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on behalf of the
ATLAS and CMS Collaborations

SEARCHES FOR SUPERSYMMETRY

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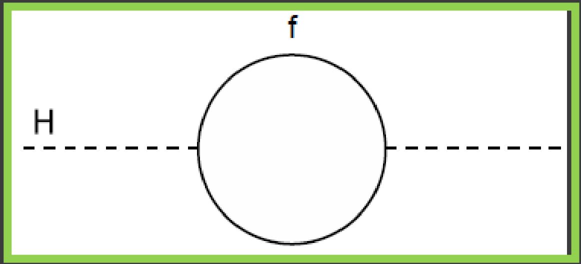
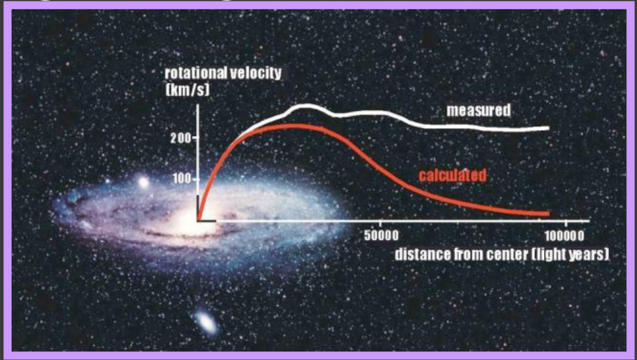
Outline of the talk

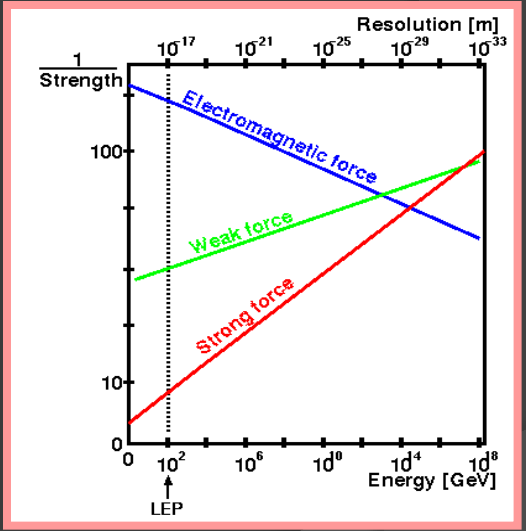
- Why Supersymmetry
- ATLAS & CMS at the LHC
- SUSY searches
  - Squarks (1st and 2nd generation) and gluinos
  - Direct pair production of 3rd generation squarks
  - Electroweak production of charginos, neutralinos, sleptons
  - R-parity violating scenarios and long-lived particles
- Summary of results
- Conclusions

Why Supersymmetry

- The Standard Model (**SM**) does not explain many problems:
  - **Hierarchy problem**: SM needs incredible fine tuning for m_H stability;
  - **Dark Matter**: the SM doesn't have a good candidate;
  - **Gauge coupling unification**: in the SM there is no unification of coupling constants at high energies.



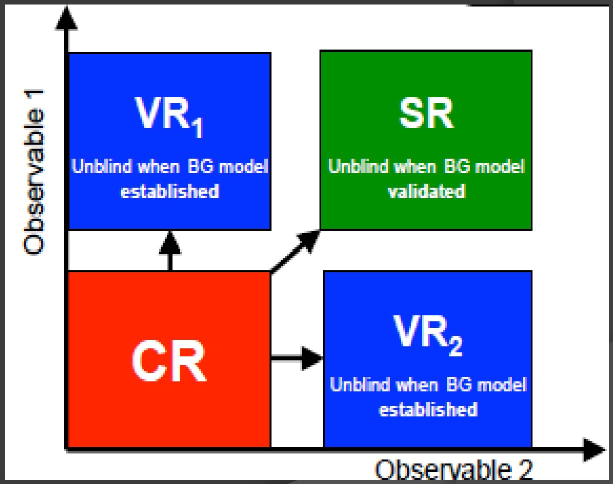




- Supersymmetry (**SUSY**) could actually solve such problems by introducing a «sparticle» for each SM particle, differing by ½ spin unit.
- If R-parity is conserved, the Lightest SUSY Particle (**LSP**) provides a natural Dark Matter candidate. $R : (-1)^{3(B-l)+2s}$

SUSY search strategy

- Usually a simplified signal model is picked.
- SUSY search is optimized for:
  - **Discovery** $\rightarrow$ *cut & count* analyses in Signal Regions (SR);
  - **Exclusion** $\rightarrow$ more elaborated methods (MVA, shape-fits).
- Main backgrounds are estimated in dedicated process-ehnanced Control Regions (CR), and then extrapolated to Validation Regions (VR) and SR.



- Whenever possible, *data-driven* methods are used for reducible backgrounds.
- Minor backgrounds estimated with MC.
- Final results obtained with a simultaneous **combined fit** of all components in CRs (and SRs for exclusion).

Discriminating variables

complexity

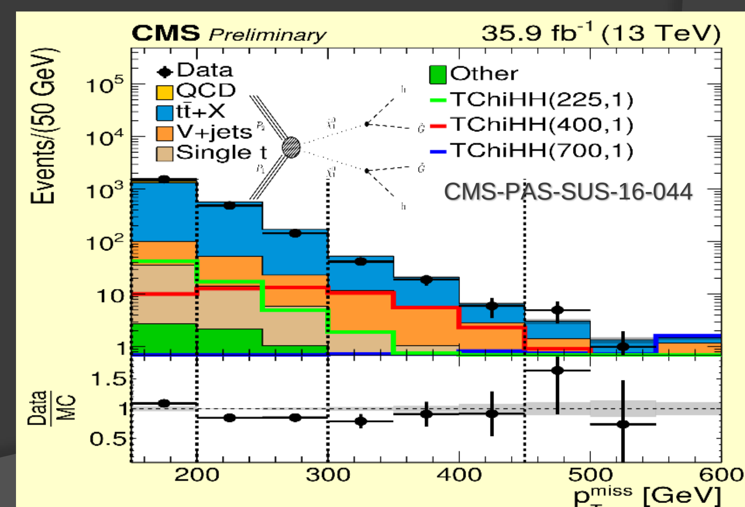
- Reconstructed object multiplicities, momenta, energies, e.g. $N_{jet/b\text{-}tag/\ell/\gamma}$, p_T, $E_{T,miss}$, …
- Scale variables, e.g. $m_{eff} = \Sigma p_T + E_{T,miss}$,
- Angular variables, e.g. **min ΔΦ**(jet, $E_{T,miss}$), …
- Mass variables, e.g. $m_{\ell\ell}$, $m_T^{b/\ell/j}$, $\Sigma m_{fat\text{-}jet}$, …
- Event shape variables, e.g. **Aplanarity**, …
- Hypothesis-based event variables e.g. m_{T2}, …
- ⋮
- More complex methods, e.g. new **recursive jigsaw reconstruction** [arxiv:1607.08307], …

- More and more complex variables are exploited to extract signal from background.

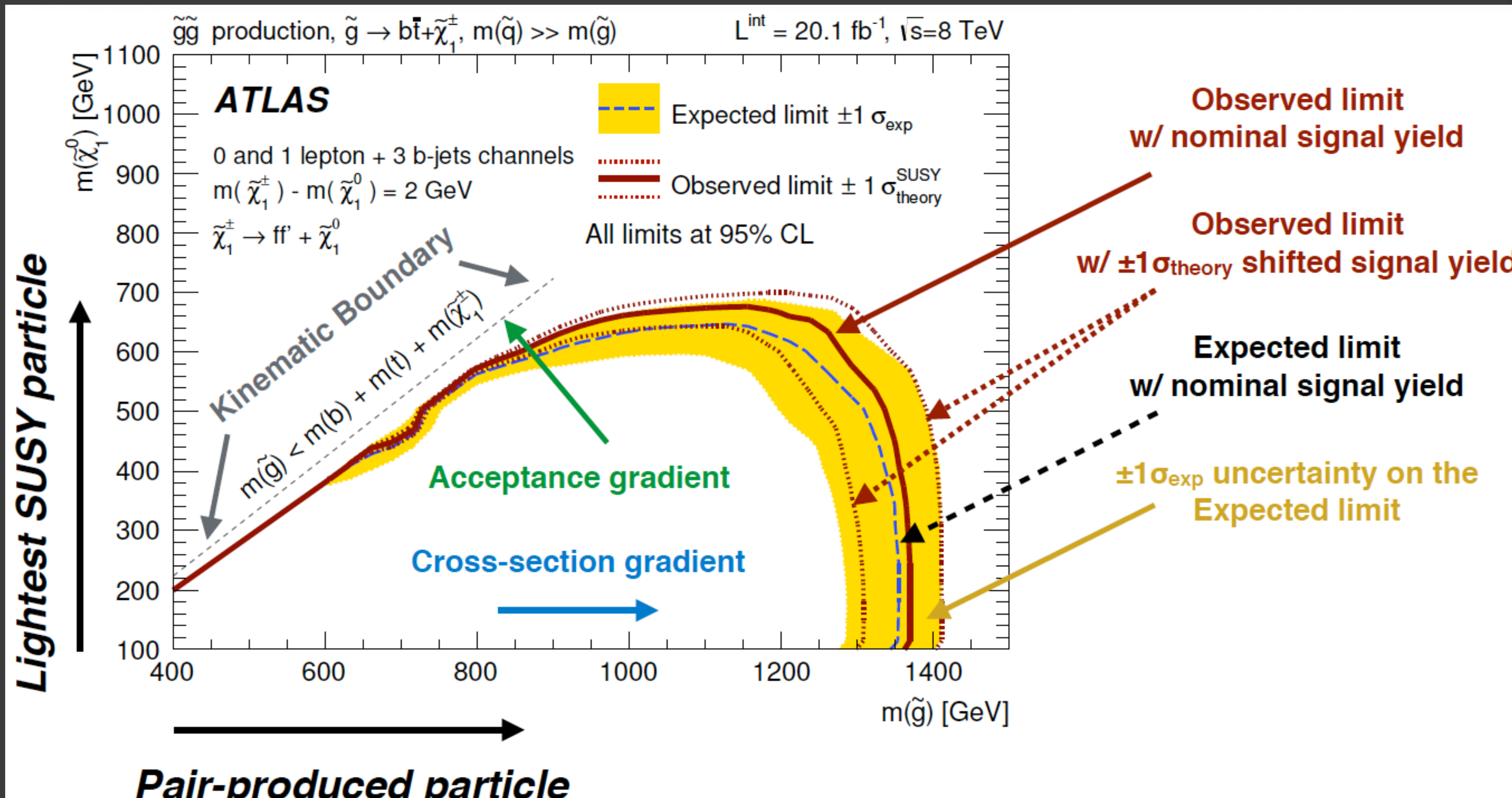
$$E_T^{miss} = -\sum_{i \in ev.} p_T^i \qquad m_{eff} = \sum_i p_T^i + E_T^{miss}$$

