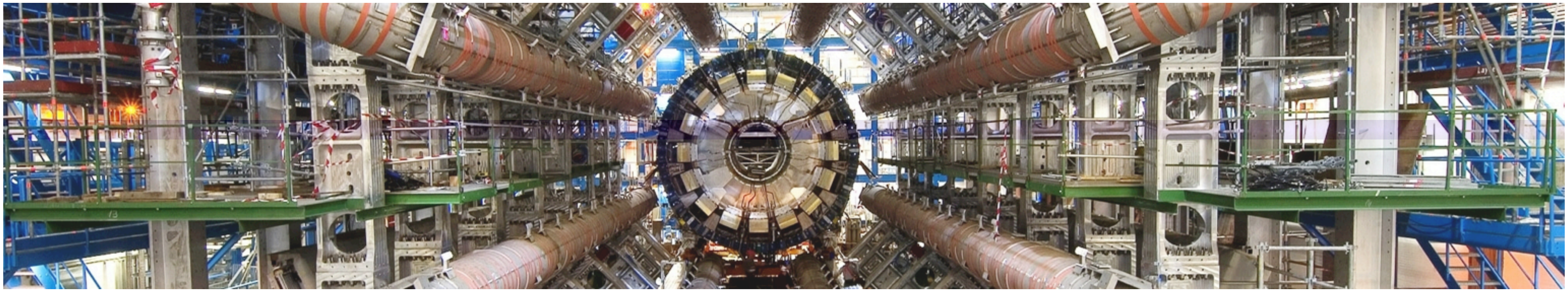

Searches for New Physics in Photon+Missing Energy Signatures at ATLAS

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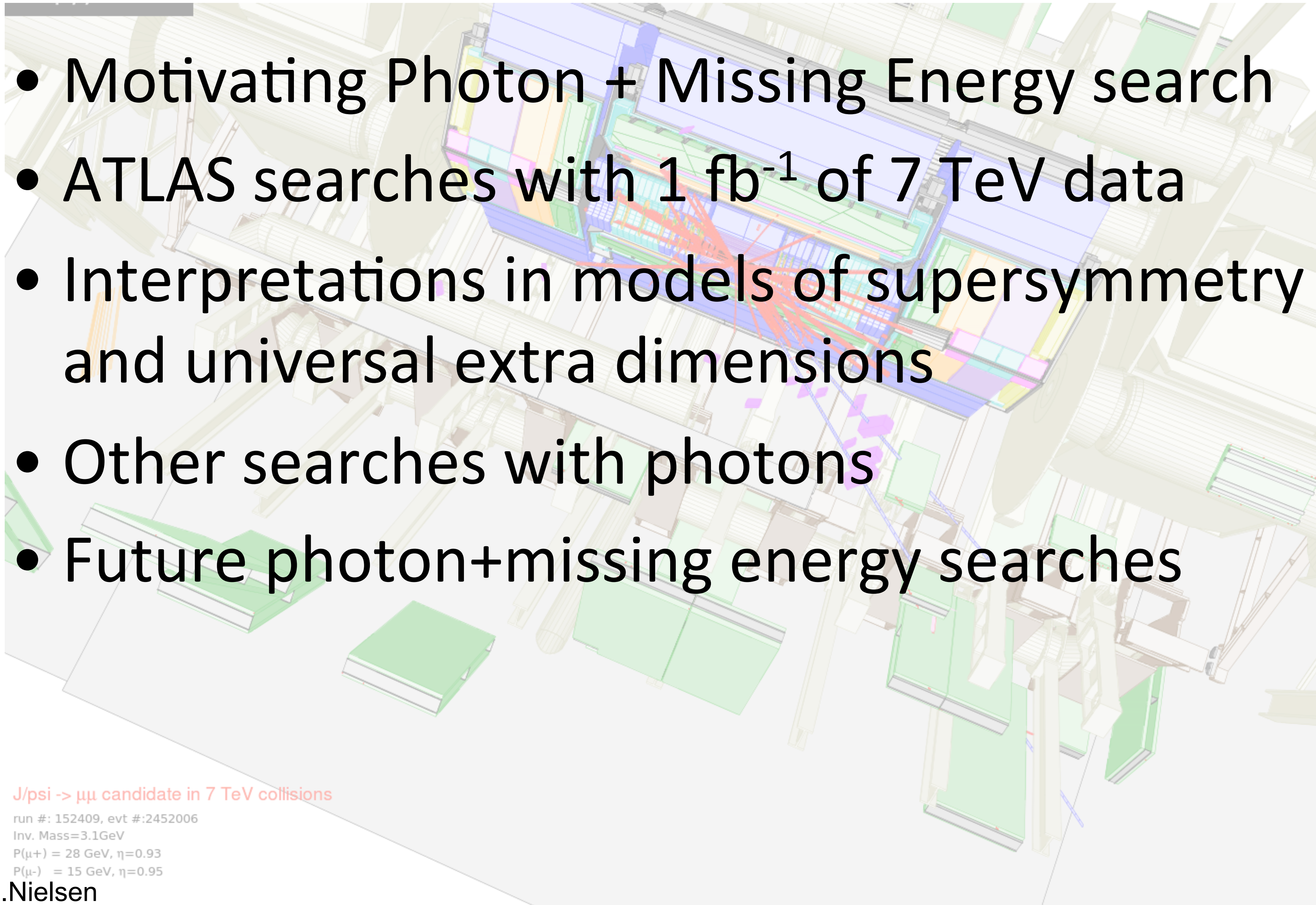
UC Davis High-Energy Seminar

June 5, 2012

Outline

- Motivating Photon + Missing Energy search
- ATLAS searches with 1 fb^{-1} of 7 TeV data
- Interpretations in models of supersymmetry and universal extra dimensions
- Other searches with photons
- Future photon+missing energy searches



Motivation for Photon+Missing Energy

- High-energy photons provide a clean signature with limited Standard Model background
  - Clean photon signature allows for low-momentum trigger threshold at hadron colliders
  - Missing energy > 100 GeV comes from high-energy neutrinos in known weak decays or from gross detector mismeasurements
- Signature-based $\gamma+E_T^{miss}$ searches have few parts, yet yield insight into several interesting models of new physics beyond the Standard Model
  - Targeting more specific $\gamma+E_T^{miss}$ signatures improves sensitivity even more
- General enough to be open to unknown frontiers

Gauge-Mediated SUSY Breaking

- SUSY breaking occurs in a “hidden” or “secluded” sector
- Standard gauge interactions communicate the breaking to the usual MSSM fields via a messenger sector
  - Main feature/consequence is no flavor violation
- Key differences with respect to mSUGRA/cMSSM
  - SUSY breaking happens at a lower mass scale
  - Lightest SUSY particle is the gravitino $\tilde{G}$, with m << GeV
- Experimental signatures determined by nature of NLSP
  - Bino, Wino, or Higgsino–like gaugino (or mixture thereof)
  - Slepton, Stau (Charged Massive Particles)
- There are still several mass scale parameters to choose…

Minimal vs General Gauge Mediation

- Certain GGM considerations raised by Ruderman & Shih [arXiv:1103.6083] are important for LHC
- In MGM, messengers couple to both the SUSY-breaking sector and to the MSSM sparticles
  - Small number of parameters control couplings and relations: tanβ, μ, M_{mess}, SUSY-breaking scale Λ, # copies of SU(5) messenger fields
  - Colored particles are much heavier than electroweak particles
- In GGM, mass relations are dropped
  - Colored particles can be much lighter than electroweak: light gluinos compare to heavy sleptons and squarks
  - Trade-off is much greater number of parameters and larger parameter space to explore

GGM Phenomenology

- We set all mass parameters (sparticle masses) to 1.5 TeV, except for the gluino and bino masses
  - This is a specific case that Tevatron cannot reach
  - Effectively shuts off weak production for this study
- SUSY pair production of color-charged sparticles through gluon interactions leads to cascade decay
  - We do not use the features of this cascade decay in our search
- If the lightest neutralino is "bino-like" [couplings similar to SM U(1) gauge boson], then $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
  - We pick coupling parameters such that this decay is prompt

Final state signature: two high-E_T photons and missing energy

Universal Extra Dimensions

- All SM fields propagate through small-scale extra dimensions with typical 1/R = TeV
- Each field appears as a tower of Kaluza-Klein states, with states for each field at $$m^2_{X^{(n)}} = \frac{n^2}{R^2} + m^2_{X^{(0)}}$$
- Radiative corrections break the tree-level degeneracy
  - Higher-n states are separated by ~100 GeV
- One possibility: cascade decays down to LKP – γ*
- If there are additional dimensions accessible only to gravity, then the LKP can decay to γ+G

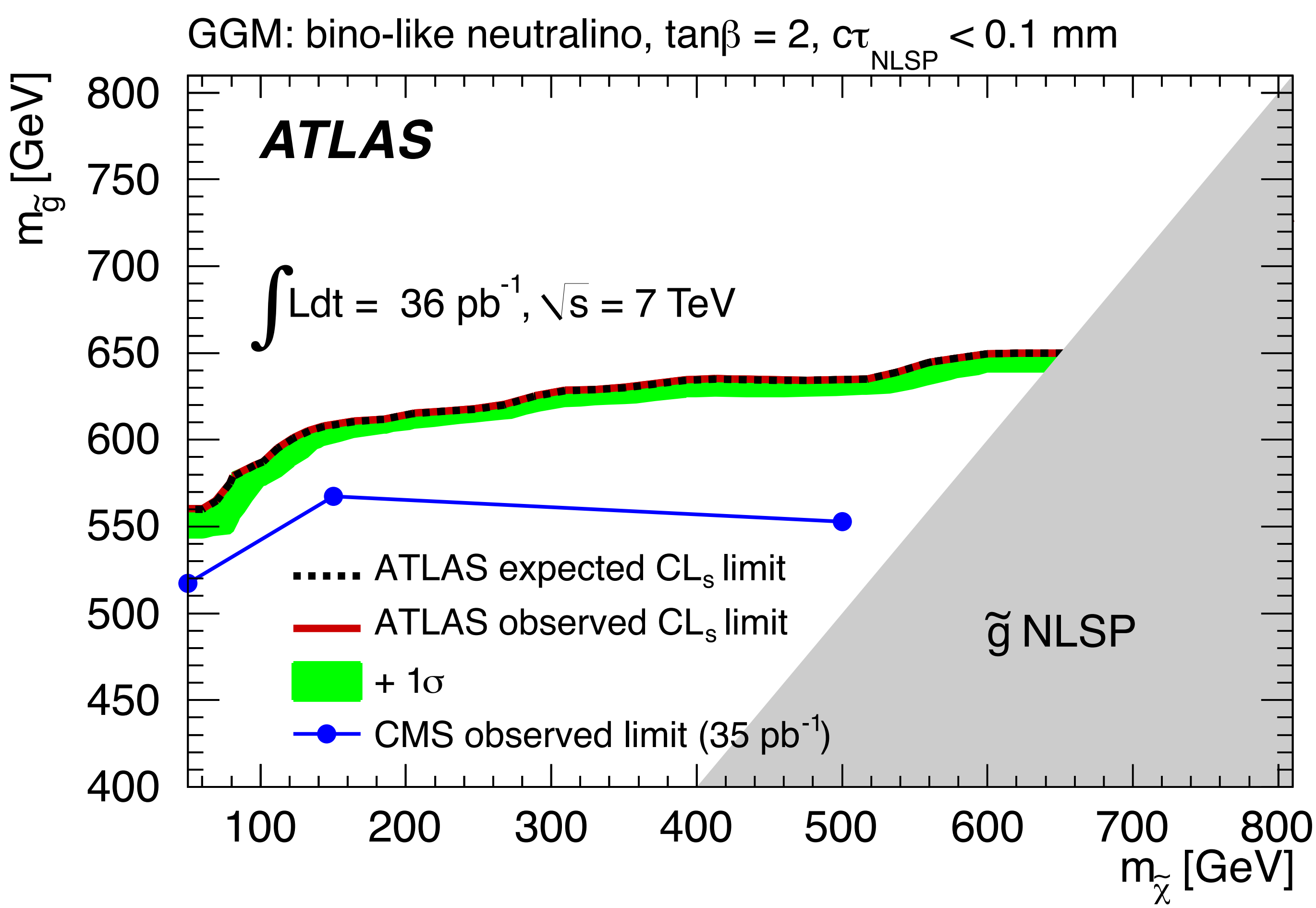
Final state signature: two high-E_T photons and missing energy

