Search for new Physics with Long-Lived Particles Decaying to Photons and Missing Energy in CMS

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The physics

A novel technique

The first search

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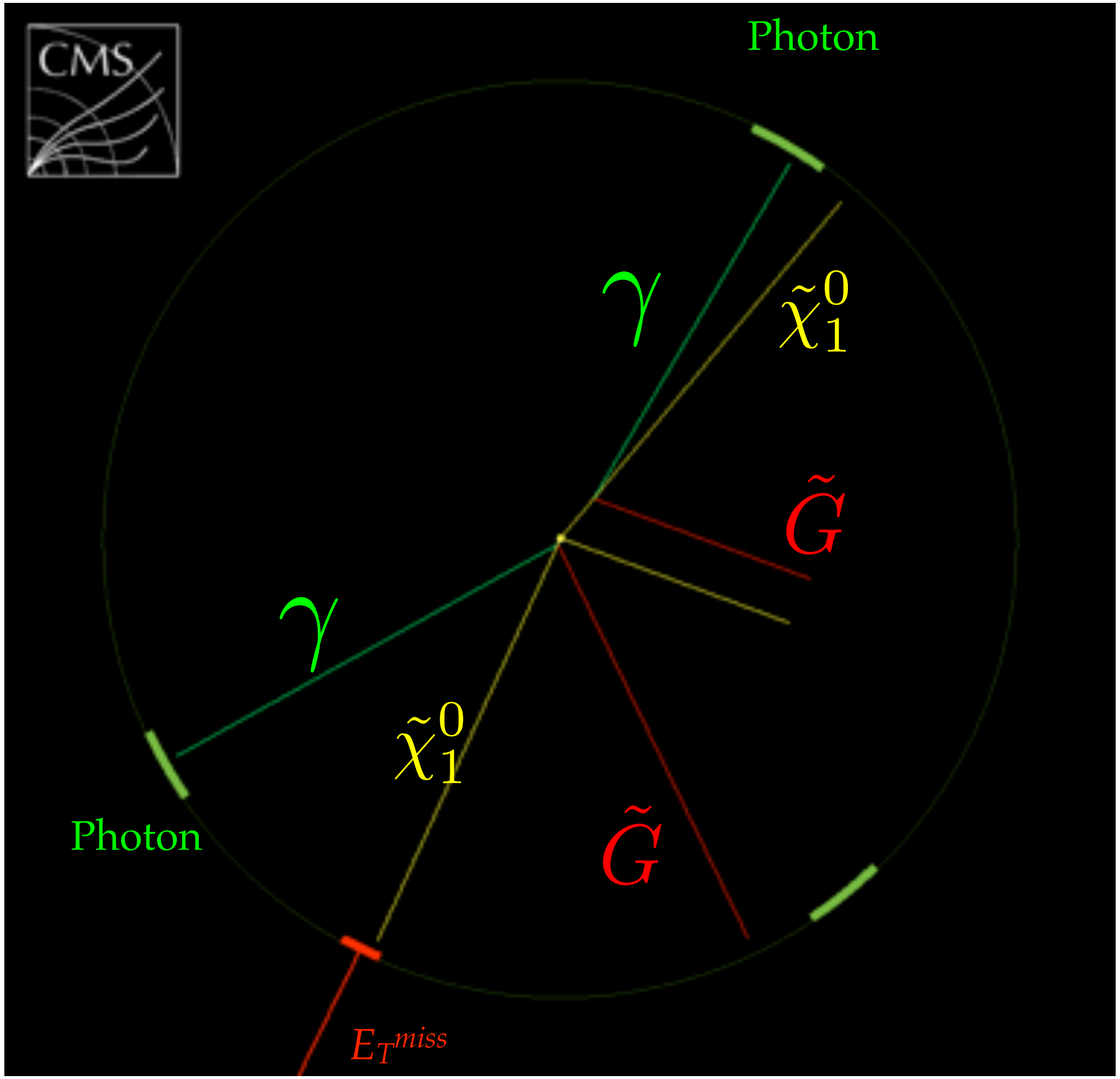
The physics

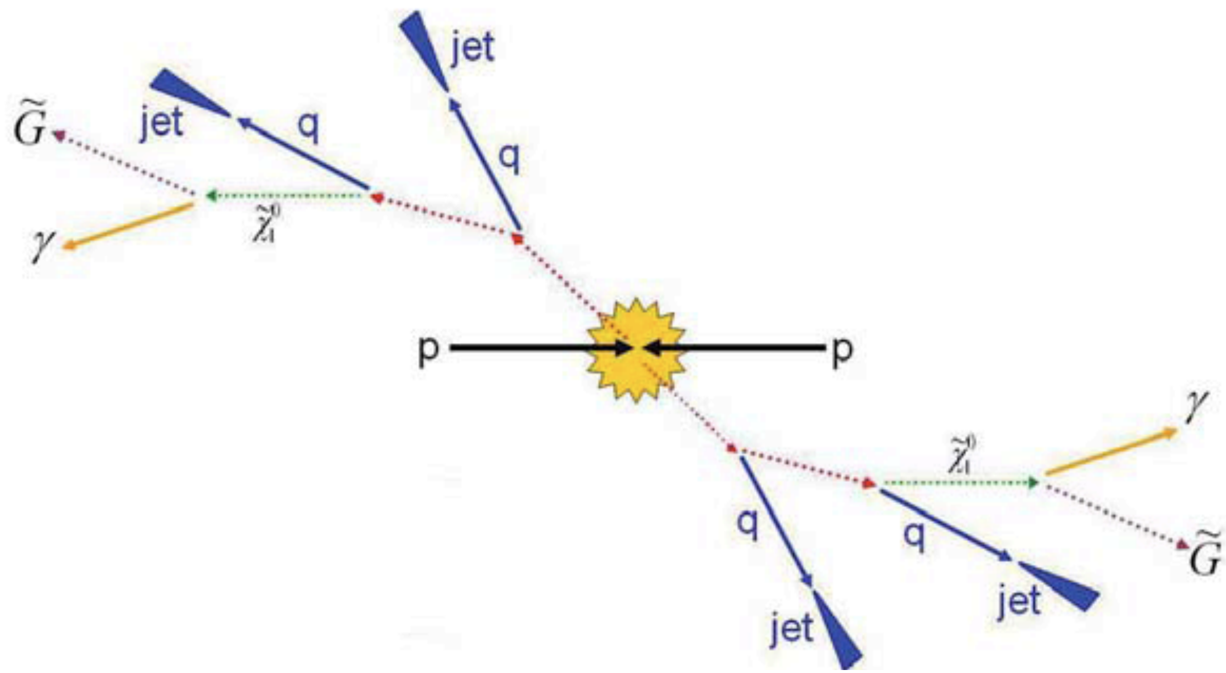
A photon, produced from a **long-lived** $\tilde{\chi}_1^0$, pointing away from the primary vertex, in a simulated SUSY event



New physics models with photons

- Gauge-mediated SUSY (GMSB) for example
  - The gravitino $\tilde{G}$ is the lightest SUSY particle (LSP)
  - The lightest **neutralino** $\tilde{\chi}_1^0$ is the next-to-lightest SUSY particle (NLSP)

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



Relevant analyses of neutralinos in CMS

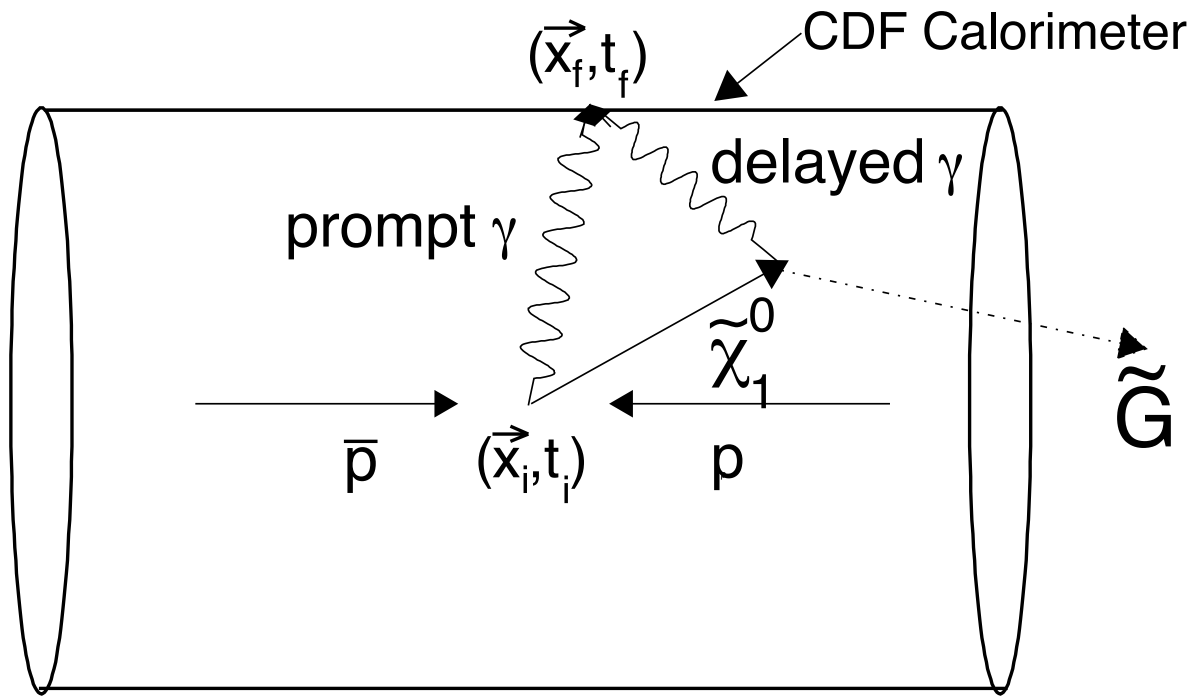
- In the decay model of neutralino into a photon plus a gravitino, for different cases, prompt or long-lived, some analyses are performed using different signatures and different methods.

	Channels	Documents
Prompt photons	Single γ + ≧3 jets	SUS-12-001
	Di-photon + jets	SUS-10-002 SUS-12-001
Displaced photons	ECAL timing	EXO-11-035
	Conversions	EXO-11-067

The long-lived neutral particles

- Massive, neutral-charge, long-lived particles → photons
  - e.g.Gauge-mediated SUSY model, Hidden Valley
- The neutralinos can have non-zero lifetimes
  - Photons are **displaced**, and not pointing back to the interaction point.

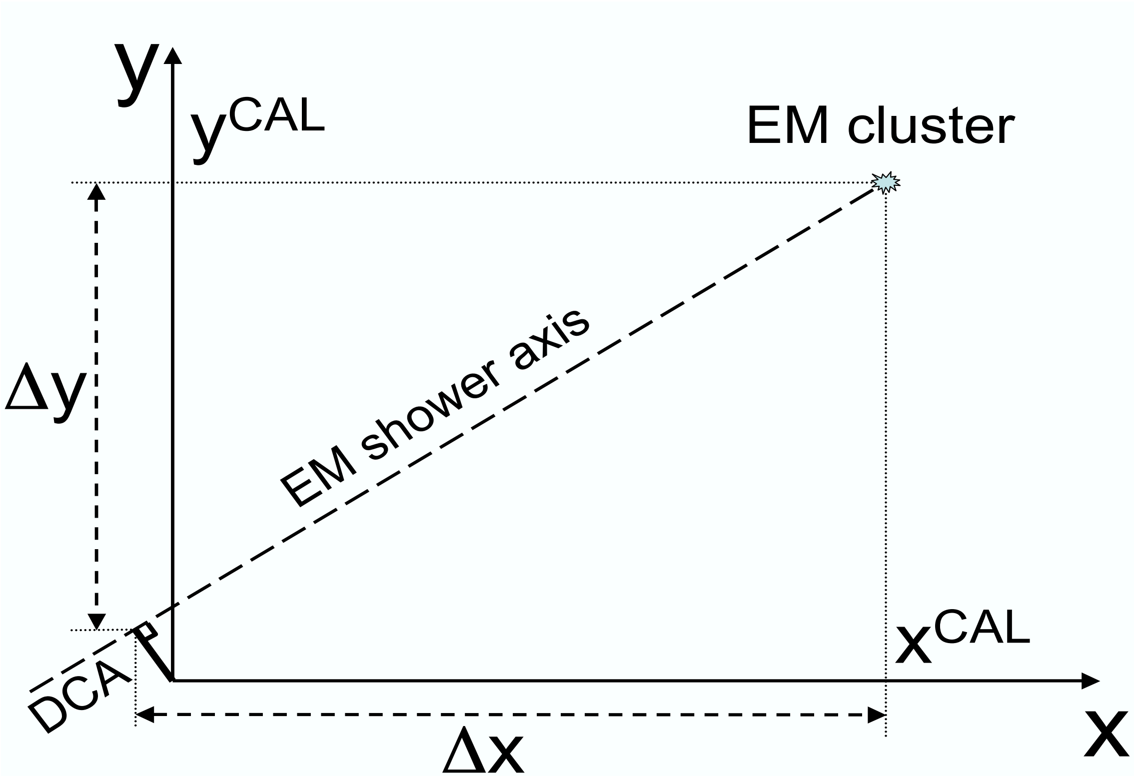
CDF: time-of-flight



CDF arXiv:0804.1043v1

Optimized for decay length O(1 m)

D0: shower direction



D0 arXiv:0806.2223v1

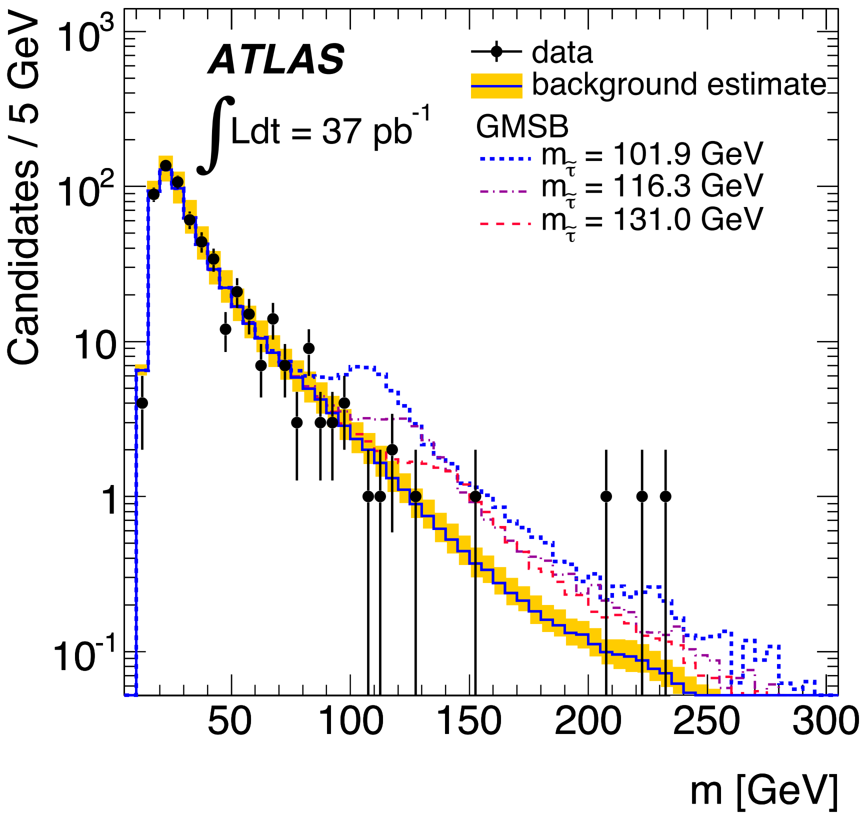
Optimized for decay length O(1 m)

ATLAS: no γ but Z

$$\tilde{\chi}_1^0 \to Z + \tilde{G}$$

ATLAS arXiv:1106.4495v2

37 pb^{-1}



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A novel technique

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The long-lived neutral particles

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  - e.g.Gauge-mediated SUSY model, Hidden Valley
- The neutral particles can have non-zero lifetimes
  - Photons are **displaced**, and not pointing back to the interaction point.

