Searches for supersymmetry in resonance production, R-parity violating signatures and events with long-lived particles at the LHC

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DIS2014

R-Parity Violating (RPV) SUSY

- Many SUSY models assume R-Parity conservation, i.e. Lighest Susy Particle (LSP) is stable
  - Typical large missing transverse energy (MET) signature
  - LSP could be Dark Matter candidate
- BUT could introduce R-parity violating terms in superpotential
  - No simultaneous lepton & baryon number violation due to proton stability

$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \kappa_i L_i H_2 + \lambda''_{ijk} \bar{D}_i \bar{D}_j \bar{D}_k$$

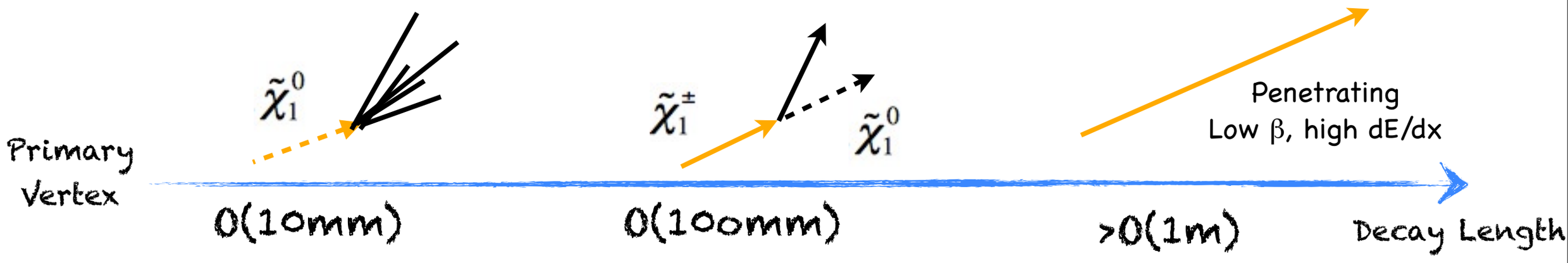
Lepton Violating Baryon Violating

  - LSP decaying to Standard Model particles

Look for no-MET signatures:

both multi-leptonic and multi-jet final states

Long-Lifetime Particles



R-Parity Violating:

- If couplings are small LSP can have long lifetime (proportional to λ^{-2})

R-Parity Conserving:

- $\Delta M(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ ~100MeV, eg AMSB, disappearing/kinked tracks
- Long-lived gluino due to heavy squark mediating its decay: R-Hadrons
- GMSB scenarios: weak coupling NLSP-gravitino → stable sleptons or delayed photons

Outline

$\sqrt{s}$=8TeV

RPV

Multi-jet resonances	ATLAS	20.3 fb^{-1}	ATLAS-CONF-2013-091
	CMS	19.3 fb^{-1}	PAS-SUS-12-015
		19.4 fb^{-1}	Phys. Let. B 730 (2014) 193-214
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RPV stop search	CMS	19.5 fb^{-1}	PRL 111, 221801 (2013)
	ATLAS	20.7 fb^{-1}	arxiv:1404.2500

Long-lived

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Non-pointing photons	ATLAS	4.8 fb^{-1} (7TeV)	Phys. Rev. D 88, 012001 (2013)

RPV searches

RPV

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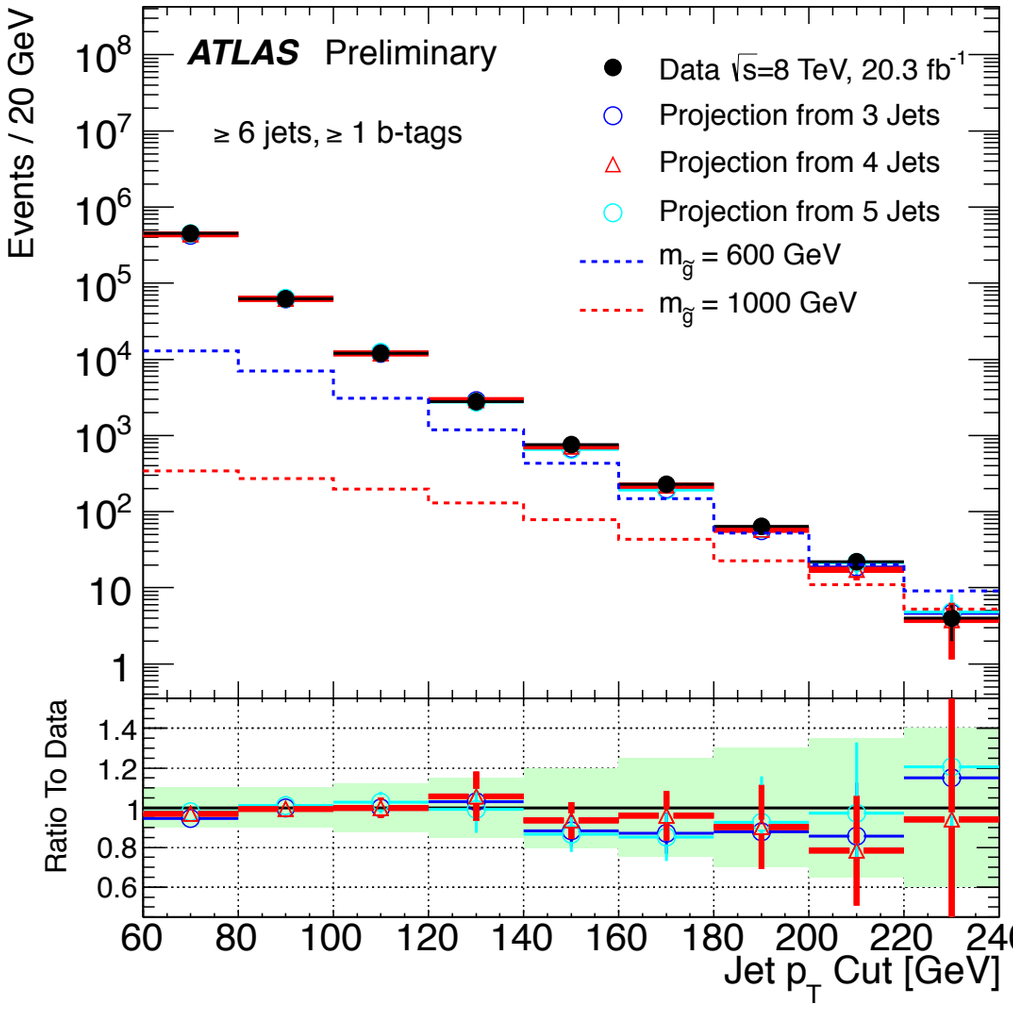
Massive particles to multi-jets

Probe baryon violating term

$$+\lambda''_{ijk}\,\bar{D}_i\bar{D}_j\bar{D}_k$$

- Each decay produces exactly one up-type and two down-type quarks
  - Large number of jets
  - Use flavor information to constrain different λ″
- Simple strategy:
  - Use number of jets, jet p_T, number of b-tags to separate signal from background
- Backgrounds:
  - Mainly QCD multi-jet production
  - tt, W+jet after b-tag
  - Estimate from data in low multiplicity control regions

ATLAS-CONF-2013-091

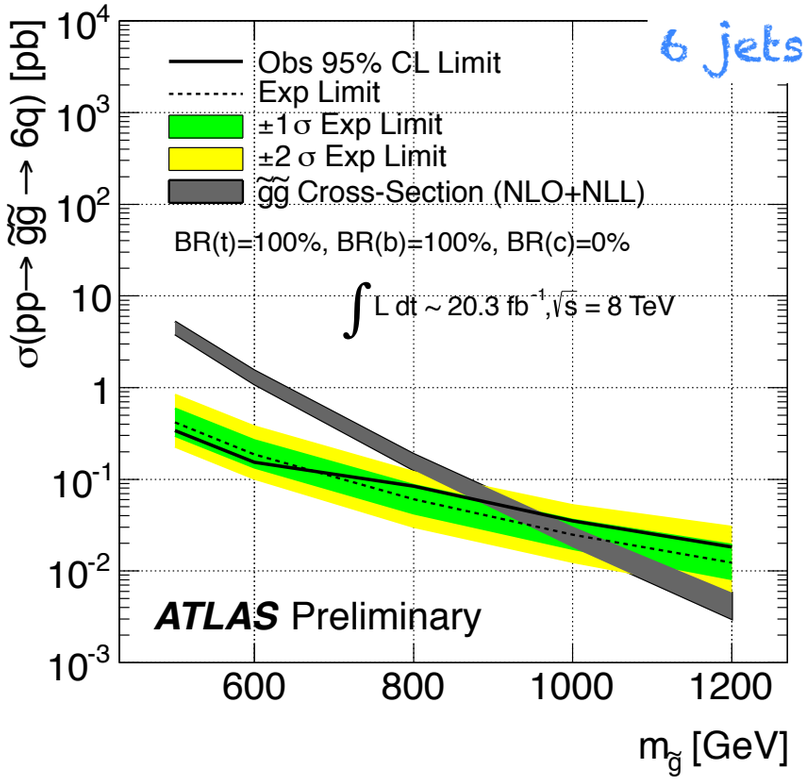


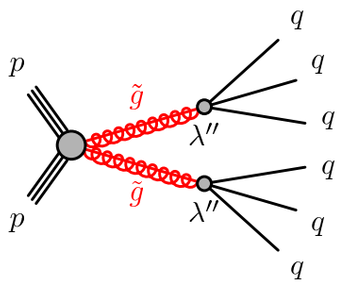
Massive particles to multi-jets

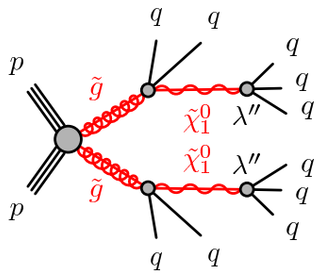
ATLAS:

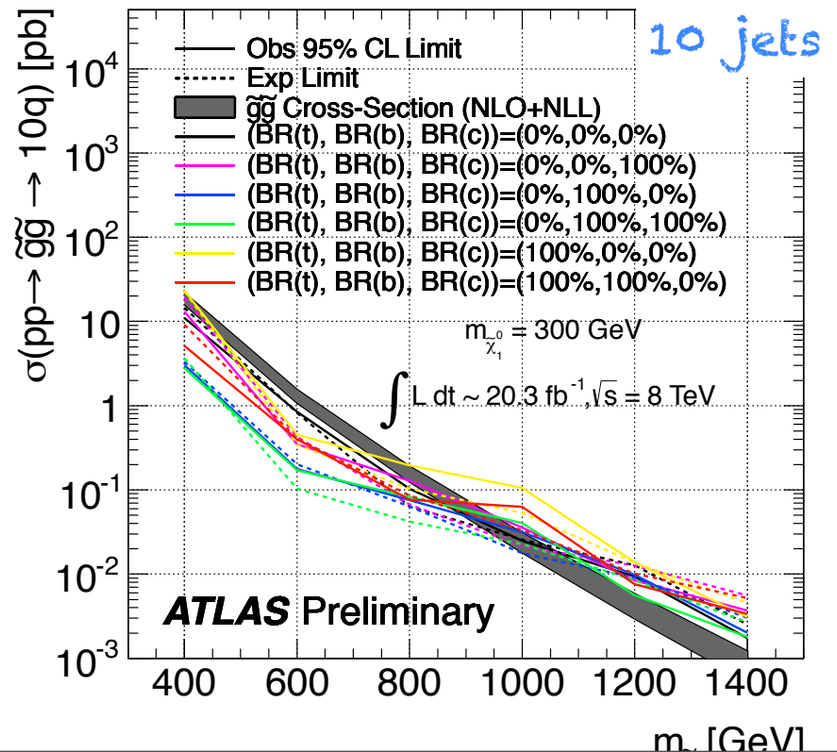
ATLAS-CONF-2013-091

- Optimize signal regions according to two different gluino decays
  - 6 or 10 jets with 0,1,2 b-tagged jets
  - Categorize limits according to BR(t), BR(b), BR(c)









Boosted gluinos ($p_T >> 2m_{\tilde{g}}$): collimated jets

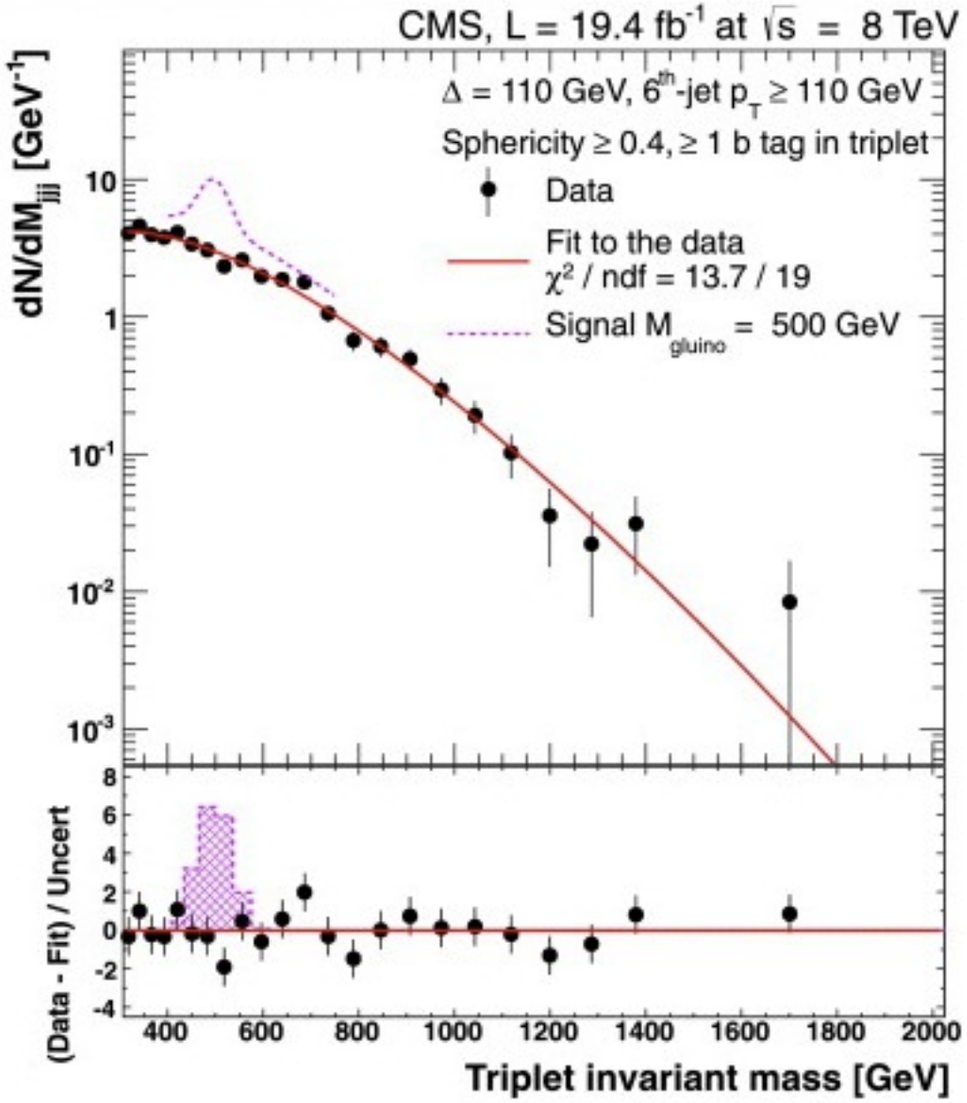
→ specific search

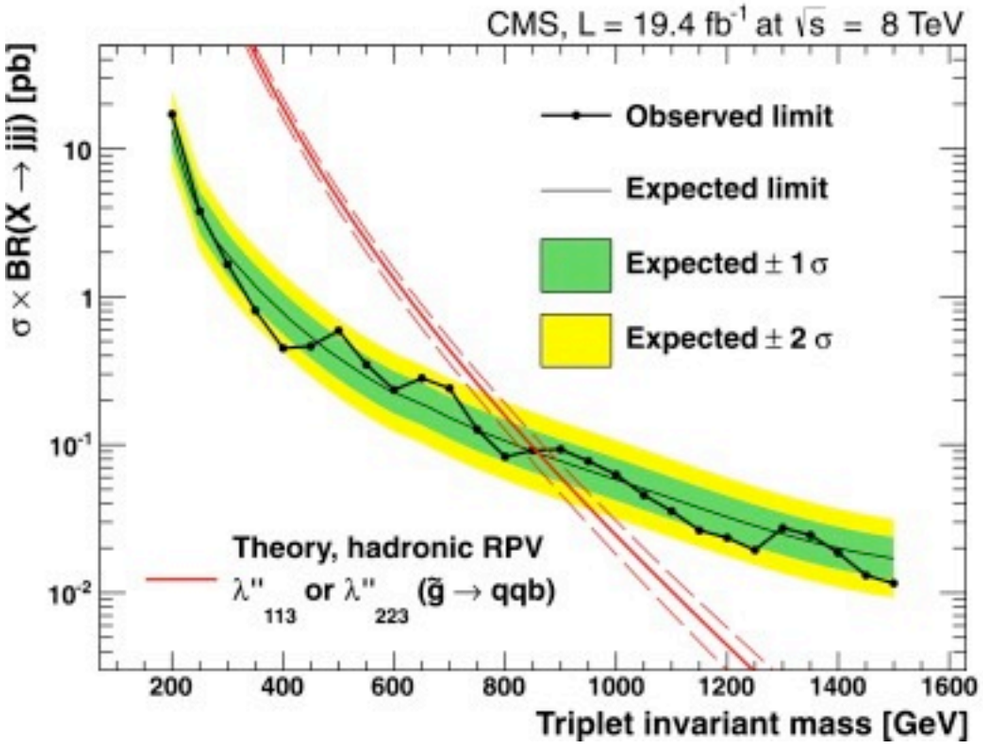
Massive particles to multi-jets

Physics Letters B 730 (2014) 193–214

CMS:

