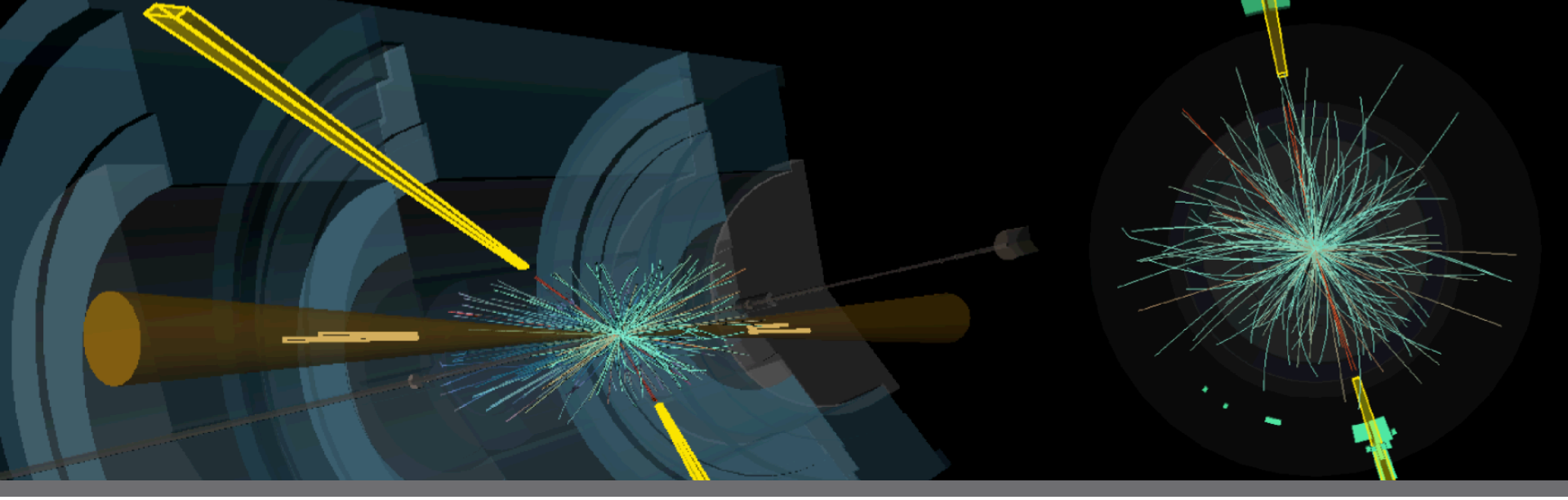

Search for a High-Mass Diphoton Resonance Using the ATLAS Detector

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The University of Wisconsin Madison

On behalf of the ATLAS Collaboration

PASCOS 2016, ICISE, Quy Nhon, Vietnam

July 13, 2016

Contents

Introduction

The diphoton final state provides a useful tool for resonance searches in ATLAS

- Smooth continuum background → **easy to model**!
- Excellent **detector resolution** for photons
- Essential to Higgs boson discovery in LHC Run 1

Data from LHC Run 2 provide new high-mass discovery opportunities with the 13 TeV center-of-mass energy

- **Previous searches** performed at 8 TeV for high-mass spin-0 and spin-2 states [3, 4]
- **Signal cross-sections increase** relative to 8 TeV collisions by 4.7× for $gg \rightarrow X$ and 2.7× for $qq \rightarrow X$ for 750 GeV signals

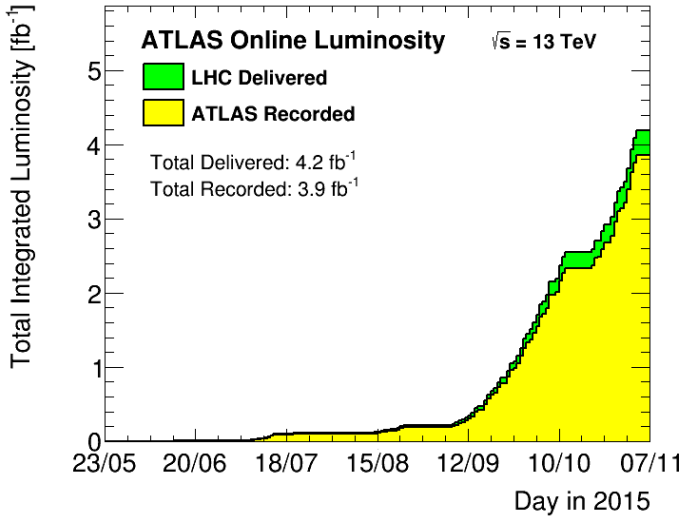
2015 ATLAS paper recently submitted to JHEP [1]

- CMS has also submitted a paper with 2015 data [2]

Data and Monte Carlo Samples

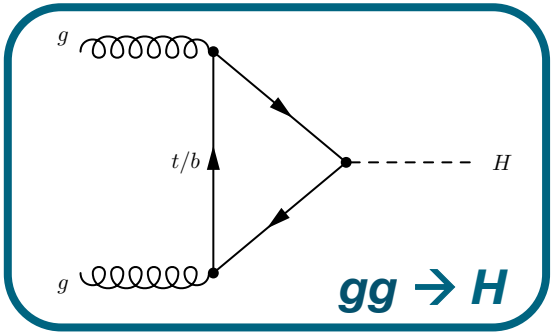
Data sample

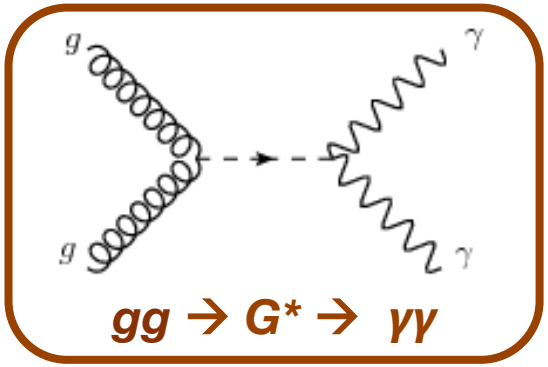
- LHC collisions collected in 2015
- **13 TeV** center-of-mass energy
- **3.2 fb^{-1}** integrated luminosity



Spin-0 signal MC

- **Extended Higgs sector** – model as SM Higgs boson produced in *gg* fusion
- **POWHEG BOX 2** used to generate *gg* → *H*
- Interfaced with **PYTHIA8** for underlying event, parton showering, hadronization



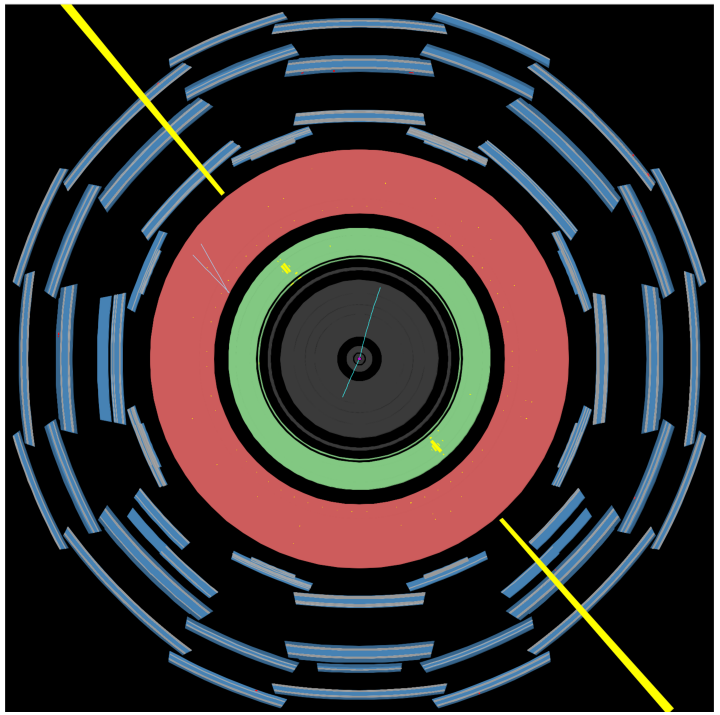


Spin-2 signal MC

- **RS graviton model** (lowest excitation)
- Generated with PYTHIA8, NNPDF23LO parton distribution functions & A14 underlying event tune

Event Selection

Event trigger: two photons passing "loose" photon ID criteria with $E_T^{Lead} > 35$ GeV & $E_T^{Sublead} > 25$ GeV



Photon Selection

- **$|\eta|<2.37$**, excluding $1.37<|\eta|<1.52$ (precision EM calorimeter region)
- **"Tight" photon identification** based on rectangular cuts on EM calorimeter shower shapes
- **Calorimeter-based isolation**: $\Sigma E_T^{(\Delta r=0.4)} < 0.022\, E_T + 2.45$ GeV
- **Track-based isolation**: $\Sigma p_T^{(\Delta r=0.2)} < 0.05\, E_T$

Spin-0 Analysis

- **$E_T^{\gamma 1}/m_{\gamma\gamma} > 0.4$, $E_T^{\gamma 2}/m_{\gamma\gamma} > 0.4$**
- Cuts very forward events
- Sub-set of spin-2 events

Spin-2 Analysis

- **$E_T^{\gamma 1} > 55$ GeV, $E_T^{\gamma 2} > 55$ GeV**
- Loose selection preserves high-mass signal acceptance

