b UNIVERSITÄT BERN

AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

ATLAS EXPERIMENT

Heavy flavour (s)quarks: Supersymmetry and Dark Matter searches at LHC

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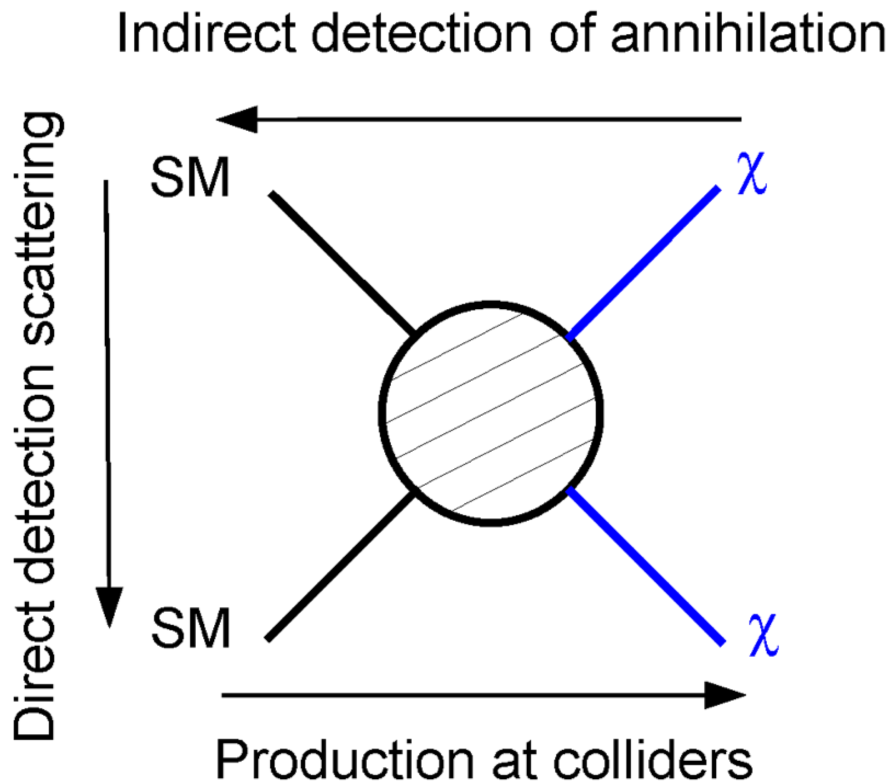
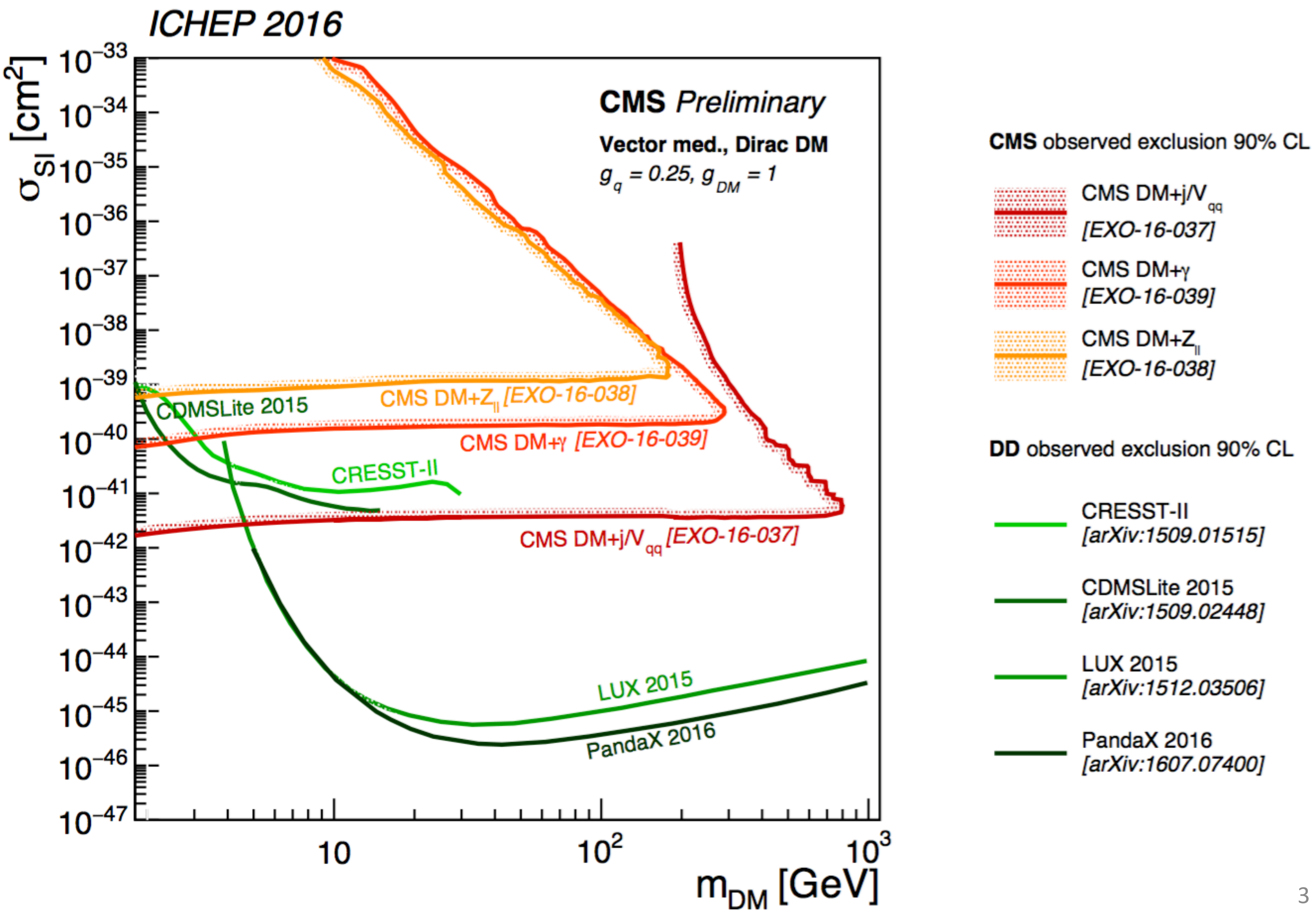
Dark Matter and colliders

Cosmological observations point to the existence of Dark Matter (DM)

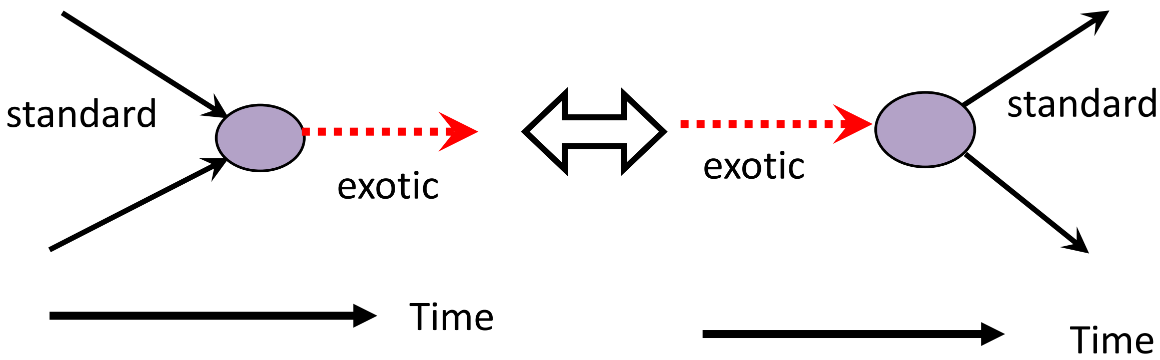
- We don't know anything about it except it interacts **gravitationally** and is **stable**
- **Particle physicists hunt for:** **W**eakly **I**nteracting, Stable, **M**assive **P**articles
- Colliders provide complementary sensitivity to direct searches



Dark Matter and colliders

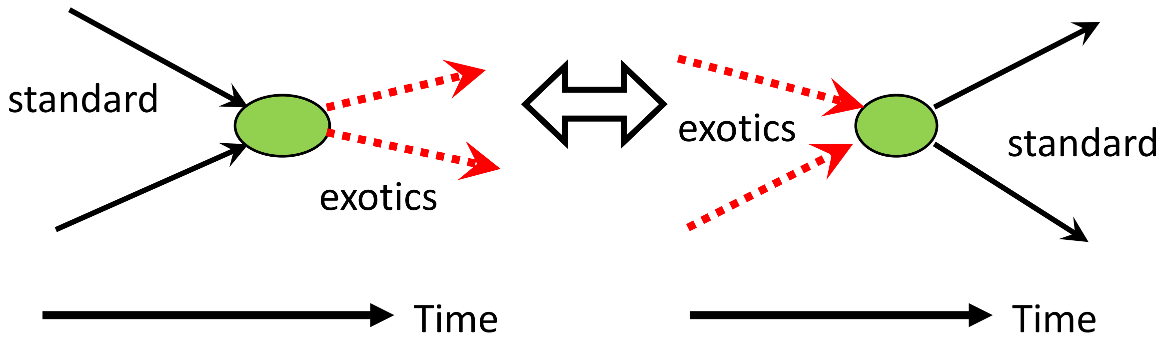


Producing Dark Matter candidates



If exotics can be produced ***singly*** they can decay

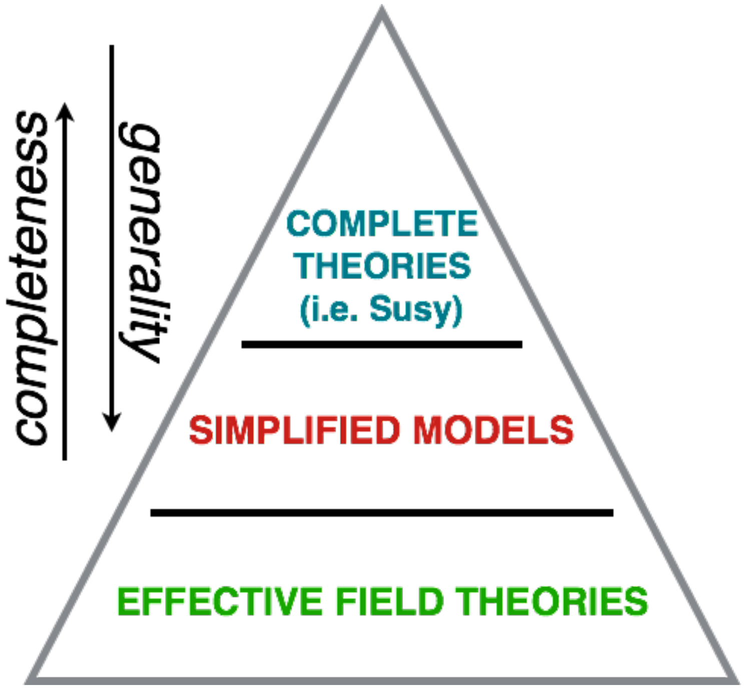
- Not a good Dark Matter candidate



If they can only be ***pair***-produced they are stable

- Only disappear on collision (rare)

Modelling guidance

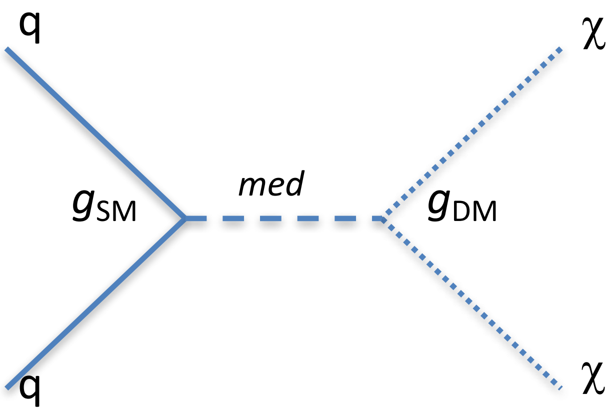


Various approaches available for DM (and in general Beyond Standard Model) searches.

Need to balance between generality and completeness.

