ATLAS Searches for New Diphoton Resonances

Nicolas Berger

Introduction

Run 1 : The γγ channel was critical for the Higgs boson discovery

+ Large yield: Small H→γγ BR but all usable

+ Smooth backgrounds

+ Excellent photon energy resolution

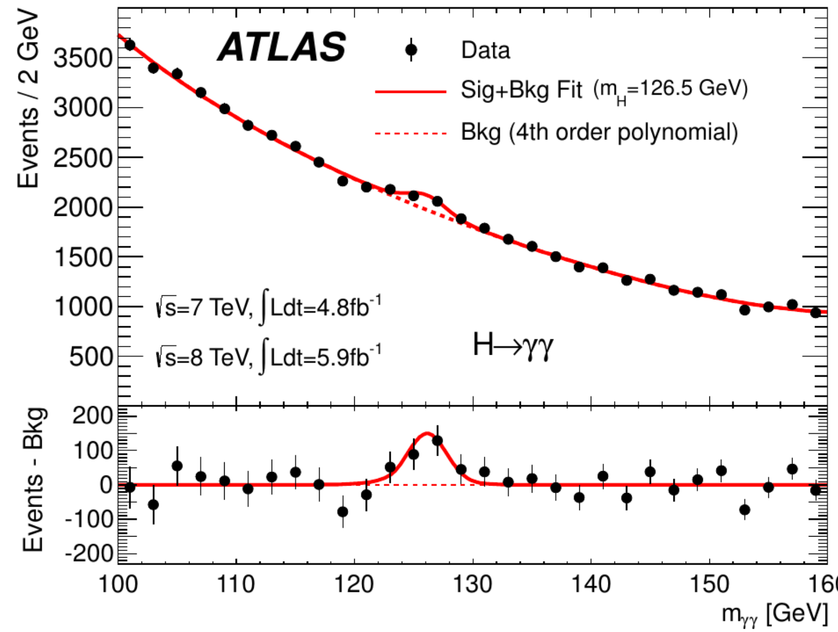
⇒ Clean signature for narrow resonances

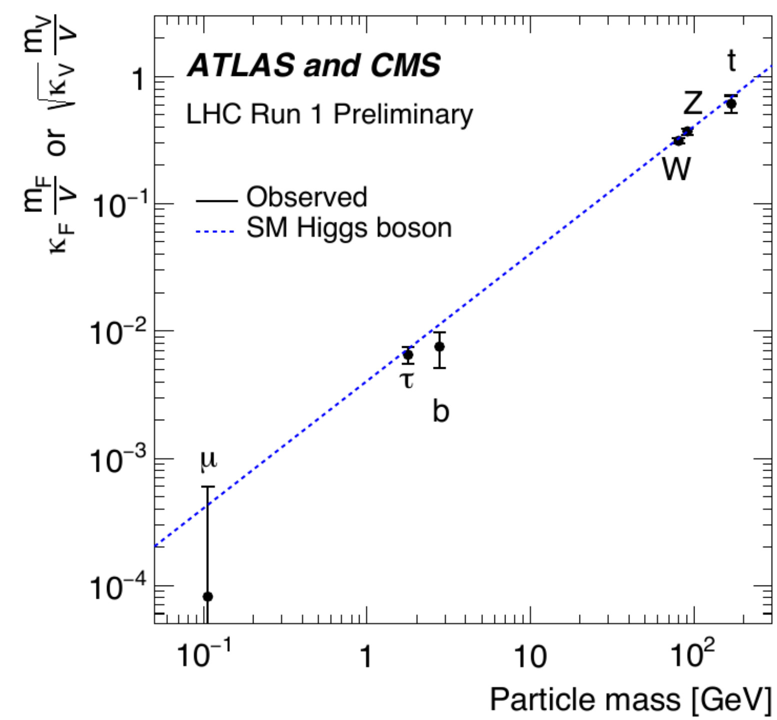
Run 2 : Focus on BSM searches but no clear indication where to look

(SM-like Higgs boson does not help)

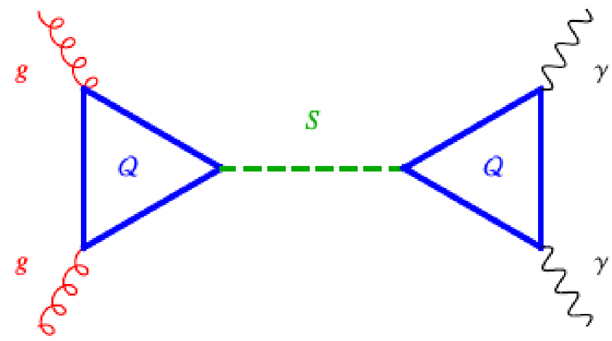
Simplest solution: look at known signatures

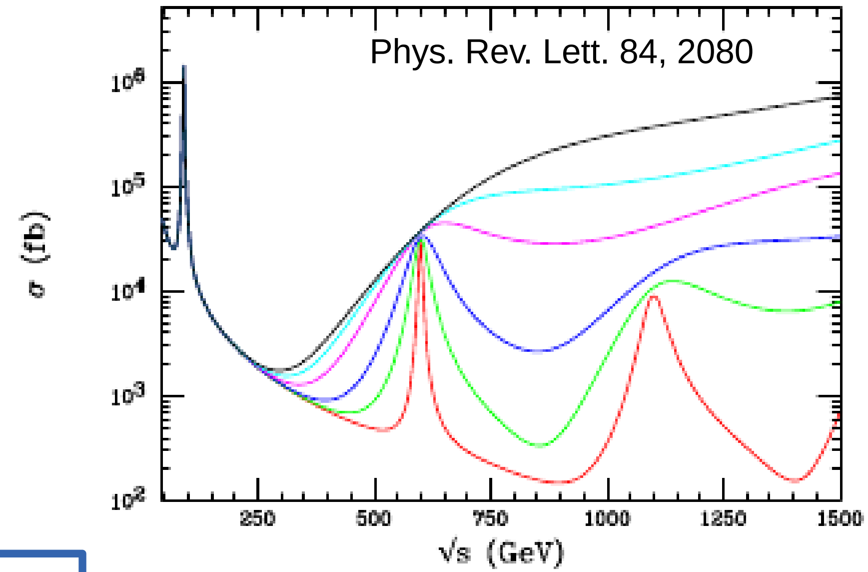
⇒ Repurpose the H→γγ search to look for resonances at higher masses





Models





Higgs-like spin-0 states

New Neutral spin-0 states (2HDM, NMSSM...)

- Typically ggF-produced, but also cascades, etc...

  ⇒ Keep analysis model-independent
- **Focus on narrow resonances:**
  - $\Gamma_{\gamma\gamma}$ usually not large
  - $B_{\gamma\gamma}=\Gamma_{\gamma\gamma}/\Gamma_X$ must be not too small
- Consider $0 \leq \Gamma_X/m_X \leq 10\%$
- $m_X > 200$ GeV to avoid issues with H and Z→ee background at lower masses

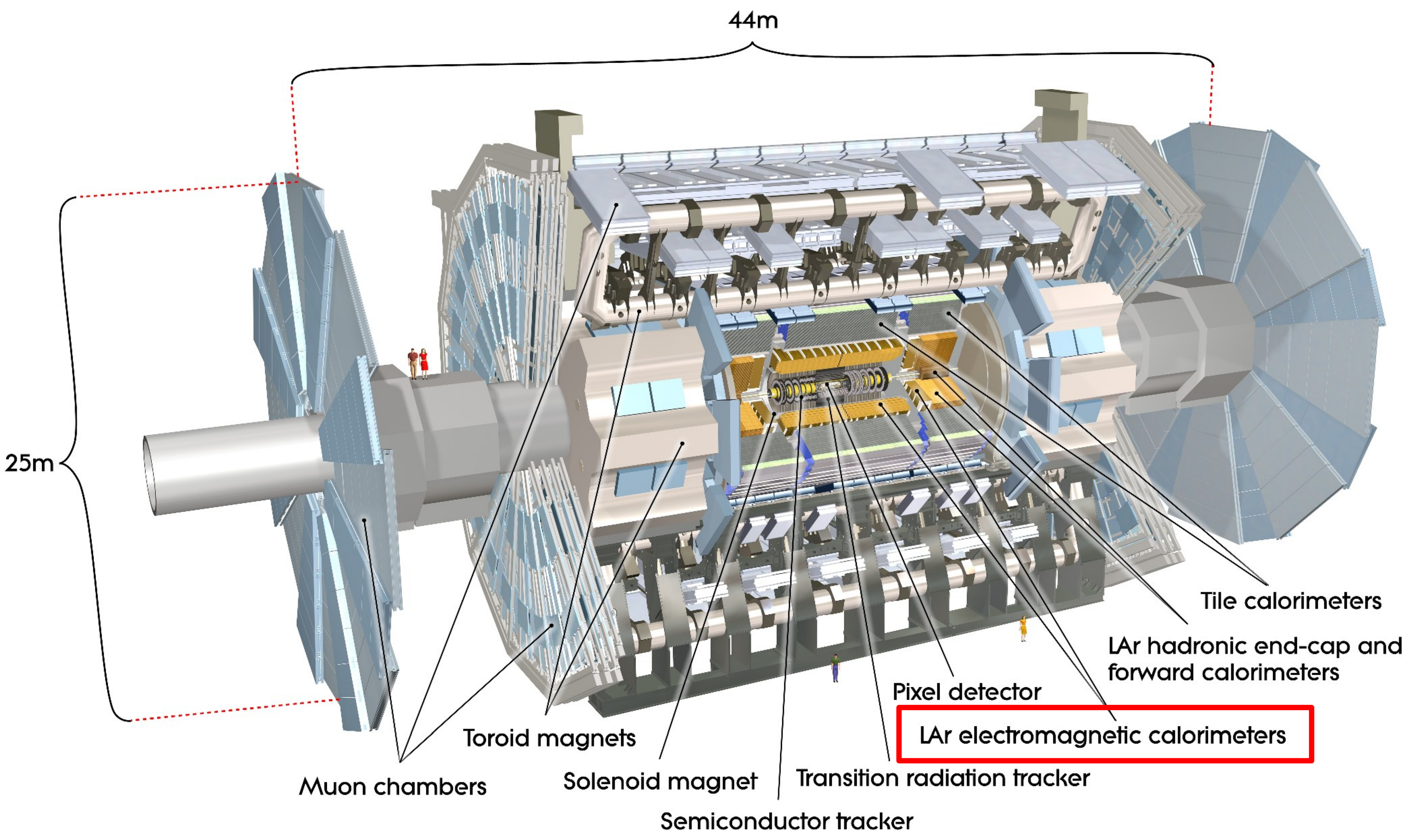
Randall-Sundrum Graviton

- Width given by parameter k/M_{pl}:

  $\Gamma_G/m_G \sim 1.44\ (k/M_{pl})^2$
- Consider $0.01 \leq k/M_{pl} \leq 0.3$

  $\Rightarrow \sim 0.01\% \leq \Gamma_G/m_G \leq \sim 11\%$
- Already excluded below ~1 TeV (for k/M_{pl}=0.01-0.1)
- Anyway used as kinematic benchmark for $m_G > 500$ GeV

ATLAS



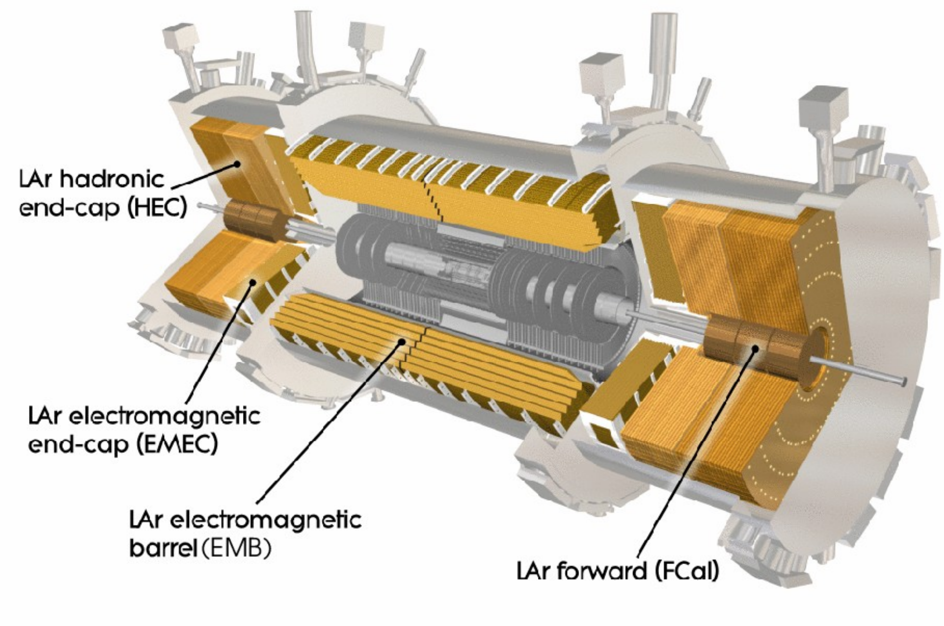
44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

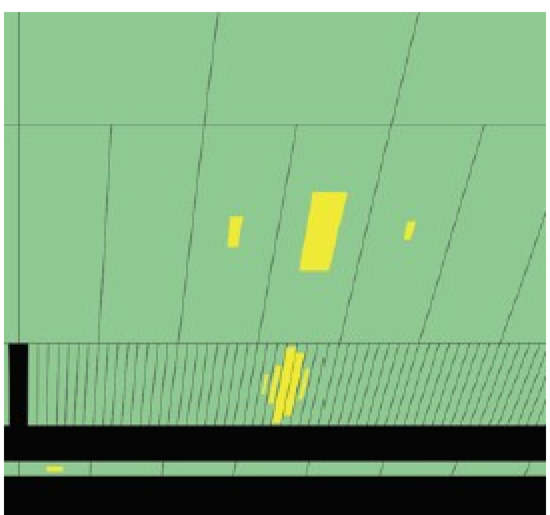
Photon Reconstruction

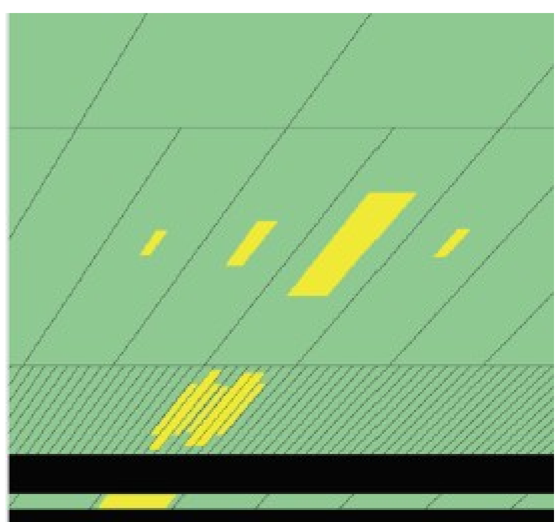
- **Photons** reconstructed from energy deposits in the EM calorimeter
- **Identified using shower shapes** in layers 1 and 2
  - **fine segmentation** of EM layer 1 critical for $\pi^0 \to \gamma\gamma$ rejection

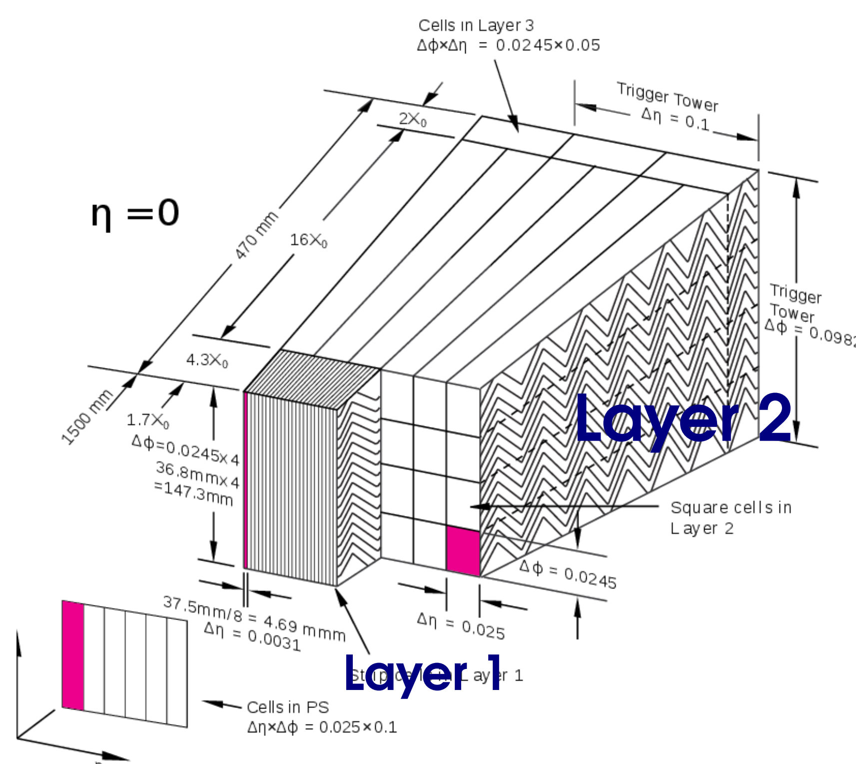
  $\rightarrow$ available only for **$|\eta|<2.37$**

  $\rightarrow$ also exclude **$1.37<|\eta|<1.52$**
- Classify as **unconverted/converted** based on track information







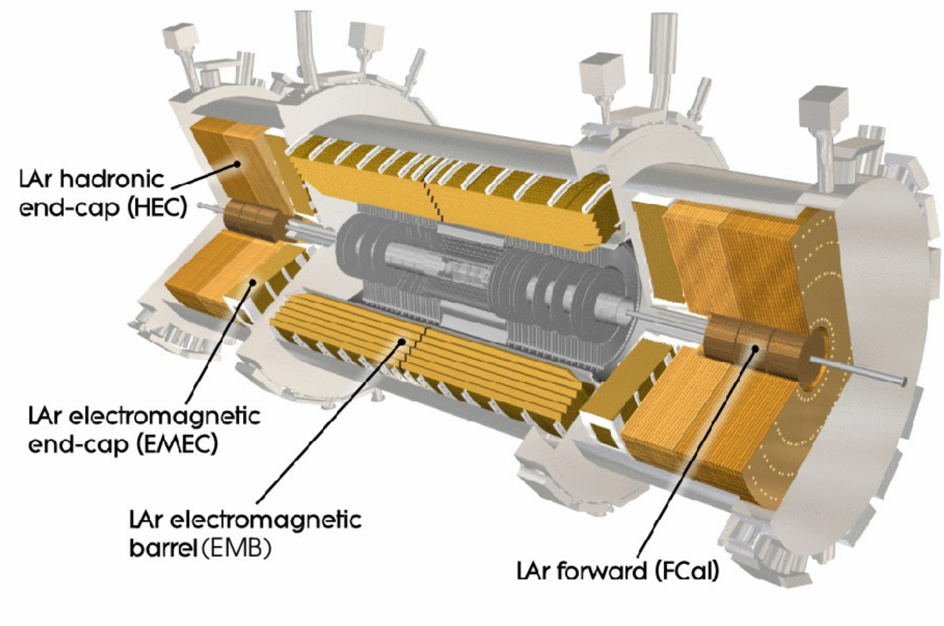


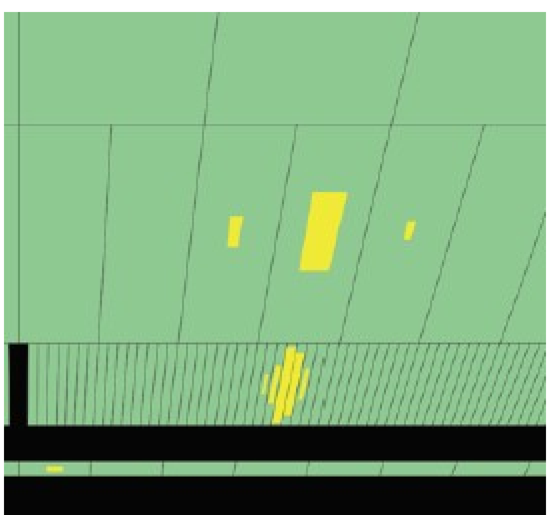
Photon Reconstruction

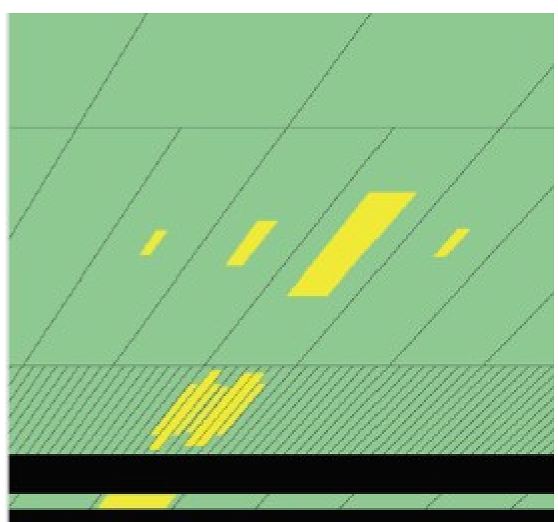
- **Photons** reconstructed from energy deposits in the EM calorimeter
- **Identified using shower shapes** in layers 1 and 2
  - **fine segmentation** of EM layer 1 critical for $\pi^0 \rightarrow \gamma\gamma$ rejection