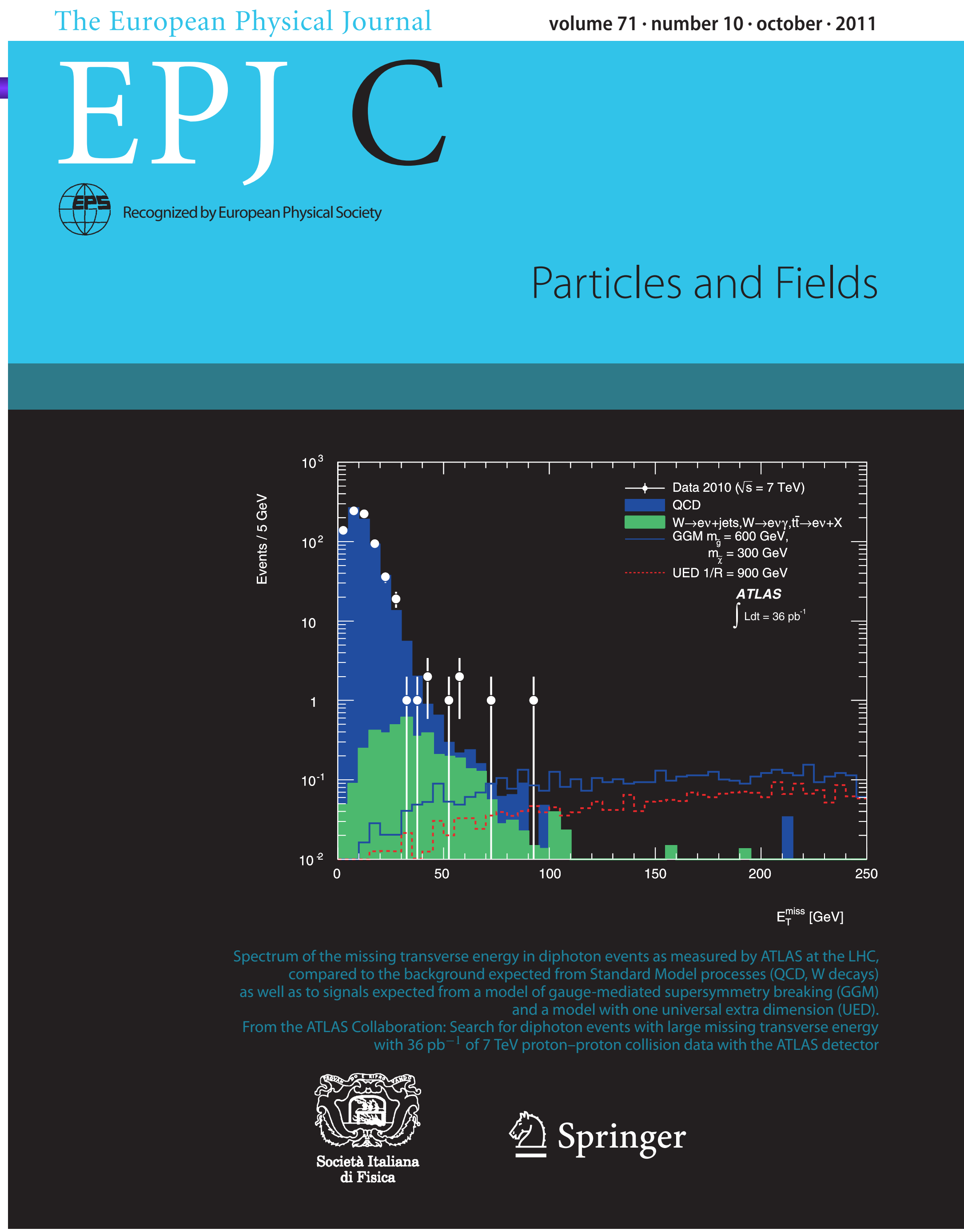
Dark Matter Connections

- Gauge mediation: gravitino is LSP, and NLSPs are short-lived, but is the dark matter purely gravitinos?
  - keV gravitinos overclose universe, but eV gravitinos are not enough to account for observed dark matter
  - Proposals of "entropy injection" after gravitino freeze-out, sufficiently diluting the keV gravitino abundance
- Universal extra dimensions
  - Possible candidates: KK photon, KK graviton with 1/R = TeV
- Collider searches can play a role in constraining dark matter candidates, especially mass or dimensional scales

Earliest ATLAS Results

- Null search result interpreted in GGM framework
  - Eur. Phys. J **C71** (2011) 1744 [arXiv:1107.0561]
  - GGM benchmark points entered in HepData




The European Physical Journal volume 71 · number 10 · october · 2011

EPJ C

Recognized by European Physical Society

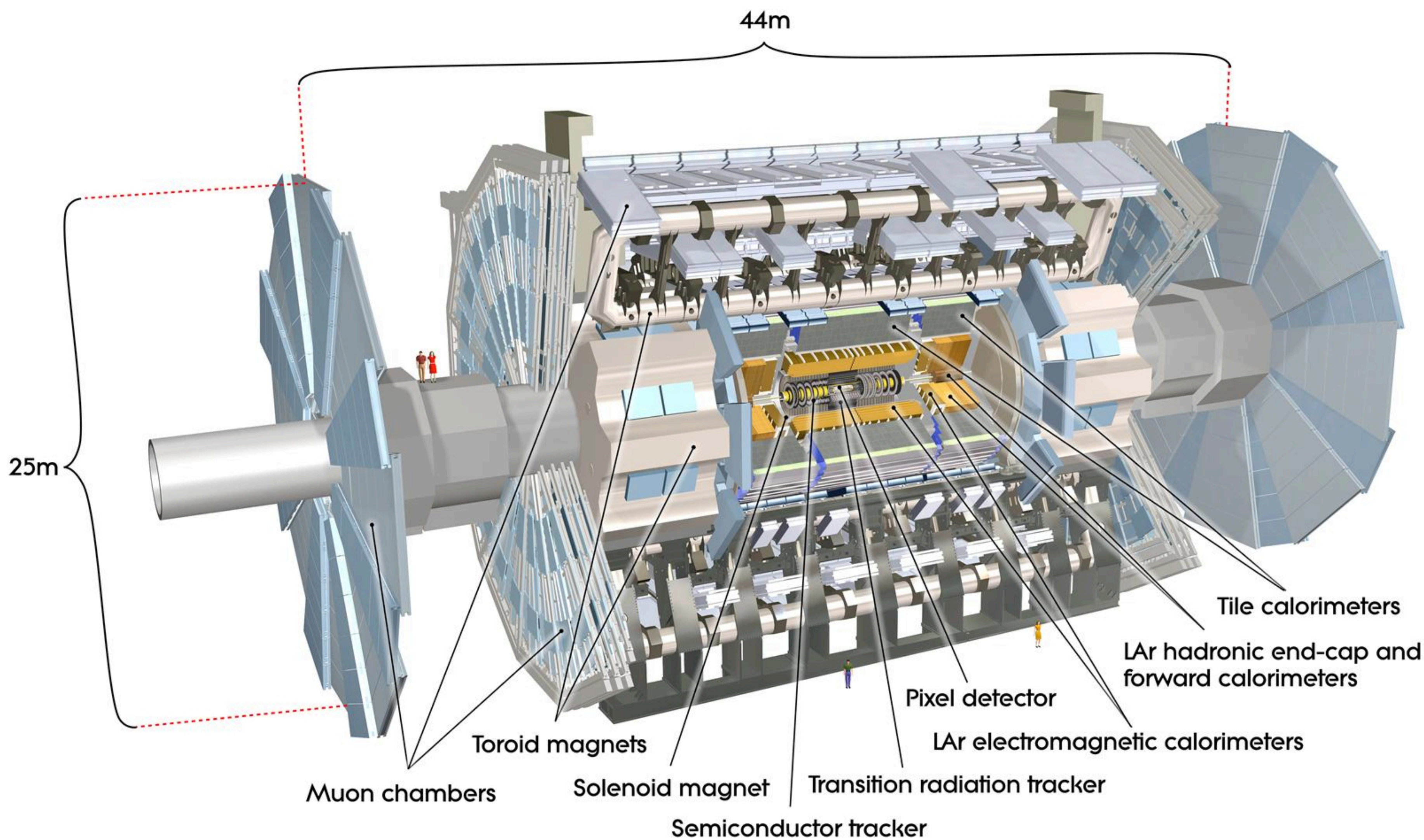
Particles and Fields

Spectrum of the missing transverse energy in diphoton events as measured by ATLAS at the LHC, compared to the background expected from Standard Model processes (QCD, W decays) as well as to signals expected from a model of gauge-mediated supersymmetry breaking (GGM) and a model with one universal extra dimension (UED).
From the ATLAS Collaboration: Search for diphoton events with large missing transverse energy with 36 pb^{-1} of 7 TeV proton–proton collision data with the ATLAS detector

Società Italiana di Fisica

Springer

Overview of ATLAS Detectors

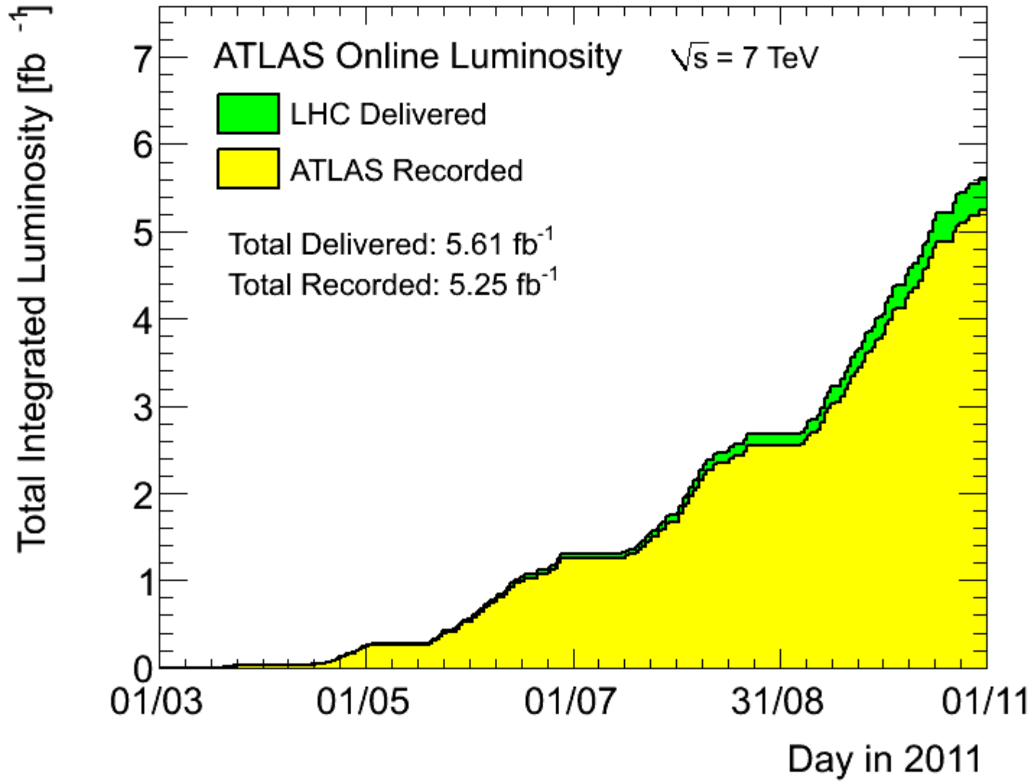


ATLAS 7 TeV Data-taking Performance

Integrated luminosity in ATLAS at 7 TeV during Mar-Nov 2011

(Stops in July and September to commission and study LHC)

Peak inst lumi: 3.7 x 10^{33} $cm^{-2}s^{-1}$



Fraction of "good quality" data collected

ATLAS 2011 p–p run												
Inner Tracking			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	97.5	99.2	99.5	99.2	99.4	98.8	99.4	99.1	99.8	99.3

