Freiburg, 15/06/2016

#BoostAndNeverLookBack

Large R jets and boosted object tagging in ATLAS

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ATLAS

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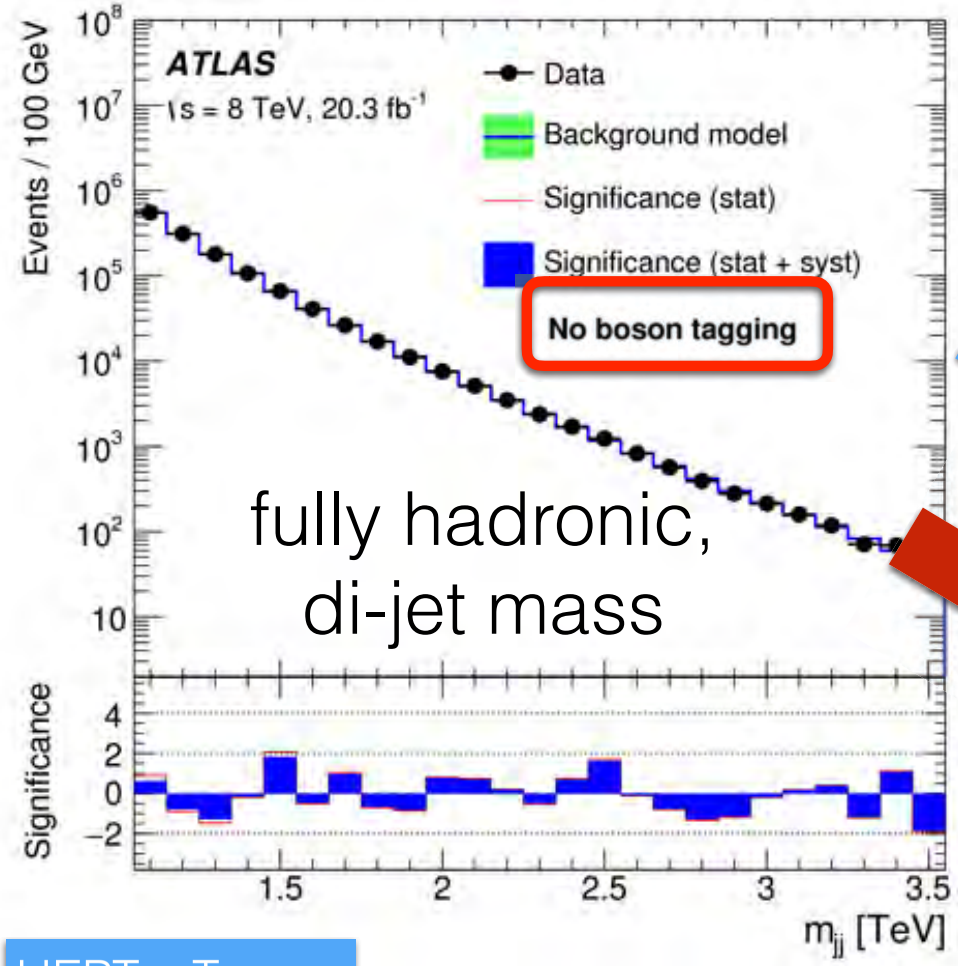
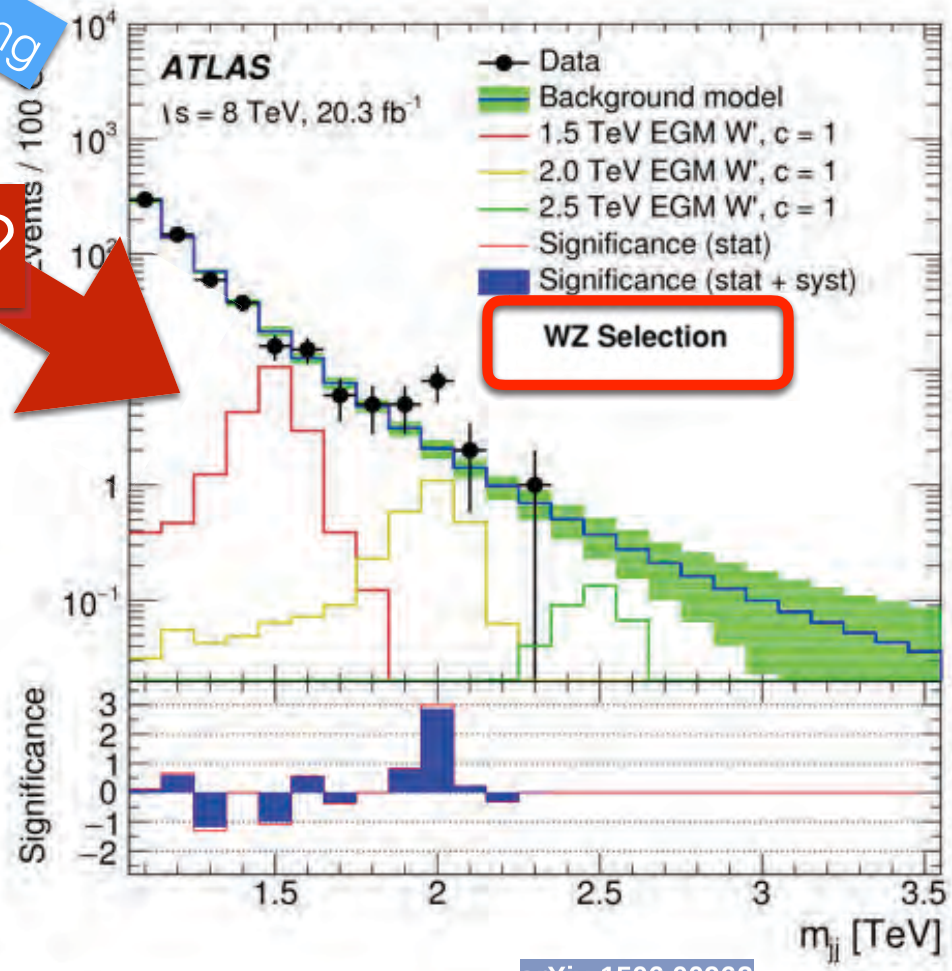
BOOST

End of last year there was a bump…



fully hadronic, di-jet mass

???



Jet substructure

large R jets

R2D2

anti k_T

grooming

subjets

HEPTopTagger

n-subjetiness

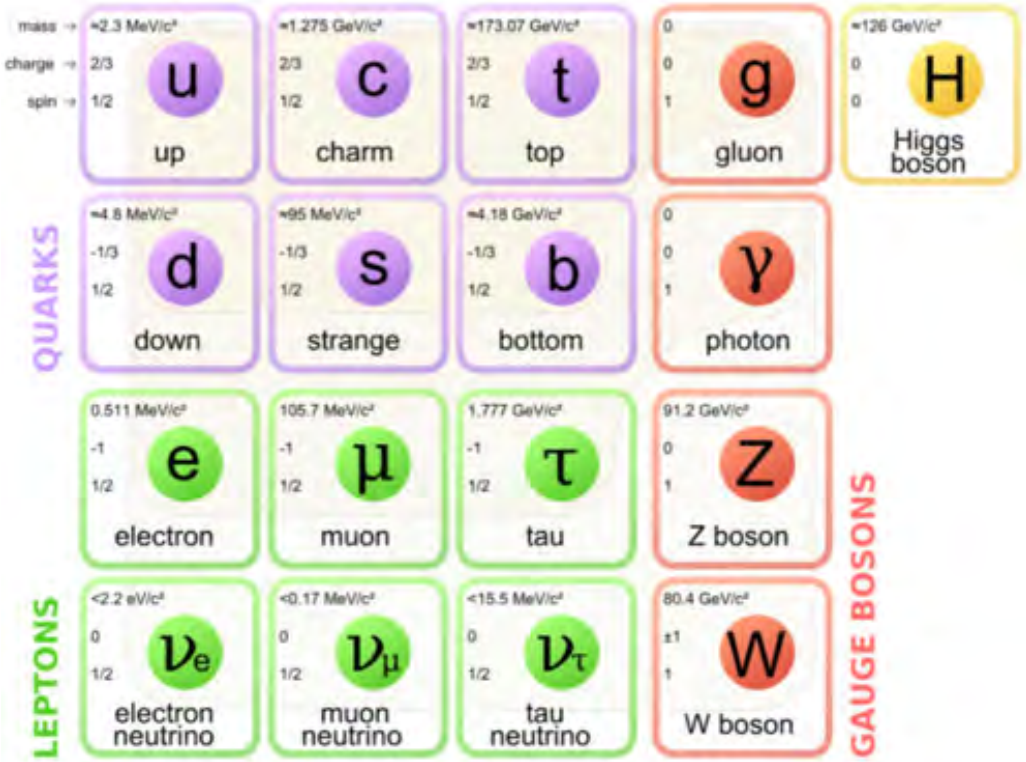
Higgs tagger

trimming

Cambridge-Aachen

arXiv:1506.00962

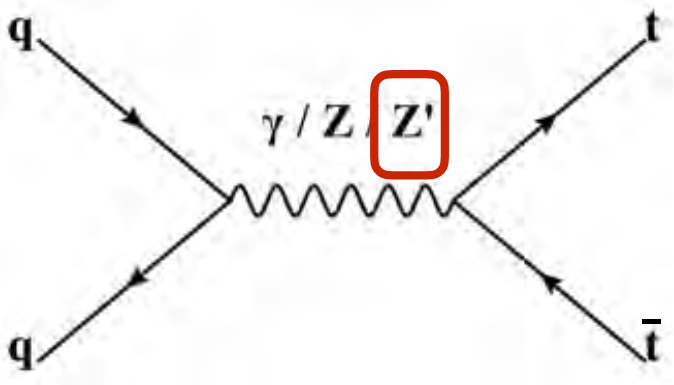
Have: Standard Model



In this context **new heavy resonances** decaying to **pairs of SM bosons (W/Z/H) or top quarks** would be nice (we need one to better calibrate our jets!)

Want: New physics!

- Extended gauge sector:
  - Z' —> $t\bar{t}$
  - W' —> WZ
- Extra dimensions:
  - G_{RS} —>$t\bar{t}$/WW/ZZ
- Susy:
  - stop decays

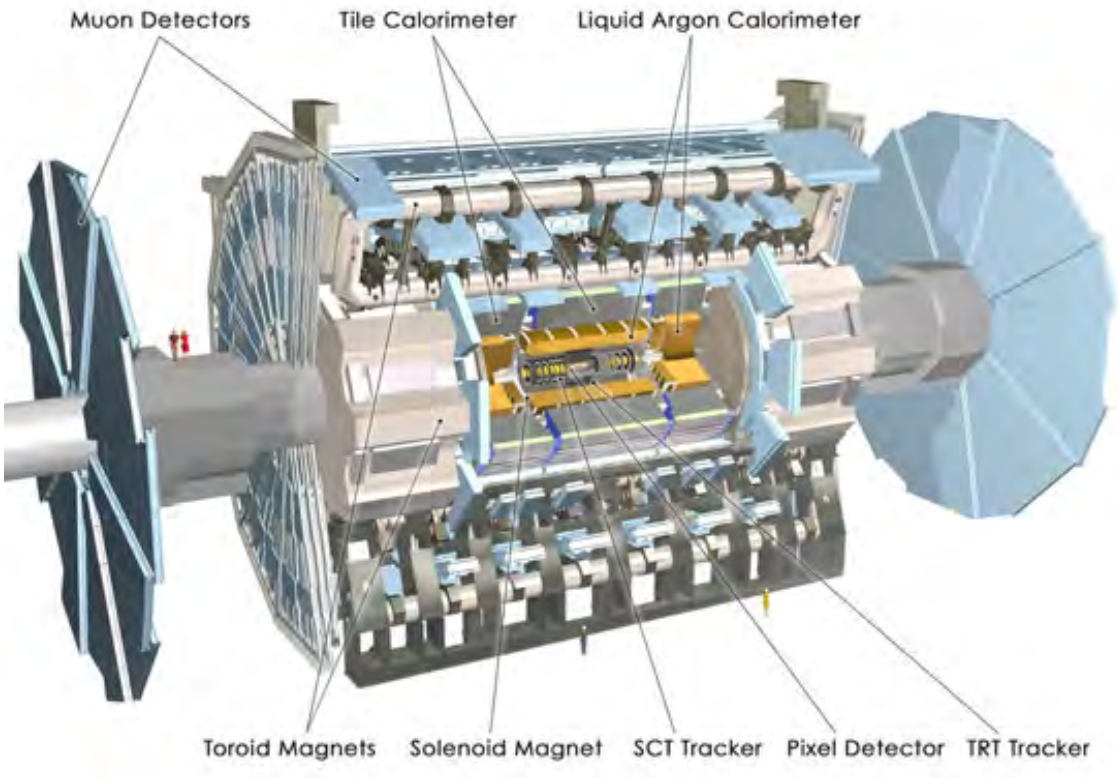


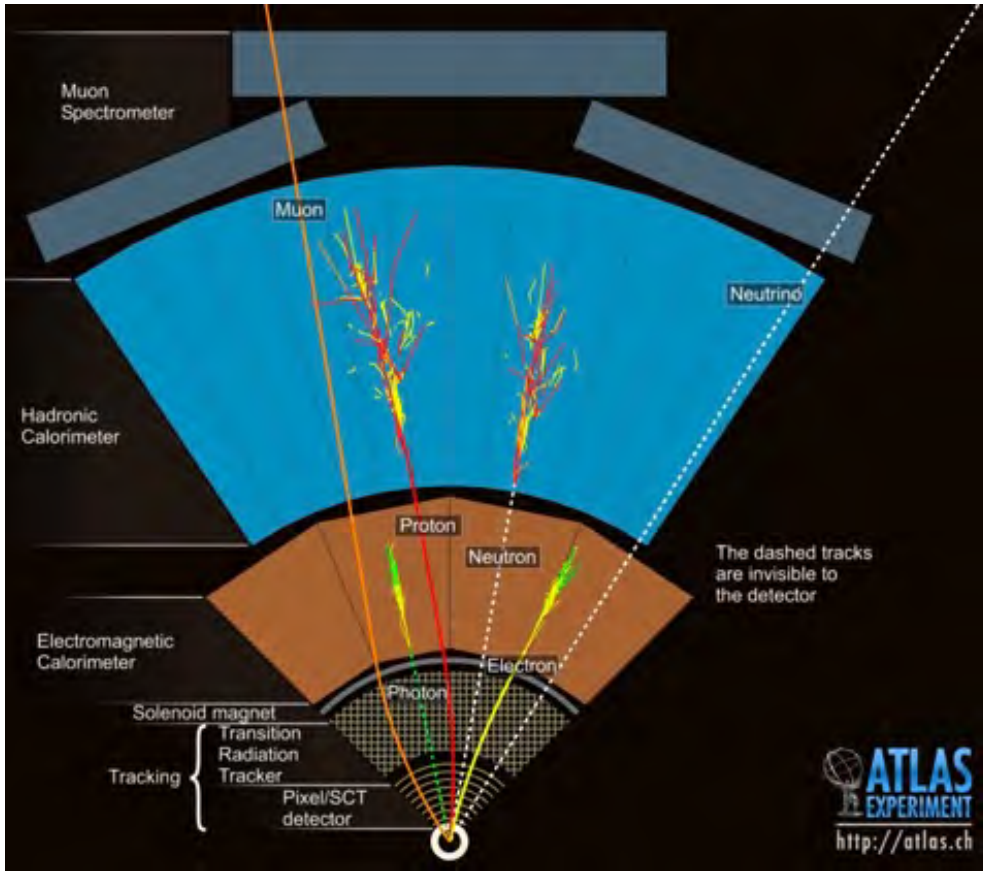
Hadronic final states?

BR(W—> hadrons) ~ 2/3

Detecting particles in ATLAS

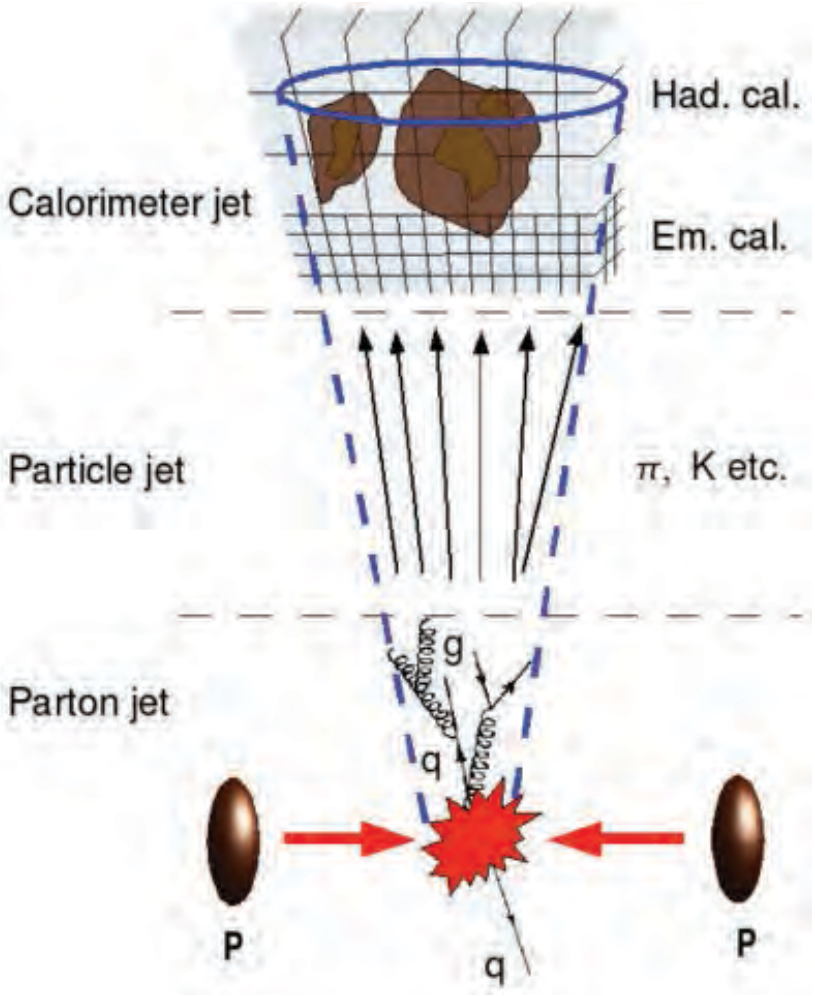
center of mass energy
LHC Run 1: 7 & 8TeV
LHC Run 2: 13TeV





How about jets?

Jets



- **Jets:** collimated bunches of stable particles originating from partons after hadronization
- **Jet finding:** an approximate attempt to reverse engineer this QM process

→ More than one way to do this!

"Sequential jet clustering algorithms"

Sequential jet clustering algorithms

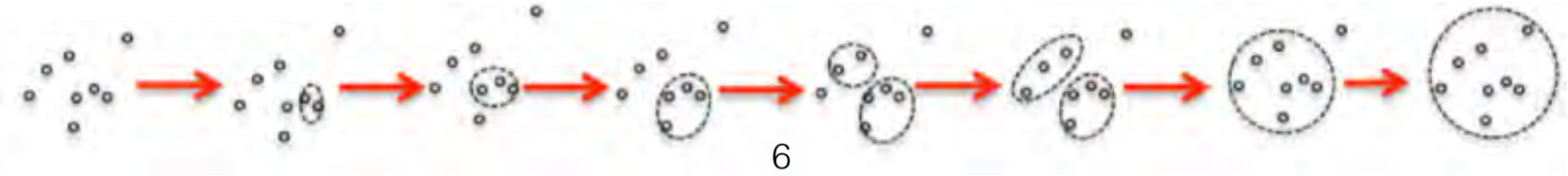
- Use clusters of calorimeter energy as input “particles” (also tracks or truth particles can be used)
- Distance:

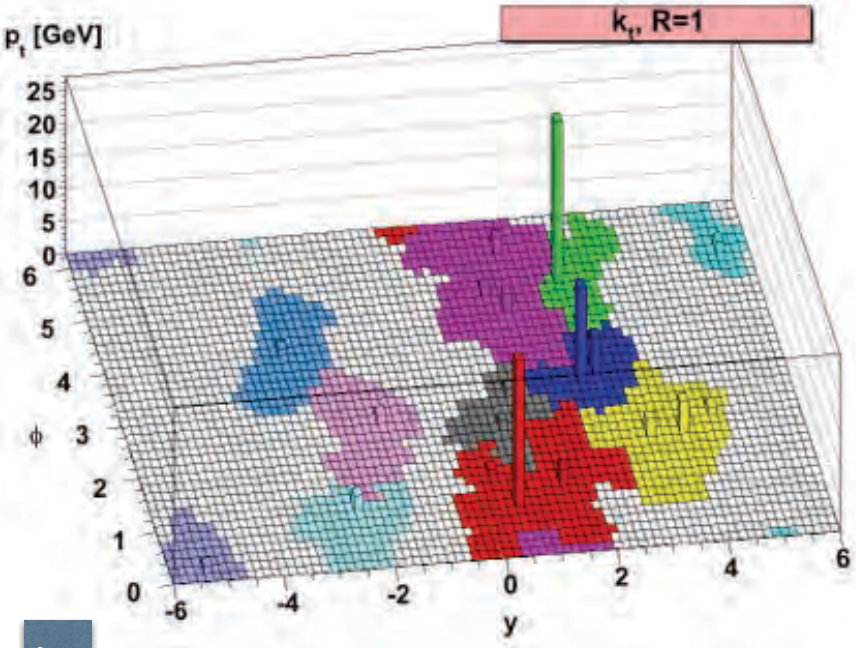
$$d_{ij} = \min(p_{Ti}^{2p}, p_{Tj}^{2p})\ \Delta R_{ij}^2 / R^2$$

- algo:

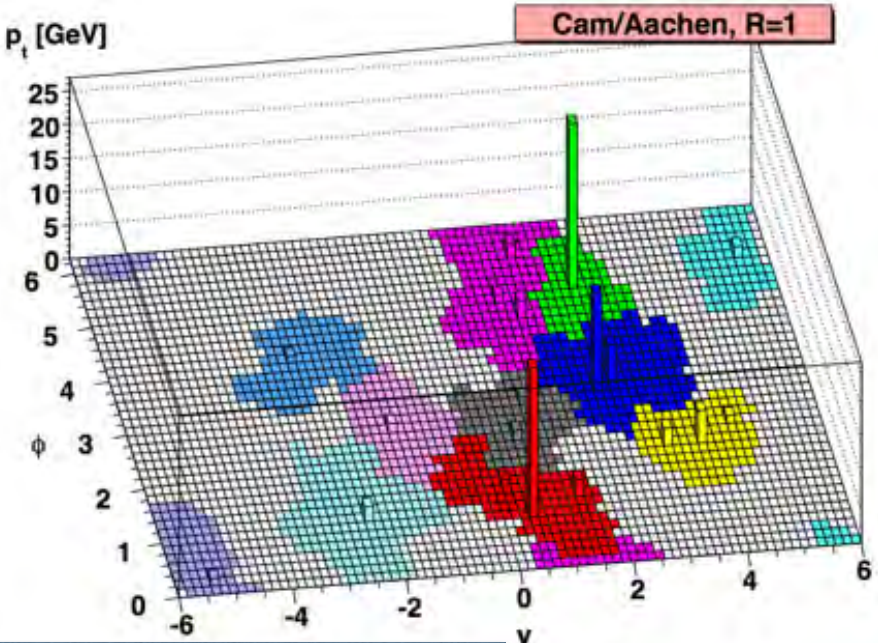
  find pair with smallest d_{ij}
  `if` $d_{ij} > d_{iB} = p_{Ti}^{2p}$ —> `i` is already a jet, remove it
  `else` —> merge `i,j`
  `repeat` until all particles are clustered into a jet

- parameters:
  - R: geometrical separation, “radius parameter”, not a radius!
  - p: energy vs geometry, 2=k_t ; 0=C/A ; -2=anti-k_t





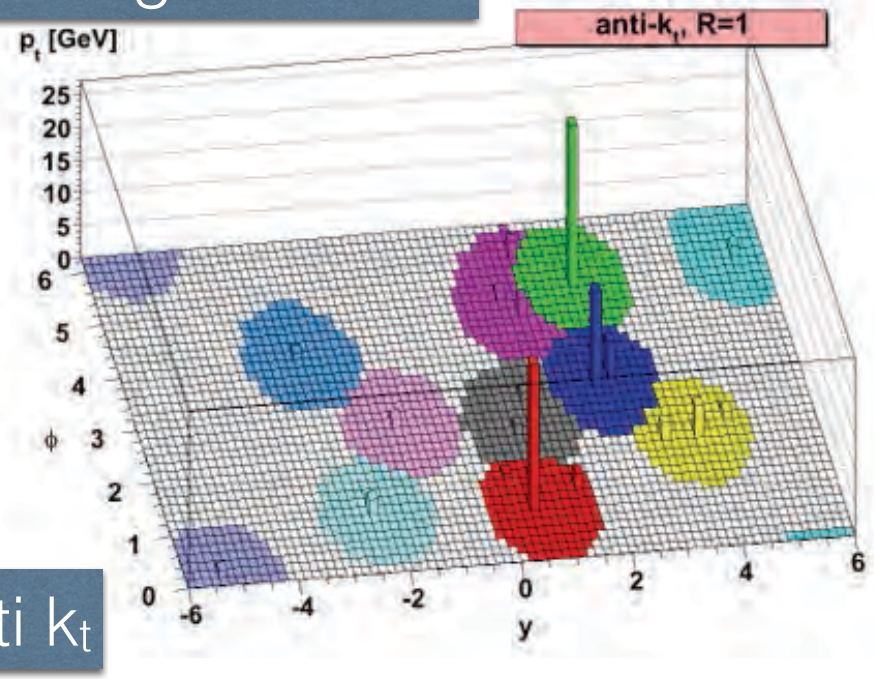
k_t



Cambridge-Aachen

Take home message:

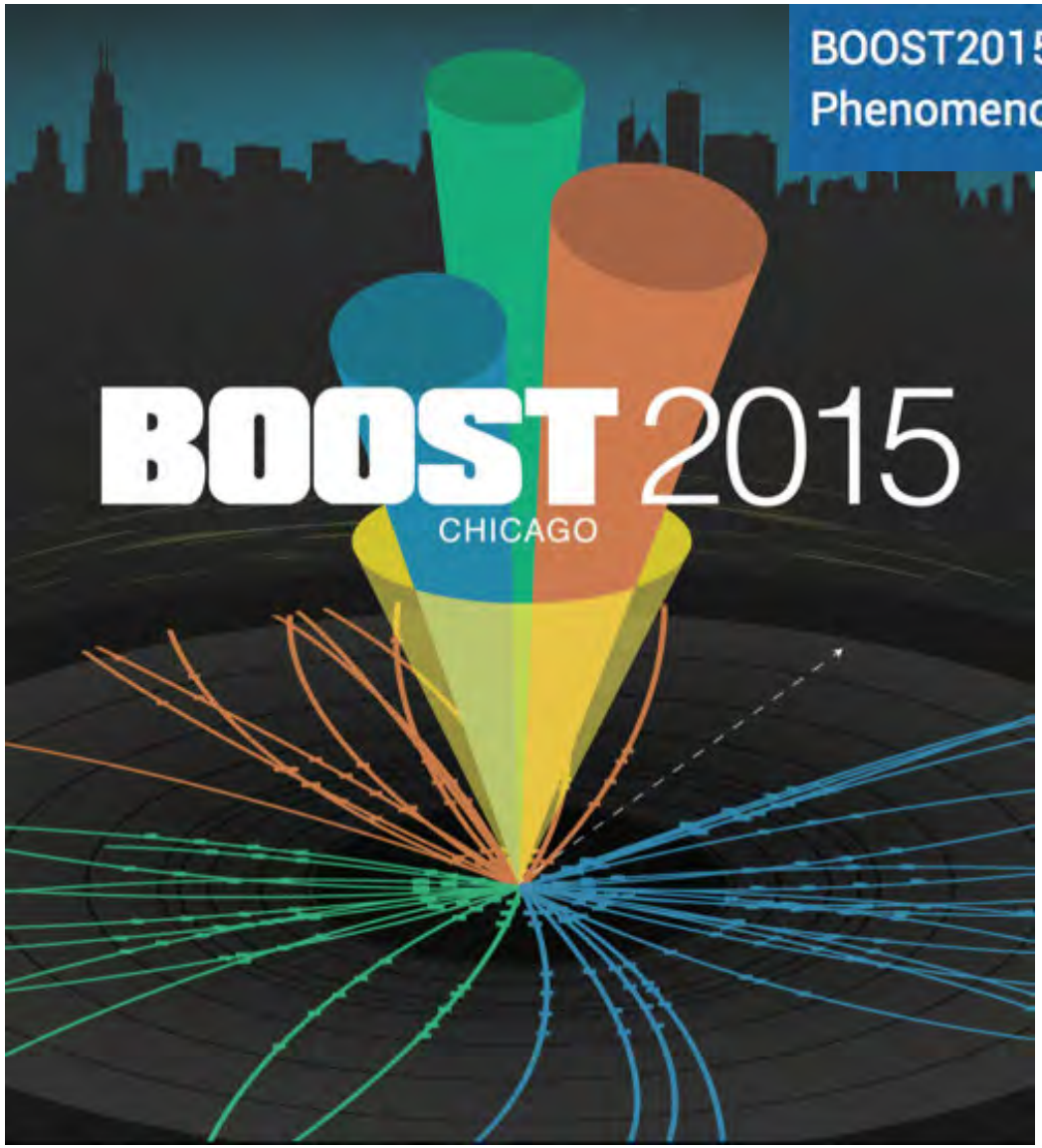
k_t	= *soft first*
C/A	= *closest first*
anti k_t	= *hard first*



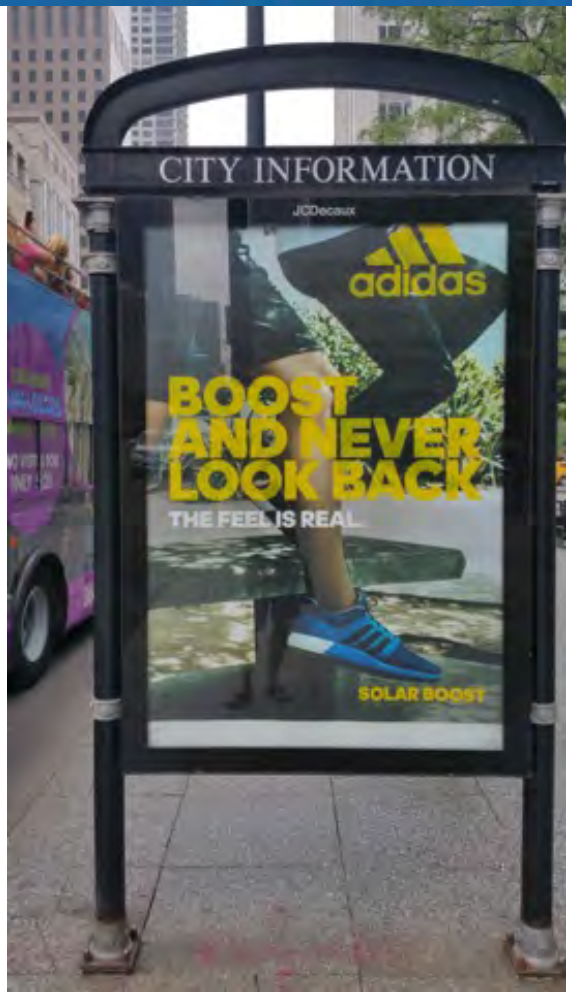
anti k_t

Towards Jetography, G. Salam, Eur.Phys.J. C67 (2010)

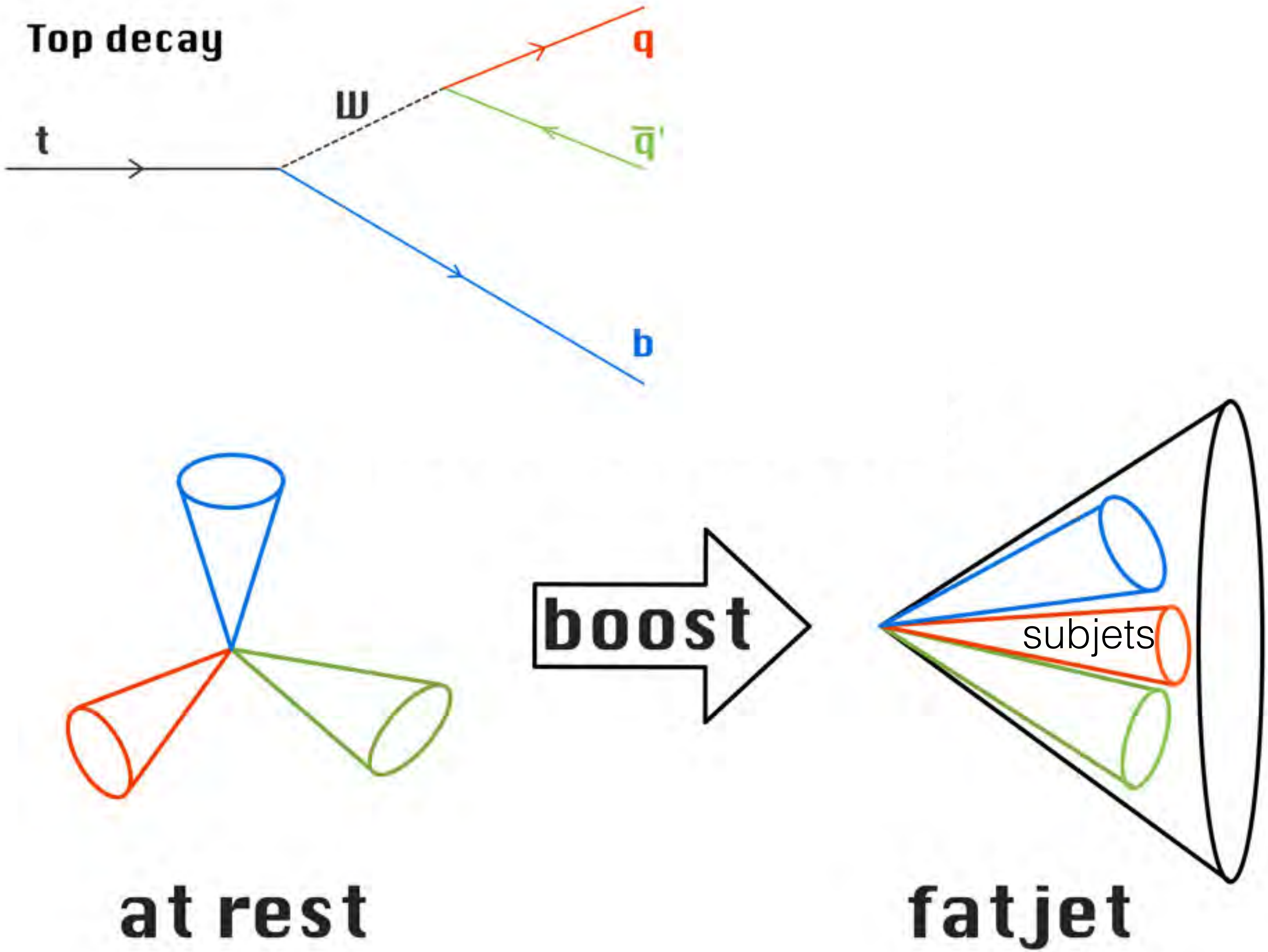
What about BOOST?

