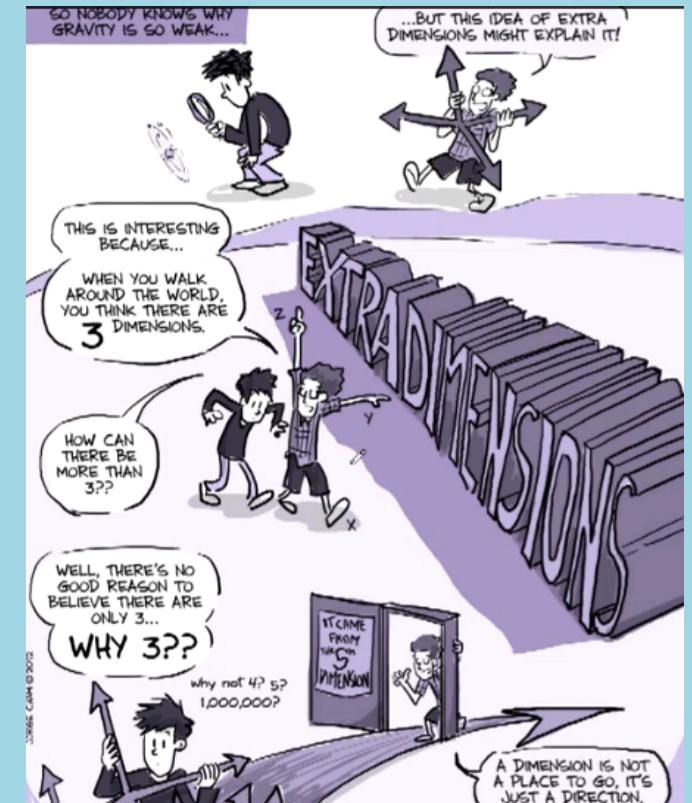
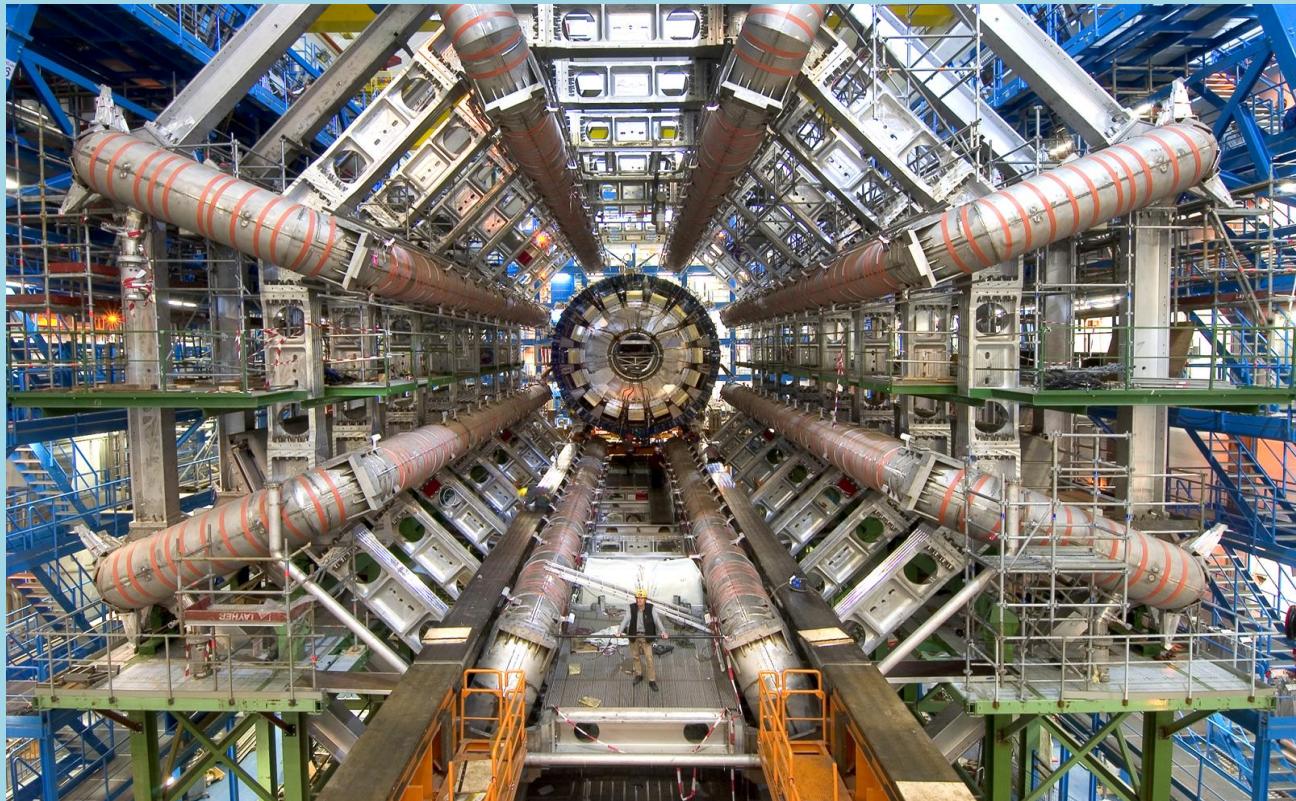


Searches for extra dimensions with ATLAS

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Why searching for extra dimensions ?

- The **hierarchy problem**:

The electroweak mass scale is very different from the Planck mass scale (M_{Pl}) ,
 $m_{W,Z} \ll M_{Pl} \sim 10^{19} \text{ GeV}$

→ Very large radiative corrections to the Higgs boson mass need to cancel out at a precision of 10^{-32}

- To avoid such a fine tuning:

- SUSY: additional contributions in the loops will stabilize the Higgs boson mass
- Extra dimensions: Gravity strength is at the same order of magnitude as the others interactions but diluted in extra spatial dimensions
 - Extra dimensions but which ones ?
 - **Universal** Extra Dimensions
 - **Warped** Extra Dimensions
 - **Large** Extra Dimensions
 - ...

The ATLAS experiment at the LHC

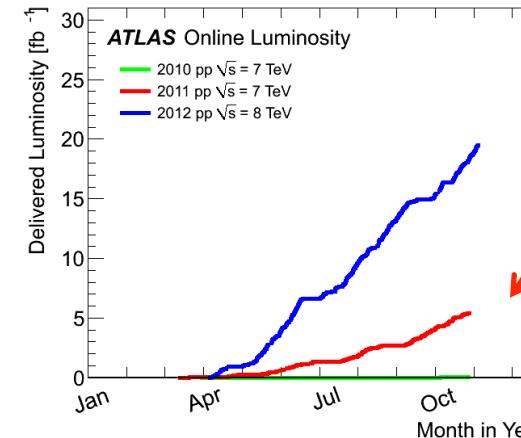
Almost 3 years of running:

~ 25 fb^{-1} of pp collisions with $\sqrt{s} = 7,8 \text{ TeV}$

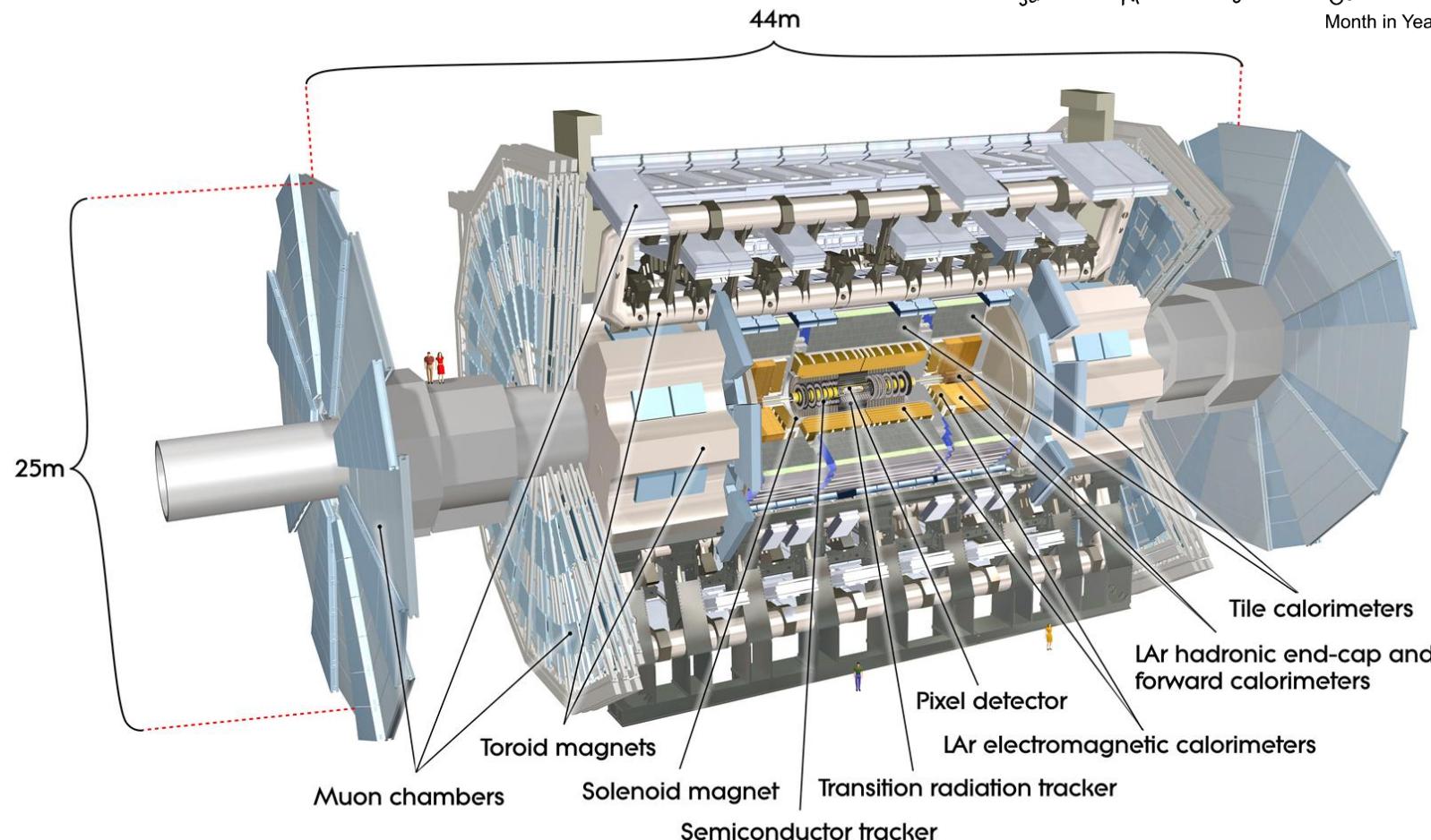
Peak luminosity: $7.7 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