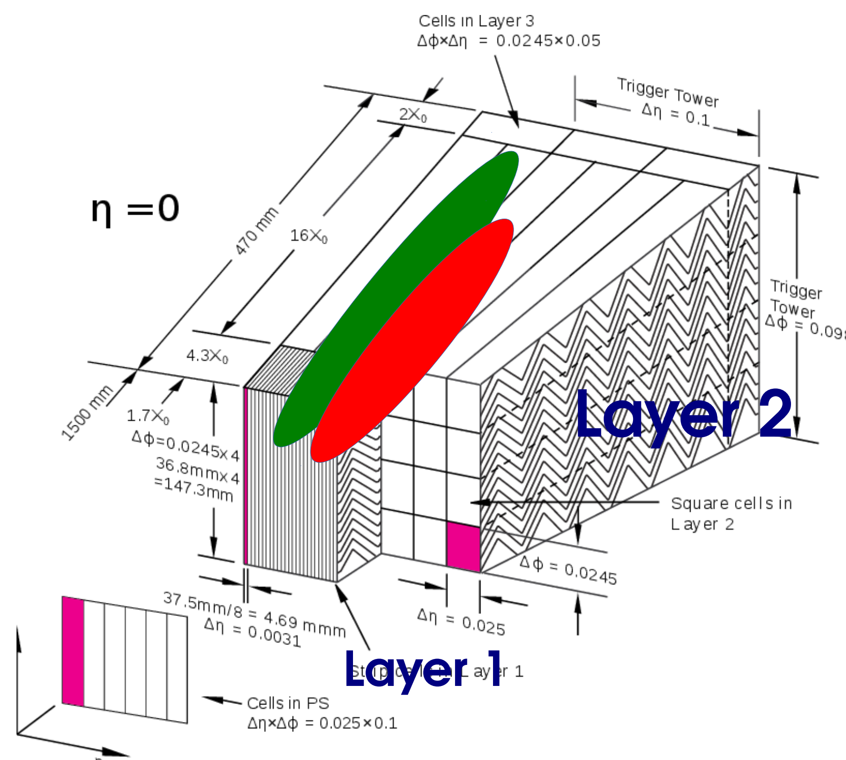
  $\rightarrow$ available only for **$|\eta|<2.37$**

  $\rightarrow$ also exclude **$1.37<|\eta|<1.52$**
- Classify as **unconverted/converted** based on track information







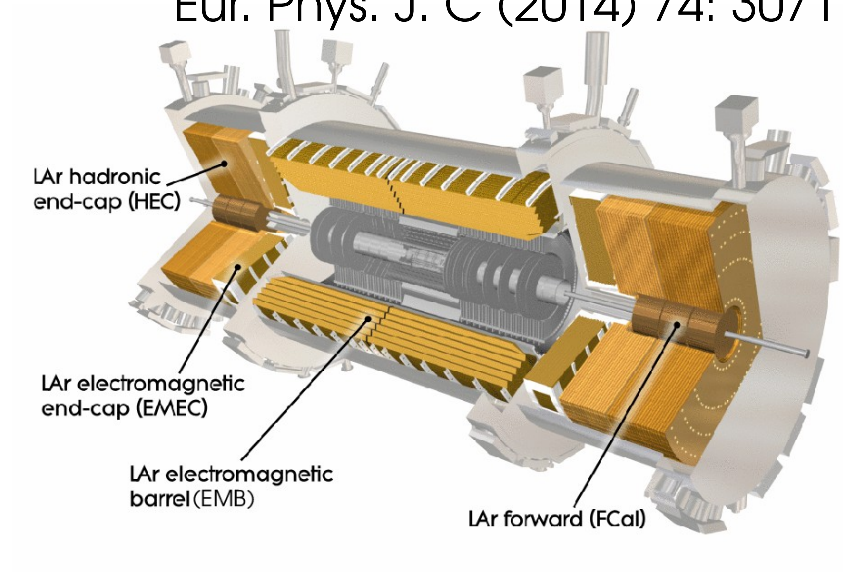


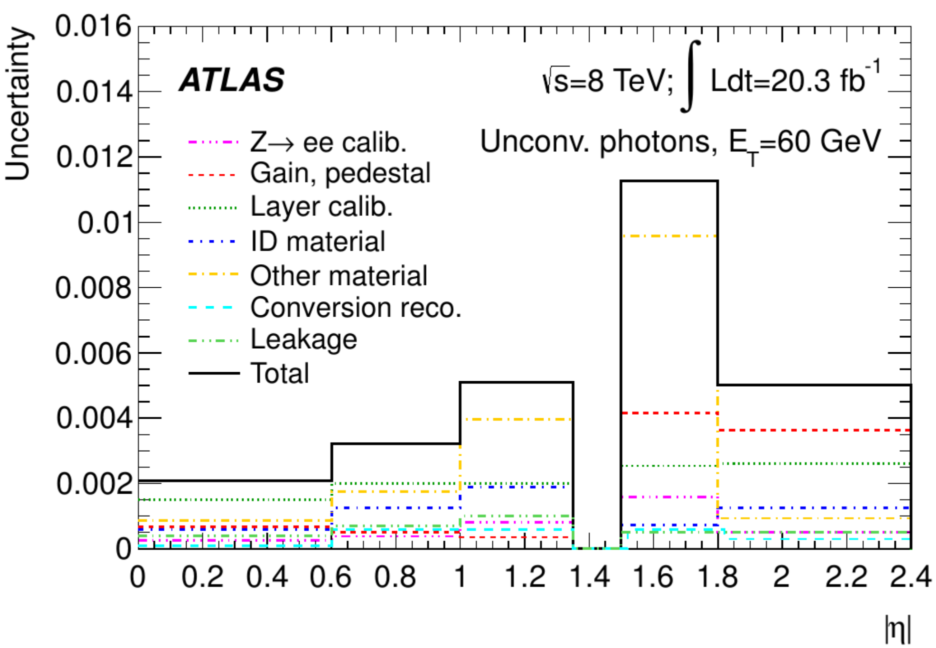
Energy Calibration

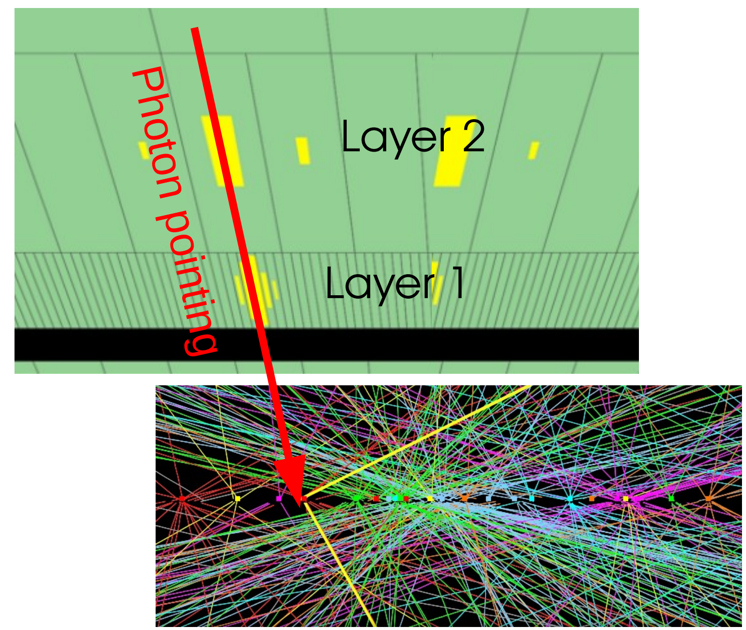
Eur. Phys. J. C (2014) 74: 3071

- Compute photon energy from cluster E_T, position, shower shape
  - Correct for upstream material
  - Adjust relative calibration of EM layers
- Final adjustment on $Z \to ee$ electrons

$\Rightarrow$ At high E_T, uncertainty ~ **0.2% to 1.2%**







$m^2 = 2E_{T1}E_{T2}$ ($1-\cos\alpha(z)$) : use calorimeter pointing to measure z

Uncertainty on mass resolution **+110% - 40%** at high invariant mass

Isolation

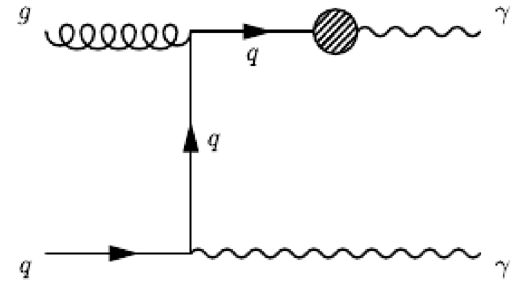
Further reject jet background by looking for activity around the photon

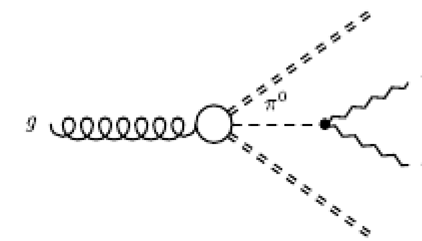
"Calorimeter Isolation" E_T^{iso}

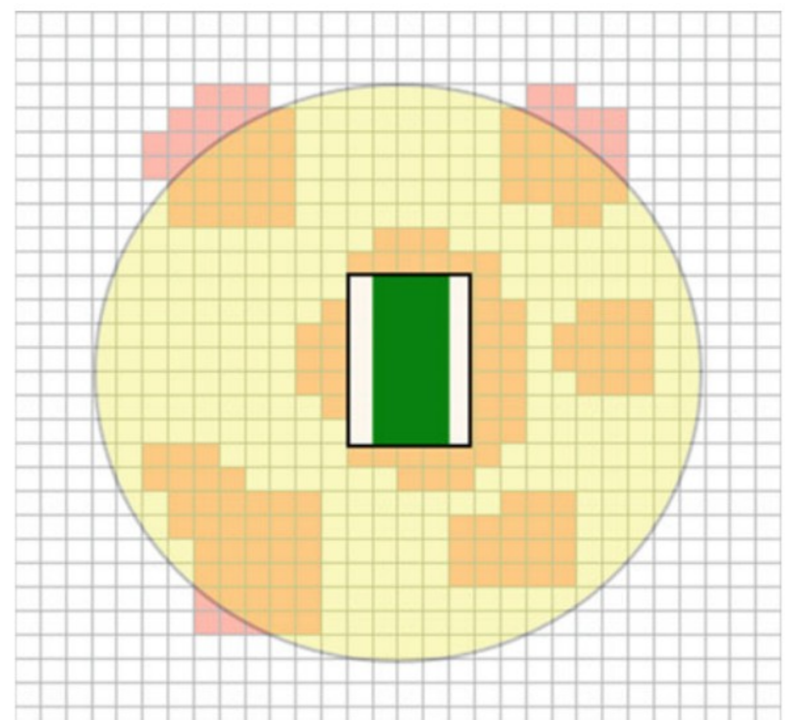
- sum E_T of clusters within $\Delta R<0.4$
- Use E_T^{iso} – 2.2% E_T to account for energy leakage outside photon cluster
- Correct for ambient energy

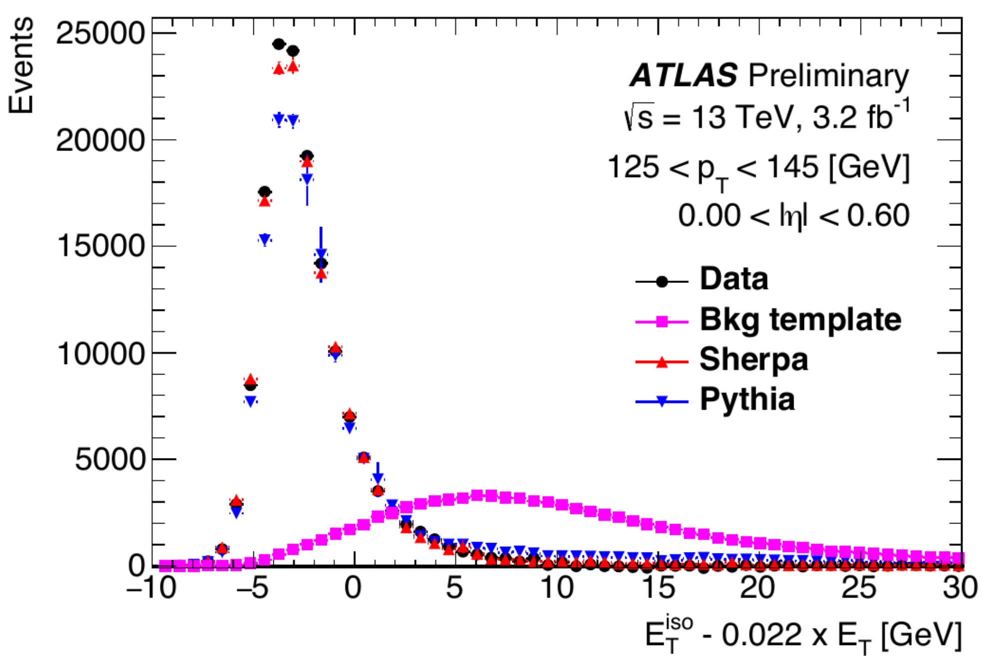
"Track Isolation": p_T^{iso}

- sum the pT of tracks within $\Delta R<0.2$





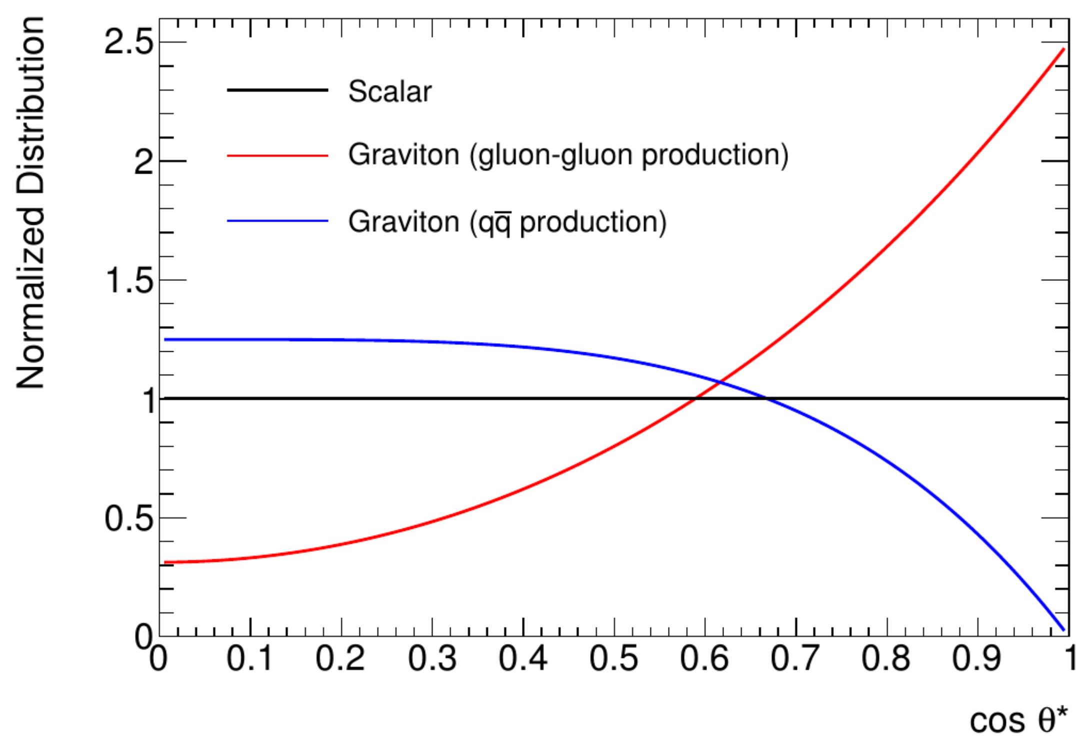




Analysis Selections

Common Selections	
Kinematic selections $E_{T1} > 40$ GeV, $E_{T2} > 30$ GeV $\lvert\eta\rvert < 2.37$, excluding $1.37 < \lvert\eta\rvert < 1.52$	**Photon identification** **Isolation:** $E_{T}^{iso}{}_{1,2} - 2.2\%\ E_{T1,2} < 2.45$ GeV $p_{T}^{iso}{}_{1,2} < 5\%\ E_{T1,2}$
spin-0	**spin-2**
$E_{T1} > 0.4\ m_{\gamma\gamma}$, $E_{T2} > 0.3\ m_{\gamma\gamma}$ +20% sensitivity	$E_{T1,2} > 55$ GeV Retains wide kinematic acceptance

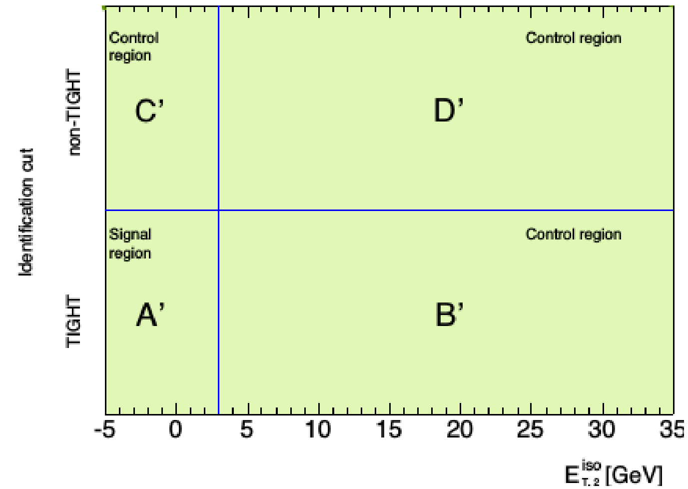
Model	$\cos\theta^*$ Distribution
Scalar	**flat**
gg→G*	$1 + 6\cos^2\theta^* + \cos^4\theta^*$
qq→G*	$1 - \cos^4\theta^*$



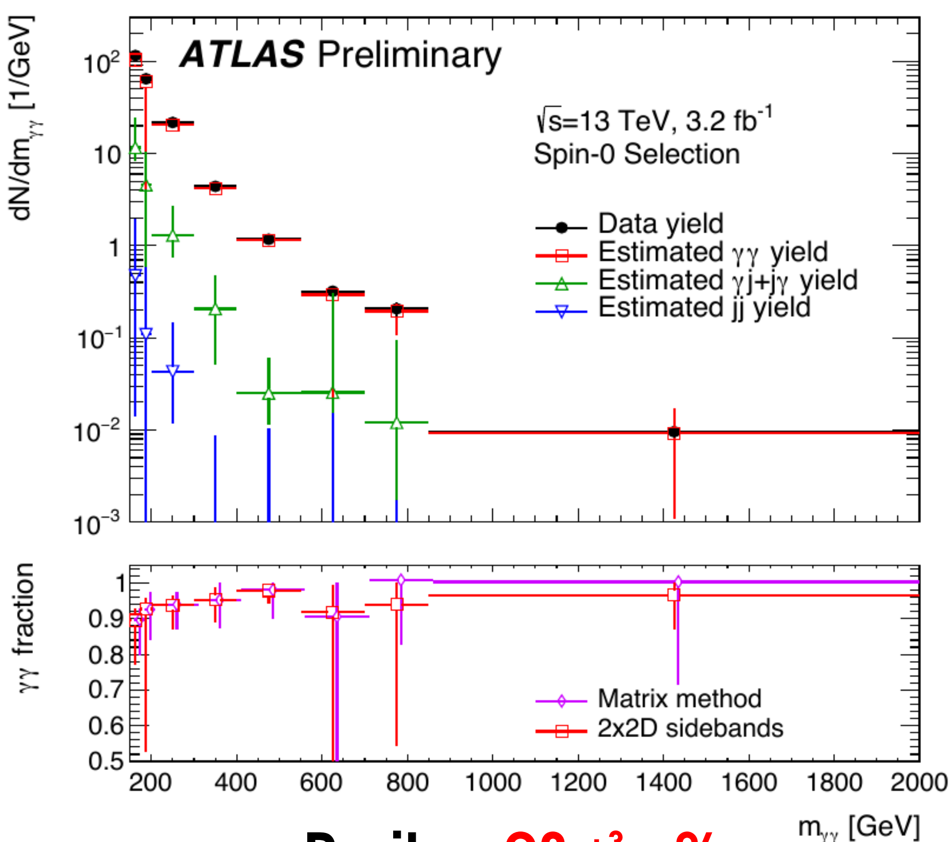
Sample Composition

Data sample: 3.2 fb^{-1} collected at 13 TeV

Measure **fraction of $\gamma\gamma$ events** in the selection using control regions in photon ID and isolation