- Simplified models are always theoretically valid (hence a good proxy for phenomenology)
- Up to the theorists to re-connect them back to the complete models

Dark Matter simplified models

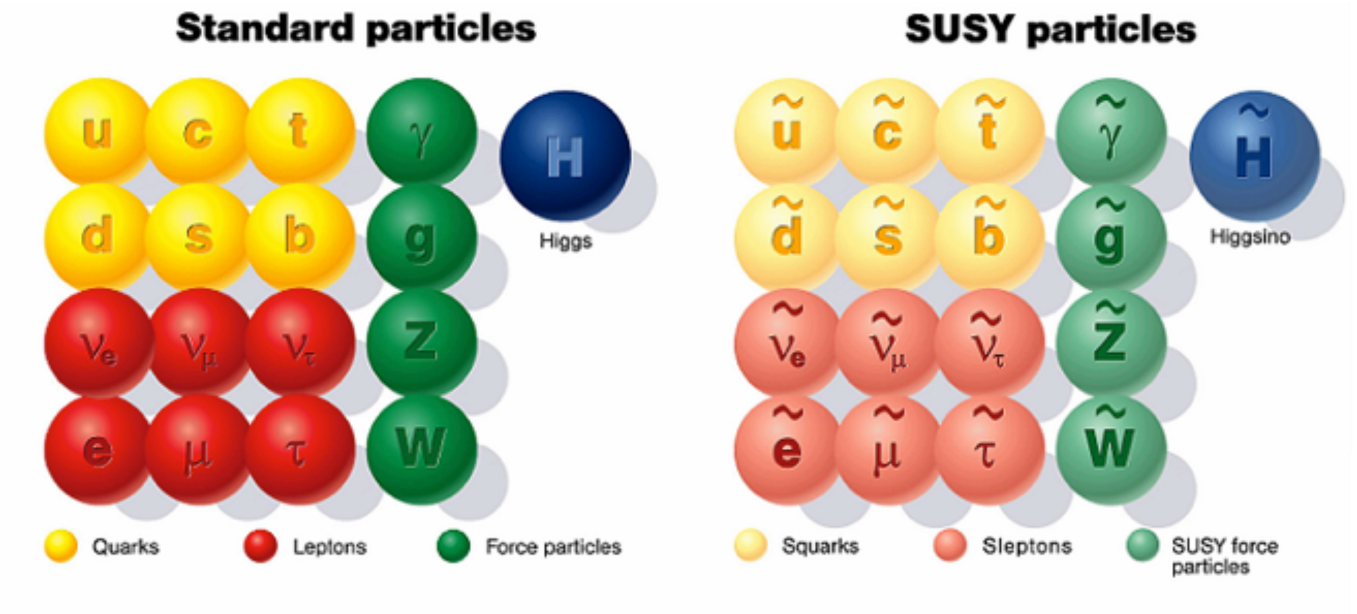


Simplified Models are used as guidance

- Reduce a complex model to a simple one with DM, a mediator between the SM and the Dark Sector, one interaction channel

- **Few free parameters:** m_{med}, m_{DM}, g_{SM}, g_{DM}, Γ_{med} **+** nature of mediator, DM and their interaction

Supersymmetry

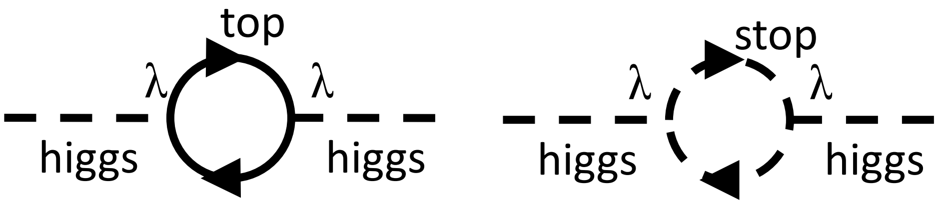


SUSY can extend the SM with new physics at the TeV scale

- Relates **each SM particle to another**
- Known as superpartner, differs by half unit of spin

- Partners not yet observed, must be heavier!
- **A broken symmetry**!

Why SUSY?



$\Delta m^2(h) \propto \Lambda^2_{cutoff}$

- **Higgs mass²**
  - Quadratic loop corrections
  - In SM natural scale
    - $\Lambda_{cutoff} \sim M_{planck}$
  - Need m(h) at 125 GeV
    - Fine tuning
    - Many orders of magnitude

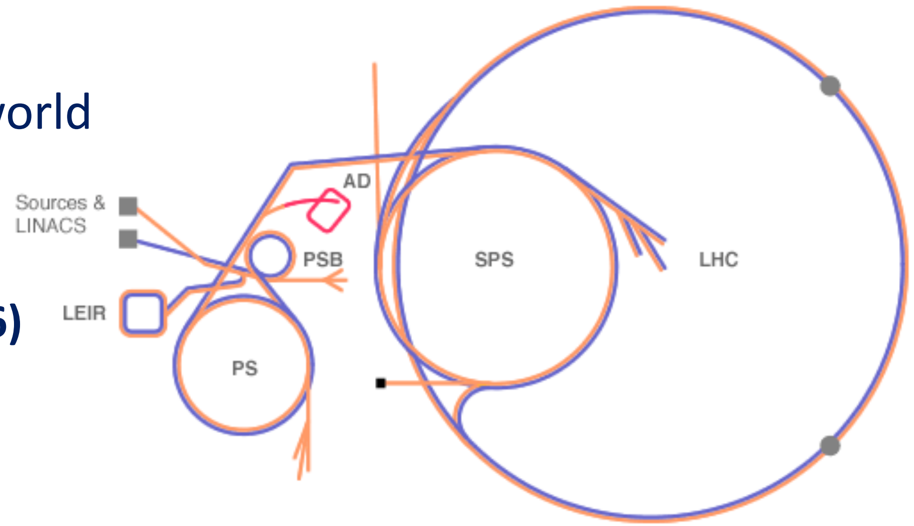
- The SUSY solution
  - 2 x top squarks
  - Factor of -1 from Feynman rules
  - Same coupling, λ
  - Quadratic corrections cancel
- **Predicts gauge unification!**

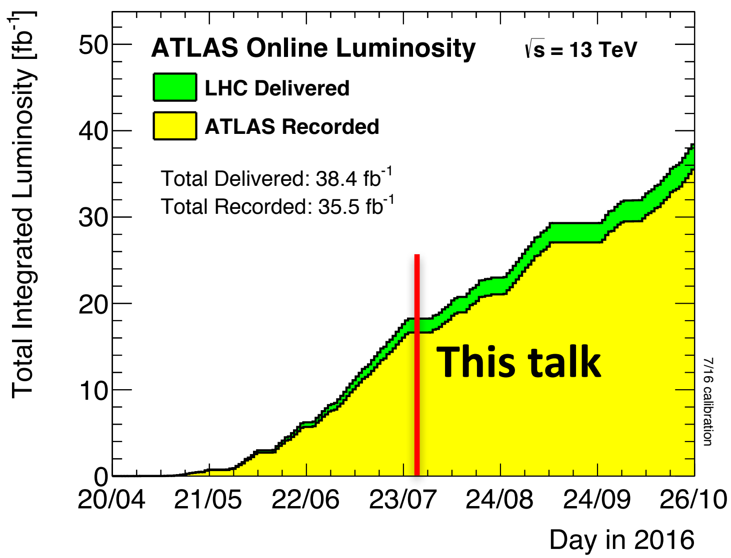
The Large Hadron Collider

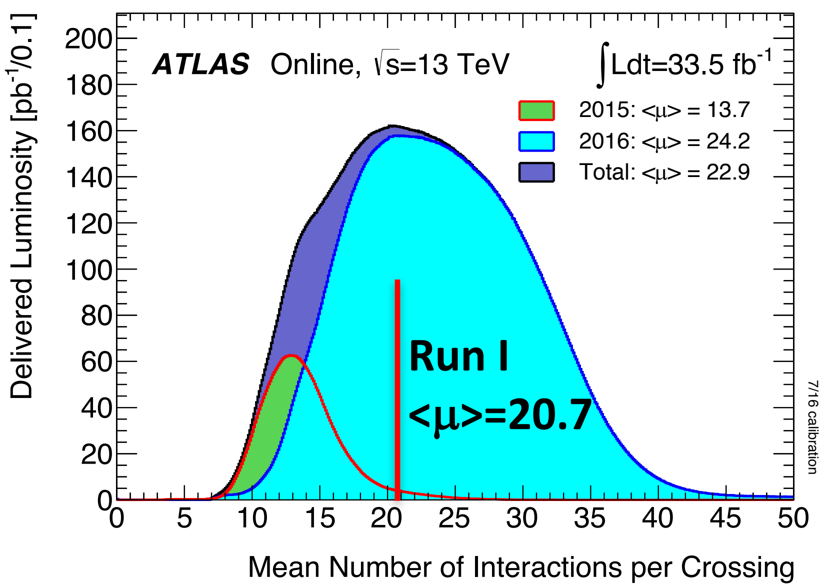
LHC at CERN is the largest collider in world

- *pp* collisions at √s = 7 TeV (2010-2011)
- *pp* collisions at √s = 8 TeV (2012)
- ***pp* collisions at √s = 13 TeV (2015-2016)**

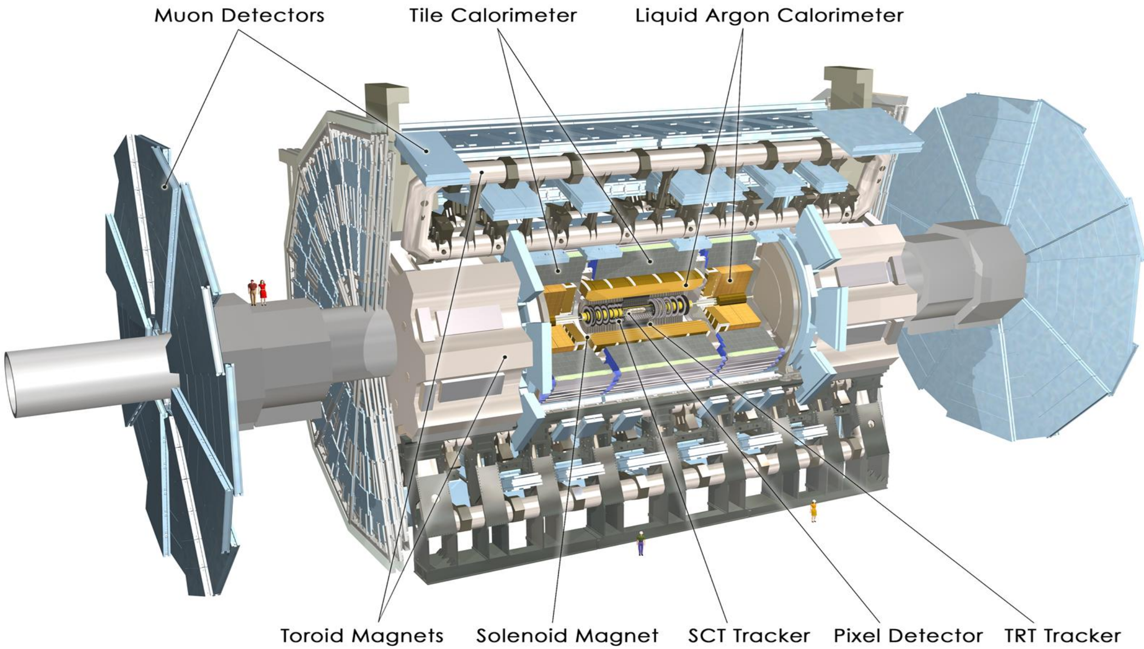
Today: data collected until ICHEP 2016







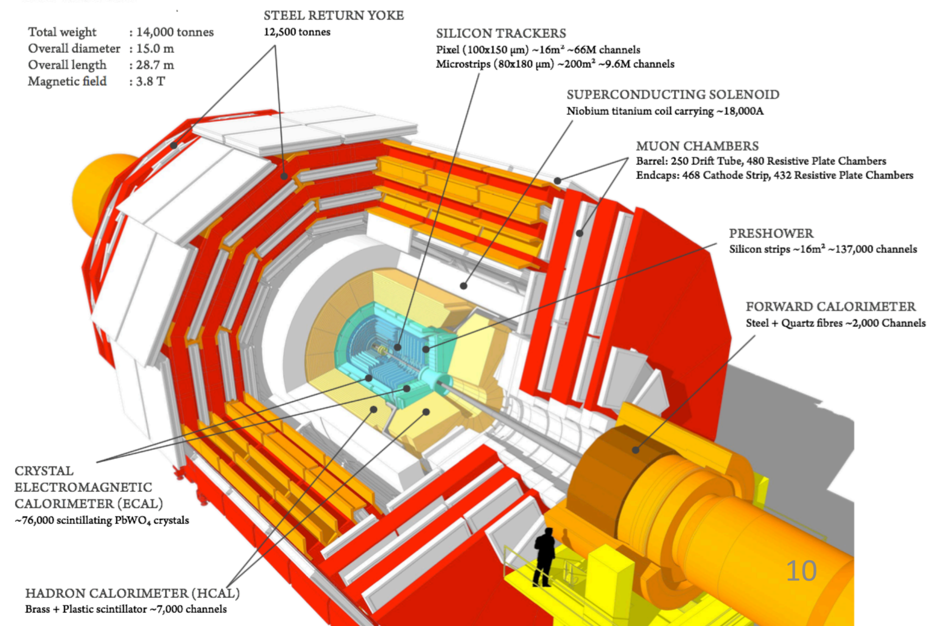
ATLAS and CMS



- Largest LHC collaborations
- General purpose experiments

Hermetic detectors with different implementations of the same concept:

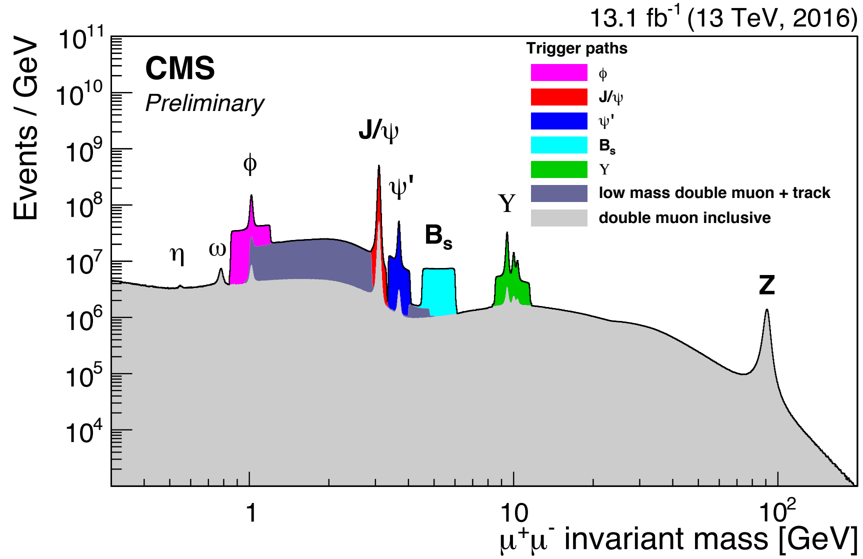
- A tracking detector
- EM and hadronic calorimeters
- Muon spectrometer

