Direct searches for a scalar top partner with the ATLAS detector at 13TeV

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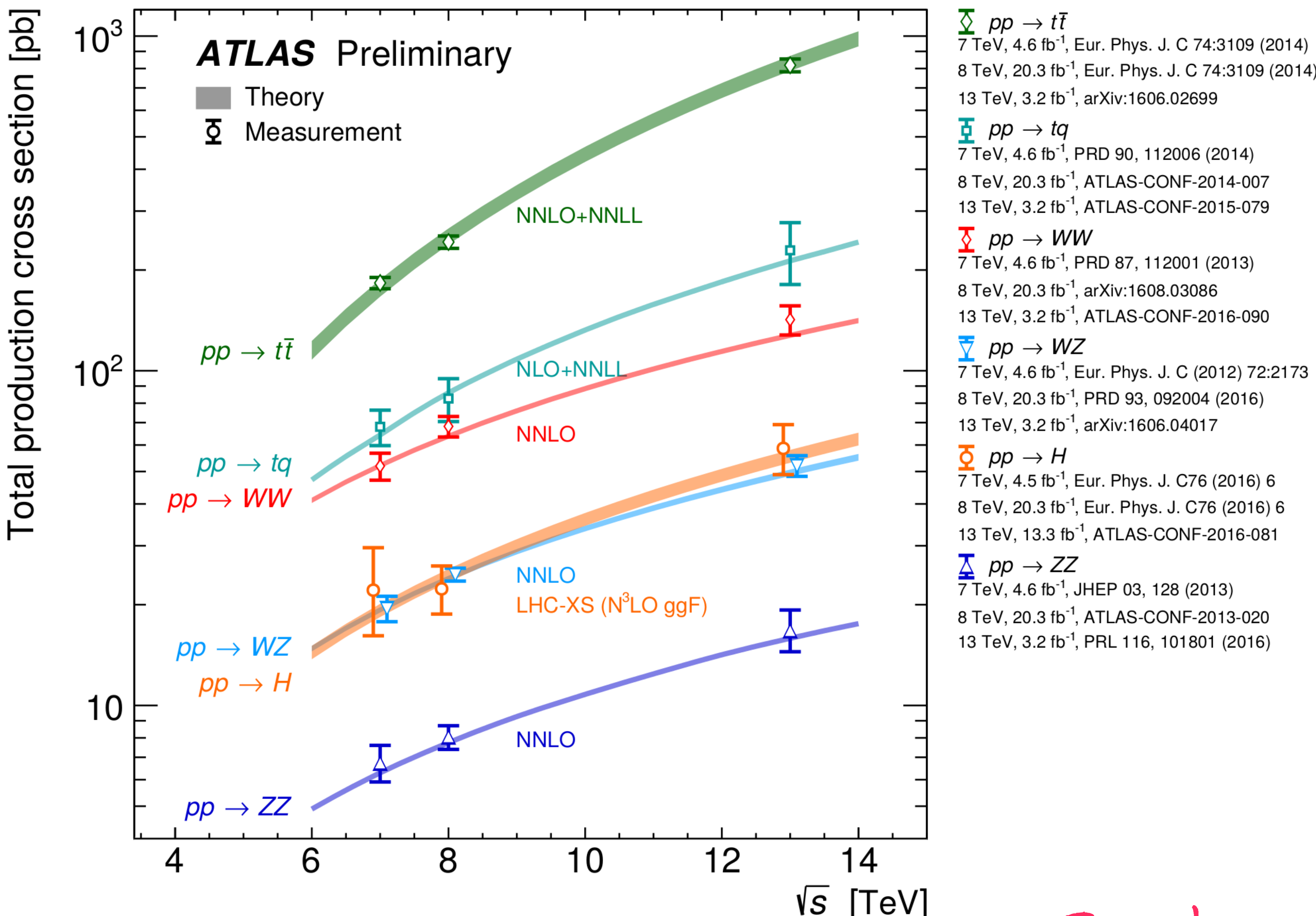
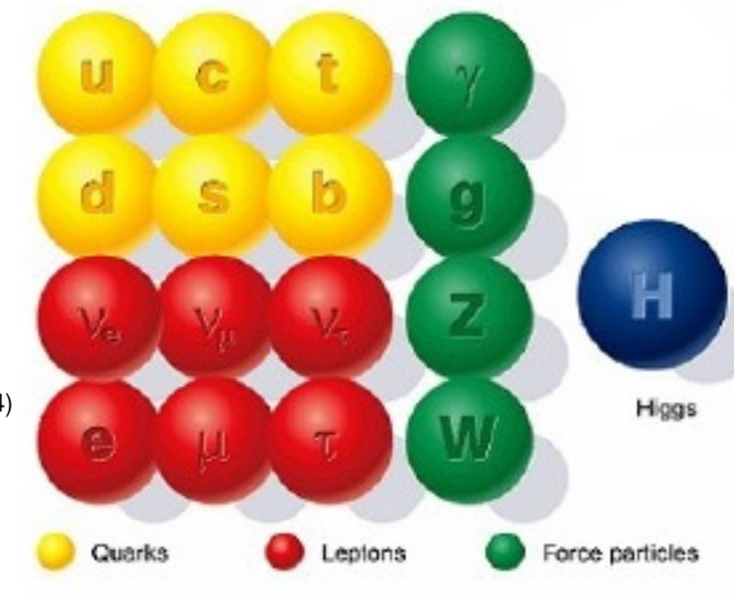
Standard Model

- Very successful theory
- Precise predictions, verified by experiments

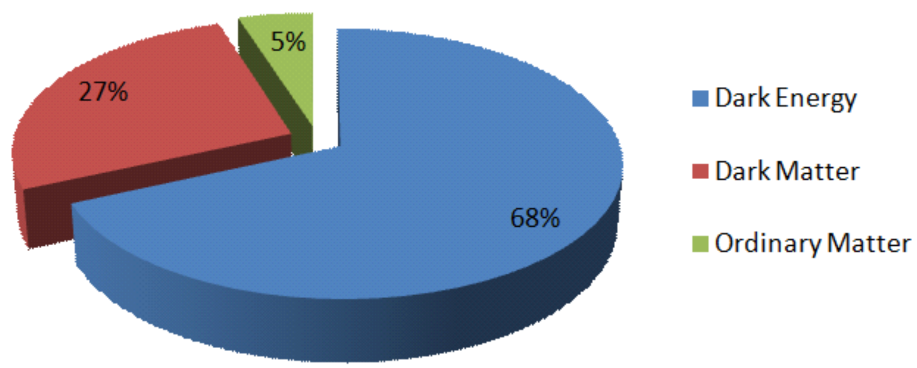


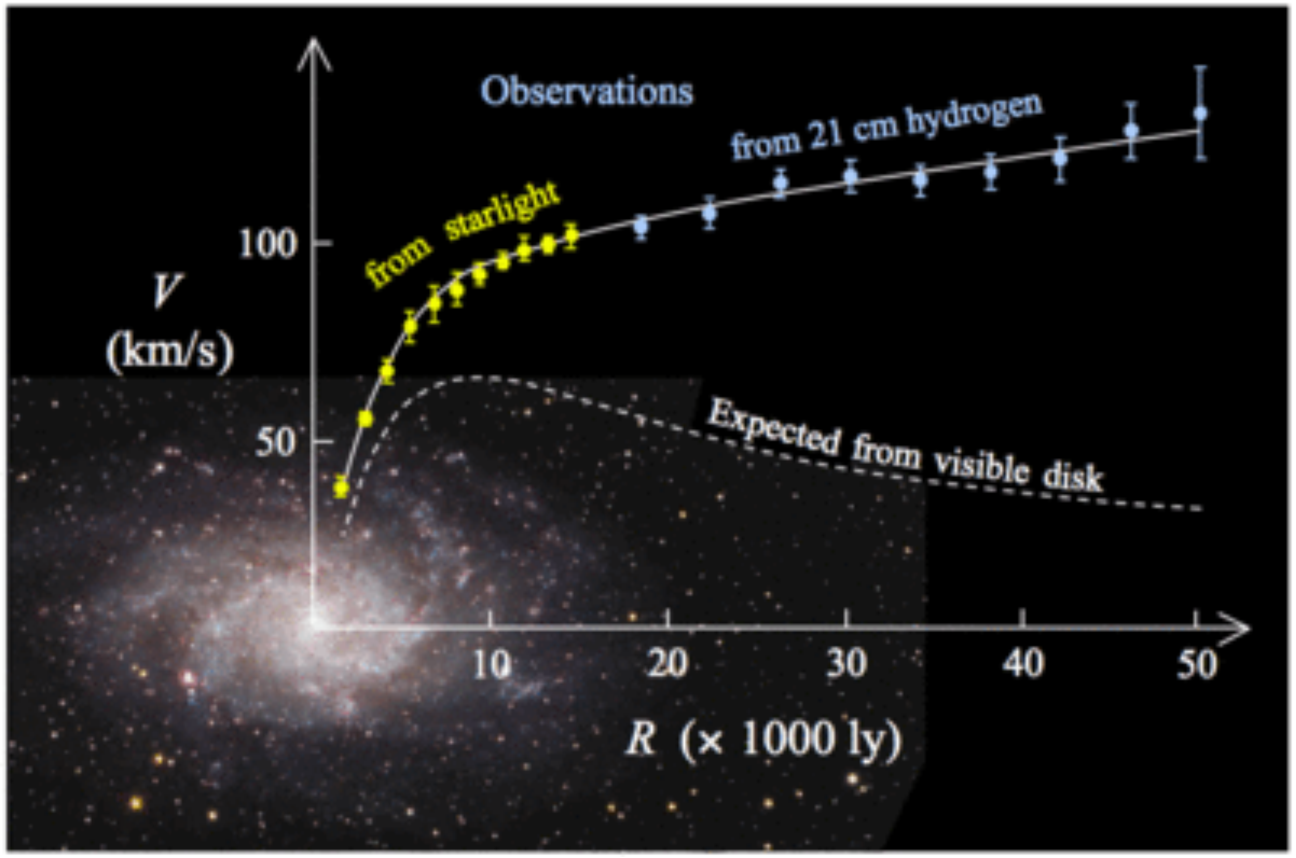


So why care about SUSY?

Dark Matter

- Strong evidence for the existence of Dark Matter from astronomical and cosmological observations



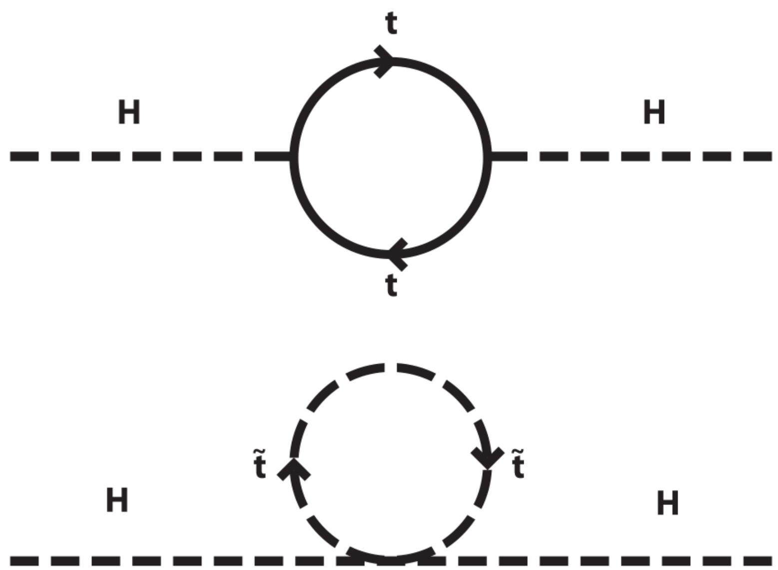


astro-ph/0608407

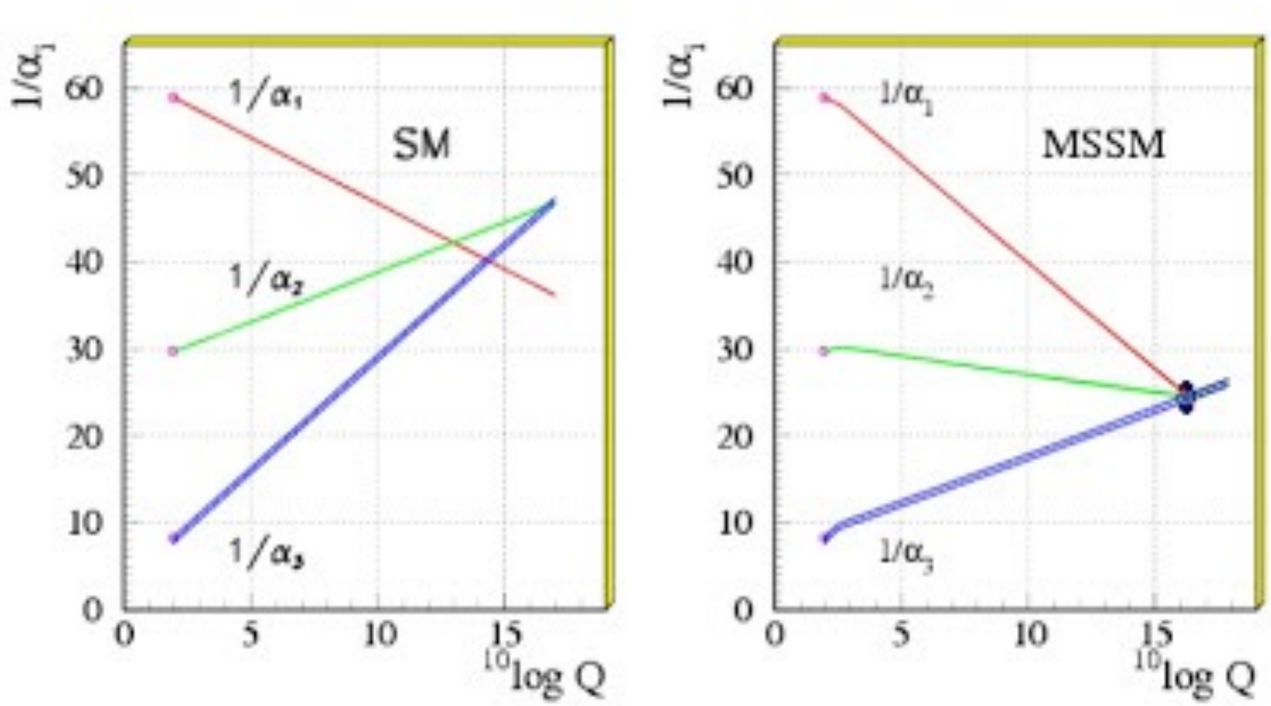
- What is the particle content of DM?
- Can we produce it at the LHC?
- SUSY provides a DM candidate

Hierarchy problem and unification

- Presence of scalar top partner cancels quadratic radiative corrections and protect Higgs mass (providing a solution to the hierarchy problem)



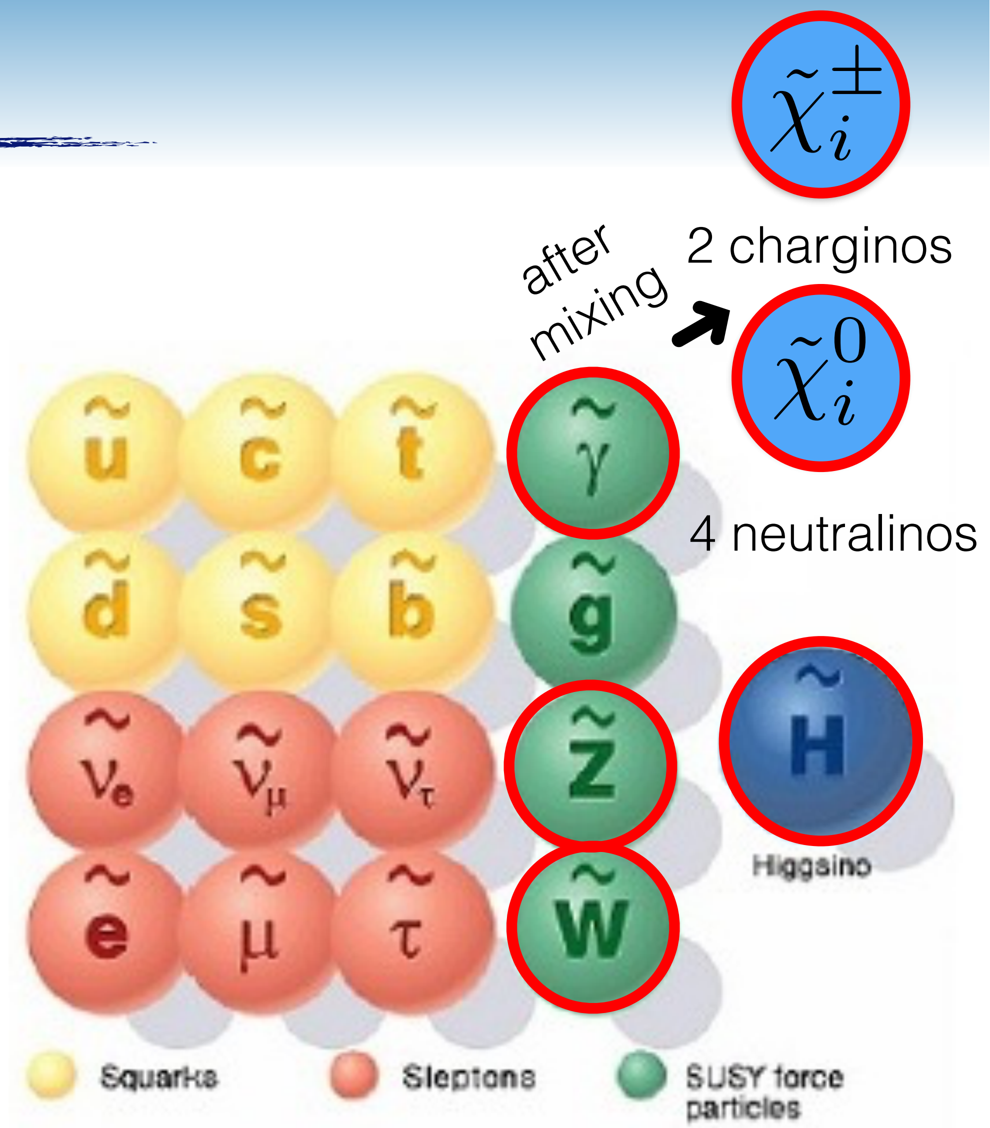
- Unification of gauge couplings



- Unification with gravity

Brief introduction to SUSY

- Features of SUSY
  - Superpartner for every SM particle
  - Scalar partner for SM fermion
  - Fermion for SM gauge boson

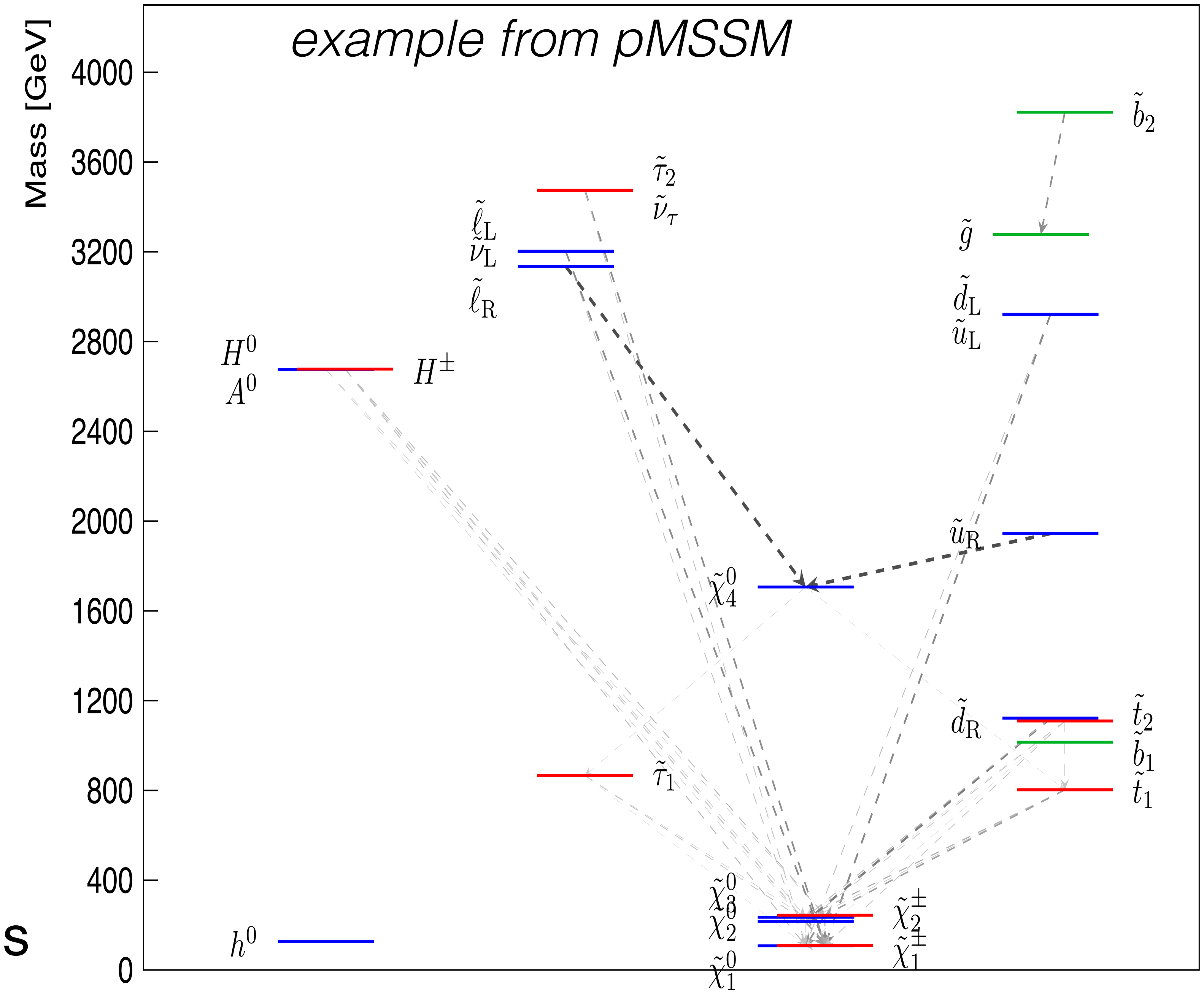


- R-parity: $R=(-1)^{3(B-L)+2S}$
  - if conserved:
  - Sparticles are produced in pairs
  - Lightest Supersymmetric Particle (LSP) *serves as DM candidate*
  - stable, electrically neutral which interacts weakly with SM particles ➜ ETmiss signature

- If SUSY was an exact theory, we would have observed Superpartners
- SUSY must be a broken symmetry
- ~100 free parameters in SUSY

SUSY parameter space

- SUSY is very broad, masses and scales not specified
  - production cross section of SUSY particles depend ***only*** on mass assumptions

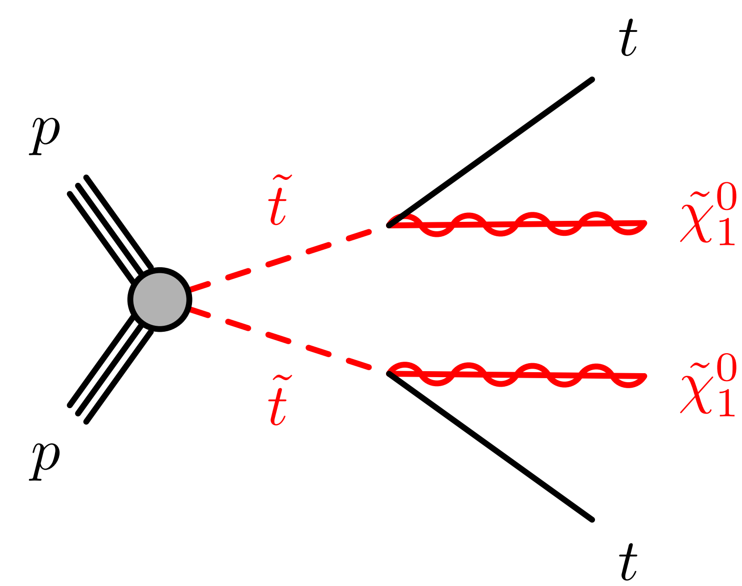


- A typical SUSY spectrum involves
  - many sparticles with different masses
  - many different possible ways to decay

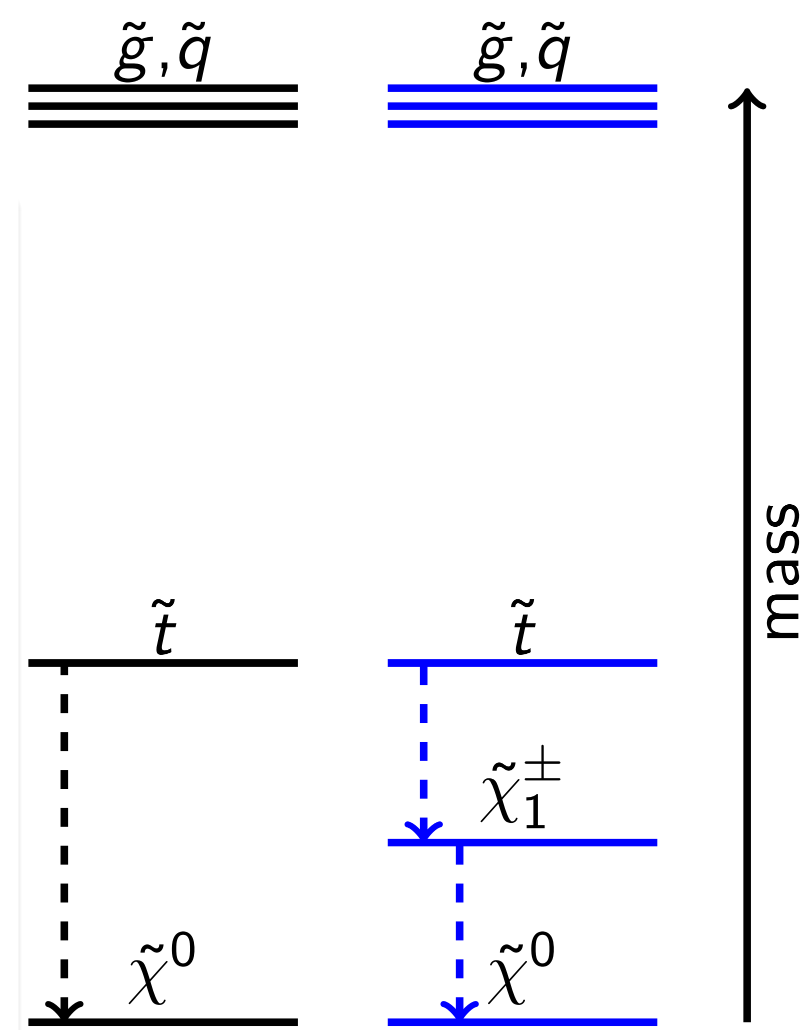
pMSSM: phenomenological Minimal SUSY Standard Model

Simplified models

- Focus on the experimental signature
  - emphasize on the basic kinematic properties that affect signal acceptance
  - leave aside competing productions and decay processes



- Interpretations are done with ***Simplified Models***
  - production of 2 sparticles: e.g. 2 stops
  - fix decay branching fraction: $\mathrm{BR}(\tilde{\mathrm{t}} \rightarrow \mathrm{t} + \tilde{\chi}_1^0) = 100\%$
  - fix mass relations between sparticles: $m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0)$
  - forget about all other sparticles

