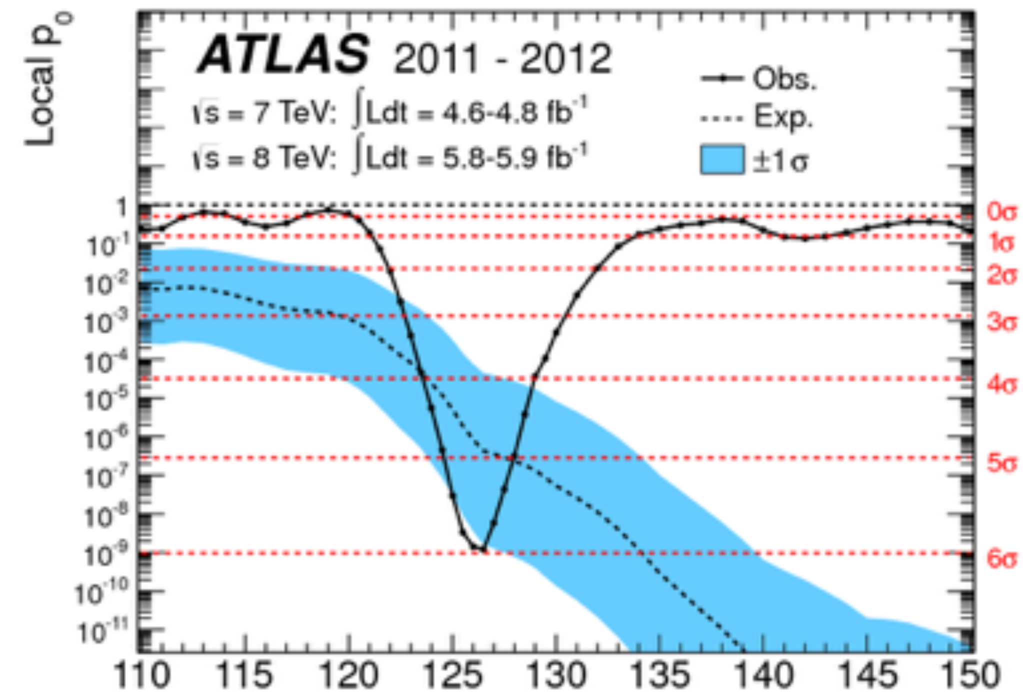
Search for new physics through $\gamma\gamma$ channel in ATLAS

Yee Chinn Yap (LPNHE, Paris), on behalf of the ATLAS Collaboration

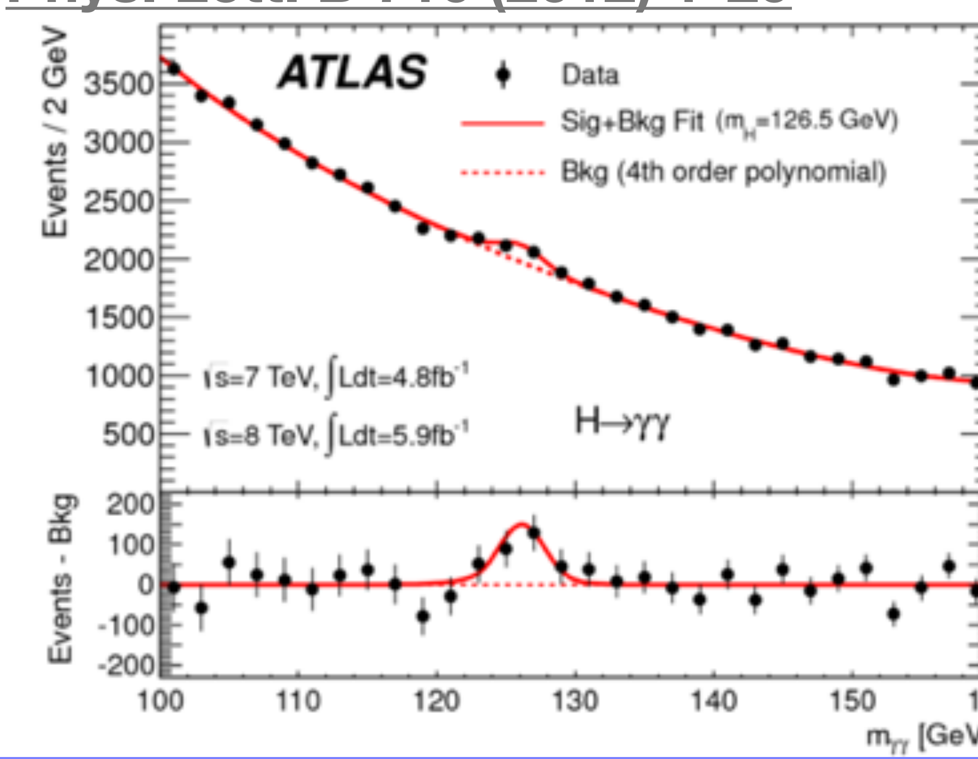
LHC Days in Split, 20th September 2016

Higgs discovery

- γγ channel played a significant role in the discovery of 125 GeV Higgs boson in 2012 despite its low branching ratio.
- Excellent mass resolution → further discovery potential.
- Will present 2 BSM searches using γγ.



[Phys. Lett. B 716 (2012) 1-29]

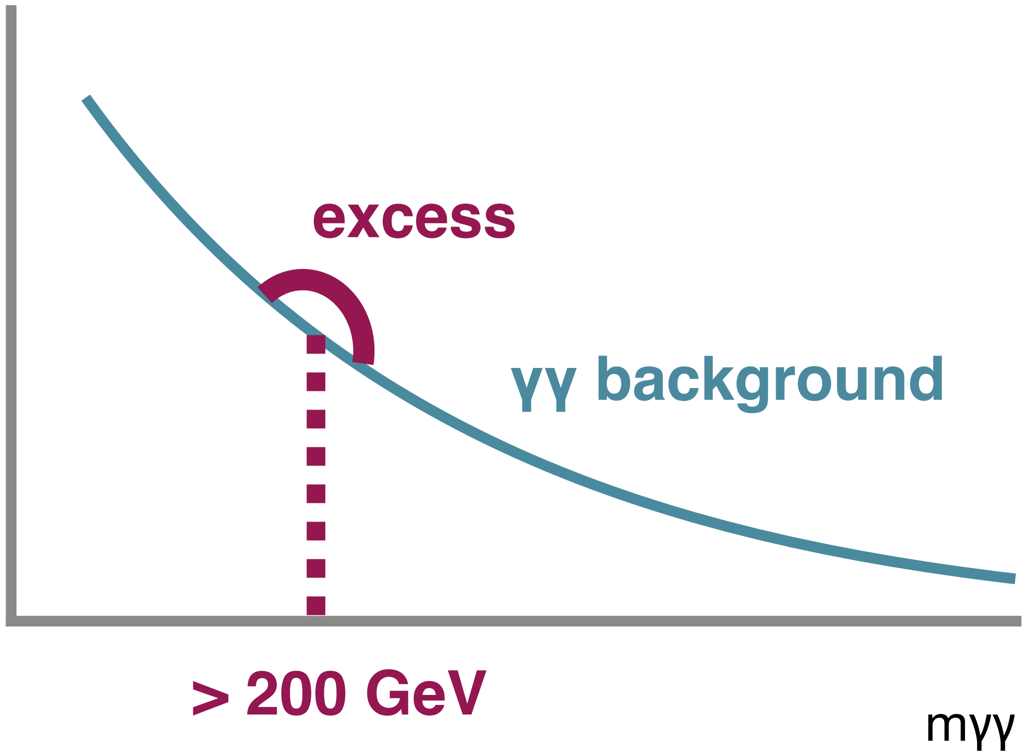


Extensions from $H \rightarrow \gamma\gamma$ search

- **High mass γγ resonance**
  - Analogous to SM Higgs search but at higher invariant mass.
  - Clean signal of two high p_T photon candidates that manifests as local excess in the diphoton mass spectrum over smooth background.
  - Predicted by extension of Higgs sector as well as extra dimensions.
  - 2015+partial 2016 dataset (15.4 fb^{-1}): ATLAS-CONF-2016-059

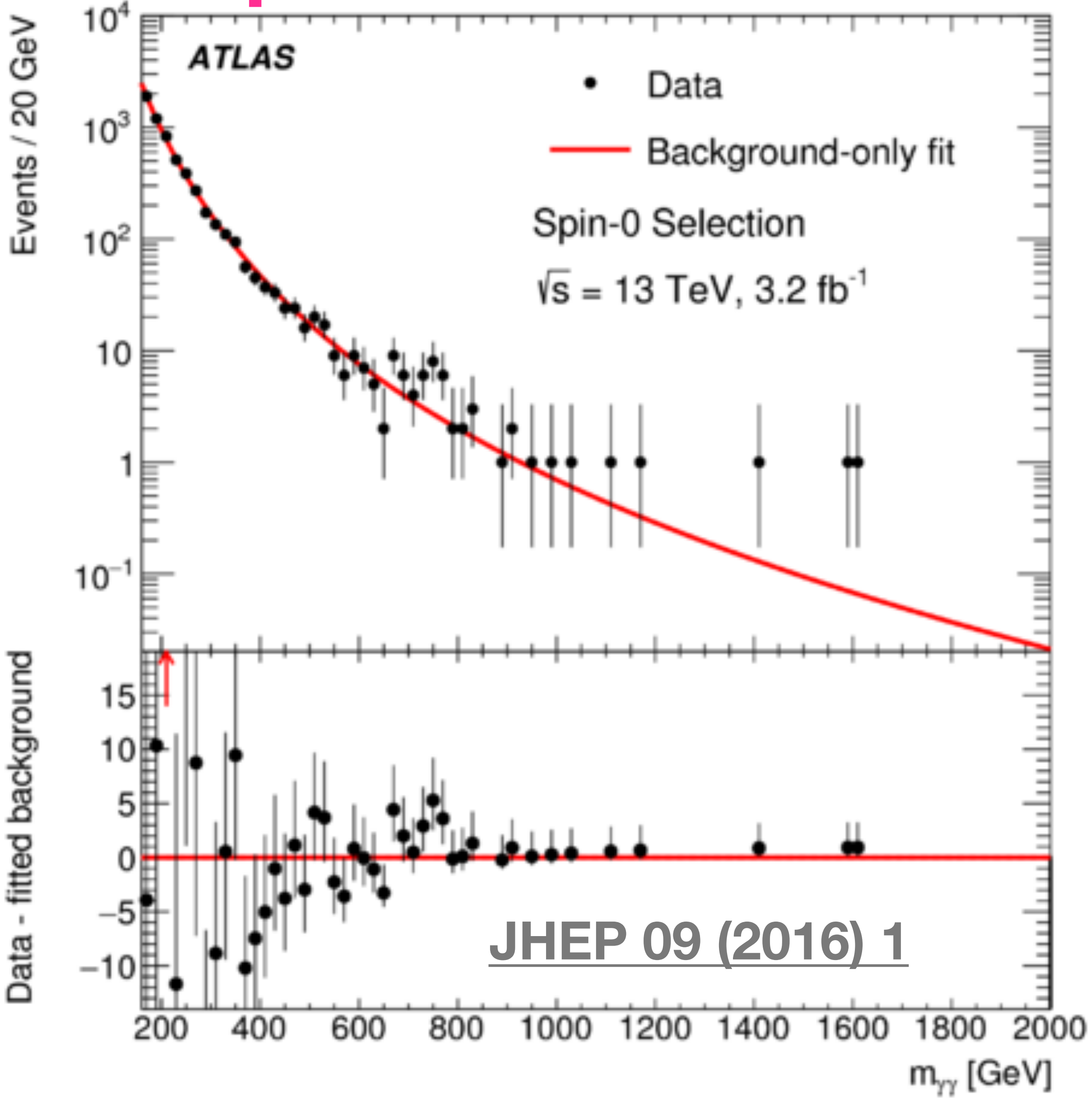
- **$h \rightarrow \gamma\gamma$ in association with missing transverse energy (E_T^{miss})**
  - Similar strategy to SM Higgs search but with requirement on E_T^{miss}.
  - Clean signal as a bump around 125 GeV over smooth background, on top of SM Higgs.
  - Dark matter (DM): Massive vector mediator emitting a Higgs boson and decaying into a pair of DM candidates. Heavy scalar decays into a Higgs and a pair or DM candidates.
  - 2015+partial 2016 dataset (13.3 fb^{-1}): ATLAS-CONF-2016-087

High mass γγ

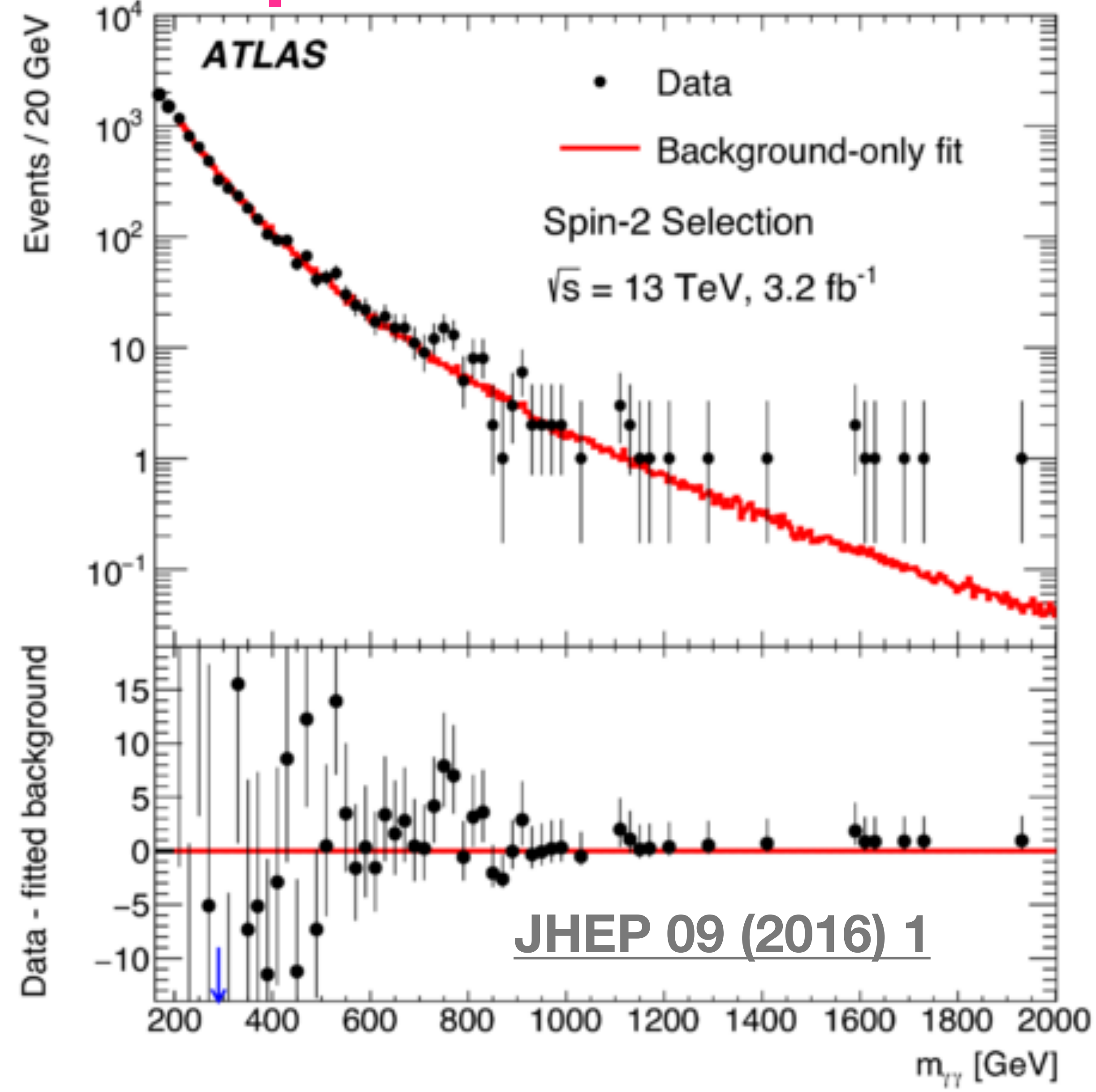


High mass γγ: Published results on 2015 data

spin-0 selection



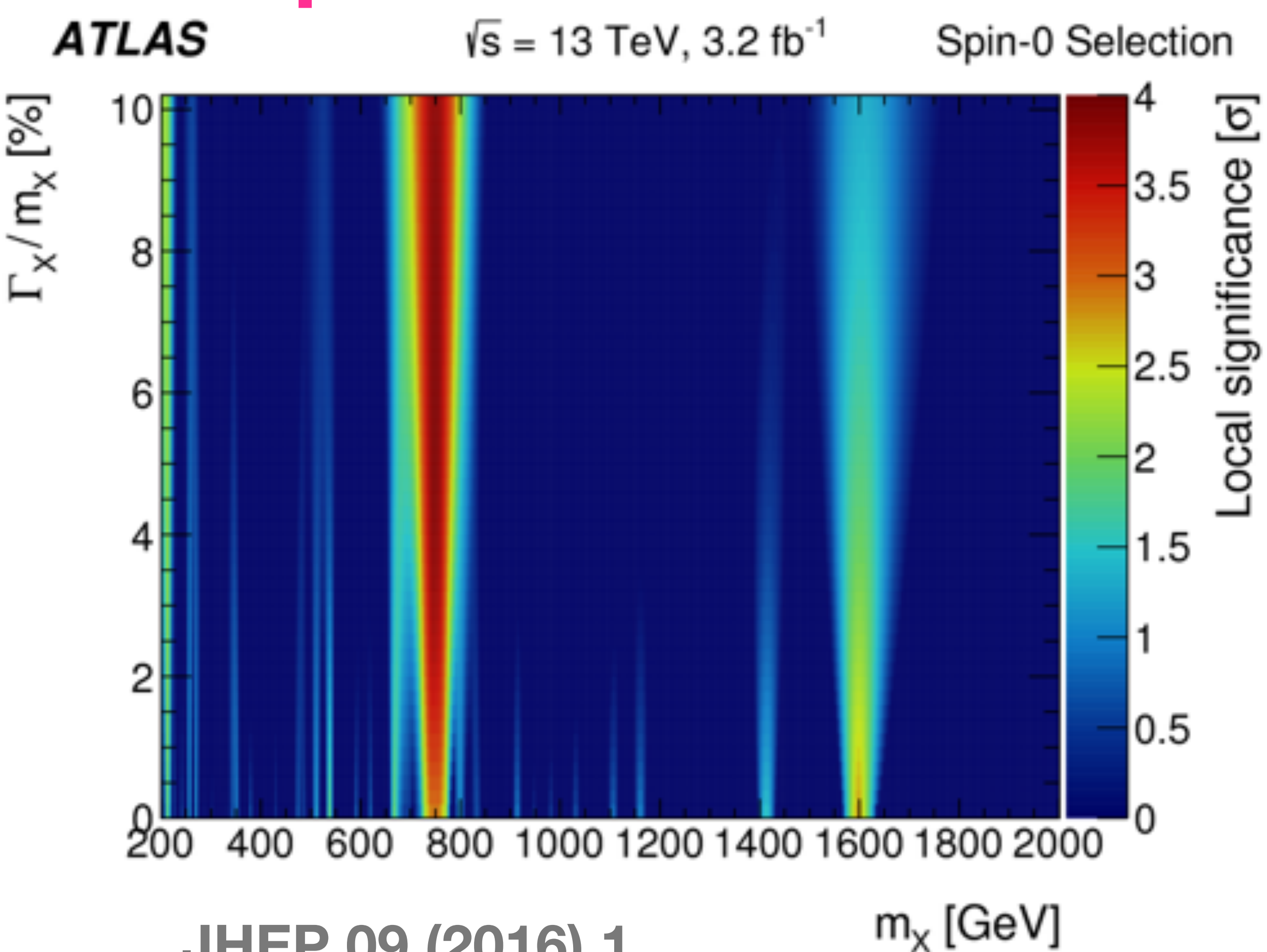
spin-2 selection



- **broad excess around 750 GeV** in both selections.

