Dark Matter searches with long-lived particles

DM@LHC 2016, March 30 - April 1, Amsterdam

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(on behalf of the CMS and ATLAS Collaborations)

Outline

- Motivation, theoretical aspects
- Search for Heavy Stable Charged Particles (HSCP) - **13 TeV**
- Search for Metastable Heavy Charged Particles - **13 TeV**
- Search for chargino (disappearing tracks !) - **8 TeV**
- Search for neutral long-lived particle (LLP) in photon+missing E_T final state - **8 TeV**
- Summary

Disclaimer : only a few selected long-lived searches will be discussed

Motivation

Why some particles are long-lived?

- Several New Physics models could give rise to new, massive particles, with relatively long lifetimes.
- LLP can arise in a model if any of the following conditions are present:
  - ➡ Very small coupling in decay chain.
  - ➡ Strong virtuality (heavy particle mediates the decay)
  - ➡ Very small mass differences in decay chain (not much phase space for decay)

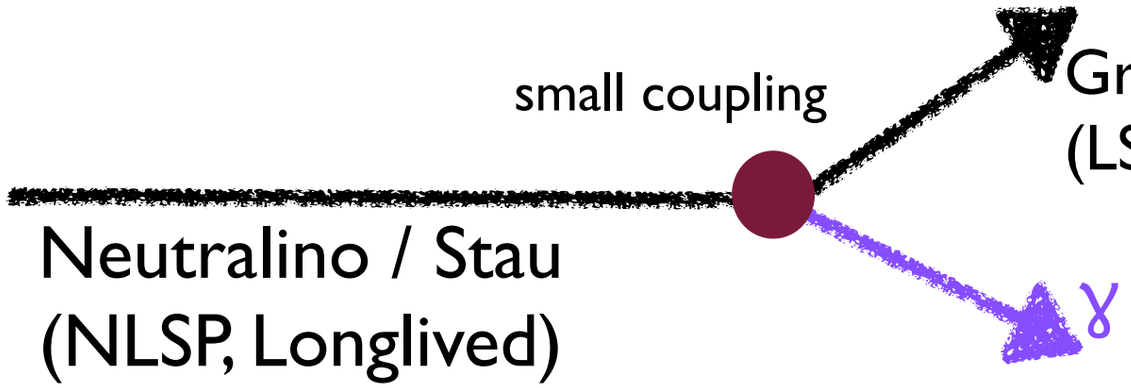
LLP is not dark-matter (DM) candidate

LLP is next-to-lightest supersymmetric particle (NLSP).

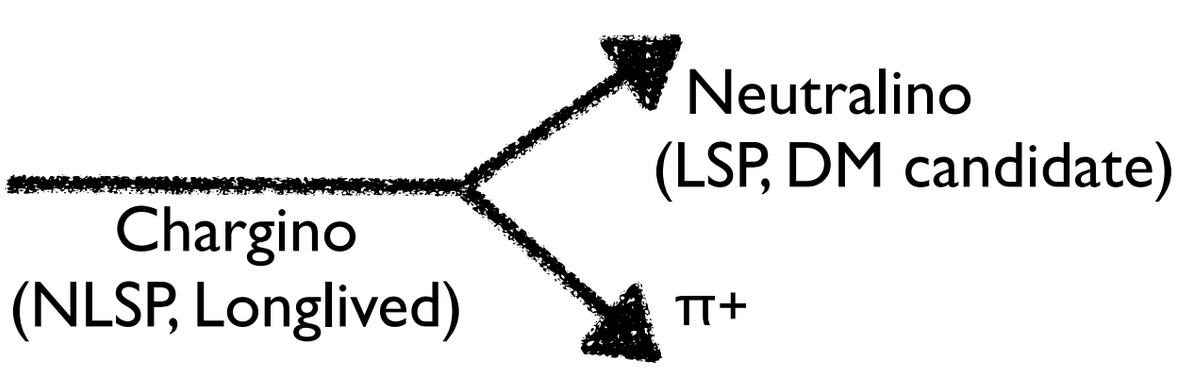
- NLSP → LSP (DM candidate, Missing E_T). But, missing E_T not the only signature for LLP searches
- NLSP → LSP decay may not happen within detector volume !

Motivation

(Some) Theoretical Models predicting long-lived particles



Gauge-mediated Supersymmetry breaking (GMSB)



Anomaly-mediated Supersymmetry breaking (AMSB)

Constrained mass spectrum.

Masses of lightest chargino and lightest neutralino are nearly degenerate.

Gluino have long lifetime because of strong virtuality

Will combine with SM quarks and gluons to form "R-hadrons"

Electroweakino LSP → DM candidate.

Split Supersymmetry

Mass(scalar)>>Mass(fermion)

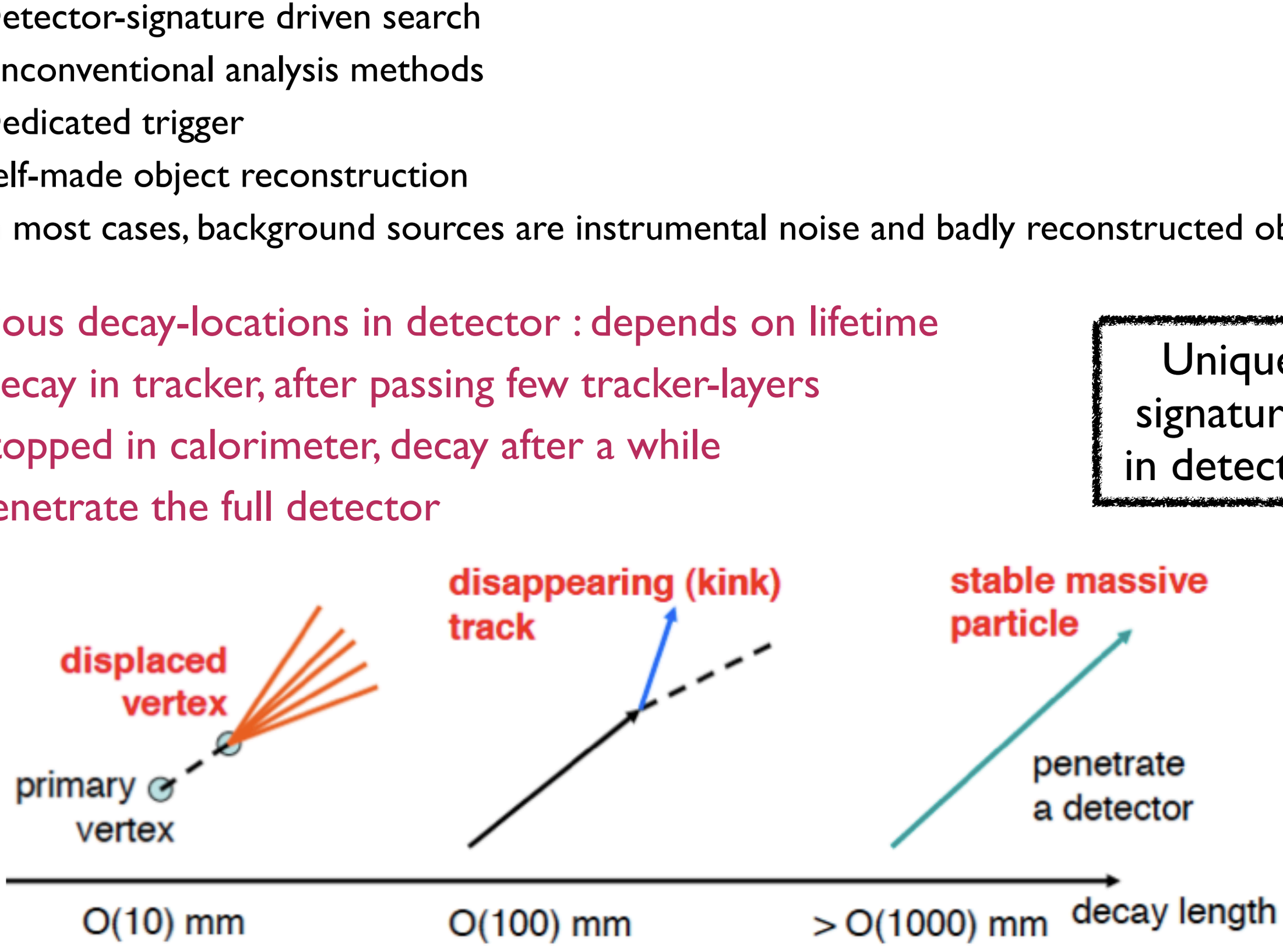
Analysis features

- Detector-signature driven search
- Unconventional analysis methods
- Dedicated trigger
- Self-made object reconstruction
- In most cases, background sources are instrumental noise and badly reconstructed objects

Various decay-locations in detector : depends on lifetime

- Decay in tracker, after passing few tracker-layers
- Stopped in calorimeter, decay after a while
- Penetrate the full detector

Unique signatures in detector



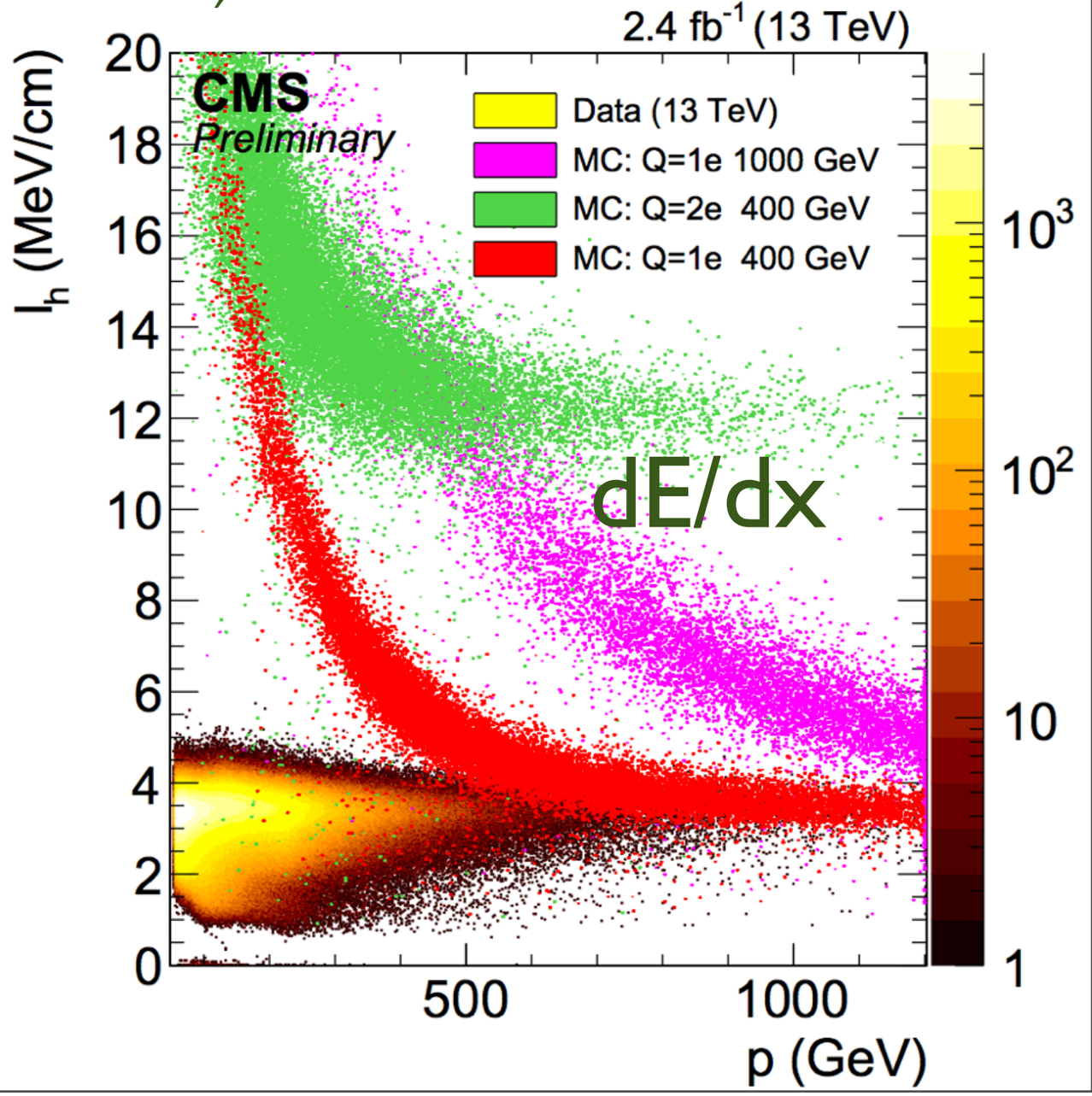
Search for Heavy Stable Charged Particles in CMS
Signature of HSCP

13 TeV
2.4 fb^{-1}

CMS PAS EXO-15-010

Heavy Stable Charged Particle (HSCP)

- Heavy : Slow moving (β<1) → longer time-of-flight (TOF) to the outer detectors
- Stable w.r.t detector : Long-lived (lifetime > few ns)
- Charged : **|Q|=1e**, |Q|<1e, |Q|>1e
  - |Q|≥1e → high dE/dx



Signature

- Anomalously high energy deposition in silicon tracker
- Long time-of-flight to the muon detectors

Background from instrumental sources

Types of HSCP

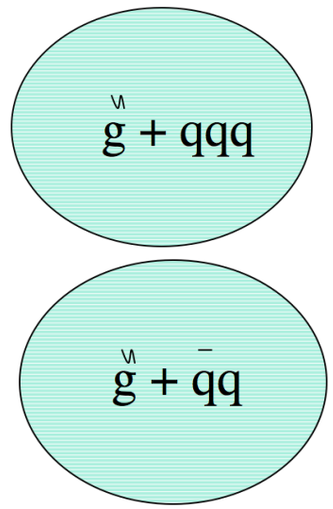
Hadron-like & Lepton-like

Search for Heavy Stable Charged Particles in CMS
Hadron-like HSCP

13 TeV
2.4 fb^{-1}

CMS PAS EXO-15-010

- **Hadron-like** HSCP (Electric charge + Color charge)
  - Pair-production of gluino or stop.
  - Form bound states with SM quarks or gluons → **R-hadrons**
  - R-hadrons : Charged or neutral at production. May flip sign in detector (nuclear interaction) $R^+ + n \rightarrow R^- + p + \pi^+$



Search for Heavy Stable Charged Particles in CMS
Lepton-like HSCP

13 TeV
2.4 fb^{-1}

CMS PAS EXO-15-010

- **Lepton-like** HSCP (Only electric charge)
  - Stau NLSP long-lived, decays to gravitino LSP
- Production of stau at LHC :
  - Direct pair-production
  - Via production of heavier supersymmetric particles, leading to one or more stau(s) at the end of the decay chain (GMSB benchmark scenario SPS7)

"Muon-like" signature

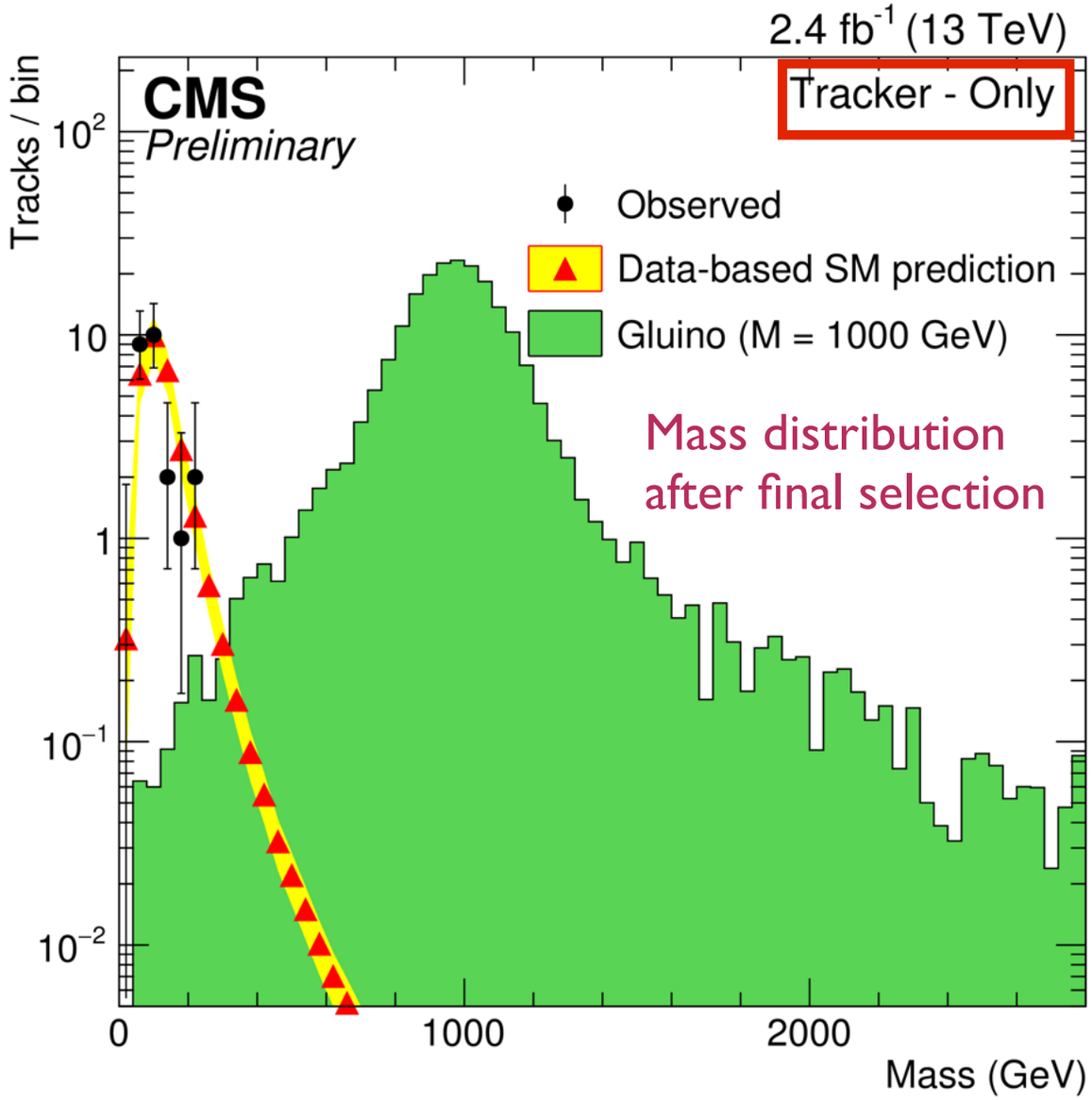
Search for Heavy Stable Charged Particles in CMS

Results

CMS PAS EXO-15-010

Search in two ways :

- **"tracker-only" analysis** - require tracks be reconstructed in the silicon detectors
- **"tracker+TOF" analysis** - requiring tracks reconstructed in both silicon detectors and muon system



13 TeV
2.4 fb^{-1}

Data-driven background estimation

Mass estimated from dE/dx and *p*

Data agrees well with SM background

Search for Heavy Stable Charged Particles in CMS

Results

13 TeV
2.4 fb^{-1}

CMS PAS EXO-15-010

Results for |Q|=1e

Model	Analysis	Limit
Gluino f=0.1, Cloud Model	Tracker Only	M>1590 GeV
Stop Cloud Model	Tracker Only	M>1020 GeV
Stau GMSB SPS7	Tracker+TOF	M>480 GeV

Hadron-like HSCP

Lepton-like HSCP

Improved limits w.r.t Run-I

- Different models for strong interaction of R-hadron with detector material :
  - Cloud Model (R-hadron composed of a spectator HSCP surrounded by cloud of colored, light constituents.)
  - Charge-suppressed model "CS" (almost all R-hadrons flip to neutral)
- How often gluino forms neutral hadron with gluon? f=0.1, 0.5 considered

CMS EXO-12-026 [JHEP 07 (2013) 122] →7+8 TeV

More info

Metastable heavy charged particle search
in ATLAS at 13 TeV with 3.2 fb^{-1} data