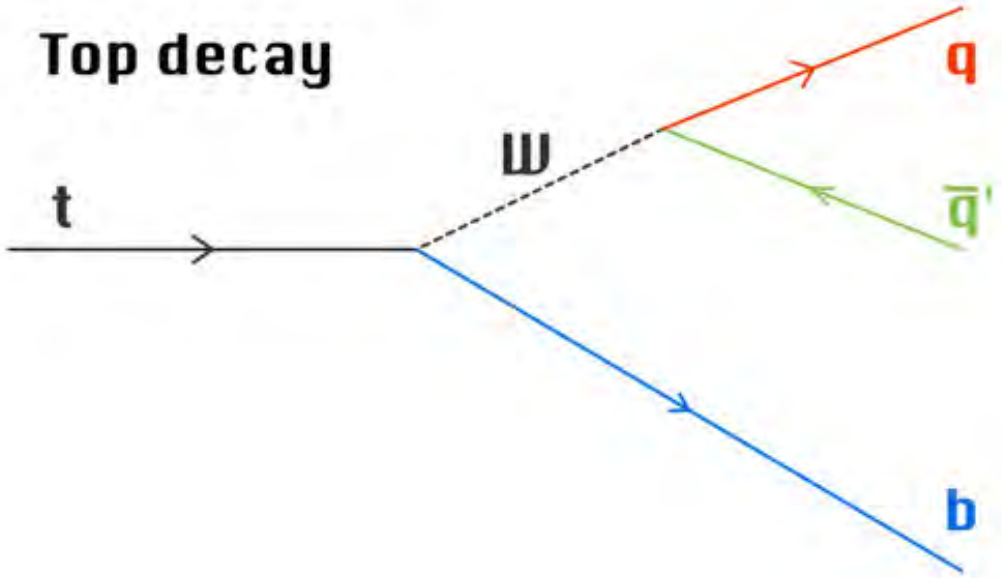


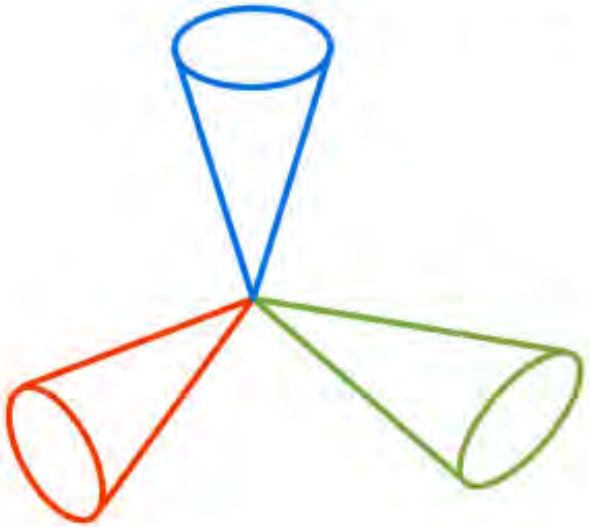
BOOST2015: 7th International Workshop on Boosted Object Phenomenology, Reconstruction and Searches in HEP



What about BOOST?

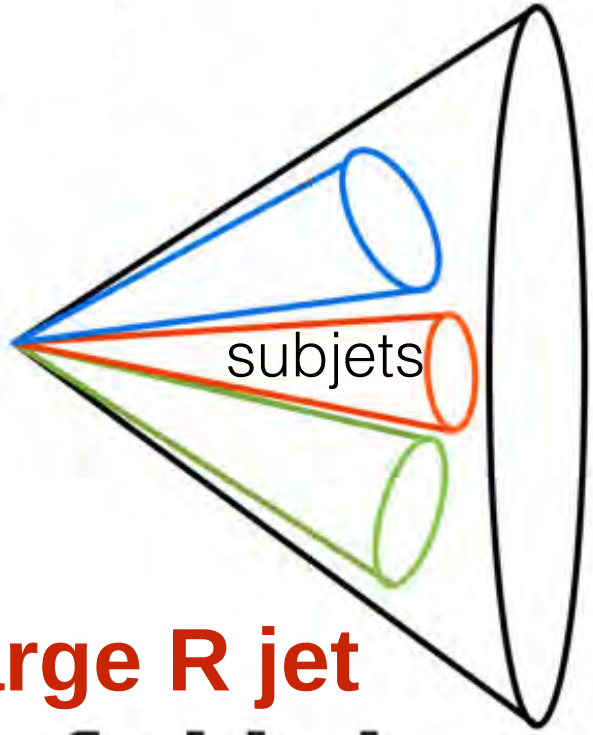

Top decay
t
W
q
q̄'
b
boost
subjets
at rest
fatjet





at rest

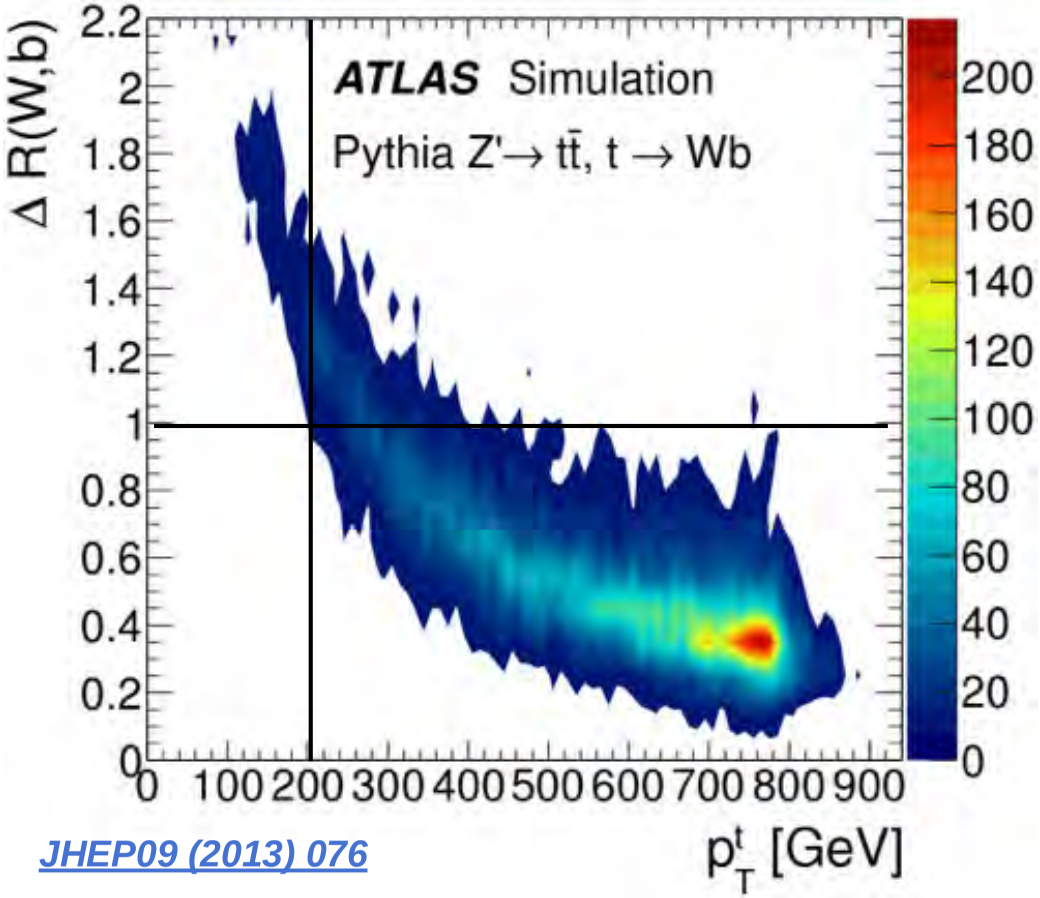
boost



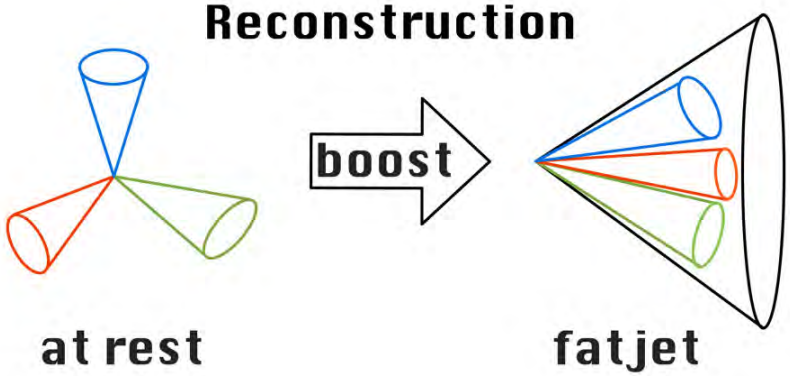
large R jet

~~fatjet~~

Angular separation



JHEP09 (2013) 076



Rule of thumb:

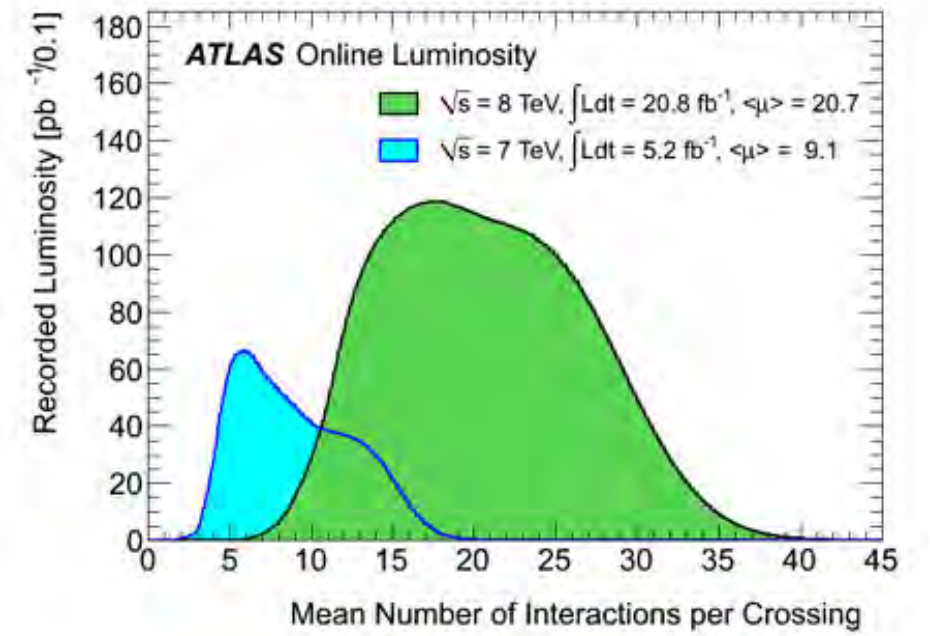
$$\Delta R \simeq 2m/p_T$$

standard jet in ATLAS: R= 0.4

p_T>200GeV to contain
W in R=1.0 jets
top in R=1.5 jets

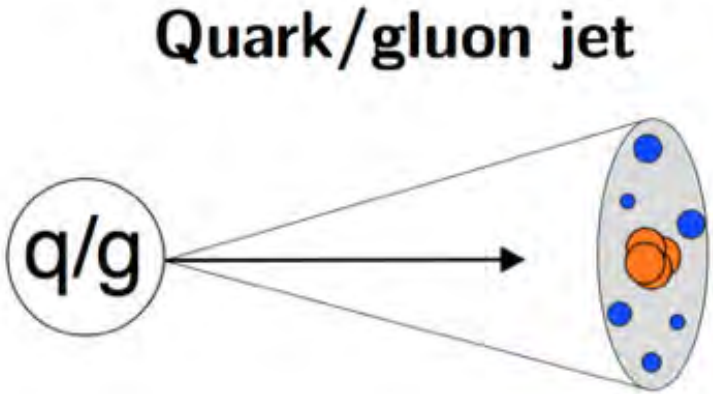
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

Two problems

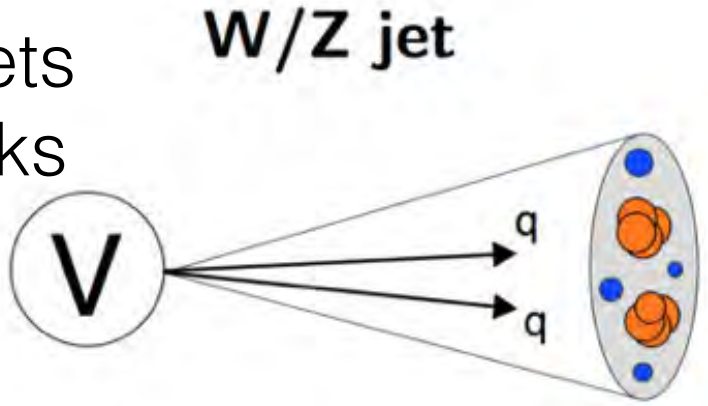


Larger jets pick up more “junk”!

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults



How to reject jets from light quarks and gluons?

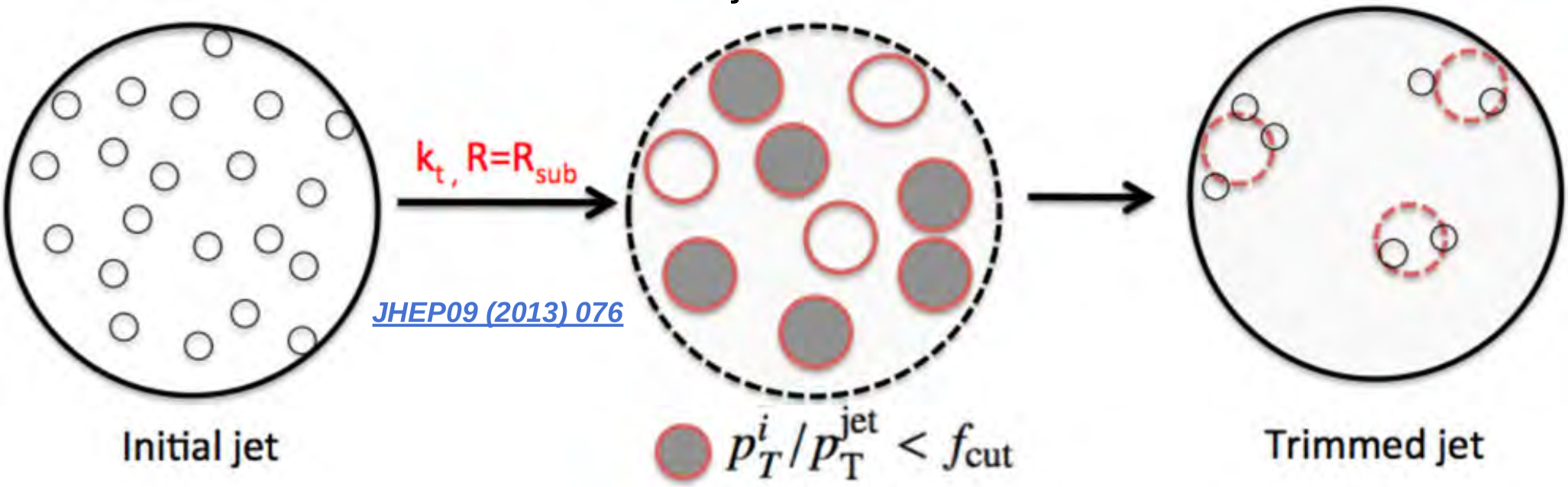


JHEP 02 (2010) 084

One easy example:

Trimming

recluster into small subjets



remove low p_T subjets

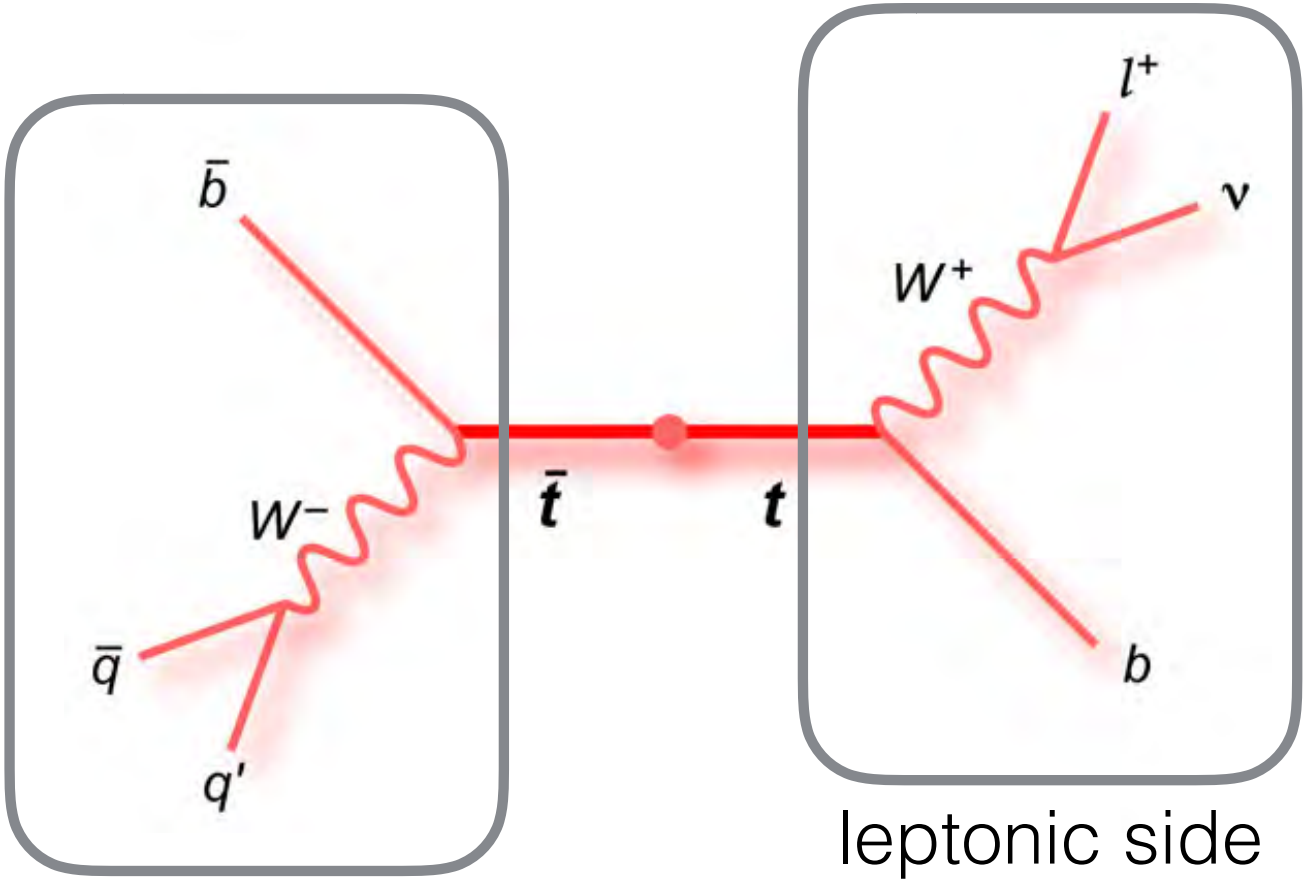
ATLAS typical values (for R=1.0 jets):

Run 1: R_{sub}=0.3, f_{cut} = 0.05

Run 2: R_{sub}=0.2, f_{cut} = 0.05

We'll see this at work in a bit!

Side note: lep+jets $t\bar{t}$

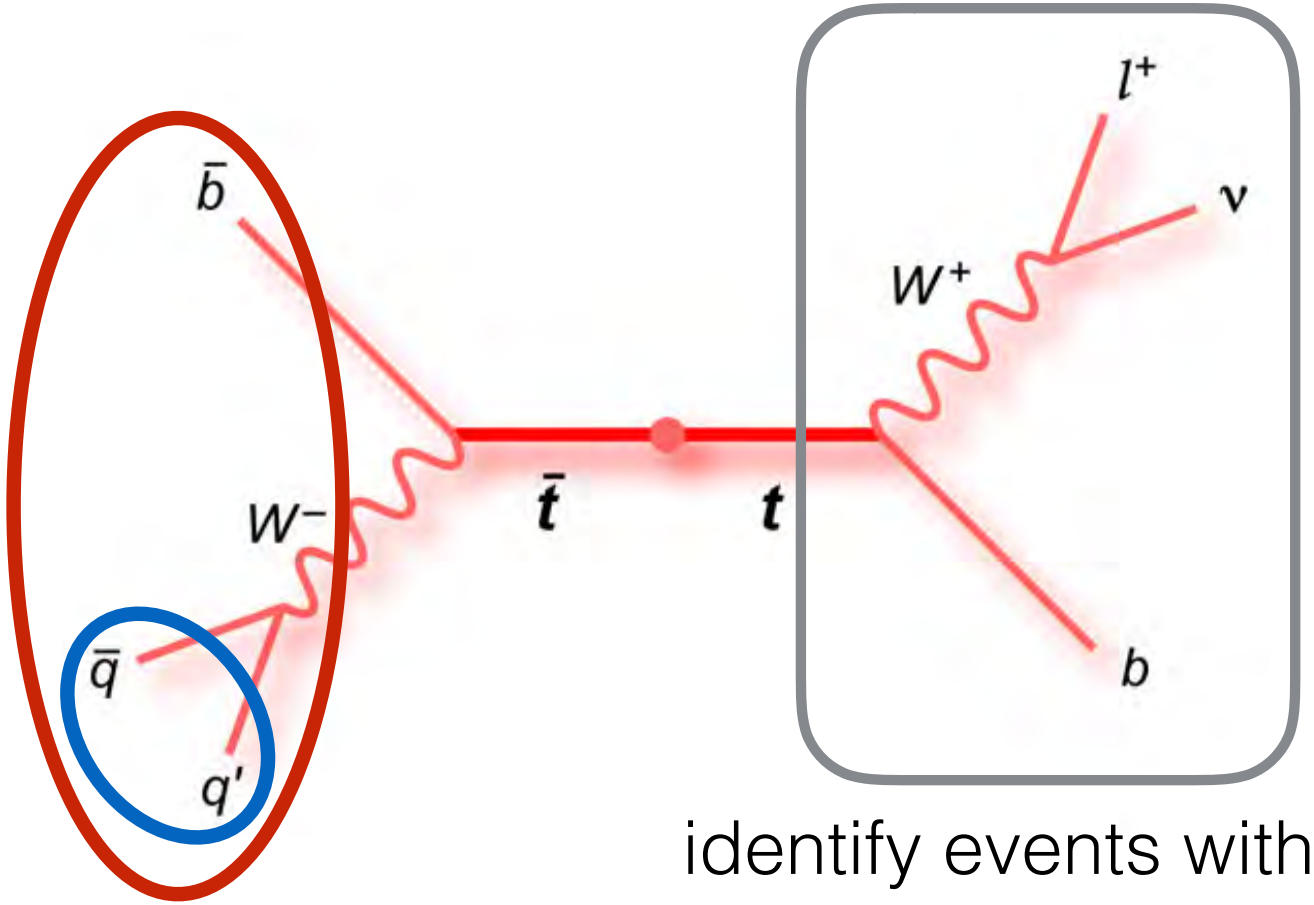


Graph by D0 experiment

Side note: lep+jets $t\bar{t}$

study large R jets
in data for
top decays
W decays

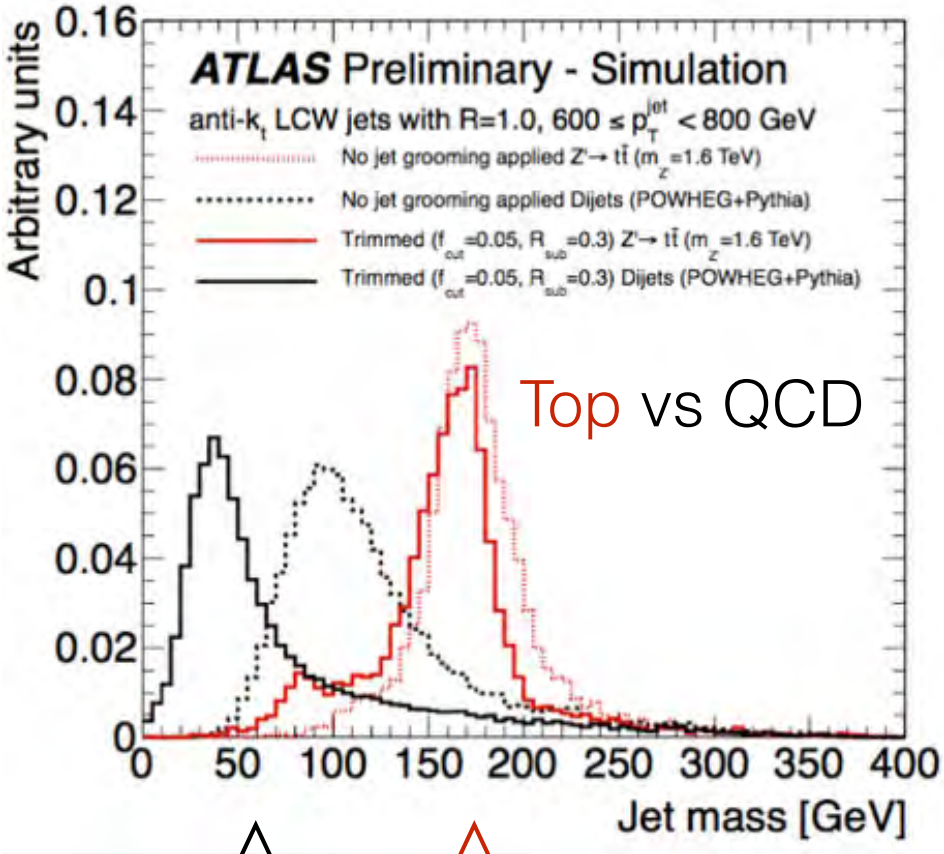
require BOOST:
p_T>200GeV



identify events with

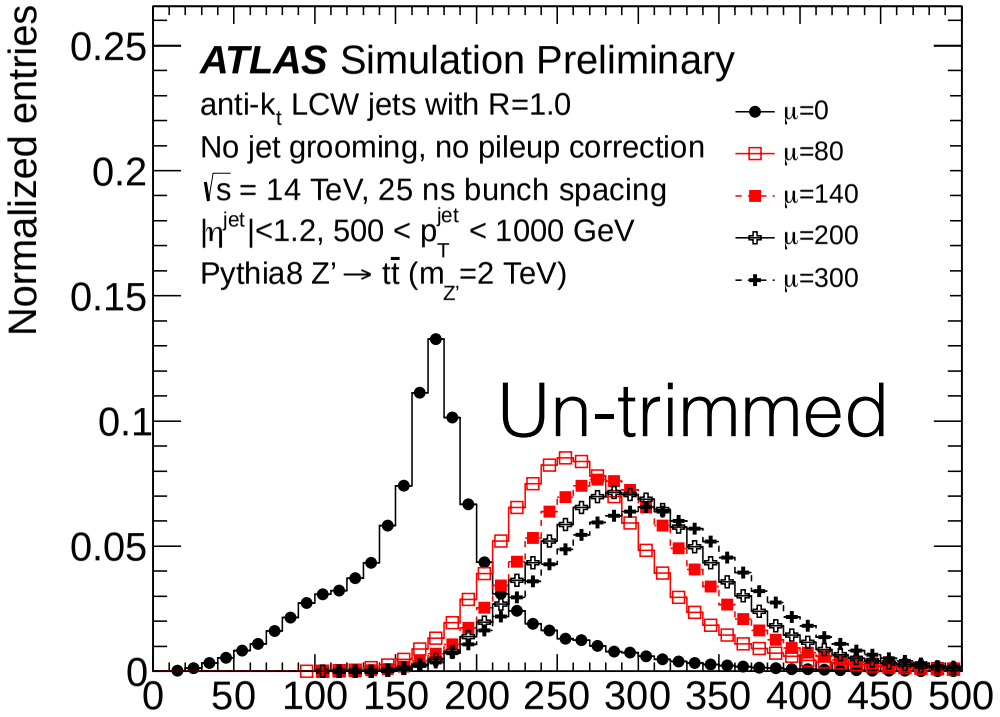
Graph by D0 experiment

Jet mass



$$m_{jet}^{2} = \left(\sum_i E_i\right)^2 - \left(\sum_i p_i\right)^2$$

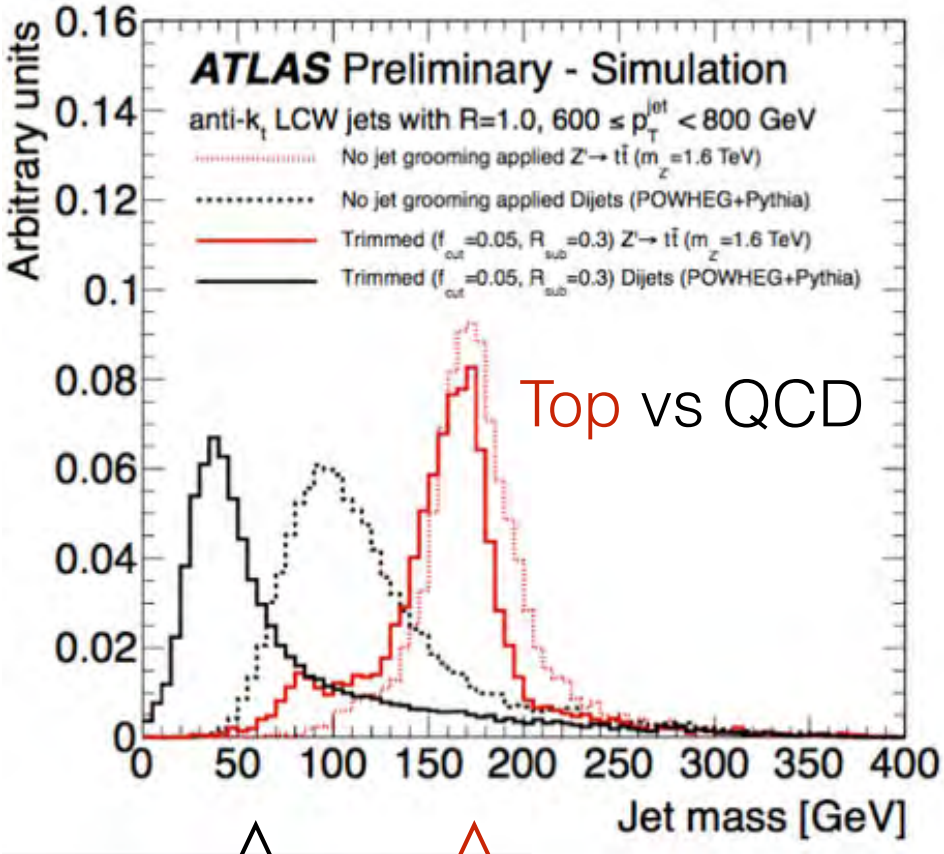
where i = all clusters



Trimming signal and background

JHEP09 (2013) 076

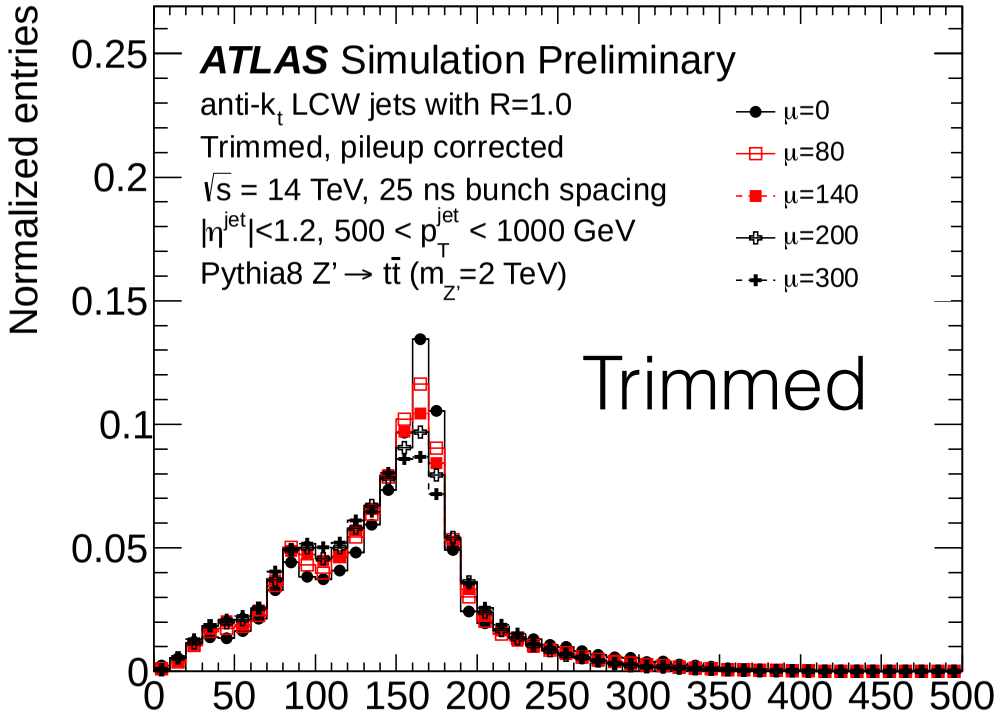
Jet mass



Top vs QCD

$$m_{jet}^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i p_i\right)^2$$

where i = all clusters



Trimming signal and background

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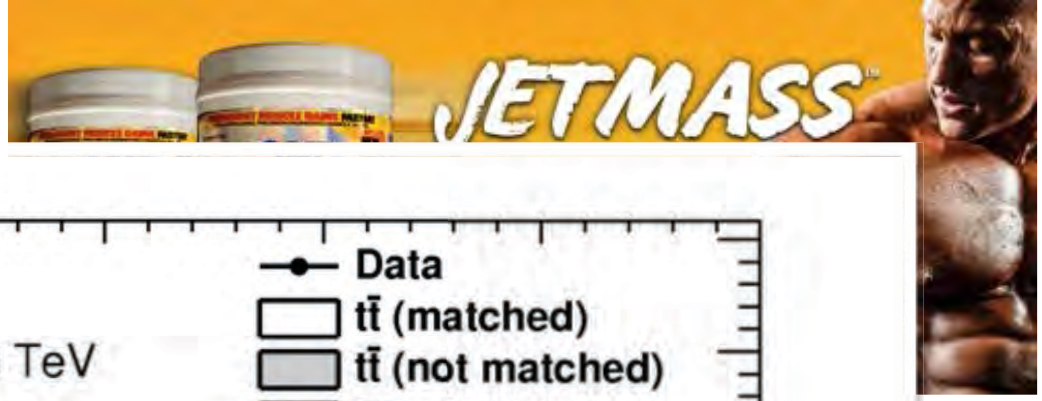
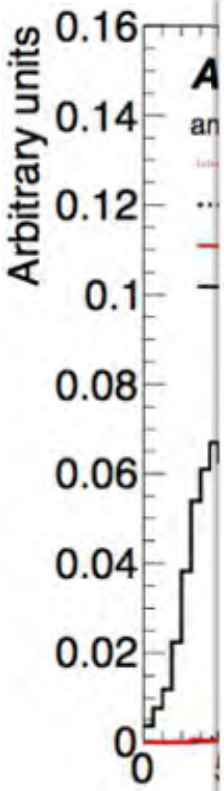
Jet mass





arXiv:1603.03127

Trimming signal and background

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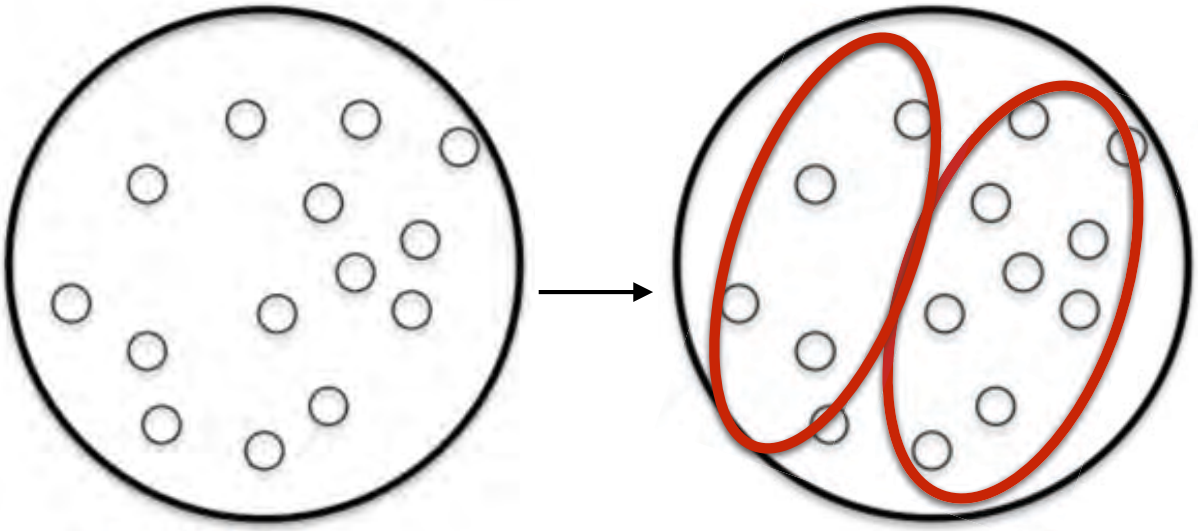
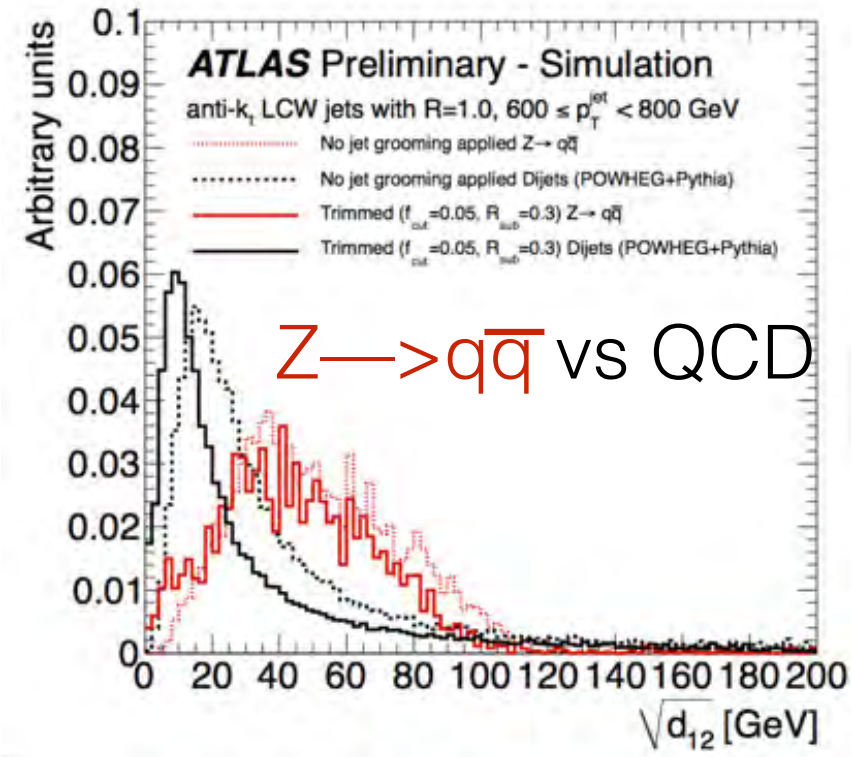
k_T splitting scales

go back one step in the k_T clustering



$$d_{12} = min(p_{T,1}, p_{T,2})\Delta R_{12}$$



Example: Z —>$q\bar{q}$:

- symmetric two-body decay:
  both subjets apart and of similar p_T —> large d_{12}
- For top decay: go back one more step: d_{23}

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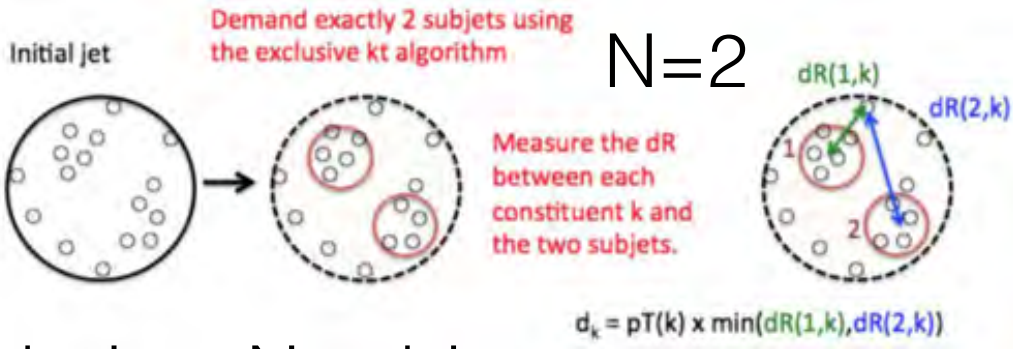
n-subjetiness

JHEP 03 (2011) 015



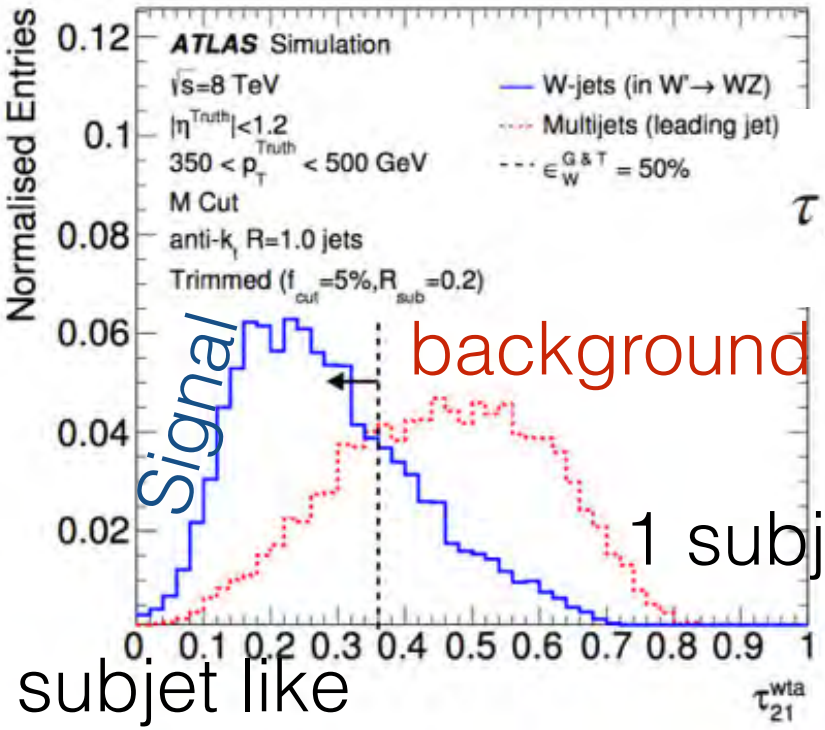
Observables related to N_{subjet}

- reclusters jet constituents with k_T into N subjets
- subjets define axes within the jet

$$\tau_N = \frac{1}{d_0}\sum_k p_{Tk} \times \min(\delta R_{1k}, \delta R_{2k}, \ldots, \delta R_{Nk}) \ , \quad \text{with} \quad d_0 \equiv \sum_k p_{Tk} \times R$$

constituent k

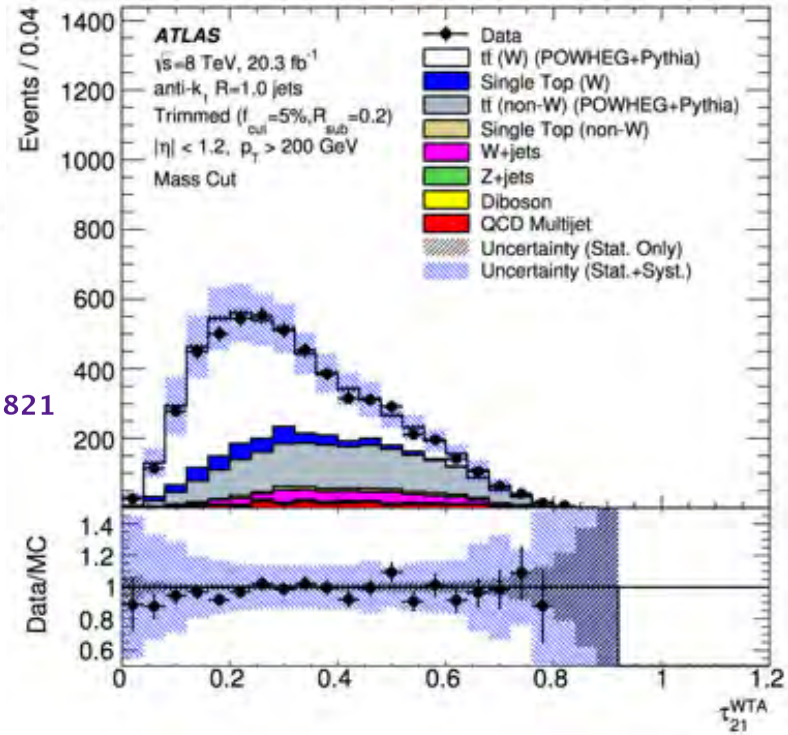
distance of k to subjet i



ratio:

$$\tau_{21} = \frac{\tau_2}{\tau_1}$$

arXiv:1510.05821



JHEP 12 (2014) 009

Energy correlation functions

no subjets!

$$E_{CF0}(\beta) = 1,$$

$$E_{CF1}(\beta) = \sum_{i \in J} p_{T_i},$$

$$E_{CF2}(\beta) = \sum_{i<j \in J} p_{T_i} p_{T_j} \left(\Delta R_{ij}\right)^{\beta},$$

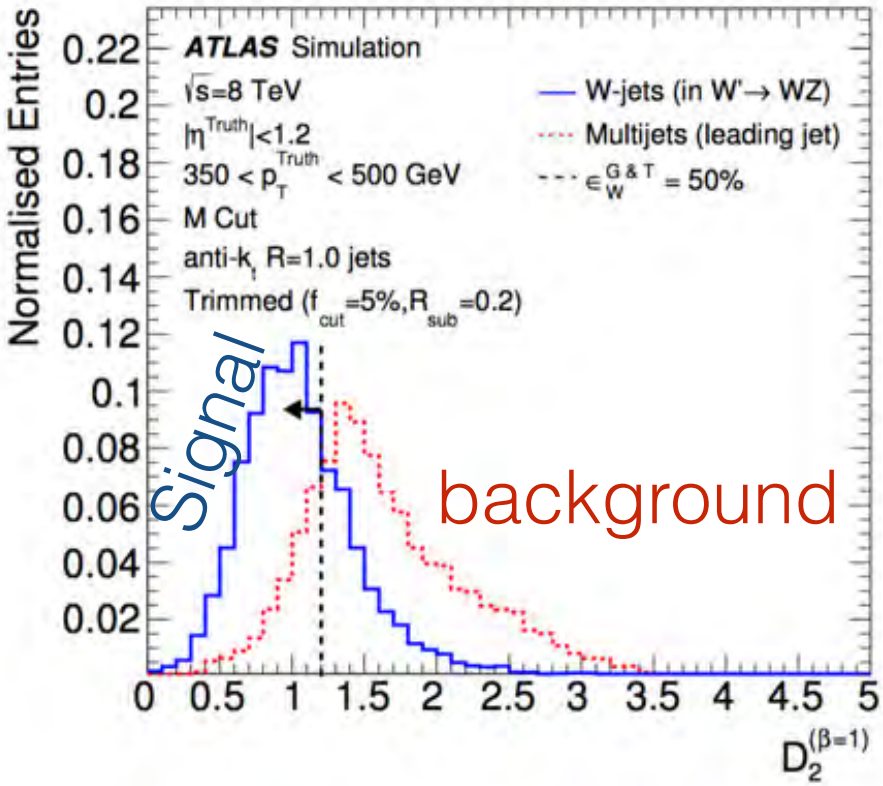
$$E_{CF3}(\beta) = \sum_{i<j<k \in J} p_{T_i} p_{T_j} p_{T_k} \left(\Delta R_{ij} \Delta R_{ik} \Delta R_{jk}\right)^{\beta},$$

m of particle in 2-body decay for beta=1

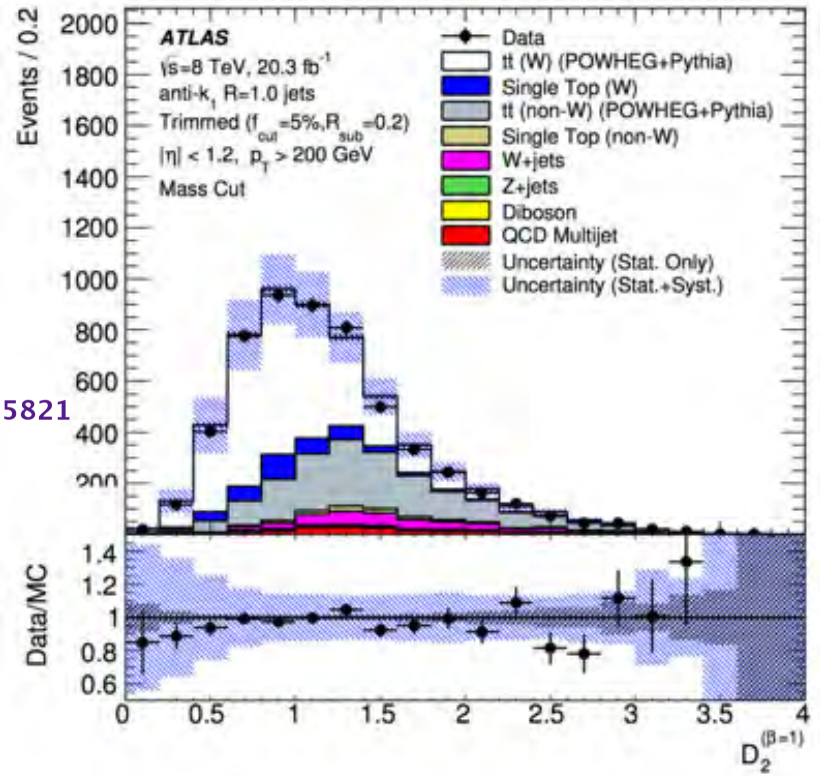
$$e_2^{(\beta)} = \frac{E_{CF2}(\beta)}{E_{CF1}(\beta)^2},$$

$$e_3^{(\beta)} = \frac{E_{CF3}(\beta)}{E_{CF1}(\beta)^3}.$$

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}.$$



arXiv:1510.05821



Building a "simple" W tagger

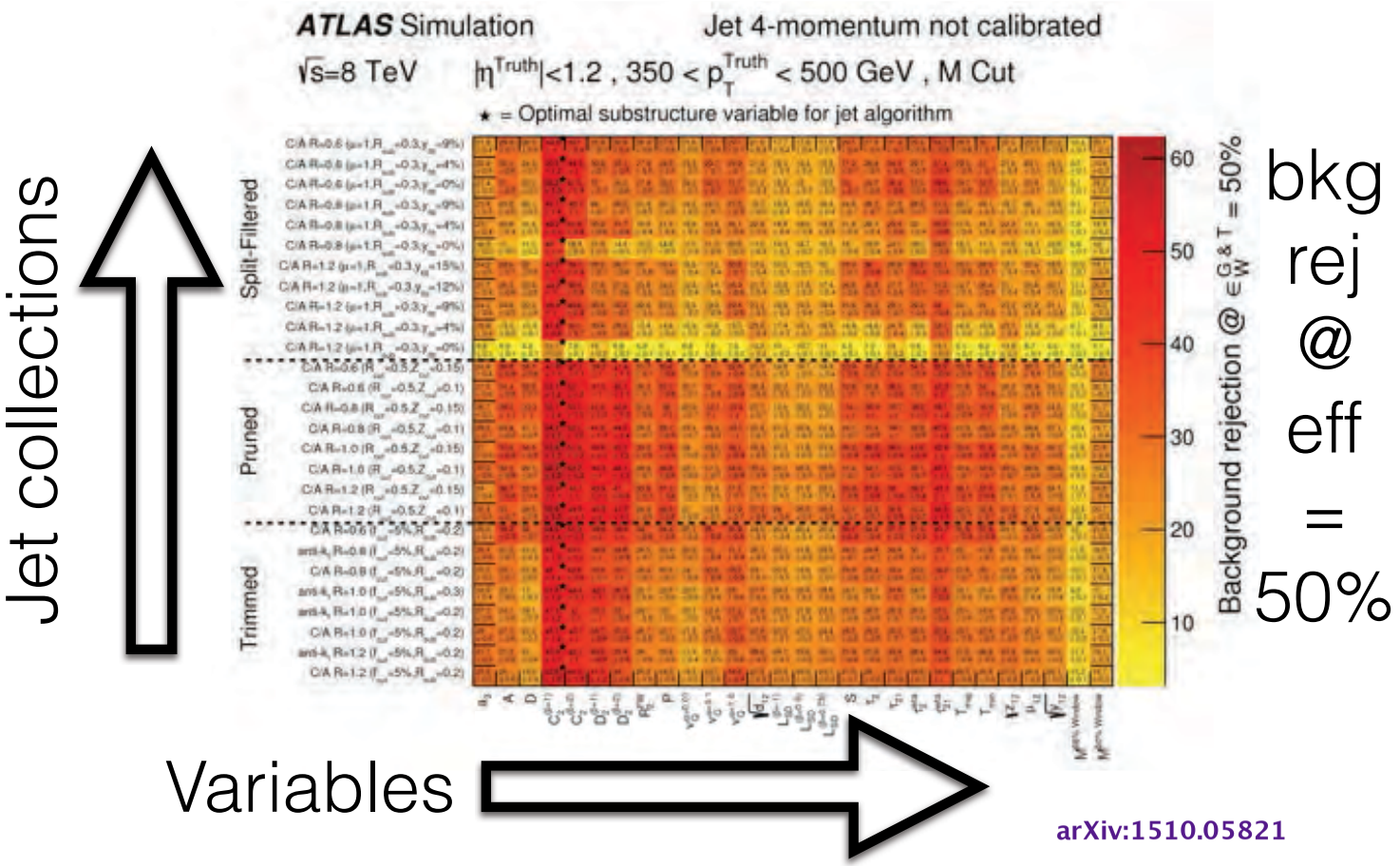
Pick the following:

- Jet type and radius parameter, e.g. anti k_T R=1.0
- Groomer and its parameters, e.g. trimming, R_{sub}=0.3, f_{cut}=5%
- Choose substructure variables (of course there are many more!)

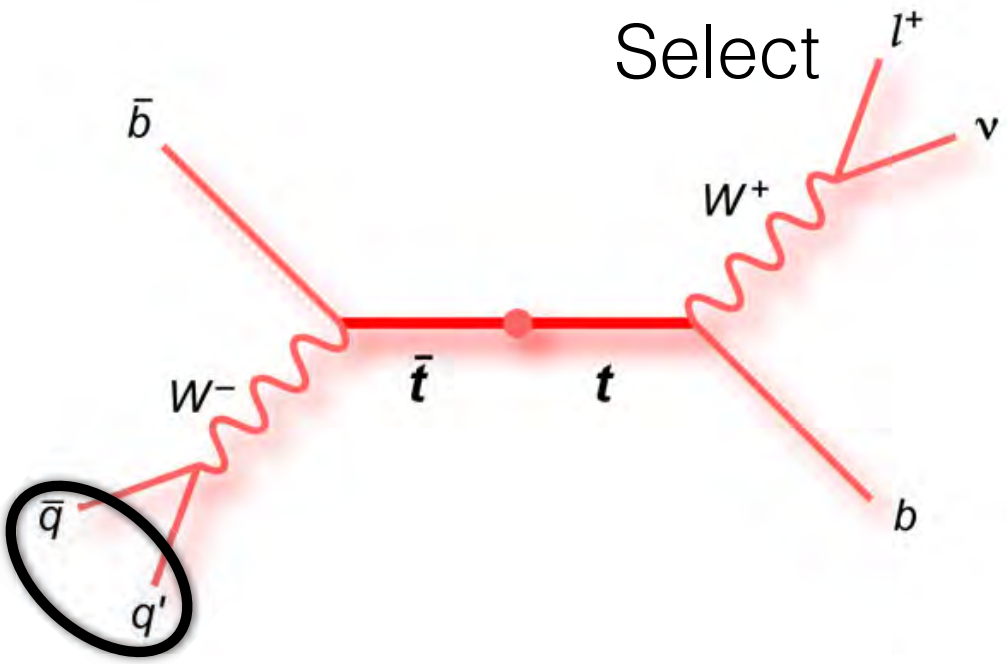
Compare rejection @ fixed signal efficiency

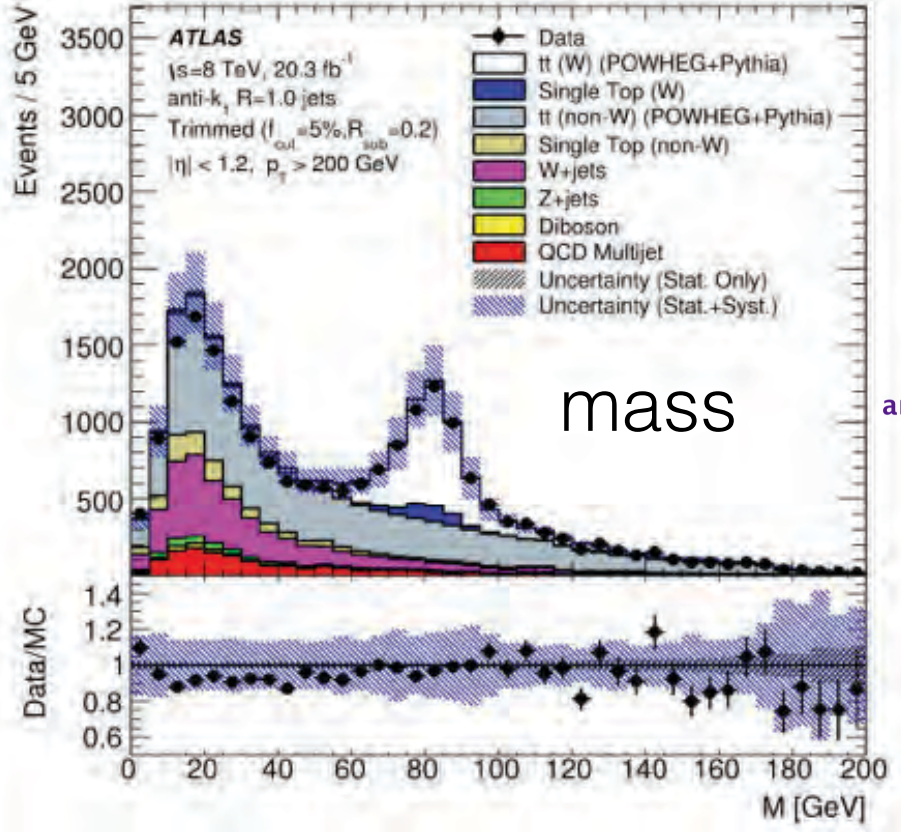
W vs Z

Are the "same", apart from the mass cut!

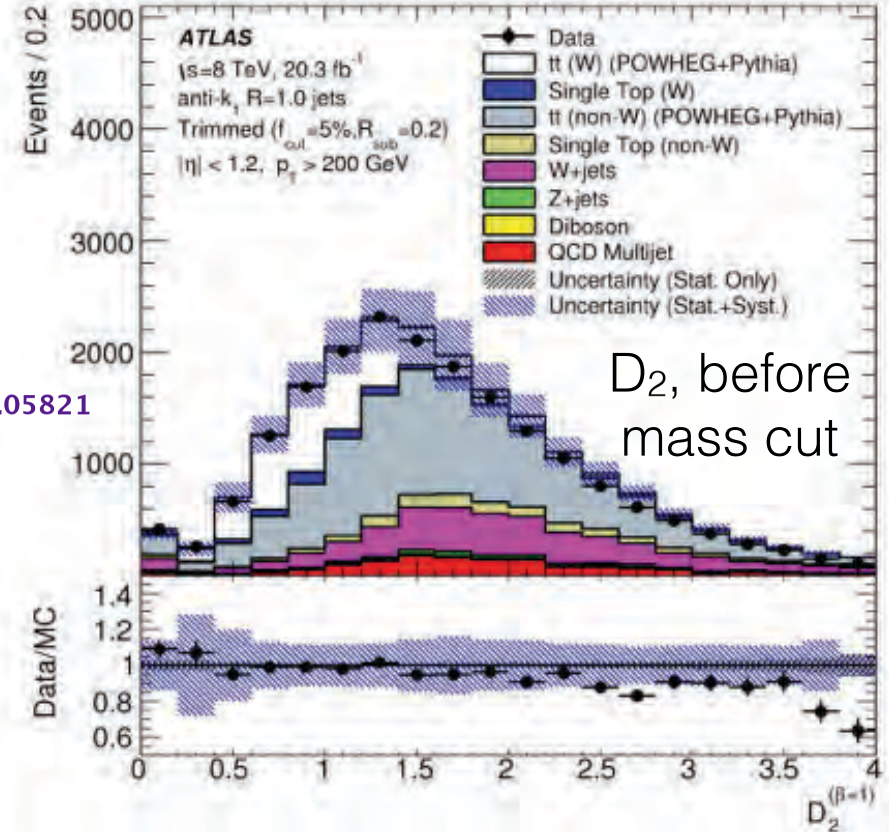


Run 1 boson tagging in data

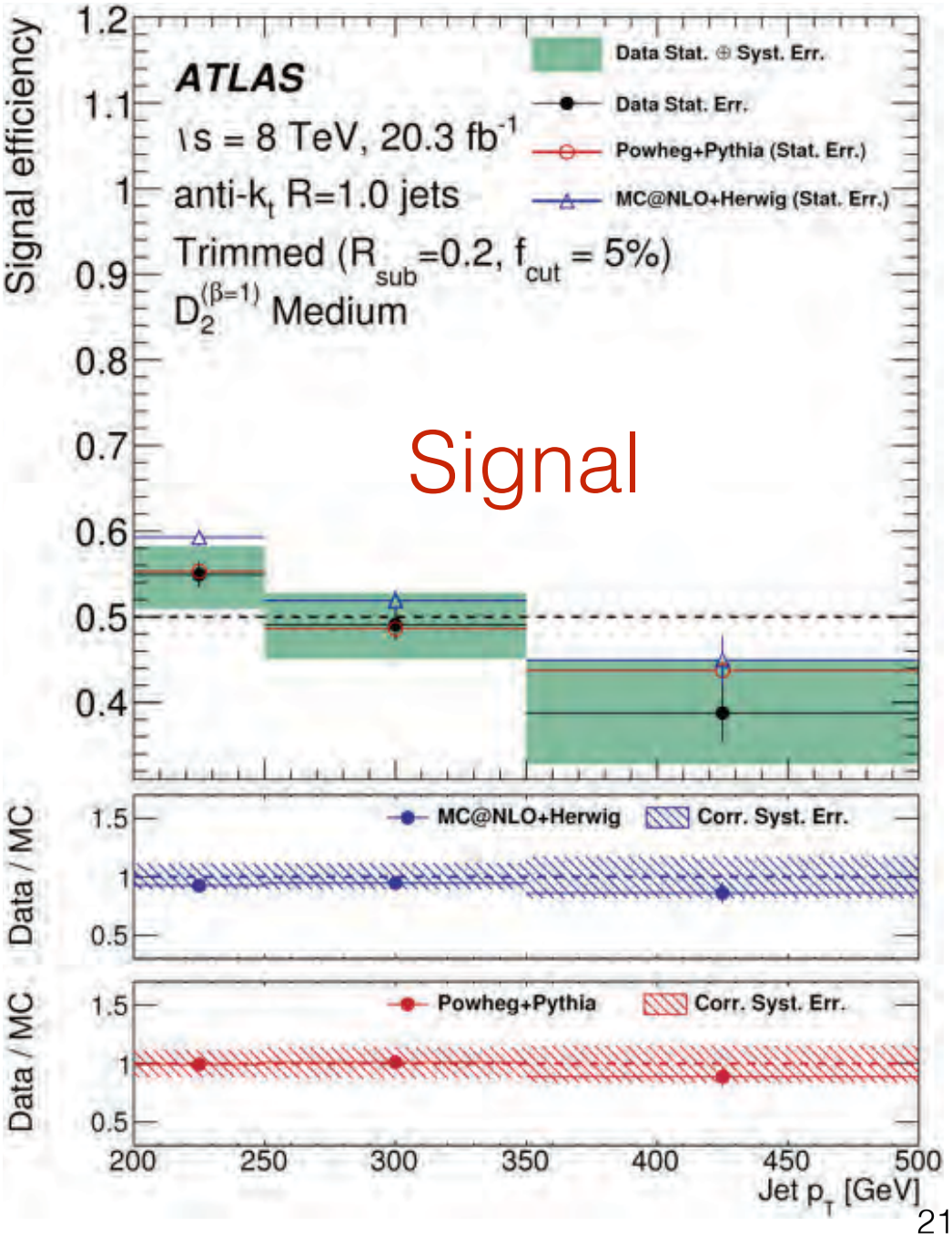


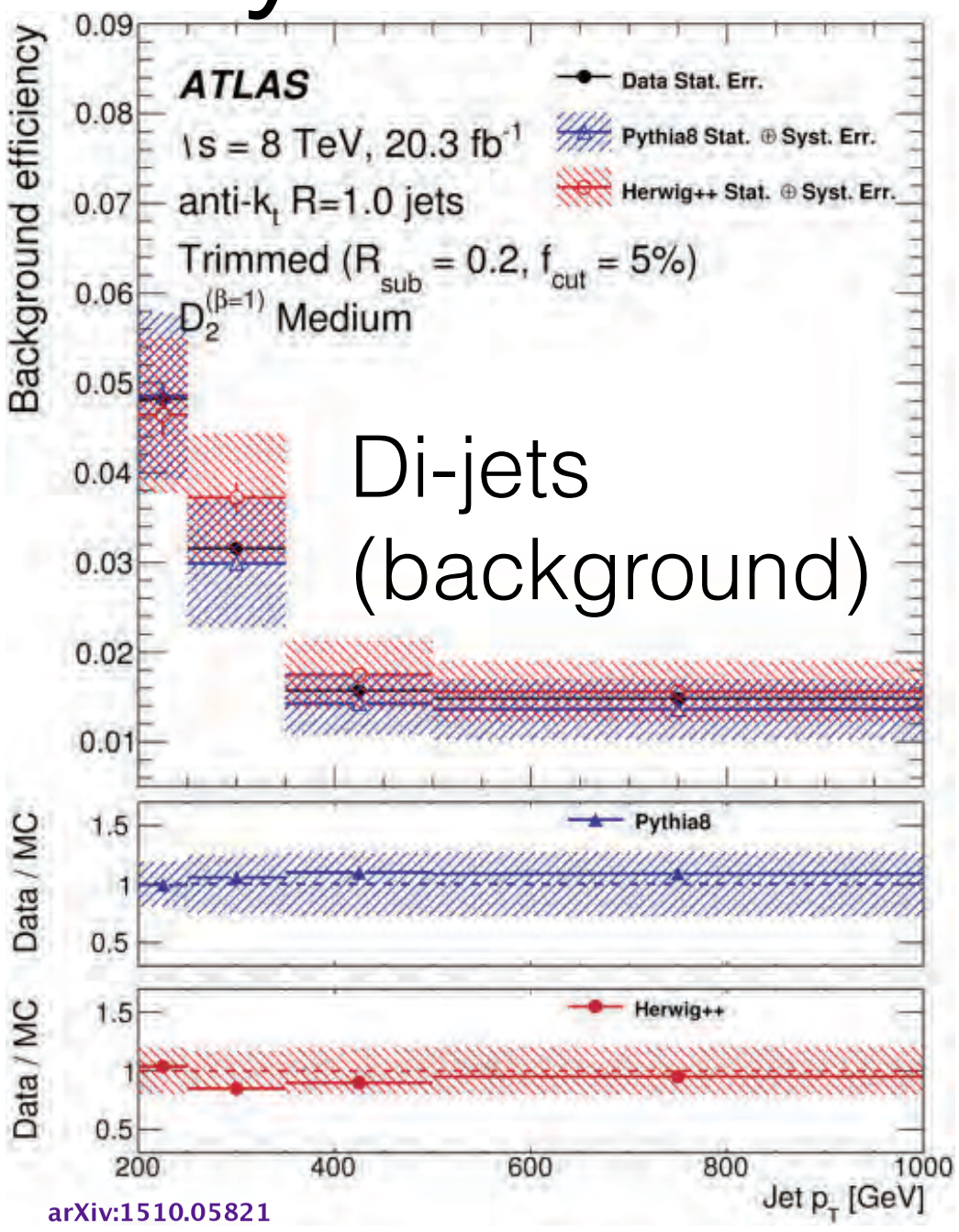


arXiv:1510.05821

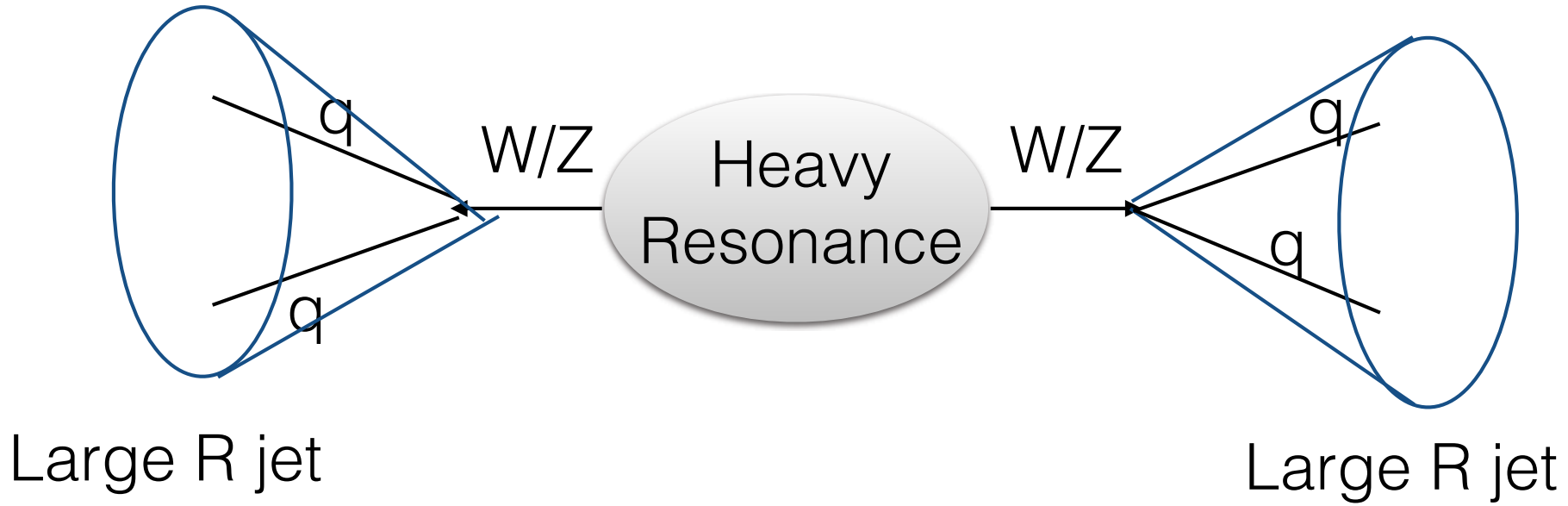


Efficiency

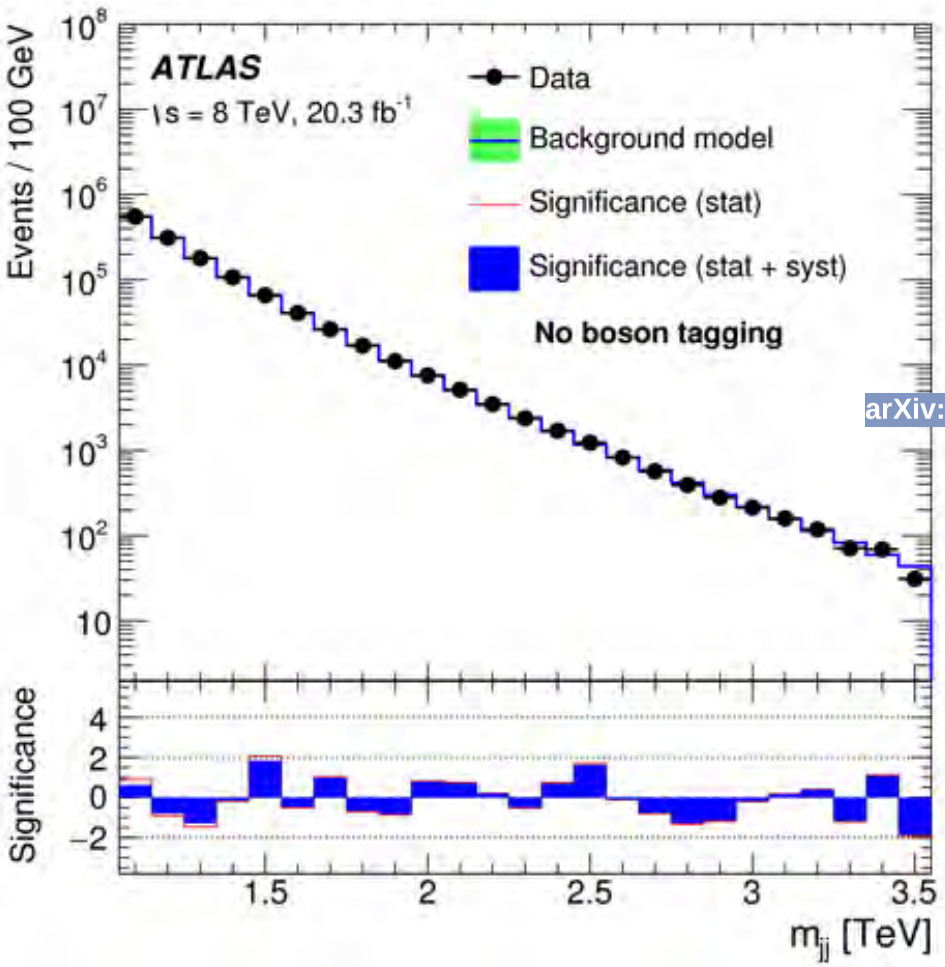


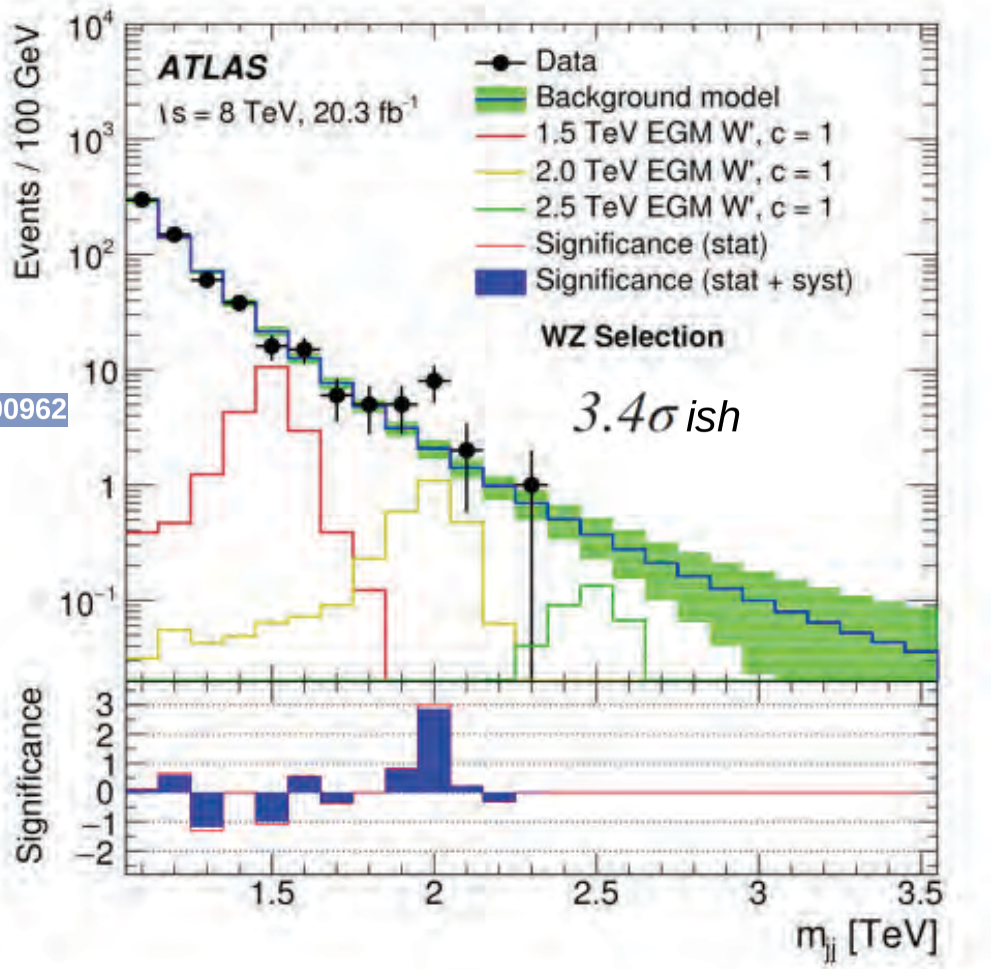


arXiv:1510.05821


q
q
W/Z
Heavy
Resonance
W/Z
q
q
Large R jet
Large R jet

Back to the start!