But, wait...

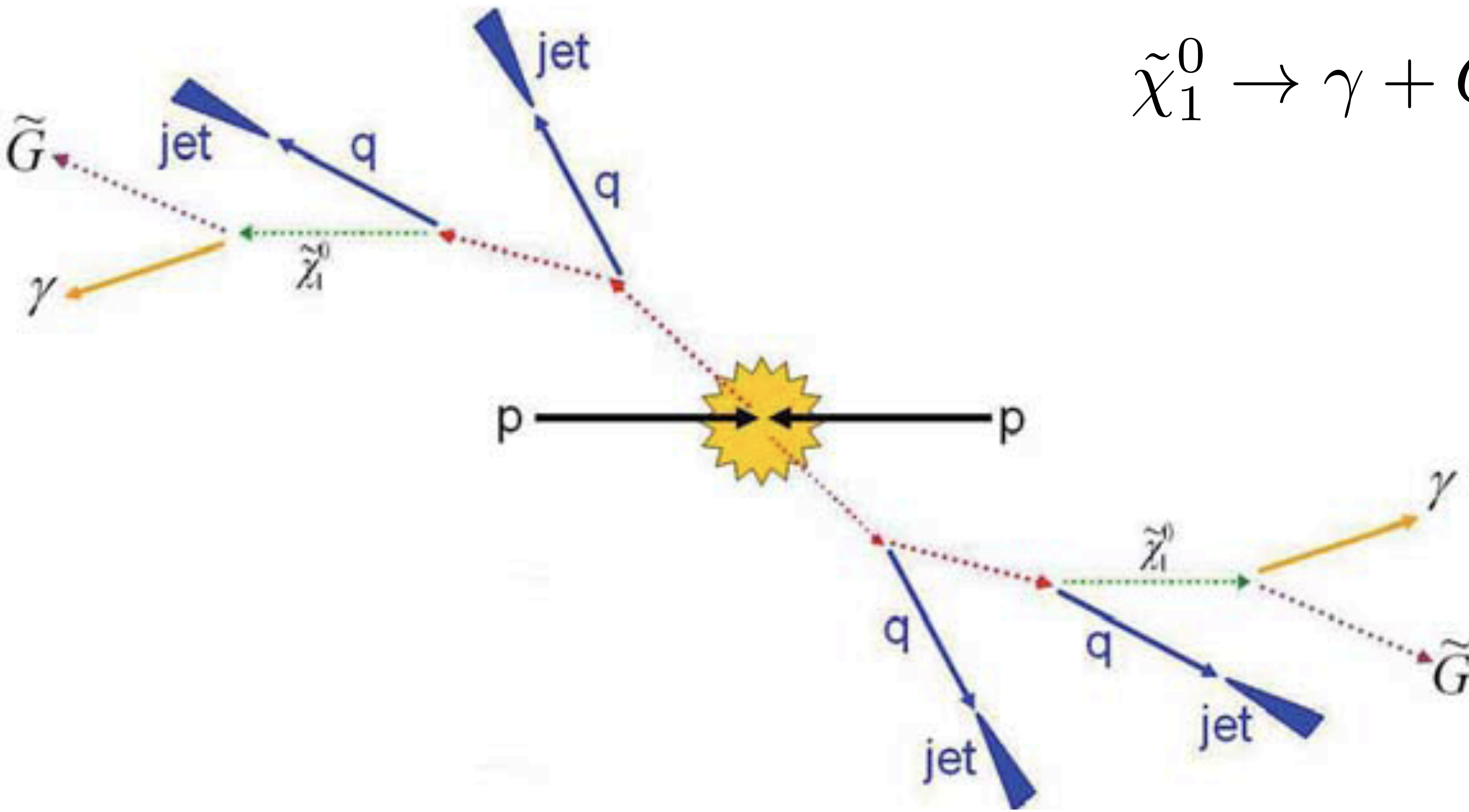
Photons can not be readily assigned to a given interaction vertex.

If γ converts into $e^{+}e^{-}$?

Take gauge-mediation as a case study.....