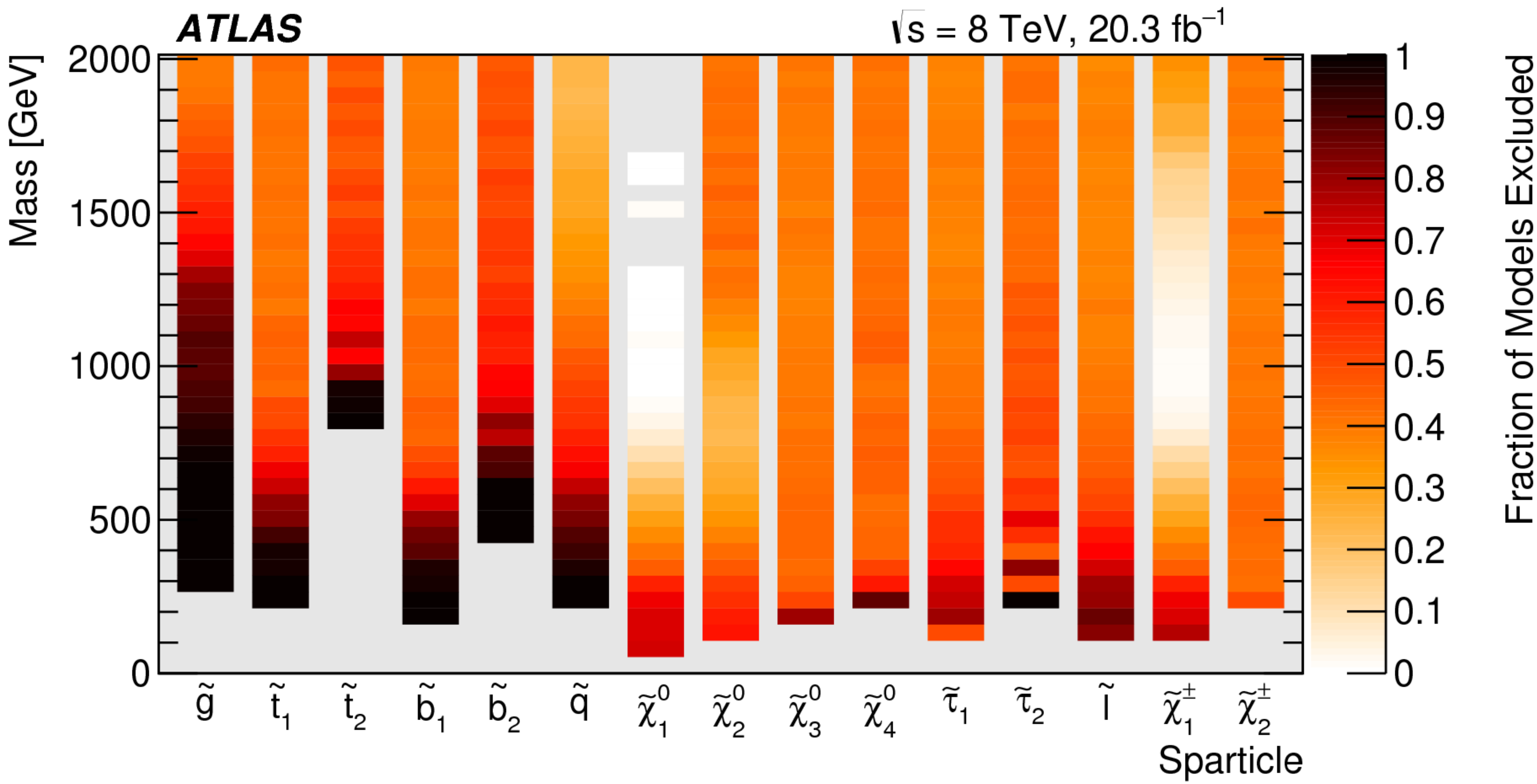


pMSSM interpretations from Run I

- Re-interpretation of 22 ATLAS SUSY analyses in a 19 parameter pMSSM model
- To be taken *cum grano salis*

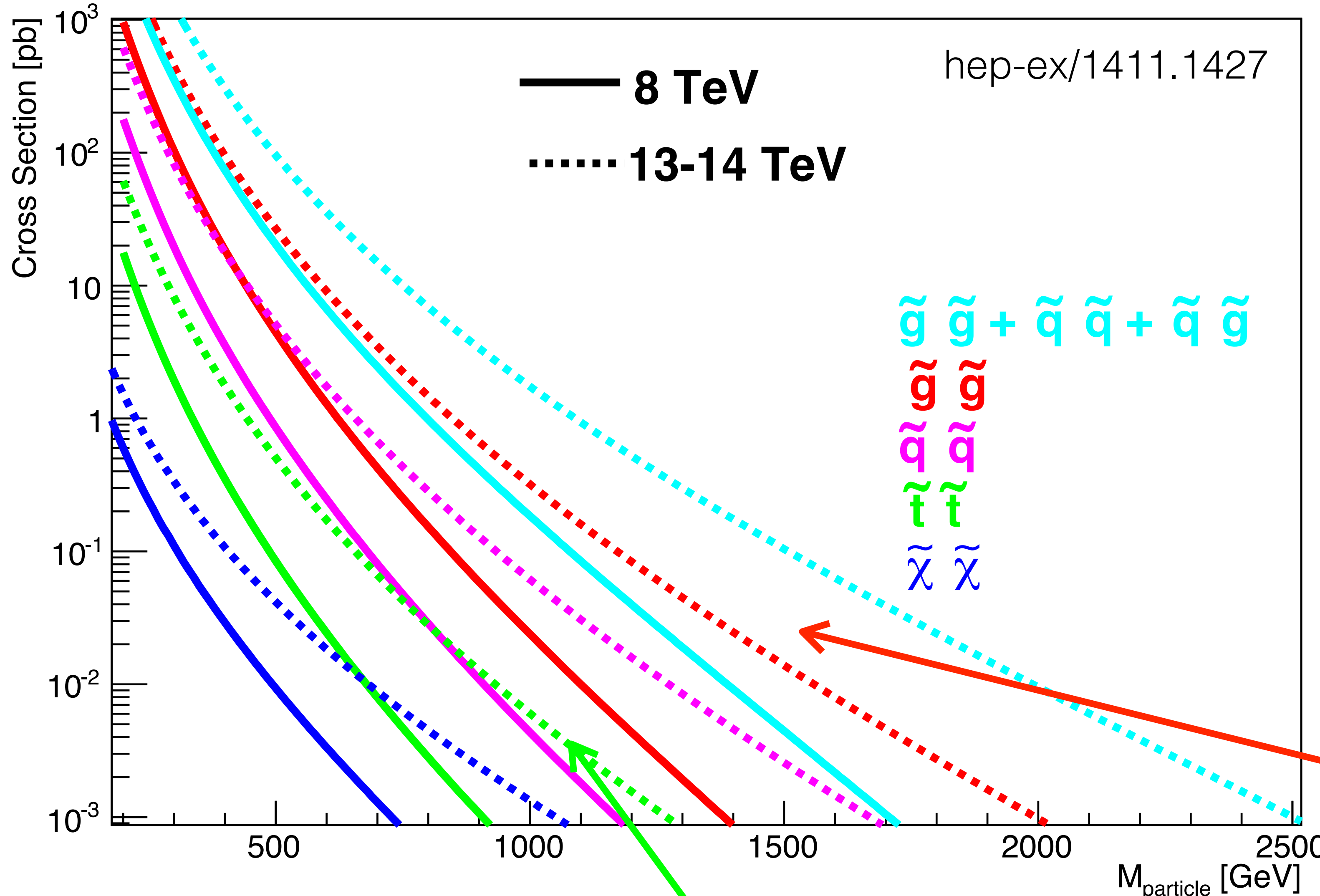
assumptions

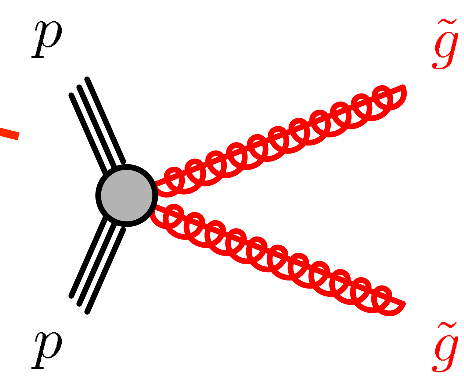
- ☑ R-parity conservation with neutralino being the LSP
- ☑ minimal flavor violation and no CP violation



500 millions pMSSM points randomly sampled, with ~300,000 models surviving theory and non-LHC experimental constraints

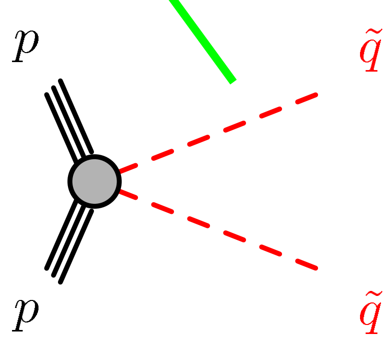
SUSY production cross sections at the LHC





gluino pair production

inclusive searches for squarks and gluinos



squarks pair production

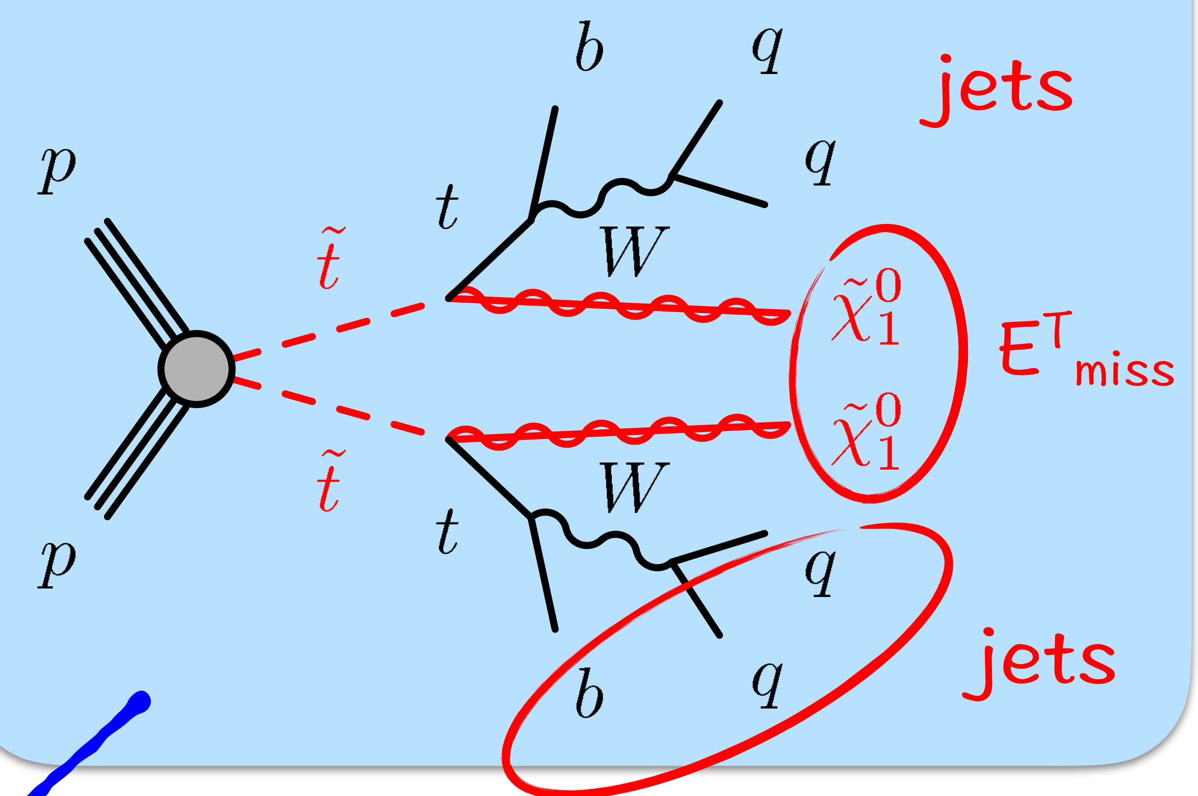
final state similar to SM bkg ($\tilde{t}$, $\tilde{b}$)

$8\ \text{TeV} \rightarrow 13\ \text{TeV} \Rightarrow \sigma(\text{SUSY})$ grows:

- $\sigma(\tilde{g}\tilde{g}) \times 30$ for $m_{\tilde{g}} = 1.4$ TeV
- $\sigma(\tilde{t}\tilde{t}) \times 8$ for $m_{\tilde{t}} = 700$ GeV
- $\sigma(\tilde{\chi}\tilde{\chi}) \times 4$ for $m_{\tilde{\chi}} = 500$ GeV

Signals of interest: stop decays

$$\tilde{t} \rightarrow t\ \tilde{\chi}_1^0\ with\ \Delta M(\tilde{t}, \tilde{\chi}_1^0) > m(t)$$

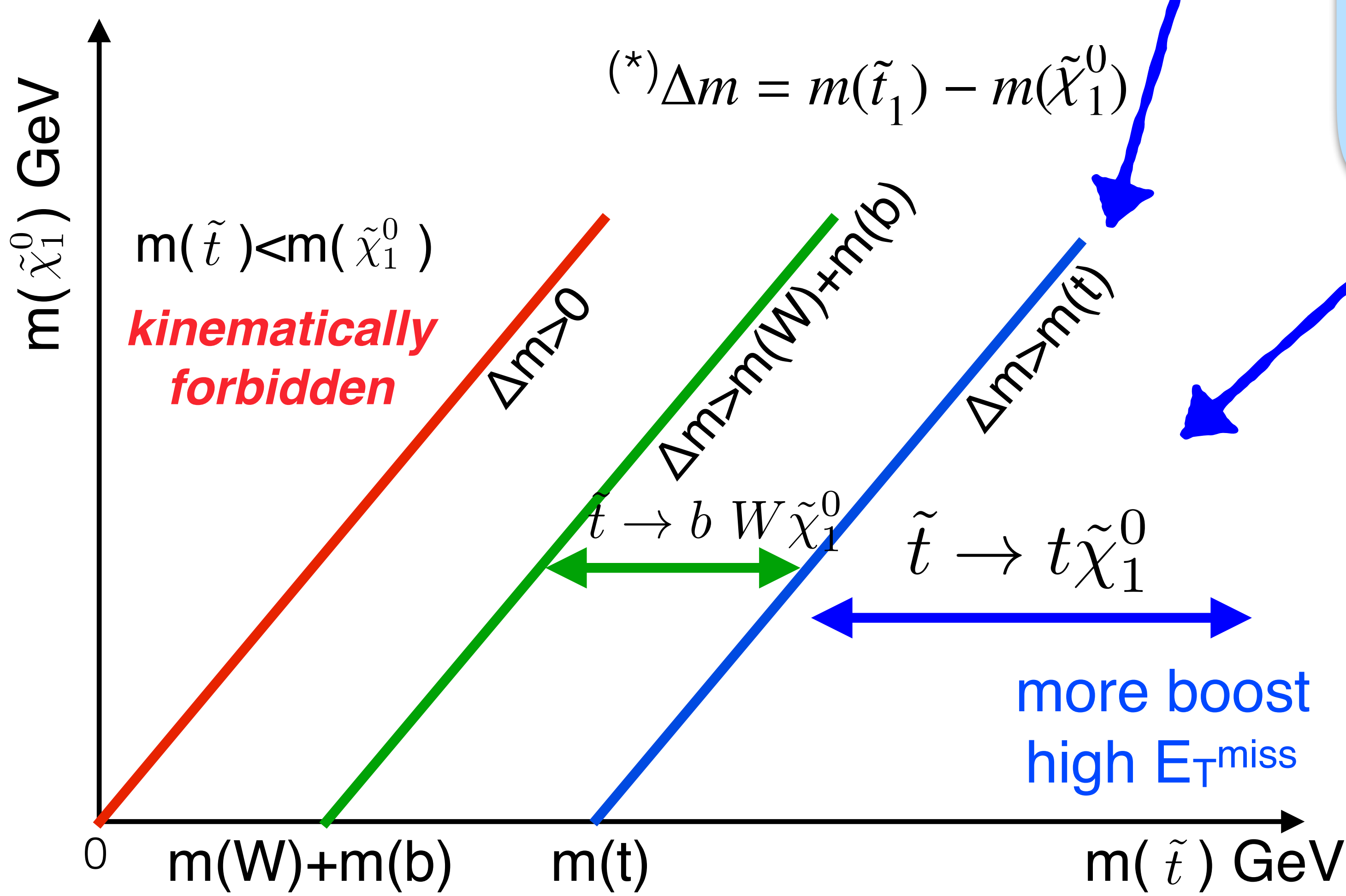


final state: jets+E^T_{miss}

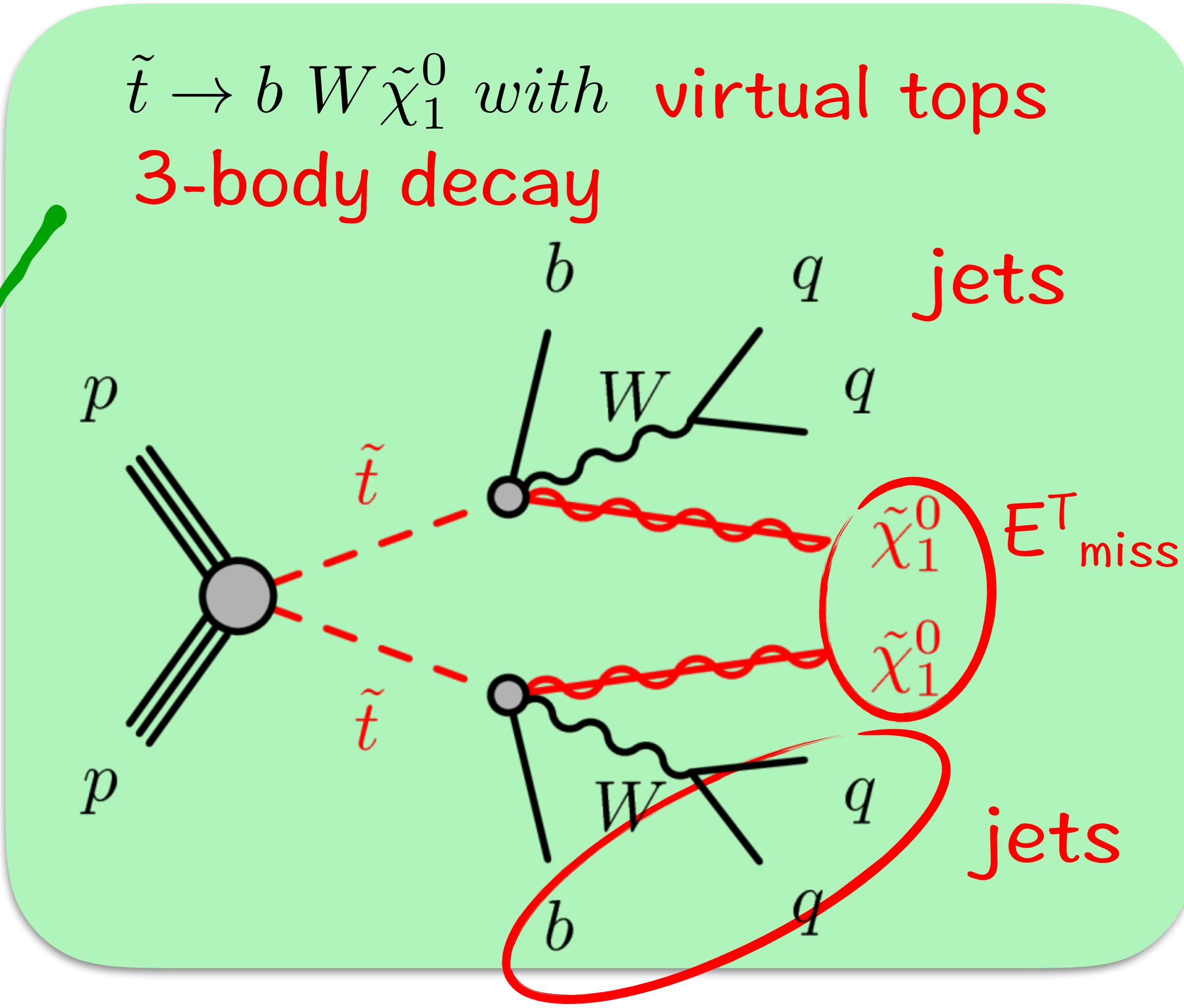
*W can decay leptonically

$$\tilde{t} \rightarrow t\ \tilde{\chi}_1^0\ with\ \Delta M(\tilde{t}, \tilde{\chi}_1^0) \sim m(t)$$

diagonal region



Signals of interest: stop decays



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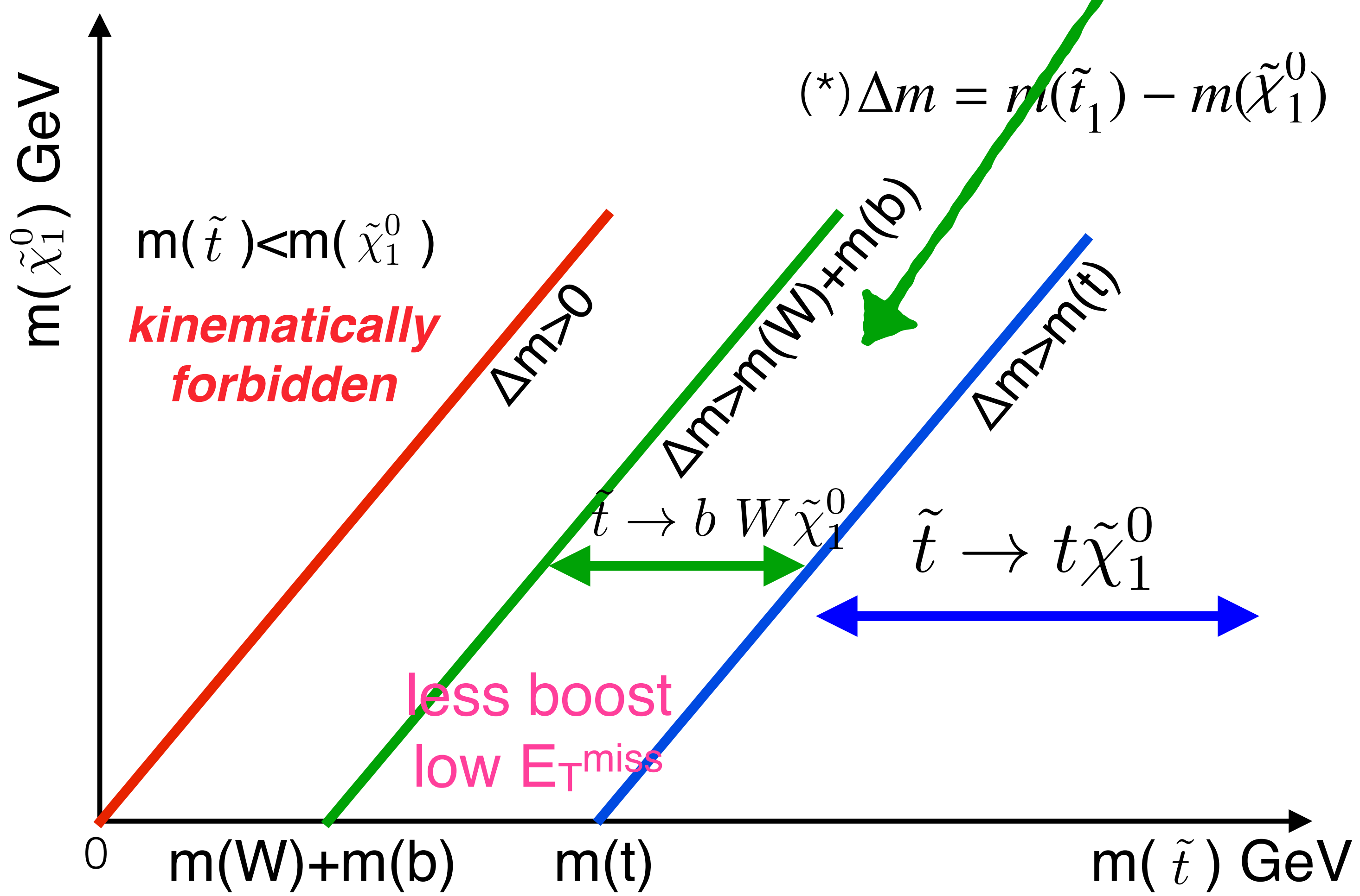
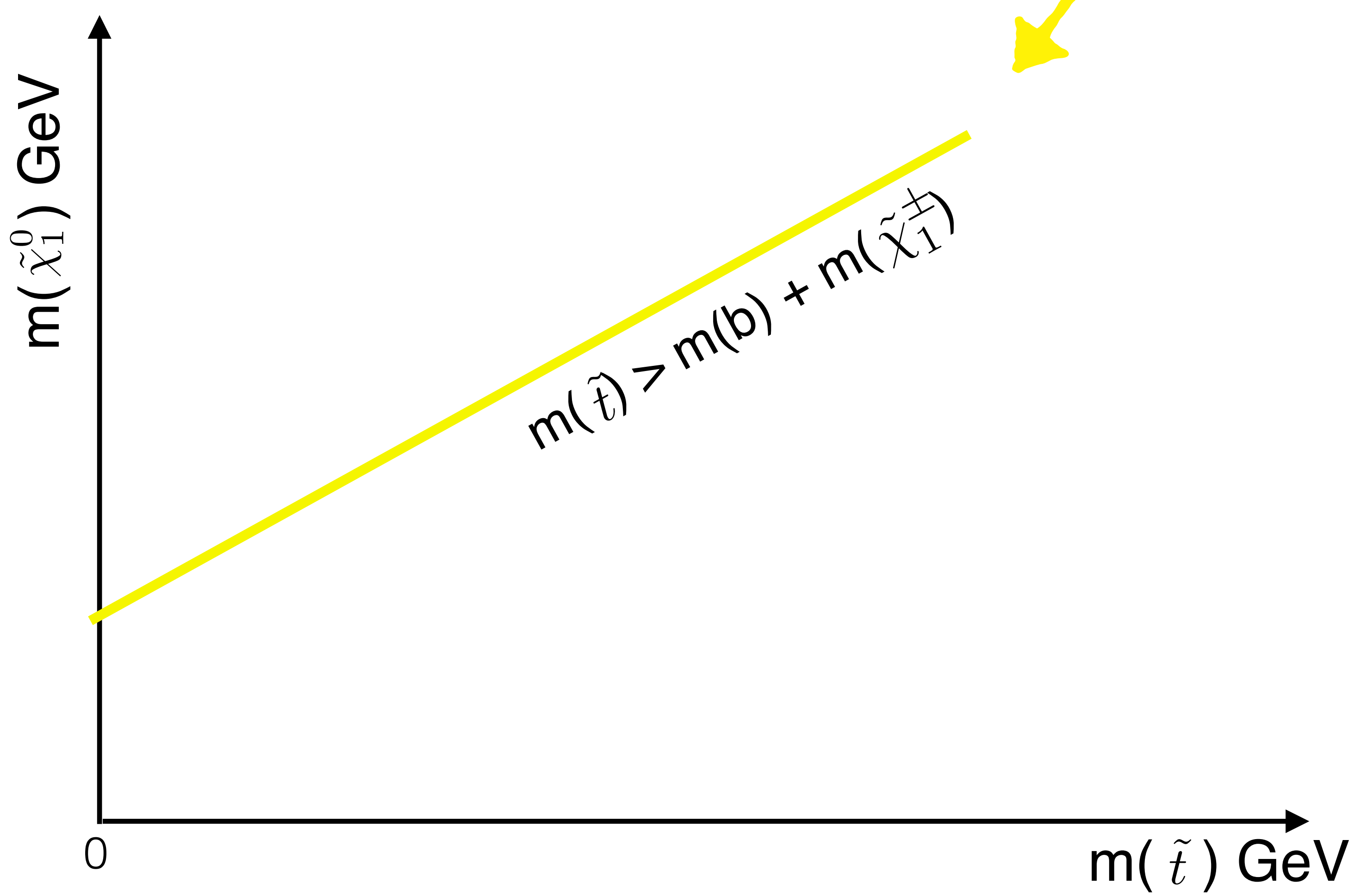
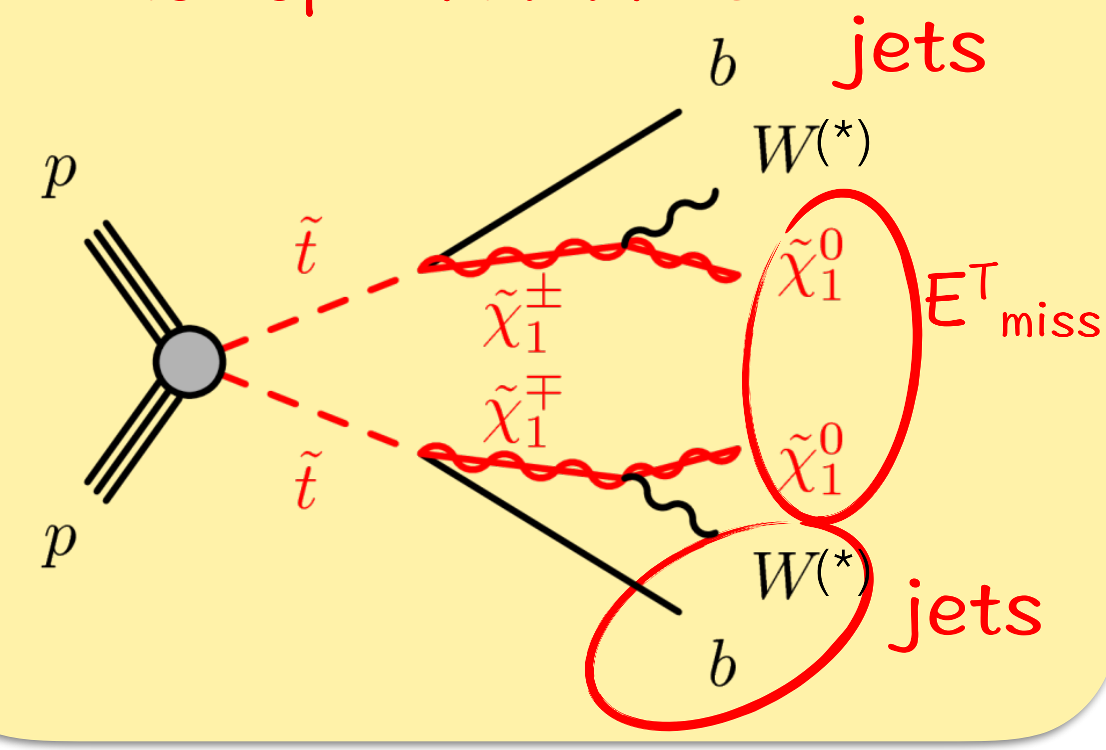