- Look for 3 light-flavor or 2 light + 1 heavy-flavor jets
- Trigger on 6 high p_T jets
- Form jet triplets and use mass to separate background (QCD, combinatorics, t-tbar)
- Combine 3 signal regions: light flavor, low mass heavy flavor, high mass heavy flavor



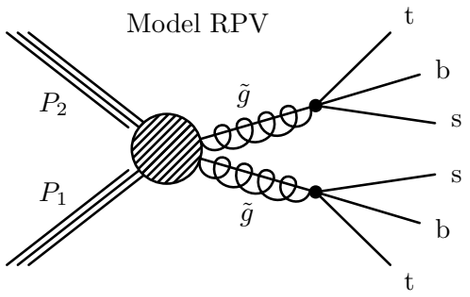


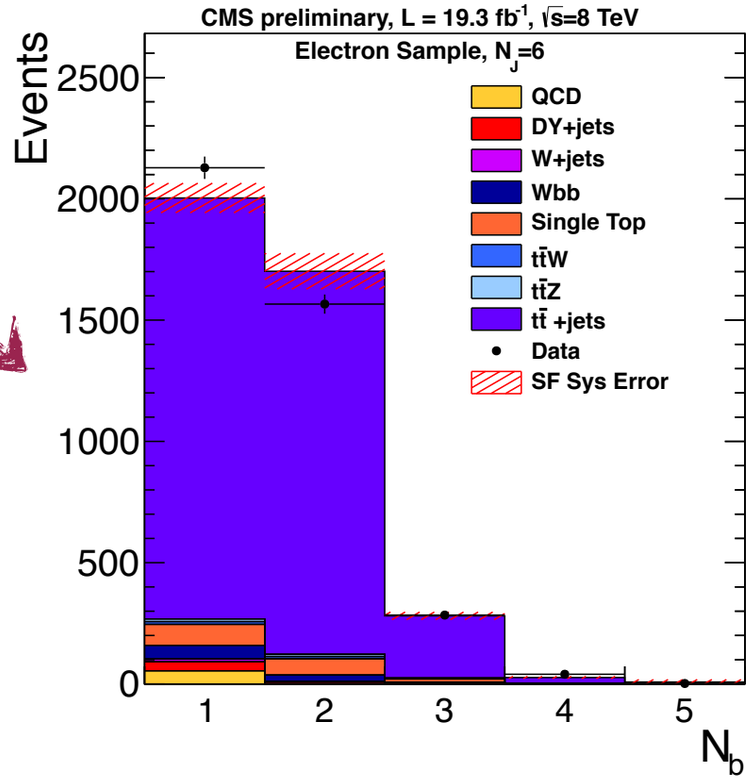
Decays to least one heavy flavor excluded up to $m_{\tilde{g}}$<835GeV
Decays to light quarks up to $m_{\tilde{g}}$<650GeV

Massive particles to multi-jets

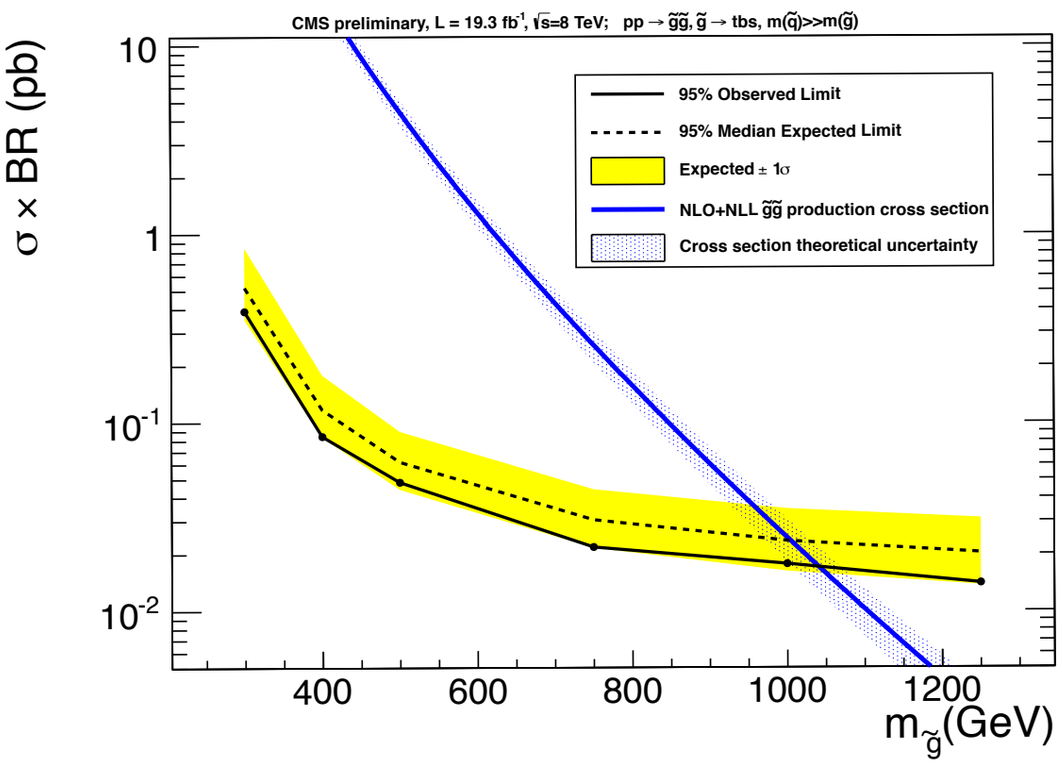
CMS: Simplified benchmark model $\tilde{g} \to tbs$

- Require high p_T leptons (e,μ)
  - Rely on lepton triggers
- Use b-tagged jets multiplicity to separate signal from background
  - Estimate from MADGRAPH
- Combine 3 signal regions: 6, 7, ≥8 jets





PAS-SUS-12-015



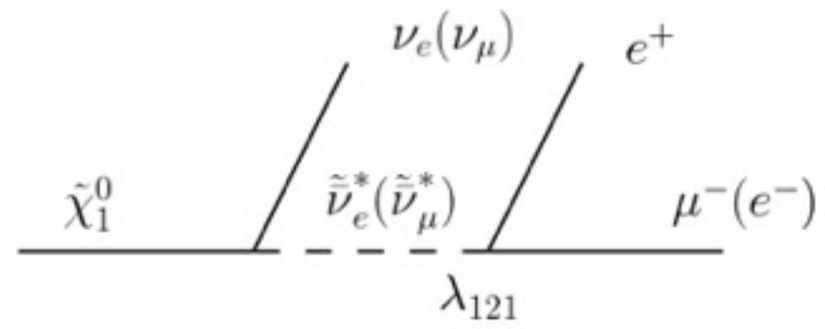
- Searches for massive particles decaying to multi-jets exclude gluinos up to 900-1000 GeV in several RPV scenarios

Multi-leptons searches

Probe lepton violating term

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k$$

- Expect large number of leptons produced by SUSY decays
- Typical selection criteria:
  - Inclusive single and double electron and muon trigger
  - high p_T isolated leptons
  - Di-lepton Z mass window



- High signal to background ratio:
  - Irreducible background: 4 leptons from Standard Model
    - mostly heavy boson production -> tth, zh, Wh, WZ (+jets), ZZ (+jets), ZZtt, WWZ, WZZ

← from MC

  - Reducible background: at least one fake lepton

← from DATA

Multi-leptons searches

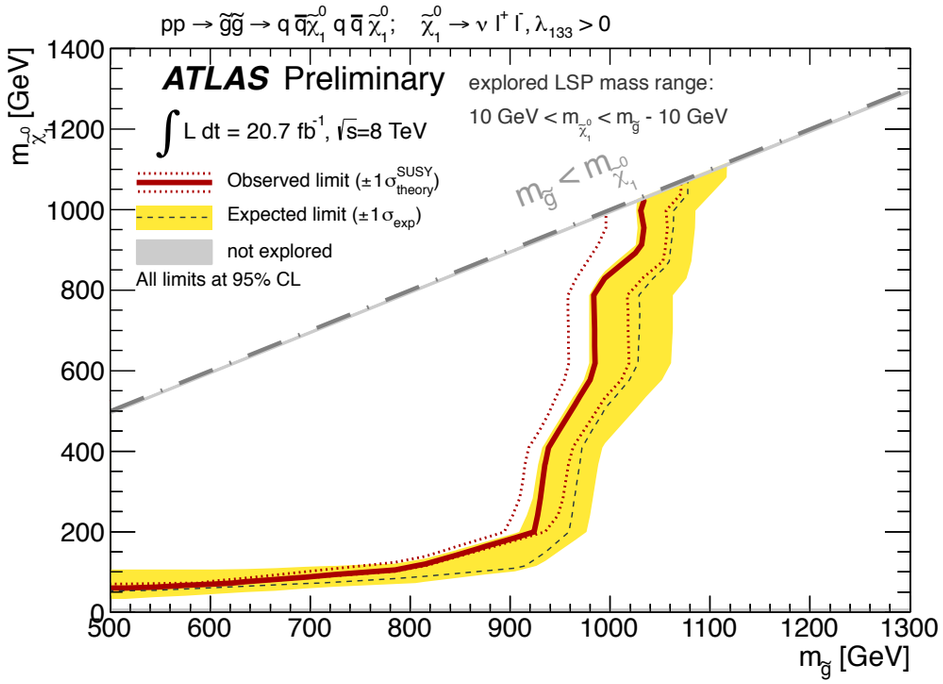
ATLAS-CONF-2013-036

PAS-SUS-13-010

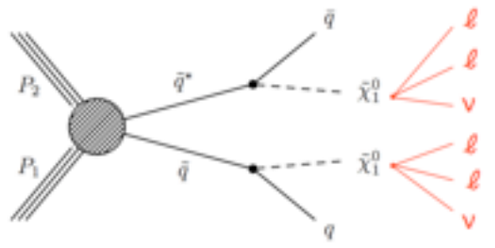
ATLAS:

- ≥ 4 leptons (e,μ,τ) (p_T> 10 GeV)
- ≥ 1 above trigger threshold
- Z Candidate veto
- 2 Signal regions

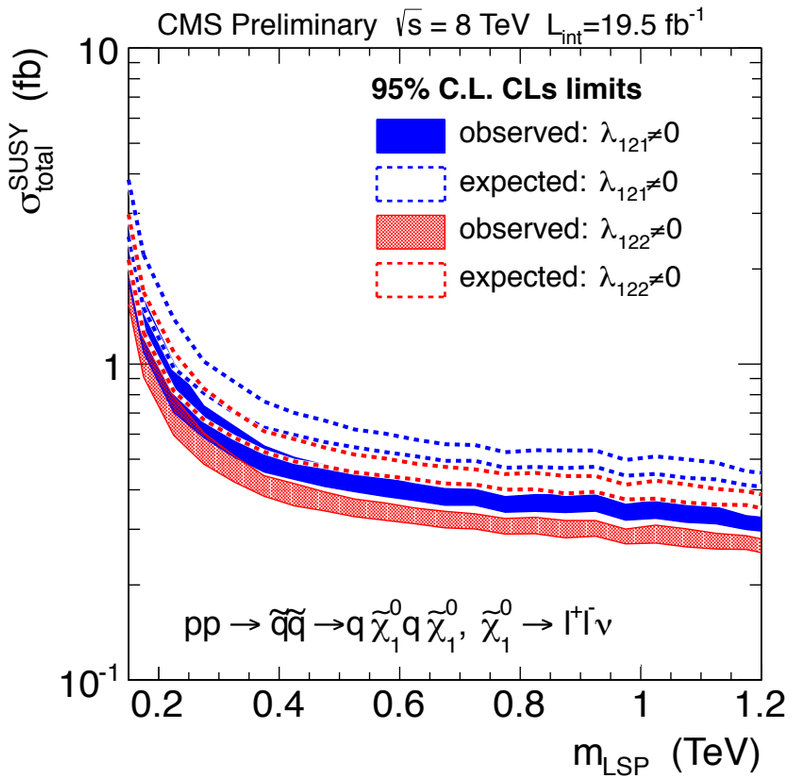
SR	$N_{(e,\mu)}$	N(τ)	E^T_{miss} or m_{eff} [GeV]
$SR0noZ_b$	$\geqslant 4$	$= 0$	> 75 or > 600
$SR1noZ$	$= 3$	$\geqslant 1$	> 100 or > 400



CMS:



- 4 leptons (e,μ): p_T> 20 (highest), 10 GeV
- 1 opposite sign, same flavor pair
- define di-lepton mass regions according to Z



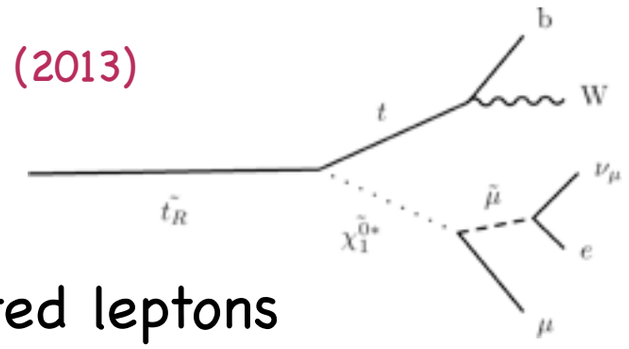
CMS constrains also generic RPV susy

Multi-leptons searches

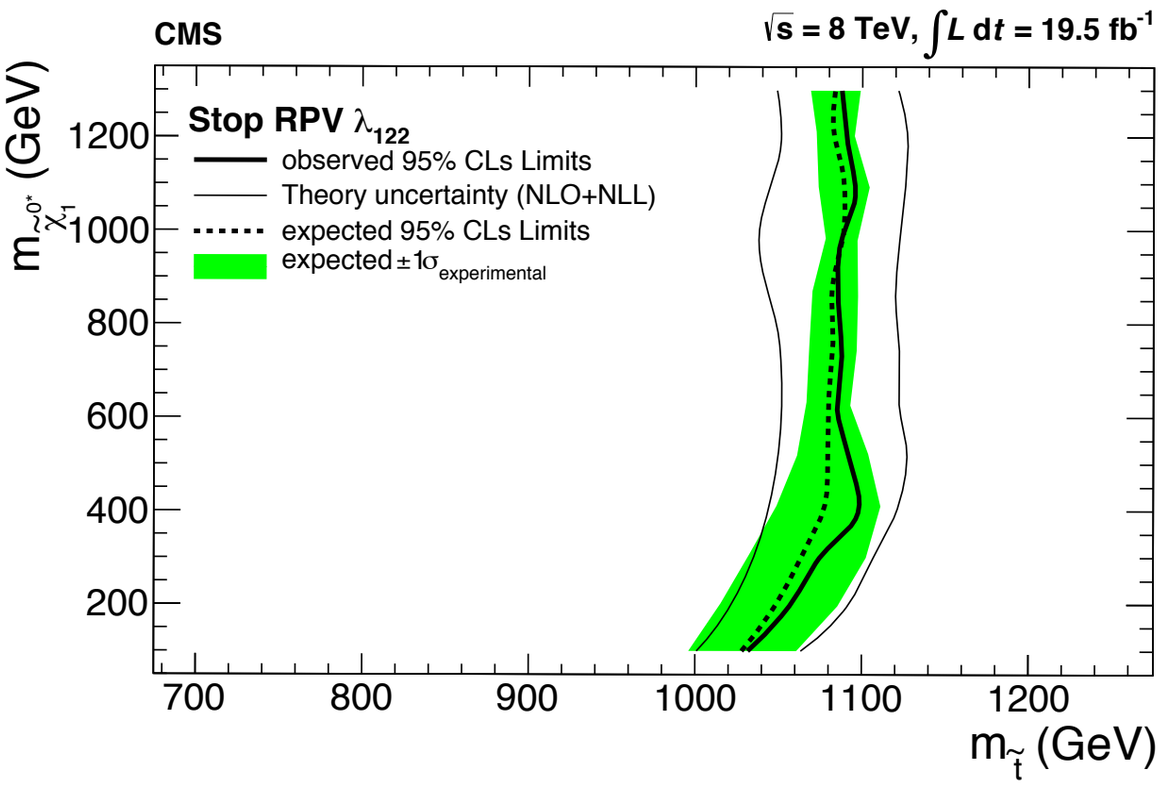
Stop in RPV models

CMS:

PRL 111, 221801 (2013)