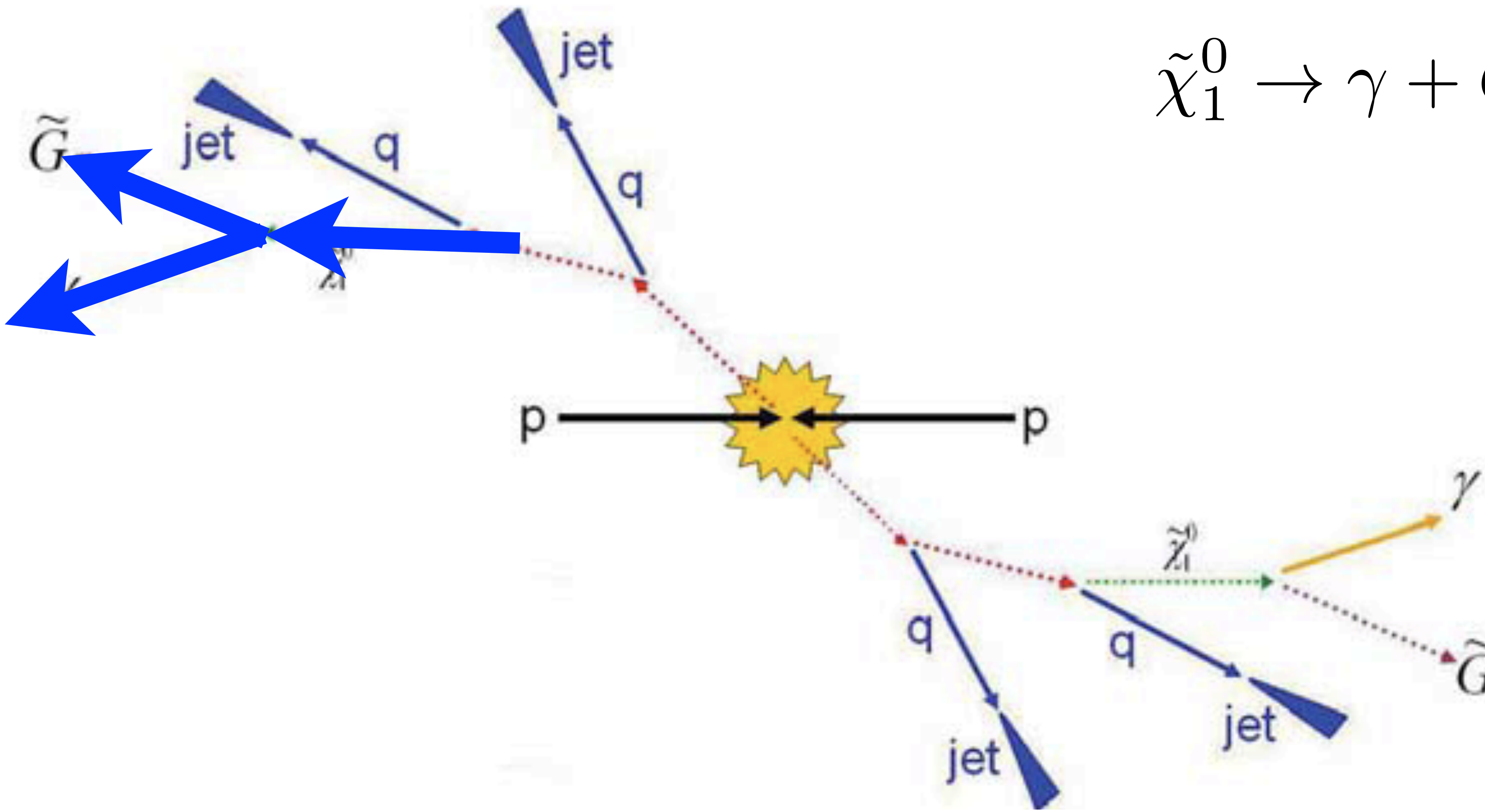
Gauge-mediated SUSY breaking

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



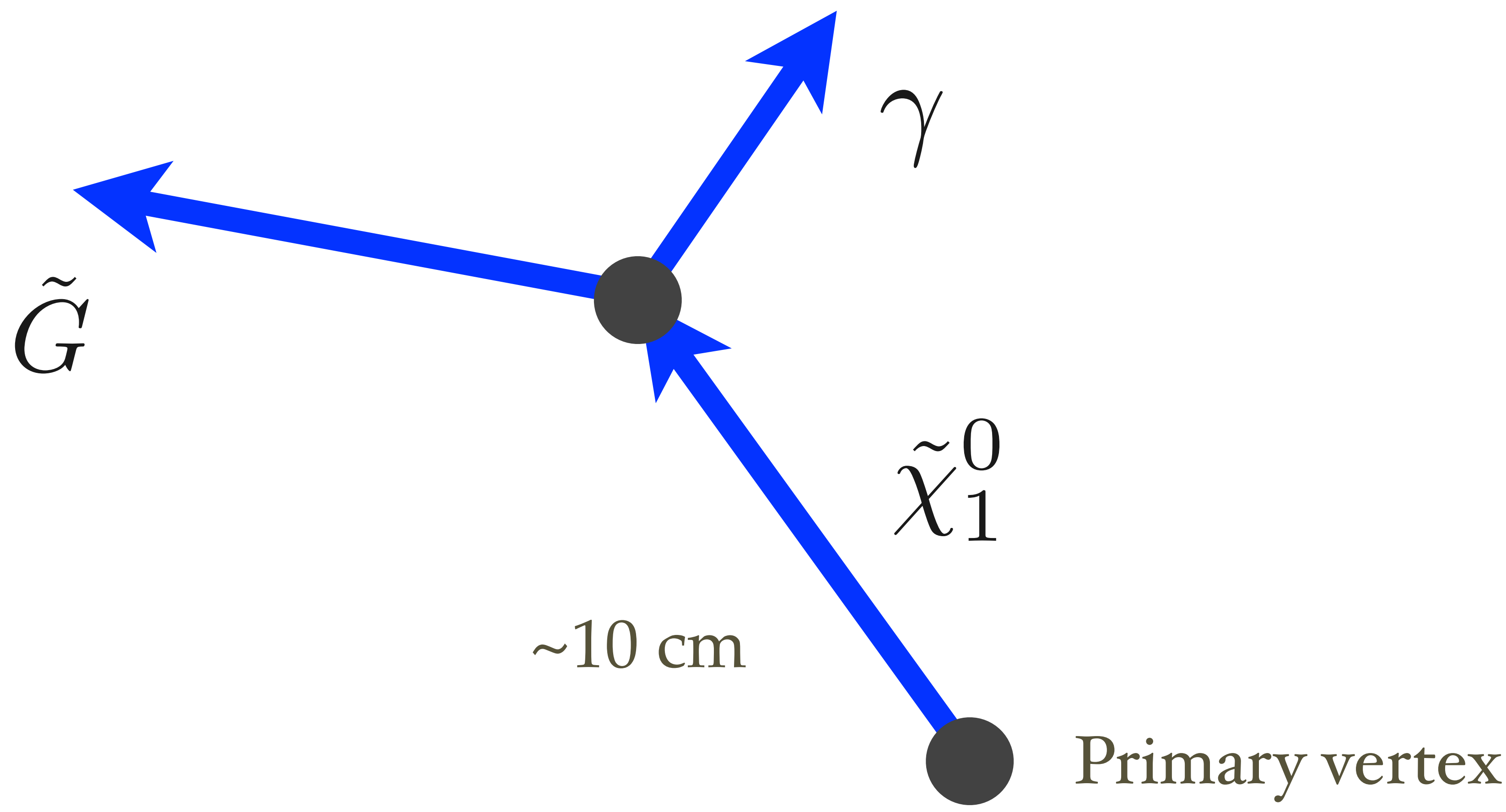
Gauge-mediated SUSY breaking

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

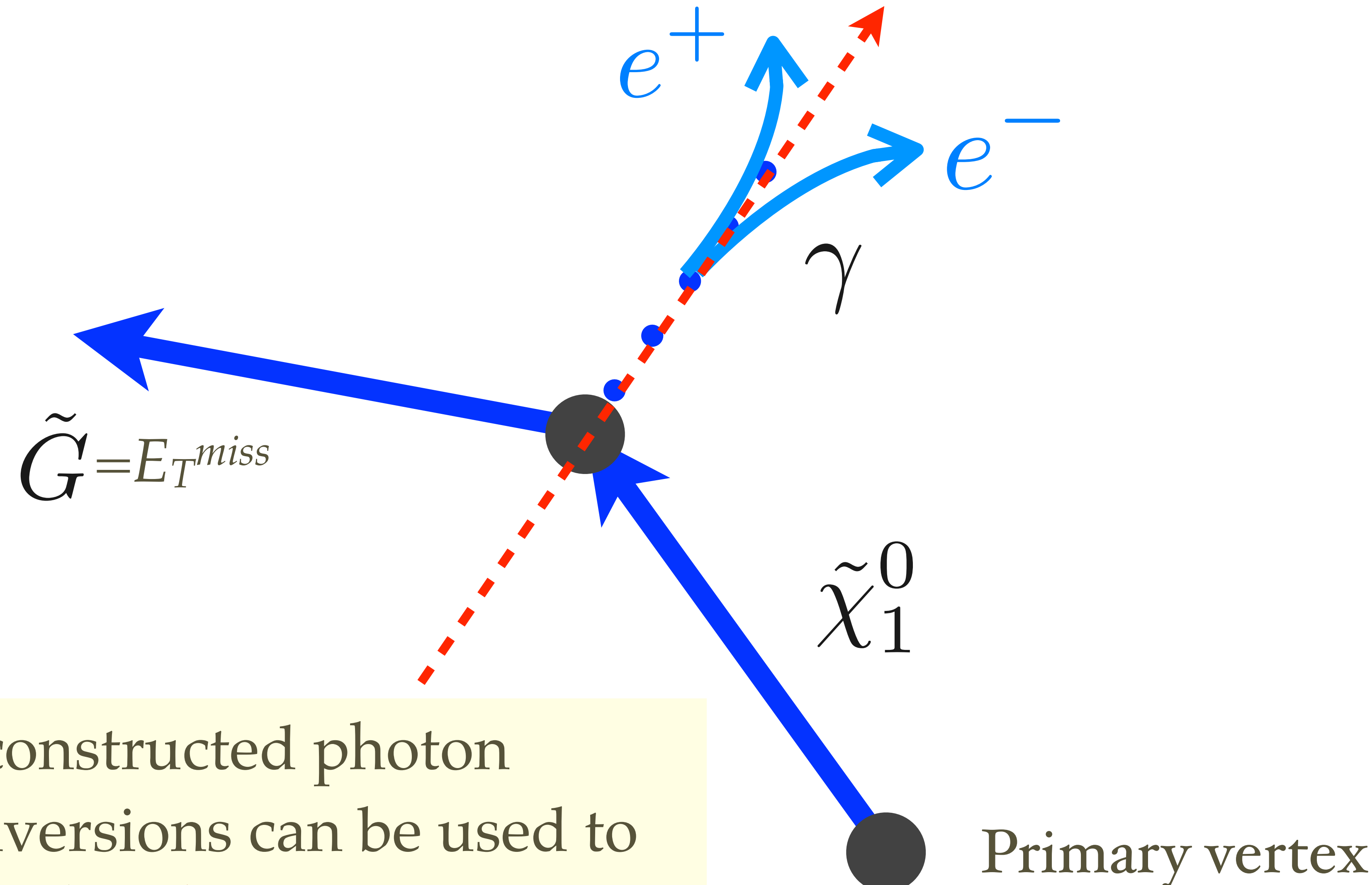


Both γ and $\tilde{G}$ are invisible!

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



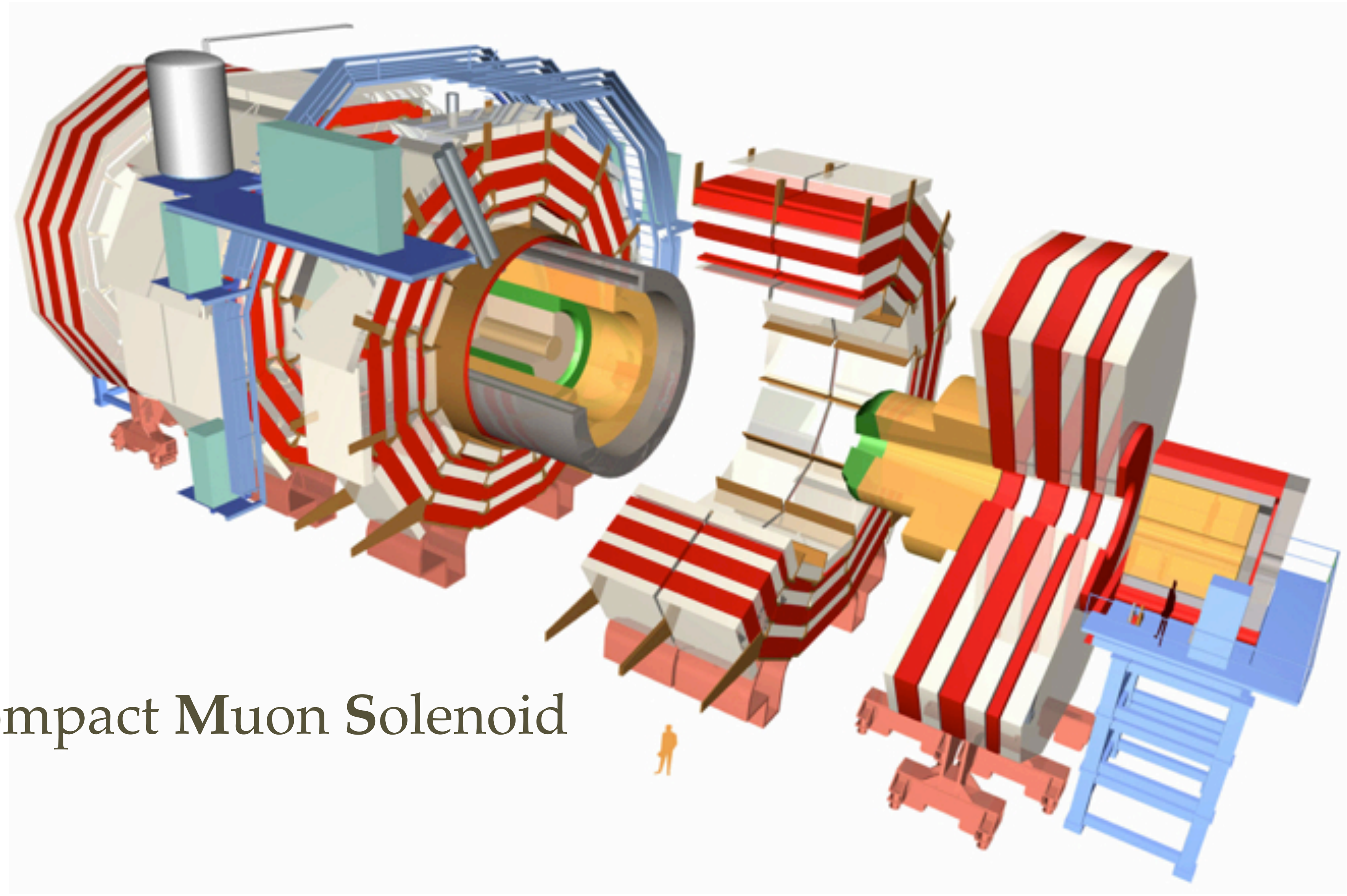
Use photon conversion!



- Reconstructed photon conversions can be used to give the photon direction.

How do we get photon conversions?

