Searches for Long-lived Particles and Leptoquarks at CMS

James Hirschauer
Fermilab
(for CMS)

Implications of LHC results for TeV-scale physics
26-30 March 2012
CERN

Outline

Search	Int. Luminosity	Documentation
Slow HSCP	4.7/fb	EXO-11-022 (1.1/fb, 4.7 /fb coming soon)
Stopped HSCP	0.9/fb	EXO-11-020
Displaced Leptons	1.1/fb	EXO-11-004
Displaced Photons (using conversions)	2.1/fb	EXO-11-067
2nd Generation Leptoquarks (μμjj,μνjj)	2.0/fb	EXO-11-028
3rd Generation Leptoquarks (bbνν)	1.8/fb	EXO-11-030

Updates in progress!

Introduction : Long-lived Particles

- Many models of new physics predict **long-lived massive particles** including SUSY, Extra dimensions, Hidden valley.
- Experimentally challenging.
- Detection strategies depend on **charge** and **$\beta\gamma c\tau$**:

Charge	$\beta\gamma c\tau$	Example	Detection Strategy
Charged	~cm - detector scale	Gluino, stop	**Stopped HSCP**: Isolated, out-of-time energy in calorimeter.
Charged	> detector scale		**Slow HSCP**: Ionization (dE/dx) and time-of-flight.
Neutral	~cm - detector scale	$H \to XX \to 4l$, GMSB NLSP neutralino	Displaced photons, Displaced leptons
Neutral	> detector scale	SUSY LSP	Large MET

Slow HSCP

Triggers:

- Single μ, MET (for charge suppression models)
- 75% (10%) efficiency for staus with $\beta = 0.6$ (0.45)

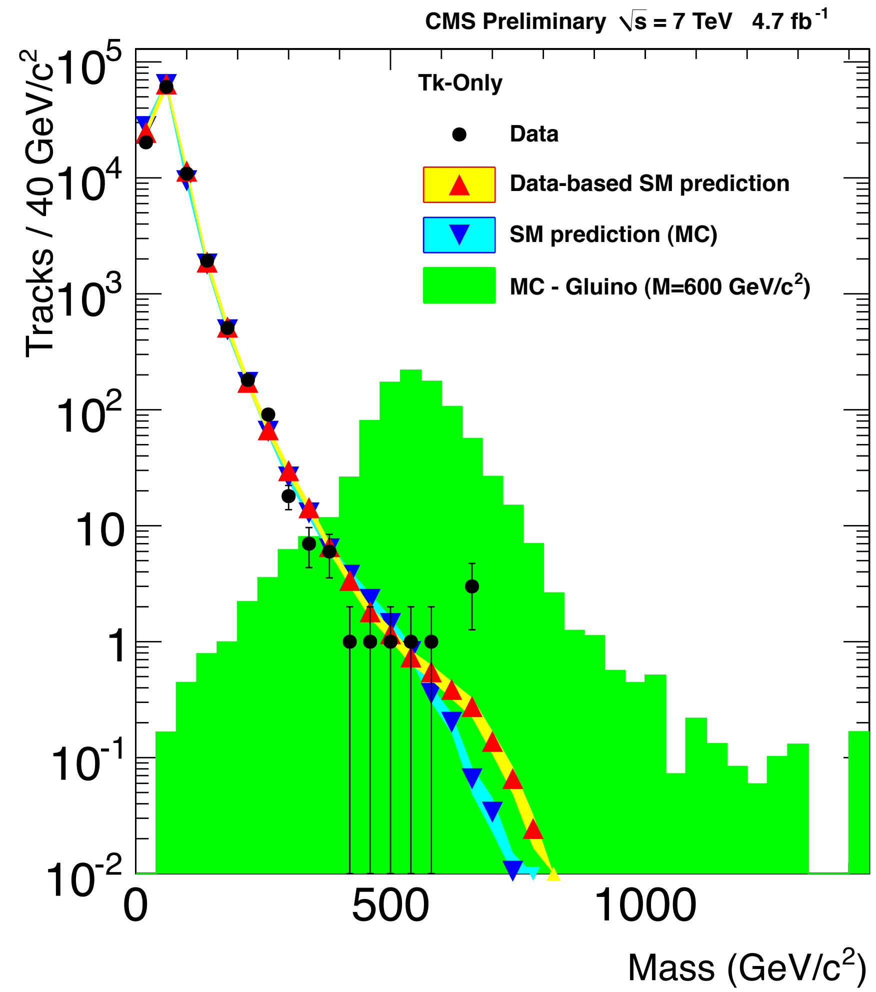
Two selection strategies:

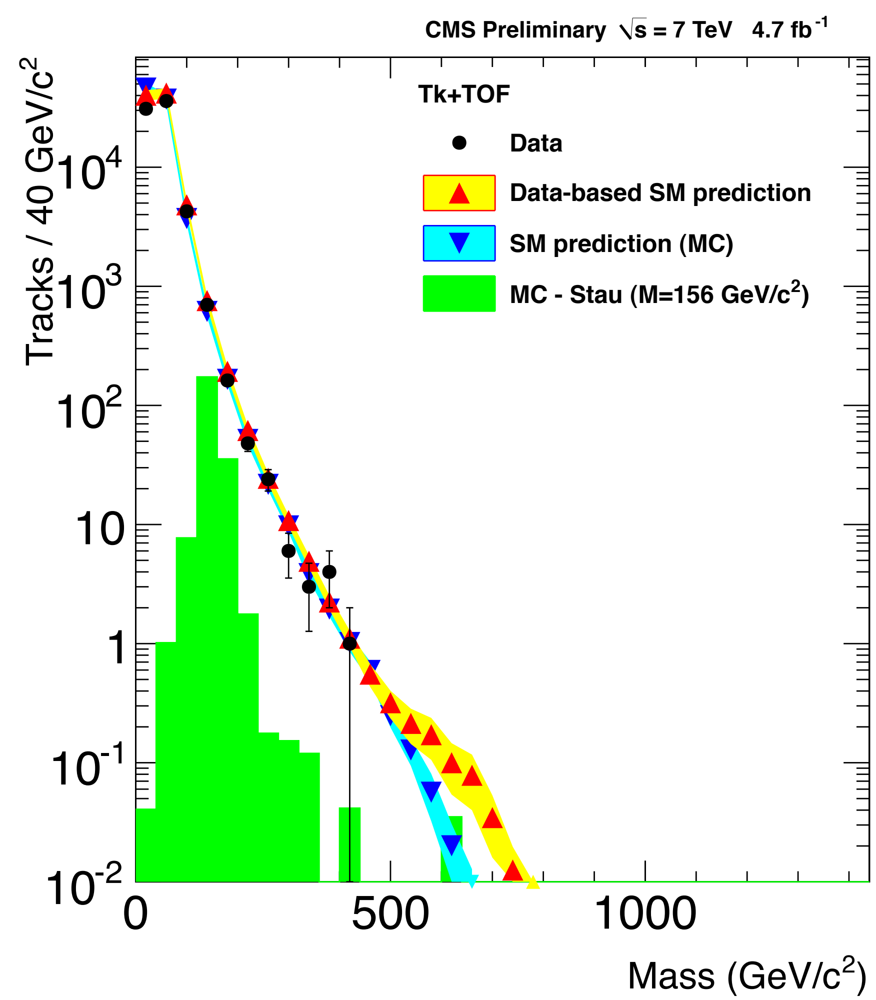
- **Tracker-only** : large dE/dx + large p_T
- **Tracker+TOF**: Tracker-only + μ-like + long time-of-flight (β^{-1} from μ system)

Data-driven background estimation:

From uncorrelated sidebands in β^{-1} , dE/dx MIP-compatibility (I_{as}^{*}), and p_T (w/ correction for η-dependence of dE/dx).

*Defined in backup slides.

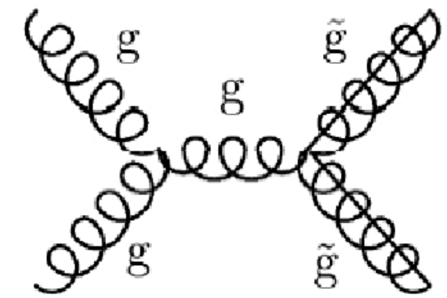


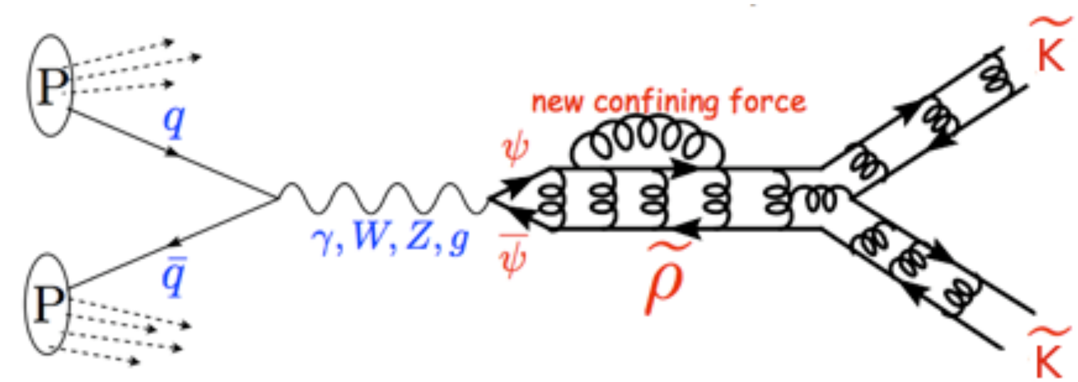


Slow HSCP

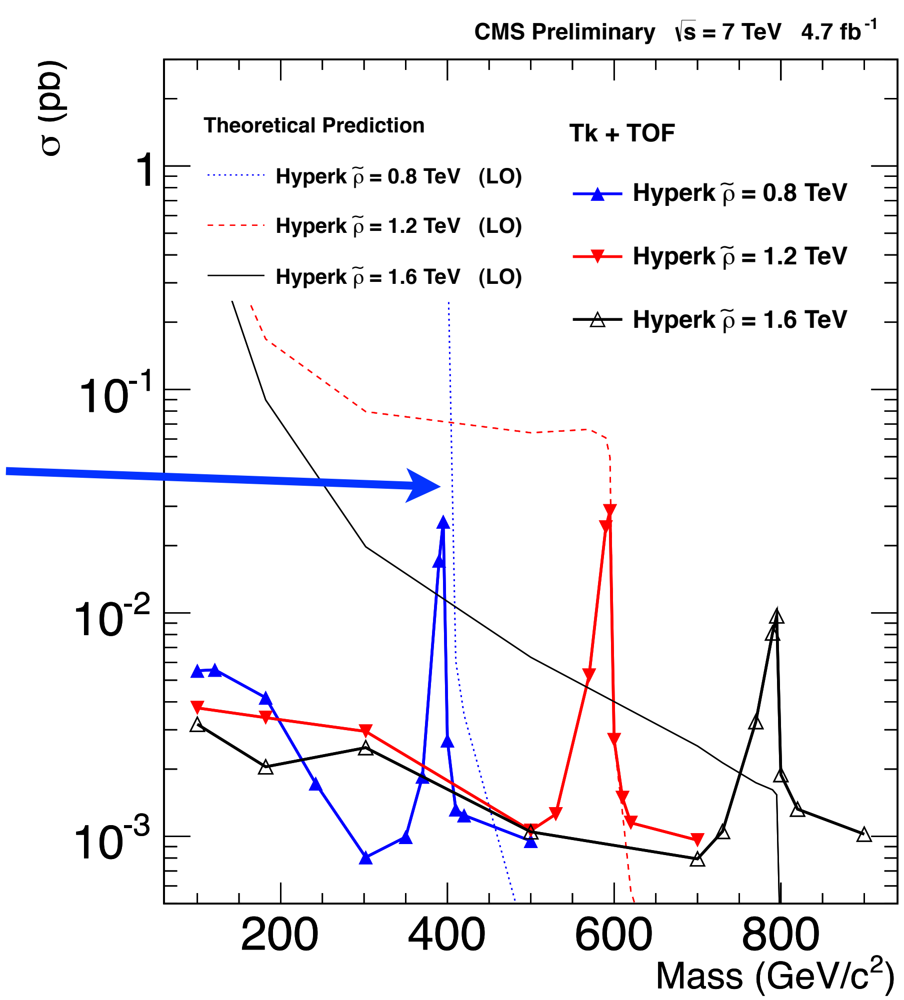
95% CLs mass limits for

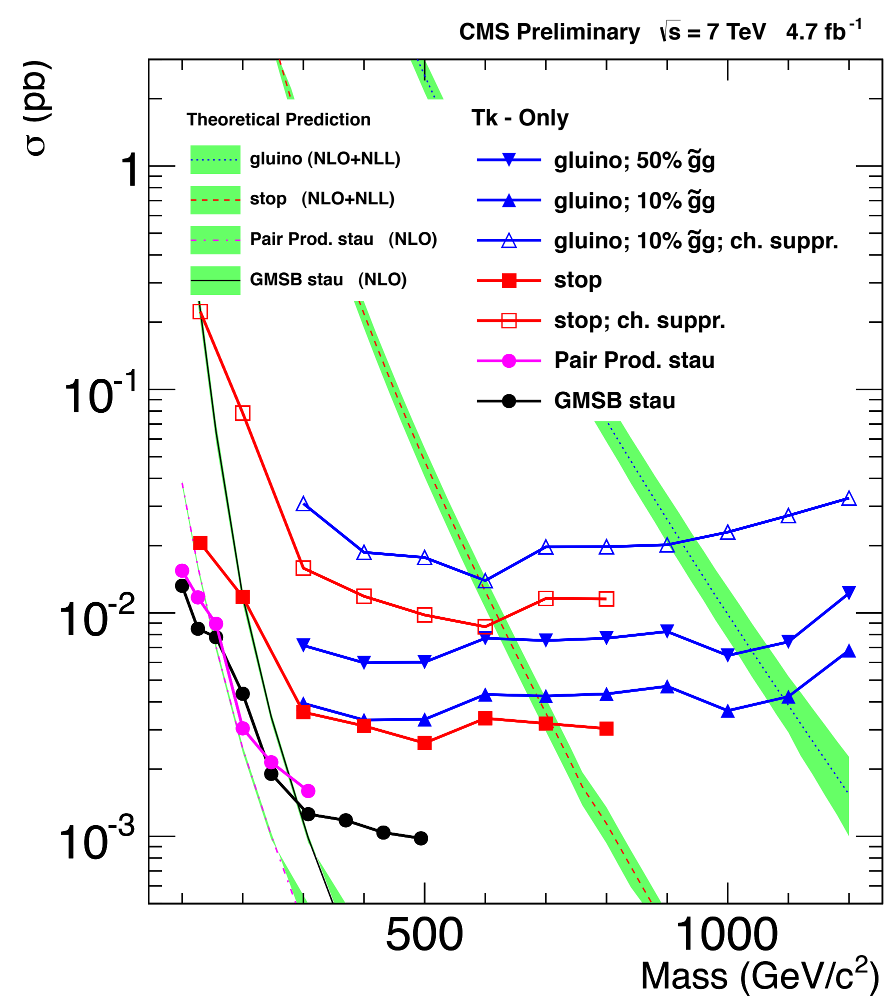
- **R-hadrons**: gluino, stop
  - Two interaction models: **cloud** and conservative **charge suppression**
  - R-gluonball fractions: 0.1, 0.5
- **Lepton-like:**
  - **stau** (direct pair production, GMSB)
  - **Hyper-kaon** (DY+range of $M_{hyper-\rho}$)





Kinematic threshold for resonant production.