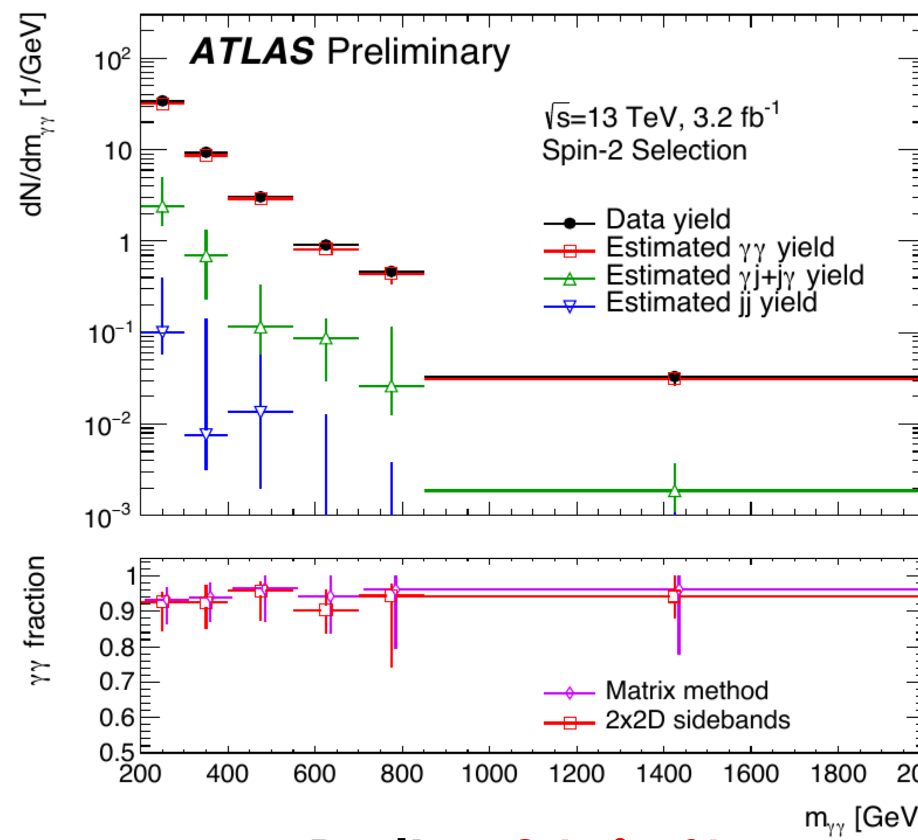


spin-0



$\gamma\gamma$ Purity : 93^{+3}_{-8} %

spin-2



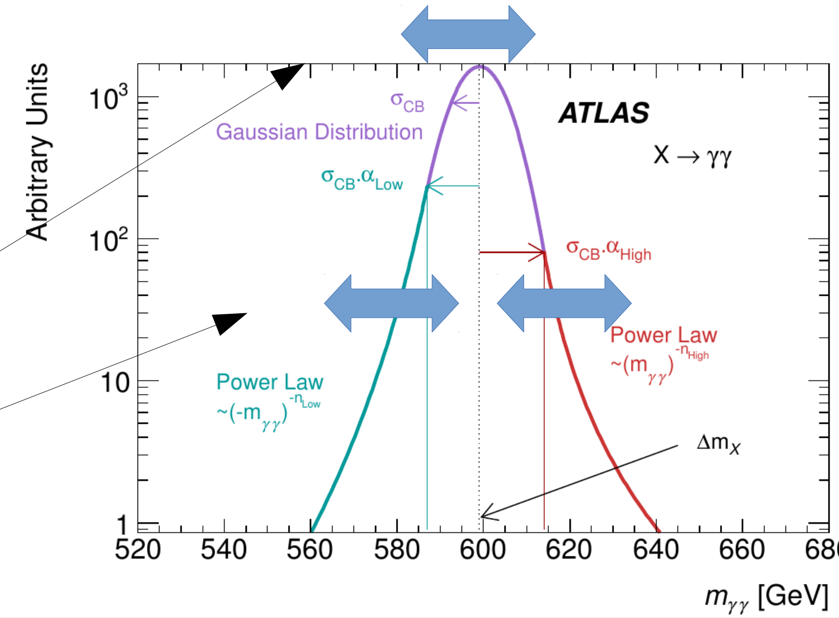
$\gamma\gamma$ Purity : 94^{+3}_{-7} %

Signal Modeling

Model using "**Double-Sided Crystall Ball**" Shape

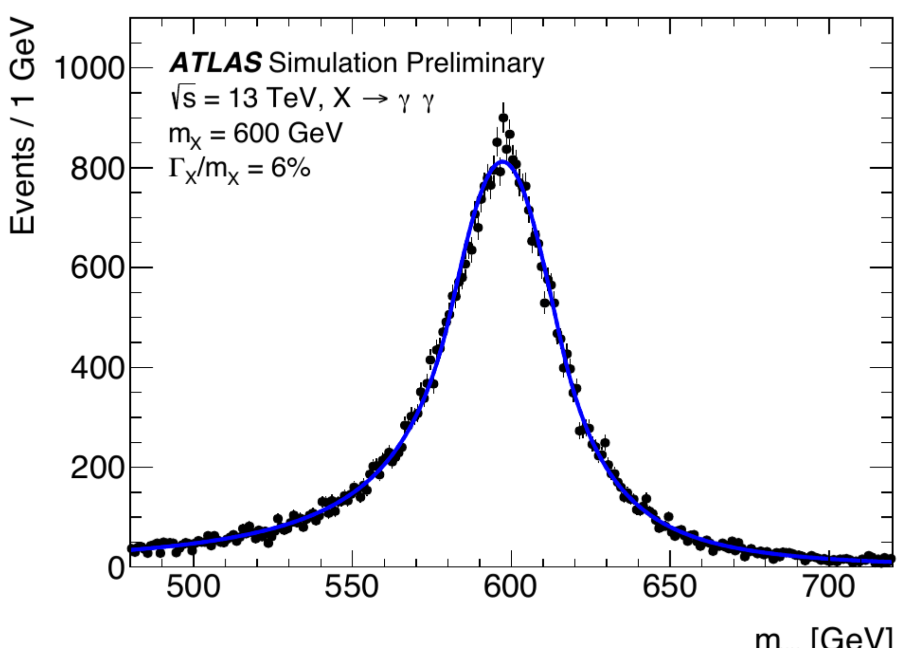
Parameters fitted from simulation

- Energy scale syst. : move peak position
- Resolution syst. : broaden/narrow the peak



spin-0

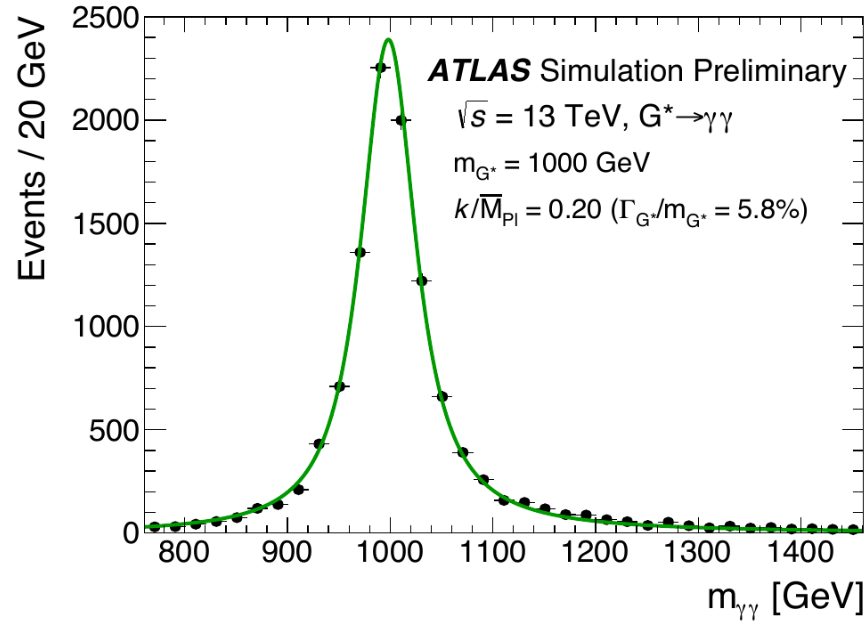
Interpolate DSCB as function of m_X and Γ_X



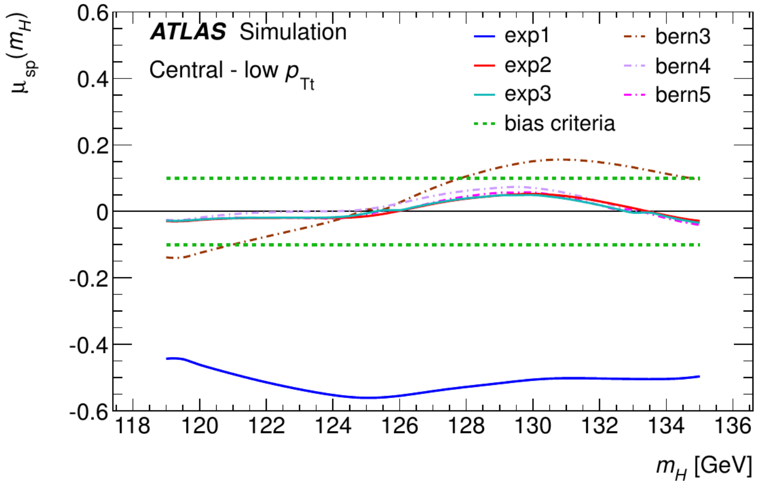
spin-2

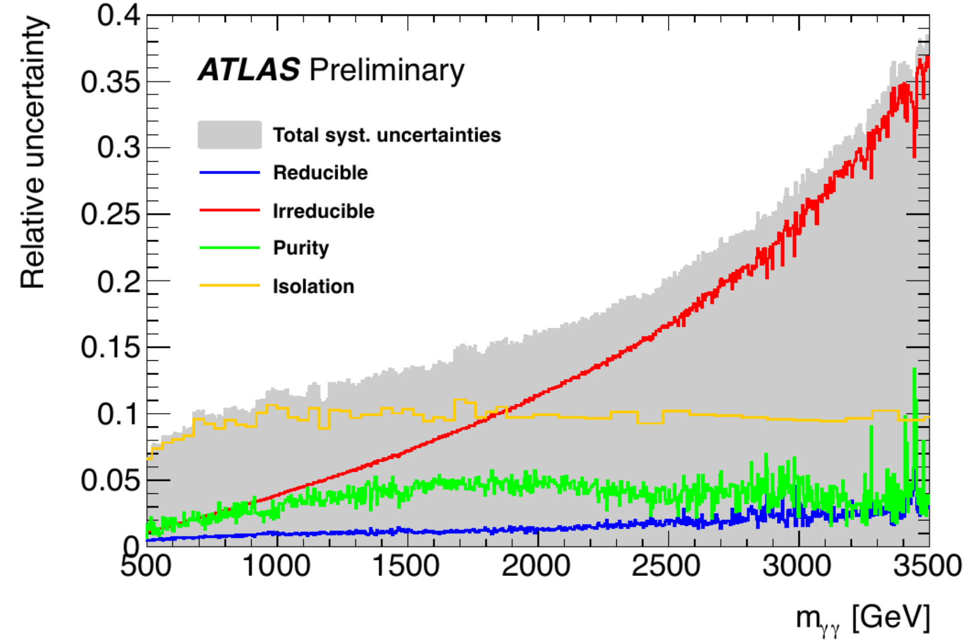
Interpolate resolution as function of m_G

convolute with BW lineshape



Background Modeling





spin-0

Find **function** that describes bkg $\gamma\gamma$ MC

+data-driven reducible bkg

Check all variations: scales/PDF/purity...

Require max deviation from MC < 20% σ_{signal}

Check:

$$f_{(k)}(x; b, \{a_k\}) = N(1 - x^{1/3})^b x^{\sum_{j=0}^{k} a_j (\log x)^j}$$

$$x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$$

k=0 fulfills all conditions

Check in data using F-test: **OK**

- **N, a, b free in the fit**

spin-2

Directly **use prediction from bkg $\gamma\gamma$ MC**

+data-driven reducible bkg

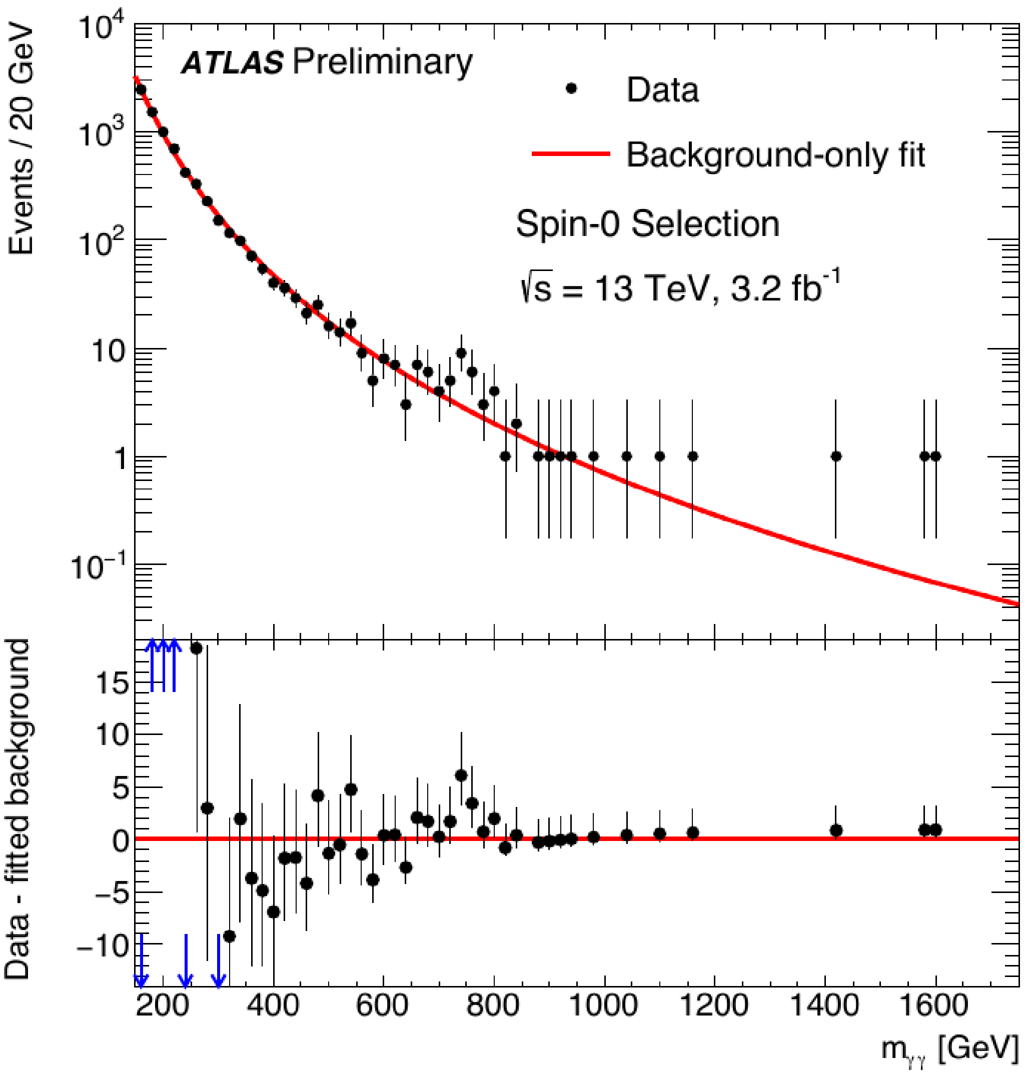
$\gamma\gamma$: use Sherpa, reweighted to diphox to account for NLO effects

- Normalization is free
- 4 **constrained** deformations:
  - theory (gg, gjet+jetjet) uncert.
  - purity uncertainty
  - isolation uncertainty

Mass Spectra

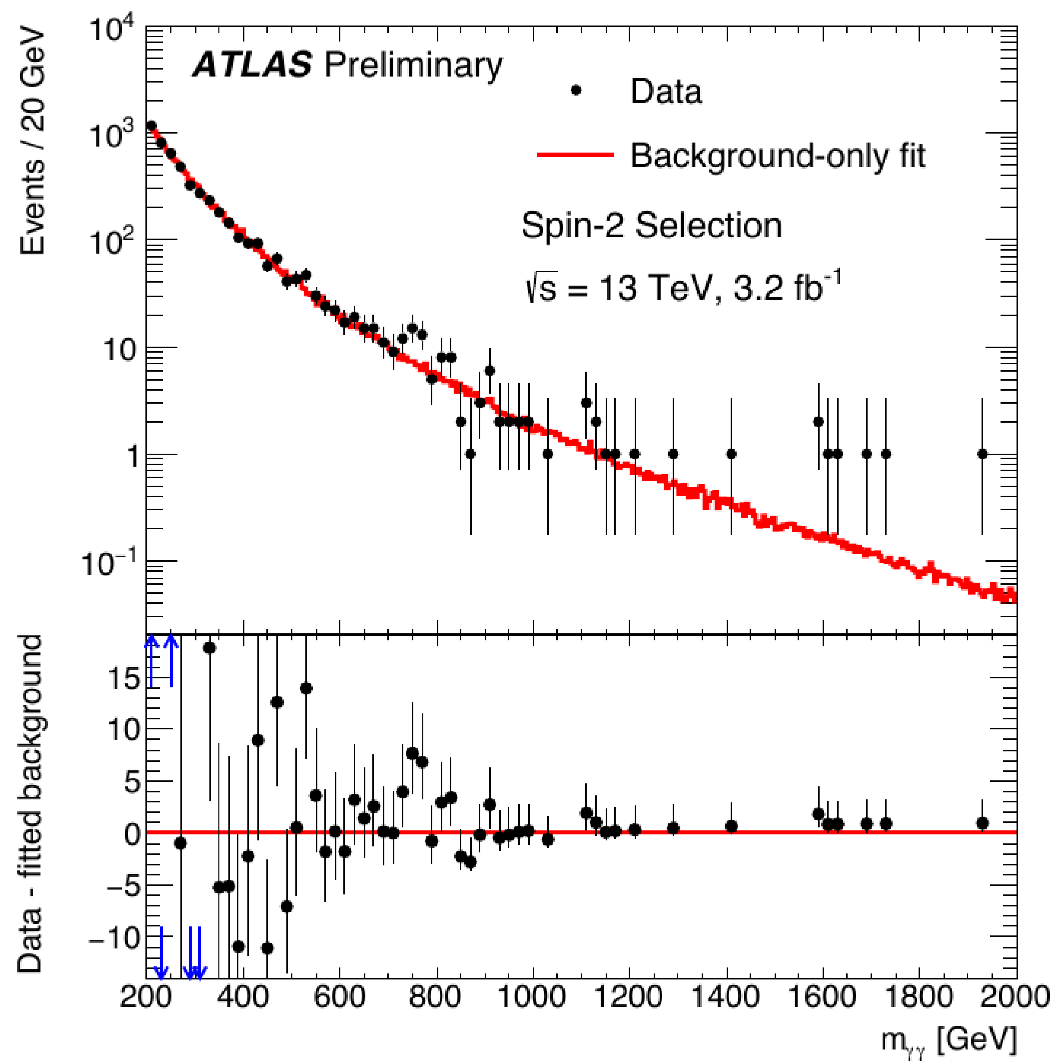
ATL-CONF-2016-018

spin-0



2878 events in $m_{\gamma\gamma}$ > 200 GeV

spin-2



5066 events in $m_{\gamma\gamma}$ > 200 GeV

Signal Measurement

spin-0
Compute σ_{fid} in truth-level fiducial acceptance **E_{T1} > 0.4 $m_{\gamma\gamma}$, E_{T2} > 0.3 $m_{\gamma\gamma}$ $\lvert\eta\rvert$<2.37** **+ particle-level isolation selection matching experimental isolation cuts** $\Rightarrow$ Weak dependence on production process

