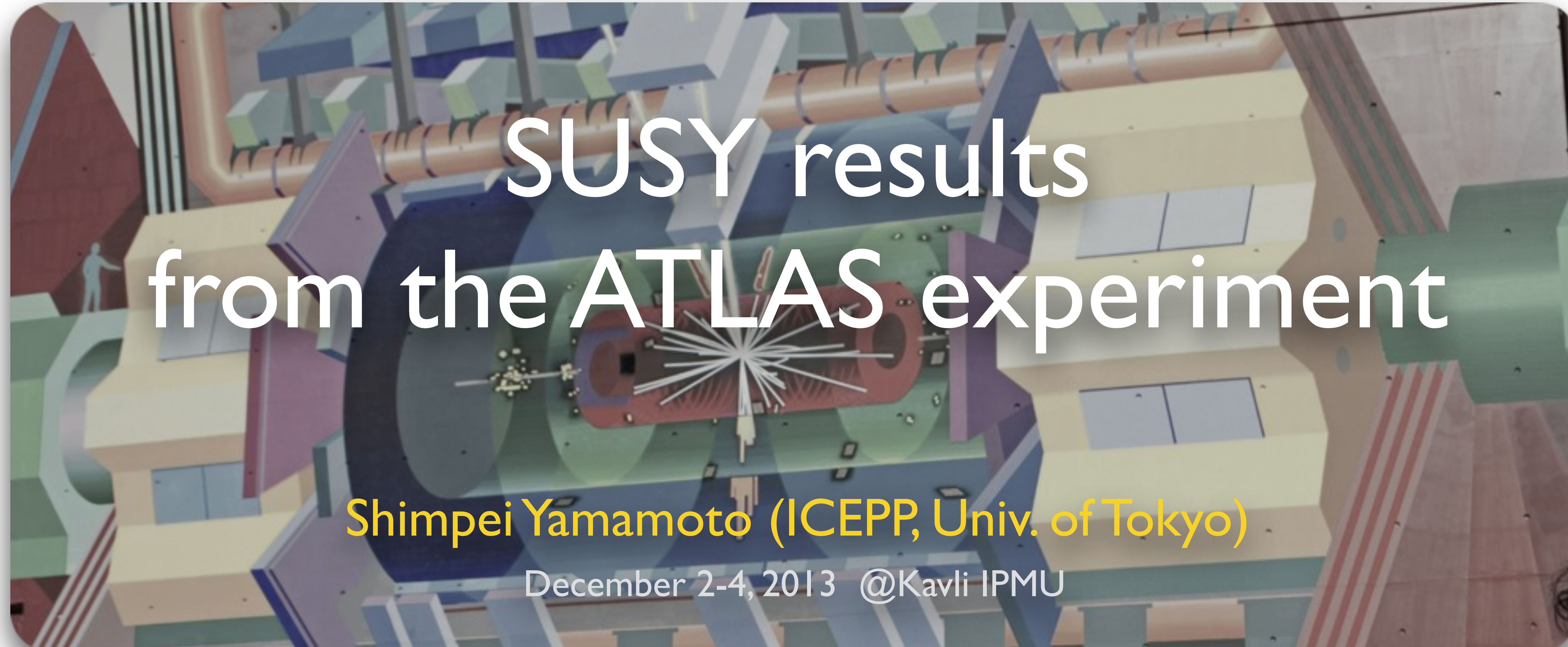


SUSY results from the ATLAS experiment

Shimpei Yamamoto (ICEPP, Univ. of Tokyo)

December 2-4, 2013 @Kavli IPMU

Outline

- Introduction
  - General search strategy
  - Data up to LHC long shutdown I
  - Detector & basic performances
- Search programs
  - Inclusive searches for squark/gluino production
  - 3rd generation squark production
  - Electroweak gaugino/slepton production
  - Searches with odd tracks/signatures
  - RPV decays
- Summary

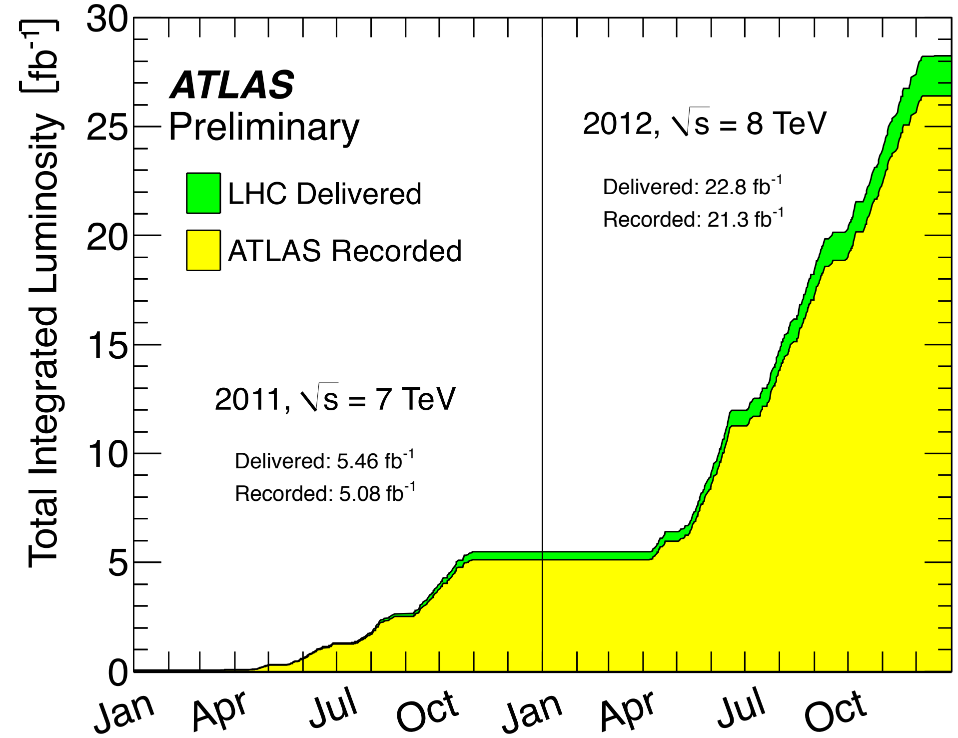
General search strategy

- Lots of SUSY models on market (or arise every day!)
  - Dedicated analysis for each model (top-down approach) may give the best search sensitivity, but experimentalists cannot do that..
- We then adapt the bottom-up approach:
  - Identify event topologies/signatures that could be much distinctive when compared to SM and capture essential features of SUSY particle decays.
  - Develop an analysis (way to control background) for each signal topology.

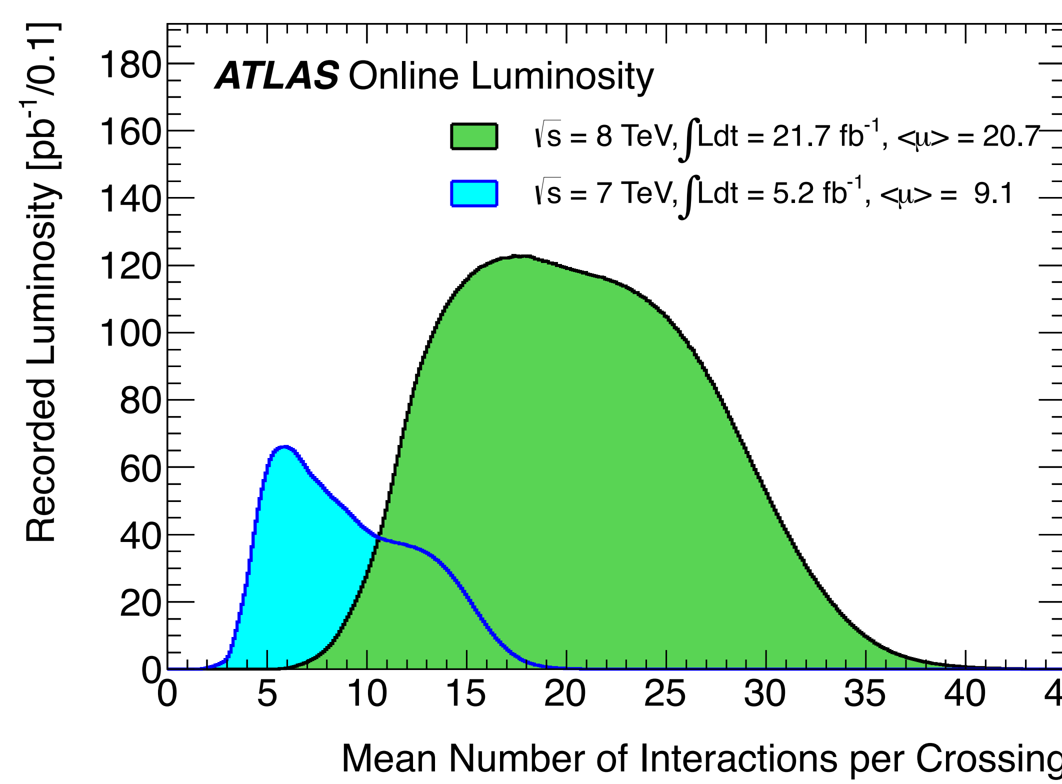
- Our job in the experiment: **"develop analyses to access signal event topologies that are expected to appear in all possible sparticle decays"**

Data up to LHC long shutdown 1

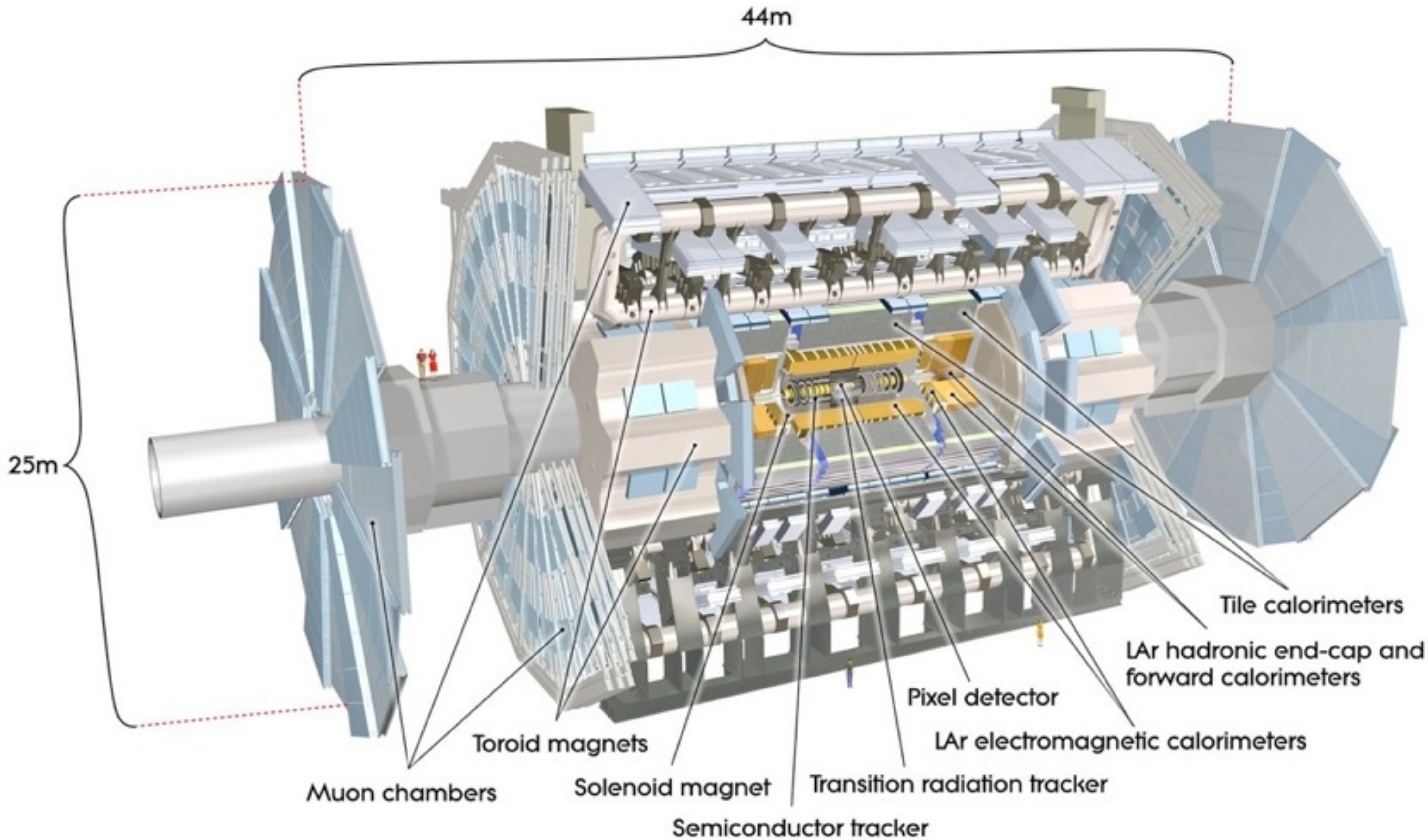
- Could accumulate 21.3 fb^{-1} of 8TeV pp collision data in 2012 thanks to increased luminosities.



- The price to pay for this is pileup:
  - ~20 pp interactions per bunch crossing.
  - Lots of effort to fully understand detector responses and better physics performances.



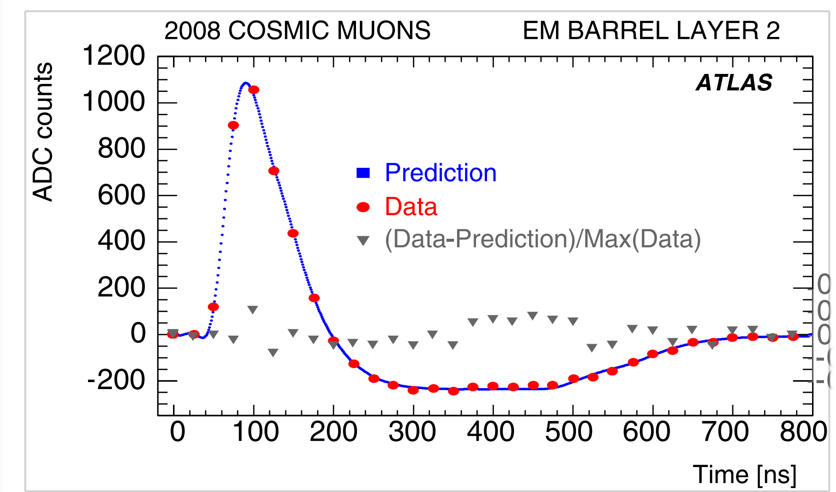
ATLAS detector

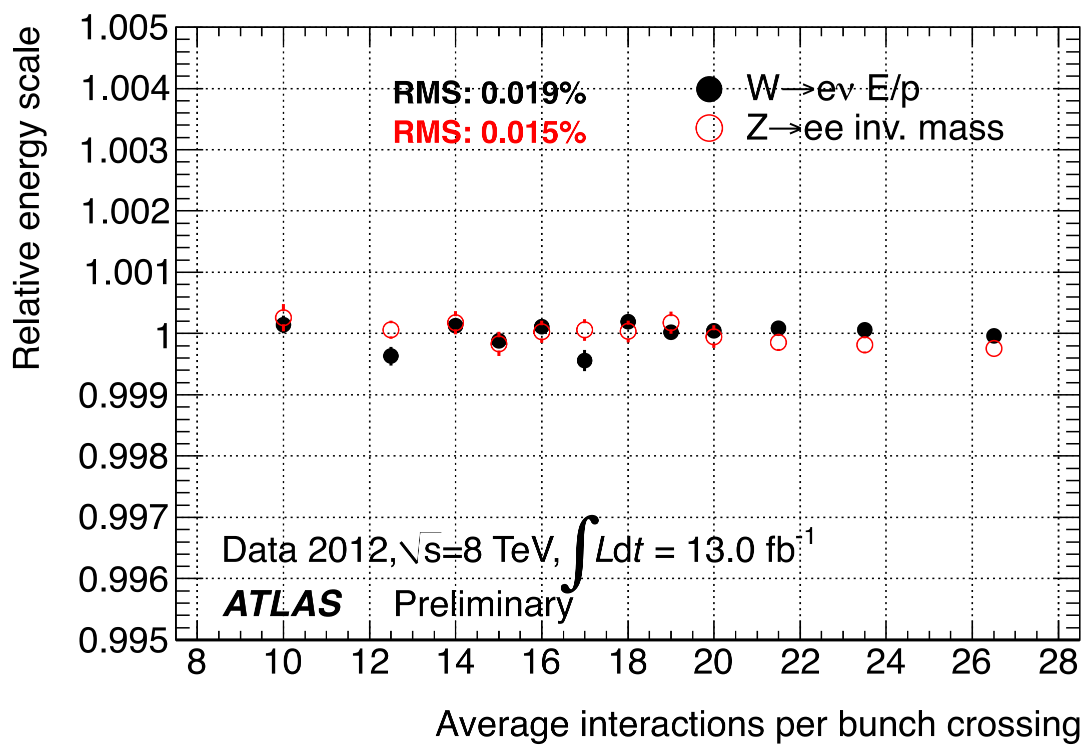


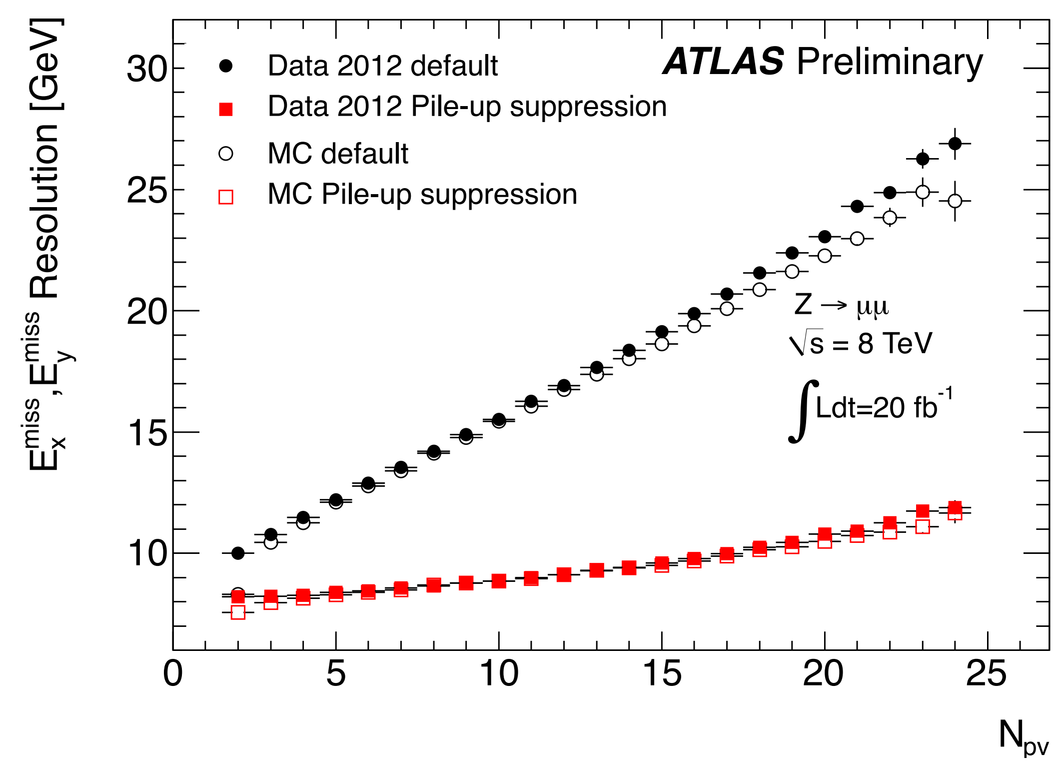
- General purpose detector: designed for the detection of SUSY decay products.
  - Superb performance in Run-1, providing excellent reconstruction performances for electrons, muons, taus, photons, (b-)jets and MET.

