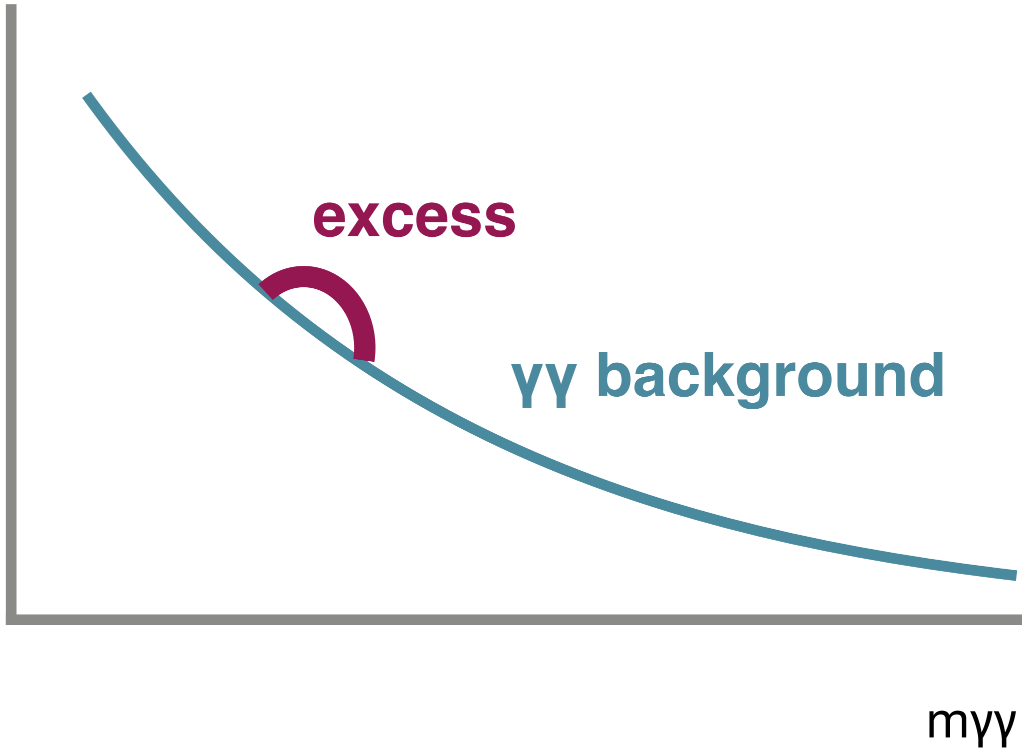
High mass diphoton resonance searches in ATLAS

Yee Chinn Yap (LPNHE, Paris)

GDR Terascale@Nantes, 24th May 2016

Introduction

- Motivations:
    - Several extensions of SM predict high-mass states that could decay to 2 photons, like extended Higgs sector, extra dimensions, etc.
    - **Many models** also predict a diphoton resonance, given the number of papers appearing on arXiv after last December.
- Experimental signature:
    - **Clean signal** of **two high p_T photon candidates** that manifests as local excess in the diphoton mass spectrum over smooth background.
- Assumes diphoton resonance to be either spin-0 or spin-2.
- Strong involvement of the French labs (LPNHE, LAPP, LPSC, LAL, CEA).



High mass diphoton searches at 7, 8 and 13 TeV

Title	Reference	$\sqrt{s}$	Mass range	Spin-0	Spin-2
Search for extra dimensions using diphoton events in 7 TeV proton–proton collisions with the ATLAS detector	Phys. Lett. B 710 (2012) 538-556	7 TeV	> 500 GeV		✓
Search for scalar diphoton resonances in the mass range 65-600 GeV with the ATLAS detector in pp collision data at $\sqrt{s}$ = 8 TeV	Phys. Rev. Lett. 113, 171801	8 TeV	65 - 600 GeV	✓	
Search for high-mass diphoton resonances in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector	Phys. Rev. D 92, 032004 (2015)	8 TeV	409 - 3000 GeV		✓
Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector	ATLAS-CONF-2015-081 **DEC 2015**	13 TeV	200 - 1700 GeV	✓	
Search for resonances in diphoton events with the ATLAS detector at $\sqrt{s}$ = 13 TeV	ATLAS-CONF-2016-018 **MORIOND 2016**	13 TeV	200 - 2000 GeV (spin-0) and 500 - 3500 GeV (spin-2)	✓	✓

- This talk covers the latest results which was presented at Moriond EW.

Analysis overview

- Two analyses (spin-0 and spin-2) with slightly different signal models, selection cuts and strategies.

Spin-0 analysis

- Extended from 125 GeV Higgs analysis. Analysis optimised for Higgs-like signal.
- Aims to be as model-independent as possible ☛ limit on fiducial cross-section.
- Narrow (4 MeV, negligible wrt detector resolution) to large widths.

Spin-2 analysis

- Randall-Sundrum graviton as benchmark.
- Higher mass range (since RS graviton limit is set at ~3.6 TeV).

Event selection

	Spin-0	Spin-2
trigger	2 photons with p_T > 35 (25) GeV passing loose photon identification criteria based on electromagnetic shower shapes.	
p_T	$p_T^{\gamma 1}/m_{\gamma\gamma}>0.4$, $p_T^{\gamma 2}/m_{\gamma\gamma}>0.3$	2 γ with p_T > 55 GeV
η	$\|\eta_\gamma\| < 2.37$ excluding $1.37 < \|\eta_\gamma\| < 1.52$	
isolation	calorimeter cone and track isolation	
photon identification	tight identification criteria	

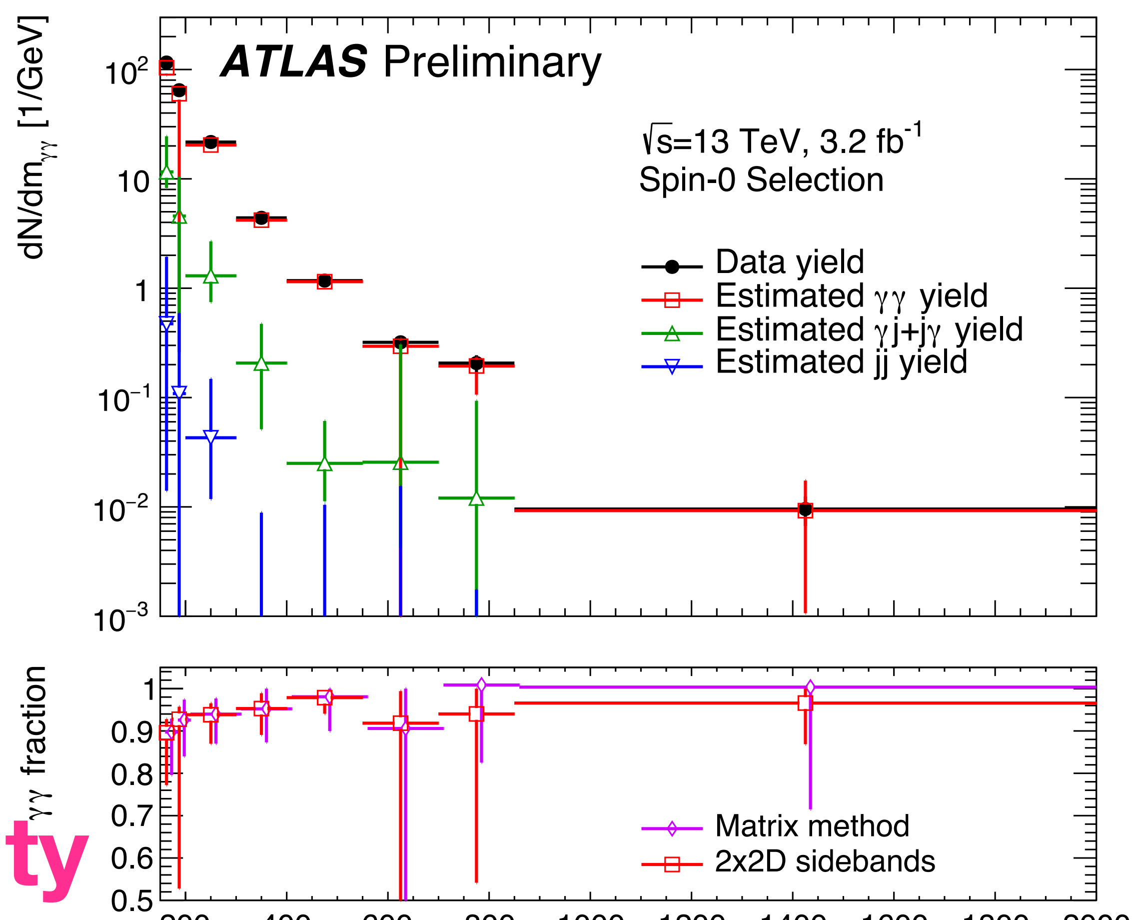
- Common cuts except on p_T:
  - For spin-0, relative p_T cut has been chosen to increase significance for high mass Higgs-like signal (20% gain in expected sensitivity for m_X > 600 GeV).
  - Spin-2 analysis selects event with p_T > 55 GeV to preserve acceptance in forward region.

Background composition

- Background in diphoton spectrum composed primarily of QCD **γγ** direct production (irreducible) and **γ-jet**, **jet-γ**, **jj** (reducible, from jets misidentified as photons).

- **High purity**: **93^{+3}_{-8}%** for spin-0 selection and **94^{+3}_{-7}%** for spin-2 selection.
  - This is used to add γγ with reducible background to predict background shape.

Purity



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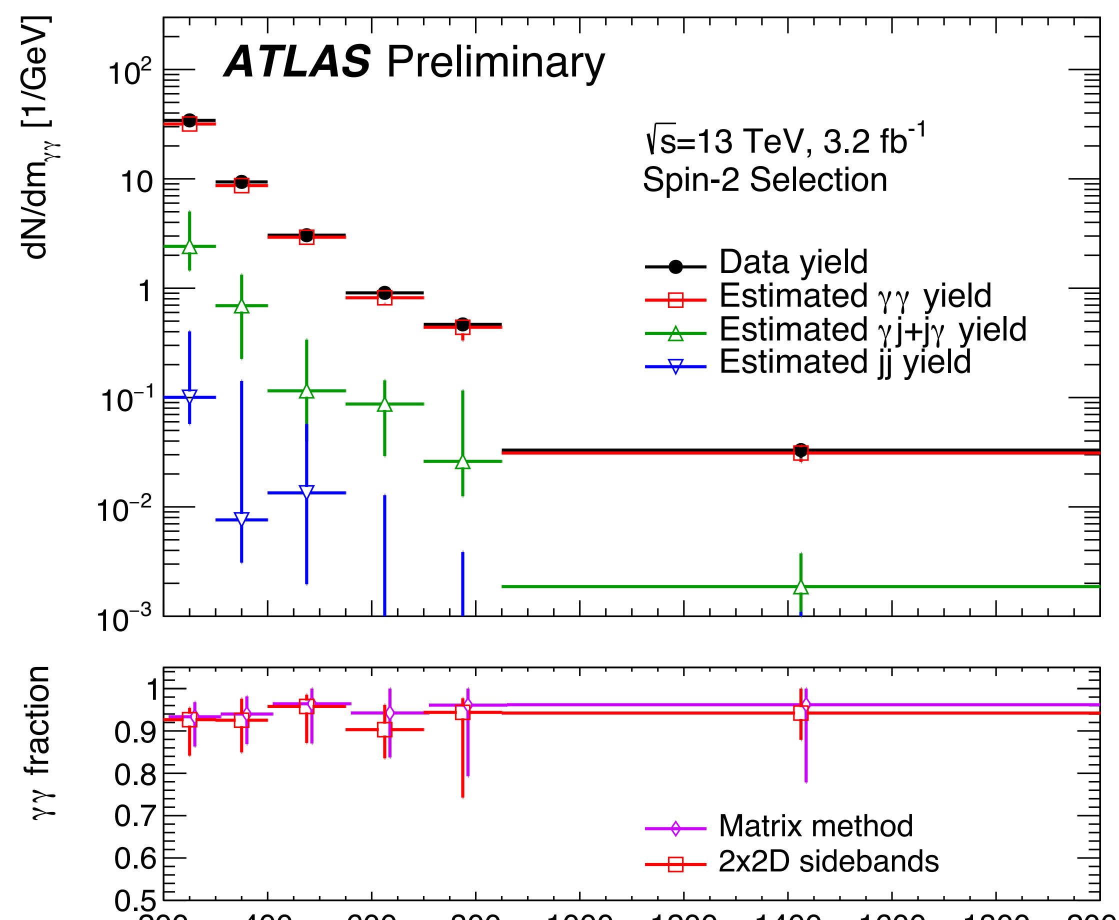

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Background modelling for spin-0 analysis

- Search range from 200-2000 GeV.

- **Function** fitted on data is chosen ☛ data-driven background estimation.
  - Function **validated on background template** which is composed of
    - MC Sherpa γγ
    - data-driven reducible bkg.

    } Normalised according to purity
  - All parameters free in the fit.

- Choice of function
  - Bias from choice of function estimated as **"spurious" signal.** Perform **S+B fit on background-only template** for various signal mass hypotheses.
  - Function required to pass the criteria where the "spurious" signal must be less than 20% of the uncertainty of the fitted signal yield over the full mass range.

$$f_{(k)}(x;b,\{a_k\}) = N(1-x^{1/3})^b x^{\Sigma_{j=0}^{k} a_j (\log x)^j}, x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$$

  - 2-parameter function (k=0) passes this test.

- Background uncertainty from envelop of fitted "spurious" signal.

Background modelling for spin-2 analysis

- Background **template** method
  - In order to get reliable background estimation up to 3-4 TeV where there is no event in data for a functional form fit.
  - 200-500 GeV range used as a control region.
  - Search range between 500-3500 GeV.
- Diphox NLO computation used to predict the background shape of γγ at parton level.
- Background template is composed of:
  - Sherpa LO MC reweighted to Diphox NLO.
  - γ-jet and dijet estimated from data.

} Normalised according to purity

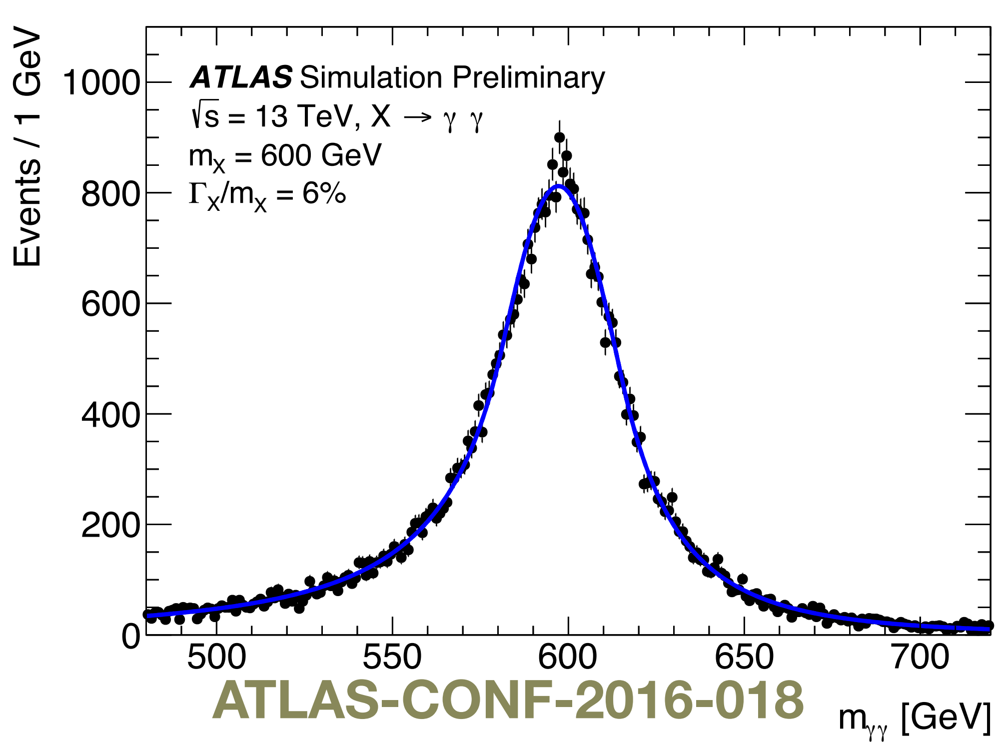
Signal modelling

Spin-0 analysis

- Heavy Higgs-like model. PowHeg line shape convoluted to detector response (gluon-gluon fusion 4 MeV width).
- $m_X \pm 2\Gamma_X$ to reduce model-dependence and interference effects in the off-shell region.
- Γ_X from narrow to 10% m_X.

Spin-2 analysis

- RS graviton model generated with Pythia.
- Analytical convolution of theoretical line-shape with detector response.
- k/M_{Pl} from 0.01 to 0.3 (narrow to ~11% m_{G^*}).