Signal Modeling

$$N \cdot \begin{cases} e^{-0.5t^2} & \text{if } -\alpha_{\text{low}} \geq t \geq \alpha_{\text{high}} \\ e^{-0.5\alpha_{\text{low}}^2} \left[\frac{\alpha_{\text{low}}}{n_{\text{low}}} \left(\frac{n_{\text{low}}}{\alpha_{\text{low}}} - \alpha_{\text{low}} - t \right) \right]^{-n_{\text{low}}} & \text{if } t < -\alpha_{\text{low}} \\ e^{-0.5\alpha_{\text{high}}^2} \left[\frac{\alpha_{\text{high}}}{n_{\text{high}}} \left(\frac{n_{\text{high}}}{\alpha_{\text{high}}} - \alpha_{\text{high}} + t \right) \right]^{-n_{\text{high}}} & \text{if } t > \alpha_{\text{high}}, \end{cases}$$

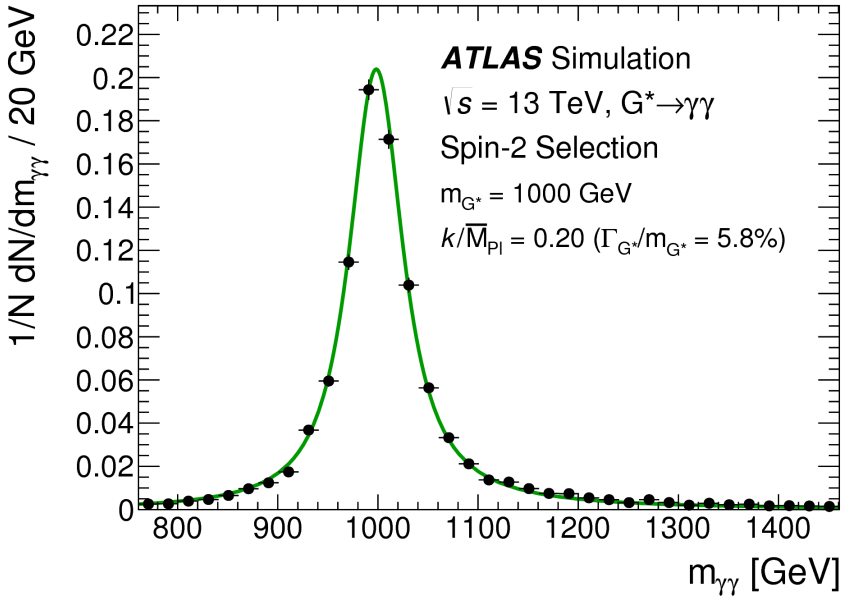
Double-sided Crystal Ball PDF

Detector resolution parameterized as function of m_X or m_{G^*}

- Peak described by double-sided Crystal Ball function
- Variables such as mean and width are parameterized with polynomials over m_X or m_{G^*}

Large width signals

- **Spin-0**: parameterize double-CB shape as function of width in addition to m_X
- **Spin-2**: convolve detector resolution with theoretical line-shape

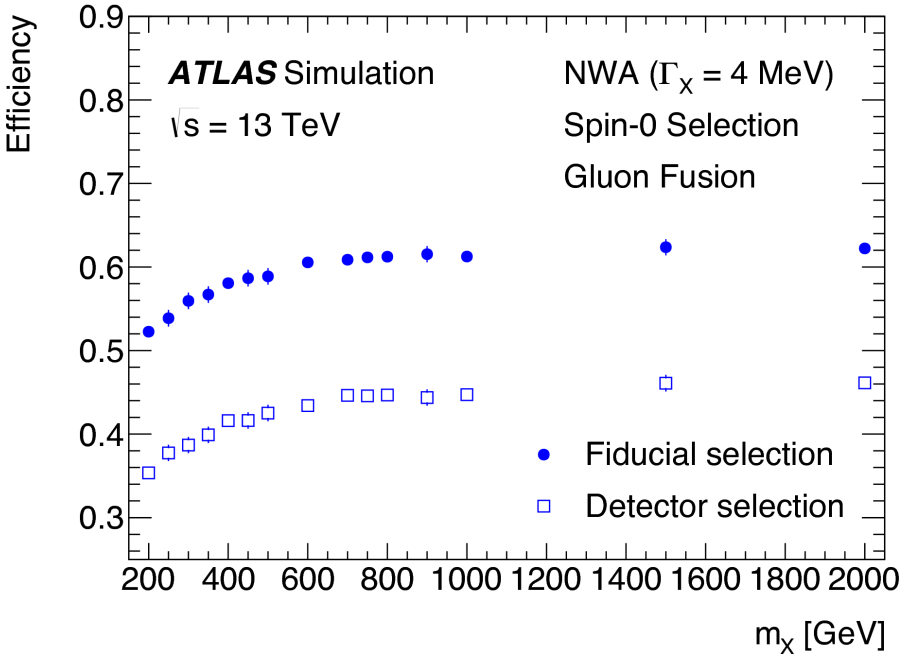


Signal Acceptance and Efficiency

Trigger efficiency > 99% for *gg* produced signal events

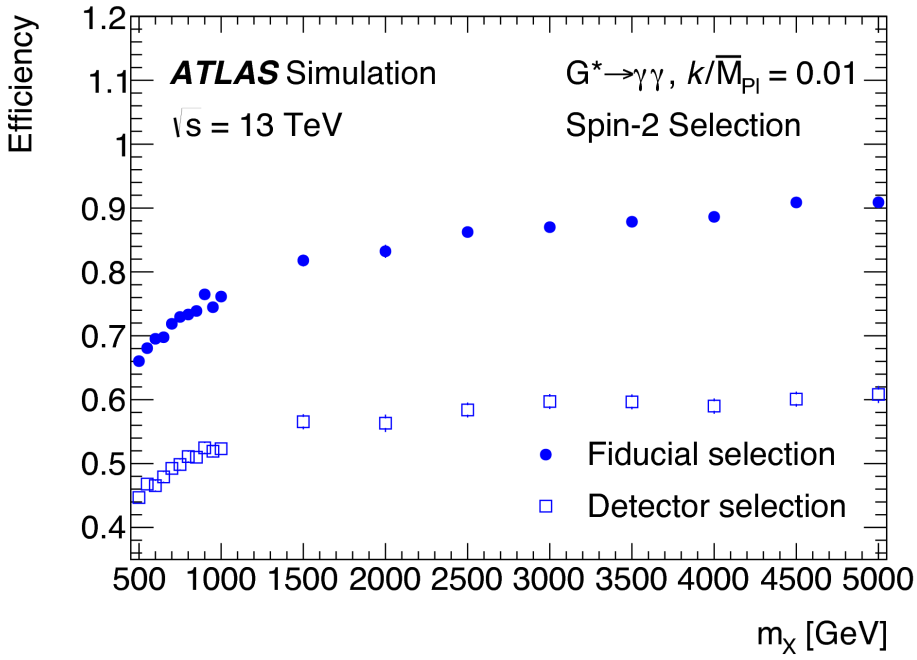
Acceptance and efficiency increase with mass

Spin-0



$\varepsilon \times A$ = 35% - 45% for
200 GeV < m_X < 2 TeV

Spin-2



$\varepsilon \times A$ = 45% - 60% for
500 GeV < m_X < 5 TeV

Signal Systematic Uncertainties

Uncertainty	Spin-2 search	Spin-0 search
Signal mass resolution (mass dependent)	$^{+(30-60)\%}_{-(20-40)\%}$	$^{+(40-60)\%}_{-(30-45)\%}$
Signal photon identification (mass dependent)	±(2–3)%	
Signal photon isolation (mass dependent)	±(2–1)%	±(4–1)%
Signal production process	N/A	±(3–6)% depending on Γ
Trigger efficiency	±0.6%	
Luminosity	±5.0%	

Systematic uncertainties from reconstruction and event selection affect the event yield and mass resolution

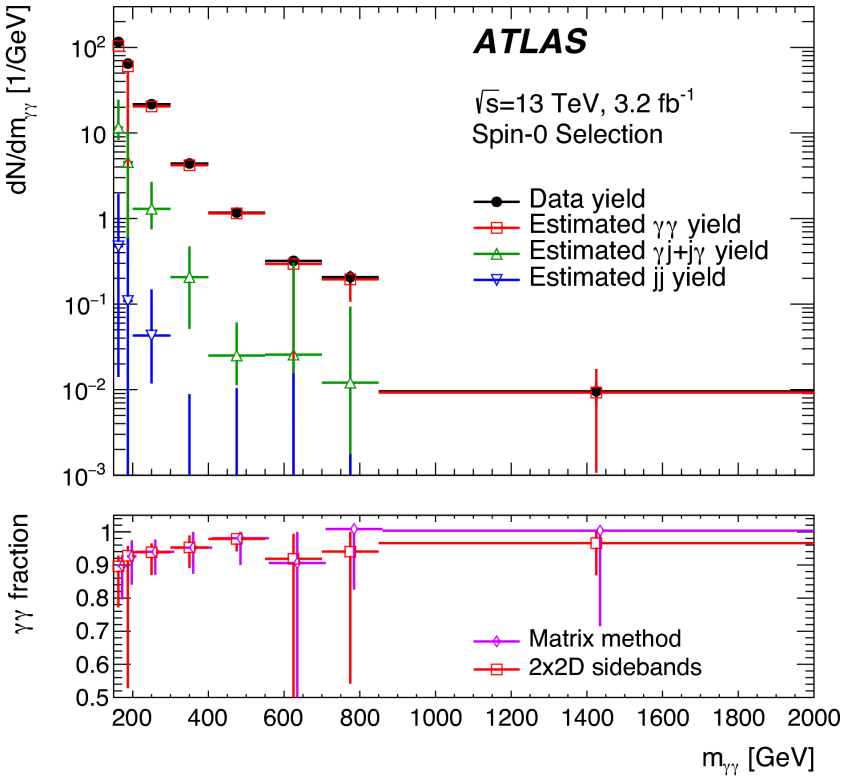
- Luminosity (± 5%) is dominant yield systematic uncertainty
- $m_{\gamma\gamma}$ resolution uncertainty varies from -20% to +60%

