TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Physik Institut für Kern- und Teilchenphysik

Measurements of prompt photon production with the ATLAS detector

Frank Siegert

on behalf of the ATLAS collaboration

ICHEP 2020

CERN

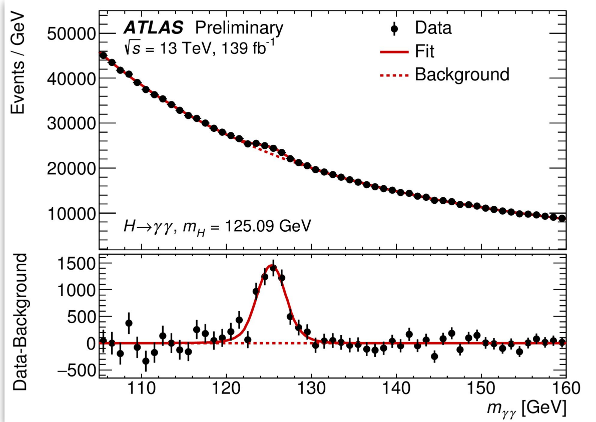
ATLAS EXPERIMENT

Emmy Noether-Programm

Deutsche Forschungsgemeinschaft DFG

Why are we interested in prompt photons?

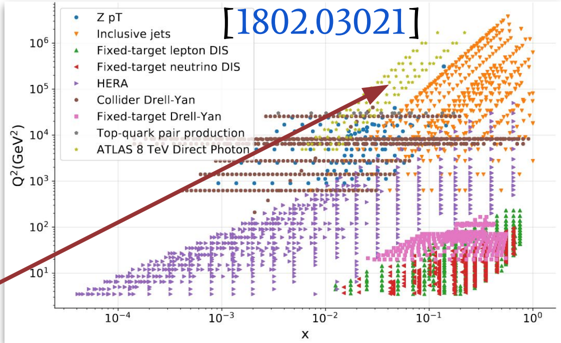
[ATLAS-CONF-2019-029]

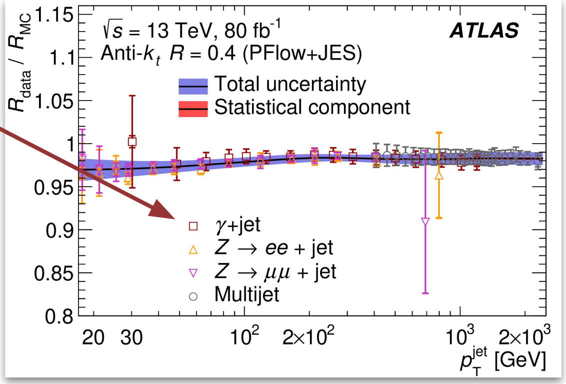


- Prompt photon pairs relevant for SM Higgs measurements and BSM resonance searches

- Single-photon (+ jets) for PDFs and jet calibration

[1802.03021]





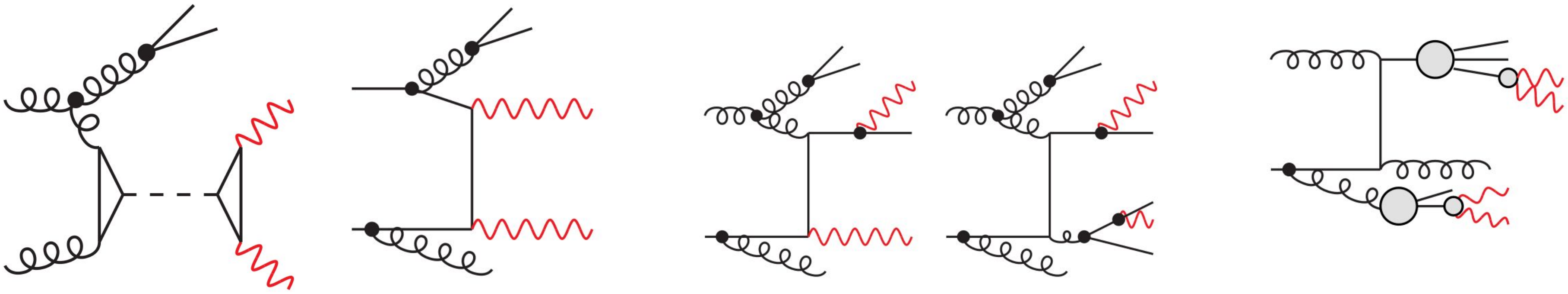
[2007.02645]

- **Prompt photons are interesting in themselves as testing ground for perturbative QCD**
    - Non-trivial QCD effects despite QED core process

⤳ later!

Sources of photons at the LHC

- Possible photon (pair) production mechanisms at the LHC:



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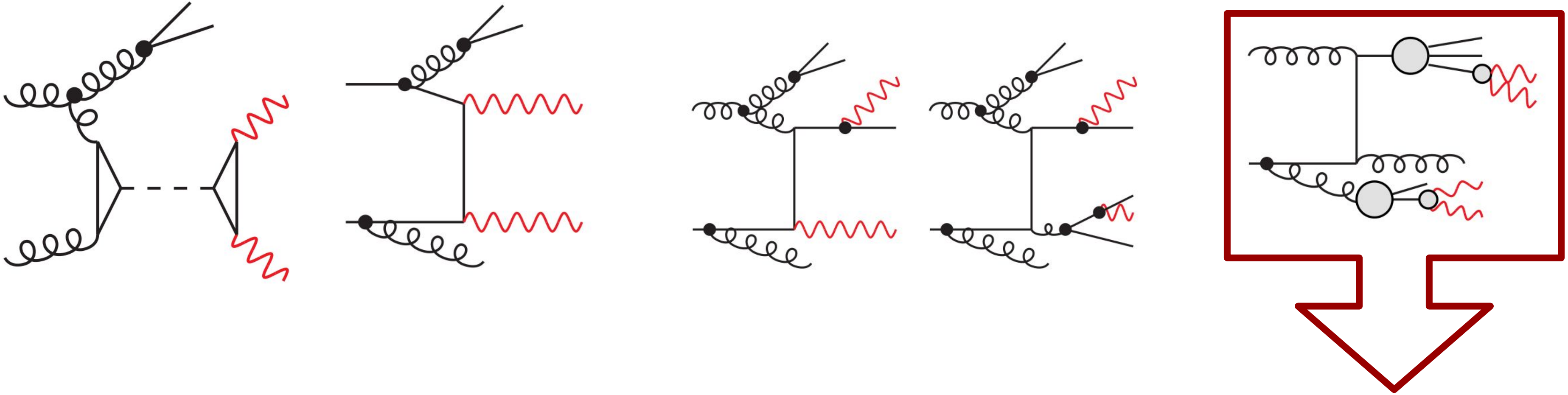

Non-prompt photons from hadron decays (e.g. $\pi^0 \rightarrow \gamma\gamma$):
Here: Main background!

Sources of photons at the LHC

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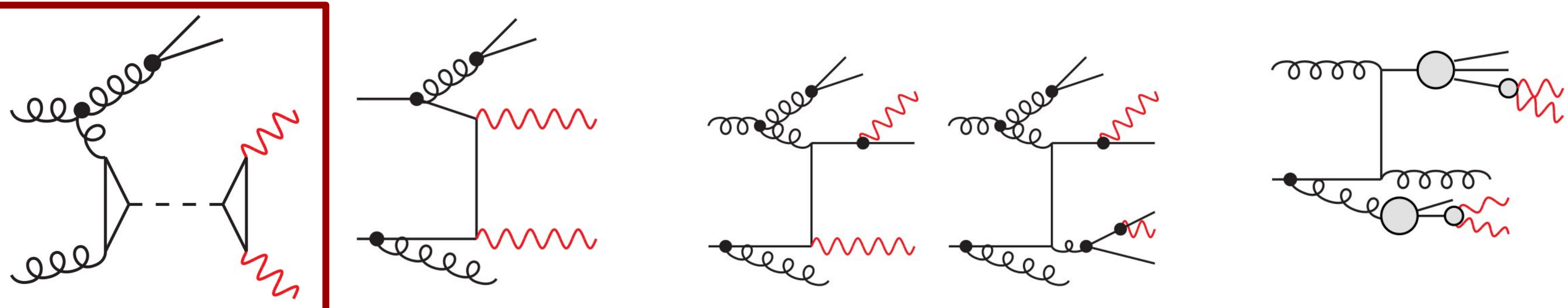


Resonant production of photon pairs (e.g. gg → H → γγ):

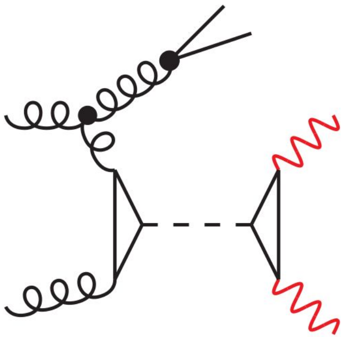
Here: Negligible (but included).