$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}$$

$$m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2}, \mathbf{p}_T^{miss} - \mathbf{q}_T)\right)\right]$$



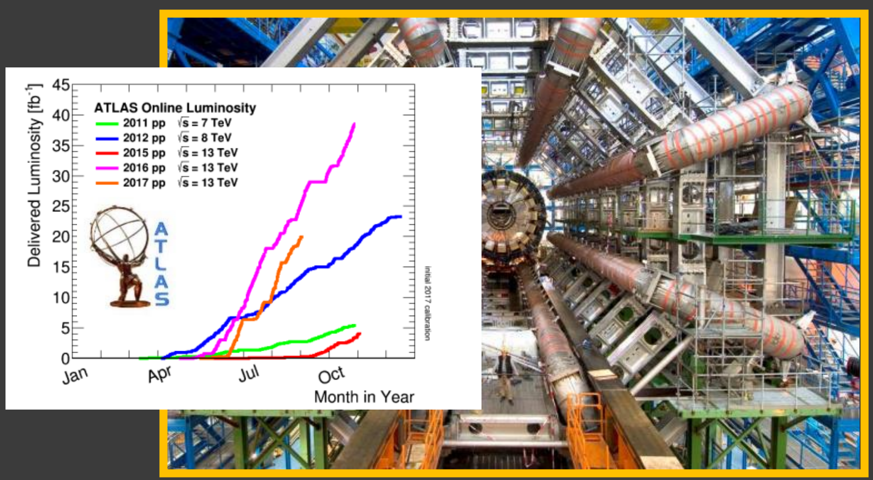
Interpretation of results

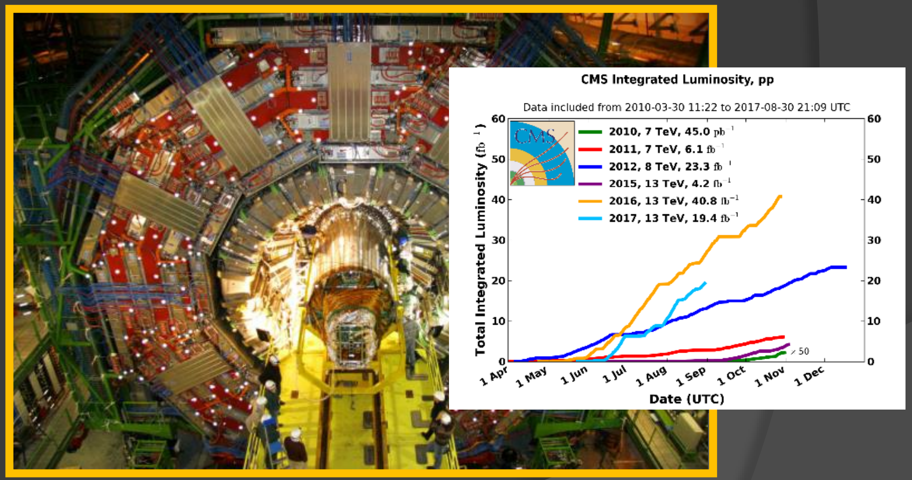


- Results are usually shown in bi-dimensional slices of SUSY particle masses or dedicated observables.
- Typically limits are computed at 95% confidence level (CL).

ATLAS & CMS experiments at the LHC

- Delivered luminosity per experiment @ 7/8/13 TeV by the LHC (proton–proton collisions):
  - 5 & 25 fb^{-1} (2011-12) @ 7 & 8 TeV.
  - 36 fb^{-1} (2015-16) & ~20 fb^{-1} (so far in 2017) @ 13 TeV.





- LHC provides the best possible environment to search for new phenomena in high energy physics.

Recent ATLAS & CMS SUSY results

- List of SUSY papers with $\sqrt{s}$ = 13 TeV and L ~ 36 fb^{-1}

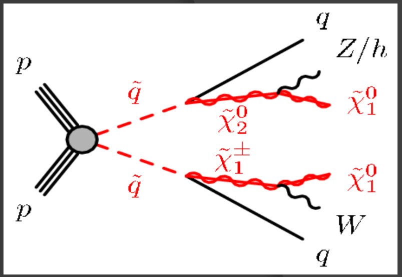
monojet (compressed squarks)	ATLAS-CONF-2017-060
EWK 2/3L	ATLAS-CONF-2017-039
2b + MET (sbottom)	ATLAS-CONF-2017-038
stop B-L (RPV)	ATLAS-CONF-2017-036
stop 1L with DM+HF	ATLAS-CONF-2017-037
displaced vertices+MET	ATLAS-CONF-2017-026
stop 2x2	ATLAS-CONF-2017-025
0L 2-6 jets	ATLAS-CONF-2017-022
multi-b jets	ATLAS-CONF-2017-021
stop 0L	ATLAS-CONF-2017-020
disappearing tracks	ATLAS-CONF-2017-017
EWK di-tau	1708.07875
stop 2L	1708.03247
0L 7-11 jets	1708.02794
stop in Z/h	1706.03986
SS/3L + jets	1706.03731
RPV 1L	1704.08493

0L + top tag	CMS-PAS-SUS-16-050
1L compressed stop	CMS-PAS-SUS-16-052
Hadronic staus	CMS-PAS-SUS-17-003
Ewkino combination	CMS-PAS-SUS-17-004
1L RPV	CMS-PAS-SUS-17-040
1L + jets + MET with ΔΦ	CMS-PAS-SUS-16-042
multilepton EWK	CMS-PAS-SUS-16-039
multileptons + jets	CMS-PAS-SUS-16-041
2L soft	CMS-PAS-SUS-16-048
Razor + Higgs → gg	CMS-PAS-SUS-16-045
stop 2L	CMS-PAS-SUS-17-001
2OS leptons	CMS-PAS-SUS-16-034
photon+MET	CMS-PAS-SUS-16-046
Higgsinos in 4b	CMS-PAS-SUS-16-044
sbottom & compressed stop	1707.07274
photon+HT	1707.06193
stop 0L	1707.03316
EWK W(1l)H(bb)	1706.09933
stop 1L	1706.04402
1L + jets + MET with MJ	1705.04673
0L + jets with MT2	1705.04650
0L + jets with MHT	1704.07781
2SS leptons	1704.07323

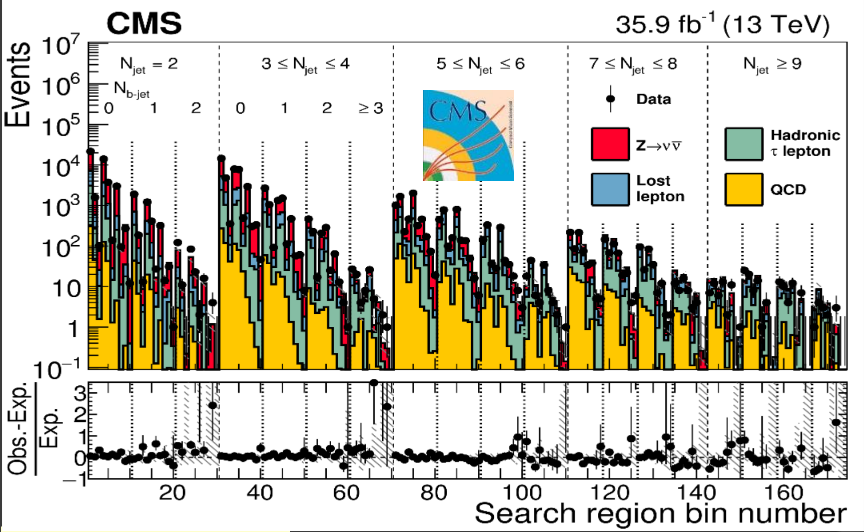
- So many new analyses:
  - here only focus on few of them and on summarized results;
  - further detail given in the BSM parallel sessions.

Inclusive searches without leptons

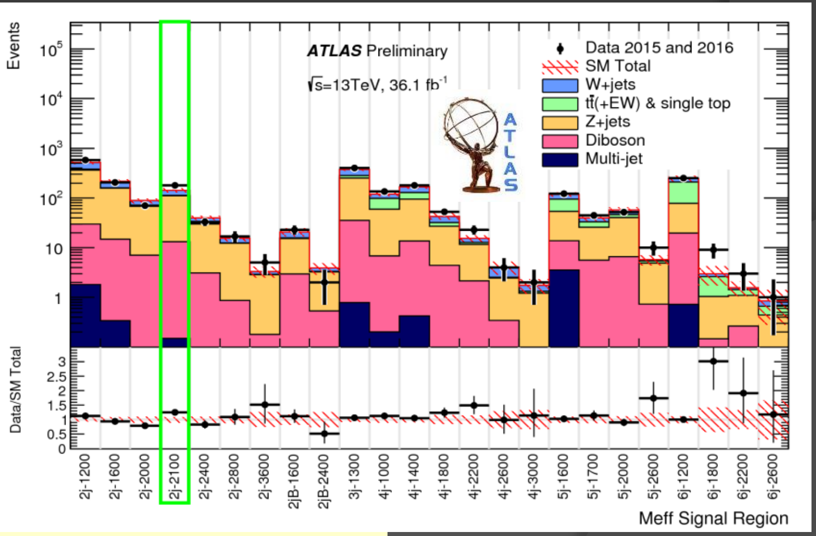
- Inclusive searches with R-parity conserved are characterized by large E_T^{miss} (due to LSP).
- Target is high-mass **gluinos** and **squarks**.



