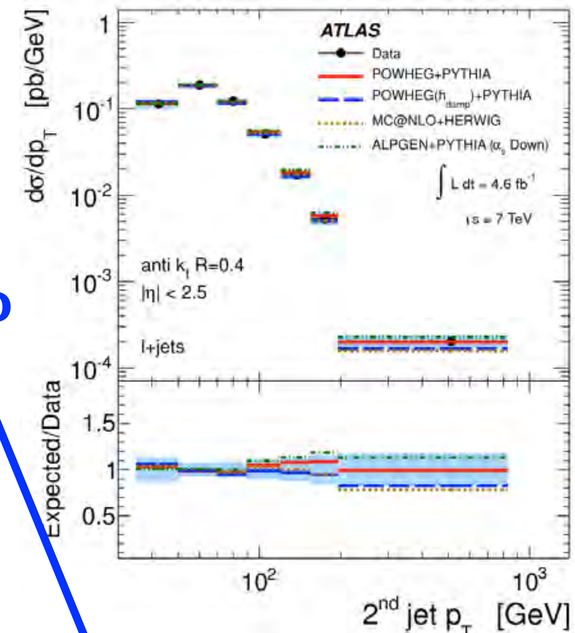
Differential (l+jets): jet p_T

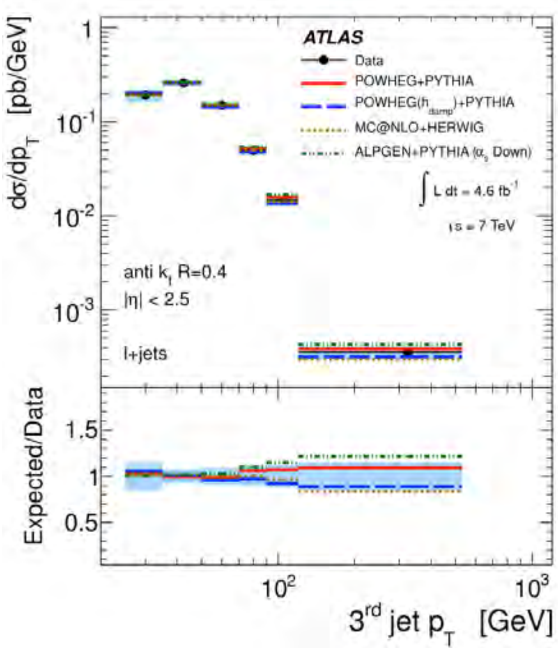


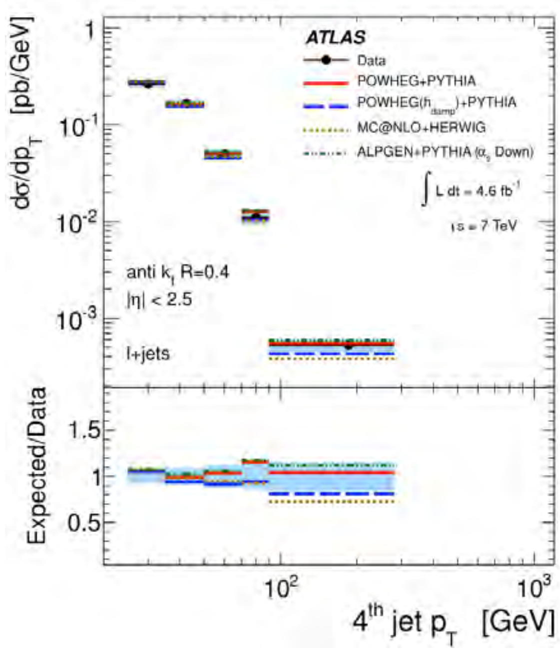
Powheg+Pythia in reasonable agreement

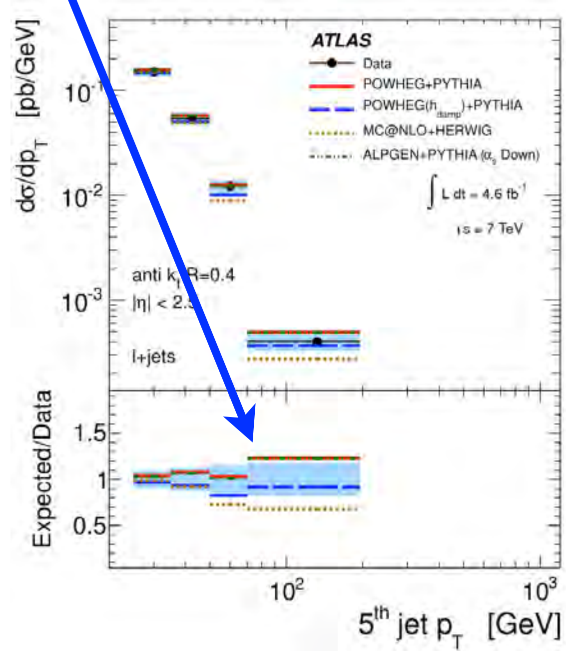
Powheg+Pythia with damping softer, due to damping of hardest emission

→ matter of tuning
(hdamp=mtop works best)



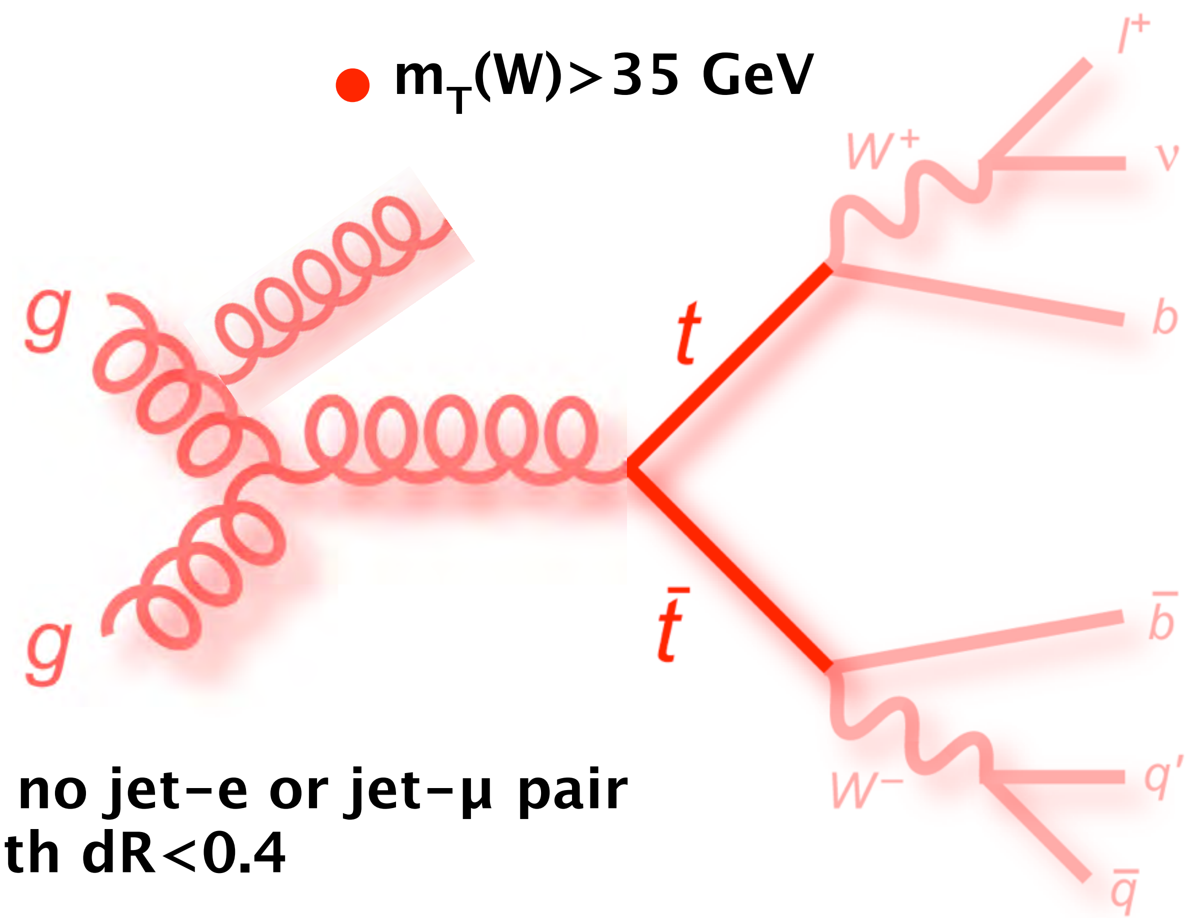






Fiducial Kinematic Phase Space

- no additional e or μ with p_t>15 GeV & |η|<2.5
- $m_T(W)$>35 GeV
- exactly one isolated e or μ with |η|<2.5, p_t>25 GeV (including clustering with γ in cone ΔR=0.1)
- $E_{t,miss}$ > 30GeV
- ≥ 3 Jets with p_t>25 GeV & |η|<2.5 incl. ≥1 b-tagged jet
- jets: anti-k_t R=0.4, clusters all but prompt particles (i.e. e, μ, ν from hadronic decays are inside jets)



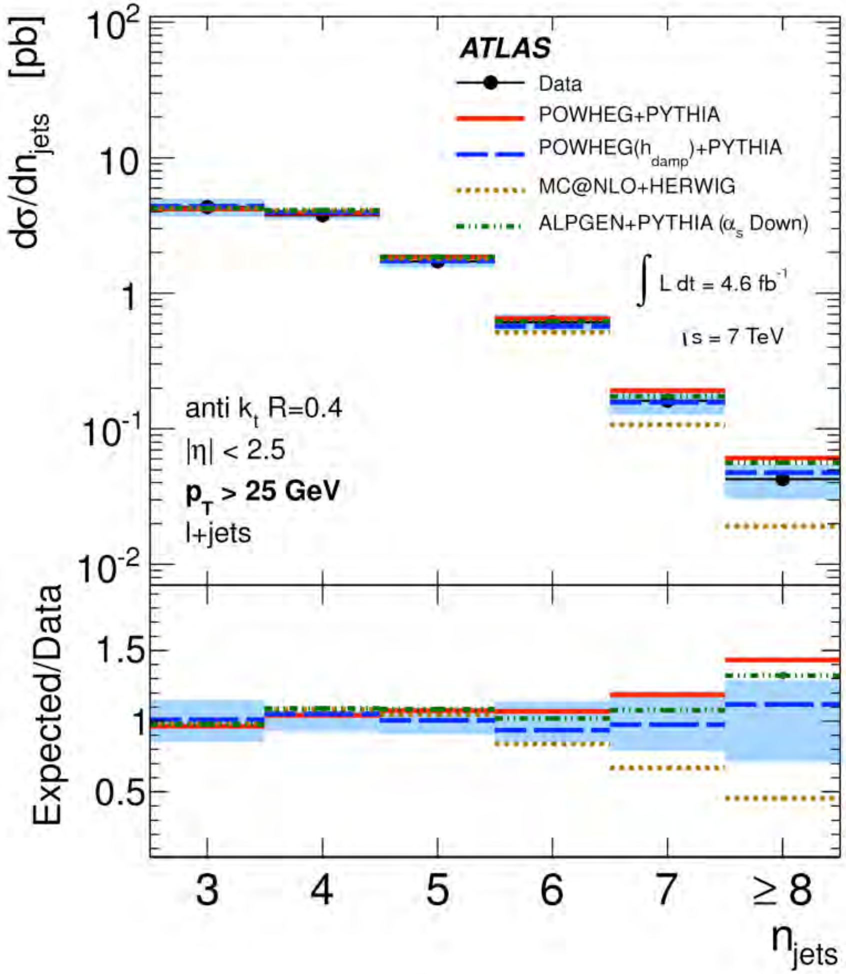
- no jet-e or jet-μ pair with dR<0.4
- no jet-jet pair with dR<0.5

- background subtraction
- corrections to particle level

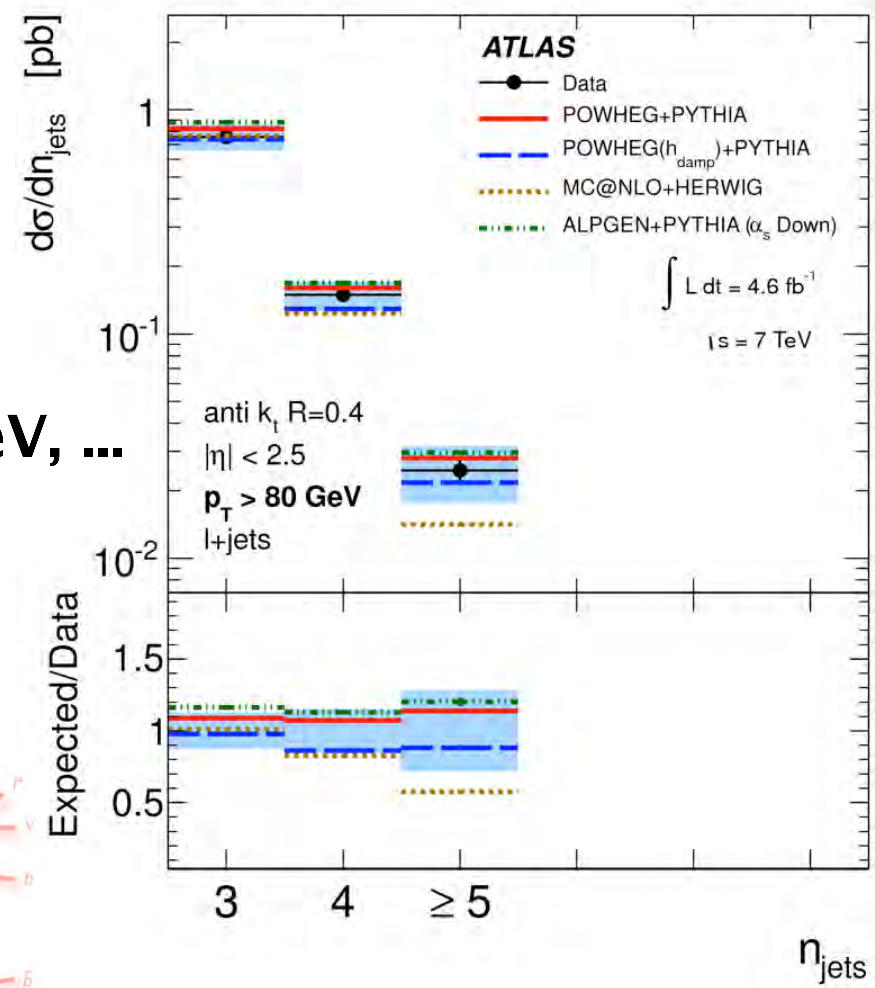
→ reduced dependence on MC model

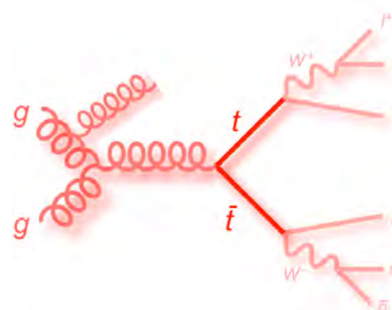
Jet Multiplicities

- uncertainties dominated by JES and MC modeling of QCD radiation



... 40, 60 GeV, ...



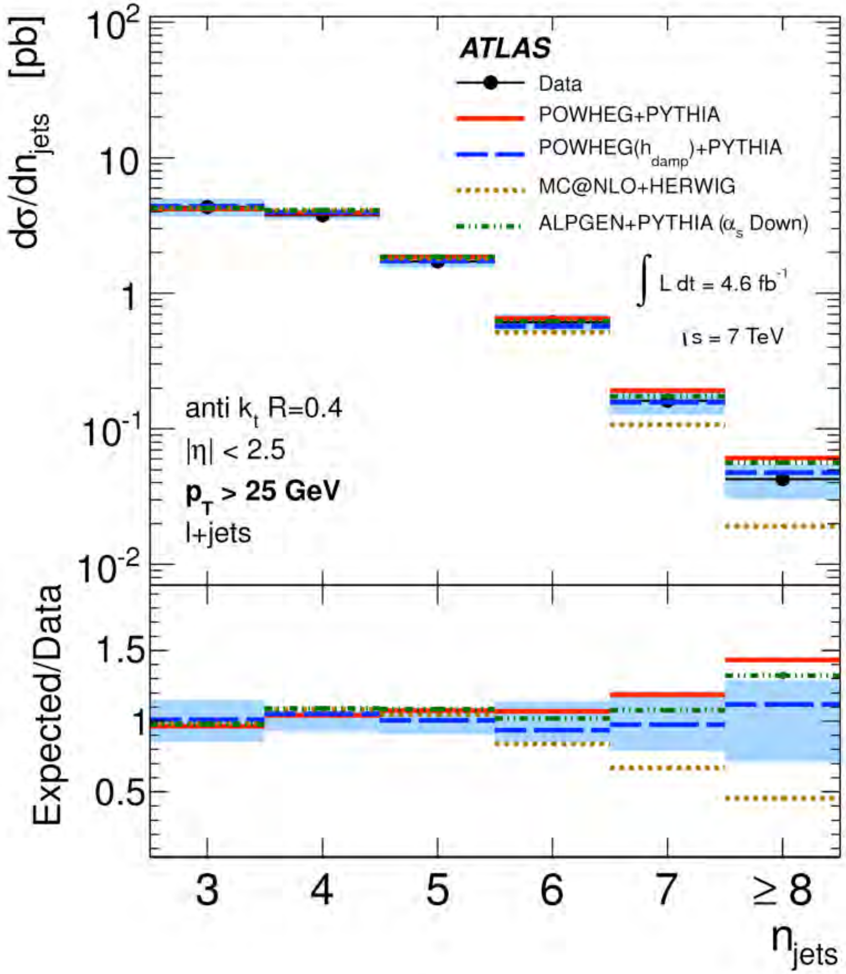


JHEP 1501, 020 (2015)

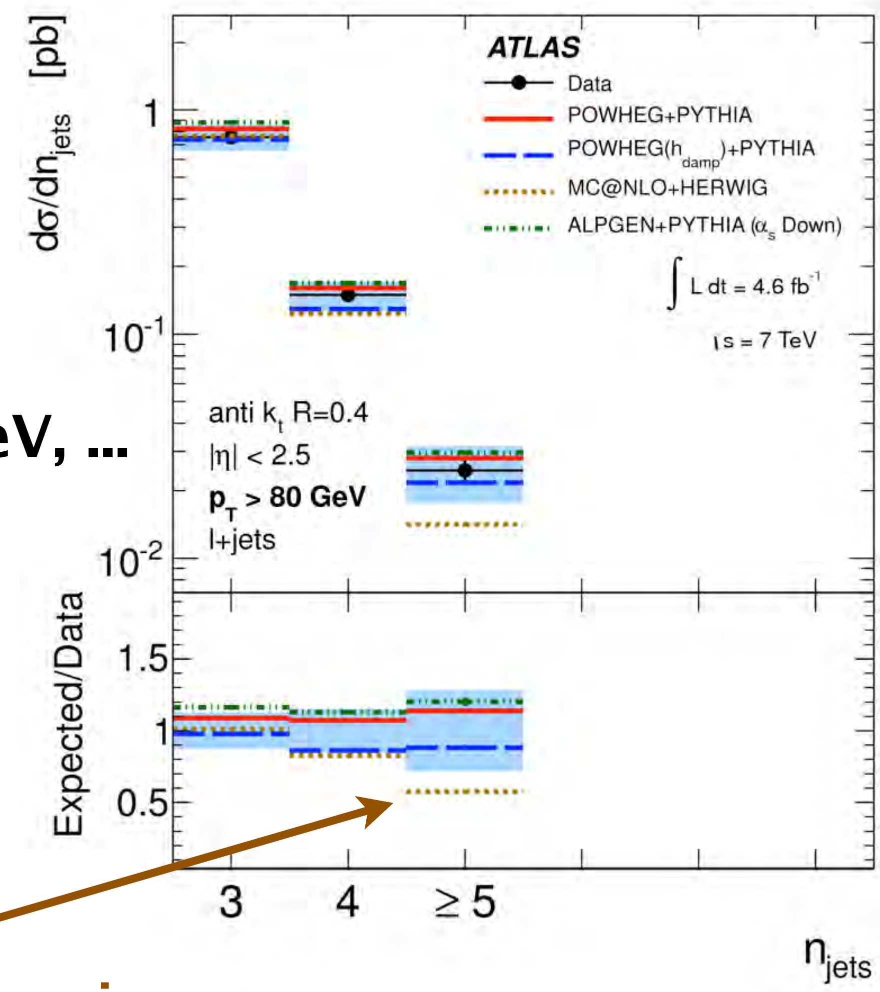
→ **high sensitivity on higher order QCD modeling of MC generators**

Jet Multiplicities

- Uncertainties dominated by JES and MC modeling of QCD radiation



… 40, 60 GeV, …

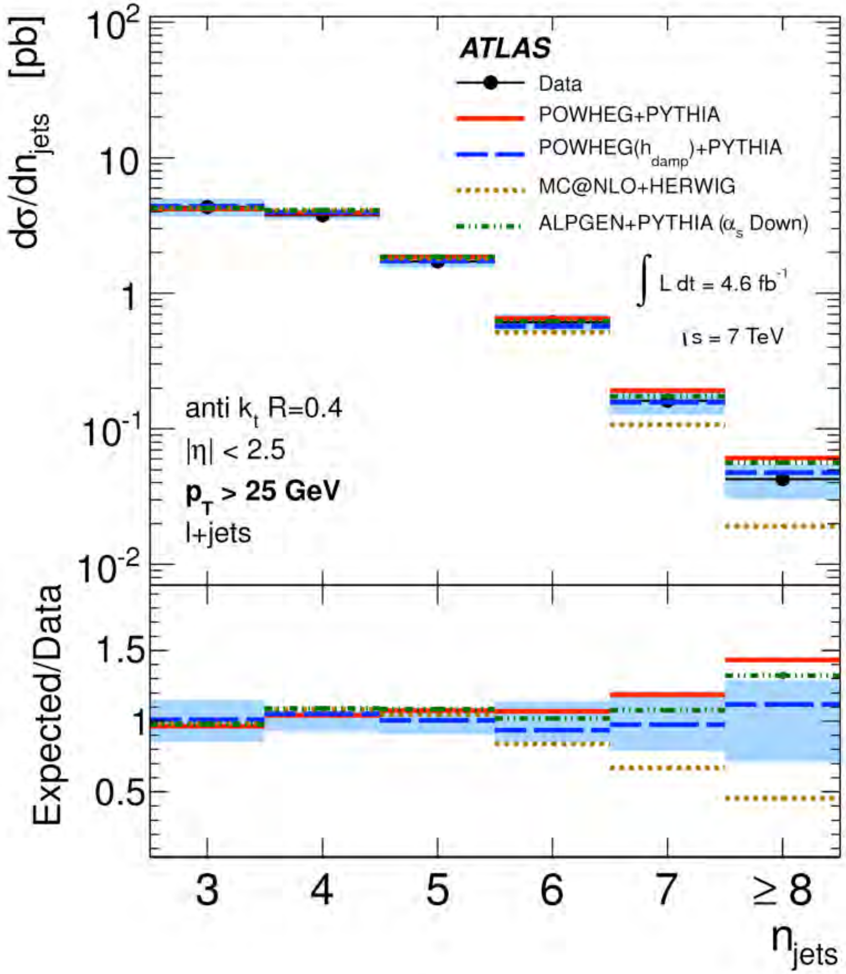


ALPGEN+Pythia ok

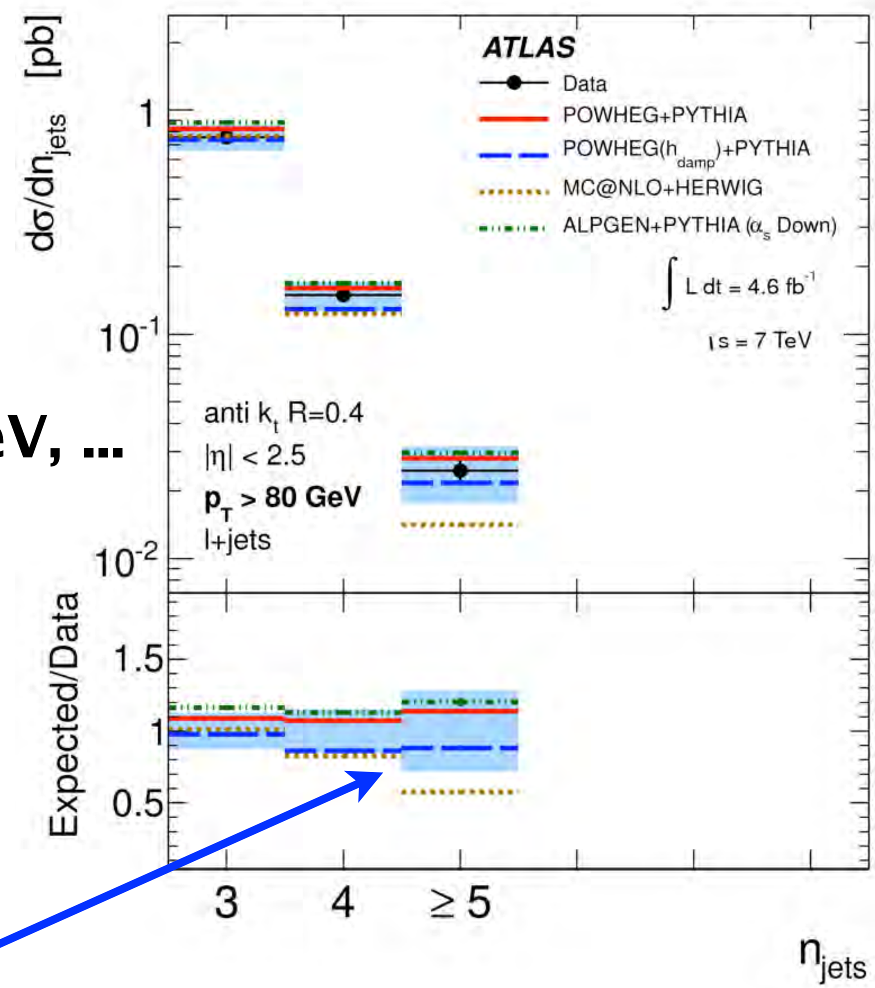
MC@NLO+Herwig disfavoured (since those come mostly from parton showers)

Jet Multiplicities

- Uncertainties dominated by JES and MC modeling of QCD radiation

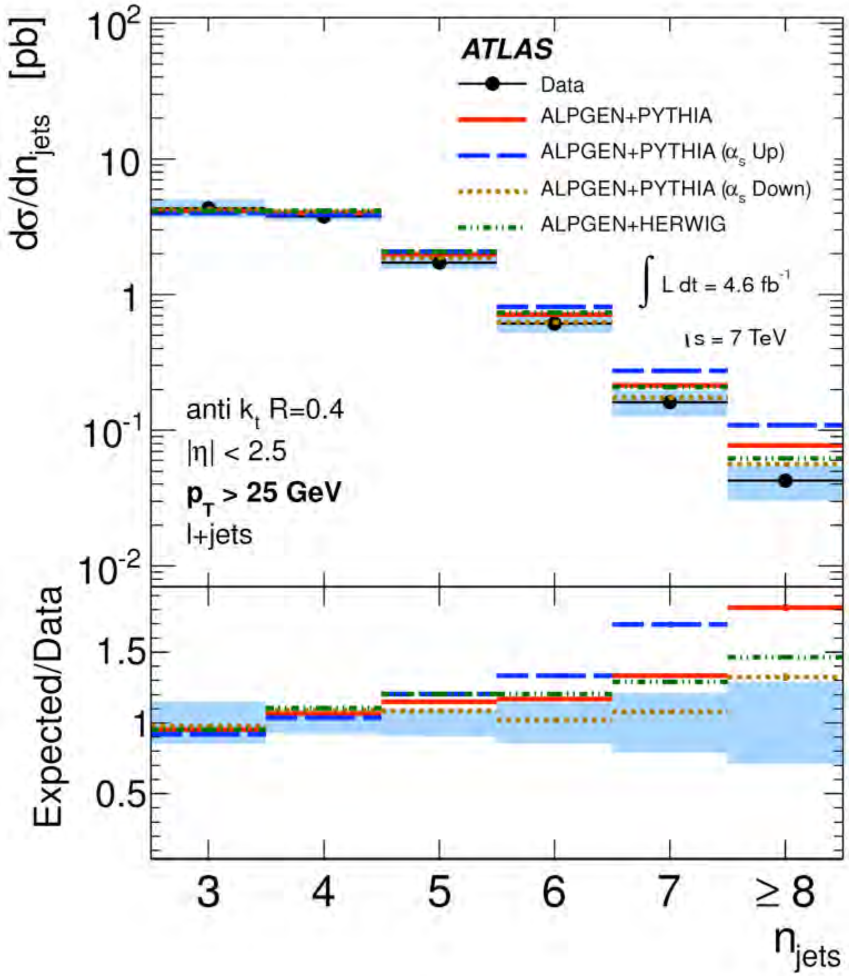


… 40, 60 GeV, …

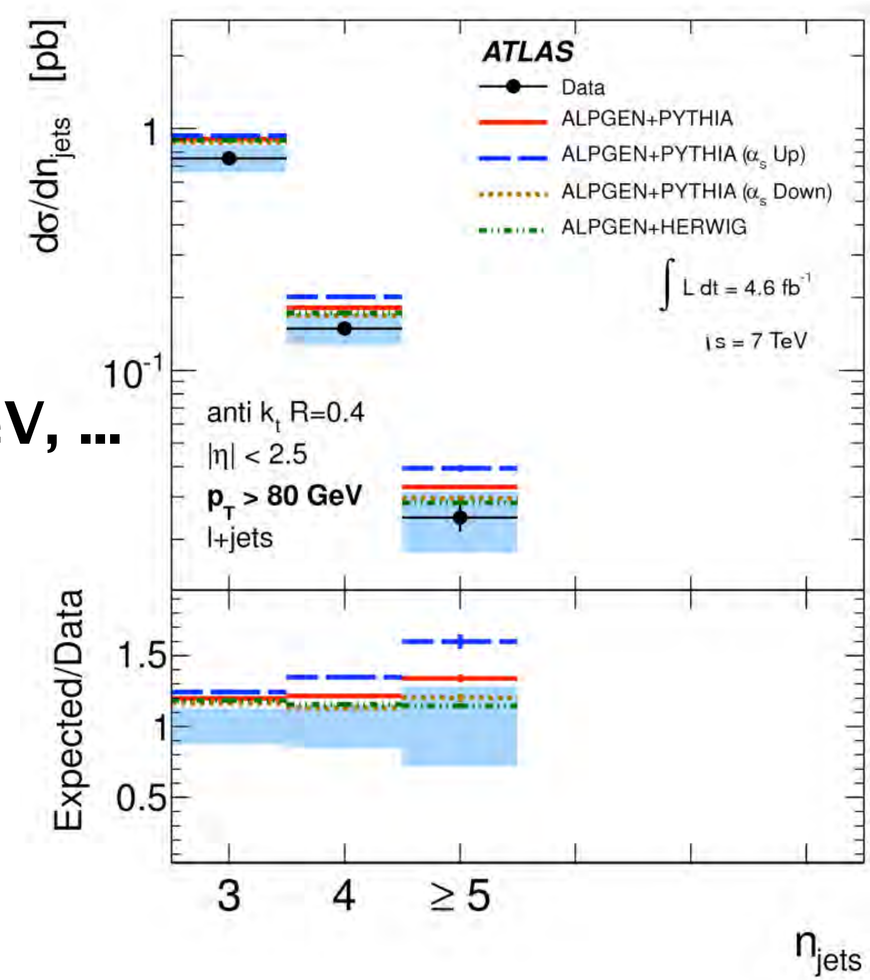


Powheg+Pythia with damping of the hardest emissions is best (high n_{jets} still get large contributions from the matrix element)

