SUSY Searches in ATLAS and CMS

Caroline Collard (IPHC Strasbourg)

On behalf of the ATLAS and CMS Collaborations

Outline

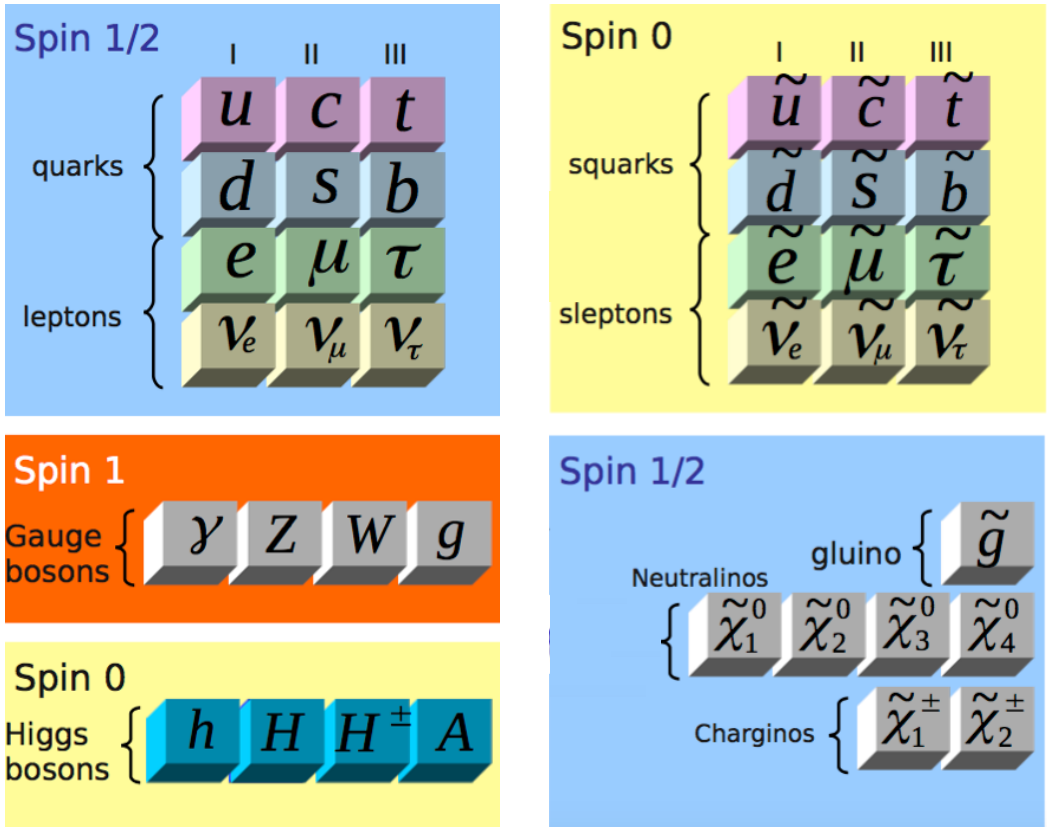
- Generalities
- New results at 13 TeV based on 2016 data
  - Gluinos
  - Squarks of 1st and 2nd generations
  - Stops
  - Sbottoms
  - EWKinos
- Conclusions

Other experimental talks on SUSY today:
- Marc Besancon (EWKinos@CMS)
- Edoardo Gorini (SUSY@ATLAS)
- Batool Safarzadeh Samani (Stop@CMS)

Generalities

Naive Introduction

Supersymmetry (SUSY) = new symmetry between forces and matter.
➔ Complete spectrum of partners to standard model particles, with same quantum numbers except for the spins which are different by 1/2 unit, and heavier.



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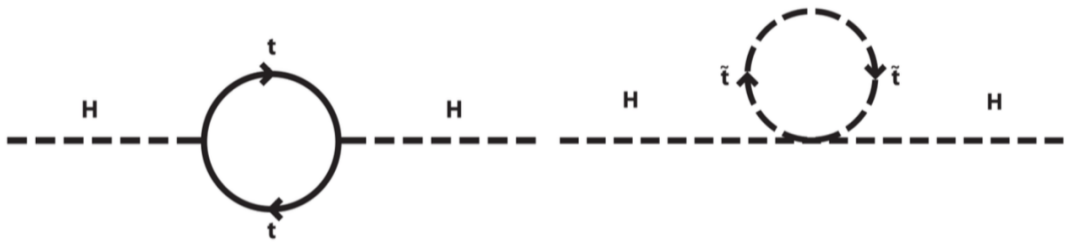
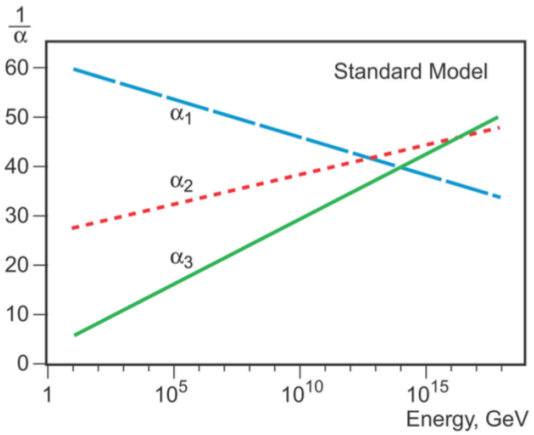
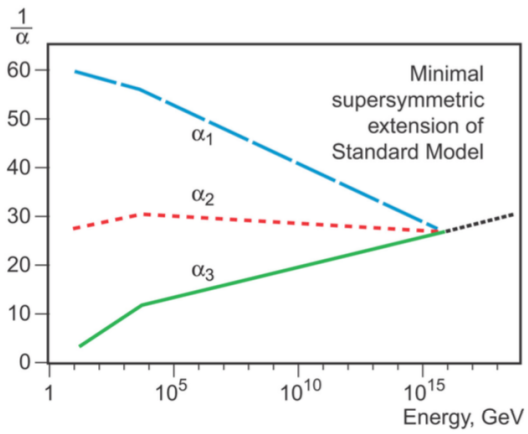






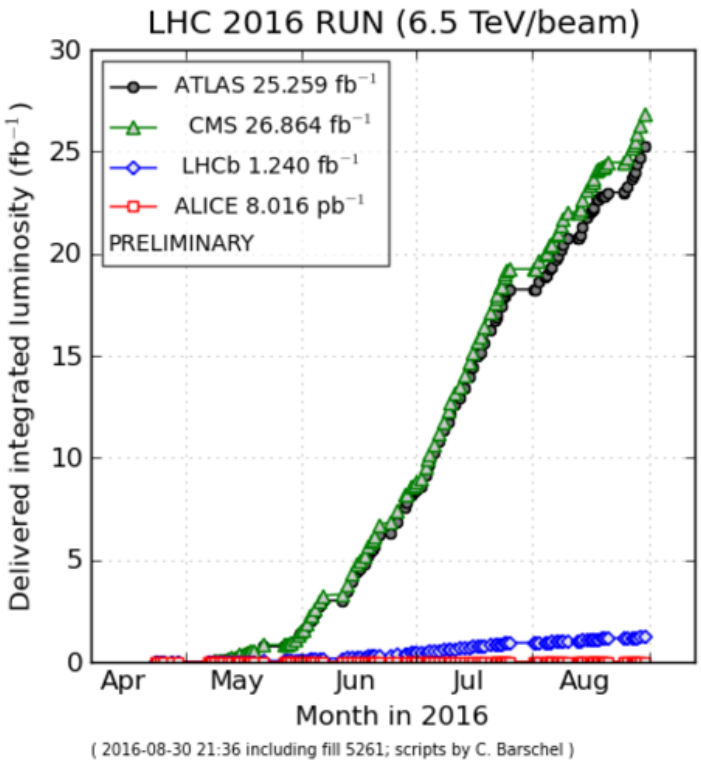
Why do people like Susy so much?

- Stabilize the Higgs boson mass,
- Provide a Dark Matter candidate if the R-parity is conserved,
- Realize the grand unification of the gauge couplings

The present situation

- LHC is performing extremely well:
  - Collisions at $\sqrt{s}$ (Run2)= 13 TeV
  - Peaks at instantaneous luminosity already exceeding the design value
  - Integrated luminosity already reaching the target value for 2016 (25 fb^{-1})

    → Is SUSY around the corner?



- Challenges for the experiments:
  - Need to keep trigger rates under control
  - Deal with increasing number of Pile-Up events
  - Follow the data-taking conditions with online and offline calibrations

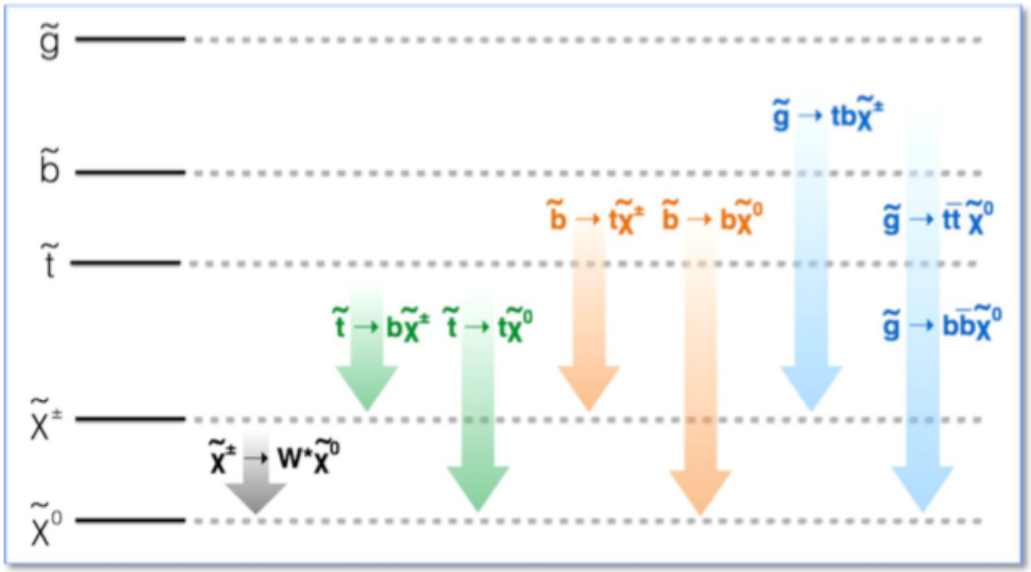
Which SUSY to search for?

- The potential parameter space is enormous:
  cMSSM (4+1), pMSSM (19), MSSM (105), NMSSM, …

- Some scenarios are privileged in our searches:
  - R-Parity conserved with lightest SUSY particle (LSP) = $\tilde{\chi}_1^0$
    - Dark Matter candidate
    - Classical SUSY signature with high transverse missing energy (MET)
    - Strong or electroweak production
  - Gauge mediated symmetry breaking (GMSB)
    - Decay chain terminated with low mass and invisible particles
    - Typical signature: MET from $\tilde{G}$, photons or Z from last decay step
  - R-Parity violating
    - Coupling strongly constrained (proton stability)
    - Loose MET handle for background reduction
    - Alternative signature, like high jet multiplicity

Use of SMS

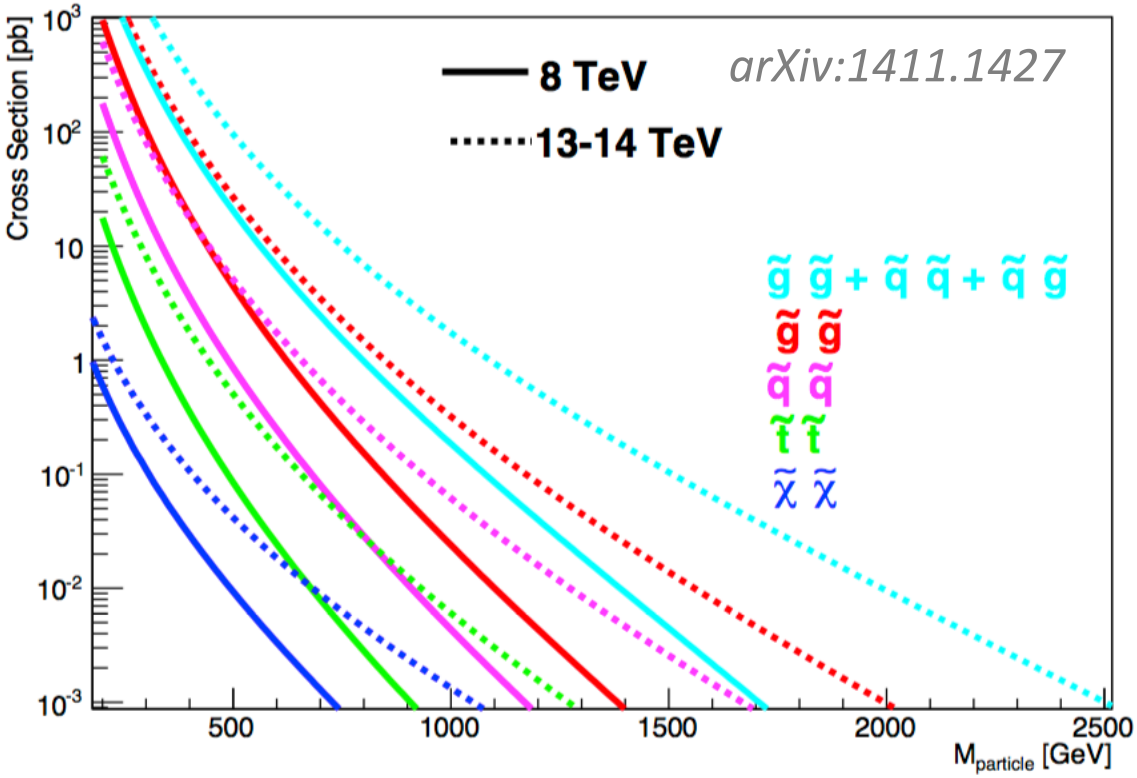
- SMS (Simplified Models Spectra):
  - Reduce the SUSY spectrum to only particles you are looking at
  - Instead of scanning SUSY model parameters, scan over masses
  - Consider only 1 or 2 decay modes → BR often fixed to a value (100%)



- Very useful to define the signal regions (as closely related to experimental observables) and to interpret the results. Usually the masses of SUSY particles are scanned in 2 dimensions.