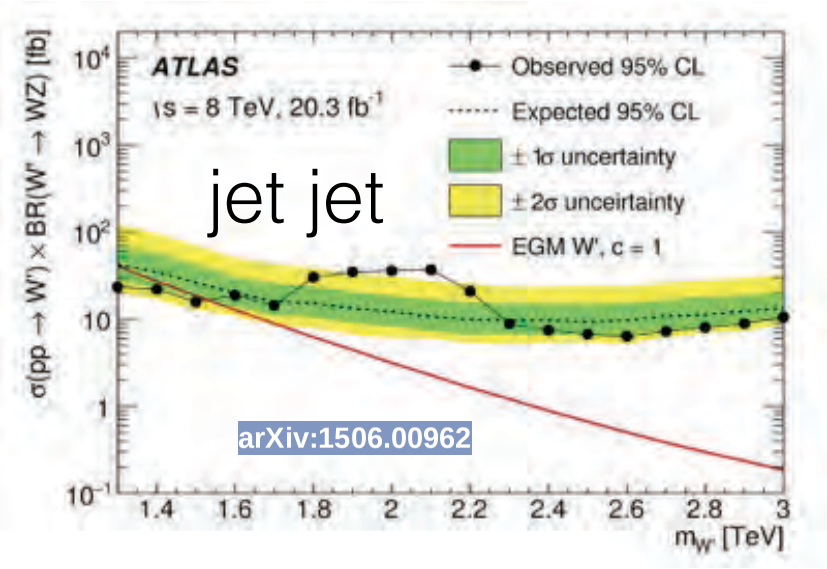
Full disclosure: C/A R = 1.2 jets, modified mass-drop filtering (actually no mass drop), $R_{sub} = 0.3$

$n_{tracks} < 30$

Also WW,ZZ.

Limits on high mass resonance and other final states

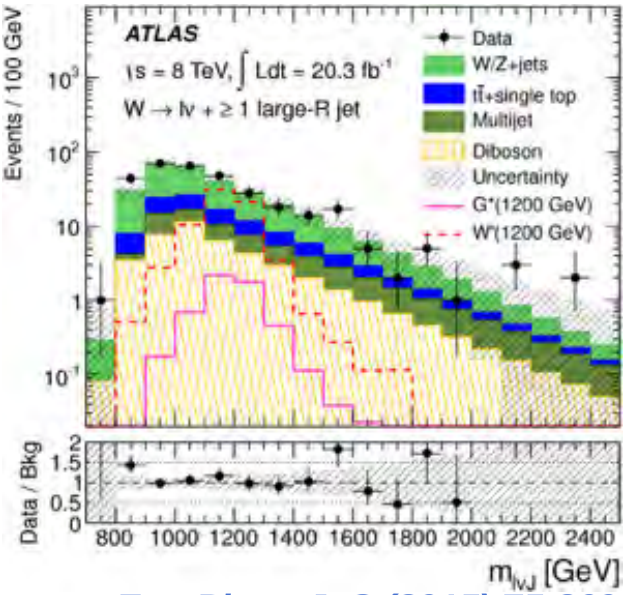
jet jet



No bump in leptonic channels!

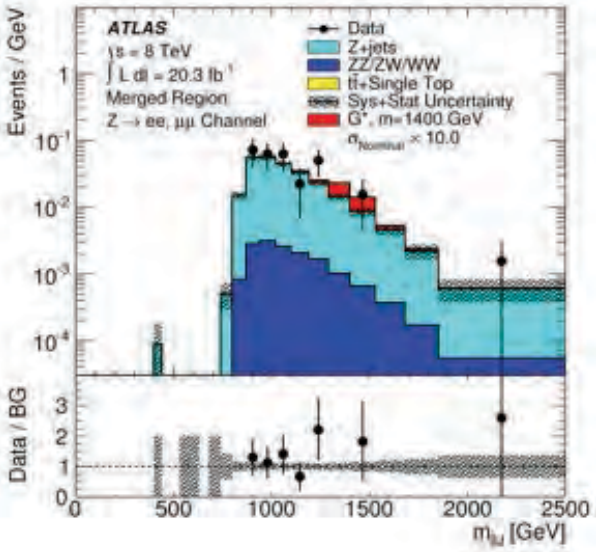
Run 2 will have to tell!

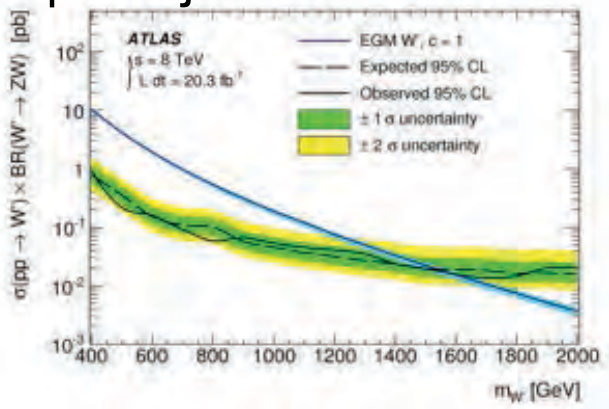
lep, neutrino + jet



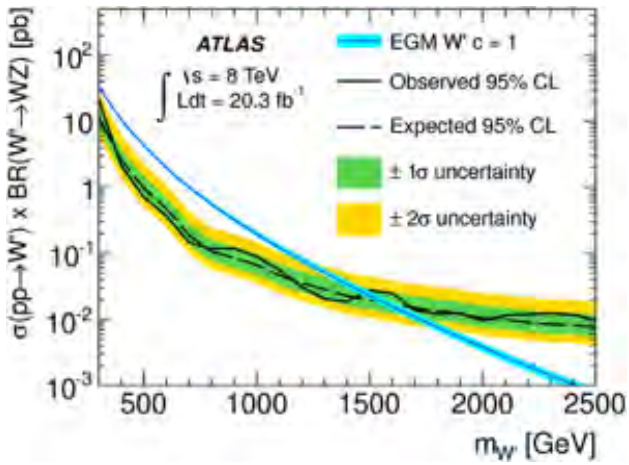
Eur. Phys. J. C (2015) 75:209

2 lep + jet



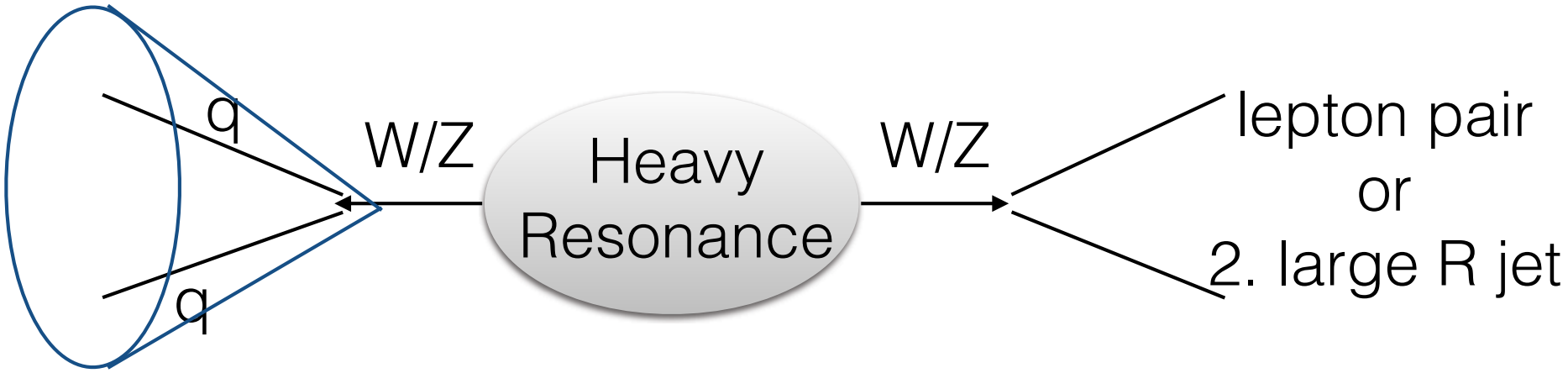


Eur. Phys. J. C (2015) 75:69



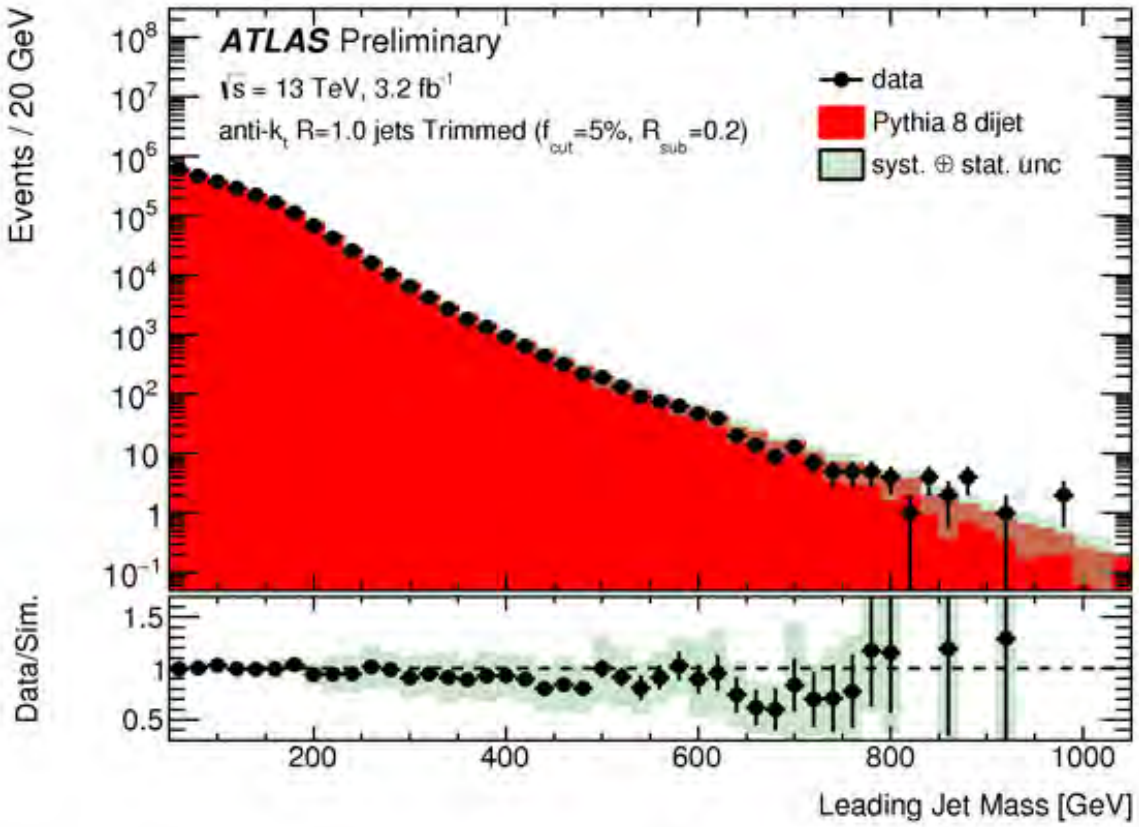
On to Run 2

Di-boson searches:



Large R jet

Basics in Run 2 data

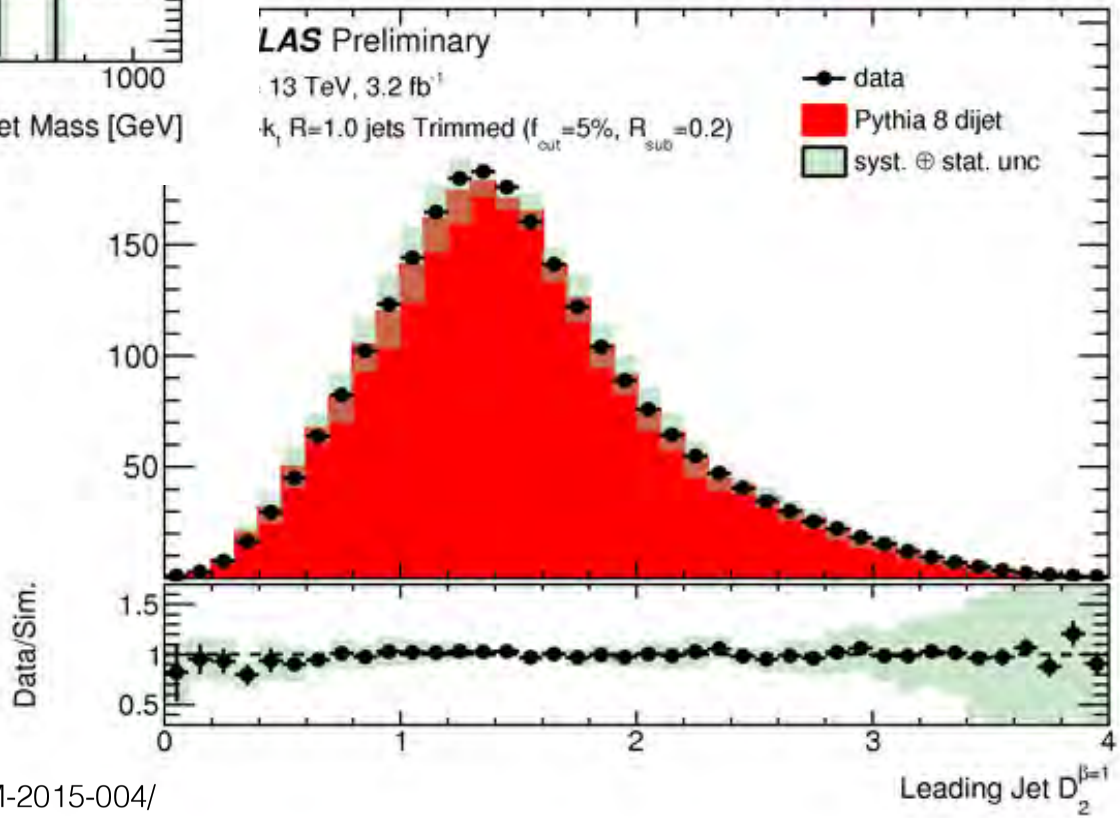


Multi jet background

==

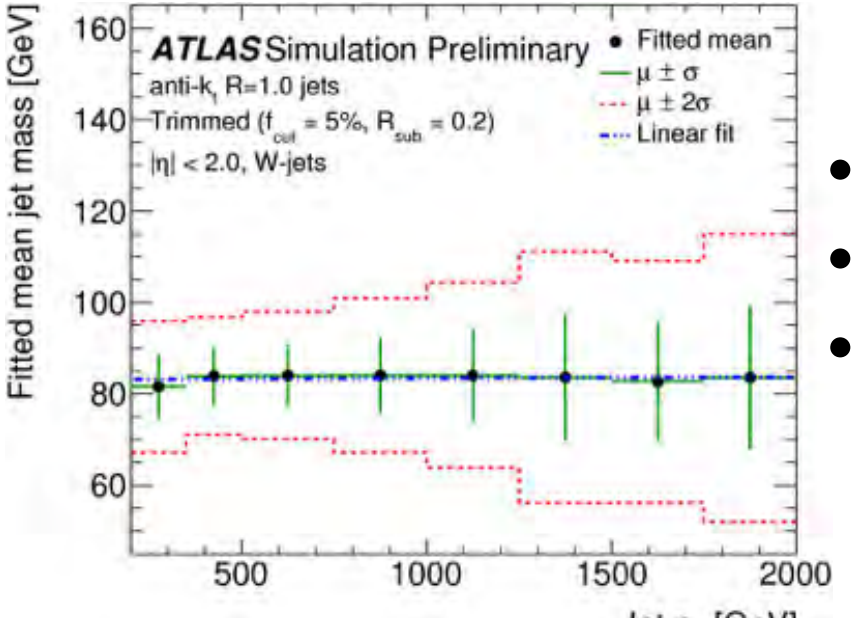
fake bosons

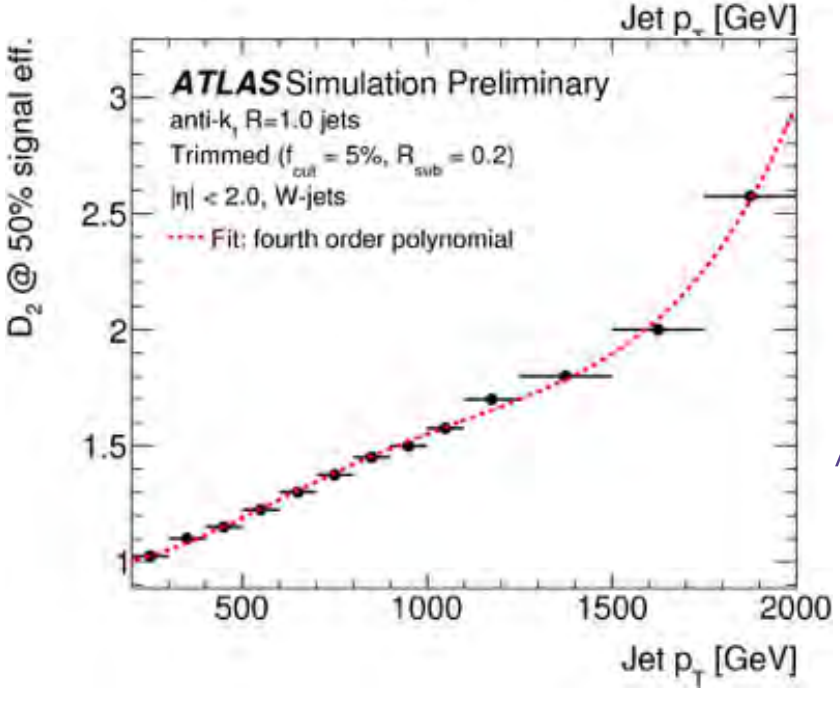
Looking good!



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2015-004/

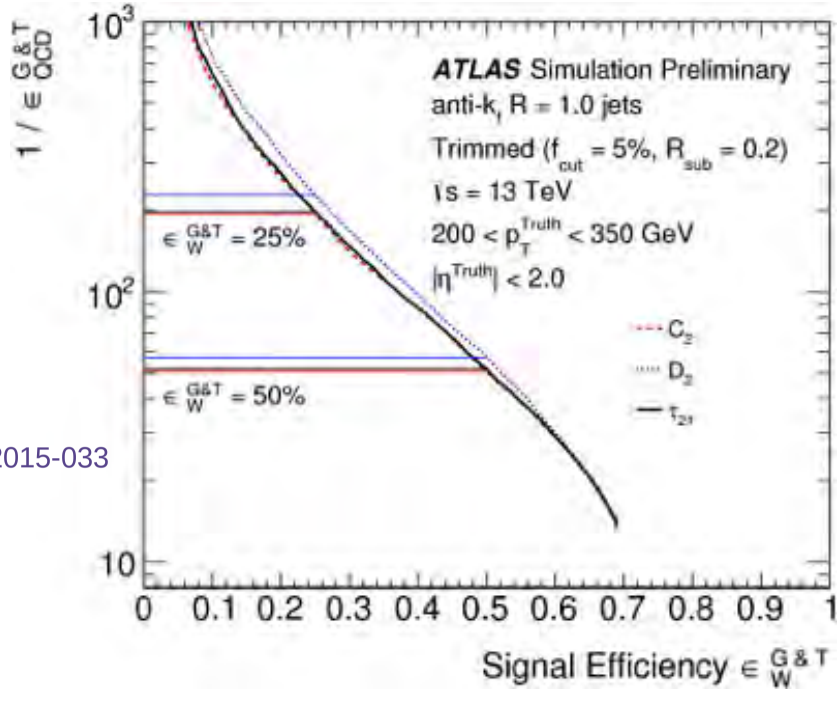
Simple Run 2 tagger





W/Z boson tagger based on:

- anti k_T, R=1.0, R_{sub}=0.2, f_{cut}=5%
- Mass and D_2
- Constant signal efficiency (25% and 50%)



ATL-PHYS-PUB-2015-033

Run 2 di-boson (W/Z) searches

Channel	VV —> JJ	VV—> J ll	VV —> Jlν	VV—> Jνν
Trigger	Large R jet, 360GeV	electron/muon triggers	electron/muon triggers	MET trigger, 80GeV
Large R jet	2 with p_T>400/200 GeV	1 with p_T>200 GeV	1 with p_T>200 GeV	1 with p_T>200 GeV
Boson Tag	50% W/Z + N_{track}<30	50% W/Z	50% W/Z	50% W/Z
Leptons/MET	no	e^+e^- / $\mu^+\mu^-$ compatible with Z decay	MET>100GeV 1 e or mu	MET>200 GeV
Backgrounds	mutlijet, shape fit in data	Z+jets, from m_J sideband	W+jet m_J sideband top b-tagged CR	Zmumu and btagged
ATLAS-CONF	2015-073	2015-071	2015-75	2015-068

Run 2 di-boson (W/Z) searches

Channel	VV —> JJ	VV—> J ll	VV —> Jlν	VV—> Jνν
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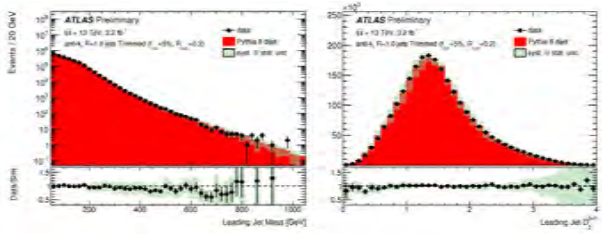
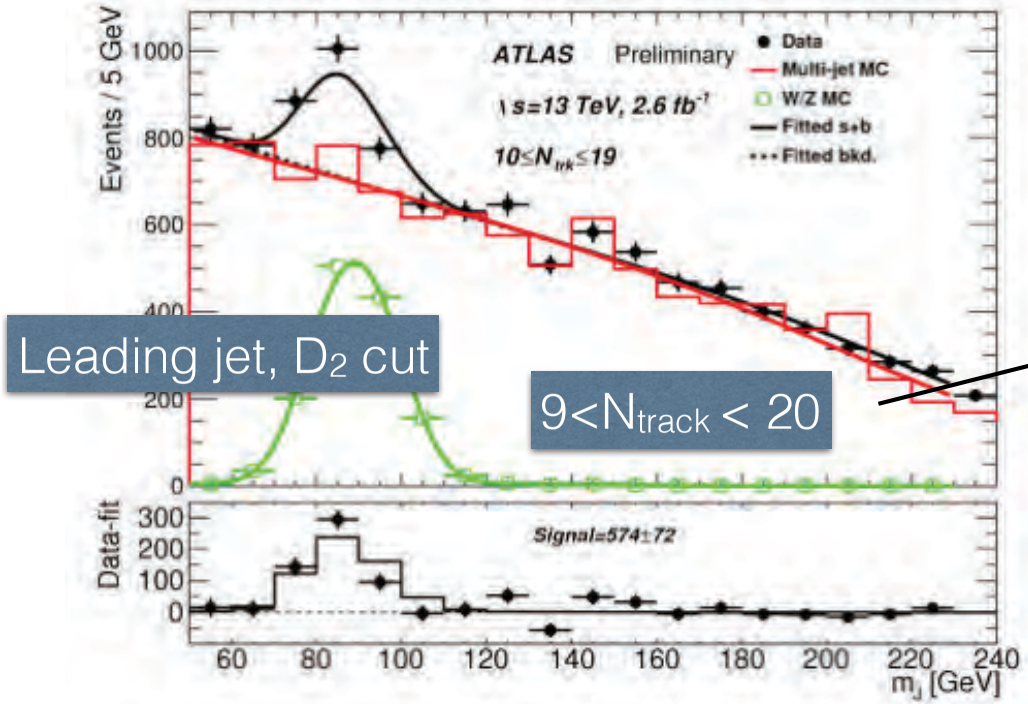
Large R jet	2 with p_T>400/200 GeV	1 with p_T>200 GeV	1 with p_T>200 GeV	1 with p_T>200 GeV
Boson Tag	50% W/Z + N_{track}<30	50% W/Z	50% W/Z	50% W/Z
Leptons/MET	no	e^+e^- / $\mu^+\mu^-$ compatible with Z decay	MET>100GeV 1 e or mu	MET>200 GeV
Backgrounds	mutlijet, shape fit in data	Z+jets, from m_J sideband	W+jet m_J sideband top b-tagged CR	Zmumu and btagged
ATLAS-CONF	2015-073	2015-071	2015-75	2015-068

Fully hadronic search == Tagging in action



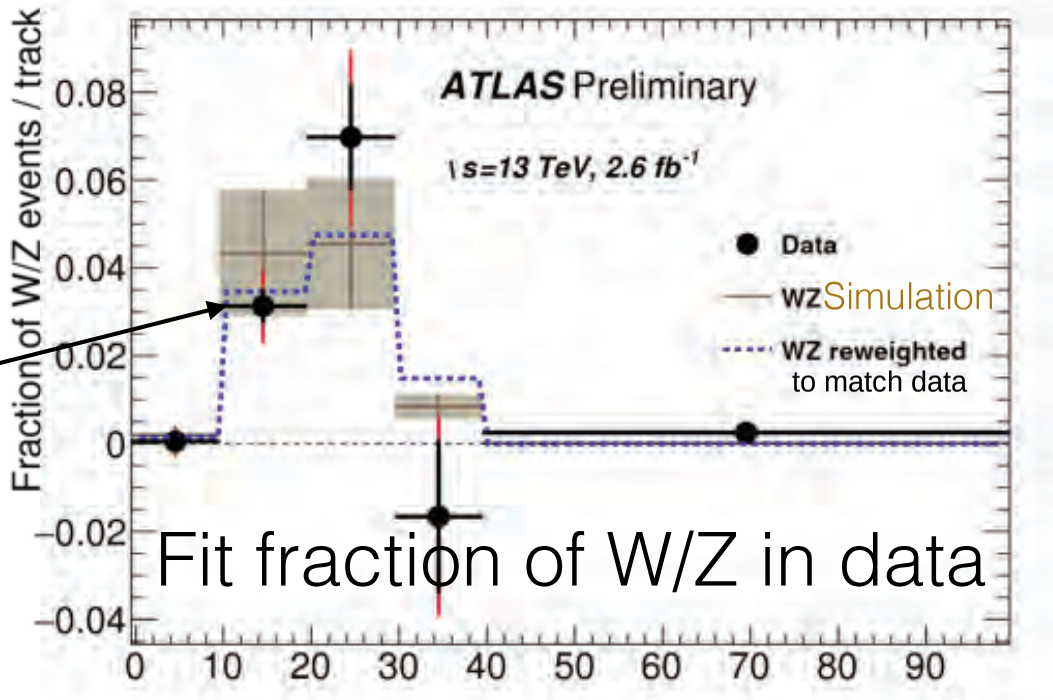
- 2 large R jets, W or Z tagged, ε_{signal}=50%, rej>90%
- N_{track}<30, exploiting bigger track multiplicity in background, ~30% improvement in sensitivity
- efficiency checked in data

