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Recent QCD results from ATLAS

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Outline:

- Charged-particle event shapes
- W+2-jet production
- Inclusive-jet and multijet cross sections
- Inclusive-photon, photon+jet and diphoton production

Jets at LHC

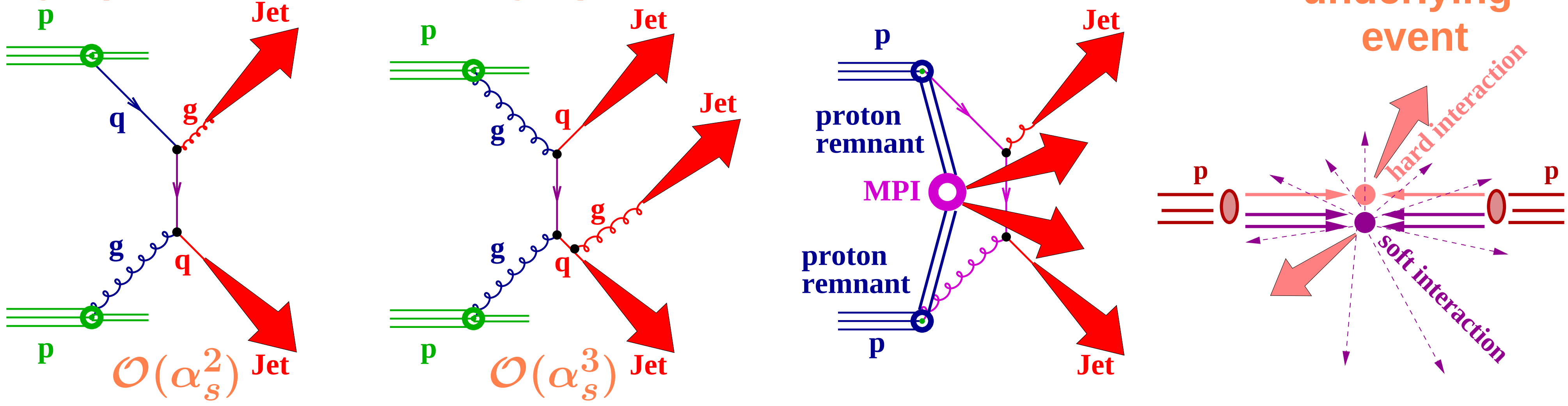
- QCD processes are dominant in hadron colliders
  $\rightarrow$ background to new physics $\Rightarrow$ need good understanding of multijet events
- Jet physics at LHC

$$\sigma_{pp\rightarrow \text{jets}} = \sum \int dx_{p_1}\, f_{a/p_1}(x_{p_1}, \mu_F) \int dx_{p_2}\, f_{b/p_2}(x_{p_2}, \mu_F)\, \hat{\sigma}_{ab\rightarrow \text{jets}}(\mu_R, \alpha_s, x_{p_1}, x_{p_2})$$

  – tests of pQCD and measurements of QCD parameters (α_s)
  – constraints on PDFs (especially, gluon density in the proton at high x)
  – tuning of Monte Carlo models

- Jet production at LHC:

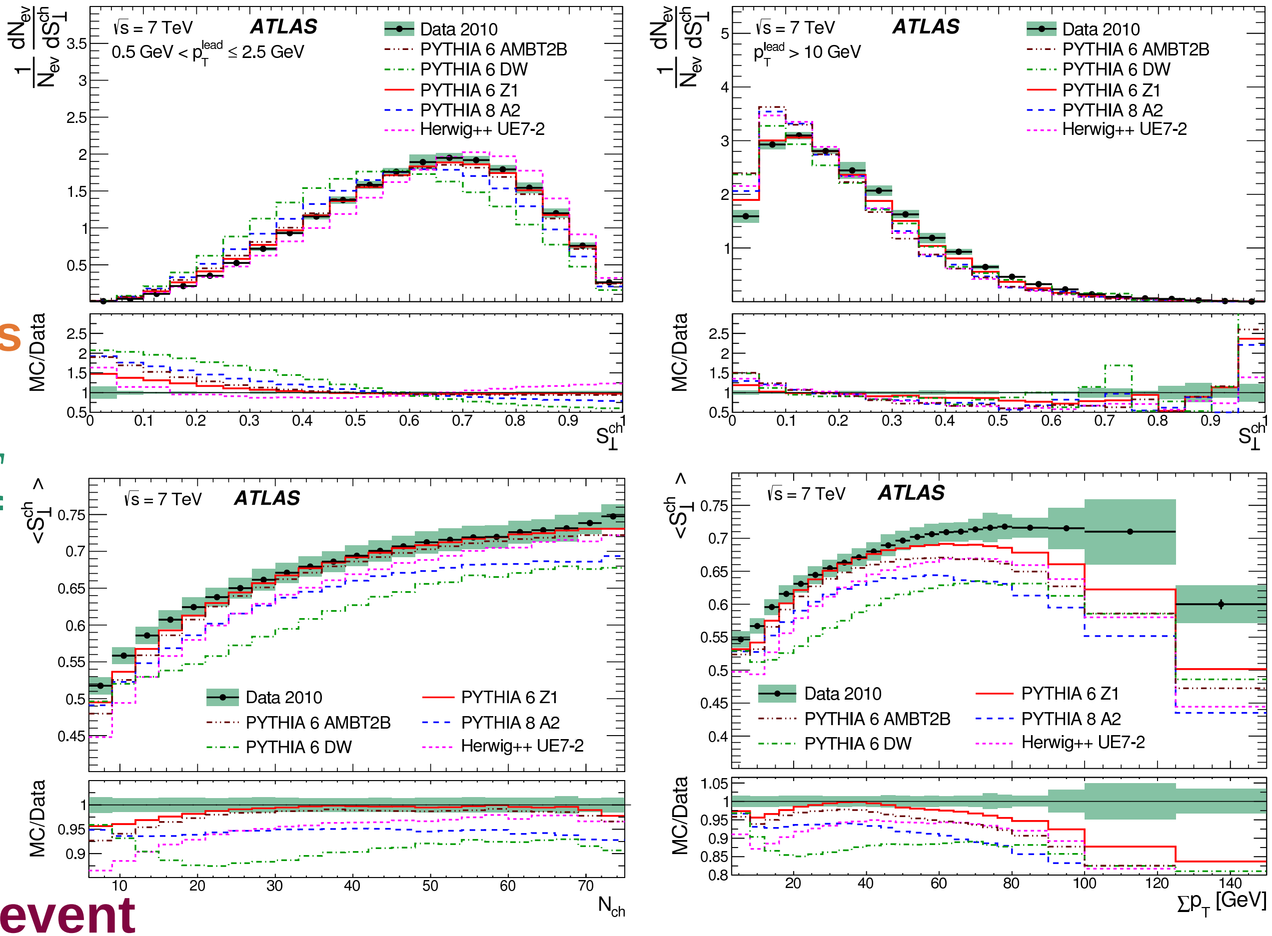
dijet production | multijet production | multiparton interactions | soft underlying event



