Search for SUSY and UED in Final States with Photons and Missing Transverse Momentum with the ATLAS Detector with 1.07 fb^{-1} of Data

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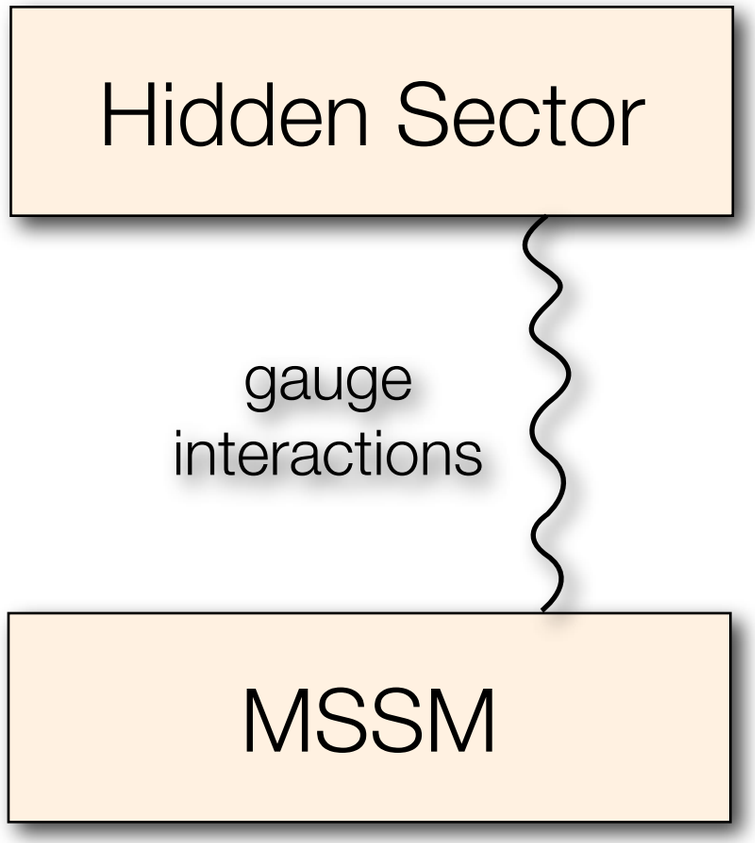
Introduction

- Outline
  - Introduction to GMSB and UED
  - Event selection
  - Background modeling
  - Signal grids
  - Systematic uncertainties
  - Results and interpretation in the models

- Builds on 2010 analysis: arXiv:1107.0561v2 [hep-ex]
  - Submitted to EPJC Letters

Gauge-Mediated SUSY Breaking (GMSB)

- A hidden sector is responsible for SUSY breaking.
- Standard gauge interactions transmit the SUSY breaking to the MSSM
- Gauge interactions are flavor-blind: no flavor problem
- Common Features:
  - Mass scale for the SUSY breaking is much lower than mSUGRA
  - The LSP is the gravitino
  - NLSP determines experimental signature



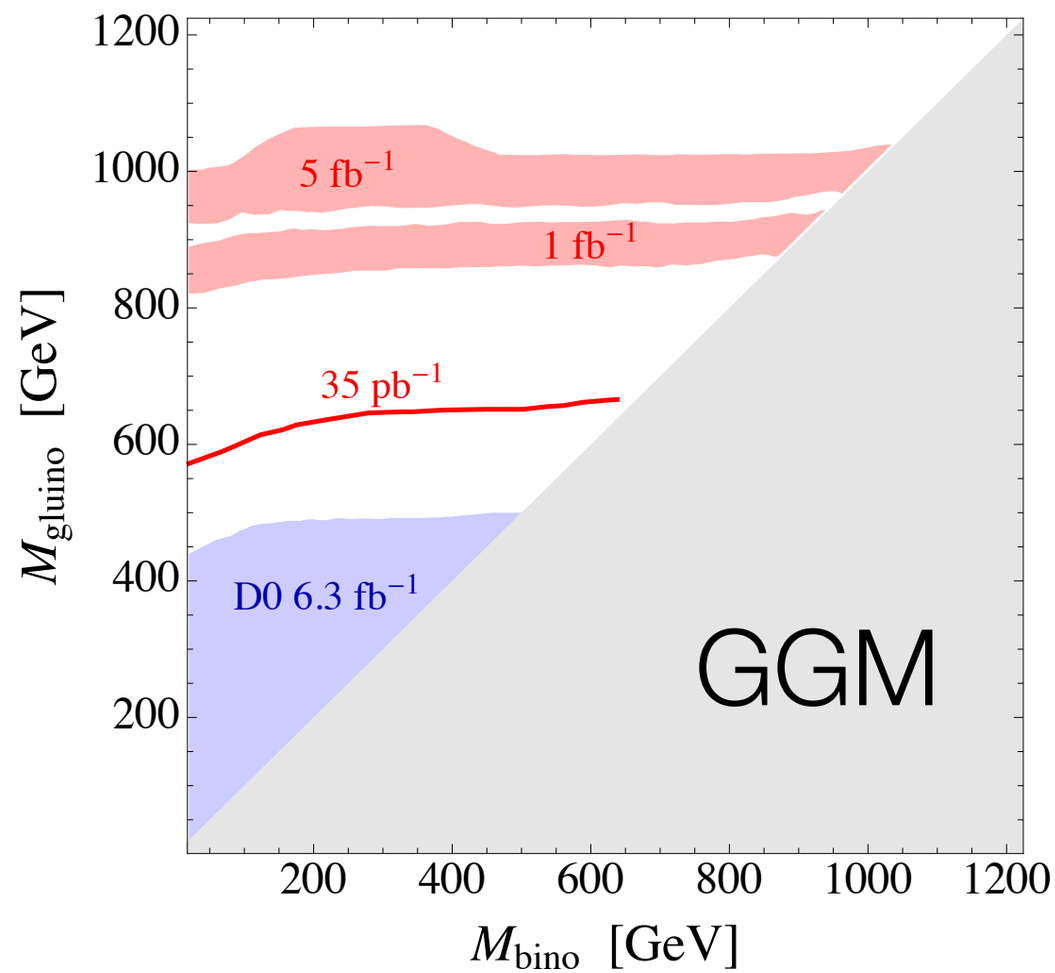
Minimal and General Gauge Mediation

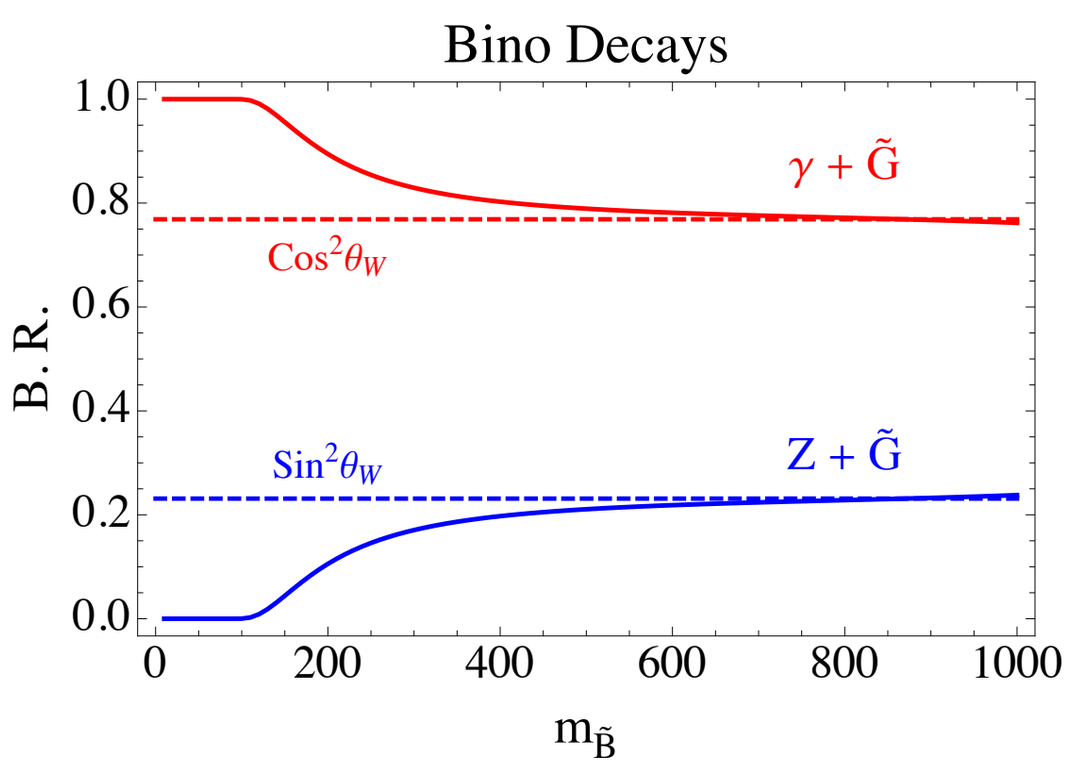
- Minimal Gauge Mediation (MGM):
  - Simple model with one mass scale for the symmetry breaking (Λ) and messengers of mass M_{mess}.
  - Snowmass SPS 8 is an example with one set of messengers arXiv:hep-ph/0202233v1
  - Gluinos much heavier than neutralinos because $M_a = \frac{\alpha_a}{4\pi}\Lambda$
- General Gauge Mediation (GGM):
  - "in the limit that the MSSM gauge couplings $\alpha_i \rightarrow 0$, the theory decouples into the MSSM and a separate hidden sector that breaks SUSY" (arXiv:0801.3278v3 [hep-ph])
  - The MGM mass hierarchy between gluinos and neutralinos is not required.

Bino NLSP

plots from arXiv:1103.6083v1 [hep-ph]
Joshua T. Ruderman and David Shih

- If $|M_1| << \mu$ and $|M_1| < |M_2|$, the NLSP is bino-like
- Assuming R-parity, two sparticles are produced, which cascade down to the bino NLSPs
- The bino decays to a photon or a Z + gravitino (we study the photon case)

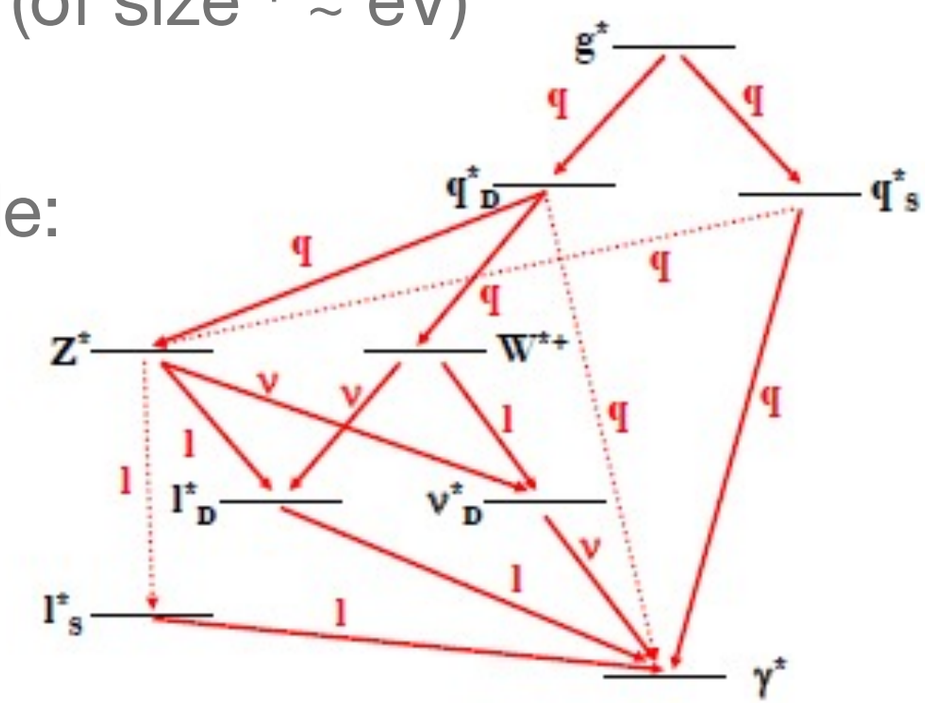




- Signature: **two high p_T photons + E_T^{miss}**

Introduction to Universal Extra Dimensions (UED) with One Extra Dimension

- **Universal**: ALL SM particles propagate into the extra dimensions with compactification scale R (1/R ~ 1 TeV)
- quark and gluon KK excitations are pair produced, and cascade decay down to Lightest KK Particle: γ^*
- If the "thick brane", where the SM particles propagate, is embedded in a larger space of (4+N)-dim (of size^{-1} ~ eV) where only gravitons propagate:
  - gravity mediated decays become possible: $\gamma^* \rightarrow \gamma$ + Graviton
- Signature: **two high p_T photons + E_T^{miss}**