Signals of interest: stop decays



$\tilde{t} \rightarrow b\, \tilde{\chi}_1^{\pm} \rightarrow bW^{(*)}\tilde{\chi}_1^0$ *with* $m(\tilde{\chi}_1^{\pm}) = 2m(\tilde{\chi}_1^0)$

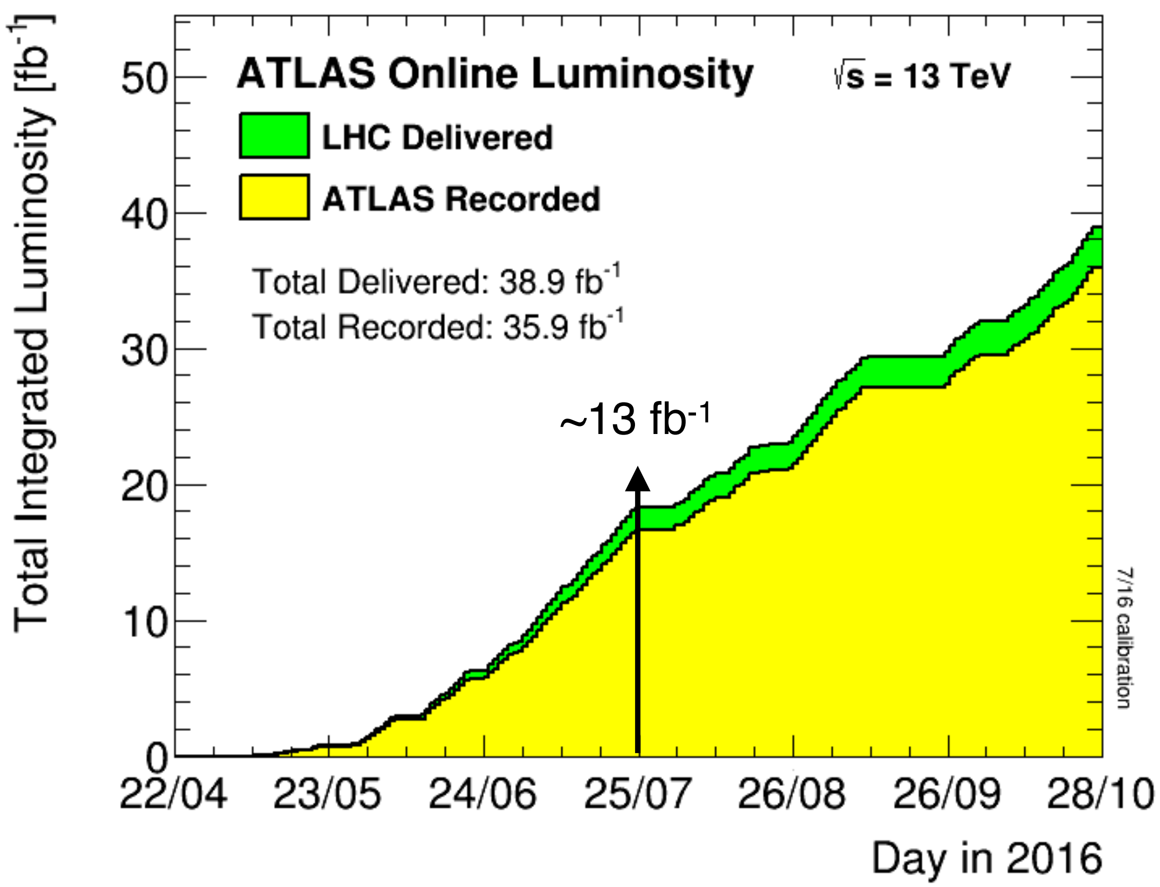
no top candidates

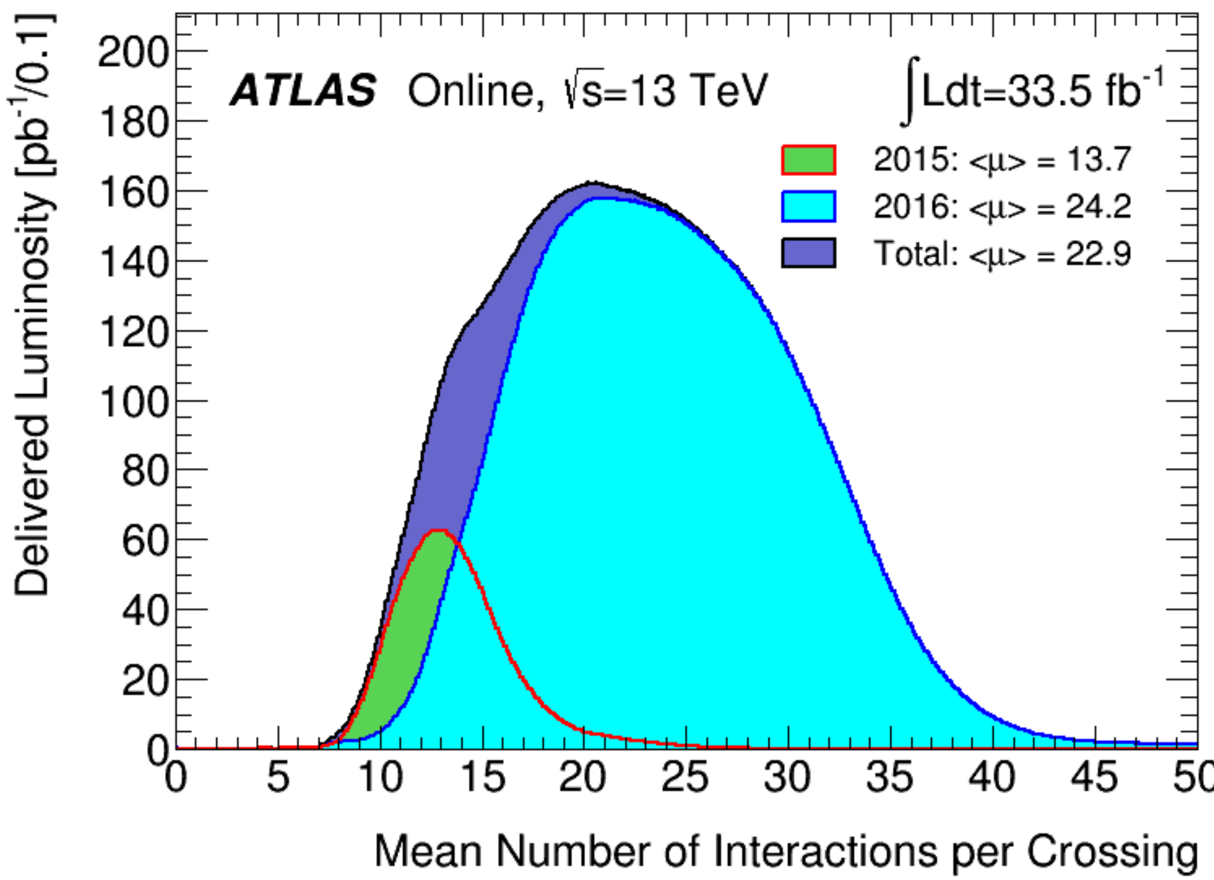


final state: jets+E^T_{miss}

Experimental setup

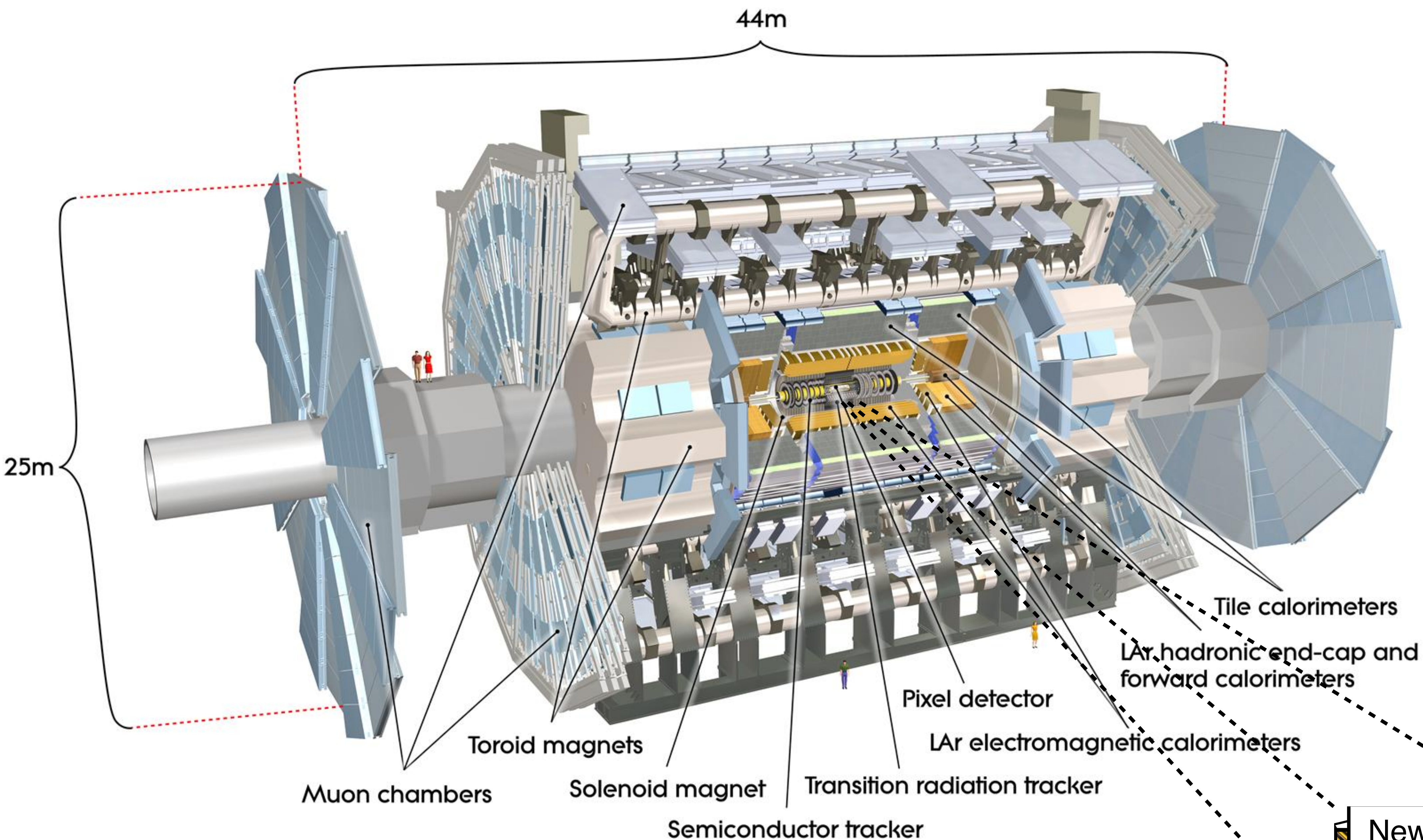
Run II 13TeV dataset





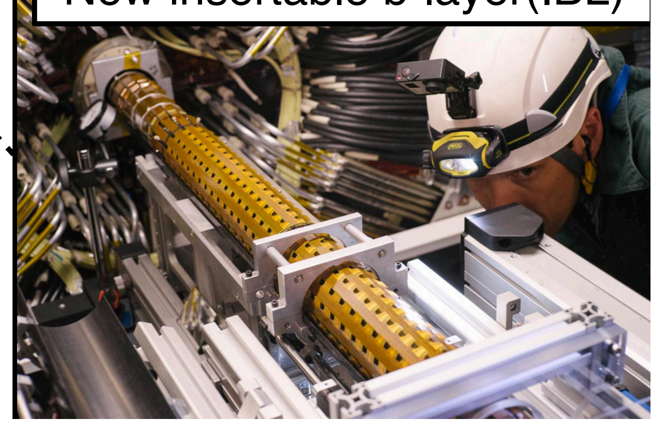
- LHC has shown excellent performance in Run II
- pile-up increases with luminosity

The ATLAS detector



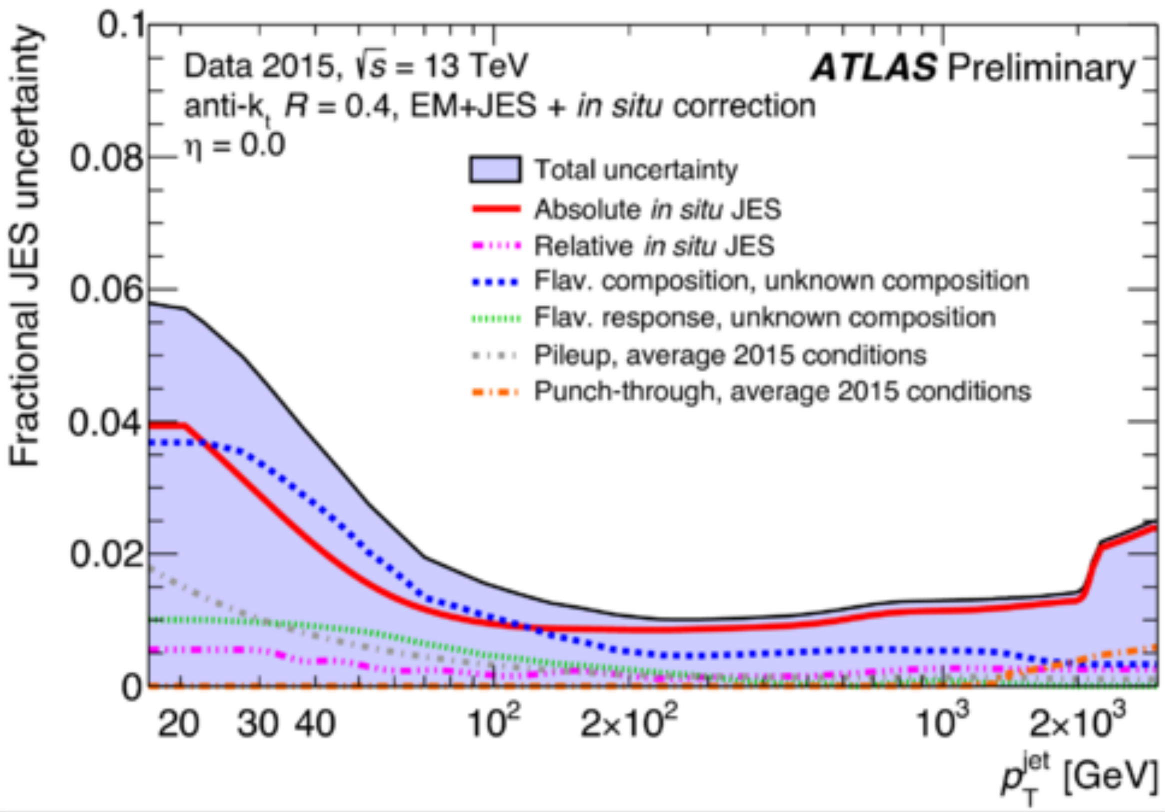
Run II

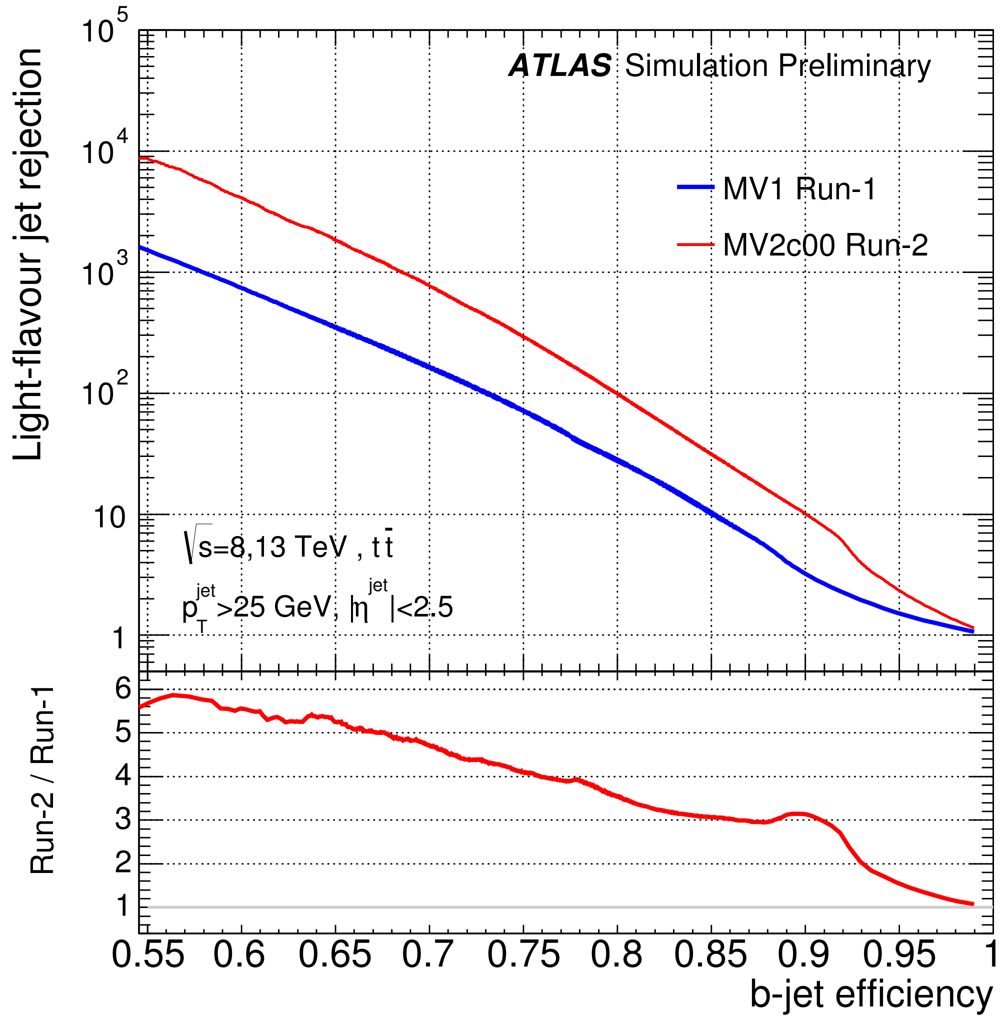
New insertable b-layer(IBL)



Detector performance

- Understanding the detector: very important task!
- Use Run I knowledge to extrapolate systematic uncertainties for Run II
- b-jets: improvements in algorithms and new IBL
- b-tagging efficiency increase by 10% for the same light-flavor rejection





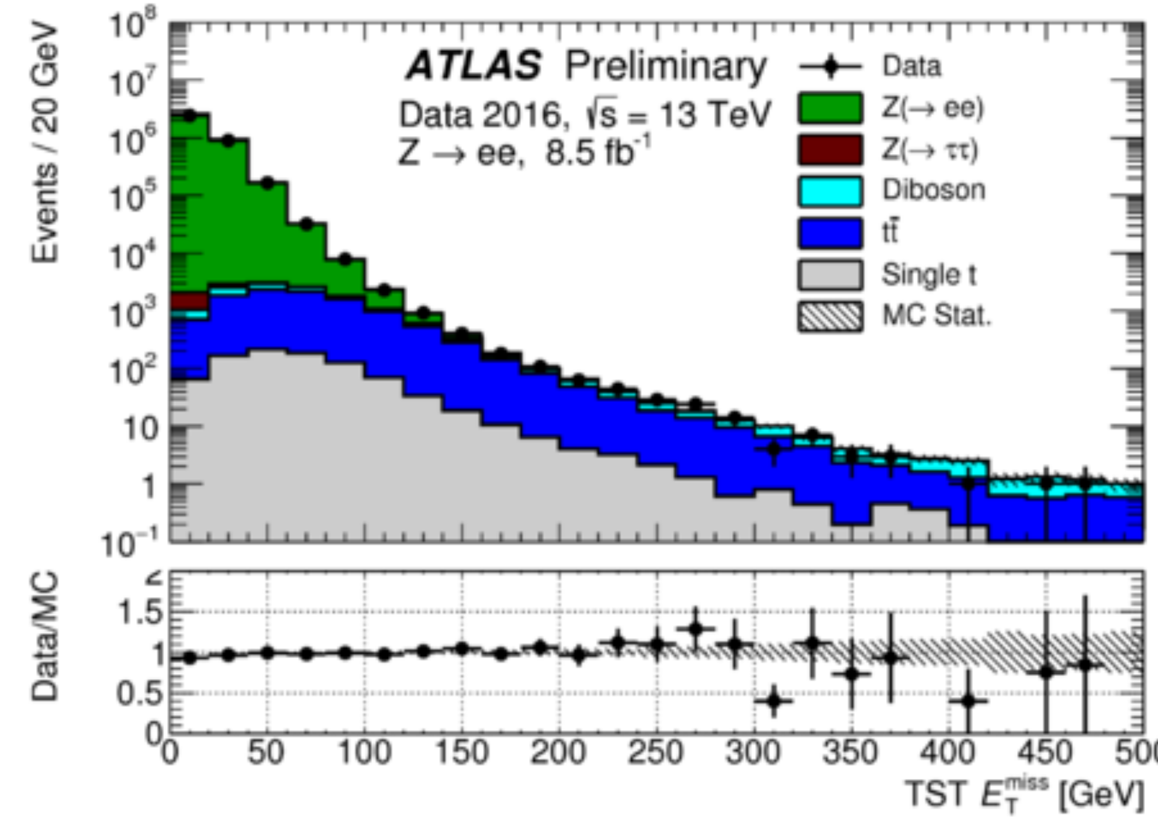
Detector performance

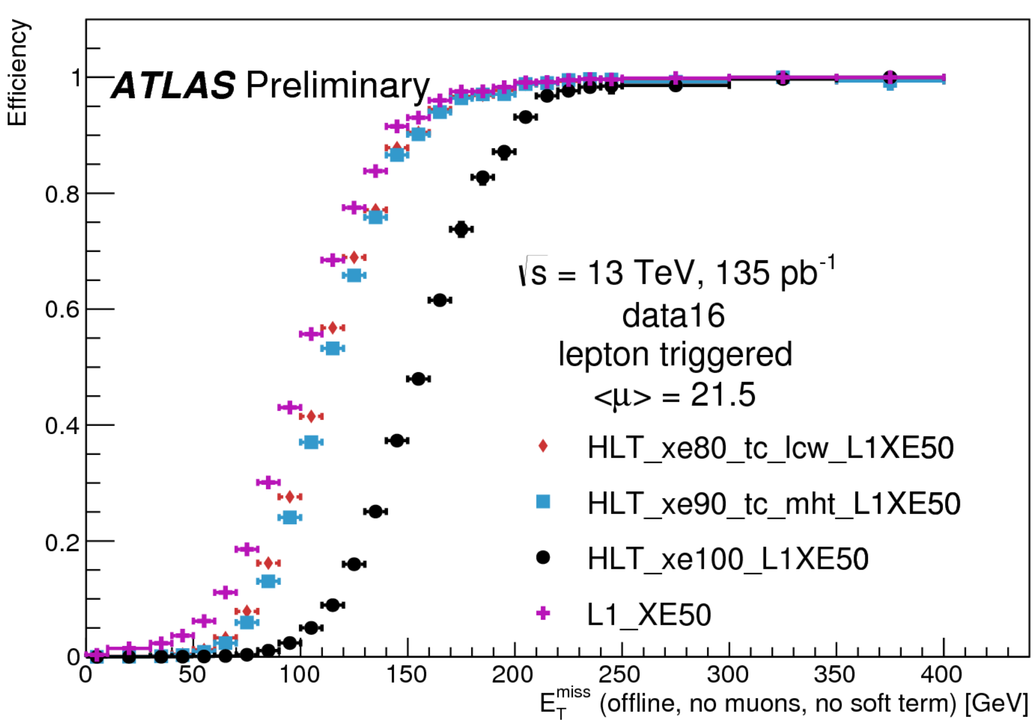
- Missing transverse momentum:

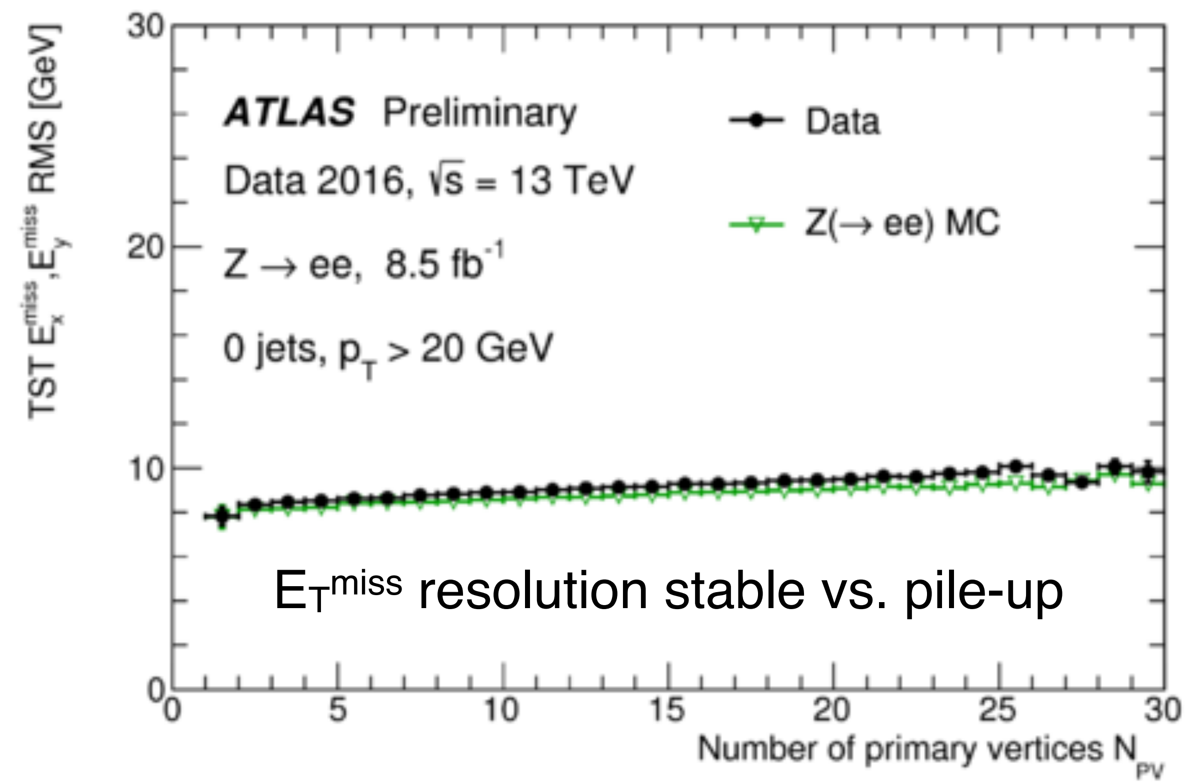
$$E_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2}$$

where $E_{x(y)}^{\mathrm{miss}} = -\sum E_{x(y)}$ summed over all calibrated e, γ, μ, τ and jets plus a track-based "soft" term (TST)

- Strong discriminating power for R-parity conserving SUSY with LSP escaping detection
- E_T^{miss} trigger (offline > 250 GeV)