What are the associated cross sections?

- Pair production of SUSY particles if R-parity is conserved.
- Cross-sections depending on the mass of the SUSY particles.
- Large increase of the cross-sections of massive particles at 13 TeV:



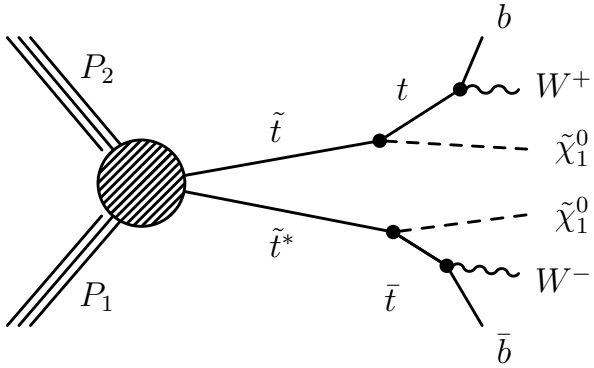
$\sigma(\tilde{g}\tilde{g}) \times 30$ for $m(\tilde{g}) = 1.4$ TeV
$\sigma(\tilde{t}\tilde{t}) \times 8$ for $m(\tilde{t}) = 700$ GeV
$\sigma(\tilde{\chi}\tilde{\chi}) \times 4$ for $m(\tilde{\chi}) = 500$ GeV

In contrast to SM: $\sigma(t\bar{t}) \times 3.3$

$\Rightarrow$ S/B boost !

How do we search for susy?

example: the stop pair production



1. Select you preferred signal, with its associated decay. It can be classified as a function of the lepton #: 0l, 1l, 2l, ...

2. Play with the different observables to enrich S/B

   - Standard SM objects: isolated leptons, jets, b-jets, MET = $|-\Sigma(\text{particle})\ p_T|$
   - Composite, boosted objects: topness, boosted W and top taggers, jet substructure
   - Kinematic variables to reconstruct mass of intermediate states: m_T of (l, MET) or (b, MET), m_{T2}, m_{CT}, …
   - Hadronic/total energy: $H_T = \Sigma(\text{jets})\ |p_T|$, $M_{HT} = |\Sigma(\text{jets})\ p_T|$, $m_{eff} = \Sigma(\text{jets, leptons})\ |p_T| + \text{MET}$, …
   - Event kinematics: hemispheres, razor, recursive jigsaw reconstruction,…

How do we search for susy?

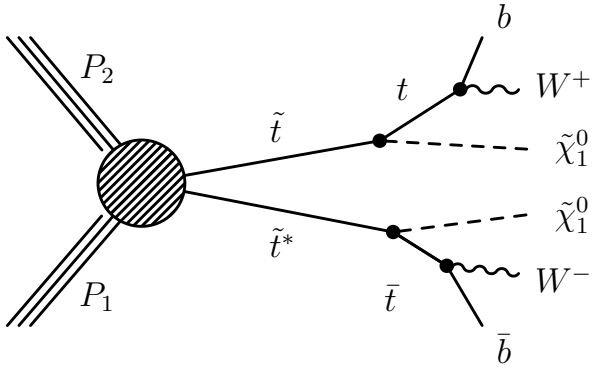
1. Select you preferred signal, with its associated decay. It can be classified as a function of the lepton #: 0l, 1l, 2l, ...

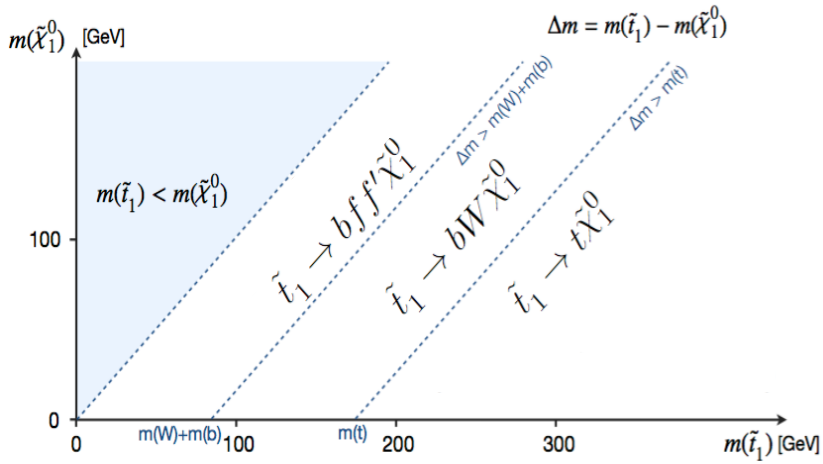
2. Play with the different observables to enrich S/B

3. Optimize your selection depending on the parameter space: High Δm, compressed spectra, ... → several signal regions (SR)

4. Different approaches can be used: multi-variate (with BDT) or cut&count. In Run2 mainly cut&count approach.

example: the stop pair production





(not considering $\tilde{t}_1 \to$ b $\tilde{\chi}_1^{\pm}$ or $\tilde{t}_1 \to$ c $\tilde{\chi}_1^0$ in this figure)

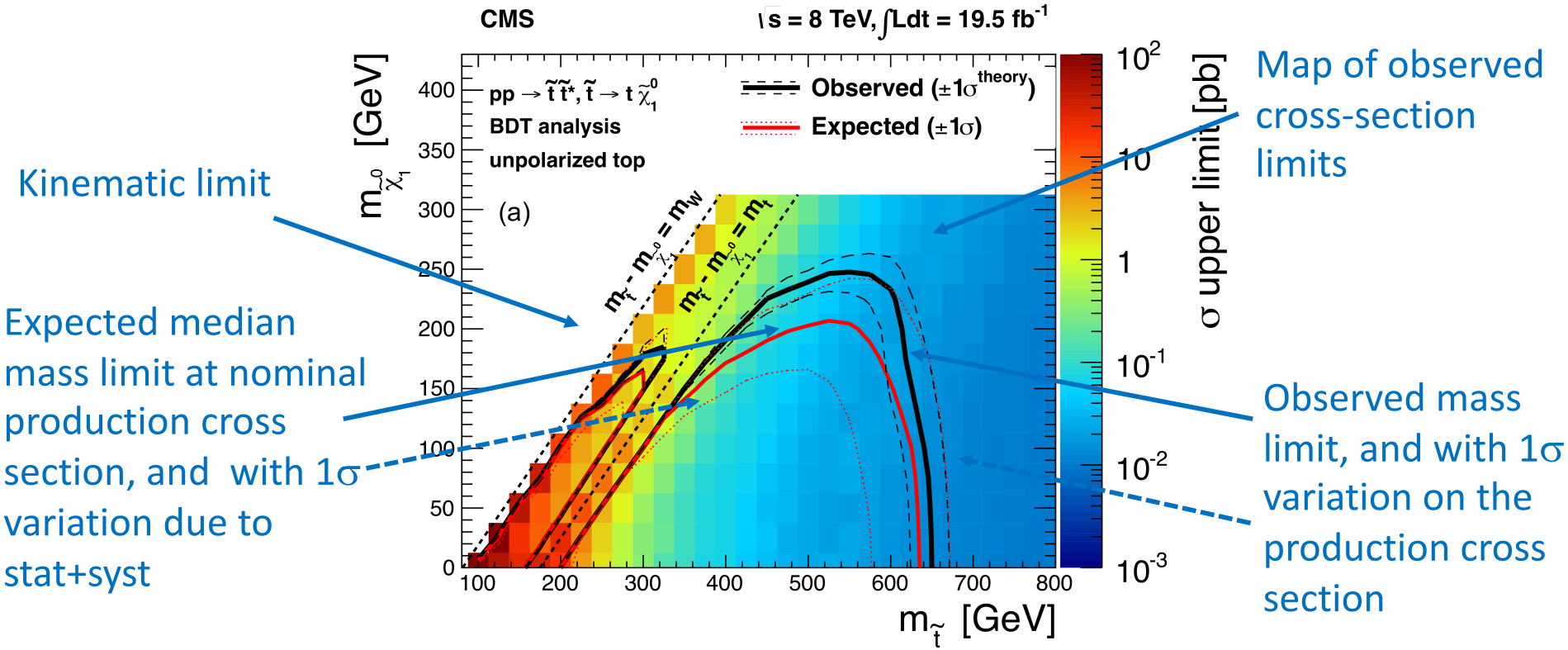
Background estimate

- SUSY analyses can not rely on perfect modeling in MC to estimate background yields in SR.
- Major backgrounds are estimated with data-driven techniques using orthogonal control regions (CR), typically by varying the lepton multiplicity or the b-jet multiplicity.
  - Otherwise stay as close as possible to the signal regions (~ same binning)
  - If statistically limited, an integration over some variables is done
  - Use of Transfer Factors (Control region → Signal region)
- Yields of Rare backgrounds are taken from simulation
  - reweighted to the most accurate cross-section and to known mis-modeling of the simulation (ex: PU)
  - all uncertainties (theory – experimental) are taken into account

Interpretation of the results

- If no excess is observed in data, limits are derived based on the different SR (with the possibility to also have aggregated SR).

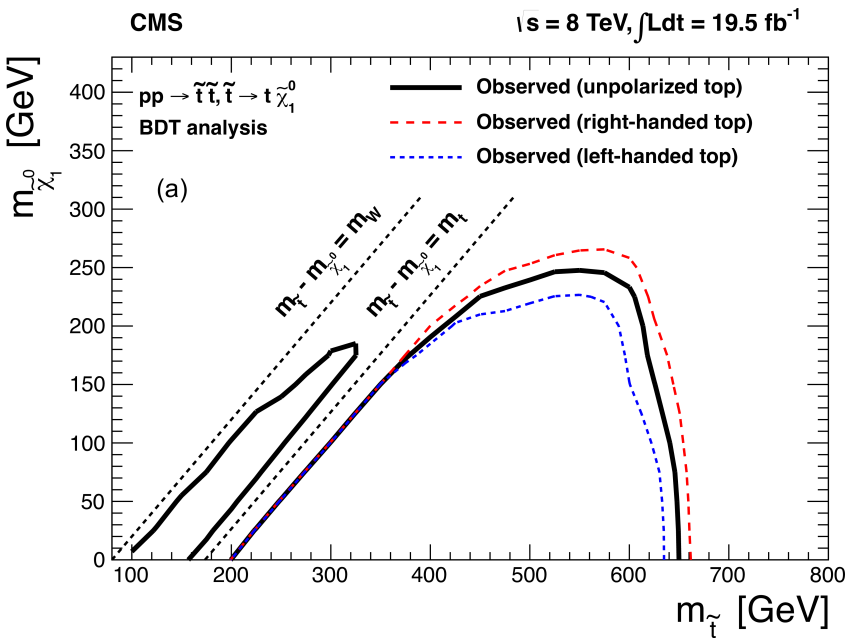
example: the stop pair production (Eur. Phys. J. C 73 (2013) 2677)



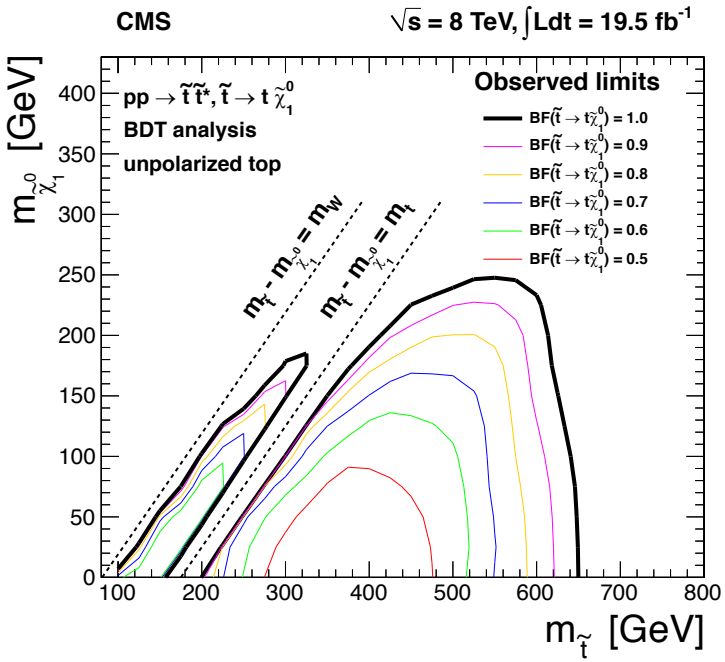
Interpretation of the results

- Remember that there are always some assumptions hidden in those limits

example: the stop pair production (Eur. Phys. J. C 73 (2013) 2677)