(~30 interactions per bunch crossing)

ATLAS overall data-taking efficiency: 93.7%



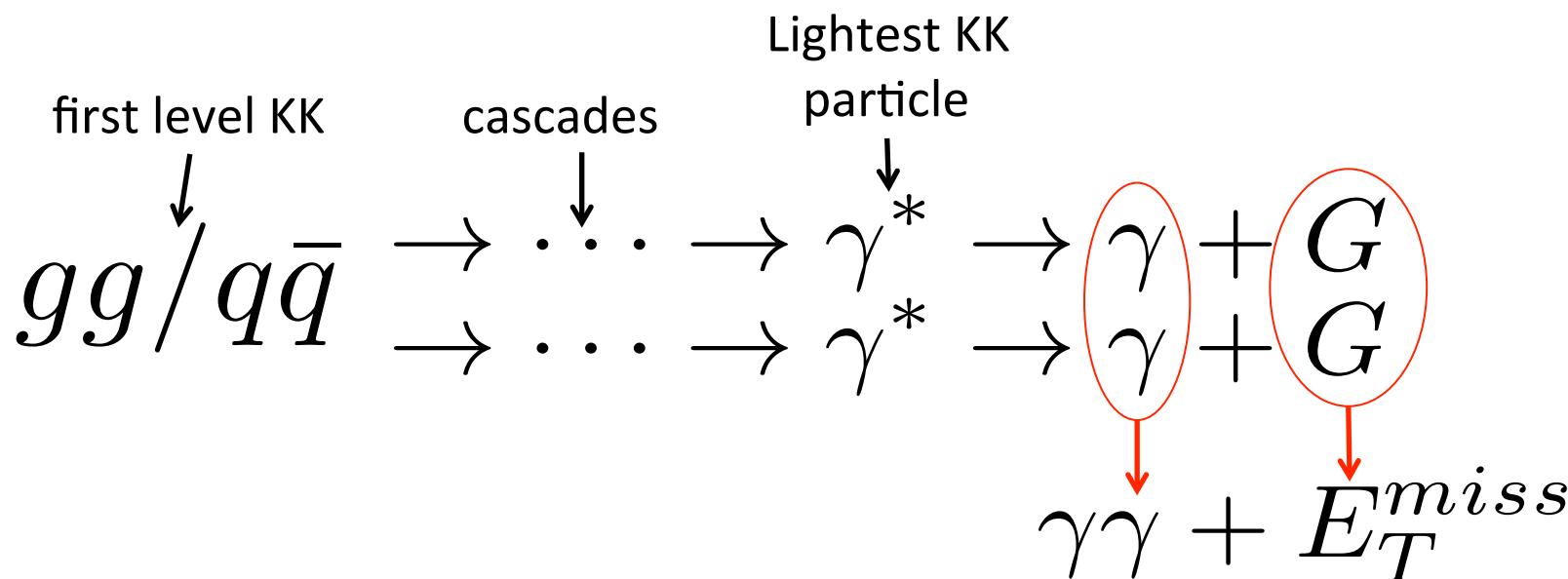
Used by the
searches
presented in
this talk



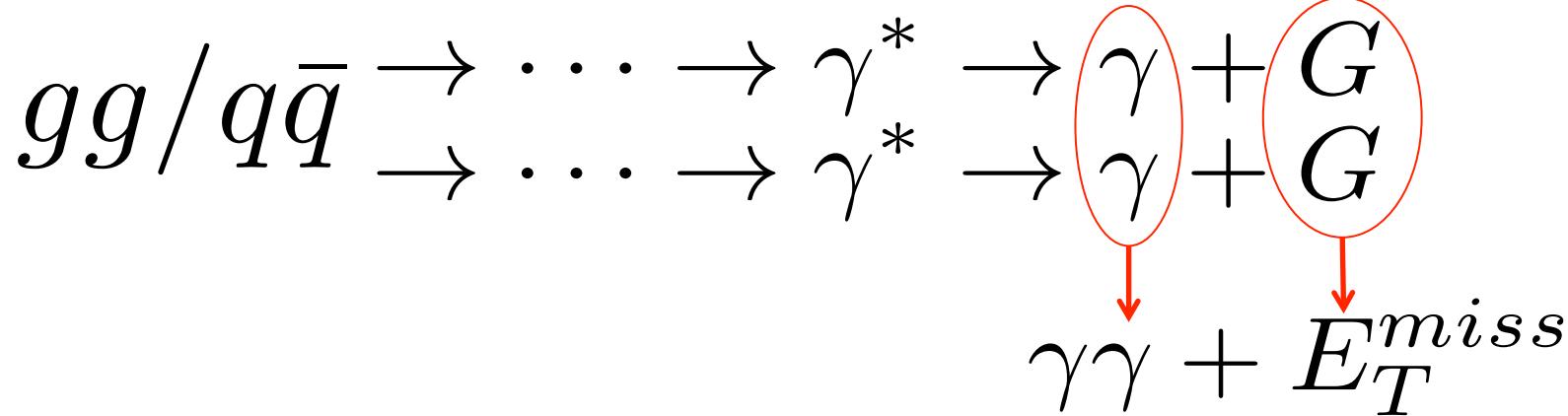
Universal Extra Dimensions: Diphoton + E_T^{miss} events

arXiv:1209.0753, sept. 2012, submitted to PLB

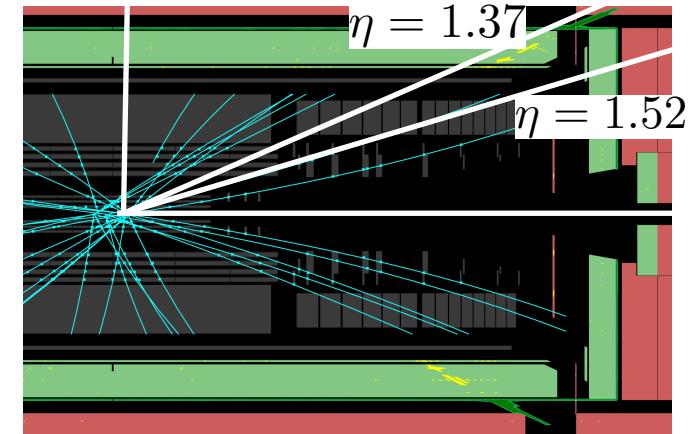
- Additional spatial dimensions in which **all** SM fields propagate
- **Compactified** extra dimensions:
 - Kaluza-Klein (**KK**) towers are predicted for each SM particle
- This analysis considers a **single** UED with compactification radius $R \sim 1 \text{ TeV}^{-1}$
- If the UED model is embedded in a larger space with $N \text{ eV}^{-1}$ -sized dimensions accessible **only** to gravity, then the **decay chain** is:



Universal Extra Dimensions: Diphoton + E_T^{miss} events



- Trigger: two photons with $E_T > 20$ GeV
- Data analysis:
 - Two photons with:
 - $p_T > 50$ GeV and $|\eta| < 2.37$ ($1.37 < |\eta| < 1.52$ excl.)
 - Identified (shower shape requirement)
 - Isolated (calorimetric cone isolation)
 - Large E_T^{miss} requirement:** $E_T^{\text{miss}} > 200$ GeV
 - Total visible transverse energy (H_T) requirement: $H_T > 600$ GeV
 - Photons far away from the E_T^{miss} direction: $\Delta\phi_{\min}(\gamma, E_T^{\text{miss}}) > 0.5$



Universal Extra Dimensions: Diphoton + E_T^{miss} events

Background estimation:

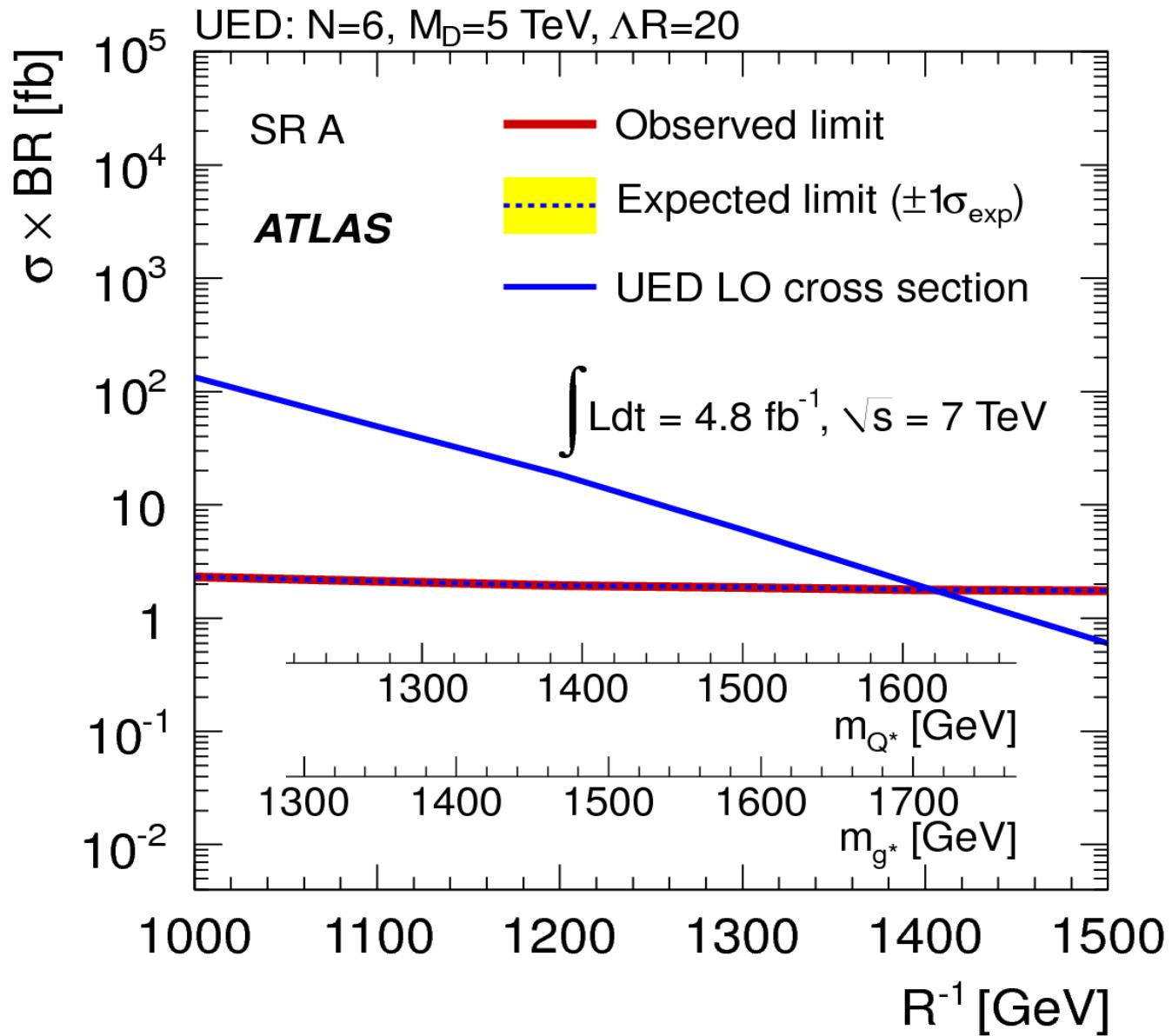
- QCD: $\gamma\gamma$, $\gamma+\text{jet}$ and multijet events
 - Data control sample selected by reverting the ID requirement on one of the photons
 - Estimation with a H_T “sidebands method”
- Electroweak: $W+X$ and $t\bar{t}$
 - “electron-photon” control sample passing the analysis selection
 - Scaled by the probability for an electron to be misreconstructed as a good photon.
- Irreducible: $W+\gamma\gamma$ and $Z+\gamma\gamma$
 - negligible from MC simulation

