The hunt for SUSY at ATLAS: status and challenges for Run2

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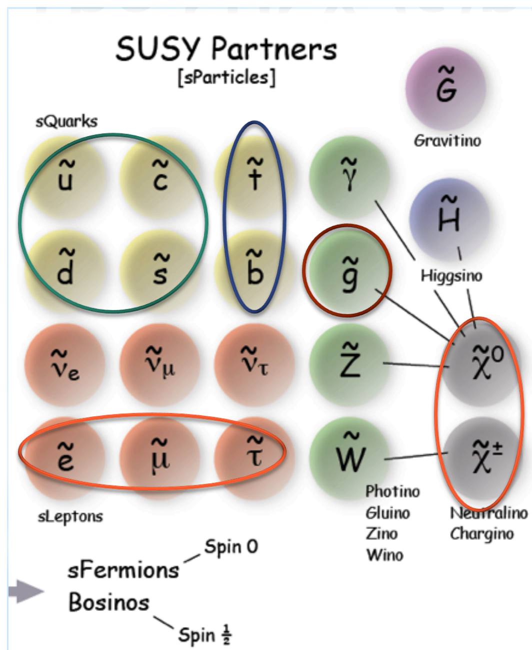
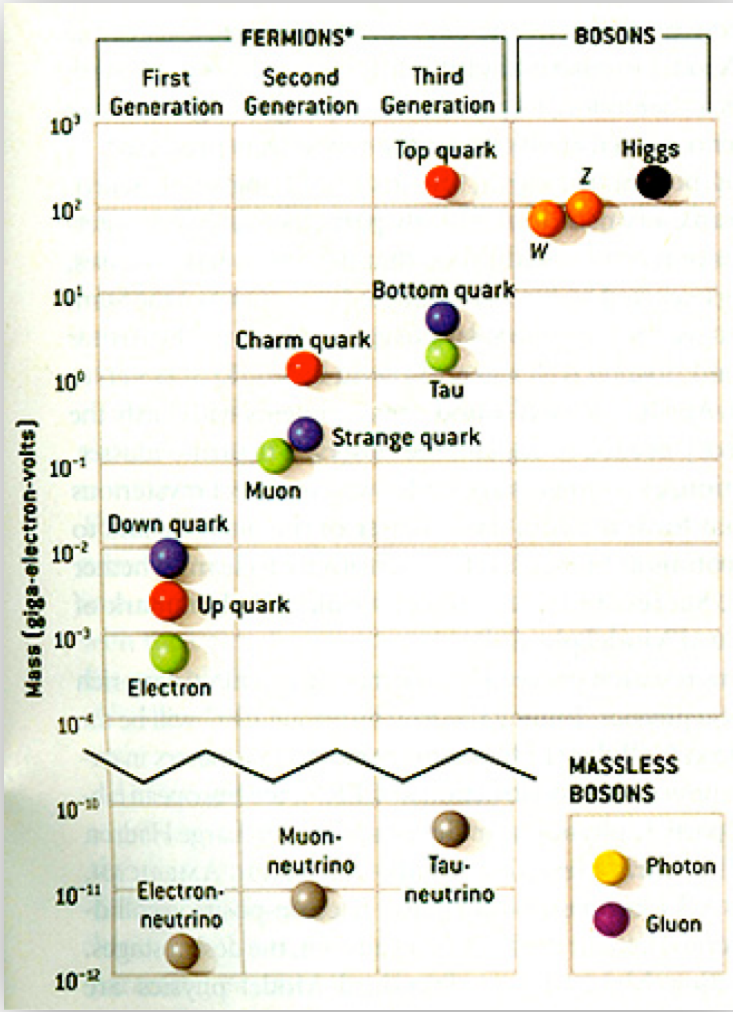


HEP Seminar, 11/11/2015

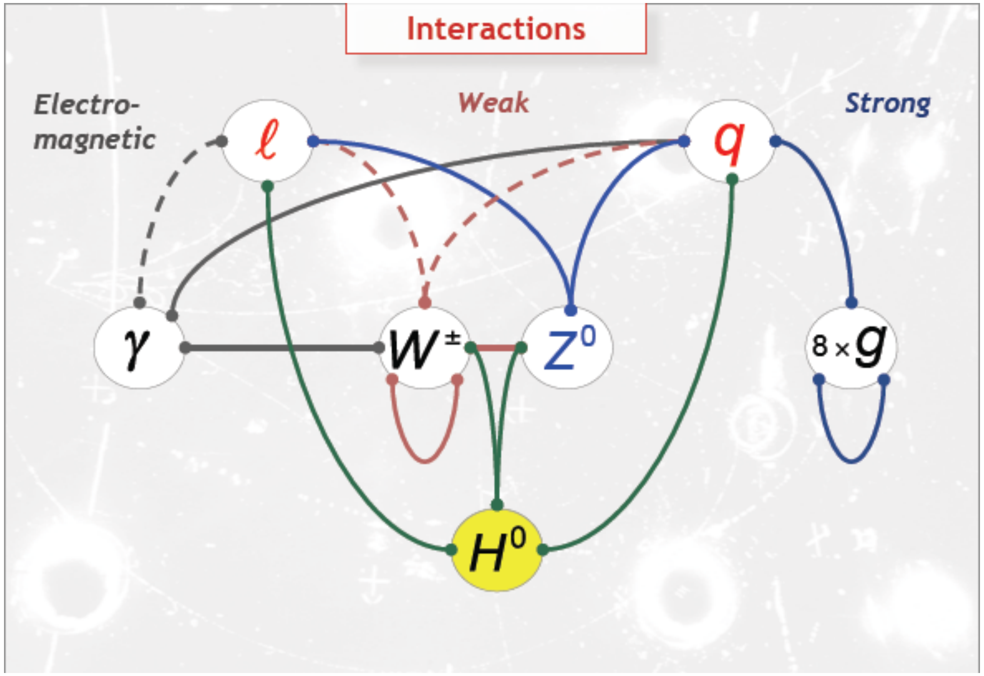
The Standard Model

- Matter is made out of fermions:
  - 3 generations of quarks and leptons

24 elementary matter particles and 3 forces



- Forces are carried by Bosons:
  - Electroweak: γ,W,Z, Strong: gluons



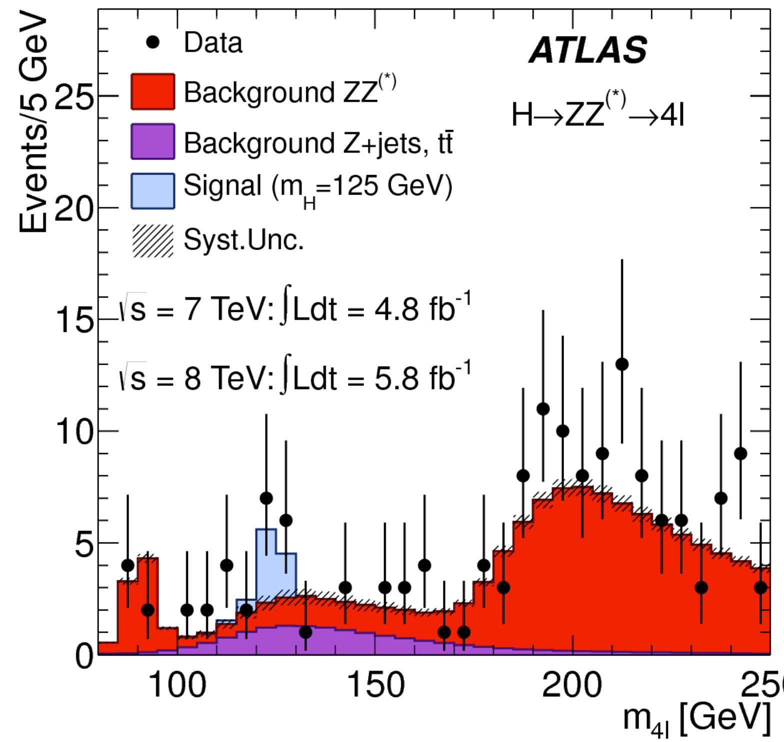
SM particles have no inherent mass
Gain mass by passing through a field → the ***Higgs field***

The origin of masses: the Higgs boson

Electroweak Symmetry Breaking 'Mechanism' theorized in 1964

Higgs boson observed at the LHC 50 years later → 125.5 GeV!

Higgs and Engler on July 4, 2012



- Enormous resonance of this discovery around the world !!
- **Nobel Prize in 2014** to theorists of the EWSB mechanism
- **Special Breakthrough prize to ATLAS and CMS** spokes for the **achievement** (unfortunately not split among collaborators at that time, but special founding created for students at least in ATLAS)

The origin of masses: the Higgs boson

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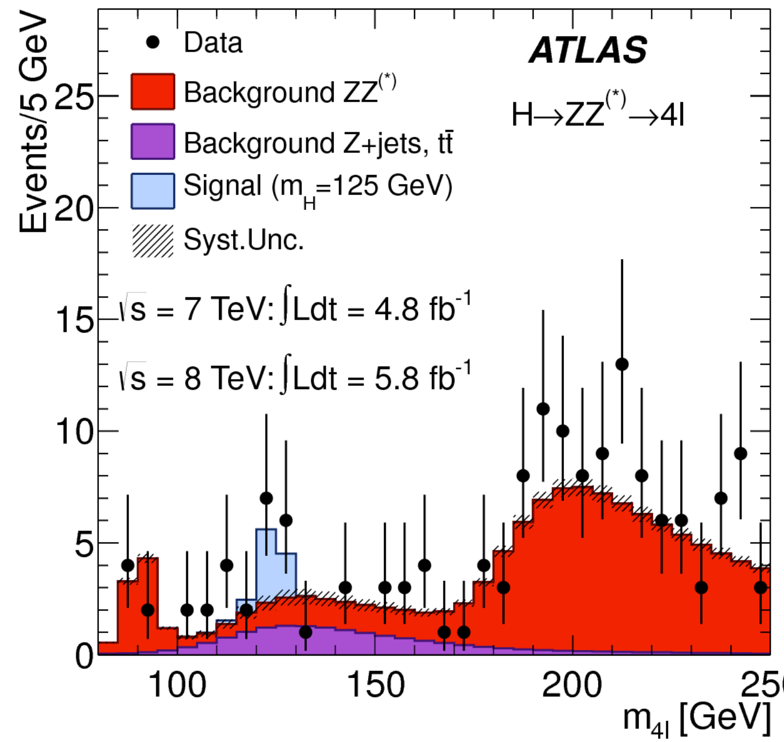


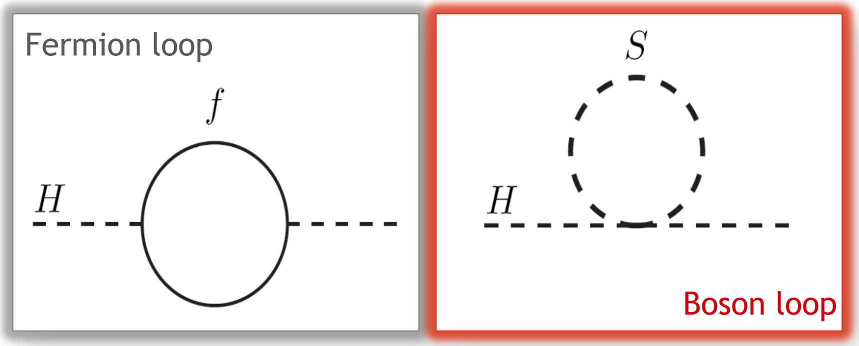
DOES THE HIGGS DISCOVERY COMPLETE OUR UNDERSTANDING OF NATURE ?

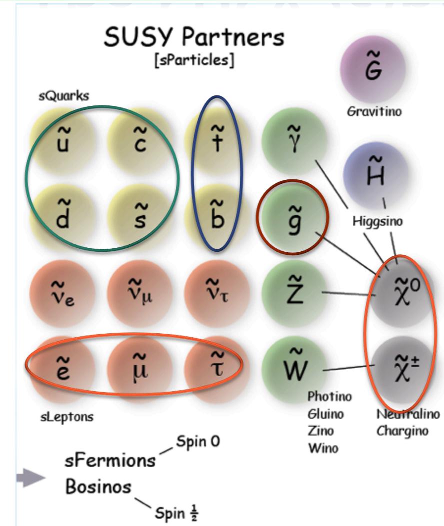
NOPE! The Standard Model is theoretically incomplete

Supersymmetry

New spin-based symmetry relating fermions and bosons

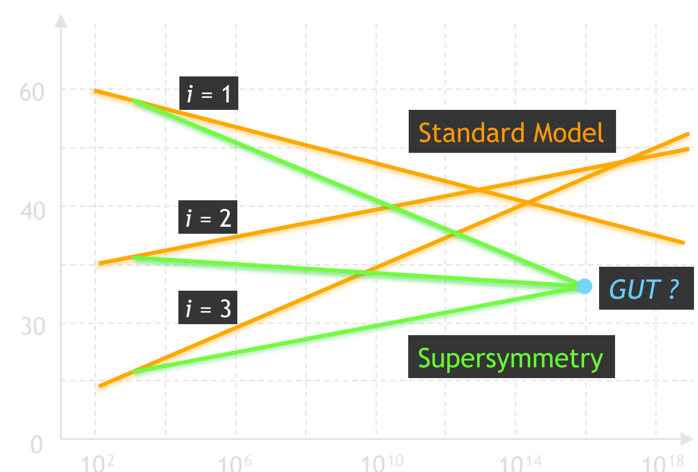
→ more than doubles the particle spectrum w.r.t. the Standard Model.





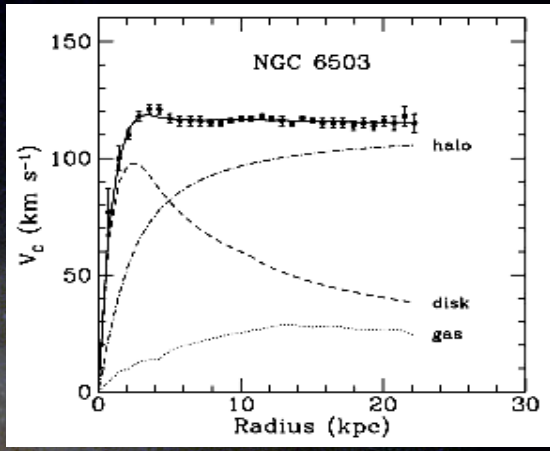
- **Naturally solves the gauge hierarchy problem**
- **Predicts an elementary Higgs scalar …**
  - ‘intriguing’ SM-like limit

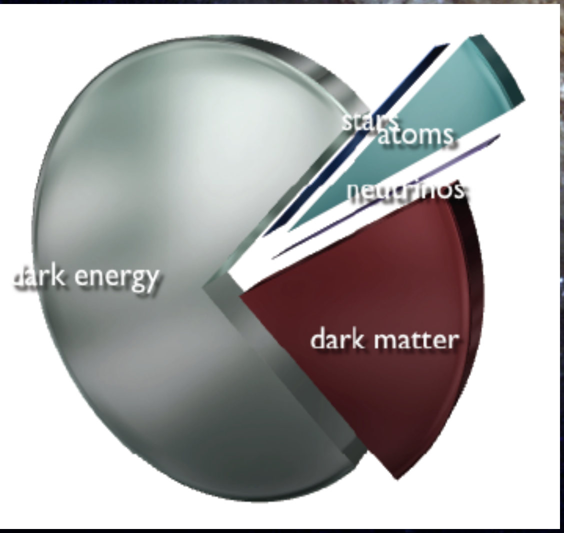
  → mass below 135 GeV (in the MSSM)
- **Allows grand unification of forces**
- **SUSY with R-parity (*) conservation predicts a suitable Dark Matter candidate**



(*) relates B, L, S quantum numbers

What is the Dark Matter?





Standard Model only accounts for 20% of the matter of the Universe

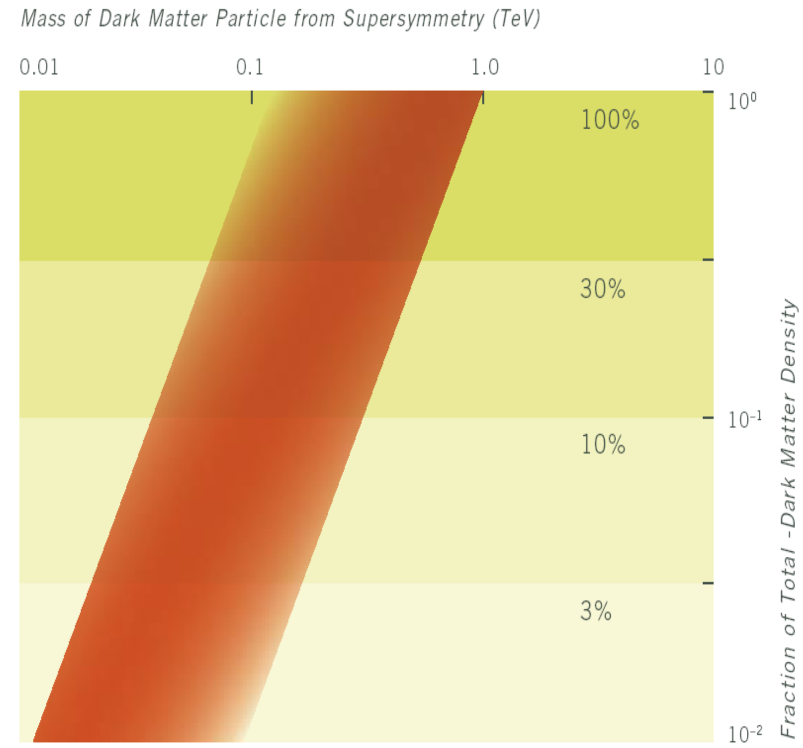
In SUSY the lightest supersymmetric particles (LSP) can explain the rest of the matter..

The LSP and Dark Matter

- The amount of dark matter relic density is inversely proportional to the annihilation cross section:

$$\Omega_{DM} \sim \langle \sigma_A v \rangle^{-1}$$

$$\sigma_A \sim \alpha^2 / m^2$$



HEPAP 2006 LHC/ILC Subpanel

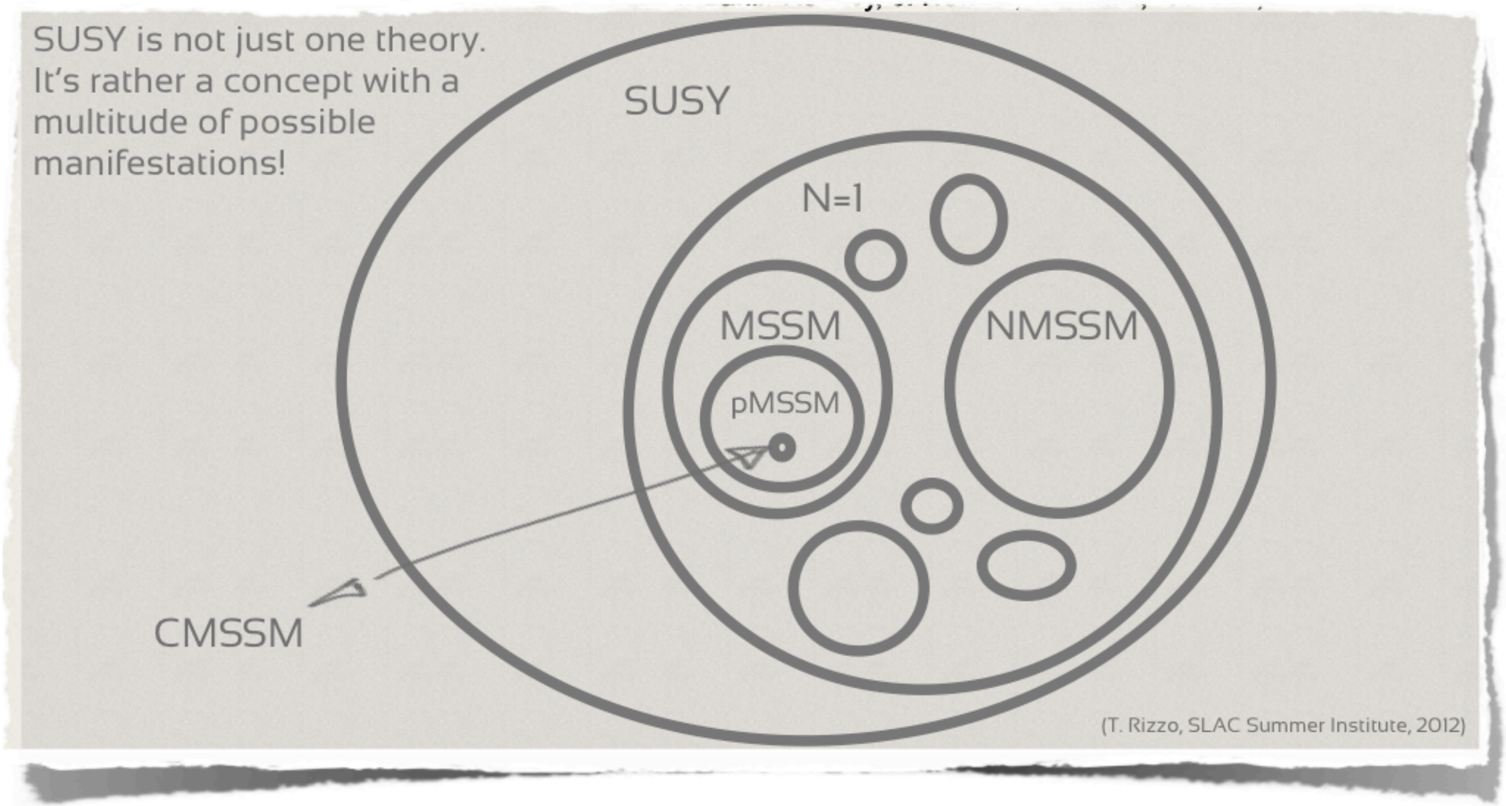
Remarkable "coincidence":

Ω_{DM} ~ 0.1 for m ~ 100 GeV – 1 TeV!

Supersymmetry independently predicts particles with about the right density to be dark matter !

SUSY phase space

SUSY widely considered to remain the chief amongst BSM proposals - although the most simplistic versions tightly constrained by experimental results

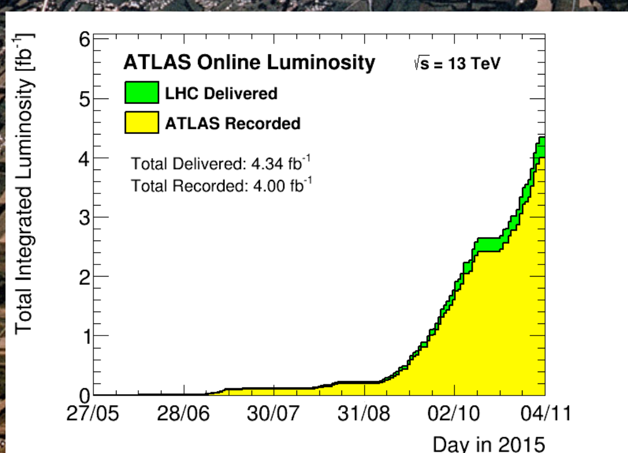


- Almost impossible to exclude, but can tightly constrain the large variety of models and efficiently look for an hint of new physics. But for this, we need a solid experimental environment and an even more solid strategy…

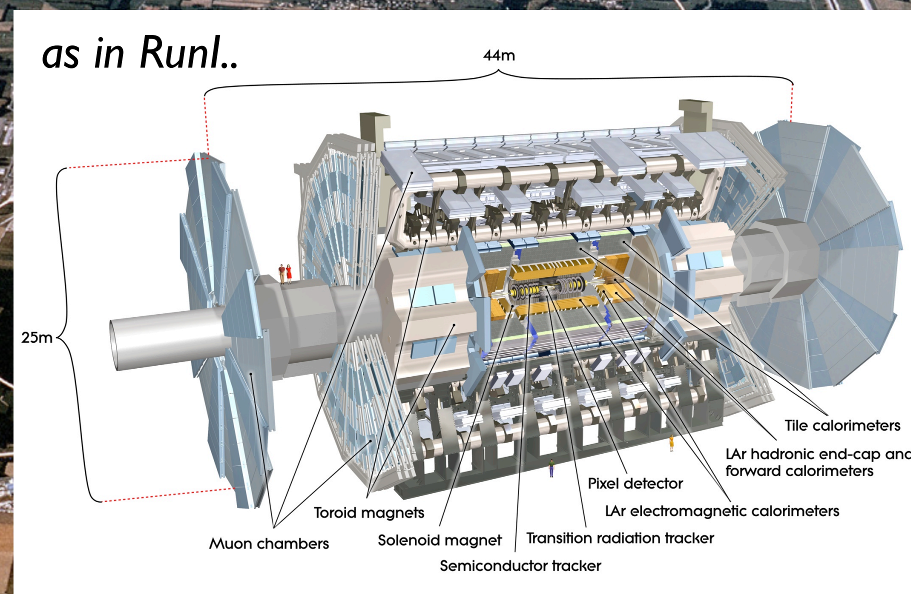
The ATLAS experiment at the LHC

27 km circumference

So far:
7/8/13 TeV proton–proton collisions
5 fb^{-1} /exp. 2011 @ 7 TeV
25 fb^{-1} /exp 2012 @ 8 TeV
~4 fb^{-1} /exp 2015 @ 13 TeV
2.76 TeV Pb–Pb collisions

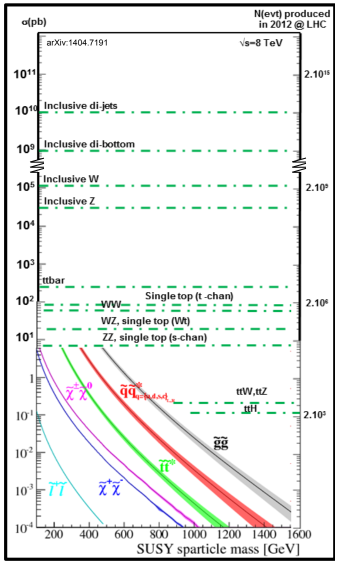


as in RunI..

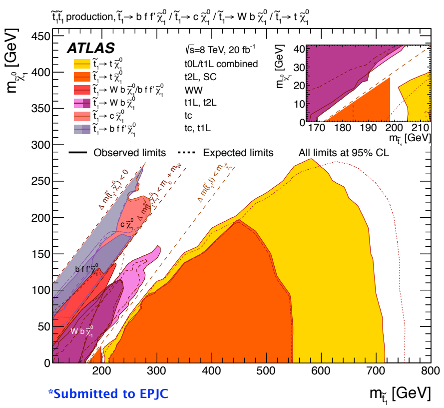


outline – strategy and results so far

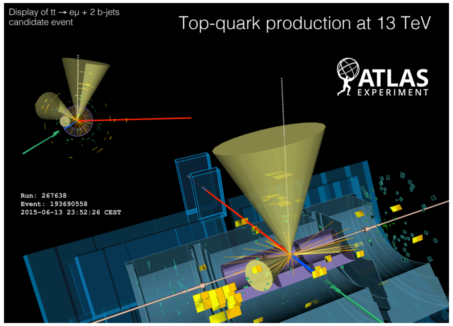
- Theoretical challenges: which model
- Experimental challenges:
  - Trigger
  - Discriminants and tools
  - Background strategies
- The Run 1 legacy: highlights
  - Strong production
  - Third generation
  - EWK production
  - Long Lived particles
- Towards Run 2:
  - What we expect
  - Where we stand



arXiv:1506.08616v1*



*Submitted to EPJC



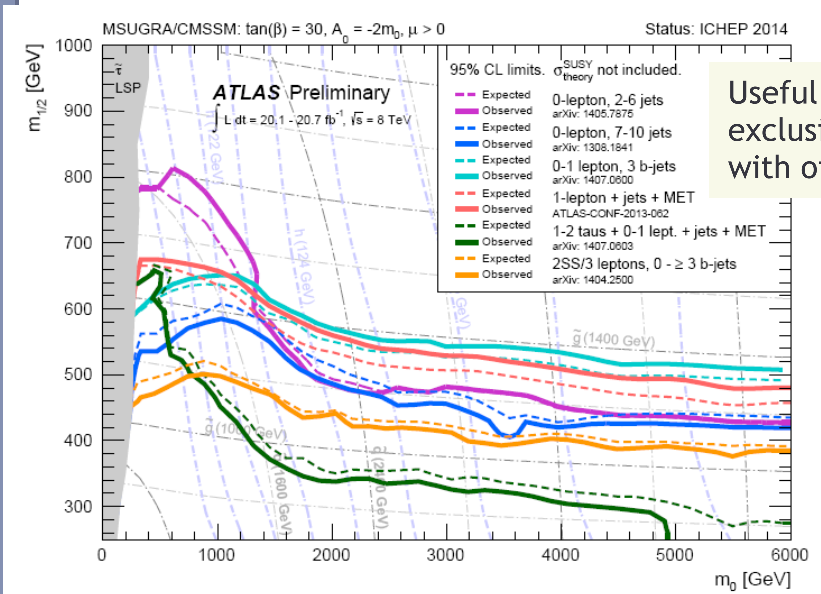
.. Of course, a personal selection ☺

The ‘theory challenges’: which target?