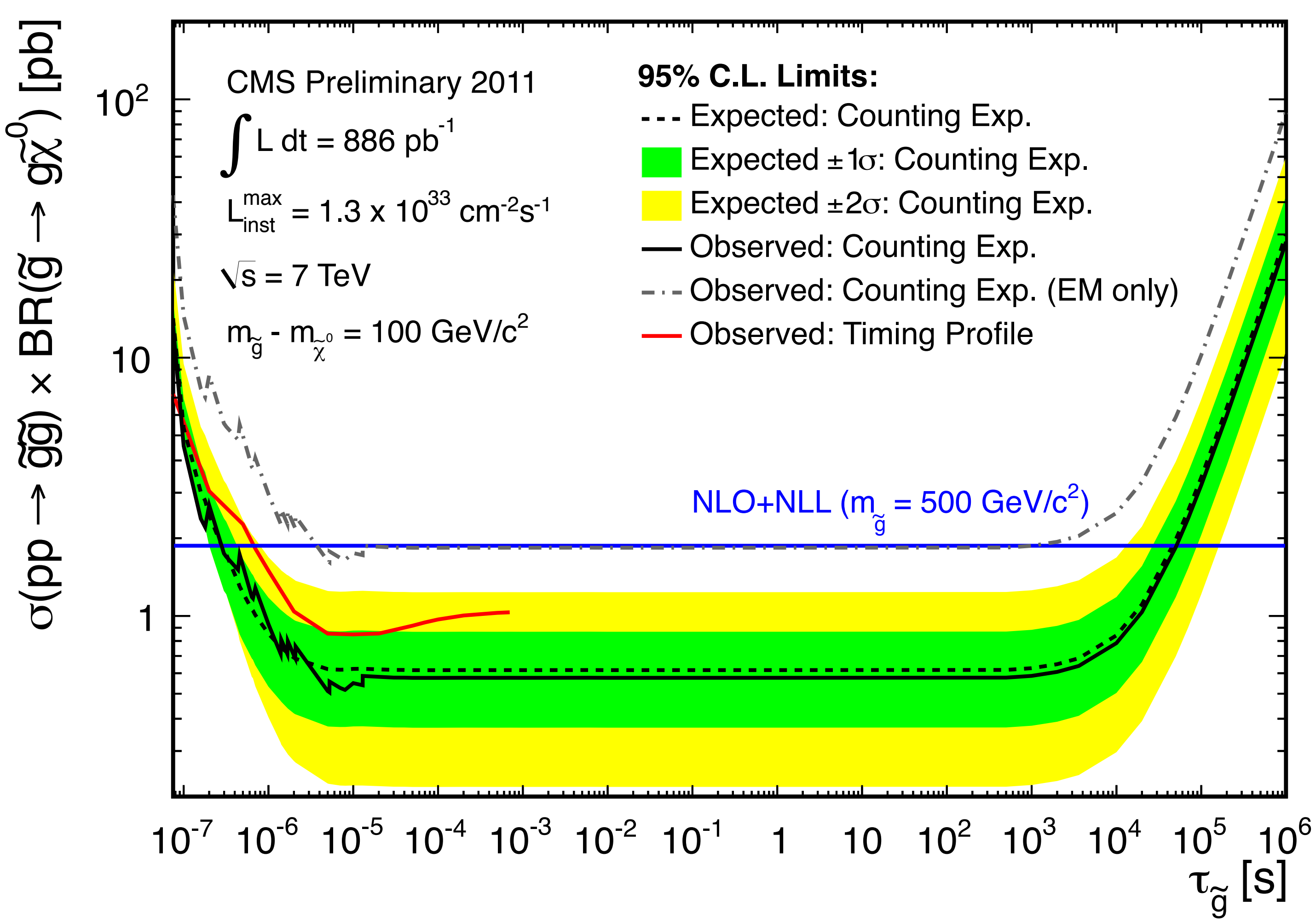
Stopped HSCP

Trigger: 50 GeV single jet trigger with BPTX veto in triggered bunch crossing (BX) ±1 BX. 168 hours live time.

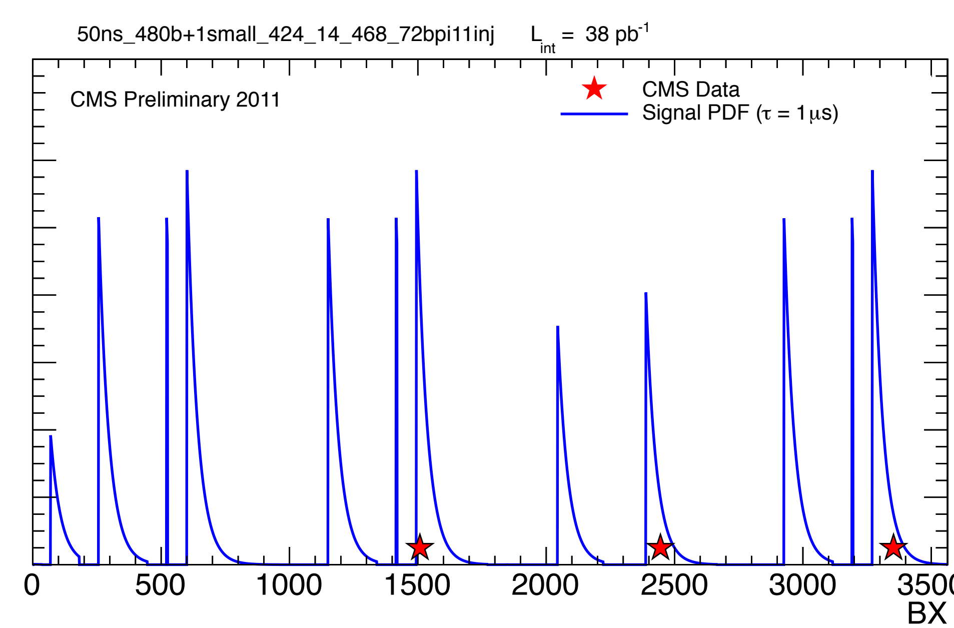
Background rate:

- 1.7±0.7e-5 Hz from beam-related, cosmic rays, and detector noise.
- Signal efficiency ~13%.
- Noise and cosmic rates from 2010 data (36 pb^{-1}).

Methods: Counting experiment and timing profile analysis (for τ<0.7ms).

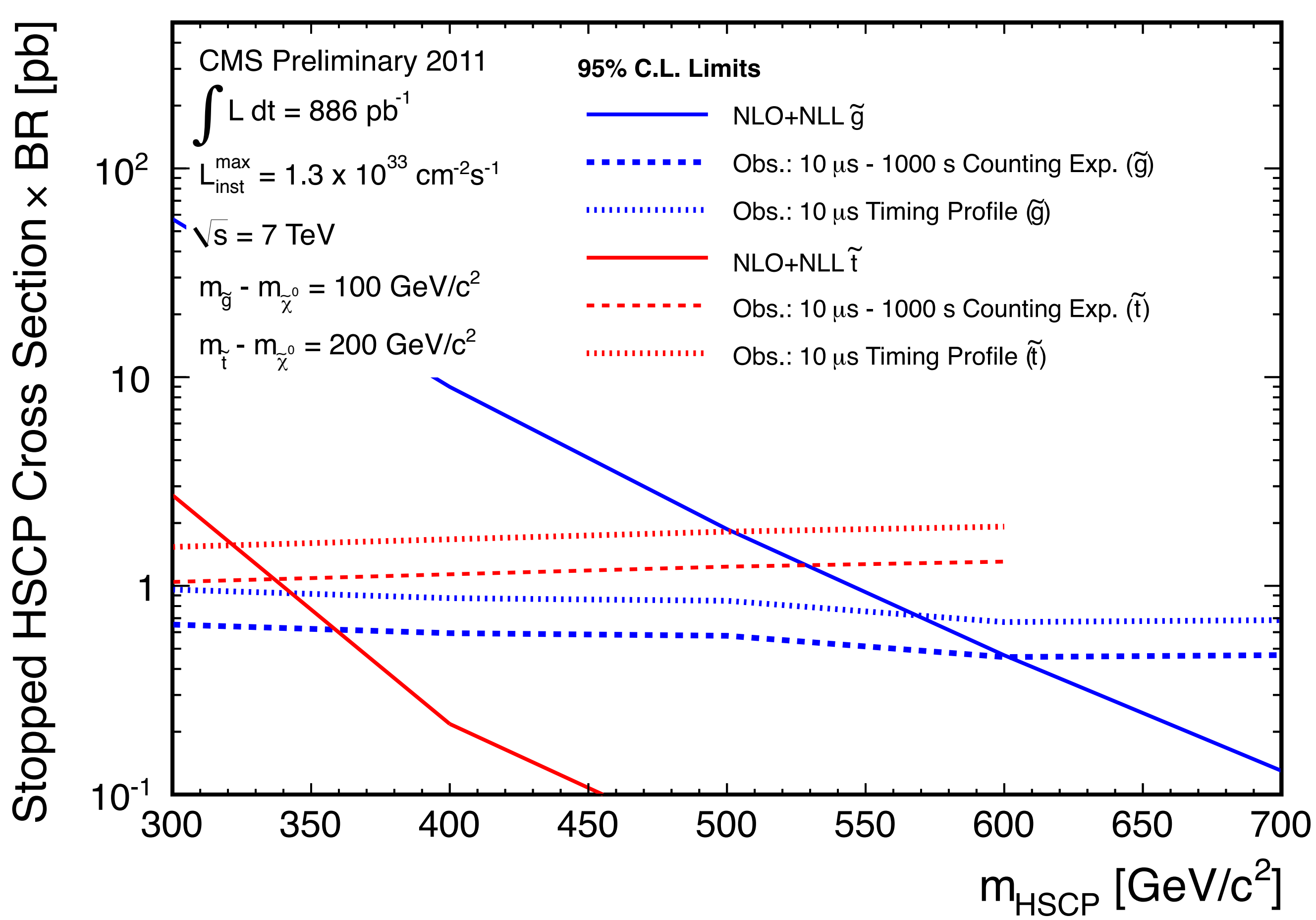


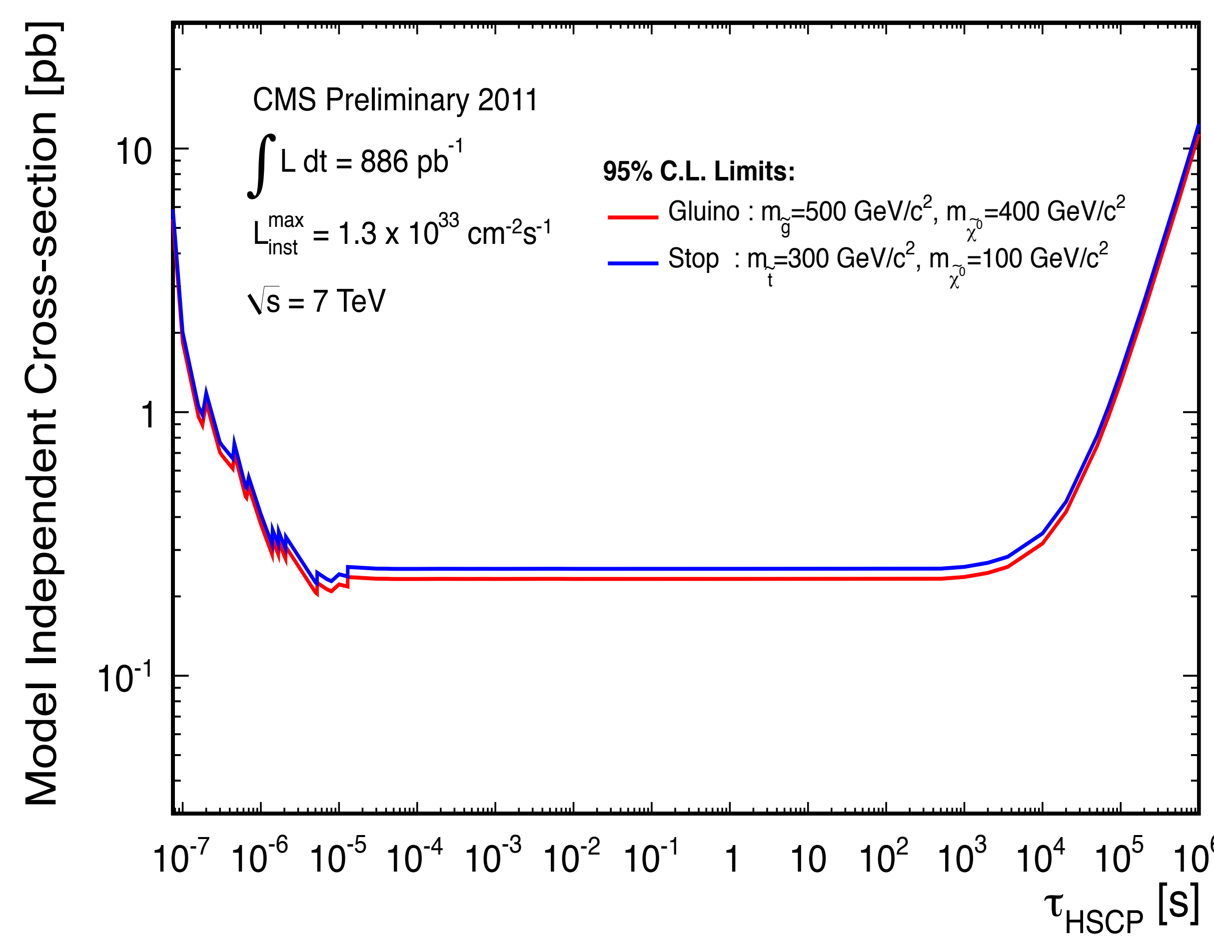
Lifetime	$L_{eff}(pb^{-1})$	Expected Bg	Observed
75 ns	4.3	0.11 ± 0.05	0
100 ns	12.5	0.35 ± 0.14	0
1 μs	139	3.3 ± 1.3	4
10 μs	352	10.1 ± 4.1	9
30 μs - 10^3 s	360	10.4 ± 4.2	10
10^4 s	268	10.4 ± 4.2	10
10^5 s	65	10.4 ± 4.2	10
10^6 s	7.5	10.4 ± 4.2	10



Stopped HSCP

- 95% CL mass exclusion limits assuming $10^{-6} < \tau < 10^{3}$ s:
  - $m_{gluino} < 601$ GeV
  - $m_{stop} < 337$ GeV
- 95% CL limits on cross section x BR x stopping efficiency are **independent of interaction model**.