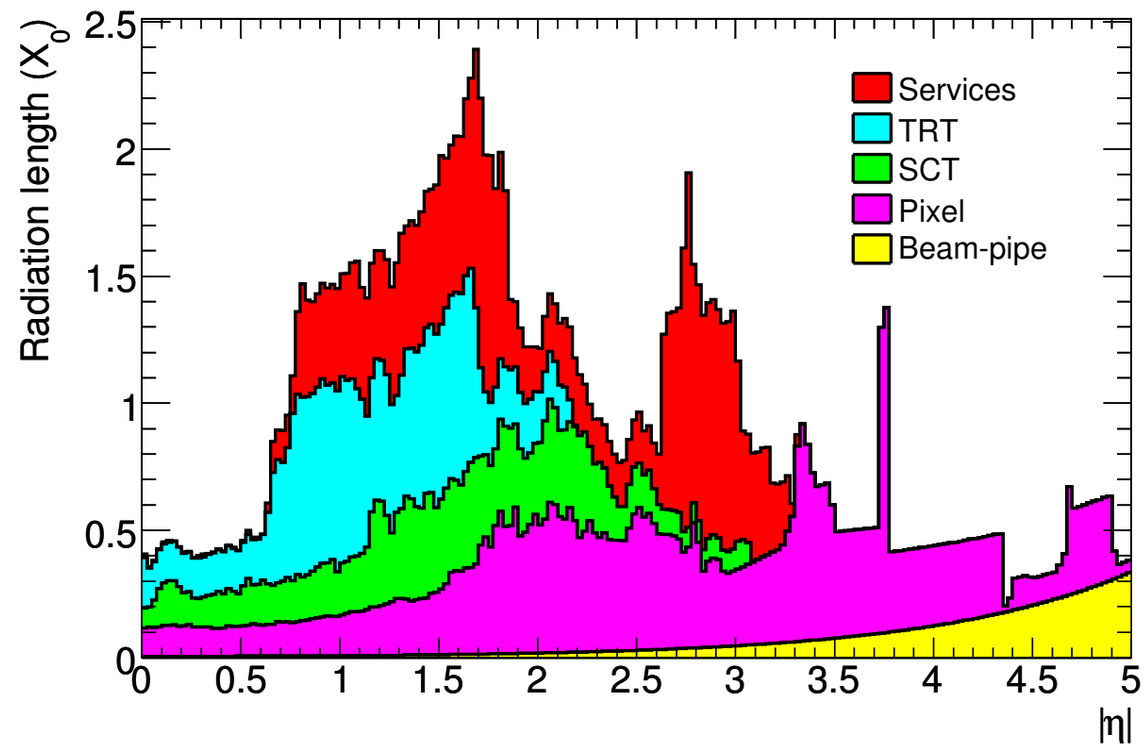


Selection Criteria for the Summer 2011 Analysis: 1.07 fb^{-1}

- Trigger: 2 loose egamma objects, $p_T > 20$ GeV
- Require two tight photons
  - $p_T > 25$ GeV
  - $|\eta| < 1.81$ but not in the crack region, $1.37 < |\eta| < 1.52$
  - Calorimeter iso: E_T ($R < 0.2$, excluding core) < 5 GeV
    - corrected for energy leakage outside of core and pileup.
  - Not touching a problematic calorimeter area
- $E_T^{miss} > 125$ GeV, based on local-calibrated topoclusters + muons
- primary vertex with > 4 tracks
- Reject events with:
  - *bad* jets likely from noise, spikes, cosmics, beam background
  - photons that fail LAr cleaning or timing, or electrons that fail timing.
  - selected muon with $|z_0| > 1$ mm or $|d_0| > 0.2$ mm wrt PV

Discriminating Photons From Electrons

- Due to the many interaction lengths in front of the calorimeter, a large fraction of the photons convert.
- Standard way to discriminate photons from electrons—vetoing for hits or tracks—significantly lowers efficiency



- Solution: reconstruct conversions:
  - 2-track conversion: two tracks with electron-like transition radiation, consistent with coming from a massless particle
  - 1-track conversion: one track with electron-like transition radiation, with missing hits in initial live layers.
- Ambiguity resolution heuristic to chose electron/photon interpretation

Background Modeling

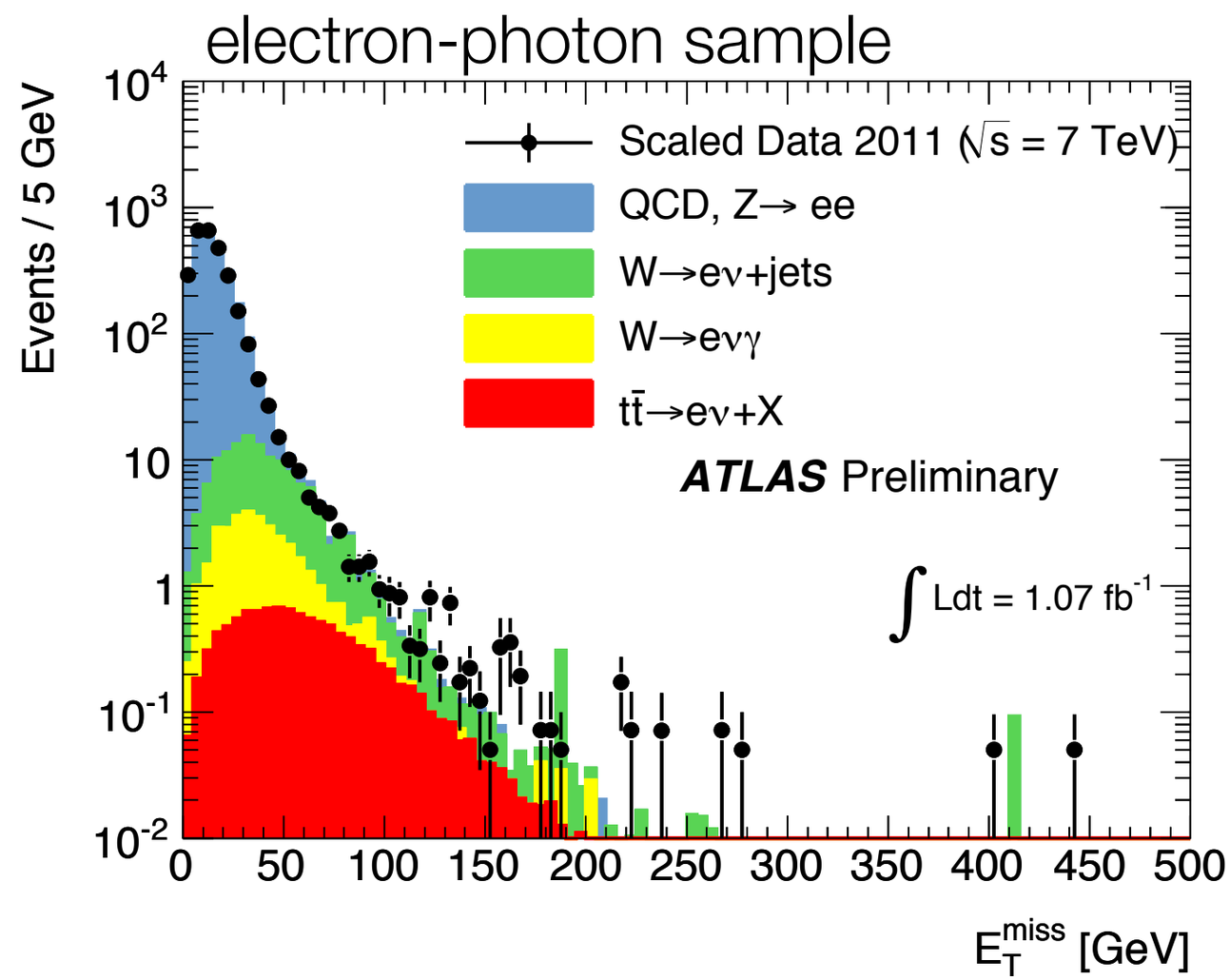
- Most background is modeled from from data
- Only model E_T^{miss} distribution
  (inspired by similar searches at D0: [doi:10.1103/PhysRevLett.105.221802])
- **Instrumental E_T^{miss} background:** di-γ, γ+jets, dijets
  - model using "QCD" and ee data samples
- **Genuine E_T^{miss} background:**
  - electron faking photon: W+γ, W+jets, ttbar
    - model using eγ data sample
  - irreducible: Z + γγ, W + γγ
    - from MC, scaled to NLO.
- **Cosmic background:** found to be negligible in signal

The QCD Control Samples

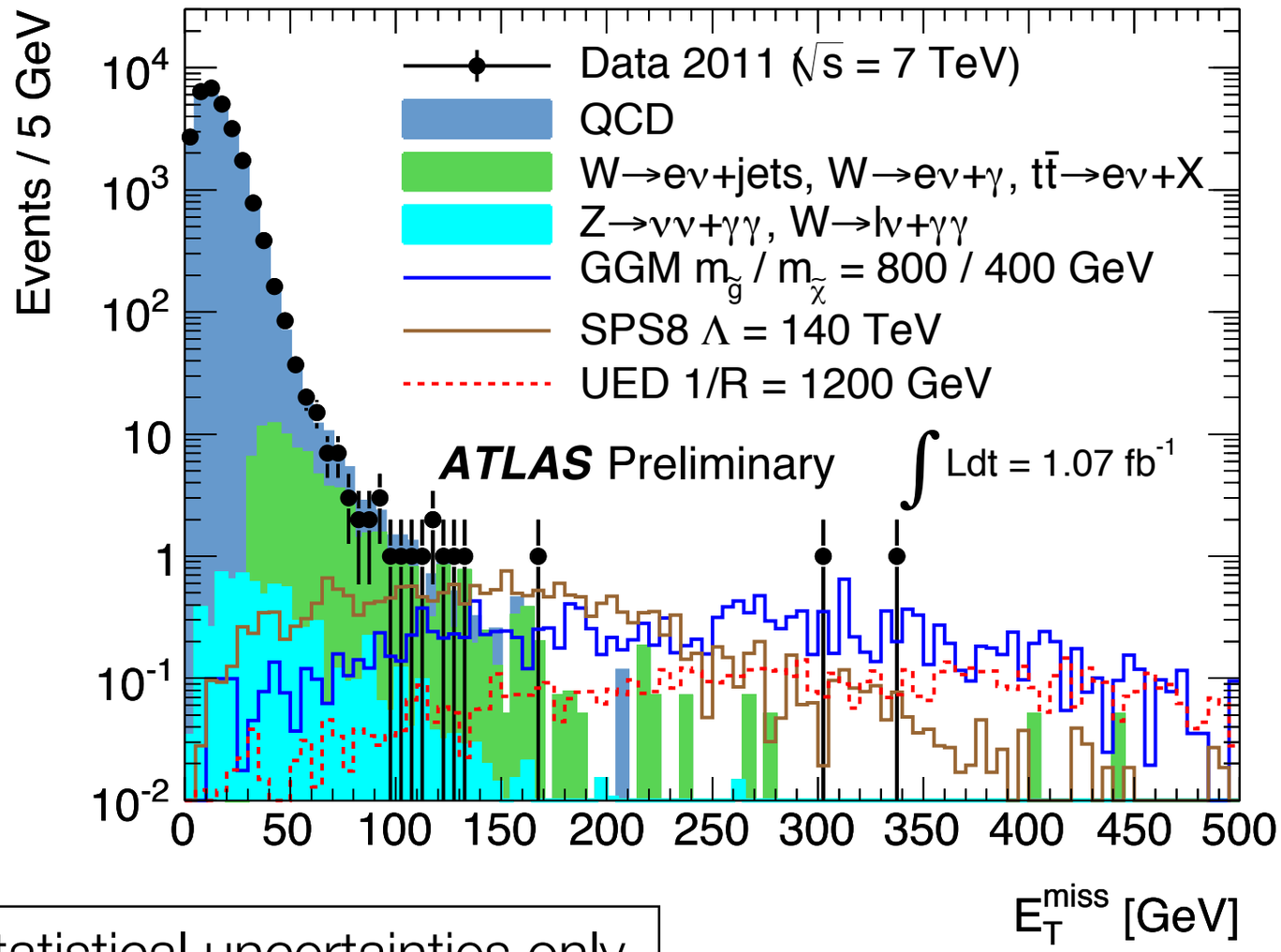
- Model SM γ-jets, dijets, and diphoton using a QCD control sample
  - Require two egamma objects with p_T > 20 GeV at trigger
  - **pseudo-photon**: passes loose but fails some tight criteria
  - sample definition: **at least one pseudo-photon**
  - Veto events with electrons that pass medium or two tight photons
  - Apply timing cut on pseudo-photons to suppress cosmics (|t| > 10 ns: veto event)
- Use Z → ee (0 jets) as alternate model in systematics studies. (It was found to model SM diphoton events well)
- Normalized in E_T^{miss} < 20 GeV range; systematic by varying 10 GeV subranges: 0-10 GeV, 1-11 GeV, ... 18-28 GeV