Usually ‘signal regions’ are defined considering various models

‘Full’ Physics models

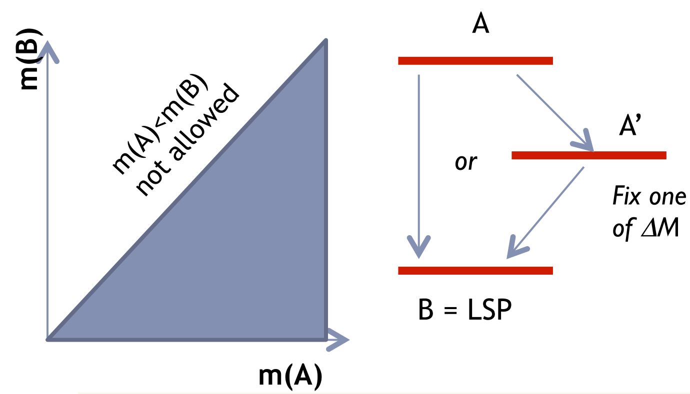
- SUSY breaking @ high scale → specific spectrum at EWK scale
- mSUGRA, Gauge Mediated Symmetry Breaking, Anomalous MSB, Minimal SUSY (MSSM)



Useful to calibrate our exclusion and compare with other results

Simplified models

- Described by a minimal set of parameters (particle masses, cross section)
- Most models: fixed BR to final state of interest (e.g. 100%)



Very helpful to design analyses and understand loop-holes.

Generalized models

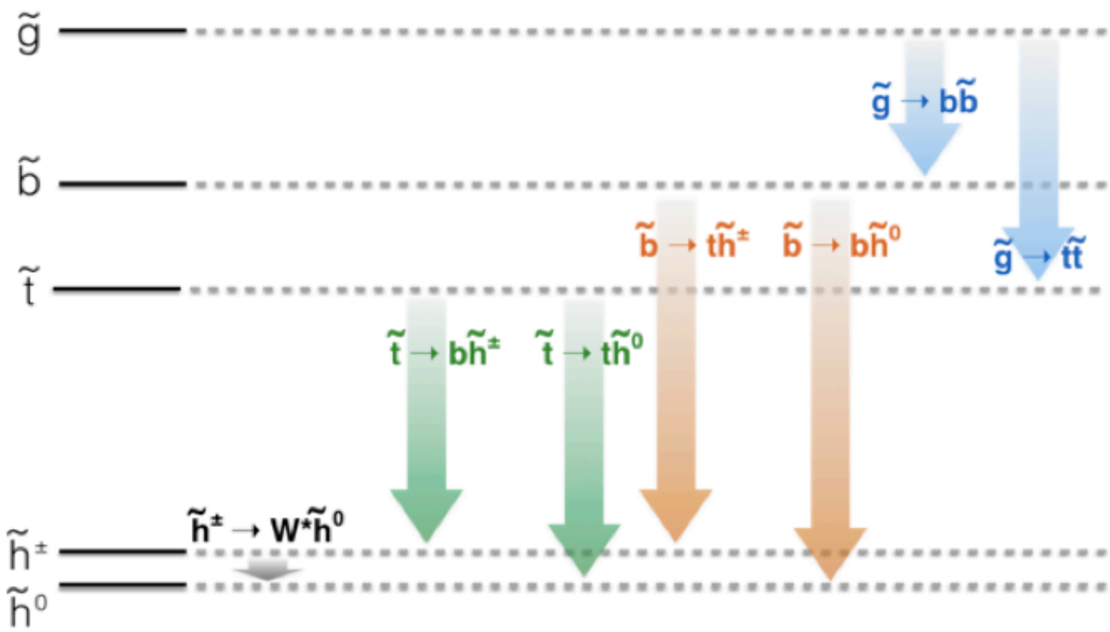
- Parameters @ EWK scale → spectrum at EWK scale
    - Set considering also indirect constraints
- pMSSM, General Gauge Mediated …

The 'theory challenges': which target

- Simplified model definitions must also be inspired by some guiding principles. In Run1, **naturalness** has been a very important one

- At least one light (< 135 GeV) neutral Higgs
- m ($\tilde{t}$, $\tilde{b}$, $\tilde{\chi}$) < 1 TeV to compensate top and W contributions to Higgs
- LSP often is $\tilde{\chi}_1^0$, large higgsino component

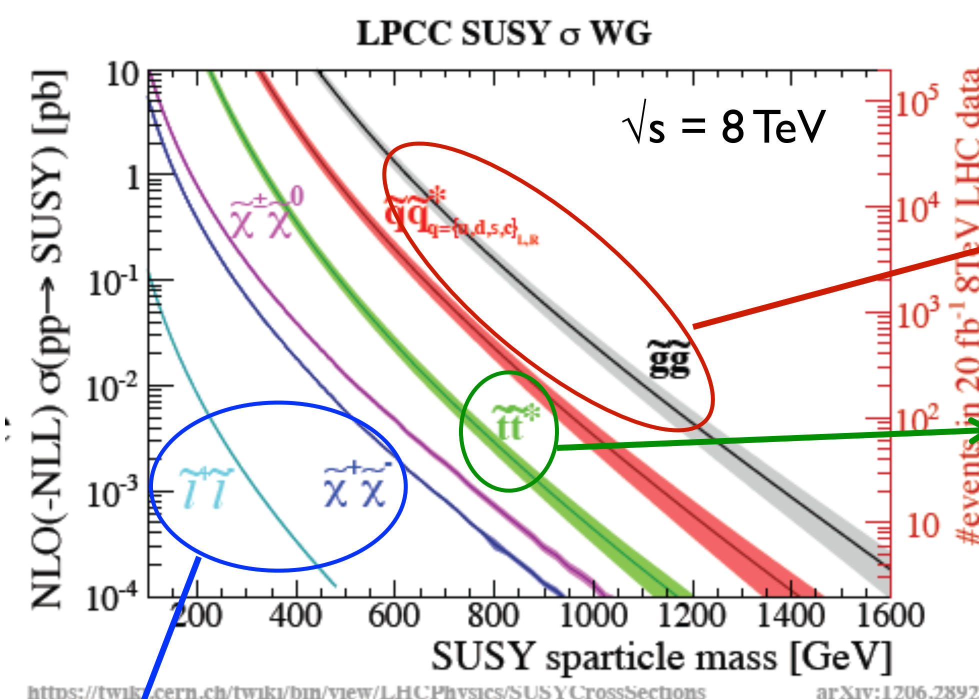
- To avoid large FCNC: squarks, sleptons of 1st and 2nd generations heavy and degenerate



Higgsinos almost degenerate (very difficult to probe)

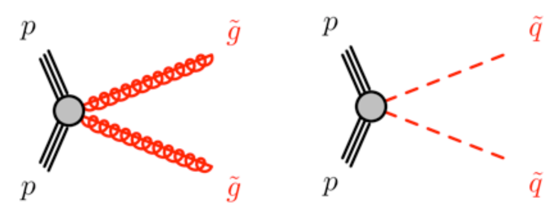
SUSY search @ LHC

ATLAS search program is designed to provide coverage for a broad class of SUSY models. Searches are split in terms of **(1) targeted production** (2) expected phenomenology



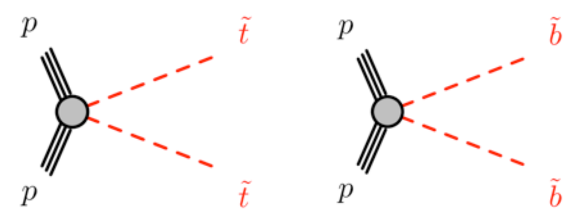
Gluinos and 1st, 2nd generation squarks:

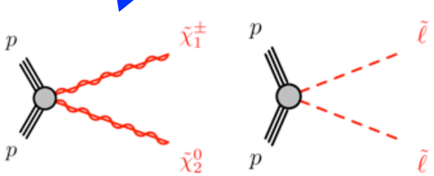
- high cross section up to ~ 1 TeV mass



Top and bottom squarks

- high cross section up to ~ 0.5 TeV





Charginos, neutralinos, sleptons:

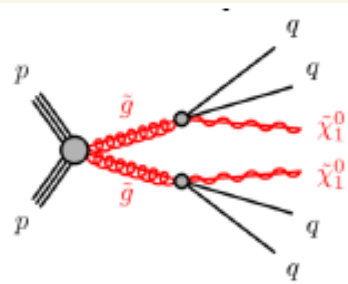
- overall small cross section, feasible with current dataset

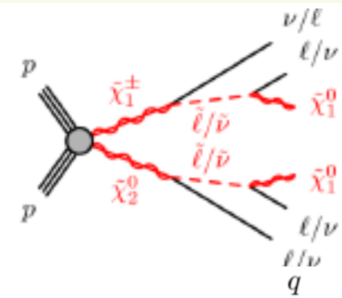
SUSY search @ LHC

ATLAS search program is designed to provide coverage for a broad class of SUSY models. Searches are split in terms of (1) targeted production **(2) expected phenomenology**

If R-parity is conserved (RPC)

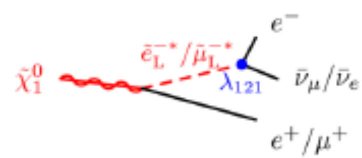
→ sparticles produced in pairs at colliders
→ Lightest Supersymmetric Particle lead to high **missing transverse momentum (E_T^{Miss})** final states

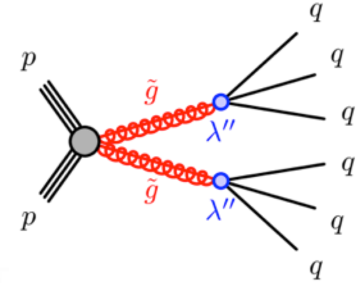




If R-parity is violated (RPV)

→ LSP not stable, rich and diverse phenomenology depending on the involved parameters (λ, λ’,λ”)
→ search strategy based on **large object multiplicity**



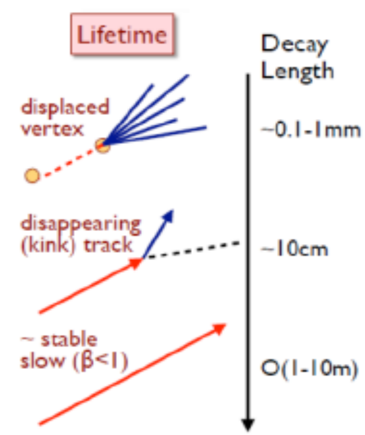


Long Lived (LL) particles

could be produced in RPV and RPC scenarios. E.g.:

- **in RPV:** if lambda couplings are very small
- **in RPC:** If very heavy squarks mediate gluinos decay:
  - Long-lived gluinos → R-hadrons (eg. Split SUSY)

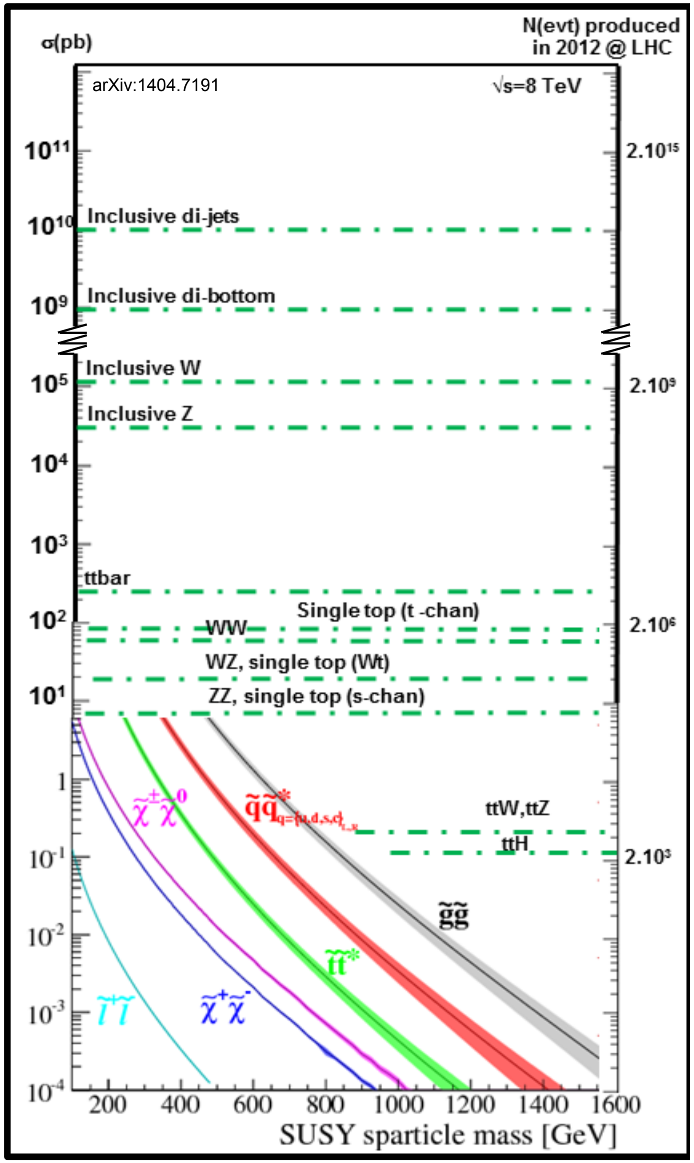
→ use **distinct signature of particles with lifetime** e.g displaced vertex (DV)



the experimental challenges

- **Large phase space to cover.**
  - Many production modes and decay channels.
  - Multiple final states to explore.
- **Cross sections tiny with respect to the Standard Model processes.**
- **Searches target on a phase-space that is experimentally complicated.**
  - Tails of distributions in multi-object final states.
  - Require
    - efficient trigger selections;
    - powerful discriminating variables;
    - complex background determination techniques.

⇒ A real experimental challenge!

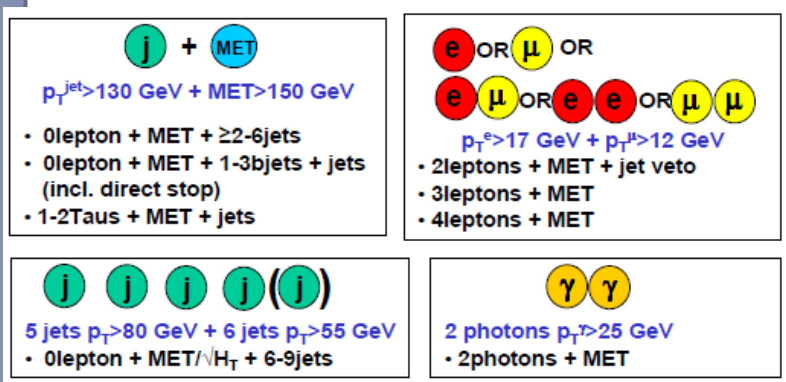


The quest for SUSY – step 1: the trigger

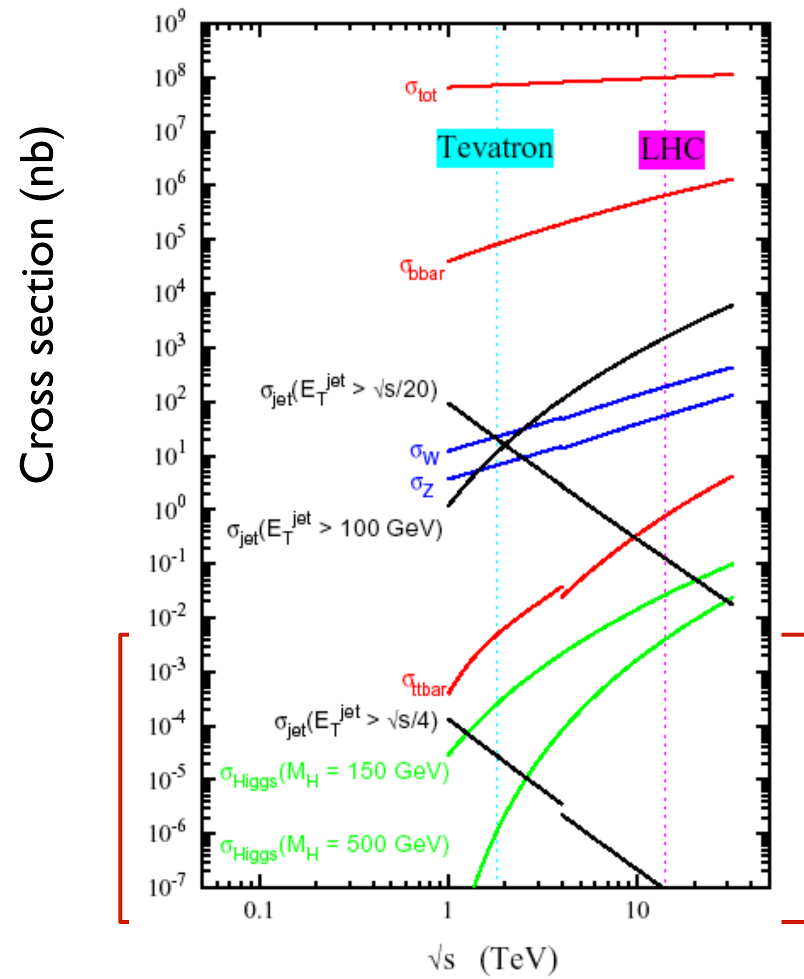
Typical triggers used for searches:

Object	Unprescaled thres.
j	$p_T^{jet} > 350$ GeV
MET	MET>170 GeV
e	$p_T > 25$ GeV
μ	$p_T > 20$ GeV
γ	$p_T > 85$ GeV

Combination of requirements can be considered



Work on the plateau (>95% efficient, low systematics)



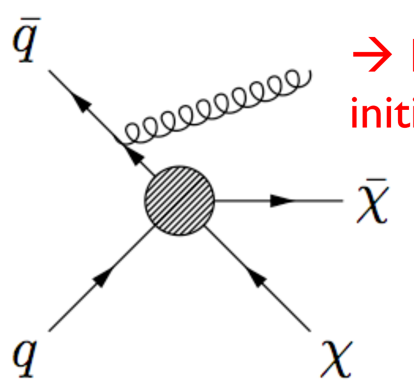
For 13 TeV
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerPublicResults#Public_results_from_signature_gr

- A real challenge to select state with soft MET/jets
- Must make use of all possible tools
  - e.g. muon spectrometer-only triggers for DV, H_T trigger, large R-jet triggers

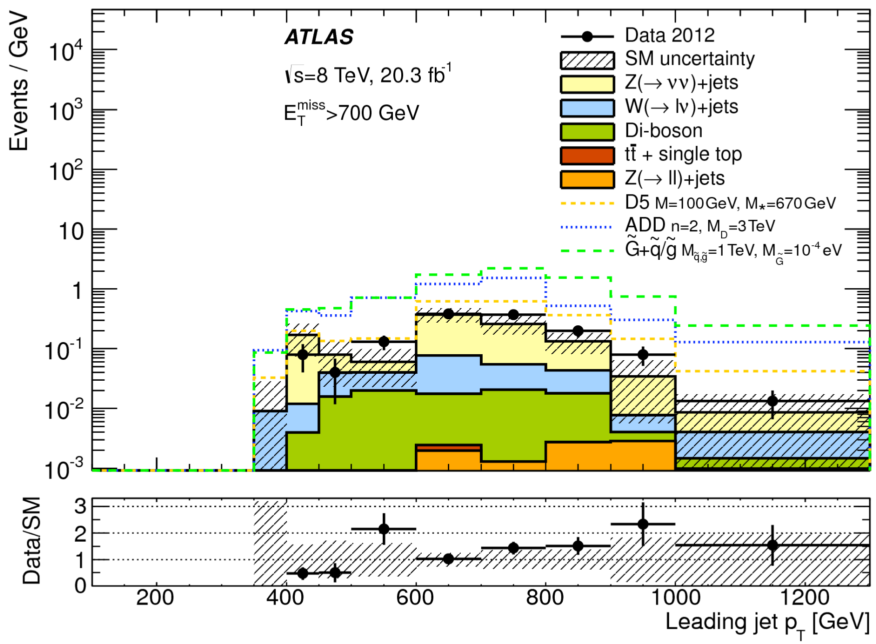
ISR jets for trigger

- SUSY scenarios where “initial” and “final” sparticles present small mass difference (compressed spectra) might be difficult to trigger on
- Use handles: Initial State Radiation jets
  - Events selected have large MET (recoil system) and possibly other soft decay products (e.g. leptons). **Typical examples:**
  - Dark Matter searches in mono-jet topology:

Eur. Phys. J. C (2015) 75:299



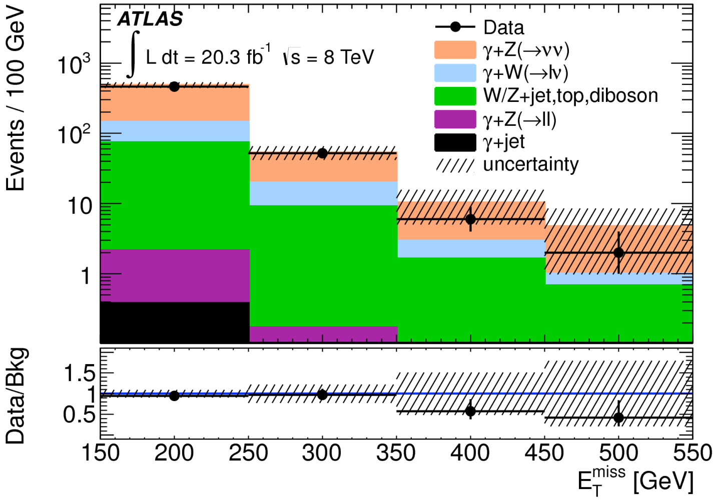
→ Energetic jet in initial state

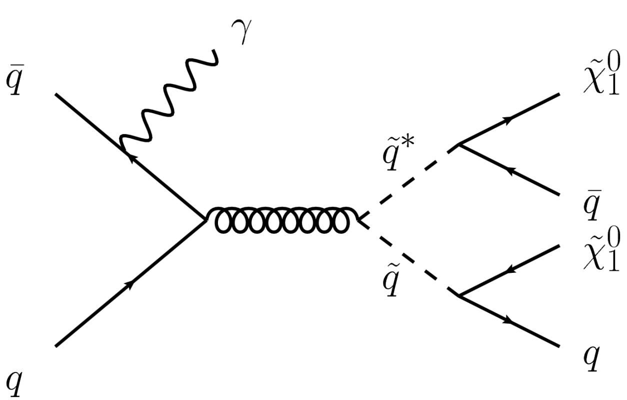


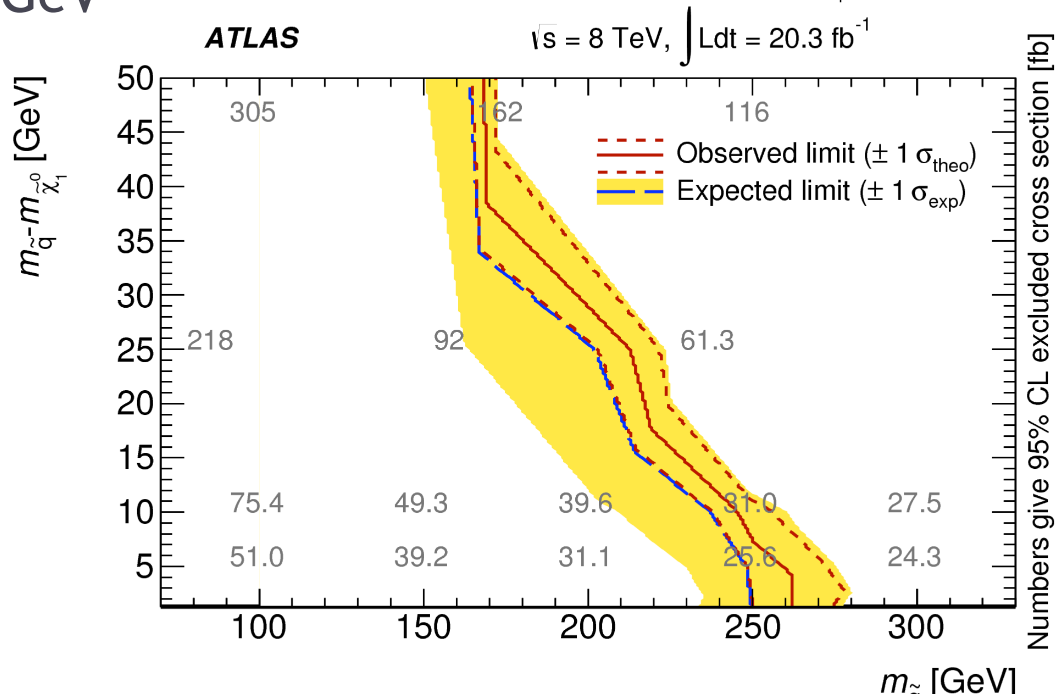
Main challenge: getting ISR-modeling in MC simulation for signal and background

Photons to "trigger" compressed scenarios

- Radiated photons from initial-state or final-state quarks or from intermediate squarks might allow to explore very compressed region in SUSY
- Photon+Missing E_T search:
  - Reach as low as ΔM ~ 1 GeV



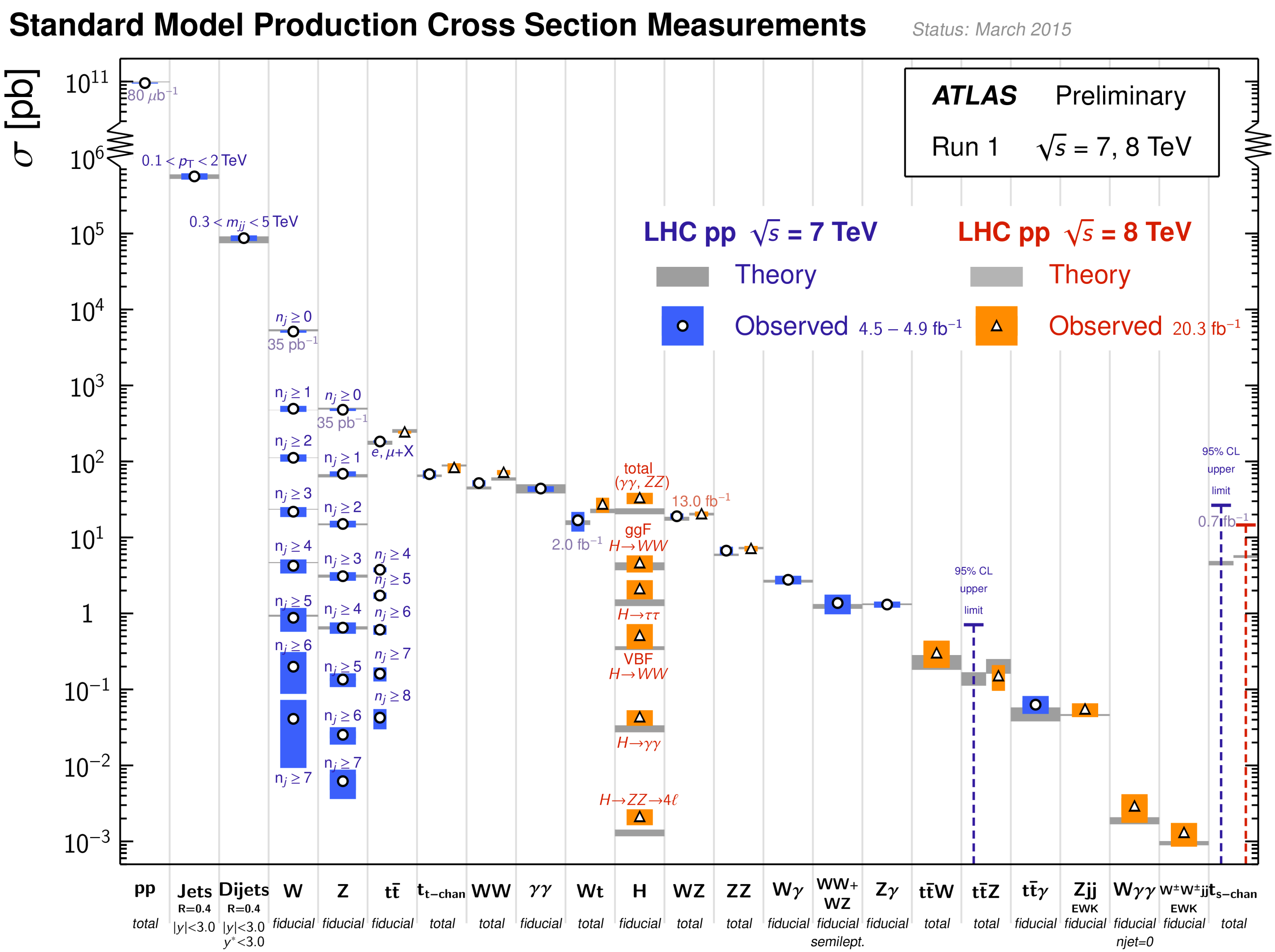




Phys. Rev. D 91, 012008 (2015)

The hunt for SUSY – Step 2: deal with the SM

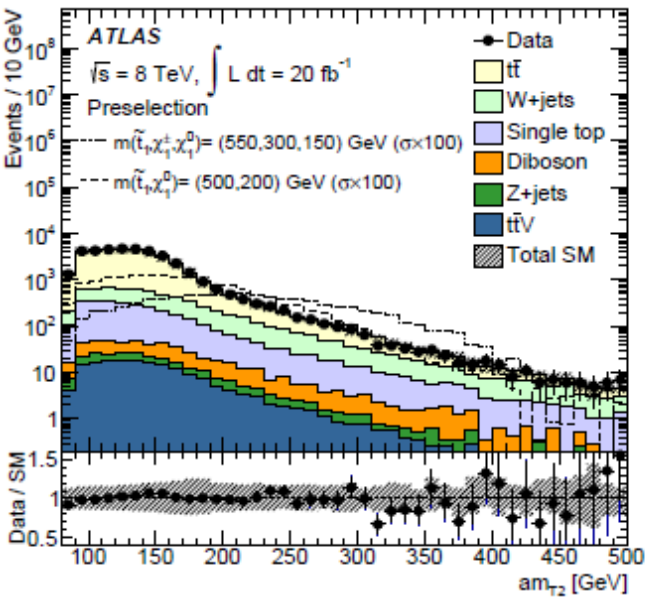
SM processes measured at ATLA with extremely high precision



The hunt for SUSY – Step 2: deal with the SM

- Need to exploit at best the expected features of targeted SUSY events: e.g. for prompt production and decays, the kinematic phase space of interest is usually different from SM measurements (tail at high p_T)
- **Basic tools**
  - Jets, b-jets, leptons (including taus)
  - E_T^{Miss} (in RPC SUSY, from the LSPs)
- **Complex tools**
  - Used as discriminating quantities
  - Meff = E_T^{Miss} + Σ of jets (leptons) p_T, $H_T = \Sigma\, p_T$, transverse mass m_T, m_{T2}, am_{T2}, m_{CT}, α_T, Razor …

often developed specifically for SUSY searches



The hunt for SUSY – Step 2: deal with the SM

- Various general approaches for ultimate bkg determination and estimate of systematics:

SM background with large cross section and "fakes"

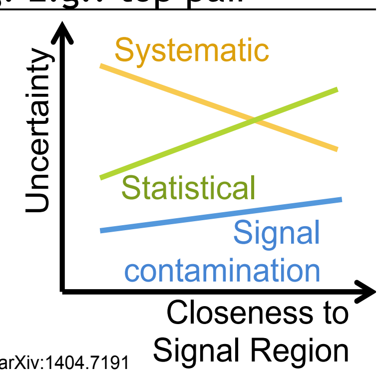
→ *Data-driven methods: E.g.*

• 'Jet Smearing' for multijet or Z+jets background due to fake E_T^{Miss}
• 'Matrix Method' for misidentified leptons
• New ideas depending on analysis to reduce systematics: e.g. multijet template method for RPC and RPV multijet searches.

