Searches for Long-Lived Particles in ATLAS and CMS

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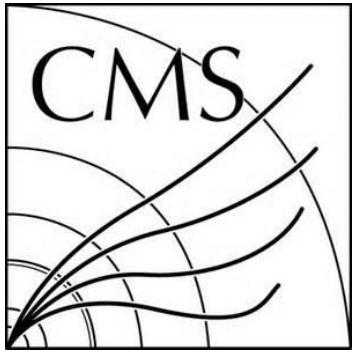


16th August 2014

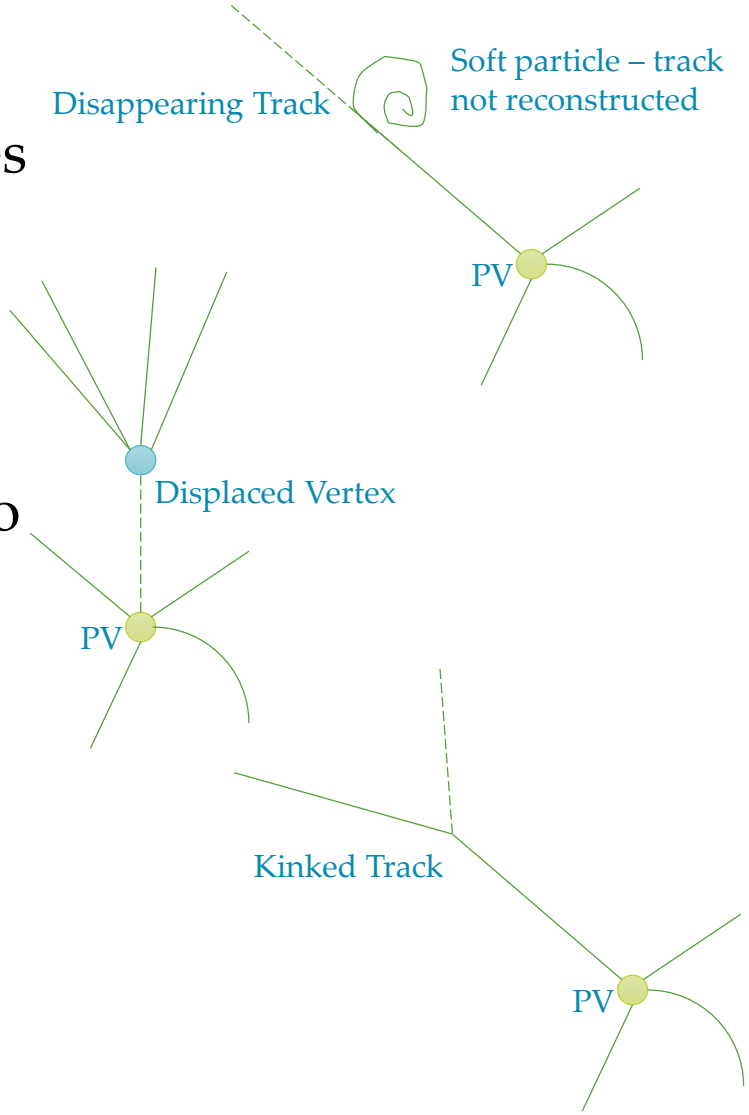
Why Long-Lived Particles?

- LLPs are predicted by a wide variety of models
  - Hidden Sectors, RPV violating decays, Split-SUSY, AMSB, GMSB, etc.

- LLP decays have unusual and interesting signatures
  - May be overlooked or misidentified by searches not dedicated to LLPs
  - May require customized triggers or other algorithms for each search

Detecting LLPs

- Identification/discriminating variables depends on properties of the LLP
  - Lifetime? Charge? Decay products? Decay position in detector?
- Highly ionizing → High $\frac{dE}{dx}$
- Low β → Long time-of-flight (TOF) to systems with good timing resolution
- Charged LLP decay in detector → Kinked or disappearing tracks
- Neutral LLP → MET, displaced vertices, non-pointing objects
- Stopped in detector → Decay in different bunch-crossing



Models + Signatures Examples

- Anomaly Mediated SUSY Breaking (AMSB)
- Gauge Mediated SUSY Breaking (GMSB)
- Split-SUSY

R-parity conserving models

- R-Parity Violating (RPV)
- Hidden Sector (HS)
- And many more!
- Degenerate masses, small couplings, conserved quantum numbers → LLPs

Model	Displaced Vertex	Disappearing/ Kinked Tracks	Non-pointing Objects/Lepton Jets	dE/dx or ToF	Out-of-time Decays
AMSB		X			
GMSB				X	
Split-SUSY				X	X
RPV	X		X		
HS	X		X		

$\sqrt{s}$ = 8 TeV

ATLAS and CMS Recent Results

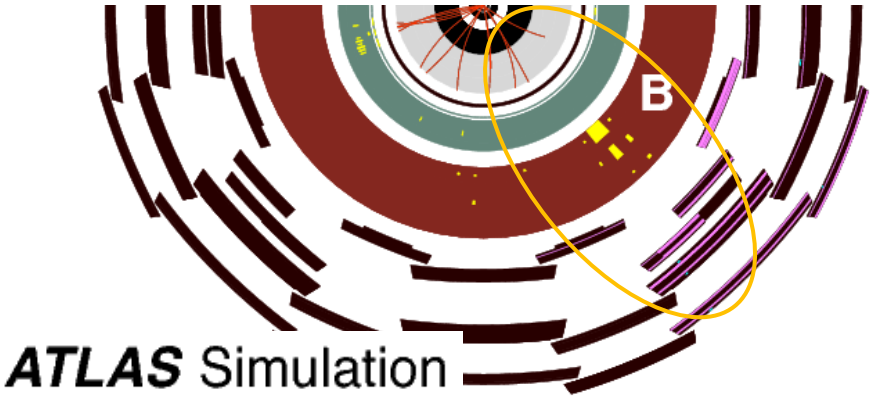
Search	ID	Model
Neutral LLPs decaying in the HCal	**ATLAS-CONF-2014-041**	**HS – Higgs-like communicator**
Meta-stable gluinos	**ATLAS-CONF-2014-037**	**Split-SUSY**
Long-lived sleptons	ATLAS-CONF-2013-058	GMSB
Long-lived stopped, out-of-time R-hadrons	Phys. Rev. D 88 112003	Split-SUSY
Muon + displaced vertex	ATLAS-CONF-2013-092	RPV
Disappearing Tracks	**Phys. Rev D 88112006**	**AMSB**

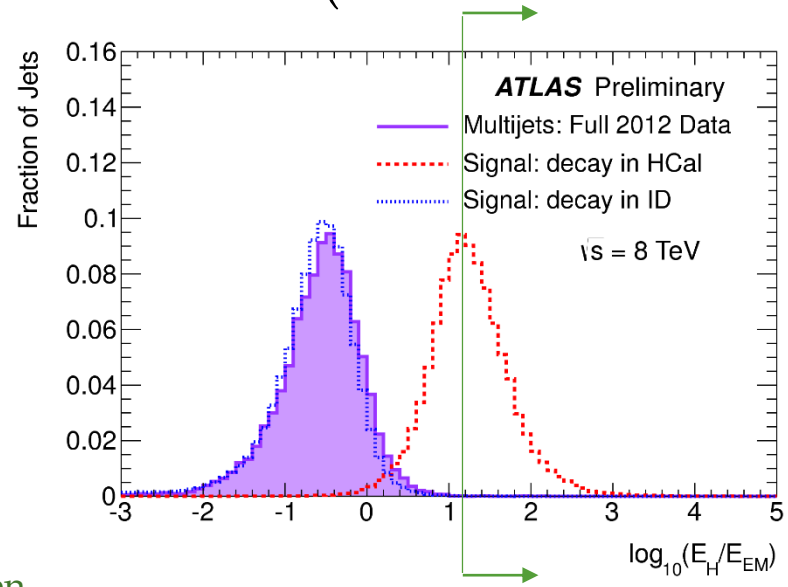
BOLD = Presented in this talk

Search	ID	Model
Displaced SUSY	**CMS B2G-12-024**	**RPV**
Displaced leptons	**CMS EXO-12-037**	**RPV or HS with Higgs-like communicator**
Displaced Jets	CMS EXO-12-038	HS with heavy Higgs
Heavy Stable Charged Particles	**JHEP 07 (2013) 122**	**GMSB, Split-SUSY**
HSCP Reinterpretation	**CMS EXO-13-006**	**pMSSM**