Real E_T^{miss} background (electron faking photon)

- Use eγ events from data.
  - Assumption: electron fakes a photon.
- Need to subtract out the Z and QCD contribution to avoid double-counting.
  - Use QCD sample normalized to eγ in E_T^{miss} < 20 GeV,
  - Z→ee as systematic
- Scale the sample by the e→γ fake rate / electron efficiency. (~6% in barrel, 17% in endcaps)
- use MC normalized to data as systematic



The Experimental Results



In Signal region (E_T^{miss} > 125 GeV)

Total predicted background:

4.1 ± 0.6(stat) ± 1.4(syst) events

Total observed:

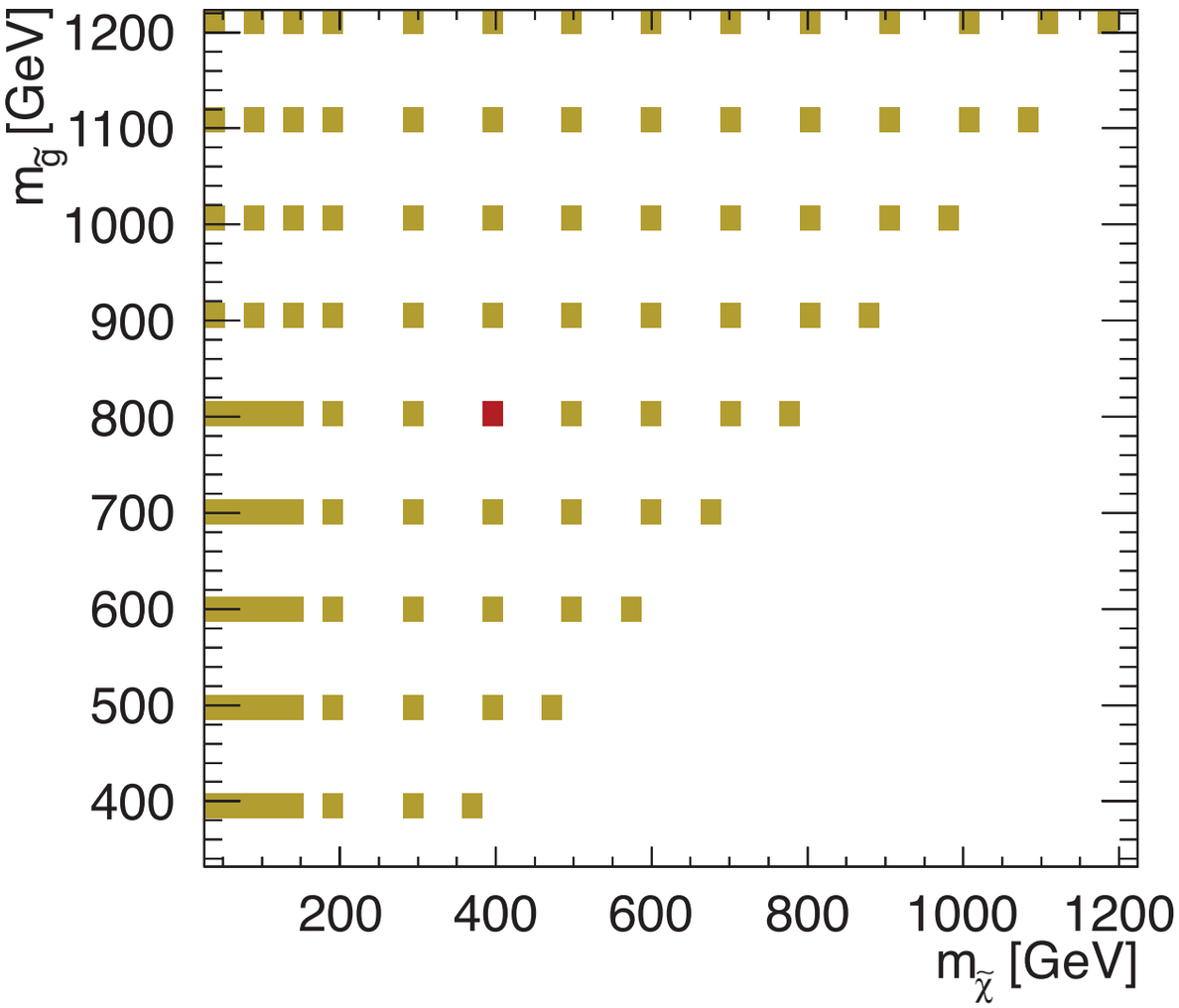
5 events

Statistical uncertainties only

E_T^{miss} range [GeV]	Data events	Predicted background events				Expected signal events		
		Total	QCD	$W/t\bar{t}(\rightarrow e\nu)+X$	Irreducible	GGM	SPS8	UED
0 - 20	20881	-	-	-	-	0.20 ± 0.05	0.22 ± 0.04	0.02 ± 0.01
20 - 50	6304	5968 ± 29	5951 ± 28	13.3 ± 8.1	3.6 ± 0.3	0.45 ± 0.08	1.5 ± 0.1	0.11 ± 0.01
50 - 75	86	87.1 ± 3.3	60.9 ± 2.8	25.2 ± 1.7	1.0 ± 0.2	0.48 ± 0.08	2.2 ± 0.1	0.14 ± 0.01
75 - 100	11	14.7 ± 1.2	6.7 ± 0.9	7.4 ± 0.8	0.52 ± 0.10	0.8 ± 0.1	2.1 ± 0.1	0.15 ± 0.01
100 - 125	6	4.9 ± 0.7	1.6 ± 0.4	3.0 ± 0.5	0.32 ± 0.08	1.2 ± 0.1	2.5 ± 0.1	0.29 ± 0.02
> 125	5	4.1 ± 0.6	0.8 ± 0.3	3.1 ± 0.5	0.23 ± 0.05	17.2 ± 0.5	13.0 ± 0.3	9.67 ± 0.11

GGM Signal Samples

- Created a 2D grid in gluino and Bino mass for GGM
- Turn off squark production for more independence to its mass
- M_2 = 1.5 TeV, μ = 1.5 TeV, tan β = 2
- $c\tau_{NLSP}$ = 0.1 mm (allowed to increase somewhat in low Bino mass extension, but < 1 mm)
- All soft parameters are set to 1.5 TeV
- Go down to a bino mass of 50 GeV.
- Use SUSPECT, SDECAY, and PYTHIA for event generation
- Use Prospino 2.1 for cross section calculation.



SPS8 and UED Grid Points

- SPS8: minimal GMSB (MGM) with
  - N_{mes} =1, tanβ=15, μ>0, M_{mes}/Λ = 2
  - Λ varies in steps of 10 TeV in the range 50 - 250 TeV
  - Use ISAJET for mass spectrum and decay table, then Herwig++ for generation.
  - Cross sections calculated with Prospino. K-factors are 1.1 – 1.5
- UED Simulated at various 1/R values
  - ΛR = 20, N = 6, M_D = 5 TeV
  - Because only have LO calculations, do not include PDF and scale uncertainties

Signal $1/R$ [GeV]	Cross section [pb]	$\gamma\gamma$ B.R.
1000	0.133	100%
1100	0.0521	95%
1200	0.0205	90%
1250	0.0129	83%
1300	0.00803	75%
1350	0.00498	67%
1400	0.00312	60%
1500	0.00120	50%

Systematics

- PDF errors are estimated by weighting 44 error PDFs from CTEQ6.6m and using the Hessian method
- Scale: factorization and renormalization scale ×2, ×1/2
- Photon ID/Iso: systematics related to data/MC differences and correction.
  - Also includes extra material
- E_T^{miss}: due to topocluster energy scale and resolution uncertainties.
- Pileup uncertainty by varying MC pileup configuration

Source of uncertainty	Uncertainty		
	GGM	SPS8	UED
Integrated luminosity	3.7%	3.7%	3.7%
Trigger	0.6%	0.6%	0.6%
Photon identification	3.9%	3.9%	3.7%
Photon isolation	0.6%	0.6%	0.5%
Pileup	1.3%	1.3%	1.6%
E_T^{miss} reconstruction and scale	1.7%	5.6%	0.7%
LAr readout	1.0%	0.7%	0.4%
Signal MC statistics	2.9%	2.3%	1.8%
Total signal uncertainty	6.6%	8.3%	6.0%
PDF and scale	31%	5.5%	–
Total	32%	10%	6.0%

Representative points:

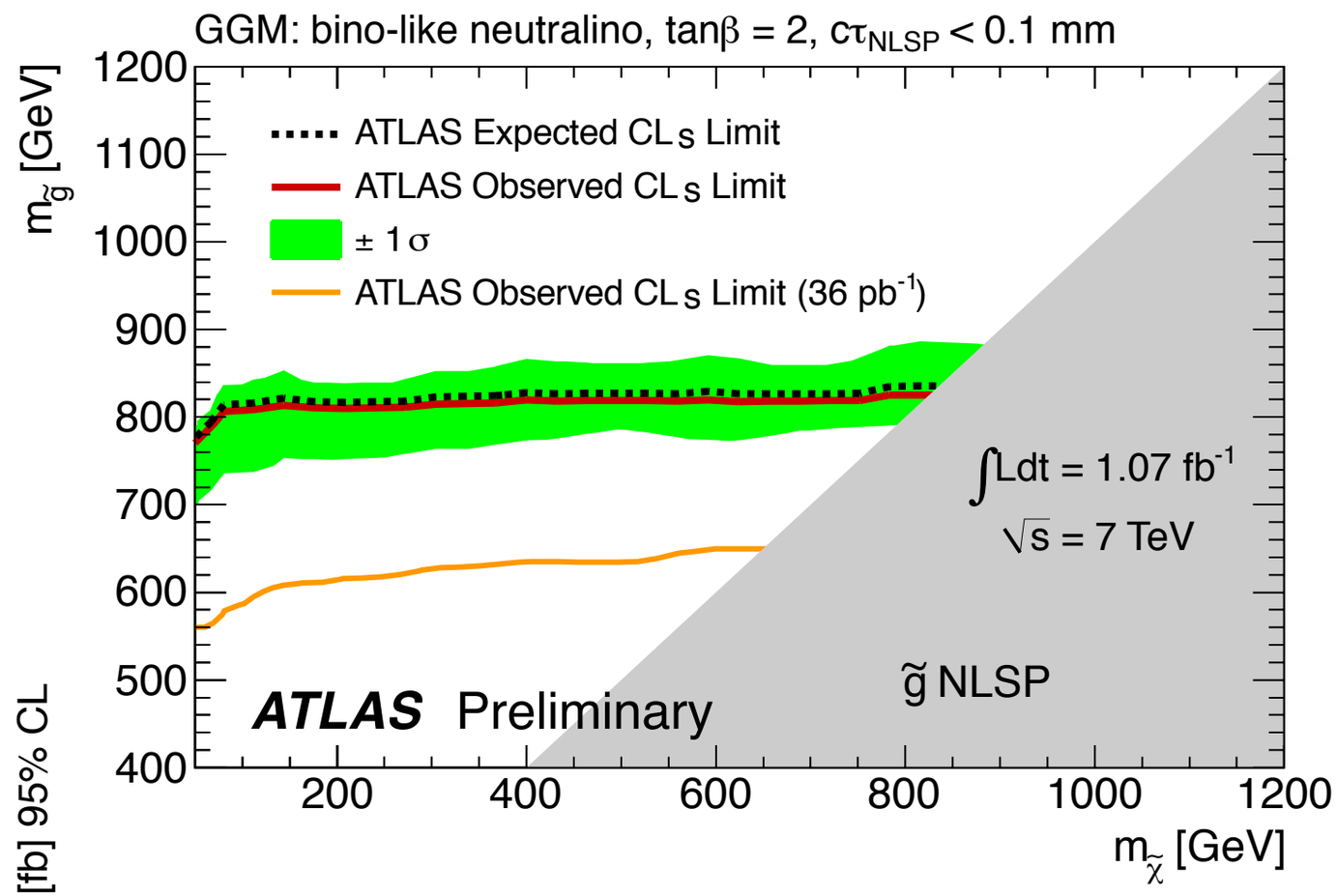
GGM with $m_{gluino}/m_{neutralino}$ = 800/400 GeV

