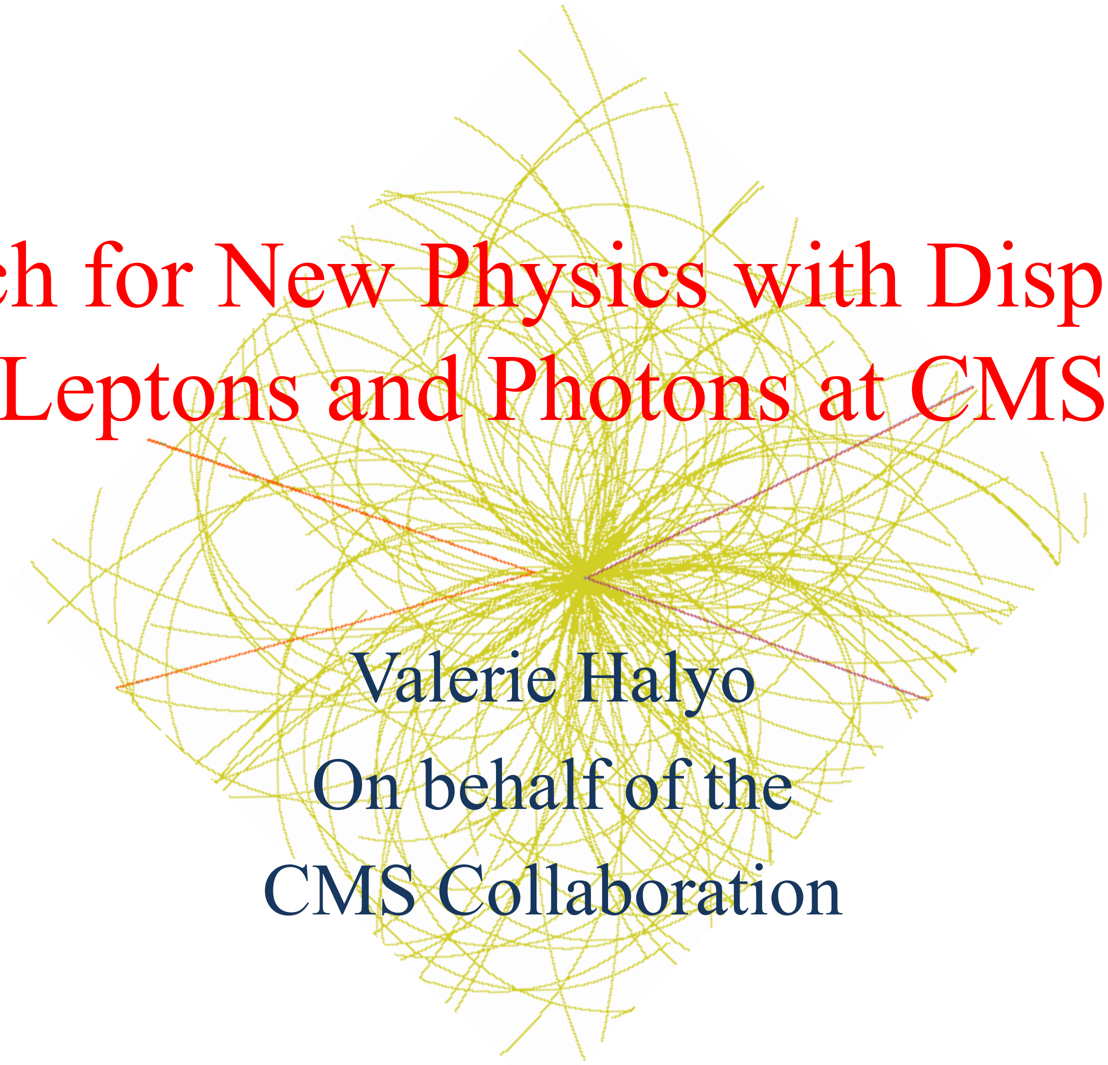
Search for New Physics with Displaced Leptons and Photons at CMS



Valerie Halyo
On behalf of the
CMS Collaboration

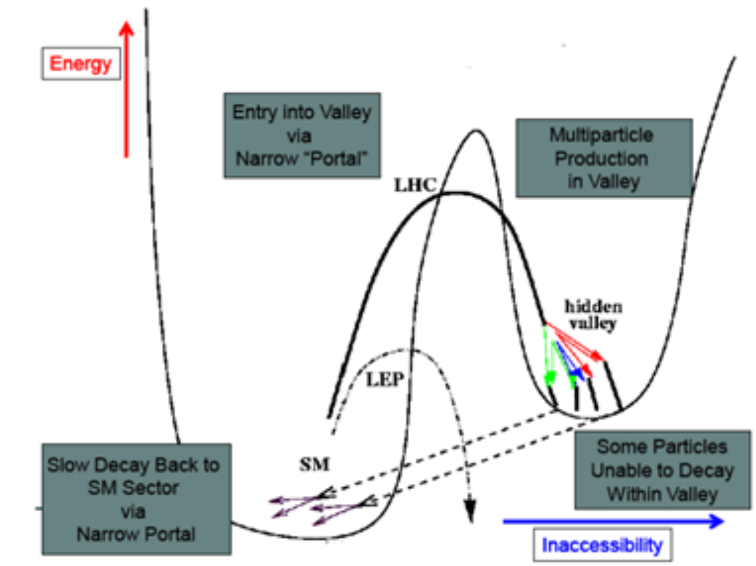
Motivation

- Independent of any theoretical motivation these new topological signatures provide clear evidence for physics beyond the SM

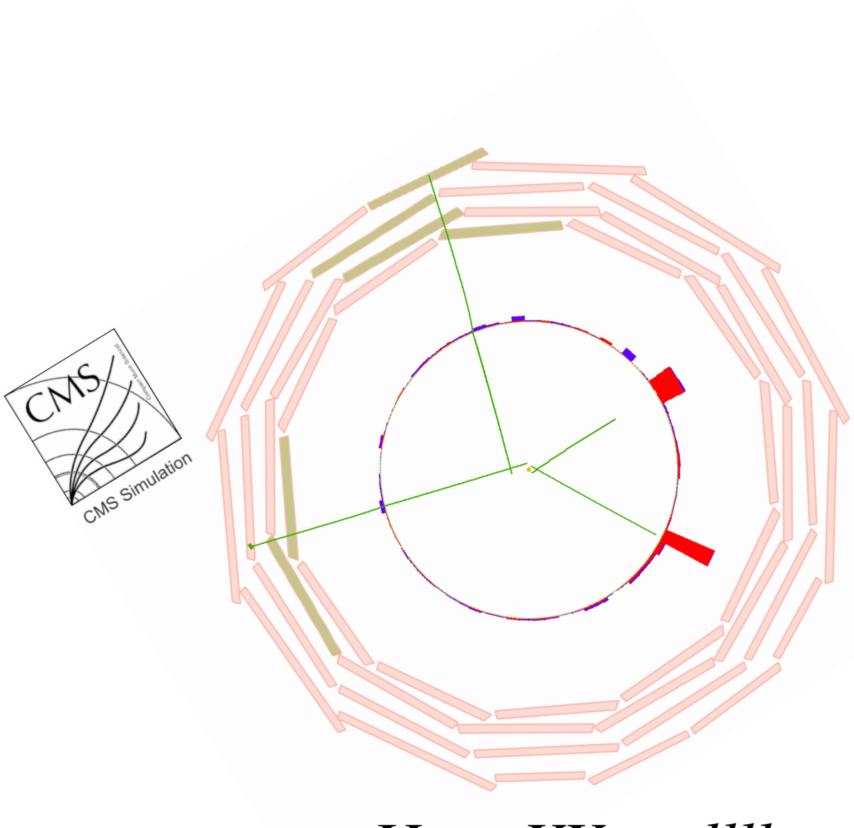
- We search for the two following signatures:
  - Displaced lepton pair produced inside the CMS tracker
  - Long-lived particle decay into photon(s) + X

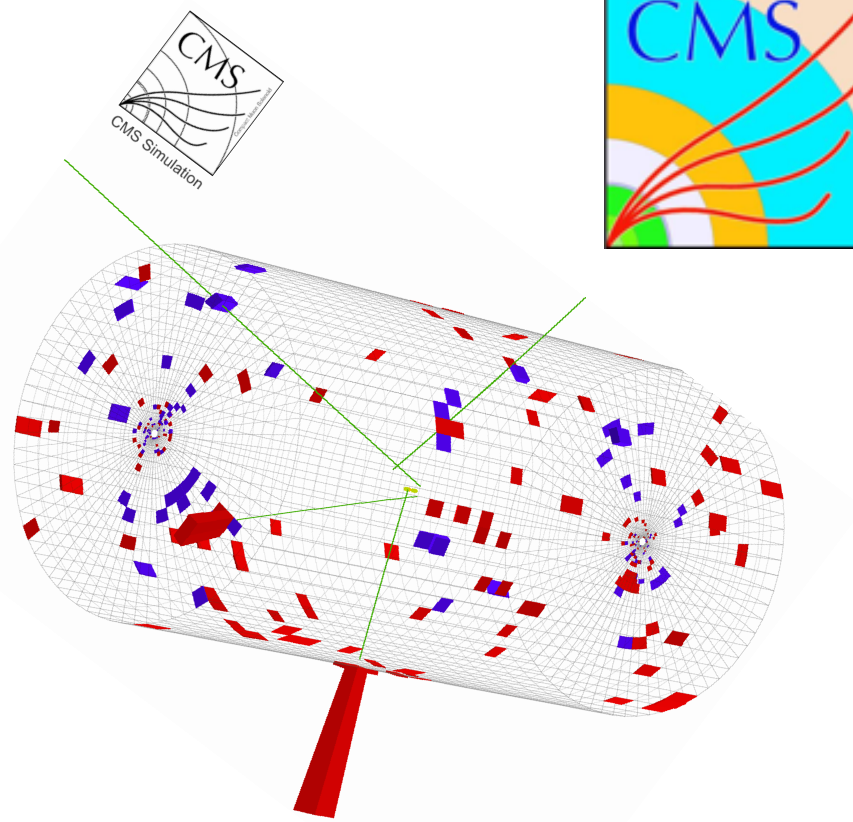
Many models predict long-lived exotica that could decay inside CMS:

- “Hidden Valley” models (right)
- GMSB SUSY: $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$ with weak coupling
- Weakly R-parity violating SUSY
- “split SUSY”: long-lived gluinos (squarks very heavy)



graph by Matt Strassler





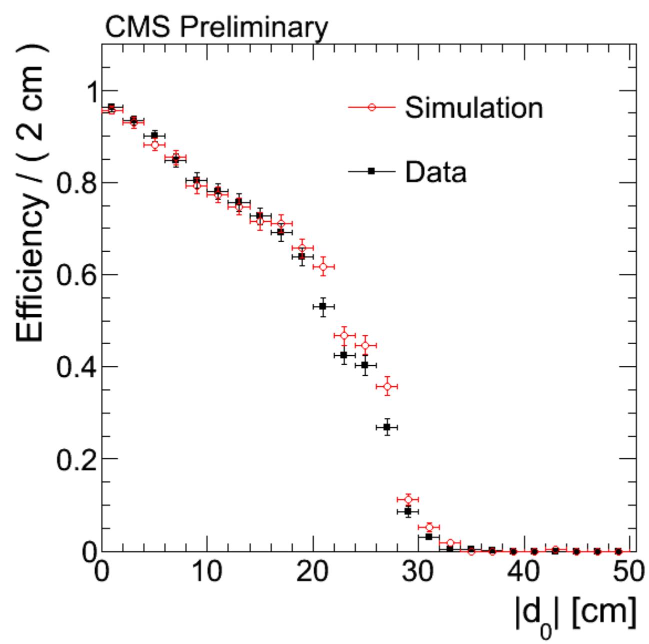
$gg \rightarrow H \rightarrow XX \rightarrow llll$

L = 4.1 fb^{-1} (electron) L = 5.1 fb^{-1} (muon)

Heavy Resonances Decaying to Long-Lived Neutral Particles in the Displaced Lepton Channel (PAS: EXO-11-101)

Identification of displaced leptons

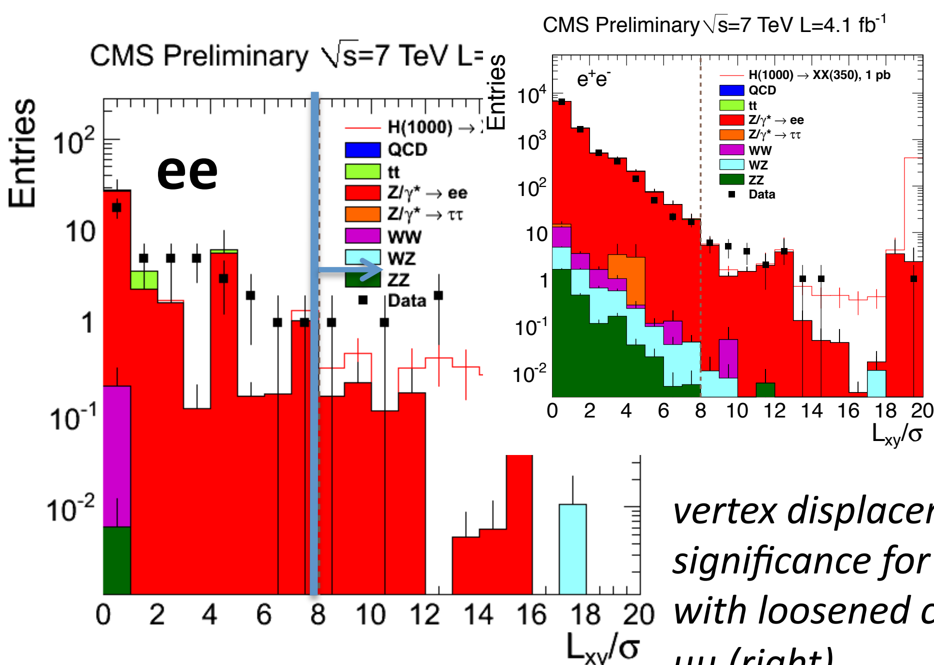
- Standard CMS lepton identification is **less efficient** because it is designed for prompt leptons
- Instead, identify displaced leptons by looking for **tracks** which match an object from a **specialized displaced lepton trigger**
- Require that tracks are:
  - High P_T and Isolated
  - Have a significant transverse displacement d_0
  - Match a trigger object
  - For electrons, are also matched to a deposit in the EM calorimeter (provides better energy resolution than the track momentum)



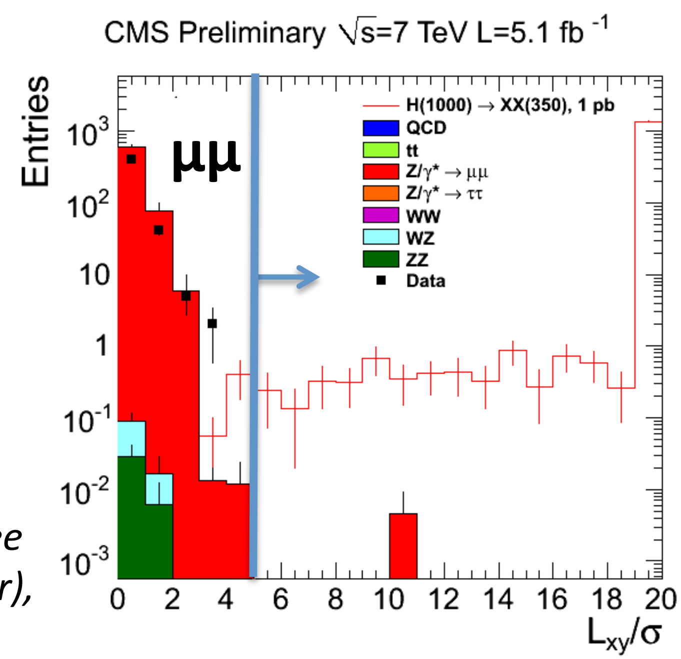
tracking efficiency** for displaced leptons, as determined from **cosmic ray data

Identification of candidates

- Reconstruct X candidates by looking for dilepton pairs that make a **significantly displaced** vertex
- Also require vertex flight direction collinear with candidate momentum and reject back-to-back muons (cosmics)
- Signal efficiency range 4-30% (electrons), 5-50% (muons)



vertex displacement significance for ee (left), ee with loosened cuts (center), μμ (right)



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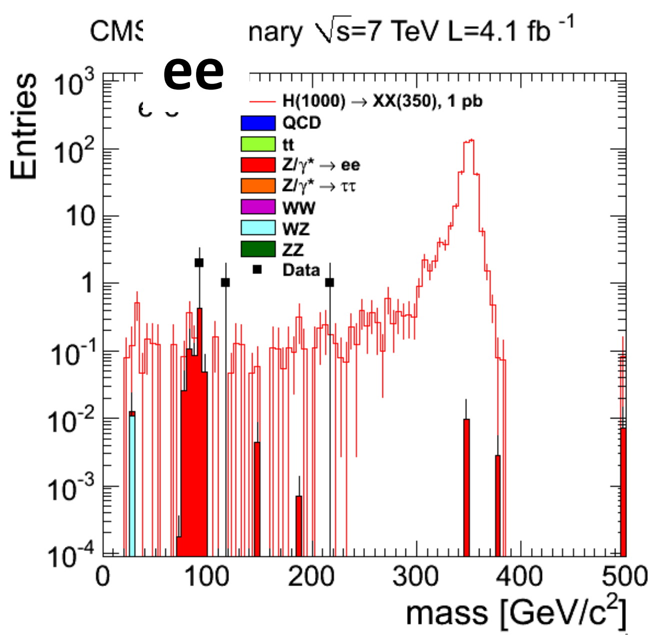
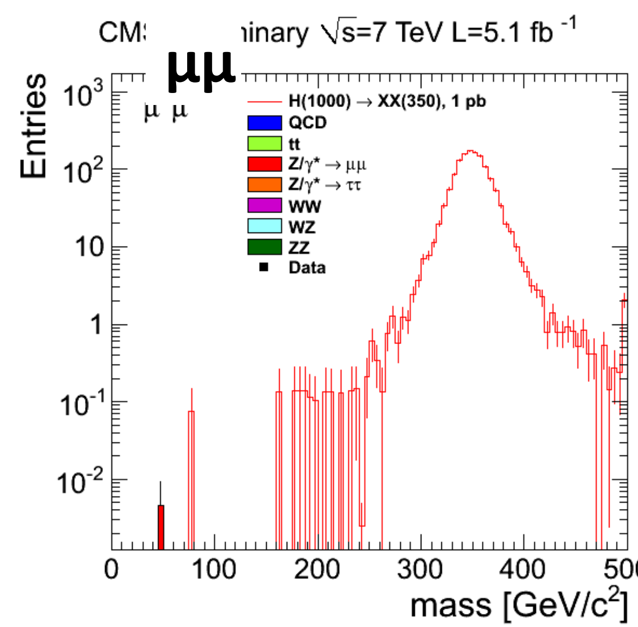
Results: Dilepton Mass Distribution

We look for a signal as a narrow resonance in the mass spectrum.

