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Photon and photon+jet production with the ATLAS detector

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Outline:

- Physics with photons
- Photons with the ATLAS detector
- Inclusive photon production
- Photon + jet production
- Photon pair production
- Summary

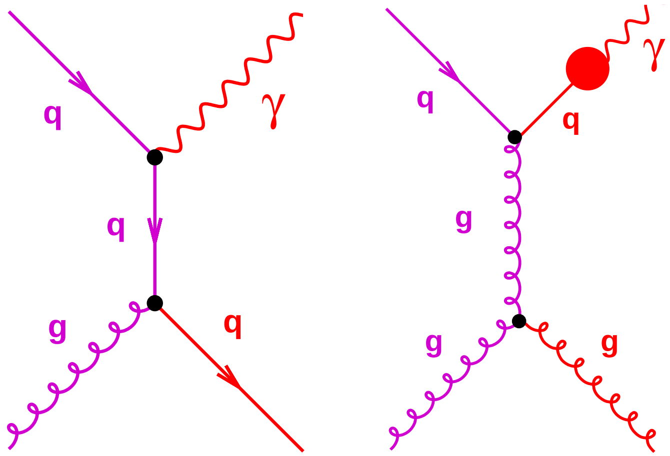
ATLAS

Prompt photons in pp collisions at LHC

- **Measurements of the production of high p_T prompt photons (in association with jets) and pairs of photons in hadron colliders provide**

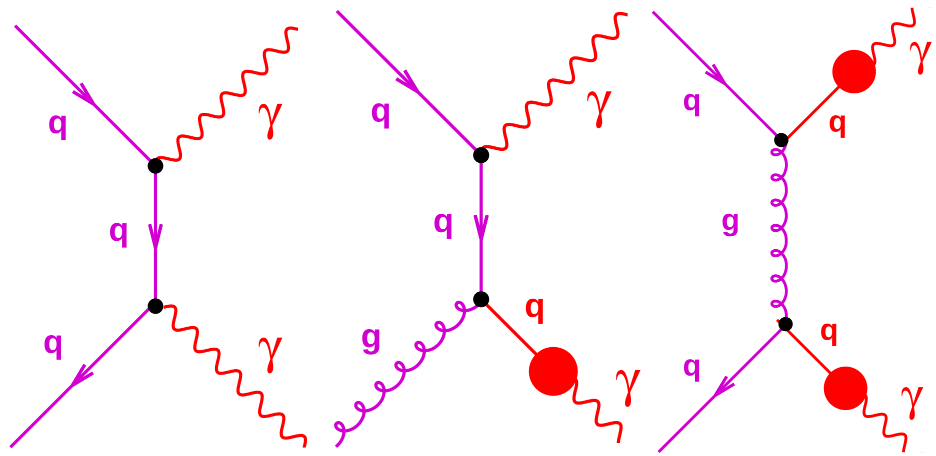
  $\longrightarrow$ **tests of pQCD predictions in a cleaner reaction than jet production**
  $\longrightarrow$ **constraints on the proton PDFs (especially gluon PDF: $qg \to q\gamma$ dominant)**
  $\longrightarrow$ **input to understand QCD background to Higgs production and BSM searches (tuning of Monte Carlo models)**

- **Prompt photons in pp collisions are produced via two mechanisms:**
  $\longrightarrow$ **direct-photon (DP) and fragmentation (F) processes**



Prompt photon (plus jet) production

$$pp \longrightarrow \gamma(+\mathrm{jet}) + \mathrm{X}$$



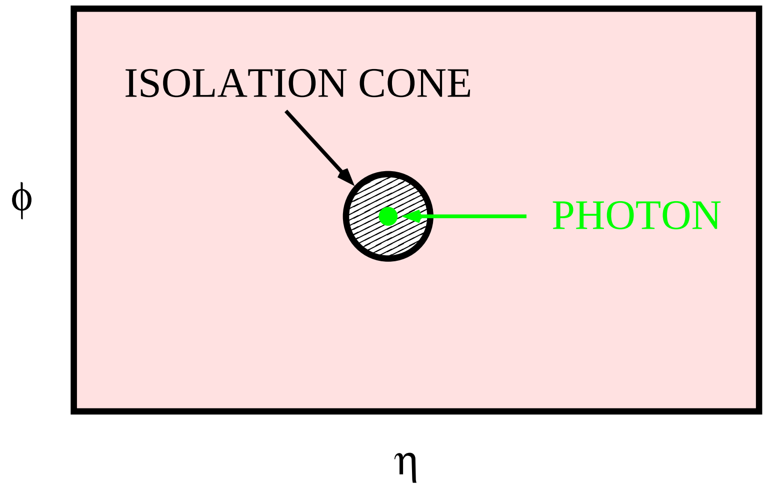
Diphoton production

$$pp \longrightarrow \gamma\gamma + \mathrm{X}$$

Prompt photons in pp collisions: isolation

- In addition to prompt photons, photons are produced copiously inside jets (eg, π^0 decays)
  $\Rightarrow$ it is essential to require isolation to study prompt photons in hadron colliders

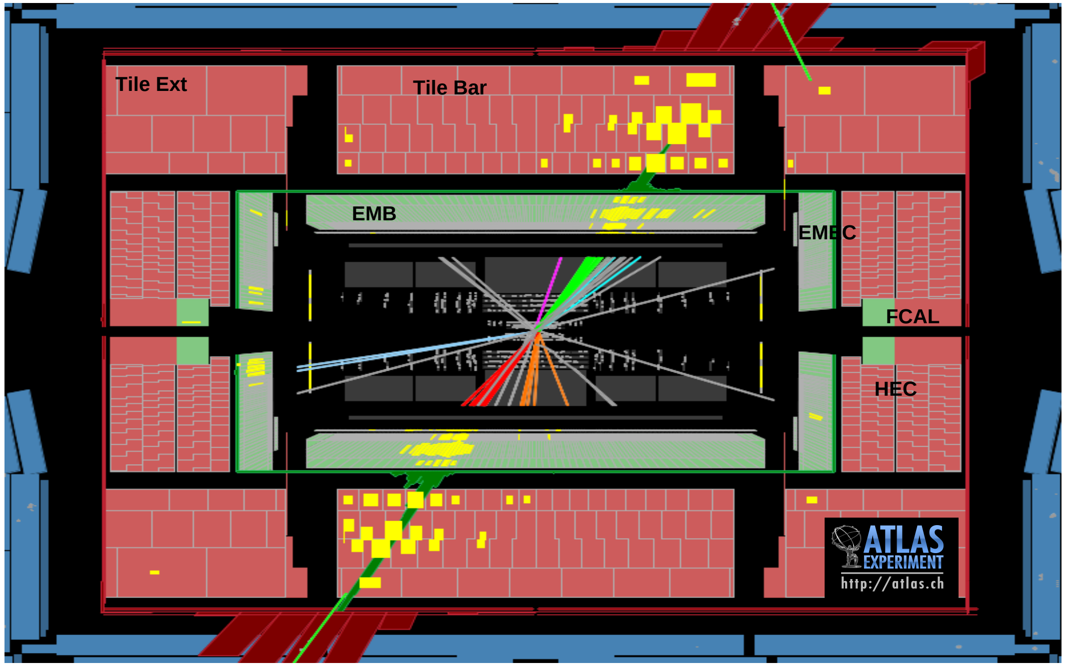
- This is achieved by requiring, eg
  $$E_{\mathrm{T}}^{\mathrm{iso}} \equiv \sum_i E_T^i < E_T^{\mathrm{max}}$$
  with the sum over the particles (except the photon!) inside a cone of radius R centered on the photon in the $\eta - \phi$ plane



- The isolation requirement suppresses mostly the contribution of photons inside jets (from π^0's and other neutral mesons decays) and the fragmentation contribution

Photons with the ATLAS detector

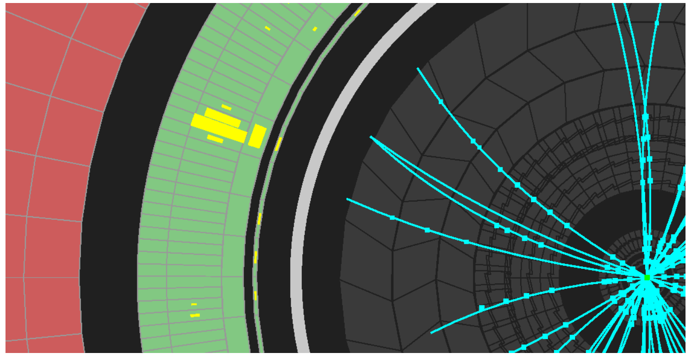
The ATLAS detector



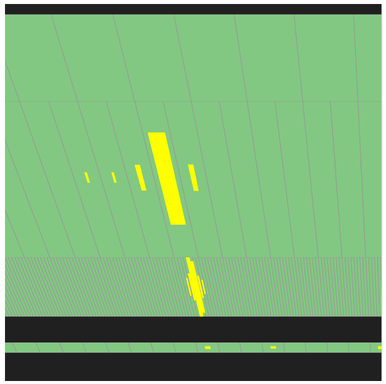
- Inner detector (ID): tracking and PI in $|\eta| < 2.5$ (silicon pixels and strips, TRT)
- Calorimeters:
  electromagnetic (LAr) $\rightarrow$ barrel: $|\eta| < 1.475$, endcap: $1.375 < |\eta| < 3.2$ (and forward: $3.1 < |\eta| < 4.9$); three longitudinal layers
  hadronic (scintillator/steel, LAr/Cu, LAr/W) $\rightarrow$ barrel: $|\eta| < 0.7$, extended barrel: $0.8 < |\eta| < 1.7$, endcap: $1.5 < |\eta| < 3.2$ and forward: $3.1 < |\eta| < 4.9$