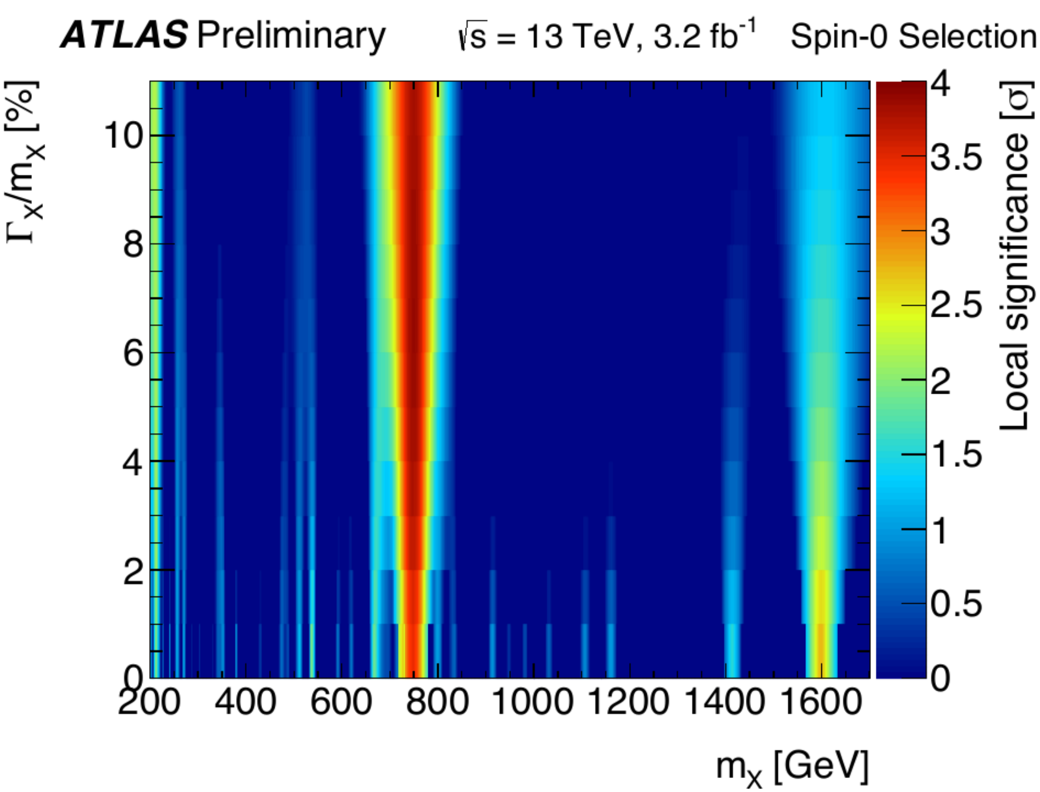
spin-2
Use **total σ** for the RS graviton model

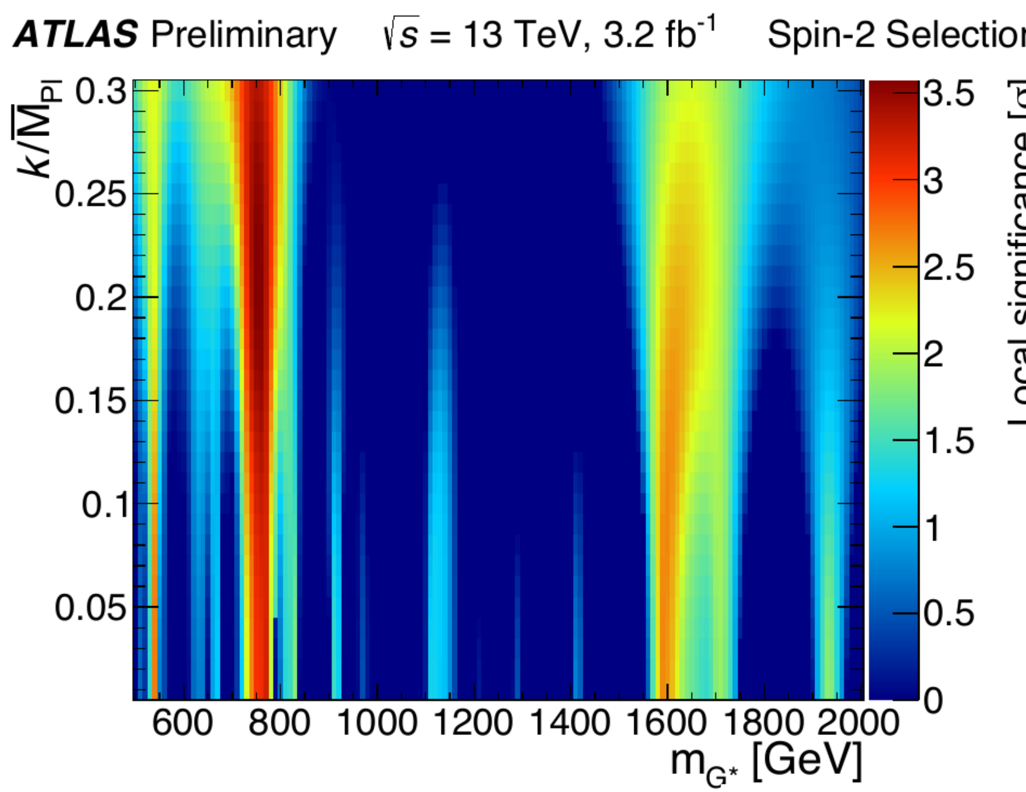
Uncertainty	spin-2 search	spin-0 search	
Background (mass dependent)	$\pm$ 7% to $\pm$ 35%	spurious signal 20 – 0.04 events for Γ/M=6%	p_0 and limit
Signal mass resolution (mass dependent)	$(^{+55}_{-20})\% - (^{+110}_{-40})\%$		p_0 and limit
Signal photon identification (mass dependent)	$\pm(3-2)\%$		limit
Signal photon isolation (mass dependent)	$\pm$(3-1)%	$\pm$(4-1)%	limit
Signal production process	N/A	$\pm$(3-6)% depending on Γ	limit
Trigger efficiency	$\pm$0.6%		limit
Luminosity	$\pm$5.0%		limit

Significance

ATL-CONF-2016-018

spin-0 | **spin-2**





spin-0

Largest **local** significance

3.9σ @ m_X ~ 750 GeV, Γ_X/m_X ~ 6%

Global Z = 2.0σ over

200 GeV < m_X < 2 TeV, 1% ≤ Γ_X/m_X ≤ 10%

spin-2

Largest **local** significance

Γ_X/m_X ~ 6%

3.6σ @ m_X ~ 750 GeV, k/M_{pl} ~ 0.2

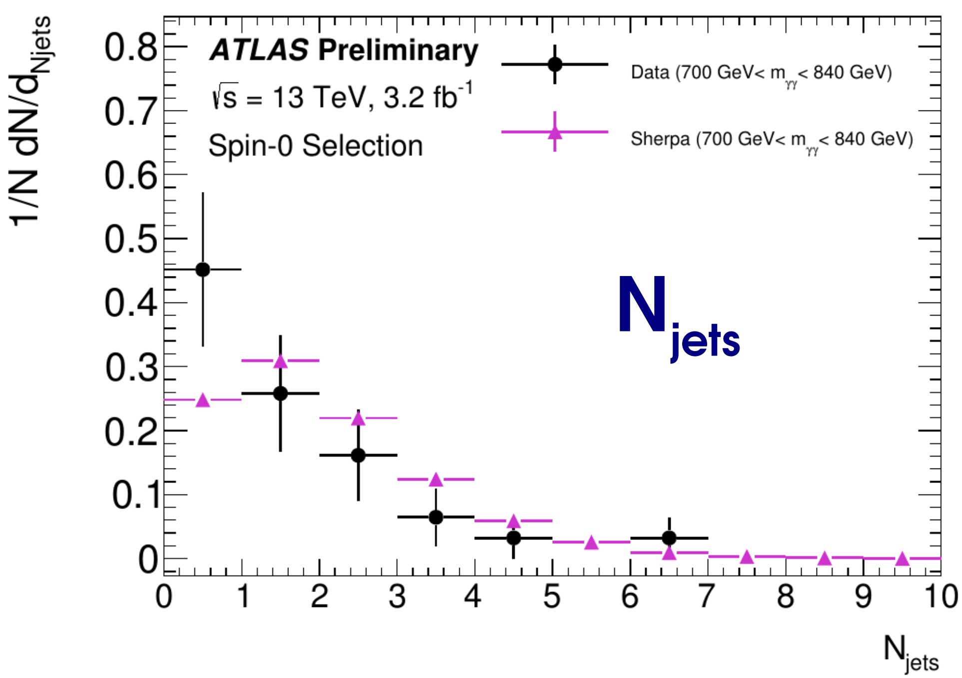
Global Z = 1.8σ over

500 GeV < m_X < 3.5 TeV, 0.01 < k/M_{pl} < 0.3

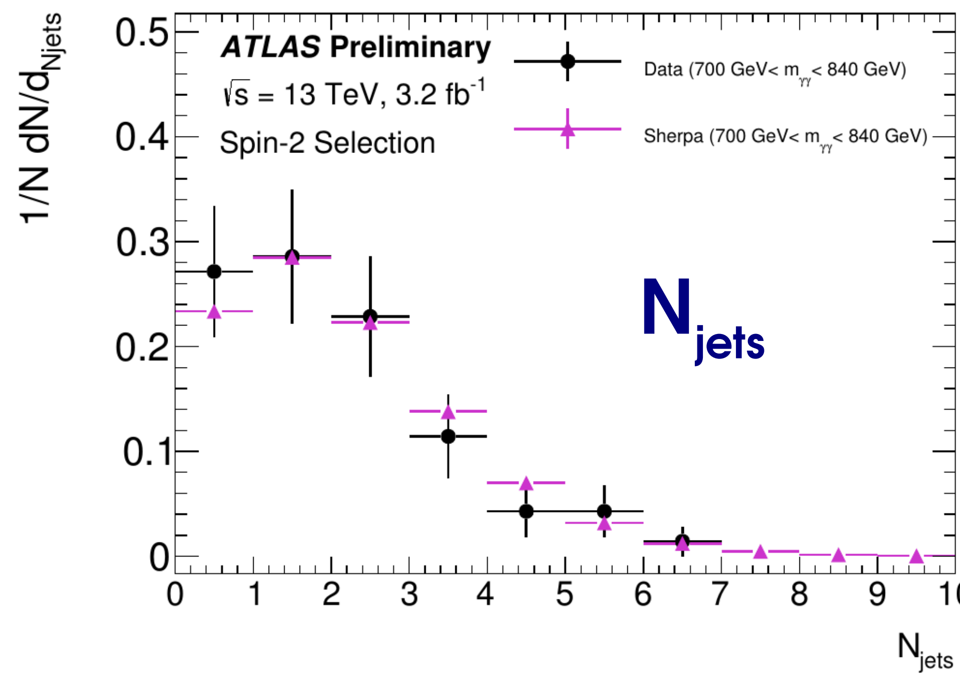
Properties of the Excess

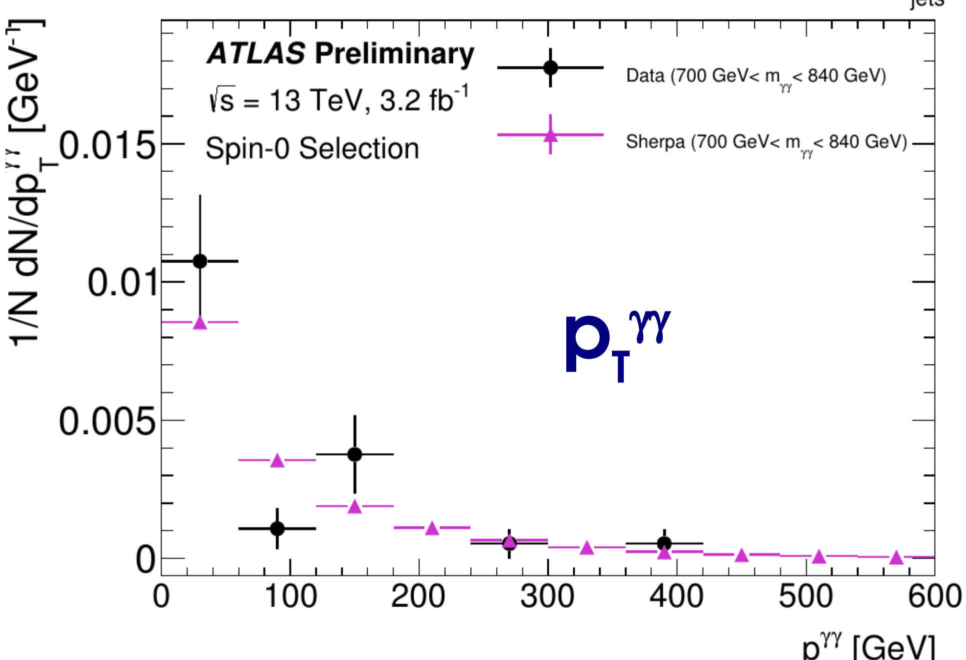
ATL-CONF-2016-018

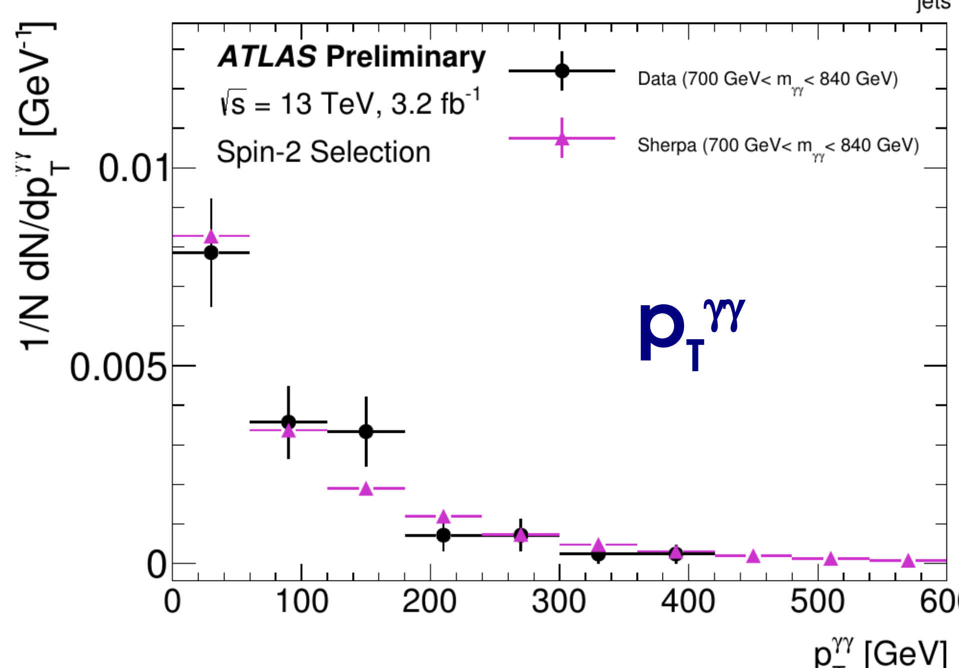
spin-0



spin-2



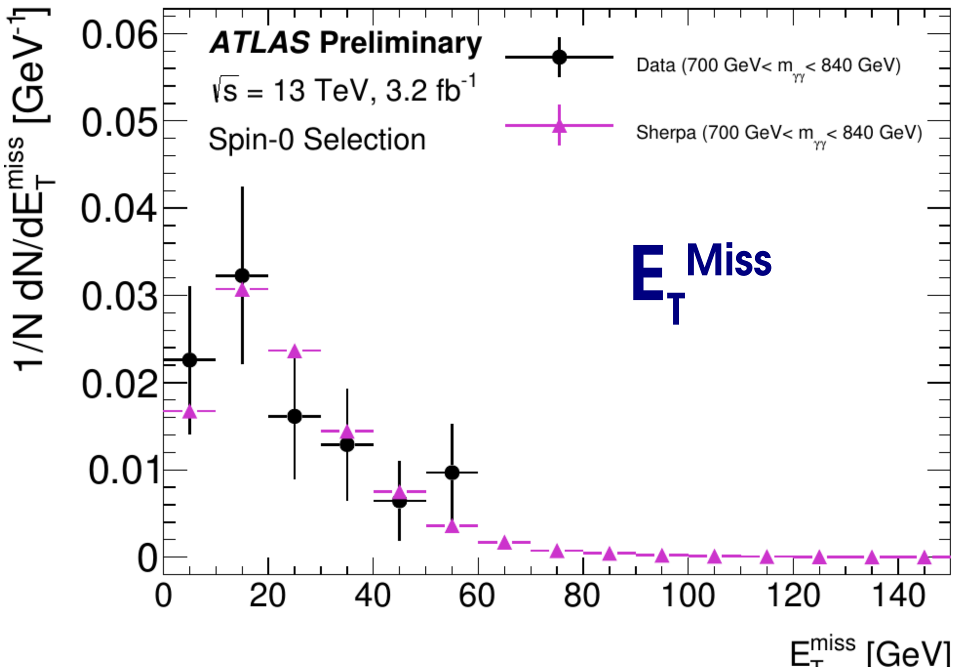


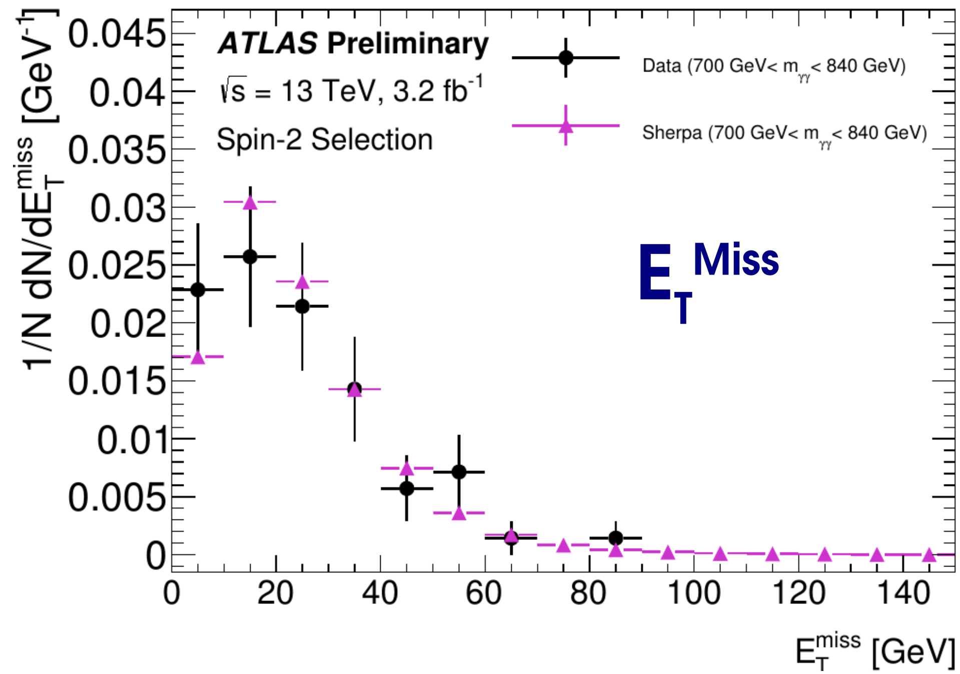


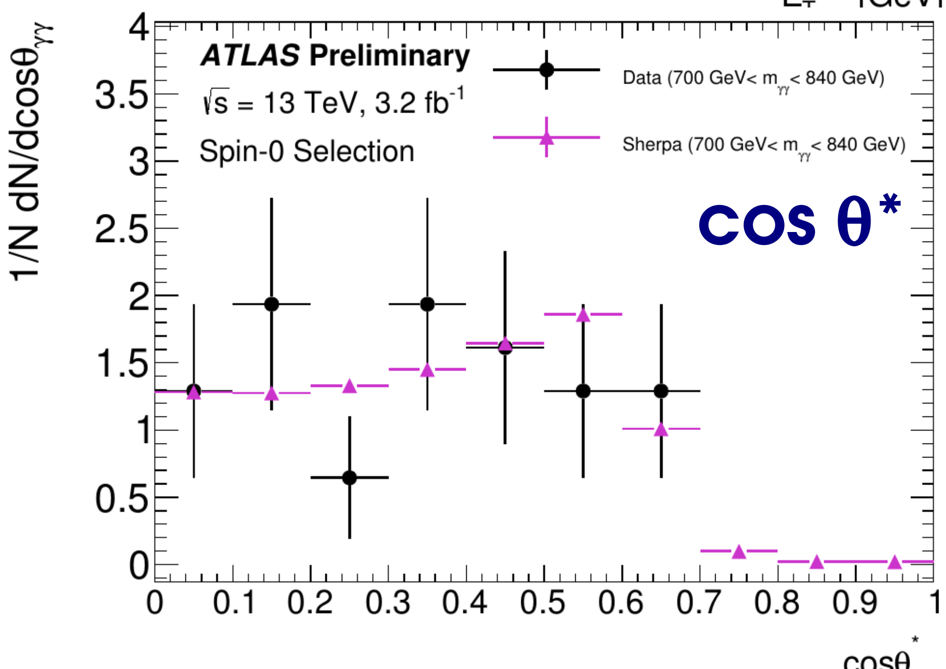
Properties of the Excess (2)