Impact of the top polarization

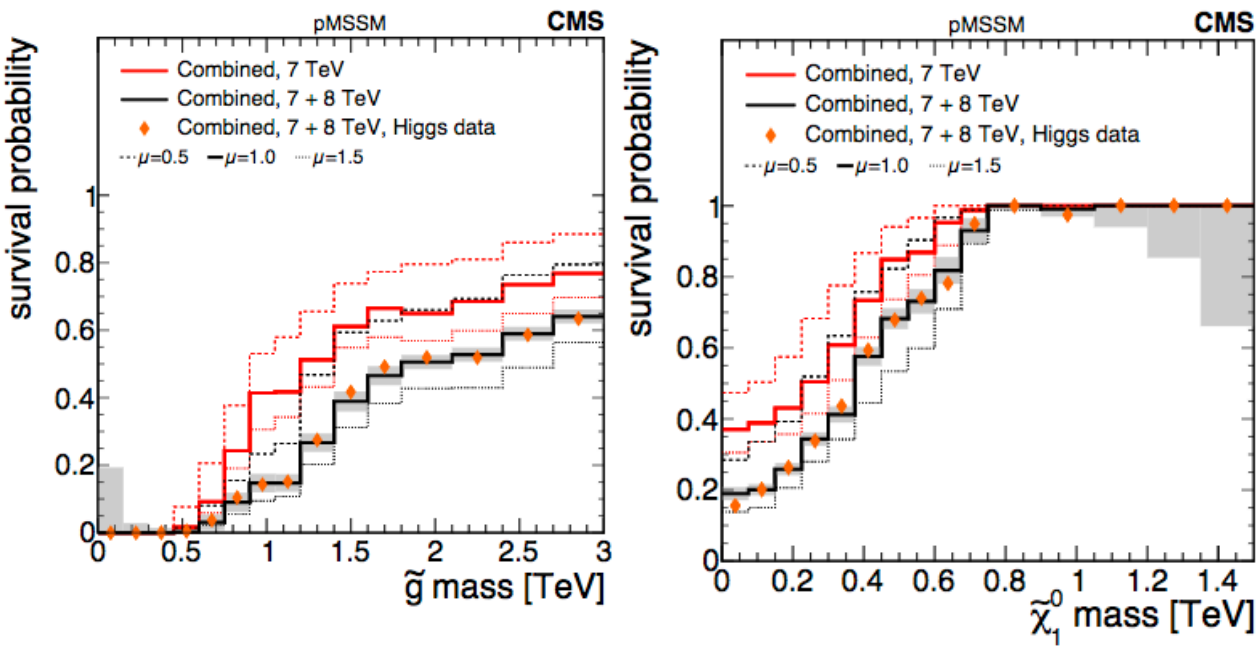


and of the BR on the limits

Reinterpretation

- SMS limits can be reinterpreted in other models.

Example: Reinterpretation within the pMSSM (MSSM in 19-dim subspace, assuming no CPV couplings, R-Parity conserved, degeneration of 1st and 2nd gen, MFV) of CMS searches (CMS, arXiv:1606.03577): Bayesian analysis including 11 CMS analyses @7 and 8 TeV. Goal: understand the impact of model parameters, limitation of SMS approach and search for "holes" in the experimental searches for MSSM, using scans of pMSSM parameter space.



(Similar study from ATLAS: JHEP 10 (2015) 134)

ATLAS-CONF-2016-*
CMS PAS SUS-16-*

New results with 13-18/fb at 13 TeV

A lot of new results this summer!

ATLAS : 12 CONF notes for ICHEP + 4 new CONF notes in August
CMS : 14 PAS for ICHEP + (7 PAS or papers on 2015 data only 2.3-2.7/fb)

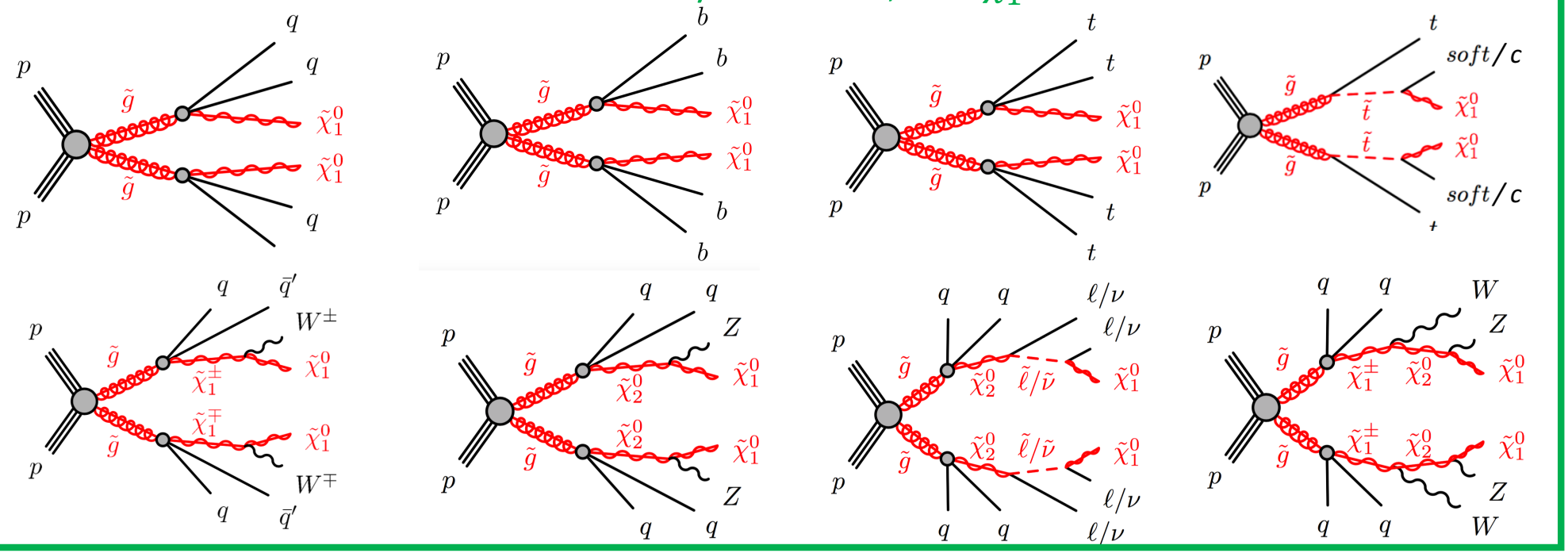
1. Gluinos

037, 052, 054, 057, 066, 077, 078, 094, 095

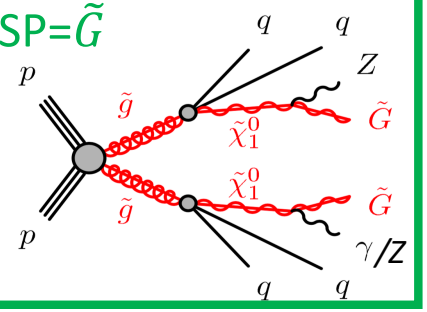
014, 015, 016, 019, 020, 021, 022, 030

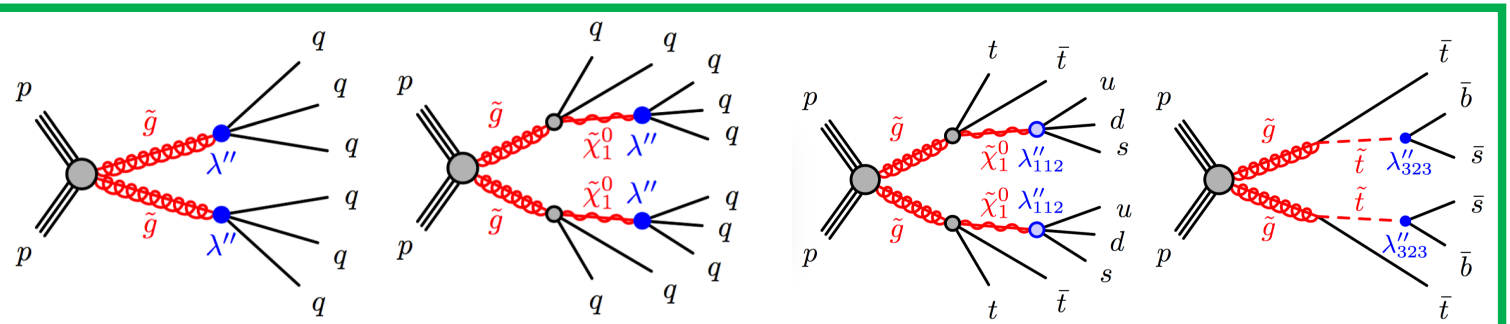
Highest SUSY production cross section → Plenty of searches in 2016!

R-Parity conserved, LSP=$\tilde{\chi}_1^0$



R-Parity conserved, LSP=$\tilde{G}$





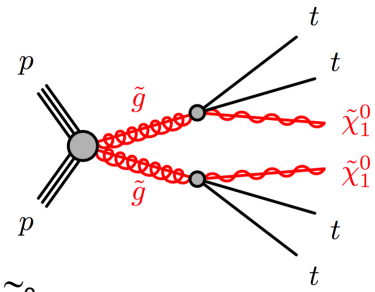
R-Parity violated

1. Gluinos

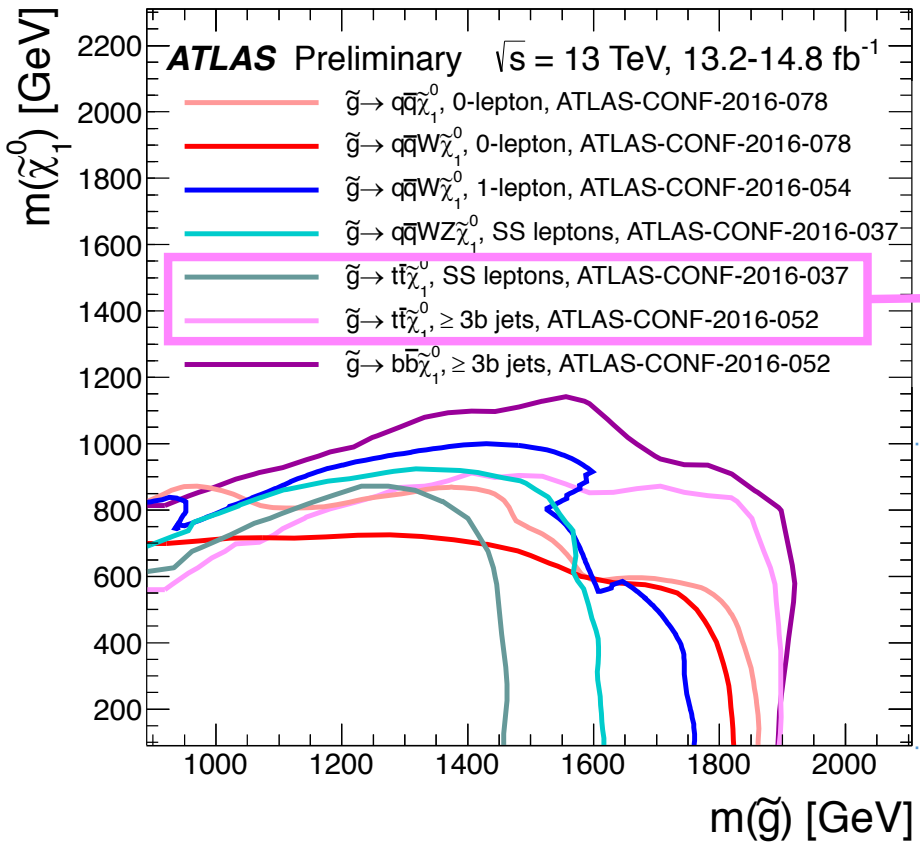
R-Parity conserved, LSP=$\tilde{\chi}_1^0$

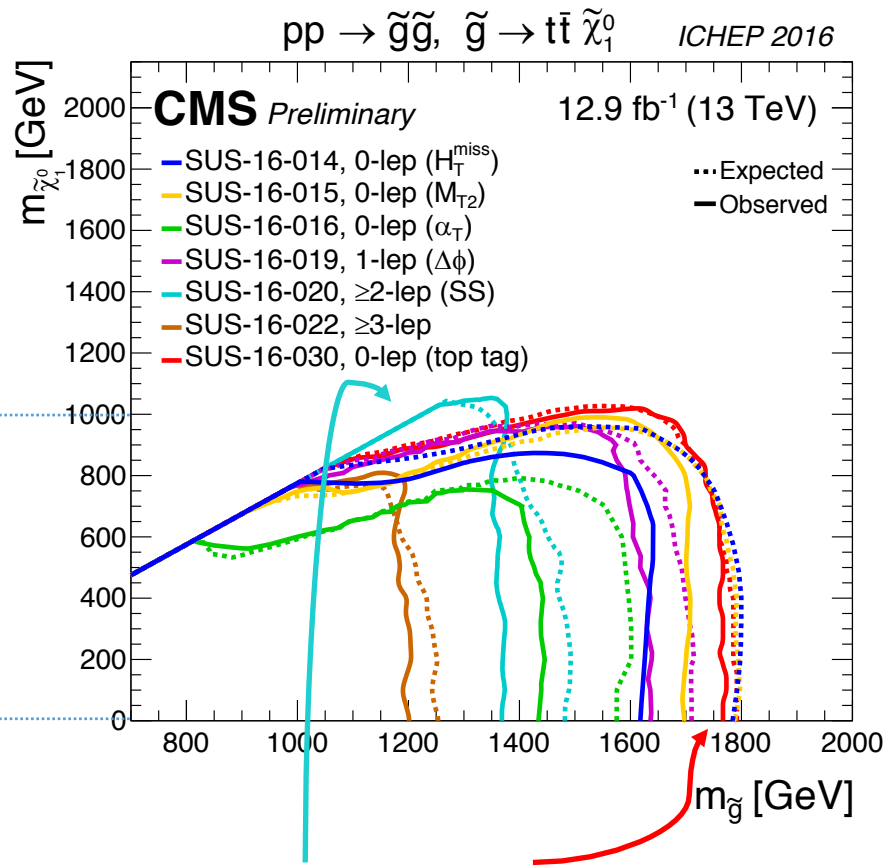
037, 052, 054, 077, 078, 095

014, 015, 016, 019, 020, 022, 030



Similar limits for ATLAS and CMS.