Event shapes: understanding the soft underlying event

- Charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$

- Event shapes (eg thrust, sphericity) are sensitive to hadronisation and energy flow
  - $\longrightarrow$ useful to characterize the properties of the soft underlying event and other non-perturbative effects
  - $\longrightarrow$ observables useful to help tuning the models



- $S_\perp = 1$ for isotropic events
  - $\longrightarrow$ high mean value at low p_T
- $S_\perp = 0$ for balanced dijet events
  - $\longrightarrow$ low mean value at high p_T
  - $\longrightarrow$ decrease of $\langle S_\perp \rangle$ at high p_T interpreted as emergence of jets
- Comparison to LO MC based on different tunes
  - $\longrightarrow$ PYTHIA6 tune Z1 (tuned to LHC data) closest to data
- Sensitivity to soft underlying event

$\Rightarrow$ these measurements have the potential to improve further the MC tunes

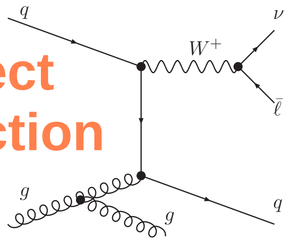
PRD 88 (2013) 032004

$W(\to \ell\nu)$+2-jet events: measuring multiparton interactions

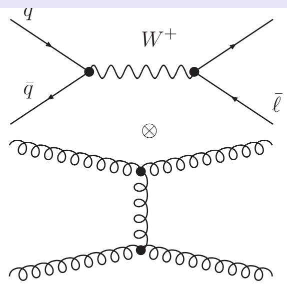
$pp \to W(\to \ell\nu) + 2\text{jets}$: double-parton interactions

$\mathcal{L} = 36$ pb^{-1}

direct interaction



double-parton interaction



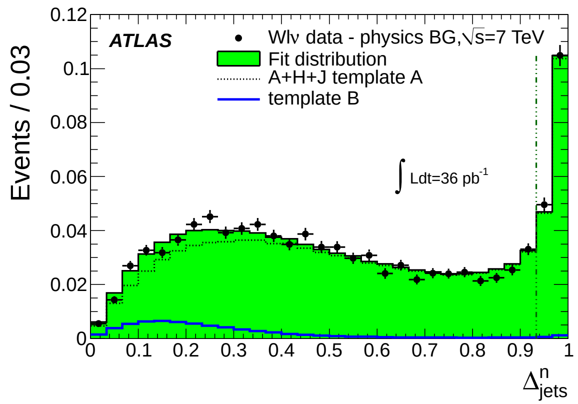
- Extraction of fraction $f_{\rm DP}$ of W+2-jet events with jets originating from hard DPI using a fit, based on templates, to the data distributions:

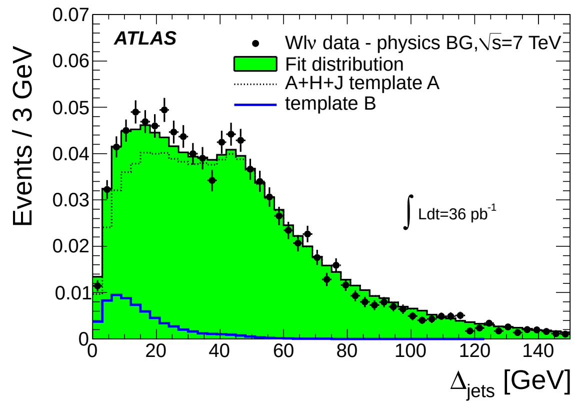
$$\Delta_{\rm jets} = |\vec{p}_T^{\,J_1} + \vec{p}_T^{\,J_2}|$$

$$\Delta^{n}_{\rm jets} = \frac{|\vec{p}_T^{\,J_1} + \vec{p}_T^{\,J_2}|}{|\vec{p}_T^{\,J_1}| + |\vec{p}_T^{\,J_2}|}$$

$\longrightarrow$ Value obtained from $\Delta^{n}_{\rm jets}$:

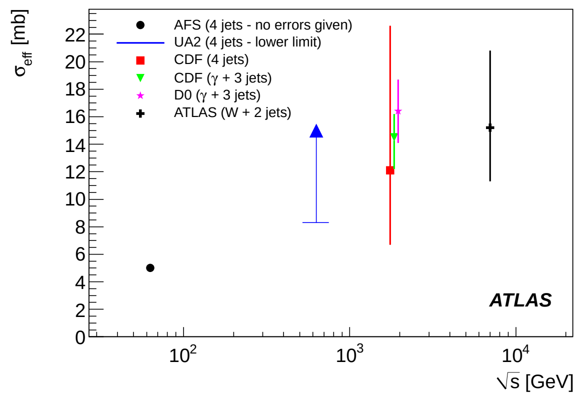
$f_{\rm DP} = 0.08 \pm 0.01$(stat)$\pm 0.02$(sys)





- The fraction $f_{\rm DP}$ is directly related to the effective area parameter for DPI and was used to extract $\sigma_{\rm eff}$:

$$\sigma_{\rm eff}(7\ {\rm TeV}) = 15 \pm 3(\text{stat})^{+5}_{-3}(\text{sys})\ \text{mb}$$



- Sensitivity to multiparton interactions

  $\Rightarrow$ measured value of effective area parameter for DPI consistent with other experiments at lower $\sqrt{s}$

NJP 15 (2013) 033038

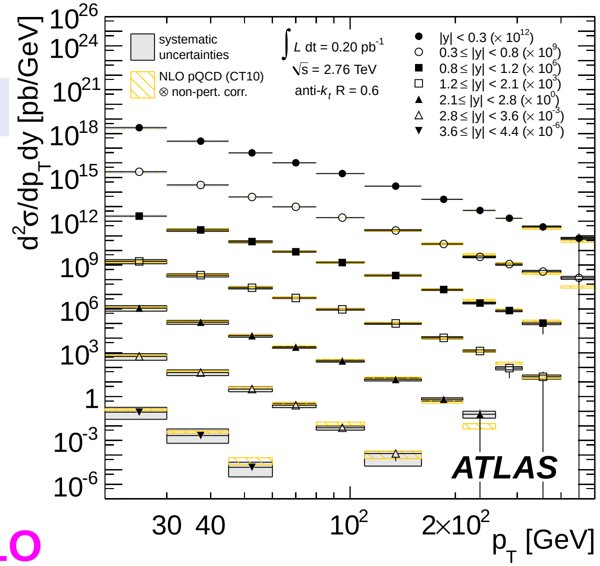
Inclusive-jet cross sections at $\sqrt{s} = 2.76$ TeV: testing pQCD

$pp \to \text{jet} + X$: inclusive-jet cross sections

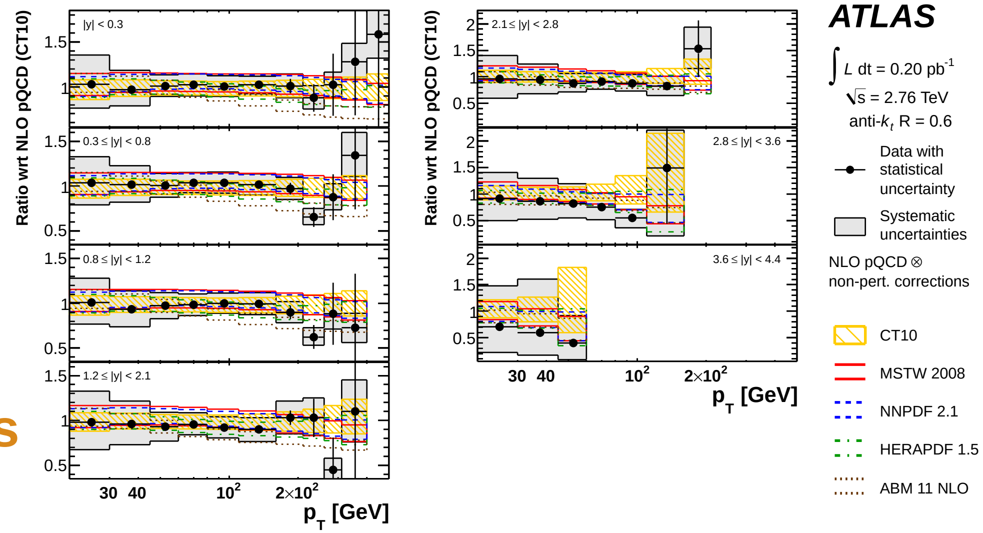
$\mathcal{L} = 0.2$ pb^{-1}

- Jet search: anti-k_T algorithm with $R = 0.4$ and $R = 0.6$
- Jets with $20 < p_T^{\text{jet}} < 430$ GeV and $|y^{\text{jet}}| < 4.4$
- Centre-of-mass energy: $\sqrt{s} = 2.76$ TeV

$R = 0.6$



- Experimental uncertainties:
  - $10 - 30\%$ in central rapidity region, higher in other regions
  - dominated by the jet energy scale in all regions
- Comparison to NLO predictions (NLOJET++)
  - $\longrightarrow$ $\mu_R = \mu_F = p_T^{\max}(y_i)$
  - $\longrightarrow$ PDFs: CT10, MSTW2008, NNPDF 2.1, HERAPDF 1.5, ABM 11 NLO
  - $\longrightarrow$ corrected for non-perturbative effects
  - $\longrightarrow$ theoretical uncertainties:
    - $5 - 15\%$ for high/low p_T ($|y| < 0.3$)
    - $10 - 80\%$ for high/low p_T ($3.6 < |y| < 4.4$)
    - in high p_T region, dominated by PDF uncertainty