Performance

- Pileup effect: severe especially for calorimeter energy measurement.
  - Electron response stability: OK
    - Bunch-integrated pileup contribution cancels thanks to bipolar pulse shape
  - Less pileup dependence on jet/MET measurement due to corrections to compensate pileup noise etc.
    - Also can see that MC simulation reasonably describe the data!







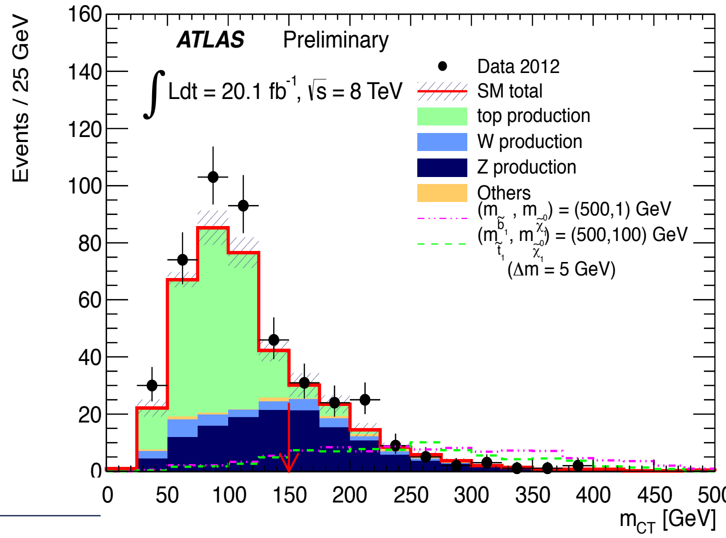
Triggers in 8TeV run

Signature	Offline selection	Trigger selection L1	Trigger selection EF	L1 Peak (kHz) $L_{peak} = 7\times10^{33}$	EF Ave (Hz) $L_{ave} = 5\times10^{33}$
Single leptons	Single muon $p_T > 25$ GeV	15 GeV	24 GeV	**8**	**45**
	Single electron $p_T > 25$ GeV	18 GeV	24 GeV	**17**	**70**
Two leptons	2 muons $p_T > 6$ GeV	$2 \times 6(4_{EOF})$ GeV (also 2mu4 barrel only)	2 × 6 GeV	**3**	**2**
	2 muons $p_T > 15$ GeV 2 muons $p_T > 20,10$ GeV	2 × 10 GeV 15 GeV	2 × 13 GeV 18,8 GeV	**1** **8**	**5** **8**
	2 electrons, each $p_T > 15$ GeV	2 × 10 GeV	2×12 GeV	**6**	**8**
	2 taus $p_T > 45, 30$ GeV	15,11 GeV	29,20 GeV	**12**	**12**
Two photons	2 photons, each $p_T > 25$ GeV 2 loose photons, $p_T > 40,30$ GeV	2 × 10 GeV 12,16 GeV	2 × 20 GeV 35, 25 GeV	**6** **6**	**10** **7**
Single jet	Jet $p_T > 360$ GeV	75 GeV	360 GeV	**2**	**5**
E_T^{miss}	$E_T^{miss} > 120$ GeV	40 GeV	80 GeV	**2**	**17**
Multi-jets	5 jets, each $p_T > 60$ GeV 6 jets, each $p_T > 50$ GeV	4×15 GeV	5 × 55 GeV 6 × 45 GeV	**1**	**8**
b-jets	*b* + 3 other jets $p_T > 45$ GeV	4 × 15 GeV	4 × 45 GeV + *b*-tag	**1**	**4**
TOTAL				**< 75**	**~ 400 (ave)**

Primer of SUSY search

Discriminant used to distinguish signals from SM background

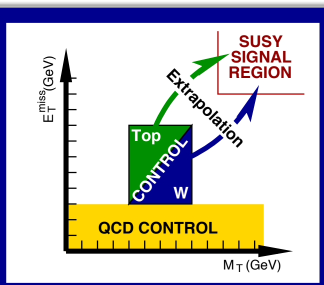
- **Missing transverse momentum (MET):** calculated based on calorimeter energies and reconstructed muons.
  - LSPs(neutralino, gravitino) escape from detection $\Longrightarrow$ large MET
- **Jet multiplicity**
  - Enhance squark/gluino decays, reduce multijet background
- **b-jet:** Flavor tagging using 3D tracking impact parameter (e.g., 60% efficiency, <1% mis-tag rate)
  - 3rd gen. squark decays, top, …
- **Transverse mass (m_T)**
  - Separate from W+jets
- **Scalar sum of visible objects (H_T), effective mass ($m_{eff}=H_T+MET$)**
  - Large values expected when heavy particles are produced
- **Contraverse mass (m_{CT})** $m_{\mathrm{CT}}^2 = \left(E_{\mathrm{T}}^{b_1} + E_{\mathrm{T}}^{b_2}\right)^2 - \left|\mathbf{p}_{\mathrm{T}}^{b_1} - \mathbf{p}_{\mathrm{T}}^{b_2}\right|^2$
  - Separate from ttbar
- …



Primer of SUSY search

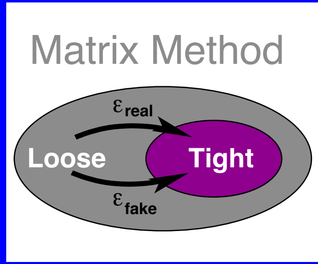
SM Backgrounds:
top pairs, single top, V+jets, dibosons, multijets,...

Main irreducible Backgrounds:
- Normalize MC prediction in dedicated Control Regions
- Extrapolate to Signal Regions using MC



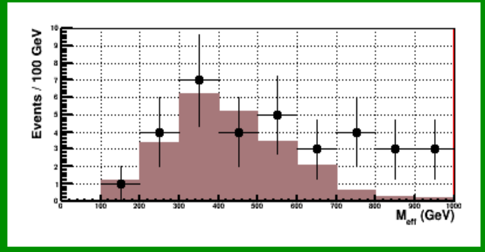
Minor irreducible Backgrounds:
- Pure MC based prediction

Reducible (fake) Backgrounds:
- Fully data driven method
  - Matrix method
  - Jet smearing
  - Templates



Validation Region:
- Cross check back–ground predictions
- Closer to SR

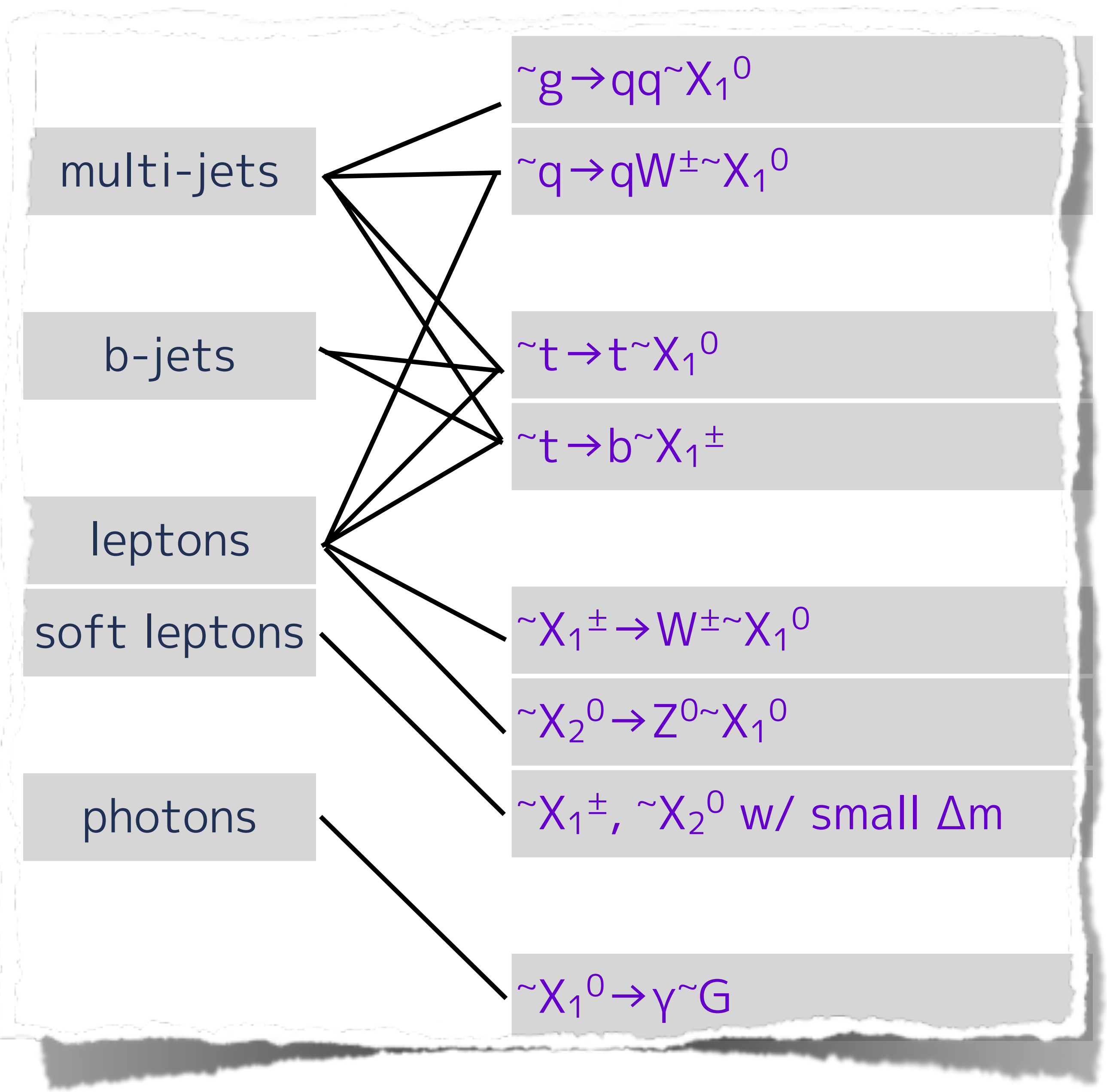
Signal Region:
- Look for excess

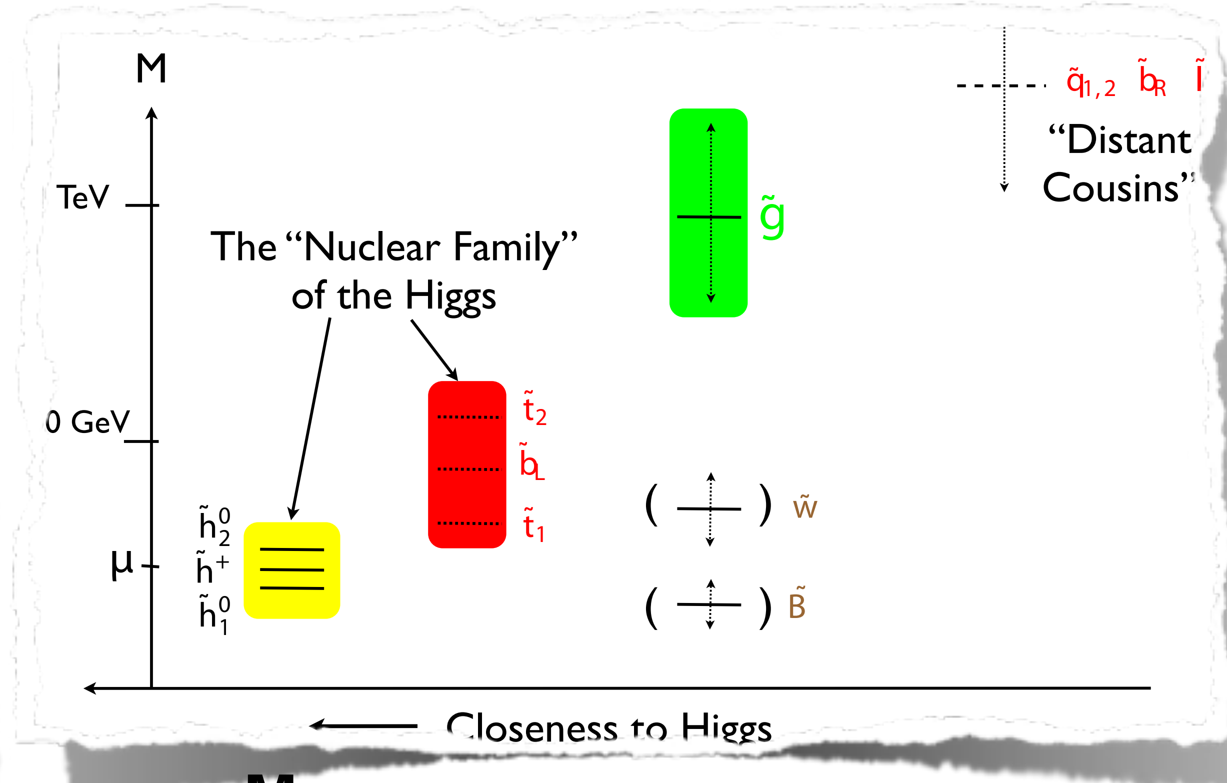


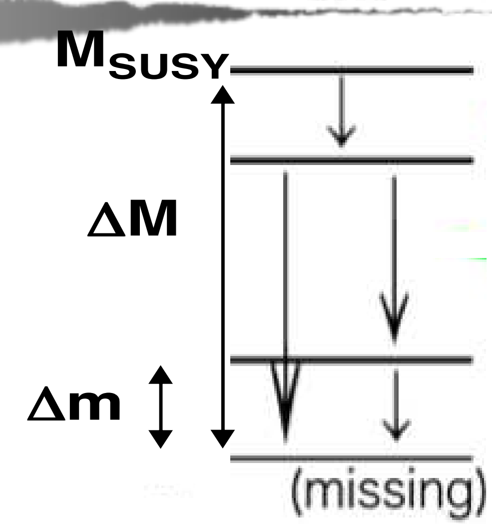
Combined global fit:
Consider experimental and theoretical uncertainties

Search programs

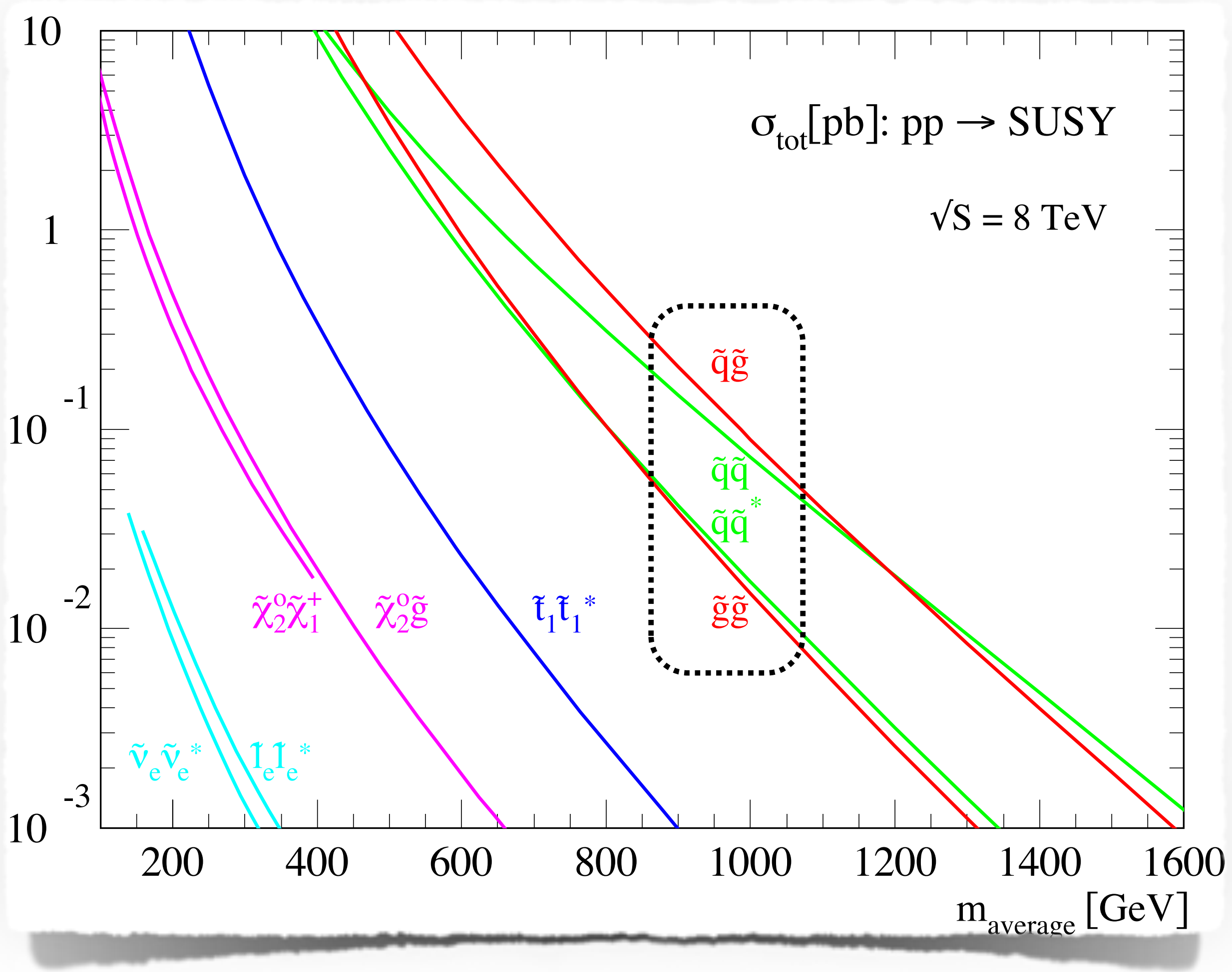
- Again, topology-based analyses developed to cover all possible decay signatures by adopting given triggers and discriminants (previously listed).