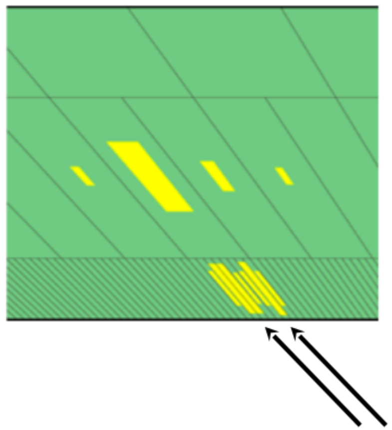
are the main components for photon reconstruction and identification in ATLAS

Photon reconstruction and identification in ATLAS LAr Calorimeter



- **Reconstruction:**
  - — First layer: high granularity in η direction
  - — Second layer: collects most of the energy
  - — Third layer: used to correct for leakage
- Cluster of EM cells without matching track: "unconverted" photon candidate
- Cluster of EM cells matched to pairs of tracks: "converted" photon candidate
- **Identification:**
  - — To discriminate signal vs background: shape variables from the lateral and longitudinal energy profiles of the shower in the calorimeters; "loose" (including leakage in hadronic calorimeter and width of shower) and "tight" (to discriminate single-photon showers from overlapping nearby showers) identification criteria are defined





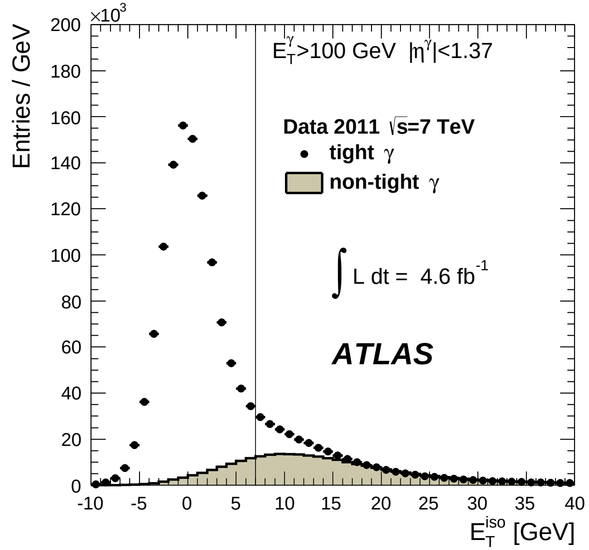
(ATLAS Collab, PRD 83 (2011) 052005)

$\pi^0 \rightarrow \gamma\gamma$

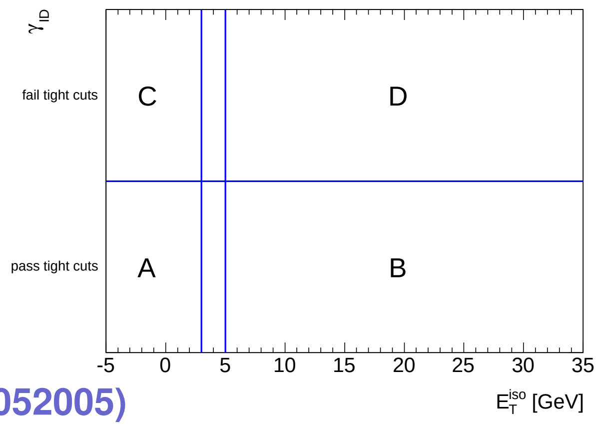
- Efficiency: $97\ (85)\%$ for loose (tight) photons with $E_T^{\gamma} > 20$ GeV

Photon isolation and background subtraction in ATLAS

- $E_{\rm T}^{\rm iso}$ is computed using calorimeter cells (EM and HAD) in a cone of $R=0.4$, excluding the contribution from the photon
- The leakage of the photon energy is subtracted (few $\%$)
- The underlying event and pileup contribute to $E_{\rm T}^{\rm iso}$!
  $\rightarrow$ correction computed using the jet-area method
  (M. Cacciari et al, JHEP 0804 (2008) 005)
- After these corrections, the $(E_{\rm T}^{\rm iso})^{\rm cor}$ distribution is centered at zero
- A photon candidate is considered isolated if
  $$(E_{\rm T}^{\rm iso})^{\rm cor} < (E_{\rm T}^{\rm iso})^{\rm cut}$$



- However, residual background still expected even after tight identification and isolation requirements
- A data-driven method used to avoid relying on detailed simulations of the background processes:
  $\rightarrow$ two-dimensional sideband method based on γ_{ID} vs $E_{\rm T}^{\rm iso}$ plane and corrected for signal leakage



- Purity: $\gtrsim 90\%$ for $E_{\rm T}^{\gamma} > 40$ GeV (ATLAS Collab, PRD 83 (2011) 052005)

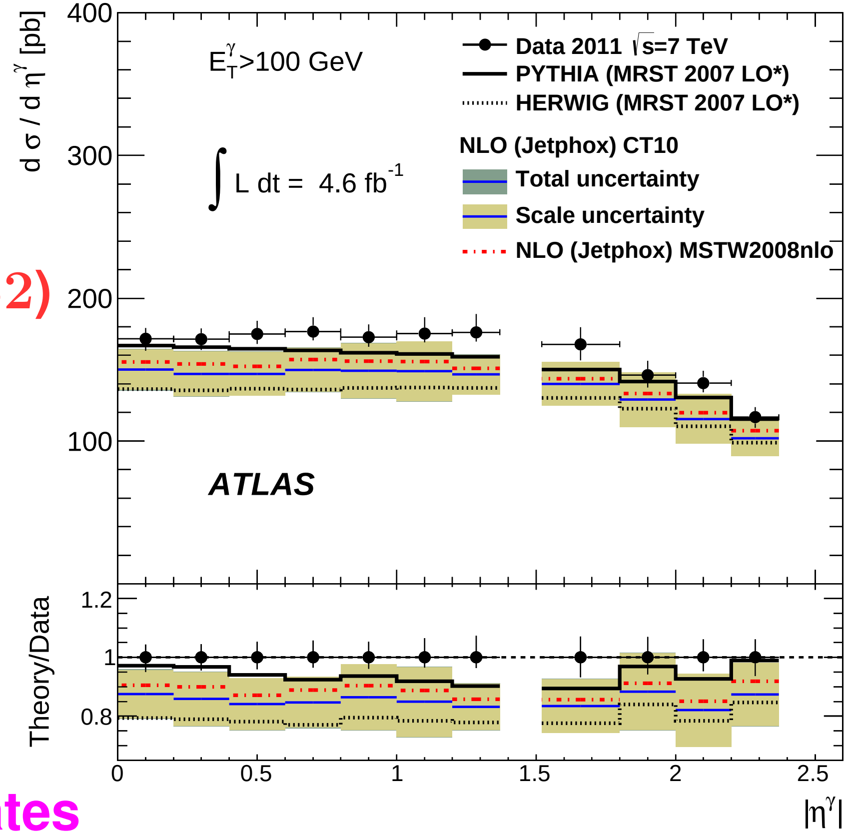
Inclusive photon production

Inclusive isolated photons: testing pQCD

$pp \rightarrow \gamma + \mathrm{X}$: inclusive isolated-photon cross sections

$\mathcal{L} = 4.6$ fb^{-1}

- Photon selection: $E_{\mathrm{T}}^{\gamma} > 100$ GeV and $|\eta^{\gamma}| < 2.37$ excluding the region $1.37 < |\eta^{\gamma}| < 1.52$
- Photon isolation: $E_{\mathrm{T}}^{\mathrm{iso}}(R = 0.4) < 7$ GeV

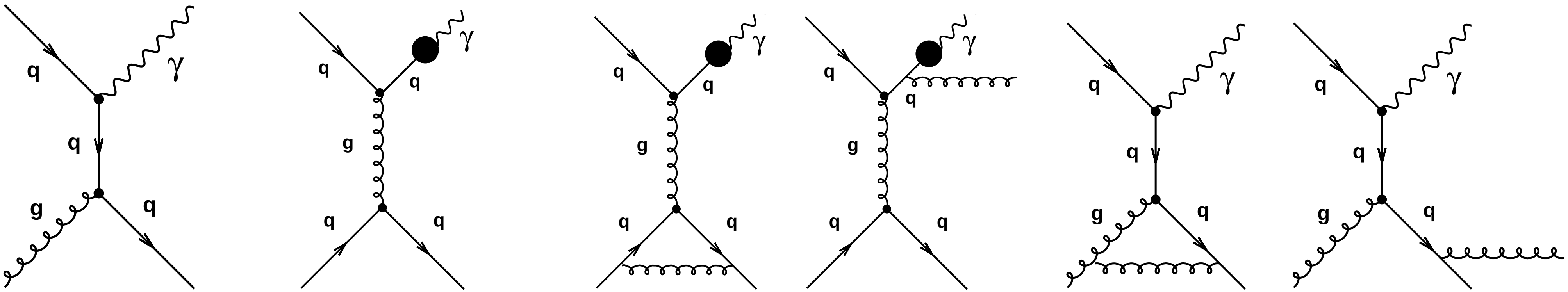


- **Experimental uncertainties:**
  - $\rightarrow \approx 6\ (7)\%$ for $|\eta^{\gamma}| < 1.37$ $(1.52 < |\eta^{\gamma}| < 1.52)$
  - $\rightarrow$ dominated by photon energy scale $(2\ (6)\%$ at low (high) $E_{\mathrm{T}}^{\gamma})$

