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SUSY Searches with Displaced Vertices in CMS

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On behalf of the CMS collaboration

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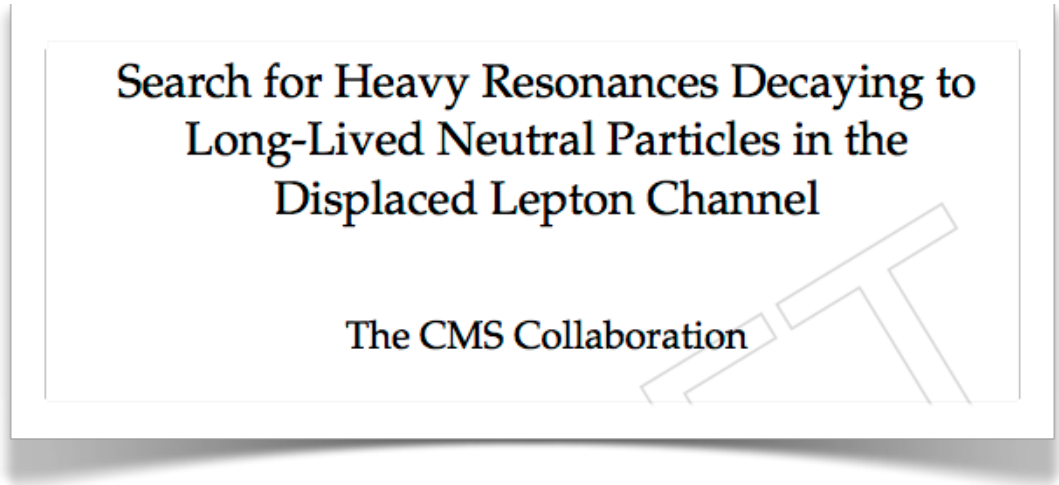
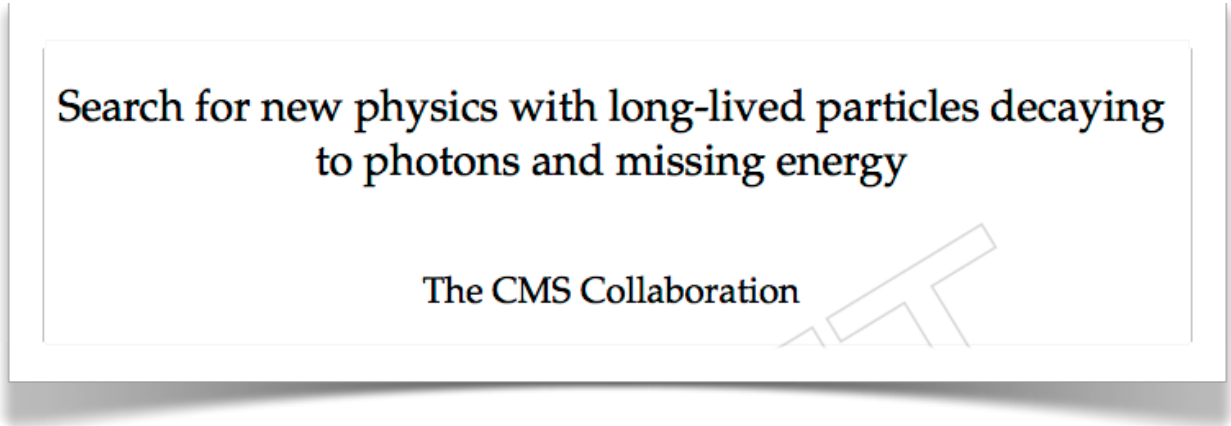
Two analyses in CMS

- Long-lived neutral particles to **displaced leptons**
  - Analysis at CMS: EXO-11-004
  - 1.1 /fb



- Long-lived neutral particles to **displaced photons**
  - Analysis at CMS: EXO-11-067
  - 2.1 /fb