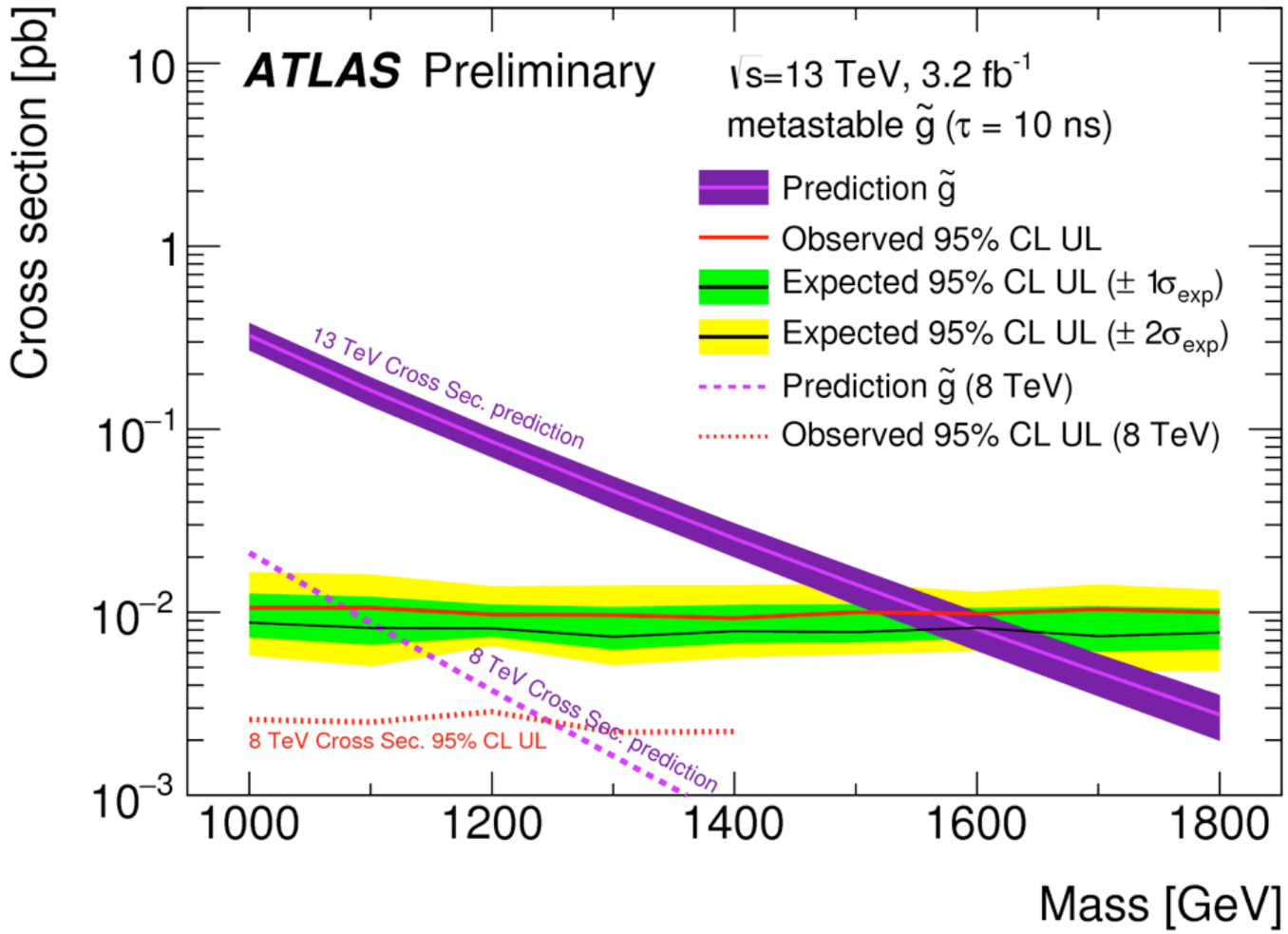
13 TeV
3.2 fb^{-1}

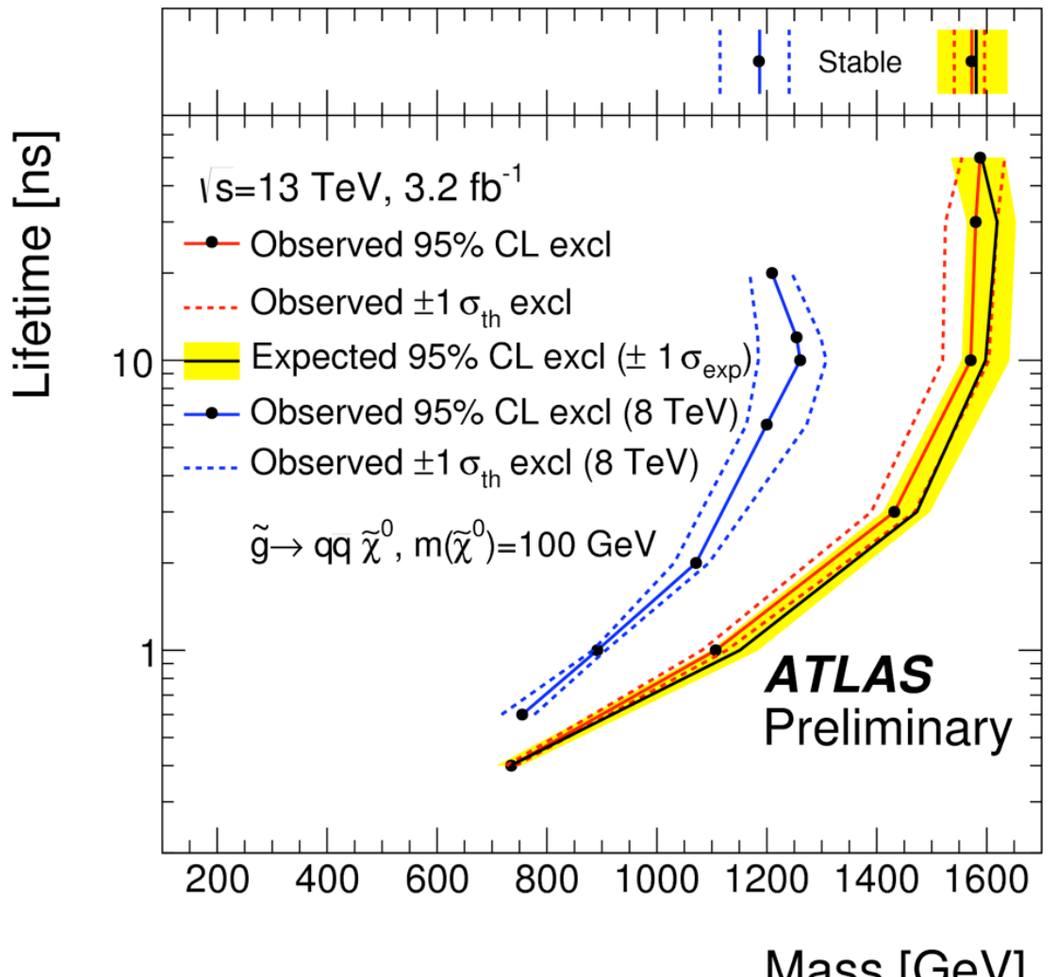
Signature

- High missing E_T
- At least one high-p_T, isolated, good track
- Anomalously large energy loss in pixel detector

Theoretical Interpretation

- Split-SUSY : NLSP Gluino long-lived
- Gluino → Neutralino (LSP, DM candidate)





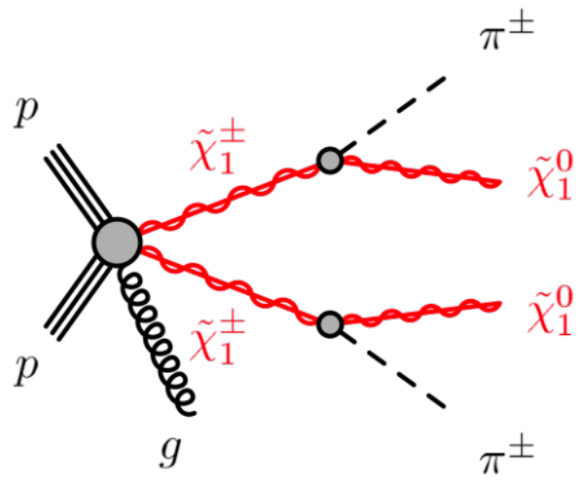
Long-lived chargino search in ATLAS

Signature and Theory

Phys. Rev. D 88, 112006 (2013)

Signature

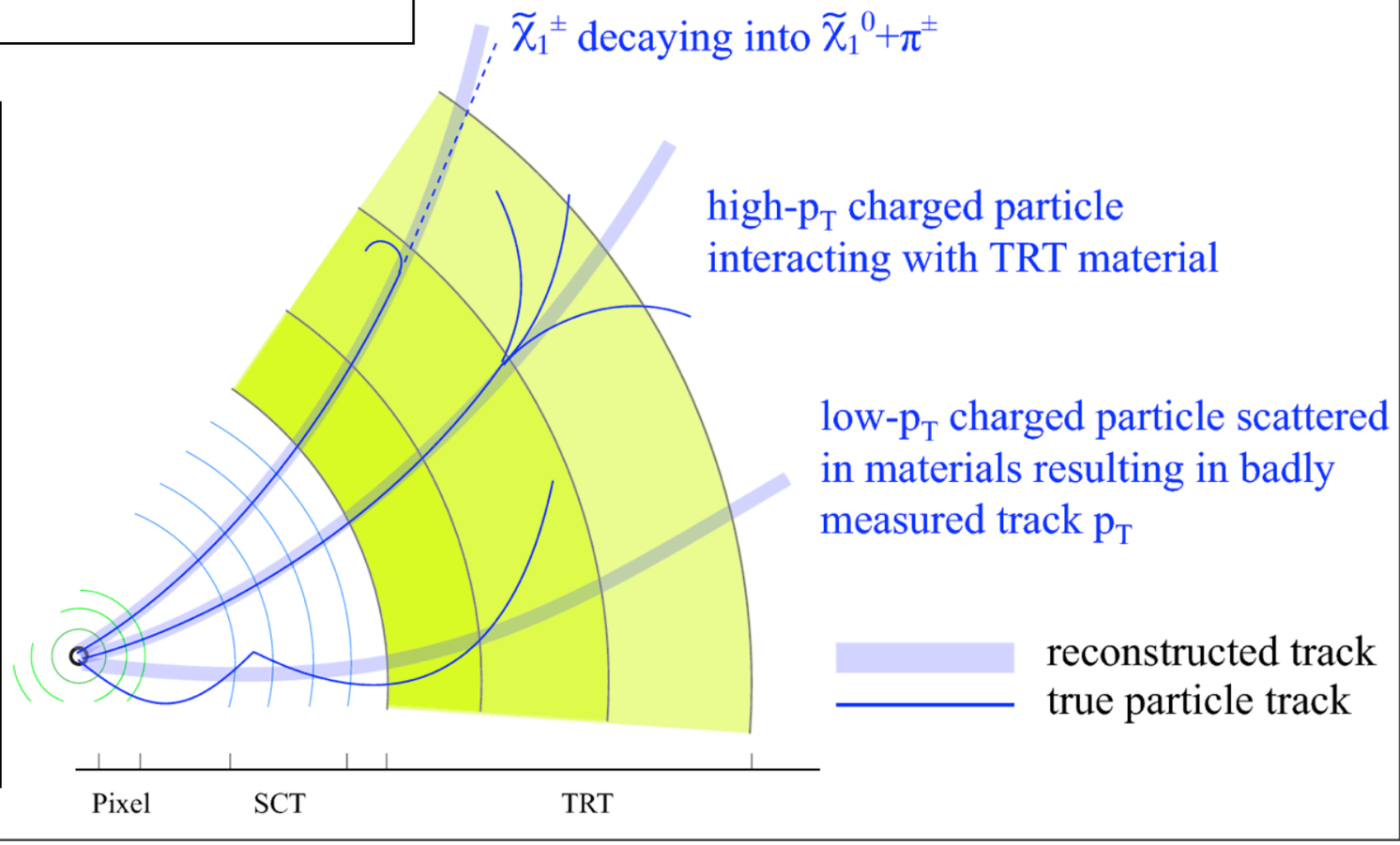
- One or two **disappearing track(s)**
  - High-p_T, isolated track, missing hits in outer layer of tracker
  - No matching hit in muon detector
  - Little or no calorimeter energy deposit
- Missing E_T (DM candidate)



8 TeV
20.3 fb^{-1}

Theoretical Interpretation

- **AMSB** : Lightest chargino slightly heavier than lightest neutralino (LSP)
- Chargino predominantly decays to neutralino (missing E_T) and soft pion
- Constrained phase phase : Chargino long-lived (lifetime≥0.2 ns)



Long-lived chargino search in ATLAS

Event Selection, Backgrounds, Results

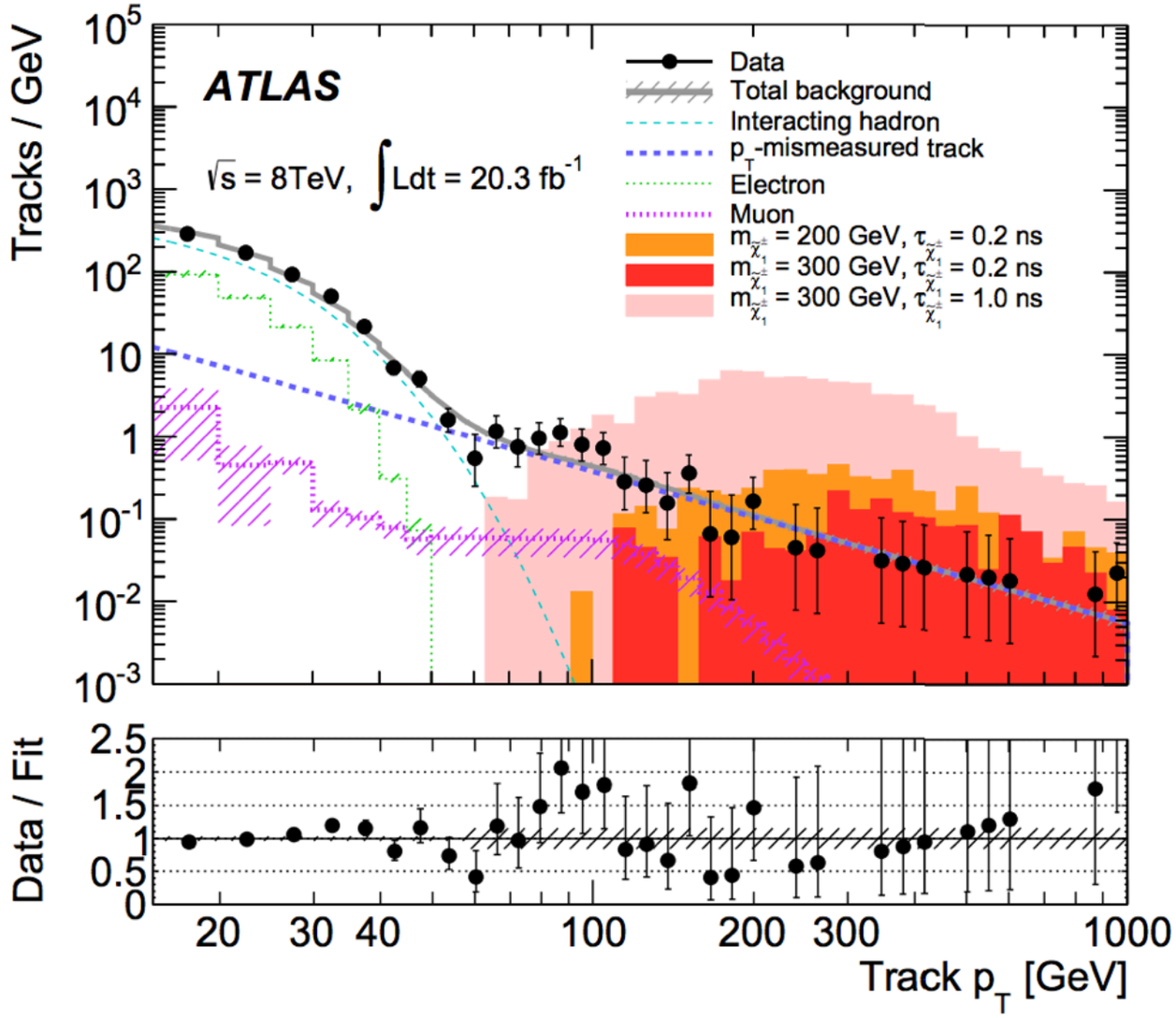
Phys. Rev. D 88, 112006 (2013)

8 TeV
20.3 fb^{-1}

Signature : disappearing track

Dedicated trigger to suppress multijet background :

- At least one high-p_T jet (ISR-jet)
- Large missing E_T
- $\Delta\phi(\text{jet}, E_{T\text{miss}})>1$



Backgrounds (mimic disappearing-tracks)

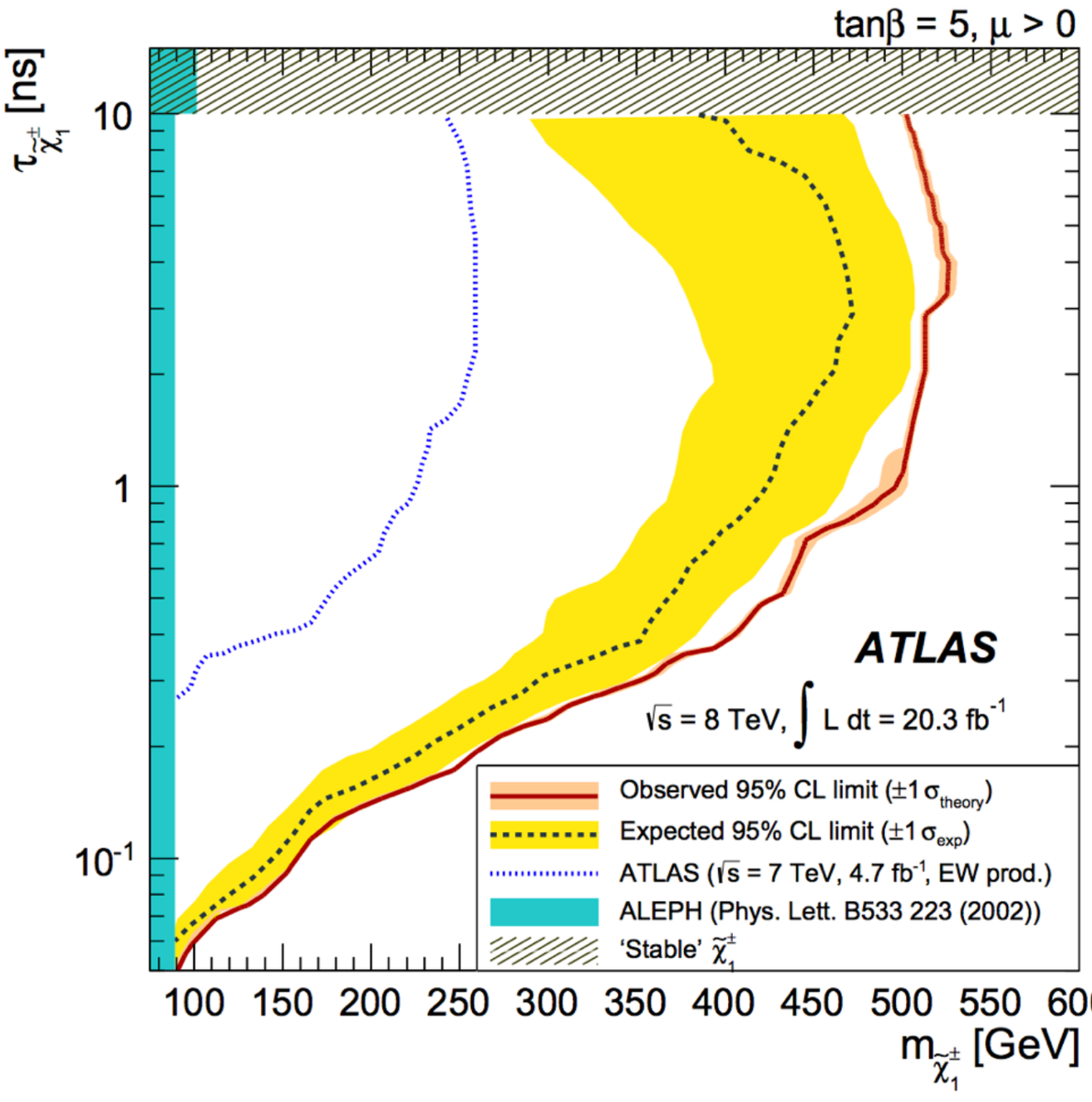
- Charged hadrons interacting with tracker material
- Charged leptons losing momenta in tracker due to scattering or bremsstrahlung → not correctly identified
- Tracks with mis-measured p_T

- ~2σ excess around 90 GeV
- Discrepancy is not consistent with any signal hypothesis studied in this analysis

Long-lived chargino search in ATLAS

Results

Phys. Rev. D 88, 112006 (2013)



Signature : disappearing track

8 TeV
20.3 fb^{-1}

Chargino excluded upto 270 GeV for lifetime=0.2 ns in AMSB

CMS limit 260 GeV with 19.5 fb^{-1} data JHEP 01 (2015) 096

tanβ : Ratio of Higgs vacuum expectation values at electroweak scale
μ : Sign of the higgsino mass term

LLP search in photons+MET final state in CMS

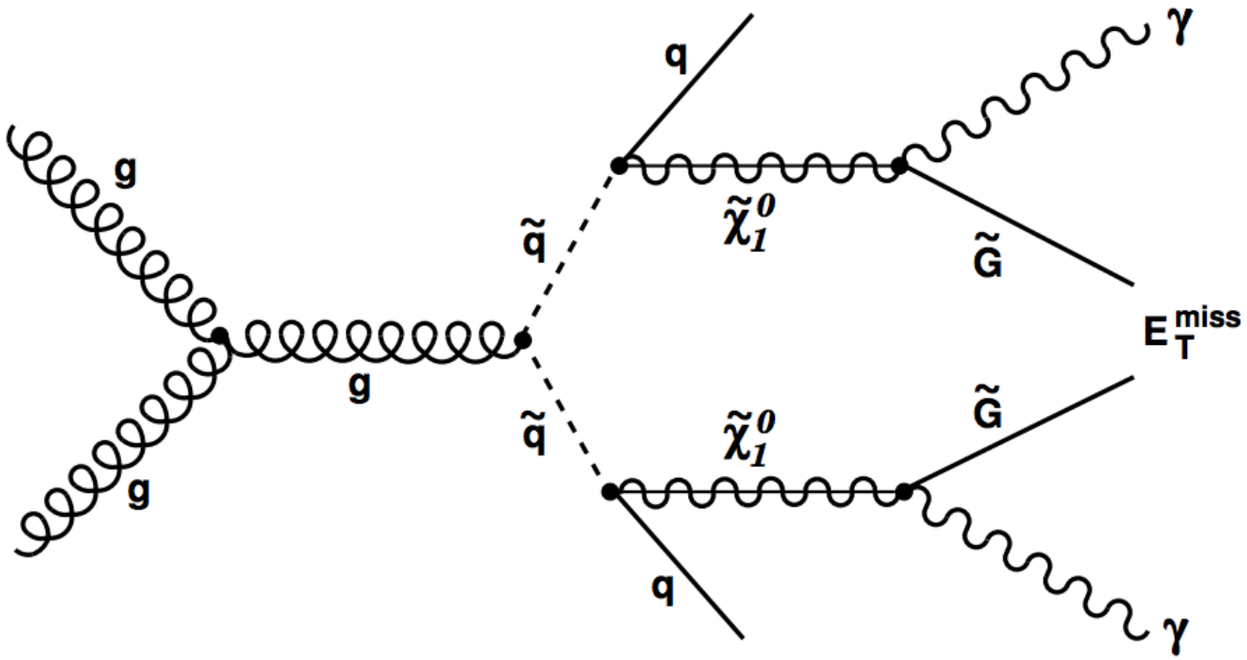
Theory, Signature, Event Selection

CMS PAS EXO-14-017

8 TeV
19.7 fb^{-1}

Theoretical interpretation

- ✦ GMSB (benchmark SPS8)
- ✦ Lightest neutralino is NLSP → long-lived. **Neutral LLP**
- ✦ Pair-production of neutralino → decay to gravitino(LSP) and photon
- ✦ Consider lifetime ($c\tau$) of neutralino between 0.4 cm to 100 cm



Signature

- At least two high-p_T, isolated, good photons
  - ➡ At least one of them converted (e^+e^-)
- At least two jets
- Missing E_T (DM candidate)

Main background γ+jet

LLP search in photons+MET final state in CMS

Results

8 TeV
19.7 fb^{-1}

CMS PAS EXO-14-017

No excess observed in data.