High mass γγ: Published results on 2015 data

spin-0 selection



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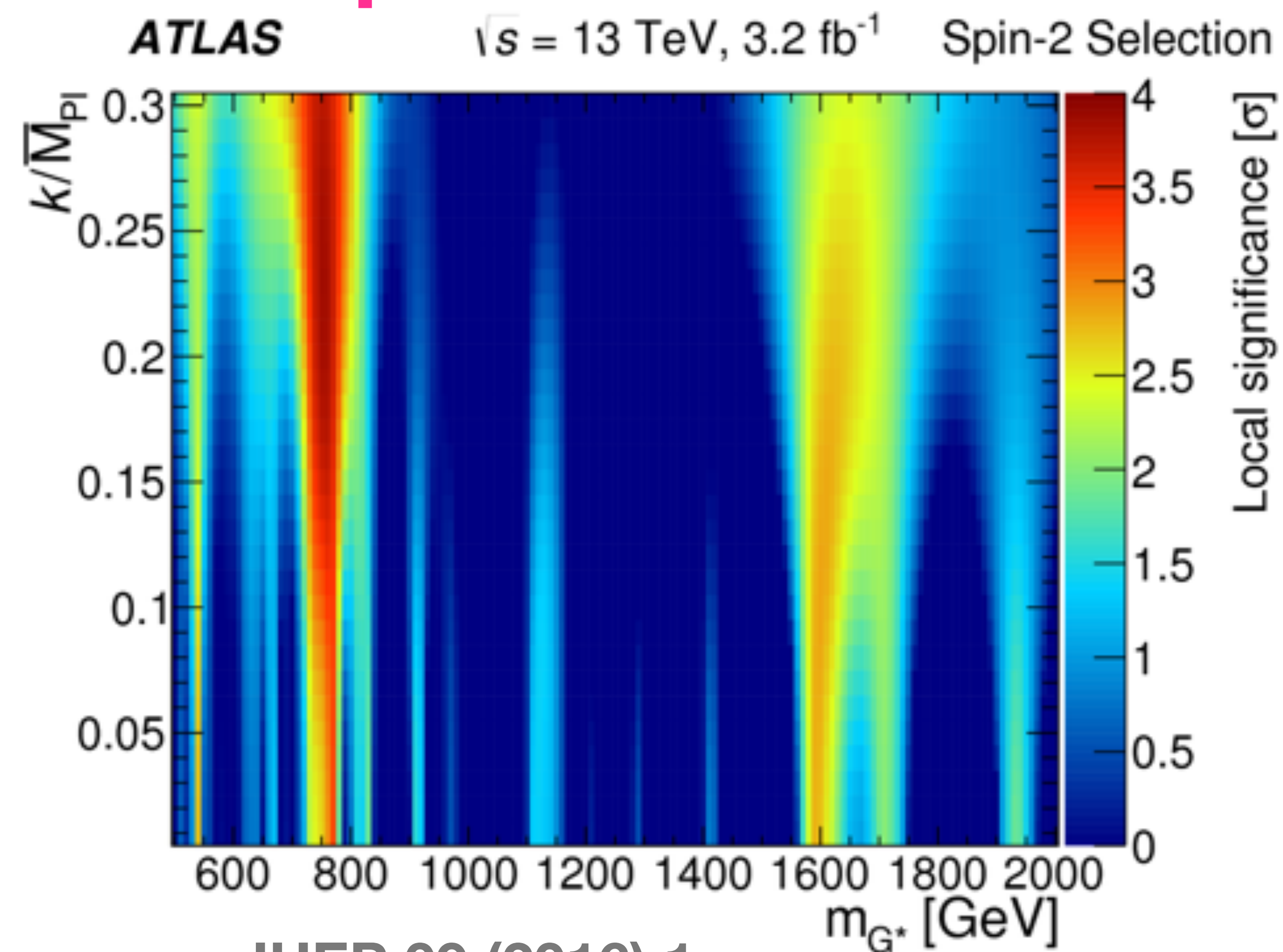
spin-2 selection



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- Local significance of **3.8-3.9σ** around 750 GeV with best fit width of ~6% (45 GeV).
- Taking into account look elsewhere effect in the search region, global significance is **2.1σ**.

High mass γγ: Benchmark models and selections

- Benchmark models:
  - Scalar singlet (spin-0)
    - Extension from H→γγ analysis.
    - Background modelling using functional form.
    - Cut on $p_T/m_{\gamma\gamma}$.
  - Randall-Sundrum graviton model (spin-2)
    - High invariant mass range (limits up to 5 TeV).
    - Background modelling using MC template.
    - Looser kinematic cuts to maximise acceptance.

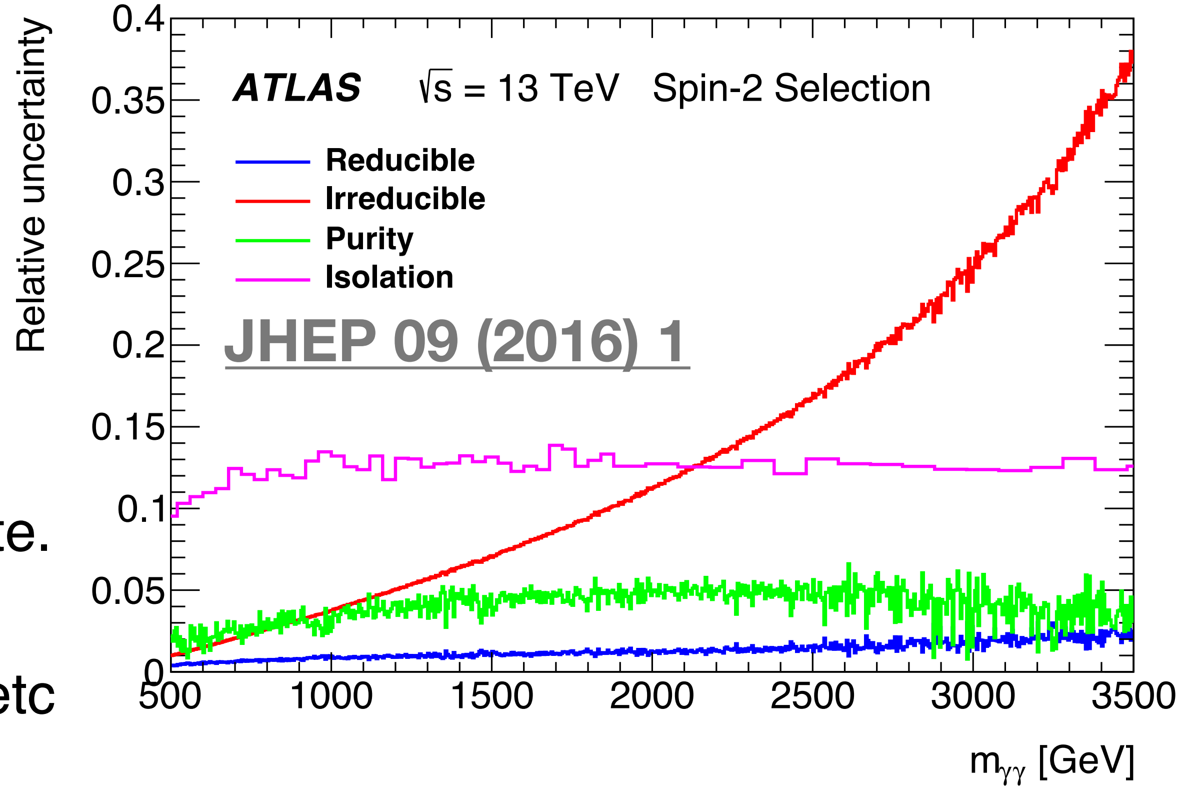
	Spin-0	Spin-2
trigger	2 photons with p_T > 35 (25) GeV passing loose photon identification criteria based on electromagnetic shower shapes.	
p_T	**$p_T^{\gamma 1}/m_{\gamma\gamma}>0.4$, $p_T^{\gamma 2}/m_{\gamma\gamma}>0.3$**	**2 γ with p_T > 55 GeV**
η	$\|\eta_\gamma\| < 2.37$ excluding $1.37 < \|\eta_\gamma\|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

High mass γγ: Background modelling

- Background composed primarily of QCD γγ direct production (**irreducible**) and γj, jγ, jj (**reducible**, from jets misidentified as photons).
- Purity studies show γγ fraction to be high: $93^{+3}_{-8}\%$ ($94^{+3}_{-7}\%$) for spin-0 (spin-2) selection.
- Background template built from above components with the measured purity.
- Spin-0:
  - **Functional form approach**: function fit to data with free parameters.

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

  - **Uncertainties** : Spurious signals from S+B fits to background template to estimate potential bias.



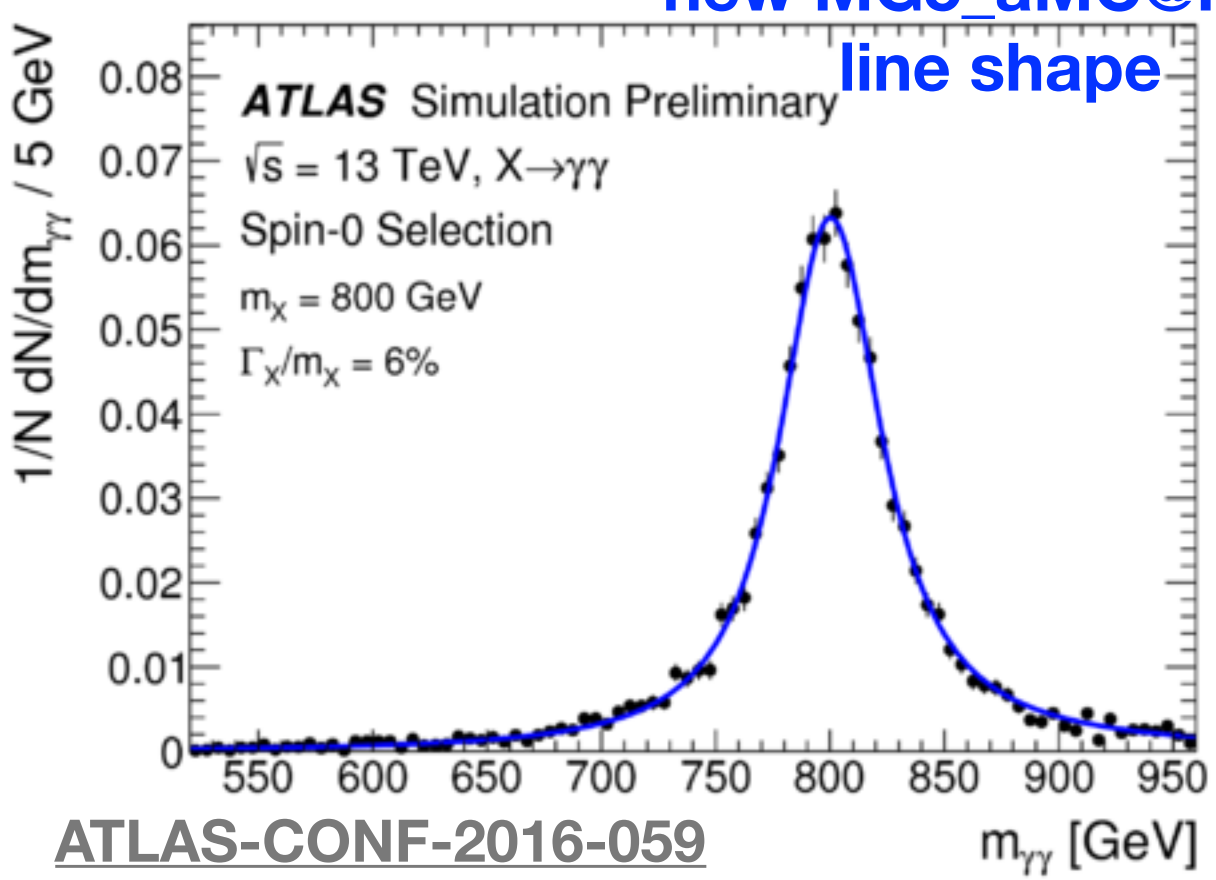
- Spin-2:
  - **Template approach**: Fit with background template.
  - **Uncertainties**: from MC statistics, theoretical, background shape and composition uncertainty, etc

High mass γγ: Signal modelling

- **Spin-0 analysis**
  - Scalar singlet model in MG5_aMC@NLO (was using PowHeg heavy Higgs-like model for 2015 results).
  - Convolution of the theoretical line shape with detector response.
  - Γ_X from narrow to 10% m_X.

- **Spin-2 analysis**
  - RS graviton model generated with Pythia.
  - Convolution of theoretical line-shape with detector response.
  - k/M_{Pl} from 0.01 to 0.3 (narrow to ~13% m_{G^*}).

new MG5_aMC@NLO line shape



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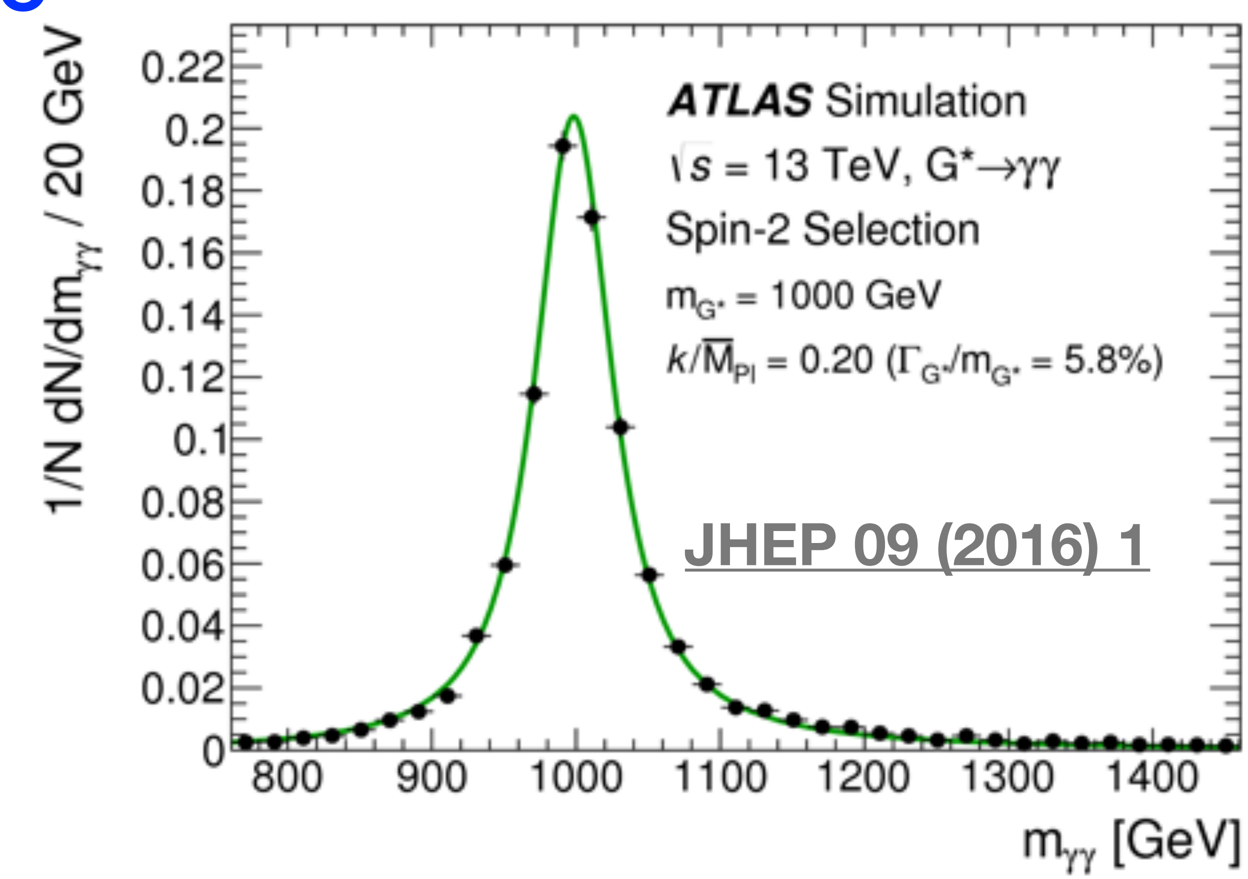

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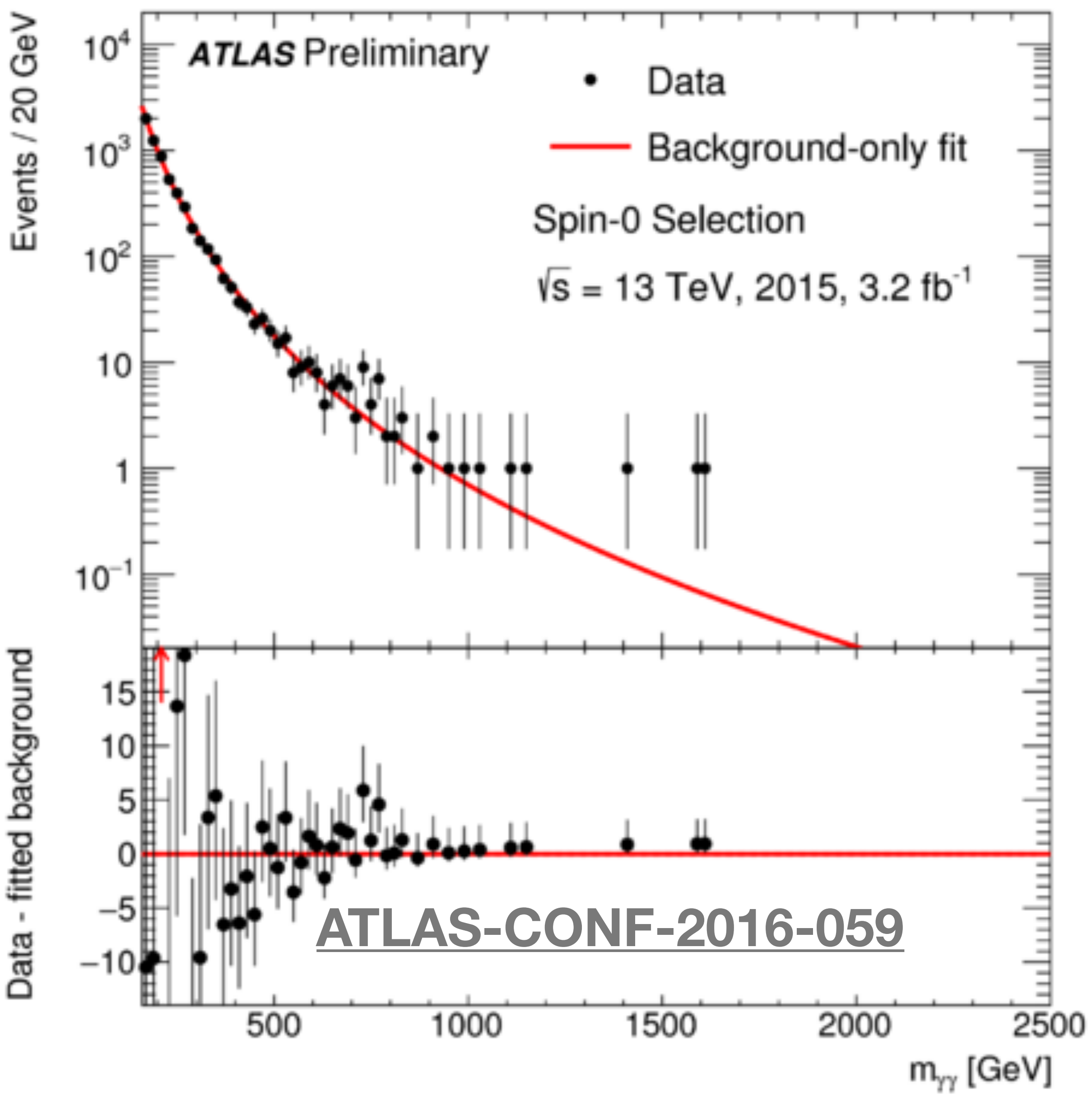
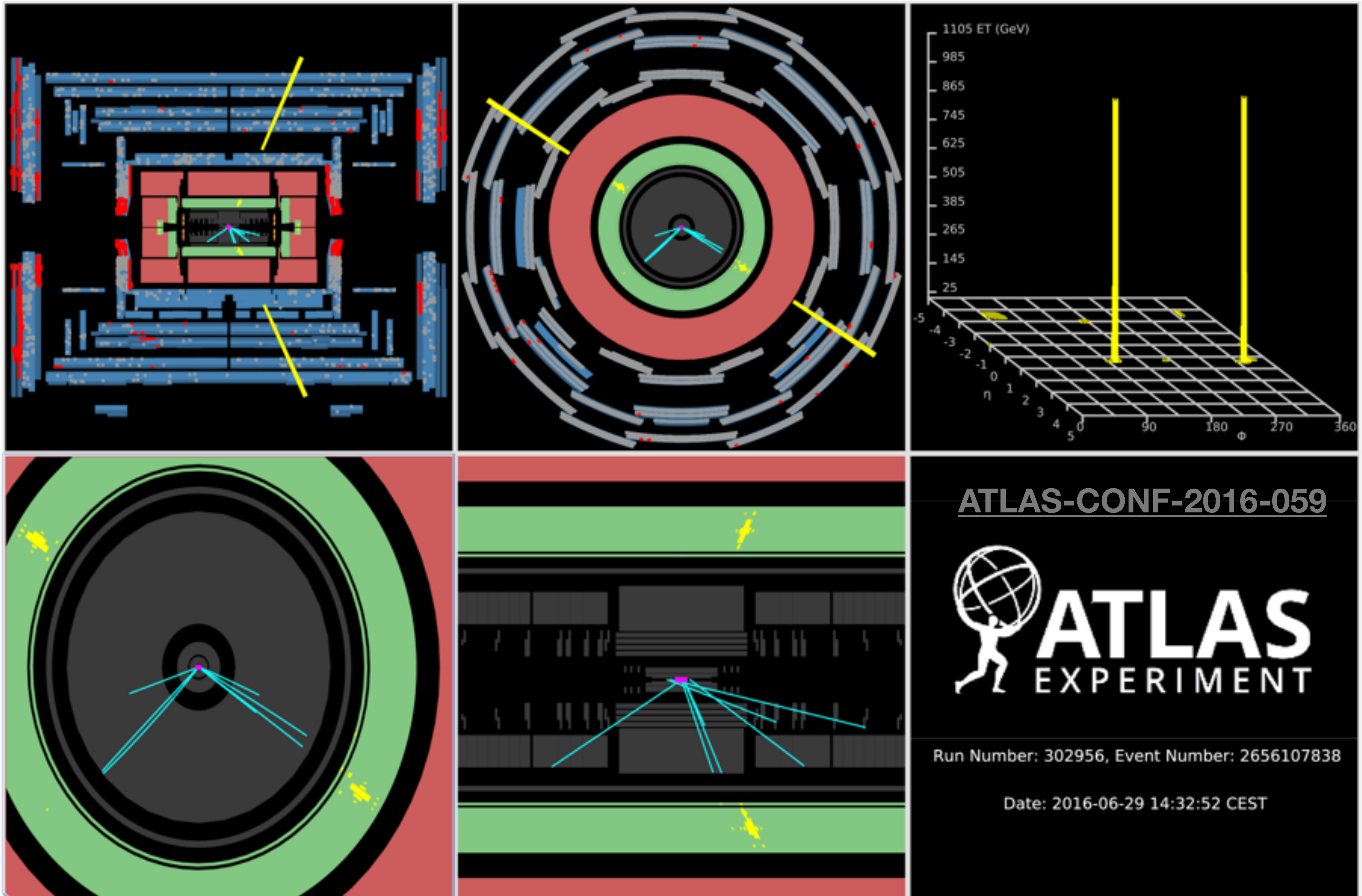
High mass γγ: New results