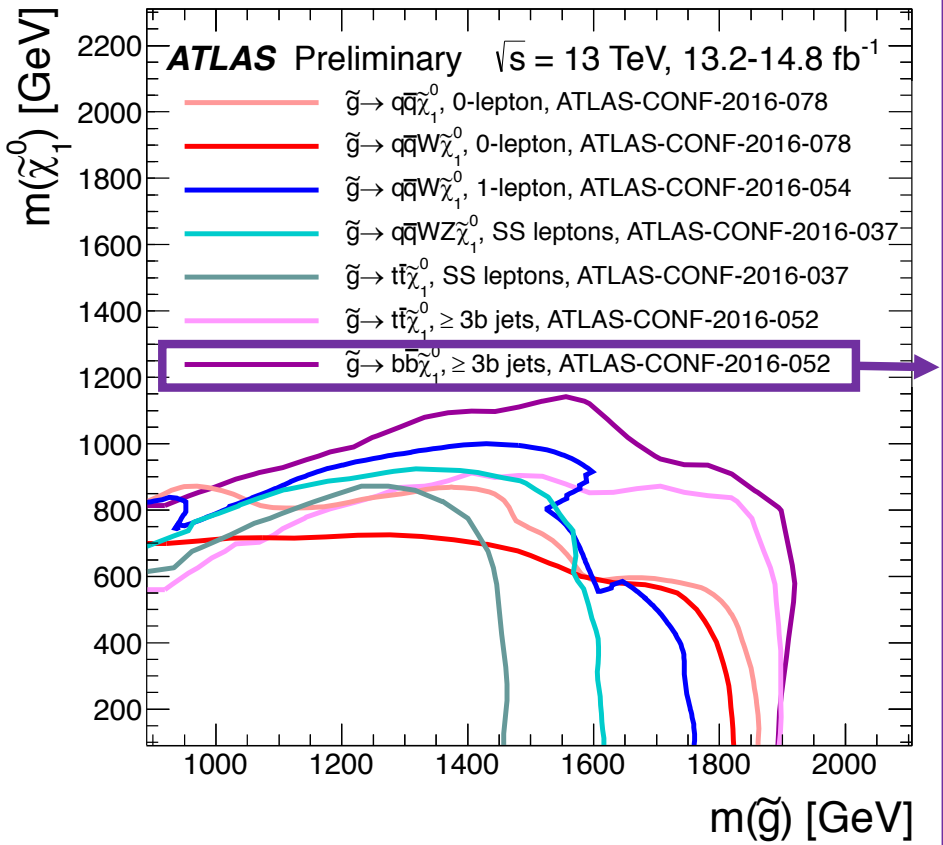
Complementarity of the analyses (Same Sign 2l and 0-lep)

1. Gluinos

R-Parity conserved, LSP=$\tilde{\chi}_1^0$

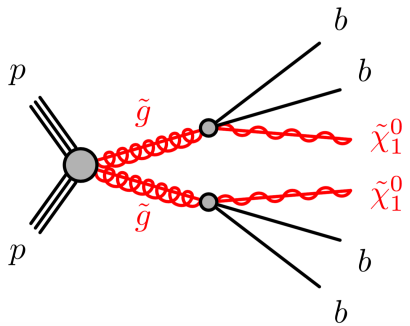
037, 052, 054, 077, 078, 095

014, 015, 016, 019, 020, 022, 030

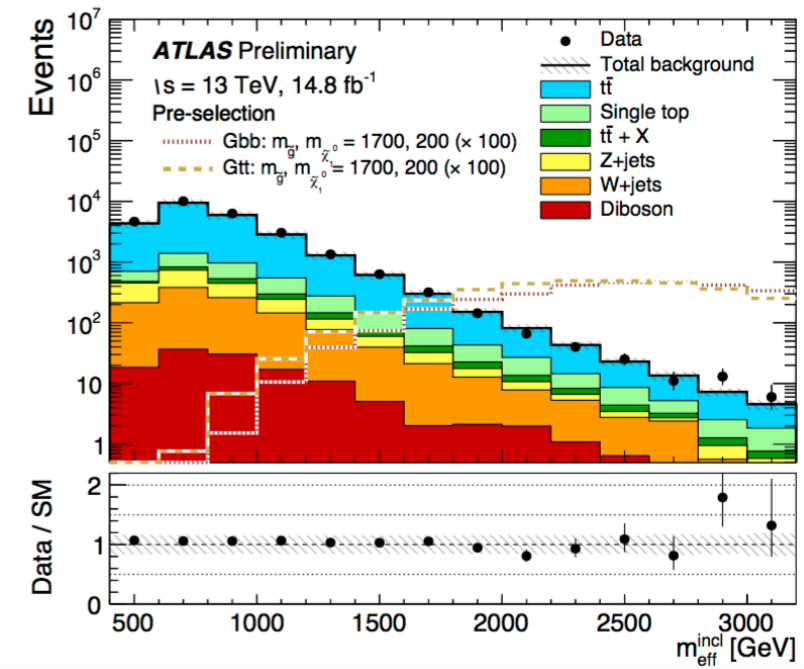


Hadronic search with ≥ 3 b-jets among 4 jets, using 2015 +2016 data (14.8/fb).

(ATLAS-CONF-2016-052)



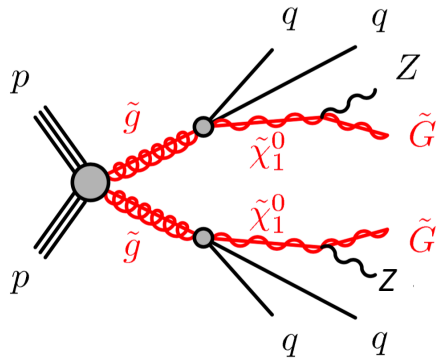
Key variables: p_T(jets), #b-jets, MET, m_{eff}, $\Delta\phi$(j,MET)



Improvement by 220 GeV w/respect to 2015 limits

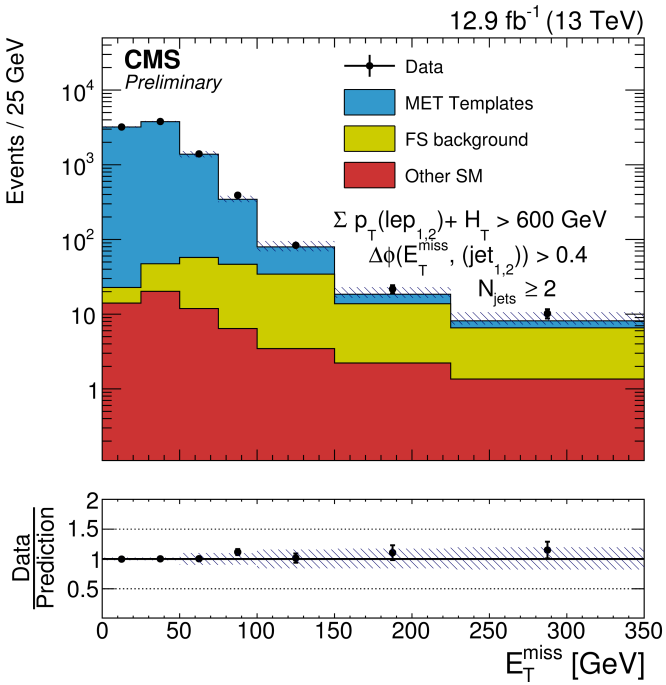
1. Gluinos

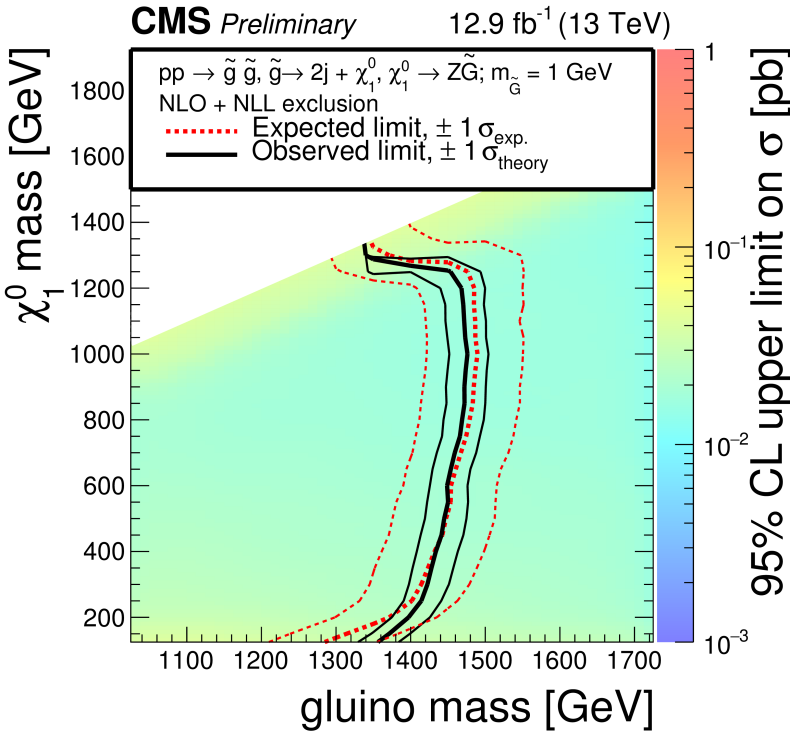
R-Parity conserved, LSP=$\tilde{G}$



Search with 2 leptons (Opposite Sign, Same Flavour → on-Z), jets, MET, using 2016 data (12.9/fb). (CMS PAS SUS-16-021)

Key variables: #jets, #b-jets, H_T, MET
+ 1 SR motivated by the ATLAS 3.0 σ excess at 8 TeV and 2.2 σ at 13 TeV (2015)
→ no excess in CMS