ATLAS – Neutral LLPs Decaying in the HCal 1

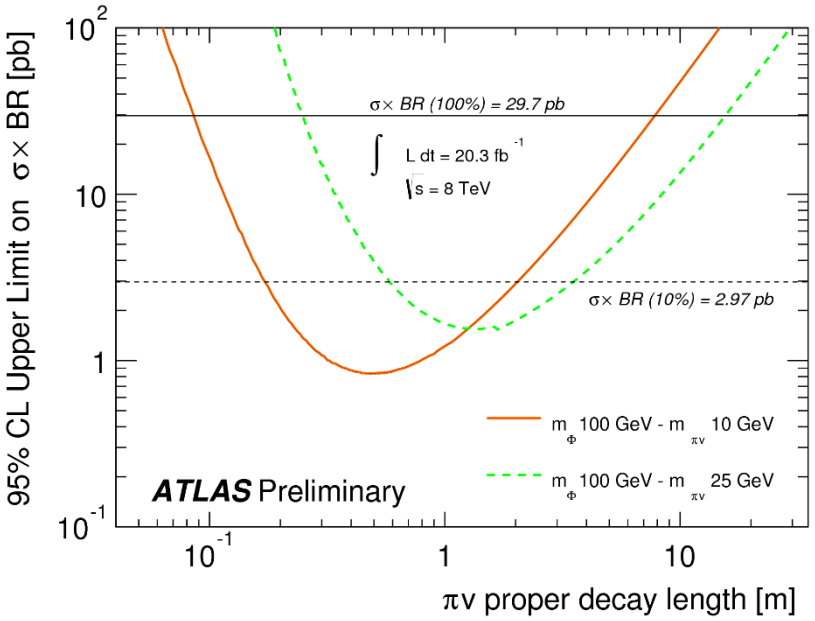
- A neutral scalar (100-140 GeV) decays to a pair of neutral LLPs (10-100 GeV) which in turn decay to heavy fermions $\Phi_{HS} \rightarrow \pi_v \pi_v$ $\pi_v \rightarrow f\bar{f}$
- If such neutral LLPs decay in the hadronic calorimeter (HCal), the result will be:
  - One narrow jet per LLP (fermion pairs have no time to separate)
  - No inner detector tracks pointing towards the jet
  - Little to no energy in the electromagnetic calorimeter (which is closer to the beampipe



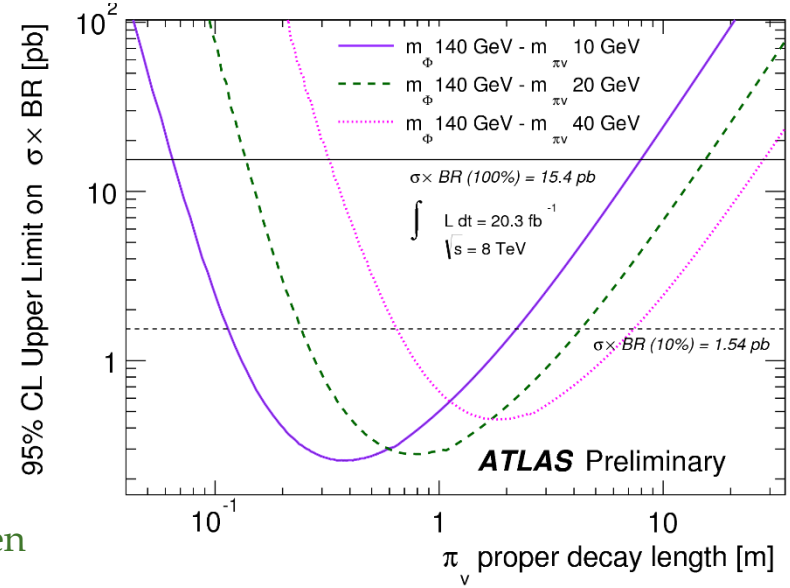


ATLAS – Neutral LLPs Decaying in the HCal 2

- Use a **dedicated trigger** to search for jets
- Only seeking signal in the HCal reduces multijet background
  - Cosmic and beam-halo backgrounds reduced by timing and MET cuts
- Set limits on mean $c\tau$ of the LLPs



MC sample m_Φ, $m_{\pi v}$ [GeV]	excluded range 30% BR $\Phi_{HS} \rightarrow \pi_v\pi_v$ [m]	excluded range 10% BR $\Phi_{HS} \rightarrow \pi_v\pi_v$ [m]
126, 10	0.10 - 4.38	0.13 - 2.30
126, 25	0.27 - 10.01	0.37 - 5.12
126, 40	0.54 - 12.11	0.86 - 5.62

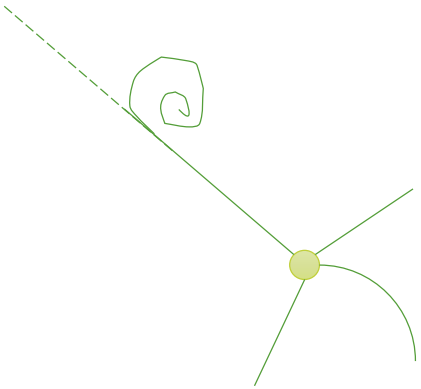


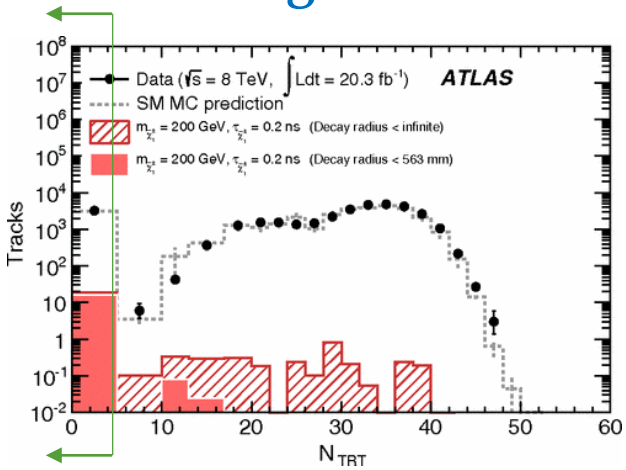
ATLAS-CONF-2014-041

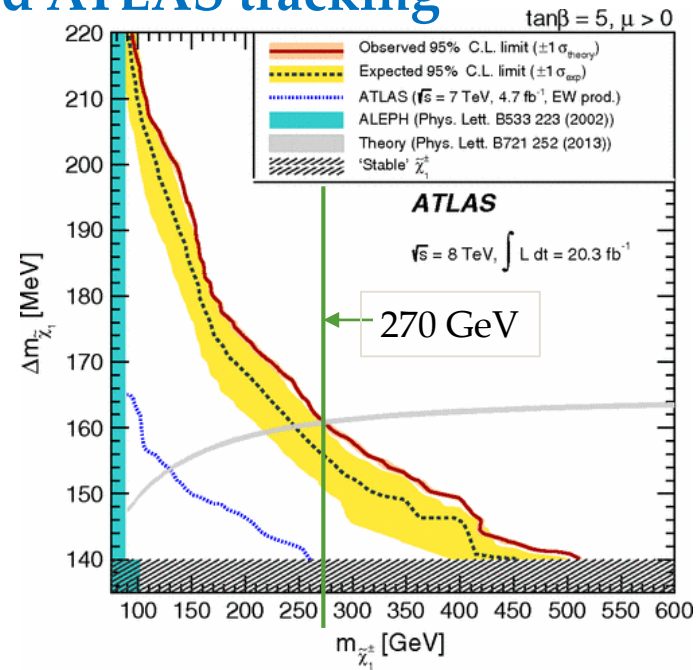
AMSB

ATLAS – Disappearing Tracks

- Lightest chargino nearly degenerate with lightest neutralino (the LSP), leading to a long lifetime $\tilde{\chi}_1^{\pm} \rightarrow \pi^{\pm}\tilde{\chi}_1^0$
- If decay in inner detector, where track hits can be reconstructed with high resolution → track will not extend the full width of the tracker (soft $\pi^{\pm}$ not reconstructed)
- Use a **dedicated trigger** and **append standard ATLAS tracking algorithm with additional stage**