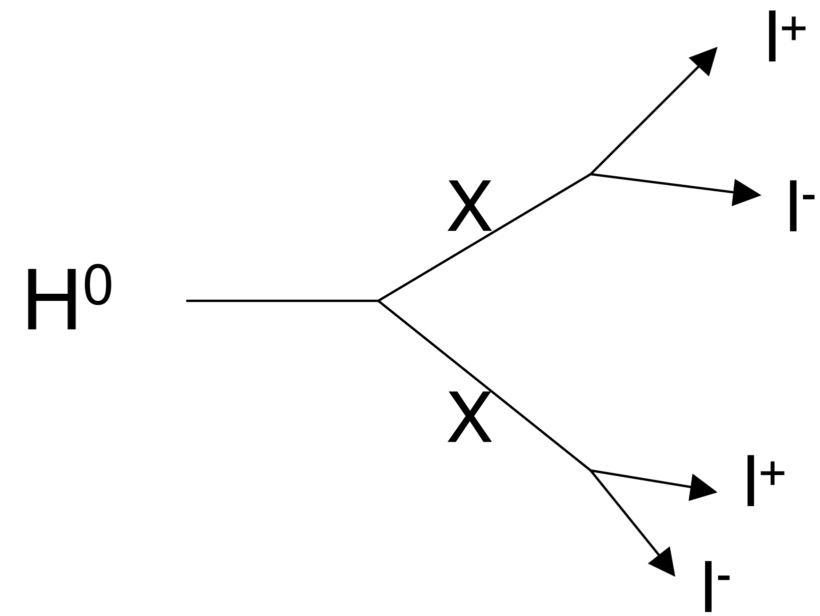


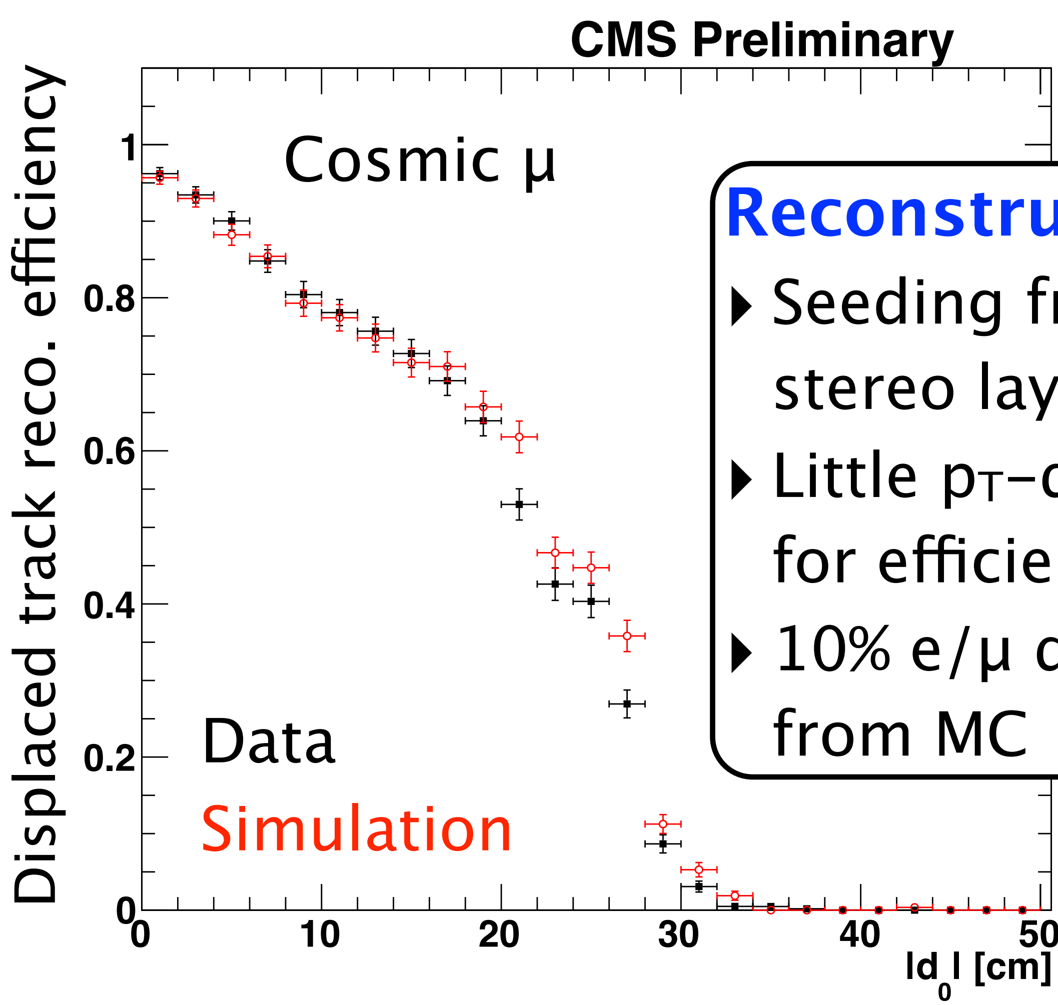


Displaced Lepton Pair

New physics model:

- $gg \rightarrow H^0 \rightarrow 2X$, $X \rightarrow l^+l^-$
- X is long-lived, spin 0
- Consider $200 < M_H < 1000$ GeV and $20 < M_X < 500$ GeV.
- Assume ee/μμ are each 50% of l^+l^- width.





Reconstruction:

- Seeding from SST stereo layers
- Little p_T-dependence for efficiency
- 10% e/μ difference from MC

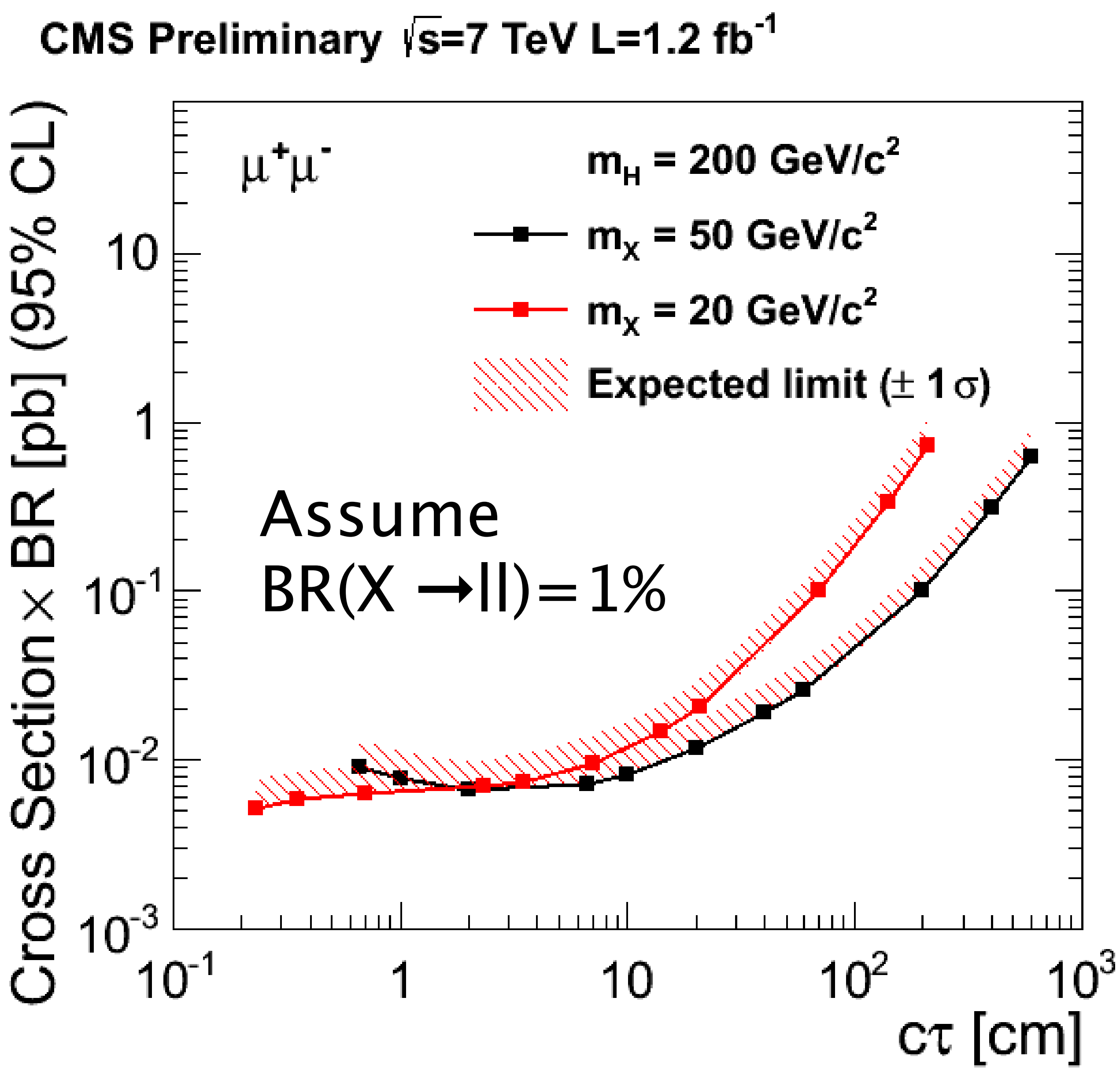
Selection:

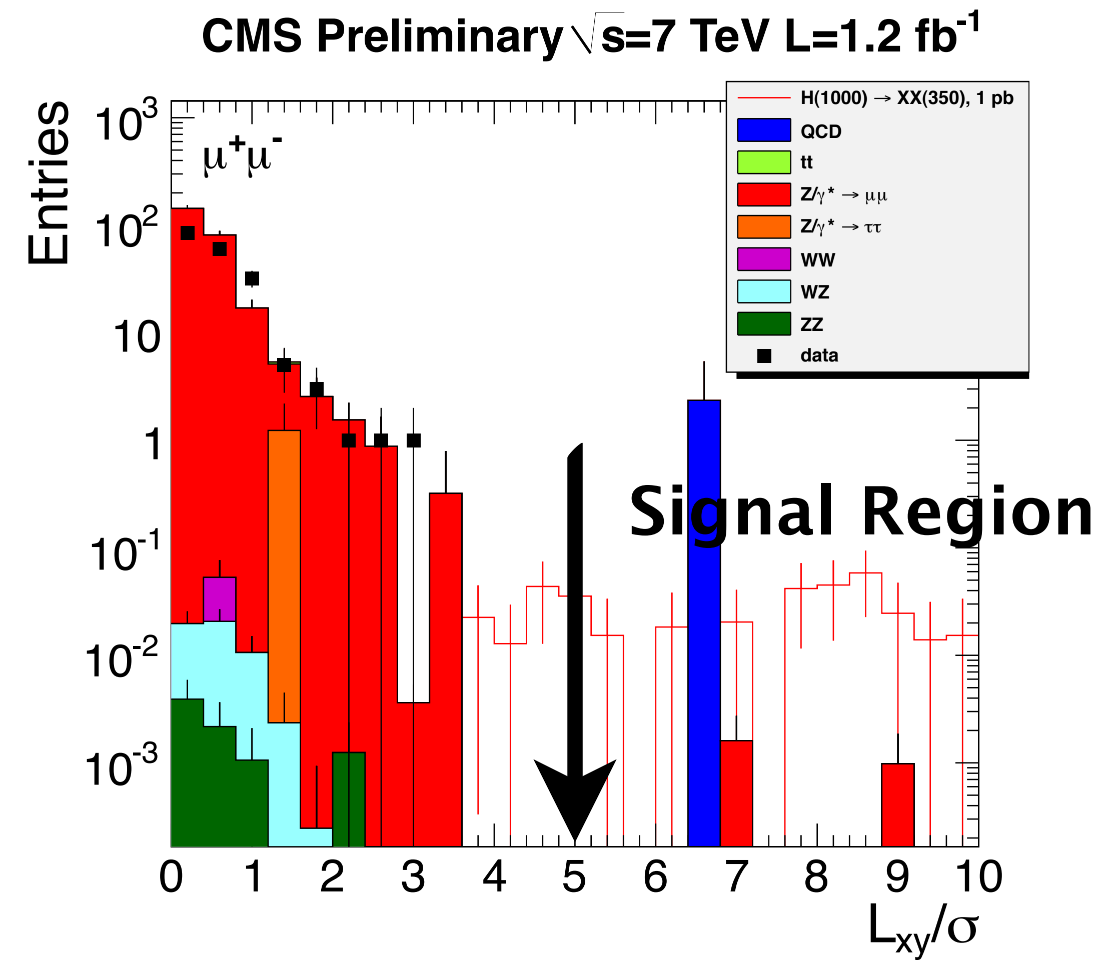
- track and event quality,
- isolated tracks,
- transverse decay length significance > 8 (5)*,
- no back-to-back tracks,
- dilepton $\vec{p}$ collinear with primary and displaced vertices,
- signal efficiency = 20–30% (10–20%)*

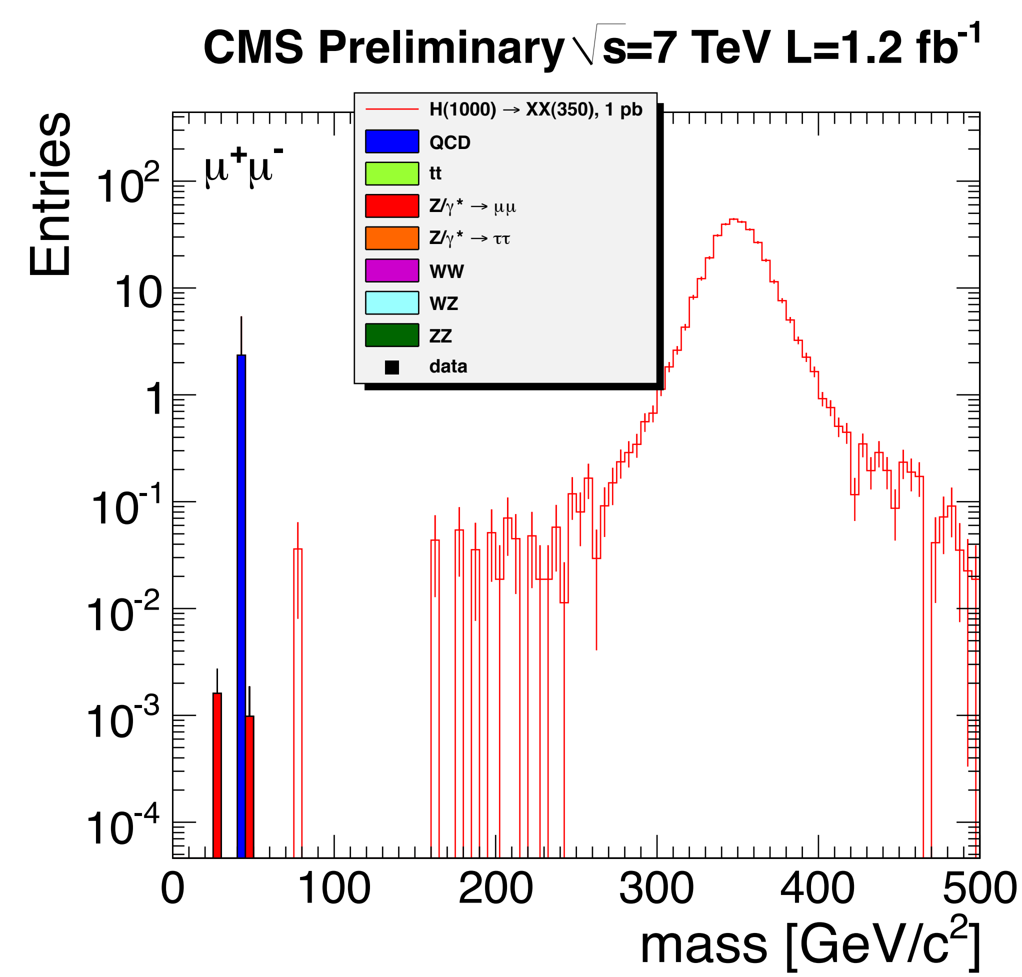
* for muon (electron)

