Search for New Physics with Long-Lived Particles at the LHC

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New Physics and Long-Lived Particles

Long-lived exotic particles (LLP) with **striking signatures** **predicted by many extensions of the Standard Model**

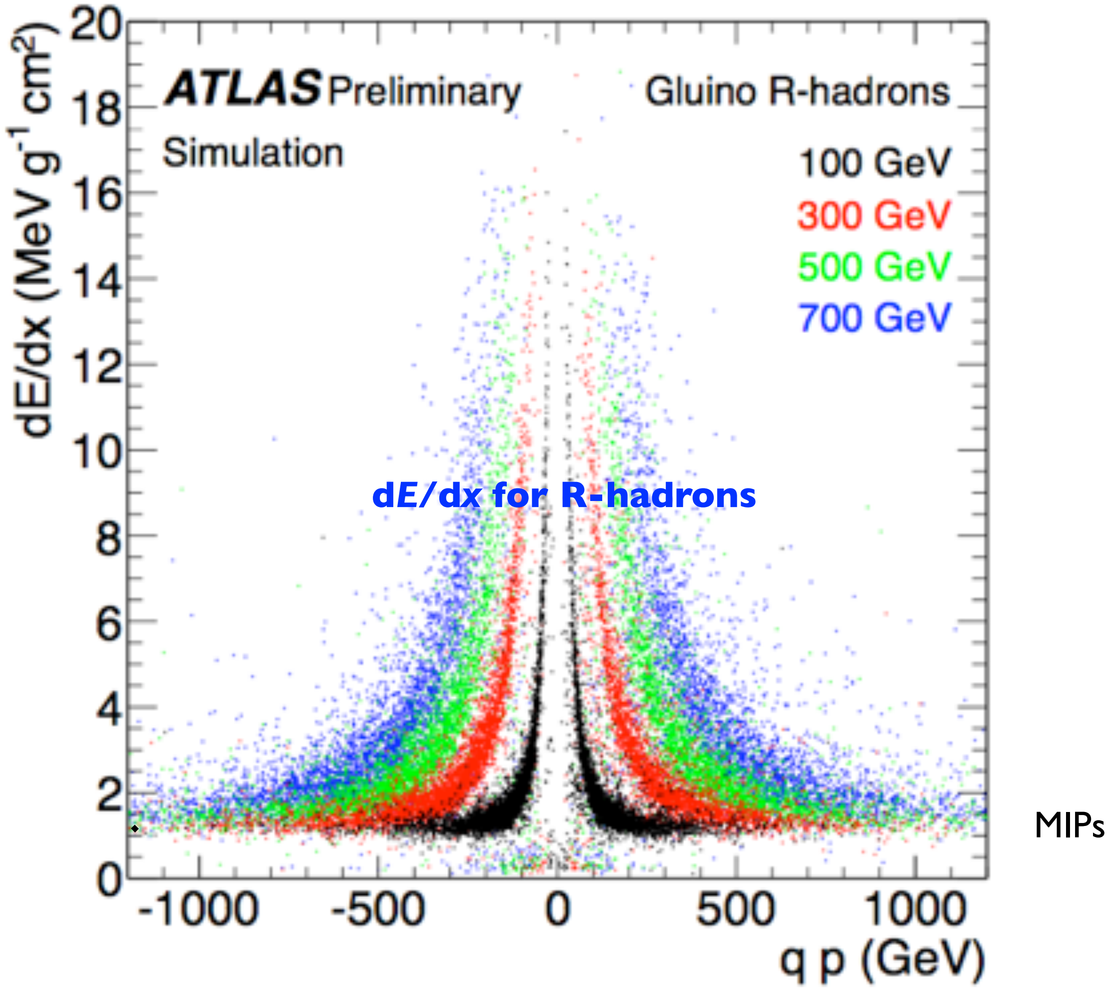
- **Heavy, long-lived, charged particles** (R-hadrons, Sleptons)
  - speed < c
  - charge not equal to ±1e
  - lifetimes > few ns. Travel distances larger than the typical collider detector and appear stable
- **Particles decaying in the detector far from interaction point** (neutralinos in GMSB, mass-degenerate gauginos, particles of a Hidden Sector)
  - decay in displaced vertexes (jets, leptons, photons)
  - delayed interaction with calorimeters due to extra flight-length

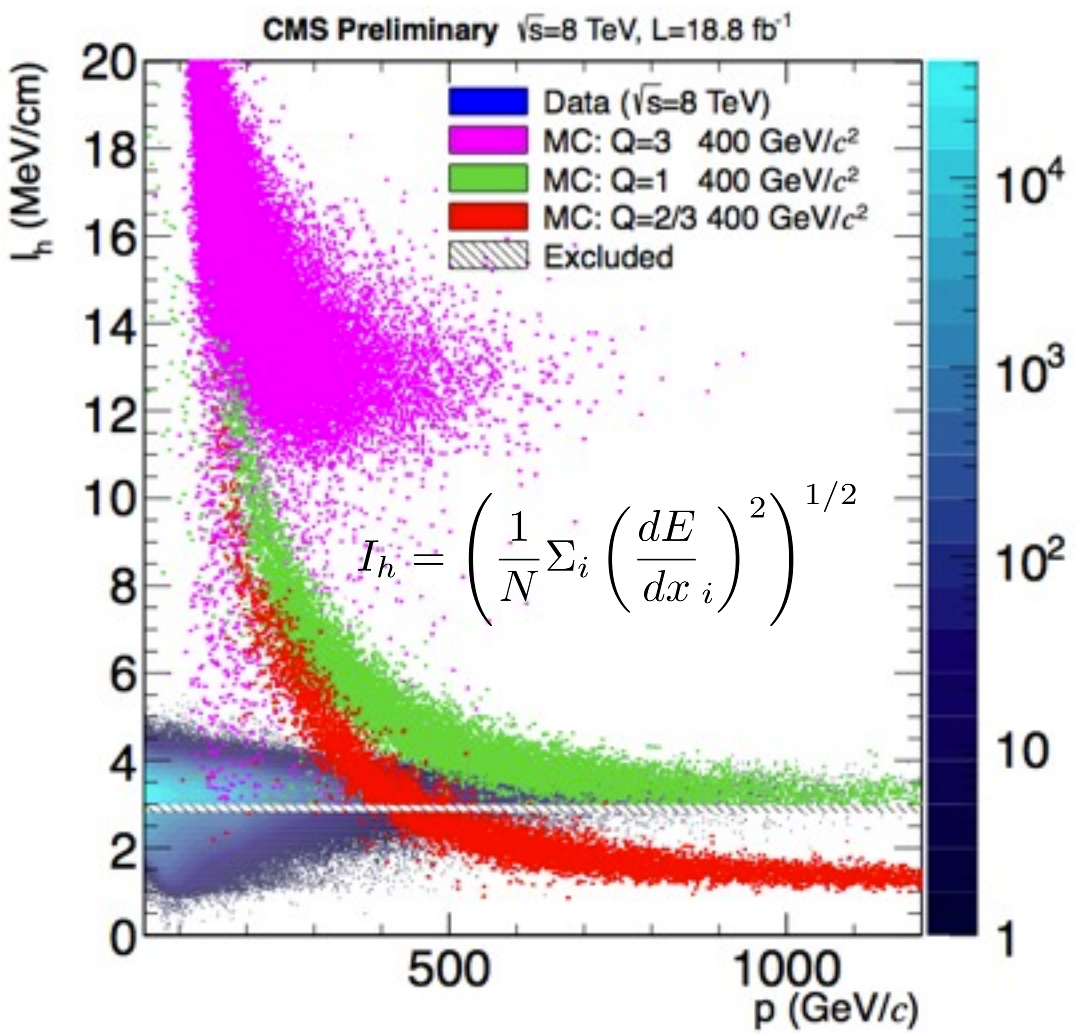
TYPICAL LONG-LIVED ANALYSIS

- **Detector-based exotic signatures** required:
  - dE/dx
  - time of flight
  - displaced vertex
  - disappearing tracks
  - stopped particles
- **Possible additional requirements** to identify SUSY-like topology:
  - MET
  - large jet activity (H_T, p_T(leading jet)>threshold)
  - the less the extra requirements, the smaller the model dependence
- **Specific control samples** to model exotic signature in detector:
  - non-trivial job. LLP signatures look like detector noise
  - deep knowledge of detector performance

SIGNATURES: DE/DX

- **Large ionization** left in tracker detectors by high mass **R-hadrons or sleptons**
- **Enhanced if charge ≠ 1**

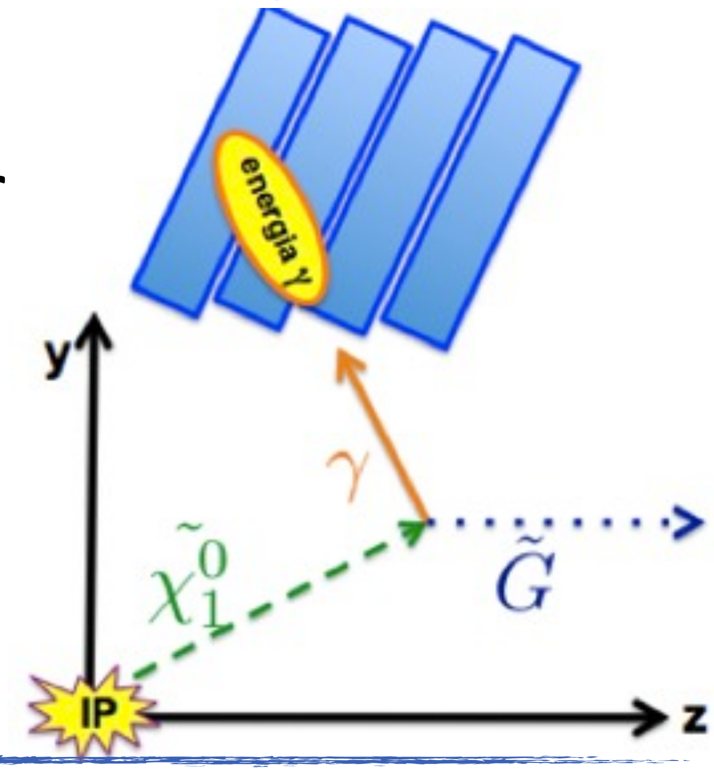




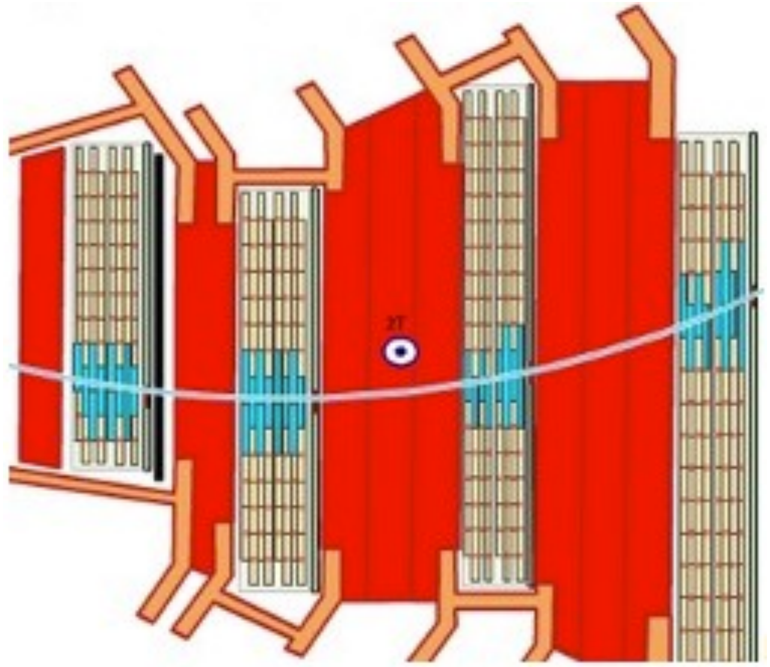
Signatures: Time of Flight

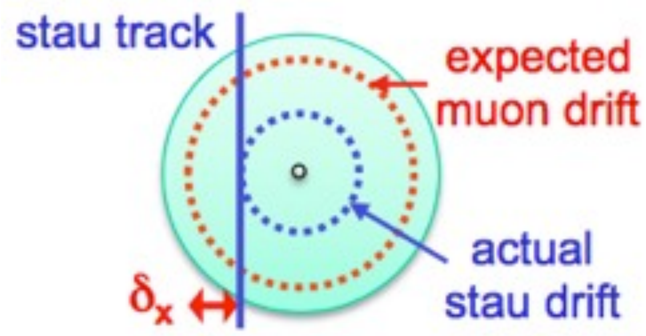
Neutral particles

- **produced in flight** (also from slow particles) and far from beam spot
- **time of arrival at calorimeter longer** than for SM contribution coming from beam spot
- tagged looking at measured timing



Slow moving high mass stable charged particles identified using **timing measured in muon system and calorimeter**