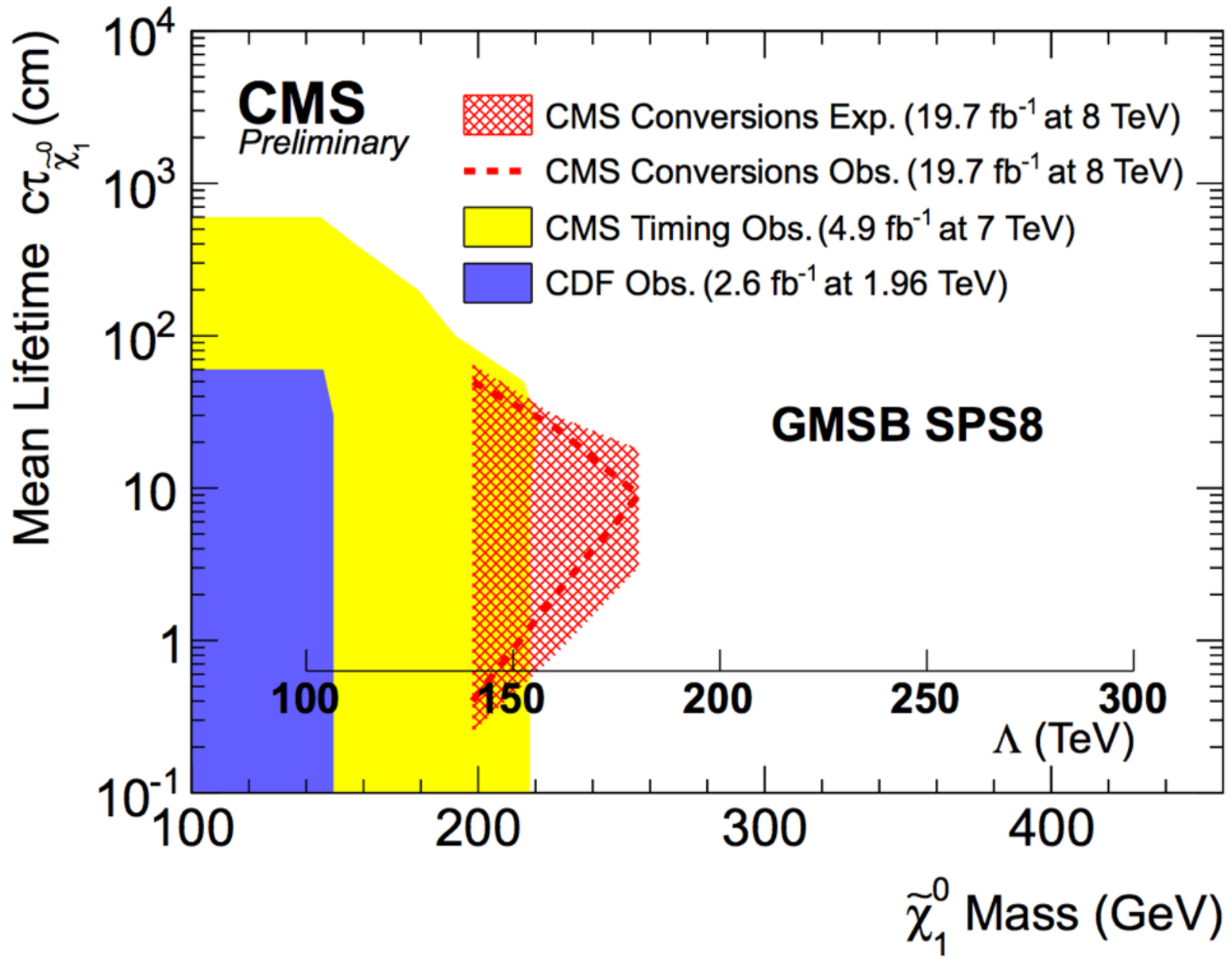
Exclusion Plot

Neutralino excluded upto 250 GeV for lifetime=10 cm in GMSB

↓

~0.3 ns

CMS 7 TeV in plot : arxiv1212.1838

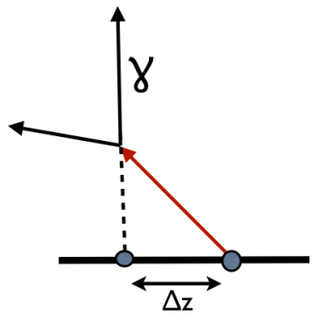


LLP search in photons+MET final state in ATLAS
Analysis strategy and Results

Signature : Non-pointing and delayed photons + Missing E_T

8 TeV
20.3 fb^{-1}

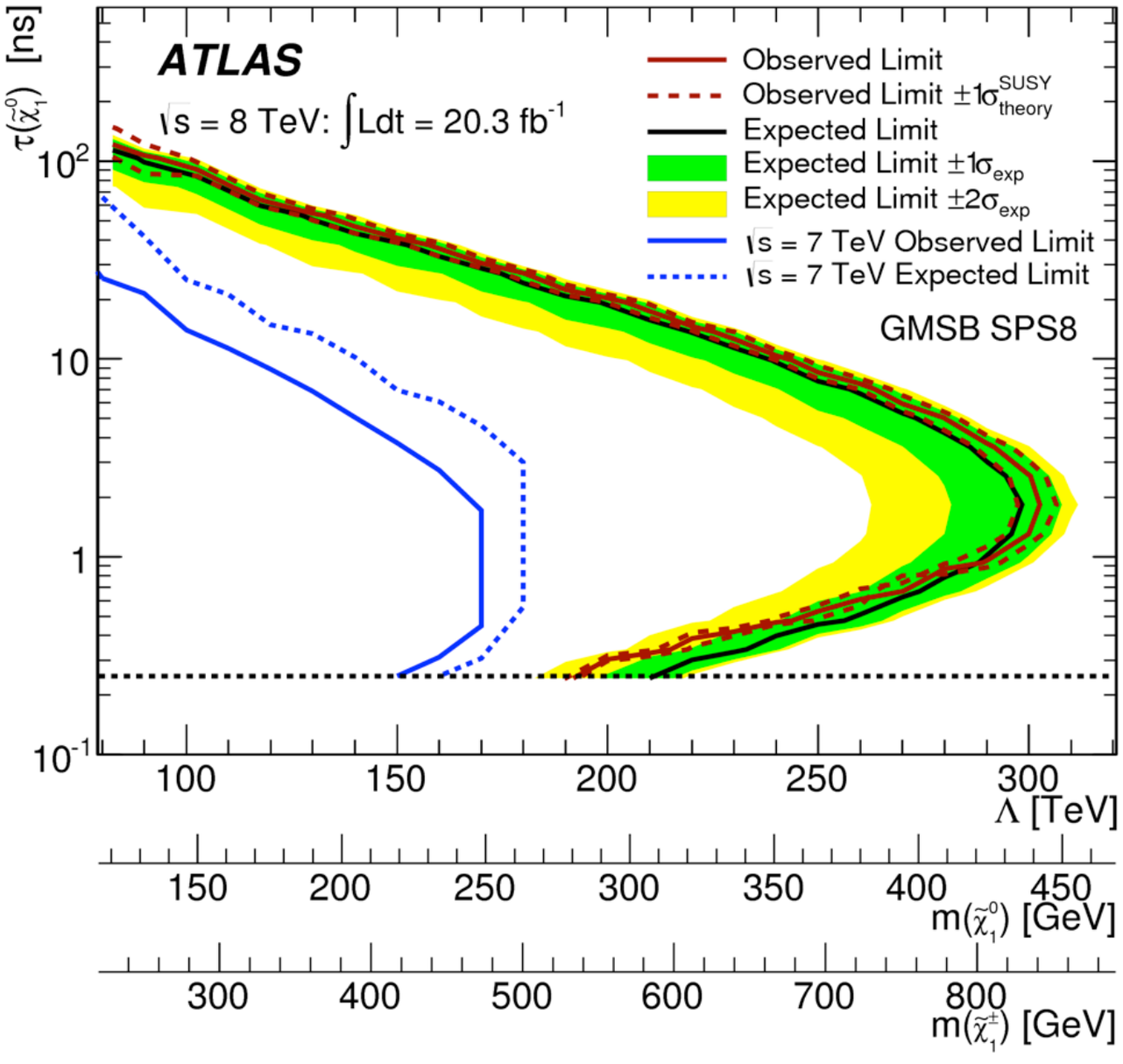
Δz of photon



arrival time of photon at ECAL (t_γ)

Use of both variables greatly improves the sensitivity

ATLAS limits stronger than CMS due its LAr ECAL's ability to reconstruct photon's direction.



arxiv 1409.5542

Some other LLP searches

that are not covered in this talk

- **Search for decays of stopped LLP** [CMS EPJC 75 (2015) 151] [ATLAS Phys. Rev. D 88, 112003 (2013)]
  - gluino, stop, sbottom (R-hadron) : Low kinetic energy, come to rest within detector
- **LLP pair-produced, decays to ee/ μμ/ eμ**. [CMS PRD 91 (2015) 052012] [CMS Phys. Rev. Lett. 114 no. 6, (2015) 061801] [ATLAS Phys. Rev. D 92, 072004 (2015)]
  - Displaced di-lepton vertex.
- **LLP pair produced, decays to di-jet** [CMS PRD 91 (2015) 012007] [ATLAS Phys. Rev. D 92, 072004 (2015)]
  - Displaced di-jet vertex
- **LLP decaying to lepton-jets** [ATLAS arxiv1409.0746]
  - Low mass dark-photon decays to collimated e/μ/pions

...and some other theoretical models that predicts LLP

Hidden Valley Scenarios

Stealth-SUSY

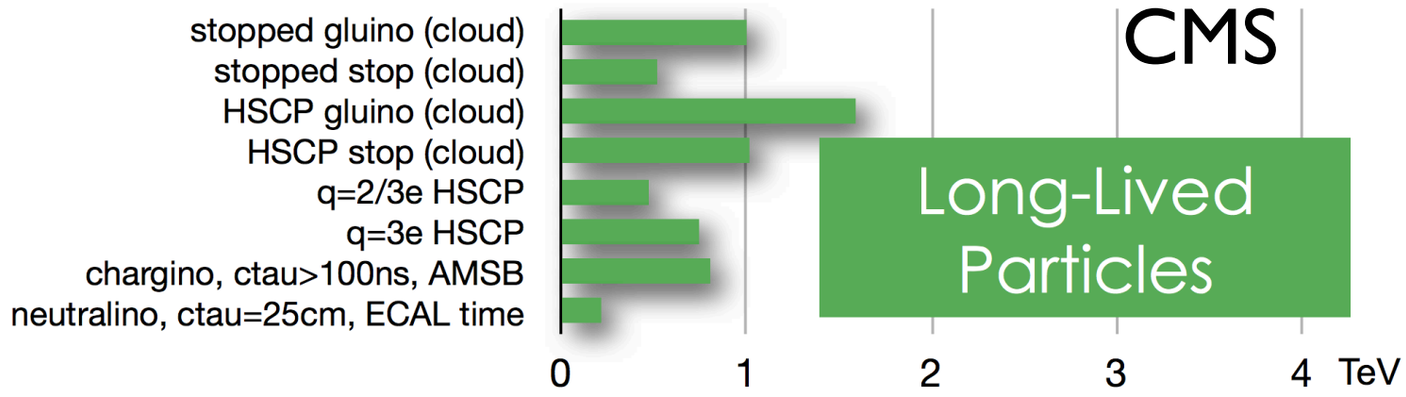
SUSY with very weak R-parity violation

.....

Summary

- Both ATLAS and CMS have made great effort to search for LLP. Complementary way to search for Dark-Matter.
- Wide range of analyses, looking for many different signatures, and often using the detector in interesting and "non-standard" ways.
- Various models used for interpretation. No sign of new physics so far.
- Limits are put on these new models : best limits till now.
- Stay tuned for 2016 data !

Thank You !



Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$ 495 GeV
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 850 GeV
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 1.54 TeV
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0 \to \tilde{\tau}(\tilde{e},\tilde{\mu}) + \tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV
	GMSB, $\tilde{\chi}_1^0 \to \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 440 GeV
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV

ATLAS

Extra Slides

HSCP search, CMS, 13 TeV

Hadron-like

Gluino and Stop signal sample generated : 300-2600 GeV
Gluinos are generated under the high squark mass (10 TeV) assumption.
PYTHIA v8.153 with the default tune CUETP8M1 is used

Lepton-like

Particle mass spectrum and decay table are produced with the program ISASUGRA version 7.69.
Parameter Λ is varied from 31 to 160 TeV, with fixed parameters Nmes = 3, tanβ = 10, μ > 0,
Cgrav = 10000, and Mmes/Λ = 2. The large value of Cgrav results in a long-lived stau.
The produced SUSY mass spectrum is input to PYTHIA v6.4 with Z2star tune

$$I_h = \left(\frac{1}{N} \sum_i^N c_i^{-2} \right)^{-1/2}$$

ci -> charge per unit path length in the sensitive part of the silicon detector of the i-th track measurement.

$$I_{as} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{i=1}^{N} \left[P_i \times \left(P_i - \frac{2i-1}{2N} \right)^2 \right] \right)$$

used to reject bkg

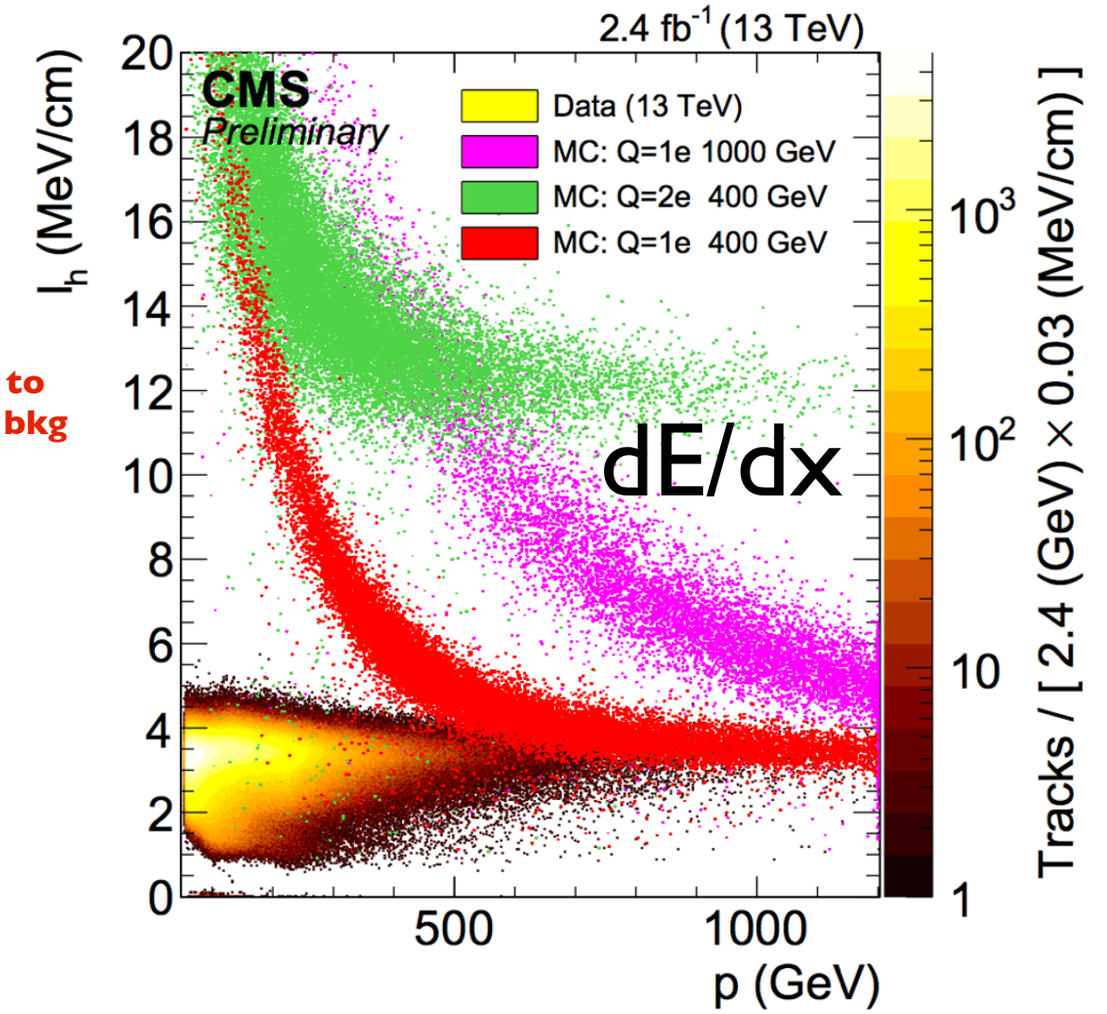
N : number of measurements in the silicon-tracker
Pi : probability for a mip to produce a charge smaller or equal to that of the i–th measurement

$$I_h = K \frac{m^2}{p^2} + C.$$

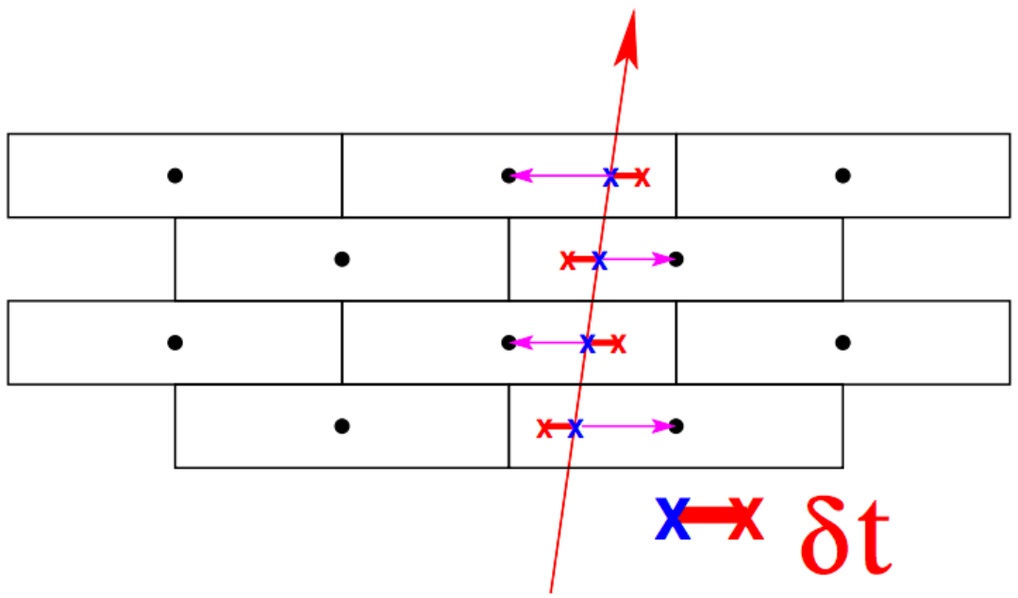
Mass

→ assumes |Q| = 1e particles

K = 2.535 ± 0.001 MeV cm−1 and C = 3.339 ± 0.001 MeV cm−1



HSCP search, CMS, 13 TeV



time-of-flight

$$\beta^{-1} = 1 + \frac{c\delta_t}{L}$$

Trigger : High-pT muon trigger OR high PF MET trigger

ETmiss trigger can recover some events in which the HSCP is charged in the tracker and neutral in the muon subsystem.