Total events passing all cuts in data:

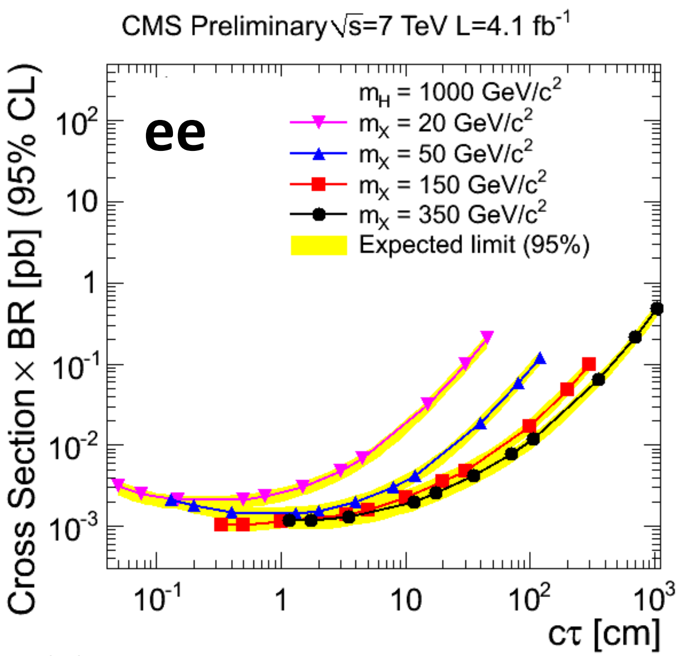
- 0 events in muon channel, 4 in electron channel
  consistent with background expectation $0.02^{+0.09}_{-0.02}$ and $1.38^{+1.78}_{-1.19}$
- Main systematic: Tracking efficiency 20%





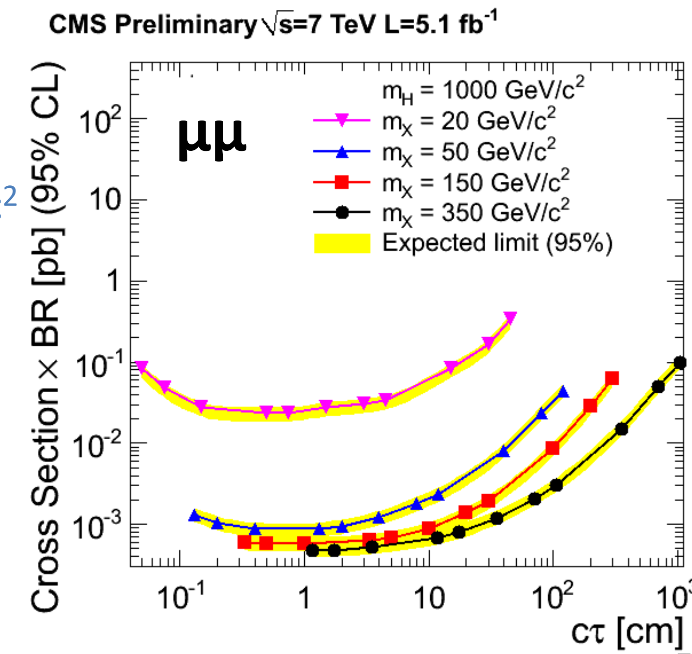
Upper limits using CLs

- Fit signal & background PDFs for the mass spectrum to observed data to set limits on H → XX cross-section using CL_s technique
- Include signal efficiency, cross-section, and systematic uncertainties in limit-setting procedure
- Set limits for a variety of H and X mass combinations



m_H = 1000 GeV/c^2

Limits ~ 0.7-10fb



Displaced Photons:

I Long-Lived Particles Decaying to Photons and Missing Energy (PAS EXO-11-067, hep-ex/1207.0627v1)

II Search for Long Lived Particles using Displaced Photons in the pp Collisions at (PAS EXO-11-035)

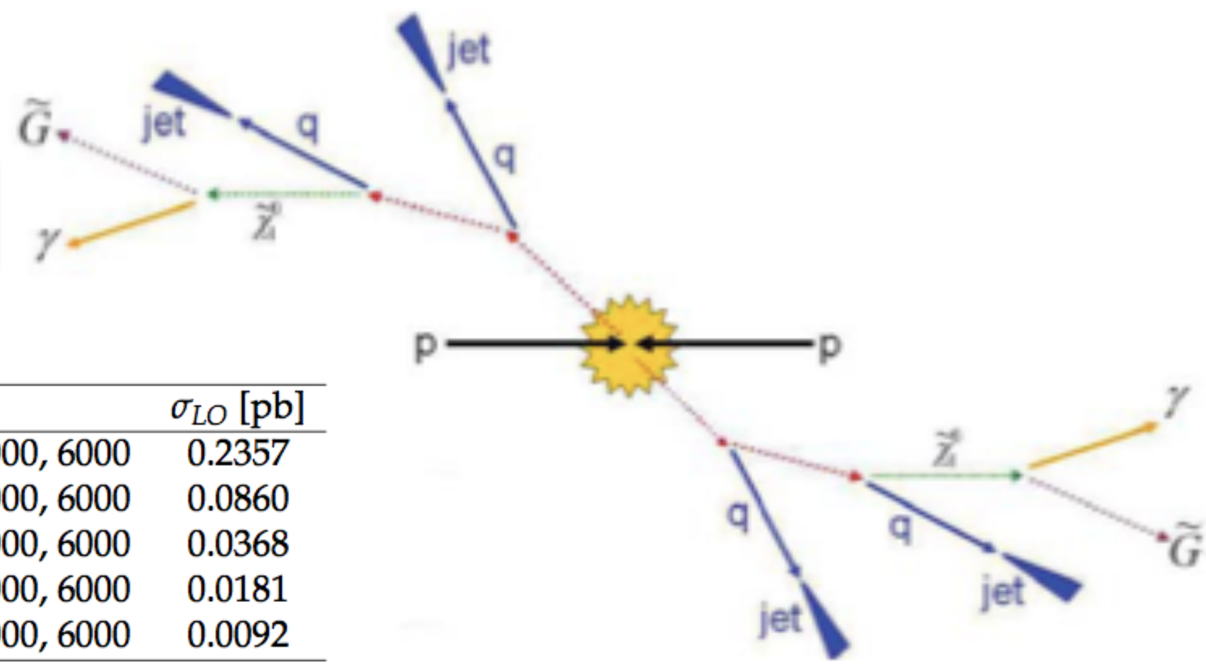
Displaced photons

Case Study: Gauge-mediated SUSY (GMSB)

• The gravitino is the lightest SUSY particle (LSP)

• The lightest **neutralino is the next-to-lightest SUSY particle (NLSP)** and is long-lived

$$\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$$

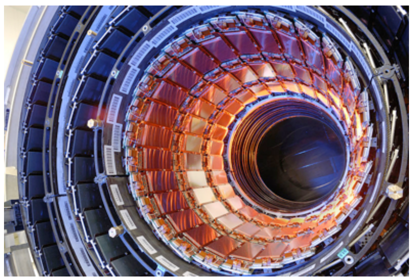


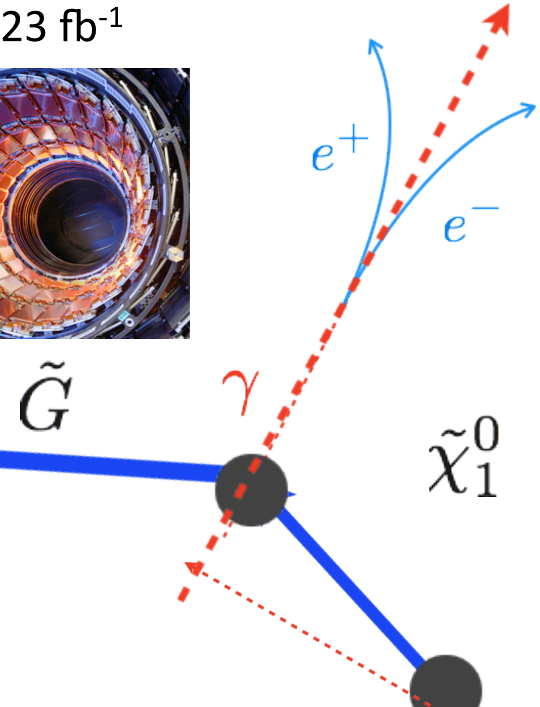
Λ [GeV]	$c\tau$ [mm]	σ_{LO} [pb]
100	1, 250, 500, 2000, 4000, 6000	0.2357
120	1, 250, 500, 2000, 4000, 6000	0.0860
140	1, 250, 500, 2000, 4000, 6000	0.0368
160	1, 250, 500, 2000, 4000, 6000	0.0181
180	1, 250, 500, 2000, 4000, 6000	0.0092

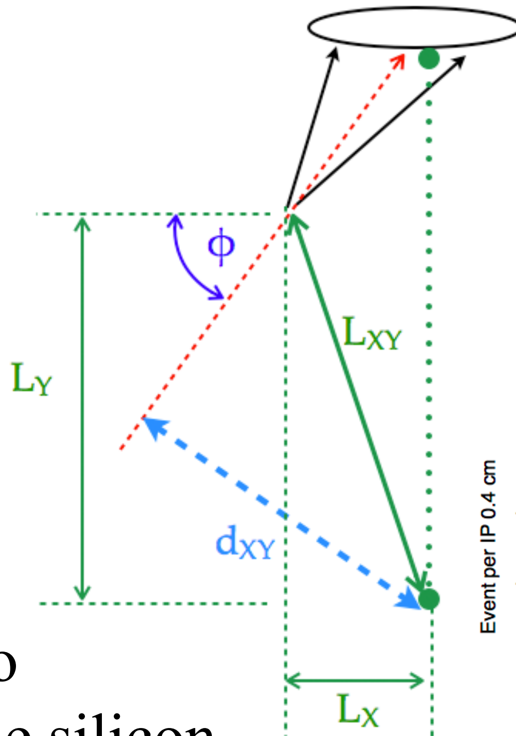
Novel Technique I: Photon Conversion

L = 2.23 fb^{-1}

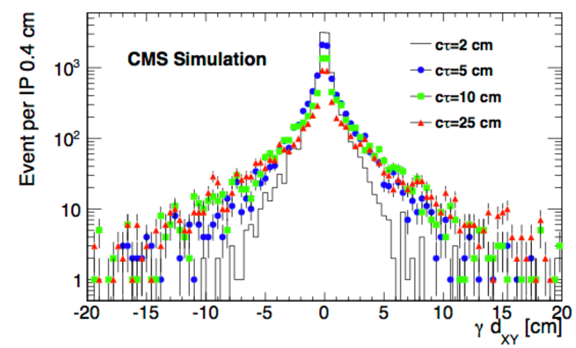
(PAS: EXO-11-067/hep-ex/1207.0627v1)