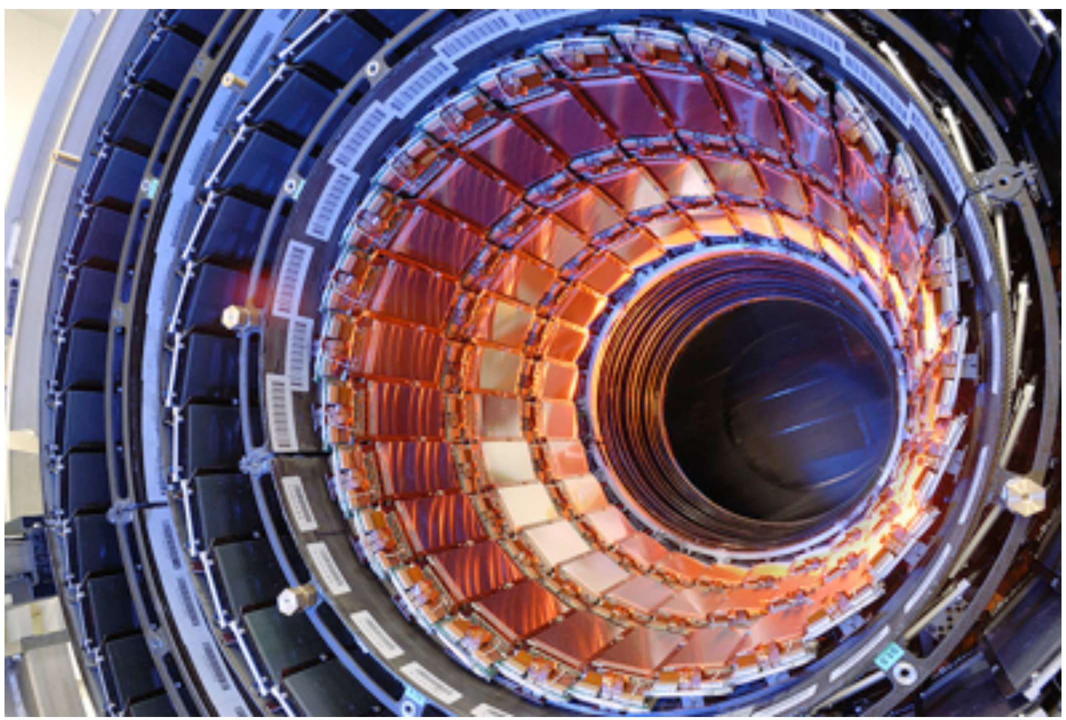
The CMS

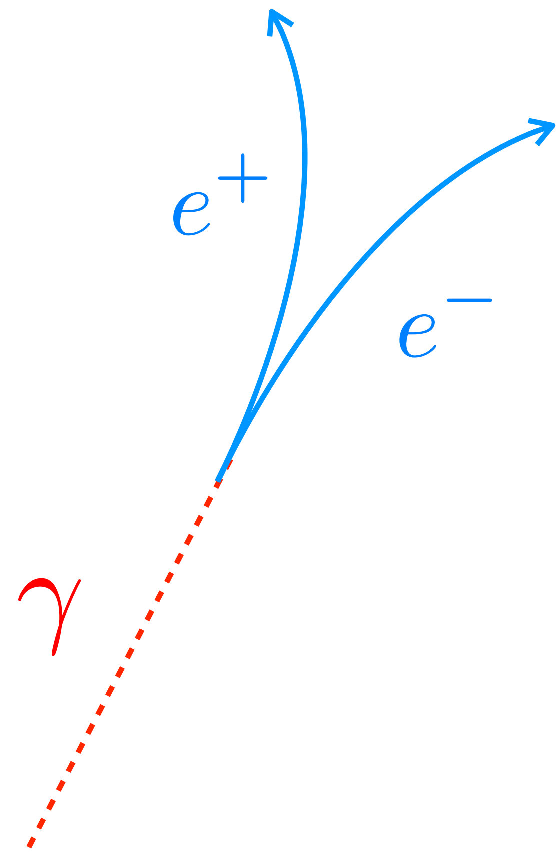


Compact Muon Solenoid

The photon conversion

CMS silicon tracker:
A beautiful and heavy machine





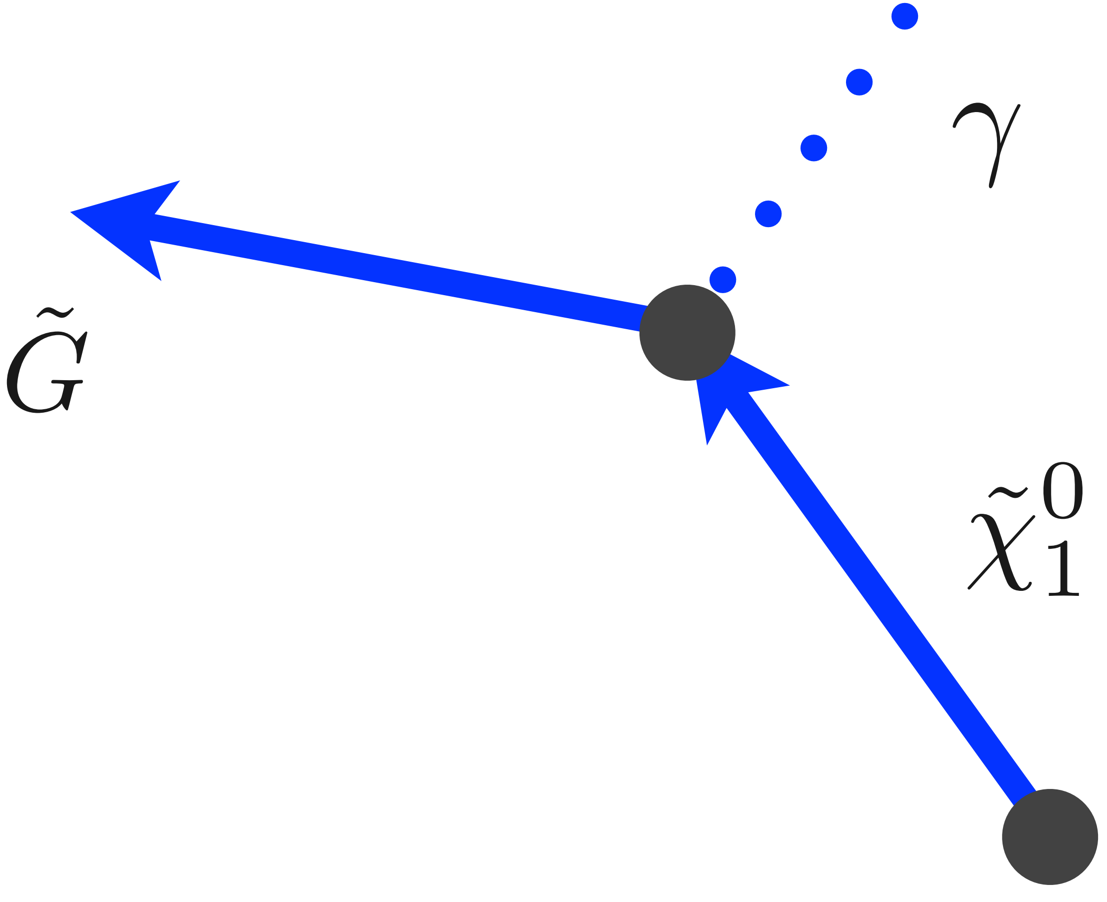
Photon conversion in the CMS tracker

- Tons of silicon material in the CMS tracker

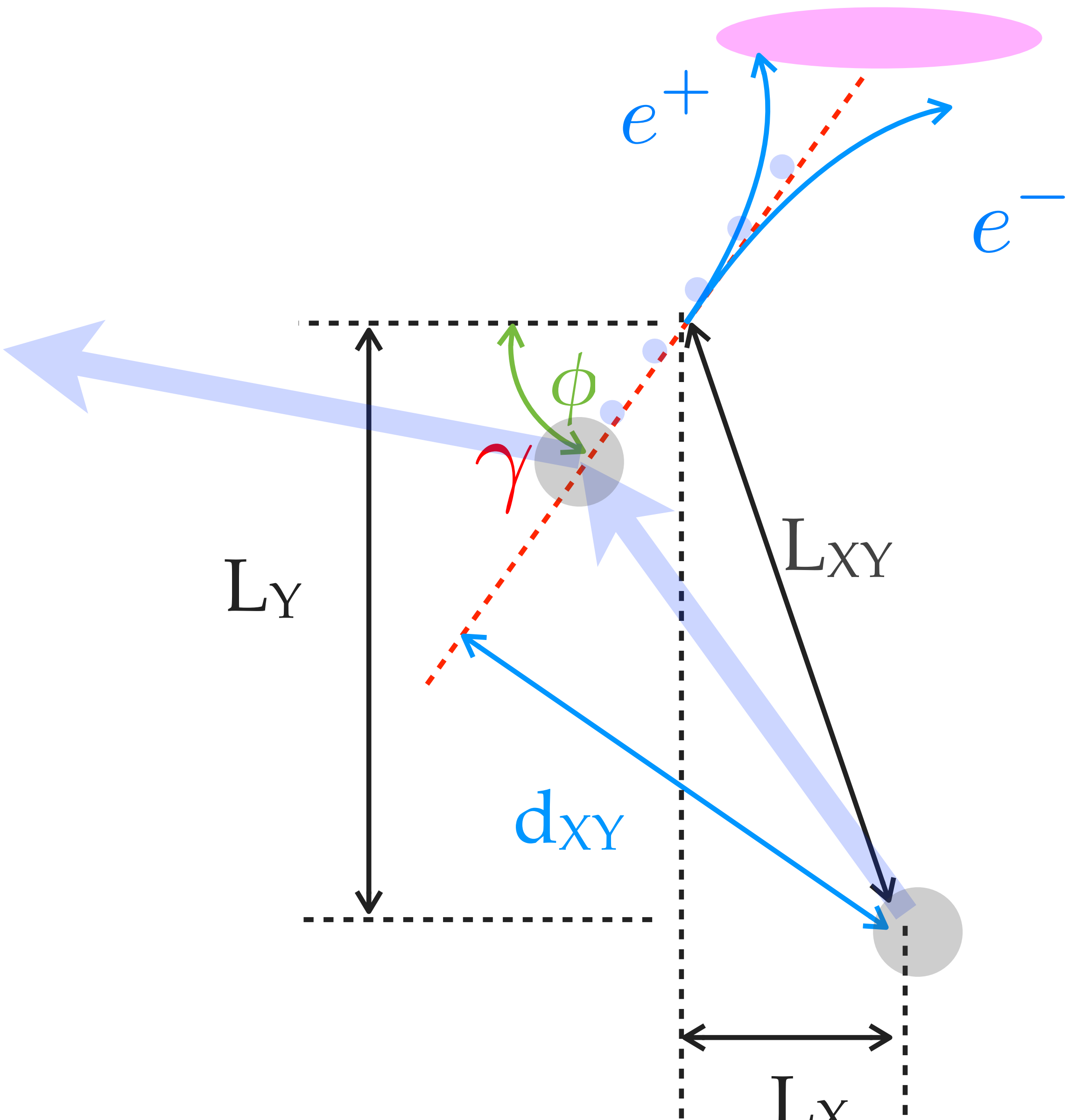
- About 50% photons can convert into e^+e^- pairs by interacting with the silicon material.

- **Photon conversions are reconstructed using the CMS reconstruction software.**

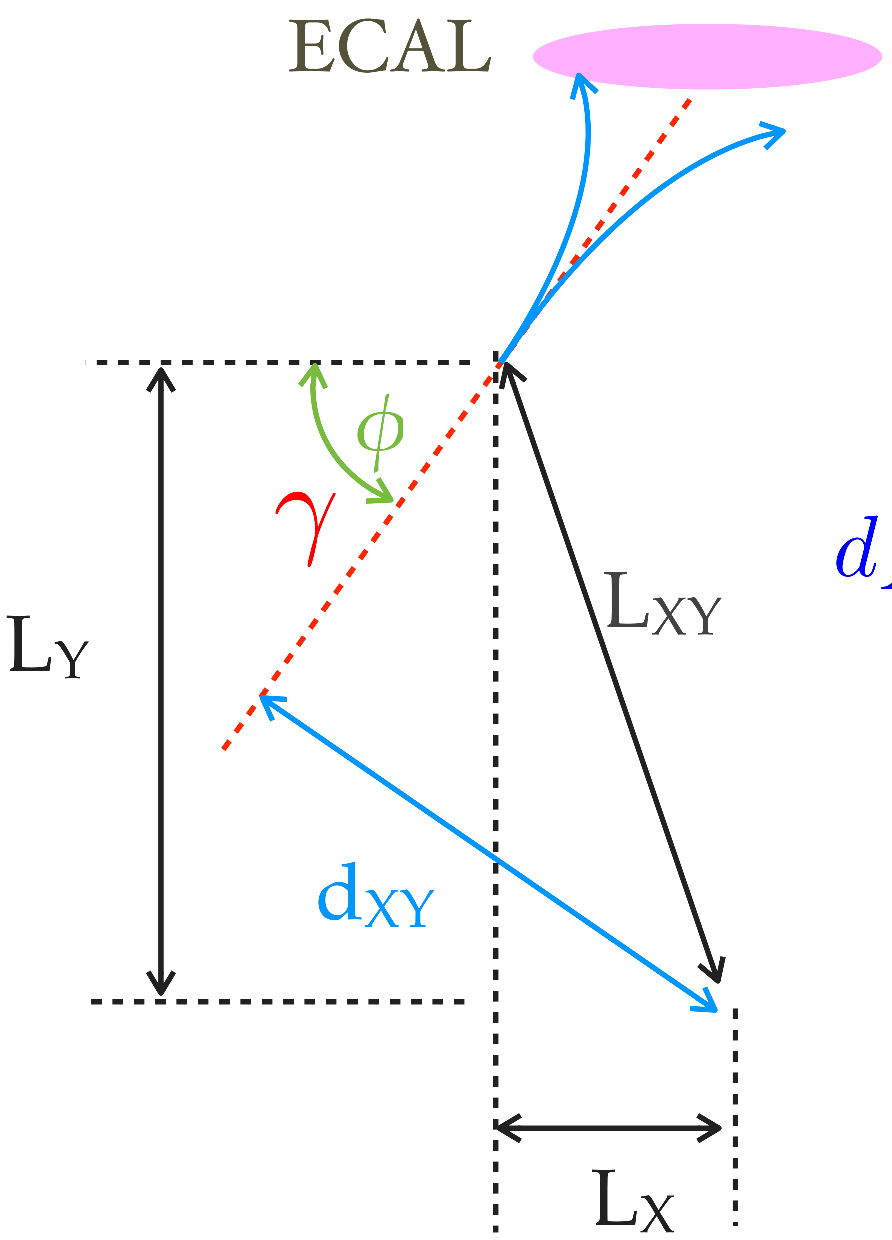
A new technique



A new technique



Photon impact parameter (IP)



$$d_{XY} = -L_X \cdot \sin\phi + L_Y \cdot \cos\phi$$

if $d_{XY} \neq 0$, it should come from a long-lived particle.

Well, it is *not a totally new technique*

Back to early 1980's in Mark II......

......when a high energy group can have less than 100 people

VOLUME 48, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JANUARY 1982

Measurement of the τ Lifetime

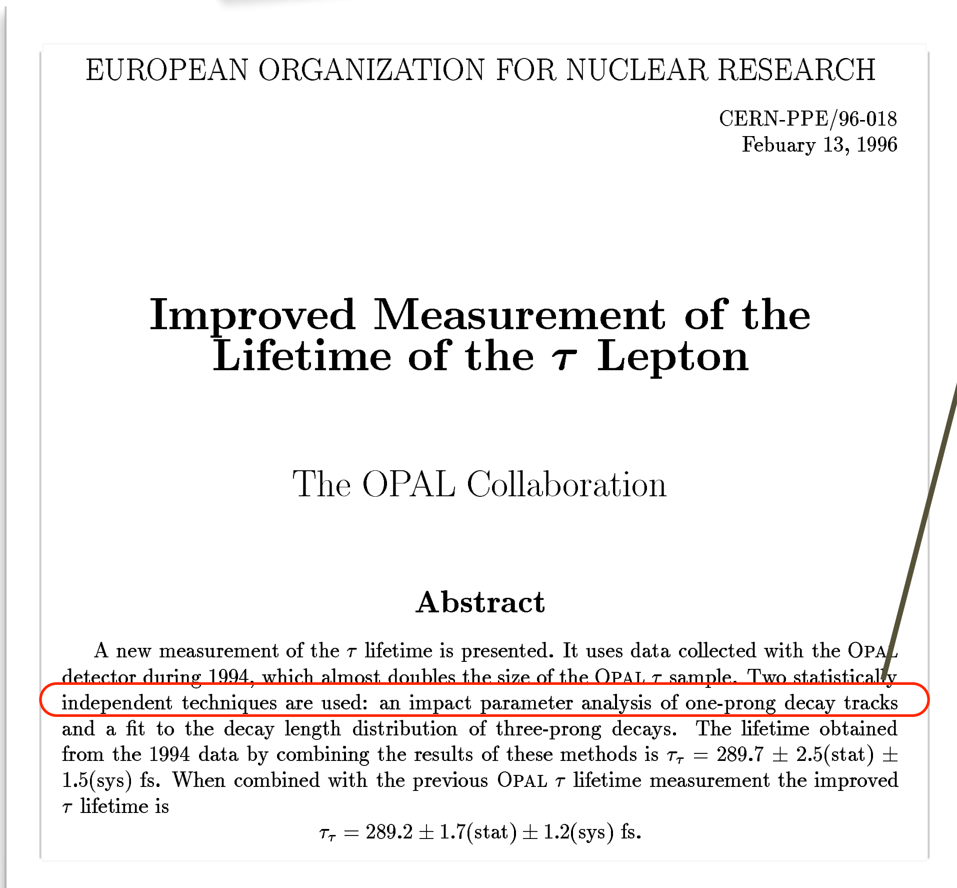
G. J. Feldman, G. H. Trilling, G. S. Abrams, D. Amidei, A. Bäcker,[a] C. A. Blocker, A. Blondel,[b] A. M. Boyarski, M. Breidenbach, D. L. Burke, W. Chinowsky, M. W. Coles,[c] G. von Dardel,[d] W. E. Dieterle, J. B. Dillon, J. Dorenbosch,[e] J. M. Dorfan, M. W. Eaton, M. E. B. Franklin, G. Gidal, L. Gladney, G. Goldhaber, L. J. Golding, G. Hanson, R. J. Hollebeek, W. R. Innes, J. A. Jaros, A. D. Johnson, J. A. Kadyk, A. J. Lankford, R. R. Larsen, B. LeClaire, M. Levi, N. Lockyer, B. Löhr,[f] V. Lüth, C. Matteuzzi, M. E. Nelson, J. F. Patrick, M. L. Perl, B. Richter, A. Roussarie,[g] D. L. Scharre, H. Schellman, D. Schlatter, R. F. Schwitters, J. L. Siegrist, J. Strait, R. A. Vidal, I. Videau,[b] Y. Wang,[h] J. M. Weiss, M. Werlen,[i] C. Zaiser, and G. Zhao[h]

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Department of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 16 October 1981)

1-prong τ decay


an impact parameter analysis of one-prong decay tracks


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PPE/96-018
Febuary 13, 1996

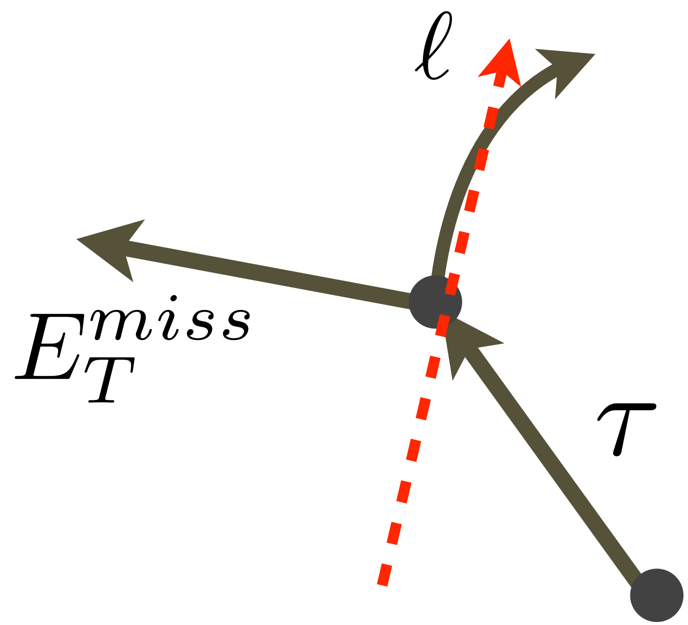
Improved Measurement of the Lifetime of the τ Lepton

The OPAL Collaboration

Abstract

A new measurement of the τ lifetime is presented. It uses data collected with the OPAL detector during 1994, which almost doubles the size of the OPAL τ sample. Two statistically independent techniques are used: an impact parameter analysis of one-prong decay tracks and a fit to the decay length distribution of three-prong decays. The lifetime obtained from the 1994 data by combining the results of these methods is $\tau_\tau = 289.7 \pm 2.5(\mathrm{stat}) \pm 1.5(\mathrm{sys})$ fs. When combined with the previous OPAL τ lifetime measurement the improved τ lifetime is

$$\tau_\tau = 289.2 \pm 1.7(\mathrm{stat}) \pm 1.2(\mathrm{sys})\ \mathrm{fs}.$$



Almost the same kinematics

1-prong τ decay in 1980's

+

Photon conversion in the CMS tracker in 2010's.