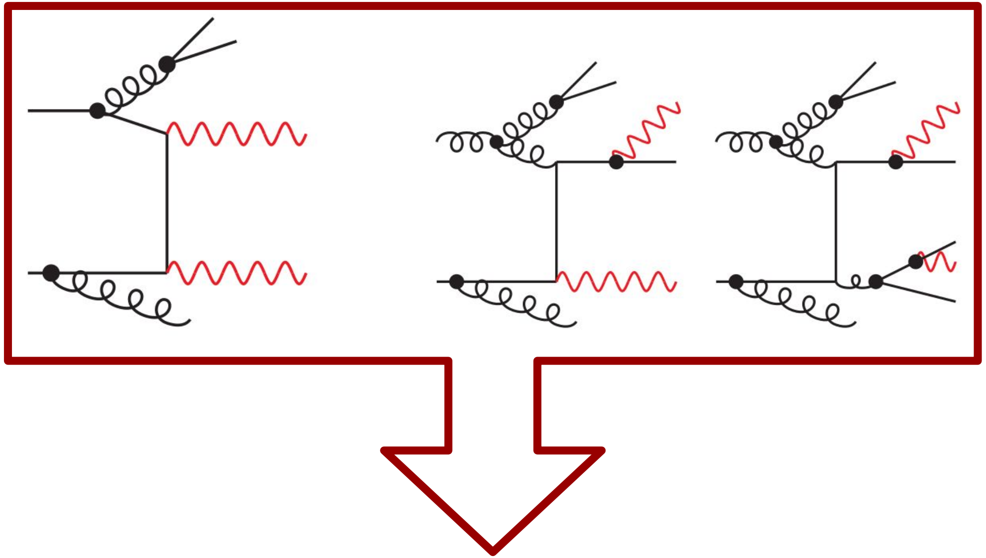
See dedicated ATLAS searches/measurements

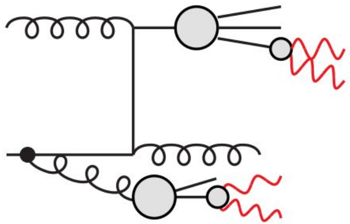
in presentations by [Antoine], [Yufeng], [Alex], [Artem]

Sources of photons at the LHC

- Possible photon (pair) production mechanisms at the LHC:

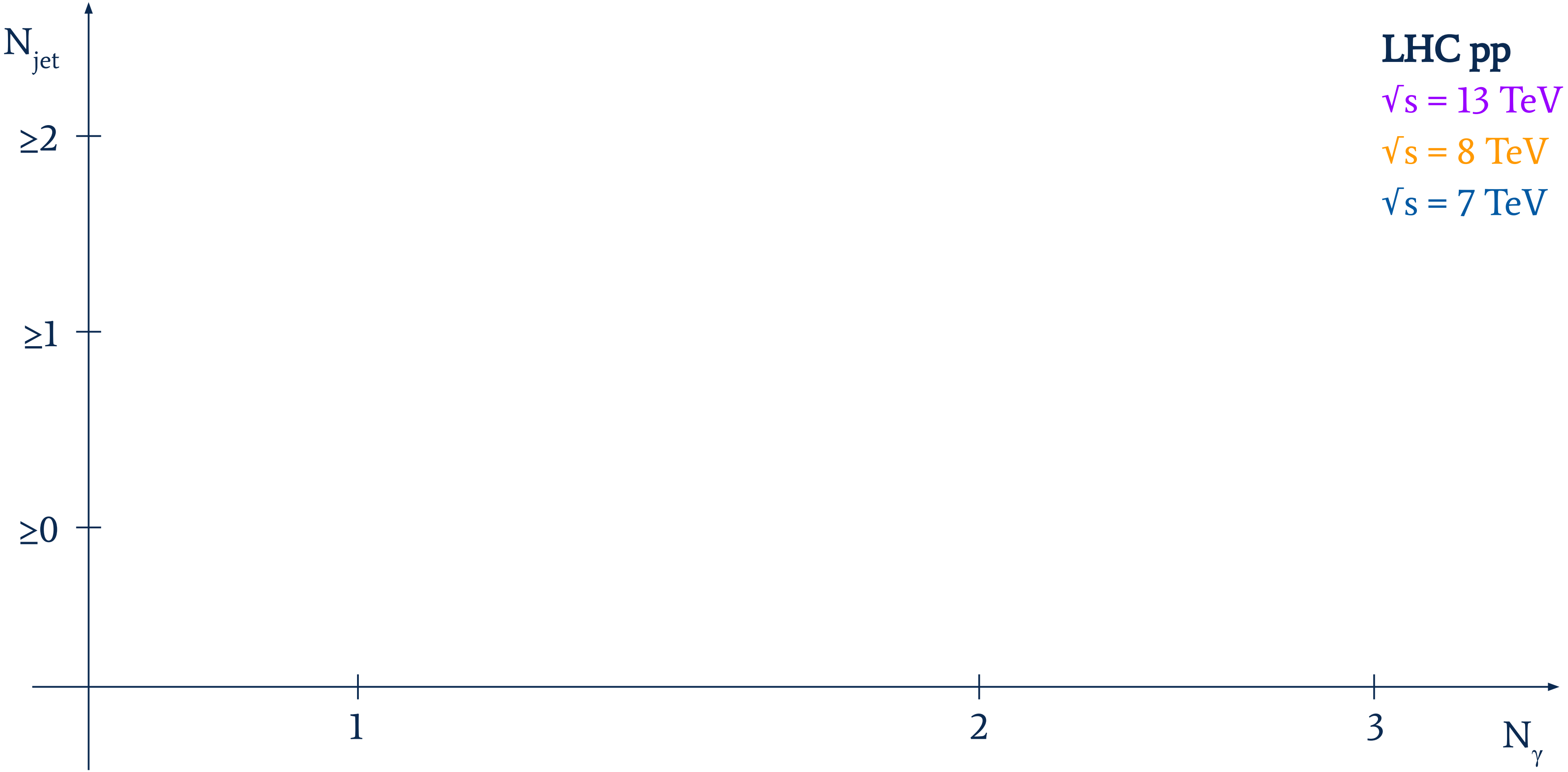






Continuum production of photon (pairs):
Theoretical description by “direct” and “fragmentation” production.
Experimentally: Isolated photons with strict EM shower identification.

Landscape of ATLAS prompt photon measurements



Landscape of ATLAS prompt photon measurements

LHC pp

√s = 13 TeV

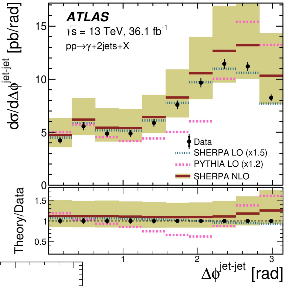
√s = 8 TeV

√s = 7 TeV

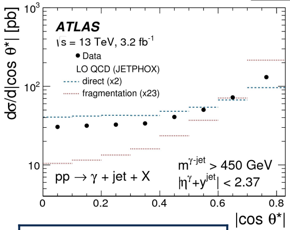
N_{jet}

≥2

1611.06586
1912.09866



≥1



1203.3161
1307.6795
1611.06586
1801.00112

≥0

1012.4389
1108.0253
1311.1440
1605.03495
1701.06882
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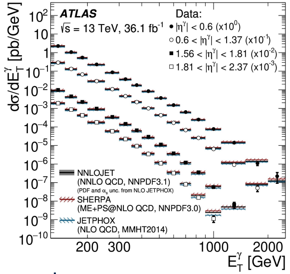
1908.02746



1 2 3 N_{γ}

Landscape of ATLAS prompt photon measurements

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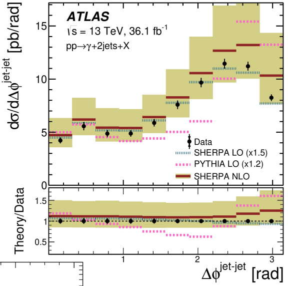

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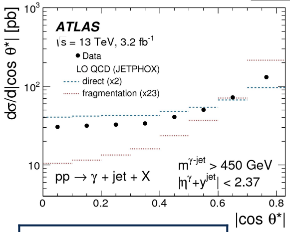

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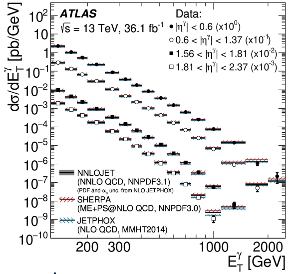
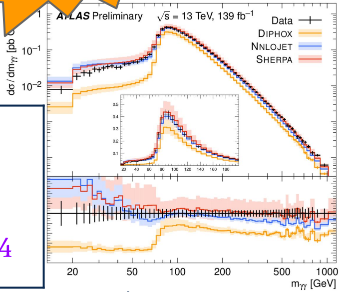