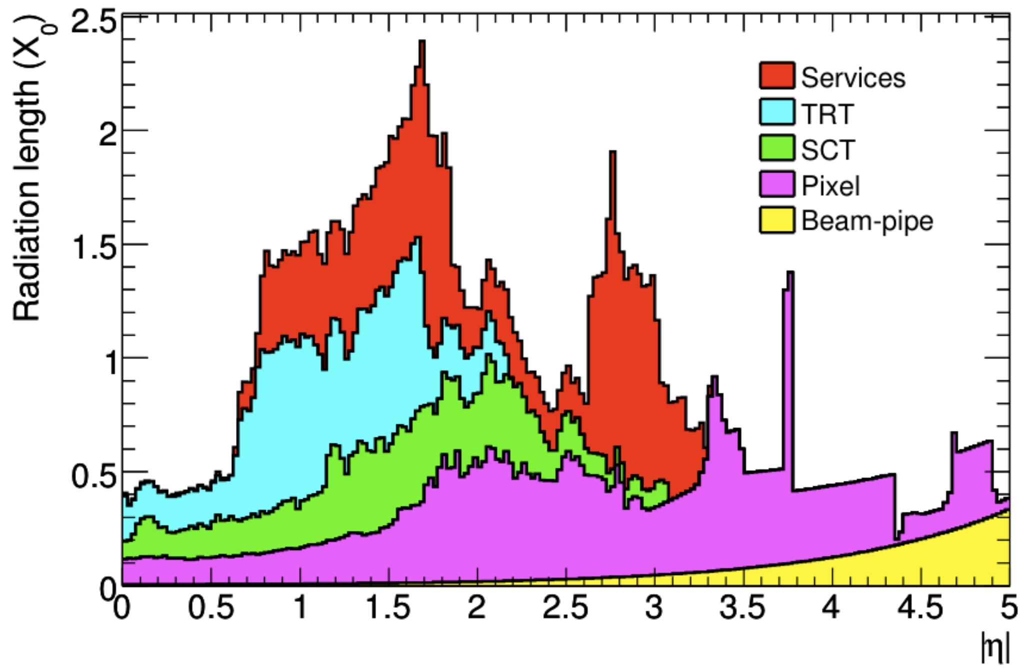
Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and October 30th (in %), after the summer 2011 reprocessing campaign

Photon Reconstruction Improvements

How to reduce e→γ fakes and reduce large background contribution?

Define categories of

- 2-track conversions: Transition Radiation consistent with electron; reconstructed vertex
- 1-track conversions: Transition Radiation consistent with electron, missing hits in live pixel layers



Electrons not consistent with 1-track conversions are rejected.

ATLAS Search with 1 fb^{-1} at 7 TeV

- Non-resonant diphoton search with large missing E_T
  - Assume diphotons are prompt (short-lived parent)
  - Appropriate for gauge mediation models with Bino NLSP and for 1 UED models

- Increased data (x30) gives hope for candidate events!

- Re-optimize event selection to maximize sensitivity
  - Expect largest background contrib from W+jets (incl. top quark)
  - Re-evaluate missing E_T calculation and cut value

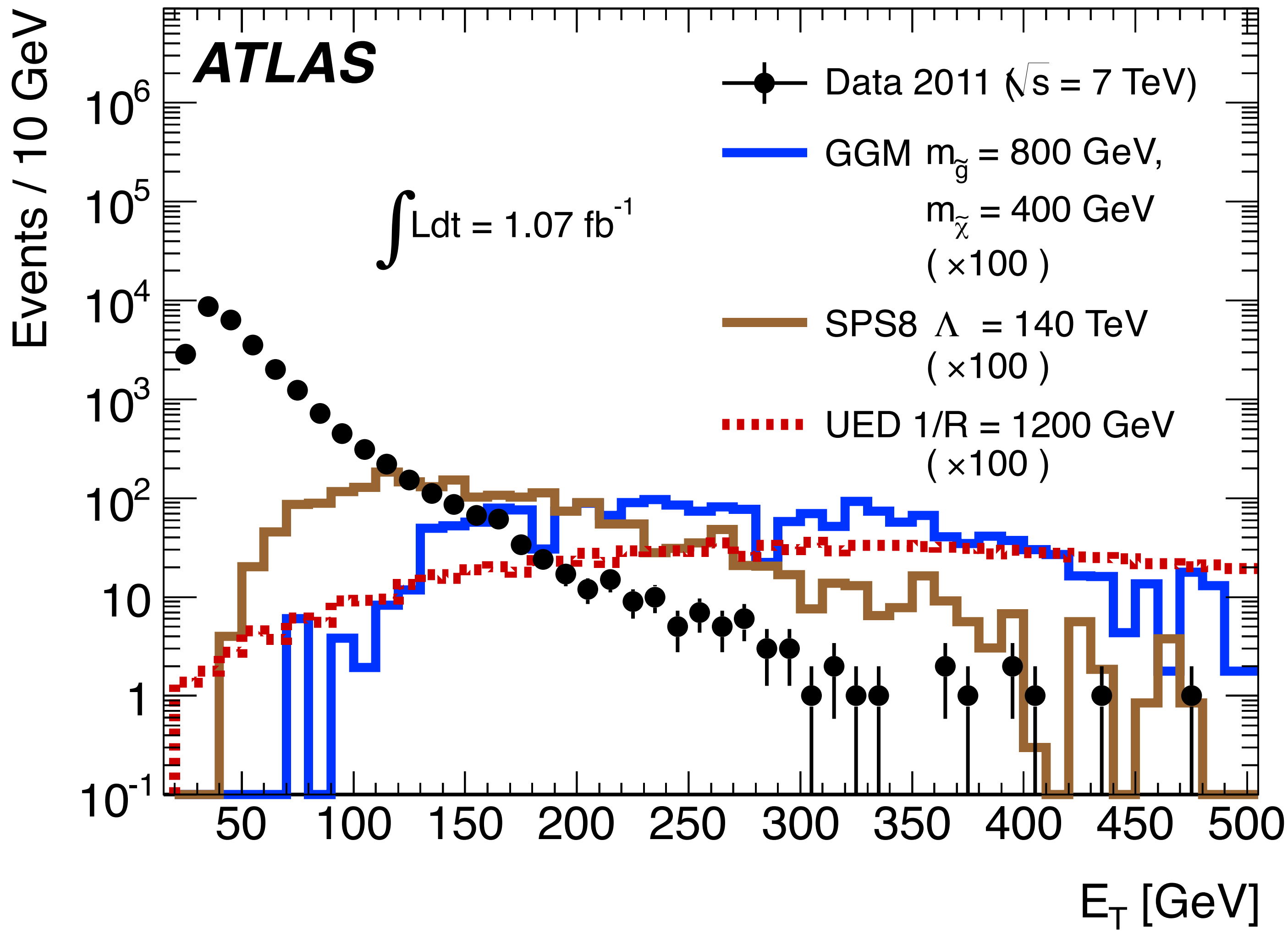
Event Selection Criteria

- Diphoton trigger: 2 loose e/γ objects with E_T>20 GeV
- Two photons with tighter offline selection
  - E_T > 25 GeV, $|\eta|$<1.81 (excluding barrel/endcap crack region)
  - Calorimeter-based isolation to reject jets: not more than 5 GeV of additional energy within cone of $R=\sqrt{(\Delta\phi^2+\Delta\eta^2)}=0.2$
- Missing transverse energy > 125 Gev
  - Calculated from locally-calibrated calorimeter clusters
- Primary vertex with at least 4 tracks
  - This has little rejection power: initial state color must hadronize

- Reject events with muon $|z_0|$ > 1 mm or $|d_0|$ > 2 mm

Typical Photon Energies

- High-mass particles in decay chain lead to high-E_T γ
  - But note scale factors for signal! Need missing E_T cut



Background Modeling

Simplify by modeling only the missing E_T distribution
[based on D0 technique in *PRL 105 (2010) 221802*]

- Instrumental E_T^{miss} from mismeasurement: γγ, γ-jet, dijet
  - Modeled with "pseudo-photon" data template normalized to γγ data sample in background-dominated region
- Real E_T^{miss} from neutrinos in final state with fake photon
  - Electron faking photon: W+γ, W+jets (incl. top pairs)
  - Modeled using e+γ control sample scaled by e->γ fake rate
- Irreducible, but tiny: Z+γγ, W+γγ
  - calculated with electroweak Monte Carlo programs

Instrumental Missing ET Backgrounds

Encompasses $\gamma\gamma$, γ-jet, dijet with no true missing energy

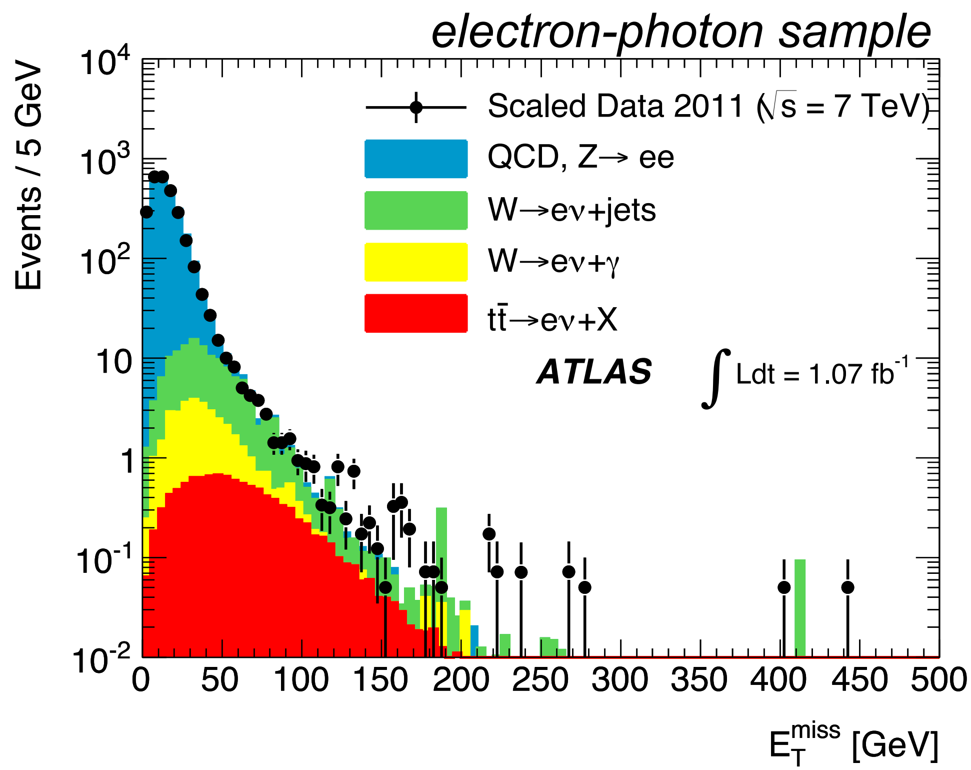
- Define *pseudo-photon*: passes loose requirements but fails at least one tight criterion
- Control sample template constructed with
  - Two e/g trigger objects with ET>20 GeV (quite loose)
  - At least one *pseudo-photon* (veto evts with 2 tight photons)
- Absolute normalization given by fit to $E_T^{miss} < 20$ GeV
  - Some uncertainty from template composition; cross-check using a 0-jet $Z(e^+e^-)$ sample

Prediction for this background category: 0.8±0.3±0.6 events

Real Missing ET Backgrounds

Encompasses W+γ, W+jet, ttbar -- with or without true γ

- Scale eγ data by e→γ fake rate (measured in Z peak)
- First, subtract contributions from instrumental bkgds
- Second, apply fake rate scaling to obtain prediction for the contribution to γγ