=

Search for new physics with long-lived particles decaying to photons

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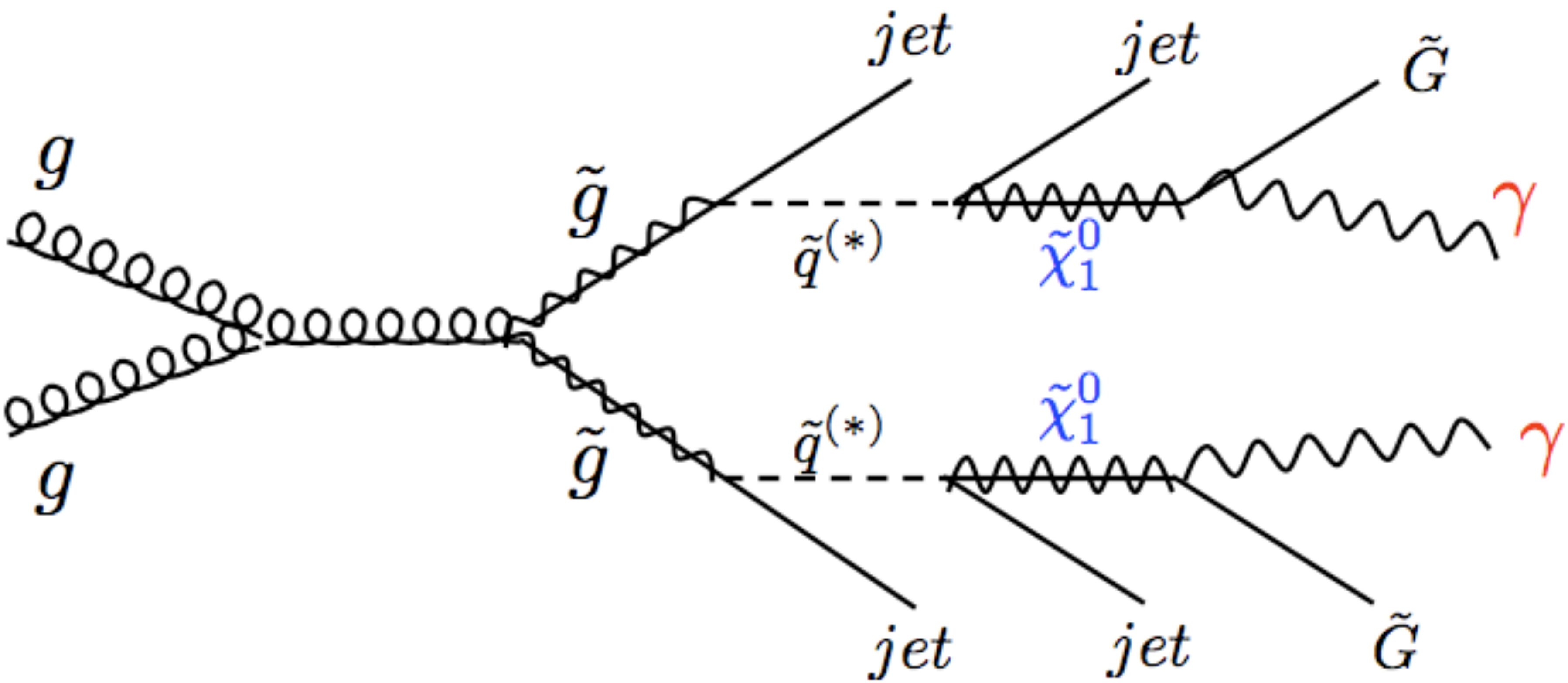
The first search

for long-lived particles decaying to photons using this technique.

Feynman diagram

Take gauge-mediation as a case study.....



CMSPAS-EXO-11-067

The signatures of signal

Gluinos decaying through shell squarks to jets and neutralinos

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

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

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

The strategy of search

- $\gamma+\gamma$ in the final state
  - Diphoton trigger
  - Examine the γ impact parameter for every single converted photon
- E_T^{miss} and presence of jets
- Background estimation using low E_T^{miss} control samples.

Datasets

- 7 TeV collision data 2.23 fb^{-1} in the CMS, first half of 2011
- Monte Carlo: minimal GMSB di-photon
  - The kinematics is same as in General GMSB (GGM).
  - Lifetime range 0.1 ns to 1 ns
    - $c\tau$ 2 cm, 5 cm, 10 cm and 25 cm
  - Neutralino mass 140 GeV - 252 GeV
    - Signal selection efficiency is not sensitive to the neutralino mass for this mass range.

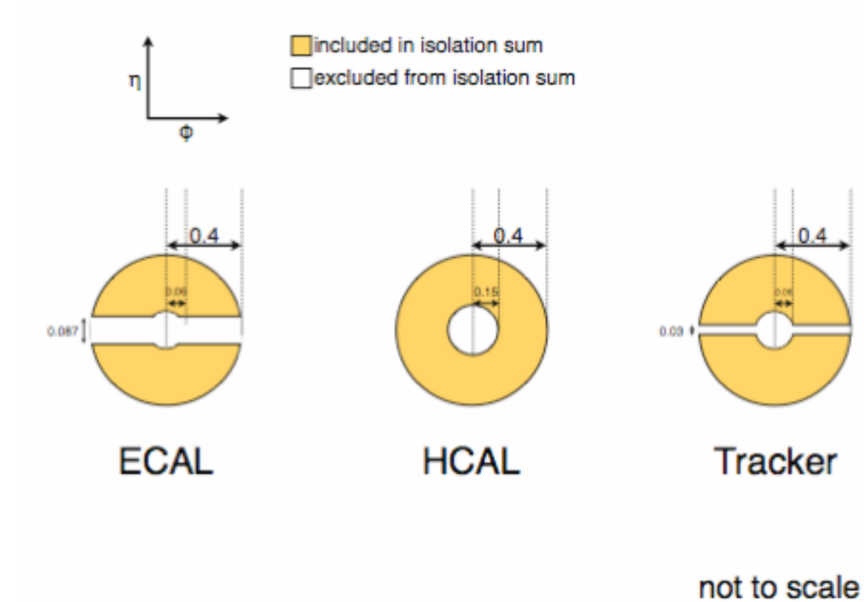
Triggers

- Diphoton trigger
  - At least two energetic photons in the final state
- E_T cut of >45 GeV and >30 GeV for leading and sub-leading photons.
  - To be on the plateau of trigger efficiency
- Any photons with E_T>45 GeV in ECAL barrel
  - The analysis is on every single photon conversion.

Photon selection

- ECAL barrel only, E_T>45 GeV
- H/E<0.05
- $\sigma_{i\eta i\eta}$<0.011
- Isolations
  - ECAL isolation E_T<$0.006E_T$ + 4.2 GeV
  - HCAL isolation E_T<$0.0025E_T$ + 2.2 GeV
  - Tracker isolation E_T<$0.001E_T$ + 2.0 GeV
- Electron veto, with conversions

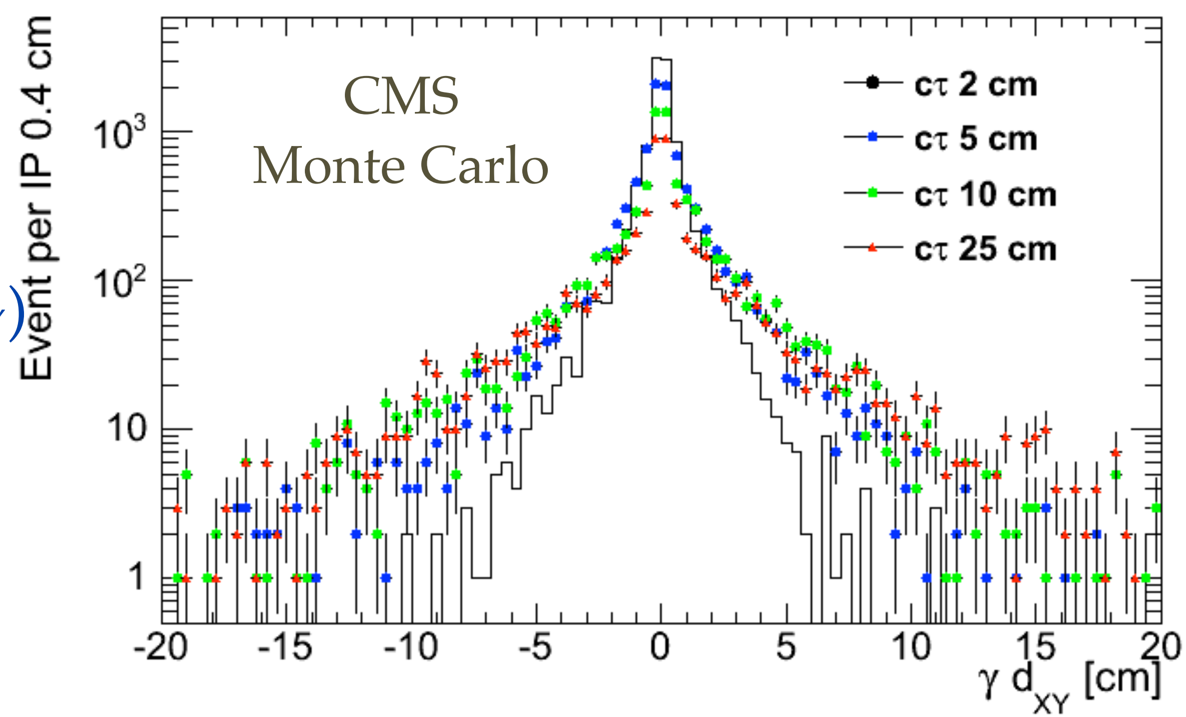
Photon isolation cones (CMSPAS-SUS-12-001)



Photon IP

- Long-lived neutralinos decay into displaced photons
  - Photons convert into e^+e^- pairs
  - Large photon IP is expected.

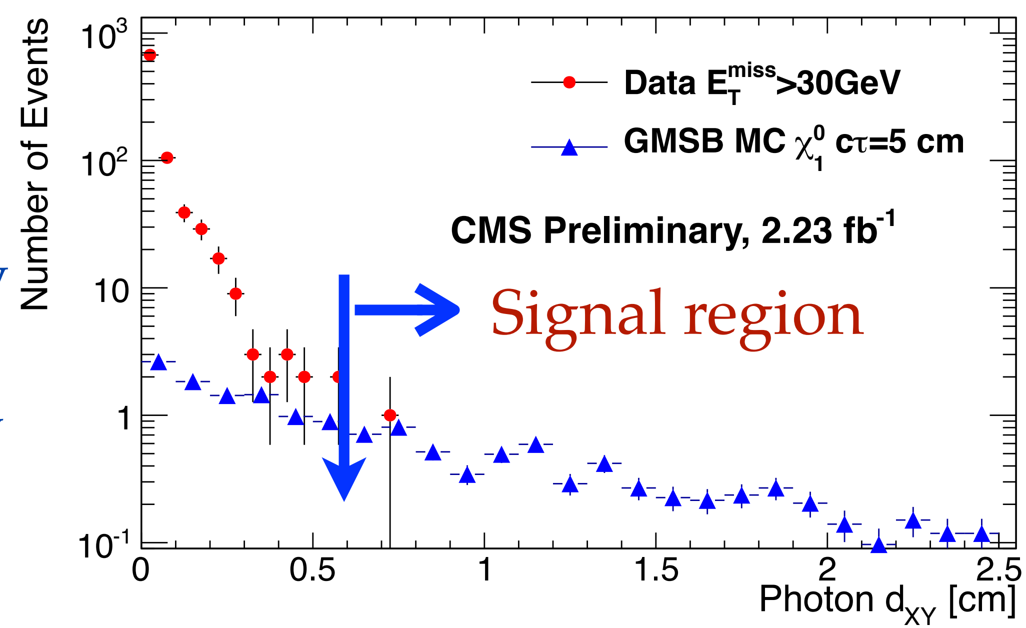
Reconstructed Transverse IP (d_{XY}) in Monte Carlo (PYTHIA6)



Photon IP d_{XY}

- Photon impact parameters (IP) : to quantify the "displaced photons".
- Transverse IP d_{XY} is used.
  - Less sensitive to the pile-up conditions.
- $|d_{XY}|$>0.6 cm, optimized by the average expect limit of cross section.

d_{XY} distribution for data with E_T^{miss}>30 GeV compared with signal simulation for $c\tau = 5$ cm normalized to the integrated luminosity of the data.



Cut flow table

- Triggers and selection cuts are applied sequentially.
- Overall efficiency for cτ=5 cm is 1.58%.
- 1 event of data passes all selection criteria.

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

Event selection efficiency

- Overall event efficiency depends on neutralino lifetimes
  - Conversion efficiency dependence.
- Upper limits of cross section depend on neutralino 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%

The background

- γ's and jets in the final state

- Main background
  - Single γ + jets: real energetic photons
  - QCD multijet: jets misidentified as photons

No true large E_T^{miss}

- Negligible background
  - W+jets etc: no energetic photons.

