Search for Supersymmetry at the LHC

GK Workshop Bad Liebenzell 2014 – Part III

Isabell-A. Melzer-Pellmann

Recap

Yesterday we discussed:

- Gluinos and 1st/2nd generation squarks
- Third-generation squarks

Next:

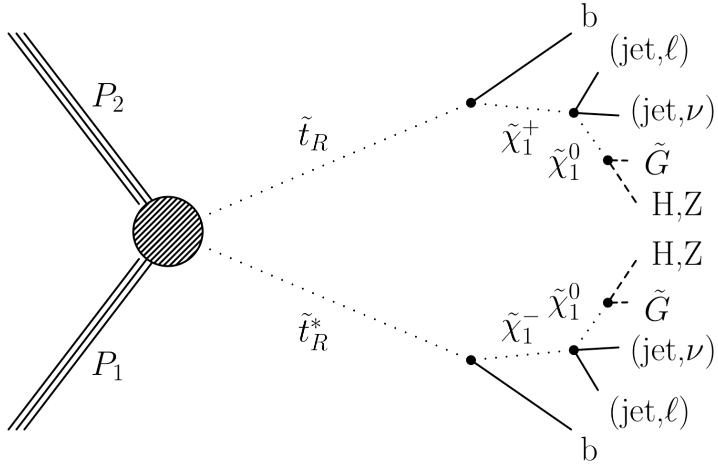
⇨ **Finish with third-generation squarks in GMSB** ⇦

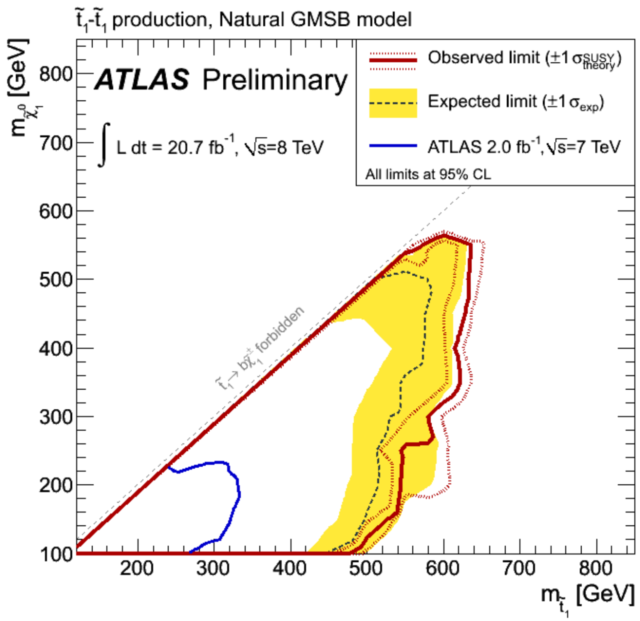
ATLAS-CONF-2013-025
CMS-PAS-SUS-13-002

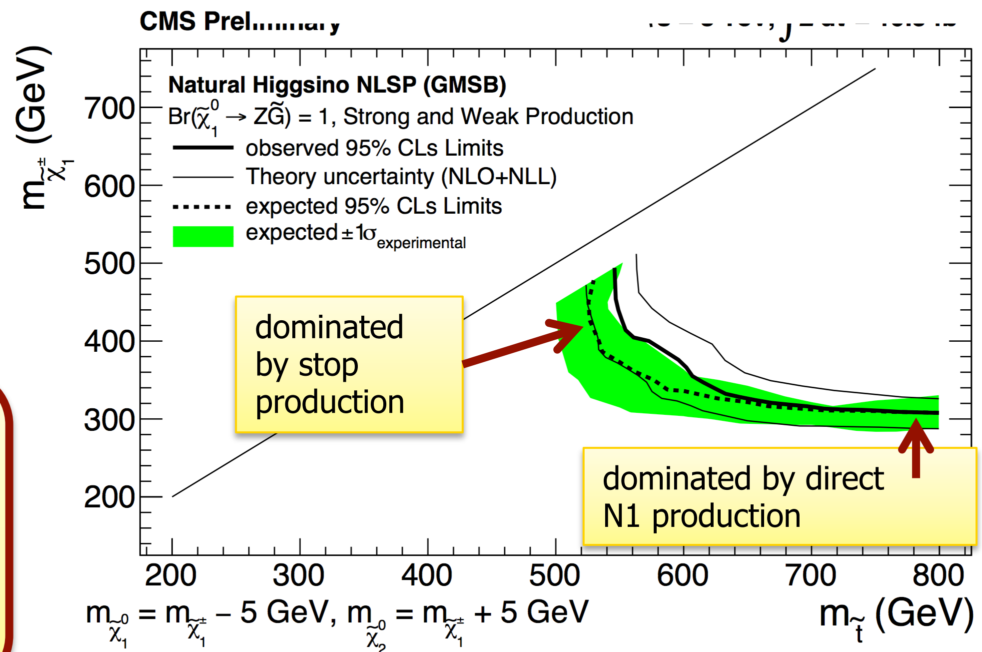
Stops in GMSB

If $\tilde{\chi}_1^0$ NLSP and higgsino-like: decay via Z or h

→ Search for ttZZ/hh or bWZZ/bWhh







Limits strongest for BR($\tilde{\chi}_0^1 \rightarrow Z\tilde{G}$)=1
Exclude stop masses up to 600 GeV
Reduced to 300 GeV for BR ($\tilde{\chi}_0^1 \rightarrow h\tilde{G}$)=1

Summary on Stop

Plain vanilla scenarios for 'natural' stop and sbottom almost all excluded

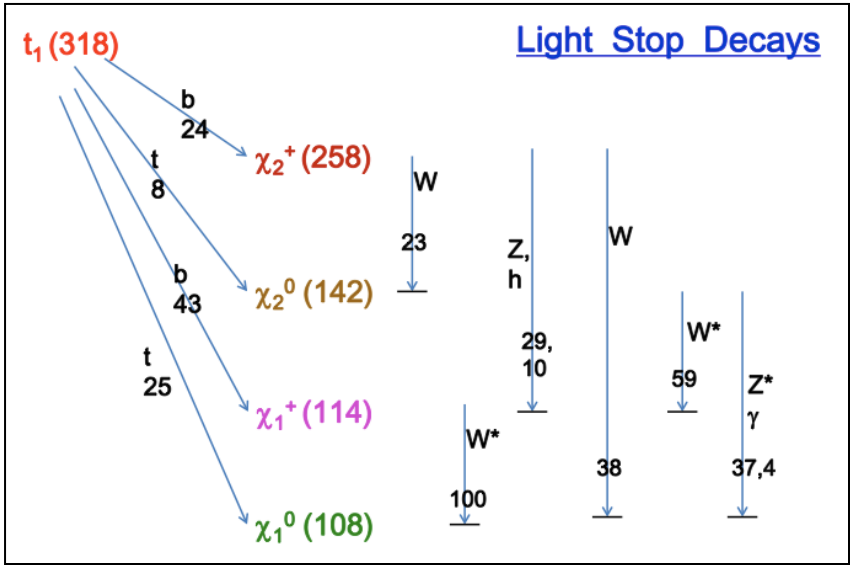
- Second SUSY crisis after no Higgs found at LEP2?
- Generate lots of new ideas to evade these constraints

Naturalness guide not applicable to Higgs?

Higgs mass stabilized by other mechanism?

SUSY fine-tuned?

Clearly the situation can be **more complex and signal may well hide**…



…and what about EWKinos?

Where we are

⇨ Electroweak SUSY sector ⇦

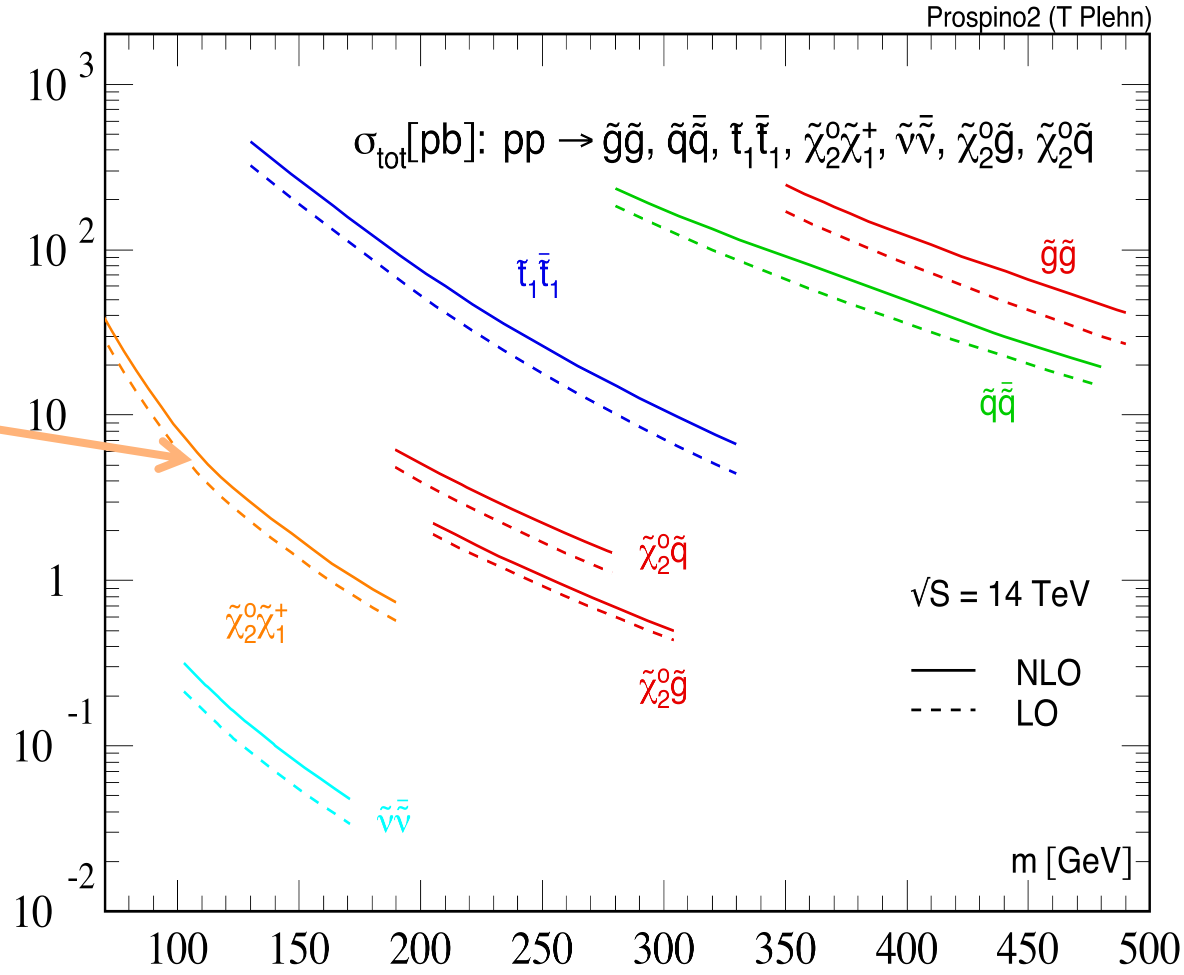
- Search for neutralino-chargino production
  - Neutralino = LSP
  - Gravitino = LSP
- Escape routes:
  - R-parity violation
  - Long-lived particle searches
  - Beyond MSSM signatures
- Outlook

Neutralino-Chargino Production

Reminder: Cross section tiny compared to other searches!

Look for these guys now!

Advantage:
Decays often include 3 or 4 leptons
→ low SM background



Reminder EWKinos

Every gauge field has a spin ½ partner → mixing

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

Bino, Wino, Higgsino → Neutralinos

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
neutralinos	1/2	−1	$\widetilde{B}^0 \ \widetilde{W}^0 \ \widetilde{H}_u^0 \ \widetilde{H}_d^0$	$\widetilde{N}_1 \ \widetilde{N}_2 \ \widetilde{N}_3 \ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm \ \widetilde{H}_u^+ \ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm \ \widetilde{C}_2^\pm$

Charginos

$$\begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$

Masses of the gauge eigenstates depend on 4 parameters

M1, M2, μ, tanβ

Bino Wino Higgsino

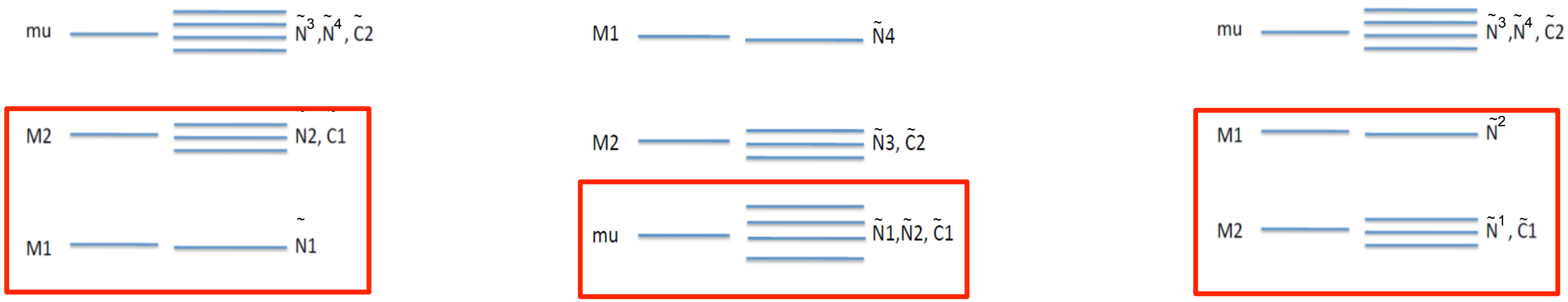
EWKinos

Mass spectra depend on the mass hierarchy of the EWKino mass parameters

~SUGRA
Bino-Wino case
Open Spectra

~Natural
Higgsino case
Compressed spectra

~ AMSB
Wino case
Degenerate spectra



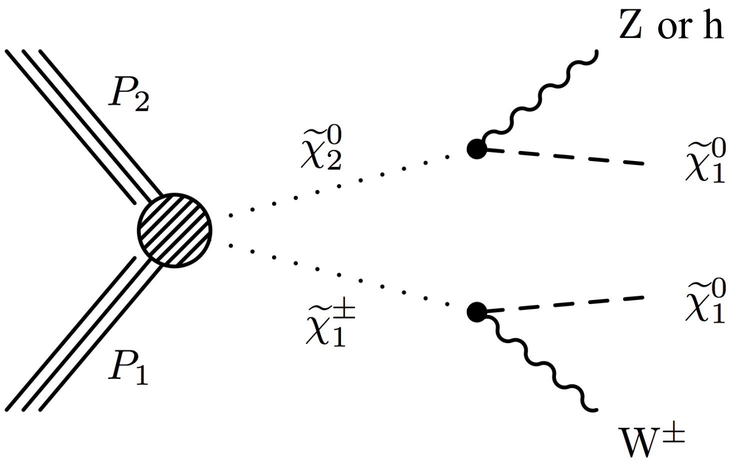
If μ is **large**, the lightest chargino is a Wino, with mass M_2
→ its interactions to fermion and sfermions are governed by gauge couplings
If $\mathbf{M_2}$ is **large**, the lightest chargino is a Higgsino, with mass μ
→ its interactions are governed by Yukawa couplings

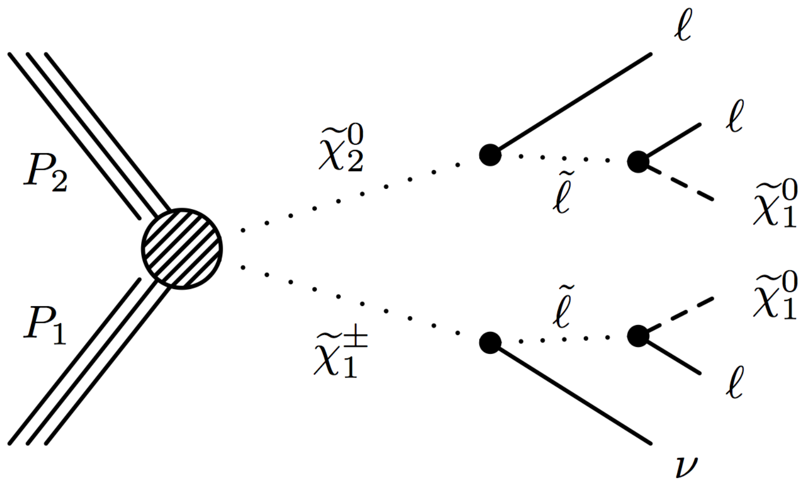
Couplings to SM particles:

- (W-Bino, Z/γ-Wino) ~ 0
- (W/Z/γ-Higgsino) ~ small
- (W-Wino, Z/g-Bino) ~ large

Search for Neutralino-Chargino Production

Most searches in EWKino sector concentrate on N2-C1 production
Many different decay possibilities, e.g.:





→ Search in lepton final states:

- 3 leptons + MET
- 2 leptons + 2 jets + MET
- 1 lepton + 2b (from h decay)

Search for Neutralino-Chargino Production: Multilepton Search

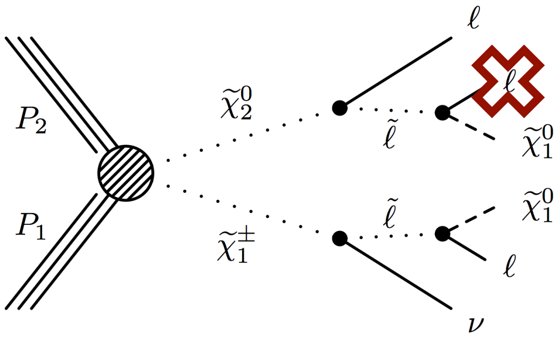
SUS-13-006
arXiv:1405.7570

3-lepton search:

- N(lepton)= 3 (including max 1 τ_{had})
- B-jet veto (suppresses ttbar)
- MET > 50 GeV (suppresses Z+jets)

Backgrounds:

- non-prompt leptons → data-driven
- WZ & rare from MC with corrections from data



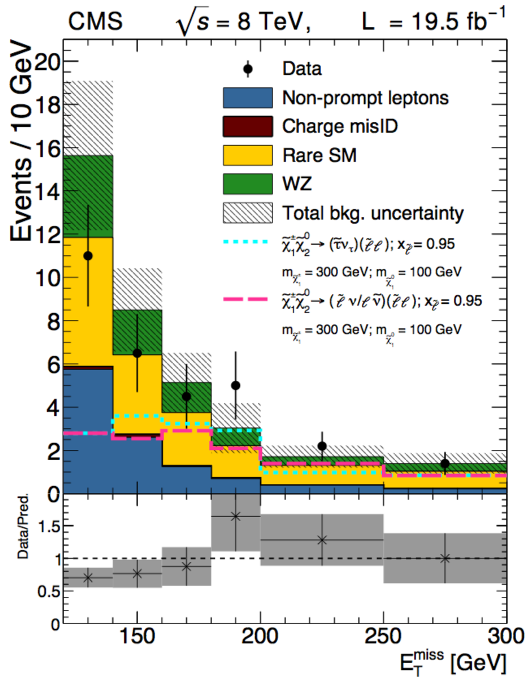
If small mass-splitting, one lepton might be lost!