Motivation for the displaced lepton search

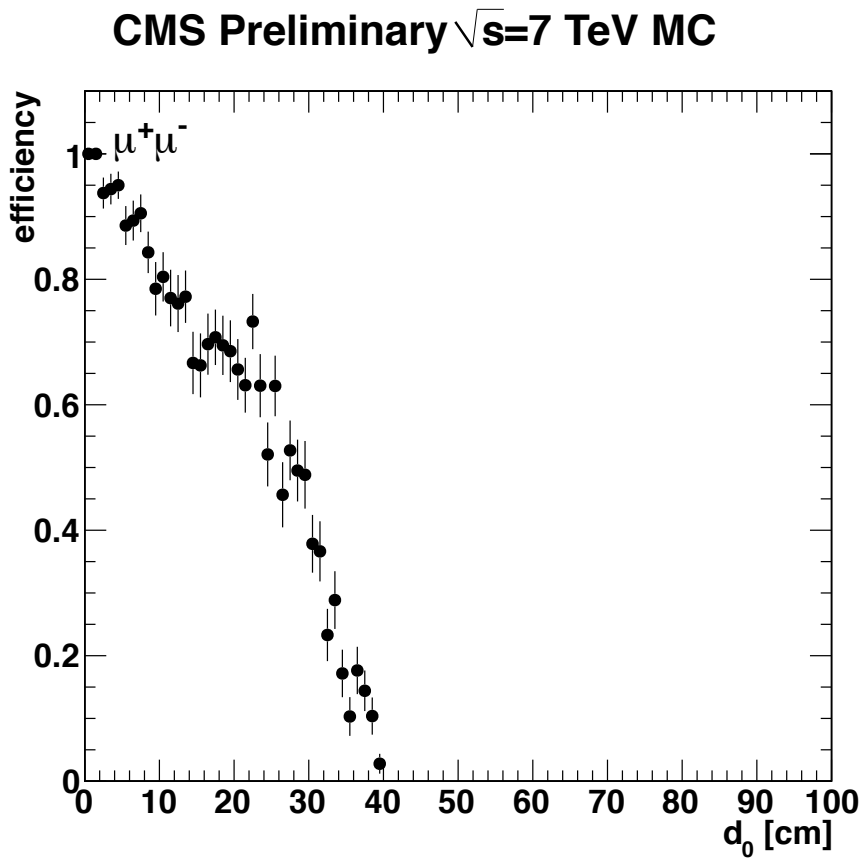
- Massive, neutral-charge, long-lived particles → leptons
  - Higgs bosons decaying to two long-lived, massive, neutral particles
    - **They can be SUSY Higgs, or Higgs in some other models.**
  - Each have a finite branching ratio to decay to dileptons.

$$H^0 \rightarrow 2X, X \rightarrow \ell^+\ell^-$$

- Signature: One or two **displaced vertices** formed by a pair of oppositely charged leptons (electrons or muons)
  - Electron channel: two identified electrons
  - Muon channel: two identified muons
- Key point: **to make use of displaced track reconstruction**.

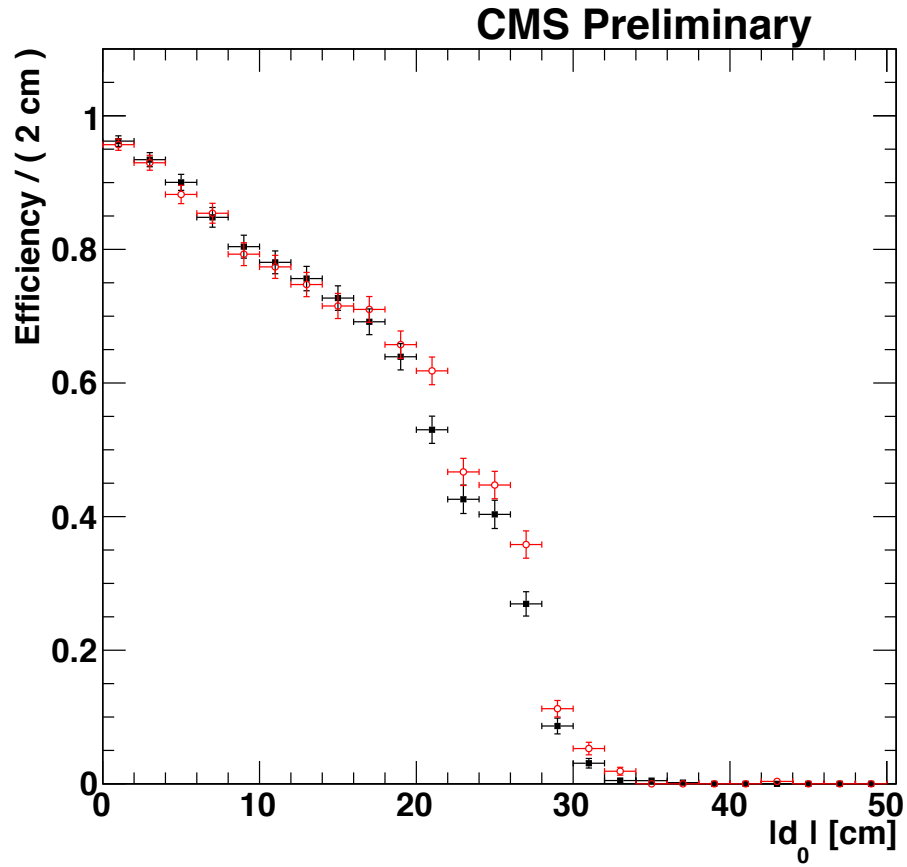
Displaced track reconstruction

- "Iterative tracking" algorithm in CMS.
  - Five iterations for different purpose
  - First iteration to find tracks originating near the primary vertex, using seeds in pixel tracker.
  - **Additional steps** for very low momentum tracks and **highly displaced tracks**.
- Tracking efficiency for single isolated particles can reach the transverse impact parameter d_0 up to 40 cm.
- Displaced lepton identification
  - By matching tracks to lepton trigger objects.