- A huge number of exclusive SRs is defined and analyzed for gluino/squark searches.
- The highest excess of events shows a 2.14 σ local significance.



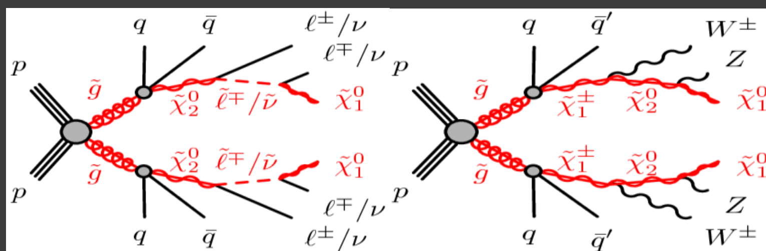
PAS-SUS-16-033



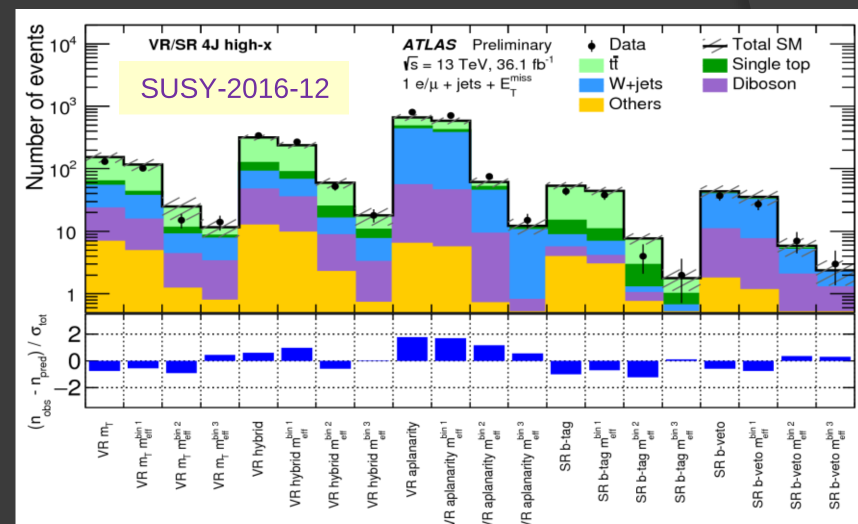
ATLAS-CONF-2017-022

Inclusive searches with leptons

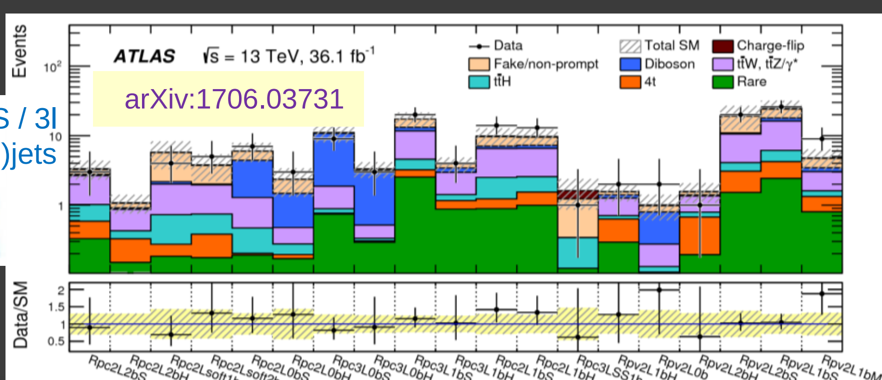
- Final states including leptons usually target long chains.
  - Various analyses combine searches for 1, 2 or more leptons.

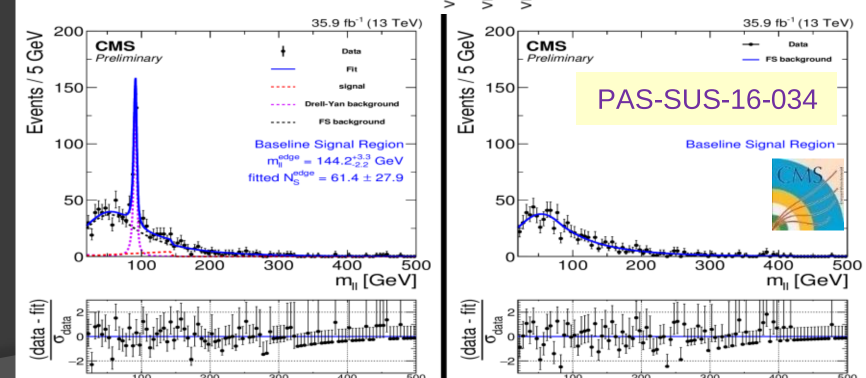


  - 1-lepton final states look for inclusive production of W/Z.
  - 2-lepton same-flavour seaches look for Z peak or shapes in m_{ll}.



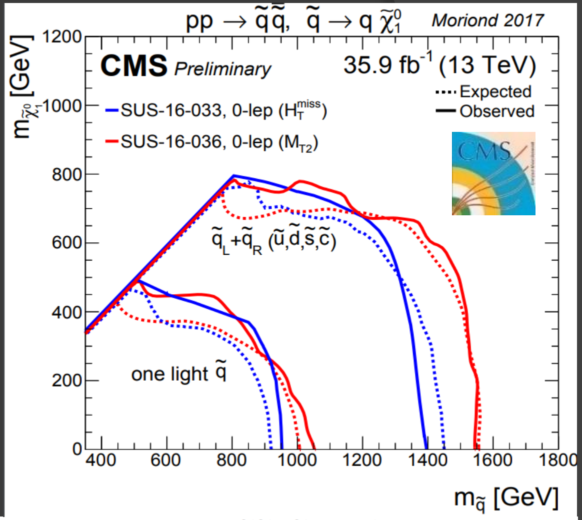
2l SS / 3l
+ (b-)jets



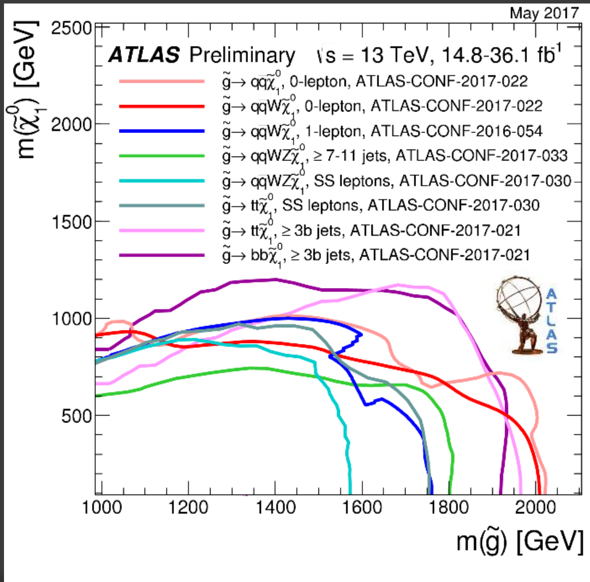


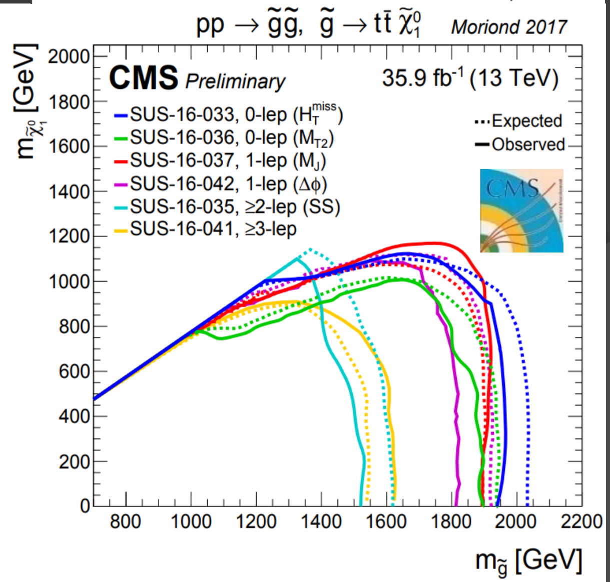
Inclusive searches summary plots

- Searches are interpreted in terms of exclusion limits on the mass of (1st and 2nd generation) squarks or gluinos, taking into account a variety of hypotheses for their decay.