2-lepton (same-sign) search:

- 2 same-sign leptons
- MET > 120 GeV
- no third lepton with m_ll around Z mass

Backgrounds:

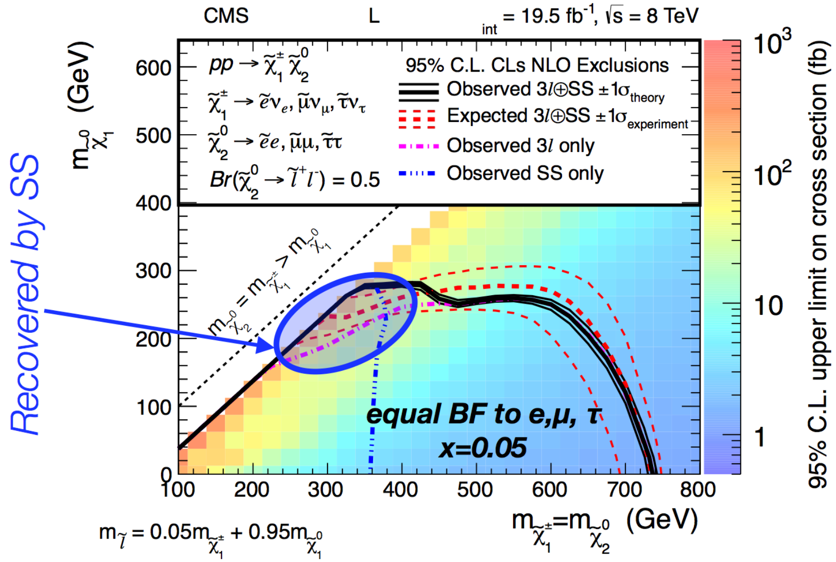
- Rare SM decays → MC
- WZ → MC
- Fake leptons → data-driven
- Charge flips → data-driven

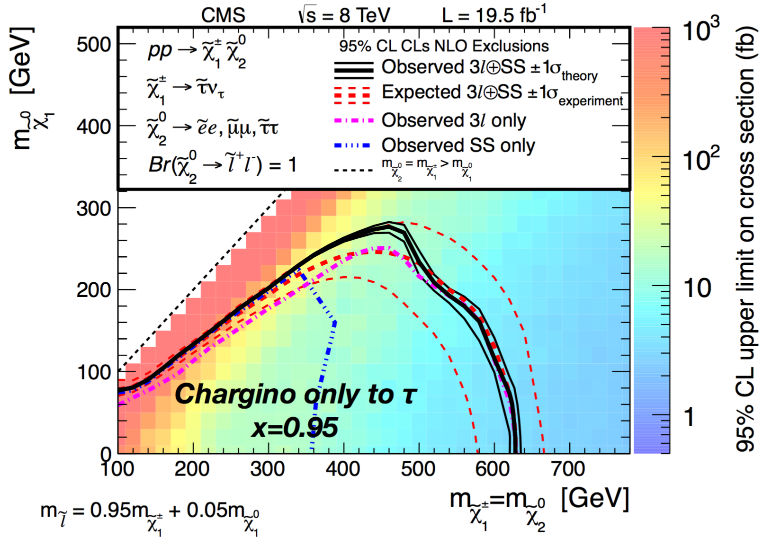


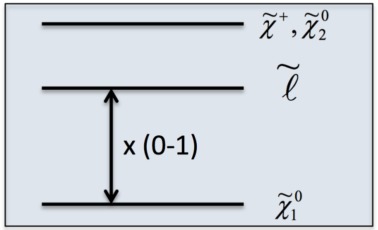
Search for Neutralino-Chargino Production: Multilepton Search Results

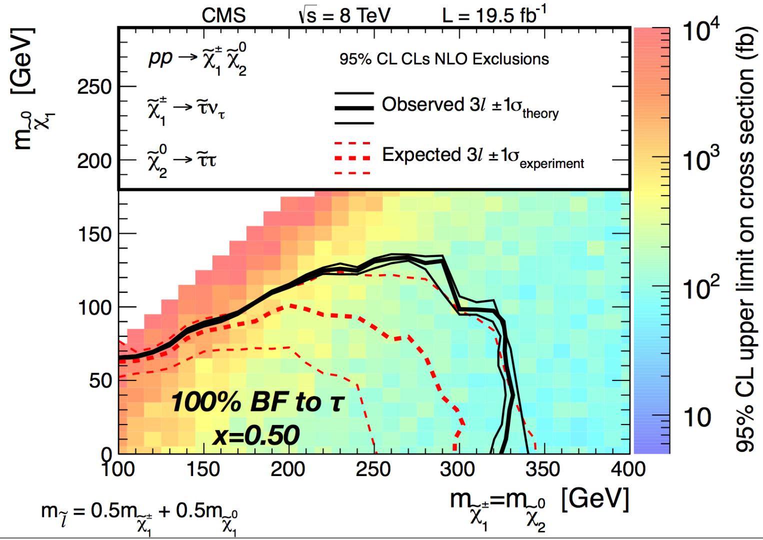
SUS-13-006
arXiv:1405.7570

Results for slepton intermediate state depend on lepton flavor







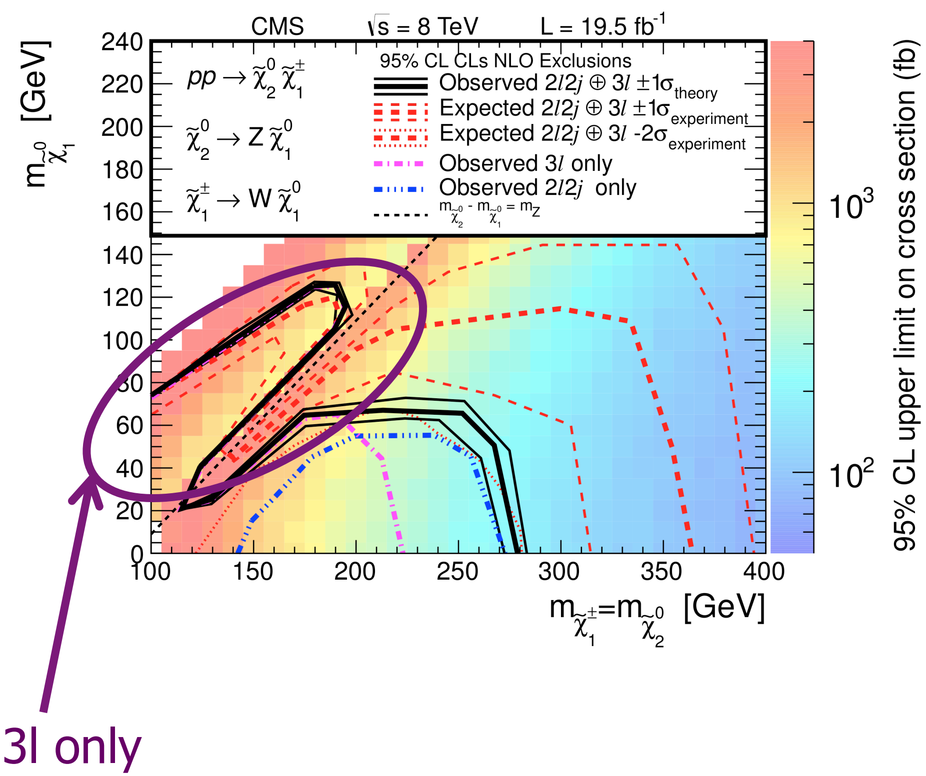


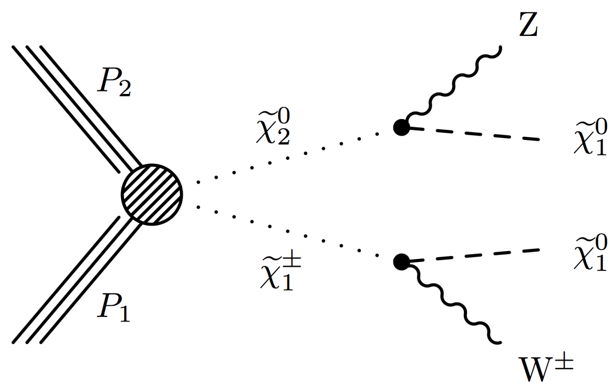
Limits on χ^0_2 / χ^{+-}_1 span from 325 to 750 GeV! χ^0_2
Lower sensitivity for decays to τ

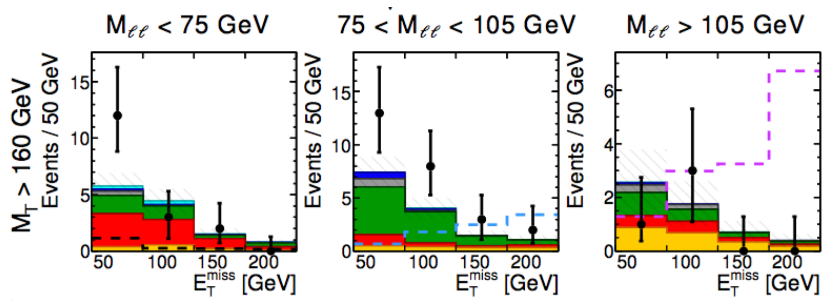
Search for Neutralino-Chargino Production: Multilepton Search Results

SUS-13-006
arXiv:1405.7570

Results for decays including Z and W



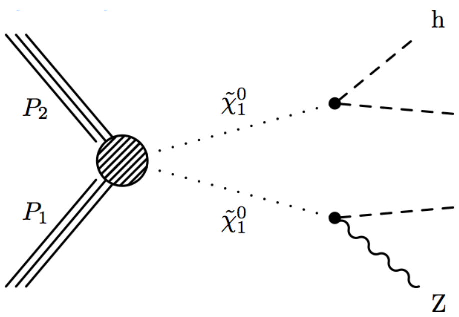




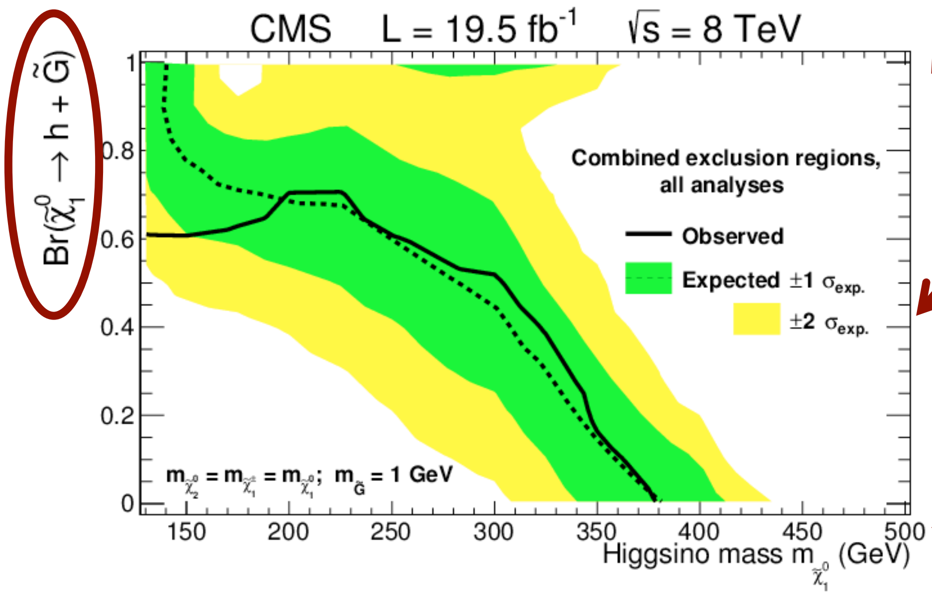
Expected limit better than observed due to underprediction in the 3l analysis

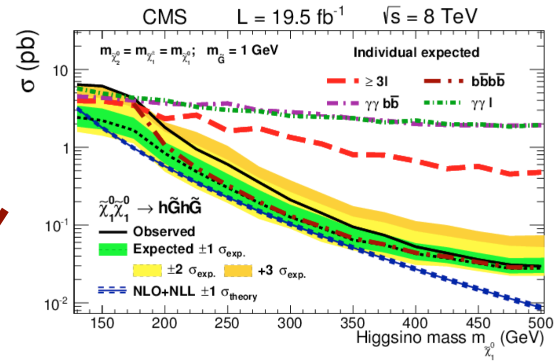
Search for Neutralino-Chargino Production in GMSB (Gravitino=LSP)

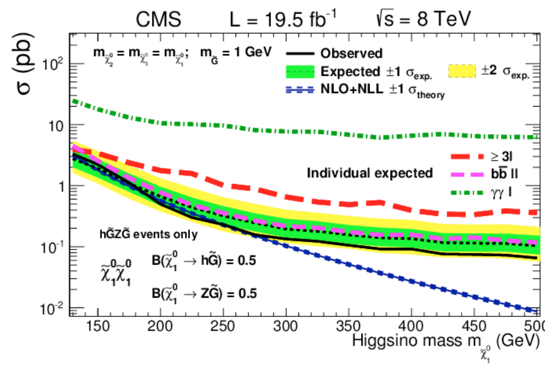
Higgsino NSLP:

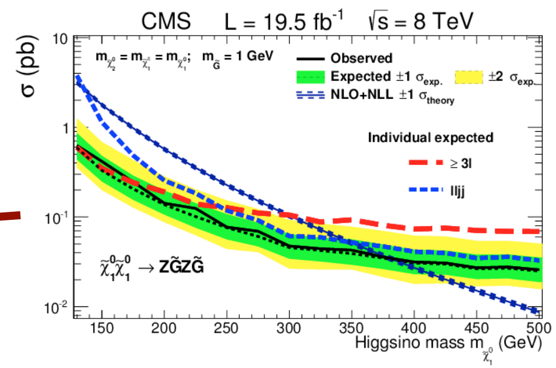


→ hh, Zh, ZZ final states









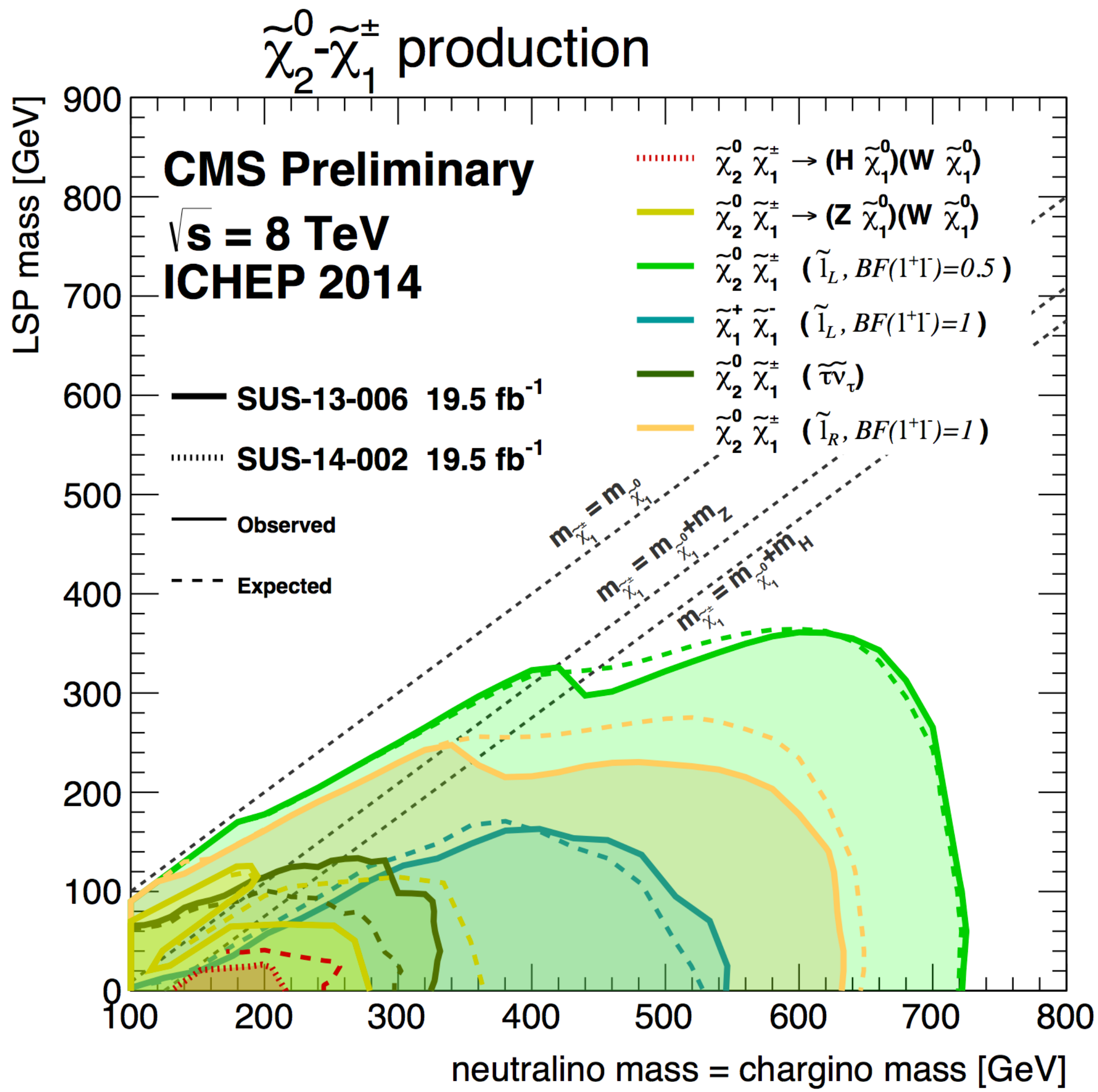
Best limit for ZZ, no limit for hh final state!

Summary on EWKino Searches

Limits depend on final state (weaker limit for tau final states)

Probing chargino-neutralino masses up to 200-700 GeV

Higgsino masses probed up to 210 GeV (380 GeV in the GMSB model)



Where we are...