Offline Preselection

	Trk-only	Trk+TOF	
Track Type	Inner Track	Global Muon	
$\lvert\eta\rvert$	< 2.1		Reinforce trigger requirements
p_T (GeV)	> 55		
d_z and d_{xy} (cm)	< 0.5		Vertex association
σ_{p_T}/p_T	< 0.25		Track quality
Track χ^2/dof	< 5		
# Pixel Hits	> 1		
# Tracker Hits	> 7		
Frac. Valid Hits	> 0.8		
# dE/dx Measurements	> 5		dEdx quality
dE/dx Strip Shape Test	yes		
$\Sigma p_T^{trk}(\Delta R < 0.3)$ (GeV)	< 50		Loose Isolation (→ dEdx quality)
$E_{cal}(\Delta R < 0.3)/p$	< 0.3		
# TOF Measurements	/	> 7	TOF quality
$\sigma_{1/\beta}$	/	< 0.15	
$1/\beta$	/	> 1	

HSCP search, CMS, 13 TeV

	Selection cuts				Number of events $\sqrt{s} = 13$ TeV	
	p_T (GeV)	I_{as}	$1/\beta$	Mass (GeV)	Pred.	Obs.
Trk-only	> 65	> 0.3	-	> 0	28.8 ± 6.1	24
				> 100	17.8 ± 3.8	13
				> 200	2.6 ± 0.6	2
				> 300	0.53 ± 0.12	0
				> 400	0.16 ± 0.035	0
Trk+TOF	> 65	> 0.175	> 1.250	> 0	17.9 ± 3.6	13
				> 100	4.1 ± 0.8	3
				> 200	0.60 ± 0.12	0
				> 300	0.12 ± 0.024	0

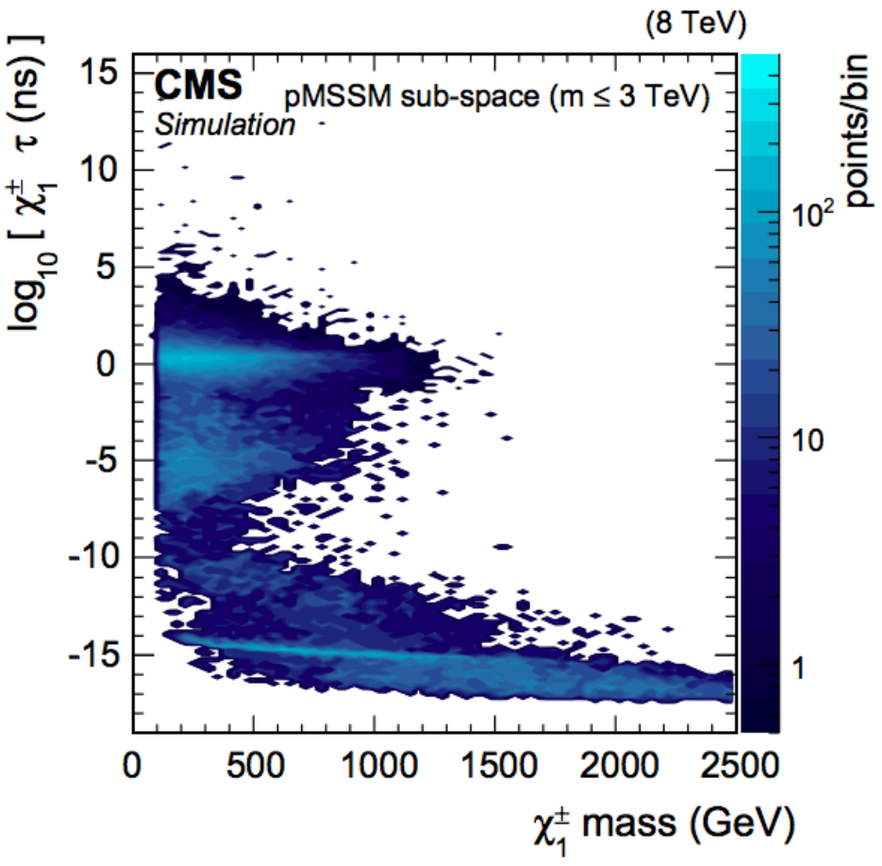
Gluino Signal Eff ~ 2% - 26%

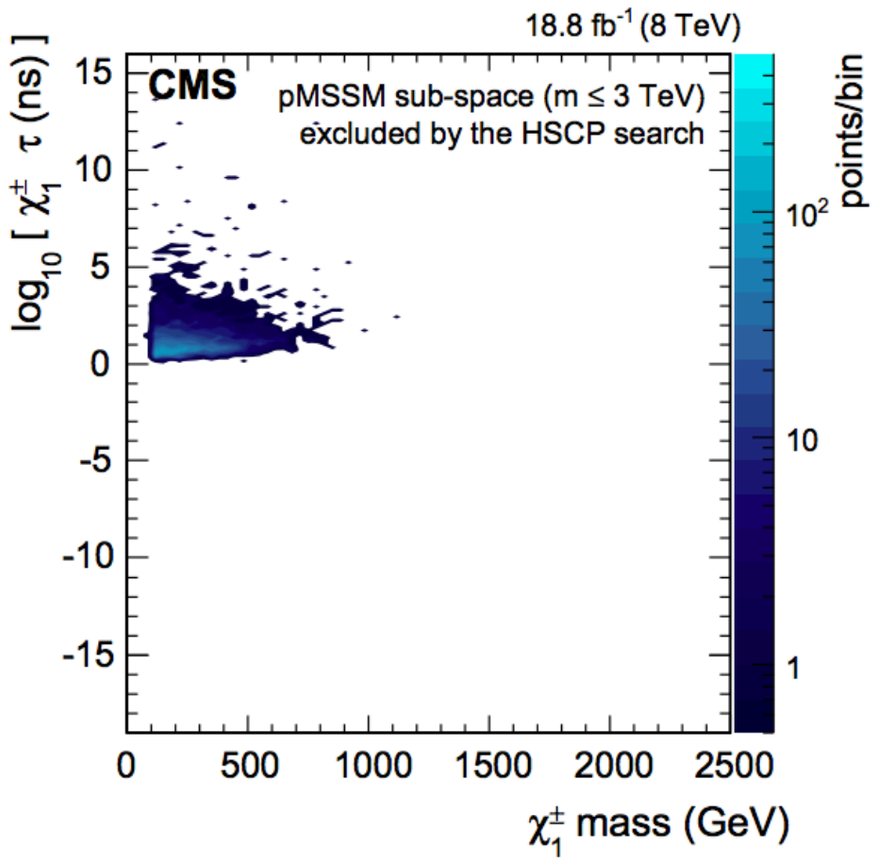
Gluino :
Mass 400 GeV, xs=95 pb
Mass 2400 GeV, xs=0.00013 pb

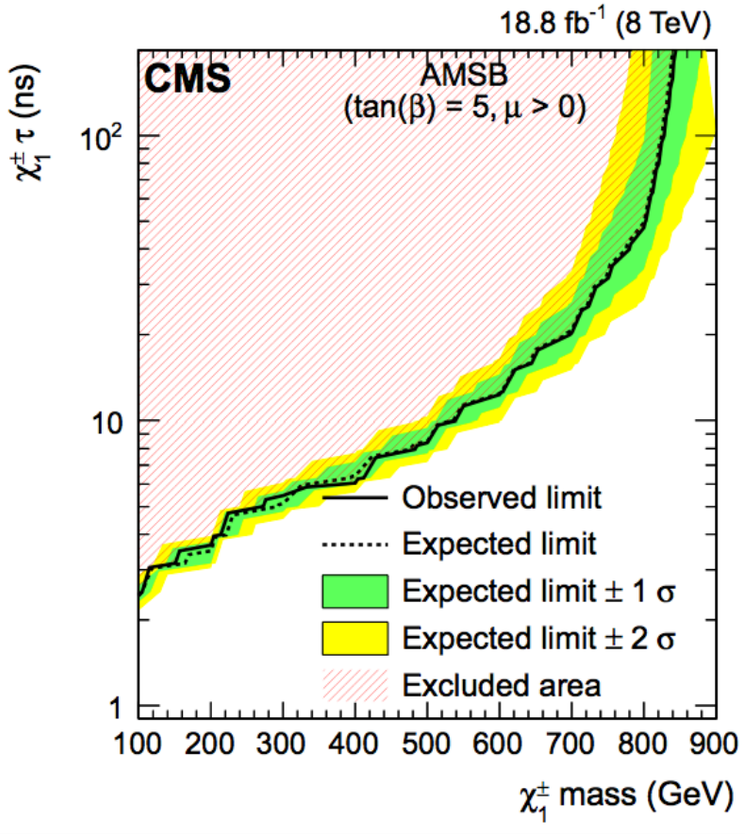
Stop
Mass 200 GeV, xs=61 pb
Mass 2200 GeV, xs=6.0E-06 pb

HSCP search, CMS, 8 TeV

Constraints on the pMSSM, AMSB model and on other models from the search of HSCP







Reinterpretation

Table 3 The pMSSM parameter space

$-3 \le M_1, M_2 \le 3$ TeV
$0 \le M_3 \le 3$ TeV
$-3 \le \mu \le 3$ TeV
$0 \le m_A \le 3$ TeV
$2 \le \tan\beta \le 60$
$0 \le \tilde{Q}_{1,2}, \tilde{Q}_3 \le 3$ TeV
$0 \le \tilde{U}_{1,2}, \tilde{U}_3 \le 3$ TeV
$0 \le \tilde{D}_{1,2}, \tilde{D}_3 \le 3$ TeV
$0 \le \tilde{L}_{1,2}, \tilde{L}_3 \le 3$ TeV
$0 \le \tilde{E}_{1,2}, \tilde{E}_3 \le 3$ TeV
$-7 \le A_t, A_b, A_\tau \le 7$ TeV

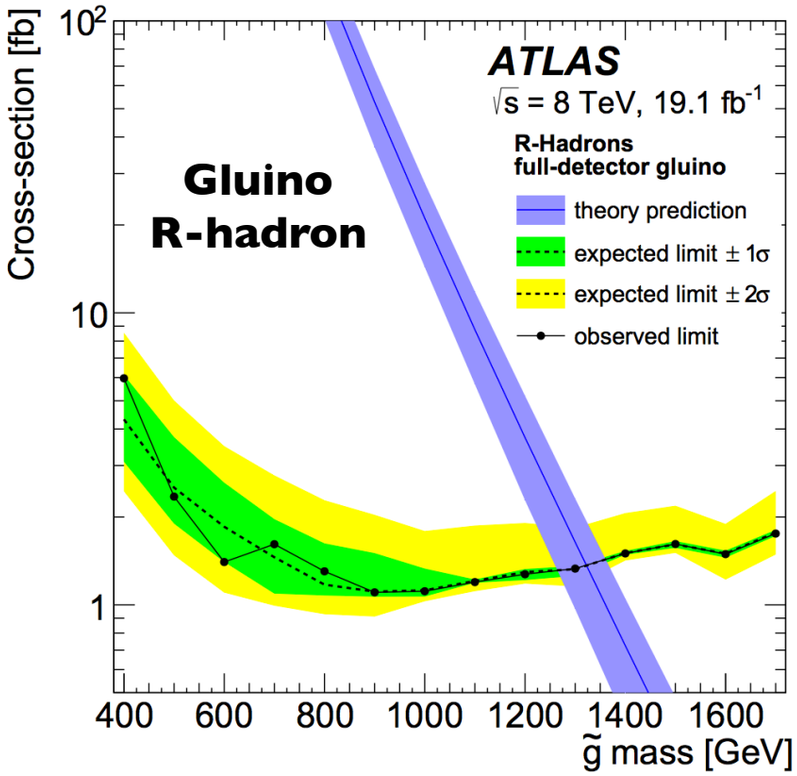
R-hadron and stau search in ATLAS

Results

8 TeV
19.1 fb-1

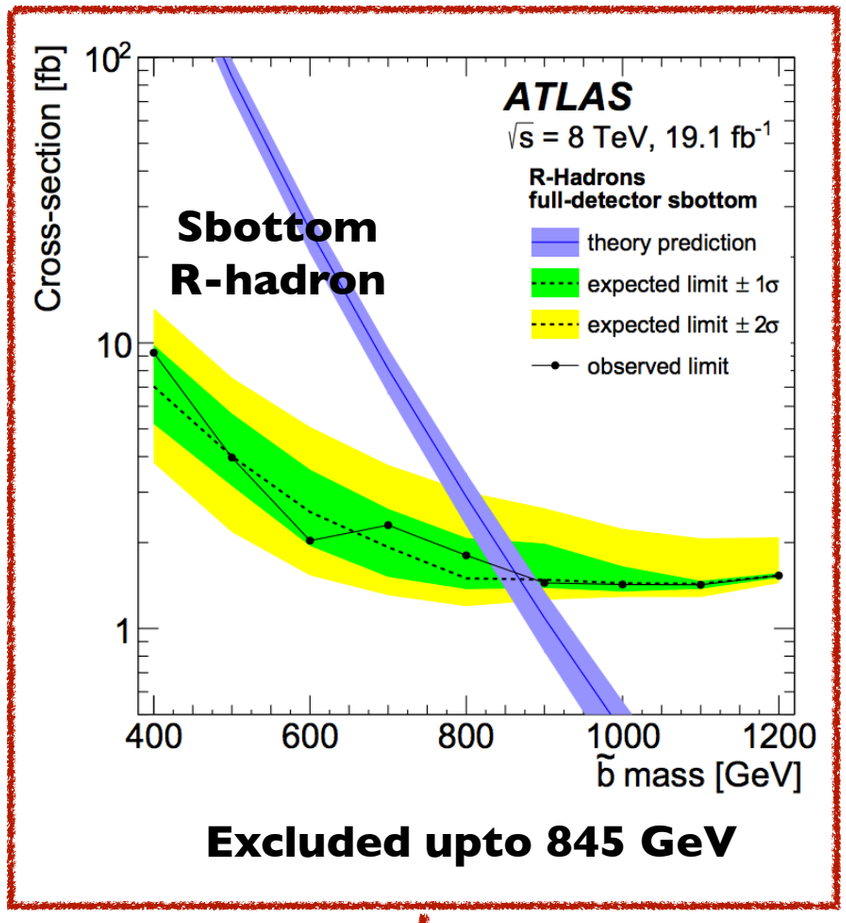
JHEP 01 (2015) 068

Theoretical interpretation : Split-SUSY / GMSB



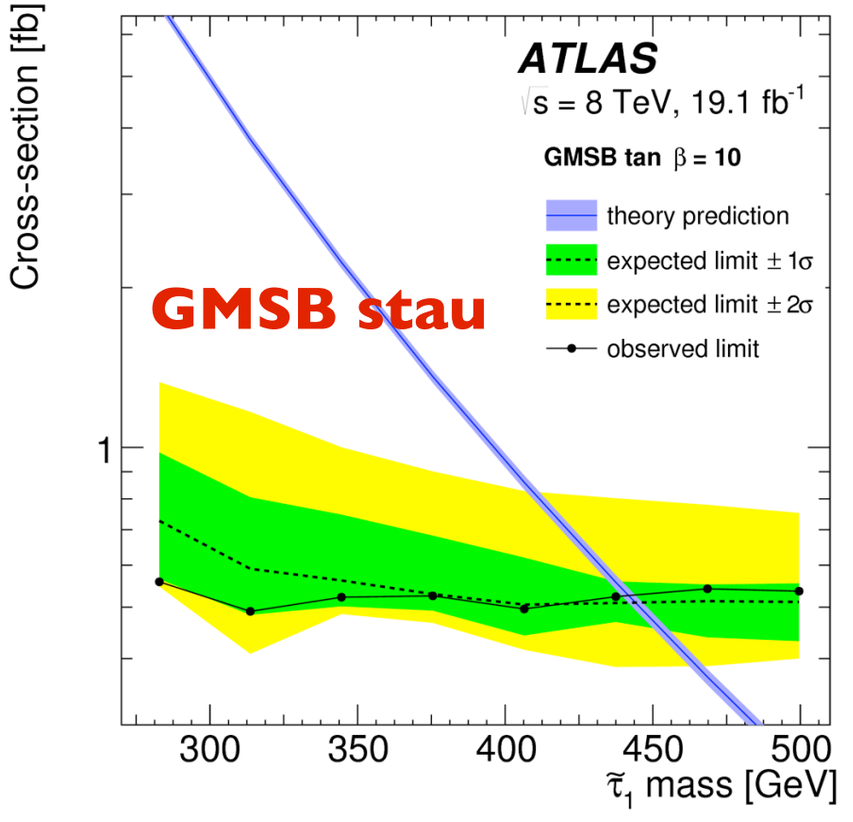
Excluded upto 1270 GeV

f=0.1



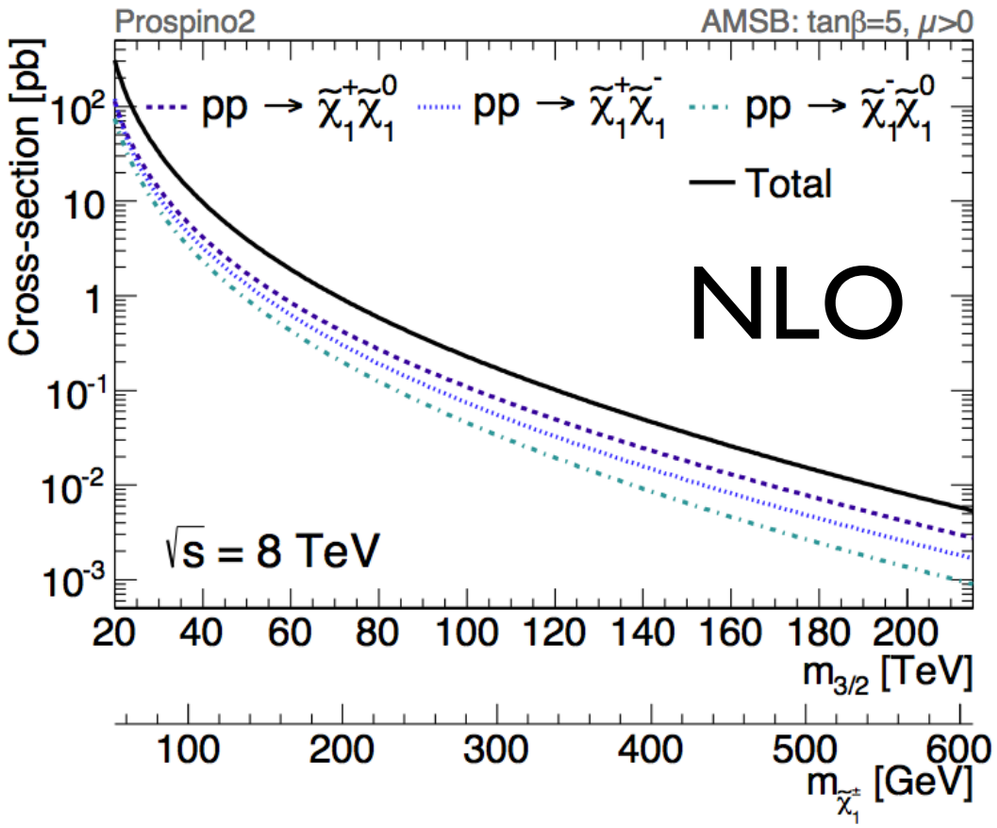
Excluded upto 845 GeV

(Not searched in CMS)



Excluded upto 440 GeV

Chargino search (Disappering track !) 8 TeV ATLAS



Pair-production of chargino or chargino-neutralino associated production

Large value of 1 TeV is used for m0 in order to prevent the appearance of a tachyonic slepton.

The SUSY mass spectrum and the decay tables are calculated with the Isasusy from Isajet v7.80. The corresponding MC signal samples are produced using Herwig++ 2.5.2 with CTEQ6L1 parton distribution functions.

TABLE II. Summary of systematic uncertainties [%] on the expected number of signal events for $m_{\tilde{\chi}_1^\pm} = 200$ GeV and 300 GeV.