Data-driven background

- **Signal region**
  - Data for E_T^{miss}> 30 GeV
- **Background region**
  - Data for E_T^{miss}< 20 GeV as control region

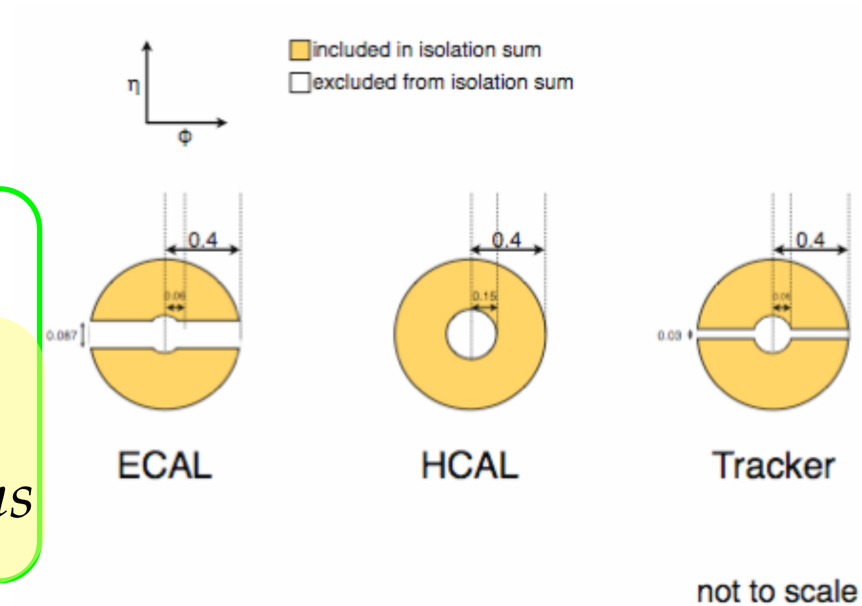
Data-driven background

- **Is this estimation a good description of the background?**
  - Control samples in data: "fake photons"
    - Similar selection of photons, but reversed isolations
    - Contain jets and photons from π^0s
  - Compare d_{XY} distributions for fake photons and isolated photons

The fake photons

- ECAL barrel only, E_T>45 GeV
- H/E<0.05
- $\sigma_{i\eta i\eta}$<0.011

Same as isolated photons



Photon isolation cones (CMSPAS-SUS-12-001)

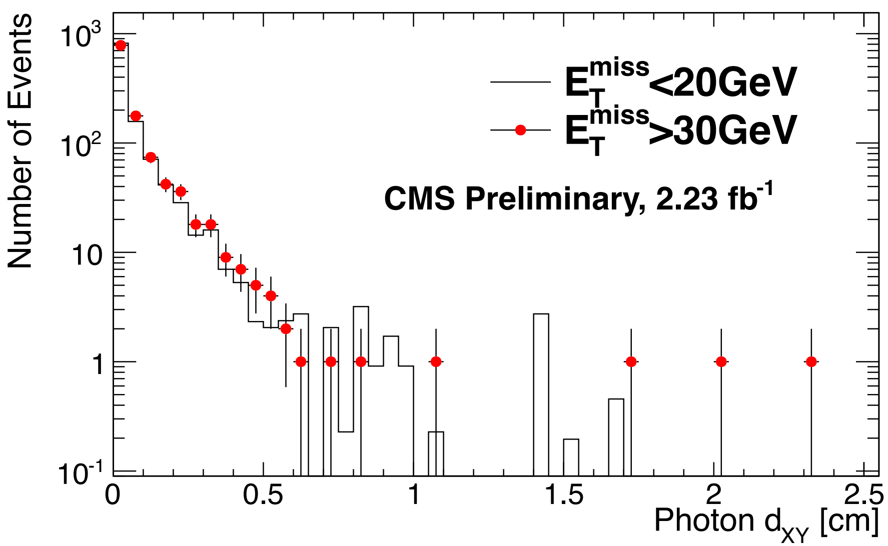
- **Not** satisfying at least one:
  - ECAL isolation E_T<$0.006E_T$ + 4.2 GeV
  - HCAL isolation E_T<$0.0025E_T$ + 2.2 GeV
  - Tracker isolation E_T<$0.001E_T$ + 2.0 GeV

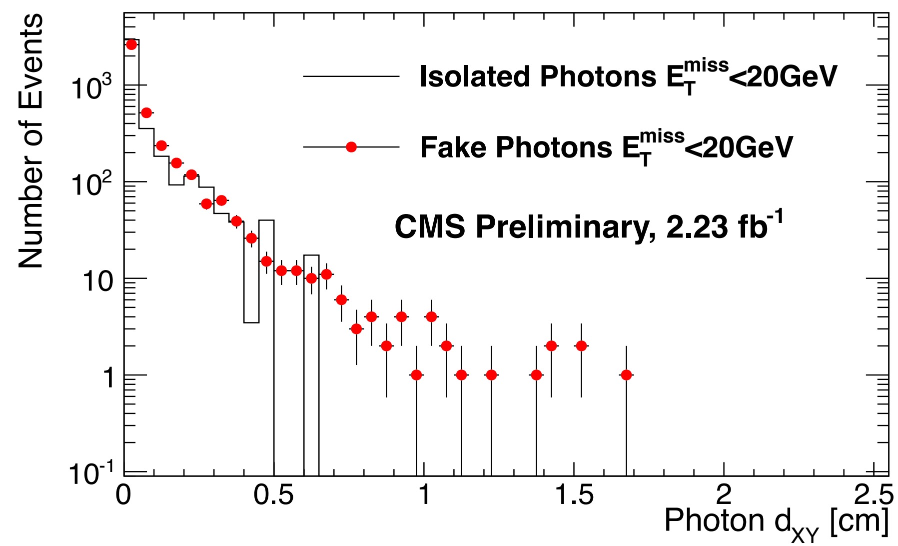
Reversed isolations

- Electron veto, with conversions

Fake photons as control samples

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



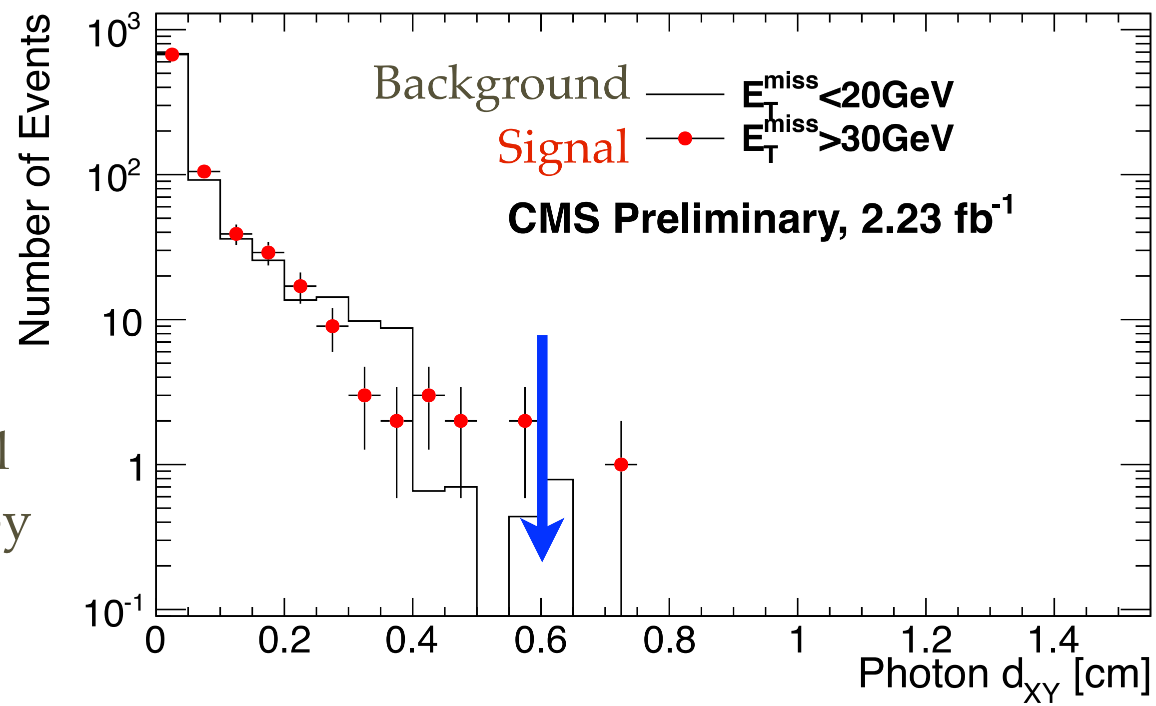


Agreement of the d_{XY} distributions of fake photons and isolated photons.
We conclude that the background estimation is sufficient.

Background estimation

- E_T^{miss}< 20 GeV of data as control region is a good description of the background.
- Background of $0.78^{+1.25}_{-0.48}$ events.

Isolated photon d_{XY} distribution: background region compared to the signal region, normalized by the total number of conversions, re-weighted by the conversion vertex χ^2 probability.

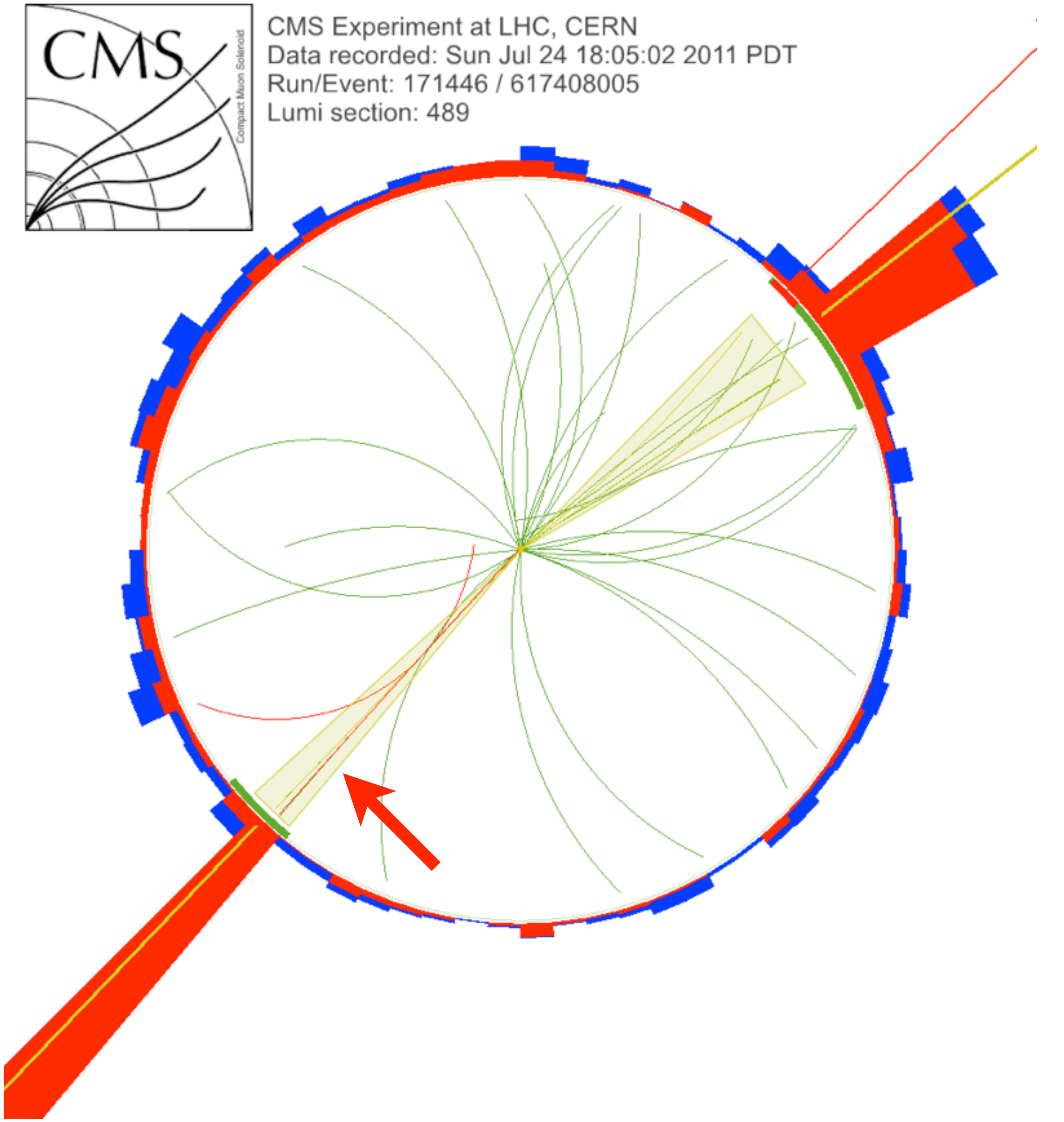


Systematic uncertainties

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	20.6
Photon d_{XY} resolution	< 0.5
Total	25

CMSPAS-EXO-11-067

Results

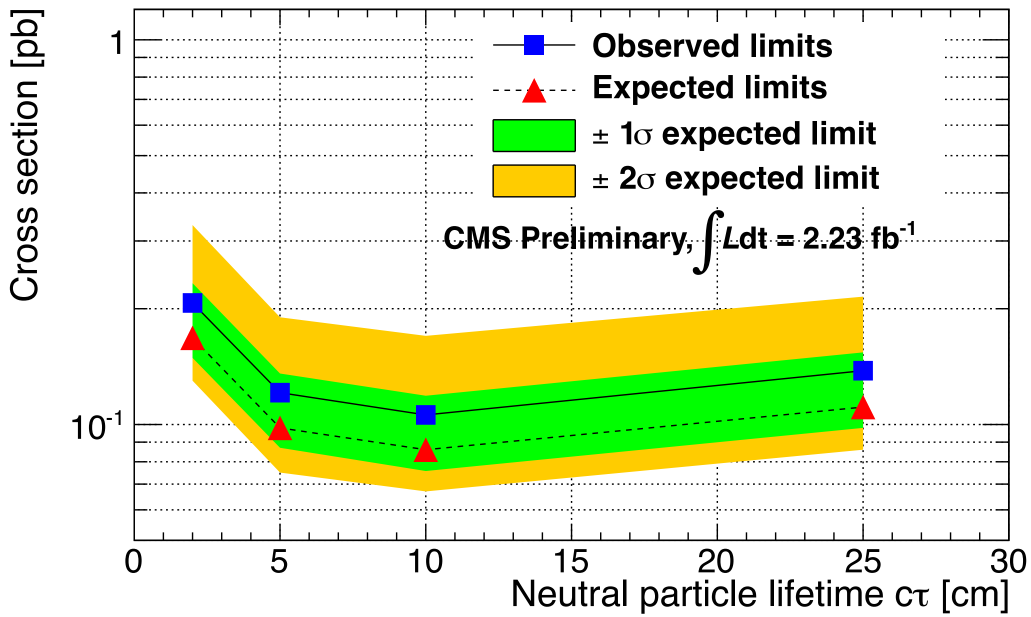


- Observe one event.
  - ⭐ d_{XY}=-0.74 cm
- CLs limit with likelihood-ratio at 95% CL, using the log-normal uncertainties.