- Test of pQCD
  - $\Rightarrow$ description of data within uncertainties
- Sensitivity to proton PDFs
  - $\Rightarrow$ regions of phase space where data have the potential to constrain the pPDFs

EPJ C 73 (2013) 2509

Ratios of inclusive-jet cross sections: testing pQCD

$pp \to \text{jet} + \text{X}$: **inclusive-jet cross sections**

$\mathcal{L} = 0.2 - 36$ pb^{-1}

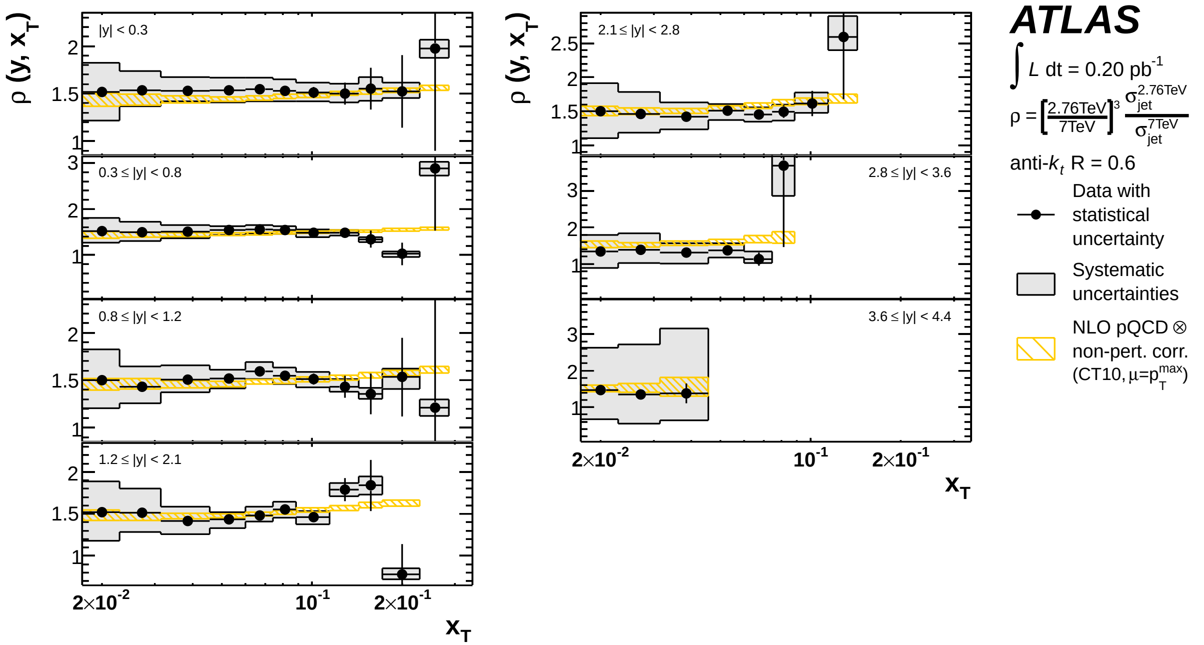
- Measurement of ratios of cross sections for $\sqrt{s} = 2.76$ TeV and 7 TeV

  $\rho(y, x_T) = \frac{F(y, x_T, 2.76 \text{ TeV})}{F(y, x_T, 7 \text{ TeV})}$ with $x_T = 2p_T/\sqrt{s}$ and

  $F = \frac{s}{8\pi} x_T^3 \frac{d^2\sigma}{dx_T dy}$ dimensionless scale-invariant cross section

- **Measurement of $\rho(y, x_T)$ provides more stringent tests of pQCD, since correlated experimental and theoretical uncertainties cancel in the ratio**

- **Experimental uncertainties:**
  – $5 - 20\%$ in central rapidity region
- **Theoretical uncertainties:**
  – $< 2\%$ ($|y| < 0.3$)
  – $2 - 10\%$ ($3.6 < |y| < 4.4$)



- **Stringent test of pQCD**
  $\longrightarrow$ good description of data
  $\longrightarrow$ $1.1 < \rho(y, x_T) < 1.5$
  $\Rightarrow$ **approximately constant behaviour, as expected from asymptotic freedom and evolution of PDFs**