ATLAS-CONF-2015-073



Leading jet, D_2 cut

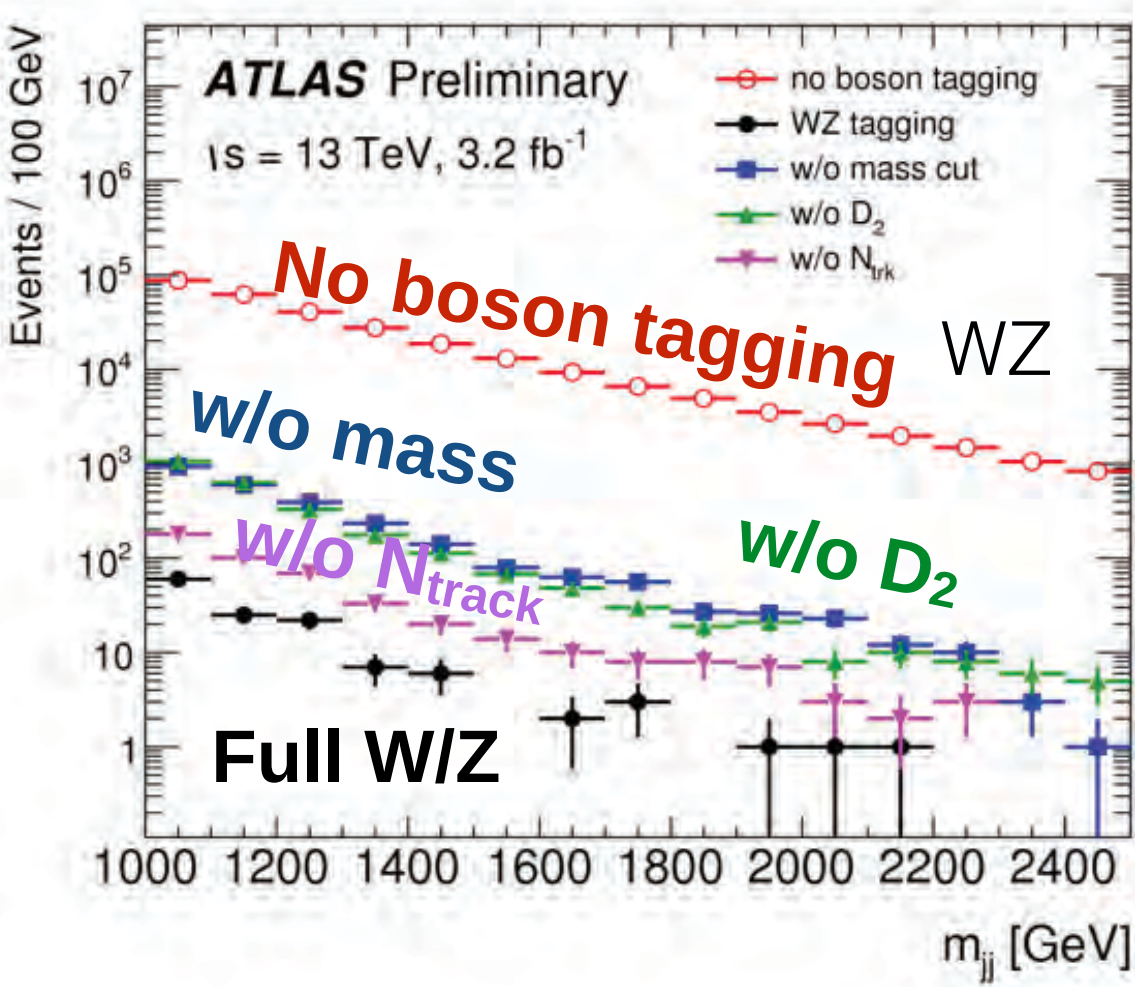
$9<N_{track}<20$

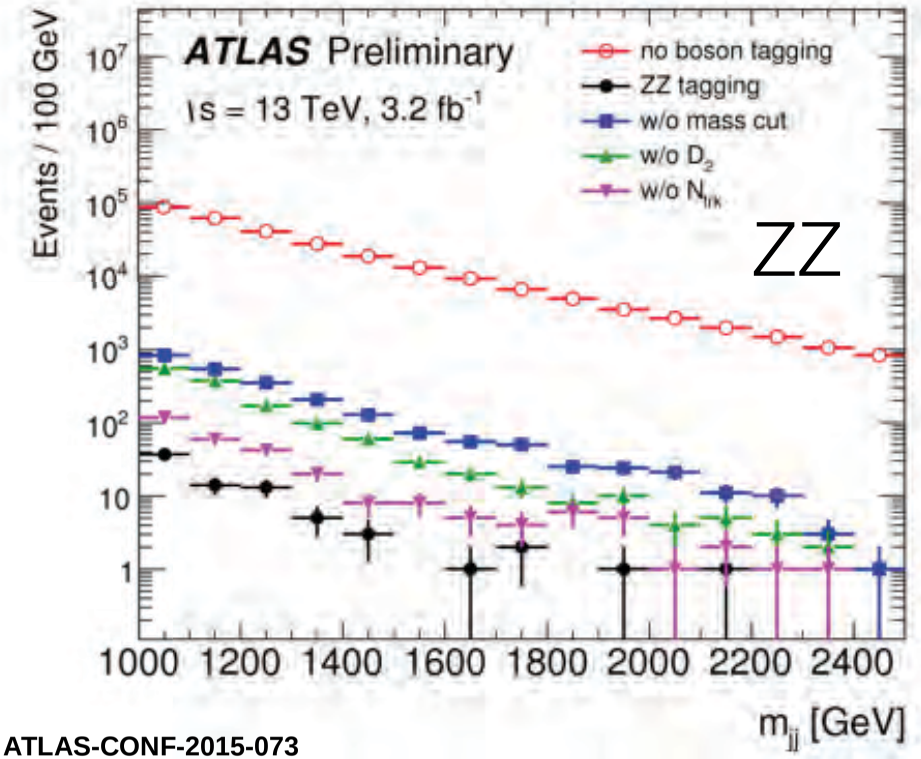


Fit fraction of W/Z in data

- In data lower by 5%+- 6% —> 6% systematic uncertainty

Evolution in data





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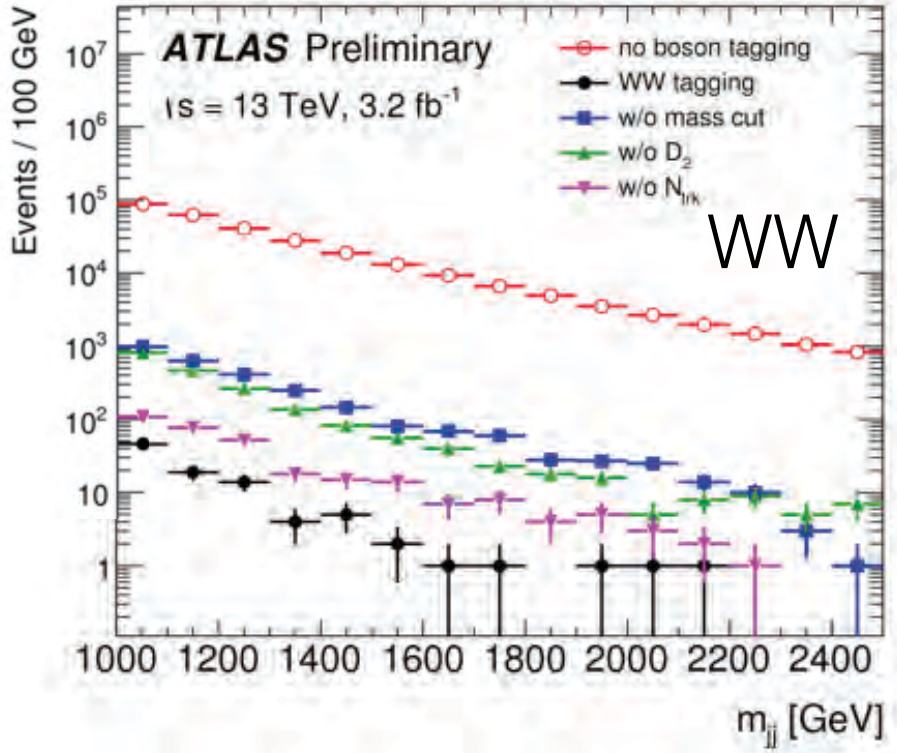
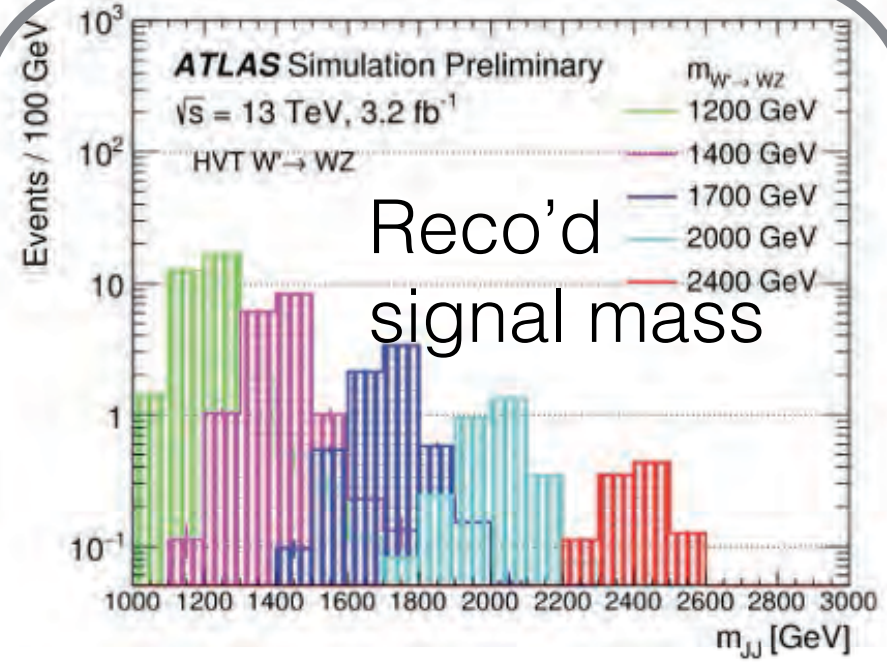
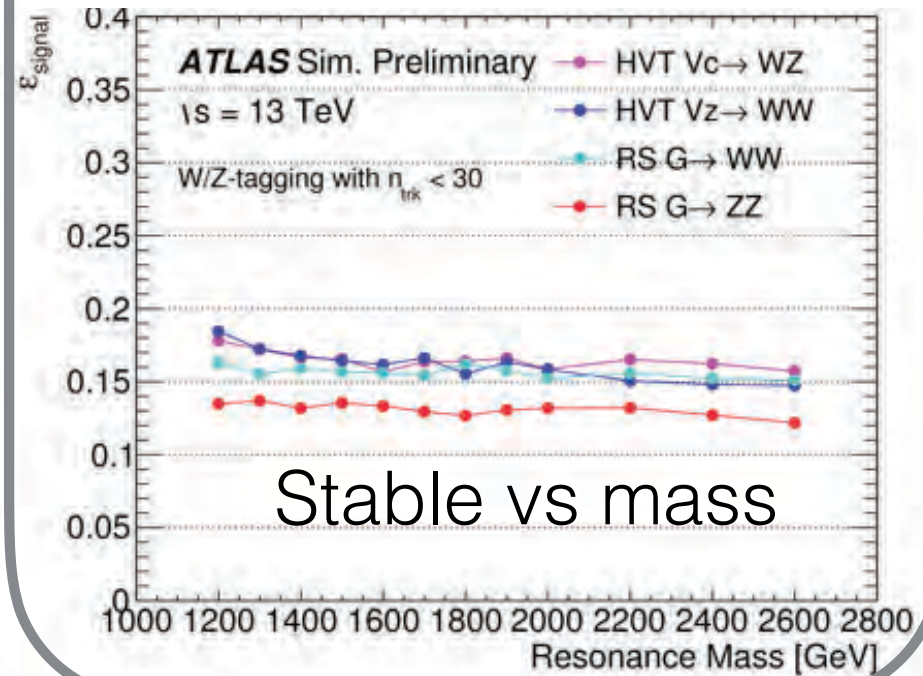


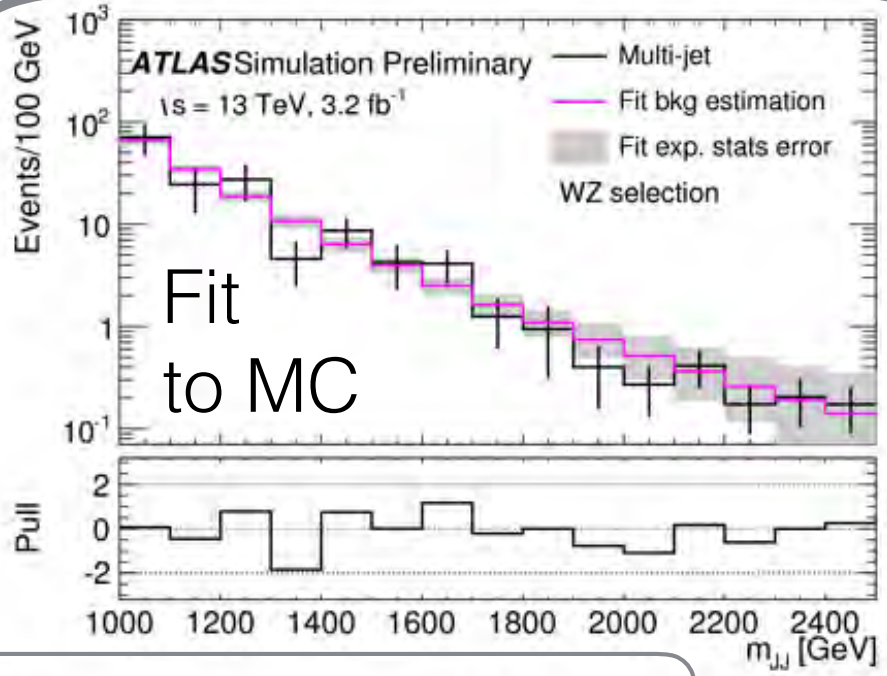
Signal eff. & background fit



Reco'd signal mass



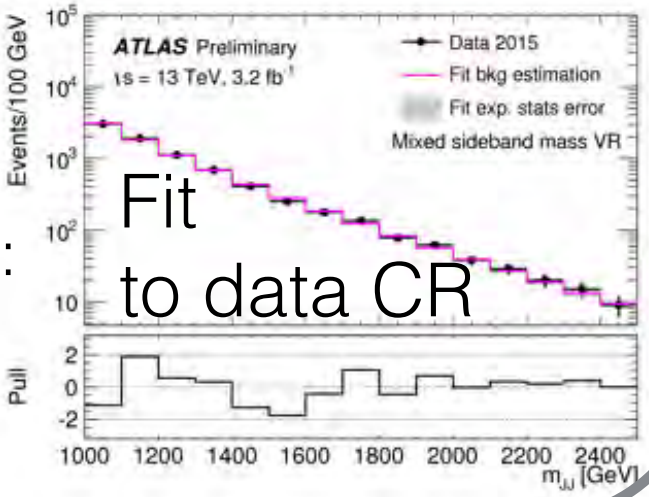
Stable vs mass



Fit to MC

$$\frac{dn}{dx} = p_1(1-x)^{p_2+\xi p_3}\, x^{p_3} \qquad x = m_{JJ}/\sqrt{s}$$

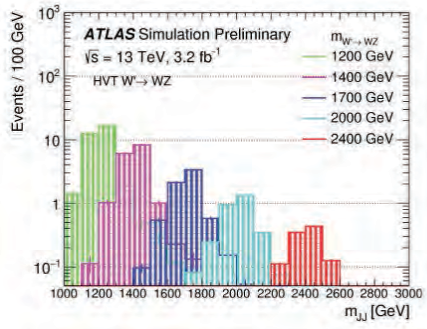
Low/high m_J control region:



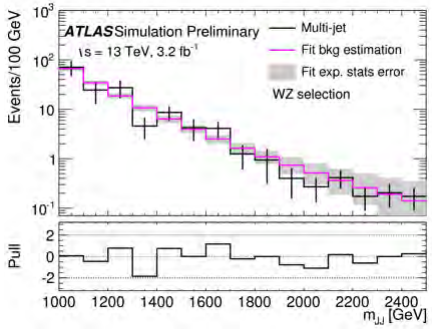
Fit to data CR

Putting it all together

ATLAS-CONF-2015-073



+



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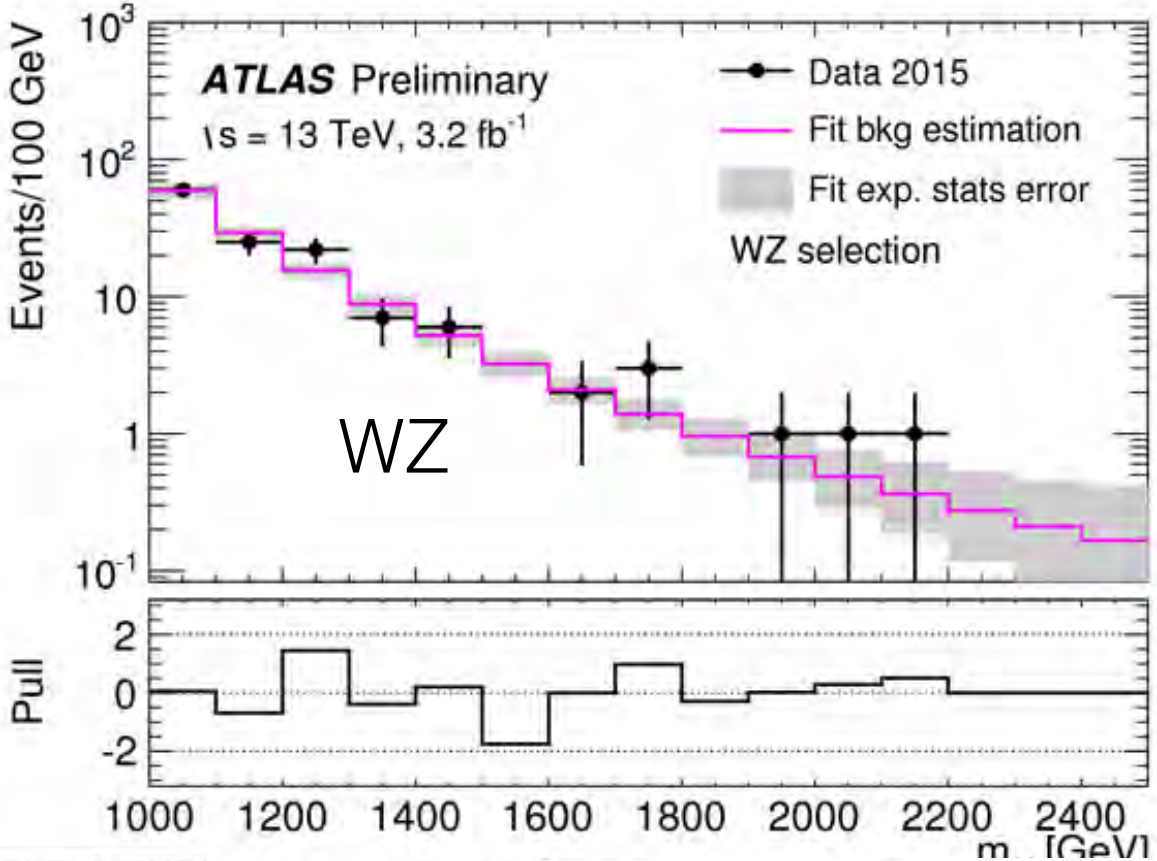
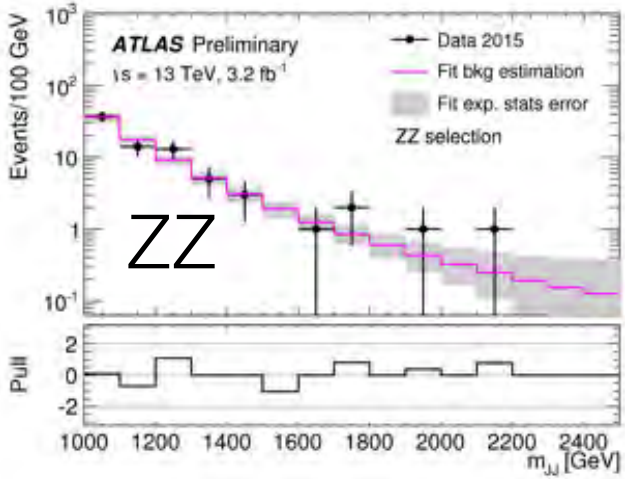
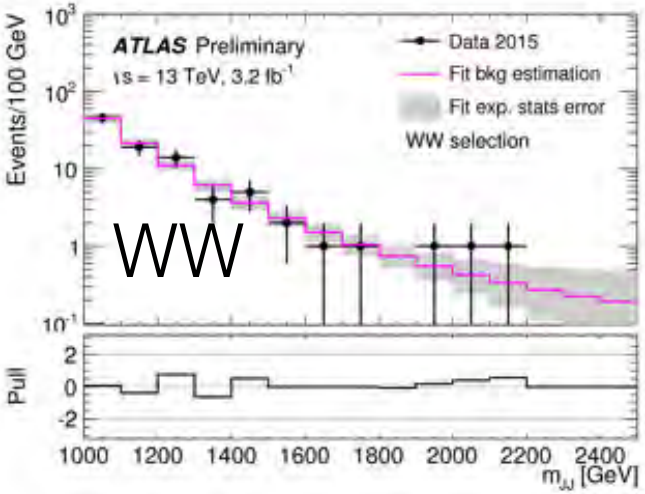
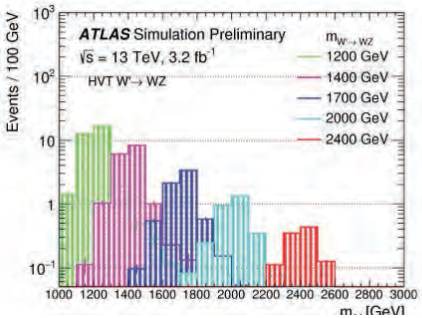


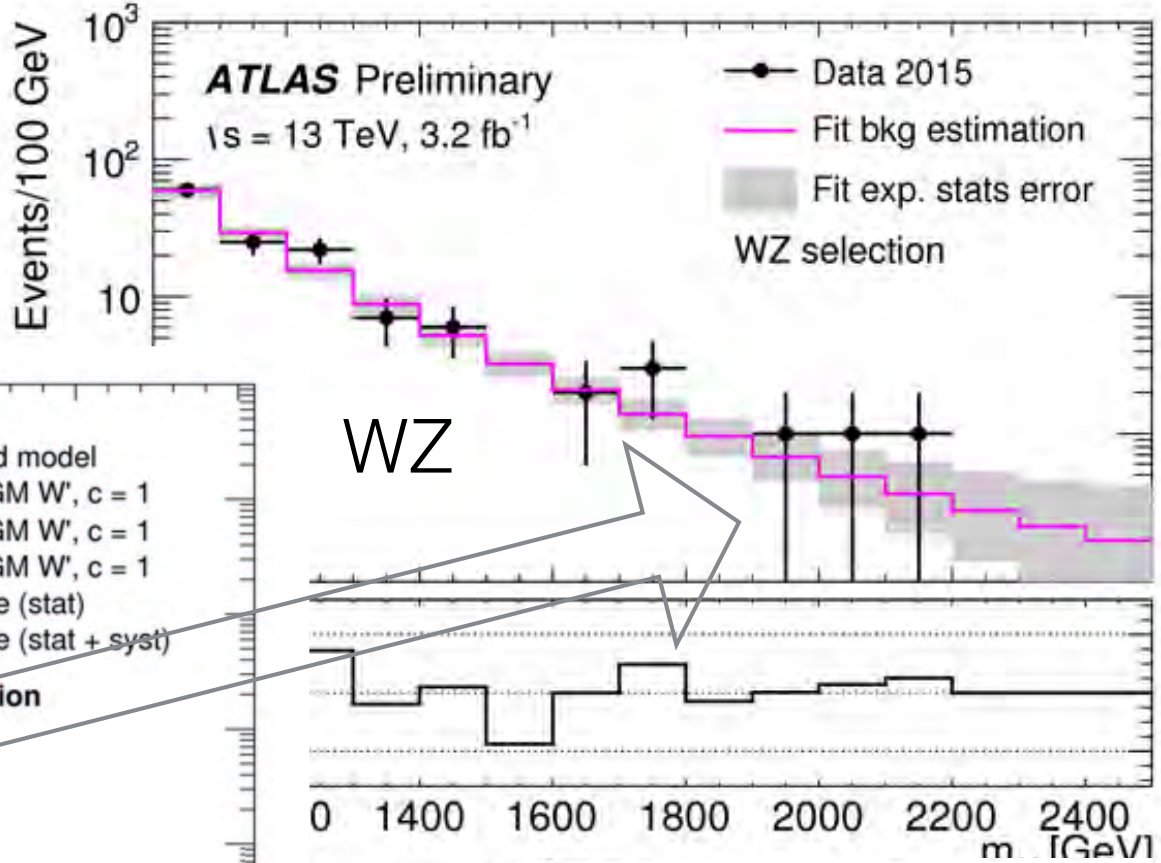


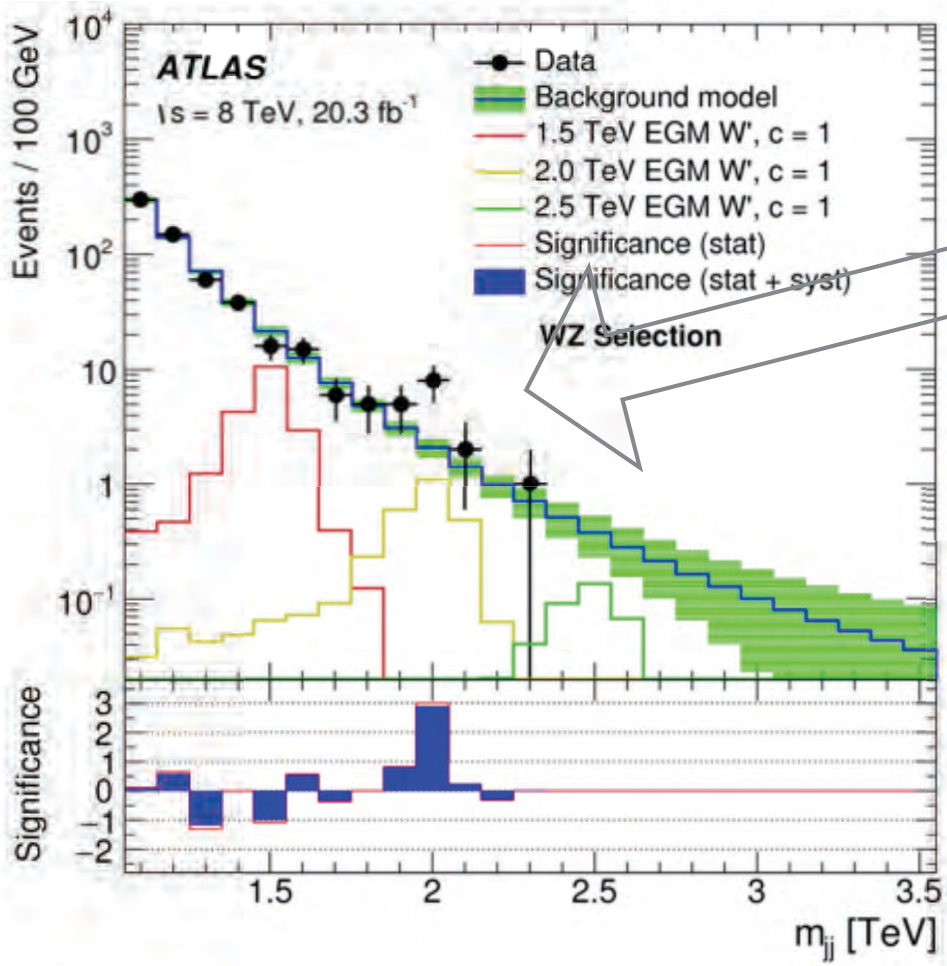


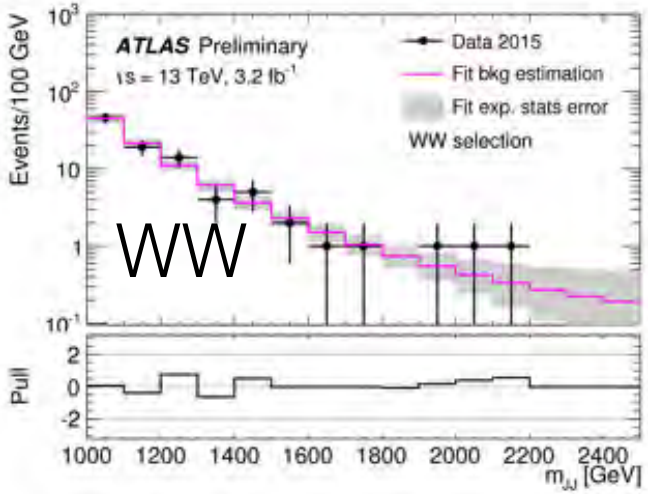
Putting it all together

ATLAS-CONF-2015-073

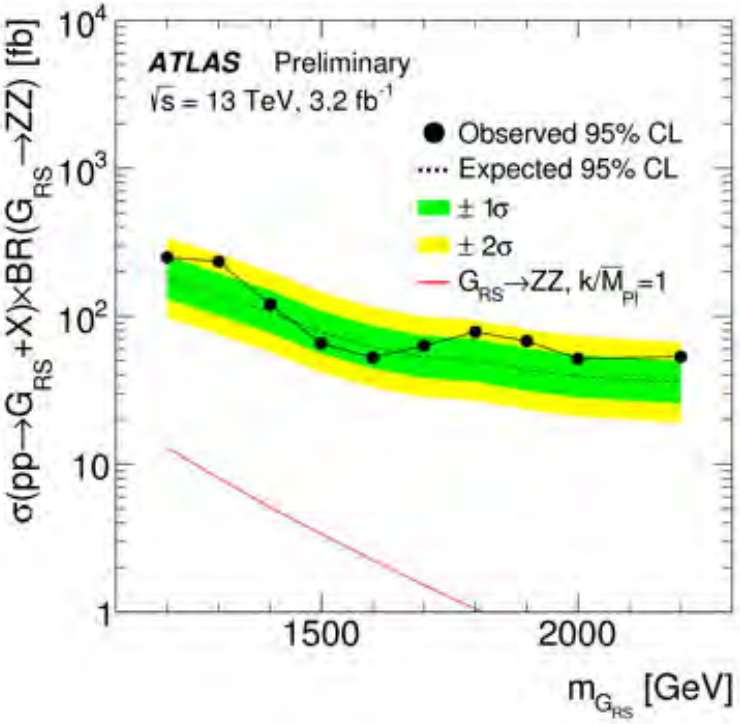


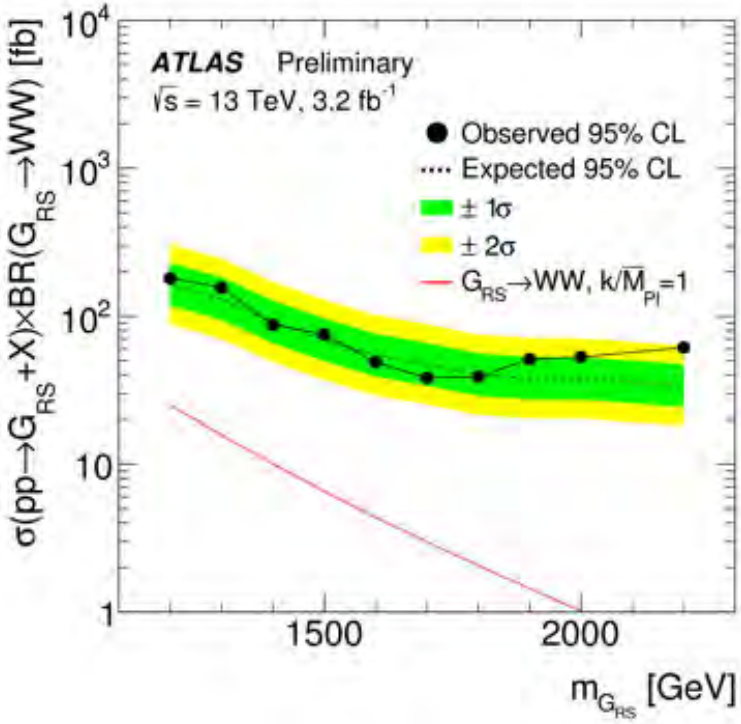






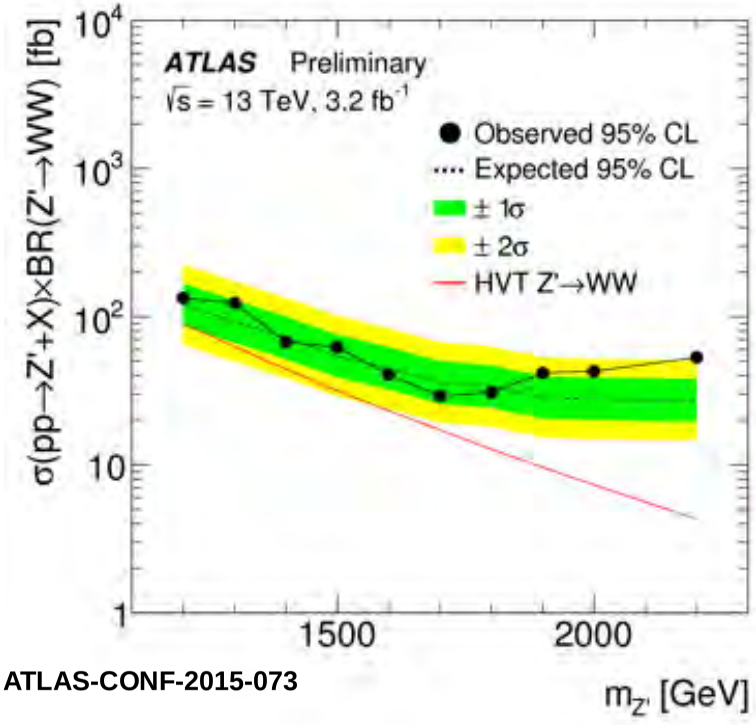
Limits

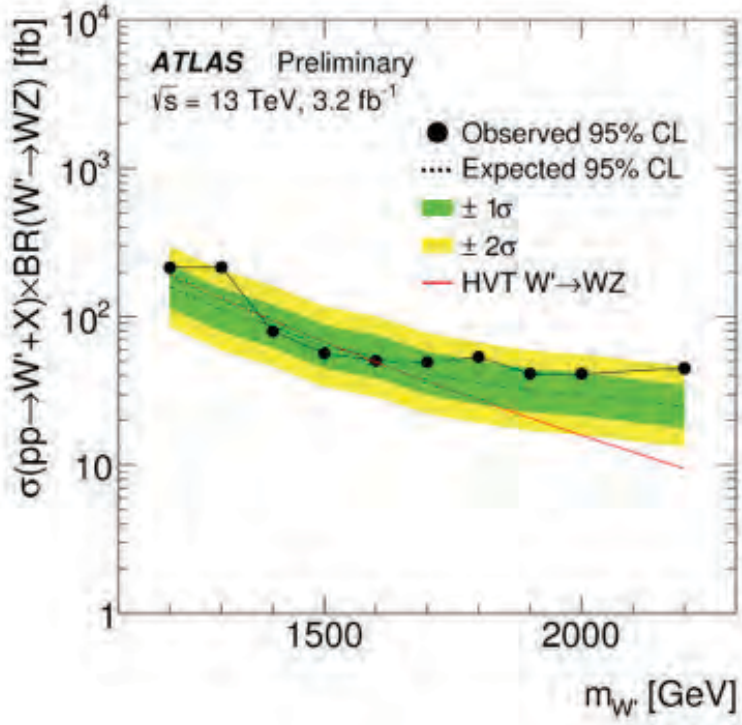




Run 1 excess not excluded

Need more data

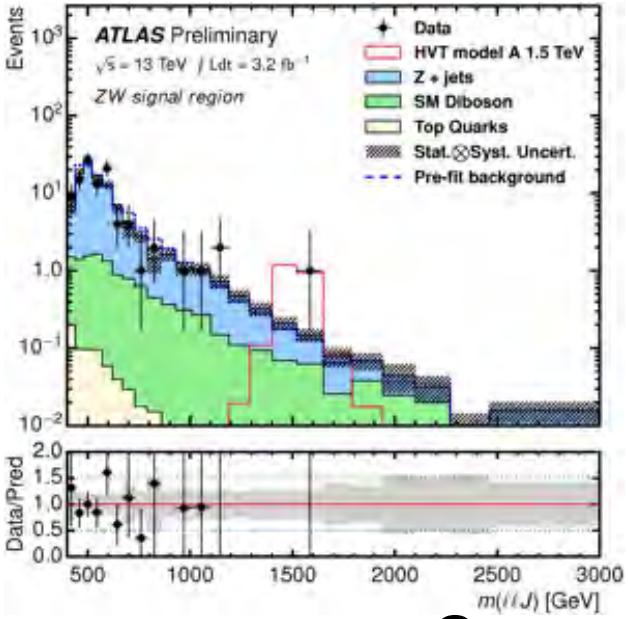




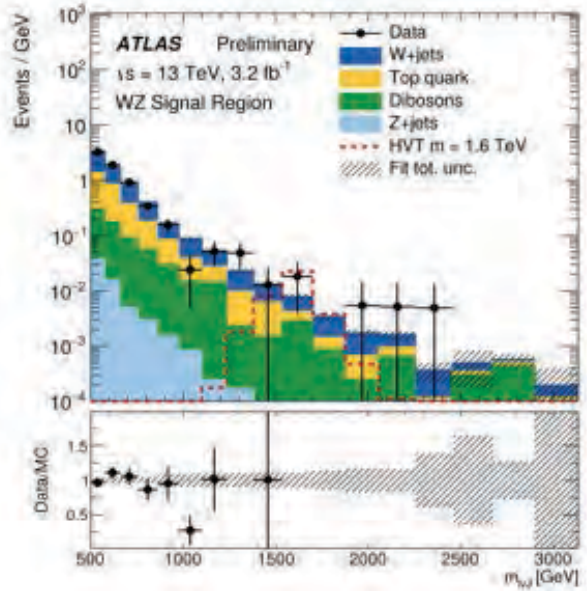
ATLAS-CONF-2015-073

The other channels

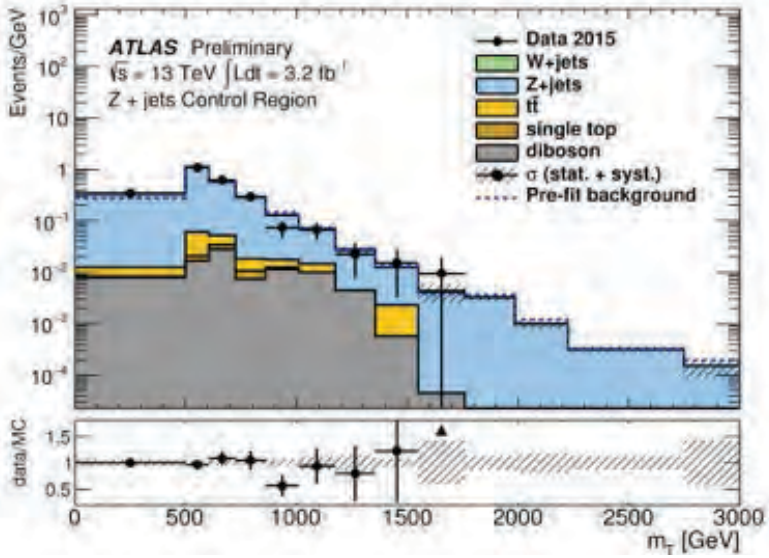
J ll



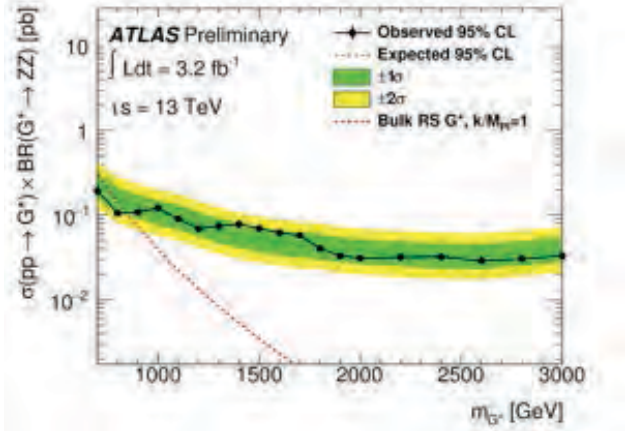
J lν



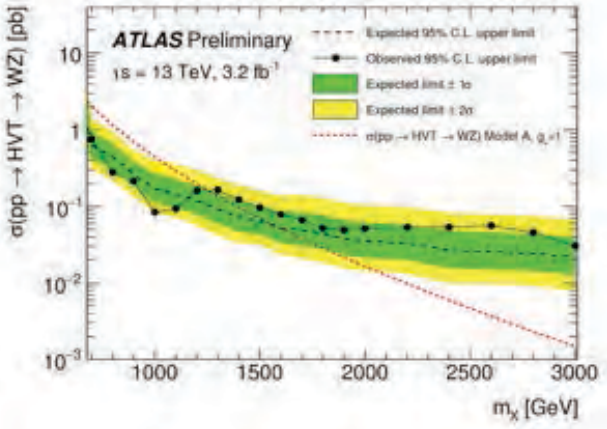
J νν



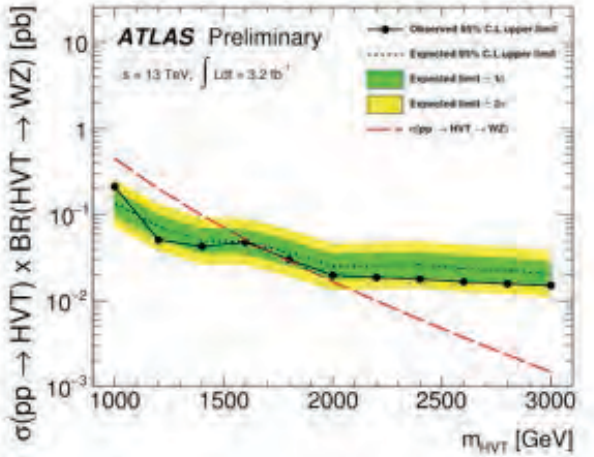
Same conclusion —> Need more data!