$$\beta^{-1} = 1 + \frac{\delta_x}{L}\frac{c}{v_{drift}}$$

averaged over all layers

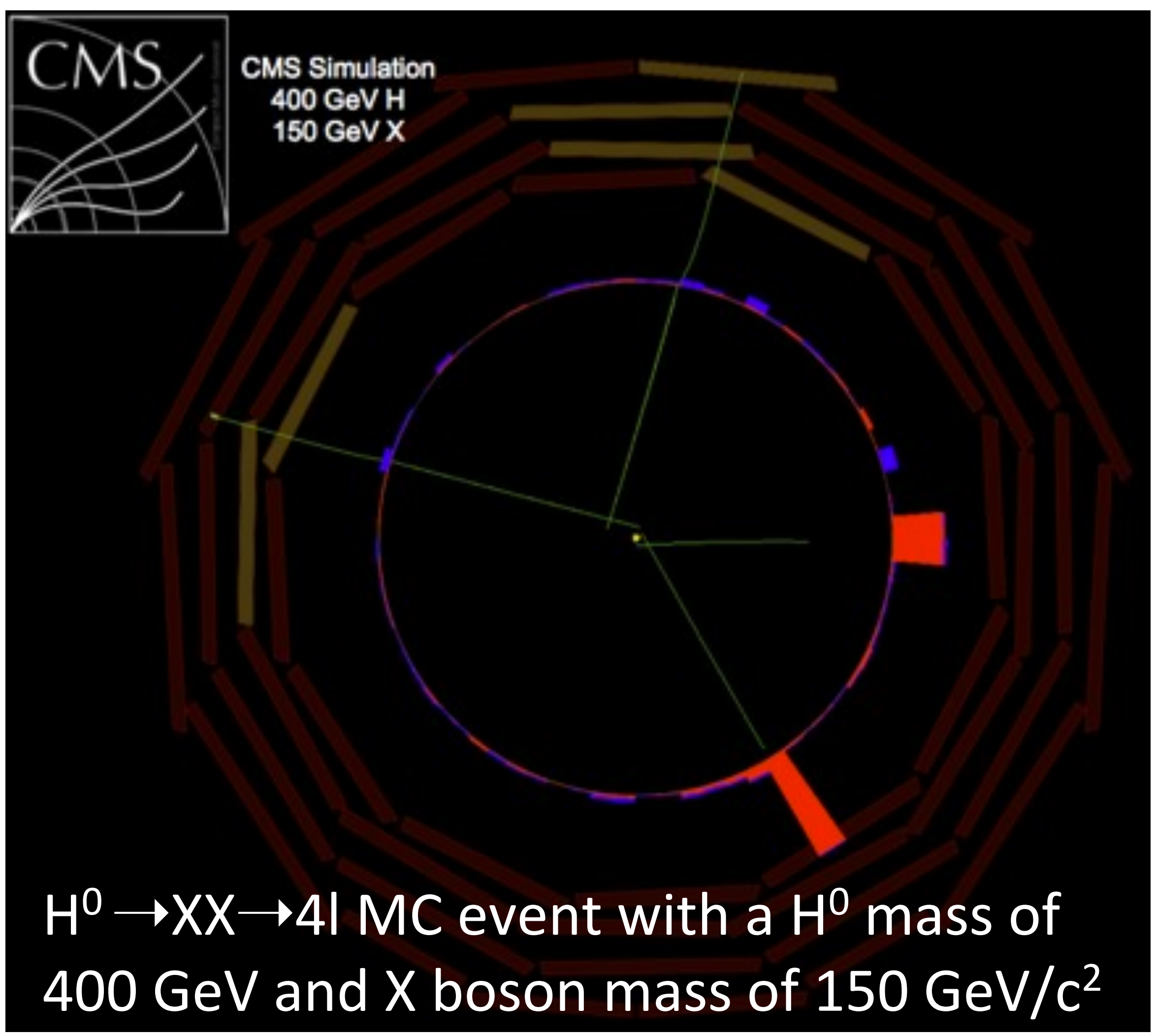
example for CMS drift tubes

L=flight distance

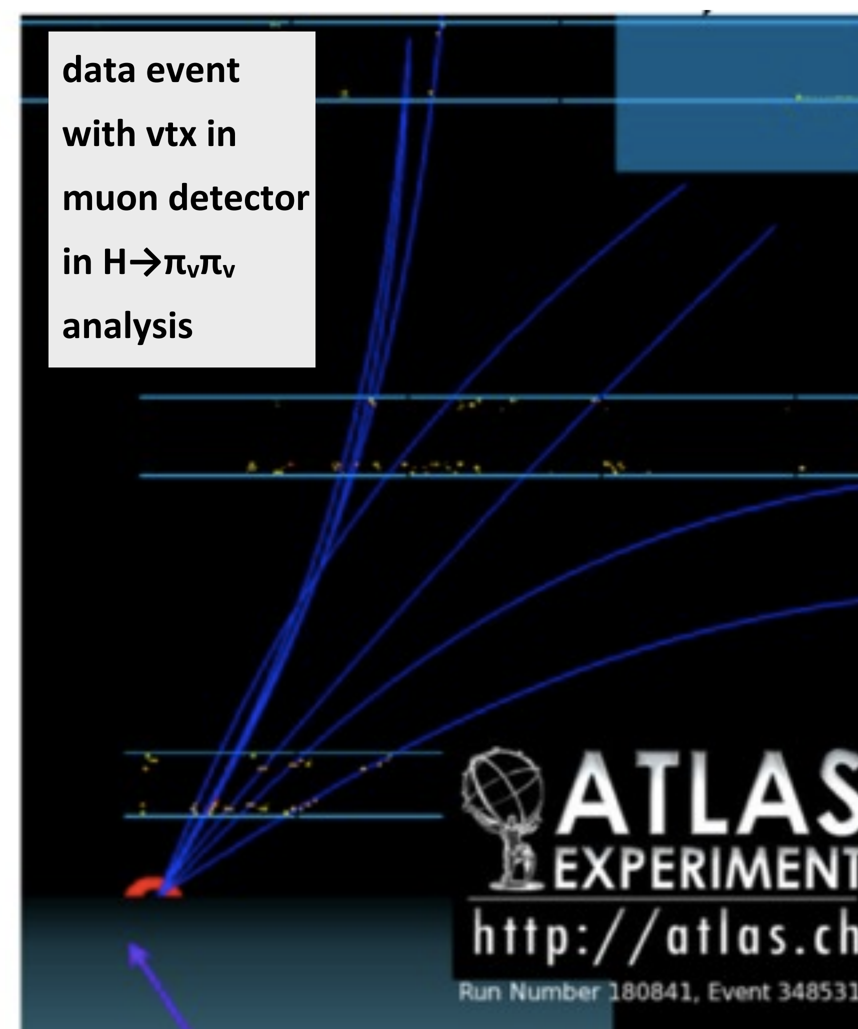
β obtained as an average over the detector hits

SIGNATURES: DISPLACED VERTEXES

- **Long-lived particles decaying in charged particles** (hadrons, leptons) **identified via vertexing**
- **Requirement of small activity** along the track in detector sectors closer to the beamspot



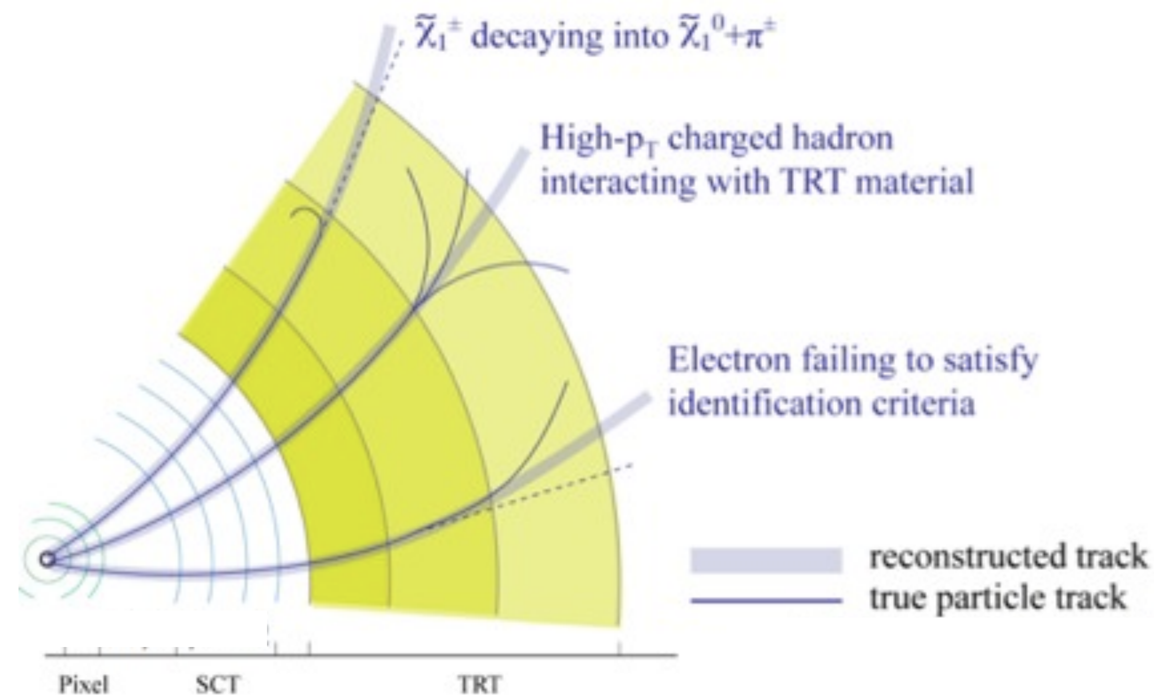
$H^0 \to XX \to 4l$ MC event with a H^0 mass of 400 GeV and X boson mass of 150 GeV/c^2



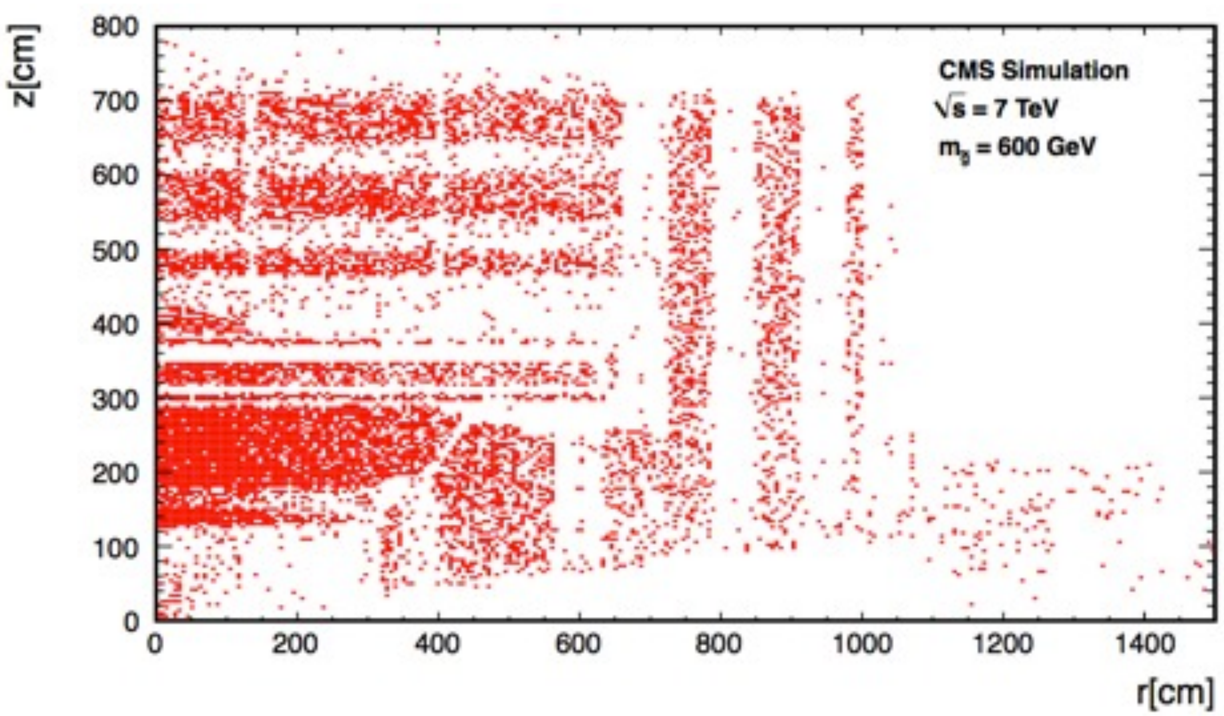
SIGNATURES: DISAPPEARED/STOPPED PARTICLES

Long-lived charged exotic particles decaying in flight within the detector

- identified as **truncated tracks**
- **small activity in the calorimeter** along the propagated track direction
- track inefficiency need to be modeled carefully



Stopping position in r-z view for a 600 GeV gluino



- **charged particles** with low velocity may **stop in detector volume**
  - preferentially in the densest detector elements (calorimeters)
- When decaying, **energy deposit similar to jet**
- **Searched when no pp collision** (gaps between proton bunches)

FIRST SUMMARY ON LONG-LIVED SEARCHES

- **Several striking exotic signatures**
  - some searches use more than one
- **Very generic searches**, driven by signatures
  - open-minded searches
  - **models are used as benchmark** to report results
- **Limits are very model dependent**
- Results are **limited by detector acceptance and triggers** (non-standard signatures)
  - difficult to find good control samples
- **Experimentally challenging analyses**
  - look where background for SM analyses is
  - implementation of ad-hoc triggers

HEAVY STABLE CHARGED PARTICLES

- **sleptons**: massive, charged and metastable in GMSB
- **R-hadrons**: bound states formed by **squarks and gluinos** hadronizing with a light SM quarks system, several **electric charges** (and the electric charge can change due to nuclear scattering in the detector)

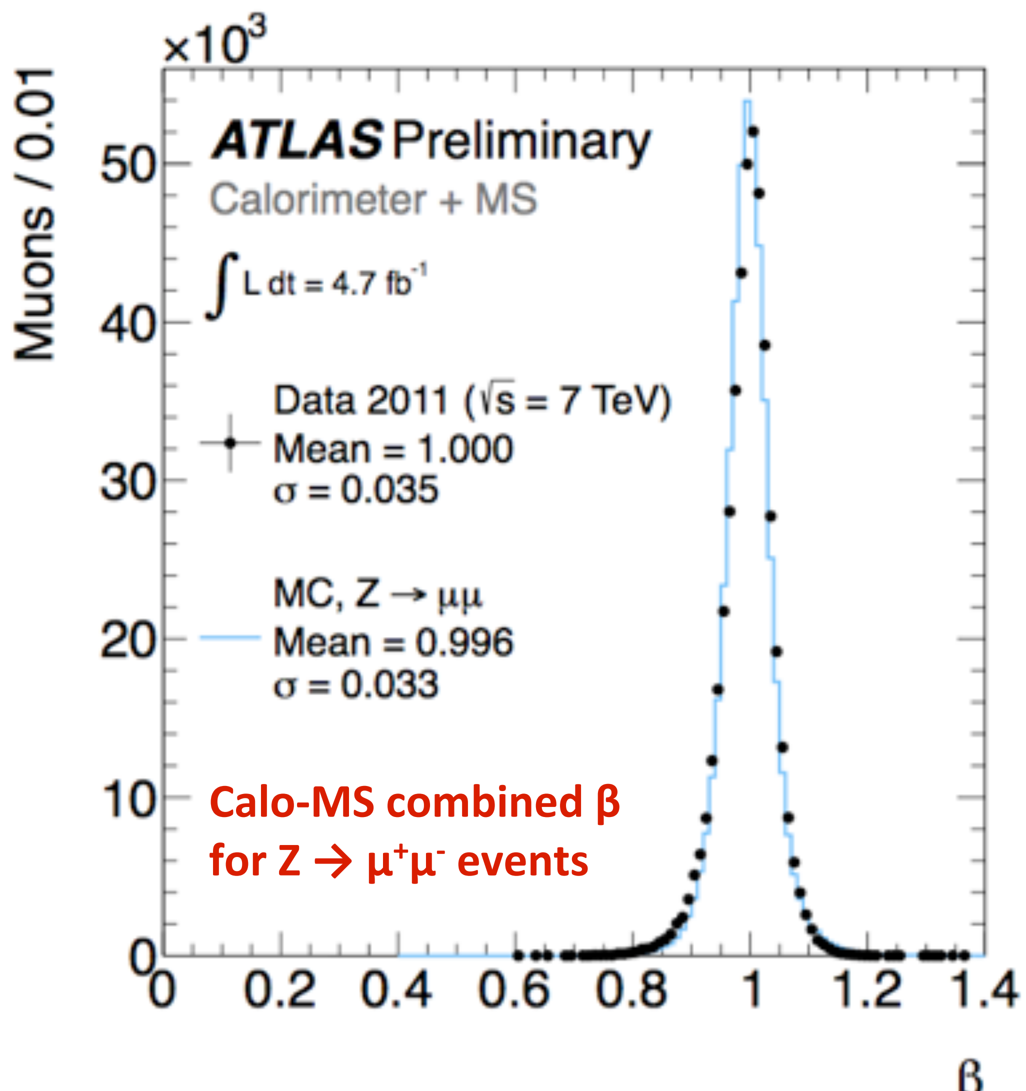
	composition	notation
R-mesons	$R = \tilde{g}q\bar{q}, (\tilde{q}\bar{q})$	R^+, R^-, R^0
R-baryons	$R = \tilde{g}qqq, (\tilde{q}qq)$	R^{++}, R^+, R^-, R^0
R-gluinoballs	$R = \tilde{g}g$	R^0

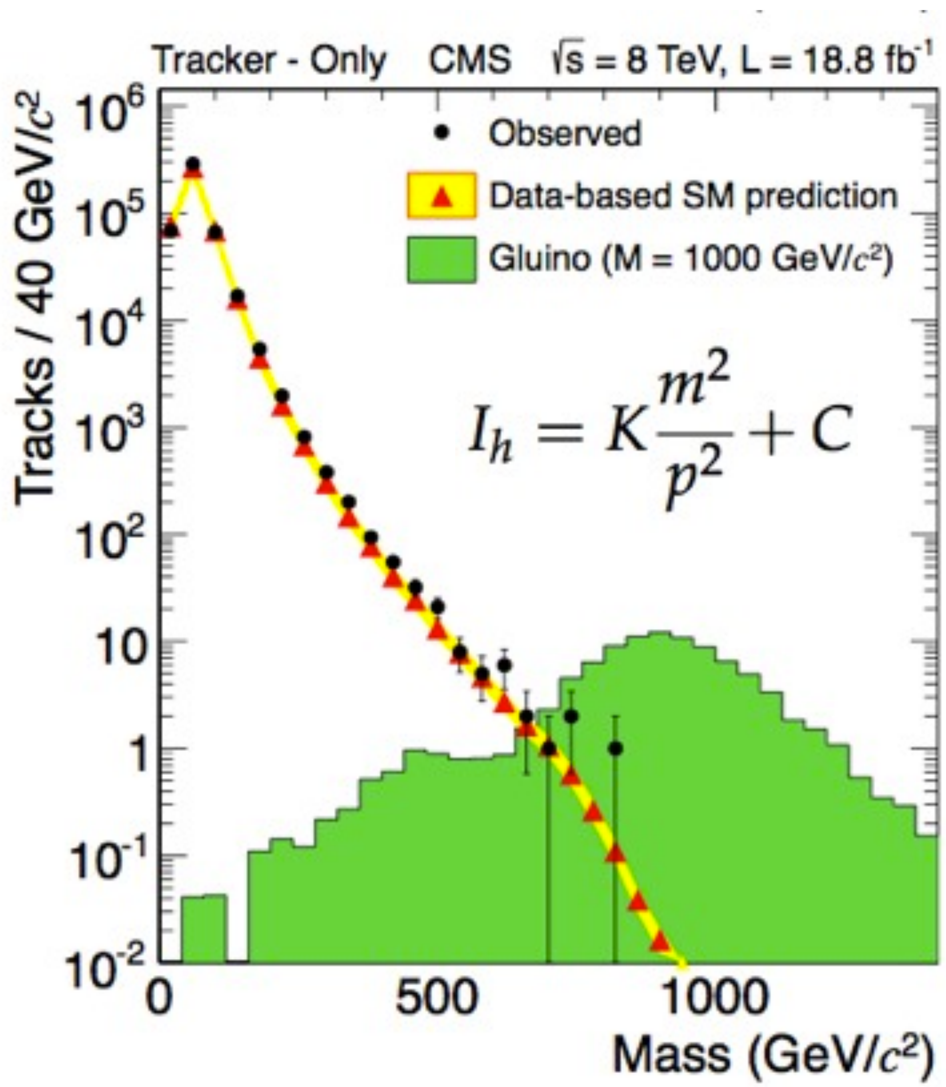
arXiv:hep-ph/0611040

SMP	LSP	Scenario	Conditions
$\tilde{\tau}_1$	$\tilde{\chi}_1^0$	MSSM	$\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, μ, $\tan\beta$, and A_τ) close to $\tilde{\chi}_1^0$ mass.
	$\tilde{G}$	GMSB	Large N, small M, and/or large $\tan\beta$.
		$\tilde{g}$MSB	No detailed phenomenology studies, see [23].
		SUGRA	Supergravity with a gravitino LSP, see [24].
	$\tilde{\tau}_1$	MSSM	Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large A_τ.
		AMSB	Small m_0, large $\tan\beta$.
		$\tilde{g}$MSB	Generic in minimal models.
$\tilde{\ell}_{i1}$	$\tilde{G}$	GMSB	$\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and μ.
	$\tilde{\tau}_1$	$\tilde{g}$MSB	$\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.
$\tilde{\chi}_1^+$	$\tilde{\chi}_1^0$	MSSM	$m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg |\mu|$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll |\mu|$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{GS} = -3$.
		AMSB	$M_1 > M_2$ natural. m_0 not too small. See MSSM above.
$\tilde{g}$	$\tilde{\chi}_1^0$	MSSM	Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY.
	$\tilde{G}$	GMSB	SUSY GUT extensions [25–27].
	$\tilde{g}$	MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.
		GMSB	SUSY GUT extensions [25–29].
$\tilde{t}_1$	$\tilde{\chi}_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and M_3, small $\tan\beta$, large A_t.
$\tilde{b}_1$			Small $m^2_{\tilde{q}}$ and M_3, large $\tan\beta$ and/or large $A_b \gg A_t$.