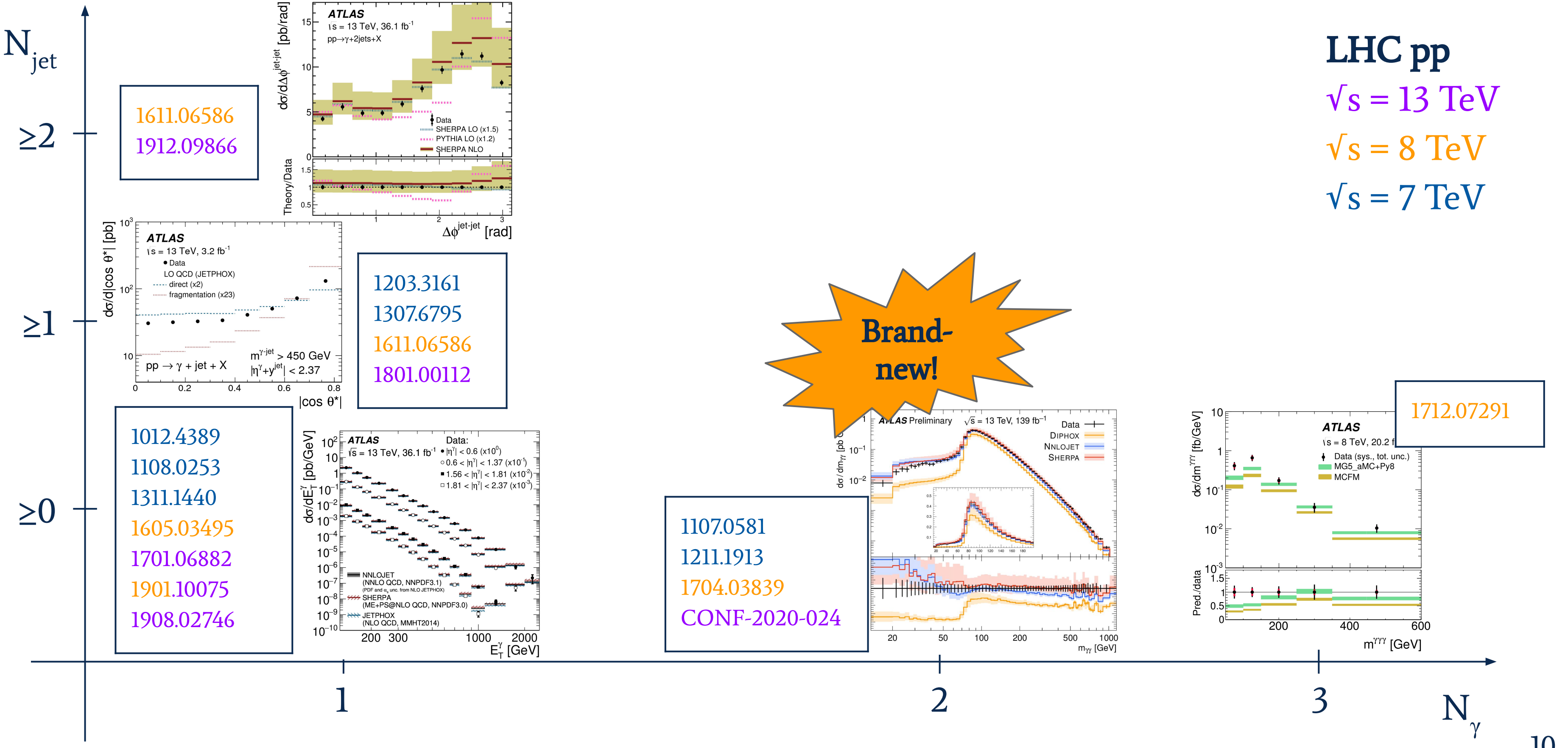
Brand-new!

1107.0581
1211.1913
1704.03839
CONF-2020-024



1
2
3
N_γ

Landscape of ATLAS prompt photon measurements



Landscape of ATLAS prompt photon measurements

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LHC pp

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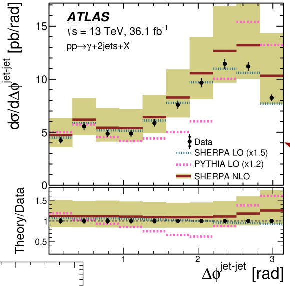
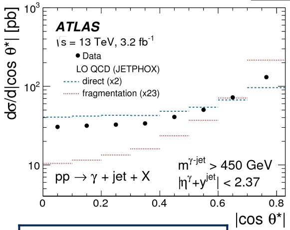


Today's focus:

- γ + 2 jets @ 13 TeV
- γγ @ 13 TeV

Brand-new!

≥1



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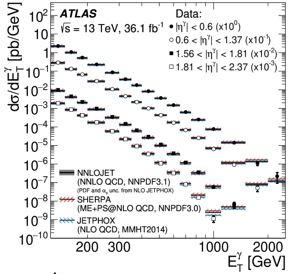

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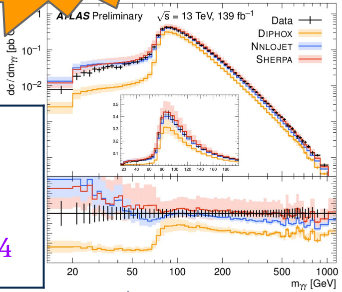
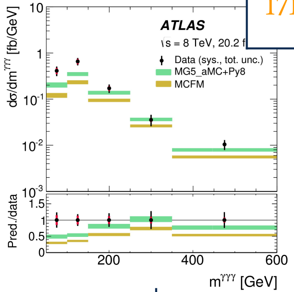


1712.07291



1 2 3

N_{γ}

Analysis definitions

Full Run2!

γ + 2 jets @ 13 TeV with 36/fb

- Fiducial phase space:

Requirements on photon	$E_T^\gamma > 150$ GeV, $\lvert\eta^\gamma\rvert < 2.37$ (excluding $1.37 < \lvert\eta^\gamma\rvert < 1.56$) $E_T^{iso} < 0.0042_T^\gamma + 4.8$ GeV (reconstruction level) $E_T^{iso} < 0.0042_T^\gamma + 10$ GeV (particle level)		
Requirements on jets	at least two jets using anti-k_t algorithm with $R = 0.4$ $p_T^{jet} > 100$ GeV, $\lvert y^{jet}\rvert < 2.5$, $\Delta R^{\gamma-jet} > 0.8$		
Phase space	**total**	**fragmentation enriched** $E_T^\gamma < p_T^{jet2}$	**direct enriched** $E_T^\gamma > p_T^{jet1}$
Number of events	755 270	111 666	386 846

- Observables constructed from final state of photon + jet + jet
  - $E_T(\gamma)$, $p_T(j)$, $y(j)$
  - $\Delta y(\gamma, j)$, $\Delta\Phi(\gamma, j)$
  - $\Delta y(j_1, j_2)$, $\Delta\Phi(j_1, j_2)$

γγ @ 13 TeV with 139/fb

- Fiducial phase space:

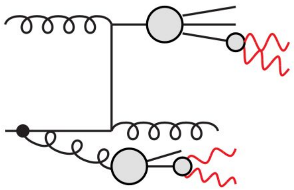
Selection	Detector level	Particle level
Photon kinematics	$E_{T,\gamma_{1(2)}} > 40(30)\ GeV$,	$\lvert\eta_\gamma\rvert < 2.37$ excluding $1.37 < \lvert\eta_\gamma\rvert < 1.52$
Photon identification	tight	stable, not from hadron decay
Photon isolation	$E_{T,\gamma}^{iso,0.2} < 0.05 \cdot E_{T,\gamma}$	$E_{T,\gamma}^{iso,0.2} < 0.09 \cdot E_{T,\gamma}$
Diphoton topology	$N_\gamma \geq 2, \quad \Delta R_{\gamma\gamma} > 0.4$	

- Observables constructed from two photons in final state
  - $E_T(\gamma_1)$, $E_T(\gamma_2)$
  - $m(\gamma\gamma)$, $p_T(\gamma\gamma)$, $\Delta\Phi(\gamma,\gamma)$
  - $\phi_\eta^* = \tan\frac{\pi - |\Delta\phi_{\gamma\gamma}|}{2} \sin\theta_\eta^*$ $\quad a_{T,\gamma\gamma} = 2 \cdot \frac{|p_{\gamma_1}^x p_{\gamma_2}^y - p_{\gamma_1}^y p_{\gamma_2}^x|}{|(p_{\gamma_1} - p_{\gamma_2})_T|}$

$$|\cos\theta^*|^{(CS)} = \left| \frac{\sinh(\Delta\eta_{\gamma\gamma})}{\sqrt{1 + (p_{T,\gamma\gamma}/m_{\gamma\gamma})^2}} \cdot \frac{2E_{T,\gamma_1}E_{T,\gamma_2}}{m_{\gamma\gamma}^2} \right|$$

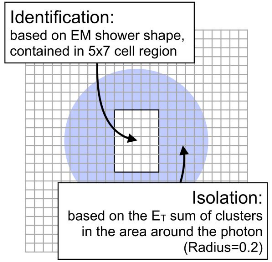
Main background: jets misidentified as photons

Common main background:
jet → ... + $\pi^0(\rightarrow\gamma\gamma)$

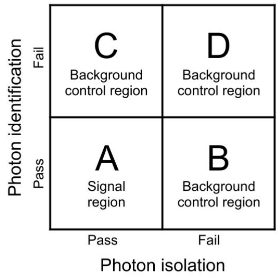


- Estimated using background-enriched control regions with looser selections on photon **identification** and **isolation**
- Basic idea for **γ+2j** analysis:
  Sideband (“ABCD”) technique

$$N_A^{\mathrm{sig}} = N_A - R_{\mathrm{bg}} \cdot (N_B - f_B N_A^{\mathrm{sig}}) \cdot \frac{(N_C - f_C N_A^{\mathrm{sig}})}{(N_D - f_D N_A^{\mathrm{sig}})}$$



Cells at the 2nd layer of the EM calorimeter



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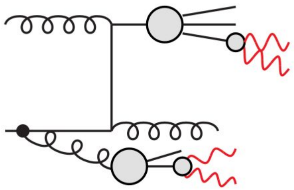

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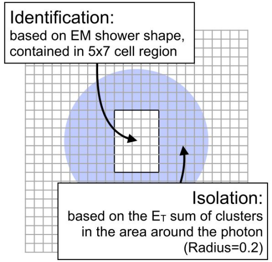

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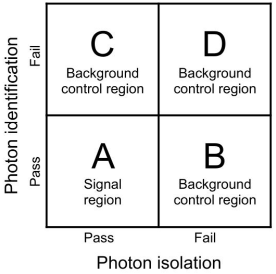
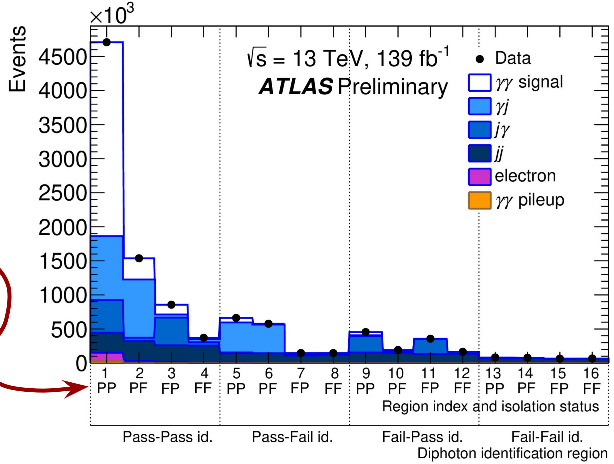