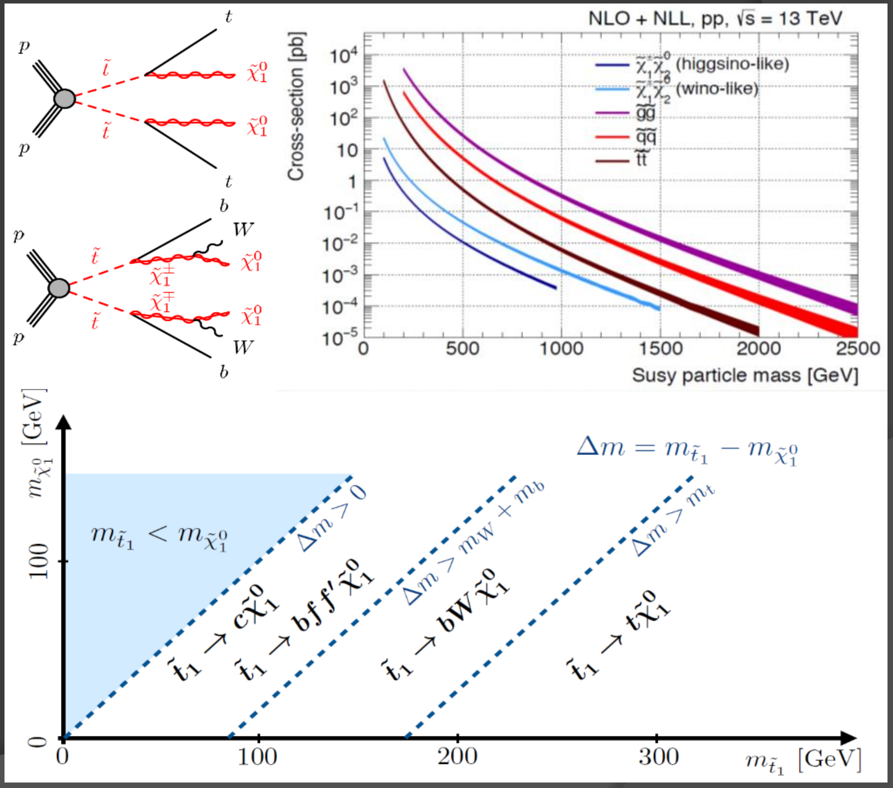
- Exclusion limits are becoming more and more stringent and sensitivity is beyond 2 TeV for the first time.





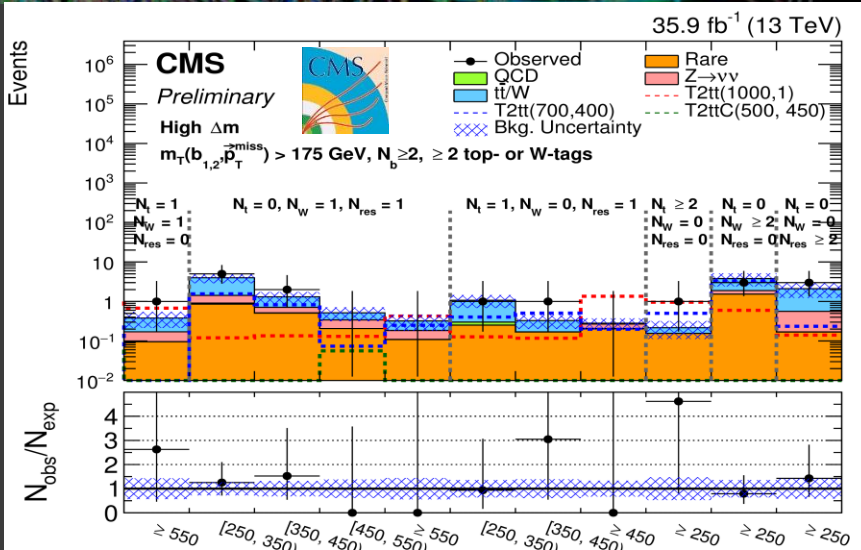
Direct production of 3rd gen. squarks

- Many sophisticated analyses aim at **bottom** and **top** squarks.
  - Fundamental theoretical role (m_H radiative corrections, natural SUSY).
  - Challenging experimental searches (lower rates, different models, according to SUSY mass spectra).
- Stop pair production is a possibility if gluino pair production is not observed.
  - Much lower cross section at any mass scale for $\tilde{t}\tilde{\bar{t}}$ compared to $\tilde{g}\tilde{g}$.
- Due to the large top mass, stop decay phenomenology can be complex: 2-, 3-, 4-body.
  - top + LSP → 0l,1l,2l + b-jets + E_T^{miss}

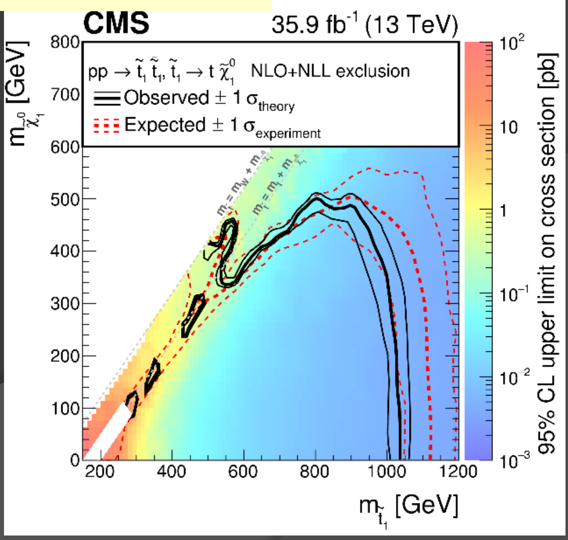


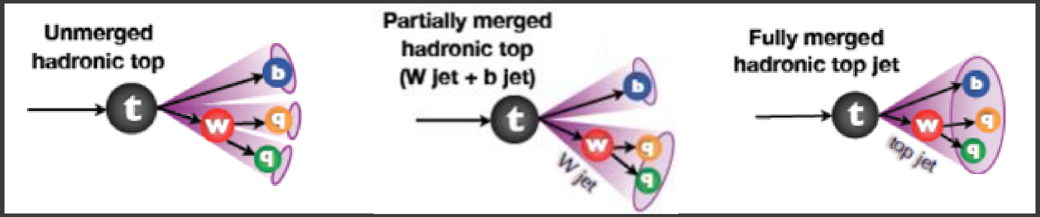
Top squark searches

- A variety of R-Parity conserving models are studied, including compressed ones ($m_{stop} \approx m_{LSP}$).
- Many different SRs are considered for a variety of signatures.
  - e.g. in the case of 0 leptons, dedicated searches depending on the boost of the top quark.



PAS-SUS-16-049 - 1707.03316

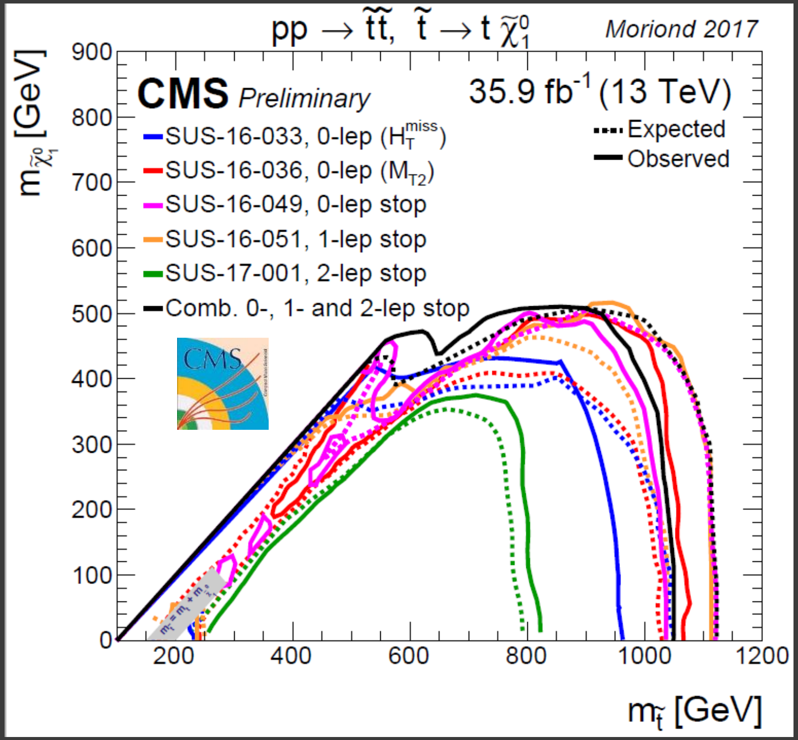


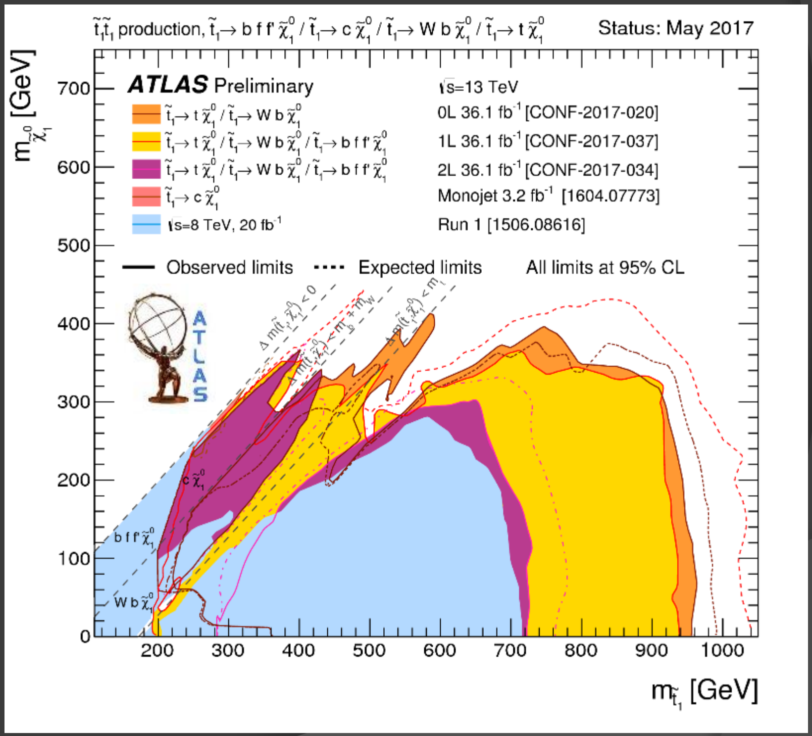


- No excess of events is observed over a wide area of the m_{stop}-m_{LSP} plane.