HSCP: Analysis Technique

- **Information from dE/dx and p_T** (tracker) used to calculate **mass**
- **Time of flight** from muon detector and calorimeters to **measure β**
  - calibrated using cosmics and $Z \to \mu^+\mu^-$
- **Background** dominated by high p_T, **mis-reconstructed muons**

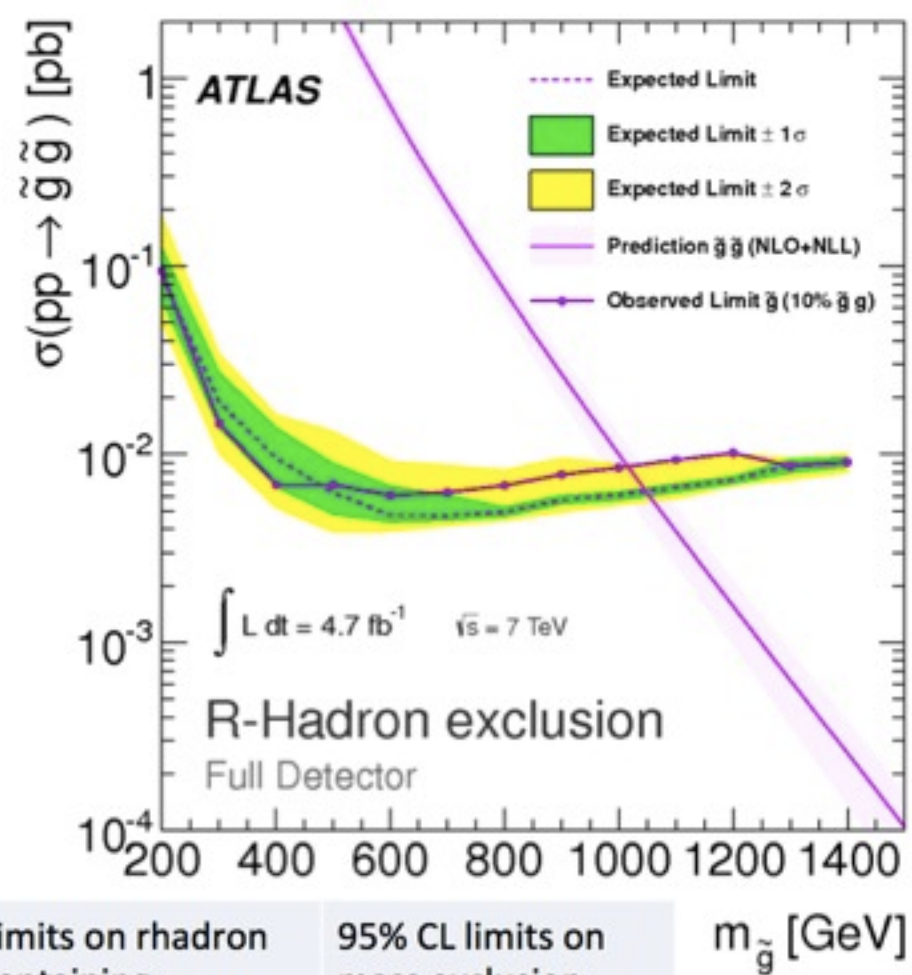




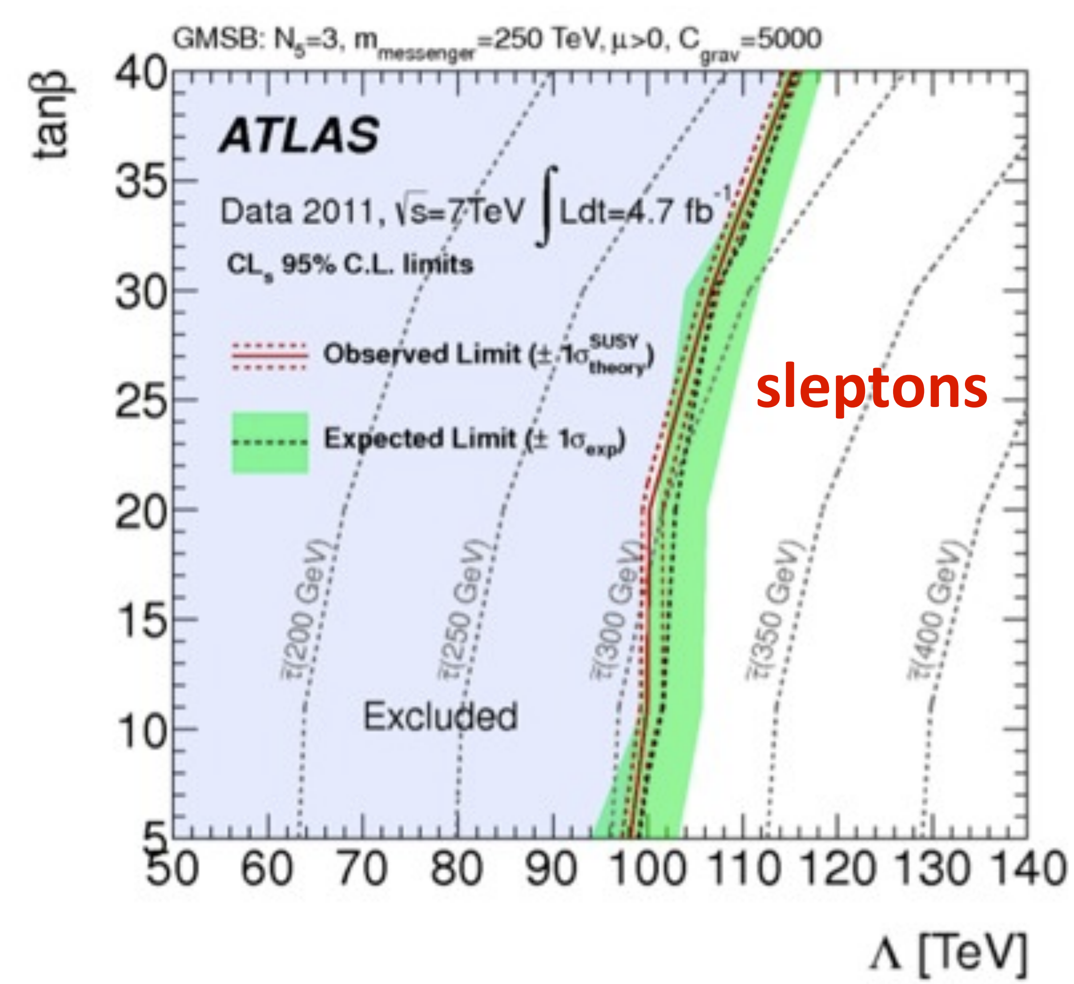
HSCP RESULTS: ATLAS

- **No indication of signal** above expected background
- Cross-section **limits at 95% confidence level** → translating into limits on the **R-hadron/slepton mass**

http://arxiv.org/abs/1211.1597



Limits on rhadron containing	95% CL limits on mass exclusion
gluino	985 GeV
stop	683 GeV
sbottom	612 GeV

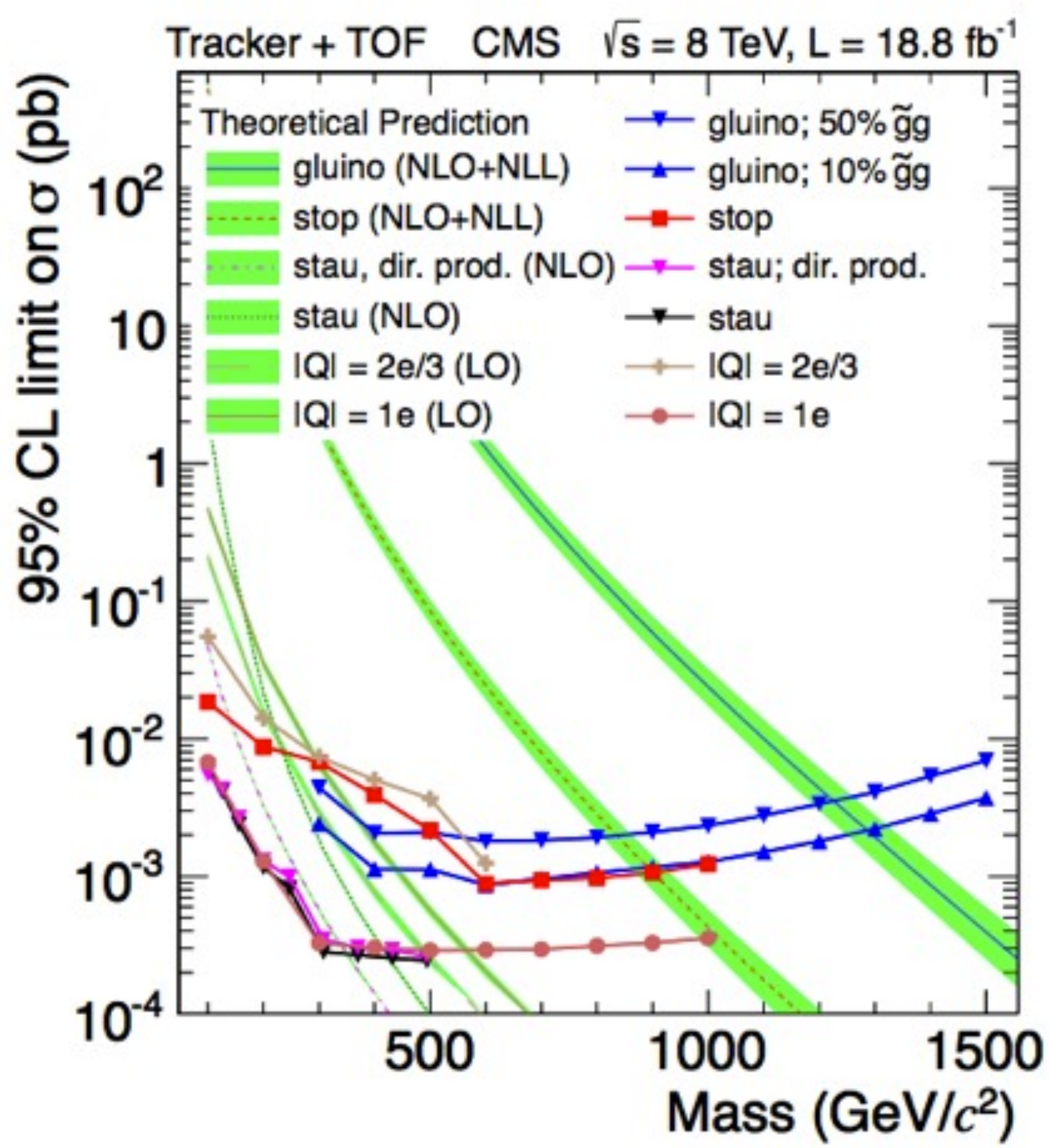


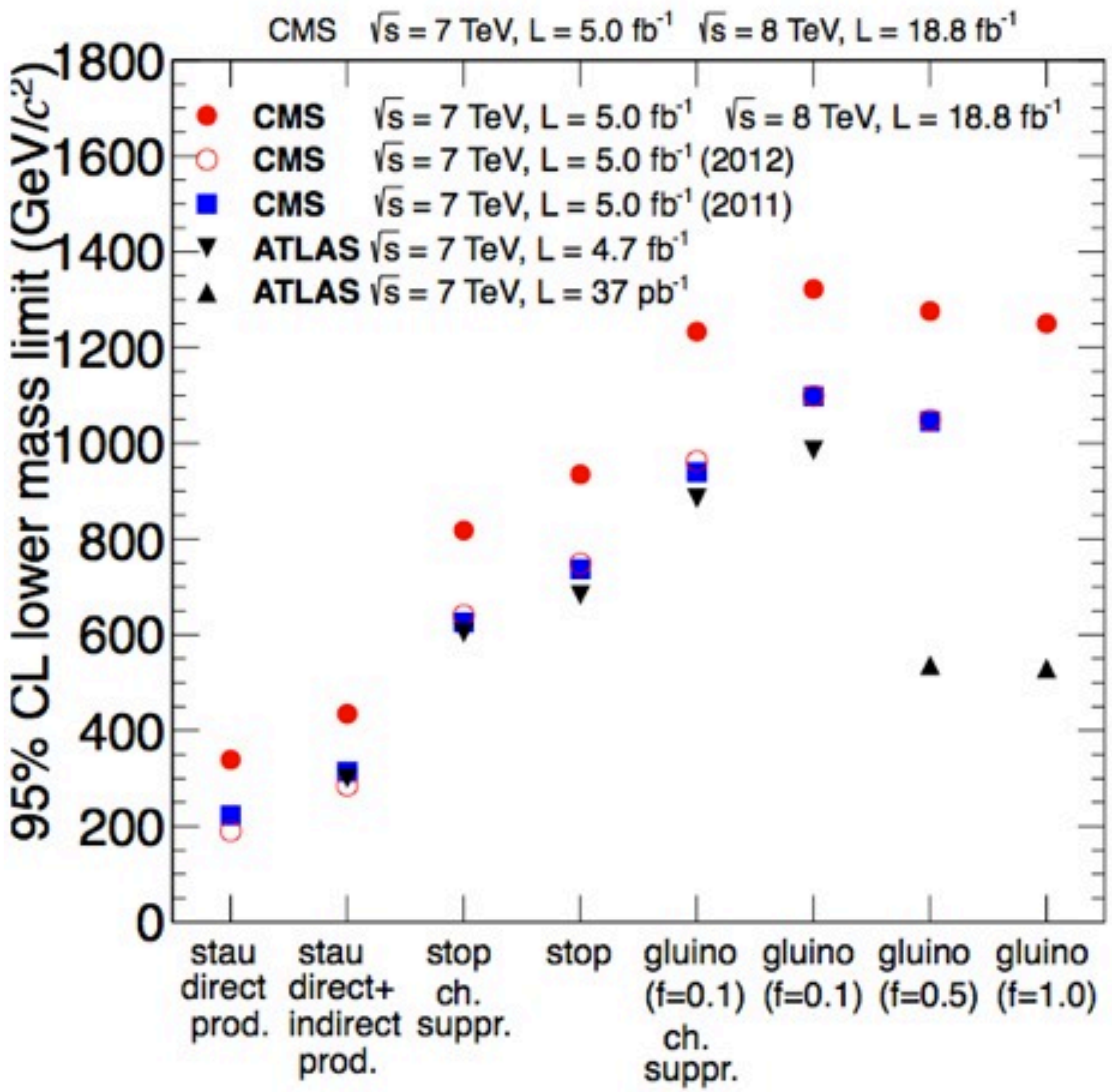
***m*(GMSB τ̃)**	> 300 - 268 GeV, 5<tanβ<40
***m*(directly produced sleptons)**	> 278 GeV, 5<tanβ<40