- For **γγ**: ABCD-based likelihood fit
  + extension to "4D" (i=1 … 16)
  + more processes p=γγ, γj, jγ, jj(, ee, PU)

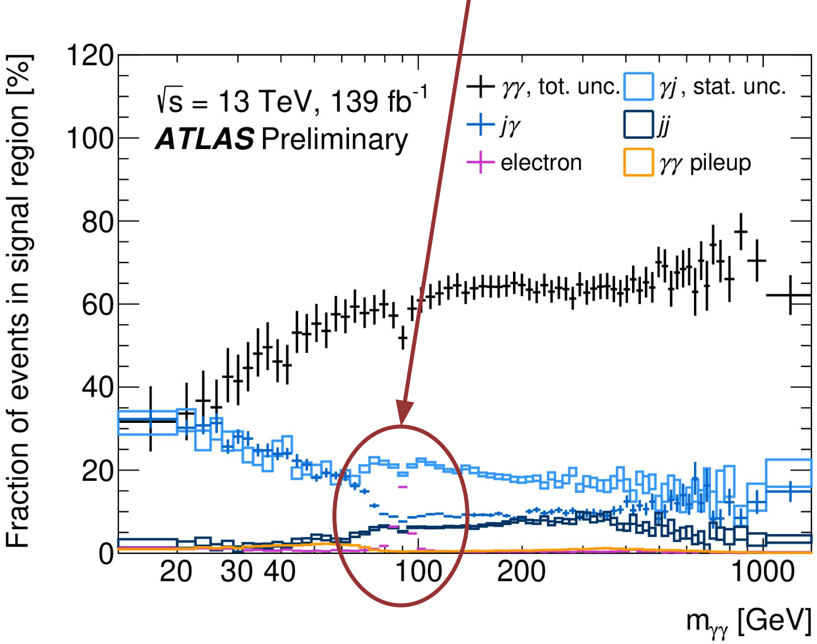
$$f_{p,i} = f_{p,i}(\varepsilon^{\text{iso}}_{p,o_1}, \varepsilon^{\text{iso}}_{p,o_2}, R^{\text{iso}}_p, \varepsilon^{\text{id}}_{p,o_1}, \varepsilon^{\text{id}}_{p,o_2}, R^{\text{id}}_p, R^{\text{iso-id}}_{p,o_1}, R^{\text{iso-id}}_{p,o_2})$$

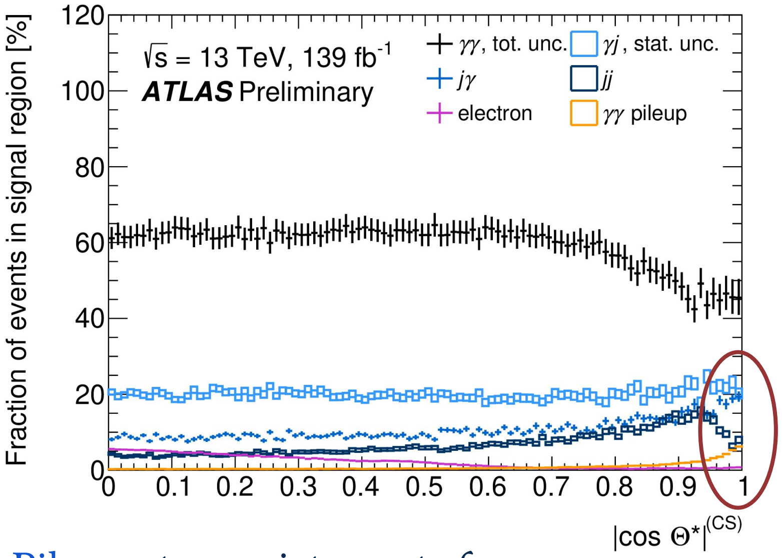
$$\begin{cases} \varepsilon^{\text{iso}}_{p,o_1} \quad \varepsilon^{\text{iso}}_{p,o_2} \quad \varepsilon^{\text{id}}_{p,o_1} \quad \varepsilon^{\text{id}}_{p,o_2} & \text{for } i=1 \\ \varepsilon^{\text{iso}}_{p,o_1} \quad (1-\varepsilon^{\text{iso}}_{p,o_2}) \quad \varepsilon^{\text{id}}_{p,o_1} \quad \varepsilon^{\text{id}}_{p,o_2} & \text{for } i=2 \\ (1-\varepsilon^{\text{iso}}_{p,o_1}) \quad \varepsilon^{\text{iso}}_{p,o_2} R^{\text{iso}}_p \quad \varepsilon^{\text{id}}_{p,o_1} \quad \varepsilon^{\text{id}}_{p,o_2} & \text{for } i=3 \\ \dots \\ (1-\varepsilon^{\text{iso}}_{p,o_1} R^{\text{iso-id}}_{p,o_1}) \quad (1-\varepsilon^{\text{iso}}_{p,o_2} R^{\text{iso}}_p R^{\text{iso-id}}_{p,o_2}) \quad (1-\varepsilon^{\text{id}}_{p,o_1}) \quad (1-\varepsilon^{\text{id}}_{p,o_2} R^{\text{id}}_p) & \text{for } i=16 \end{cases}$$



Subleading backgrounds in γγ

- Photons faked by (or radiated off) **electrons**
  - Estimated by MC
  - 3% inclusively
  - Significant only in $m_{\gamma\gamma} \sim m_Z$

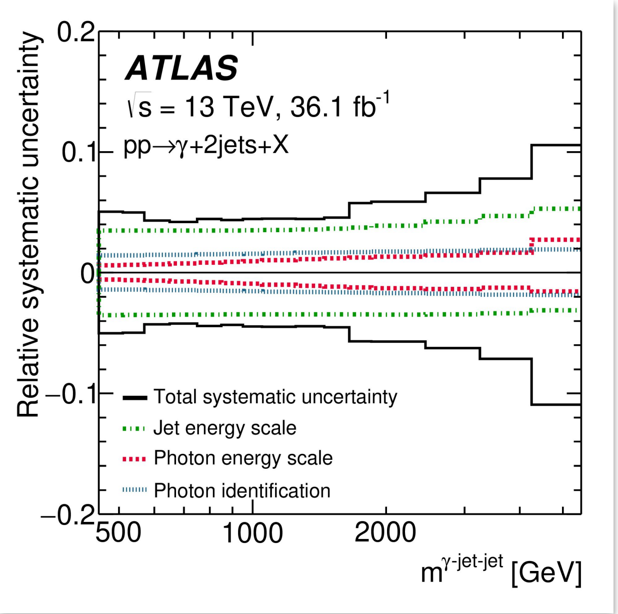


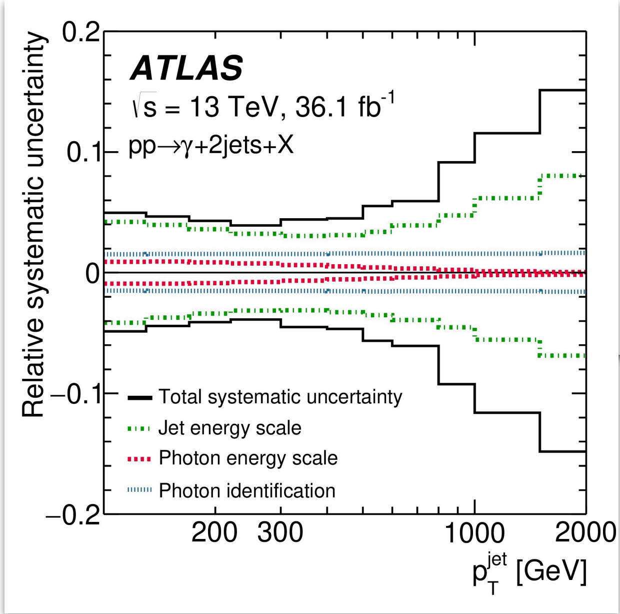


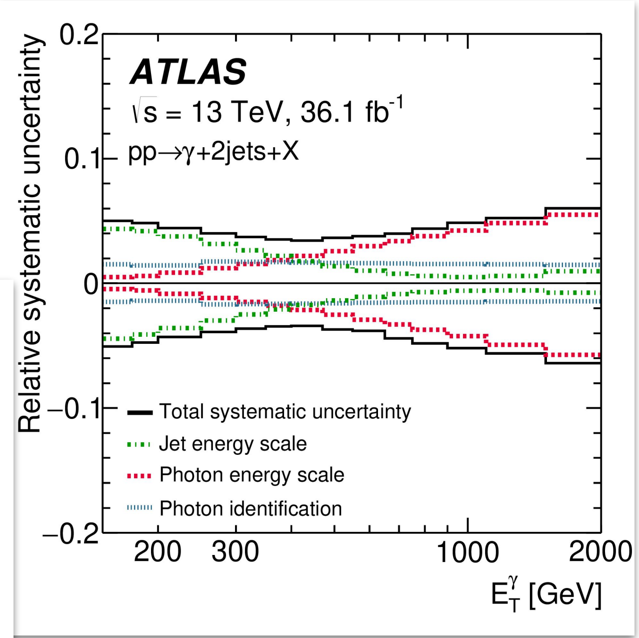
- Pile-up: two γ+jet events from **different pile-up vertices**!
  - 1% inclusively
  - Significant only in cos θ* → 1 configurations
  - Sophisticated data-driven estimation

Uncertainties in γ+2j

- Total uncertainties in 3% - 15% range
  - Dominated by **jet/photon energy scale** uncertainties
- Note: Negligible background fit uncertainty due to high E_T → high signal purity (>95%)