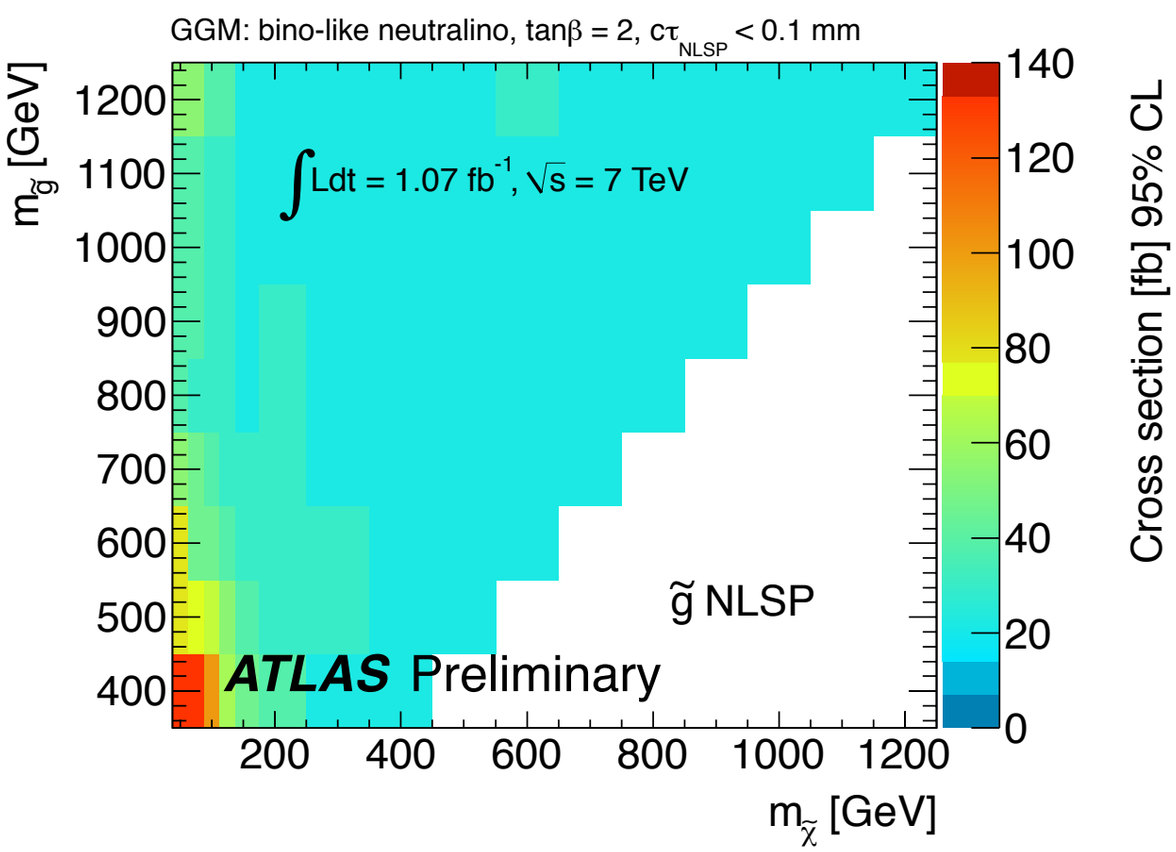
SPS8 with Λ = 140 TeV

UED with 1/R = 1200 GeV

GGM Results

- CL_s is used
- $\sigma < 25 - 44$ fb for GGM with
  - $m_{bino} = 150$ GeV
  - $m_{gluino} = 400$ GeV – 1200 GeV



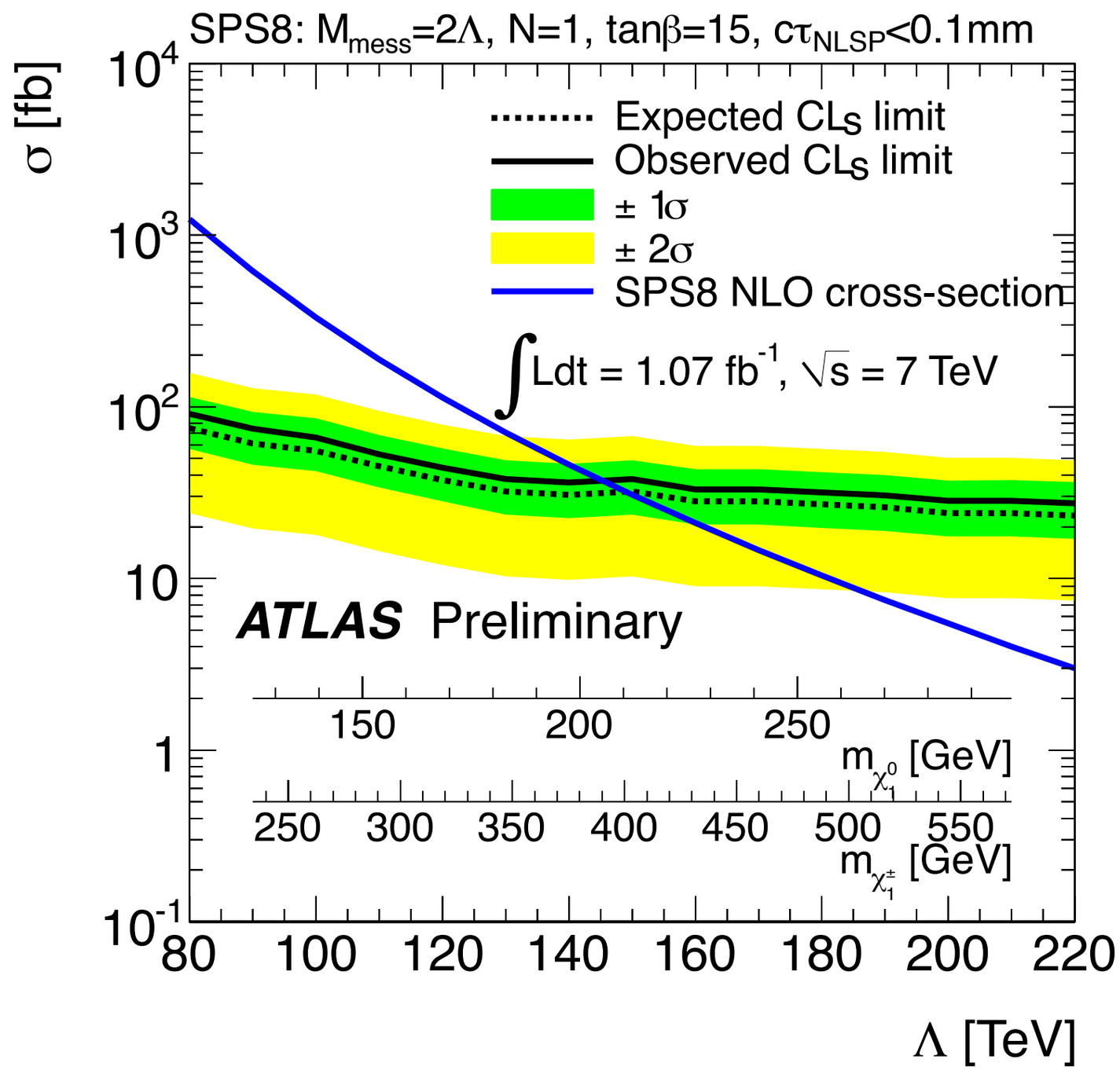


$M_{gluino} > 776$ GeV

for $M_{bino} > 50$ GeV

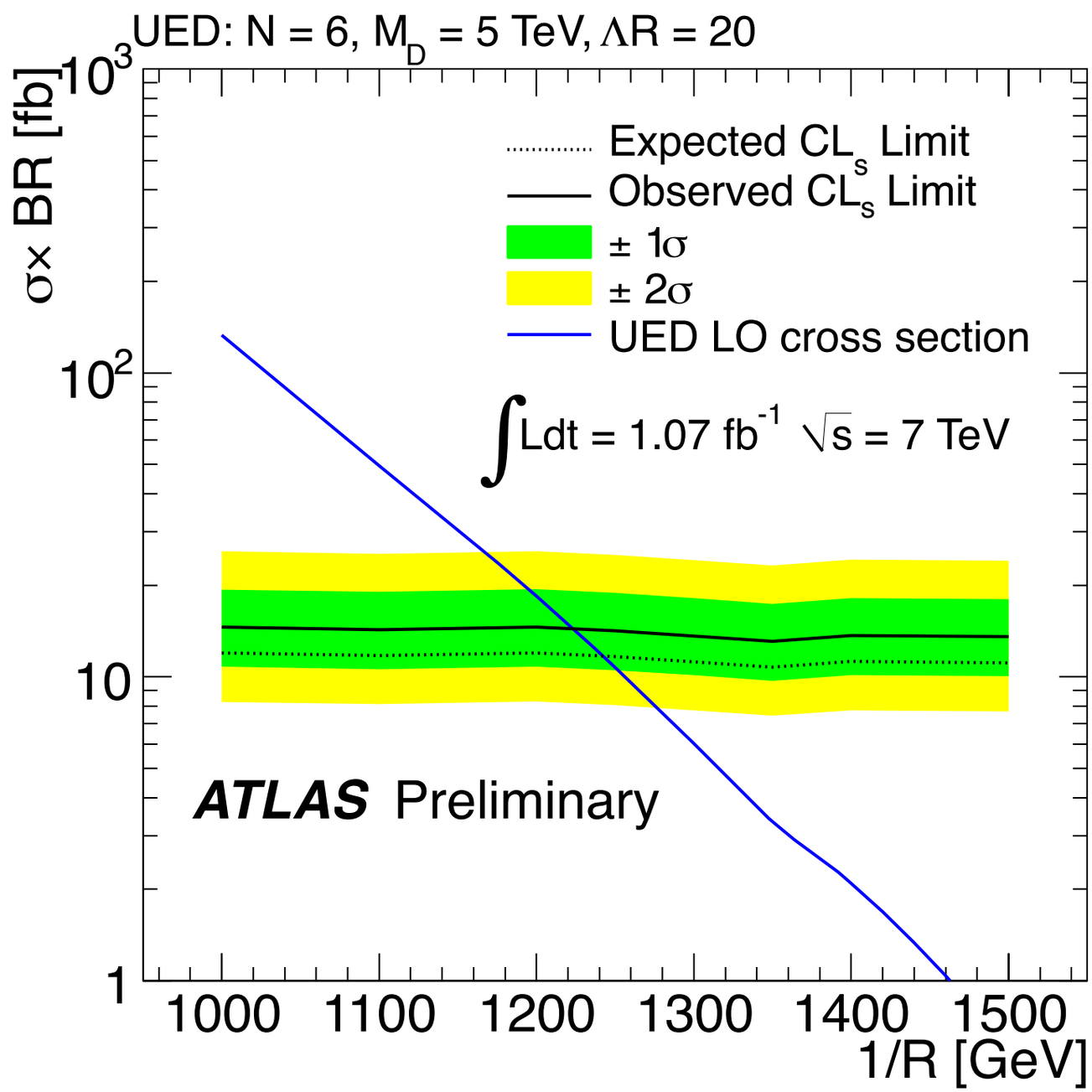
SPS8 Benchmark Result

- Using CLs
- **Λ > 145 TeV** at 95% CL (Λ > 150 TeV expected)
- D0 has set a limit of Λ > 124 TeV (arXiv:1008.2133v1)
- σ < 27 – 91 fb
- Best current limit.