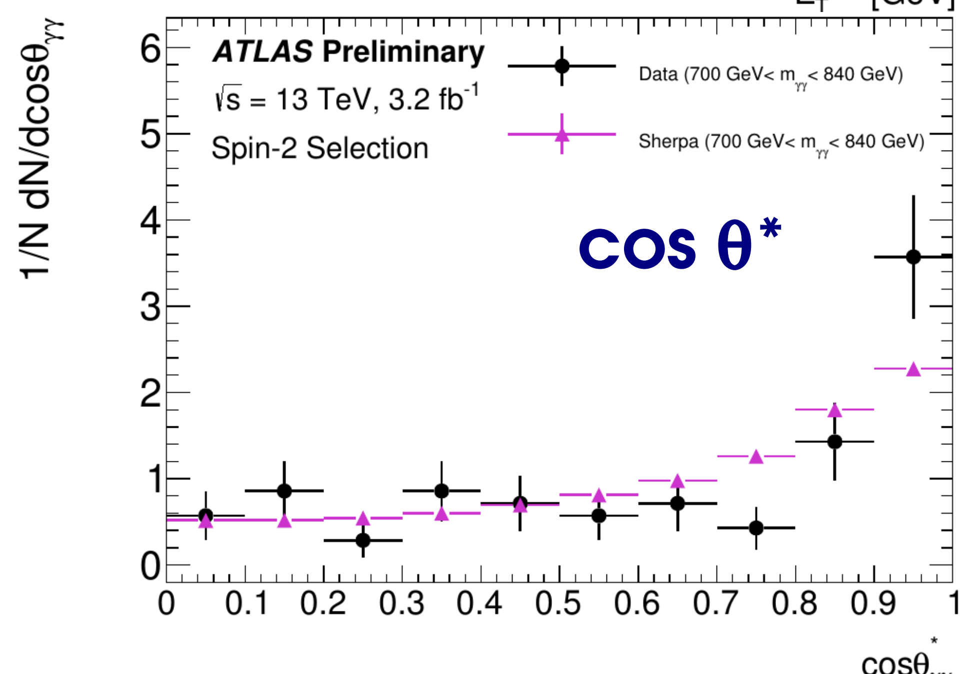
ATL-CONF-2016-018

spin-0	spin-2









8 TeV Analyses : Scalar Search

Phys. Rev. Lett. 113, 171801

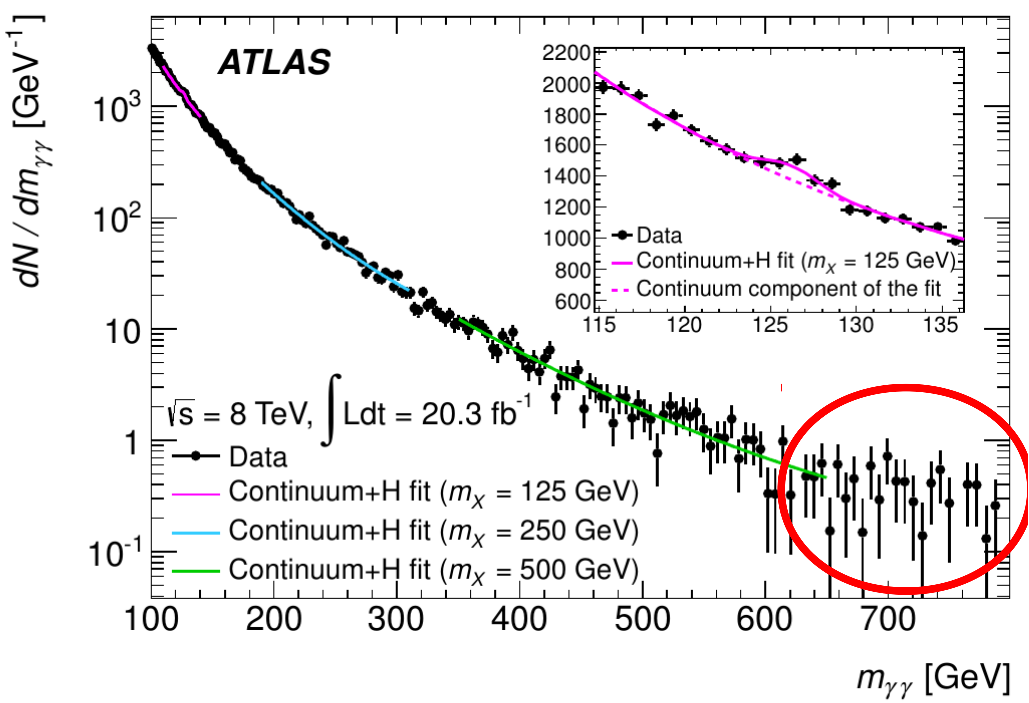
Similar Analysis to the 13 TeV version

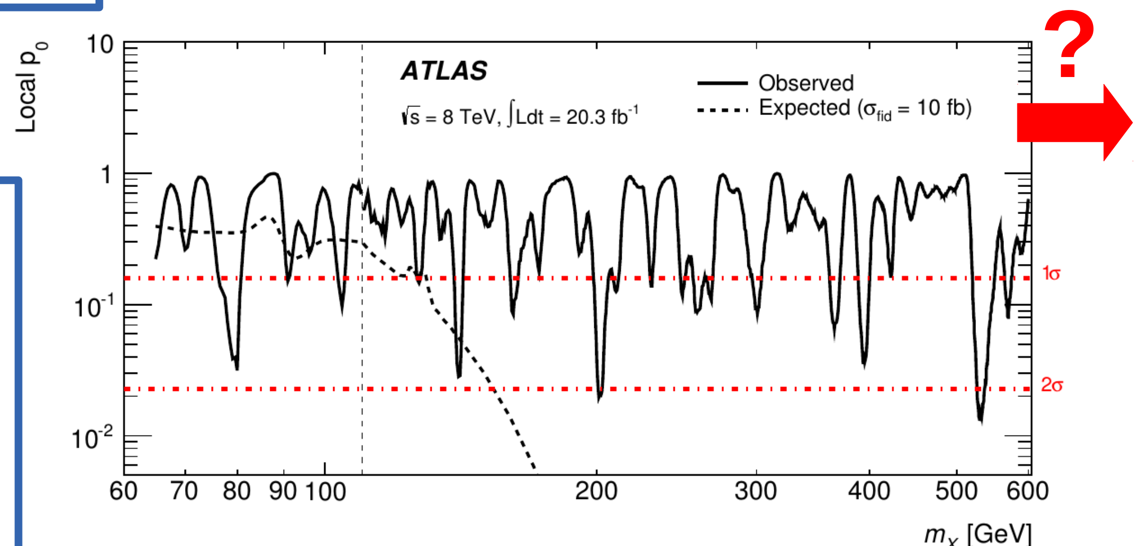
Differences:

- **Bkg modeling** using simpler exp(ax^2+bx) form in **sliding window** around the tested mass point (±200 GeV at m_X = 600 GeV)

⇒ Stop at m_X = 600 GeV (not enough data)

- **Photon energy calibration** was an older Run 1 version
- **Analysis only for narrow resonances**





Updates:

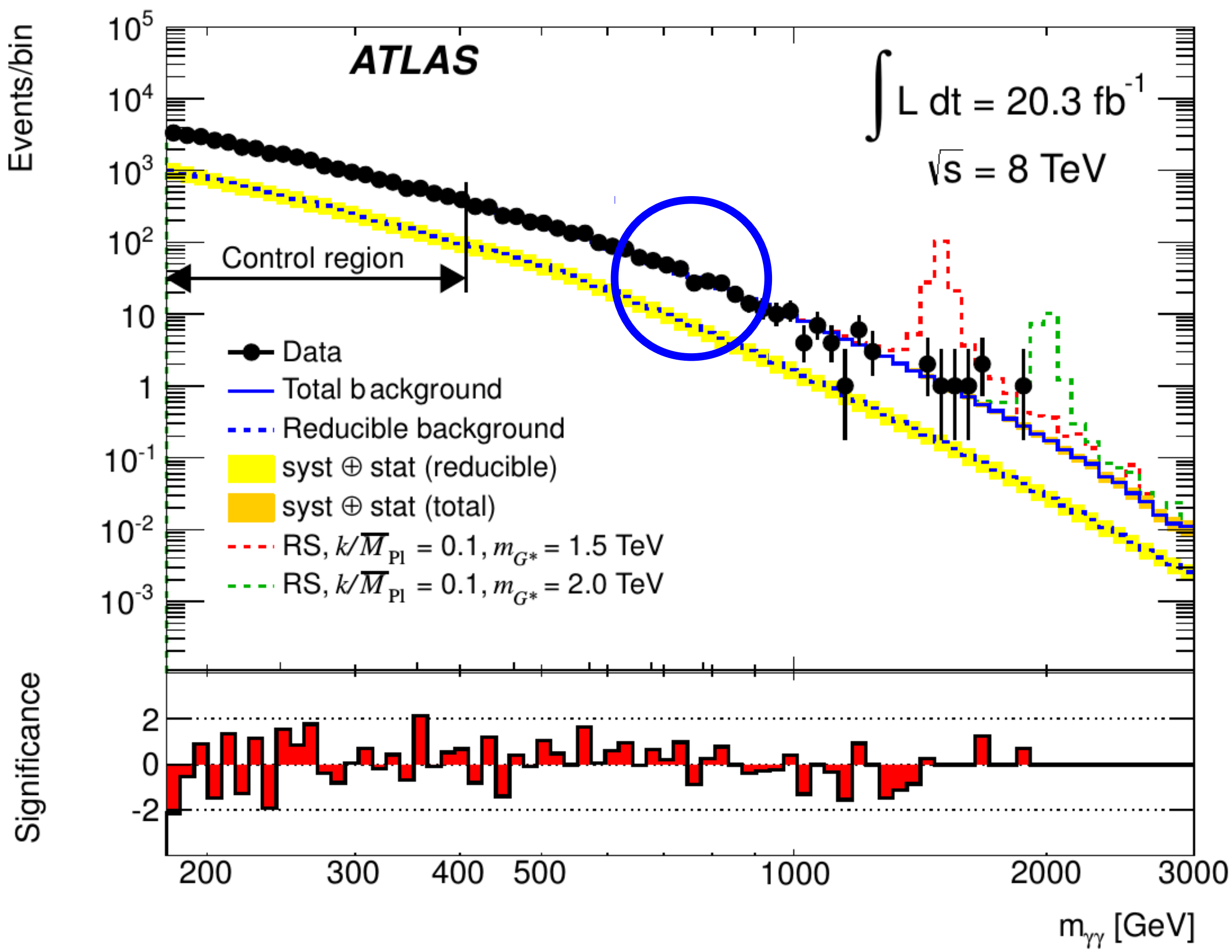
- Use same bkg modeling as for Run 2
- Update photon calibration (needed for 8 TeV vs. 13TeV compatibility test)
- Consider wider resonances

8 TeV Analyses : Exotics Search

PRD 92, 032004 (2015)

Also similar analysis to 13 TeV. Main differences:

- Old Run-1 photon calibration
- Significance measured by counting inside a mass window ("BumpHunter" method)



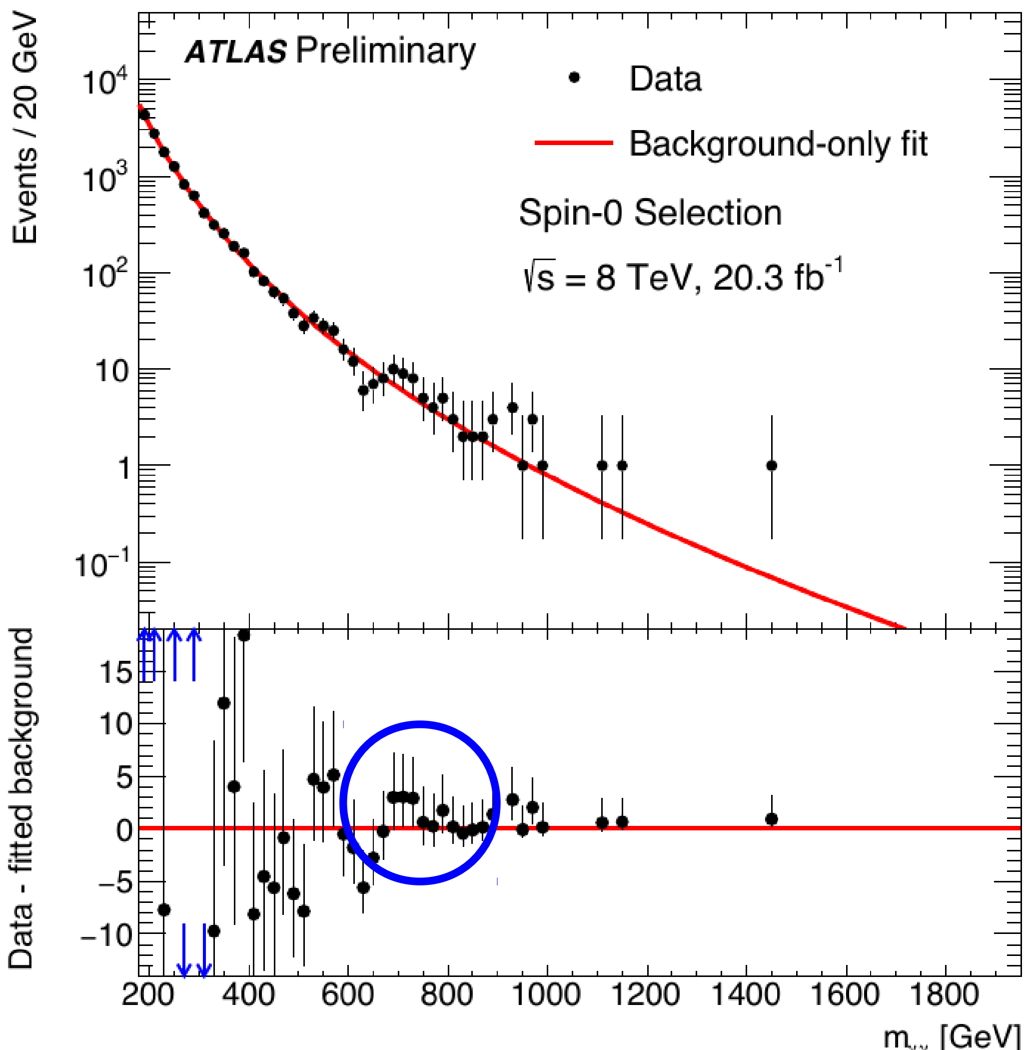
Updates:

- Use most recent photon energy calibration
- Use same analysis method and as 13 TeV analysis

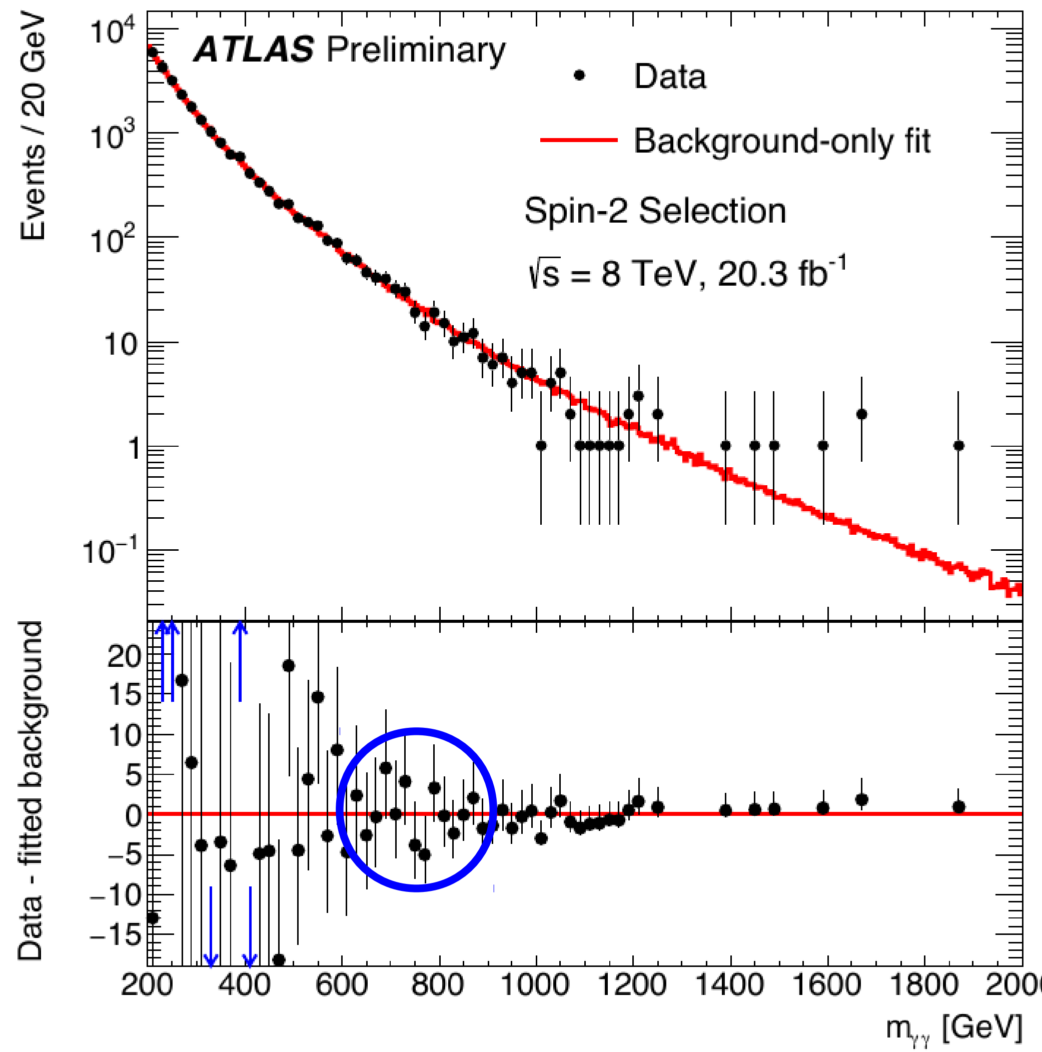
8 TeV Spectra for Updated Analyses

ATL-CONF-2016-018

spin-0



spin-2



1.9σ excess @

m_X = 750 GeV, Γ/m = 6%

No excess

8 TeV vs. 13 TeV Compatibility

ATL-CONF-2016-018

- Need to assume a production cross-section ratio for 8 TeV vs. 13 TeV. Two choices considered
  - **single production through gluon fusion: $\sigma_{13\ TeV}/\sigma_{8\ TeV} = 4.7$**
  - **single production through qq annihilation: $\sigma_{13\ TeV}/\sigma_{8\ TeV} = 2.7$**
- In both cases, assuming
  - Γ/m = 6% for scalar
  - k/M_{pl} = 0.21 for graviton

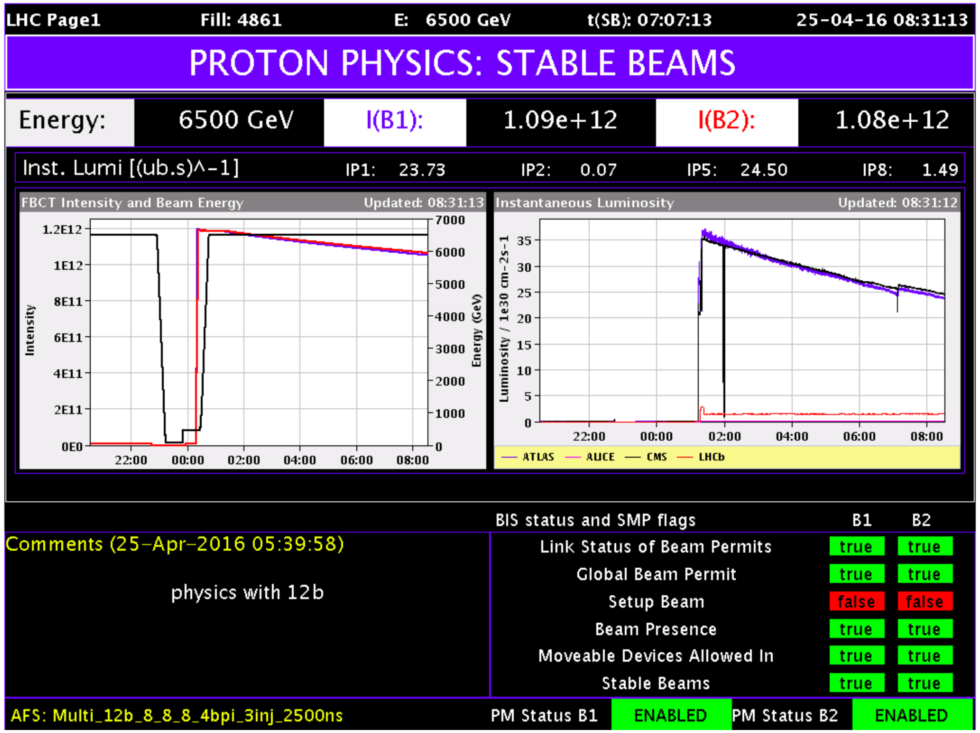
Compatibility	Scalar	Graviton
$gg \to X$	**1.2σ**	**2.7σ**
$qq \to X$	**2.1σ**	**3.3σ**

Everything is compatible, some cases more than others...