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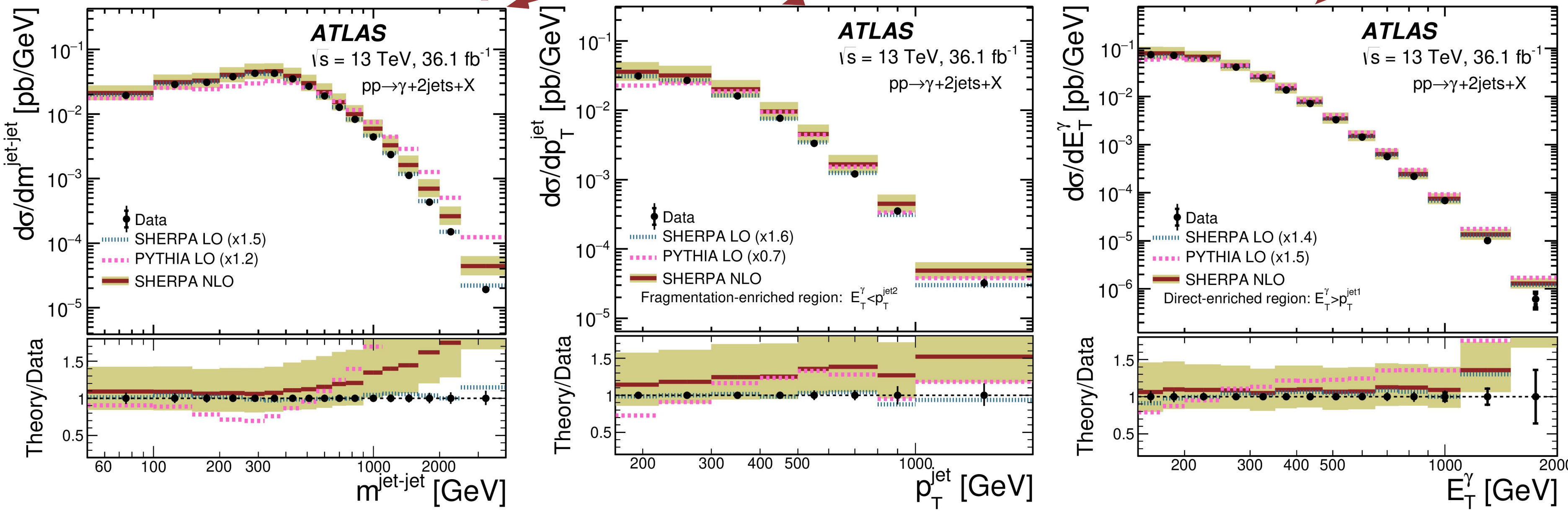
Results for γ+2j

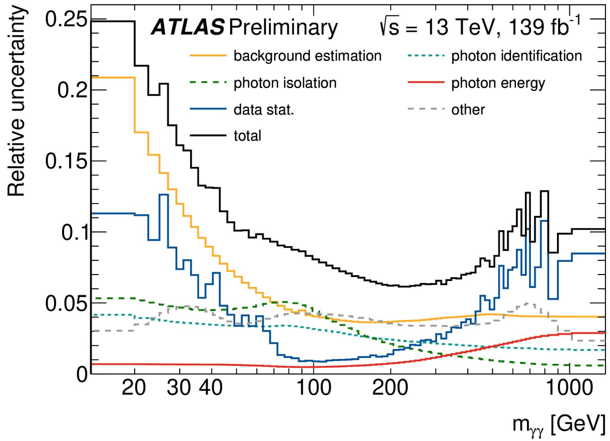
Phase space	total	fragmentation enriched $E_T^\gamma < p_T^{jet2}$	direct enriched $E_T^\gamma > p_T^{jet1}$

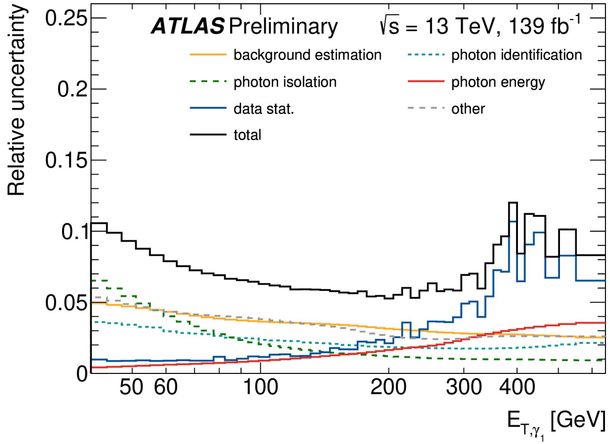
- 3 regions × 9 photon+jet+jet observables
- MC description fair, but with some challenges:
  - **High m_{jj} mismodelling** (similar to Z+jets!)
  - Parton shower (Pythia): **mismodelling of p_T's**



Uncertainties in γγ

- Dominant uncertainties:
  - Jet **background estimation** uncertainty from variation of fit assumptions
  - Modelling of **photon isolation** variable in MC and with pile-up
- Photon energy/identification only subleading
  - Different from γ+2j, where background unc negligible
- Total integrated uncertainty: 7.8% (syst) + 0.3% (stat)
- Largest uncertainties in **low $m_{\gamma\gamma}$** region: 25%
  - First measurement in this region!
  - Low purity and low data statistics in this multi-jet dominated region → large background estimation unc

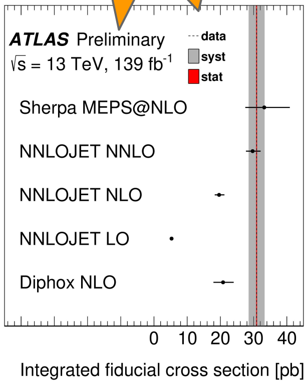


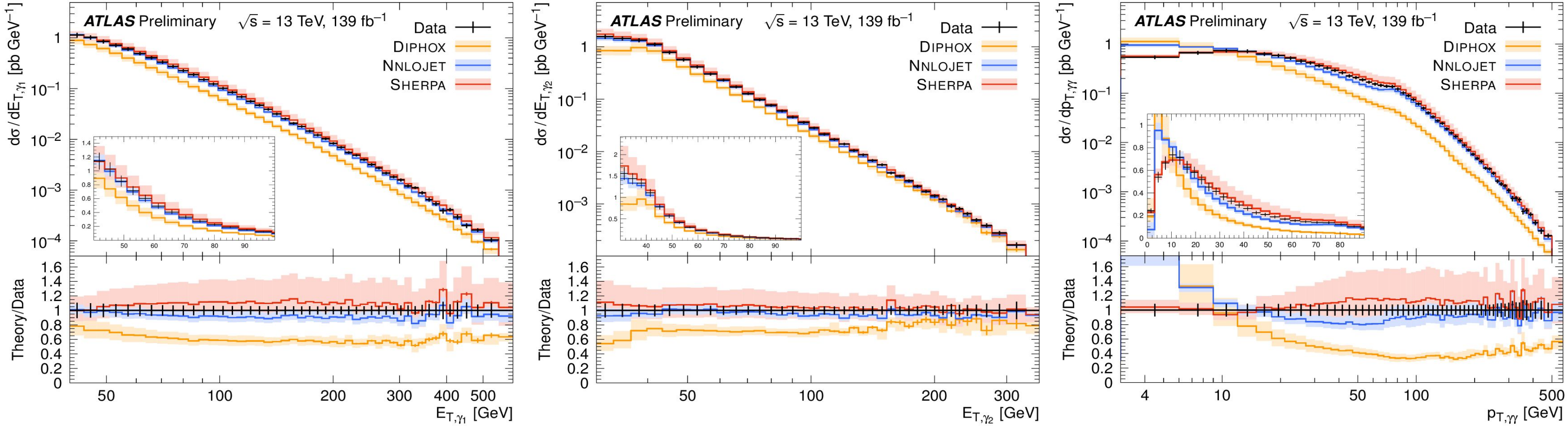


Results for γγ

Brand-new!

- Impressive impact from perturbative QCD even on **inclusive γγ rate**!
  - Generally good modelling of **perturbative regions** by the most precise predictions at NNLO and multi-leg merged NLO
  - Fixed-order predictions not valid in **soft/collinear regions**, e.g. low $p_T(\gamma\gamma)$
- Theory prediction uncertainties dominated by QCD scale variations
  - Subleading uncertainties from PDFs, α_S, fragmentation scale (Diphox)





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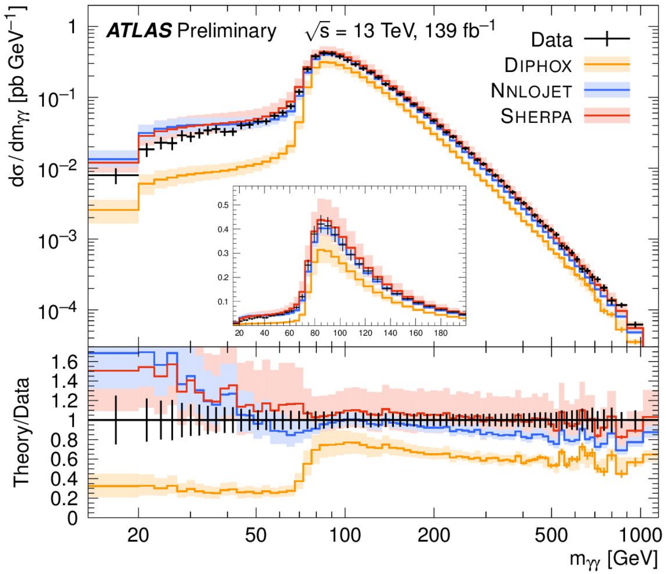
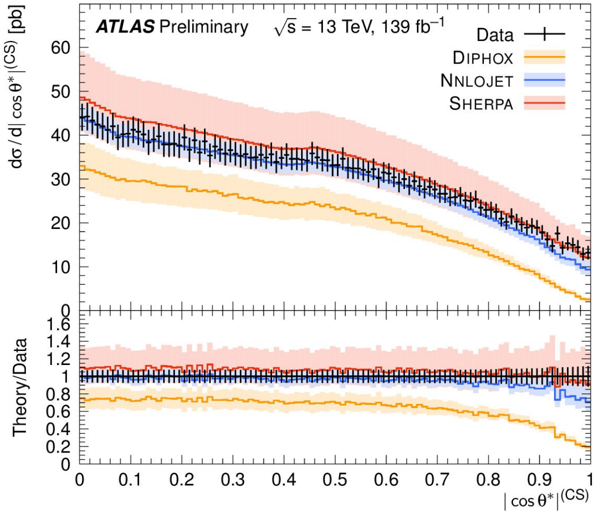
Results for γγ

Brand-new!