QCD	$0.07 \pm 0.00 \pm 0.07$
Electroweak ($W + X$ and $t\bar{t}$)	$0.03 \pm 0.03 \pm 0.01$
$W(\rightarrow l\nu) + \gamma\gamma$	< 0.01
$Z(\rightarrow \nu\bar{\nu}) + \gamma\gamma$	< 0.01
Total	$0.10 \pm 0.03 \pm 0.07$
Observed	0

Universal Extra Dimensions: Diphoton + E_T^{miss} events

- UED signal generated with PYTHIA 6
- Signal efficiency $\sim 30\%$
- Signal uncertainty $\sim 6\%$
- PDFs and scale uncertainties are not included

Limit: $1/R < 1.40 \text{ TeV}$



Warped Extra Dimensions

Postulated by Randall and Sundrum (RS): Phys. Rev. Lett. 83 (1999) 3370

- Gravity is the **only** field allowed to propagate into the five-dimensional space (**bulk**)

- The strength of gravity is diluted through a warp factor **k**:

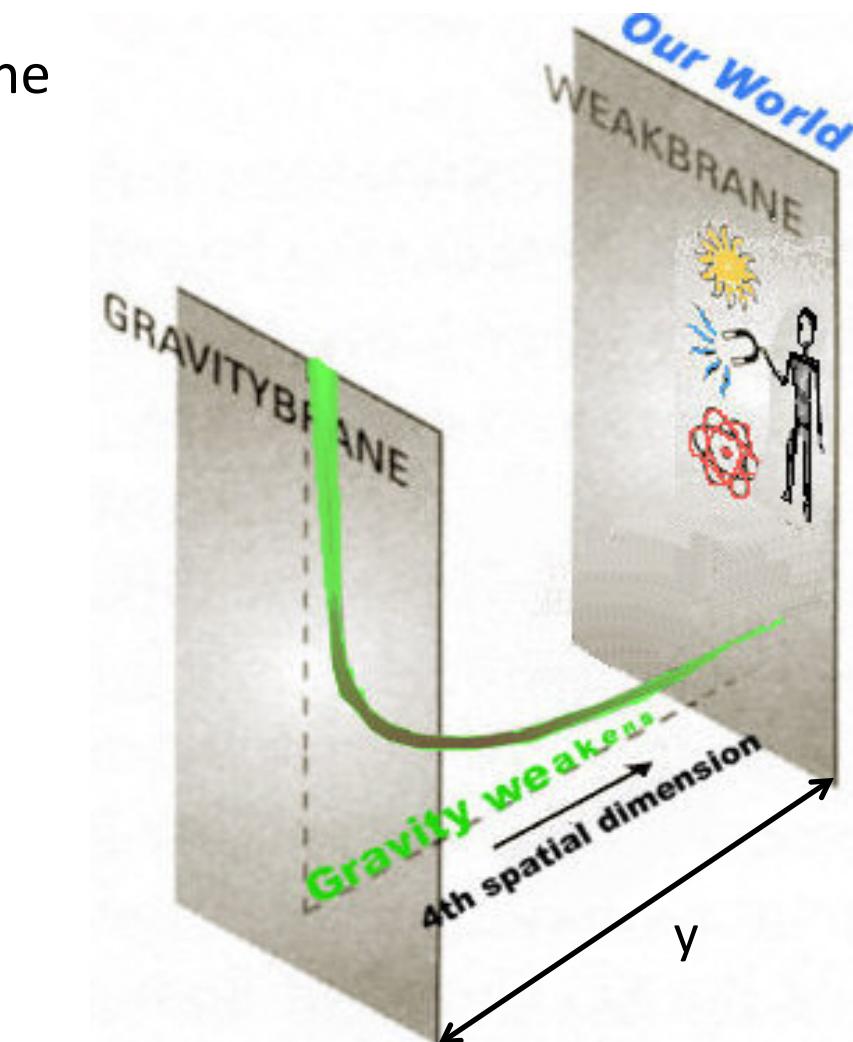
$$ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$$

- The **compactification** leads to a series of equally spaced Kaluza-Klein resonances

→ Search for a **narrow resonance** in the detector

- Model parameterization:

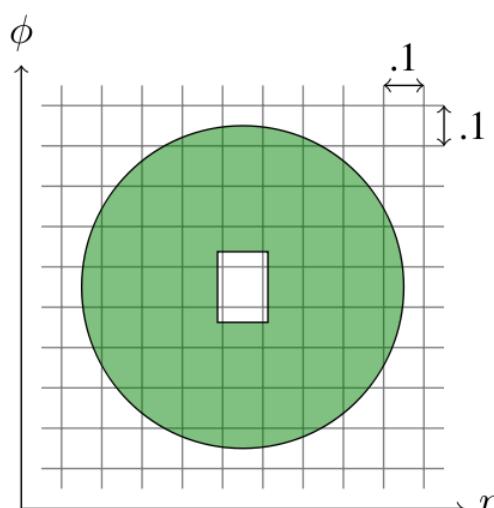
- Mass of the lightest KK tower: **m_G**
- Coupling of the graviton to the SM fields: **k/M_{Pl}**



Warped Extra Dimensions: Dilepton Events

$q\bar{q}/gg \rightarrow G \rightarrow l^+l^-$

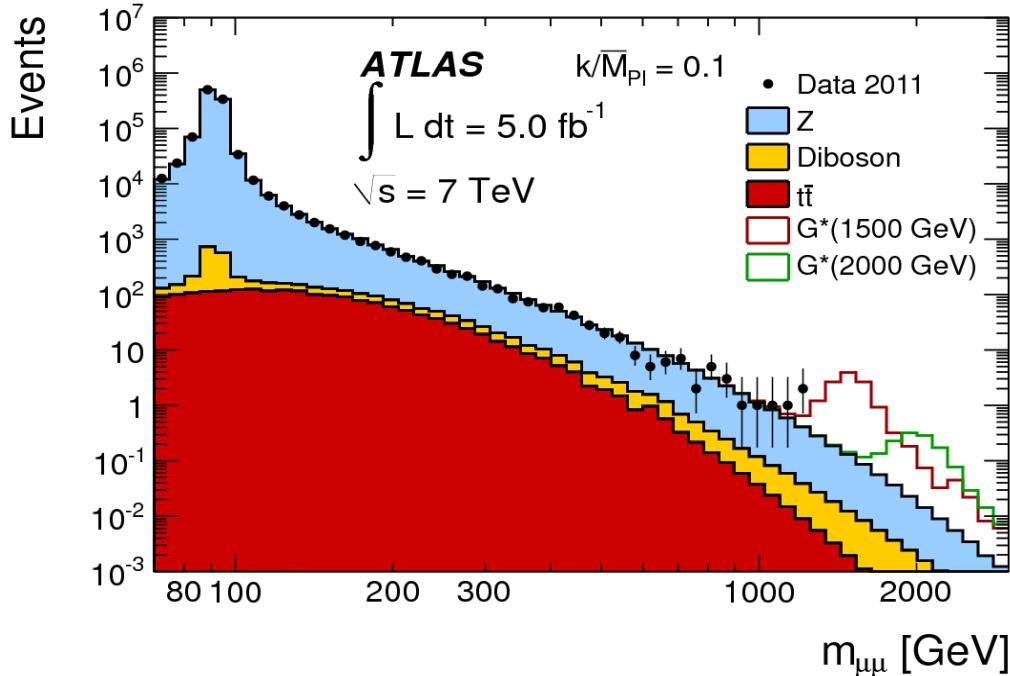
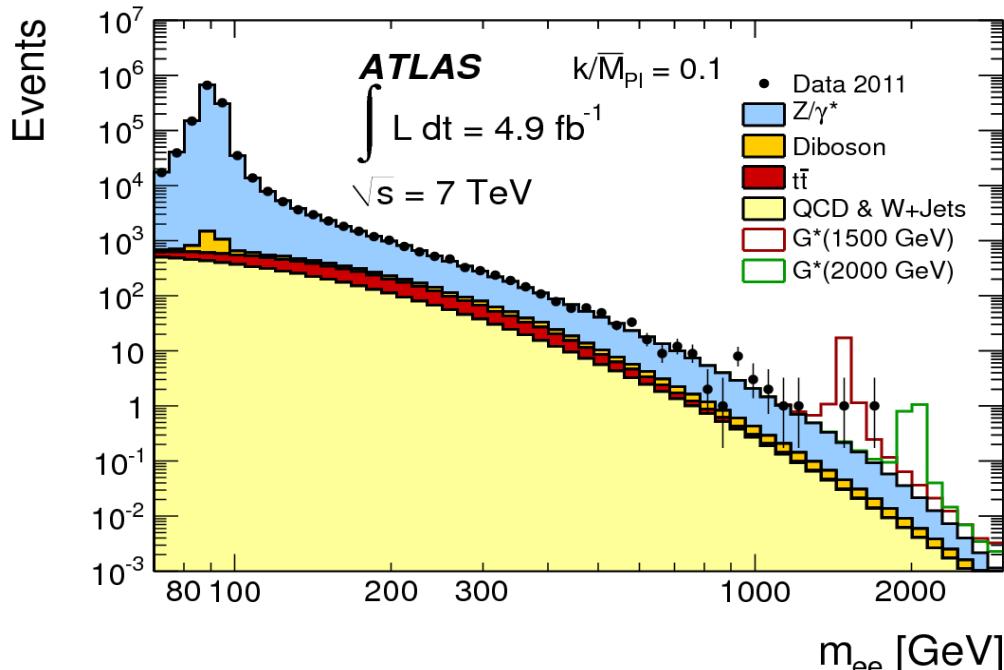
arXiv:1209.2535, Sept. 2012, submitted to JHEP

	e ⁺ e ⁻ channel	μ ⁺ μ ⁻ channel
Trigger	Diphoton trigger with $p_T > 20$ GeV	Single muon trigger with $p_T > 22$ GeV
Data selection	<p>Two electrons candidates with:</p> <ul style="list-style-type: none"> - $p_T > 25$ GeV - $\eta < 2.47$ ($1.37 < \eta < 1.52$ excl.) - Identified (shower shape + track requirements) <p>Highest p_T electron is isolated: $E_T(\text{iso}) < 7$ GeV Calorimetric cone ($dR=0.2$) isolation with leakage and pileup correction</p>	<p>Two opposite charge muons with:</p> <ul style="list-style-type: none"> - $p_T > 25$ GeV - $\eta < 2.4$ - Impact parameter requirement : Remove cosmic rays background 