Prediction for this background category: 3.1±0.5±1.4 events

Backgrounds Prediction in Sidebands

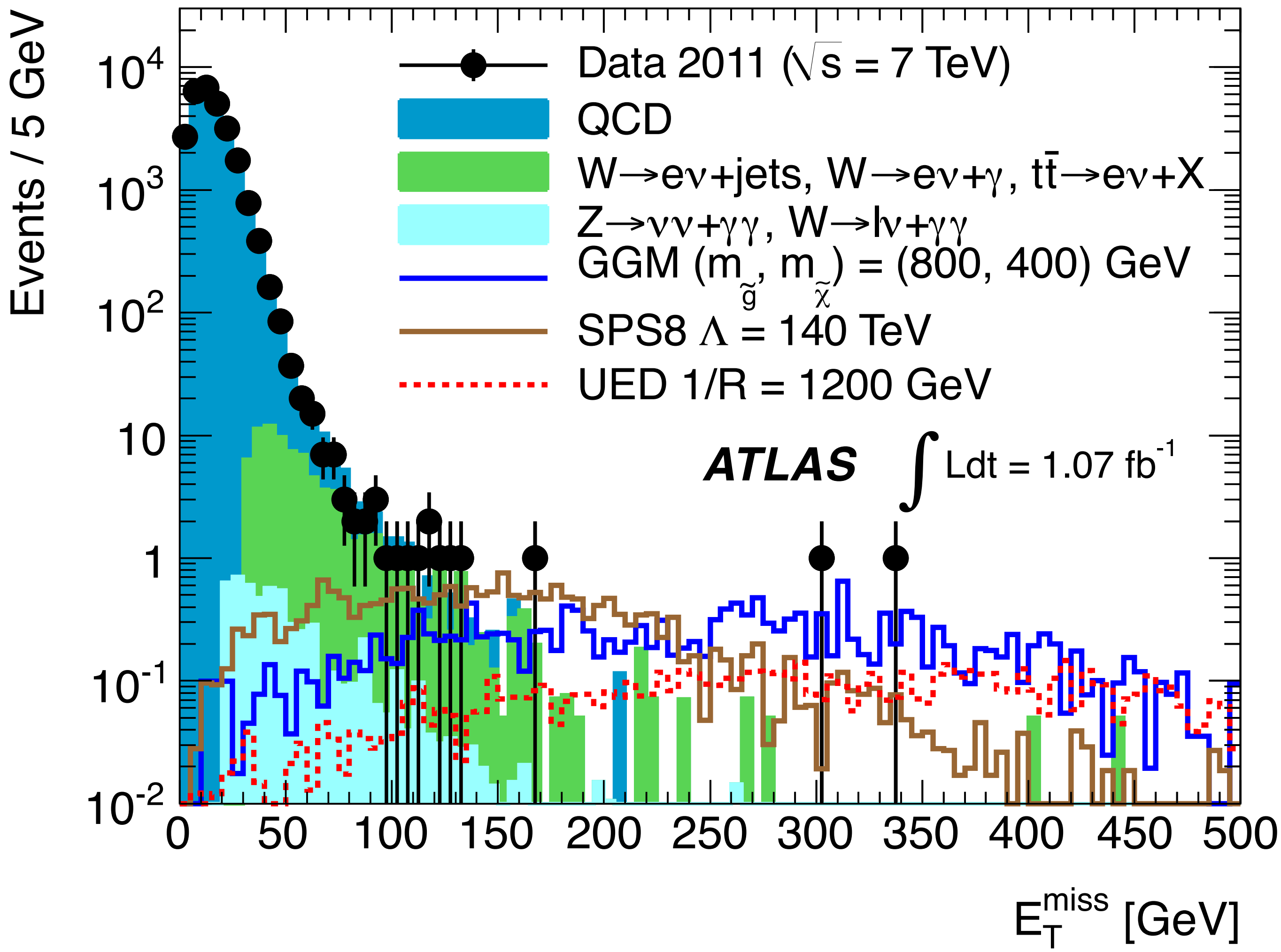
- Sum all backgrounds, including irreducible contribution
- Compare in various sideband regions of the relevant kinematic distribution, here E_T^{miss}

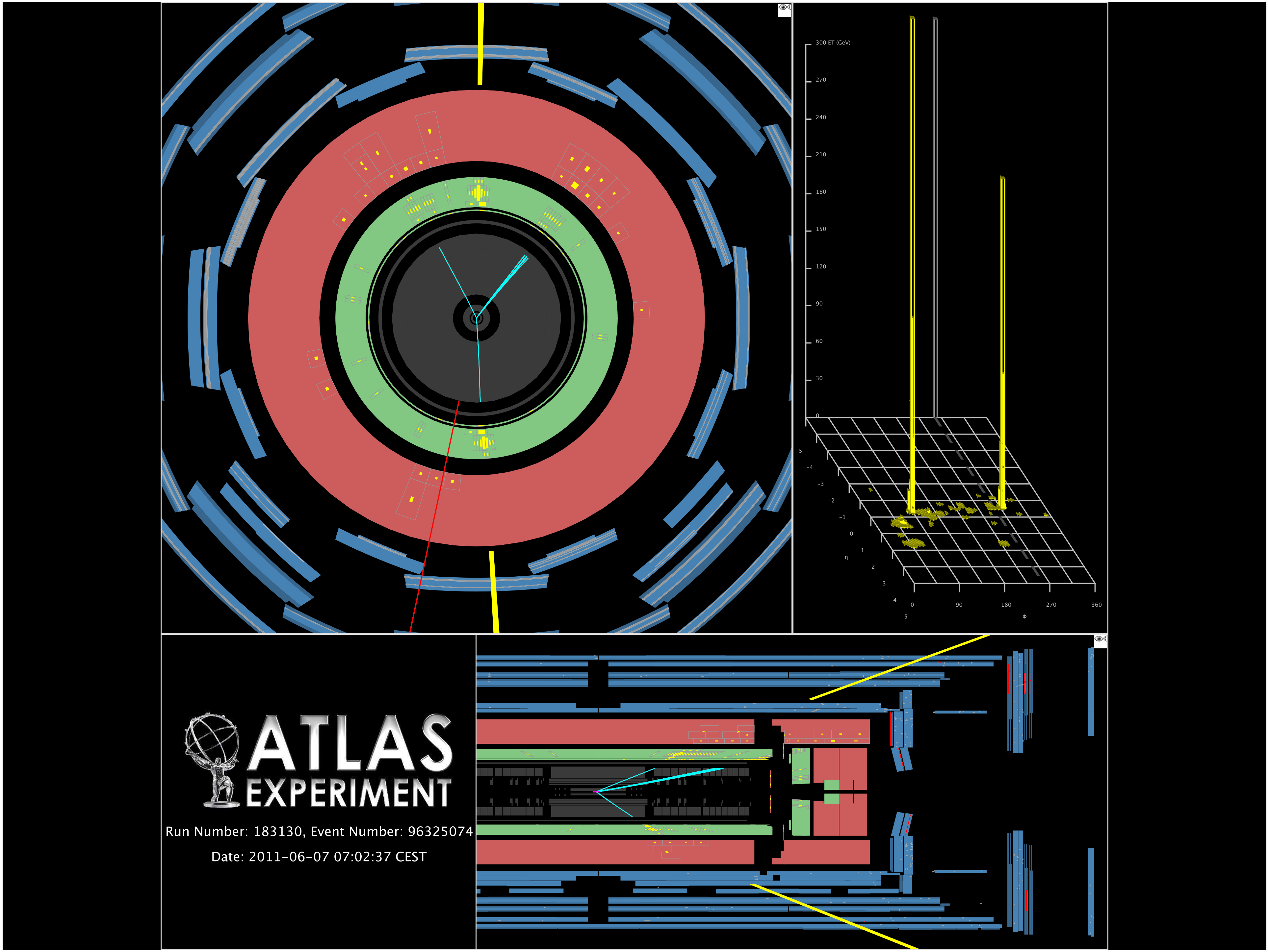
E_T^{miss} range [GeV]	Data events	Predicted background events (Stat. uncerts only)			
		Total	QCD	$W/t\bar{t}(\to e\nu)+X$	Irreducible
0–20	20881	–	–	–	–
20–50	6304	5968 ± 29	5951 ± 28	13.3 ± 8.1	3.55 ± 0.35
50–75	86	87.1 ± 3.3	60.9 ± 2.8	25.2 ± 1.7	1.01 ± 0.16
75–100	11	14.7 ± 1.2	6.7 ± 0.9	7.4 ± 0.8	0.52 ± 0.10
100–125	6	4.9 ± 0.7	1.6 ± 0.4	3.0 ± 0.5	0.32 ± 0.08

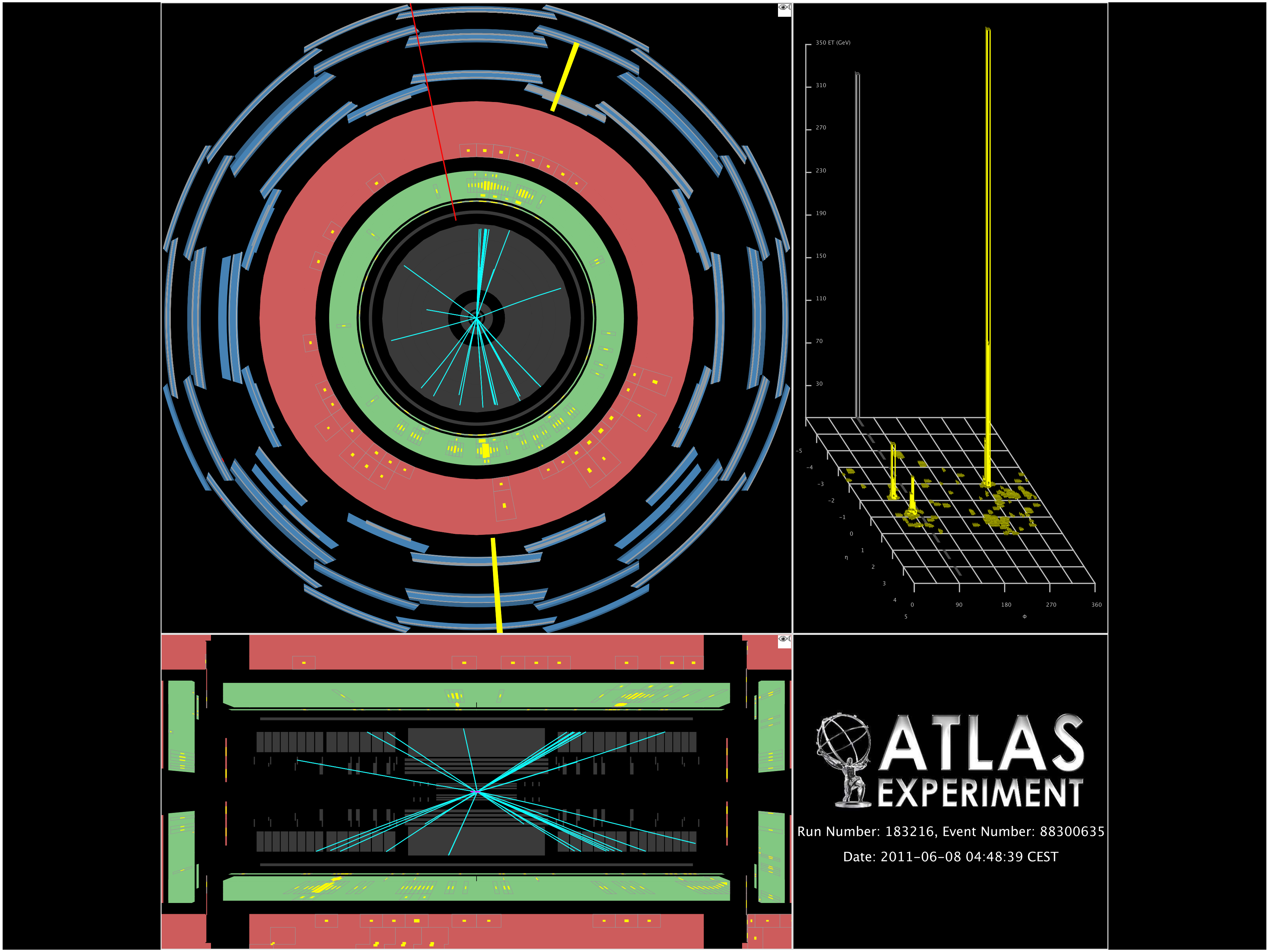
- Recall that the dominant backgrounds are predicted from orthogonal control samples
  - Expect signal contamination in those regions to be small

Results from Photon+MET Data

- Expect 4.1±0.6 events at high E_T^{miss} ; observe 5
  - Model-indep. limit on new physics: <7.1 events @ 95% CL