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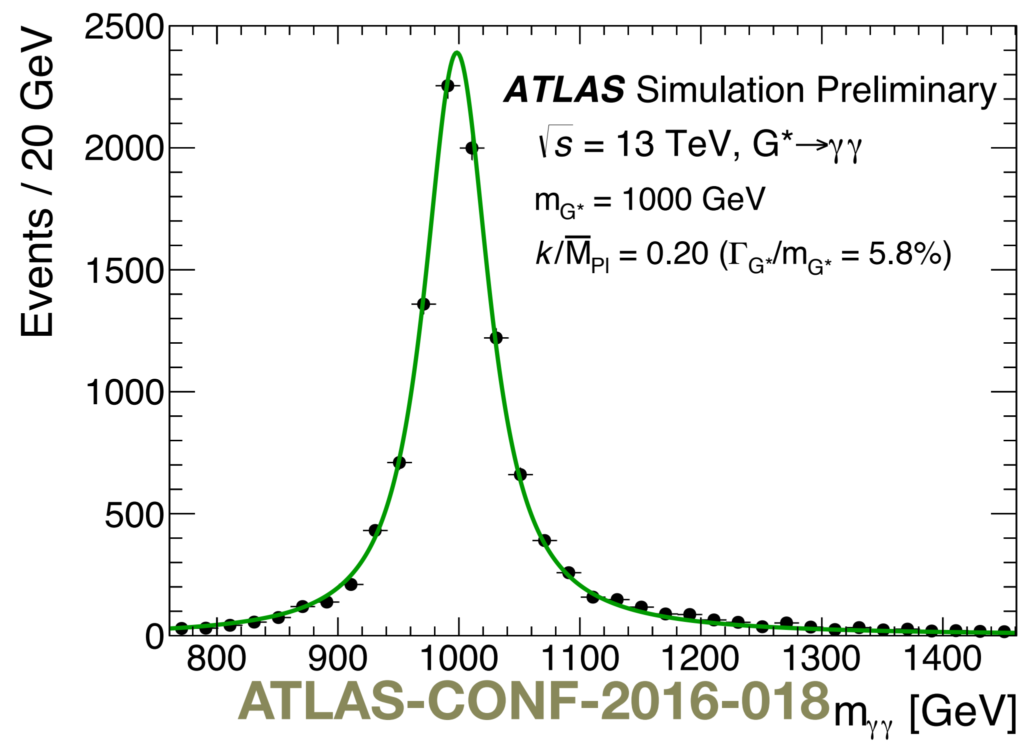

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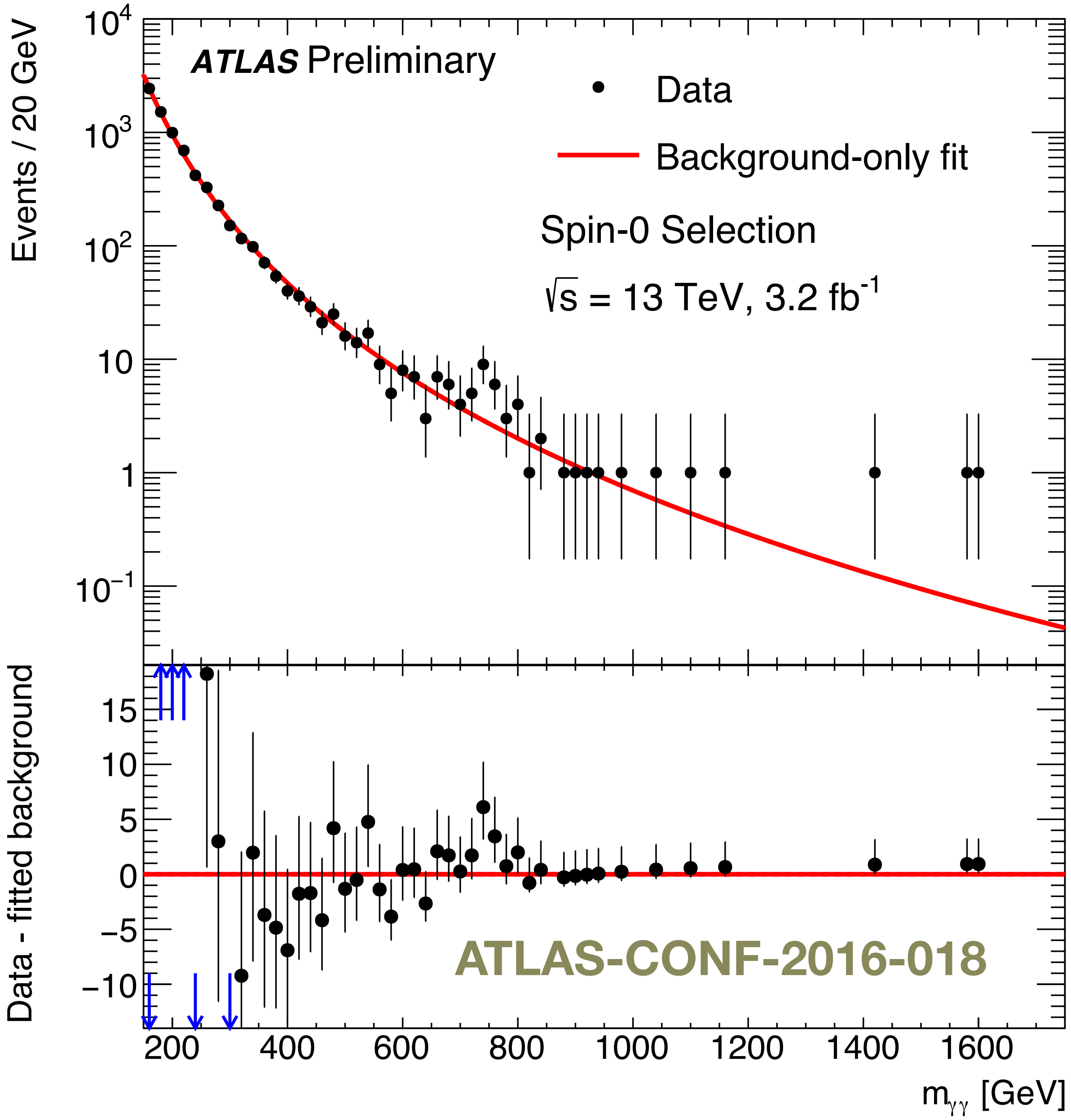
Results: invariant mass distributions

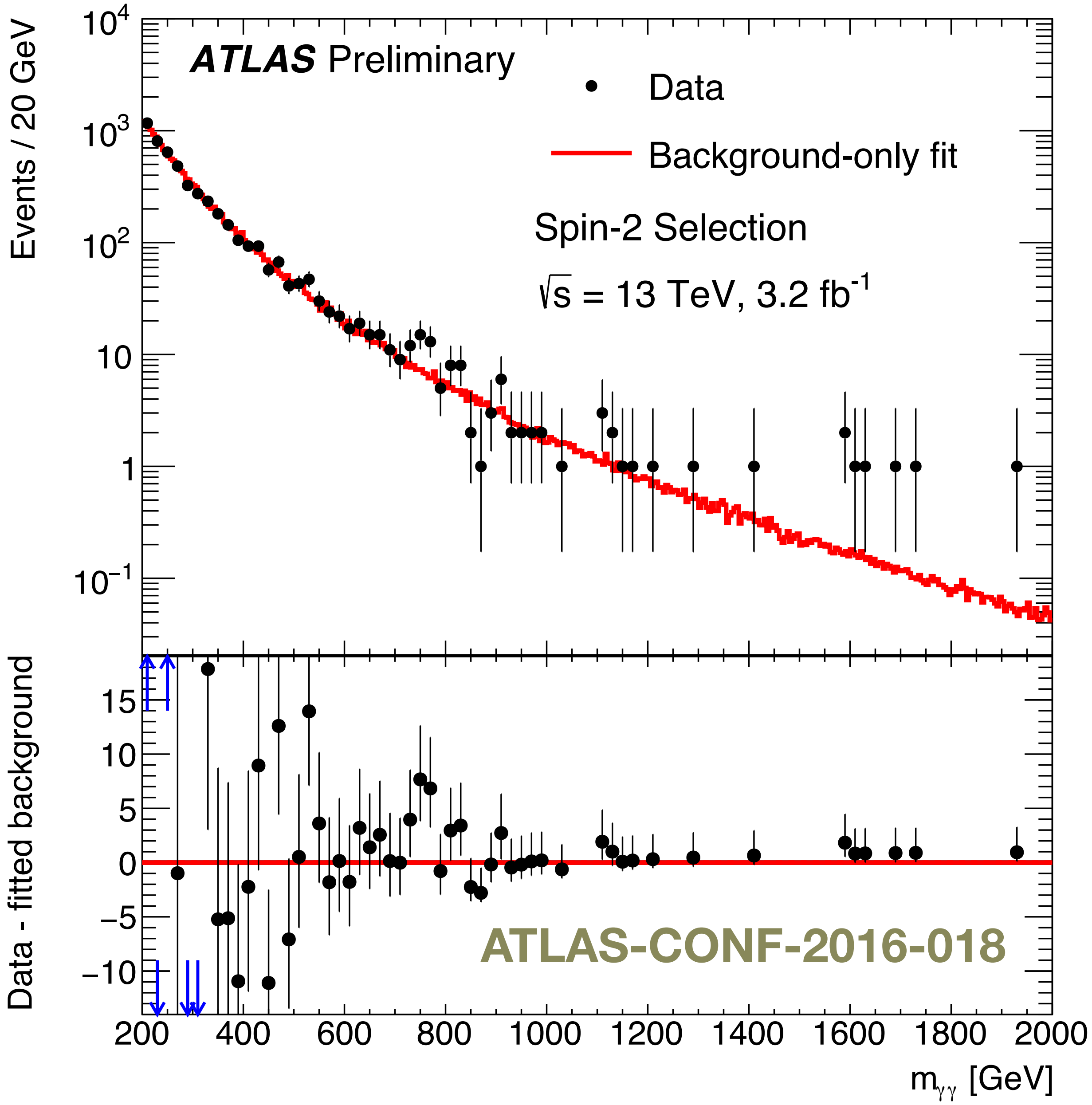
Spin-0 analysis

functional form background



Spin-2 analysis

background template



Results: significances

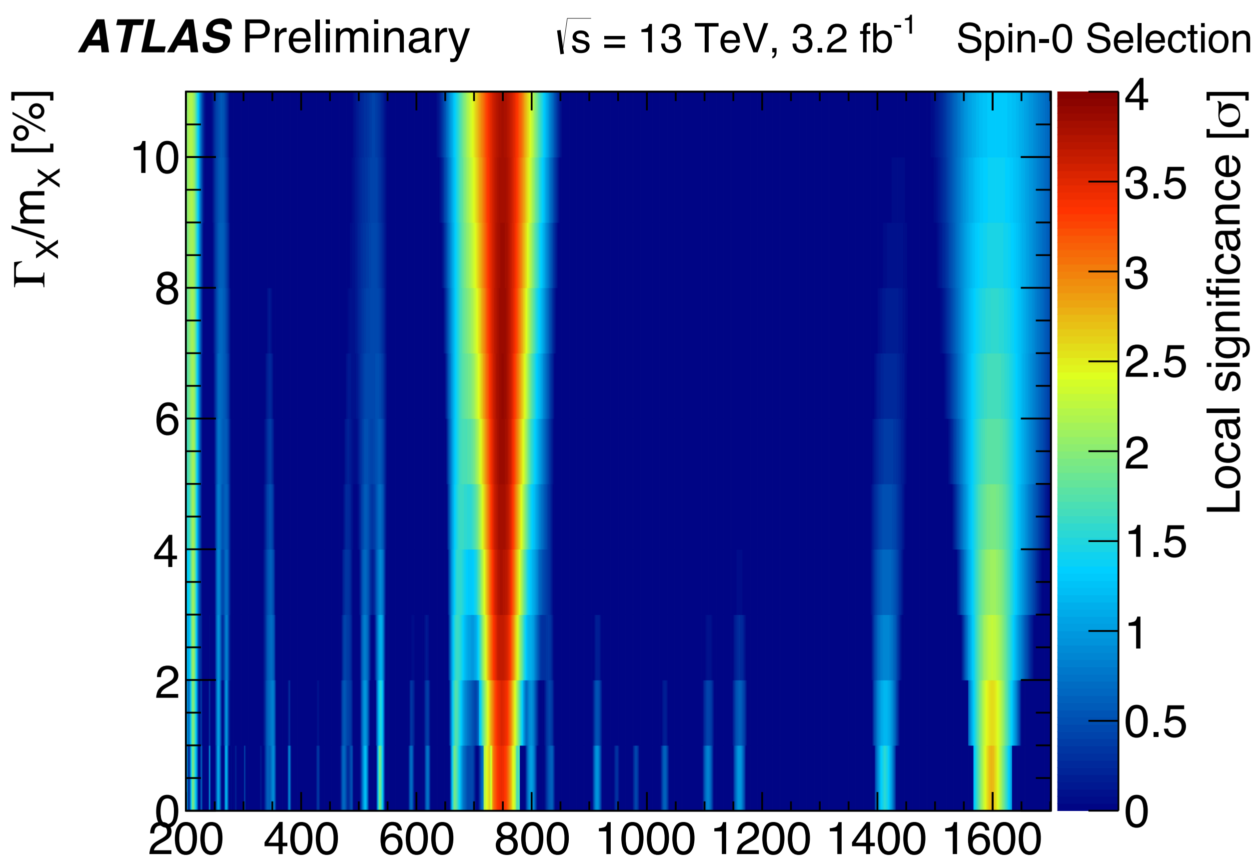
Given the large search range, need to consider look-elsewhere-effect ☛ global significance

Spin-0 analysis

- Largest deviation from B-only hypothesis at
  - $m_X \sim 750$ GeV, $\Gamma_X \sim 45$ GeV (6% m_X)
  - **local Z = 3.9σ, global Z = 2.0σ**.

Spin-2 analysis

- Largest deviation from B-only hypothesis at
  - $m_{G^*} \sim 750$ GeV, $k/M_{Pl} \sim 0.2$ ($\Gamma_G \sim 6\%$ m_{G^*}).
  - **local Z = 3.6σ, global Z = 1.8σ.**



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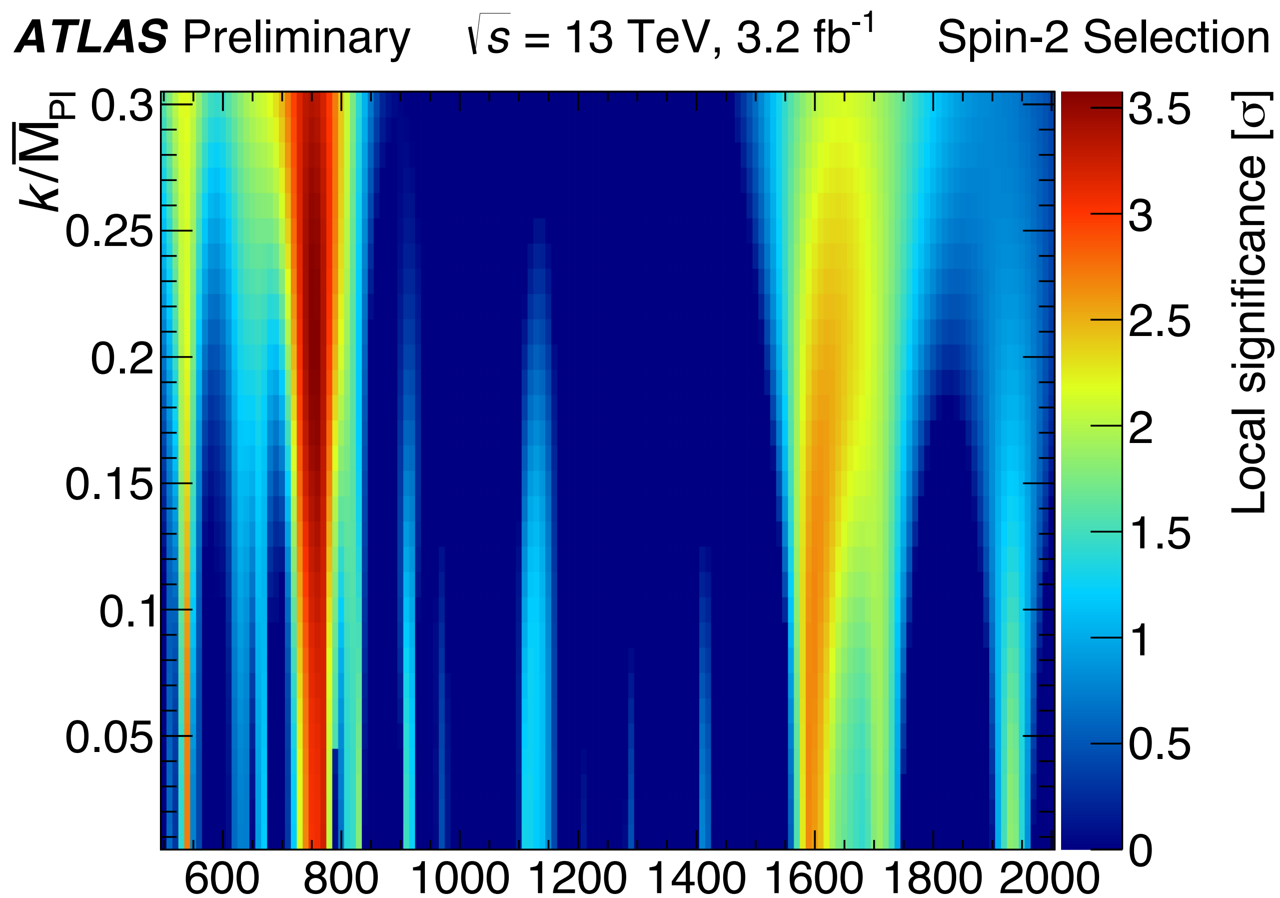

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Results: limits

Spin-0 analysis

- fiducial cross-section.

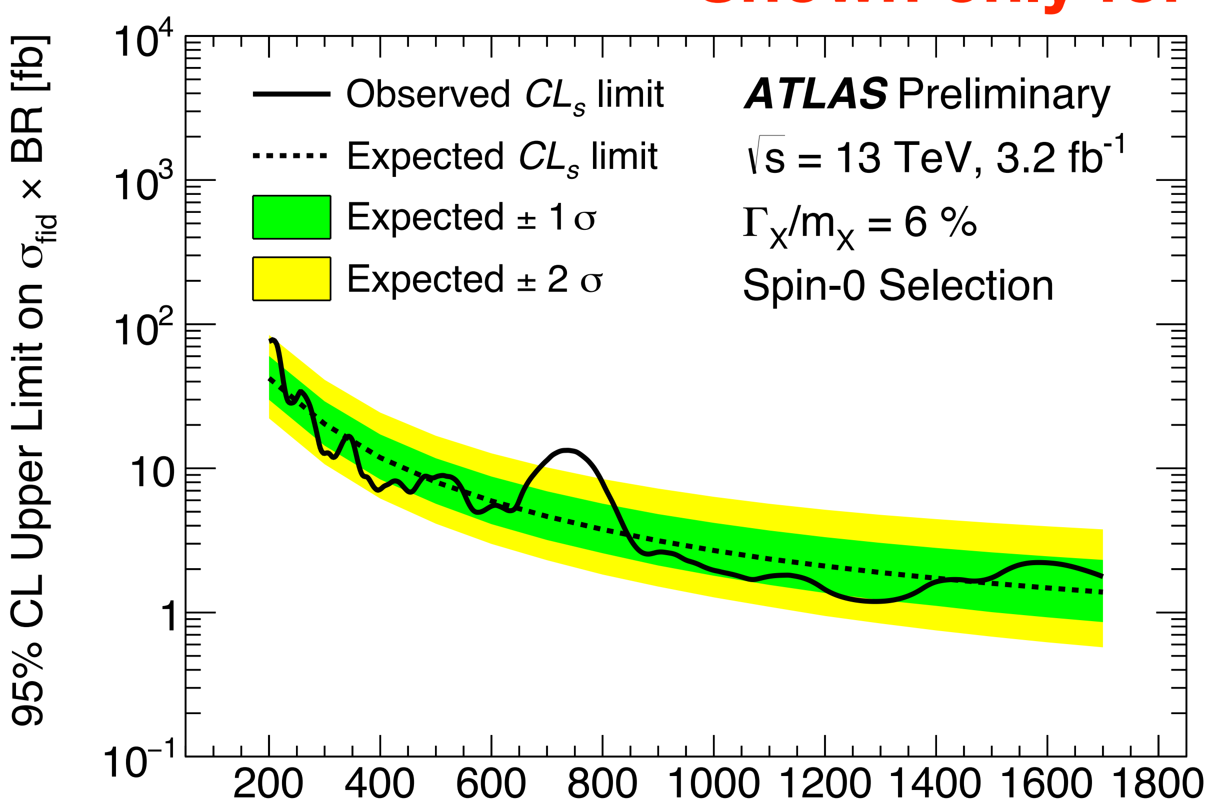
Fiducial acceptance:

- $E_T^{\gamma 1}/m_{\gamma\gamma} > 0.4$, $E_T^{\gamma 2}/m_{\gamma\gamma} > 0.3$
- $|\eta_\gamma| < 2.37$
- E_T^{iso} ($\Delta R=0.4$) $< 0.05E_T^{\gamma} + 6$GeV
- $m_X \pm 2\Gamma_X$

Spin-2 analysis

- production cross-section of RS graviton.

