SEARCH FOR DI-PHOTON RESONANCES WITH THE ATLAS EXPERIMENT

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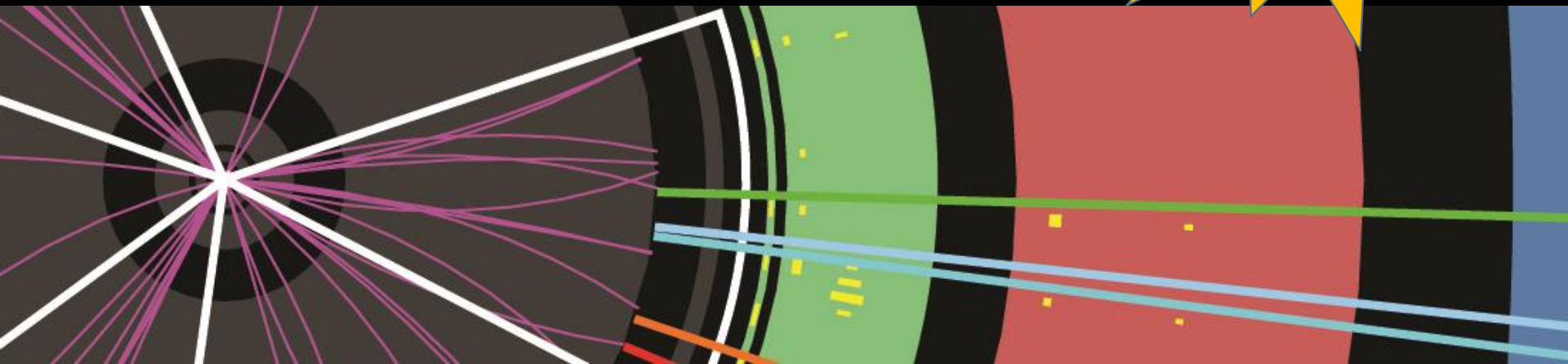
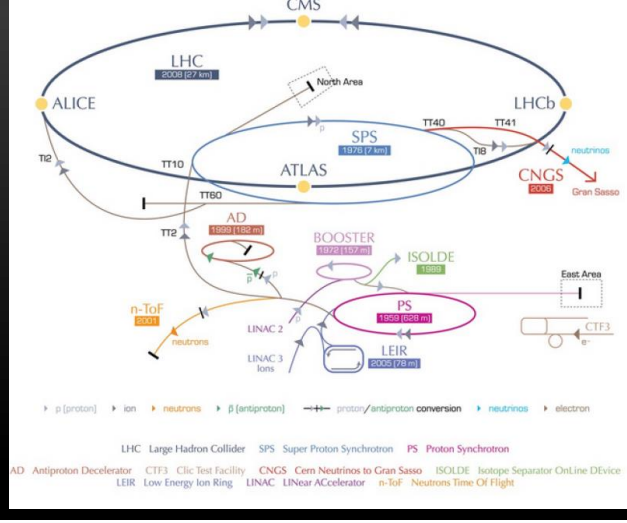
On behalf of the ATLAS collaboration

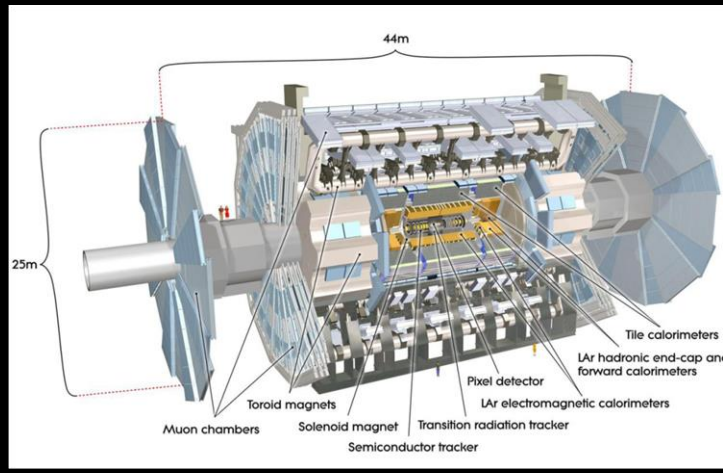
Updated paper results



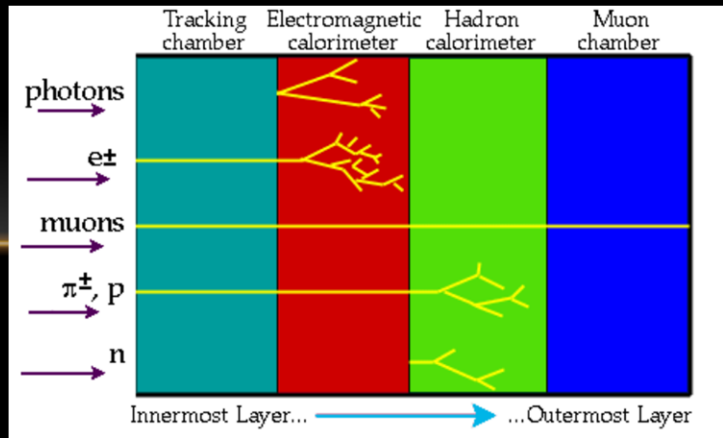


- ATLAS is one of the four main experiments at the LHC

- ATLAS (A Toroidal LHC ApparatuS)
  - 4 levels of detectors
    - Inner detector (pixel, strip, TRT)
    - Electromagnetic calorimeter
    - Hadronic calorimeter
    - Muon detector (MDT, CSC, RPC, TGC)



- Reconstruction and identification of objects (photons, muons, jets) is achieved using information from all detectors



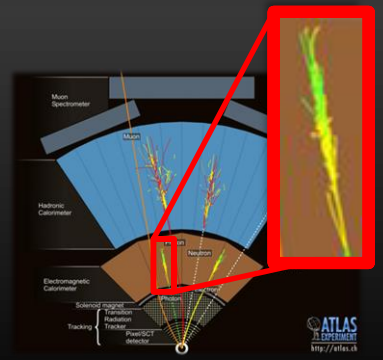
RECONSTRUCTION AND IDENTIFICATION OF PHOTONS

- Photons reconstruction
  - From energy deposits in the electromagnetic calorimeter
  - Tracks to determine if the candidate is *electron* or *photon converted/unconverted*
  - Photons cluster reconstruction efficiency close to 100 %
  - Photons classification efficiency: 96%

- Photon identification
  - Based on discriminating variables measured in the calorimeters (different for converted/unconverted)
  - Two standard identification criteria: loose and tight
  - Tight ID efficiency: 85% at E_T ~ 50 GeV, 95% at E_T ~ 200 GeV

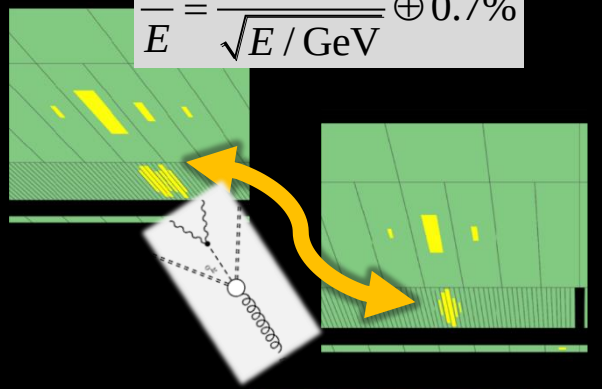
- Isolation in the calorimeter
  - Energy in a cone in the calorimeter of $\Delta R=\sqrt{(\Delta\varphi^2+\Delta\eta^2)}=0.4$
- Isolation in the inner detector
  - Tracks in the inner detector in a cone of $\Delta R= 0.2$

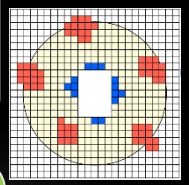
- Uncertainty on:
  - Photon energy scale at high E_T is (0.5–2.0)% (depending on η)
  - Photon energy resolution for E_T = 300 GeV is (30–45)% (depending on η)

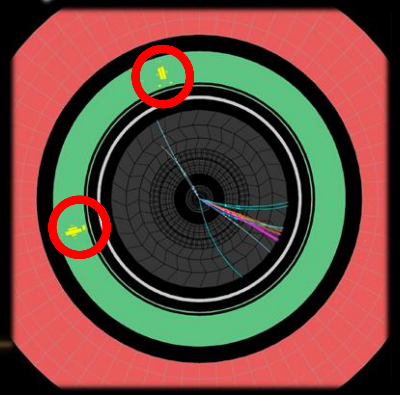


Calorimeter Energy resolution

$$\frac{\sigma}{E}=\frac{10-17\%}{\sqrt{E/\mathrm{GeV}}}\oplus 0.7\%$$



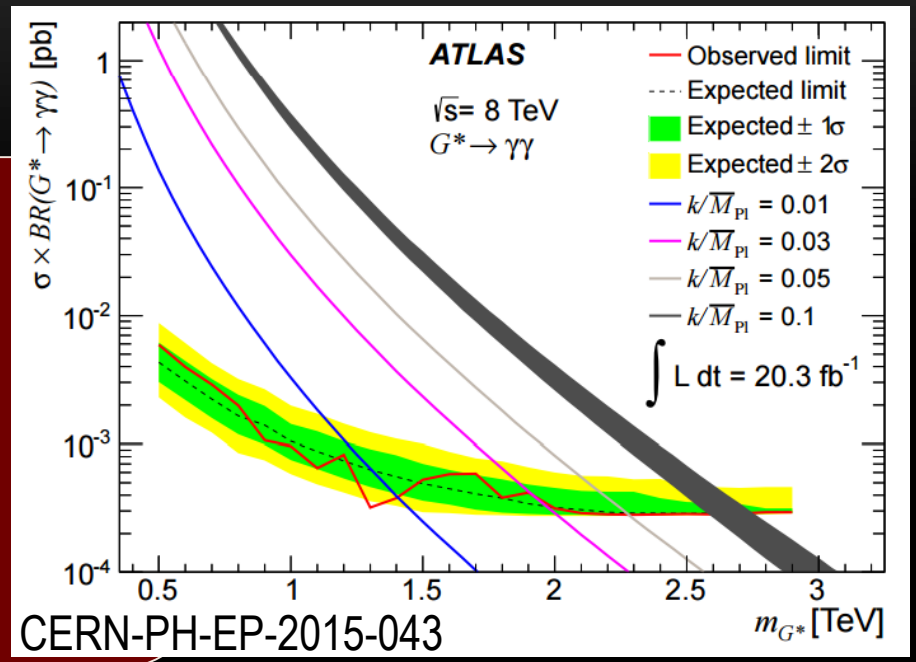




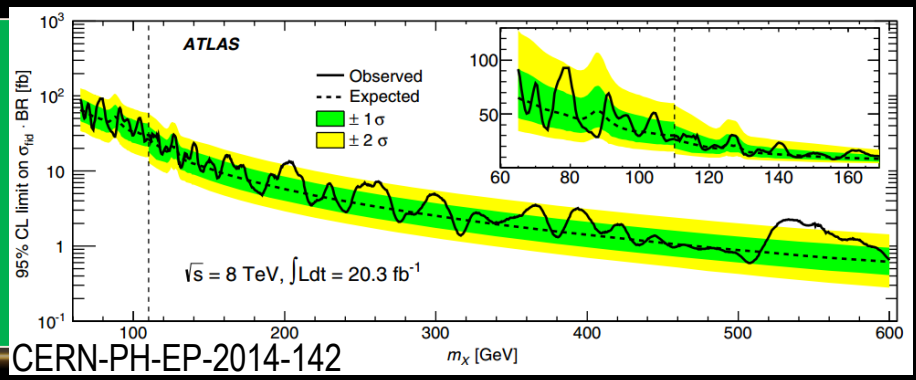
RESONANCES IN THE DIPHOTON CHANNEL

- Current di-photon searches ongoing in the ATLAS experiment:

- **Search for Graviton (spin 2)**
  - Randall Sundrum (RS) model
  - Additional dimensions where only gravity propagates → Reduced effective value of the Planck scale in the SM brane
- For graviton the coupling with the SM k/M_{pl} is proportional to the width of the resonance
  - M_G and k/M_{pl} are free parameters
- For 8 TeV analysis Graviton with $k/M_{pl} = 0.1$ excluded to 2.66 TeV



- **Search for another Higgs (spin 0)**
  - Several extension of Higgs sector foresee additional scalar states
  - Narrow or wide resonance
- For 8 TeV analysis search up until 600 GeV, no significant excess found



DI PHOTON SELECTION

- Tight identification criteria, $|\eta| < 2.37$, removing crack region

Graviton (spin 2)
- $P^{\gamma}_{T} > 55$ GeV

Higgs (spin 0)
- Leading (subleading) photon
- $P^{\gamma}_{T}/M_{\gamma\gamma} > 0.4$ (0.3)
- (better sensitivity for spin 0 resonance)