- 2015 data:
  - Reanalysed with improved photon reconstruction algorithms.
  - The local significance of the largest excess in spin-0 selection **decreased from 3.9 σ to 3.4 σ**.
  - The corresponding best-fit mass and width also changed.
    - m_X: 750 GeV→730 GeV, Γ_X/m_X : 6%→8% (partly due to change in signal model).
- 2016 data:
  - Impressive performance of the LHC with **peak luminosity beyond design**.
  - Only spin-0 analysis presented. Extended acceptance of the spin-2 selection is susceptible to pile-up.
  - ATLAS data-taking efficiency > 90%. **12.2 fb^{-1} of 2016 data analysed for ICHEP**, giving **15.4 fb^{-1} in total** combining 2015+2016.



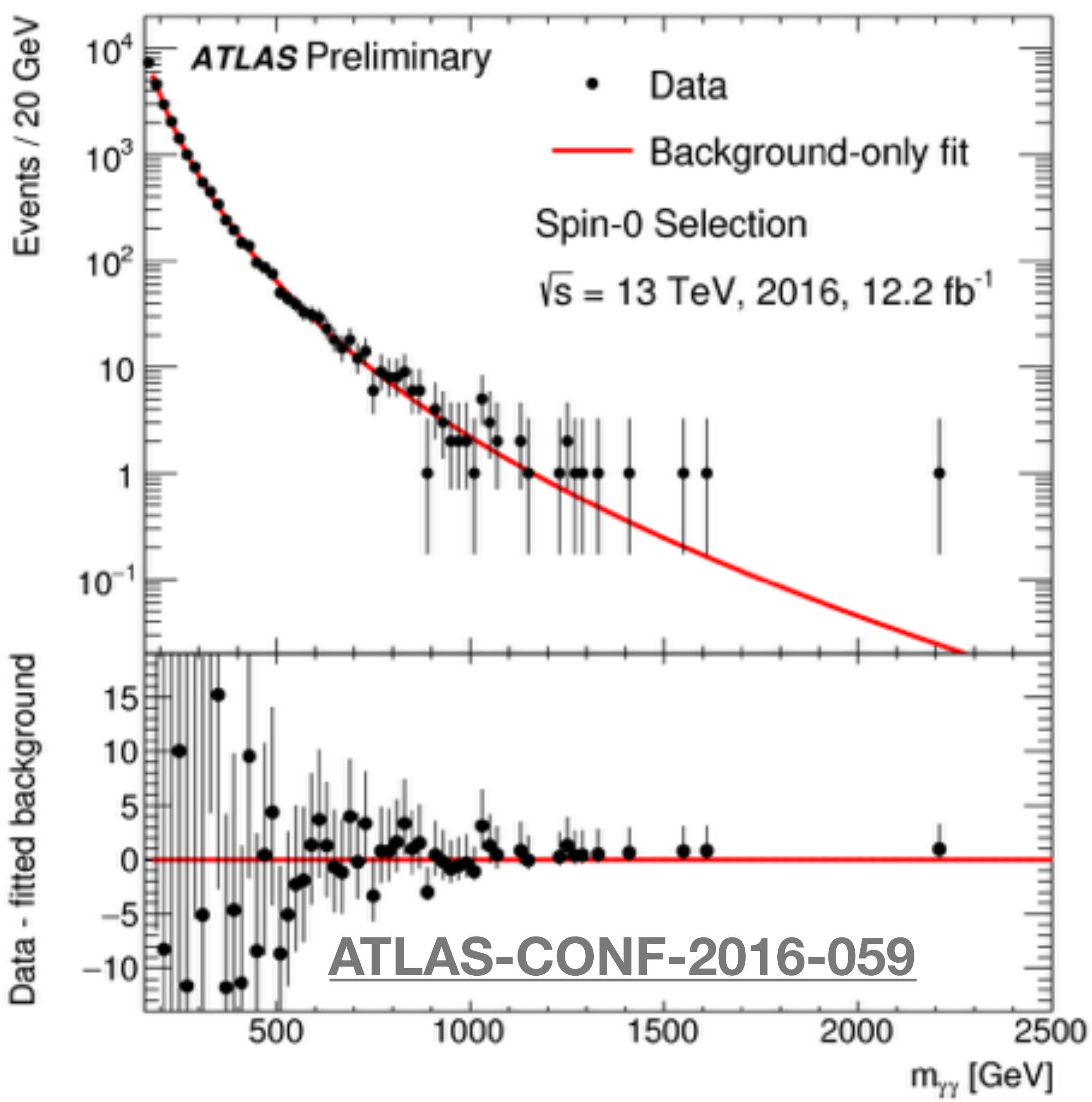
High mass γγ: 2.2 TeV γγ event



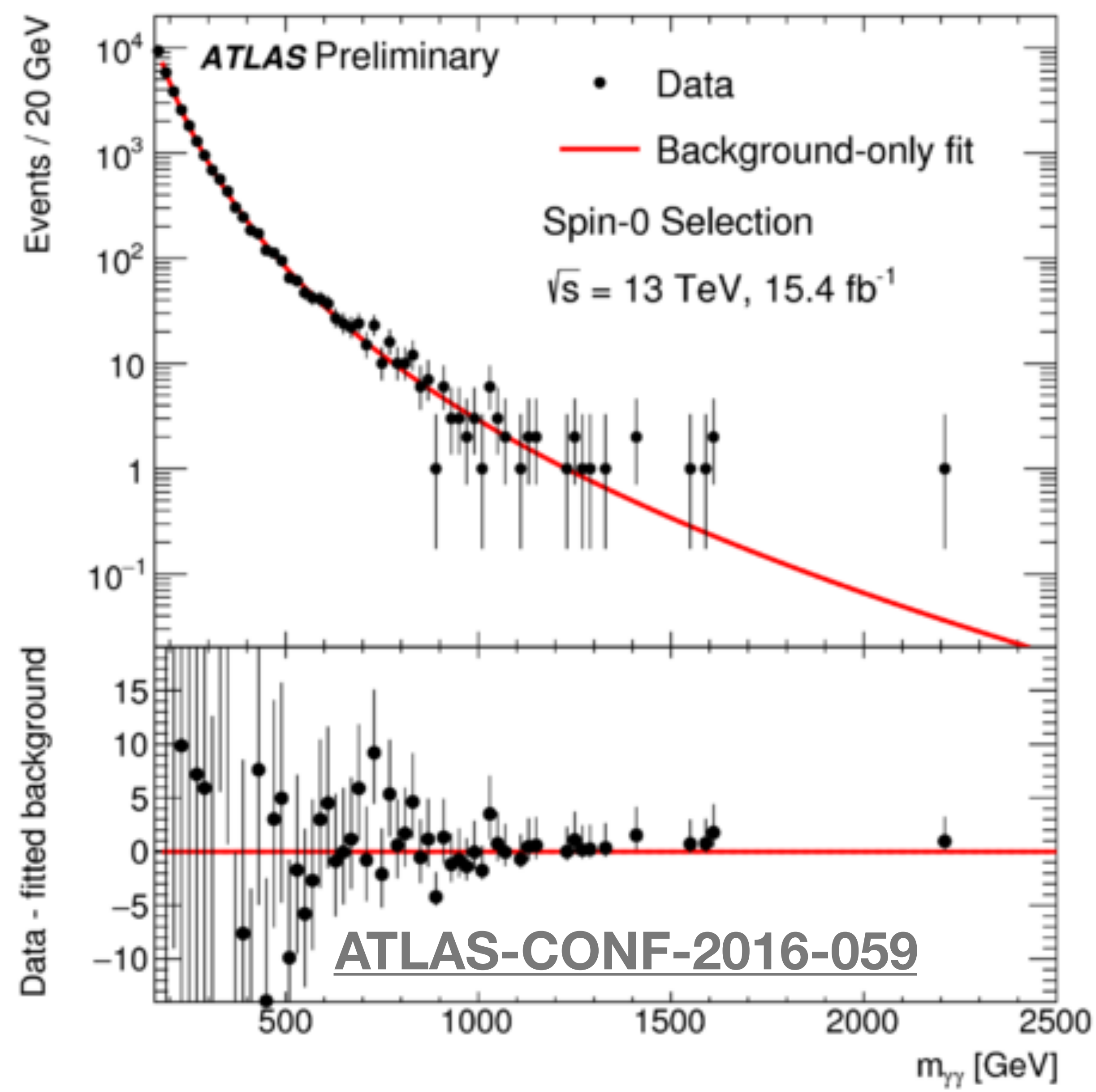
High mass γγ: New results with 2015+2016 data

- No significant excess in 2016 data. **Compatibility** between 2015 and 2016 datasets for signal cross-section at 730 GeV large width is **2.7 σ**.

2016

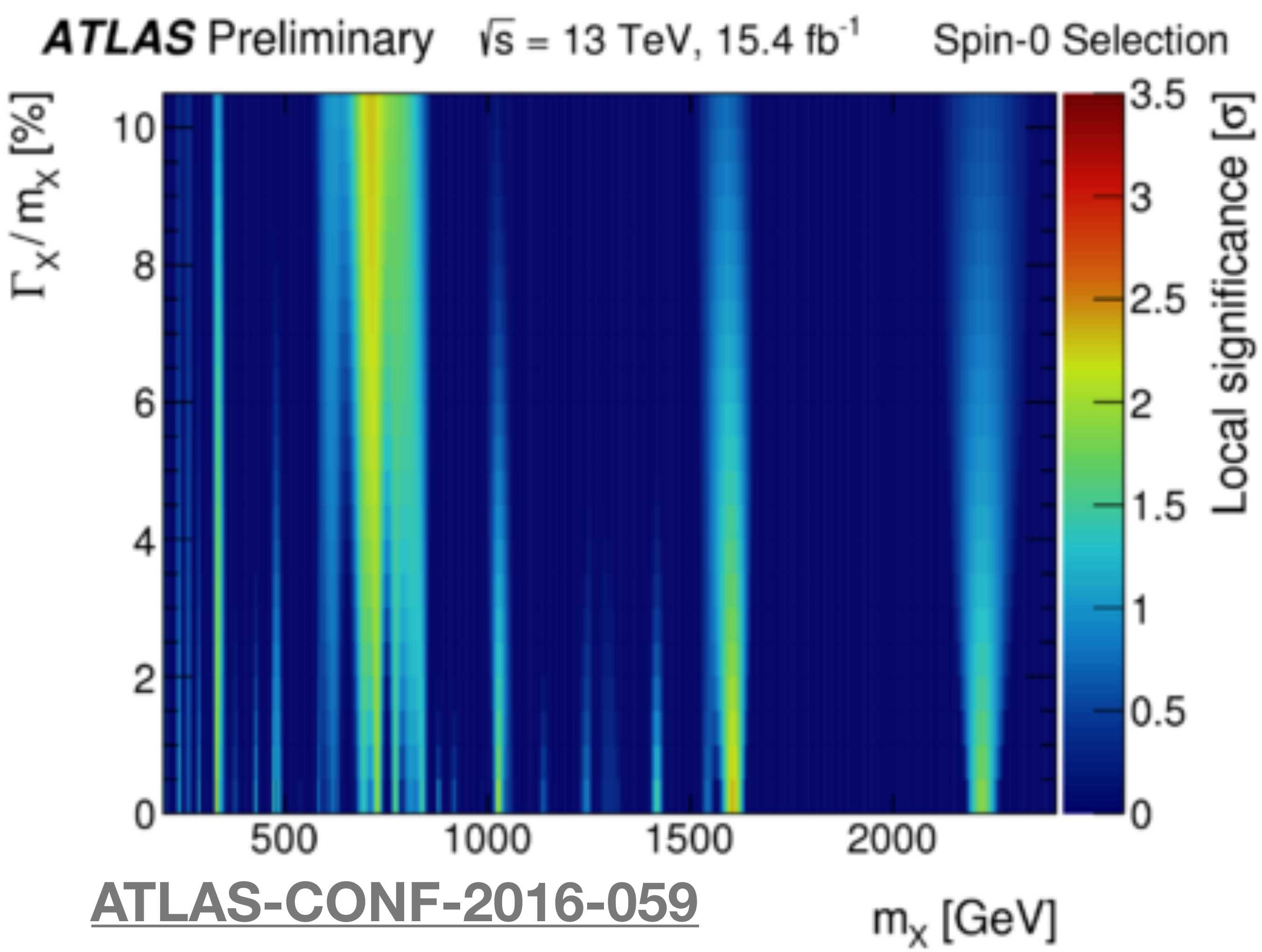


2015+2016



High mass γγ: New results with 2015+2016 data

- **Combined dataset** shows **no significant excess** in the 2D search region.
- Largest deviation is at 1600 GeV (narrow) with local significance of 2.4 σ (<1σ global).
- In the 700–800 GeV mass range the largest local significance is 2.3 σ for a mass near 710 GeV and a relative width of 10%.



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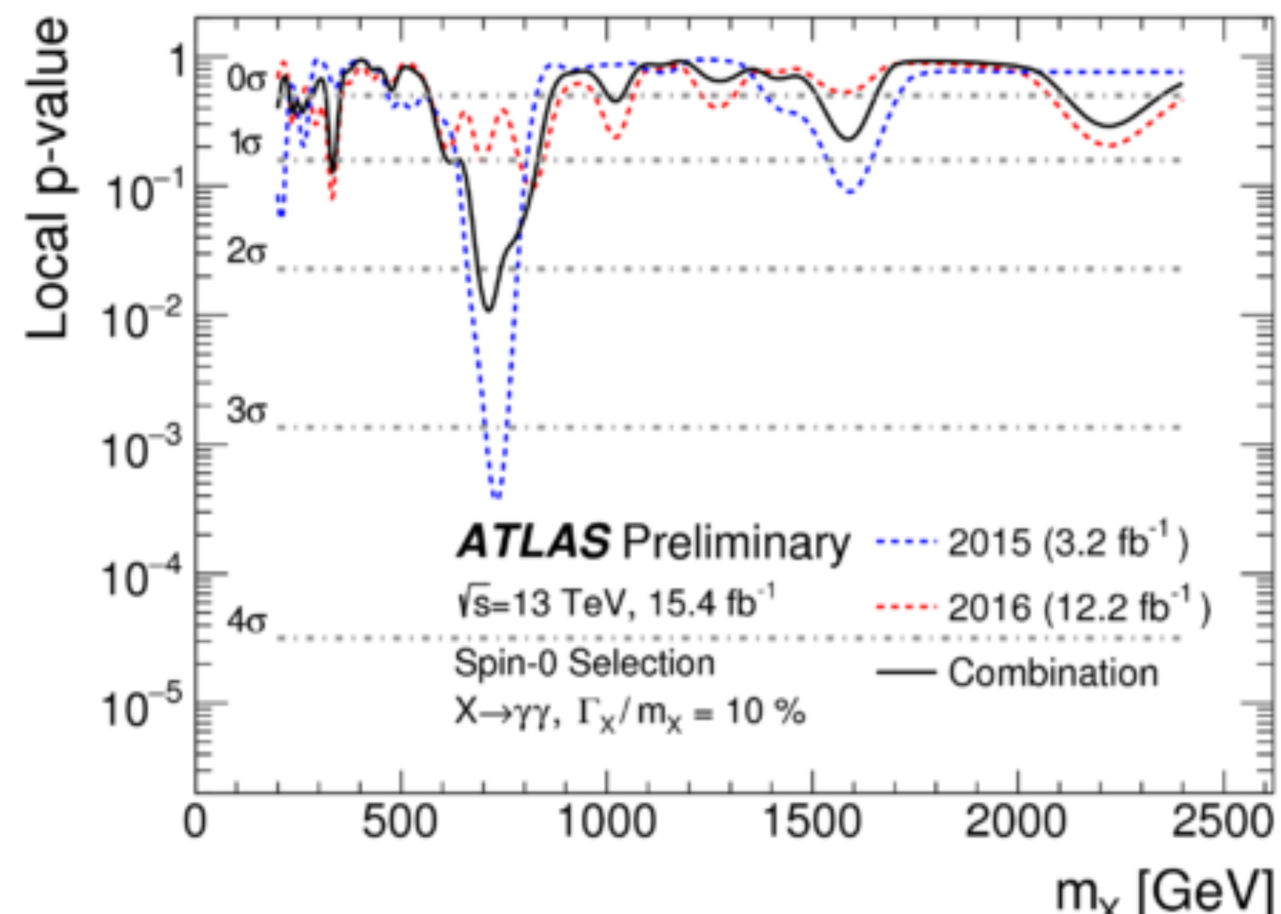