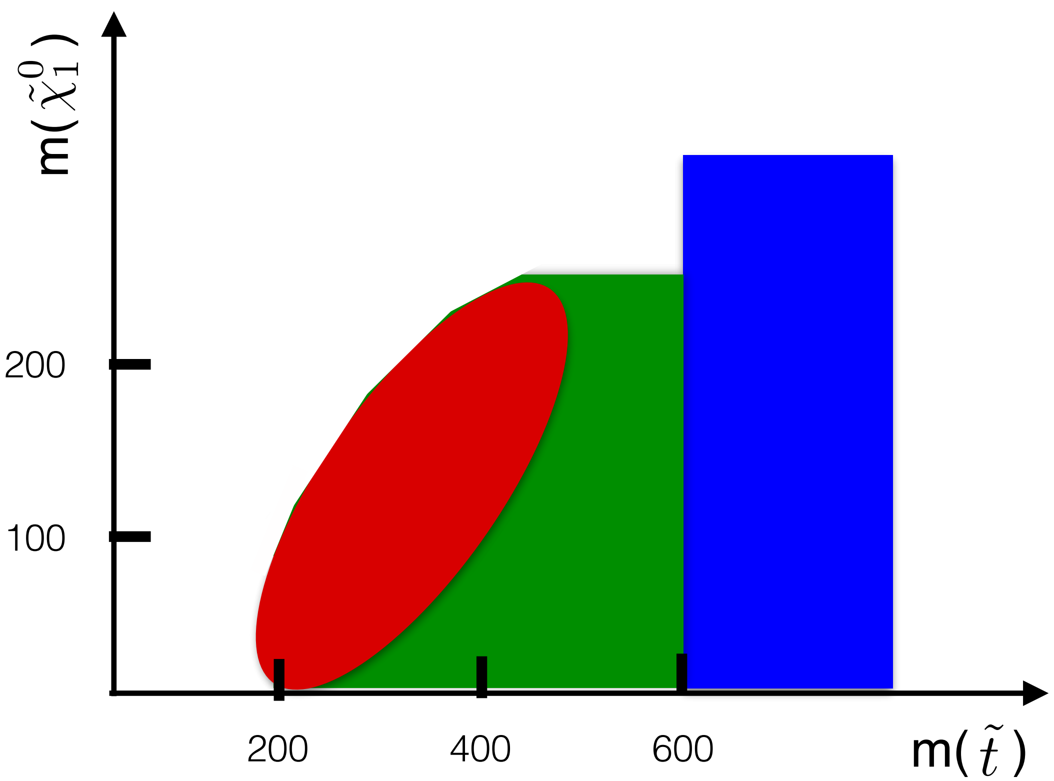


E_T^{miss} resolution stable vs. pile-up

SUSY Analysis Primer

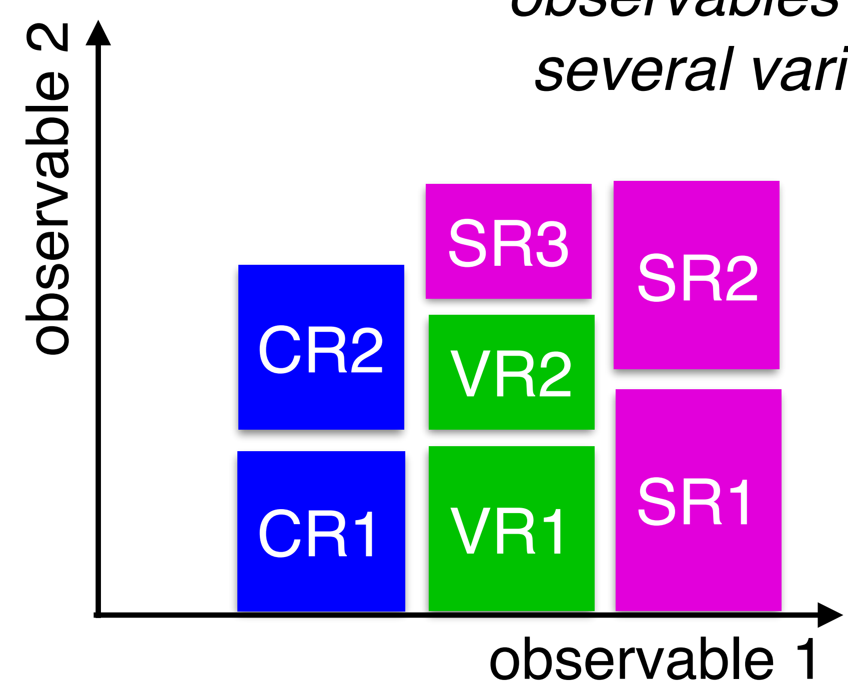
or typical workflow of a SUSY search

- Divide signal grid into **Signal Regions (SR)** with similar final state kinematics
  - Optimize for S/B using variables describing topology and kinematics



- For main irreducible backgrounds ($t\bar{t}$, V+jets)
  - High purity **Control Regions (CR)** (normalization factors from data)
  - **Validation regions (VR)** closer to the SR to test extrapolation (normalization and shape)
  - Predict yields in blinded SRs

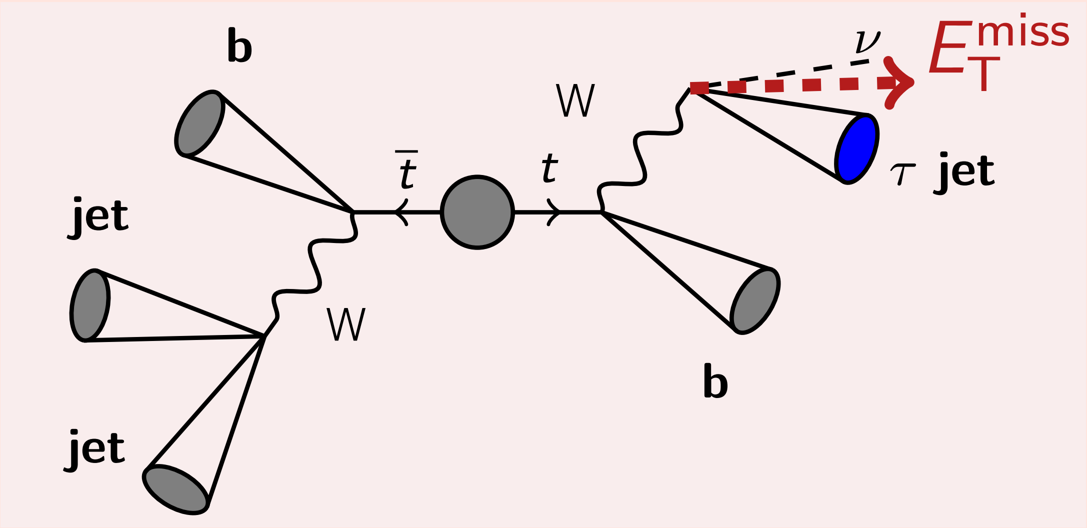
**observables can be several variables*



- Unblind the data and look for excesses

SM backgrounds

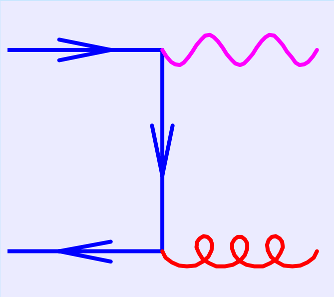
- Semi-leptonic $t\bar{t}$



- ☑ W-bosons decay into τ + E^T_{miss} (E^T_{miss} near τ jet)
- ☑ τ decay hadronically, they mimic jets but have less tracks associated with jets
- ☑ only 1 reconstructed top

- V+jets

- ☑ $Z/W + b\bar{b}, c\bar{c}$ from gluons
- ☑ $Z \to \nu\nu$
- ☑ $W \to \ell\nu$



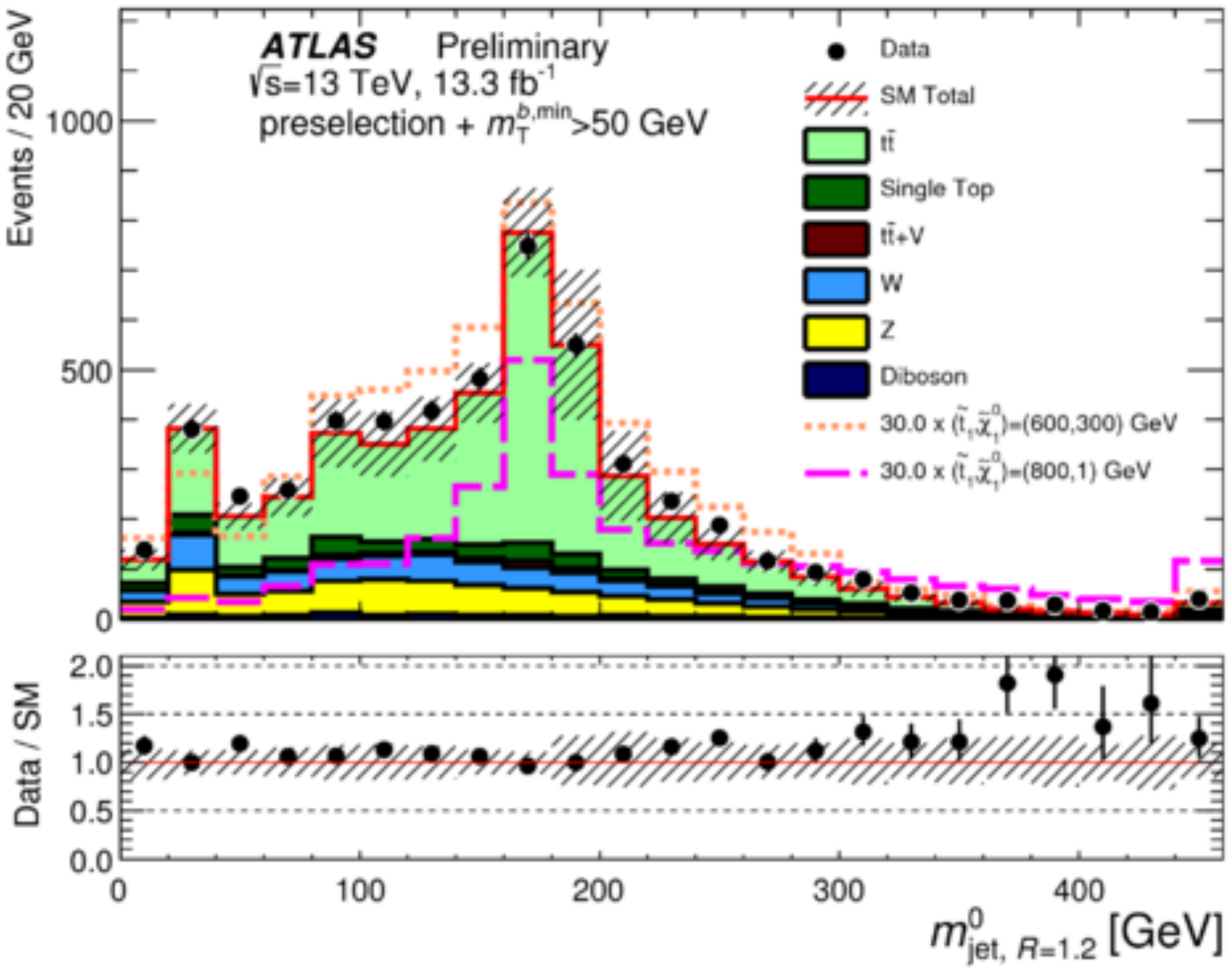
- hadronic $t\bar{t} + Z \to \nu\nu$

- ☑ irreducible background
- ☑ 2 tops, 2 b-jets and E^T_{miss}

- single top

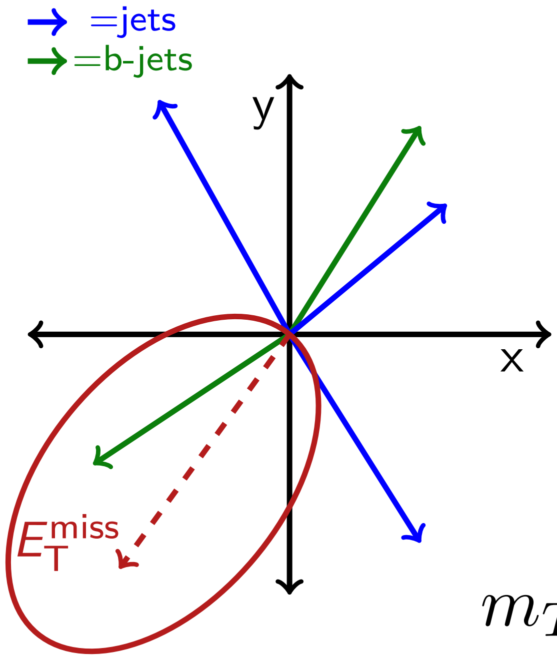
How to discriminate signal from background?

- E^T_{miss}: strong discriminator
  - Remove (hadronic) $t\bar{t}$ and multijets
  - E^T_{miss} depends on the mass splittings, varies from 250 to 500 GeV



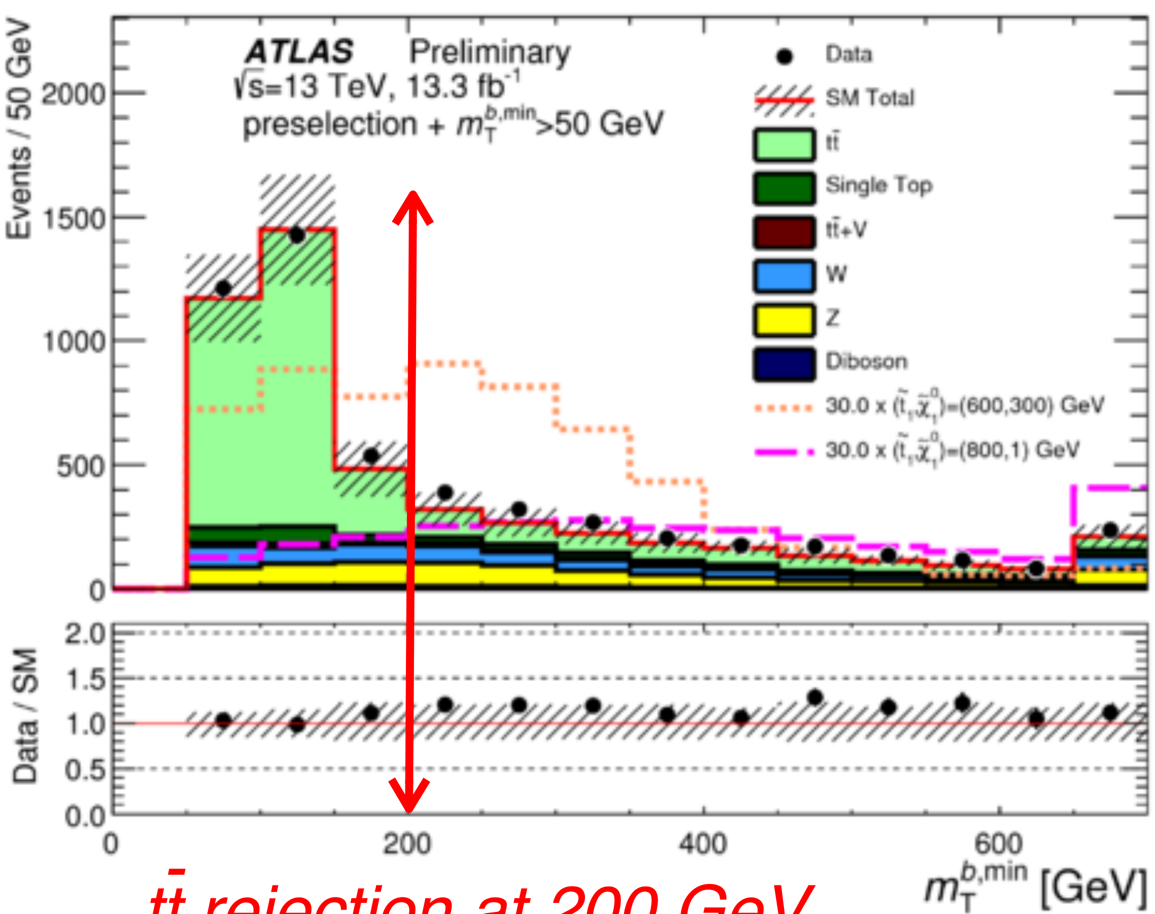
- Top reconstruction
  - ensures background rejection (except for $t\bar{t}$+V)
  - semi-leptonic $t\bar{t}$ should have only 1 top
  - W/Z+jets should have 0 tops

How to discriminate signal from background?



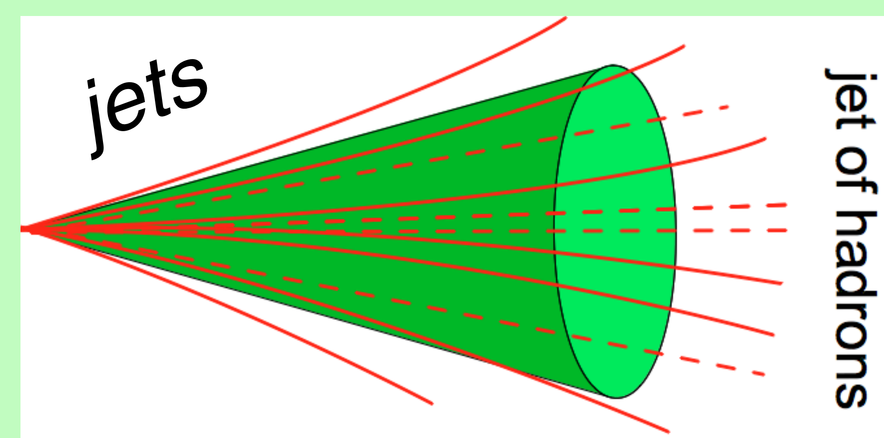
$$m_T = \sqrt{p_T^1 p_T^2 cos(\Delta\phi)}$$

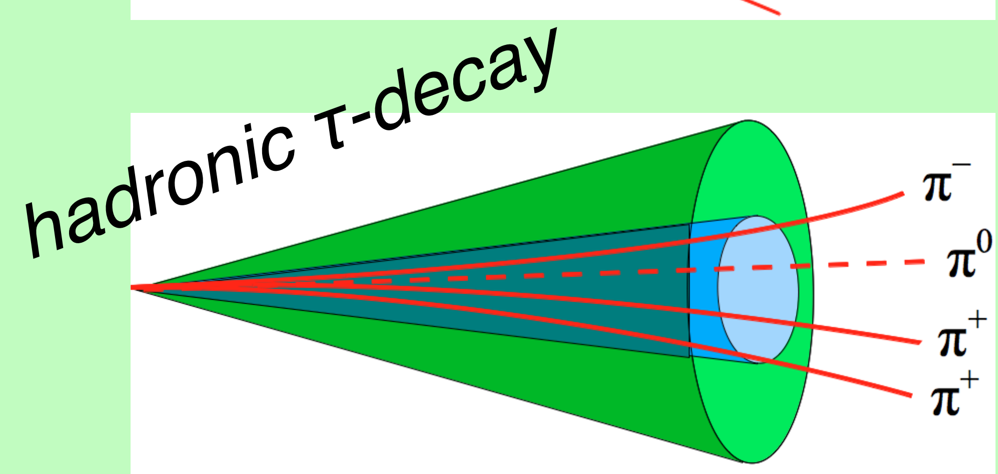
$$m_T^{b,min} = m_T(bjet \text{ closest to } \mathrm{E_T^{miss}}, \mathrm{E_T^{miss}})$$



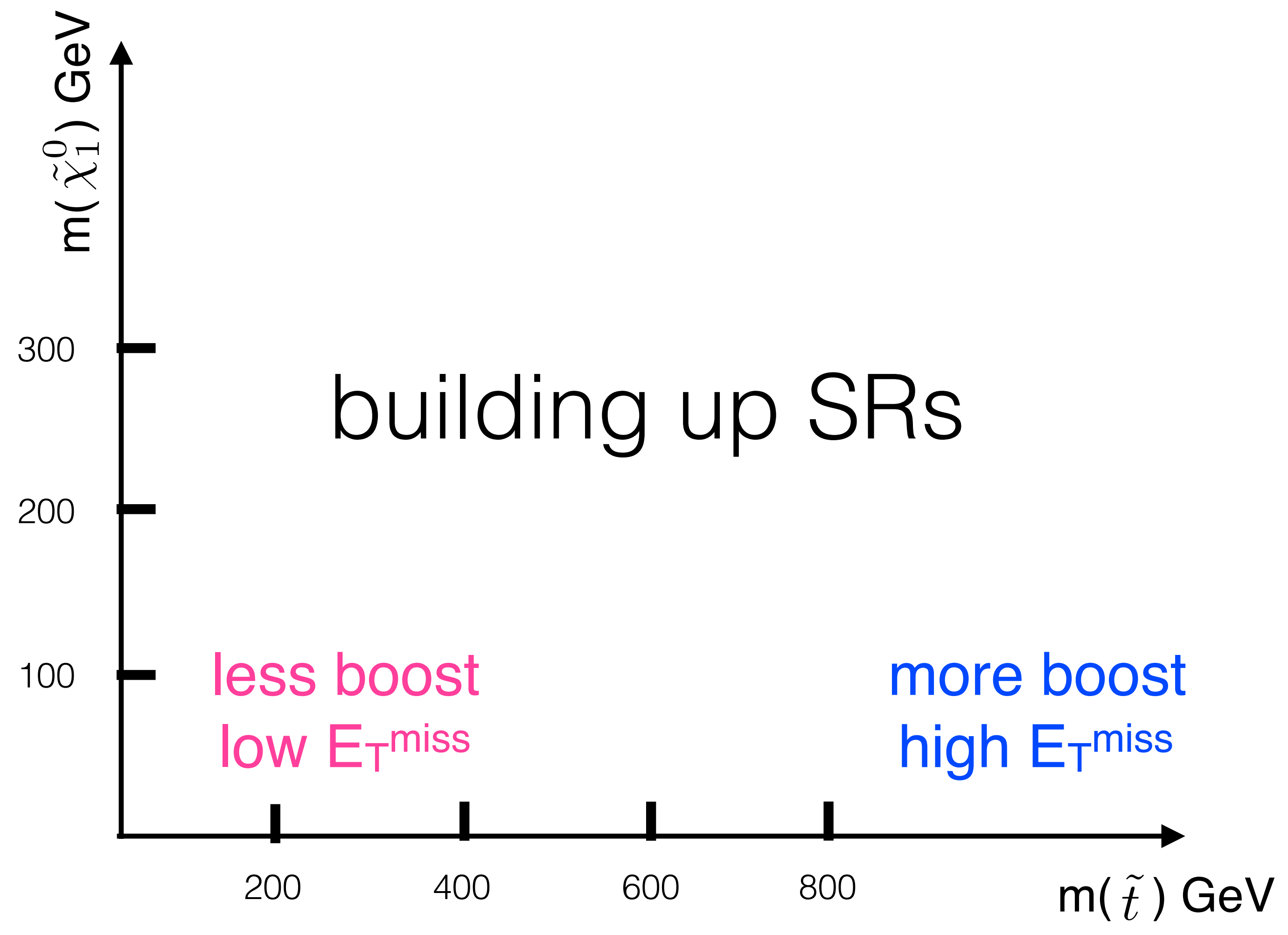
tt̄ rejection at 200 GeV

- τ-veto
  - ☑ semi-leptonic tt̄ rejection
- τ identified by:
  - ☑ Jet with ≤ 4 tracks
  - ☑ $\Delta\phi(jet, E_T^{miss})$ small



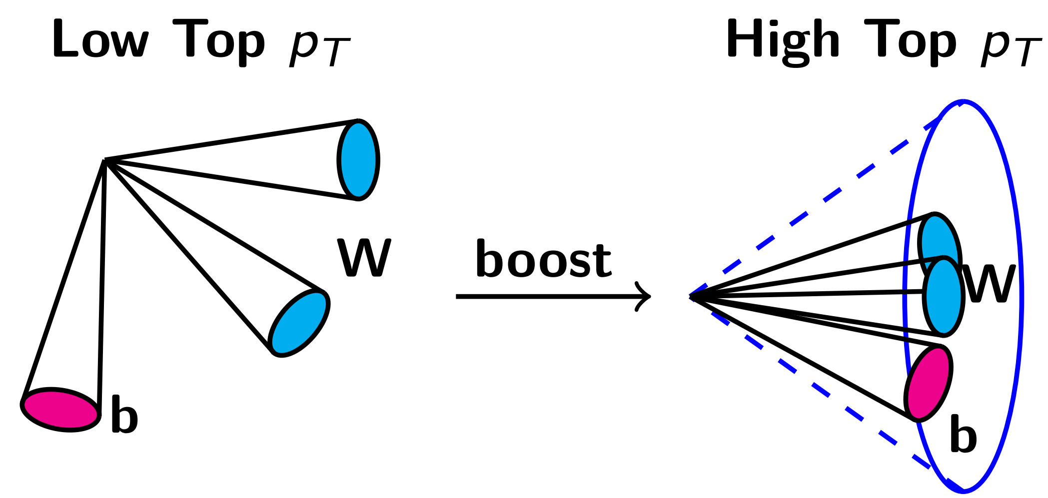


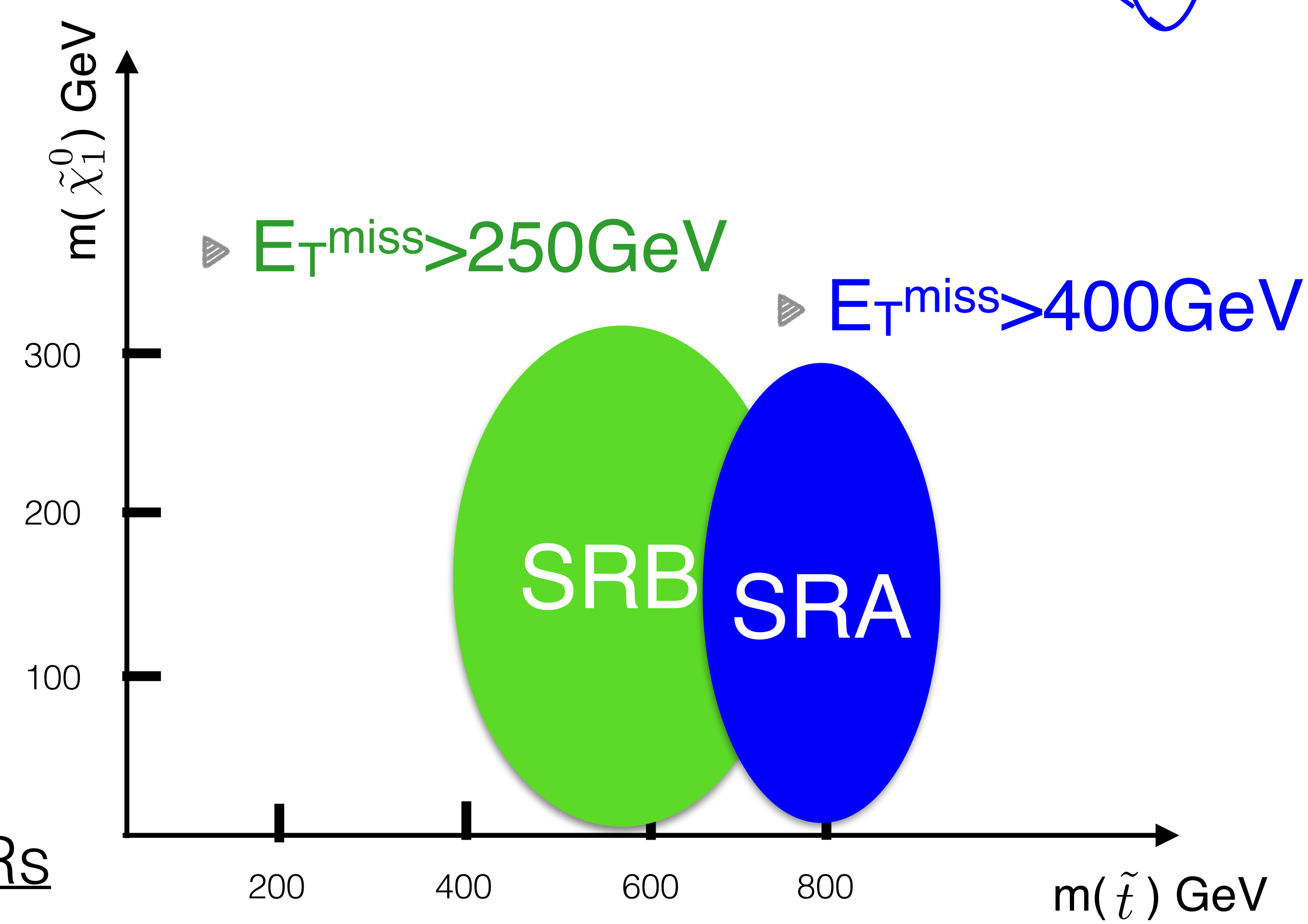
Signal Regions definitions



Signal Regions definitions

- **SRs aiming high mass splitting (high E_T^{miss})**
  - at high stop masses, tops can have high pT and be boosted
  - jets from top become collimated
- Top reconstruction from jets within a certain cone size
  - anti-kT algorithm but with R=1.2
  - for W candidates R=0.8
- SR categories according to top reconstruction