3rd generation summary

- In the most favourable scenarios sensitivity exceeds 1 TeV.
  - Almost no gaps are left to investigate for top squark decays.
  - Other decay modes (via Higgs boson or charginos) not shown here.

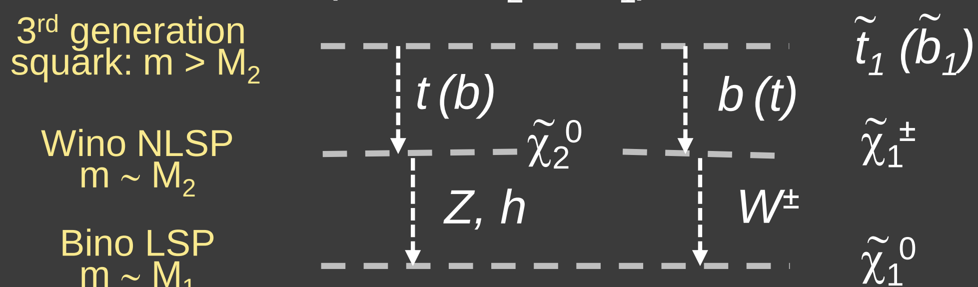




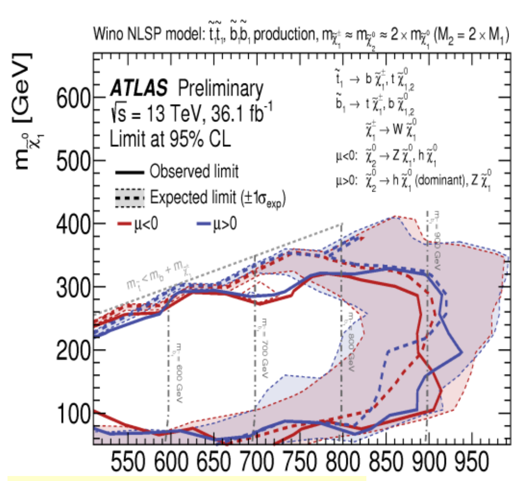
- Also for bottom squarks, exclusion limits go beyond 1 TeV.

More realistic models for stop

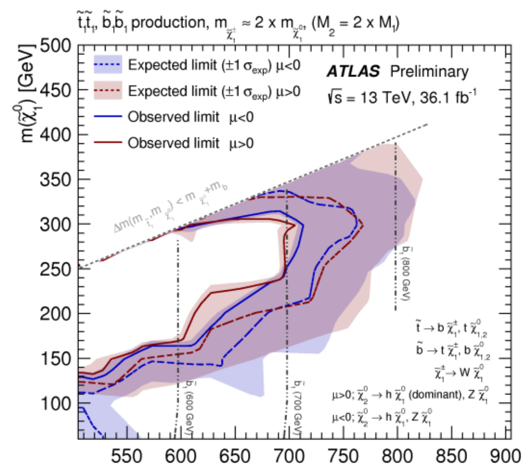
- Simplified **pMSSM** oriented models are also studied if $\tilde{t} \rightarrow t\ \tilde{\chi}_1^0$ is too simple.
- Various possible spectra are examined: more complex phenomenology, reduced sensitivity.
  - For instance, **bino** can be the LSP (mass M_1) and **wino** the NLSP (mass $M_2 = 2M_1$).



- Stop mass is excluded up to 885 GeV (940 GeV) in scenarios with $\mu<0$ ($\mu>0$) and a 200 GeV $\tilde{\chi}_1^0$.
- These realistic models are also studied by CMS (1707.03316, 1706.04402, CMS-PAS-17-001).



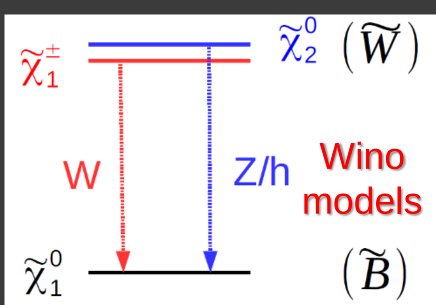
ATLAS-CONF-2017-037

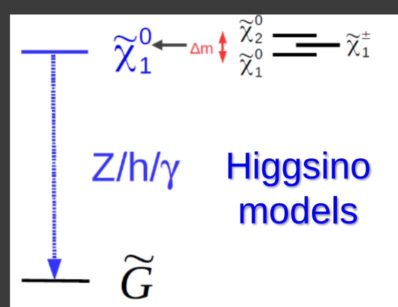


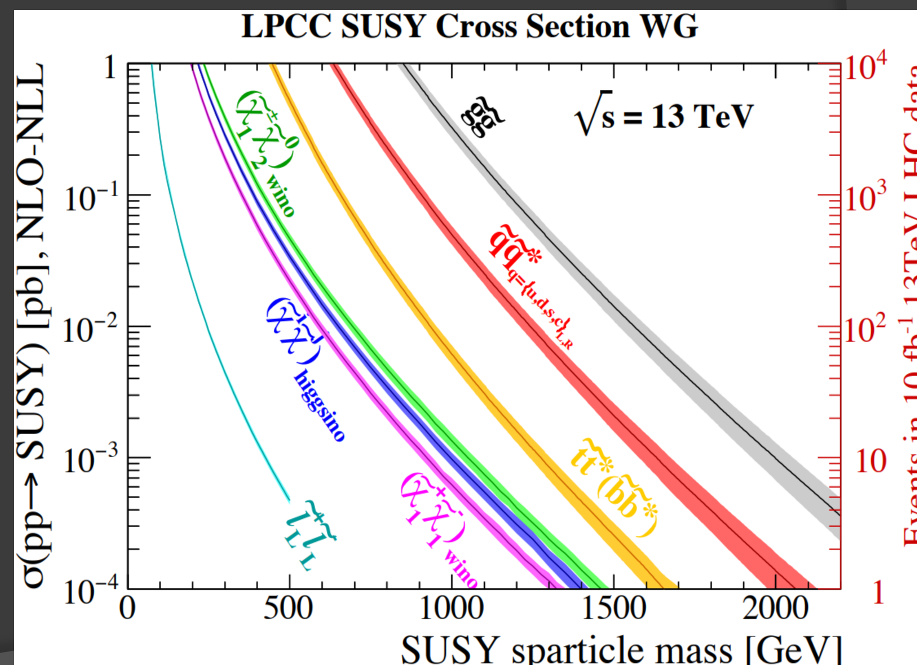
ATLAS-CONF-2017-034

Electroweak production of sparticles

- SUSY can be produced via **EW** interaction, through direct production of chargino, neutralinos, sleptons.
  - Cross sections depend on the EW state composition ($\widetilde{W}$, $\widetilde{B}$, $\widetilde{H}$) and on chirality (for sleptons).
  - EW sector could be the only accessible at the LHC if colored sparticles have mass above 3-4 TeV.
- A huge variety of signatures is tested, mainly exploiting the multi-lepton nature of final states.



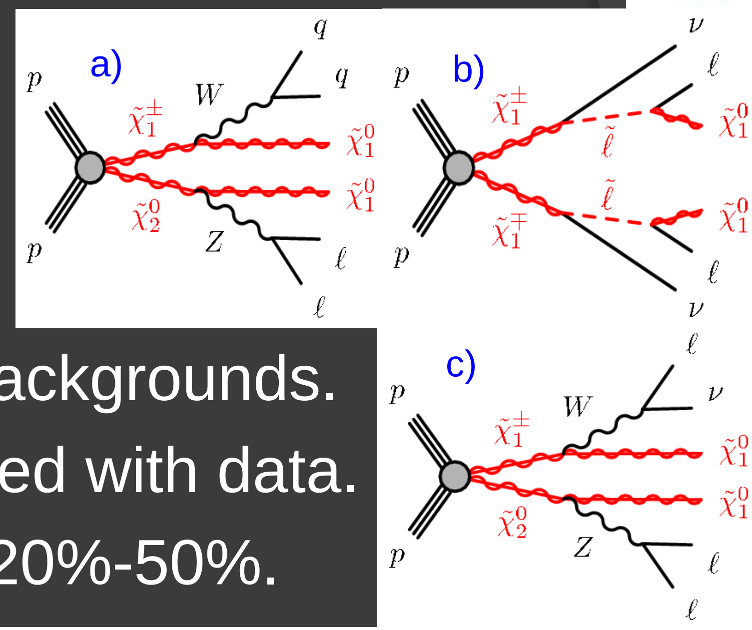




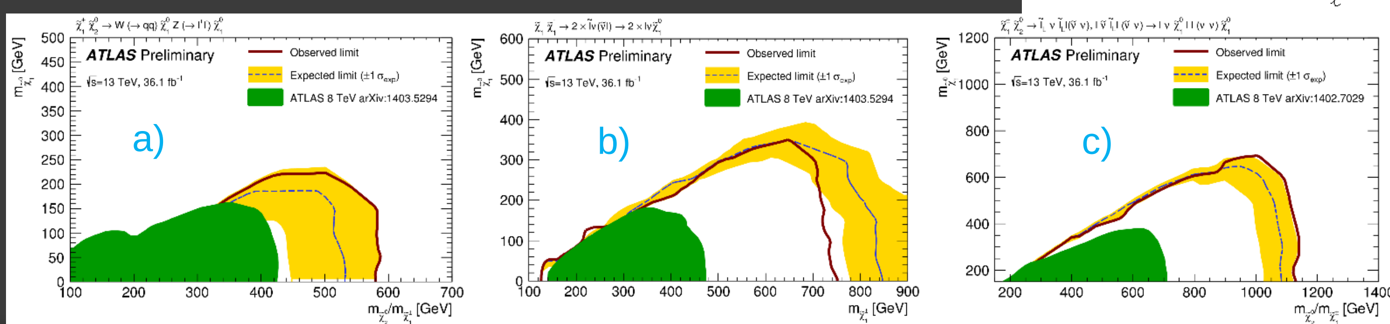
Electroweak prod. with 2/3 leptons

ATLAS-CONF-2017-039

- SUSY EW production with 2 or 3 leptons final states is possible with few decays mediated via bosons or via sleptons:
  - Different channels: 2l+jets / 2l+0jets / 3l .
  - All channels have large E_T^{miss}.