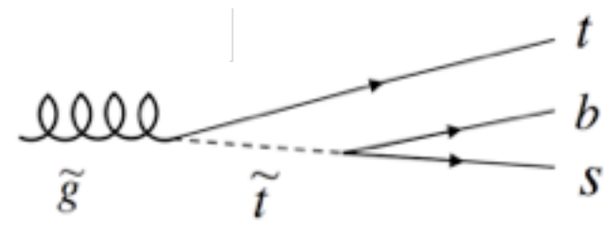


- ≥ 3 isolated leptons (e/μ/τ)
- Z boson veto
- ≥ 1 b-jet



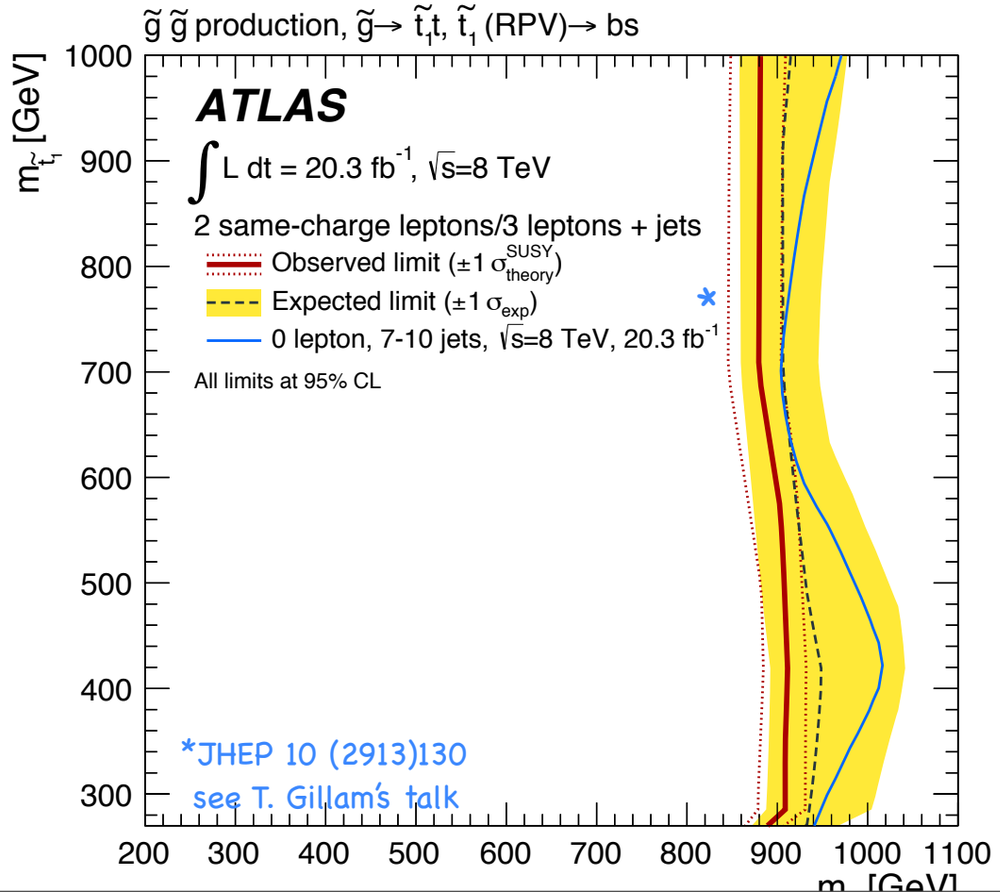
ATLAS:

arxiv:1404.2500



- 2 same sign or 3 (no charge constraint) leptons (e/μ)
- ≥ 3 b-jets, ≥ 5 jets
- m_{eff}> 350 GeV

$$m_{\text{eff}} = E_{\text{T}}^{\text{miss}} + \sum p_{\text{T}}^{\ell} + \sum p_{\text{T}}^{\text{jet}}$$



- Searches for massive particles decaying to multi-jets exclude gluinos up to 900-1000 GeV in several RPV scenarios
- Lepton Flavor Violation multi-lepton searches exclude
  - NLSP gluinos up to 1-1.4TeV
  - stops up to 1.1TeV
  - LSP neutralinos up to 400-800 GeV

Long-lived particle searches

RPV

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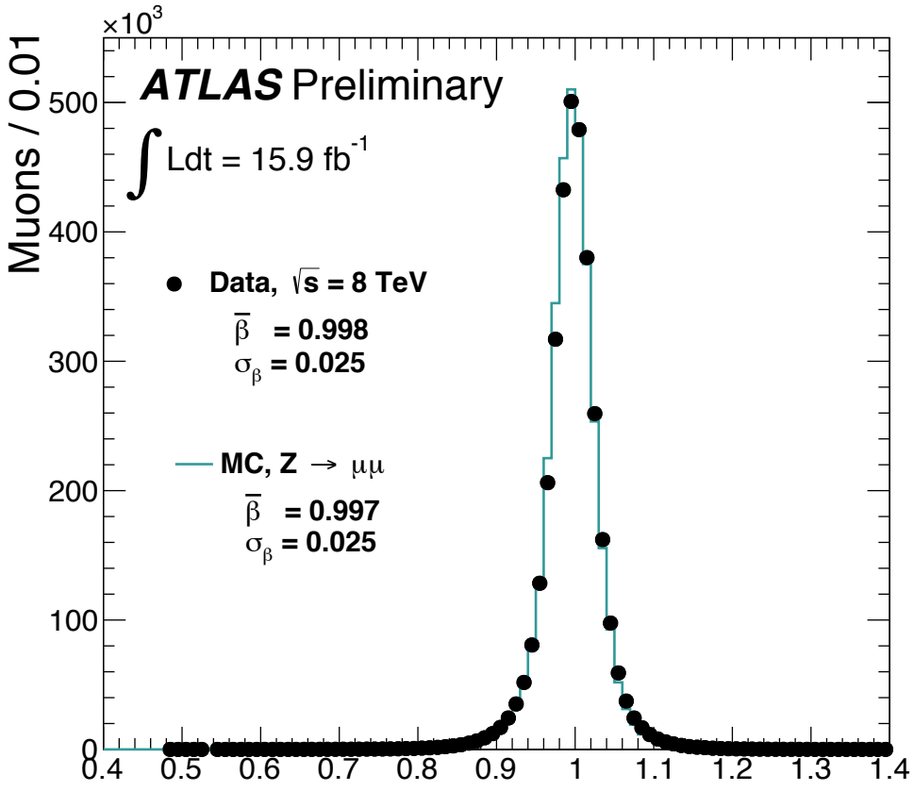
Stable Massive Particles (SMP)

"stable" wrt detector scale

- Allowed by many models: mGMSB, splitSUSY, MSSM, UED...
- Two main classes of particles:
  - Lepton-like → no strong interactions
  - Hadron-like → color-charged, hadronize to form"R-Hadrons" with quarks/gluons
- Striking signatures:
  - Slowly moving particle, typically reconstructed as a muon
    - High momentum
    - Anomalously high ionization energy loss (dE/dx)
    - Large time-of-flight
  - Might need specific reconstruction/trigger

Ex: ATLAS-CONF-2013-058



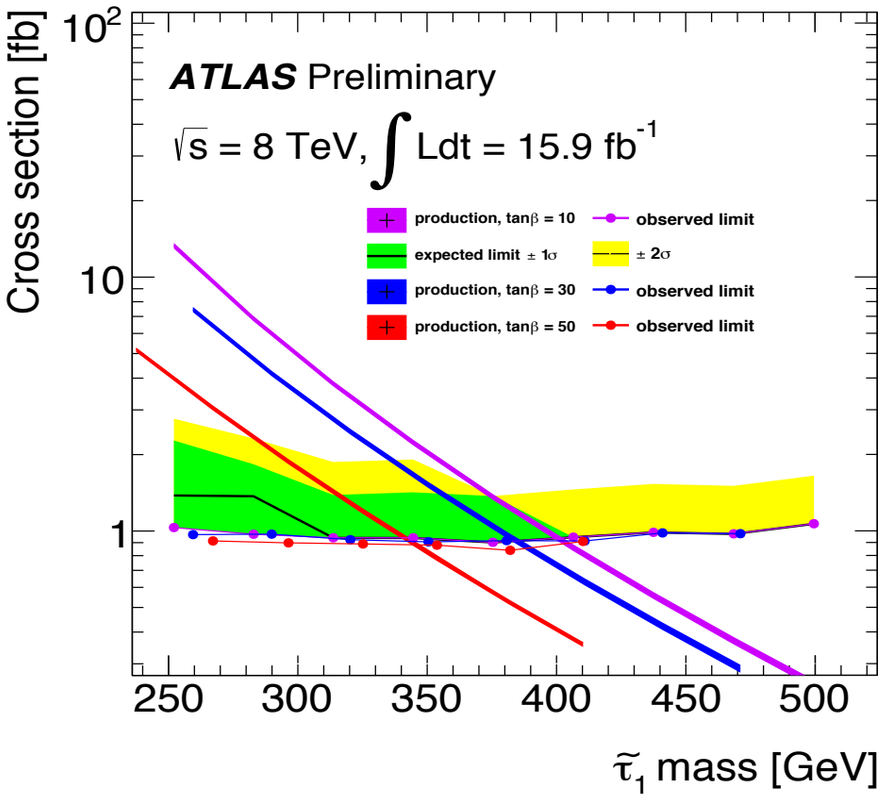
Muon system + calorimeter + inner tracker combined β resolution: ~2.5%

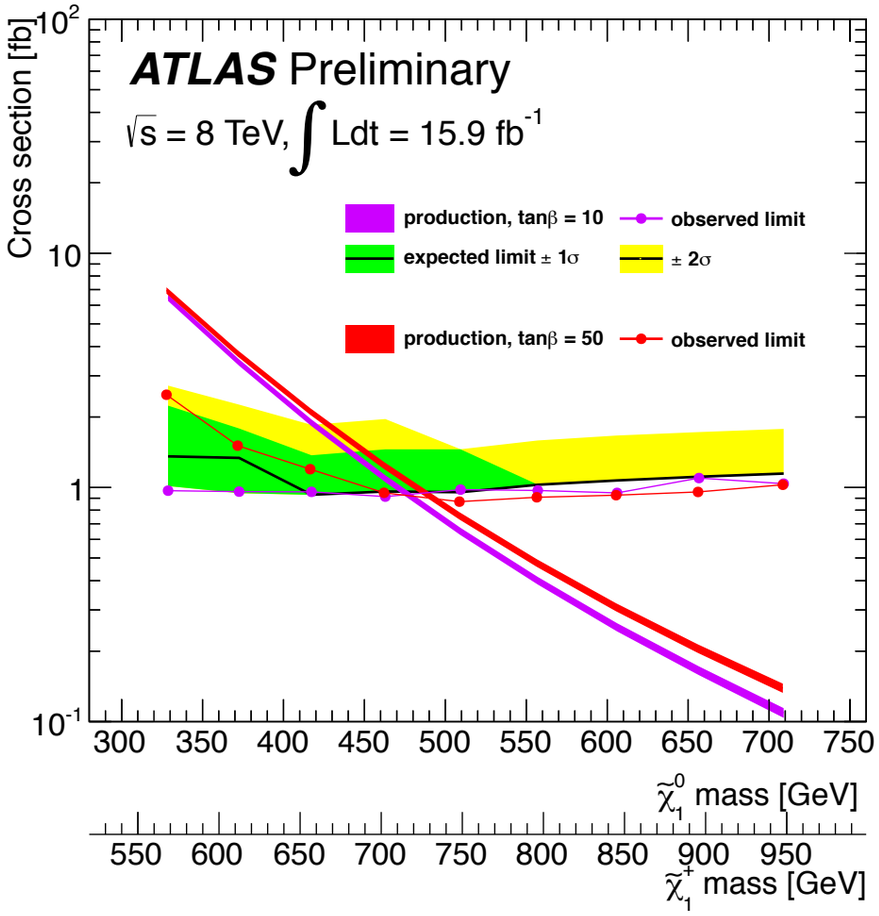
SMP: sleptons

ATLAS: ATLAS-CONF-2013-058

- Benchmark model: GMSB with $\tilde{\tau}_1$ NLSP
- $\tilde{\tau}_1$ mass estimated using $m=p/(\gamma\beta)$
- Small background: mis-measured high p_T muons

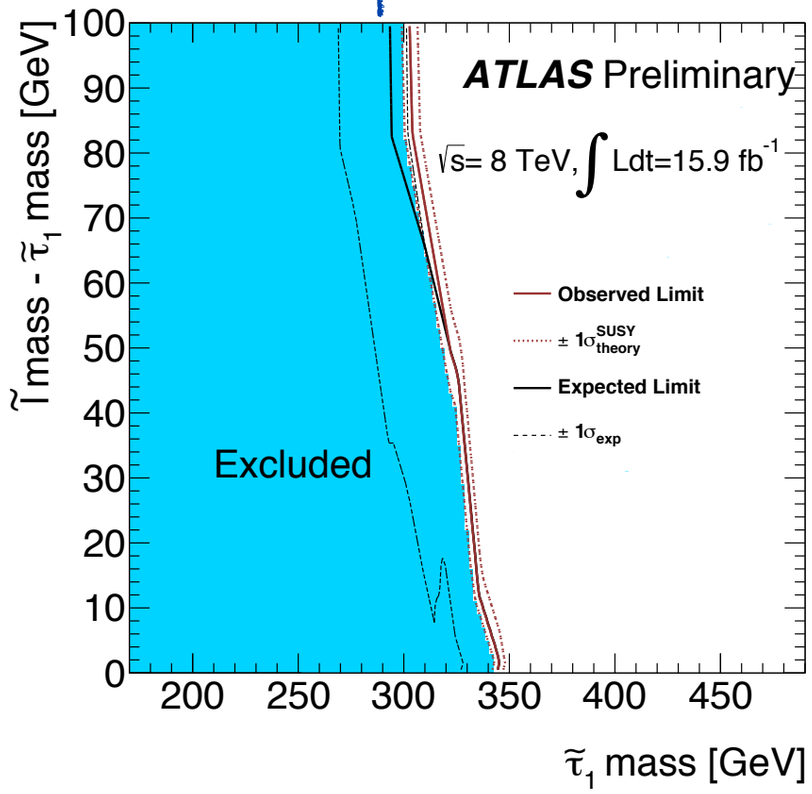
GMSB





chargino/ neutralino production

Direct production:

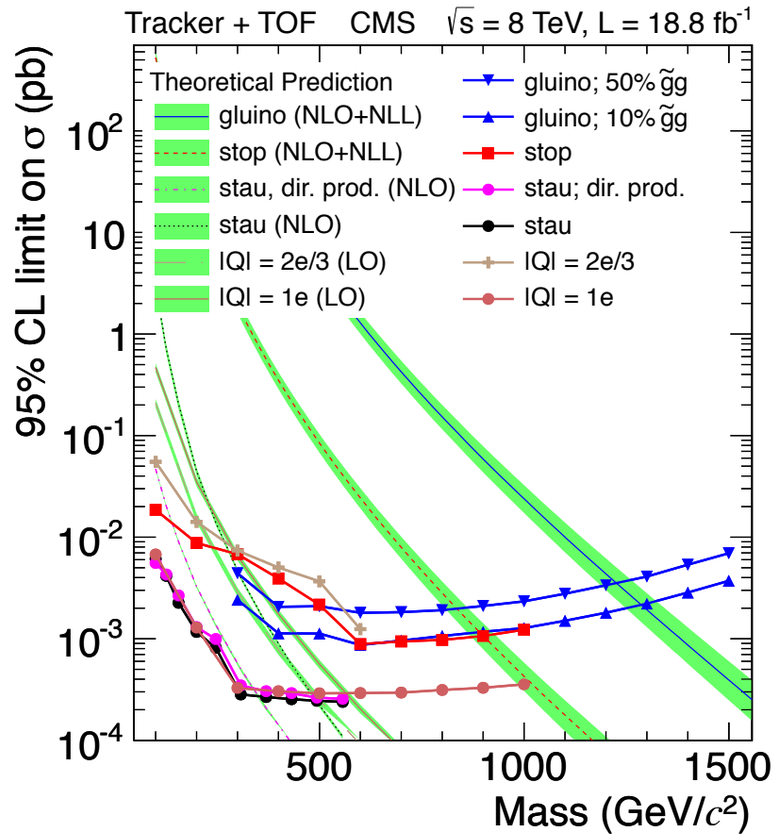


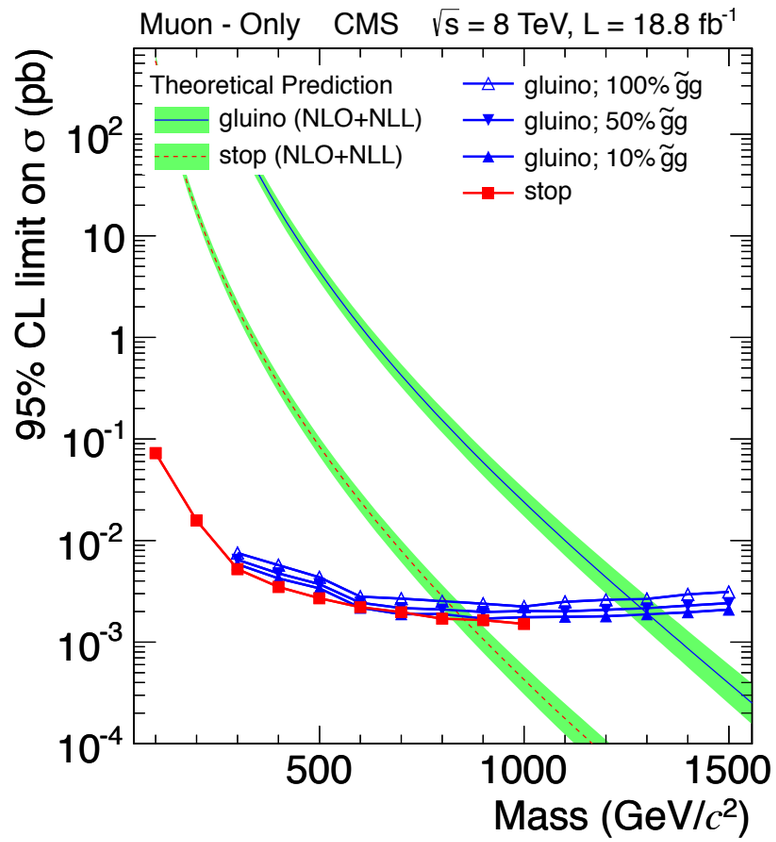
SMP: R-Hadrons

JHEP07(2013)122

CMS:

- Benchmark models
  - direct gluino and stop pair productions
- Large uncertainties on R-Hadrons' strong interactions with detector material
- Use different search strategies:
  - tracker only (dE/dx)
  - muon only (TOF)
  - tracker + muon system
  - ~6.5% resolution on 1/β
- Muon-only and tracker-only allow for R-Hadron charge flipping in calorimeter or tracker material

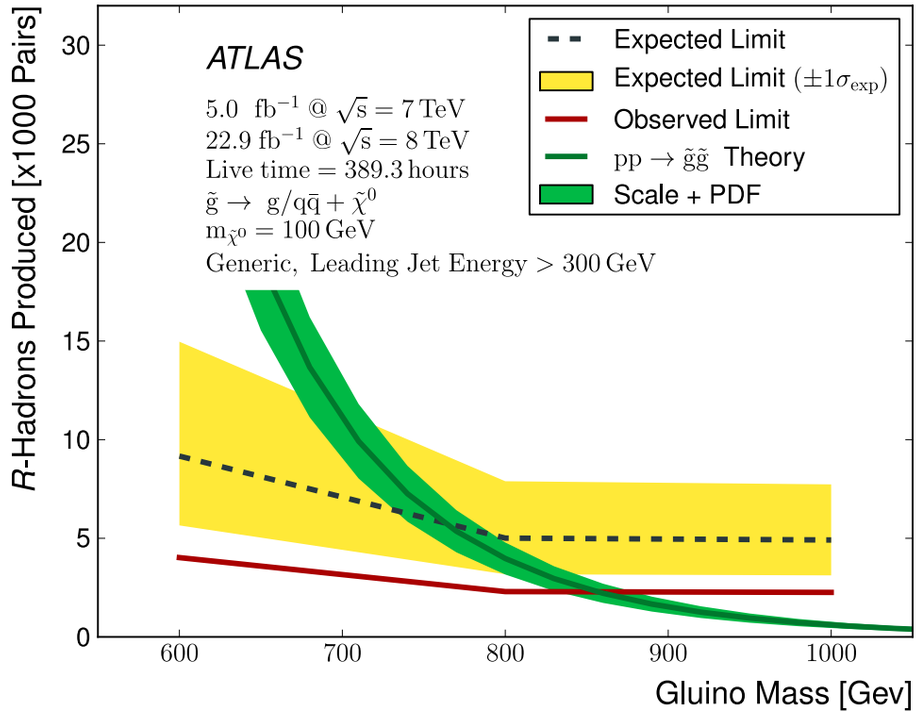


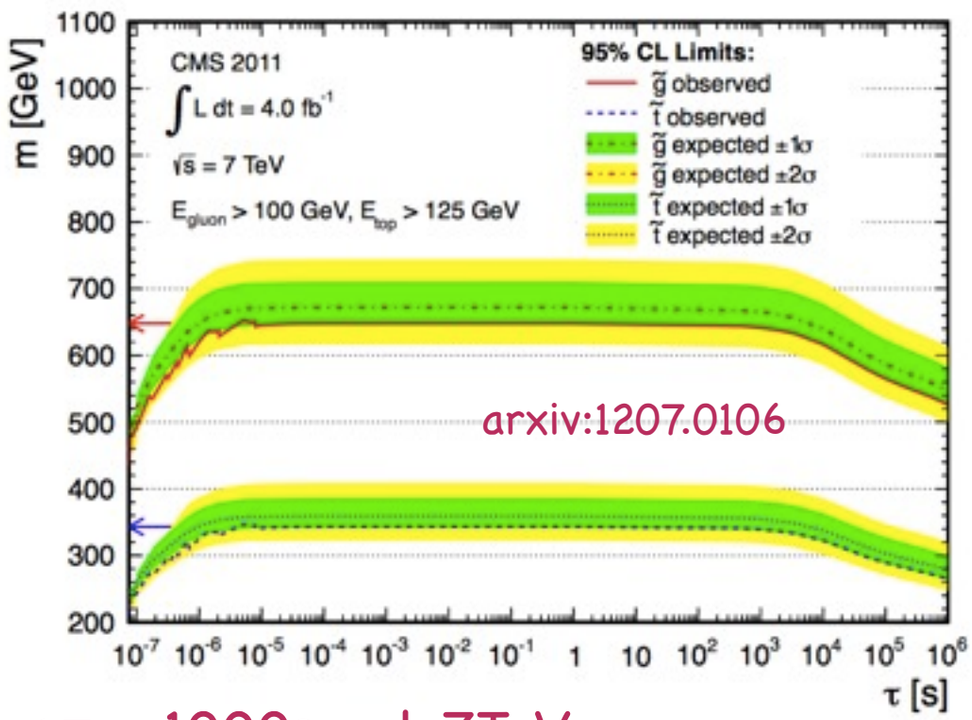


Stopped gluinos

ATLAS: Phys. Rev. D 88, 112003 (2013)

- R-Hadrons loose momentum and come to rest
  - Decay to neutralinos + hadronic jets
- Selection:
  - Trigger on empty bunch crossings with calorimeter activity.
  - Leading jet: $|\eta|$< 1.2, E_{jet}>100, 300 GeV
  - Muon activity veto
- Main backgrounds: Cosmic rays and beam halo
- Limits:
  - $m_{\tilde{g}}$< 832GeV excluded, for 1 μs < $\tau_{\tilde{g}}$<1000s
  - $m_{\tilde{g}}$< 600GeV excluded for lifetimes up to 2 years!
- Also exclude long-lived stops and sbottoms

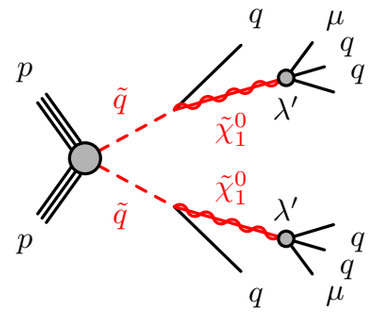




CMS excludes $m_{\tilde{g}}$ < 640GeV, for 1 μs < $\tau_{\tilde{g}}$ <1000s at 7TeV

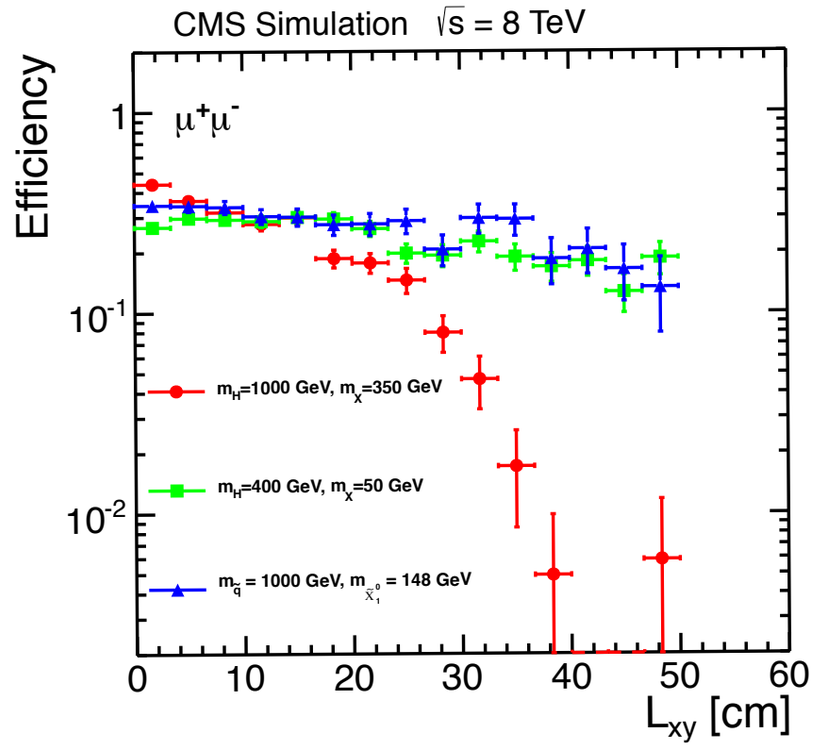
- Searches for massive particles decaying to multi-jets exclude gluinos up to 900-1000 GeV in several RPV scenarios
- Lepton Flavor Violation multi-lepton searches exclude
  - NLSP gluinos up to 1-1.4TeV
  - stops up to 1.1TeV
  - LSP neutralinos up to 400-800 GeV
- Stable Massive Particle searches exclude:
  - gluinos up 1.2-1.3 GeV
  - stops up to 800- 900 GeV
  - sleptons up to 350-500 GeV

Displaced vertices

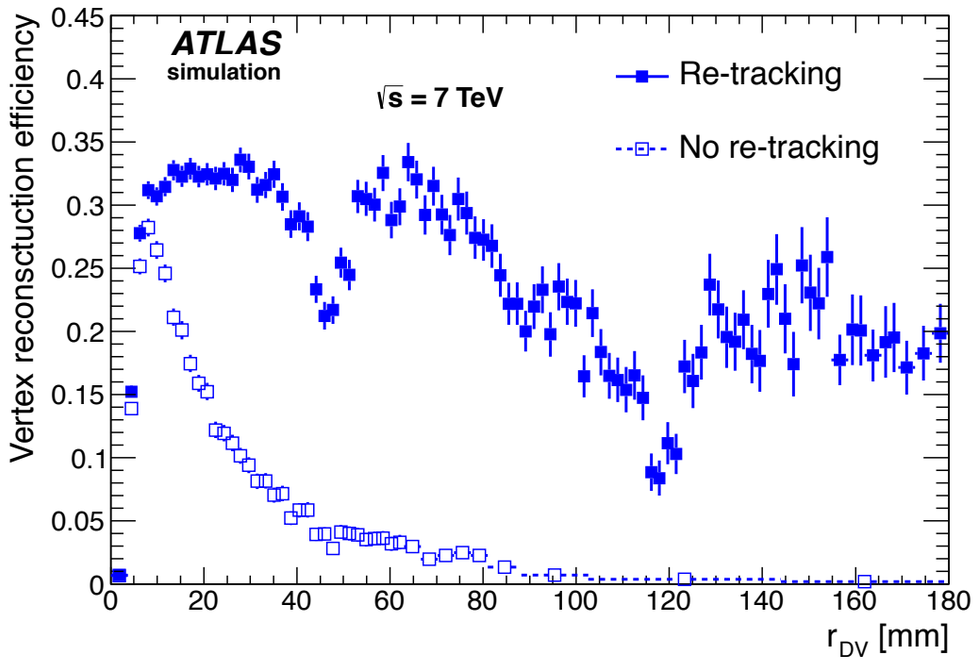


LSP decays far from interaction point
~ 1mm-10cm

- Signatures: multi tracks displaced vertex (high pt leptons or jets)
- Cons: standard reco has low efficiency
  - ATLAS has specific tracking and displaced vertex reconstruction
  - CMS uses inner tracker only (no lepton reconstruction)
- Pro: Relatively low background
  - Cosmic rays, random combinations of tracks, hadronic interactions with material



PAS EXO12037



Phys. Lett. B 719 (2013) 280–298

Displaced vertices

PAS-EXO-12-037
ATLAS-CONF-2013-092

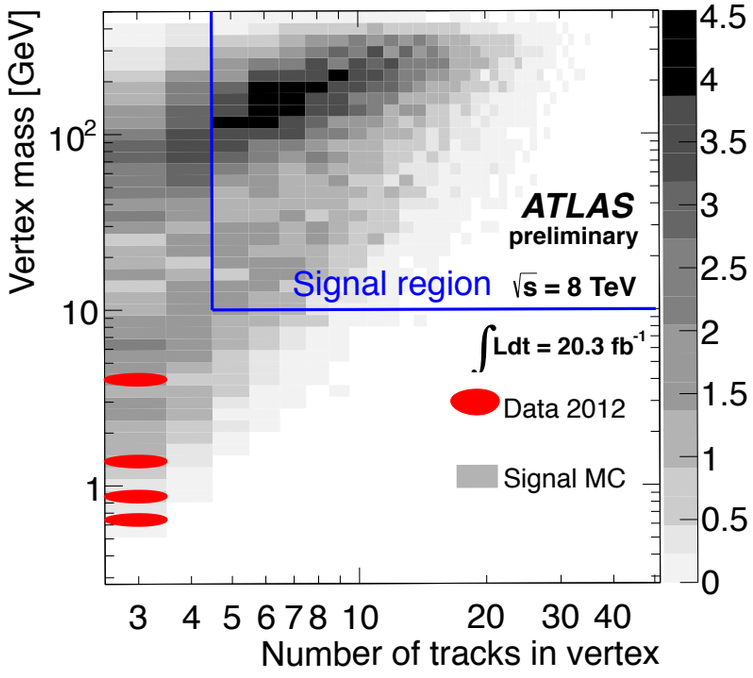
Multi-tracks displaced vertex with one or two leptons

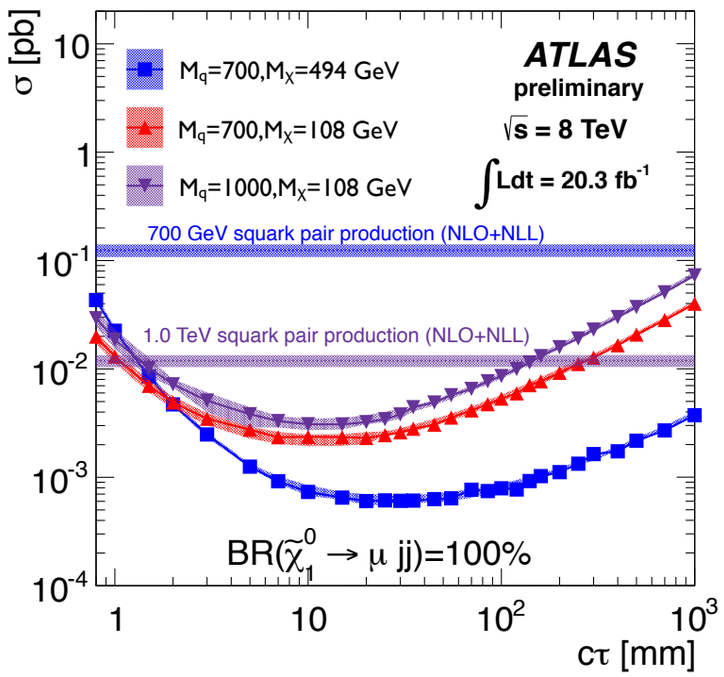
ATLAS:

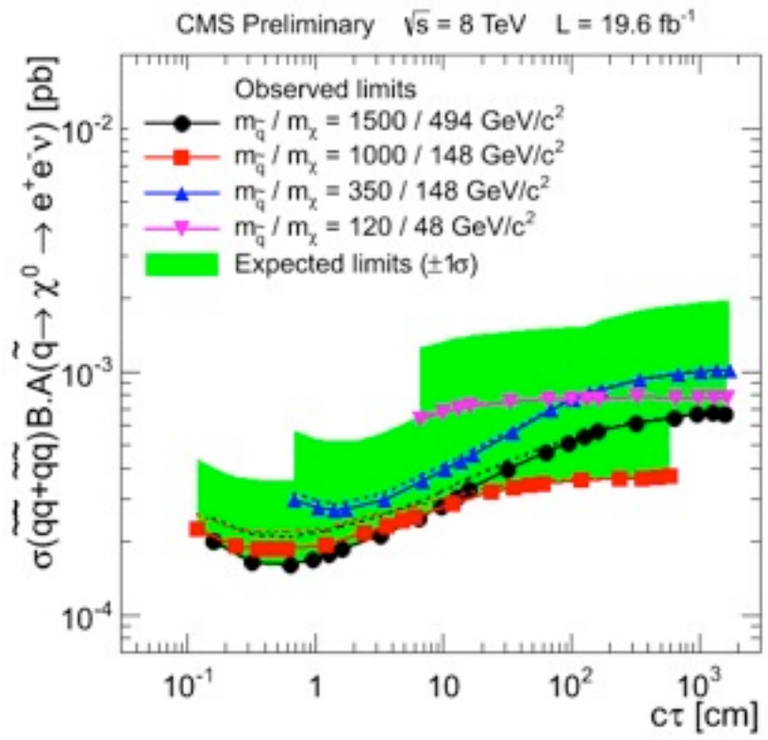
- High-pt muon trigger (pt>40 GeV)
- Specific tracking and displaced vertex reconstruction
- Veto vertices in high density regions to reduce background from hadronic interactions (expect 0.02+/-0.02 events).