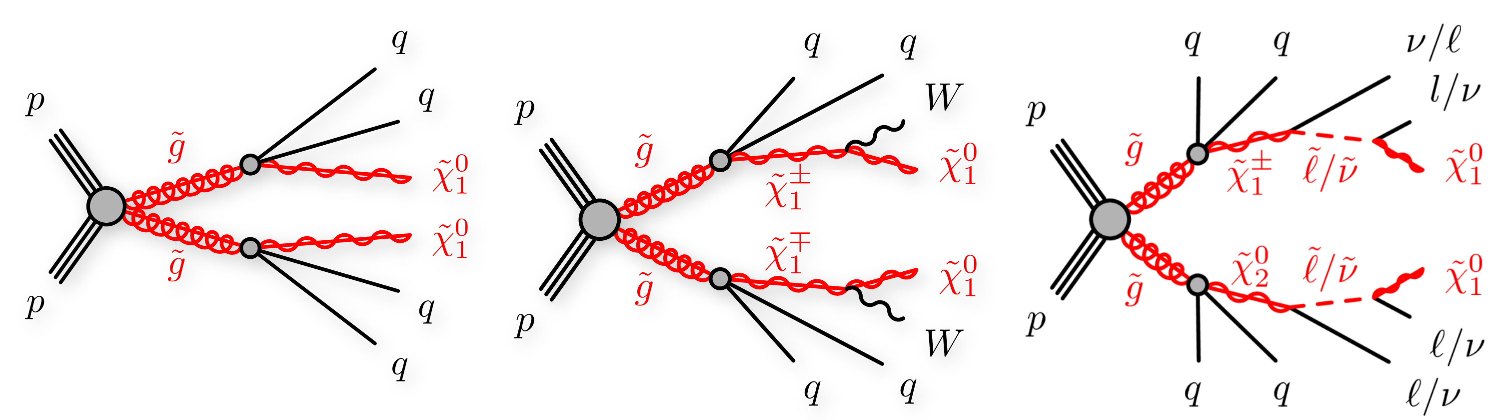
squark/gluino production



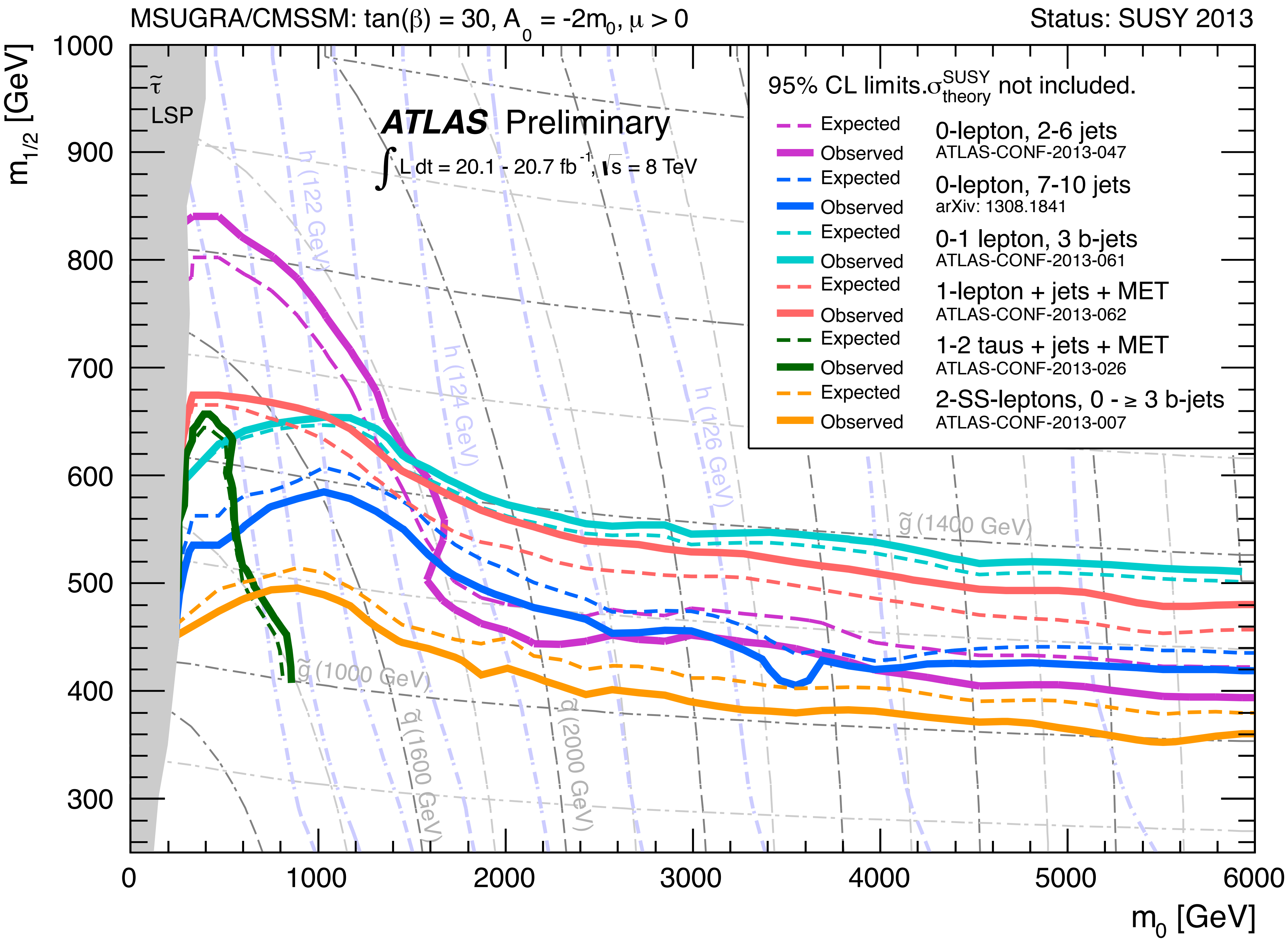
Inclusive searches with jets+MET+X

- Can start by broad and inclusive searches in jets+MET+X final states to explore squark/gluino production.
  - Large production cross section via strong interaction
  - Excesses expected to appear in large MET & m_{eff} regions where few SM background expected.
- Very powerful analyses!
  - Can address with early data sample, statistics does not help because the cross section steeply drops when squark/gluino mass increases.
  - Performed with several signal search regions that are (nearly) orthogonal.

0-lepton + 2-6 jets + MET
0-lepton + 7-10 jets + MET Sig.
1-2 leptons + jets + MET
2-lepton + jets + MET
1-2 taus + jets + MET



MSUGRA/CMSSM exclusion: 2013 summer

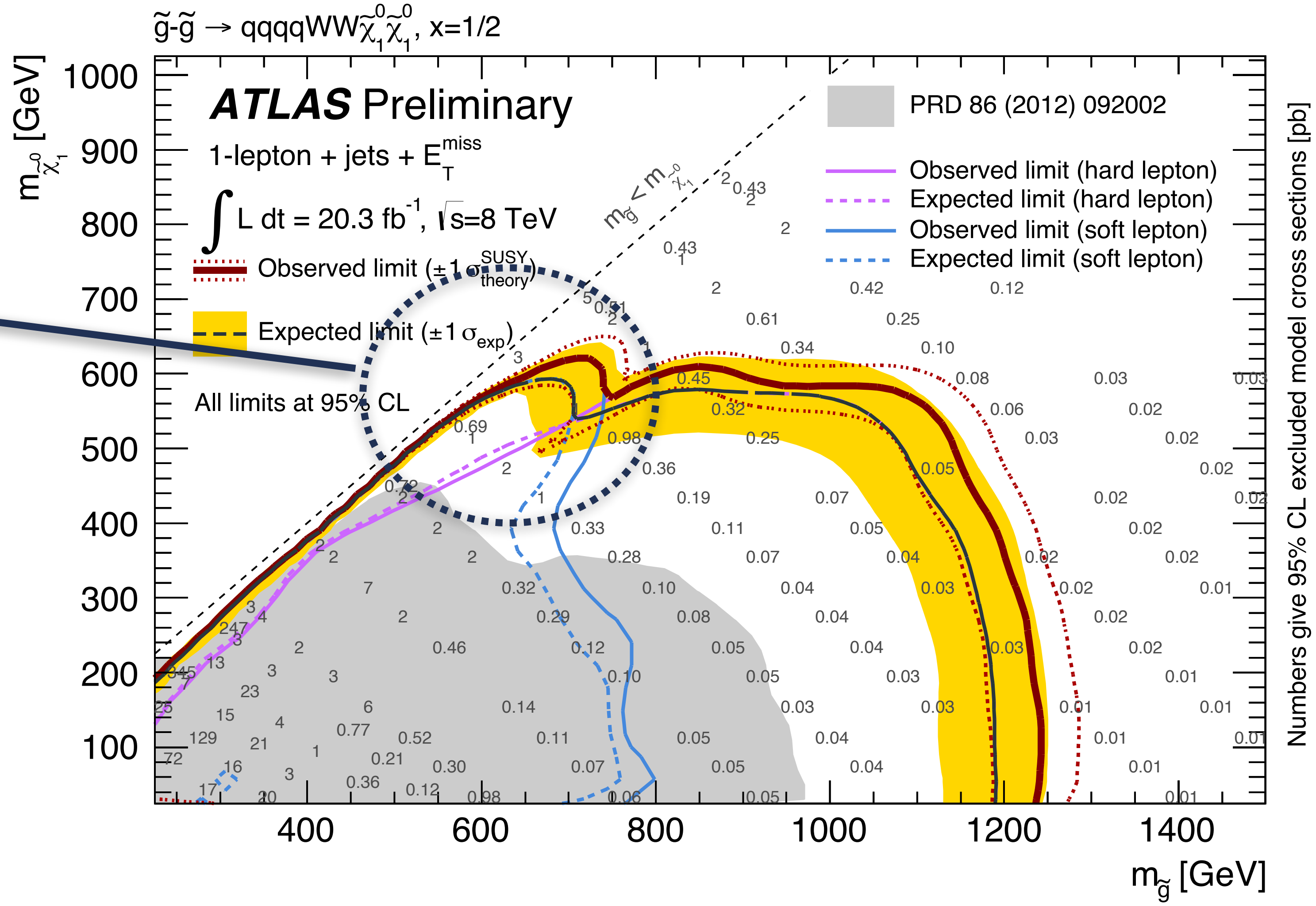


- Gluino masses below ~1.3 TeV for any squark mass

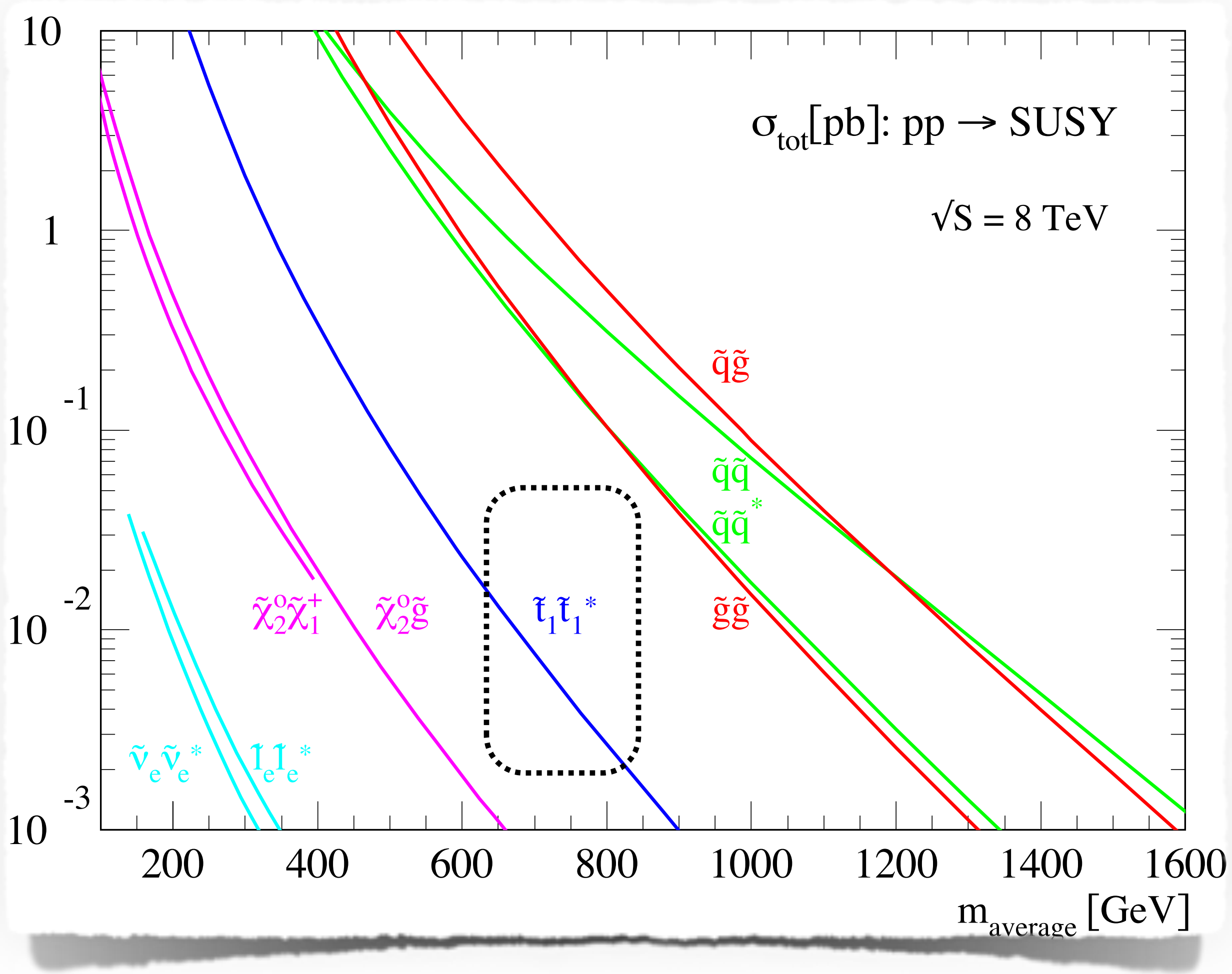
Accessing the corner of parameter space

- The inclusive searches are powerful, but there could be the corners of parameter space that they cannot address..
  - **Compressed mass spectrum leads to softer kinematics.**

- Soft lepton selection and ISR jet tagging extend the reach to compressed scenarios.
  - [6/10, 25] GeV for muon/ electron
  - **Excluding gluinos below 700GeV for the gluino-LSP mass gap > 25GeV**