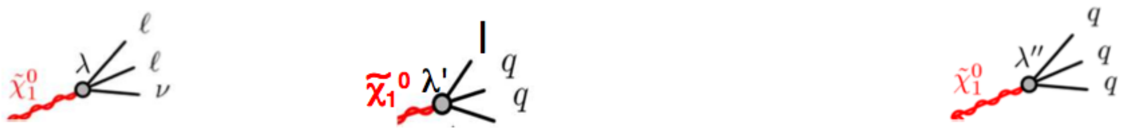
- Escape routes:

⇒ **R-parity violation** ⇐

  - Long-lived particle searches
  - Beyond MSSM signatures
- Outlook

R-Parity Violation

Proton decay only forbids simultaneous violation of lepton and baryon number… but not one **or** the other:



$$W = W_{MSSM} + \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\text{Lepton Number Violation (LFV)}} + \kappa_i L_i H_u + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{Baryon Number Violation (BNV)}}$$

- Add 48 new Yukawa couplings and 96 complex parameters
- Allows the LSP to decay

→ **Considerable change in the final states!**

→ **Background generally lower (no LFV nor BNV in SM), though lower MET than in RPC**

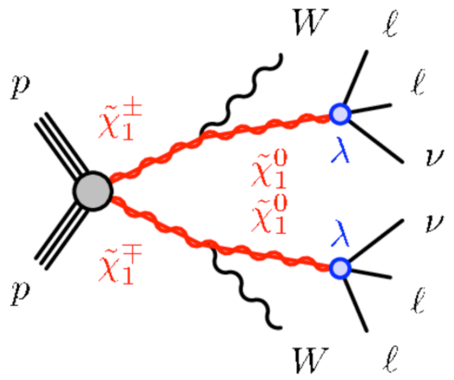
R-Parity Violation: Example for Lepton Flavor Violation

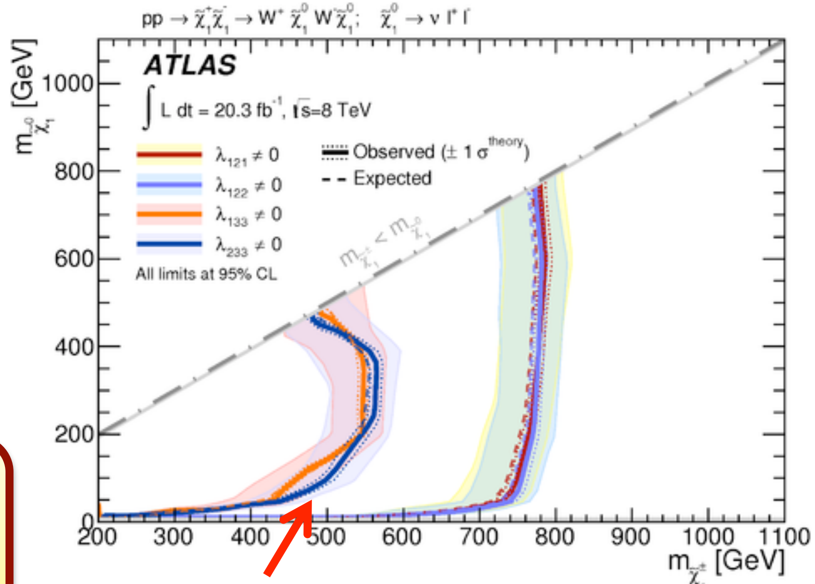
Phys. Rev. D. 90, 052001 (2014)
arxiv:1405.5086

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

Characteristic for $\tilde{\chi}_1^0$ LSP, $\lambda_{ijk} \neq 0$: final states with **many leptons**

- Event selection:
  - 2 to 4 leptons (OSSF pairs > 20 GeV)
  - Several signal regions (MET > 50 to 100 GeV, or m_{eff} > 600 GeV)





Very strong limits for direct chargino production (reminder: no limit in RPC)
Exclude charginos up to 750 GeV

Limits weaker for decays including τ

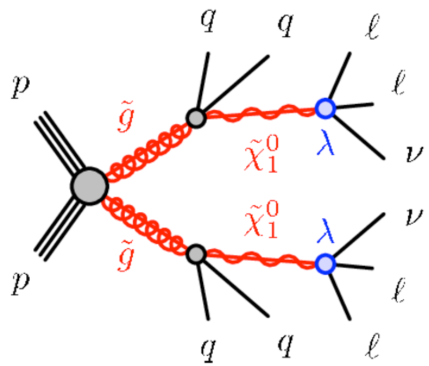
R-Parity Violation:
Example for Lepton Flavor Violation

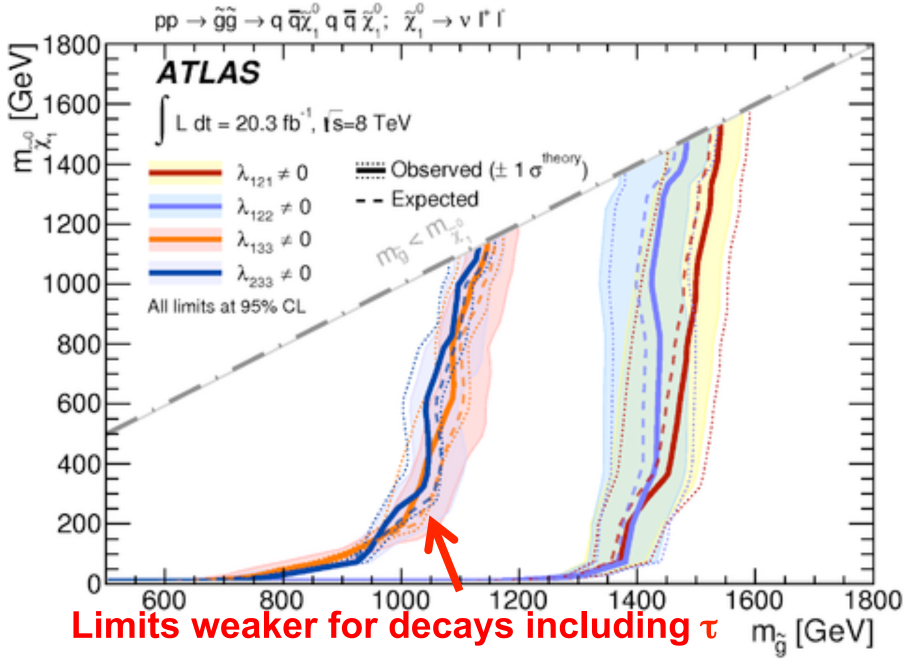
Phys. Rev. D. 90, 052001 (2014)
arxiv:1405.5086

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

Characteristic for $\tilde{\chi}_1^0$ LSP, $\lambda_{ijk} \neq 0$: final states with **many leptons**

- Event selection:
  - 2 to 4 leptons (OSSF pairs > 20 GeV)
  - Several signal regions (MET > 50 to 100 GeV, or m_{eff} > 600 GeV)





Limits weaker for decays including τ

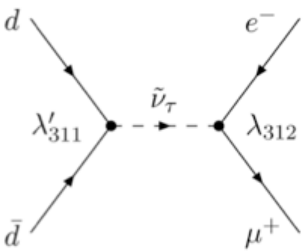
Strong limits for gluino production as well!
Exclude gluinos up to 1.5 TeV

R-Parity Violation:
Example for Lepton Flavor Violation

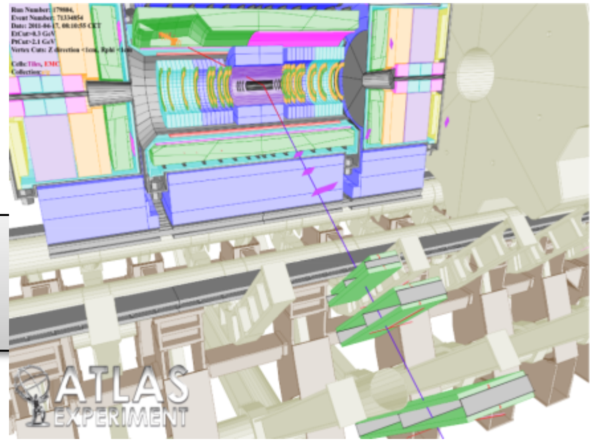
arxiv:1212.1272

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

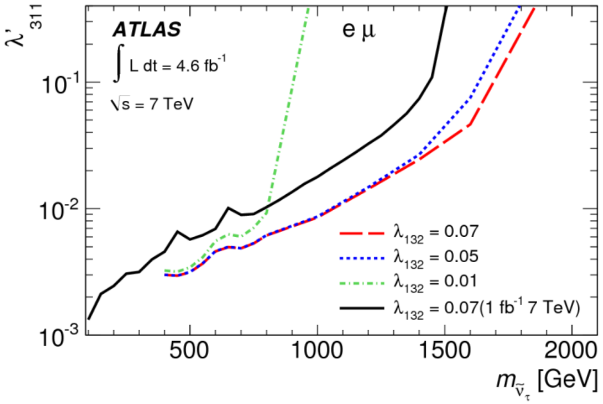
Characteristic for λ'_{311}, $\lambda_{i32} \neq 0$: **eμ, eτ, $\mu\tau$ resonance**



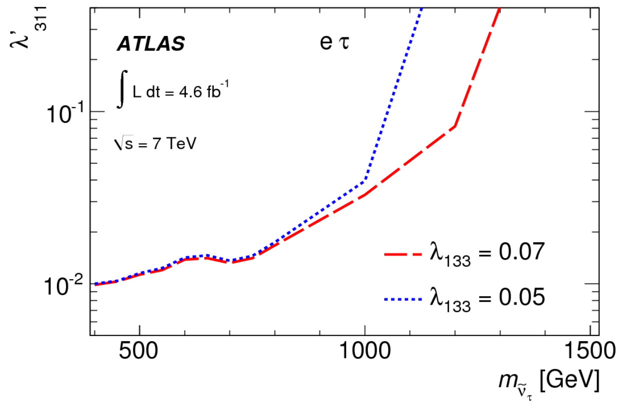
$\Delta\phi$ (e, μ)~π
MET=132 GeV
no Jet !



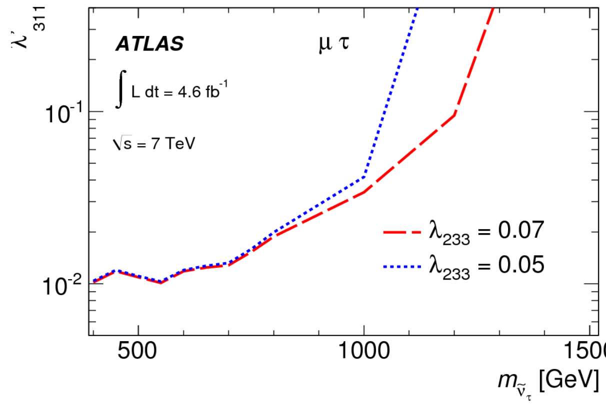
λ'_{311}, λ_{132}



λ'_{311}, λ_{133}



λ'_{311}, λ_{233}



Coupling strength at % level excluded for λ'_{311}, λ_{132} if m(ν_τ) < 1 TeV

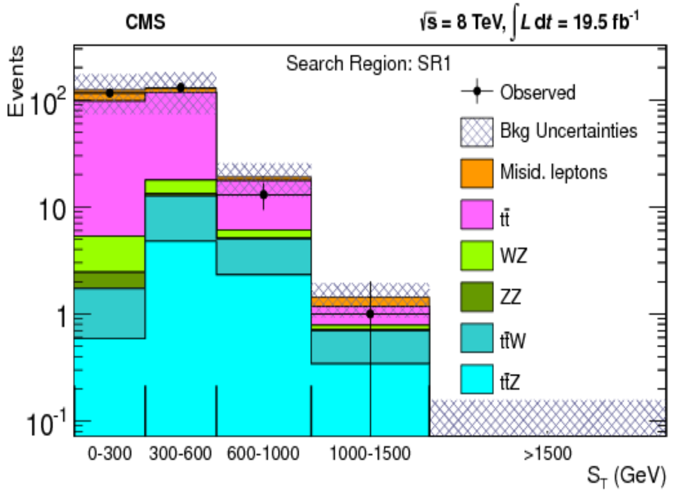
R-Parity Violation: Stop

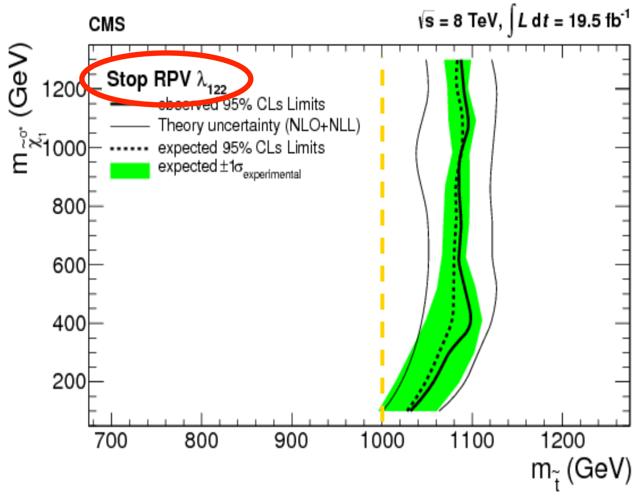
SUS-13-003
PRL 111, 221801 (2013)
arXiv:1306.6643

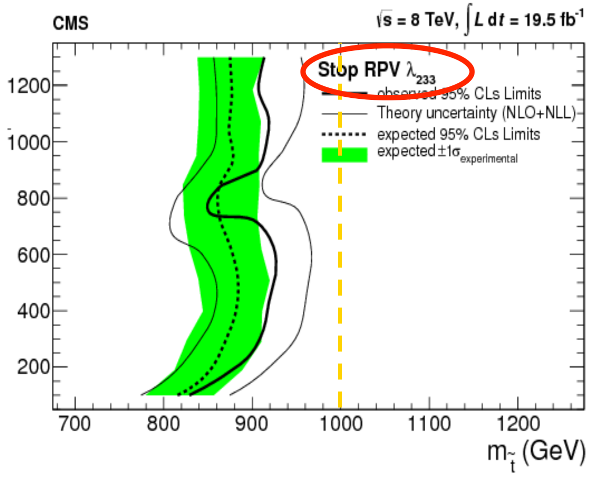
$$W = W_{MSSM} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Stop search with RPV decay

- pp → $\tilde{t}\tilde{t}$ → $t\chi_1^0 t\chi_1^0$ → 4 l (+jets)+MET
- Assume Bino-like neutralino







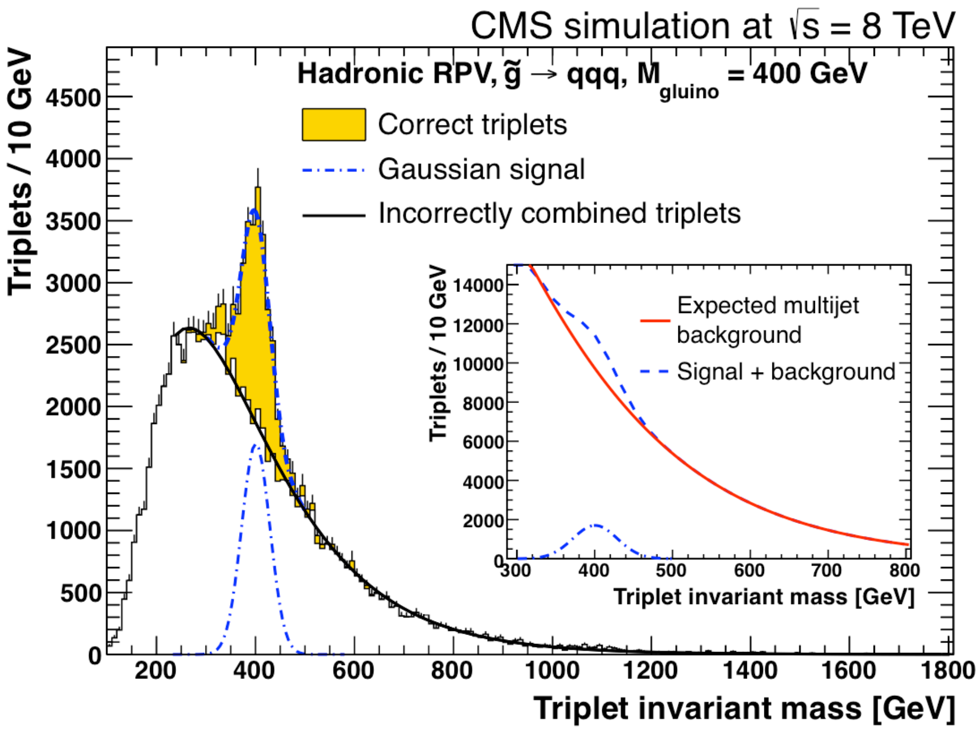
Stronger limits on stop than in RPC!

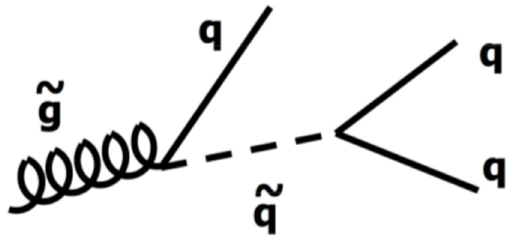
R-Parity Violation: Example for Baryon Flavor Violation

ATLAS-CONF-2013-091
CMS-PAS-EXO-12-049

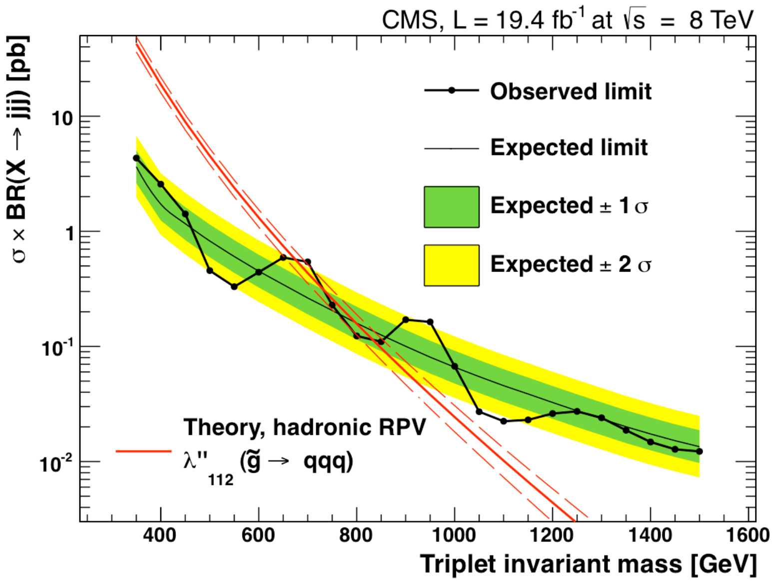
$$W = W_{MSSM} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Characteristic: final states with many jets, no E_T^{miss}



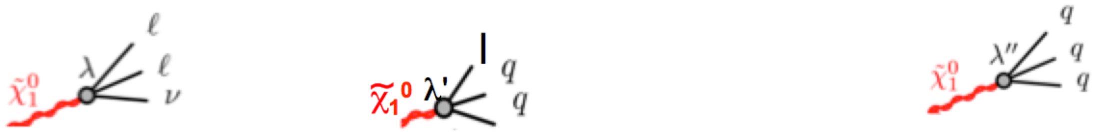


$m(\tilde{q}) >> m(\tilde{g})$



Exclude gluinos up to 800 GeV

RPV – Conclusion



$$W = W_{MSSM} + \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\text{Lepton Number Violation (LFV)}} + \kappa_i L_i H_u + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{Baryon Number Violation (BNV)}}$$

- Several couplings tested (not yet all…)
- Still a large spectrum not covered (e.g. we generally assume χ_1^0 LSP and decay)
- Generally stronger limits than for Standard SUSY (RPC)

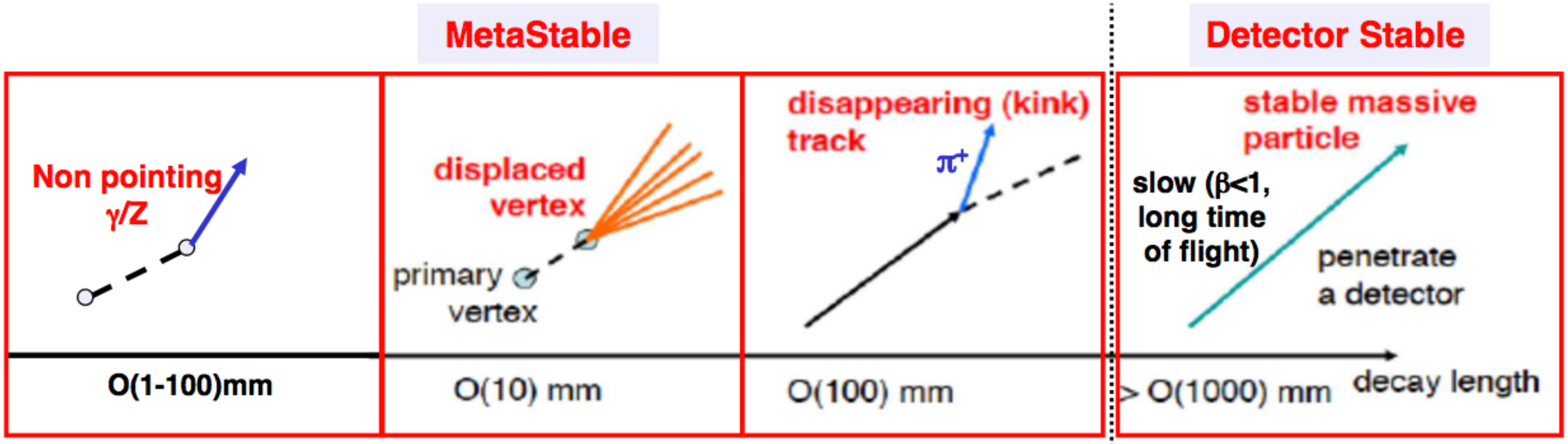
Where we are...