Shown only for width = 6% m_X ($k/M_{Pl} = 0.20$)



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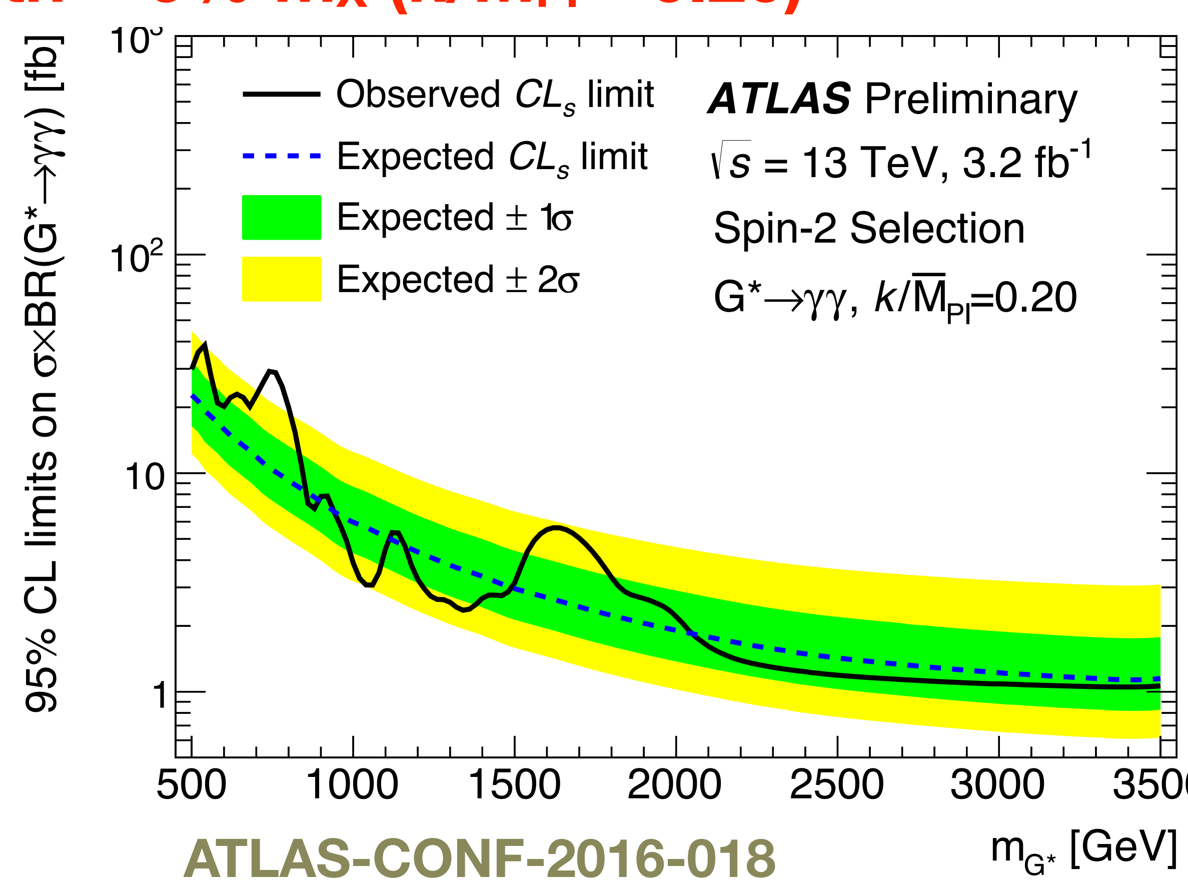

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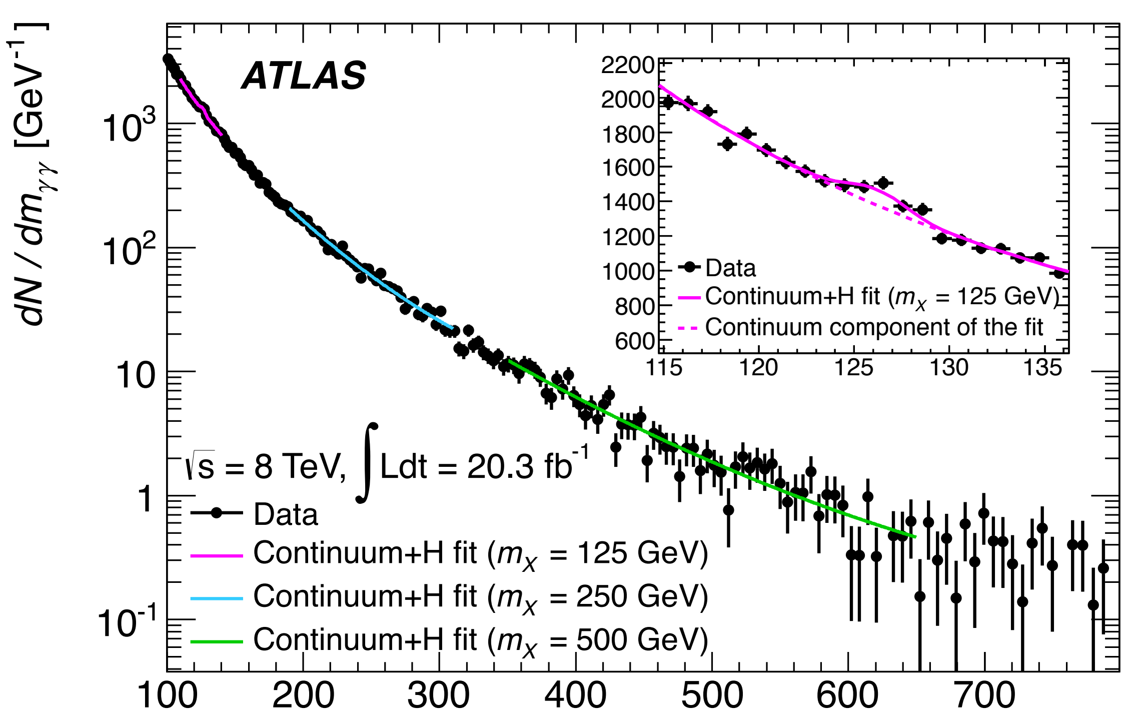
Compatibility with 8 TeV results (I)

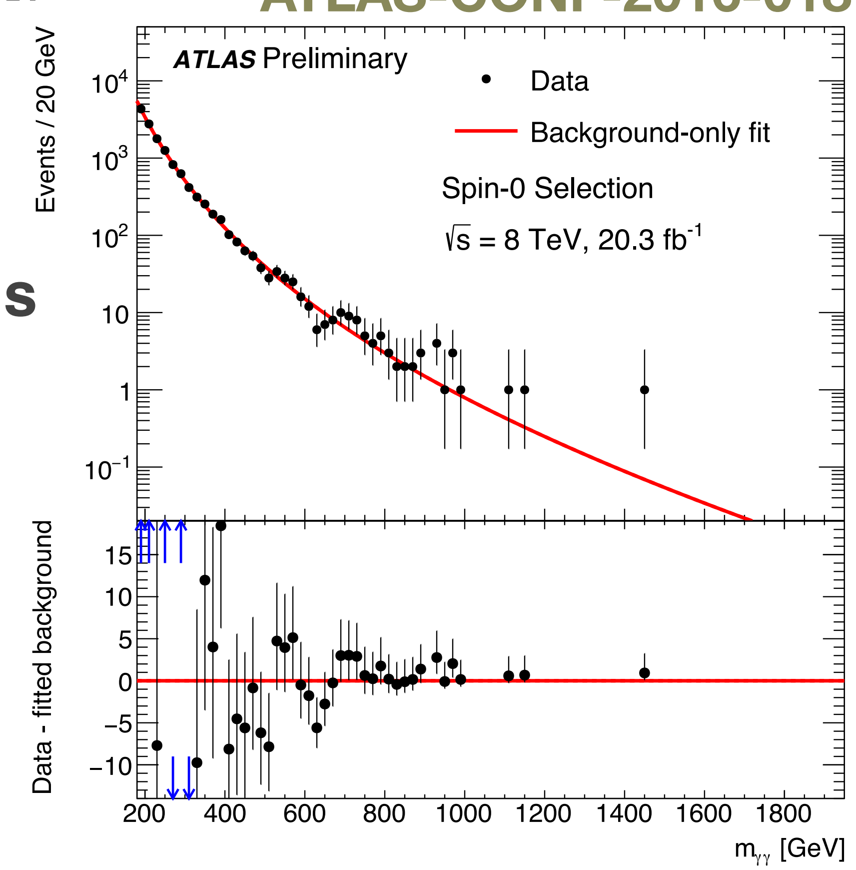
- We observe an excess in 2015 13 TeV data. Is it compatible with 8 TeV results? No excess was reported in 8 TeV results.
- 8 TeV spin-0 analysis stopped at 600 GeV due to insufficient sideband for “sliding-window” fit.
- To ease compatibility study, 8 TeV data has been **re-analysed using the latest run-1 photon calibration and detector geometry**.
  - Use fitting procedure of run-2: **functional form over the full mass range for spin-0** and background template for spin-2 (unchanged wrt run-1)
  - Event selections are unchanged w.r.t. to published 2012 analysis.



Phys. Rev. Lett. 113, 171801

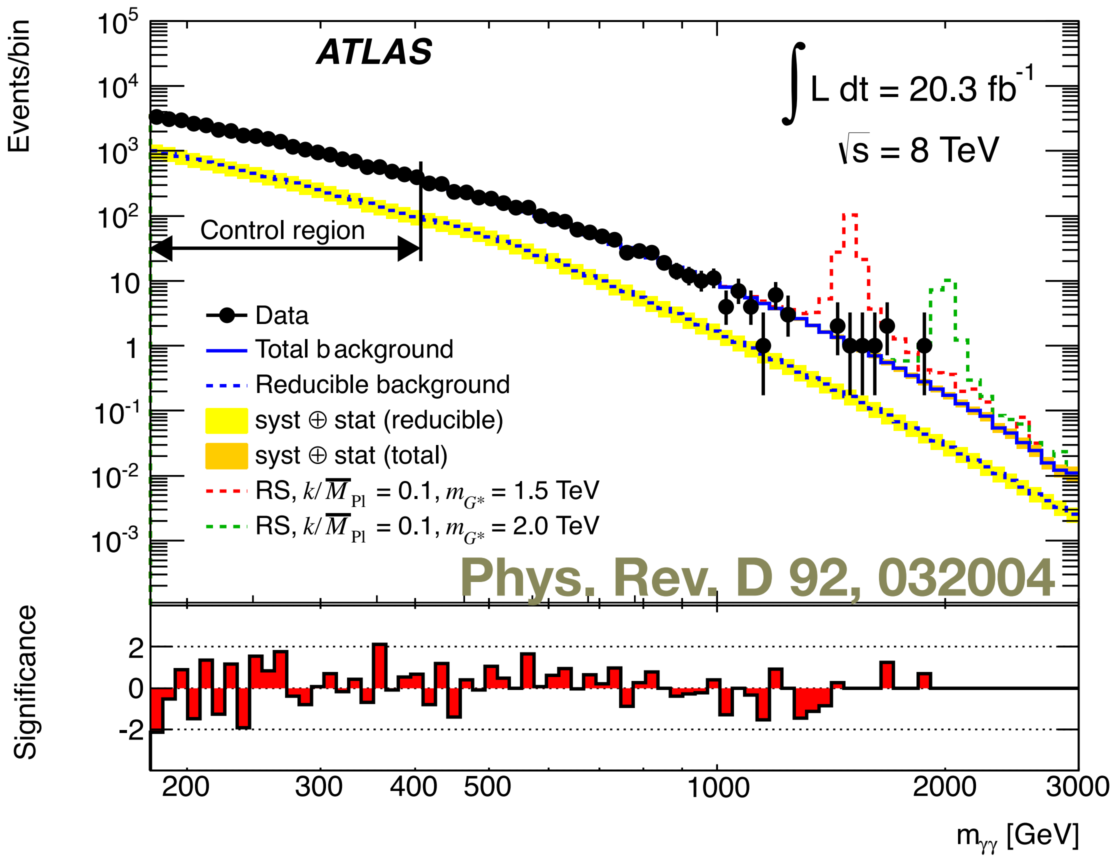
Spin-0 analysis

ATLAS-CONF-2016-018

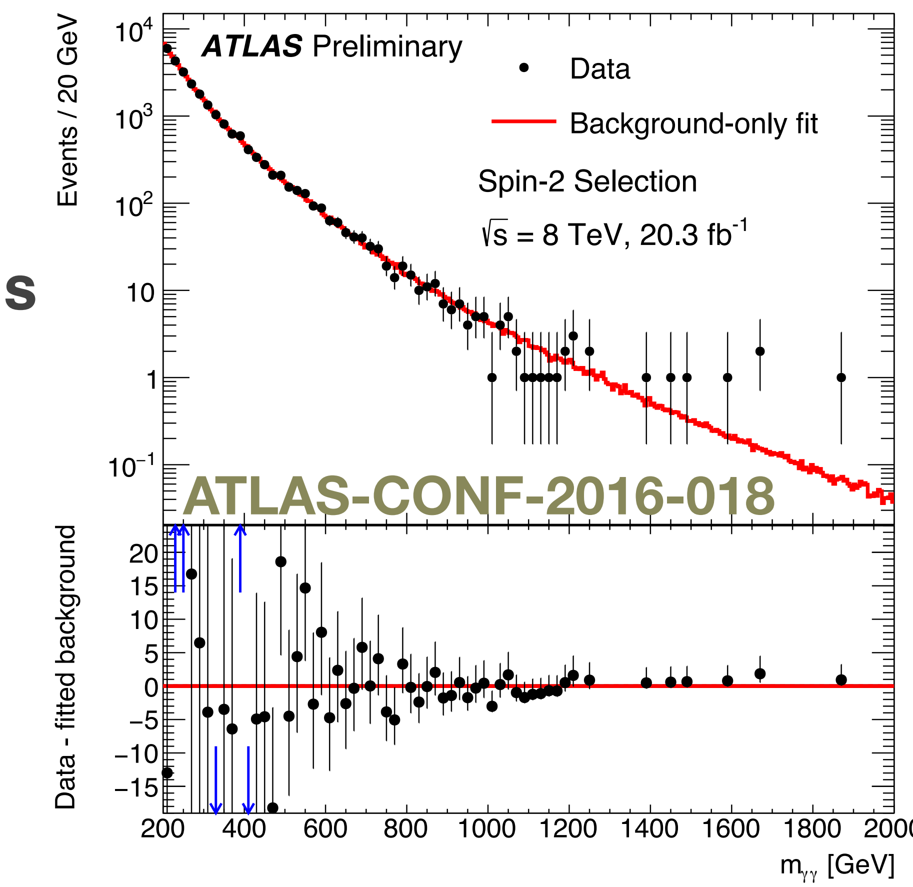


Compatibility with 8 TeV results (II)

- With the spin-0 selection, 1.9 σ deviation is seen at 750 GeV for Γ_X/m_X = 6% (the value of largest significance of the excess at 13TeV). No excess with the spin-2 selection.



Spin-2 analysis



Production mode	σ(13TeV)/σ(8TeV)	Compatibility between 8 TeV and 13 TeV results	
		Spin-0	Spin-2
gg	4.7	1.2 σ	2.7 σ
qq	2.7	2.1 σ	3.3 σ

Checks on excess region vs sidebands

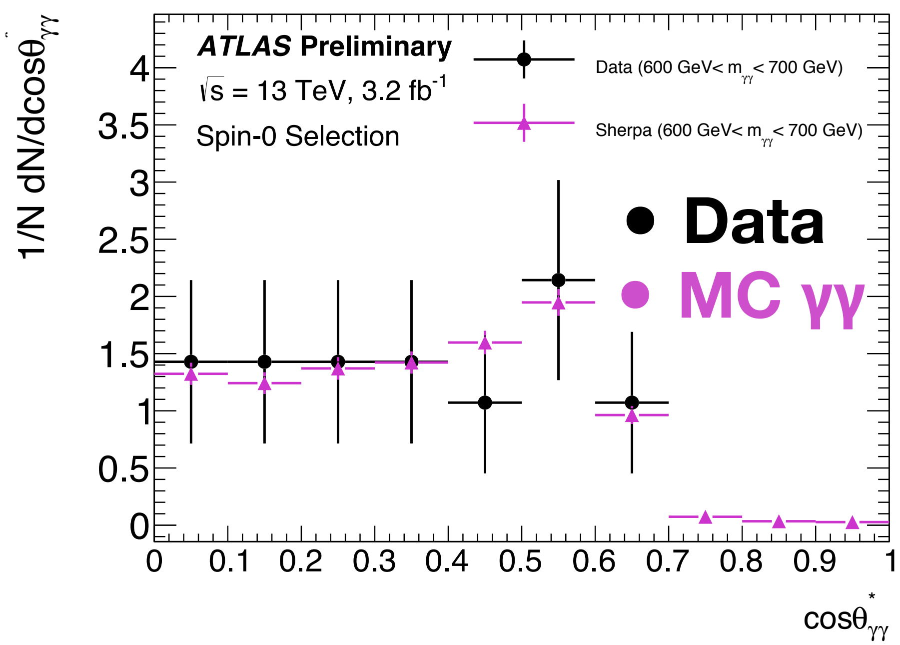
- No detector or reconstruction effect that could explain the larger rate is found.
- Purity studies on data also point to very high purity around 750 GeV.
- Kinematic properties of those events are also studied, and the excess region has distributions that are similar to the side bands.
- However, too low statistics to conclude on anything.