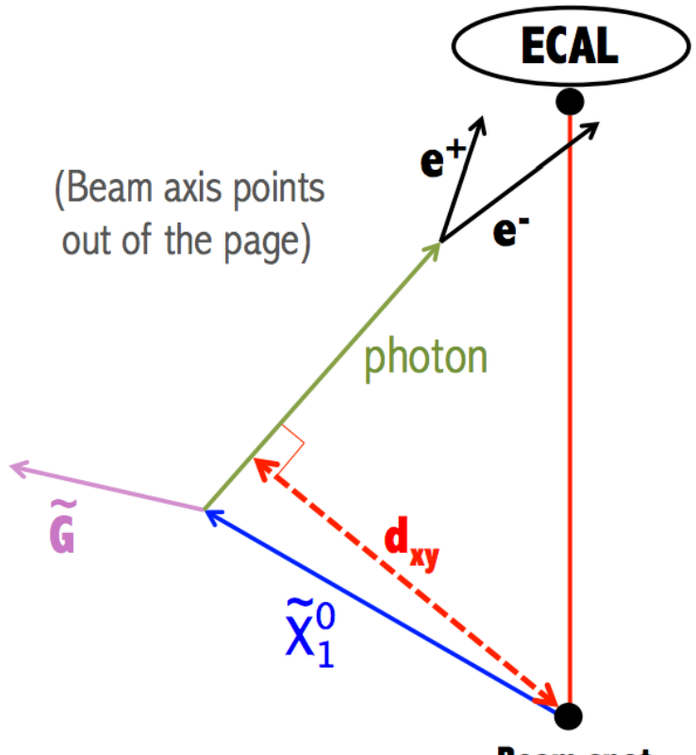
	200 GeV	300 GeV
(Theoretical uncertainty)		
Cross-section	6.4	6.8
(Uncertainty on the acceptance)		
Modeling of initial/final-state radiation	14.5	16.4
JES/JER	3.9	6.0
Trigger efficiency	4.5	4.5
Pile-up modeling	0.5	0.5
Track reconstruction efficiency	2.0	2.0
Luminosity	2.8	2.8
Sub-total	16.1	18.4

TABLE I. Summary of selection requirements and data reduction for data and expected signal events ($m_{\tilde{\chi}_1^\pm} = 200$ GeV, $\tau_{\tilde{\chi}_1^\pm} = 0.2$ ns). The signal selection efficiencies are also shown in parentheses. Signal efficiencies are low at the first stage due to the trigger based on a jet from initial-state radiation.

Selection requirement	Observed events	Expected signal MC events (efficiency [%])
Quality requirements and trigger	20479553	1873 (8.8)
Jet cleaning	18627508	1867 (8.8)
Lepton veto	12485944	1827 (8.6)
Leading jet $p_{\mathrm{T}} > 90$ GeV	10308840	1571 (7.4)
$E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV	6113773	1484 (7.0)
$\Delta\phi_{\mathrm{min}}^{\text{jet-}E_{\mathrm{T}}^{\mathrm{miss}}} > 1.5$	5604087	1444 (6.8)
High-p_{T} isolated track selection	34379	21.9 (0.10)
Disappearing-track selection	3256	18.4 (0.087)

Simulation uses the PYTHIA 6.4

Neutralino search (Photon+MET) 8 TeV CMS



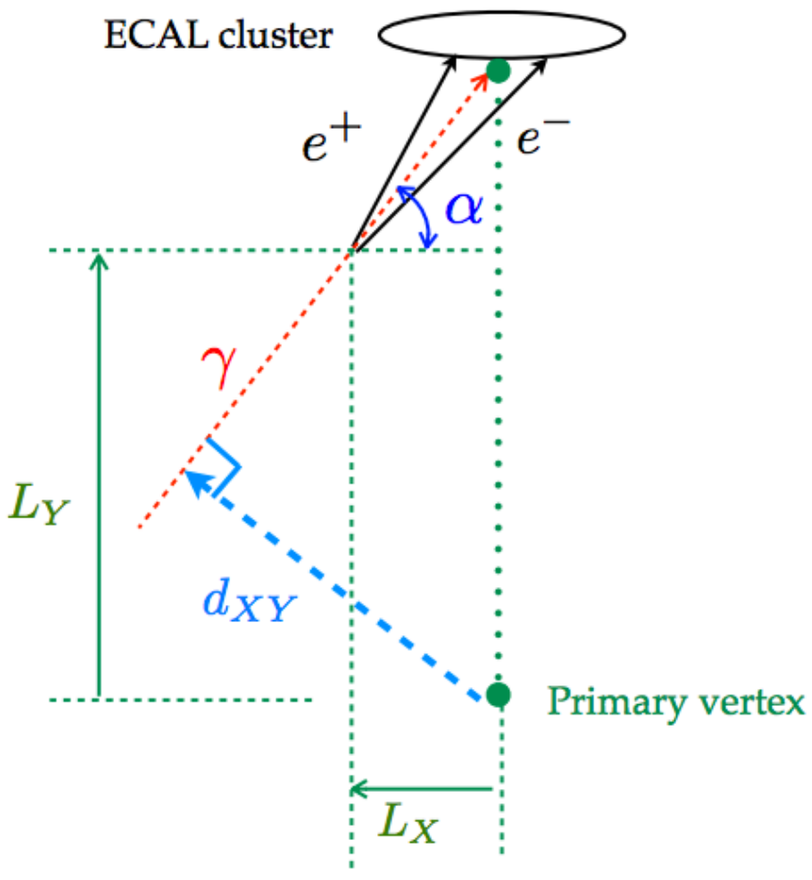


Table 2: Cutflow for signal ($c\tau = 0.4$ cm and $c\tau = 20$ cm) and the expected SM backgrounds.

	GMSB (180, 0.4)	GMSB (180, 20)	SM bkg. estimate (CR1)	Data
All	285	285	-	5.21e+11
Preselection	182	176	-	7.34e+10
$E_T^{miss} > 60$	174	167	-	1.86e+09
Num. jets ≥ 2	102	98	-	4.55e+08
Num. phot. ≥ 2	41	41	-	1.42e+06
Num. conv. ≥ 1	5.0 ± 0.4	3.7 ± 0.8	3.5 ± 2.2	4

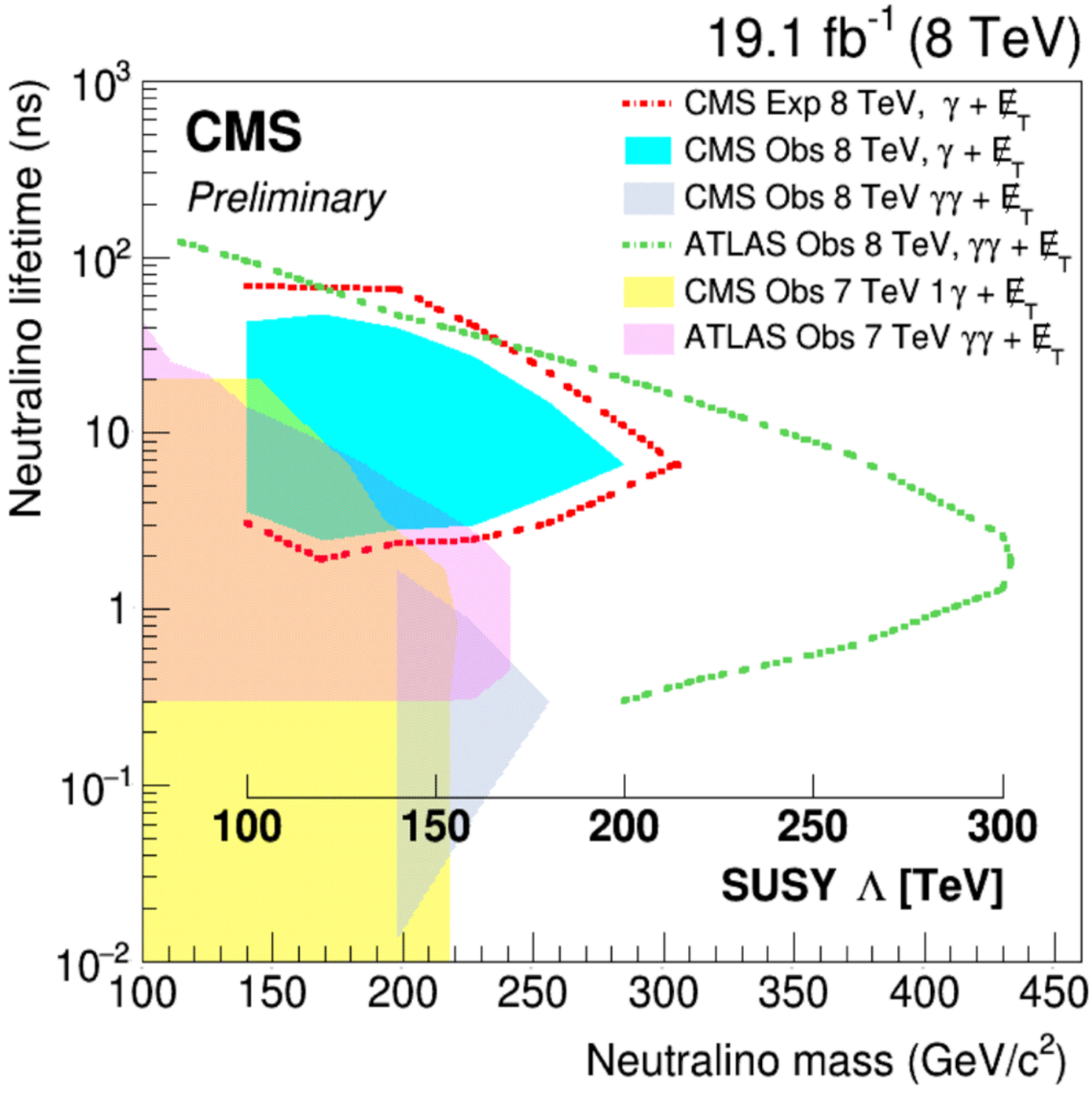
	Isolation pass	**Isolation reject**
MET < 30 GeV	CR1	CR2
MET > 60 GeV	Signal Region	CR3

Figure 4: Definition of the background control regions.

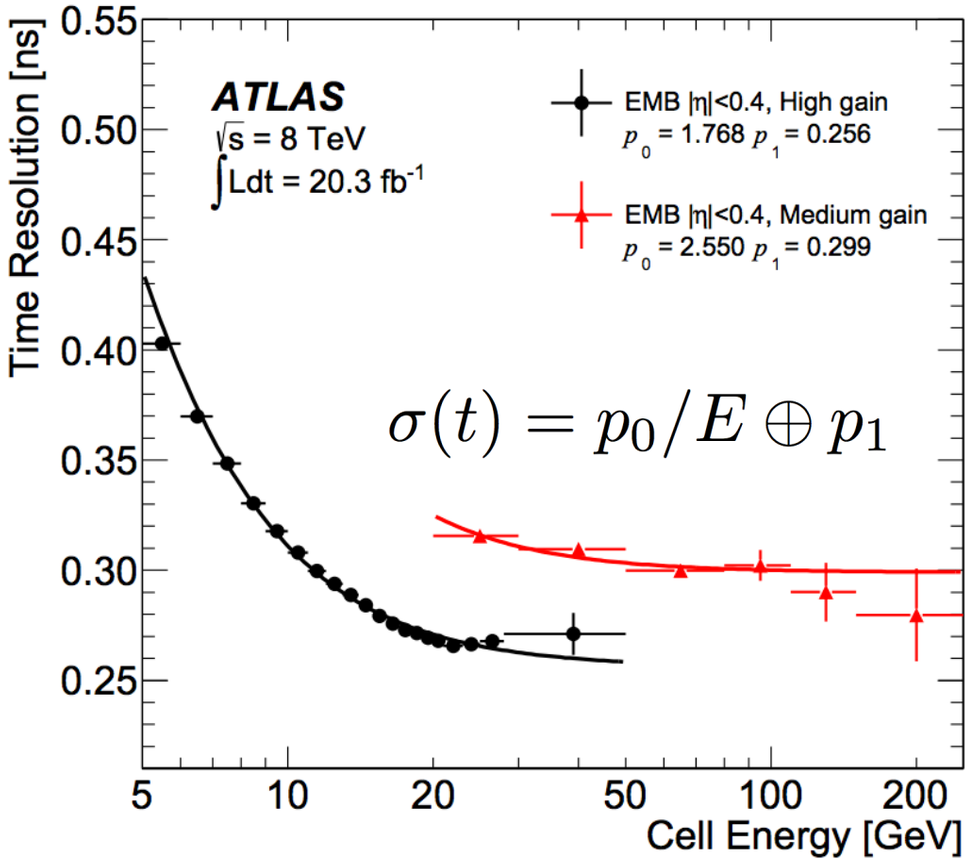
Table 1: Systematic uncertainties on the signal efficiency.

Source	Uncertainty (%)
Luminosity	2.6
Statistical	< 1
Jet energy scale	0.2
Photon energy scale	0.2–0.4
Conversion reconstruction eff.	7–45
Uncertainty at finite $\lvert d_{XY} \rvert$	40

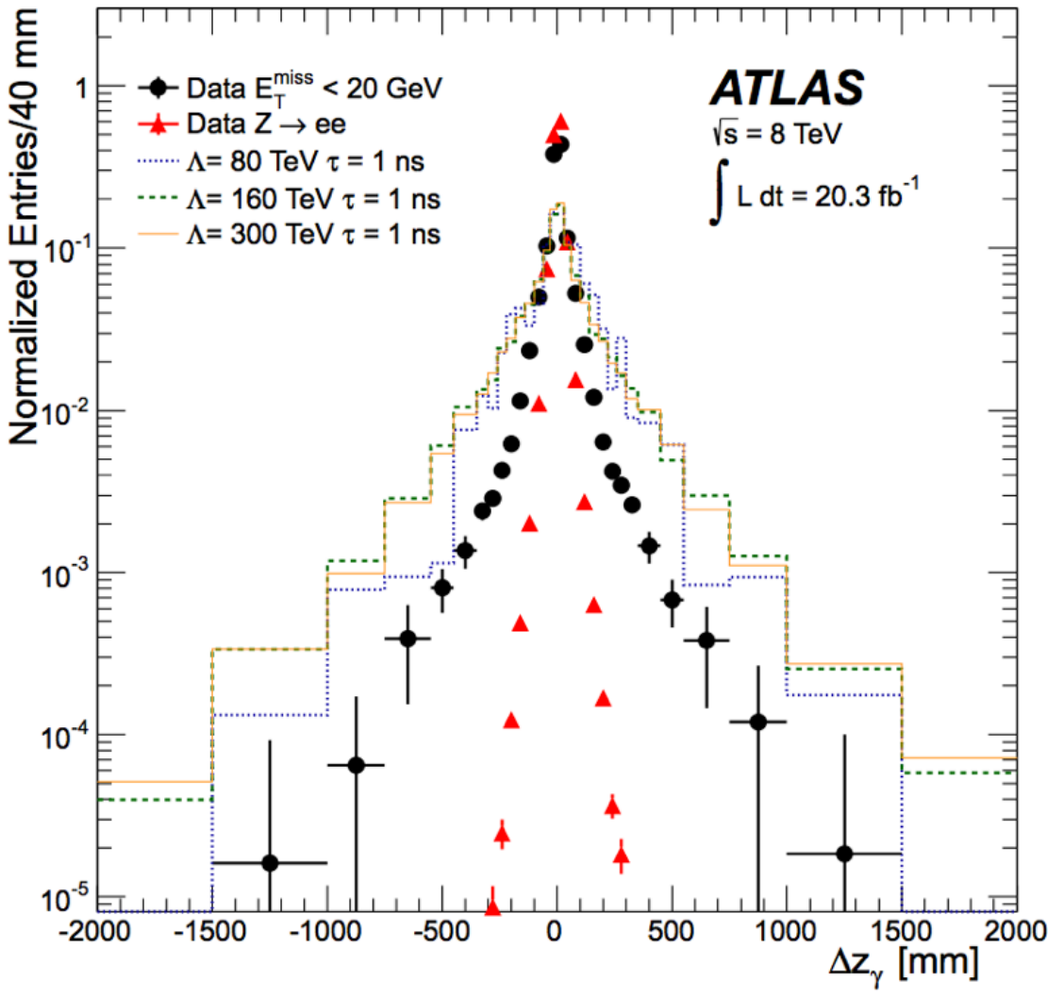
Neutralino search (Photon+MET) 8 TeV CMS

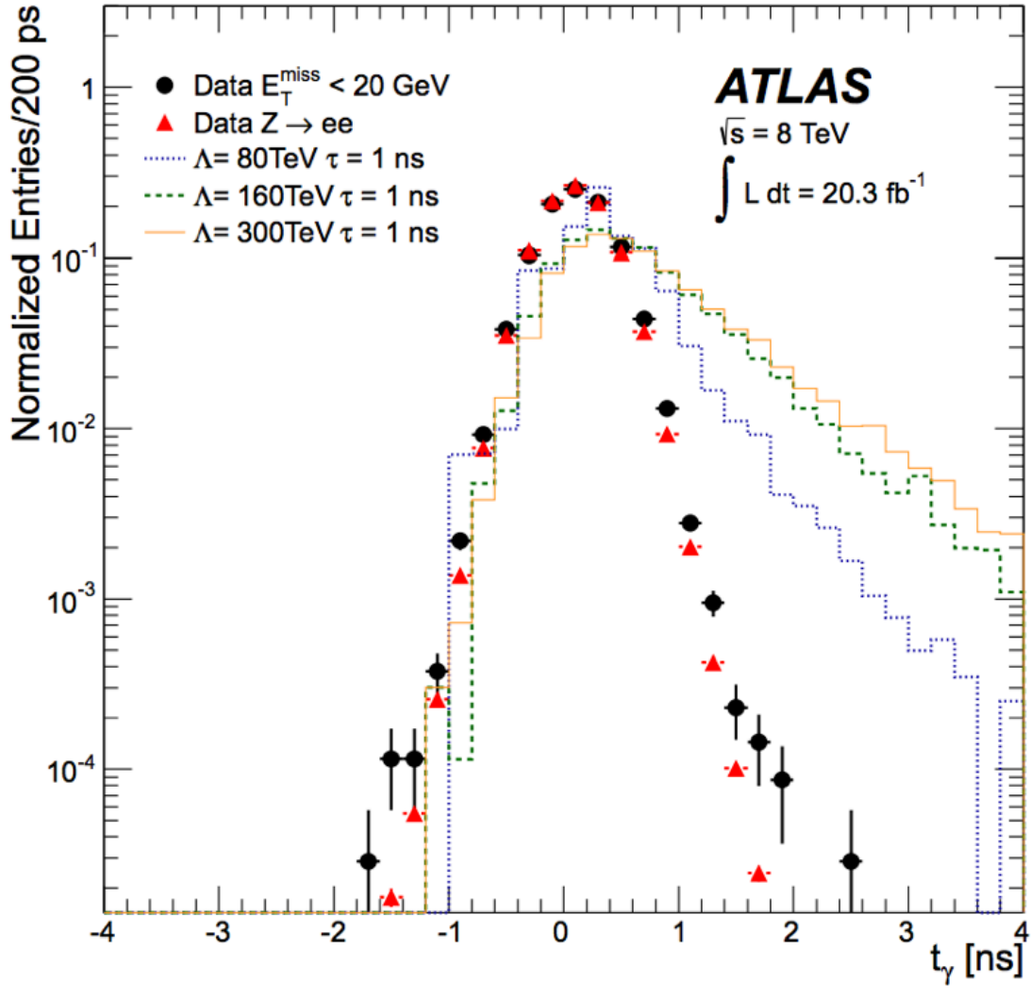


Neutralino search (Photon+MET) 8 TeV ATLAS



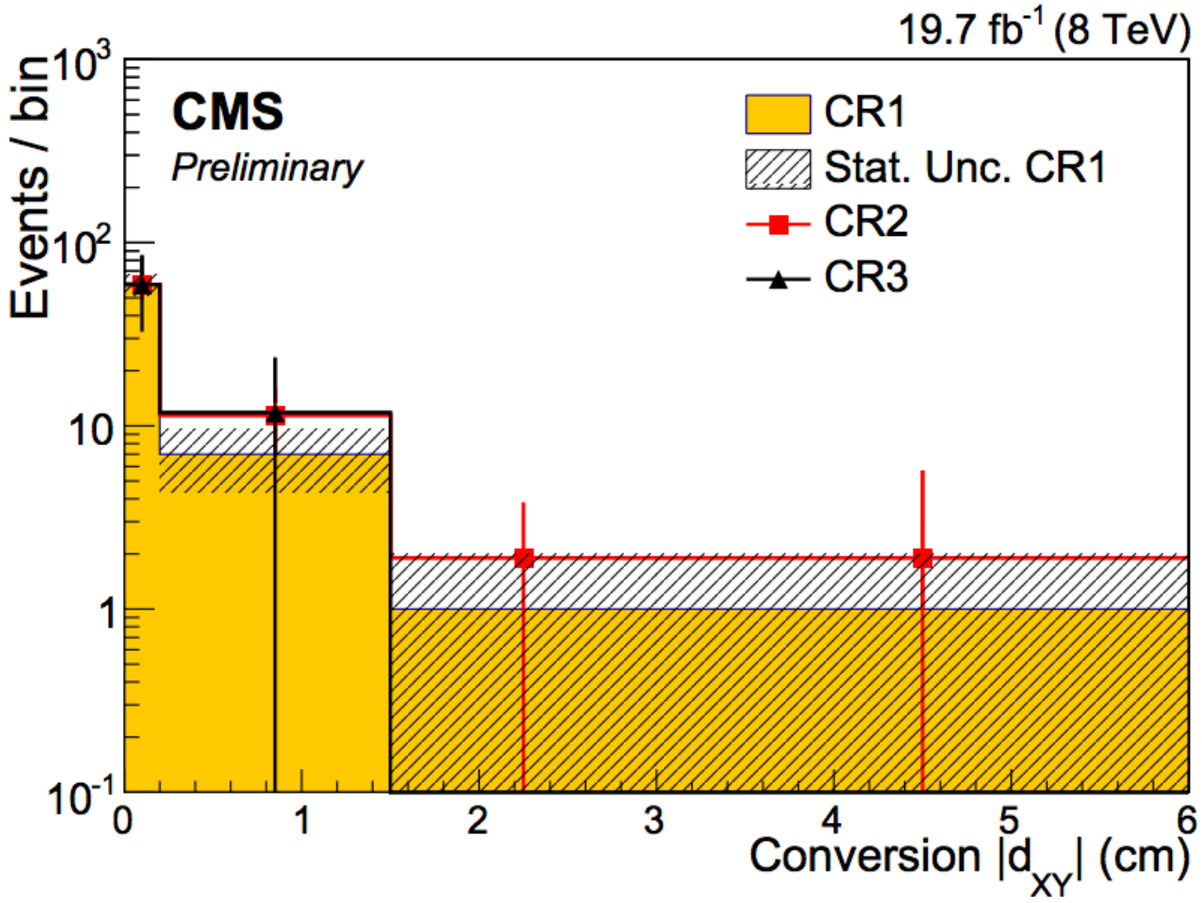
τ	Signal acceptance times efficiency [%]		
[ns]	$\Lambda = 80$ TeV	$\Lambda = 160$ TeV	$\Lambda = 320$ TeV
0.5	8.4 ± 0.6	30 ± 1	46 ± 2
2	5.1 ± 0.3	21 ± 0.2	33.0 ± 0.3
6	1.7 ± 0.1	7.3 ± 0.1	12.5 ± 0.2
10	0.86 ± 0.03	3.71 ± 0.06	6.45 ± 0.09
40	0.089 ± 0.004	0.38 ± 0.01	0.70 ± 0.02
100	0.016 ± 0.001	0.070 ± 0.002	0.129 ± 0.004