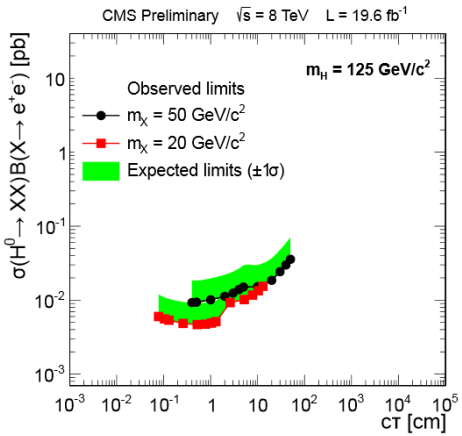


Phys. Rev. D 88 112006

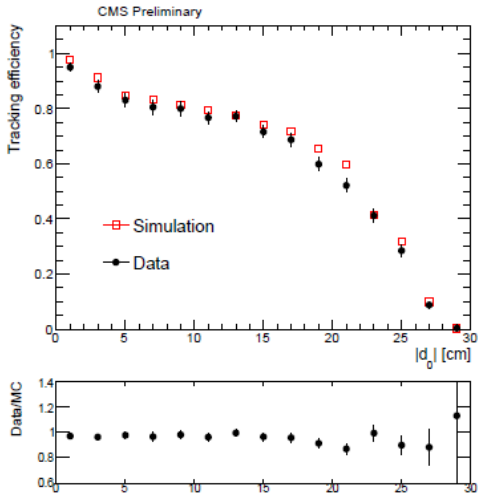
RPV, HS

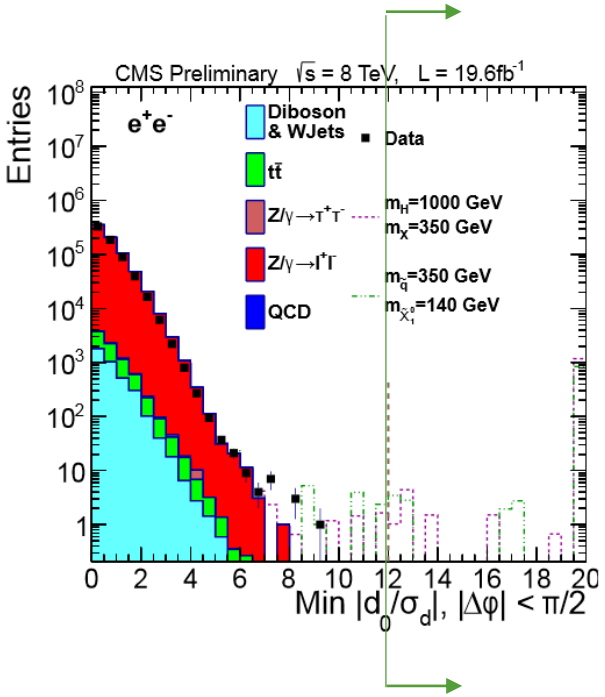
CMS – Displaced Leptons

- Neutral LLP decay to dileptons in the inner tracker $H \to XX$ $X \to \ell^+\ell^-$ $\tilde{q} \to q\tilde{\chi}^0$ $\tilde{\chi}^0 \to \ell^+\ell^-\upsilon$
  - Seek pairs of lepton tracks with high transverse impact parameter d_0 originating from the same displaced vertex
- Standard lepton IDing for inner tracker poor for displaced leptons
  - **Base identification on match to trigger object**
- Use standard tracking algorithms
  - **Determine efficiency vs d_0** using cosmic events



CMS EXO-12-037



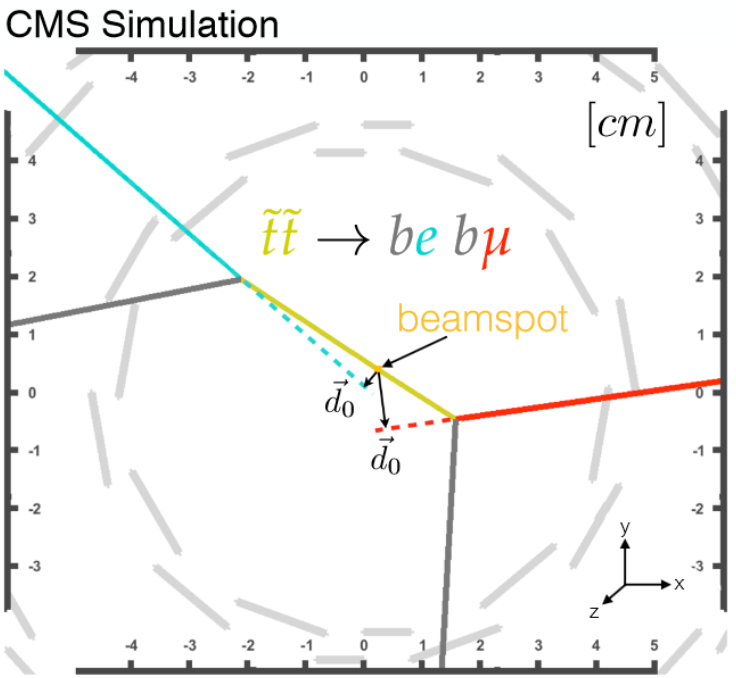


CMS – Displaced SUSY1

- Attempt to create a **generalized** search for non-pointing leptons, built around an R-parity violating model $pp \to \tilde{t}_1\tilde{t}_1$ $\tilde{t}_1 \to bl$
- LSP (a $\tilde{t}_1$) decays to a lepton and a b in the inner tracker
- Search for a pair of opposite-sign leptons with high (> 100 μm) impact parameter d_0
- Background is a function of d_0
- d_0 is a function of LLP lifetime

Search Regions

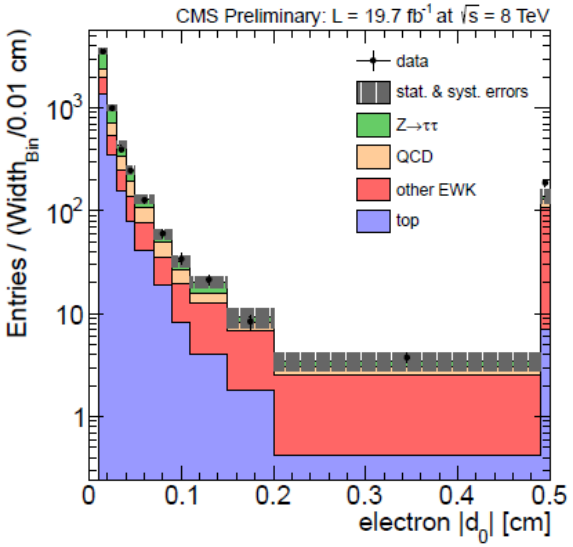
μ $\lvert d_0 \rvert$ / e $\lvert d_0 \rvert$	> 1000 μm	> 500 μm	> 200 μm
> 1000 μm	Exclusive	Intermediate	Loose
> 500 μm	Intermediate	Intermediate	Loose
> 200 μm	Loose	Loose	Loose