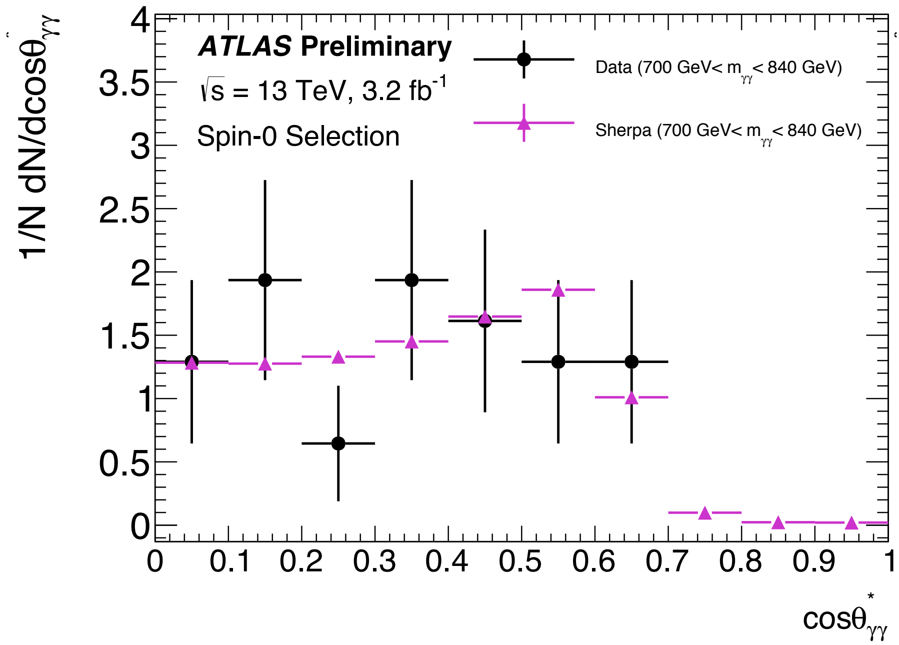
Properties of the excess: cos $\theta^*_{\gamma\gamma}$

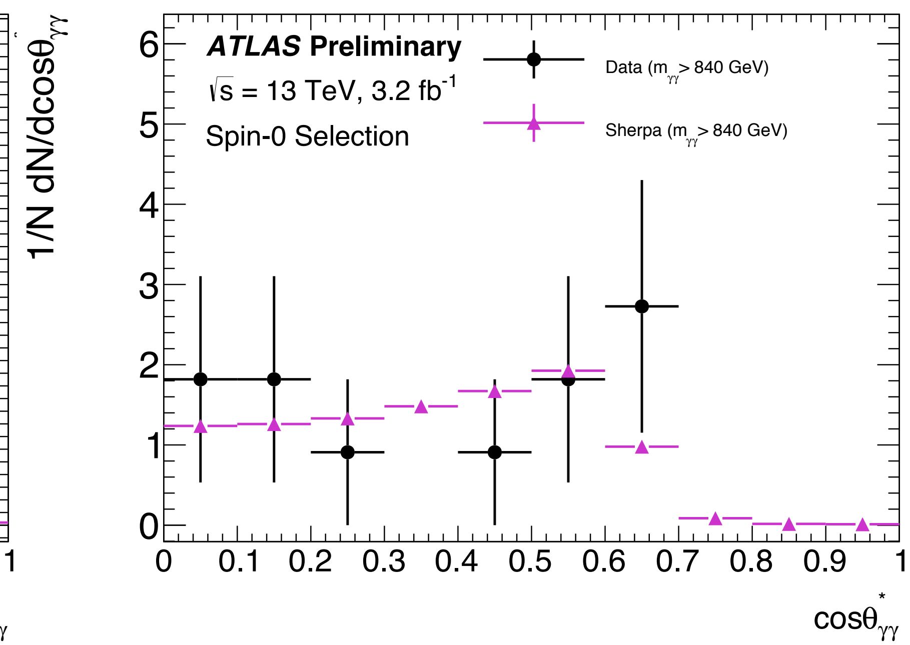
Spin-0 analysis

excess region

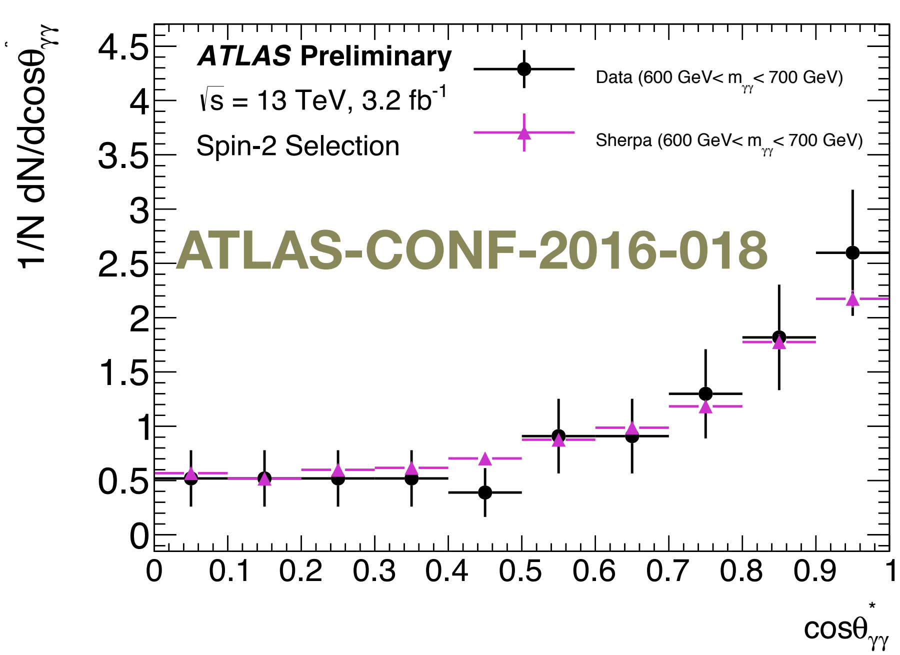
mγγ = [600-700] GeV | **mγγ = [700-840] GeV** | **mγγ = [840-∞] GeV**

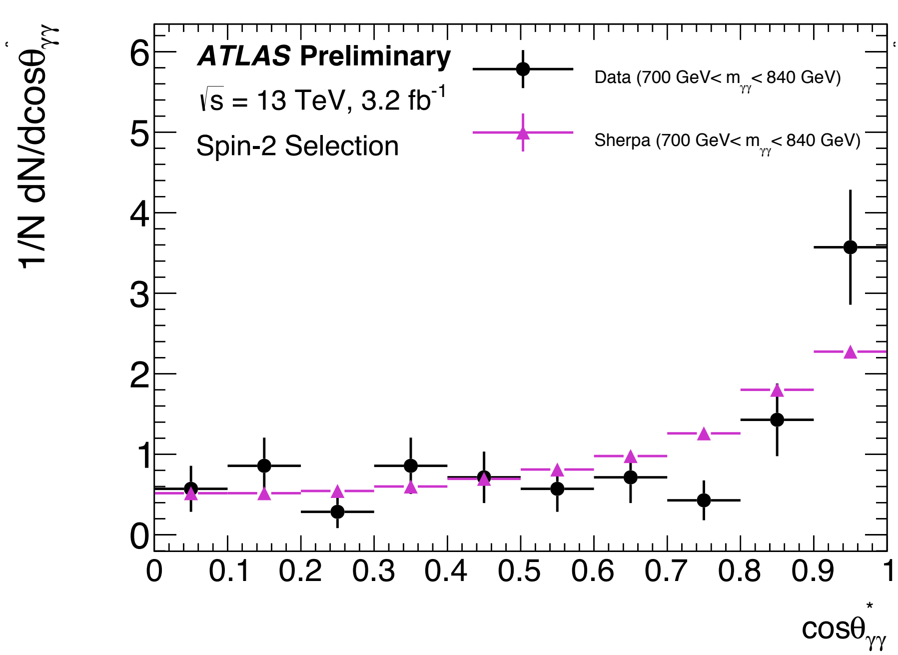


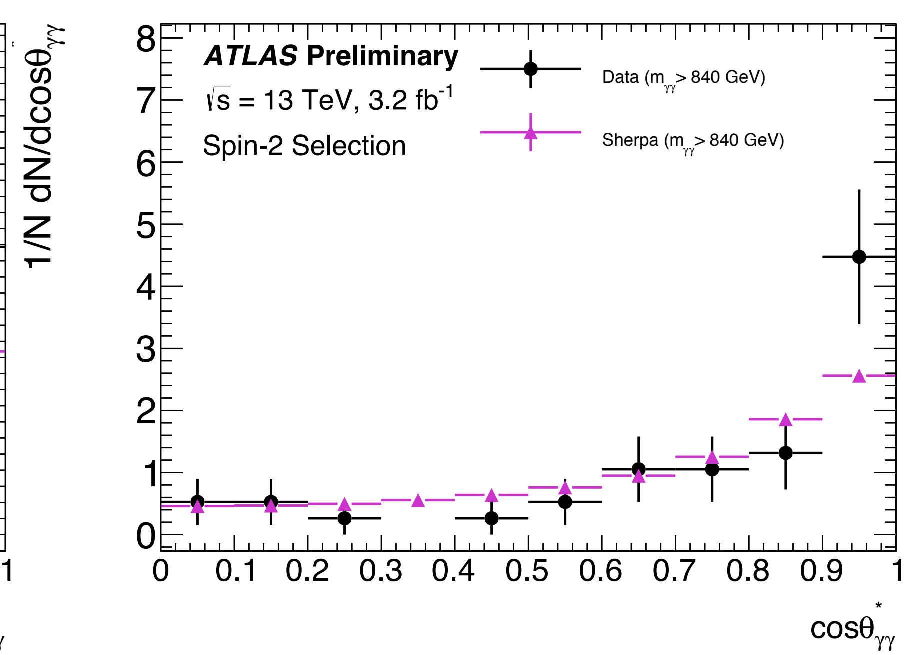




Spin-2 analysis



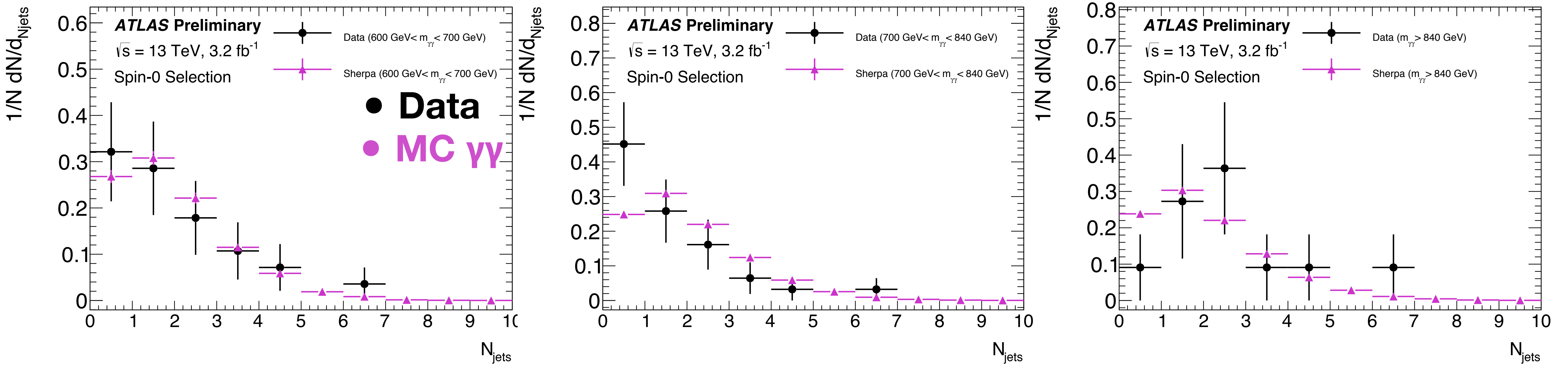




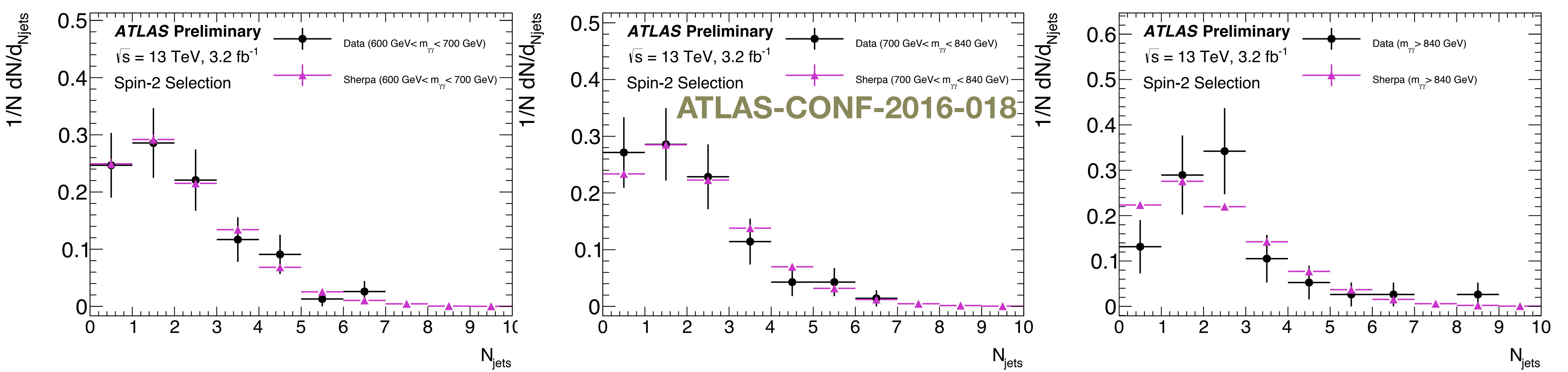
Properties of the excess: number of jets

Spin-0 analysis

mγγ = [600-700] GeV	excess region mγγ = [700-840] GeV	mγγ = [840-∞] GeV



Spin-2 analysis



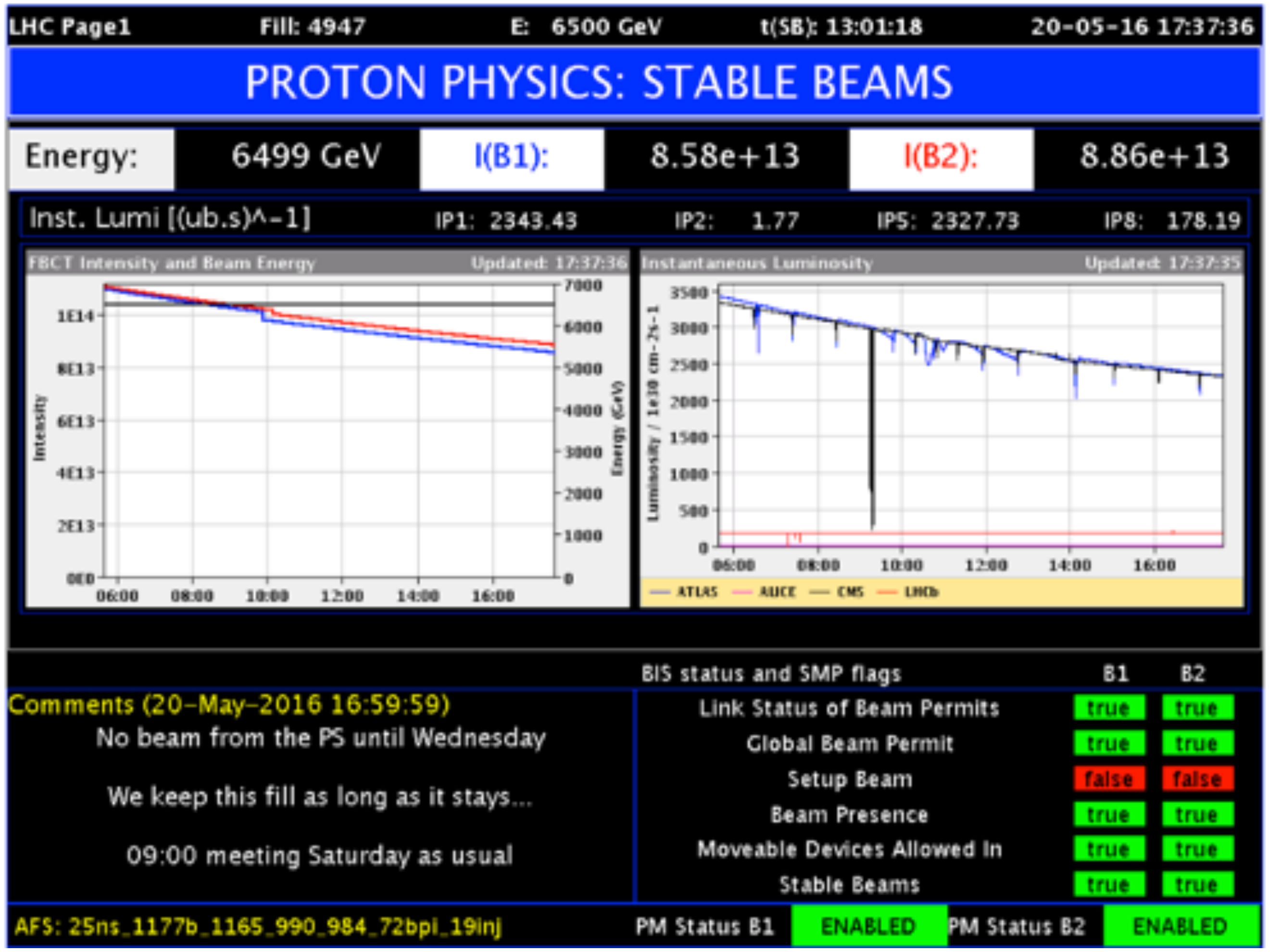
Summary

- The search for diphoton resonance, with either spin-0 or spin-2, has been performed with 3.2 fb^{-1} of pp collision data at $\sqrt{s}$=13TeV.

- Most of the diphoton spectrum is consistent with background-only hypothesis apart from a **3.9 (3.6) σ** deviation around **750 GeV** with **width ~6%** of the mass **(k/M_{Pl}=0.2)** for spin-0 (spin-2).

- Given the large look-elsewhere effect, the **global significance is 2.0 (1.8) σ** for the spin-0 (spin-2) analysis.

- 2016 LHC data-taking is underway, soon we'll have more data to conclude on the nature of the observed excess.