Strong Coupling and Parton Showers



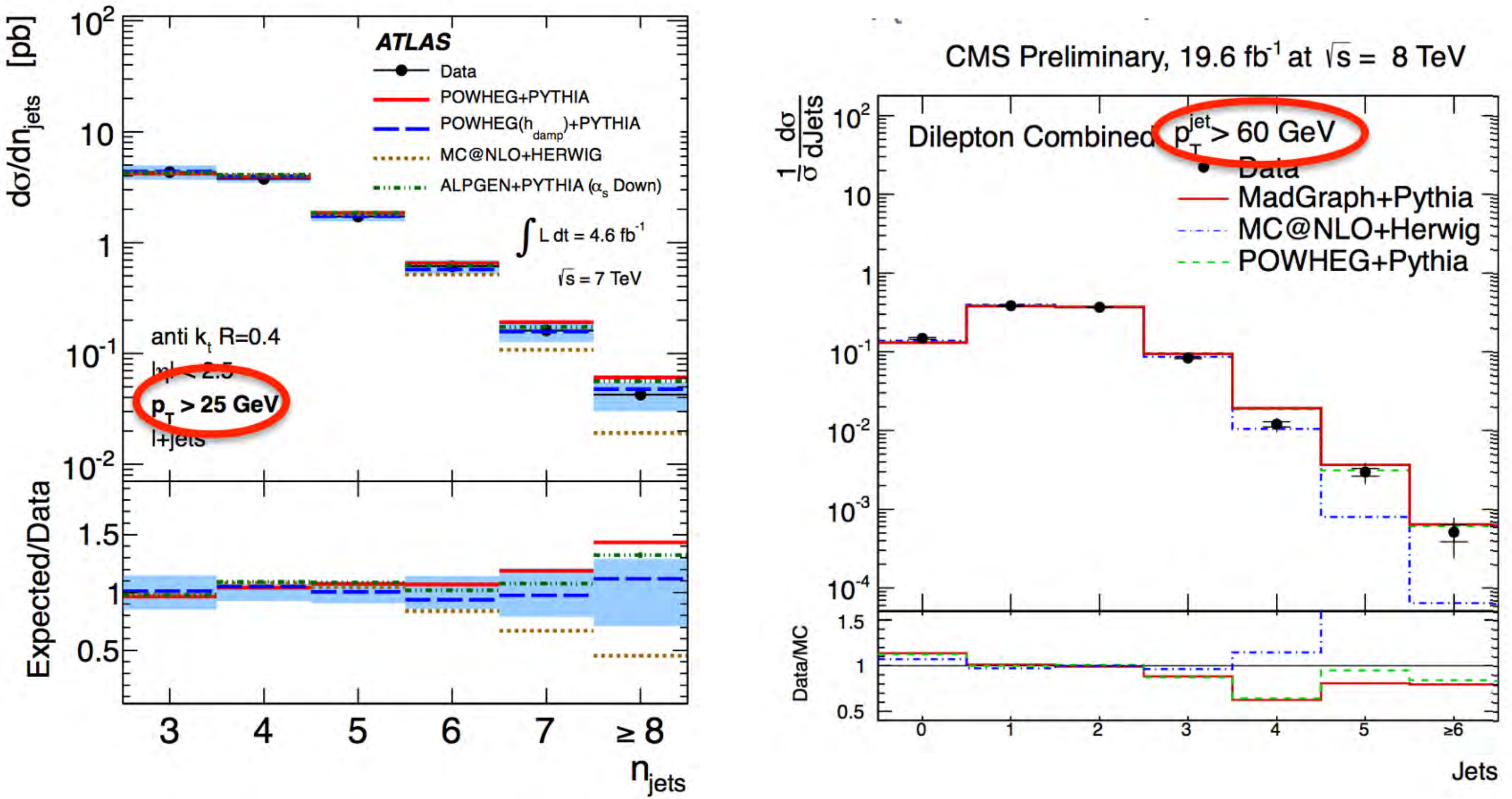
... 40, 60 GeV, ...



- → high sensitivity on α_S and parton showers
- → very valuable for improving models and reduce uncertainties
- → used for MC tuning: `ATL-PHYS-PUB-2015-007`
- → improves our understanding of higher order QCD calculations

Differential: jet multiplicities

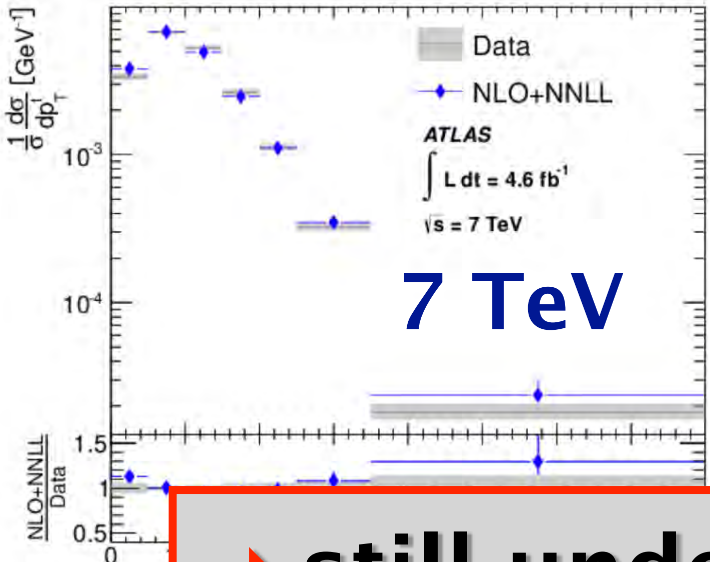
J. Katzy

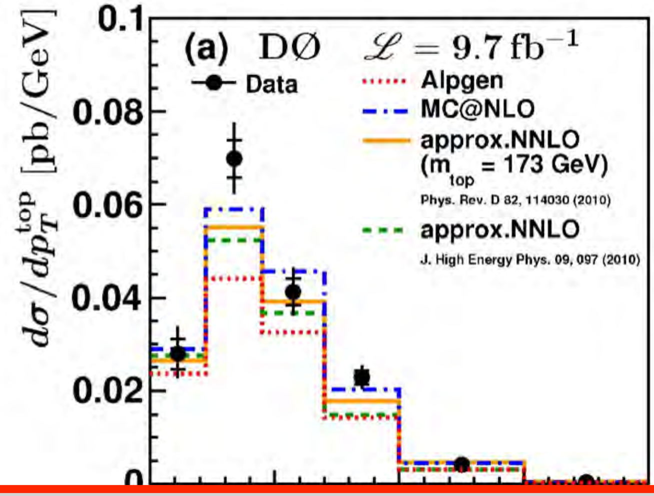


→ **large differences between generators: helps to improve**

Differential: top p_T

C. Diez

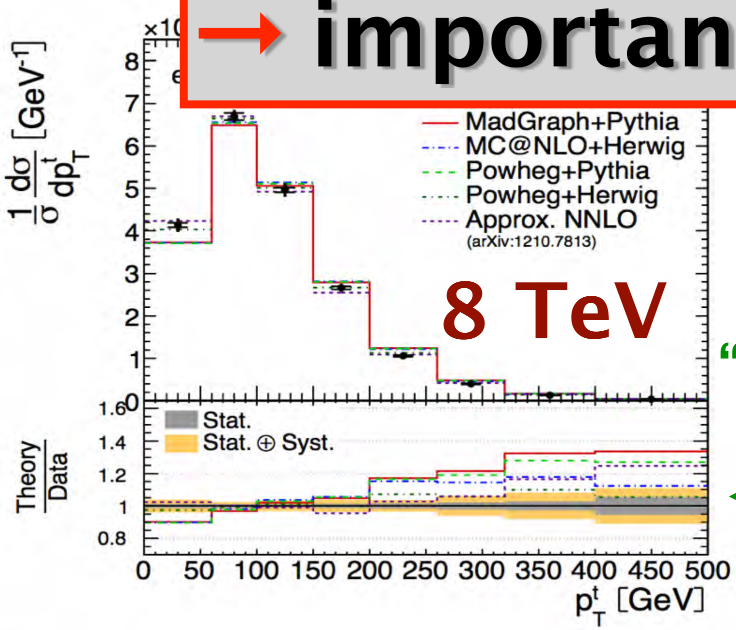




2 TeV

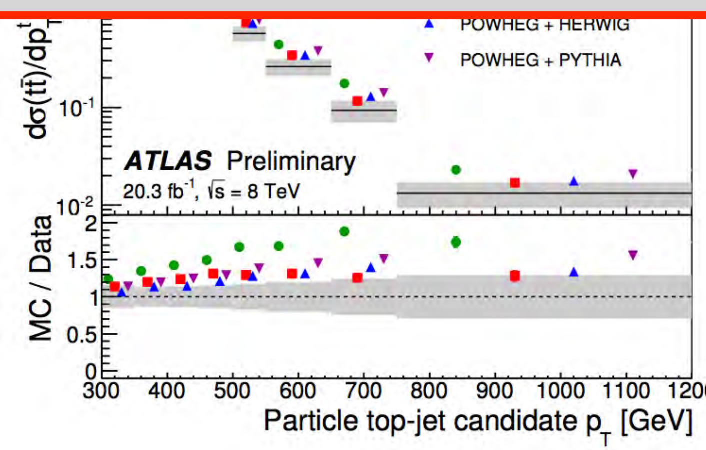
→ still under investigation

→ important info for MC modeling



Herwig "reshuffling" helps

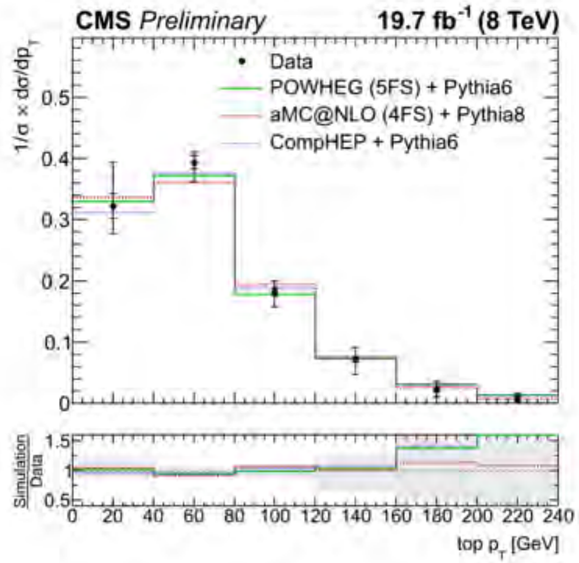
8 TeV



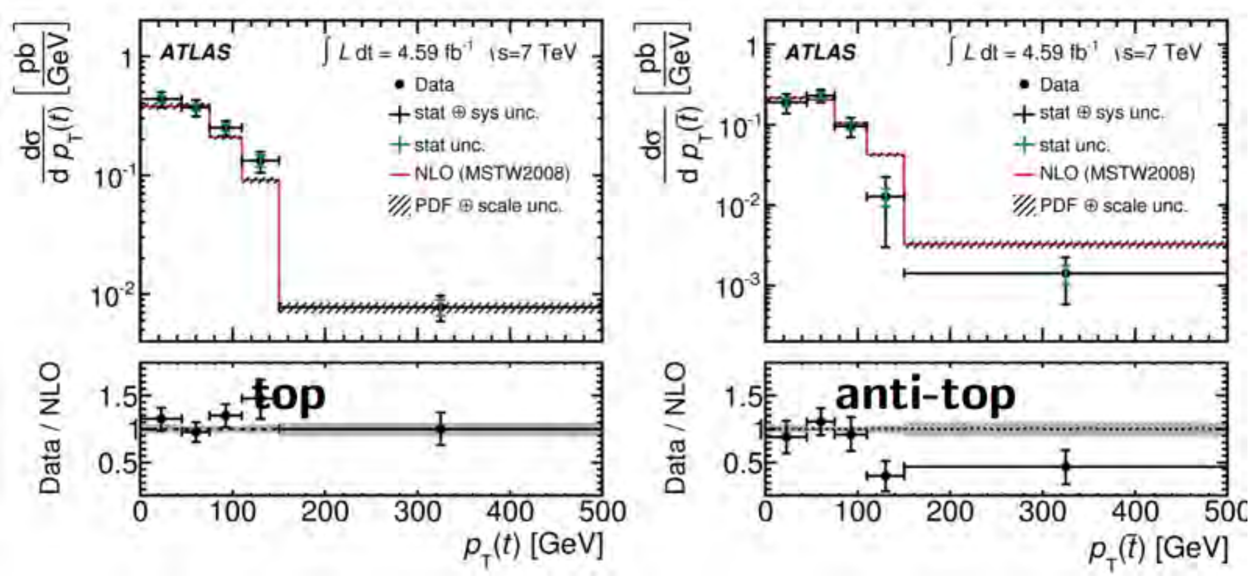
→ still much softer in data

Differential single top: top p_T

C. Diez



8 TeV



7 TeV

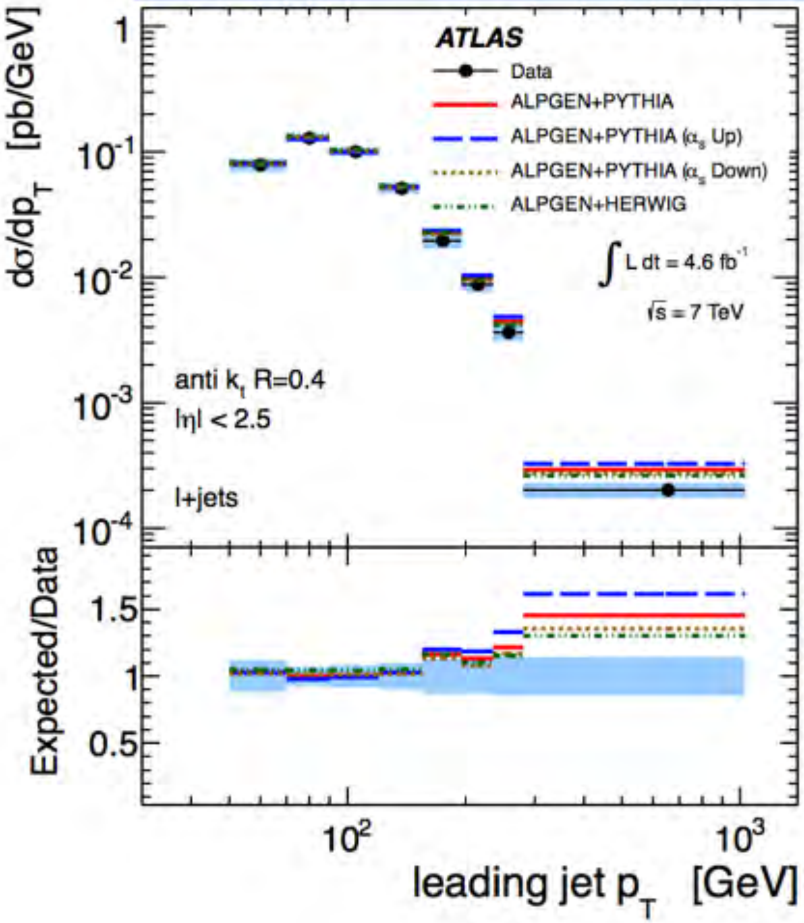
→ good description

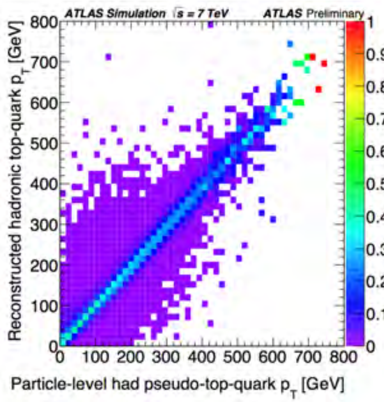
Top decay products: pseudo-top

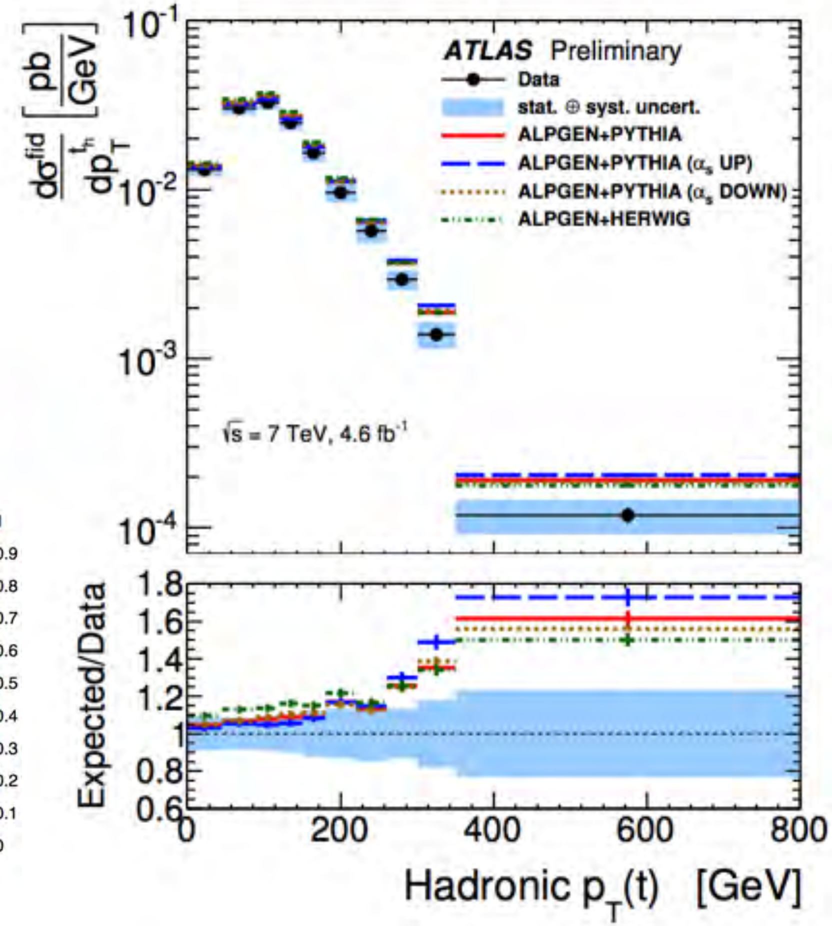
Fiducial phase space:
>=1 b-jet, 1 lepton, >=3 jets,
1st jet p_t>50 GeV, 2nd jet p_t>35 GeV

J. Katzy

Fiducial phase space:
2 b-jets, 1 lepton, >=4 jets



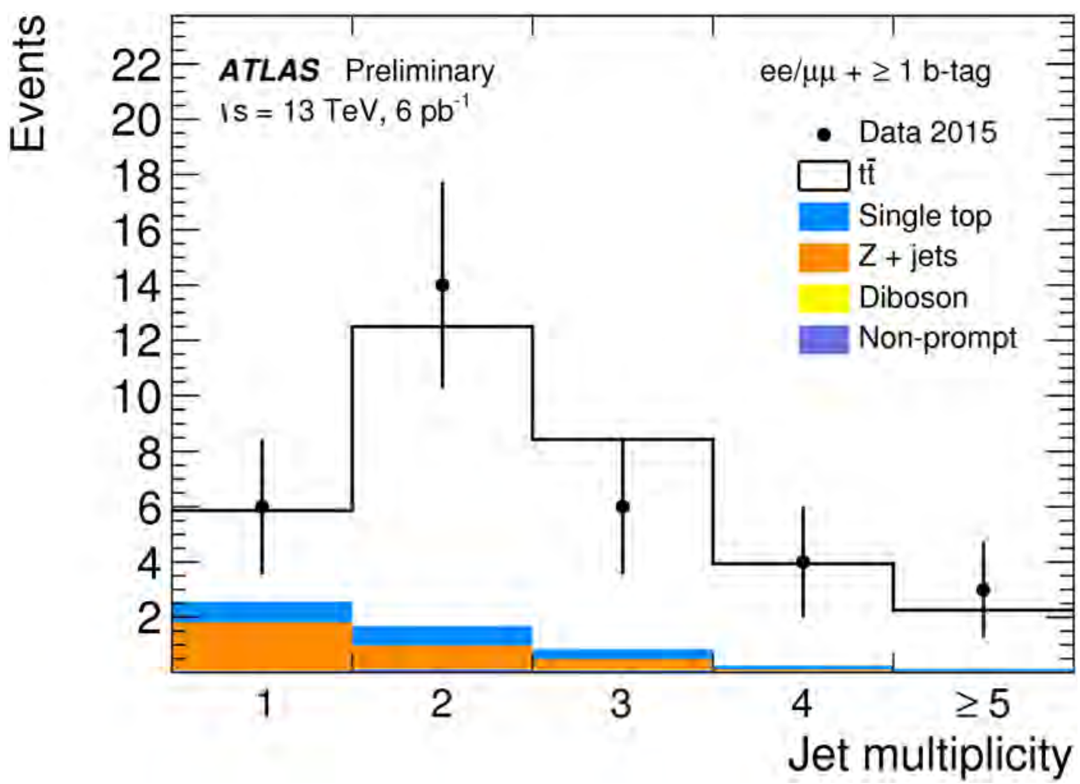


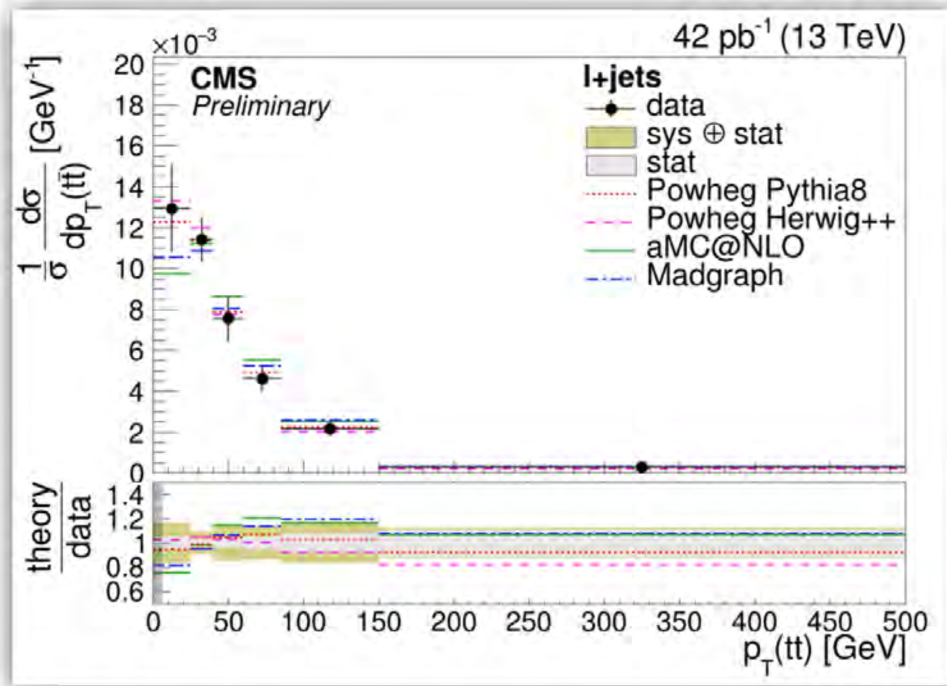


→ reconstruct tops on particle level

→ very valuable for theorists today and in future

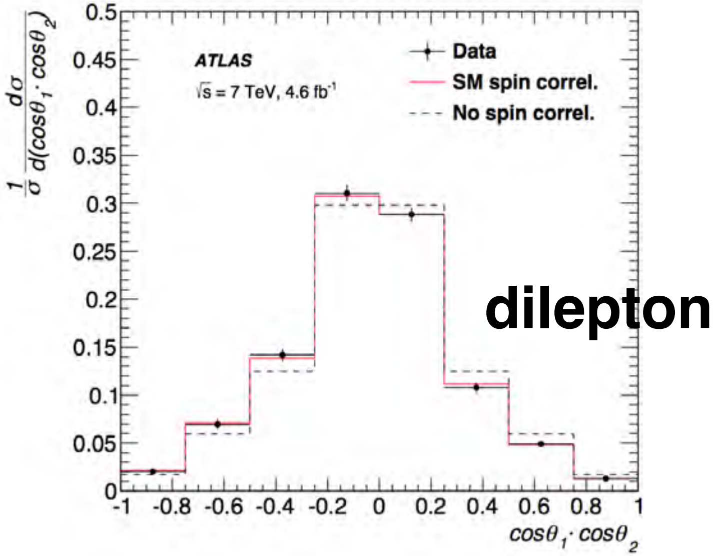
Differential: top pair p_T

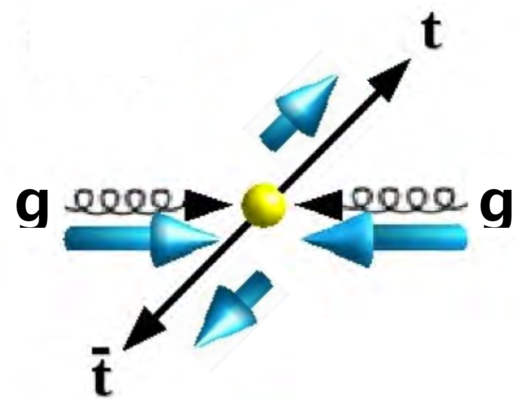




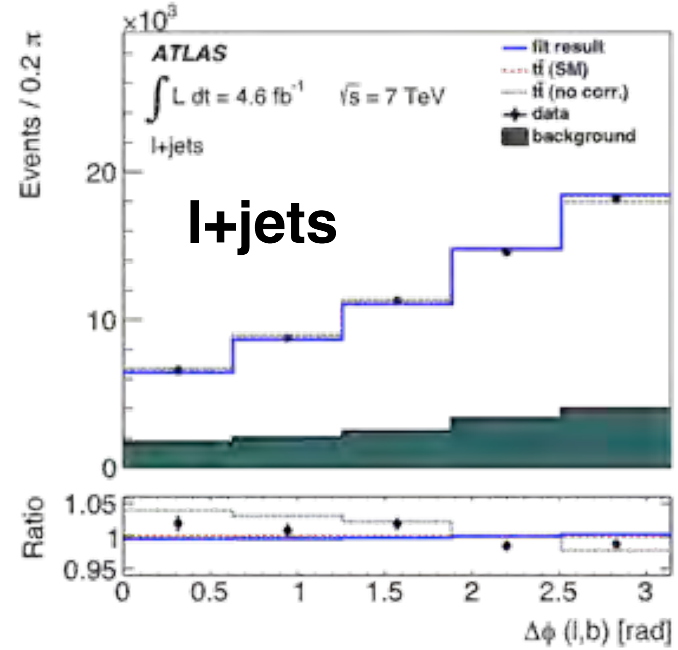
→ **good agreement with new MC tools so far, but low statistics still**

Polarisation and Spin Correlation

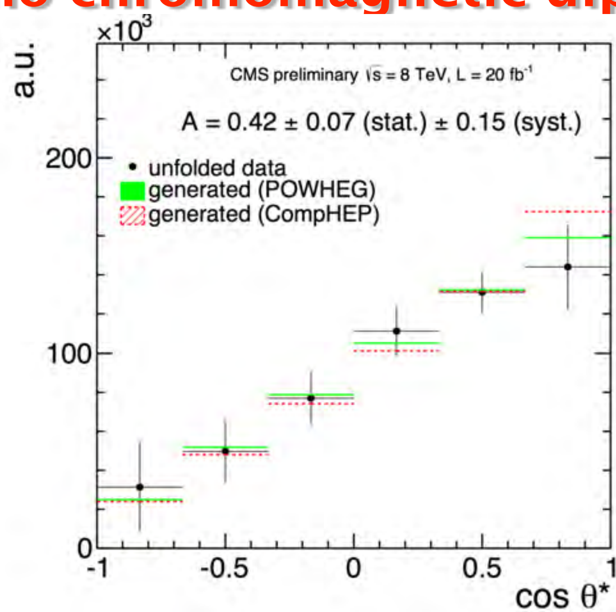




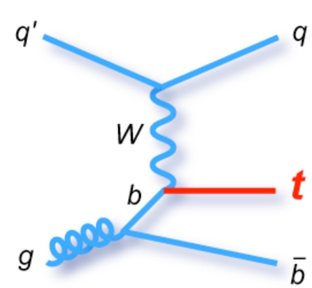
→ spins of tt pairs: correlated as in SM