- Escape routes:
  - R-parity violation
  - **⇒ Long-lived particle searches ⇐**
  - Beyond MSSM signatures
- Outlook

"SUSY Exotica"

Apart from the LSP other particles could be long-lived as well:

- Very weak $\tilde{\chi}_1^0$-gravitino coupling [GMSB]
  → Non pointing γ or Z
- RPV: Lifetime proportional to λ^{-2}, λ'^{-2}, λ''^{-2}
  → Displaced vertex if λ, λ', λ'' ~0(10^{-5})
- Low mass difference, e.g $\Delta M(\tilde{\chi}^{\pm}\tilde{\chi}^0)$~100 MeV [AMSB]
  → Soft pion emitted, kinked track
- Stable Massive Particle
  → Stable R-hadron (gluino or squark), sleptons

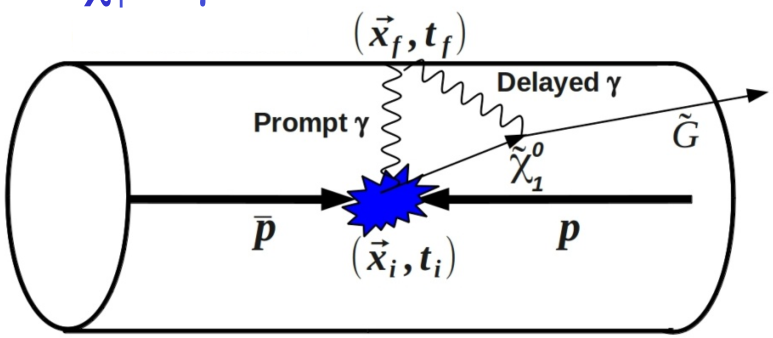


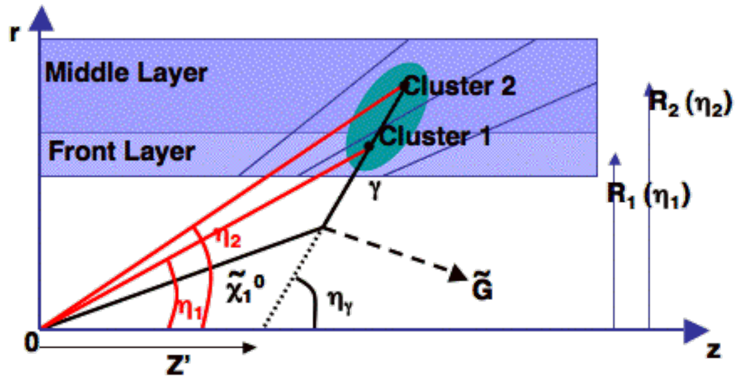
SUSY:
Non-pointing photons

arXiv:1207.0627, 1212.1838, 1304.6310

Non pointing photons could have several signatures

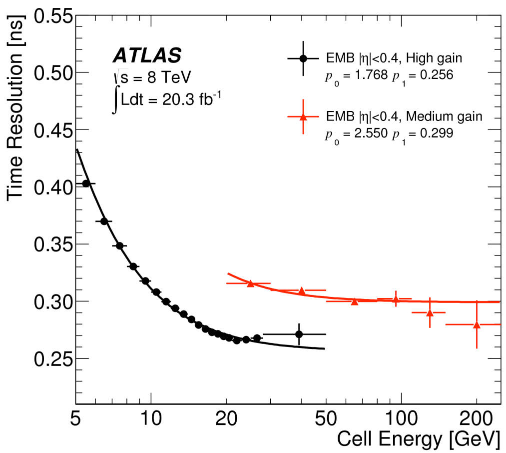
- For all studies assume strong production, GMSB and NLSP bino-like: $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$

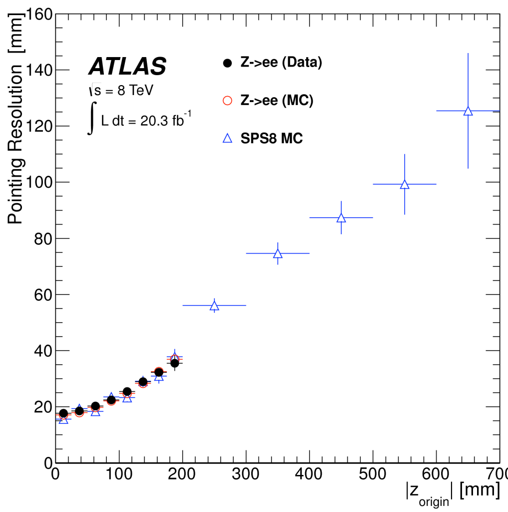




Late arrival in the EM calorimeter (t_γ)
➔ Need excellent calorimeter timing resolution

Not pointing to the primary vertex

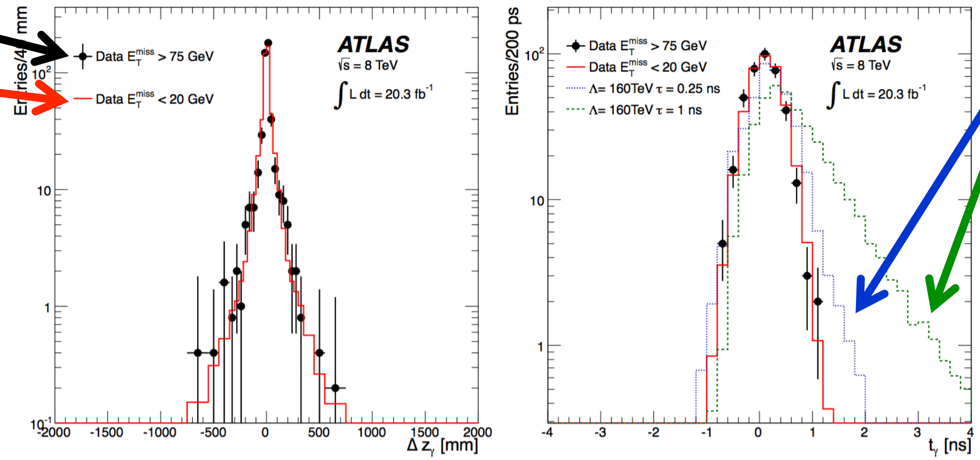




SUSY: Non-pointing photons Result

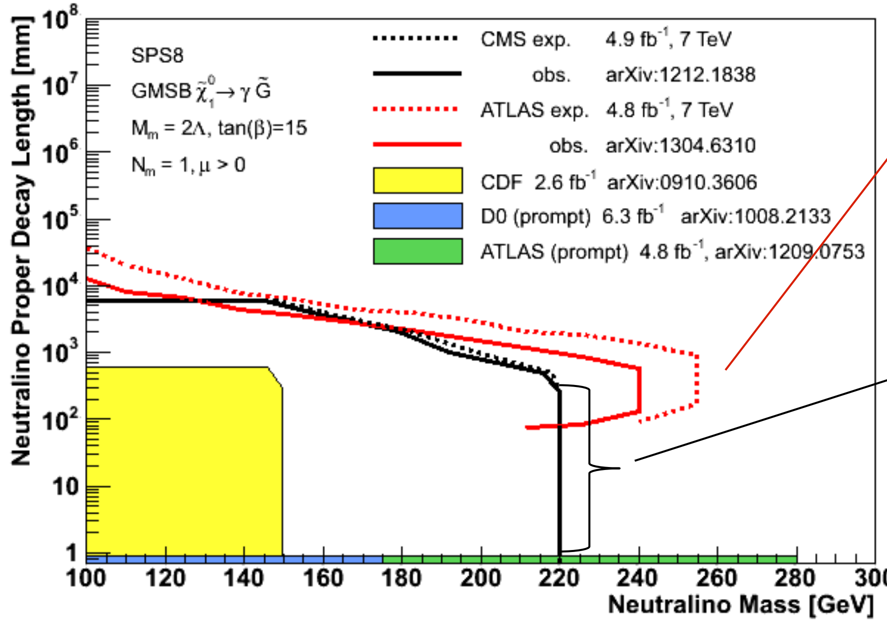
SR

CR



Example signals

Comparing ATLAS and CMS limits:

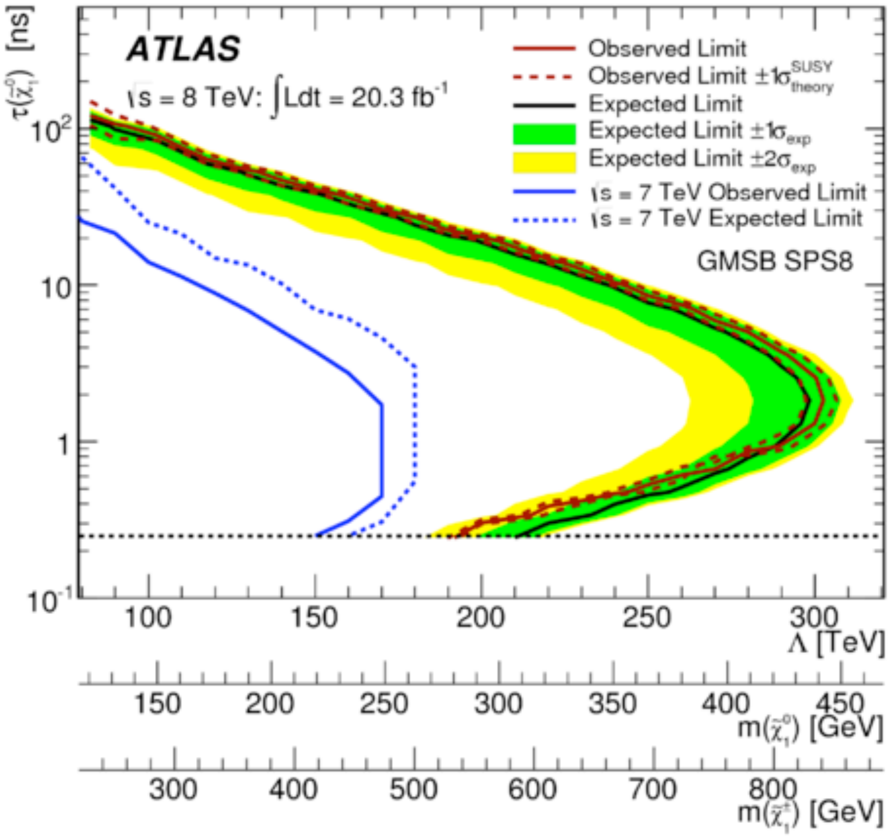


Benefit from better timing resolution and non-pointing geometry

Benefit from tighter E_T^{miss} and $E_T(\gamma)$ cuts

SUSY: Non-pointing photons Result

8 TeV extends 7 TeV result by factor 2



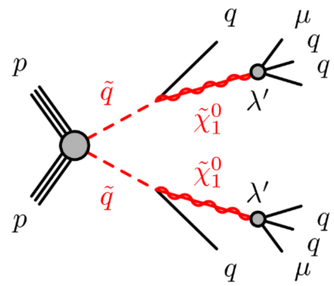
Exclude neutralinos up to 450 GeV (for $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$)

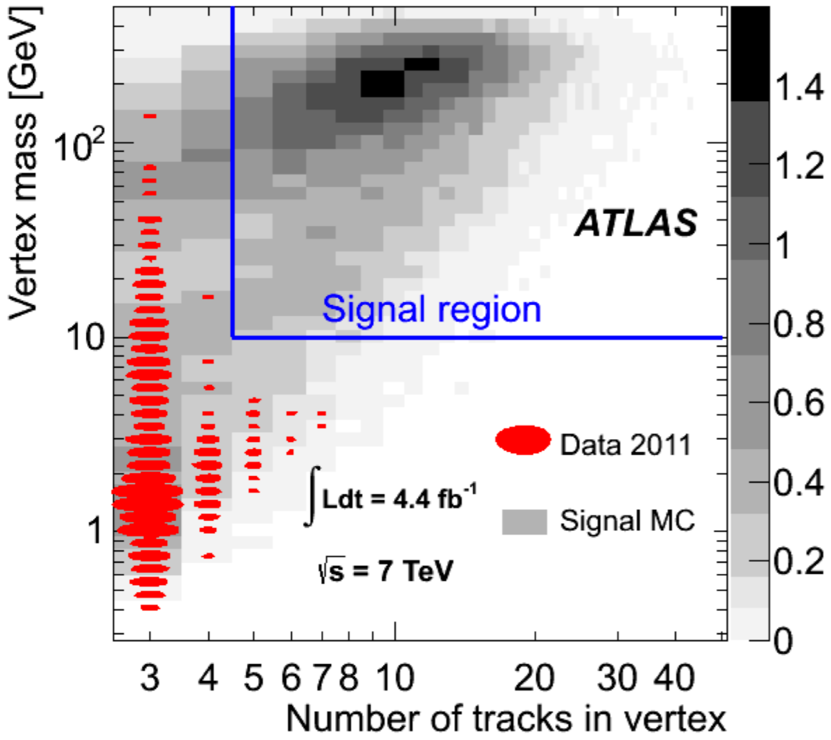
RPV SUSY:
Example for Displaced Vertex

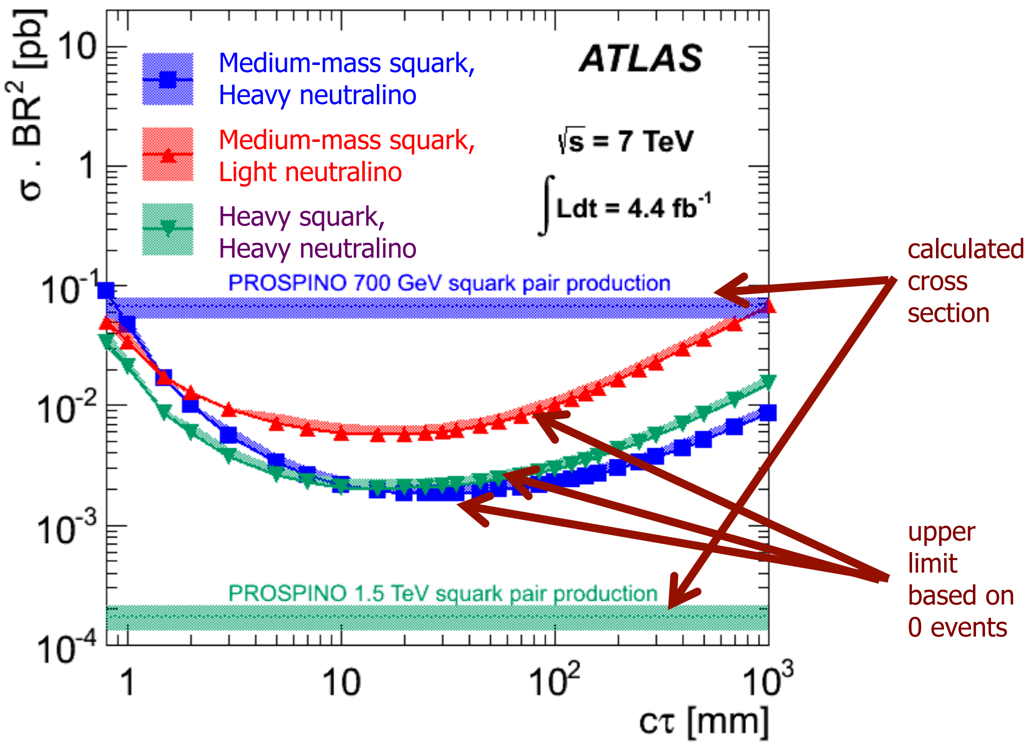
arXiv:1210.7451

High mass displaced vertex with multiple tracks and a muon

- Assume RPV with $\lambda'_{2ij} \neq 0$
- Need dedicated tracking to increase signal efficiency
- Background-free in *displaced vertex mass – N_{track}* plane