Displaced track finding efficiency

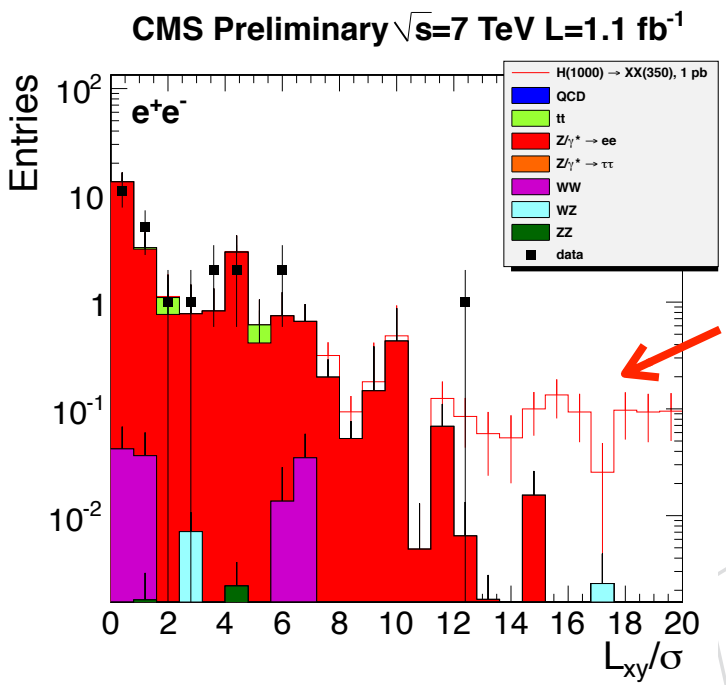
- Cosmic muons are used to model the displaced track finding efficiency.
  - An abundant source of very displaced tracks.
- Data and simulation **agree** to within 10%.



Efficiency of the tracker to find a track given a cosmic muon reconstructed in the muon chambers, as a function of the transverse impact parameters. Data is in black full points, and simulation in red open points.

Searches at CMS

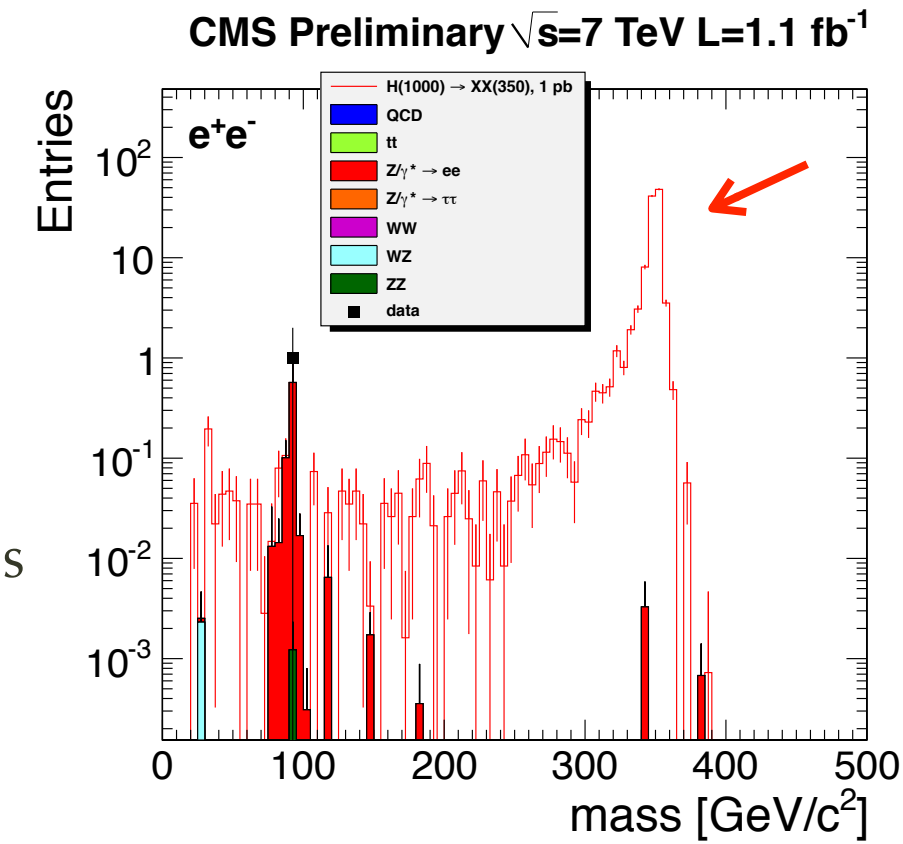
- One or two **displaced vertices in the final state**.
- Monte Carlo signal $H^0 \to 2X, X \to \ell^+\ell^-$
  - Variety of Higgs masses and X lifetimes
  - **Upper limits are set as function of X mass and lifetime.**
- Background: QCD, $t\bar{t}$, $Z/\gamma \to \ell^+\ell^-$, $W^{\pm}/Z$ with leptonic decays.