- **Comparison to LO MC predictions**
  - $\rightarrow$ good description of data by PYTHIA
  - $\rightarrow$ HERWIG describes shape but underestimates normalisation

ATLAS Collab, PRD 89 (2014) 052004

NLO QCD calculations for inclusive photon production



$$\sigma_{pp\to\gamma+X} = \sum_{i,j,a} \int_0^1 dx_1\, f_{i/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{j/p}(x_2,\mu_F^2)\ \hat{\sigma}_{ij\to\gamma a} +$$

$$\sum_{i,j,a,b} \int_{z_{\min}}^1 dz\, D_a^\gamma(z,\mu_f^2) \int_0^1 dx_1\, f_{i/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{j/p}(x_2,\mu_F^2)\ \hat{\sigma}_{ij\to ab}$$

- The calculations include NLO corrections for direct-photon and fragmentation and implement the photon isolation requirement at "parton" level
- Corrections for hadronisation and underlying event needed ($E_{\mathrm{T}}^{\mathrm{iso}}$ calculation)
- Theoretical uncertainties: higher orders, PDF-induced uncertainty, uncertainty on α_s and on non-perturbative corrections

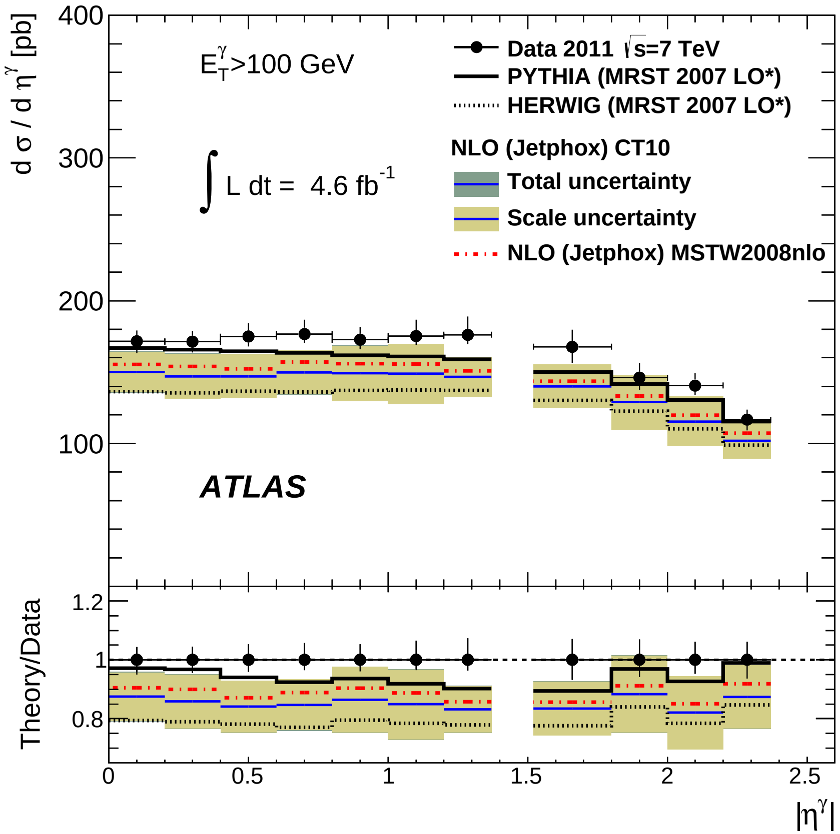
JETPHOX (S. Catani et al, JHEP 0205 (2002) 028)

Inclusive isolated photons: testing pQCD

$pp \to \gamma + X$: inclusive isolated-photon cross sections

$\mathcal{L} = 4.6$ fb^{-1}

- Photon selection: $E_T^\gamma > 100$ GeV and $|\eta^\gamma| < 2.37$ excluding the region $1.37 < |\eta^\gamma| < 1.52$
- Photon isolation: $E_T^{\rm iso}(R = 0.4) < 7$ GeV



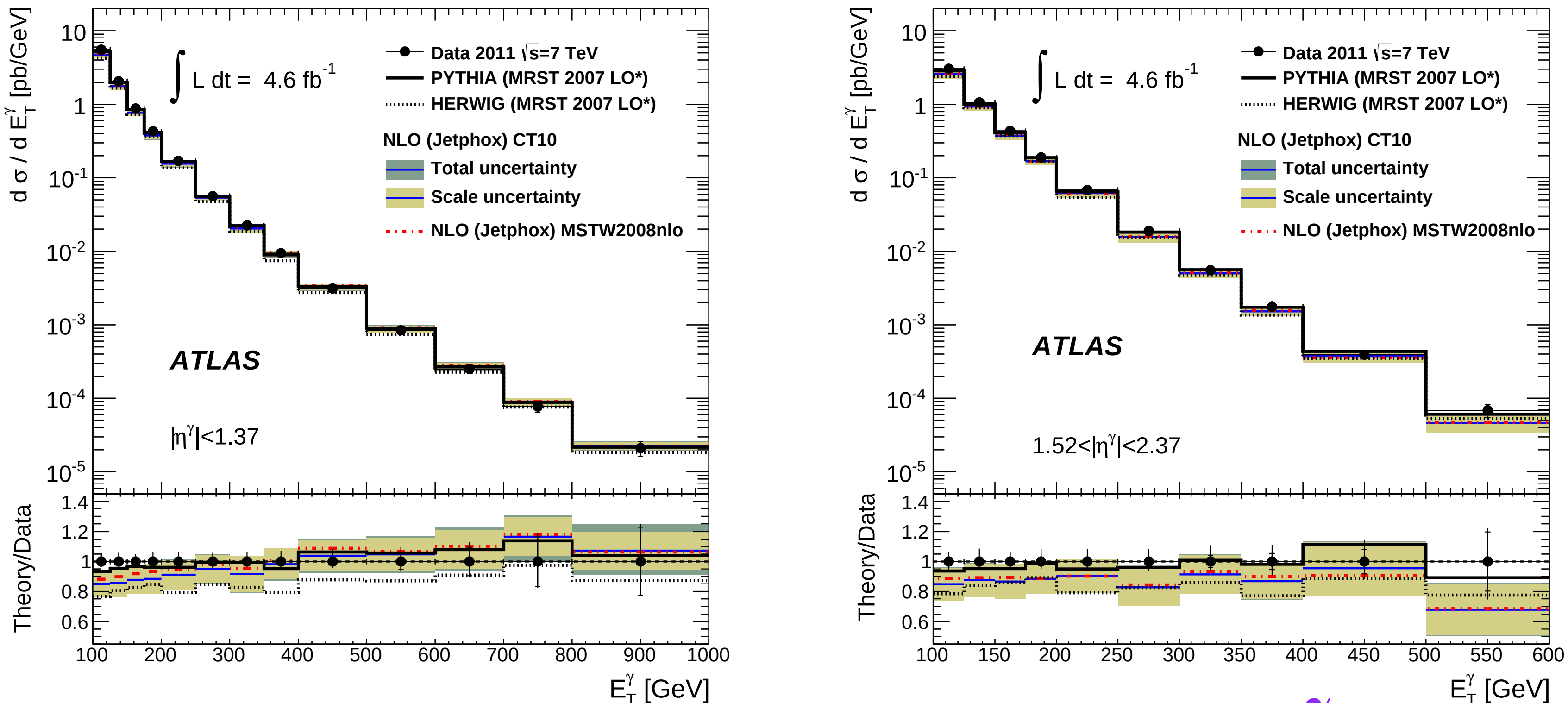
- Theoretical uncertainties:
  - $\to$ terms beyond NLO: $12 - 20\%$
  - $\to$ PDFs: $5\ (15)\%$ at $E_T^\gamma \sim 100\ (900)$ GeV
  - $\to$ value of α_s: 4.5% in average
  - $\to$ NP corrections: negligible

- Comparison to NLO predictions (JETPHOX)
  - $\to$ $\mu_R = \mu_F = \mu_f = E_T^\gamma$; PDFs: CT10, MSTW2008NLO; FF: BFG set II; $\alpha_s(m_Z) = 0.118$
  - $\to$ consistent with data within uncertainties

ATLAS Collab, PRD 89 (2014) 052004

Inclusive isolated photons: sensitivity to proton PDFs

$pp \to \gamma + X$: **inclusive isolated-photon cross sections** $\mathcal{L} = 4.6$ fb^{-1}



- The NLO calculations agree with the data up to the highest E_T^γ measured (1 TeV)
- Sensitivity to proton PDFs:
  - → NLO calculation based on MSTW2008NLO higher than CT10 and closer to data at low E_T^γ
  - → theoretical uncertainties due to PDF become significant at high E_T^γ
    - ⇒ these measurements have the potential to constrain further the pPDFs