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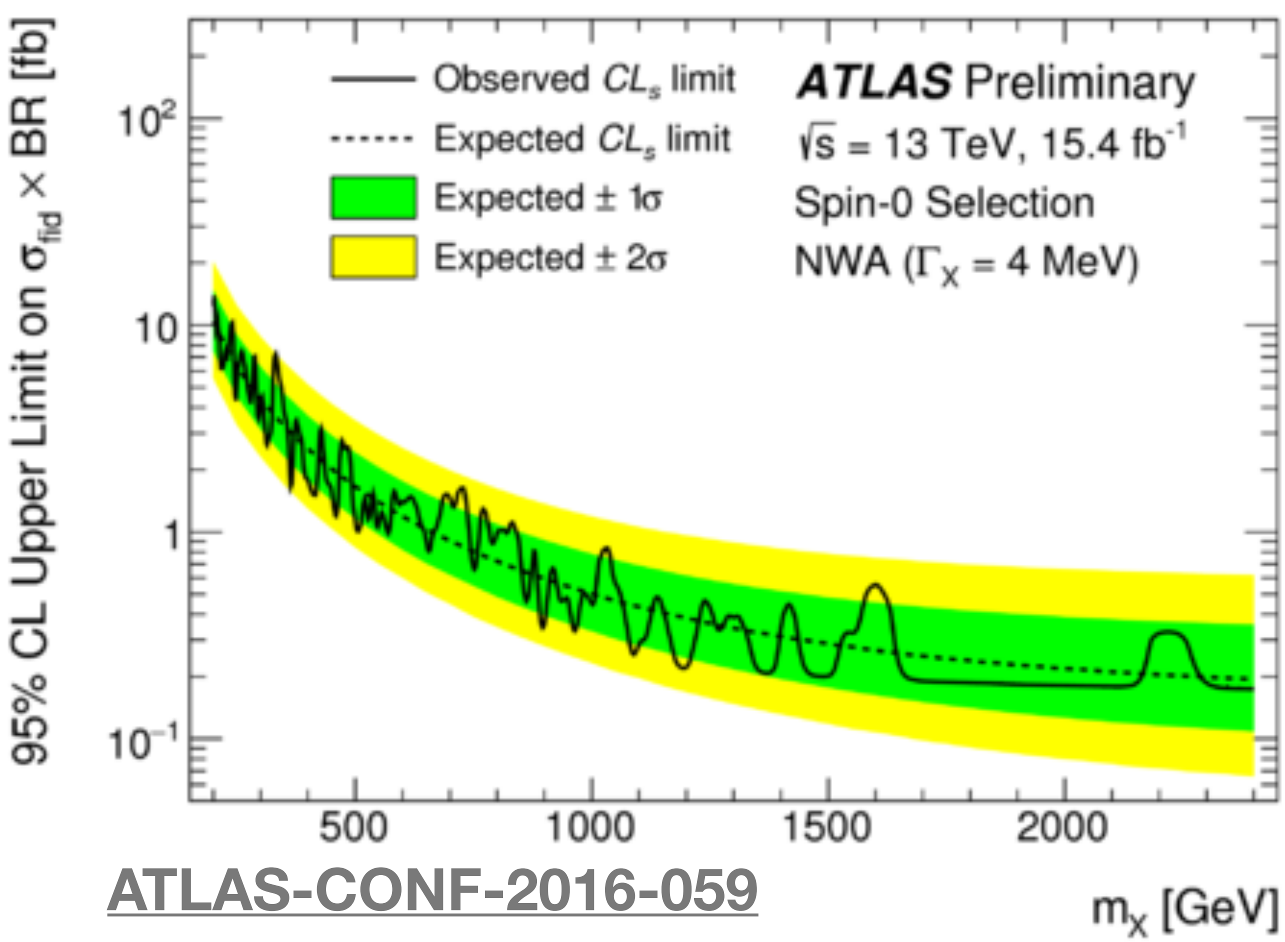
High mass γγ: Upper limits on fiducial cross-section

- Limits on fiducial cross-sections in order to be more model-independent.

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} ($\Delta R=0.4$) $< 0.05 E_T^\gamma + 6$GeV



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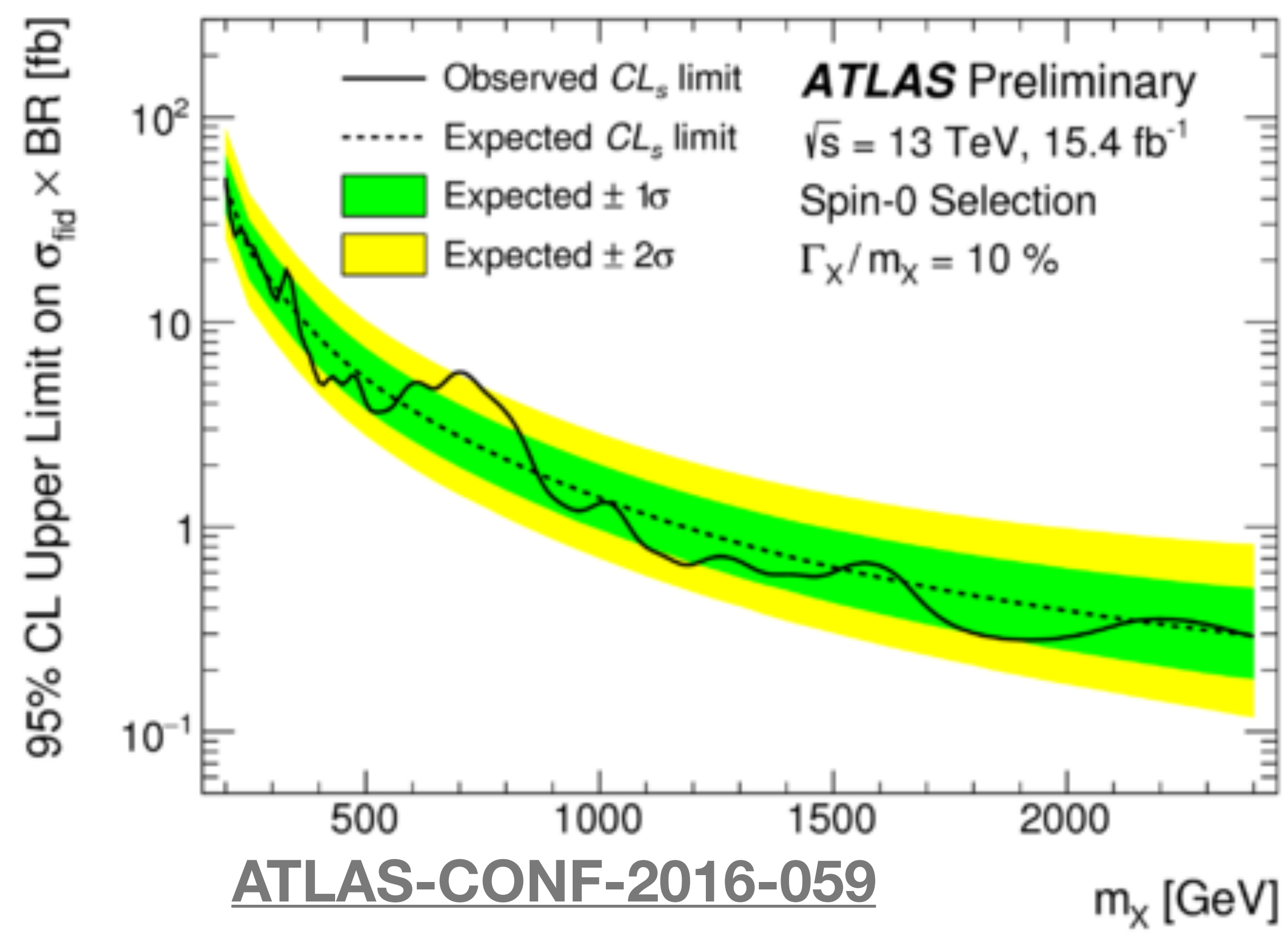

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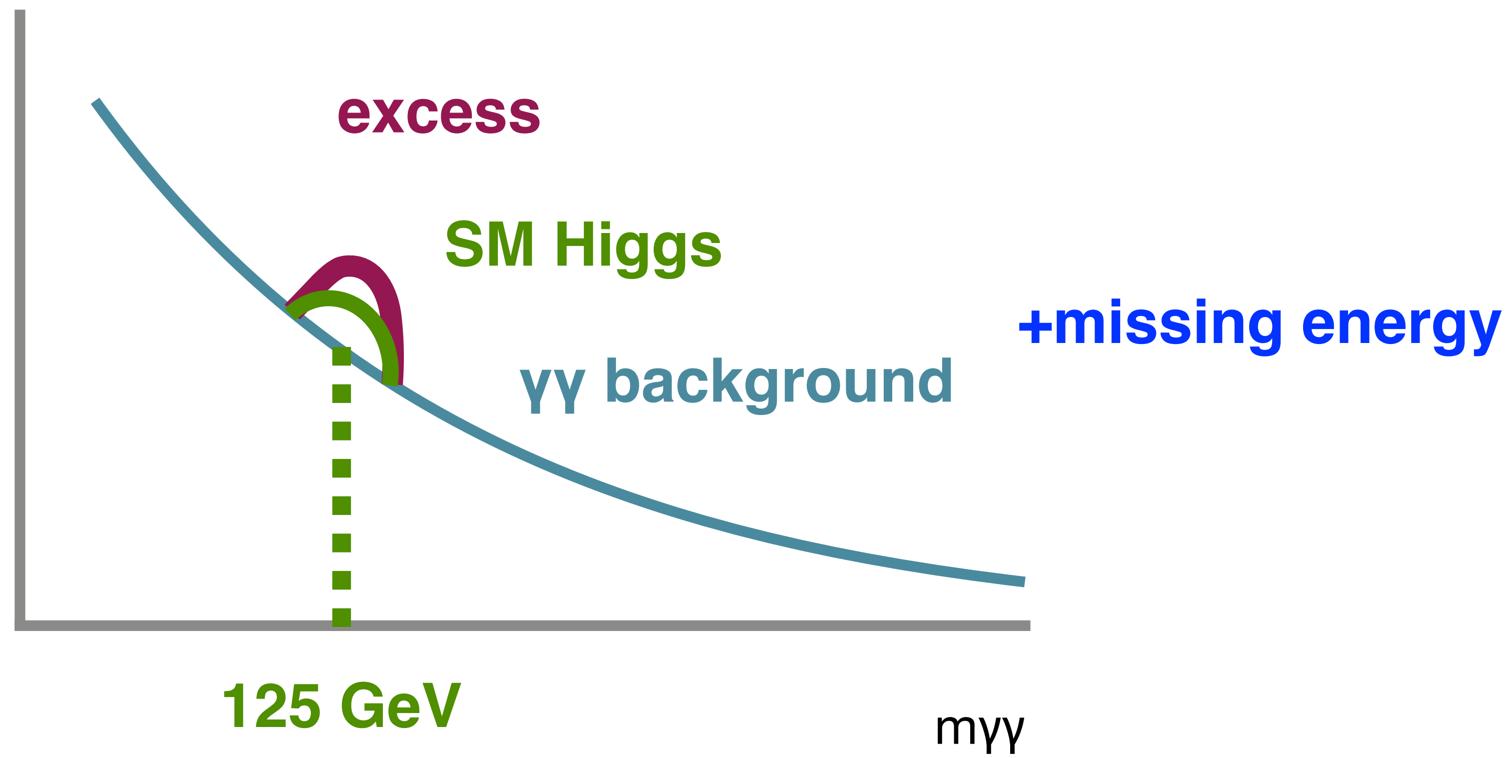
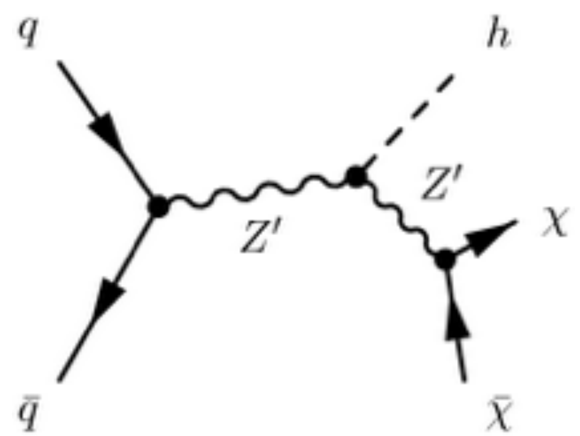
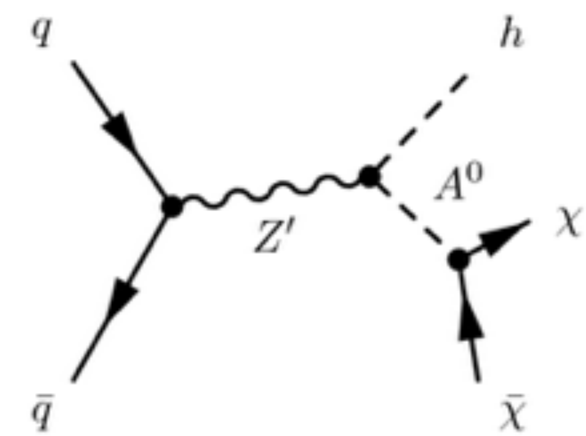
$h \rightarrow \gamma\gamma + E_T^{miss}$



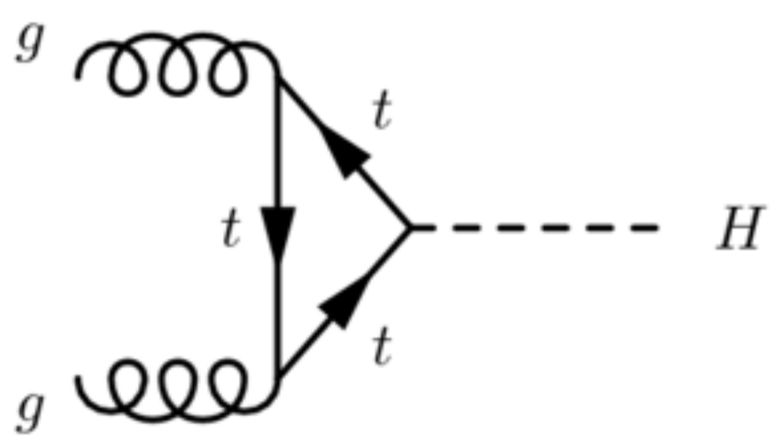
$\gamma\gamma+E_T^{miss}$: Signal models

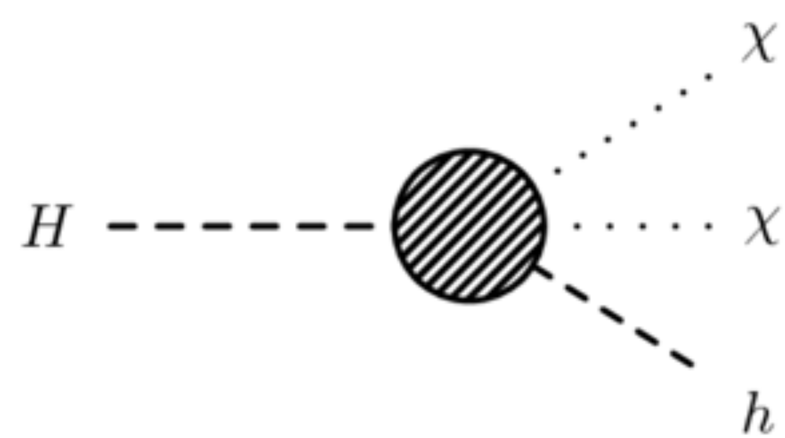
- Three theoretical models:
  - Simplified models (recommended by LHC Dark Matter Forum).
    - Z'_B model
    - Z'-2HDM model (DM couples to pseudoscalar)





  - Heavy scalar produced in ggF decays into a Higgs boson and two DM candidates. EFT approach. $2m_h < m_H < 2m_{top}$.





$\gamma\gamma+E_T^{miss}$: Event selection and categorisation

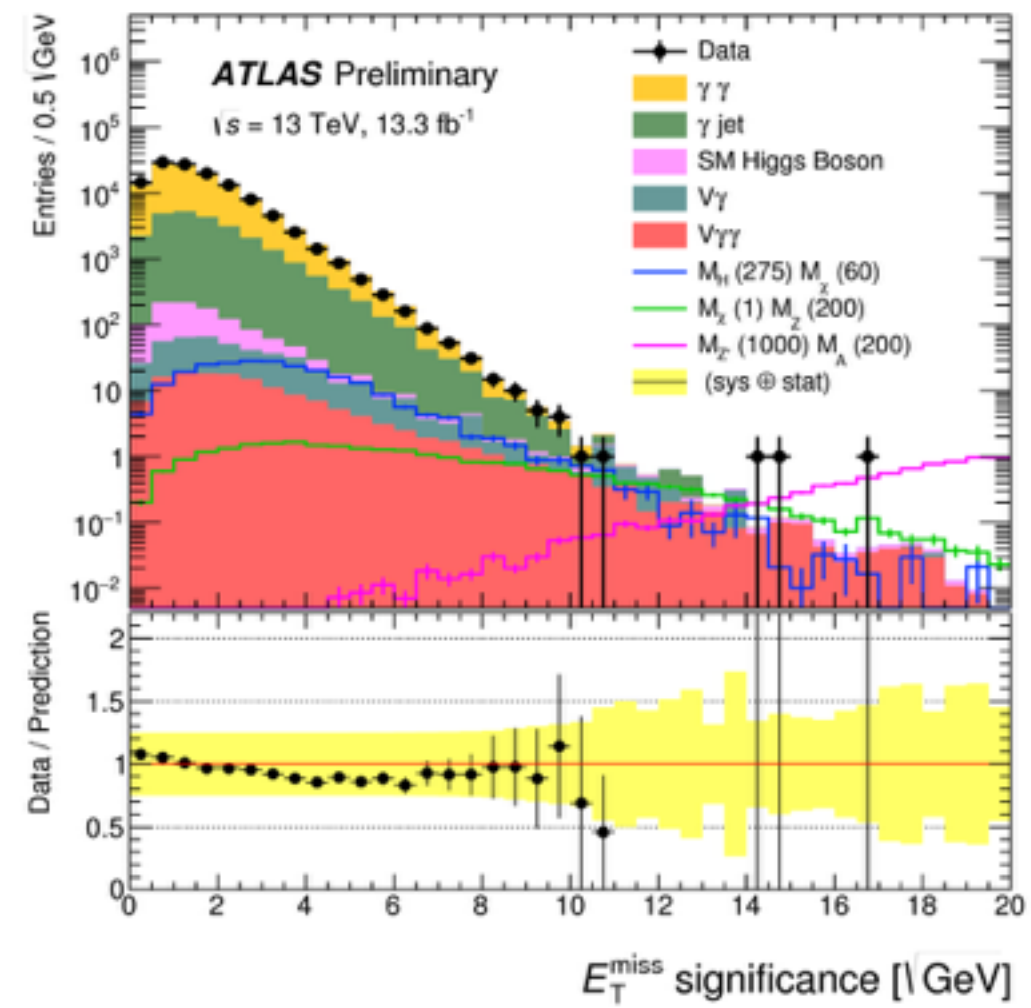
- Event selection follows closely the standard $H\rightarrow\gamma\gamma$ analysis.
- E_T^{miss} is calculated wrt to the diphoton vertex including track-based soft term (less sensitive to pile-up).
- Pile-up degrades E_T^{miss} performance. Use E_T^{miss} significance: $S_{E_T^{miss}} = E_T^{miss}/\sqrt{\sum E_T}$
- 4 categories defined:

Category	$S_{E_T^{miss}}$ [$\sqrt{\text{GeV}}$]	$p_T^{\gamma\gamma}$ [GeV]	
High $S_{E_T^{miss}}$, high $p_T^{\gamma\gamma}$	>7	>90	→ Z'$_B$ and Z'-2HDM models
High $S_{E_T^{miss}}$, low $p_T^{\gamma\gamma}$	>7	≤ 90	Heavy scalar (all 4 categories)
Intermediate $S_{E_T^{miss}}$	>4 and ≤ 7	>25	
Rest	-	>15	

- In Z'$_B$ and Z'-2HDM models, the Higgs boson recoils against the DM pair, resulting in larger E_T^{miss} and large p_T of the diphoton candidate. → use only high-E_T^{miss}-significance-high-$p_T^{\gamma\gamma}$ category.
- In heavy scalar model, E_T^{miss} and $p_T^{\gamma\gamma}$ can span a large range. All 4 categories are used.

$\gamma\gamma+E_T^{miss}$: E_T^{miss} significance, signal and background modelling

- Data and MC comparison of E_T^{miss} significance shows good agreement within uncertainties.