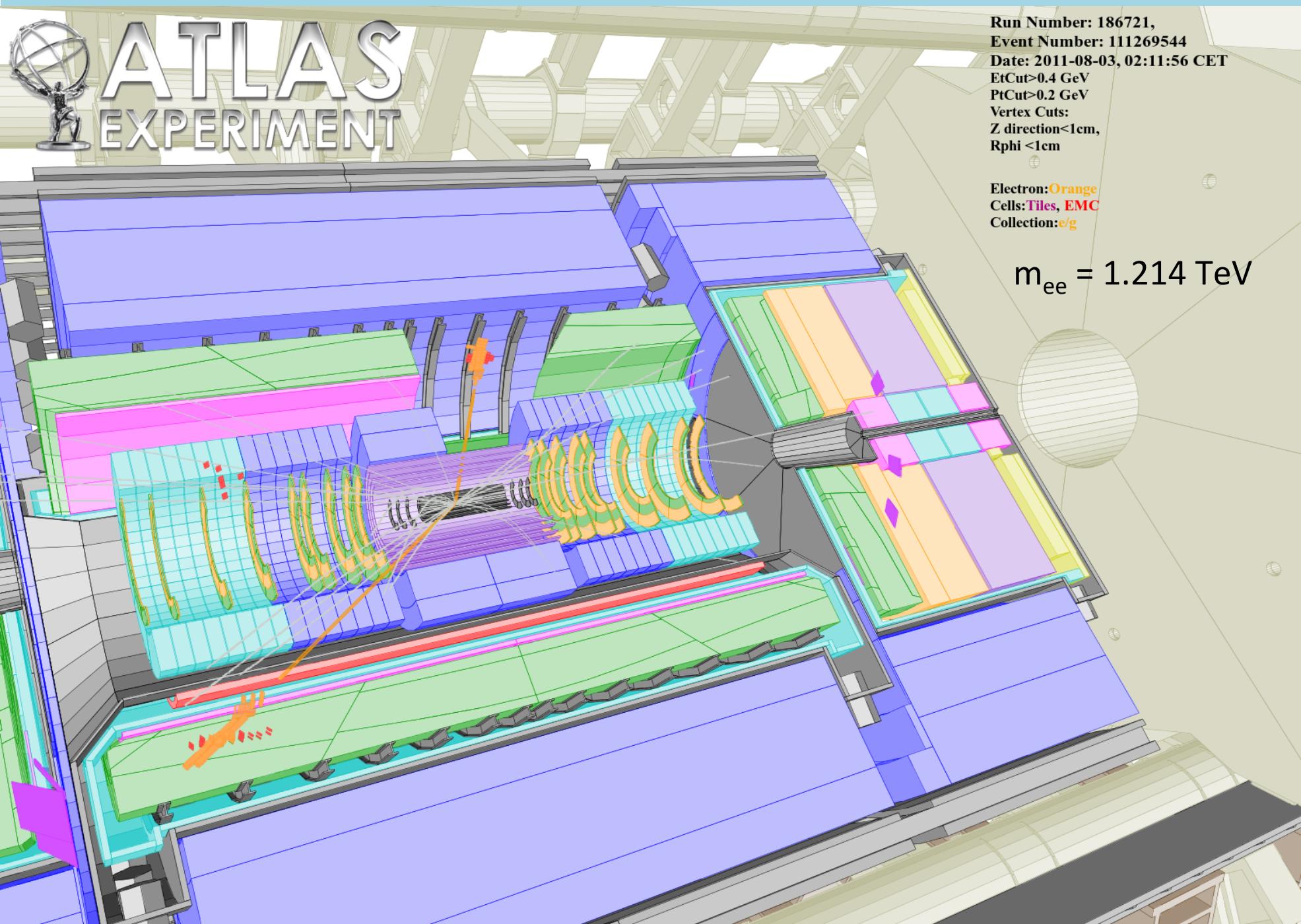
Warped Extra Dimensions: Dilepton Events

Background estimation:

- Drell-Yan, $t\bar{t}$ and dibosons:
 - $m_{||}$ shapes are taken from MC simulations
 - Normalized to the most precise available theoretical predictions
- QCD and W+jets:
 - data driven estimate
- The total prediction is normalized to the data under the Z peak (70 GeV – 110 GeV)
- At $m_{||} = 2$ TeV, 34% uncertainty on the background for dielectrons and 21% for dimuons dominated by theoretical uncertainties
- Search for a bump and no significant excess found for $m_{||} > 130$ GeV

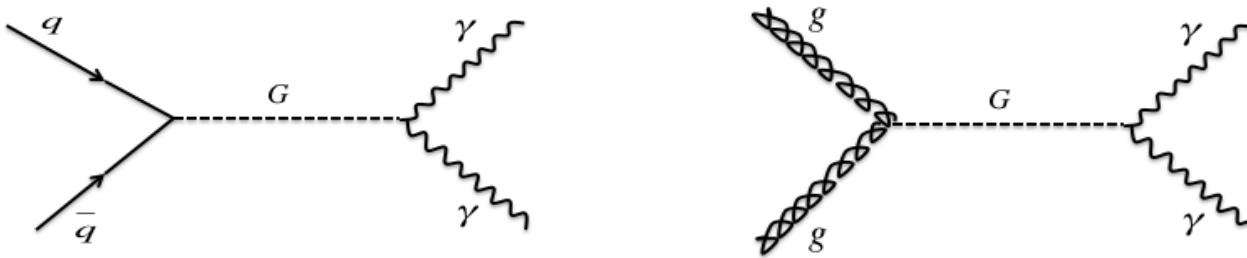


Dielectron candidate event



Warped Extra Dimensions: Diphoton Events

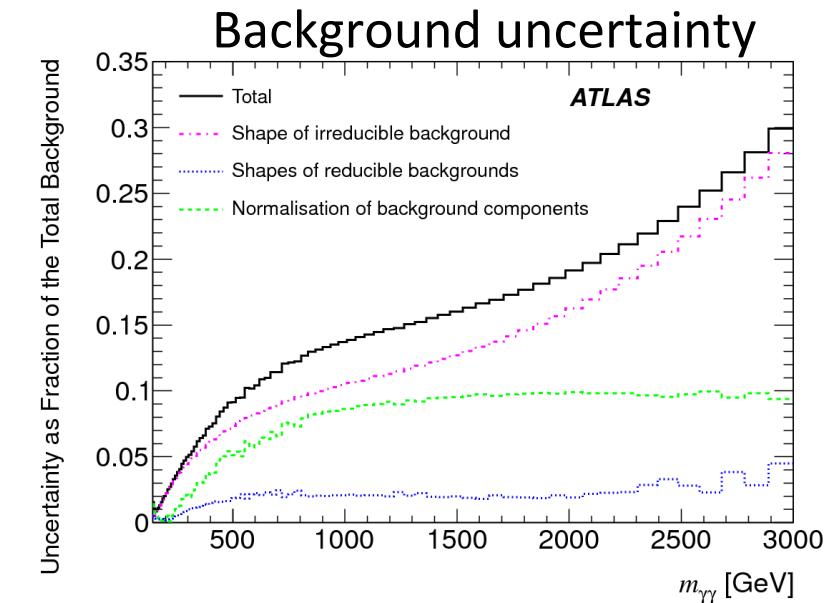
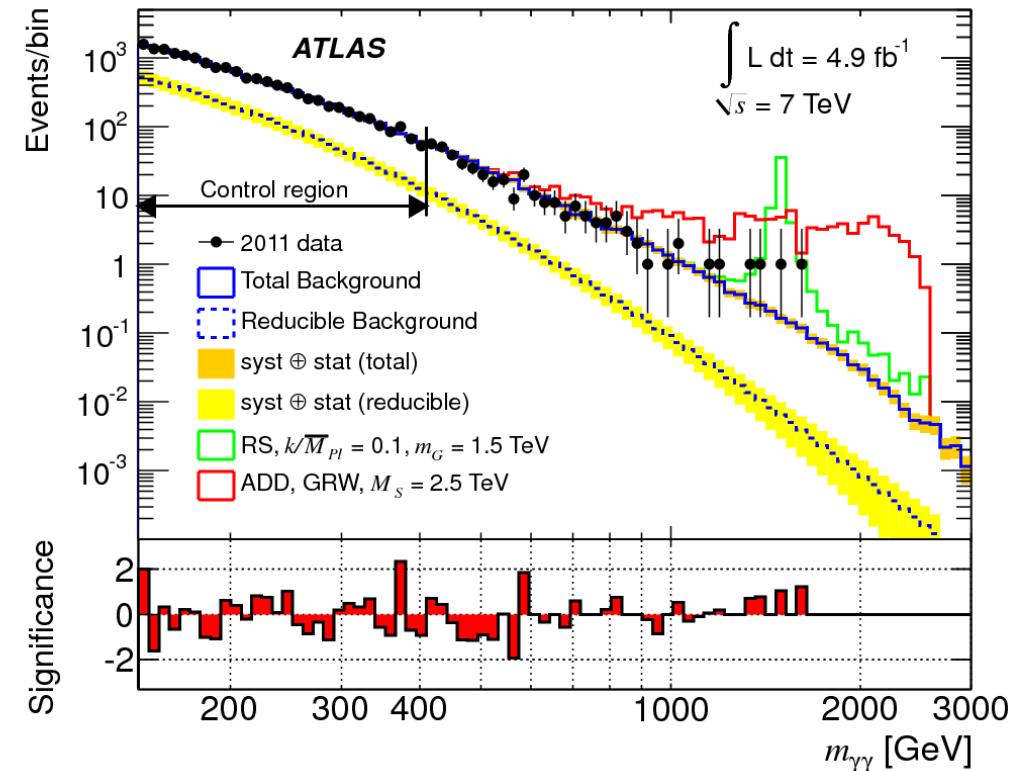
arXiv:1210.8389, Oct. 2012, submitted to PLB