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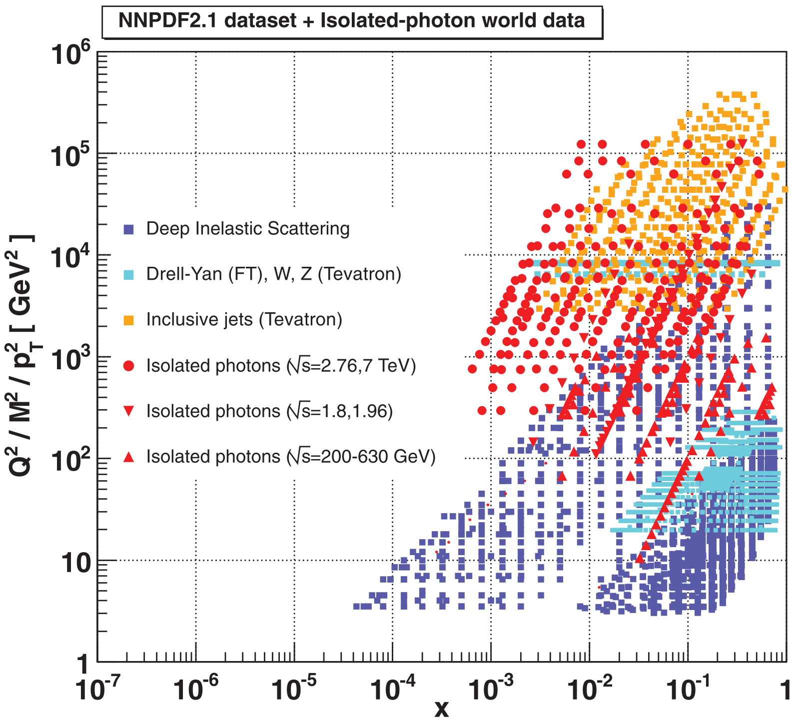
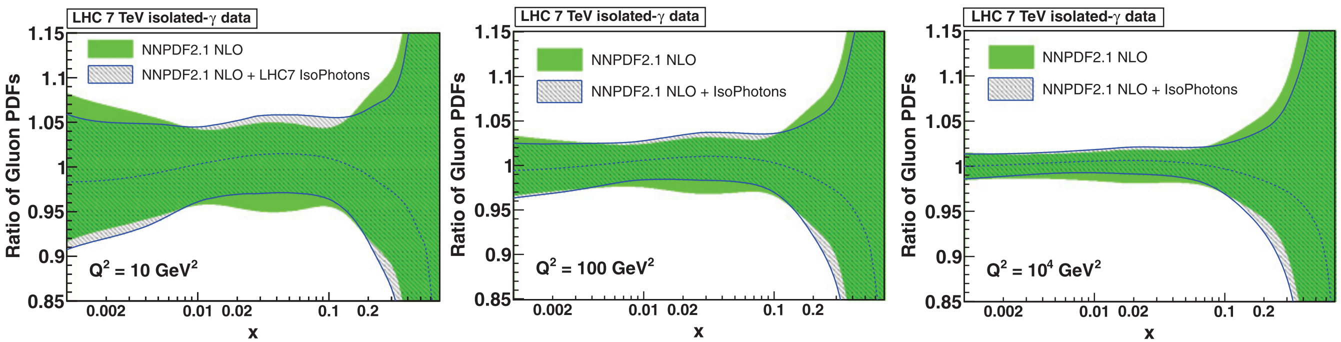
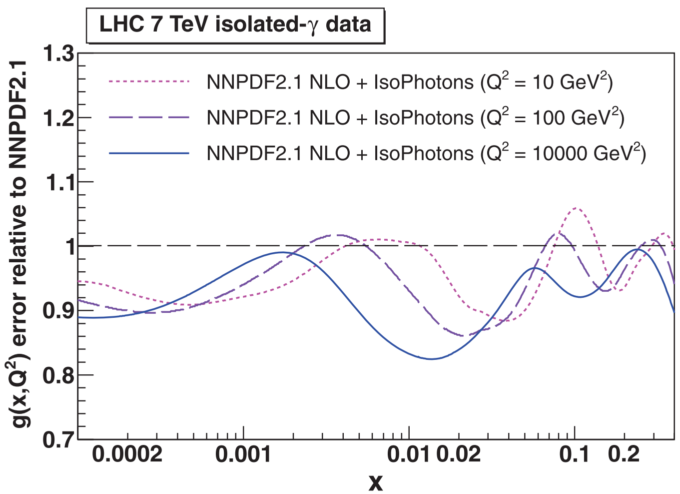
Impact of inclusive isolated photon measurements at LHC on PDFs



- Study of the impact on the gluon density of existing isolated-photon measurements from a variety of experiments, from $\sqrt{s} = 200$ GeV up to 7 TeV
  - $\rightarrow$ those at LHC are the most constraining datasets
  - $\rightarrow$ reduction of gluon uncertainty up to 20% localised in the range $x \approx 0.002$ to 0.05
    - $\Rightarrow$ improved predictions for low mass Higgs production in gluon fusion: **PDF-induced uncertainty decreased by 20%**





(See Peter Bussey's talk)

ATLAS Collab, ATL-PHYS-PUB-2013-018 D d'Enterria and J Rojo (NPB 860 (2012) 311)

Photon+jet production

Isolated photons in association with jets: testing colour dynamics

$pp \to \gamma + \text{jet} + X$: isolated-photon plus jet cross sections

$\mathcal{L} = 37$ pb^{-1}

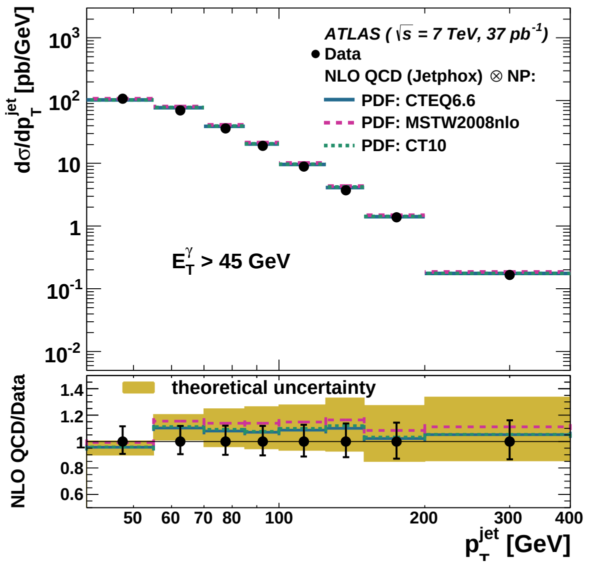
- Jet identification: anti-k_t algorithm with $R = 0.6$

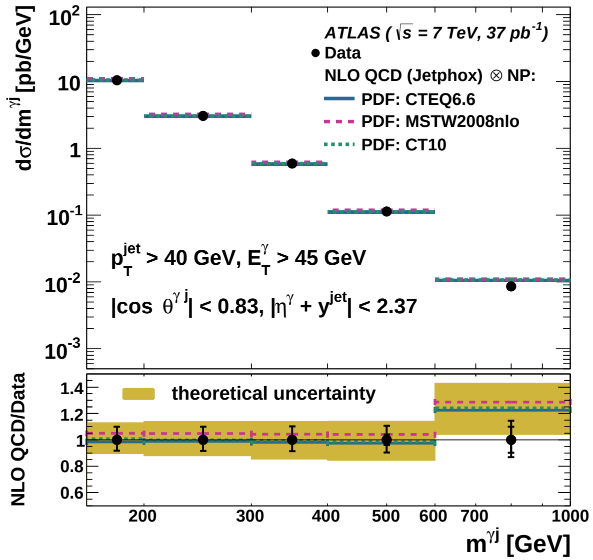
  (see Nuno Anjos's talk)
- At least one jet with $p_T^{\text{jet}} > 40$ GeV and $|y^{\text{jet}}| < 2.37$
- Photon selection: $E_T^{\gamma} > 45$ GeV and $|\eta^{\gamma}| < 2.37$ excluding the region $1.37 < |\eta^{\gamma}| < 1.52$ and $E_T^{\text{iso}} < 4$ GeV
- Additional requirements for $d\sigma/dm^{\gamma j}$: $|\cos\theta^{\gamma j}| < 0.83$ and $|\eta^{\gamma} + y^{\text{jet}}| < 2.37$

- Experimental uncertainties $\approx 10\%$ (dominated by jet energy scale)
- Theoretical uncertainties $\approx 10\%$ (dominated by terms beyond NLO)
- Comparison to NLO predictions (JETPHOX)

  $\to$ $\mu_R = \mu_F = \mu_f = E_T^{\gamma}$; PDFs: CTEQ6.6, CT10, MSTW2008NLO; FF: BFG set II; $\alpha_s(m_Z) = 0.118$; corrected for non-perturbative effects