For "Irreducible" and large SM backgrounds (real MET)

→ *'Semi' data-driven methods*

- Normalisation done in dedicated Control Regions (CR) enriched in specific bkg. E.g.: top pair production, W+jets…
- Compromise between closeness to SR, statistics, handling of uncertainties



For "Irreducible" and rare SM backgrounds

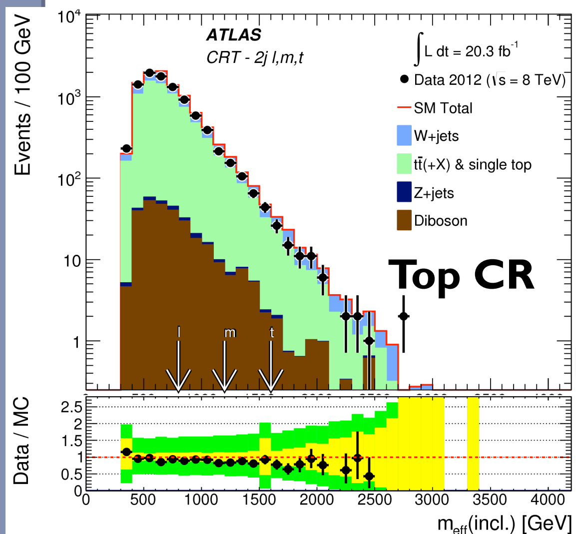
→ *Monte Carlo predictions*

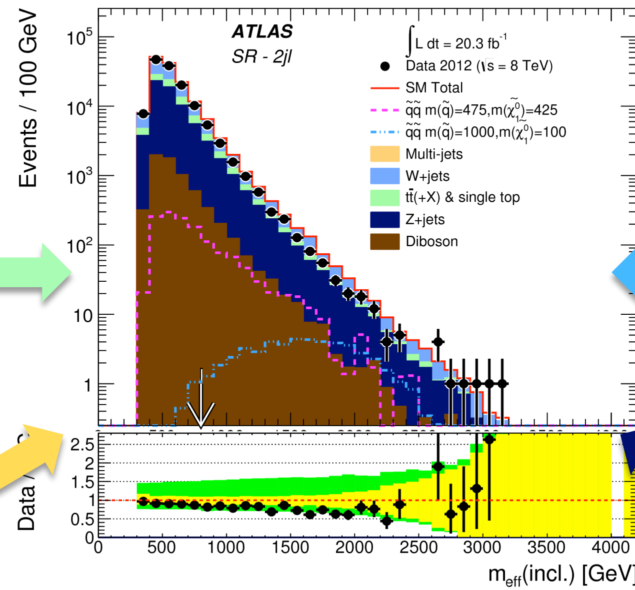
Validation of Background estimates in dedicated samples

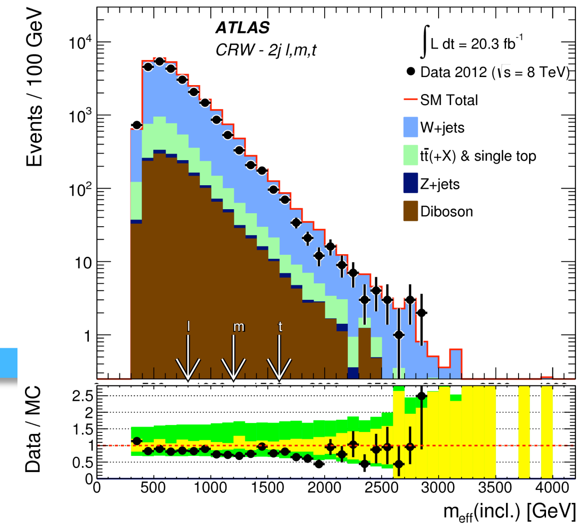
Example: 0-lepton inclusive 2-6 jets

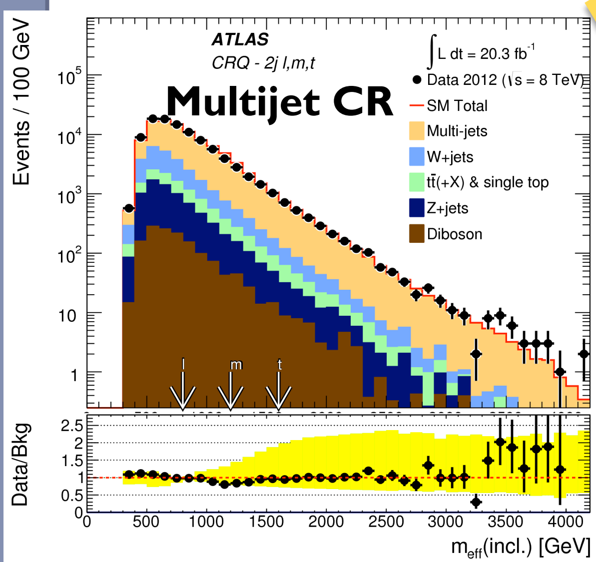
- Searches in inclusive jets + E_t^{miss} events

W+jets CR

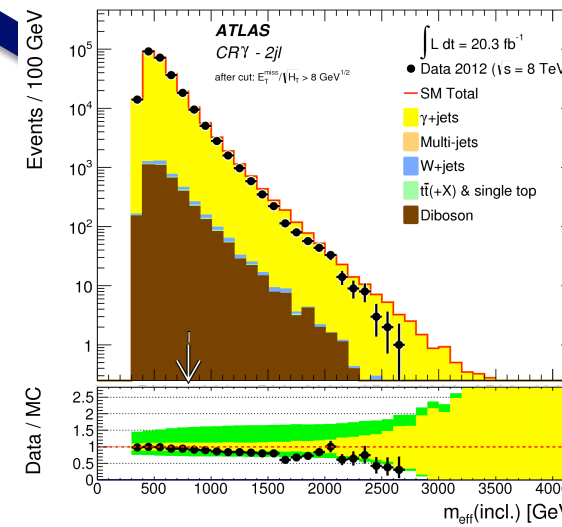








Normalizations obtained in all CR and extrapolated to signal regions simultaneously by combined maximum likelihood fit



γ+jets used for Z+jets CR

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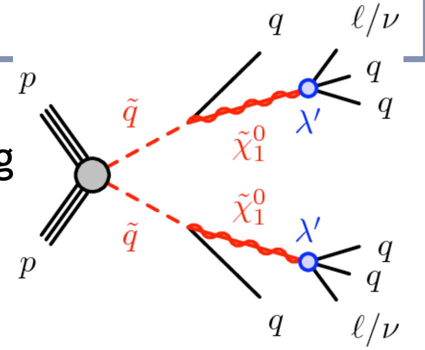
  transverse mass m_T, m_{T2}, am_{T2}, m_{CT}, α_T, Razor …
- **Special tools - examples**
  - **Long-Lived**: exploit the detector at best
    - Displaced Vertex (DV)
    - Non-prompt and delayed photons

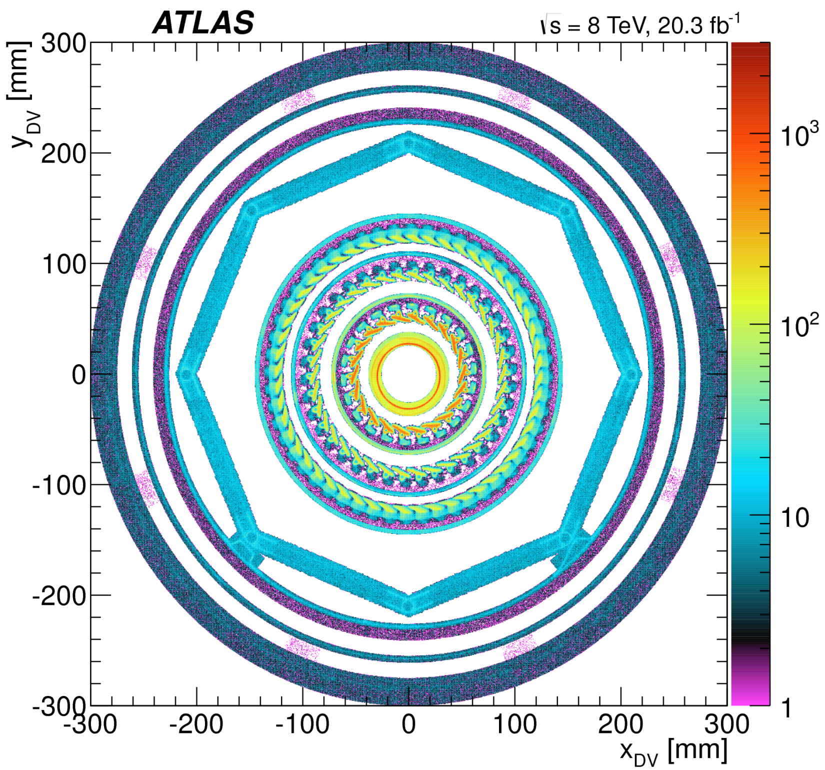
arXiV:1504.05162

Long-Lived particles: Displaced vertex

- Particles with average decay lengths of a few cm could decay within the tracking detector to give rise to displaced vertices.
- **DV:** 2 opposite sign leptons (ee, eμ, μμ) or multi-track
- Various combinations of DV+X: DV+e/μ; DV+jets; DV+MET

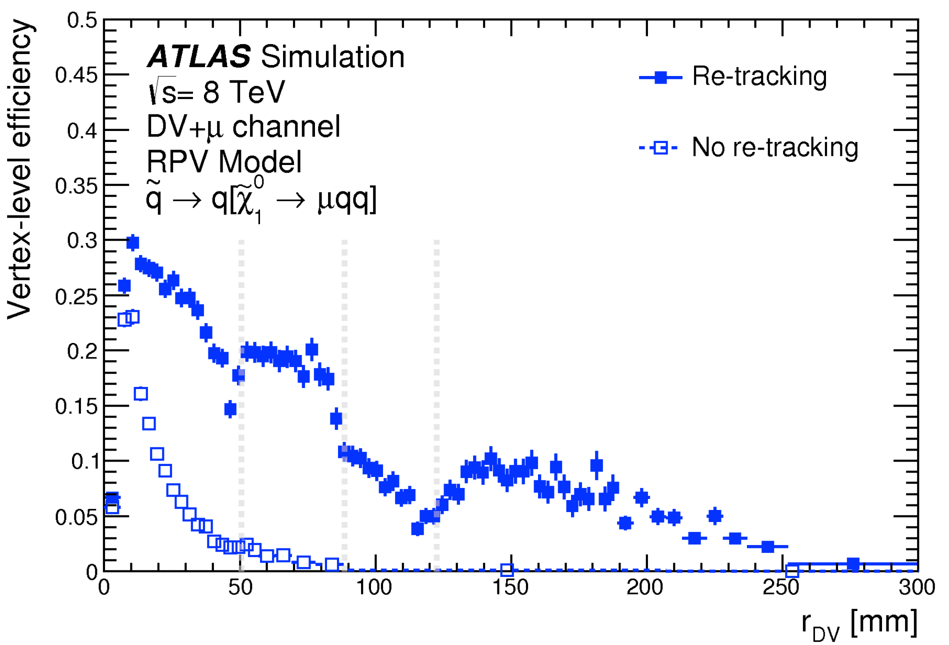
e.g





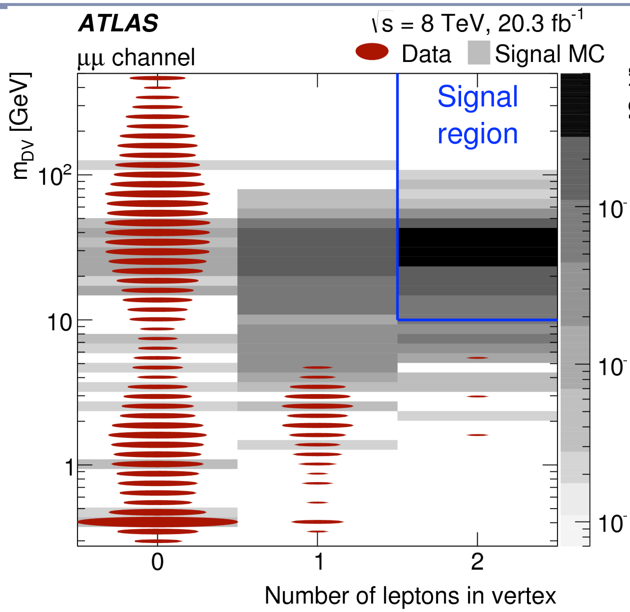
Veto vertices in dense material regions. Perform re-tracking →

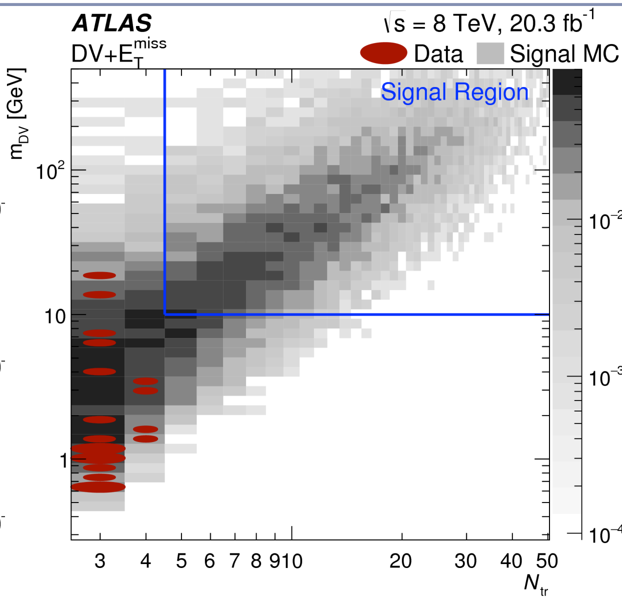
Look for high-mass, high-track multiplicity vertices or for di-lepton pairs forming a high-mass vertex



http://arxiv.org/abs/1504.05162

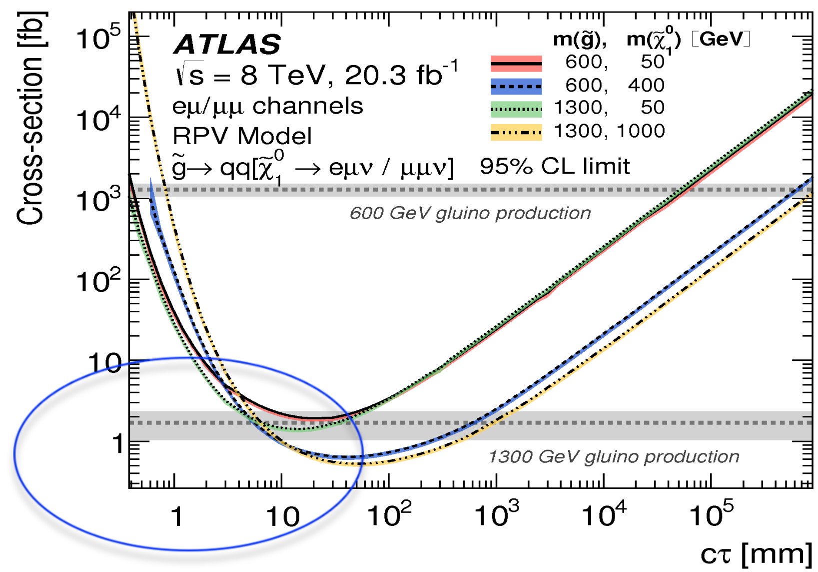
Results for DV analysis





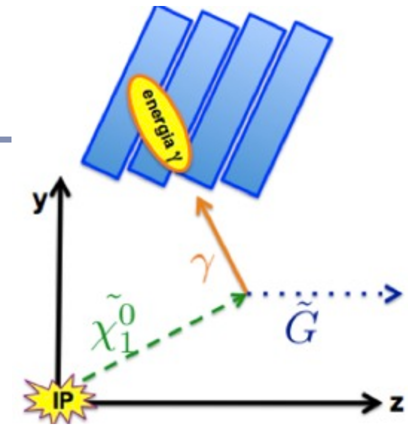
- Very powerful type of analyses → Low background
- Mostly 'accidental' crossing of low-mass or low-Ntrack vertex
- **No events found**

Results constraint various scenarios with non-prompt gluino/squark decays



Sensitivity here recovered with dE/dx analysis (see back-up)

non-prompt and delayed photons

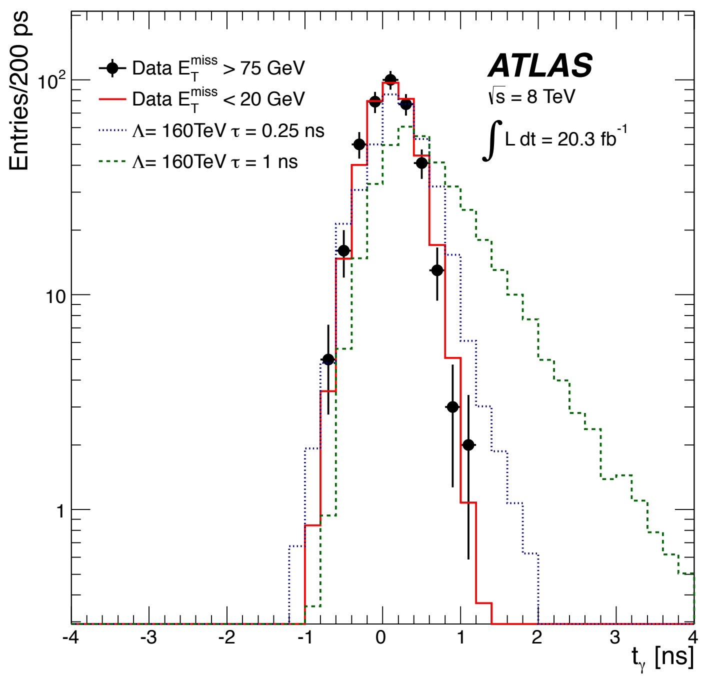


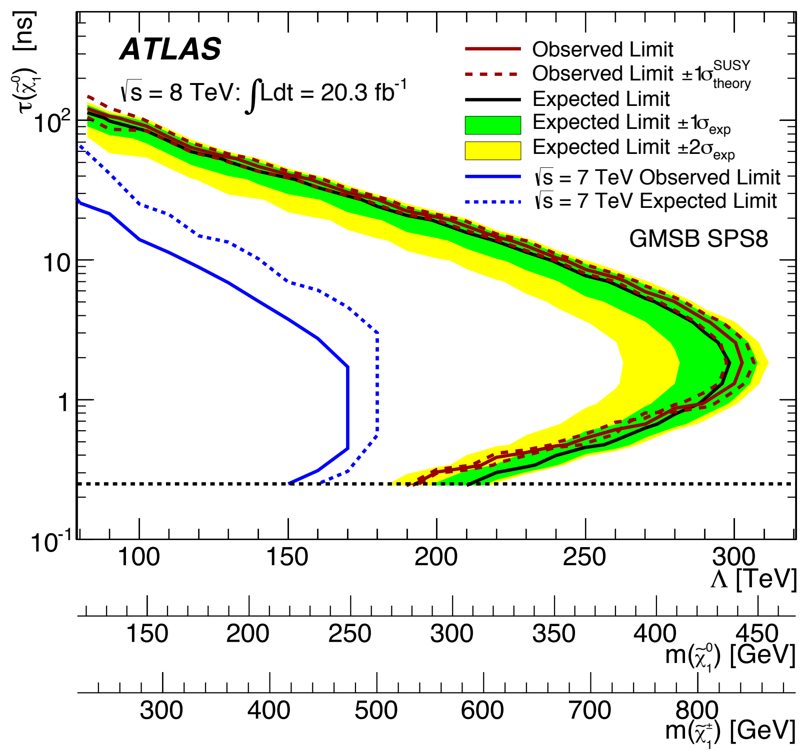
- **ATLAS:** Di-photon + Missing E_T final states: one prompt, one non-prompt photon
  - Exploit ATLAS capability to make precise measurements of **flight direction and time**

arXiV:1409.5542

Target:
Strong and EWK production in Gauge Mediated Scenarios (GMSB)

$$\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$$





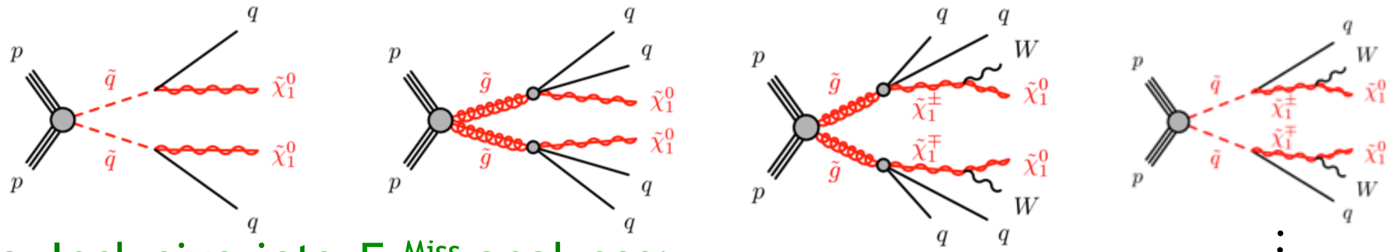
SUSY at the end of Run 1:
gathering everything together

- Strong production searches
- Third generation searches
- EWK SUSY searches

→ Constraints in case of prompt and Long-Lived particles

Highlights on squark/gluino production

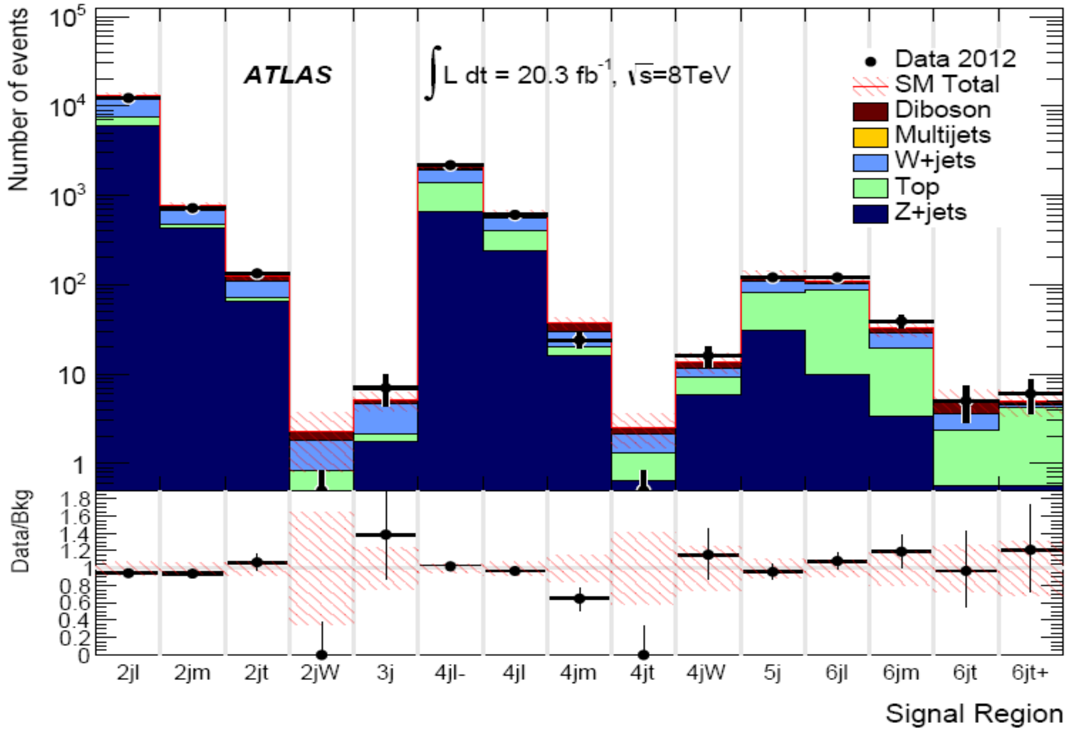
- Possibly complex final states, great variety of signatures → main target of inclusive searches with several jets, possibly leptons and large E_T^{Miss}



- *Example:* Inclusive jets+E_T^{Miss} analyses:

ATLAS: 1405.7875

- Minimum Jet multiplicity (2 to >=6j)
- Use **Effective Mass** (M_{eff}= E_T^{Miss} +Sum p_T jets)
  - Thresholds from 800 GeV to 2.2 TeV
- But also: presence of boosted W→qq'
  - Also merged products → jet mass (60-100 GeV)



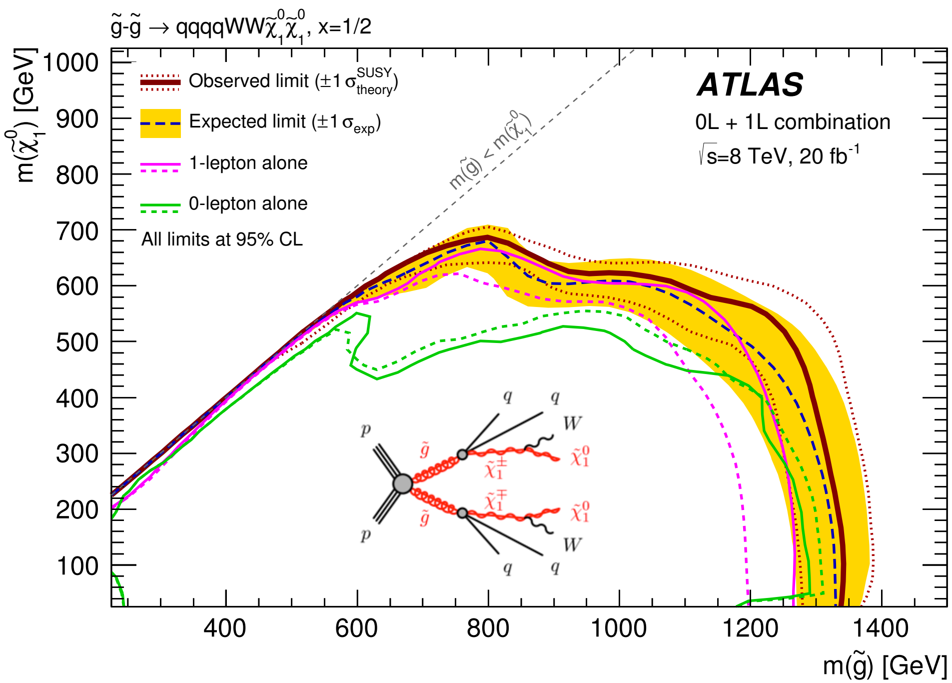
ATLAS Summary paper on strong production