Limits

Upper limits on the cross section for such particles from pair production decaying into a photon and invisible particles are set as a function of the long-lived particle's lifetime.

- **Model-independent** upper limits
  - Long-lived neutral particles
  - A function of neutral particle lifetime.



CMSPAS-EXO-11-067

$c\tau$ [cm]	2	5	10	25
σ [pb] 95% C.L	0.21	0.12	0.11	0.14

Three sparkling points

Model-independence

Lifetime sensitivity

Low $E_{\mathrm{T}}^{\mathrm{miss}}$ thereshold

Model-independence

New physics: two long-lived X^0s from pair production

$$X^0$$

γ + invisible particles

Z + invisible particles

something else
+invisible particles

Model-independence

$$X^0$$

$\gamma + \text{invisible particles}$

$Z + \text{invisible particles}$

something else
+invisible particles

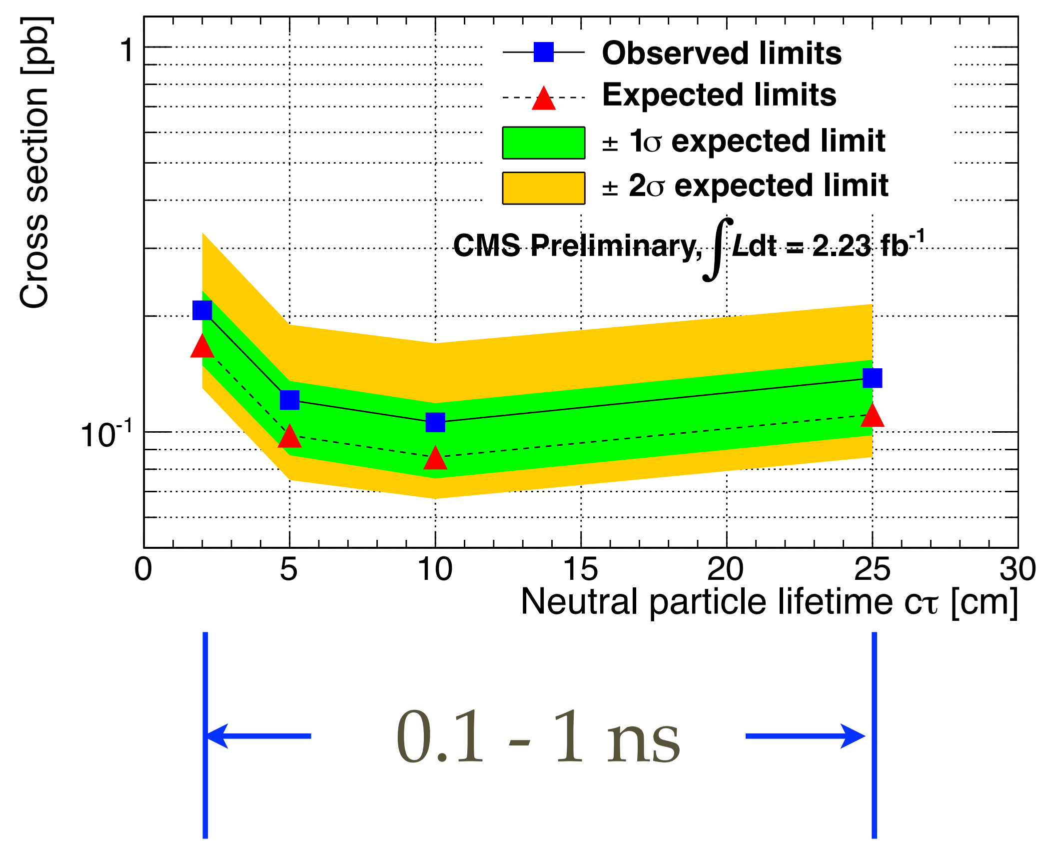
diphoton channel

$$\boxed{\begin{array}{l} X^0 \to \gamma + \text{invisible particles} \\ X^0 \to \gamma + \text{invisible particles} \end{array}} = \sigma \times \underline{BF_{two\ photons}}$$

Theoretical branching ration

The lifetime sensitivity

- Conversion method is sensitive to short lifetime.
  - d_{XY} resolution <0.06 cm
- Other methods have constraints from detector performance.
  - CDF and D0 about 1 to 10 ns



One more thing

- A relatively low E_T^{miss} threshold (30 GeV)
  - Some other SUSY searches involving photons
    - SUSY diphoton analysis (CMSPAS-SUS-12-001): E_T^{miss}>100 GeV
  - Photon impact parameter helps reducing the background.
  - The gap between 30 GeV - 100 GeV
    - Good for some SUSY models with low E_T^{miss}

Analysis summary available online

Available on the CERN CDS information server **CMS PAS EXO-11-067**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-exotica@cern.ch 2011/10/31

Search for new physics with long-lived particles decaying to photons and missing energy

The CMS Collaboration

Abstract

A search for long-lived neutral particles decaying into a photon and invisible particles is performed. In the context of gauge mediated supersymmetry with the lightest neutralino as the next-to-lightest supersymmetric particle and the gravitino as the lightest supersymmetric particle, the neutralino can decay into a gravitino and a photon with a nonzero lifetime. The impact parameter of the photon relative to the beam-beam collision point can be reconstructed using converted photons. The method is sensitive to lifetimes of the order of $\mathcal{O}$(0.1 ns). The data sample corresponds to an integrated luminosity of 2.1 ± 0.1 fb^{-1} recorded in the first part of 2011 by the CMS experiment at the LHC at $\sqrt{s} = 7$ TeV. The search is performed using events containing photons, missing transverse energy and jets. Upper limits at the 95% confidence level are presented on the cross section for such particles from pair-production, each of which decays into a photon and invisible particles.

http://cdsweb.cern.ch/record/1394286

The paper draft is in the final reading stage. Going to publish very soon.

Conclusion: general

- **A novel technique**: photon impact parameter using photon conversions
  - An appropriate technique to search for new physics with long-lived particles decaying into photons.

- A search in the final state of photons plus jets plus E_T^{miss}, with large photon impact parameter, has been performed.
  - Approved analysis (Oct 2011)
    - Hongliang Liu as the contact person.
  - Presented by Hongliang Liu on behalf of CMS, in Berkeley SUSY workshop (Oct 2011).

Conclusion: sparkling points

1. **Model-independent** upper limits on the cross section for such particles from pair-production decaying into a photon and invisible particles are set as the function of the long-lived particle lifetime.

2. Sensitive to shorter lifetime (0.1 ns to 1 ns)

3. Relatively lower E_T^{miss} cut (30 GeV)

   - ⭐ Much lower than E_T^{miss} cut in other SUSY search involving photons

Outlooks

- 16 fb^{-1} in 2012!
- Some other GMSB models, e.g. General GMSB (GGM)
  - Higher cross section for better discovery potentials
- Hidden valley models with long-lived neutral particles.
- Recast the analysis for other models
  - Interpretation for some specific models

A little bit on history

- This analysis started at a coffee table in building 40 cafeteria.
  - Prof. Yury Gershteyn (Rutgers), Prof. Gail Hanson (UCR) and Hongliang Liu (UCR)
- Two more analysts were invited to join
  - Hongliang invited Dr. Alexander Ledovskoy (U Virginia) and Prof. Nancy Marinelli (U Notre Dame)
- Some posters and presentations in CMS meetings.

Cited by some papers and talks

- Y. Kats, P. Meade, M. Reece, D. Shih, “The Status of GMSB After 1/fb at the LHC” http://arxiv.org/abs/1110.6444, 2011
- CMS Collaboration, “Search for Supersymmetry in Events with Photons, Jets and Missing Energy”, CMSPAS-SUS-12-001, 2012
- J. Hirschauer, "Long-lived Particles at CMS", Implications of LHC results for TeV-scale physics, March 2012, CERN
- J. Chen, “Long-lived particles”, Search2012: Workshop on characterization of new physics, March 2012, College Park, MD

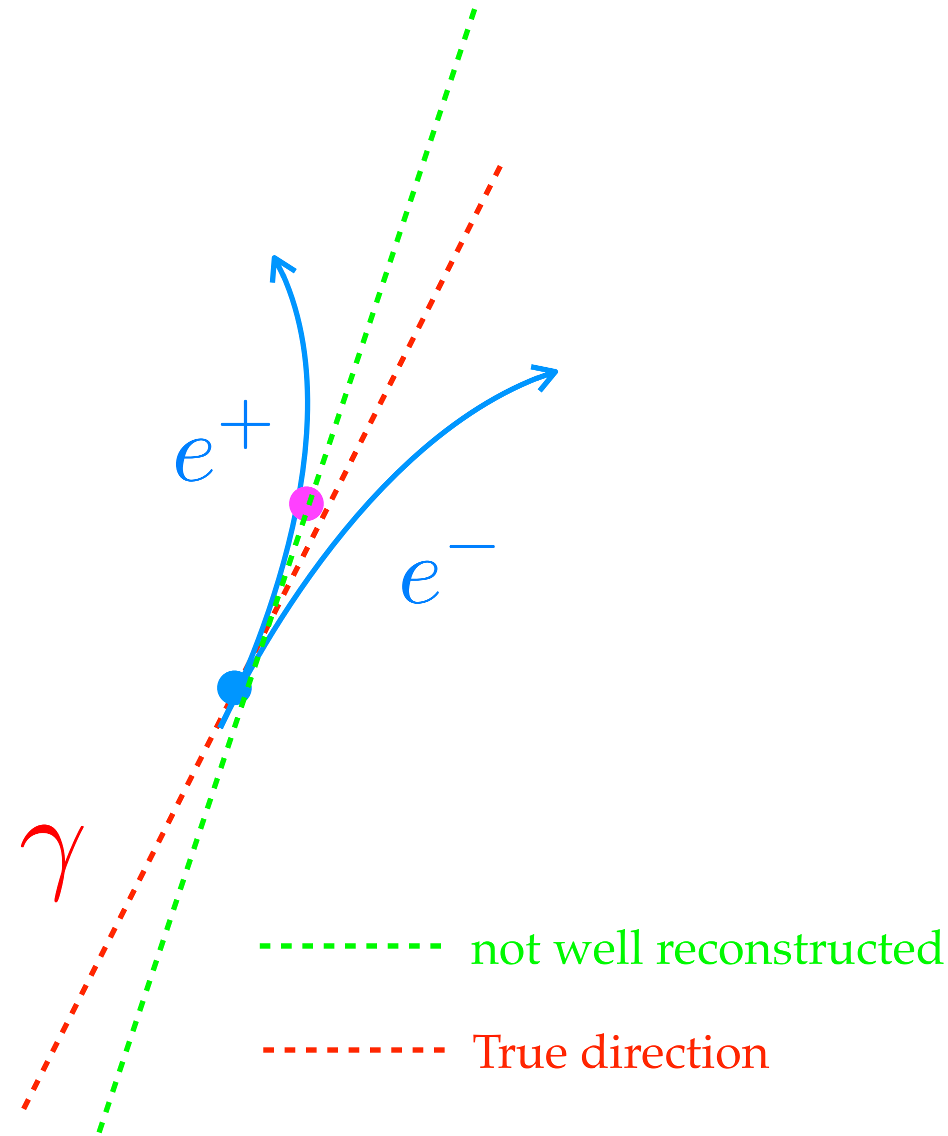
Backup slides

Symbols and jargons

- Gravitino $\tilde{G}$
- Neutralino $\tilde{\chi}_1^0$
- Pseudorapidity $\eta = -\ln\tan\frac{\theta}{2}$
- Primary vertex
- Secondary vertex
- $E_T{}^{miss}$
- Conversion: “Converted photon” or “Photon conversion”

d_{XY} resolution, why reweighting?

- Photon d_{XY} is correlated to the conversion vertex quality.
  - Vertex with bad $\chi 2$ probability has bad resolution.
  - The photon direction is affected.



The sign of d_{XY}

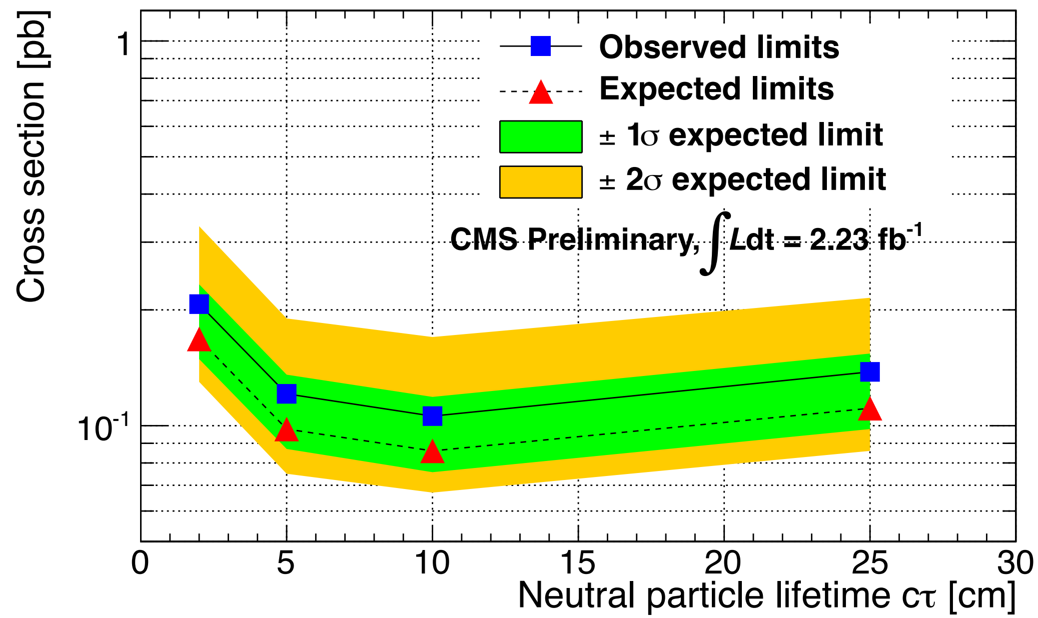
- No additional assignment of a +/- sign, such like in the τ lifetime measurement.
  - The thrust axis method works for τ, but not good for GMSB due to kinematics
- d_{XY} has its nature +/- sign w.r.t the primary vertex.