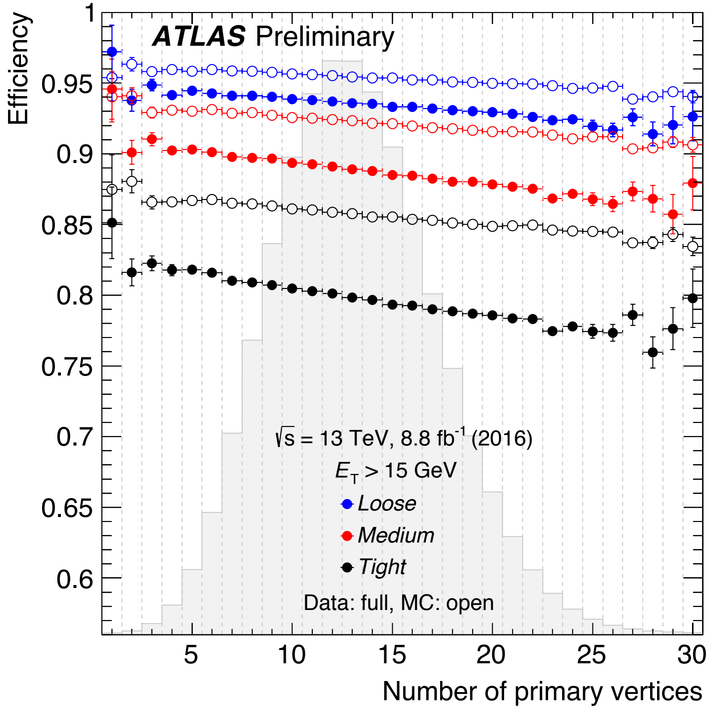


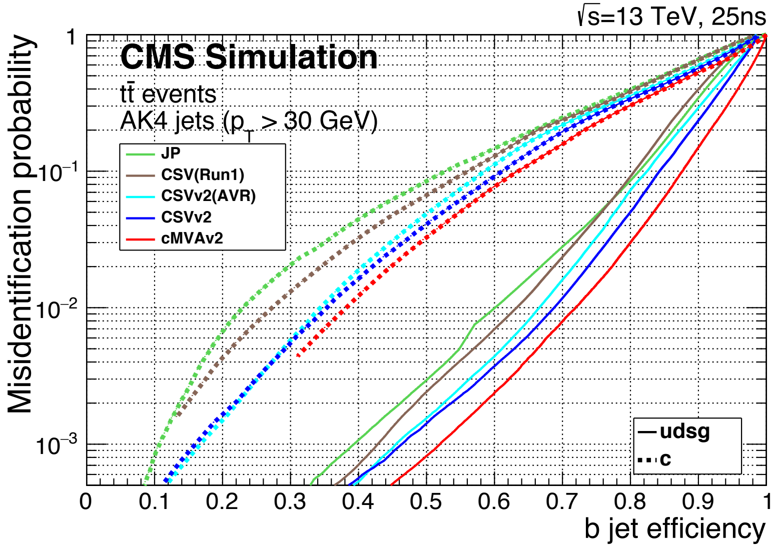
Detector performance

Impressive performances

- Precision attained in LHC run 1 surpassed, even in a harsher environment





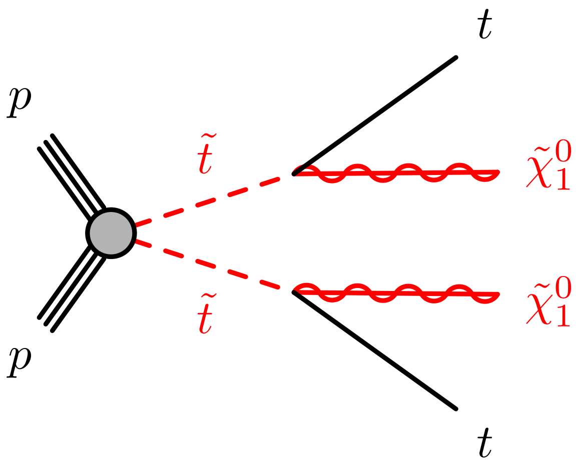


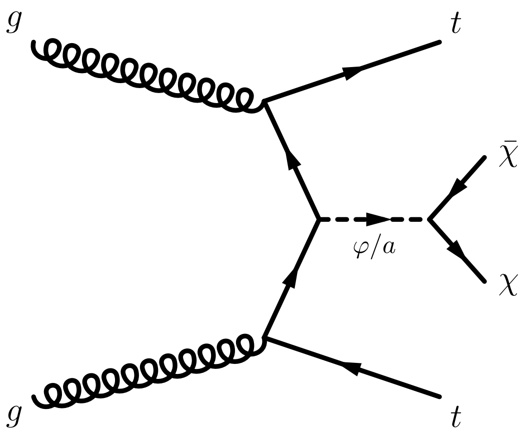
Heavy flavour + E_T^{miss}

At the LHC, extracting signals from the large QCD background can be challenging.

- Final states with rich phenomenology have multiple handles to reject backgrounds.

- Today, I will be focusing on models where DM is produced in the decay of coloured scalars (top squarks) or neutral scalars (higgs-like mediators), in events with:
  - Top pairs
  - Momentum imbalance (E_T^{miss}, in the transverse plane)





Useful links to dig deeper

CMS SUSY results

ATLAS SUSY results

Recent Supersymmetry Preliminary Results

CMS-PAS-SUS-16-031	Search for supersymmetry in events with at least one soft lepton, low jet multiplicity, and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV		October 2016
CMS-PAS-SUS-16-027	Search for direct top squark pair production in the dilepton final state at $\sqrt{s} = 13$ TeV		October 2016
CMS-PAS-SUS-15-009	Search for natural supersymmetry in events with top quark pairs and photons in pp collisions at $\sqrt{s} = 8$ TeV		October 2016
CMS-PAS-SUS-16-025	Search for new physics in the compressed mass spectra scenario using events with two soft opposite-sign leptons and missing transverse momentum at 13 TeV		August 2016
CMS-PAS-SUS-16-028	Search for direct top squark pair production in the single lepton final state at $\sqrt{s} = 13$ TeV		August 2016
CMS-PAS-SUS-16-021	Search for new physics in final states with two opposite-sign, same-flavor leptons, jets, and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV		August 2016
CMS-PAS-SUS-16-029	Search for direct top squark pair production in the fully hadronic final state in proton-proton collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 12.9 fb^{-1}		August 2016
CMS-PAS-SUS-16-026	Search for electroweak production of charginos and neutralinos in the WH final state at 13 TeV		August 2016
CMS-PAS-SUS-16-024	Search for electroweak SUSY production in multilepton final states in 12.9 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV		August 2016
CMS-PAS-SUS-16-022	Search for supersymmetry with multileptons in 13 TeV data		August 2016
CMS-PAS-SUS-16-016	An inclusive search for new phenomena in final states with one or more jets and missing transverse momentum at $\sqrt{s} = 13$ TeV with the α_T variable		August 2016
CMS-PAS-SUS-16-015	Search for new physics in the all-hadronic final state with the M_{T2} variable		August 2016
CMS-PAS-SUS-16-014	Search for supersymmetry in events with jets and missing transverse momentum in proton-proton collisions at 13 TeV		August 2016
CMS-PAS-SUS-16-012	Search for supersymmetry in events with a Higgs decaying to two photons using the razor variables		August 2016
CMS-PAS-SUS-16-013	Search for R-parity-violating SUSY in final states with zero or one lepton and large multiplicity of jets and b-tagged jets		August 2016
CMS-PAS-SUS-16-019	Search for supersymmetry in events with one lepton and multiple jets in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2016		August 2016
CMS-PAS-SUS-16-030	Search for supersymmetry in the all-hadronic final state using top quark tagging in pp collisions at $\sqrt{s} = 13$ TeV		August 2016
CMS-PAS-SUS-16-020	Search for SUSY in same-sign dilepton events with 12.9 fb^{-1} of pp collision data at 13 TeV		August 2016
CMS-PAS-SUS-16-023	Search for supersymmetry in final states with at least one photon and E_T^{miss} in pp collisions at $\sqrt{s} = 13$ TeV		August 2016
CMS-PAS-SUS-16-011	Search for new physics in the one soft lepton final state using 2015 data at $\sqrt{s} = 13$ TeV		June 2016
CMS-PAS-SUS-14-020	Search for R-parity violating supersymmetry with displaced vertices	Submitted to PRD	June 2016
CMS-SUS-14-006	Search for top squark pair production in compressed-mass-spectrum scenarios in proton-proton collisions at $\sqrt{s} = 8$ TeV using the α_T variable	Submitted to PLB	29 May 2016
CMS-PAS-SUS-15-012	Search for supersymmetry in events with photons and missing transverse energy		April 2016
CMS-PAS-SUS-16-007	Search for direct production of top squark pairs decaying to all-hadronic final states in pp collisions at $\sqrt{s} = 13$ TeV		March 2016
CMS-PAS-SUS-16-001	Search for direct production of bottom and light top squark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV		March 2016

papers

Short Title of Paper	Date	$\sqrt{s}$ (TeV)	L (fb^{-1})	Document	Plots+Aux. Material	Journal
1-2 taus + Etmiss	07/2016	13	3.2	1607.05979	Link (+data)	Submitted to EPJC
di-photon + MET	6/2016	13	3.2	1606.09150	Link	Accepted by EPJC
2b + MET	6/2016	13	3.2	1606.08772	Link (+data)	EPJC, (2016) 76:547
LLP (pixel+Tile)	6/2016	13	3.2	1606.05129	Link (+data)	Physics Letters B (2016), pp. 647-665
1L stop	6/2016	13	3.2	1606.03903	Link (+data)	Phys. Rev. D 94 (2016) 052009
multi b-jets	5/2016	13	3.2	1605.09318	Link (+data)	Phys. Rev. D 94 032003
1L 2-6 jets	5/2016	13	3.2	1605.04285	Link (+data)	Eur. Phys. J. C 76 (2016) 565
0L 2-6 jets	5/2016	13	3.2	1605.03814	Link (+data)	Eur. Phys. J. C (2016) 76: 392
monojet (compressed squarks) NEW	4/2016	13	3.2	1604.07773	Link	Phys. Rev. D 94 (2016) 032005
LLP with pixel dE/dx	4/2016	13	3.2	1604.04520	Link (+data)	Phys. Rev. D 93, 112015 (2016)
2 same sign or 3 leptons	2/2016	13	3.2	1602.09058	Link (+data)	EPJ C, 76(5), 1-26
0L 7-10 jets	2/2016	13	3.2	1602.06194	Link (+data)	Phys. Lett. B 757 (2016) 334

conference notes

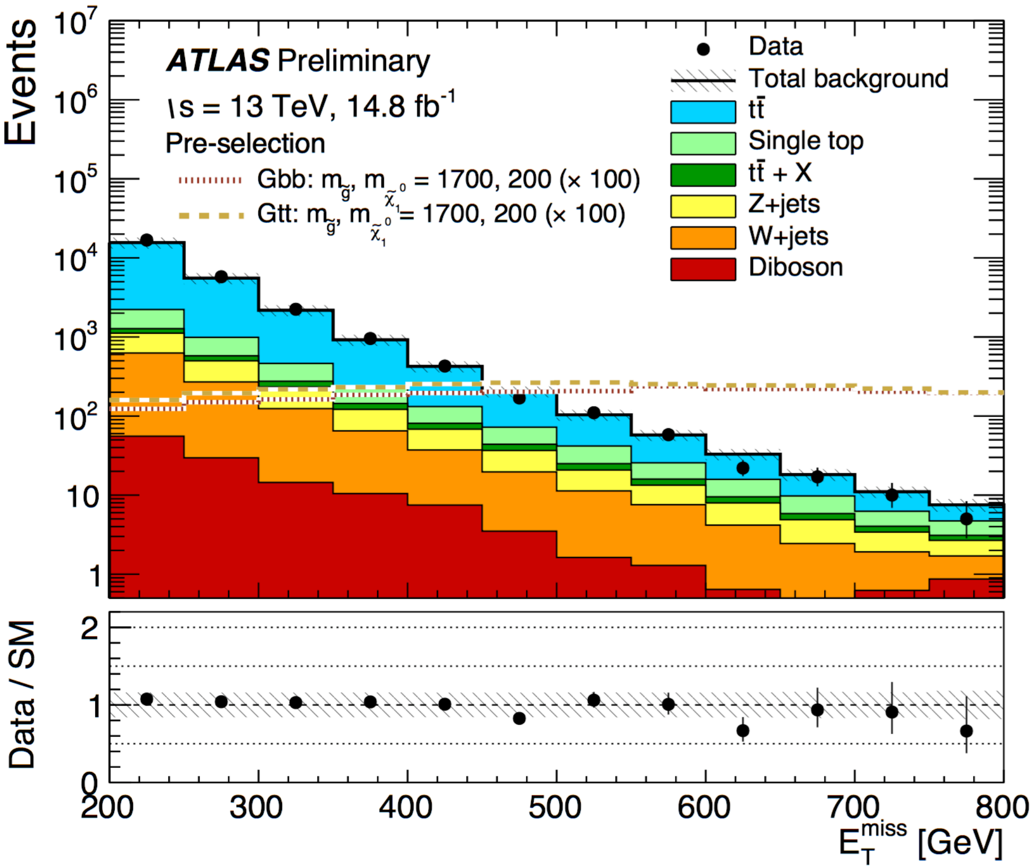
Short Title of preliminary conference note/paper	Date	$\sqrt{s}$ (TeV)	L (fb^{-1})	Document	Plots
2L+jets+MET (Z/edge)	9/2016	13	14.7	ATLAS-CONF-2016-098	Link
EWK 2/3L	9/2016	13	14.8	ATLAS-CONF-2016-096	Link
EWK di-tau	9/2016	13	14.8	ATLAS-CONF-2016-093	Link
0L 8-10 jets (RPC gluinos)	9/2016	13	18.2	ATLAS-CONF-2016-095	Link
RPV 1L+multijets	9/2016	13	14.8	ATLAS-CONF-2016-094	Link
0L 2-6 jets (squark/gluinos)	8/2016	13	13.3	ATLAS-CONF-2016-078	Link
1L 2-6 jets (squark/gluinos)	8/2016	13	14.8	ATLAS-CONF-2016-054	Link
SS/3L + jets (squarks/gluinos)	8/2016	13	13.2	ATLAS-CONF-2016-037	Link
0/1L + 3b jets (squarks/gluinos)	8/2016	13	14.8	ATLAS-CONF-2016-052	Link
photon + jets	8/2016	13	13.3	ATLAS-CONF-2016-066	Link
stop 0L	8/2016	13	13.3	ATLAS-CONF-2016-077	Link
stop 1L	8/2016	13	13.3	ATLAS-CONF-2016-050	Link
stop 2L	8/2016	13	13.3	ATLAS-CONF-2016-076	Link
stop2 (3L)	8/2016	13	13.3	ATLAS-CONF-2016-038	Link
stop stau	8/2016	13	13.3	ATLAS-CONF-2016-048	Link
4 lepton (RPV EWK)	8/2016	13	13.3	ATLAS-CONF-2016-075	Link
multijet (RPV)	8/2016	13	14.8	ATLAS-CONF-2016-057	Link
Stop to qq (RPV)	8/2016	13	15.6	ATLAS-CONF-2016-084	Link
Stop to bs (RPV)	5/2016	13	3.2	ATLAS-CONF-2016-022	Link
2L stop	3/2016	13	3.2	ATLAS-CONF-2016-009	Link