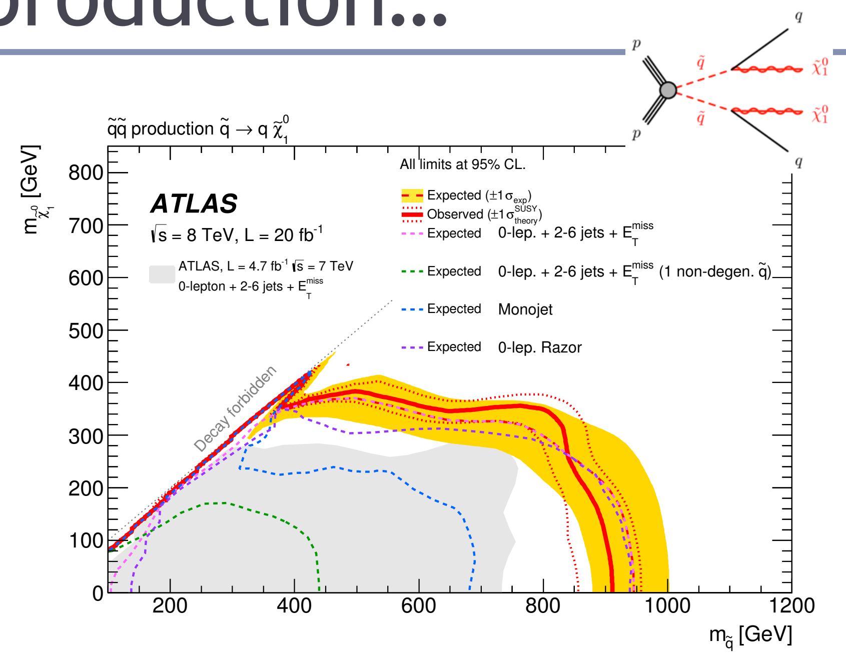
- http://arxiv.org/pdf/1507.05525v1.pdf
- Several simplified and phenomenological models considered – results from 0l, 1l, multi-bjets and tau-based analyses reinterpreted and combined, plus new analyses added

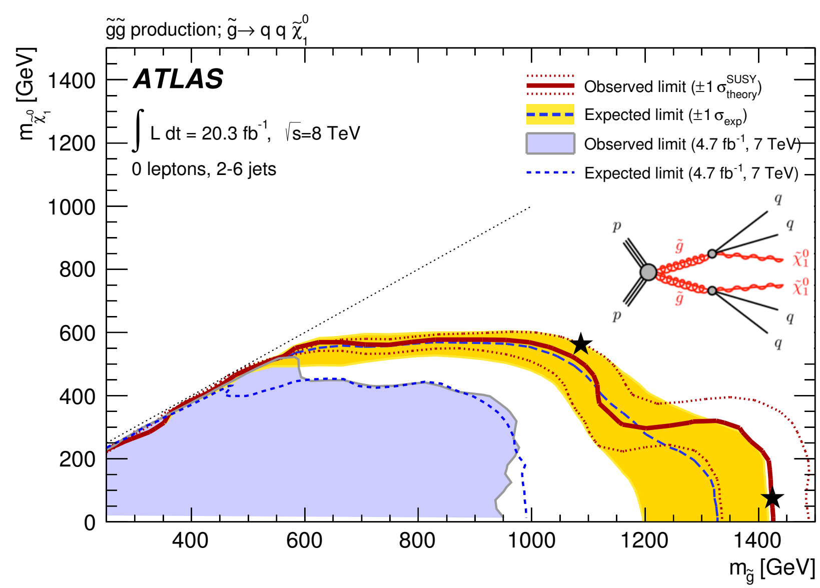
Short analysis name and corresponding reference	Acronym	Signal region name
Monojet [21]	MONOJ	M1, M2, M3
0-lepton + 2–6 jets + E_T^{miss} [20]	0L	2jl, 2jm, 2jt, 2jW, 3j, 4jW, 4jl-, 4jl, 4jm, 4jt, 5j, 6jl, 6jm, 6jt, 6jt+
0-lepton + 4–5 jets + E_T^{miss} (⋆)	0L	4jt+, 5jt
0-lepton + 7–10 jets + E_T^{miss} [22]	MULTJ	8j50, 9j50, 10j50 (multi-jet+flavour stream), 7j80, 8j80, (multi-jet+flavour stream), 8j50, 9j50, 10j50 (multi-jet+M_J^{Σ} stream)
0-lepton Razor (•)	0LRaz	SR_{loose}, SR_{tight}
1-lepton (soft+hard) + jets + E_T^{miss} [23]	1L(S,H)	3-jet/5-jet/3-jet inclusive (soft lepton), 3-jet/5-jet/6-jet (hard lepton)
1-lepton (hard) + 7 jets + E_T^{miss} (⋆)	1L(H)	7-jet
2-leptons (soft) + jets + E_T^{miss} [23]	2L(S)	2-jet (soft dimuon)
2-leptons (hard) + jets + E_T^{miss} [23]	2LRaz	≤ 2-jet/3-jet
2-leptons off-Z [24]	2L-offZ	SR-2j-bveto, SR-2j-btag, SR-4j-bveto, SR-4j-btag, SR-loose
Same-sign dileptons or 3-leptons + jets + E_T^{miss} [25]	SS/3L	SR3b, SR0b, SR1b, SR3Llow, SR3Lhigh
Taus + jets + E_T^{miss} [26]	TAU	1τ (Loose, Tight), 2τ (Inclusive, GMSB, nGM, bRPV), $\tau + l$ (GMSB, nGM, bRPV, mSUGRA)
0/1-lepton + 3b-jets + E_T^{miss} [27]	0/1L3B	SR-0l-4j-A, SR-0l-4j-B, SR-0l-4j-C, SR-0l-7j-A , SR-0l-7j-B, SR-0l-7j-C, SR-1l-6j-A, SR-1l-6j-B, SR-1l-6j-C

A few results on prompt production…

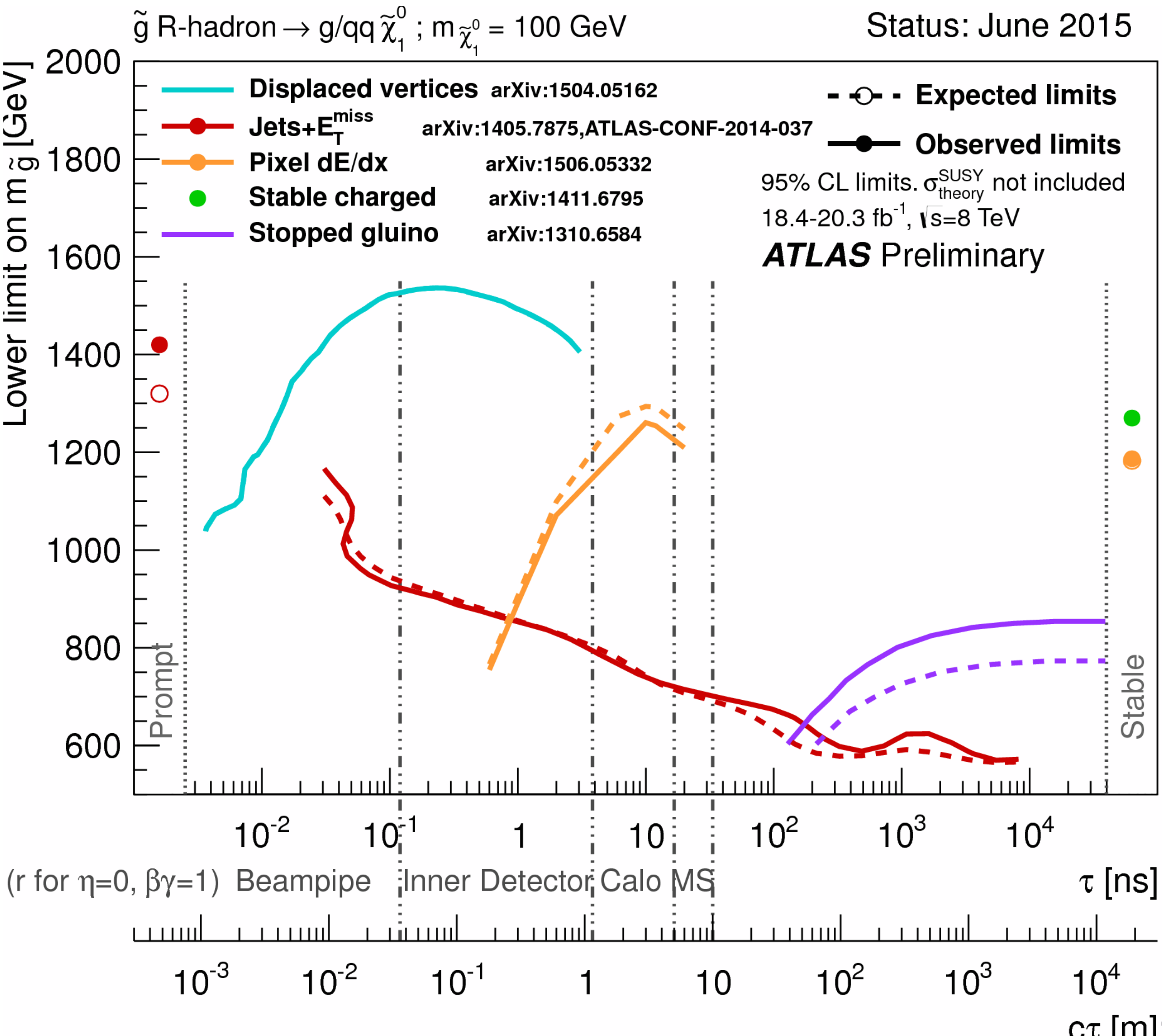
- Several constraints placed under various hypothesis of mass hierarchy, relevant to set the stage for Run 2 searches

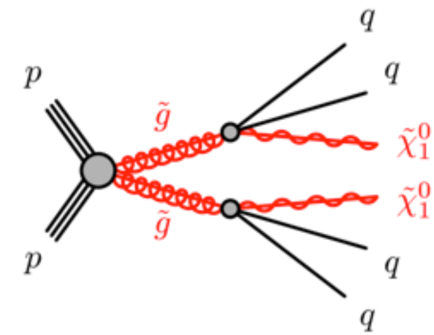






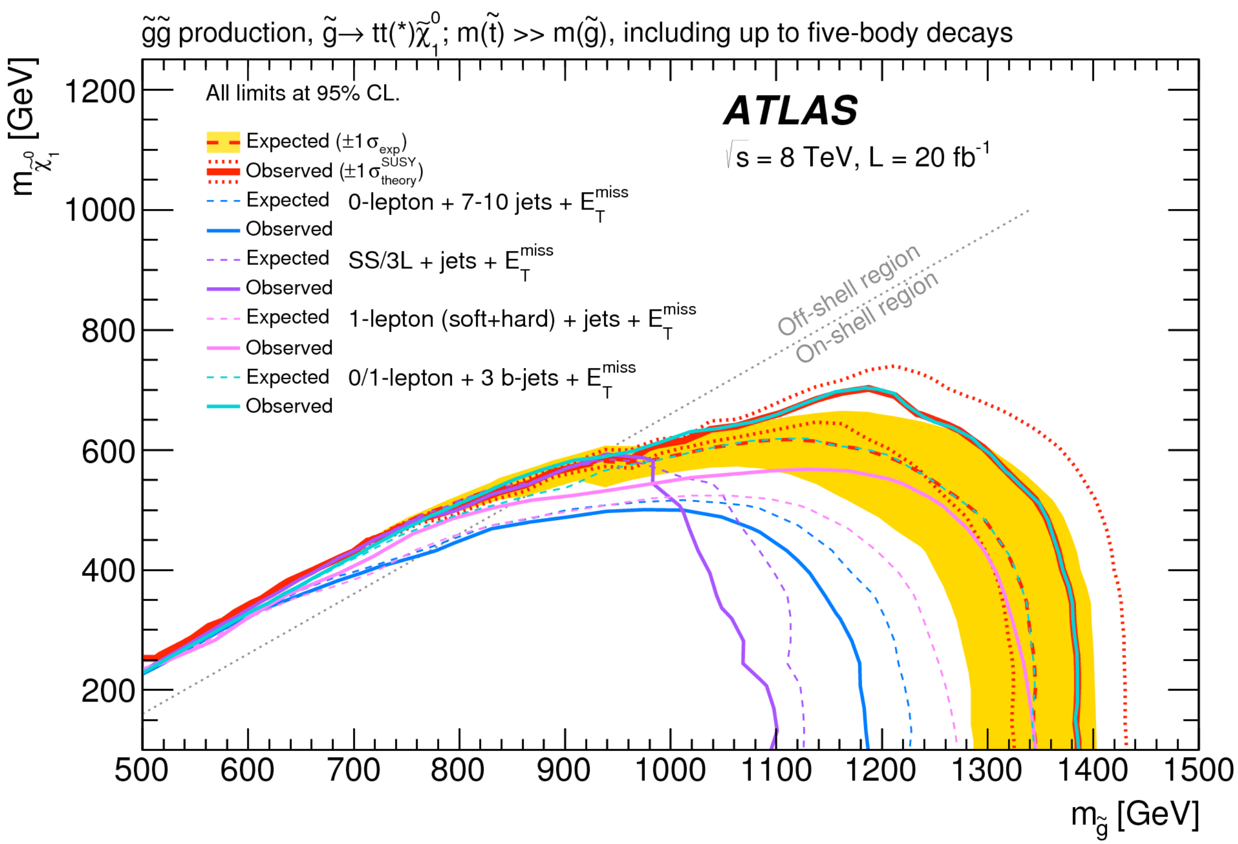
… and extending the life range !

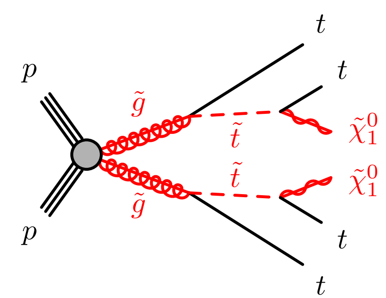




Gluinos and third generation

- One of the most targeted process: gluino in top pair
  - Natural scenarios: 1st and 2nd generation squarks are very heavy, only gluinos and stop accessible …
- Consider off-shell decays of top quarks as well!





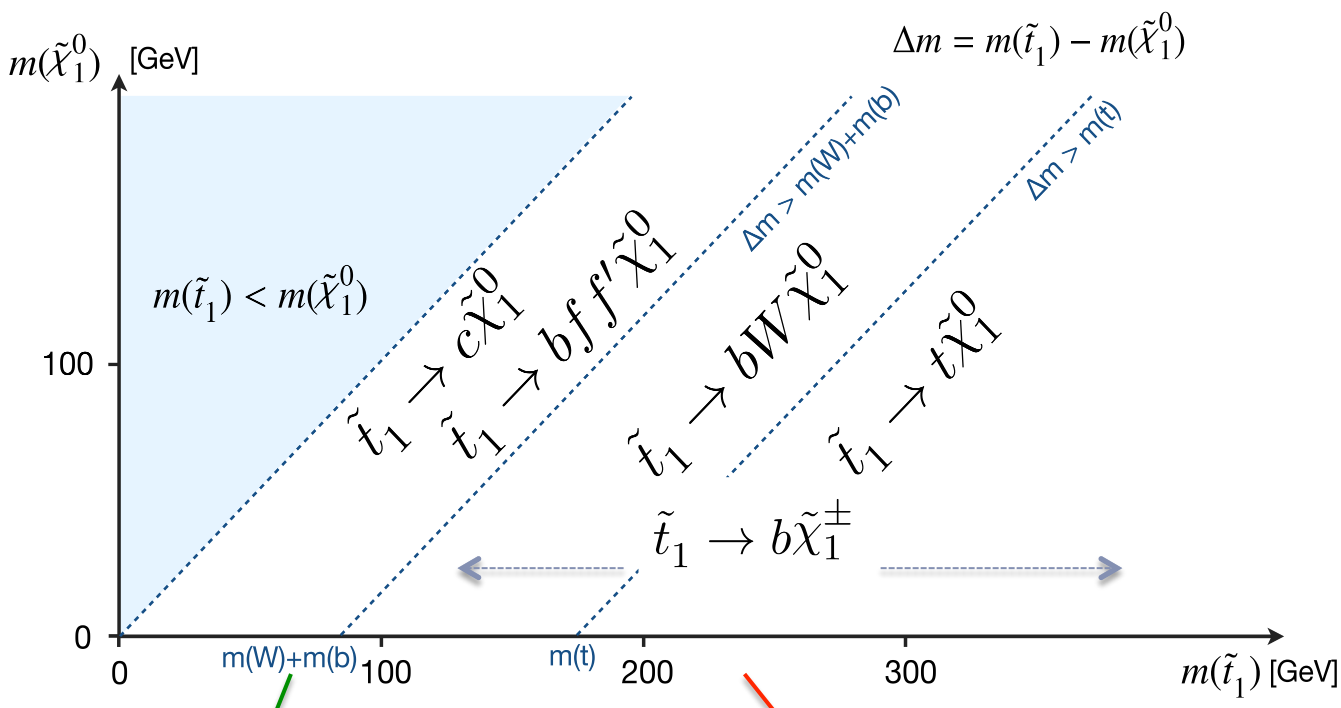
Constraints up to 1.4 TeV gluino mass…

What if gluinos are not there?

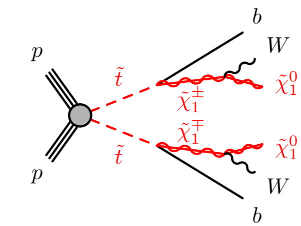
Direct third generation squark pair production

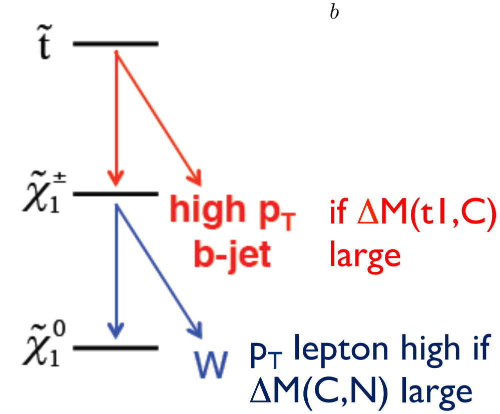
- Stop and sbottom have an important role in regularizing the higgs mass
- Several complex decay modes possible and final states analyzed!

Top squarks (stop)



For decay modes involving charginos:



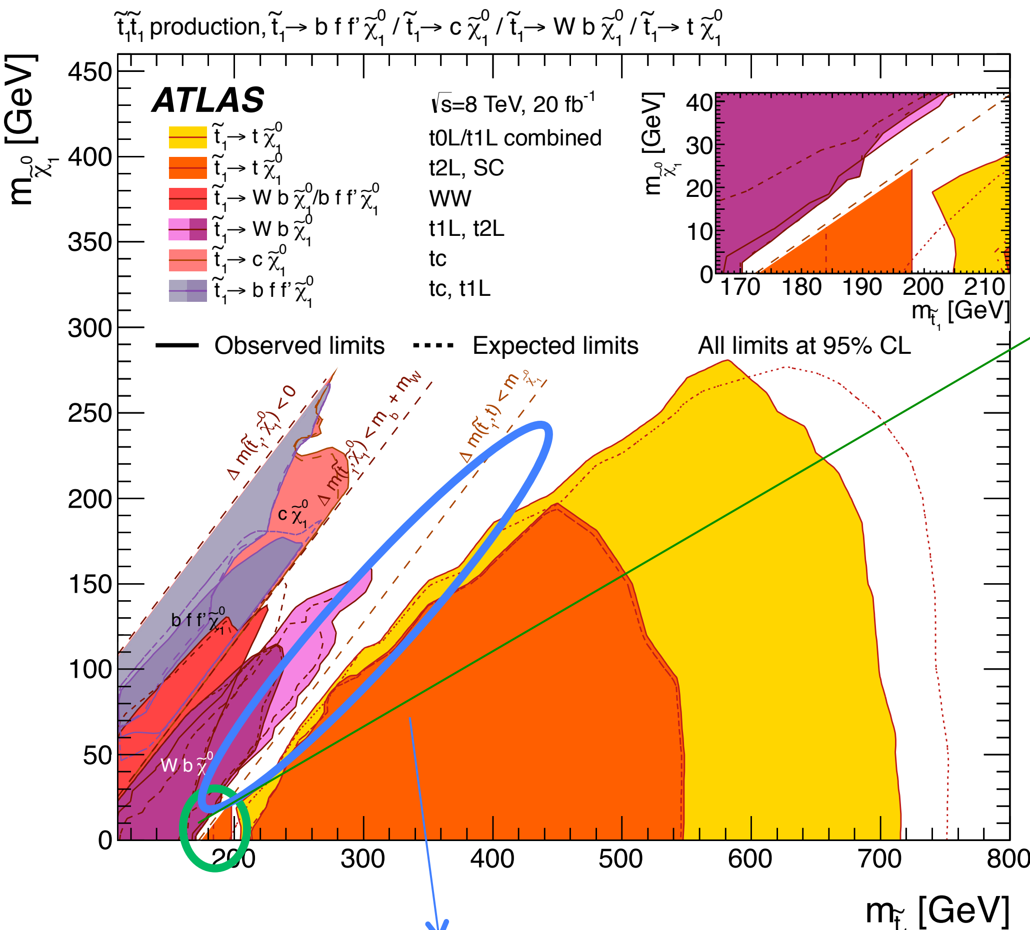


"Compressed" scenarios:
- mono-jet
- Soft-leptons

Exploit 0,1,2 leptons final states
Complex discriminating variables
Use boosted objects to reject SM top background

Top squark summary

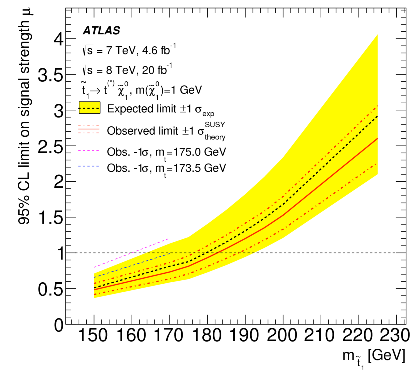
arXiv:1506.08616v1*



Also: M(stop) ~ m(top)+m(neut1): Compressed regions indirectly accessed via stop2 searches: Stop2 → stop1 + Z/higgs, Stop1 → t + Neut1

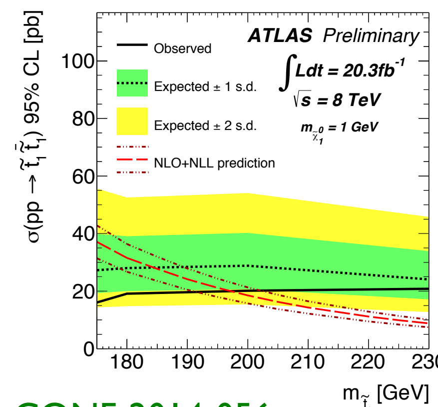
M(stop) ~ m(top):

- Constraints from σ(tt̄) measurement



Onshell & offshell stop

- Constraints from top-antitop spin correlations (exploit that stop is scalar)



ATLAS-CONF-2014-056

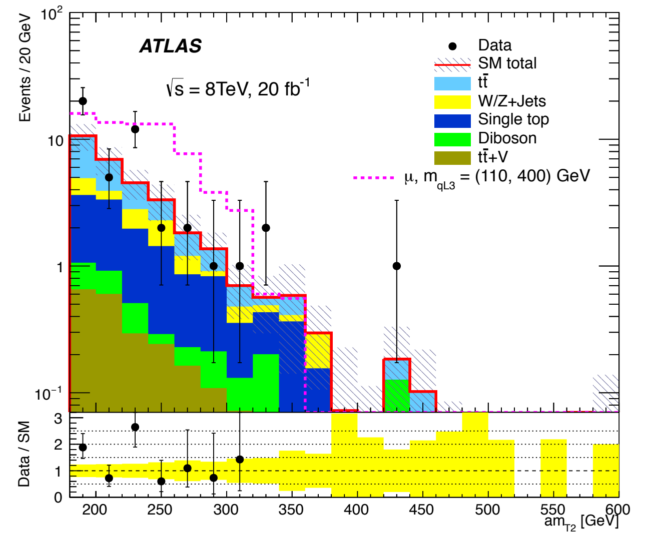
full exploitation of Run 1 results: new analyses

- **Stop/sbottom** in compressed scenarios
  - Competing BR for $\tilde{t}_1 \to t\tilde{\chi}_1^0, \tilde{t}_1 \to b\tilde{\chi}_1^\pm$
    $\tilde{b}_1 \to b\tilde{\chi}_1^0, \tilde{b}_1 \to t\tilde{\chi}_1^\pm$

$$\tilde{t}_1\tilde{t}_1 \to t\tilde{\chi}_1^0 b\tilde{\chi}_1^\pm \to tb\tilde{\chi}_1^0\tilde{\chi}_1^0 f f'$$

soft

1l+2b+MET final states



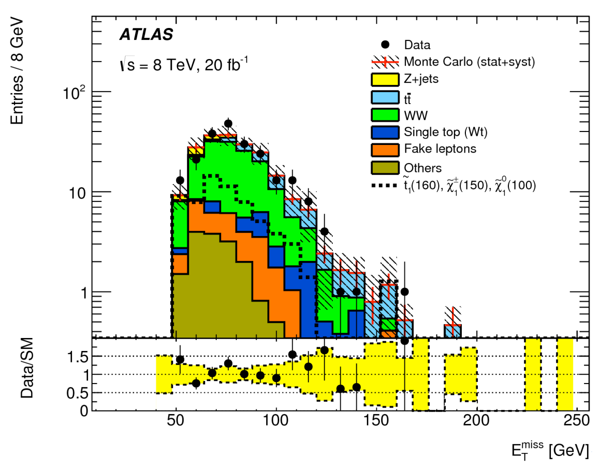
- **WW-like stop** (e.g. target: stop ~ 200 GeV, charg-neut ~10 GeV)
  - Inspired by WW cross section ‘excess’
  - Consider 2lepton Different-Flavor final states
  - WW normalization from data in CR
  - Dedicated variables used

$$\Delta X = \frac{(p_z(\ell_1) + p(\ell_2))}{\sqrt{s}}$$

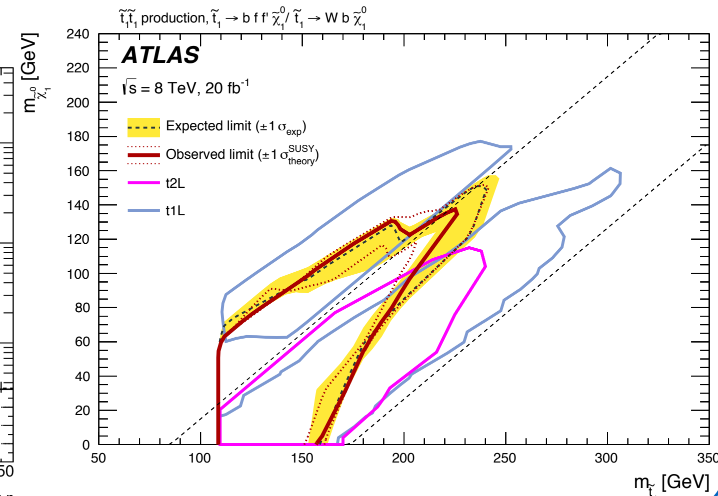
higher longitudinal boost for signal (gg initiated)

$$R_2 = \frac{E_T^{miss}}{E_T^{miss} + p_T(\ell_1) + p_T(\ell_2)}$$

higher for signal $(2\nu + 2\tilde{\chi}_0 + 2b)$



covering transition between 3-body and 4-body decays of light stop



full exploitation of Run 1 results: new analyses

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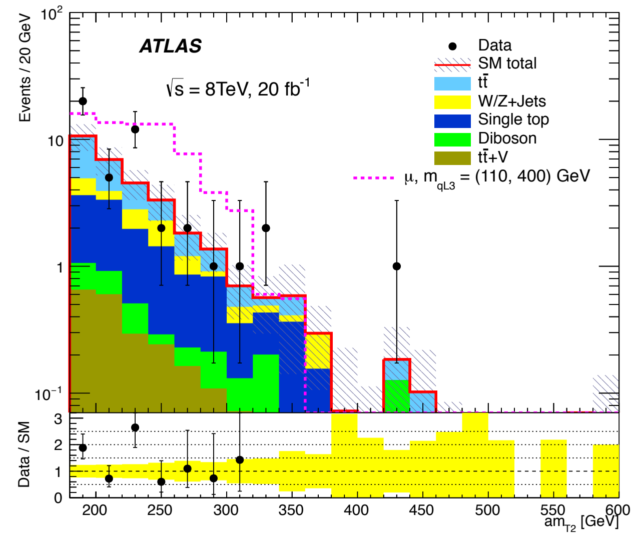
    $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$

$$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 b\tilde{\chi}_1^\pm \rightarrow tb\tilde{\chi}_1^0\tilde{\chi}_1^0 f f'$$

soft

1l+2b+MET final states



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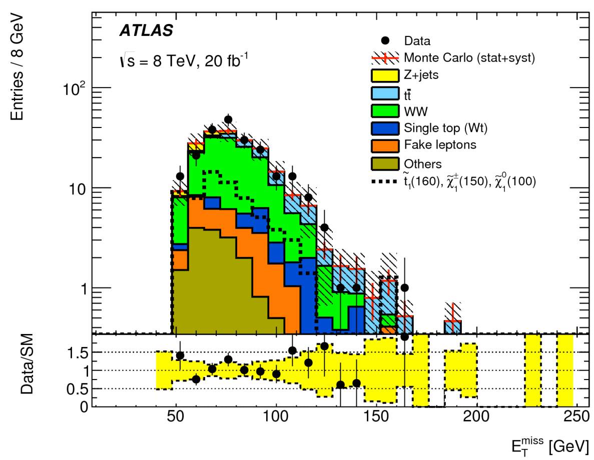
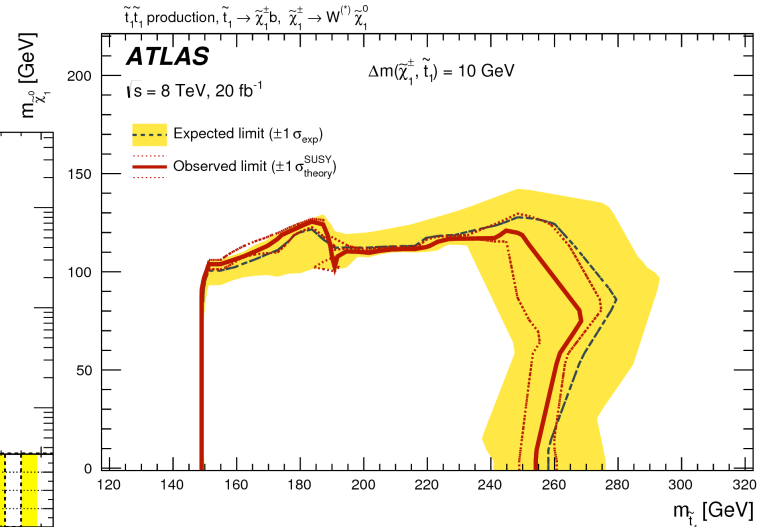
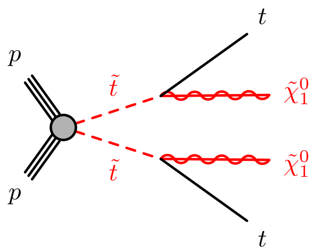
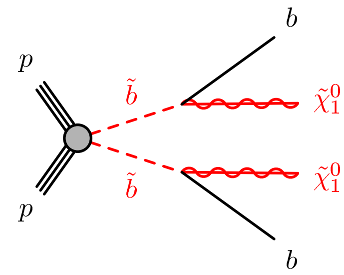