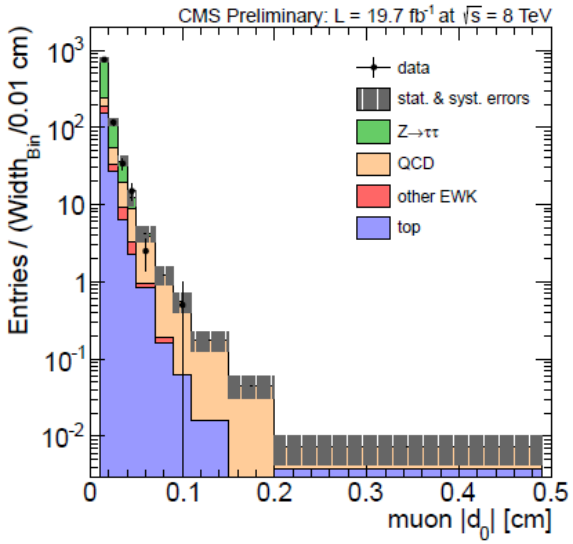


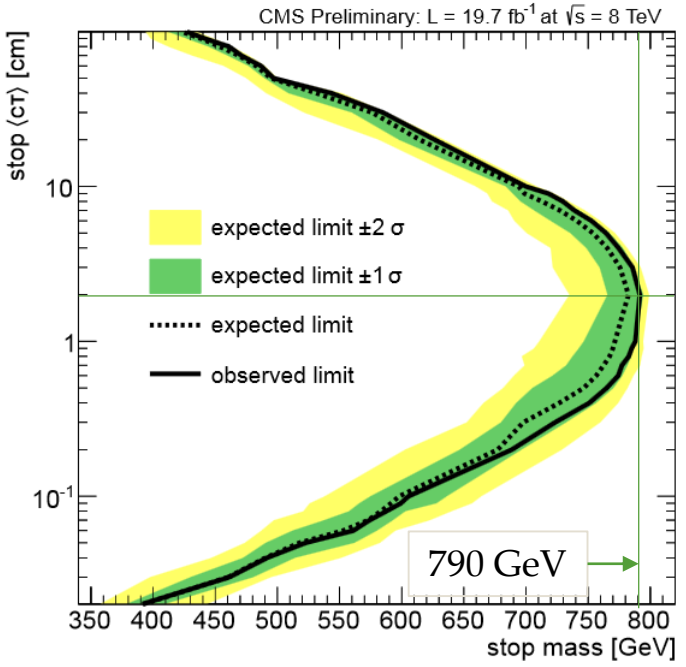
CMS B2G-12-024

CMS – Displaced SUSY 2

- Push for **model independence**: No E_T^{miss} cut, leptons not required to originate at the same vertex, hadronic activity is not required
- Use standard muon and electron identification algorithms, but use custom scale factors (removing d_0 and z_0 requirements of standard algorithms) for differences in data/MC reconstruction efficiencies





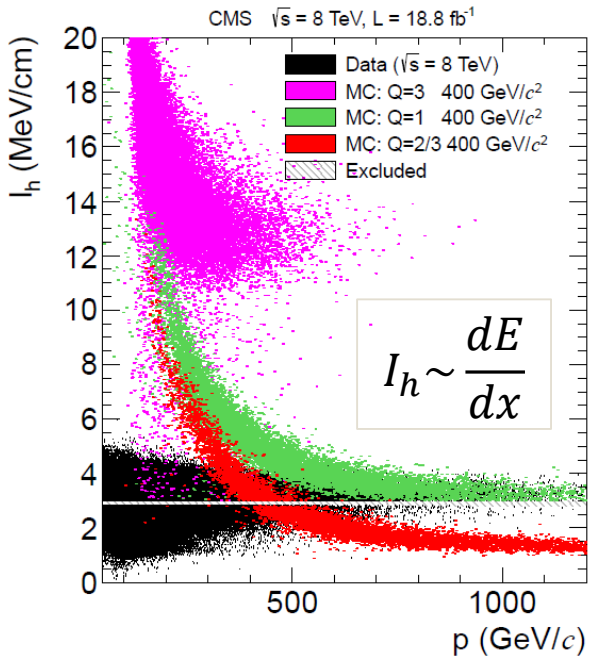


CMS B2G-12-024

GMSB, Split-SUSY, etc.

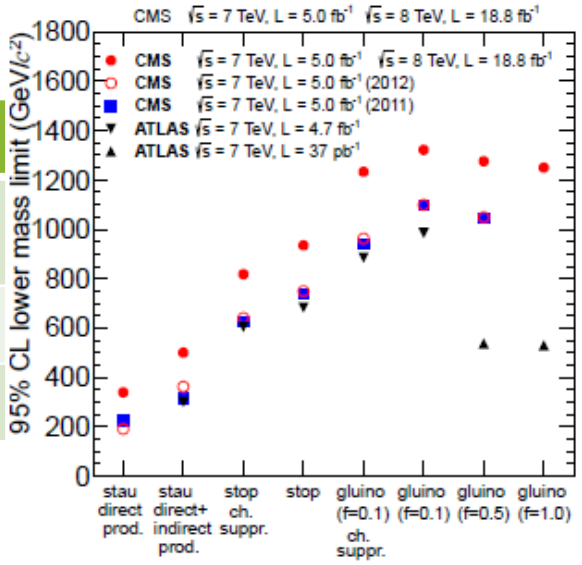
CMS – Heavy Stable Charged Particles

- Consider low β, $(e/3 \leq Q \leq 8e)$ particles and bound states from a **variety of models**
  - R-hadron interaction with detector uncertain → Two models considered
- Search for tracks with anomalous dE/dx or long TOF to the MS



HSCP	$\tilde{\tau}_1$	$\tilde{t}_1$	$\tilde{g}$	l
Model	GMSB	Direct Production	Split-SUSY	$SU(2)_L$ neutral
Class	Leptonic	Hadronic	Hadronic	Leptonic

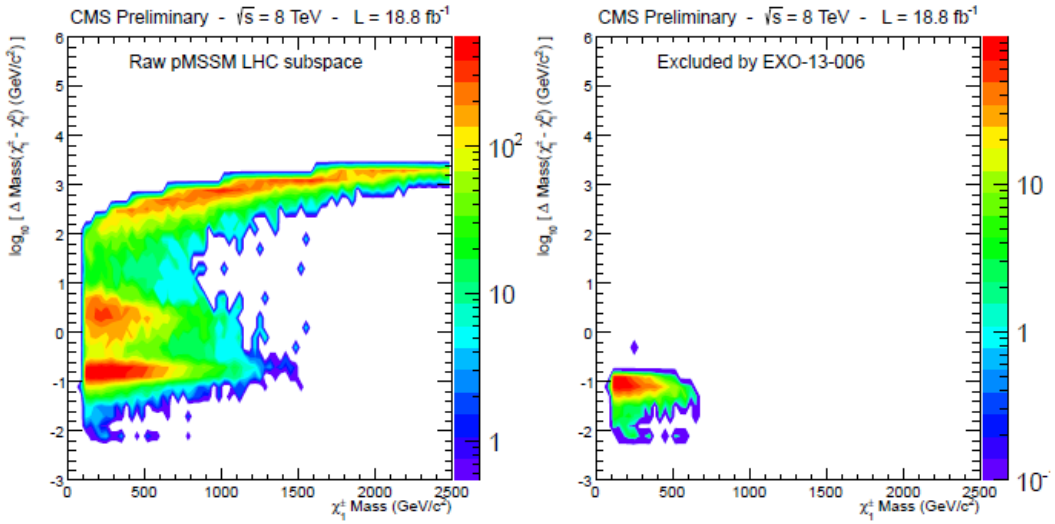
Charge	dE/dx	MS
Q = e	High	Used alone or with inner tracker
Q < e	Low	Not used
Q > e	Very High	Always used

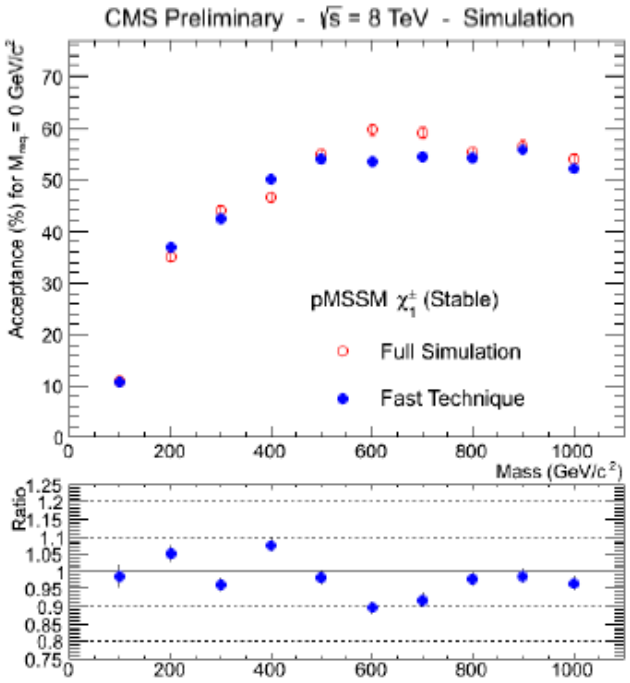


CMS EXO-12-026

CMS – HSCP Reinterpretation

- A technique is developed to **adapt the results** of the previous slide's search to other models predicting long-lived lepton-like particles
- Selection requirements on dE/dx, p_T, m, and TOF → probability as a function of $\boldsymbol{k}$, β, and η that a particle will pass the selection criteria
- Use to limits on chargino lifetime in the phenomenological minimal SUSY standard model (pMSSM)