- Trigger: two photons with $E_T > 20$ GeV
- Data selection:
 - At least two photons with:
 $E_T > 25$ GeV and $|\eta| < 2.37$ ($1.37 < |\eta| < 1.52$ excl.)
 - Require the two highest pT photon:
 - Identified (Shower shapes requirements)
 - Isolated: calorimetric cone ($dR=0.4$) isolation
 $E_T(\text{Iso}) < 5$ GeV

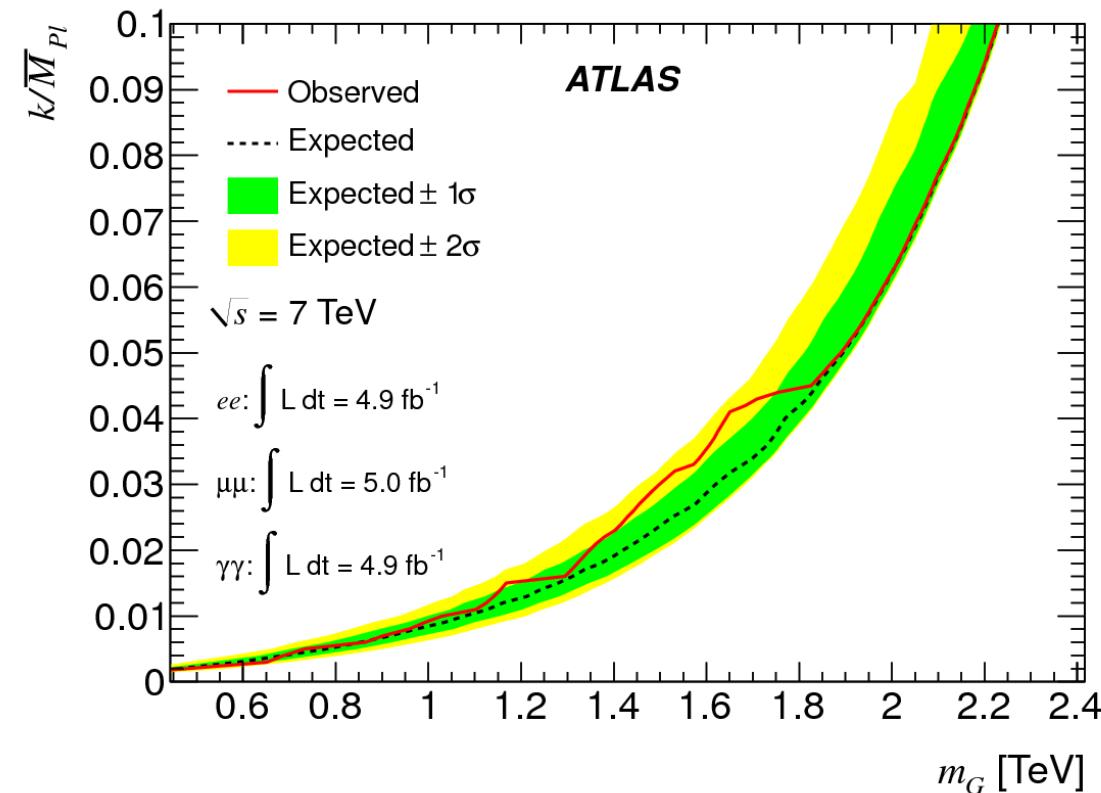
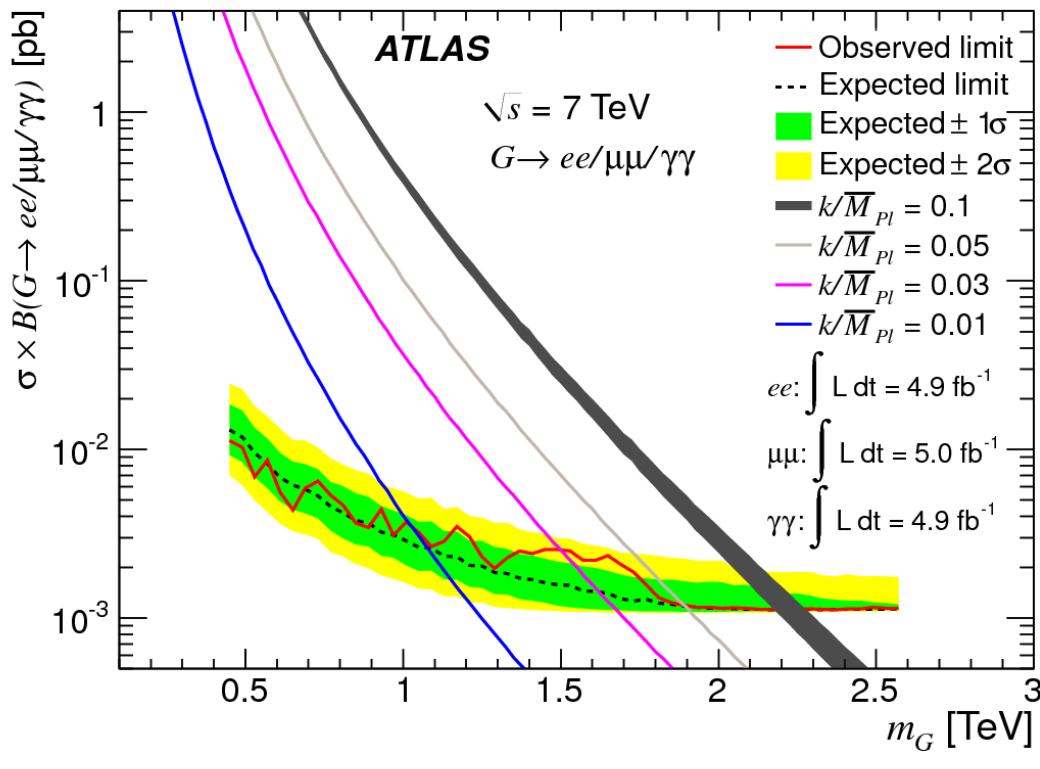
Warped Extra Dimensions: Diphoton Events

- Background estimation:
 - SM $\gamma\gamma$ production is estimated with MC simulations
 - $\gamma+\text{jet}$ and **dijets events** with jets faking photons (reducible background) are taken from data control samples
 - background from electrons faking photons (such as $Z \rightarrow ee$ events) are negligible
- Use the data control region:
 - Background composition
 - Background normalization
- Search for a bump and no significant excess found in the full spectrum
→ We can set limit on RS models



Warped Extra Dimensions: Limits

- RS models simulated with PYTHIA 6.4



Channel(s) Used	95% CL Observed (Expected) Limit [TeV]			
	k/\overline{M}_{Pl} Value			
	0.01	0.03	0.05	0.1
$G \rightarrow \gamma\gamma$	1.00 (0.98)	1.37 (1.49)	1.63 (1.73)	2.06 (2.05)
$G \rightarrow ee/\mu\mu$	0.92 (1.02)	1.49 (1.53)	1.72 (1.81)	2.16 (2.17)
$G \rightarrow \gamma\gamma/ee/\mu\mu$	1.03 (1.08)	1.50 (1.63)	1.89 (1.90)	2.23 (2.23)

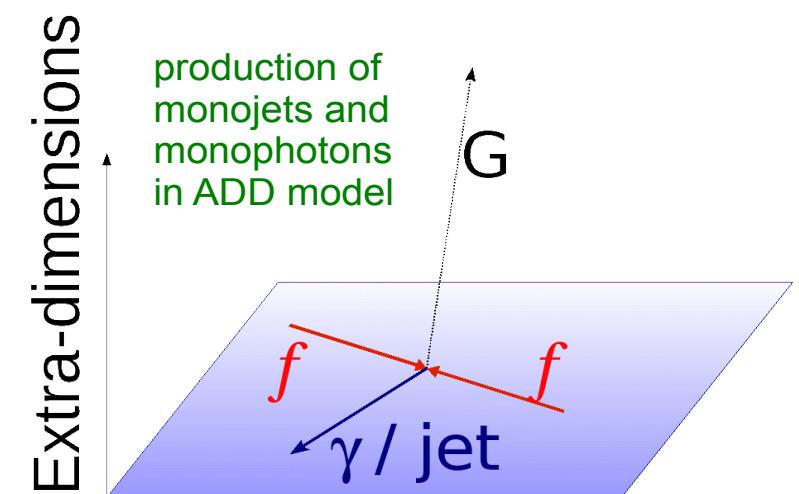
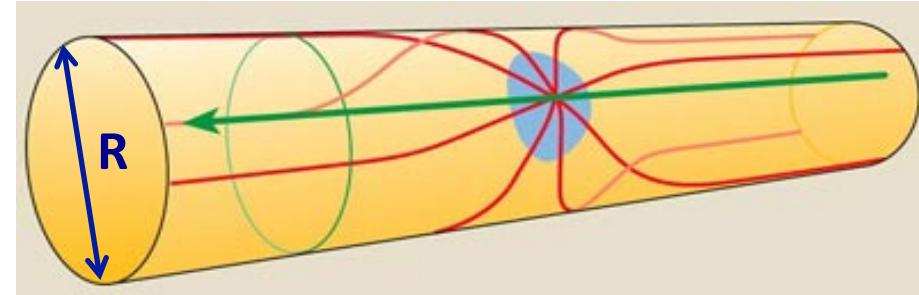
Large Extra Dimensions

Postulated by Arkani-Hamed, Dimopoulos, Dvali (ADD): Phys. Lett. B 429 (1998) 263