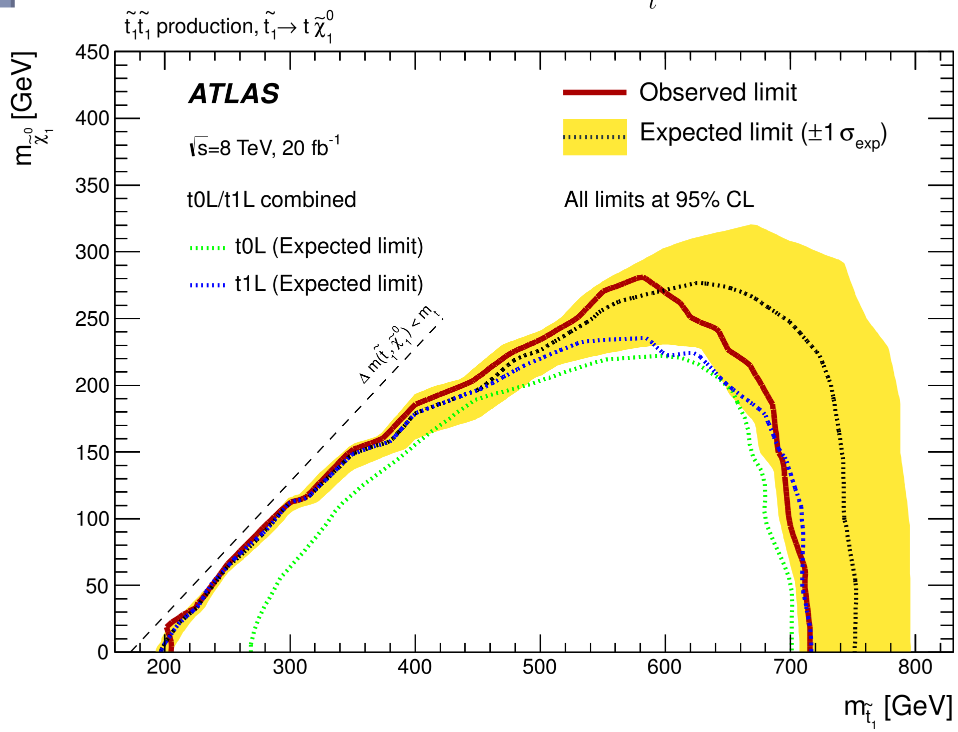


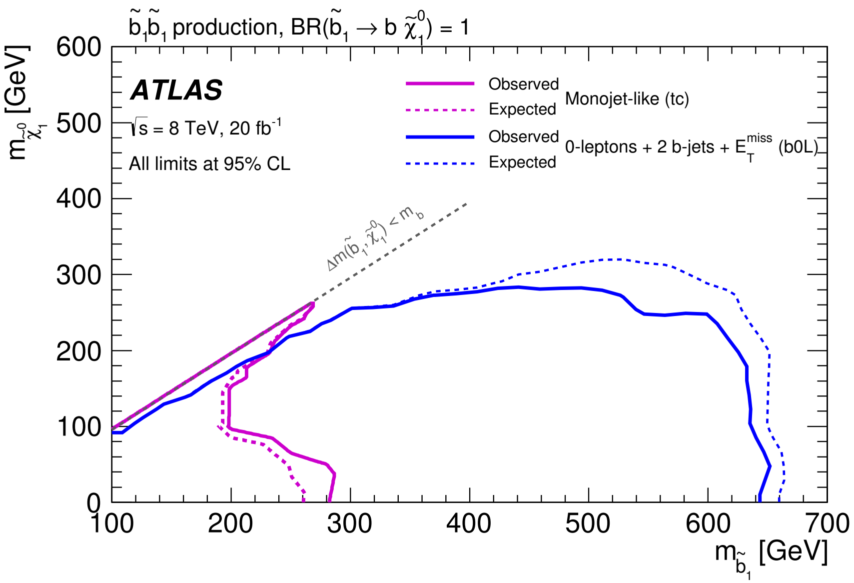
combinations on stop and sbottom

- Most stringent constraints from combination of various analyses



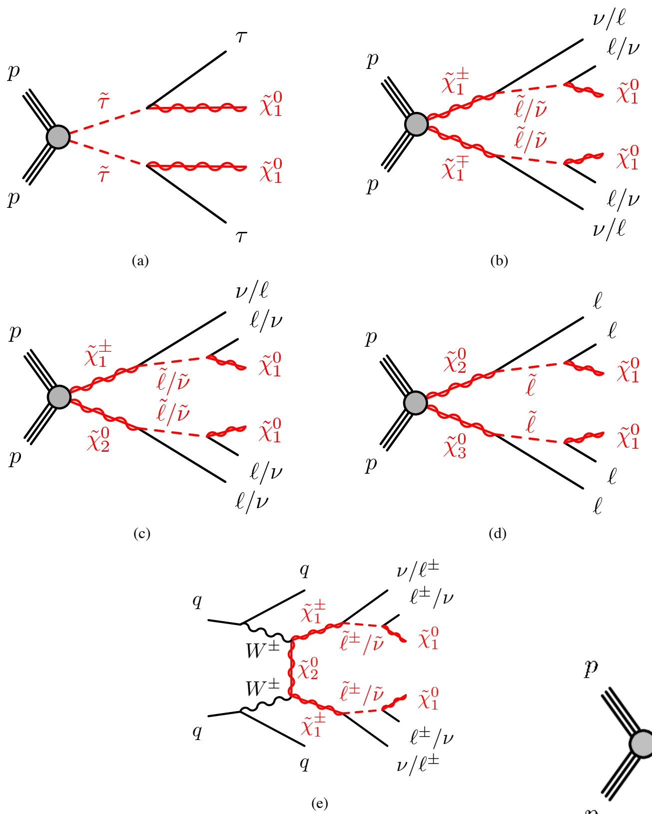


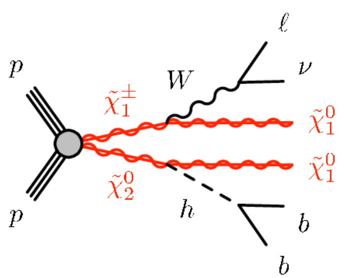


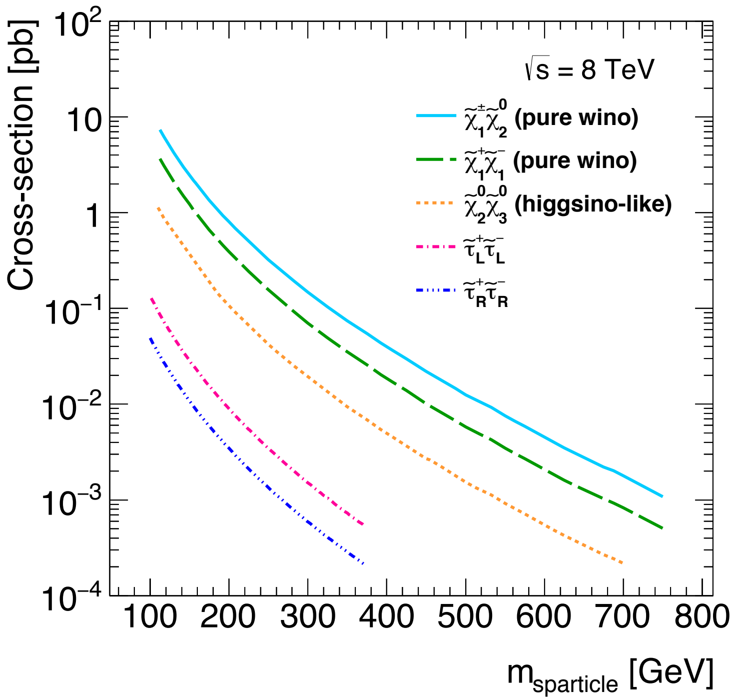


EWK chargino-neutralino production

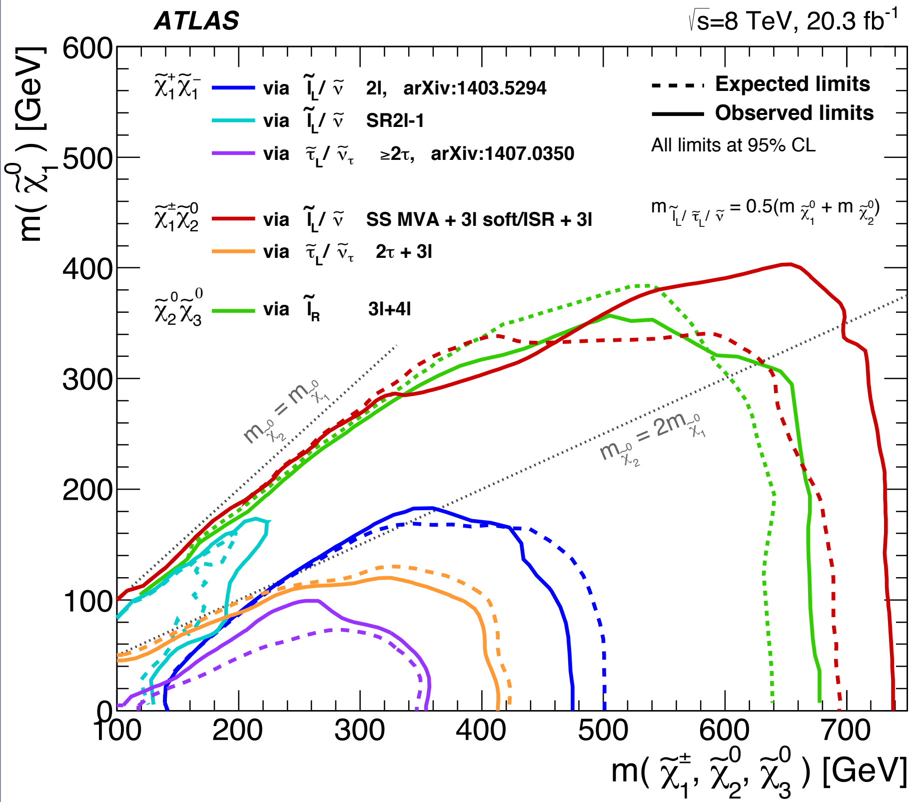
Mixture of super-partners of W,Z and Higgs (among them, the LSP) and sleptons (in particular, super-partners of taus) might be the only accessible SUSY particles: EWK SUSY searches are fundamental (and very challenging)!

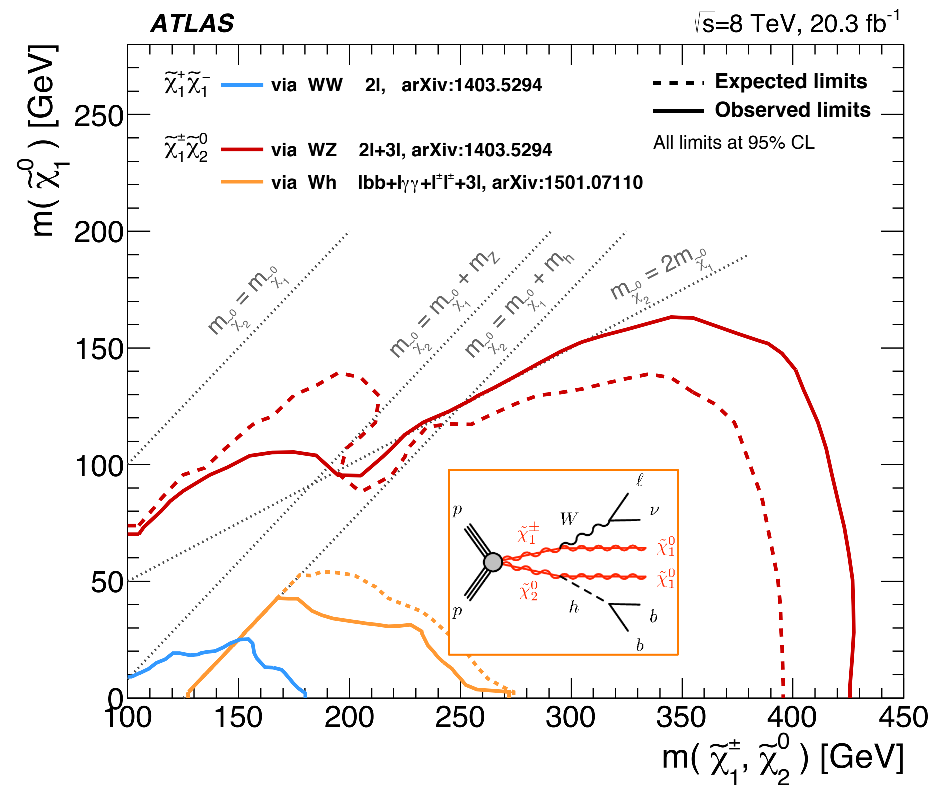






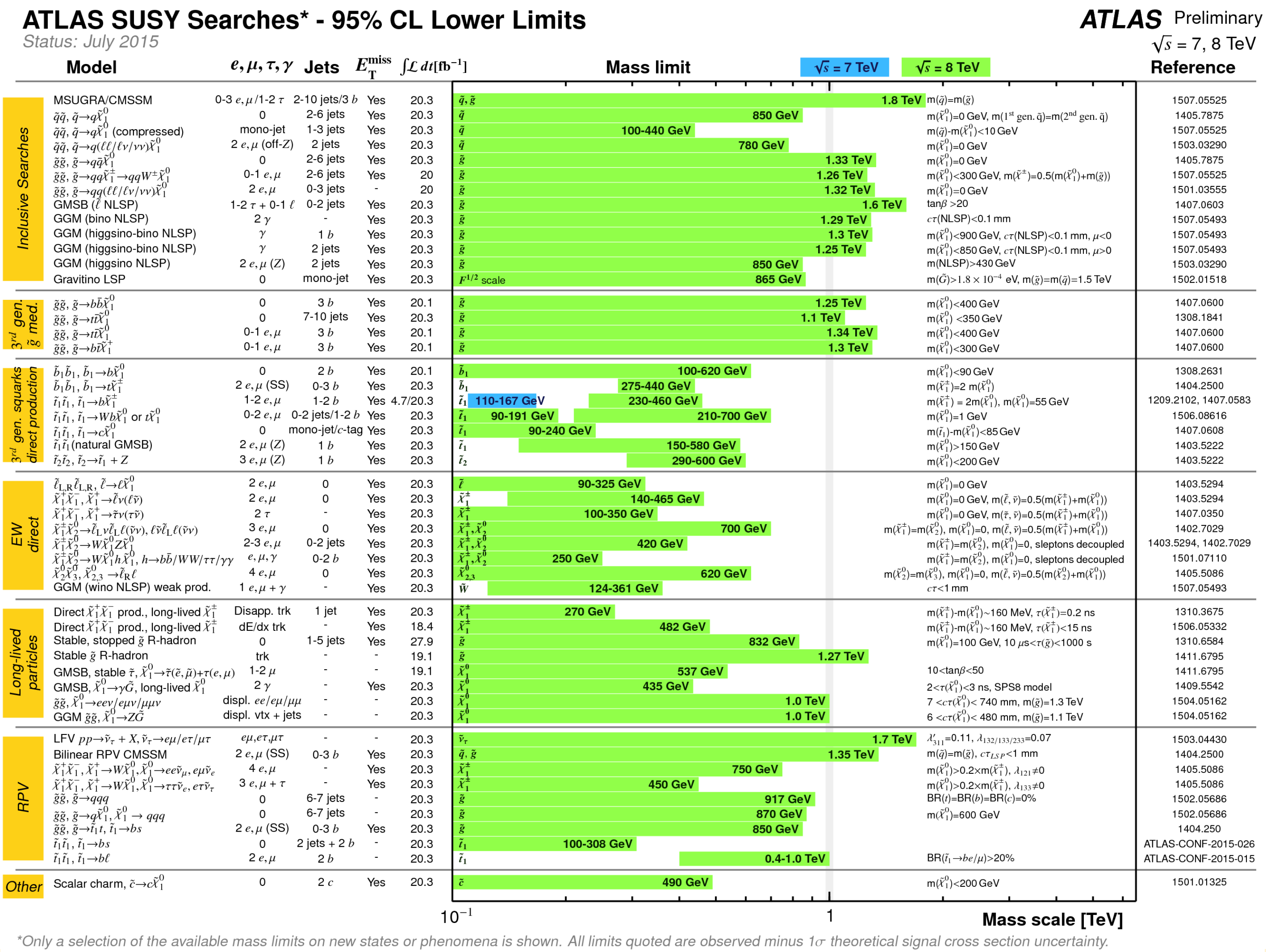
EWK chargino-neutralino production





- Constraints on chargino/next-to-lightest neutralinos up to 740 GeV (if decays are mediated by sleptons); up to ~ 430 GeV for WZ-decays; little or no constraints for compressed scenarios → a challenge for Run II
- **Great emphasis** on decay channels involving the higgs boson

Grand summary for exclusion of SUSY



Stringent constraints beyond TeV-scale ….

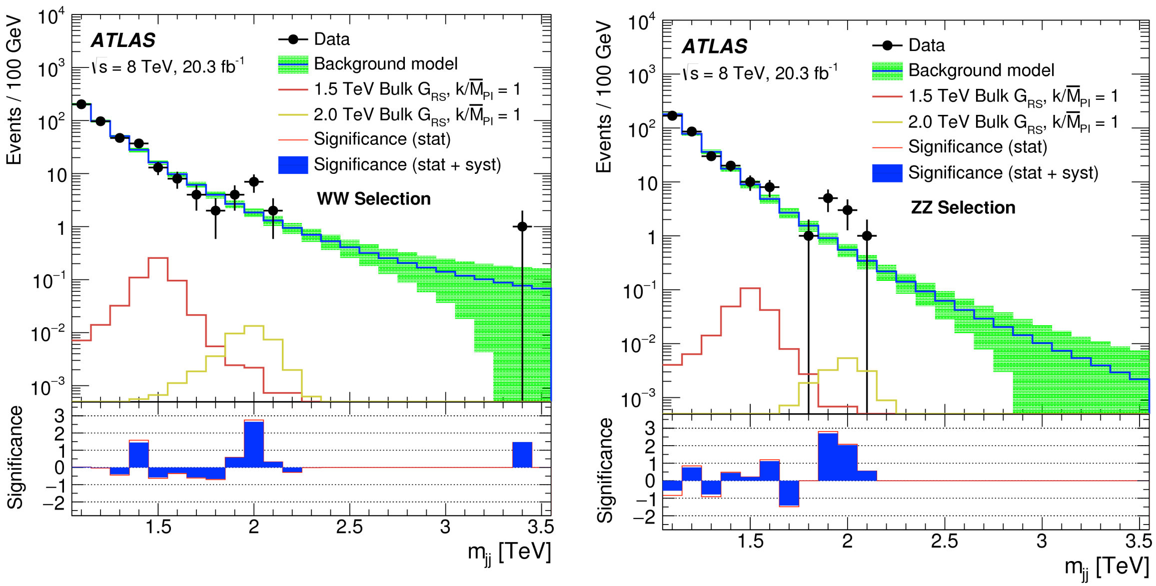
Exciting hints?

Not unexpectedly, a few of these searches ended up showing some anomaly, something to check in Run-2

- 2lepton edges
- 2lepton Z-boson regions
- Multi b-jets + Missing E_T

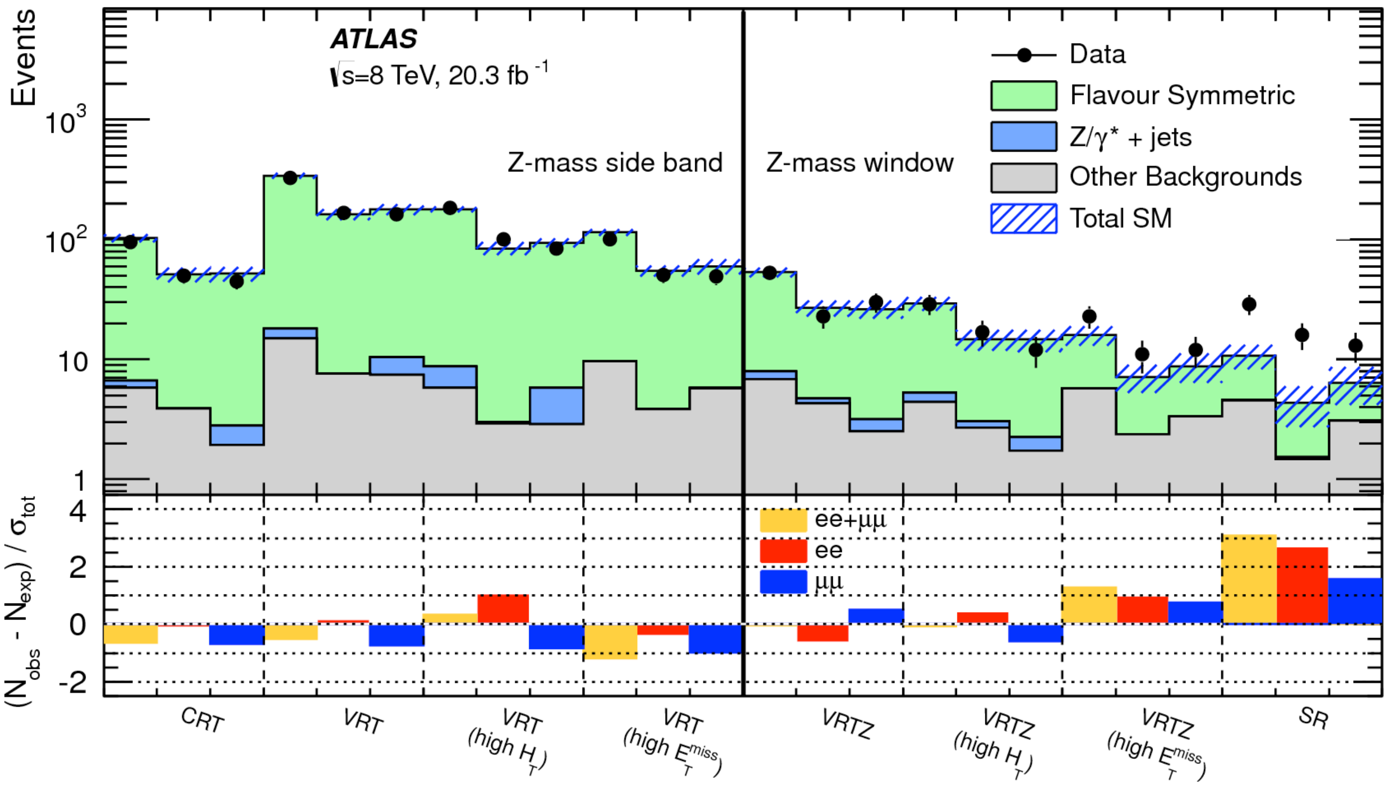
Look at ATLAS and CMS together

A note on its own ..
- but won't talk about it ☺

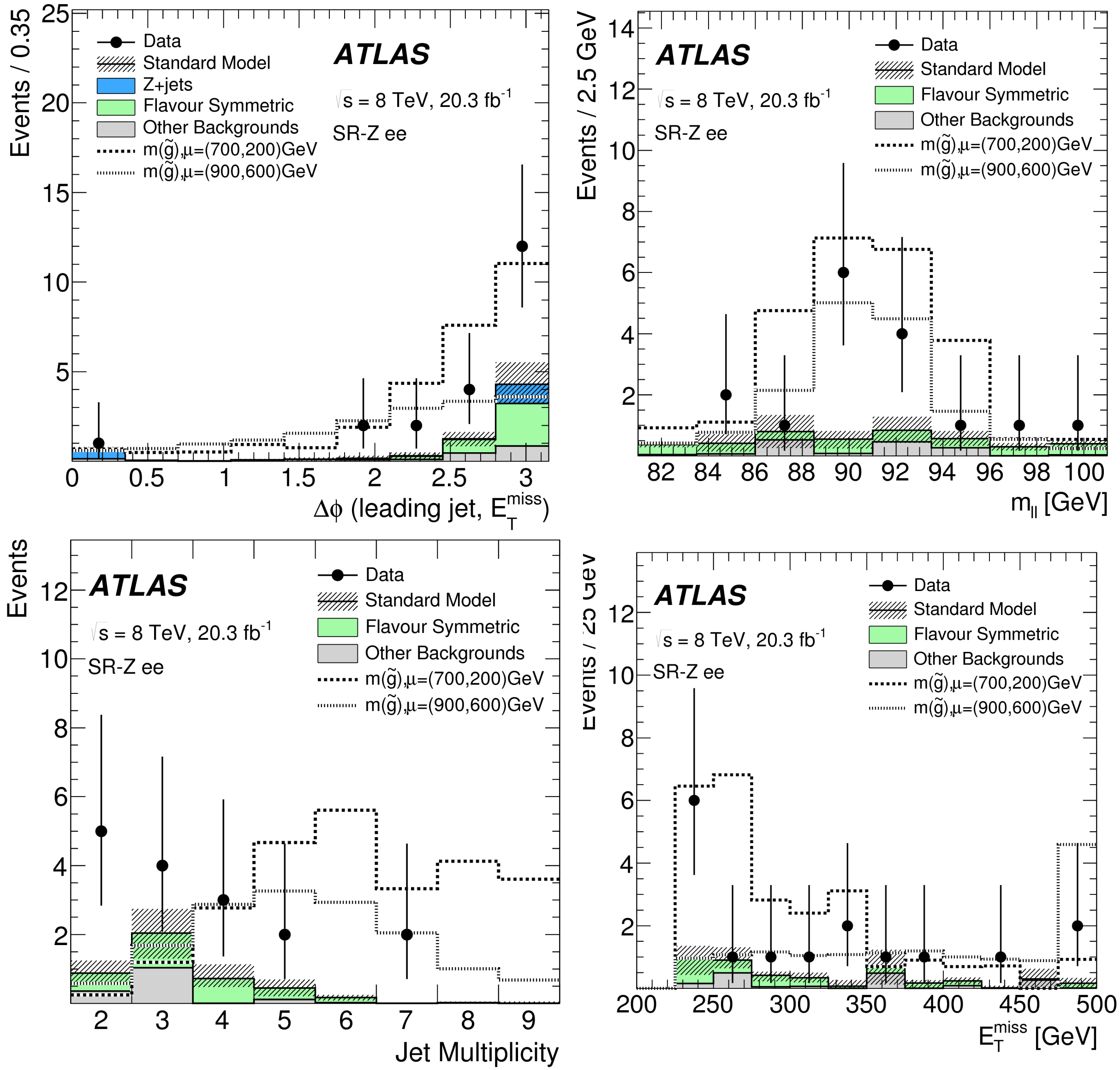


interesting discrepancies: 2 lepton strong

- ATLAS searches for strongly produced SUSY particles in final states with 2 leptons consistent with Z boson, jets, MET and HT
- Semi-data driven background for all major background
- 1.7 sigma excess in μμ, 3.0 sigma in ee
  - Not confirmed by CMS although search is different