Split-SUSY

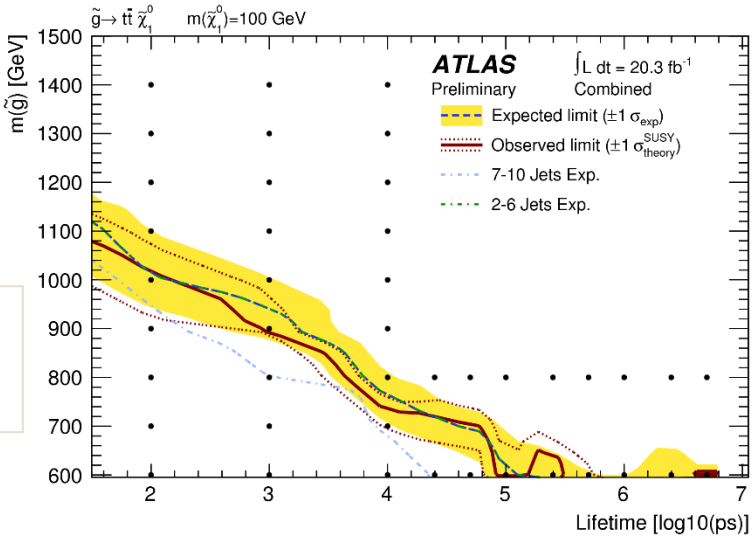
ATLAS – Metastable Gluinos

100% BR $\tilde{g} \to t\bar{t}\tilde{\chi}^0$ OR
50% $\tilde{g} \to q\bar{q}\tilde{\chi}^0$, 50% $\tilde{g} \to g\tilde{\chi}^0$

- **Reinterpret** two searches for promptly decaying gluinos and squarks to search for long-lived gluinos decaying inside the detector
  - First search for gluinos with mid-range lifetimes
- Follow full simulation-digitization-reconstruction train signal samples → generic model of hadronization
- Maintain signal region definitions, background yields and uncertainties, and statistical treatment of parent searches

Jet Number	b-Jets	E_T^{miss}
7-10	0, 1, ≥2	✓
2-6	-	✓

Limits set for $\tau = 1$ ns and $m_{\tilde{\chi}_1^0} = 100$ GeV:
$\tilde{g} \to t\bar{t}\tilde{\chi}^0$: 900 GeV $\tilde{g} \to q\bar{q}\tilde{\chi}^0 (g\tilde{\chi}^0)$: 850 GeV



ATLAS-CONF-2014-037

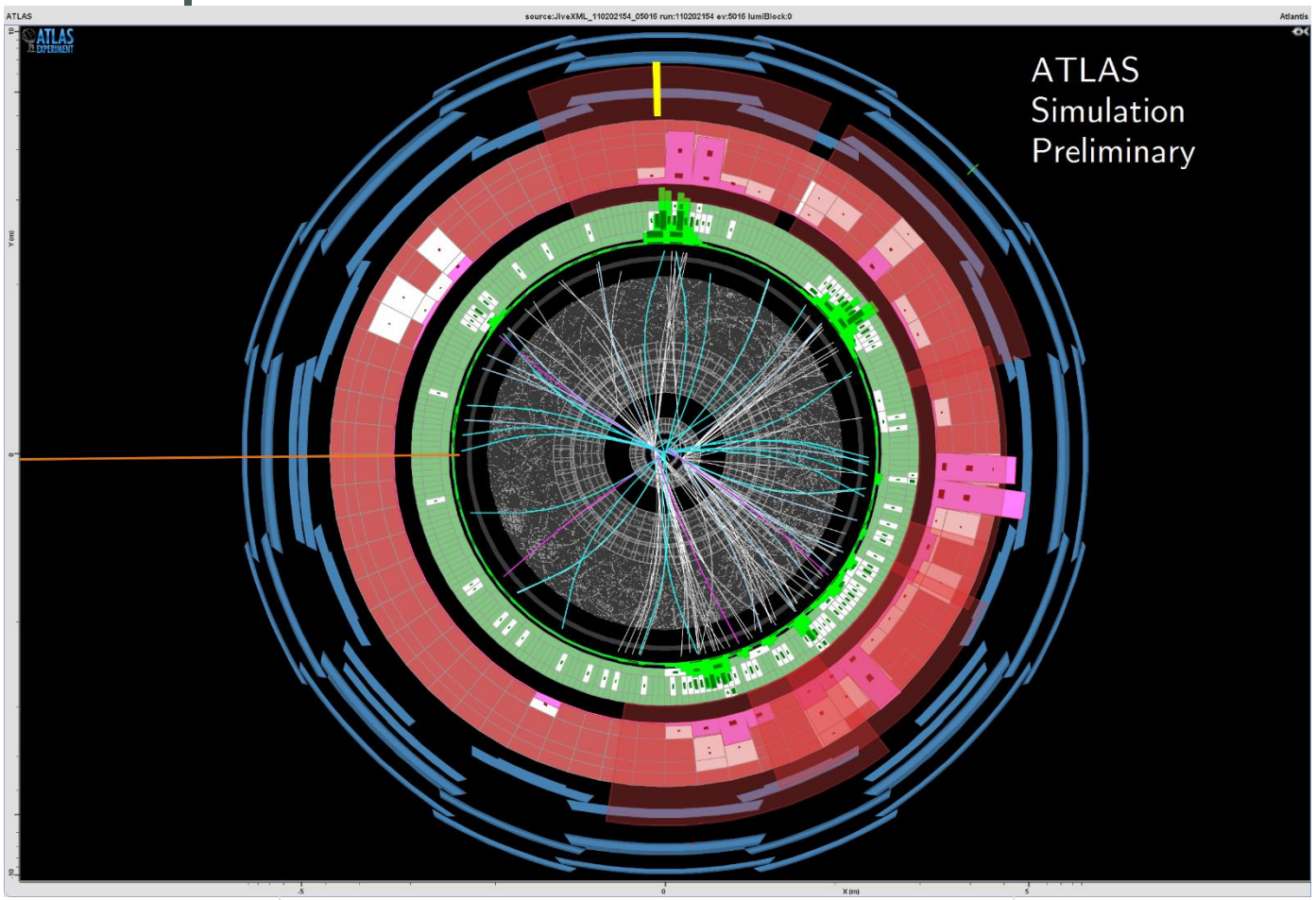
Run 2 and LLPs

- Higher energy allows for a greater mass reach, but…
- Every analysis has questions to answer:
  - Will changes to default tracking, etc algorithms require the creation of analysis dedicated algorithms where standard ones were previously used?
  - Similarly, do custom triggers have to be added or reconfigured (this should be done already!)?
  - How will pileup, and pileup removal, affect those searches requiring isolation or triggering and searching for non-pointing tracks and jets?

Conclusions

- LLPs appear in a variety of models
  - Challenges to LLP searches encourage signal-based development of analyses
  - Variety of LLPs and models that produce them encourage model-independence of interpretation of results
- So far, no evidence of new physics has been detected
- Both ATLAS and CMS have a variety of published results and studies will continue and expand in 2015
  - Higher energy → Greater mass reach for LLPs and their parents
  - Higher luminosity → Challenge for searches with track isolation, etc

Backup Slides



Meta-stable gluinos: Decay to tops

Models and Signatures

- **Anomaly Mediated SUSY Breaking (AMSB)**
  - Long lived charginos decay to neutralinos
    - Disappearing/kinked tracks
- **Gauge Mediated SUSY Breaking (GMSB)**
  - Lightest neutralino decays to a photon and gravitino
    - TOF to photon production + MET
  - Lightest slepton decays to a lepton and gravitino
    - $\frac{dE}{dx}$ and TOF
- **Split SUSY**
  - Decay of long lived gluinos and R-hadrons
    - $\frac{dE}{dx}$ and TOF or out-of-time decays