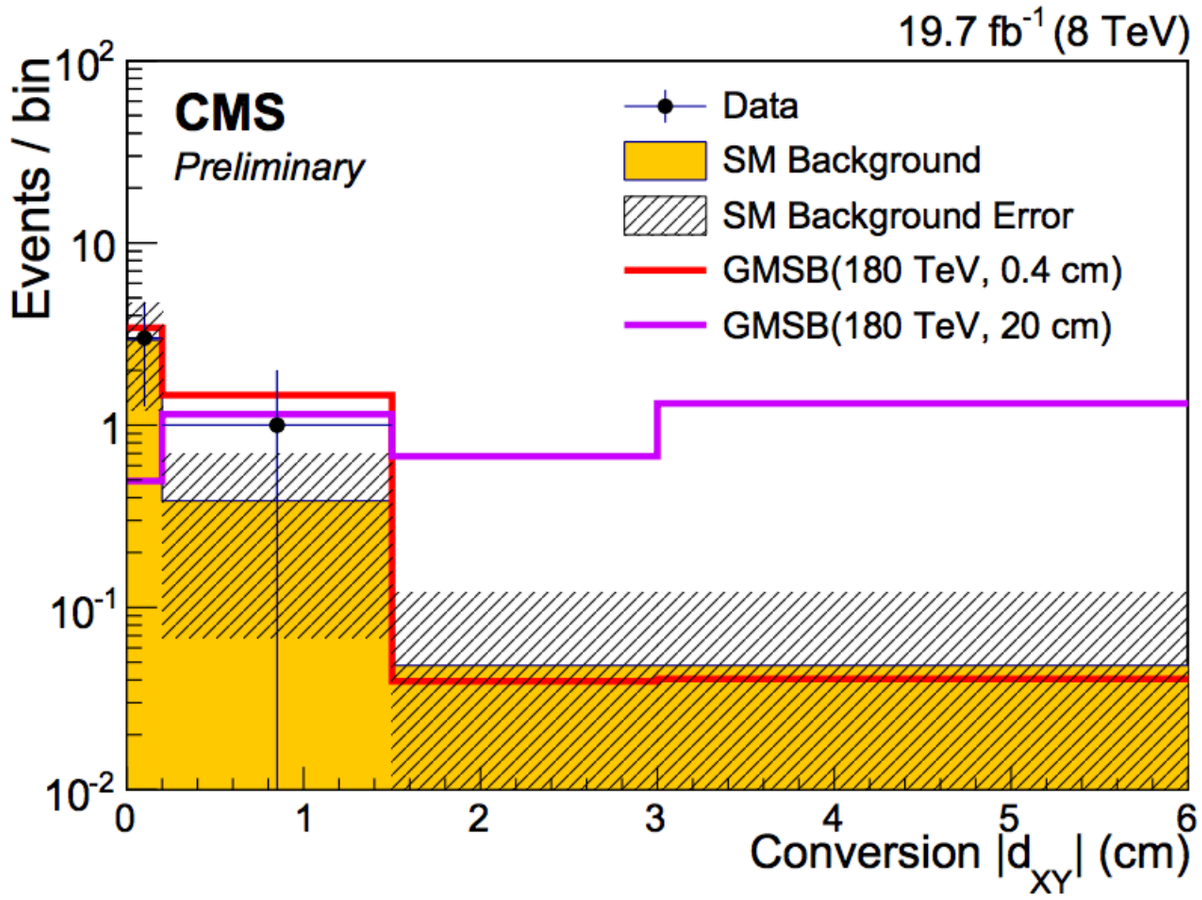




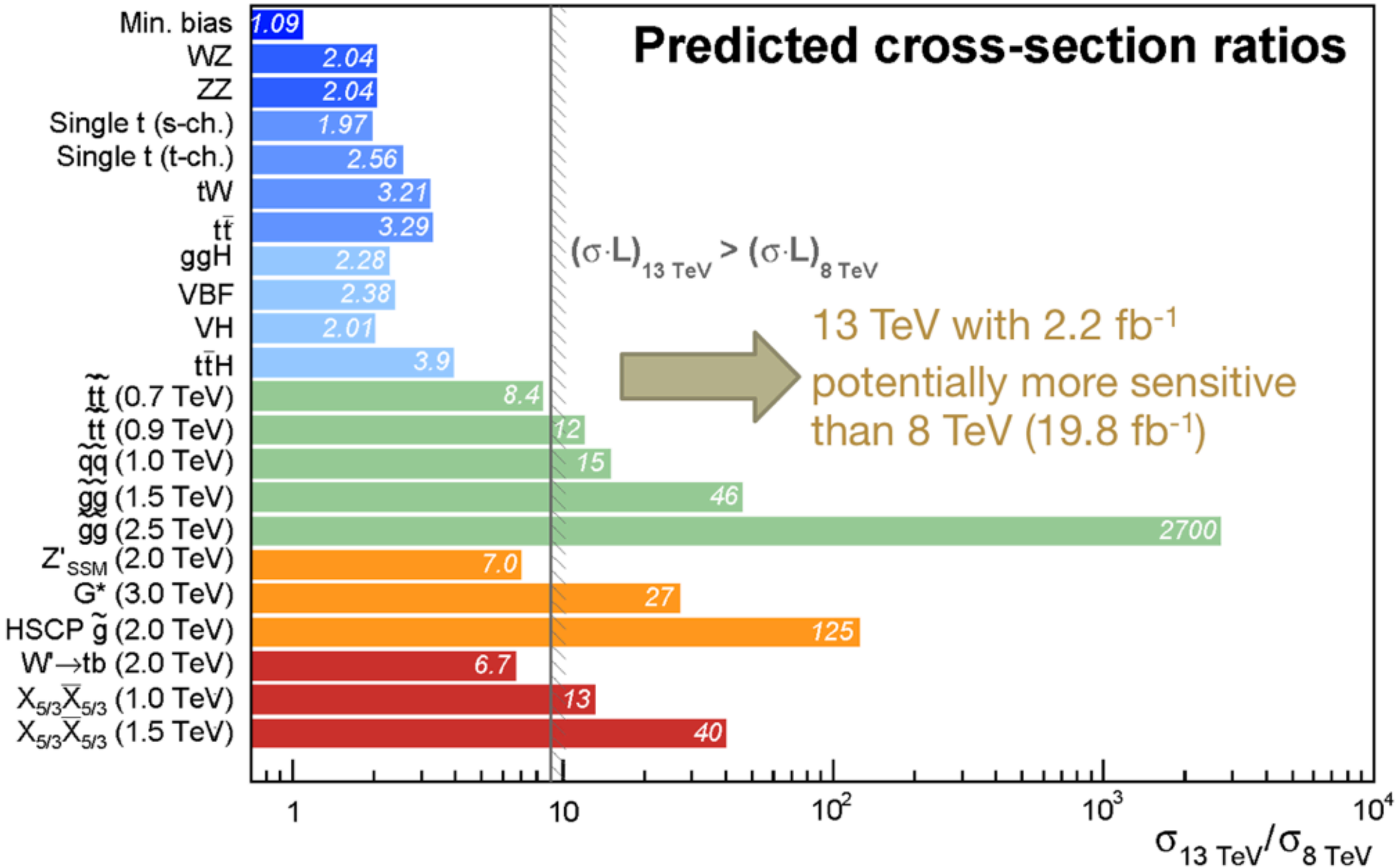
	Isolation pass	Isolation reject
MET < 30 GeV	CR1	CR2
MET > 60 GeV	Signal Region	CR3

Figure 4: Definition of the background control regions.





Reminder: increased reach @ 13 TeV



The Snowmass Points and Slopes: Benchmarks for SUSY Searches

SPS 7: GMSB scenario with $\tilde{\tau}$ NLSP

The NLSP in this GMSB scenario is the lighter stau, with allowed three body decays of right-handed selectrons and smuons into it. The decay of the NLSP into the Gravitino and the τ in this scenario can be chosen to be prompt, delayed or quasi-stable.

Point:

$$\Lambda = 40\,\mathrm{TeV}, \quad M_{\mathrm{mes}} = 80\,\mathrm{TeV}, \quad N_{\mathrm{mes}} = 3, \quad \tan\beta = 15, \quad \mu > 0.$$

Slope:

$$M_{\mathrm{mes}}/\Lambda = 2, \quad \Lambda \text{ varies.}$$

The point equals GMSB point 1 of the "Points d'Aix". The slope equals model line D.

SPS 8: GMSB scenario with neutralino NLSP

The NLSP in this scenario is the lightest neutralino. The second lightest neutralino has a significant branching ratio into h when kinematically allowed. The decay of the NLSP into the Gravitino (and a photon or a Z boson) in this scenario can be chosen to be prompt, delayed or quasi-stable.

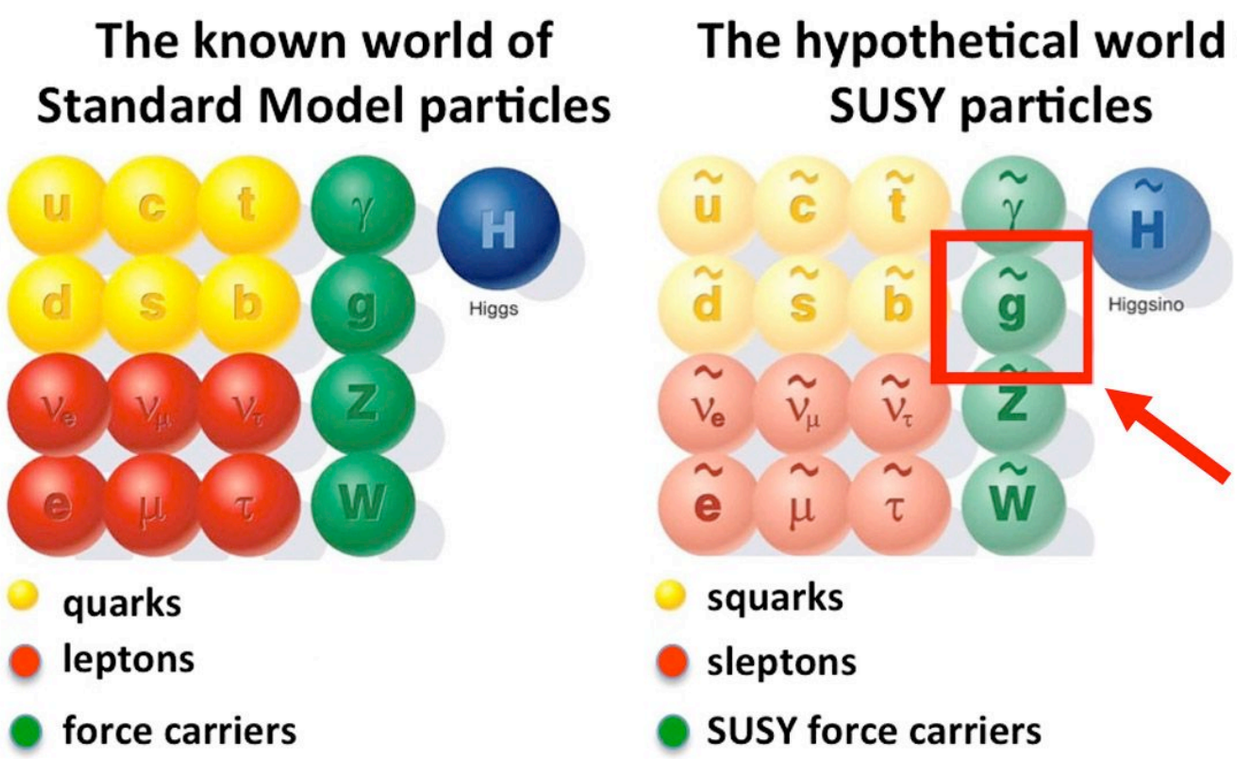
Point:

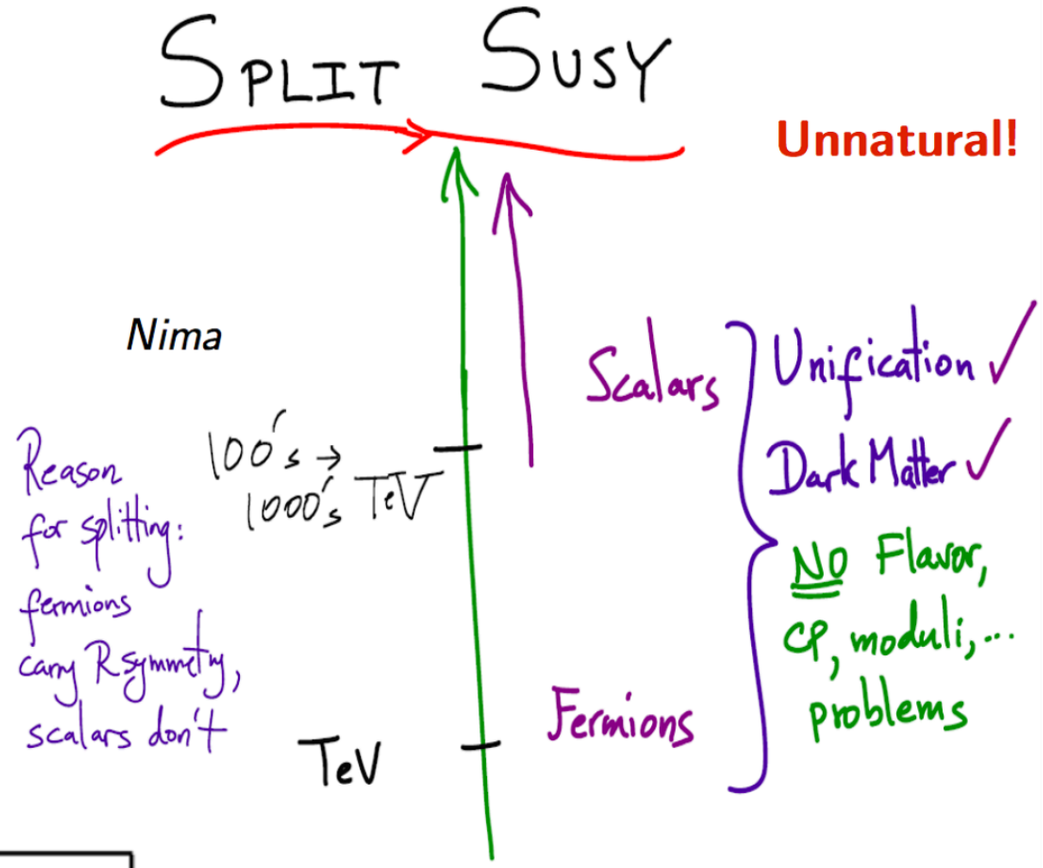
$$\Lambda = 100\,\mathrm{TeV}, \quad M_{\mathrm{mes}} = 200\,\mathrm{TeV}, \quad N_{\mathrm{mes}} = 1, \quad \tan\beta = 15, \quad \mu > 0.$$

Slope:

$$M_{\mathrm{mes}}/\Lambda = 2, \quad \Lambda \text{ varies.}$$

The point equals GMSB point 2 of the "Points d'Aix". The slope equals model line E.





Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	$+1$	$H_u^0 \;\; H_d^0 \;\; H_u^+ \;\; H_d^-$	$h^0 \;\; H^0 \;\; A^0 \;\; H^\pm$
squarks	0	-1	$\widetilde{u}_L \;\; \widetilde{u}_R \;\; \widetilde{d}_L \;\; \widetilde{d}_R$ $\widetilde{s}_L \;\; \widetilde{s}_R \;\; \widetilde{c}_L \;\; \widetilde{c}_R$ $\widetilde{t}_L \;\; \widetilde{t}_R \;\; \widetilde{b}_L \;\; \widetilde{b}_R$	(same) (same) $\widetilde{t}_1 \;\; \widetilde{t}_2 \;\; \widetilde{b}_1 \;\; \widetilde{b}_2$
sleptons	0	-1	$\widetilde{e}_L \;\; \widetilde{e}_R \;\; \widetilde{\nu}_e$ $\widetilde{\mu}_L \;\; \widetilde{\mu}_R \;\; \widetilde{\nu}_\mu$ $\widetilde{\tau}_L \;\; \widetilde{\tau}_R \;\; \widetilde{\nu}_\tau$	(same) (same) $\widetilde{\tau}_1 \;\; \widetilde{\tau}_2 \;\; \widetilde{\nu}_\tau$
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	$\widetilde{W}^\pm \;\; \widetilde{H}_u^+ \;\; \widetilde{H}_d^-$	$\widetilde{C}_1^\pm \;\; \widetilde{C}_2^\pm$
gluino	1/2	-1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	-1	$\widetilde{G}$	(same)

18.6 fb−1

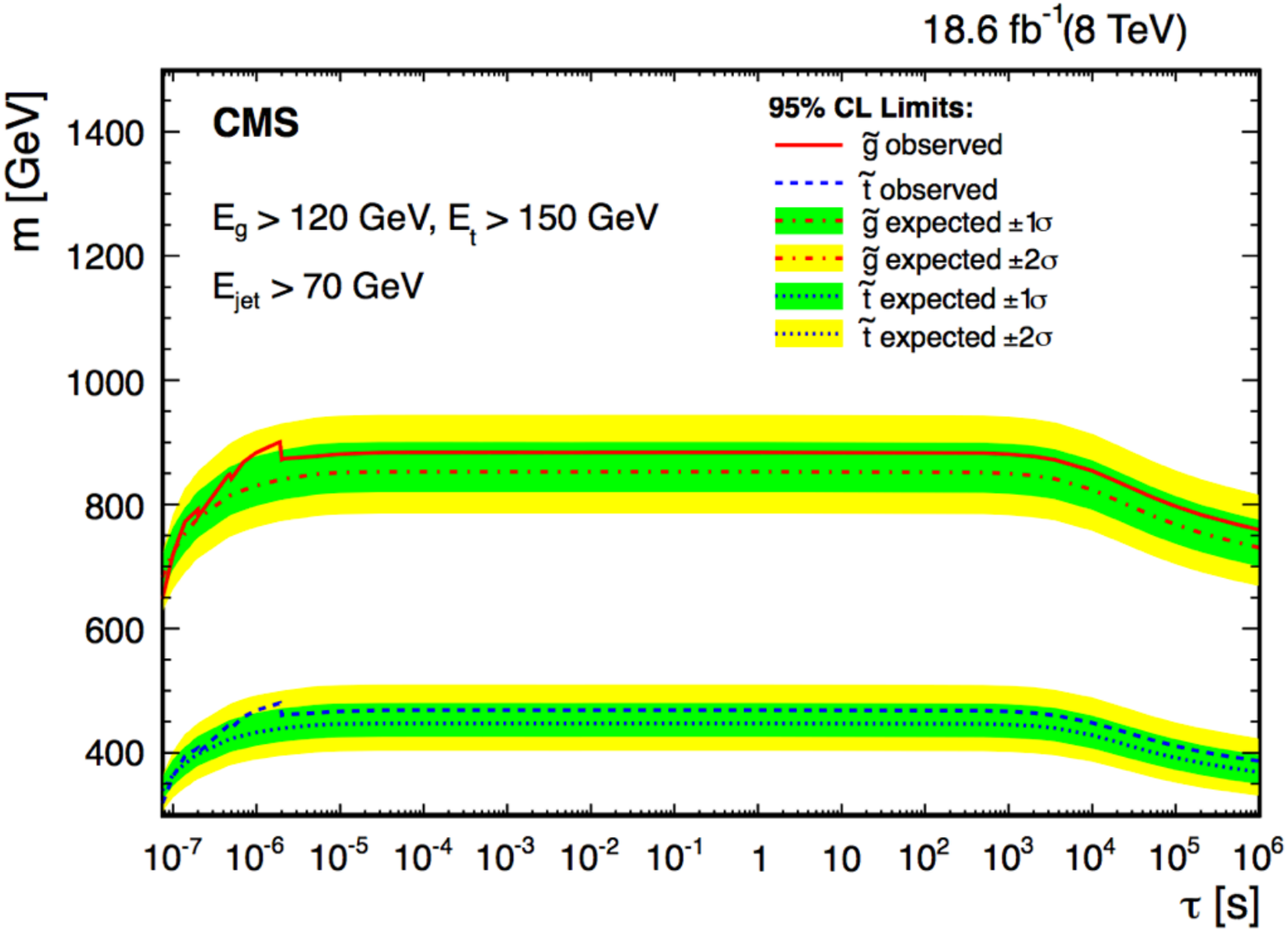
Search for decays of stopped LLP (8 TeV, CMS)

Signature : (Sufficiently jet-like) energy deposit in calorimeter appearing at times that are well separated from any p-p collisions.