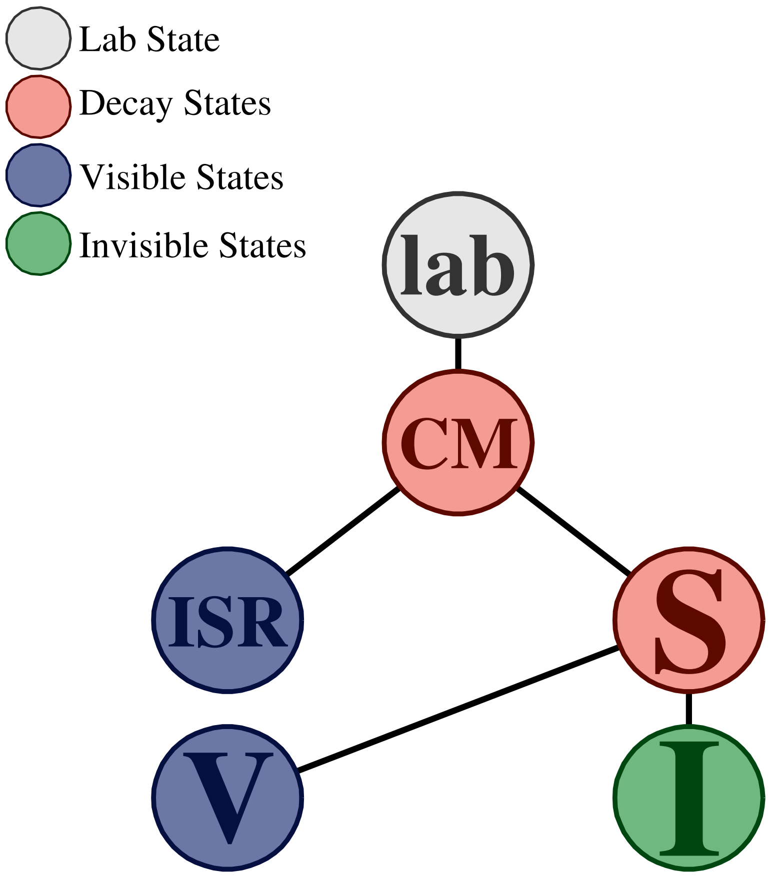




SRA and SRB sets of SRs

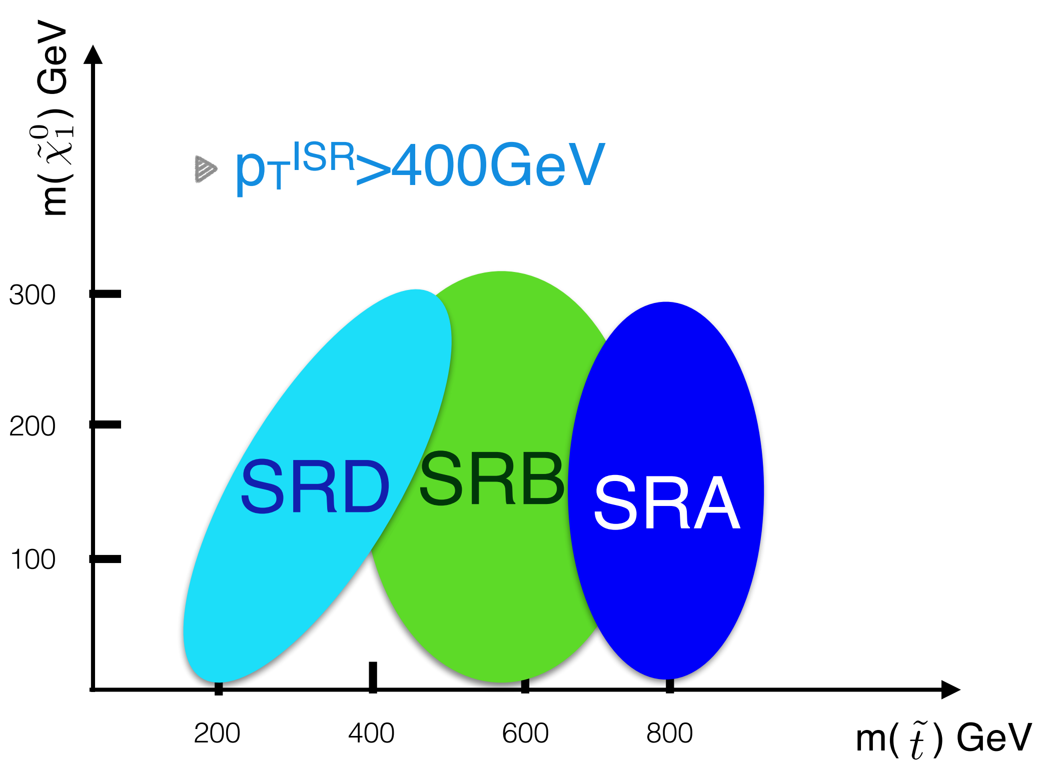
Signal Regions definitions

- **SRs aiming very compressed region (low E_T^{miss})** (including 3-body decays)
- ISR boost of the di-top-squark system in the transverse plane
  - Jigsaw technique is used to decide which jets belong to the ISR system vs. the sparticle system



arXiv:1607.08307

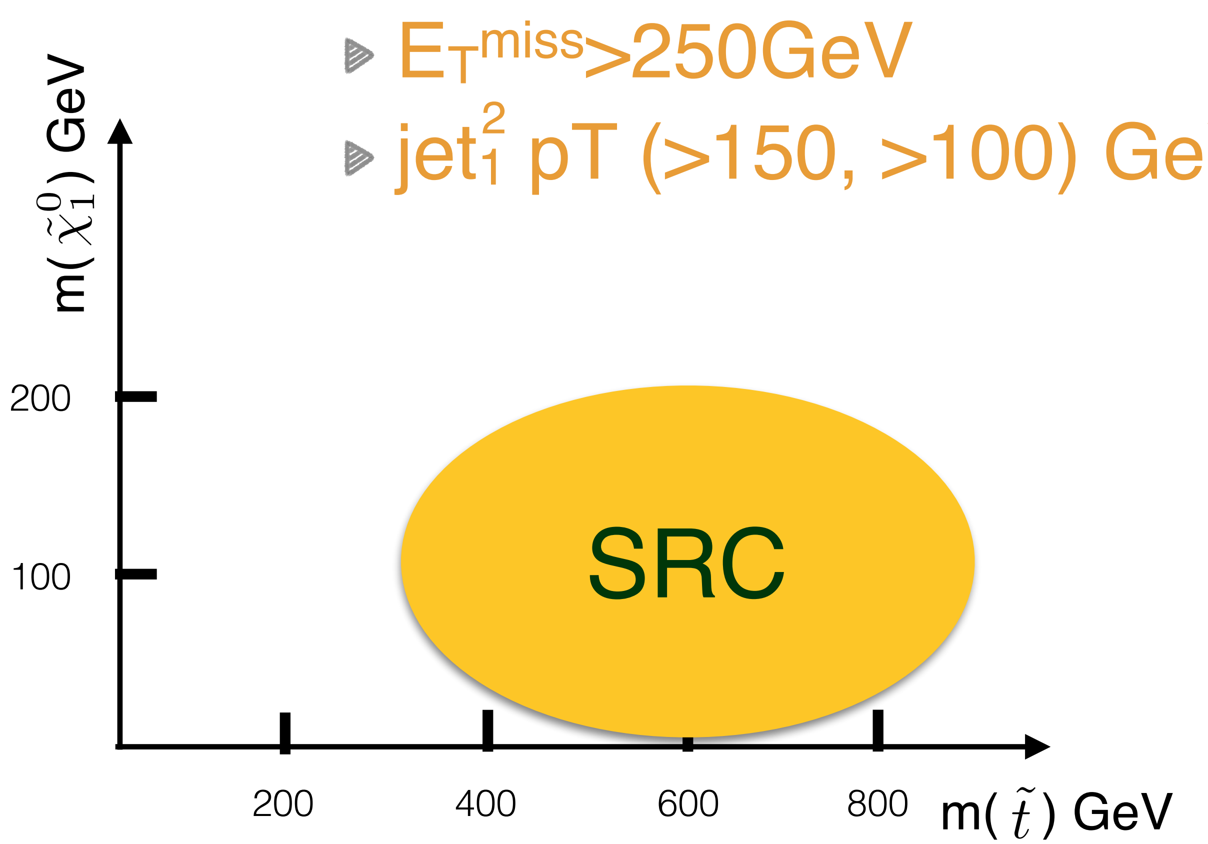
- Discriminating variables:
  - ☑ $p_T^{\rm ISR}$
  - ☑ $R_{\rm ISR} \equiv \frac{E_{\rm T}^{\rm miss}}{p_{\rm T}^{\rm ISR}} \sim \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{t}}}$



SRD sets of SRs

Signal Regions definitions

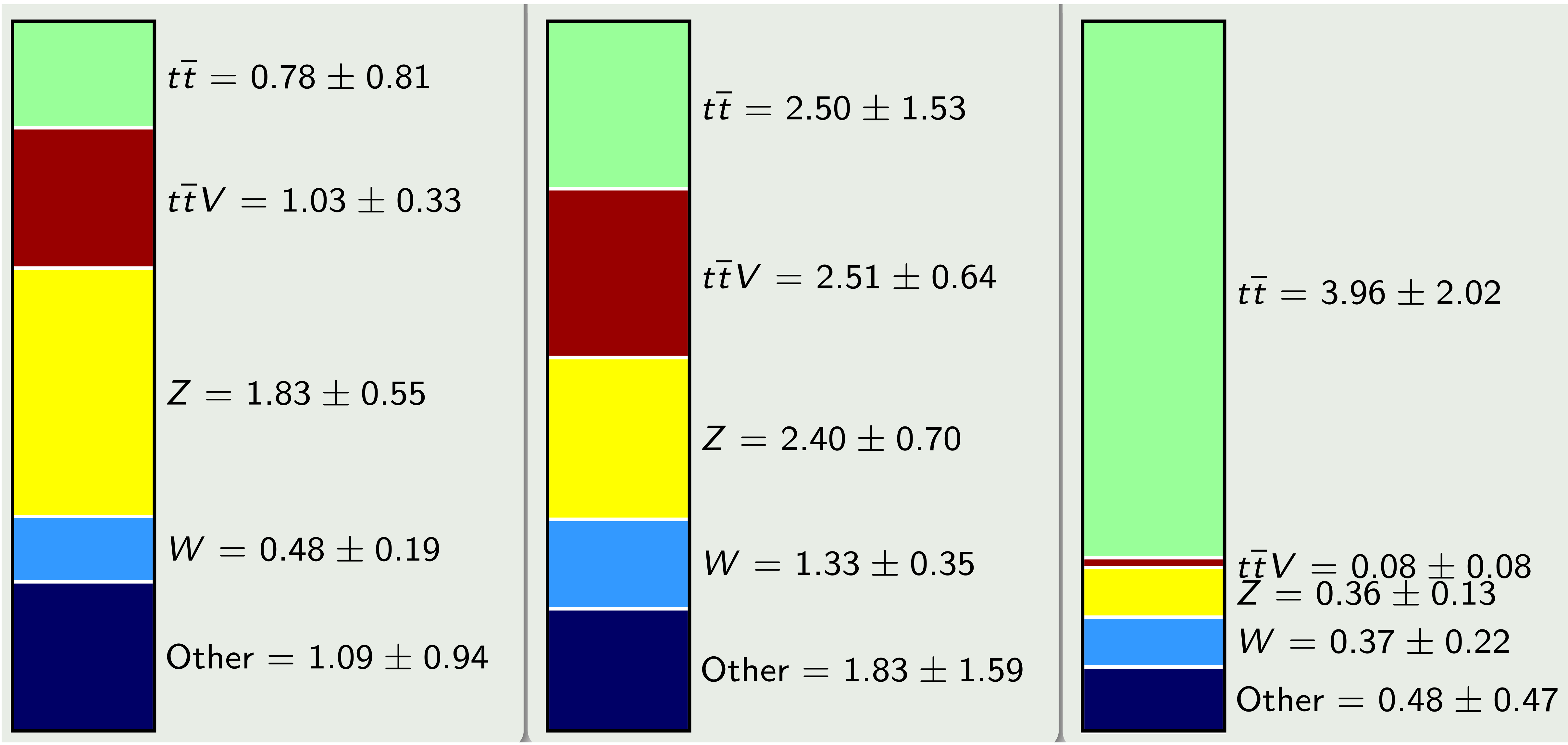
- SRs aiming at $\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}$
  - best sensitivity when vetoing top events