Displaced Lepton Pair

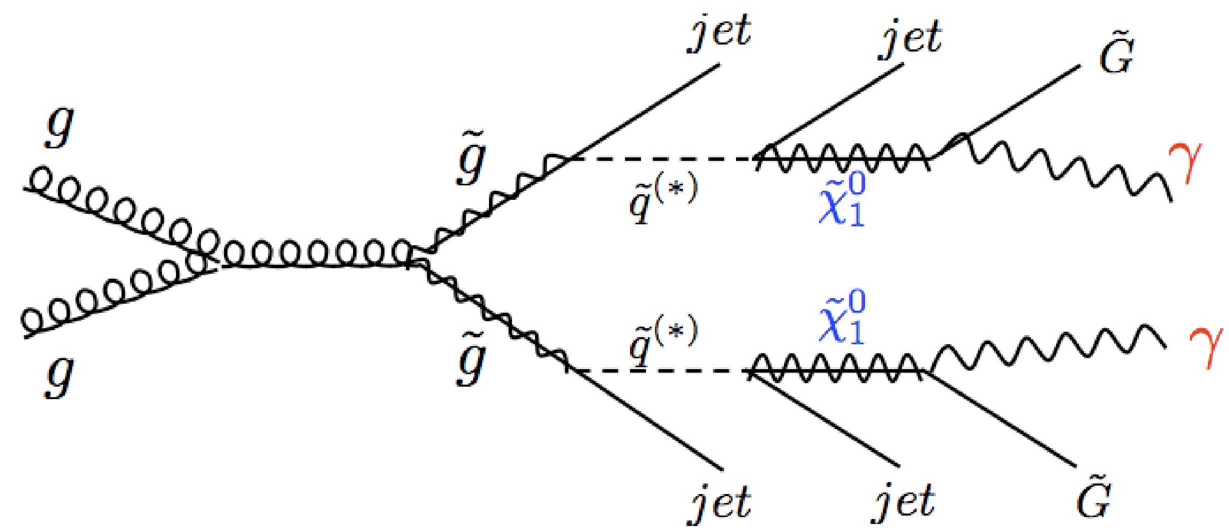
- Background estimate from fit to MC.
- $L_{XY} \approx$ 4cm for backgrounds.
- 95% CL_S cross section limits vs. $c\tau$
  - Typically 3–30 fb for $c\tau \approx$ 1 meter.







Displaced Photons

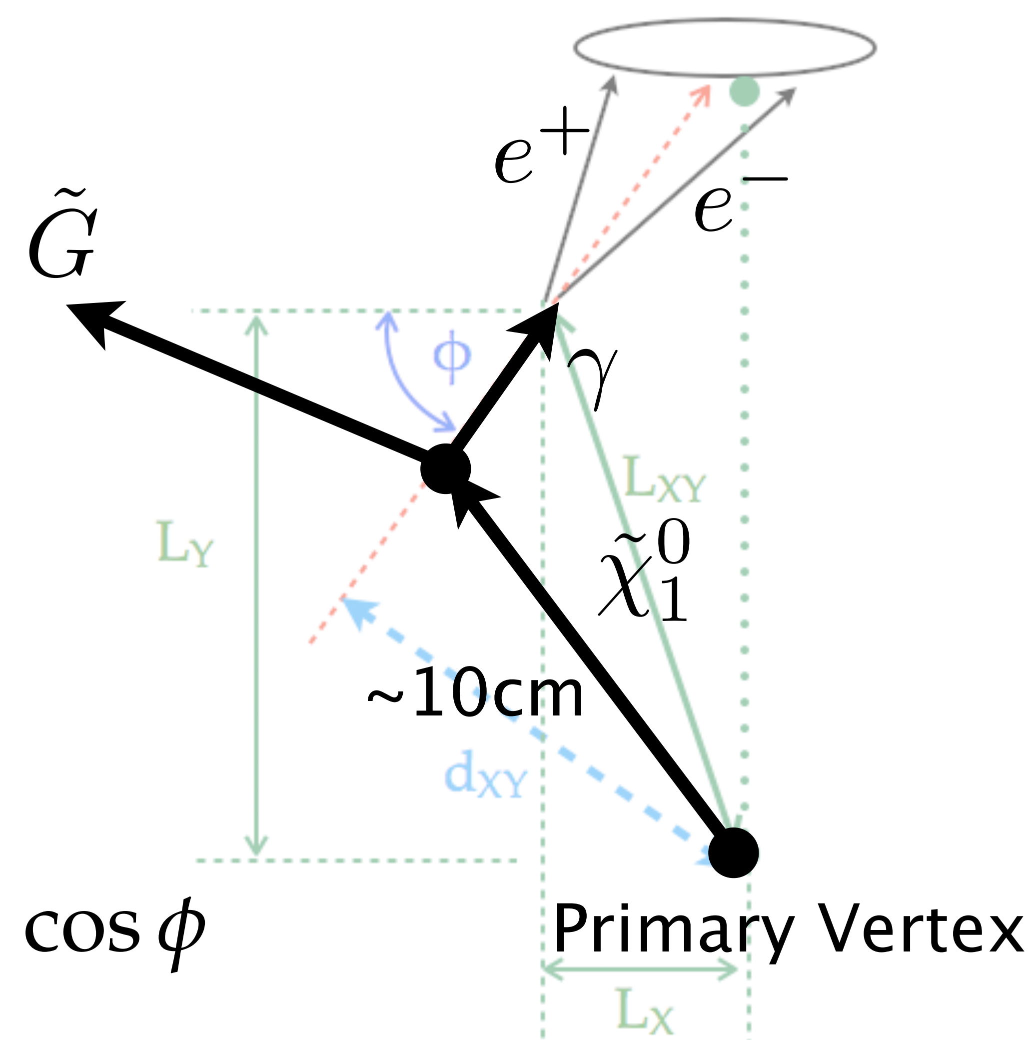


New physics model:

- GMSB SPS8: $\tilde{\chi}_1^0 \to \gamma\tilde{G}$
- 2 < neutralino cτ < 25cm
- high p_T jets, MET, displaced diphotons

Conversion Reconstruction:

- Determine photon impact parameter (d_{XY}) from γ → ee conversions in tracker.
  - Complementary to analysis of timing/ shape of showers in EM calorimeter (for signals with cτ~1m).
- Reco efficiency of 6-7%.
- Z → μμγ studies:
  - ~20% uncertainty on efficiency
  - Negligible uncertainty on d_{XY} resolution.

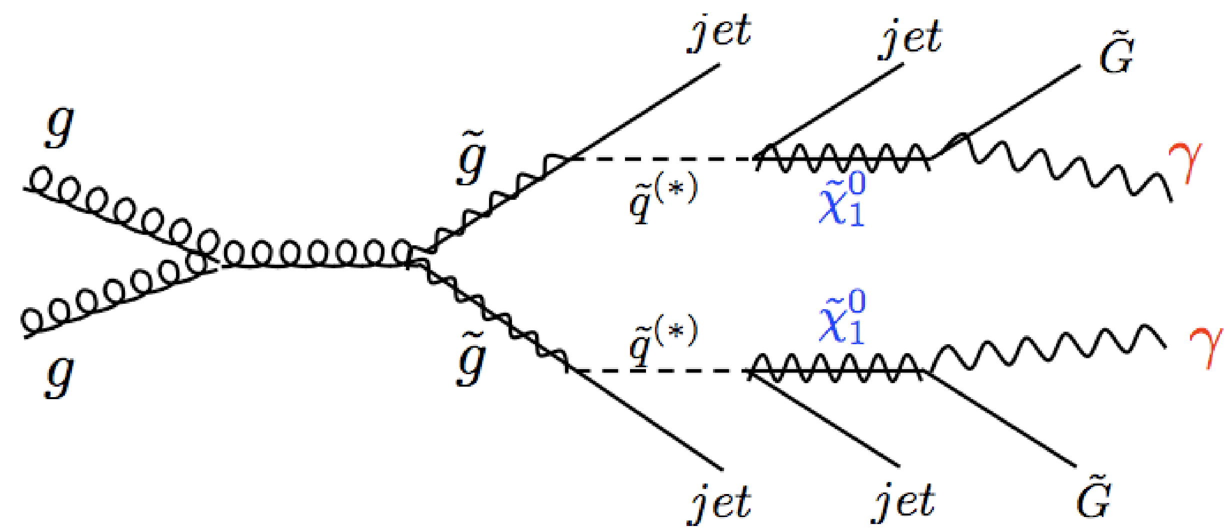


$$d_{XY} = -L_X \cdot \sin\phi + L_Y \cdot \cos\phi$$

Displaced Photons

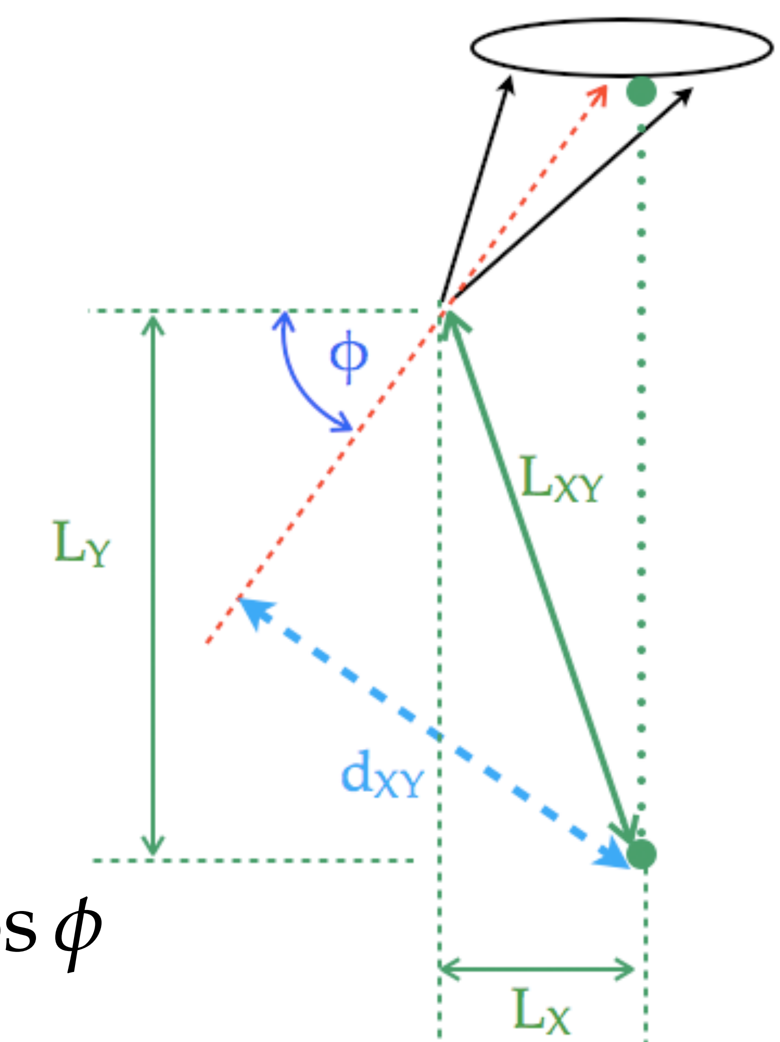
New physics model:

- GMSB SPS8: $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$
- 2 < neutralino cτ < 25cm
- high p_T jets, MET, displaced diphotons



Conversion Reconstruction:

- Determine photon impact parameter (d_{XY}) from γ → ee conversions in tracker.
  - Complementary to analysis of timing/ shape of showers in EM calorimeter (for signals with cτ~1m).
- Reco efficiency of 6-7%.
- Z → μμγ studies:
  - ~20% uncertainty on efficiency
  - Negligible uncertainty on d_{XY} resolution.