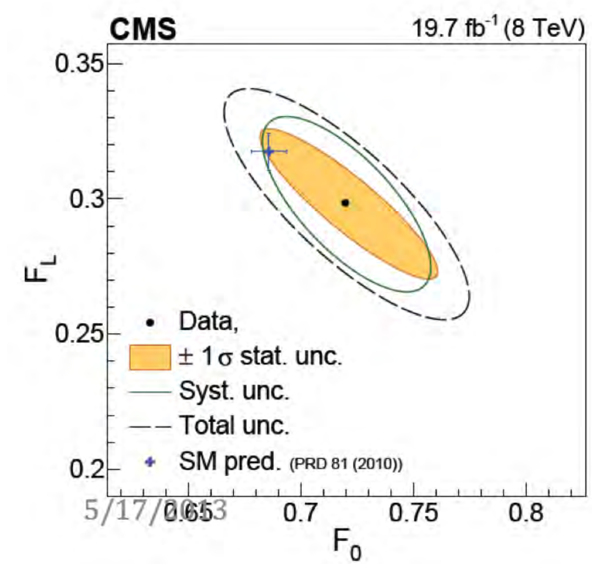


→ no chromomagnetic dipole moments



no new physics



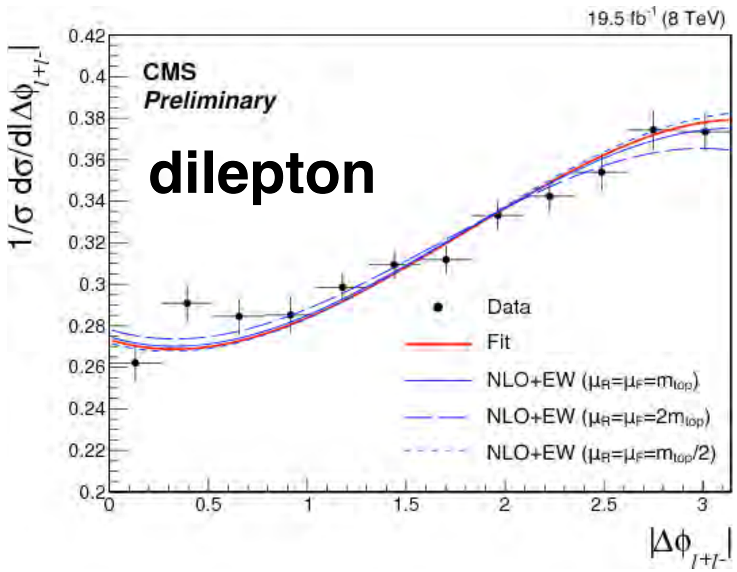


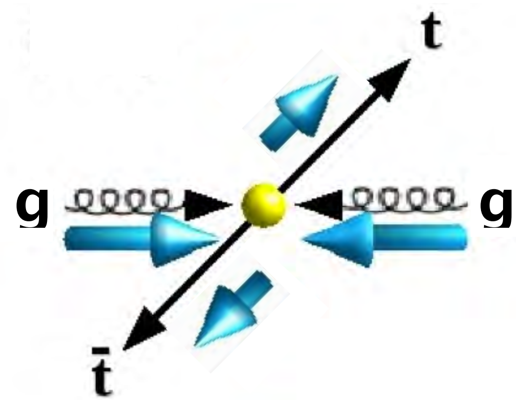
5/17/2013

→ top quarks polarised as in SM

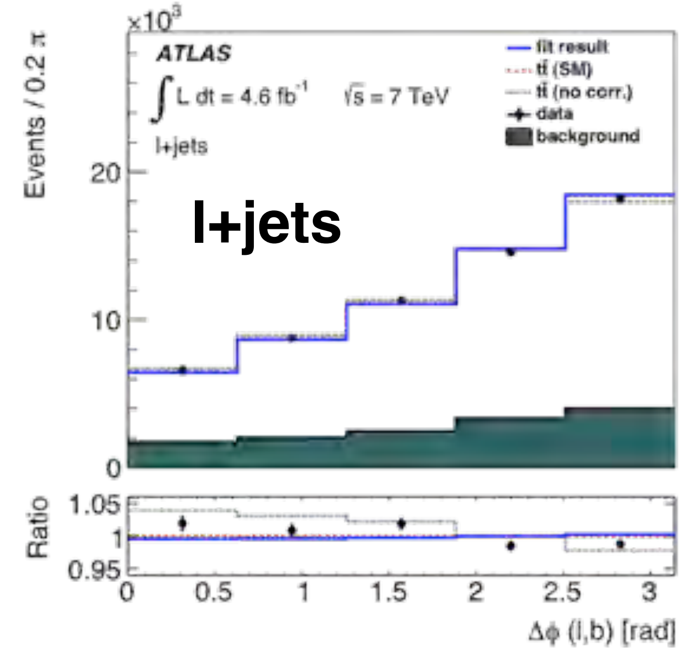
→ W polarisation as in SM

Polarisation and Spin Correlation

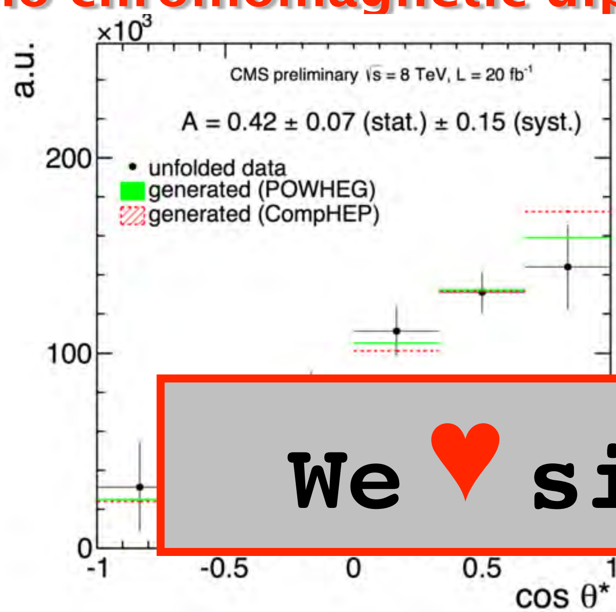




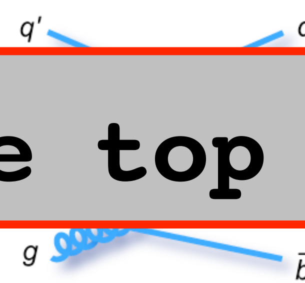
→ spins of tt pairs: correlated as in SM

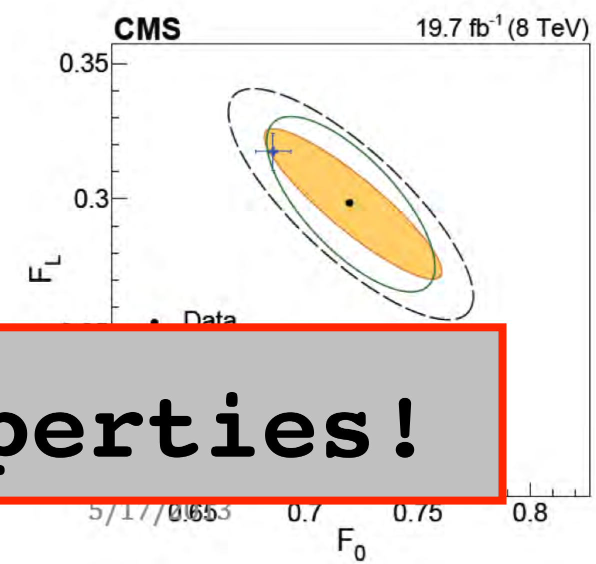


→ no chromomagnetic dipole moments



no new physics





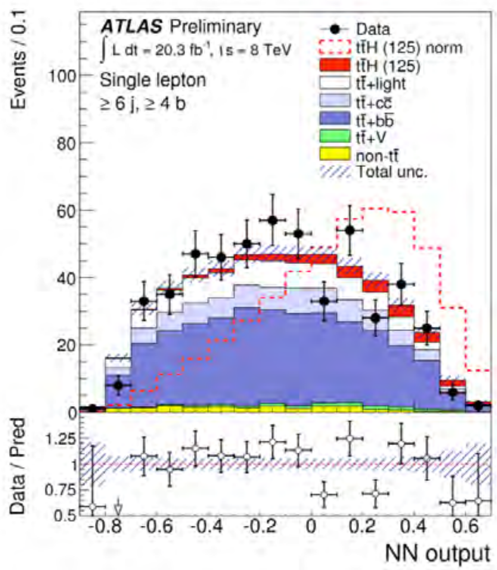
We ♥ single top properties!

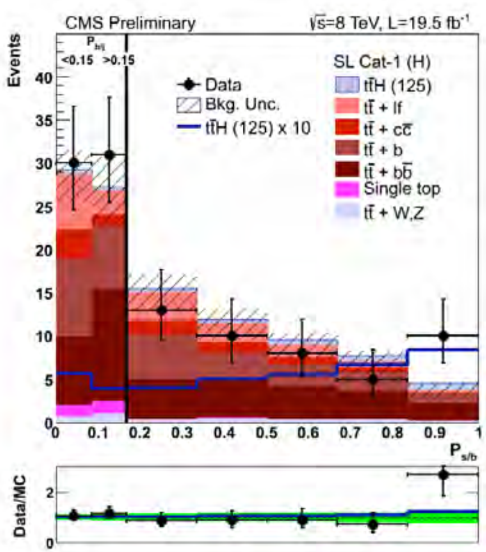
→ top quarks polarised as in SM

→ W polarisation as in SM

Search for ttH production

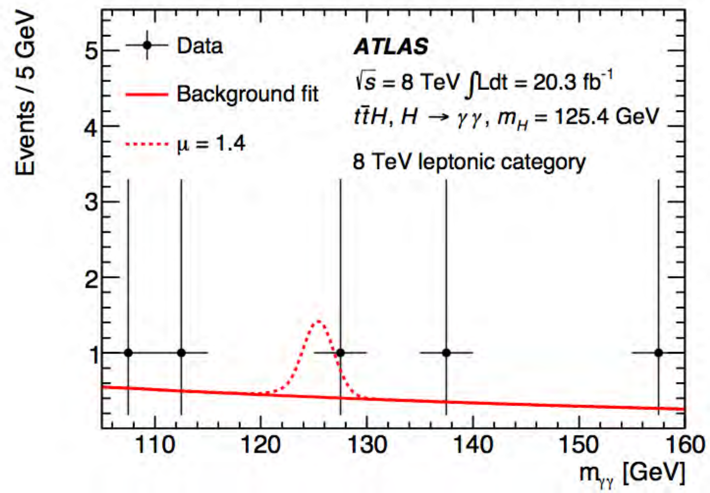
H→bb

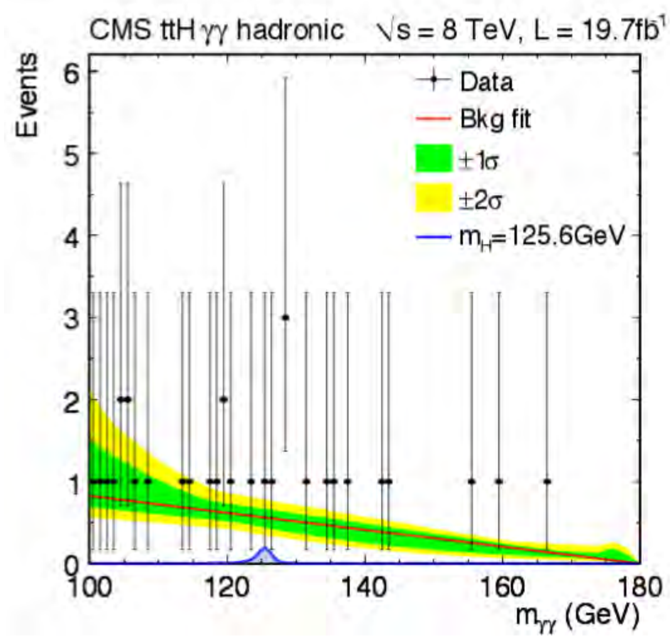




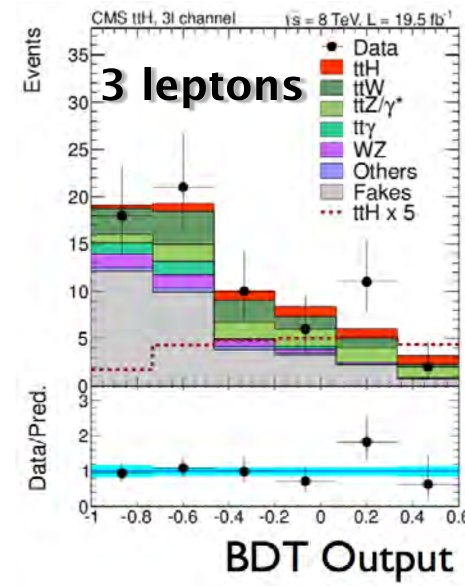
matrix element

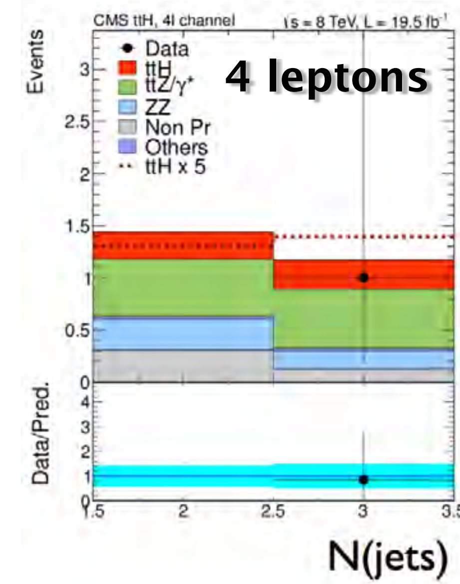
H→γγ





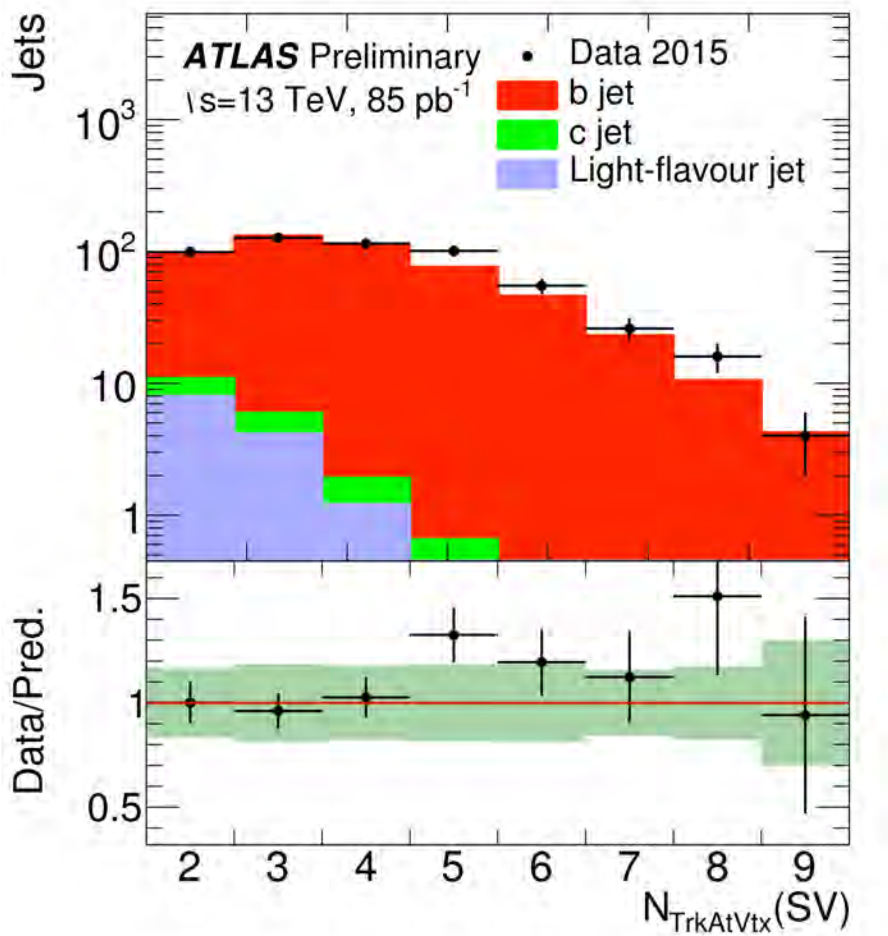
H→WW, ZZ





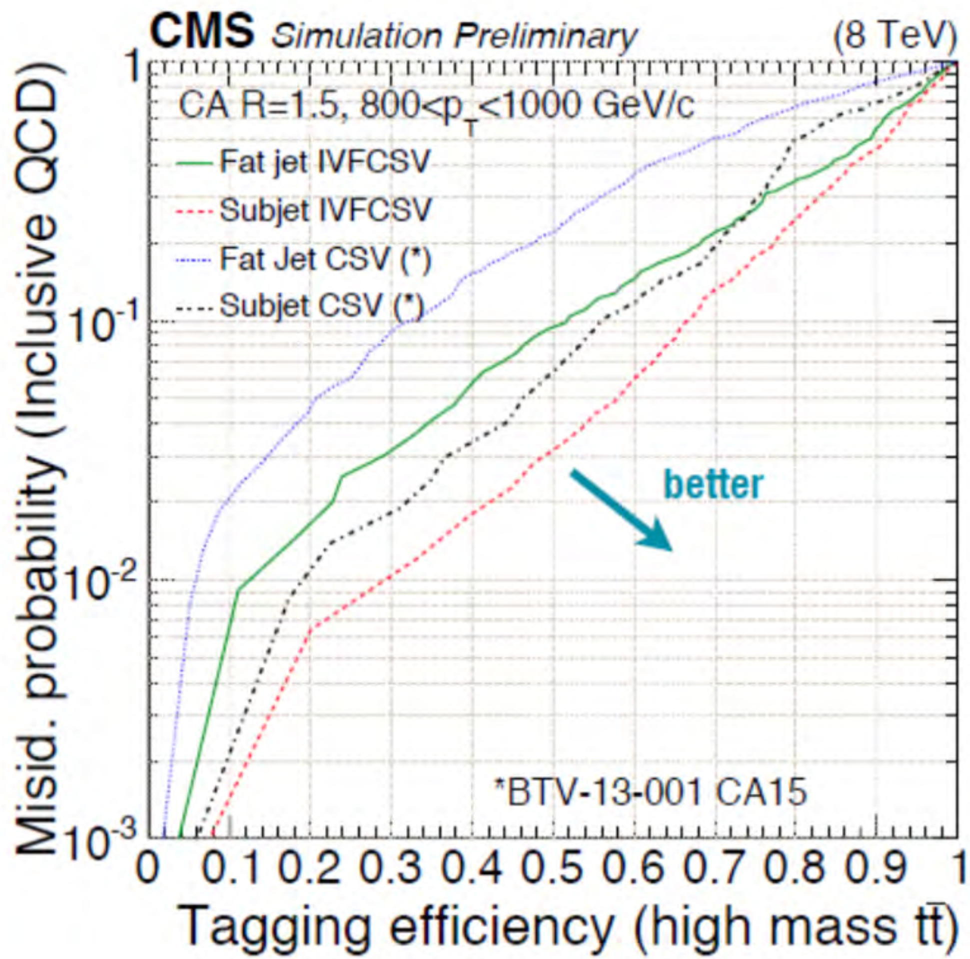
Tools from and for tops

b-tagging from top pairs (eμ)



→ **great importance for all types of physics**

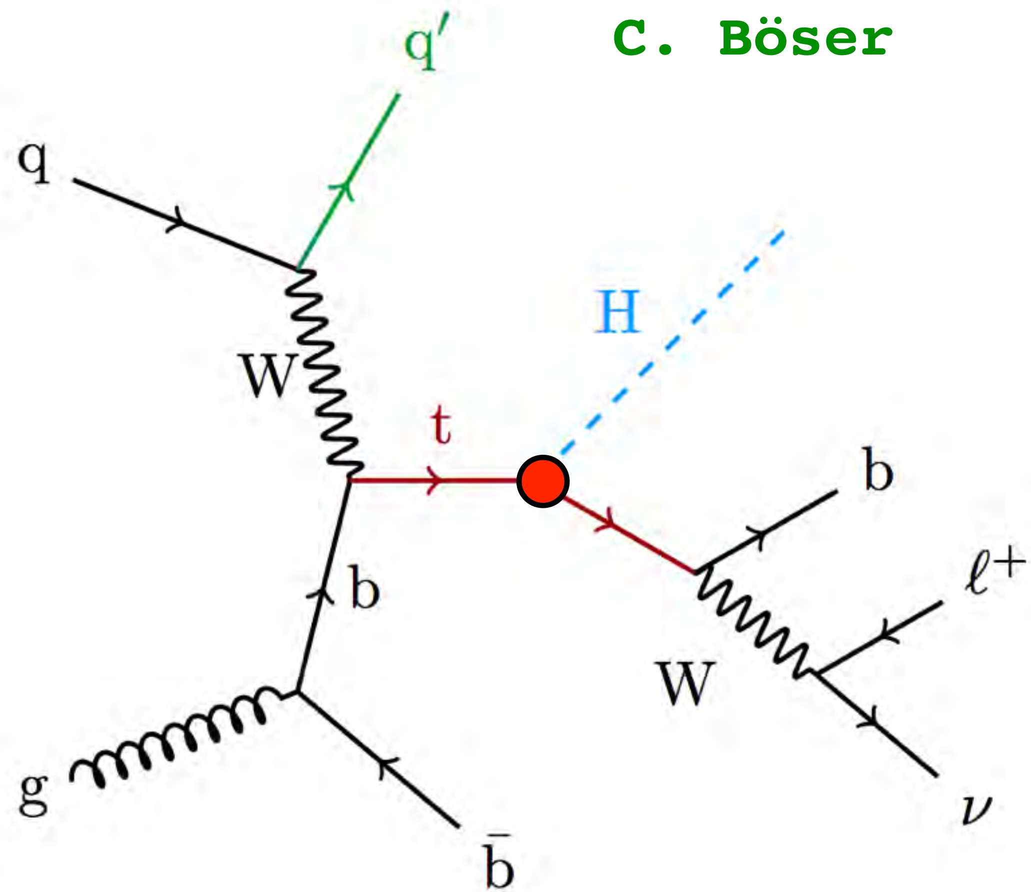
t-tagging in boosted topologies



→ **huge improvements**

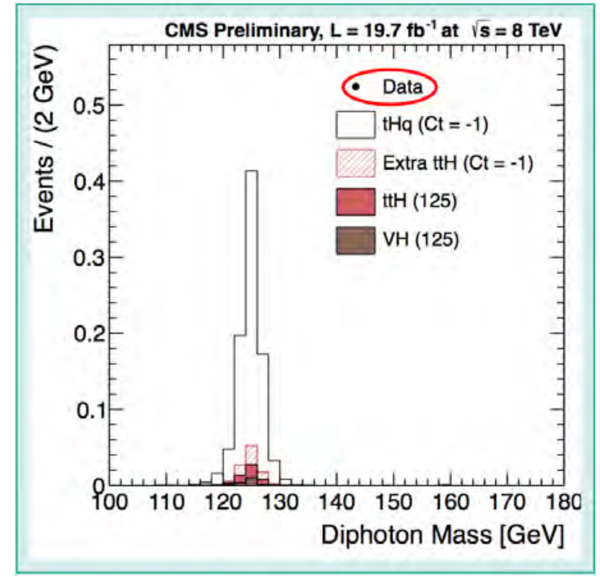
Search for tHq production

C. Böser



H→γγ

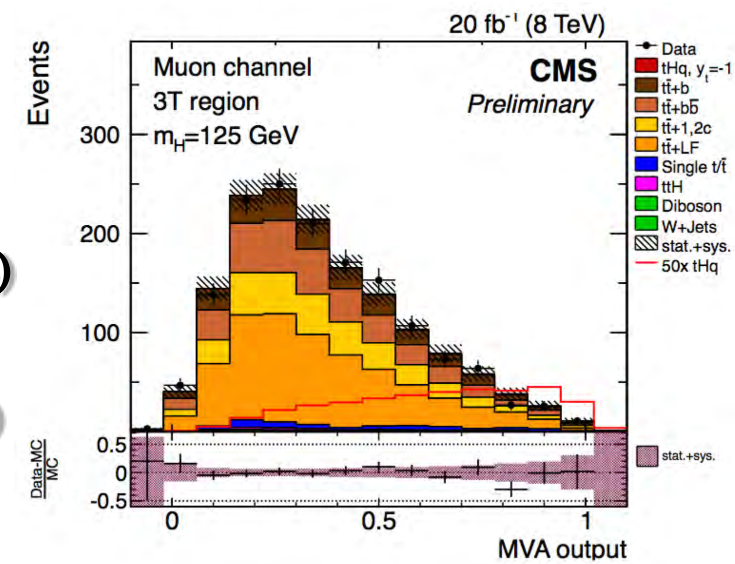
$4.1 \times \sigma/\sigma(\kappa_t)$ expected



H→bb

$5.1 \times \sigma/\sigma(\kappa_t)$ expected

$7.6 \times \sigma/\sigma(\kappa_t)$ observed

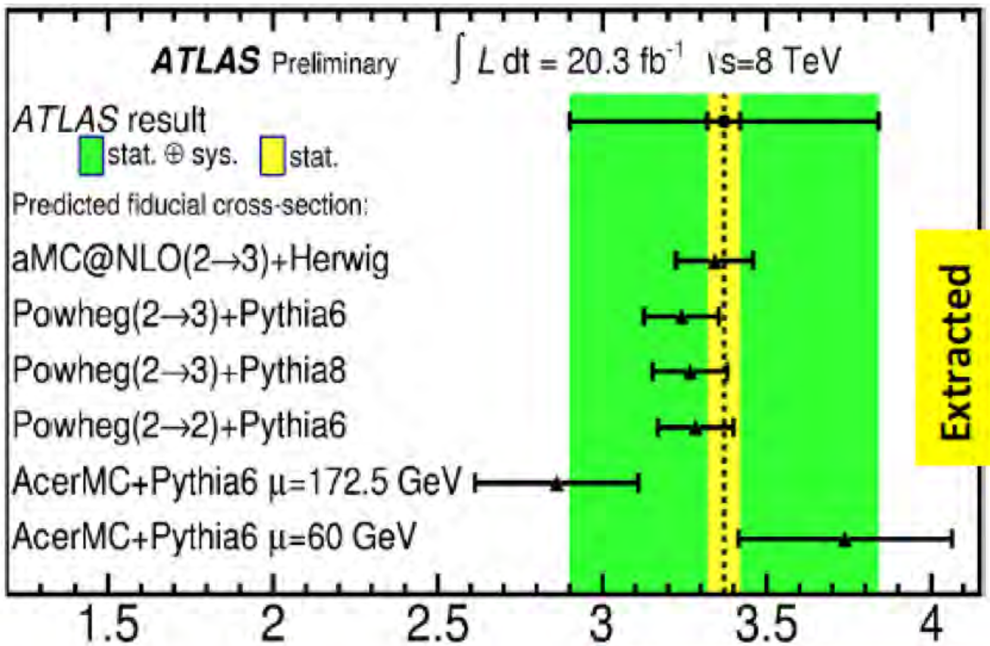


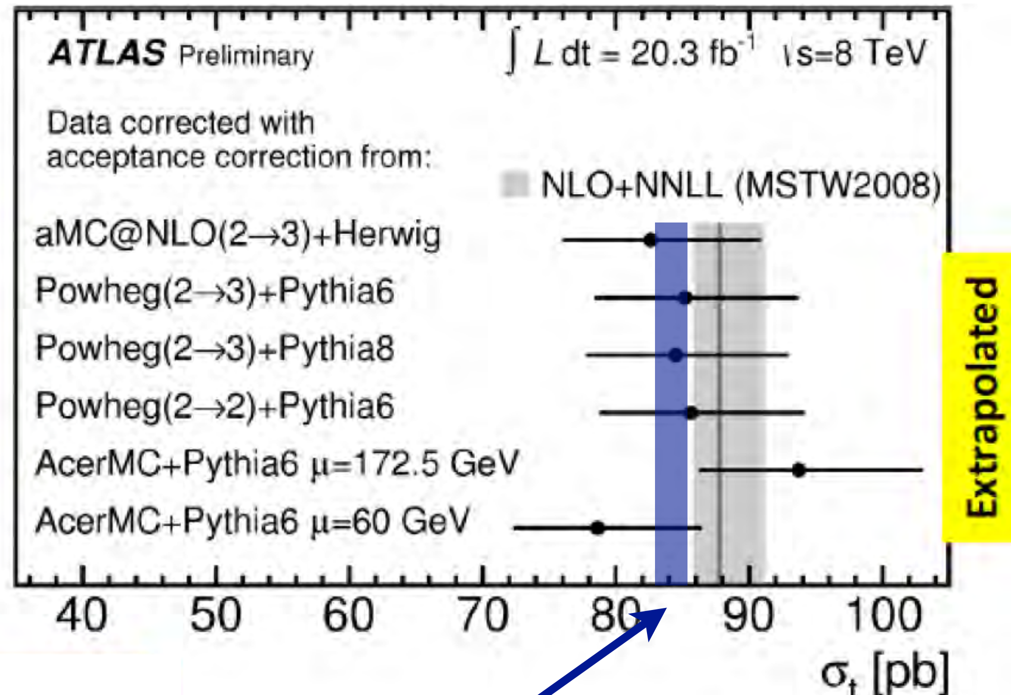
in case top Yukawa coupling $\kappa_t = y_t / y_t^{SM} = -1$ coupling: cross section can be enhanced by factor 13