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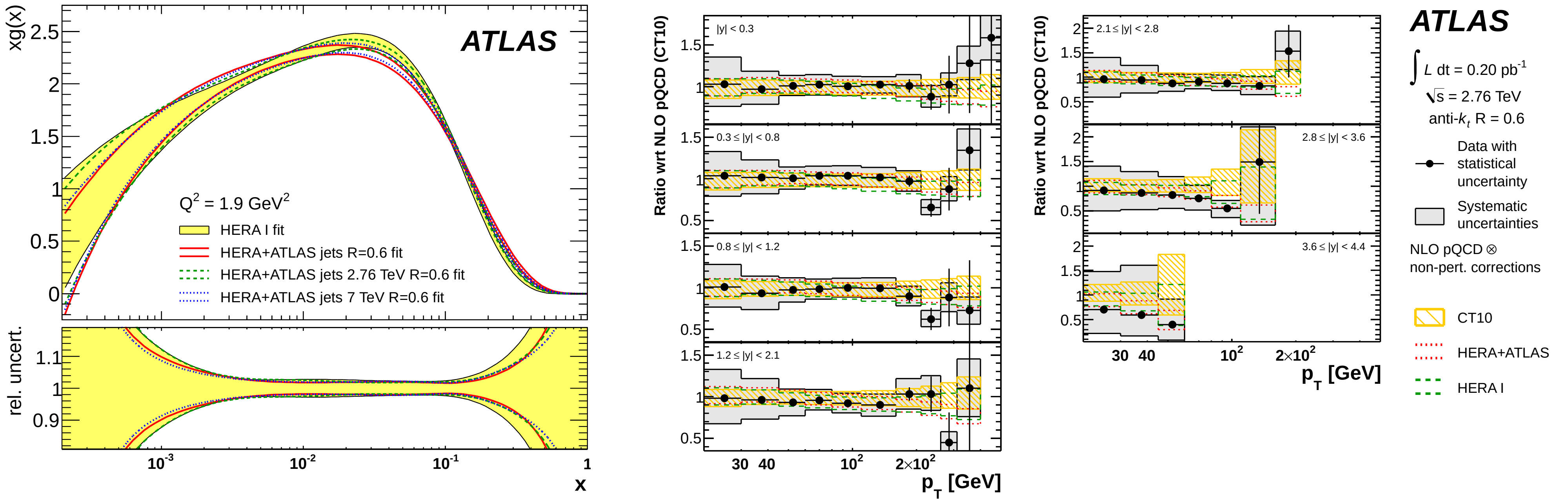
Inclusive-jet cross sections: determining the proton PDFs

$pp \longrightarrow \text{jet} + \text{X}$: inclusive-jet cross sections

- Inclusion of inclusive-jet cross sections at $\sqrt{s} = 2.76$ and 7 TeV in a NLO QCD fit together with HERA I data



- Impact on the proton PDFs when including ATLAS jet data:
  - $\Rightarrow$ the gluon distribution tends to be harder than with HERA data alone
  - $\Rightarrow$ the sea quark distribution tends to be softer than with HERA data alone
  - $\Rightarrow$ the description of the data is improved, especially in high $|y|$ region (high x)

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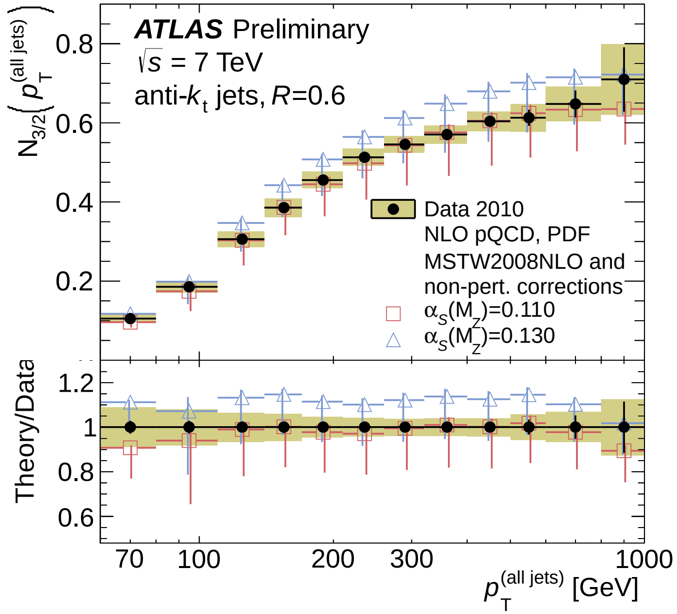
Multijet ratios: testing pQCD and determining α_s

$pp \longrightarrow$ jet + jet (+jet) + X: multijet cross sections

- Jet search: anti-k_T algorithm with $R = 0.6$
- At least two/three jets with $p_T^{jet} > 40$ GeV and $|y^{jet}| < 2.8$ and $p_{T,lead}^{jet} > 60$ GeV
- Measurement of:

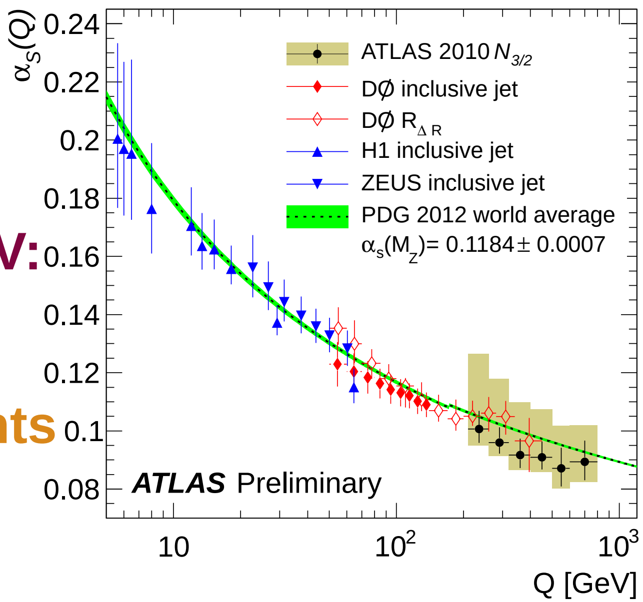
$$N_{3/2}(p_T^{(all\ jets)}) = \frac{\sum_i^{N_{jet}} (d\sigma_{N_{jet}\geq 3}/dp_{T,i}^{jet})}{\sum_i^{N_{jet}} (d\sigma_{N_{jet}\geq 2}/dp_{T,i}^{jet})}$$