Back-up

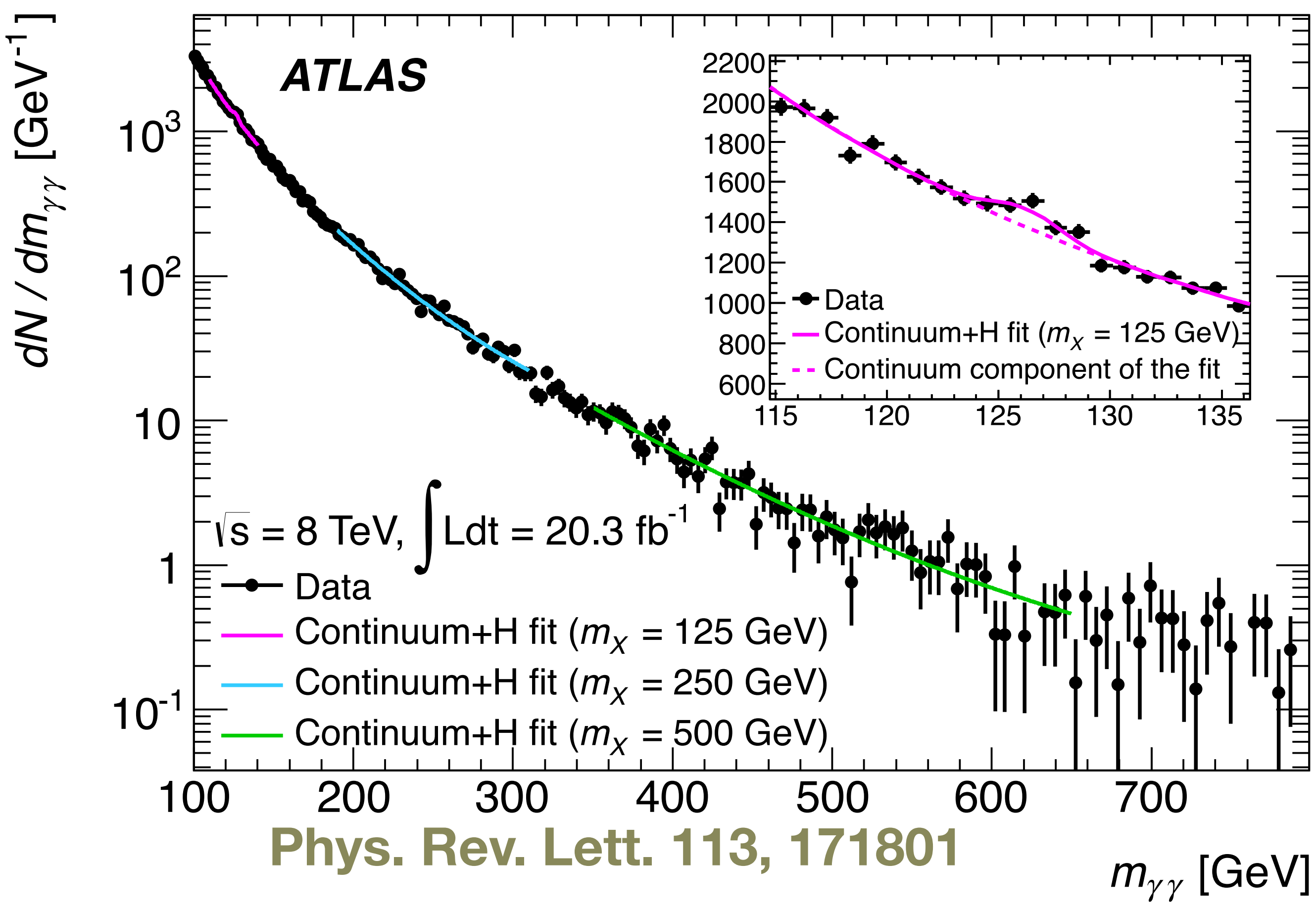
French labs involvement

- **LPNHE**
  - Sandrine Laplace, Stefano Manzoni, Giovanni Marchiori, José Ocariz, Lydia Roos, Yee Yap
- **LPSC**
  - Fairouz Malek, Thomas Meideck, Elisabeth Petit, Jan Stark
- **LAPP**
  - Nicolas Berger, Marco Delmastro, Kirill Grevtsov, Thibault Guillemin, Remi Lafaye, Alexis Vallier, Isabelle Wingerter-Seez
- **LAL**
  - Marc Escalier, Louis Fayard, Christophe Goudet, Jean-Baptiste de Vivie de Regie
- **CEA**
  - Matthias Saimpert

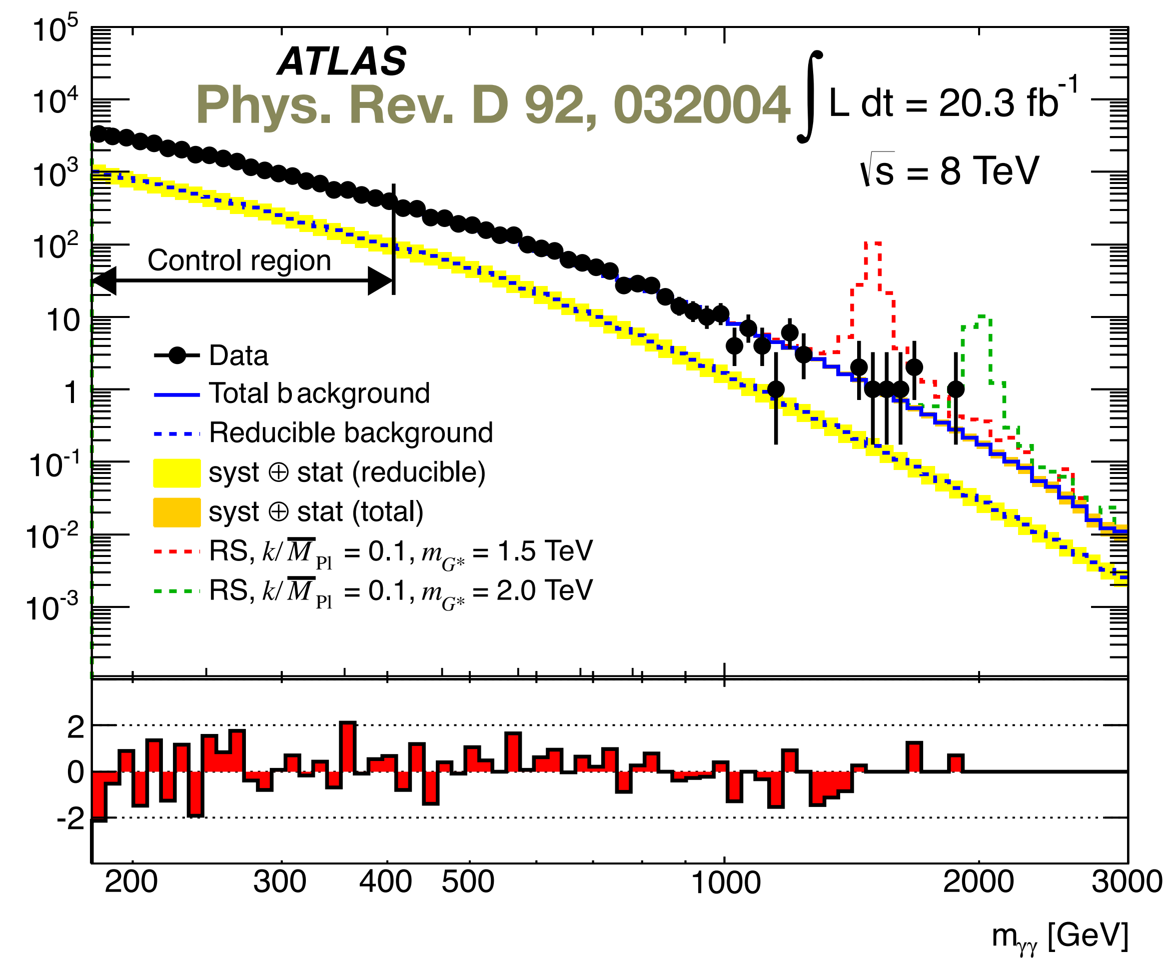
Recap of Run-I results

- Spin-0 search in the mass range 65-600 GeV
- No excess was found. Limits on fiducial cross-sections were set.

- Spin-2 search in the mass range 409-3000 GeV
- A lower limit of 2.66 (1.41) TeV at 95% CL is set on the mass of the lightest graviton for couplings of k/M_{Pl}=0.1 (0.01).



Phys. Rev. Lett. 113, 171801

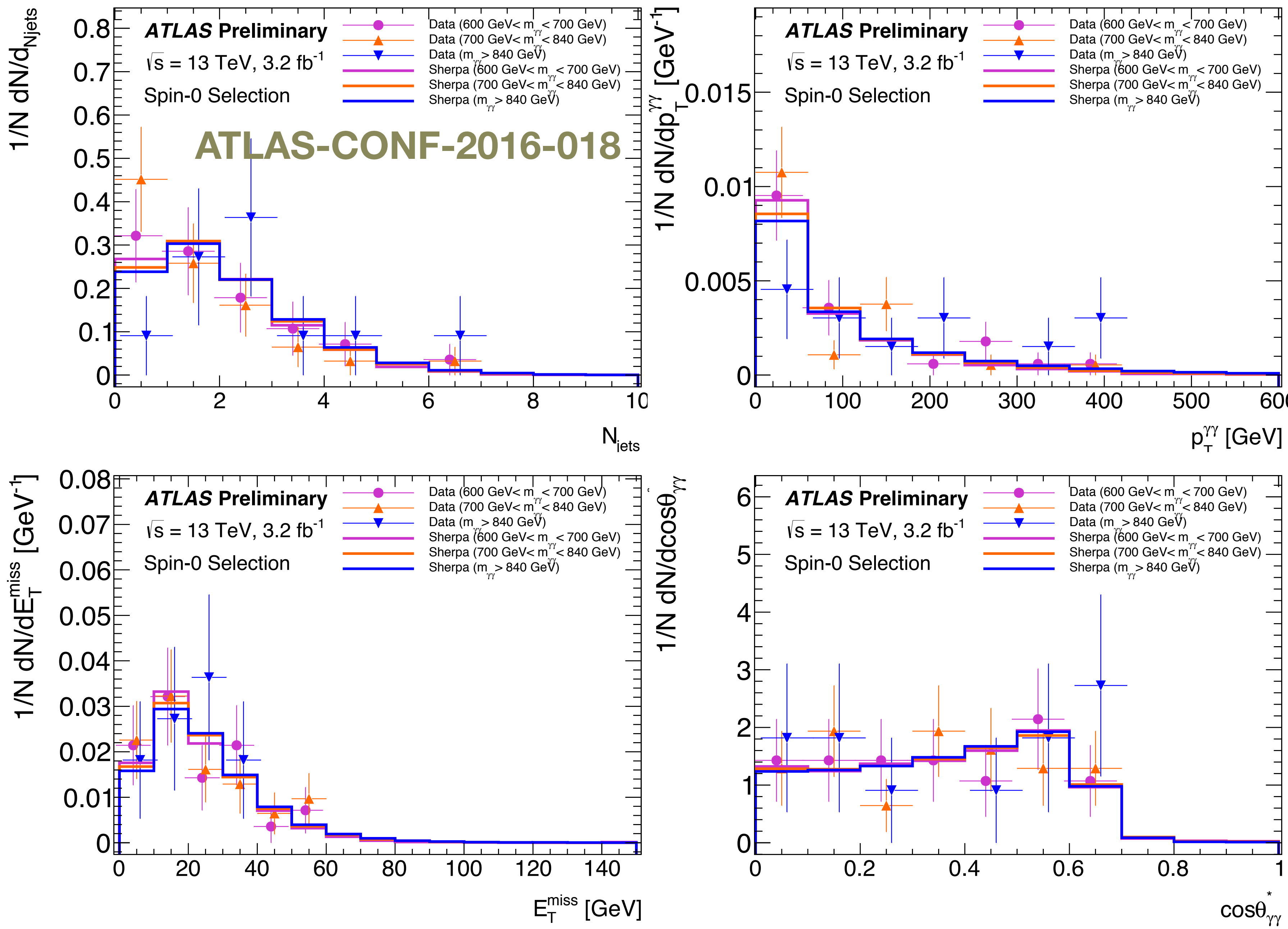


Systematics

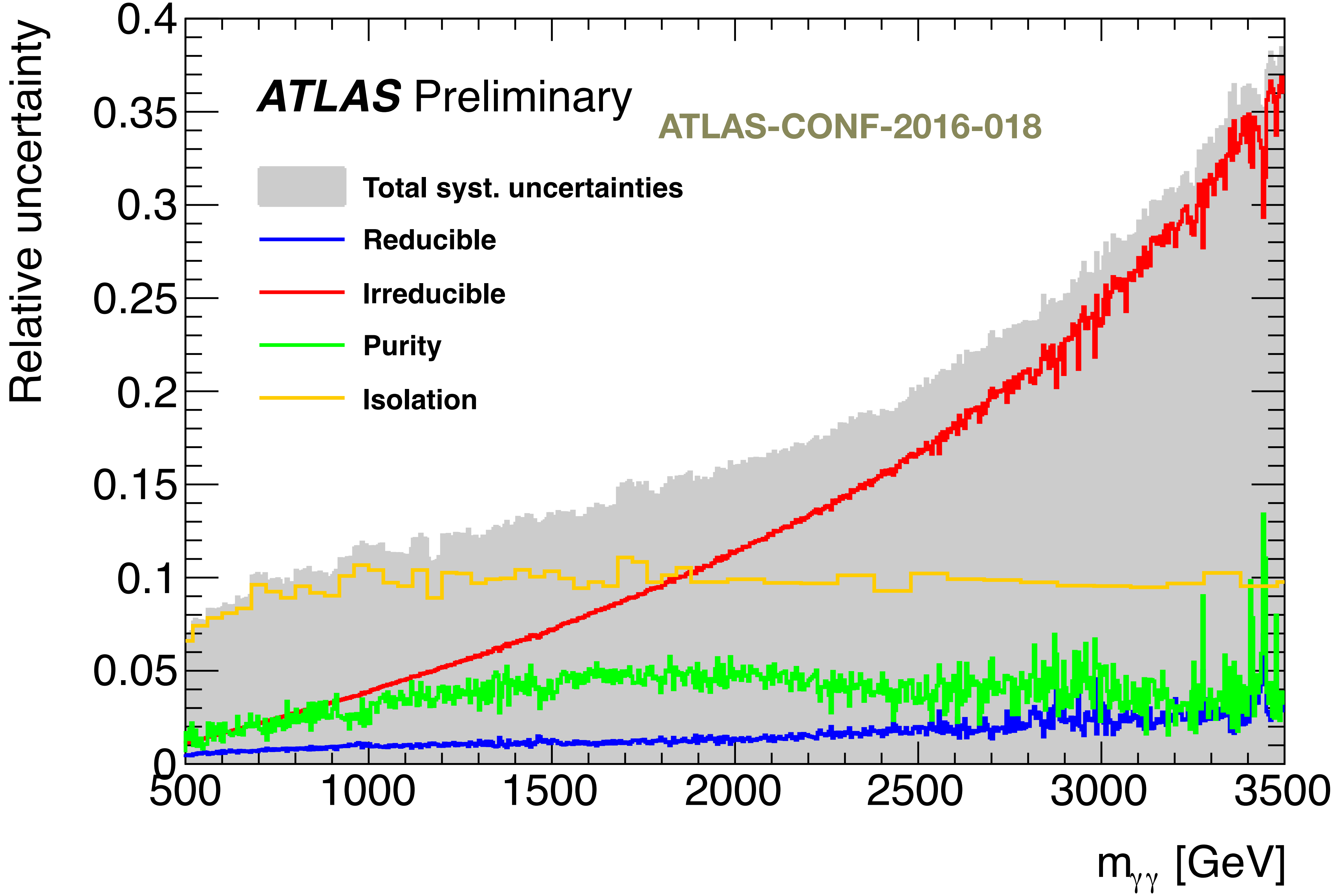
Uncertainty	spin-2 search	spin-0 search	
Background (mass dependent)	$\pm$ 7% to $\pm$ 35%	spurious signal 20 – 0.04 events for Γ/M=6%	p_0 and limit
Signal mass resolution (mass dependent)	$(^{+55}_{-20})\% - (^{+110}_{-40})\%$		p_0 and limit
Signal photon identification (mass dependent)	$\pm(3-2)\%$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

Properties of the excess

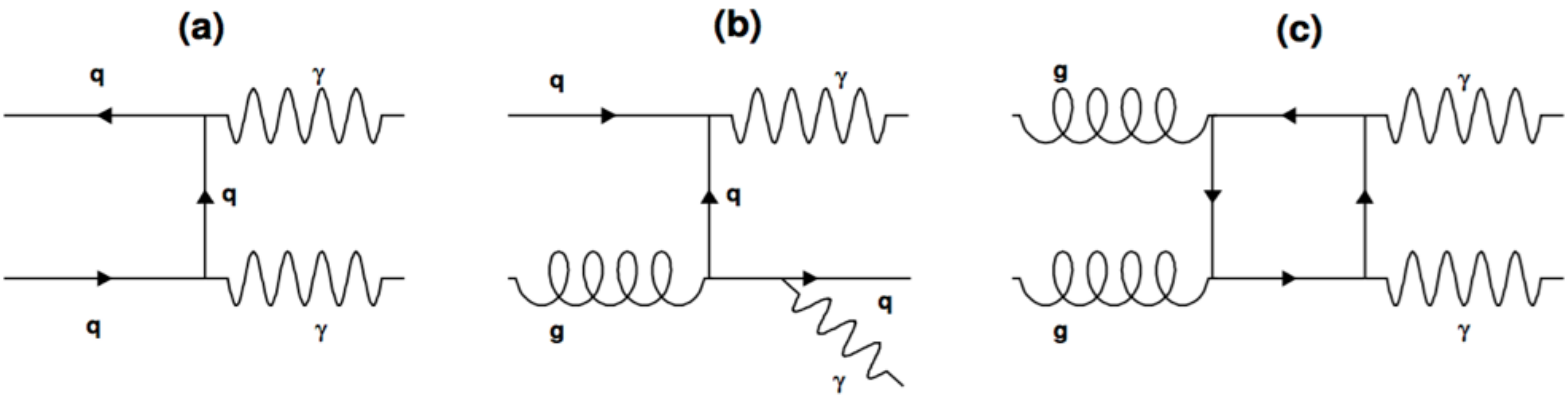
- No detector or reconstruction effect that could explain the larger rate is found. Purity studies on data also point to very high purity around 750 GeV.
- Kinematic properties of those events are also studied, and nothing significant is observed.
- Statistics is too low to conclude on anything.