Look for photons with significant d_{XY} to identify long-lived particles

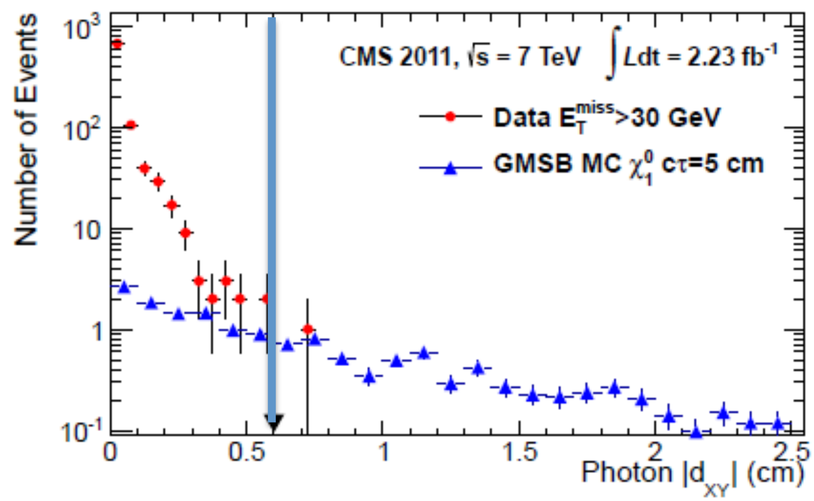


~ 50% photons can convert into e^+e^- pairs by interacting with the silicon material in tracker.

Reconstructed converted photons yields the photon direction

Selection Criteria

- Di-photon Trigger
  - Online: at least 2 energetic photons in the final state
  - Offline: E_T cut of $>45\ GeV$ and $>30\ GeV$ for leading and sub-leading photons selected on the plateau of the trigger efficiency
- Photon Id
  - Any ECAL Barrel photon with $E_T>45\ GeV$ satisfying:
  - *Track + ECAL + HCAL Isolation*
  - *Prompt Electron veto*



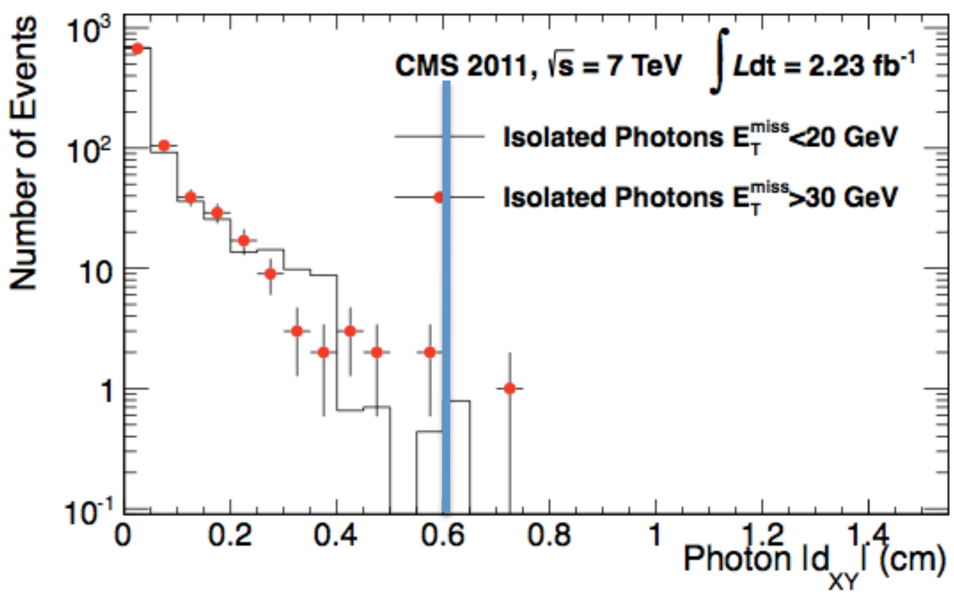
- Photon $|d_{XY}|>0.6$ cm, optimized by the average expect limit of production cross section.

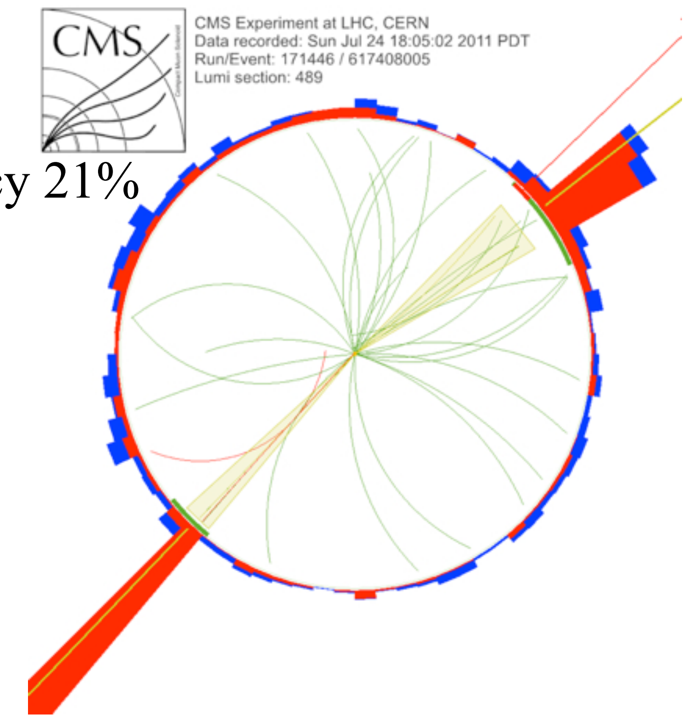
** Efficiency for c τ =5 cm is 1.58%.

Result: Photon d_{xy} Distribution

- E_T^{miss}< 20 GeV of data was used as control region to describe signal region E_T^{miss}> 30 GeV
- Background of $0.78^{+1.25}_{-0.48}$ events expected; one signal event observed

Main Systematic: Conversion reconstruction efficiency 21%





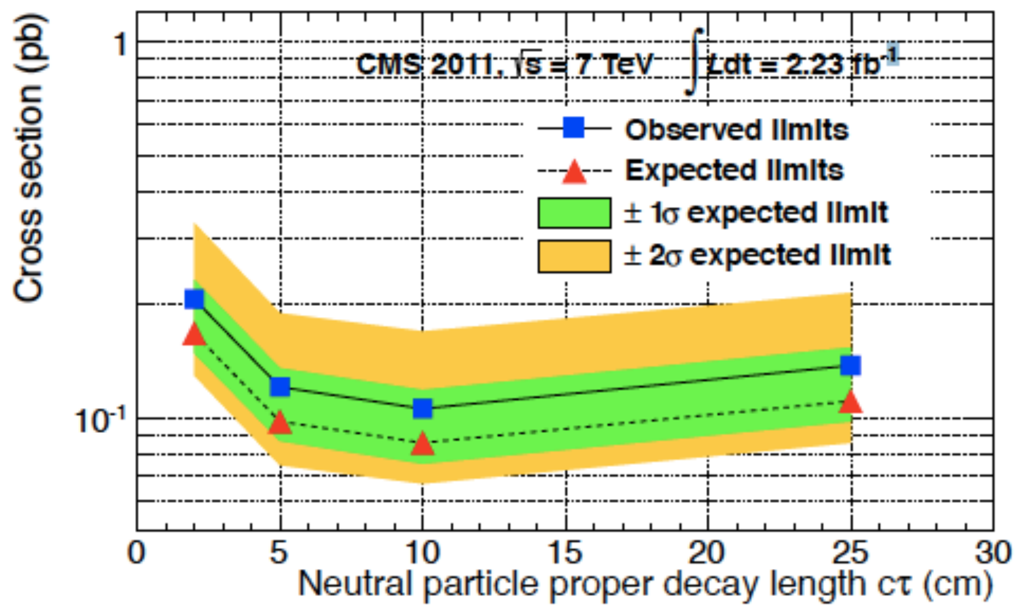
$|d_{XY}|$=0.74 cm E_T^{miss} = 44.9 GeV

Upper Limit Using CLs

Novel technique leads to new 95% CL upper limits on the cross-section for pair production of neutral particles, each of which decays into a photon and invisible particles. Limits are set as **a function of the long-lived particle's lifetime.**

Strengths of this result:

- **applicable to a general class of new physics**
- **sensitive to short lifetimes (good d_{XY} resolution)**
- **requires lower missing ET than many SUSY photon searches**



|- 0.1 - 1 ns -|

$c\tau$ (cm)	2	5	10	25
σ (pb) 95% CL	0.21	0.12	0.11	0.14

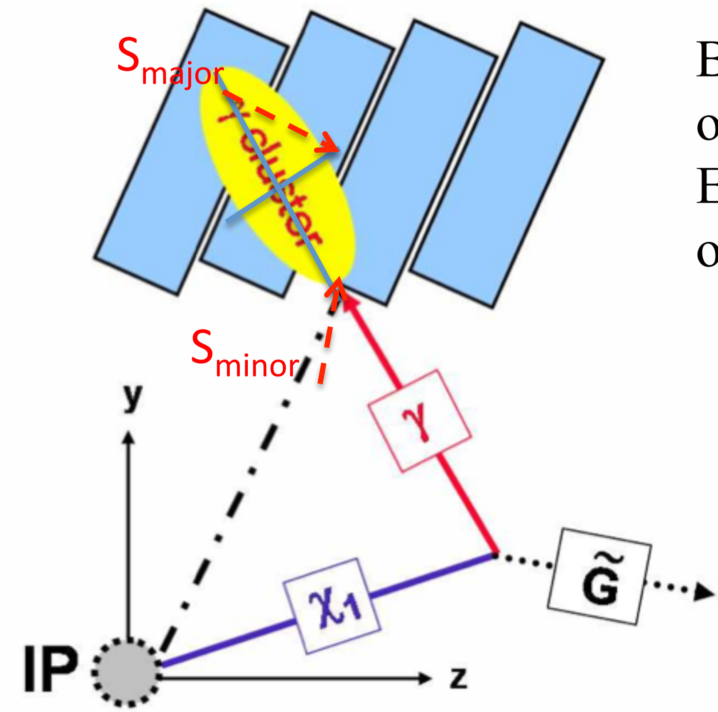
(PAS: EXO-11-067/hep-ex/1207.0627v1)