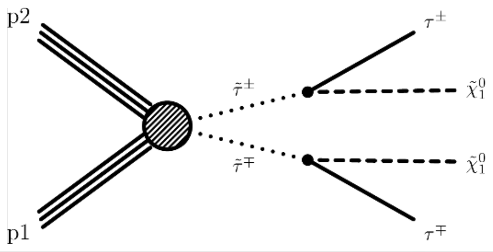
- Various CRs are used for different backgrounds.
- Non prompt background are estimated with data.
- Error on background estimation is ~20%-50%.
- No signal excess is found in 36 fb^{-1}.



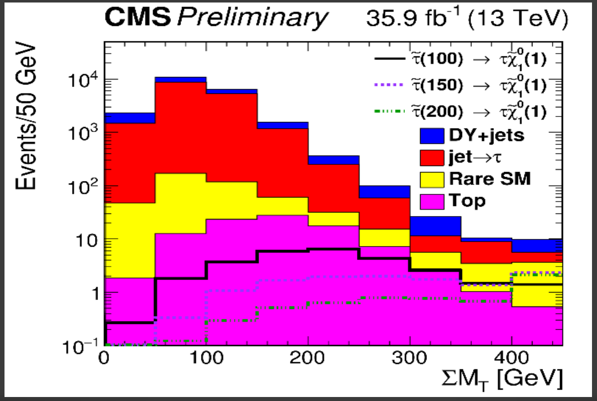
Search for stau in all hadrons

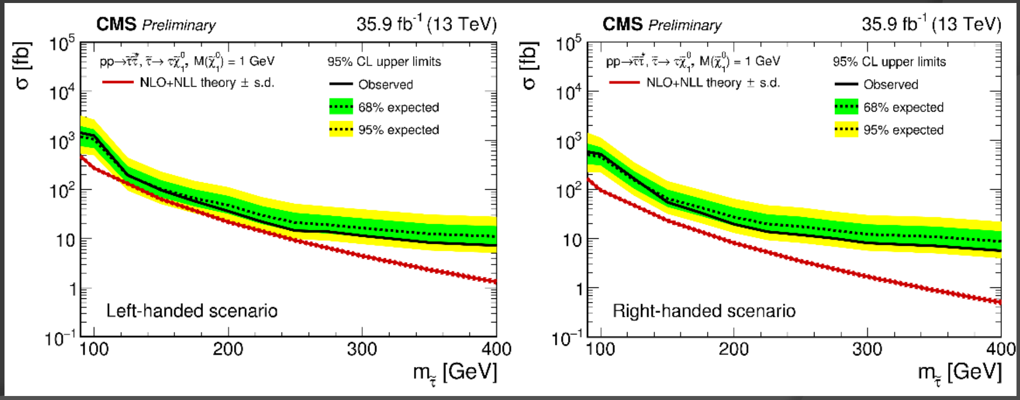
PAS-SUS-17-003

- Powerful exclusions are possible in decays via sleptons.
- Interest toward slepton direct production has increased recently, e.g.: search for two hadronically decaying τ leptons + E_T^{miss}.



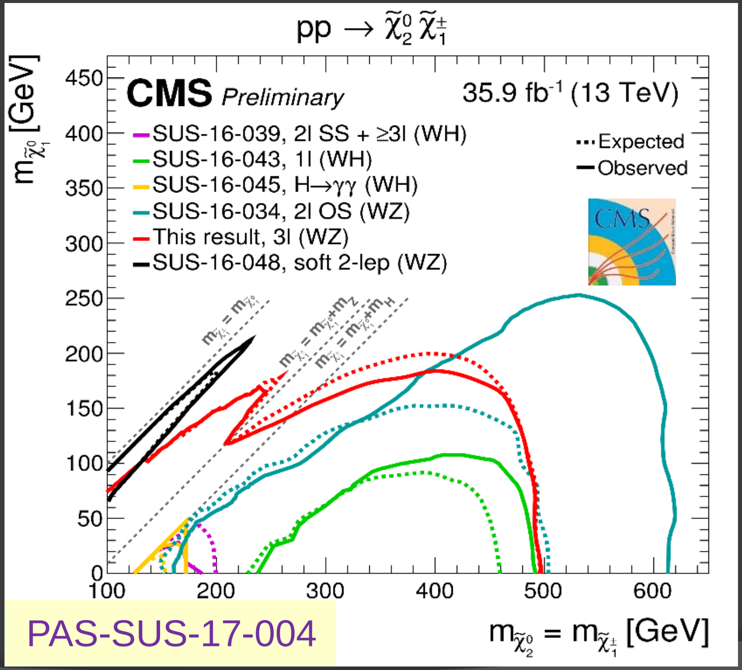
- Results are interpreted as upper limits on the cross section for tau slepton pair production in different helicity scenarios.
  - Plots assume a fixed LSP mass of 1 GeV.

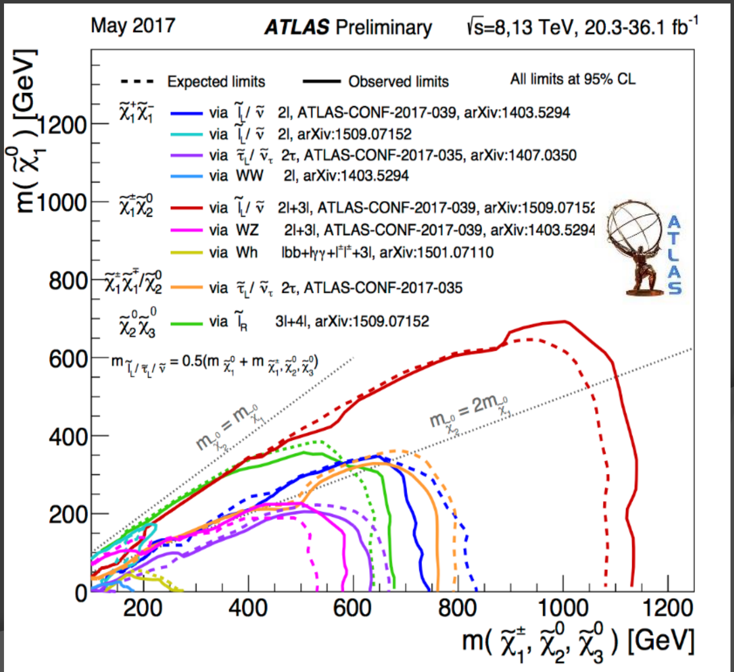




EW production summary

- The statistical combination of results for all the electroweak production searches are shown here for various chargino / neutralino pair production.
  - For decays via W/Z/h bosons the sensitivity is up to ~600 GeV.
  - For decays via sleptons the sensitivity exceeds 1 TeV.

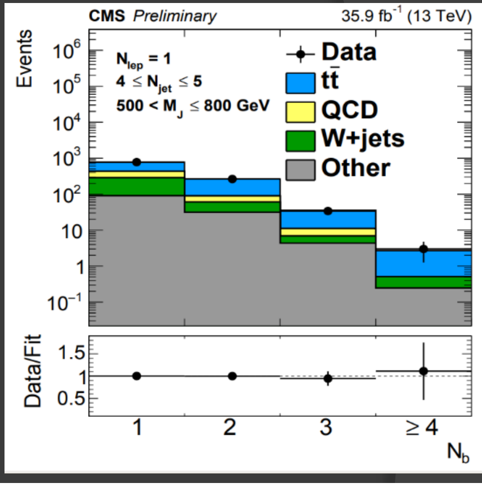


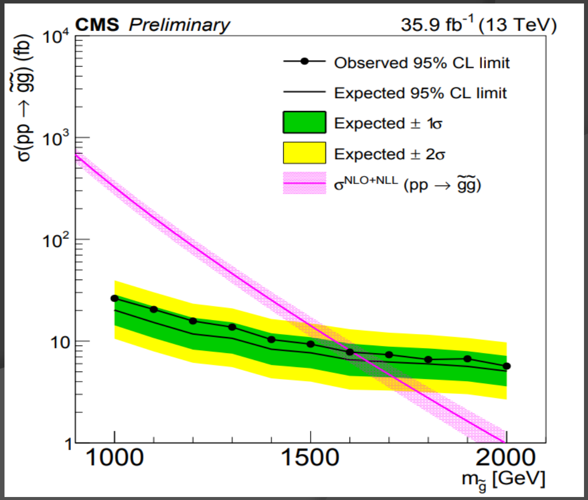


RPV searches: 1 lepton & multi-jet

PAS-SUS-16-040

- There is no theoretical reason why in SUSY R-parity shouldn't be violated (**RPV**).
- RPV searches are not based on E_T^{miss}.
  - Example of selection: 1 isolated lepton ($p_T > 20$ GeV) and a wide number of jets and b-jets.
- Background estimation shows excellent agreement with real data.
- Results are given using a benchmark minimal-flavor-violating model with gluinos produced in pair and decaying promptly: $\tilde{g} \rightarrow tbs$.
- Values of gluino masses below 1.61 TeV are excluded at 95% CL.