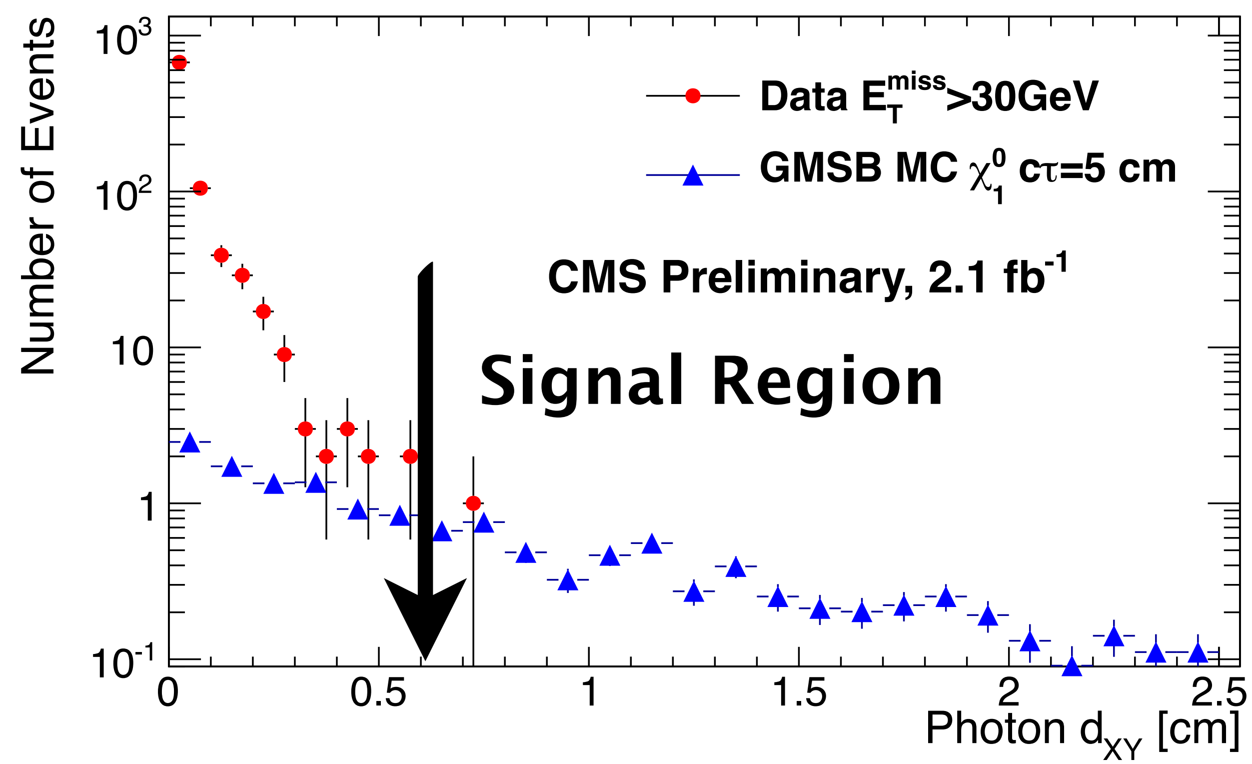


$$d_{XY} = -L_X \cdot \sin\phi + L_Y \cdot \cos\phi$$

Displaced Photons

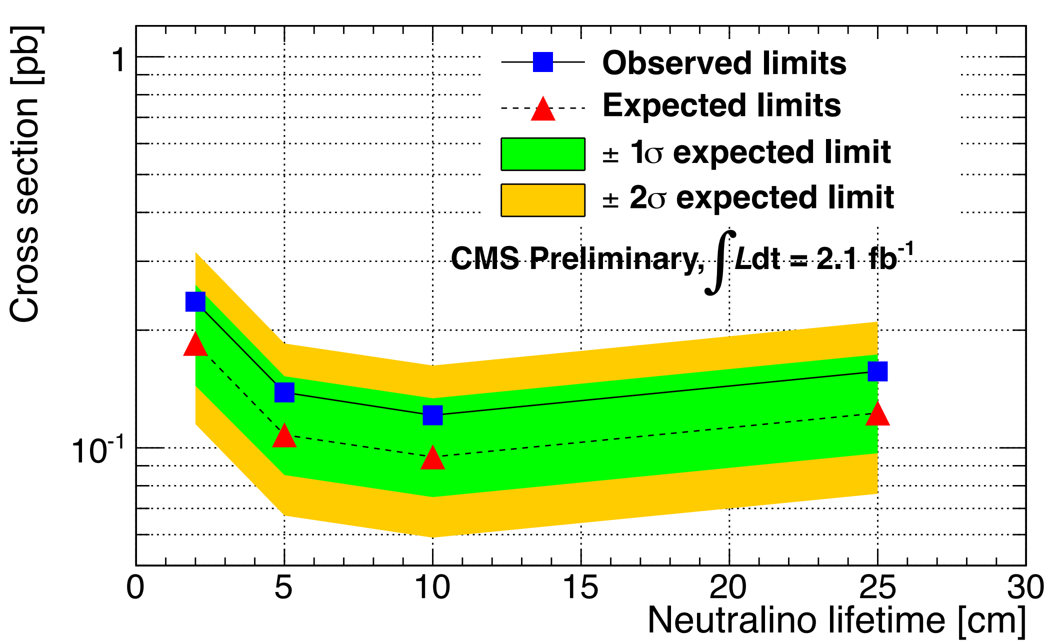
Data-Driven Bkg. Estimation:

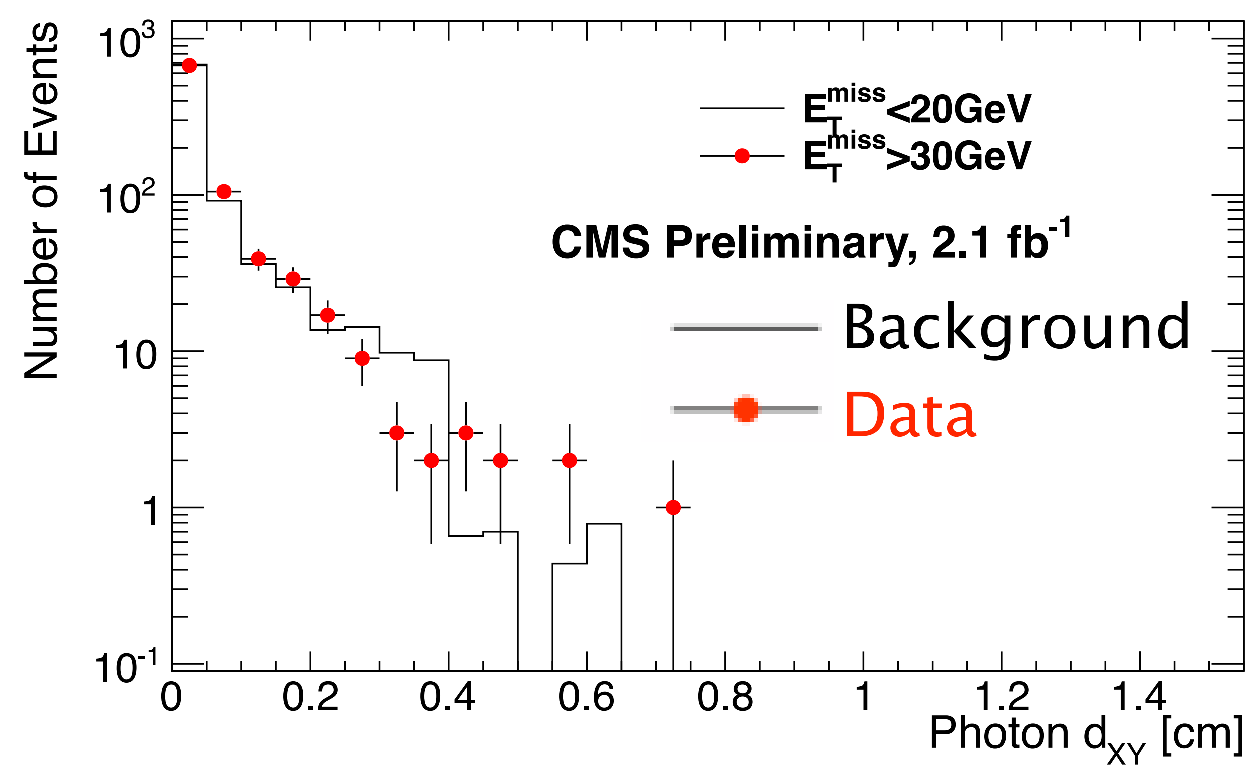
- Compare d_{XY} in isolated/non-isolated and high-MET/low-MET regions → **d_{XY} shape independent of MET and isolation**.
- Use low-MET control sample for background shape.



Cross section limits

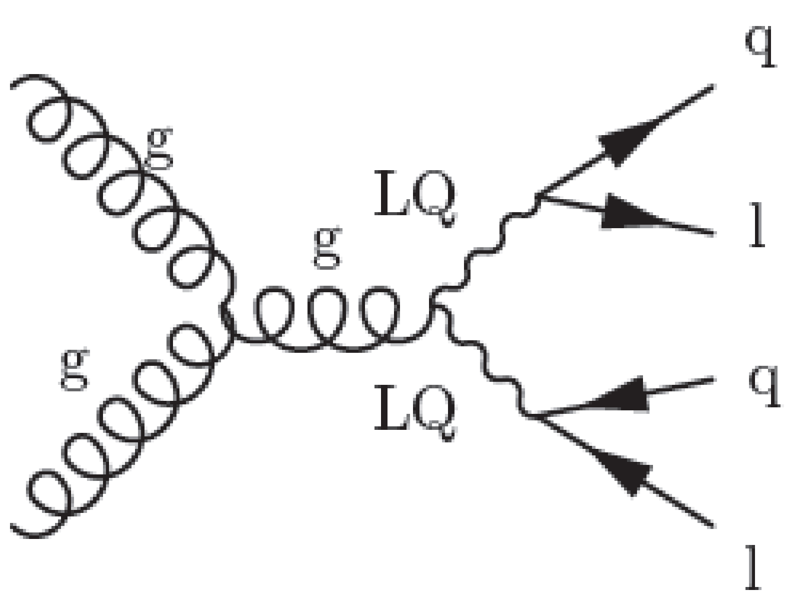
- 95% CL_S, 0.1-0.25 pb depending on cτ:

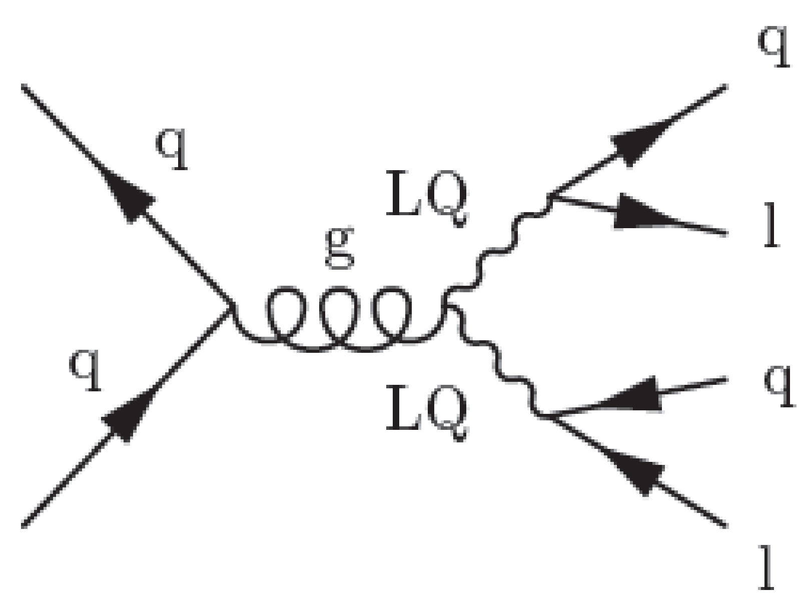




Introduction : Scalar Leptoquarks

- Predicted by many BSM theories including versions of GUTs, technicolor, and superstring-inspired E_6.
  - Natural explanation for observed quark-lepton symmetry of SM.
- Carry both baryon and lepton number.
- Assume coupling only within a single generation.
- Produced dominantly via qq and gg annihilation.
  - Cross section determined by model-independent LQ-gluon coupling.
- Today, discuss **μμjj/μνjj** and **bbνν** final states.
  - eejj/eνjj [results from 2010 data]; update coming soon.





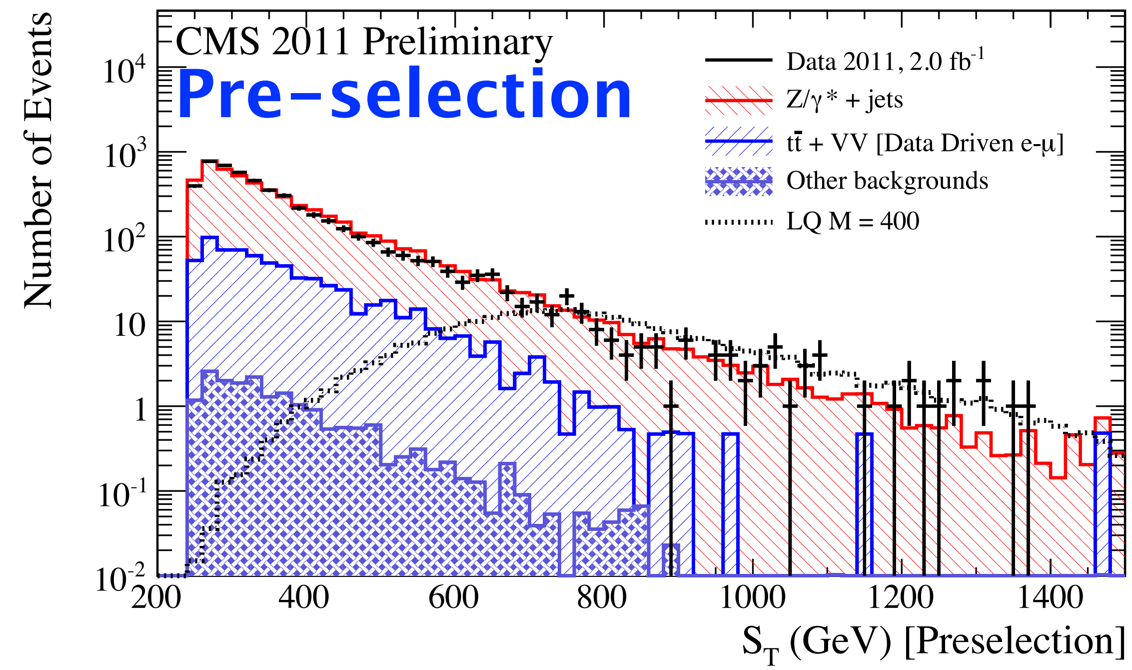
2^{nd} Generation Leptoquarks

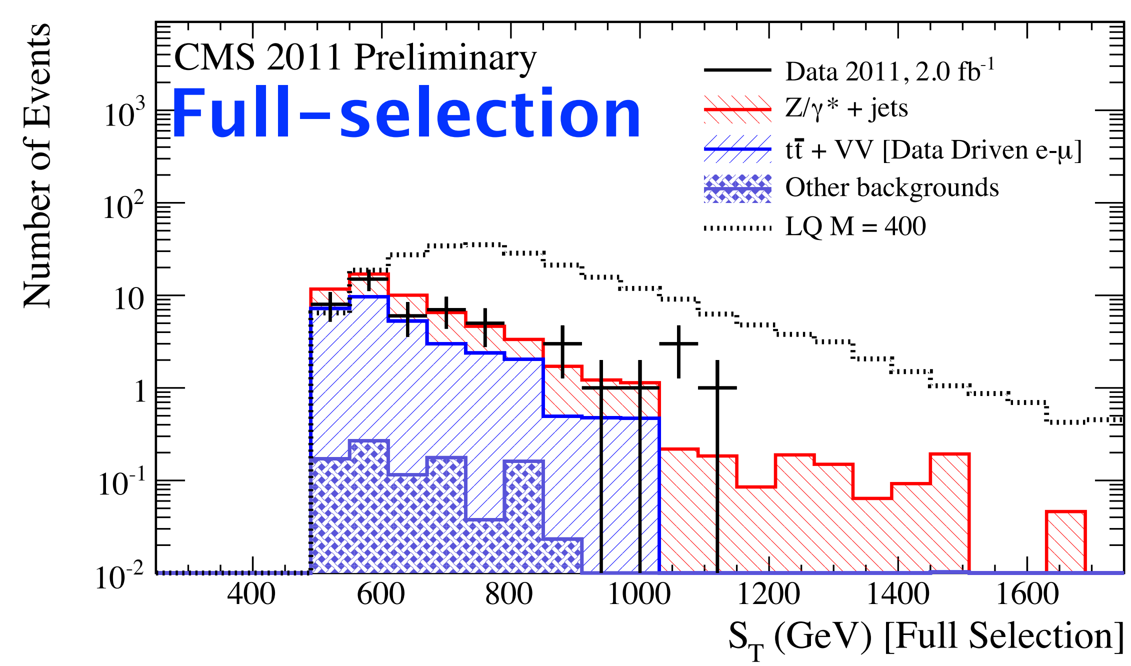
Data driven background estimation:

- Normalization for Z+jets.
- Norm and shape for ttbar.