→ Search is dominated by statistical uncertainty

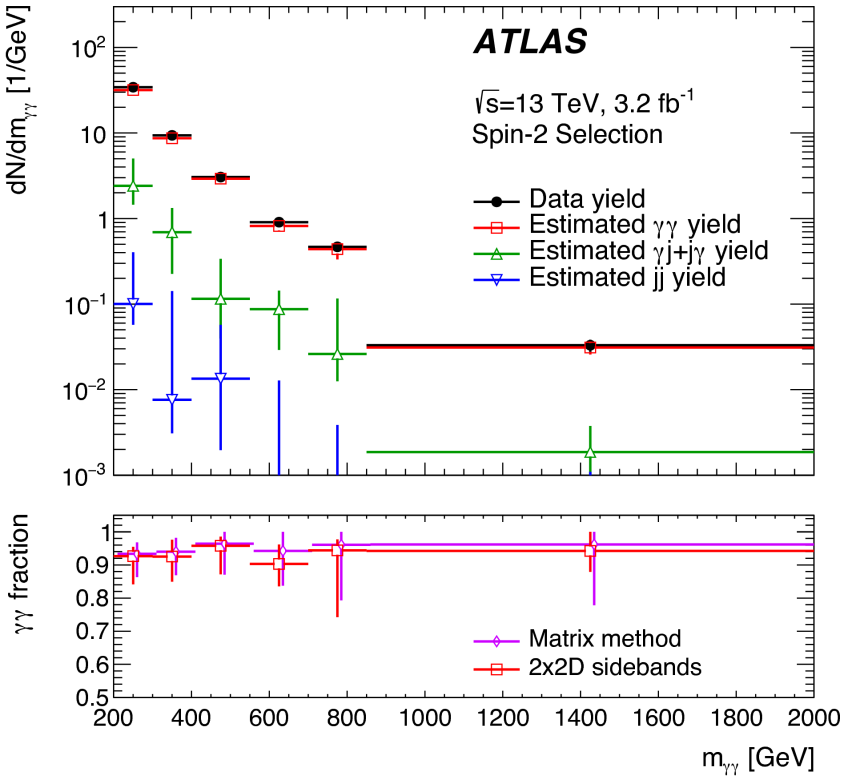
Background is mostly irreducible $\gamma\gamma$, with some reducible γ-jet/jet-γ and di-jet contamination

- Diphoton purity increases with $m_{\gamma\gamma}$

Spin-0 $\gamma\gamma$ purity: 93^{+3}_{-8}%



Spin-2 $\gamma\gamma$ purity: 94^{+3}_{-7}%



Background Modeling

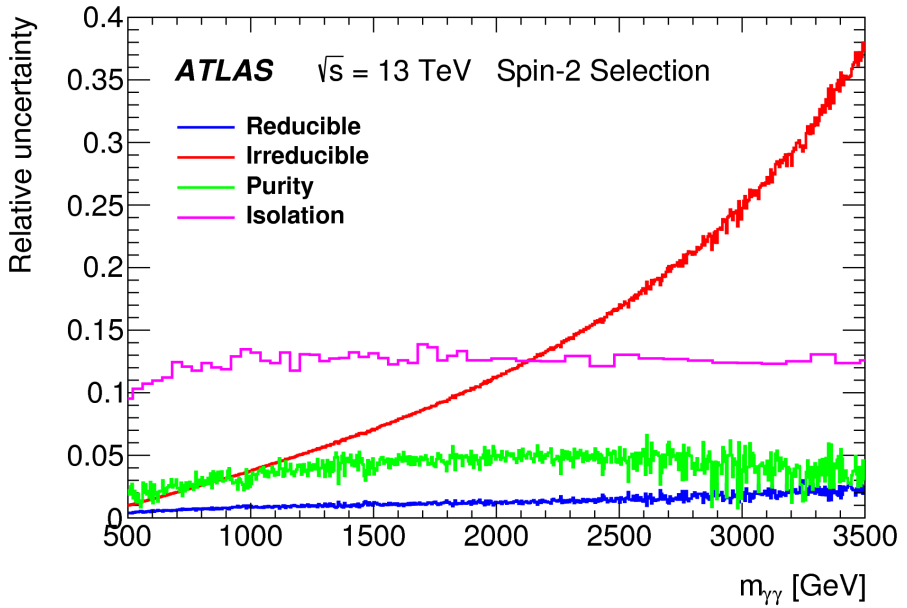
Spin-0: Fit background with analytic PDF

- Unconstrained background PDF only requires one systematic
- Test many functions, choose the one with smallest bias on fitted signal
- **"Spurious signal" modeling systematic** is number of signal events fitted to background-only Monte Carlo

$$F[x] = N\,(1 - x^{1/3})^{b}\,x^{a\,\log(x)}, \text{ where } x = (m_{\gamma\gamma} / \sqrt{s})$$

Spin-2: Template histogram for high-mass sensitivity

- ***γγ* background:** LO Sherpa MC re-weighted to NLO Diphox
- ***γ*-jet background:** from loose-ID data control regions
- **Combine *γγ* and *γ*-jet** components using the purity measured for $m_{\gamma\gamma} < 500$ GeV
- **Fit $m_{\gamma\gamma}$** from 200 GeV to 5 TeV
- **Systematics** from purity, MC, data control region, parton isolation



The data are modeled by: $N_S f_S(m_{\gamma\gamma}) + N_B f_B(m_{\gamma\gamma})$

- N_S and N_B are fitted number of signal & bkg. events
- f_S & f_B are the invariant mass distributions

Local *p*-value determines compatibility of background hypothesis with data

- Evaluated by scanning the **q_0 test statistic** →

$$q_0(m_X, \alpha) = -2 \log \frac{L(0, m_X, \alpha, \hat{\hat{\nu}})}{L(\hat{\sigma}, m_X, \alpha, \hat{\nu})}$$

- Asymptotic approximation for q_0: $f(q_0|\mu=0) \sim \frac{1}{2}\chi^2 + \delta(q_0)$

95% confidence-level exclusion-limits are computed with modified Frequentist (CL_S) approach

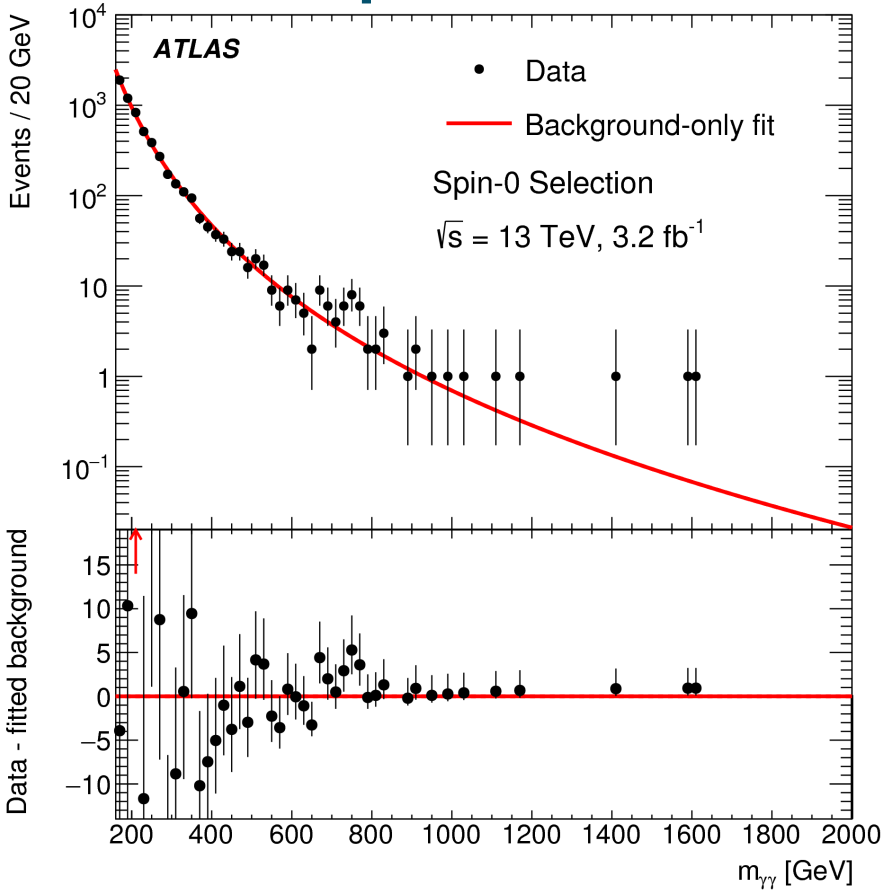
- **$CL_S = p_S / (1 - p_B)$**, using the q_μ test statistic