- Isolation $< 0.022 * P^{\gamma}_{T} + 2.45$ GeV
- Isolation (tracks) $< 0.05 * P^{\gamma}_{T}$
- Efficiency of isolation over tight ID for 2 photons: 90% to 96% (P_T 100,150 [GeV])
- Overall selection efficiency for a signal 70 % (spin 2) 60 % (spin 0)

Analysis strategy

- Select pure diphoton sample
- Model signal using MC
- Background using MC and data-driven methods
- Test the background only hypothesis over the signal+background hypothesis on data

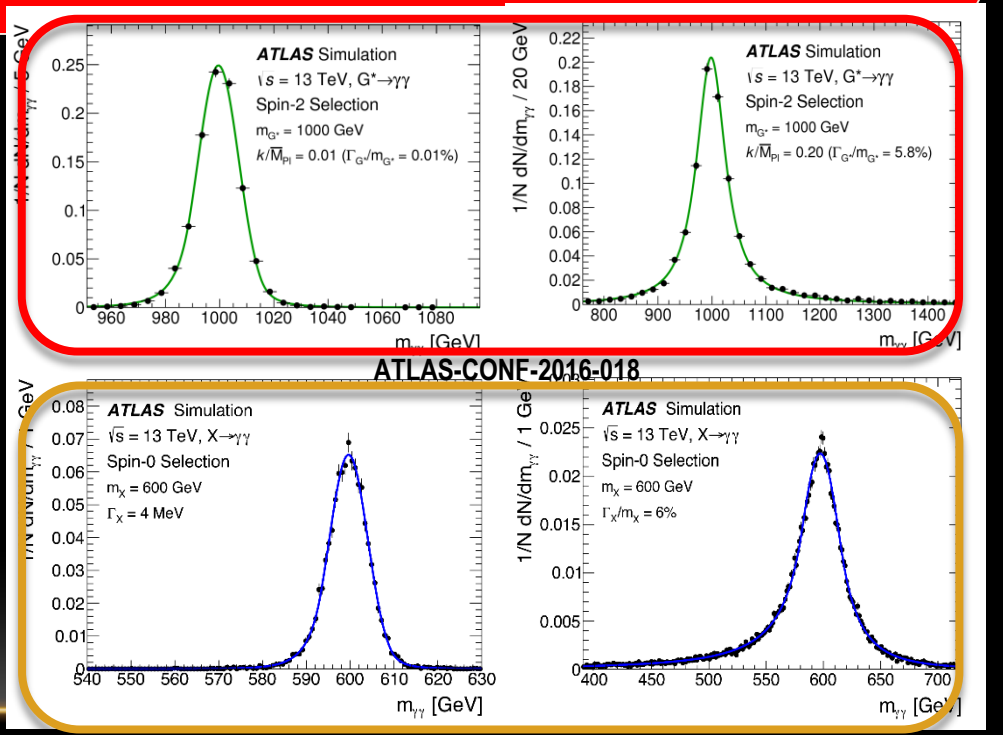
SIGNAL PARAMETERIZATION

- The mass distribution is described by the convolution:
  - Of the detector resolution (a double sided crystal ball, DSCB) fitted on zero width samples ($k/M_{pl} = 0.01$)
  - With the predicted distribution of the mass line-shape at generator level (Breit Wigner - like)

- For spin-0, the line shape is described by an effective DSCB function
  - DSCB parameters are functions of mass and width of the scalar particle

Double Sided Crystal Ball (DSCB):

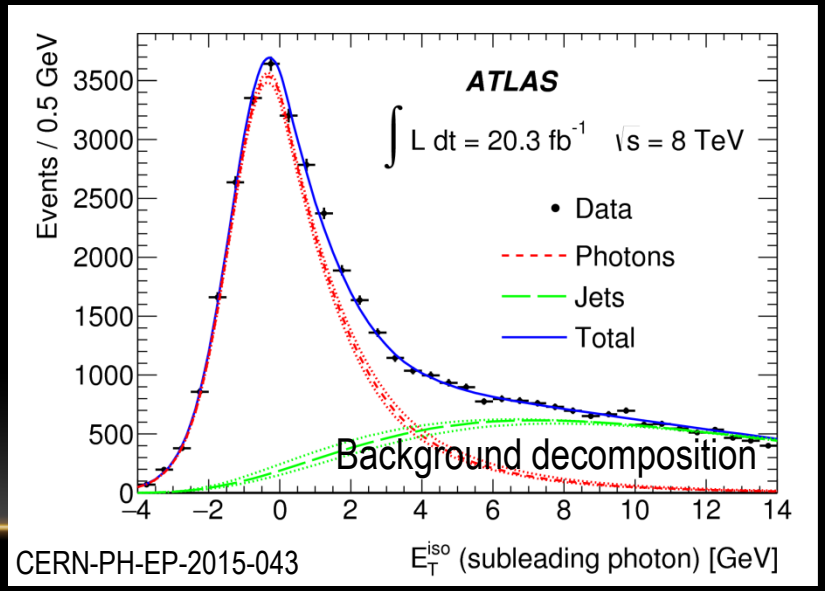
$$N \cdot \begin{cases} e^{-0.5t^2} & \text{if } -\alpha_{\text{low}} \geq t \geq \alpha_{\text{high}} \\ e^{-0.5\alpha_{\text{low}}^2}\left[\frac{\alpha_{\text{low}}}{n_{\text{low}}}\left(\frac{n_{\text{low}}}{\alpha_{\text{low}}} - \alpha_{\text{low}} - t\right)\right]^{-n_{\text{low}}} & \text{if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



BACKGROUND MODELING (SPIN 2)

- Irreducible background shape (two photon from SM)
  - Shape is from LO MC (Sherpa after detector simulation) with NLO correction factors (diphox MC) as a function of $M_{\gamma\gamma}$
- Reducible background shape from a fit to data, in control regions, inverting photon identification criteria
  - eg: tight, anti-tight for γ-jet background

- **Fractions of [γγ, γ-jet, jet-γ, jet-jet] are determined from data**
  - In a control region [200-500] GeV
  - Isolation template fit: study the shape of the isolation variable to get the background decomposition
- Technique explained here: CERN-PH-EP-2015-043



BACKGROUND MODELING (SPIN 0)

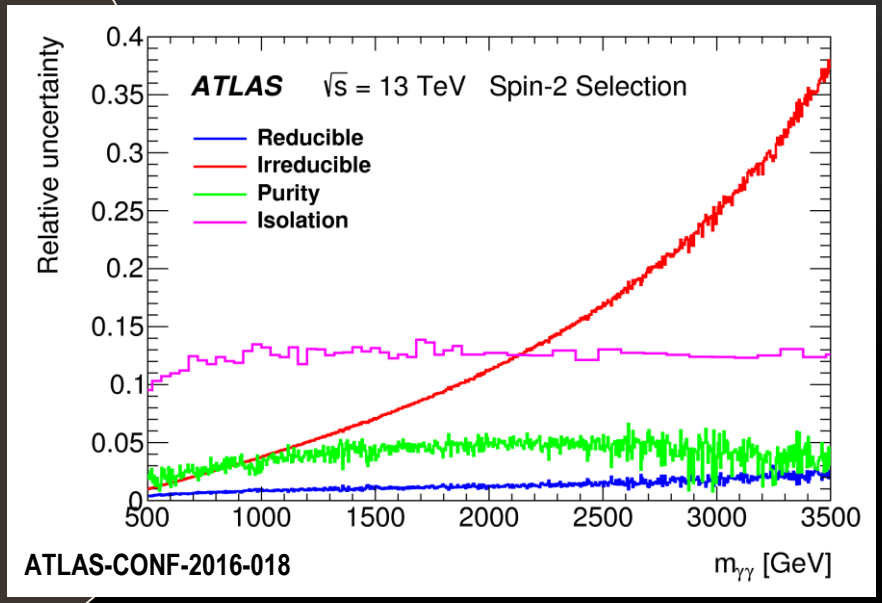
- Background is fitted to data with a functional form
- Spurious signal (SS) to test functional forms:
  - Using a very high statistic MC (irreducible) and data from control region (reducible) to build a full background template
  - Fit the template with signal + background (to be tested) for each mass hypotesis
  - SS is the number of fitted signal events on the background template
  - SS used as a systematic (centered at 0) uncertainty on Nsignal

- Function chosen from a family of nested function

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

- Number of free parameters = k + 2
- k = 0 was chosen with Fisher test
  - On functions passing spurious signal test
  - Minimum number of parameters to follow the background distribution

- Systematic errors on background (spin 2)
  - PDF variations of NLO MC
  - Reducible: variation of the control region definition
  - On background decomposition
  - On isolation: matching reco/parton isolation selections
- Systematic errors on background (spin 0):
  - Spurious signal for the chosen function
- Around 750 GeV error of 2-4 % on the background estimation



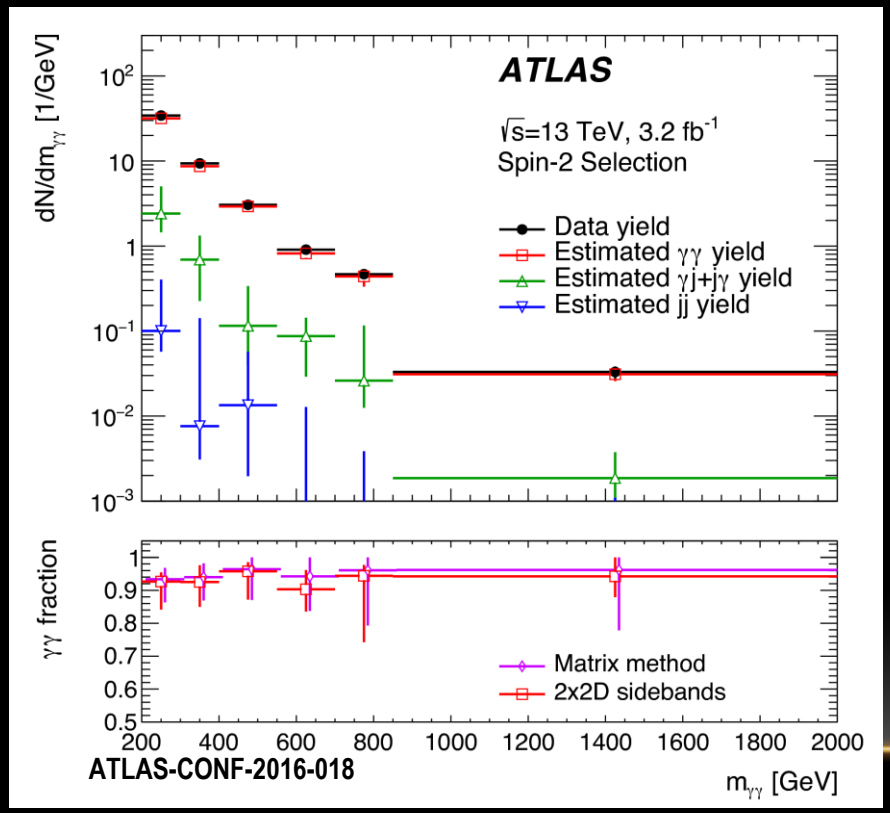
Investigated signal region	Background from MC extrapolation	Background from functional form
$m = 750$ GeV, $\Gamma/m = 6\%$		
720–780 GeV, spin-2 selection	$20.1 \pm 0.3 \pm 0.7$	$21.9 \pm 1.2 \pm 0.4$
720–780 GeV, spin-0 selection	$6.7 \pm 0.1 \pm 0.4$	$6.8 \pm 0.7 \pm 0.3$
$m = 1500$ GeV, $\Gamma/m = 6\%$		
1440–1560 GeV, spin-2 selection	$1.14 \pm 0.02 \pm 0.09$	$1.51 \pm 0.27 \pm 0.08$
1440–1560 GeV, spin-0 selection	$0.32 \pm 0.01 \pm 0.04$	$0.33 \pm 0.11 \pm 0.04$