- Critical velocity : 0.45c
- 281 hours of active dedicated-trigger
- Observed : 10 events. Expected : 13.2 +3.6 -2.5 events

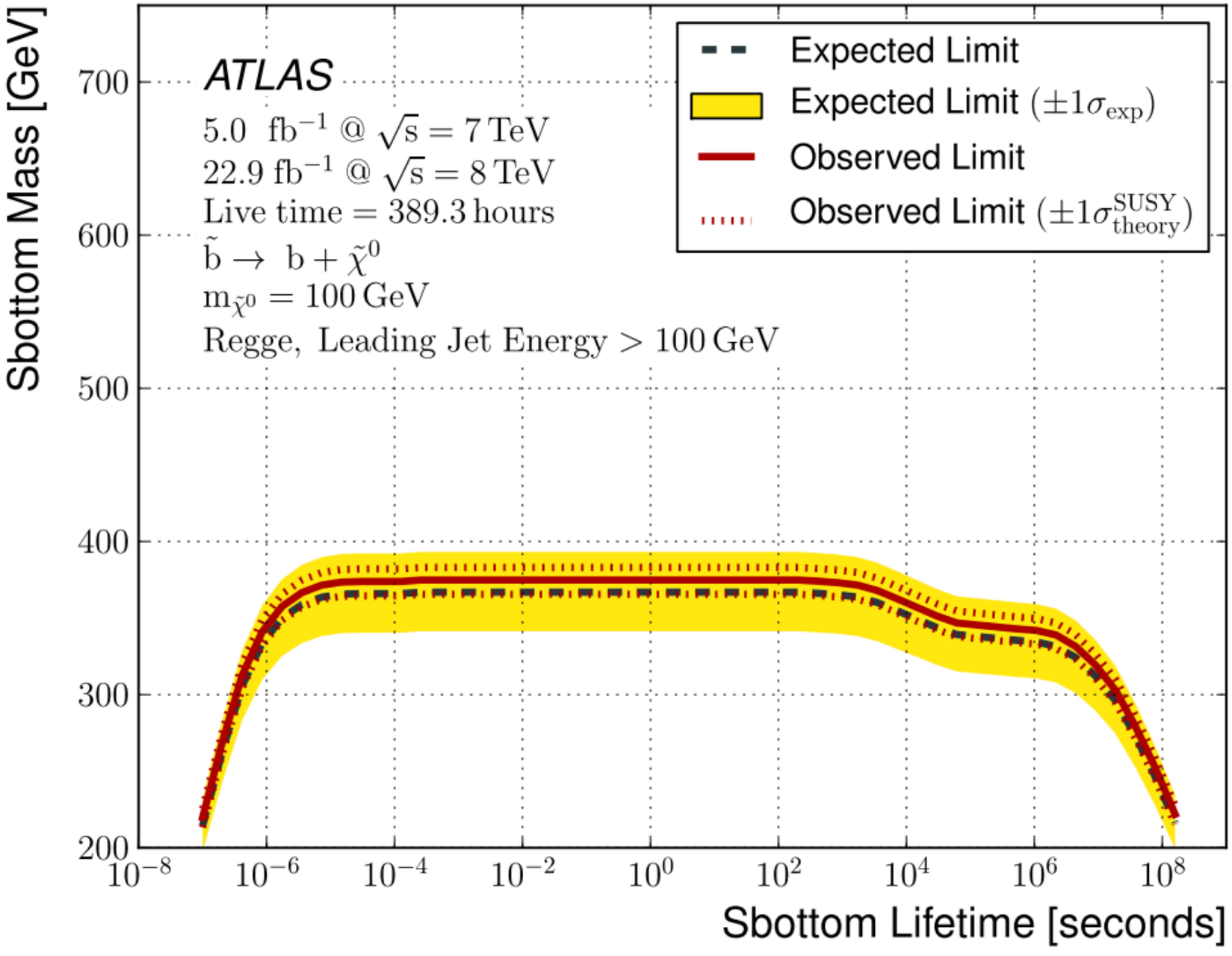
$\tilde{g} \rightarrow g\tilde{\chi}^0$

$\tilde{t} \rightarrow t\tilde{\chi}^0$



5.0 fb−1 + 22.9 fb-1

Search for decays of stopped LLP (7+8 TeV, ATLAS)



Selection criteria
Trigger
Leading jet $\lvert\eta\rvert < 1.2$
Number of jets < 6
Fractional $E_{\mathrm{T}}^{\mathrm{miss}} > 0.5$
Leading jet n90 > 3
Leading jet width > 0.04
Leading jet tile E frac. > 0.5
Leading jet energy > 50 GeV
Muon segment veto
Leading jet energy > 100 GeV
Leading jet energy > 300 GeV

LLP to ee/ μμ/ eμ

CMS

1)

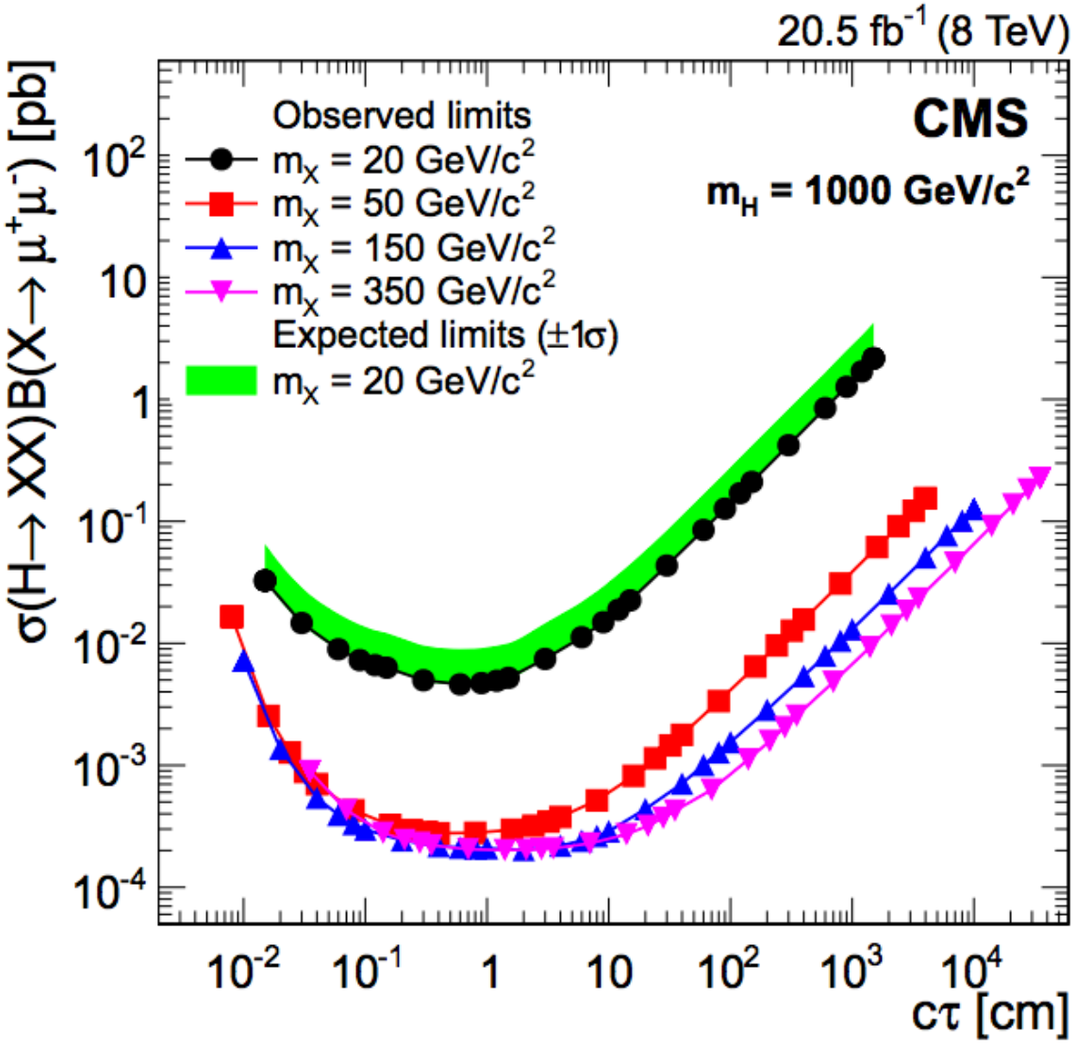
$gg \rightarrow H \rightarrow XX$

$X \rightarrow l^+ l^-$

2)

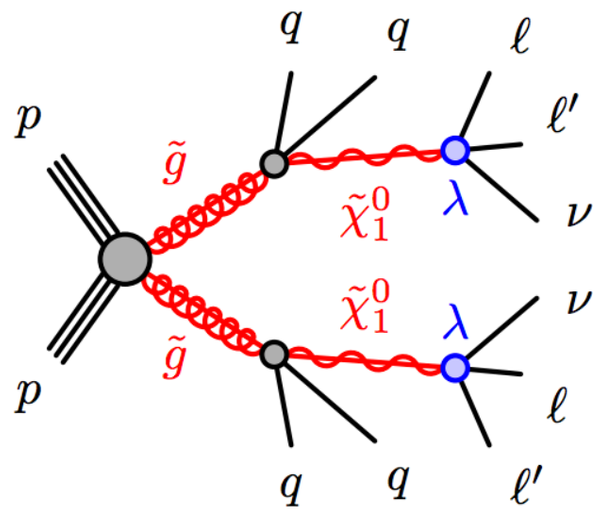
Pair-produced squark

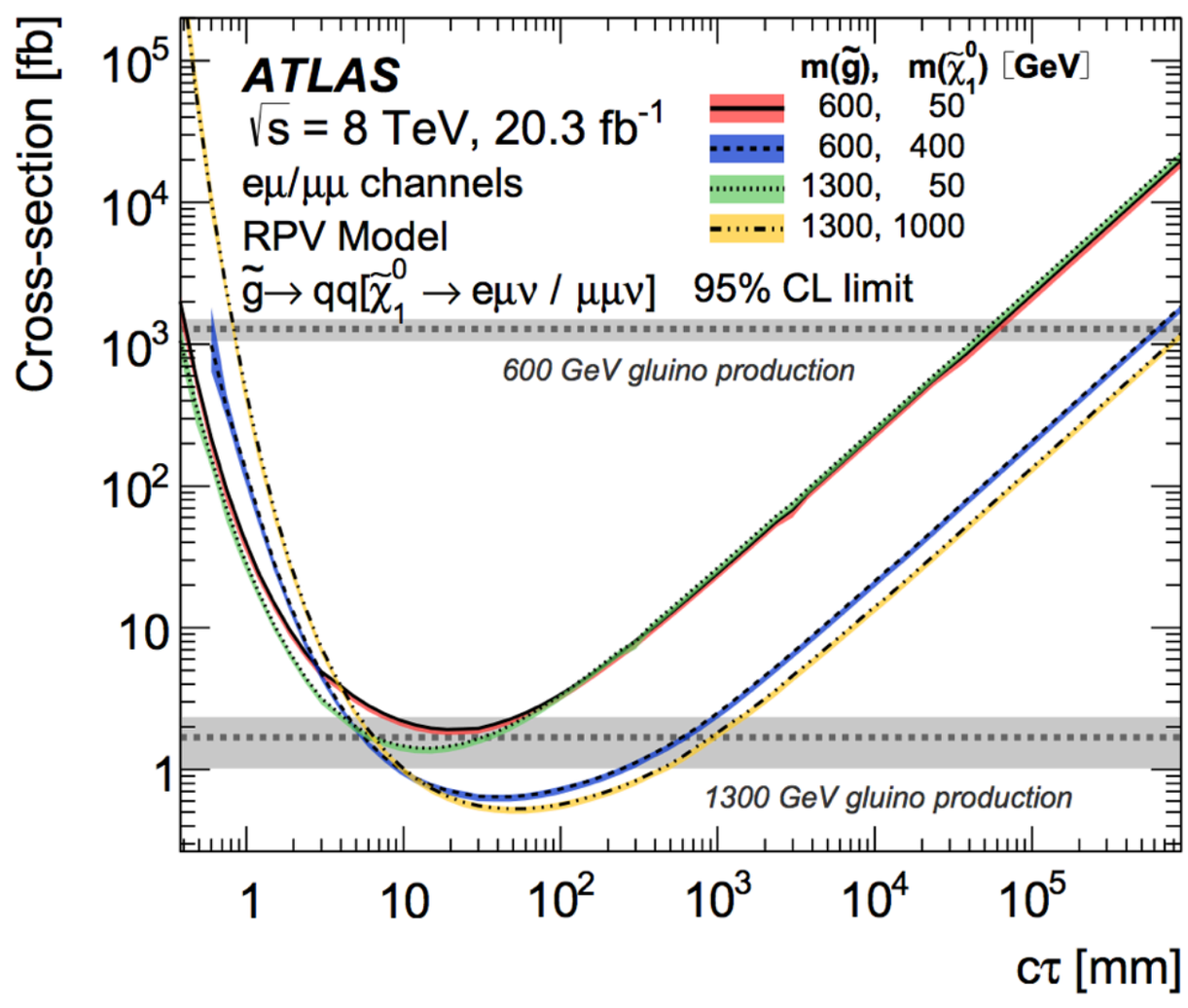
$\tilde{q} \rightarrow q\tilde{\chi}^0$, $\tilde{\chi}^0 \rightarrow \ell^+\ell^-\nu$



ATLAS

RPV SUSY





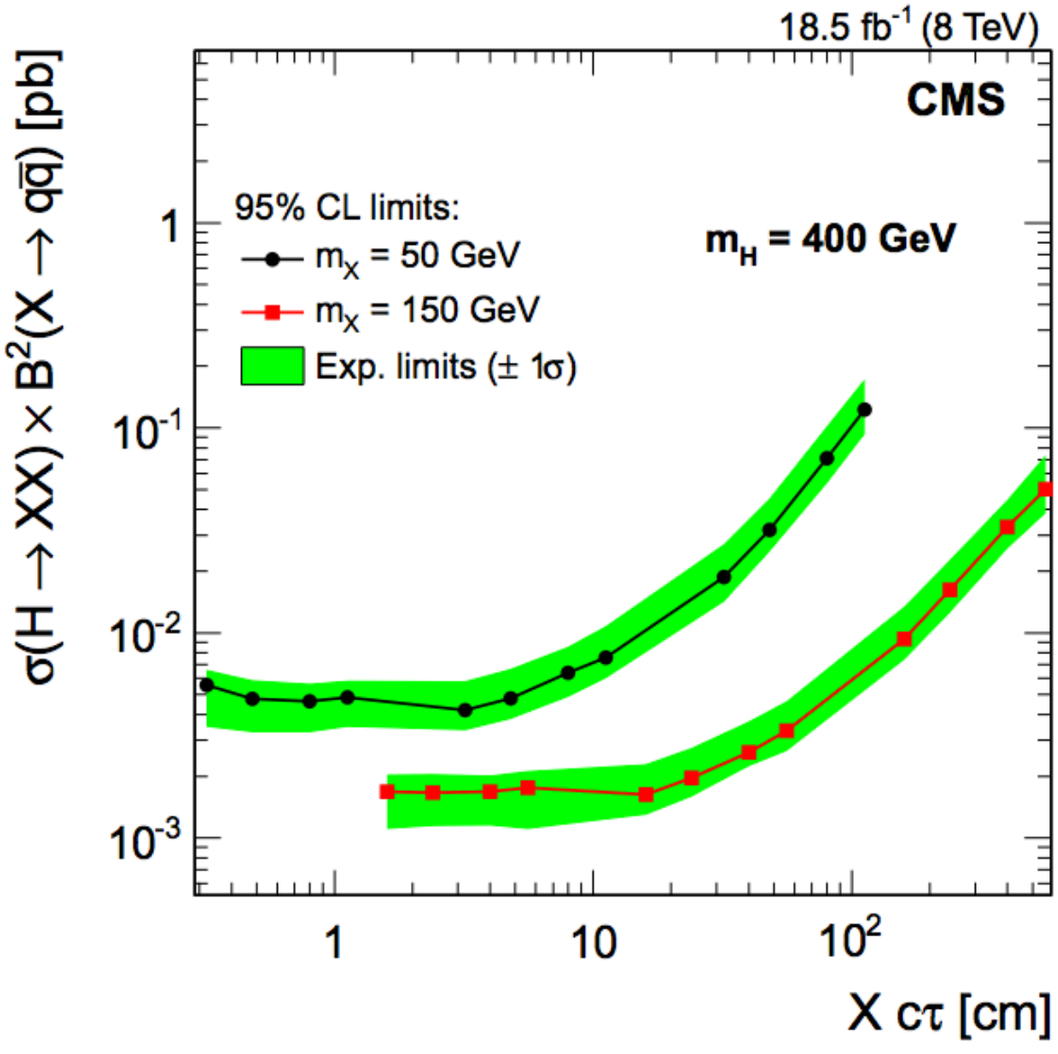
LLP to jets

CMS

1)
$gg \rightarrow H \rightarrow XX$
$X \rightarrow qq$

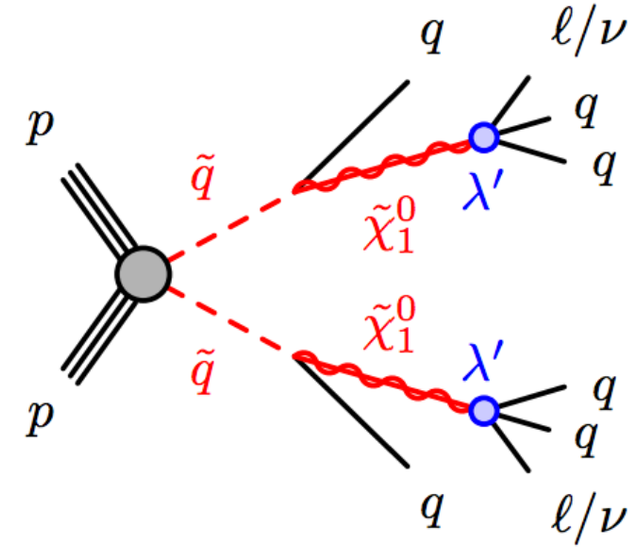
2)
Pair-produced squark

$\tilde{q} \rightarrow q\tilde{\chi}_1^0 \rightarrow qq'\bar{q}''\mu$

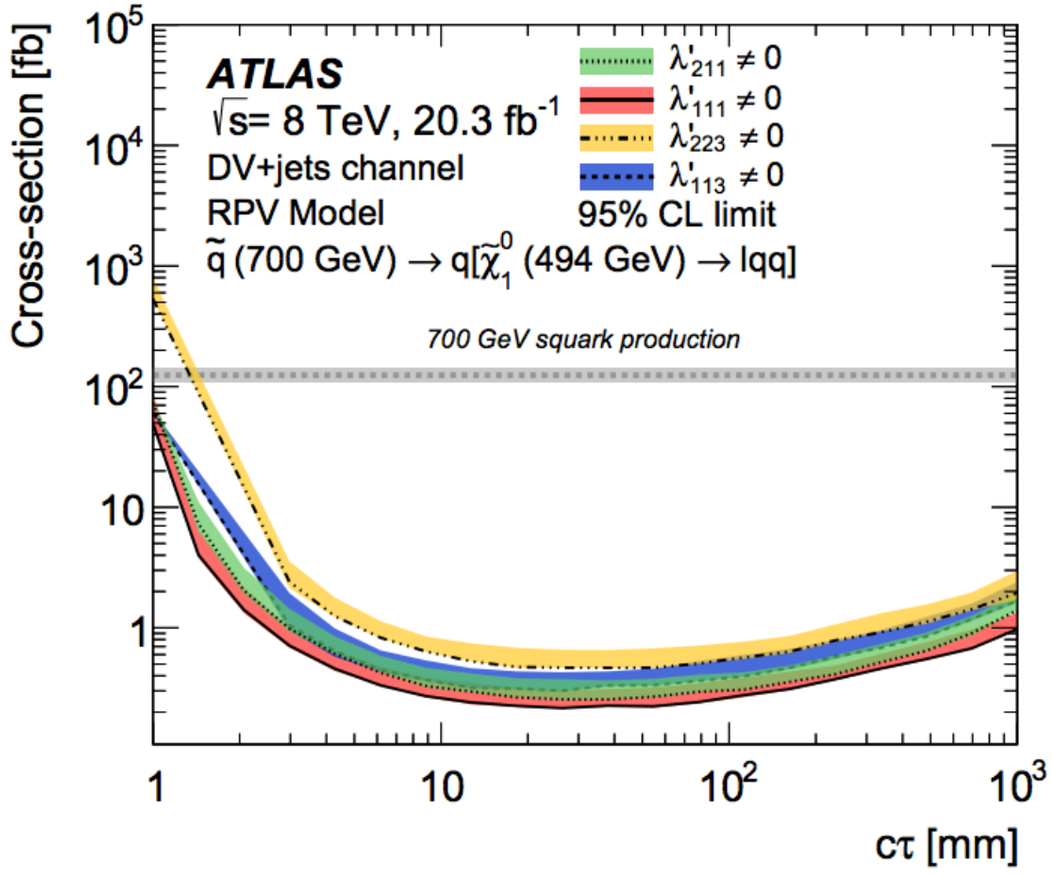


ATLAS

RPV SUSY



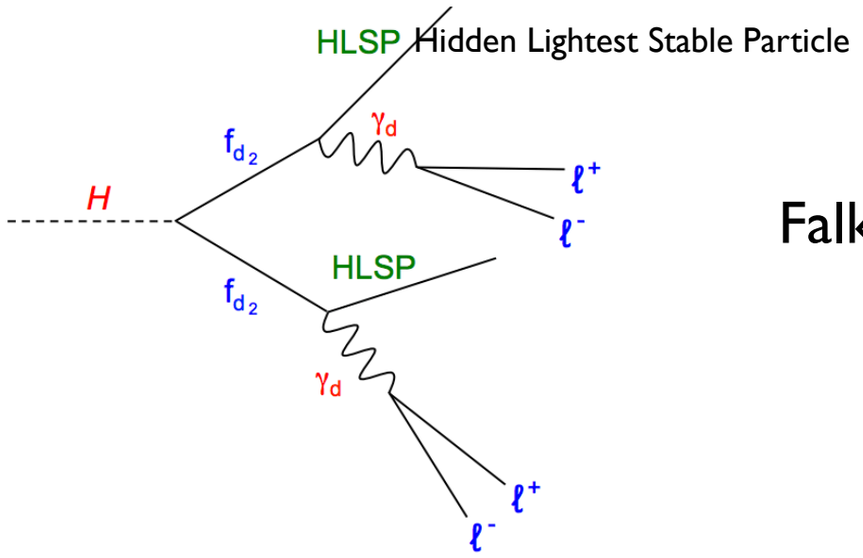
Channel	Upper limit on visible cross section [fb]
DV+jet	0.14