The transverse decay length significance of the candidates for the dielectron channel.

Signal and background

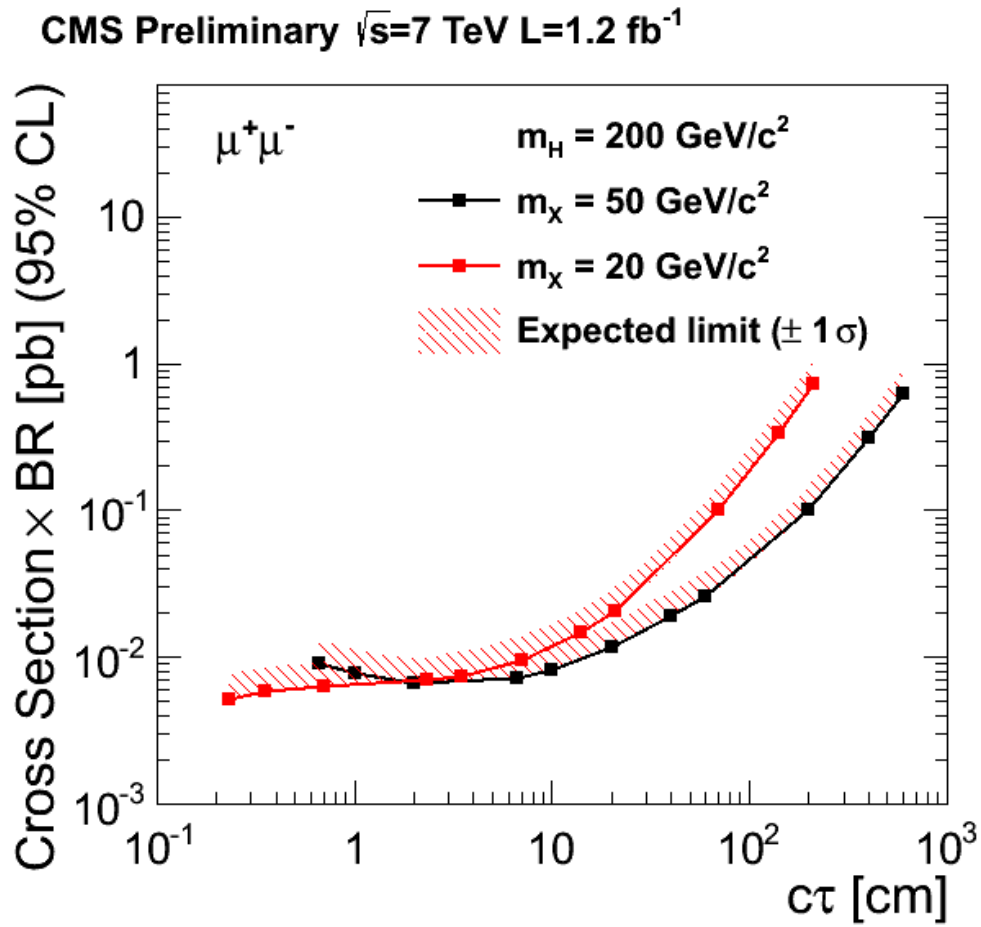
- Signal : a **narrow resonance** in the mass spectrum.
- Background estimation
  - Integrated over the entire dilepton mass spectrum
    - 0.79±0.99 events for electron channel
    - 0.02±2.28 events for muon channel



Reconstructed dilepton mass in the dielectron channel after all selection cuts have been applied

Results

- Upper limits on σB can be set as a **function of X lifetime**, for **different X mass**.
  - σ: cross section of XX pair-production
  - B: branching ratio of X→ll
- Muon channel for example.
  - Higgs mass of 200 GeV/c^2
- Higgs masses of 200-1000 GeV/c^2 and X boson masses of 20-350 GeV/c^2
  - limits are typically in the range **0.003-0.03 pb**
  - X bosons transverse decay length less than about 1 meter.



95% C.L upper limits on σB for the muon channel for a Higgs mass of 200 GeV/c^2.

Motivation for the displaced photon search

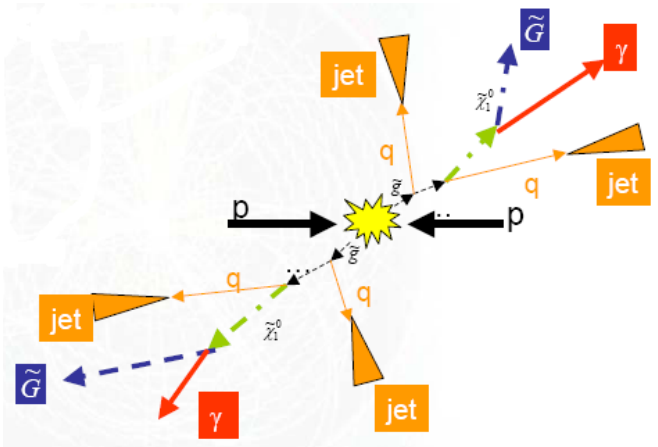
- Massive, neutral-charge, long-lived particles → photons
  - e.g. Hidden Valley, Gauge-mediated SUSY model
- Gauge-mediated SUSY model for example
  - Neutralinos as NLSP: can have **non-zero lifetimes**
  - Photons are **displaced**, and **not pointing back** to the interaction point.
  - Very light Gravitino: LSP
- However, photons can **not** be readily assigned to a given interaction vertex.