CMS:

- Combine ee and μμ channels
- trigger on calo energy depositions and muons
- rely on Inner Tracker reconstruction
- give σA limits







Displaced vertices

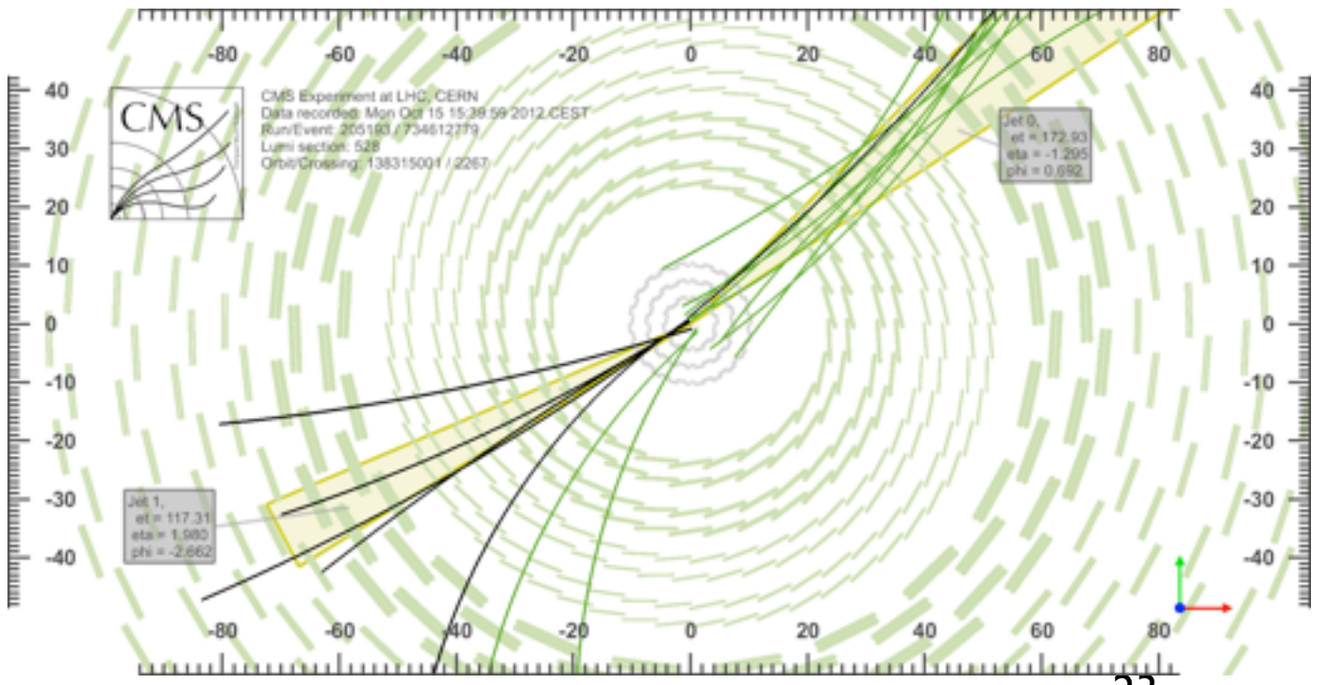
PAS-EXO-12-038

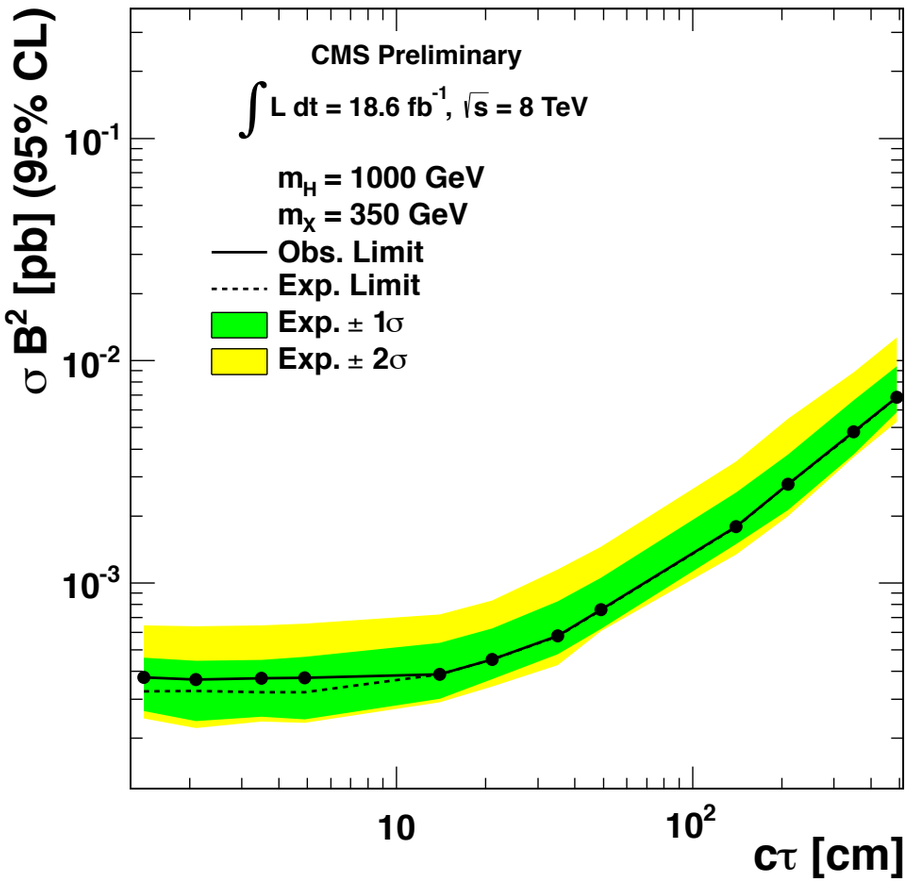
Long-lived neutral particles decaying to quarks

$$H^0 \rightarrow 2X^0$$
$$X^0 \rightarrow q\bar{q}$$

CMS:

- H_T>300GeV trigger
- 2 jets made of large impact parameter tracks
- Fit secondary vertex from jet tracks
- Estimate background in control regions
- Use $K_s \rightarrow \pi\pi$ to model tracking systematics

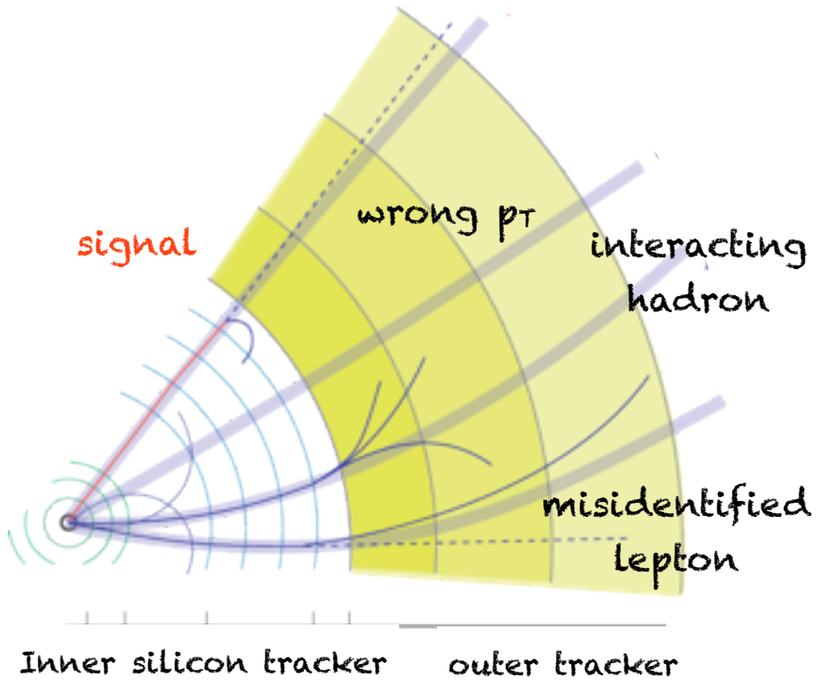




Limits depend on $c\tau$, m_H and m_X : cross sections excluded in 0.3-1 fb range

Disappearing tracks

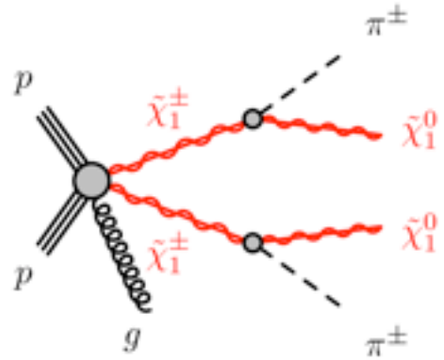
Phys. Rev. D 88, 112006 (2013)



ATLAS:

- AMSB models: $\Delta M(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ ~ 160 MeV

→ lifetime O(0.1ns)



- Signature:

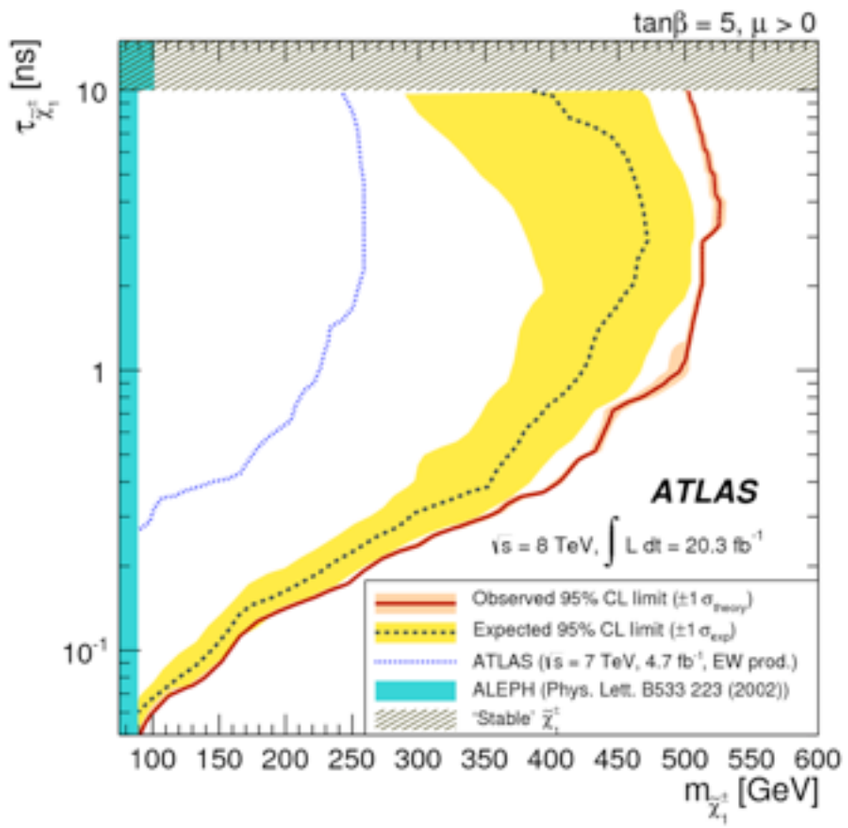
  "disappearing tracks" inside tracking detector

- Strategy:

  Well reconstructed tracks in inner (silicon) tracker, low number of hits in outer tracker

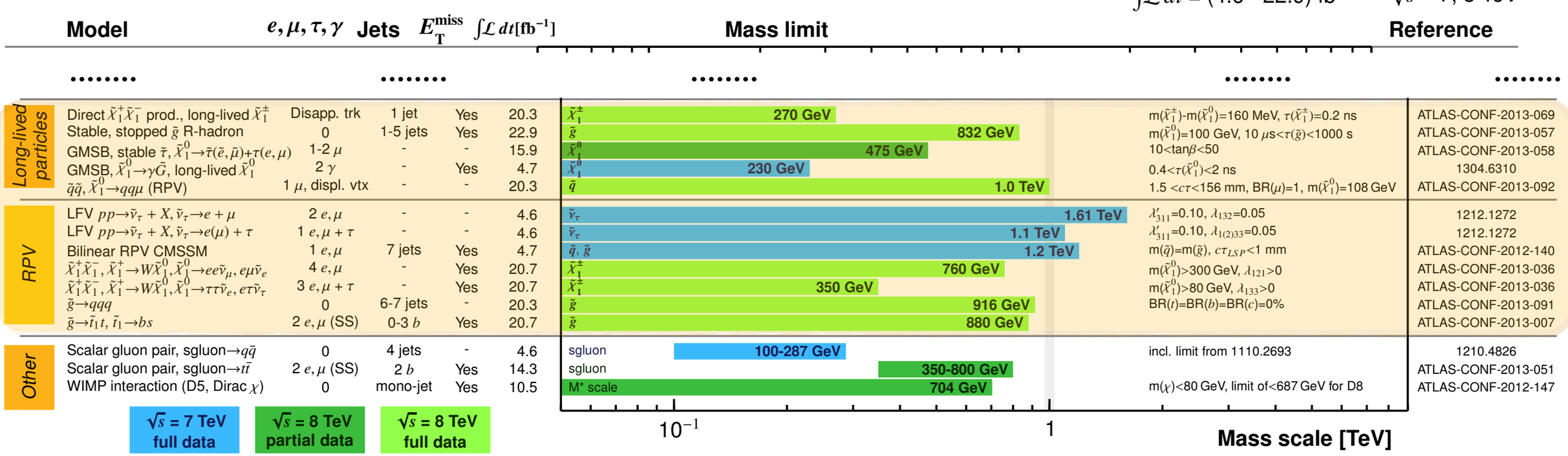
- Background from fit to the p_T spectrum of disappearing tracks

- No excess over SM background is observed



- Searches for massive particles decaying to multi-jets exclude gluinos up to 900-1000 GeV in several RPV scenarios
- Lepton Flavor Violation multi-lepton searches exclude
  - NLSP gluinos up to 1-1.4TeV
  - stops up to 1.1TeV
  - LSP neutralinos up to 400-800 GeV
- Stable Massive Particle searches exclude:
  - gluinos up 1.2-1.3 GeV
  - stops up to 800- 900 GeV
  - sleptons up to 350-500 GeV
- Displaced vertices/Disappearing tracks searches exclude:
  - squarks pair production excluded up to 2-5 fb depending on neutralinos lifetimes and masses
  - charginos up 270 GeV

Where do we stand



*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.

RPV sector still less constrained than "other SUSY"

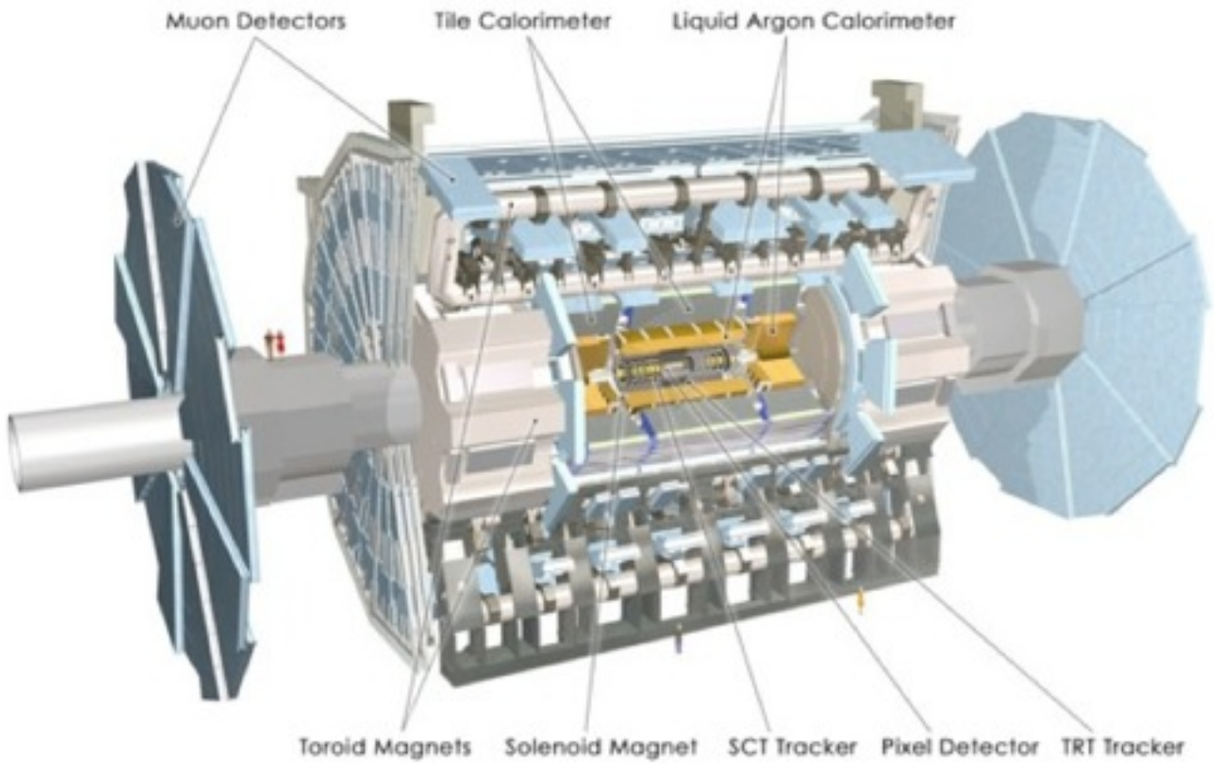
- LHC experiments probes a wide range of RPV and Long Lived Particles signatures
  - Require non standard analysis techniques and push detectors to their limits
  - No excess over SM has been observed yet
- Available space shrinks rapidly ... and LHC Run II is right behind the corner

Thank you

Questions?