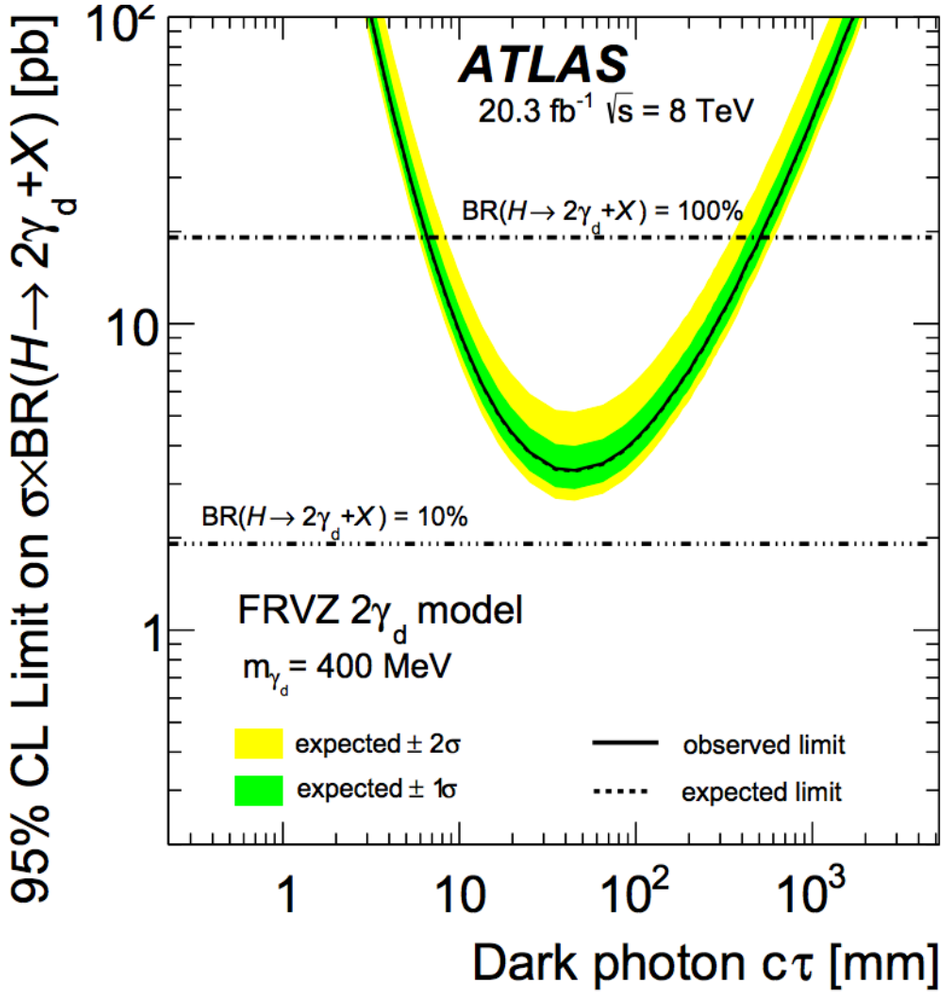
Search for Lepton-jets (ATLAS)

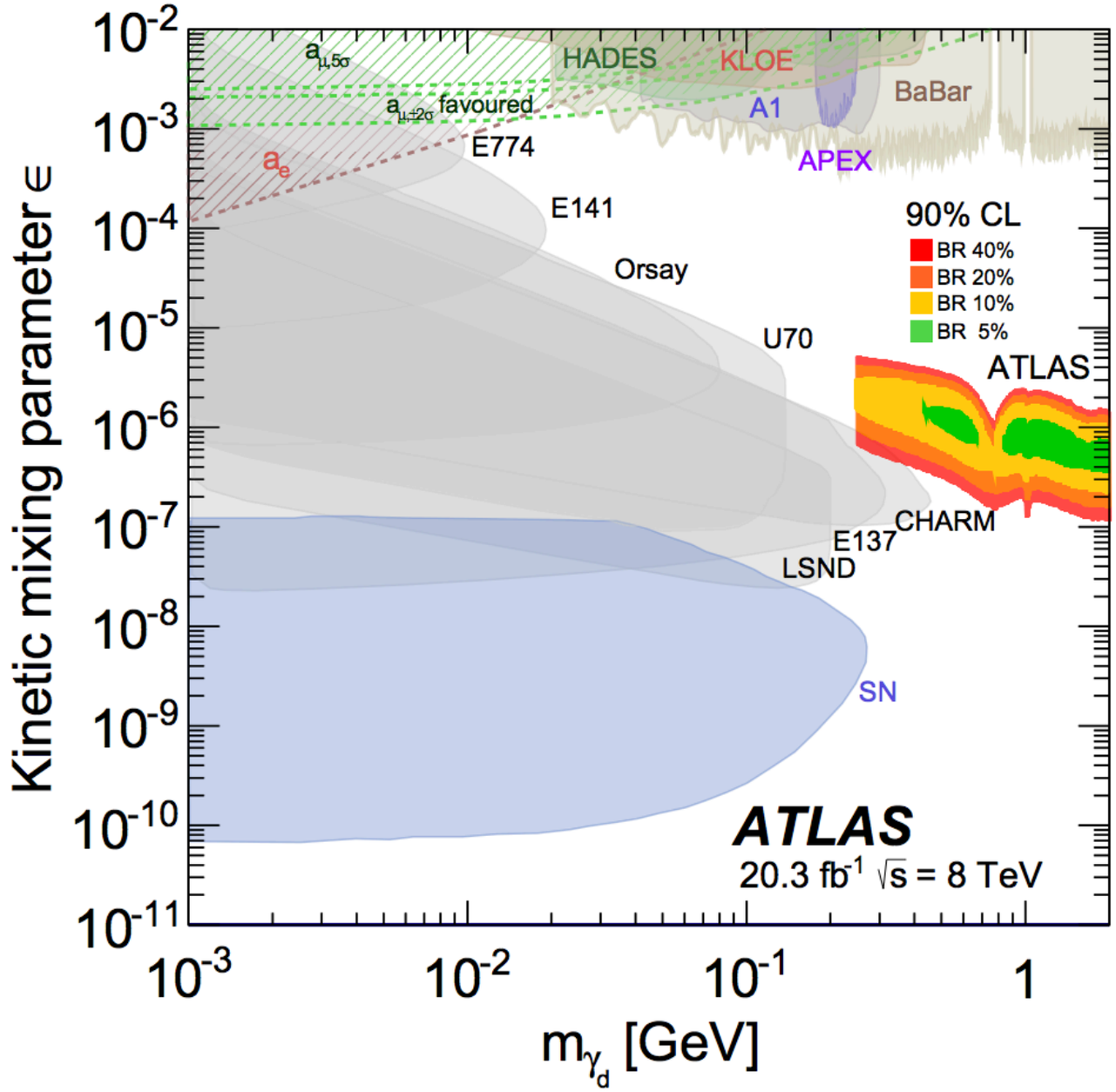
Use the muon spectrometer (MS) for the reconstruction of tracks which originate from a secondary vertex .

The high-resolution, high-granularity measurement capability of the ATLAS "air-core" Muon Spectrometer is ideal for this type of search



Falkowski–Ruderman–Volansky–Zupan (FRVZ) model

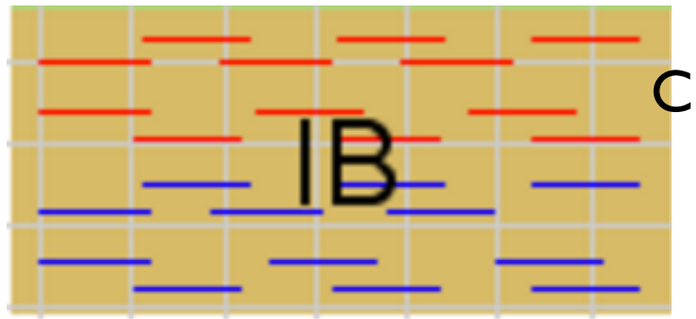




ATLAS and CMS Detectors

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)	4 T solenoid + return yoke
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$	Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T + 0.005$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	$PbWO_4$ crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass + scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)	$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)

Aspect	ATLAS	CMS
Overall diameter (m)	22	15
Overall length (m)	46	20



CMS

ATLAS TRT

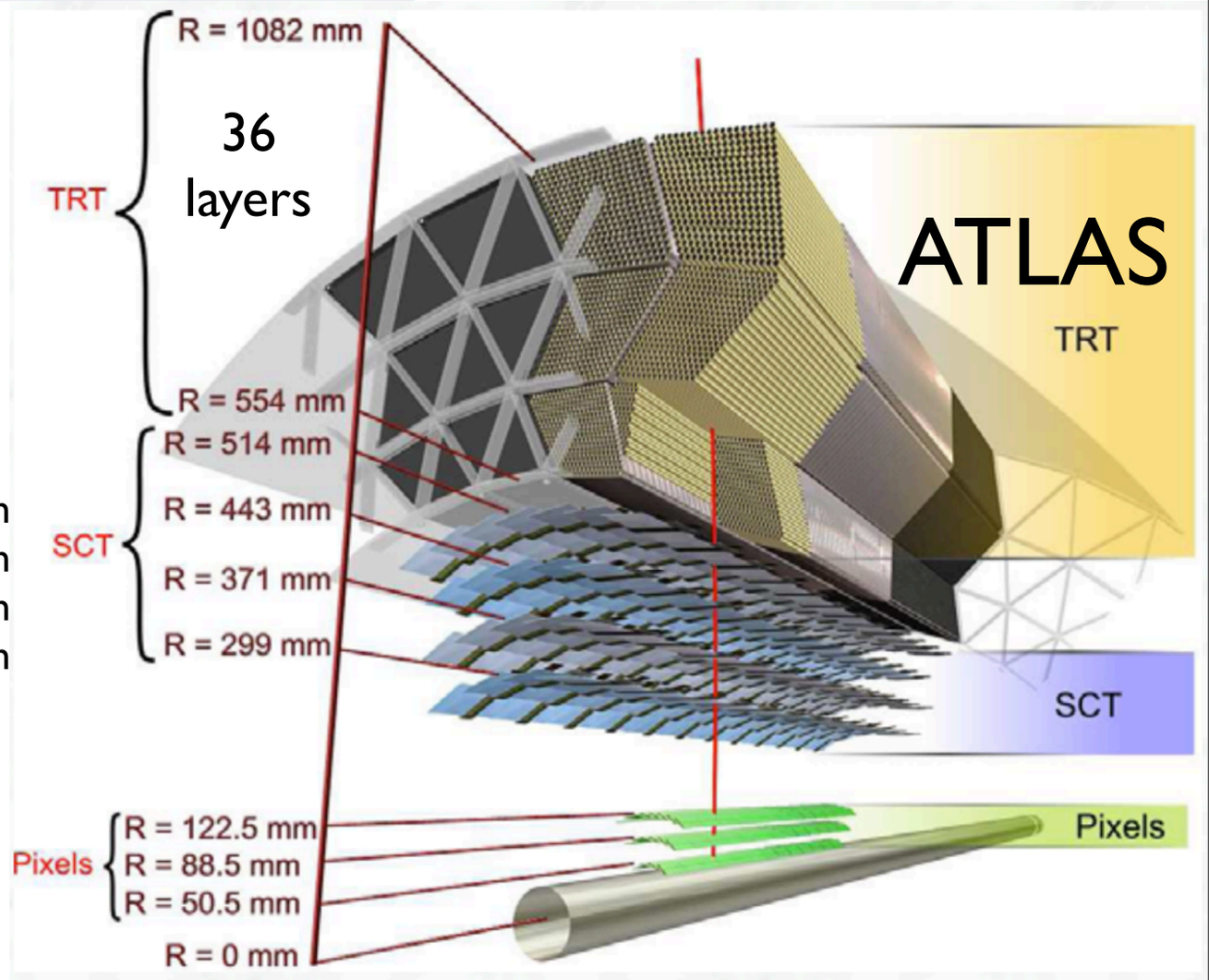
Basic detector element:
drift-tube (=straw tube) with 4mm diameter,
in the centre a 0.03mm diameter
gold-plated tungsten wire

50,000 straws in Barrel,
each straw 144 cm long.
The ends of a straw are read out separately

CMS Outer barrel : 1080 mm, 965 mm, 868 mm, 782 mm, 696 mm, 610 mm

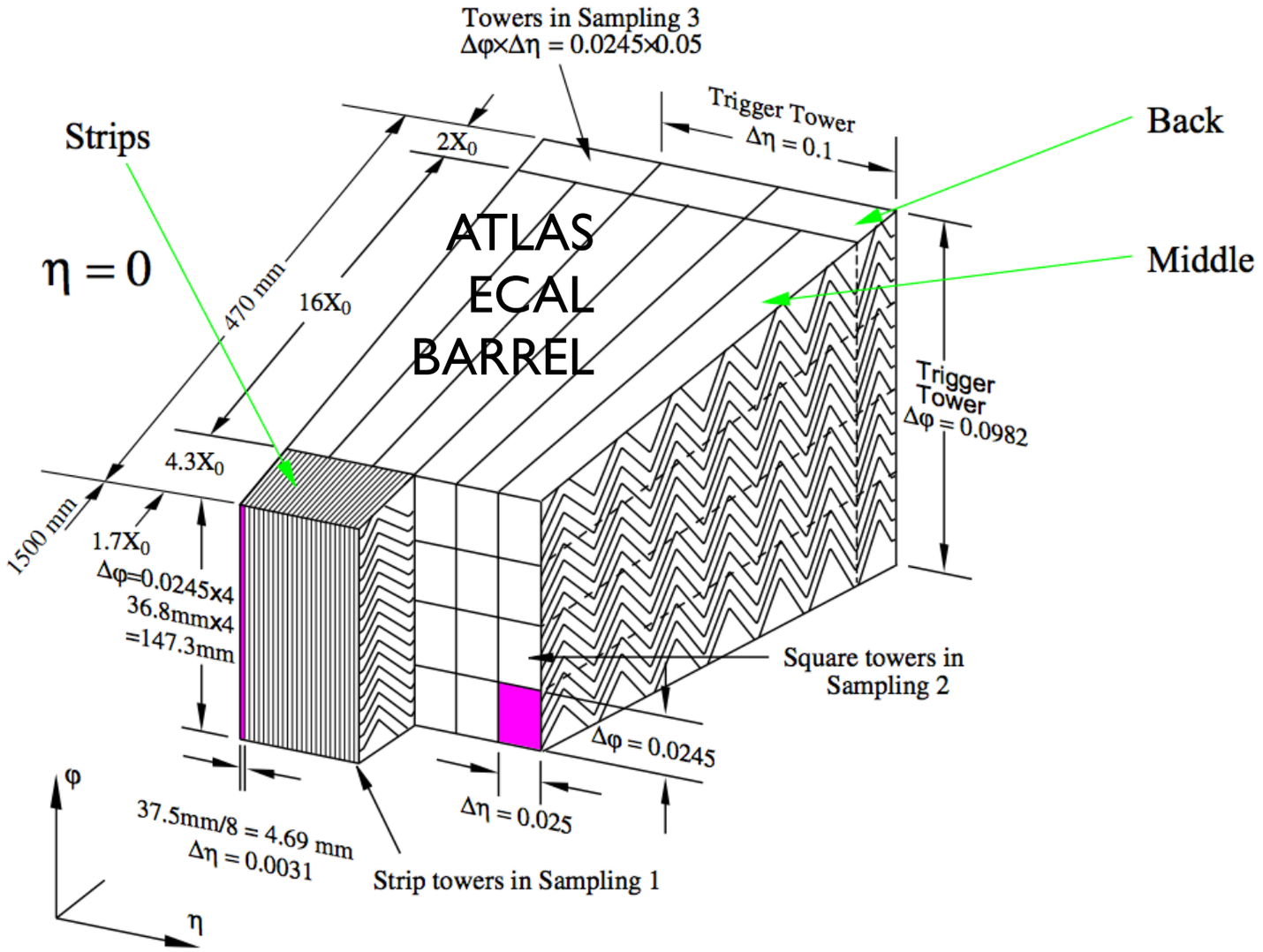
CMS Inner barrel : 520 mm, 430 mm, 340 mm, 250 mm

CMS Pixel : 110 mm, 72 mm, 43 mm



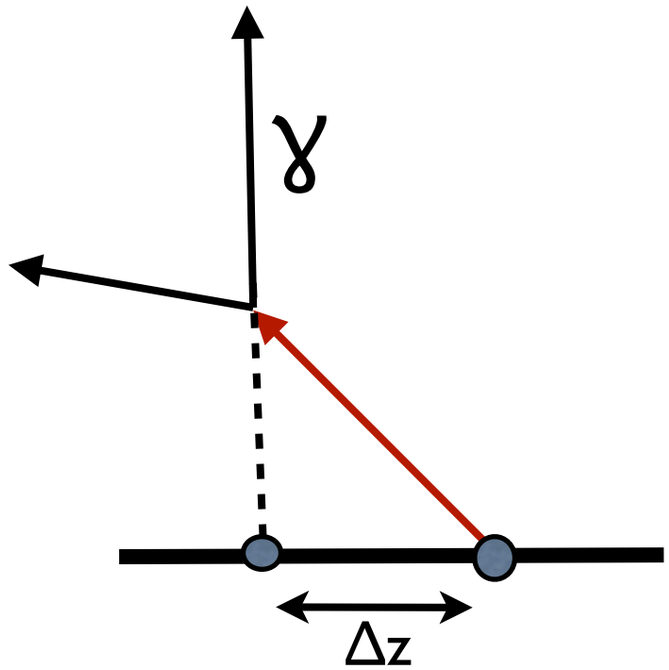
ATLAS and CMS Detectors

Aspect	ATLAS	CMS
ECAL Inner radius (m)	~1.2	~1.29



CMS ECAL

- Crystals shaped like truncated pyramids
- Barrel section:
  - Made of 61,200 crystals
  - Front face: 22x22mm = 1x1 R_M ~ 1°x1°
  - Length: 230mm = 25.8 X_0
  - Most energy (~94%) from a single particle will be contained in 3x3 crystals


γ
Δz