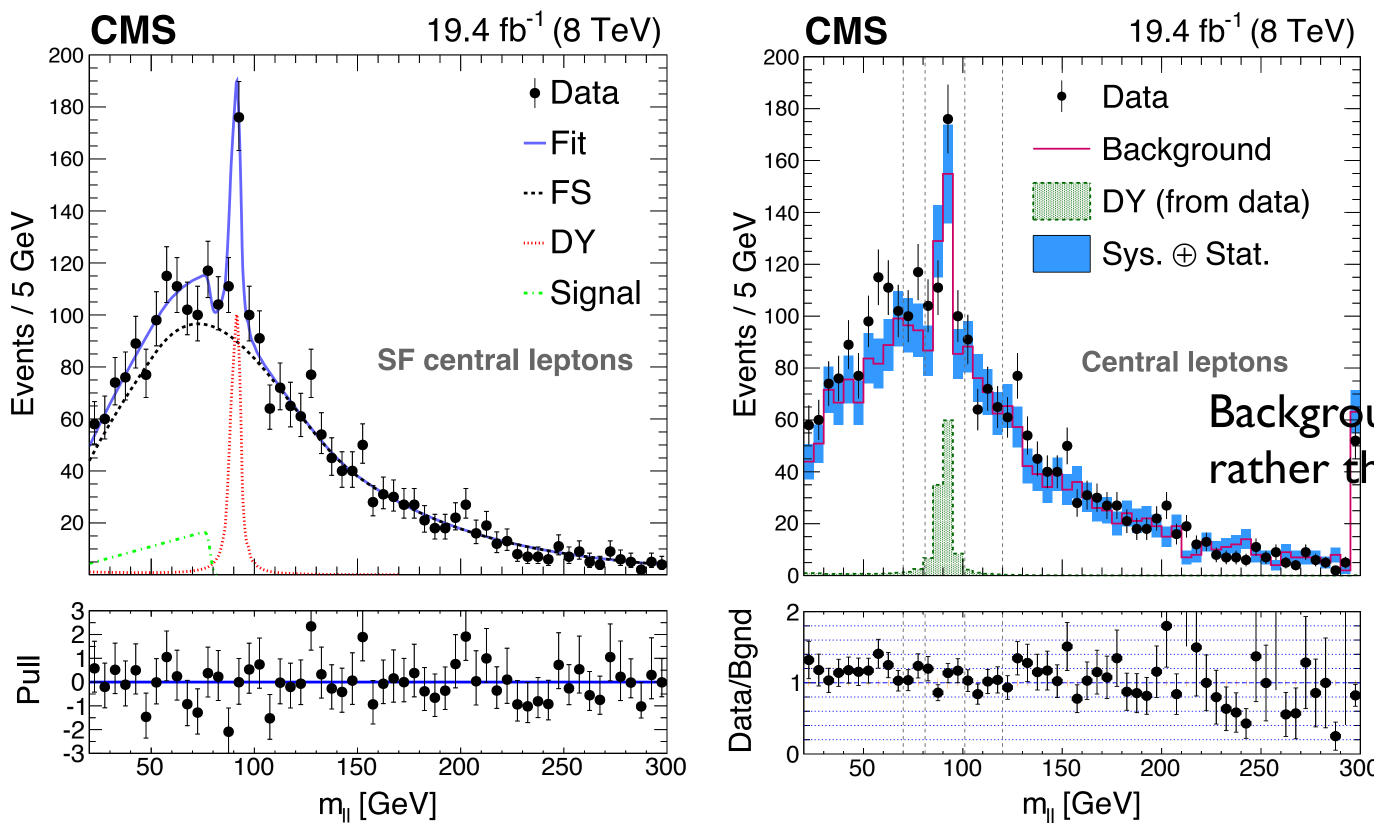


2l ATLAS: ee kinematic distributions



interesting discrepancies: 2-lepton edge

- Search for strongly produced SUSY particles in final states with 2 leptons, jets and MET
- Data-drive methods (fit and from control regions)
- Excess in low mll (20-70 GeV): 2.6 sigma
  - Not confirmed by ATLAS in a similar analysis



Background from CR rather than from fit

interesting discrepancies: 3-lepton + bjets

http://arxiv.org/pdf/1404.5801.pdf

- Search for SUSY in events with 3 or more leptons and b-jets
- Good agreement between data and SM predictions in all region except one
  - 4 leptons (1 tau), Z-veto and low MET
  - Obs: 15 events, Pred: 7.5+/-2.0
- Not confirmed by ATLAS which uses this as validation region

≥4 leptons $H_T > 200$ GeV	$m_{\ell^+\ell^-}$	E_T^{miss} (GeV)	$N_{\tau_h}=0, N_b=0$ Obs.	Exp.	$N_{\tau_h}=1, N_b=0$ Obs.	Exp.	$N_{\tau_h}=0, N_b\geq1$ Obs.	Exp.	$N_{\tau_h}=1, N_b\geq1$ Obs.	Exp.
OSSF0	—	(100, ∞)	0	$0.01^{+0.03}_{-0.01}$	0	$0.01^{+0.06}_{-0.01}$	0	$0.02^{+0.04}_{-0.02}$	0	0.11 ± 0.08
OSSF0	—	(50, 100)	0	$0.00^{+0.02}_{-0.00}$	0	$0.01^{+0.06}_{-0.01}$	0	$0.00^{+0.03}_{-0.00}$	0	0.12 ± 0.07
OSSF0	—	(0, 50)	0	$0.00^{+0.02}_{-0.00}$	0	$0.07^{+0.10}_{-0.07}$	0	$0.00^{+0.02}_{-0.00}$	0	0.02 ± 0.02
OSSF1	Off-Z	(100, ∞)	0	$0.01^{+0.02}_{-0.01}$	1	0.25 ± 0.11	0	0.13 ± 0.08	0	0.12 ± 0.12
OSSF1	On-Z	(100, ∞)	1	0.10 ± 0.06	0	0.50 ± 0.27	0	0.42 ± 0.22	0	0.42 ± 0.19
OSSF1	Off-Z	(50, 100)	0	0.07 ± 0.06	1	0.29 ± 0.13	0	0.04 ± 0.04	0	0.23 ± 0.13
OSSF1	On-Z	(50, 100)	0	0.23 ± 0.11	1	0.70 ± 0.31	0	0.23 ± 0.13	1	0.34 ± 0.16
OSSF1	Off-Z	(0, 50)	0	$0.02^{+0.03}_{-0.02}$	0	0.27 ± 0.12	0	$0.03^{+0.04}_{-0.03}$	0	0.31 ± 0.15
OSSF1	On-Z	(0, 50)	0	0.20 ± 0.08	0	1.3 ± 0.5	0	0.06 ± 0.04	1	0.49 ± 0.19
OSSF2	Off-Z	(100, ∞)	0	$0.01^{+0.02}_{-0.01}$	—	—	0	$0.01^{+0.06}_{-0.01}$	—	—
OSSF2	On-Z	(100, ∞)	1	$0.15^{+0.16}_{-0.15}$	—	—	0	0.34 ± 0.18	—	—
OSSF2	Off-Z	(50, 100)	0	0.03 ± 0.02	—	—	0	0.13 ± 0.09	—	—
OSSF2	On-Z	(50, 100)	0	0.80 ± 0.40	—	—	0	0.36 ± 0.19	—	—
OSSF2	Off-Z	(0, 50)	1	0.27 ± 0.13	—	—	0	0.08 ± 0.05	—	—
OSSF2	On-Z	(0, 50)	5	7.4 ± 3.5	—	—	2	0.80 ± 0.40	—	—

≥4 leptons $H_T < 200$ GeV	$m_{\ell^+\ell^-}$	E_T^{miss} (GeV)	$N_{\tau_h}=0, N_b=0$ Obs.	Exp.	$N_{\tau_h}=1, N_b=0$ Obs.	Exp.	$N_{\tau_h}=0, N_b\geq1$ Obs.	Exp.	$N_{\tau_h}=1, N_b\geq1$ Obs.	Exp.
OSSF0	—	(100, ∞)	0	0.11 ± 0.08	0	0.17 ± 0.10	0	$0.03^{+0.04}_{-0.03}$	0	0.04 ± 0.04
OSSF0	—	(50, 100)	0	$0.01^{+0.03}_{-0.01}$	2	0.70 ± 0.33	0	$0.00^{+0.02}_{-0.00}$	0	0.28 ± 0.16
OSSF0	—	(0, 50)	0	$0.01^{+0.02}_{-0.01}$	1	0.7 ± 0.3	0	$0.00^{+0.02}_{-0.00}$	0	0.13 ± 0.08
OSSF1	Off-Z	(100, ∞)	0	0.06 ± 0.04	3	0.60 ± 0.24	0	$0.02^{+0.04}_{-0.02}$	0	0.32 ± 0.20
OSSF1	On-Z	(100, ∞)	1	0.50 ± 0.18	2	2.5 ± 0.5	1	0.38 ± 0.20	0	0.21 ± 0.10
OSSF1	Off-Z	(50, 100)	0	0.18 ± 0.06	4	2.1 ± 0.5	0	0.16 ± 0.08	1	0.45 ± 0.24
OSSF1	On-Z	(50, 100)	2	1.2 ± 0.3	9	9.6 ± 1.6	2	0.42 ± 0.23	0	0.50 ± 0.16
OSSF1	Off-Z	(0, 50)	2	0.46 ± 0.18	15	7.5 ± 2.0	0	0.09 ± 0.06	0	0.70 ± 0.31
OSSF1	On-Z	(0, 50)	4	3.0 ± 0.8	41	40 ± 10	1	0.31 ± 0.15	2	1.50 ± 0.47
OSSF2	Off-Z	(100, ∞)	0	0.04 ± 0.03	—	—	0	0.05 ± 0.04	—	—
OSSF2	On-Z	(100, ∞)	0	0.34 ± 0.15	—	—	0	0.46 ± 0.25	—	—
OSSF2	Off-Z	(50, 100)	2	0.18 ± 0.13	—	—	0	$0.02^{+0.03}_{-0.02}$	—	—
OSSF2	On-Z	(50, 100)	4	3.9 ± 2.5	—	—	0	0.50 ± 0.21	—	—
OSSF2	Off-Z	(0, 50)	7	8.9 ± 2.4	—	—	1	0.23 ± 0.09	—	—
OSSF2	On-Z	(0, 50)	*156	160 ± 34	—	—	4	2.9 ± 0.8	—	—

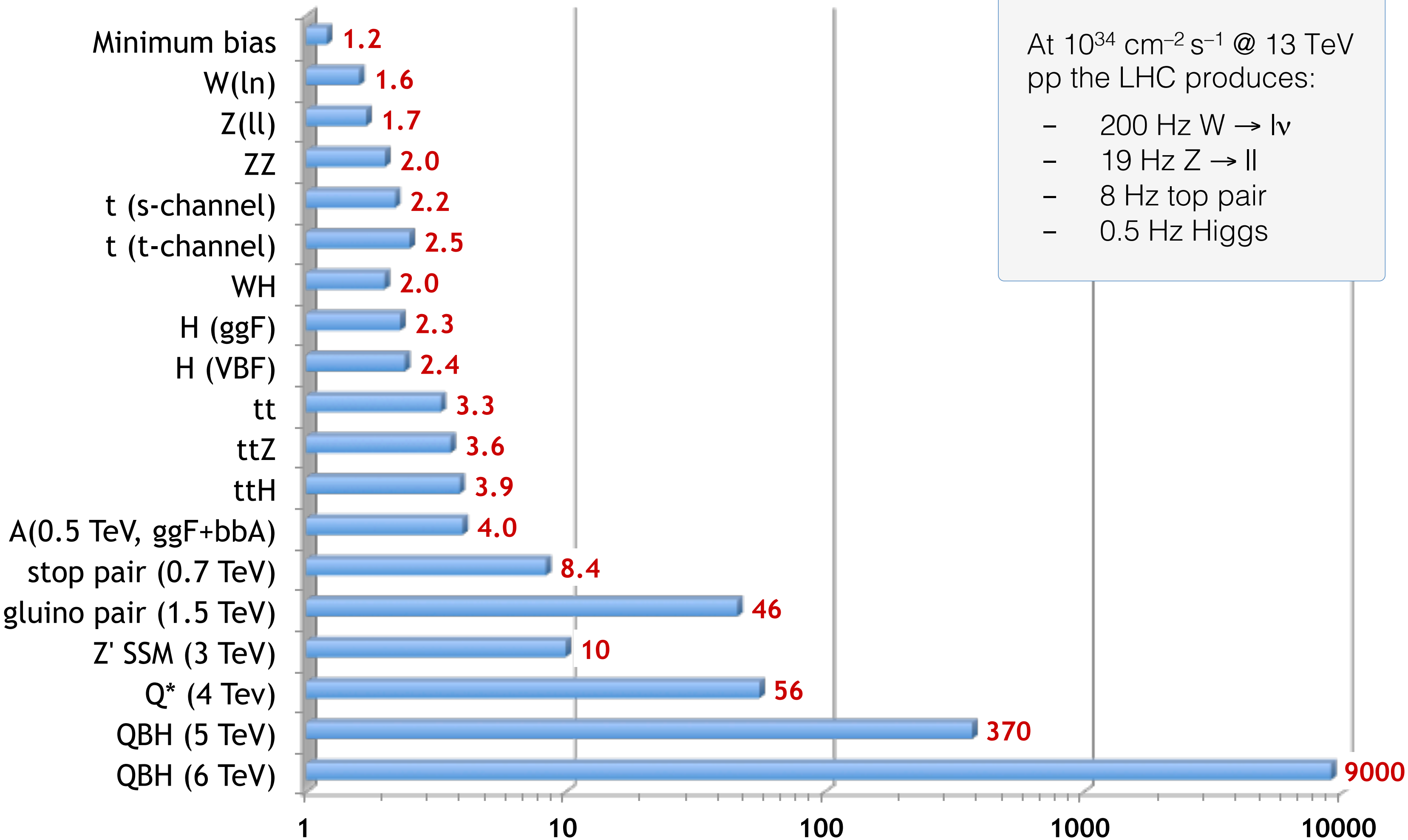
SUSY @ the end of Run 1

- Most simplistic version of SUSY under stress
  - Partially true also for 'Natural' SUSY, although depends *e.g.* on level of fine-tuning
- Still, lot of open suitable scenarios. A few examples:
  - Generic SUSY models explaining higgs mass indicate top squarks up the TeV range → not yet fully covered
    - If there are such 'light' stops, gluinos might be in the 2-3 TeV range → not yet reached
  - Decays of sparticle in most of SUSY models are complex:
    - Limitations on our analyses and constraints: often valid only if a sparticle decays 100% in one mode
  - High scalar masses (O(10 TeV)) foreseen in several models (e.g. Split SUSY)
    - Focus on EWK sector, where boundaries are less stringent
  - More on the EWK sector: Low higgsino mass scenarios lead to "compressed" SUSY spectra (low ΔM Next-LSP – LSP) → difficult to corner because of low cross sections + low acceptances
  - R-parity violation scenarios not fully covered:
    - Lack of handles such as missing transverse momentum, complex phenomenology, possibly long-lived particles

Towards Run 2

- Challenges
- Projections

13 TeV / 8 TeV inclusive pp cross-section ratio



At 10^{34} cm^{-2} s^{-1} @ 13 TeV pp the LHC produces:

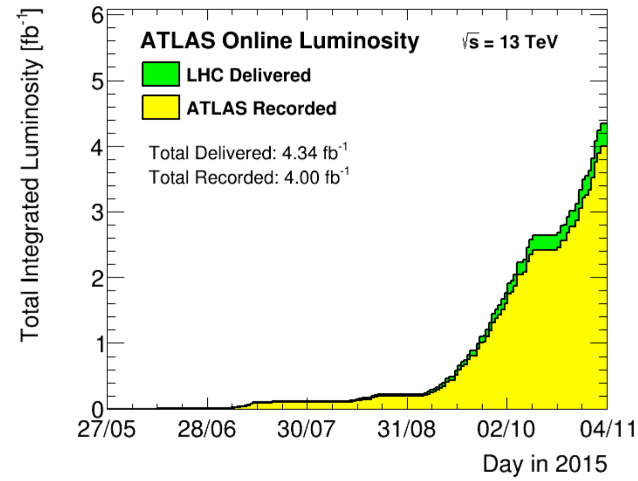
- 200 Hz $W \to l\nu$
- 19 Hz $Z \to ll$
- 8 Hz top pair
- 0.5 Hz Higgs

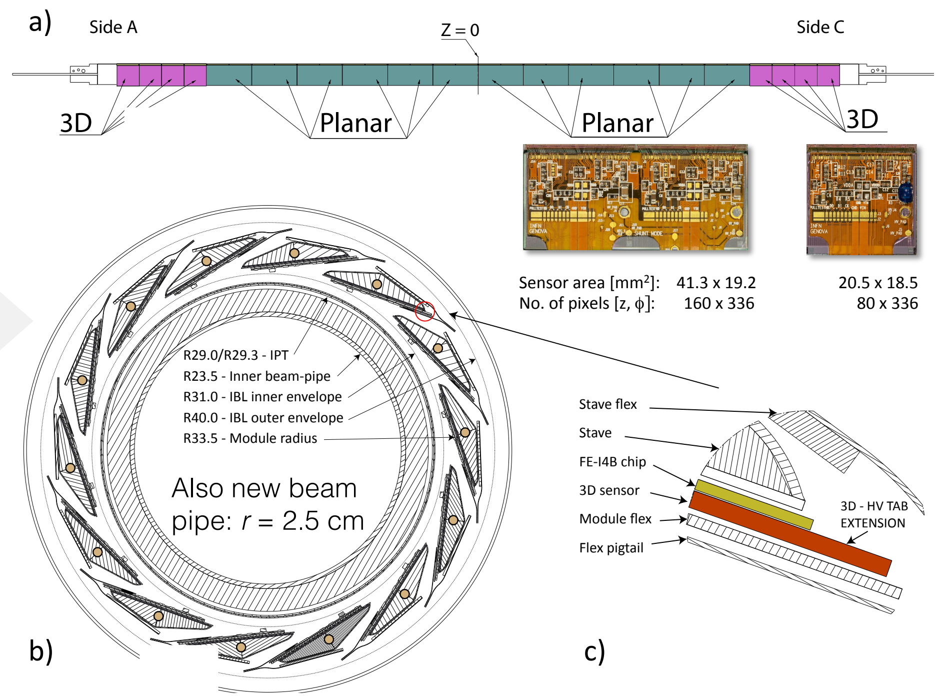
Run 2 ATLAS performance so far ..

- **.. Excellent!!**
- During the Long ShutDown, the detector went through a set of upgrades
  - Infrastructure (magnet, muon chamber shielding …)
  - Consolidation
  - Improved L1 trigger and new central trigger processor
  - New Insertable B-layer

    4^{th} layer of pixel at 3.3 cm from beam
  - New software, production system, analysis model

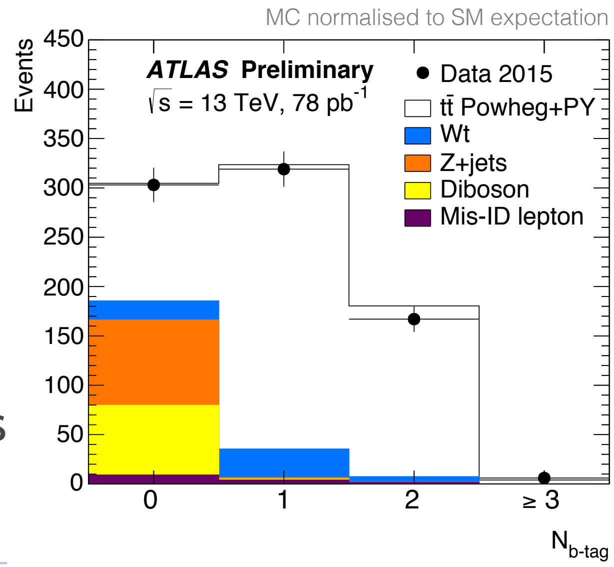
Many people from Liverpool gave CRUCIAL contributions!!





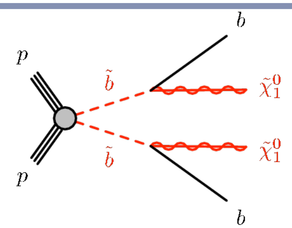
new and old challenges ahead..

- Trigger strategy:
  - Exploit more approaches as scouting and delayed/parking
    - Very difficult to cope with the 100 kHz L1 trigger rate, might have to make a priori choices
  - Develop / use more dedicated triggers
    - displaced vertex, "Fat" jets …
- Keep working on 'new' discriminants or techniques!
  - Eg.: boosted tools for heavy particles
  - Boosted W/top 'tagging'
- Background strategies:
  - Clearly, developing or use more data-driven methods will help
  - Still, can't deny the relevance to use appropriate and up-to-date Monte Carlo generators

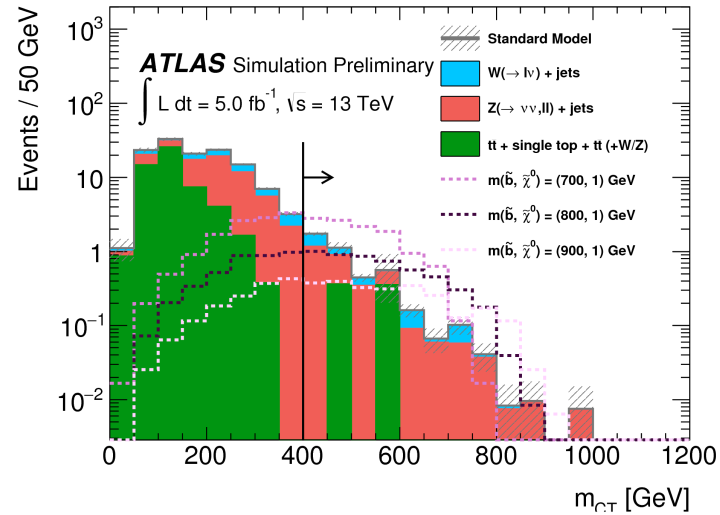


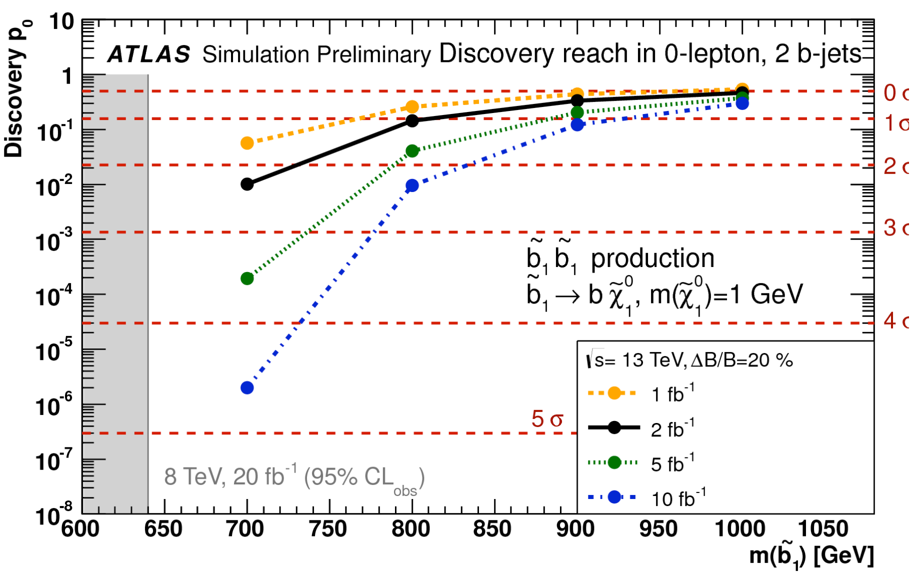
Prospects: Sbottom @ 13 TeV

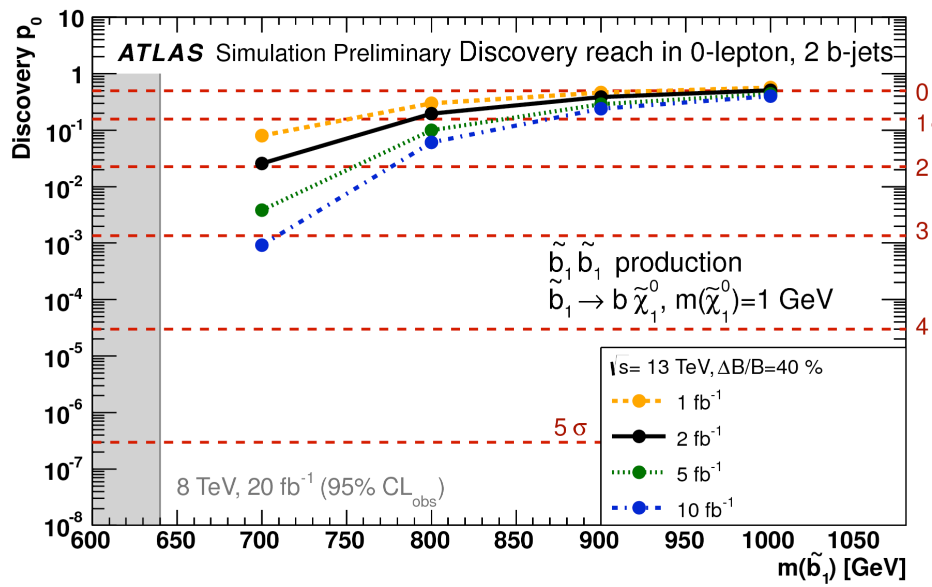
- 2 b-jets + MEt



- Can reach 3 sigma evidence for sbottom mass ~ 700 GeV with 5/fb if SM background uncertainties ~ 20-25%

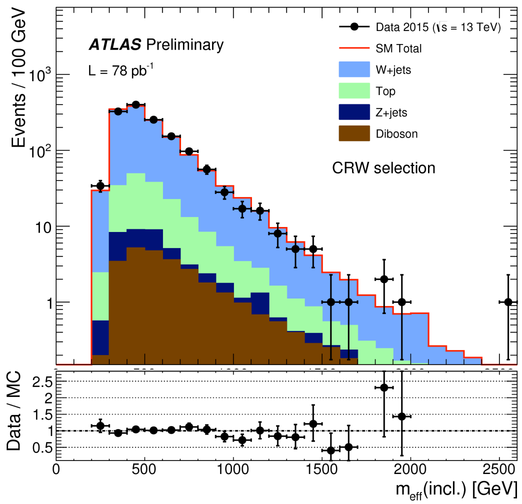


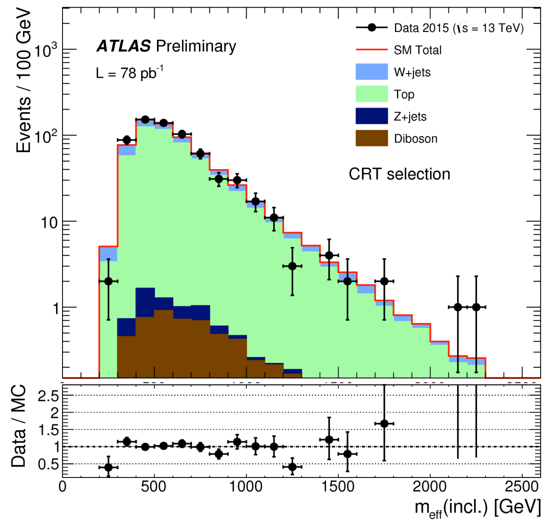


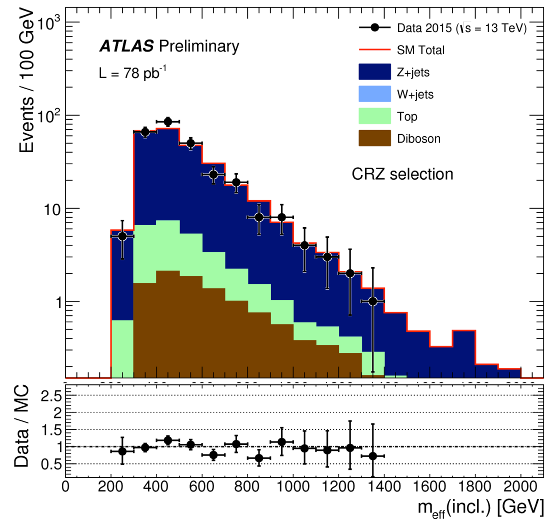


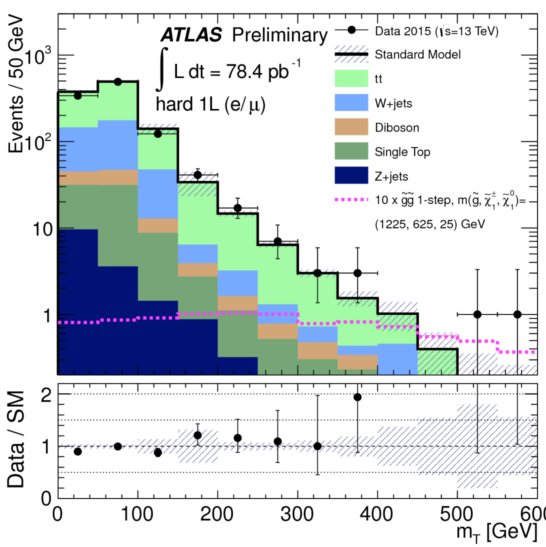
13 TeV Results: 0l,1l+jets, multijets

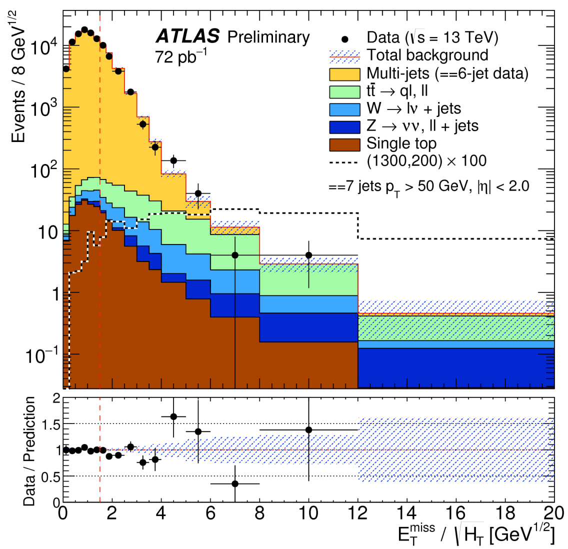
- First 50ns data collected by ATLAS











Promising results

Summary & conclusions

- Many reasons to be interested in SUSY → *increasingly* the best (or least bad?) solution to hierarchy problem, provide good Dark Matter candidate etc.
- SUSY is a beautiful theoretical framework:
  - Very diverse phenomenology, experiments must have a wide search strategy (while keeping an eye on possible indirect constraints)
- LHC Run 1 has set stringent exclusion limits:
  - Under stress simplest version of SUSY, but with many open points and exciting opportunities → just hitting the ‘regimes’ indicated by the higgs mass !
- LHC Run2 will offer the possibility to explore various SUSY scenarios.
  - we learned a lot along the way – so let’s use that!
- New projects and experiments might also give extra guidance..