A precise determination of SM backgrounds: the problem

- SM backgrounds are **not small**
- There are uncertainties in
  - Cross sections
  - Kinematical distributions
  - Detector response

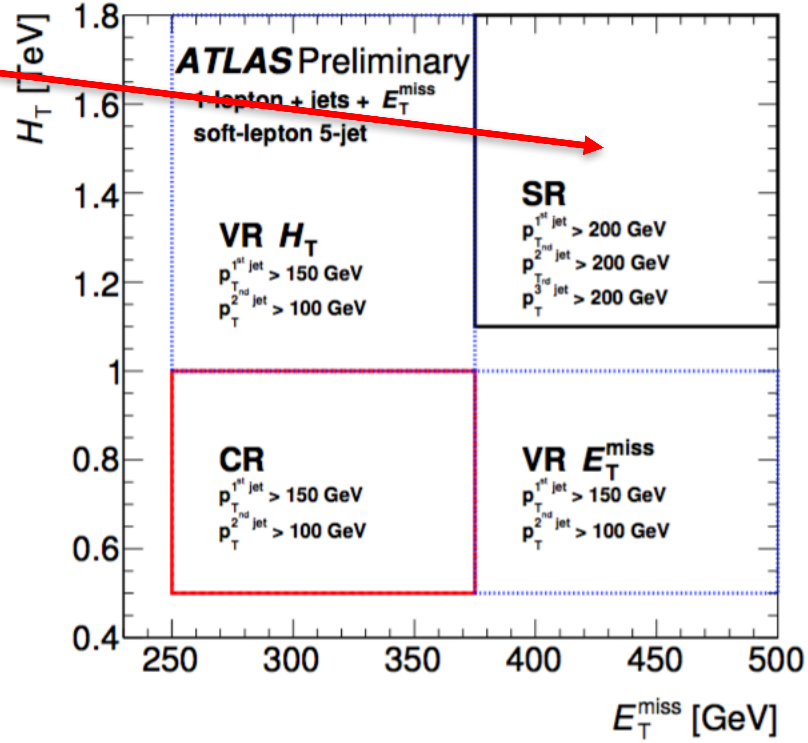
Best approach:

- **Keep it simple**



Common analysis strategies

1. Define a *signal region* (SR) based on signal kinematic features
2. Estimate the Standard Model processes in the SR:
    1. **Data-driven** reducible backgrounds ('fakes')
    2. Define a *control region* (CR) for each of the major irreducible backgrounds to normalise MC yields to data
    3. Minor backgrounds are taken from **MC simulation** only
3. Check background estimation against data in *validation regions* (VR)



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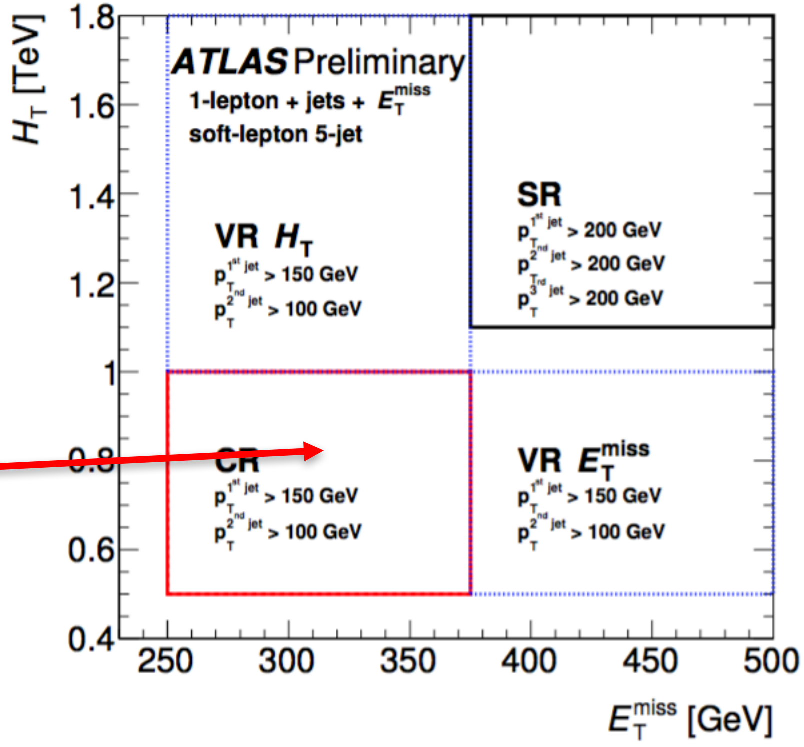

$$N(\mathrm{SR}) = (N^{\mathrm{Data}}(\mathrm{CR}) - N_{\mathrm{others}}(\mathrm{CR}))\frac{N^{\mathrm{MC}}(\mathrm{SR})}{N^{\mathrm{MC}}(\mathrm{CR})}$$

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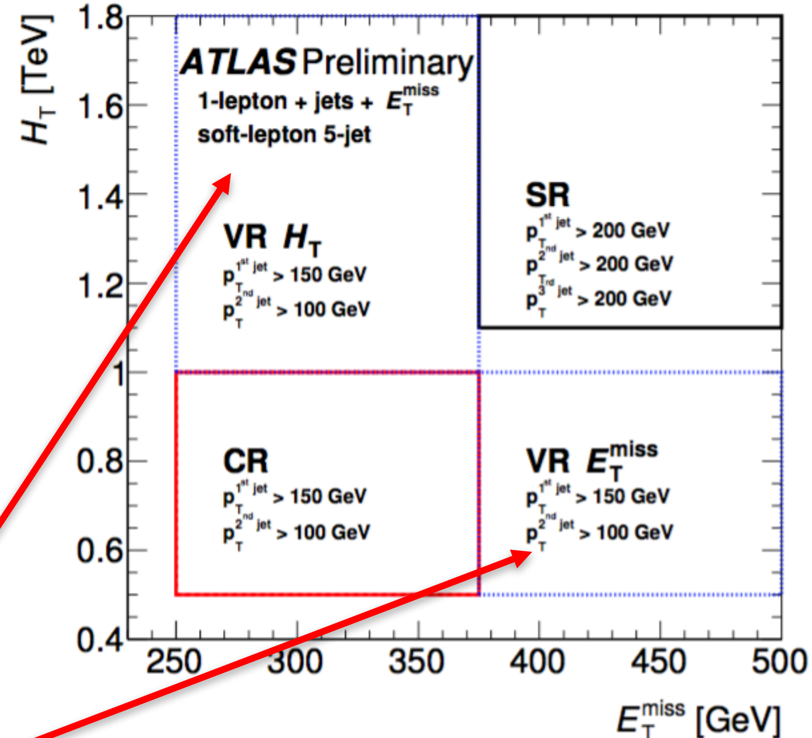
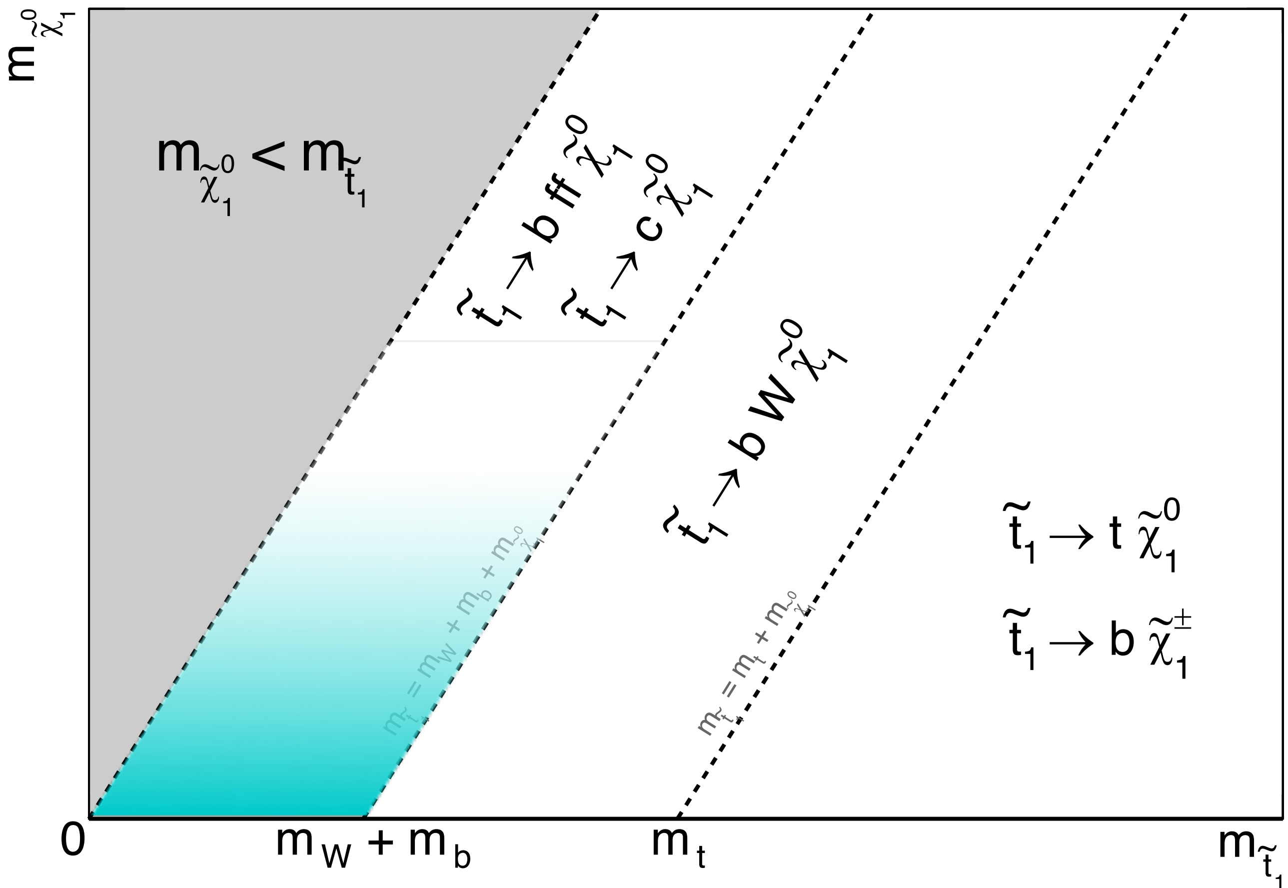
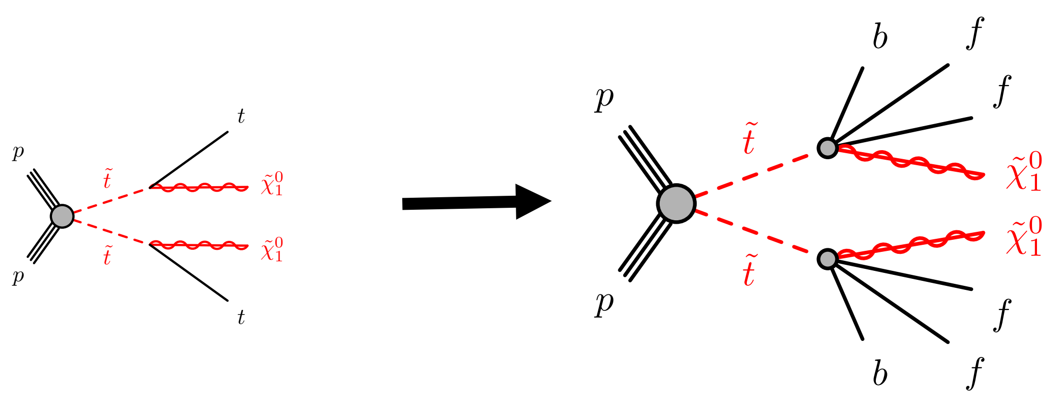
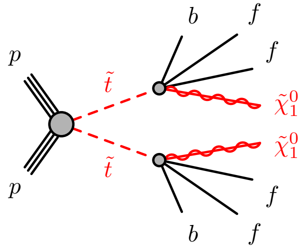