Fit Strategy

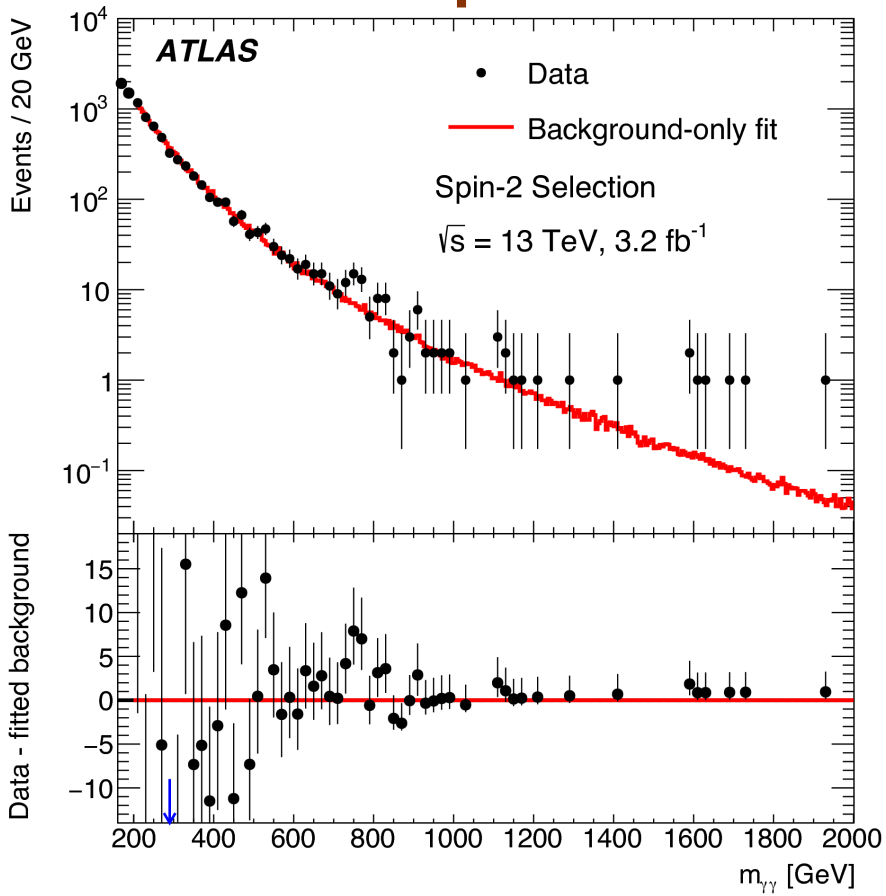
Perform un-binned maximum likelihood fits to $m_{\gamma\gamma}$

- **Spin-0**: Fit $m_{\gamma\gamma} > 150$ GeV, search above 200 GeV
- **Spin-2**: Fit $m_{\gamma\gamma} > 200$ GeV, search above 500 GeV

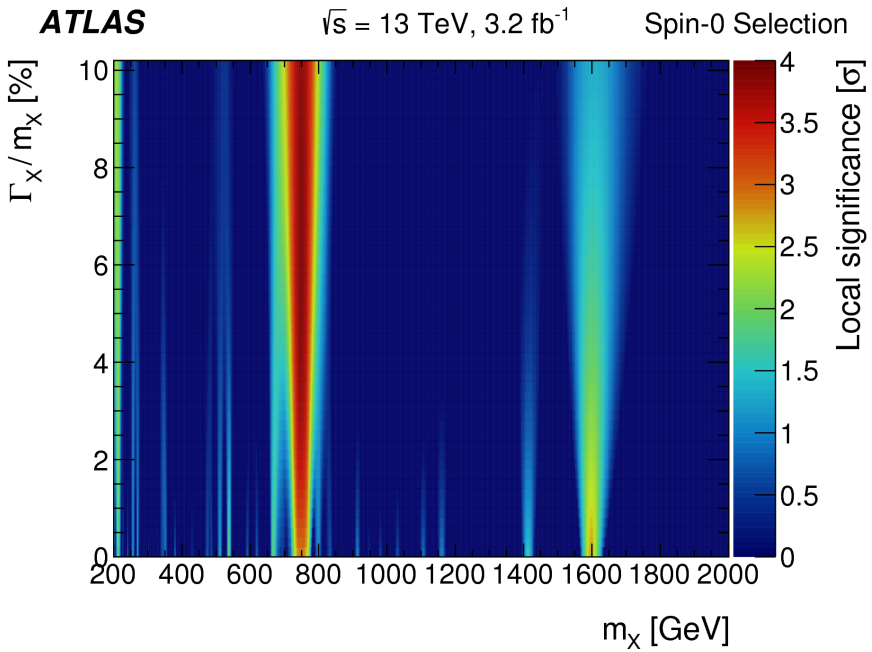
Spin-0

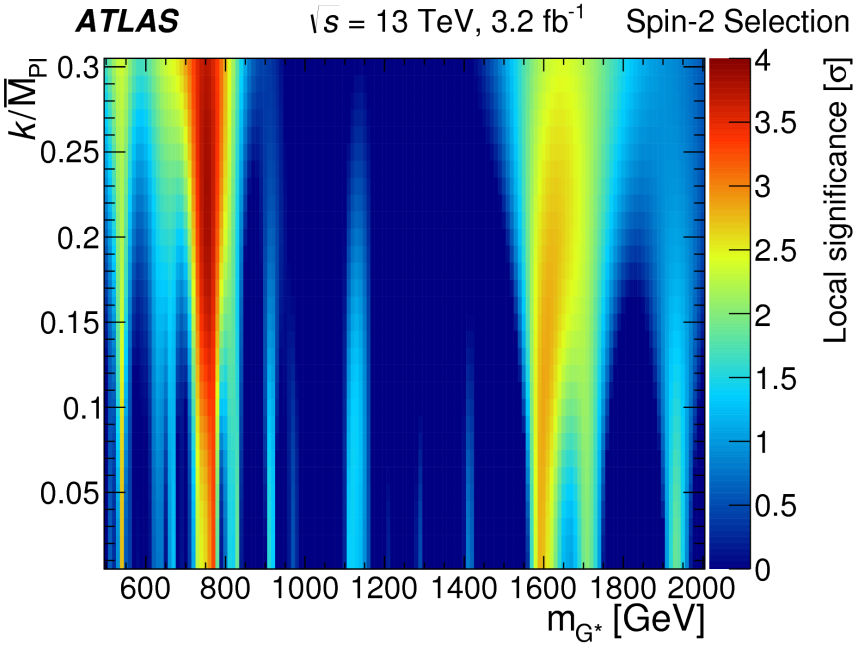


Spin-2



Compatibility with Background Hypothesis: p_0 Results





Spin-0
Maximum Likelihood Fit:

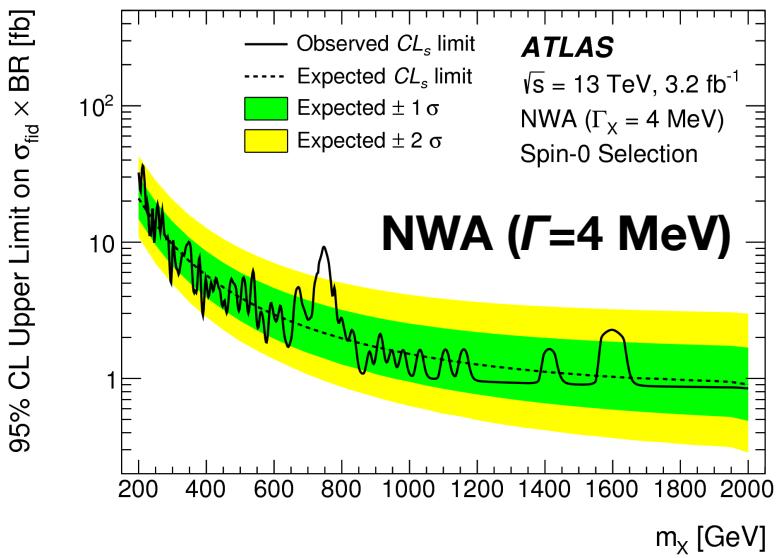
- m_X = 750 GeV
- Γ_X / m_X = 6%
- Local significance = 3.9σ
- Global significance = **2.1σ**

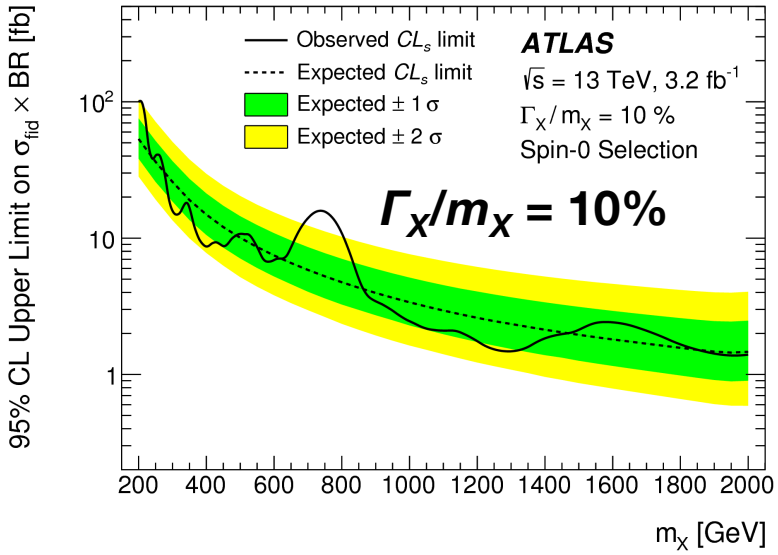
Spin-2
Maximum Likelihood Fit:

- m_{G^*} = 750 GeV
- κ / M_{Pl} = 0.23
- Local significance = 3.8σ
- Global significance = **2.1σ**

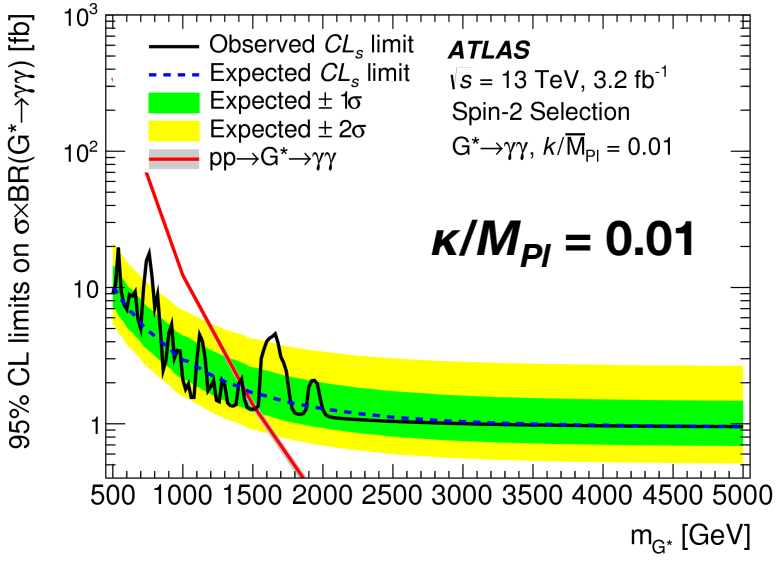
95% *CL* Limits on Signal Production

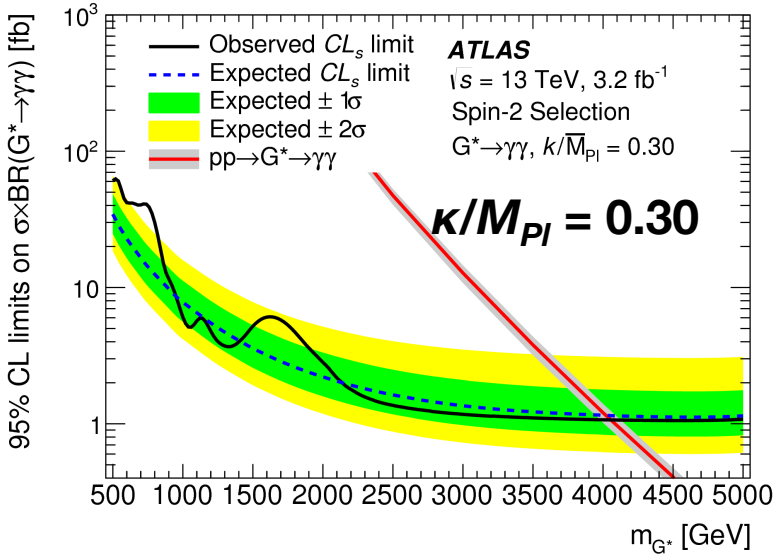
Spin-0 Exclusion





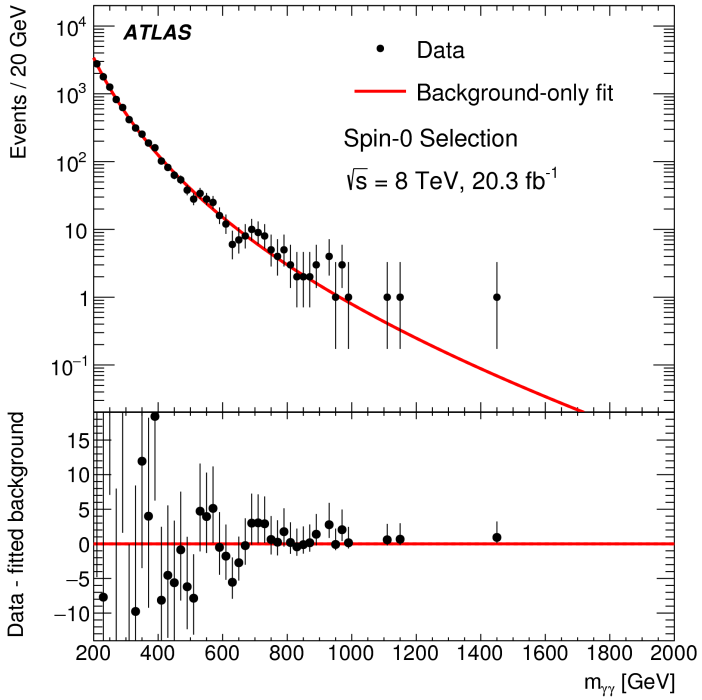
Spin-2 Exclusion



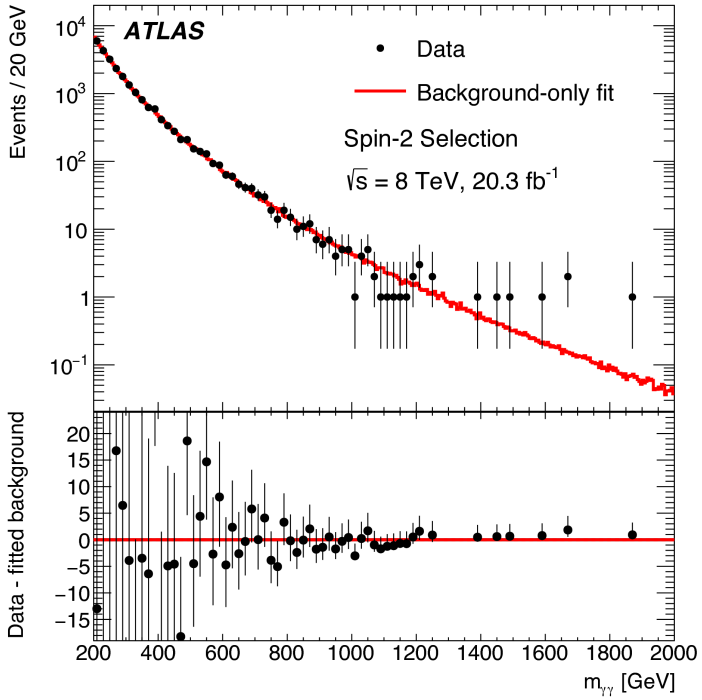


Compatibility of 8 TeV results with 13 TeV excess at 750 GeV estimated assuming *gg* or *qq* production

Spin-0



Spin-2



Production	Spin-0 Free-Width	Spin-0 NWA	Spin-2 Free-Width	Spin-2 NWA
gg → *X*	2.7σ	2.2σ	1.2σ	1.5σ
qq → *X*	3.3σ	2.4σ	2.1σ	2.0σ

Summary & Outlook

Search for spin-0 and spin-2 diphoton resonances performed using 3.2 fb^{-1} of data with ATLAS

- **Excesses** of **3.9σ** and **3.8σ** observed near a mass of 750 GeV in the **spin-0** and **spin-2** searches
- **Global significance** of both observations is **2.1σ**

Compatibility of 8 TeV data calculated for excess in 13 TeV data at 750 GeV

- **1.2σ - 2.7σ** tension assuming a *gg*-produced signal
- **2.0σ - 3.3σ** tension assuming a *qq*-produced signal

Stay tuned for updates with 2016 data!

- Significantly larger integrated luminosity at $\sqrt{s}$=13 TeV

References

[1] *Search for resonances in diphoton events at √s=13 TeV with the ATLAS detector*
http://arxiv.org/abs/1606.03833

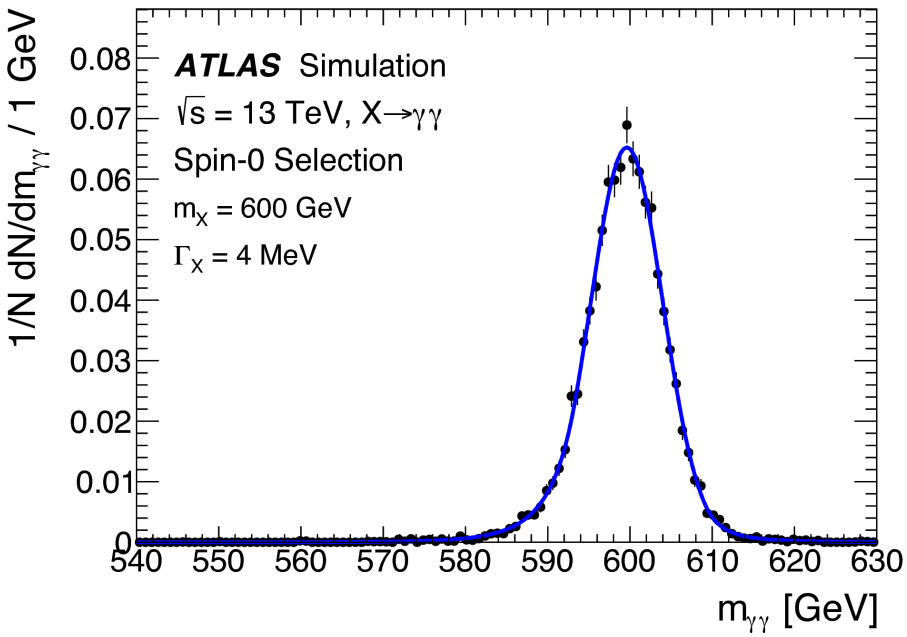
[2] *Search for resonant production of high-mass photon pairs in proton-proton collisions at √s=8 and 13 TeV*
http://arxiv.org/abs/1606.04093