- Postulate n flat extra spatial dimensions with a compactification radius R
- Gravity is the **only** field propagating in the bulk
- The compactification with $R \sim O(\text{mm})$ leads to a continuum spectrum of KK excitations
- The 4D Planck scale M_{Pl} is related to the fundamental Planck scale M_D :

$$M_{Pl}^2 \sim M_D^{2+n} R^n$$

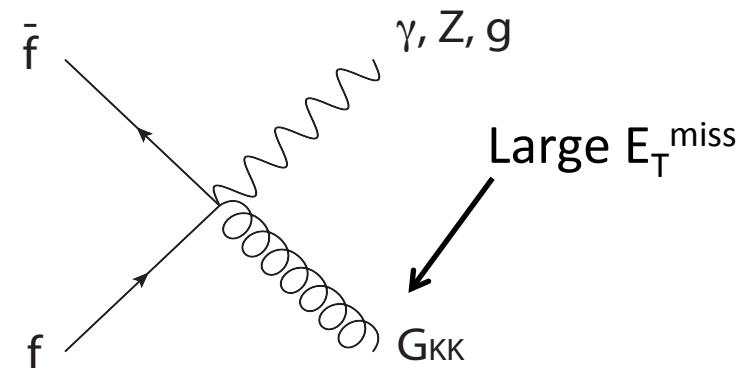
- Direct graviton emission depends directly on M_D
 - **Monophoton/Monojet** searches
- Virtual exchange depends on the ultraviolet cutoff (M_S) of the KK spectrum
 - **Diphoton, Dilepton** searches



Large Extra Dimensions: Monophoton events

arXiv:1209.4625, Sept. 2012, submitted to PRL

- Trigger:
 - $E_T^{\text{miss}} > 70 \text{ GeV}$
- Data selection
 - Large E_T^{miss} requirement : $E_T^{\text{miss}} > 150 \text{ GeV}$
 - A photon with :
 - $p_T > 150 \text{ GeV}$ and $|\eta| < 2.37$ ($1.37 < |\eta| < 1.52$ excl.)
 - Allow at most one jet:
 - $p_T > 30 \text{ GeV}$ and $|\eta| < 4.5$
 - Photon and (possible) jet far away from the E_T^{miss} direction:
 - $\Delta\phi(\gamma, E_T^{\text{miss}}) > 0.4$, $\Delta\phi(\text{jet}, E_T^{\text{miss}}) > 0.4$, $\Delta R(\gamma, \text{jet}) > 0.4$
 - Veto events with identified leptons:
 - Reduce $W + \gamma$, $Z + \gamma$ background
 - Cleaning cut applied to suppress fake calorimeter signal, cosmic rays

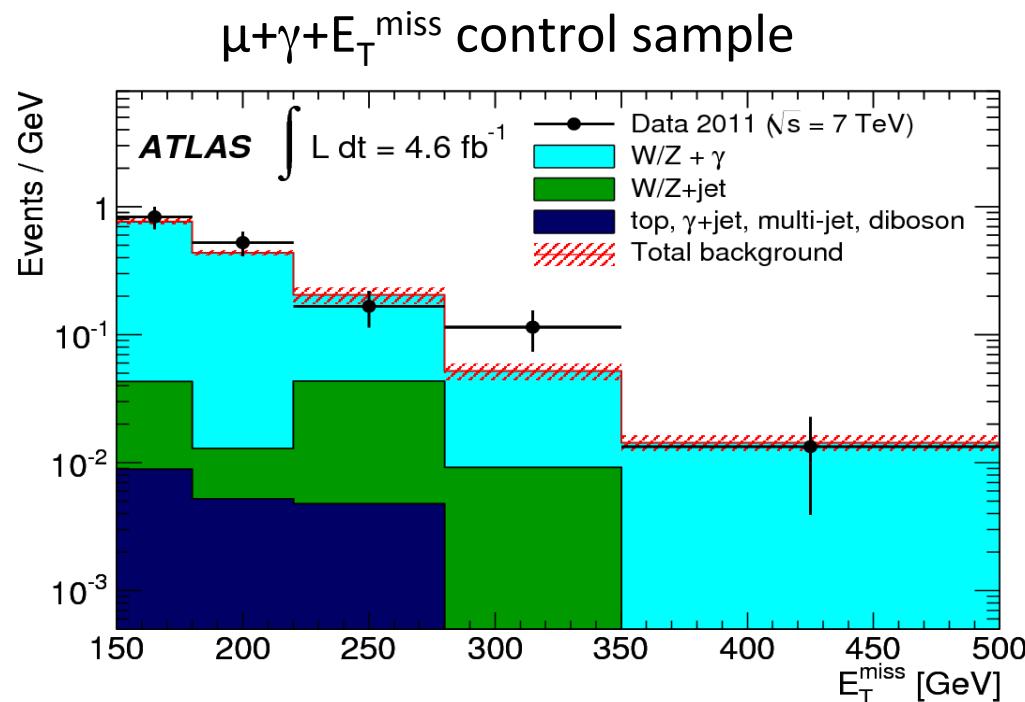


ATLAS-CONF-2012-020

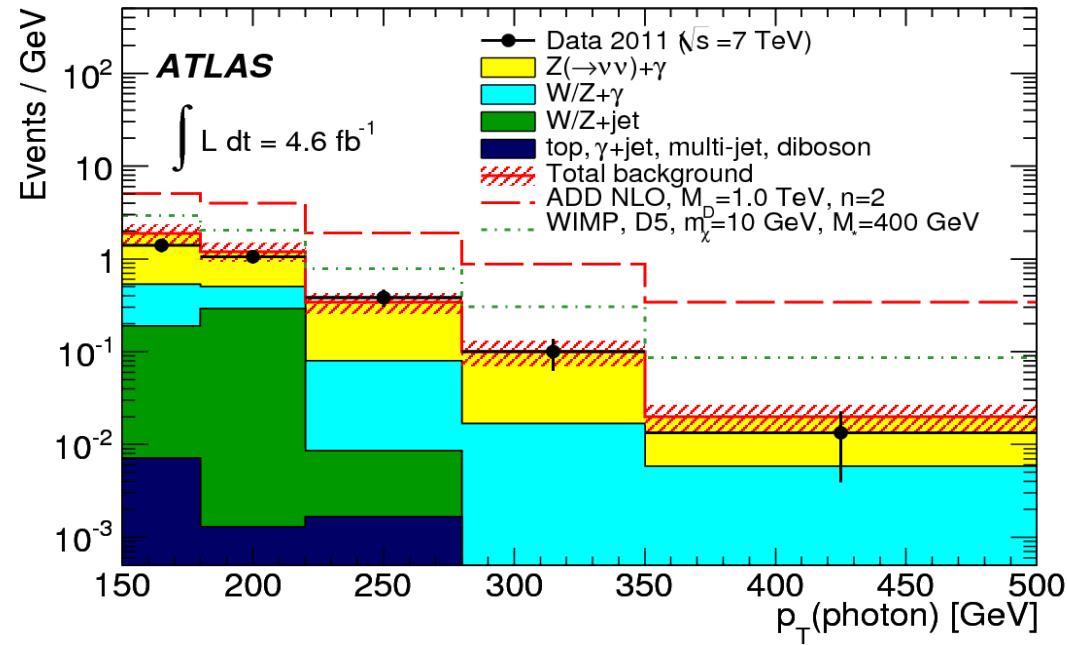
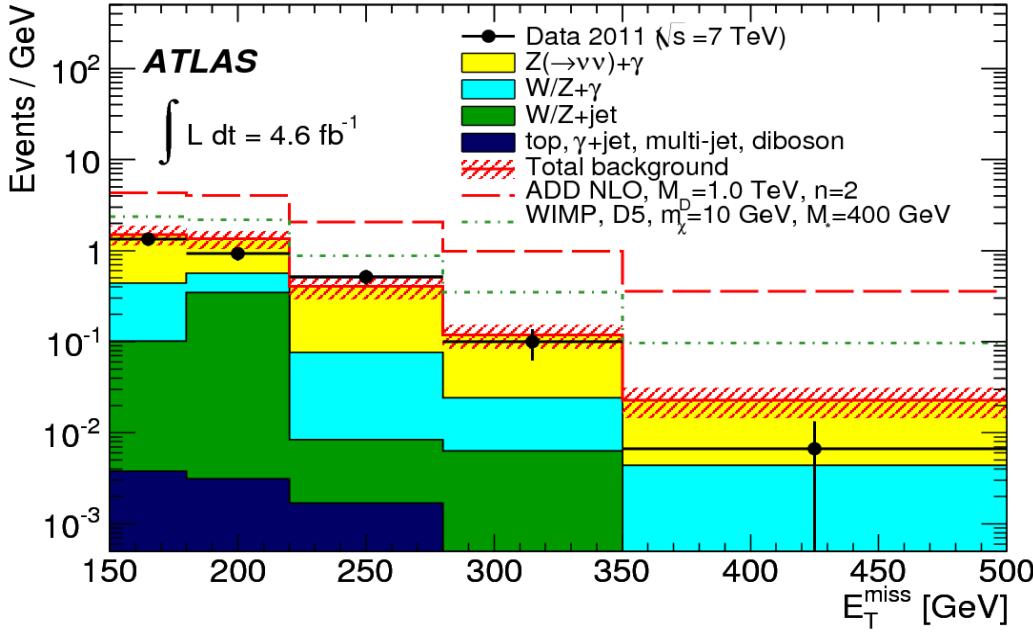
Large Extra Dimensions: Monophoton events

- Background estimation:
 - $Z(\rightarrow \nu\nu) + \gamma$, $Z(\rightarrow l^+l^-) + \gamma$ and $W + \gamma$ obtained from MC simulations.
 - Normalization obtained from a data control sample
 - $W/Z + \text{jets}$: jet $\rightarrow \gamma$ and $e \rightarrow \gamma$ fake from data driven estimate
- Given the good agreement between data and expectation, limits can be set on ADD models parameters