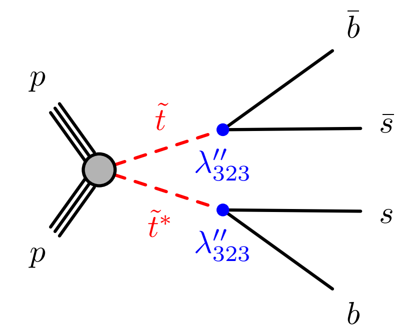
Long time ago, they told us SUSY was just around the corner. It might still be true. We just need to find the right one …

Back-up

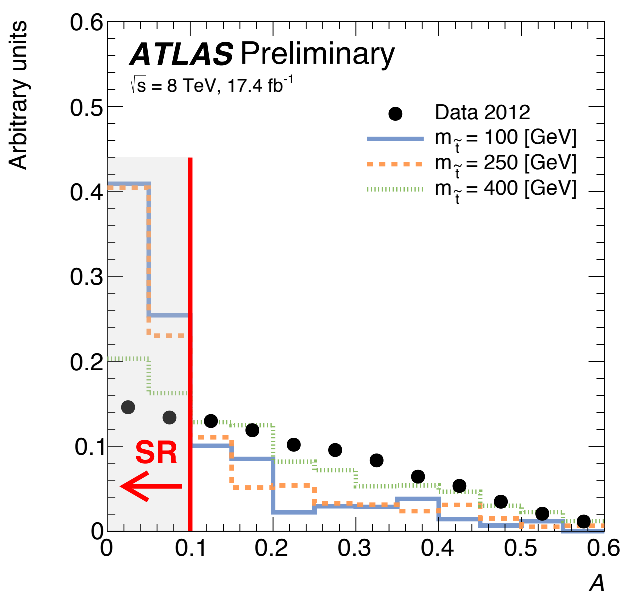
RPV searches for stop (2x2 jets)

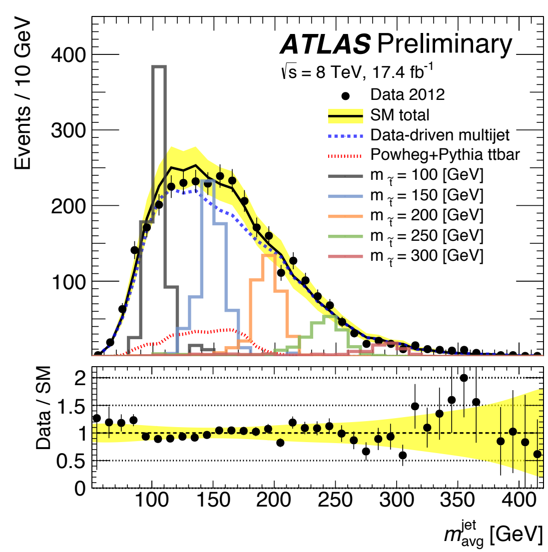
- Limits from LEP and CDF: < 100 GeV
- **ATLAS** search exploits merging of stop decay products with a radius $\Delta R = m_{stop}/p_T$ (initial stop pT);

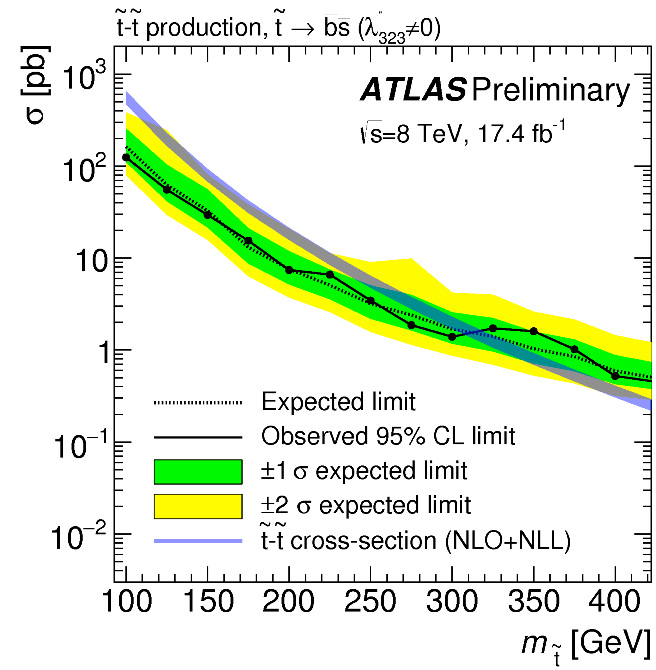
➔ Large R jets with $m_{Jet} \sim m_{stop}$



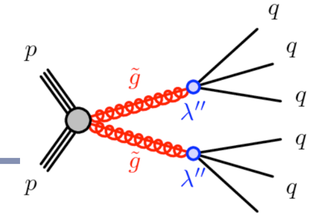
$$\mathcal{A} = \frac{|m_1 - m_2|}{m_1 + m_2}$$



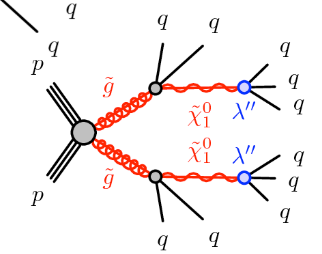




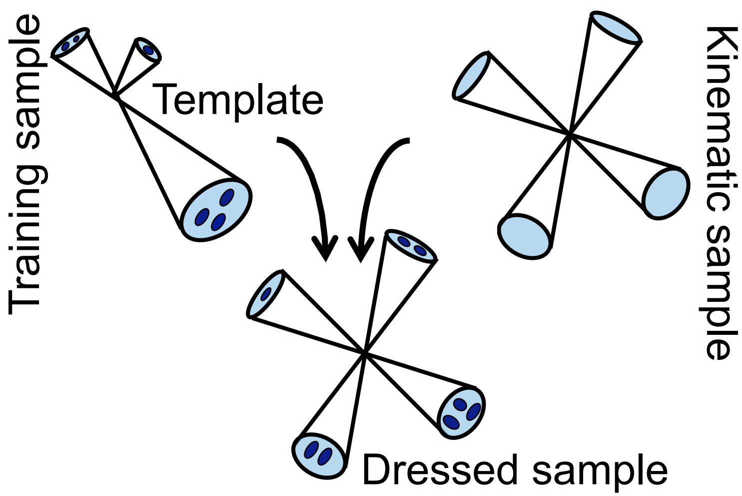
RPV multijet searches (prompt)

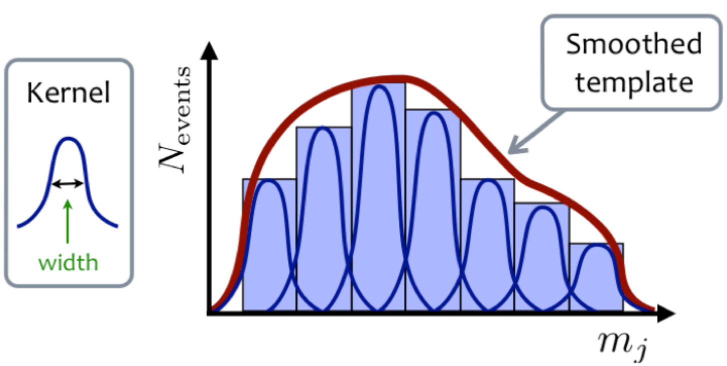


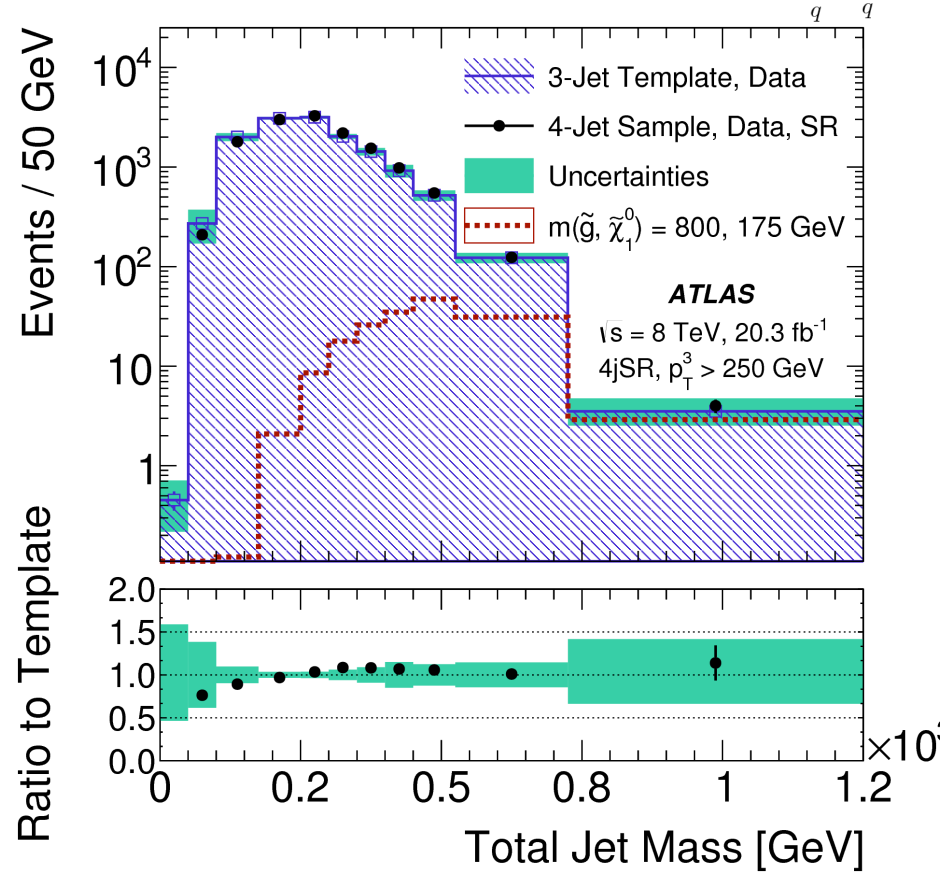
- Search for strongly-produced SUSY particles in final states with high jet multiplicity and no MET.
- Additional requirement on number of b-jet or M_J.



drawings from T. Cohen



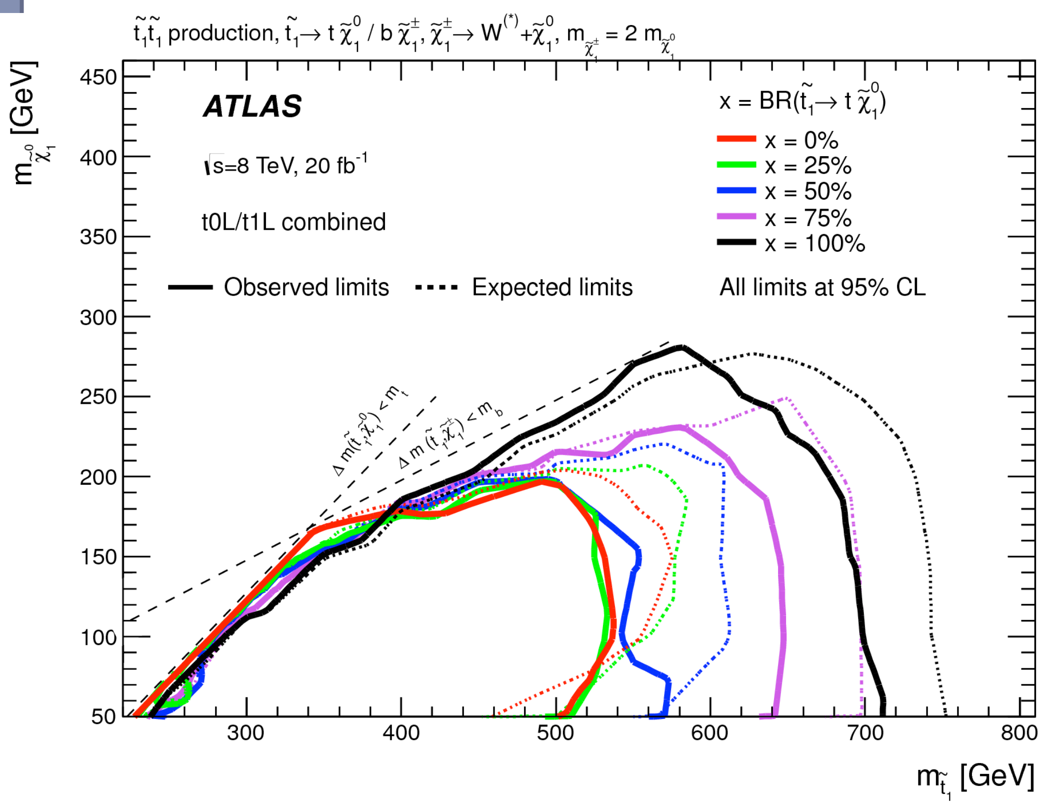


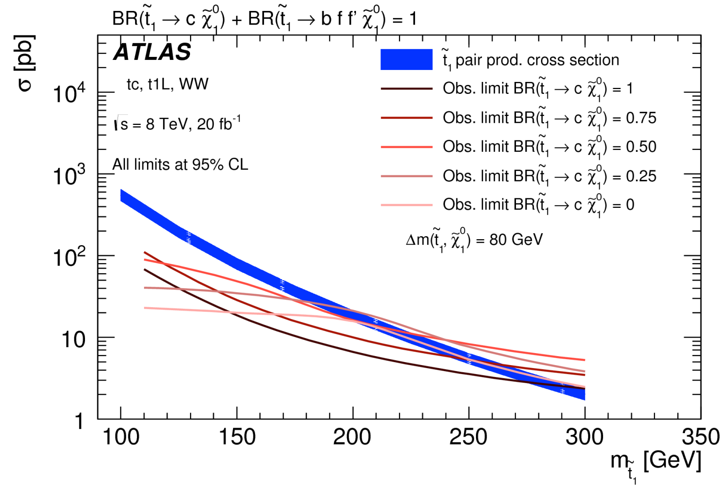


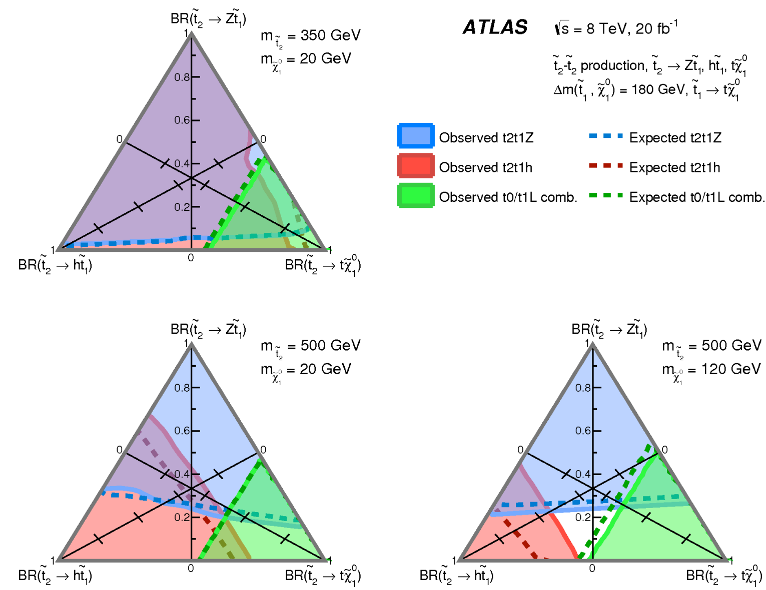
Exclusion limits up to 1 TeV gluino masses

full exploitation of Run I data: mixed decays

- If we relax the BR = 100% assumption on one mode or the other, sensitivity might change quite significantly:
  - E,g. low ΔM (stop, neut): 4-body VS charm-decay
  - E.g. top+neutralino VS b+chargino
  - E.g. stop2 in stop1H/stop1Z/topNeut

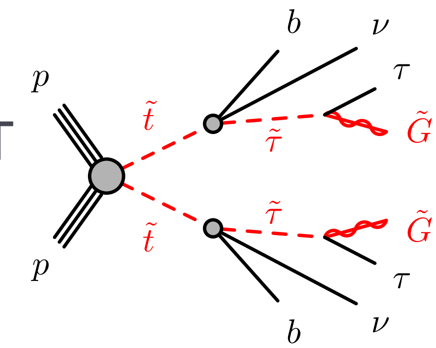




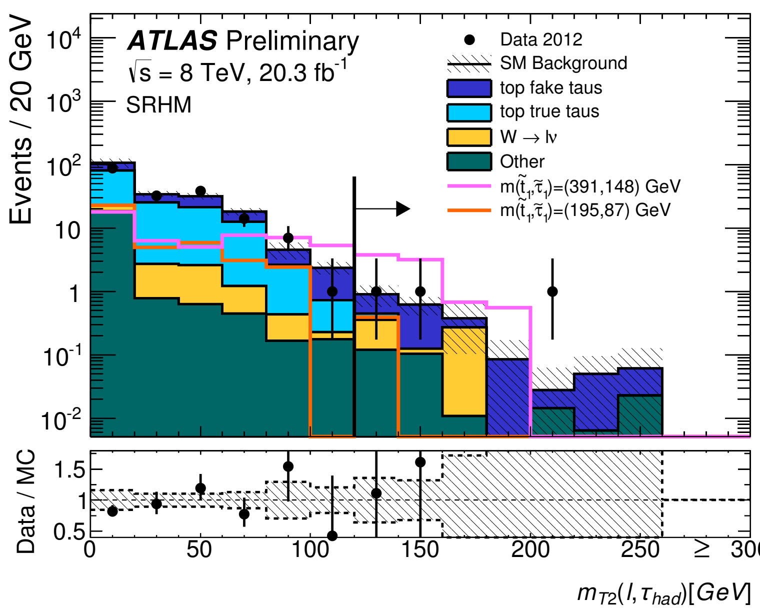


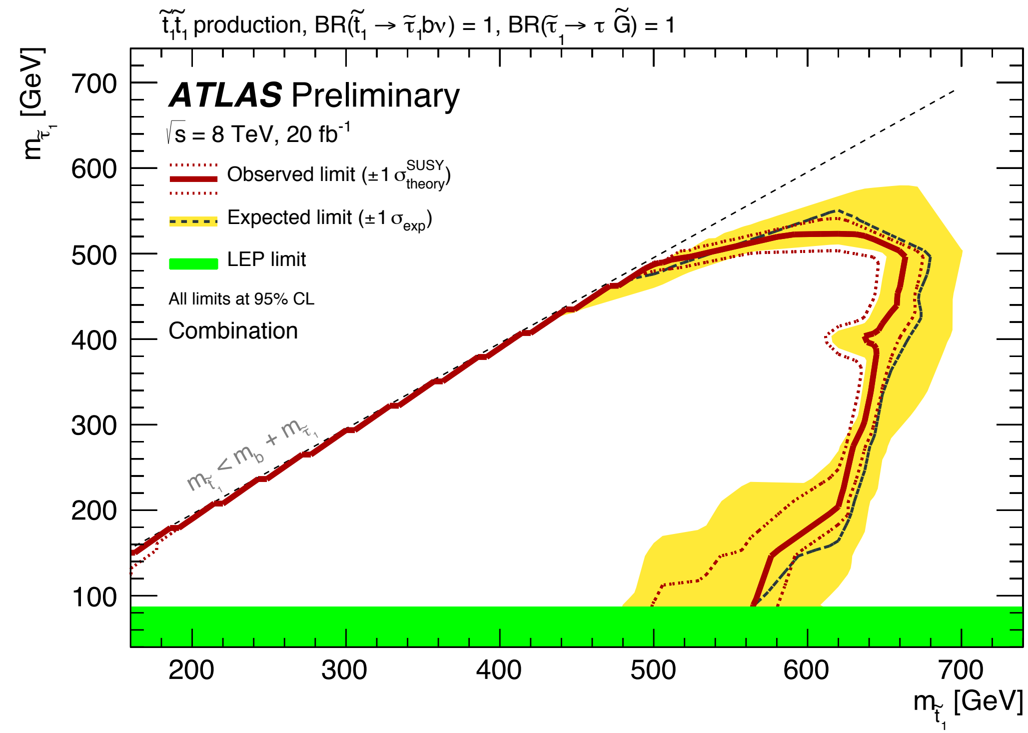
full exploitation of Run 1 results: new models

- **Stop in stau**
  - GMSB inspired, dedicated searches in 2tau+2b+MET



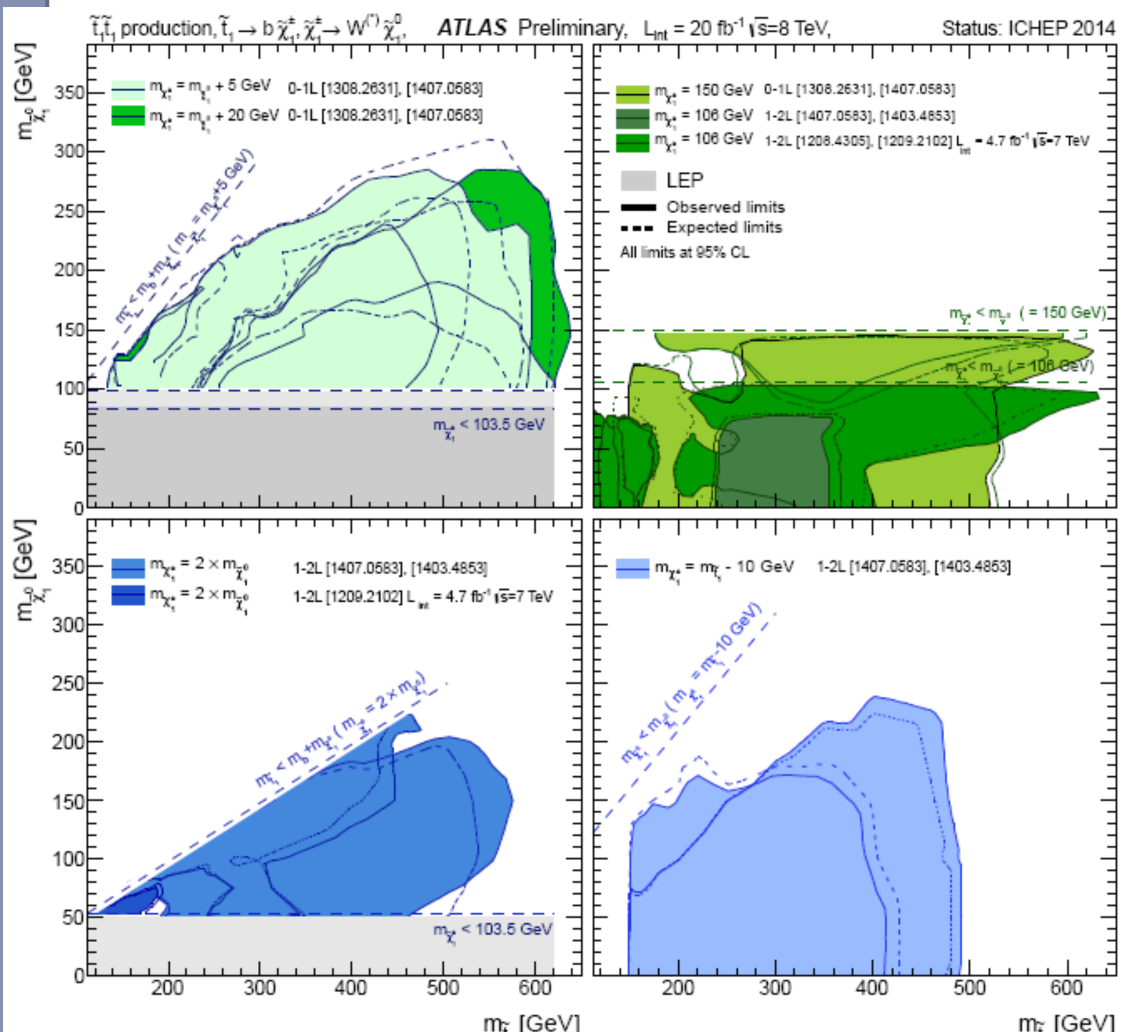
- Split by tau decay modes to maximize sensitivity (had-had, lep-had, lep-lep)
  - mT and mT2 discriminants used

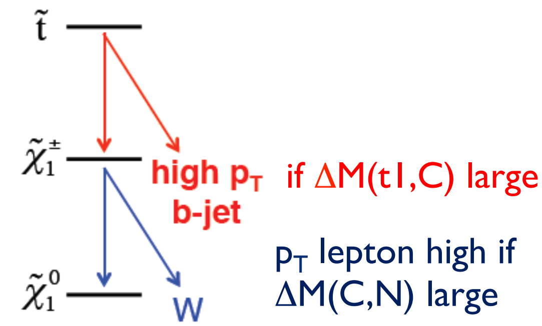




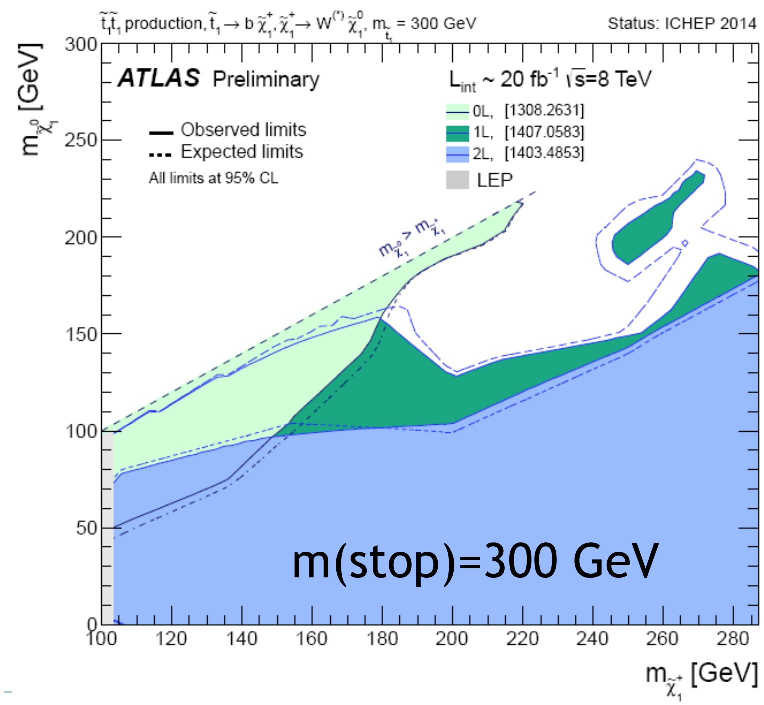
Top squark summary: ATLAS (II)

- Various assumptions of ΔM(stop-chargino) and ΔM(chargino-neutralino)

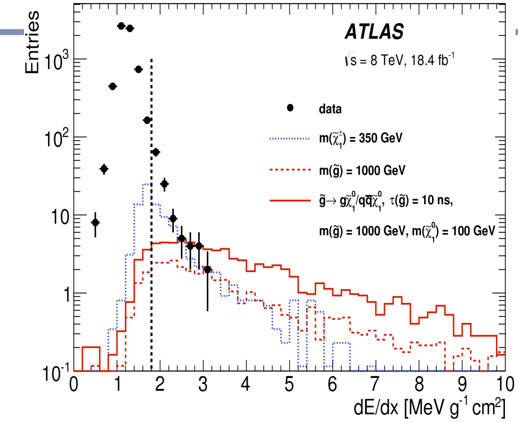




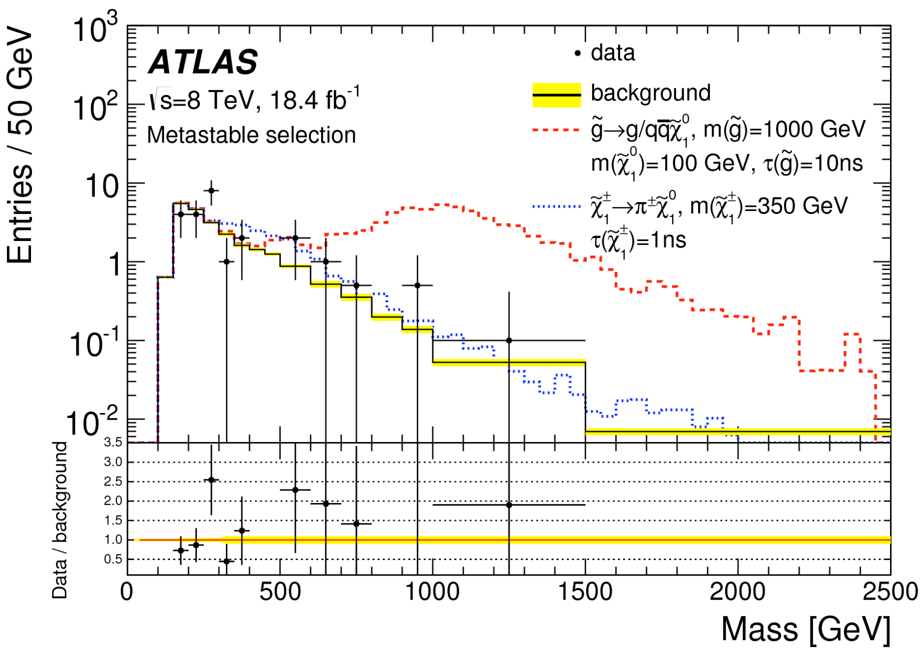
Fixed mass stop, function of chargino-neutralino mass