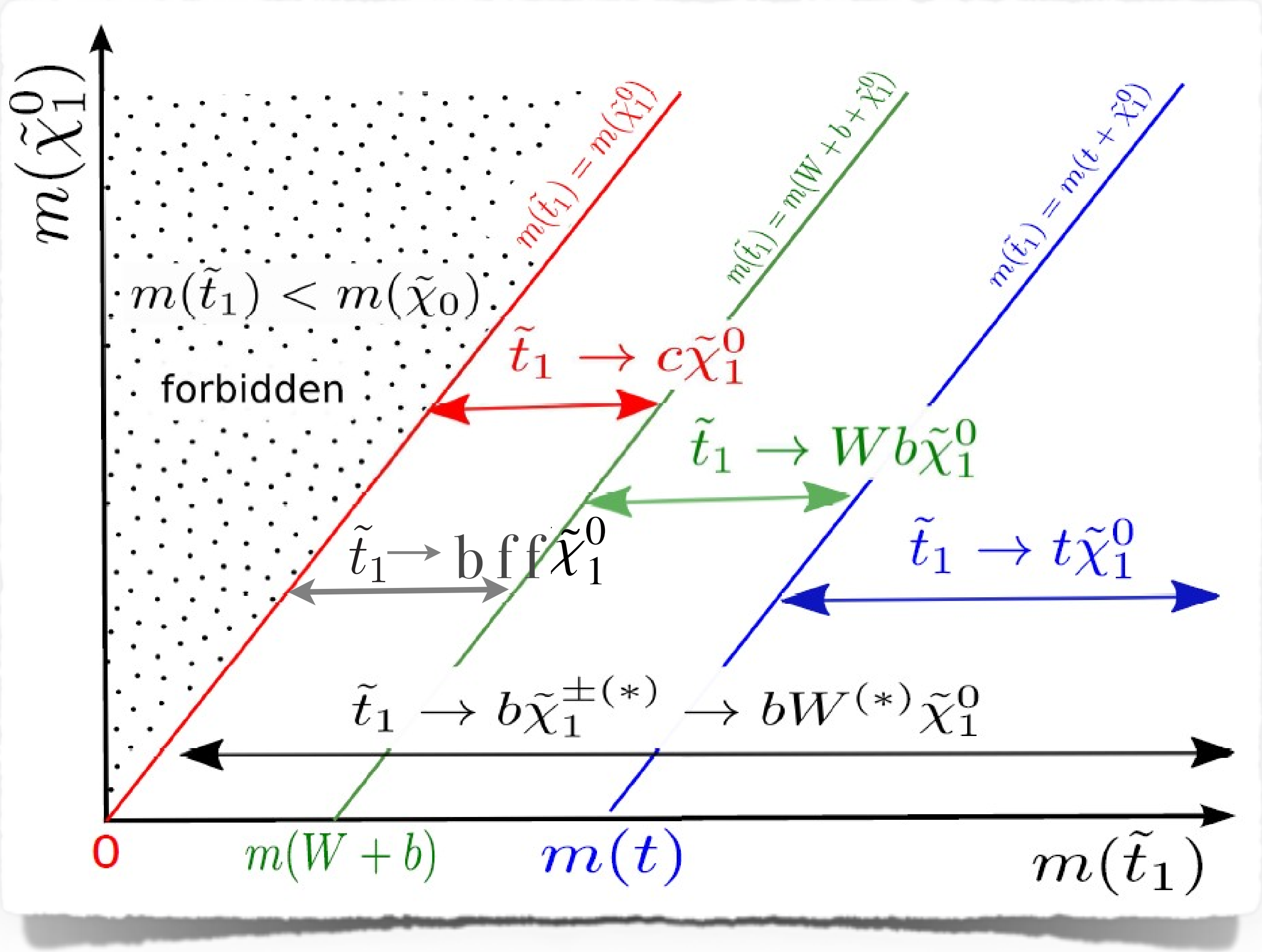


3rd gen. squark production



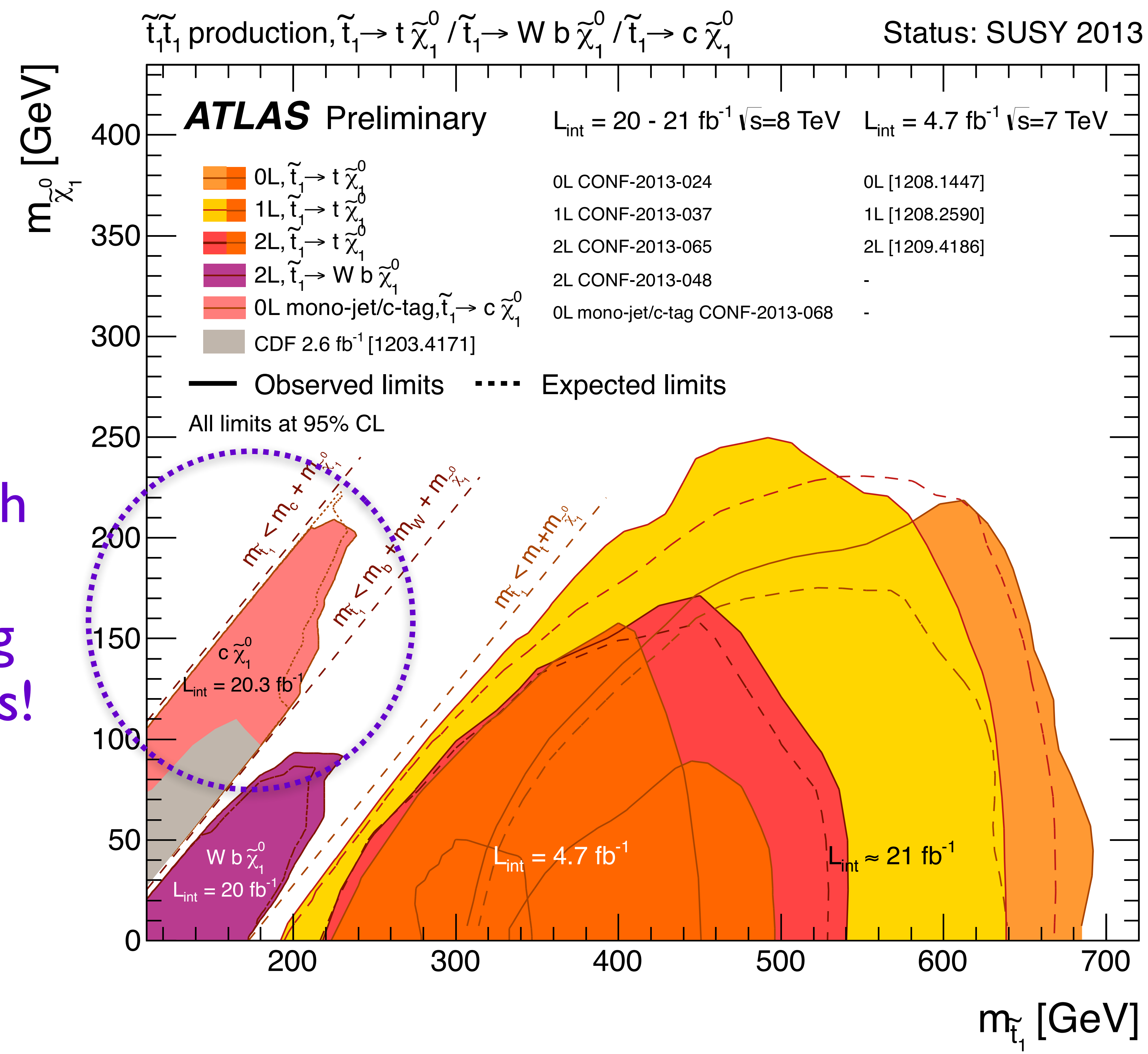
Stop decays

- Many possible decay modes depending on stop-LSP mass relation:
- Dedicated analyses to explore each decay/signal topology.



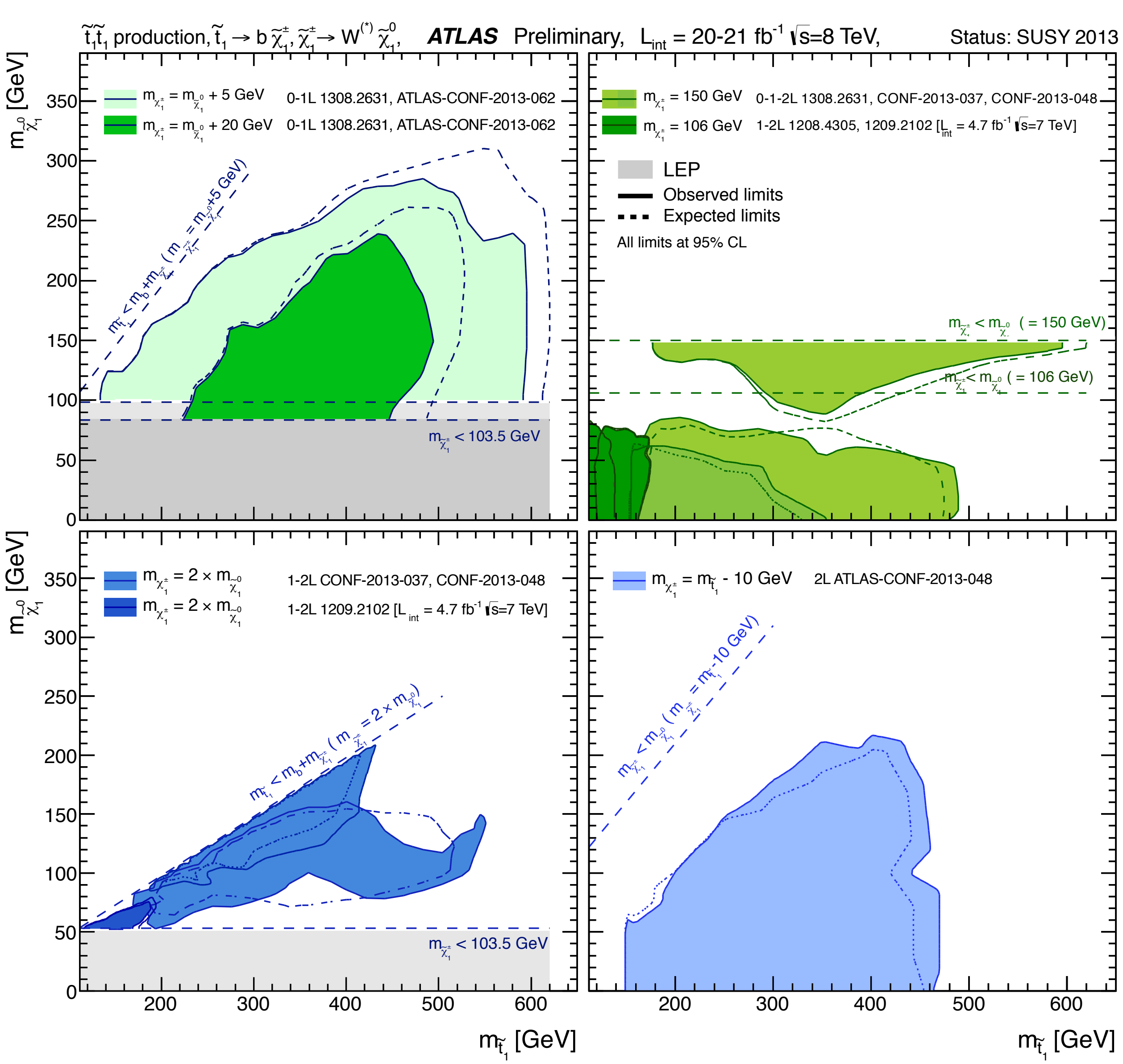
0-leptons + 6-jets (2 b-jets) + MET
1-lepton + 4-jets (2 b-jets) + MET
2-leptons (+ 2 b-jets) + MET
charm / mono-jet + MET
Z(ll) + 2 b-jets + MET
…

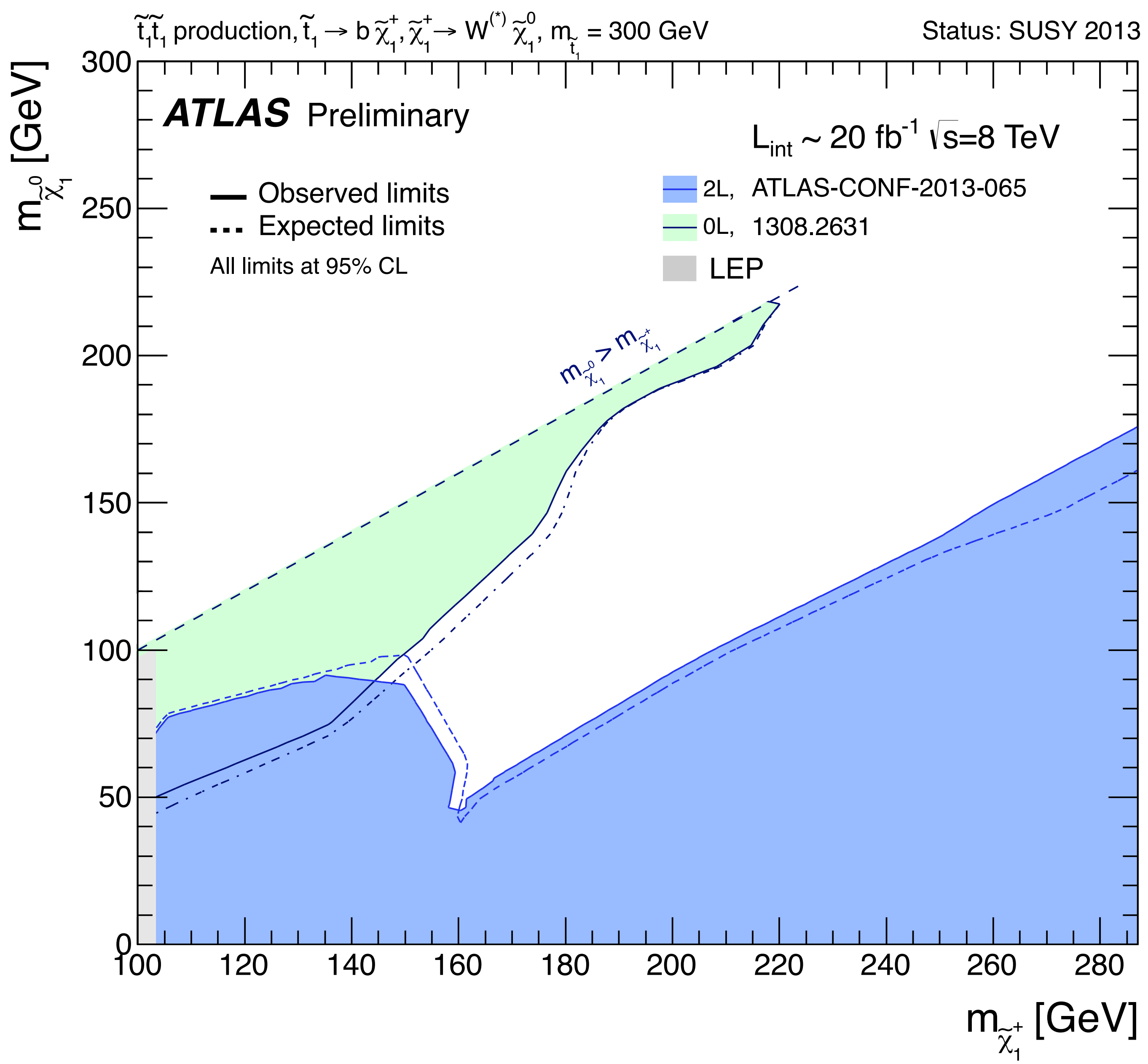
Summary: stop to t/b/c+LSP



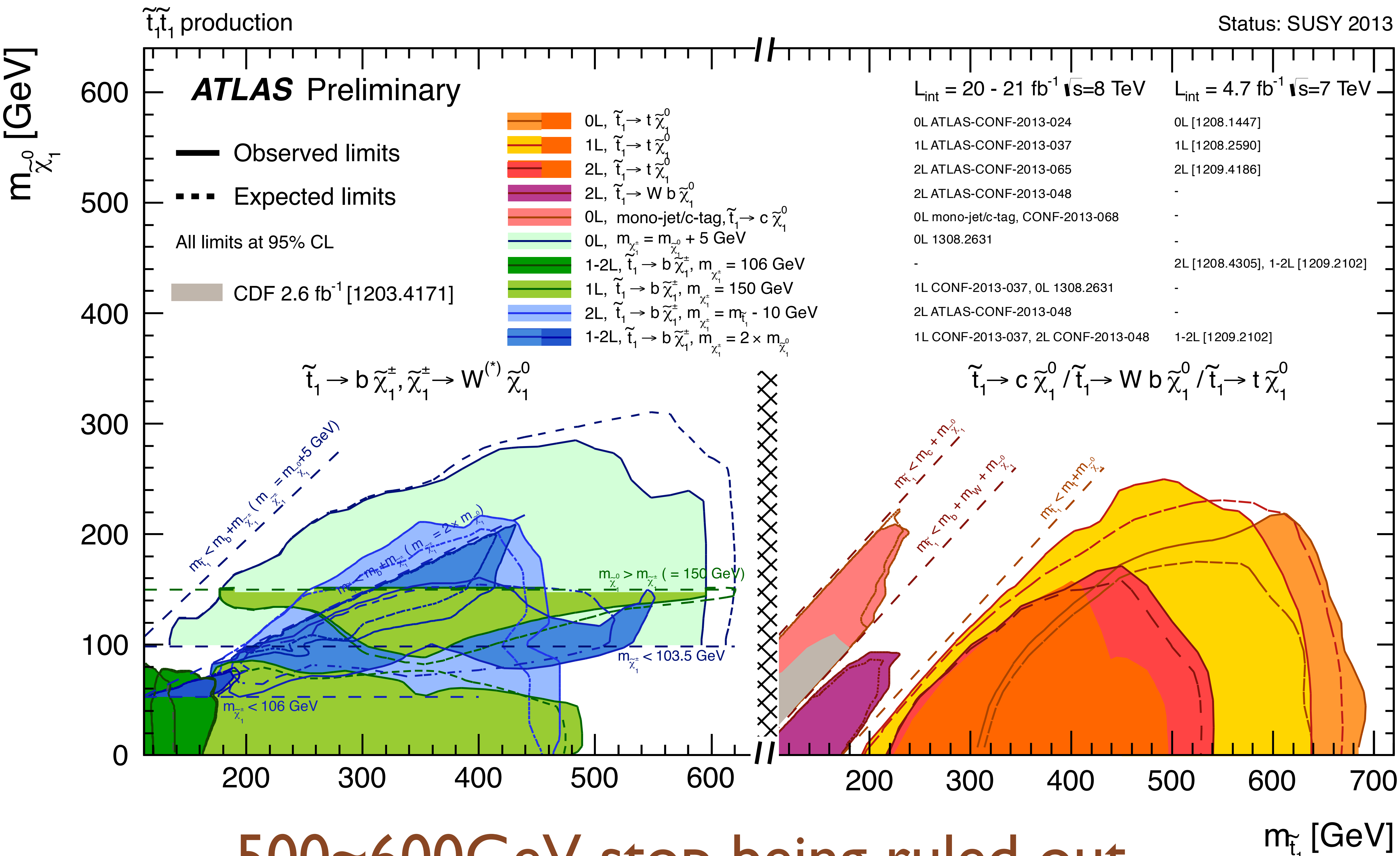
Could extend the reach along the diagonal by adopting the ISR jet tag & charm tag techniques!