Conclusion and Prospects

- Excesses seen at **m_X~750 GeV, Γ/m~6%** in both the scalar and graviton searches.
  - Scalar: **3.9σ local** significance, **2.0σ global** in 2015 data
  - Graviton: **3.6σ local** significance, **1.8σ global** in 2015 data

- The LHC restarted ahead of schedule last month:



Conclusion and Prospects

- Excesses seen at **m_X~750 GeV, Γ/m~6%** in both the scalar and graviton searches.
  - Scalar: **3.9σ local** significance, **2.0σ global** in 2015 data
  - Graviton: **3.6σ local** significance, **1.8σ global** in 2015 data

On Friday 29 April 2016, a short circuit in one of the electrical transformers cut power to the LHC. It was caused by a beech marten (Image: Margot Frenot/CERN)

At around 5:30 am on Friday 29 April 2016, a small beech marten found its way onto a large, open-air electrical transformer situated above ground at CERN, causing a short circuit and cutting the power to part of the Large Hadron Collider (LHC).

The concerned part of the LHC stopped immediately and safely. Since then the entire machine has remained in standby mode.

When the little animal jumped onto the transformer, it created a small electrical arc, damaging high-voltage transformer connections.

Conclusion and Prospects

- Excesses seen at **m_X~750 GeV, Γ/m~6%** in both the scalar and graviton searches.
  - **Scalar**: **3.9σ local** significance, **2.0σ global** in 2015 data
  - **Graviton**: **3.6σ local** significance, **1.8σ global** in 2015 data

On Friday 29 April 2016, a short circuit in one of the electrical transformers cut power to the LHC. It w
marten (Image: Margot Frenot/CERN)

At around 5:30 am on Friday 29 April 2016, a small beech marten found its way onto a large, open-air electrical transformer situated above ground at CERN, causing a short circuit and cutting the power to part of the Large Hadron Collider (LHC).

The concerned part of the LHC stopped immediately and safely. Since then the entire machine has remained in standby mode.

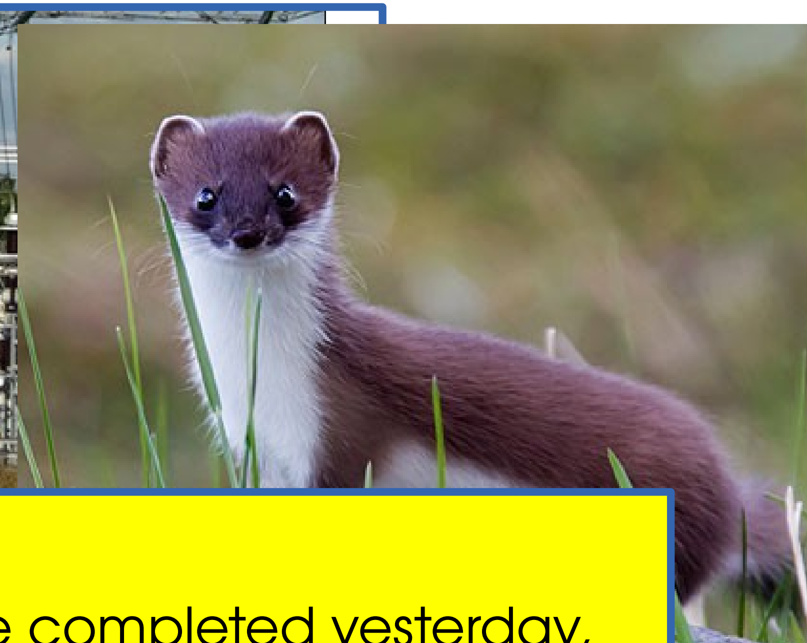
When the little animal jumped onto the transformer, it created a small electrical arc, damaging high-voltage transformer connections.

Conclusion and Prospects

- Excesses seen at **m_X~750 GeV, Γ/m~6%** in both the scalar and graviton searches.
  - Scalar: **3.9σ local** significance, **2.0σ global** in 2015 data
  - Graviton: **3.6σ local** significance, **1.8σ global** in 2015 data

On Friday

marten (



Latest News: Electrical repairs were completed yesterday, collisions expected to restart tomorrow – stay tuned!

At around

situated ab

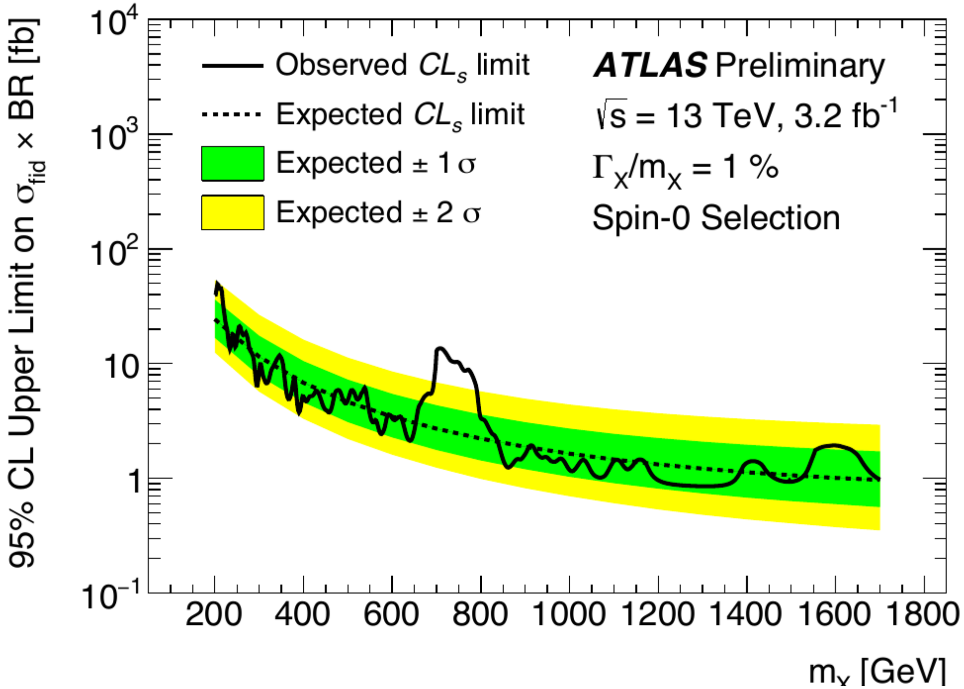
The conce

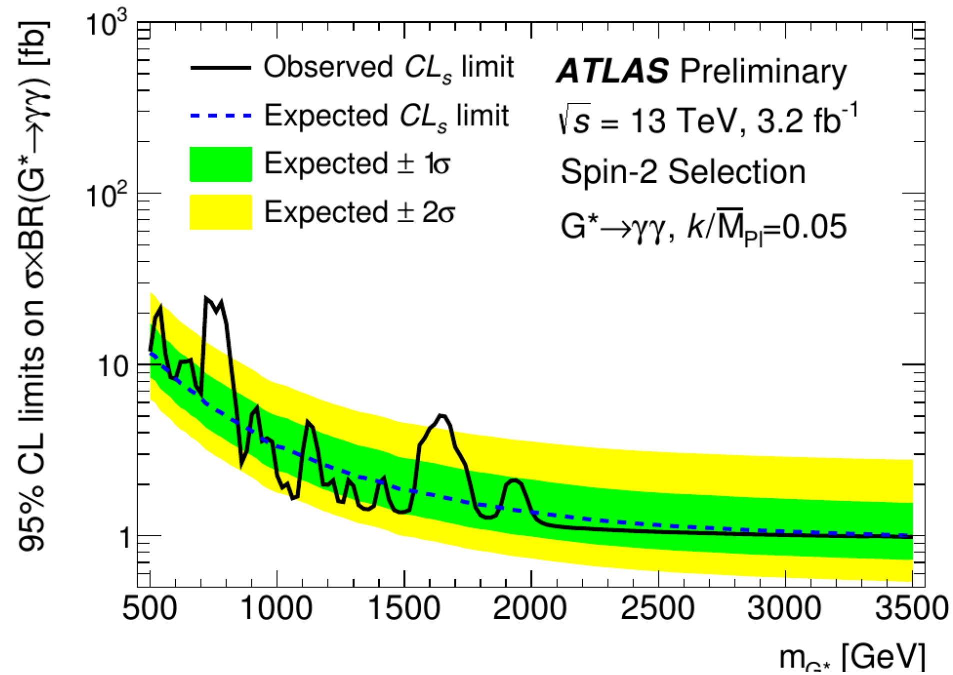
When the little animal jumped onto the transformer, it created a small electrical arc, damaging high-voltage transformer connections.

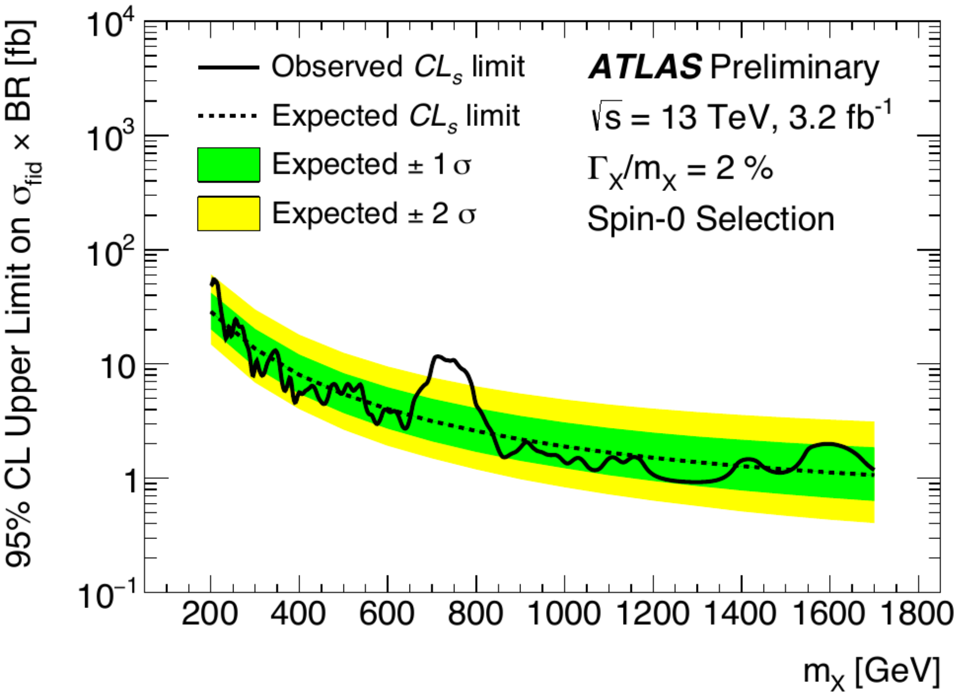
Backup

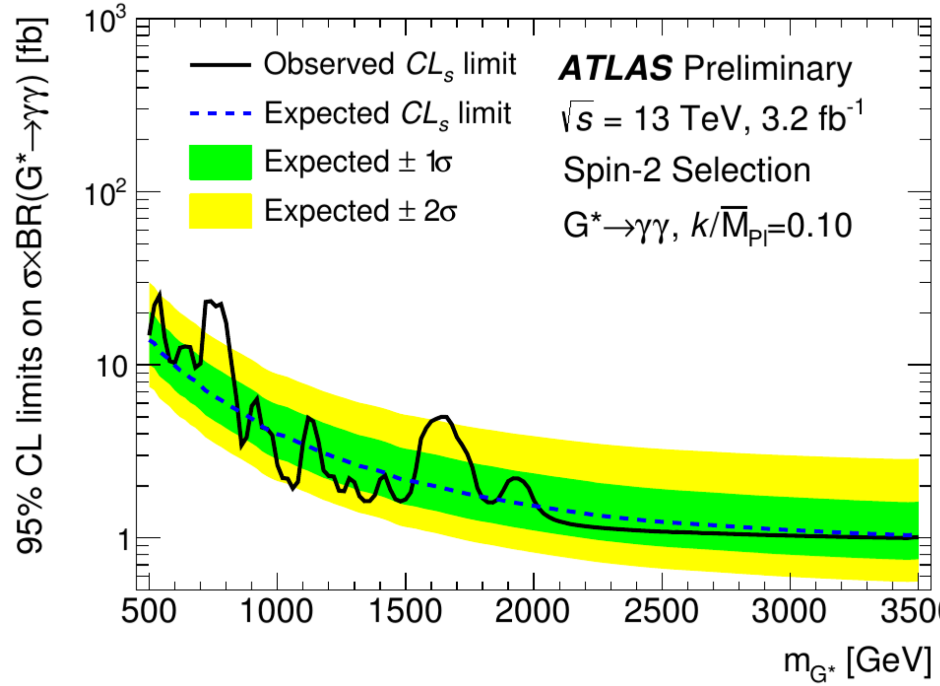
Upper Limits on Scalar $\sigma_{fid} \times B_{\gamma\gamma}$

ATL-CONF-2016-018



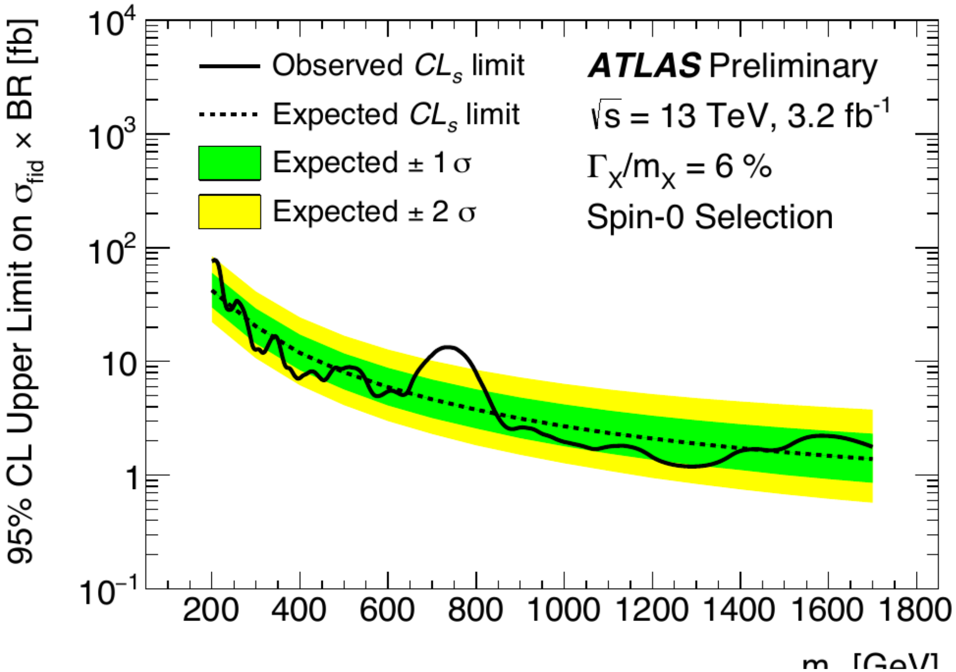


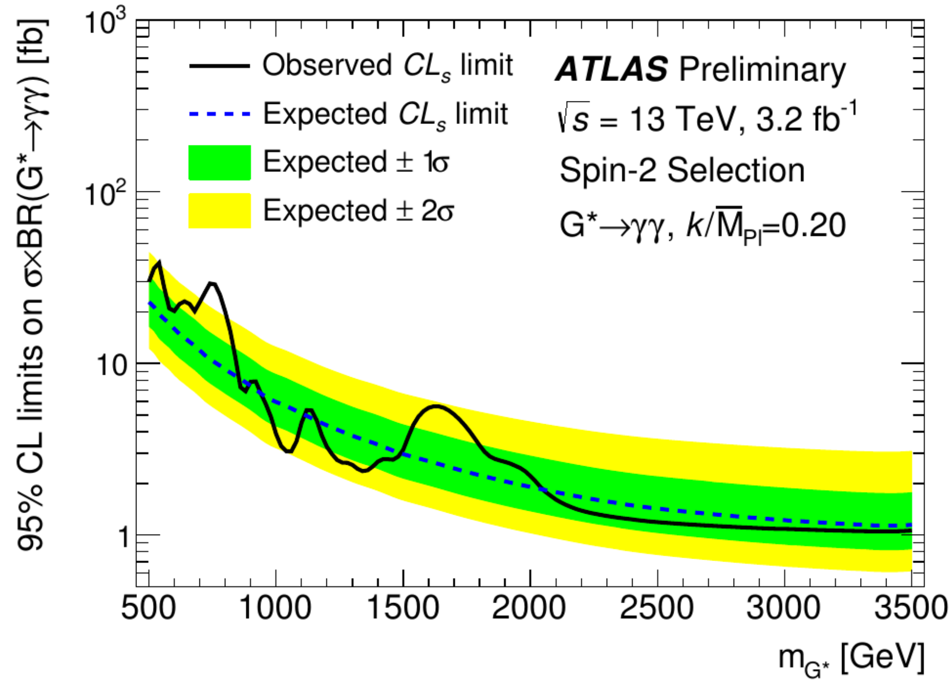


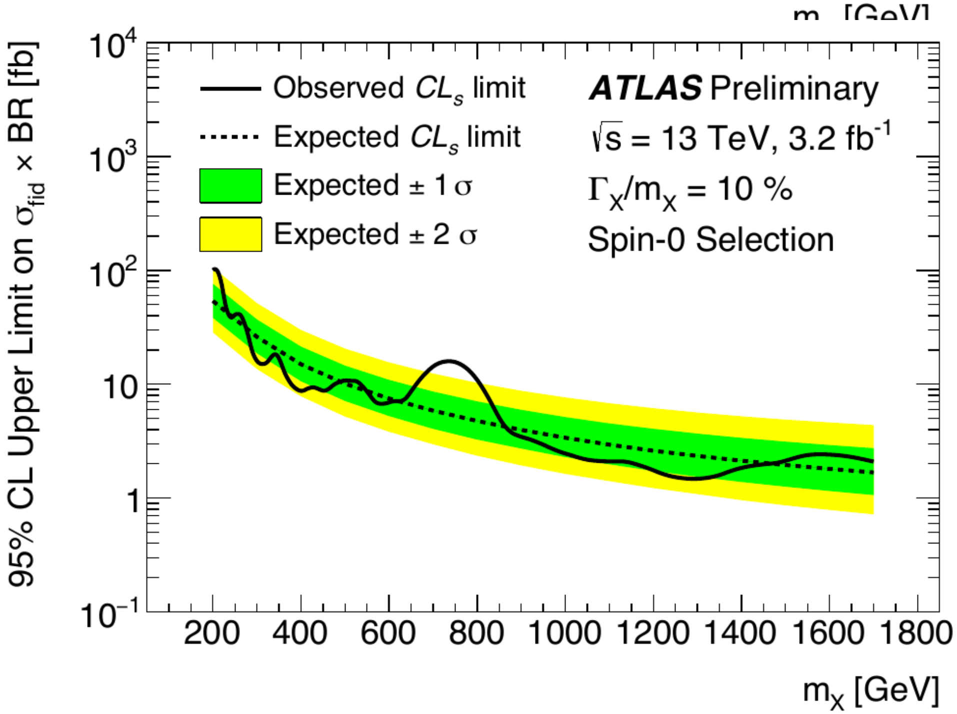


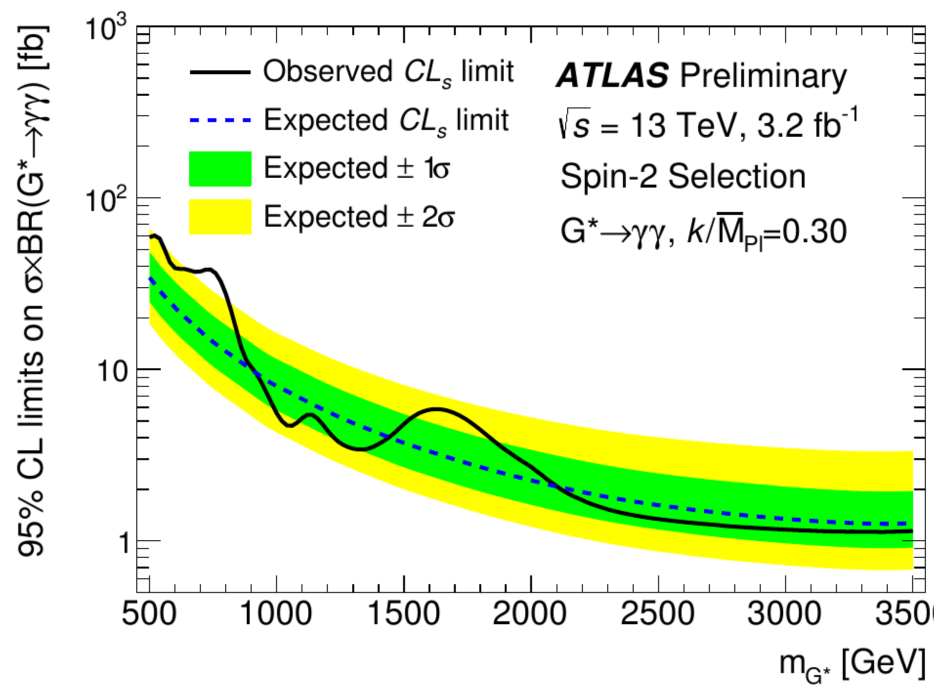
Upper Limits on Graviton $\sigma \times B_{\gamma\gamma}$