UED Result and Statistical Interpretation

- CL_s is used
- Model specific limit:
  1/R > 1226 GeV at 95% CL
  (1/R > 1243 GeV expected)
- Cross section limit:
  $\sigma < 15 - 27$ fb
- Previous ATLAS limit:
  1/R < 961 GeV
  [arXiv:1107.0561v2 [hep-ex]]



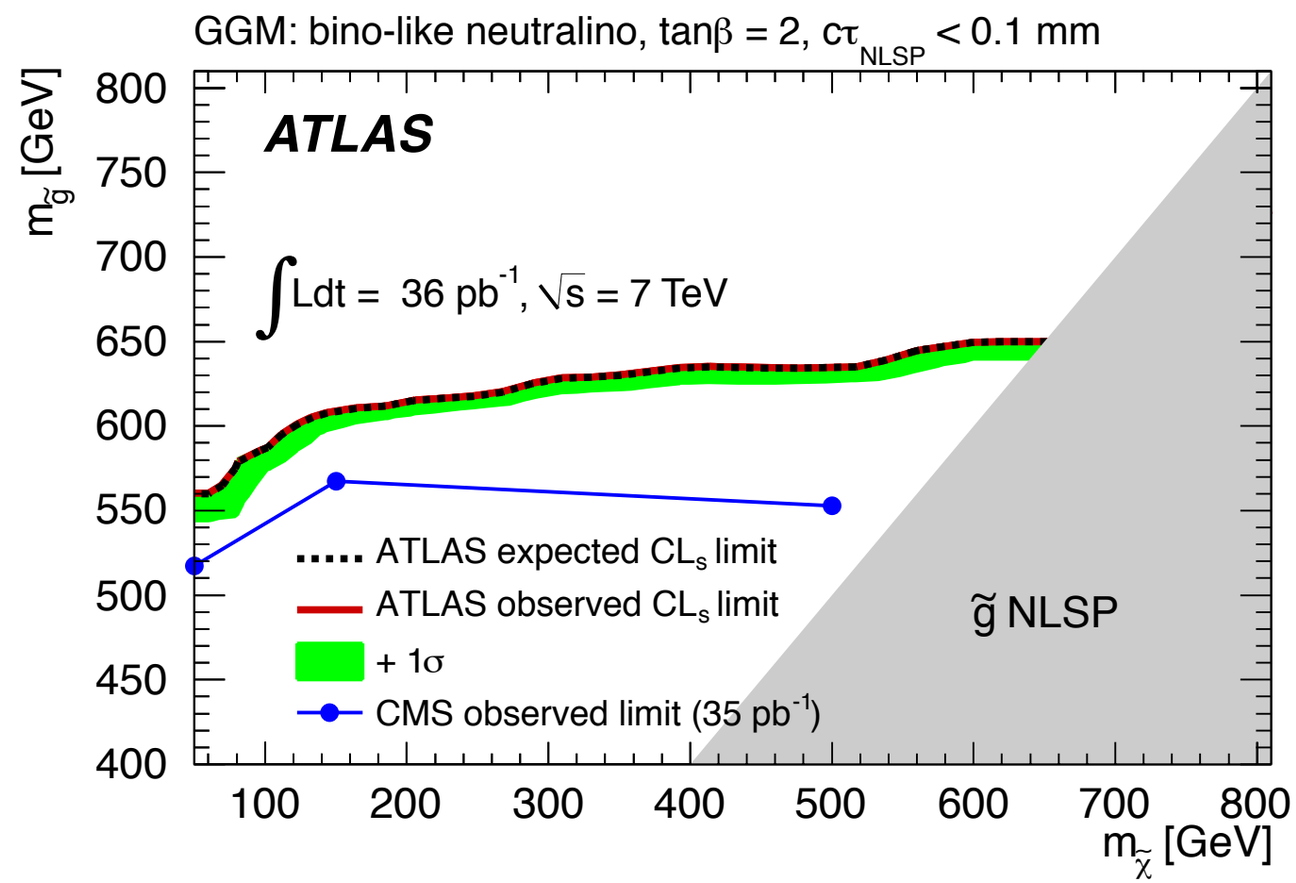
Conclusion

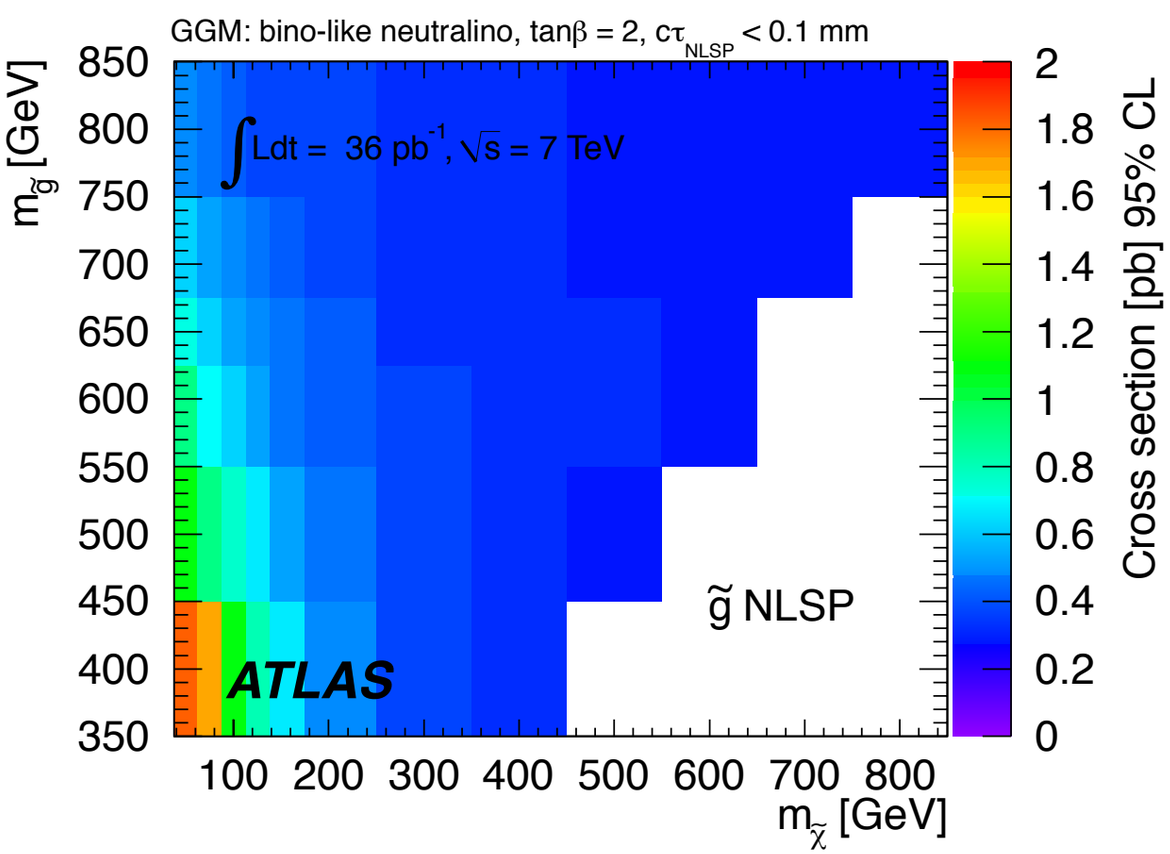
- This is a search for GGM and UED events in the $\gamma\gamma + E_T^{miss}$ channel in 1.07 fb^{-1} of data from 2011 at the LHC using the ATLAS detector.
- Background is estimated mainly from data:
  $4.1 \pm 0.6(stat) \pm 1.6(sys)$ for $E_T^{miss} > 125$ GeV
- Number of observed events: 5:
- Results are interpreted for bino-like GGM, SPS8, and UED models:
  - GGM: $M_{gluino} > 776$ GeV for $M_{bino} > 50$ GeV
  - SPS8: $\Lambda > 145$ TeV
  - UED1/R > 1226 GeV

Backup

GGM Results with 2010 Data

- CL_s is used: model-independent 95% CL upper limit of 3.0 events
- CMS results from: https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsSUS10002/table_mass_limits.txt





M_{gluino} > 560 GeV

for M_{bino} > 50 GeV

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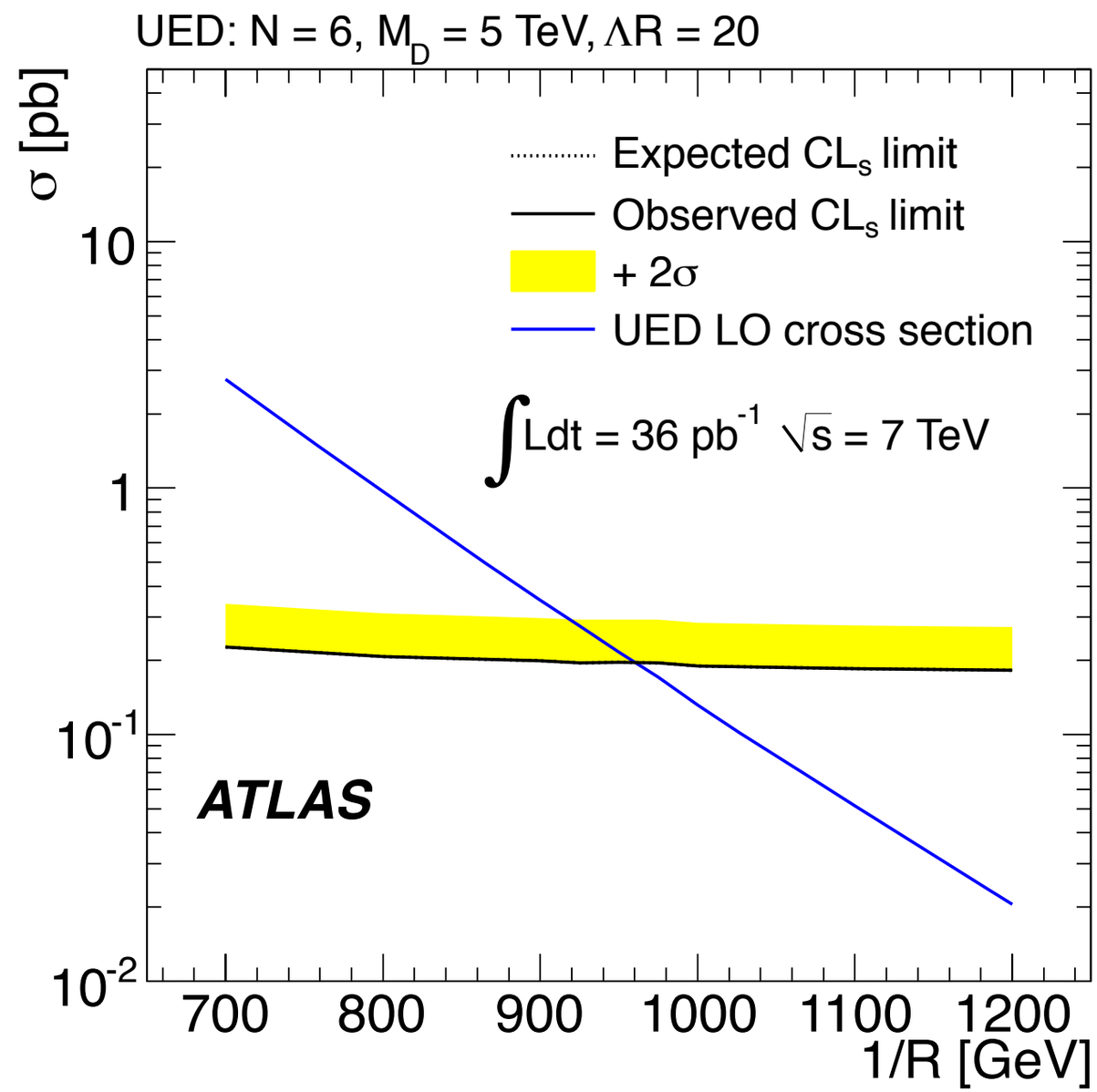
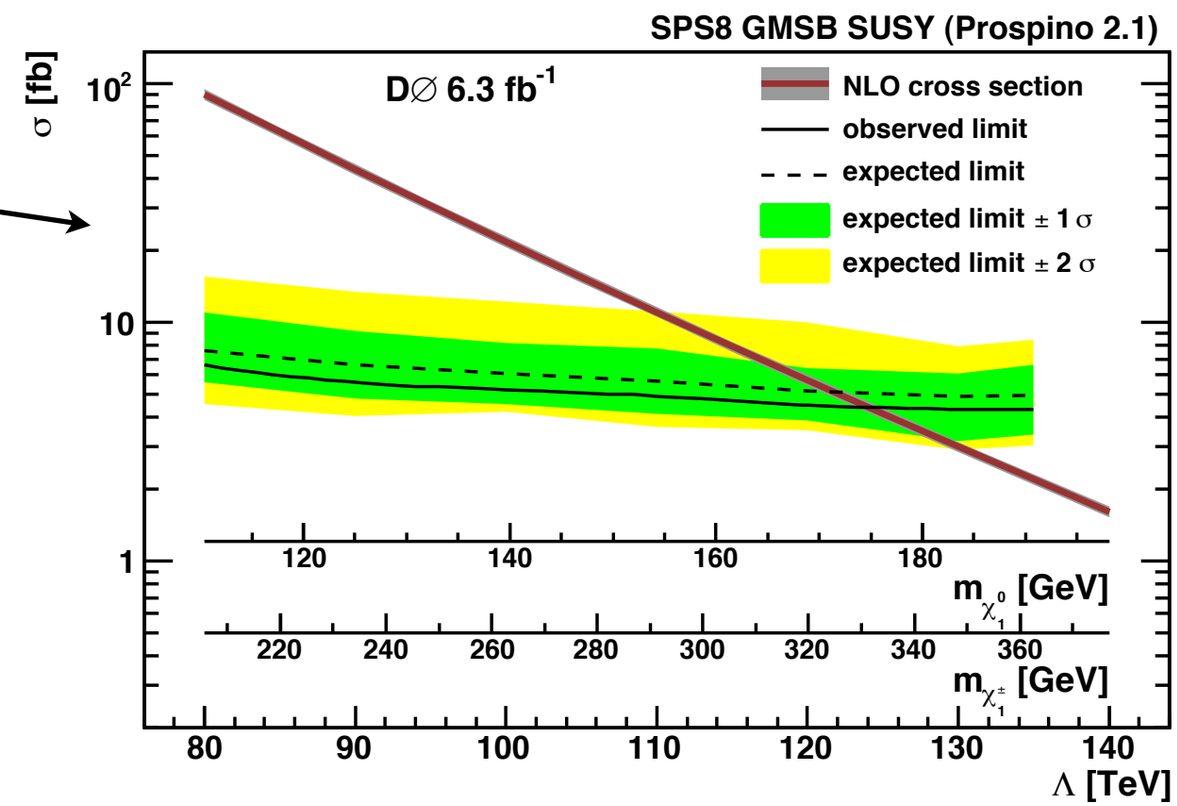
UED Result and Statistical Interpretation: 2010 Data