Summary: stop to b+chargino



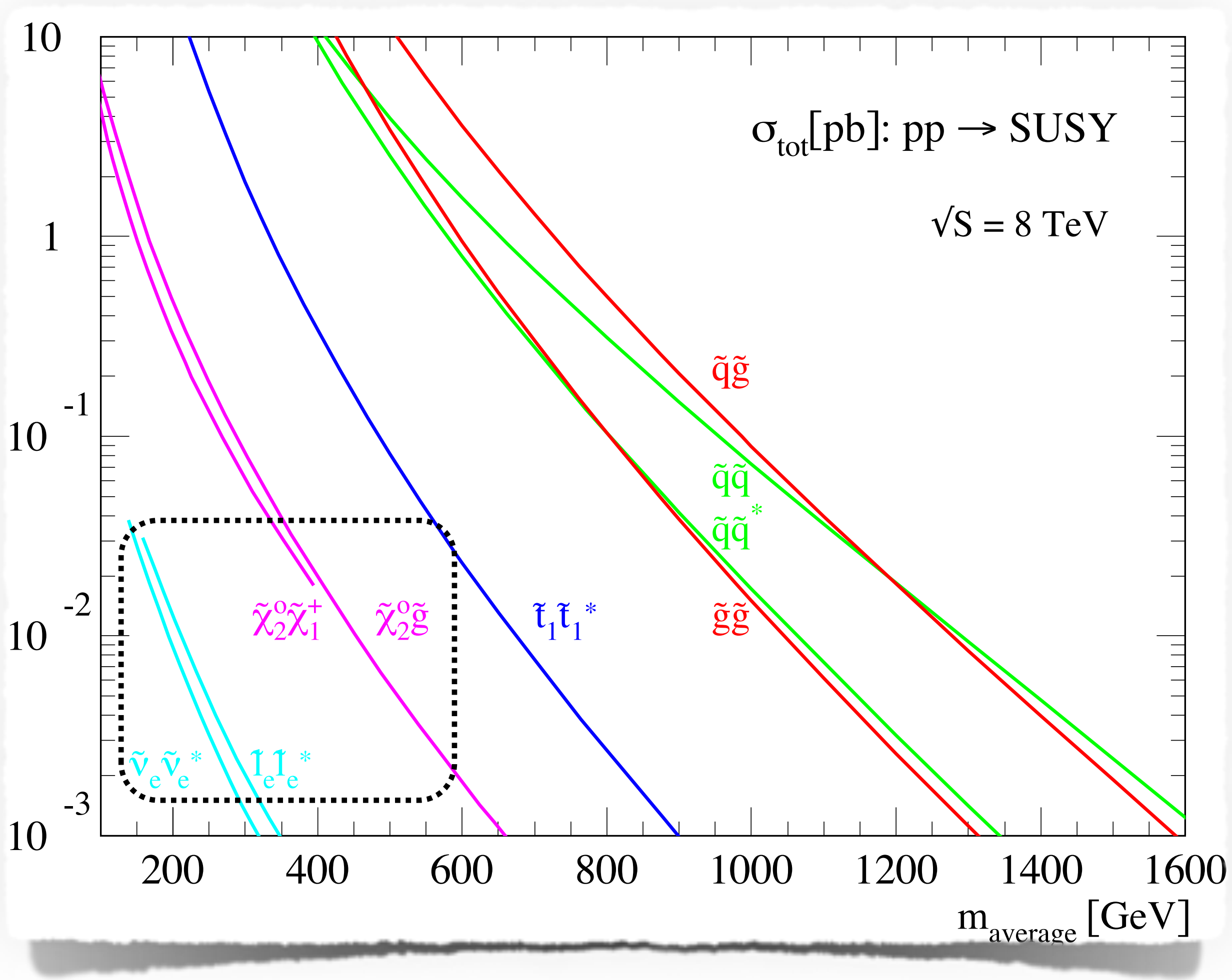


Direct stop search summary



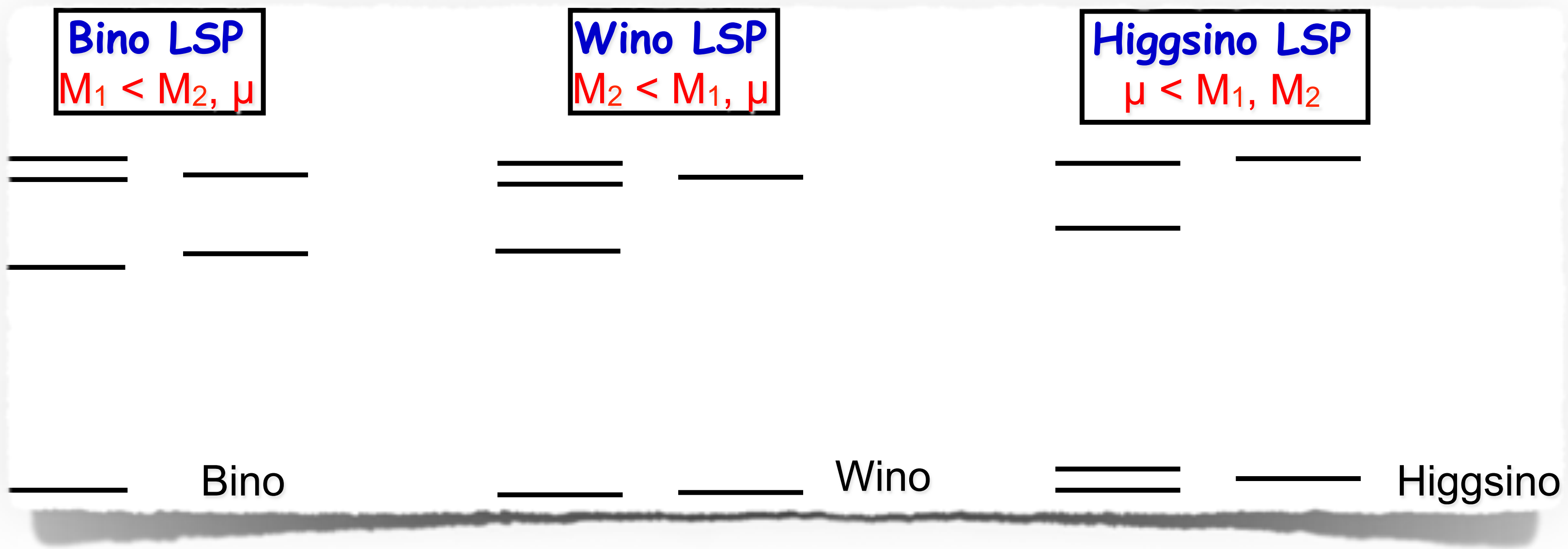
500~600GeV stop being ruled out…

gaugino/slepton production



M_1, M_2, and μ

- Decay mode/cross section determined by the order of M_1, M_2, and μ



- In natural SUSY scenarios (Bino LSP), EW gaugino decays lead to high lepton multiplicities.
  - Dedicated analyses performed depending on the lepton multiplicity

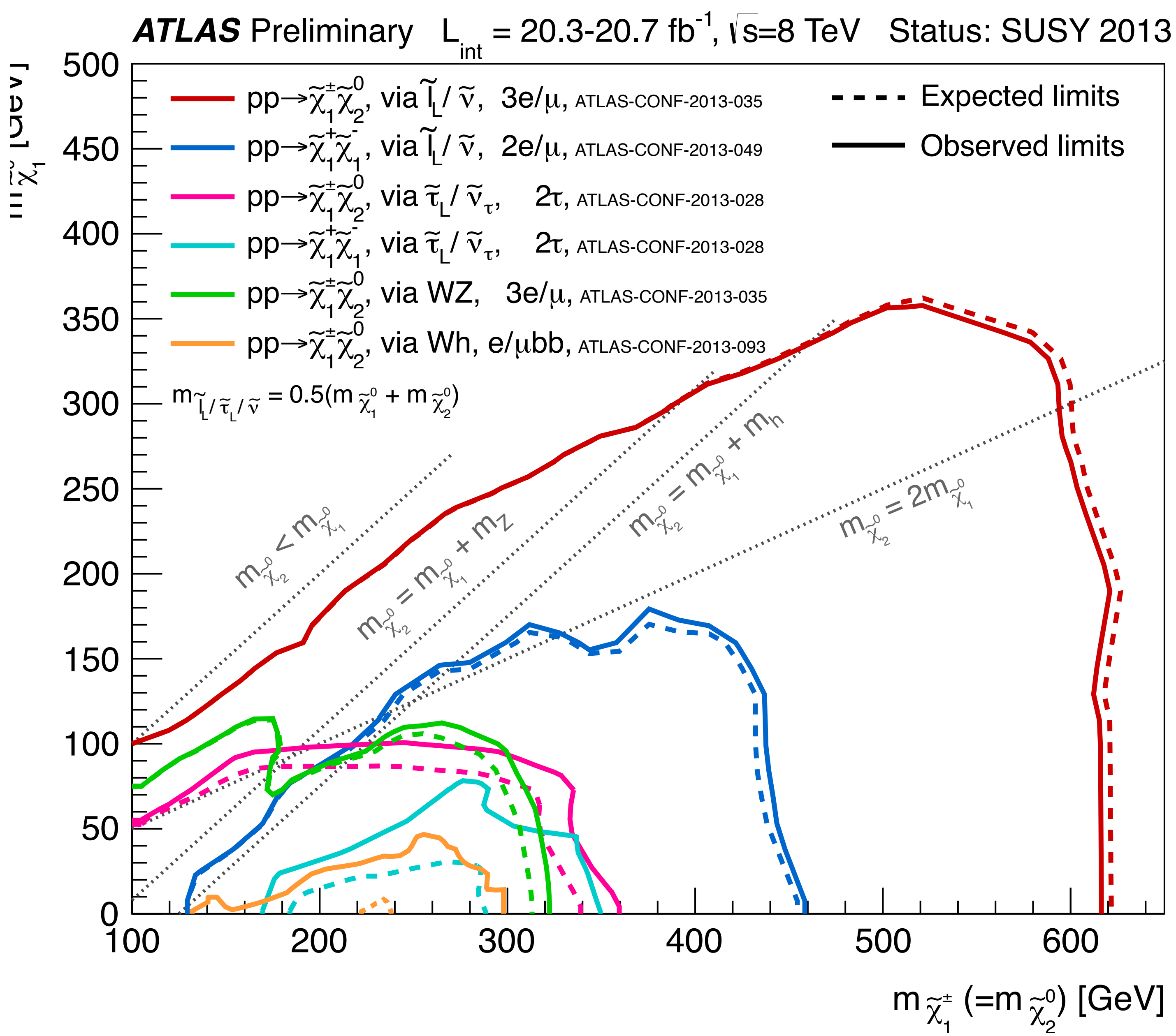
Chargino Pair Production $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ 2L 2τ

Chargino-Neutralino Production $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 2τ 3L 1L

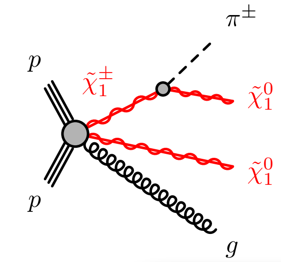
Neutralino Pair Production $\tilde{\chi}_2^0 \tilde{\chi}_3^0$ 4L

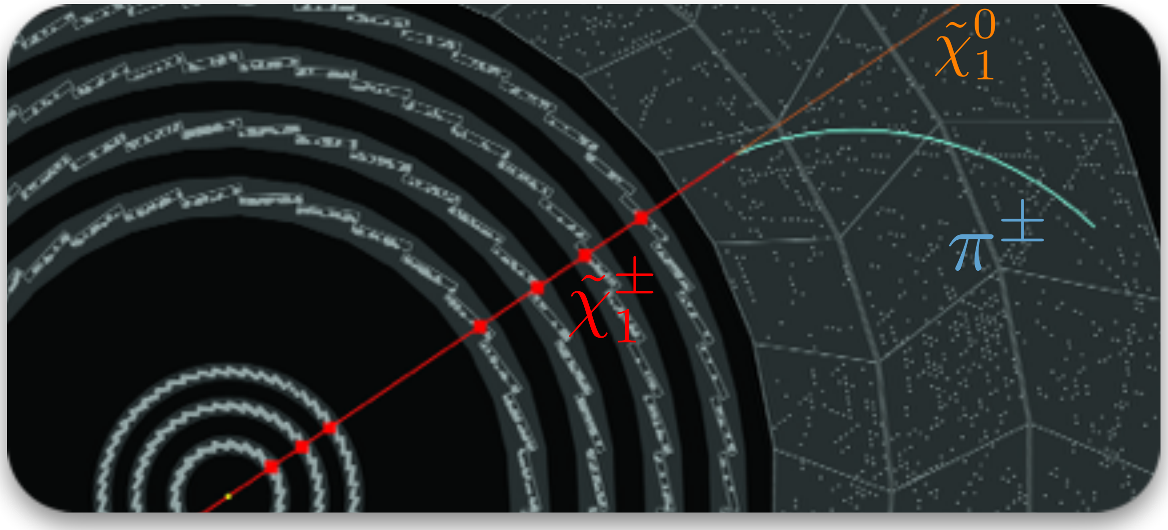
Summary: EW gaugino production

- Constraint on N1-C1(N2) masses by searches with multilepton final states
  - Weakly constrained in the case that gauginos decay via gauge bosons

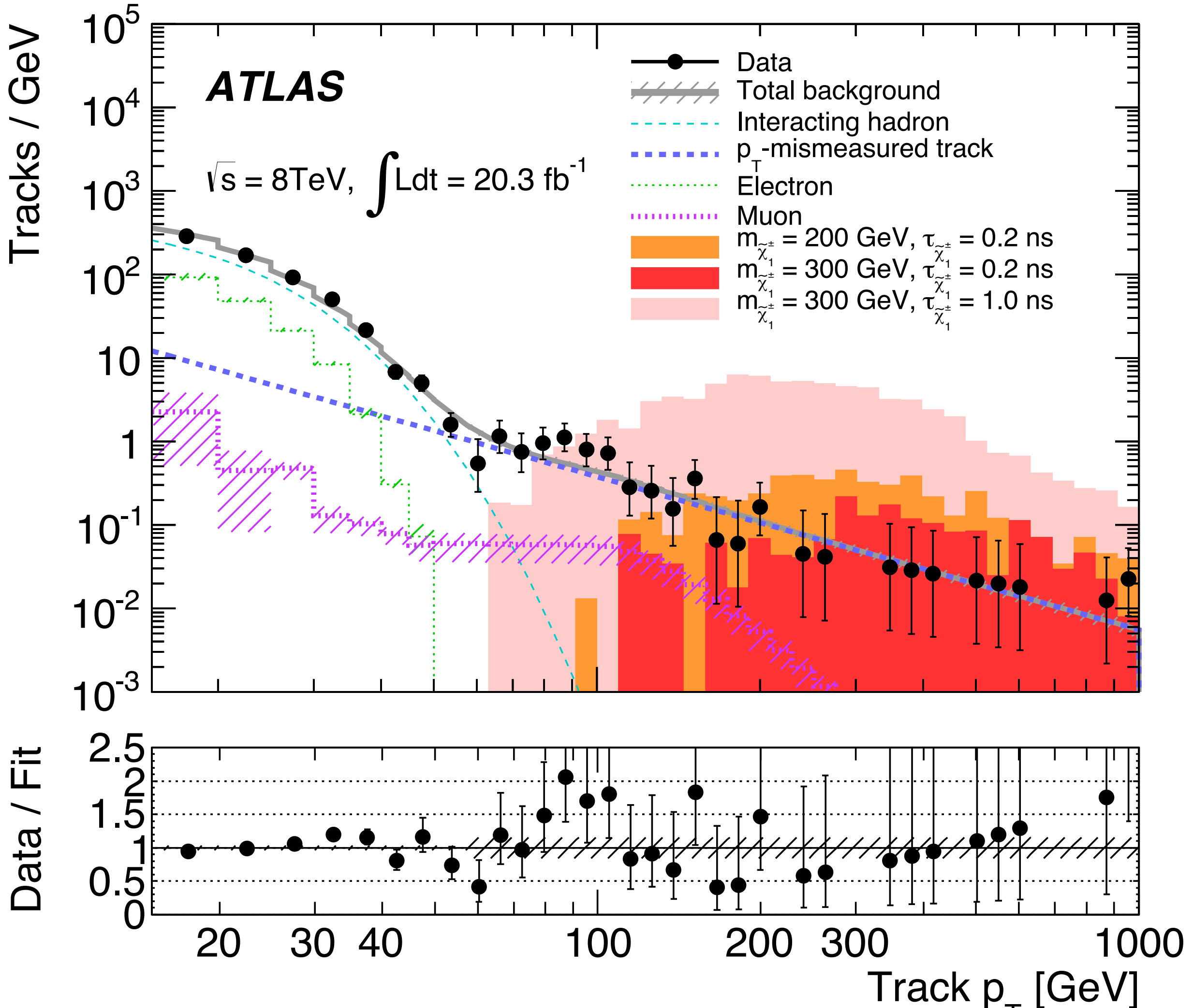


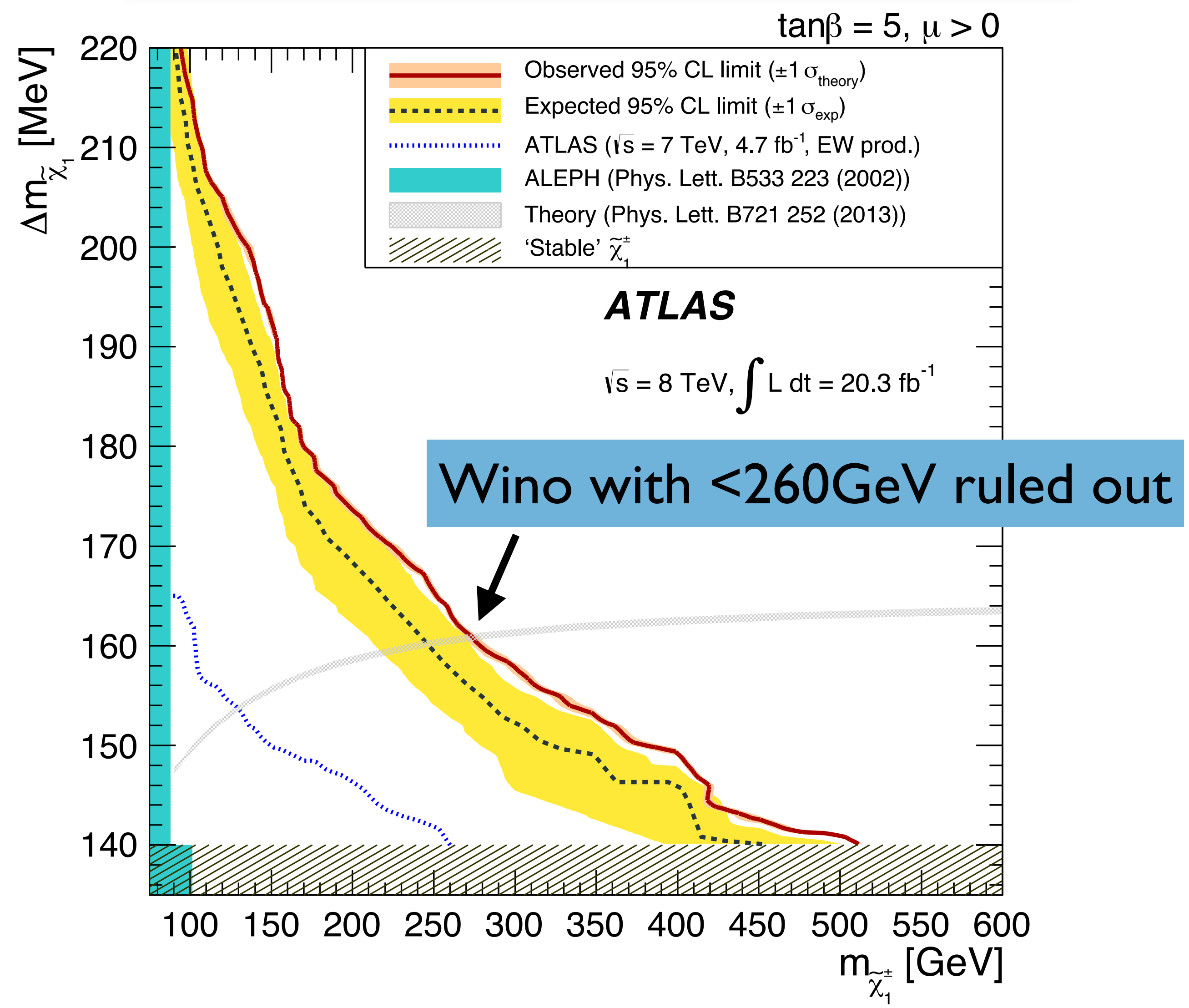
Wino-LSP case





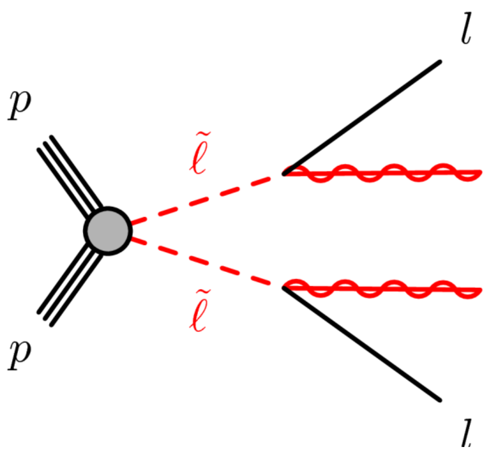
- Wino-LSP scenarios (AMSB, PGM,…) predicts the mass-degenerate C1 that could have a significant lifetime.
  - Decaying C1 could be reconstructed as a "high-pT disappearing track"
  - Explored in the events having **ISR jet + disappearing track**