HSCP Results: CMS

- **Results with ~19fb^{-1}. No excess observed**
- Results for **fractional/multiple charge too**

http://arxiv.org/abs/1305.0491



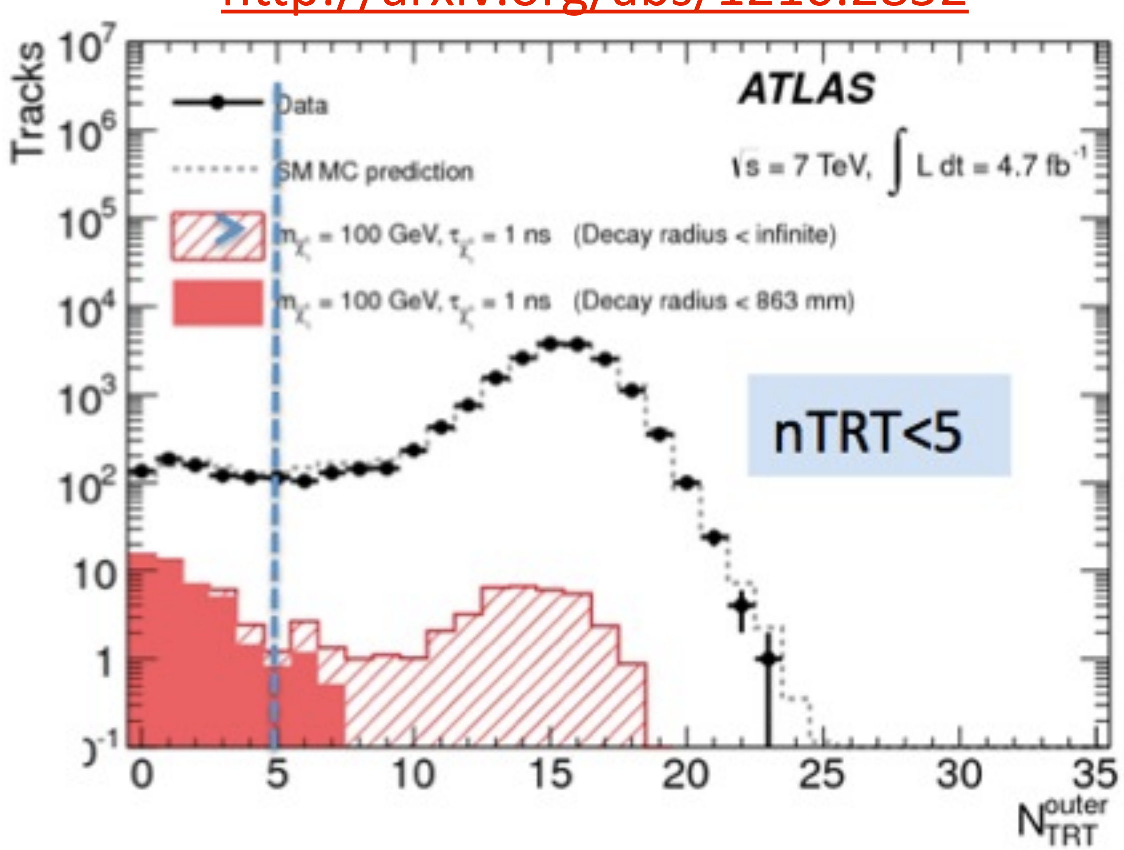


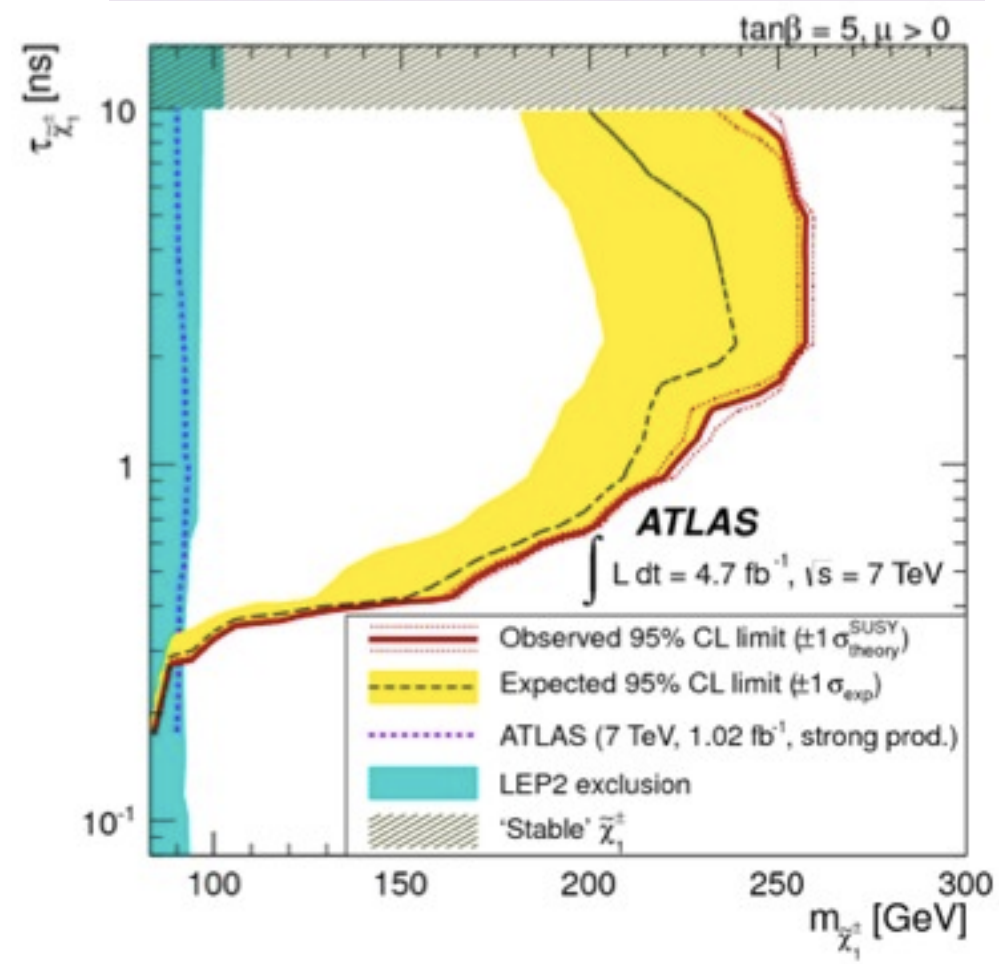
Disappearing Tracks

- In scenarios with **mass-degenerate gauginos** (predicted by AMSB)
  - chargino lifetime O(0.1 ns), decay to neutralino and low E pion
- Selected as tracks with **missing hits in transition radiation trk (TRT)**
- Triggered **with ISR jet**
- **No excess**

For Δm ~ 160 (170) MeV (most probable in AMSB), m(chargino) up to 103 (85) GeV is excluded

http://arxiv.org/abs/1210.2852

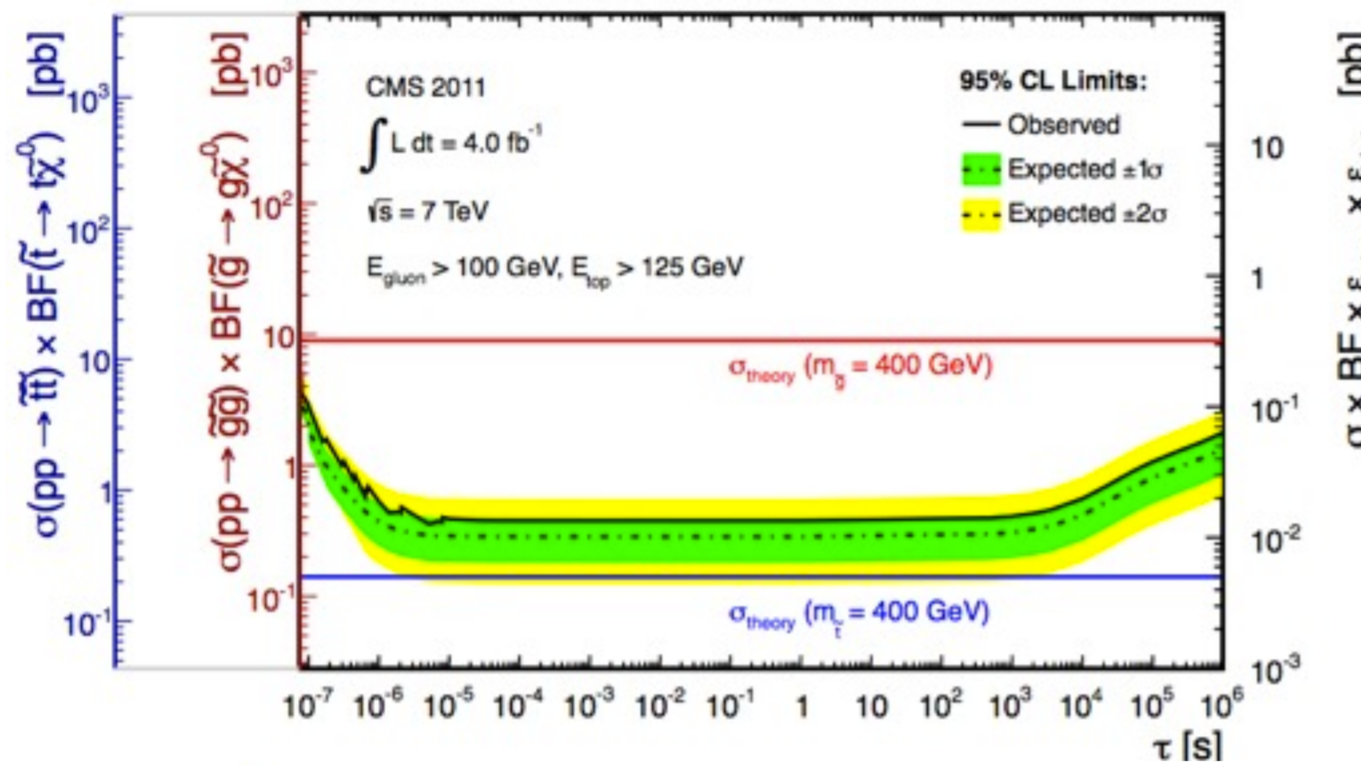


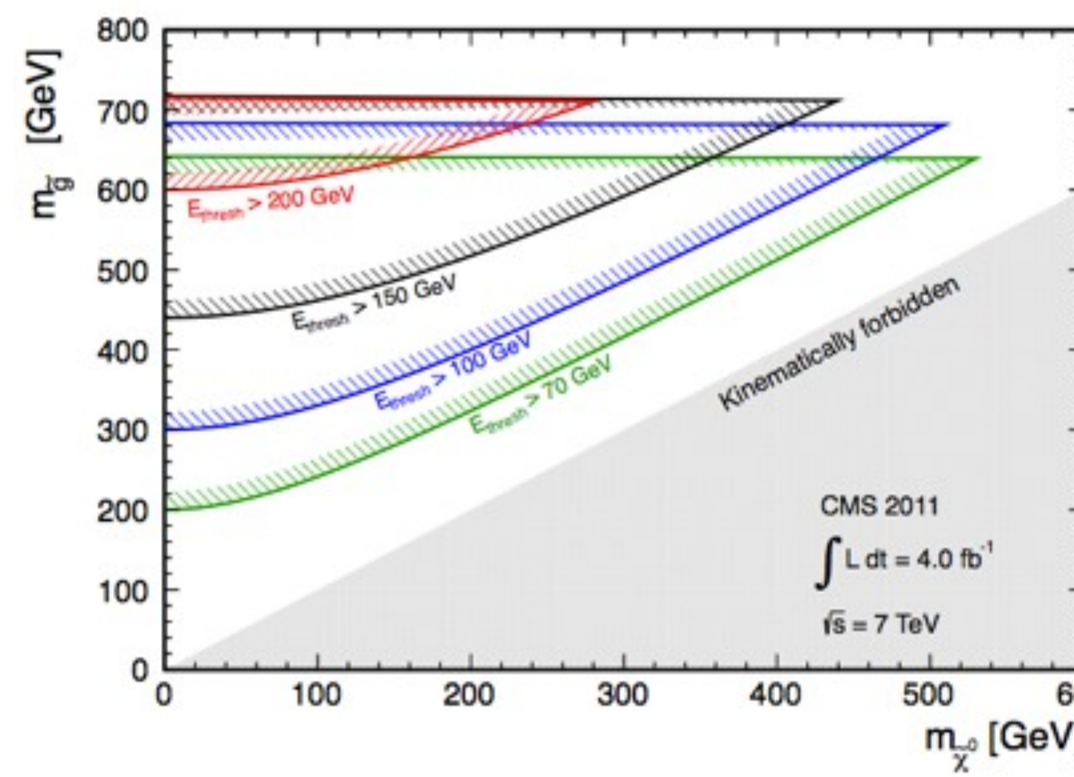


Stopped Particles

http://arxiv.org/abs/1207.0106

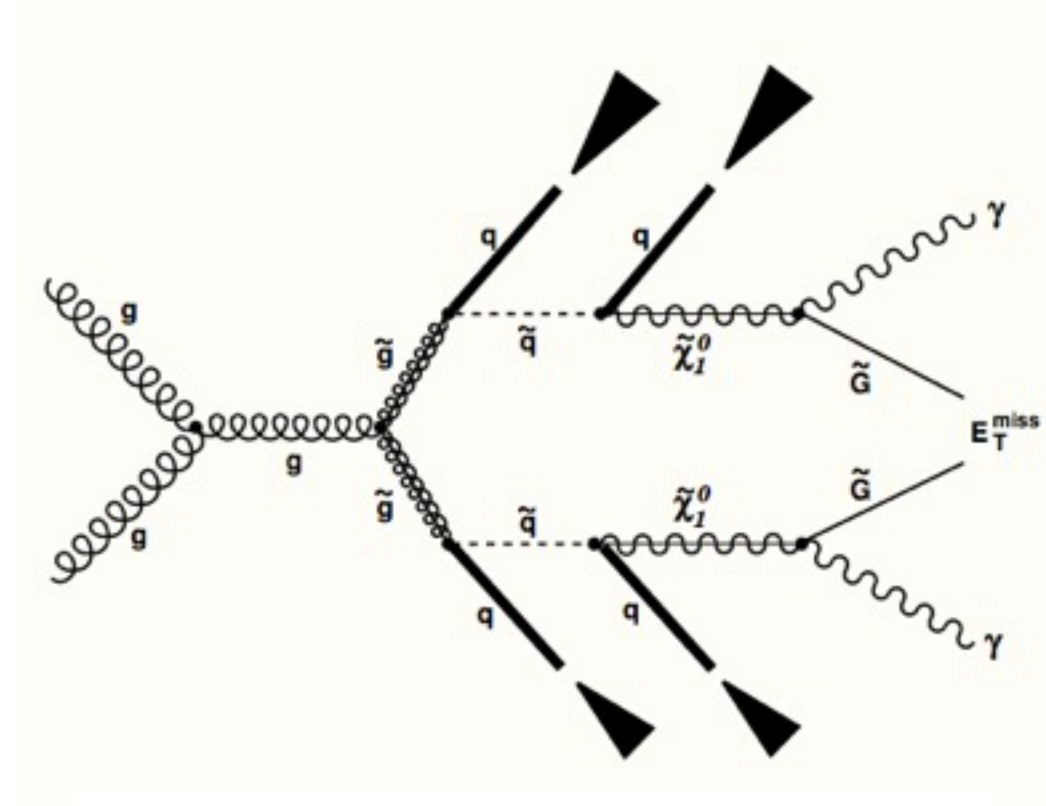
- **Dedicated calorimeter trigger** to selected events in **gaps between LHC beam crossings**
  - p_T(jet)>50GeV
- Search interval of 246 hours
- **Selection based on jet p_T (>70GeV) and criteria to reject residual backgrounds**
  - beam halo, cosmics, out-of-time pp collisions, detector noise
- Limits presented in a **long-lived gluino or stop in R-hadrons scenario**