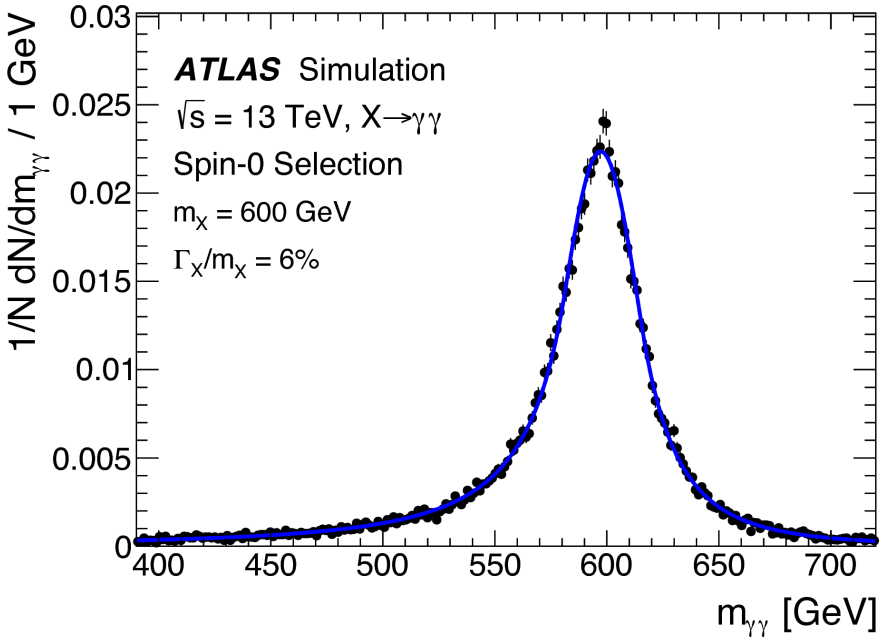
[3] *Search for Scalar Diphoton Resonances in the Mass Range 65-600 GeV with the ATLAS Detector in pp Collision Data at √s=8 TeV*
http://arxiv.org/abs/1407.6583

[4] Search for diphoton resonances in the mass range from 150 to 850 GeV in pp collisions at sqrt(s)=8 TeV
https://arxiv.org/abs/1506.02301

Appendix

Spin-0 Signal Modeling

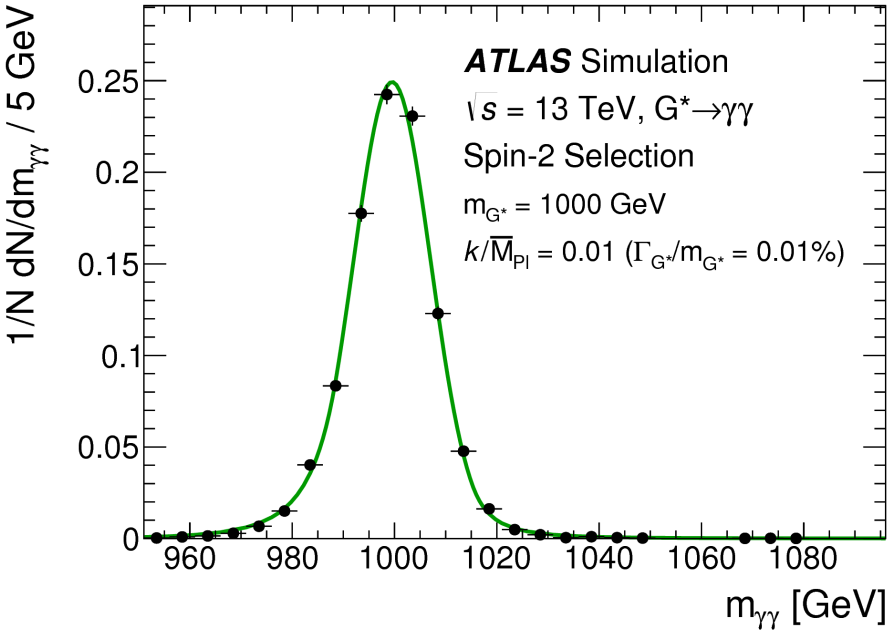


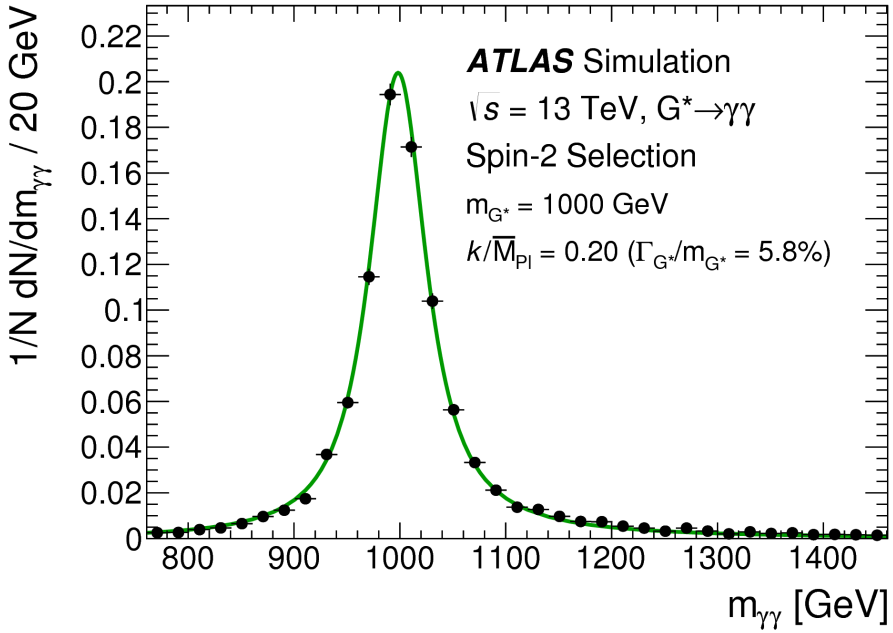


Spin-0 invariant mass distribution modeled with a double-sided Crystal Ball PDF

- Double-sided Crystal Ball PDF parameterized as a function of m_X
- Large width signal are also modeled by the double-sided Crystal Ball PDF by fitting large width samples and interpolating

Spin-2 Signal Modeling



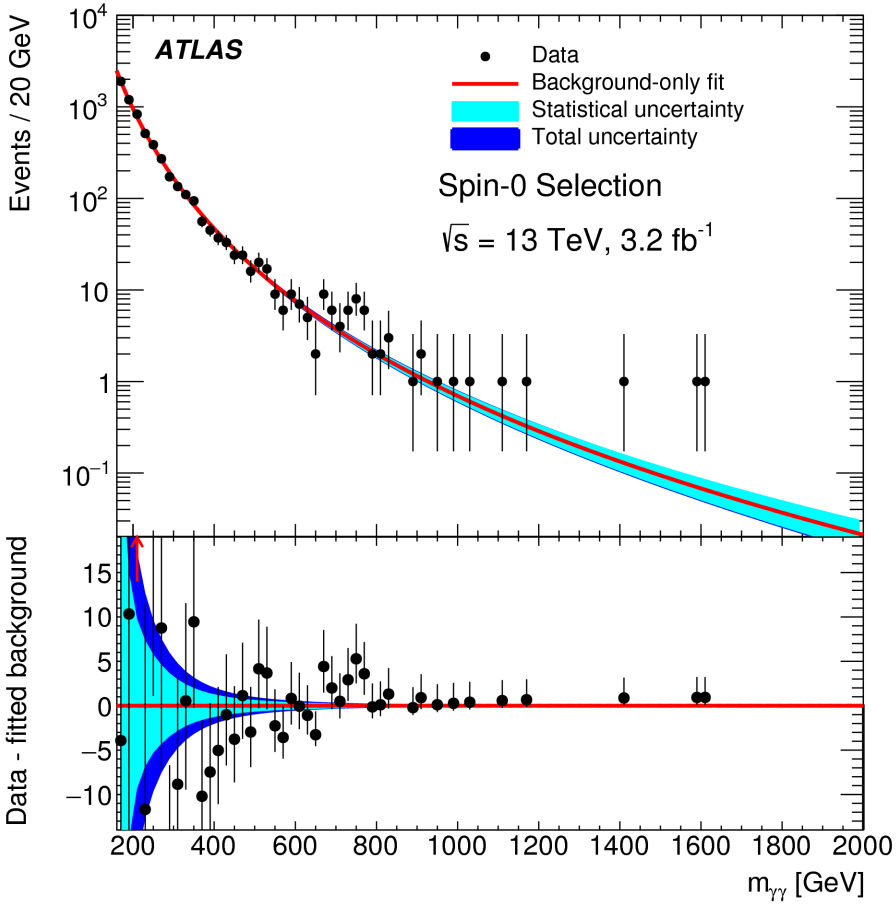


Spin-2 signal modeled by convolution of detector resolution and theoretical line-shape