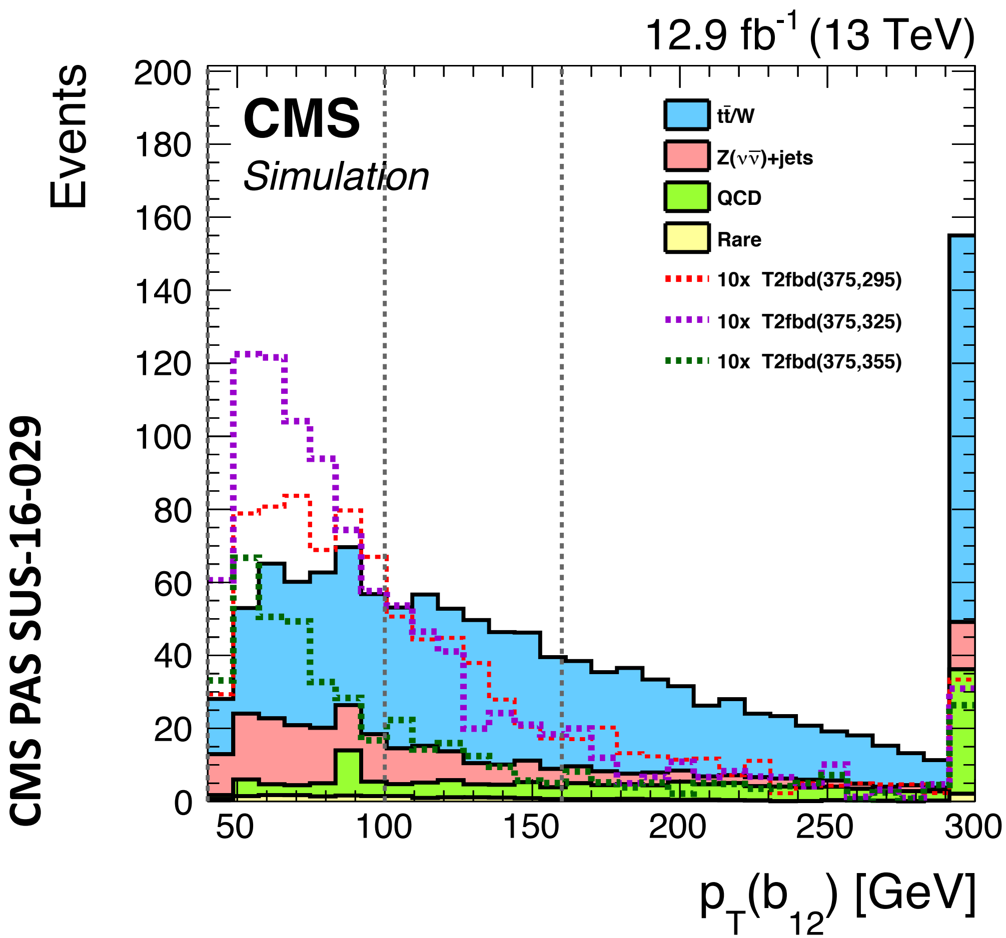
STOP FOUR BODY DECAYS







CMS: multi-jet



Compressed spectrum

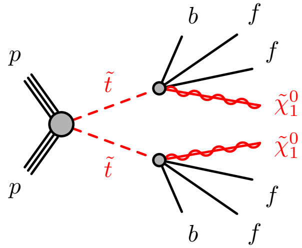
- **Select t_1 pairs recoiling against initial-state radiation** (ISR)

Selects events with **no** identified, isolated **lepton**

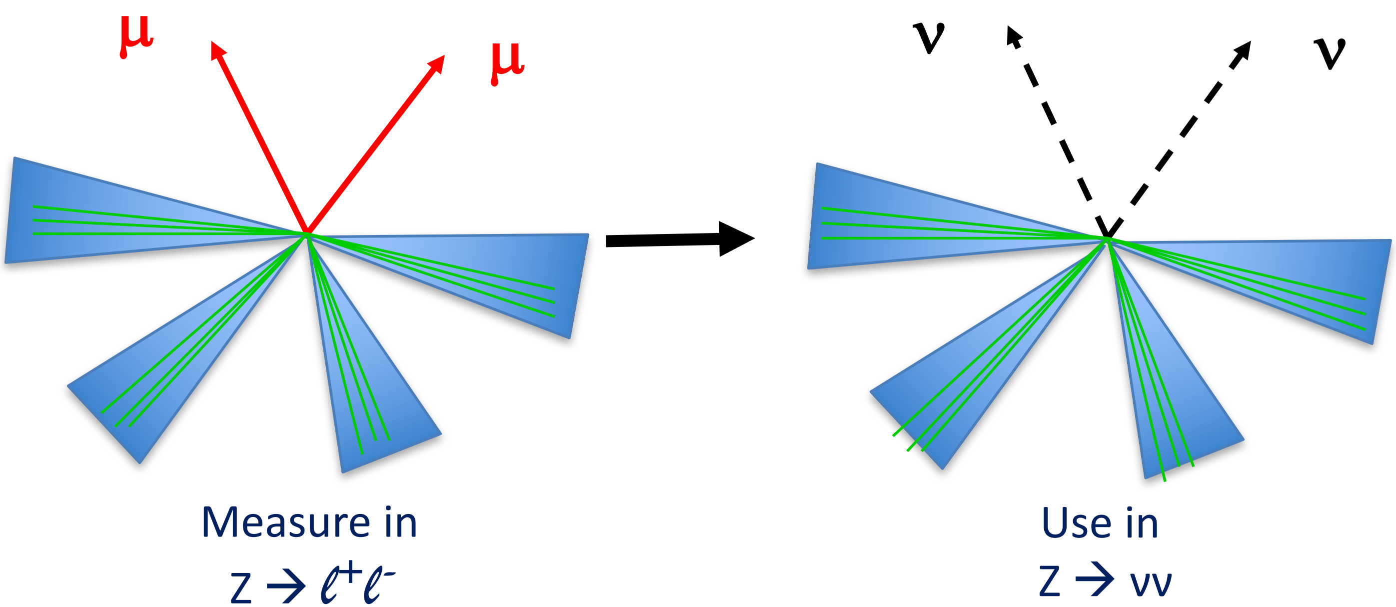
- E_T^{miss}> 250 GeV
- p_T^{ISR}> 250 GeV

Statistically combine multiple independent selections to maximise sensitivity

Consider: p_T^{ISR}, E_T^{miss}, N_{jet}, $N_{b\text{-}jet}$

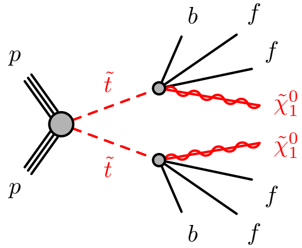


Predicting Z→νν + jets



Measure the normalization

- Good match (same process)
- Statistics limited



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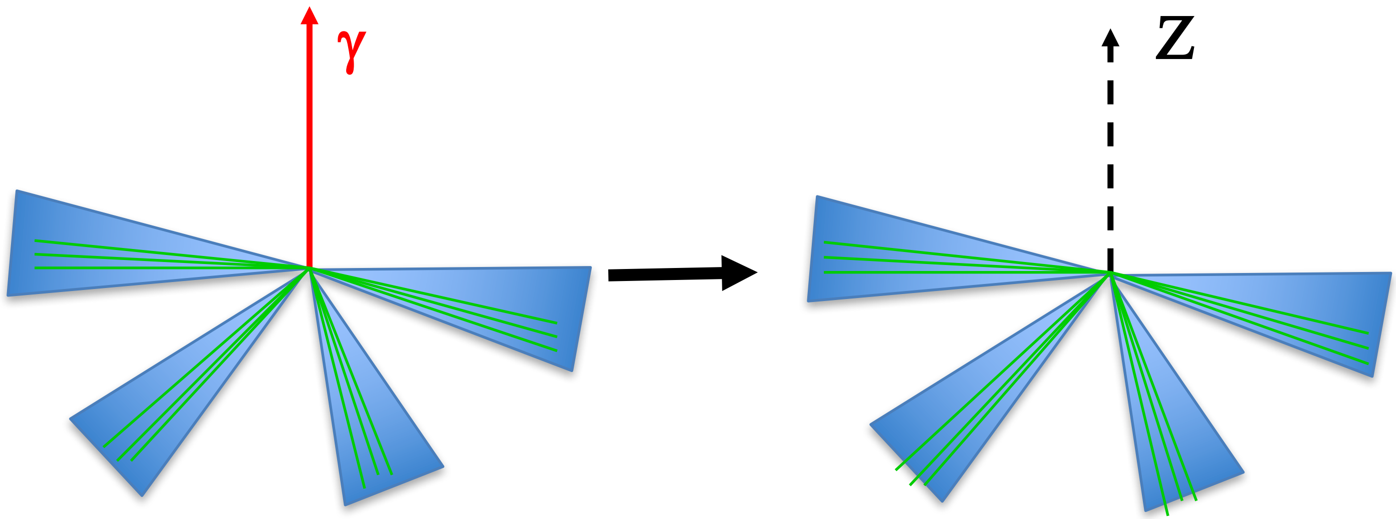
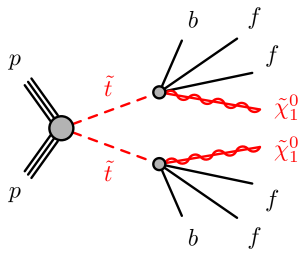