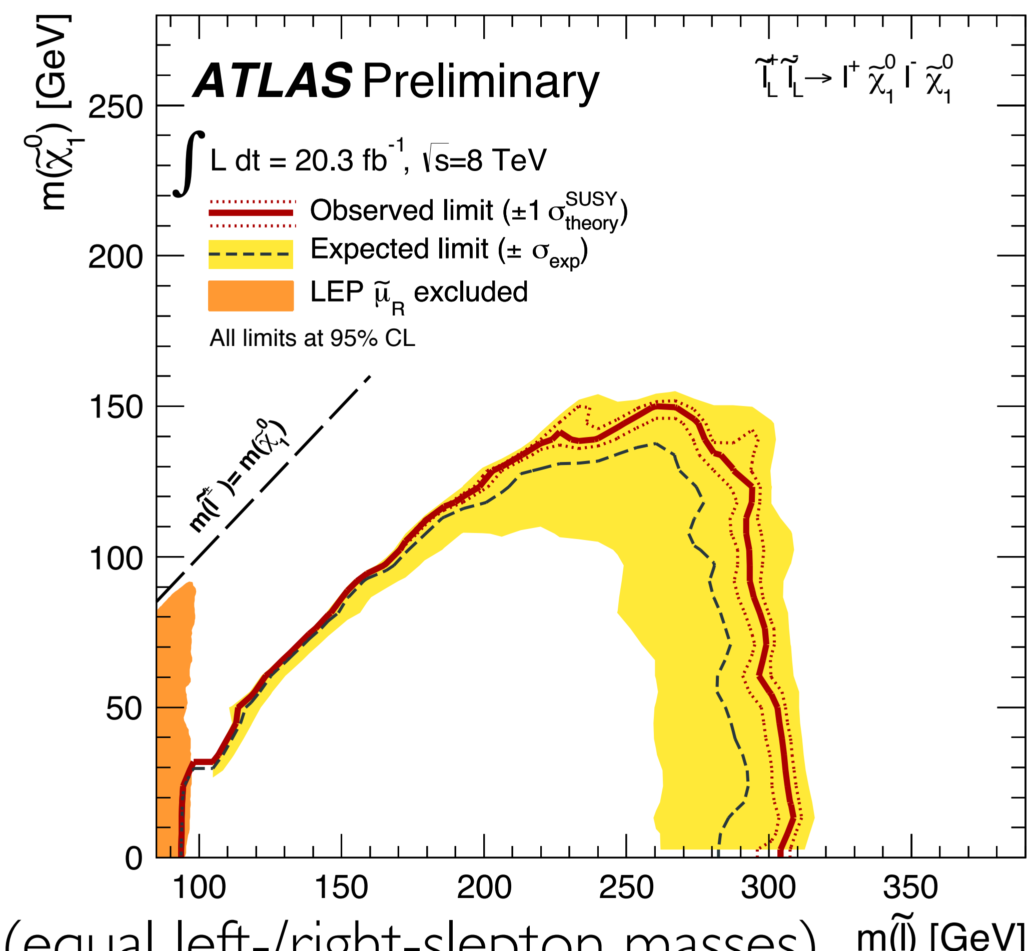




Slepton production

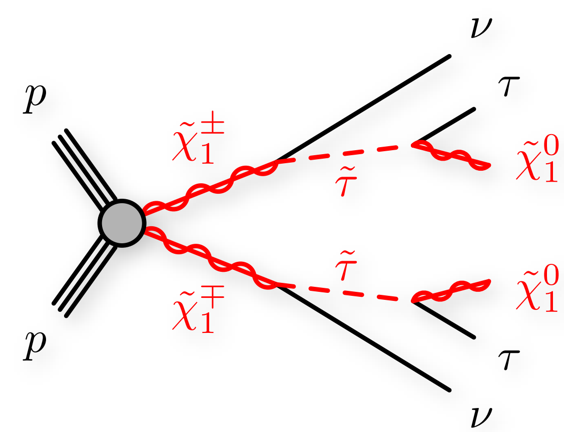
2-leptons+0-jet+MET

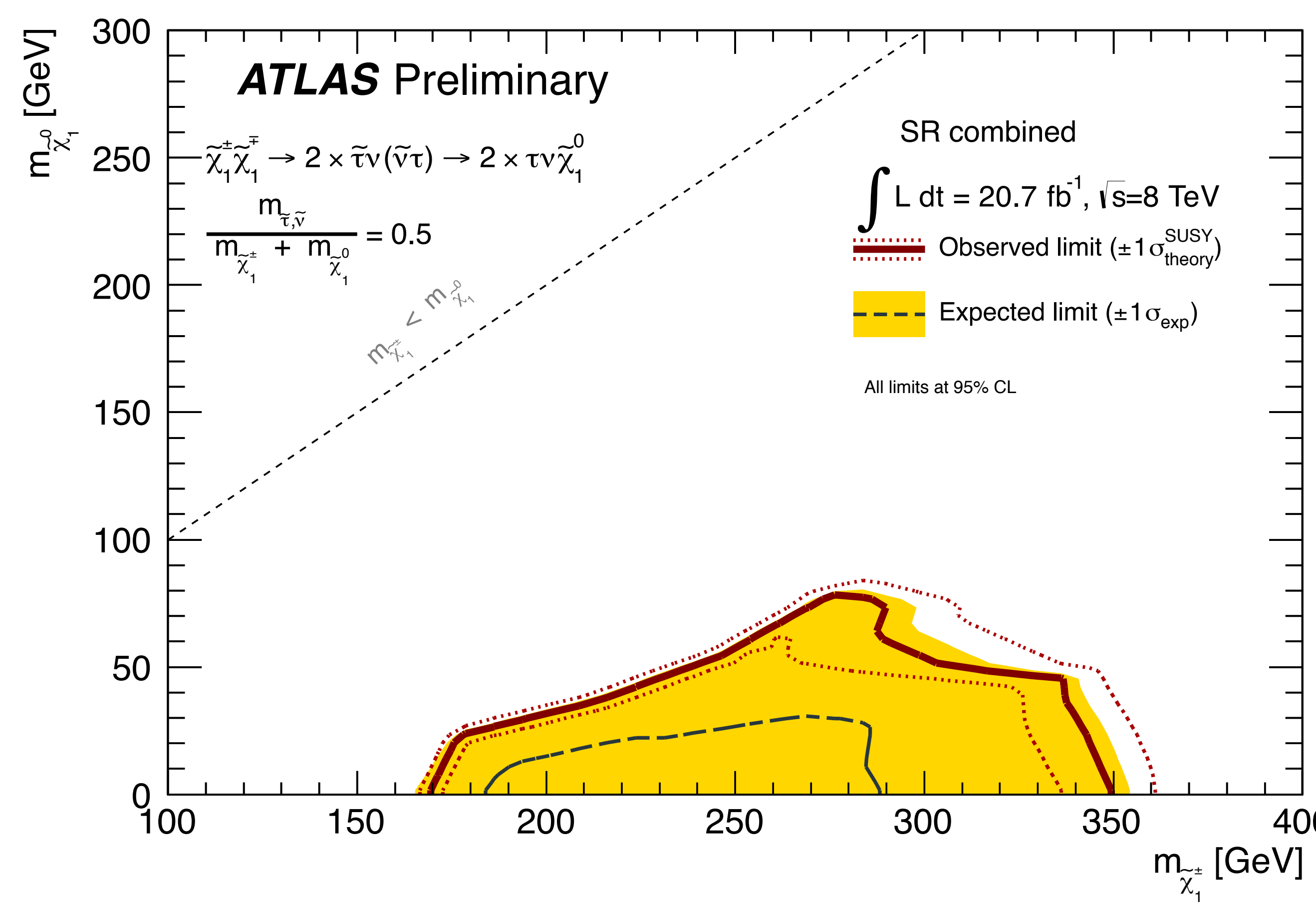




(equal left-/right-slepton masses)

2-taus+0-jet+MET





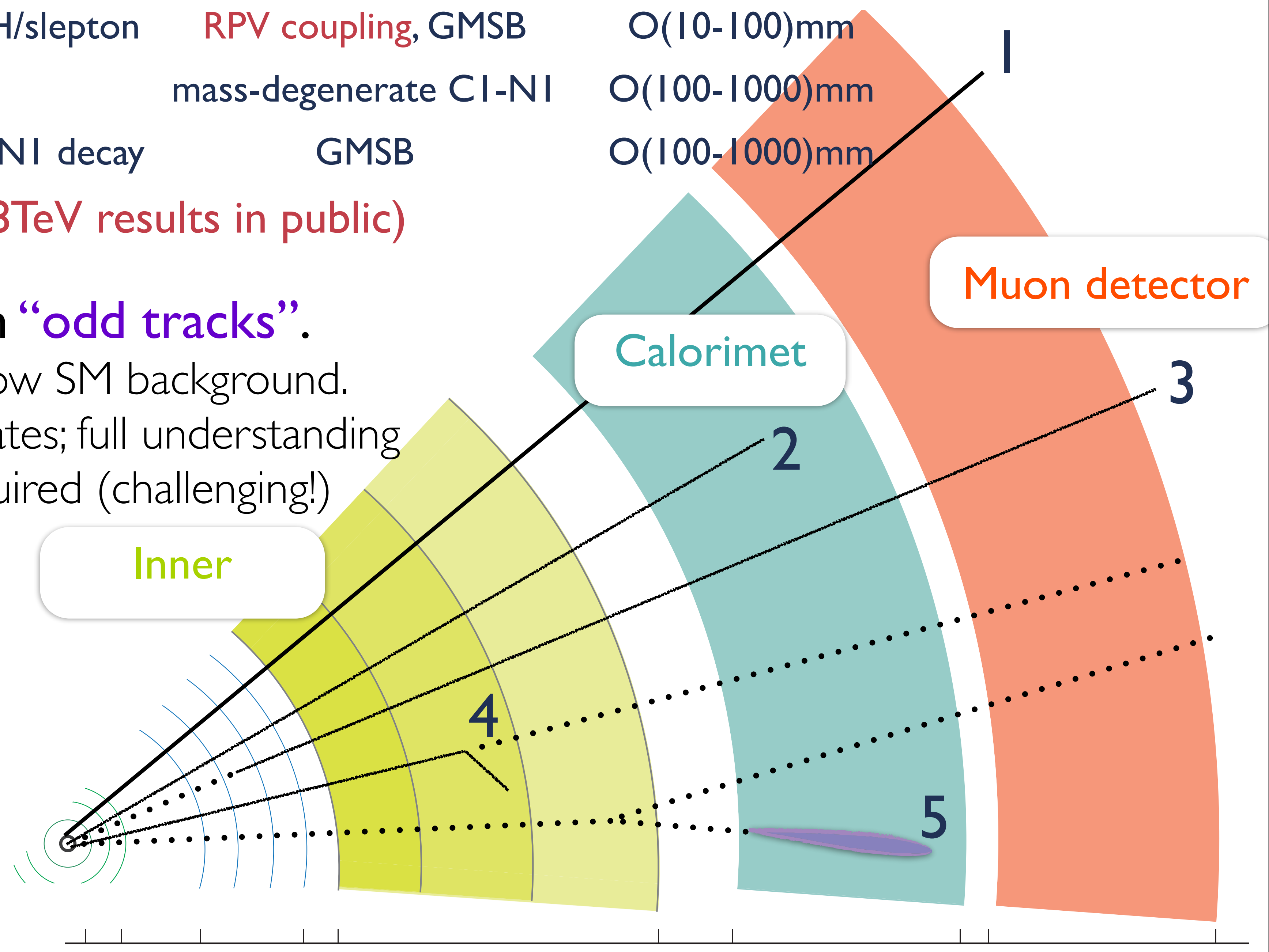
Searches with odd tracks/ signatures

Odd signatures

	Signature	Particle	Typical scenario	decay length (cτγ)
1	low β (large dE/dx)	Slepton, R-hadron	GMSB, split-SUSY	>1000mm
2	Stopped particle	R-hadron	split-SUSY	—
3	Displaced vertex	N1 decay, Z/H/slepton	RPV coupling, GMSB	O(10-100)mm
4	Disappearing track	C1	mass-degenerate C1-N1	O(100-1000)mm
5	Non-pointing photon	Photon from N1 decay	GMSB	O(100-1000)mm

(8TeV results in public)

- **LLPs in SUSY events result in "odd tracks".**
  - Very distinctive signatures, very low SM background.
  - Instrumental background dominates; full understanding of the detector performances required (challenging!)



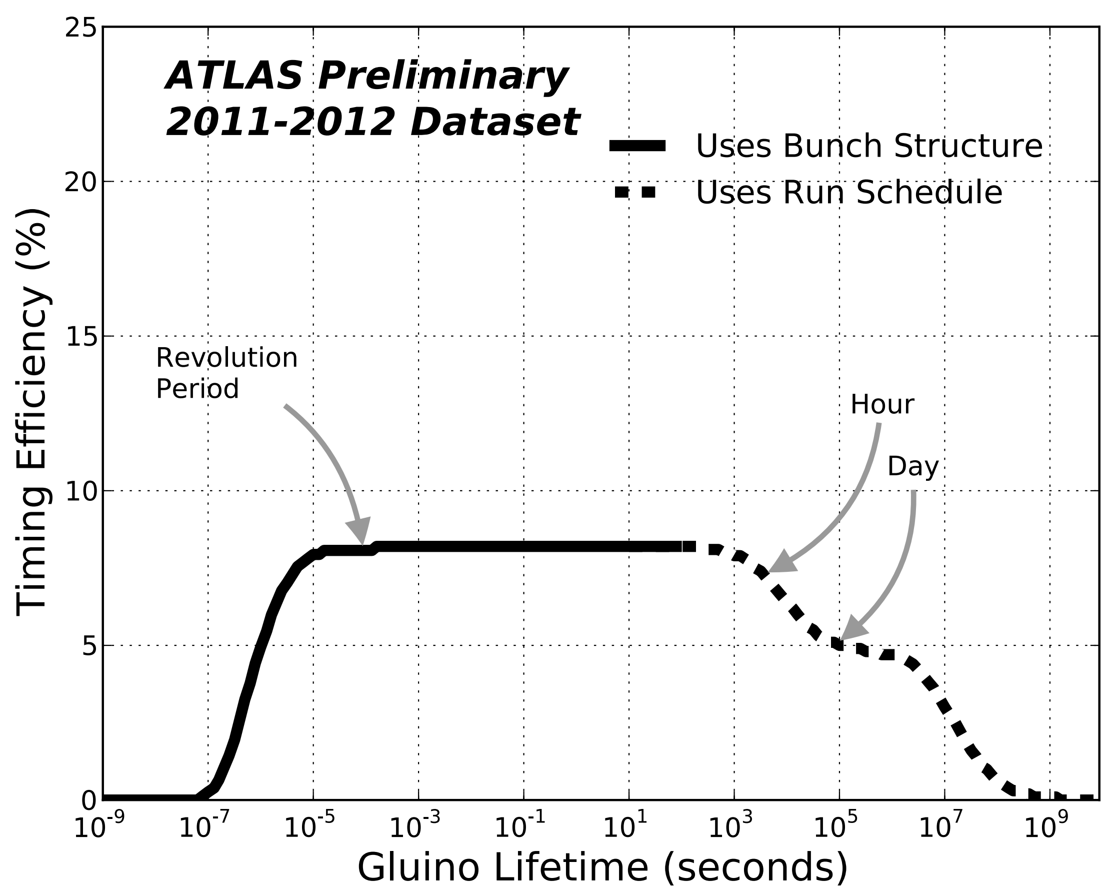
Stopped R-hadron

- Gluino could be meta-stable (split-SUSY) and form R-hadrons, can get stuck in the calorimeter and decay much later.
- **Look for energetic jets via gluino decays in empty bunches.**

The signal efficiency depends on the lifetime.

$$\varepsilon_{stop} \times \varepsilon_T(\tau) \times \varepsilon_{reco}$$

- ε_{stop}: stopping fraction
- $\varepsilon_T(\tau)$: probability to decay in an empty bunch (timing acceptance)
- ε_{reco}: reconstruction efficiency



Stopped R-hadron

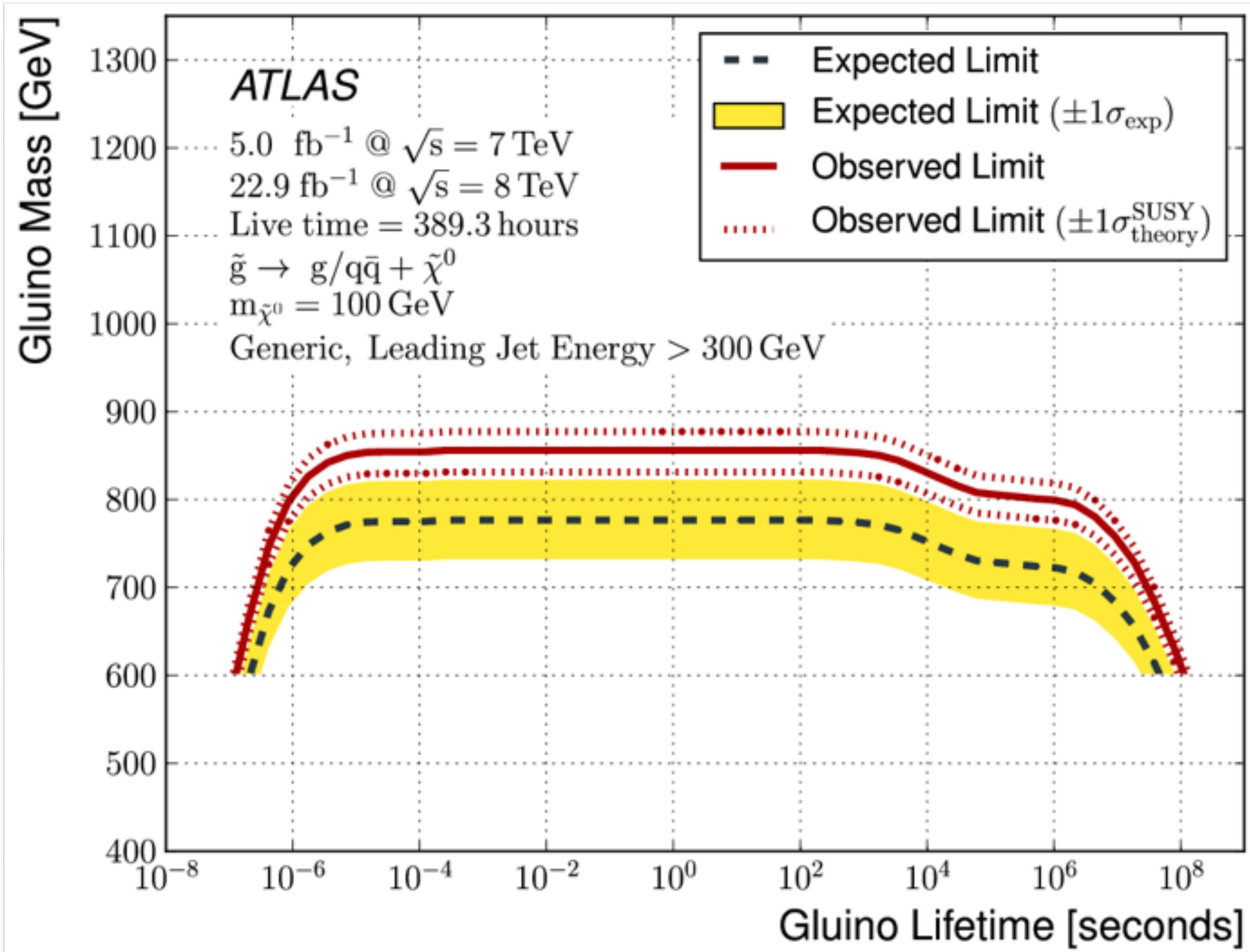
- Gluin... hadr... ...uch later.
- Look... ...unches.