SRC sets of SRs

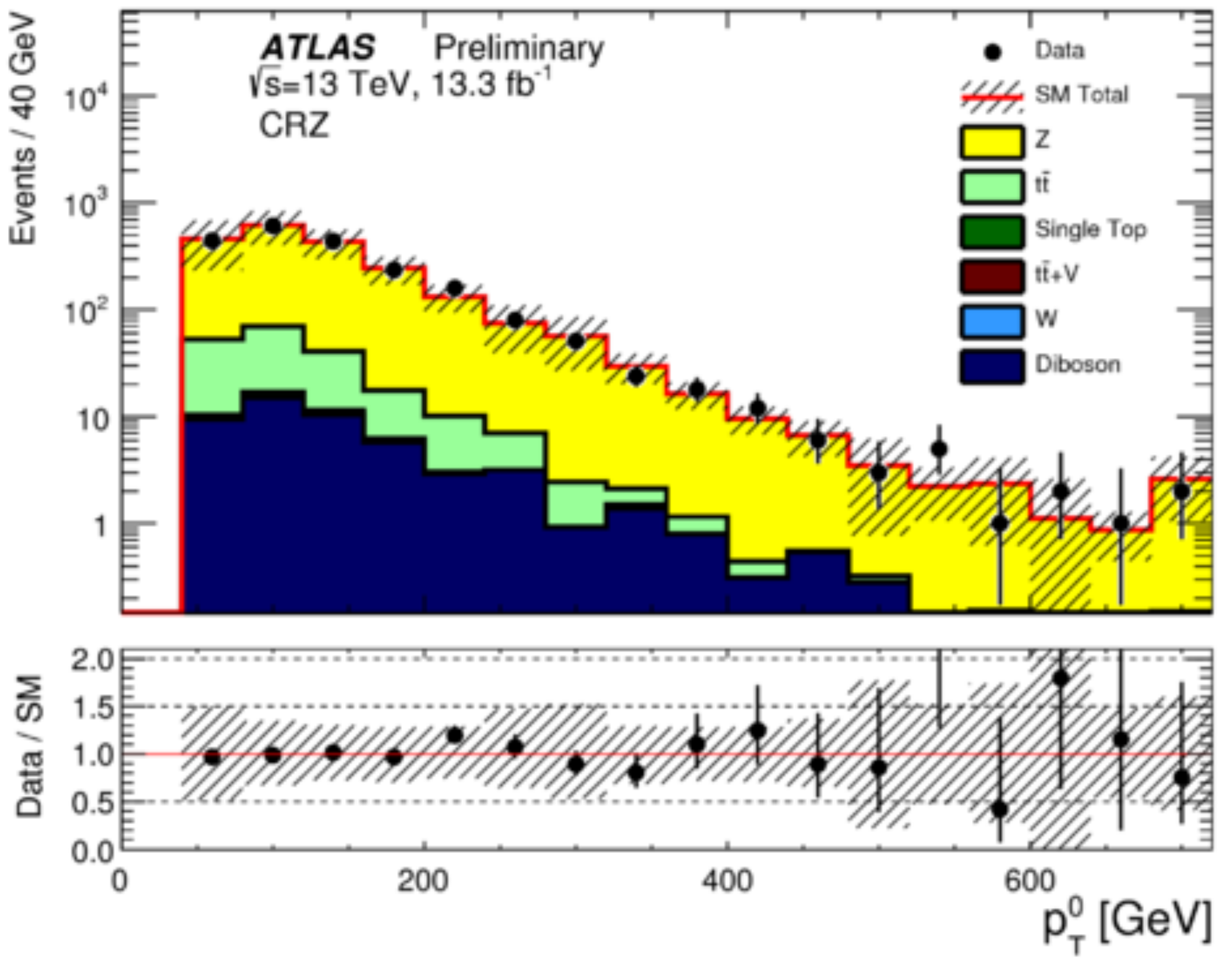
Background composition

High stop mass (TT) **Low stop mass (TT)** **Compressed region**

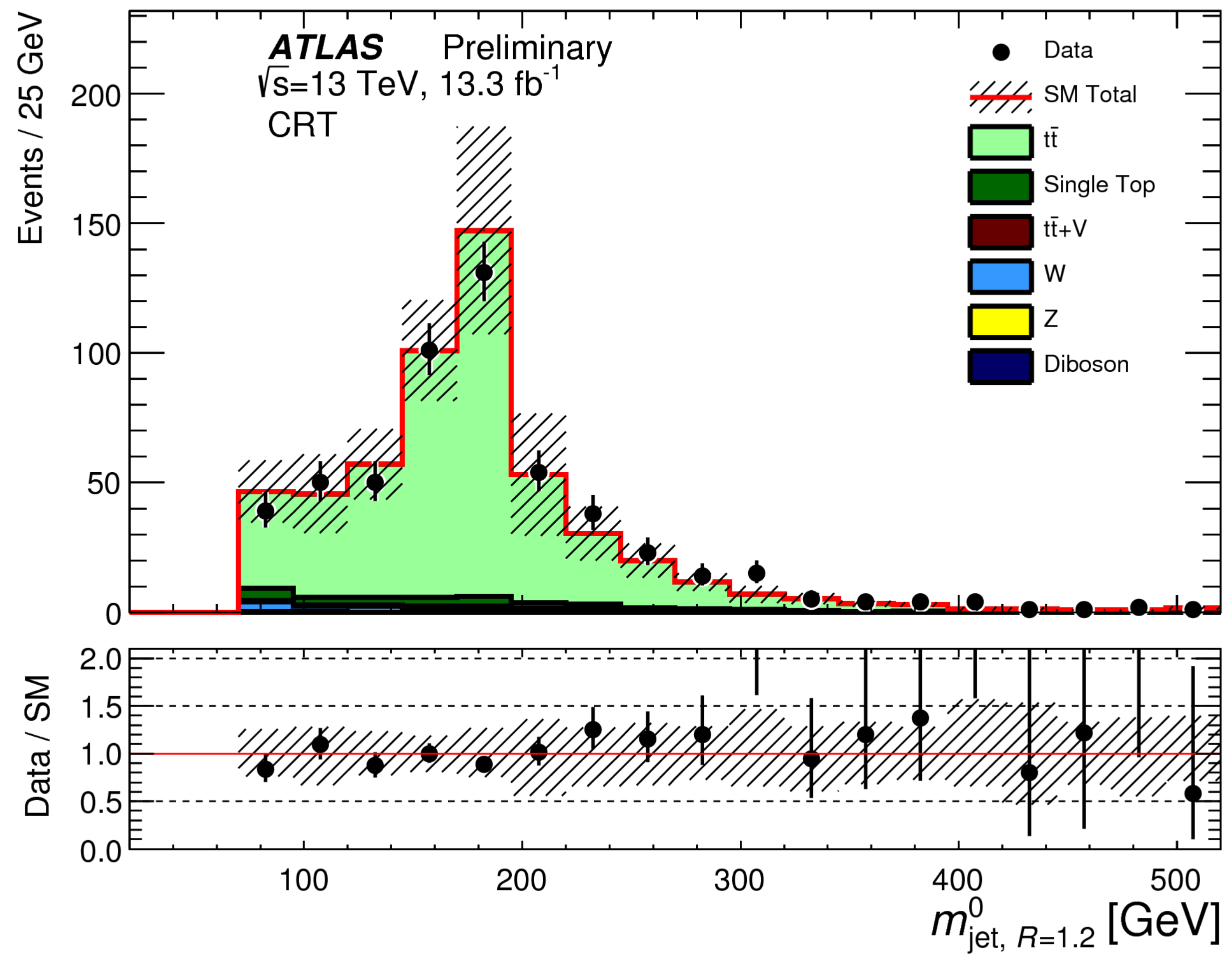


Other: single top, dibosons and multi jet

Control Regions



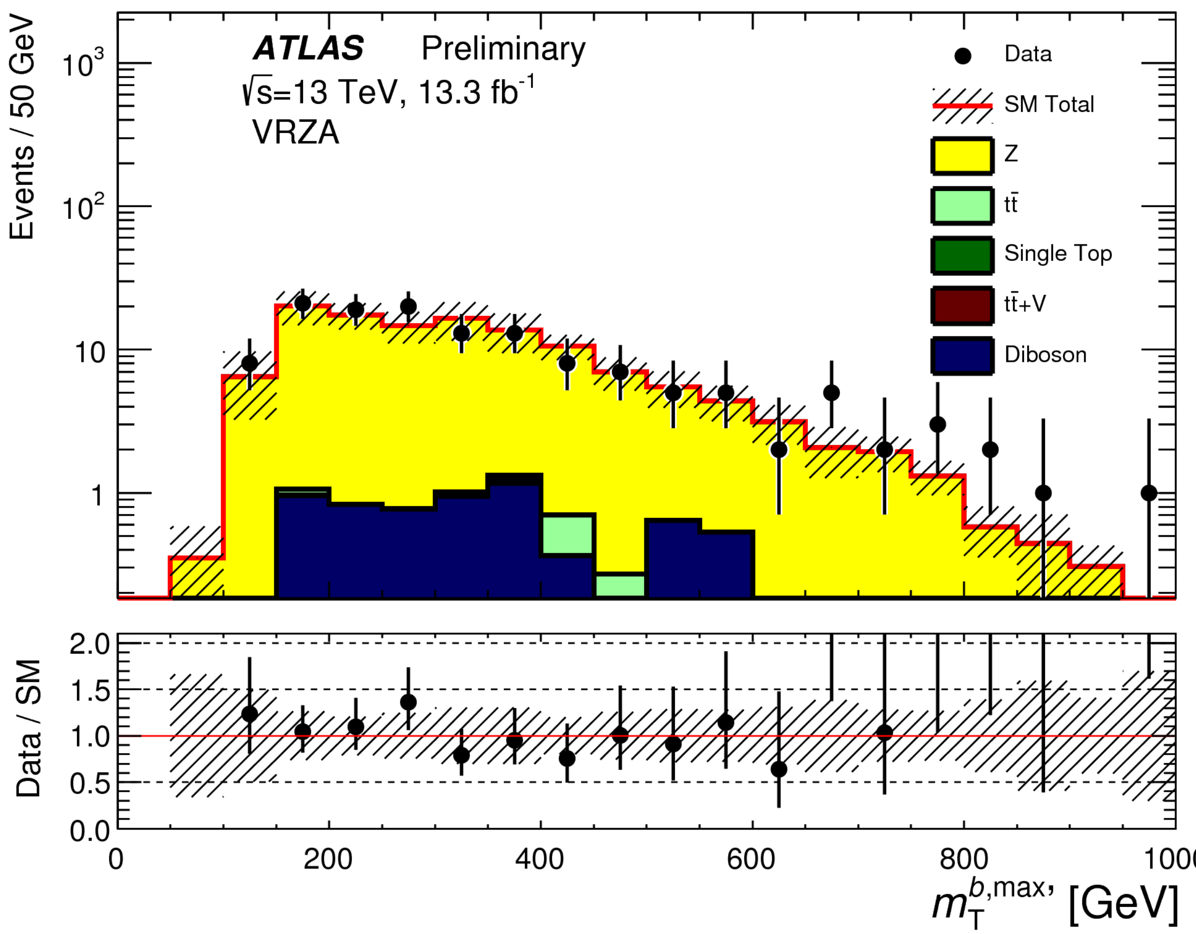
Z CR

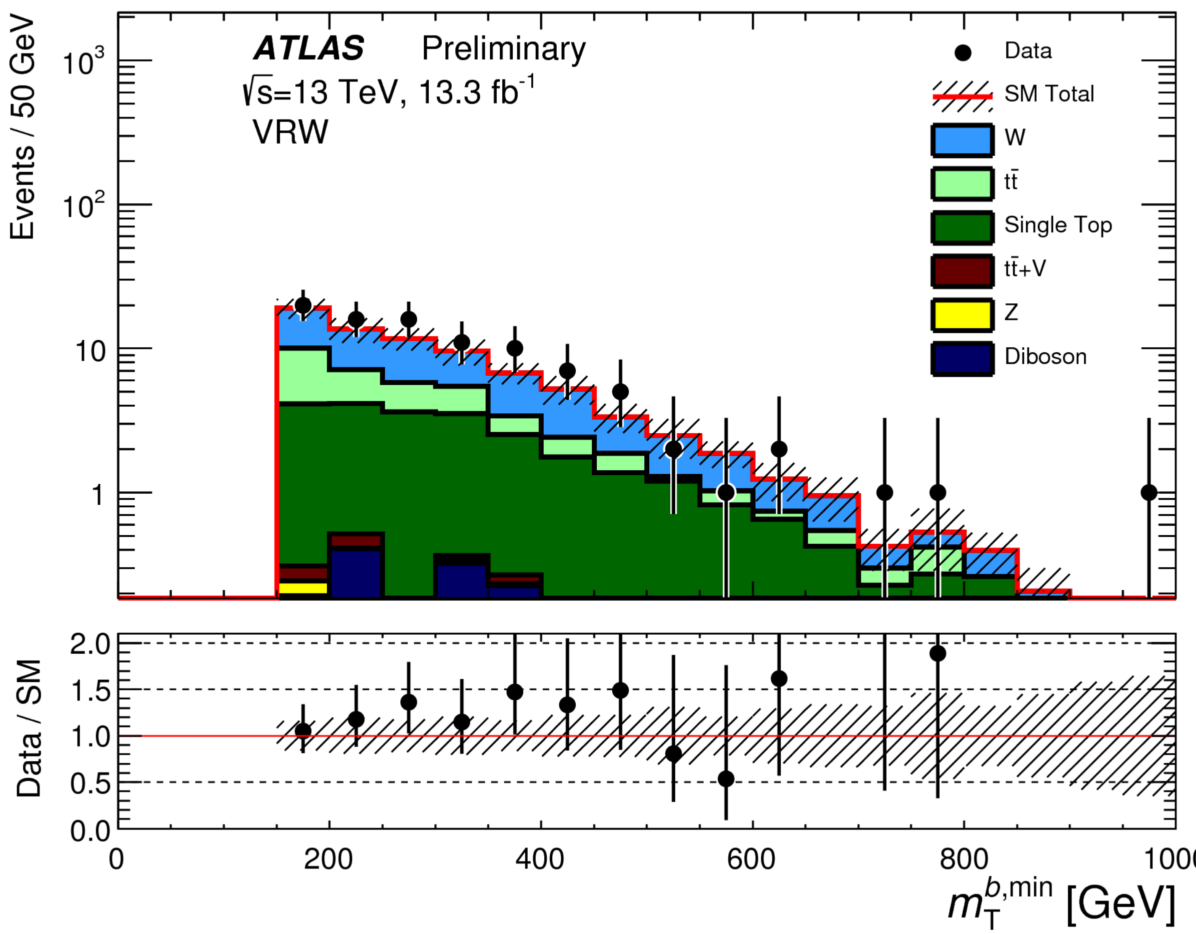


$t\bar{t}$ CR

Control Regions

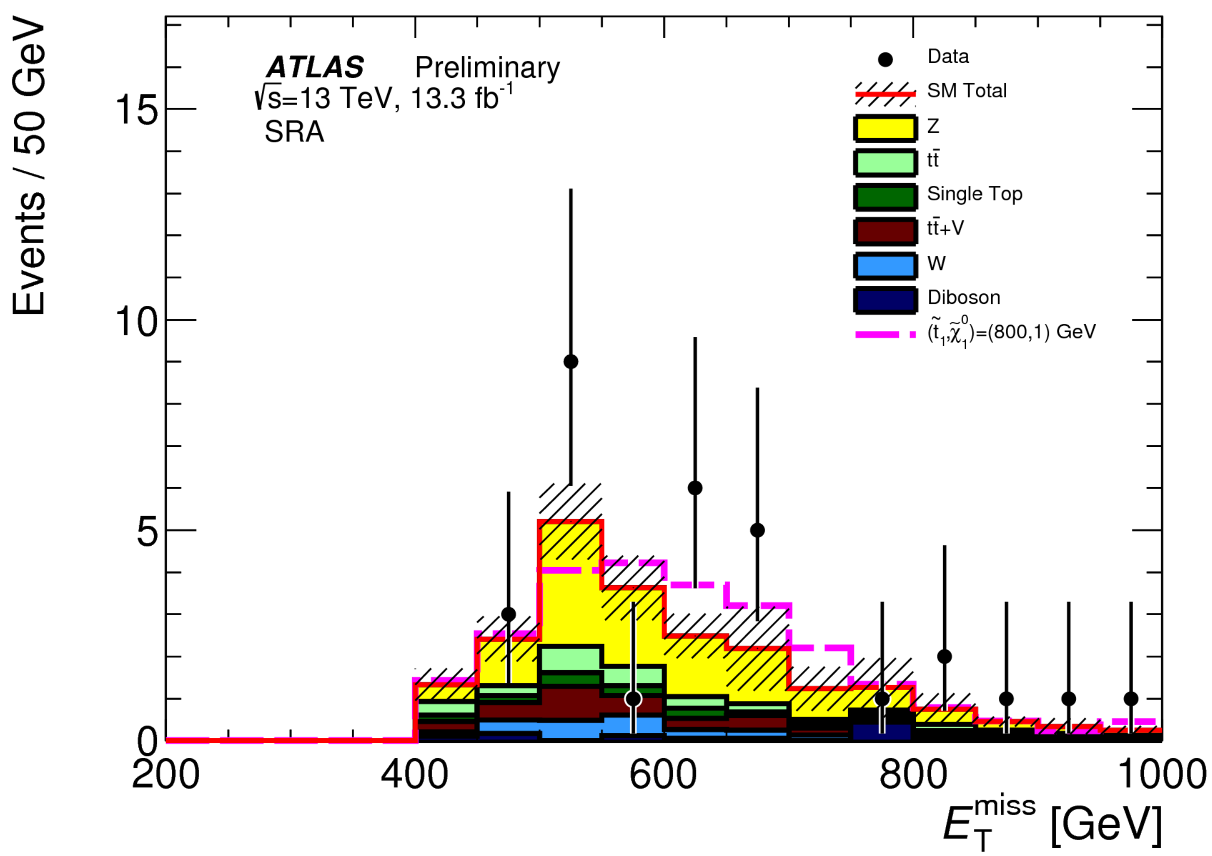
Validation Regions checks

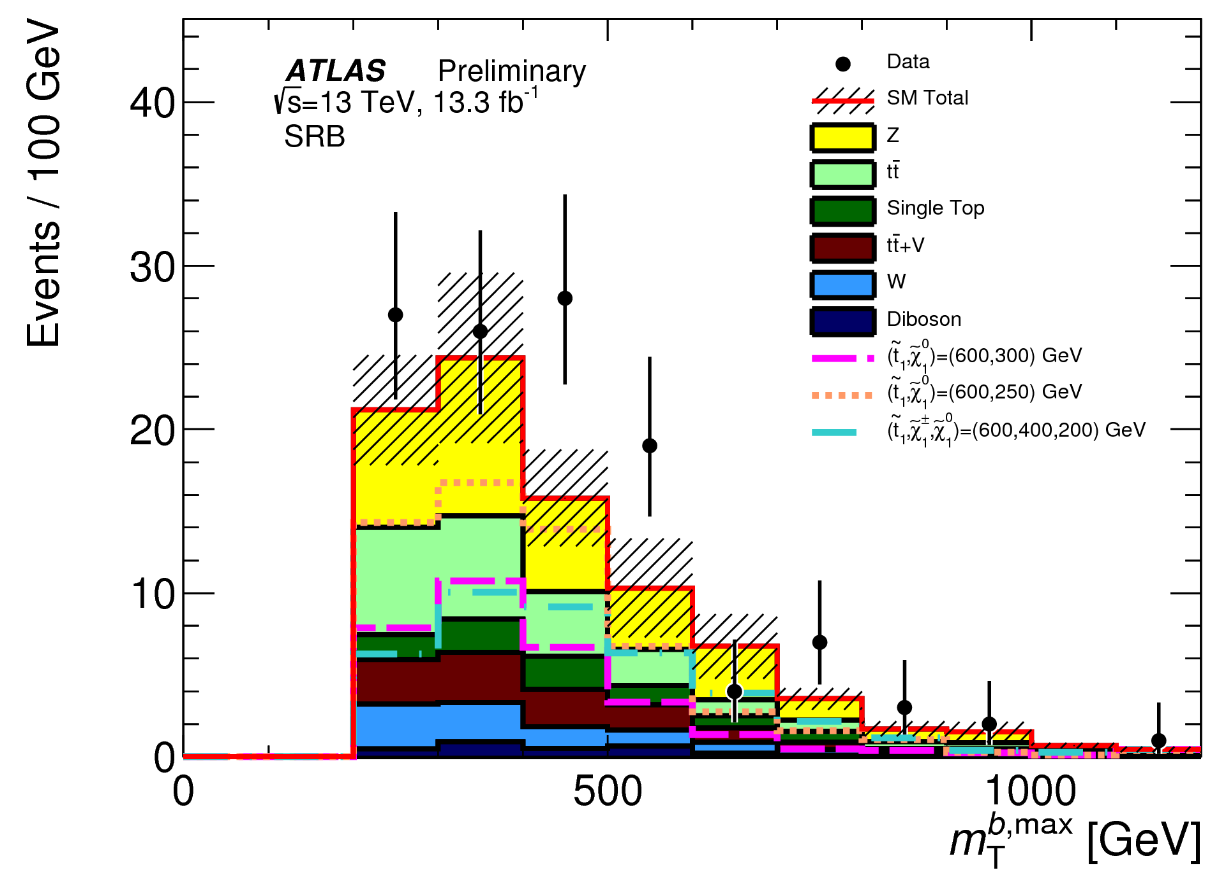




- Distributions of variables used in SRs are checked in VRs to validate the extrapolation

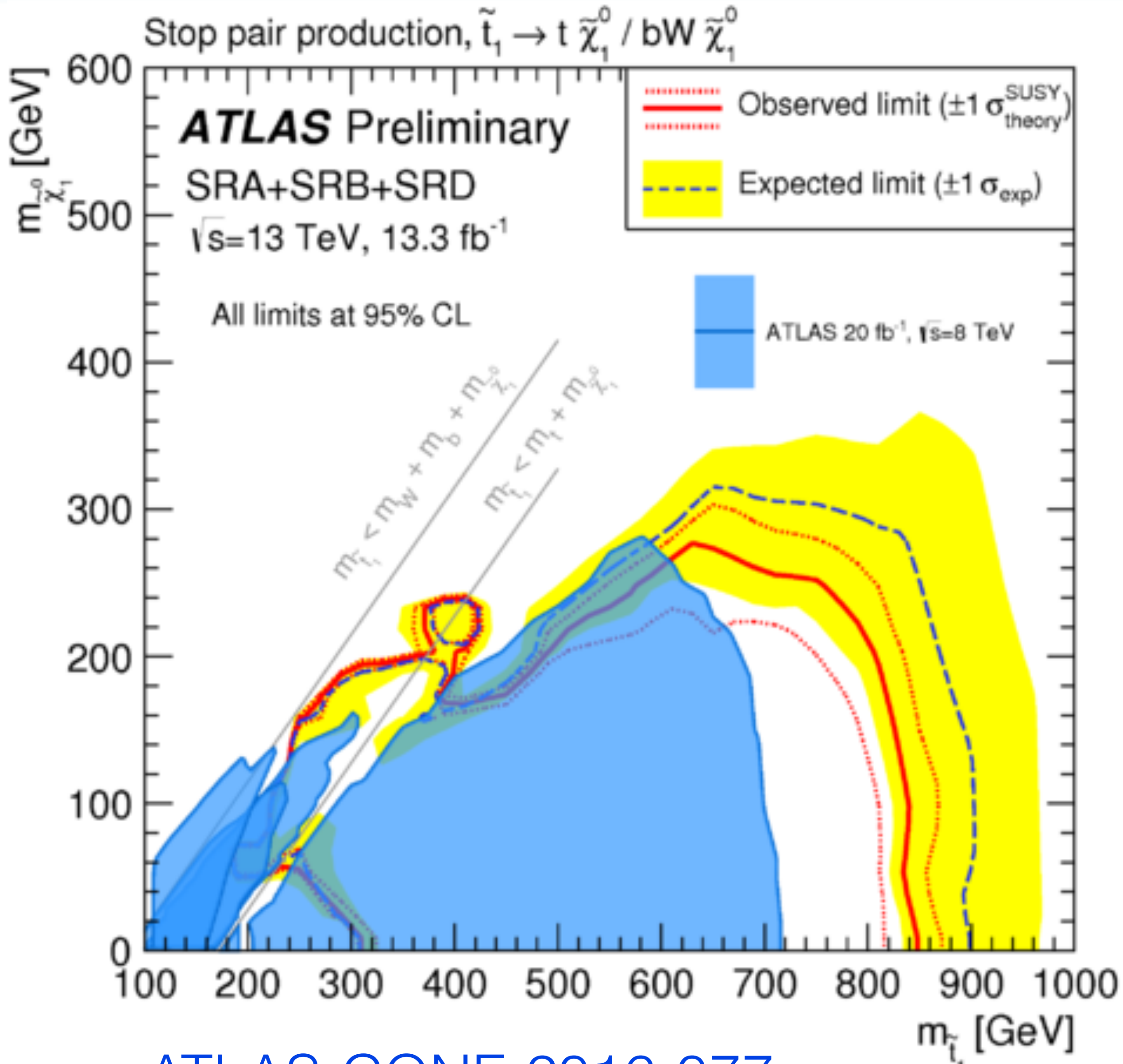
Results: unblinding examples





Number of events	**SRA-TT**	**SRB-TT**	**SRD1**	**SRD5**
Observed	8	17	4	11
Exp background	5.2 ± 1.4	10.6 ± 2.3	4.3 ± 1.9	11.6 ± 3.6

Limits from 0L and 1L channels on $\tilde{t} \rightarrow t\, \tilde{\chi}_1^0$



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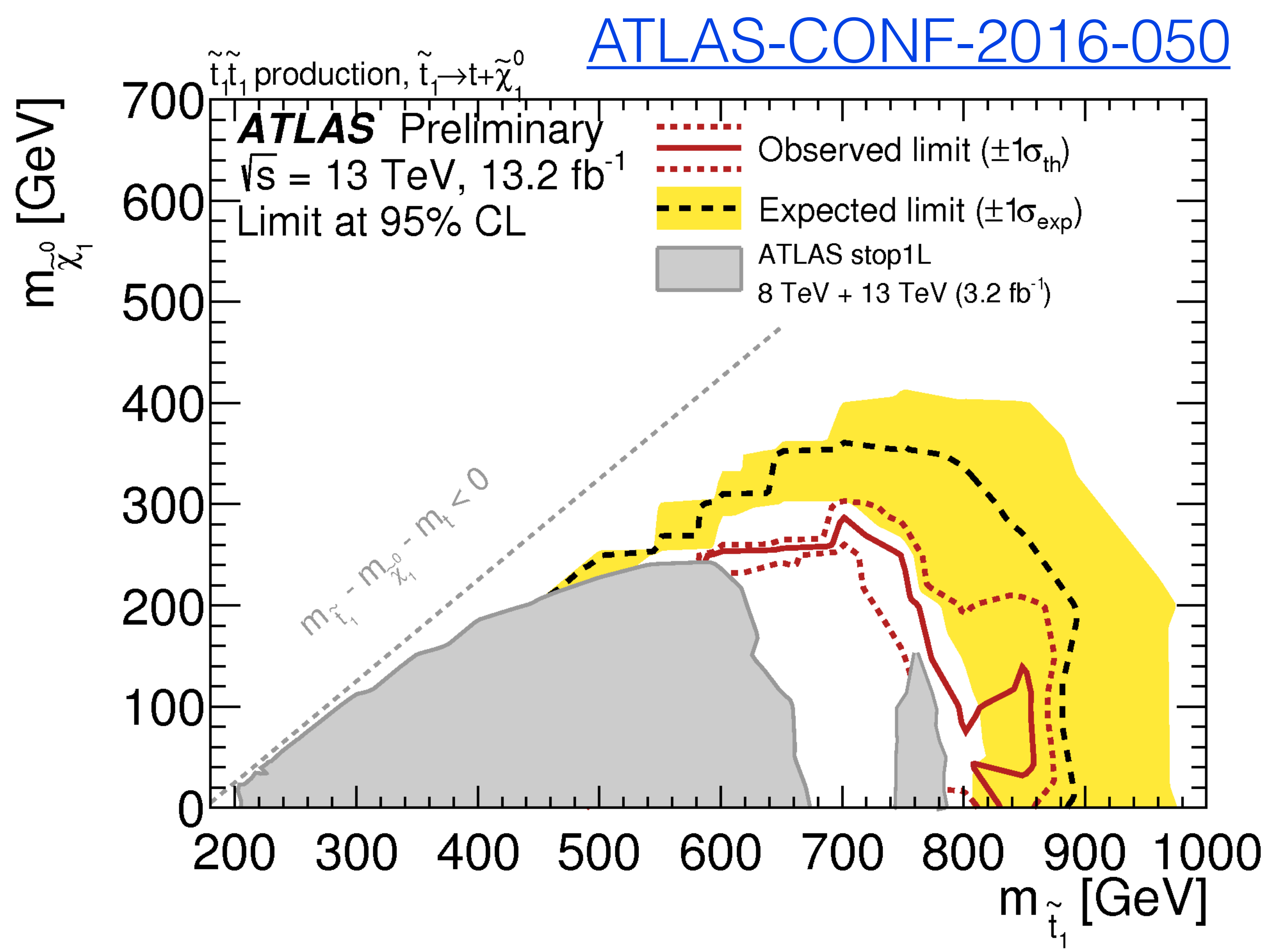
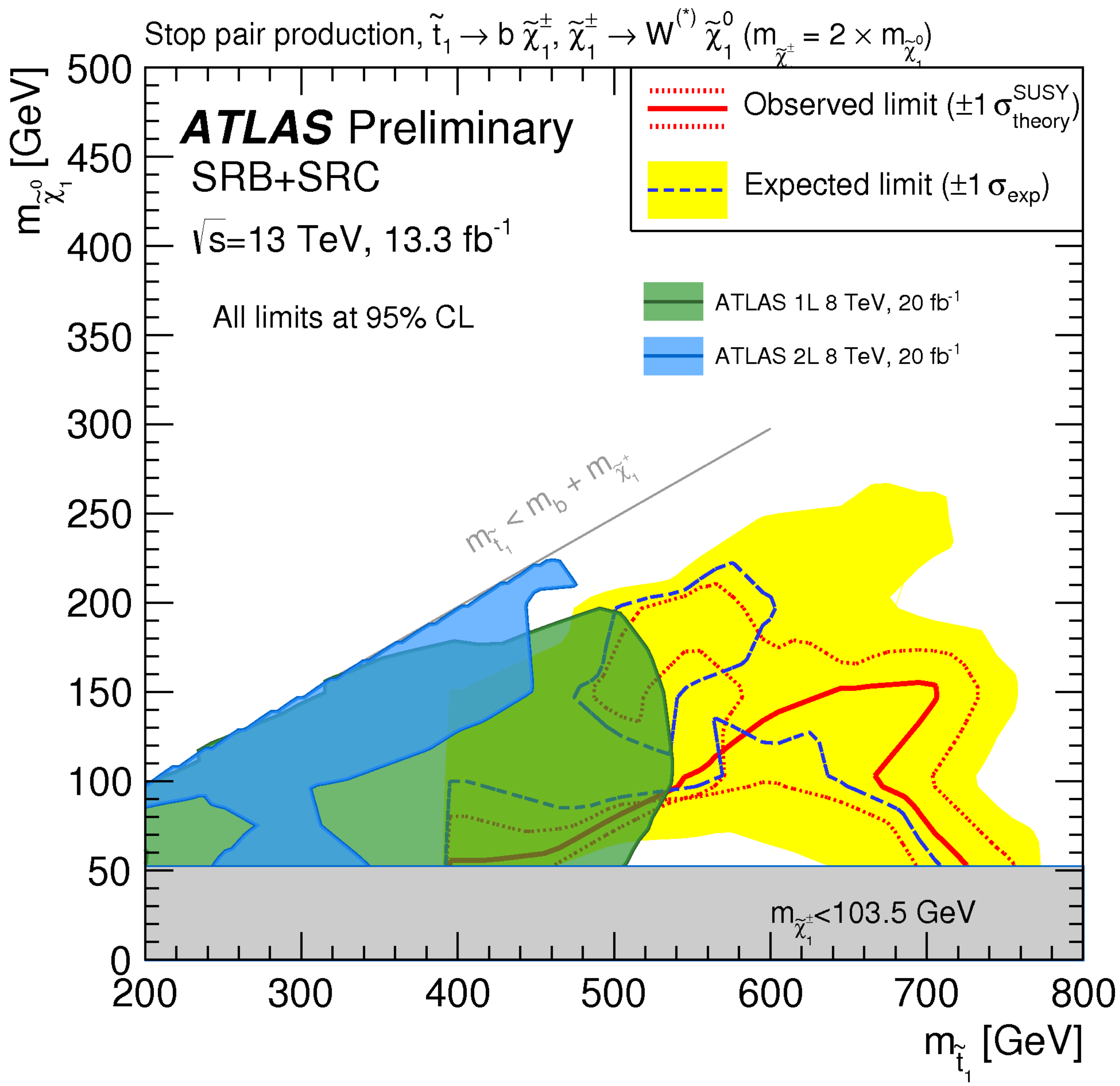


- Limits assume 100% decay $\tilde{t} \rightarrow t\, \tilde{\chi}_1^0$
- At high stop, low LSP masses:
  - Expected limit ~ 900 GeV
  - Observed limit ~ 820 GeV
- Sensitivity on the kinematic boundary due to ISR
- Similar sensitivity from 0L and 1L

Limits from 0L on $\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}$

- Limits assume 100% decay $\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}$



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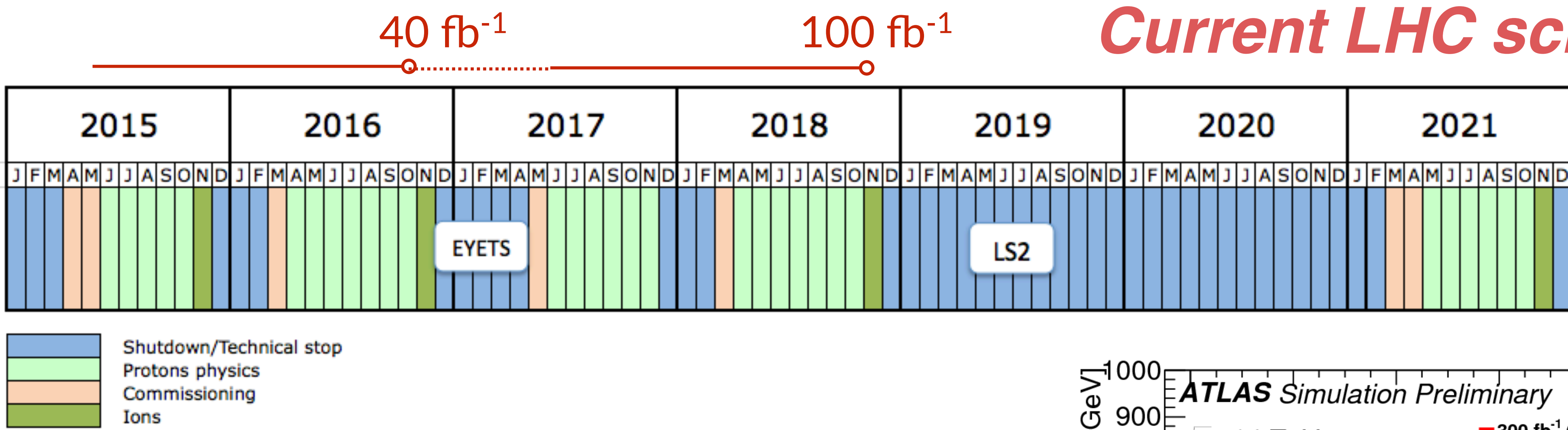
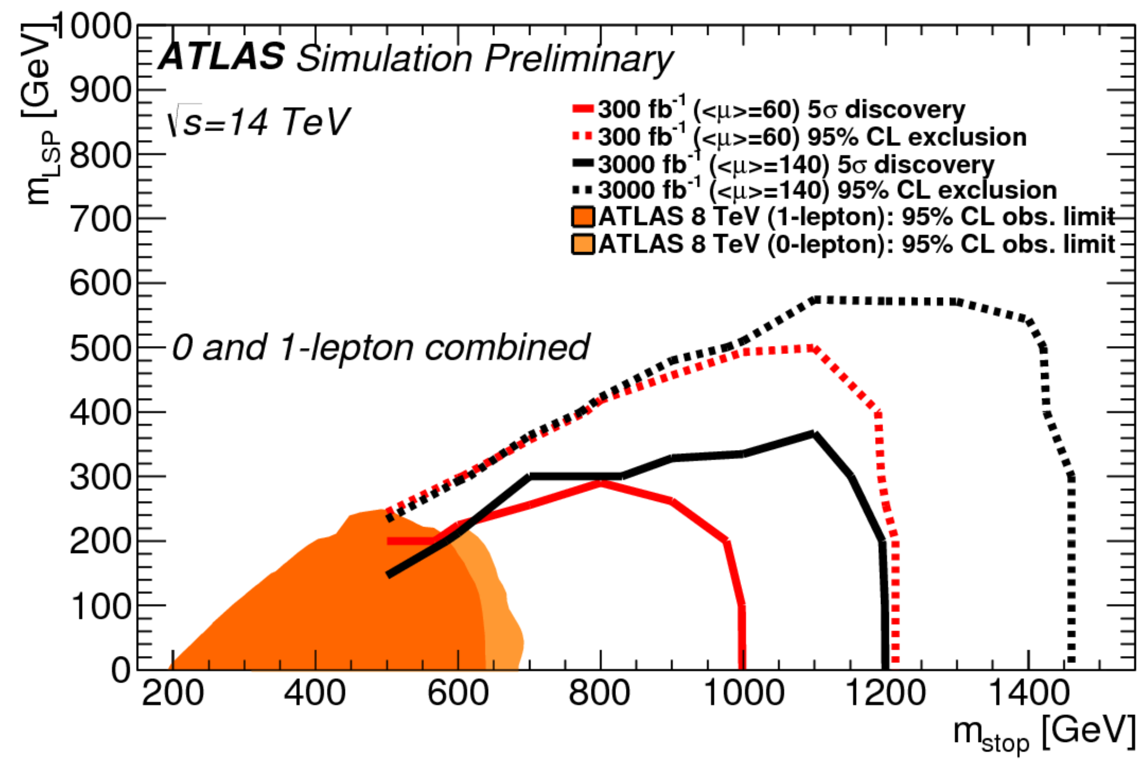
Future prospects

Current LHC schedule



- Will more data provide more insight? HL-LHC foresees 3000 fb^{-1}
- What if there is no hint of SUSY by the end of Run II?
- Discovery reach growth will be slower

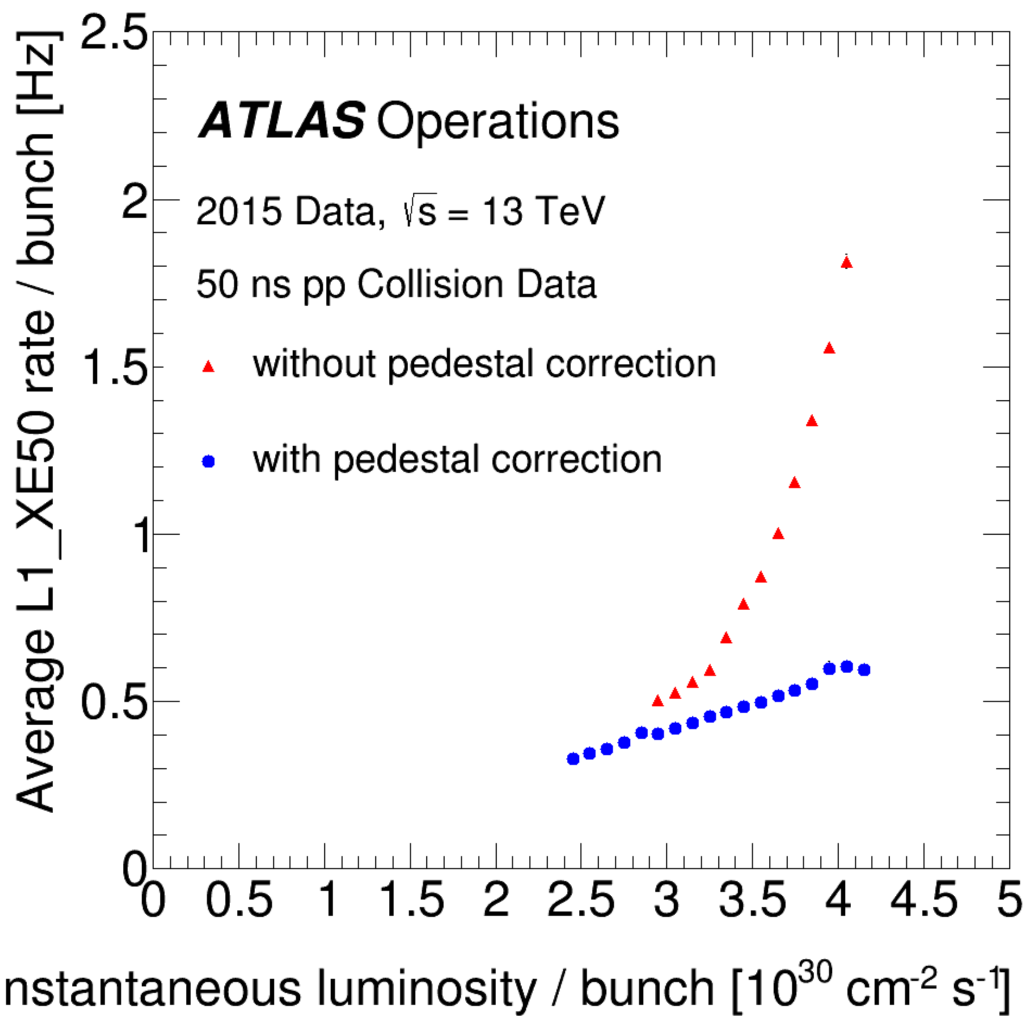


- We can try to be more clever with:
  - ☑ More sophisticated techniques that may yield greater sensitivity
  - ☑ Could benefit from better top reconstruction
  - ☑ More boosted top decays at high stop mass

→ gFEX

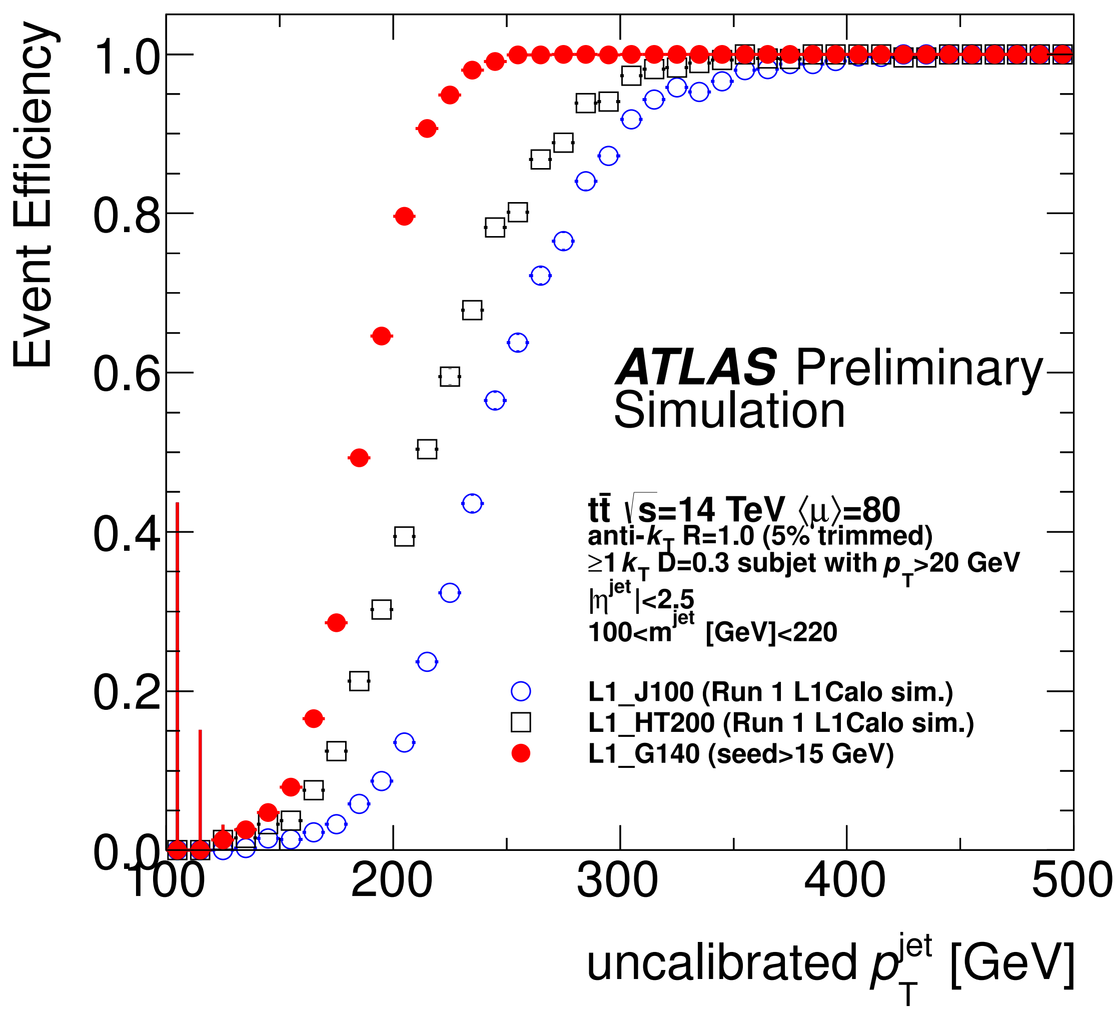
global Feature Extractor (gFEX) in a nutshell