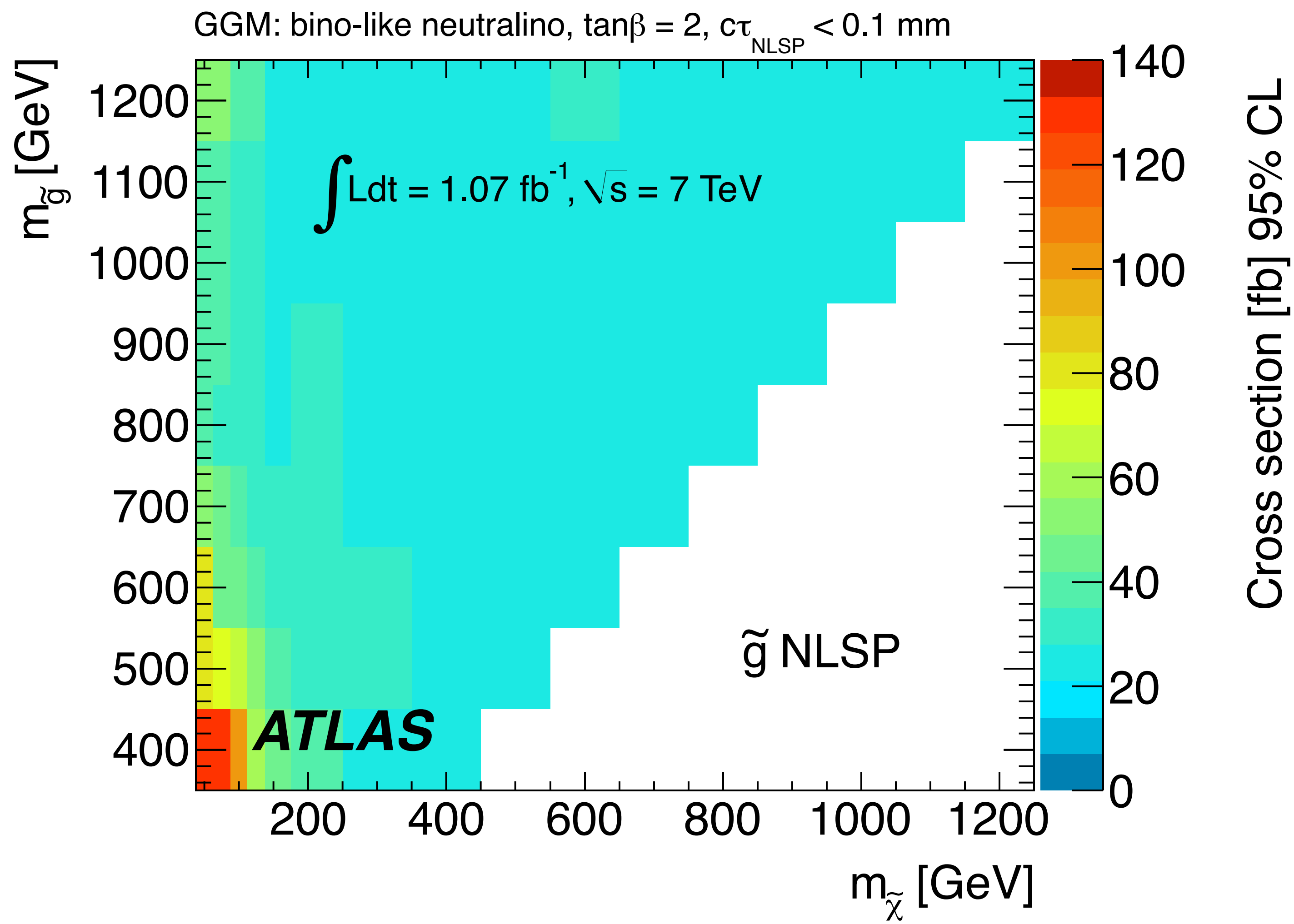



ATLAS
EXPERIMENT
Run Number: 183130, Event Number: 96325074
Date: 2011-06-07 07:02:37 CEST


350 ET (GeV)
310
270
230
190
150
110
70
30
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ
ATLAS
EXPERIMENT
Run Number: 183216, Event Number: 88300635
Date: 2011-06-08 04:48:39 CEST

Limit on Production Cross Sections

- Provide direct exclusion on gluino pair cross section
  - Assumes specific kinematics due to masses

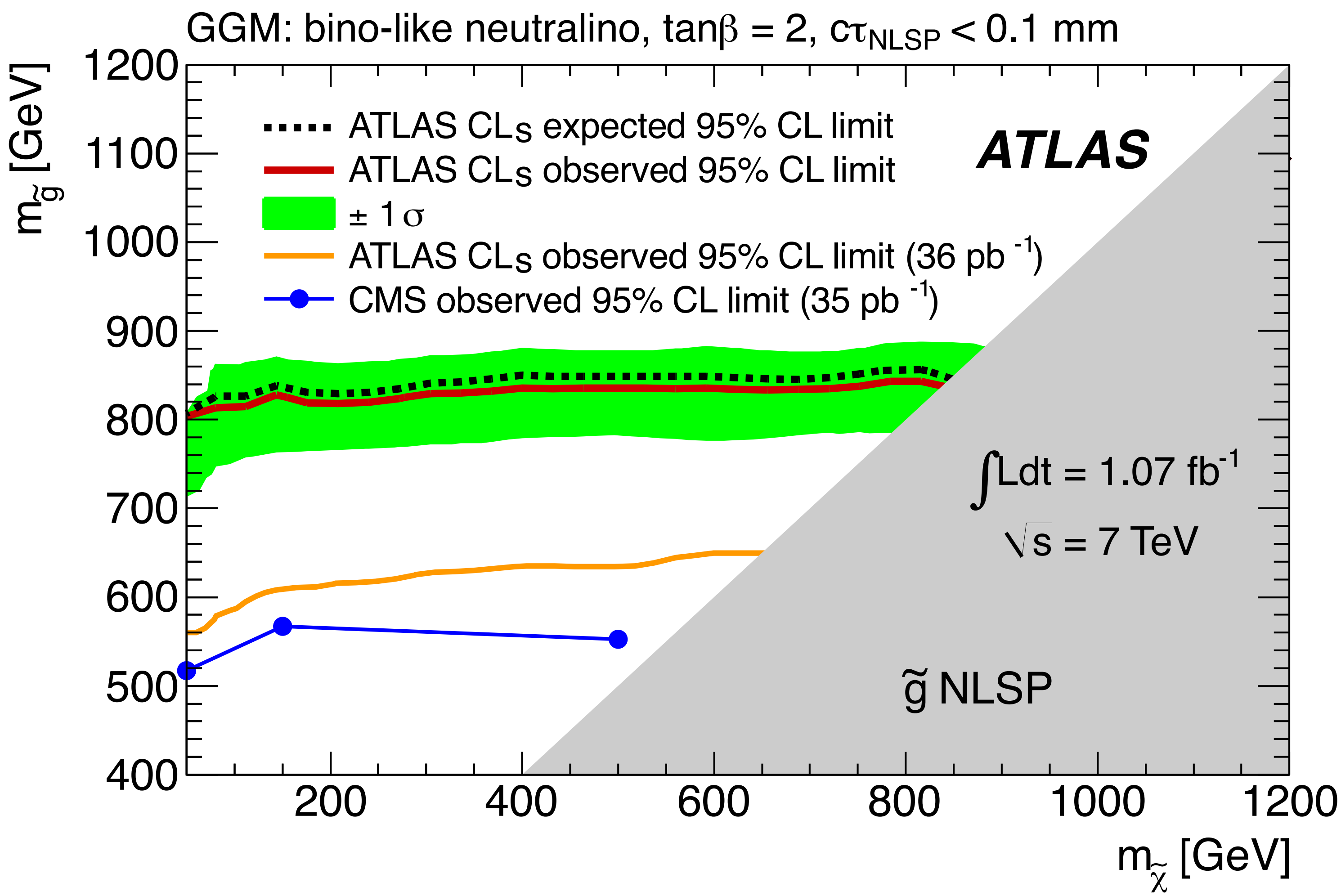


Signal Uncertainties

- SUSY signals are calculated at NLO with Prospino, and UED signals are calculated with new Pythia process
- Major signal uncertainties include:
  - PDF errors (esp. GGM at low x, high Q^2)
  - Renormalization/factorization scale variation (/2, *2)
  - Photon and missing energy reconstruction
- Total uncertainties for GGM case ($m_{\tilde{g}}$ = 800 GeV)
  - Experimental uncertainties 6.6%
  - PDF and scale uncertainties: 31% (~10% for min. GMSB, UED)
  - These uncertainties vary over the benchmark planes
- Much discussion on quoting experimental and theoretical uncertainties separately, but they're combined here

Interpretation in General Gauge Mediation

- Simplified model focused on gluino pair production
- All soft parameters are set to 1.5 TeV (decoupled)

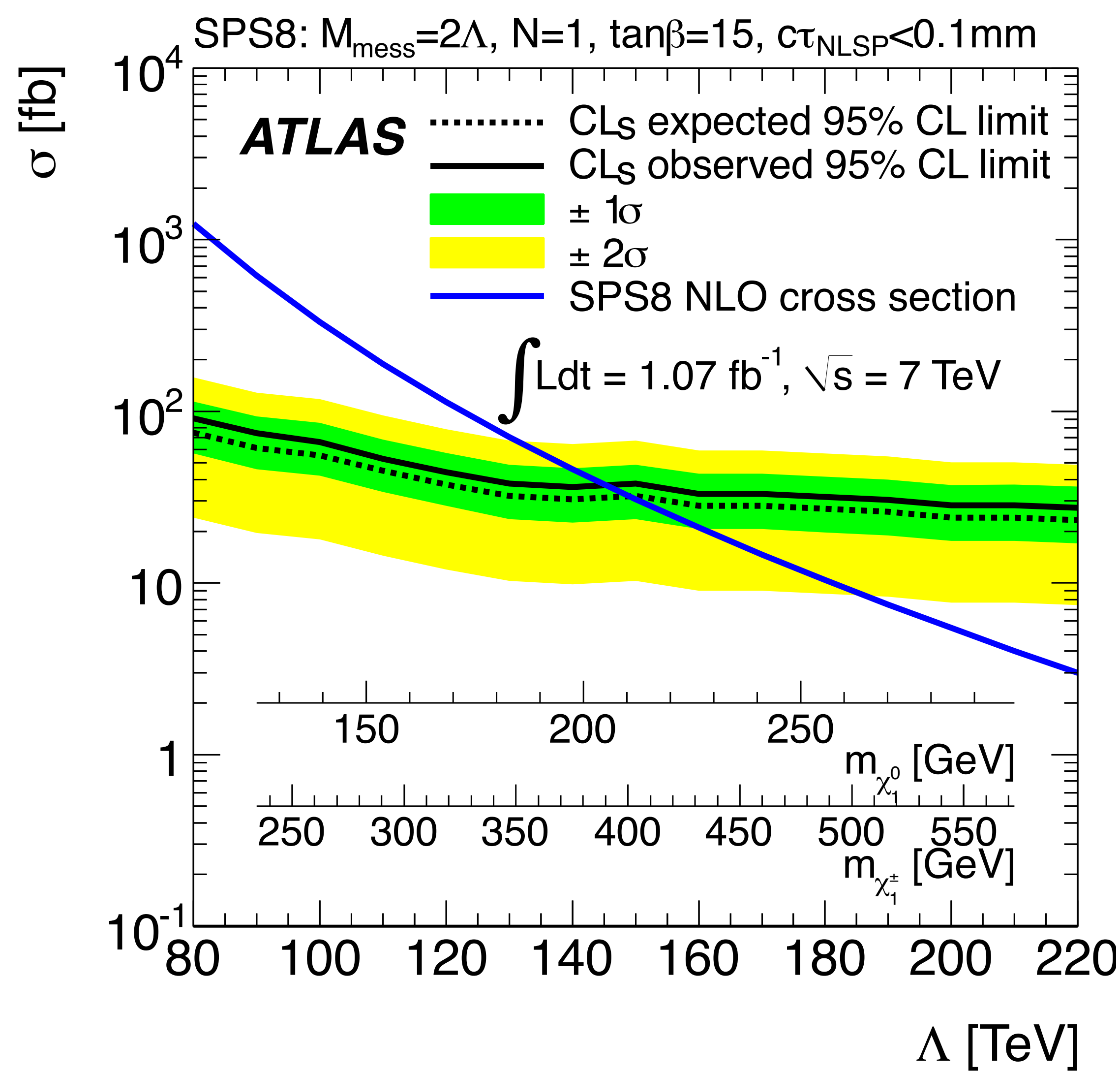


Interpretation in Minimal Gauge Mediation

- Snowmass Points and Slopes [arXiv:hep-ph/0202233] define GMSB benchmark with neutralino NLSP
  - mGMSB parameters: N_{mess} =1; $\tan\beta$=15, μ>0, M_{mess}/Λ = 2
  - This is actually a slope, with Λ as independent scale variable
  - Point 8 (SPS8) is defined with Λ=100 TeV, giving $m_{\tilde{g}}$ = 820 GeV
- Tevatron has good sensitivity to direct neutralino production in this scenario, but LHC has caught up
  - This was one original motivation for considering GGM at LHC
- Snowmass benchmarks are not sacred, but they provide illustration of sensitivity to strong and weak production
  - Our own GGM points are preserved in HEPDATA database