Displaced Photon: Technique II

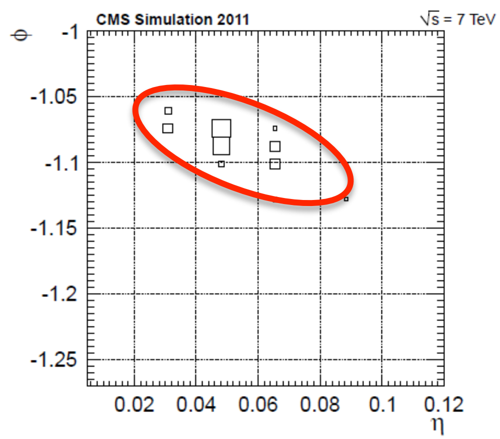
Search for GMSB with Displaced Photons

(PAS: EXO-11-035)

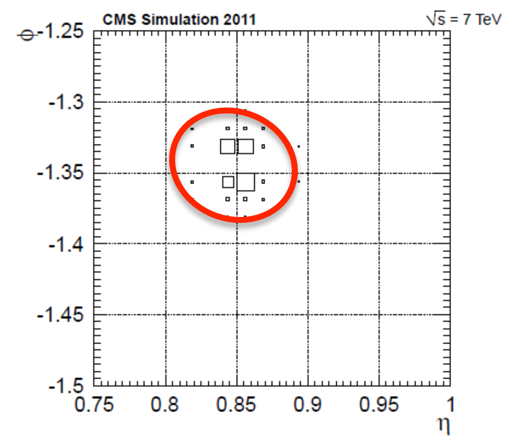
L = 4.86 fb^{-1}



Basic principle: search for an excess of events over SM expectation in distributions of missing ET and ECAL time (time of impact of the photon on the surface of the ECAL)



Displaced photon



Prompt photon

D0 (6.3 fb^{-1}): Di-photon prompt

Mass(χ^0_1) > 175 GeV/c^2 *PRL 105, 221802 (2010)*

CDF (2.6 fb^{-1}): Di-photon non-prompt

Mass(χ^0_1) > 149 GeV/c^2 , lifetime (χ^0_1) > 2 ns

PRL 104, 011801 (2010)

Selection Criteria

Goal: Look for events with one isolated, high-Pt photon in association with at least 3 jets

Online trigger: Photon with Et>90, Et>90 + 3Jets Pt>25

Offline:

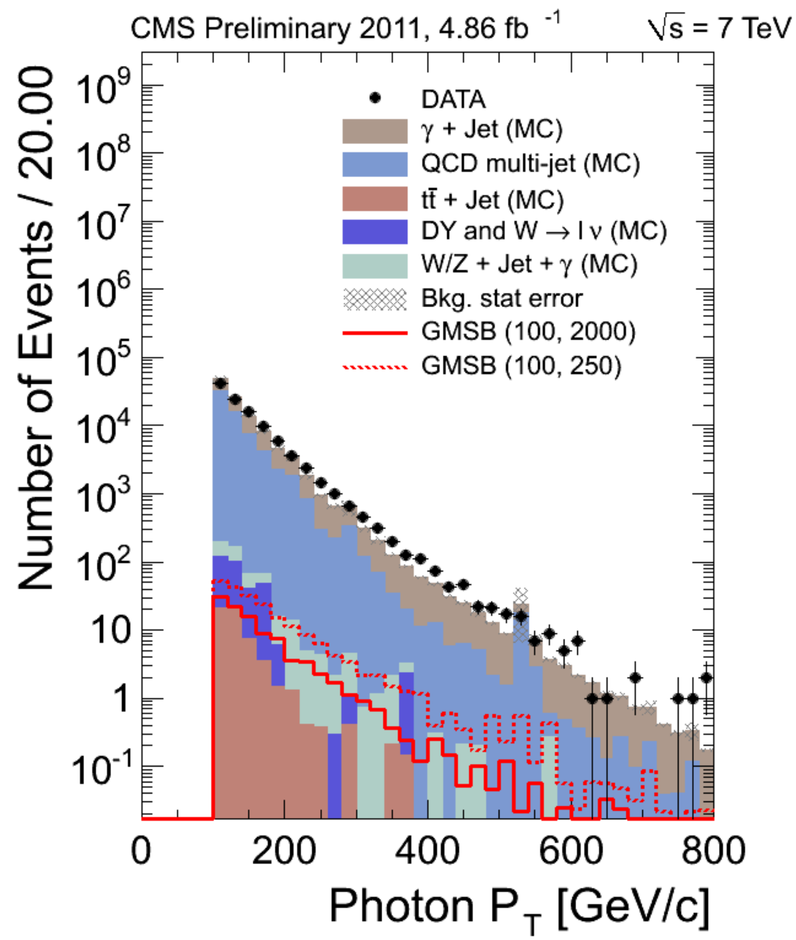
- Photon with Et>100GeV
- Isolated (Tracker+ECAL+HCAL)
- Photon not associated to electron:

ΔR (γ, electron) > 0.25

- Photon not overlapping to jets:

ΔR (γ, jet) > 0.5

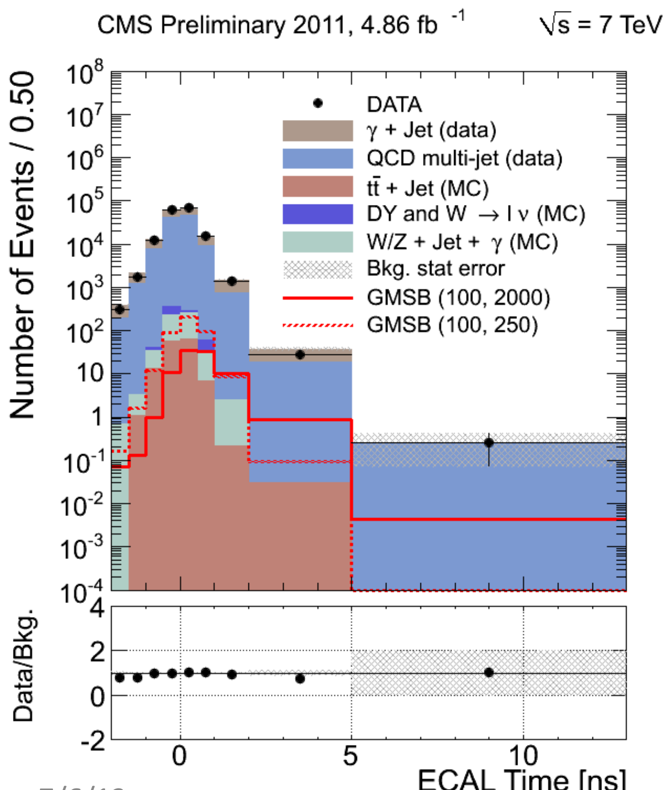
- 3 Jets with Pt >35 GeV

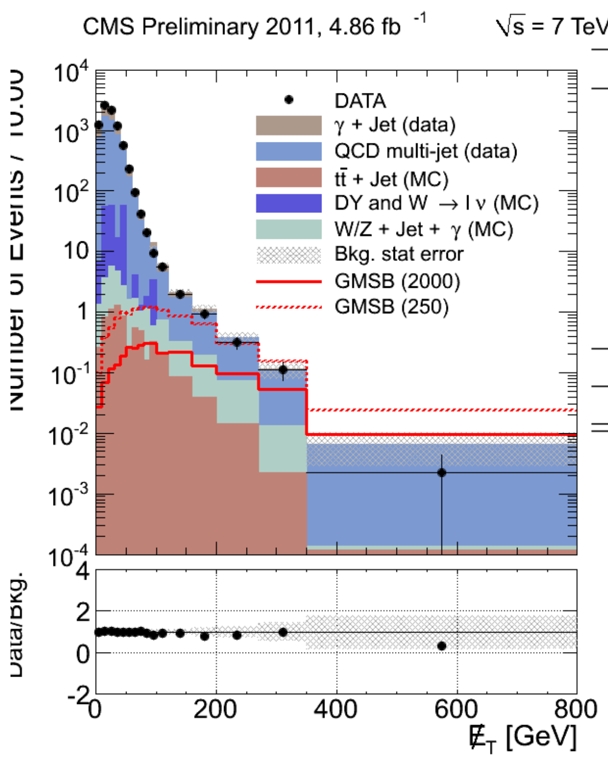


data-driven techniques used to estimate main backgrounds;

MET and ECAL Timing

- Good agreement of the main discriminating variables MET and ECAL Timing between data and expected background over their full range
- Full shapes of these distributions used to search for an excess (more sensitive than cut-and-count approach) over the SM background
- Main Systematic: Uncertainty on the background shape (stat)