ATL-CONF-2016-018



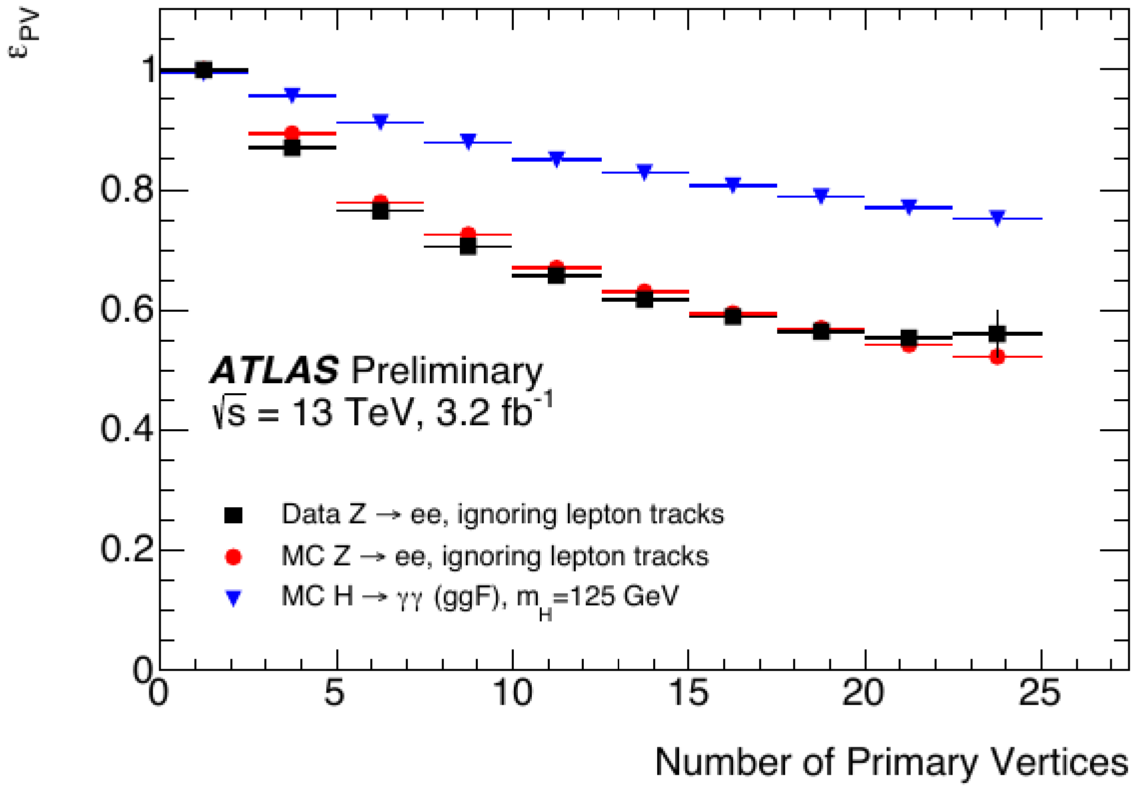




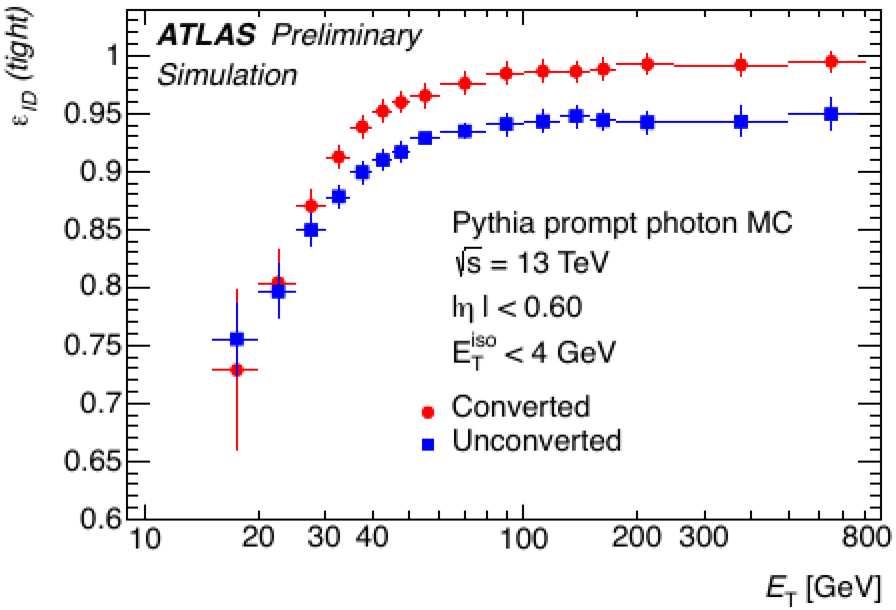


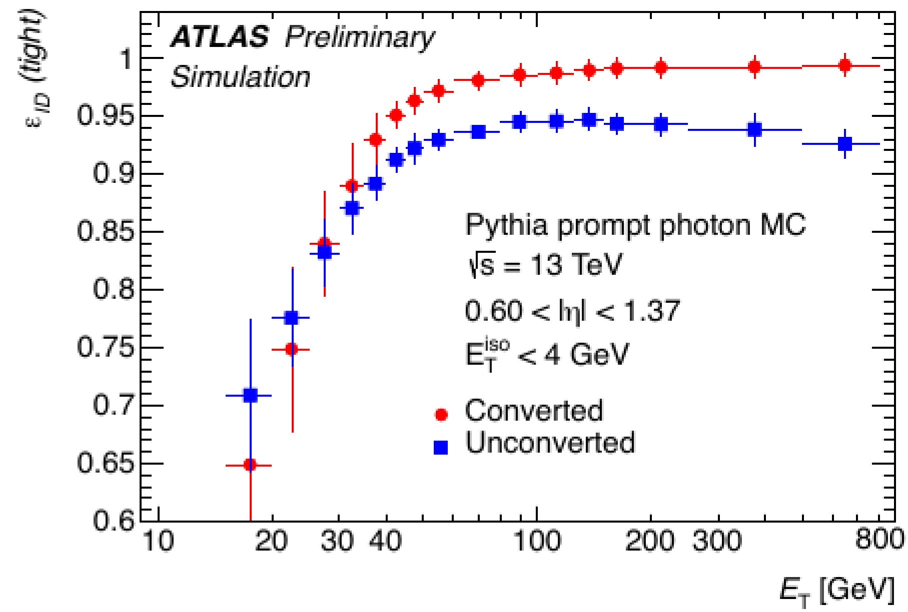
Photon pointing

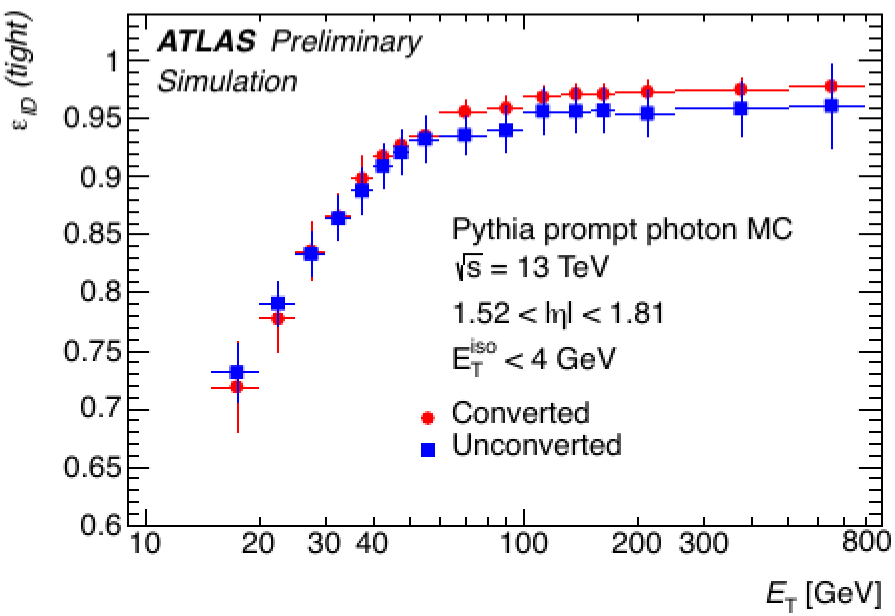
- z position of diphoton primary vertex obtained by combining average beam-spot position with photon pointing, enhanced by using tracks from photon conversions with conversion radii in Si volume
  - ✓ Resolution ~15 mm in z direction
- NN discriminant with $\Sigma p_T, \Sigma p_T^2$, diphoton balancing with vertex tracks, trajectory from calorimeter segmentation (z pointing) to choose best vertex candidate
  - ✓ After this procedure contribution of the opening angle resolution to the mass resolution is negligible.
  - ✓ Efficiency to reconstruct the correct primary vertex within ±0.3 mm is about 88%.

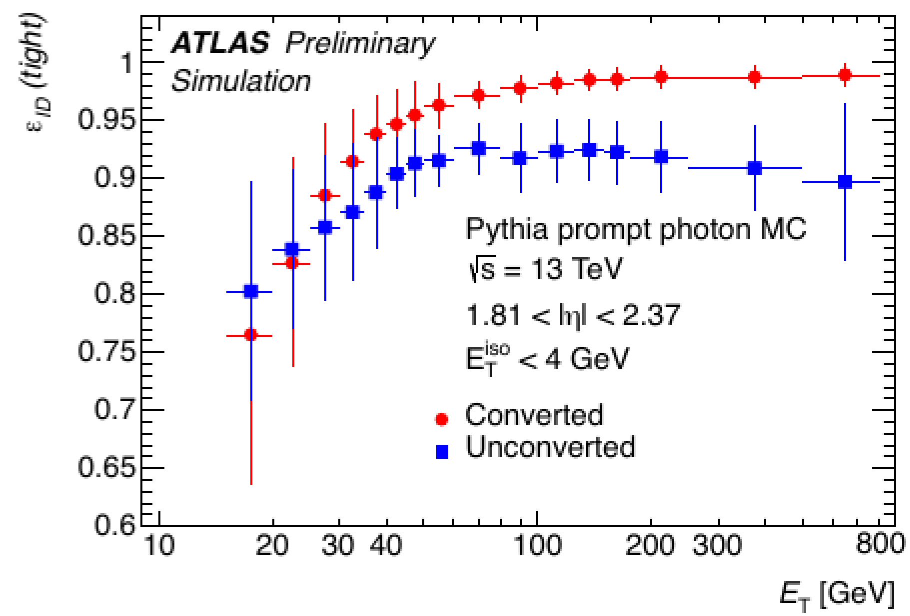


Photon identification 2015





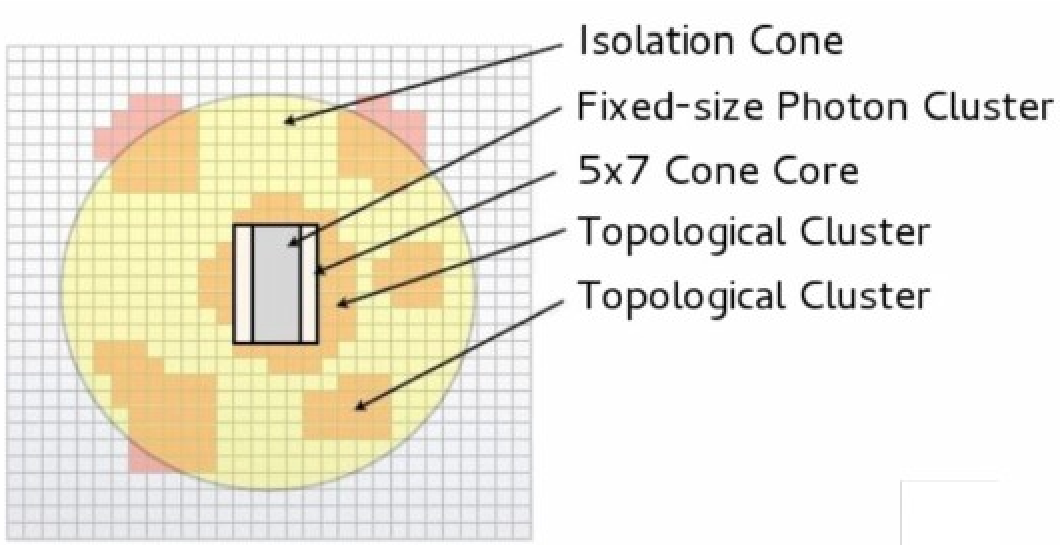


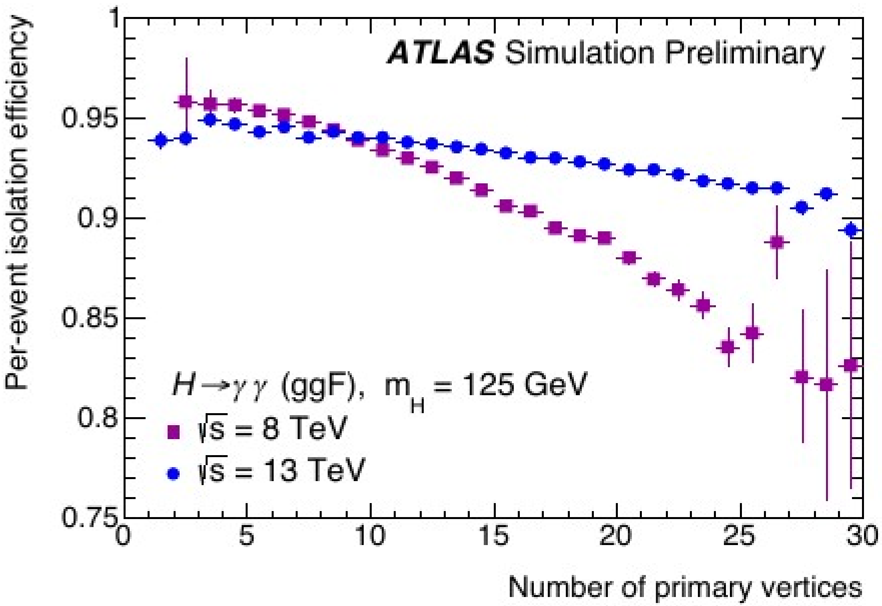


Photon isolation

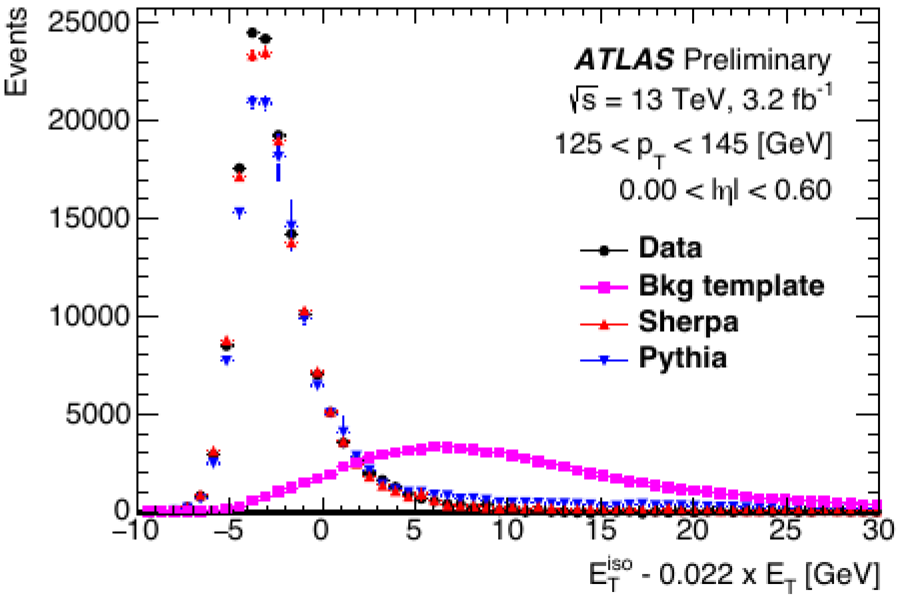
- Calorimetric isolation energy corrected event-by-event
  - ✓ Leakage of photon cluster
  - ✓ Underlying event and pileup contributions
    - Average correction for 1 PV ~540MeV

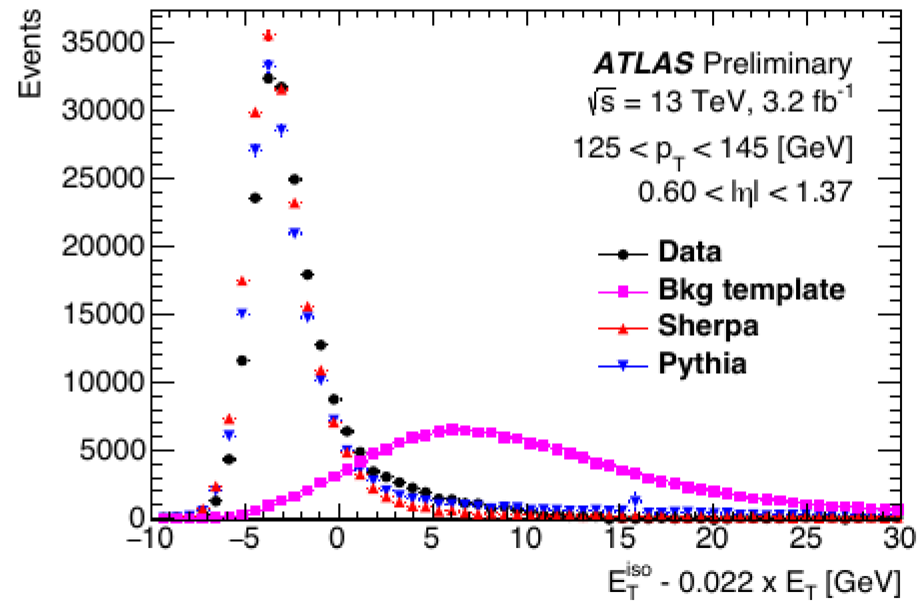
Cacciari, Salam and Soyez, JHEP 04, 005 (2008)
Cacciari, Salam and Sapeta, JHEP 04, 065 (2010)