Measure in
γ + jets

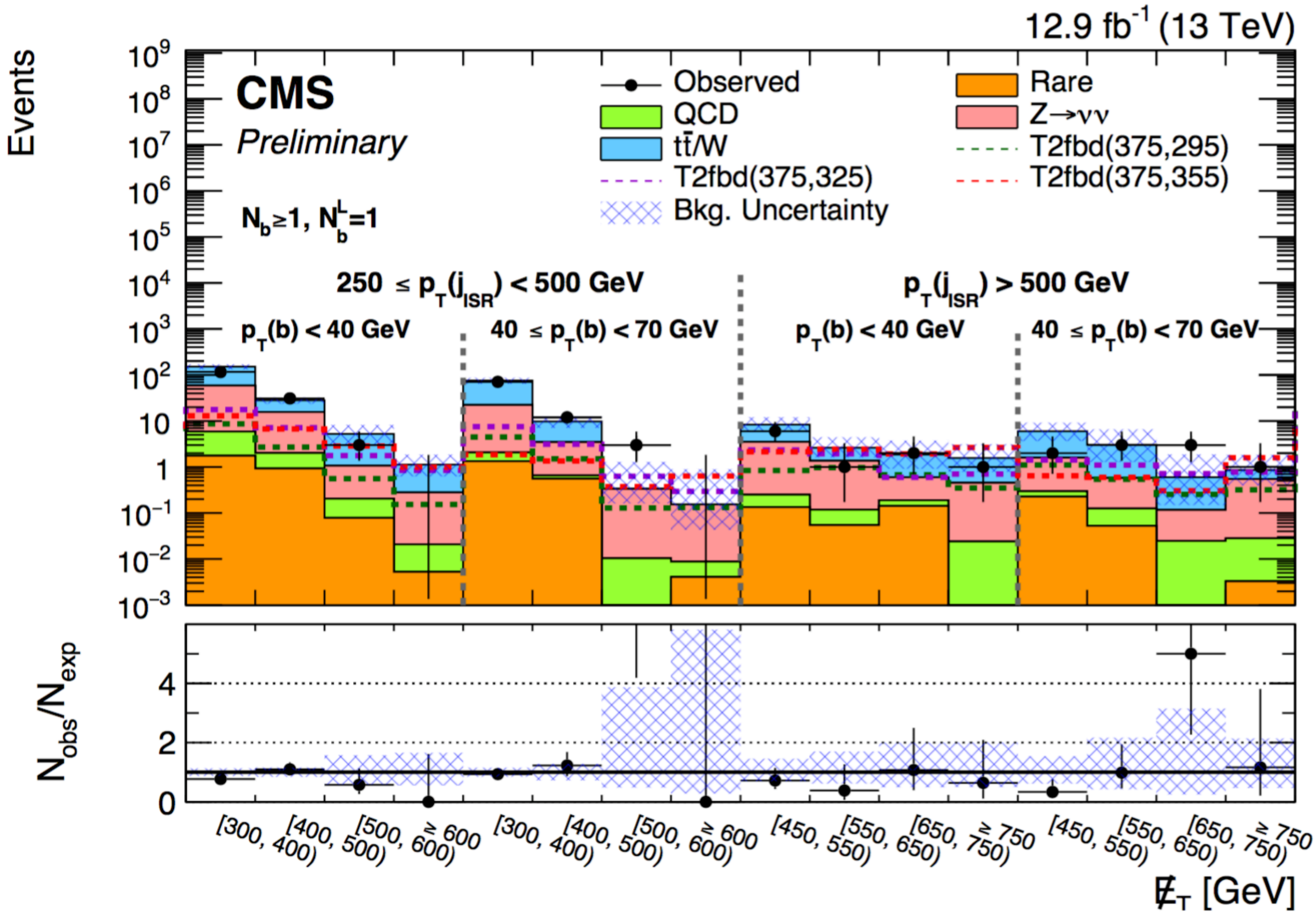
Use in
Z+jets

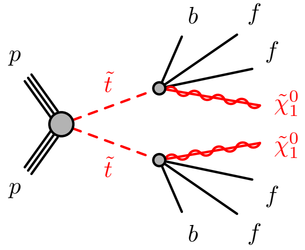
Measure the kinematic distributions

- Add γ to E_T^{miss}
- Plenty of statistics
- Valid for $p_T(\gamma)$ > 130 GeV

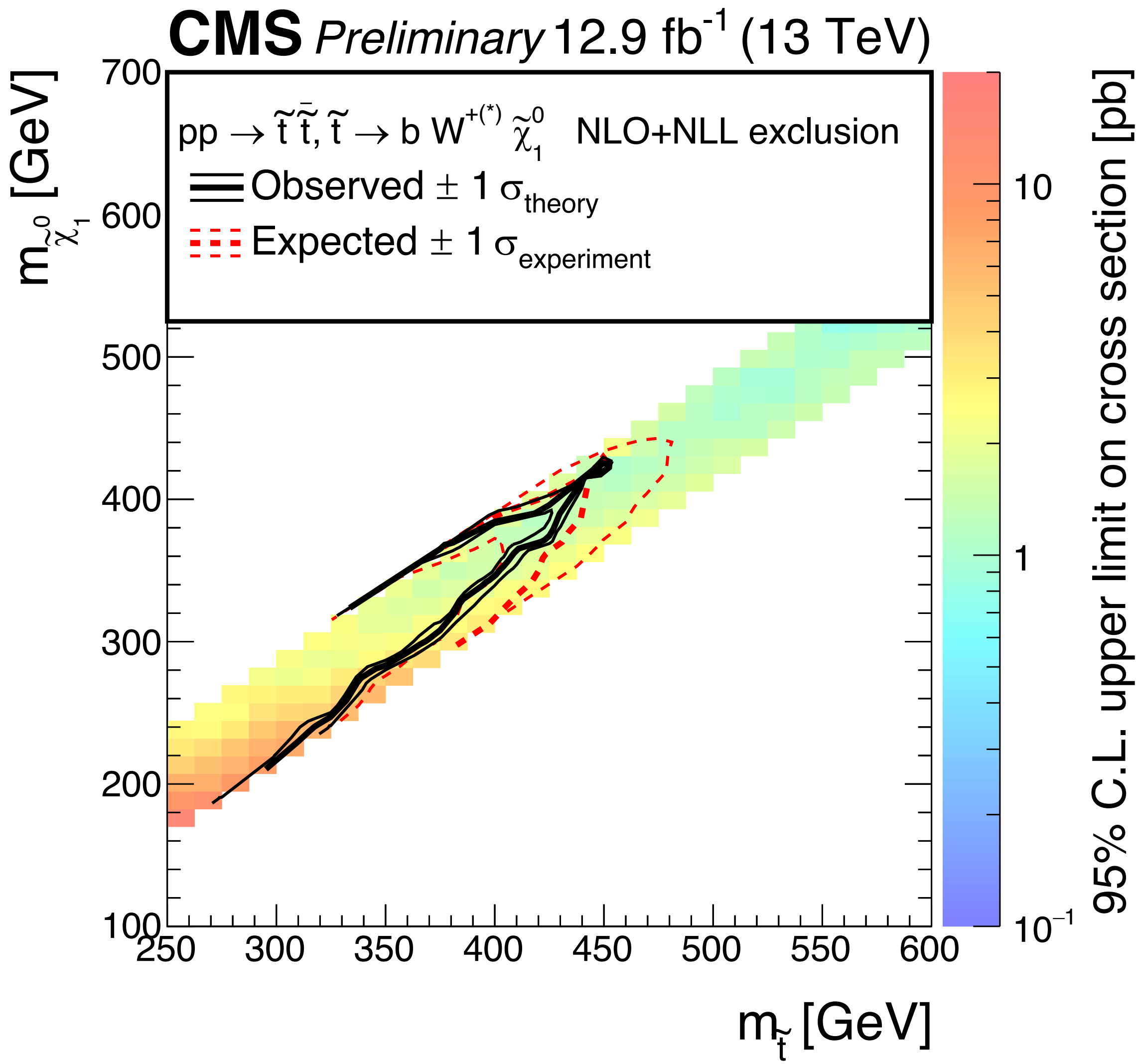


Observation





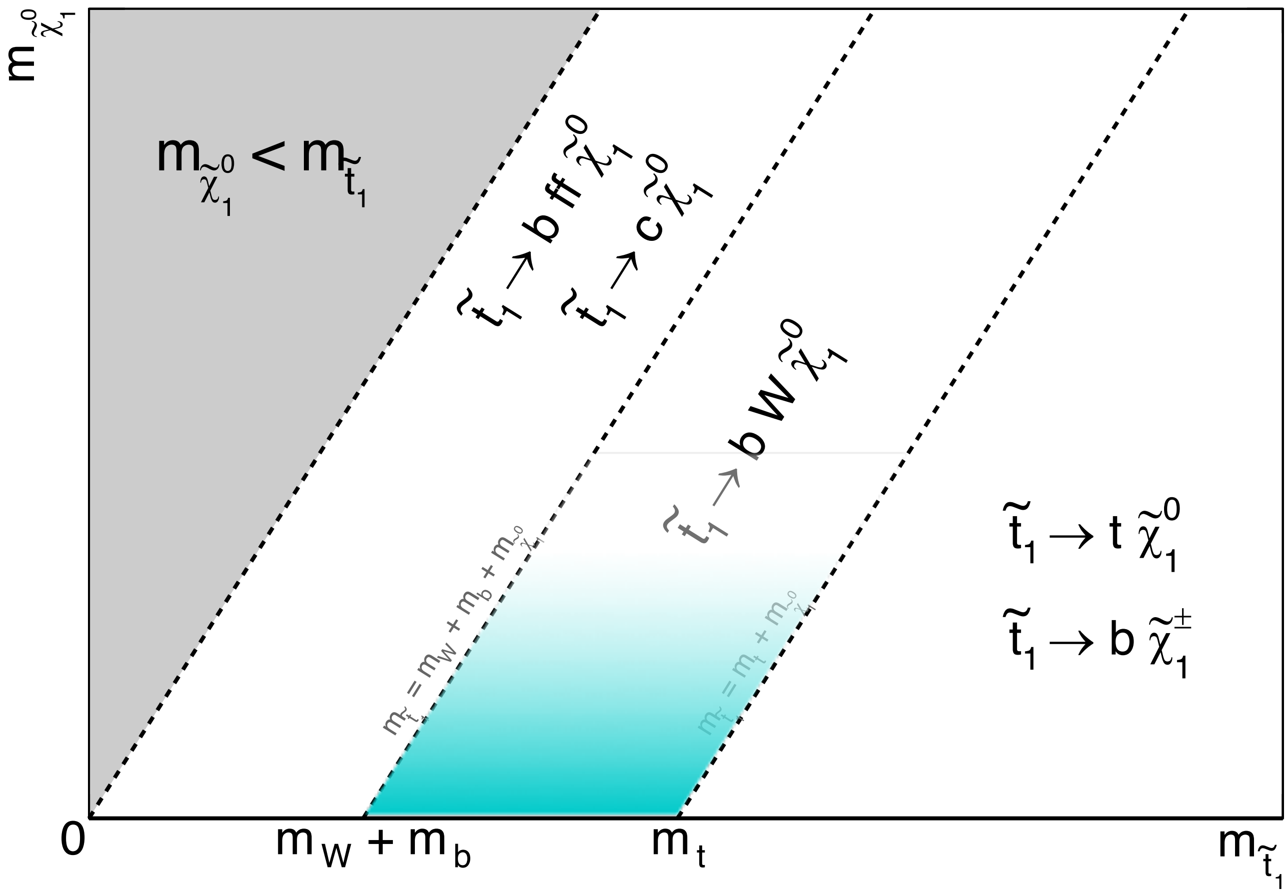
Interpretation

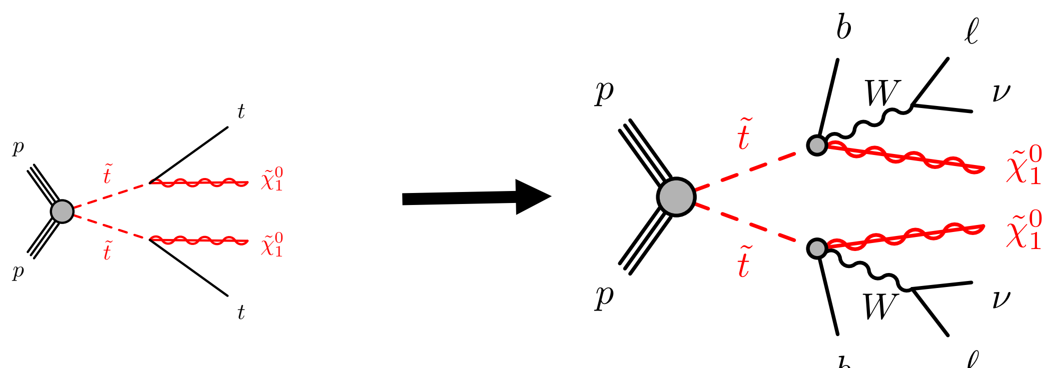


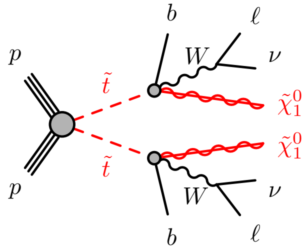
Data has been found in agreement with SM predictions.

- All SR bins are fit simultaneously in order to **evaluate the cross section excluded at 95% CL**.
- If the 95% upper limit on the production cross section is below the theoretical cross section, the signal models are considered to be excluded by the analysis.

STOP THREE BODY DECAYS







ATLAS: two leptons

Search aimed at scenarios

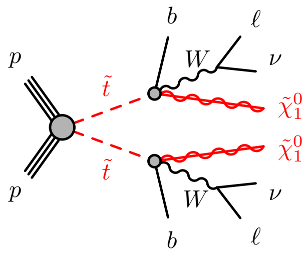
$$m(W) < \Delta m(t_1, \chi^0{}_1) < m(t)$$

- Doesn't use ISR to boost objects
- b-jets often too soft to be reconstructed or identified
  - Consider only the two leptons and the E_T^{miss}

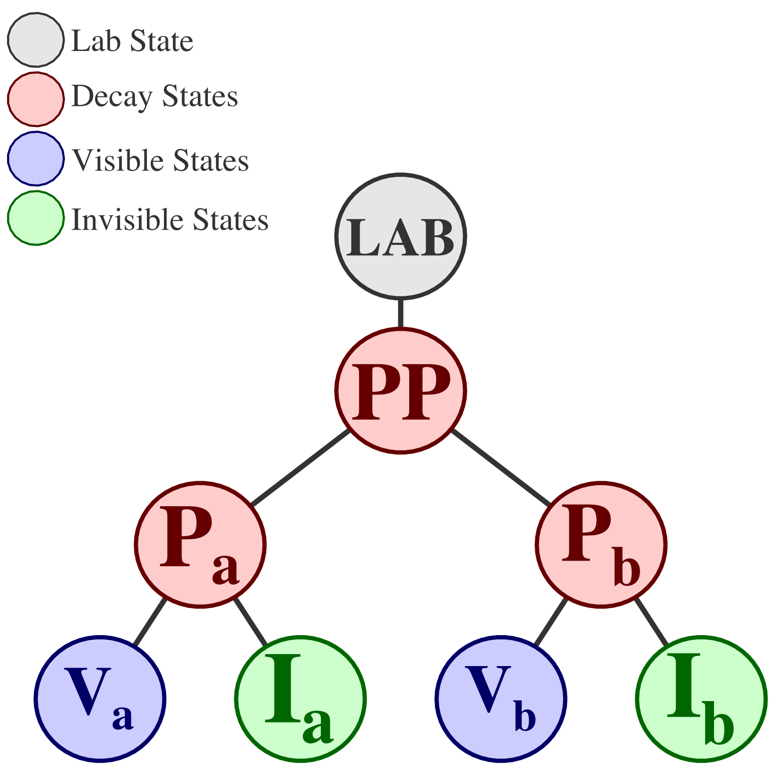
ATLAS-CONF-2016-076

Selection based on "recursive jigsaw" (RJR) variables

- A special technique to reconstruct the decay chain of a system with multiple invisible particles
- **First implementation in ATLAS for ICHEP**

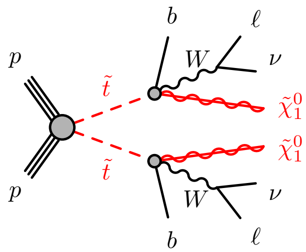


The Recursive Jigsaw

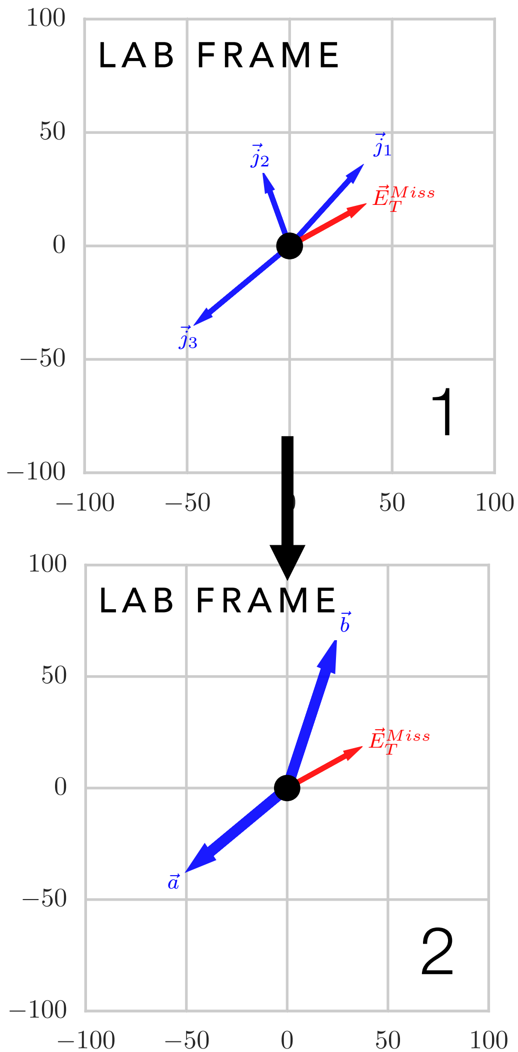


The Recursive Jigsaw Reconstruction provides an approximate way to solve kinematic ambiguities, **assuming a known decay tree**.