Uncertainty of conversion efficiency

- a scale factor is calculated from a comparison of $Z \rightarrow \mu\mu\gamma$ between data and Monte Carlo.
- Such scale factors are used in "tag-and-probe" efficiencies, for example.

The trend of the limit

- Efficiency goes up from $c\tau$ =2 to 5 cm, then drops at $c\tau$=10 to 25cm
  - d_{XY}>0.6 cm threshold reduces the efficiency for small cτ
  - Longer lifetime means more far displaced photons, which gives difficulties of tracking and conversion finding.

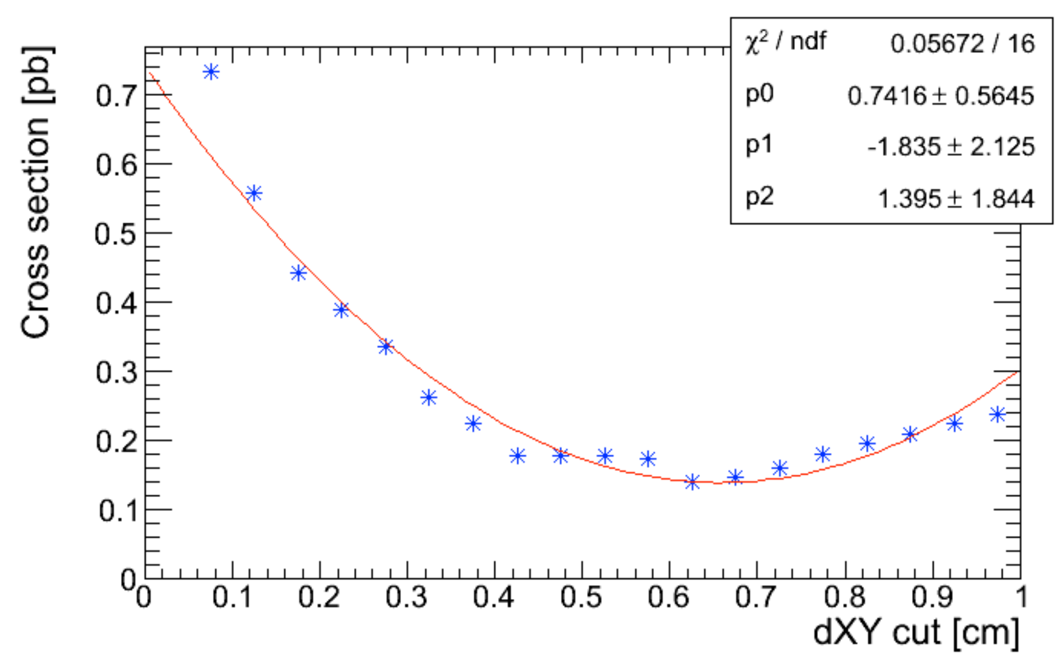


The kinematics

- Neutral particles about 100 GeV, e.g. neutralinos
- invisible particles sub-GeV, e.g. gravitinos

Optimization of d_{XY} threshold

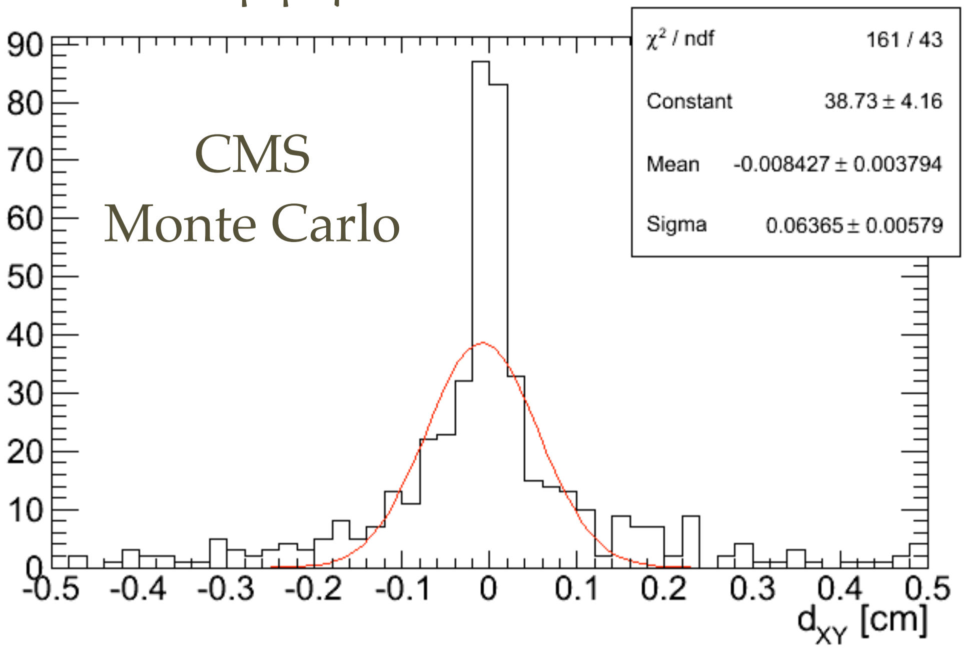
- By the averaged expected limits of cross sections
- It is consistent with optimization by signal significance as we have tested.



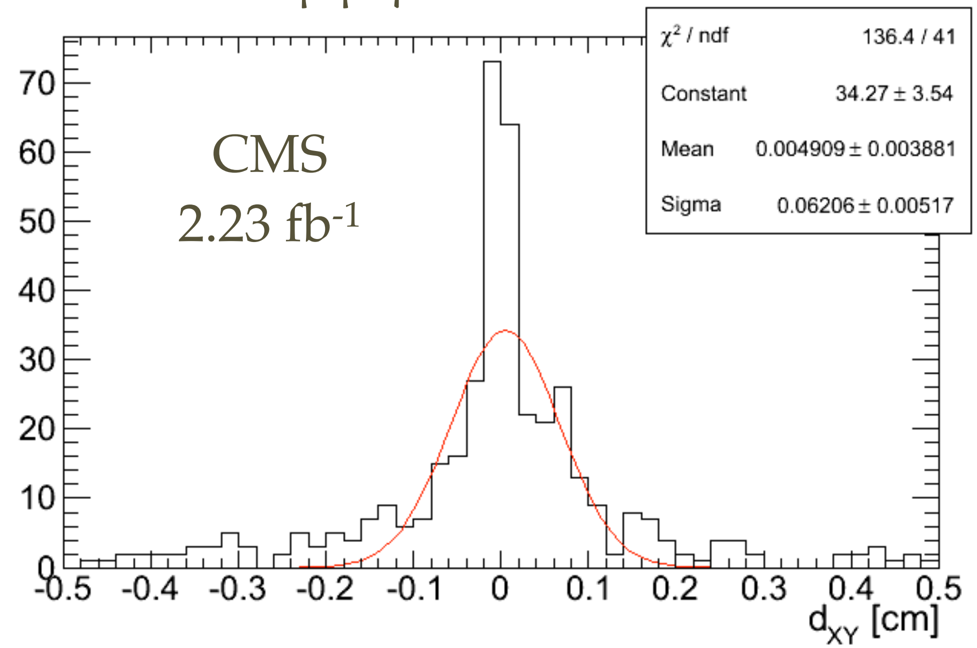
d_{XY} resolution

- By comparing the d_{XY} distribution for photon conversions in the $Z \rightarrow \mu\mu\gamma$ decay

$Z \rightarrow \mu\mu\gamma$ Drell-Yan MC



$Z \rightarrow \mu\mu\gamma$ Data 2.23 fb^{-1}



Gauge mediation models

- Gauge-mediated supersymmetry breaking (GMSB)
- Minimal GMSB (MGM or GMSB)
  - Simplest GMSB: one parameter for the messenger mass scale
  - Cons: the sparticle spectrum is pushed very high.
- General GMSB (GGM)
  - More than one parameter, but not calculable till 2008
  - (Meade 2008) proposed a simple framework for counting allowed parameters
    - three real parameters for the sfermion masses
    - three complex parameters for the gaugino masses
- Other GMSB models: e.g. low scale GMSB (Mason 2009)
  - SM-like Higgs
  - Low mass neutralino, not presence of jets

The gravitino as LSP

- Gravitino as Lightest Supersymmetric Particle (LSP)
  - a universal prediction of gauge mediation models
- A superpartner of the graviton
  - Spin 3/2
- If R-parity is conserved, the gravitino does not decay.
  - Escape undetected
  - Apparently imbalanced energy in the detector: $E_T{}^{miss}$

The lightest neutralino as NLSP

- Next to Lightest Supersymmetric Particle (NLSP)
  - In gauge mediation, the NLSP type largely determines the inclusive collider signatures.
  - If the gravitino is the LSP, the lightest MSSM superpartner (lightest neutralino) is the NLSP.
- Linear combination of gauge eigenstates
  - bino, wino and higgsino-like (Meade 2008, 2009)

NLSP lifetime in GMSB

- Decided by gravitino mass
  - In min GMSB, an artificial factor C_grav

$$m_{\tilde{G}} = \frac{C_{grav}}{\sqrt{3}} \cdot \frac{F_0}{M_p} \sim C_{grav} \left(\frac{\sqrt{F_m}}{100\mathrm{TeV}} \right)^2 2.4\mathrm{eV}$$

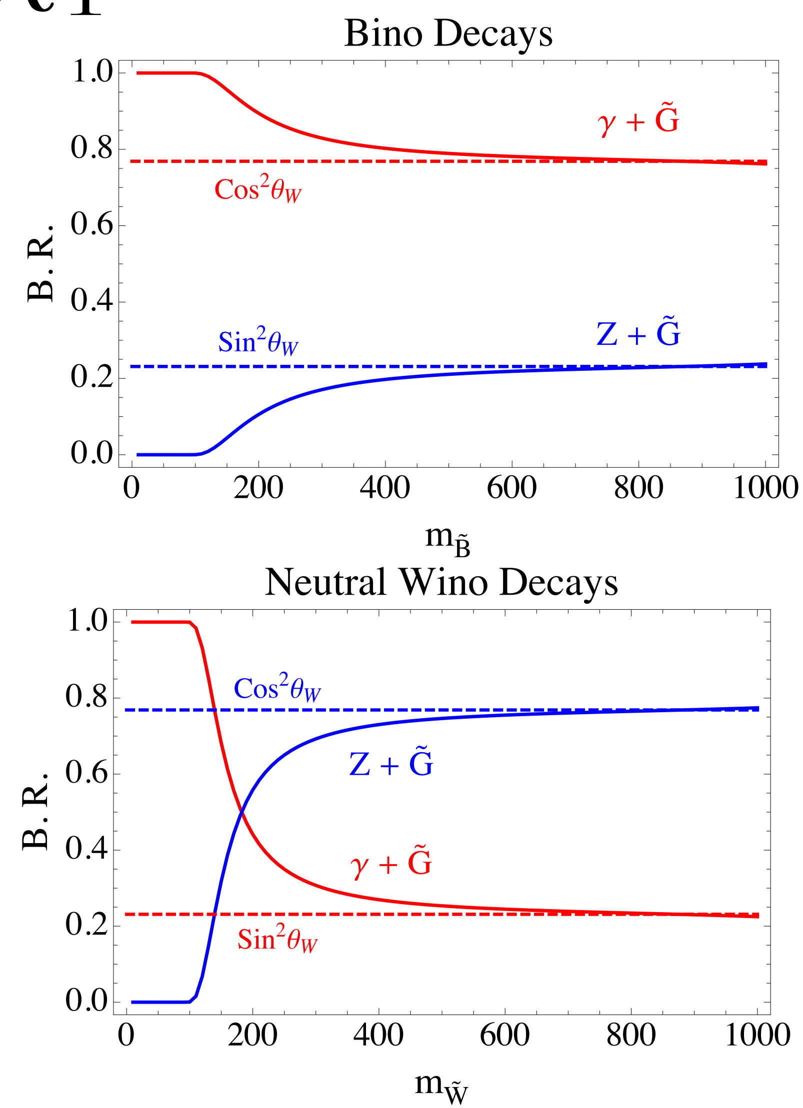
  - In General GMSB (GGM), gravitino mass is used.

Three decay modes of neutralinos

- General neutralinos have three decay modes
  - ☆ $\tilde{\chi}_1^0 \to \gamma + \tilde{G}$
  - ☆ $\tilde{\chi}_1^0 \to Z + \tilde{G}$
  - ☆ $\tilde{\chi}_1^0 \to h + \tilde{G}$

Bino and wino like $\tilde{\chi}_1^0$

- Both NLSPs can decay into photon or Z plus gravitino.
- For bino-like NLSP, neutralinos mostly decay into photons and gravitinos.
- A factor of weak mixing angle θ_W.
- For wino-like co-NLSP, the branching ratio is flipped.



The bino and neutral wino NLSP branching ratios to Z or γ plus gravitino (Ruderman 2011)

Conversion reco in CMS

- Merge 3 algorithms
  - ECAL-seeded conversion finding
  - Tracker-seed conversion finding
    - Originally proposed and implemented by Hongliang Liu
  - Gaussian-summation filter electron conversion finding

Applications of conversion in CMS

- Study of tracker material (CMSPAS-TRK-10-003)
- Higgs vertex determination in $H \rightarrow \gamma\gamma$ search
- Long-lived particles decay into photons.
- Conversion rejections in many analyses

Proposal: analysis

- Analysis experiences in physics involving photons
  - $H \to \gamma\gamma$ search
  - SUSY diphoton search
  - New physics with long-lived particles decay into photons
- Also interested in physics with jets and b-tagging
  - Experience in tracking

Proposal: software and detector

- Experienced in tracking
  - Developer of CMS iterative tracking software
  - Leading developer of photon conversion reconstruction in the CMS
- Detector monitoring
  - Leading developer of the Web-based monitoring for the CMS tracker (Tracker WBM)
- Grid computing for physics analyses (CRAB in the CMS)

Proposal: teaching

- Numerous of presentations in CMS meetings
- Provided several lectures and hands-on tutorials to guide new graduate students
  - The detector knowledge
  - Software and computing
- Project advisor for undergraduate thesis on solar flare detecting using the CMS detector.