  $\to$ good description of data



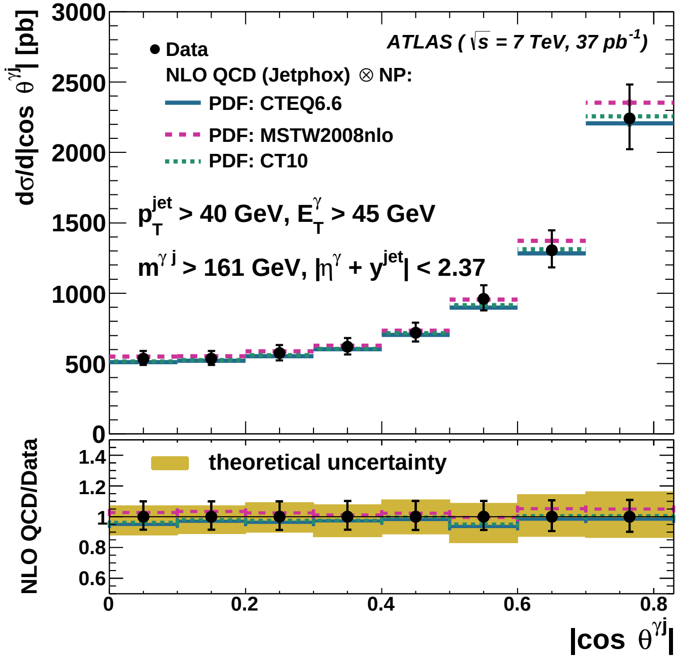


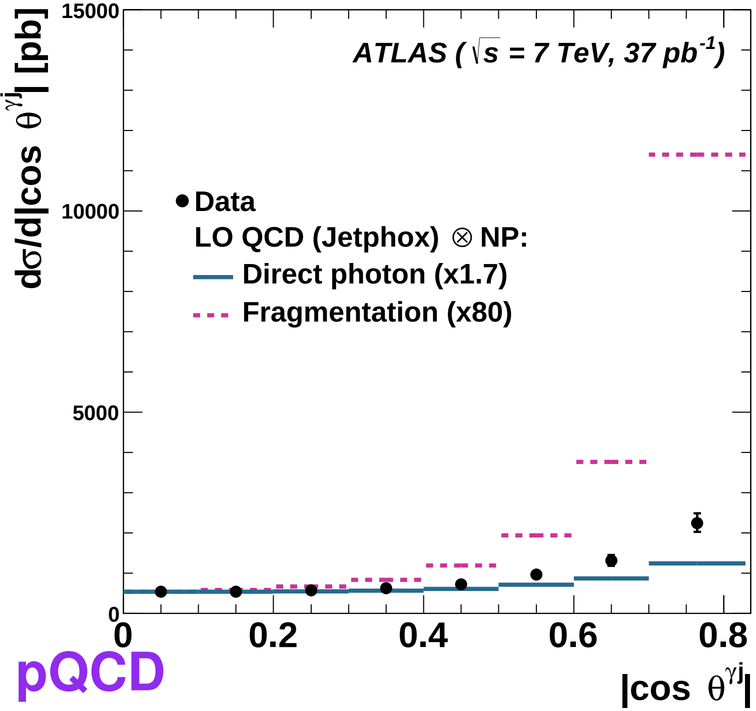
ATLAS Collab, NPB 875 (2013) 483

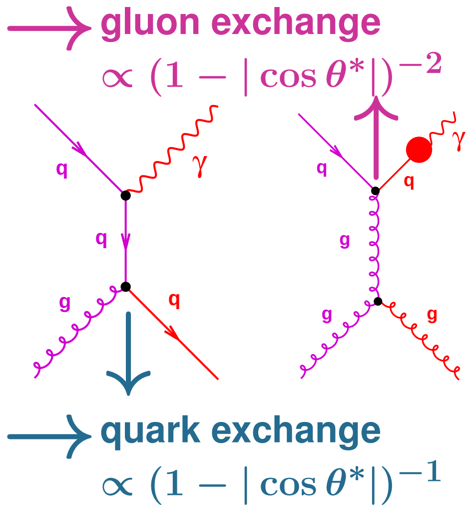
Isolated photons in association with jets: testing colour dynamics

$pp \to \gamma + \text{jet} + X$: isolated-photon plus jet cross sections $\mathcal{L} = 37$ pb^{-1}

- Additional requirements for $d\sigma/d|\cos\theta^{\gamma j}|$: $m^{\gamma j} > 161$ GeV and $|\eta^{\gamma} + y^{\text{jet}}| < 2.37$







- Good description of data by NLO pQCD
- Sensitivity to QCD dynamics:
  $\to$ shape of data much closer to DP than to F processes $\to$ consistent with dominance of processes in which a quark is being exchanged
  $\Rightarrow$ validity of the description of the dynamics of isolated-photon plus jet production in pp collisions at $\mathcal{O}(\alpha\alpha_s^2)$

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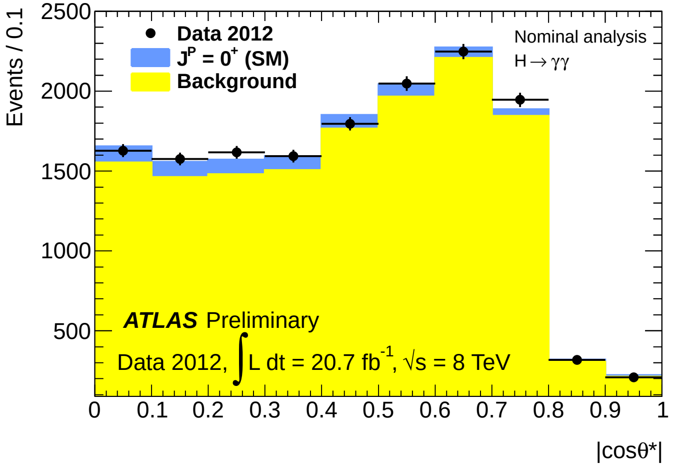
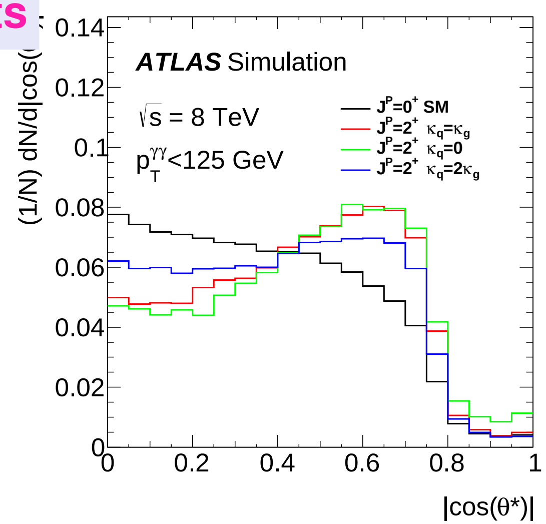
photon+jet: understanding the background to $H \to \gamma\gamma$

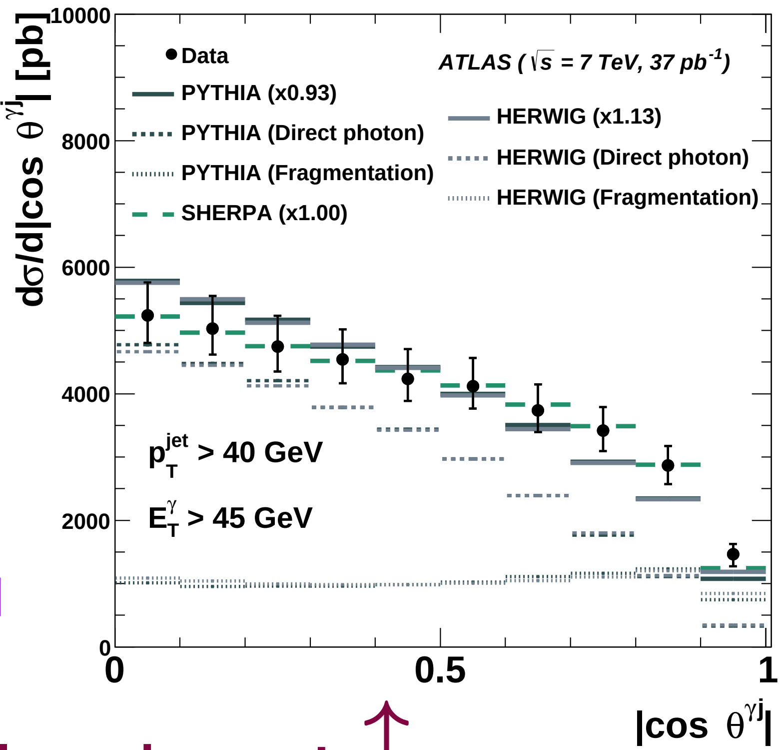
$pp \to \gamma + \text{jet} + X$: isolated-photon plus jet cross sections

$\mathcal{L} = 37\ \text{pb}^{-1}$

- Without additional requirements







- $\gamma + \text{jet}$ production is the 2nd largest source of background to $H \to \gamma\gamma$; $\cos\theta^*$ distribution used to determine the spin of the Higgs
- Measurement of $d\sigma/d|\cos\theta^{\gamma j}|$ without additional requirements ↑
- Good description of data by LO and NLO pQCD
- Understanding the photon+jet background in terms of pQCD:
  $\to$ precise understanding of this background both in normalisation and shape
  $\Rightarrow$ useful for tuning the Monte Carlo models