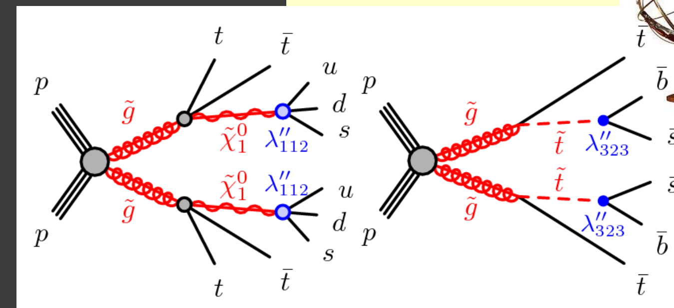




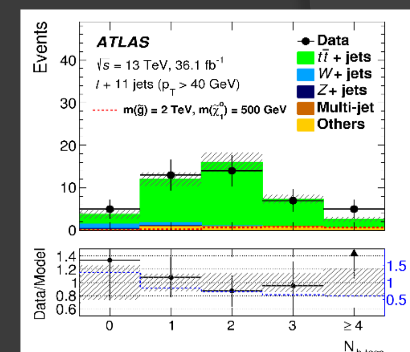
RPV searches: 1 lepton & multi-jet

arXiv:1704.08493

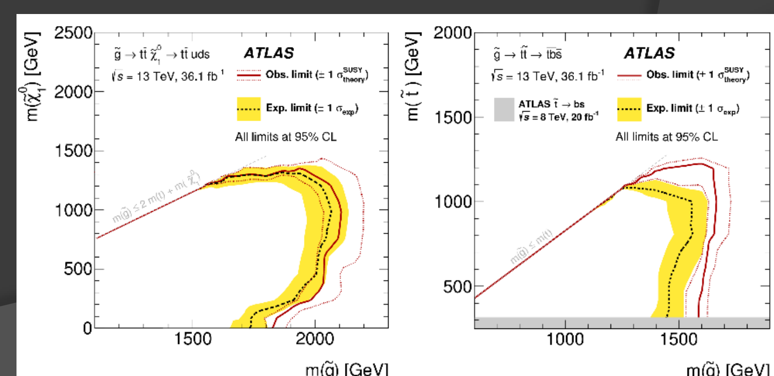
- Simplified signal benchmark models predict $\tilde{g}$ and R-hadrons production.
- Typical signature includes 1 isolated lepton, little E_T^{miss}, 8-12 jets, ≥3 b-jets.



- Nearly fully data-driven background estimation, dominated by ttbar and W/Z+jets.
- Analysis is based on a model-dependent multi-bin fit considering jet and b-jet multiplicities.



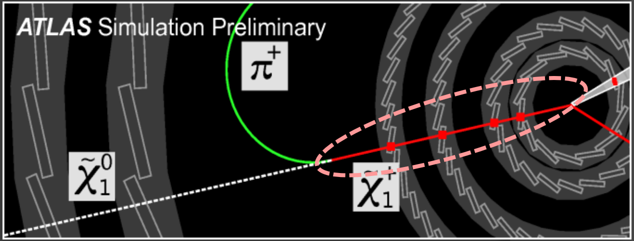
- Dedicated model-independent SRs.
- No significant excess is found and new lower limits on masses are set:
  - **Gluino**: between 1.65 to 2.10 TeV;
  - **Stop**: between 1.10 and 1.25 TeV.



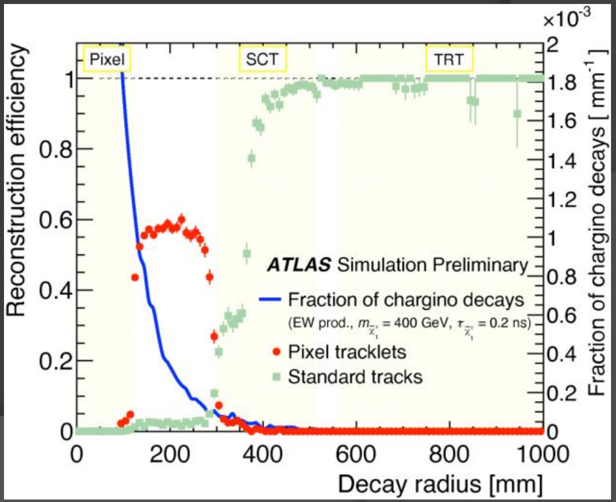
RPV searches: disappearing tracks

ATLAS-CONF-2017-017

- Events with large E_T^{miss}, high p_T jets and a short track: $\tilde{\chi}_1^{\pm}$ NLSP almost degenerate with $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$ *(soft)* $\Rightarrow$ not reconstructed π^+ disappearing track in ID.



- Long-lived chargino decay, common to Wino LSP scenario, relevant for SUSY Dark Matter searches.
- **Disappearing condition:** Tracking algorithm with shorter tracks than standard tracks (tracklets). Looking for tracklets with hits only in pixel-detector (pixel tracklets): efficiency up to 60% at radius < 300 mm.

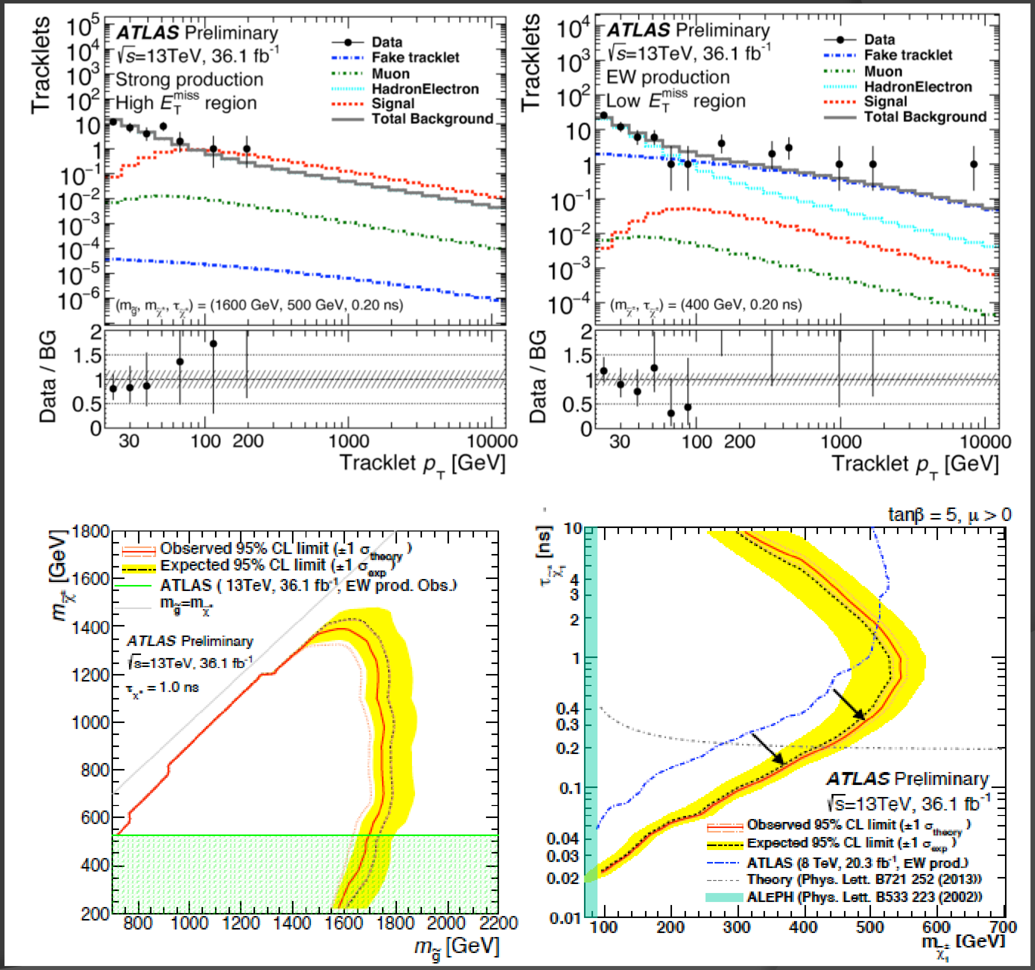


- Sensitivity improved in Run 2 with **IBL**.