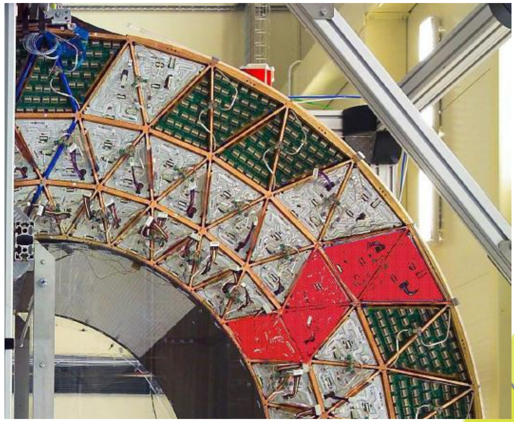


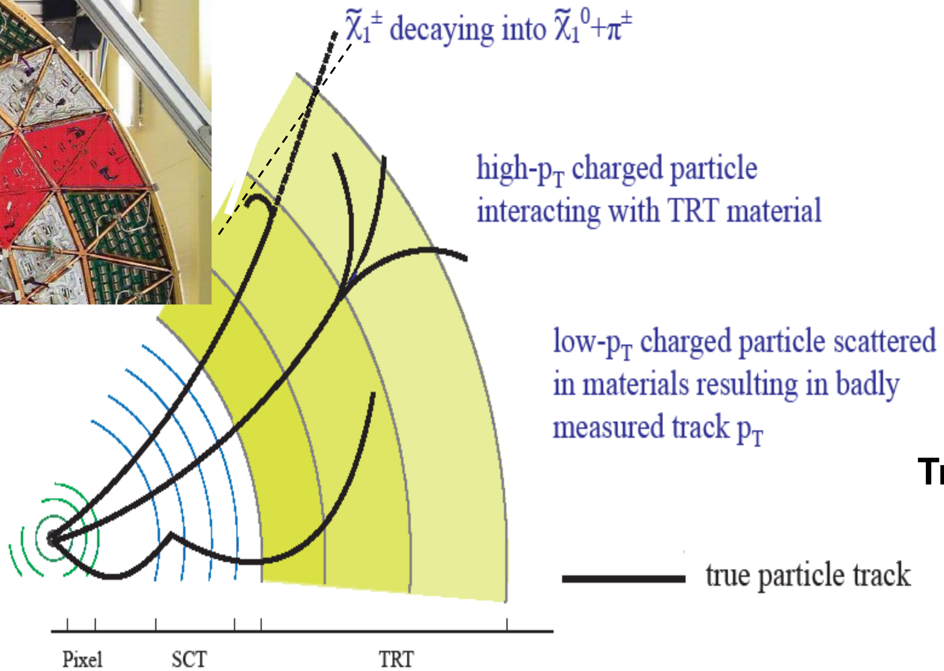
Disappearing Track / Kink: Example

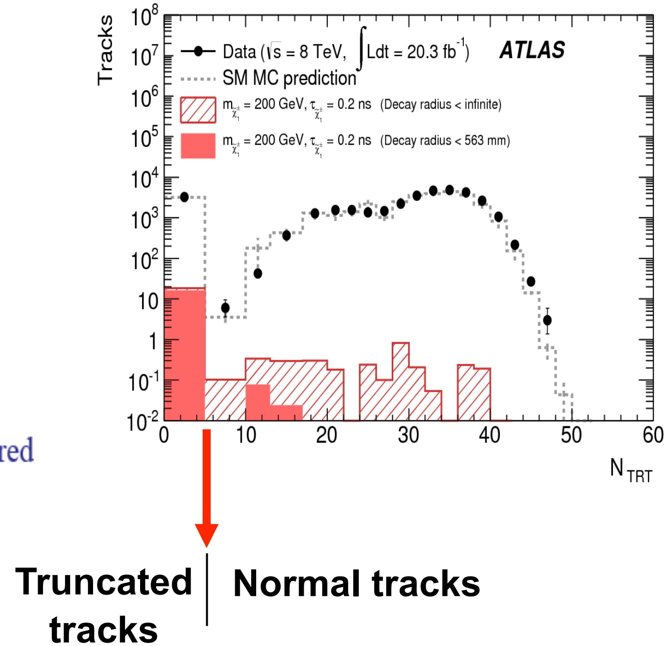
Phys. Rev. D 88, 112006 (2013)
arXiv:1310.3675

Direct production of a metastable $\chi_1^\pm$

- Motivated by AMSB, but model independent results
- $\tilde{\chi}_1^\pm \rightarrow$ soft $\pi^+ + \tilde{\chi}_1^0$: Disappearing track in the TRT
- Remove background : N_{TRT} + highest p_T isolated track



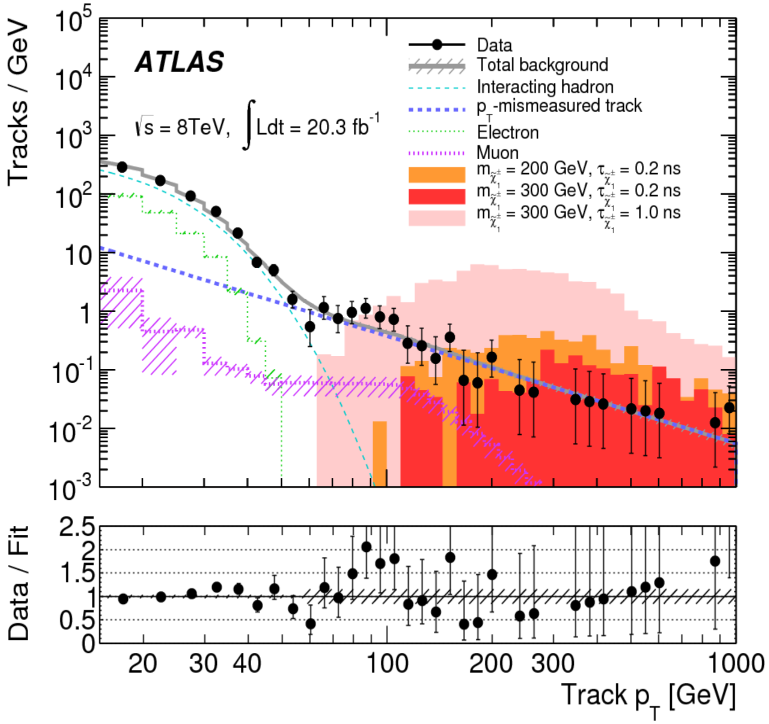


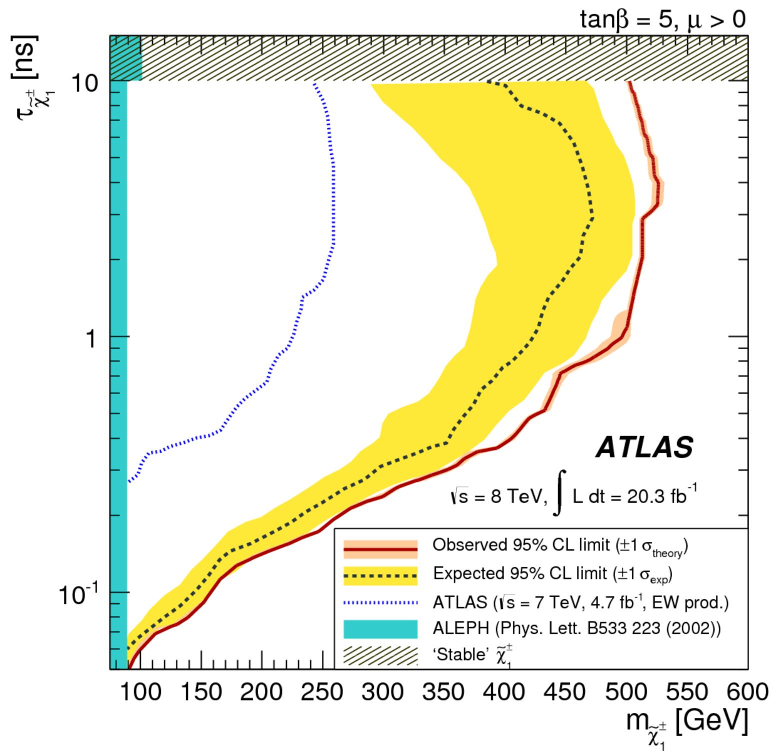


Disappearing Track / Kink: Results

Phys. Rev. D 88, 112006 (2013)
arXiv:1310.3675

Direct production of a metastable $\chi_1^\pm$





Good candidate for minimum unnatural SUSY model
Exclude chargino masses up to 500 GeV

Detector-Stable Particles: Introduction

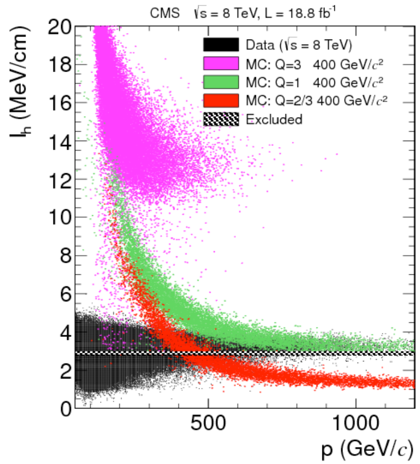
hep-ph/0611040

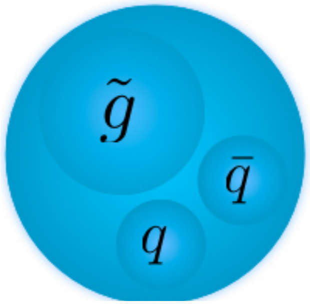
Several candidates for colored particles:

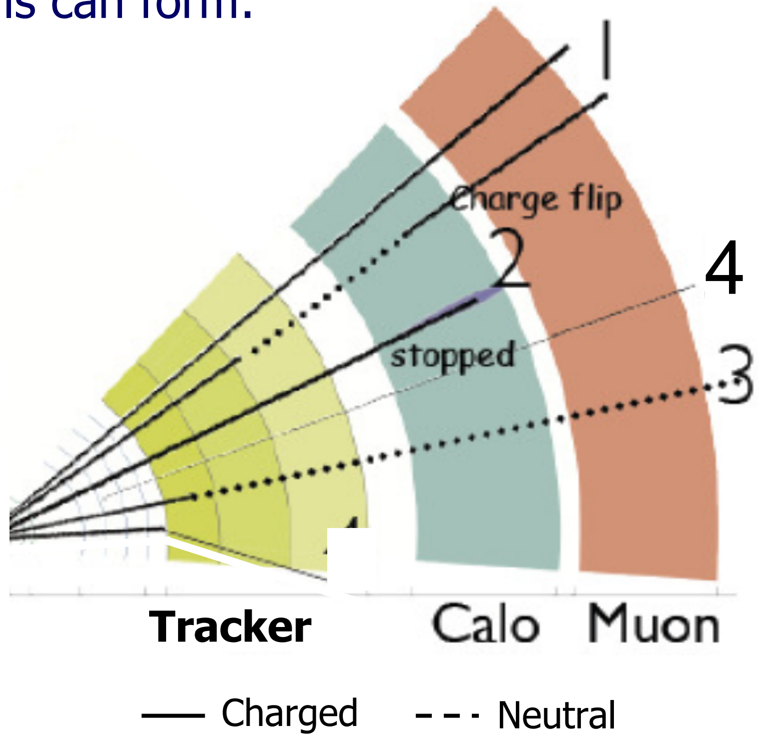
- **Gluino is the LSP** (SUSY GUT extension)
- Very weak coupling of **NLSP=$\tilde{g}$ with $\tilde{G}$=LSP** (SUSY GUT)
- **Squarks decoupled or $\Delta m(\tilde{g}/\tilde{q}-\tilde{\chi}_1^0)$ ~ O(100 MeV)** (e.g. Split SUSY*)

→ If lifetime > hadronization time scale ~O(10^{-24} s) then gluino / squark (especially $\tilde{t}_1$ and $\tilde{b}_L$) R-hadrons or gluinoballs can form:

- Detector stable
- Highly-ionising particle
- Slow moving (non-relativistic)
- **Can change sign**







Decay to LSP is suppressed because of very high mass virtual squarks

Detector-Stable Particles: Introduction

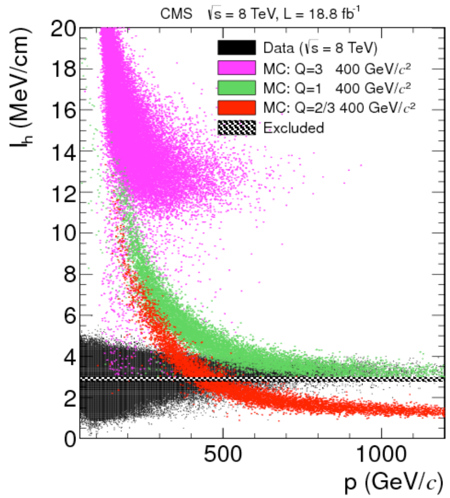
hep-ph/0611040

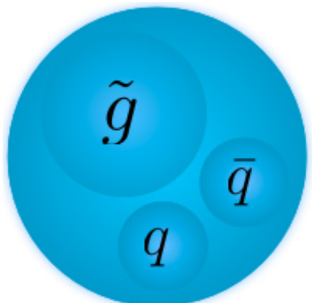
Several possibilities for non-colored particles:

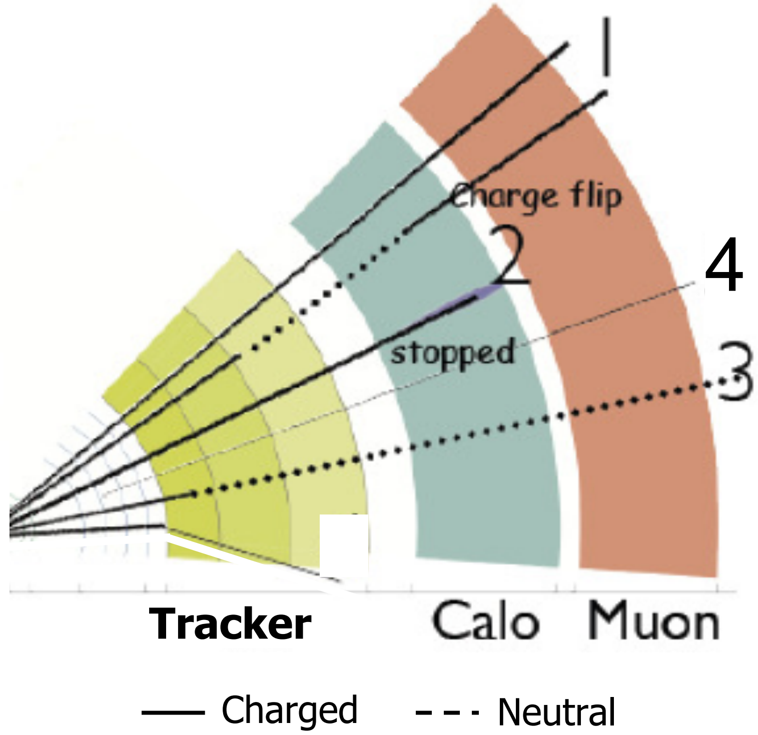
- **Slepton is the LSP** (SUSY GUT extension)
- Very weak coupling of **NLSP=$\tilde{l}$ with $\tilde{G}$=LSP**
- Low mass difference **$\Delta m(\tilde{l}-\tilde{\chi}_1^0)$ ~ O(100 MeV)**

→ Long-lived sleptons manifest as a heavy muon, charged and penetrating:

- Detector stable
- Highly-ionising particle
- Slow moving (non-relativistic)
- **Cannot change sign**



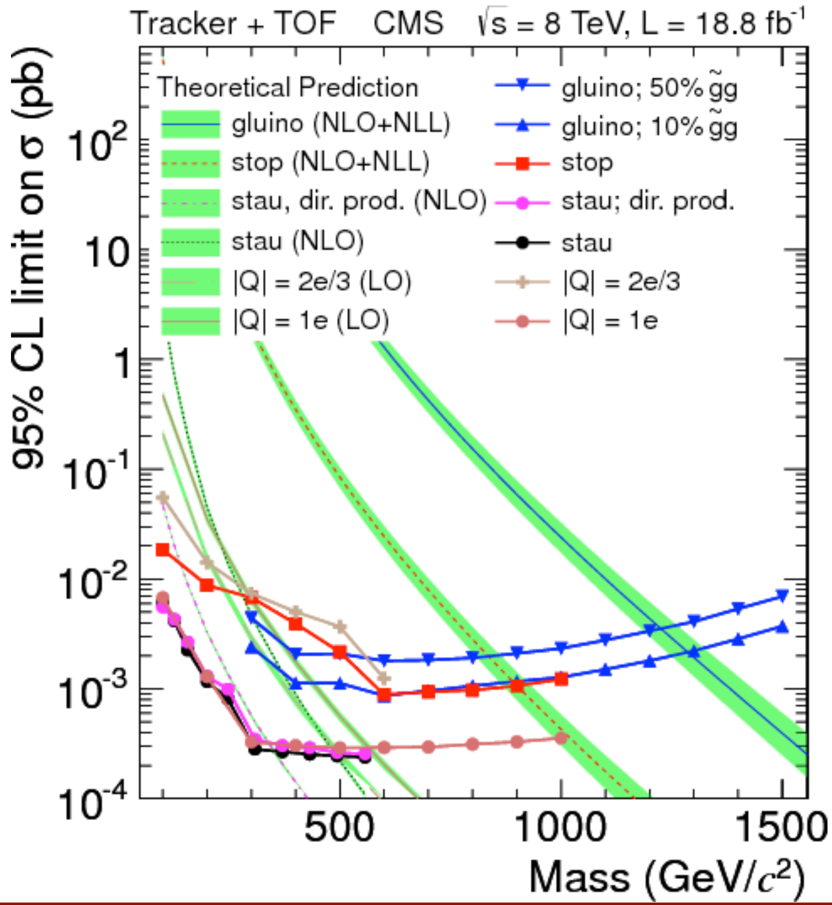




Detector-Stable Particles: Results

EXO-12-026
10.1007/JHEP07(2013)122
arXiv:1305.0491

Model-independent limits (just relying on the MSSM production cross section)

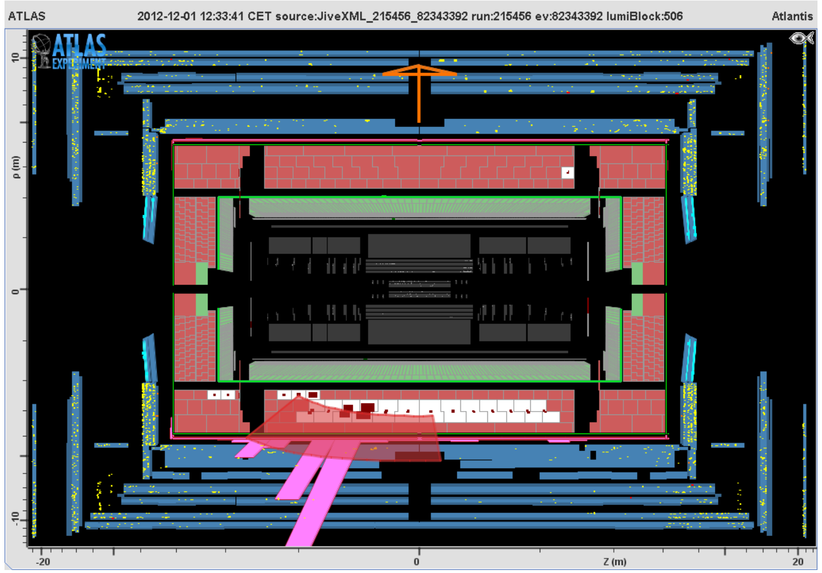


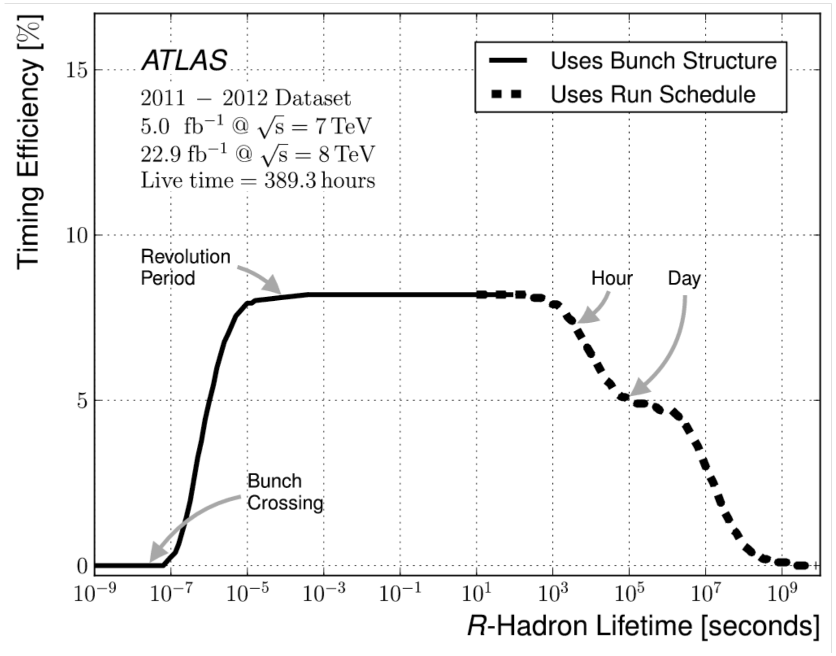
Generally stronger limits than in prompt SUSY searches