ATLAS Collab, NPB 875 (2013) 483

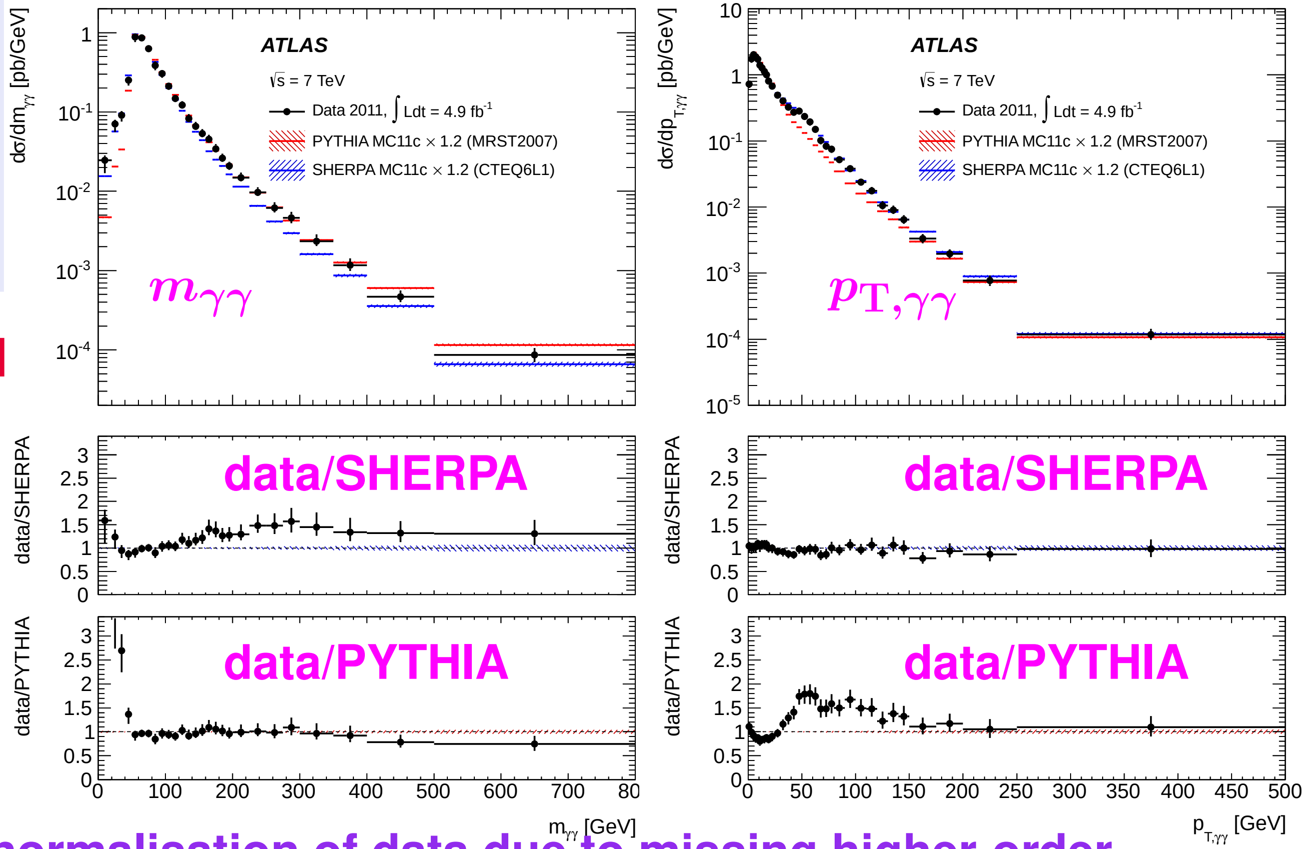
Photon pair production

Isolated photon pairs: understanding the QCD background

$pp \to \gamma\gamma + \mathrm{X}$: isolated photon-pair cross sections

$\mathcal{L} = 4.9$ fb^{-1}

- **Photon-pair selection:**
  $E_{\mathrm{T}}^{\gamma} > 25,\ 22$ GeV and $|\eta^{\gamma}| < 2.37$
  excluding $1.37 < |\eta^{\gamma}| < 1.52$ and
  $E_{\mathrm{T}}^{\mathrm{iso}} < 4$ GeV
- $\Delta R^{\gamma\gamma} > 0.4$



- **Main irreducible background to $H \to \gamma\gamma$**
- **Comparison to LO predictions**
  → PYTHIA: LO ME plus parton shower
  → SHERPA: also includes diphoton higher-order real-emission ME (two additional partons)

→ both models underestimate normalisation of data due to missing higher-order contributions

→ PYTHIA describes $m_{\gamma\gamma}$, except at low values, better than SHERPA

→ good description at low $p_{T,\gamma\gamma}$ thanks to soft-gluon resummation

→ SHERPA describes $p_{T,\gamma\gamma}$ overall thanks to additional tree-level higher orders

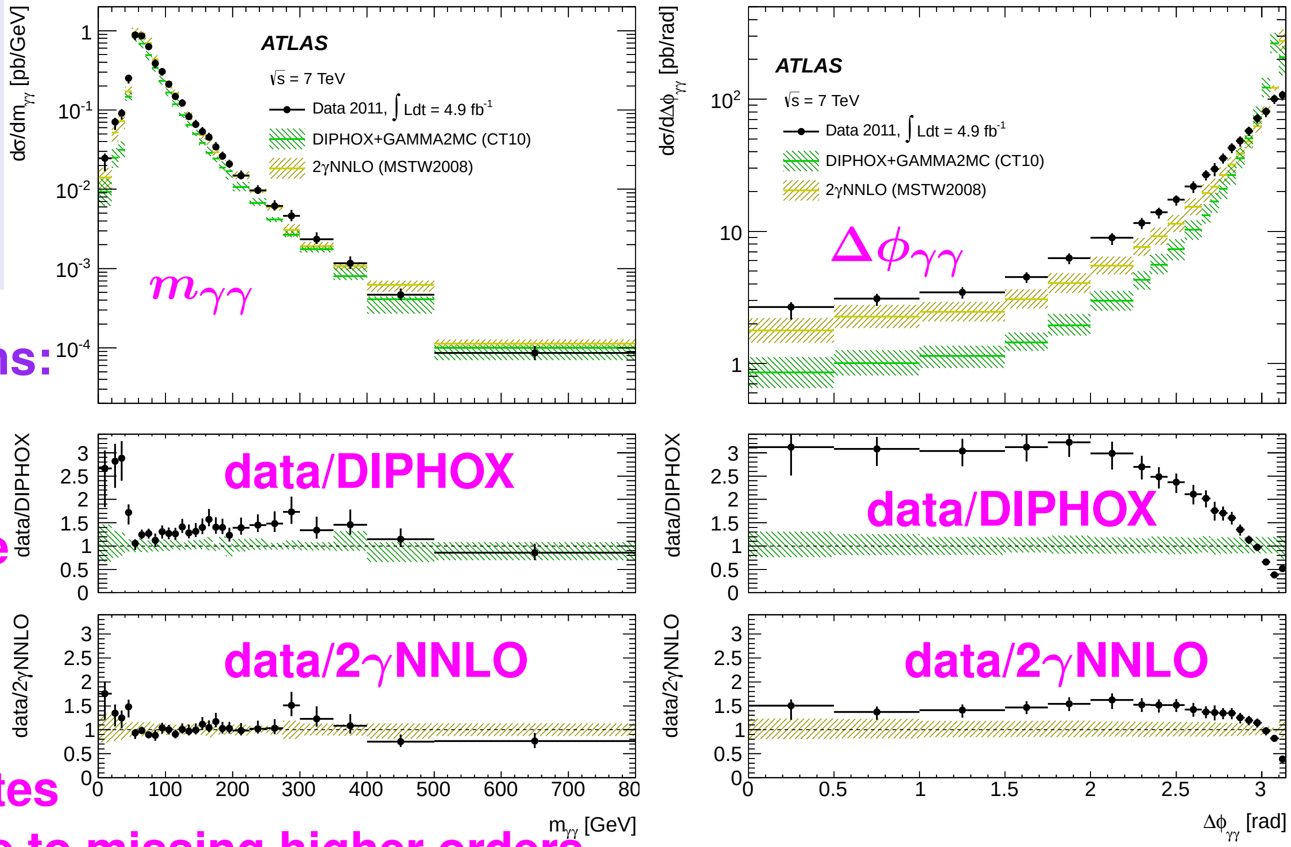
ATLAS Collab, JHEP 01 (2013) 086

Isolated photon pairs: understanding the QCD background

$pp \to \gamma\gamma + X$: isolated photon-pair cross sections

$\mathcal{L} = 4.9$ fb^{-1}

- **Photon-pair selection:**
  $E_T^\gamma > 25,\ 22$ GeV and $|\eta^\gamma| < 2.37$
  excluding $1.37 < |\eta^\gamma| < 1.52$ and
  $E_T^{\rm iso} < 4$ GeV
- $\Delta R^{\gamma\gamma} > 0.4$



- **Comparison to pQCD predictions:**
  - → DIPHOX: NLO DP and F contributions
  - → 2γNNLO: NNLO DP
  - → DIPHOX: fails to describe the data for $\Delta\phi_{\gamma\gamma} \sim \pi$ and low $m_{\gamma\gamma}$ due to importance of soft-gluon resummation in this region and underestimates the data everywhere else due to missing higher orders
  - → 2γNNLO: is closest to data, but still below in regions where the fragmentation contribution is more significant
- **Sensitivity to higher orders:**
  ⇒ improved calculations are needed to understand fully diphoton production