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- Double-sided Crystal Ball function is used to model the signal shape as well as background from SM Higgs in each category.
- Non-resonant background modelling is data-driven using functional form with similar spurious signals procedure.
  - Simple exponential for high-E_T^{miss}-significance category.
  - Intermediate and rest categories use exponential of 2nd order polynomial.
- Fit performed in the range $105 < m_{\gamma\gamma} < 160$ GeV.

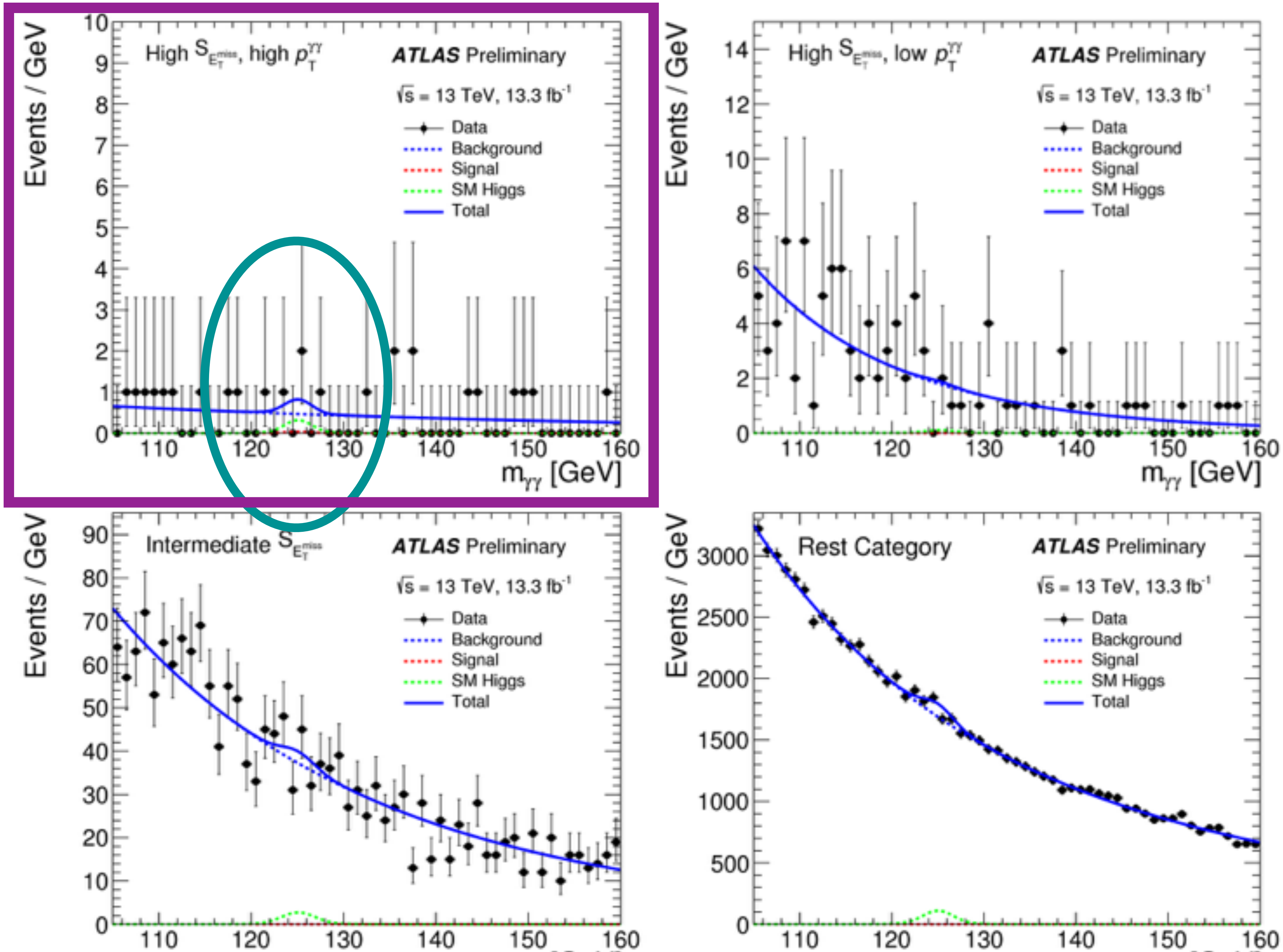
γγ+E_T^{miss}: Results

- γγ mass fit over 4 categories

Sensitive to DM models

No excess on top of SM Higgs background

No excess in other categories



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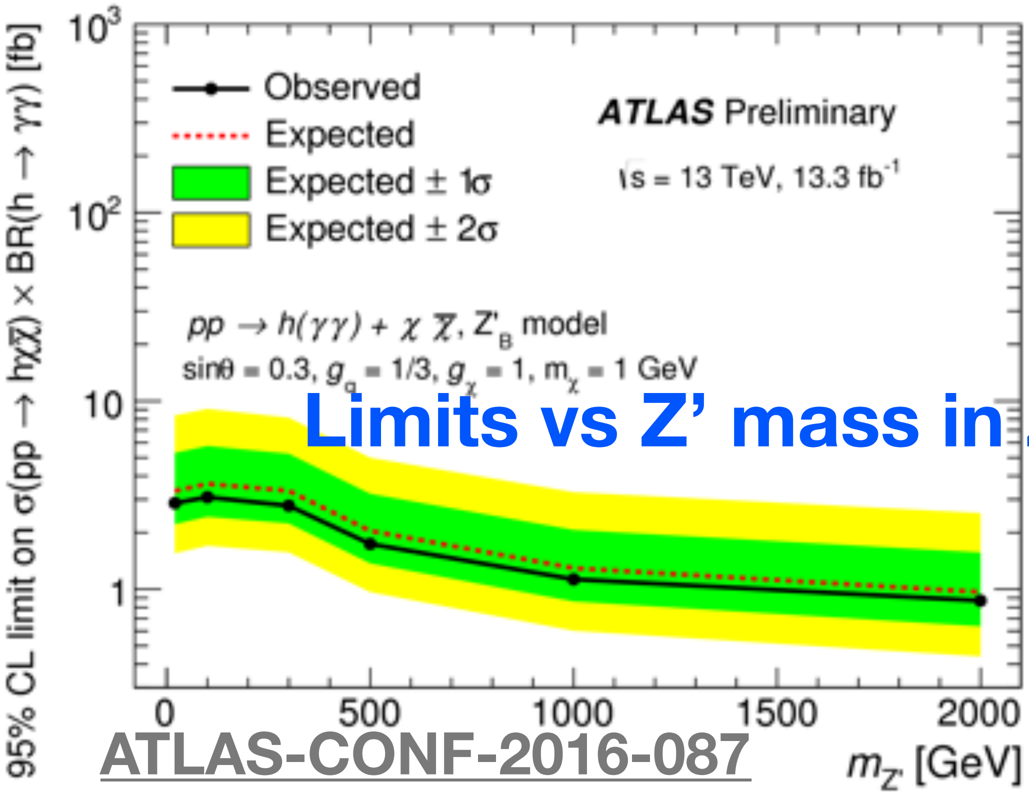
$\gamma\gamma+E_T^{miss}$: Limits

Limits vs Z' and A^0 mass in Z'-2HDM model



Limits vs Z' mass in Z'_B model

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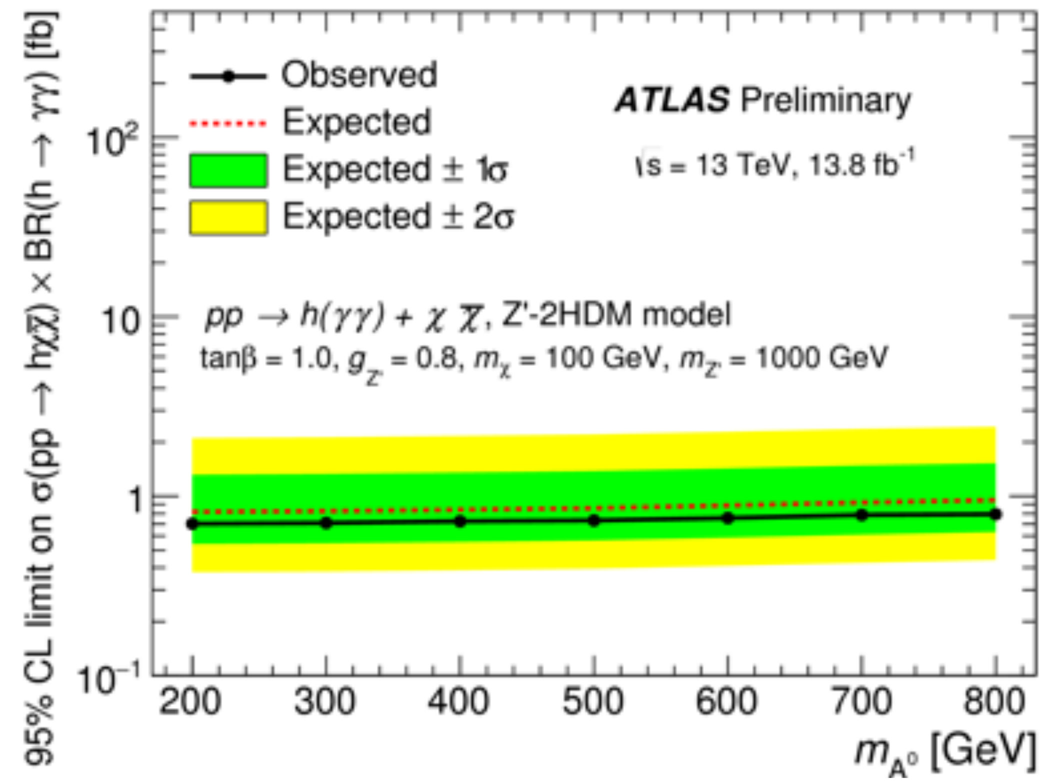
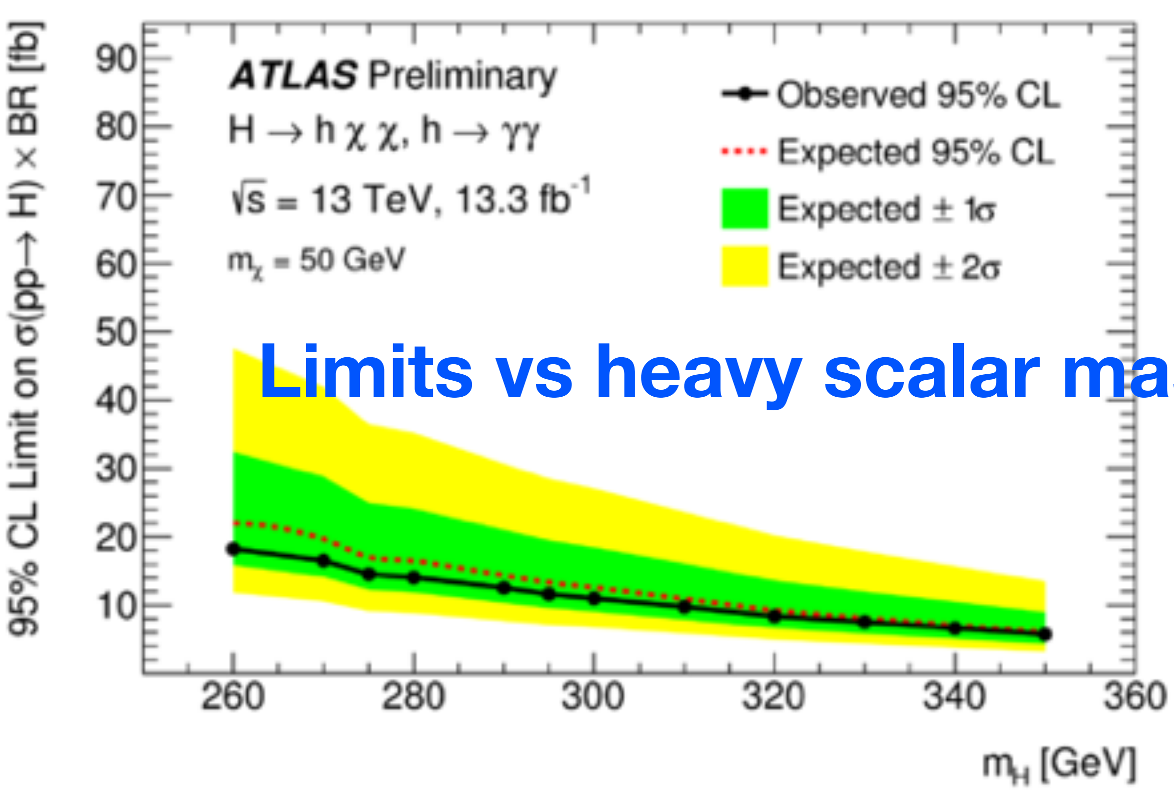
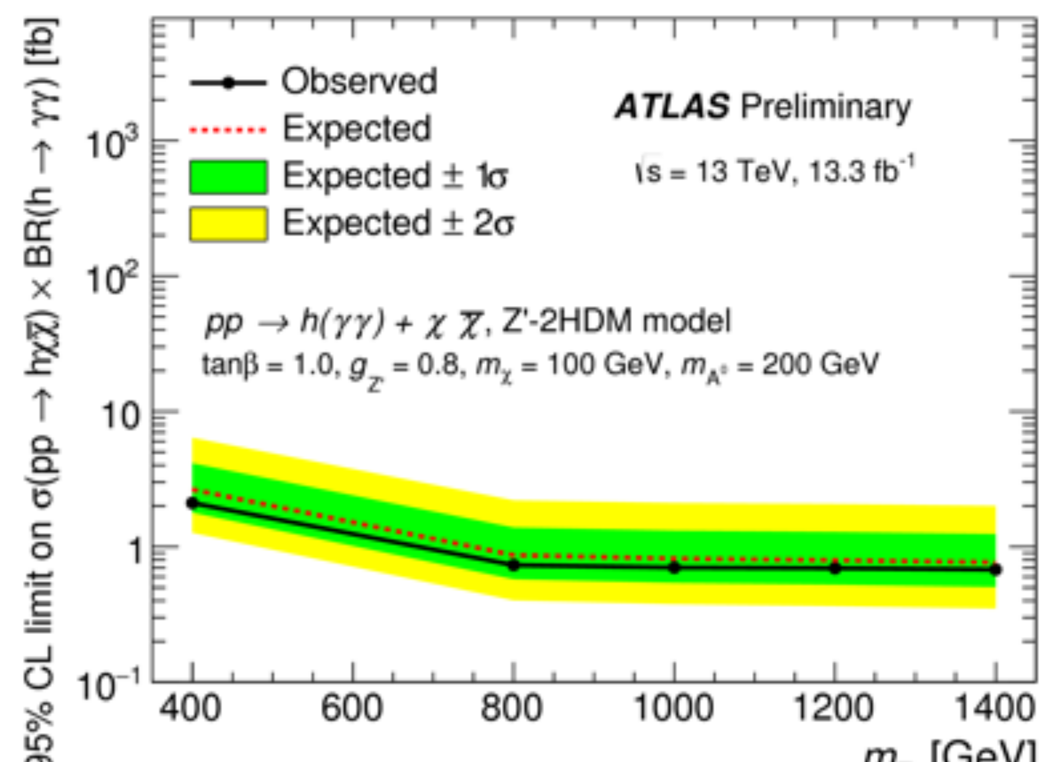


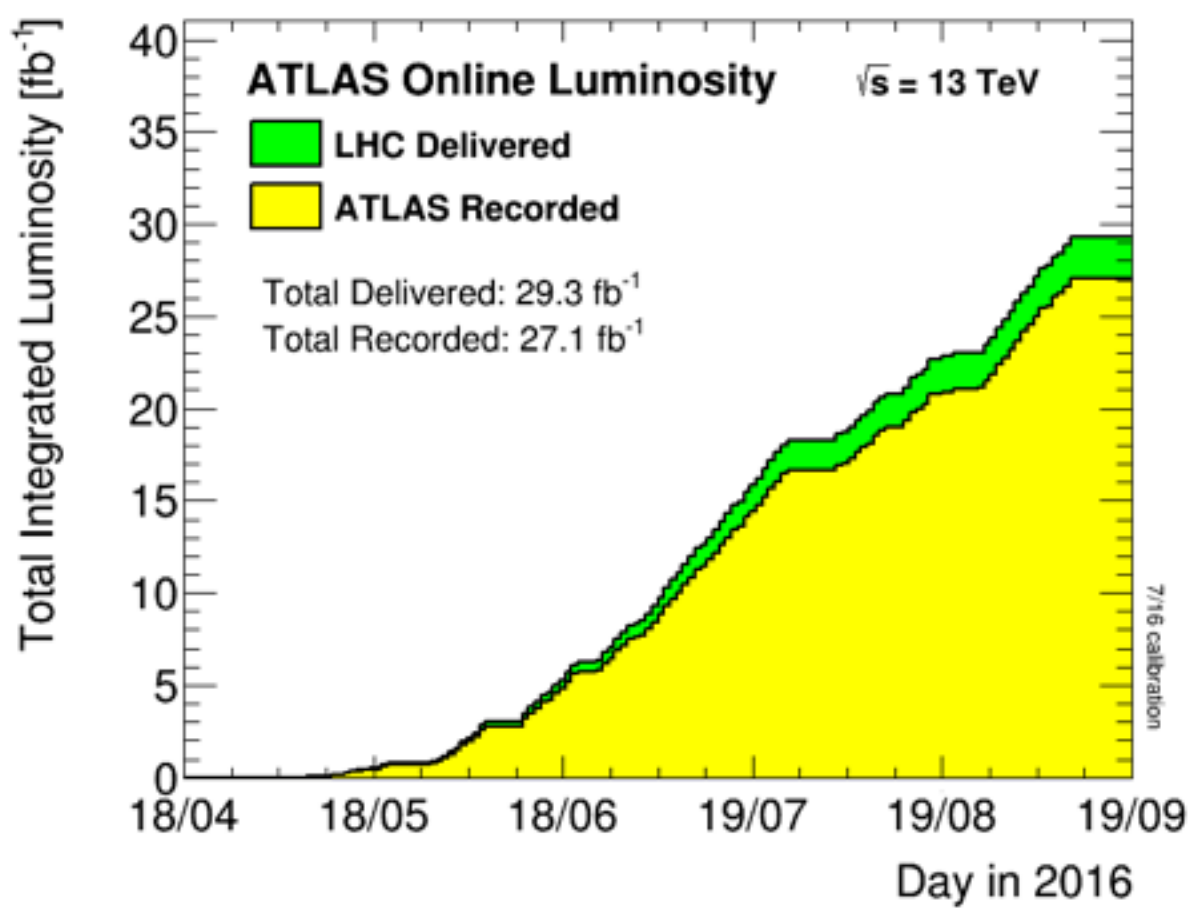


Limits vs heavy scalar mass



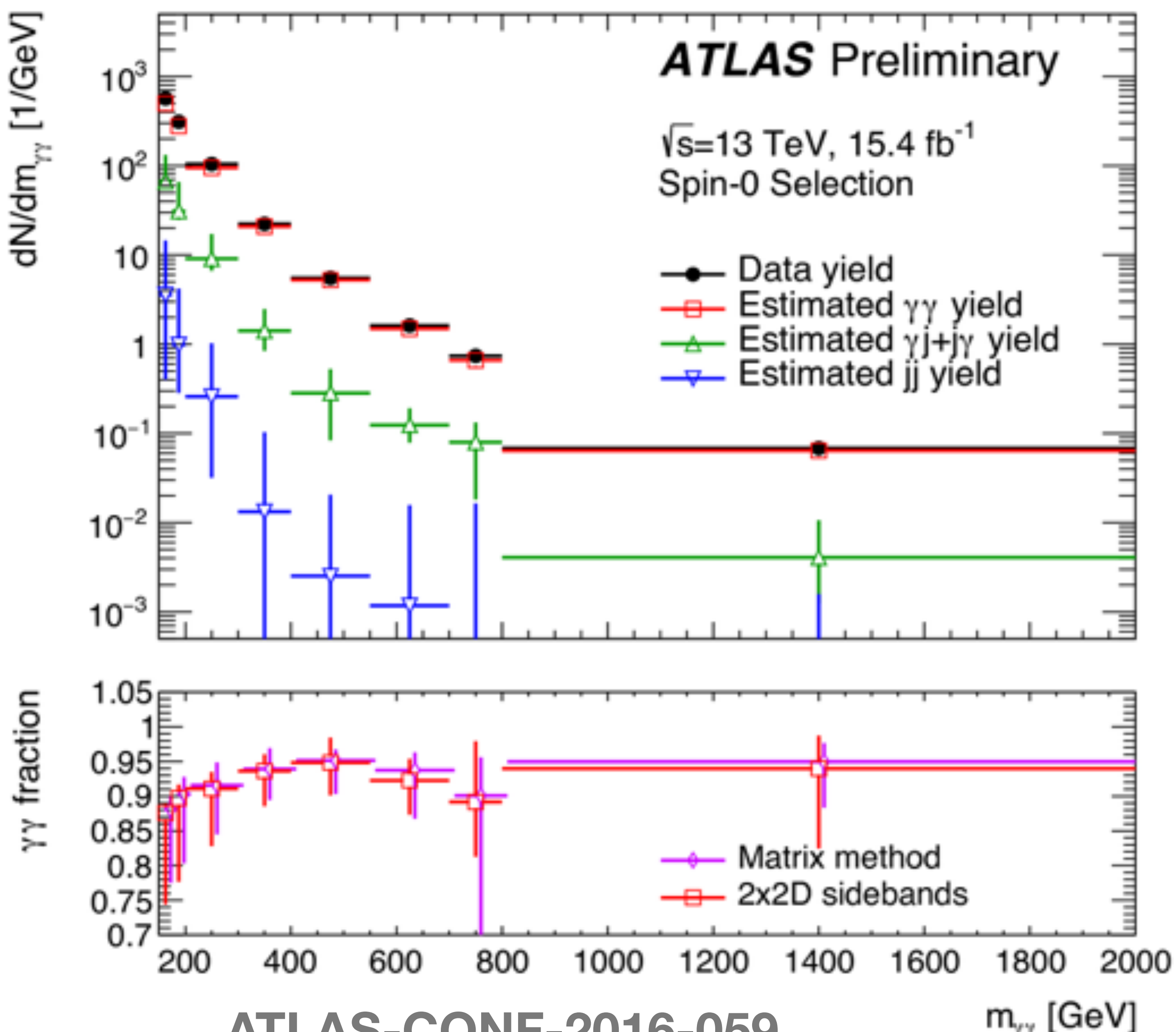
Summary

- New physics search in **high mass γγ** and **h→γγ+E_T^{miss}** reported.
    - **No significant excess** observed in combined 2015+2016 dataset.
- 3.9σ 750GeV diphoton excess in 2015 data decreases to 3.4σ after reanalysis.
    - Excess not seen in 2016 data. 2015 - 2016 compatibility at level of 2.7σ. Combined local significance is 2.3σ (<1σ global).
- h→γγ+E_T^{miss} results interpreted in the context of 3 theoretical models.
- 2016 data taking going well. Stay tuned for more!