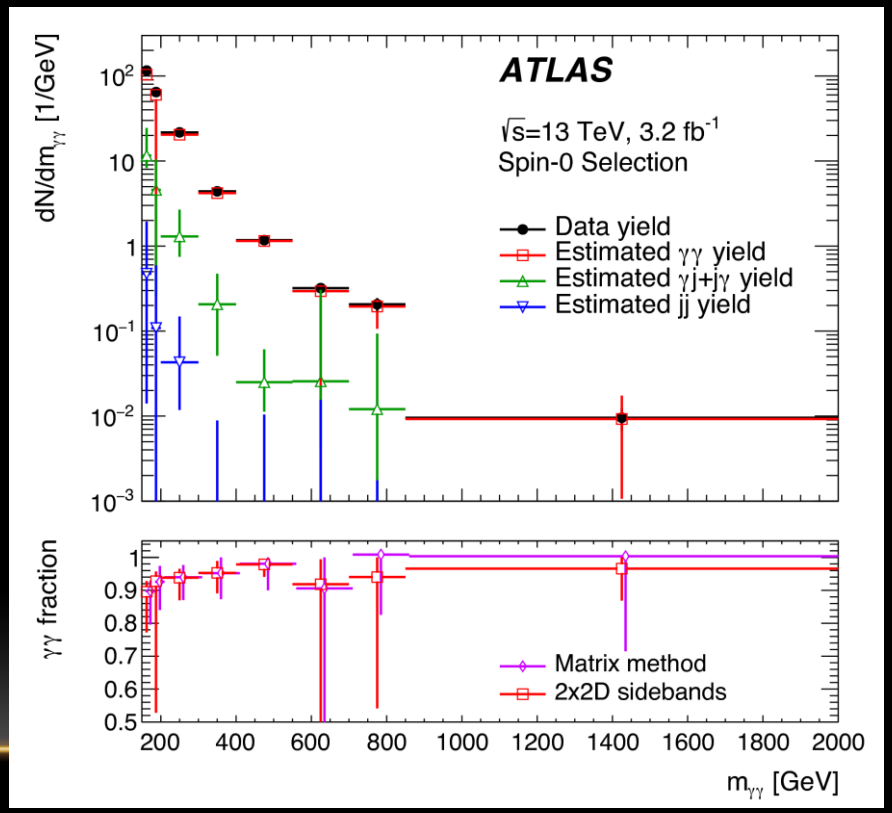
- Systematic errors on signal
  - Shape: energy resolution
  - Yield: Identification, Isolation, ATLAS recorded luminosity

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)	$\pm(2\text{–}3)\%$	
Signal photon isolation (mass dependent)	$\pm(2\text{–}1)\%$	$\pm(4\text{–}1)\%$
Signal production process	N/A	$\pm(3\text{–}6)\%$ depending on Γ
Trigger efficiency	$\pm 0.6\%$	
Luminosity	$\pm 5.0\%$	

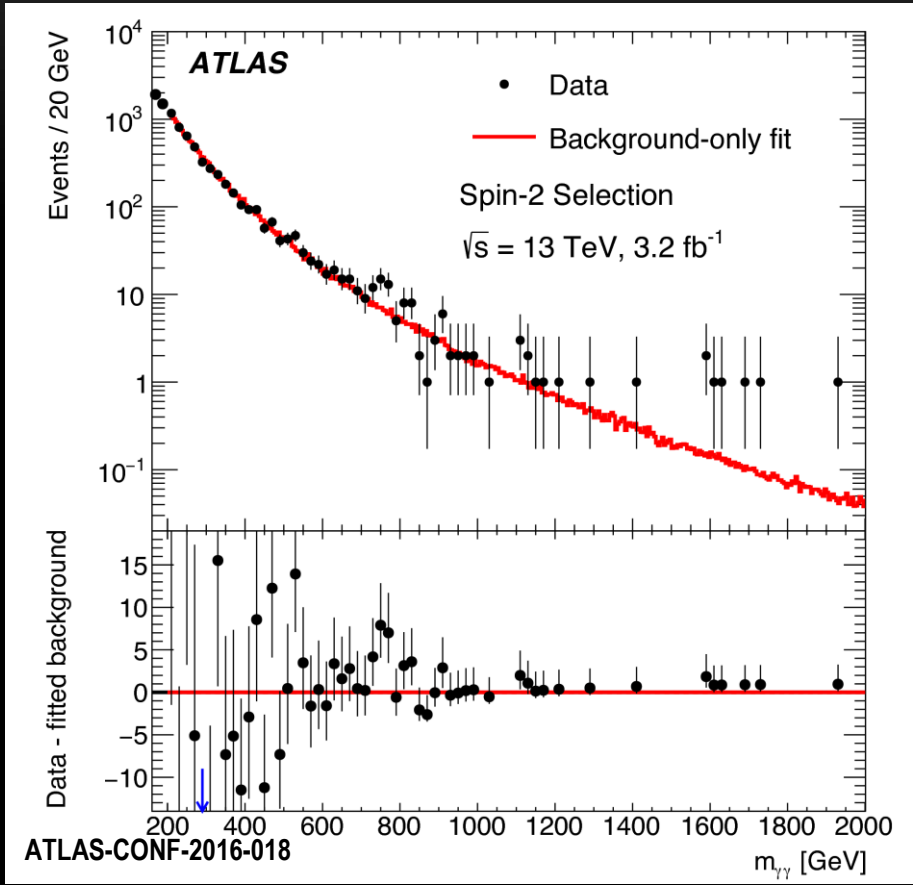
PURITY OF THE SELECTED DI-PHOTON SAMPLE

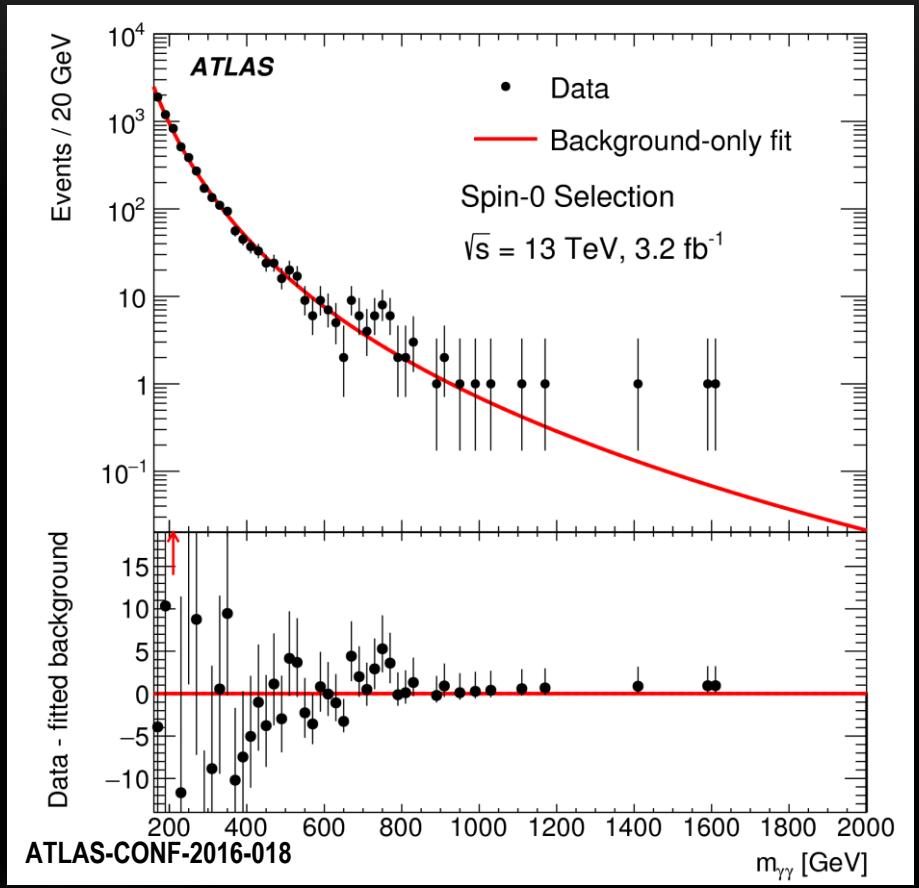
- Purity of data was checked with two different techniques using independent assumptions
  - 4x4 matrix method
  - 2x2D sidebands method
  - Purity is > 90% over the whole mass spectrum for both selections





DI-PHOTON CANDIDATES INVARIANT MASS IN DATA, 3.2 FB^{-1}, √S = 13 TEV





STATISTIC ANALYSIS

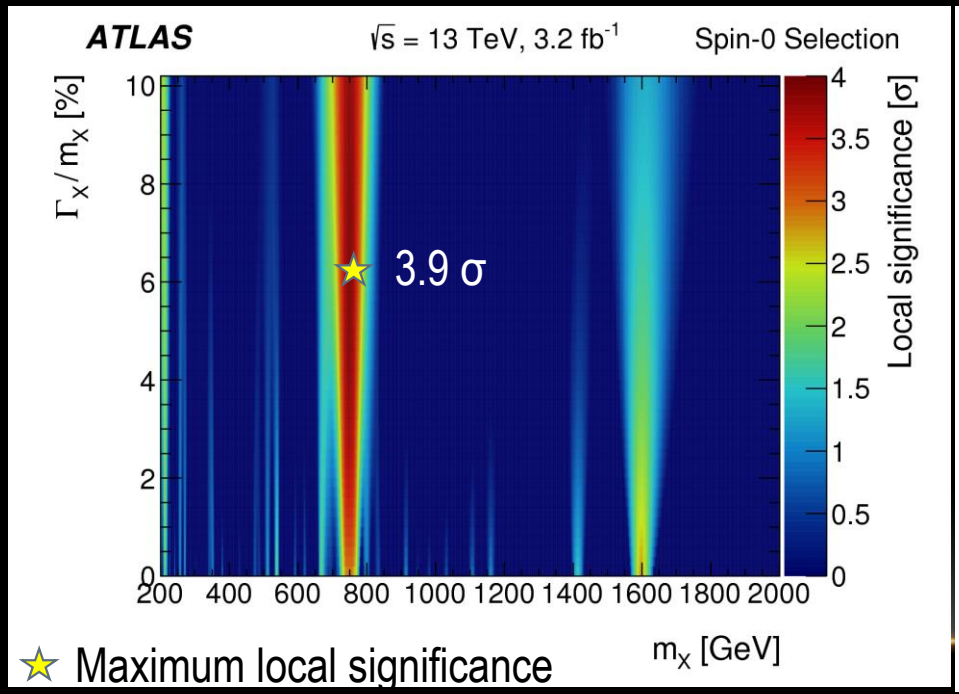
- Test of the compatibility of the data with the background only hypothesis
  - Using frequentist techniques and profile likelihood ratio for μ (signal) ≥ 0
  - Test each [mass, width] to find maximum local significance
- Maximum local significance around 750 GeV
  - k/M_{pl} = 0.23 (for spin 2) corresponding to Γ = 57 GeV
  - Γ = 45 GeV (for spin 0)

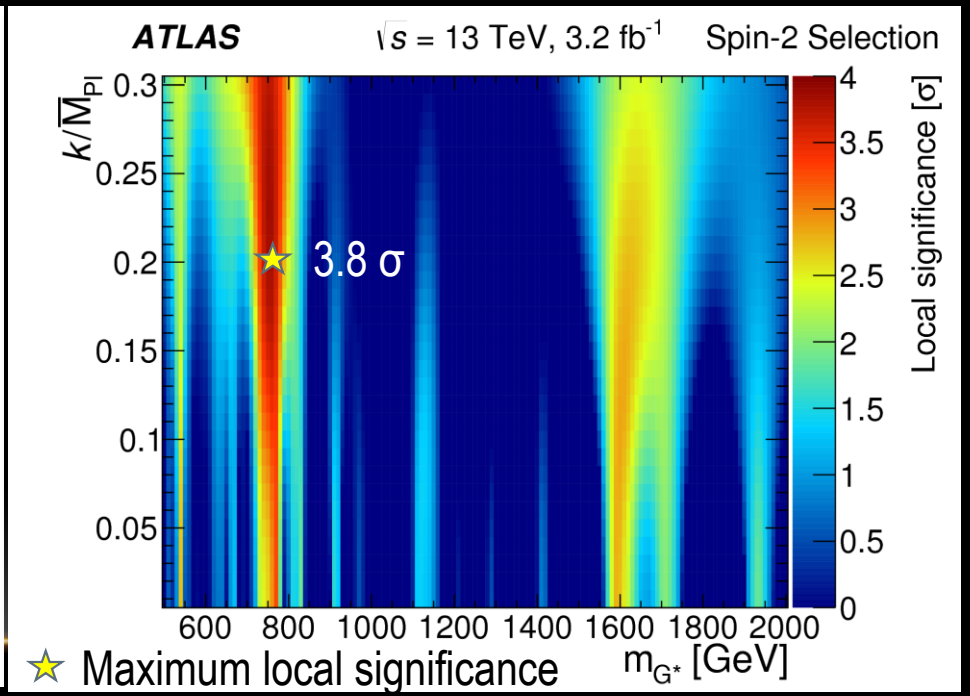
Updated

Signal + background model

$$N_S f_S(m_{\gamma\gamma}) + N_B f_B(m_{\gamma\gamma}),$$

ATLAS-CONF-2016-018





LOCAL AND GLOBAL SIGNIFICANCE

- Local significance is not sufficient need to evaluate the «look elsewhere effect»
  → Global significance
  - Searched in a large bidimensional phase space for (M_X, Γ_X)
  - To evaluate this effect background-only MC toys were used
- Evaluated in the range M_G [500, 2000] GeV and k/M_{pl} [0.01, 0.3] for spin 2
- Evaluated in the range M_H [500, 2000] GeV and Γ [0%, 10%] for spin 0
- For the excess at 750 GeV **global significance** is
  - **Spin 2 selection: 2.1 σ**
  - **Spin 0 selection: 2.1 σ**
  - Statistical uncertainty from the number of pseudo-experiments is ±0.05