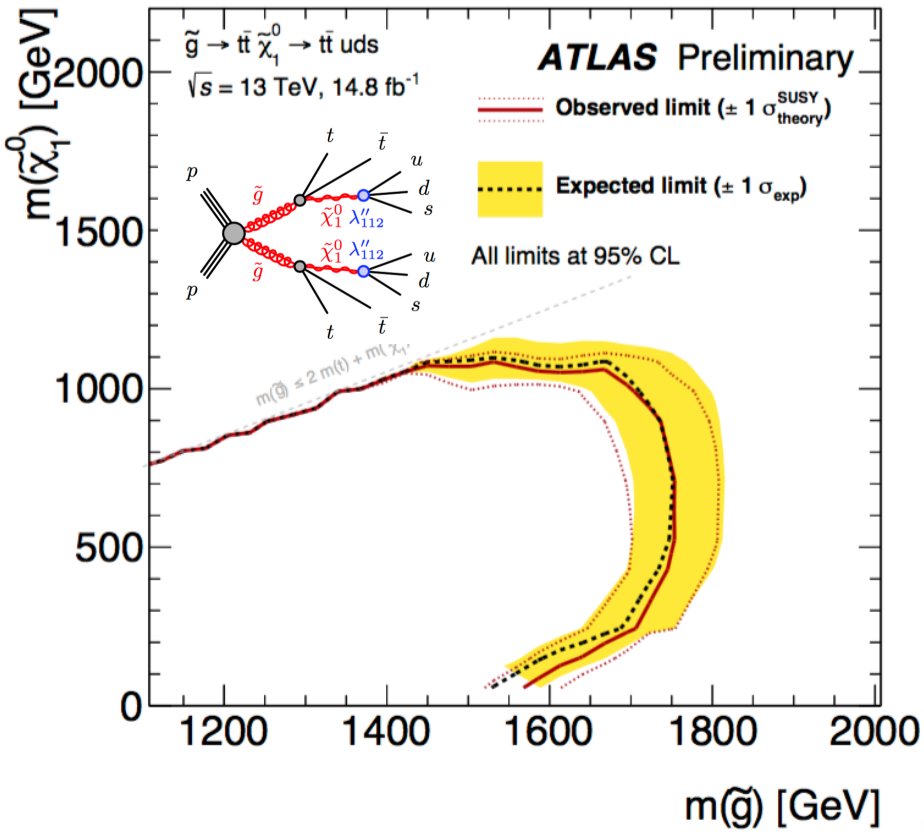


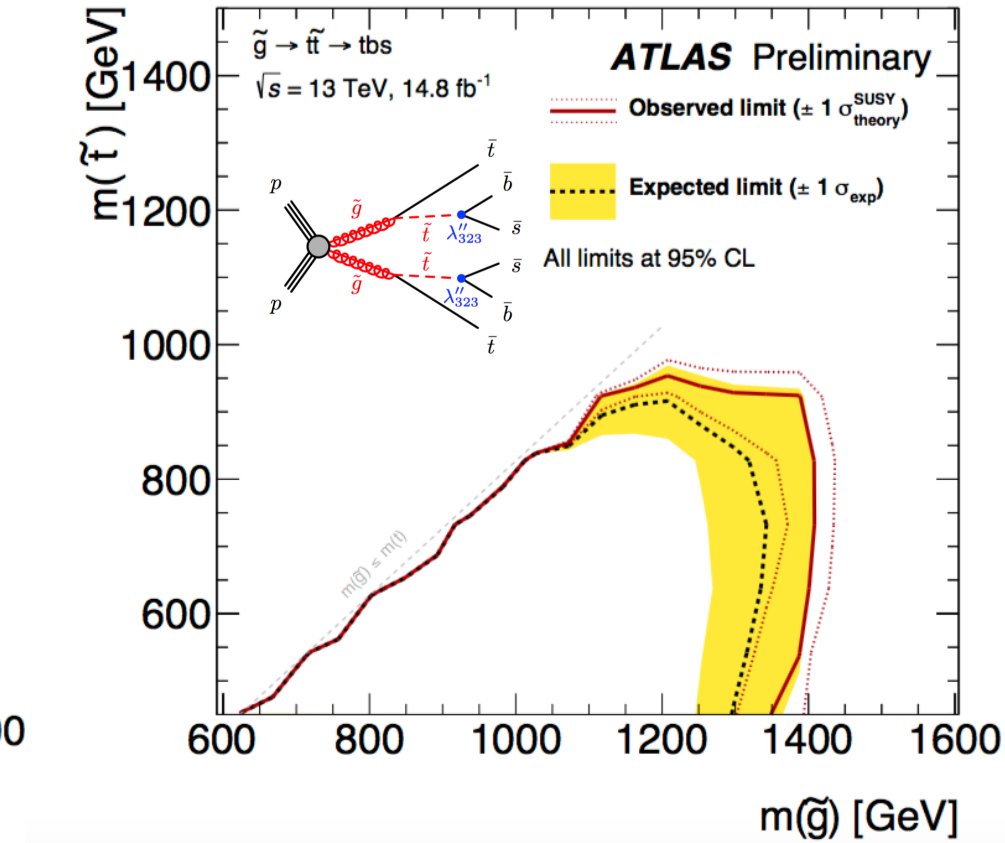
037,057, 094

1. Gluinos

R-Parity violated
(one coupling ≠0)

Search in ≥ 1 lepton (e/μ) + ≥ 8-10 jets, 0 or ≥ 3 b-jets, no MET (RPV)
using 2015 +2016 data (14.8/fb).
(ATLAS-CONF-2016-094)

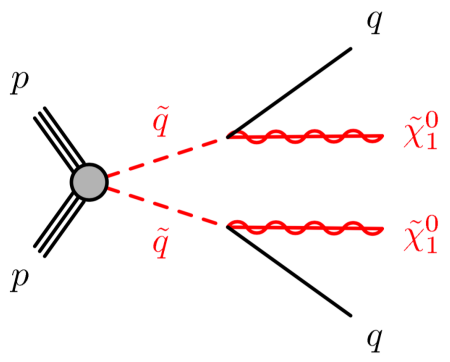


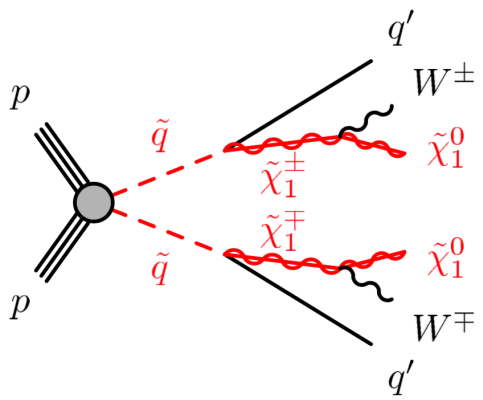


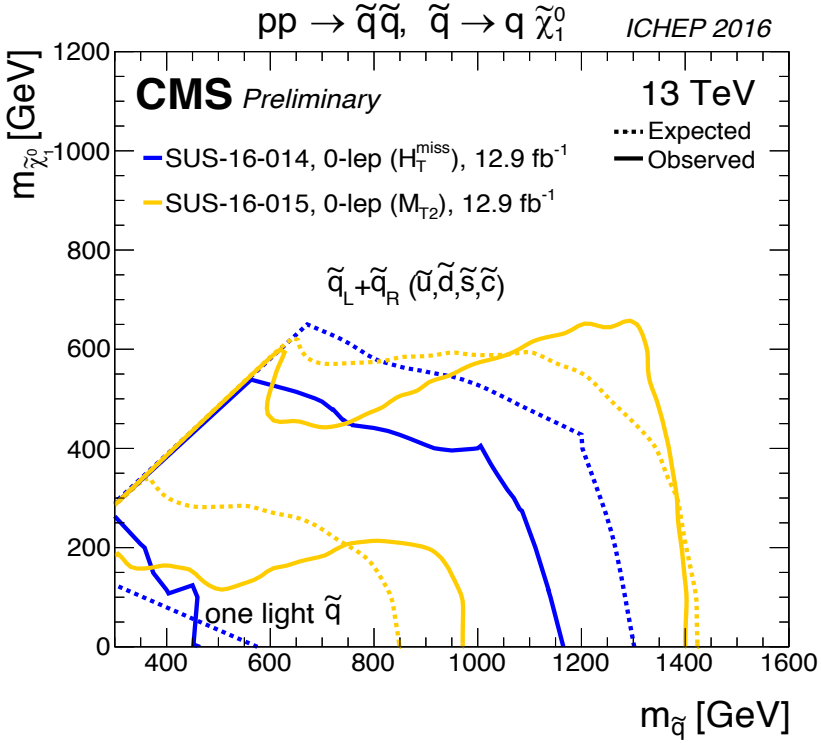
2. Squarks of 1st 2 generations

054, 078

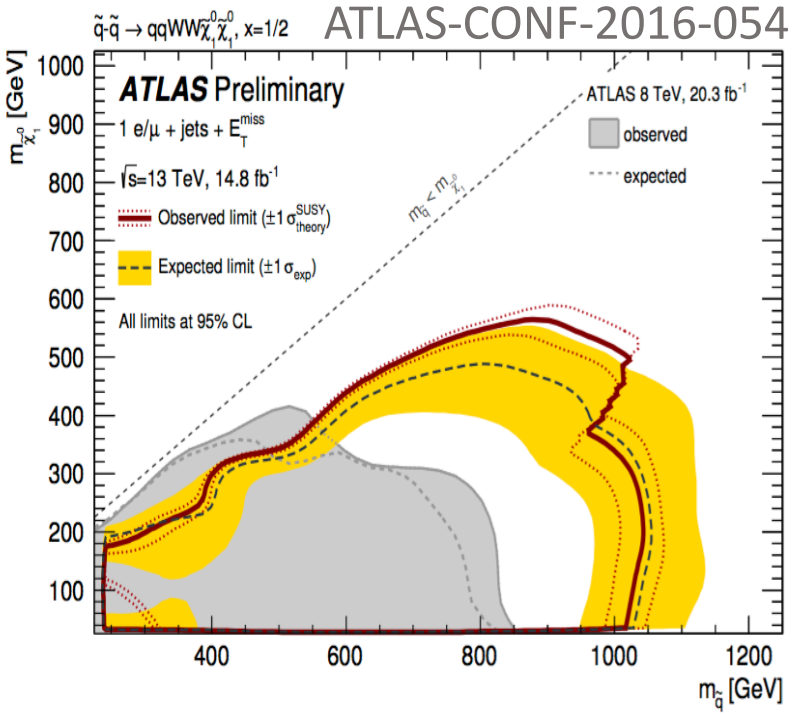
014, 015







ATLAS-CONF-2016-054



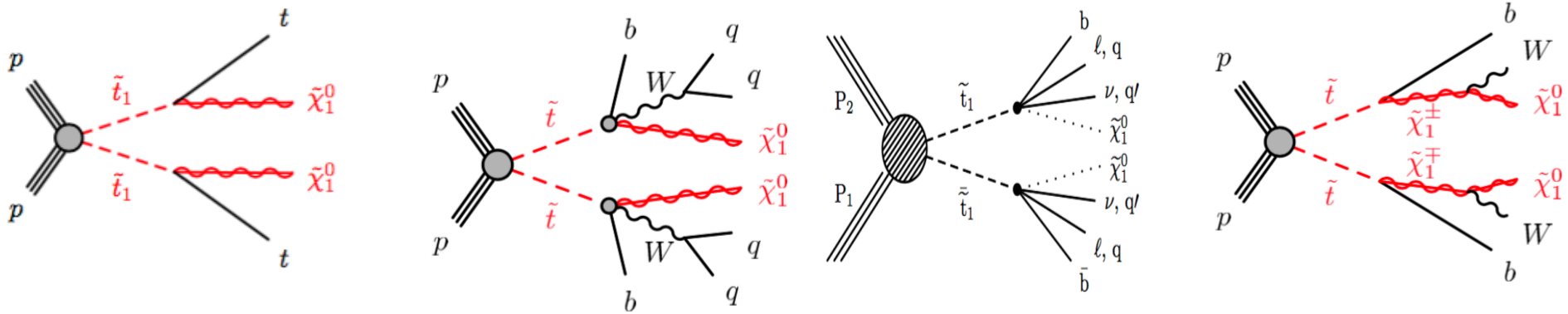
3. Stops

038, 048, 050, 076, 077, 084

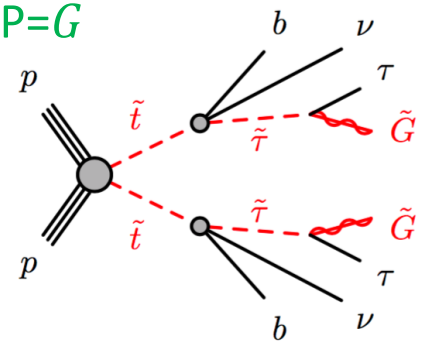
014, 015, 016, 025, 028, 029, 030

In Natural SUSY, m_{Stop} < 1-1.5 TeV → Plenty of searches in 2016!

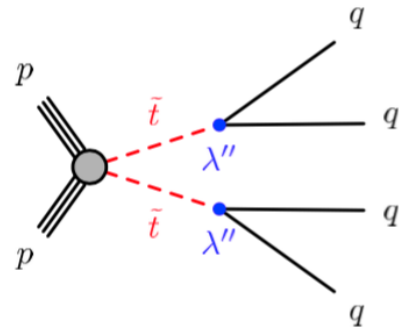
R-Parity conserved, LSP=$\tilde{\chi}_1^0$

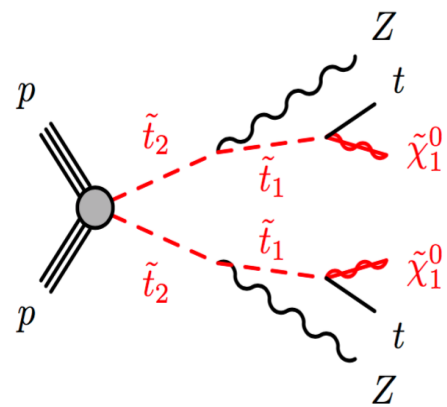


R-Parity conserved, LSP=$\tilde{G}$



R-Parity violated





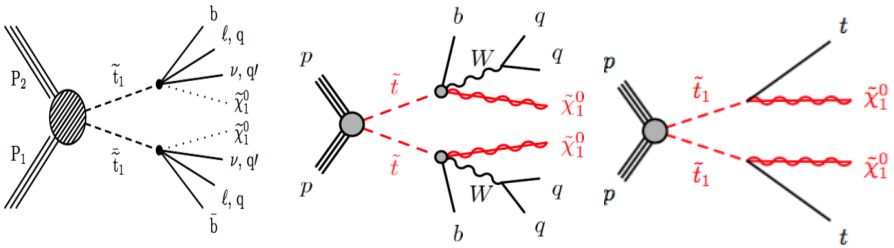
3. Stop$_1$

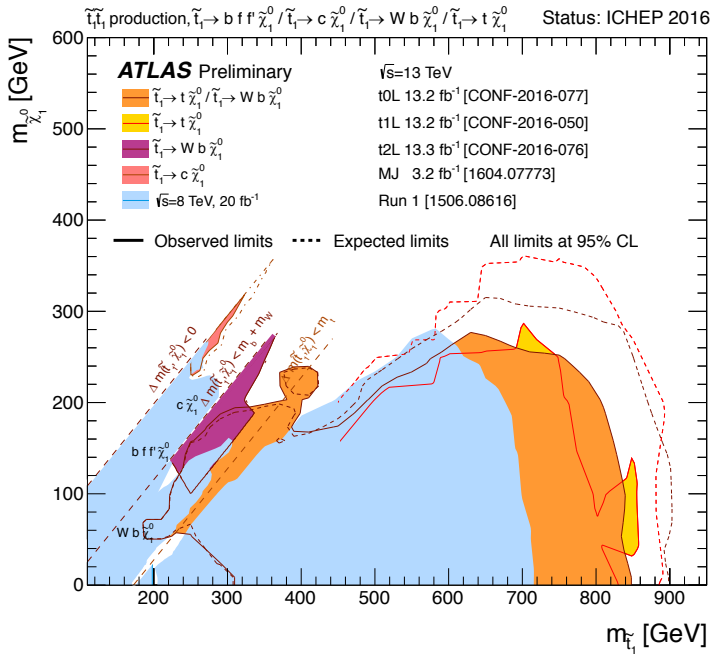
R-Parity conserved, LSP=$\tilde{\chi}_1^0$