- unknown longitudinal momenta
- combinatorial ambiguities
- kinematic ambiguities (from multiple invisible objects)



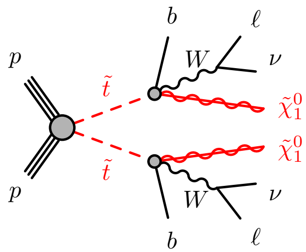
The Recursive Jigsaw



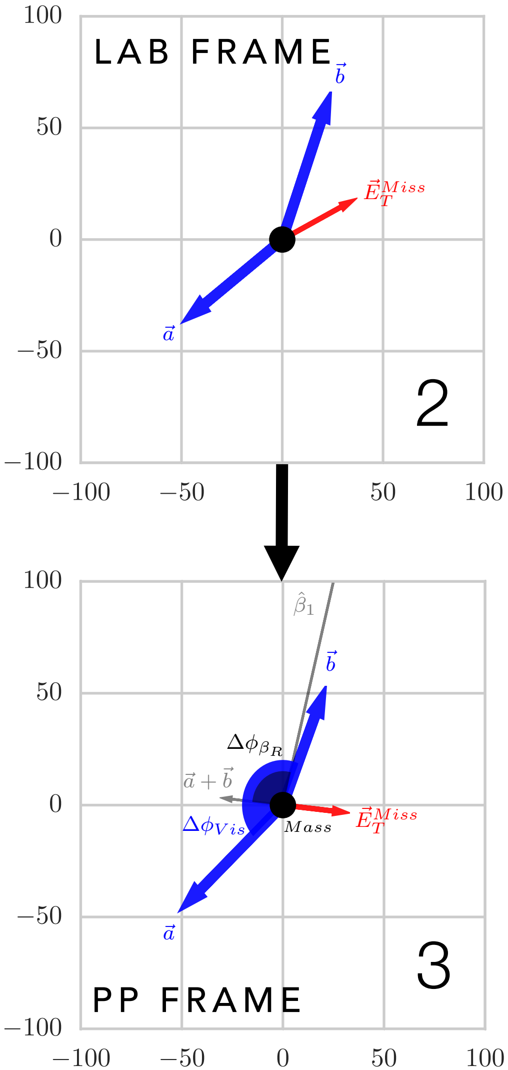
Figures by L.Lee

- Each decay step is solved by simultaneously **minimizing the masses of two daughter systems**
- Boost into the new reference frame
- Split the invisible momentum between the two

Kinematic variables are built to be invariant for longitudinal boosts



The Recursive Jigsaw



Figures by L.Lee

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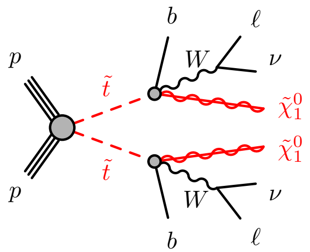
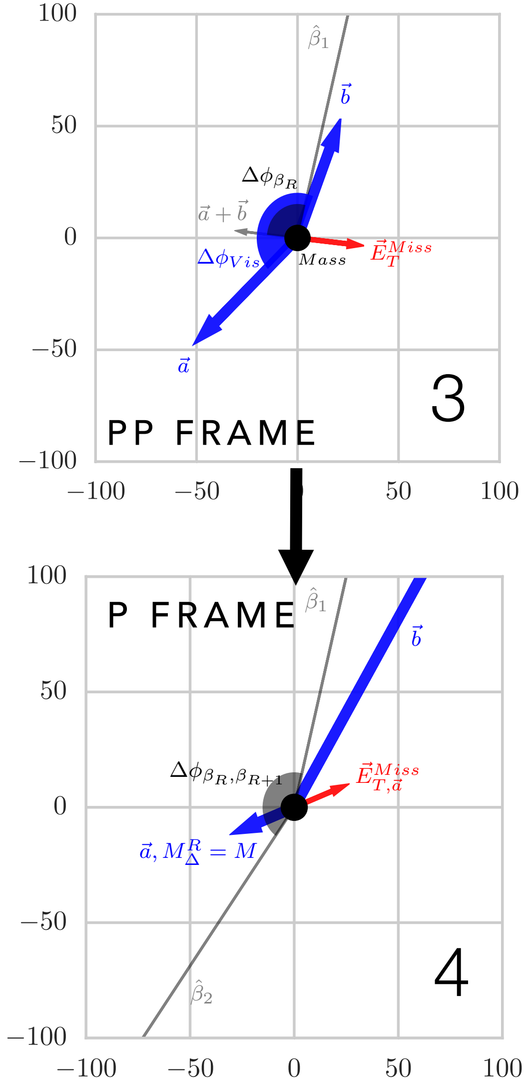


The Recursive Jigsaw



Figures by L.Lee

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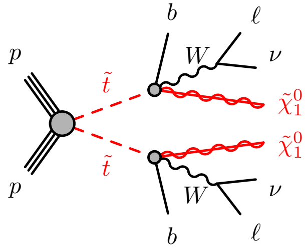


Discriminating Variables

$$R_{p_T} = \frac{|\vec{J}_T|}{|\vec{J}_T| + \sqrt{\hat{s}}_R/4}$$

R_{pT}: **ratio of *J*** (vector sum of the momenta of all visible particles and E_T^{miss}) **and *J + s*$_R$** (approximate centre of mass energy in the *PP* frame)

- Since only the leptons are considered in the visible system the *J* will be over-estimated in events with additional activity, i.e. signal and top-quark production.

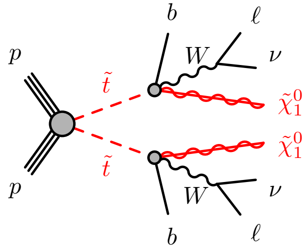
$$1/\gamma_{R+1}$$

Inverse of the Lorentz factor associated with the **boosts from the *PP* frame to the two decay frames** of the parent particles.

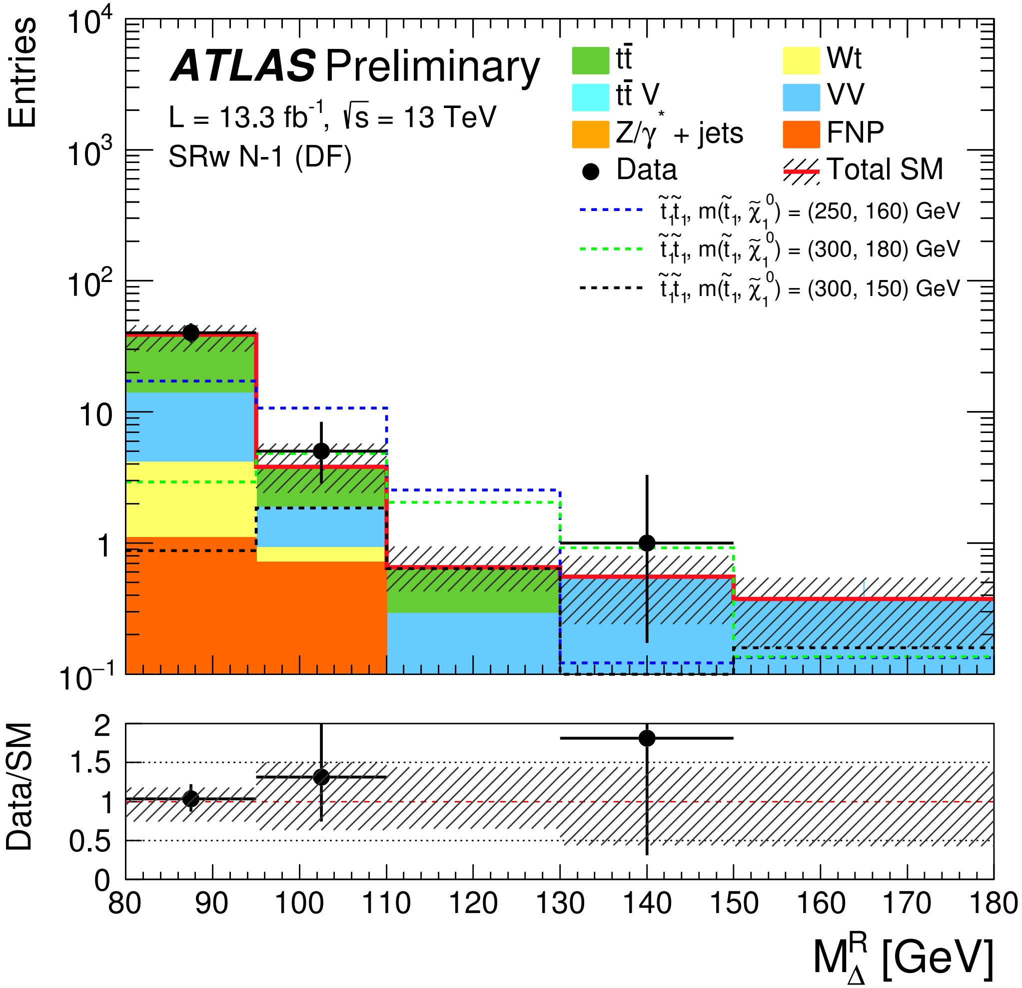
- Tending towards unity when visible particles are equal in momenta and collinear

$$M_\Delta^R = \frac{\sqrt{\hat{s}}_R}{\gamma_{R+1}}$$

This variable has a **kinematic end-point proportional to the mass-splitting** between the parent particle and the invisible particle.



Two leptons results



Two Signal Regions for:

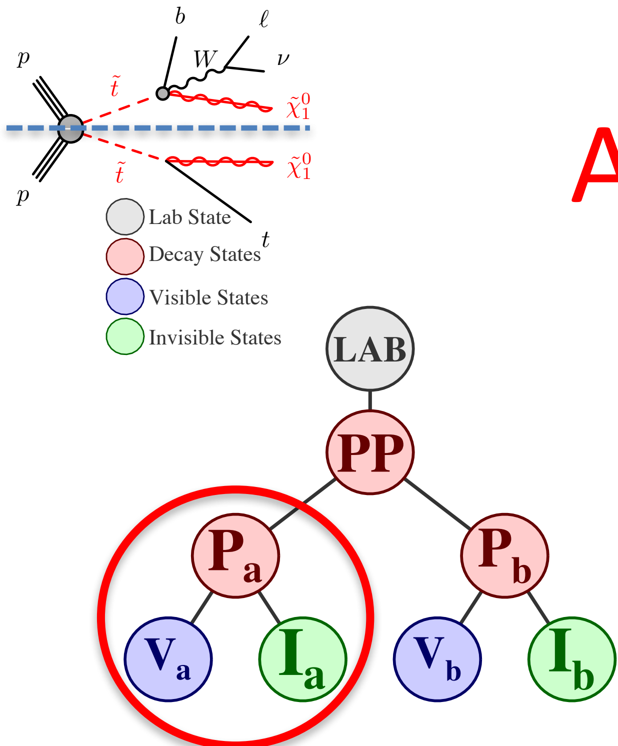
- $\Delta m(t_1, \chi^0{}_1) \sim m(W)$
- $\Delta m(t_1, \chi^0{}_1) \sim m(t)$

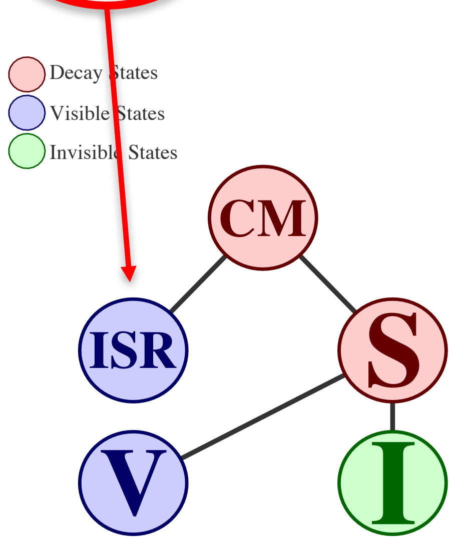
MC driven control regions for top and vector bosons pairs.

No discrepancy with respect to SM predictions found.

Region	SR_W^{3-body}-DF
Observed events	6
Total Standard Model	5.3 ± 2.2
Fitted $t\bar{t}$	2.3 ± 1.4
Wt	0.21 ± 0.08
$t\bar{t}\ V$	0.10 ± 0.03
Fitted VVDF	2.1 ± 1.1
Fitted VVSF	—
Z/γ^*+jets	—
Fake and non-prompt	0.58 ± 0.12

ATLAS: multi-jet





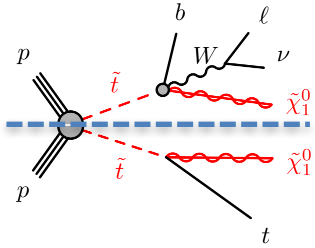
ATLAS-CONF-2016-077

The same RJR technique can be applied to the very challenging scenario $\Delta m(t_1, \chi^0_1) \sim m(t)$.

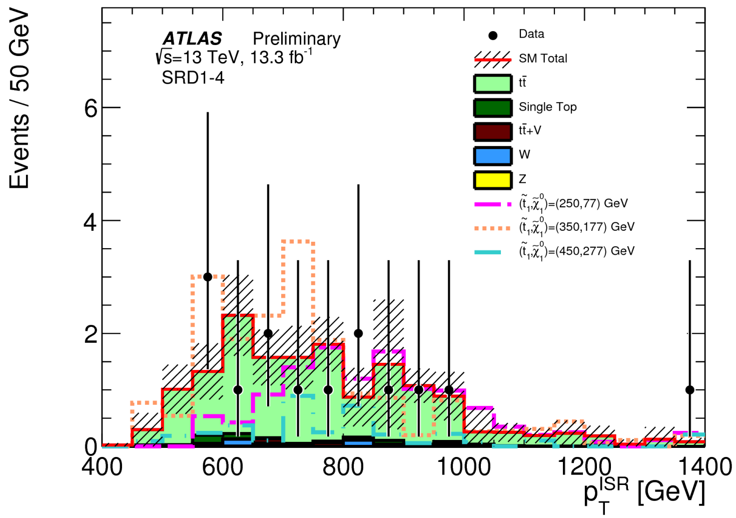
- signal topology extremely similar to SM $t\bar{t}$ production
- ISR-jet based approach to improve discrimination.

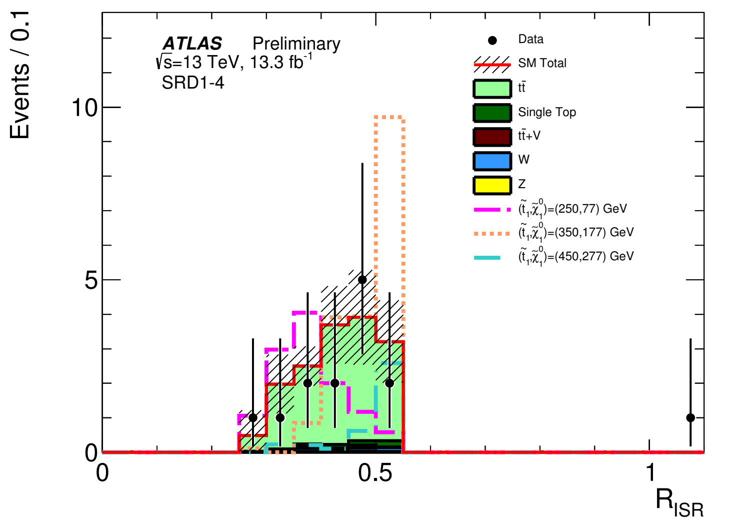
The RJR recovers efficiency in events with multiple ISR jets.