- ATLAS L1 Jet Trigger designed in Run I for narrow jets, with limited acceptance for large objects
- E^T_{miss} trigger pile-up dependent



https://gfex.cern.ch

- gFEX reads in the entire calorimeter on a single module!
- Identifies events with large-radius jets and substructure
  - ☑ improves acceptance for boosted objects
  - ☑ jet-level pile-up subtraction

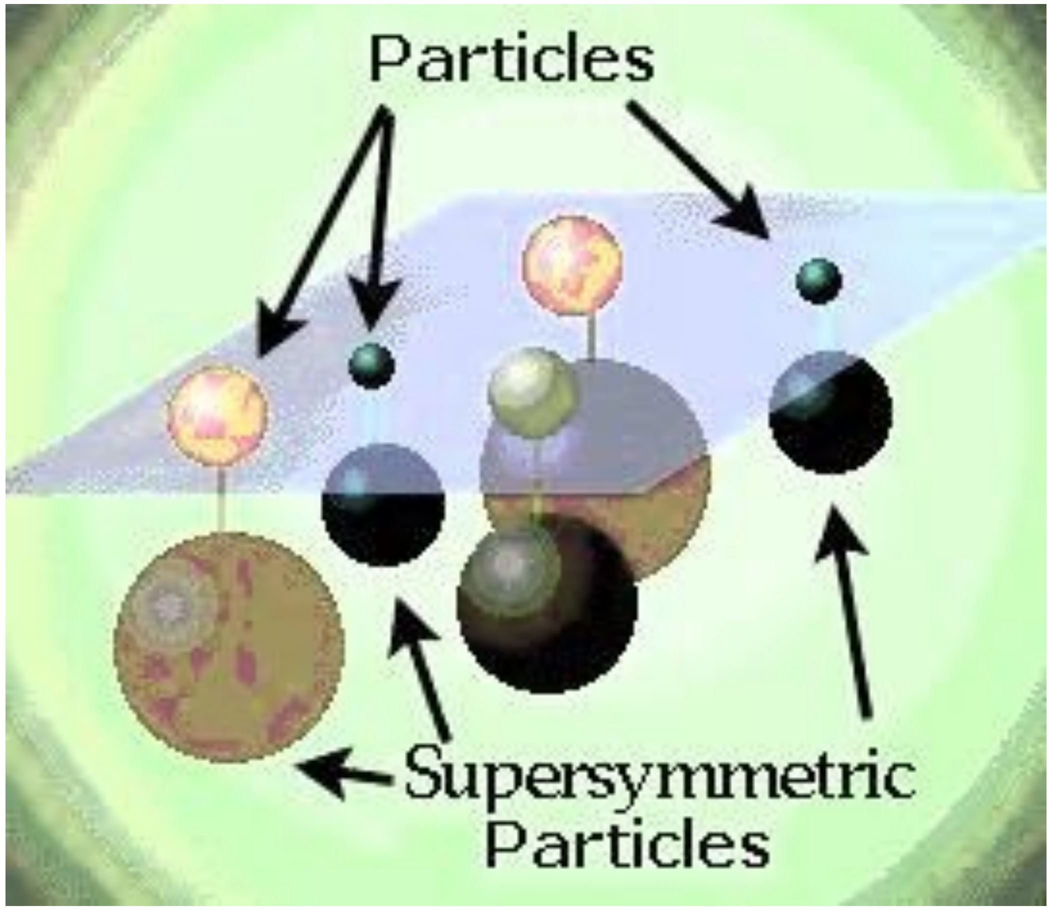


Increase trigger efficiency for boosted objects in ATLAS

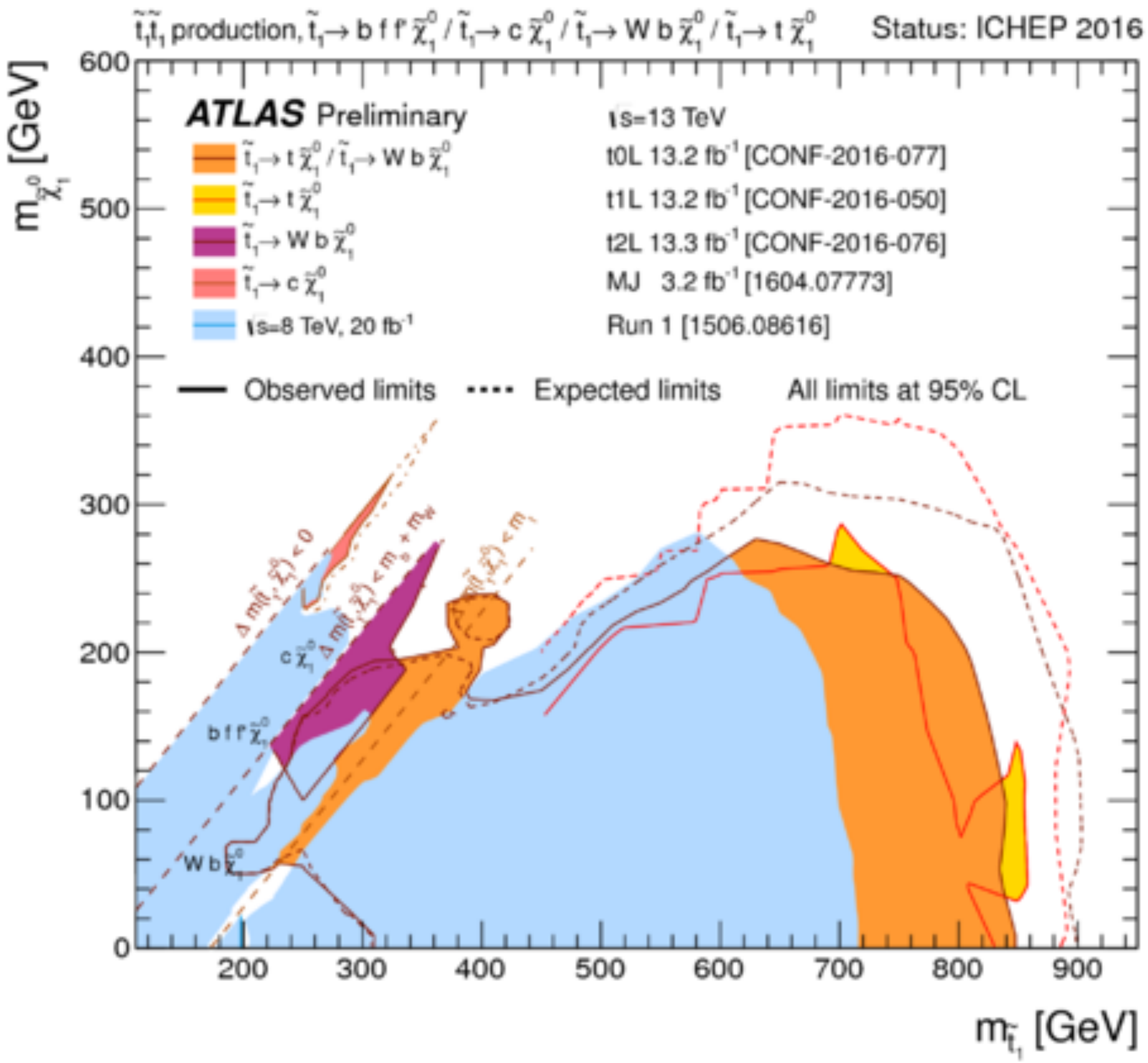
Summary

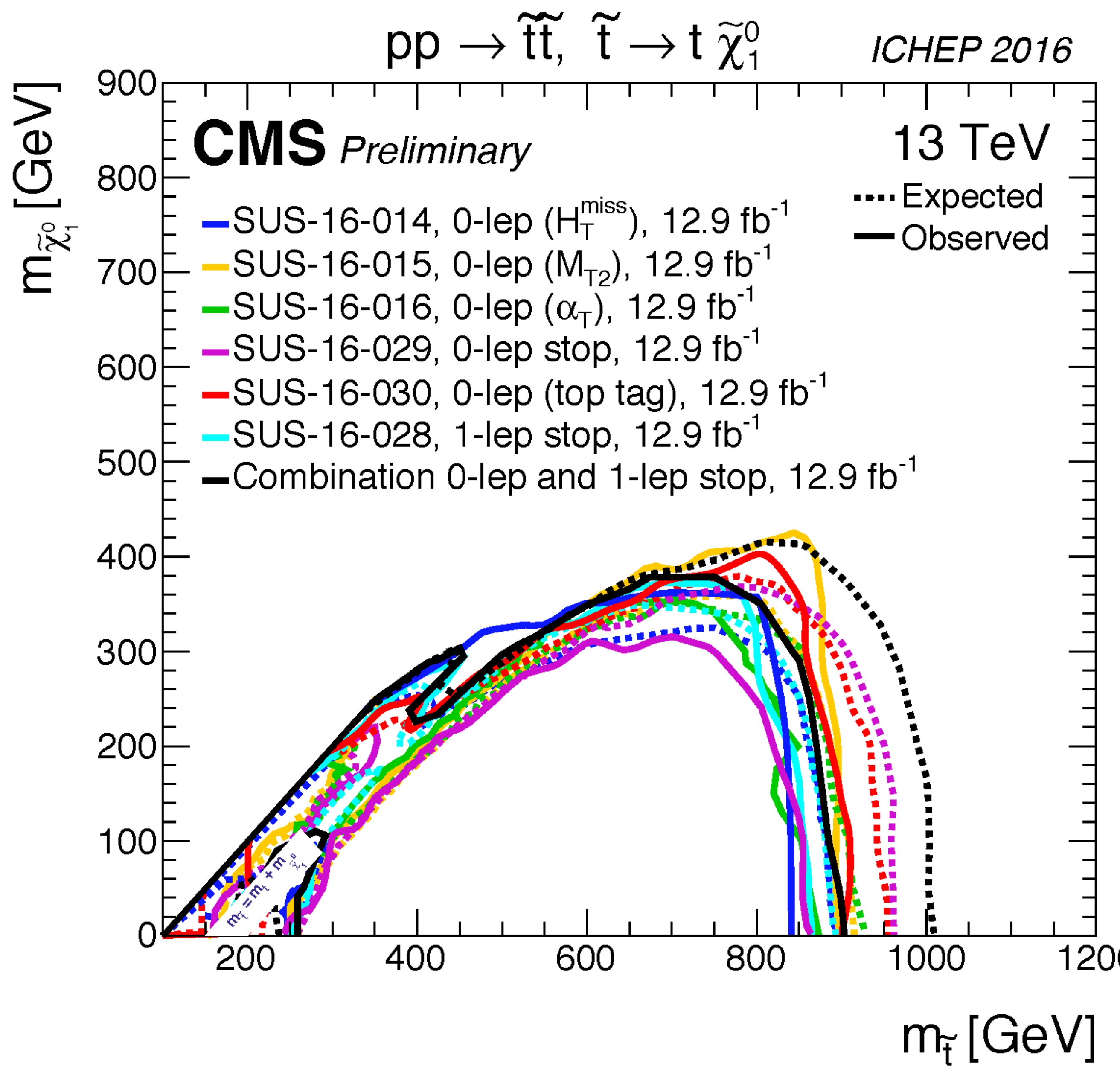
- Searches for direct stop production with the ATLAS detector
  - main decay modes $\tilde{t} \rightarrow t\ \tilde{\chi}_1^0$ and $\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}$
- First time approaching the very compressed region
- Unfortunately, no evidence for new physics found yet
- Set limits on $\tilde{t}$ and $\tilde{\chi}_1^0$ masses
  - m($\tilde{t}$)>800GeV for low m($\tilde{\chi}_1^0$)
- More Run II results (full dataset 2015+2016) in early 2017!

Extra material



ATLAS and CMS stop search status (ICHEP 2016)





SRA and SRB (high and bulk region)

Signal Region		TT	TW	T0
	$m^{0}_{\text{jet},R=1.2}$	> 120 GeV	> 120 GeV	> 120 GeV
	$m^{1}_{\text{jet},R=1.2}$	> 120 GeV	$60 - 120$ GeV	< 60 GeV
SRA	$m^{0}_{\text{jet},R=0.8}$	> 60 GeV		
	b-tagged jets	≥ 2		
	$m_{\text{T}}^{b,\text{min}}$	> 200 GeV		
	τ-veto	yes		
	$E_{\text{T}}^{\text{miss}}$	> 400 GeV	> 450 GeV	> 500 GeV
SRB	b-tagged jets	≥ 2		
	$m_{\text{T}}^{b,\text{min}}$	> 200 GeV		
	$m_{\text{T}}^{b,\text{max}}$	> 200 GeV		
	τ-veto	yes		
	$\Delta R(b,b)$	> 1.2		
	$E_{\text{T}}^{\text{miss}}$	> 250 GeV		

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SRD for compressed regions

Variable	SRD1	SRD2	SRD3	SRD4	SRD5	SRD6	SRD7	SRD8
min R_{ISR}	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60
max R_{ISR}	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75
b-tagged jets	≥ 2				≥ 1			
$N_{\mathrm{jet}}^{\mathrm{S}}$	≥ 5							
$p_{\mathrm{T}}^{\mathrm{ISR}}$	> 400 GeV							
$p_{\mathrm{T}}^{b\text{-tag},S}$	> 40 GeV							
$p_{\mathrm{T}}^{\mathrm{jet}\,4,S}$	> 50 GeV							
M_{T}^{S}	> 300 GeV							
$\Delta\phi_{\mathrm{ISR}}$	> 3.0 radians							

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SRC for bChino

Variable	SRC-low	SRC-med	SRC-high
m_{bjj}	> 250 GeV		
b-tagged jets	≥ 2		
p_T^0	> 150 GeV	> 200 GeV	> 250 GeV
p_T^1	> 100 GeV	> 150 GeV	> 150 GeV
$m_T^{b,\min}$	> 250 GeV	> 300 GeV	> 350 GeV
$m_T^{b,\max}$	> 350 GeV	> 450 GeV	> 500 GeV
$\Delta R(b,b)$	> 0.8		
$E_T^{\text{miss}}/\sqrt{H_T}$	$[5, 12]\sqrt{\text{GeV}}$	$[5, 12]\sqrt{\text{GeV}}$	$[5, 17]\sqrt{\text{GeV}}$
E_T^{miss}	> 250 GeV		

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Control Regions definitions

Selection	CRZ	CRT	CRT-ISR	CRST	CRW
Trigger	electron (muon)	E_T^{miss}			
N_ℓ	2	1			
p_T^ℓ	> 20 GeV				
$m_{\ell\ell}$	[86,96] GeV	-			
N_{jet}	≥ 4	≥ 4 (including leptons)			
jet p_T	(40, 40, 20, 20) GeV	(80, 80, 40, 40) GeV			(80, 80, 20, 20) GeV
E_T^{miss}	< 50 GeV	> 250 GeV			
$E_T^{miss\prime}$	> 70 GeV	-			
b-tagged jets	≥ 2	≥ 2	≥ 1	≥ 2	= 1
$\left\|\Delta\phi\left(\text{jet}^{0,1}, E_T^{miss}\right)\right\|$	-	> 0.4			
min $m_T(\ell, E_T^{miss})$	-	30 GeV	-	30 GeV	30 GeV
max $m_T(\ell, E_T^{miss})$	-	120 GeV	80 GeV	120 GeV	100 GeV
$m^0_{\text{jet},R=1.2}$	-	> 70 GeV	-	> 70 GeV	< 60 GeV
$m_T^{b,\min}$	-	> 100 GeV	-	> 175 GeV	-
$\Delta R(b,\ell)_{\min}$	-	< 1.5	< 2.0	> 1.5	> 2.0
m_{bb}	-	-	-	> 200 GeV	-
N^S_{jet}	-	-	≥ 5	-	-
$N^S_{b\text{-tag}}$	-	-	≥ 1	-	-
p_T^{ISR}	-	-	≥ 400 GeV	-	-

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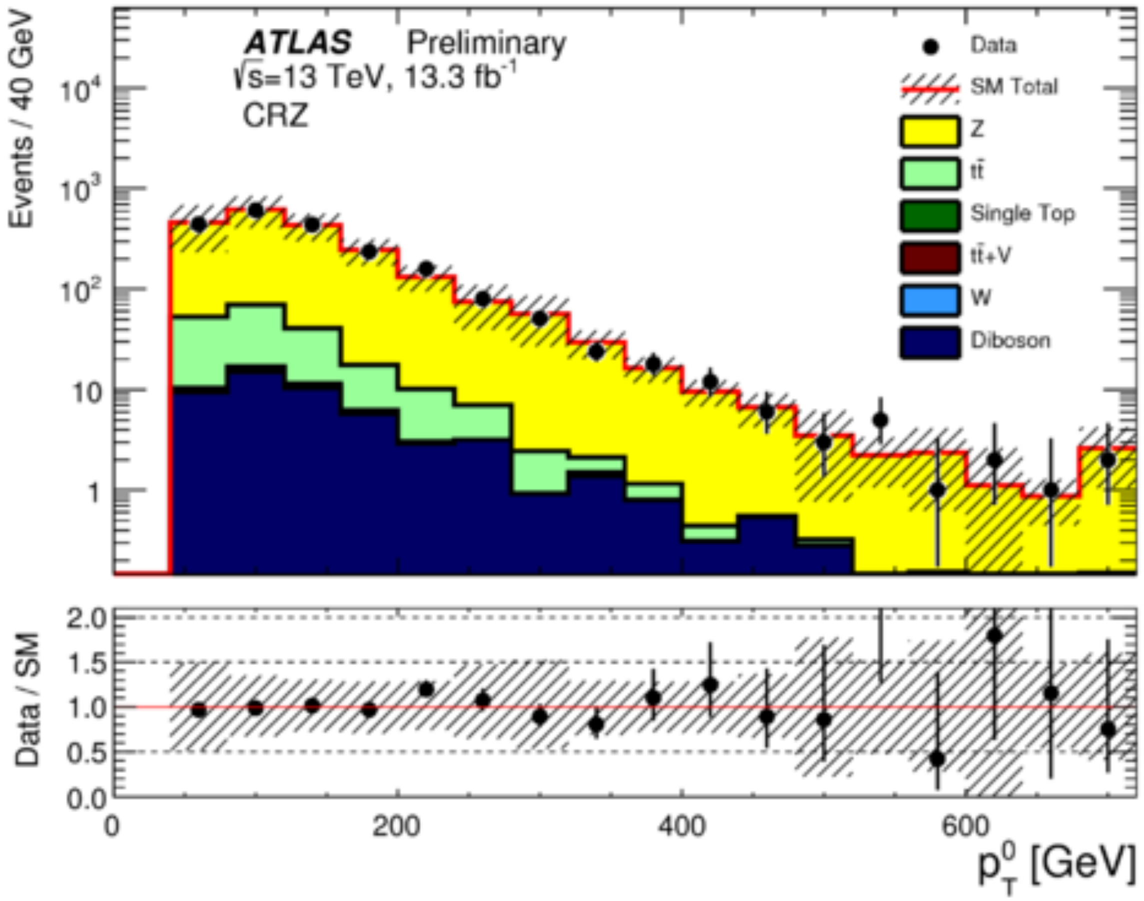
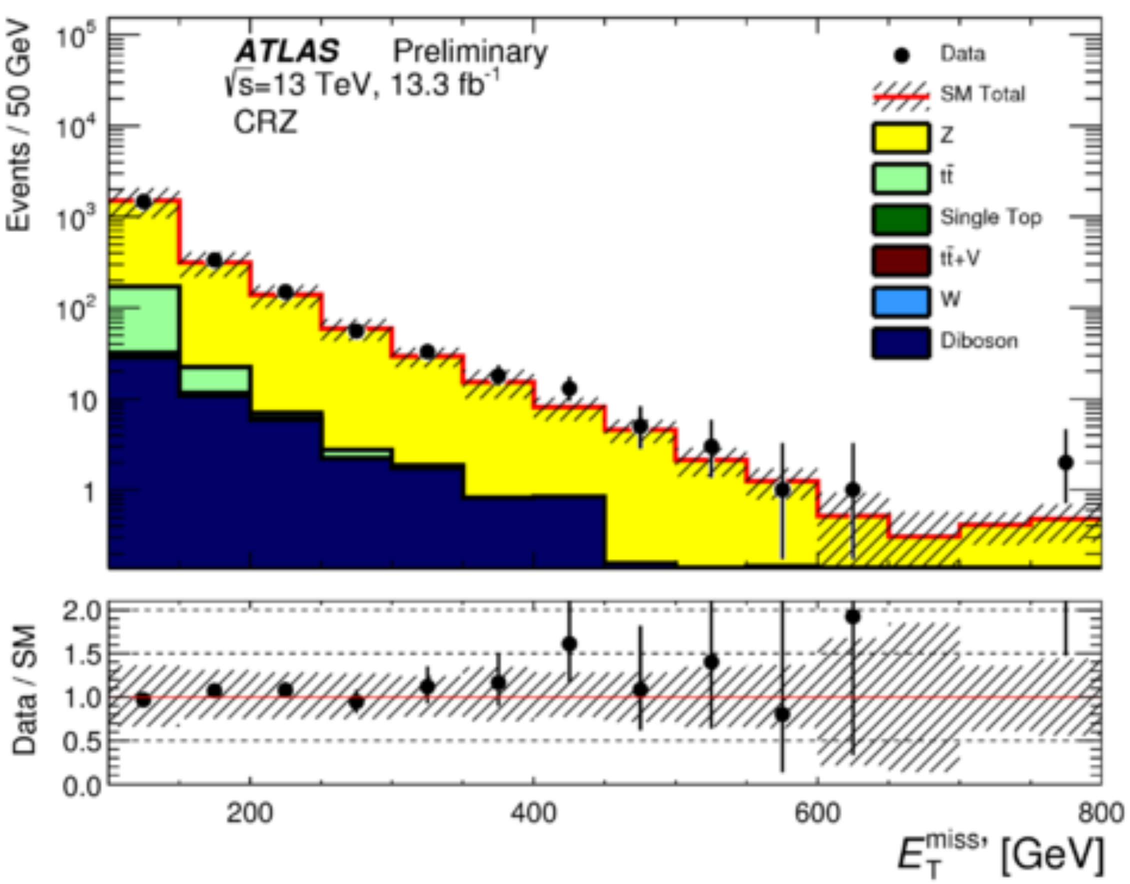
Background relationships

	Z + jets	$t\bar{t}$		W + jets	single top
	CRZ	CRT	CRT-ISR	CRW	CRST
SF	1.20±0.26	0.91±0.18	0.78±0.19	1.21±0.21	0.86±0.33
SRA	34%-58%	9%-14%	-	10%-11%	6%-9%
SRB	22%-42%	22%-25%	-	9%-13%	10%
SRC	37%-39%	6%-17%	-	18%-25%	20%-26%
SRD1-4	0%	-	91%-92%	2%	1%-4%
SRD5-8	2%-10%	-	70%-84%	5%-9%	4%-8%

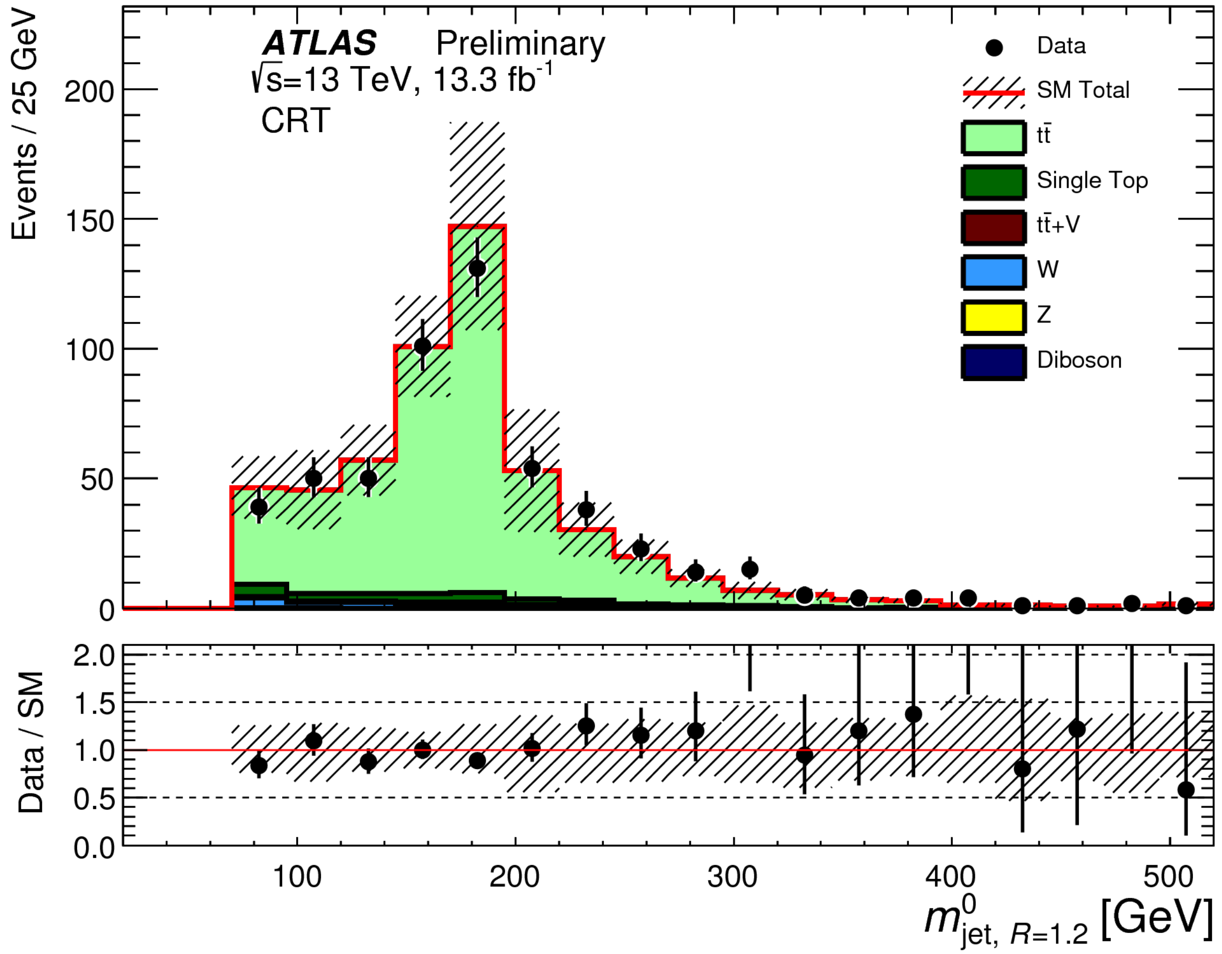
Control Regions



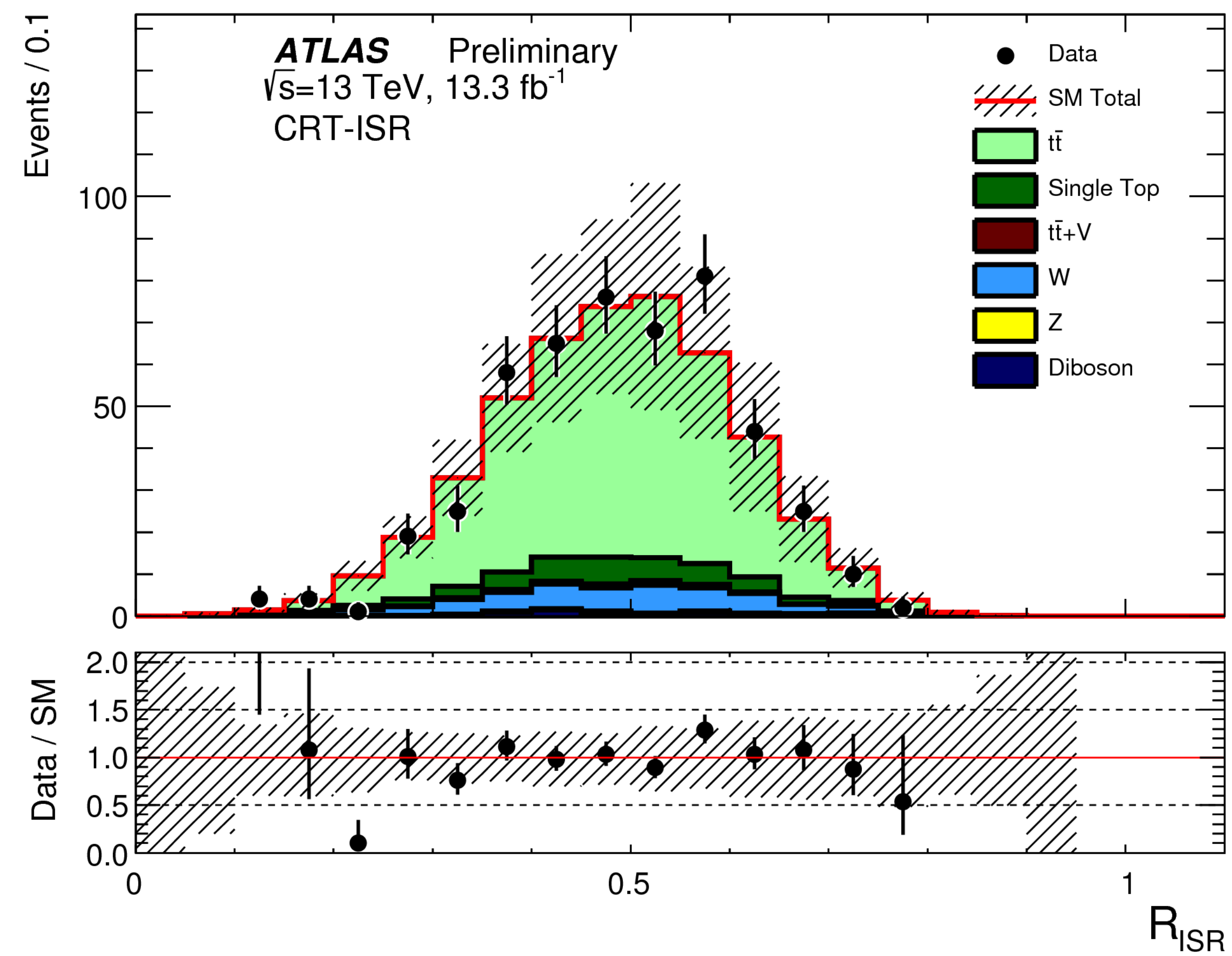
- $Z \rightarrow \nu\nu$ *+jets* is the dominant background in most SRs
  - Z CR used to estimate the normalization
  - loose jet pT requirements to ensure rich statistics sample
  - 2 b-jets, at least 4 jets