If γ converts into e^+e^-?

If R-parity is conserved, gravitinos will not decay, thus E_T^{miss} is expected.

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

Displaced photons from long-lived neutralino not pointing back to the interaction point.

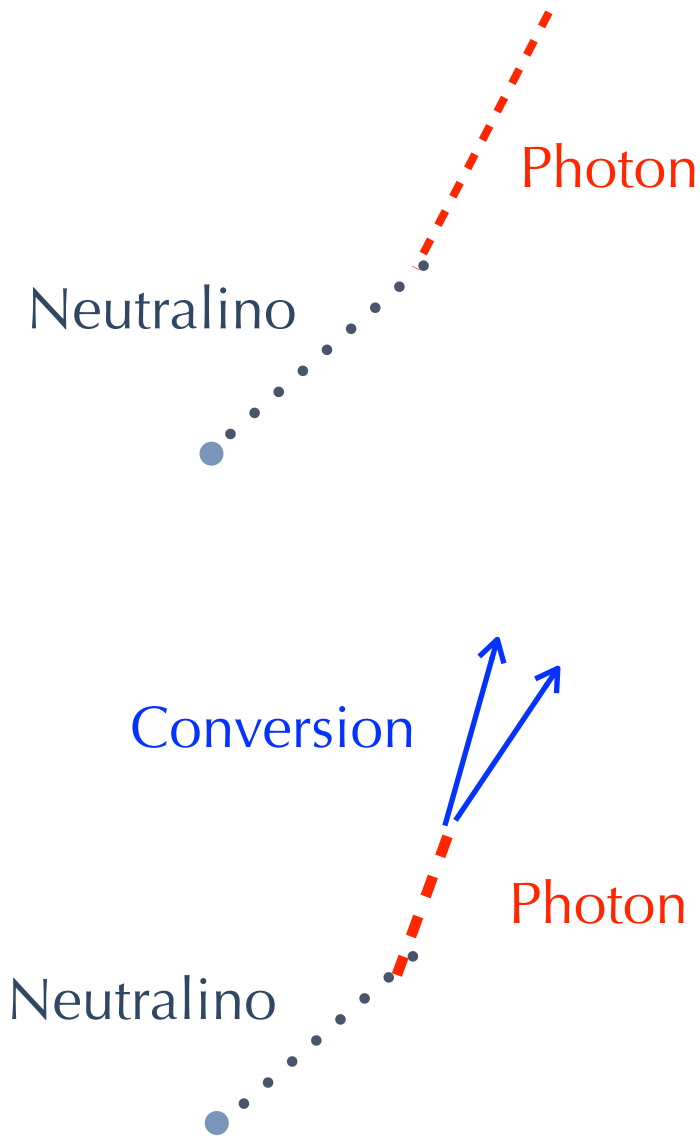


Searches at CMS

- The search strategy
  - Final states: **γ+γ** at least one conversion
    - Diphoton trigger
    - Any **isolated** photons E_T>45 GeV in **ECAL barrel**
    - **Examine d_{xy} of every single converted photon**
  - The presence of jets
  - E_T^{miss} > 30 GeV
    - Lower than E_T^{miss} cut in some other SUSY searches involving photons.
  - Low E_T^{miss} as control samples for background estimation.

The method: photon conversion

- CMS Tracker based on silicon technology
  - A substantial amount of material
  - A large fraction of photons convert into e^+e^- pairs
    - "photon conversions" or "**conversions**"
- Reconstructed photon conversions can be used to give the **photon direction**.