Models and Signatures

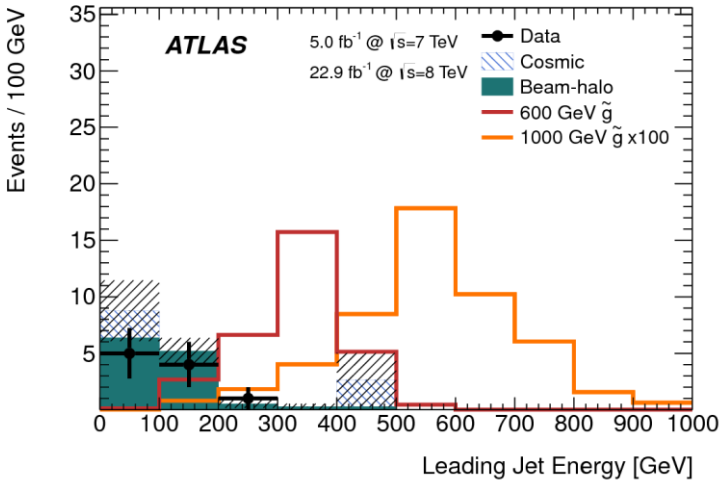
- **R-Parity Violating (RPV) SUSY models**
  - LSP is metastable and may possess a long lifetime
    - Displaced vertices, non-pointing leptons
- **Hidden Sector (HS)**
  - A hidden sector couples weakly to the SM via some communicator – SM particles can decay to HS particles, or vice versa
    - Displaced vertices, lepton jets (collimated group of leptons)
- **And more!**
  - Other models with near-degenerate mass spectra, weak couplings, etc can produce LLPs

ATLAS – Long-lived, Stopped R-Hadrons

- Considered several models for hadronization of gluinos and $\tilde{g}$, $\tilde{t}$, or $\tilde{b}$, (300-1000 GeV) decaying to hadronic jets and neutralinos
- Trigger on empty bunch-crossings, looking for events with at least one high energy jet – allows for detection of R-hadrons whose charge has changed
- Lower limits set on mass of $\tilde{g}$, $\tilde{t}$, and $\tilde{b}$

Leading jet energy (GeV)	R-hadron model	Gluino/squark decay	Neutralino mass (GeV)	Gluino/squark mass limit (GeV) Expected	Observed
100	Generic	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	$m_{\tilde{g}} - 100$	526	545
100	Generic	$\tilde{g} \to t\bar{t} + \tilde{\chi}^0$	$m_{\tilde{g}} - 380$	694	705
300	Generic	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	100	731	832
300	Generic	$\tilde{g} \to t\bar{t} + \tilde{\chi}^0$	100	700	784
300	Intermediate	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	100	615	699
300	Regge	$\tilde{g} \to g/q\bar{q} + \tilde{\chi}^0$	100	664	758
100	Generic	$\tilde{t} \to t + \tilde{\chi}^0$	$m_{\tilde{t}} - 200$	389	397
100	Generic	$\tilde{t} \to t + \tilde{\chi}^0$	100	384	392
100	Regge	$\tilde{t} \to t + \tilde{\chi}^0$	100	371	379
100	Regge	$\tilde{b} \to b + \tilde{\chi}^0$	100	334	344

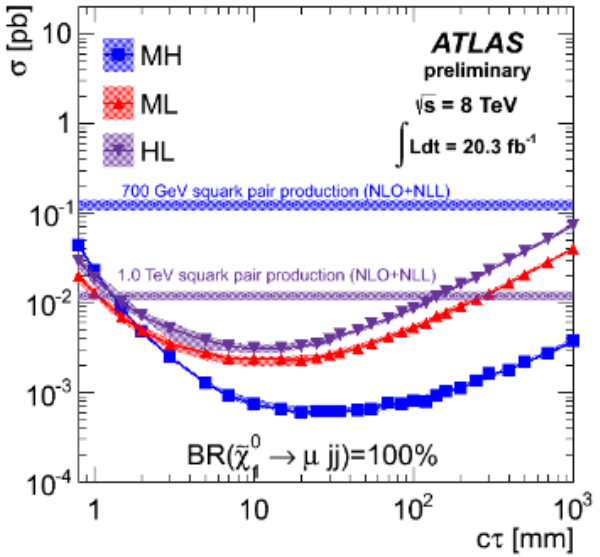
100% BR $\tilde{g} \to t\bar{t}\tilde{\chi}^0$ OR
50% $\tilde{g} \to q\bar{q}\tilde{\chi}^0$, 50% $\tilde{g} \to g\tilde{\chi}^0$
100% $\tilde{t} \to t\tilde{\chi}^0$ AND 100% $\tilde{b} \to b\tilde{\chi}^0$

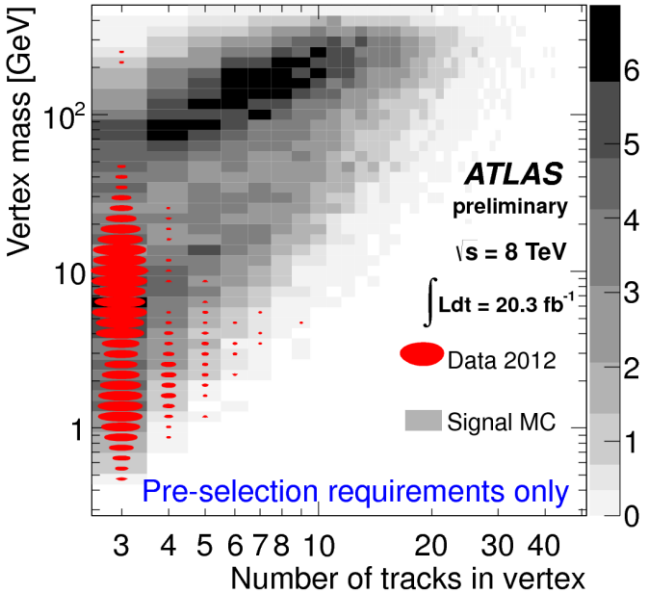


Phys. Rev. D 88 112003

ATLAS – Muon + Displaced Vertex

- A neutralino decays into a muon and quarks in the ID
- Search for a high track multiplicity displaced vertex in the inner detector with an associated non-pointing muon
- Limits set on squark pair production for a range of squark and neutralino masses