- $N_{3/2}$ is sensitive to α_s
- Comparison to NLO predictions (NLOJET++)
  - $\longrightarrow$ $\mu_R = \mu_F = p_T^{jet}$; PDFs: MSTW2008NLO; $0.110 < \alpha_s(M_Z) < 0.130$; corrected for non-perturbative effects
  - $\longrightarrow$ good description of data
- Determination of α_s from $N_{3/2}$ for $210 < p_T < 800$ GeV:

$$\alpha_s(M_Z) = 0.111 \pm 0.006\ (\text{exp.})^{+0.016}_{-0.003}\ (\text{th.})$$

  $\Rightarrow$ consistent with world average and other experiments
- Test of the energy-scale dependence of α_s:
  $\Rightarrow$ consistent with the prediction of the RGE



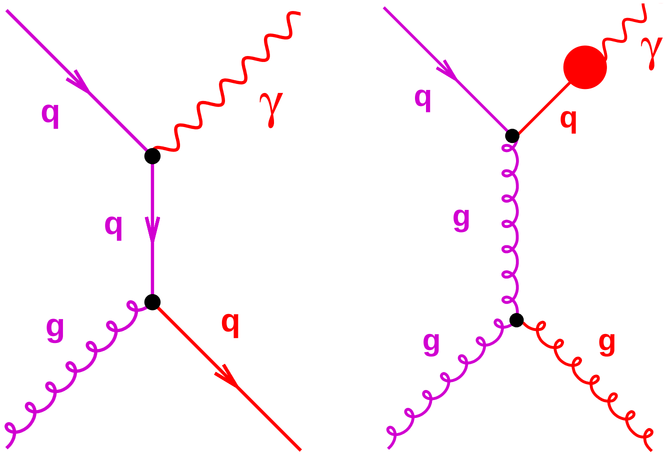
ATLAS-CONF-2013-041

Prompt photons at LHC

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

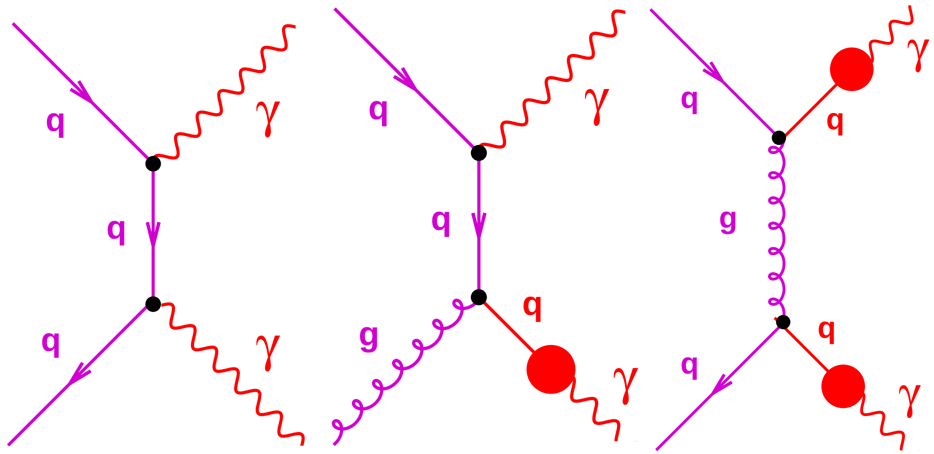
  $\longrightarrow$ tests of pQCD predictions in a cleaner reaction than jet production
  $\longrightarrow$ constraints on the proton PDFs (especially gluon PDF: $qg \longrightarrow q\gamma$ dominant)
  $\longrightarrow$ input to understand QCD background to Higgs production and BSM searches (tuning of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

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



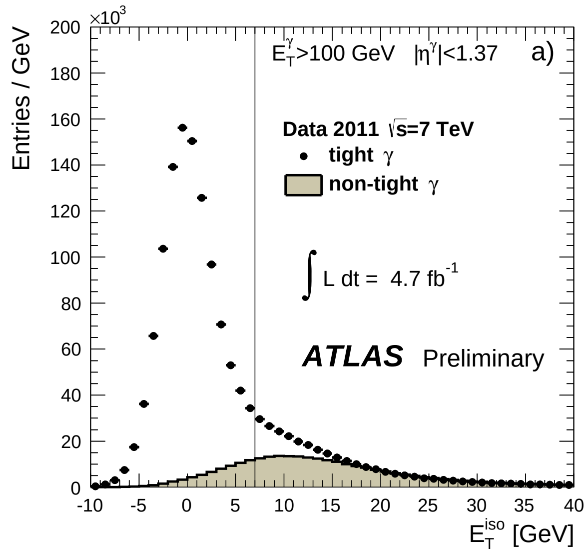
Diphoton production

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

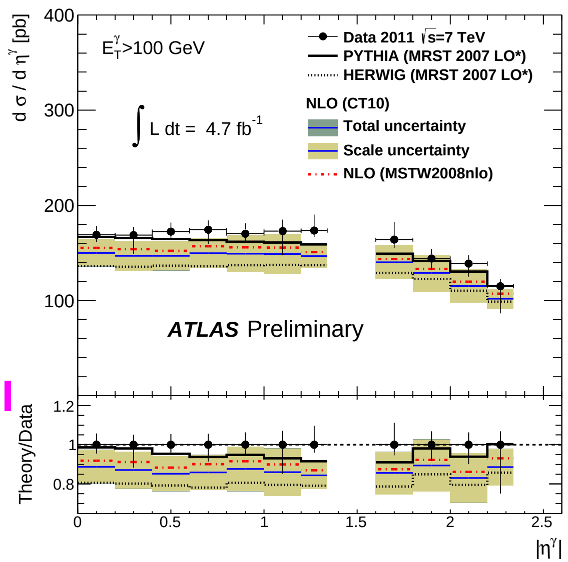
Inclusive isolated photons: testing pQCD