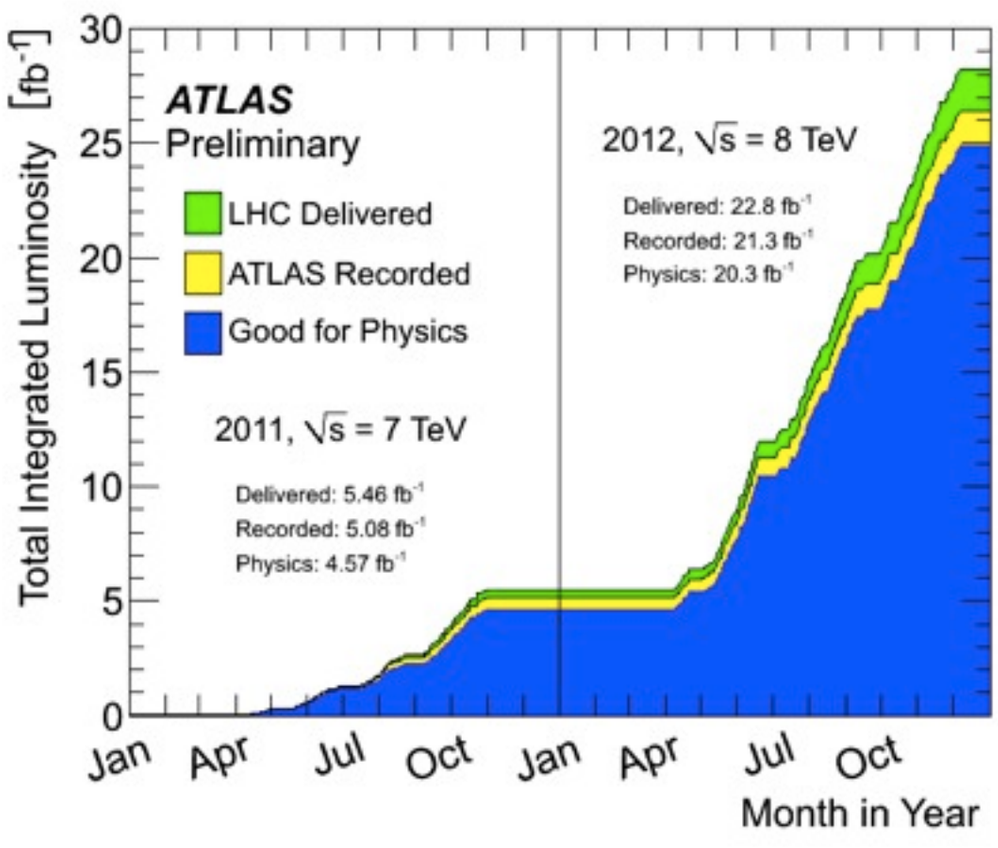
The ATLAS detector

- Coverage - almost 4π in solid angle
- B field - 2T



- **Inner Detector $|\eta|<2.5$**
  - Si Pixels, Si Strips, TRT straws
  - Precise tracking and vertexing
  - $\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\text{GeV}) \oplus 0.015$

- **EM Calorimeter $|\eta|<3.2$**
  - Pb-LAr Accordion
  - $\sigma/E \sim 10\%/\sqrt{E}$

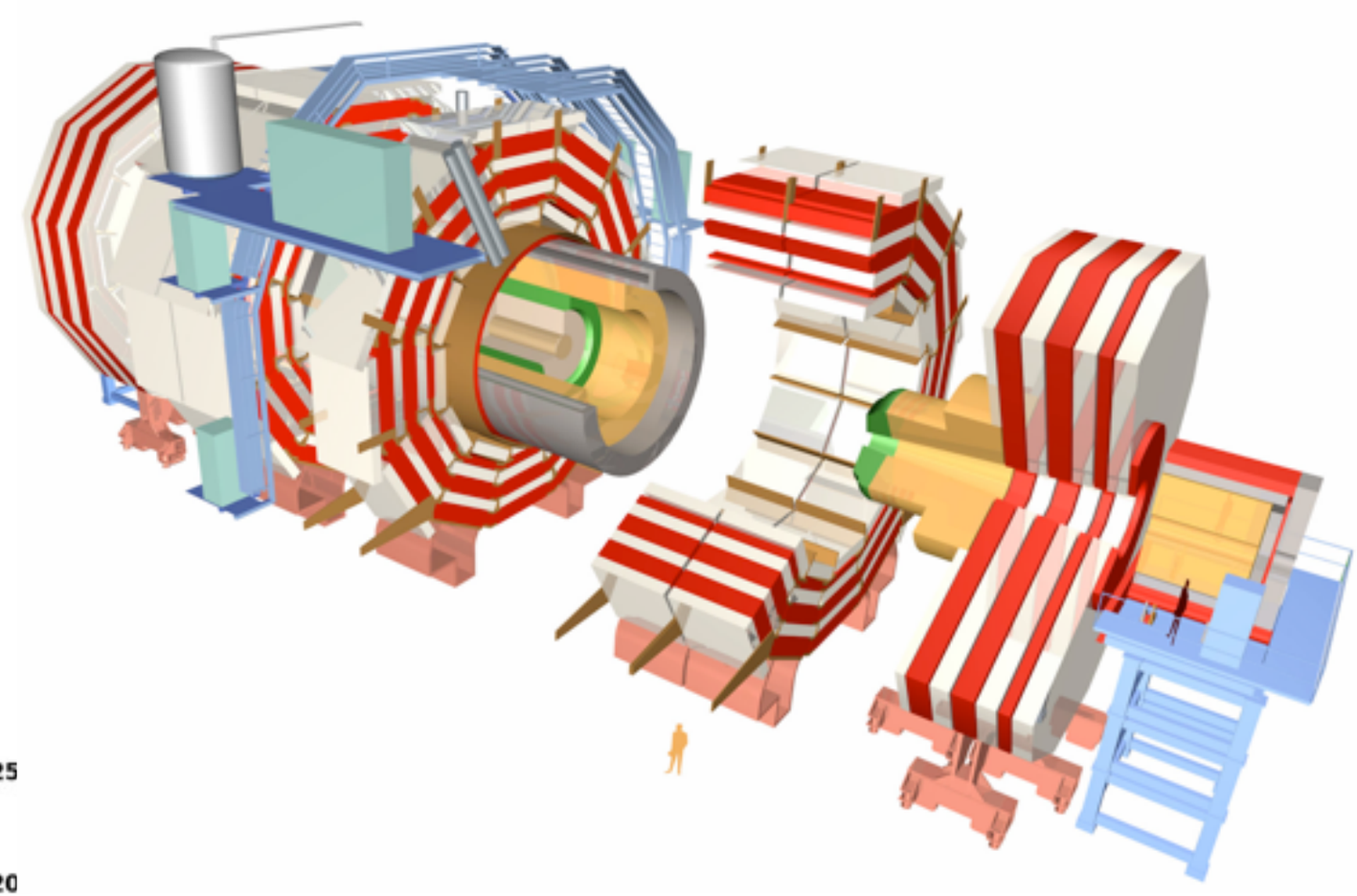


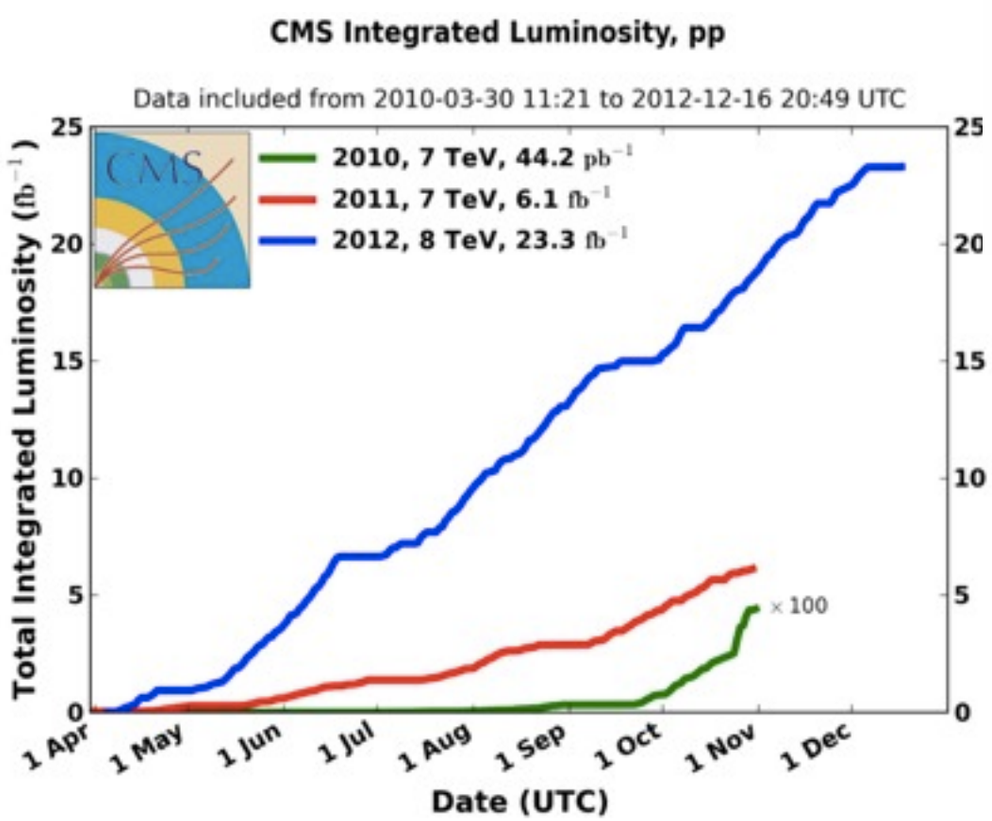
- **Hadron Calorimeter $|\eta|<5$**
  - Fe/scntillator Tiles (central)
    - $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$
  - Cu/W-LAr (fwd)
    - $\sigma/E \sim 90\%/\sqrt{E} \oplus 0.07$

- **Muon Spectrometer $|\eta|<2.5$**
  - Gas-based chamber
  - p_T res <10% up to $E_\mu \sim 1$TeV

The CMS detector

- 4T solenoid magnet
- Silicon detectors (strips/pixels)
- Muon chambers
  $\sigma(P)/P=10\%$ at 1TeV



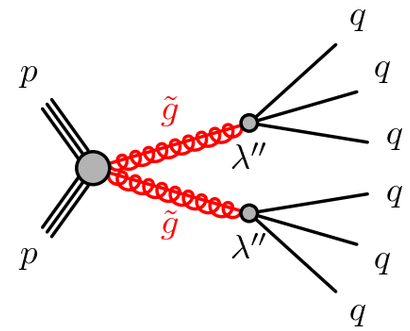


- Crystal ECAL $\sigma(E)/E=3\%/\sqrt{E} + 0.003$
- Brass/scint HCAL $\sigma(E)/E=100\%/\sqrt{E} + 0.05$

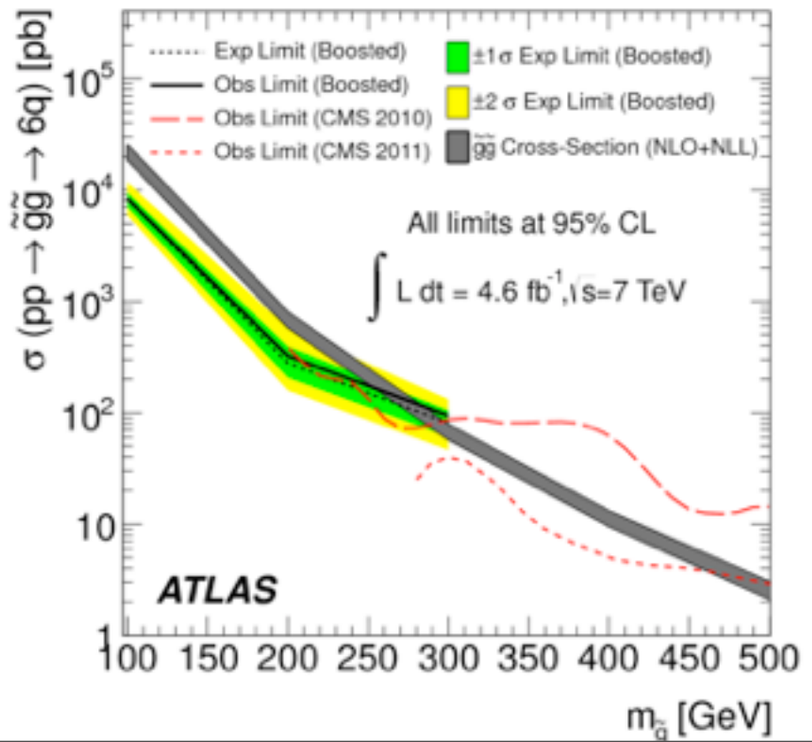
Multi-jet searches

ATLAS:

BOOSTED ANALYSIS:



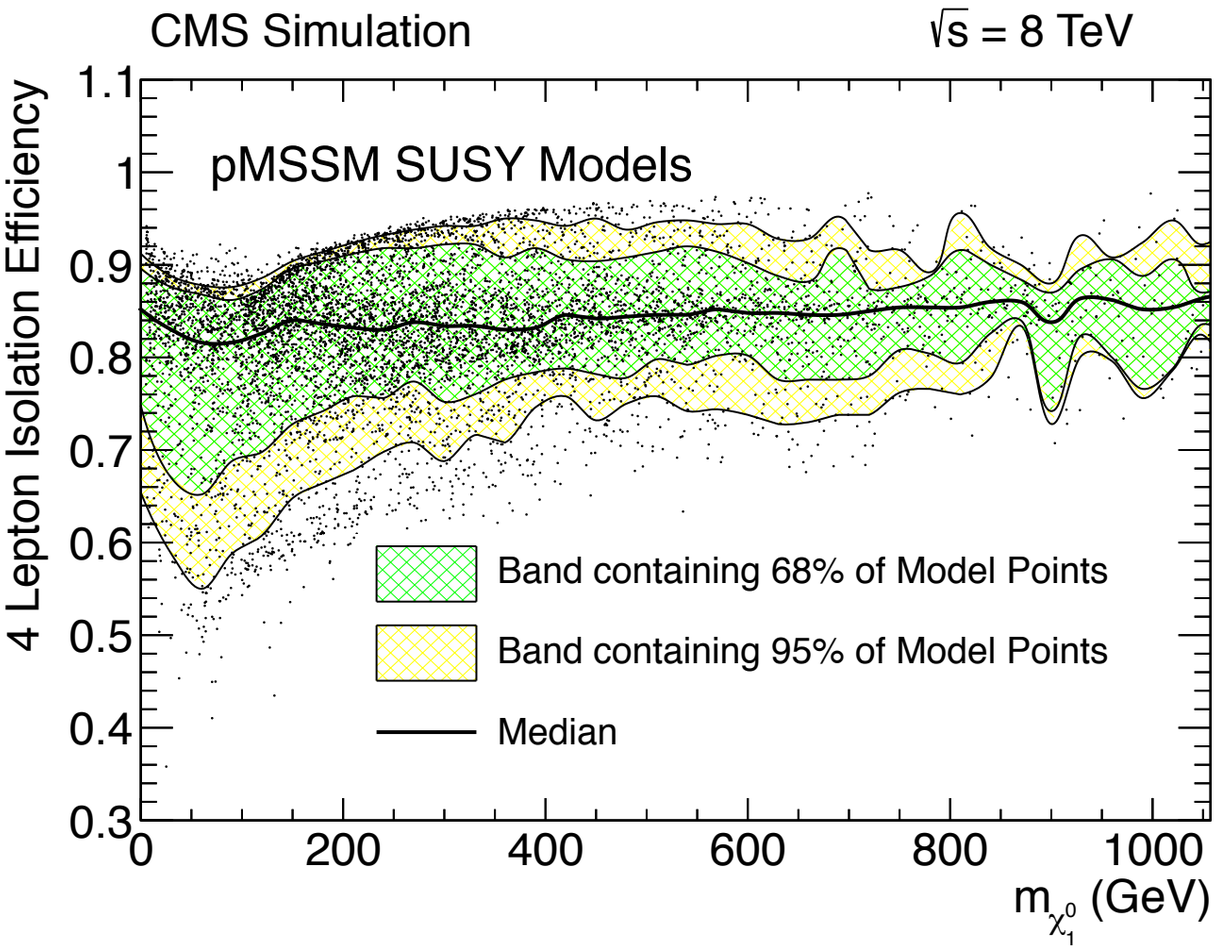
- Gluinos produced with large boost: $p_T >> 2m_{\tilde{g}}$
  - highly collimated jets each containing 3 sub-jets
- Search for large jets with substructure