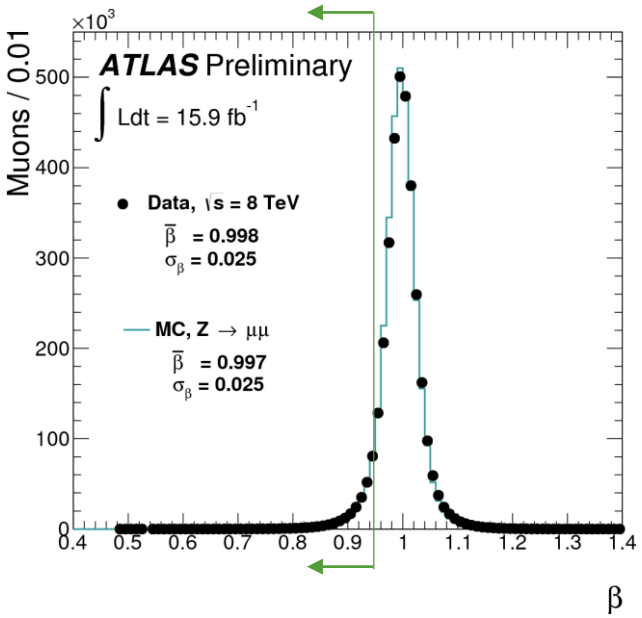


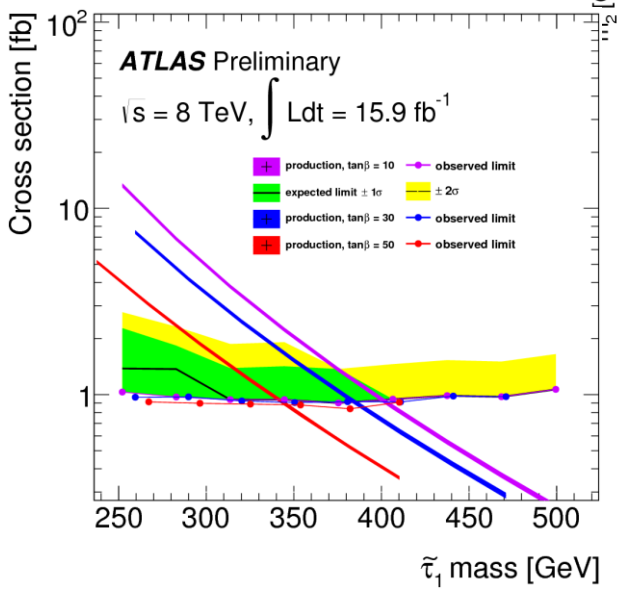


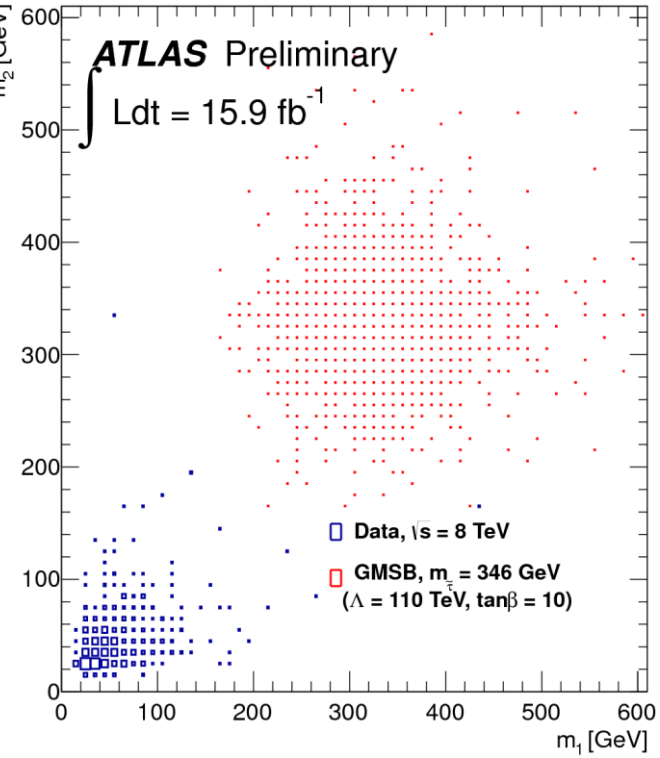
ATLAS-CONF-2013-092

ATLAS – Long-lived Sleptons

- The NLSP, the stau, decays outside of the detector, depositing energy throughout ATLAS
- Search for two high p_T, low β tracks using $\frac{dE}{dx}$ and TOF to the MS
- Limits set on stau mass

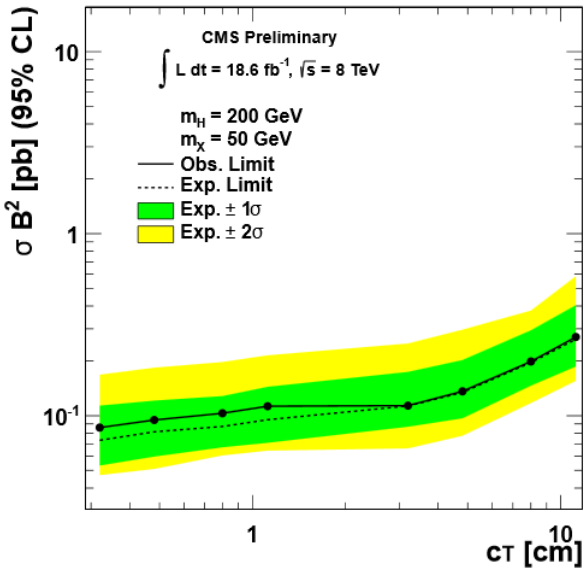


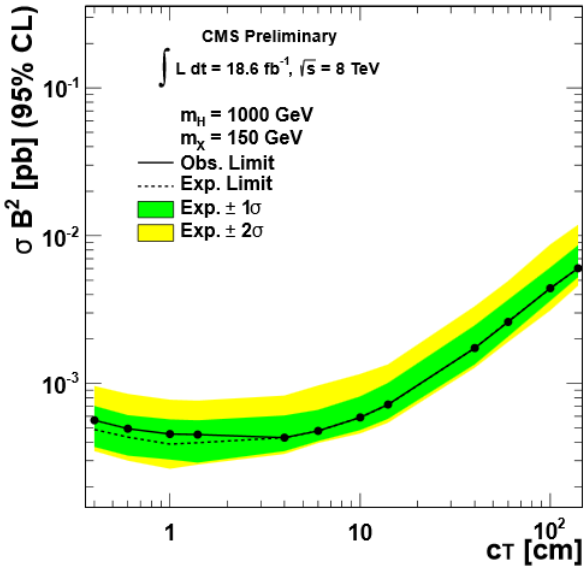


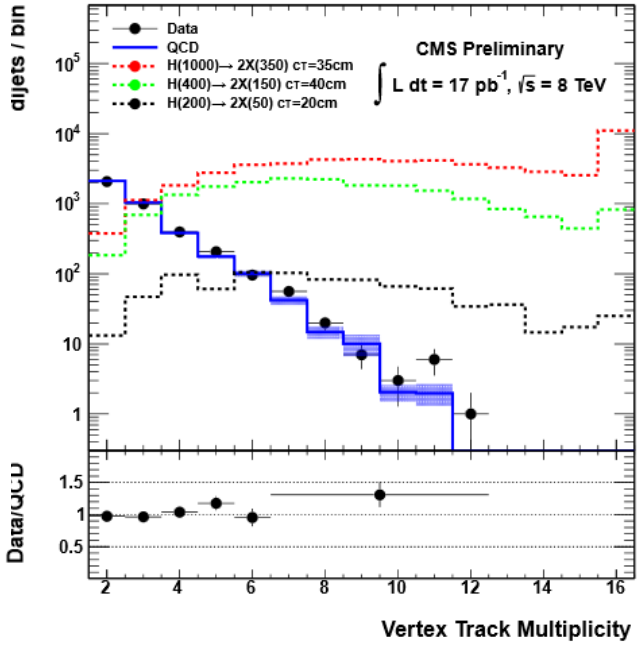


CMS – Displaced Jets 1

- A heavy Higgs-like boson (200-1000 GeV) to a pair of neutral LLPs (50-350 GeV)
- Search for pairs of jets originating from same displaced vertex with
  - Few prompt tracks and a high fraction of jet energy carried by the displaced tracks