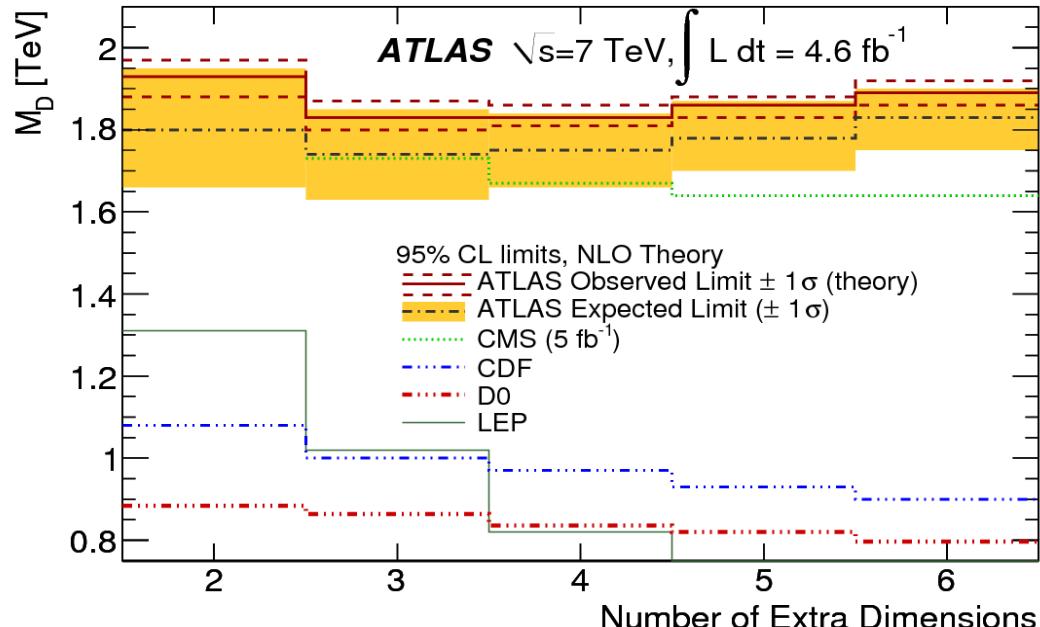
Background source	Prediction	\pm (stat.)	\pm (syst.)
$Z(\rightarrow \nu\bar{\nu}) + \gamma$	93	± 16	± 8
$Z/\gamma^*(\rightarrow l^+l^-) + \gamma$	0.4	± 0.2	± 0.1
$W(\rightarrow l\nu) + \gamma$	24	± 5	± 2
$W/Z + \text{jets}$	18	—	± 6
Top	0.07	± 0.07	± 0.01
$WW, WZ, ZZ, \gamma\gamma$	0.3	± 0.1	± 0.1
$\gamma + \text{jets}$ and multi-jet	1.0	—	± 0.5
Total background	137	± 18	± 9
Events in data (4.6 fb^{-1})	116		



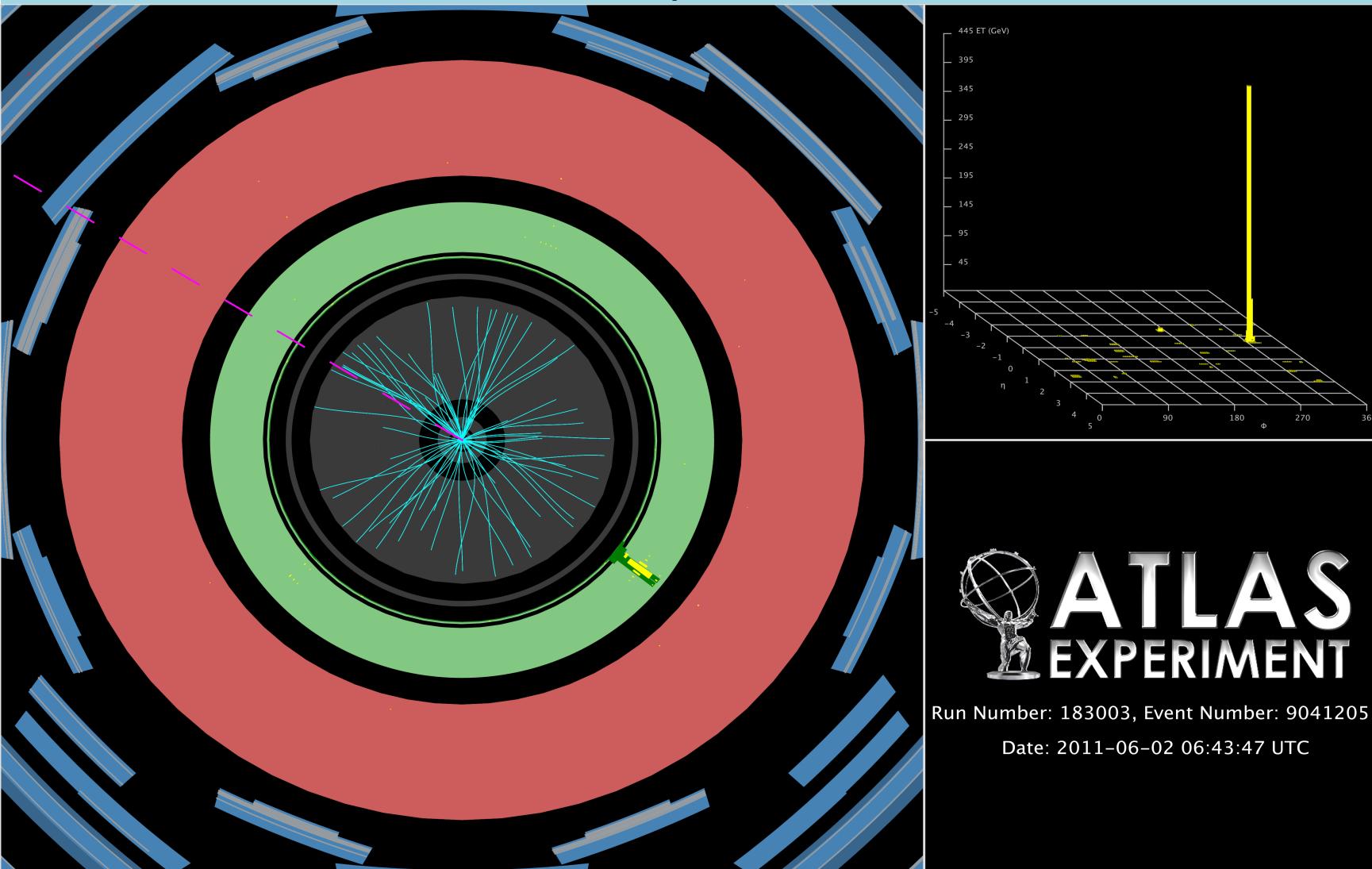
Large Extra Dimensions: Monophoton events



- ADD models simulated with Pythia 8
- Signal efficiency $\sim 20\%$
- Limit on M_D as a function of N_{ED}



Monophoton candidate event



$E_T^{\text{miss}} = 447 \text{ GeV}$

Photon $E_T = 450 \text{ GeV}$



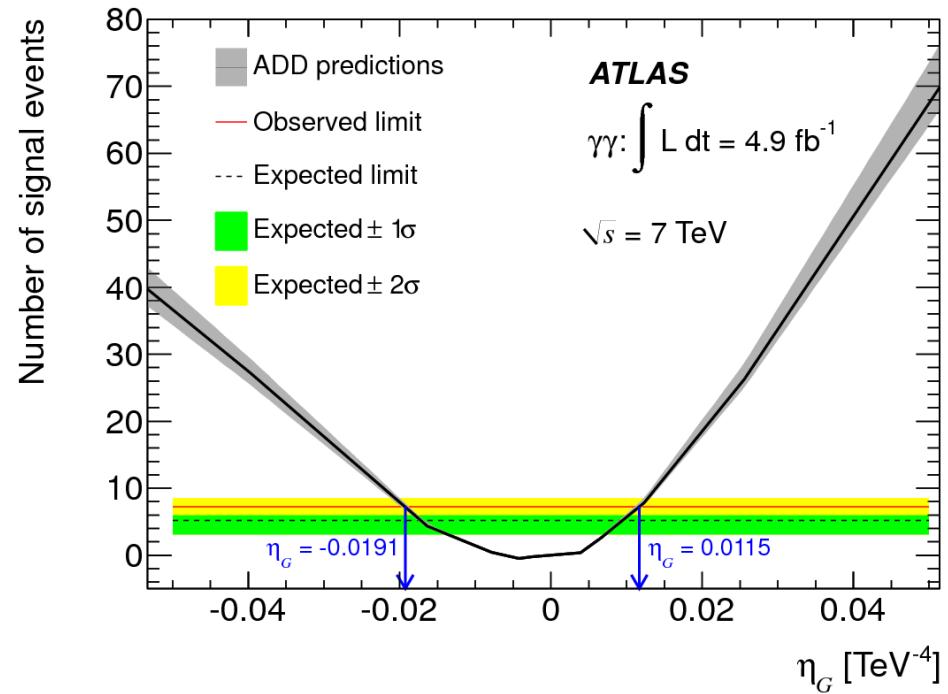
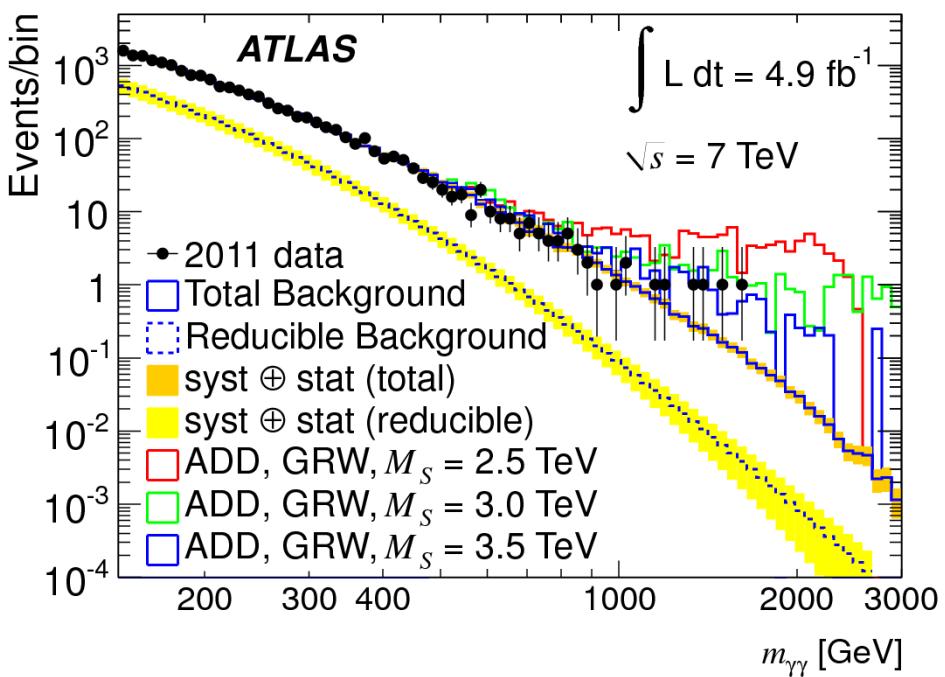
Run Number: 183003, Event Number: 90412055

Date: 2011-06-02 06:43:47 UTC

Large Extra Dimensions: Diphoton events

- Limit set on the ultraviolet cutoff of the KK spectrum: M_S
- ADD models simulated with Sherpa for various values of M_S
- Optimized search region: $m_{\gamma\gamma} > 1217 \text{ GeV}$
 - 4 observed events and 2.32 ± 0.37 expected events