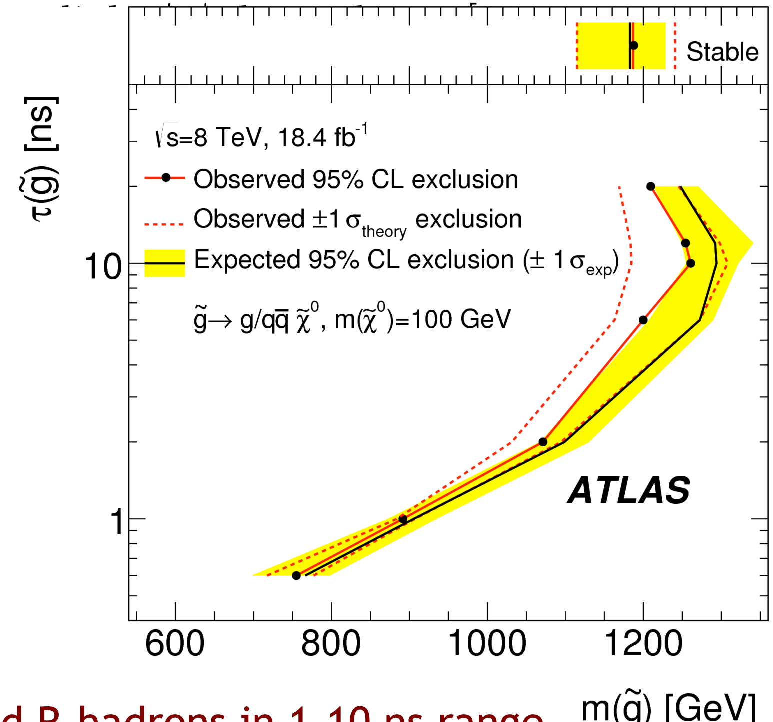


Exploit detector at best: dE/dx



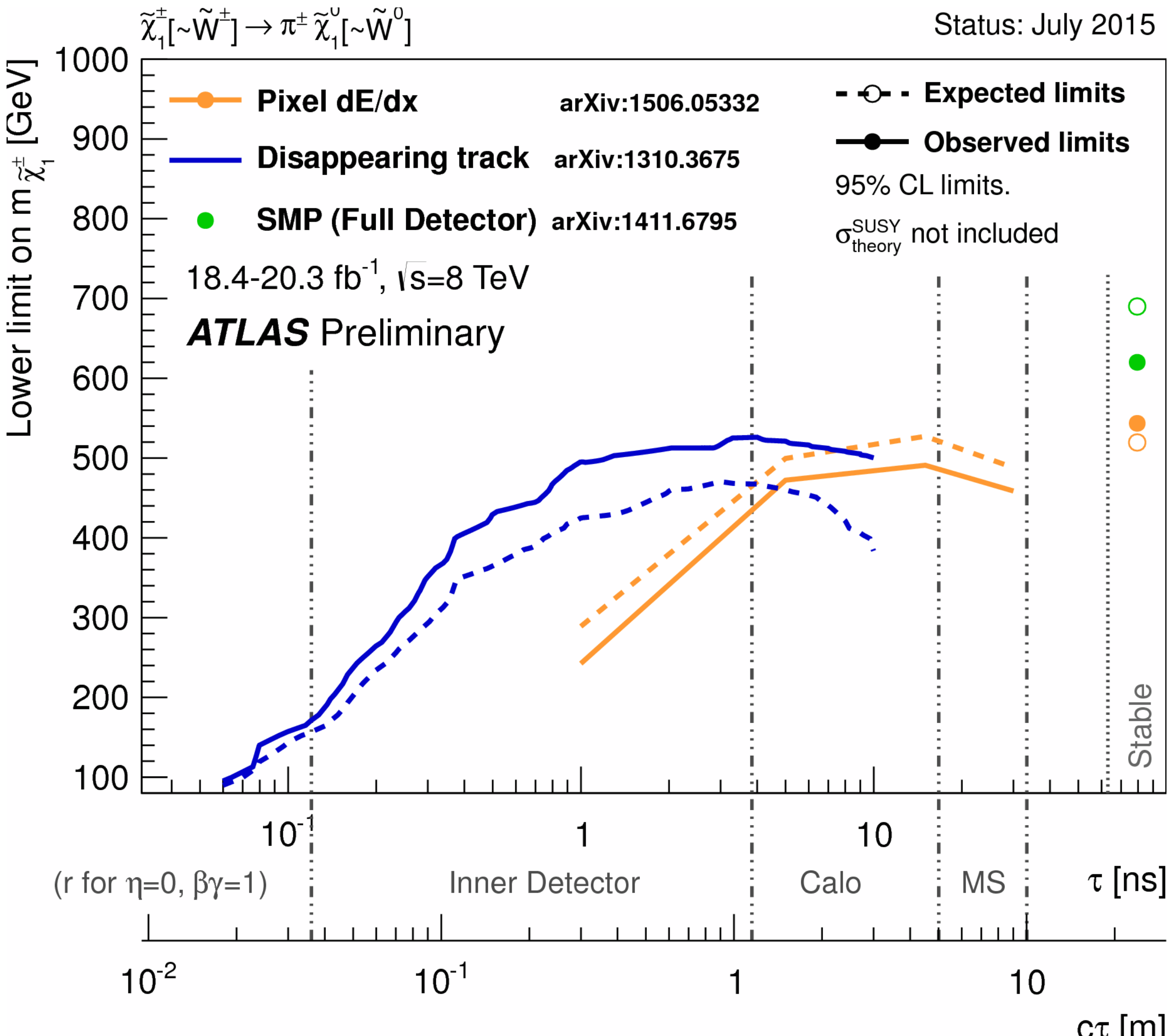
- Use pixel detector to search for (meta-)stable LLP
- LLP are seen as heavy muon-like particles with $\beta<<1$
  - High dE/dx measured in pixel detector
- Studied if particles travels at least 45 cm (in r)
- Select high momentum, isolated tracks
- High ionization: dE/dx > $1.8 - 0.034|\eta| + 0.101\eta^2 - 0.029|\eta|^3$ MeV/g cm^2





First life-time dependent mass limits for charged R-hadrons in 1-10 ns range

long-lived particles: summary chargino



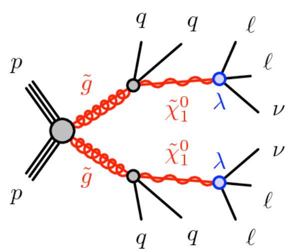
wino-like chargino and neutralino (AMSB inspired)

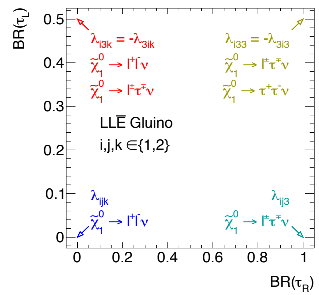
RPV results

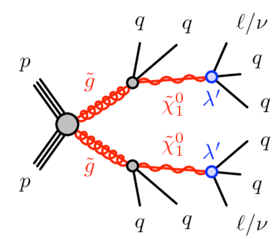
ATLAS-CONF-2015-018

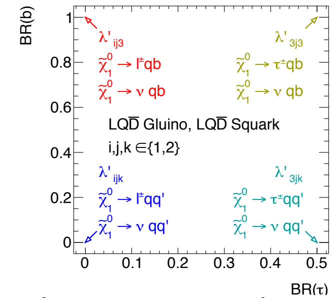
Prompt RPV

- Rich set of dedicated searches investigating RPV signatures as well as re-interpretations of RPC searches.
  - Coverage of ‘generic’ searches is sometimes broader than that of dedicated ones.

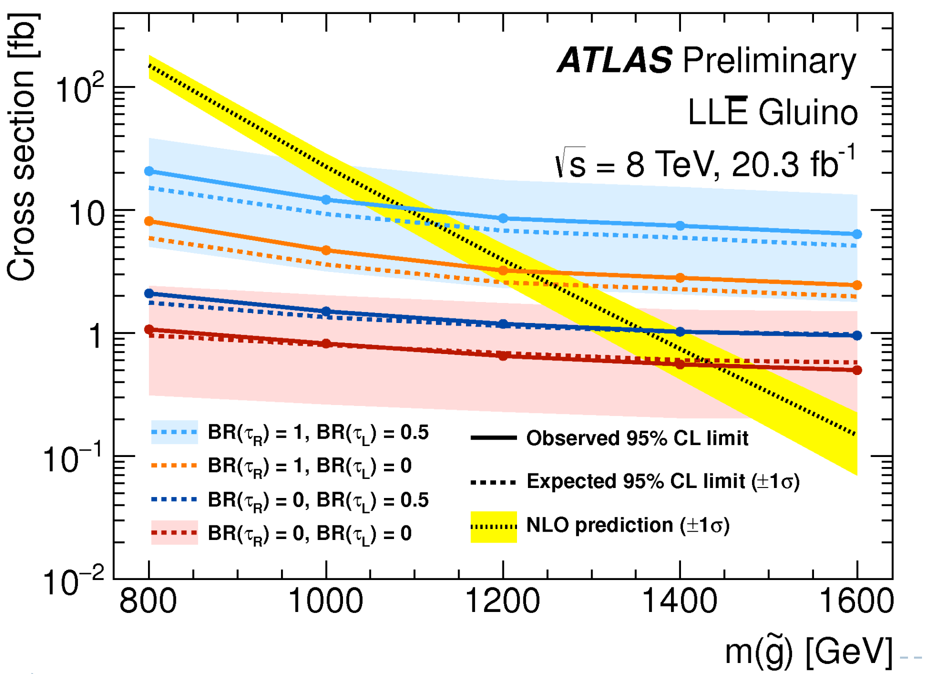




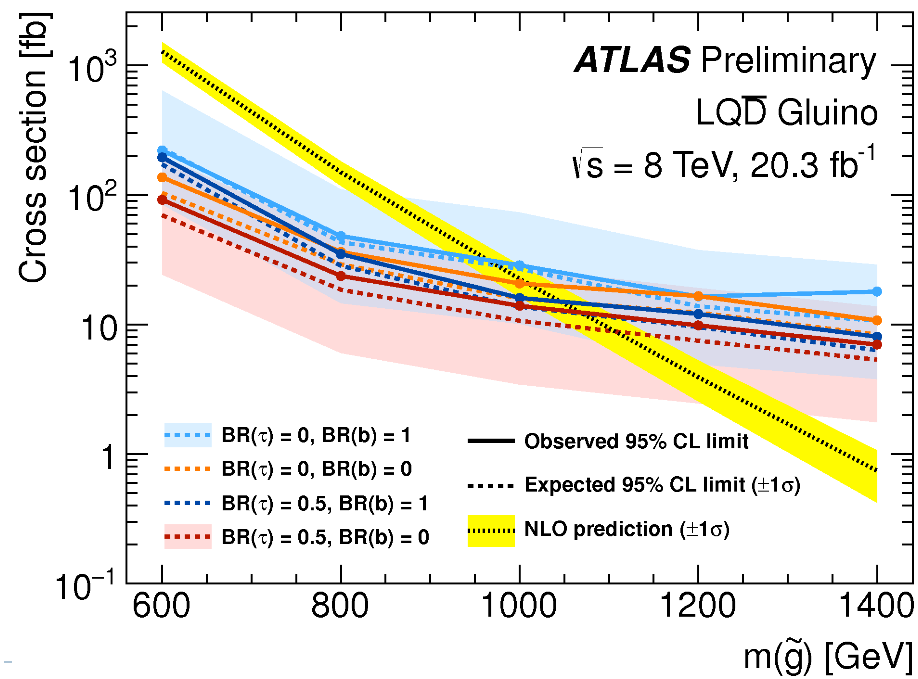




$pp \rightarrow \tilde{g}\tilde{g} \rightarrow qq\tilde{\chi}_1^0 qq\tilde{\chi}_1^0$ $\quad \tilde{\chi}_1^0 \rightarrow l^+l^-\nu$ $\quad m(\tilde{\chi}_1^0) / m(\tilde{g}) = 0.1$

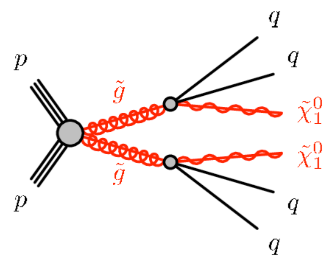


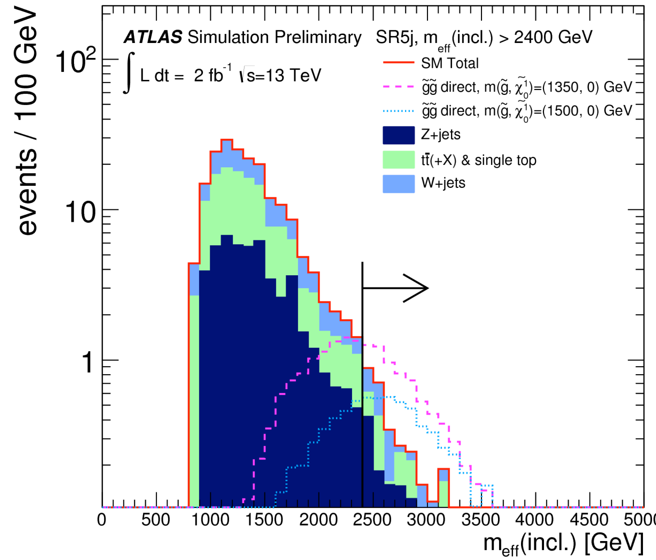
$pp \rightarrow \tilde{g}\tilde{g} \rightarrow qq\tilde{\chi}_1^0 qq\tilde{\chi}_1^0$ $\quad \tilde{\chi}_1^0 \rightarrow l/\nu\ qq$ $\quad m(\tilde{\chi}_1^0) / m(\tilde{g}) = 0.1$

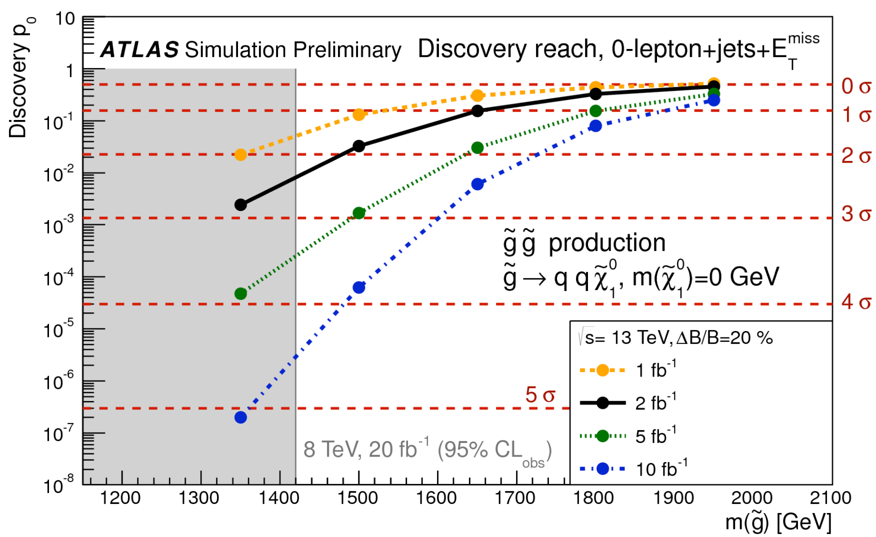


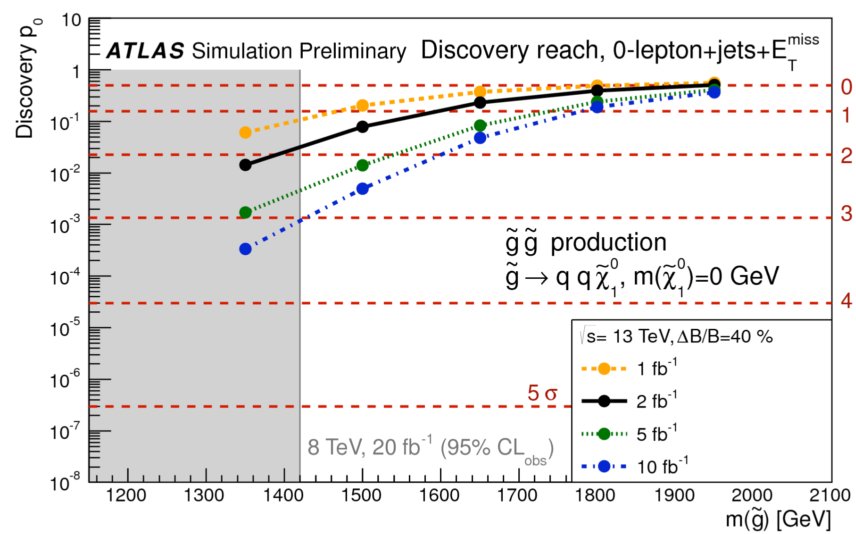
Projections: strong production @ 13 TeV

- Few analyses checked for sensitivity at a gluino/squark discovery
  - 3 sigma evidence for gluino mass ~ 1.5 TeV with 5/fb if background uncertainties ~ 20-25%
  - Good at 10/fb already …





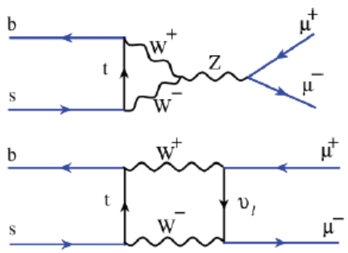




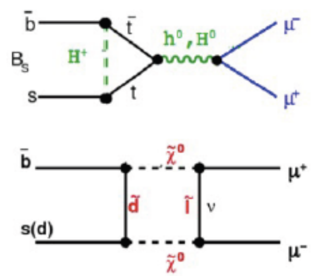
Indirect constraints

- **$B_s \rightarrow \mu\mu$:** constrain MSSM at large tan β
- BR Enhancement from many BSM models

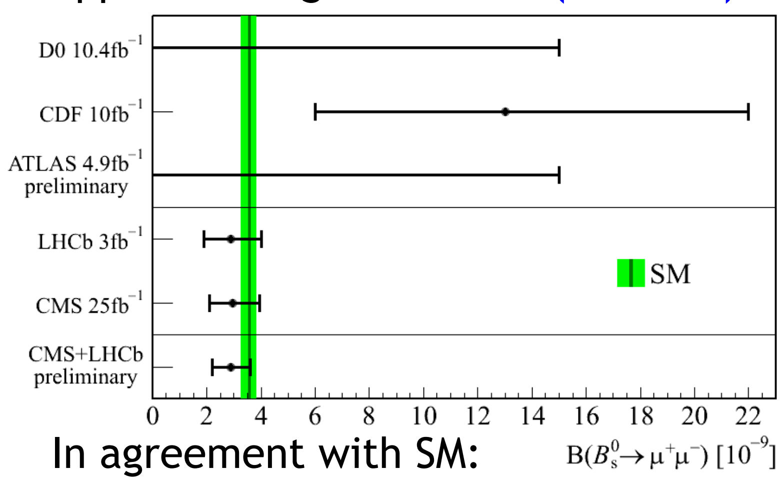
In SM:



In BSM:

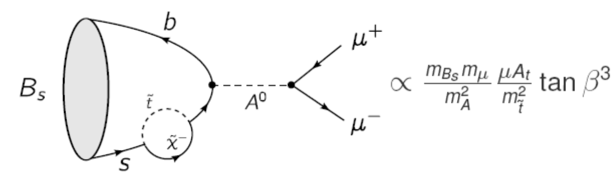


The CMS and the LHCb Collaborations have obtained a combined preliminary value of the Bs→μμ branching fraction of **$(2.9\pm0.7)\times10^{-9}$**



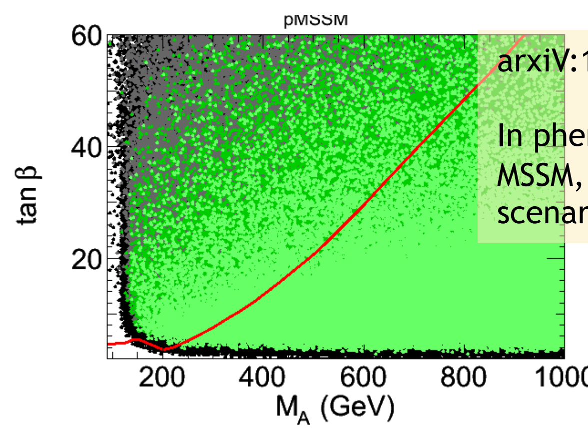
In agreement with SM:
BR=**$(3.56\pm0.30)\times10^{-9}$**

What can this tell us about SUSY?



Large tan β with light pseudoscalar Higgs disfavoured **BUT**
'Natural' (small fine tuning) MSSM scenarios barely affected

- SUSY-BR(Bs→μμ) is ~ to SM-BR or even smaller in some scenarios



arxiV:1212.4887

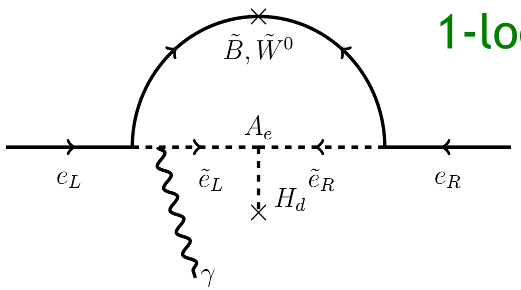
In phenomenological MSSM, only < 20-30% scenarios are excluded

Indirect constraints (II)

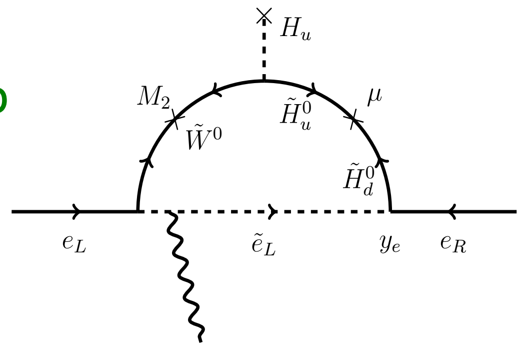
- **EDM:** As other BSM theories, SUSY predict small – yet measurable electron electric dipole moment (d_e)

(In SM, d_e ~ 10^{-44} *e* cm)

1-loop

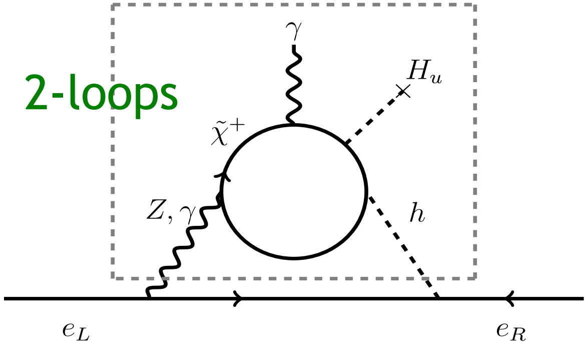


Bino-higgsino/Selectron

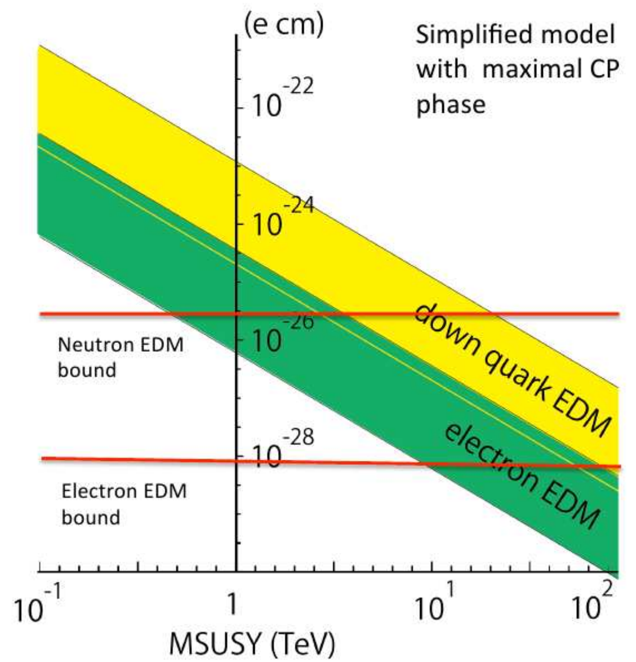


Selectron-electron-higgsino interaction

2-loops



(Hisano @ Moriond EW 2014)



ACME collaboration (arXiV:1310.7534):

- d_e = -2.1±3.7(stat)±2.5(syst) x 10^{-29} *e* cm
- $|d_e|$ < 8.7 × 10^{-29} *e* cm
  - for models where 1- (2-loop) diagrams produce d_e, bound on CP violation at energy scales **Λ ~ 3(1) TeV**

→ **Small CP phases ←→ decoupling:** Might indicate preference for **Split SUSY** and/or **1st generation squark/slepton masses** at O(10) TeV

(preserves EWK sector / naturalness)

Indirect constraints (III)

$\left(a_\mu := \frac{g_\mu - 2}{2}\right)$

- Anomalous magnetic moment: Muon g-2

$a_\mu^{SM} = (116\,591\,828 \pm 49) \times 10^{-11}$

$a_\mu^{exp} = (116\,592\,089 \pm 63) \times 10^{-11}$

$$\Delta a_\mu \equiv a_\mu(\text{exp}) - a_\mu(\text{SM}) = (26.1 \pm 8.0) \times 10^{-10}$$

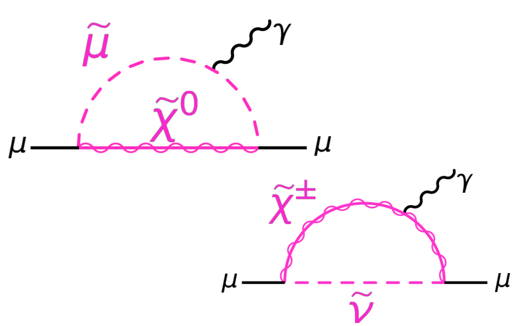
3.3 σ discrepancy → New Physics ? SUSY ?

$$\delta a_\mu \sim (\alpha_{NP}/4\pi) \times (m_\mu^2/m_{NP}^2)$$

Coupling constant of new particles to the muon

Typical scale of new particle mass

SUSY contributions to g-2:
neutralino-smuon and chargino-sneutrino loop diagrams



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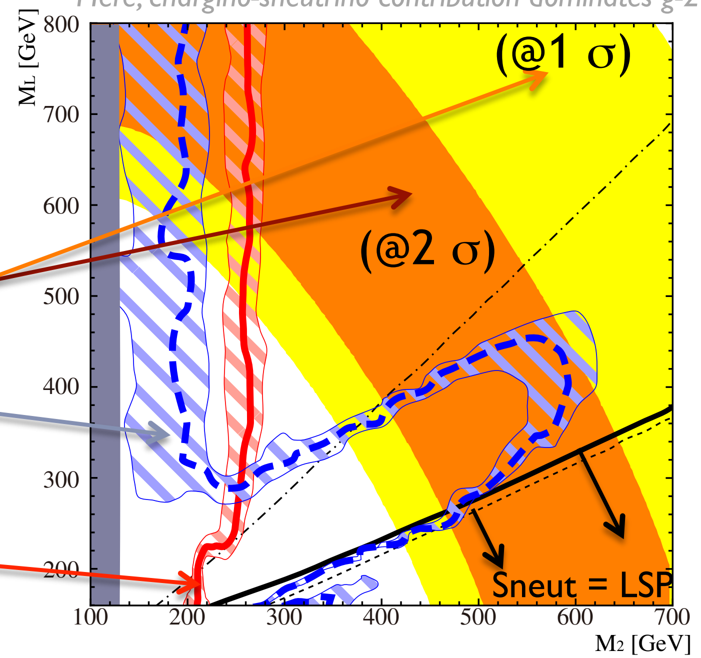
LHC and g-2 constraints

Here, chargino-sneutrino contribution dominates g-2

- SUSY explains g-2
- LEP searches
- Excluded by LHC-lepton searches
- Excluded by LHC Jet searches

M_1,M_2=bino,wino masses
μ = higgsino mass
m_L = slepton (LH component) mass



(a) $\mu = M_2$, $m_R = 3$ TeV