- $m_{\gamma\gamma}$ sculpted by $p_{T,\gamma}$ cuts
  - below peak (≤70 GeV) only populated through **multi-jet configurations**
  - best modelled by higher-order predictions, but still only barely within unc's



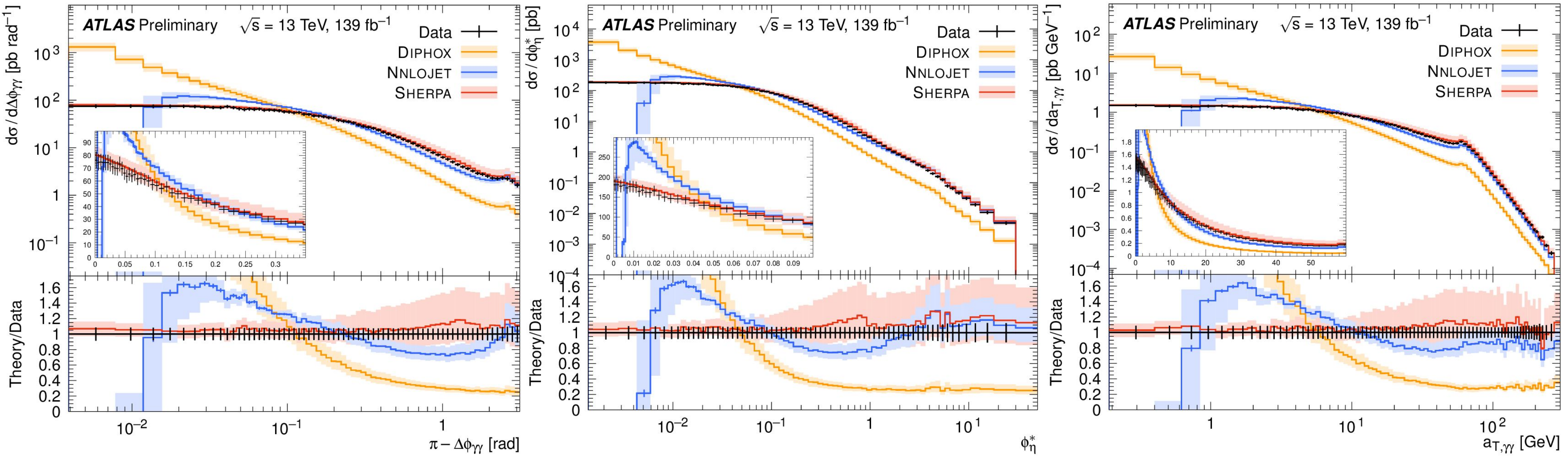
- Scattering angle with respect to beam axis in Collins-Soper frame
  - CS frame restores symmetry for configurations with $p_T(\gamma\gamma)>0$
- Interesting behaviour for $\cos\theta^* \to 1$
  - sensitive to **uncorrelated photons**, e.g. through multiple jets



Results for γγ

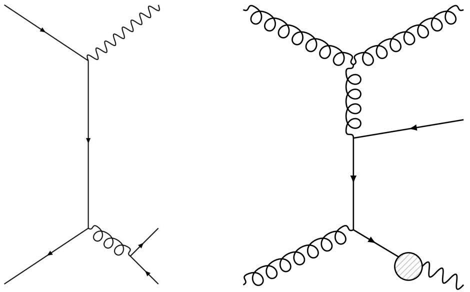
Brand-new!

- Further variables reveal similar features
  - back-to-back configuration sensitive to soft/collinear emissions
    → fixed-order not valid, well modelled by MEPS@NLO (Sherpa)
  - regions with large decorrelation modelled well in NNLO (NNLOJET) and MEPS@NLO (Sherpa), but NLO (DIPHOX) struggling, as effectively only LO accurate for these observables



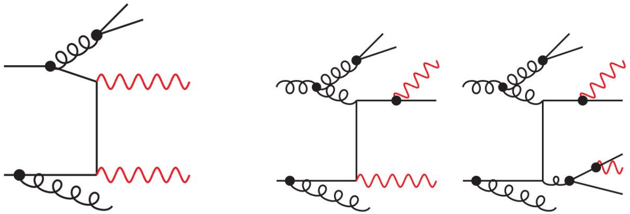
Conclusions

- Prompt photons are a pillar of the LHC physics program
  - Very active prompt photon measurement program in ATLAS



- γ+2j production measured by ATLAS with 36/fb at 13 TeV
  - Single-photon measurements in association with jets provide direct high-statistics probe of hard jet production
  - Good description by MC models with higher-order matrix elements

- γγ production measured by ATLAS with 139/fb at 13 TeV
  - Photon-pair measurements rely on lower-energy photons and background estimation is more complicated
  - Impressive performance of higher-order QCD predictions



Thanks for your attention! Questions?

Backup material

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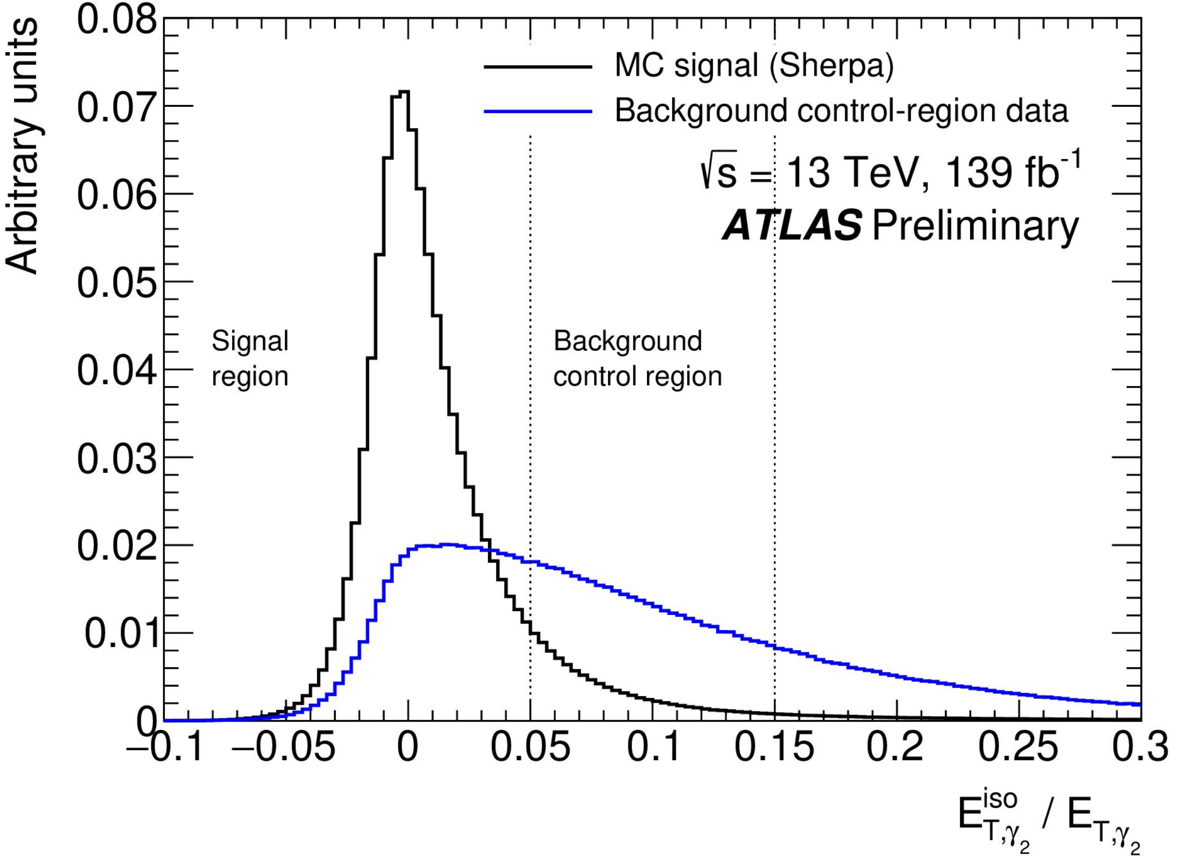
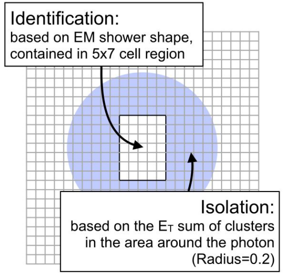
Photon isolation in signal and background

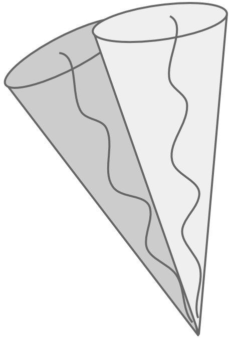


γγ: assumptions and uncertainties in fit model

- Ideal case: no correlation between isolation and identification…
  - Corresponds to R_{bg}=1 in ABCD method
  - Realistically: slight correlations, e.g. EM energy near photon candidate can distort ID variables
- … and between γ_1 and γ_2
  - Realistically: slight correlations, e.g. isolation energy for photons with small angular separation