ATLAS Collab, JHEP 01 (2013) 086

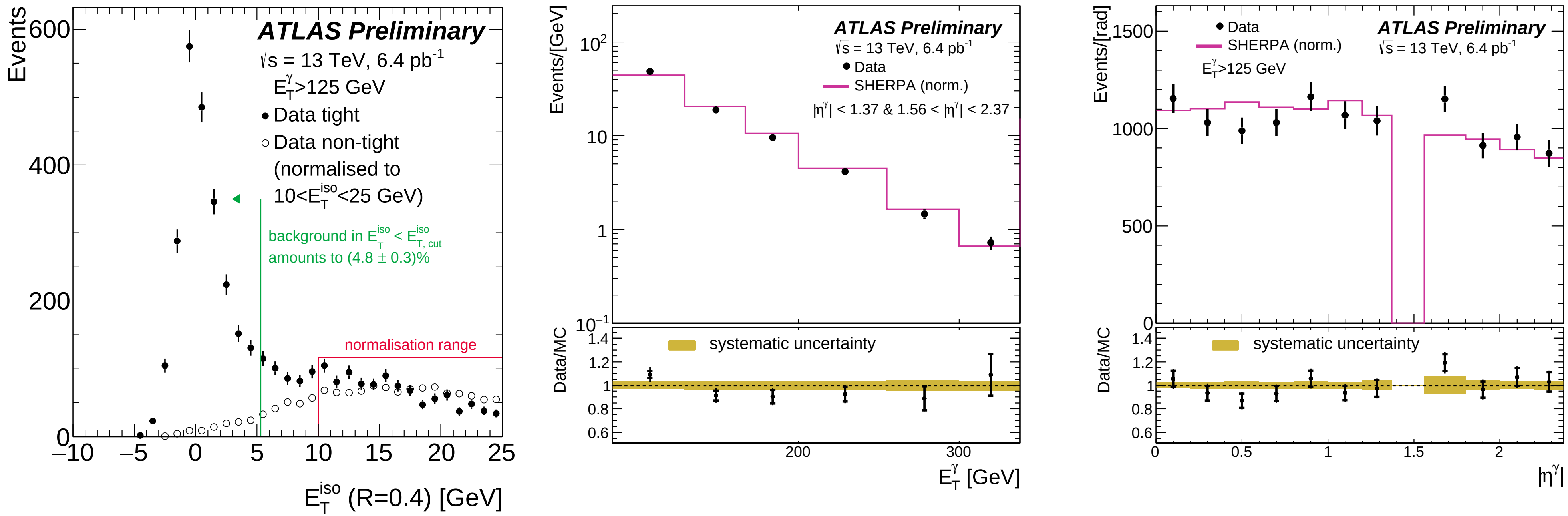
Photon production @ 13 TeV

Preview: inclusive isolated photon production @ 13 TeV

$pp \to \gamma + X$: inclusive isolated-photon distributions

$\mathcal{L} = 6.4$ pb^{-1}

- Photon selection: $E_T^\gamma > 125$ GeV and $|\eta^\gamma| < 2.37$ excluding the region $1.37 < |\eta^\gamma| < 1.56$
- Photon isolation: $E_T^{\rm iso}(R=0.4) < 4.8~{\rm GeV} + 4.2 \cdot 10^{-3} \times E_T^\gamma$



- Clear observation of isolated photon signal at 13 TeV
- Comparison to normalised LO MC predictions
  $\to$ good description of data by SHERPA 2.1

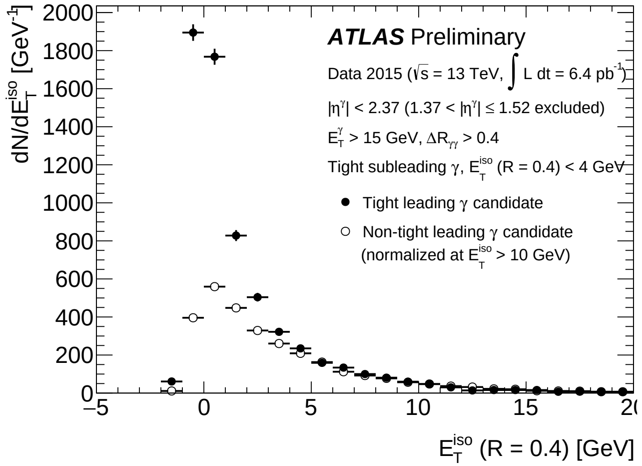
(see Nicola Orlando's talk)
ATLAS Collab, ATL-PHYS-PUB-2015-016

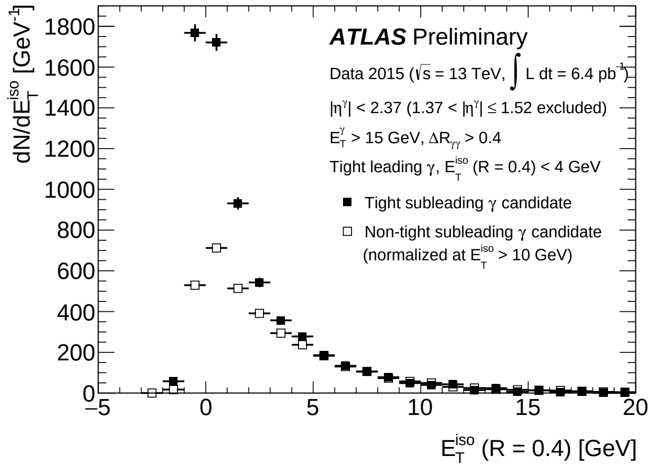
Preview: photon pair production @ 13 TeV

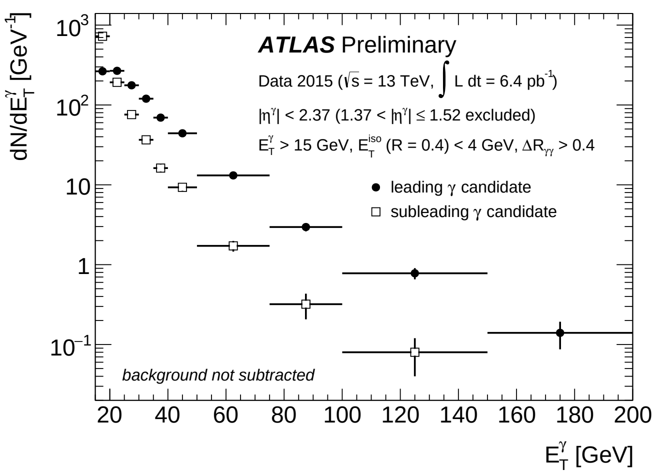
$pp \to \gamma\gamma + X$: isolated photon-pair distributions

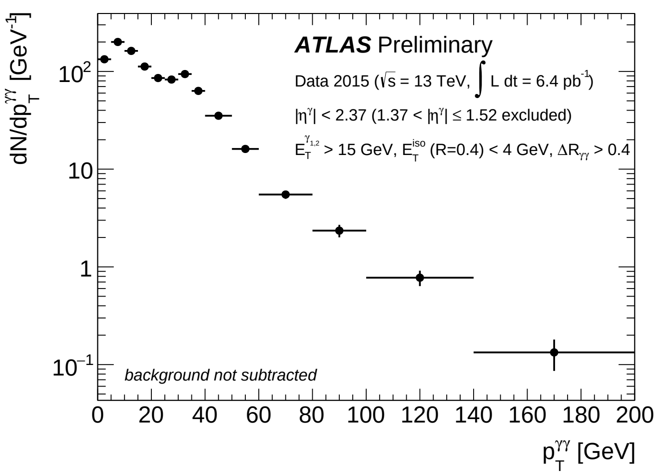
$\mathcal{L} = 6.4$ pb^{-1}

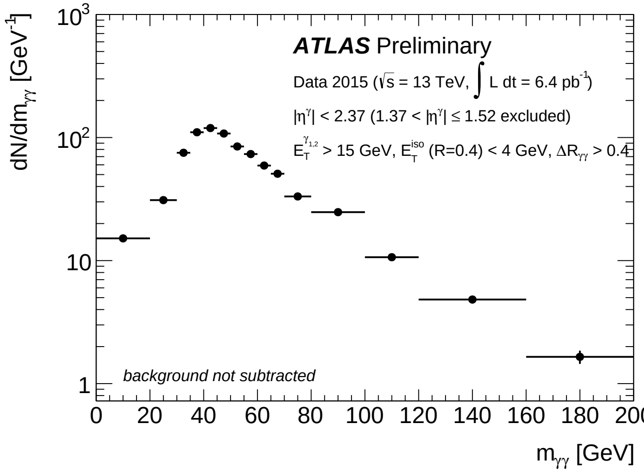
- **Photon-pair selection:**
  $E_T^\gamma > 15$ GeV and $|\eta^\gamma| < 2.37$
  excluding $1.37 < |\eta^\gamma| < 1.52$ and
  $E_T^{iso} < 4$ GeV
- $\Delta R^{\gamma\gamma} > 0.4$