→ fun in Run-II

Fiducial t-channel cross section

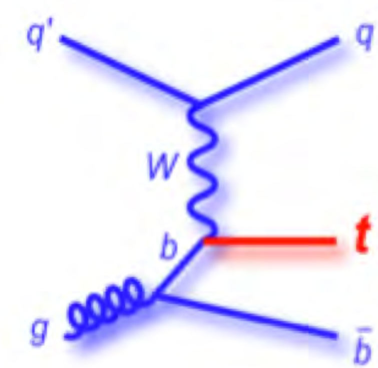
A. Jafari





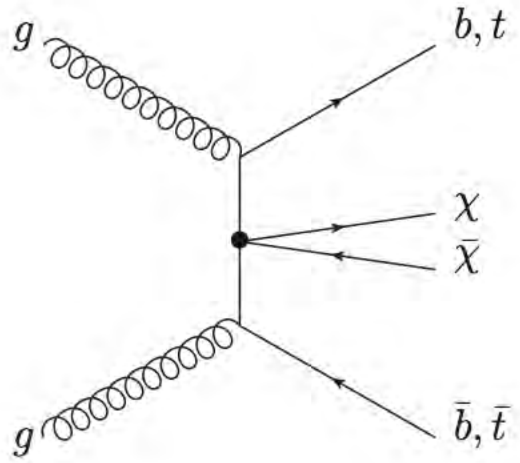
NNLO

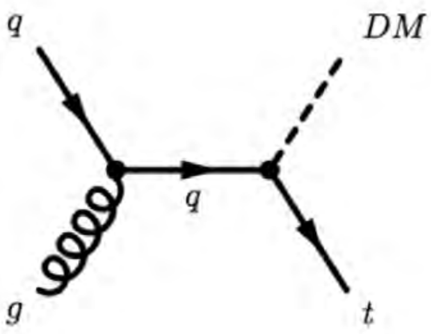
F. Caola

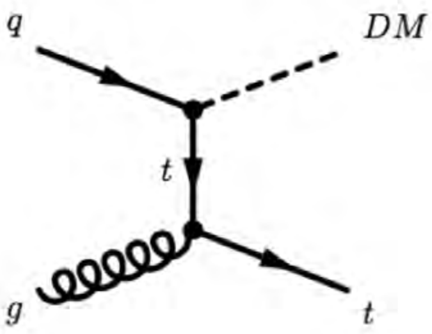


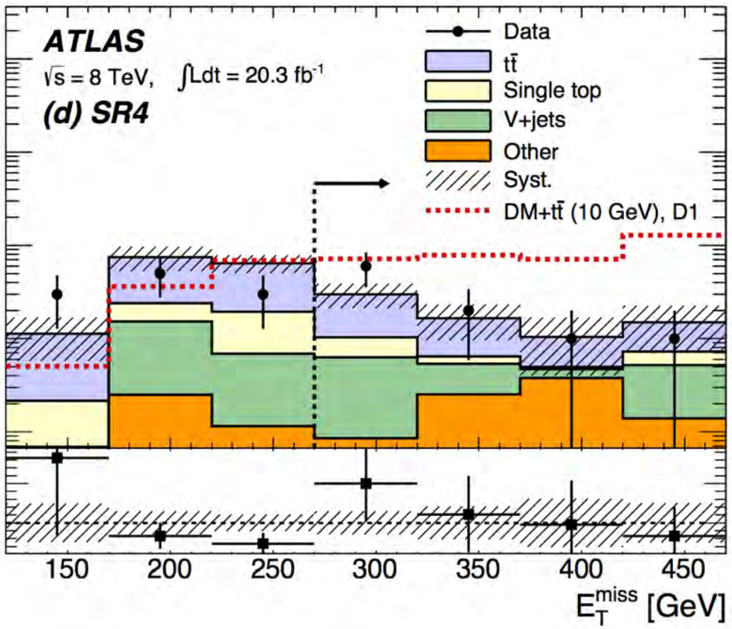
→ **good agreement with SM predictions**

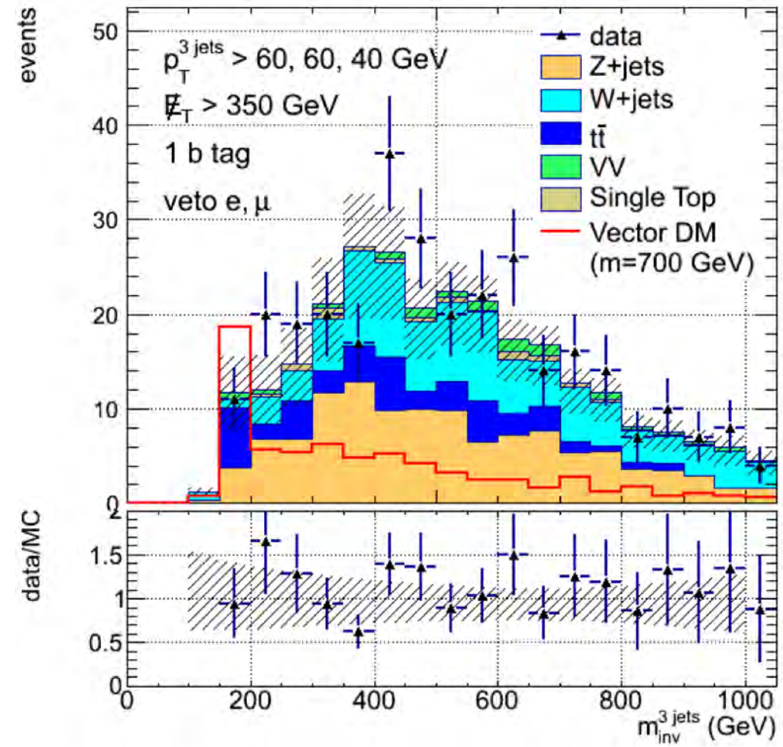
Search for dark matter







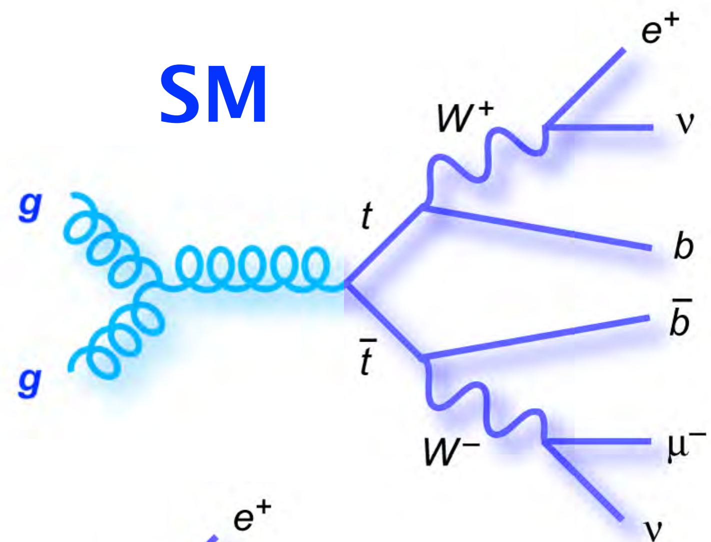


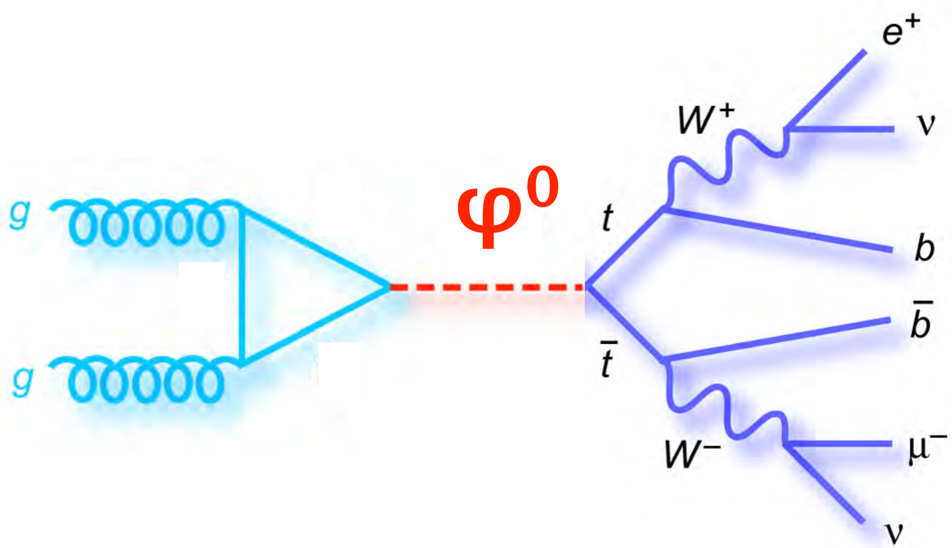


→ **no hint for dark matter**

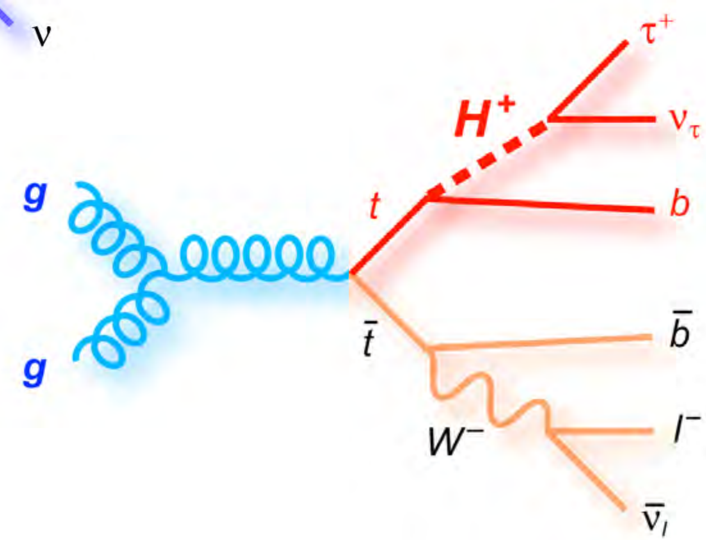
New physics impact on spin

- important test of SM and sensitive search for physics beyond
- analyse the whole chain of top pair production and top decay





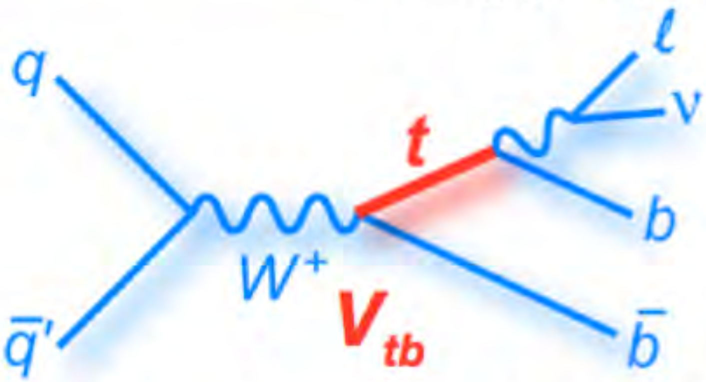
Higgs, KK gravitons, Z', stop pairs, ...



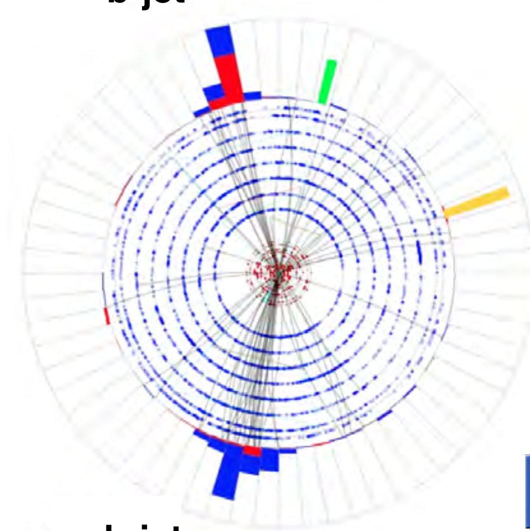
charged Higgs, b', ...

Single Top Quark Selection

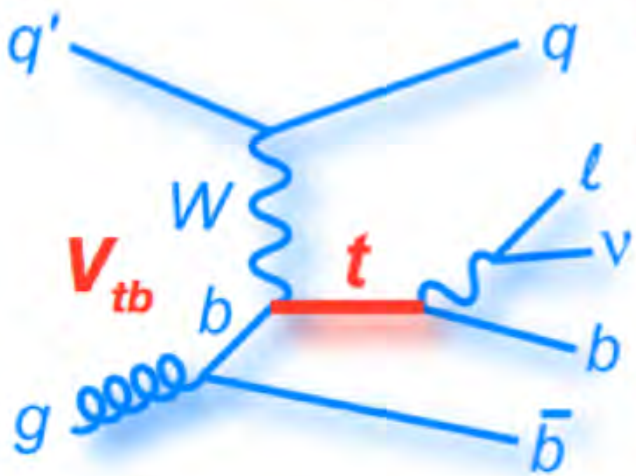
s-channel: $\sigma_s = 1.05 \pm 0.06$ pb
NLO+NNLL, $m_t = 172.5$ GeV
Kidonakis, PRD 81, 054028 (2010)



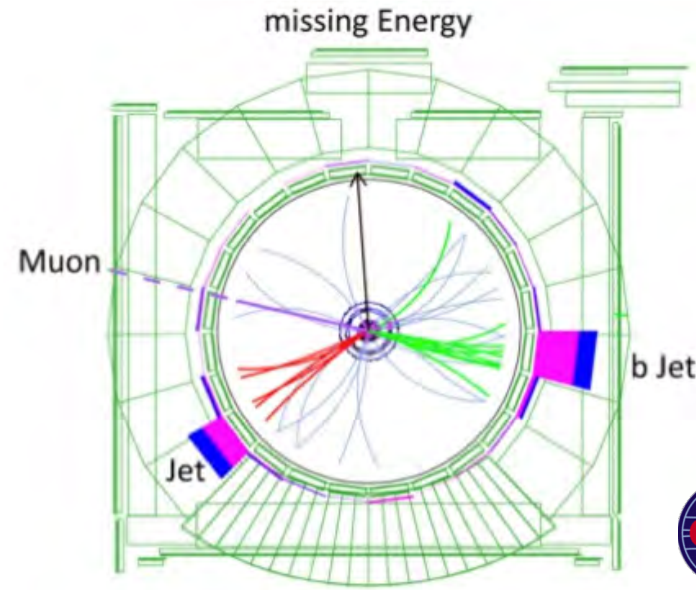
- lepton
- missing E_T
- b-jets



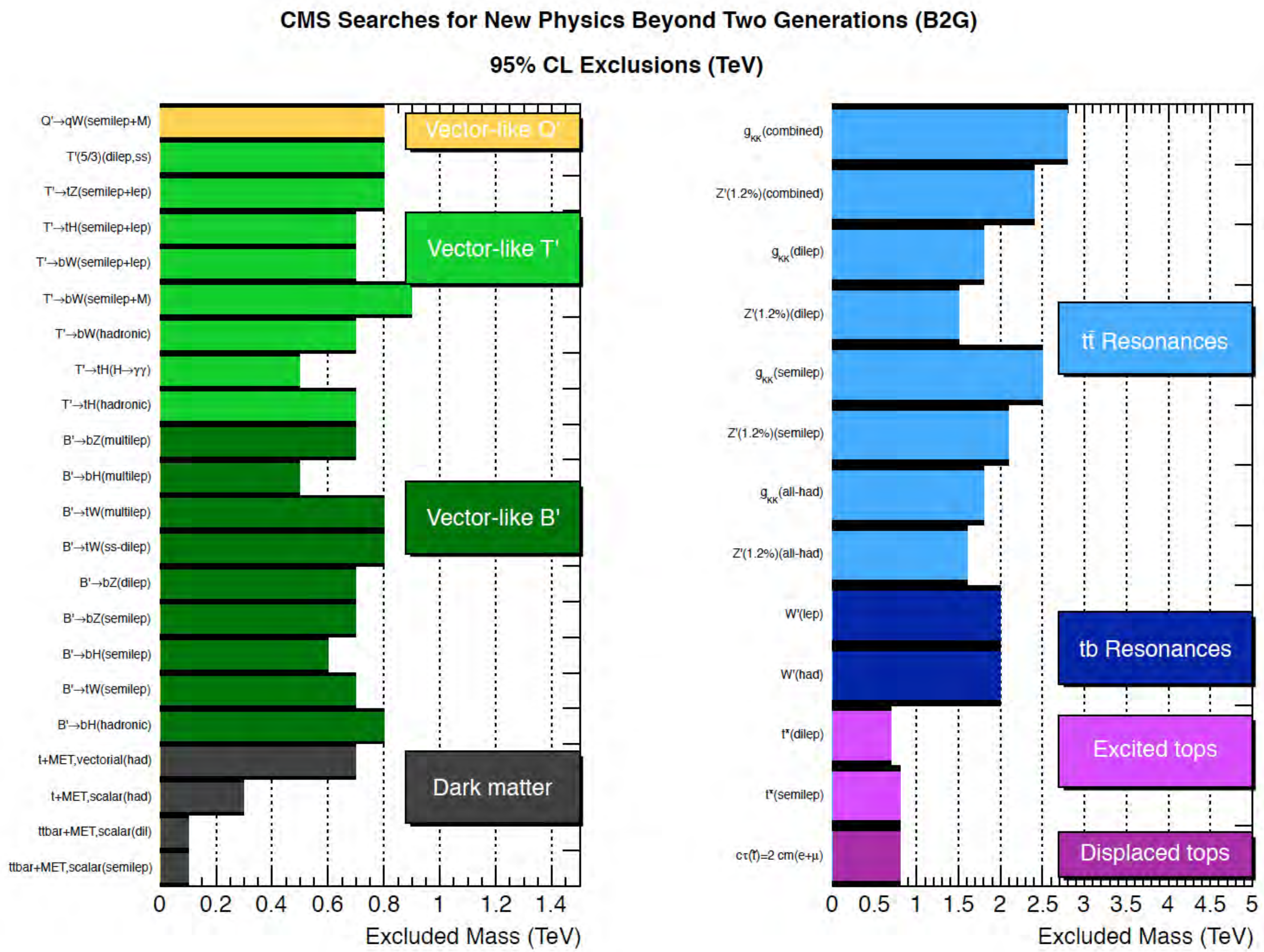
t-channel: $\sigma_t = 2.12 \pm 0.16$ pb
NLO+NNLL, $m_t = 172.5$ GeV
Kidonakis, PRD 83, 091503 (2011)



- jets
- lepton
- missing E_T
- b-jets

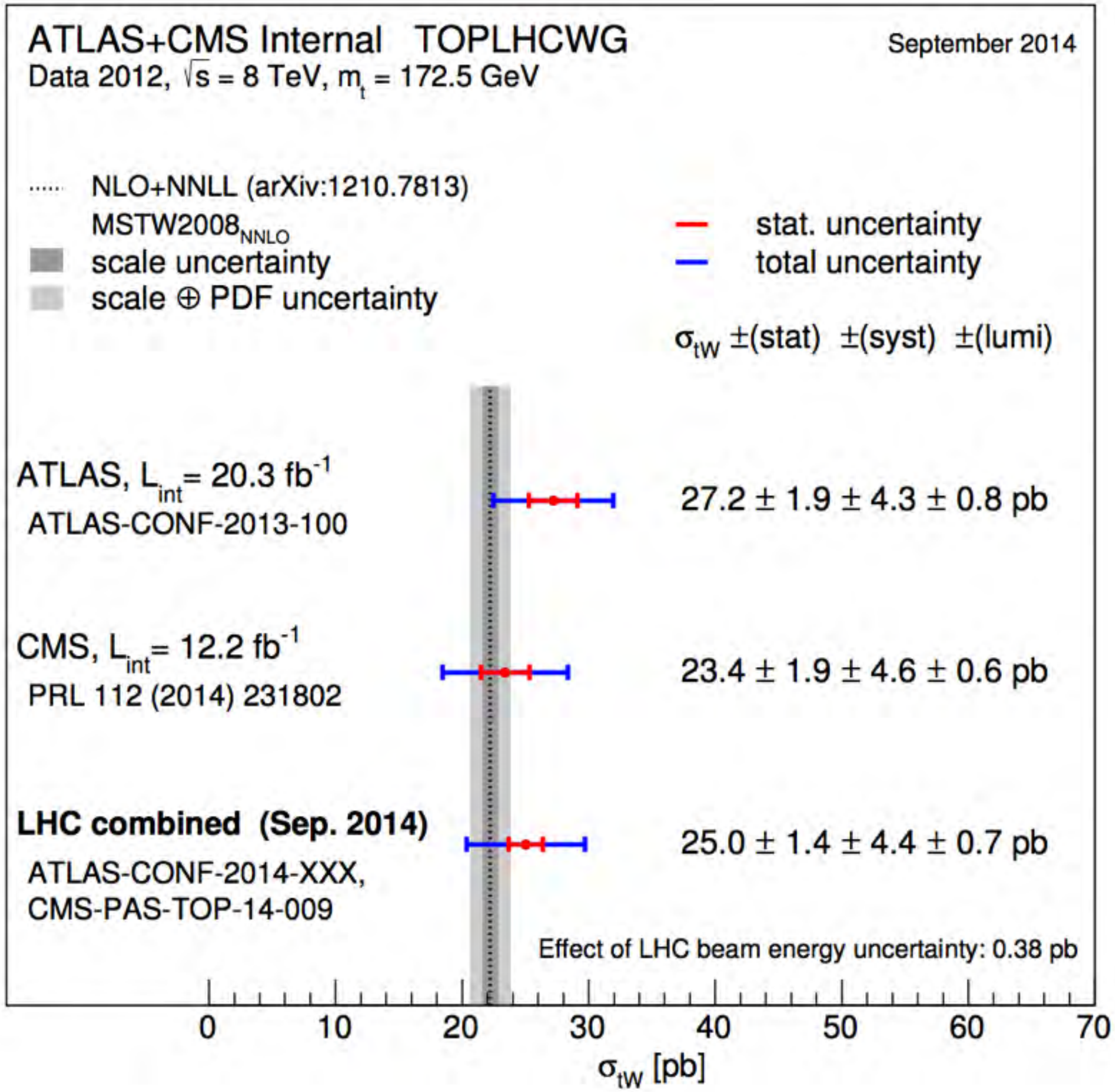


Pushing the TeV scale



→ lots of opportunities for discovery in Run-II

Single Top Wt Cross Section



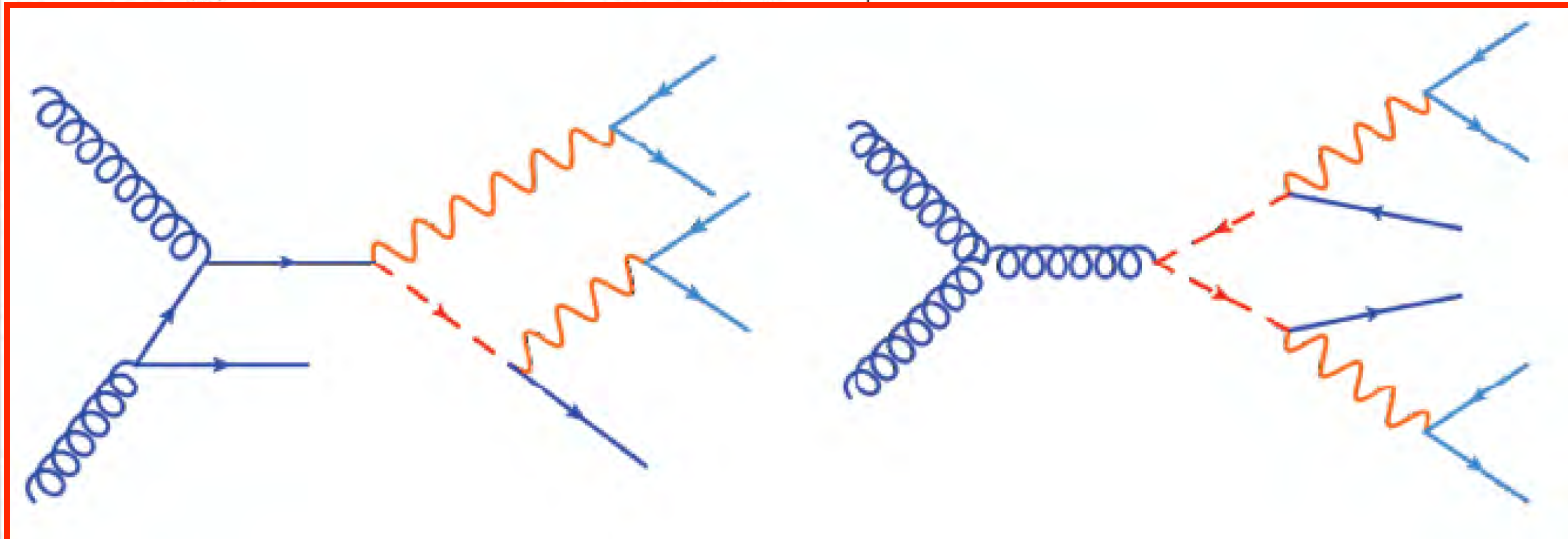
A. Jafari

Source	Uncertainty (%)	Uncertainty (pb)
Data statistics	5.5%	1.4
Simulation statistics	1.8%	0.5
Luminosity	2.7%	0.7
Theory modeling	15.8%	4.0
Background normalization	2.3%	0.6
Jets	5.3%	1.3
Detector modeling	4.9%	1.2
Total systematics (excl. lumi)	17.5%	4.4
Total systematics (incl. lumi)	17.7%	4.4
Total uncertainty	18.6%	4.7

→ observed!

Single Top Quark Cross Section

F. Caola

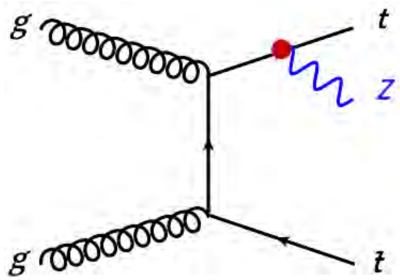


Total systematics (incl. lumi)	17.7%	4.4
	18.6%	4.7

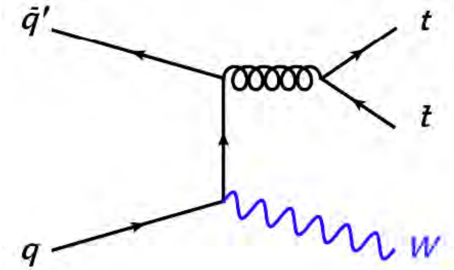
→ measure WWb cross section

(single resonant enriched)

Search for ttZ and ttW



T.V. Schroeder

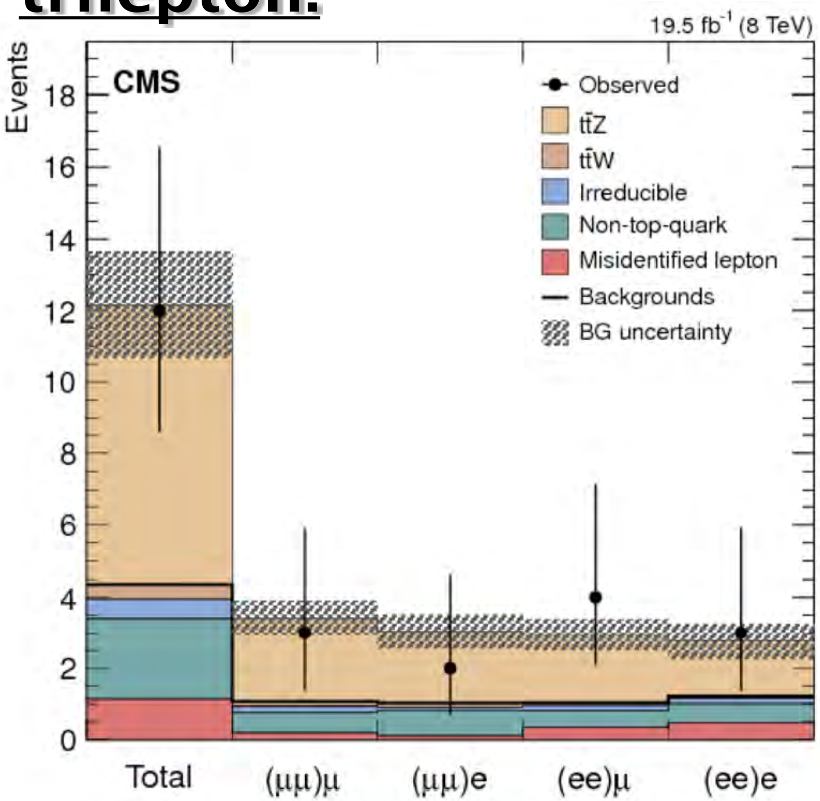


FSR

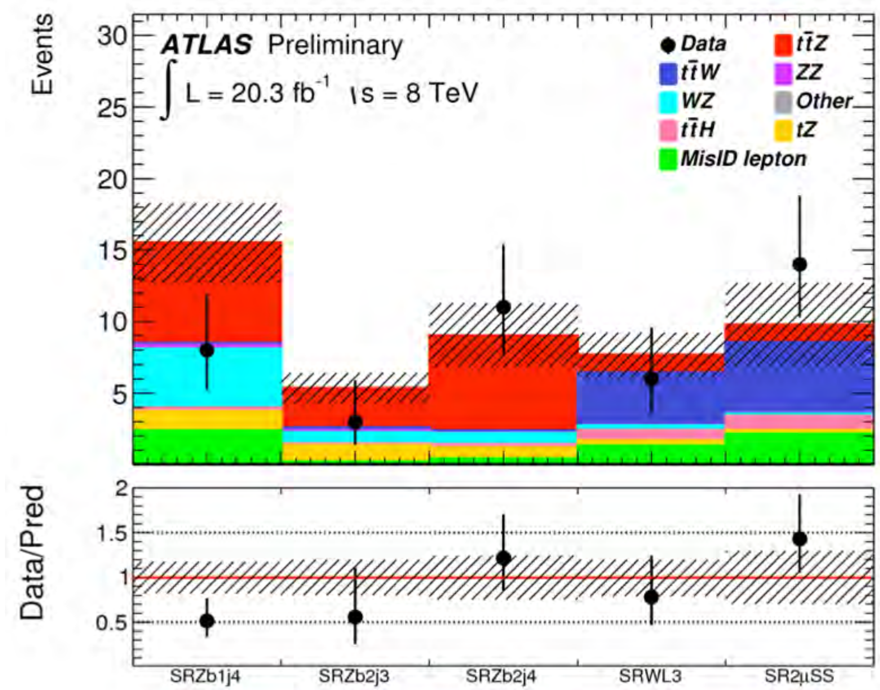
ISR

$$-i \frac{e}{\sin\vartheta_W \cos\vartheta_W}\left(T_3 - \sin^2\vartheta_W\, Q_t\right)\gamma^\mu$$

trilepton:



same sign dilepton:



$t\bar{t}Z$ $t\bar{t}W$

"Revolution" in Phenomenology

- LO QCD+parton shower generators
  Pythia, Herwig, ...