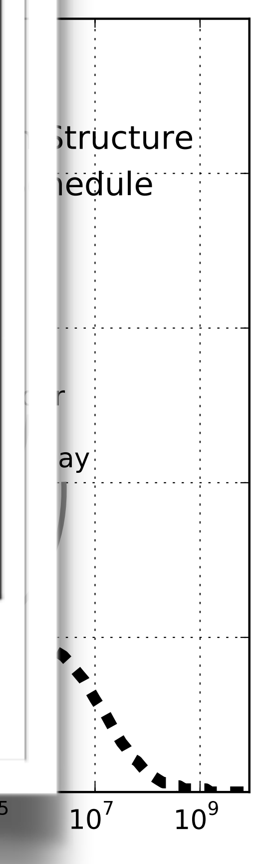
The si... on the...

ε_{stop} ×

↑

stopping fraction





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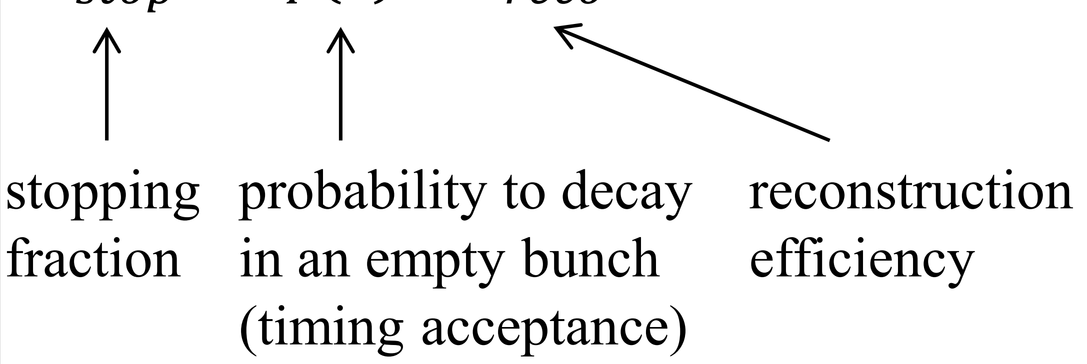
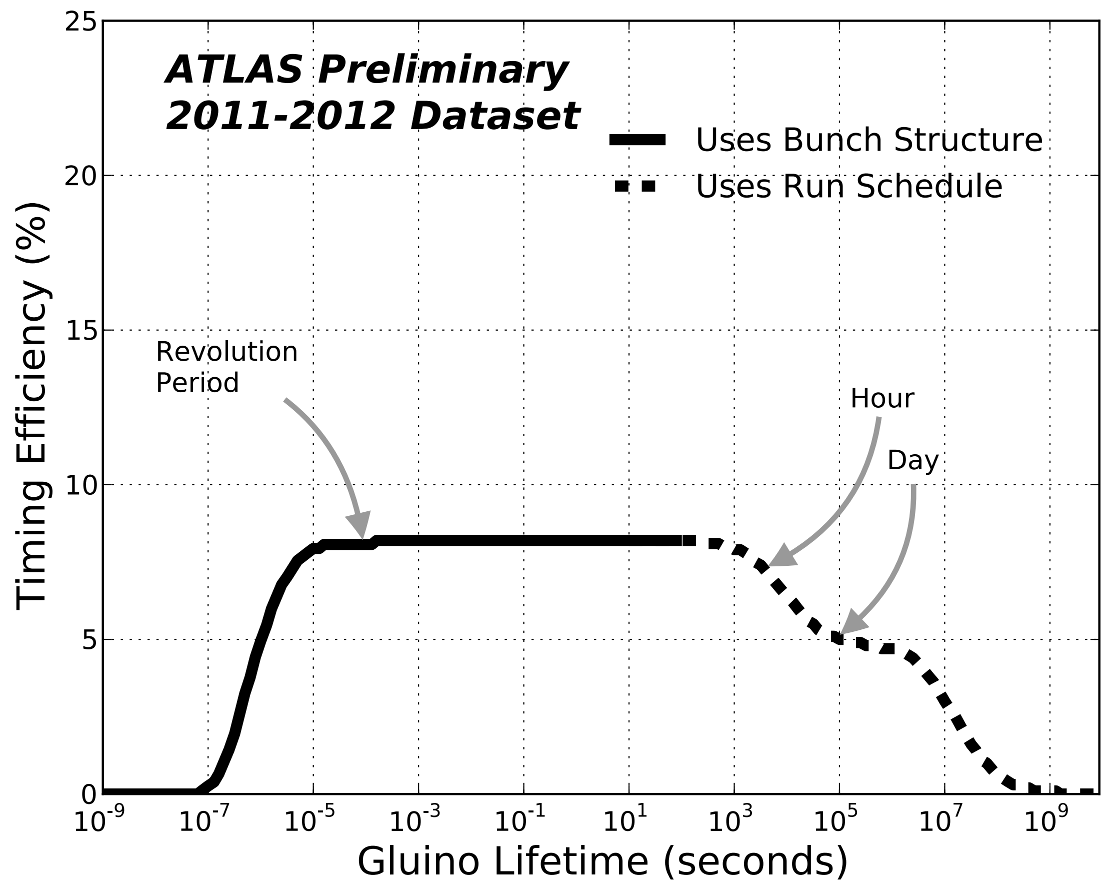




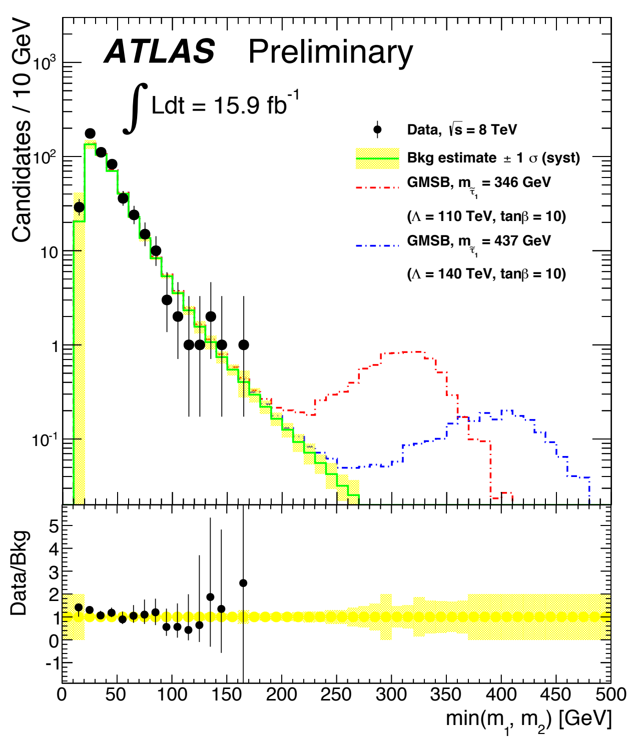
Long-lived stau

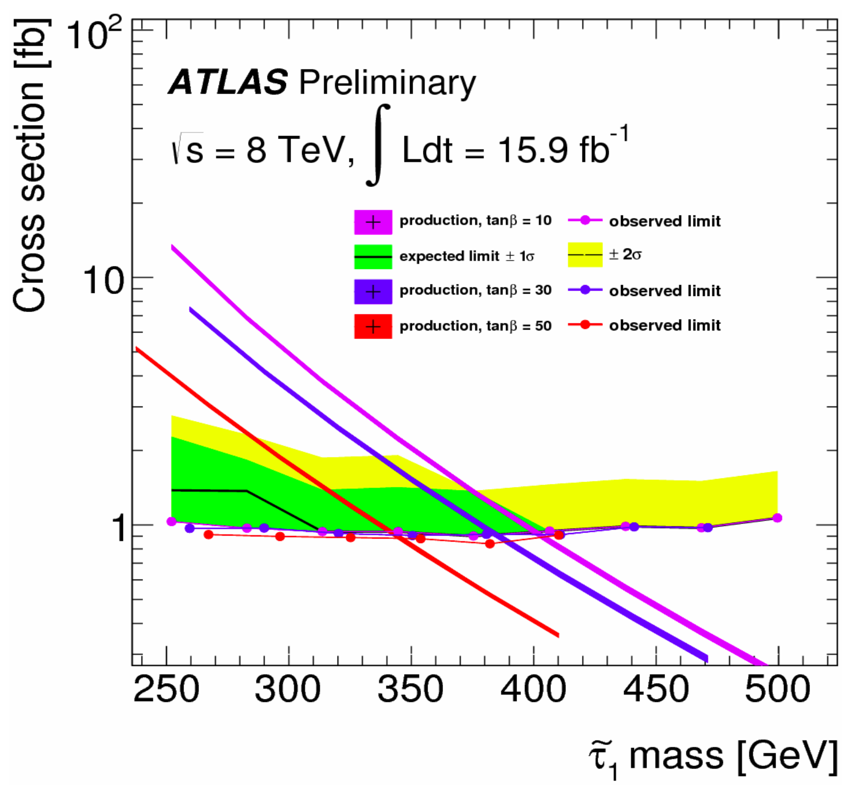
- In GMSB, signal topology characterized by sparticle-type of NLSP.
  - GMSB staus could have a significant lifetime and be observed as heavy muons.
  - Mass can be reconstructed and used as the discriminant:

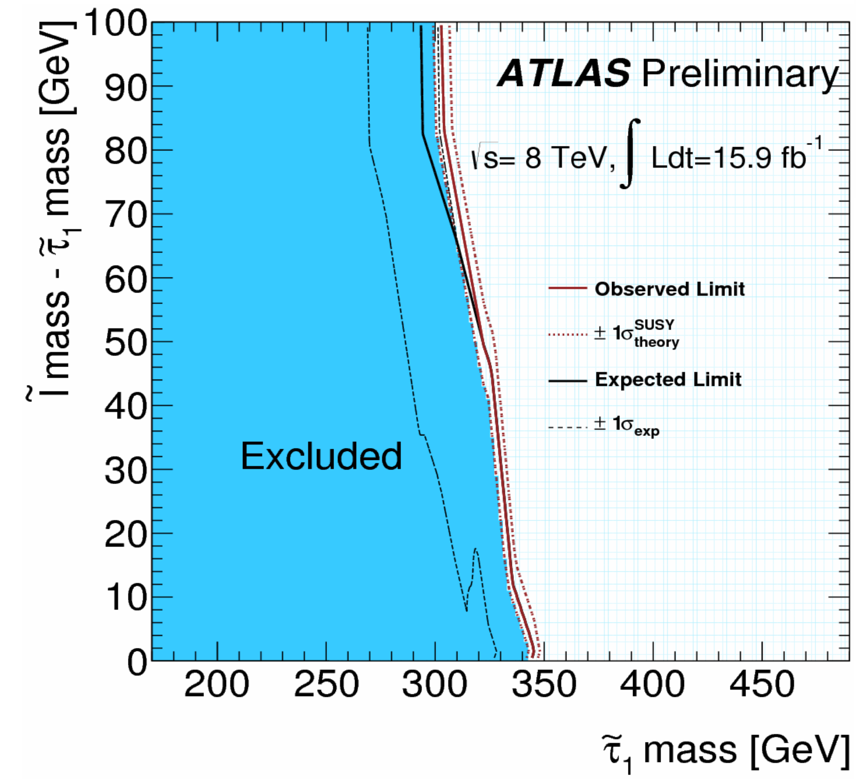
$$m = \frac{p}{\beta\gamma}$$

p → taken from track

$\beta\gamma$ → pixel (dE/dx) + calorimeter + muon detector (ToF)