Updated

- Compatibility between the two analyses is assessed with a bootstrap statistical procedure to generate pseudo-datasets
  - If spin-2 (spin-0) signal is assumed compatibility is 0.5 (0.2) σ

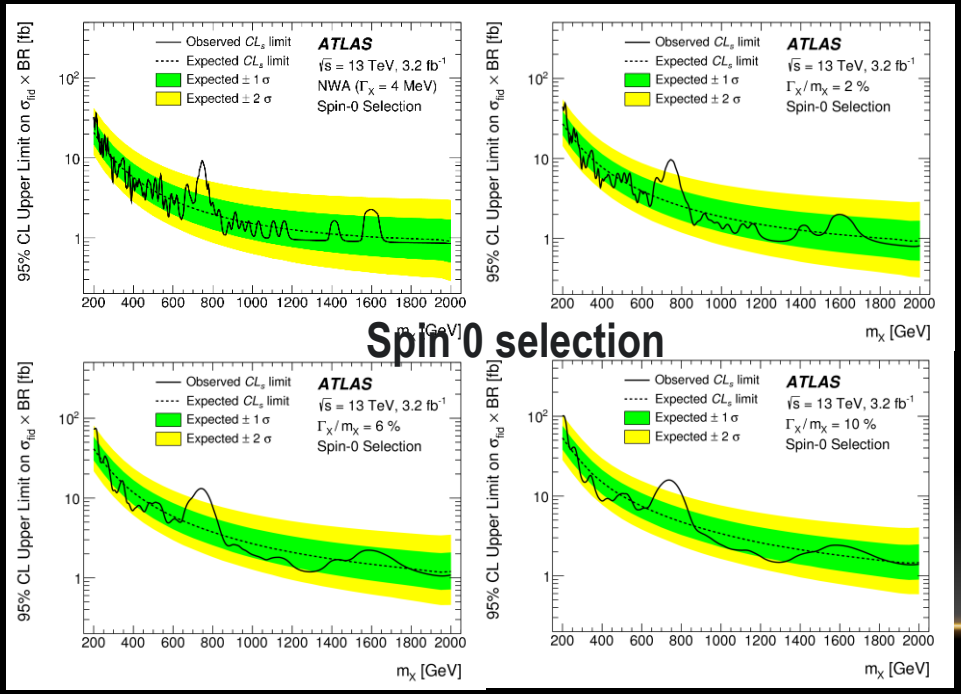
- **Assuming zero-width** spin 0 signal (NWA) a local significance of **2.9 σ** is found
  - **Difference** in likelihood ratio from best fit (with highest significance) is **2.5 σ**

New!

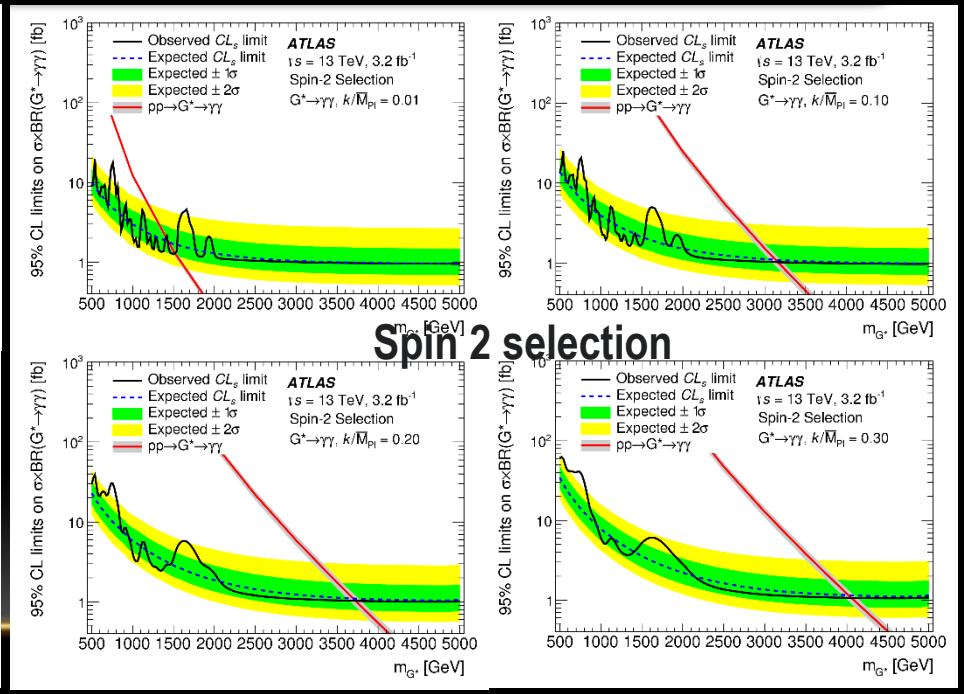
LIMITS SETTING

- For spin-0 limits are in terms of the fiducial cross section (nearly model-independent)
- For spin-2 a specific benchmark model of a spin-2 graviton
  - Observed limit is compared with theory prediction (red line)
  - Graviton with $k/M_{pl} = 0.2$ excluded for $M_G < 4$ TeV
- Observed limits are within expected limits error bands (except for 750 GeV)

New!



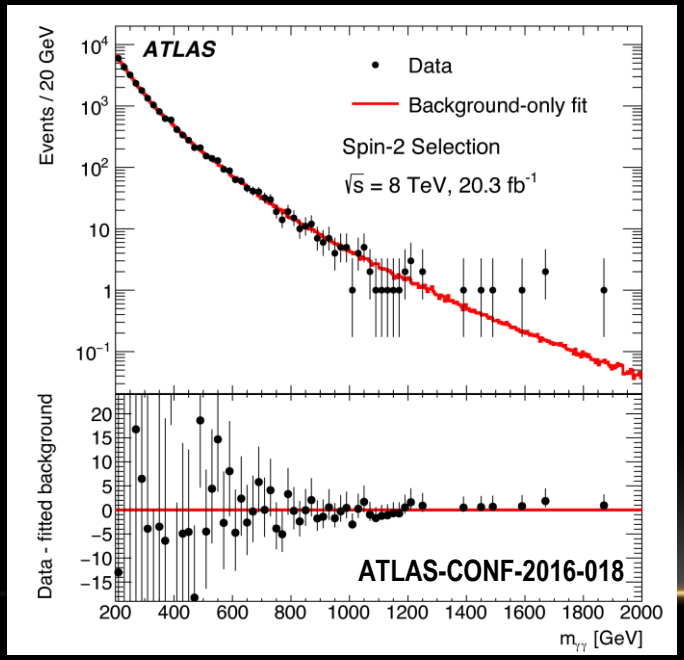
Spin 0 selection

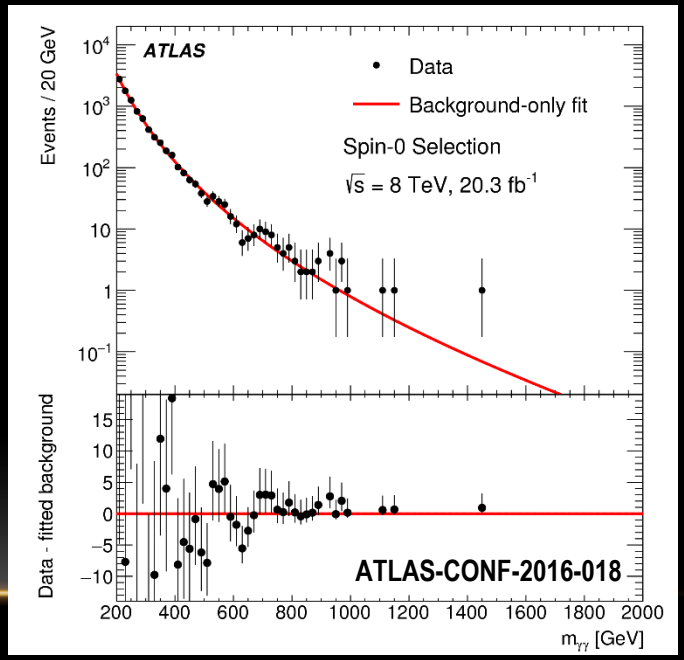


Spin 2 selection

What about run1?

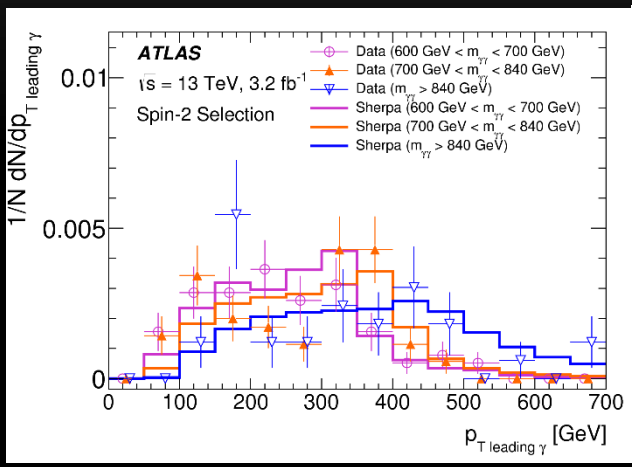
- **8 TeV data re-analysis**
- Same kinematic selection as before, update of calibration and systematics
- For spin 2 selection no significant excess is observed
- For spin 0 selection there is 2 σ significance at 750 GeV
- Increase in the cross section (for 750 GeV): 4.7 (gluon, gluon), 2.7 (q, q)
  - Spin 2 compatibility run I-II: Gluon gluon production: 2.7 σ, qq production 3.3 σ
  - Spin 0 compatibility run I-II: Gluon gluon production: 1.2 σ, qq production 2.1 σ

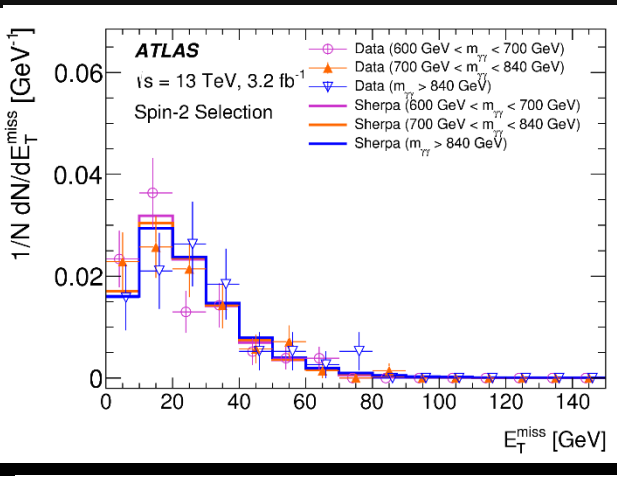


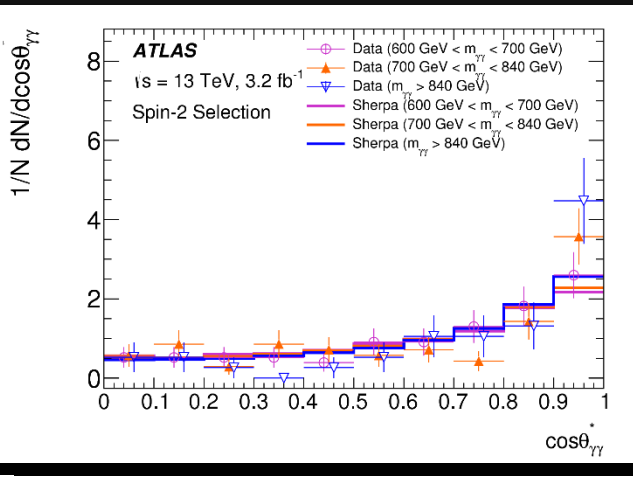


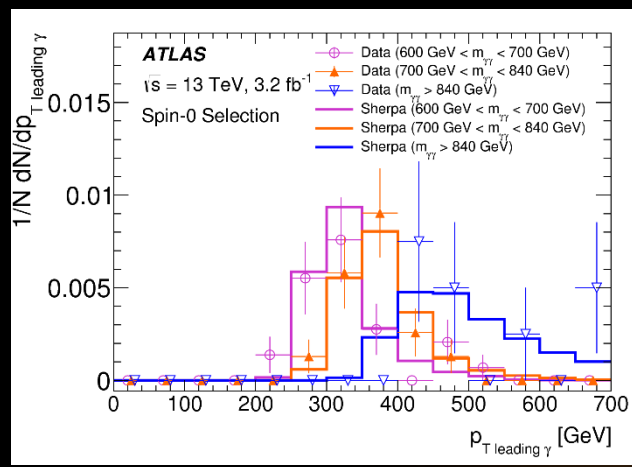
KINEMATIC PROPRIETIES OF THE EXCESS REGION

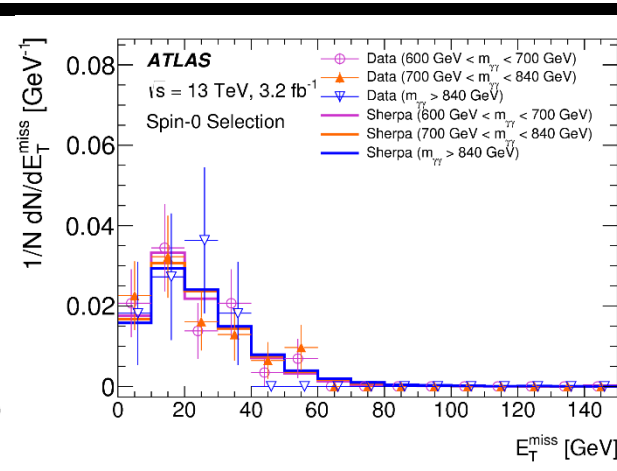
FULL COLLECTION OF PLOTS IN THE PAPER (OR IN BACKUP)