Stopped Particles

R-hadrons can also stop in the calorimeter and decay later

- Split SUSY (unnatural model): the stopped gluino is the only particle reachable at LHC
- High energetic jets in absence of collisions
- Background = calorimeter noise, cosmics and beam halo

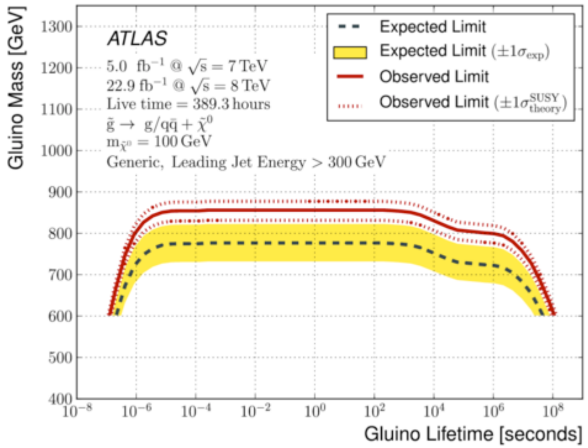


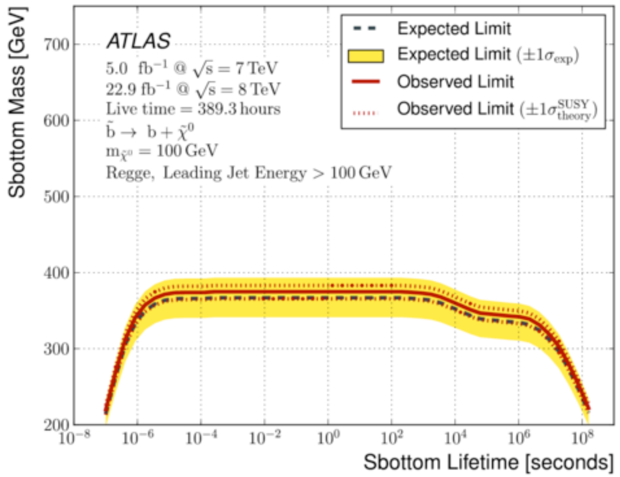


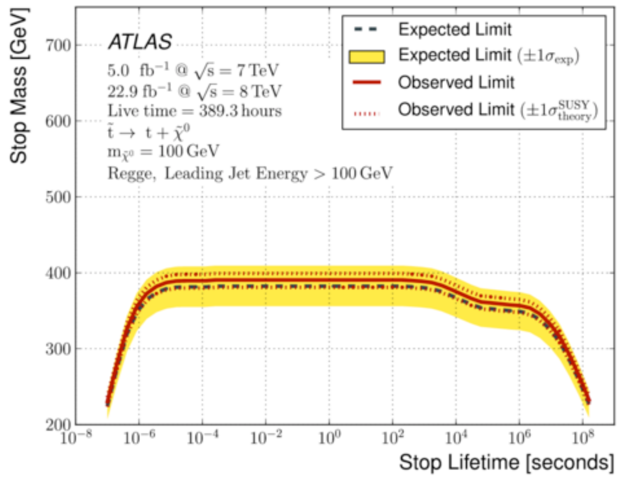
Stopped Particles

Phys. Rev. D 88, 112003 (2013)
arxiv:1310.6584

R-hadrons can also stop in the calorimeter and decay later







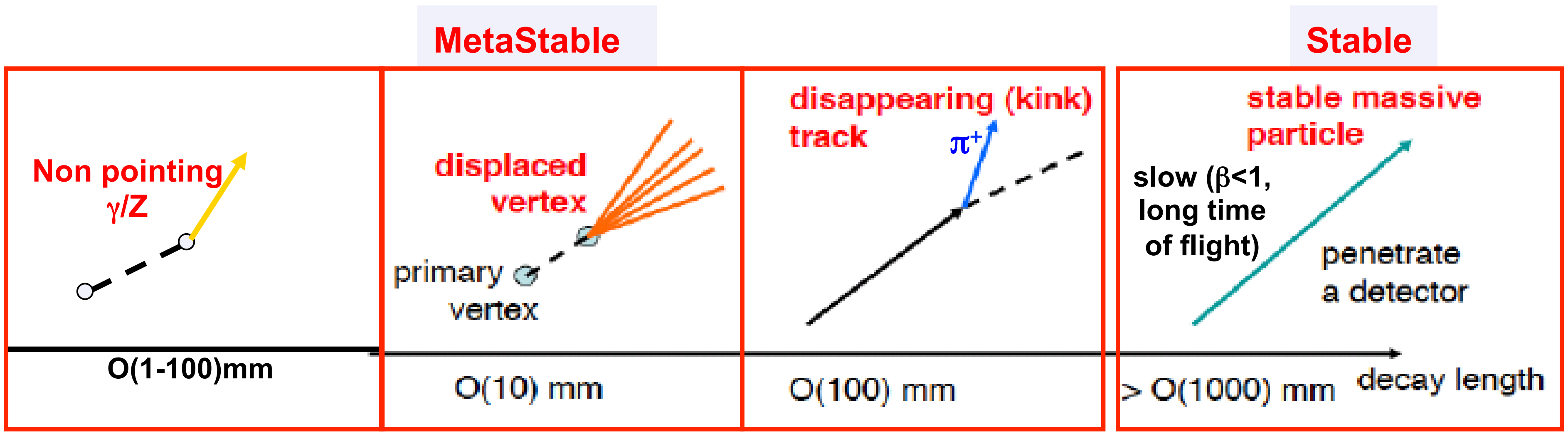
$M_{\tilde{g}} < 850$ GeV ($M_{\chi 0}$ =100 GeV) excluded for 1 ms < t < 300 hours

$M_{\tilde{b}} < 375$ GeV ($M_{\chi 0}$ =100 GeV) excluded for 1 ms < t < 300 hours

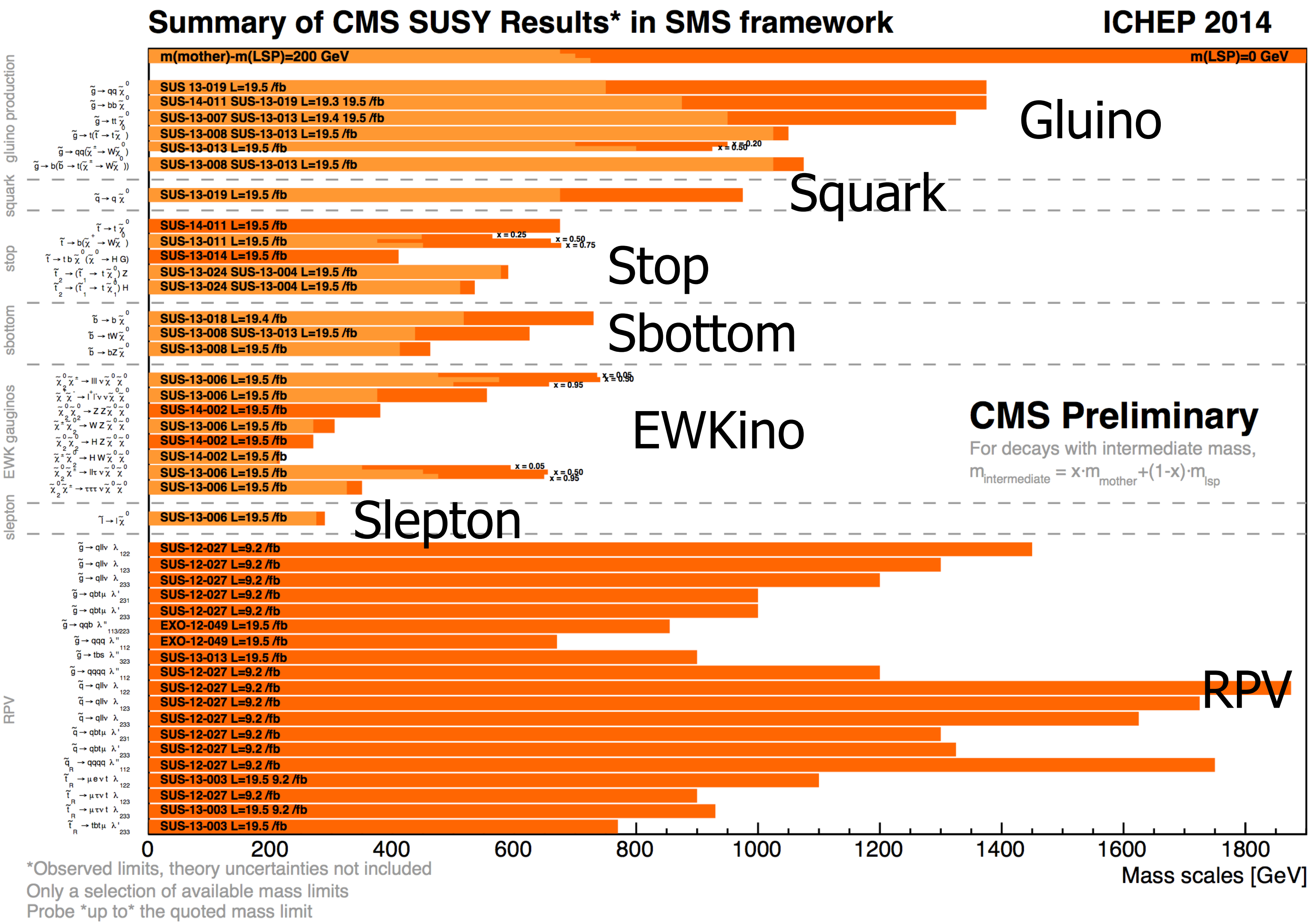
$M_{\tilde{t}} < 400$ GeV ($M_{\chi 0}$ =100 GeV) excluded for 1 ms < t < 300 hours

Long-lived Particles: Conclusion

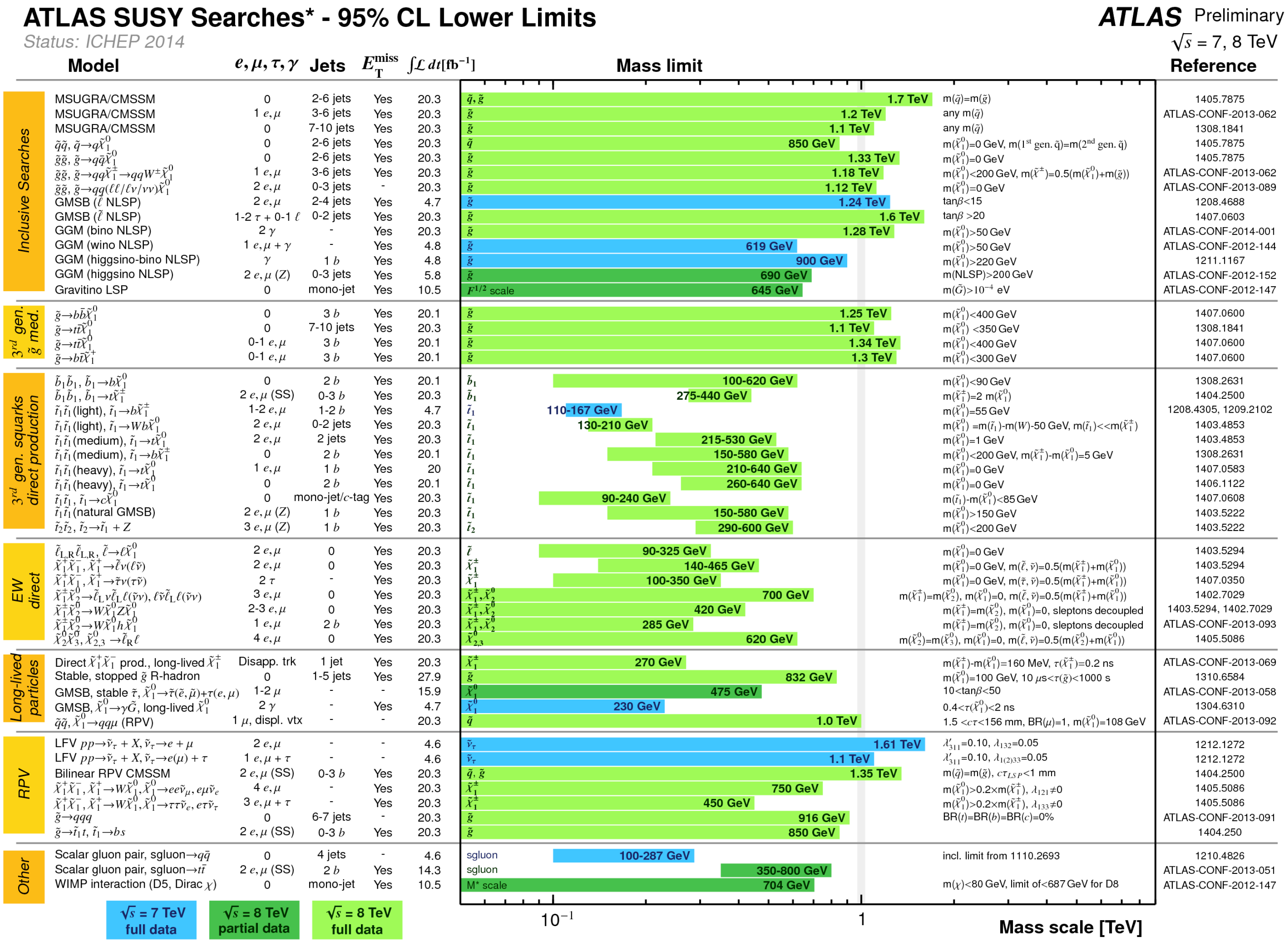
- Very well motived and can explain the absence of signal in standard SUSY searches
- Huge number of possibilities (not yet all covered)
- Striking signatures of BSM not present in the SM
  - Generally detector-oriented, background-free
  - Limits on SUSY particles generally stronger



Summary – Supersymmetry



Summary Supersymmetry



*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Where we are...

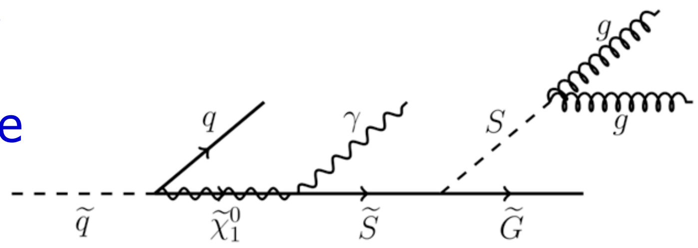
- Escape routes:
  - R-parity violation
  - Long-lived particle searches
  - **Beyond MSSM signatures**
- Outlook

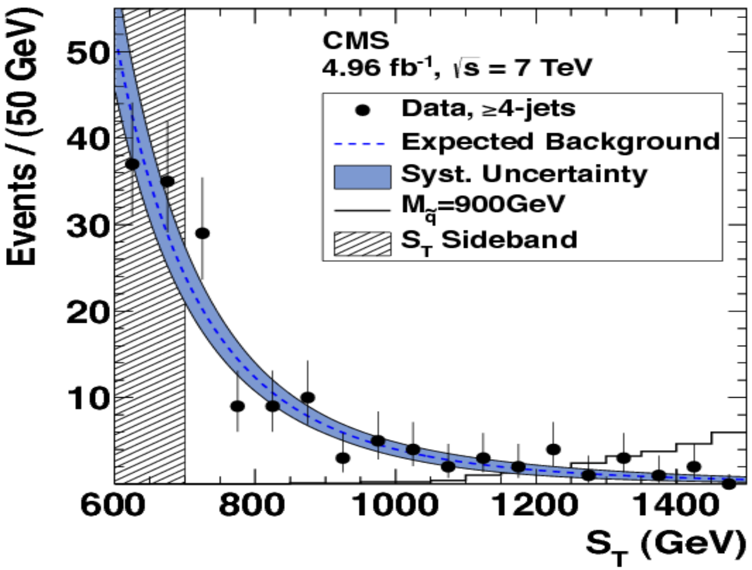
Beyond MSSM Signatures

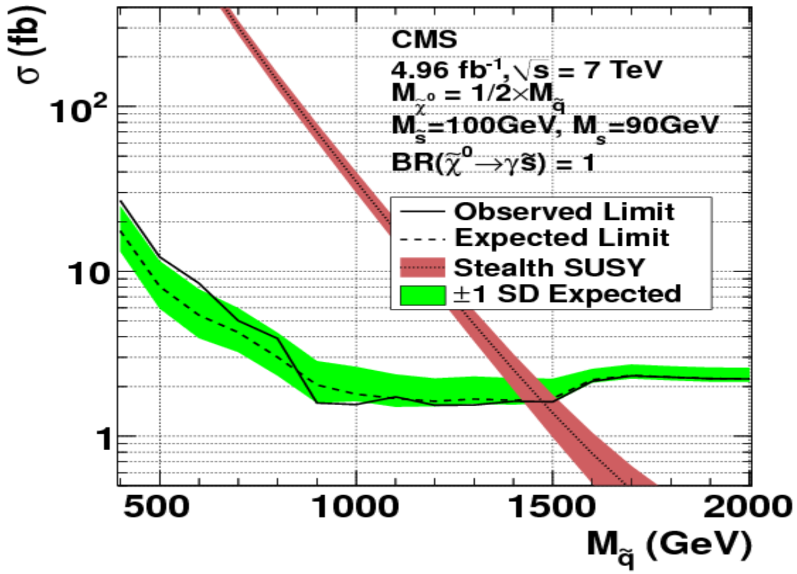
PLB 719, 42-61 (2013),
arXiv:1210.2052

Stealth SUSY:

- Invisible extra singlet and singlino are mass degenerate and light
- Reduces drastically the amount of MET since all SUSY cascade decays ends like $\tilde{S} \rightarrow S$ ($\rightarrow$jj or $\gamma\gamma$) $\tilde{G}$ with poorly boosted $\tilde{G}$
- Example: S decay to photons