$pp \to \gamma + X$: inclusive isolated-photon cross sections $\mathcal{L} = 4.7$ fb^{-1}

- **Photon identification: shower shapes in calorimeter**
- **Photon isolation:** $\rightarrow E_T^{\text{iso}} < 7$ **GeV** $\longrightarrow$
  (to remove contribution from neutral-hadron decays into photons)
- **Photon selection:**
  $\rightarrow 100 < E_T^{\gamma} < 1000$ **GeV and** $|\eta^{\gamma}| < 2.37$
  excluding the region $1.37 < |\eta^{\gamma}| < 1.52$



- **Comparison to LO MC predictions**
  $\rightarrow$ **good description of data by PYTHIA**
  $\rightarrow$ **HERWIG describes shape but underestimates normalisation**
- **Comparison to NLO predictions (JETPHOX)**
  $\rightarrow \mu_R = \mu_F = \mu_f = E_T^{\gamma}$**; PDFs: CT10, MSTW2008NLO; FF: BFG set II**
  $\alpha_s(M_Z) = 0.118$**; corrected for non-perturbative effects**
  $\rightarrow$ **consistent with data within uncertainties**

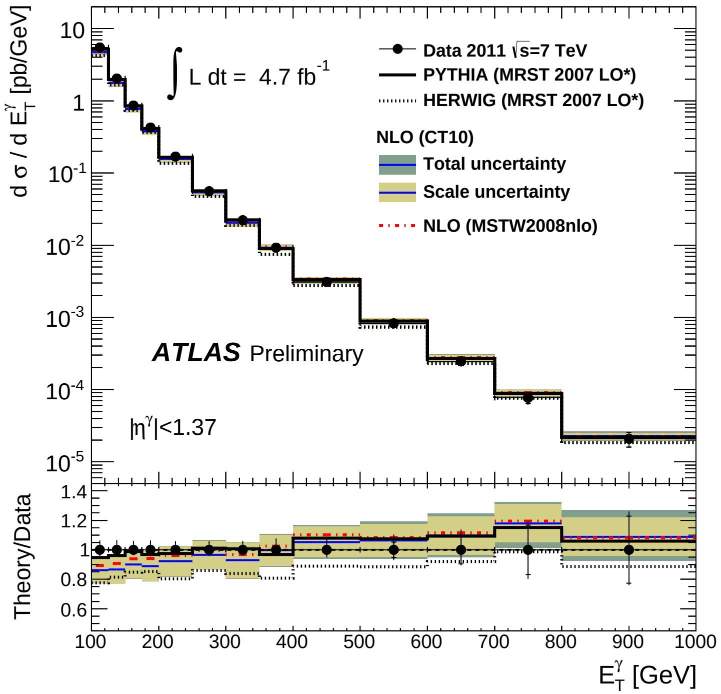


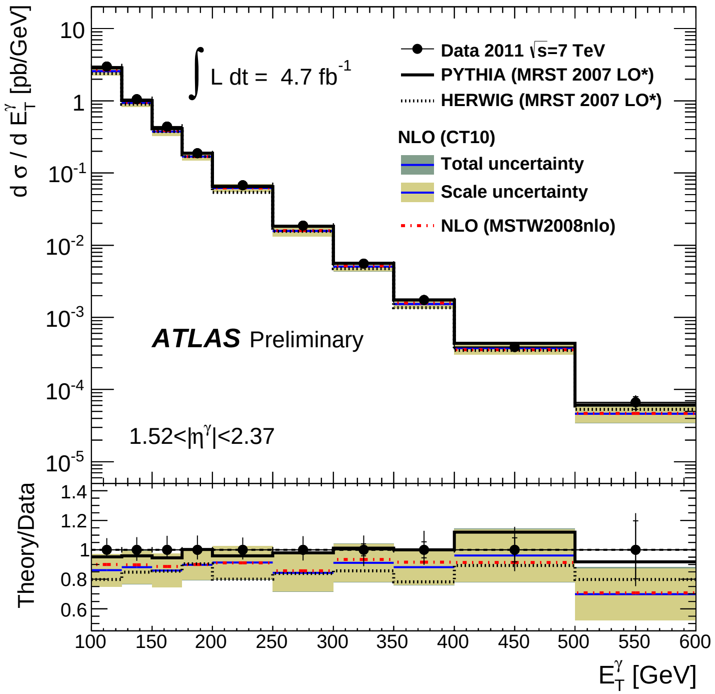
ATLAS-CONF-2013-022

Inclusive isolated photons: constraining the proton PDFs

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

$\mathcal{L} = 4.7$ fb^{-1}





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

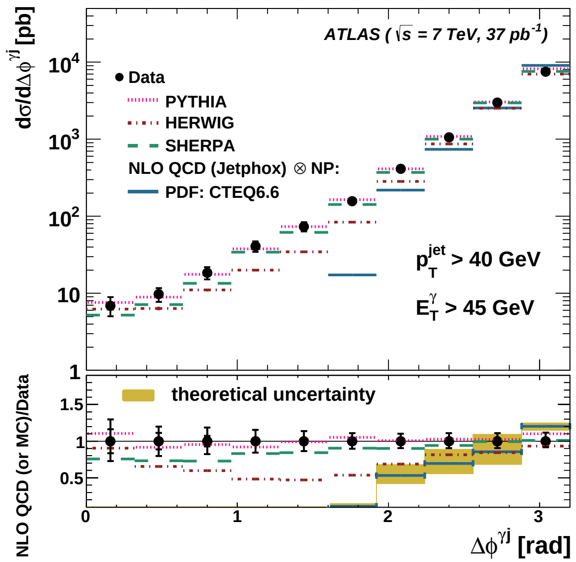
ATLAS-CONF-2013-022

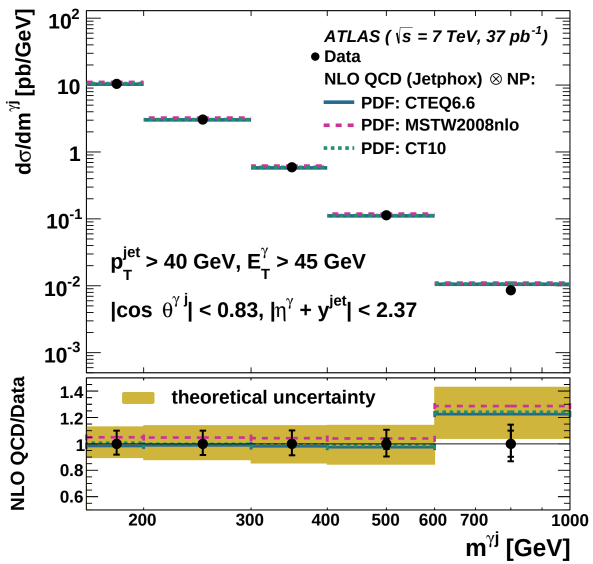
Isolated photons in association with jets: testing QCD dynamics

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

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

- Jet search: anti-k_T algorithm with $R = 0.6$