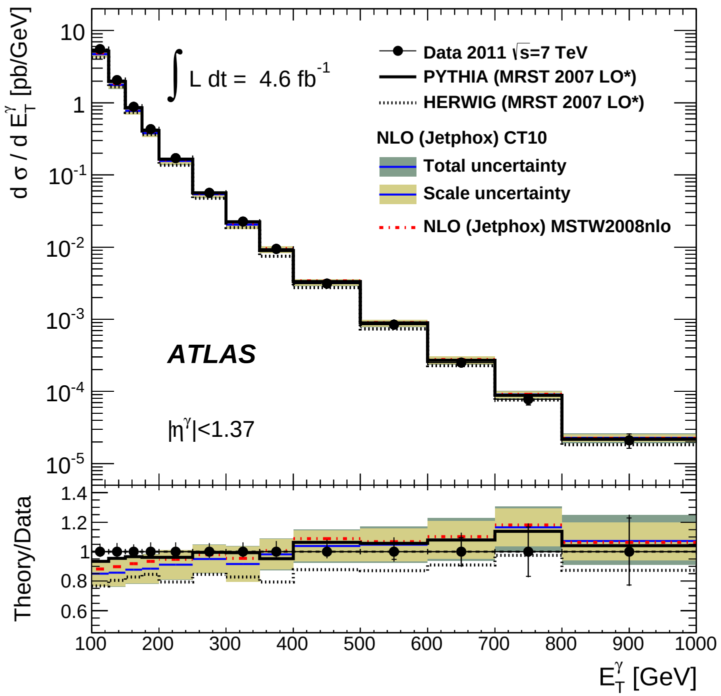


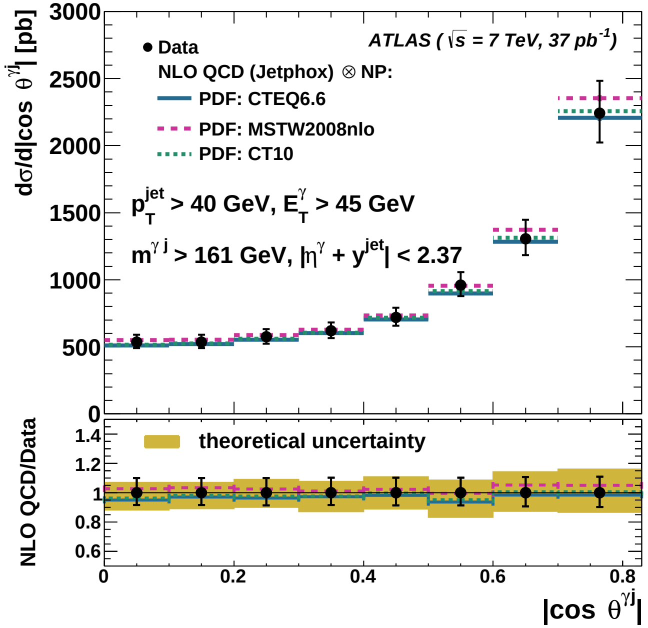


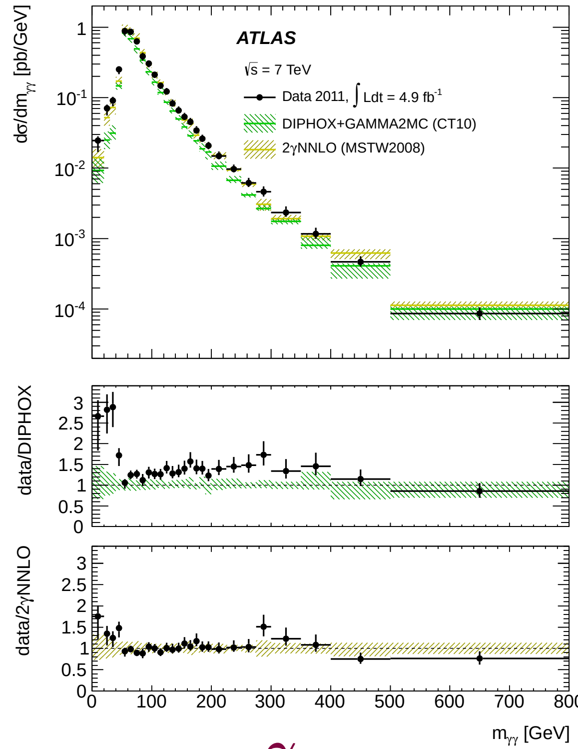
- **Clear observation of isolated photon-pair signal at 13 TeV**

(see Nicola Orlando's talk)
ATLAS Collab, ATL-PHYS-PUB-2015-020

Summary







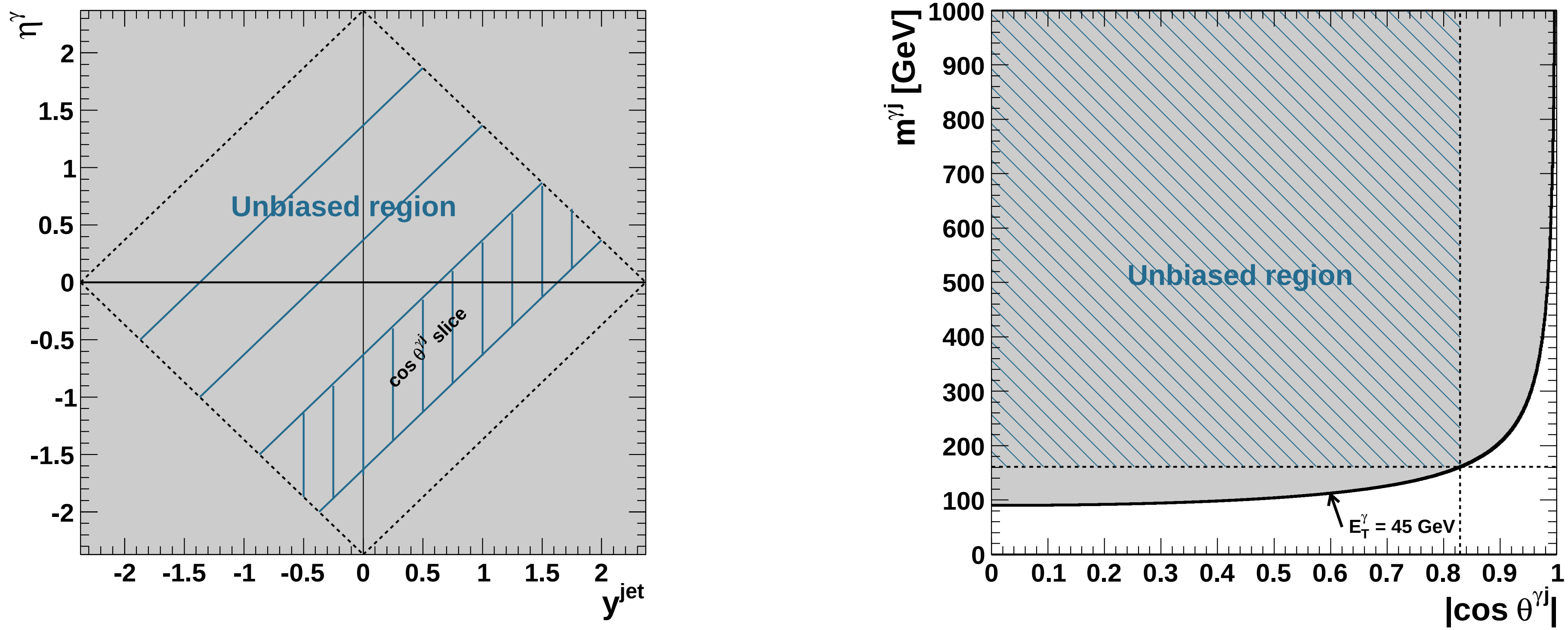
- **Exploration of isolated photon production in pp collisions up to $E_T^\gamma \sim 1$ TeV**
  $\Rightarrow$ additional experimental information on the gluon density in the proton
- **Measurements of photon+jet and diphoton production**
  $\Rightarrow$ test of colour dynamics and understanding of background to $H \to \gamma\gamma$ in terms of pQCD
- **Overall, perturbative QCD succeeds in describing the data!**
  ... new results at 8 and 13 TeV forthcoming...

Back-up slides

Isolated photons in association with jets

$pp \rightarrow \gamma + \mathrm{jet} + \mathrm{X}$: **isolated-photon plus jet cross sections** $\mathcal{L} = 37$ pb^{-1}

- **Selection of unbiased region to measure the $m^{\gamma j}$ and $|\cos\theta^{\gamma j}|$ cross sections:**
  $\rightarrow$ $|\eta^{\gamma} + y^{\mathrm{jet}}| < 2.37$, $|\cos\theta^{\gamma j}| < 0.83$ and $m^{\gamma j} > 161$ GeV



$\rightarrow$ **The first two requirements avoid the bias induced by cuts on η^{γ} and y^{jet}**
  $\rightarrow$ **slices of $\cos\theta^{\gamma j}$ have the same length along the $\eta^{\gamma} + y^{\mathrm{jet}}$ axis**

$\rightarrow$ **The third requirement avoids the bias due to $E_T^{\gamma} > 45$ GeV in the $(|\cos\theta^{\gamma j}|, m^{\gamma j})$ plane**

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