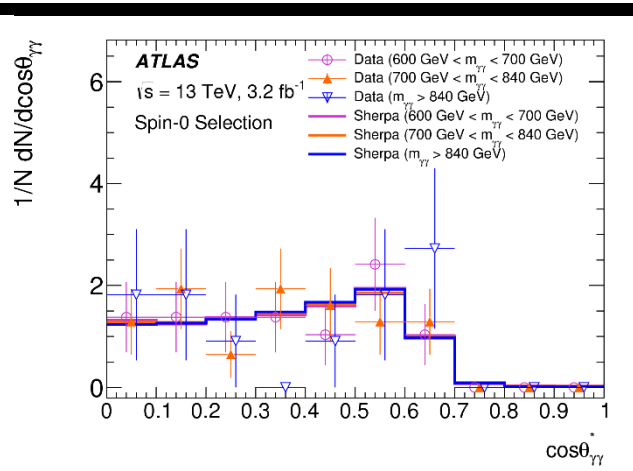












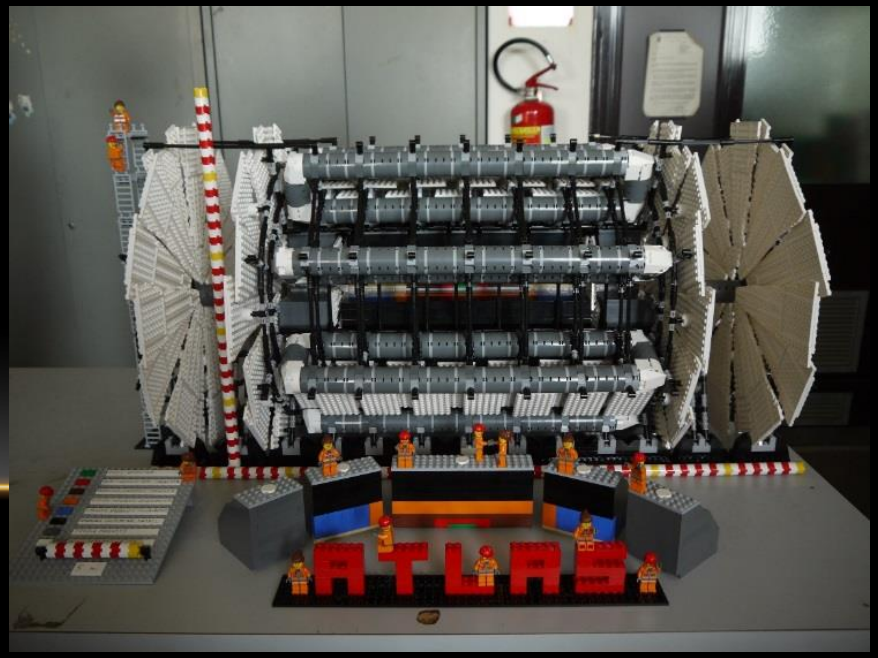
NEW EXCITING RESULTS?!

- Result for $\sqrt{s}$ = 3.2 fb^{-1} of the 2015 data campaign was reviewed
  - Plots and results are public, paper will be submitted soon!
  - Preliminary results already presented December 2015

- An interesting feature was found in the di-photon channel for an invariant mass of 750 GeV
  - Several cross checks were done (both on detector level and on kinematic level)
  - No strange behavior seen yet

- To study the nature of the feature we are looking at new data
  - An updated result with 2016 data will be released soon
  - Stay tuned!

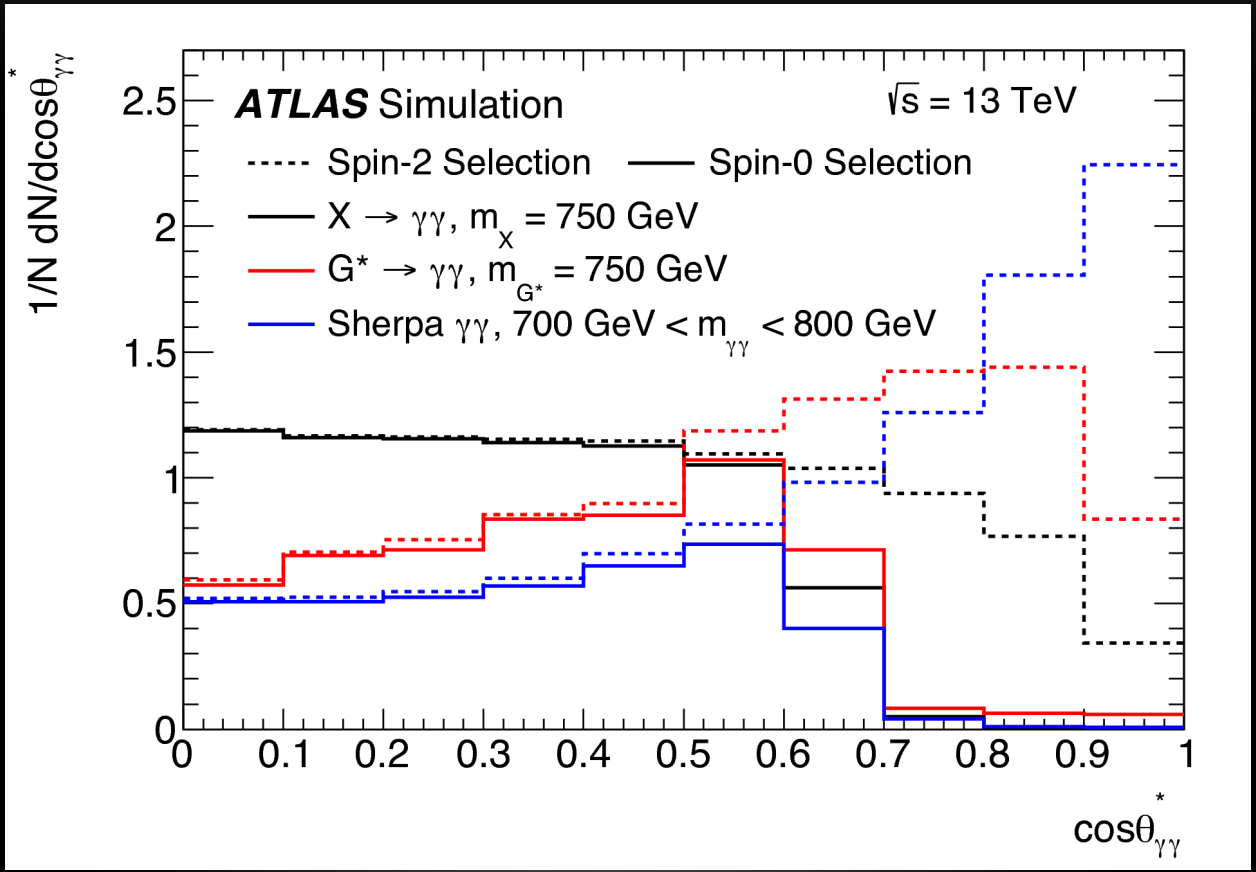
	Spin-2 Selection		Spin-0 Selection	
	Free width	Narrow width	Free width	Narrow width
	13 TeV			
Mass for the largest excess	750 GeV	770 GeV	750 GeV	750 GeV
Width over mass for the largest excess	8%	-	6%	-
Local significance	3.8	3.3	3.9	2.9
Global significance	2.1		2.1	
	8 TeV			
Local significance (at 13 TeV best-fit)	-		1.9	
	8 TeV - 13 TeV Compatibility			
gluon-gluon scaling (4.7)	2.7	2.2	1.2	1.5
quark-antiquark scaling (2.7)	3.3	2.4	2.1	2.0

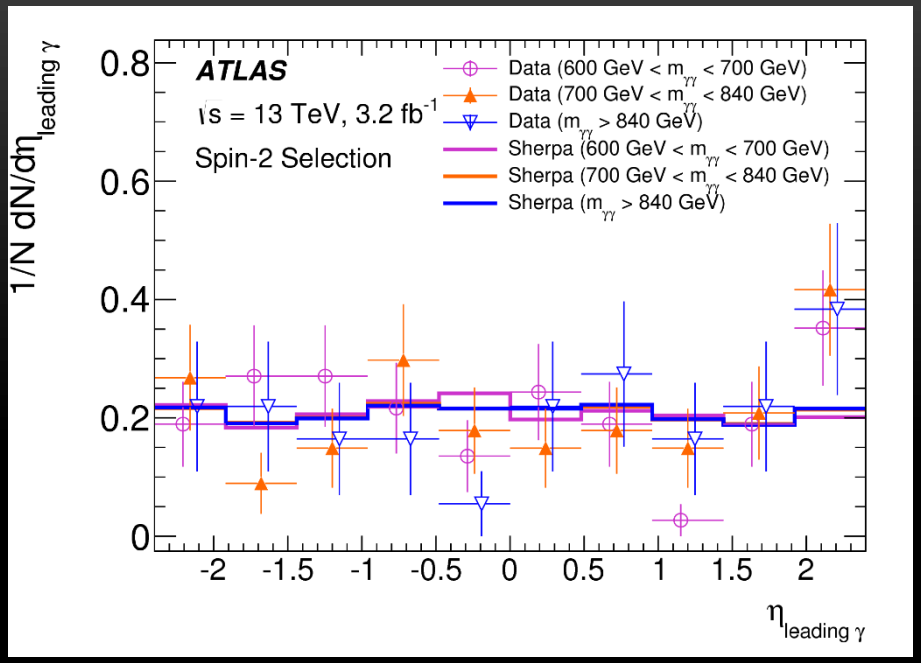


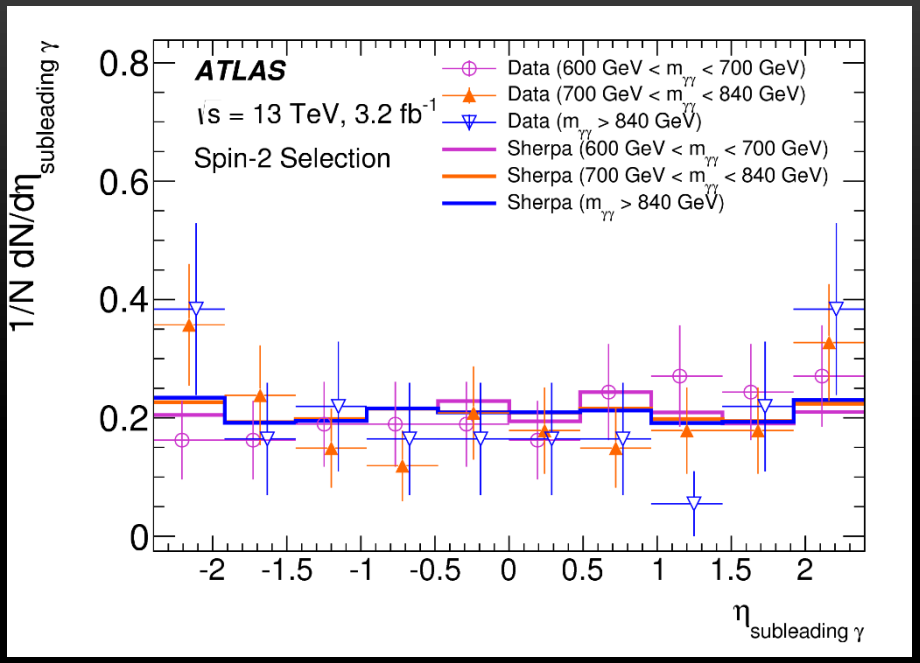
BACKUPS

RELATIVE CUTS EFFECT

Analysis	σ local	σ global	8 TeV compatibility
Scalar	3.9 σ	2 σ	1.2 σ (gg) – 2.1 σ (qq)
Graviton	3.8 σ	2.1 σ	2.7 σ (gg) – 3.3 σ (qq)