Back-up

High mass γγ: Purity and signal shape



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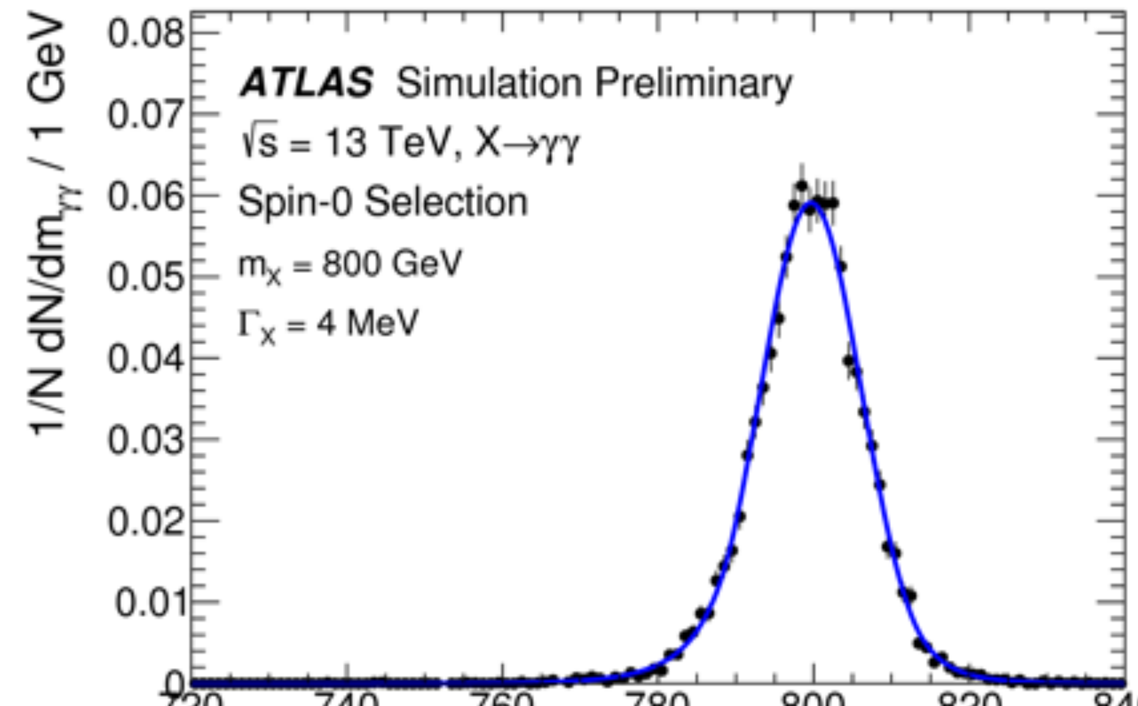

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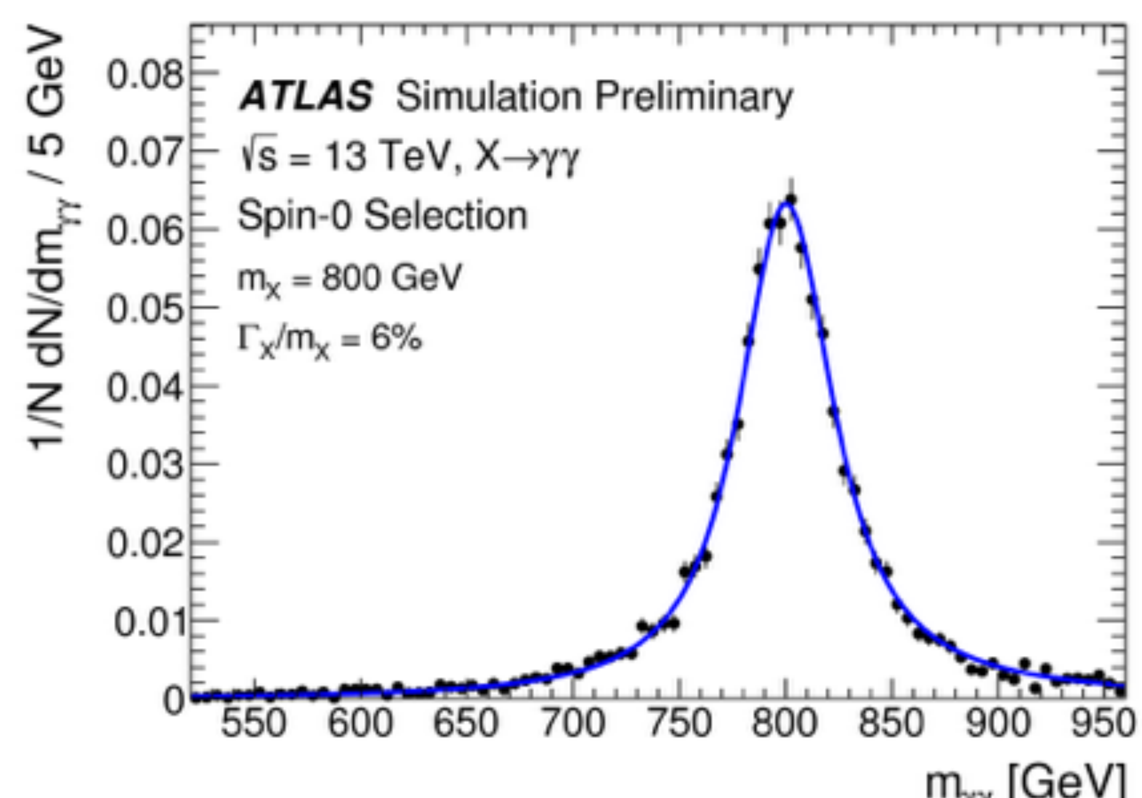
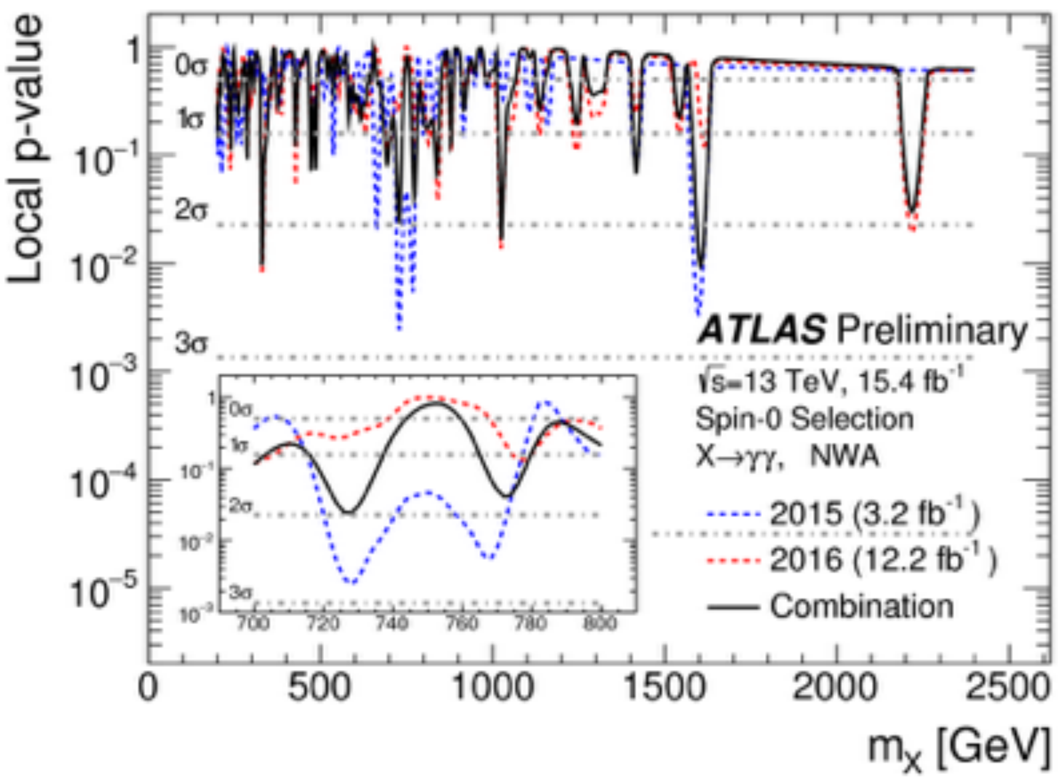
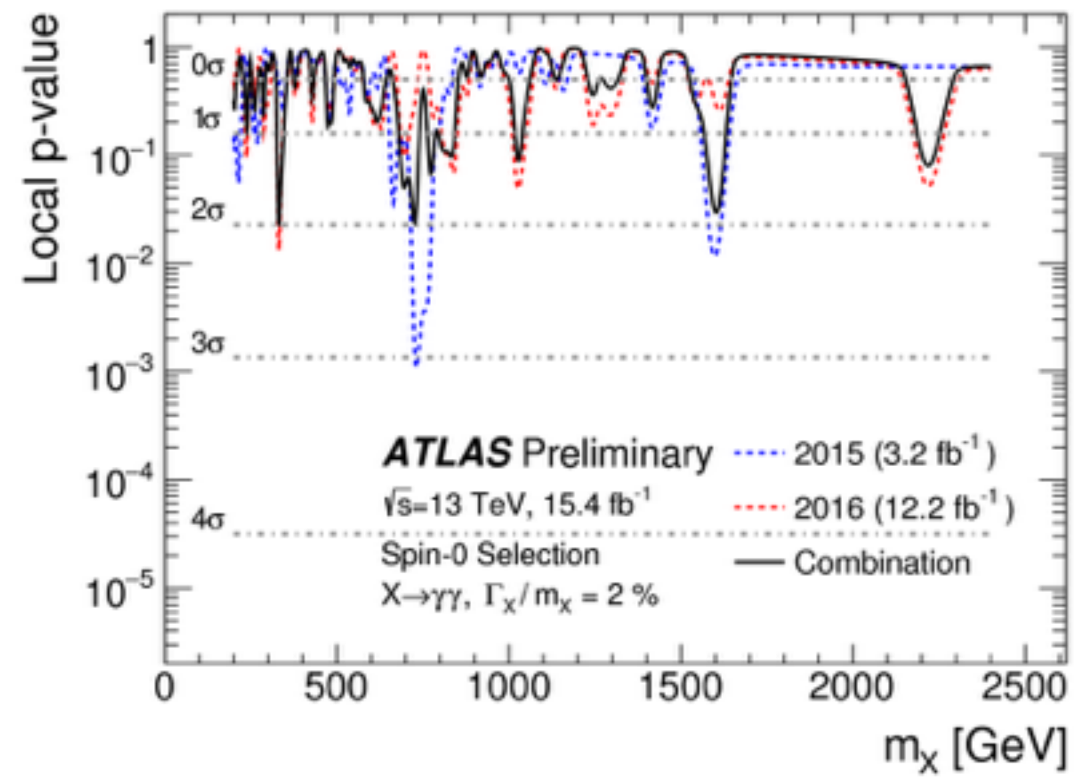
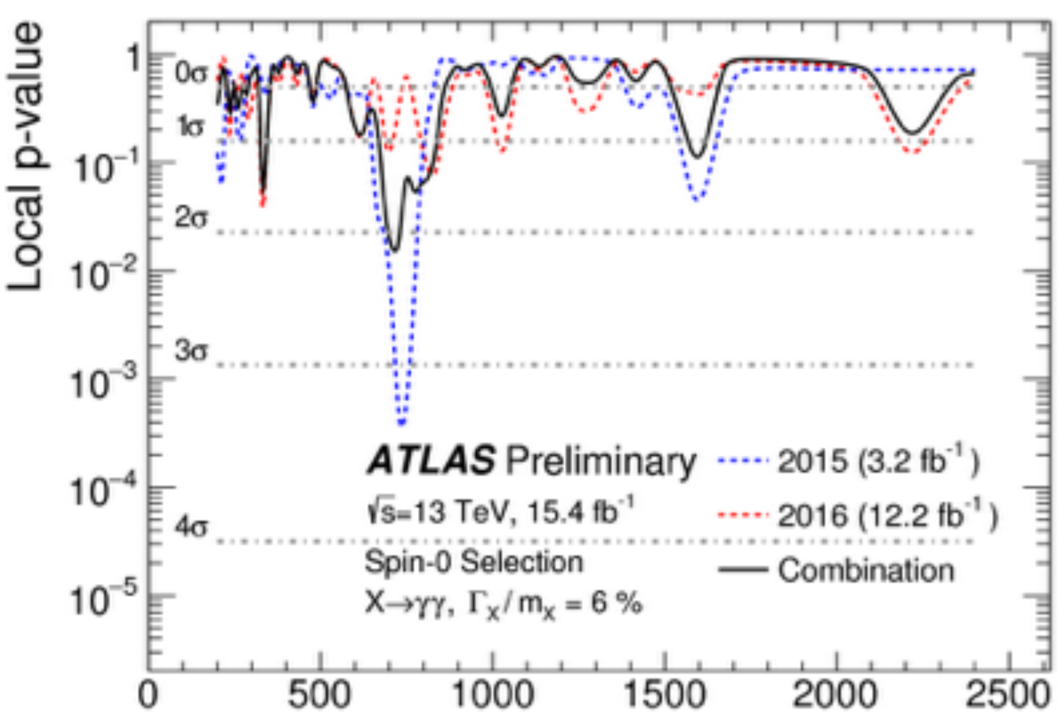
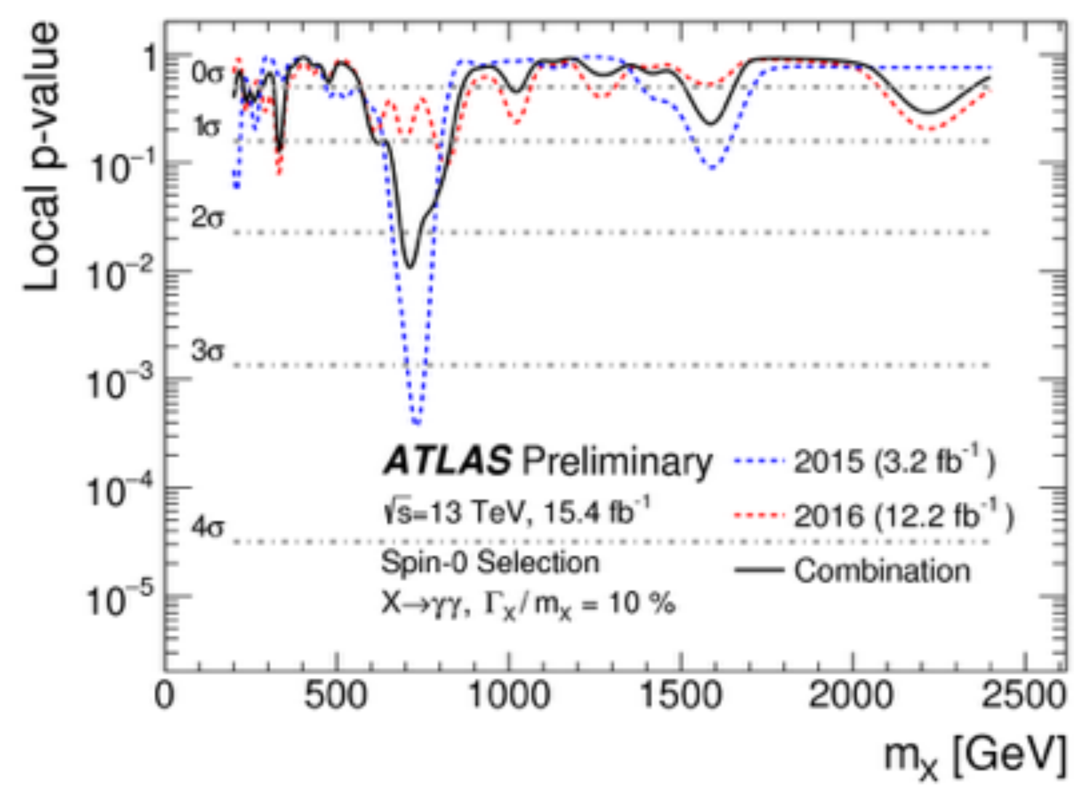