Systematics uncertainties on background template

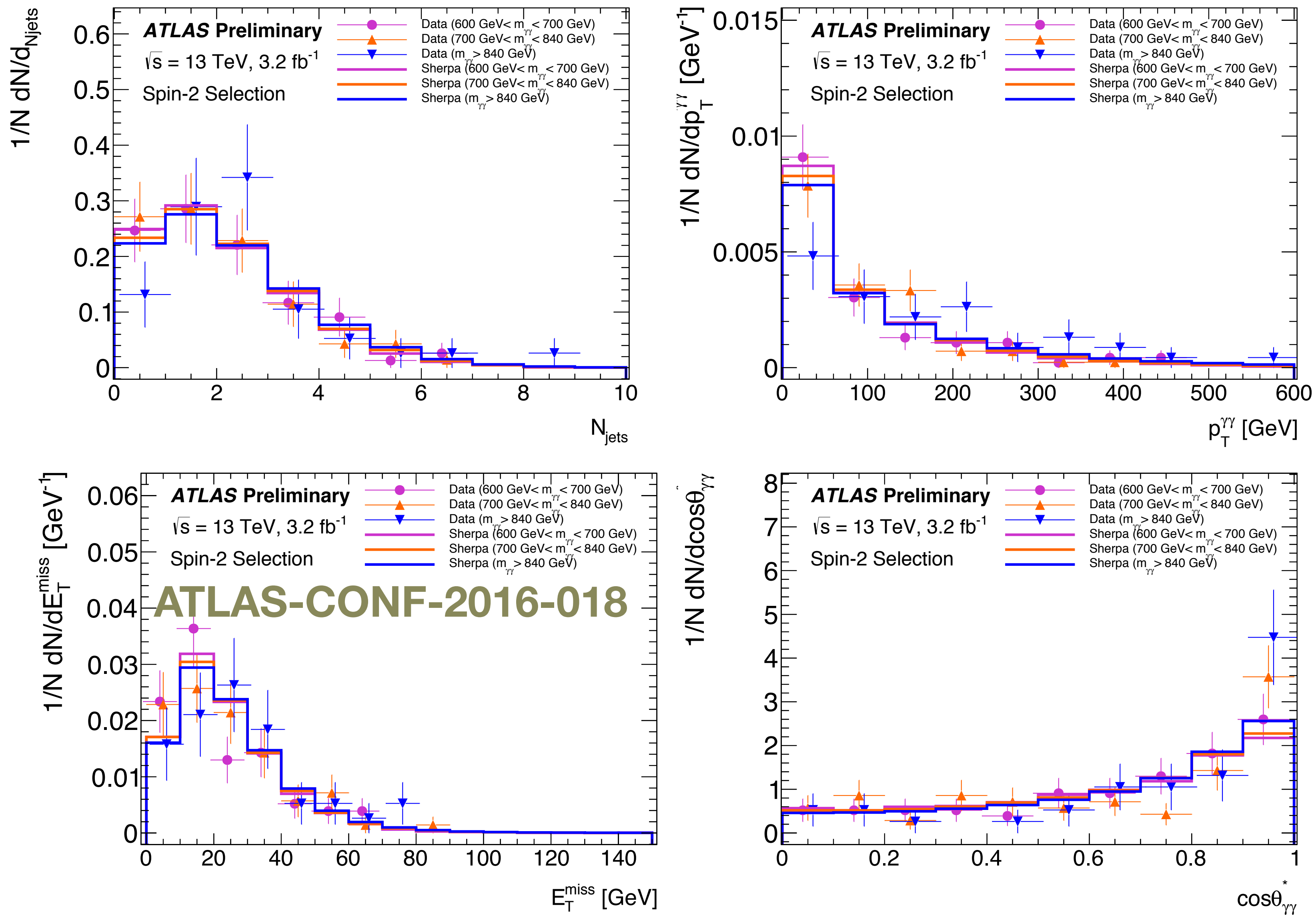


SM photon pair production



Properties of the excess (spin-2 selection)

- No detector or reconstruction effect that could explain the larger rate is found. Purity studies on data also point to very high purity around 750 GeV.
- Kinematic properties of those events are also studied, and nothing significant is observed.



F-test

- Validate the need of additional degree of freedom to describe the data.
- Background-only fits of two functions (a simplest validated function and a more complex version) to binned data.
- Test statistics F computed from resulting χ^2.
  - p_1 and p_2 : number of free parameters

$$F_{(1,2)} = \frac{\dfrac{\chi_1^2 - \chi_2^2}{p_2 - p_1}}{\dfrac{\chi_2^2}{n - p_2}}$$

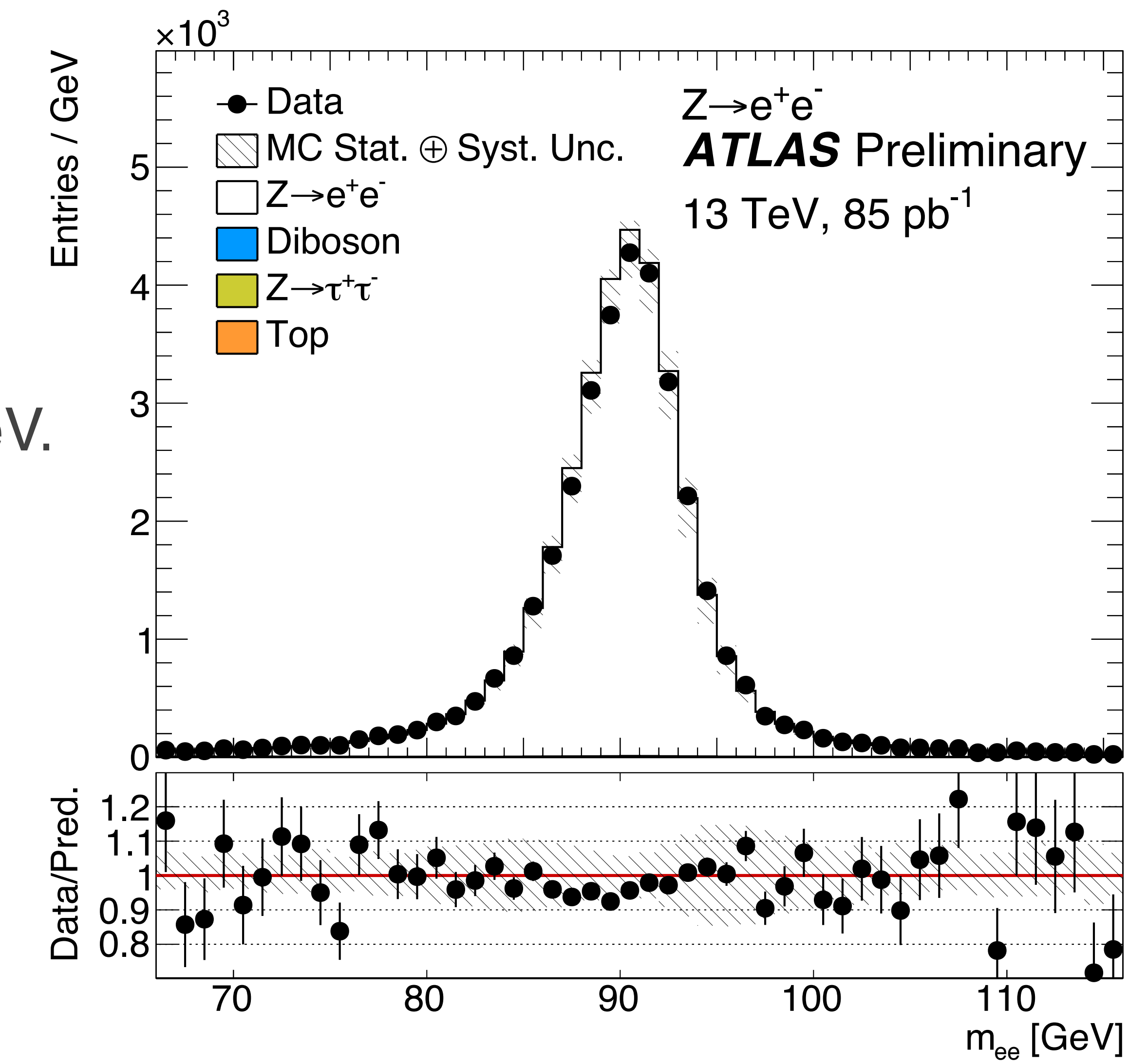
- F has Fisher distribution if added parameter is not improving the model.
- Its probability is compared with that expected from a Fisher distribution with the corresponding number of degrees of freedom. If P (F' >= F) < 5%, then the simpler function is discarded in favour of the more complex one.

Photon identification and isolation

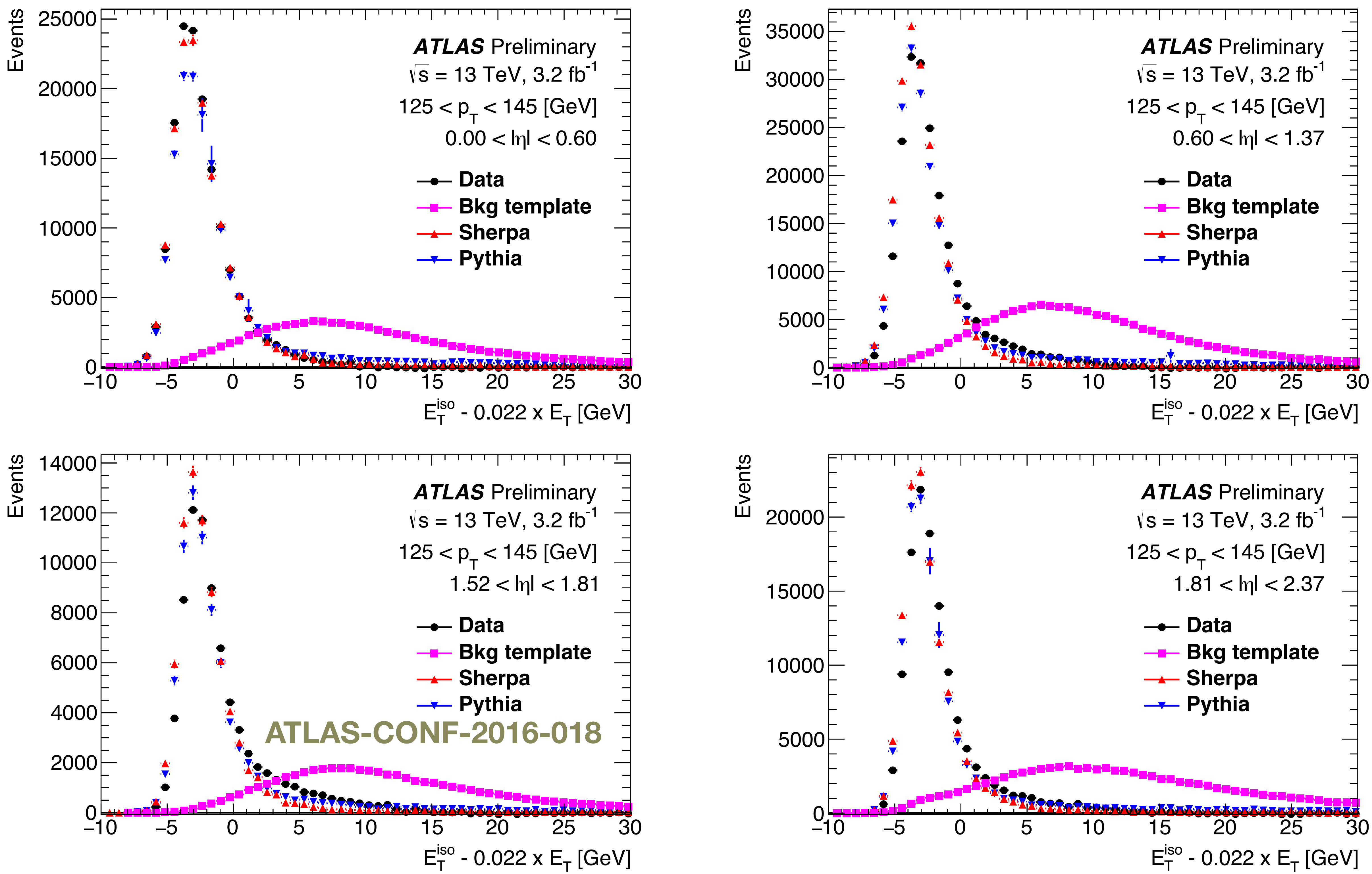
- Identification
  - efficiency of 85% (E_T~50 GeV) — 95% (E_T~200 GeV)
  - Uncertainty: full data/MC difference
    - ± 1% — ± 5% for $E_T > 50$ GeV
  - η-dependent
- Isolation
  - Calorimeter (ΔR=0.4)
    - $E_T^{iso} < 0.022\ E_T^{\gamma} + 2.45$ GeV
  - Track pT iso (ΔR=0.2)
    - $p_T^{iso} < 0.05\ E_T^{\gamma}$
  - Uncertainty: full data/MC difference

Photon energy calibration

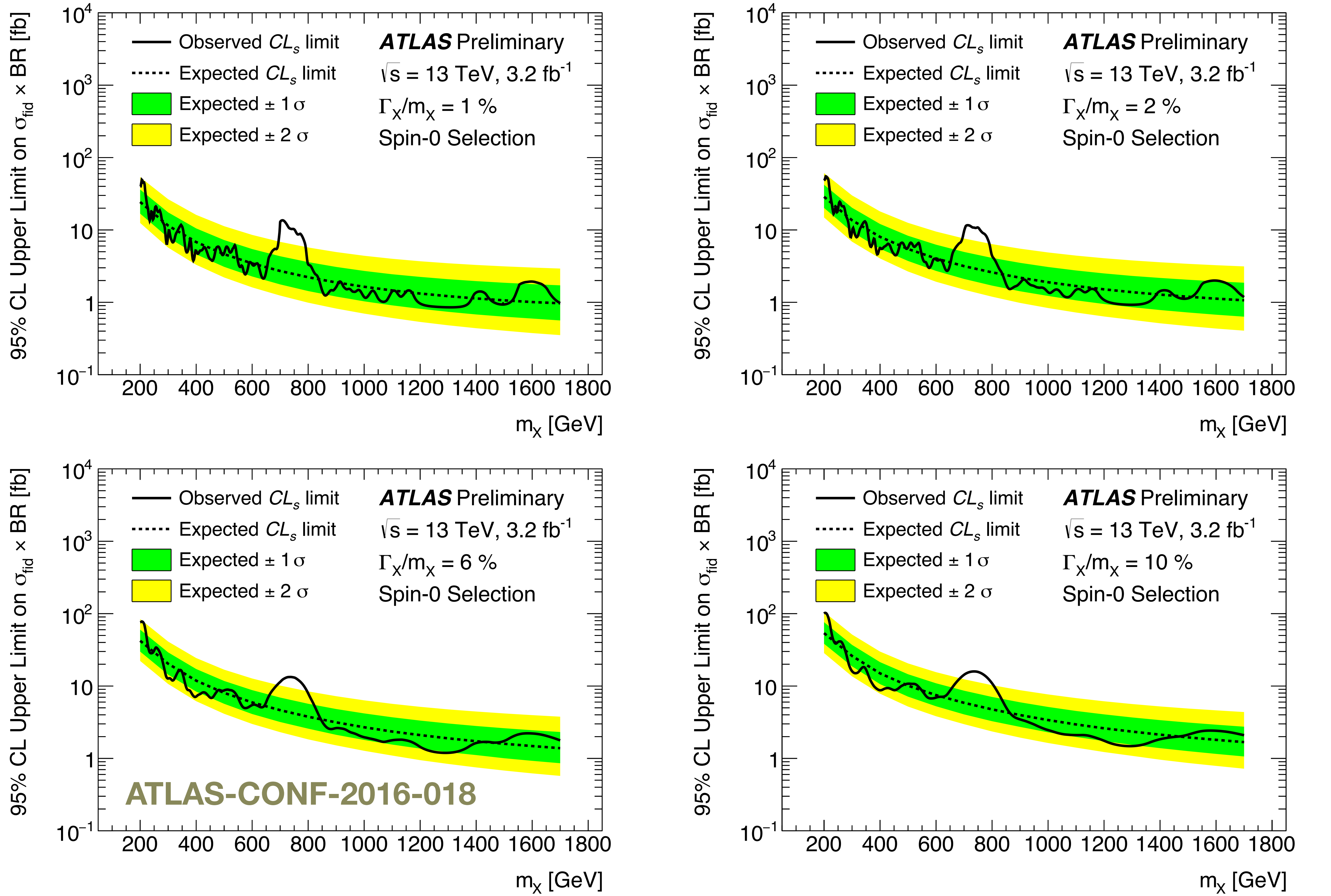
- Multi-variate regression to calibrate photon cluster energy, optimised on MC
- Energy scale and resolution corrections validated with 13 TeV Z→ee events.
- At E_T^γ>100-200 GeV, resolution dominated by constant term. c = 0.6 –1.5%
- Uncertainties
  - Energy scale: 0.4-2%
  - Energy resolution: 80-100% for E_T^γ=300 GeV.