- LO multileg generators matched with parton shower
  Alpgen+Pythia, Alpgen+Herwig, ...

- NLO+parton shower generators
  Powheg+Pythia, MC@NLO+Herwig, ...

- NLO+LO multileg generators matched with parton showers

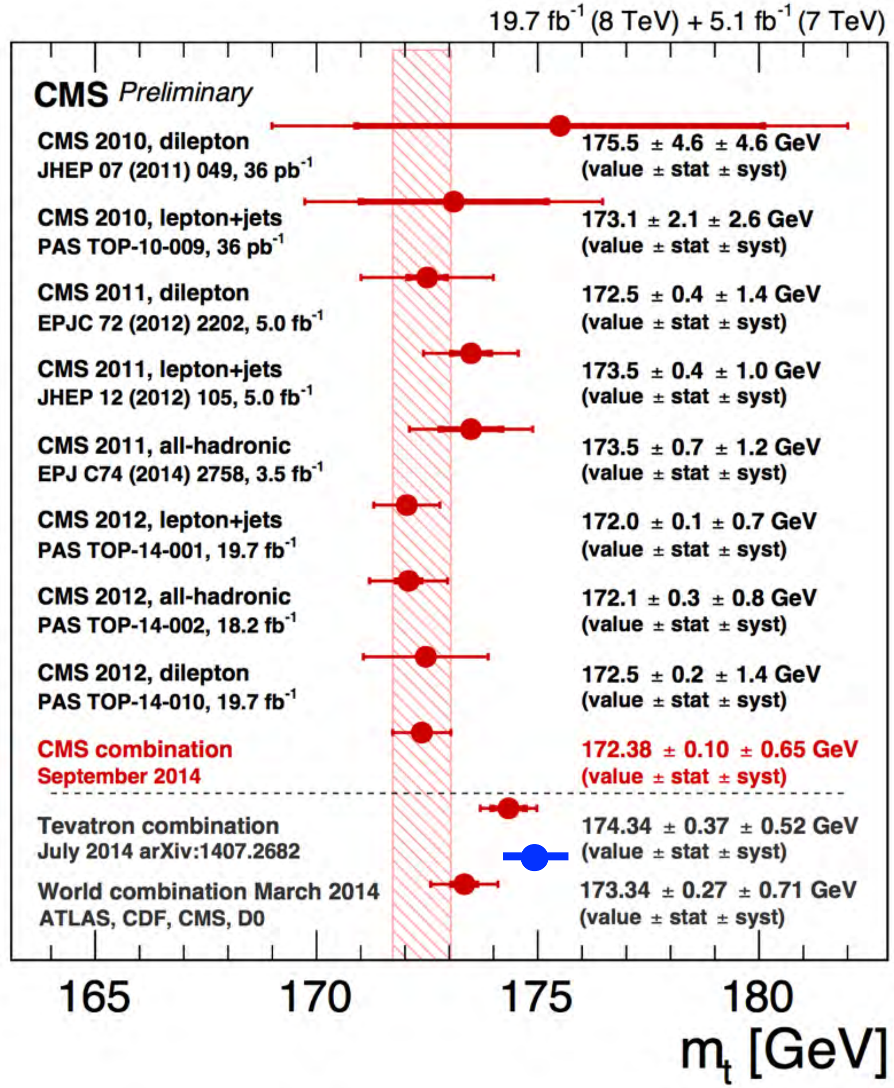
- NNLO QCD calculations
  normalisation

this analysis: $t\bar{t}$+jets

very important measurements to study higher orders QCD in a top quark environment!

CMS top mass combination

top mass crisis?



E. Schlieckau

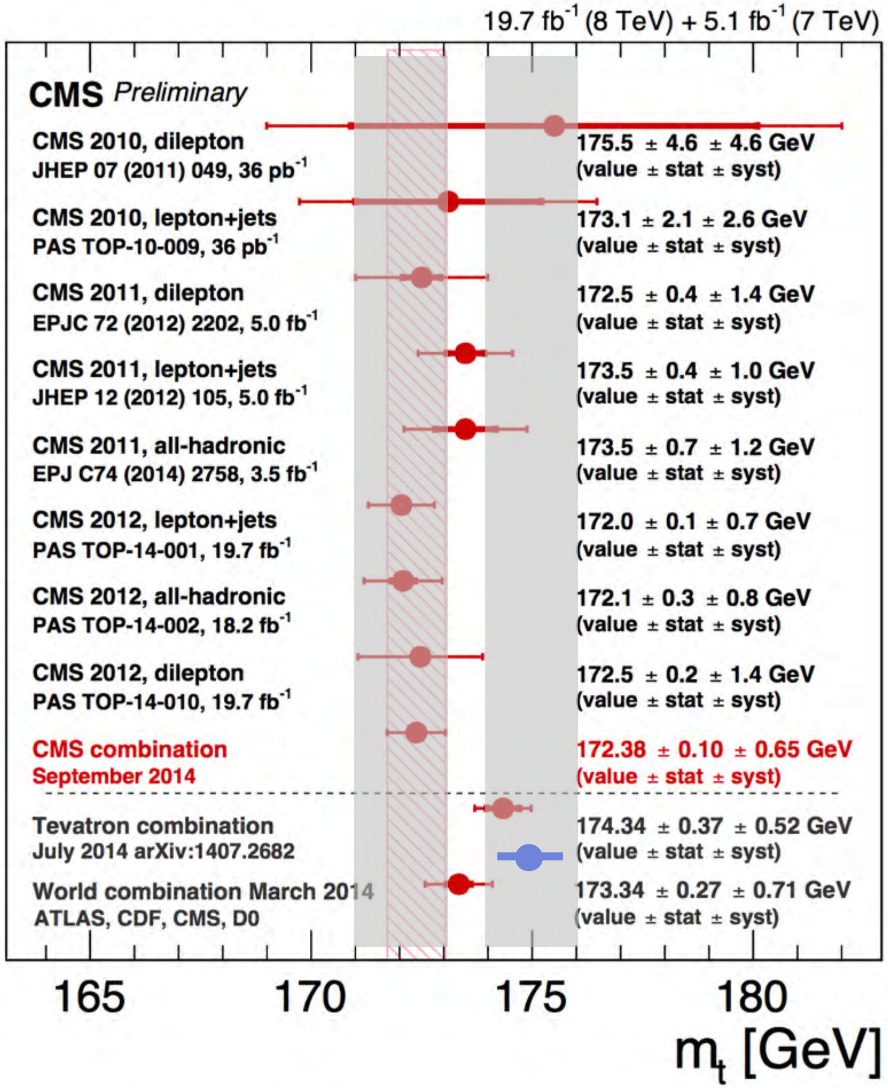
DØ l+jets, 9.7 fb^{-1}

- discussions about JES, b-JES, other systematics
- differences between CMS and D0 to be understood during combination

I am just speculating...

top mass crisis?

E. Schlieckau



DØ l+jets, 9.7 fb^{-1}

A. Hoang

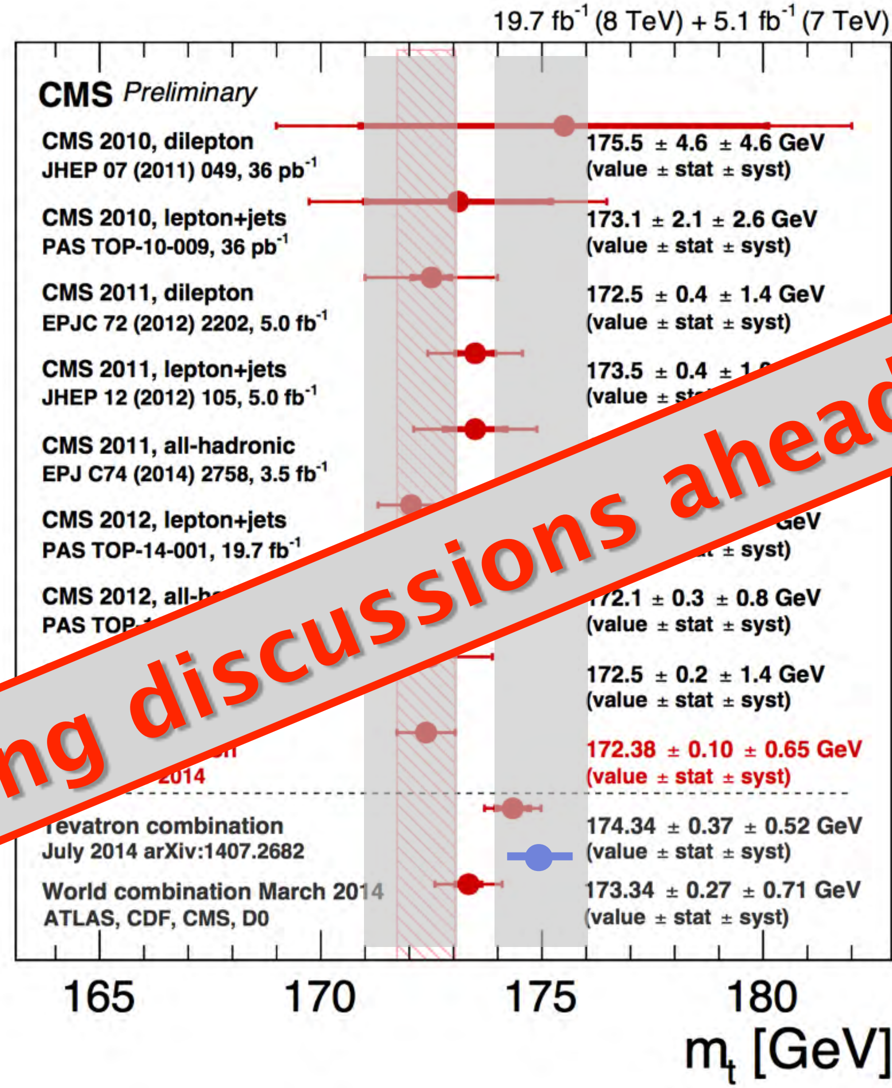
- each MC mass can shift by up to Δ≈O(1 GeV) to QFT mass
- WbWb off-shell effects: can move <m_{lb}> by O(1 GeV)

J. Winter

I am just thinking...

top mass crisis?

E. Schlieckau



→ exciting discussions ahead of us...

DØ l+jets, 9.7 fb^{-1}

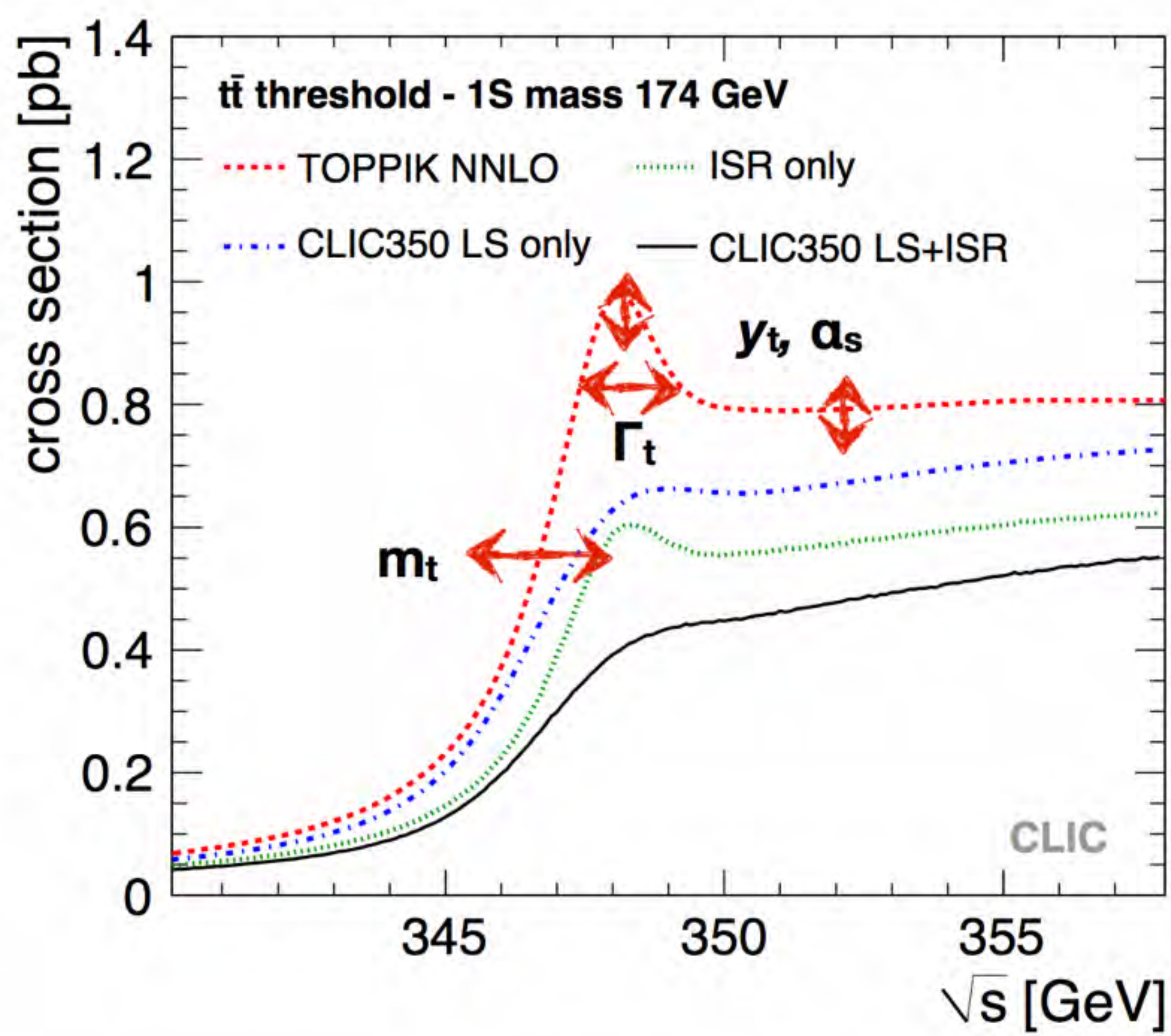
A. Hoang

- each MC mass can shift by up to Δ≈O(1 GeV) to QFT mass
- WbWb off-shell effects: can move <m_{lb}> by O(1 GeV)

J. Winter

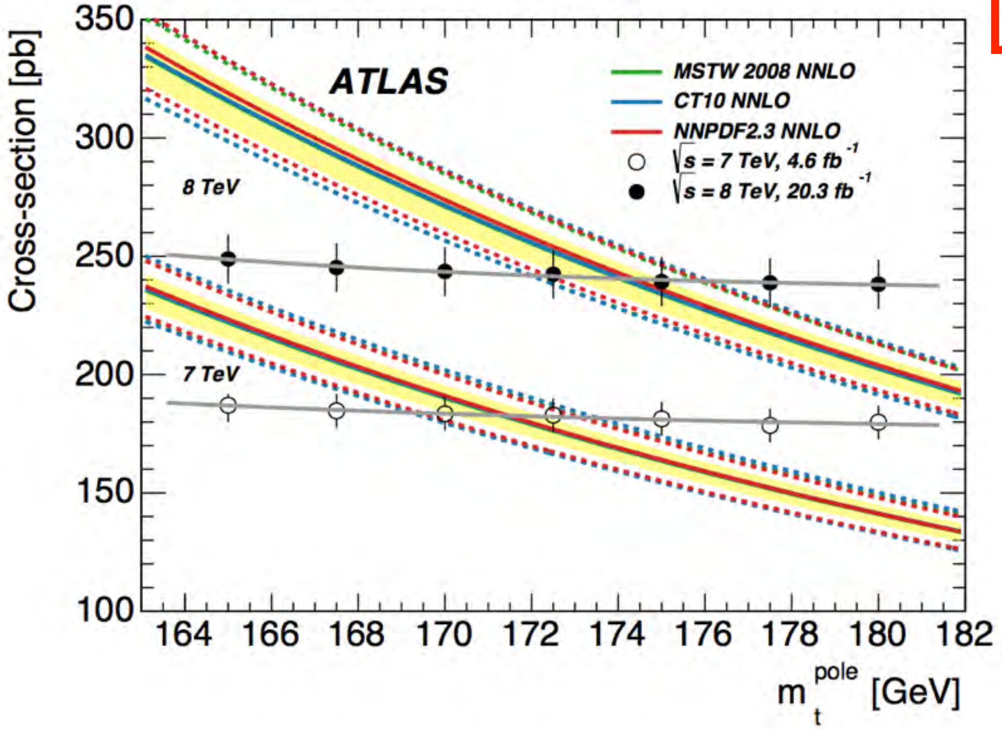
Top mass at ILC

F. Simon



→ **well-defined top mass with ~O(100 MeV) uncertainty**

Top Quark Pole Mass



$m_t^{\rm pole} = 172.9^{+2.5}_{-2.6}\,{\rm GeV}\ (\sqrt{s} = 7/8\,{\rm TeV})$

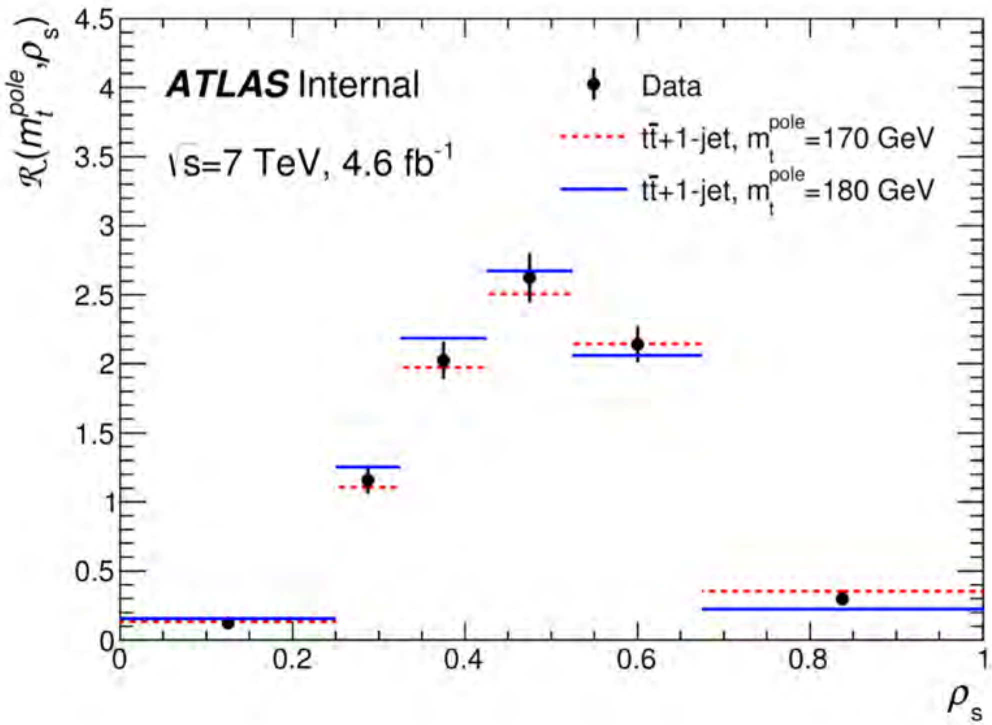
→ pole mass unambiguously!

many alternative measurements

tt+1jet: differential cross section

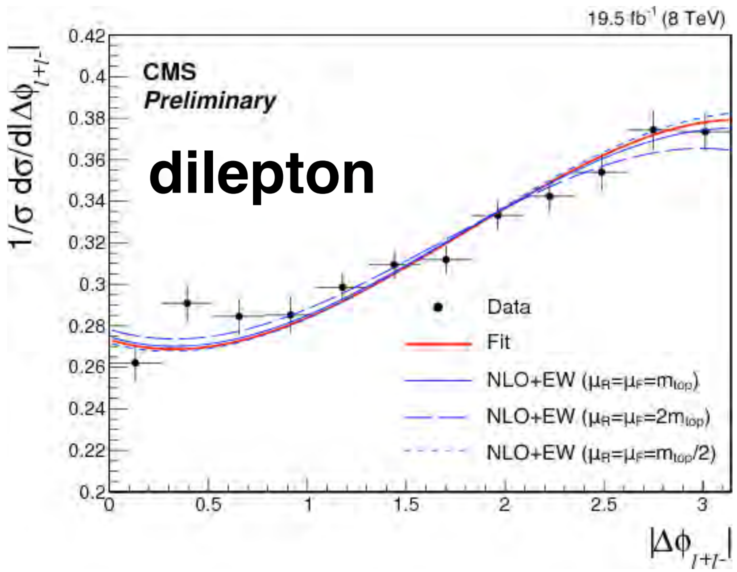
$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1-\mathrm{jet}}} \frac{d\sigma_{t\bar{t}+1-\mathrm{jet}}}{\rho_s}(m_t^{pole}, \rho_s)$$

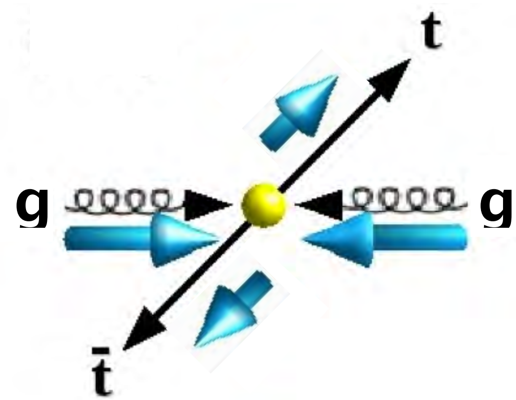
$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}} \qquad m_0 = 170\ GeV$$



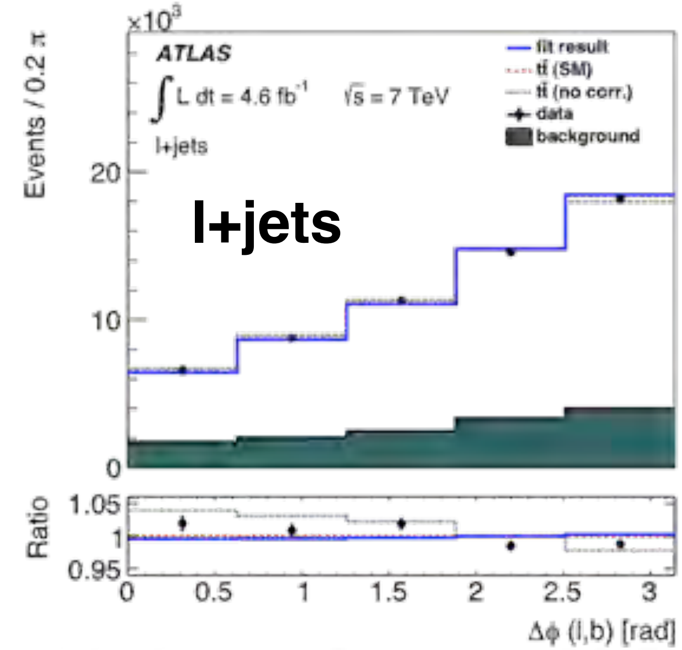
is it really the pole mass?

Polarisation and Spin Correlation

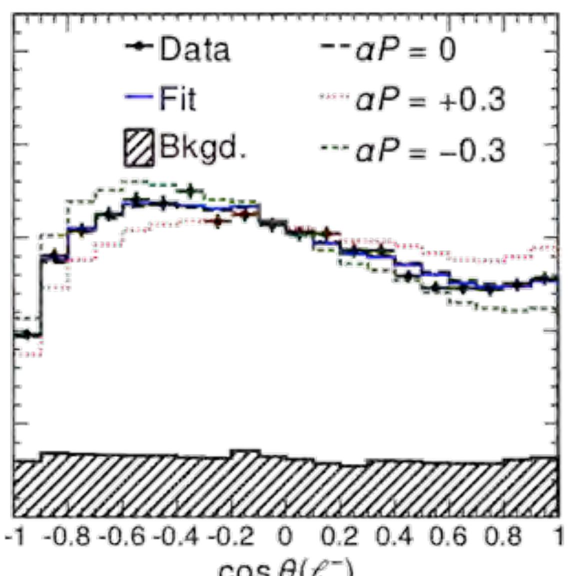




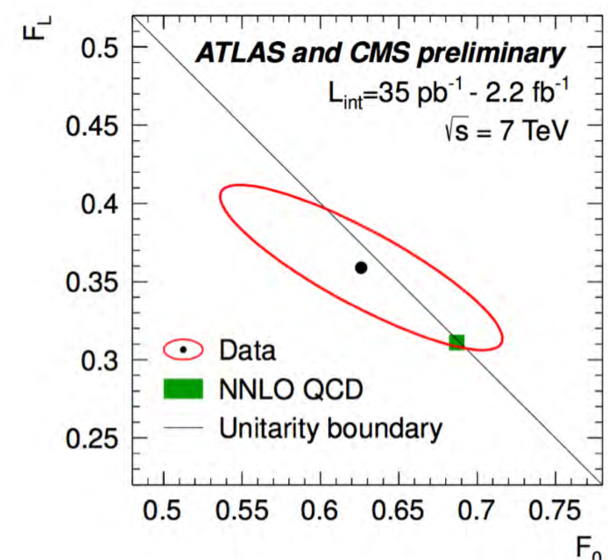
→ spins of tt pairs: correlated as in SM