ATLAS-CONF-2015-071

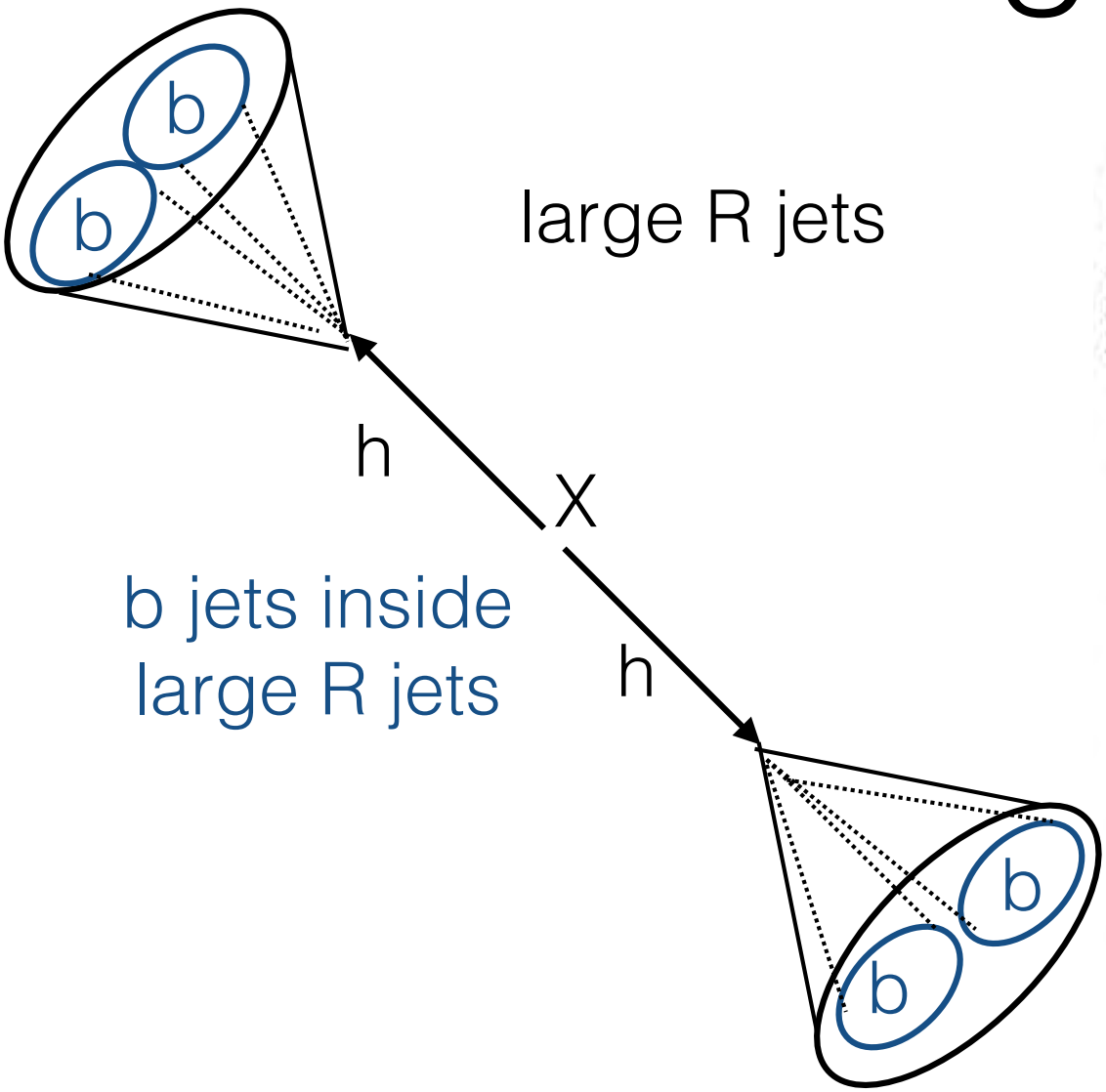


ATLAS-CONF-2015-075



ATLAS-CONF-2015-068

Boosted Higgs bosons

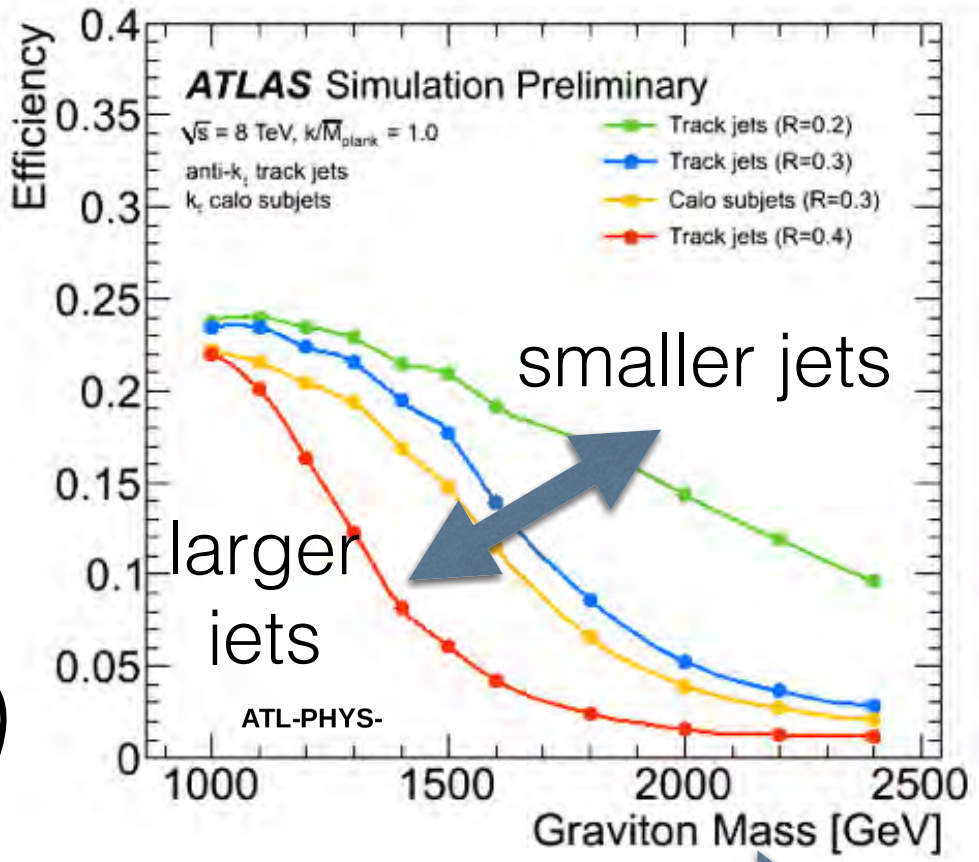


large R jets

b jets inside large R jets

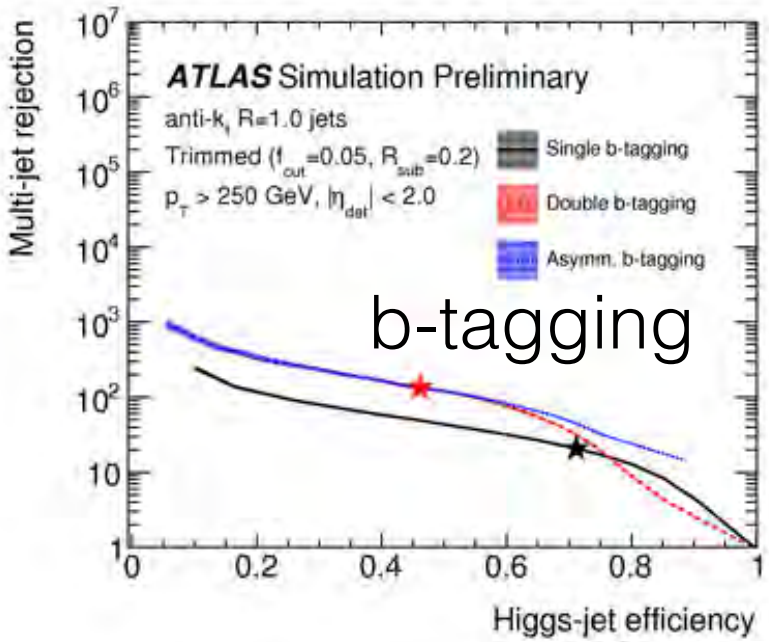
match small (R=0.2) b-tagged track jets to large R jets

RSG—>hh—>4b



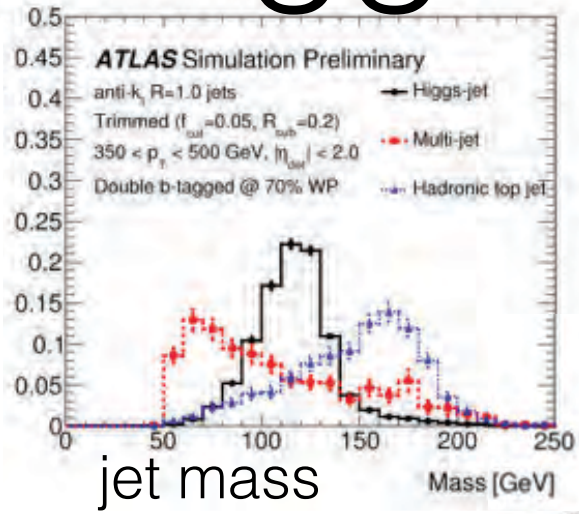
Higgs boson tagging

New in Run 2



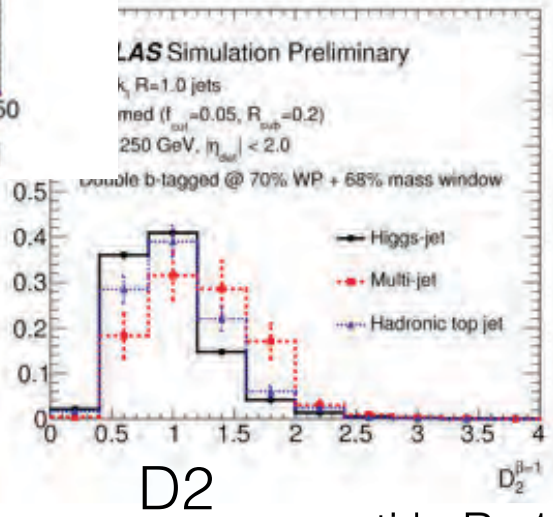
b-tagging

+



jet mass

Jet substructure

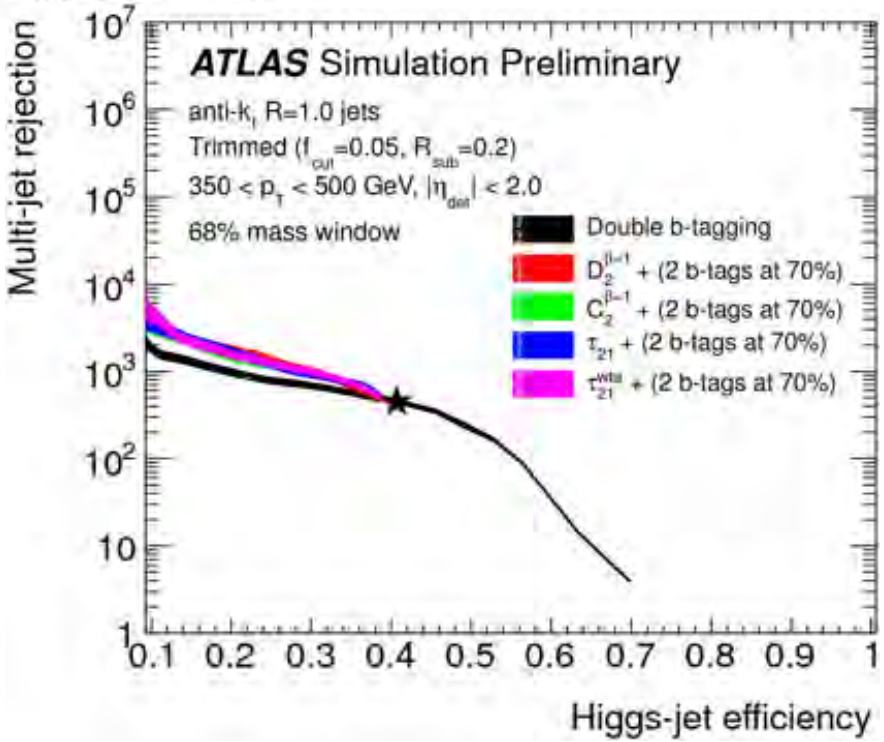


D2

anti k_T R=1.0
R_{sub}=0.2
f_{cut}=5%

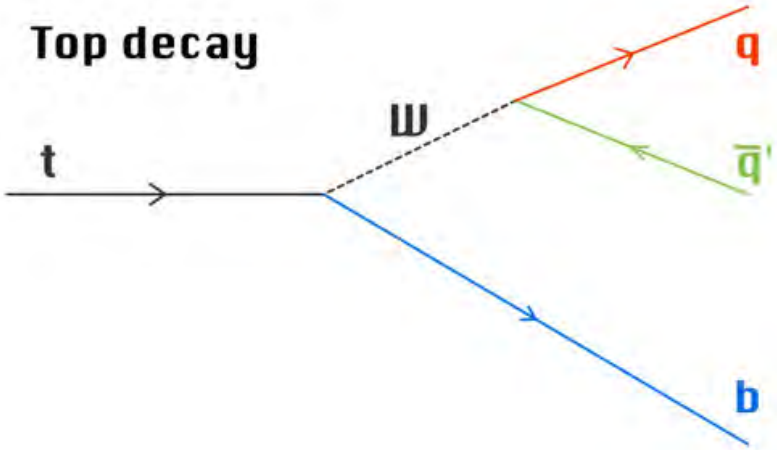
ATL-PHYS-PUB-2015-035

=



Most discrimination from b-tagging, but JSS can help.

Back to the original fat jets

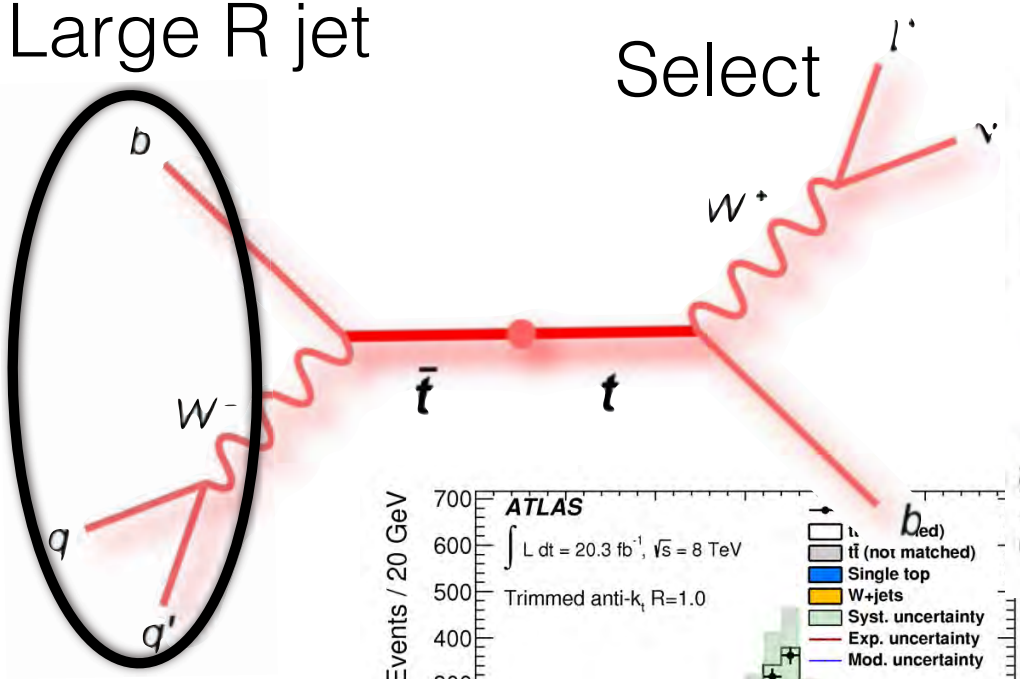


Top tagging

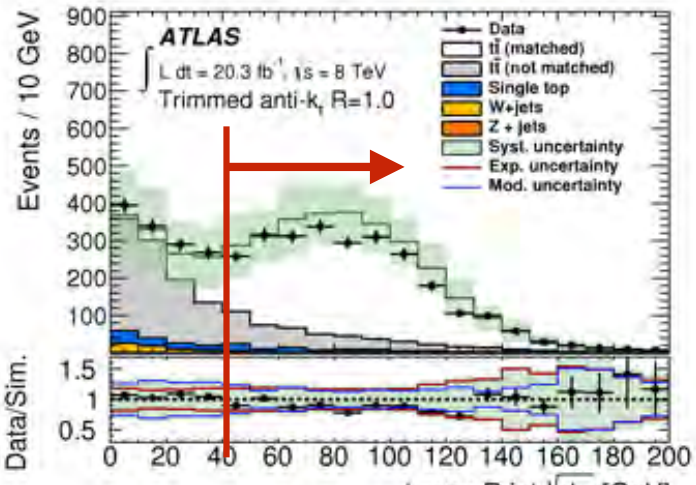
- Simple taggers possible as for boson tagging
- Top decays have a few more handles
- There are more advanced taggers on the market

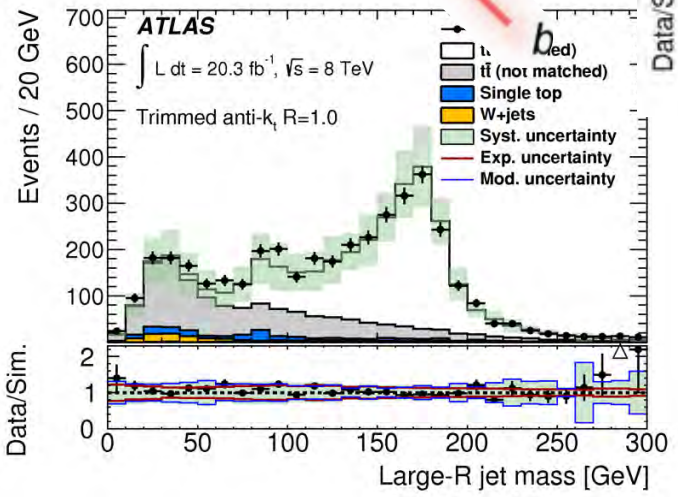
Large R jet

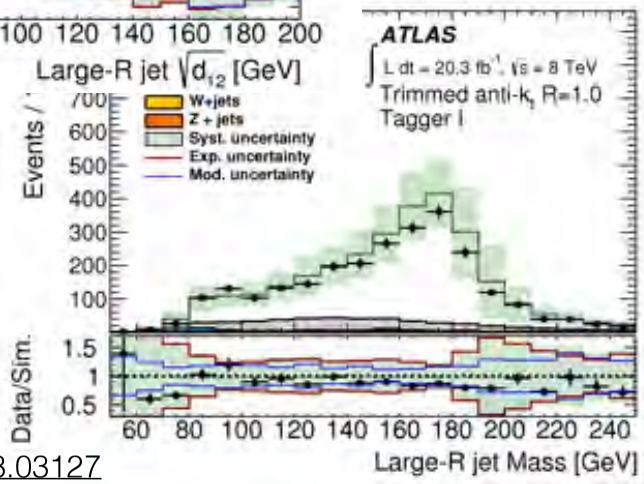
Select



Simple tagger example:





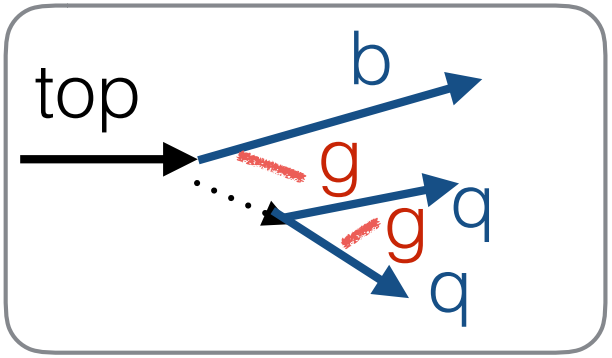


http://arxiv.org/abs/1603.03127

Adv. Tagger Example: HEPTopTagger

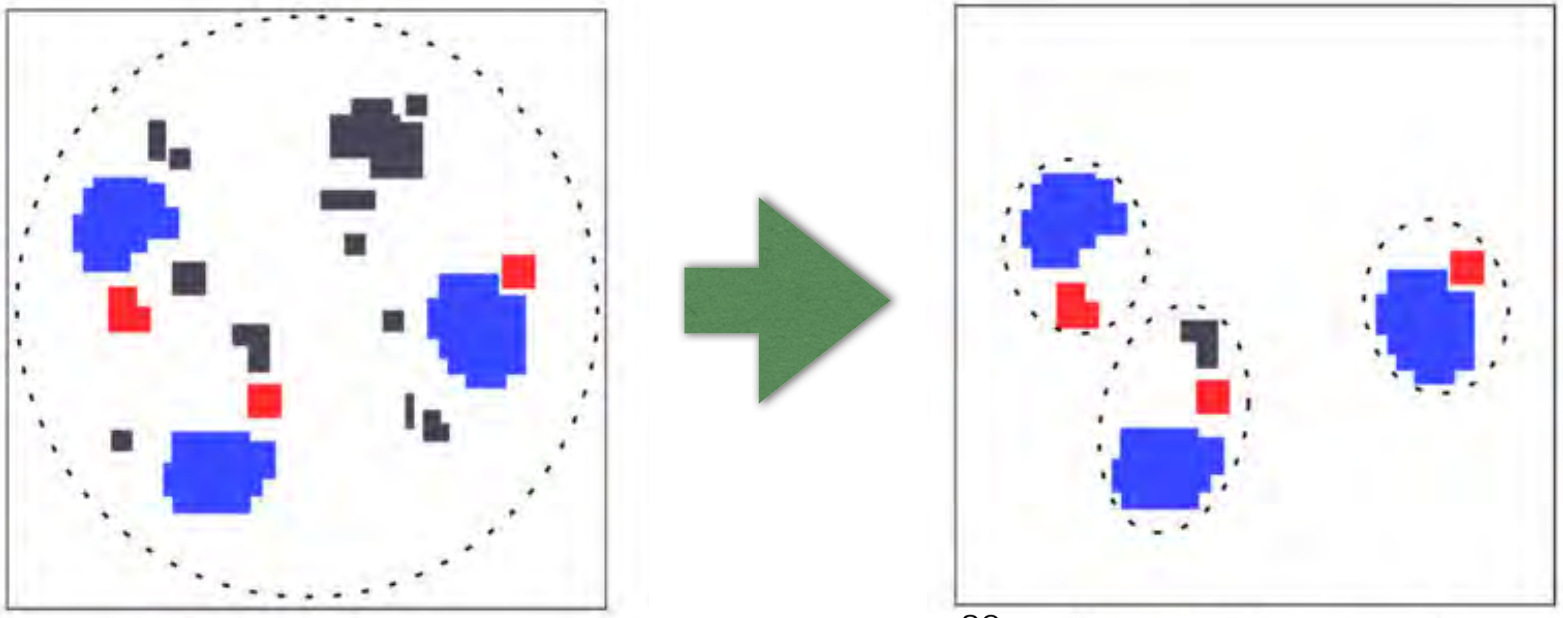
JHEP 1010 (2010) 078

- Identify top to hadron decays with p_T^{top}>200GeV
- Use Cambridge/Aachen R=1.5 jets and their substructure
- Filter against pile-up
- Identify top quarks via mass ratios



C/A R=1.5

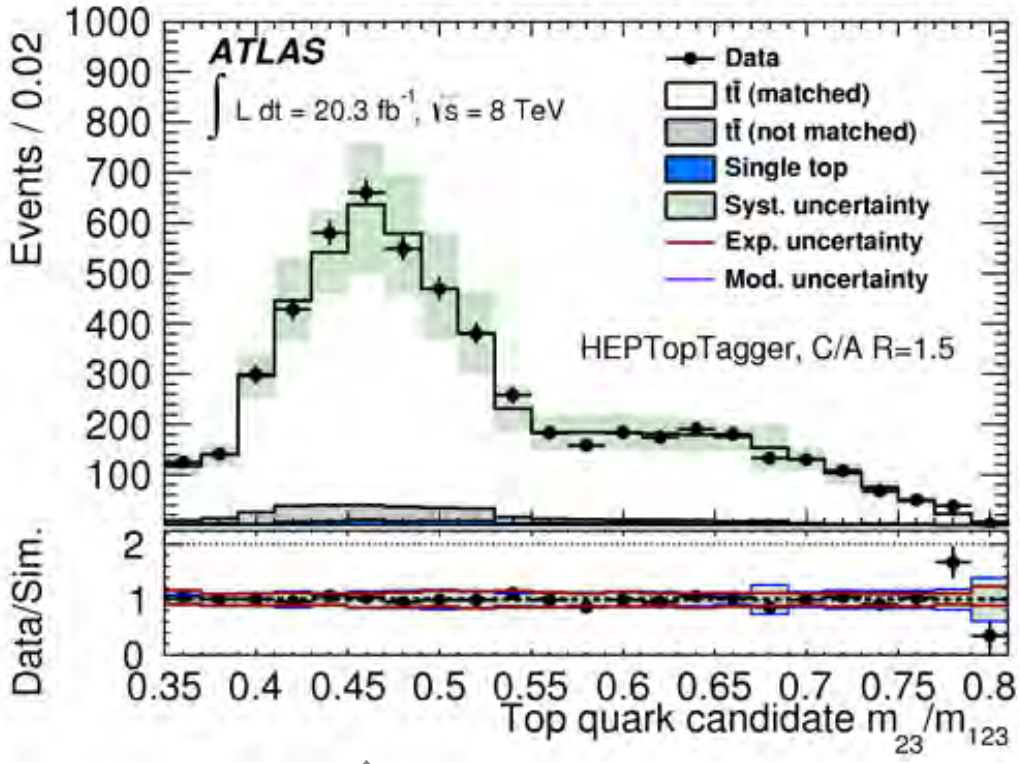
top candidate



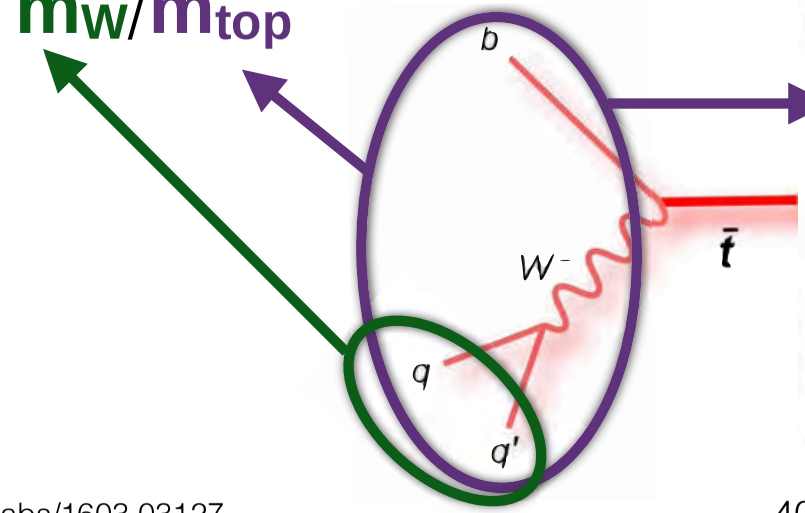
Pictures G. Kasieczka

HEPTopTagger in lep+ jet data

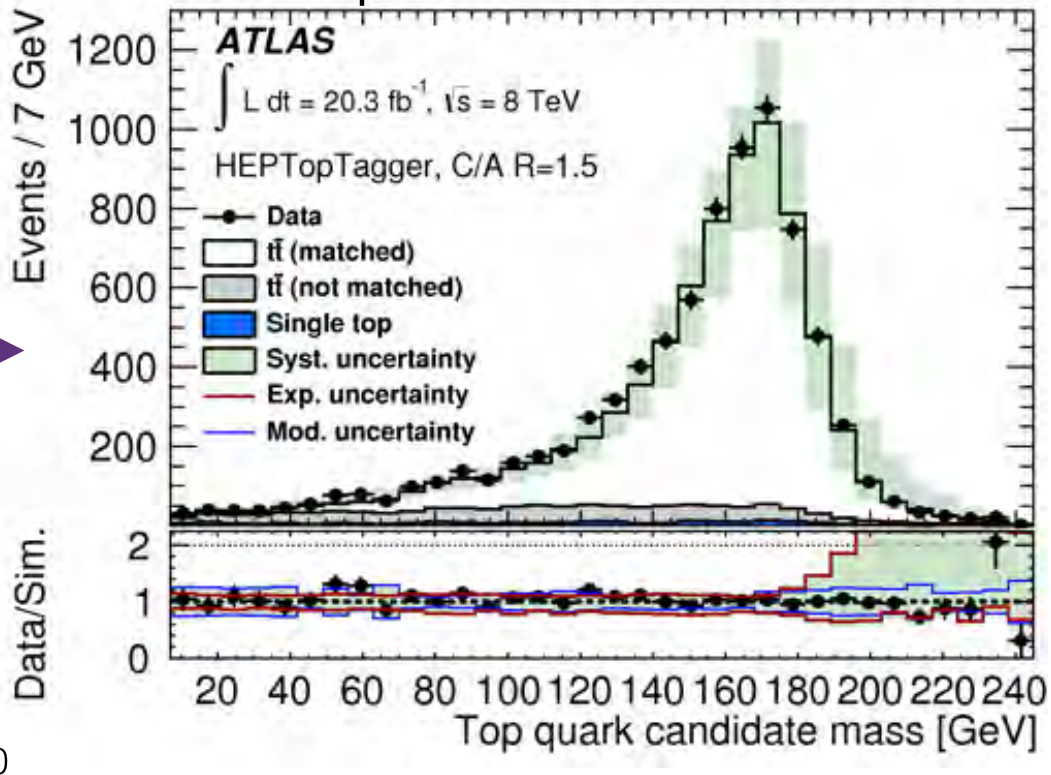
$$= \frac{\text{m(subjet 2 and 3)}}{\text{m(subjet 1, 2 and 3)}}$$