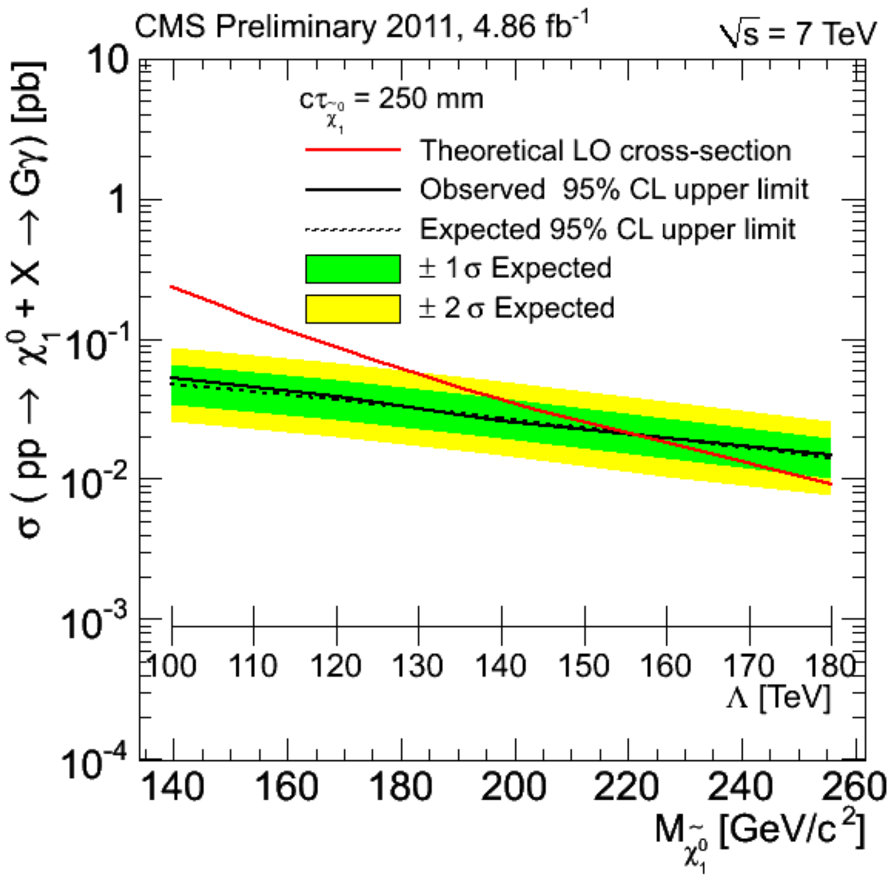


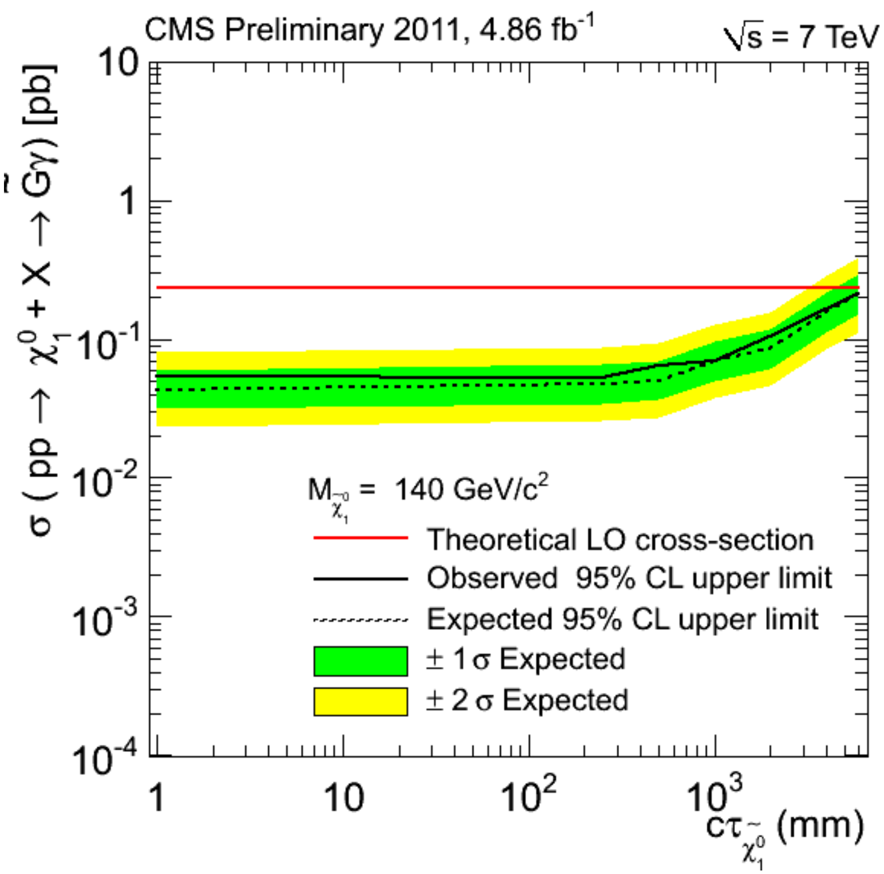


	No. Events
GMSB (100, 250)	6 ± 8
GMSB (100, 2000)	4 ± 4
multi-jet and γ+jet	80916 ± 290
$t\bar{t}$ + jet (fixed)	73
$W \to e\nu$ + jet (fixed)	116
Drell–Yan + jet (fixed)	67
W/Z + jet + γ (fixed)	215
Total background	81387
Data	81382

results of final fit to data – total background compatible with data

Exclusion Plots

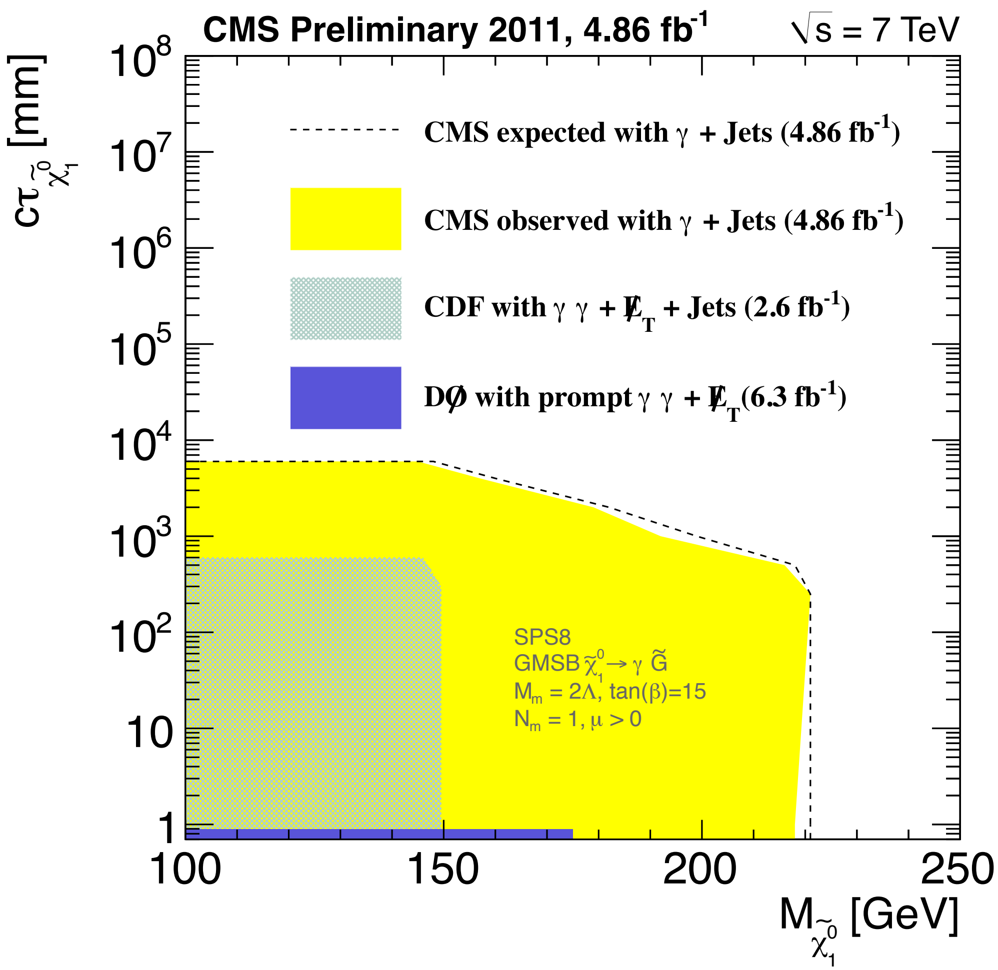




Using CL_s to set limits, can exclude χ^0_1 masses below 220 GeV, and proper decay lengths cτ below 6m

2D Exclusion Plot

2D mass-lifetime plane of the $\chi^0{}_1$



Good extension of limits set by Tevatron

New exclusions are:

Mass($\chi^0{}_1$) > 220 GeV/c^2

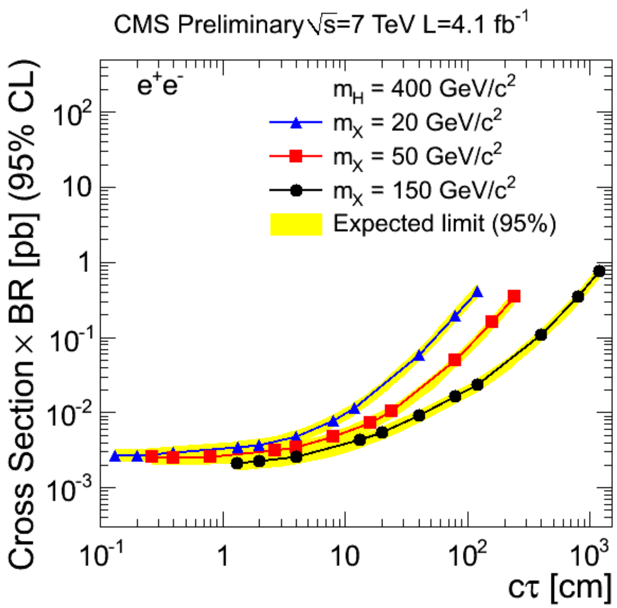
$c\tau_\chi$ <6000mm

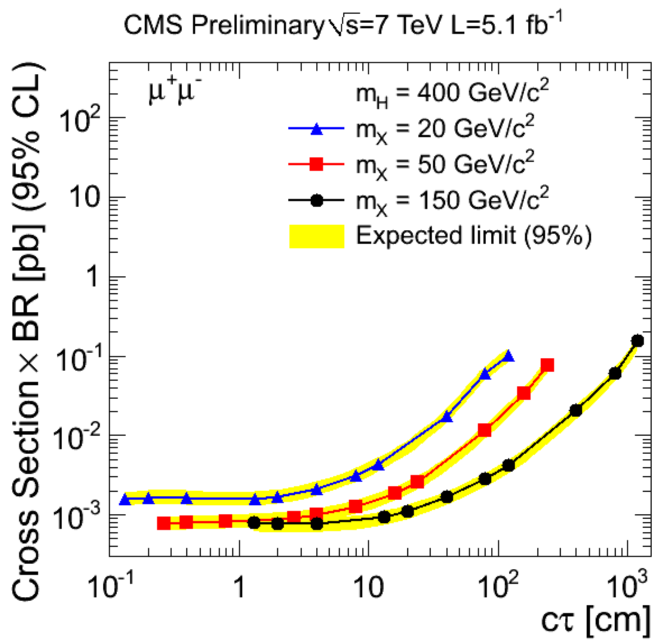
Conclusions

- First three results from CMS on distinct new topological signature involving long lived particles using 2011 data were presented
- 95% C.L. Upper Limits have been placed on the production cross section x BR $gg \rightarrow H \rightarrow XX \rightarrow llll$ for H^0 masses of 200-1000 GeV/c^2 and X boson masses of 20-350 GeV/c^2, => σ x BR ~ 0.7-10 fb, for X bosons with L_{xy} in the laboratory frame of ~ 2–100 cm (PAS EXO-11-101)
- 95% C.L. Upper Limit on the cross section for pair production of neutral particles, each decaying to one photon and MET, is 0.11-0.21 pb depending on the neutral lifetime, introducing a new technique for long-lived particles decaying to photons (PAS EXO-11-067/hep-ex/1207.0627v1)
- Upper limits at 95% C.L. were set on the GMSB cross section in SPS8, and from these upper limits a mass below 220 GeV/c^2 and below cτ *6000 mm* can be excluded for χ^0 (PAS EXO-11-035)

BACKUP

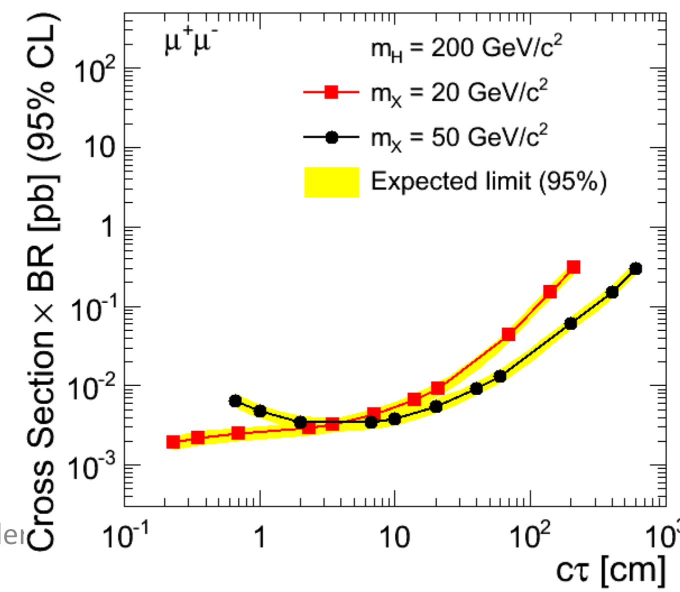
Displaced Lepton Limits (More)





Top: limits for m_H = 400 GeV/c^2

Bottom: limits for m_H = 200 GeV/ c^2
(electron efficiency is too small, so only muon limits are set here)



Event Selection Efficiency

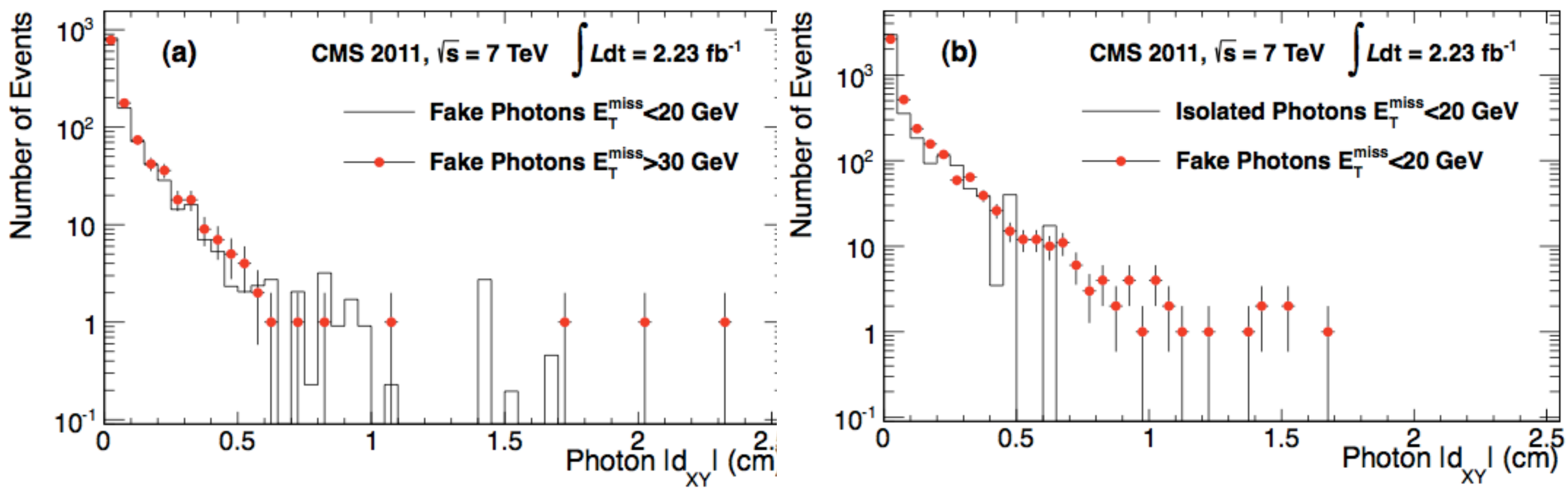
$c\tau$ [cm]	2	5	10	25
Efficiency	0.92%	1.58%	1.80%	1.39%
Statistical errors	0.05%	0.06%	0.06%	0.06%

Event selection efficiency **depends on neutralino lifetimes**

EXO-11-067

Fake photons as control samples

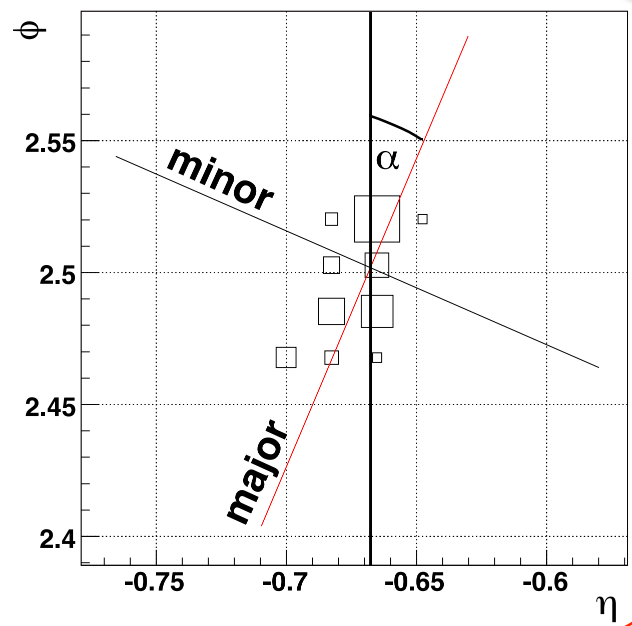
- Fake photons: One of the isolation criteria is not satisfies
- $|d_{XY}|$ distribution comparisons:
  - Fake photon $E_T^{miss}<20$ *GeV vs* $E_T^{miss}>30$ *GeV (left)*
  - Fake photon $E_T^{miss}<20$ *GeV* vs isolated photon $E_T^{miss}<20$*GeV (right*
  - Normalization by the total number of conversions, and reweighted by conversion vertex χ^2 probability.



Shape Variable

$$S_{\frac{Major}{Minor}} = \frac{S_{\phi\phi} + S_{\eta\eta} \pm \sqrt{(S_{\phi\phi} - S_{\eta\eta})^2 + 4S_{\phi\eta}^2}}{2}$$

- **Exploit shape of the energy deposit in the ECAL**
  - s_{Minor} – Low and high cuts are to select photon like objects (correlated to topological cuts)
  - s_{Major} – Make sure all correlated variables (eg. $\sigma_{i\eta i\eta}$ at HLT) does not introduce bias



Systematic Uncertainties

Source of systematic bias	Uncertainty
Luminosity	2.2%
Systematic uncertainties in the signal efficiency	
Pileup modelling	2%
Parton distribution functions	$< 1\%$
Renormalisation and factorisation scales	$< 0.5\%$
Tracking efficiency	20%
Trigger efficiency	2.6% (e), 11% (μ)
Mass resolution	0.4 % (e), 0.8 % (μ)

Systematic Uncertainties

Systematics	Uncertainty (%)
Integrated luminosity	2.2
Jet p_T / E_T^{miss} energy scale	< 0.5
Pile-up	2.5
Photon identification data/MC scale	2.6
Photon–electron difference	0.5
Conversion reconstruction efficiency	21
Photon d_{XY} resolution	< 0.5
Total	25