- CL_s is used: model-independent 95% CL upper limit of 3.0 events
- Model specific limit: **1/R > 961 GeV**
- Cross section limit: $\sigma < 0.18 - 0.23$ pb



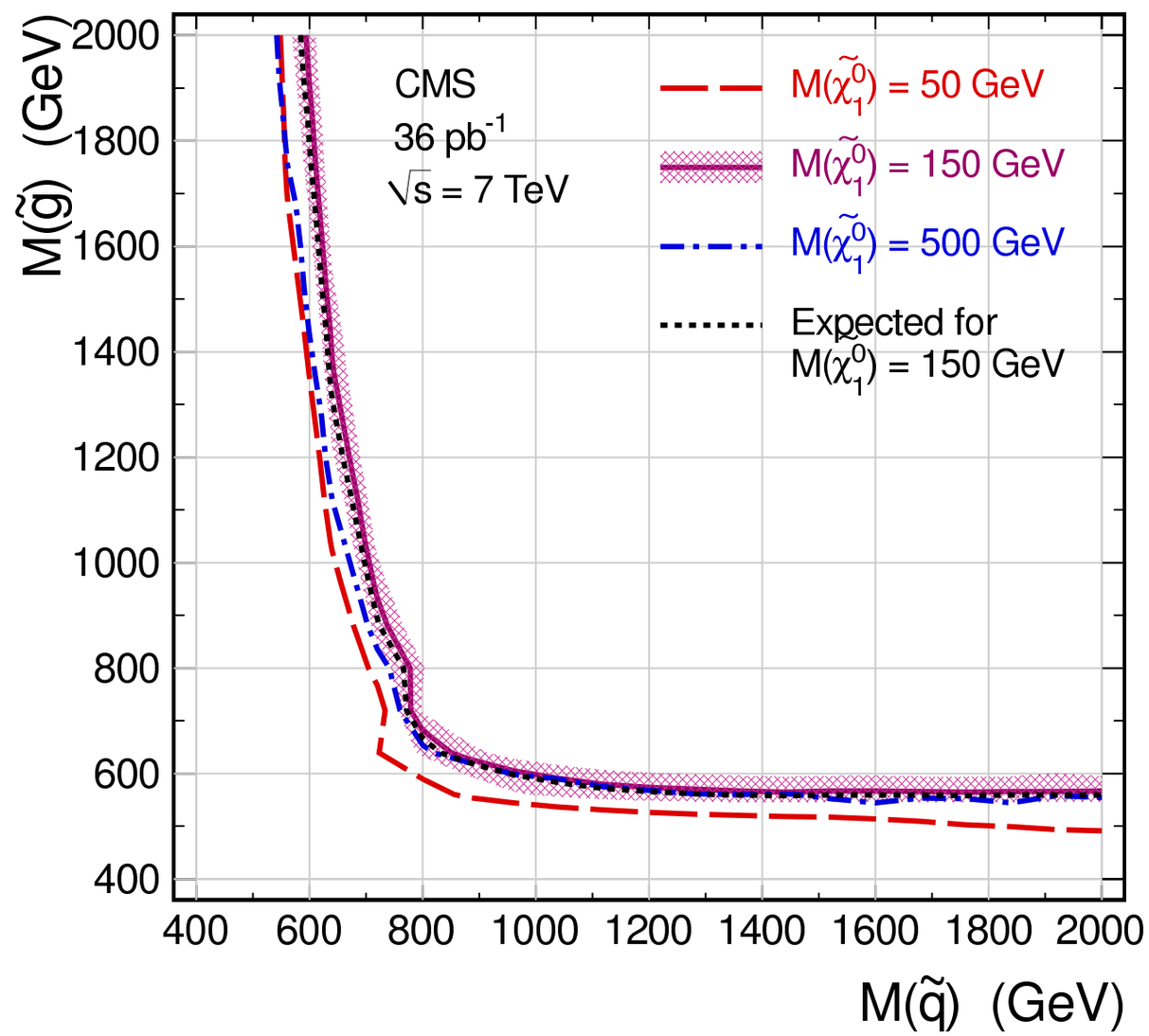
Latest D0 Result (arXiv:1008.2133v1)

- In MGM, D0 set a limit of $m_\chi > 175$ GeV in SPS8 framework.
- Current ATLAS analysis, if interpreted in the SPS8 trajectory, would produce a limit of $m_\chi > 124$ GeV
- 210 pb^{-1} would be needed to match the D0 sensitivity



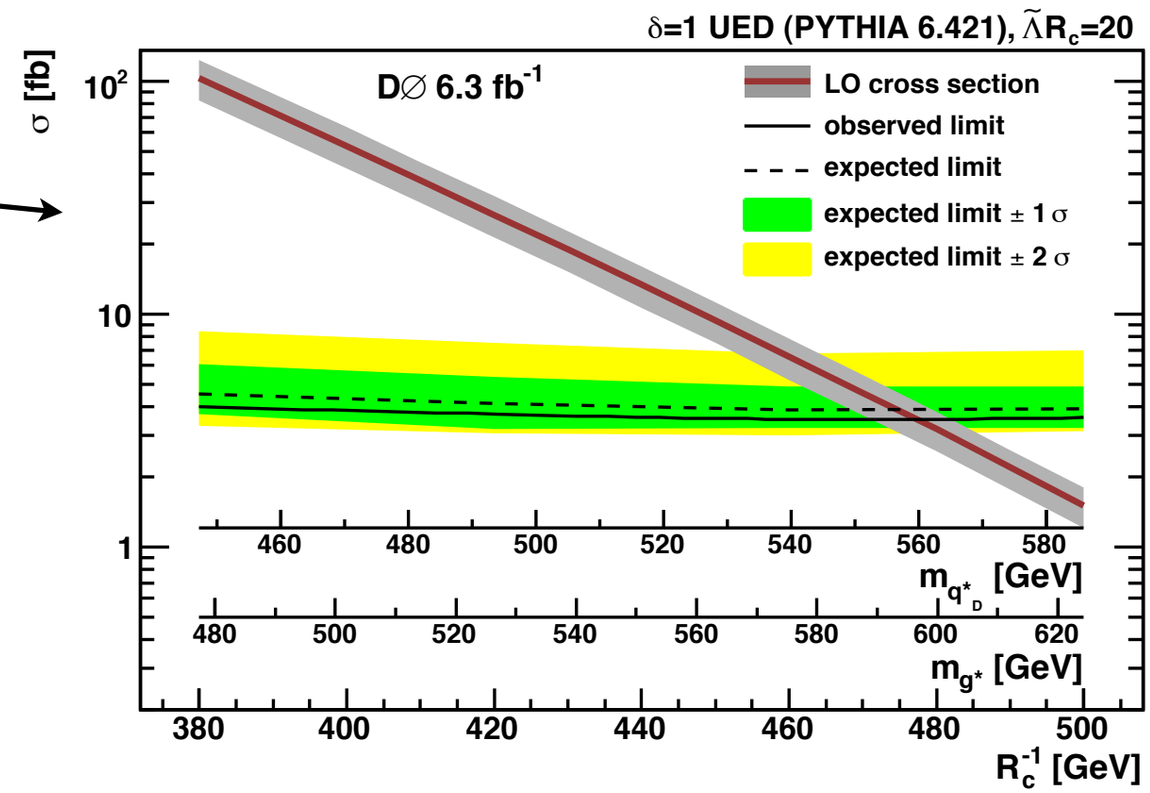
CMS Result: arXiv:1103.0953v1 [hep-ex]

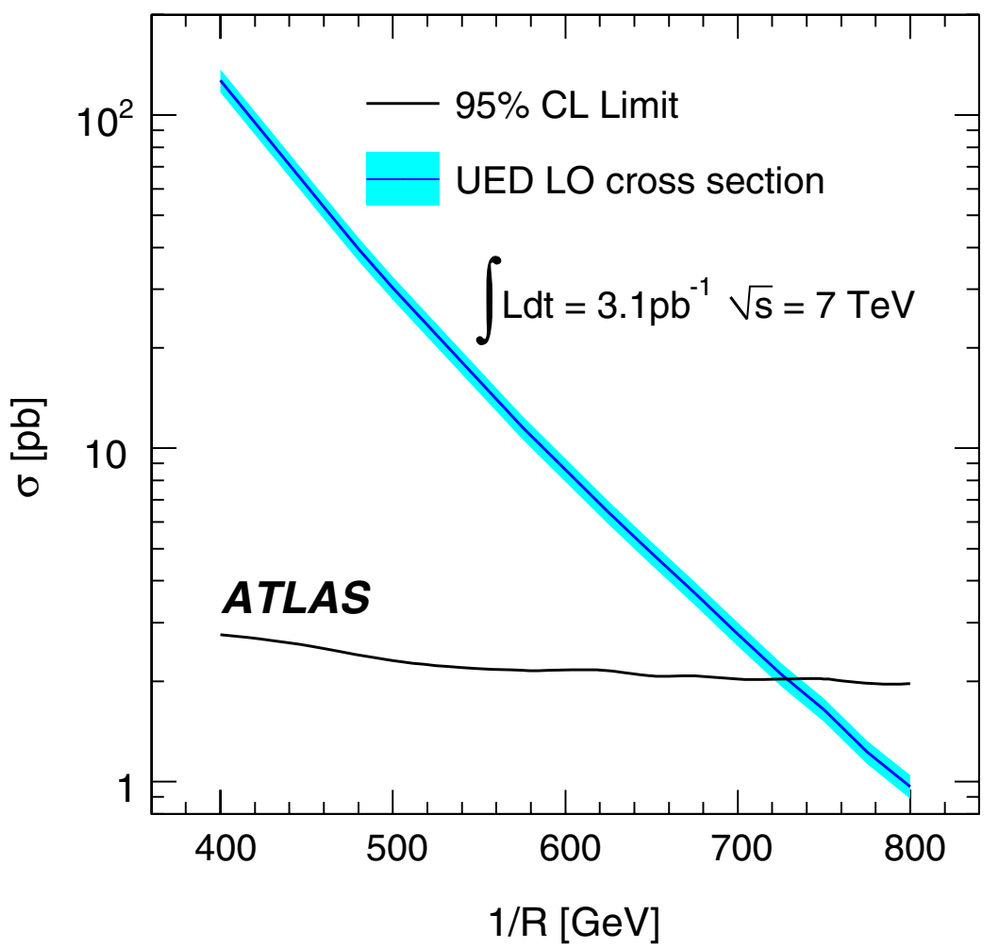
- No excess of events with $E_T^{miss} > 50$ GeV
- cross section limit between 0.3 and 1.1 pb at the 95% CL across.
- Extracted a contour while varying the gluino and squark masses