m_W/m_{top}



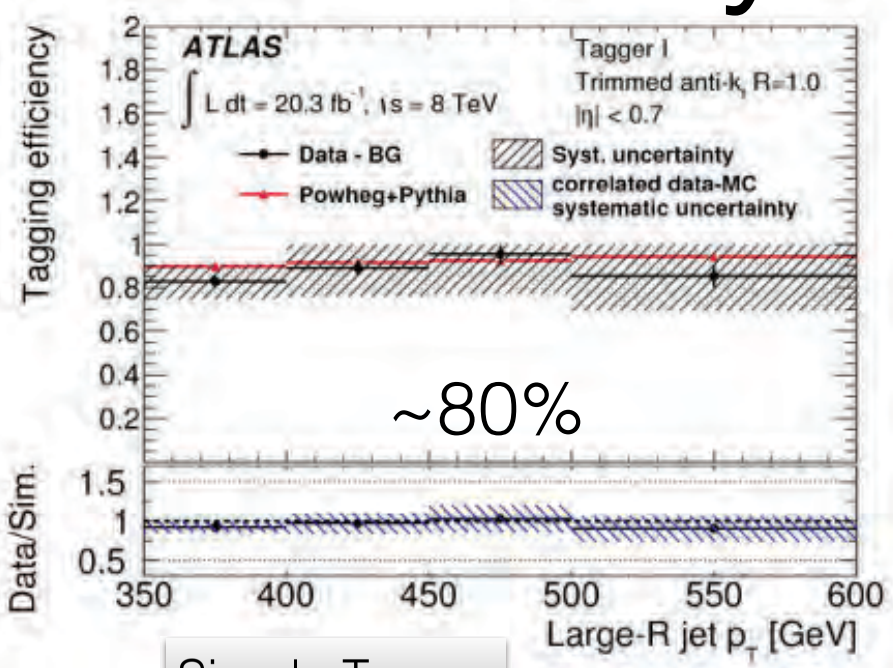
top candidate mass



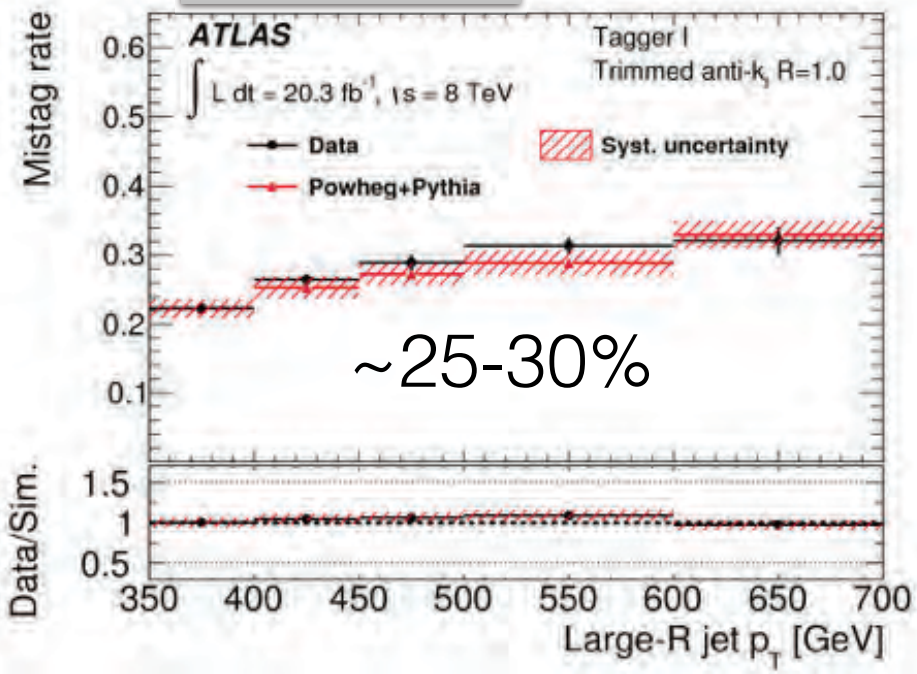
http://arxiv.org/abs/1603.03127

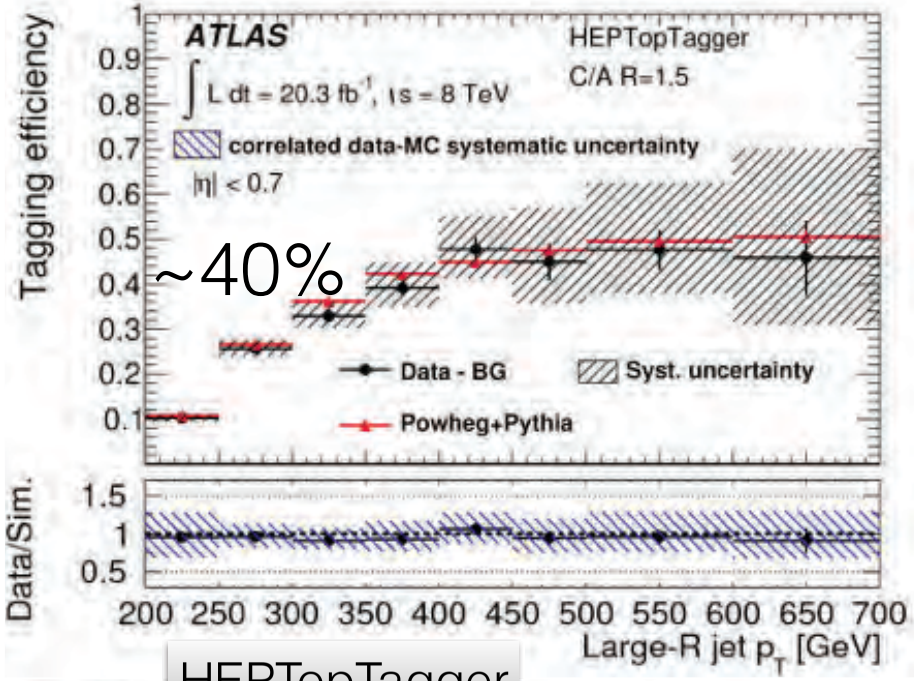
http://arxiv.org/abs/1603.03127

Efficiency measurement

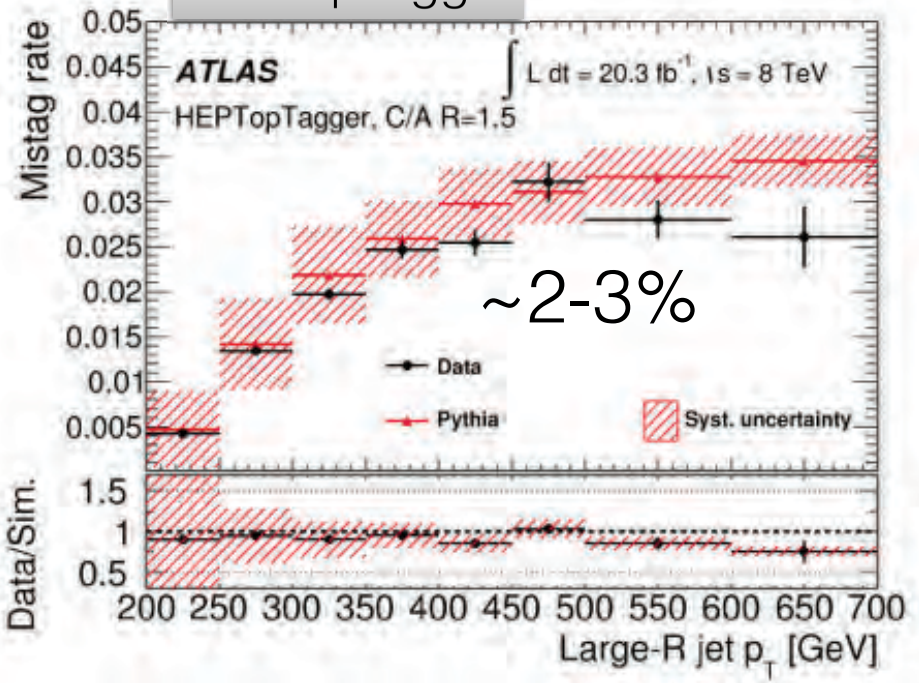


Simple Tagger



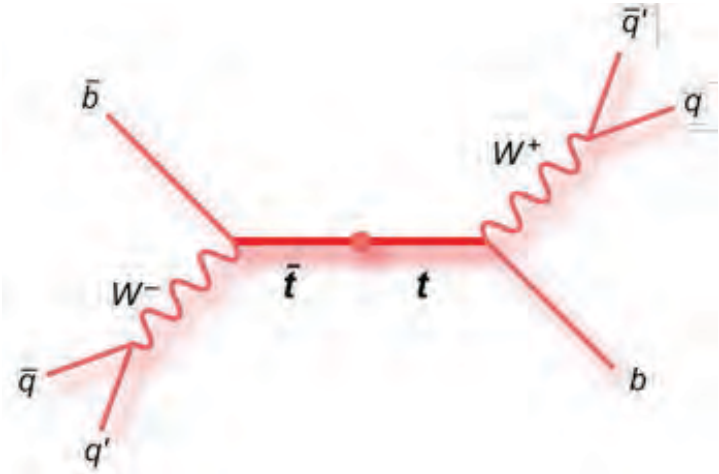


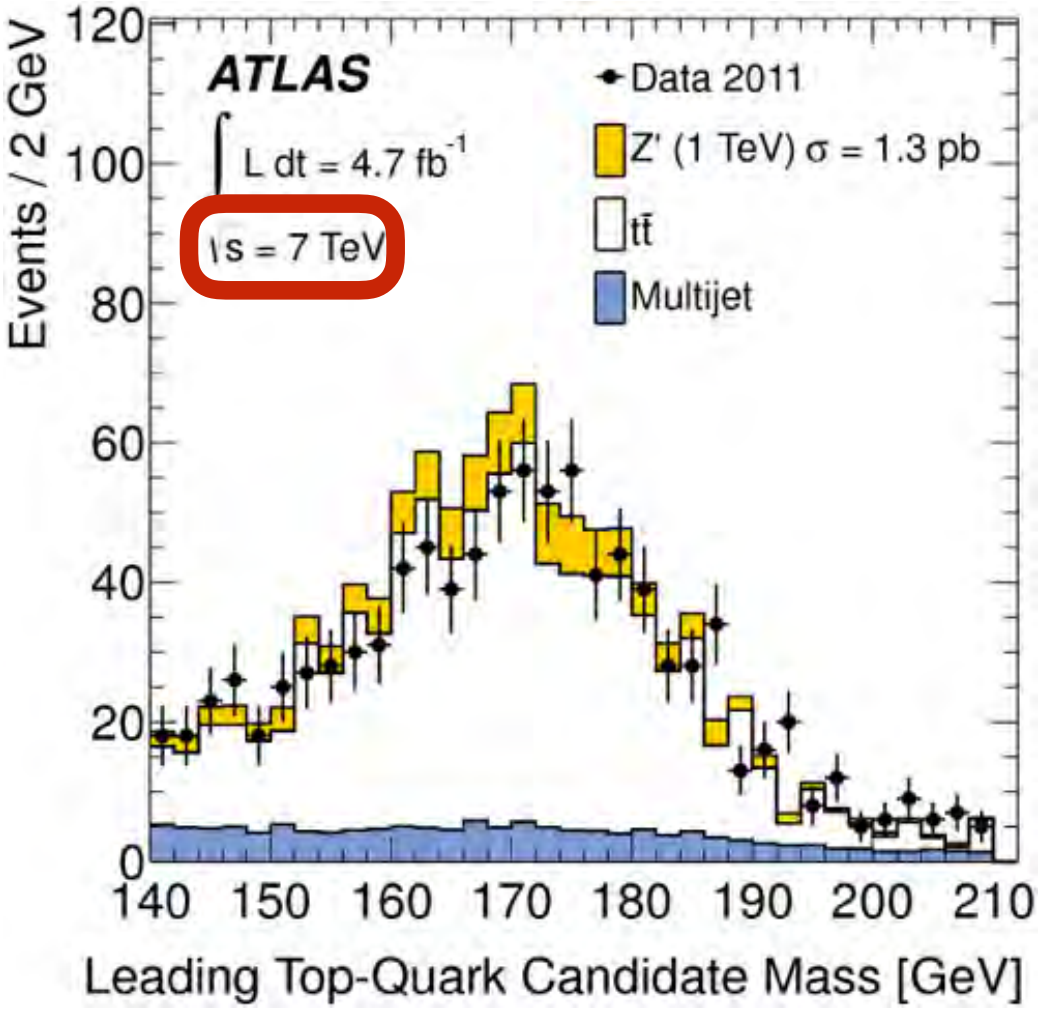
HEPTopTagger

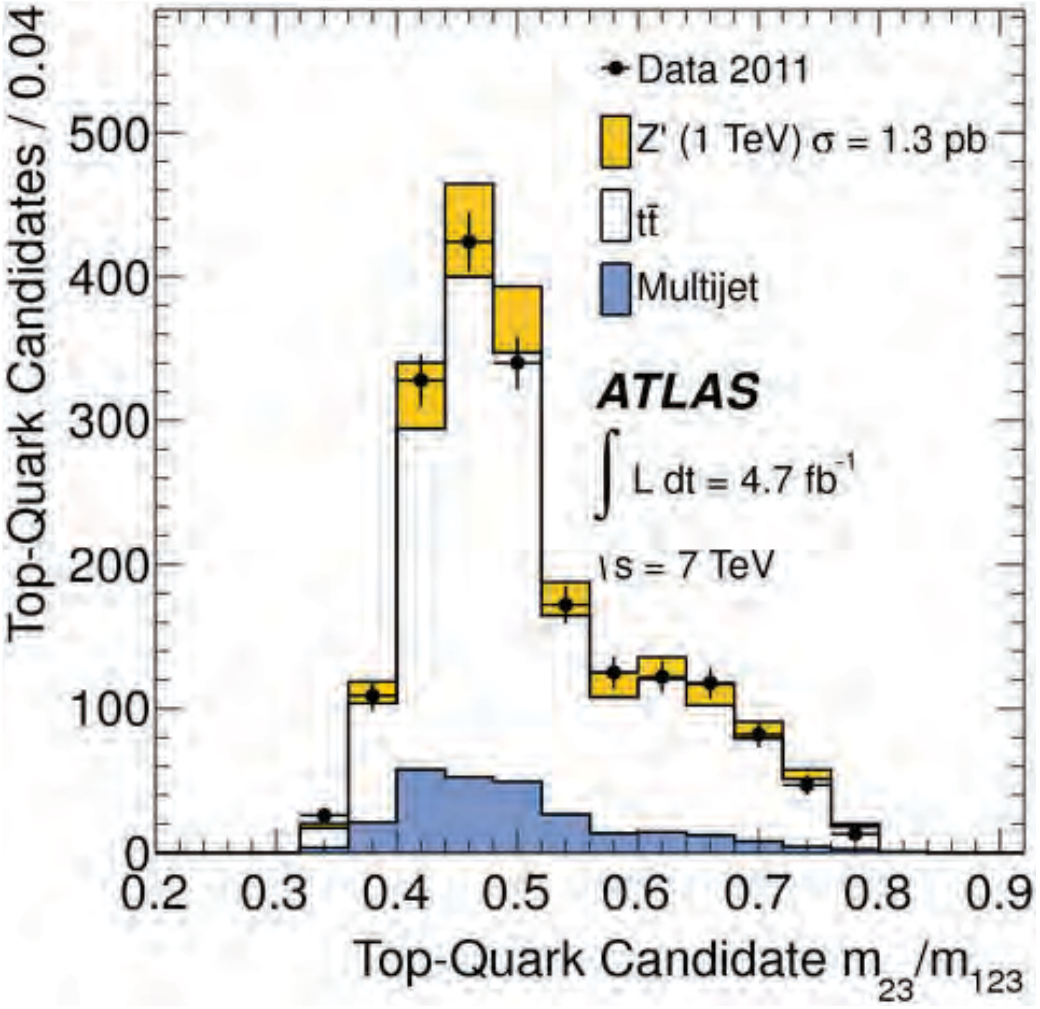


Fully hadronic $t\bar{t}$ resonance search

Lots of non top background (QCD)







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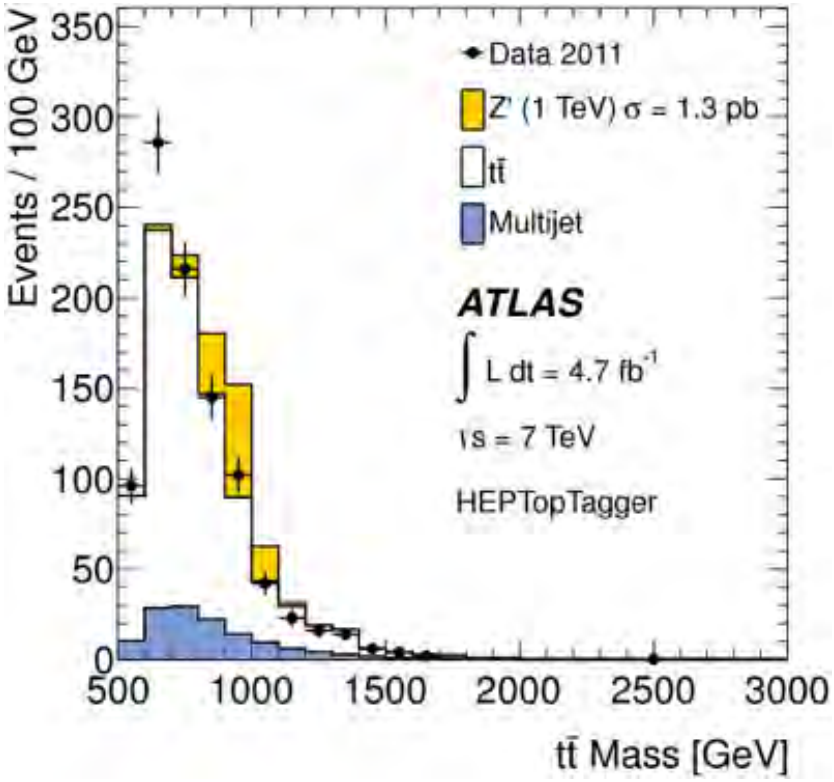
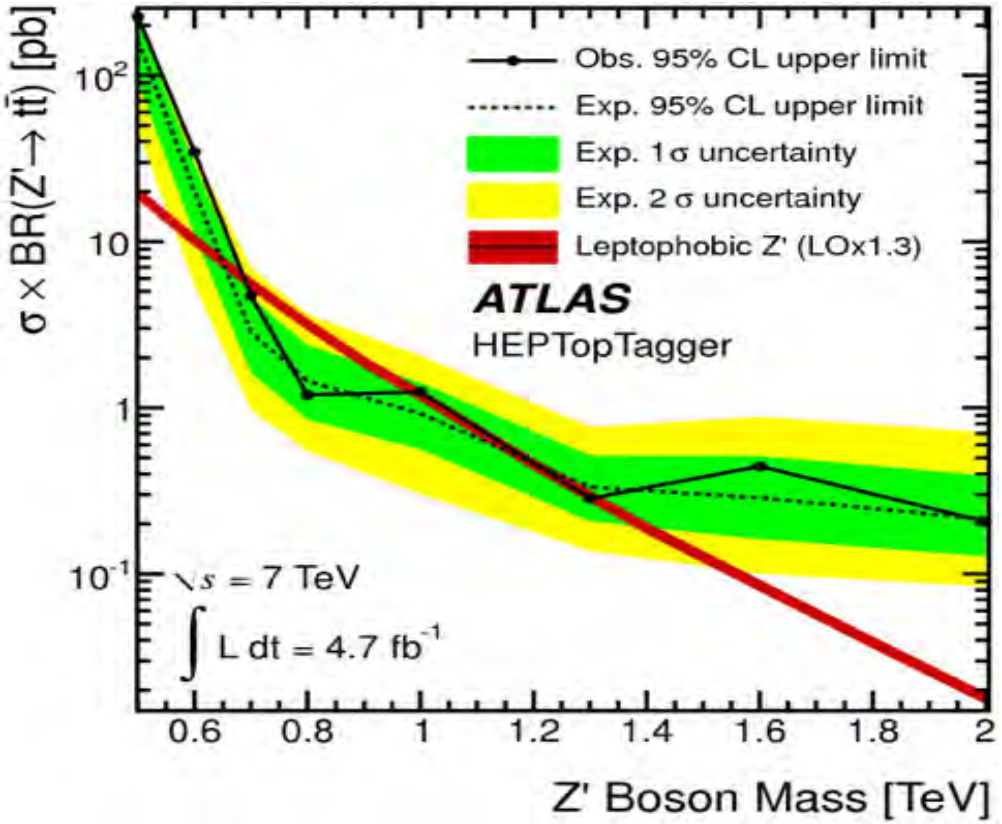
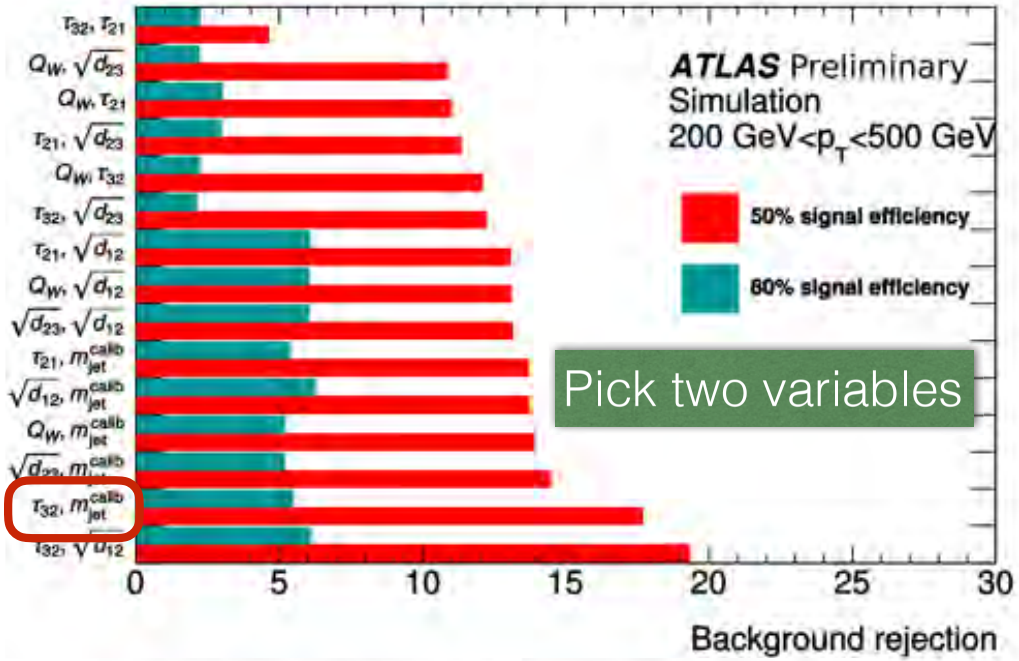
Fully hadronic $t\bar{t}$ resonance search (Run 1)

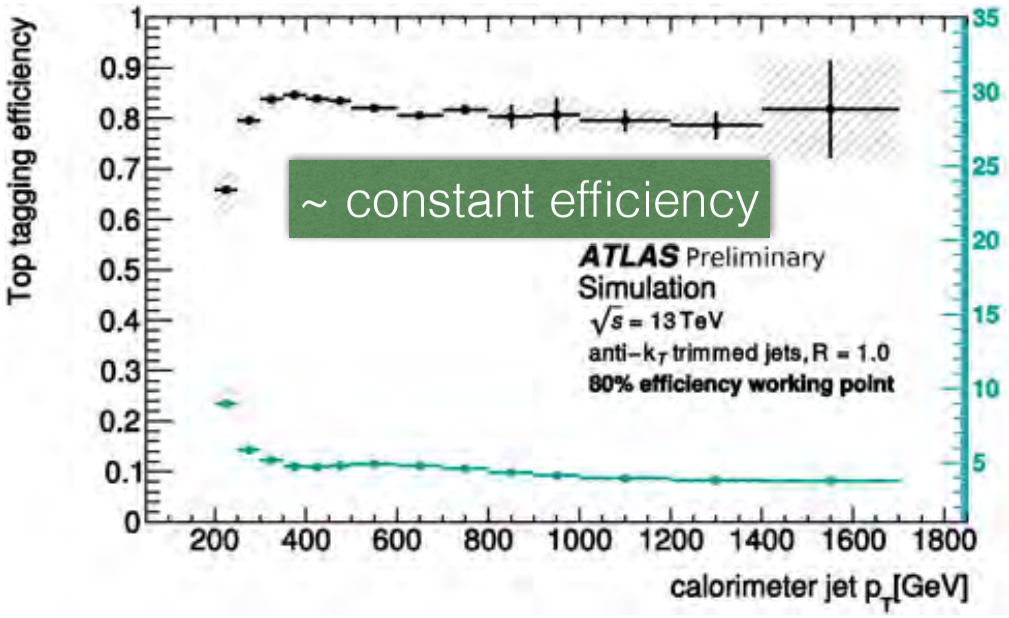


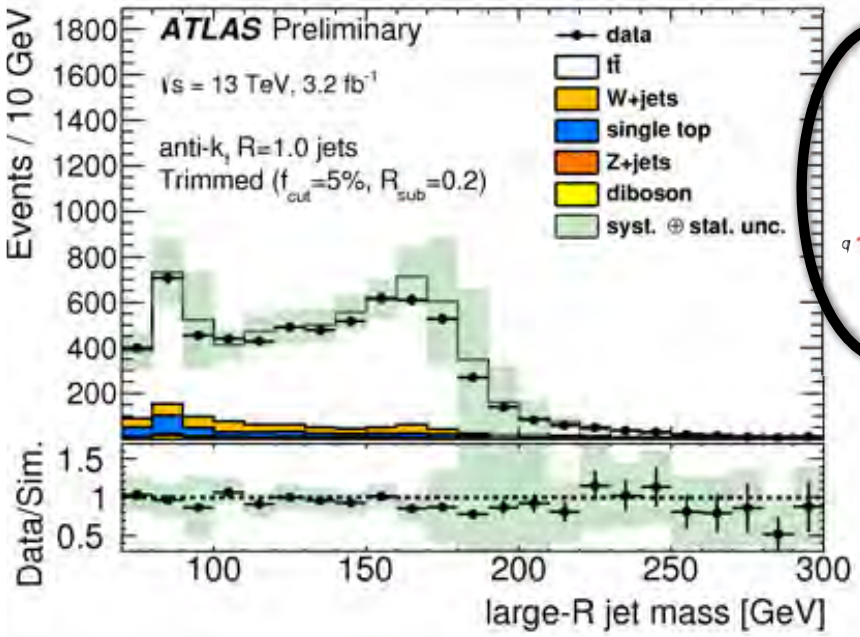


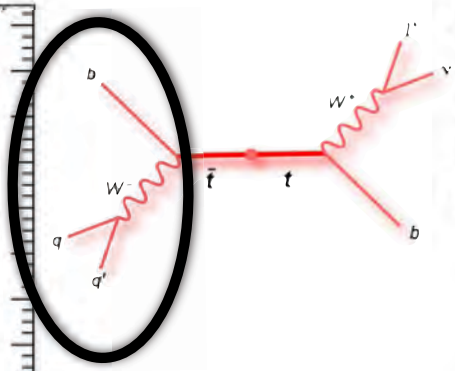
It works!

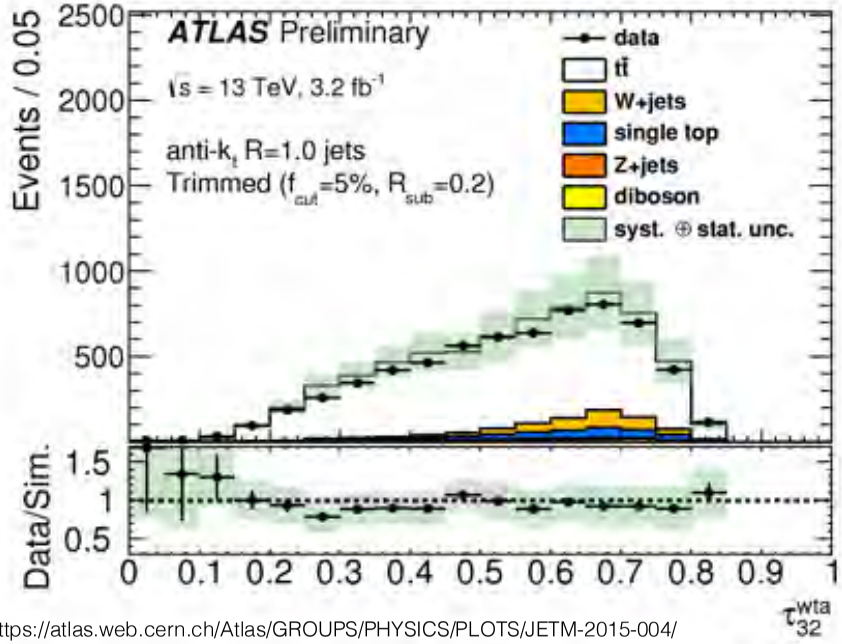
Run 2 top tagging





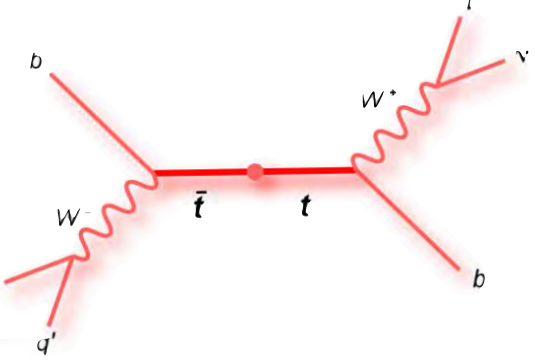


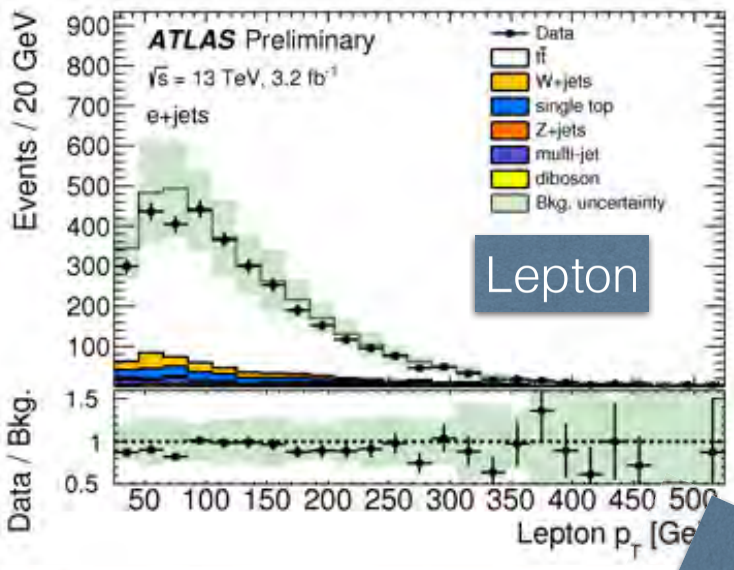


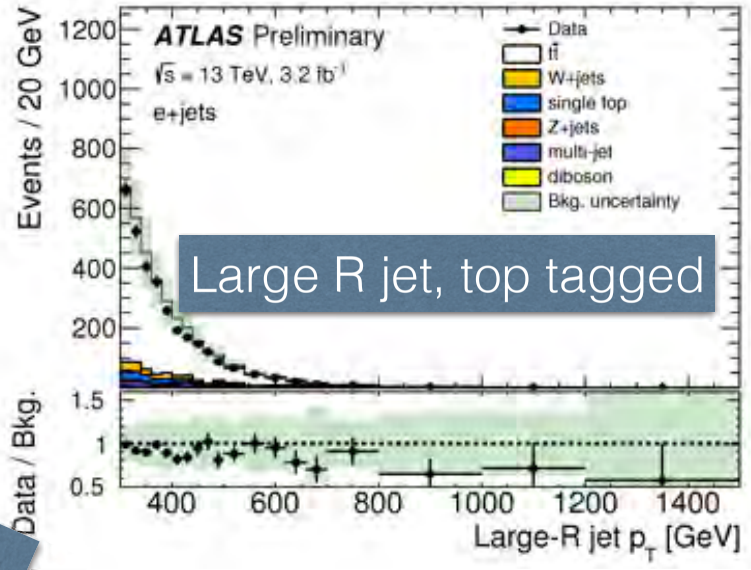


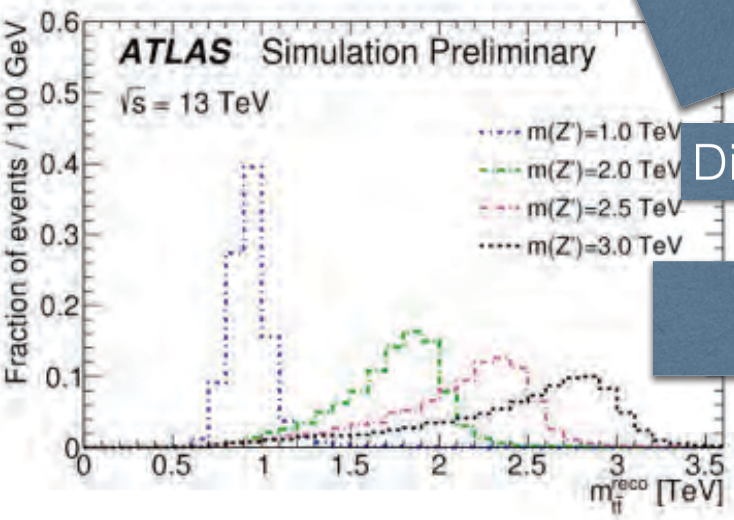
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2015-004/

$t\bar{t}$ resonance search in lepton+jet events (Run2)

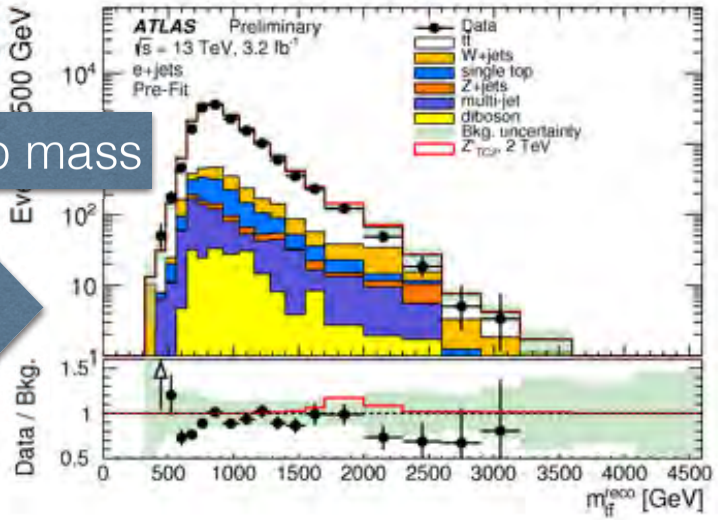








Di-top mass



main background contains top quarks

⇩

high efficiency wanted! (comes with low rejection)

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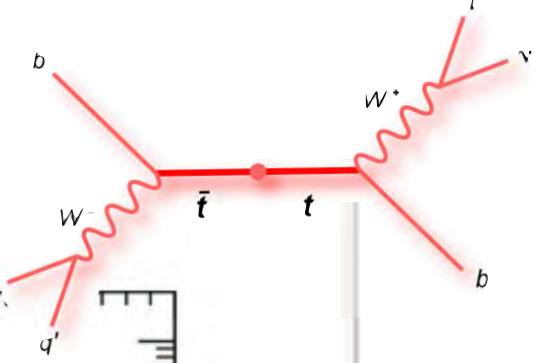
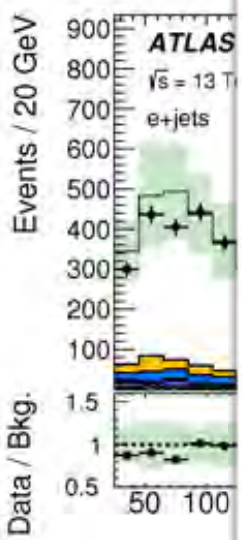
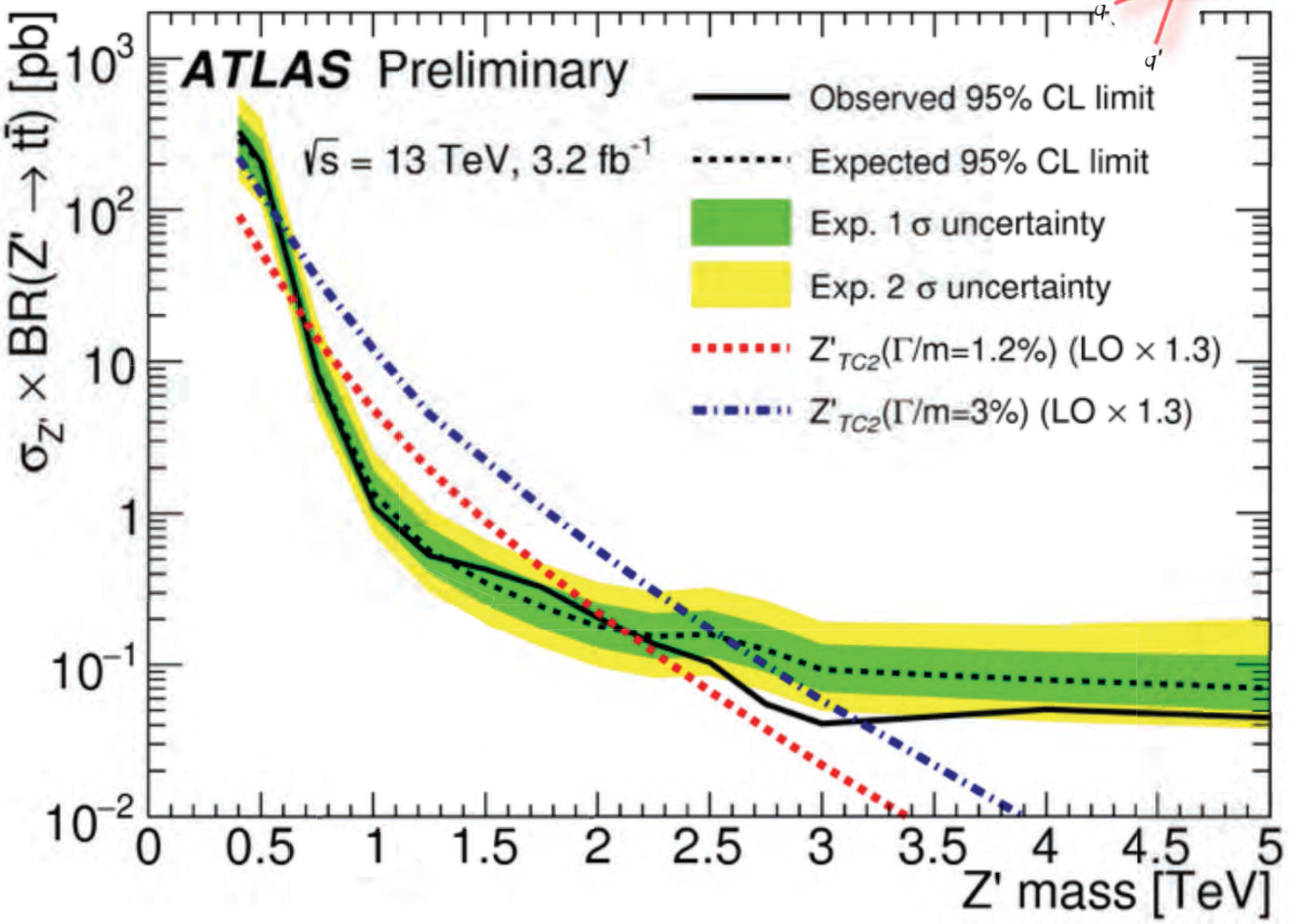
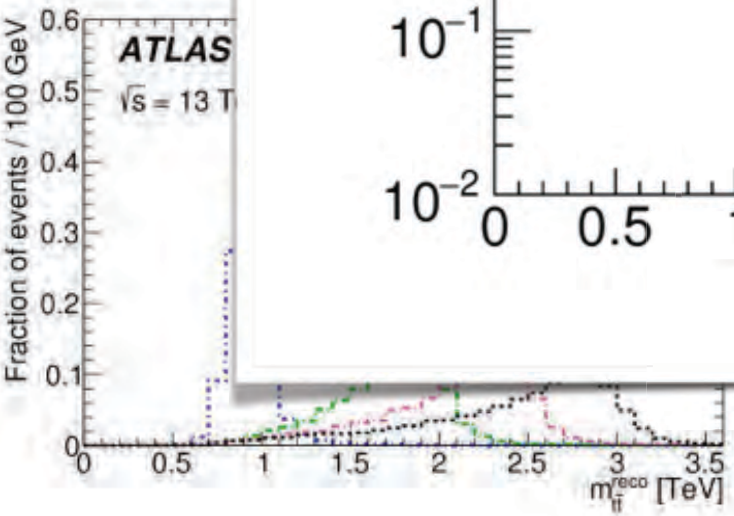
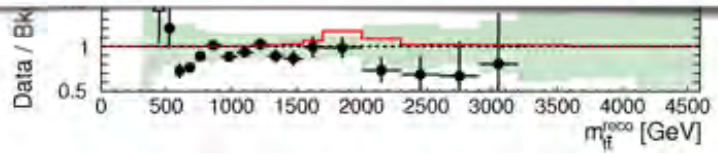
$t\bar{t}$ resonance search in lepto











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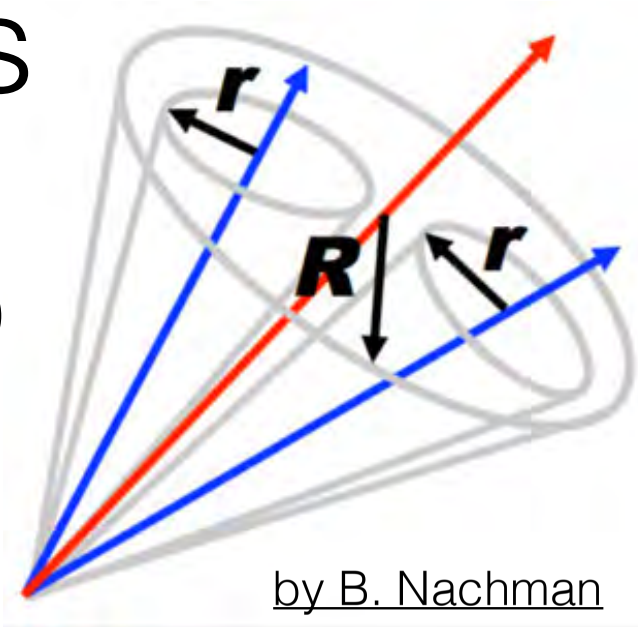
Jet Reclustering or doing it all backwards



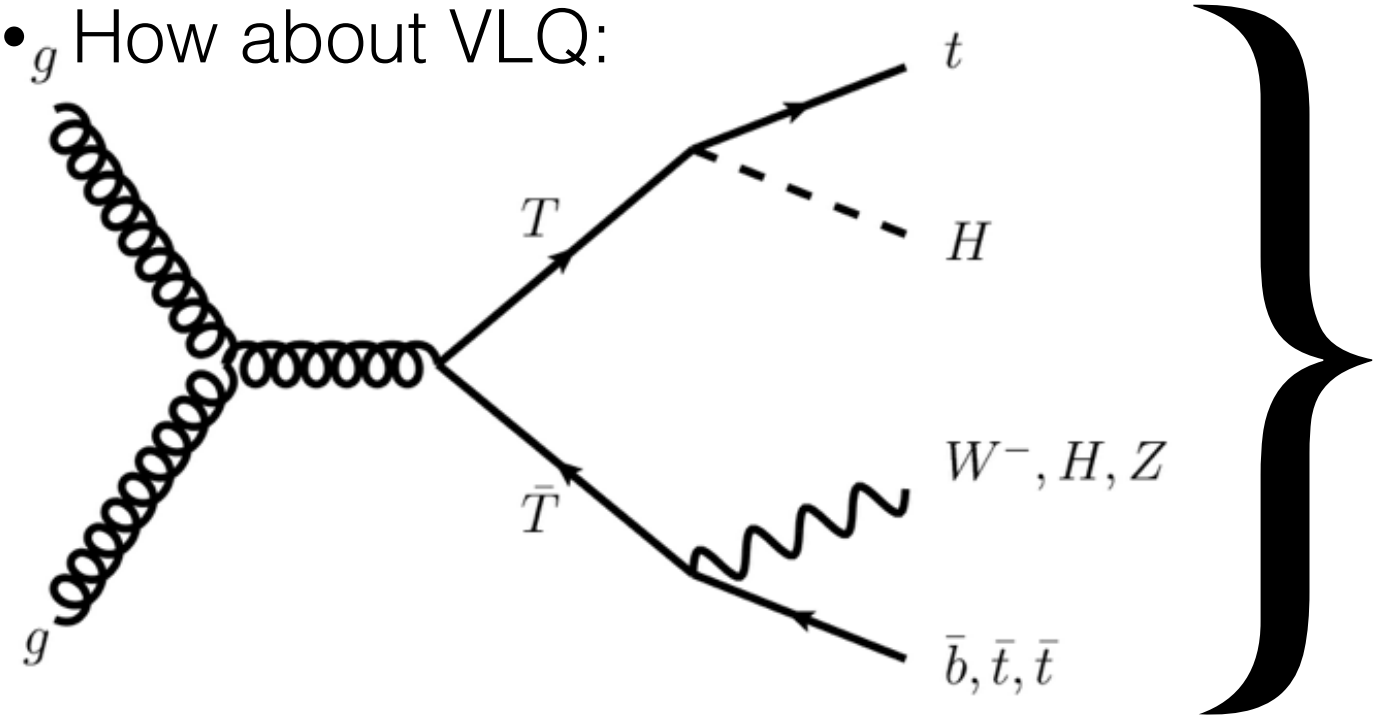
by B. Nachman

- Large R jets are great, but they require extra work (calibrations, uncertainties etc)
- **Reclustering**: Use standard small R(=0.4) jets as **inputs** to the large R jet finding!
- Advantages: inherit calibrations and uncertainties from well understood small R jets, easy to correlate with MET, faster, …
- Disadvantages: less information used, need to understand close-by-jet effects, it wasn't my idea

http://arxiv.org/abs/1407.2922

A use case

- Has been pioneered in ATLAS SUSY analyses
- How about VLQ:



Many heavy objects to tag!