ATLAS
√s = 13 TeV, 3.2 fb-1
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/dηleading γ
ηleading γ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√s = 13 TeV, 3.2 fb-1
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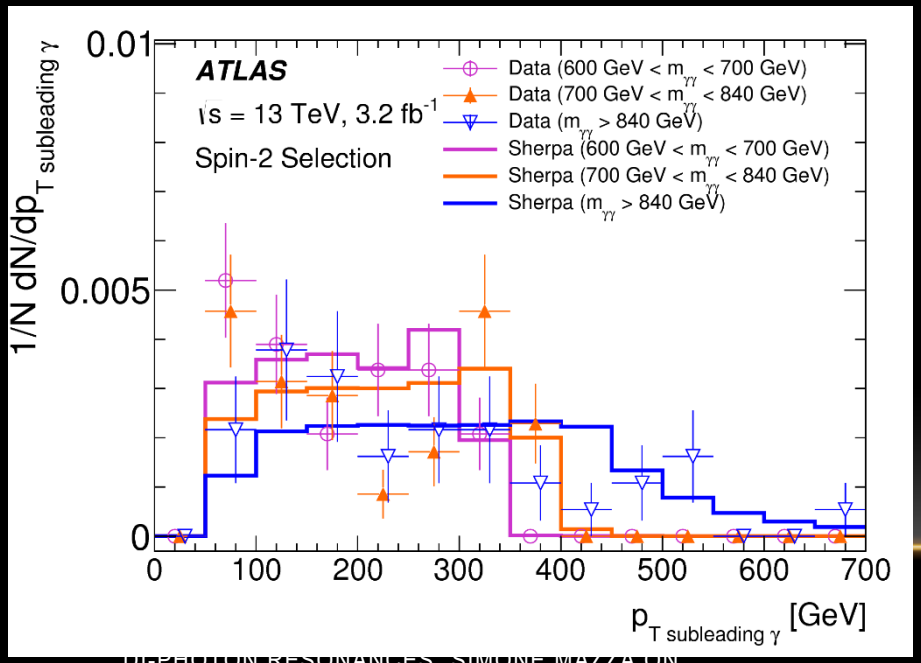
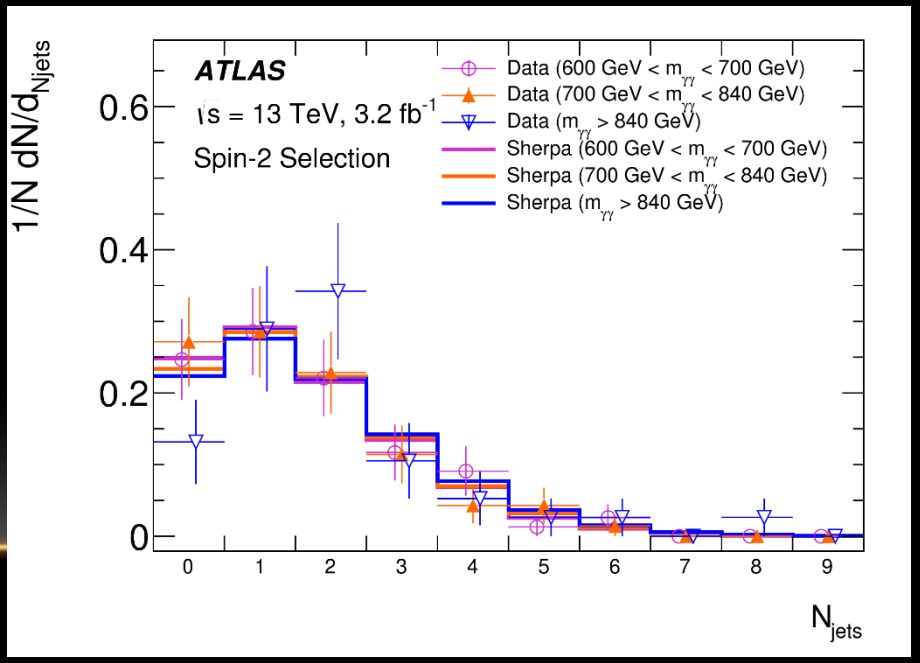
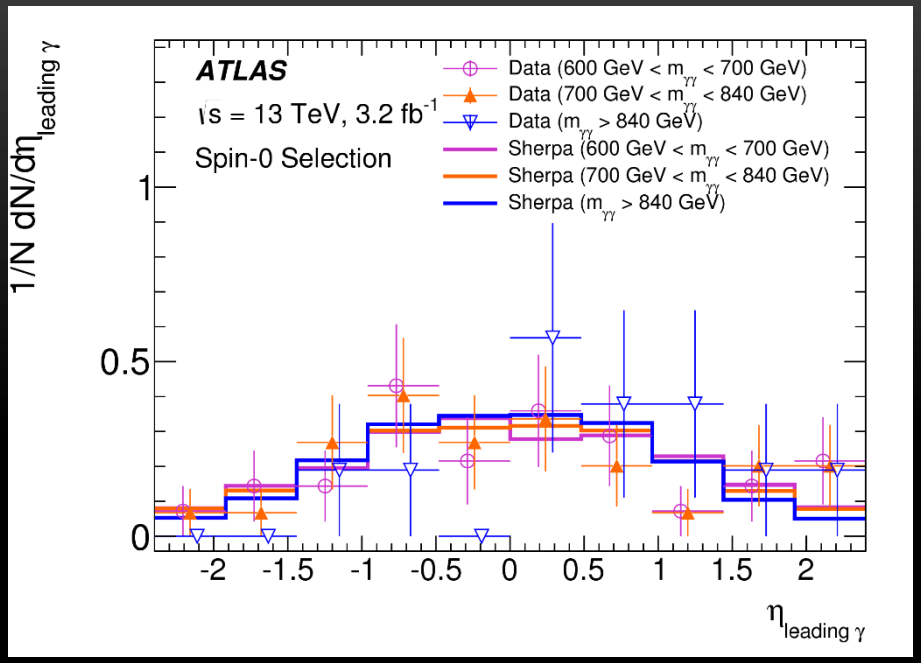
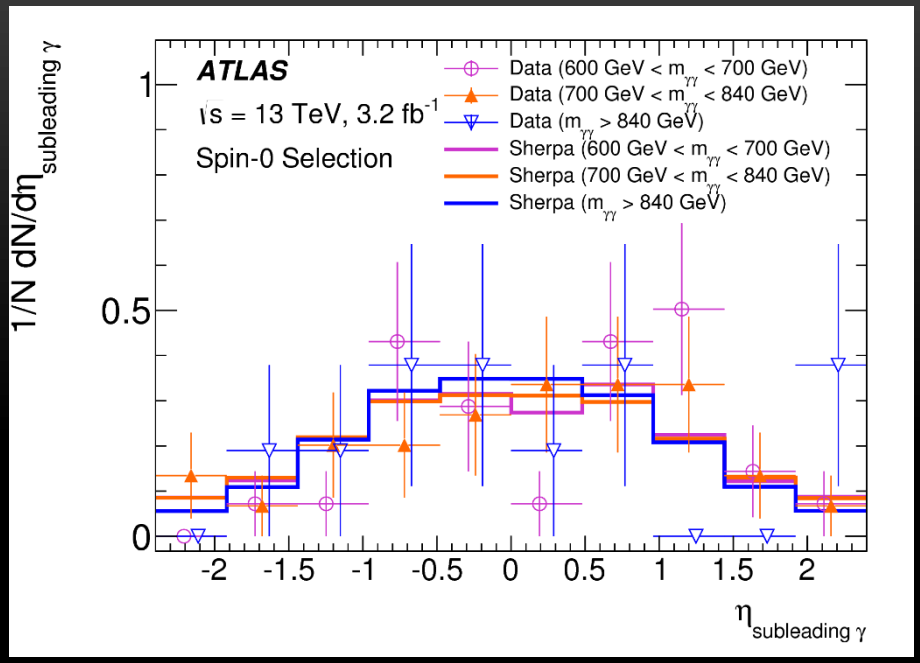
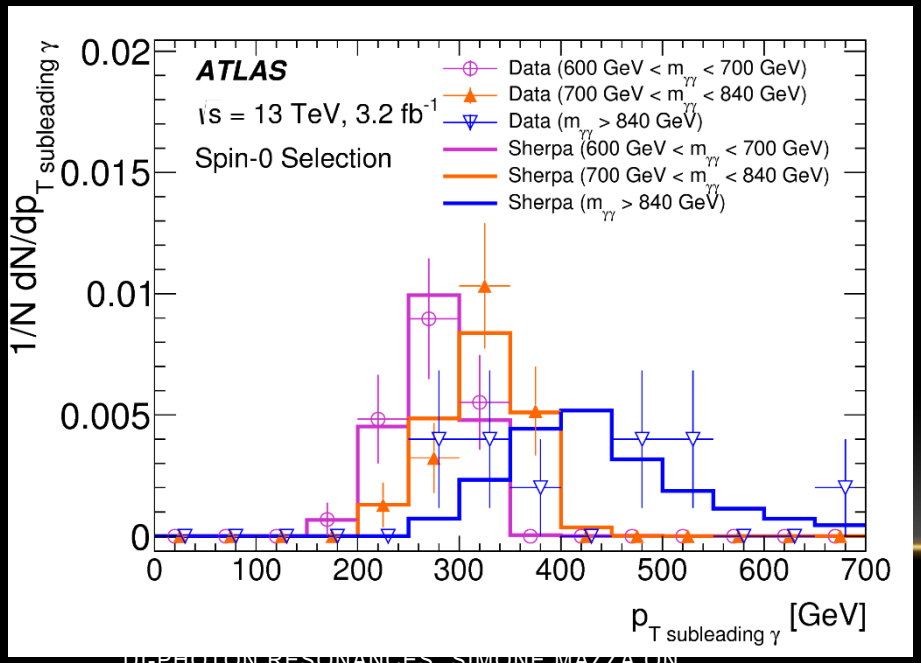
Data (mγγ > 840 GeV)
Sherpa (600 GeV < mγγ < 700 GeV)
Sherpa (700 GeV < mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dηsubleading γ
ηsubleading γ

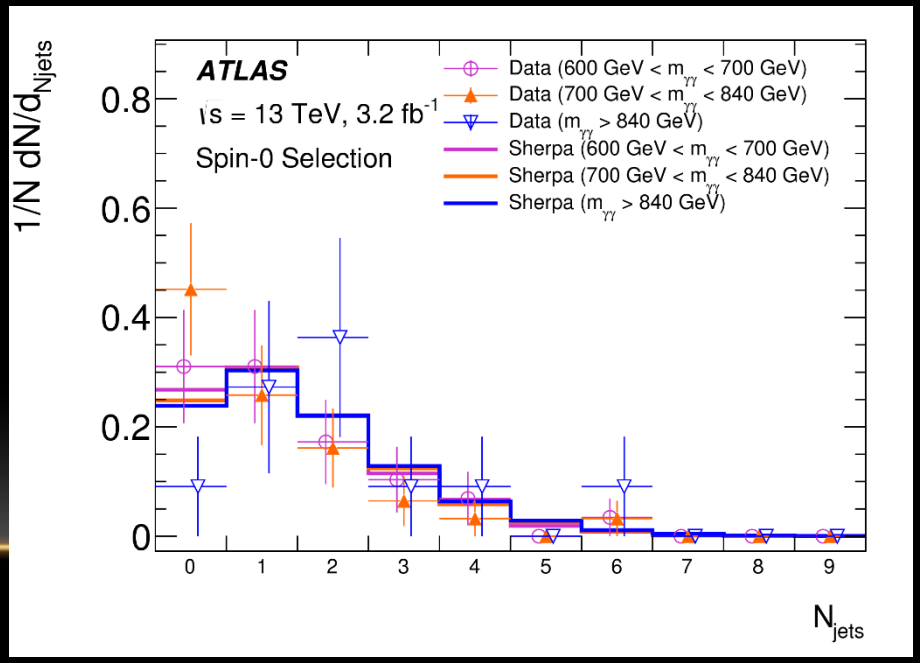

ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-2 Selection
Data (600 GeV < mγγ < 700 GeV)
Data (700 GeV < mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV < mγγ < 700 GeV)
Sherpa (700 GeV < mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dpT subleading γ
pT subleading γ [GeV]