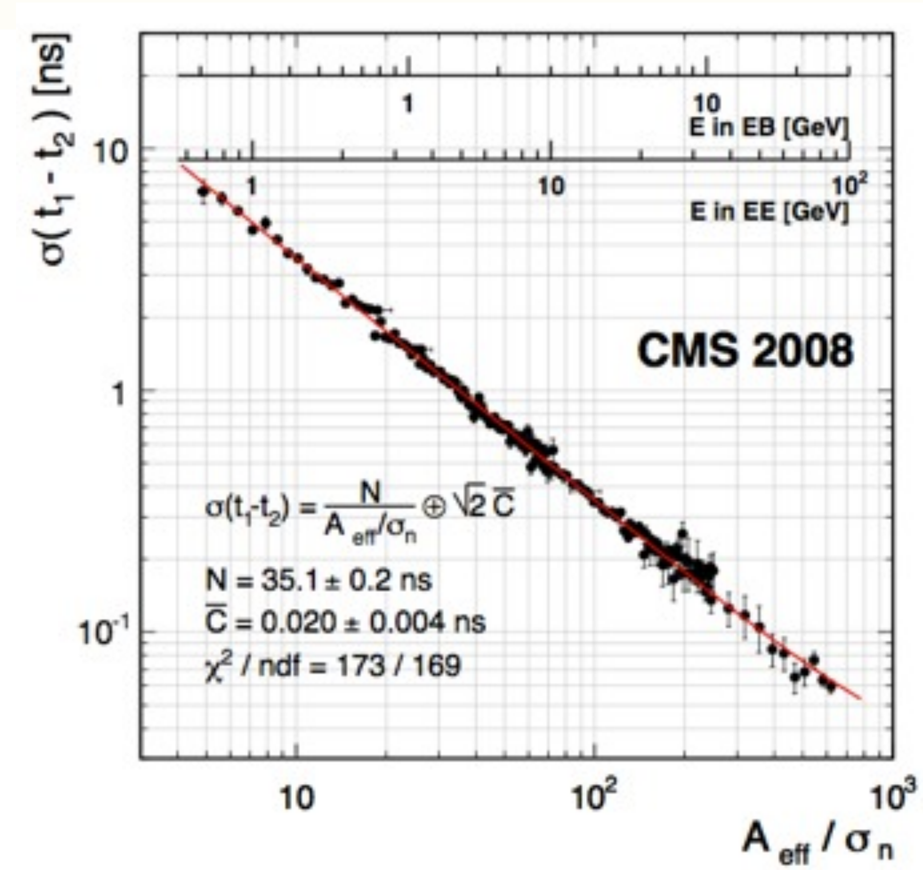




DISPLACED PHOTONS: THEORY AND ANALYSIS

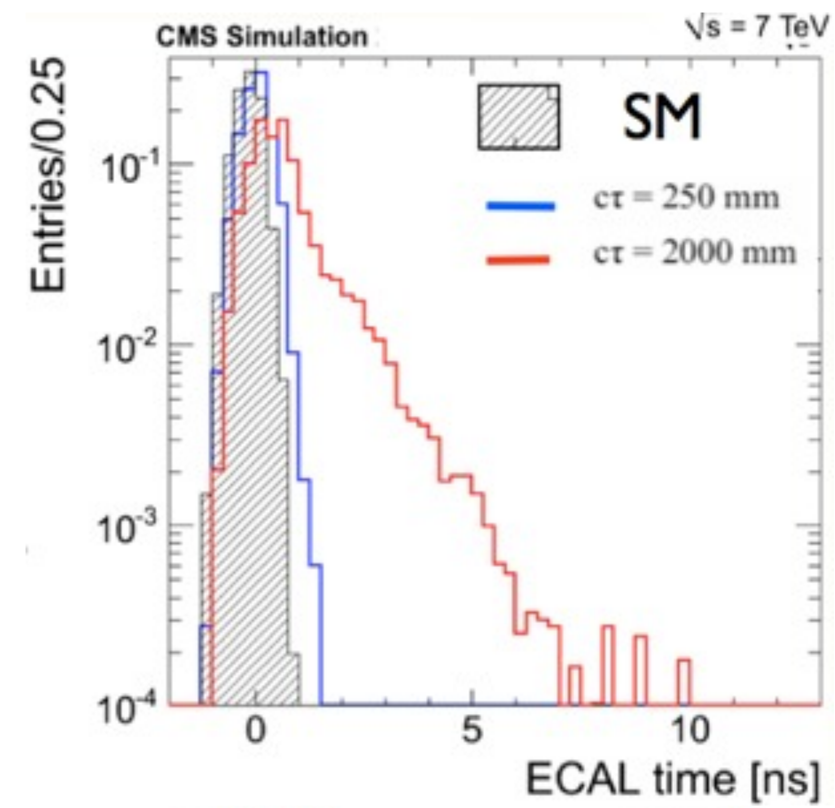
- In models like **Gauge Mediated Supersymmetry Breaking**, Neutralino decays to Gravitino (lightest susy particle)
  - Missing ET
  - high pT jets and one or two photons
- **Neutralino can be long-lived**
  - displaced/delayed photons
- **Tagged using em calorimeter time and pointing direction**
  - design time resolution: 100 ps or better
  - 1.5 cm pointing resol. with ATLAS calorimeter
- **Topology requirements**
  - >=1 γ p_T>100GeV CMS, 2 γ p_T>50GeV ATLAS
  - large Missing E_T

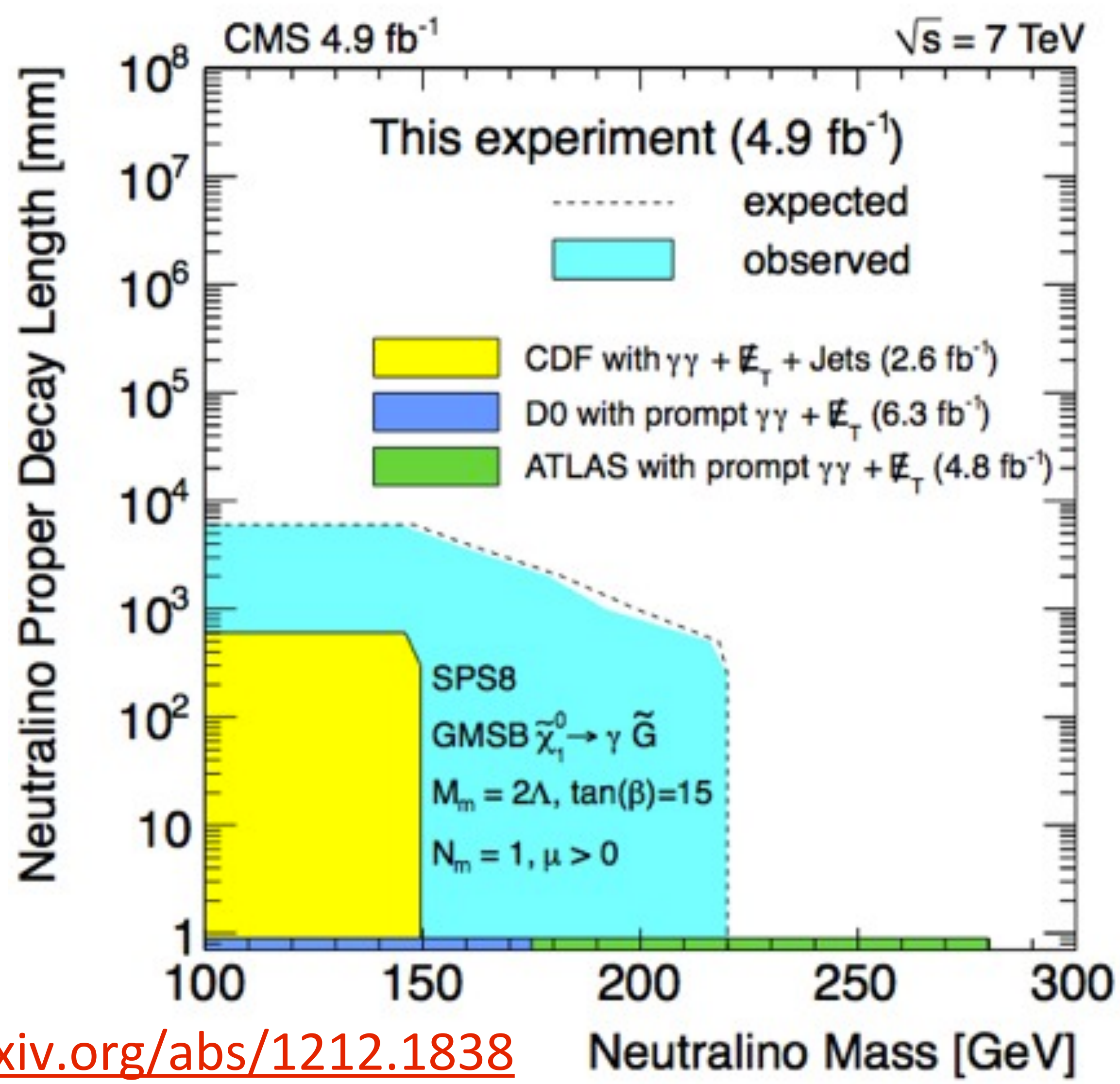


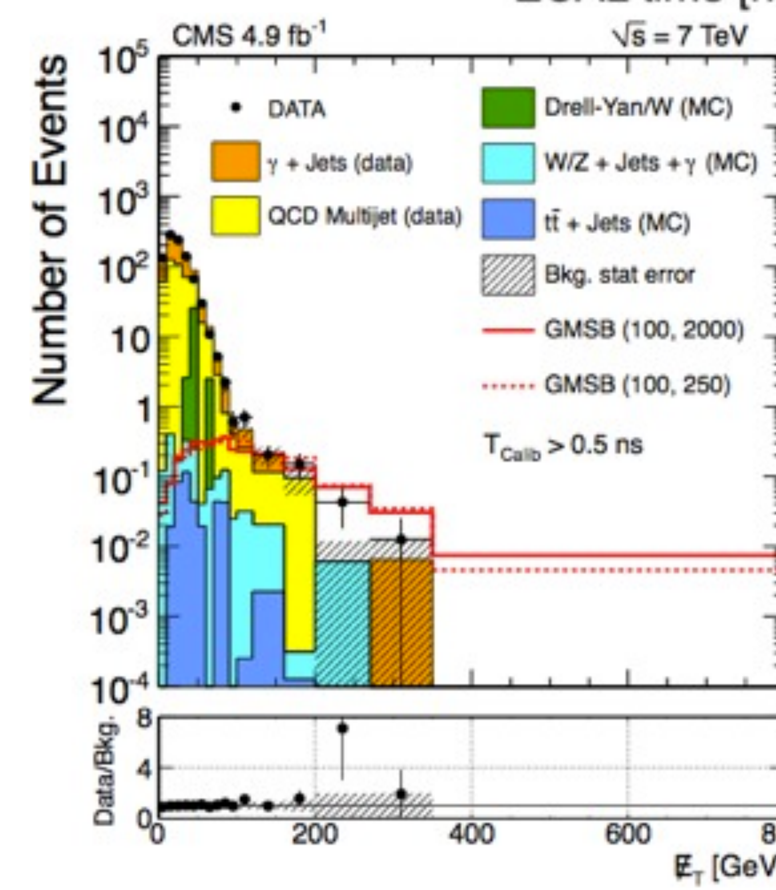


DISPLACED PHOTONS: CMS RESULTS

- Additional requirement of 3 high p_T jets
- **No excess observed**
- Limits are set varying **Neutralino masses and lifetimes**