Results for Snowmass SPS8 Benchmark

- <u>First SPS8 sensitivity at pp collider</u>
- σ<(27-91) fb or Λ>145 TeV at 95% CL
- Sensitivity to neutralino mass comes from the parameter constraints of GMSB

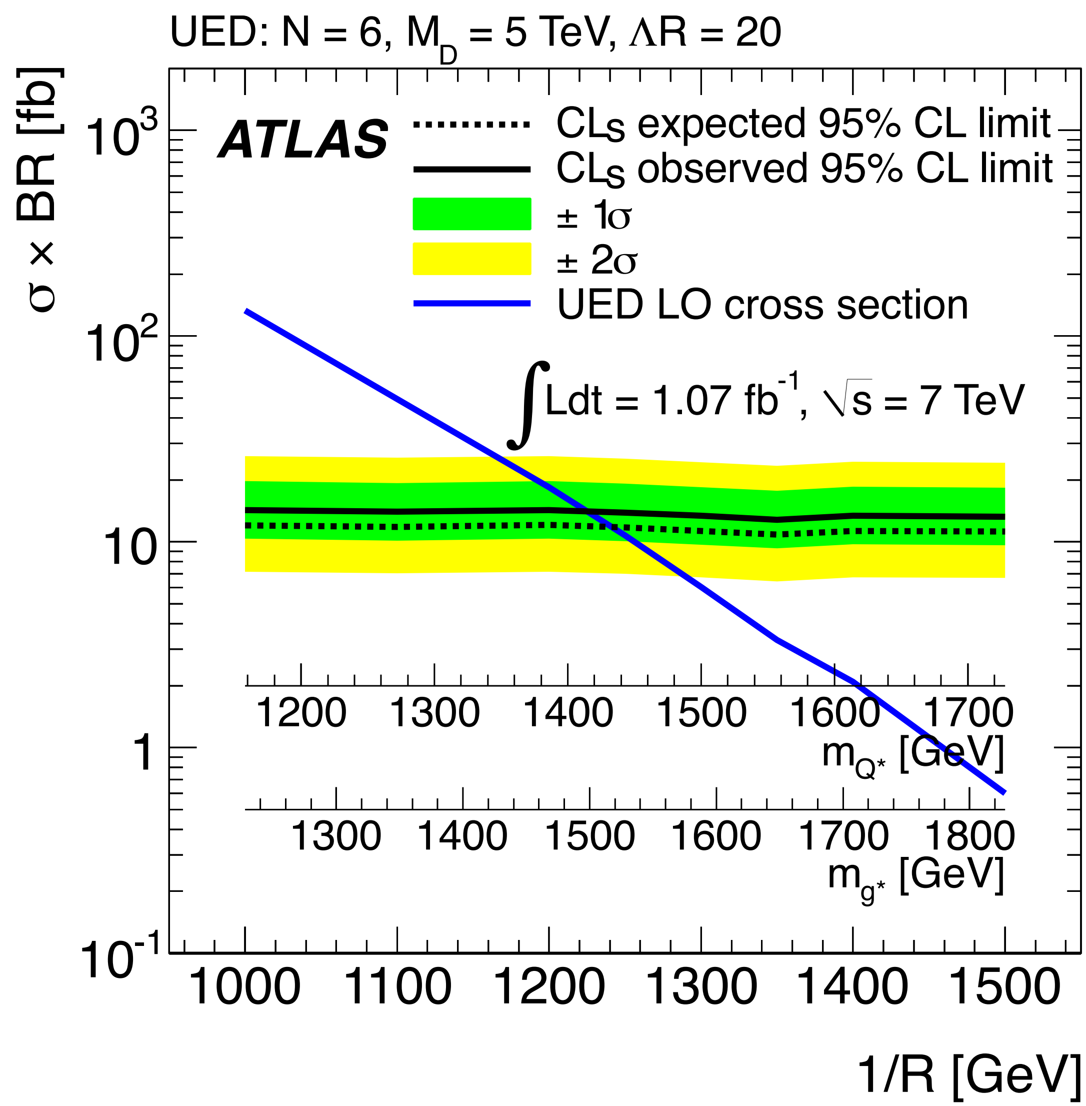


Universal Extra Dimensions

- Model of 1 UED + N extra dimensions accessed by gravity
  - Typical compactification radius: 1/R = 1200 GeV
  - Radiative mass correction cut-off scale: Λ = 20/R
- For 1/R ~ 1 TeV, the branching ratio to $\gamma\gamma$ is close to 100%
  - By 1/R ~ 1.5 TeV, the branching ratio is only 50%
- Typical first-level KK masses (vary by few % with ΛR):
  - m_{γ}^{1} = 1200 GeV
  - m_{Quark}^{1} = 1387 GeV
  - m_{gluon}^{1} = 1468 GeV

Results for Universal Extra Dimensions

- σ<(15-27) fb, depending on compactification scale 1/R
- Model-specific limit: 1/R>1.23 TeV at 95% CL
- KK quark and gluon resonance masses shown for reference



Results in Phys. Lett. B

- Published diphoton+missing energy signature search with interpretations in Phys. Lett. B 710 (2012) 519
- Total background: 4.1 ± 0.6 (stat) ± 1.6 (sys)
- 5 candidate events observed with E_T^{miss} > 125 GeV

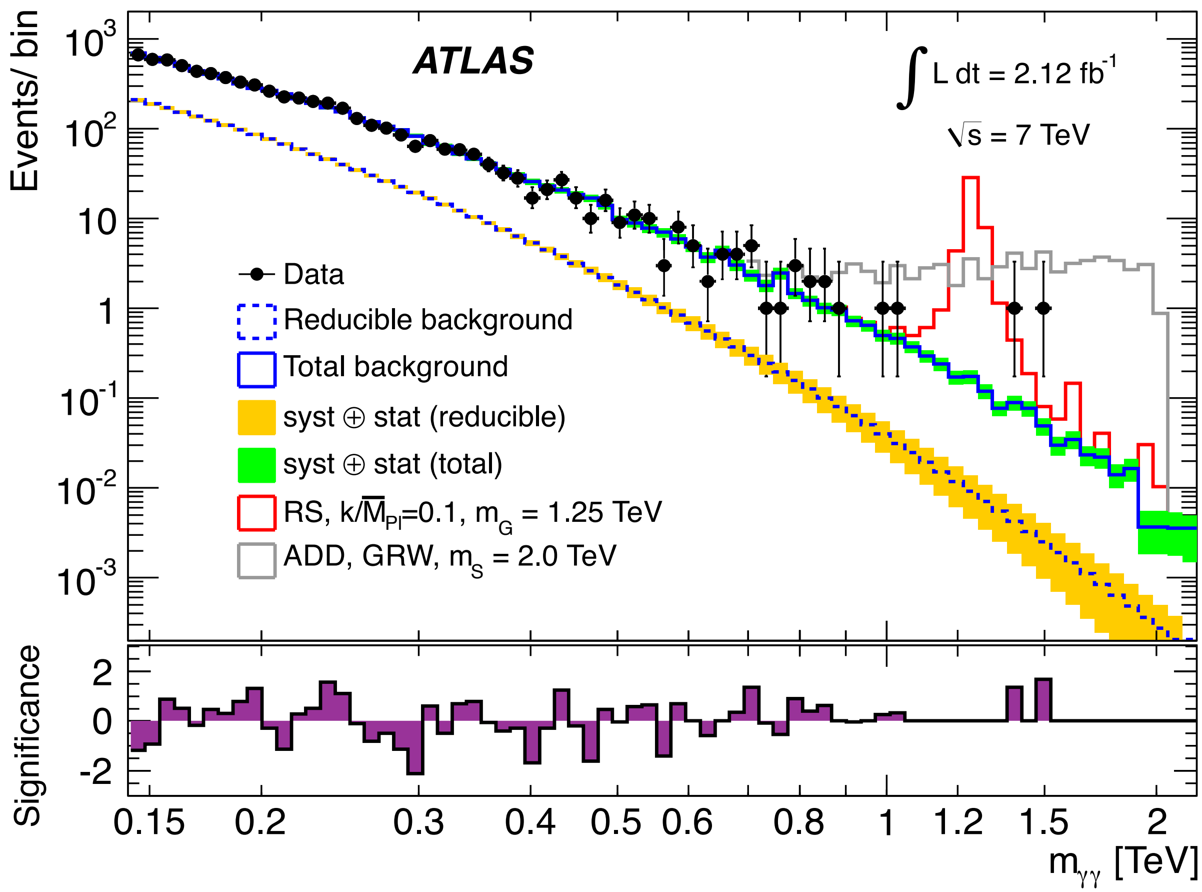
- Model-independent limit: 7.1 events at 95% CL
- Model-dependent interpretations:
  – GGM: m_{gluino} > 805 GeV as long as m_{bino} > 50 GeV
  – SPS8: Λ > 145 TeV
  – UED: 1/R > 1.23 TeV

High-Mass Diphoton Search

- Signatures are striking enough without missing energy
- One possible source of diphotons: Kaluza-Klein towers of graviton excitations due to extra dimensions
  - ADD (Arkani-Hamed—Dimopoulous—Dvali) model: flat, compactified dims. of compactification radius R give rise to resonance mass splitting of 1/R (typically small) → continuous spectrum
  - RS (Randall-Sundrum) model: warped geometry dims. give large resonance mass splitting → resonances O(1 TeV) apart
- In one case, the signal is non-resonant enhancement; in the other, a new high-mass resonance
- Decay to photon pairs is 2x the decay to lepton pairs, due to spin-2 graviton

Results of ATLAS Search

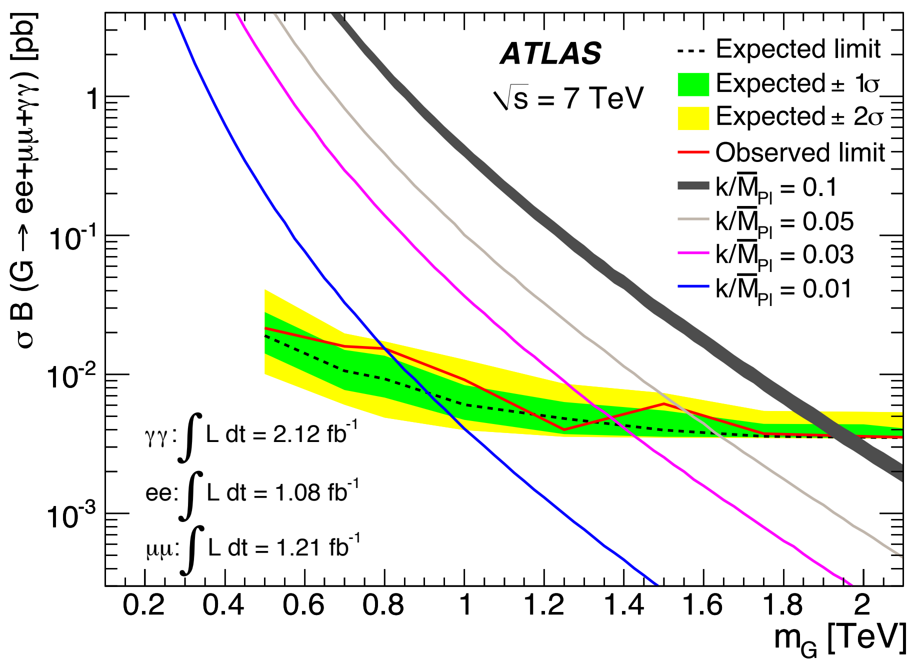
- Dominant SM $\gamma\gamma$ shape is PYTHIA reweighted to DIPHOX
- Backgrounds normalized in sideband $140 < m_{\gamma\gamma} < 400$ GeV
- p-value (prob. to find greater discrepancy) is 0.28