Conversion reconstruction in CMS

- Zero mass conversion vertex→e+e- tracks are parallel in momentum
  - **Selection** and **vertex fitting** with kinematic constraint on θ and φ
- Three algorithms of photon conversion reconstruction in CMS
  - Tracker-only
  - ECAL-seeded
  - Gaussian summation filter (GSF) electrons.
- Merged conversion collections and duplication removal.
- The transverse impact parameter d_{XY} can be calculated from photon conversions.
  - **Long-lived particle → large d_{XY}**

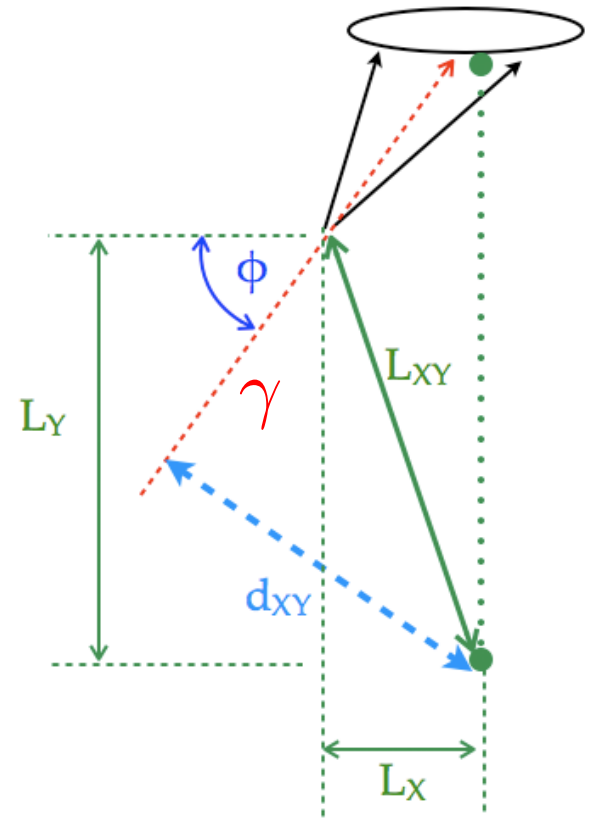


Illustration of IP calculation using photon conversion direction

Signal selections

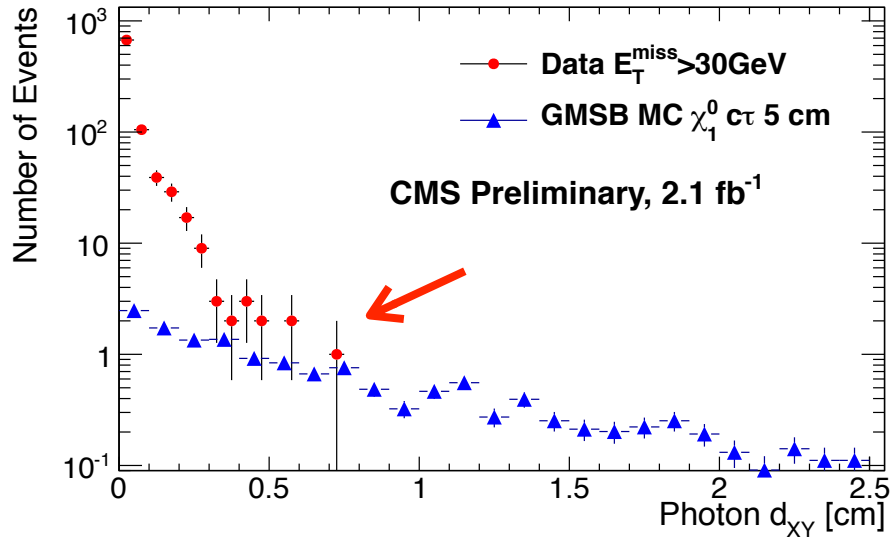
Table 1: Signal selection cut flow for $c\tau = 5$ cm

Selection	Events in Monte Carlo
Total	45057
DiPhoton trigger	39988
Photon $E_T > 45$ GeV and $E_T > 30$ GeV	37398
Any ECAL barrel photon $E_T > 45$ GeV and Photon identification	27766
Jets $p_T > 80$ GeV and $p_T > 50$ GeV	26229
Conversion selection	1602
$E_T^{miss} > 30$ GeV	1542
$d_{XY} > 0.6$ cm	711

- Acceptance times efficiency from minimal GMSB diphoton simulation, reweighted for pile-up.
- Cut on d_{XY}>0.6 cm is chosen by optimizing expected limits from background (next page).
- Signal selection efficiency depends on neutralino lifetimes

Table 2: Event selection efficiency vs $\tilde{\chi}_1^0$ lifetimes

$c\tau$ [cm]	2	5	10	25
Efficiency	0.921%	1.578%	1.797%	1.388%
Statistical errors	0.046%	0.059%	0.064%	0.055%