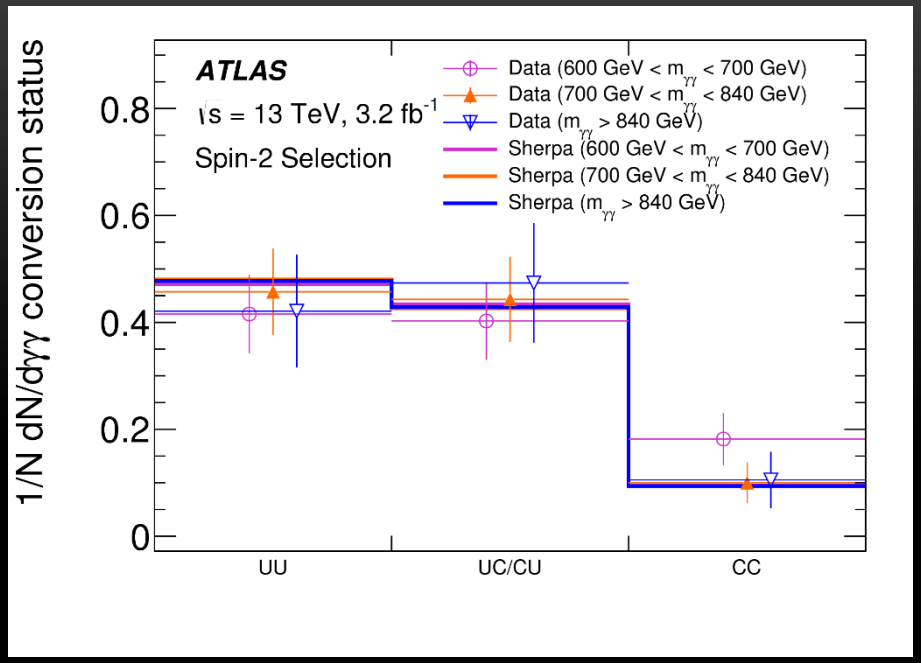

ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-2 Selection
Data (600 GeV < mγγ < 700 GeV)
Data (700 GeV < mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV < mγγ < 700 GeV)
Sherpa (700 GeV < mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dNjets
Njets

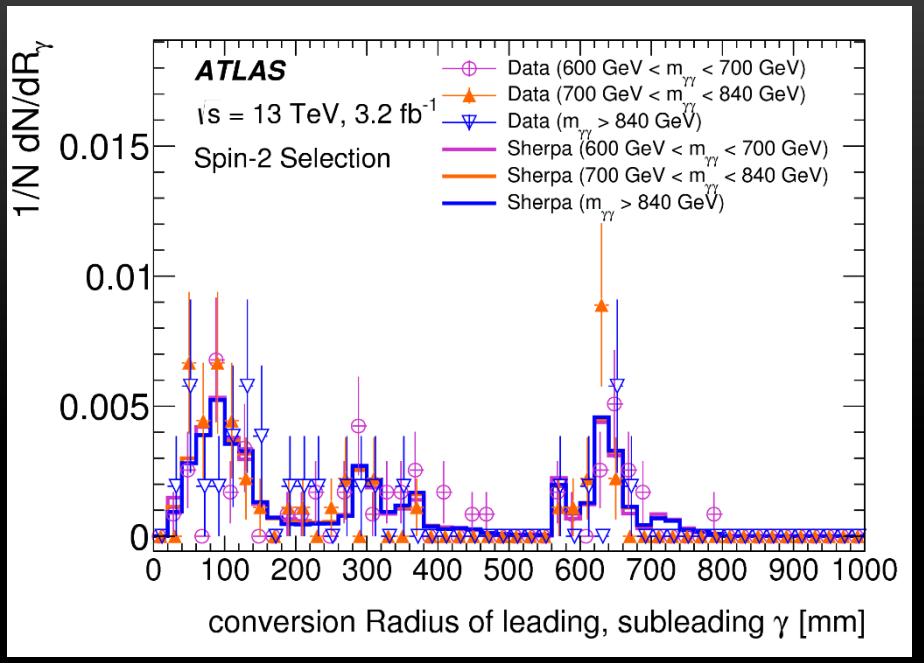

ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-0 Selection
Data (600 GeV < mγγ < 700 GeV)
Data (700 GeV < mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV < mγγ < 700 GeV)
Sherpa (700 GeV < mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dηleading γ
ηleading γ

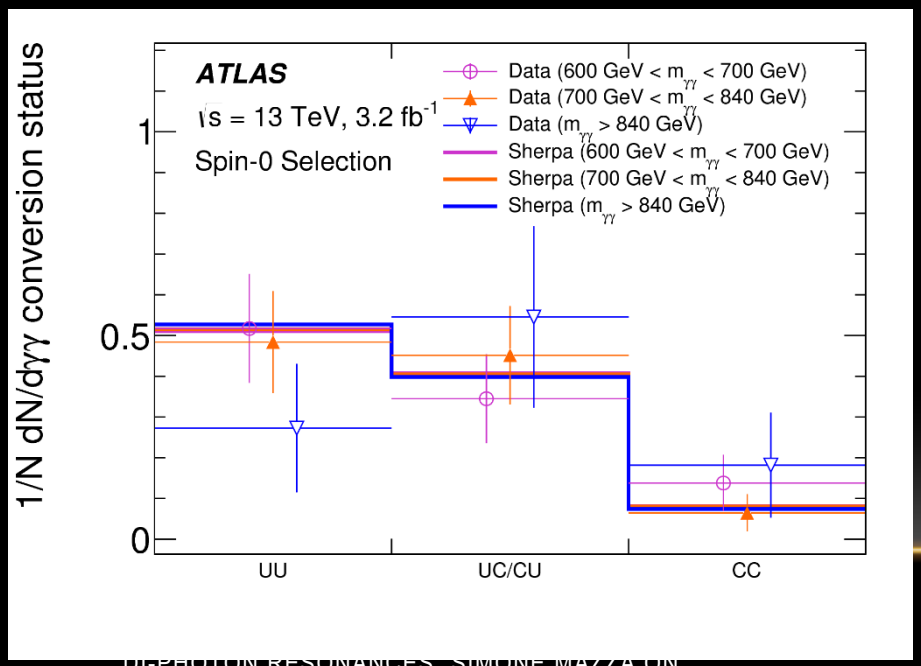

ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-0 Selection
Data (600 GeV < mγγ < 700 GeV)
Data (700 GeV < mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV < mγγ < 700 GeV)
Sherpa (700 GeV < mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dηsubleading γ
ηsubleading γ

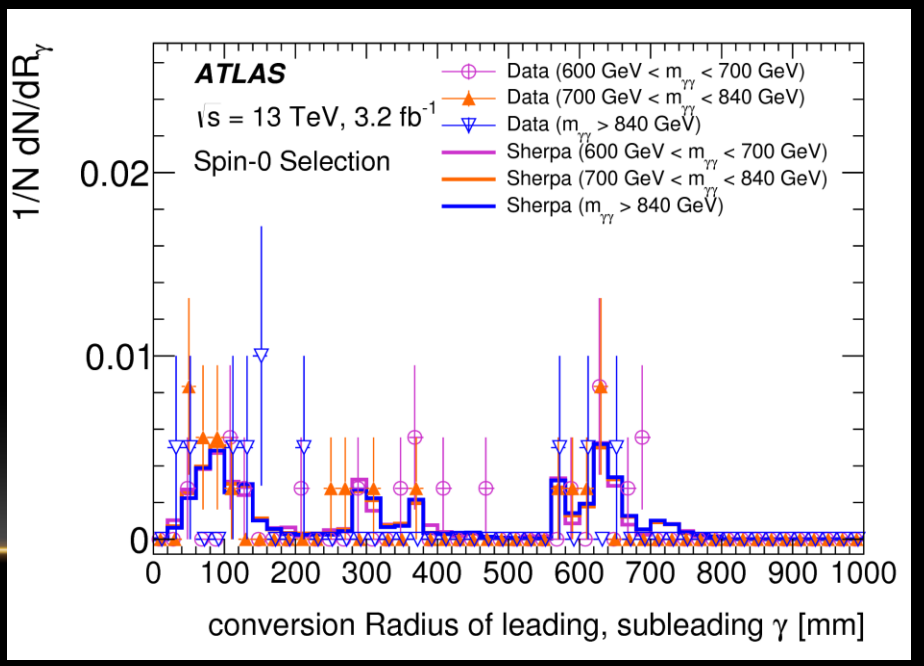

ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-0 Selection
Data (600 GeV < mγγ < 700 GeV)
Data (700 GeV < mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV < mγγ < 700 GeV)
Sherpa (700 GeV < mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dpT subleading γ
pT subleading γ [GeV]

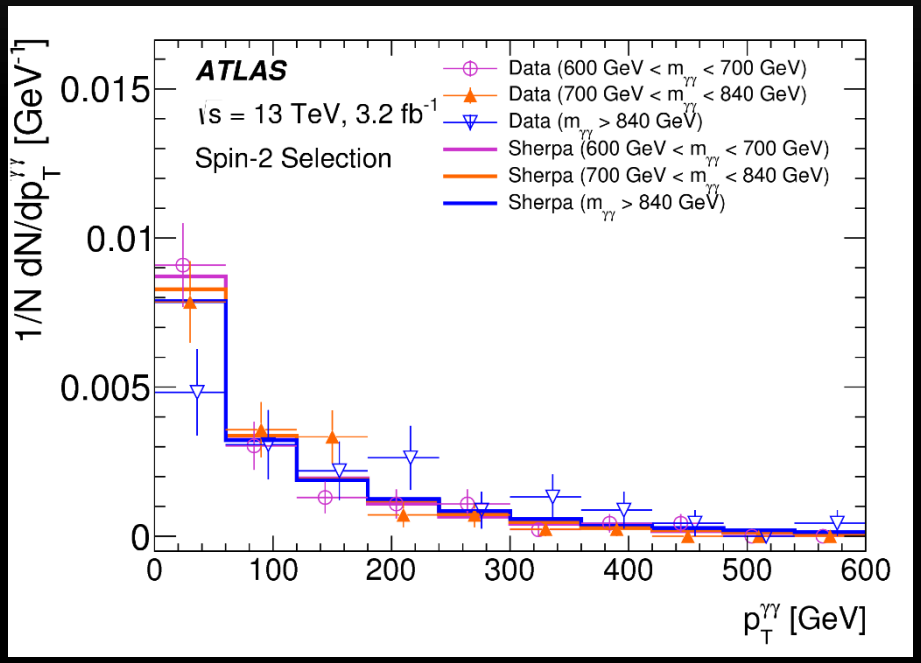

ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-0 Selection
Data (600 GeV < mγγ < 700 GeV)
Data (700 GeV < mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV < mγγ < 700 GeV)
Sherpa (700 GeV < mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dNjets
Njets

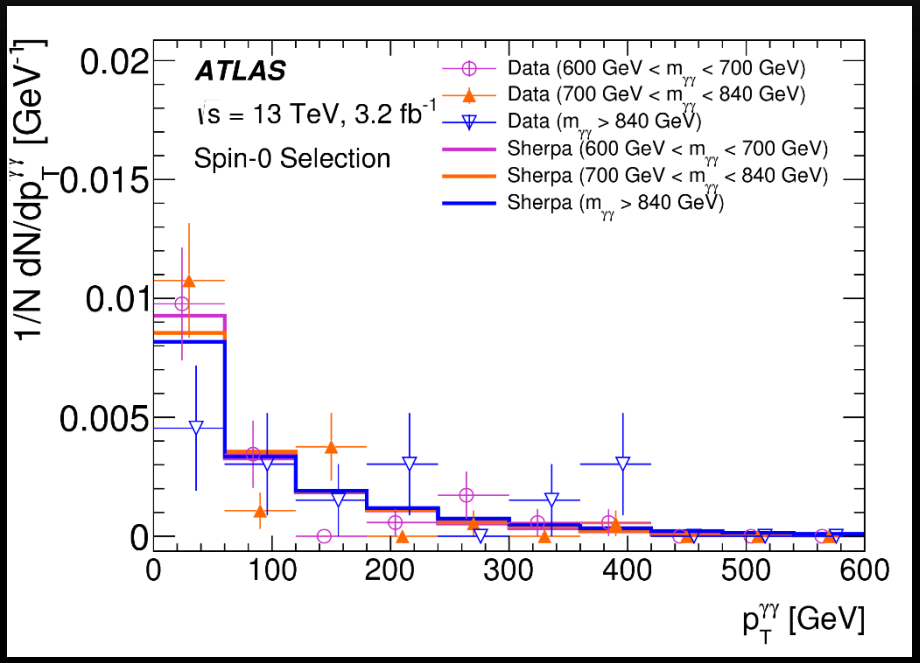

ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-2 Selection
Data (600 GeV < mγγ < 700 GeV)
Data (700 GeV < mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV < mγγ < 700 GeV)
Sherpa (700 GeV < mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dγγ conversion status
0
0.2
0.4
0.6
0.8
UU
UC/CU
CC


ATLAS
√s = 13 TeV, 3.2 fb-1
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/dRγ
0
0.005
0.01
0.015
0 100 200 300 400 500 600 700 800 900 1000
conversion Radius of leading, subleading γ [mm]


ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-0 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/dγγ conversion status
0
0.5
1
UU
UC/CU
CC


ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-0 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/dRγ
0
0.01
0.02
0 100 200 300 400 500 600 700 800 900 1000
conversion Radius of leading, subleading γ [mm]


ATLAS
√s = 13 TeV, 3.2 fb-1
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/dpTγγ [GeV-1]
pTγγ [GeV]
0
0.005
0.01
0.015
0
100
200
300
400
500
600


ATLAS
√s = 13 TeV, 3.2 fb-1
Spin-0 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/dpTγγ [GeV-1]
pTγγ [GeV]
0
0.005
0.01
0.015
0.02
0
100
200
300
400
500
600

BACKGROUND PARAMETERIZATION (SPIN 0)

- Function fit on data

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

- To choose the number of free parameters: F-Test
  - k = 0 was chosen for spin 0 selection

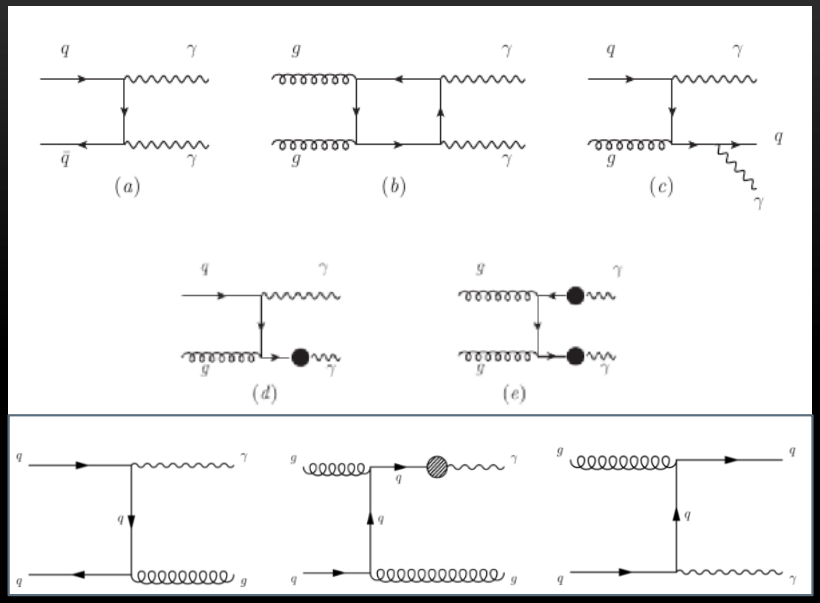
$$F = \frac{\dfrac{\sum_i (y_i - f_1(x_i))^2 - \sum_i (y_i - f_2(x_i))^2}{p_2 - p_1}}{\dfrac{\sum_i (y_i - f_2(x_i))^2}{n - p_2}}$$

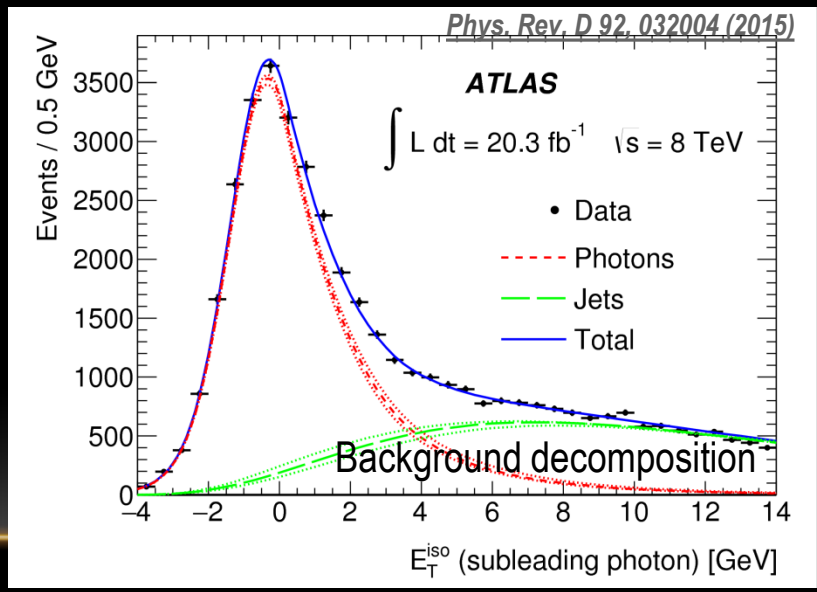
BKG PARAMETERIZATION

- Background composed by reducible (gamma-jet, di-jet) and irreducible (gamma gamma from SM)

- Irreducible shape is derived form a MC at LO (Sherpa fullsim) re-weighted with NLO corrections (diphox)
- Reducible shape is derived with a fin on data inverting ID criteria (ex: tight – antitight for gamma-jet)

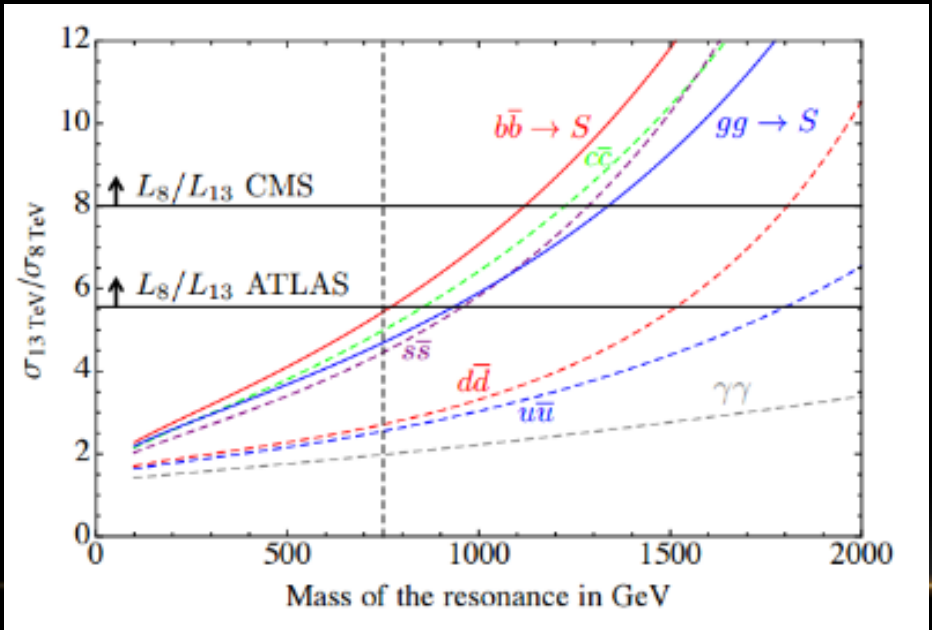
- Composition of the four components (γγ, γ-jet, jet-γ, jet-jet) is estimated with a data driven method
  - Isolation template fit
  - Studyu of the isolation variable shape in a low mass control region [200,500] GeV
- Total normalization of the background is fitted from data





What about run1?

- **8 TeV data re-analysis**
- Same kinematic selection as before, update of calibration and systematics
- For spin 2 selection no significant eccess is observed
- For spin 0 selection there is 2 σ significance at 750 GeV
- Increase in the cross section: 4.7 (gluon, gluon), 2.7 (q, q)
  - Spin 2 compatibility run I-II: Gluon gluon production: 2.7 σ, qq production 3.3 σ
  - Spin 0 compatibility run I-II: Gluon gluon production: 1.2 σ, qq production 2.1 σ



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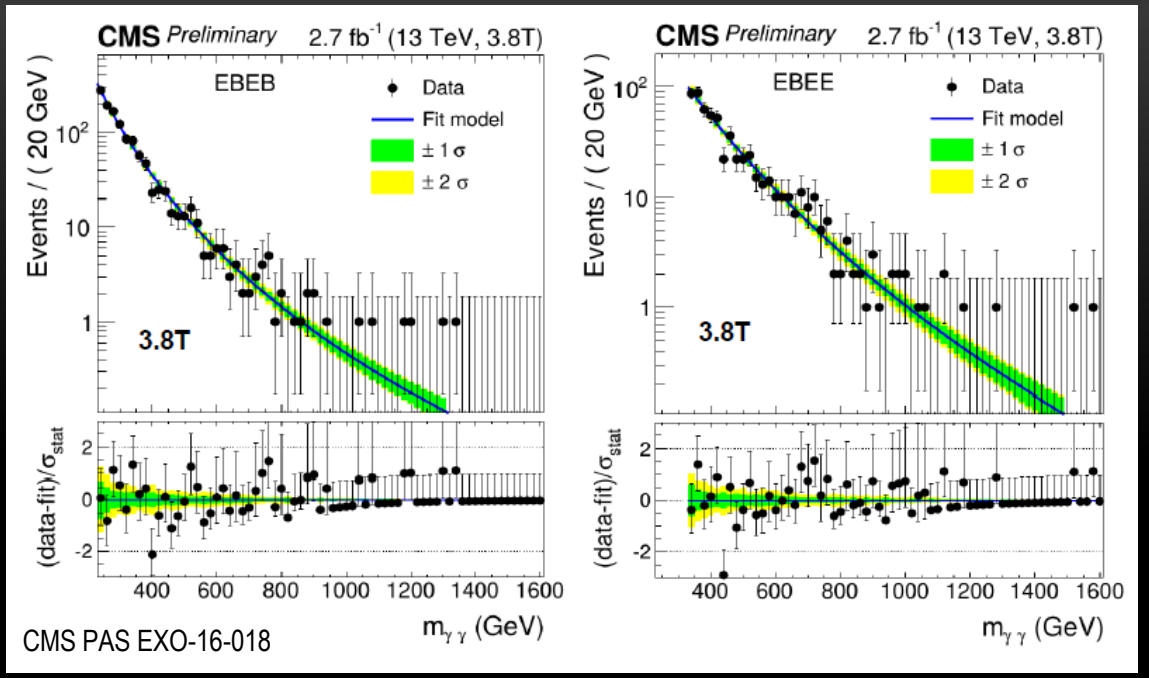
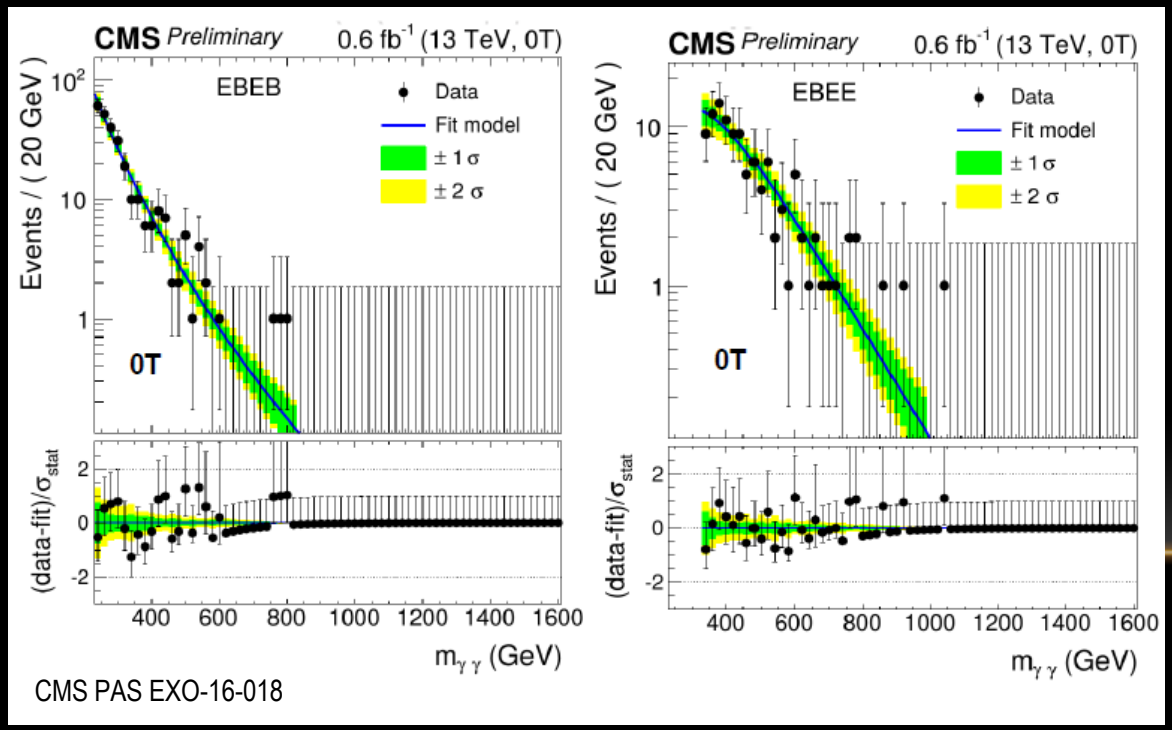


CMS PAS EXO-16-018



CMS PAS EXO-16-018