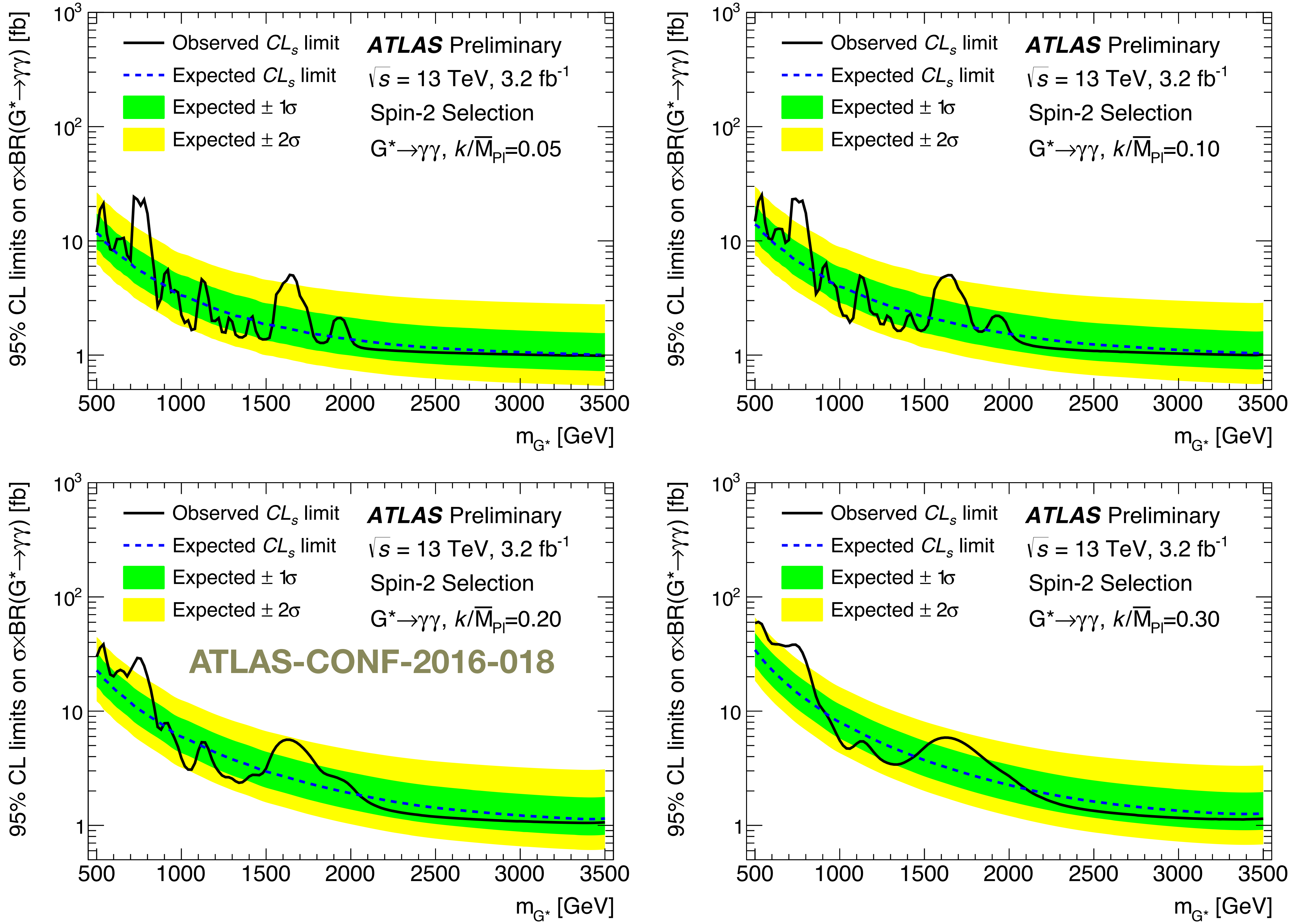
Calorimeter isolation for tight photon with $125<E_T<145$ GeV



Results: spin-0 limits



Results: spin-2 limits

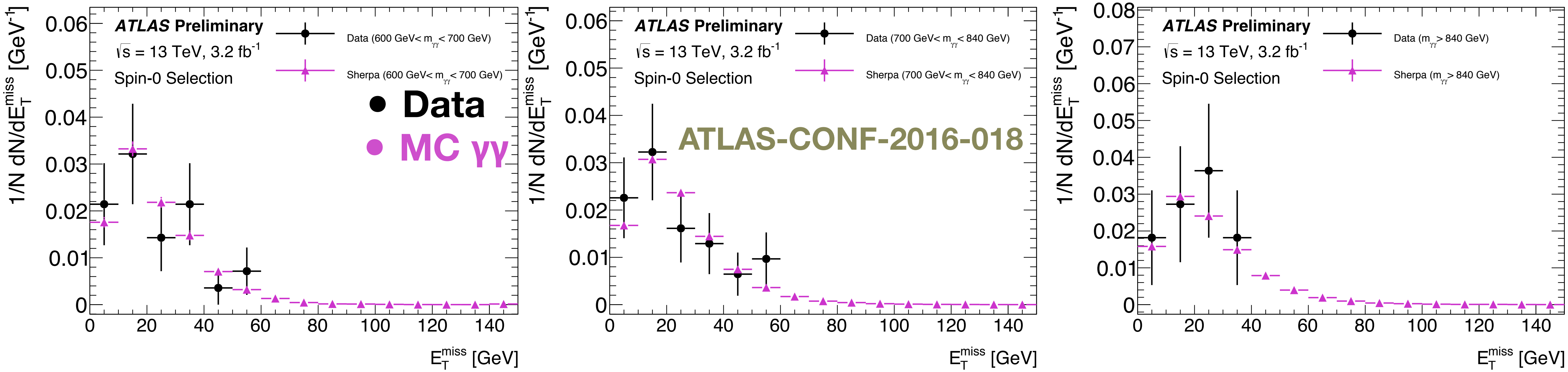


Properties of the excess: E_T^{miss}

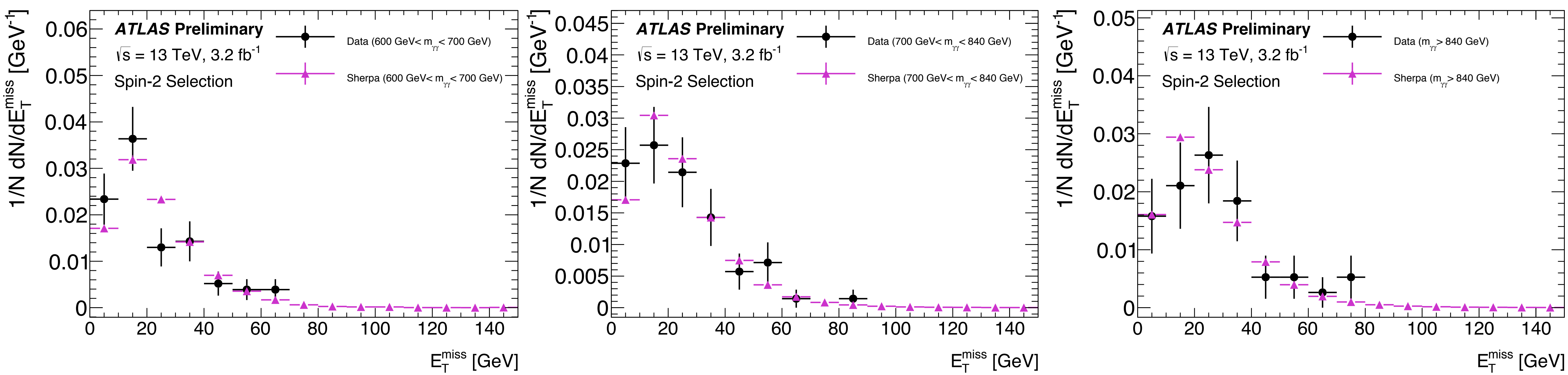
Spin-0 analysis

excess region

mγγ = [600-700] GeV | mγγ = [700-840] GeV | mγγ = [840-∞] GeV



Spin-2 analysis

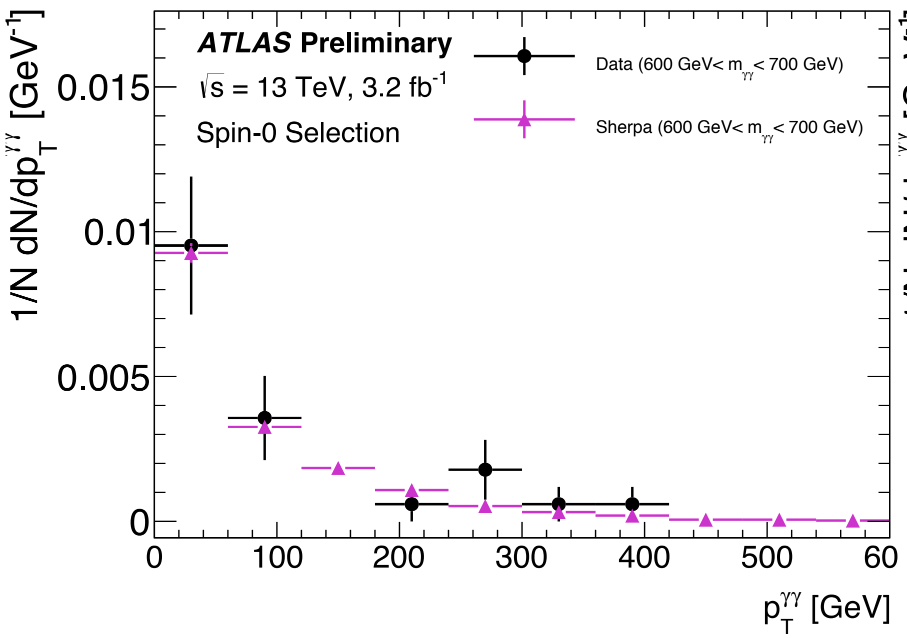


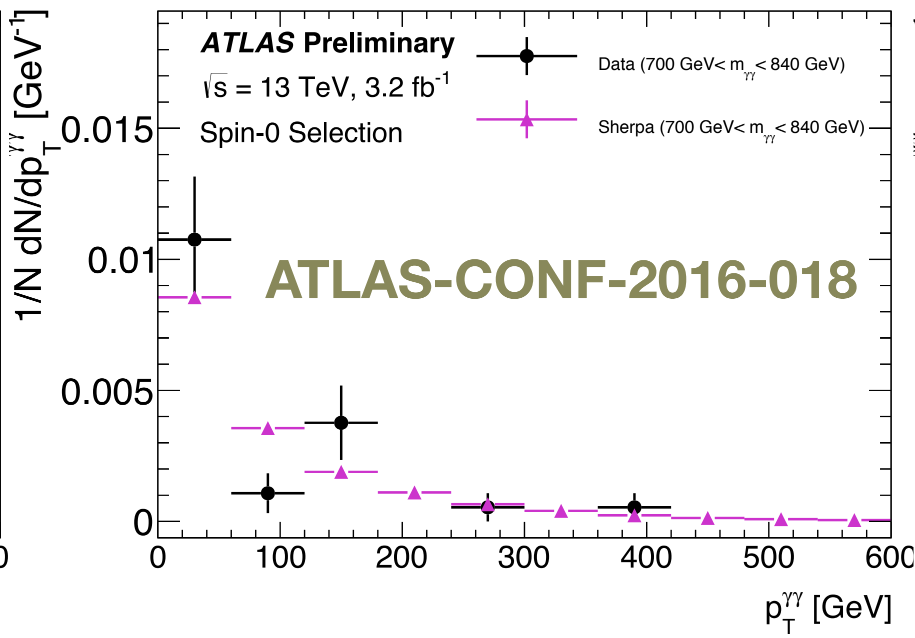
Properties of the excess: $p_T^{\gamma\gamma}$

Spin-0 analysis

excess region

mγγ = [600-700] GeV | **mγγ = [700-840] GeV** | **mγγ = [840-∞] GeV**





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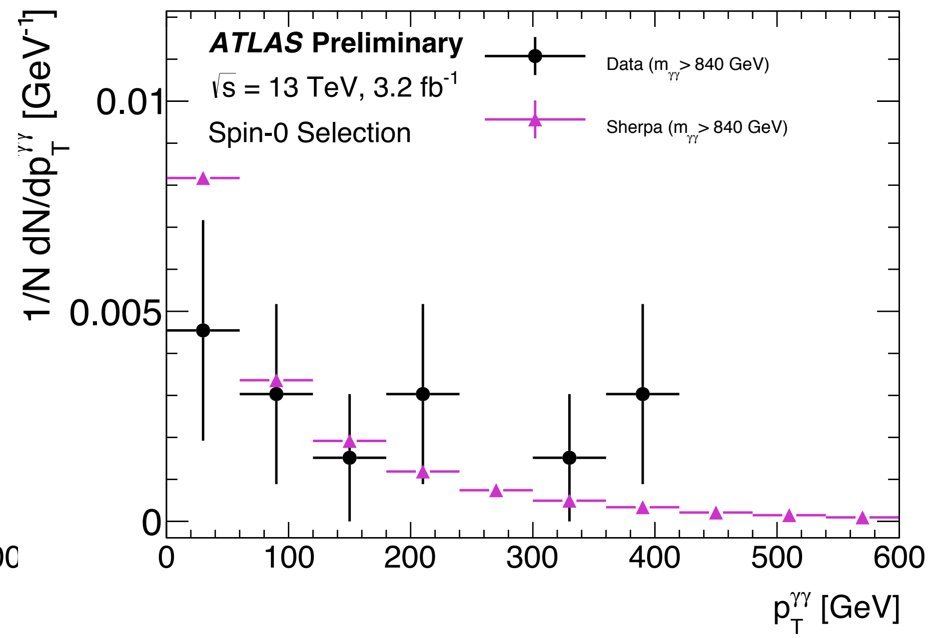
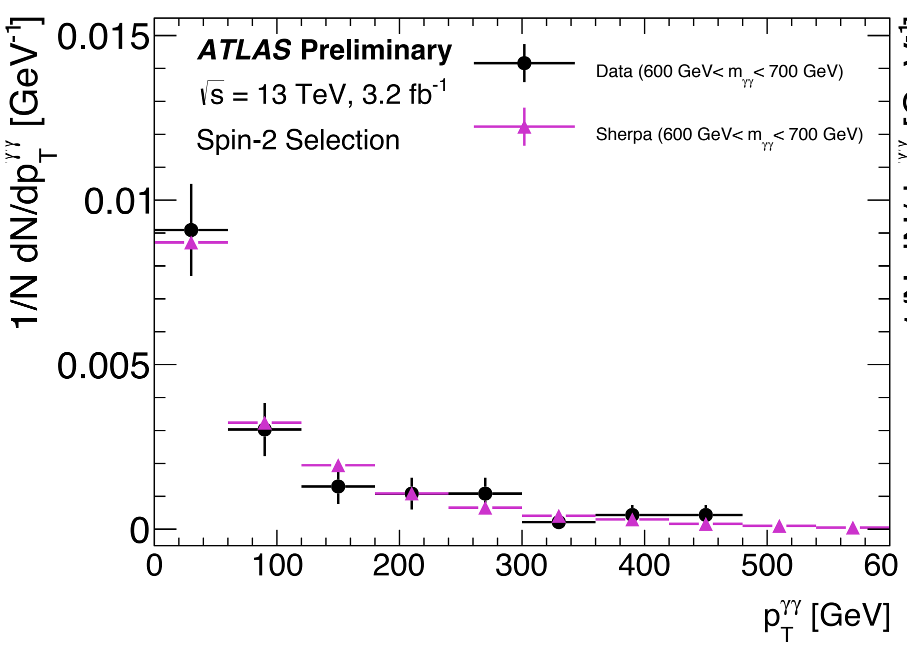
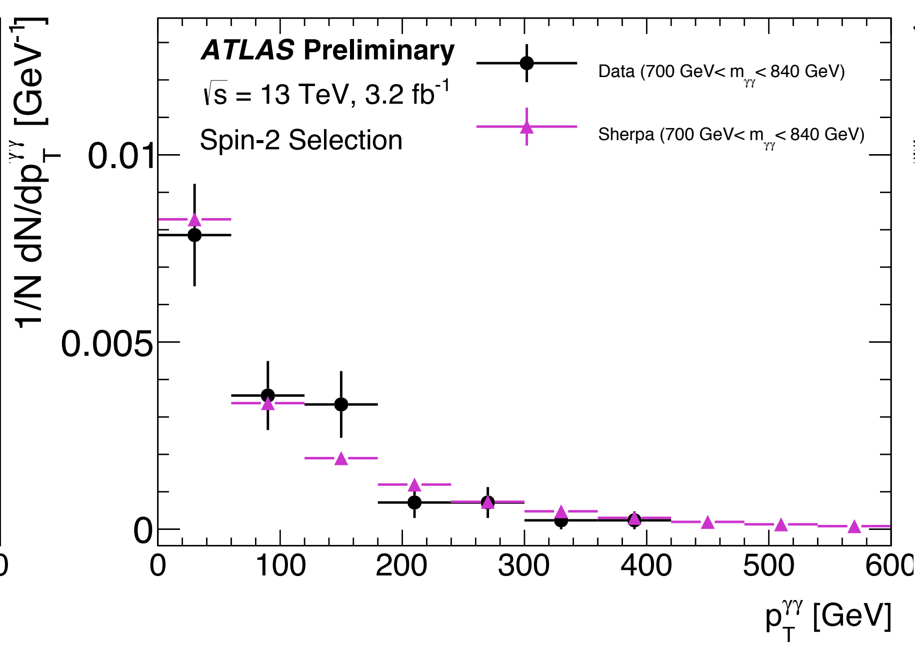
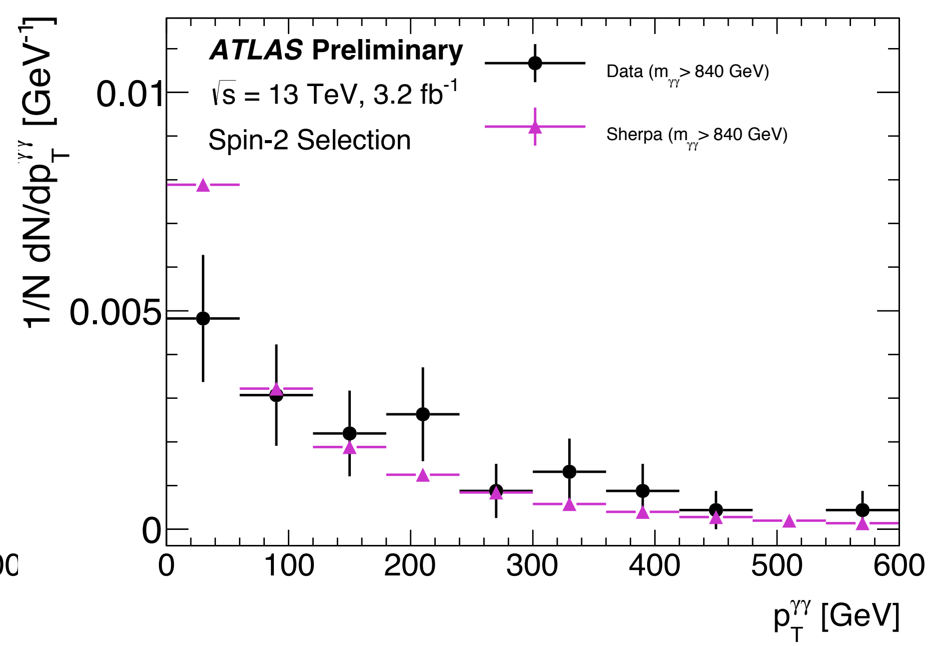