ATLAS-CONF-2012-087



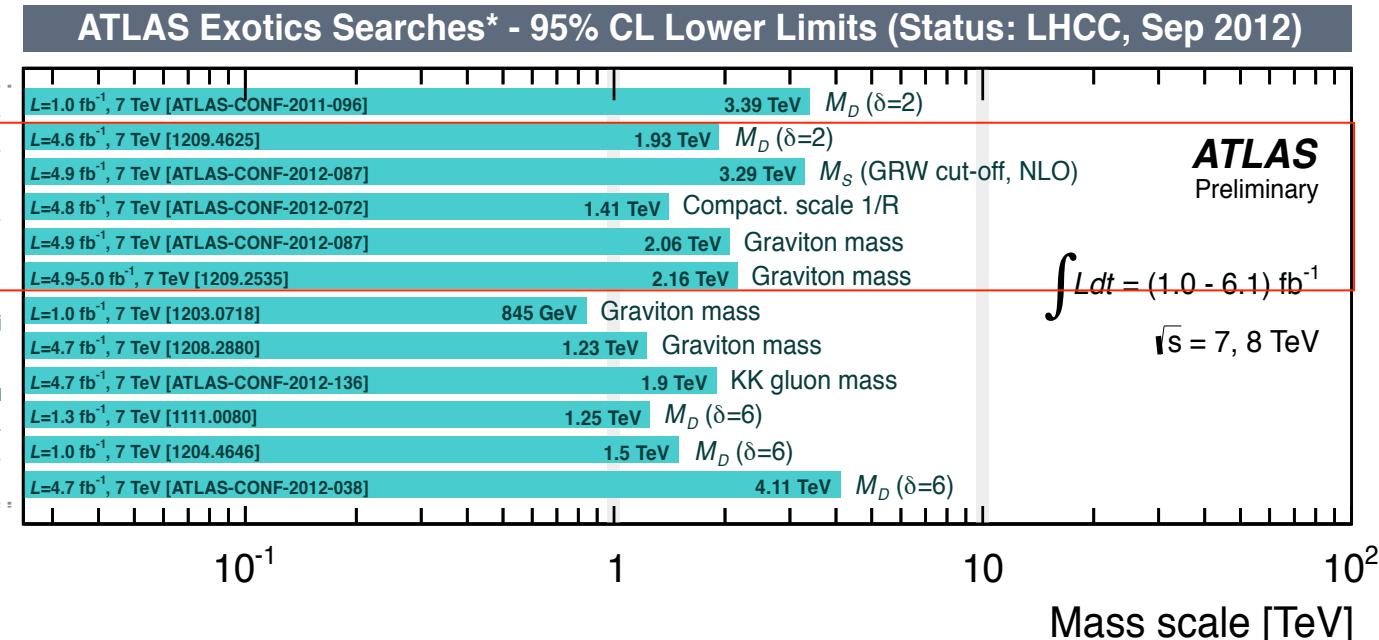
ADD Parameter	GRW	Hewett		HLZ				
		Neg.	Pos.	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
F	1	$-2/\pi$	$2/\pi$	2	1	$2/3$	$2/4$	$2/5$
$95\% \text{ CL limit}$	$\eta_G = F/M_s^4$	0.0085	-0.0159	0.0085		0.0085		
	M_s	3.29	2.52	2.94	3.92	3.29	2.98	2.77
								2.62

Conclusions

Discussed in
this talk

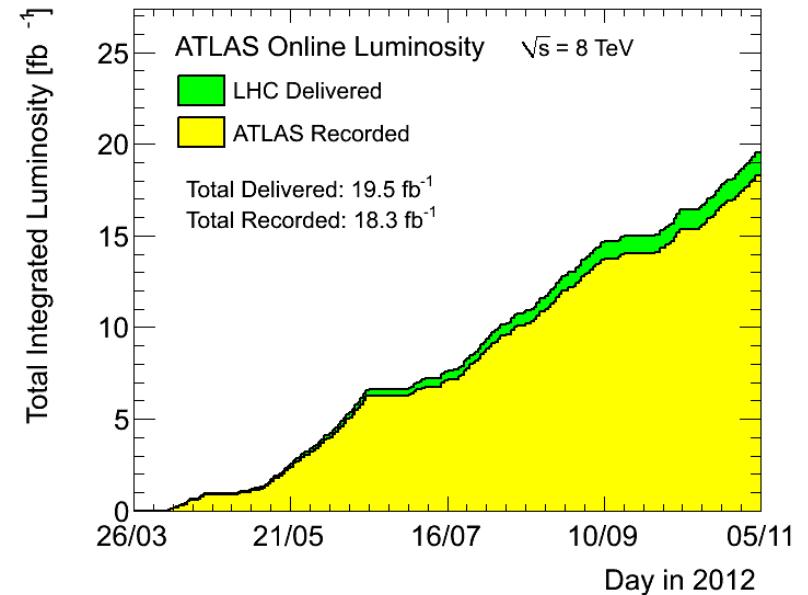
Extra dimensions

- Large ED (ADD) : monojet + $E_{T,\text{miss}}$
- Large ED (ADD) : monophoton + $E_{T,\text{miss}}$
- Large ED (ADD) : diphoton, $m_{\gamma\gamma}$
- UED : diphoton + $E_{T,\text{miss}}$
- RS1 with $k/M_{\text{Pl}} = 0.1$: diphoton, $m_{\gamma\gamma}$
- RS1 with $k/M_{\text{Pl}} = 0.1$: dilepton, $m_{\ell\ell}$
- RS1 with $k/M_{\text{Pl}} = 0.1$: ZZ resonance, m_{ZZ}
- RS1 with $k/M_{\text{Pl}} = 0.1$: WW resonance, m_{WW}
- RS with $\text{BR}(g_{KK} \rightarrow tt})=0.925$: $tt \rightarrow l+jets$, $m_{t\bar{t}\text{ boosted}}$
- ADD BH ($M_{\text{TH}}/M_D = 3$) : SS dimuon, $N_{\text{ch. part.}}$
- ADD BH ($M_{\text{TH}}/M_D = 3$) : leptons + jets, Σp_T
- Quantum black hole : dijet, $F(m_{jj})$



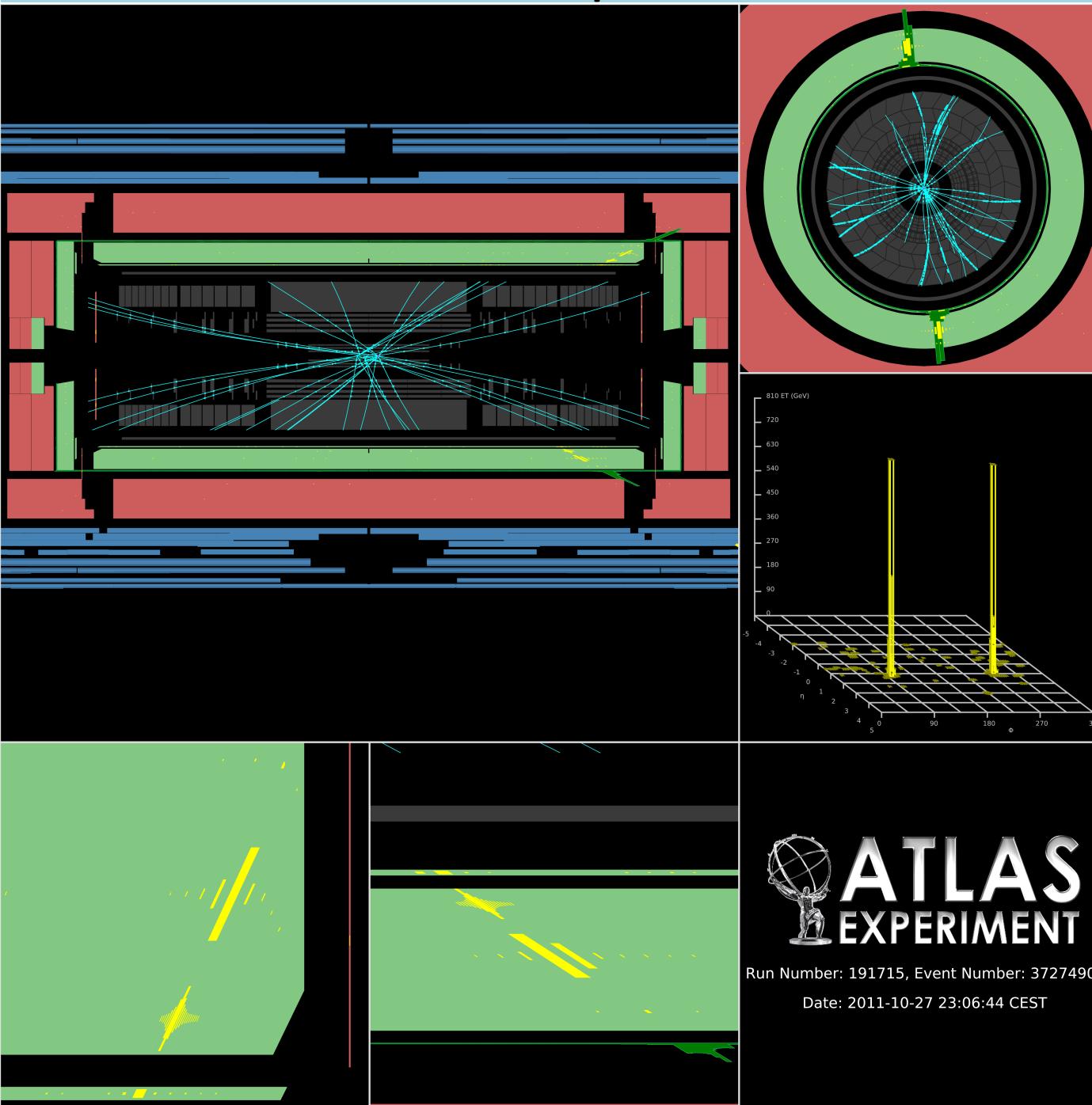
- Final states with lepton(s)/photon(s) provide clean channels to search for new phenomena
- No presence of new physics observed so far:
→ Large phase spaces of models parameters ruled out
- Already $\sim 18 \text{ fb}^{-1}$ of 8 TeV pp collisions on tape ...

Stay tuned !



Backup

Diphoton candidate event



Two very energetic back-to-back photons in the central region of electromagnetic calorimeter

$$\begin{aligned}m_{\gamma\gamma} &= 1.59 \text{ TeV} \\p_{T,1} &= 787 \text{ GeV} \\p_{T,2} &= 760 \text{ GeV}\end{aligned}$$



Run Number: 191715, Event Number: 37274906

Date: 2011-10-27 23:06:44 CEST

Monophoton events: Wimp pair production limits