Older UED Results

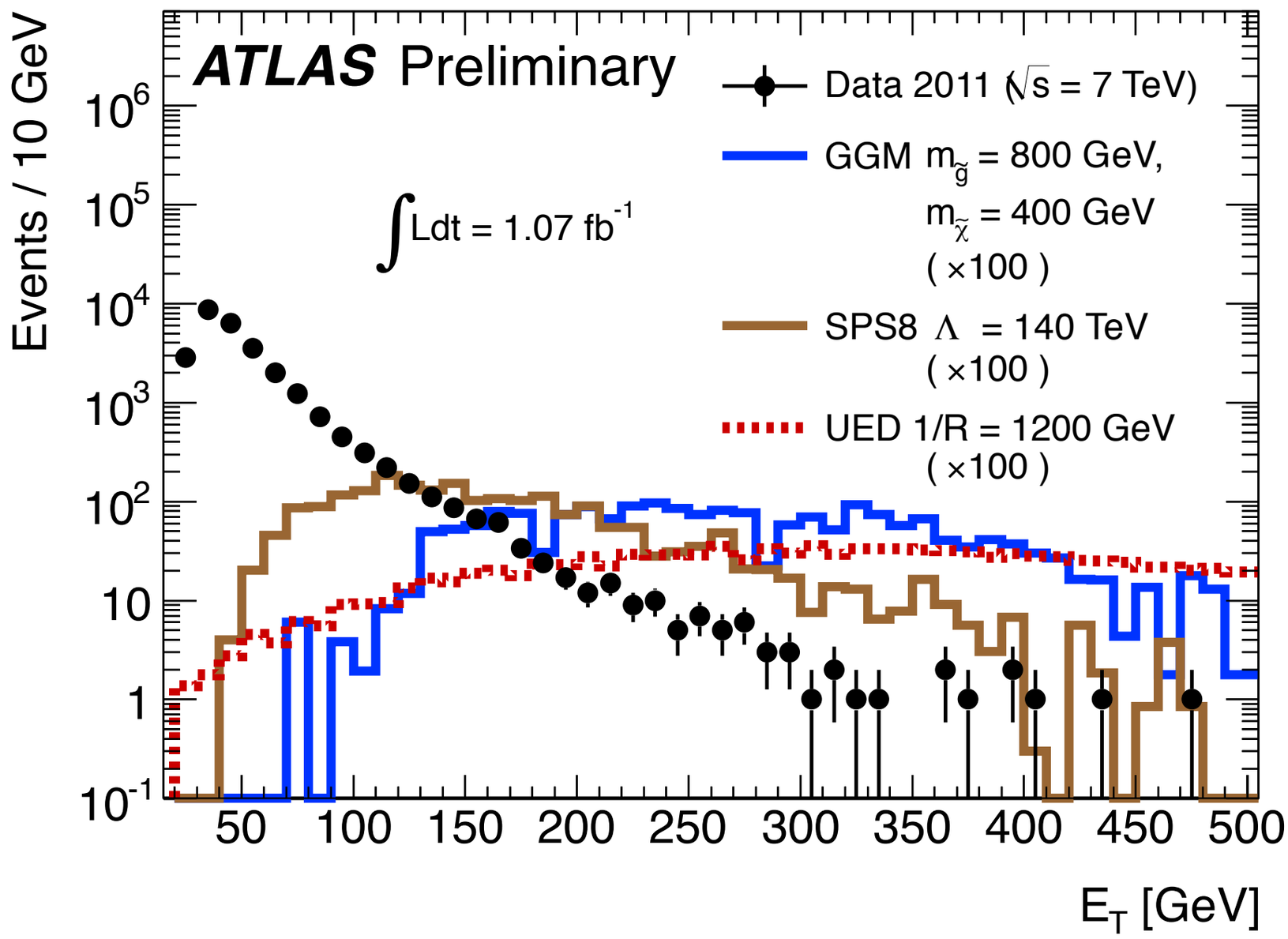
- For UED, D0 set a limit of $R^{-1} < 477$ GeV





- ATLAS set a limit of $R^{-1} < 729$ GeV

GSMB and UED Photon p_T distributions



isEM discriminating variables for photons

Category	Description	DV	Loose	Tight
Acceptance	$\|\eta\| < 2.37$, $1.37 < \|\eta\| < 1.52$ excluded	–		✓
Hadronic leakage	Ratio of E_T in the first sampling of the hadronic calorimeter to E_T of the EM cluster (used over the ranges $\|\eta\| < 0.8$ and $\|\eta\| > 1.37$)	R_{had_1}	✓	✓
	Ratio of E_T in all the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \|\eta\| < 1.37$)	R_{had}	✓	✓
EM Middle layer	Ratio between the sum $E^{S2}_{3\times7}$ of the energies of the cells contained in a 3×7 $\eta \times \phi$ rectangle (measured in cell units), and the sum $E^{S2}_{7\times7}$ of the cell energies in a 7×7 rectangle, both centered around the cluster seed	R_η	✓	✓
	Lateral width of the shower in the η direction	w_{η_2}	✓	✓
	Ratio between the sum $E^{S2}_{3\times3}$ of the energies of the cells contained in a 3×3 $\eta \times \phi$ rectangle (measured in cell units), and the sum $E^{S2}_{3\times7}$ of the cell energies in a 3×7 rectangle, both centered around the cluster seed	R_ϕ		✓
EM Strip layer	Lateral shower width for three strips around maximum strip	$w_{s\,3}$		✓
	Total lateral shower width	$w_{s\,\mathrm{tot}}$		✓
	Fraction of energy outside core of three central strips but within seven strips	F_{side}		✓
	Difference between the energy of the strip with the second largest energy deposit and the energy of the strip with the smallest energy deposit between the two leading strips	ΔE		✓
	Ratio of the energy difference associated with the largest and second largest energy deposits over the sum of these energies	E_{ratio}		✓

Jet Cleaning

	Loose	Medium = Loose OR	***under discussion*** Tight = Medium OR
HEC spikes	HECf>0.5 && |HECQ|>0.5 or |neg. E|>60GeV	HECf>1-|HECQ|	
EM coherent noise	EMf>0.95 &&|LArQ|>0.8 && |eta|<2.8	EMf>0.9 && |LArQ|>0.8 && |eta|<2.8	|LArQ|>0.95 or EMf>0.98 && |LArQ|>0.05
Non-collision background & Cosmics	|t|>25ns or EMf<0.05 && Chf<0.05 && |eta|<2 or EMf<0.05 && |eta|>=2 or FMax>0.99 && |eta|<2	|t|>10ns or EMf<0.05 && Chf<0.1 && |eta|<2 or EMf>0.95 && Chf<0.05 && |eta|<2	EMf<0.1 && Chf<0.2 && |eta|<2 or EMf<0.1 && |eta|>=2 or EMf>0.9 && Chf<0.02 && |eta|<2

The e→γ Fake Rate

- Use tag and probe based on Z events:
  - tag: Medium electron, etcone20_corrected < 5 GeV, and fired g20_loose
  - probe: egamma object that has fired g20_loose
- Let e = efficiency for true electron to satisfy electron criteria
- Let f = efficiency for true electron to satisfy photon criteria
- The scale factor (s) that the eg sample needs to be scaled is then:

$$s = \frac{f}{e} = \frac{N_{\text{pass photon}}/N_{\text{probe}}}{N_{\text{pass electron}}/N_{\text{probe}}} = \frac{N_{\text{pass photon}}}{N_{\text{pass electron}}}$$

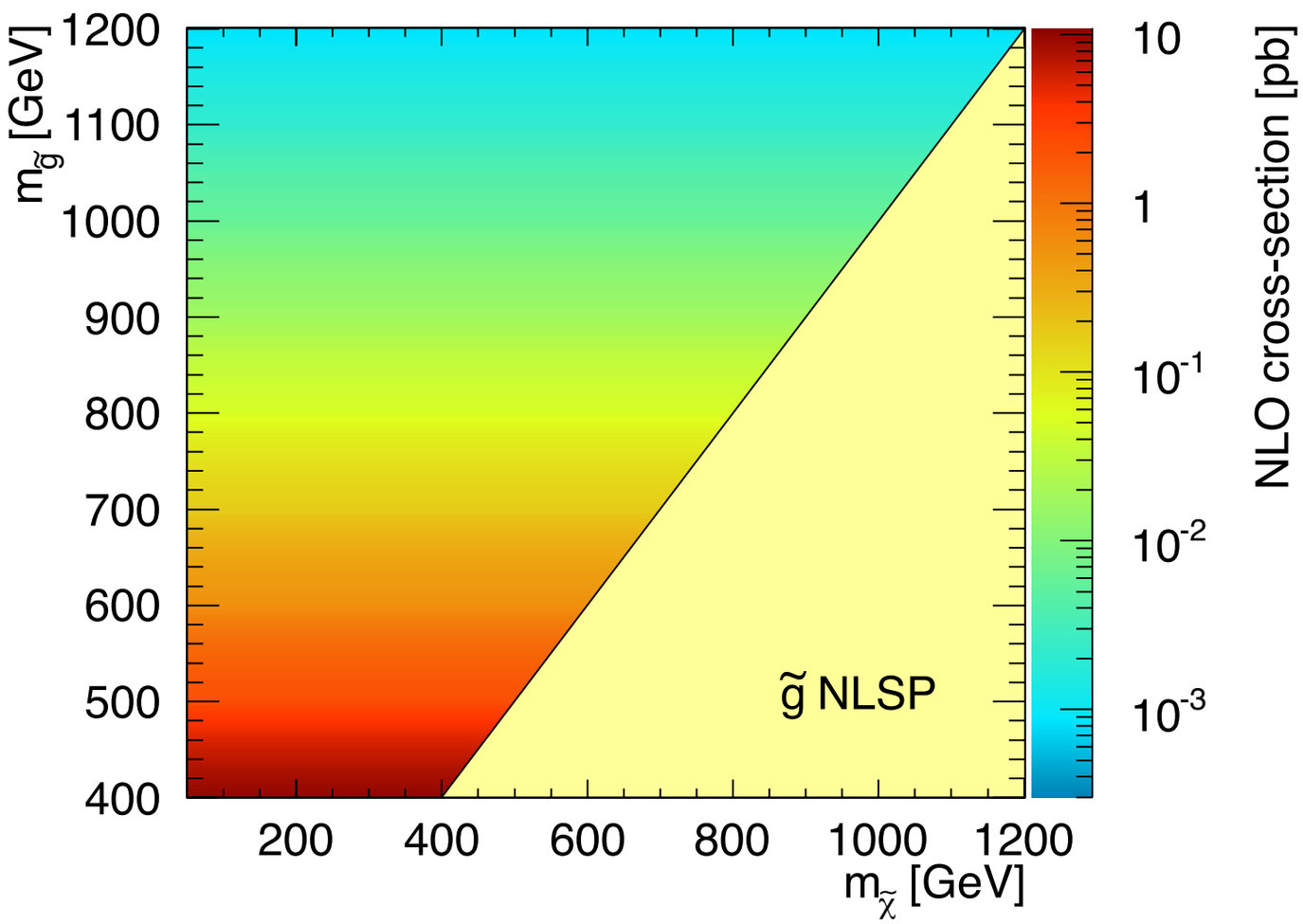
- Background subtraction can be done on the numerator and denominator. Use a Voigt function + exponential.

Cosmic Background Estimate for 2010 analysis

- Estimated using real cosmic events triggered in empty bunches.
- Look for photons passing same p_T and η cuts, but no vertex or jet cleaning requirements
  - 7395 events with one loose photon, 63 with one tight
  - 2 events with two loose photons, 0 with two tight
    - Both two-loose photon events mass $E_T^{miss} > 125$ GeV
    - Estimate 0.017 ± 0.012 (statistical errors only) for two tight
- Scaling the results to the number of colliding bunches in our sample, and assuming all of the cosmics events would pass the E_T^{miss} cut:
  - 0.079 ± 0.056 two-loose, 0.00068 ± 0.00049 two-tight events
  - Therefore apply tight timing to QCD_γ, negligible for signal

GMSB Cross Sections

GGM



SPS8

Λ[TeV	σ(LO)[pb]	σ(NLO)[pb]	K factor
50	12.2	18.0	1.482
60	4.38	6.49	1.482
70	1.83	2.69	1.468
80	0.855	1.24	1.446
90	0.436	0.617	1.415
100	0.240	0.331	1.379
110	0.141	0.189	1.341
120	0.0867	0.113	1.302
130	0.0557	0.0707	1.271
140	0.0370	0.0459	1.241
150	0.0252	0.0306	1.215
160	0.0176	0.0210	1.190
170	0.0125	0.0146	1.172
180	8.99×10^{-3}	0.0104	1.158
190	6.57×10^{-3}	7.49×10^{-3}	1.141
200	4.83×10^{-3}	5.47×10^{-3}	1.131
210	3.58×10^{-3}	4.02×10^{-3}	1.123
220	2.68×10^{-3}	2.99×10^{-3}	1.114
230	2.02×10^{-3}	2.23×10^{-3}	1.107
240	1.53×10^{-3}	1.68×10^{-3}	1.100
250	1.16×10^{-3}	1.27×10^{-3}	1.096