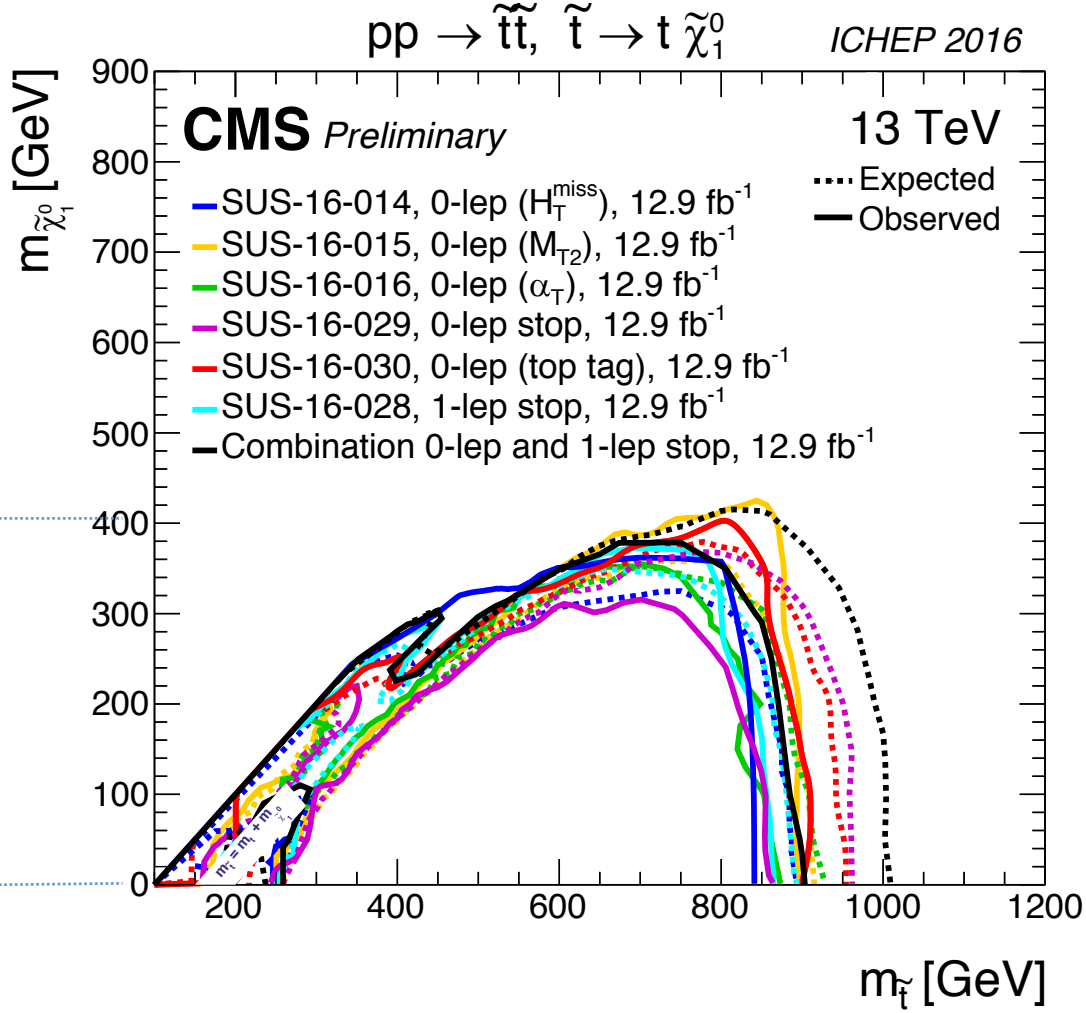
038, 048, 050, 076, 077, 084

014, 015, 016, 025, 028, 029, 030

Different channels : 0l, 1l, 2l, 2 soft l. Pushing the limits to larger m_{Stop} and m_{LSP} .
Start filling the region with $\Delta m = m_{top}$.







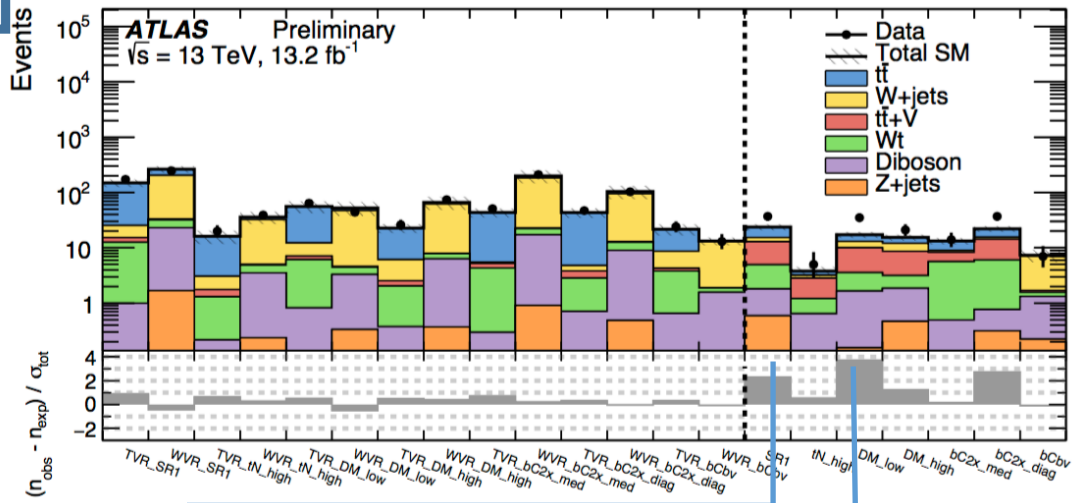
3. Stop$_1$

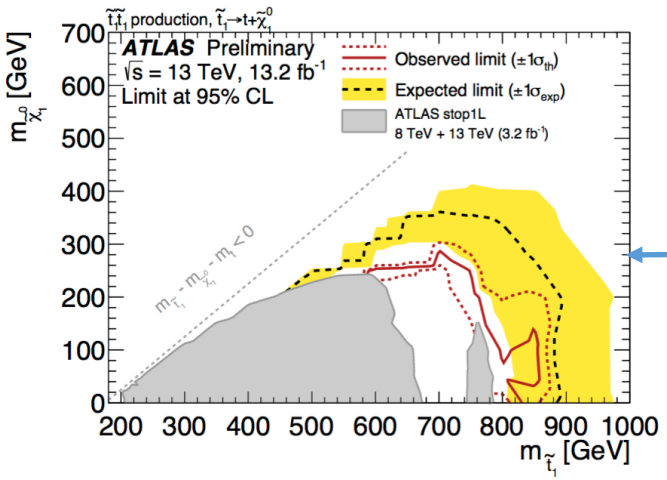
R-Parity conserved, LSP=$\tilde{\chi}_1^0$

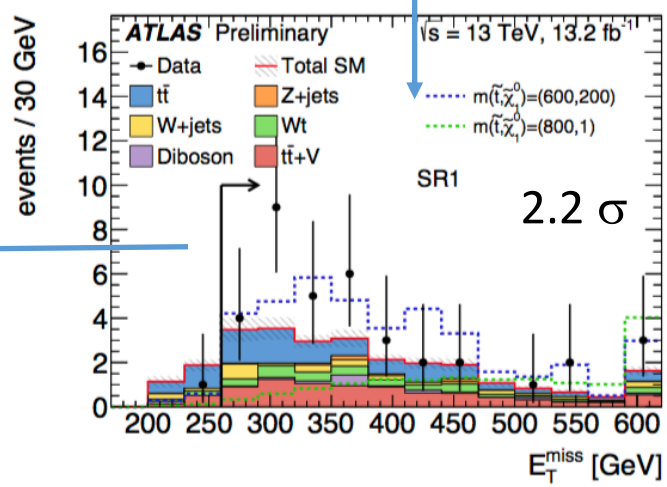
038, 048, 050, 076, 077, 084

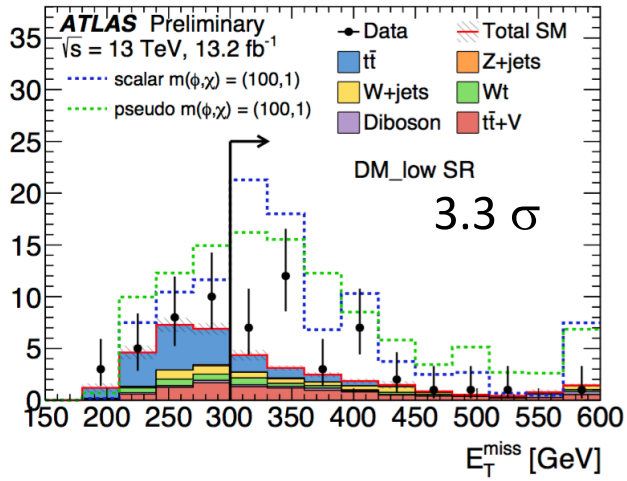
014, 015, 016, 025, 028, 029, 030

Search in 1 lepton (e/μ) + ≥ 4 jets, b-jets, hight MET & m_T(l,MET)
using 2015 +2016 data (13.2/fb).
(ATLAS-CONF-2016-050) : largest local excess of 3.3 σ







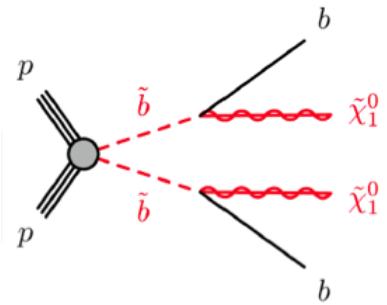


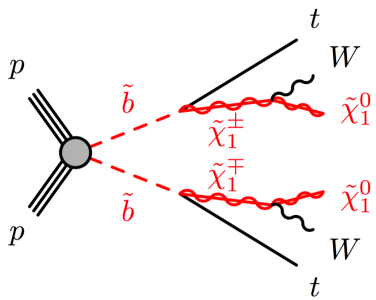
SR dedicated to $t\bar{t}$ + DM with scalar or pseudo scalar mediator