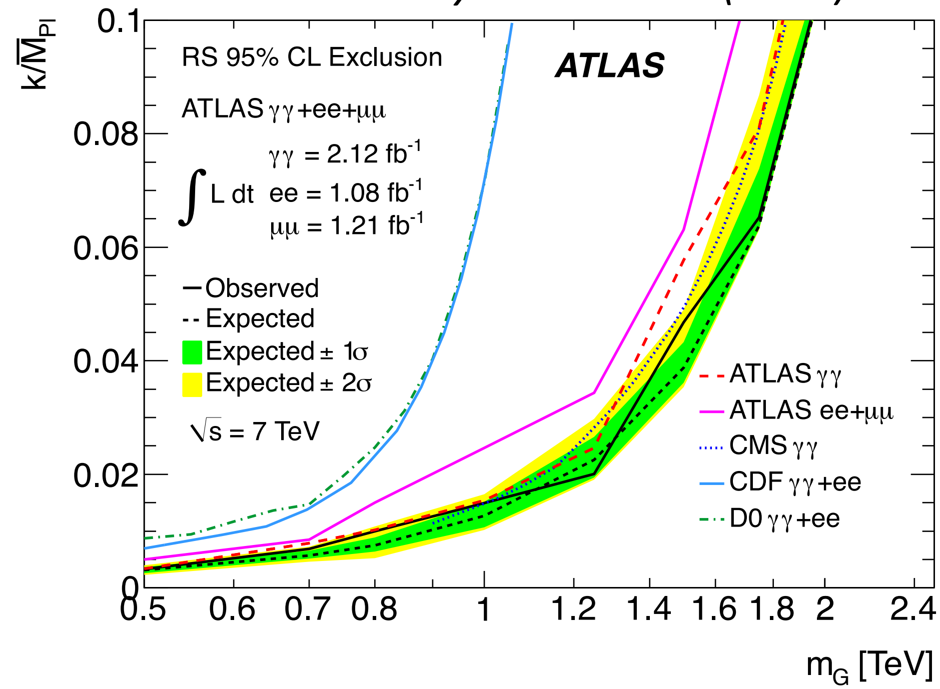


Randall-Sundrum Interpretation

- Limits on cross section, given kinematics of certain m_G
- Re-interpreted as limits on coupling to SM fields as a function of m_G

Phys. Lett. B710 (2012) 538





- Combined with similar dilepton resonance results

New Ideas for 5 fb^{-1} Analysis

- More data, but only a factor of 5; can we do better?
  - Still dominated at very high E_T^{miss} by fake photons
- Some possibilities for tightening criteria:
  - Photons should not pass "medium" electron criteria
  - Photon conversion location should not be reconstructed in pixel system (likely to be electron)

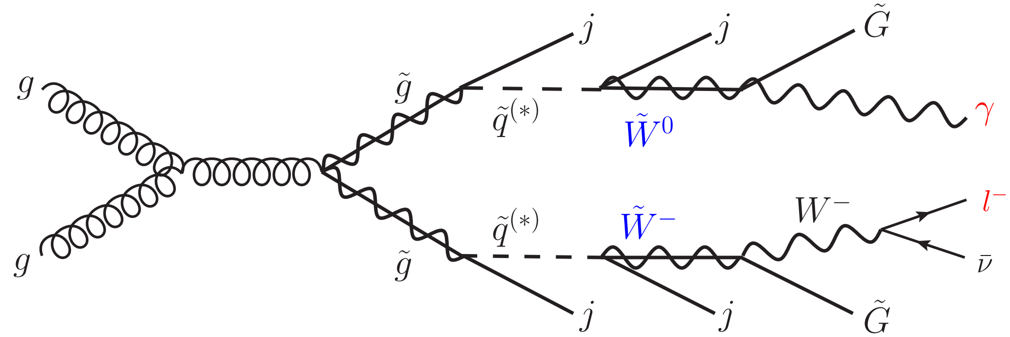
- Tuned event selections for different regions of GGM $m_{\tilde{g}}$ vs $m_{\tilde{\chi}}$ plane

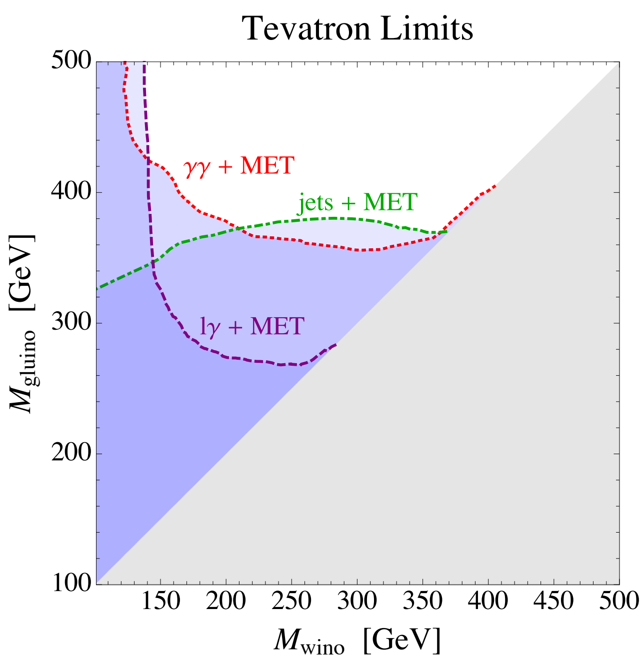
Gauge Mediation Beyond Diphotons

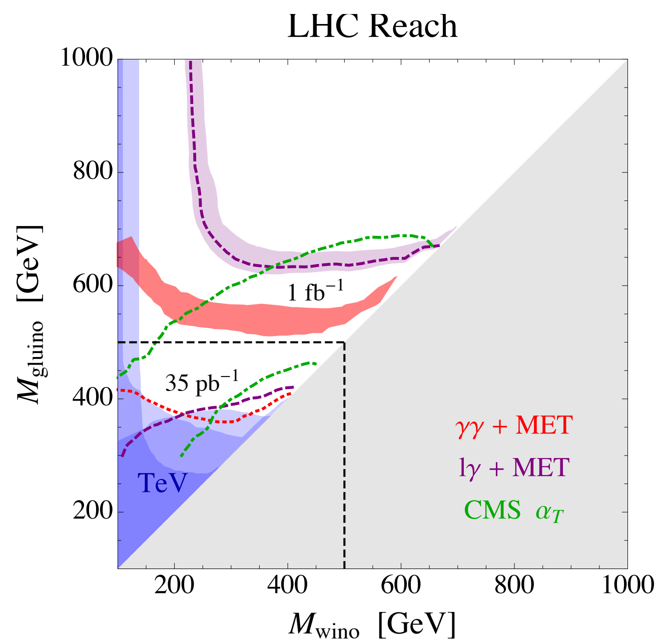
- We have been educated by Ruderman and Shih!
  - "General Neutralino NLSPs" [arXiv:1103.6083], thorough treatment of GGM neutralino signatures
- Bino, Wino, and Higgsino NLSPs (or mixtures thereof) give a rich spectrum of search signatures
  - Each final state targeted by a signature-based search
- Photon channels enjoy triggering advantage over more general jets+E_t^{miss} searches
  - Low statistics makes data-driven bkgd estimates challenging
- *Leave no stone unturned…*

Lepton+Photon+Missing Energy

- Signature of Wino NLSP
  - Charged and neutral winos are co-NLSPs



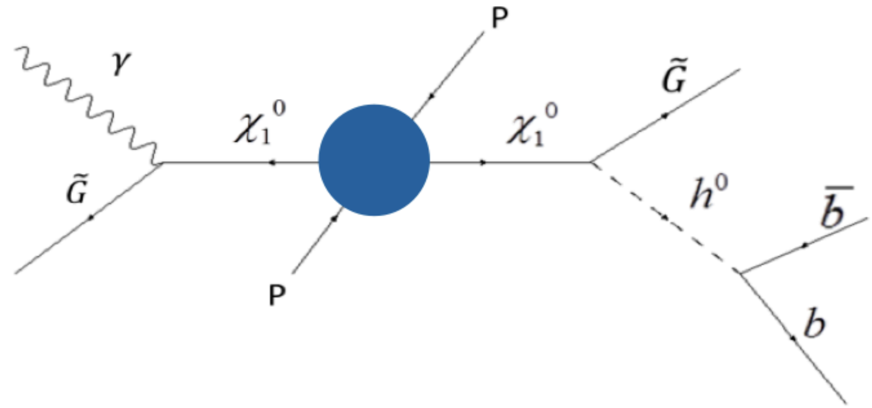


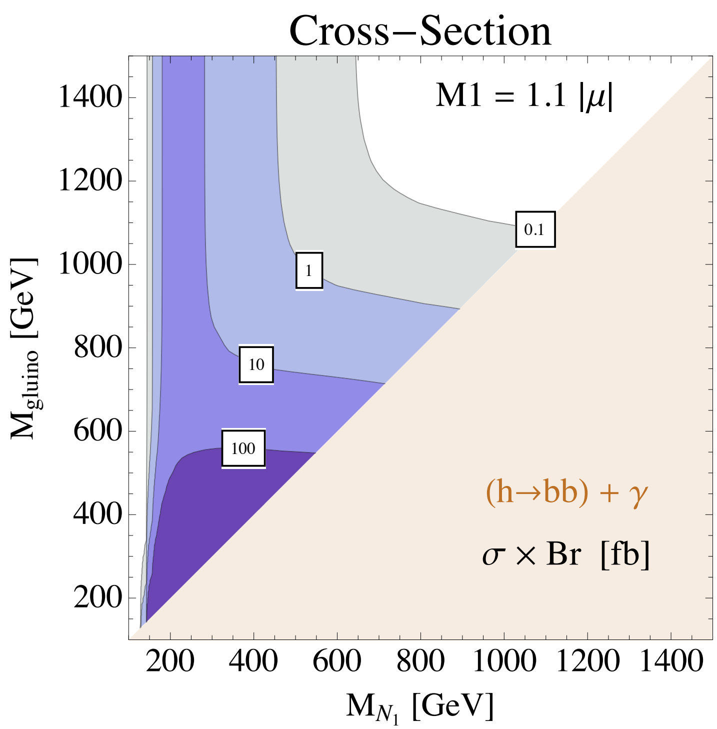


- Search at LHC benefits from strong production cross section, followed by cascade decays to winos

bb+Photon+Missing Energy

- Signature of NLSP bino-higgsino admixture
- Targeted search seems to out-perform general jets +missing energy searches