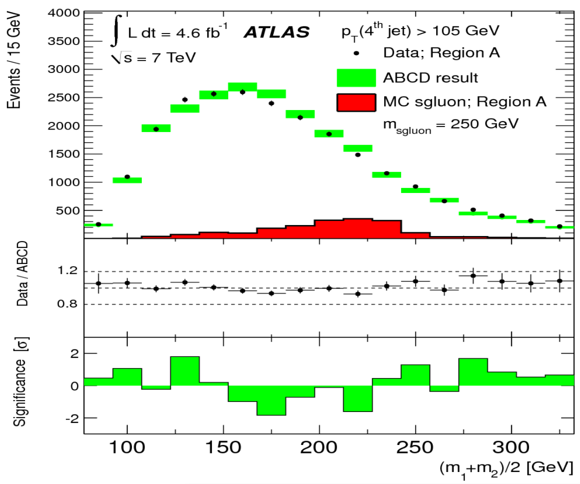


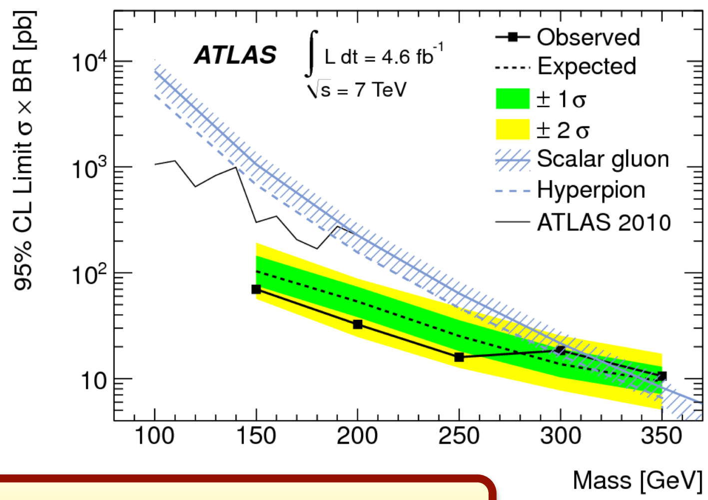
Exclude squarks up to 1.4 TeV

Beyond MSSM Signatures

R-parity concept extended to a continuous symmetry (MRSSM, SSSM):

- Gluino to be of Dirac type instead of Majorana as in the MSSM
- Sgluon completes the MSSM multiplet composed of gluons and gluinos
- Constraint on the gluino mass in the natural spectrum relaxed (radiative corrections are truncated and a lower gluino-gluino cross-section is expected compared to MSSM)
- **m(sgluon) < 350 GeV**: decay in two gluons
  → pair of two-jet resonances with equal mass
- Reconstruct 2 resonances M1, M2 with ≥4 jets p_T>80 GeV



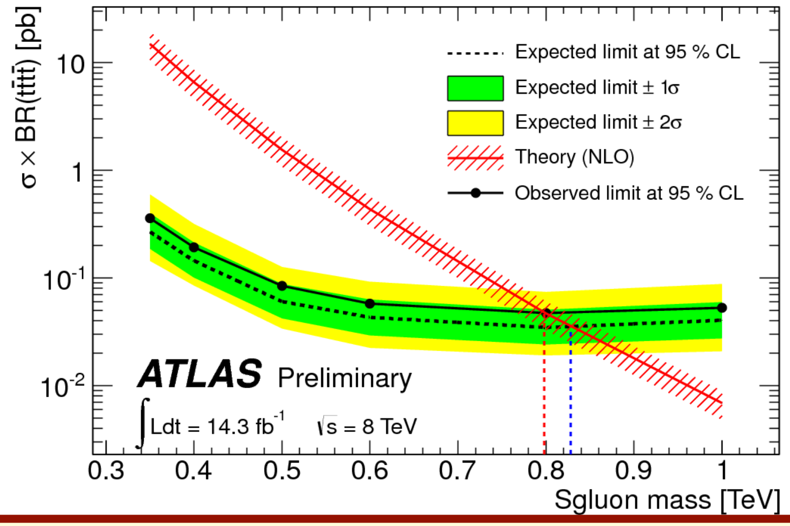


Exclude sgluons with mass < 300 GeV

Beyond MSSM Signatures

R-parity concept extended to a continuous symmetry (MRSSM, SSSM):

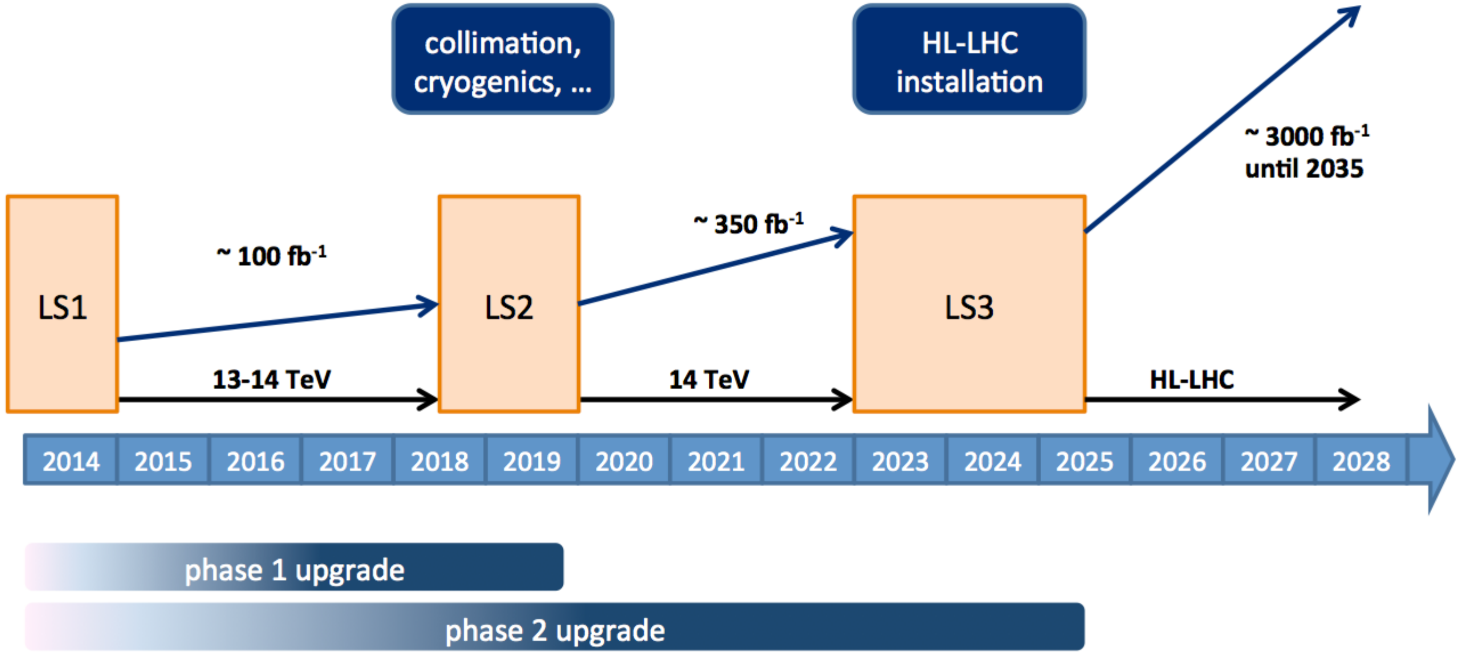
- Gluino to be of Dirac type instead of Majorana as in the MSSM
- Sgluon completes the MSSM multiplet composed of gluons and gluinos
- Constraint on the gluino mass in the natural spectrum relaxed (radiative corrections are truncated and lower gluino-gluino cross section are expected compared to MSSM)
- **m(sgluon) > 350 GeV:** decay in two top quarks → 4 top final states
- Can be accessed with 2 same-sign leptons



Exclude sgluons with mass < 800 GeV

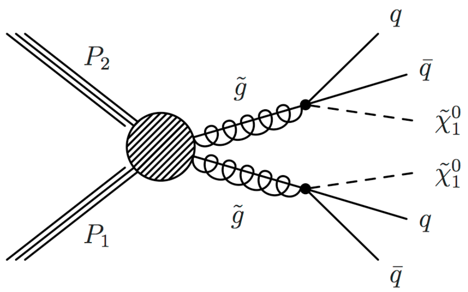
Outlook

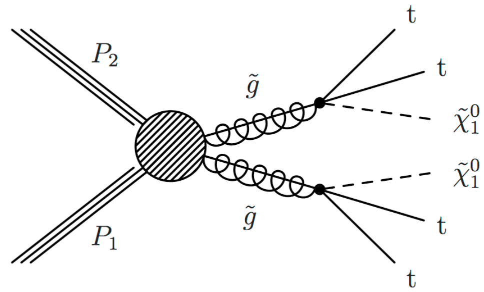
LHC has finished the 8 TeV data taking in 2012
Preparations for 13 TeV are ongoing

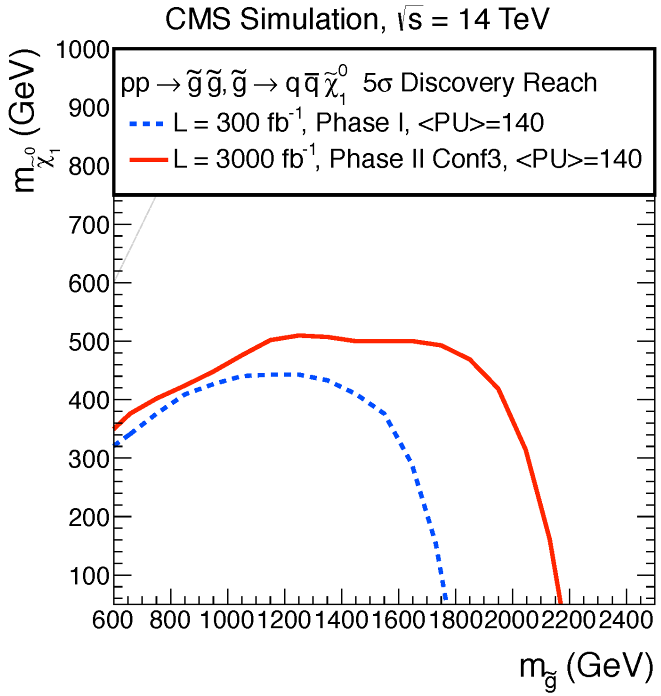


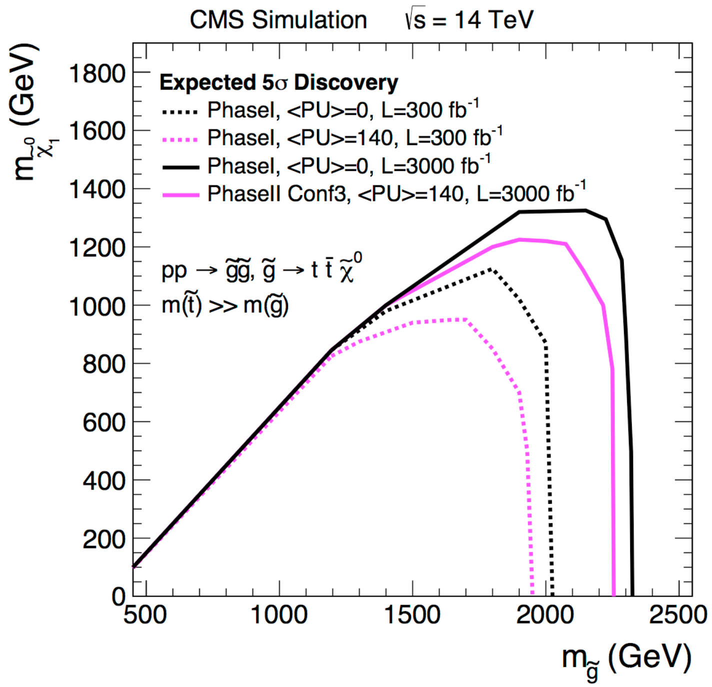
Expect exciting discoveries in the next runs!

SUSY Projections for Gluinos





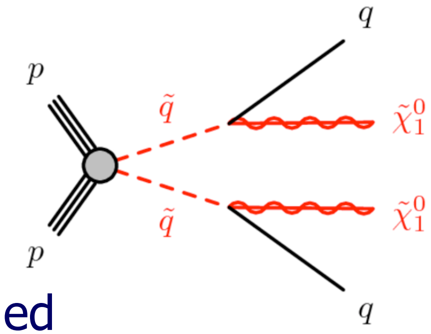




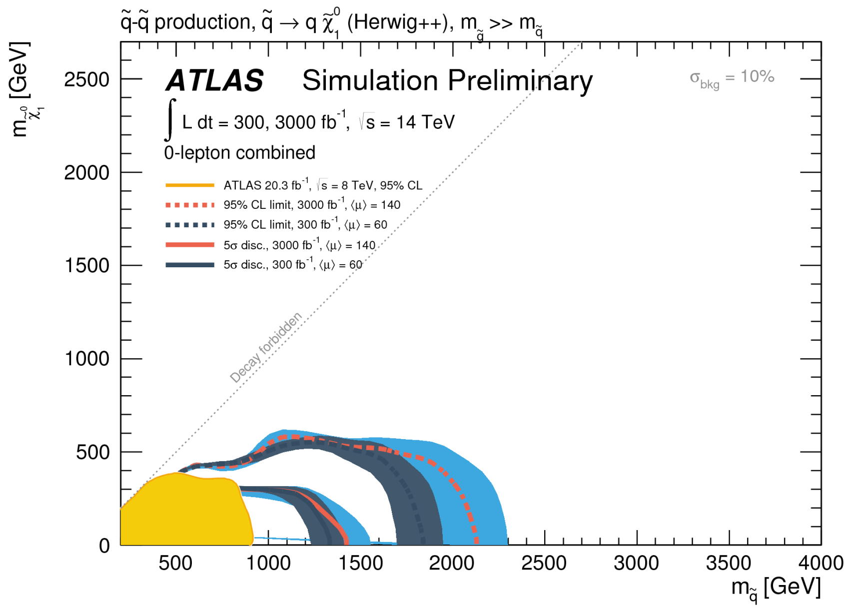
5σ discovery reach extended up to 1.8 (2.2) TeV, up to 2 (2.3) TeV for decays through top quarks

CMS-PAS-FTR-13-014

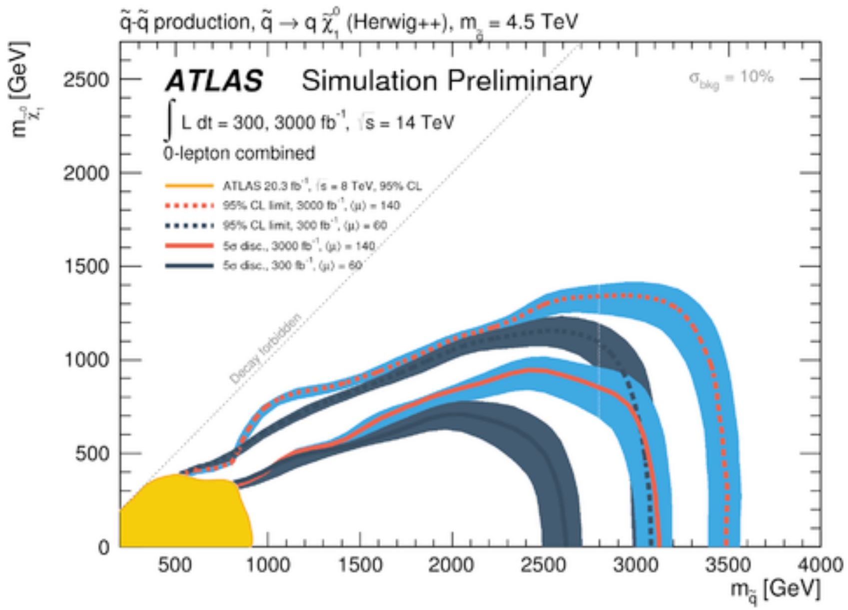
SUSY Projections for Squarks



Gluino mass decoupled



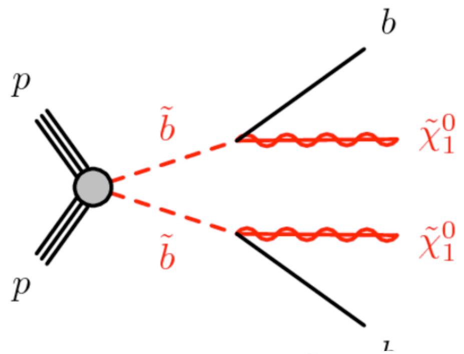
Gluino mass at 4.5 TeV

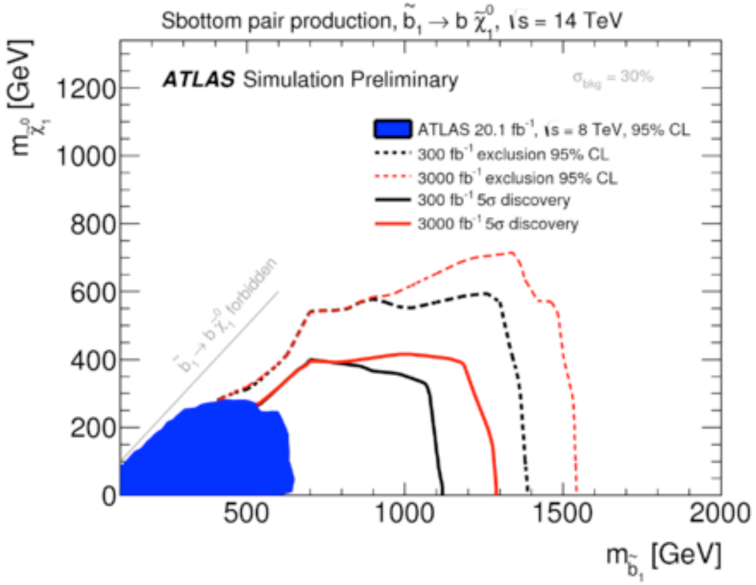


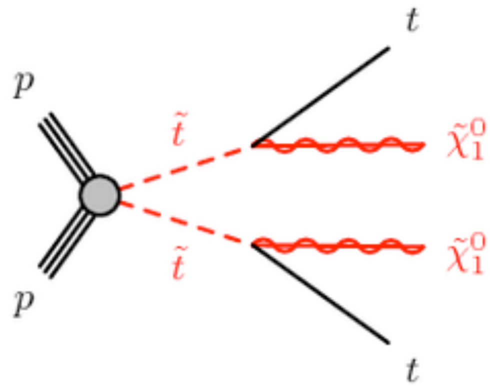
5σ discovery reach extended up to 1.4 (1.9) TeV, up to 2.6 (3) TeV for decays for m_{gluino}=4.5 TeV