→ no chromomagnetic dipole moments

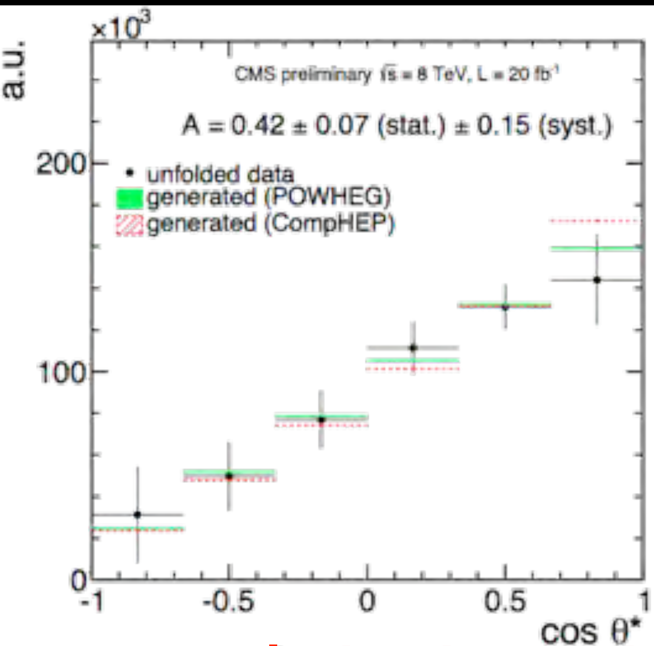


→ top quarks unpolarised



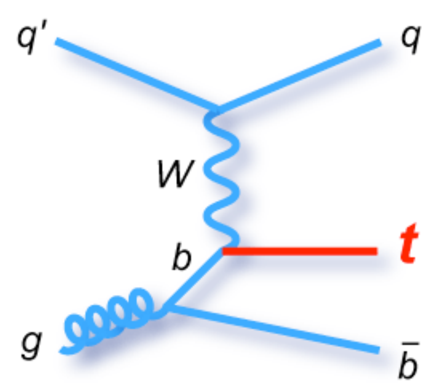
→ W polarisation as in SM

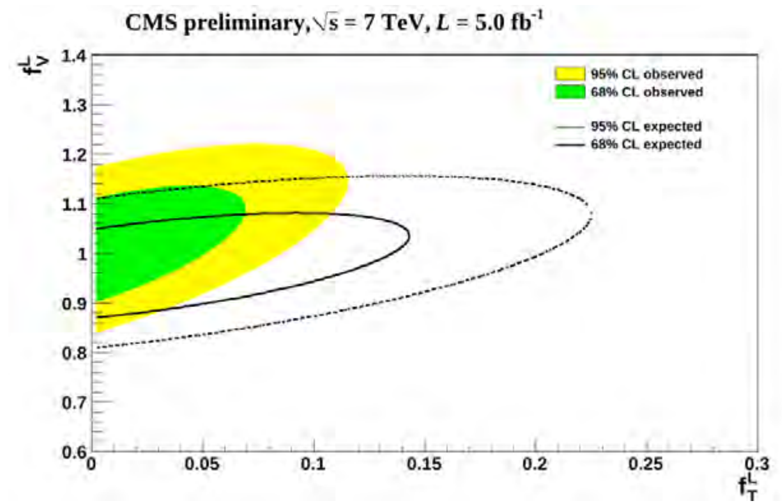
Polarisation and Couplings



→ top polarisation as in SM

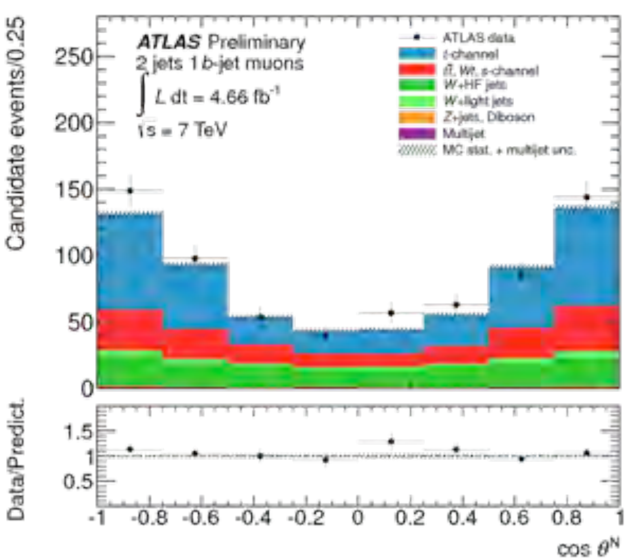
A. Jafari





→ no anomalous couplings

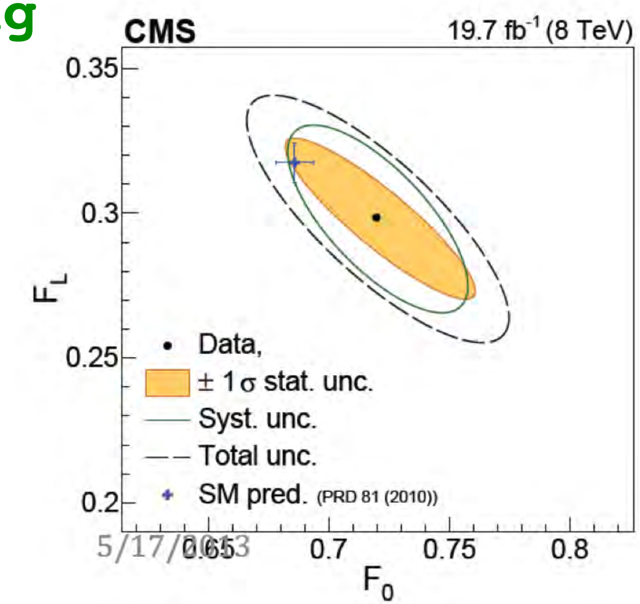
→ global analysis in the future



→ no CP-violation

no new physics

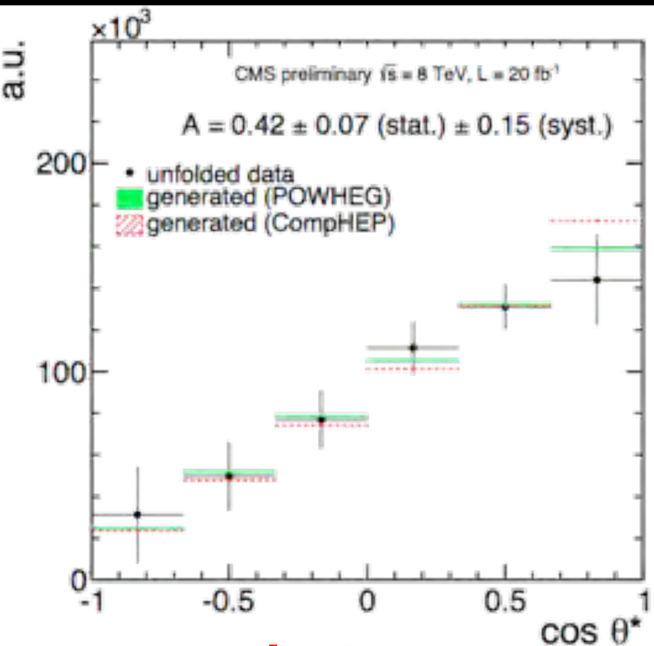
C. Zhang



5/17/2013

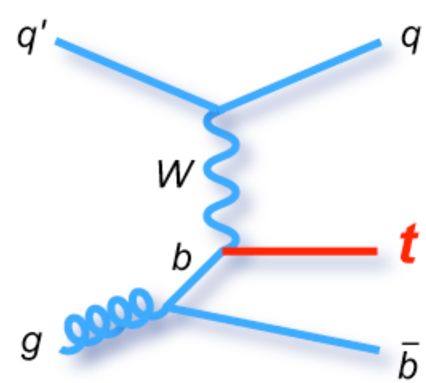
→ W polarisation as in SM

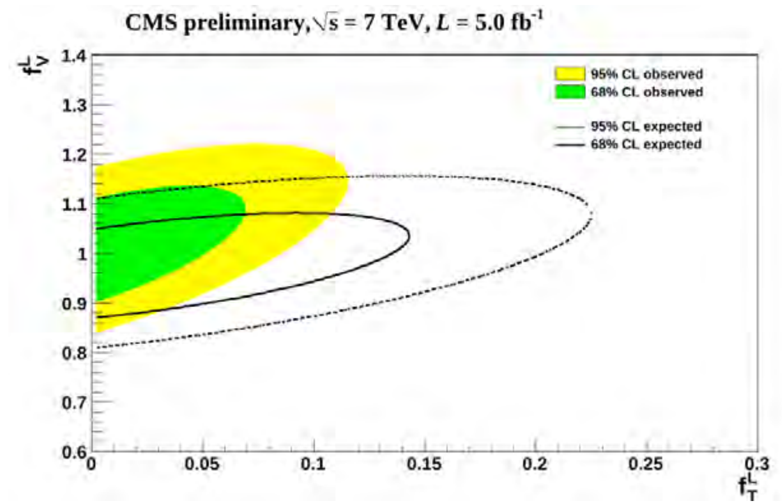
Polarisation and Couplings



→ top polarisation as in SM

A. Jafari

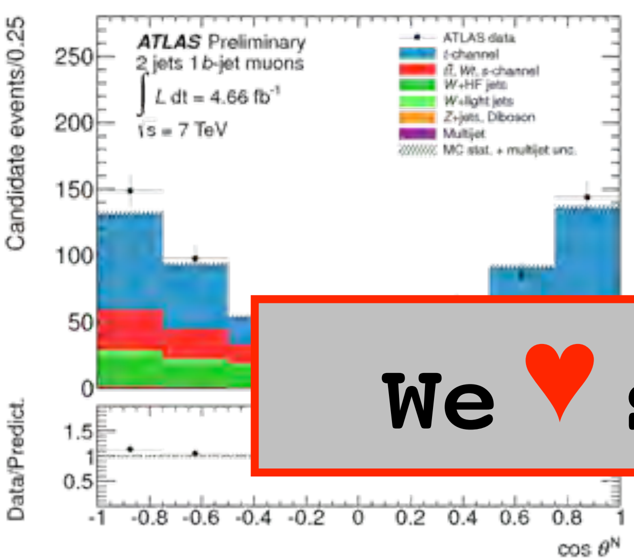




→ no anomalous couplings

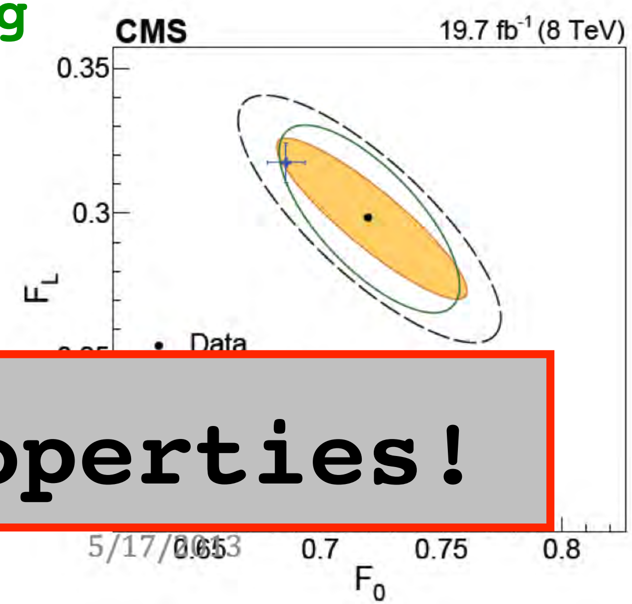
→ global analysis in the future

C. Zhang



→ no CP-violation

no new physics



→ W polarisation as in SM

We ♥ single top properties!

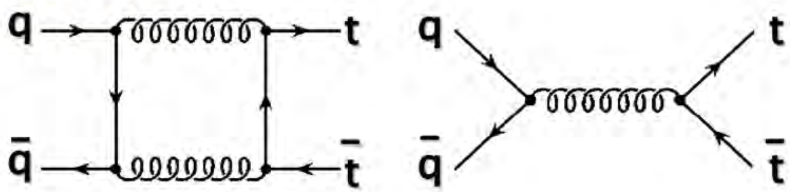
5/17/2013

Charge Asymmetry

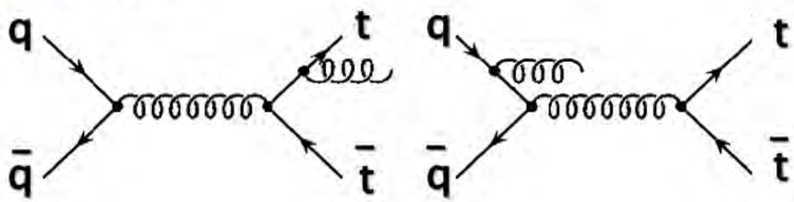
- asymmetry in $O(\alpha_s^3)$

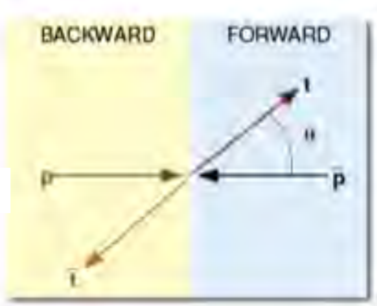
NLO QCD

interference between:



interference between:





$$A_{fb} = \frac{F - B}{F + B}$$

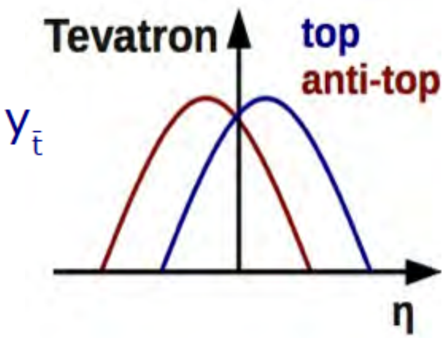
"NLO is LO for asymmetry"

- **complementary to the LHC**

Tevatron

$$\boxed{A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}}$$

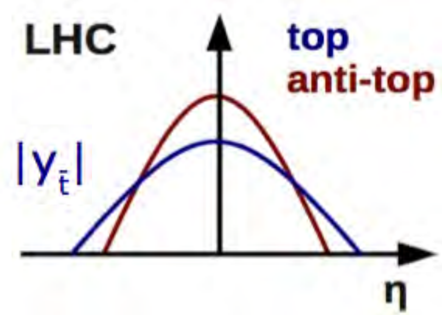
$\Delta y = y_t - y_{\bar{t}}$



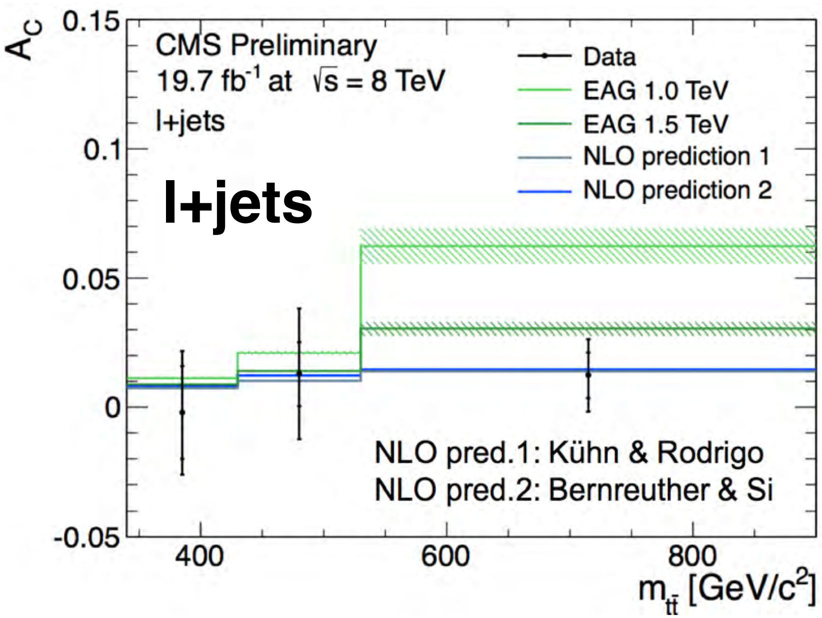
LHC

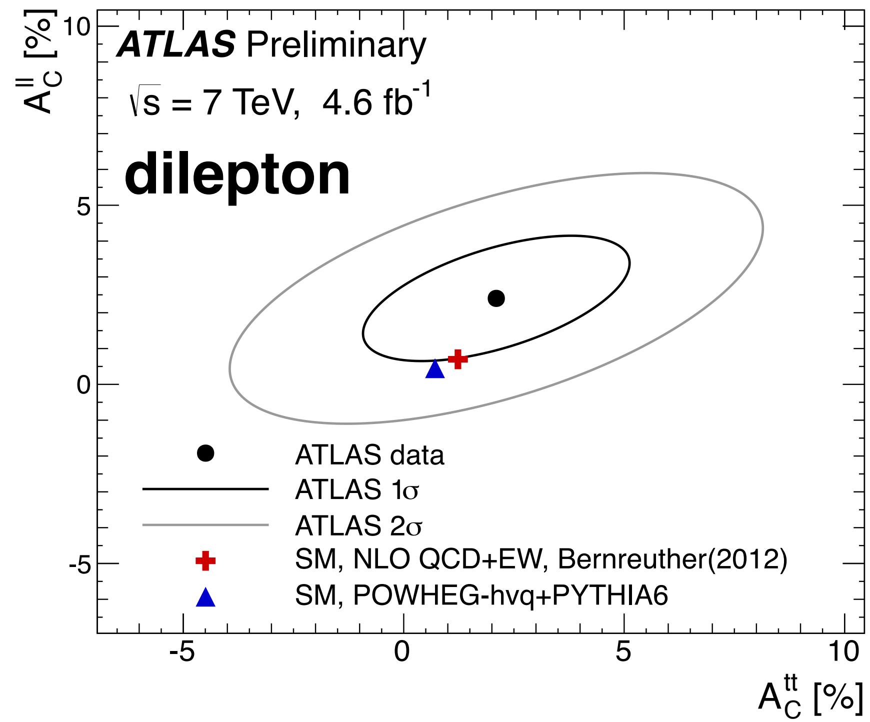
$$\boxed{A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}}$$

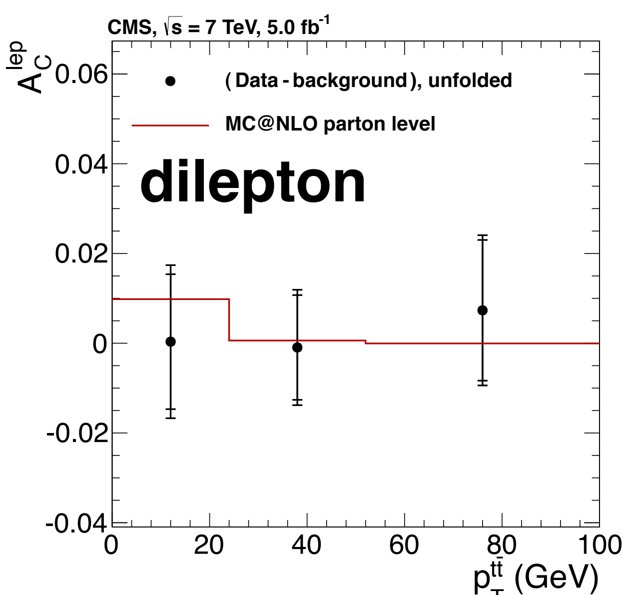
$\Delta|y| = |y_t| - |y_{\bar{t}}|$



Charge Asymmetry: LHC

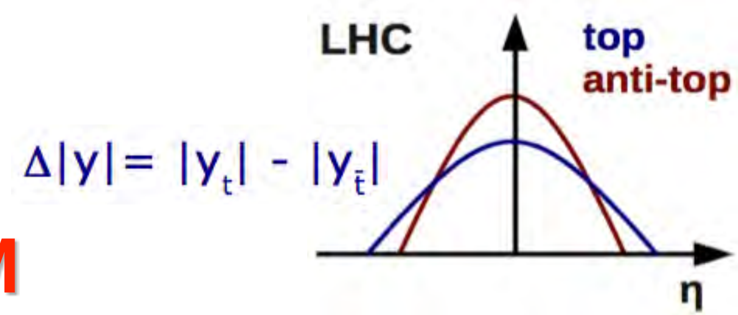






LHC

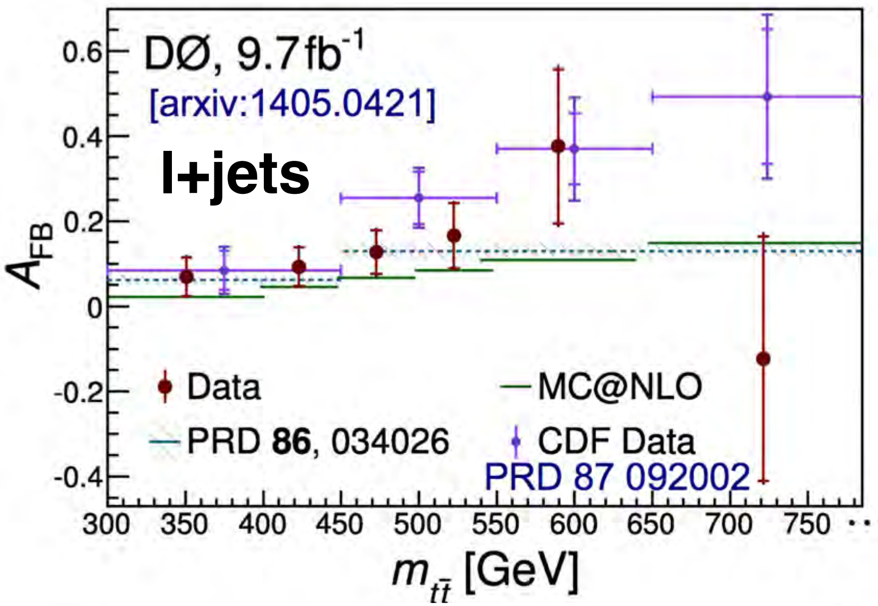
$$\boxed{A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}}$$

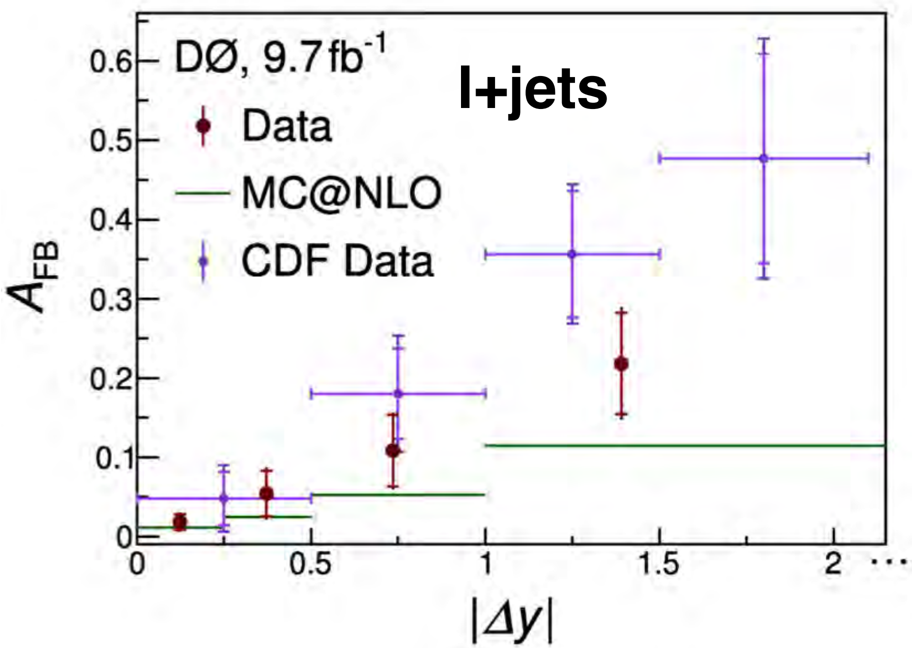


→ good agreement with SM

Charge Asymmetry: Tevatron

A. Jung

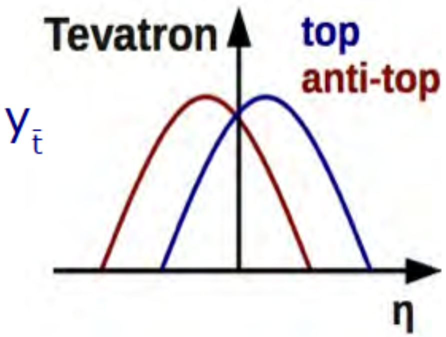


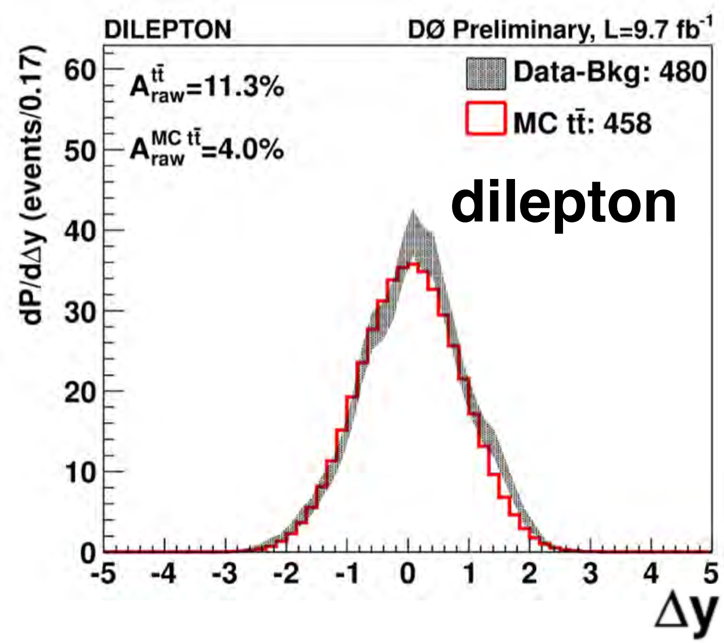


Tevatron

$$\boxed{A_{FB}^{t\bar{t}} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)}}$$

$\Delta y = y_t - y_{\bar{t}}$

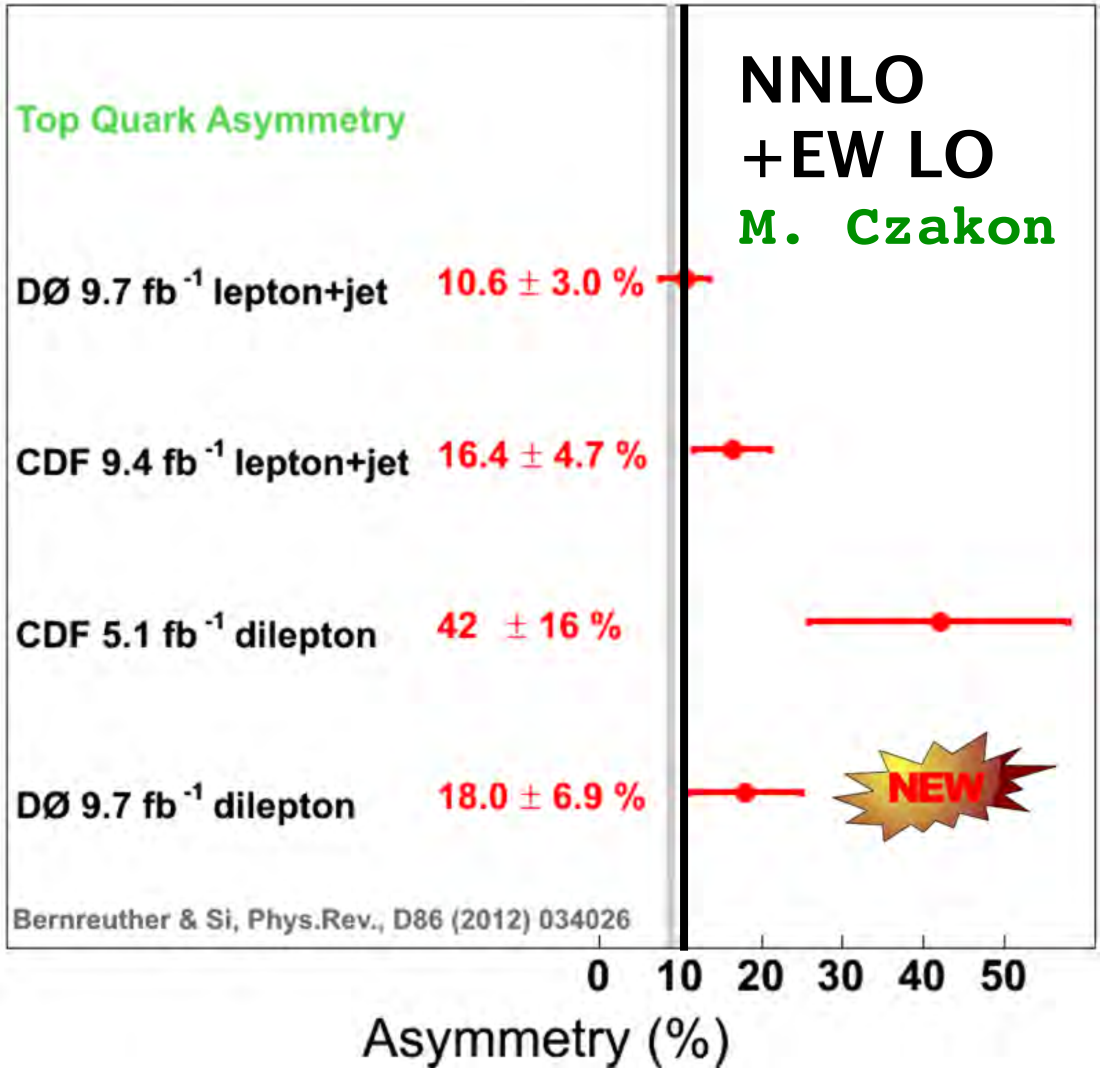




Charge Asymmetry: Tevatron

A. Jung

full dataset



no $b\bar{b}$ asymmetries at Tevatron and LHCb

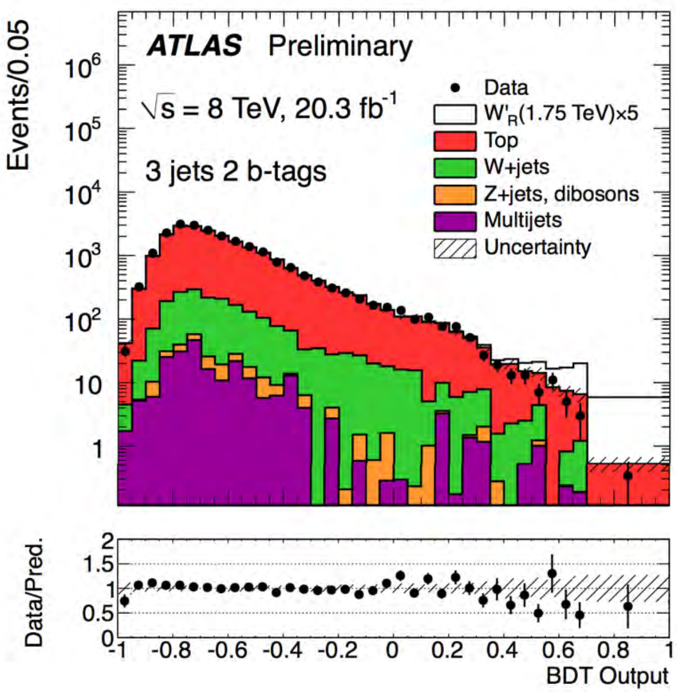
→ higher order QCD is important!