High mass γγ: 1D p0









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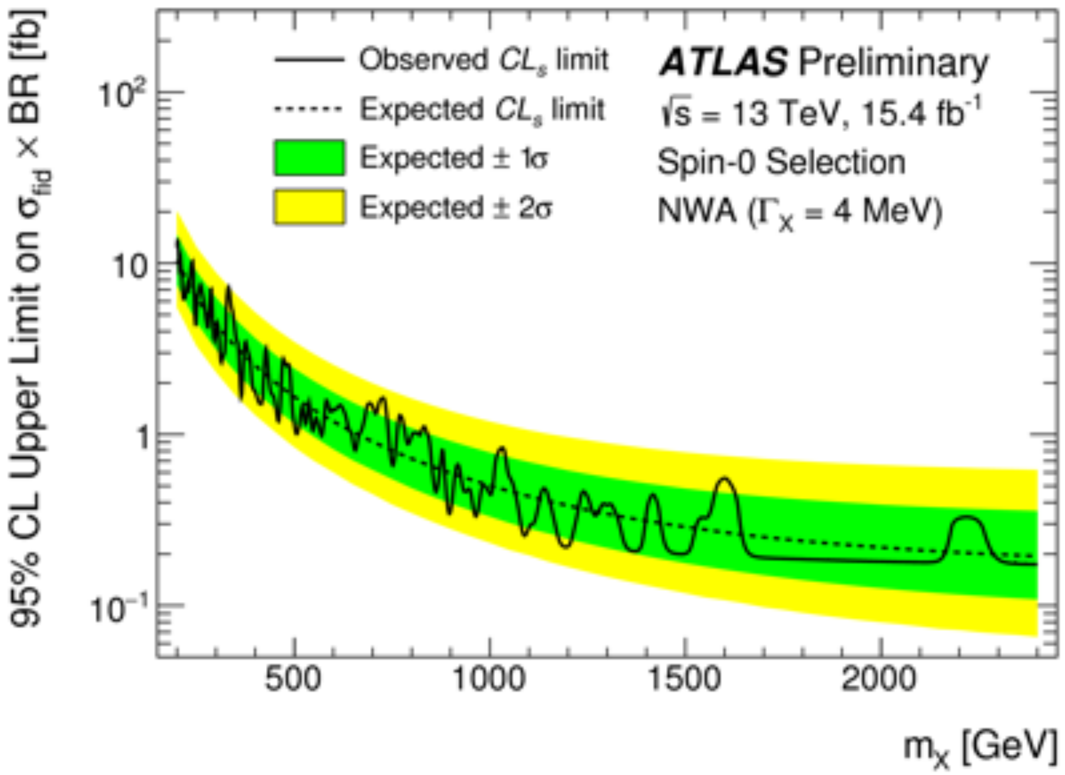
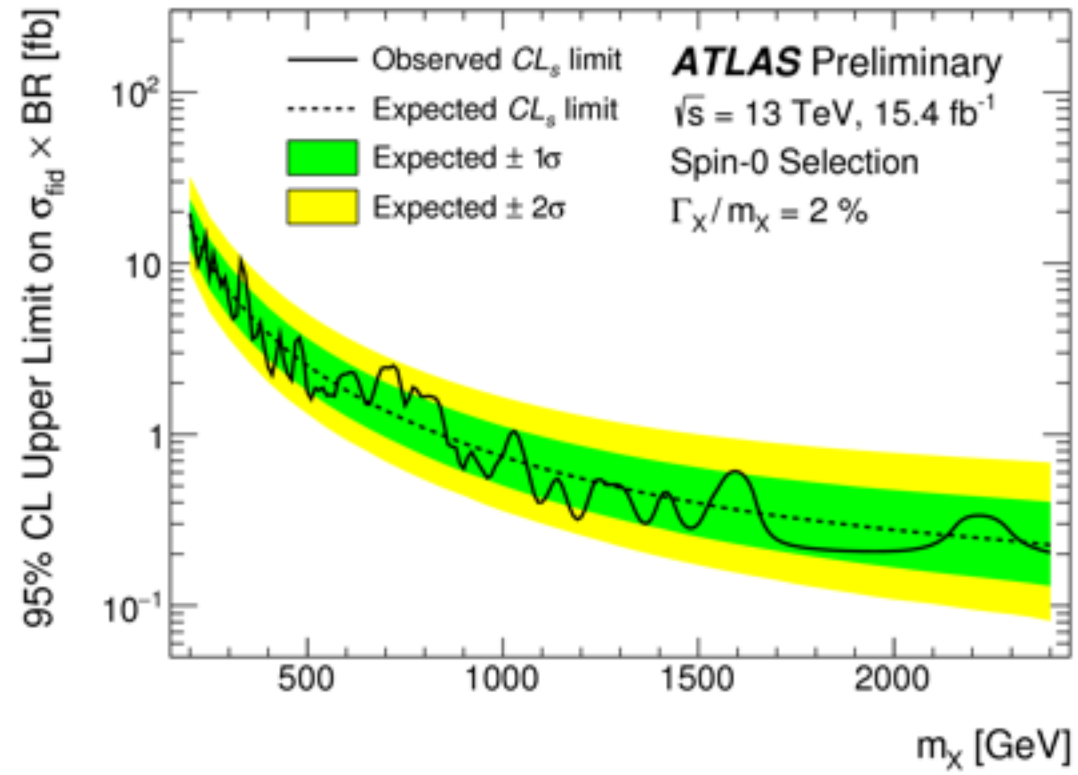
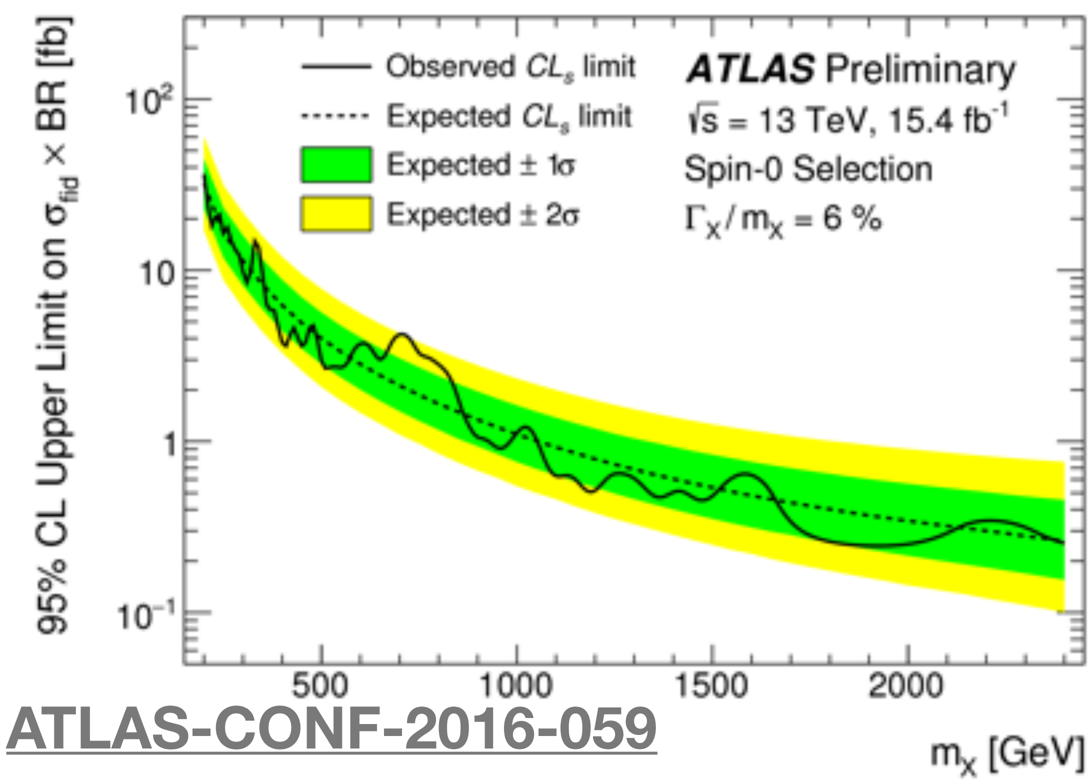
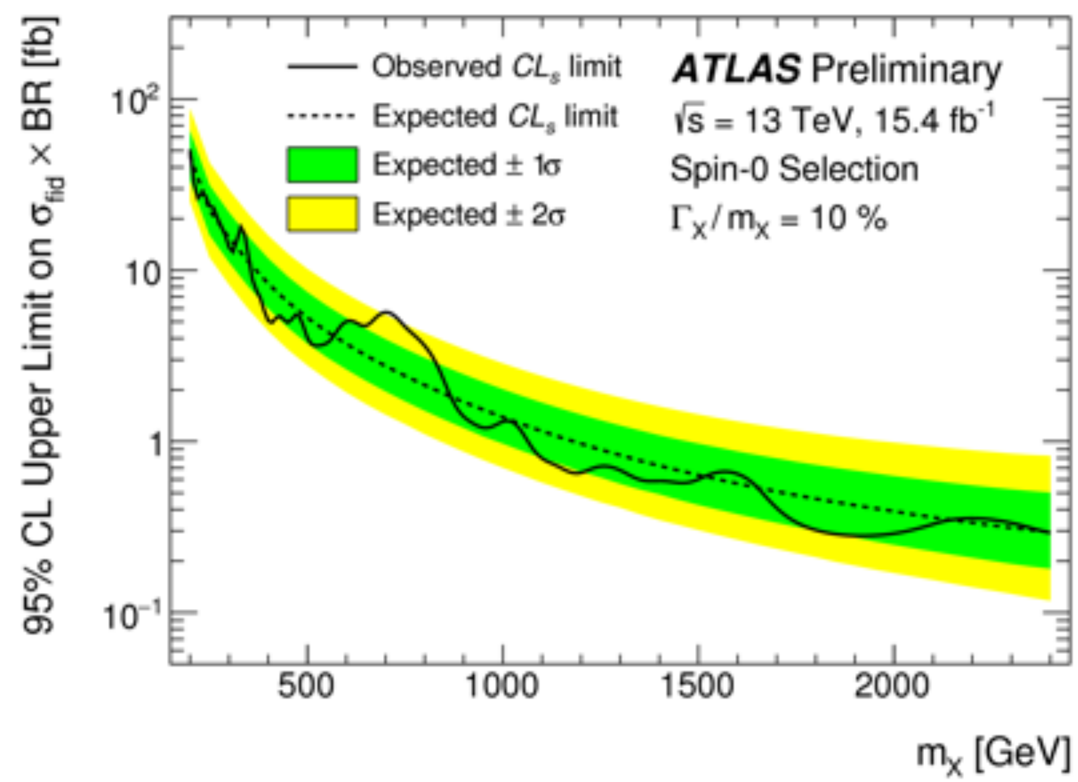
High mass γγ: 1D limits









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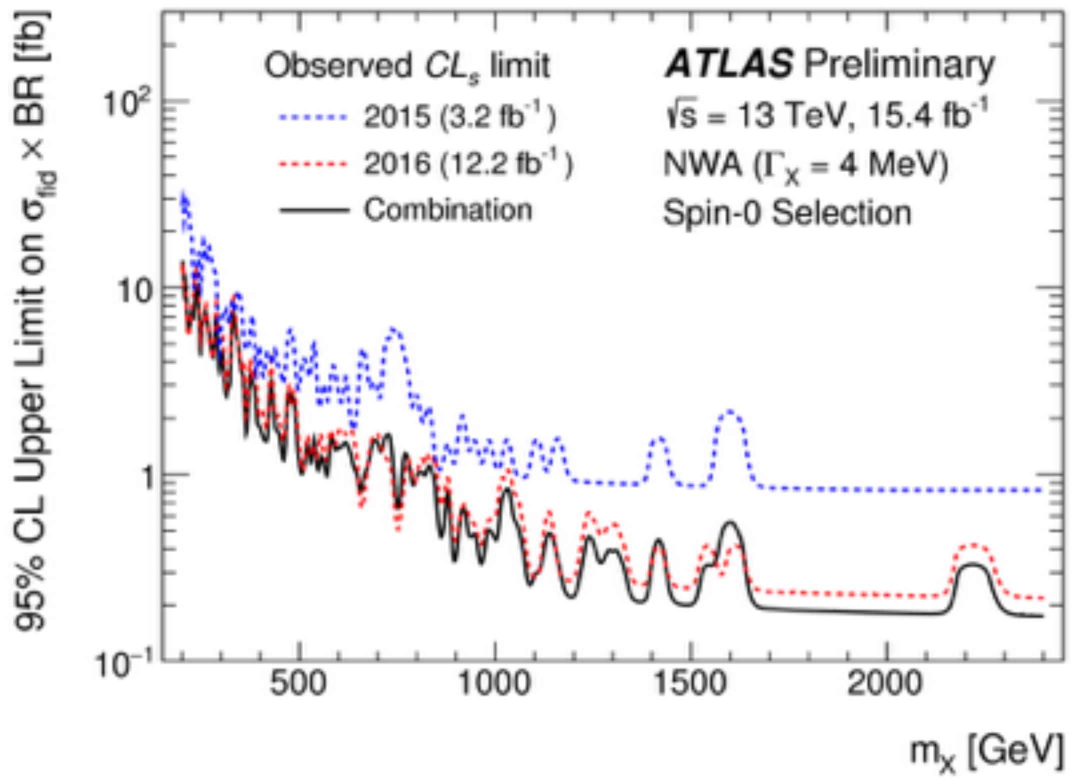
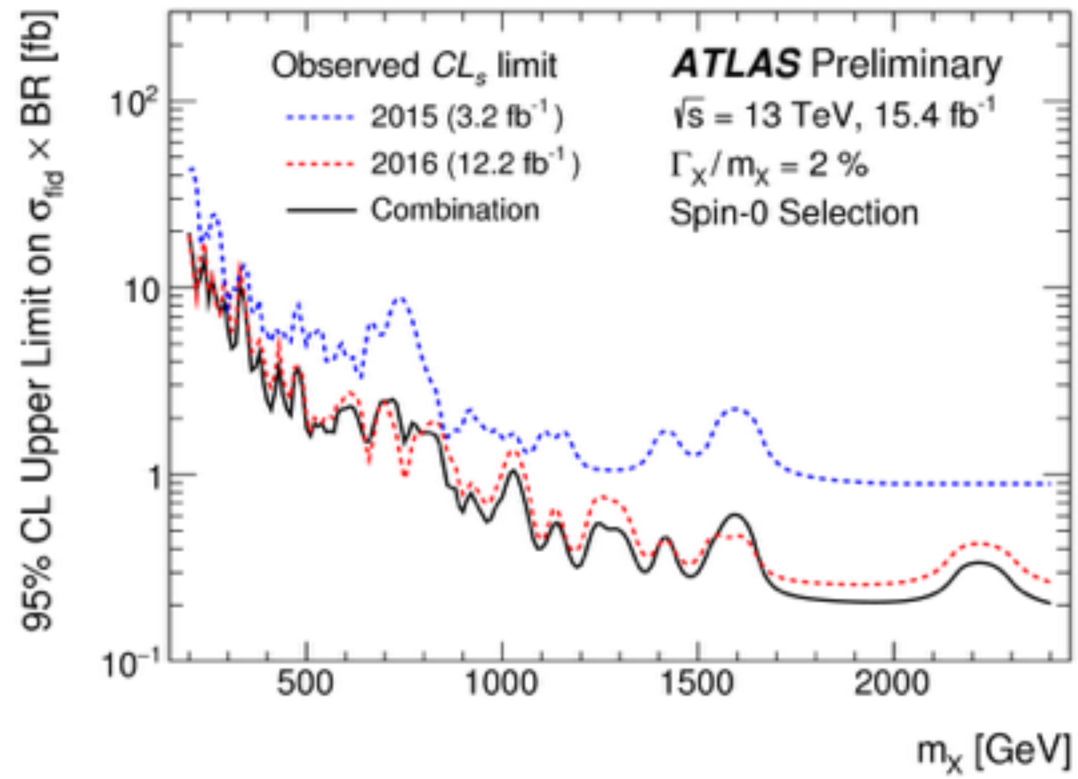
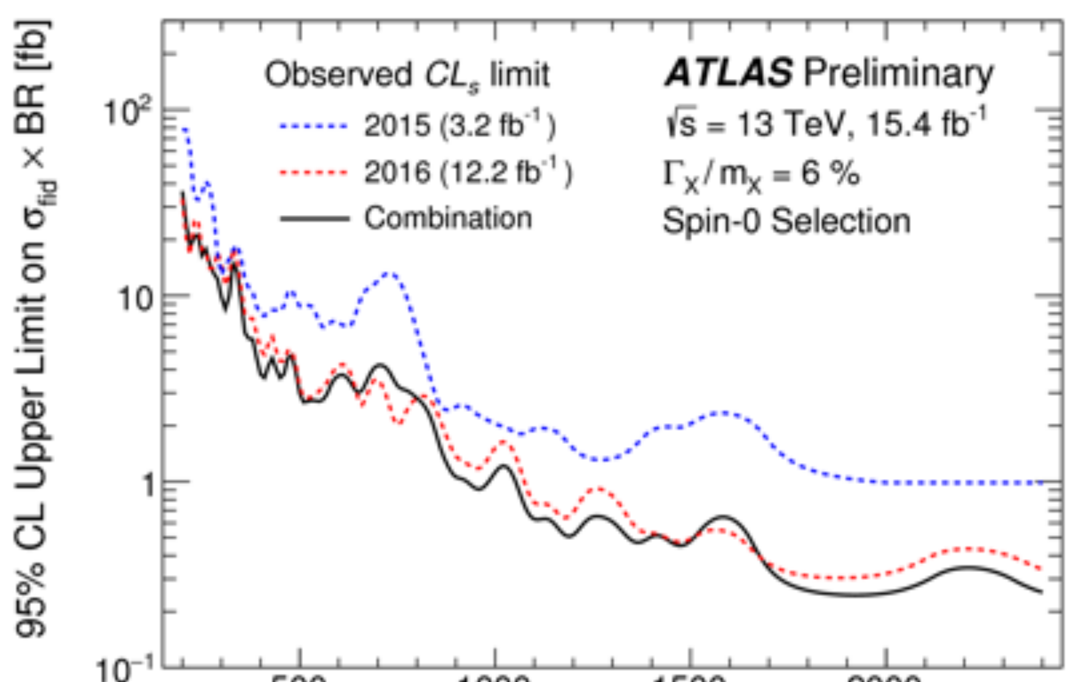
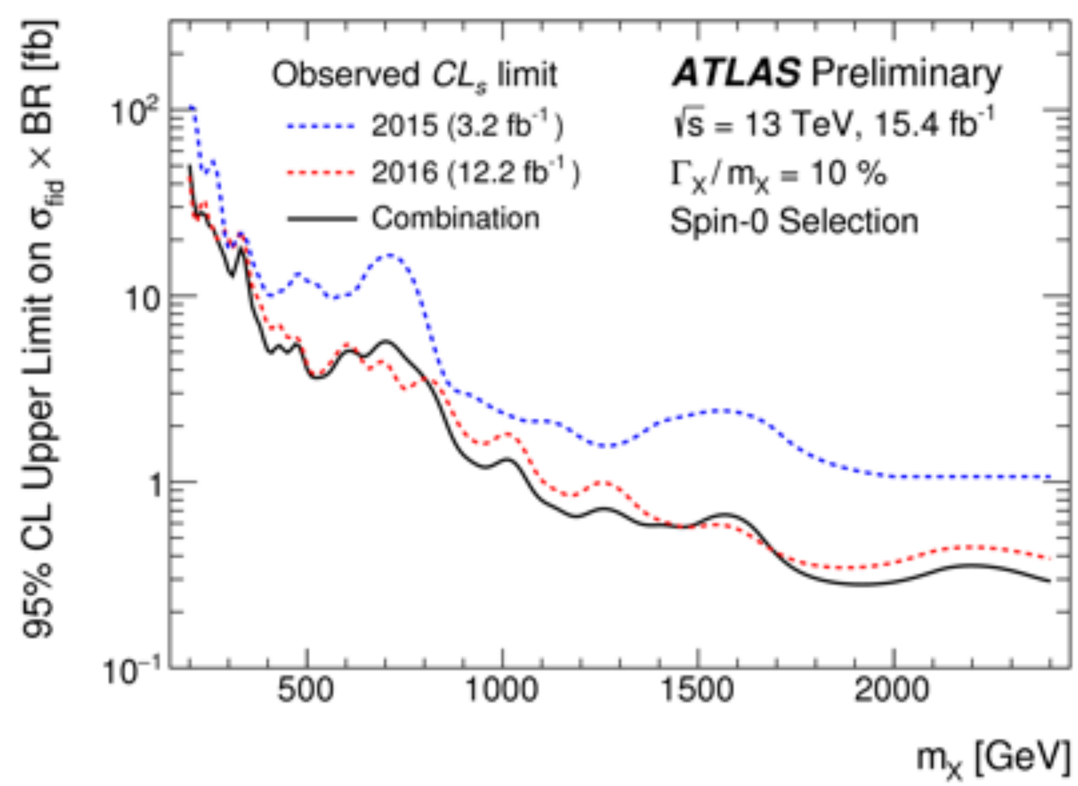
High mass γγ: 1D observed limits comparison