Selection:

- μμjj
  - $p_{T\mu}$>40GeV, $|\eta_\mu|$<2.1, p_{Tj}>30GeV
  - $M_{\mu\mu}$ (remove Z+jets),
  - Scalar sum of μμjj p_T,
  - Smaller $M_{\mu j}$ in $M_{\mu j}$–pair that minimizes LQ–$\overline{LQ}$ mass difference.
- μνjj
  - 2nd μ veto, electron veto,
  - $p_{T\mu}$>80GeV,
  - MET (remove W+jets),
  - Scalar sum of μνjj p_T,
  - $M_{\mu j}$ that minimizes ΔM(LQ,$\overline{LQ}$)

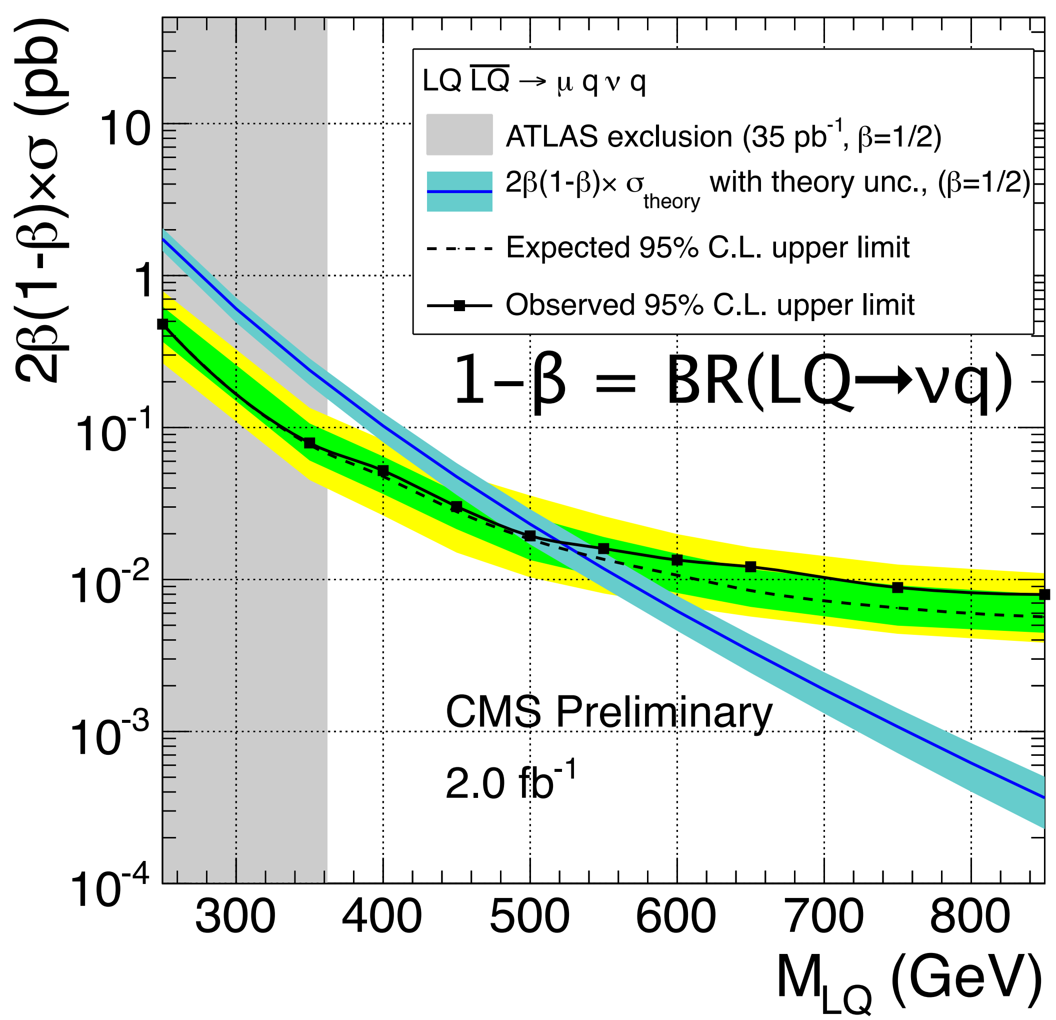


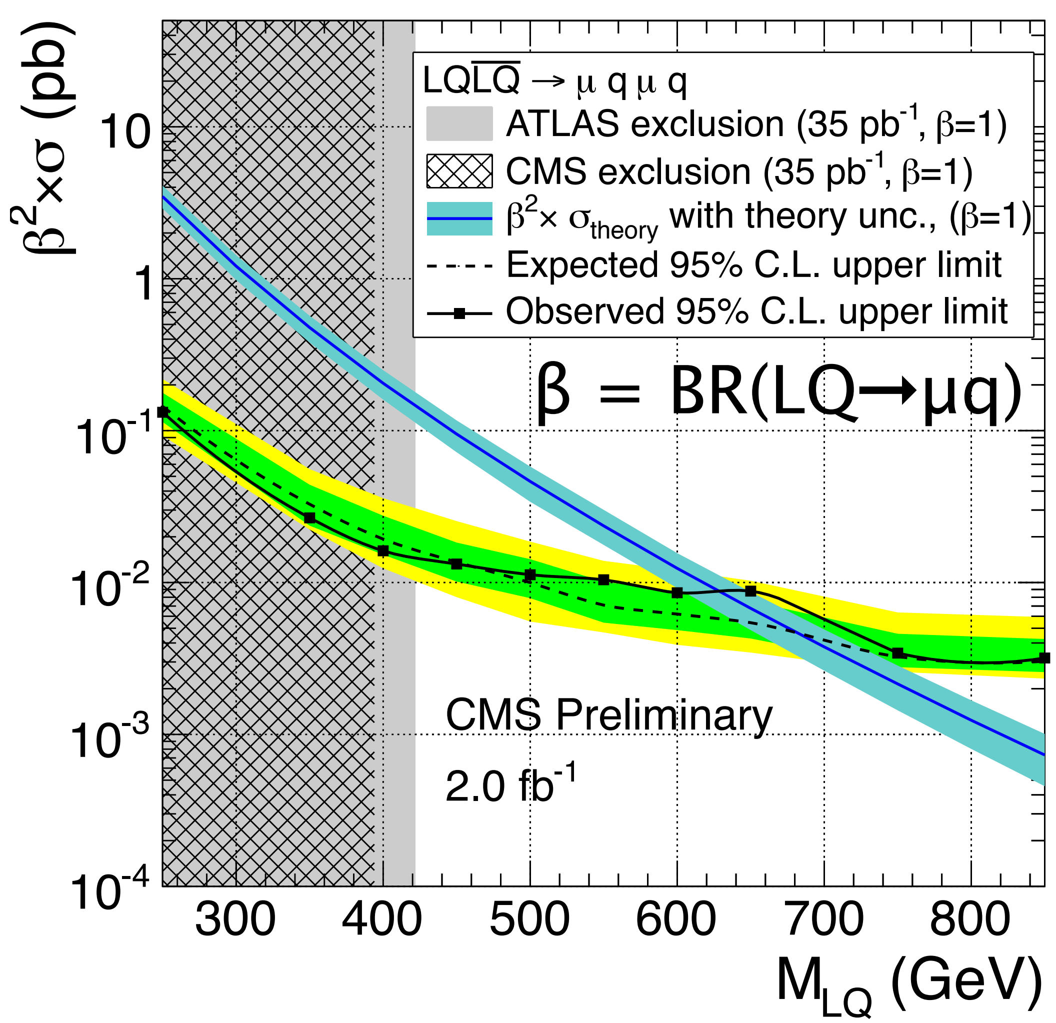


2^{nd} Generation Leptoquarks

- Statistics dominated; background modeling systematic uncertainty is largest.

- 95% CLs limits (crosscheck with Bayesian+MCMC method).
  - M_{LQ} > 632 (523) GeV, assuming β = 1.0 (0.5).





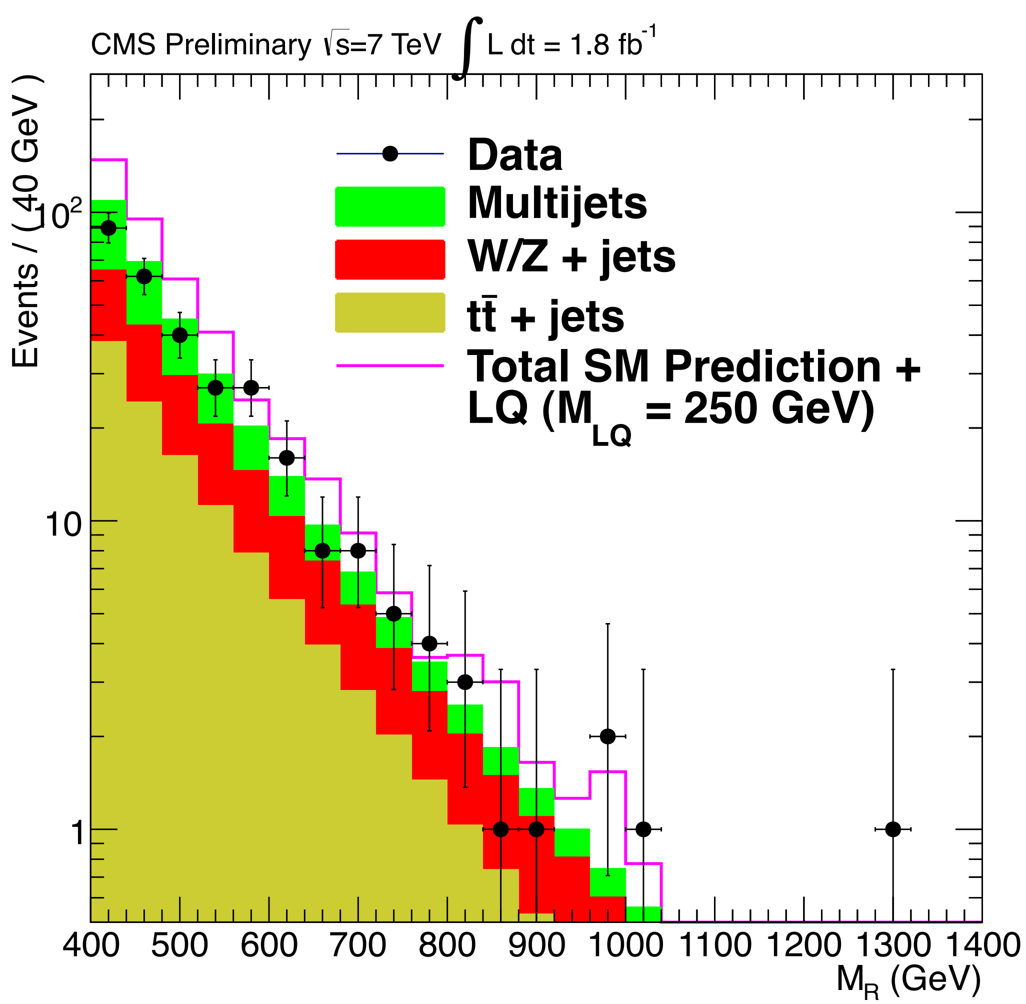
3^{rd} Generation Leptoquarks

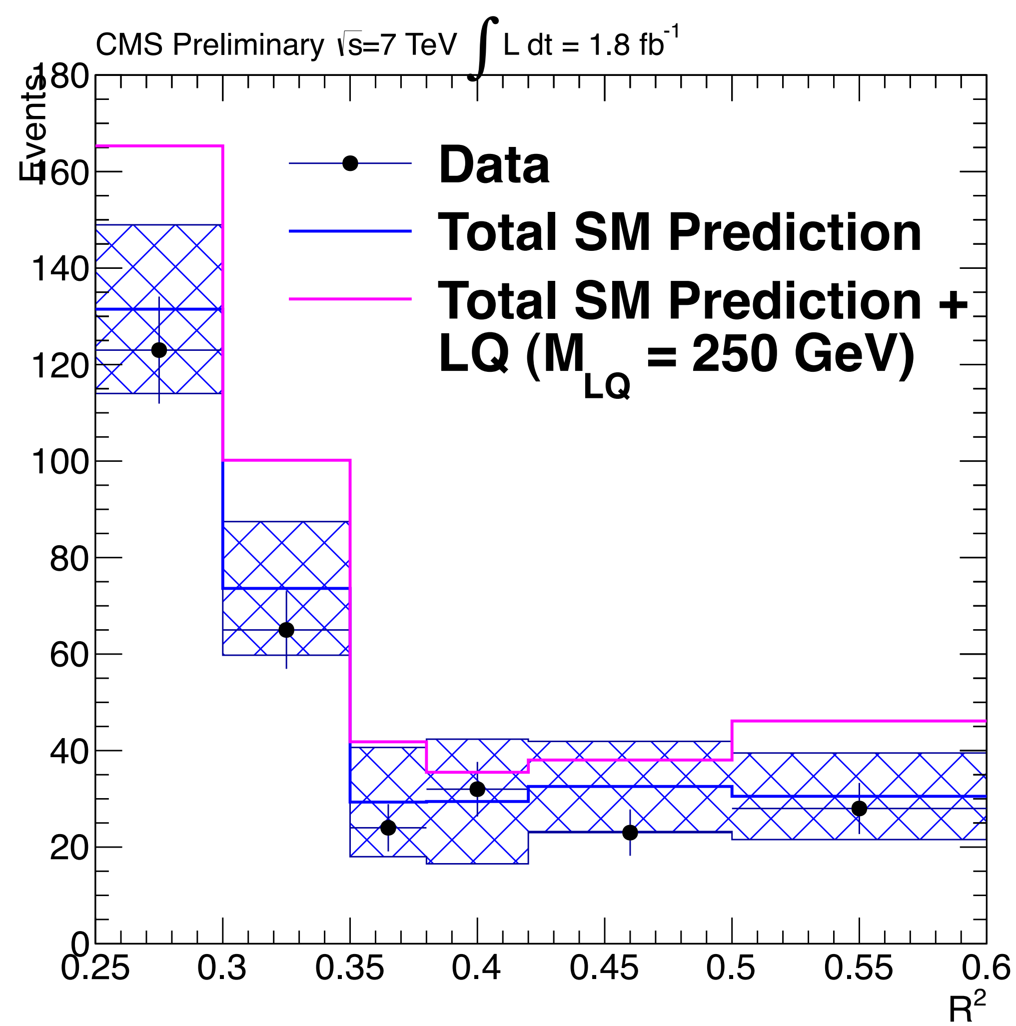
- **Razor-based analysis:** Model-independent variables to search for pair-produced particles with masses larger than those of SM particles and MET.