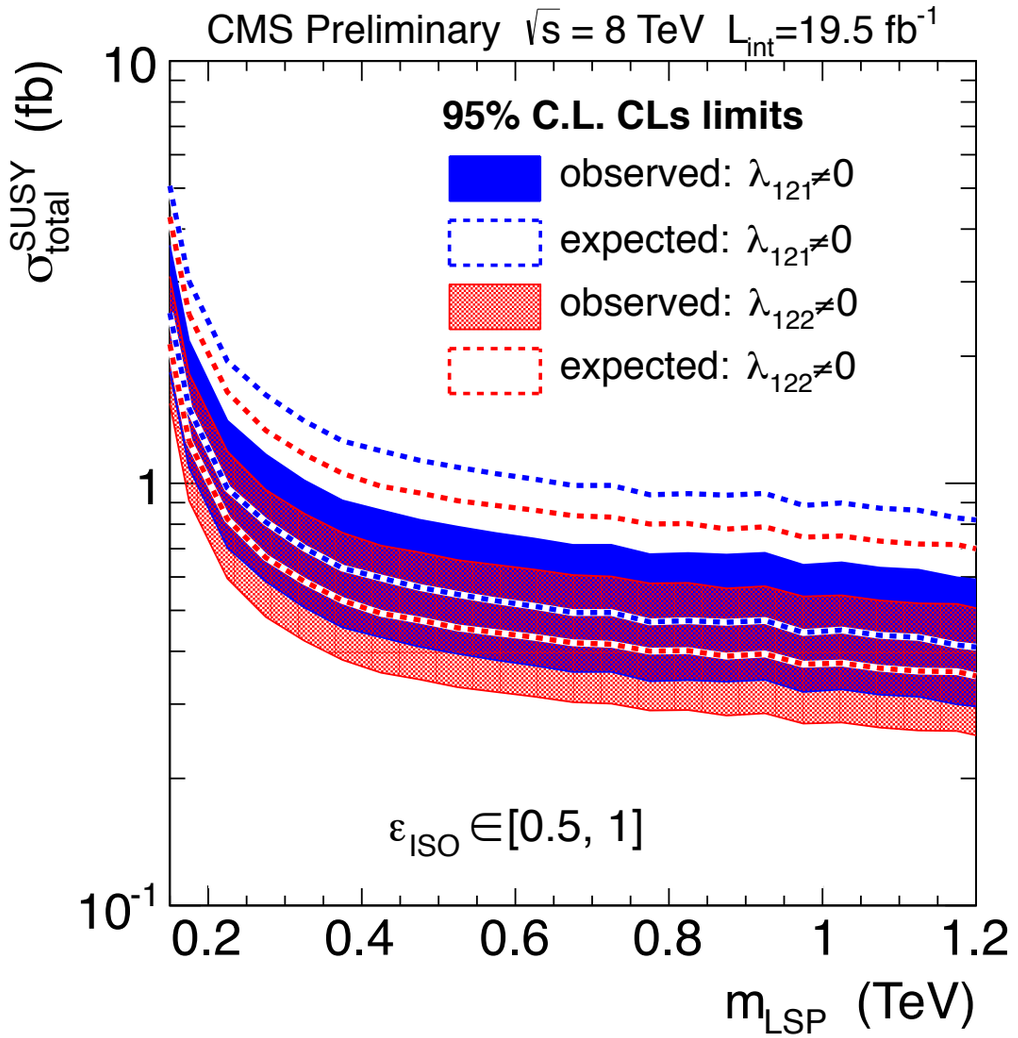


Multi-leptons searches

CMS: PAS-SUS-13-010

- Measure lepton isolation efficiency for different pMSSM models
- Calculate upper limit on σ×L×ε
- set limit on generic "RPV susy"





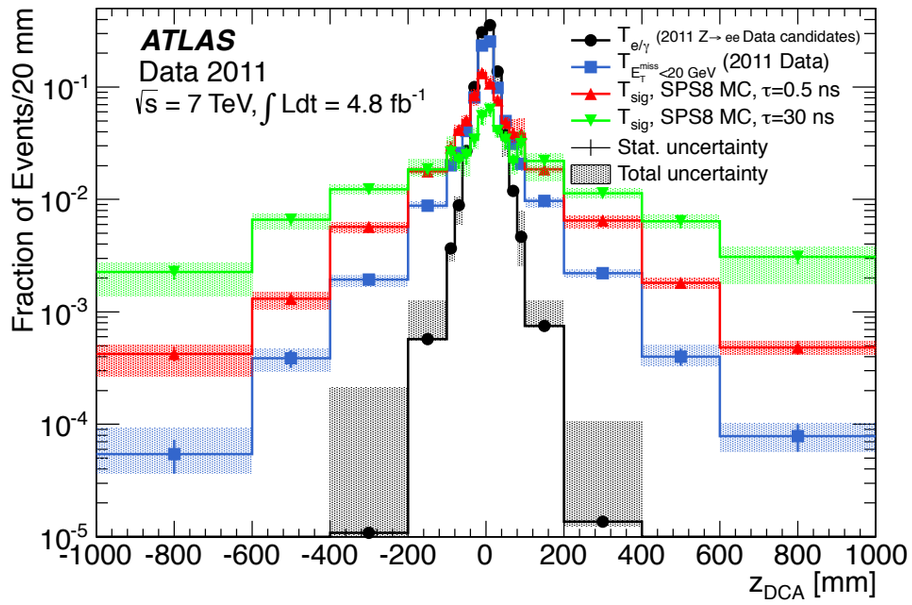
Non-pointing photons

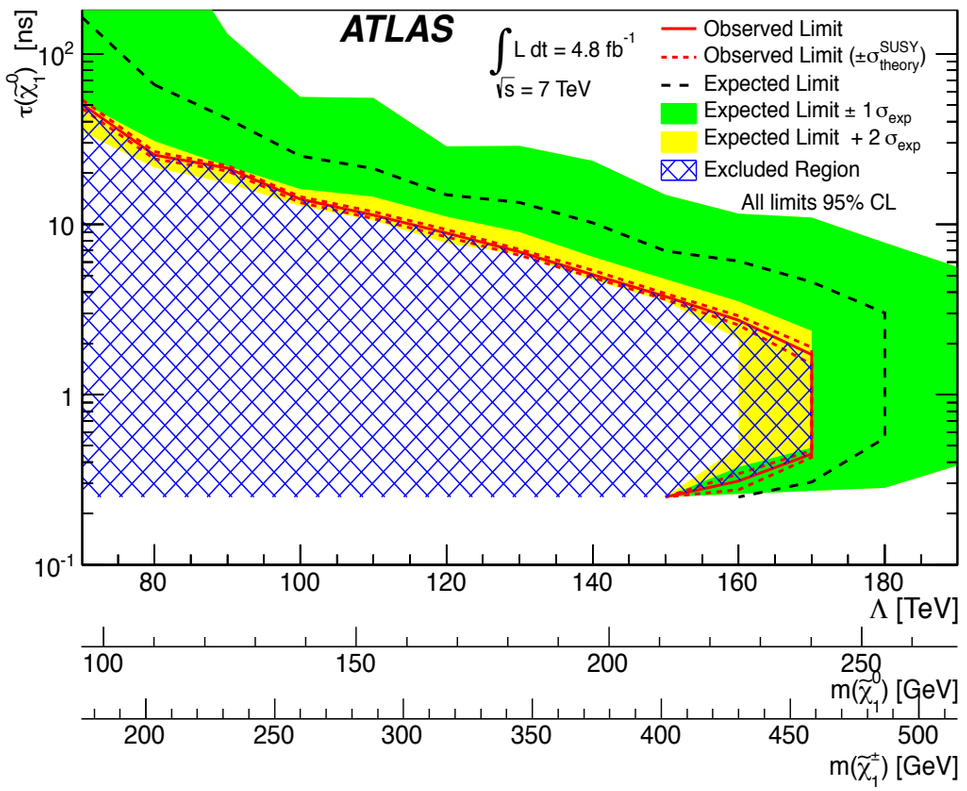
Phys. Rev. D 88, 012001 (2013)

ATLAS:

- long lived $\tilde{\chi}_1^0$ decays to γ+ gravitino
- Signature: E_T^{miss} + pairs of photons (E_T >75GeV) not pointing to primary vertex
- Pointing distribution templates generated from MC (signal) and Data (background)
- Limits obtained by fitting templates to SR pointing distribution

Pointing distribution





Multi-leptons

ATLAS-CONF-2013-007

2 Same Sign leptons

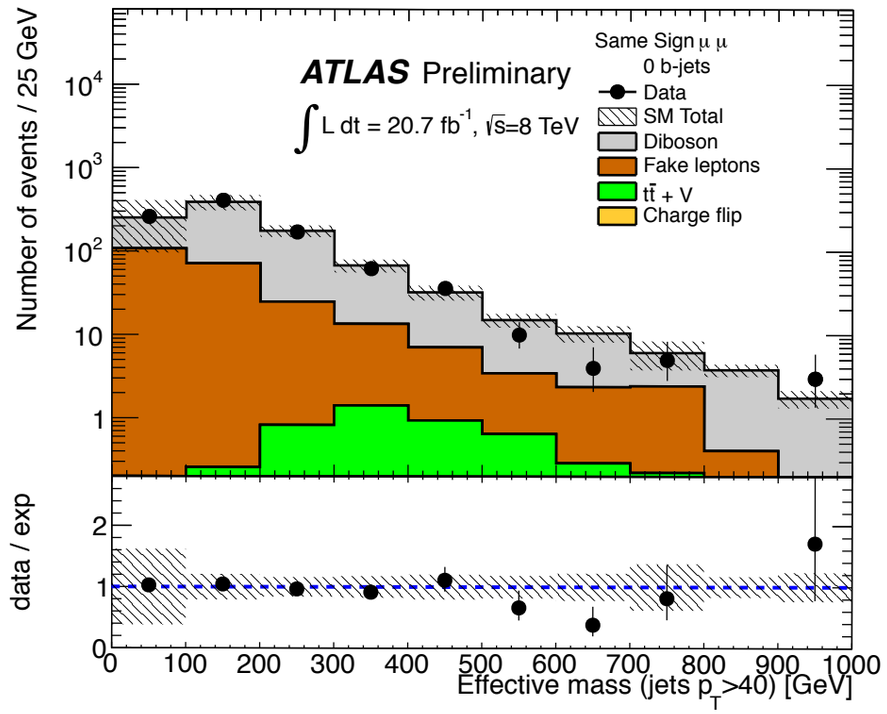
Same-sign leptons events are rare in SM

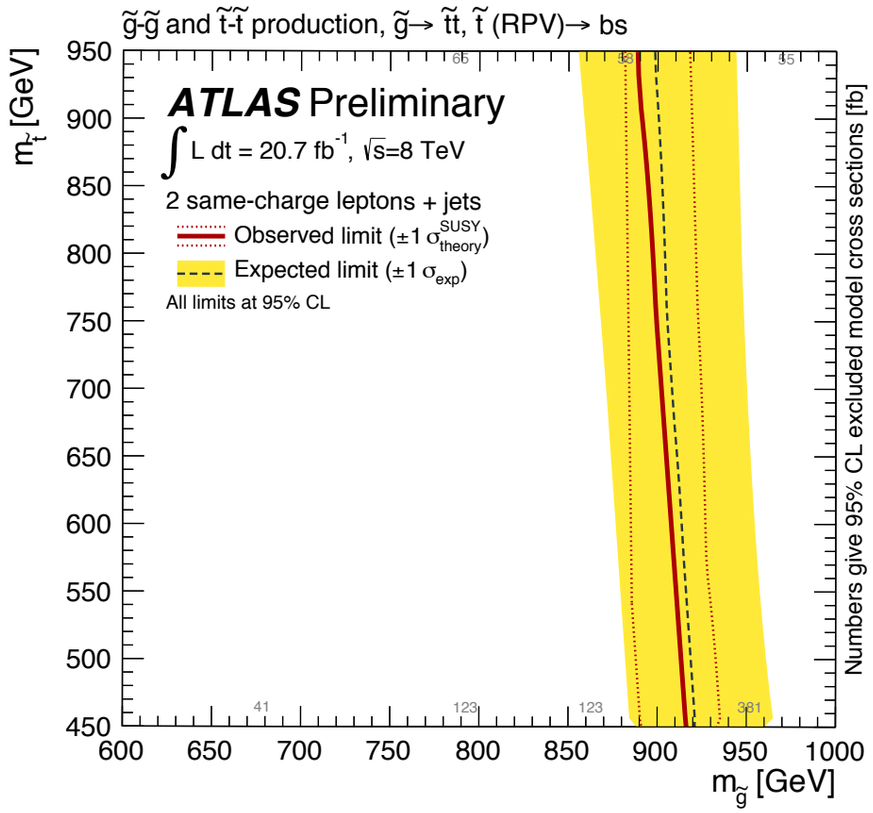
→ low background scenario

- RPV scenario:
  - gluino pair production,
  - gluino decays to $tt\tilde{}$ pair
  - assume only one RPV and baryon number violating term, $\lambda''_{323} = 1$ therefore $t\tilde{} \rightarrow b\ s$
  - Same-sign lepton combinations come from the leptonic decay of the top quark

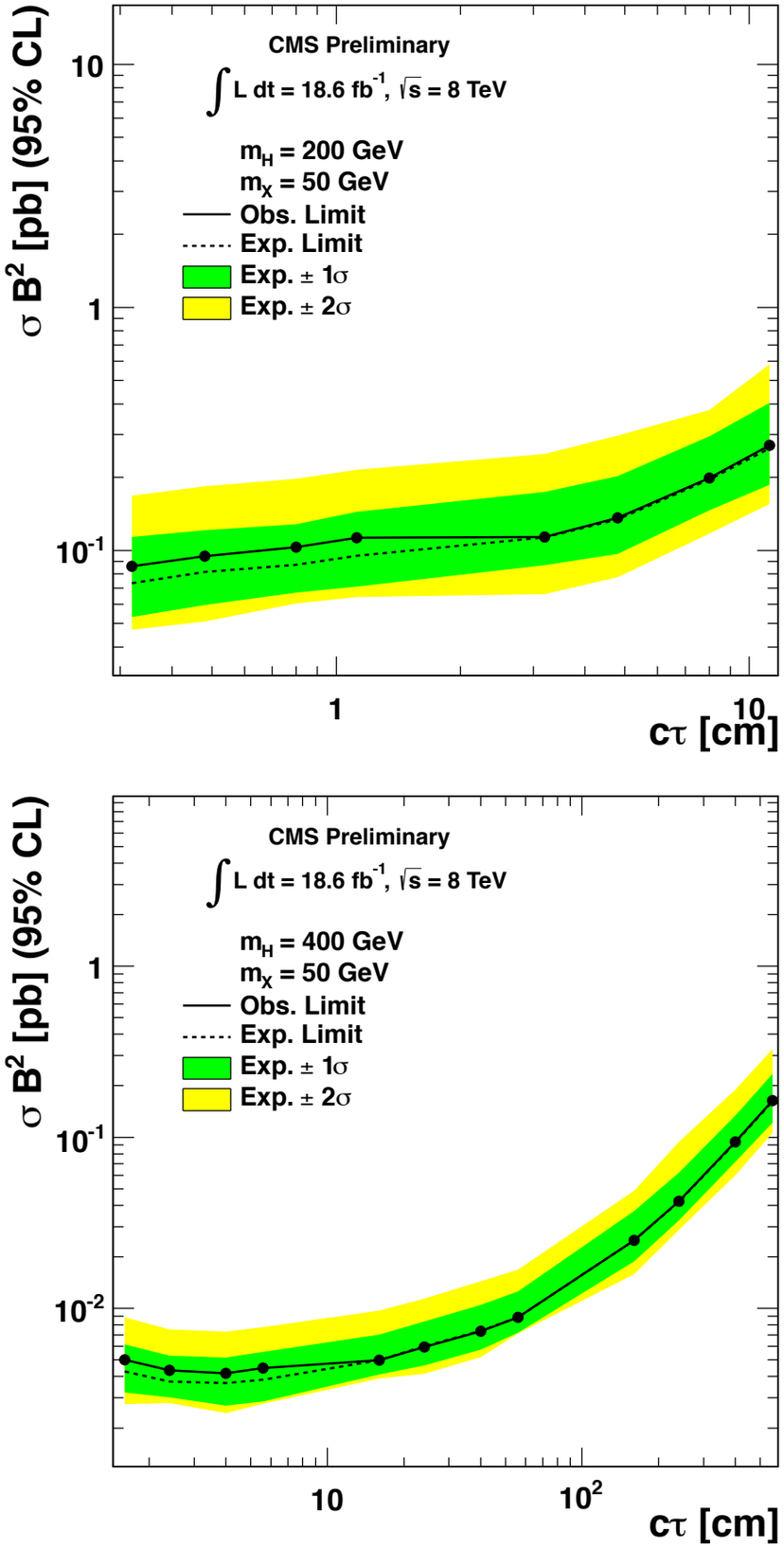
- Signal region:
  - 2 same sign light leptons (e/μ),
  - ≥ 3 b-jets, ≥ 5 jets
  - $E_{T\ miss} < 150$ GeV or $m_T < 100$ GeV

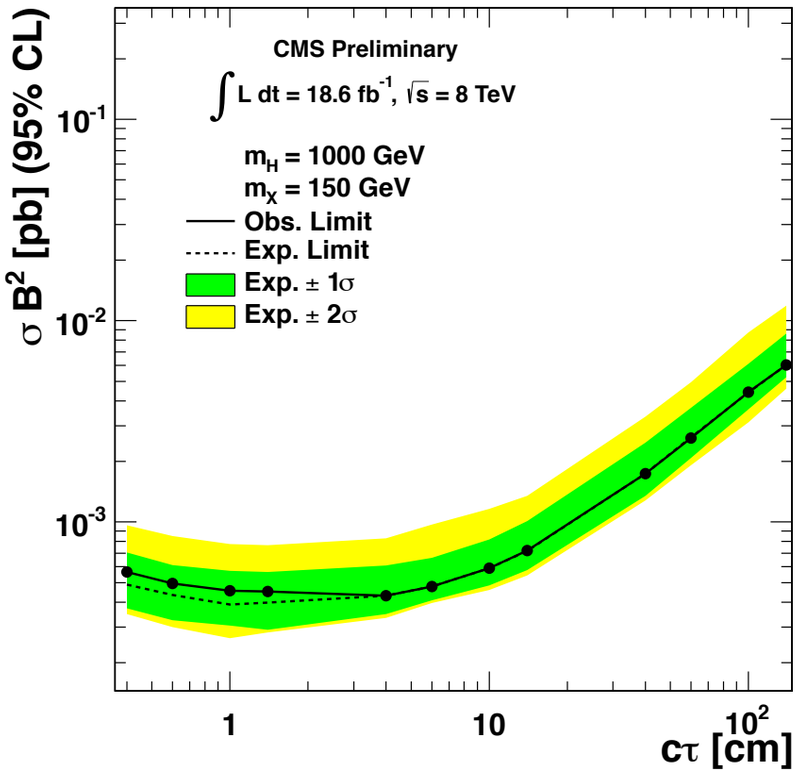
- $m_{g\tilde{}} \lesssim 860$ GeV excluded for stop mass up to 1 TeV