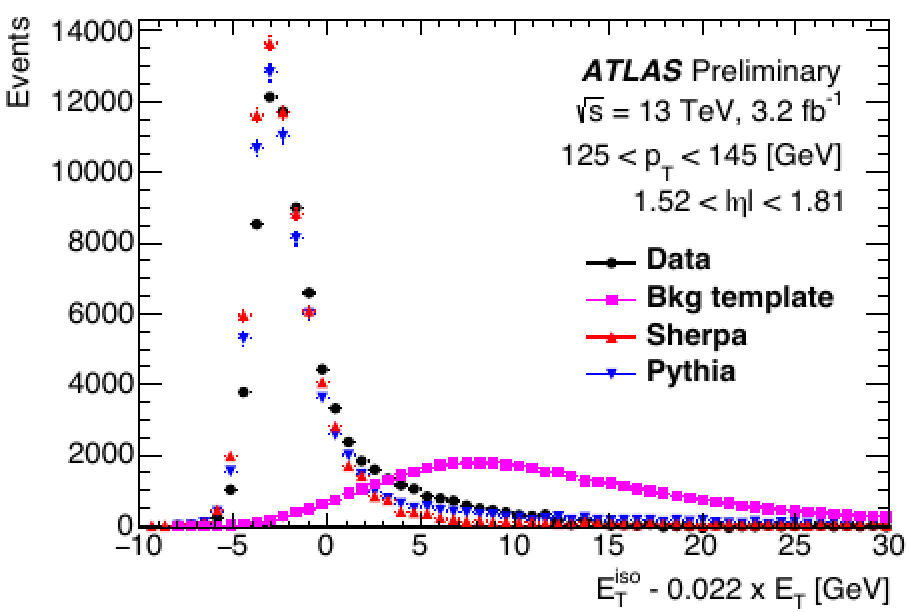


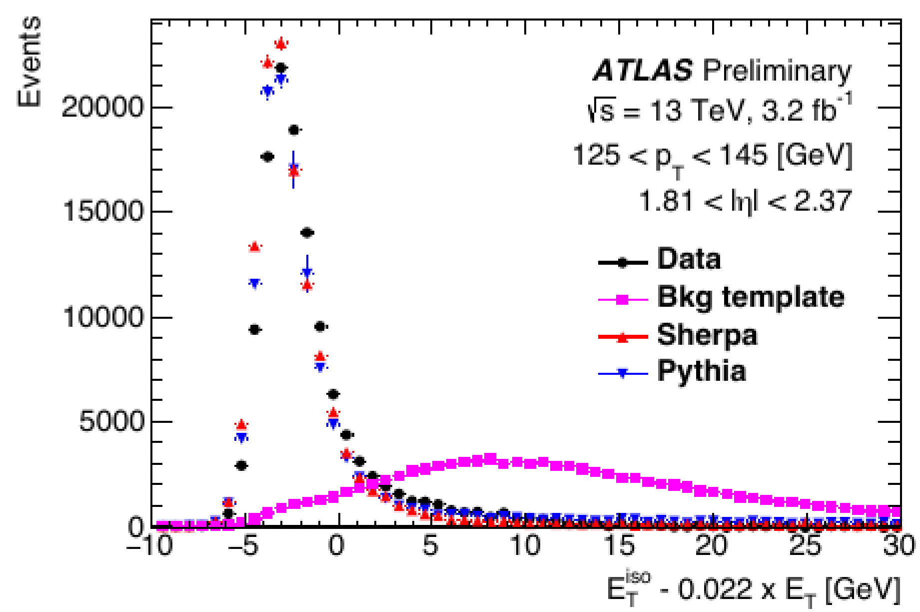


Photon isolation 2015



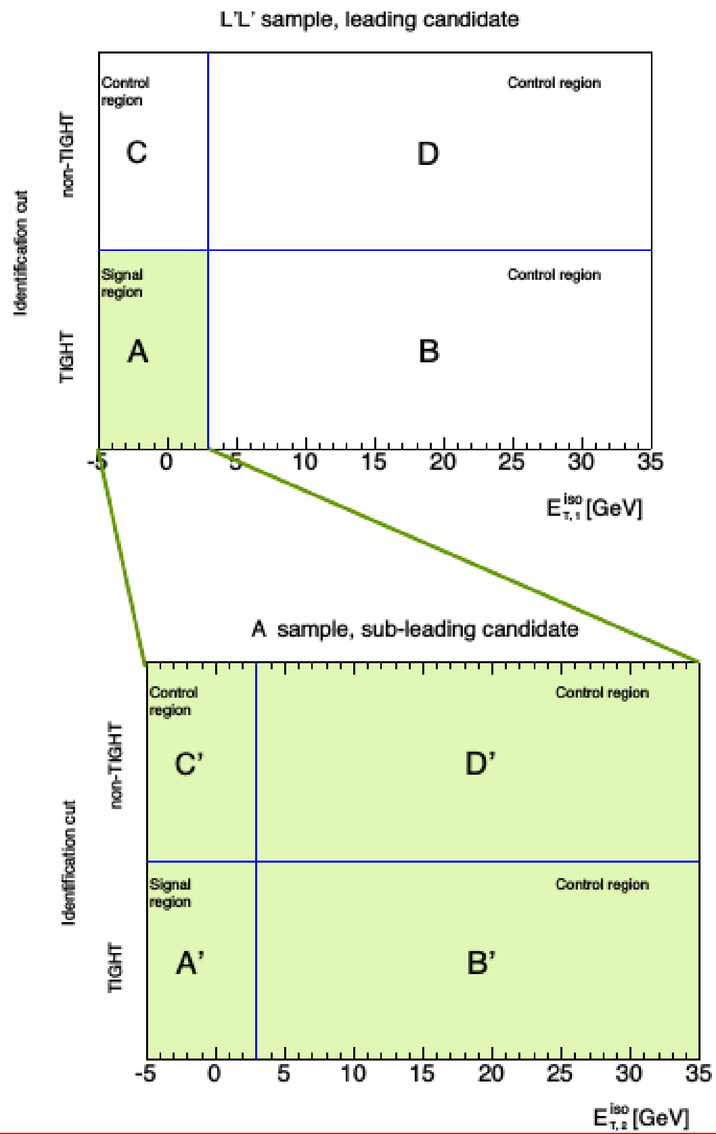




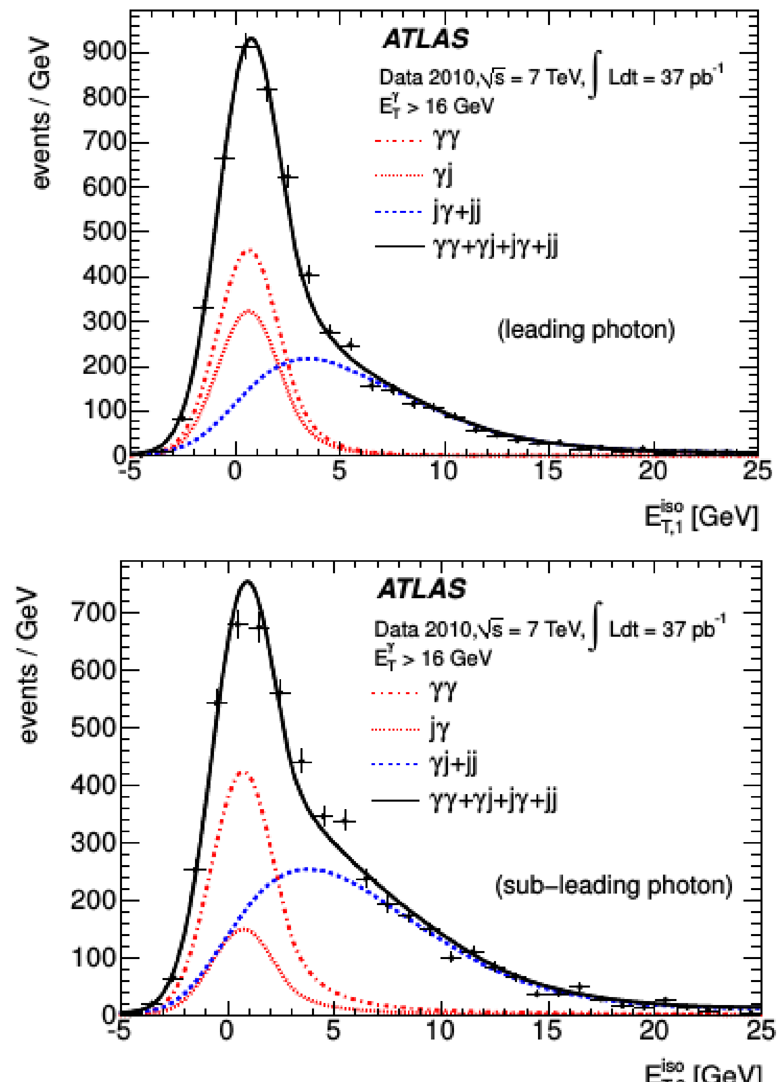


Background estimates

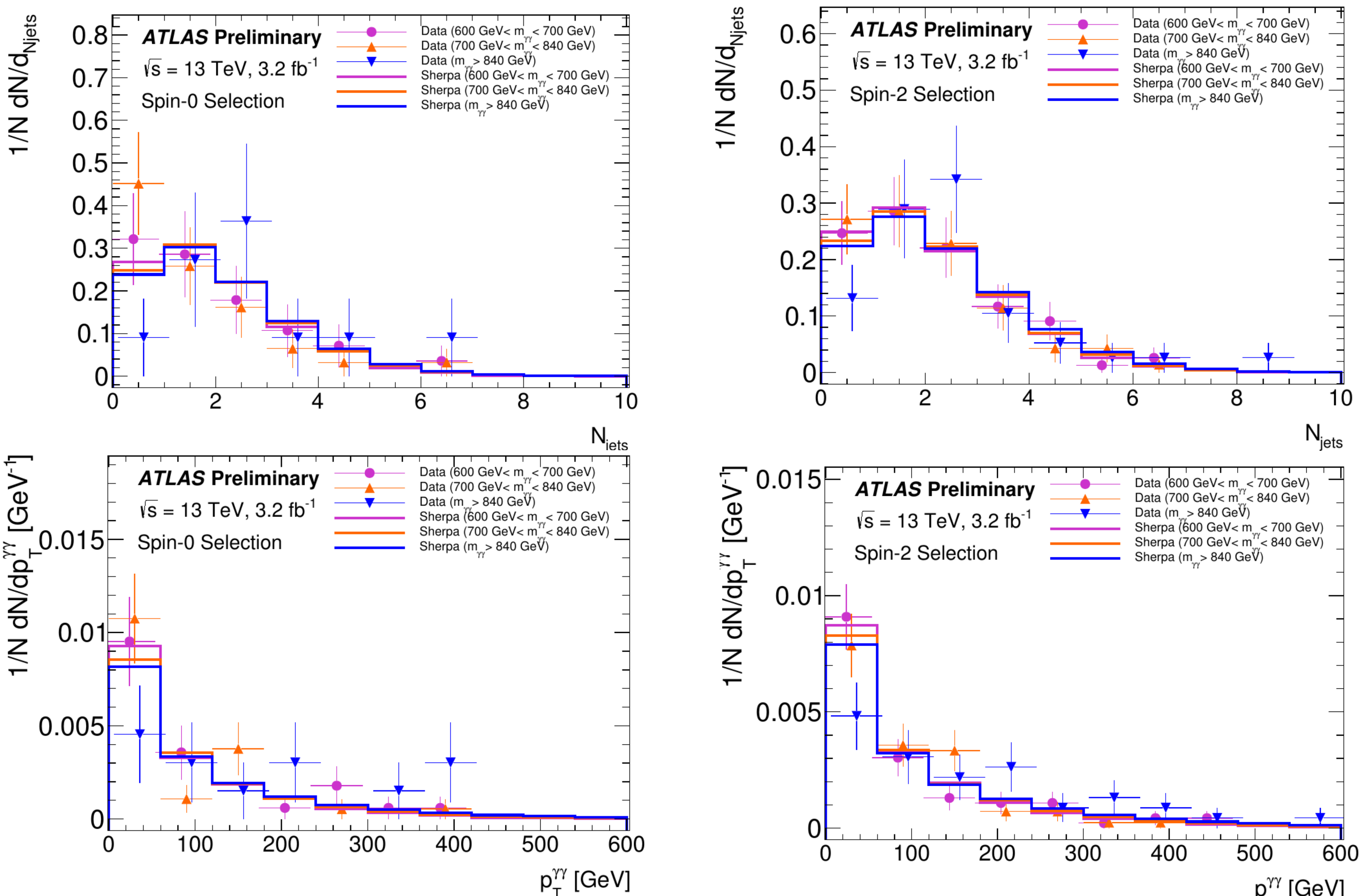
2x2D-sidebands



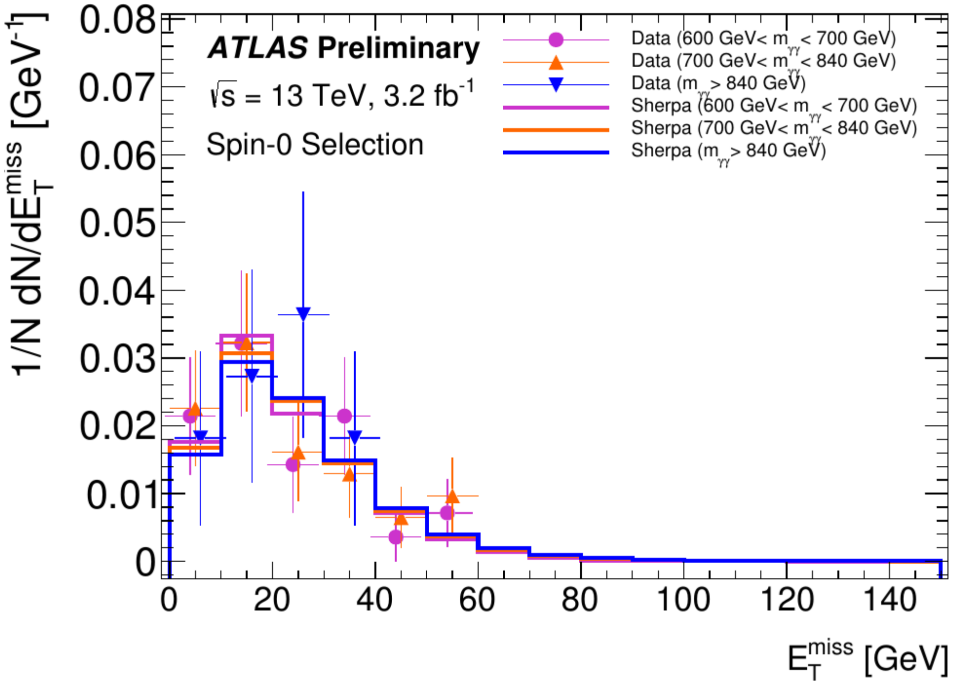
2D isolation template fit

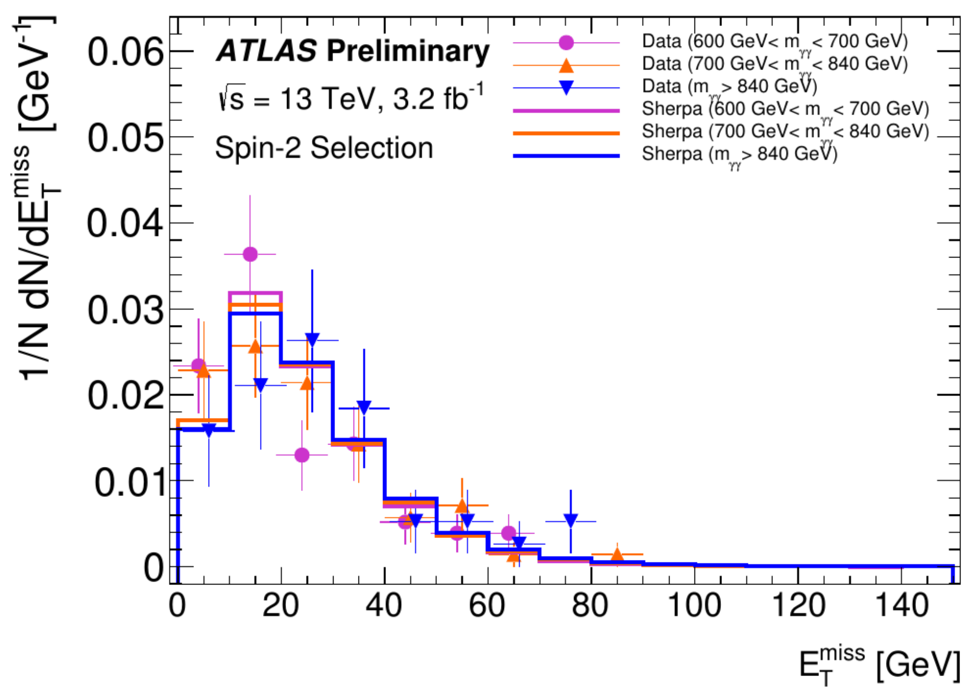


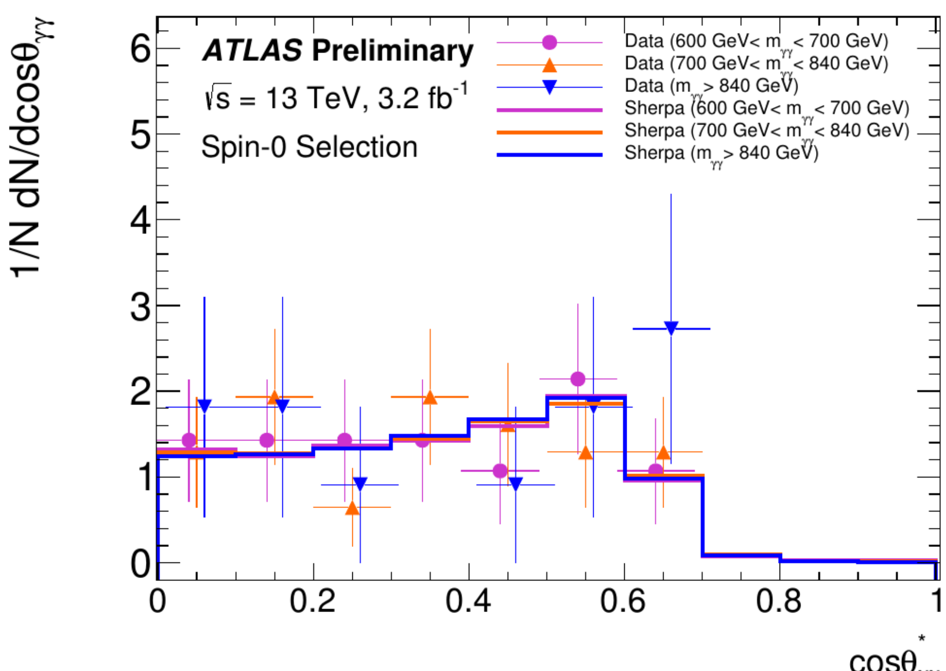
Properties

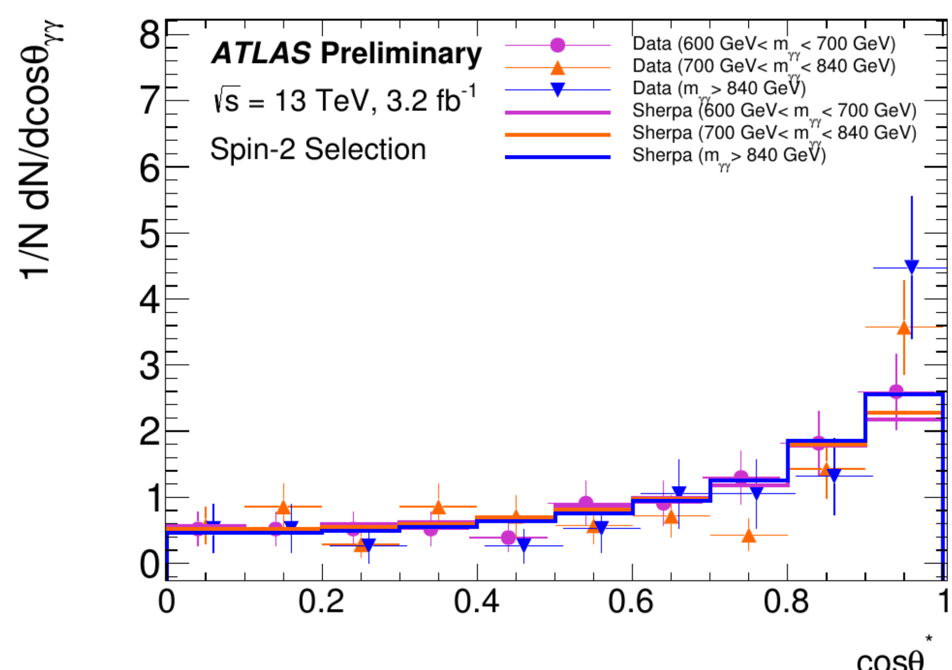

ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Spin-0 Selection
Spin-2 Selection
Data (600 GeV< mγγ < 700 GeV)
Data (700 GeV< mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV< mγγ < 700 GeV)
Sherpa (700 GeV< mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dNjets
Njets
1/N dN/dpTγγ [GeV-1]
pTγγ [GeV]

Properties (2)









Run 1 RS Graviton Limit