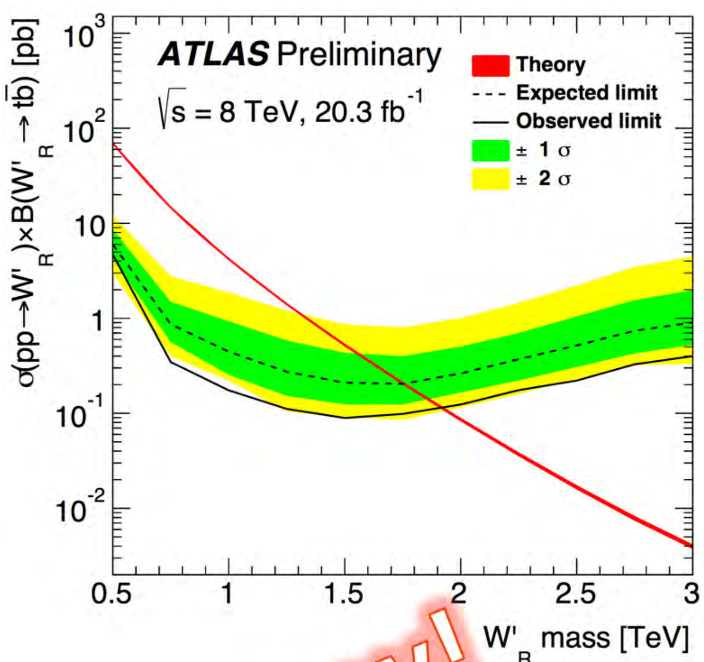
→ high precision measurement is essential

Search for W’ production

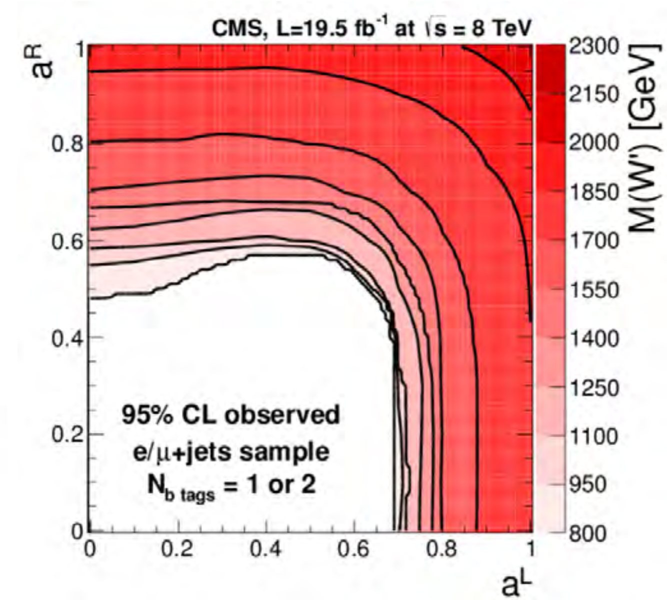
F. Canelli

→ **no new physics**

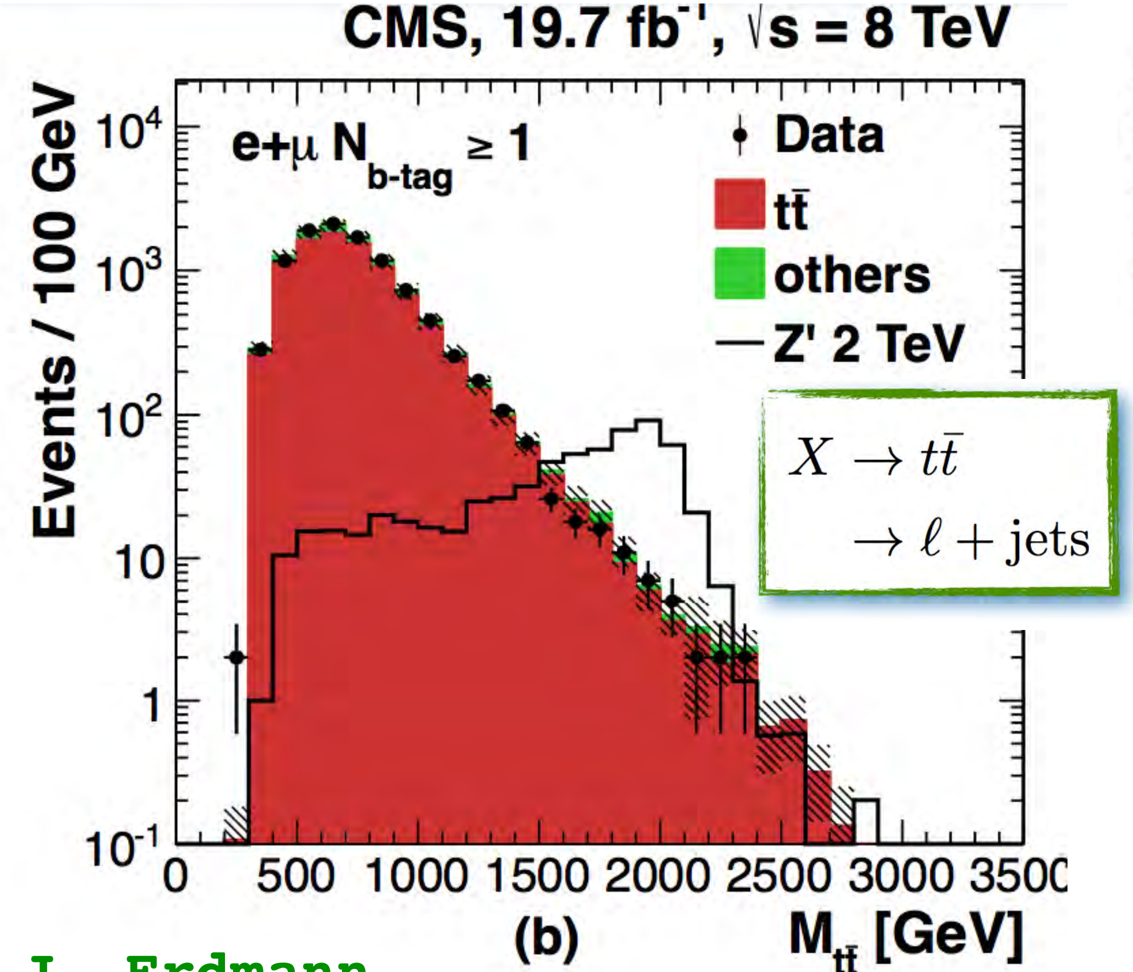


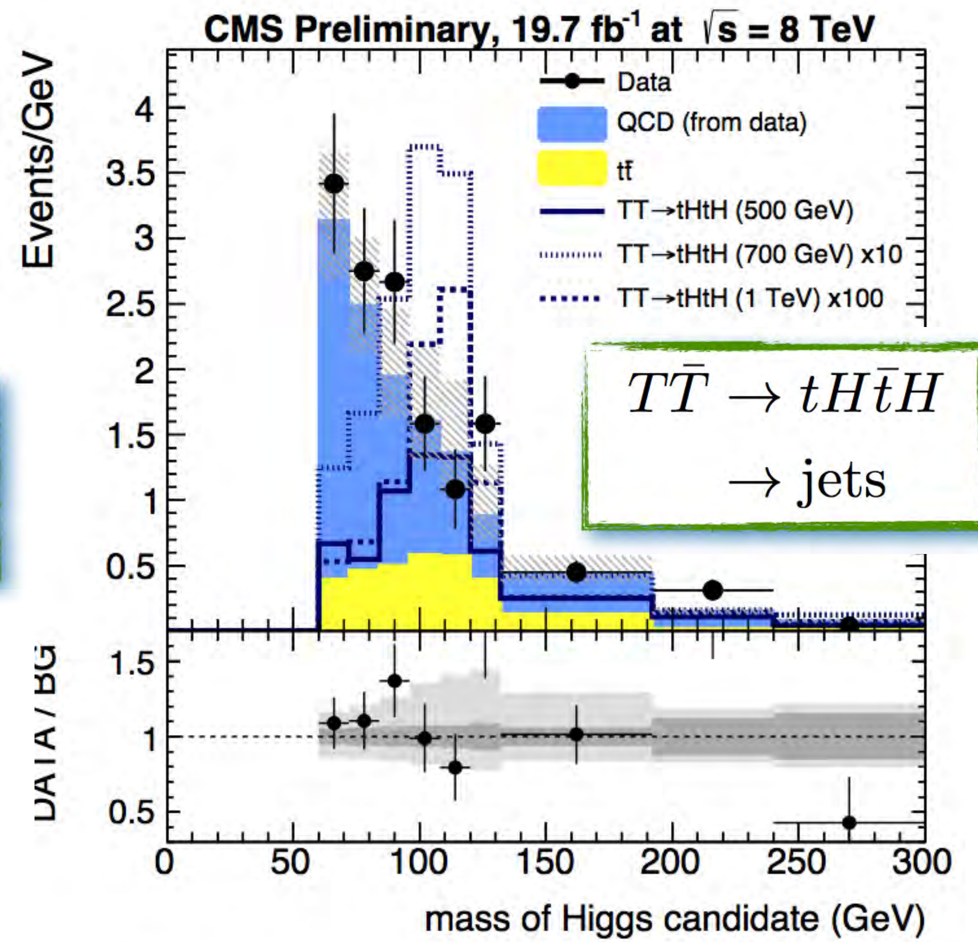


New!



Heavy resonances with boosted tops





J. Erdmann

use "boosted reconstruction"   top-, Higgs-, subjet-b tagging

→ essential for discoveries in Run-II!

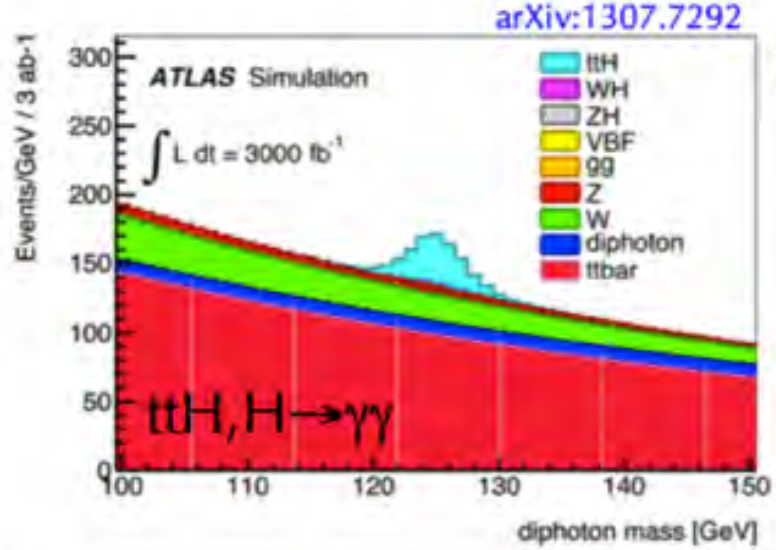
Higgs Boson Physics

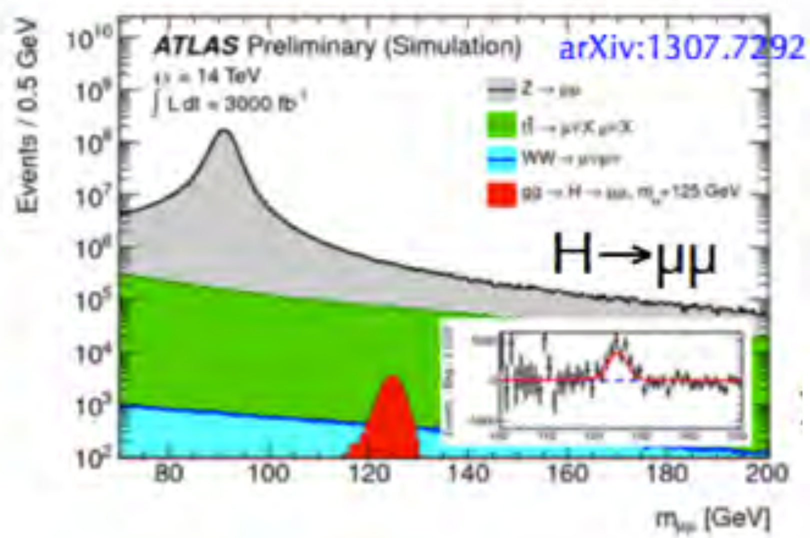
Run-2:

Observable number of Higgs events per LHC experiment		
	Run-1	Run-2
H→4leptons	20	220
VBF H→ττ	50	600
ttH		3.9x more

- improve precision by factor of ~3 (<10% for some modes)
- differential distributions
- observe coupling to fermions
- observe VBF, VH and ttH production
- probe rare decays

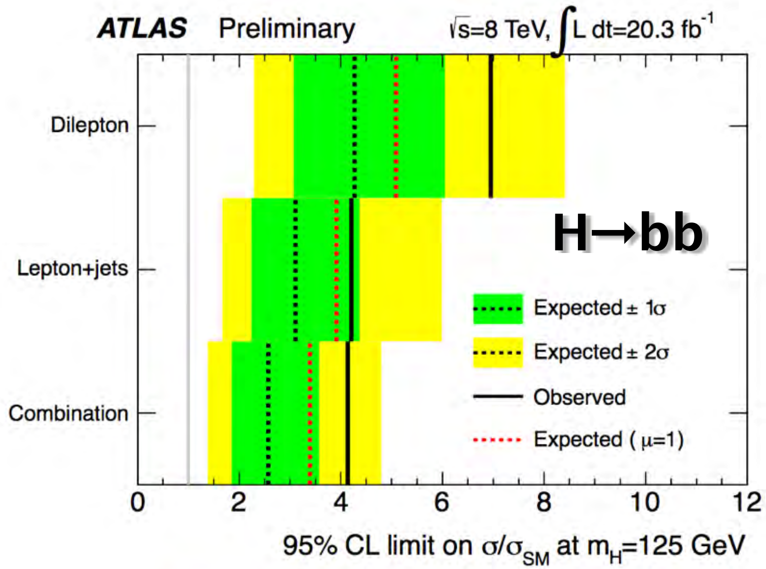
HL-LHC:

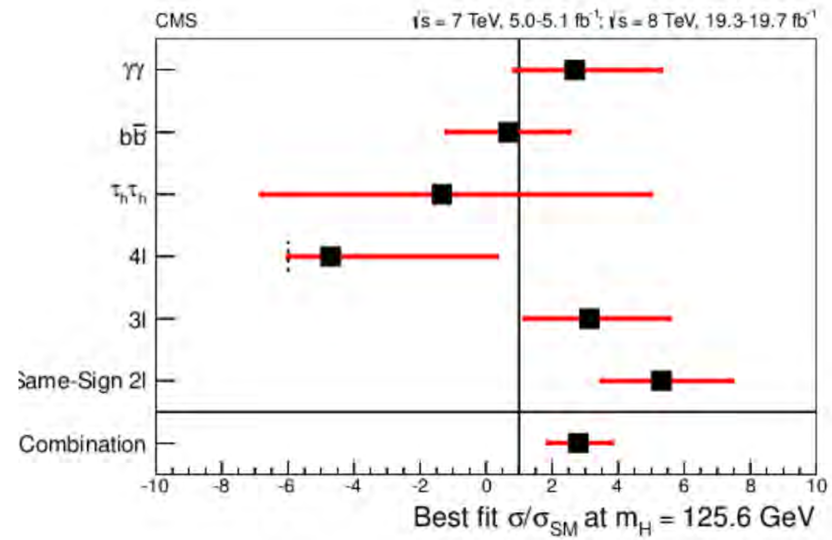




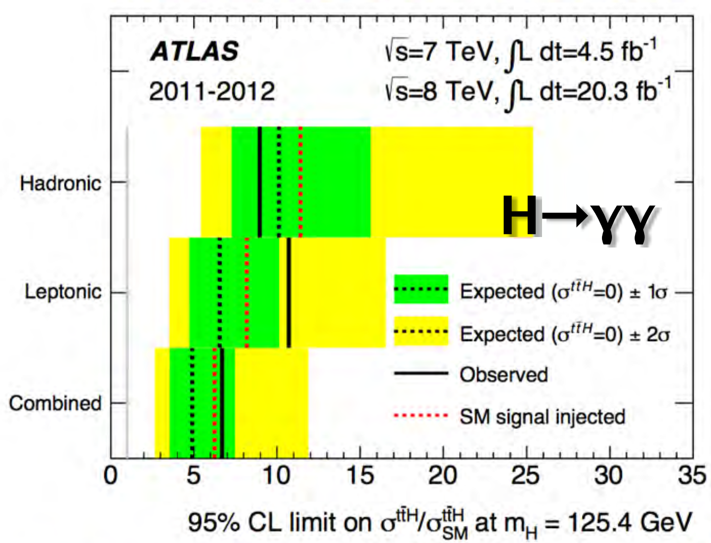
- **Higgs factory**: search for BSM

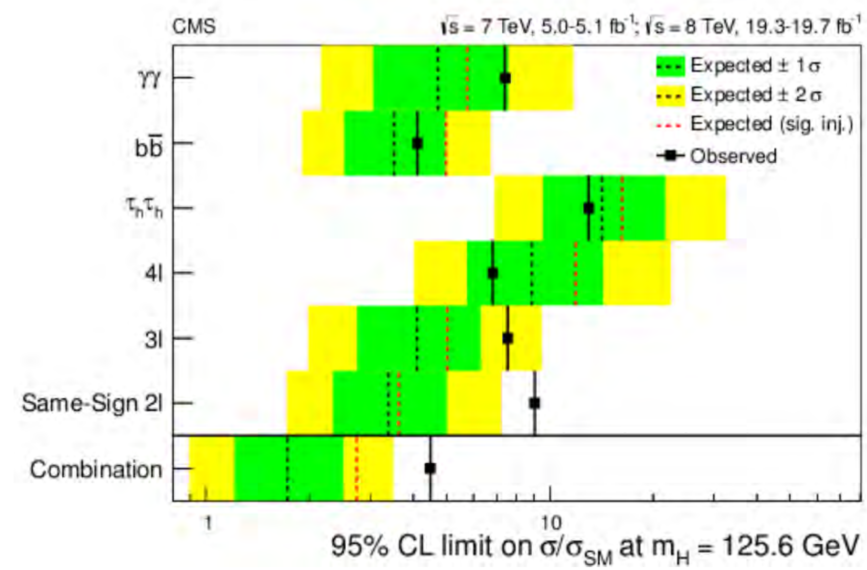
Results in ttH





Fitted σ/σ_{SM} = 2.9±2.3

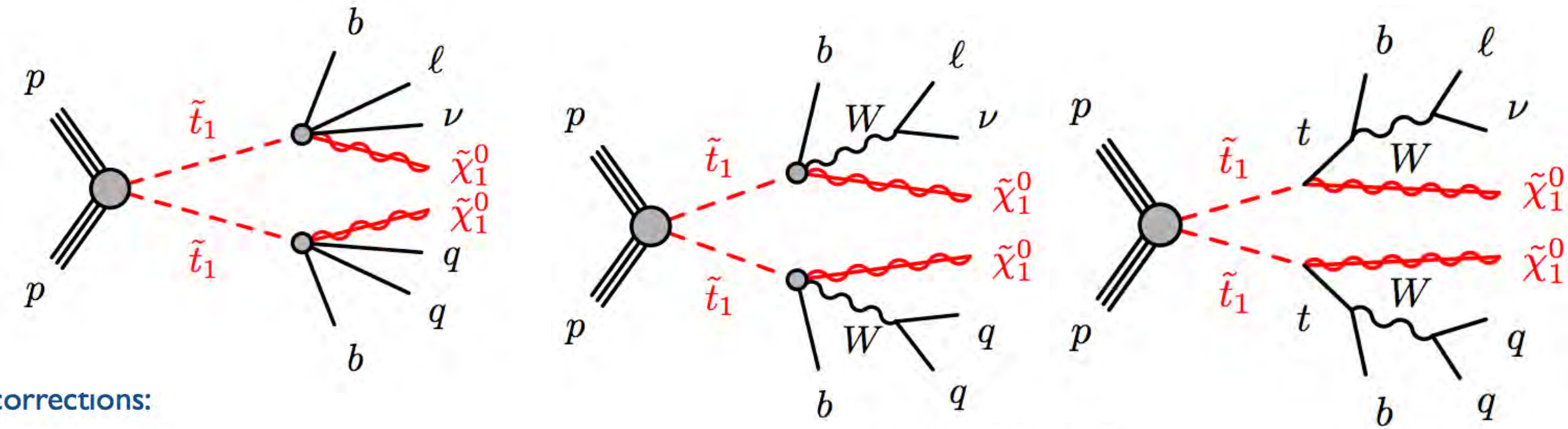




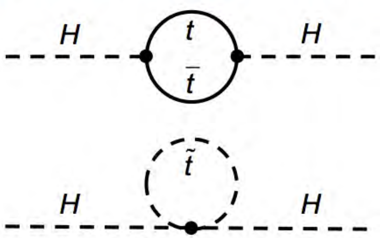
Fitted signal σ/σ_{SM} = $1.4^{+2.2}_{-1.4}$

→ observation in Run-II

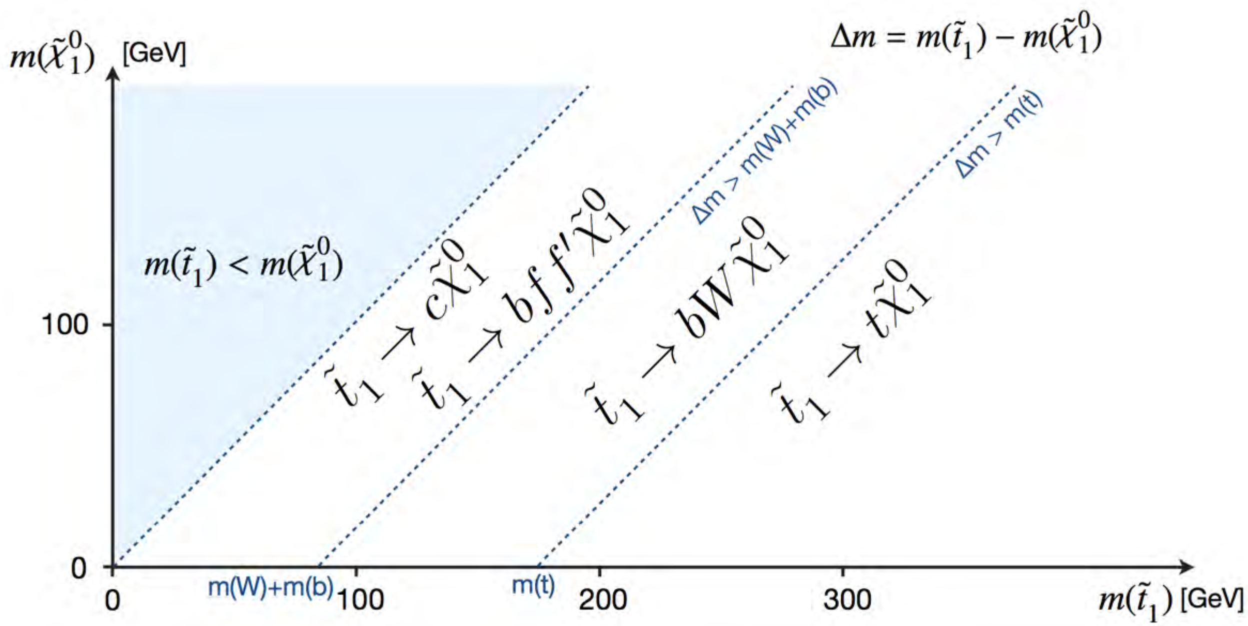
Direct searches for light stop



Recall: **Top loop** is the most i
contribution in Higgs virtual corrections:



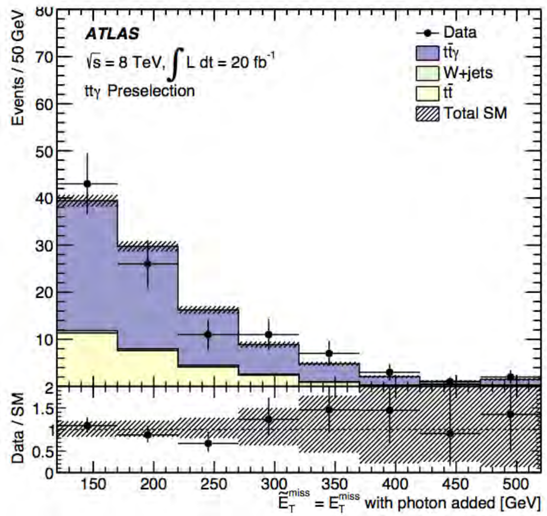
small stop mass is natural

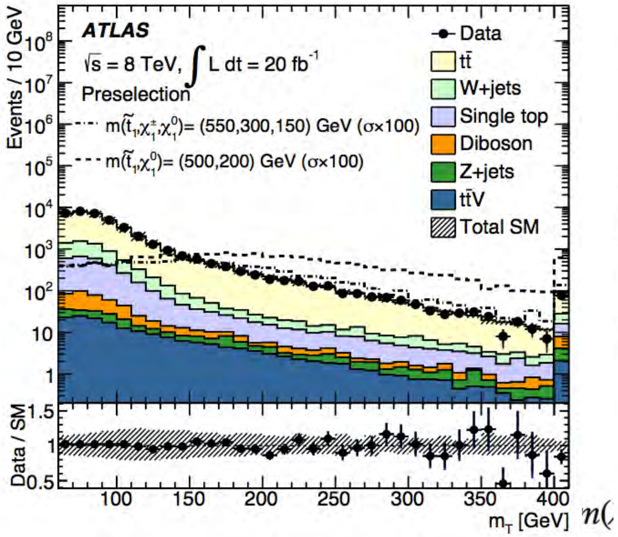


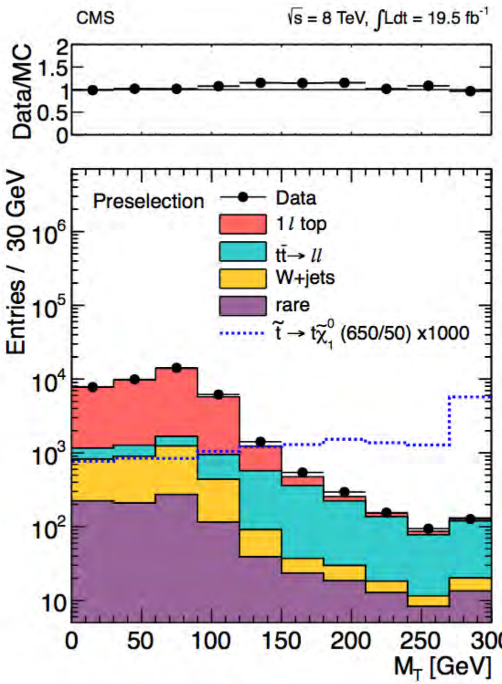
T. Eifert

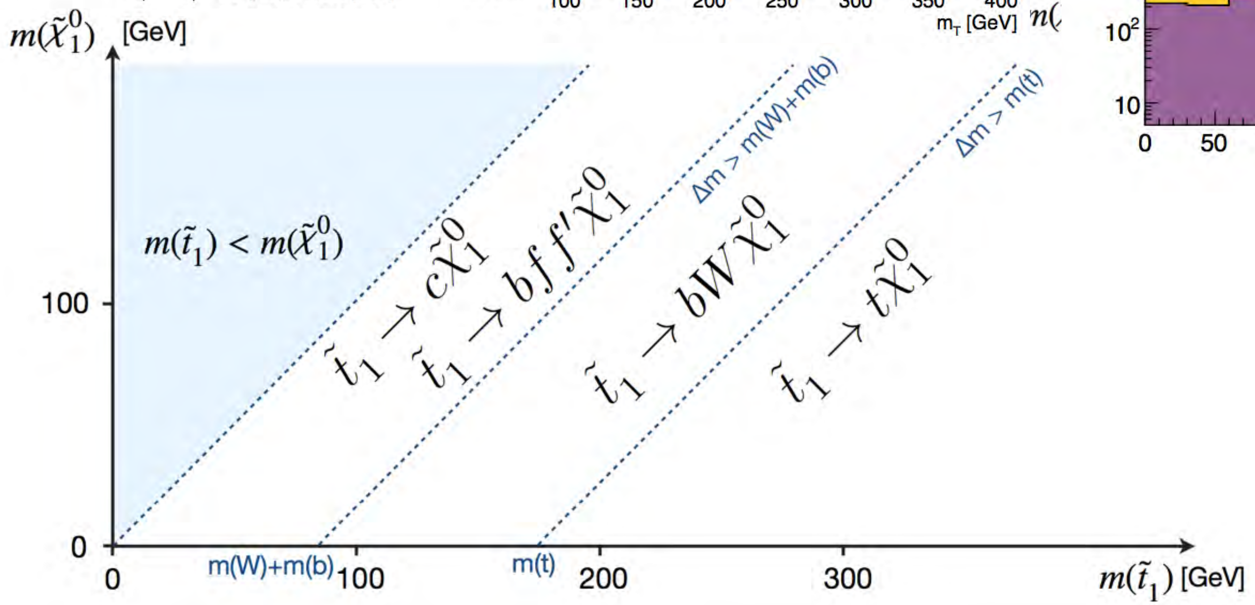
we check every little corner...