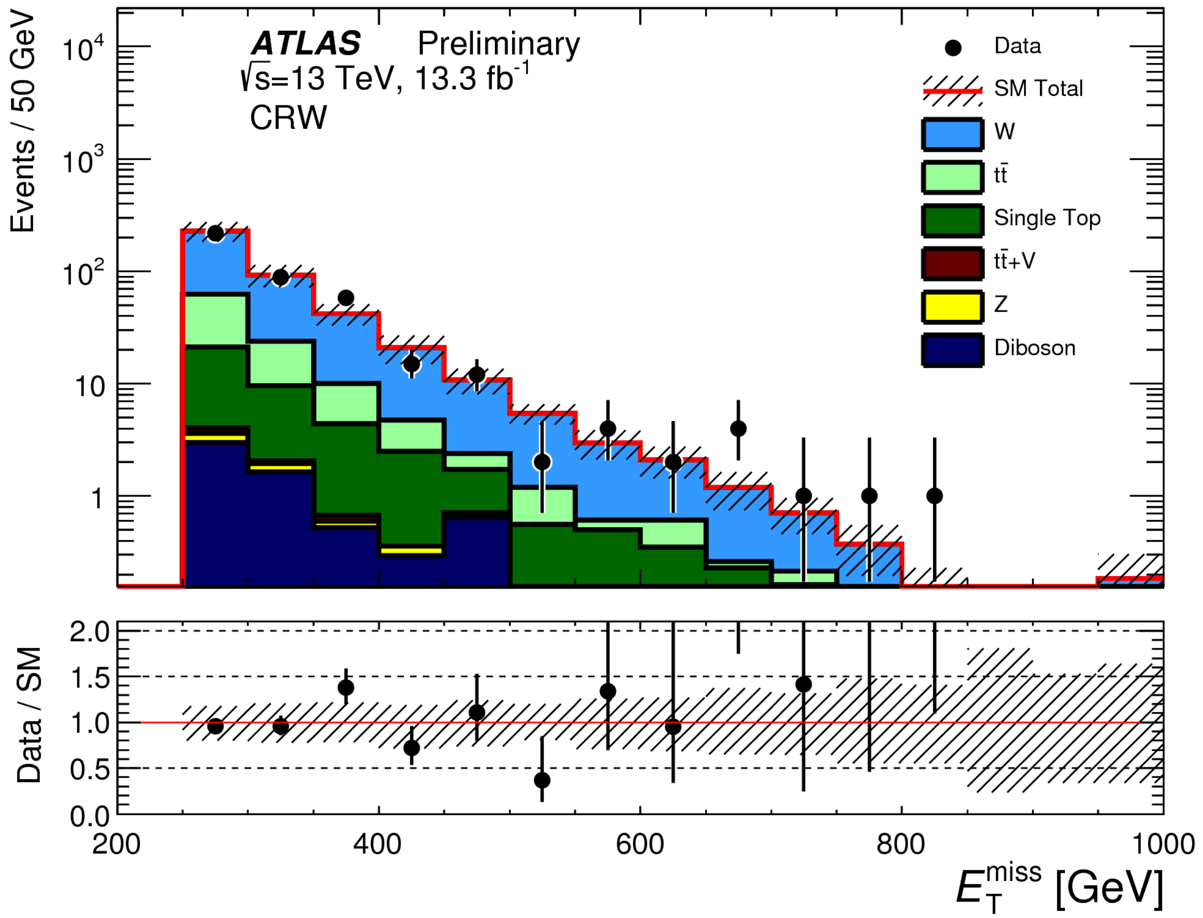
Control Regions: ttCR

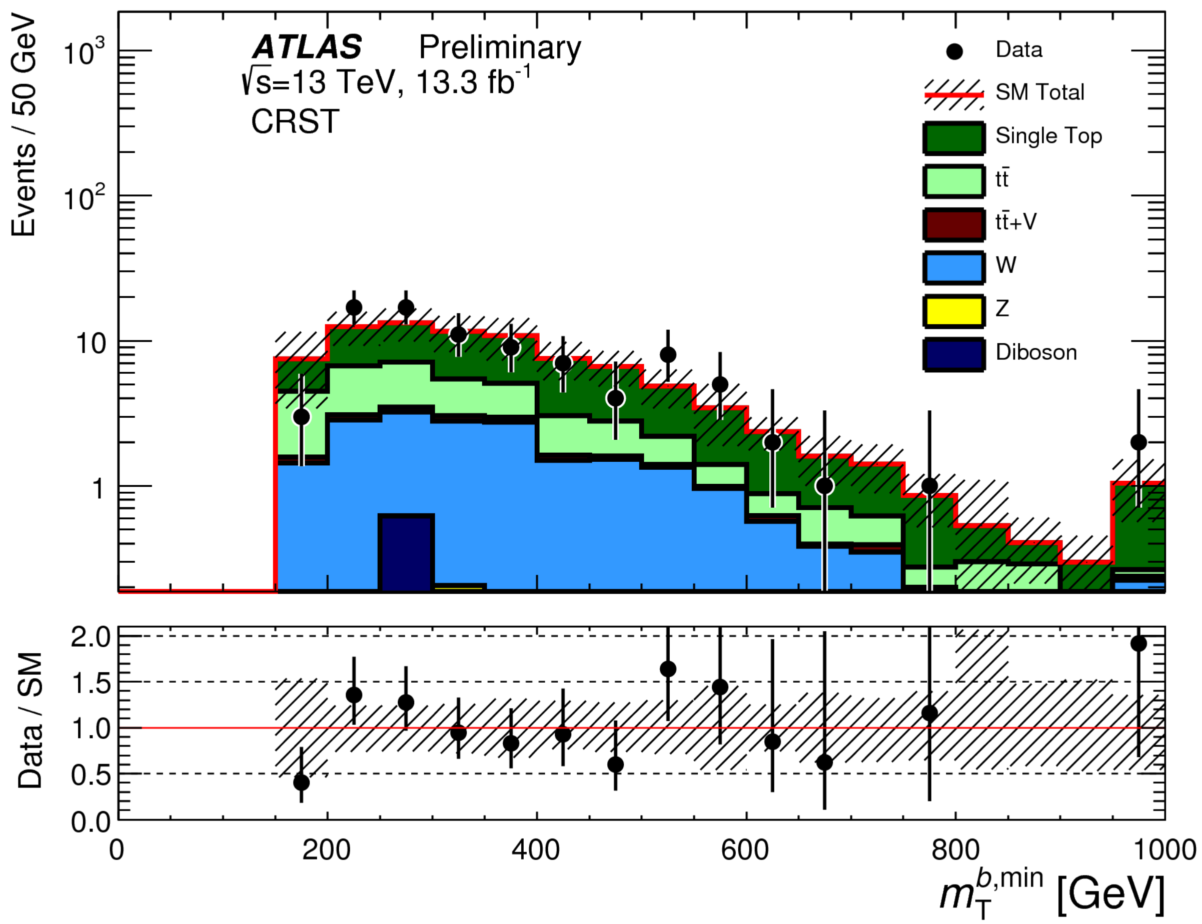


- 1 lepton CR
  - 2-bjets, $E^{T}_{miss} > 250$ GeV
  - no top reconstruction

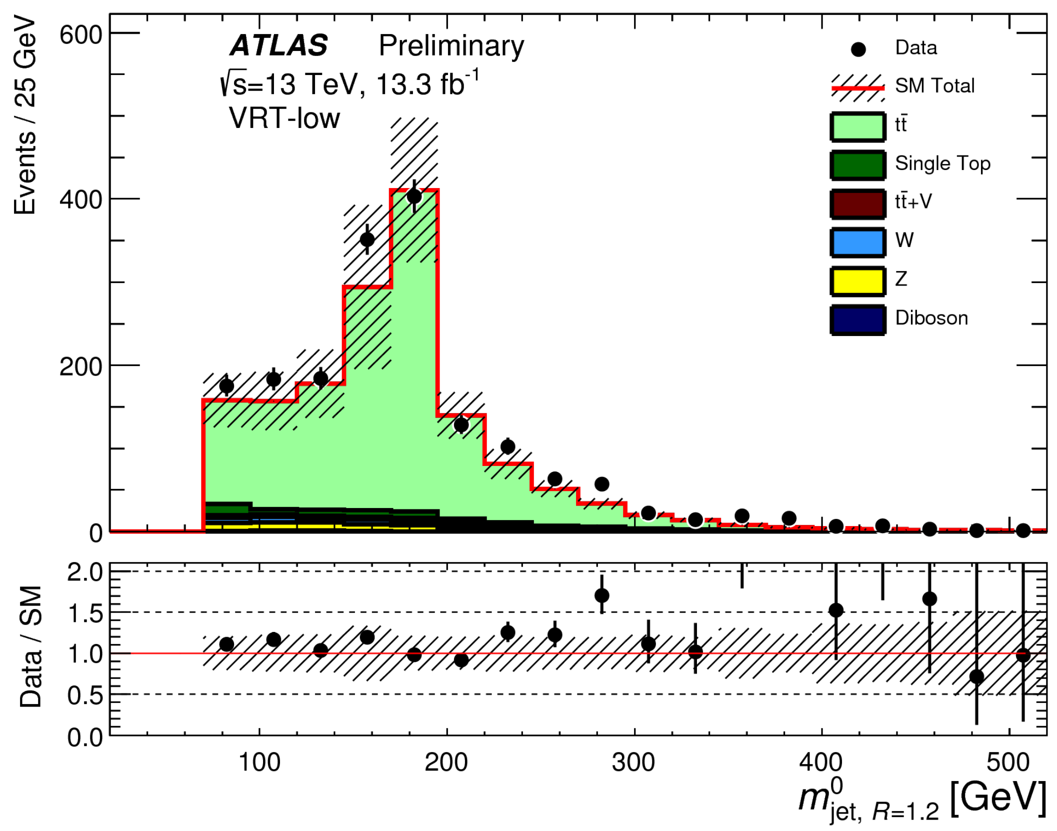


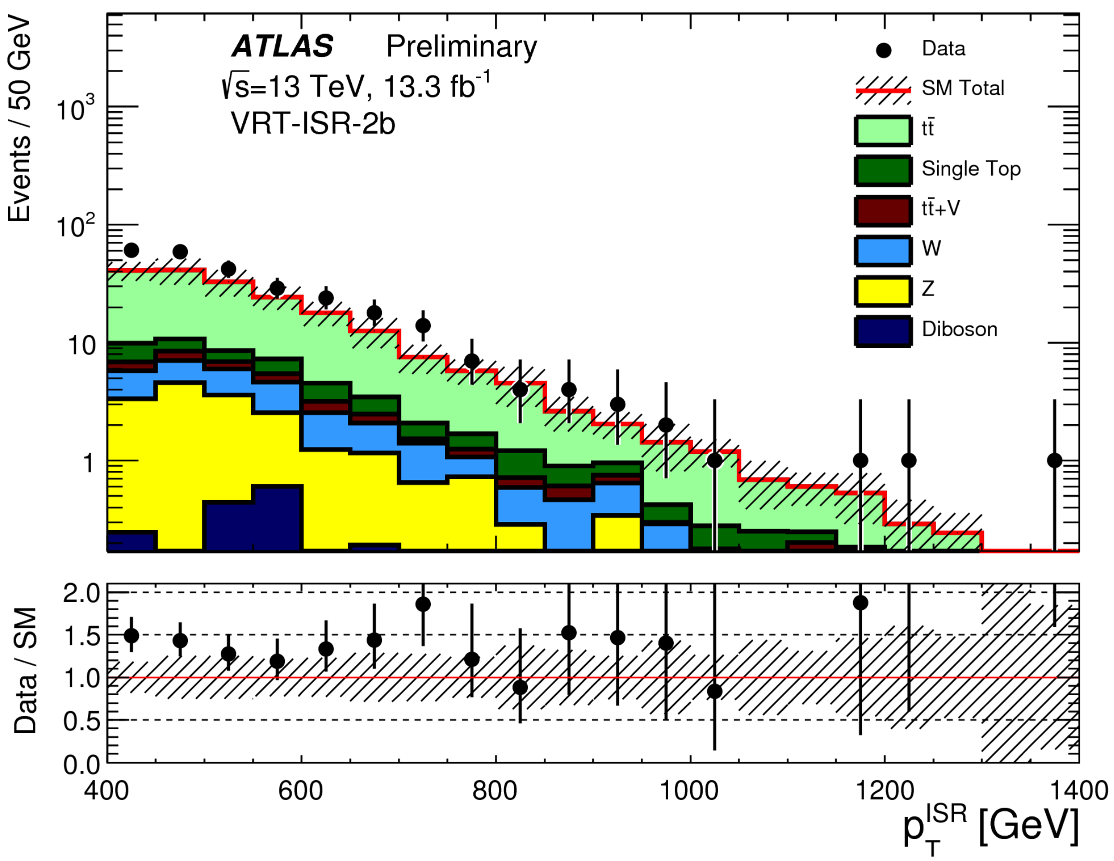
Control Regions: W and Single Top CRs





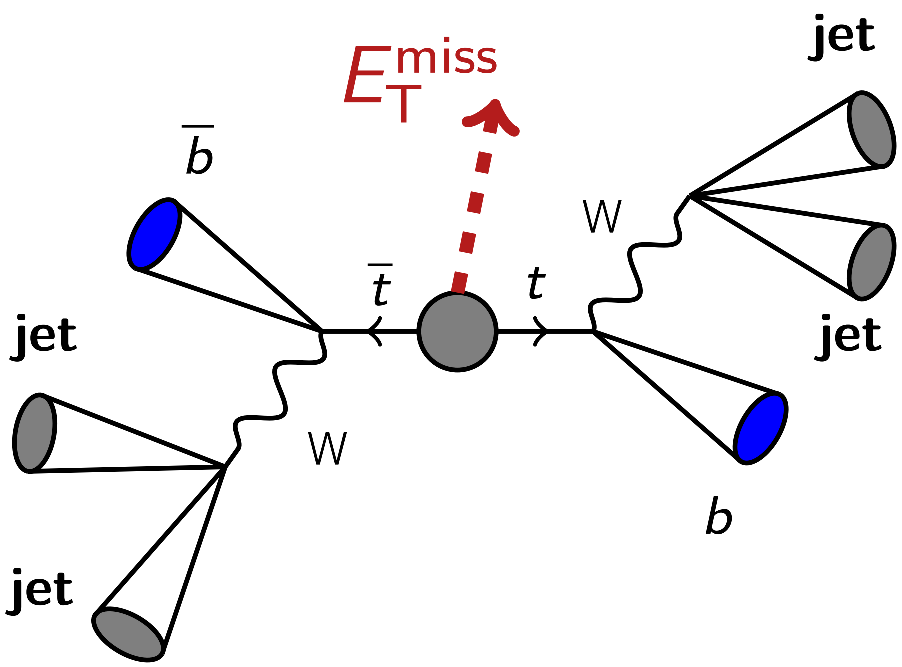
Validation Regions





Signal signature

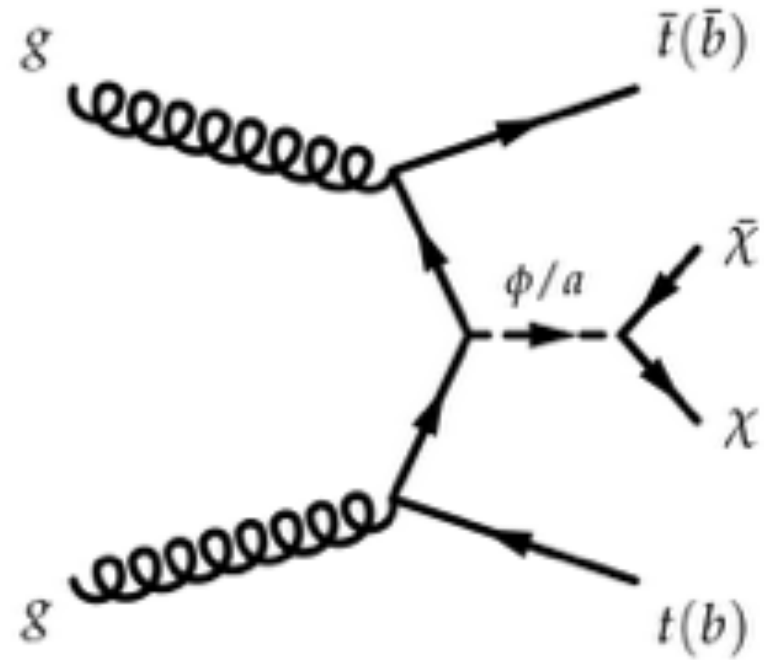
- Direct stop production with each $\tilde{t} \to t\ \tilde{\chi}_1^0$
- $\tilde{t} \to b\ \tilde{\chi}_1^{\pm}$ and DM have the same signature but different kinematics



- tops decay to W+b-quarks
- at least 2 b-jets and additional jets from the W hadronic decays
- Large missing energy from LSPs

- Ideally: 6 jets (2 b-jets) and missing energy
  - 2 Top masses can be reconstructed

Signals of interest: stop decays



- DM+HF is preferred, if mediator is a spin-0 (pseudo)scalar
  - quark mass dependence in cross section: light quark coupling is suppressed
- Same signatures in direct stop production

Limits from 0L on $\varphi/a \to \chi\chi$

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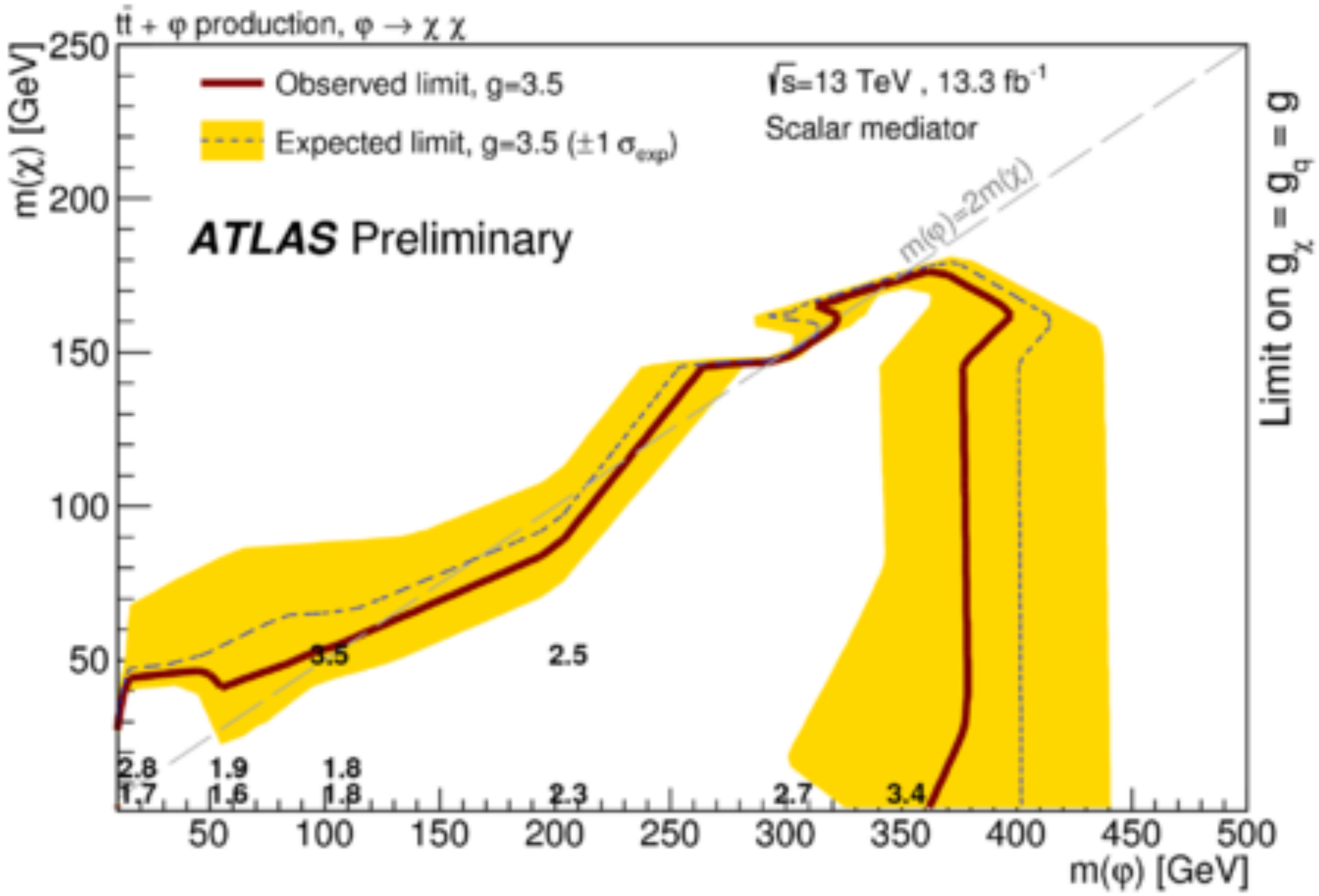
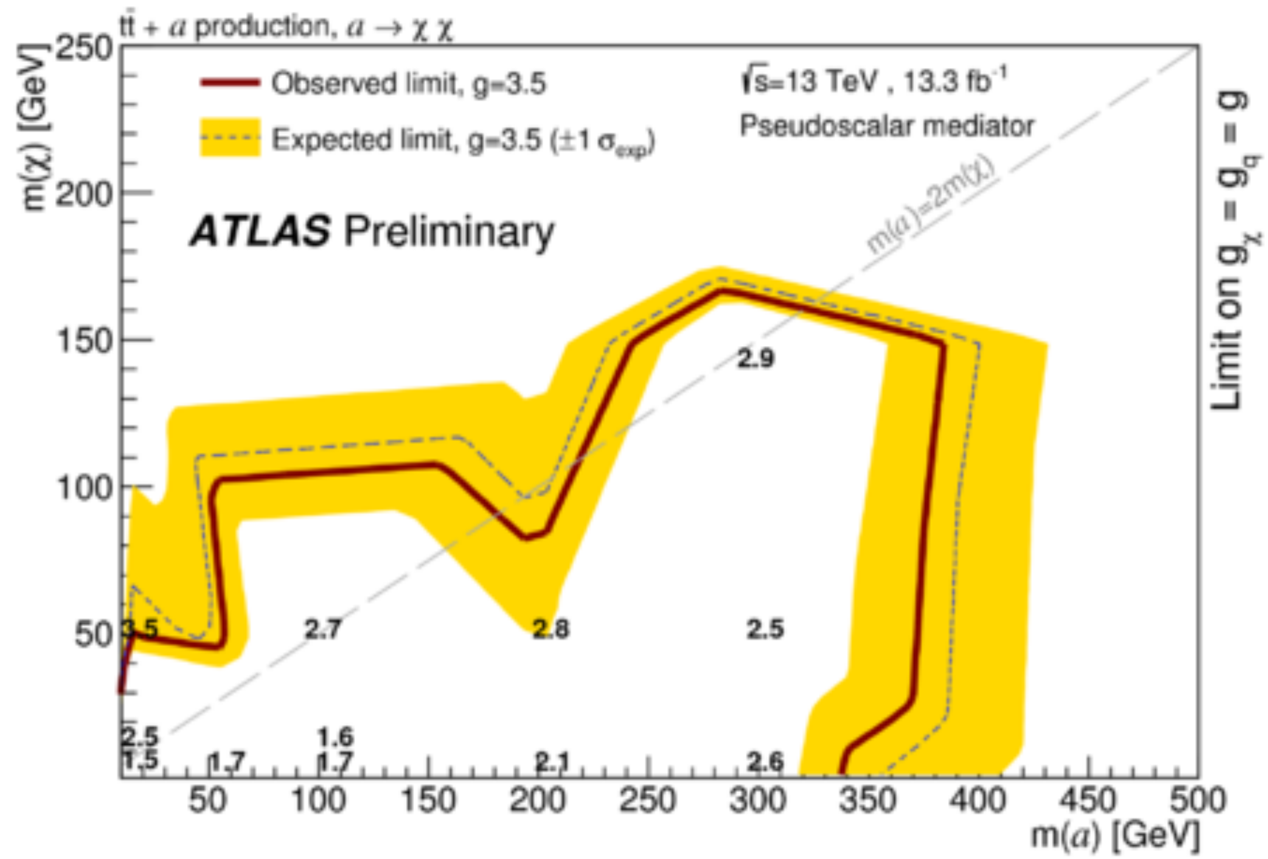
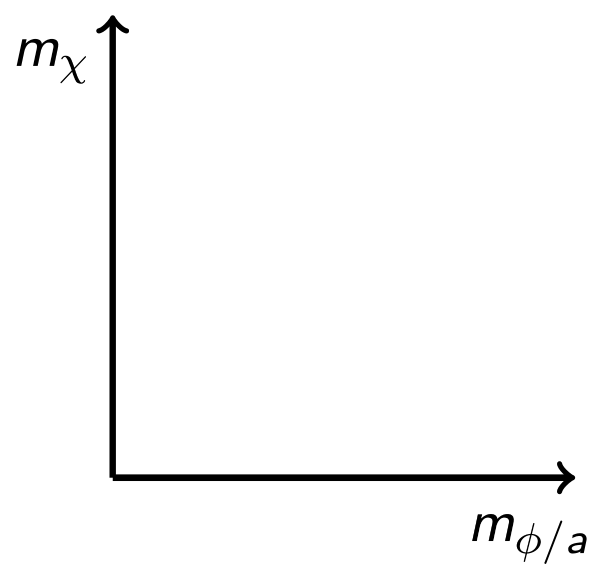




- Limits assume g=3.5
- Limits are also set on g (numbers on plot)
- Similar reach for scalar and pseudo-scalar

DM simplified models

- Same signature as stop decays but potentially different kinematics (softer)
- simplified models with four parameters (mass of mediator and DM, and the mediator-DM and mediator-SM coupling)
  - Mediator-DM and mediator-SM coupling are set to be equal (g)
  - Considered coupling ranging from 1-3.5 with limit curves using 3.5
  - Both scalar and pseudo scalar sensitivity is considered



Model parameters: $m_{\phi/a}$, m_χ, g

ATLAS

- TDAQ system @Run II
  - Level-1 Trigger @100kHz (with 2x more triggers)
  - High Level Trigger @1kHz (with faster and robust against pile-up algorithms)