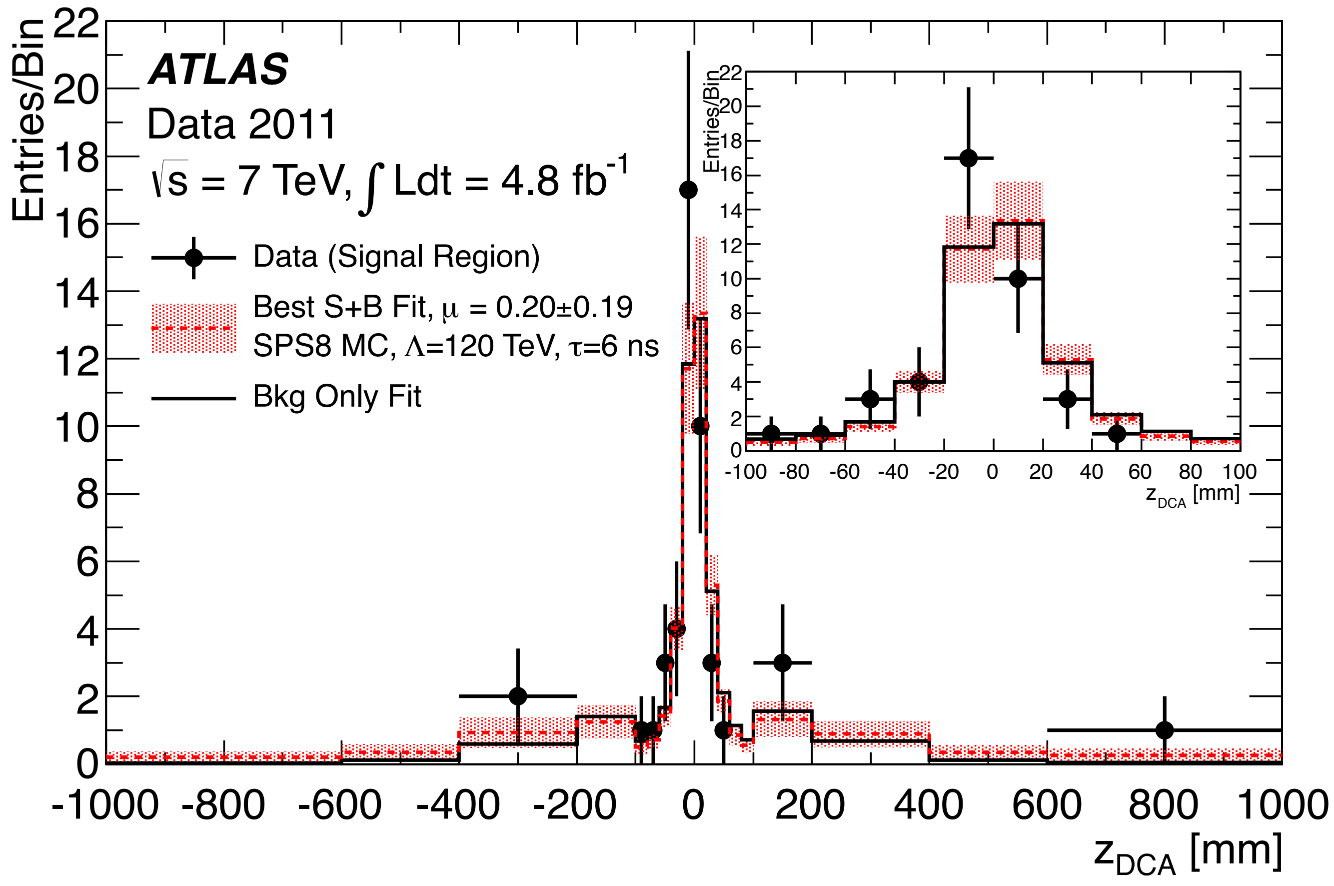


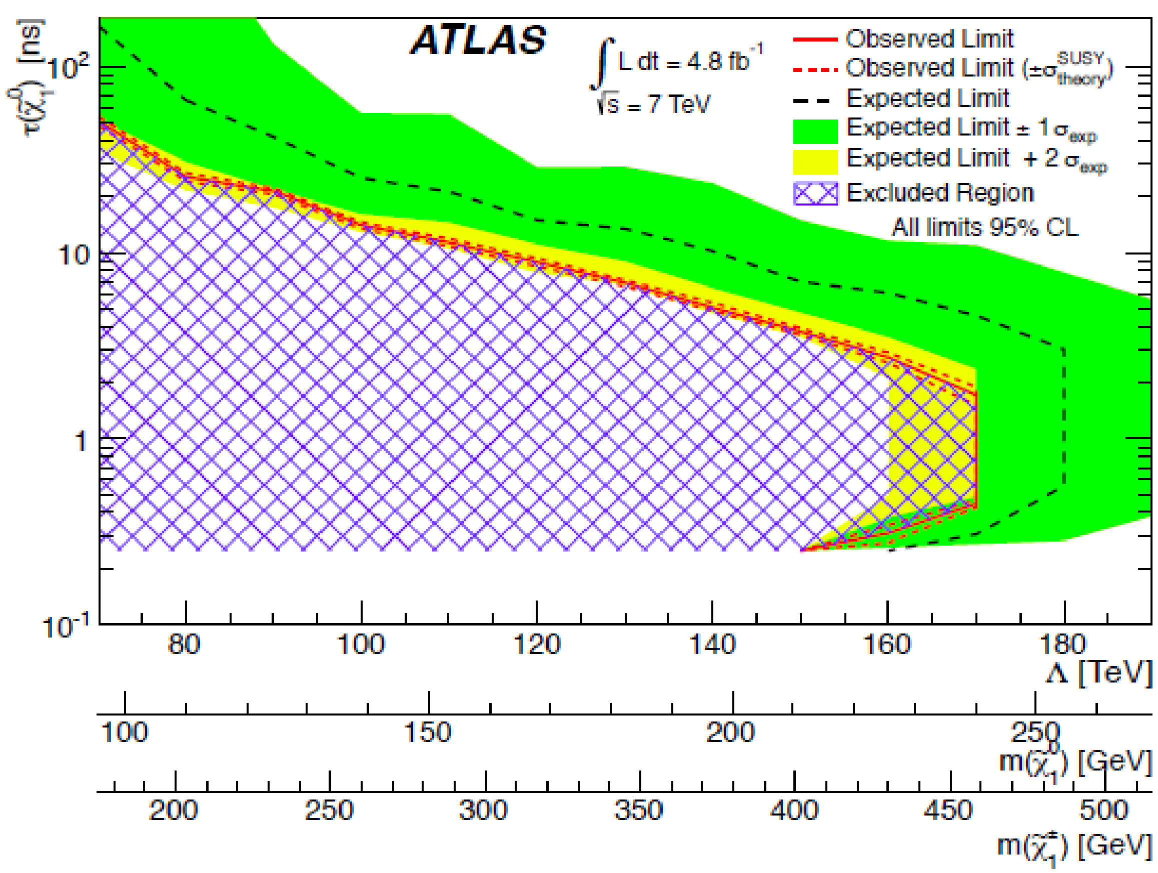




Displaced photon

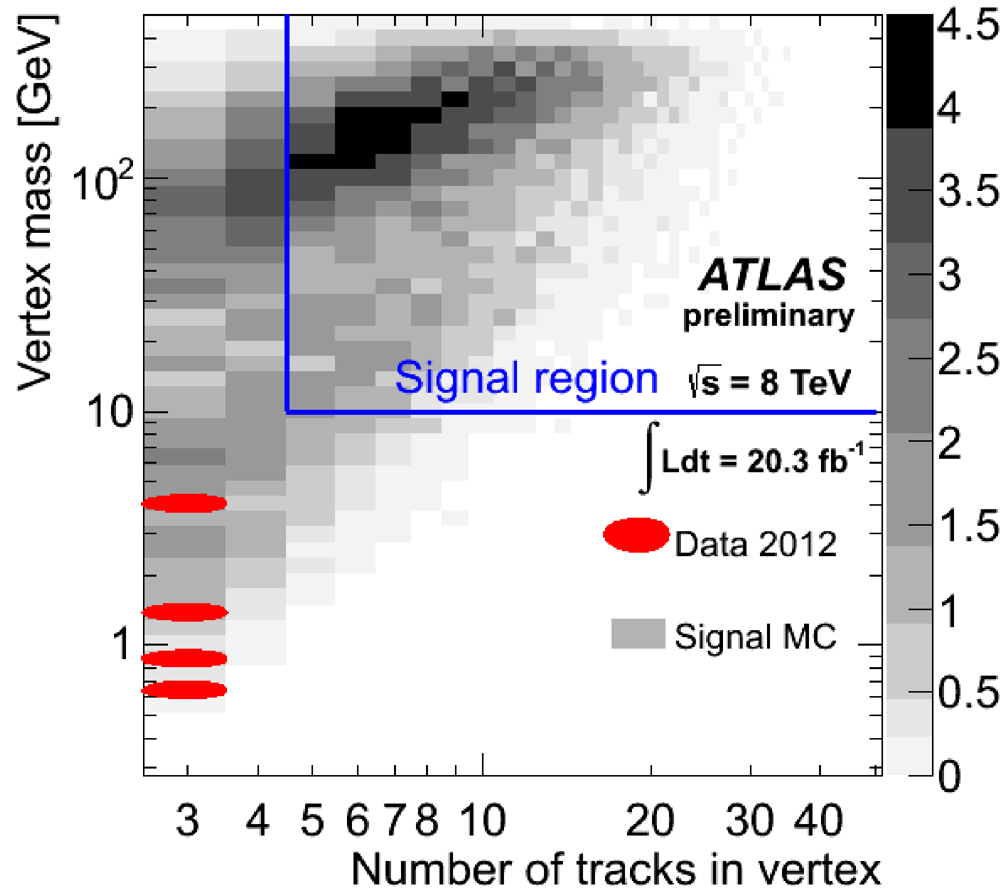
- Neutralino NSLP could a significant lifetime (GMSB), then decays to gravitino+photon.
- Use timing and shower direction to distinguish photons from displaced decays.

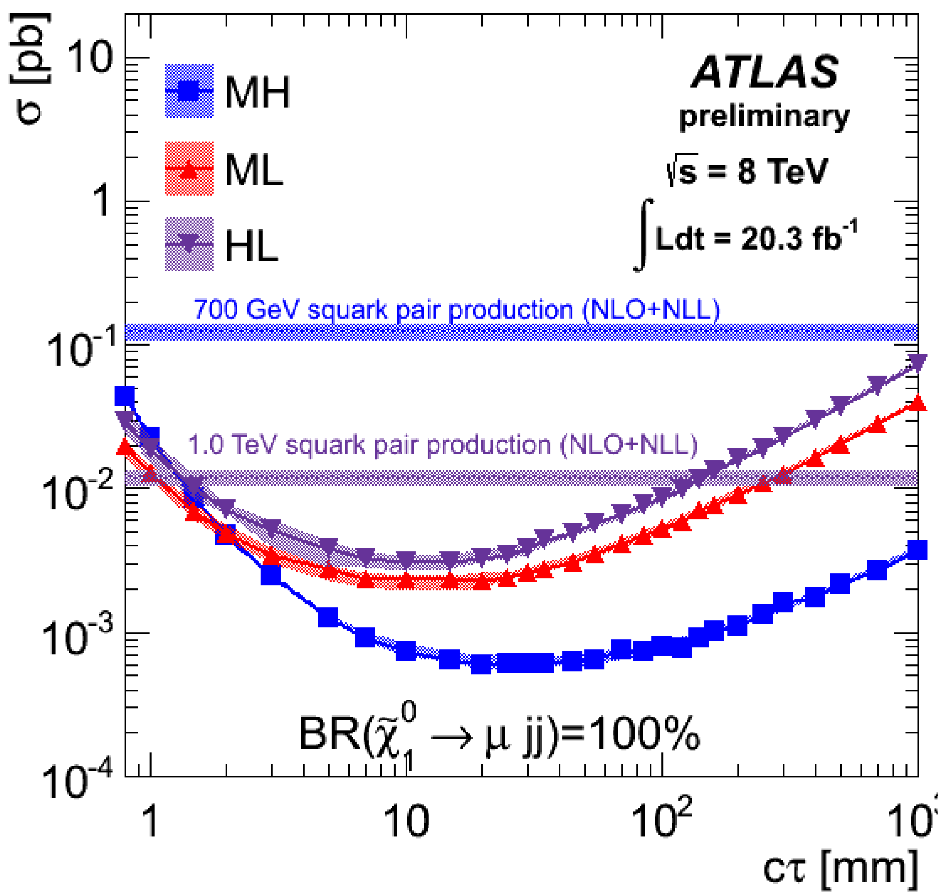




Displaced vertex

- Displaced vertices having a large mass & large track multiplicity could arise in:
  - GMSB: long-lived NLSP neutralino decay into Z/h + graviton
  - GMSB: long-lived stau that decays in the inner detector
  - Split-SUSY: long-lived gluino decays
- Provide background-free searches, no candidate events observed yet..
- At the moment, results interpreted in displaced neutralino decays via RPV coupling (mentioned later).





RPV decays

$$W = W_{\mathrm{MSSM}} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Could be non-zero?!

RPV signature

- RPV terms are allowed in the superpotential:

$$W = W_{MSSM} + \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u}_{\text{Lepton number violating}} + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{Baryon number violating}}$$

- All terms cannot appear simultaneously, protons become unstable...
- Part of them need not to be zero, leading to variety of signatures.
- LSP could decay..

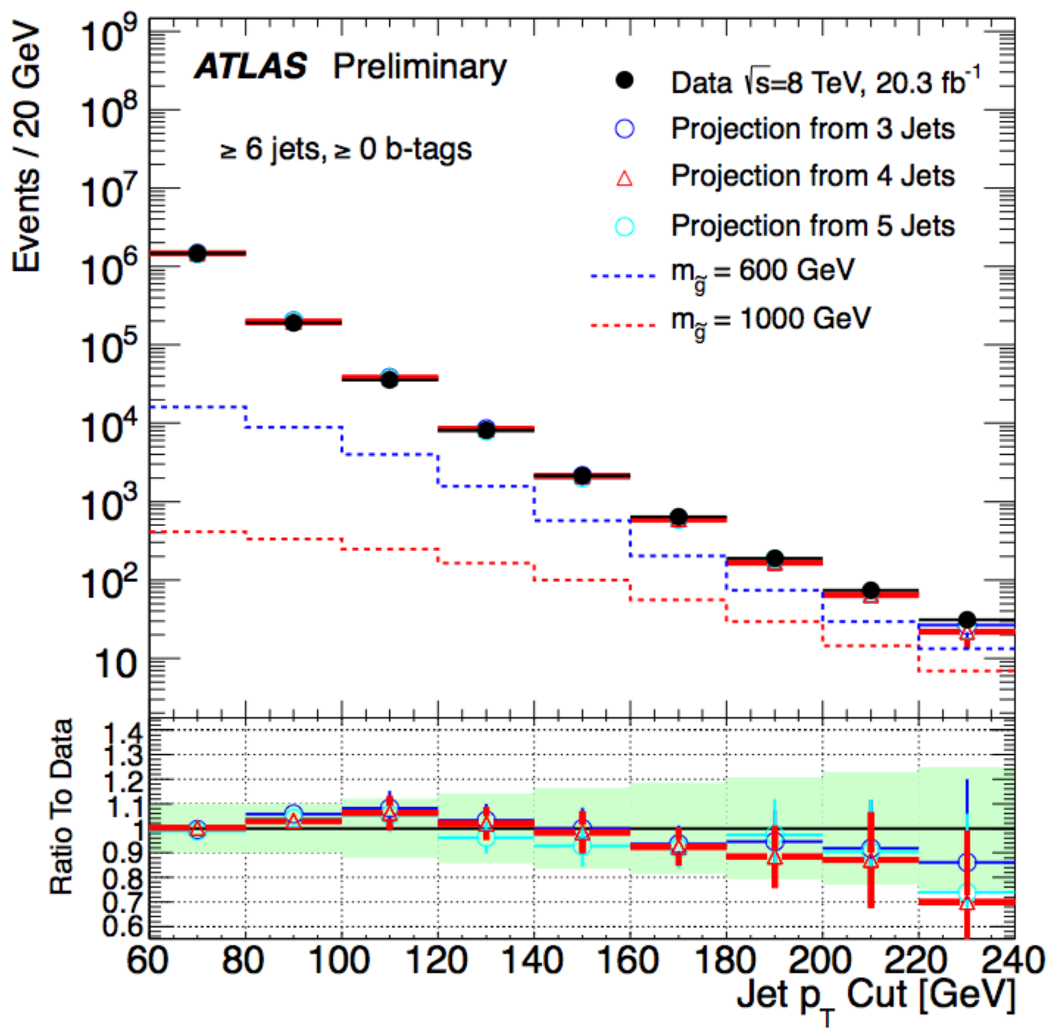
- Assume that λ has non-zero value >> large lepton multiplicity
- Assume that λ' has non-zero value >> neutralino LSP could have a significant lifetime when λ'<<~10^{-5} (decay width proportional to $(\lambda')^2$)

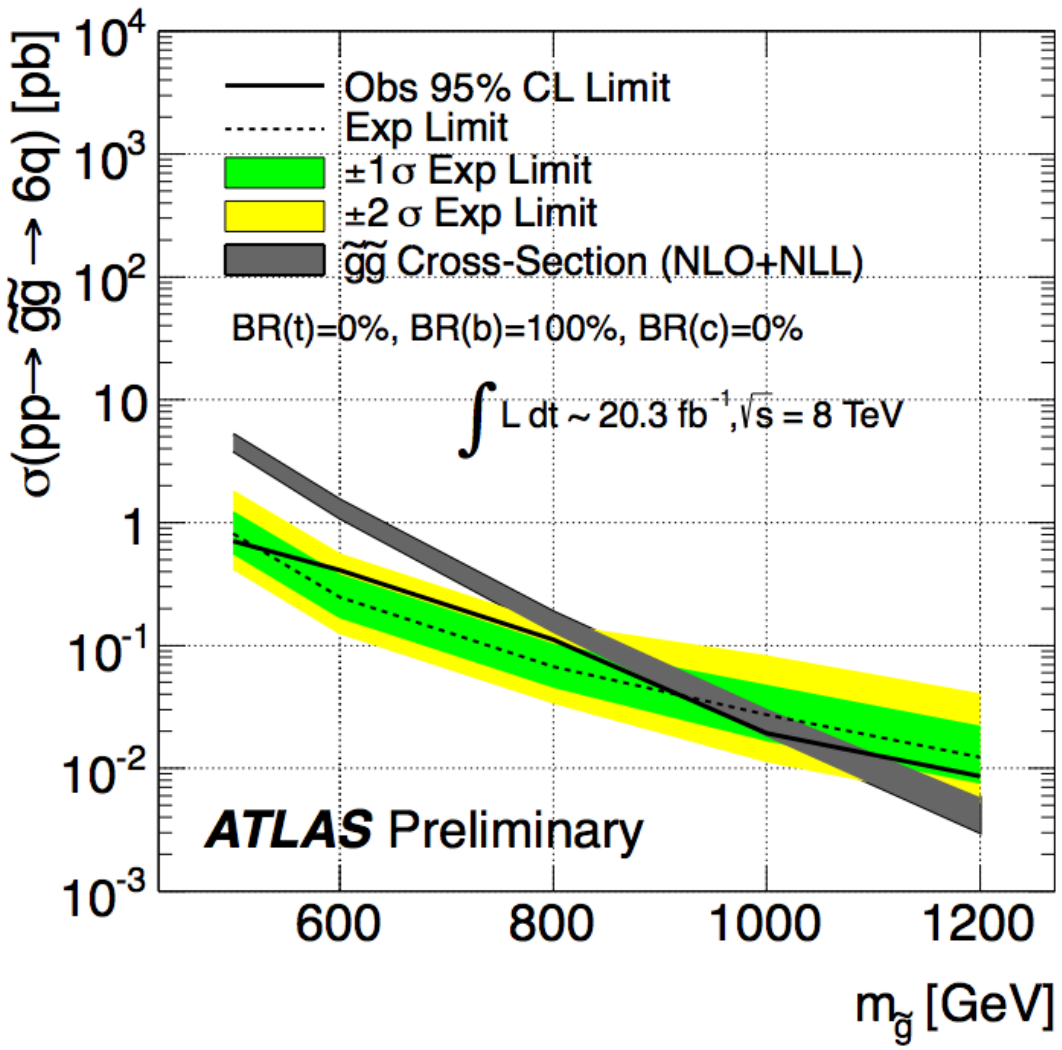
$$LQ\bar{D}(\lambda') : \ \tilde{\chi}_1^0 \rightarrow \begin{pmatrix} e, \mu, \tau \\ \nu \end{pmatrix} + 2 \text{ jets}$$

- Assume that λ'' has non-zero value >> neutralino could hadronically decay (into 3 quarks)

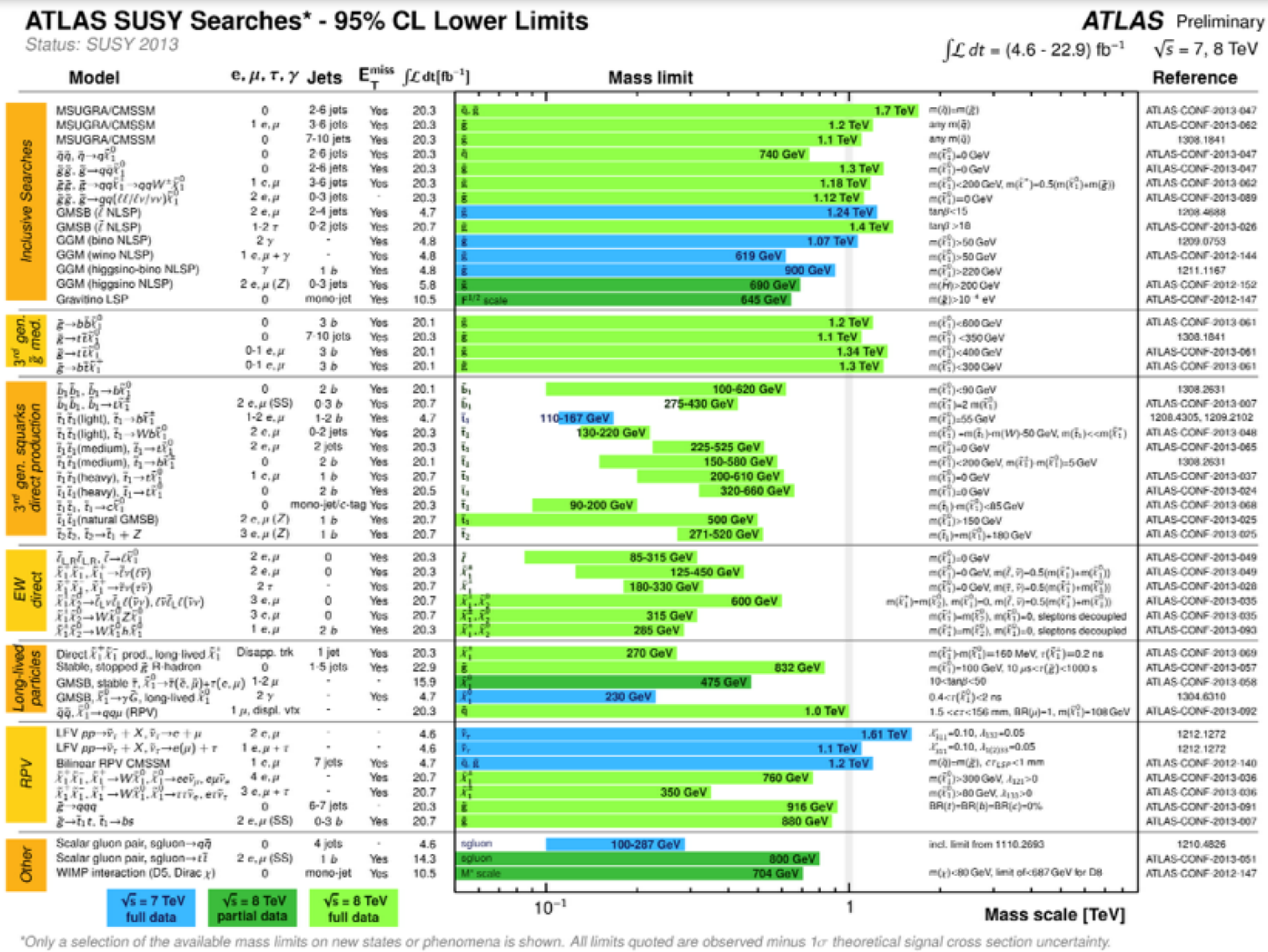
Large jet multiplicity (w/o MET)

- Hadronic RPV decay of LSP (to 3 quarks) leads to large jet multiplicity + diluted MET.
- Analysis carried out by requiring ≥6 and ≥7 jets with and without b-jet requirements





Searches for all possible SUSY decays… may complete the job for 8TeV data hopefully this winter.



Summary

- Nothing found yet in 8TeV pp collisions.. but still at the beginning of a long SUSY search program at the LHC energy frontier.
  - The colored sparticle mass reach significantly improves (up to ~3TeV) with increased beam energies.
  - 3rd. gen squarks?? The allowed parameter space has been squeezed, but there's still room that could not be accessed.
  - The sensitivity to EW production still limited by statistics. Could be addressed down to O(0.01)fb.
  - Have developed a number of new analyses that utilize ISR/soft lepton tagging and exotic tracks to cover "holes" of general/traditional searches.
  - Have nearly completed out job for 8TeV data and many search tools in hand to address all possible decays.

- LHC resumes operation in 2015 with the designed collision energy.
  - What comes in next years??