Acceptance Systematics due to E_T^{miss}: 2010 analysis

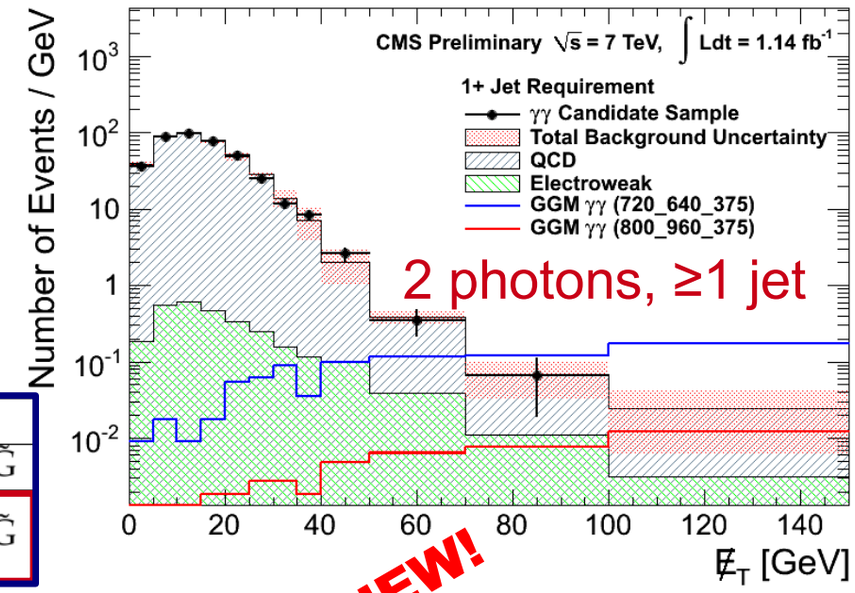
- Reminder: we use a E_T^{miss} based on the topocluster energies, corrected for muon terms.
- Method to determine systematics inspired from W/Z cross section and previous UED analyses.
  - Topocluster Energy Scale: scale topocluster energy by uncertainty
  - Smear E^{miss}_x and E^{miss}_y for uncertainty due to resolution
  - Underlying event uncertainty within statistical error of MC sample
  - Muon term uncertainty found to be negligible.
- Total uncertainty: 10.9% to 0.8% (GGM) and 2.1% to 0.9% (UED)

4. SUSY: diphoton + jet + Missing E_T

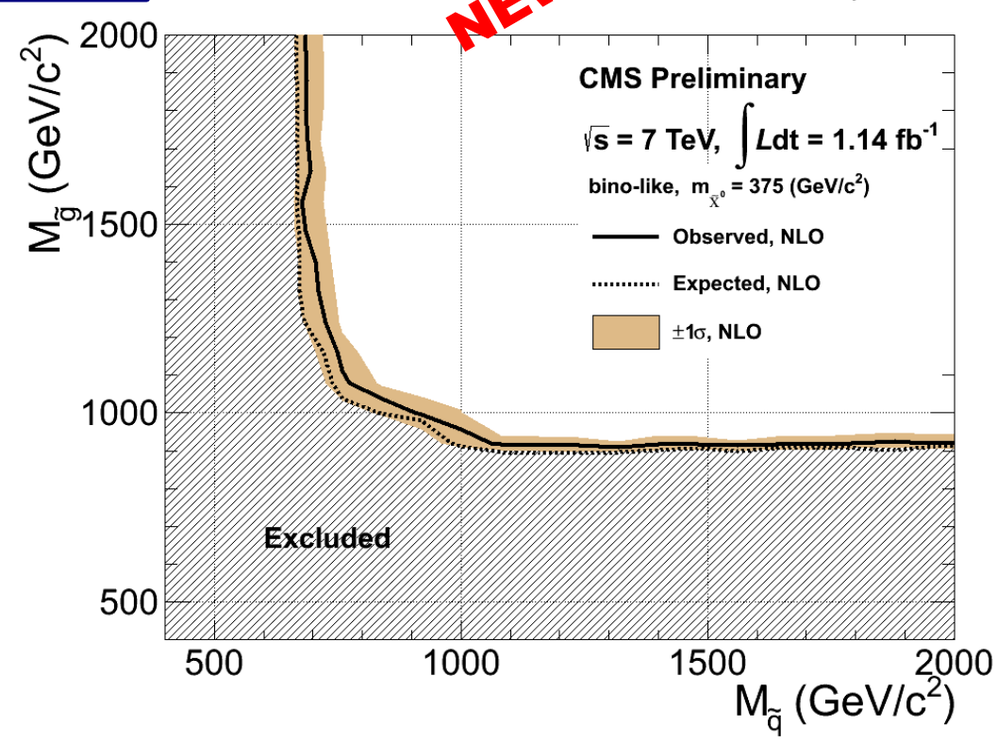
- Gauge-Mediated SUSY Breaking:
  - → LSP = Gravitino
  - → NLSP = Neutralino (and Chargino)
  - → NLSP → LSP + Photon or W or Z

NLSP type	$\gamma + 3\,\text{jets} + E_T^{miss}$	$\gamma\gamma + \text{jet} + E_T^{miss}$
Bino	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma + Z + \tilde{G}\tilde{G}$	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma\gamma + \tilde{G}\tilde{G}$
Wino	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma + Z + GG$ $\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^{\pm} \to \text{jets} + \gamma + W^{\pm} + \tilde{G}\tilde{G}$	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \gamma\gamma + \tilde{G}\tilde{G}$

$m(\chi_1^0) \approx m(\chi_1^{\pm})$
co- NLSP's



NEW!



- Consider both final states:
  - → Diphoton
  - → Single photon (next slide)

4. SUSY: photon + jets + Missing E_T

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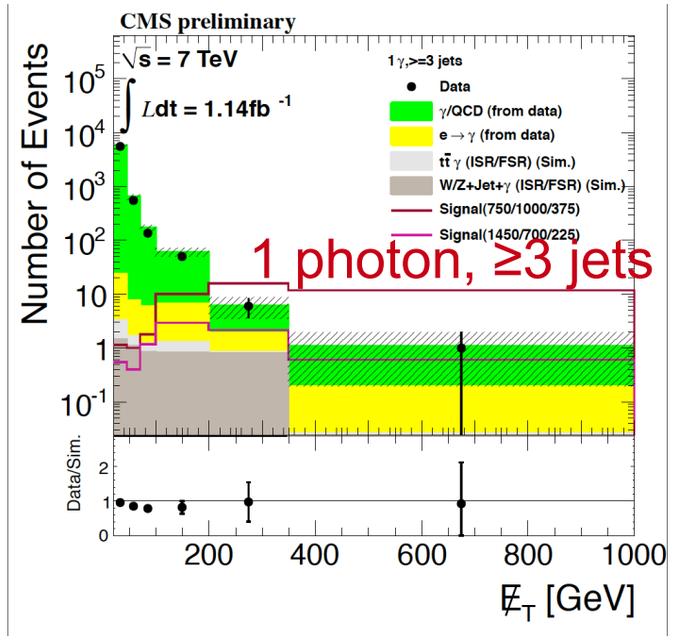
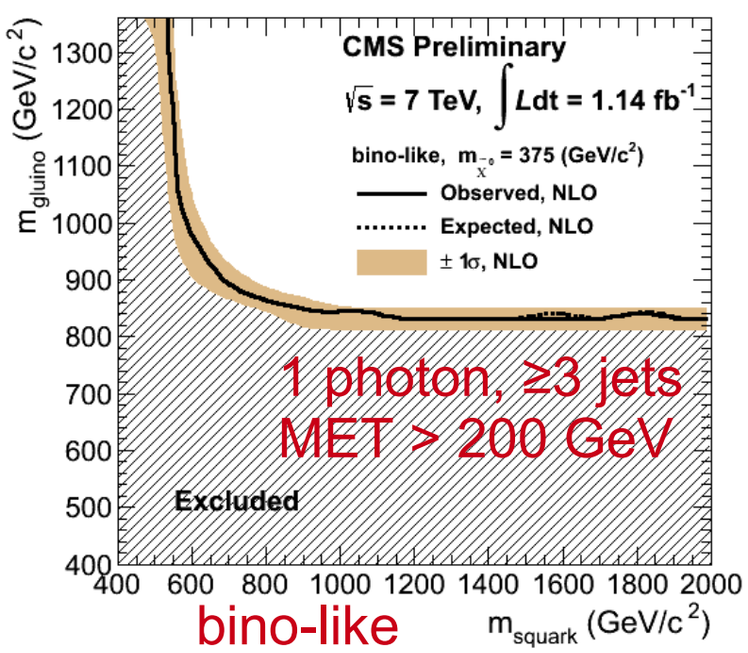
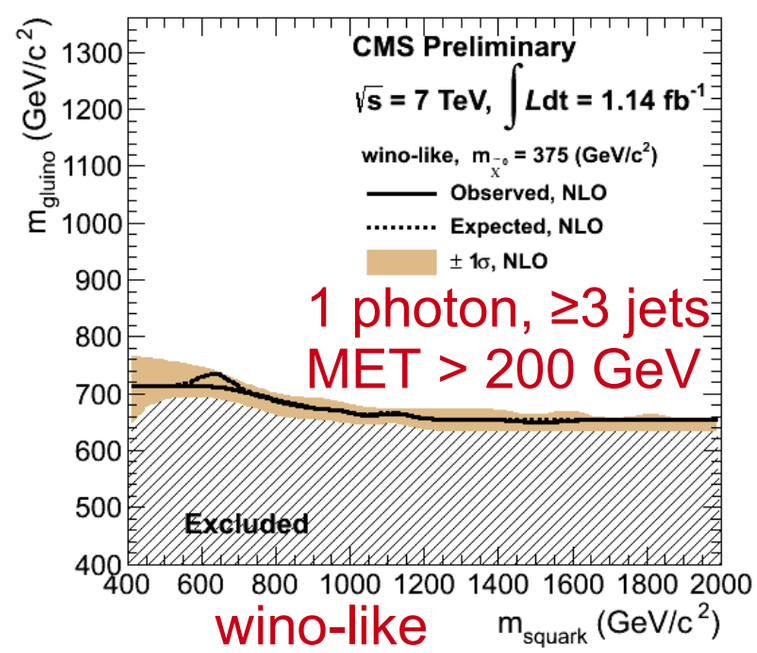


1γ, >=3 jets, MET> 200 GeV

NEW!

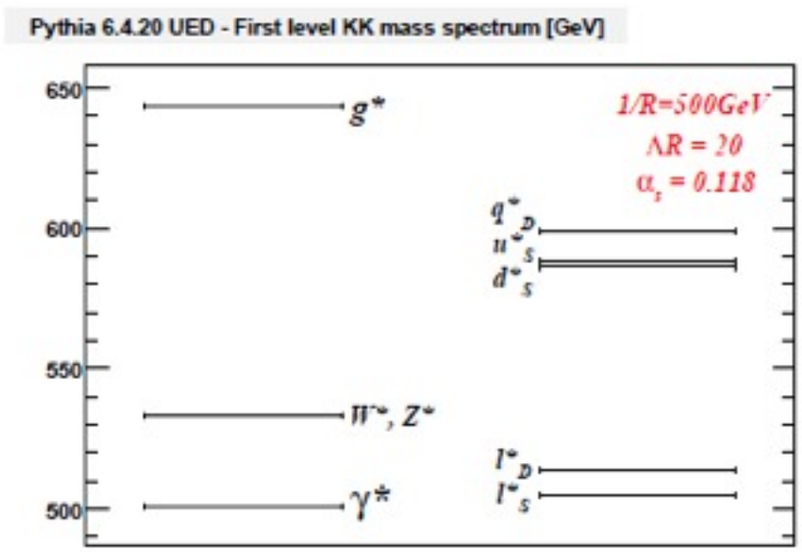


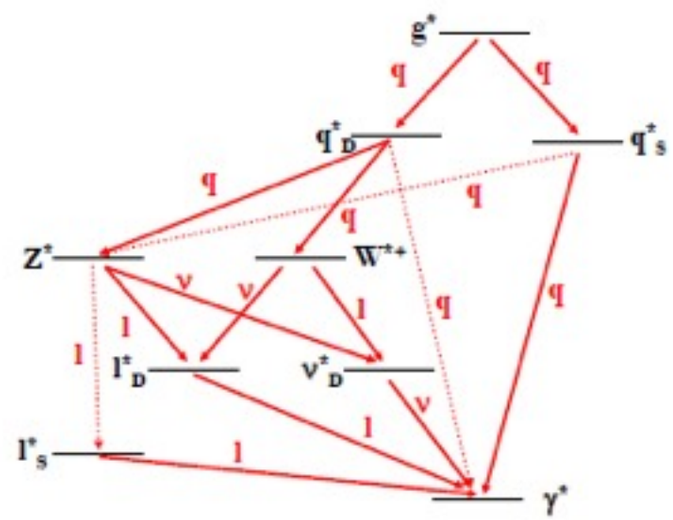
bino-like



wino-like

Introduction to Universal Extra Dimensions (UED)





- **Universal**: ALL SM particles propagate into the extra dimensions (δ = 1; 1/R~1TeV)
- n=1,2,3,… Kaluza Klein (KK) excitations for each SM particle (n=0)
- R: compactification scale
- Mass degeneracy $m_n^2=n^2/R^2 + m_{SM}^2$ lifted by radiative corrections.
- quark and gluon KK excitations cascade decay down to Lightest KK Particle: γ^*