- $N_S \geq 5$ jet
- $M_T^S > 300$ GeV
- $\Delta\phi_{ISR} > 3$ radians
- $p_T^{ISR} > 400$ GeV
- $p_T^{b\text{-}tag,S} > 40$ GeV
- $p_T^{jet4,S} > 50$ GeV



ATLAS: multi-jet





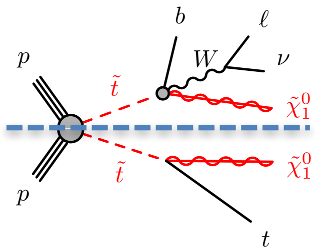
$$R_{\mathrm{ISR}} \equiv \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{p_{\mathrm{T}}^{\mathrm{ISR}}} \sim \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{t}}}$$

The final discriminant, R_{ISR} is sensitive to the mass scale of the invisible particle.

- Multiple signal regions to target different models

	SRD1	SRD2	SRD3	SRD4
Observed	4	5	9	9
Total SM	4.3 ± 1.9	7.1 ± 3.2	8.8 ± 3.4	9.4 ± 3.7

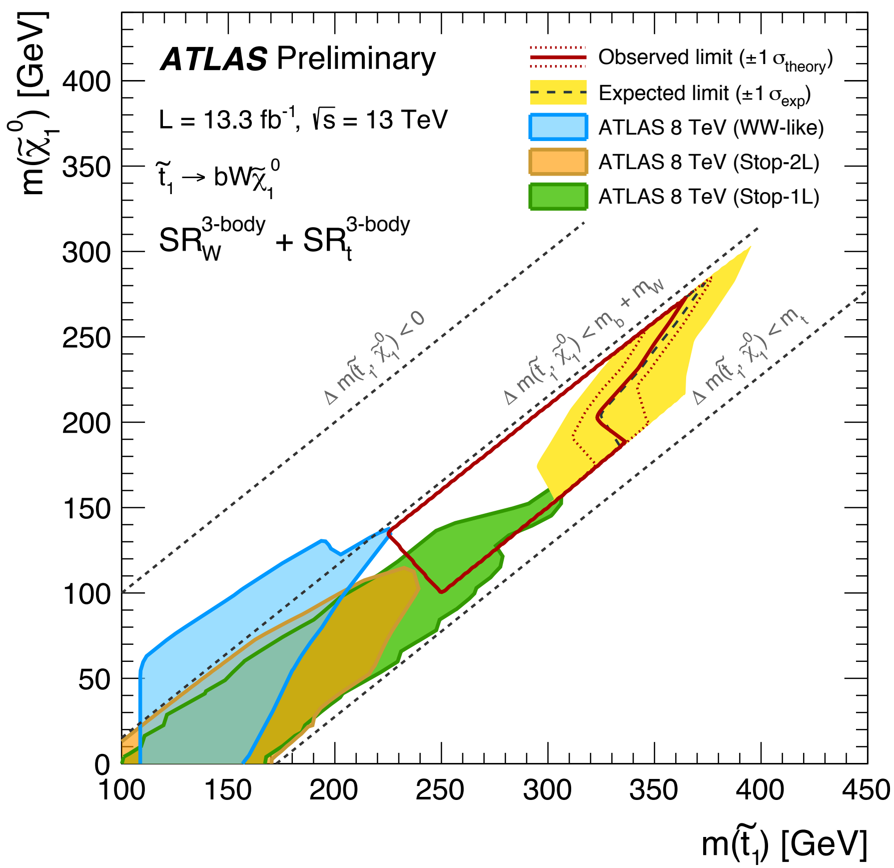
	SRD5	SRD6	SRD7	SRD8
Observed	11	6	5	1
Total SM	11.6 ± 3.6	8.6 ± 3.5	5.2 ± 2.1	2.56 ± 0.86

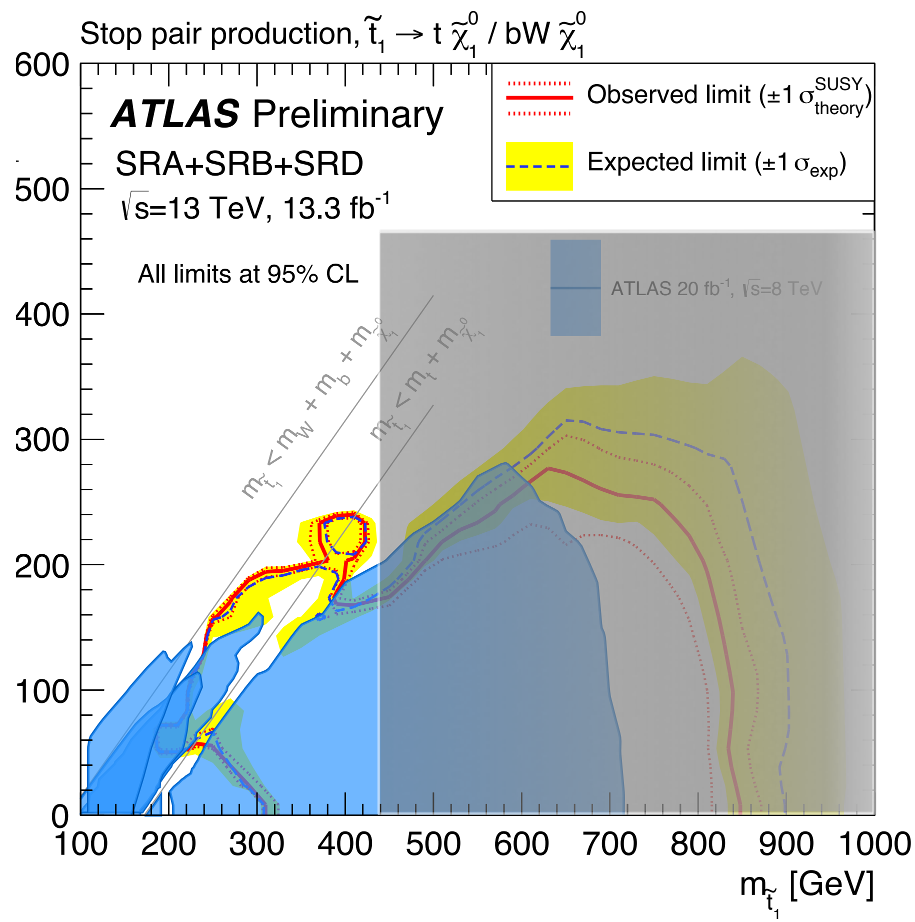


Interpretation

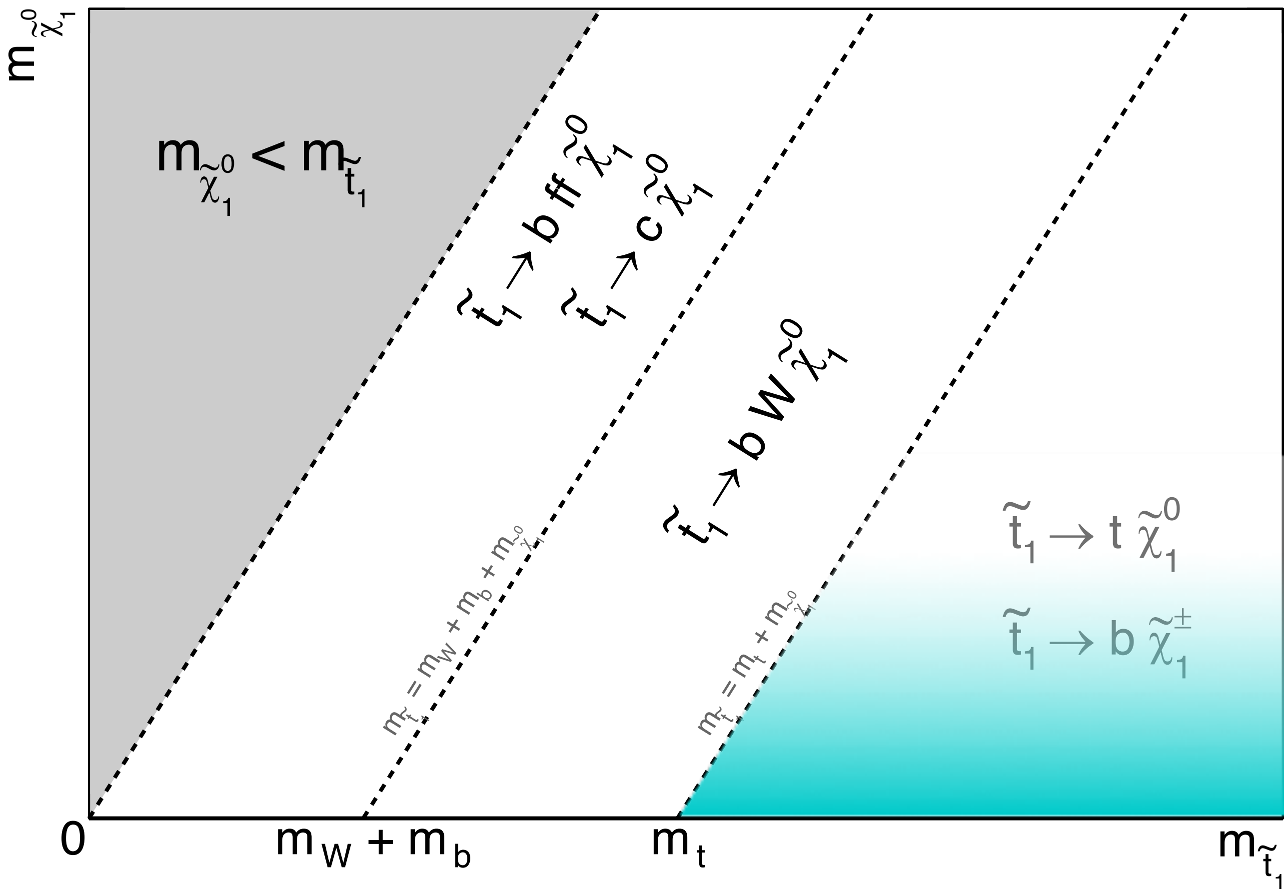
Data has been found in agreement with SM predictions.

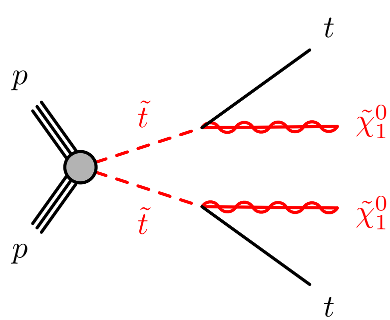
- Limits **at 95% CL** are derived using the best expected performing SR for each signal model

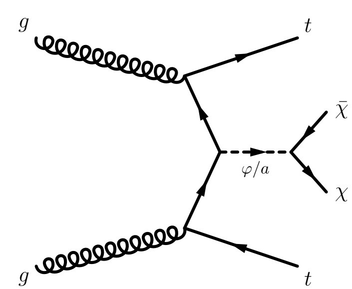


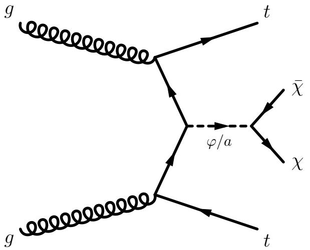


DARK MATTER AND STOP TWO BODY DECAYS





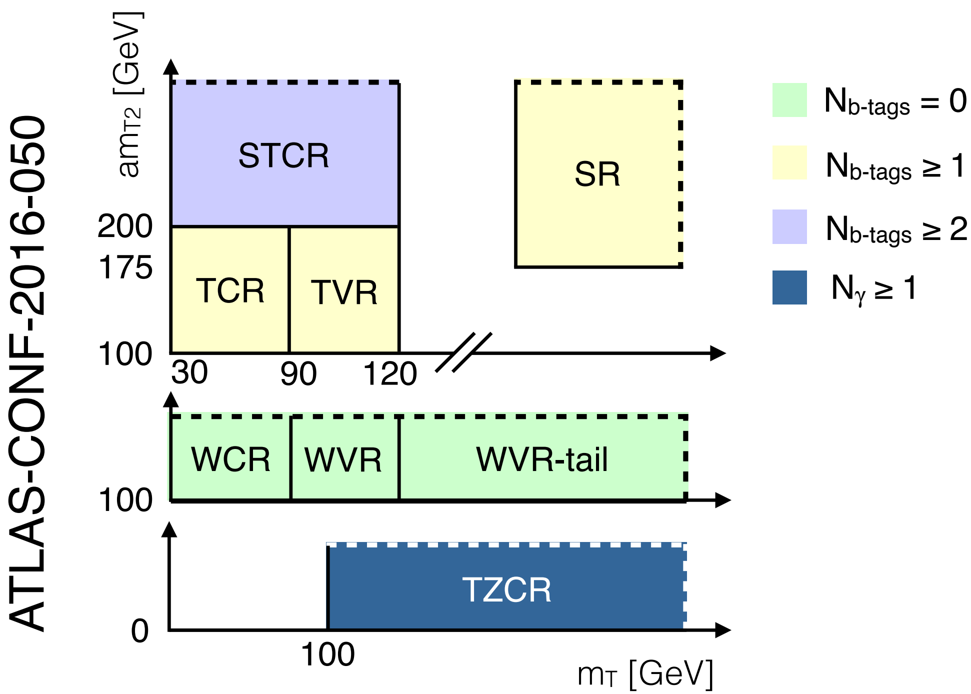




ATLAS: single lepton

Search targeting DM, heavy stop (direct and 1-step decays)

- Baseline selection requires 1 lepton, 4 jets, b-jets, high m_T



Dedicated CRs for:

- W+jets
- Ttbar
- single top