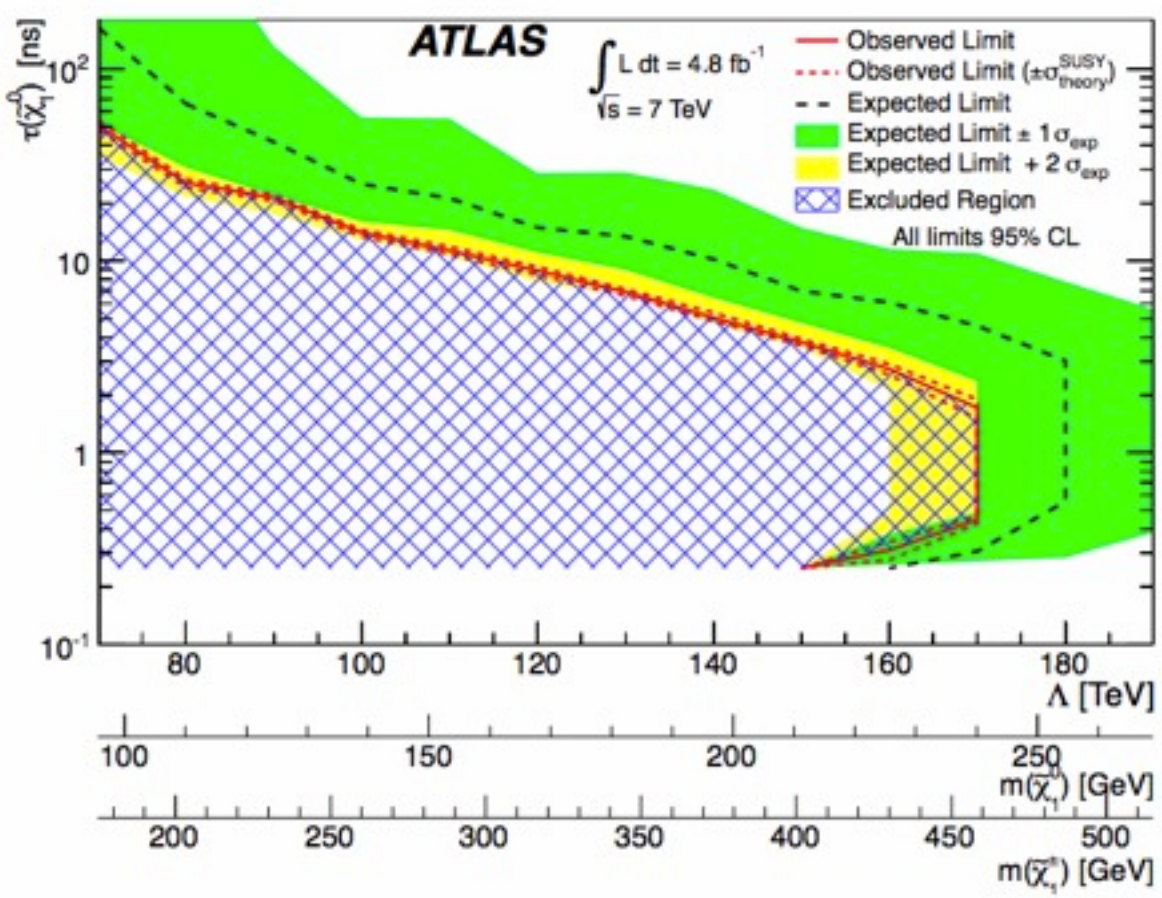


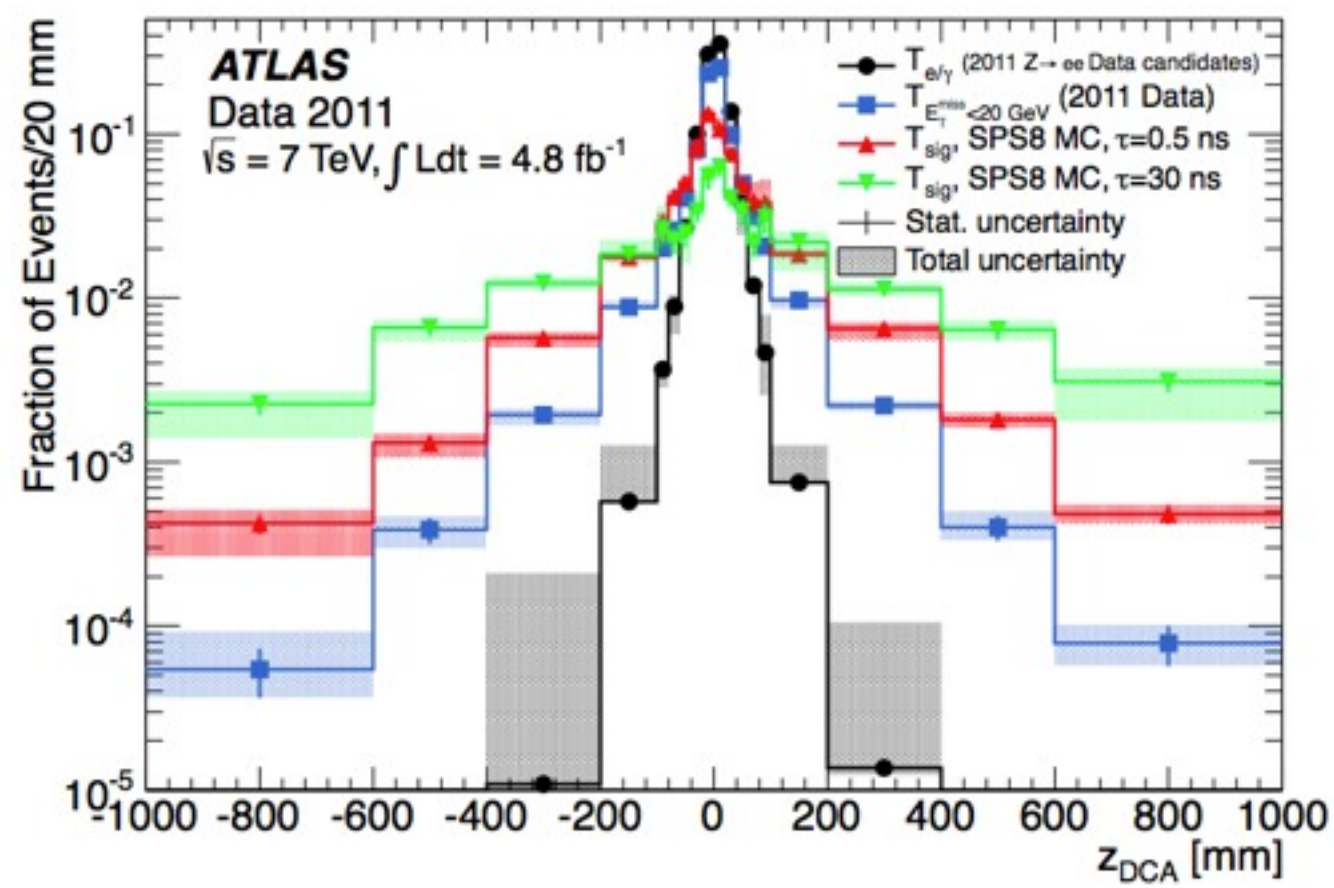


http://lanl.arxiv.org/abs/1212.1838

DISPLACED PHOTONS: ATLAS RESULTS

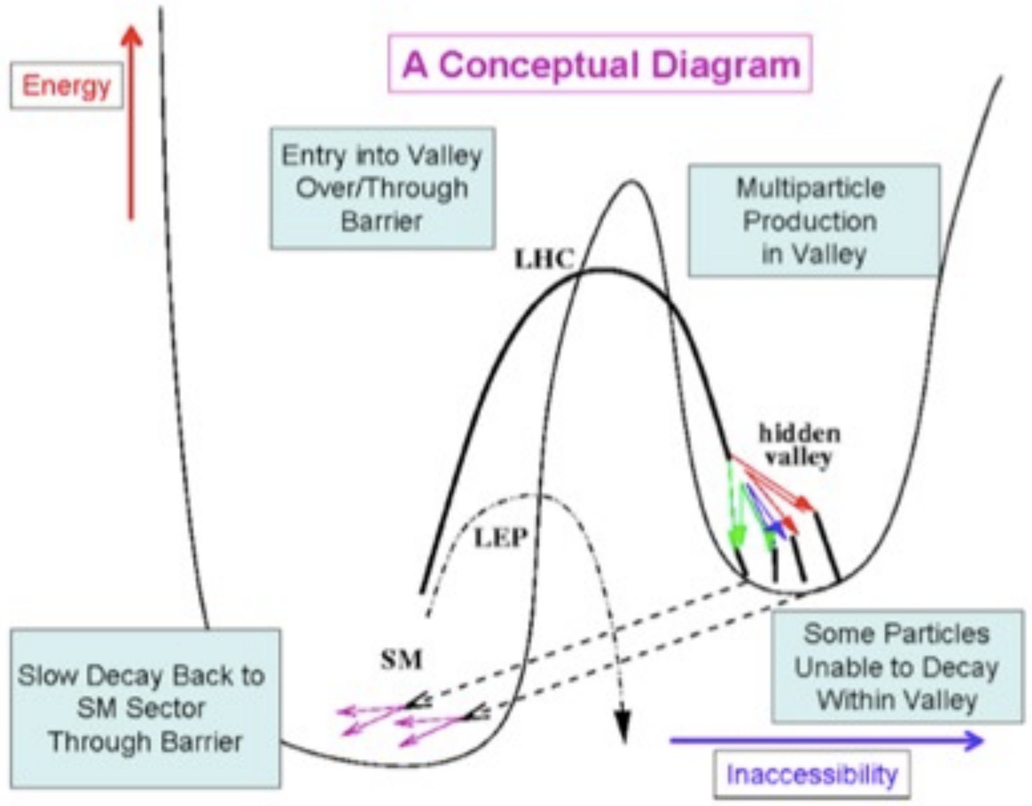
- Use of **distance of closest approach** of the projected photon direction
  - **timing** also as a crosscheck
- Requirement of two high p_T photons
- **No excess observed**





DISPLACED VERTEXES: MODELS

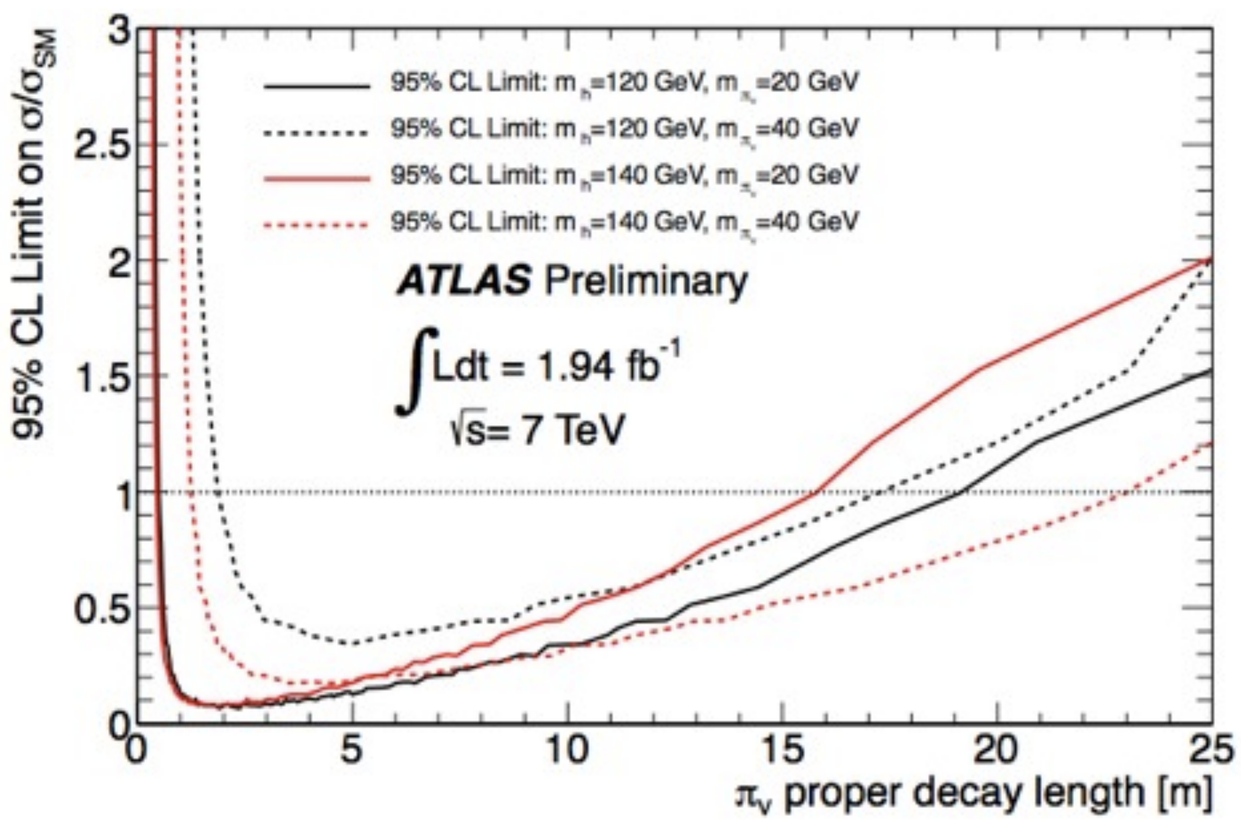
- **Hidden Sector weakly coupled to SM**
  - motivated by $(g\text{-}2)_\mu$ and Pamela results
- Communicate through **heavy mediator particles** (Higgs, Z´, loop of SUSY particles)
- **Heavy particles** (e.g. Higgs boson) **decay to particles of the hidden sector** and back to the standard sector via:
  - hadronic jets
  - collimated jets of leptons: lepton-jets
- Hidden particles can be long-lived and neutral
- **Identified reconstruction displaced vertexes**

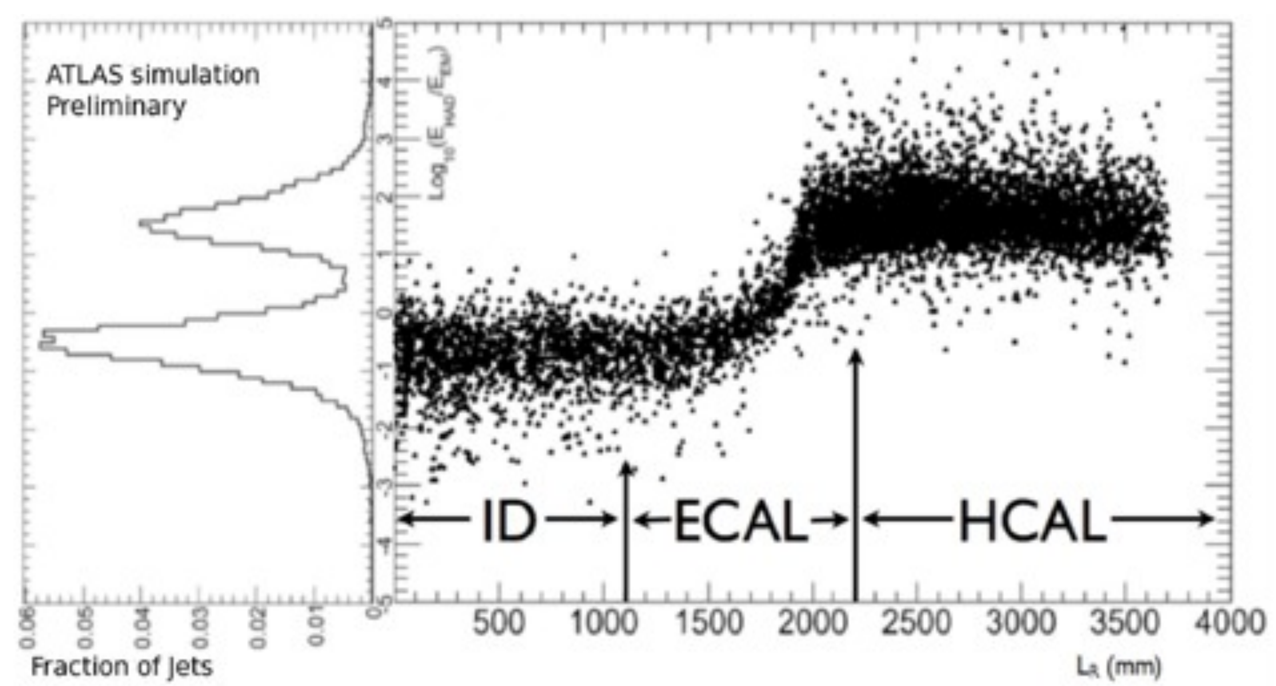


Displaced Heavy Fermions

- **Pairs of back-to-back neutral particles decaying in the muon system** (2 vertices in muon system, isolation in calorimeter)
- **Signature of H→$\pi_v\pi_v$** where π_v is a long-lived pseudoscalar from Hidden Sector decaying **to heavy fermion pair** (mainly b-bbar)
- **No excess.** Limits assuming π_v assuming 100% BR of h→$\pi_v\pi_v$
- Ongoing **developments** to use also **inner tracking and to search for π_v decaying in calorimeters**

Phys.Rev.Lett. 108 (2012) 251801





DISPLACED LEPTONS: MUON JETS IN ATLAS

- **Signature**: **two isolated boosted pairs of muons with displaced vertex** (reco'ed only with Muon System)
- Benchmark model: **$H \rightarrow 2\, f_{d2}$, $f_{d2} \rightarrow LSP + \gamma_d$**
  - γ_d is a dark photon (long-lived) and f_{d2} an hidden fermion
- **No excess:** exclusion limit as a function of proper lifetime

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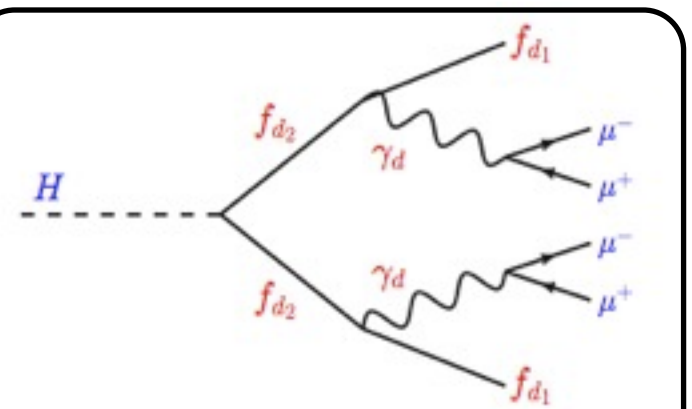
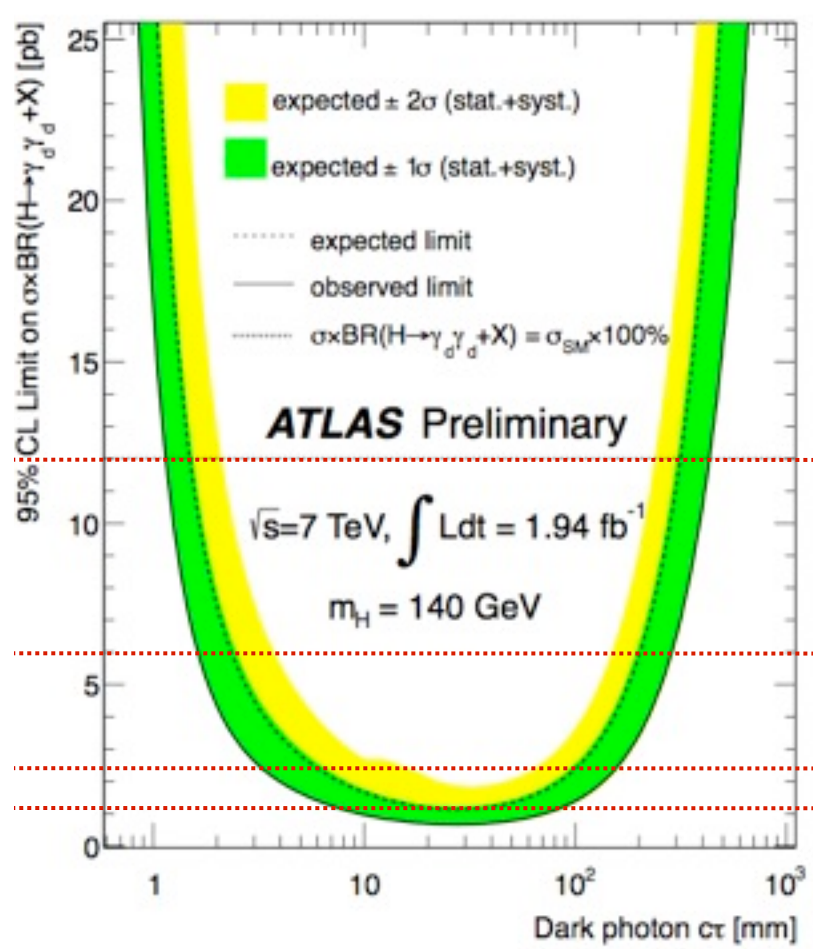


MODEL PARAMETERS

- m_h = 100/140 GeV
- m_{fd2} = 5 GeV
- $m_{fd1/LSP}$ = 2 GeV
- $m_{\gamma d}$ = 400 MeV
- BR($\gamma_d \rightarrow ee$) = 45%
- BR($\gamma_d \rightarrow \mu\mu$) = 45%
- BR($\gamma_d \rightarrow \pi\pi$) = 10%
- $c\tau(\gamma_d)$ = 47 / 36 mm