Systematic Uncertainties

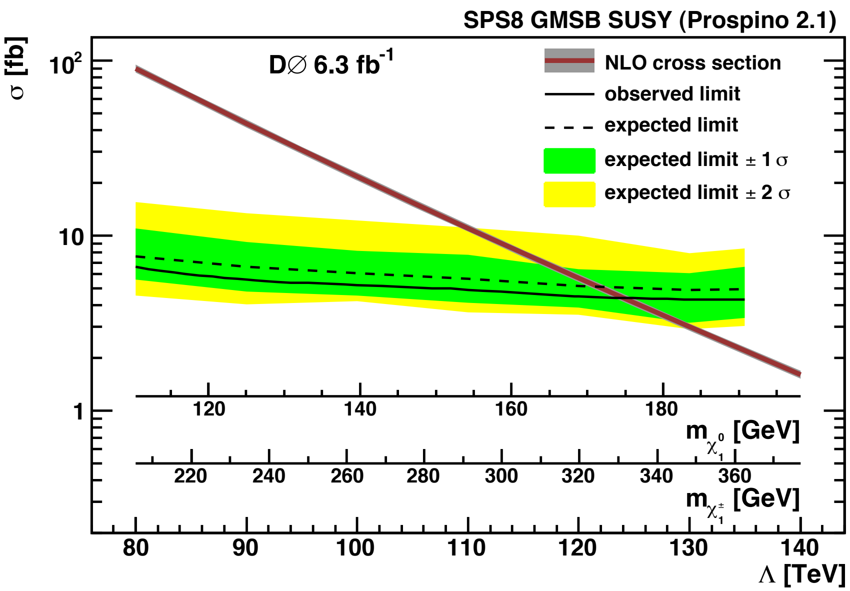
Source	Uncertainty (%)
Signal efficiency:	
Photon energy scale	< 3.0
Jet energy scale	< 0.05
Jet energy resolution	< 1.9
PDF uncertainties	< 1.7
Signal shape:	
$\not{E}_T$ resolution	< 1.5
ECAL time uncertainty	< 5.0
Background:	
Shape	< 10.5
Normalisation	< 0.3
Multi-jet/γ+ jet fraction	< 0.5
Luminosity	2.2 %

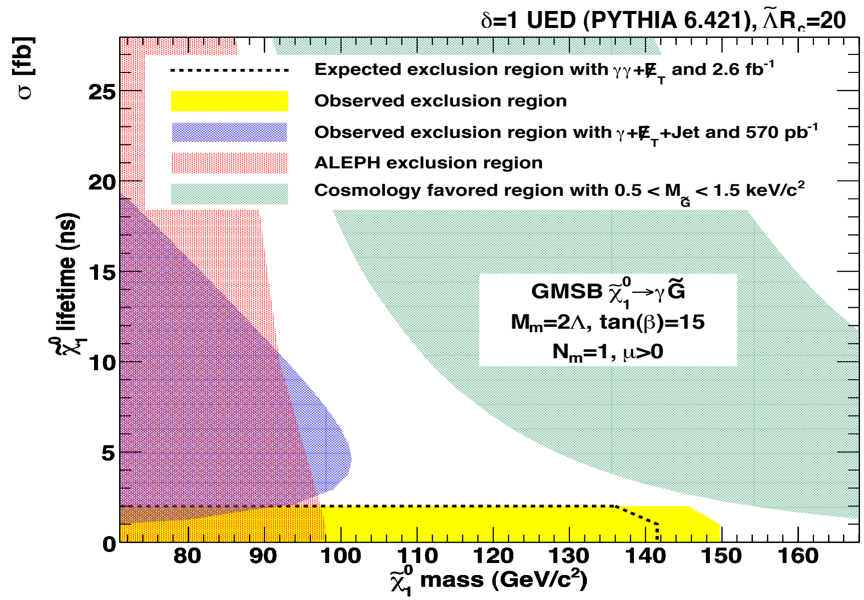
Uncertainty on signal efficiency

Uncertainty on signal shape

Uncertainty on background

Current Limits for GMSB





- **D0 (6.3 fb^{-1}): Di-photon prompt** *PRL 105, 221802 (2010)*
  Mass(χ^0_1) > 175 GeV/c^2
- **CDF (2.6 fb^{-1}): Di-photon non-prompt** *PRL 104, 011801 (2010)*
  Mass(χ^0_1) > 149 GeV/c^2 , and lifetime (χ^0_1) > 2 ns
- **CMS (2.2 fb^{-1}): Single photon non-prompt** ***EXO-11-067*** **– No interpretation**
  (4.6 fb-1): Single photon non-prompt ***EXO-11-035***
  Mass(χ^0_1) > 220 GeV/c^2 , and lifetime $c\tau$(χ^0_1) > 6000 mm
- **ATLAS (1 fb^{-1}): Di-photon prompt** *PLB 710, 519-537 (2012)*
  Mass(χ^0_1) > 145 GeV

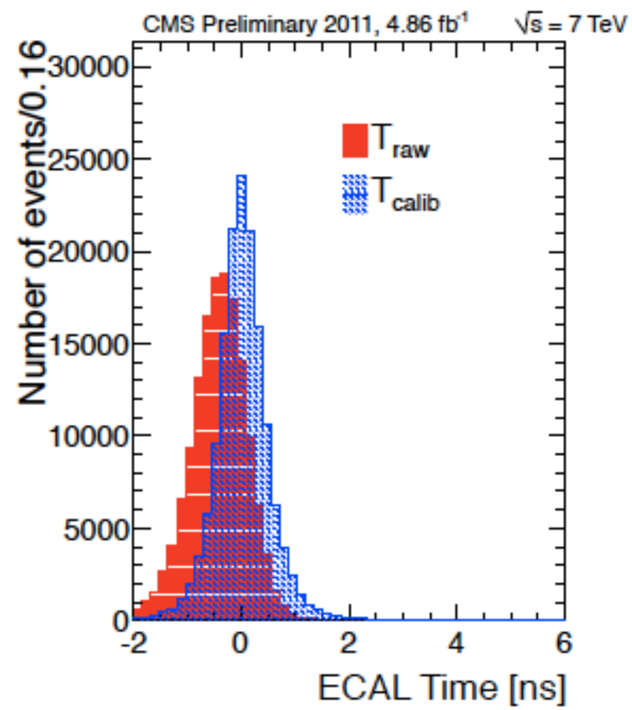
Technique II: Photon Time of Flight

1 For the ECAL time calculation: Calculate a weighted average of timing for all crystals in super-cluster

$$T = \frac{\sum \frac{T_i}{\sigma_i^2}}{\sum \frac{1}{\sigma_i^2}}$$

2 The time of the pp collision will vary event-by-event (correct for this)

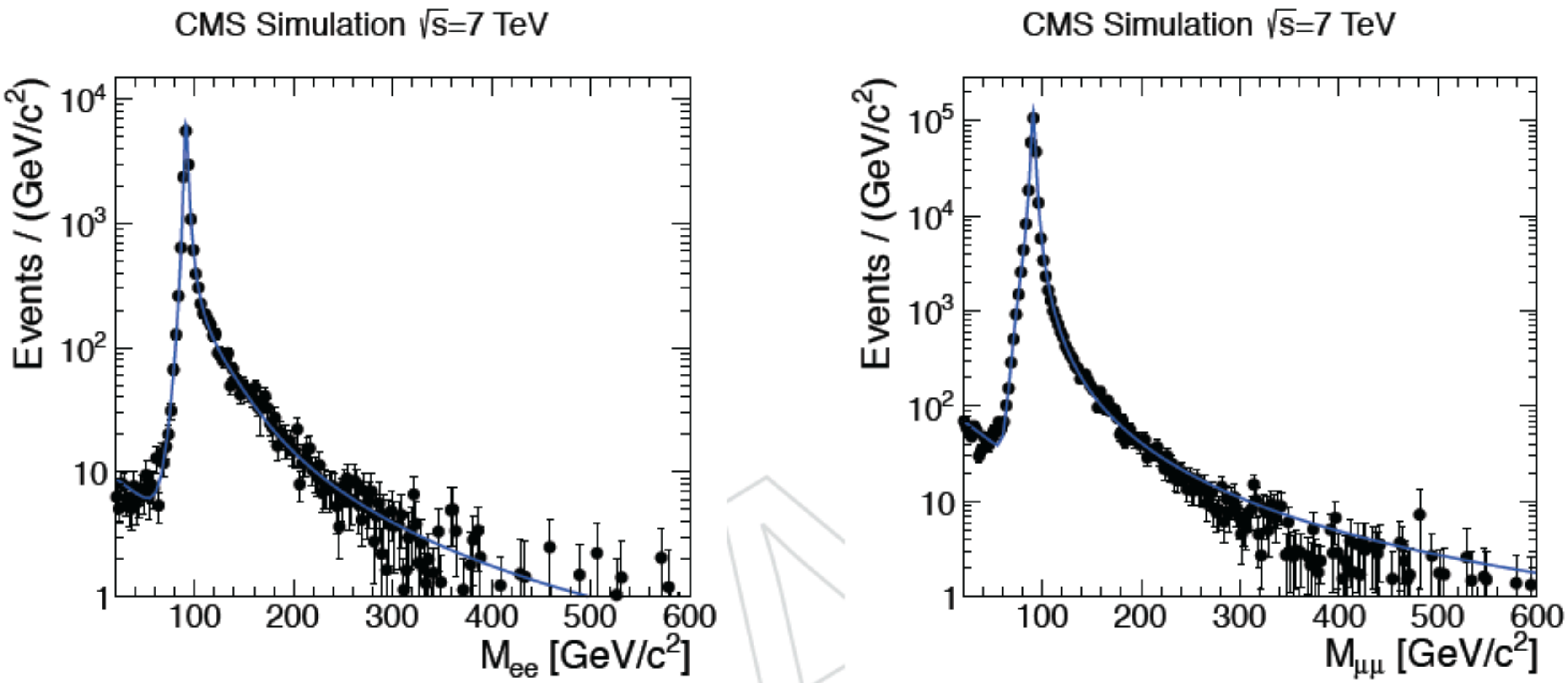
Calculate T_{corr} (corrected timing) by subtracting the mean time of the event from the signal photon (using all rechits not belonging to the two most energetic photons)



$$T_{corr} = T_{sig} - T_{mean} \qquad \sigma_{T_{corr}} = \sqrt{\sigma^2_{T_{sig}} + \sigma^2_{T_{mean}}} \simeq \sigma_{T_{mean}}$$

- This improves the timing resolution (with respect to using the ECAL time of the seed crystal only) lowering uncertainty from knowledge of the beam-spot

Background PDF



Fit of the background shape to a simulated sample with with lifetime-related selection Requirements removed, shown for the electron (left) and muon (right) channels. The shape used is that of a Breit-Wigner distribution times a turn-on function, added to an exponential term.