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}\,.$$

$$M_T^R \equiv \sqrt{\frac{\not{E}_T(p_T^{j1} + p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

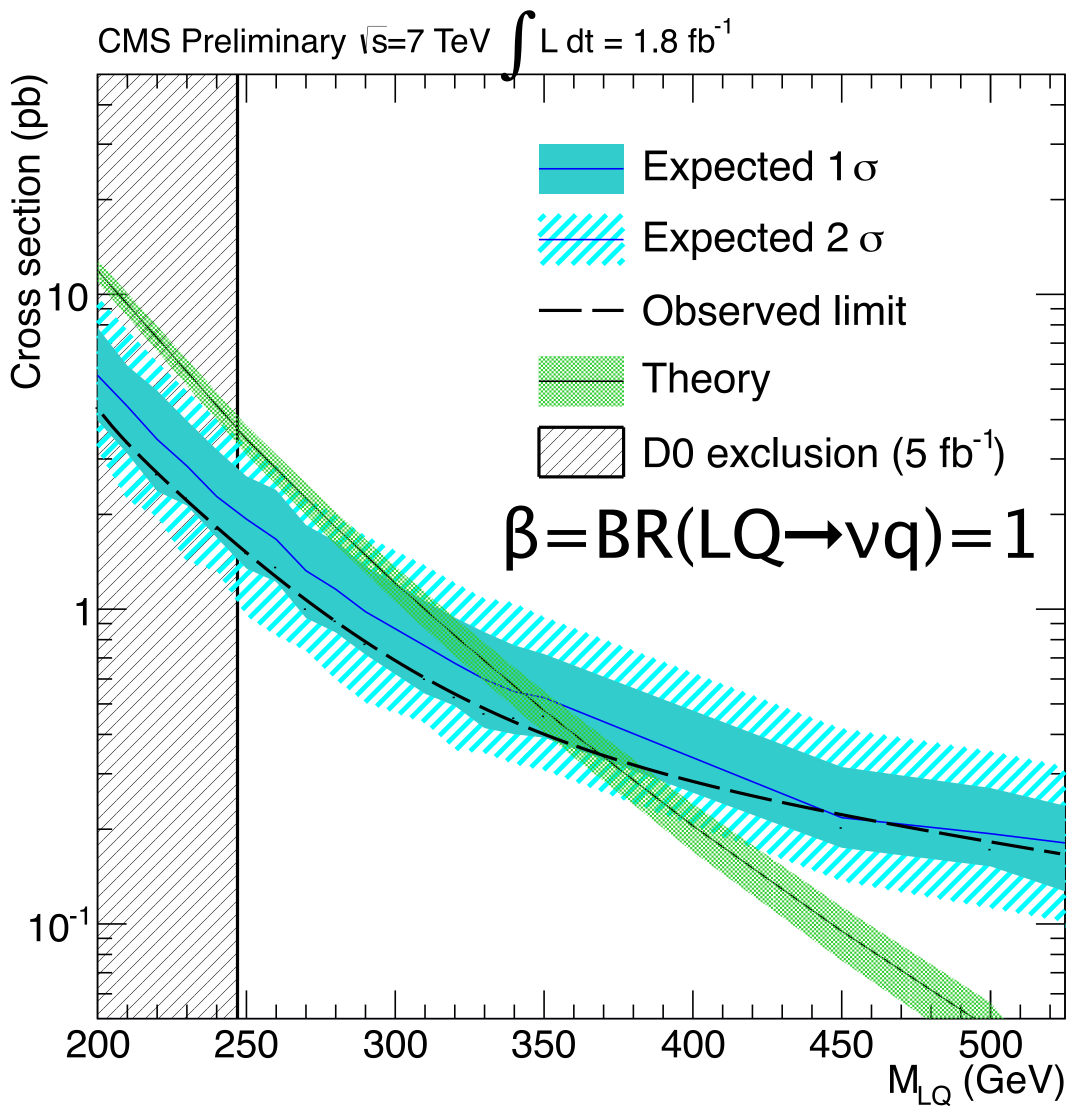
$$R \equiv \frac{M_T^R}{M_R}$$

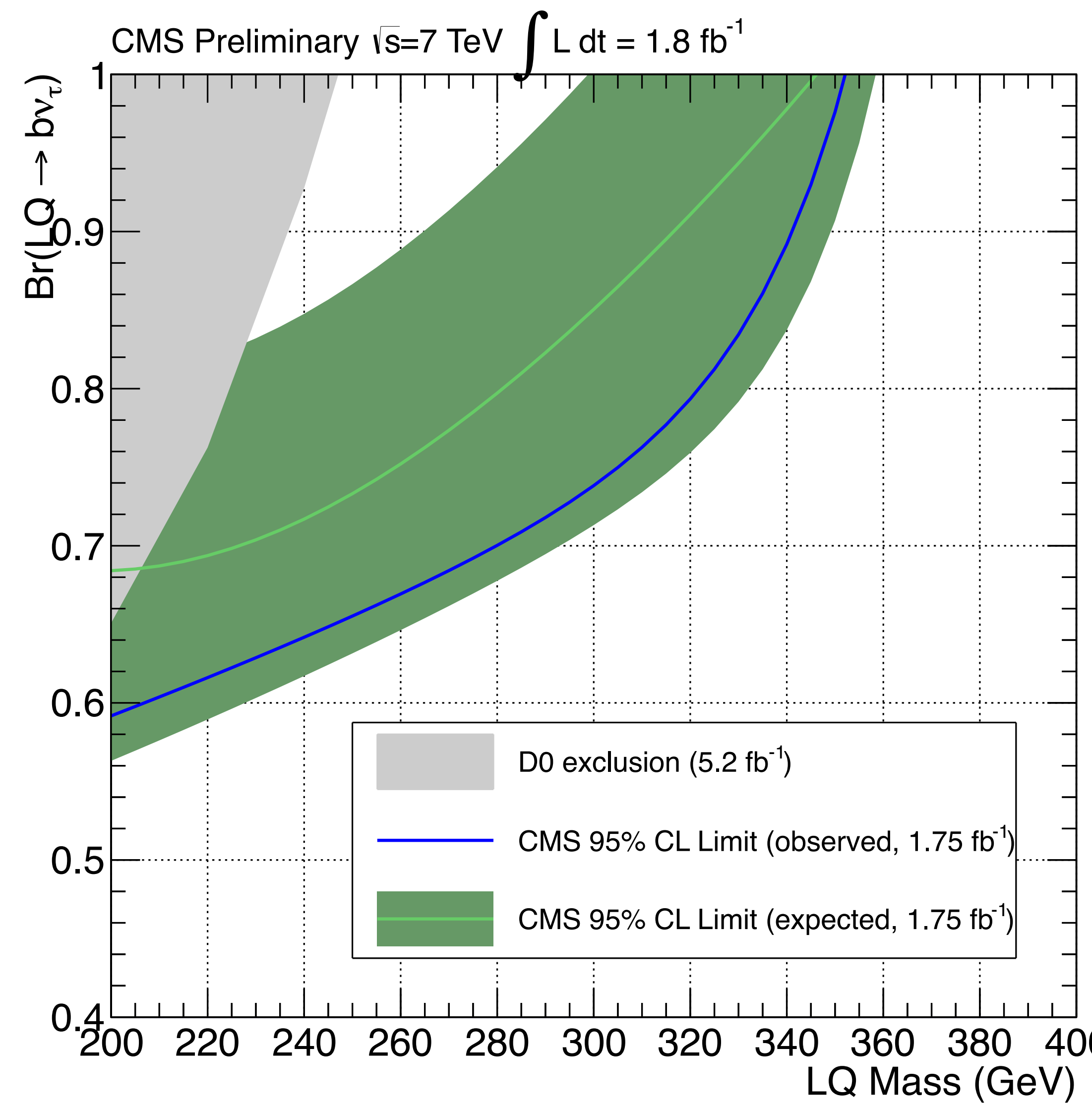




3^{rd} Generation Leptoquarks

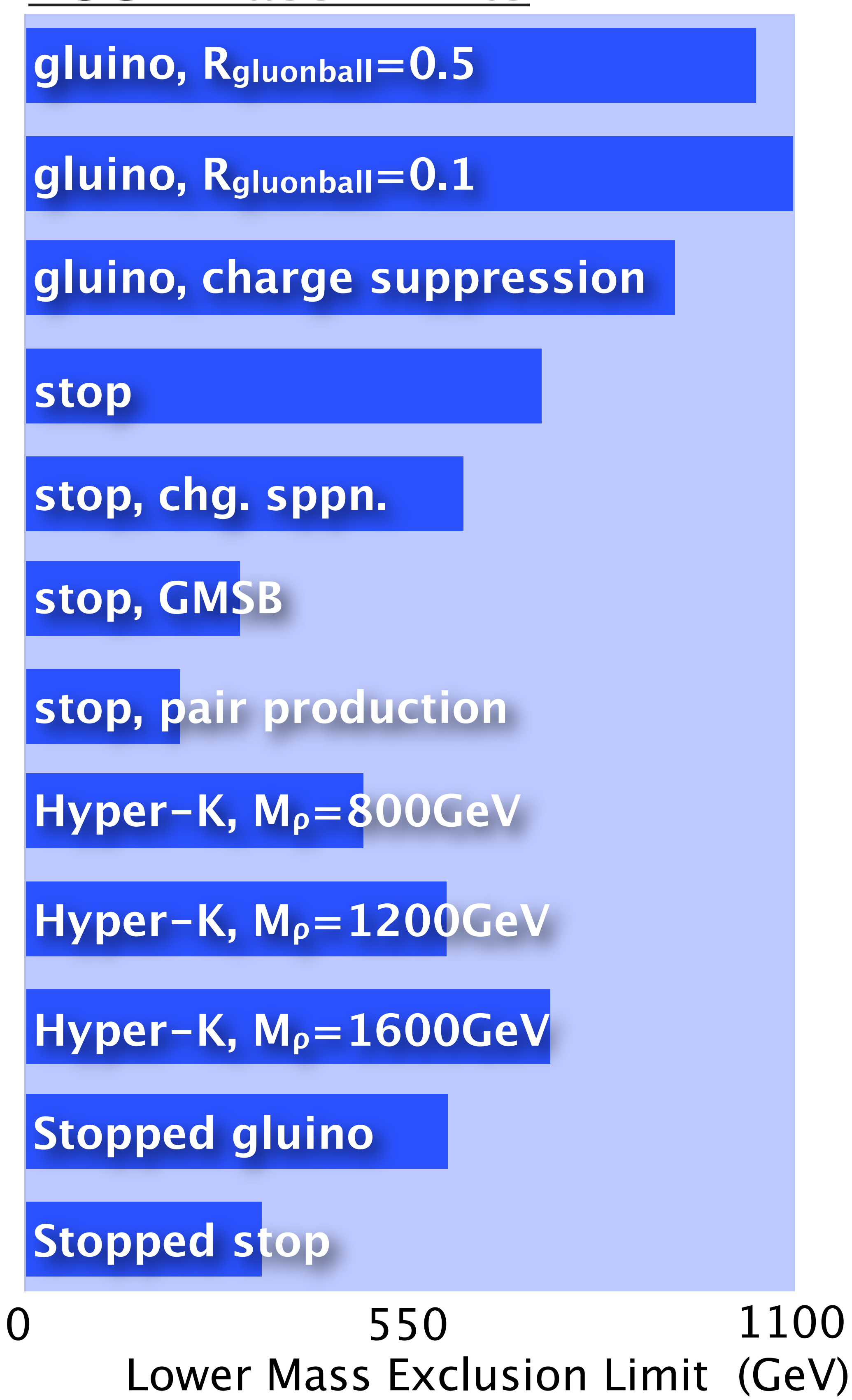
- **Data-driven background estimation** using R sidebands and signal-depleted samples from lepton triggers.
- Signal efficiency 1-10% for $200<M_{LQ}<600$ GeV.





Summary

HSCP Mass Limits



- CMS has an active search program for the “most exotic” new physics signals.
- Updates in progress and new analyses planned.