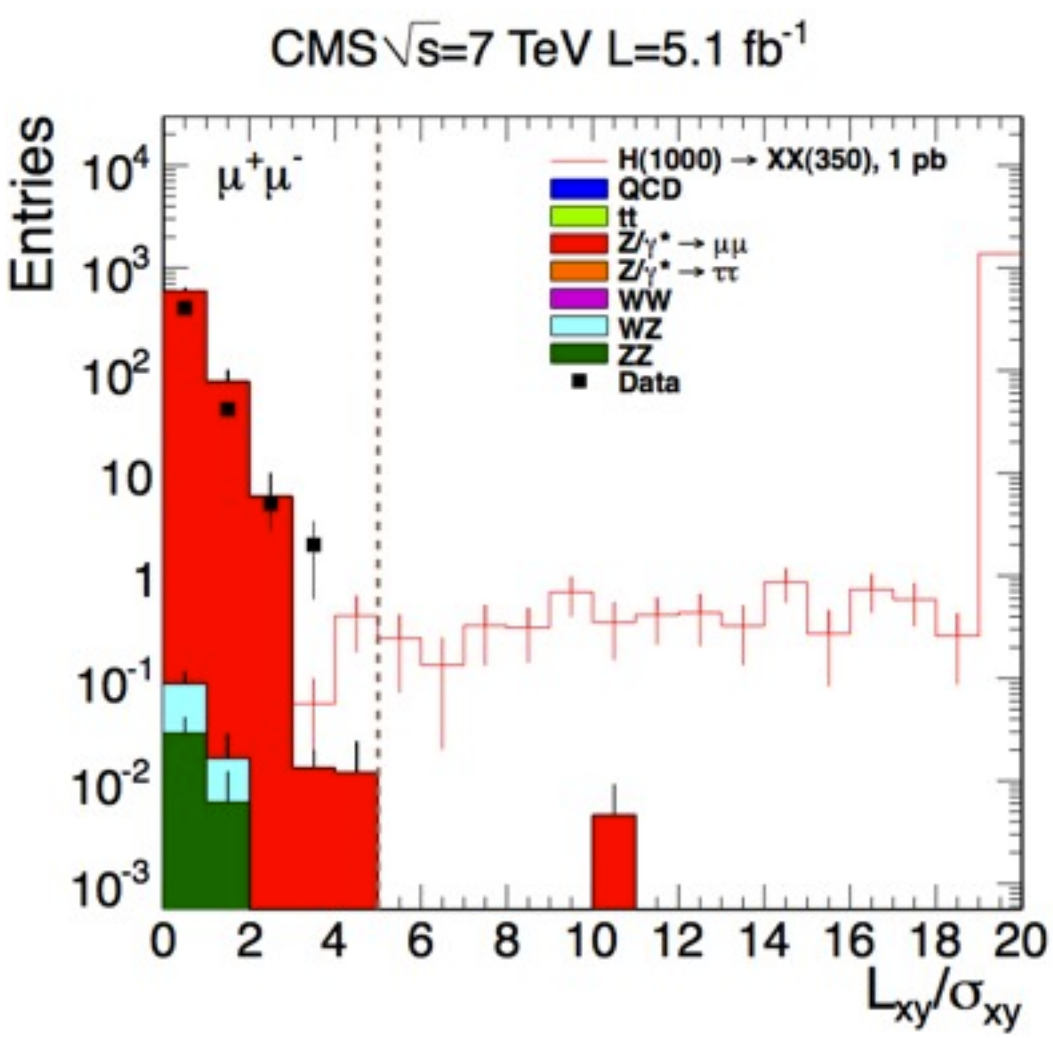


Ranges of γ_d proper decay lengths excluded at 95% CL for both Higgs masses

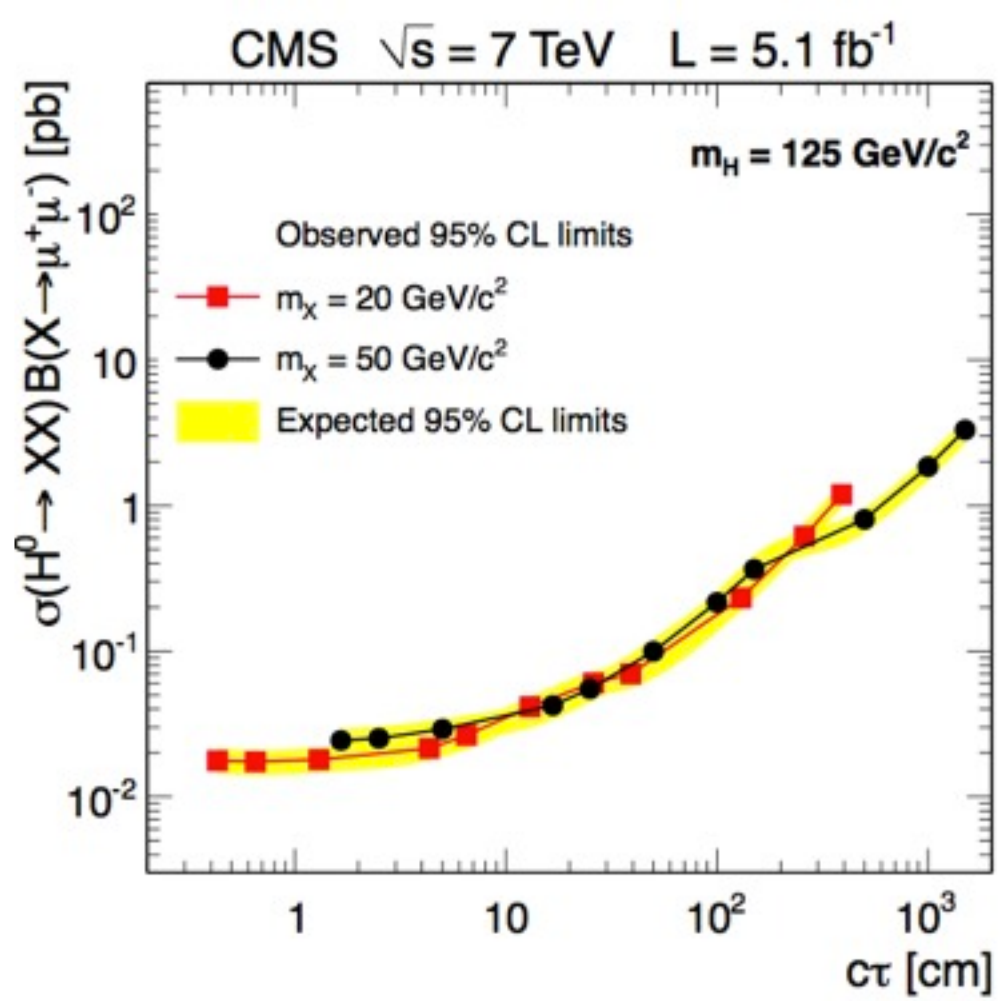
BR (%)	cτ (mm) m_H=100GeV	cτ (mm) m_H=140GeV
100	1.1÷674	1.2÷431
50	1.5÷455	1.6÷286
20	2.4÷260	3.3÷156
10	4.5÷159	7.3÷87

DISPLACED LEPTONS: CMS

- Signature of **oppositely charged leptons originating at a separated secondary vertex within the inner tracker volume**
- **Benchmark model:** Higgs → 2X, X → l^+l^-
- Main selection variable: **transverse decay length significance L_{xy}/σ_{xy}**
- **No excess**

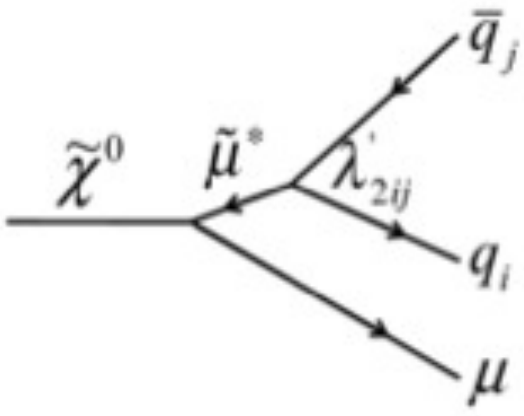


http://arxiv.org/abs/1211.2472



DISPLACED VERTEXES WITH TRACK+MUON

- In RPV SUSY, **neutralino can decay in muon + jets**
  - muon good for triggering, jets for vertexing
  - dedicated vertex reconstruction
- **No excess seen**



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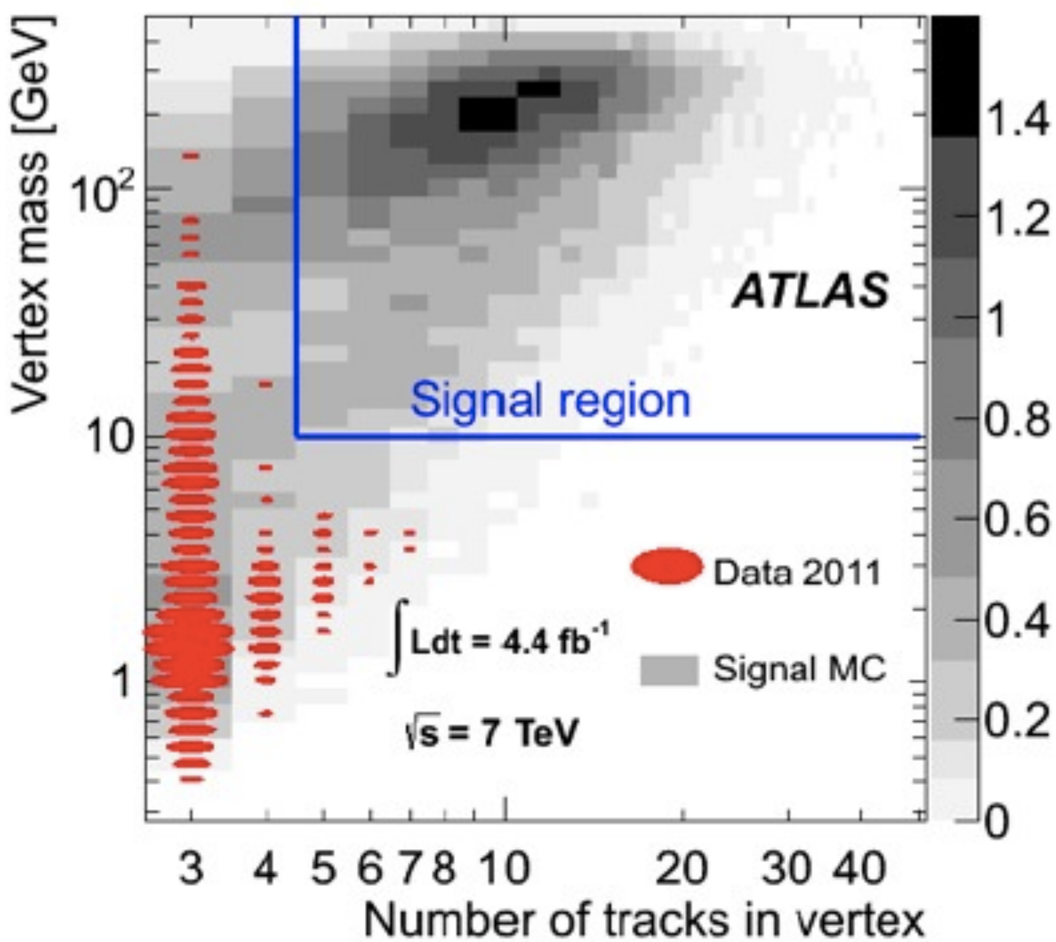
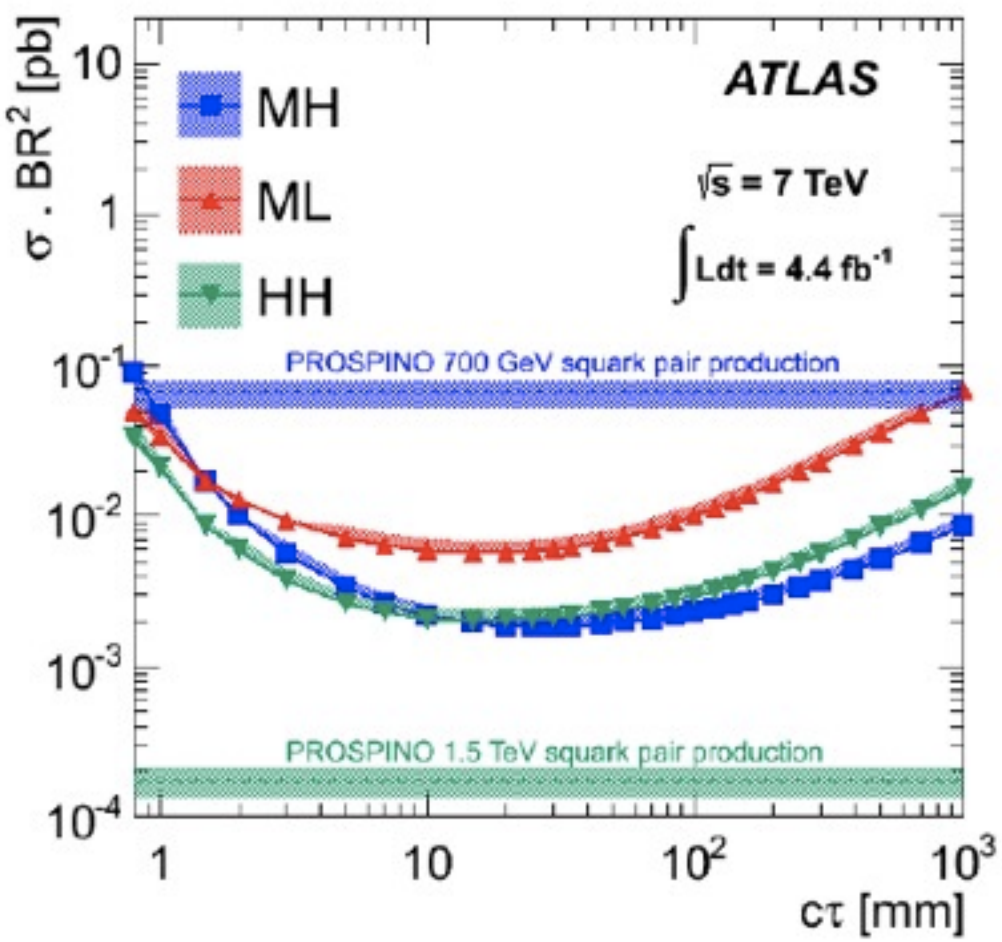




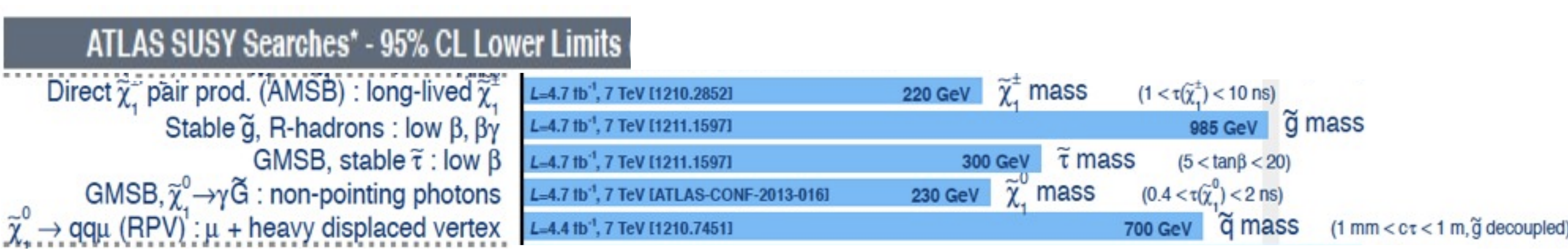
SUMMARY

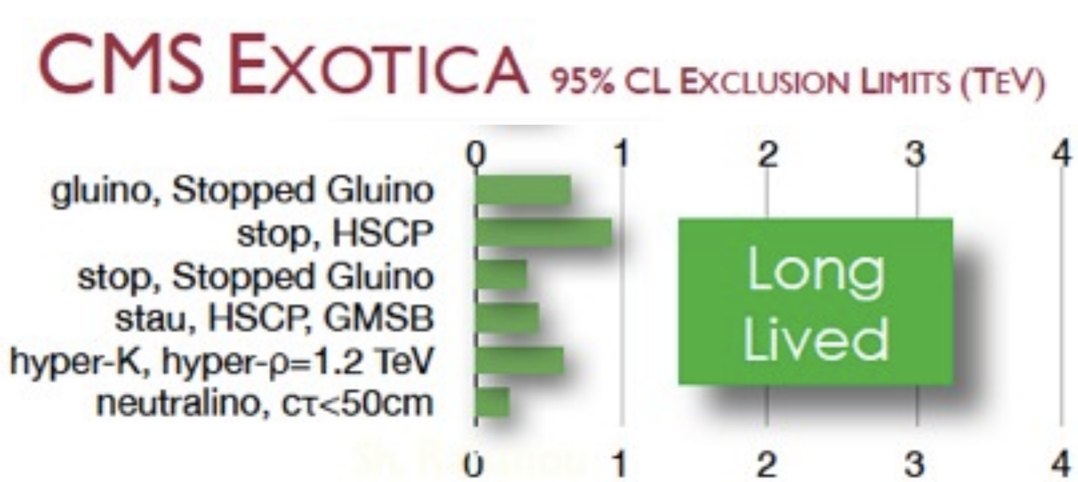
- In several **SUSY and Exotics Models interesting signatures with long-lived particles**
  - extend phase-space of searches
- **Searches for long-lived particles very challenging**
  - look where background for SM analyses is
  - full understanding of the detectors and “non-standard” analysis techniques needed
- So far, **no evidence of new physics**
- Most of the analysis **being updated and improved** with full statistics
  - we still have 20 fb^{-1} 2012 data to look at
- **Lots of space for new ideas**

Discussion

COMPARISON BETWEEN THE TWO EXPERIMENTS

Analysis	ATLAS	CMS
HSCP	4.7 fb^{-1} (7TeV)	5 fb^{-1} (7TeV) + 18.8 fb^{-1} (8TeV)
Disappearing tracks	4.7 fb^{-1} (7TeV)	work in progress
Stopped particles	31 pb^{-1} (7TeV)	4 fb^{-1} (7TeV)
Displaced photons	4.8 fb^{-1} (7TeV)	4.9 fb^{-1} (7TeV)
Displaced heavy fermions	1.9 fb^{-1} (7TeV)	work in progress
Displaced leptonjets	1.9 fb^{-1} (7TeV)	5.1 fb^{-1} (7TeV)
Displaced vertices + muon	4.4 fb^{-1} (7TeV)	-