Cells at the 2nd layer of the EM calorimeter



- Correction factors $R^{iso\text{-}id}$, R^{id}, R^{iso} taken into account in fit model
  - Estimated with MC simulation for prompt photons
  - Estimated from MC + validation region data for fake photons in γj/jγ/jj background processes:
    - $0.93 < R^{iso\text{-}id}(j) < 1.0 \quad \pm$ unc from MC statistics and $(MC - data)_{\gamma j}$ difference
    - $R^{iso}(\gamma j/j\gamma) = 0.95 \quad \pm$ 0.05 to cover difference between $MC_{\gamma\gamma}$ and jj data
    - $R^{id}(\gamma j/j\gamma)$ estimated from $MC_{\gamma\gamma}$ due to negligible impact
  - Further input parameters: selection efficiencies $\varepsilon^{iso}_{\gamma}(\gamma j/j\gamma)$ are estimated from MC
- All other parameters floating in the fit → derived from data

Backup: Pileup background

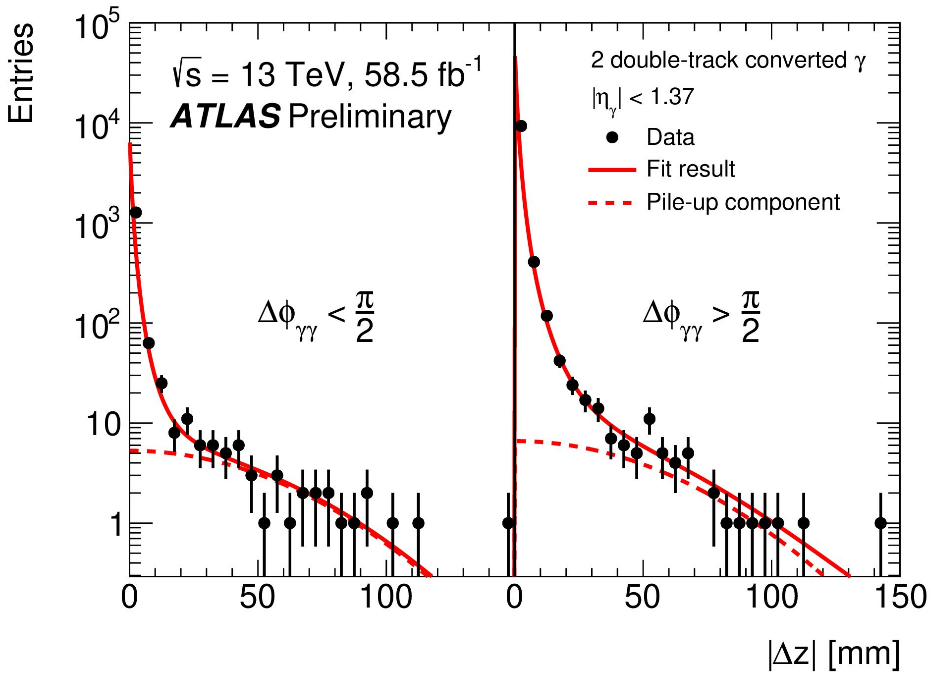
Data-driven normalisation from fit of vertex information of **converted** photons

×

Data-driven **background fit** in PU events ($|\Delta z| > 48$ mm) similar to main analysis

×

Shape in observables from **MC pseudo-sample** with two overlayed γj events



Uncertainties in γγ

- Jet **background estimation** uncertainty
  - From variations of fit assumptions: $R^{\text{iso-id}}(j)$, $R^{\text{iso}}(\gamma j/j\gamma)$
- Modelling of **photon isolation** variable
  - Peak position varied by reweighting (or not) MC to data
  - Width of distribution affected by amount of pile-up, varied by reweighting pile-up profile in simulation
- Photon energy/identification not among leading uncertainties
  - Different from γ+2j, where background unc negligible
  - Lower purity than in γ+2j due to low E_T photons: $E_{T,\gamma 1(\gamma 2)}$ > 40 (30) GeV vs. $E_{T,\gamma}$ > 150 GeV

Source	Relative uncertainty [%]
Background estimation	4.3
$R_j^{\text{iso}-\text{id}}$	4.2
$\gamma\gamma$ pile-up background	0.6
$R_{\gamma j}^{\text{iso}}$	0.5
Electron background	0.2
Photon isolation	4.0
Pile-up reweighting	3.5
Photon isolation	1.9
Photon identification	3.0
Other	4.1
Data-period stability	3.6
Luminosity	1.7
Trigger efficiency	0.7
MC Sherpa/Pythia	0.6
Signal modelling of E_{T,γ_1}	0.2
MC statistical uncertainty	0.1
Unfolding method	<0.1
Photon energy	0.5
Total systematic uncertainty	7.8
Data statistical uncertainty	0.3