Standard top, W or H taggers not ideal

- Require a lepton and MET and a few b-tags
- Reclustered large R jet(s) with m_J>100 GeV (i.e. keep H and top)

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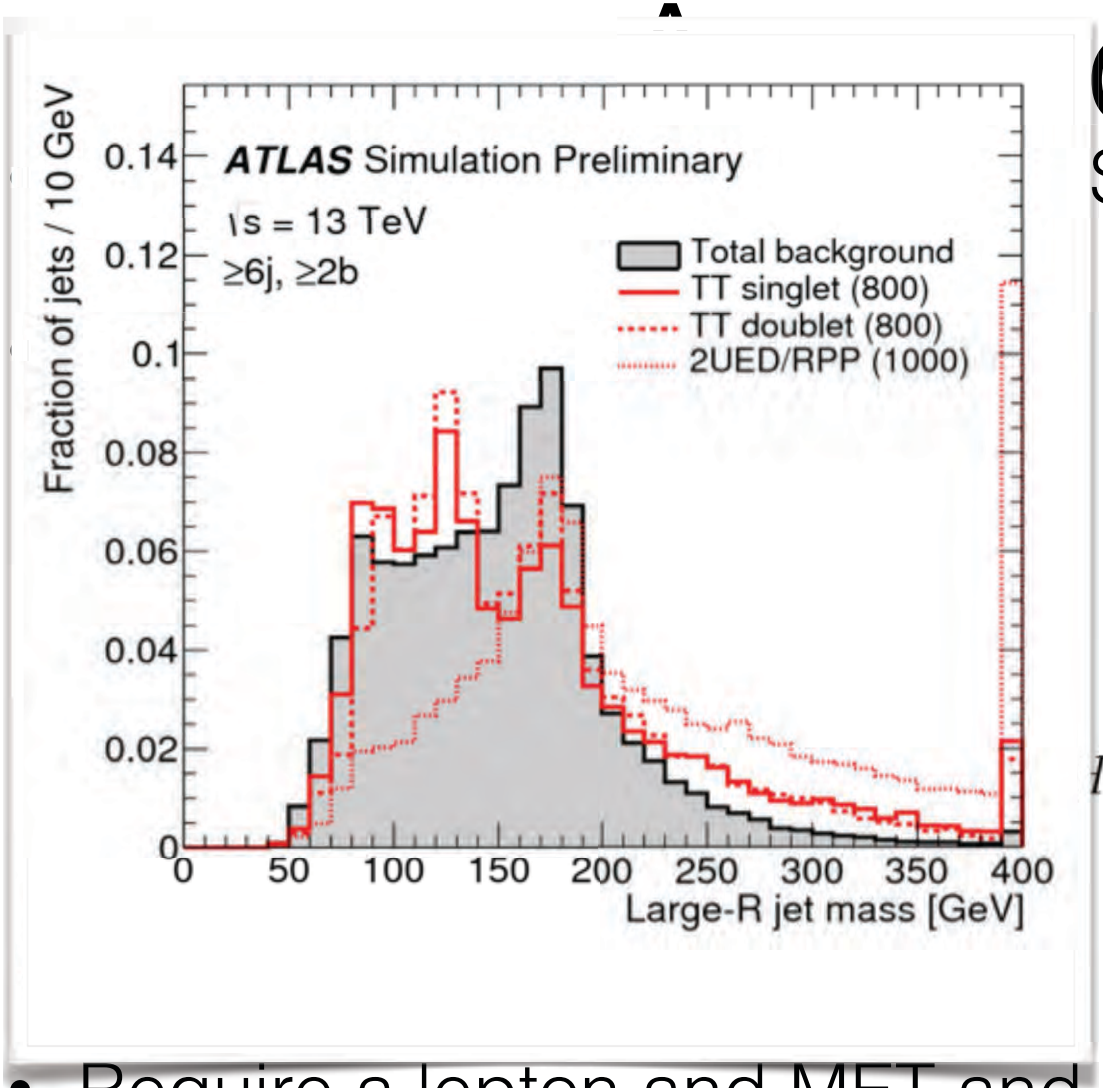
case

SUSY analyses



l, Z

Many heavy objects to tag!

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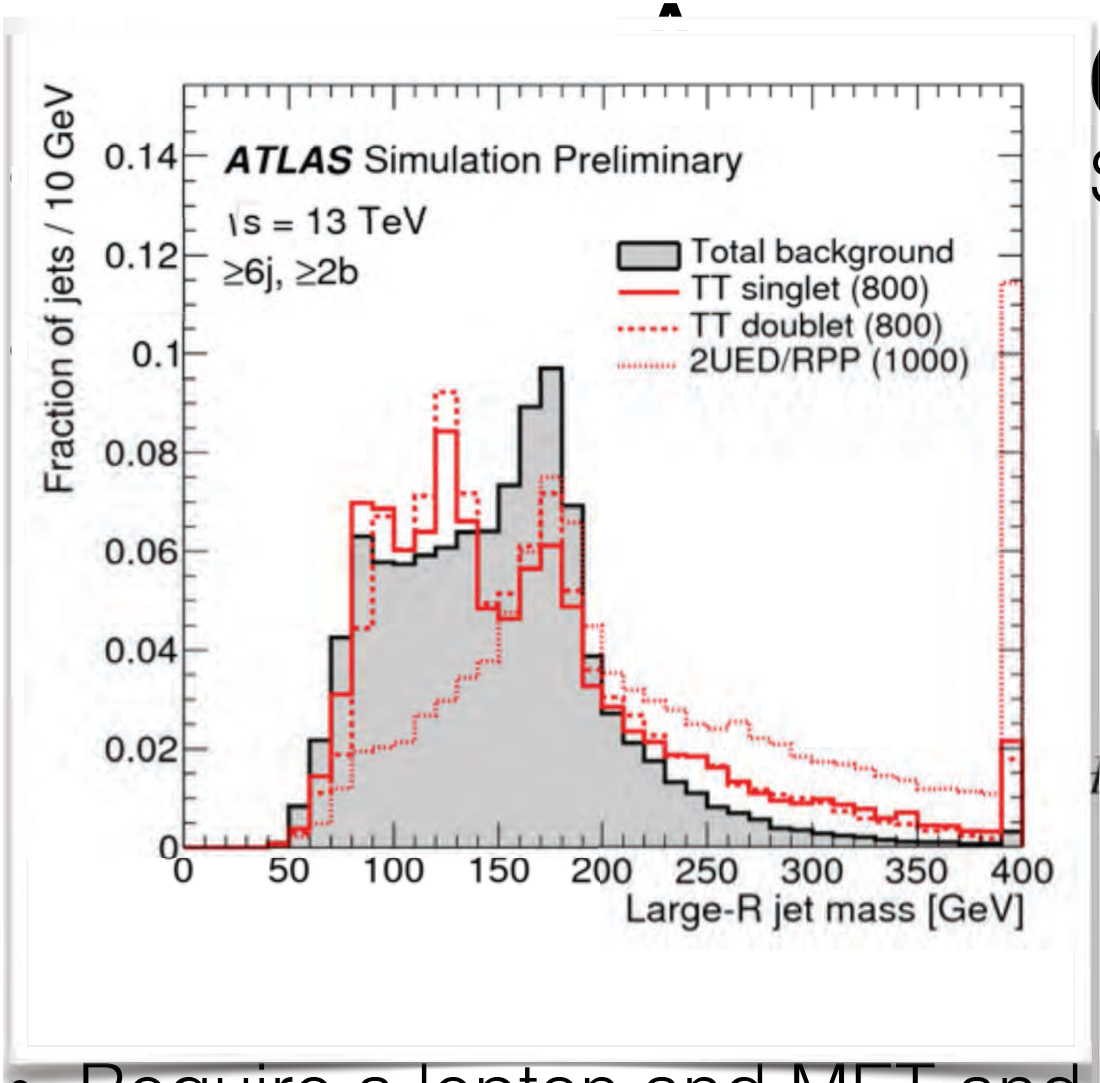
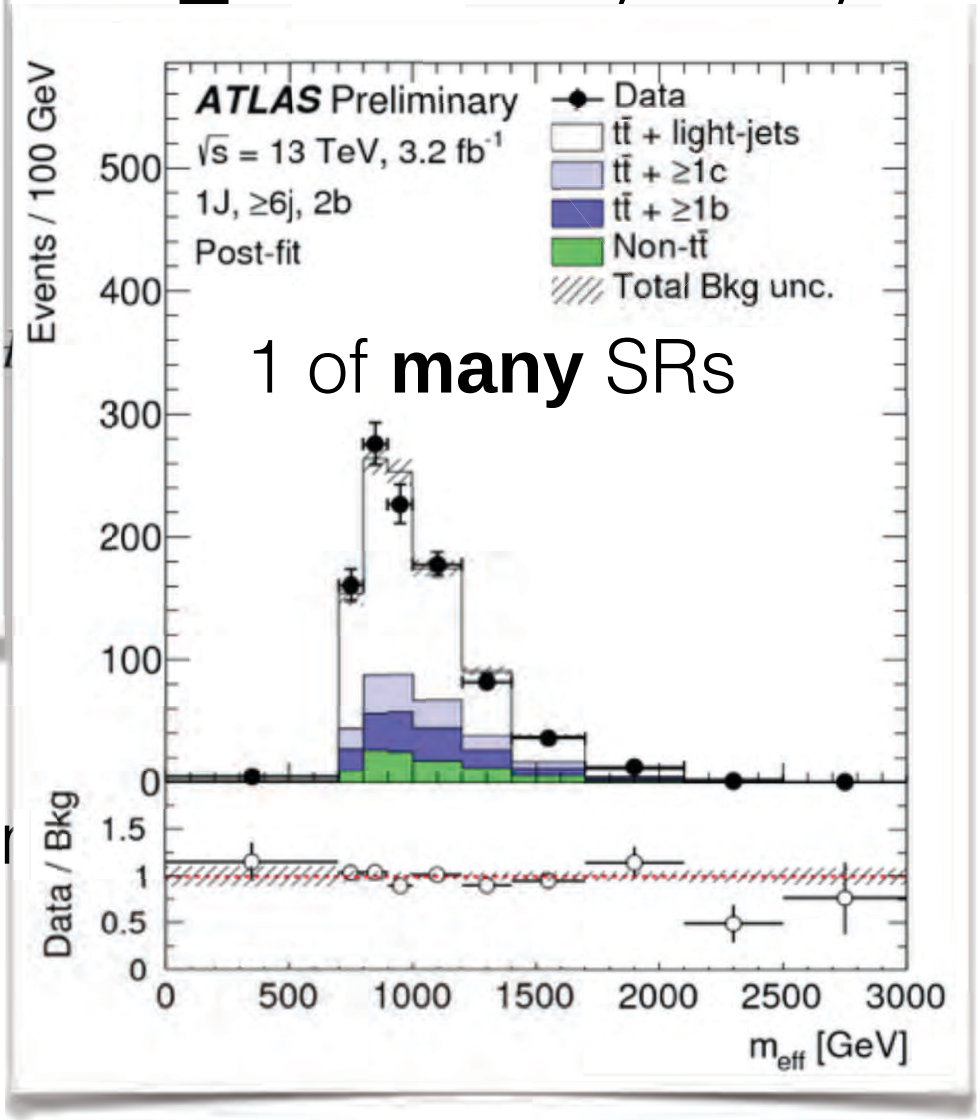
ATLAS-CONF-2016-013

case

SUSY analyses



Many heavy



1 of **many** SRs

- Require a lepton and MET and
- Reclustered large R jet(s) with r and top)

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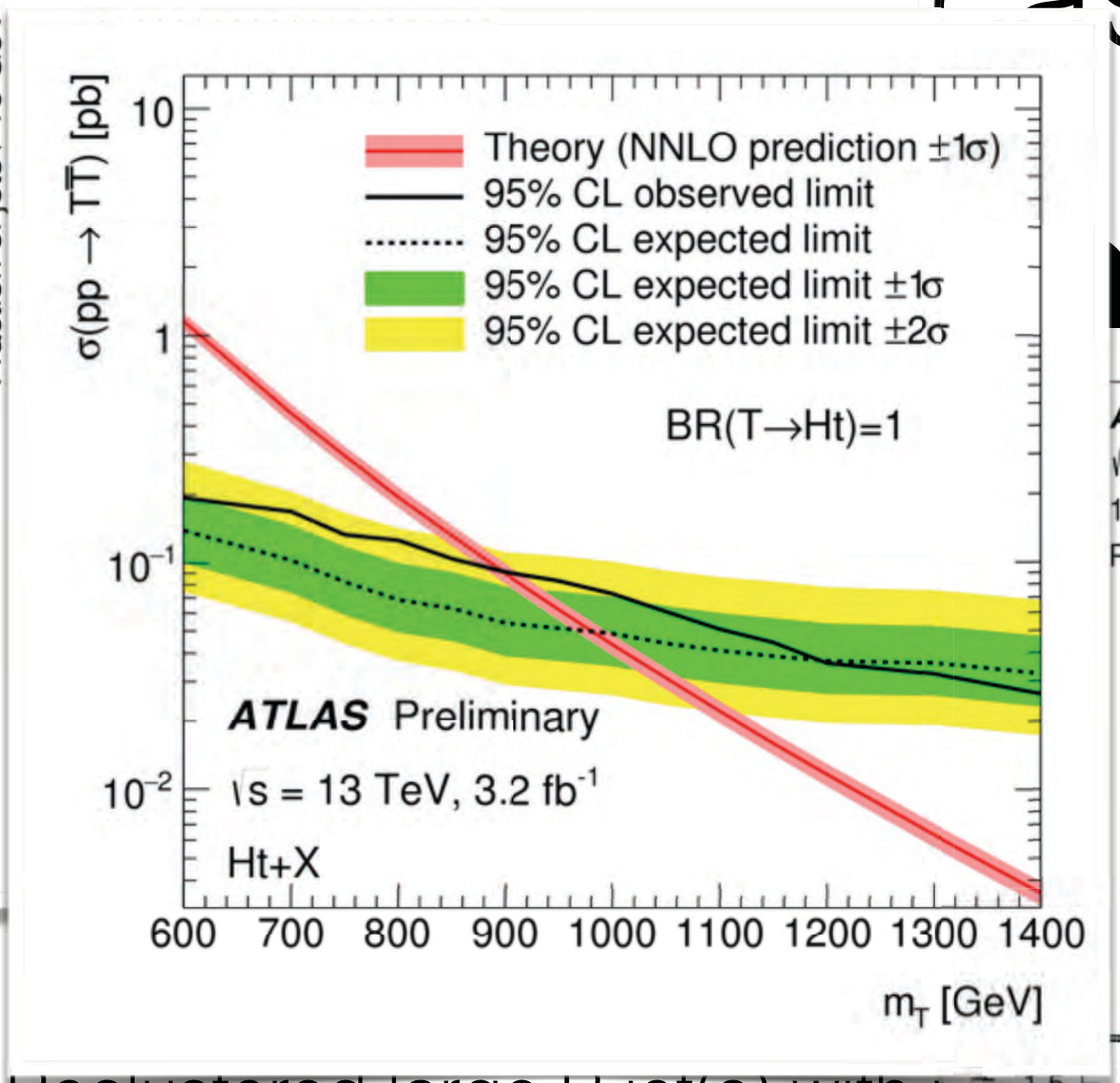
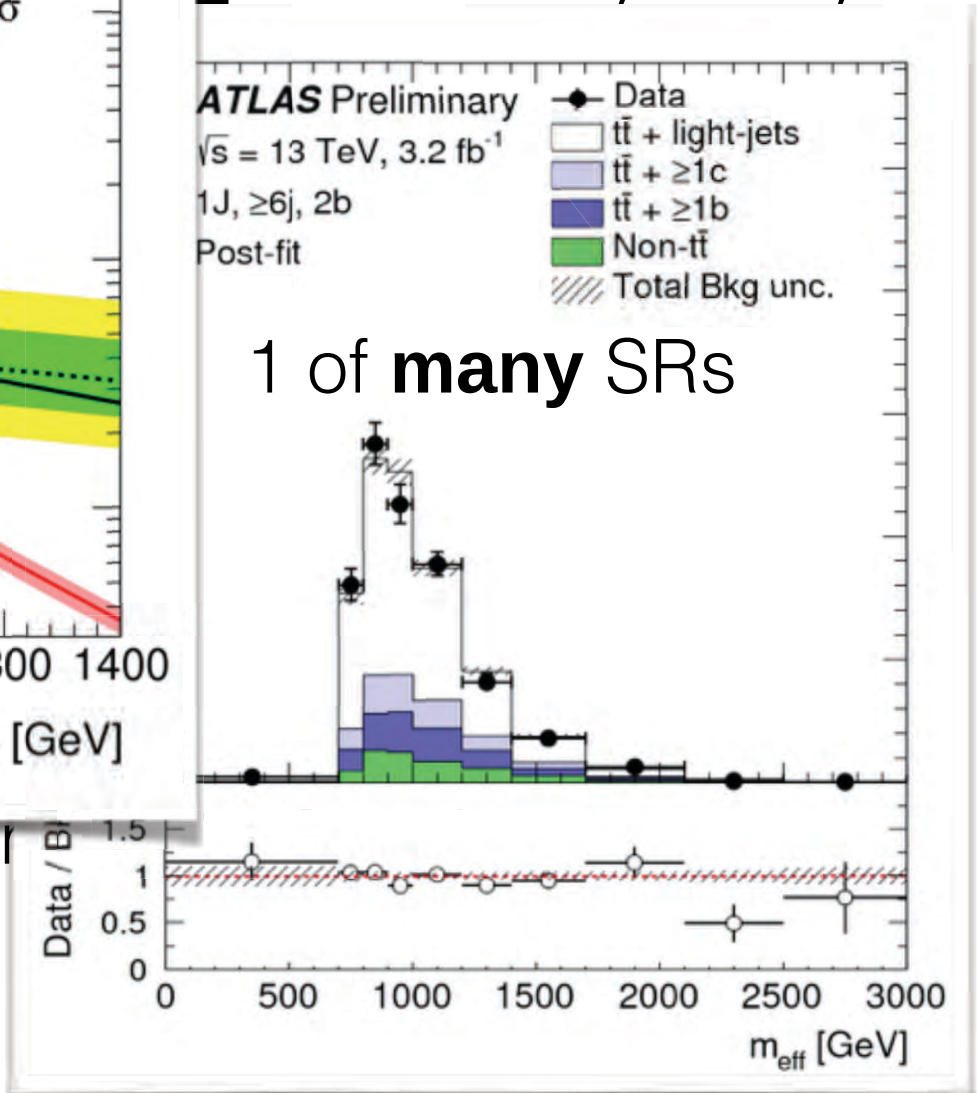
case

analyses

Many heavy





- Reclustered large R jet(s) with
and top)

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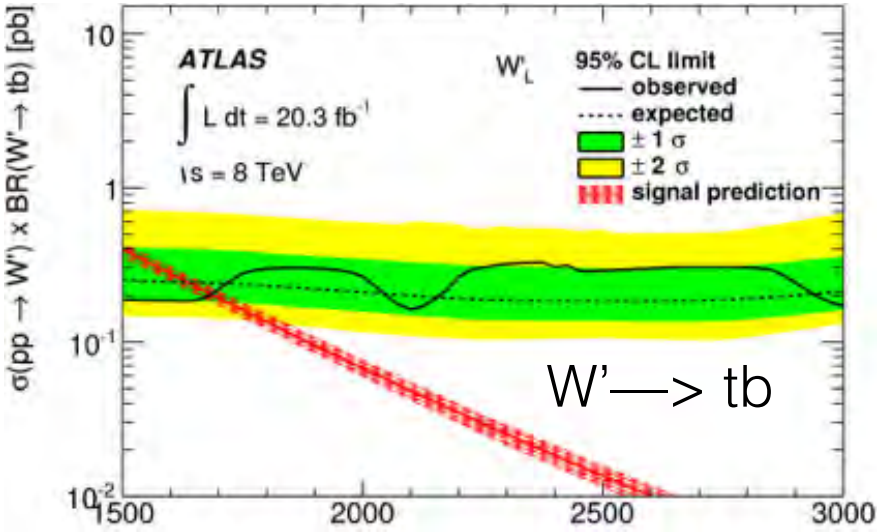
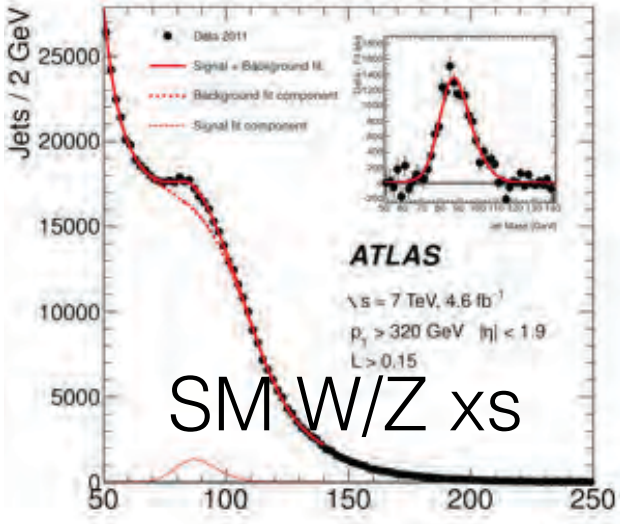
Of course there is more!



W'—> tb

Eur. Phys. J. C (2015) 75:165

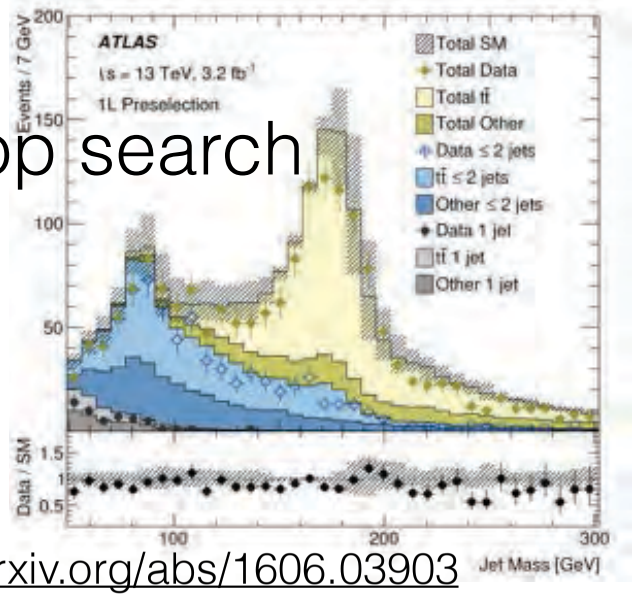


SM W/Z xs

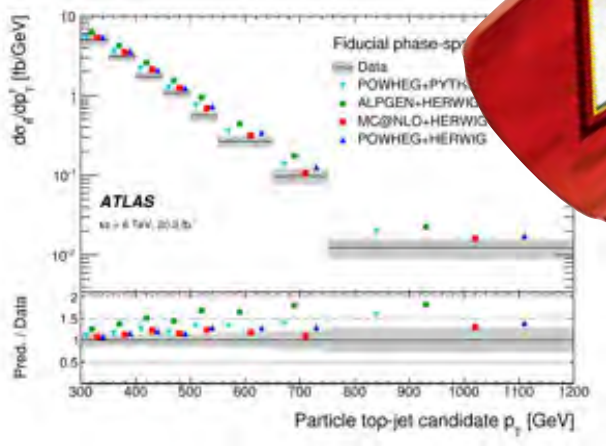
arXiv:1407.0800 Jet Mass [GeV]

There will be/ is more

stop search



http://arxiv.org/abs/1606.03903



arXiv:1510.03818

SM boosted ttbar xs

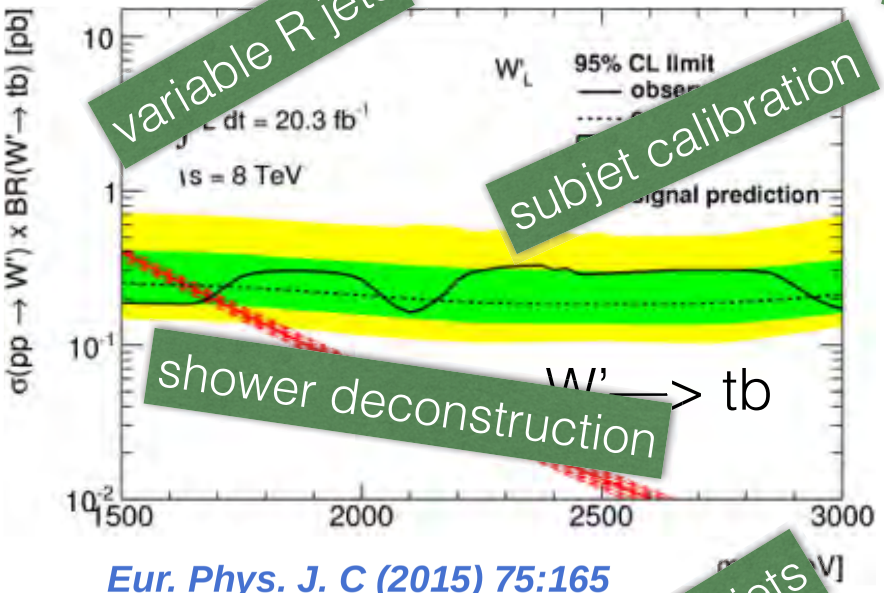
at 13TeV in Run 2!

Of course there is more!

variable R jets

subjet calibration

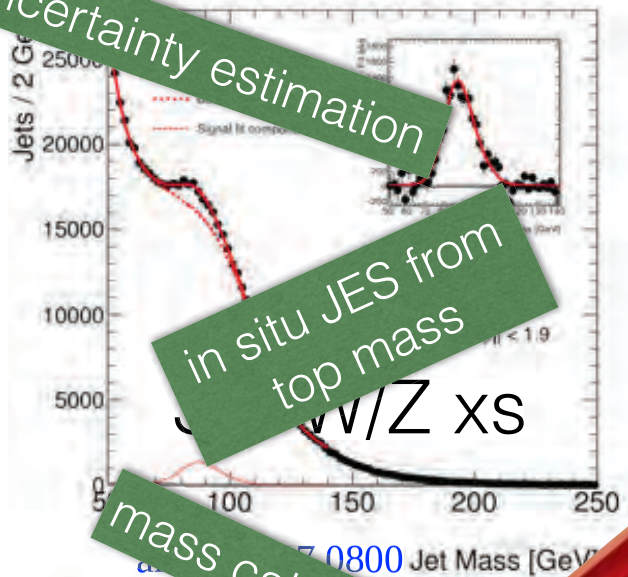
shower deconstruction



Eur. Phys. J. C (2015) 75:165

uncertainty estimation

in situ JES from top mass

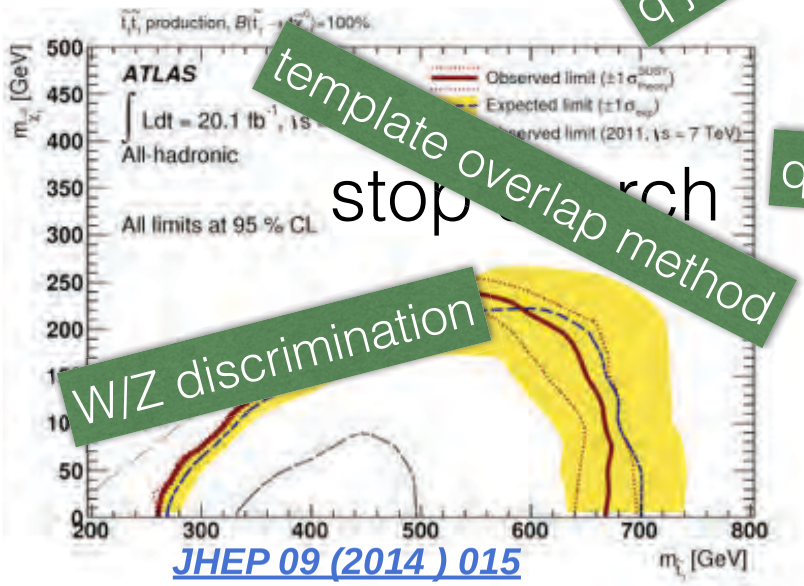


There will be more

mass calibration

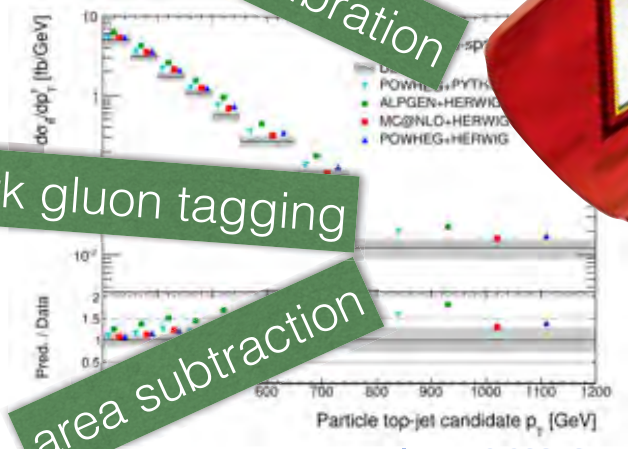
q jets

template overlap method



JHEP 09 (2014) 015

quark gluon tagging



area subtraction

W/Z discrimination

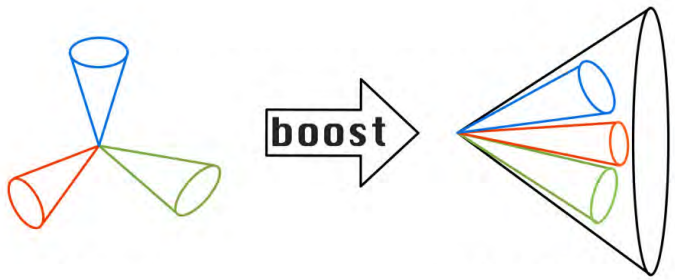
arXiv:1510.03818

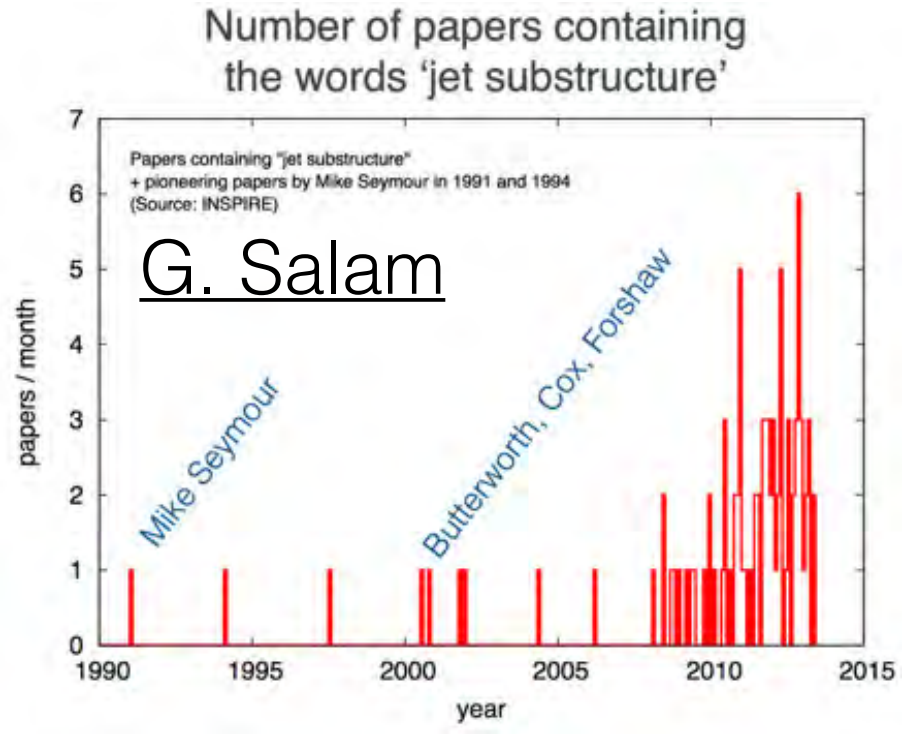
SM boosted ttbar xs

at 13TeV in Run 2!

Summary

- Dramatic increase in *understanding* of hadronic final states in the last few years
- Boosted/jet substructure techniques have been shown to *work* in Run 1 of LHC + been *employed* in analysis
- They are even more important at the *higher center of mass* energy we are running at now
- First Run 2 results are in
  —> *Tagging still works well!*
- We are already thinking about the *even more boosted regime* (not touched on today)





Closing remark