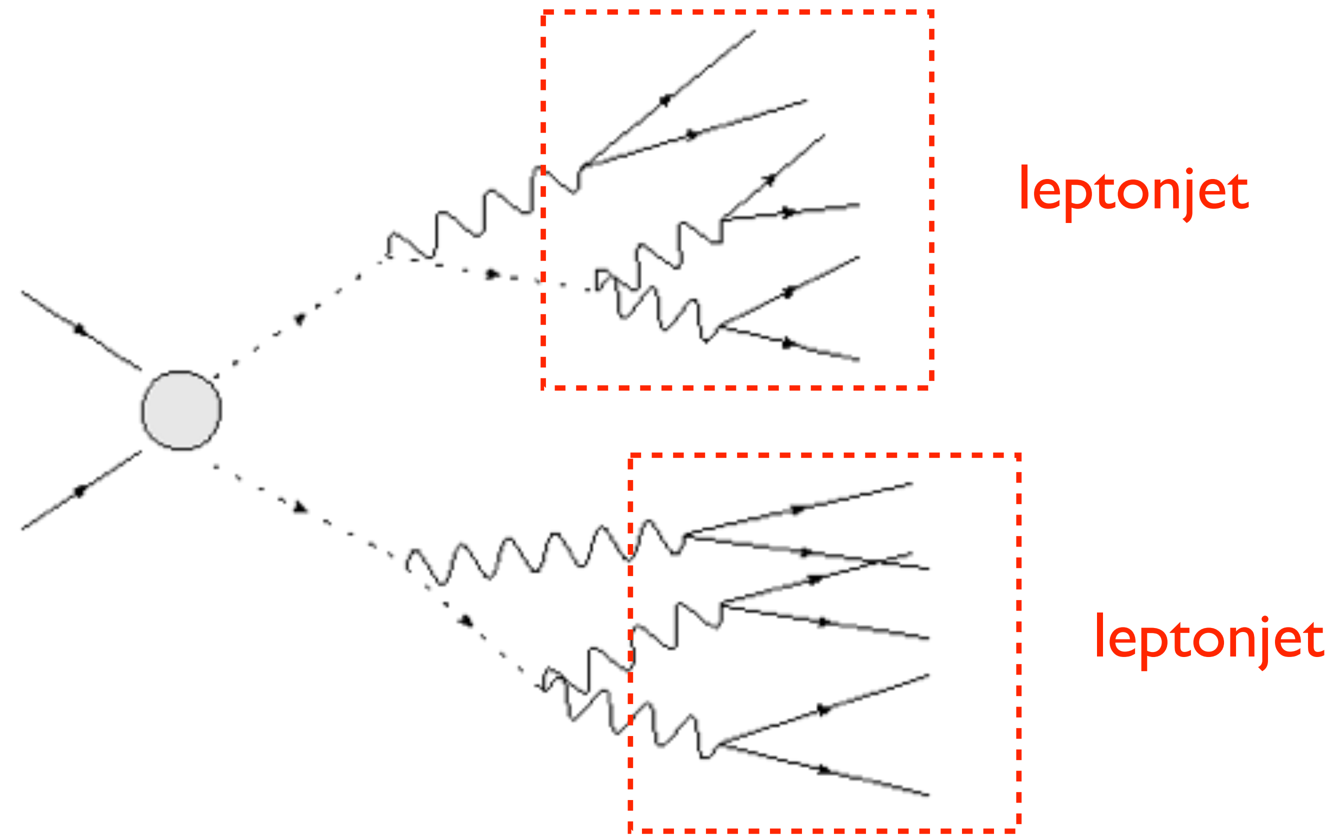


Issues for Discussion

- Current activities
  - extend analyses to the full statistics
- Model-independent approach
  - to help theoreticians in the interpretation
  - does it make sense to have a "rivet"-like approach
- Better definition of control samples
- Next LHC run
  - upgrade of the detectors (phase two / sLHC): keep in mind the LL signatures
  - develop more ad-hoc triggers
  - larger use of data parking (delayed data stream)
  - take advantage of a much larger statistics (~100 fb^{-1})
    - e.g. search for rare Higgs decays
- In general, invest more in these analyses (once most of SUSY/exotica phase space will be explored, investigate LL)
  - lot of space for master degree and PhD theses

LEPTONJETS: CURRENT ACTIVITY

- Investigate more complex decay modes → higher particle multiplicity in the final state and final states with electrons, muons and pions
- Extend search to be as more model independent as possible → constrain many theoretical models



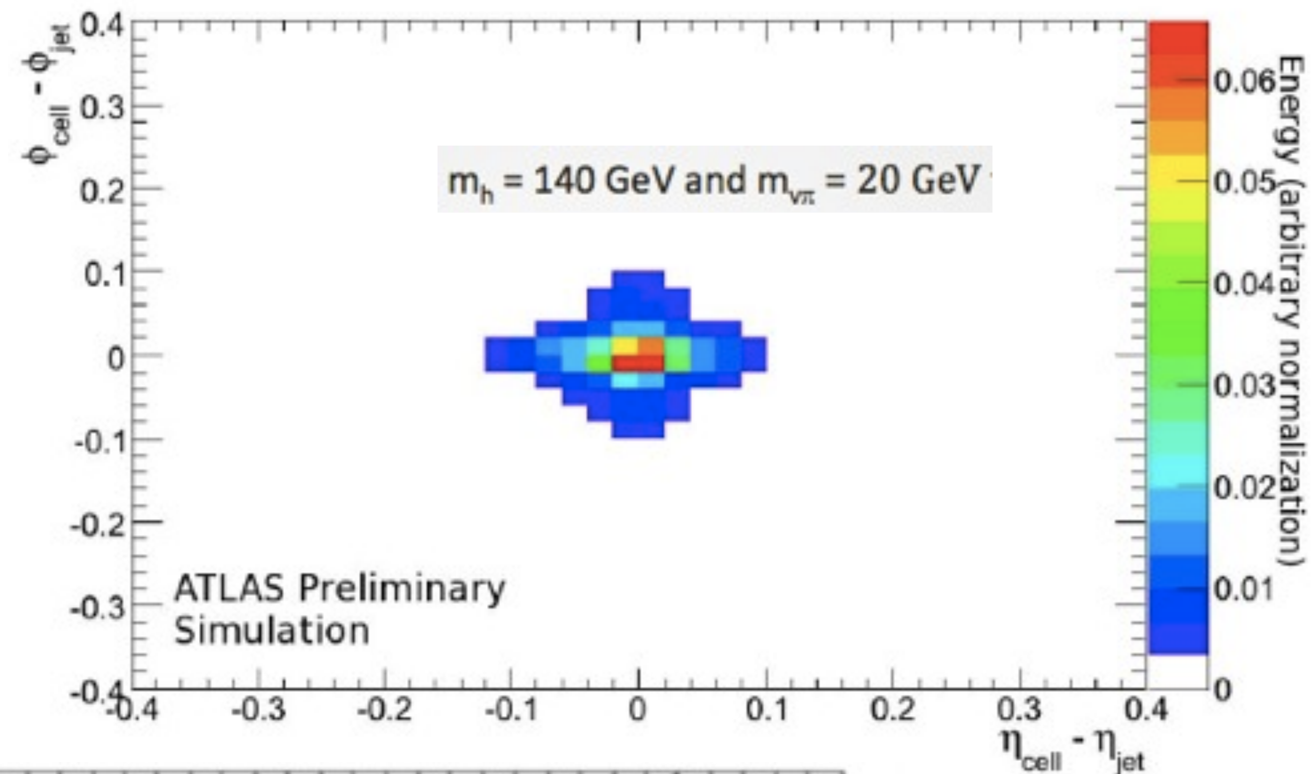
LJ 1 / LJ 2	electrons	muons	electrons +muons	light hadrons	leptons+light hadrons
electrons					
muons		only 2 μ + 2 μ in 2011			
electrons +muons					
light hadrons					
leptons+light hadrons					

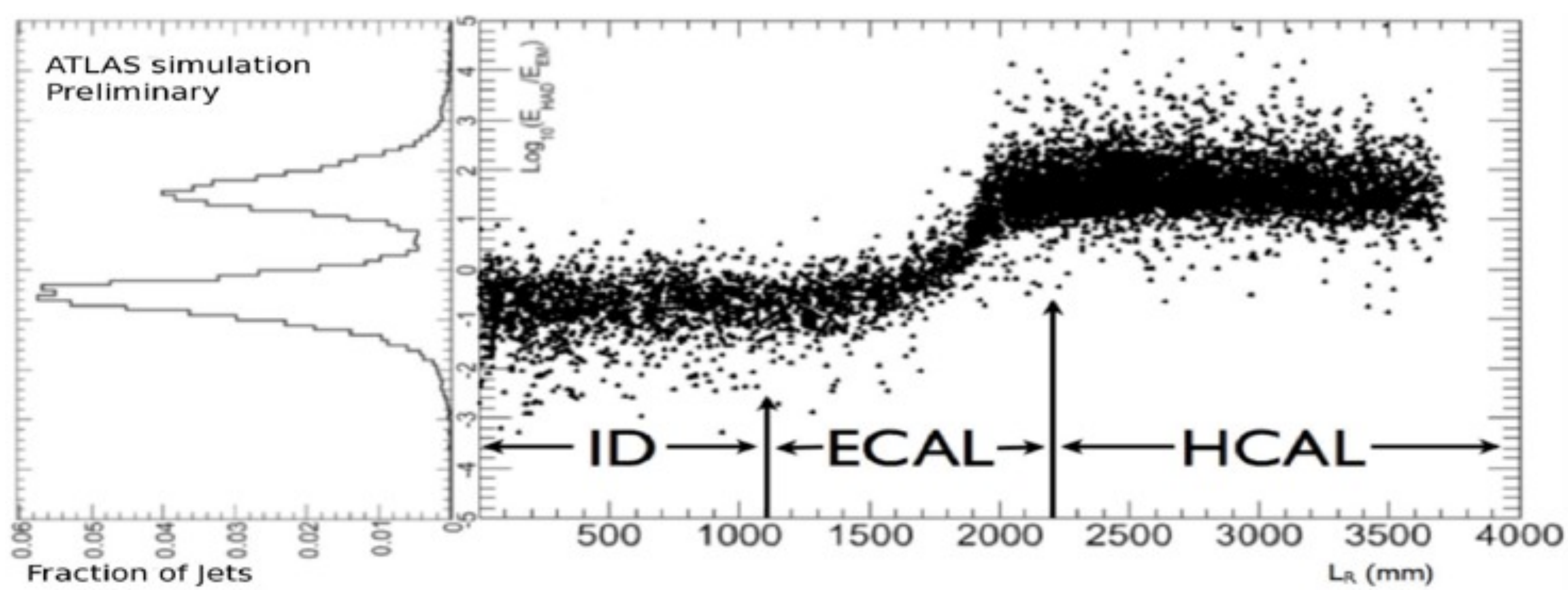
= work in progress

Very challenging search!

DISPLACED VERTICES/JETS: CURRENT ACTIVITY

- Extend previous analysis to the entire collected statistics
  - Search for displaced vertices in Muon System
  - Search for displaced vertices in Inner Tracker
  - Search for two π_v's decaying both in the Hadronic Calorimeter (well advanced)
- Signature of a π_v decaying in the HAD calorimeter:
  - narrow energy deposition in HAD calorimeter
  - anomalous $\log(E_{HAD}/E_{EM})$
  - isolation (no tracks) in ID





ATLAS-PHYS-PUB-2009-082

HSCP: CURRENT ACTIVITY

- Update of the analysis on the **8 TeV data** expected soon

- Interesting planned improvements:

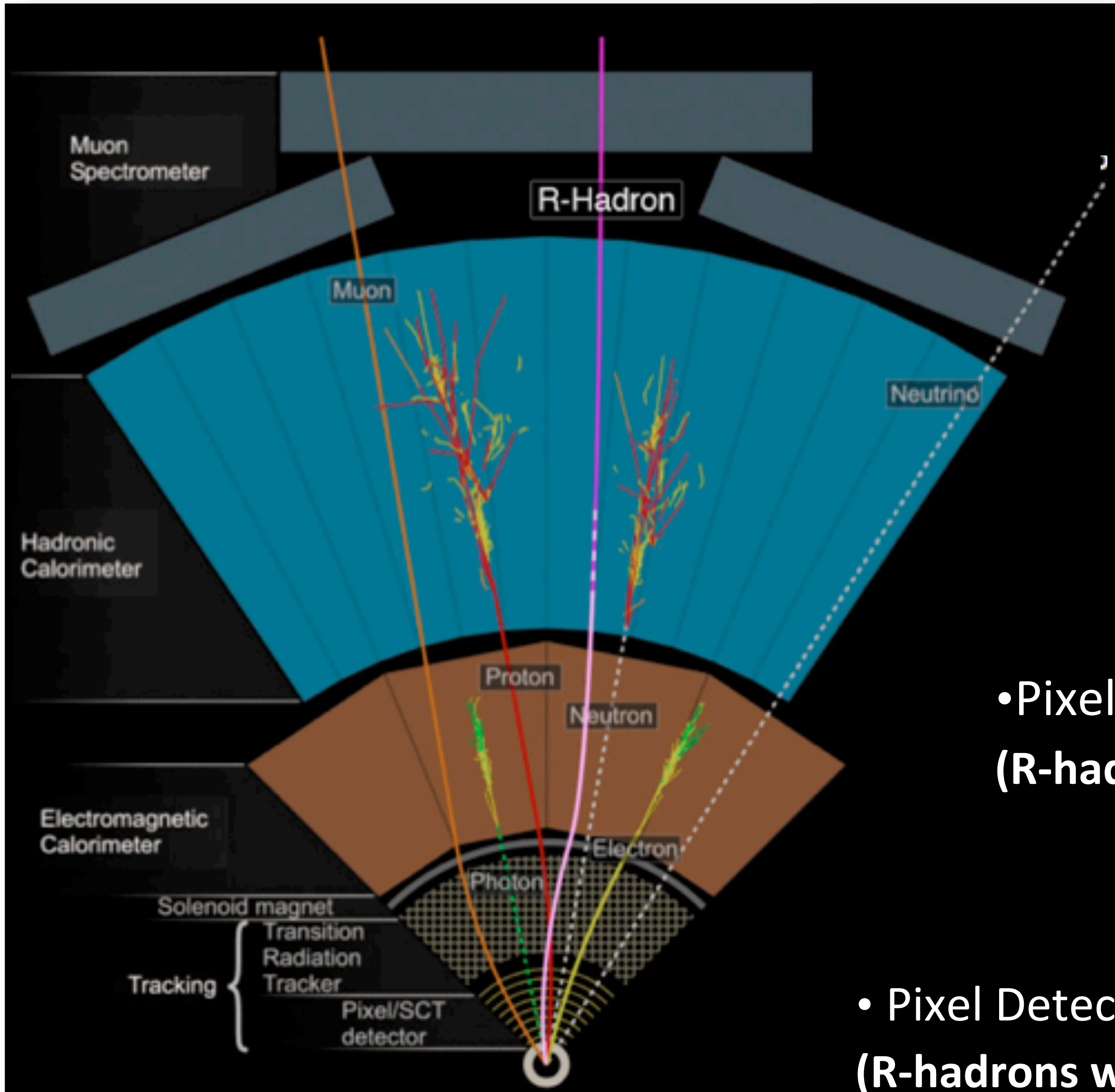
1. possibility for **R-hadrons** to **decay** or to interact with the detector material and to **change charge** (charged → neutral within a certain lifetime O(ns) only detected by ID; neutral → charged no track in the ID but detected by MS)
    - for the current analysis, only a simplified study of variation in efficiency with R-hadron lifetime → perform the new analysis as lifetime dependent (particularly sensible for ID-only approach)

2. investigating **different triggers**, both for muons and for R-hadrons

BACKUP

HSCP: Analysis Technique

Combination of **several detector inputs** to be sensitive to slepton (slow muon-like) and R-hadrons (maybe with short lifetime)



ATLAS EXAMPLE

- Muon Spectrometer + ID (β,μ-like) **(<u>sleptons</u>)**
- ID + Calo + Muon Spectrometer **(R-hadrons, <u>full-detector</u> analysis)**

- Pixel + Tracker + Tile Calorimeter (β) **(R-hadrons, <u>μ-agnostic</u> analysis)**

- Pixel Detector(dE/dx,p)+SCT(p) **(R-hadrons with short lifetimes, <u>ID-only</u> analysis)**

BECHMARK SCENARIO FOR STAU IN HSCP

Par.	Description	
Λ	SUSY breaking scale	30-160GeV depending on stau mass
M_m	Messenger mass scale	250TeV
$\tan\beta$	Ratio of Higgs vev	10
N_m	Number of SU(5) messenger multiplets	3
sign(μ)	μ from Higgs sector	positive
C_{grav}	Sets NLSP lifetime	10^4 (lifetime to avoid slepton decaying in det)