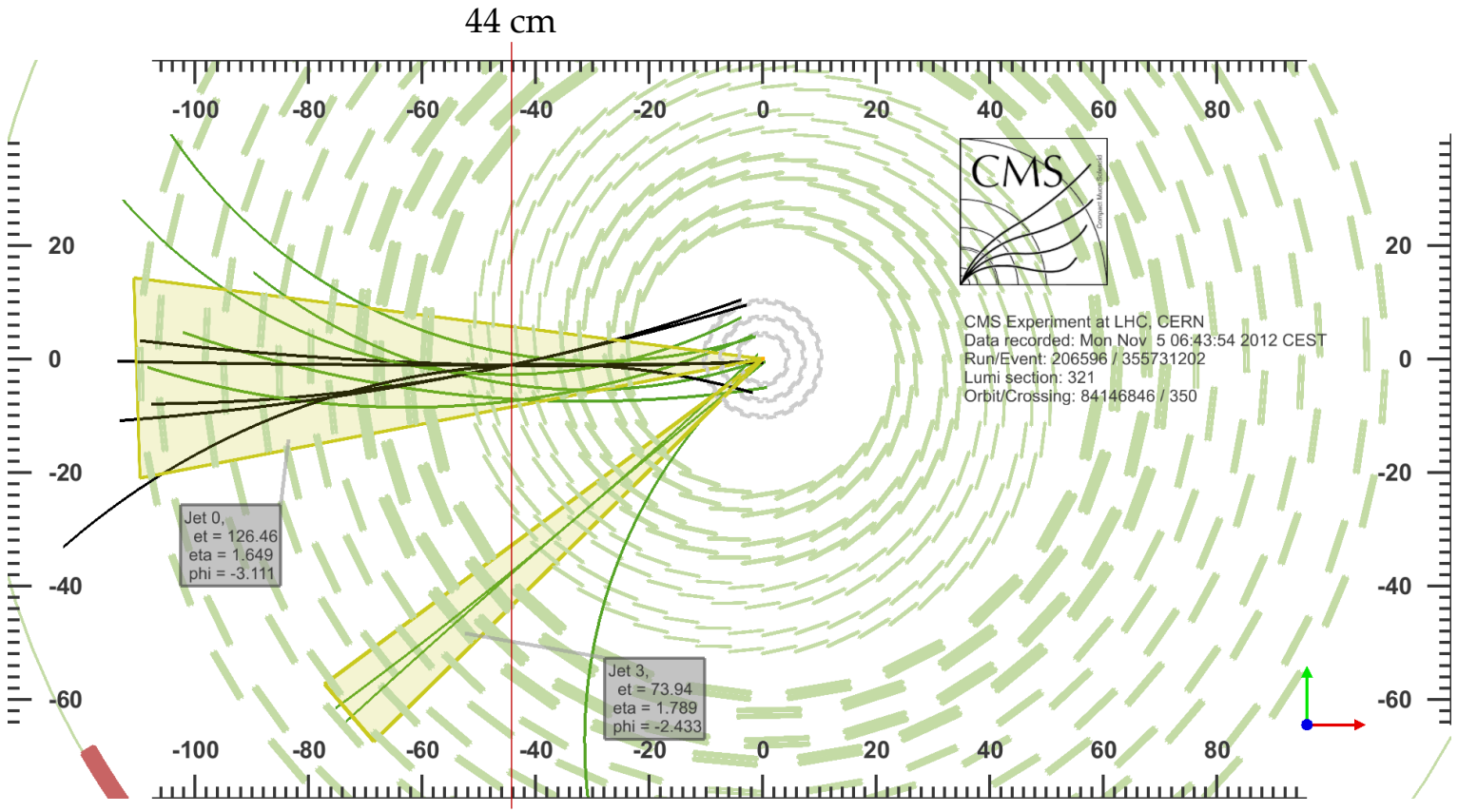




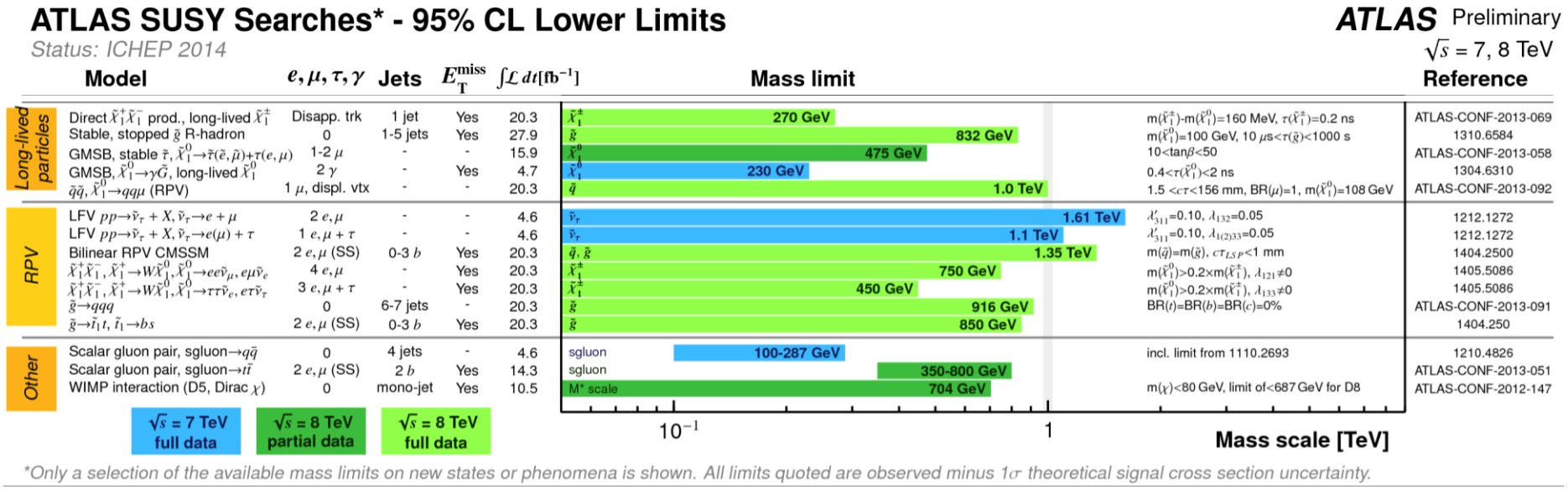
CMS EXO-12-038

CMS – Displaced Jets 2

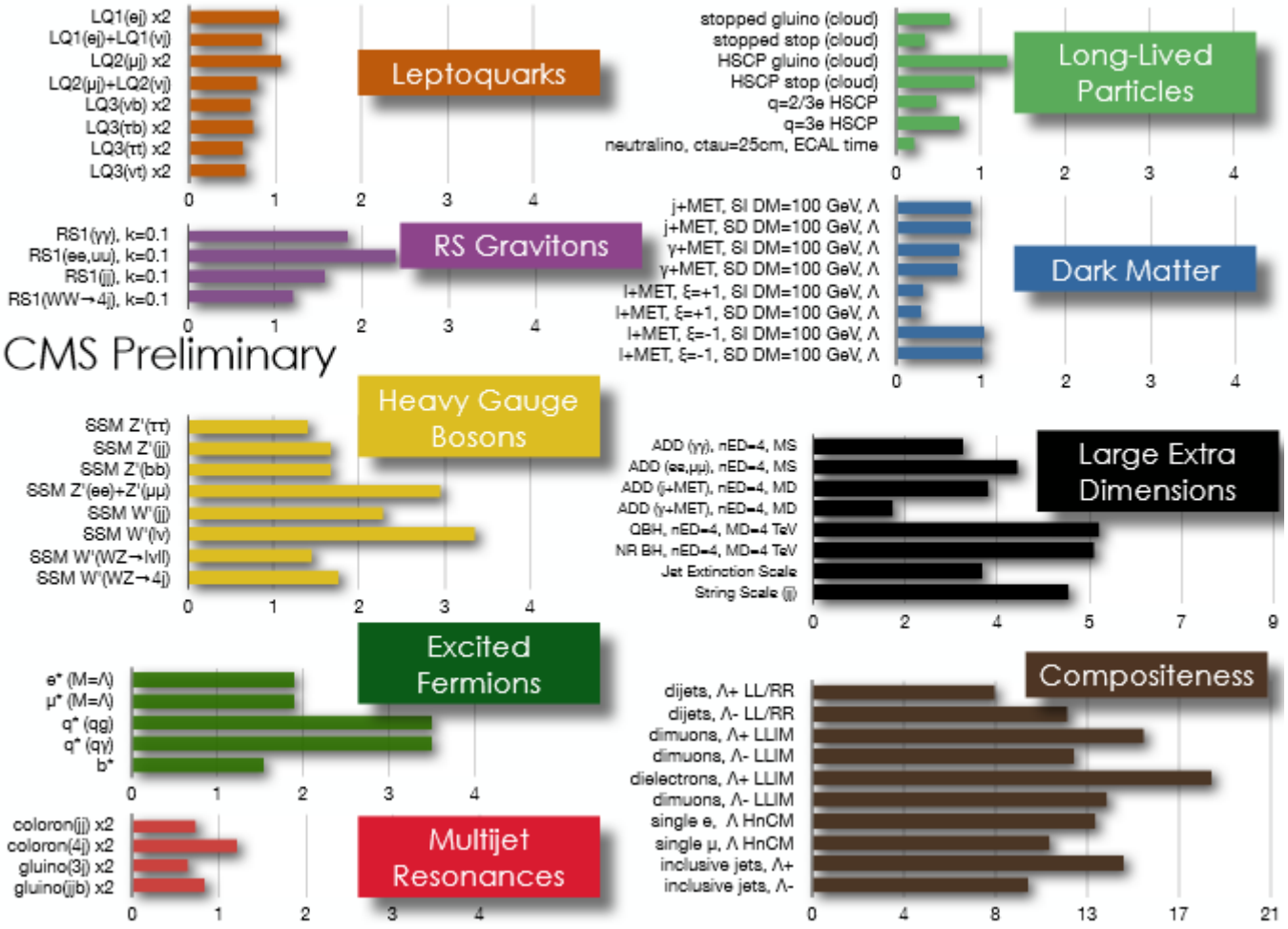
- Black: Marks tracks associated with displaced vertex



ATLAS – Current Limits



CMS – Current Limits



ATLAS Recent Results

$\sqrt{s} = 8$ TeV	• Neutral LLP decaying in HCal • Meta-stable gluinos • Muon + displaced vertex • Disappearing Tracks • Long-lived sleptons • Stopped R-hadrons
$\sqrt{s} = 7$ TeV	• Non-pointing photons • Weakly interacting LLPs in the MS • Displaced muonic jets

CMS Recent Results

$\sqrt{s} = 8$ TeV	• Displaced SUSY • HSCP decays • Neutral LLPs decaying to lepton pairs • Neutral LLPs decaying to dijets • Stopped particles
$\sqrt{s} = 7$ TeV	• HSCP decays • Stopped Particles • Long-lived neutralinos using displaced Photons • Neutral LLPs decaying to lepton pairs