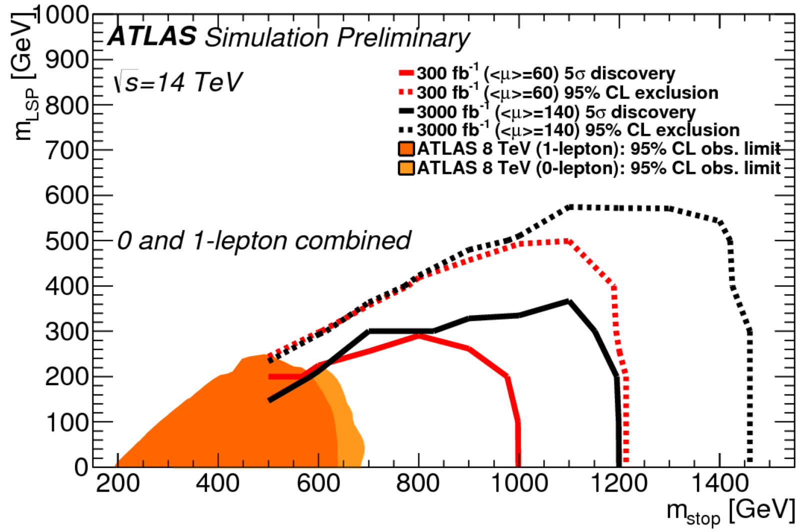
ATL-PHYS-PUB-2014-010

SUSY Projections for 3rd Gen. Squarks





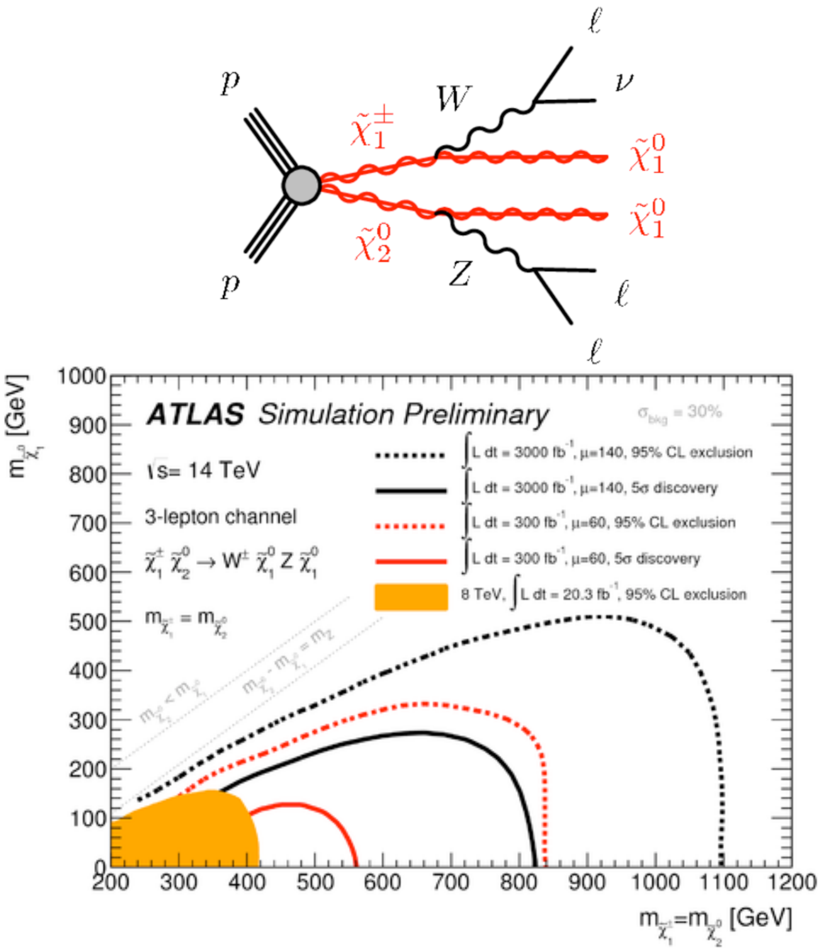


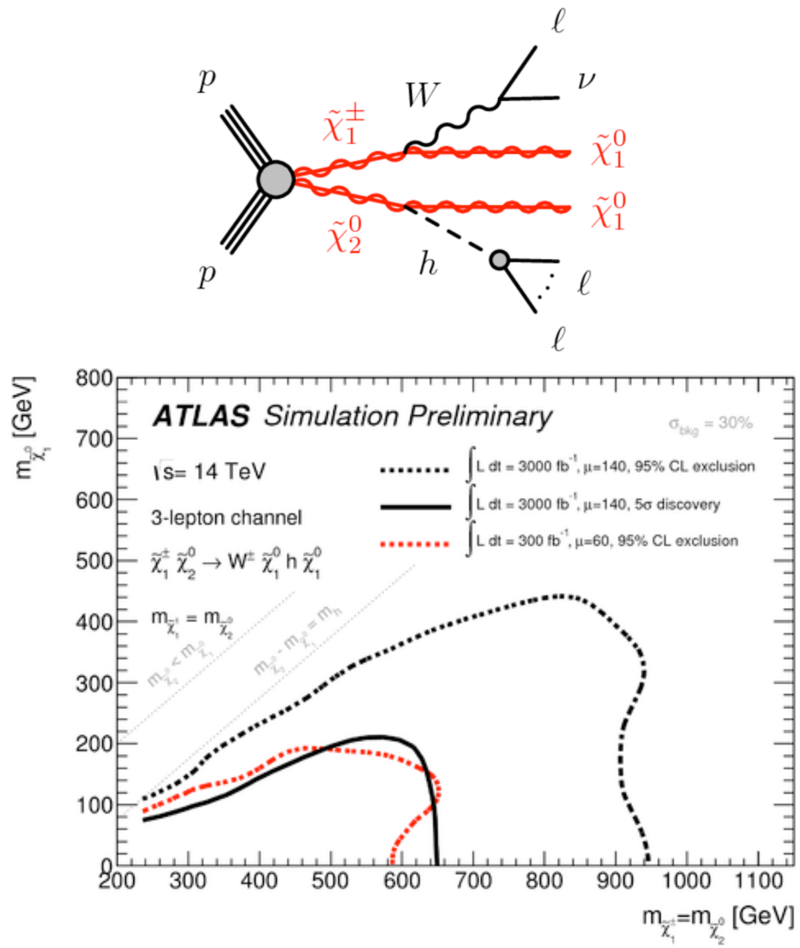


5σ discovery reach extended up to 1.1 (1.4) TeV for sbottom, up to 1 (1.2) TeV for decays for stops

ATL-PHYS-PUB-2014-010

SUSY Projections for EWKinos

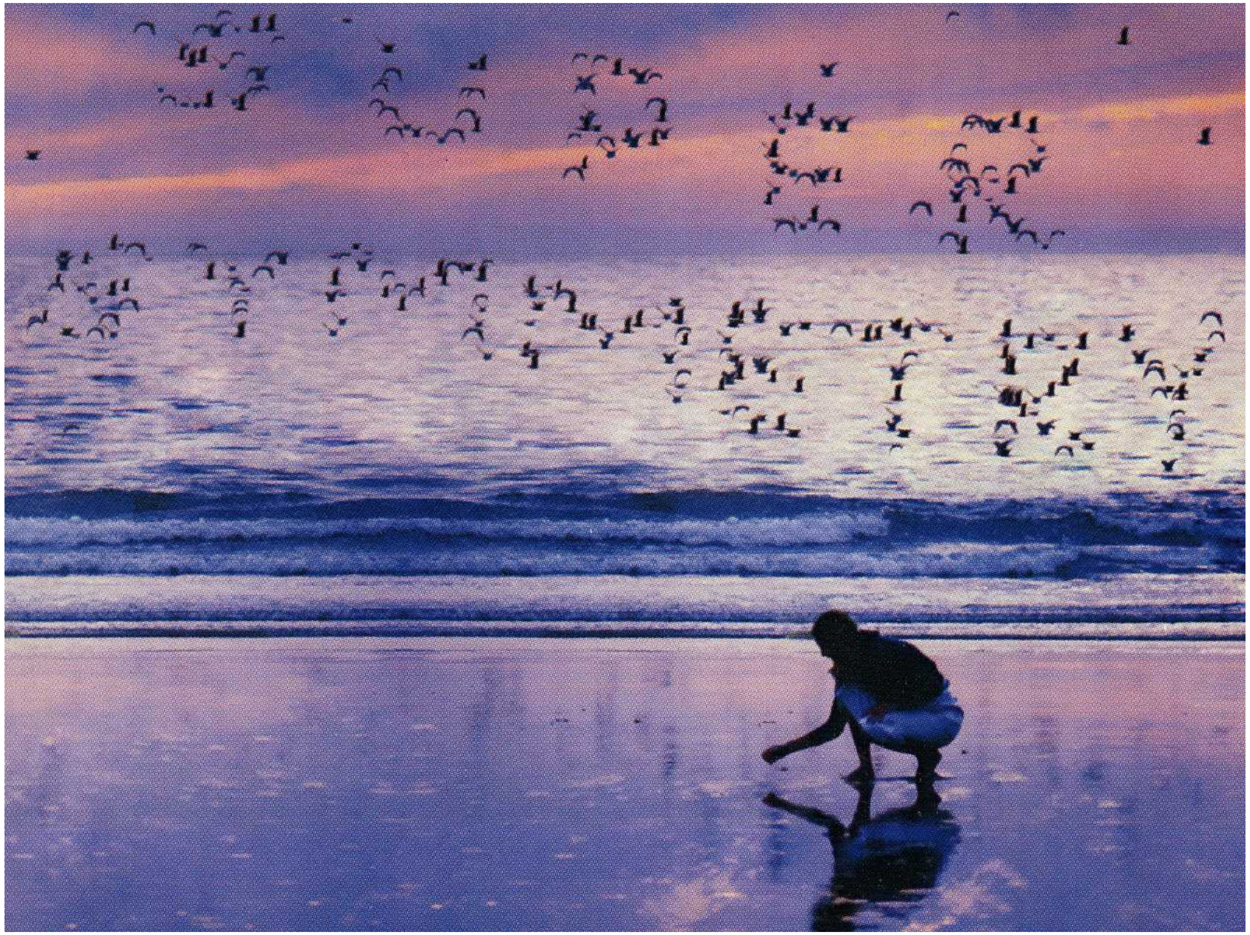




5σ discovery reach extended up to 550 (800) GeV in WZ channel, 650 GeV (only for HL-LHC) for Wh decays

Outlook

SUSY is somewhere out there…



… we just have to find it!!!

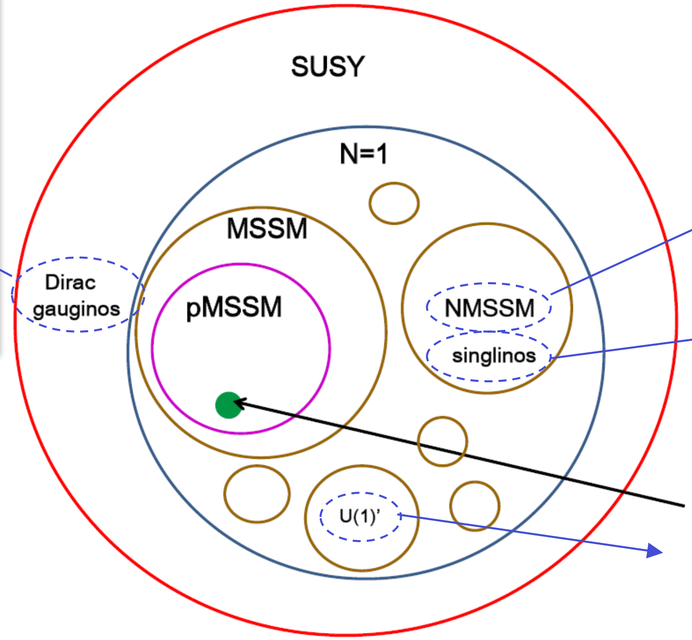
Thank you for listening…

More questions, but lecture already over?
Contact me: isabell@cern.ch

Beyond MSSM Signatures

SUSY Theory phase space

N=2/N=1 models [**0812.3586**] where for example gluinos are not Majorana particles.
Similar if R is a continuous symmetry instead of discrete [RMSSM, **0712.2039, 0810.3919**].
➔lower σ, 2x2 jet resonance or decay to two tops if possible



T. Rizzo (SLAC Summer Institute, 01-Aug-12)

Add a new scalar singlet
➔ 2 more Higgs and one more neutralino, **0910.1785**]
➔ Relax constraints from Higgs mass (i.e. reduce fine-tuning) and provide solution to the μ problem

Stealth SUSY → Invisible singlet added.
➔ Relax MET cuts **[1105.513]**

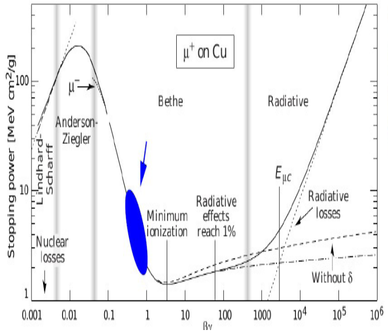
Top-down. Mediation of SUSY breaking via U(1)' . [**0910.2480**]
➔ Generally predicts Wino-like LSP

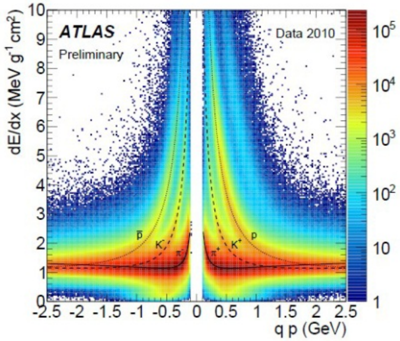
Detector Stable Particles: Examples

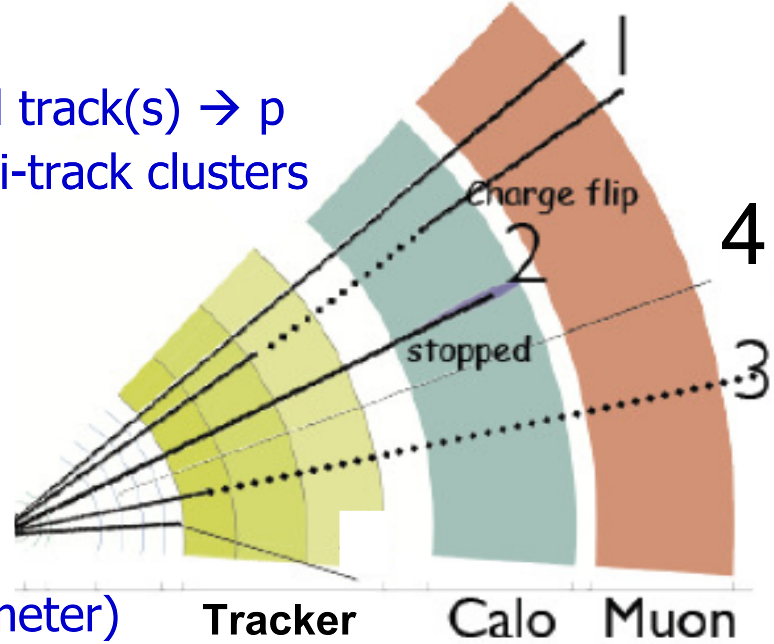
1211.1597, ATLAS-2013-058

Striking signature → Reconstruct mass

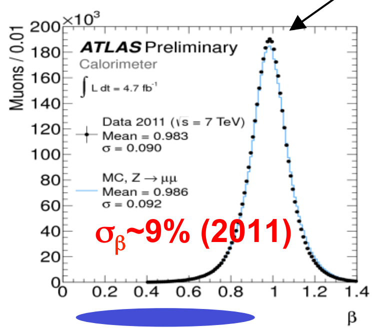
- Start from one (or two) high p_T isolated track(s) → p
- Measure $\beta\gamma$ (invert Bethe-Bloch) from Si-track clusters

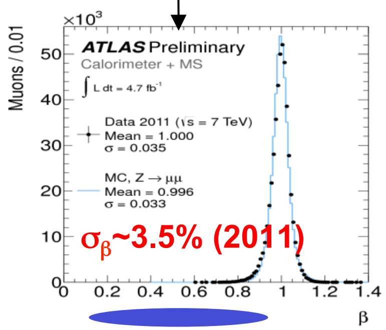


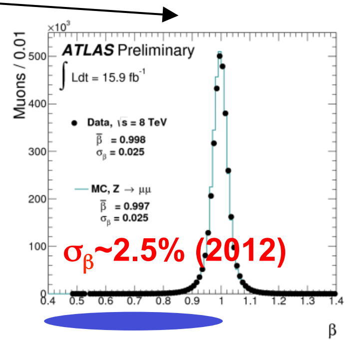




- Measure β (CAL or CAL+muon spectrometer)







Signal

→ Add the all information and compute $M = p/\beta\gamma$

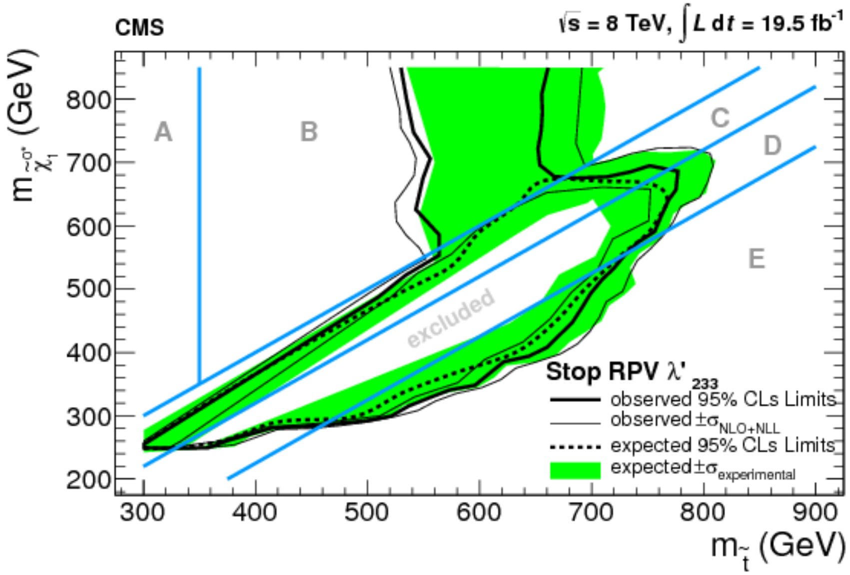
R-Parity Violation: Stop

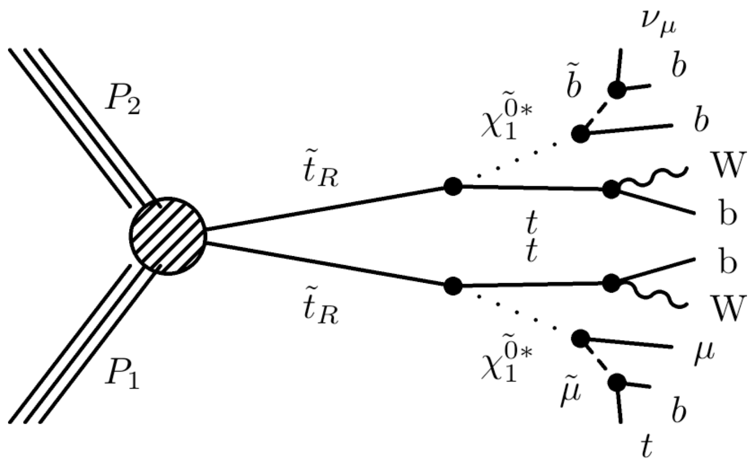
SUS-13-003
PRL 111, 221801 (2013)
arXiv:1306.6643

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

Stop search with RPV decay

- Final states:
  - 2μ +2t +2b
- Assume Bino-like neutralino





region label	kinematic region	stop decay mode(s)
A	$m_t < m_{\tilde{t}} < 2m_t, m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\nu b\bar{b}$
B	$2m_t < m_{\tilde{t}} < m_{\tilde{\chi}_1^0}$	$\tilde{t} \to t\mu t\bar{b} + t\nu b\bar{b}$
C	$m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_W + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to \ell\nu b\tilde{\chi}_1^0 + jjb\tilde{\chi}_1^0$
D	$m_W + m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_t + m_{\tilde{\chi}_1^0}$	$\tilde{t} \to Wb\tilde{\chi}_1^0$
E	$m_t + m_{\tilde{\chi}_1^0} < m_{\tilde{t}}$	$\tilde{t} \to t\tilde{\chi}_1^0$

Weaker limit depending strongly on LSP mass