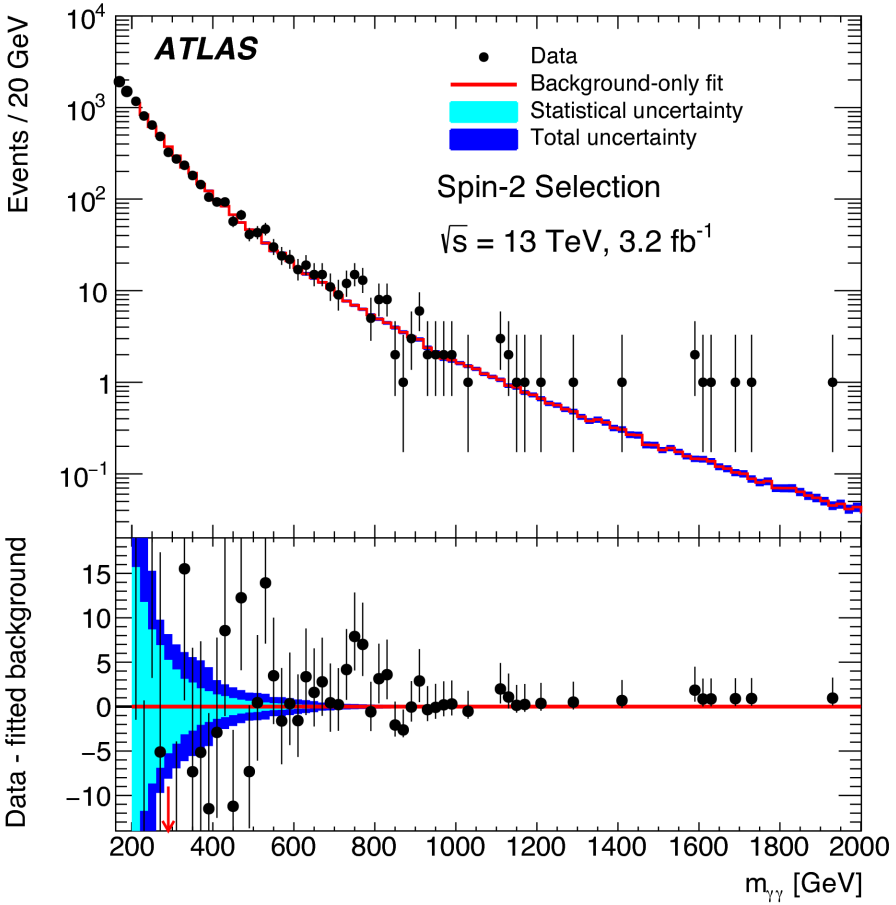
- Detector resolution modeled by double-sided Crystal Ball PDF as a function of m_{G^*}
- Description extended to larger widths by convoluting relativistic Breit-Wigner