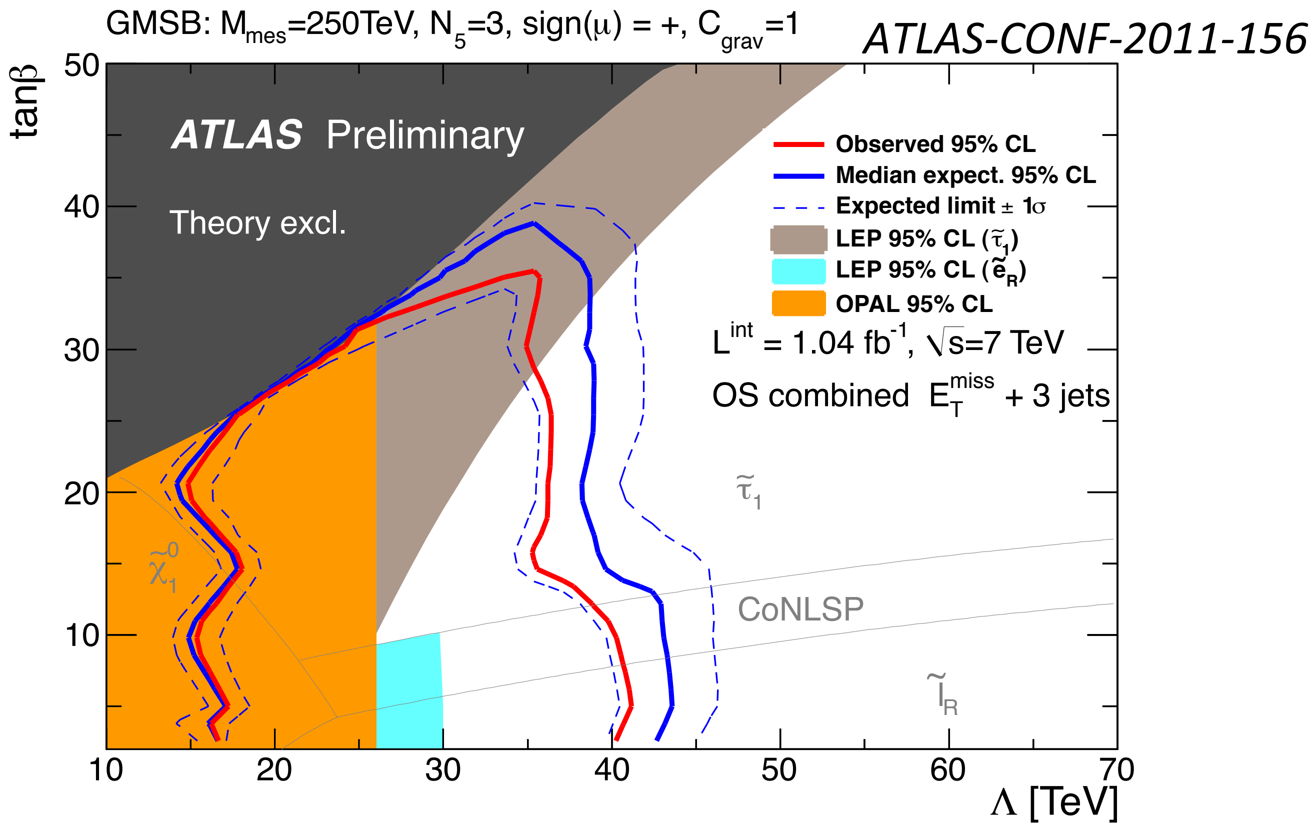




- For $|\mu|<0$ and small tan β, sizable decay to Higgs and photon
- $\gamma+b+E_T^{miss}$ is also interesting as model-independent search
- Since top quark pairs are main bkgd, use bb signature

GMSB Searches without Photons

- Search for 2 OS leptons + E_T^{miss} matches some NLSPs
- Interpreted in minimal GMSB as parameter exclusion



Plan to extend this to all relevant search signatures; some work to be done on defining common parameters

Possible LHC pp Run Schedule

- 2010-2011: 7 TeV, collected 5 fb^{-1} total
- 2012: 8 TeV, plan to collect 15 fb^{-1} more
- 2013-2014: 18-month shutdown for “Phase 0” upgrade
- 2014-2017: 13 TeV, 50 fb^{-1} (1×10^{34} $cm^{-2}s^{-1}$)
- 2018: 12-month shutdown for “Phase 1” upgrade
- 2019-2021: 13 TeV at full design luminosity, 300 fb^{-1}
- 2022: 12-month shutdown for “Phase 2” upgrade
- 2023-2030?: 13 TeV, potentially 3000 fb^{-1}

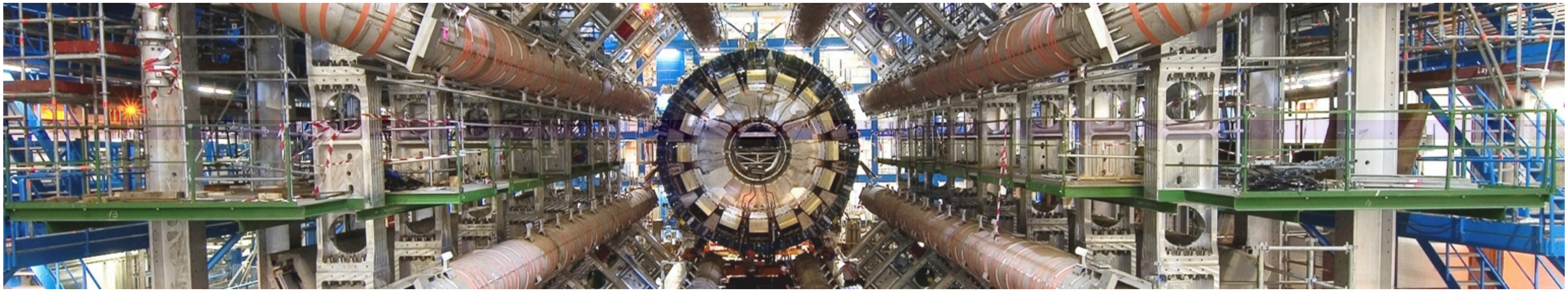
Summary

- The Large Hadron Collider is operating smoothly at 8 TeV, and the performance of the ATLAS experiment matches design expectations in most areas

- Searches for new physics in photon signatures put strong constraints on new physics models, *AND…*

- Good collaboration between experiments and theorists to understand how to probe this parameter space.

- Stay tuned for more news from the 8 TeV run this year!



Searches for New Physics in Photon+Missing Energy Signatures at ATLAS

Jason Nielsen

Santa Cruz Institute for Particle Physics

University of California, Santa Cruz

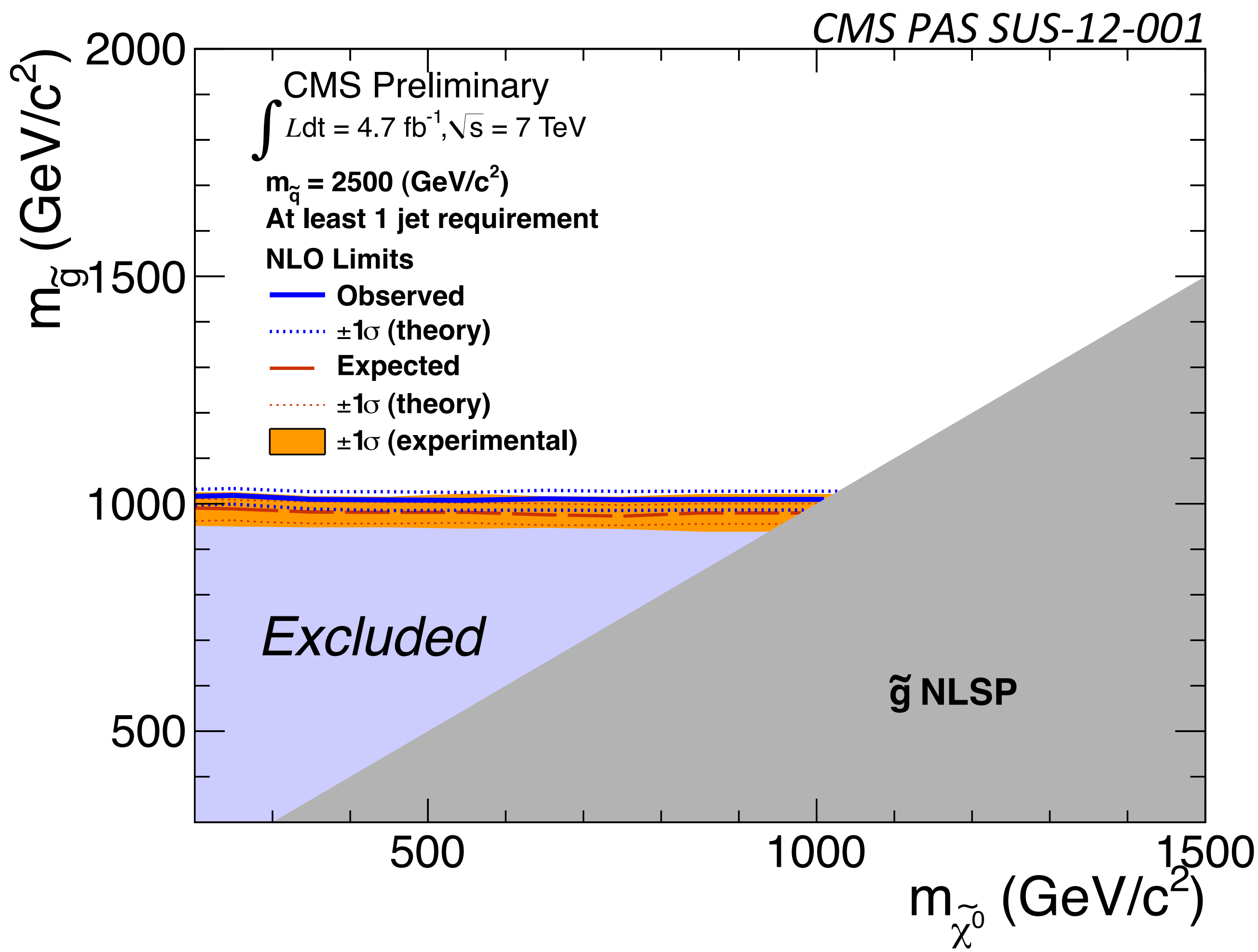
UC Davis High-Energy Seminar

June 5, 2012

Backup Slides

CMS Result in Photons+Missing Energy

- Photon E_T > 40, 25 GeV; missing E_T>100 GeV
- Jet p_T>30 GeV

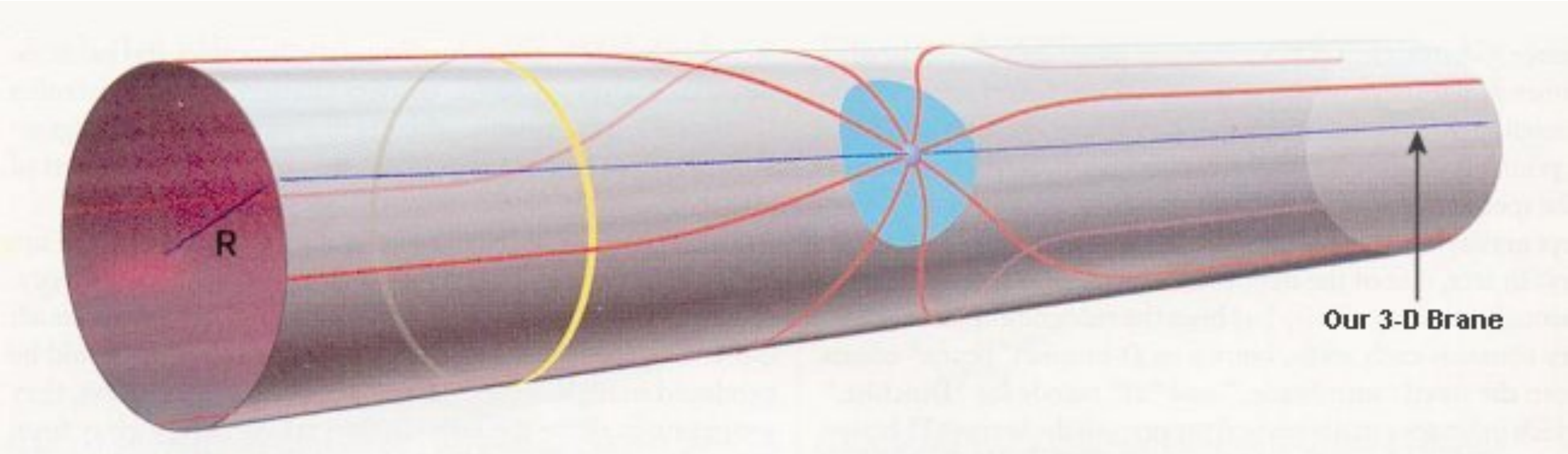


Photon Signatures of New Physics

- Clean final state signature with easily measured photons, possibly with missing transverse energy
  - Distinguish between non-resonant and resonant diphoton production: do the photons come from a single decay?
- Theories of supersymmetry predict $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
  - The gravitino could be a candidate to explain dark matter
- Extra dimensions give rise to new particle states, due to the particles confinement in the new dimensions
- Higgs boson decay $H \rightarrow \gamma\gamma$ yields a striking resonance
- These searches involve photons with E_T=20-100 GeV

Universal Extra Dimensions

- Postulate 1 or more new spatial dimensions, through which all particles propagate



SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patch*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines have filled the extra dimension, which has no further effect on the lines of force.

- All particles have higher-mass states (excitations) due to the confining compactified dimensions
  - The lightest, γ^* decays to γ+G (graviton, which doesn't interact)