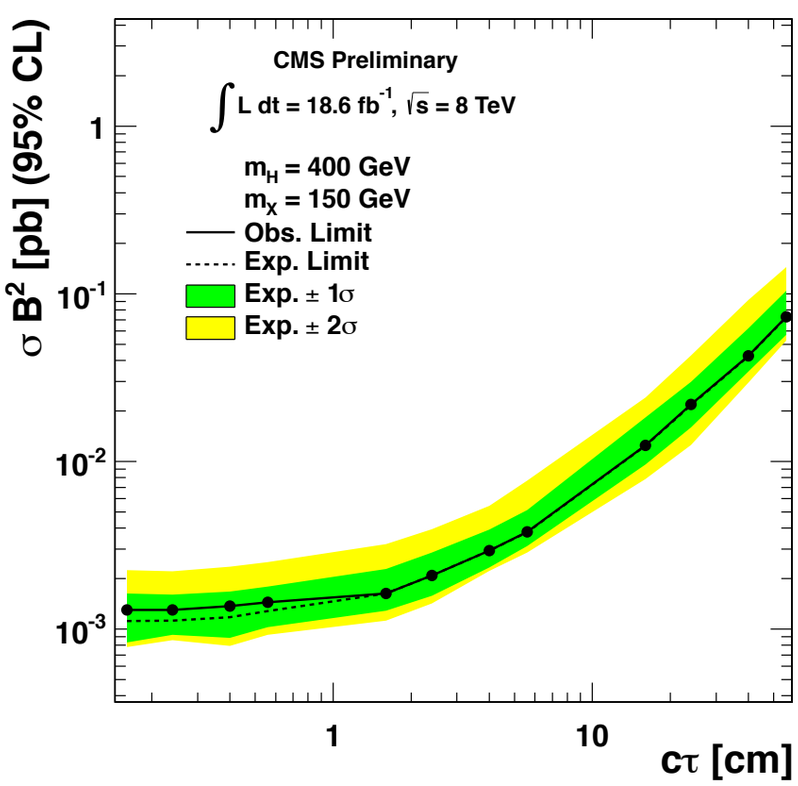




Displaced vertices- dijets

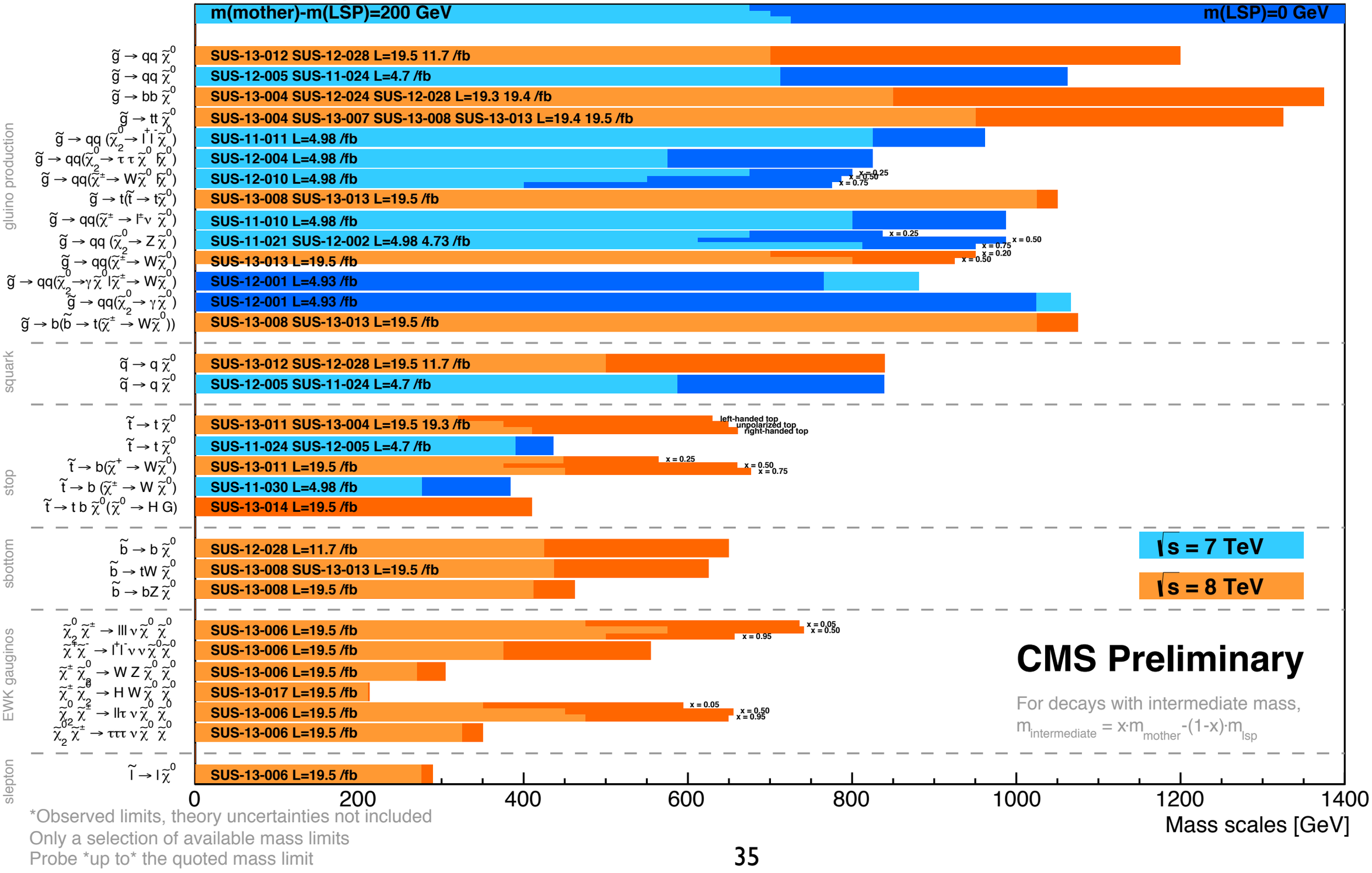






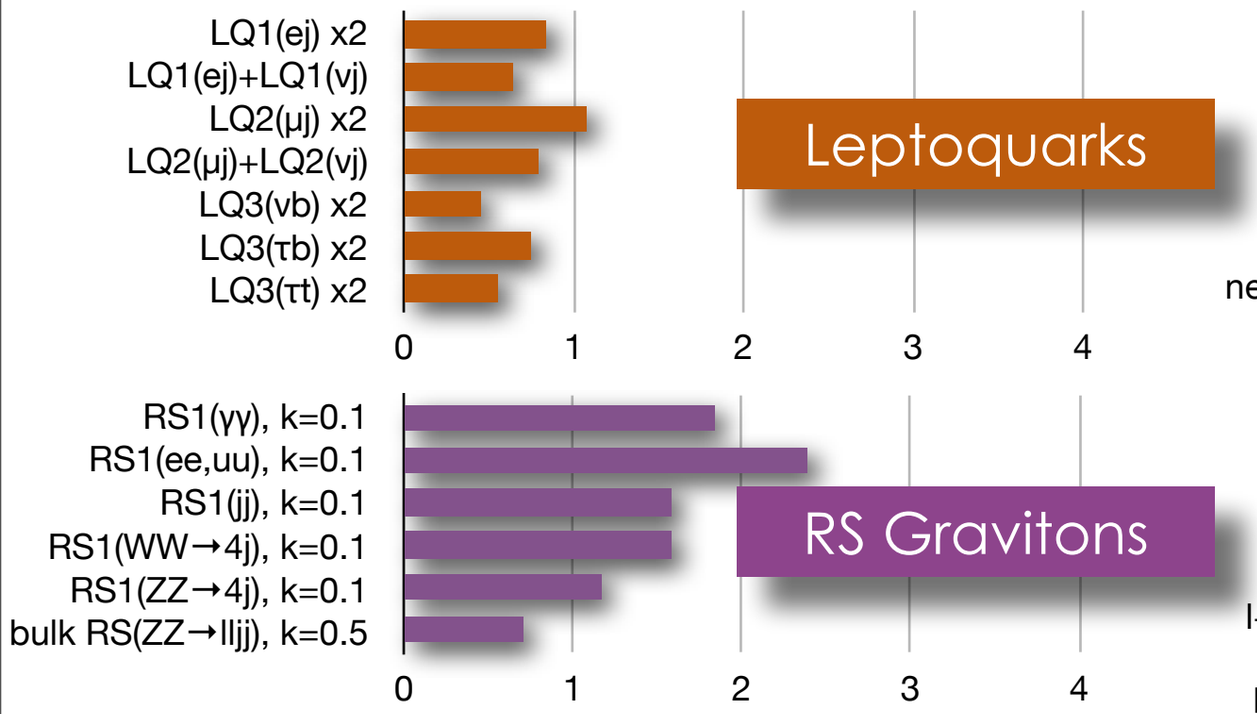
CMS

Summary of CMS SUSY Results* in SMS framework SUSY 2013



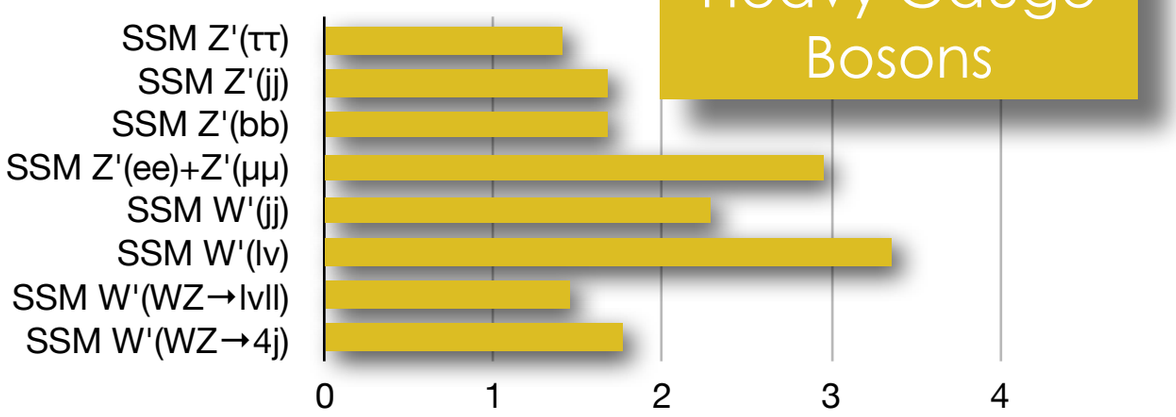
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

CMS

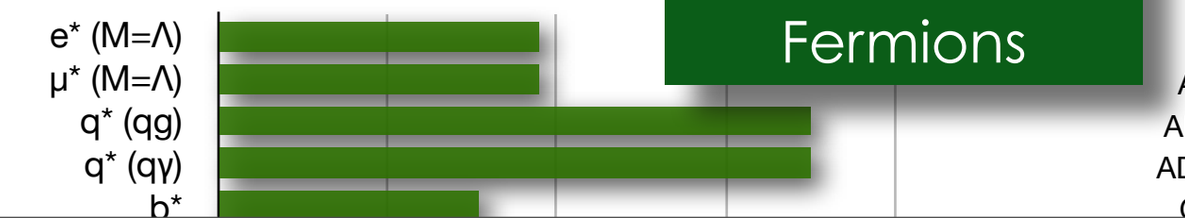


Leptoquarks

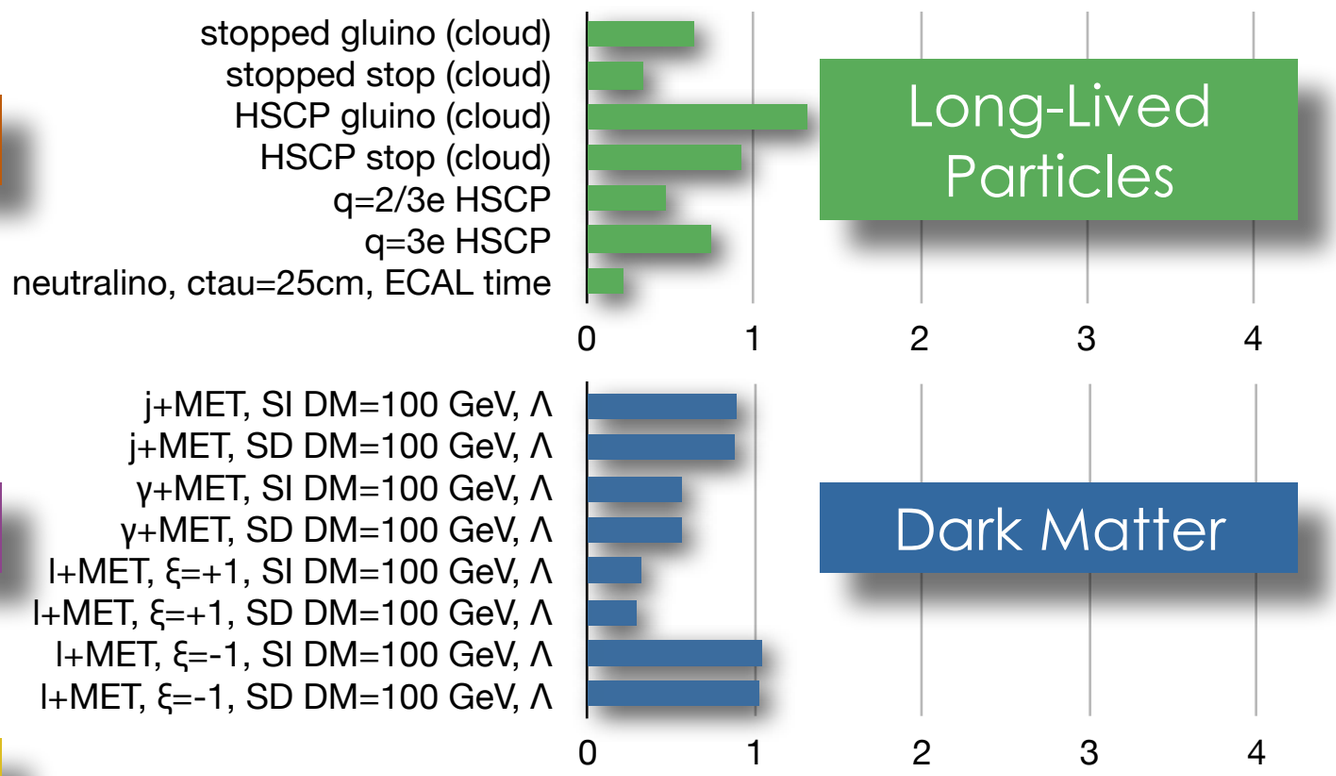
RS Gravitons



Heavy Gauge Bosons

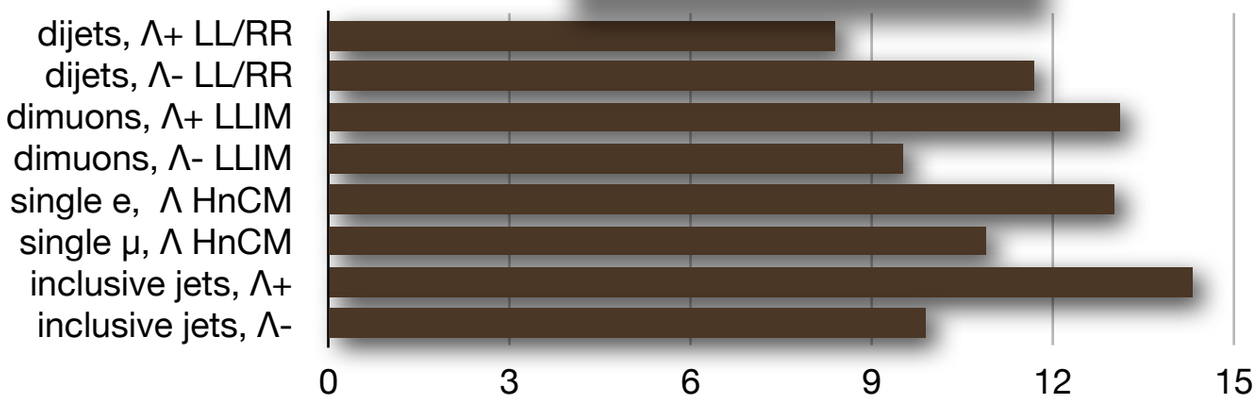


Excited Fermions



Long-Lived Particles

Dark Matter



Compositeness

Large Extra