Spin-2 analysis





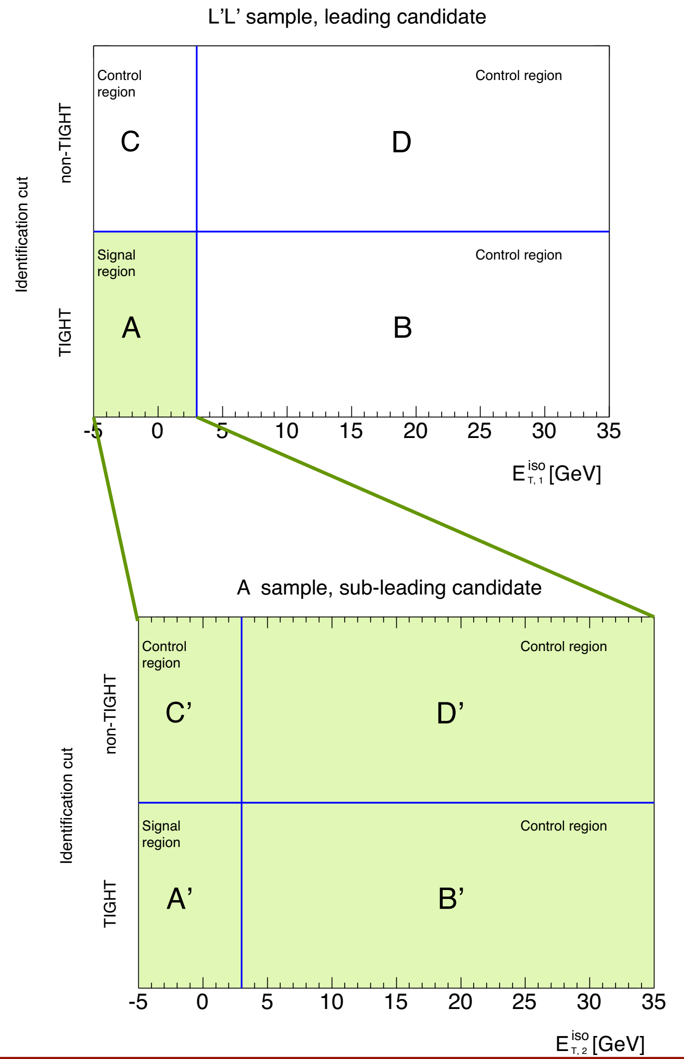


8 TeV analysis selections

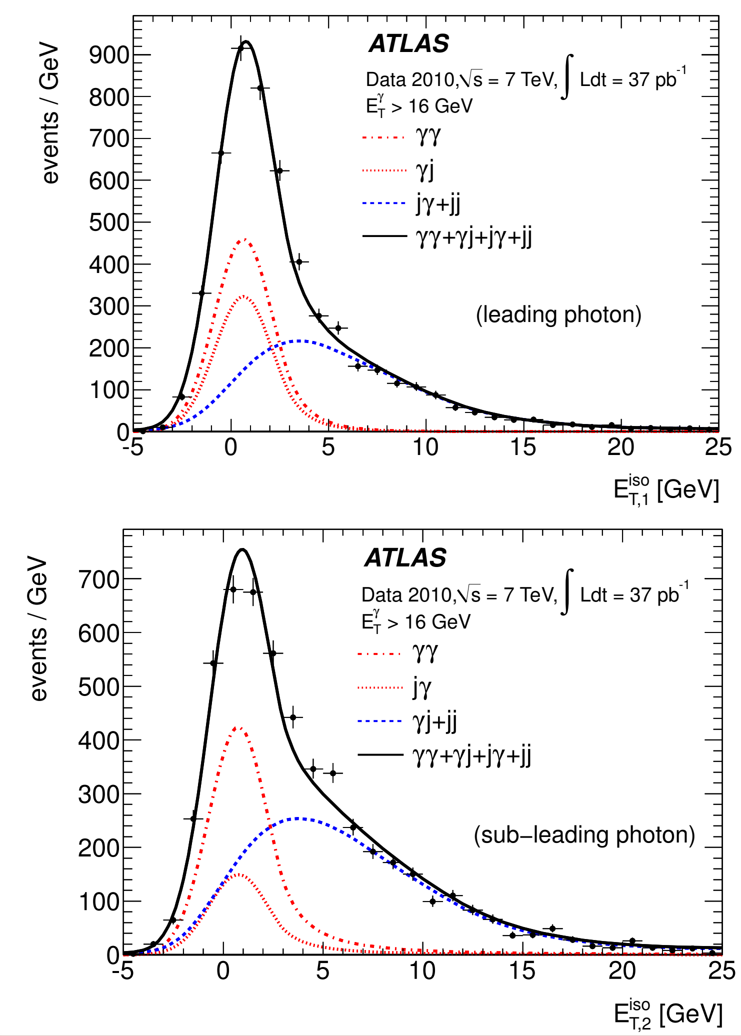
Criteria	Scalar analysis	Graviton analysis
Trigger	`EF_g35_loose_g25_loose`	
GRL	v61-pro14-02_DQDefects-00-01-00_PHYS_StandardGRL_All_Good	
LAr	LArError, TileError, event corruption	
vertex	At least one PV with 3 associated tracks or more	
Presel.	At least two photons passing loose ID, OQ, photon cleaning with $\|\eta_{S2}\|$ <1.37 or 1.56< $\|\eta_{S2}\|$ <2.37	
E_T cuts	$E_{T,1} > 0.4 \times m_{\gamma\gamma}$ and $E_{T,2} > 0.3 \times m_{\gamma\gamma}$	$E_{T,1} > 50\,\mathrm{GeV}$ and $E_{T,2} > 50\ \mathrm{GeV}$
Photon ID	Require both candidates to pass `tight` photon ID	
Isolation	$\begin{cases} E_{\mathrm{T}}^{\mathrm{iso,calo}} < 6\ \mathrm{GeV} & \text{if} \quad E_{\mathrm{T}} < 80\ \mathrm{GeV} \\ E_{\mathrm{T}}^{\mathrm{iso,calo}} < 6\ \mathrm{GeV} + 0.7\%(E_{\mathrm{T}} - 80\ \mathrm{GeV}) & \text{if} \quad E_{\mathrm{T}} > 80\ \mathrm{GeV} \end{cases}$ and $E_{\mathrm{T}}^{\mathrm{iso,track}} < 2.6\ \mathrm{GeV}$	$E_{\mathrm{T}}^{\mathrm{iso,calo}} < 8\ \mathrm{GeV} - 0.07\ \mathrm{GeV} + 4.8 \cdot 10^{-4} E_{\mathrm{T}} + 2.6 \cdot 10^{-6} \frac{1}{\mathrm{GeV}} E_{\mathrm{T}}^2$
$m_{\gamma\gamma}$	$m_{\gamma\gamma} > 150\,\mathrm{GeV}$	

Purity estimation methods

2x2D-sidebands



2D isolation template fit



Matrix Method

$$\begin{pmatrix} \mathrm{PP} \\ \mathrm{PF} \\ \mathrm{FP} \\ \mathrm{FF} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1(1-\epsilon_2) & \epsilon_1(1-f_2) & f_1(1-\epsilon_2) & f_1(1-f_2) \\ (1-\epsilon_1)\epsilon_2 & (1-\epsilon_1)f_2 & (1-f_1)\epsilon_2 & (1-f_1)f_2 \\ (1-\epsilon_1)(1-\epsilon_2) & (1-\epsilon_1)(1-f_2) & (1-f_1)(1-\epsilon_2) & (1-f_1)(1-f_2) \end{pmatrix} \begin{pmatrix} W_{\gamma\gamma} \\ W_{\gamma j} \\ W_{j\gamma} \\ W_{jj} \end{pmatrix}$$

Passes or Fails isolation cut

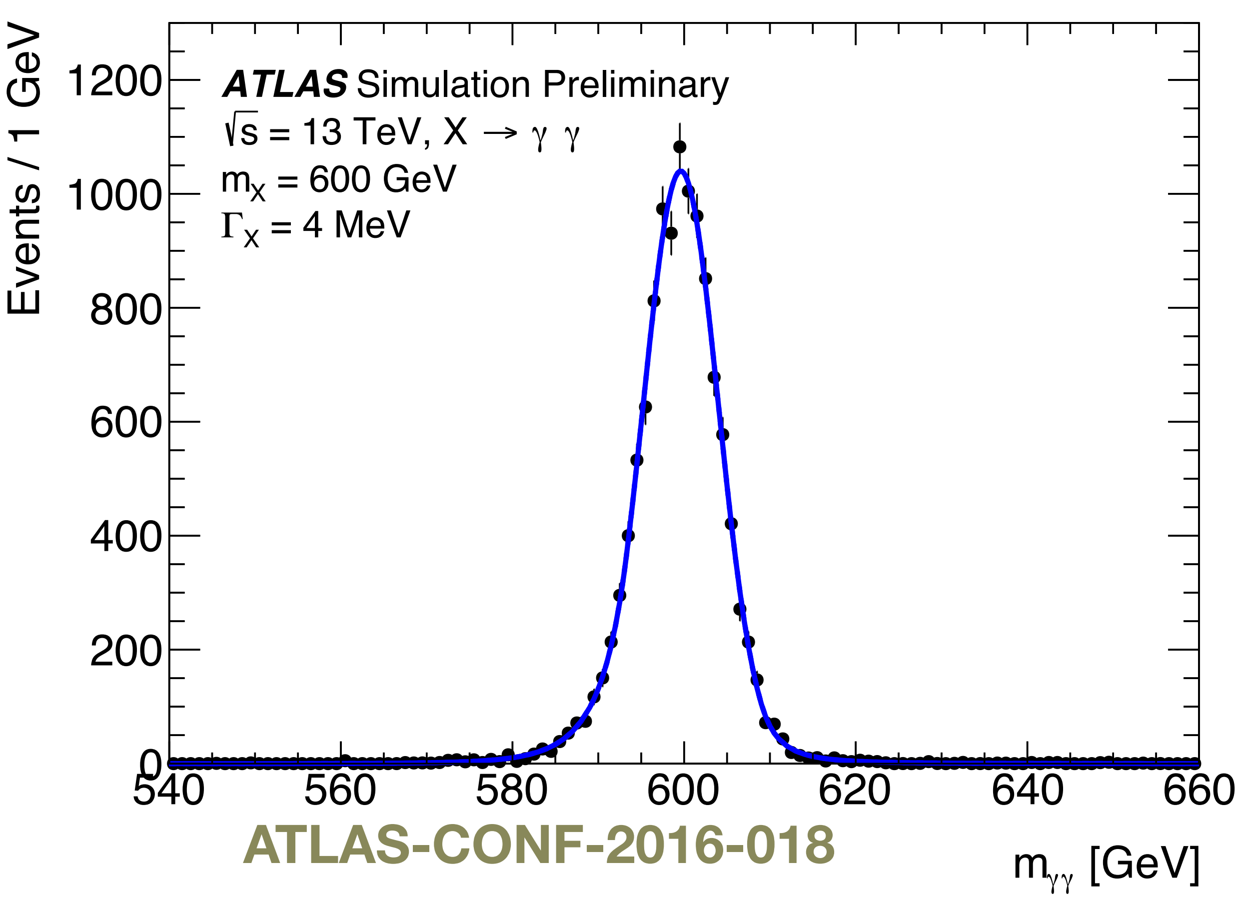
ε_i = probability for a γ to pass isolation cut (data-driven)

f_i = probability for a jet to pass isolation cut (data-driven)

Event weights

accounting for the correlation of the isolation energy of the 2 γ candidates

NWA signal modelling



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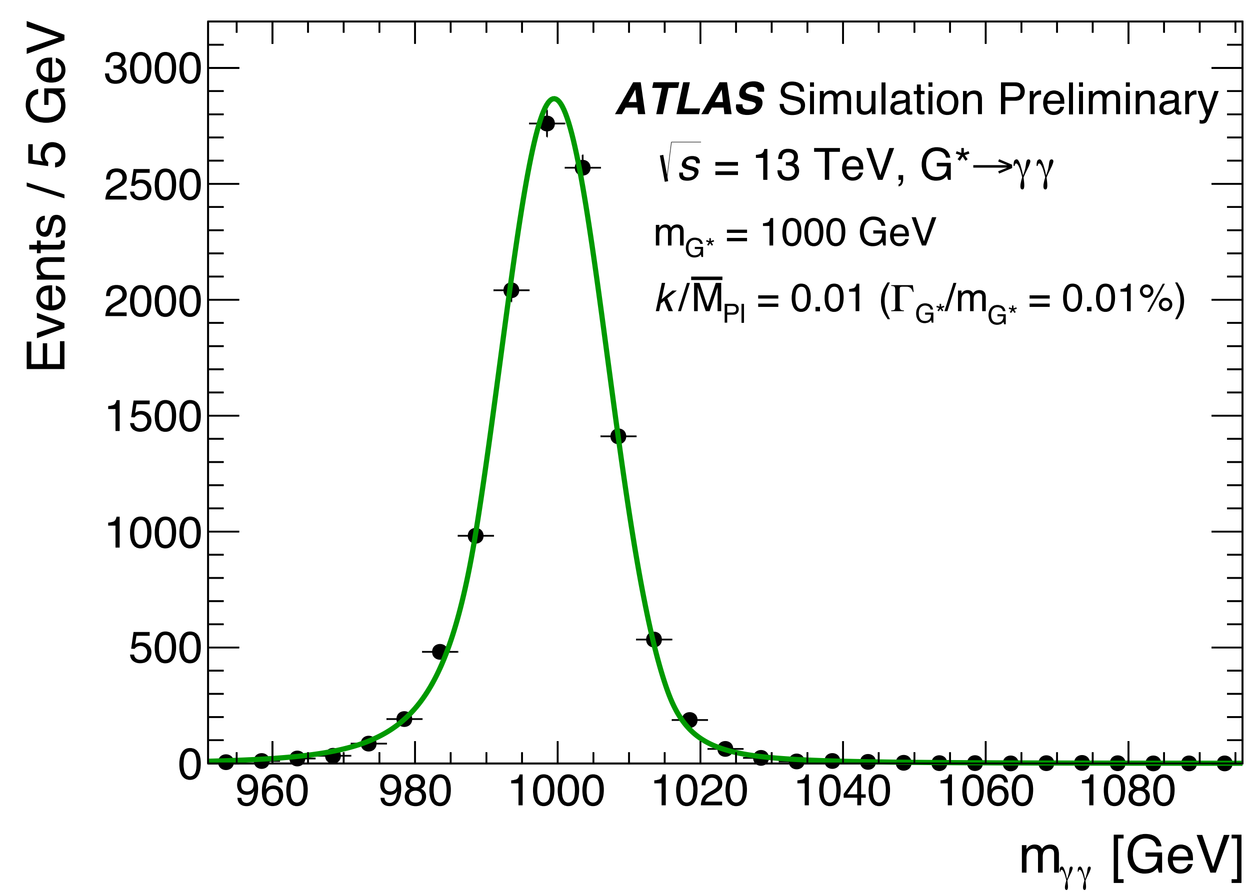
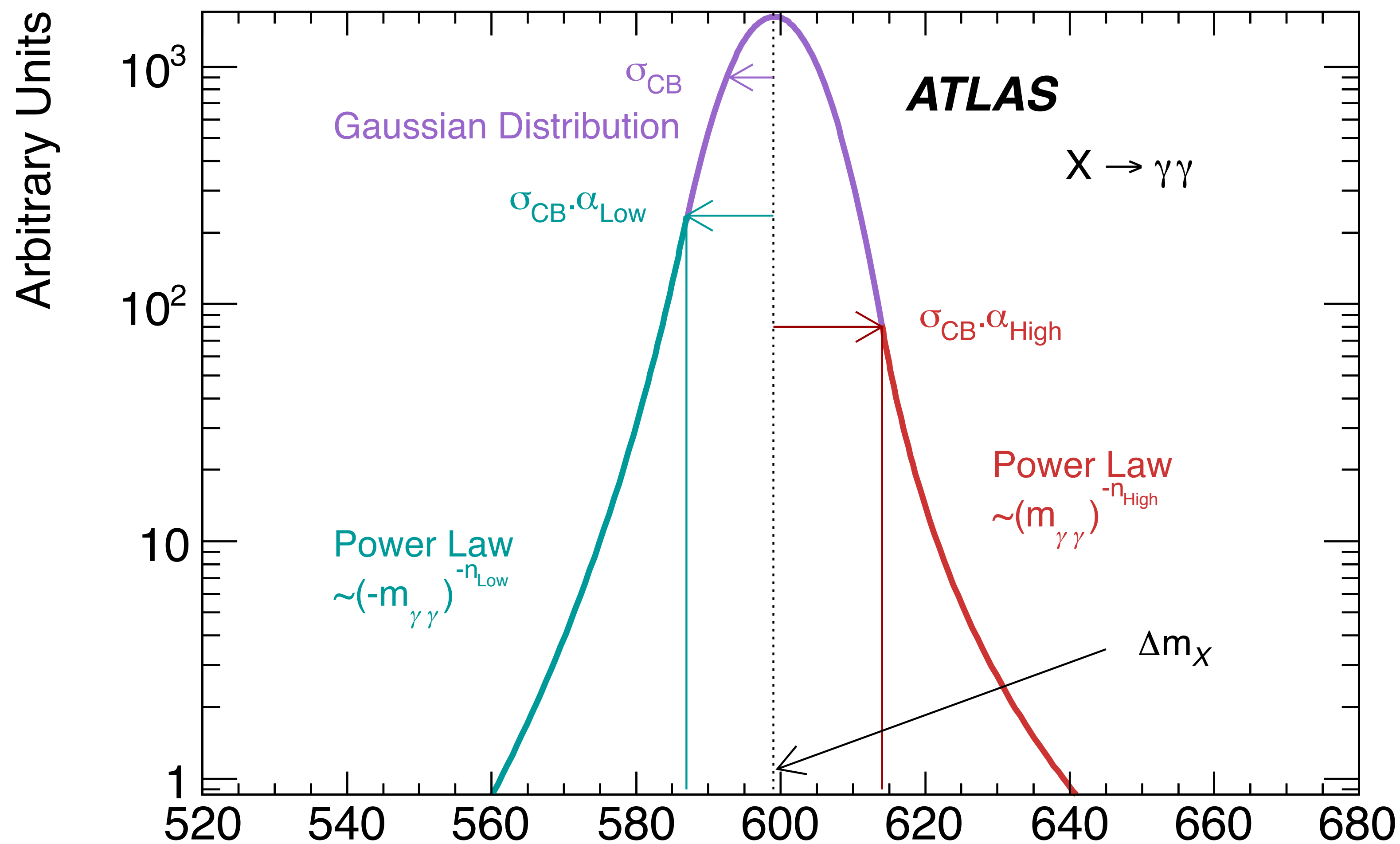


Double sided Crystal Ball function

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

$$t = \Delta m_X/\sigma_{CB}, \Delta m_X = m_X - \mu_{CB}$$



EOYE NWA results

- Local significance of 3.6 σ.