RPV searches: disappearing tracks

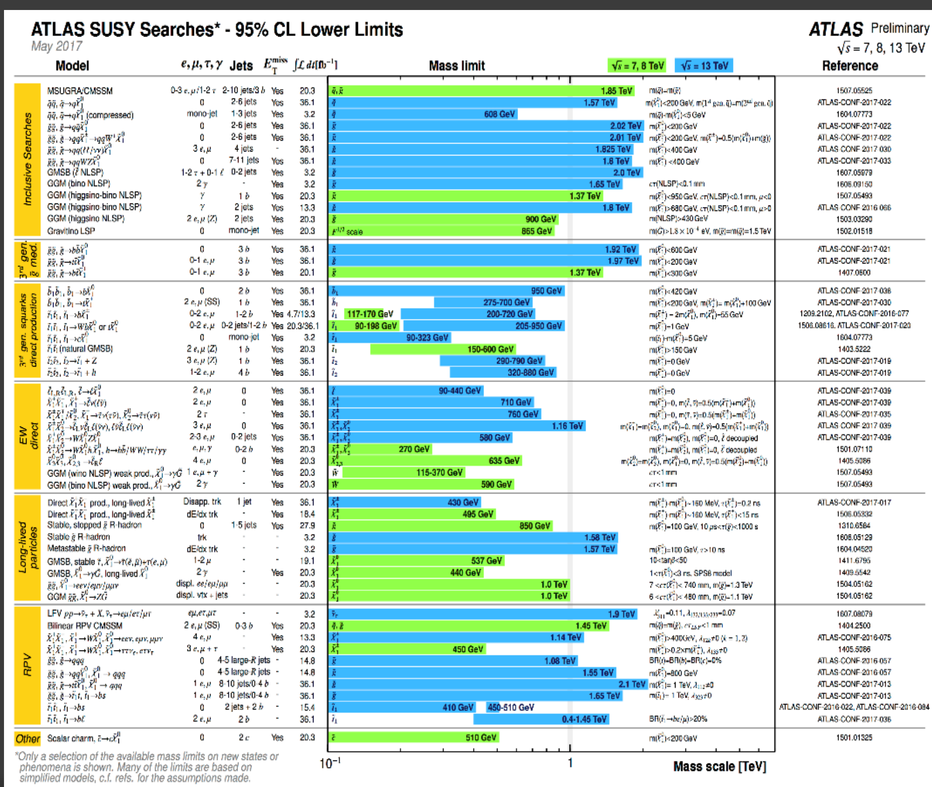
ATLAS-CONF-2017-017

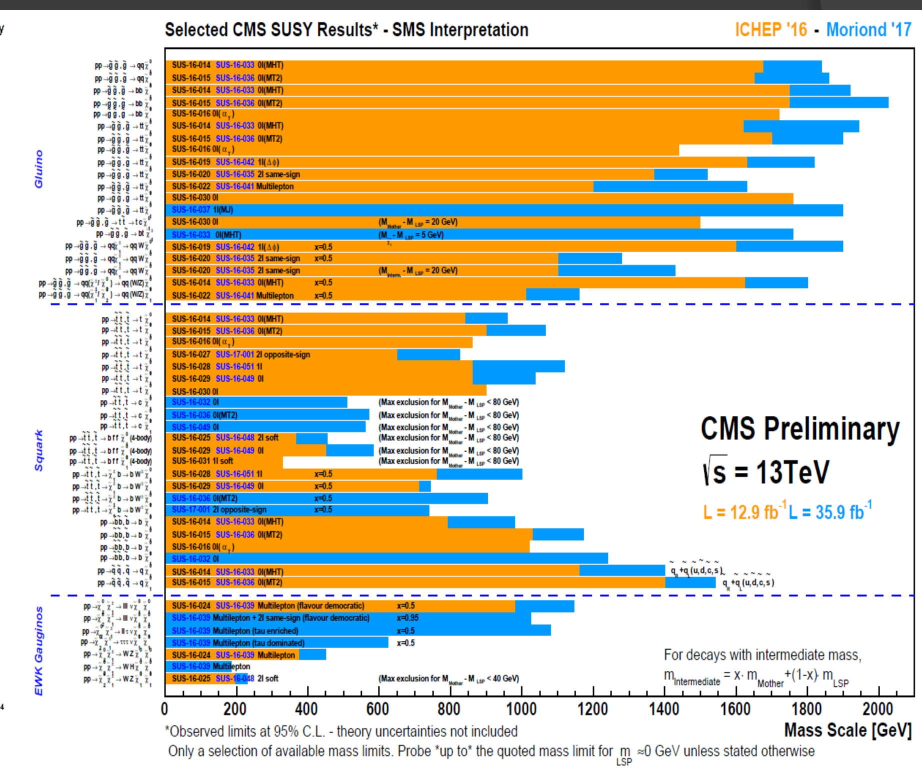
- There are two different signatures (for strong and EW productions).
- No significant excess is found above SM prediction for 36.1 fb^{-1}.
  - Strong production excludes up to 1.6 TeV for lifetimes under 1.1 ns.
  - For weak production there has been a large increase with respect to Run 1.



Grand summary of all SUSY results

- Extensive SUSY searches in all accessible channels at 13 TeV.
- SUSY is probably not be behind the corner.
- Excluded mass ranges: gluino ≳2TeV, stop ≳1TeV, EW ≳ 500 GeV.





Conclusions

- **LHC** has performed brilliantly in Run 2; the most recent **ATLAS** and **CMS** analyses are based on ~36 fb^{-1} (2015+2016).
- Many **SUSY** searches have been carried out (and many more will come with new data in 2017).
- After 7 years of LHC, still no significant deviation from SM has been found so far.
- More refined analysis strategies and more complex tools are under development and test for stronger limits on SUSY.
- Only a short summary of the SUSY searches has been shown here (details given in other talks in this conference).
- Full updated lists of results are available at the links:
  - **ATLAS**: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  - **CMS**: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS

Backup slides

SUSY terminology

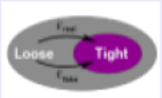
- **Natural SUSY**: With light SUSY (accessible at the LHC), SUSY can solve the hierarchy problem and keep the Higgs mass light. As SUSY particles get heavy, the second-order (log) corrections get larger, and the cancelation that protects the Higgs mass is not as satisfying. Natural SUSY is the name given to SUSY that has particles that are light enough (this is a matter of taste) to satisfactorily solve the hierarchy problem without large log corrections.
- **SUSY Higgses**: SUSY includes two doublets, giving rise to five Standard Model-sector Higgs bosons (h, H, A, H±). The Higgs found at the LHC with a mass of 125 GeV is generally identified as the h in this characterization.

Fake leptons background

Matrix method

- Fake leptonic background estimation
  - Measure real and fake efficiencies in QCD-CRs
  - Apply Matrix Method to get contribution in SR

$$\text{QCD BG} = \frac{1}{1/\epsilon_{\text{fake}} - 1/\epsilon_{\text{real}}} \cdot N_{\text{fail}} - \frac{1/\epsilon_{\text{real}} - 1}{1/\epsilon_{\text{fake}} - 1/\epsilon_{\text{real}}} \cdot N_{\text{pass}}$$



N_{pass}: Events passing the signal selection cuts (*tight*)

N_{fail}: Events satisfying relaxed lepton isolation criteria but not passing the signal selection cuts (*loose-but-not-tight*)

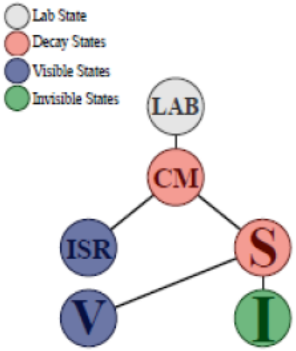
ϵ_{real}: Probability that a loose non-QCD event passes also the tight selection cuts

ϵ_{fake}: Probability that a loose QCD event passes also the tight selection cuts

Measure: ε, f, N_T, N_L

A recursive jigsaw reconstruction (RJR) technique

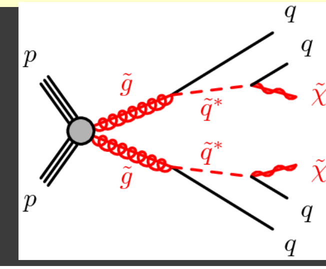
- Divide each event into an ISR and sparticle (S) hemisphere
- S → invisible (I) + visible (V) decay of stops
- Objects are grouped; maximizing the pT of S and ISR over all object assignment choices

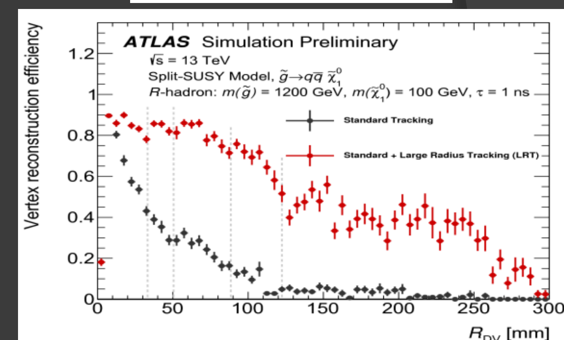


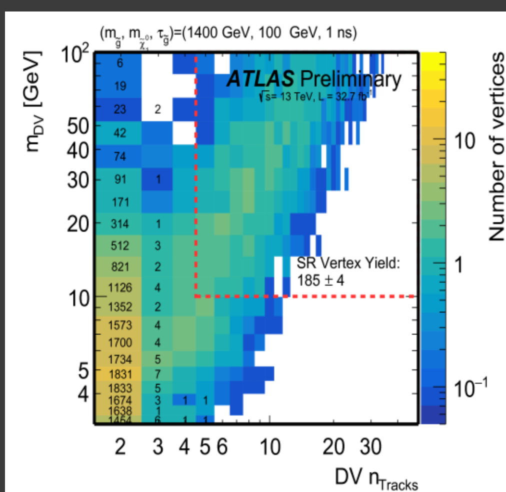
RPV searches: displaced vertices

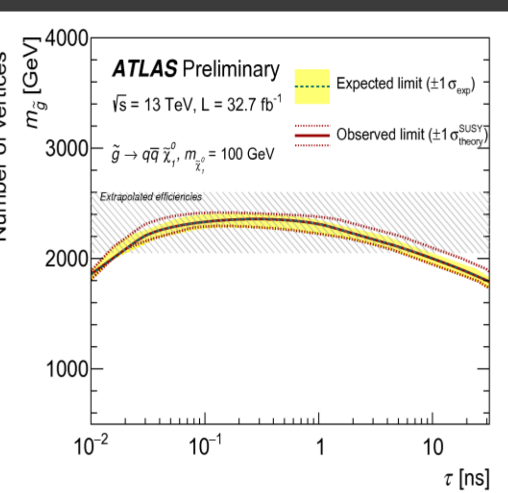
ATLAS-CONF-2017-026

- Split SUSY scenarios foresee long-life sparticles, leading to displaced vertices.
- Goal is to search for gluino decaying to virtual heavy squark (suppressed decay).
- Vertices with tracks having $|d_0|$<300 mm and $|z_0|$<1500 mm are accepted.









- No observed events.
- Excluded gluino masses up to 2.3 TeV for LSP mass of 100 GeV and lifetime between 0.02 and 10 ns.

Prospects at HL-LHC

- 14 TeV, <μ>= 200
- Total integrated luminosity 3000 fb^{-1}
- smearing function for upgraded ATLAS detector simulation
- truth level particle corrected for detector effects
- assumed 30% systematic uncertainties on the background