Direct stop searches









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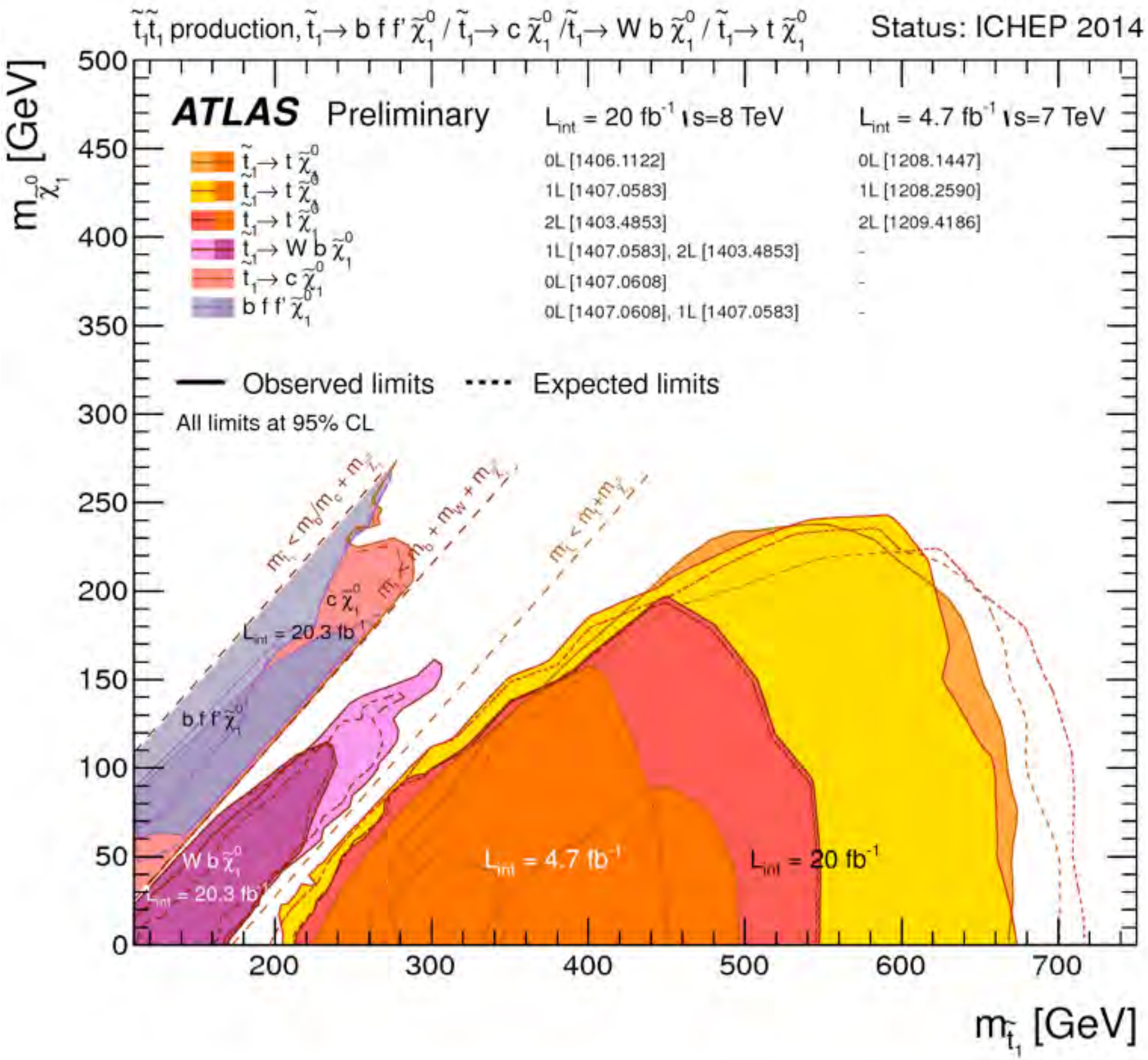
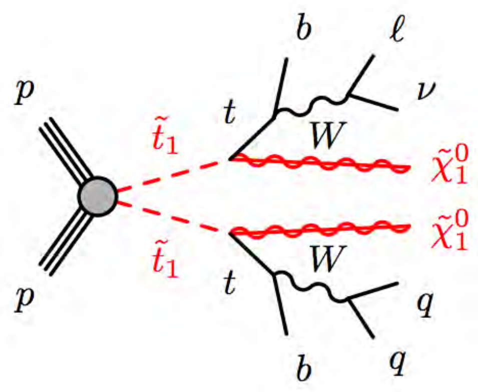
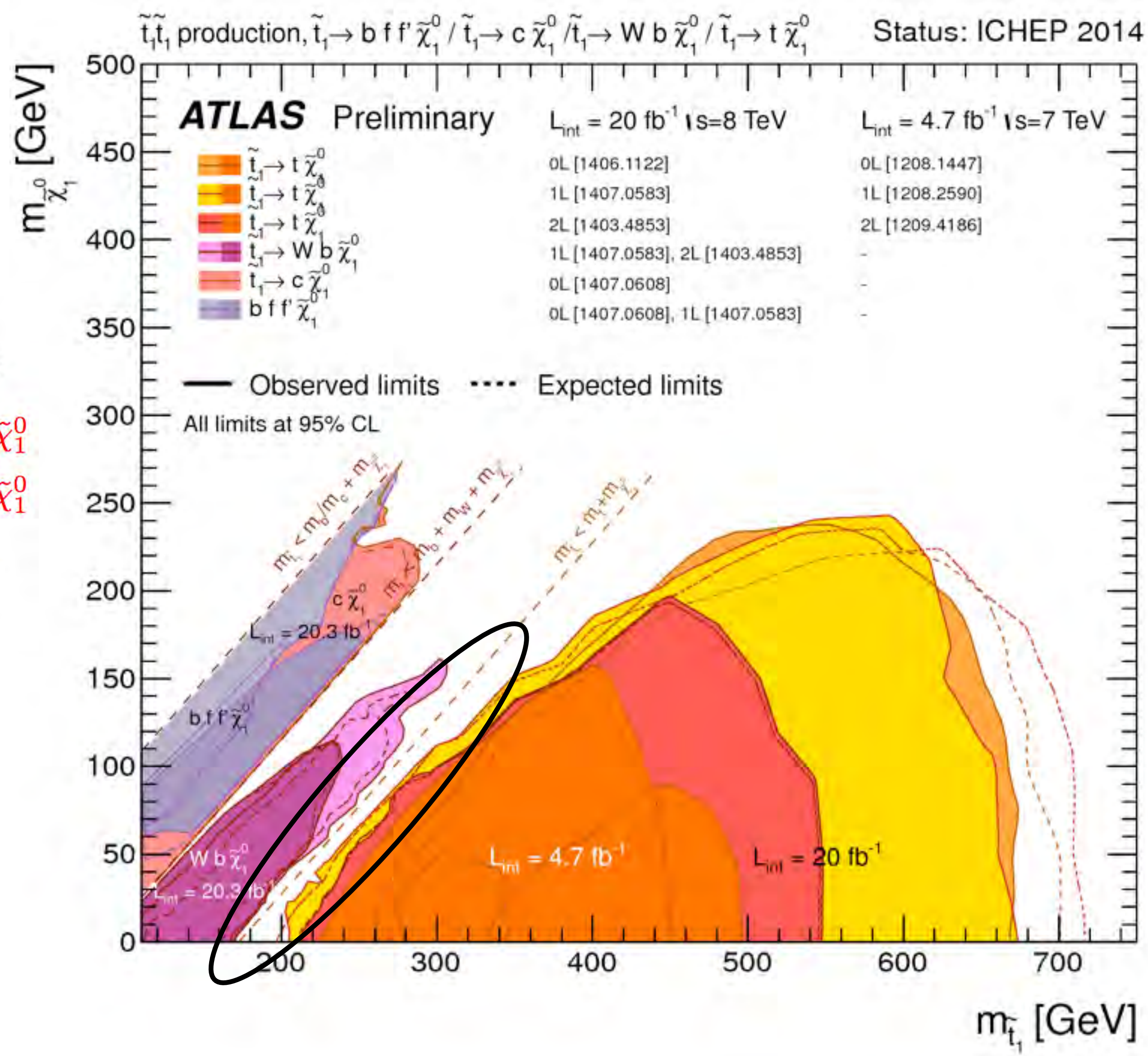


T. Eifert

we check every little corner...

Direct stop searches

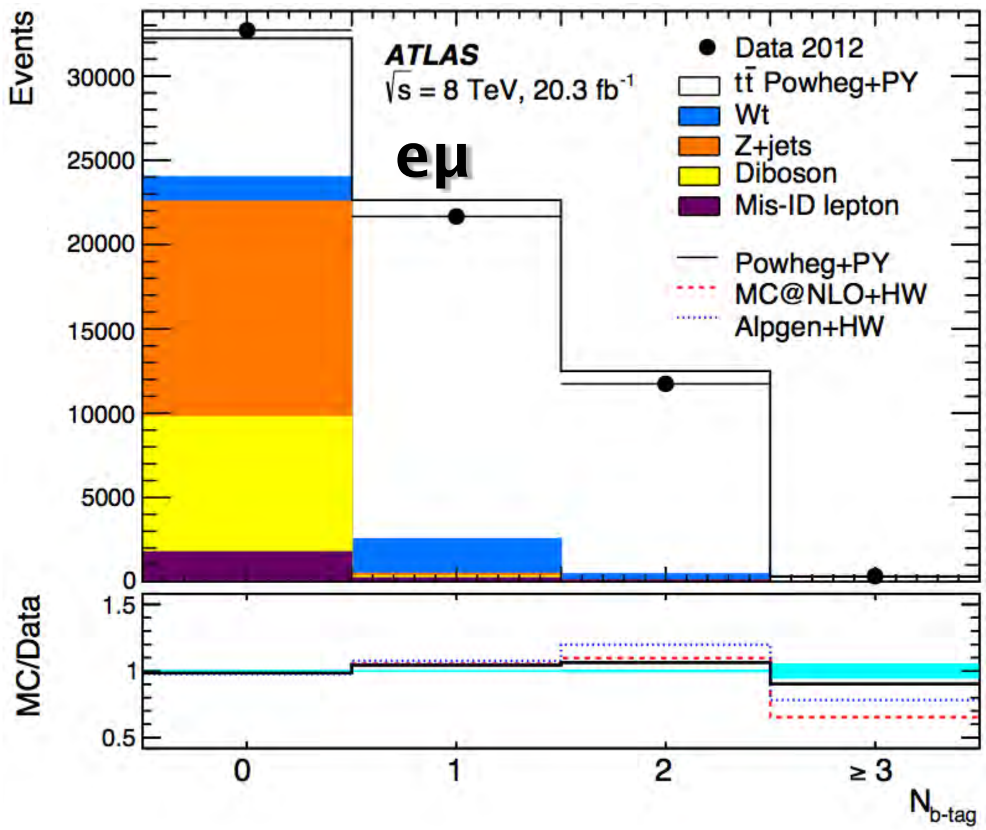


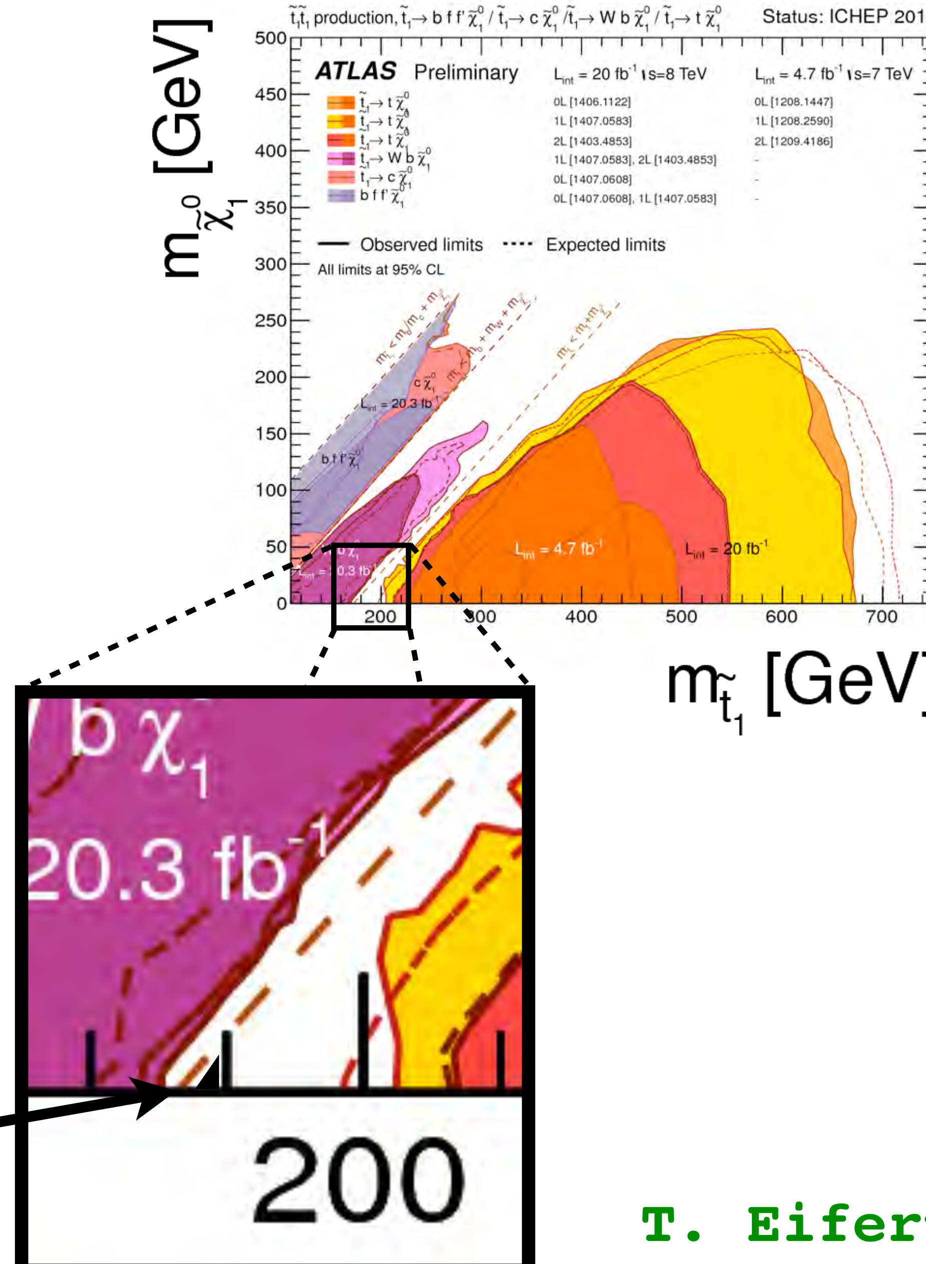


T. Eifert

we check every little corner...

Top precision for stop search

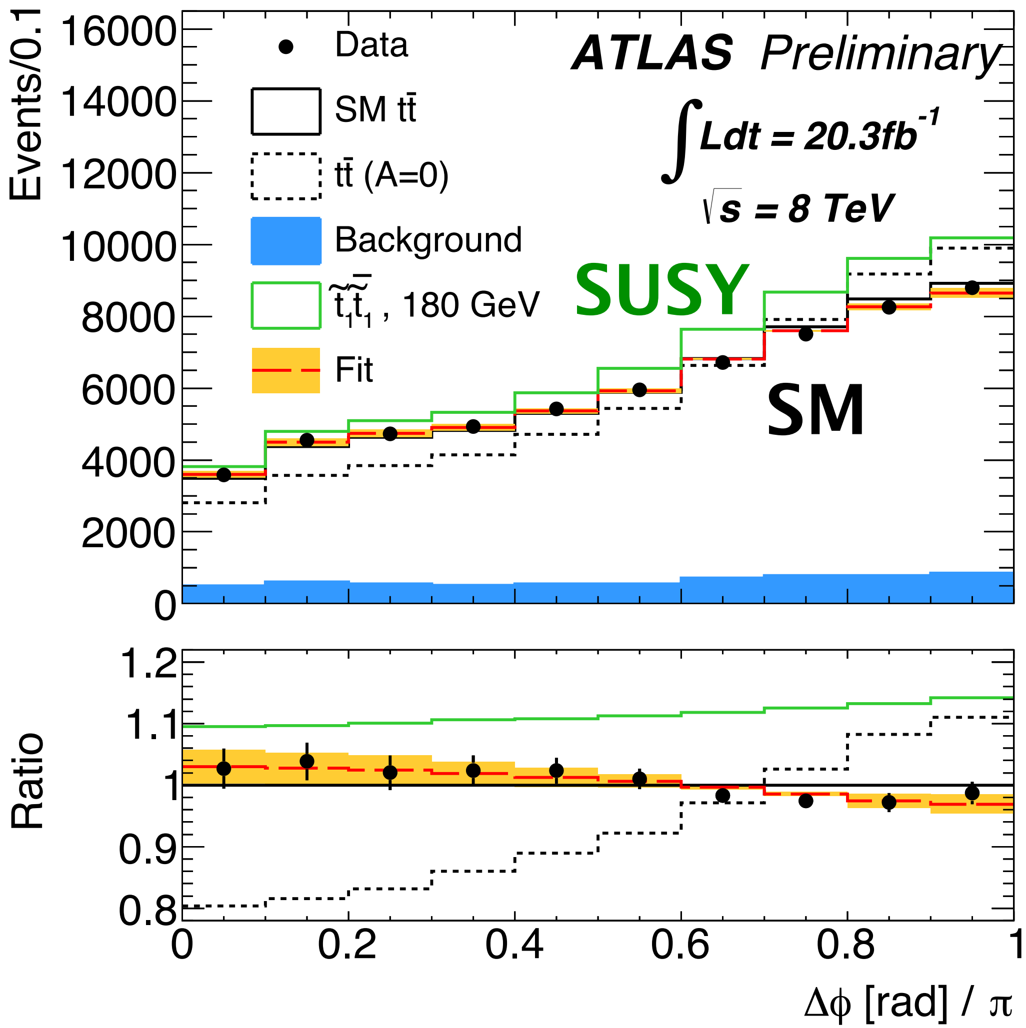


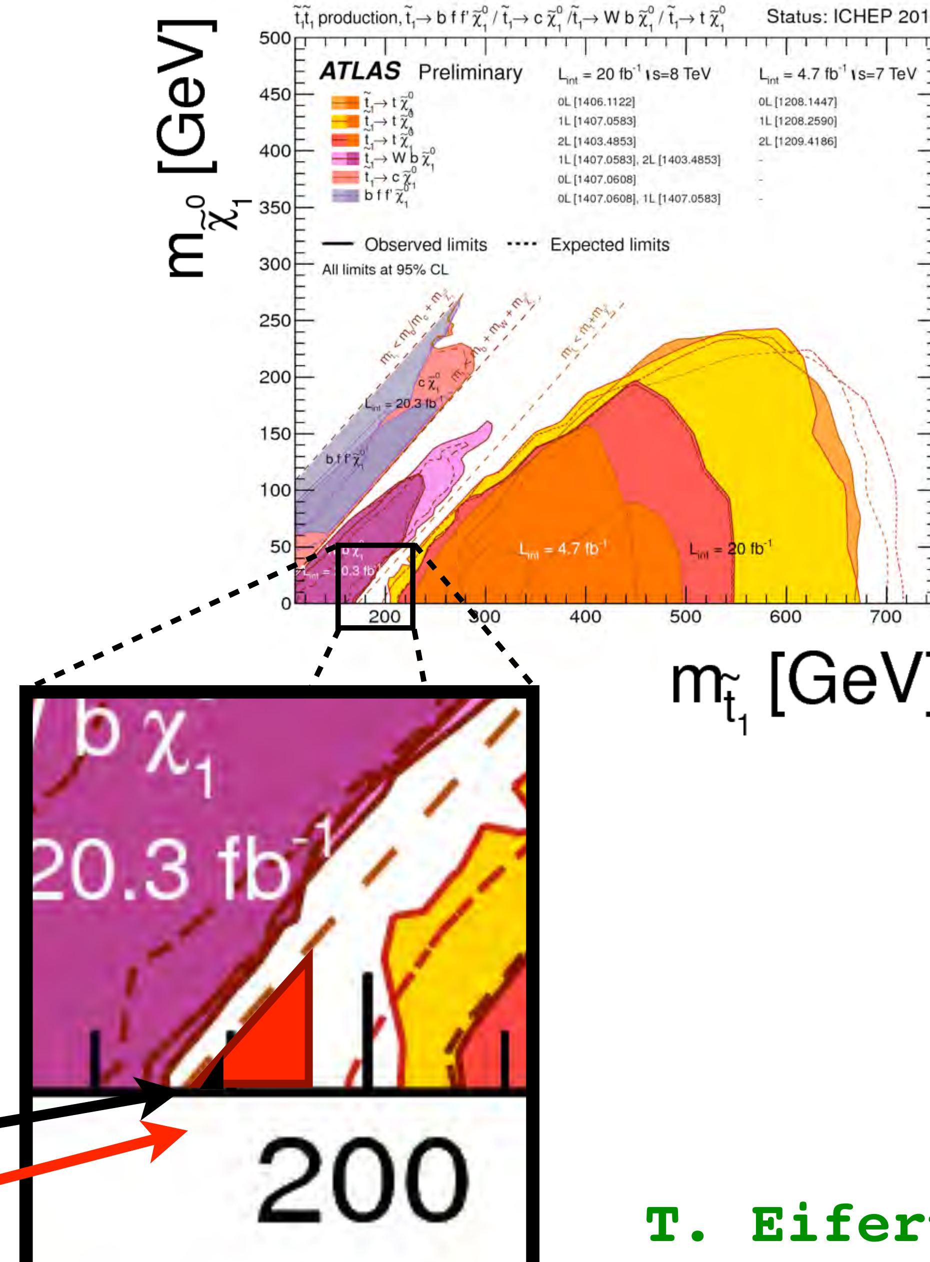


ttbar cross section

T. Eifert

Top precision for stop search





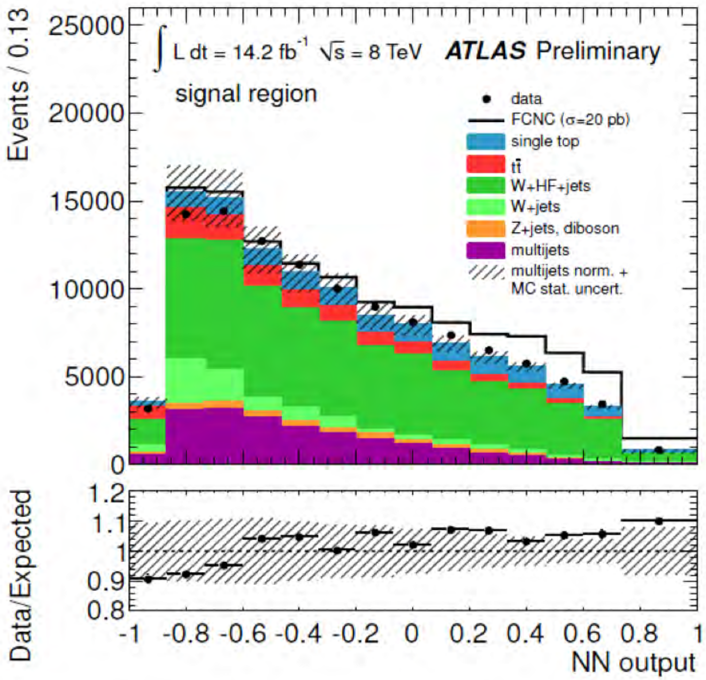
ttbar cross section

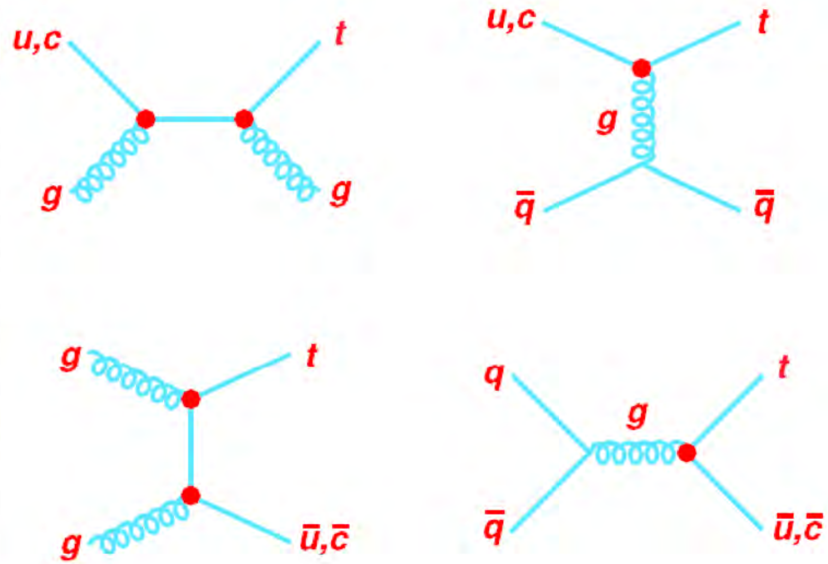
ttbar spin correlation

T. Eifert

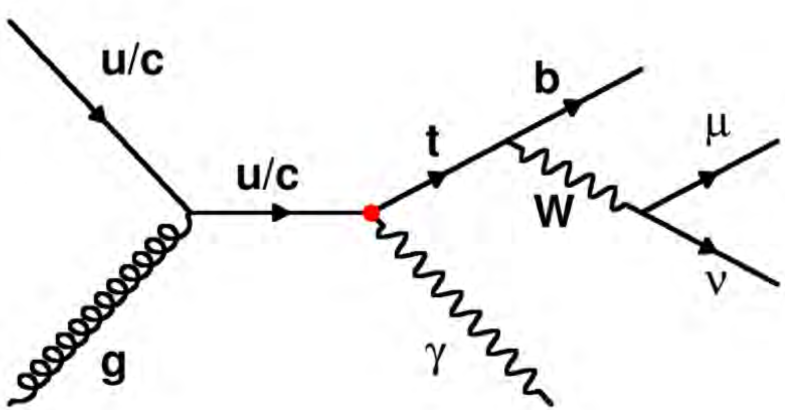
Search for FCNC

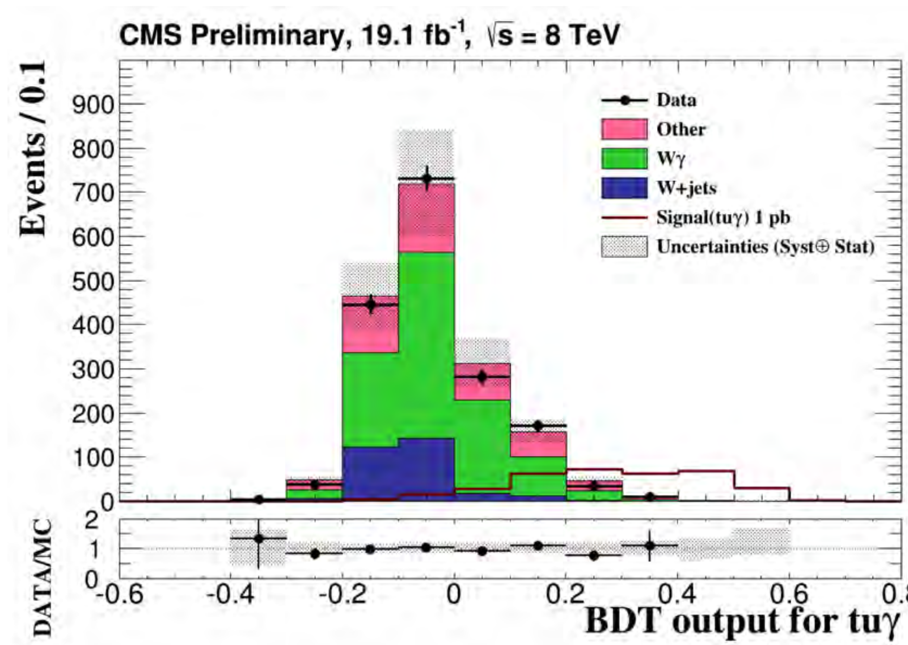
R. Goldouzian





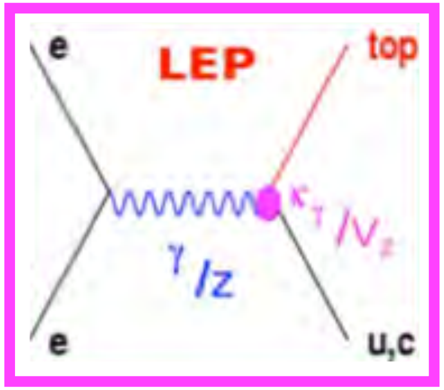
IR divergent?



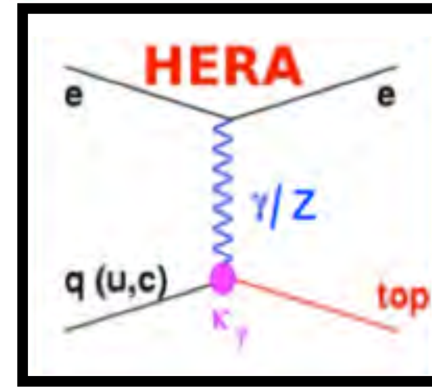


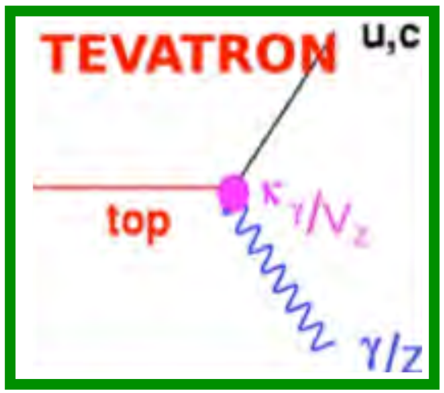
→ no hint for new physics

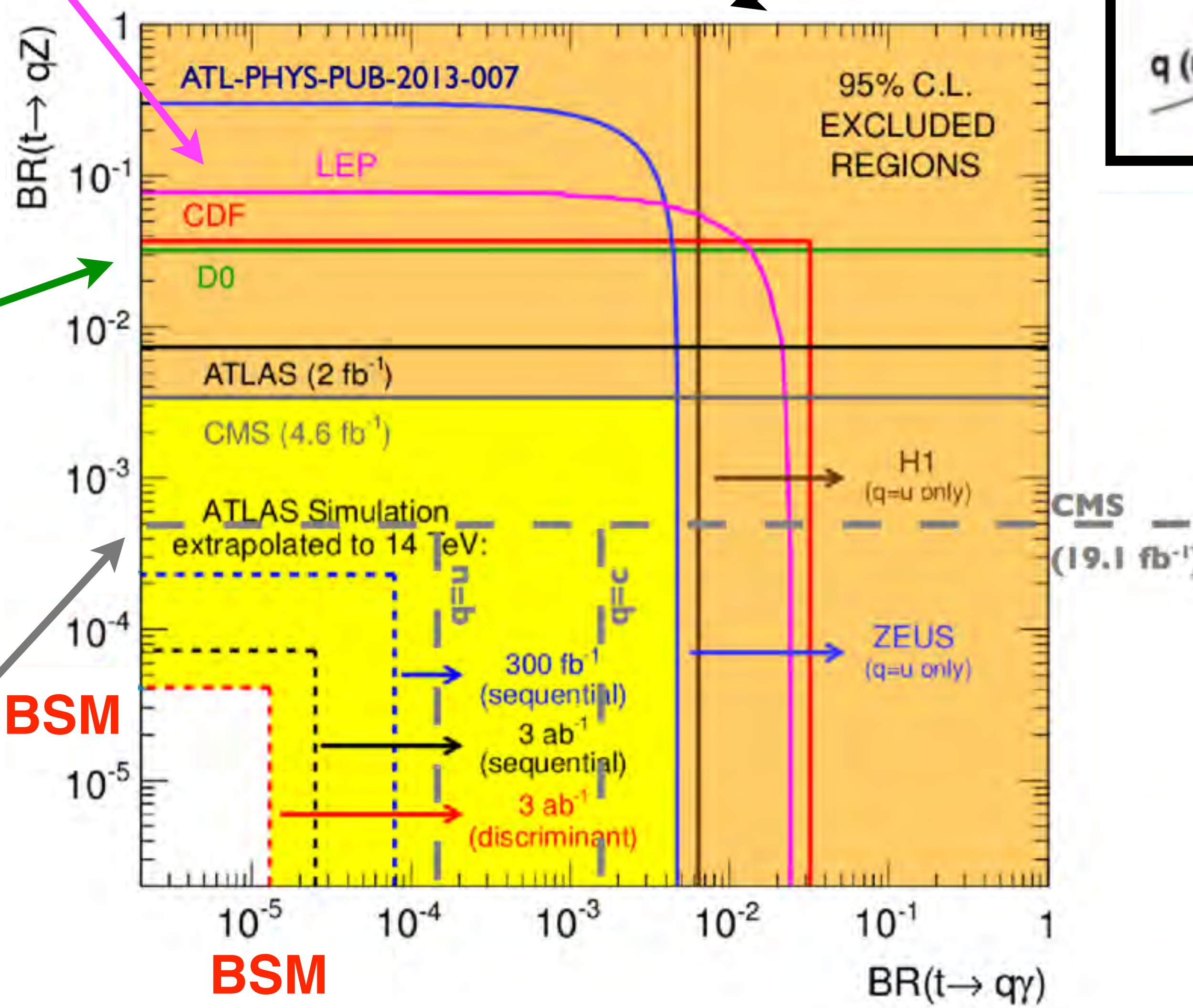
FCNC Top Couplings at



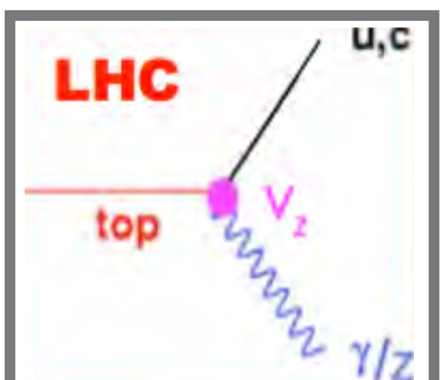
P. Silva







BSM



BSM