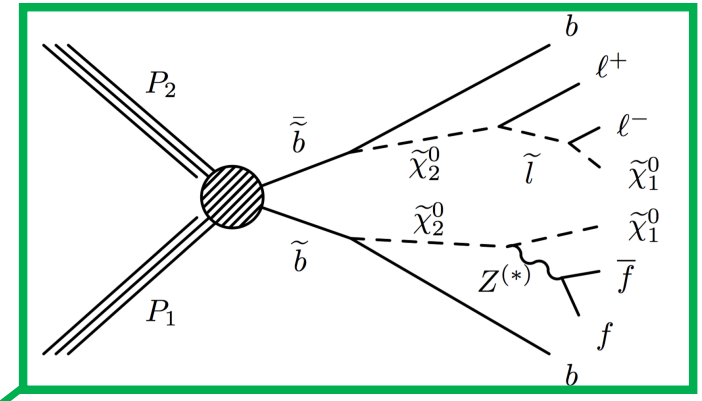
3. Sbottom

037

015, 016, 021

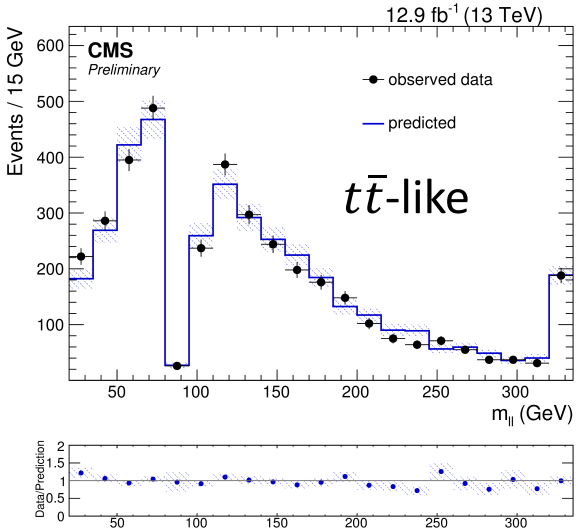


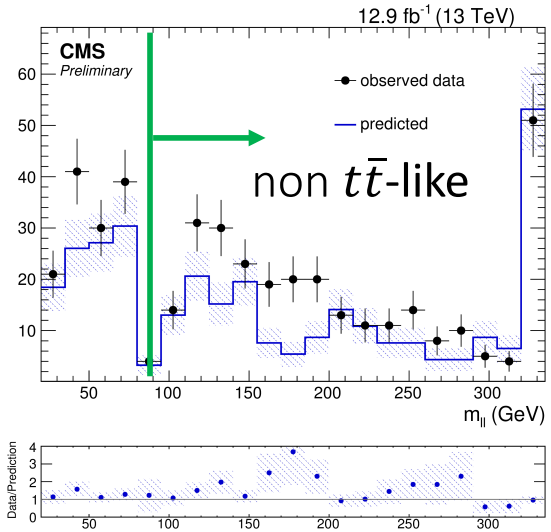


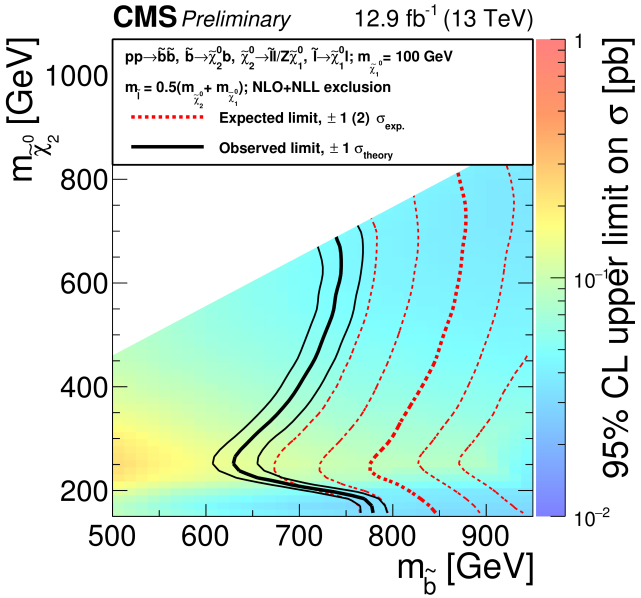


Search with 2 leptons (OS, SF → off-Z), ≥ 2 jets, MET, using 2016 data (12.9/fb) (CMS PAS SUS-16-021), also known as the dilepton mass edge analysis.

off-Z regions targeting kinematic edge in decay chain. One 3.1 σ local excess in one SR.





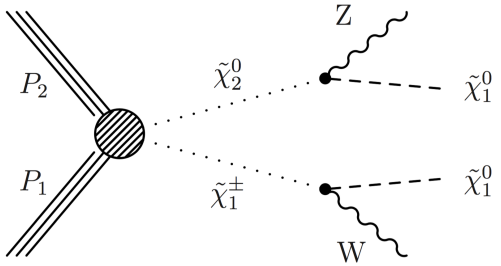


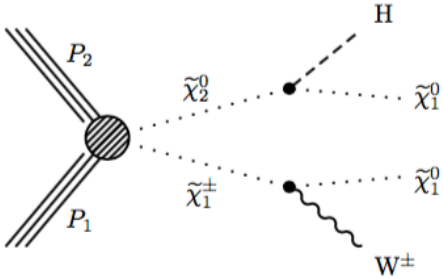
4. EWkinos

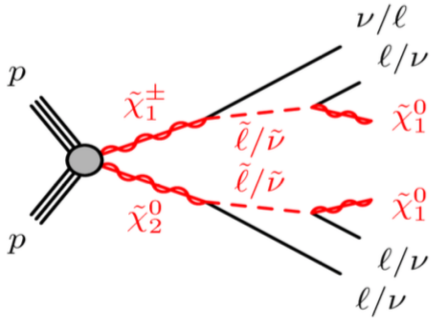
075, 093, 096

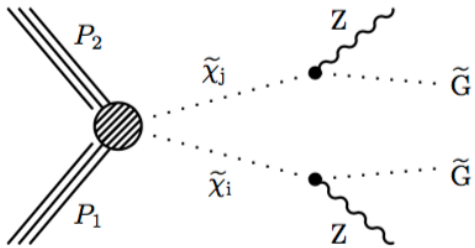
021, 024, 025, 026

Electroweak production, with low cross section.

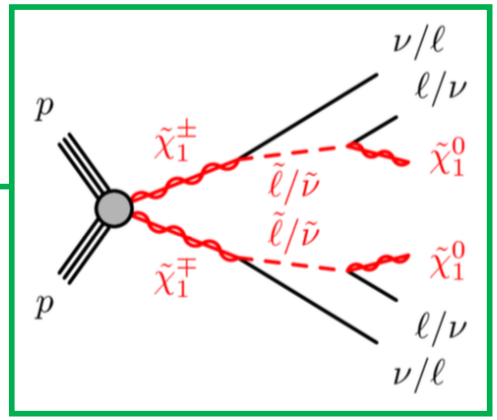


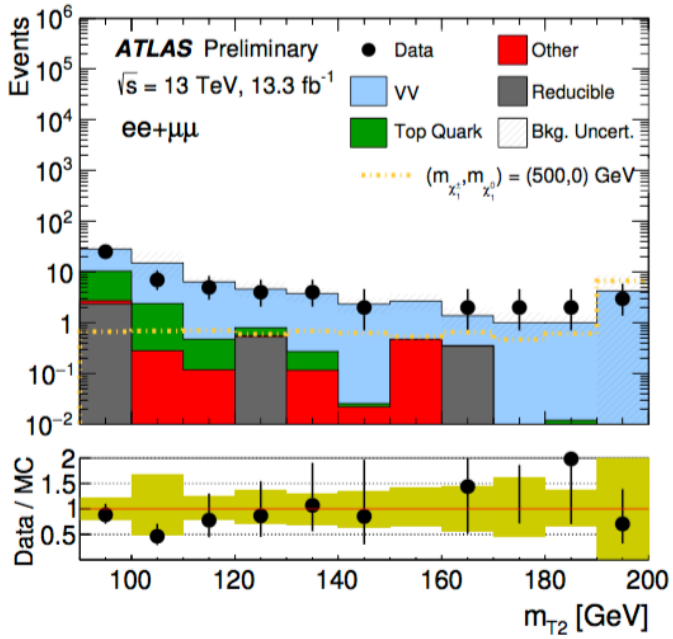


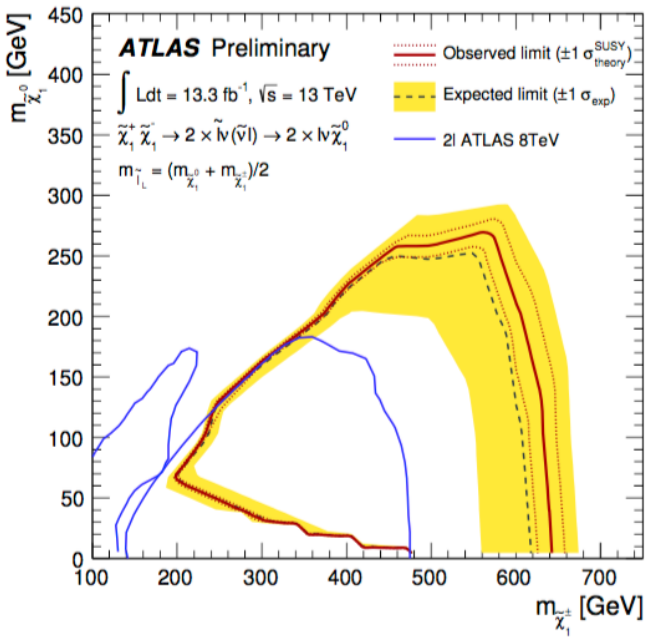


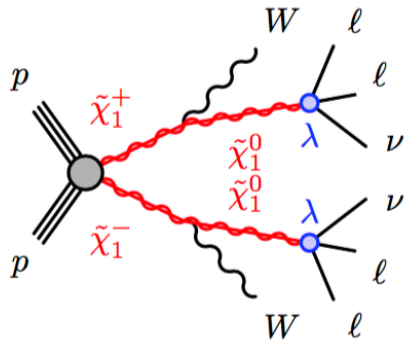


Search with =2 leptons (OS, SF off-Z or DF), MET, no jet, using 2015+2016 data (13.3/fb) (ATLAS-CONF-2016-096).