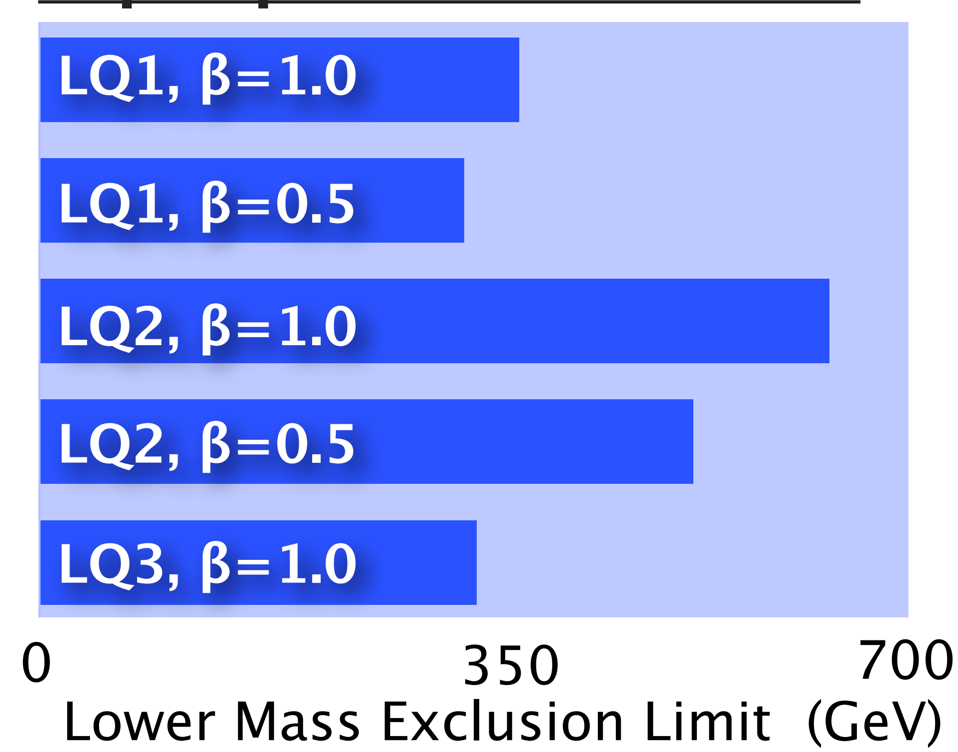
$gg \to H^0 \to 2X, X \to l^+l^-$

σxBR < 3–30 fb for c$\tau \approx$ 1 meter

GMSB neutralino

σ < 0.12–0.24 pb for cτ=2–25cm

Leptoquark Mass Limits



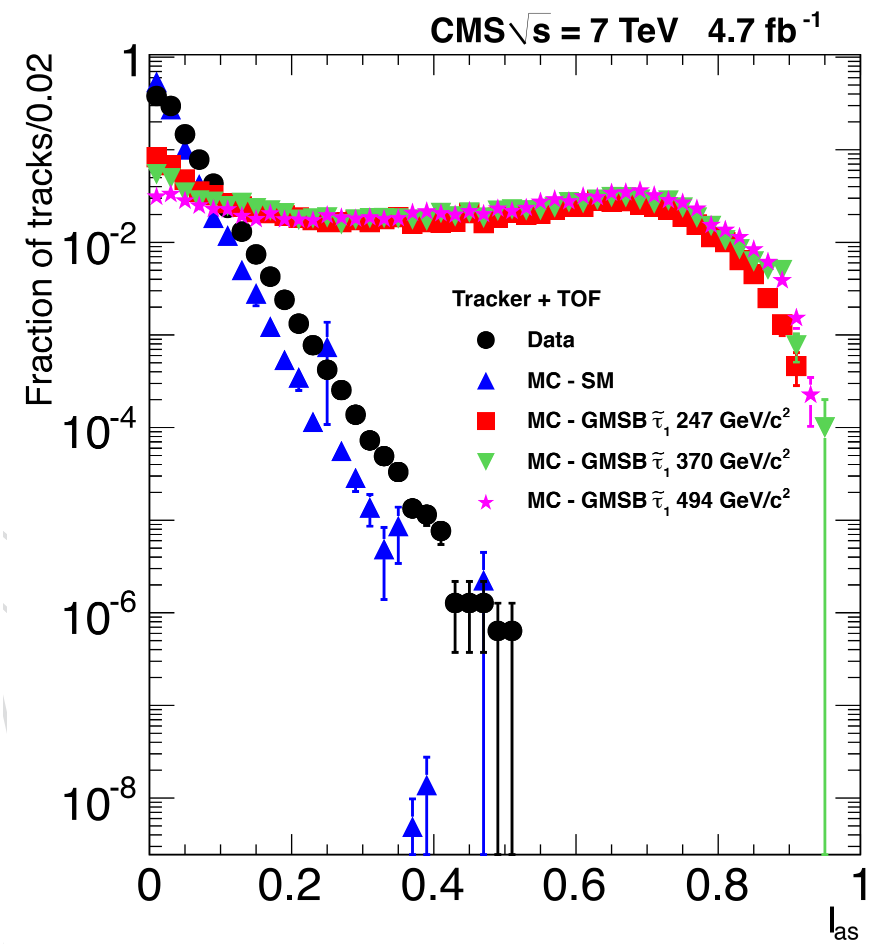
Additional Material

Slow HSCP : I_{as}

As an estimator of the degree of compatibility of the observed charge measurements with the MIP hypothesis, a modified version of the Smirnov-Cramer- von Mises [18, 19] discriminant is used (the modification applied to the original form of the discriminant eliminates the sensitivity to incompatibility with the MIP hypothesis due to low ionization):

$$I_{as} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{i=1}^{N} \left[P_i \times \left(P_i - \frac{2i-1}{2N} \right)^2 \right] \right),$$

where N is the number of charge measurements in the silicon-strip detectors, P_i is the probability for a MIP to produce a charge smaller or equal to the i^{th} charge measurement for the observed path length in the detector, and the sum is over the track measurements ordered in terms of increasing P_i. The charge probability density function used to calculate P_i is obtained using tracks with $p > 5$ GeV/c in events collected with a minimum bias trigger. Non-relativistic HSCP candidates will have the value of the discriminant I_{as} approaching unity.



Slow HSCP : I_h

The most probable value of the particle dE/dx is determined using a harmonic estimator I_h of grade $k = -2$:

$$I_h = \left(\frac{1}{N} \sum_i c_i^k \right)^{1/k},$$

where c_i is the charge per unit path length in the detector of the i^{th} measurement for a given track. In order to estimate the mass (m) of highly ionizing particles, the following relationship between I_h, p, and m is assumed:

$$I_h = K \frac{m^2}{p^2} + C.$$

Equation 3 reproduces the Bethe-Bloch formula with an accuracy of better than 1% in the range $0.4 < \beta < 0.9$, which corresponds to $1.1 < (dE/dx)/(dE/dx)_{MIP} < 4.0$. The empirical parameters K and C are determined from data using a sample of low-momentum protons.

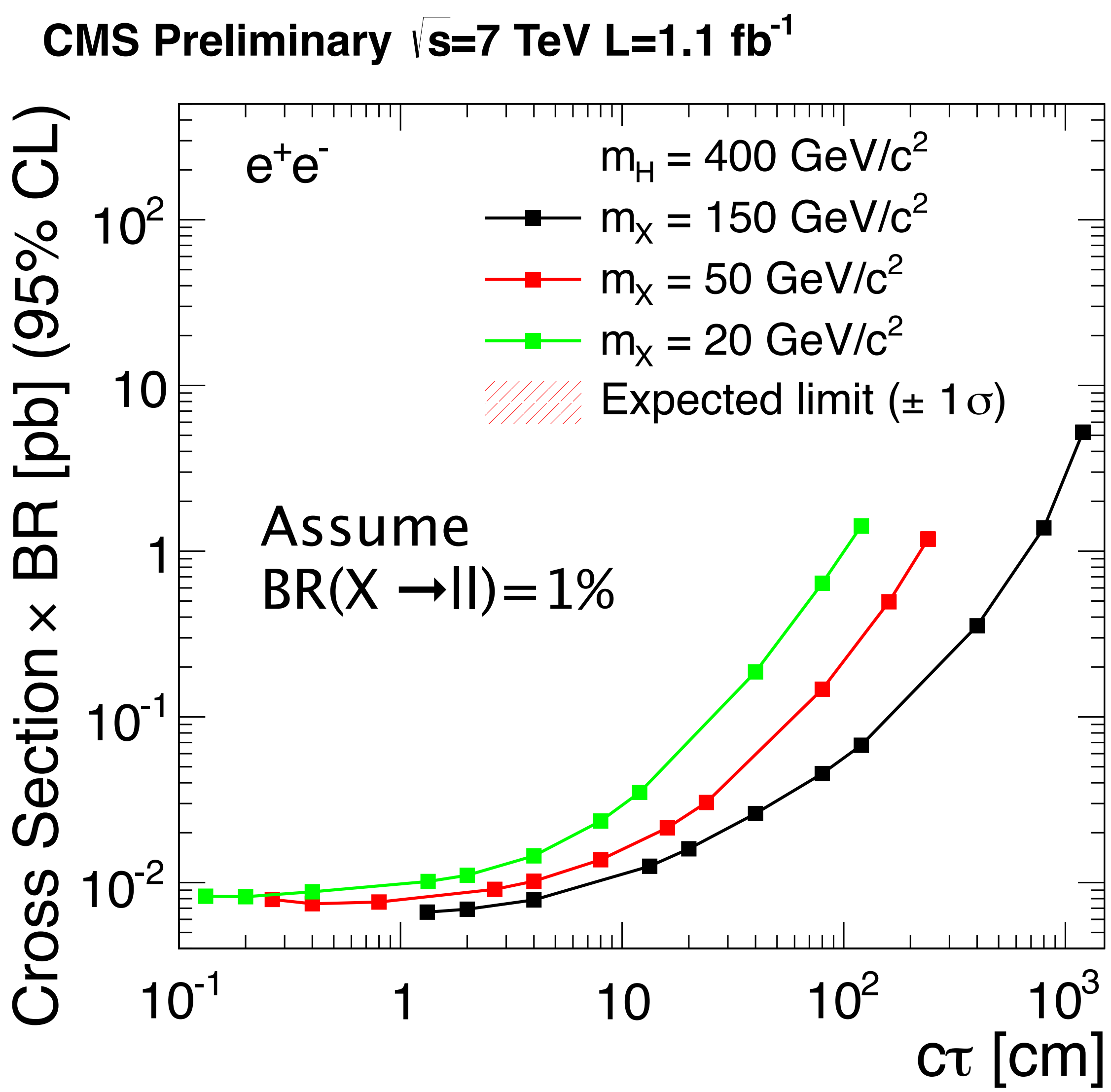
Slow HSCP : Systematic Uncertainties

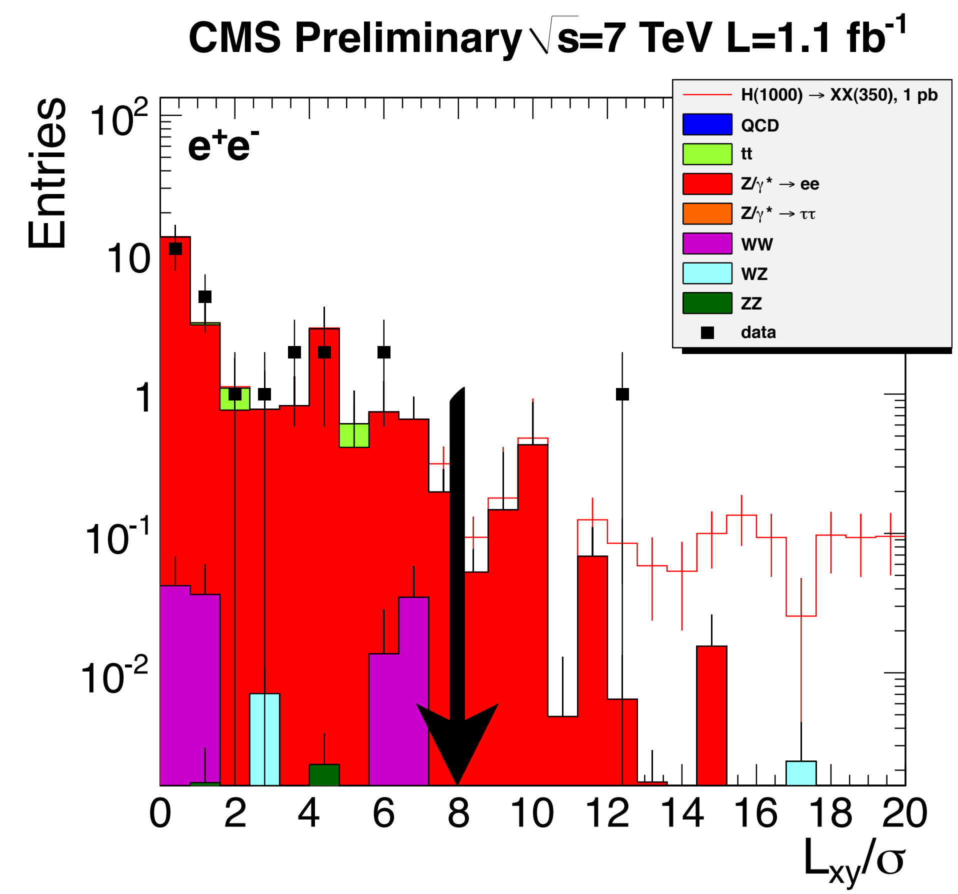
Table 2: Sources of systematic uncertainties and corresponding relative uncertainties.

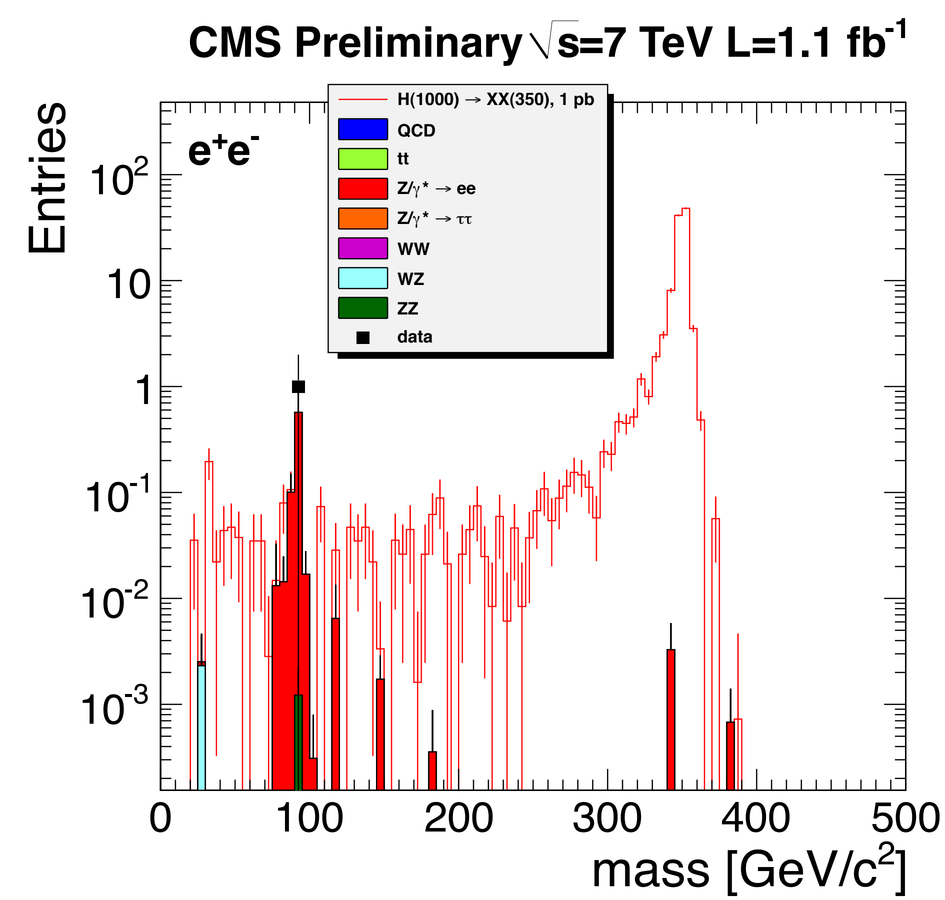
Source of systematic uncertainty	Relative uncertainty (%)
Signal acceptance:	
- Trigger efficiency	5
- Track momentum scale	< 4
- Ionization energy loss	2
- Time-of-flight	2
- Track reconstruction efficiency	< 2
- Muon reconstruction efficiency	< 2
- Pile-up	< 0.5
Total uncertainty on signal acceptance	7
Expected background	10
Integrated luminosity	4.5

Displaced Lepton Pair

- Electron channel results







3rd Gen LQ : Data Samples

Sample	R^2 cut	leptons	# b-taged jets	Comment
W/Z MC	$R^2 > 0.07$	tight μ	≥ 2	shape of W/Z+HF jets
MU	$R^2 > 0.14$	tight μ	≥ 2	shape of $t\bar{t}$+jets
MU	$R^2 > 0.14$	loose μ	≥ 1	shape of HF multijets
ELE	$0.2 < R^2 < 0.25$	tight e	$= 1$	$M_R < 600$, sideband to extract SF_{ELE}
ELE	$R^2 > 0.25$	tight e	≥ 2	ELE "signal-like" control region
HAD	$0.2 < R^2 < 0.25$	veto leptons	=1	$M_R < 600$, sideband to extract SF_{HAD}
HAD	$R^2 > 0.25$	veto leptons	≥ 2	signal box, search for LQ signal

Table 1: Summary of various samples used in the search, with a short description of their specific purpose. $M_R > 400$ is always applied in all boxes. The cuts on R^2 listed in the table are after recalculating $\not{E}_T$ and R when leptons are treated as neutrinos. Definitions of muons (μ) and electrons (e) are listed in Sec. 3.1.