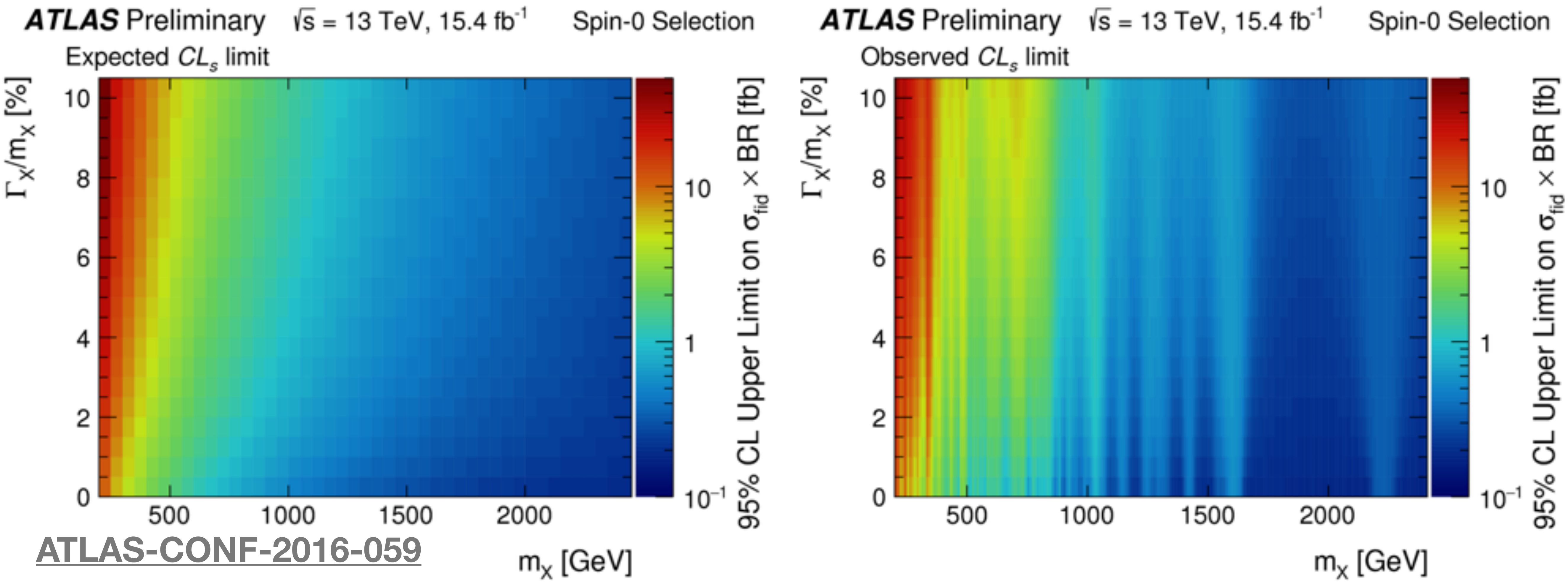






<u>**ATLAS-CONF-2016-059**</u>

High mass γγ: 2D limits



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m_X [GeV]	500	600	750	850	1000	1200	1500	2000
NWA								
$\sigma^{obs}_{95\%}$ [fb]	1.14	1.40	0.67	0.73	0.45	0.22	0.20	0.18
$\sigma^{exp}_{95\%}$ [fb]	(1.66)	(1.19)	(0.80)	(0.65)	(0.50)	(0.38)	(0.29)	(0.22)
$\pm 1\sigma$	1.16,2.42	0.82,1.76	0.55,1.21	0.44,1.0	0.33,0.78	0.25,0.62	0.18,0.48	0.13,0.39
$\pm 2\sigma$	0.84,3.47	0.60,2.55	0.39,1.79	0.31,1.48	0.23,1.19	0.17,0.96	0.12,0.79	0.08,0.66
$\Gamma_X/m_X = 6\%$								
$\sigma^{obs}_{95\%}$ [fb]	2.93	3.72	3.27	1.78	1.12	0.52	0.48	0.25
$\sigma^{exp}_{95\%}$ [fb]	(4.01)	(2.82)	(1.87)	(1.49)	(1.10)	(0.79)	(0.54)	(0.34)
$\pm 1\sigma$	2.83,5.67	2.01,4.04	1.32,2.71	1.04,2.16	0.76,1.62	0.54,1.19	0.35,0.84	0.22,0.57
$\pm 2\sigma$	2.09,7.8	1.47,5.6	0.97,3.79	0.75,3.06	0.55,2.33	0.38,1.74	0.25,1.26	0.14,0.90

High mass γγ: Systematics

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)	$\pm(2–3)\%$	
Signal photon isolation (mass dependent)	$\pm(2–1)\%$	$\pm(4–1)\%$
Signal production process	N/A	$\pm(3–6)\%$ depending on Γ
Trigger efficiency	$\pm0.6\%$	
Luminosity	$\pm5.0\%$	

γγ+MET: Event selection

<table>
<tr><td>Trigger</td><td>HLT_g35_loose_g25_loose</td><td rowspan="4">Muons</td><td>$\lvert\eta_\gamma\rvert < 2.7$</td></tr>
<tr><td rowspan="3">Photons</td><td>$\lvert\eta_\gamma\rvert < 2.37$ excluding $1.37 < \lvert\eta_\gamma\rvert < 1.52$</td><td>Medium ID, isolation</td></tr>
<tr><td>Tight photon ID, calorimeter and track isolation</td><td>pT>10 GeV</td></tr>
<tr><td>$p_T^{\gamma1} > 35$ GeV, $p_T^{\gamma1} > 25$GeV
$p_T^{\gamma1}/m_{\gamma\gamma} > 0.4$, $p_T^{\gamma2}/m_{\gamma\gamma} > 0.3$</td><td>$\lvert d_0\rvert/\sigma_{d0} < 3$, $\lvert z_0\rvert \sin\theta < 0.5$mm</td></tr>
<tr><td rowspan="4">Electrons</td><td>$\lvert\eta_\gamma\rvert < 2.47$ excluding $1.37 < \lvert\eta_\gamma\rvert < 1.52$</td><td rowspan="3">Jets</td><td>$\lvert\eta_\gamma\rvert < 4.4$</td></tr>
<tr><td>Medium LH ID, isolation</td><td>pT>25 GeV</td></tr>
<tr><td>pT>10 GeV</td><td>JVT cuts</td></tr>
<tr><td>$\lvert d_0\rvert/\sigma_{d0} < 5$, $\lvert z_0\rvert \sin\theta < 0.5$mm</td><td>ET miss</td><td>Recalculated wrt the diphoton vertex.
Using track-based soft-terms.</td></tr>
</table>

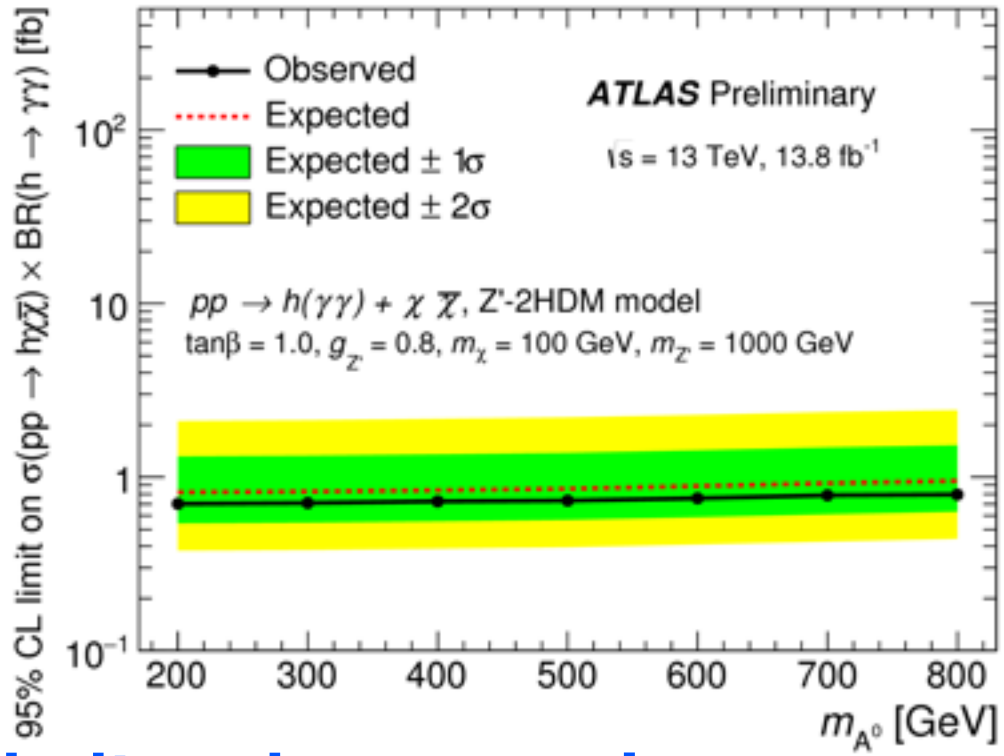
$\gamma\gamma$+MET: Signal and background MC

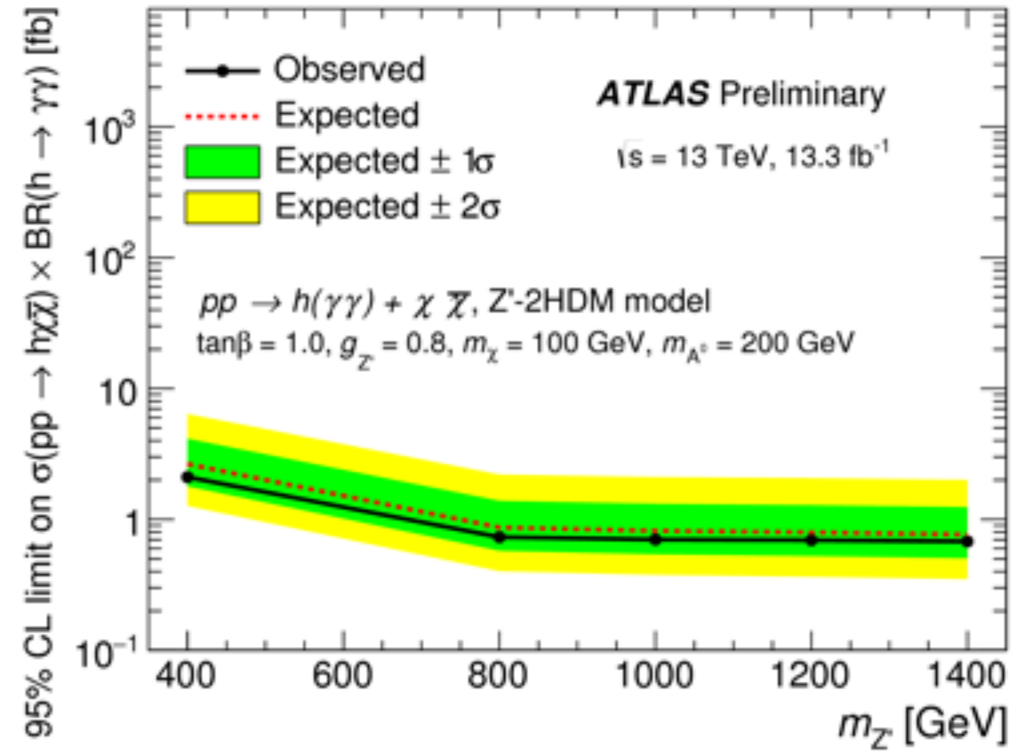
- Madgraph at LO using NNPDF3.0LO pdf.
- Z'_B model: DM particle of mass 1 GeV, coupling constant and missing parameter following recommendations: g_χ=1.0, g_q=1/3, $g_{hZ'Z'}$=$m_{Z'}$, sin θ= 0.3.
- Z'-2HDM model: m_χ=100 GeV, tan β=1.0, $g_{Z'}$=0.8.
- Heavy scalar: 260<m_H<350 GeV, m_χ=50, 60 GeV.

Process	Generators used	PDF set (ME, PS)	Tune
ggF, $h \to \gamma\gamma$	POWHEG [20] + PYTHIA 8	CT10 [21], CTEQ6L1 [22]	AZNLO [23]
VBF, $h \to \gamma\gamma$	POWHEG + PYTHIA 8	CT10, CTEQ6L1	AZNLO
Wh, $h \to \gamma\gamma$	PYTHIA 8	NNPDF2.3LO	A14
Zh, $h \to \gamma\gamma$	PYTHIA 8	NNPDF2.3LO	A14
$t\bar{t}h$, $h \to \gamma\gamma$	POWHEG + PYTHIA 8	NNPDF3.0LO, NNPDF2.3LO	A14
$b\bar{b}h$, $h \to \gamma\gamma$	POWHEG + PYTHIA 8	NNPDF3.0LO, NNPDF2.3LO	A14
$\gamma\gamma$ + 3 jets	SHERPA [24]	CT10	-
$Z\gamma \to ll\gamma$ ($l = \mu$, e, τ, or ν) + up to 3 jets	SHERPA	CT10	-
$W\gamma \to l\nu\gamma$ ($l = \mu$, e, or τ) + up to 3 jets	SHERPA	CT10	-
$Z\gamma\gamma \to ll\gamma\gamma$ ($l = \mu$, e, τ, or ν) + up to 2 jets	SHERPA	CT10	-
$W\gamma\gamma \to l\nu\gamma\gamma$ ($l = \mu$, e or τ) + up to 2 jets	SHERPA	CT10	-

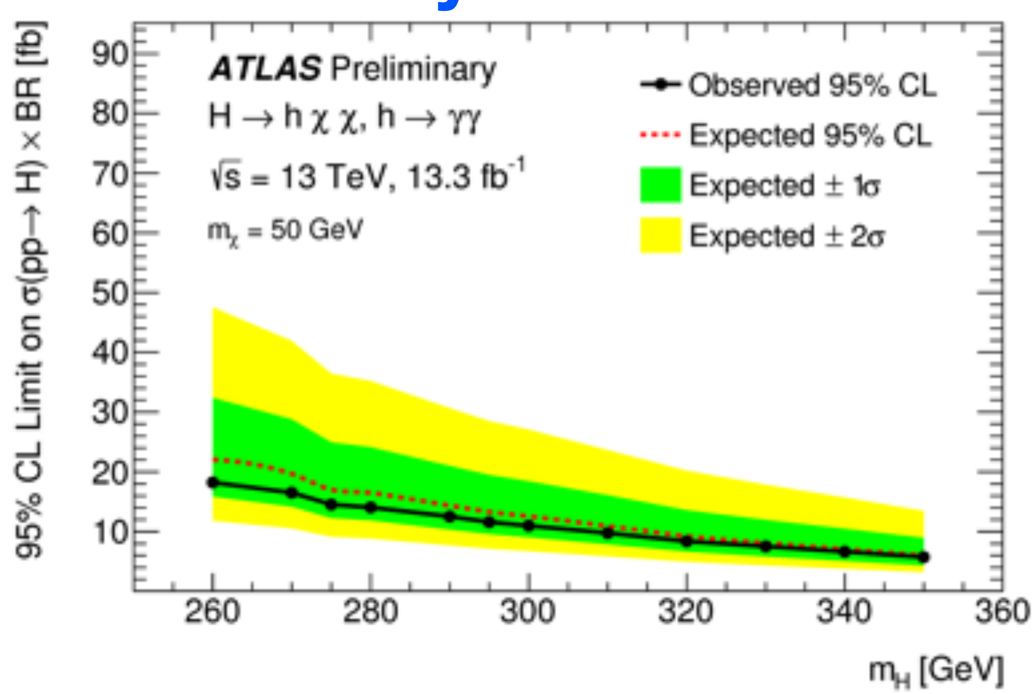
γγ+MET: Additional limit plots

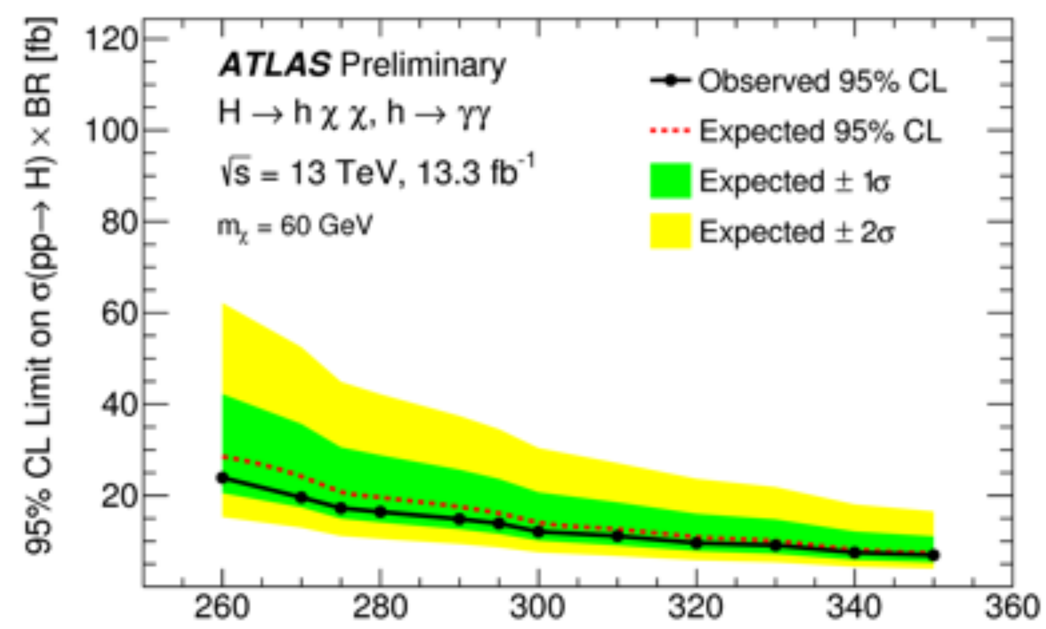
Limit on Z’ and A⁰ mass in Z’-2HDM model





Limit on heavy scalar mass





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γγ+MET: Systematic uncertainties

Source	Maximum uncertainty (%)
Experimental	
Luminosity	2.9
Trigger efficiency	0.4
Vertex selection	3.6 (Intermediate), 20 (High $S_{E_{\mathrm{T}}^{\mathrm{miss}}}$)
Photon identification efficiency	2.8
Photon energy scale	1
Photon energy resolution	2
Photon isolation efficiency	4
$S_{E_{\mathrm{T}}^{\mathrm{miss}}}$ reconstruction	1 (Rest), 20 (Intermediate and High $S_{E_{\mathrm{T}}^{\mathrm{miss}}}$)
Pile-up reweighting	1.0
Theoretical	
QCD scale uncertainty of ggF p_{T} spectrum	10 - 20
Modelling of ggH $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum	25
PDF	9
MPI	1 (Intermediate), 50 (High $S_{E_{\mathrm{T}}^{\mathrm{miss}}}$)
BR($h \to \gamma\gamma$)	4.9

γγ+MET: Event yields

Category	Intermediate $S_{E_T^{miss}}$	High $S_{E_T^{miss}}$, High $p_T^{\gamma\gamma}$	High $S_{E_T^{miss}}$, Low $p_T^{\gamma\gamma}$	Rest
Data	1862	25	98	85551
Heavy scalar, $m_H = 275\ GeV$, $m_\chi = 50\ GeV$				
Yields	54.9±1.2	5.41±0.39	6.93±0.41	102.1±1.6
Selection Eff(%)	12.32±0.26	1.21±0.09	1.55±0.09	22.89±0.35
Heavy scalar, $m_H = 275\ GeV$, $m_\chi = 60\ GeV$				
Yields	57.8±1.3	7.65±0.45	6.01±0.40	159.3±2.1
Selection Eff(%)	9.52±0.21	1.26±0.07	0.99±0.07	26.22±0.34
Z'_B model, $m_{Z'} = 200\ GeV$, $m_\chi = 1\ GeV$				
Yields	7.61 ± 0.12	7.82 ± 0.12	0.97 ± 0.04	8.32 ± 0.12
Selection Eff(%)	15.5 ± 2.0	16.5 ± 2.0	2.20 ± 0.30	17.5 ± 3.0
Z'-2HDM model, $m_{Z'} = 1000\ GeV$, $m_{A^0} = 200\ GeV$, and $m_\chi = 100\ GeV$				
Yields	0.05 ± 0.01	10.61 ± 0.11	0.002 ± 0.001	0.020 ± 0.001
Selection Eff(%)	0.34 ± 0.03	63.98 ± 0.46	0.10 ± 0.10	0.10 ± 0.02
Backgrounds				
SM Higgs boson	13.21 ± 0.13	1.26 ± 0.02	0.51 ± 0.02	527 ± 0.92
Non-resonant	1845 ± 48	24.9 ± 5.6	97 ± 11	85210 ± 330