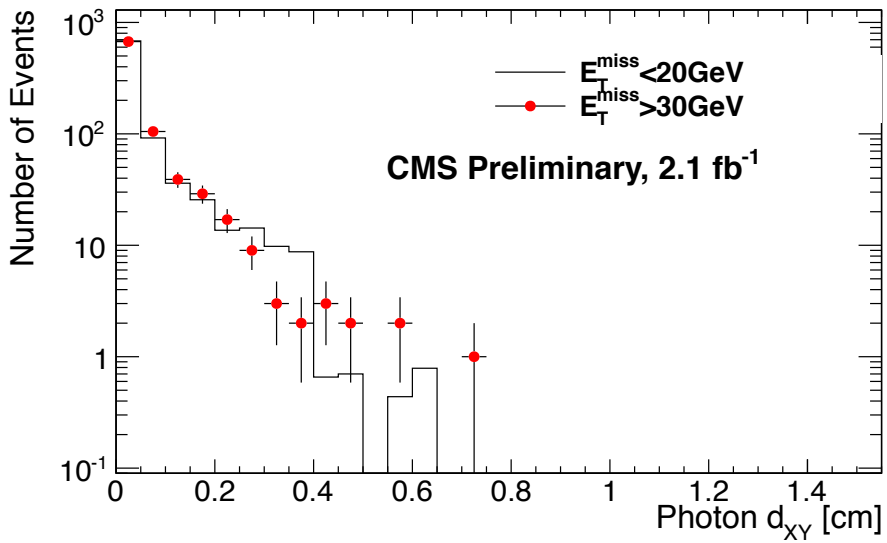
Transverse IP d_{XY} for data vs signal simulation ($c\tau$ 5 cm), normalized to the integrated luminosity of data.

One event satisfying all selection criteria is observed.

Estimation of background

No true large E_T^{miss}

- γ's and jets in the final state
  - Single γ + jets: real energetic photons
  - QCD multi-jets: jets misidentified as photons
- Data-driven estimation
  - **Data for E_T^{miss}< 20 GeV as control region**
    - Normalization by number of conversions
    - Reweighted by conversion vertex χ2 probability
  - A cut on the d_{XY}>0.6 cm
  - Total background $0.78^{+1.25}_{-0.48}$ events

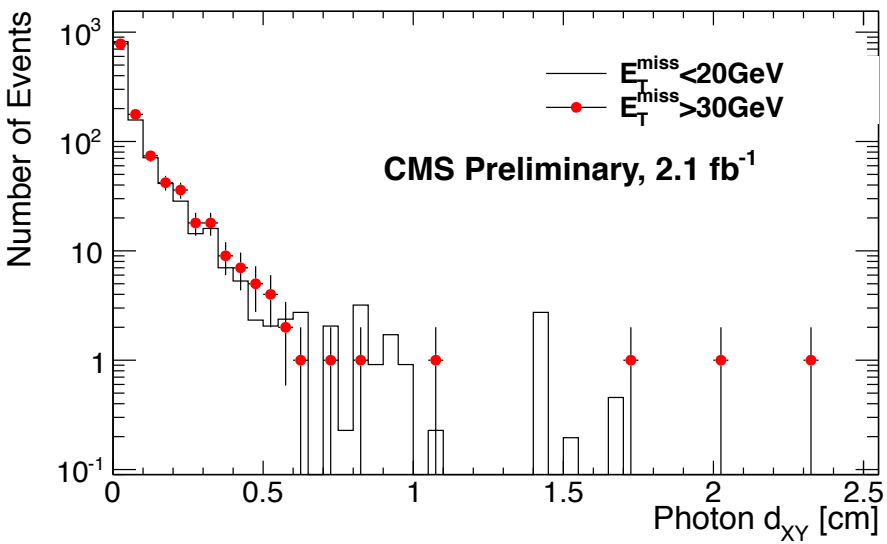


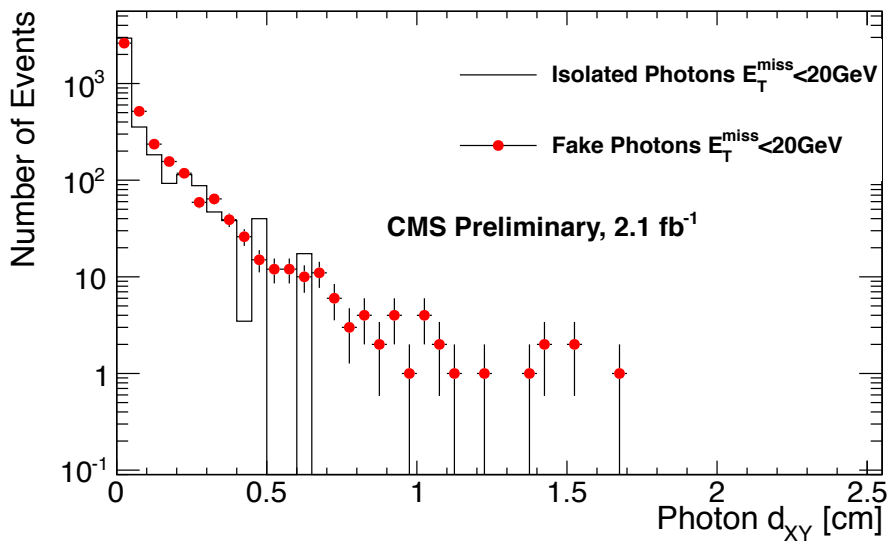
d_{XY} distribution for E_T^{miss}< 20 GeV and E_T^{miss}>30 GeV for isolated photons

- **Is this estimation a good description of the background?**
  - Control samples in data: **fake photons**
    - Non-isolated photons or jets misidentified as photons.
  - Compare d_{XY} distribution for fake photons and isolated photons

Fake photons as control samples

- d_{XY} distribution comparison
  - **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}<20GeV (right)
  - Normalization by the total number of conversions, and reweighted by conversion vertex χ^2 probability.