Background Modeling Uncertainties

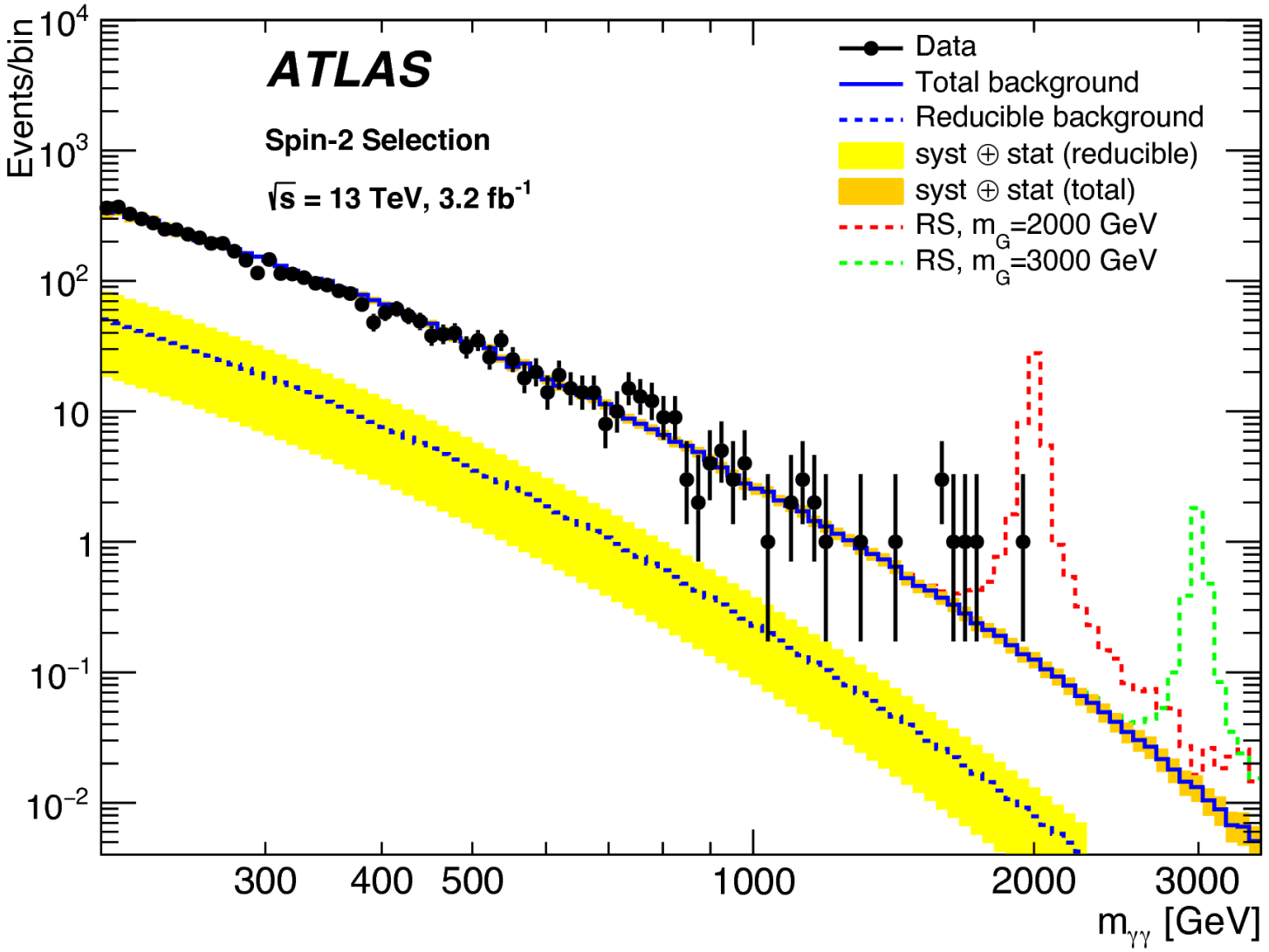
Spin-0



Spin-2

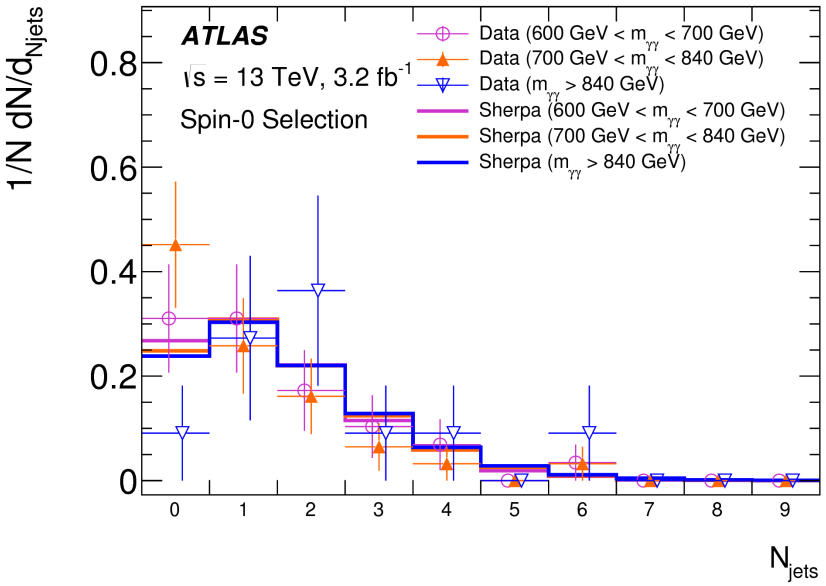


Diphoton Invariant Mass for Spin-2 Search

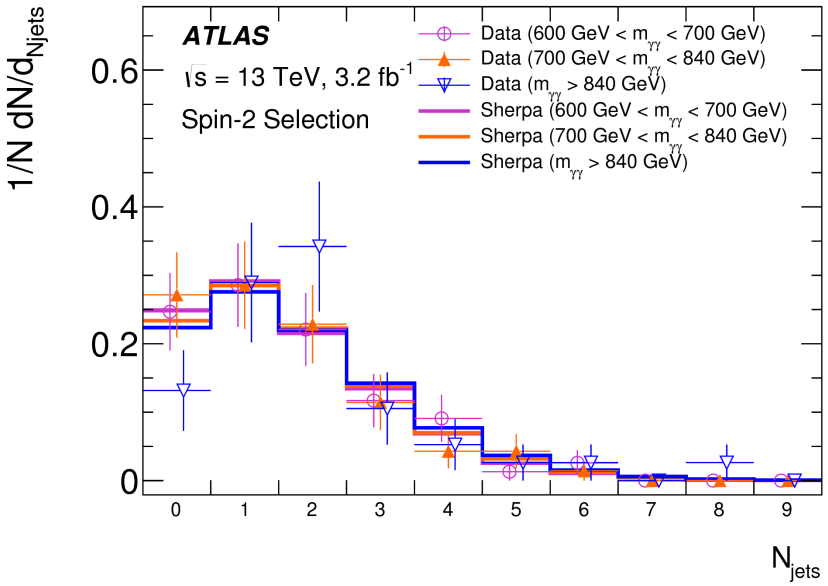


Kinematic Distributions: Number of Jets

Spin-0

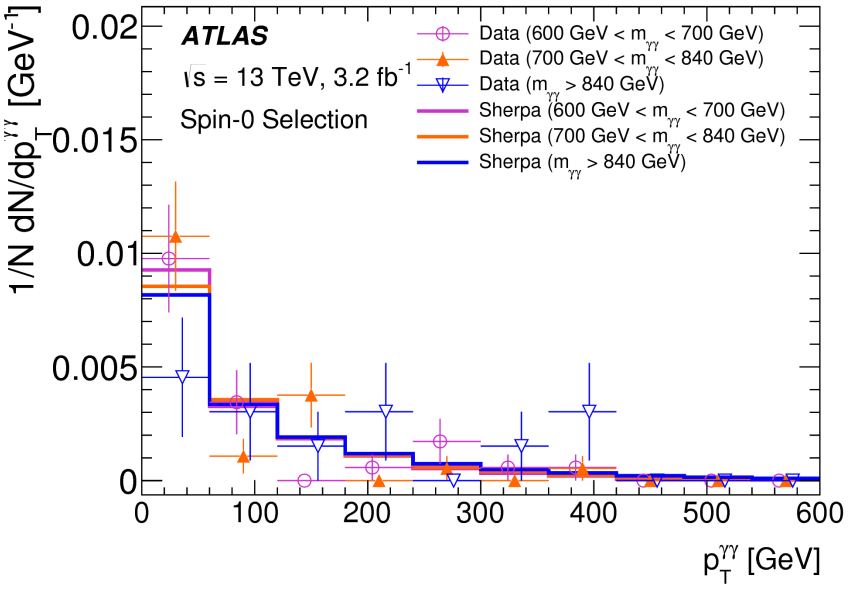


Spin-2

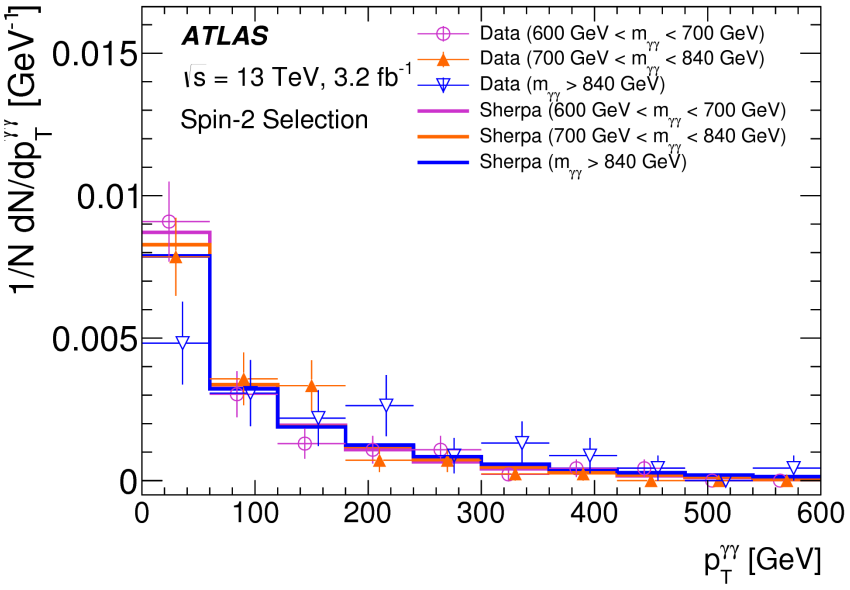


Kinematic Distributions: Diphoton p_T

Spin-0

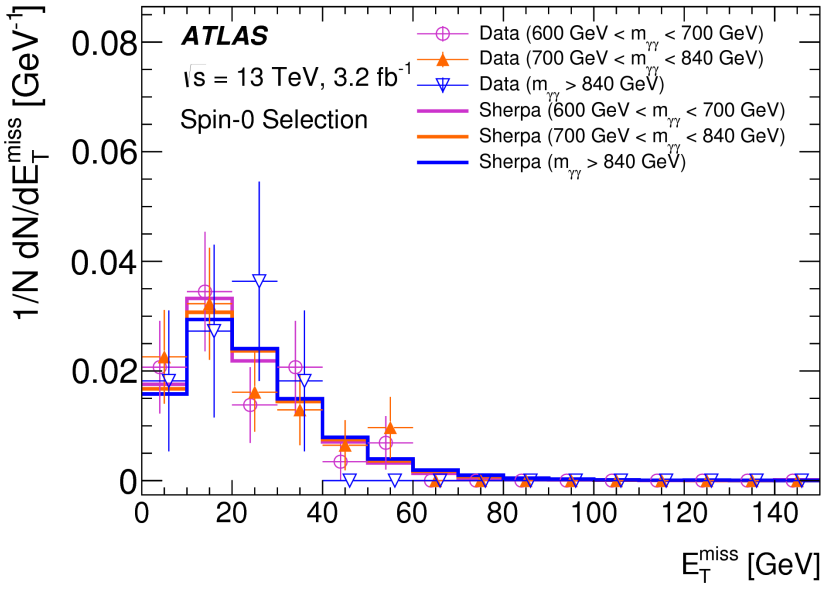


Spin-2

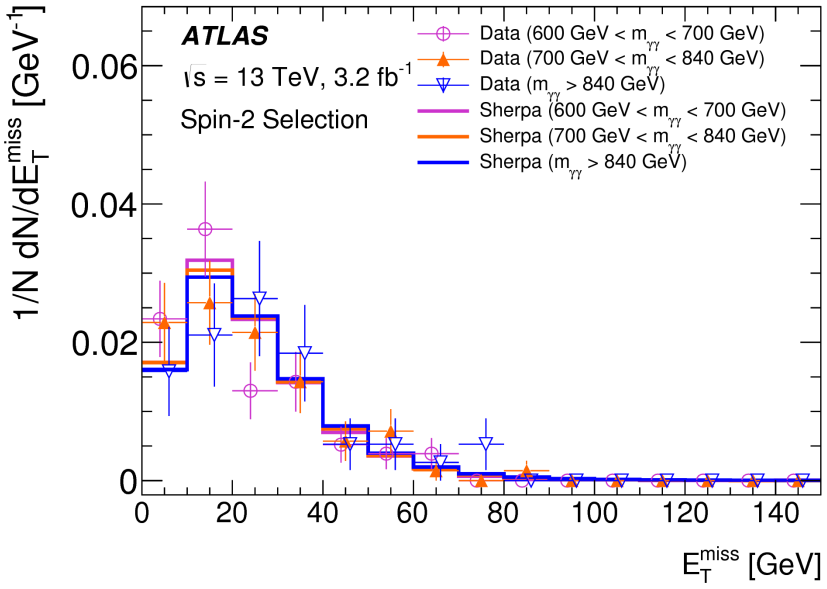


Kinematic Distributions: E_T^{Miss}

Spin-0

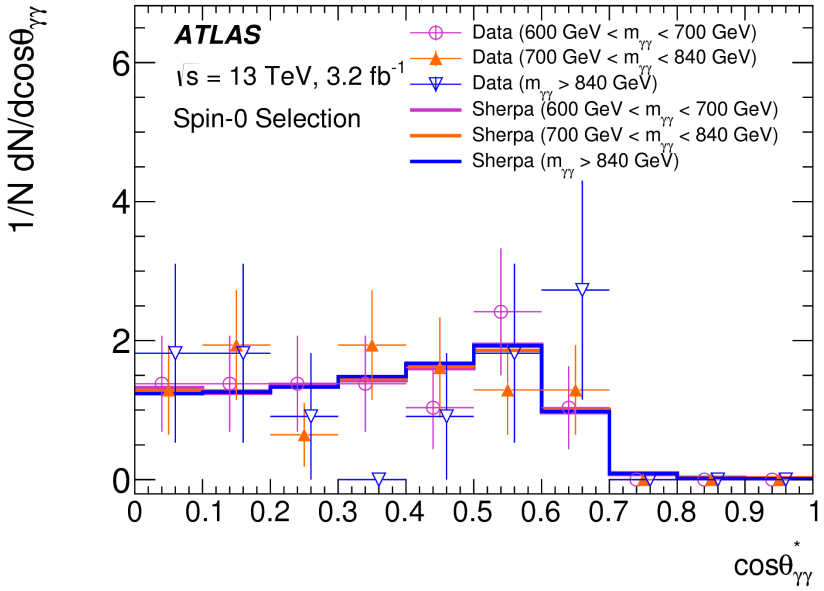


Spin-2



Kinematic Distributions: cos(θ^*)

Spin-0



Spin-2