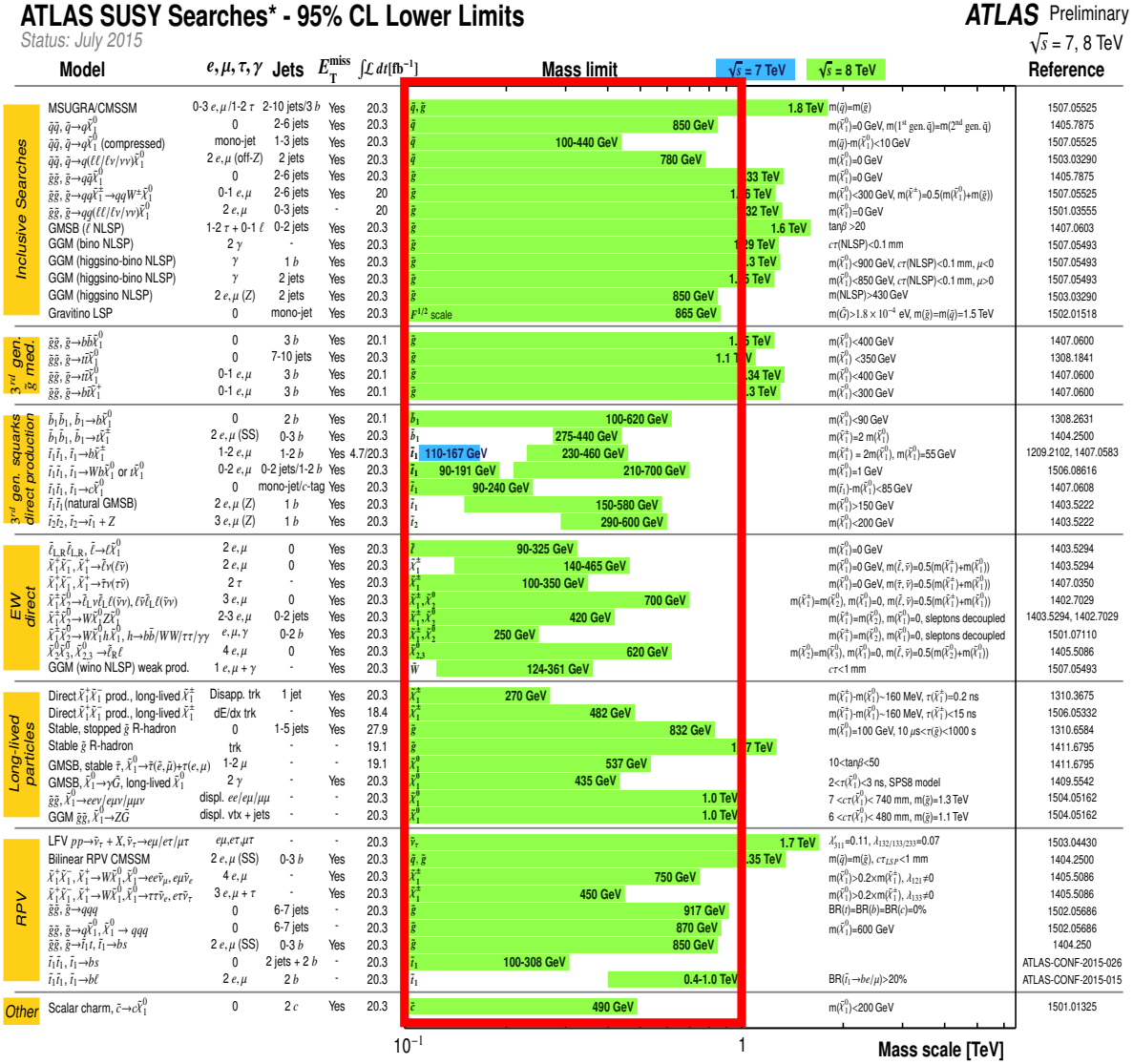






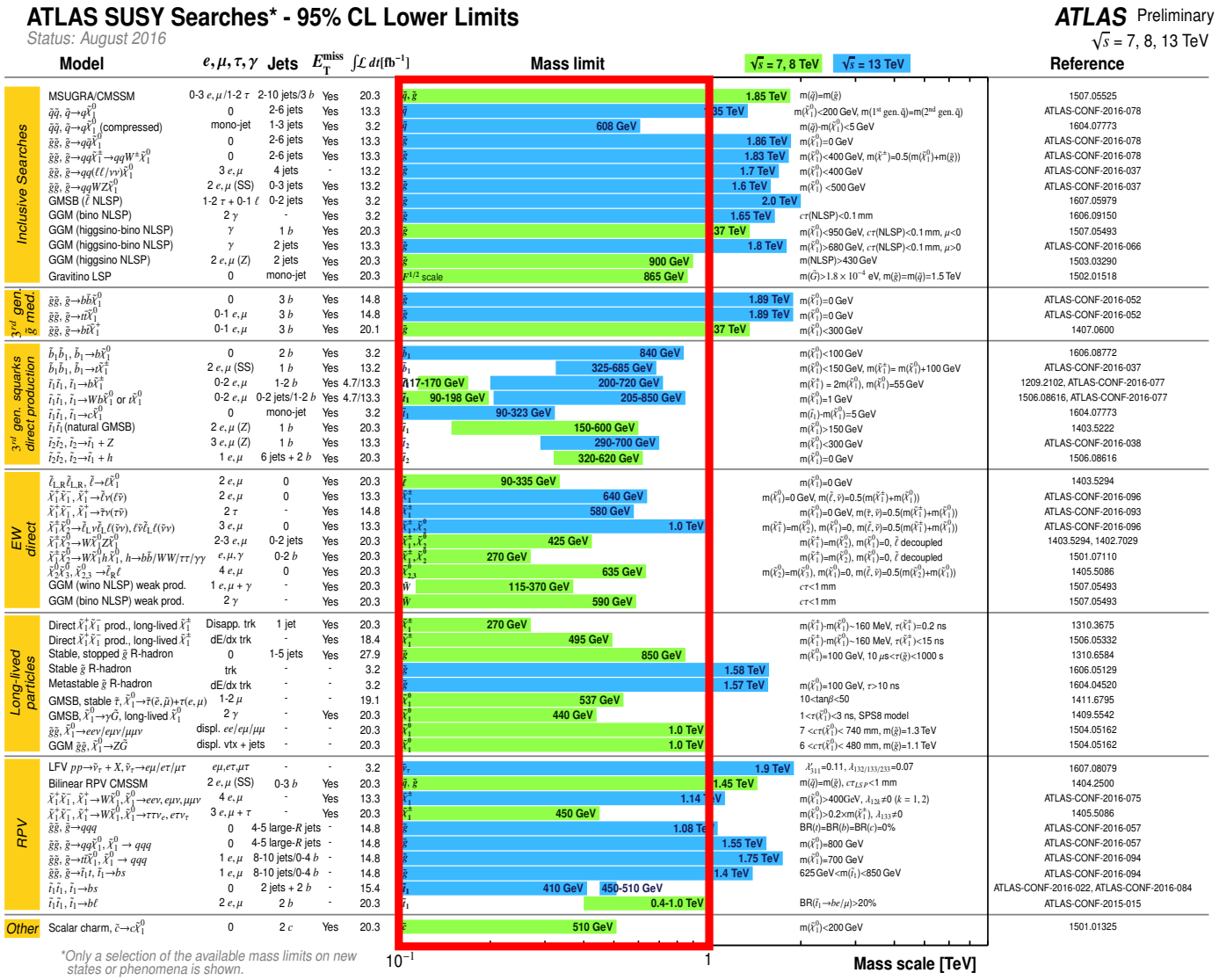
5. Summary plots

(on Run1 results)



5. Summary plots

(NOW)



Run2 Limits (when available) exceed Run1 limits!

Conclusions

- LHC is performing extremely well, allowing considerable increase in sensitivity with only a partial 2016 data set.
- Despite some small excesses, **no discovery of SUSY yet**. We are pushing the limits higher and higher : 1.9 TeV for the gluino, 900 GeV for the stop, ...
- New challenging scenarios are under study at 13 TeV like electroweak production, compressed mass spectra, …
- But a question remains: Where is this famous corner behind which SUSY is waiting for us? **Let's hope** significant deviations will be at the agenda of the next "LHC days in Split" conference.

References for ATLAS latest results

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Summer2016-13TeV

Topic	Document type	Short title (link to ATLAS Physics Briefing)	Reference and Link	Release conference
SUSY physics	Conference note	Searches for SUSY with two same-sign or three leptons and jets (briefing)	ATLAS-CONF-2016-037	ICHEP
SUSY physics	Conference note	Searches for SUSY top squarks with Z bosons (briefing)	ATLAS-CONF-2016-038	ICHEP
SUSY physics	Conference note	Searches for SUSY top squarks in events with tau leptons (briefing)	ATLAS-CONF-2016-048	ICHEP
SUSY physics	Conference note	Searches for SUSY top squarks in events with one lepton (briefing)	ATLAS-CONF-2016-050	ICHEP
SUSY physics	Conference note	Searches for SUSY in events with multiple b-jets (briefing)	ATLAS-CONF-2016-052	ICHEP
SUSY physics	Conference note	Searches for SUSY in events with one lepton (briefing)	ATLAS-CONF-2016-054	ICHEP
SUSY physics	Conference note	Searches for RPV SUSY signatures with multi-jet events (briefing)	ATLAS-CONF-2016-057	ICHEP
SUSY physics	Conference note	Searches for SUSY in events with photons and ETmiss (briefing)	ATLAS-CONF-2016-066	ICHEP
SUSY physics	Conference note	Searches for SUSY in events with four or more leptons (briefing)	ATLAS-CONF-2016-075	ICHEP
SUSY physics	Conference note	Searches for SUSY top squarks in events with two leptons (briefing)	ATLAS-CONF-2016-076	ICHEP
SUSY physics	Conference note	Searches for SUSY top squarks in events with no leptons (briefing)	ATLAS-CONF-2016-077	ICHEP
SUSY physics	Conference note	Searches for SUSY in events with jets and ETmiss (briefing)	ATLAS-CONF-2016-078	ICHEP
SUSY physics	Conference note	Searches for electroweak SUSY particles in events with two tau leptons	ATLAS-CONF-2016-093	SEARCH NEW
SUSY physics	Conference note	Searches for R-Parity violating SUSY particles in events with one lepton and jets	ATLAS-CONF-2016-094	SEARCH NEW
SUSY physics	Conference note	Searches for SUSY particles in events with large jet multiplicity	ATLAS-CONF-2016-095	SEARCH NEW
SUSY physics	Conference note	Searches for electroweak SUSY particles in events with two or three leptons	ATLAS-CONF-2016-096	SEARCH NEW

- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

References for CMS latest results

- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/ICHEP-2016.html

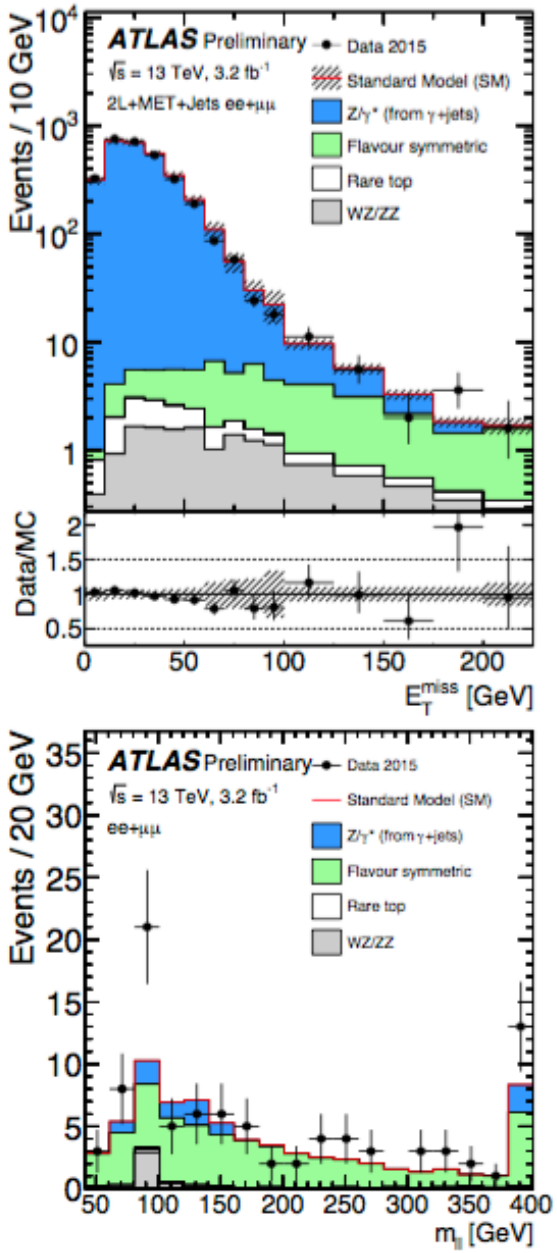
Supersymmetry

- Search for SUSY in multiple-jet final states at 13 TeV (2016 data)
- Search for SUSY in multiple-jet final states with the α_T variable at 13 TeV (2016 data)
- Search for SUSY in multiple-jet final state with the M_{T2} variable (2016 data)
- Search for SUSY in the all-hadronic final state using top quark tagging at 13 TeV (2016 data)
- Search for SUSY in one-lepton and multiple-jet final states at 13 TeV (2016 data)
- Search for SUSY in same-sign dilepton final states at 13 TeV (2016 data)
- Search for SUSY in opposite-sign, same-flavor di-lepton final states at 13 TeV (2016 data)
- Search for SUSY in soft opposite-sign leptons in the compressed mass scenario at 13 TeV (2016 data)
- Search for SUSY in opposite-sign, same-flavor di-lepton final states at 13 TeV (2015 data) *Submitted to JHEP*
- Search for SUSY in multi-lepton final states at 13 TeV (2016 data)
- Search for electroweak SUSY in multi-lepton final states at 13 TeV (2016 data)
- Search for electroweak SUSY in WH final states at 13 TeV (2016 data)
- Search for R-parity-violating SUSY in 0 or 1-lepton and large jet multiplicity final states at 13 TeV (2015 data)
- Search for SUSY in photon(s) plus MET final states at 13 TeV (2015 data)
- Search for SUSY in same-sign dilepton final states at 13 TeV (2015 data) *Submitted to EPJC*
- Search for SUSY in single-lepton final states at 13 TeV (2015 data) *Submitted to JHEP*
- Search for SUSY in all-jet final states with M_{T2} at 13 TeV (2015 data) *Submitted to JHEP*
- Search for SUSY in multi-jet final states at 13 TeV (2015 data) *Submitted to PLB*
- Search for SUSY in Higgs to di-photon final states using the razor variables at 13 TeV (2015 and 2016 data)
- Search for stop pair production in the fully hadronic final state at 13 TeV (2016 data)
- Search for stop pair production in single lepton final states at 13 TeV (2016 data)

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#ICHEP_2016

Dec 2015 (no update yet): $Z(\ell\ell)$ + jets + E_T^{miss}: results

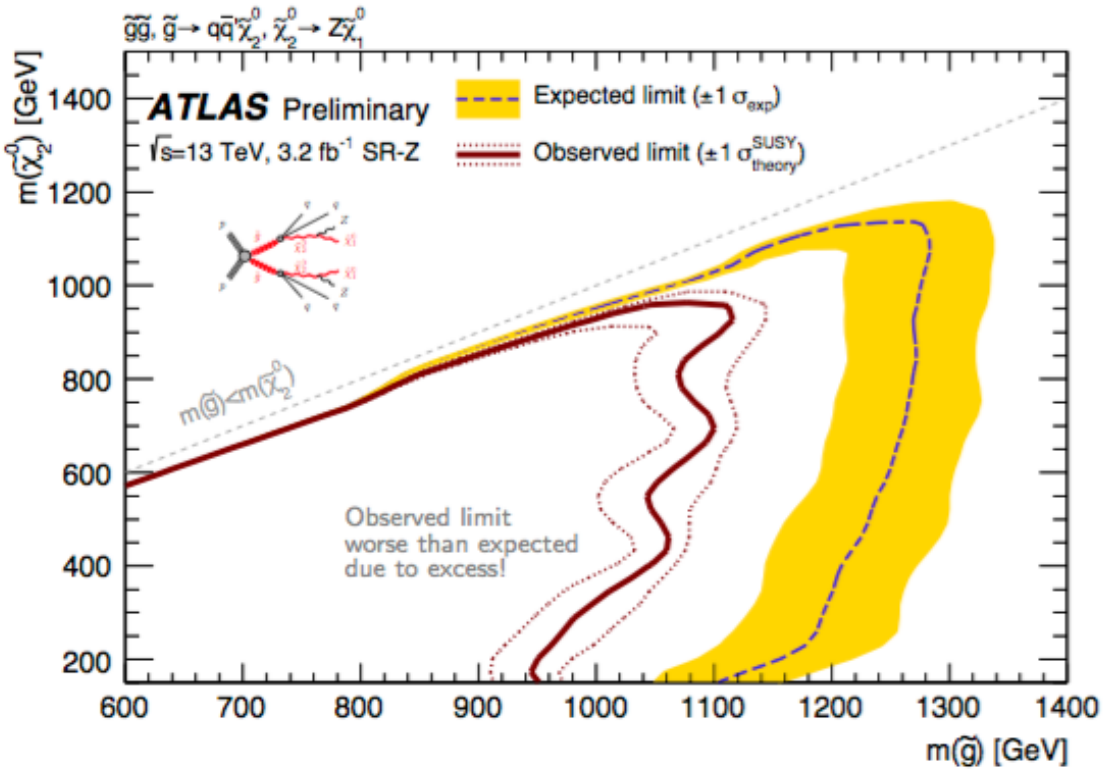
ATLAS-CONF-2015-082



Final event yield for 2015 data:

- Expected: 10.3 ± 2.3
- Observed: 21 (10 ee, 11 $\mu\mu$)
  $\Rightarrow$ 2.2σ excess

Slide from C. Ohm, Cern LHC Seminar September 2016



CMS observes 12 with $12^{+4.0}_{-2.8}$ expected (CMS-PAS-SUS-15-011)

No excess from CMS