- Agreement of the d_{XY} distributions of fake photons and isolated photons.
  - **We conclude that the background estimation is sufficient.**

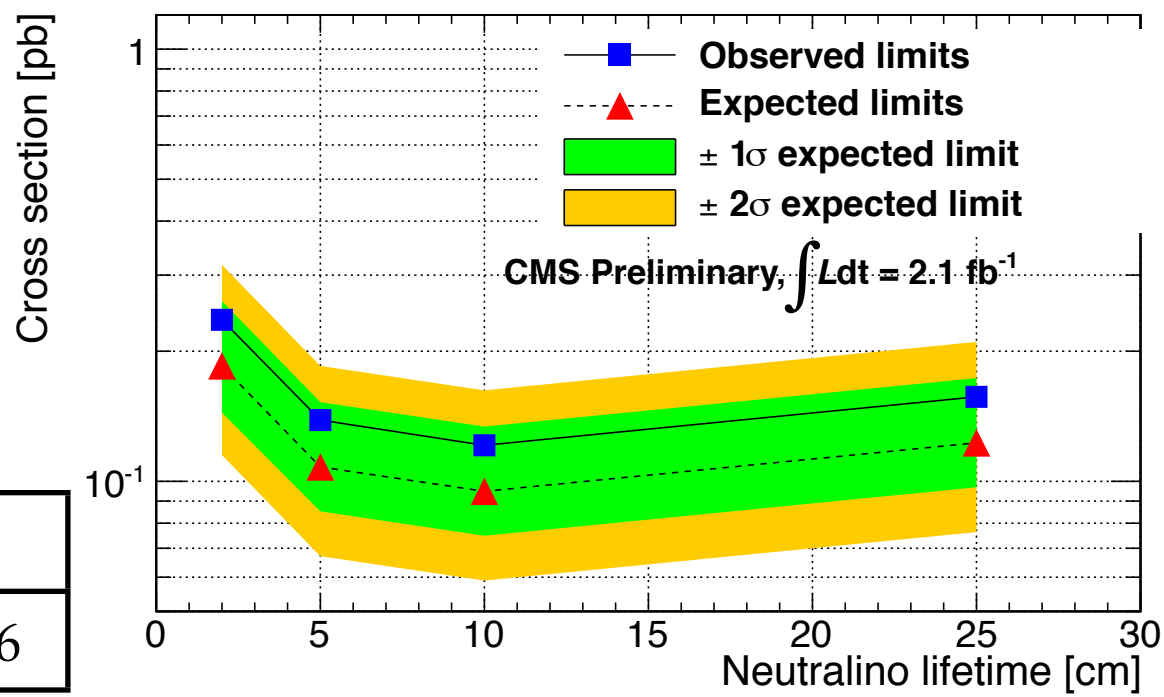
Results

- One event satisfying the selection criteria is observed.
  - Photon d_{XY}=-0.74 cm, E_T^{miss}=44.9 GeV
- Background rate $0.78^{+1.25}_{-0.48}$ event.
- CLs limit with likelihood-ratio at 95% CL, using the log-normal model

Systematics	Uncertainty (%)
Conversion efficiency	20.6
d_{XY} resolution	<0.5
Luminosity	4.5
Jet/E_T^{miss} energy scale	<0.5
Pile-up	2.5
Photon Data/MC scale	2.6
Photon ID	0.5
Total	25

Upper limits are set as a function of lifetime on the cross section for pair-production of long-lived neutral particles, each of which decays to a photon and missing energy.

cτ [cm]	2	5	10	25
σ [pb] 95% C.L.	0.24	0.14	0.12	0.16



Summary

- **Long-lived particle to leptons**
  - Iterative tracking in CMS has the capability to **find displaced tracks**.
  - Upper limits are placed on the cross section × branching ratio of the process $H^0 \to 2X, X \to \ell^+\ell^-$
  - Higgs masses of 200-1000 GeV/c^2 and X boson masses of 20-350 GeV/c^2
    - limits are typically in the range 0.003-0.03 pb
    - X bosons transverse decay length less than about 1 meter.
- **Long-lived particle to photons**
  - Photon conversion is **an appropriate technique** to search for long-lived particles decaying to photons.
  - Search in the final state of photons plus jets plus E_T^{miss}, with large photon IP.
    - Relatively lower E_T^{miss} cut (>30 GeV) compared with other SUSY searches involving photons
    - Sensitive to shorter lifetime (0.1 ns to 1 ns)
  - Upper limits are set on the cross section for pair-production of long-lived neutral particles, each of which decays to a photon and missing energy.