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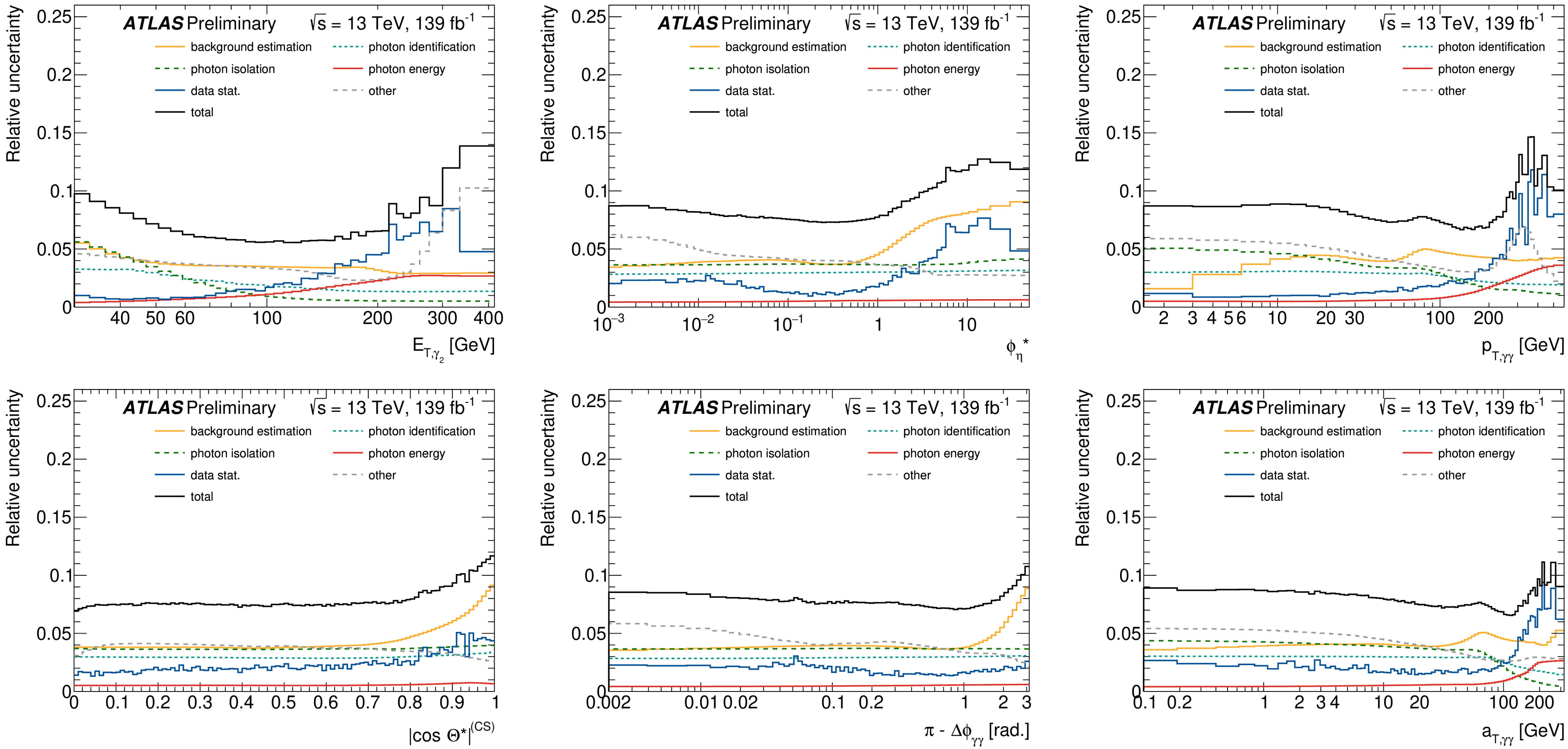
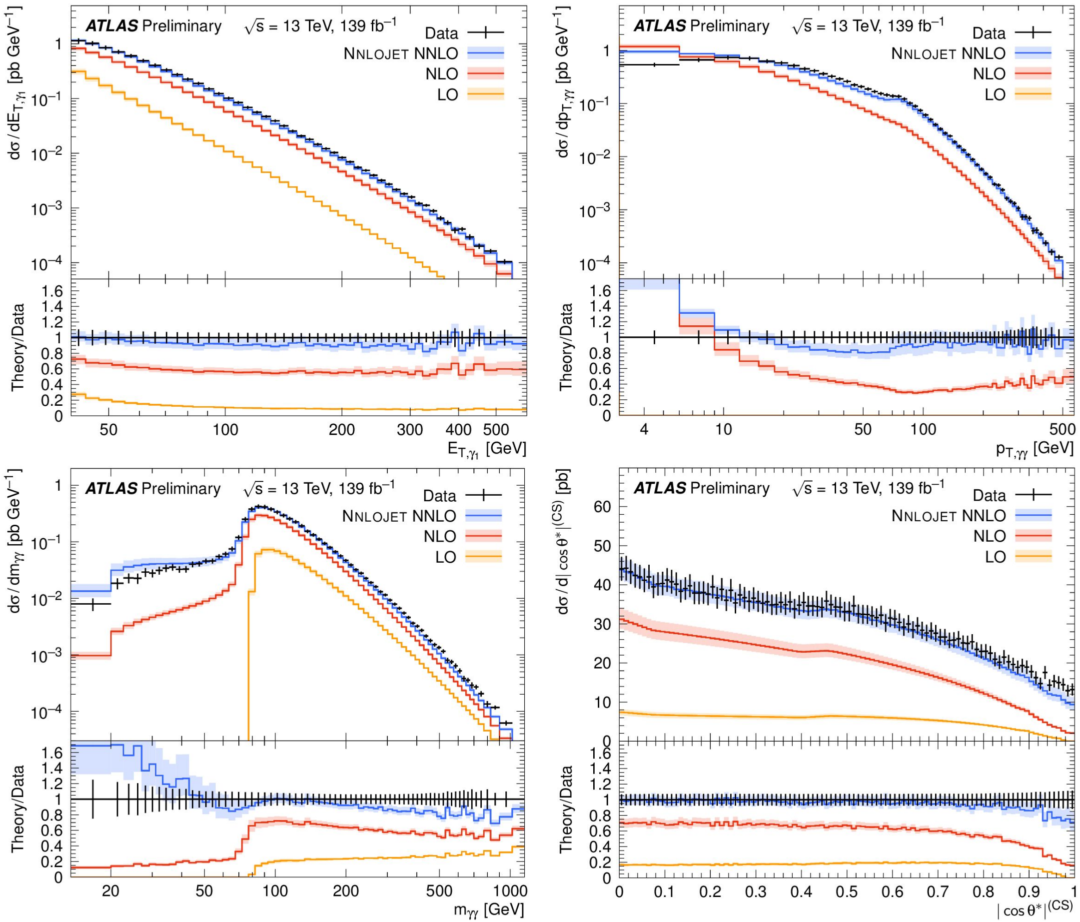
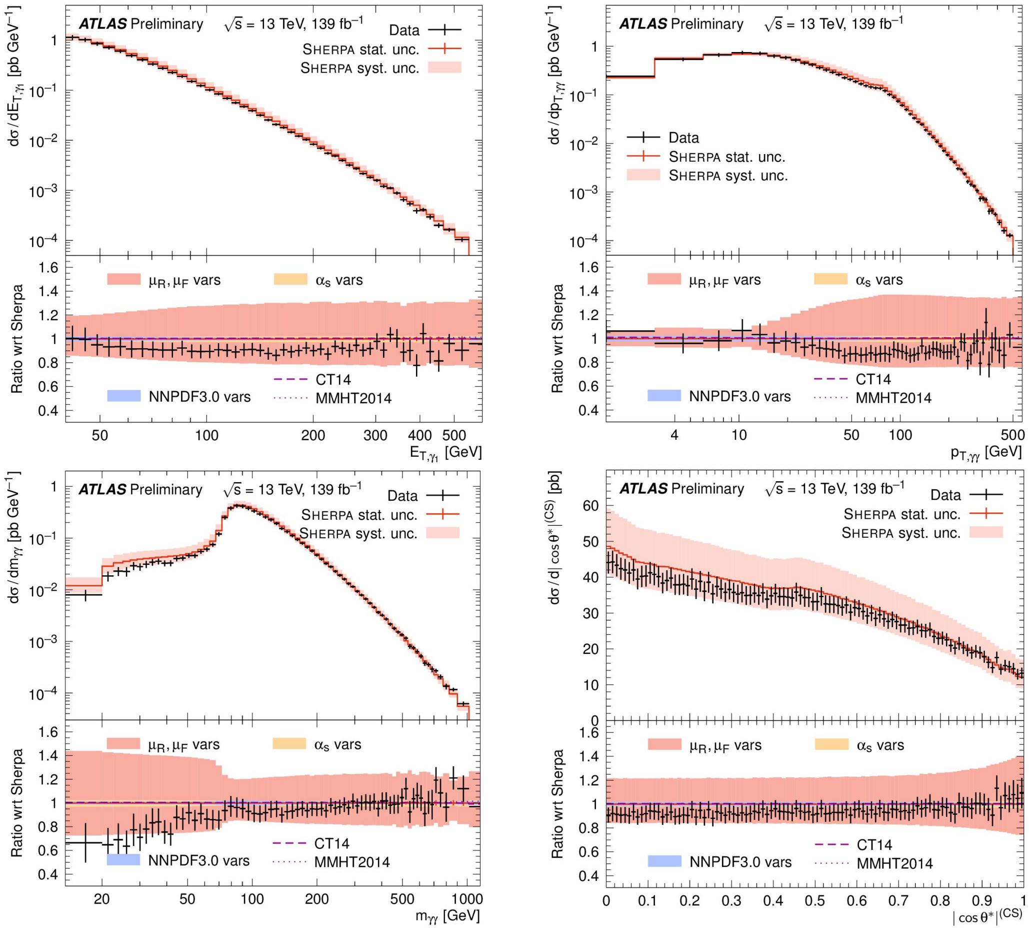
Backup: Uncertainties for γγ



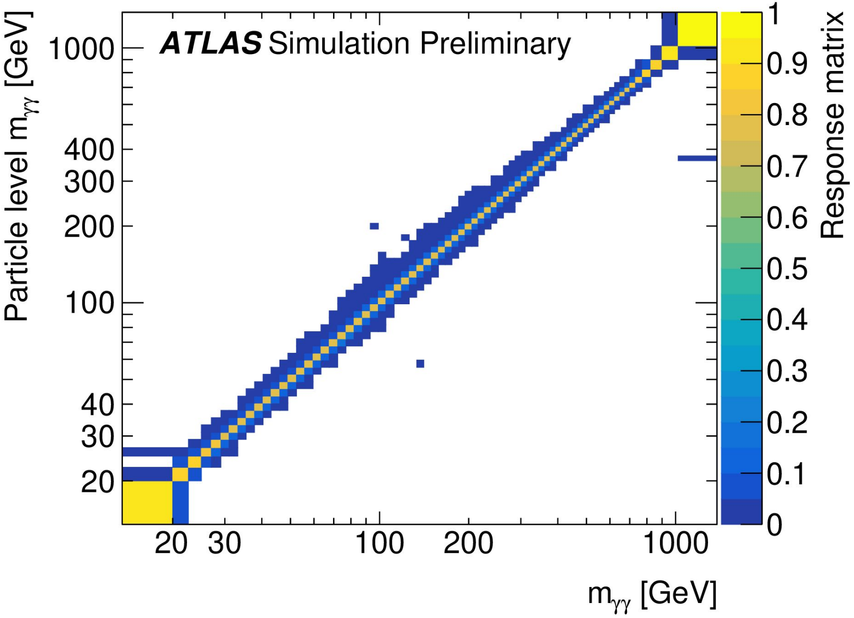
Backup: Perturbative QCD predictions

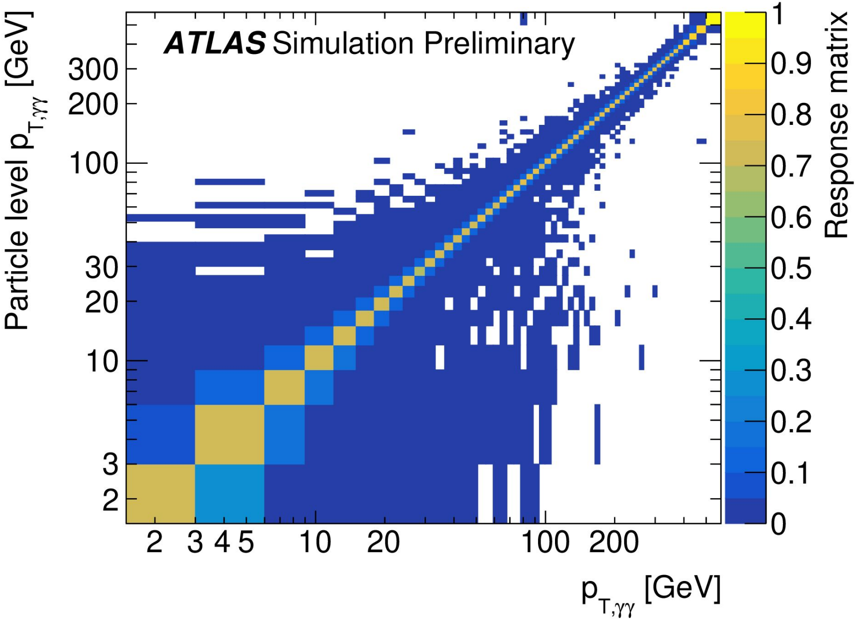


Backup: Perturbative uncertainties in Sherpa



Unfolding response matrices in $\gamma\gamma$





Inclusive isolated photon production

- ATLAS measurement of inclusive photon production with 36/fb [1908.02746]

	Phase-space region			
Requirement on E_T^γ	$E_T^\gamma > 125$ GeV			
Isolation requirement	$E_T^{iso} < 4.2 \times 10^{-3} \times E_T^\gamma + 4.8$ GeV			
Requirement on $\lvert\eta^\gamma\rvert$	$\lvert\eta^\gamma\rvert < 0.6$	$0.6 < \lvert\eta^\gamma\rvert < 1.37$	$1.56 < \lvert\eta^\gamma\rvert < 1.81$	$1.81 < \lvert\eta^\gamma\rvert < 2.37$
Number of events with $125 < E_T^\gamma < 150$ GeV	182 754	248 538	74 405	144 713
Number of events with $E_T^\gamma > 150$ GeV	2 030 144	2 696 077	814 623	1 471 953