- 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 $|\eta^{\gamma} + y^{\text{jet}}| < 2.37$





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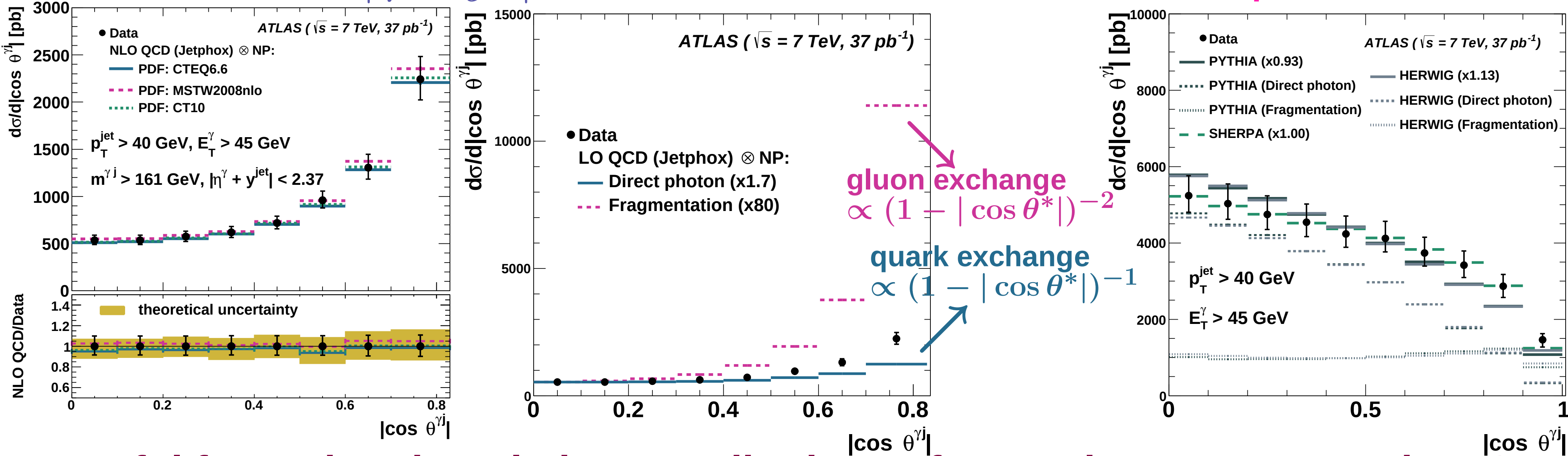
- Experimental and theoretical uncertainties $\approx 10\%$
- Comparison to LO MC predictions
  - $\longrightarrow$ good description of data by PYTHIA and SHERPA
  - $\longrightarrow$ HERWIG fails to describe the data
- Comparison to NLO predictions (JETPHOX)
  - $\longrightarrow$ $\mu_R = \mu_F = \mu_f = E_T^{\gamma}$; PDFs: CTEQ6.6, CT10, MSTW2008NLO; FF: BFG set II; $\alpha_s(M_Z) = 0.118$; corrected for non-perturbative effects
  - $\longrightarrow$ good description of data, except for $d\sigma/d\Delta\phi^{\gamma j}$ (expected since in NLO pQCD, $d\sigma/d\Delta\phi^{\gamma j} > \pi/2$ due to transverse-momentum conservation)

Isolated photons in association with jets: testing QCD dynamics

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

↓ with additional requirements: $m^{\gamma j} > 161$ GeV and $|\eta^\gamma + y^{\text{jet}}| < 2.37$

↓ without additional requirements



⇒ **Useful for tuning the relative contributions of DP and F components in MC**

- **Good description of data by NLO pQCD**
- **Sensitivity to QCD dynamics:**
  - → shape of data much closer to DP than to F processes → consistent with dominance of processes in which a quark is being exchanged
    - ⇒ 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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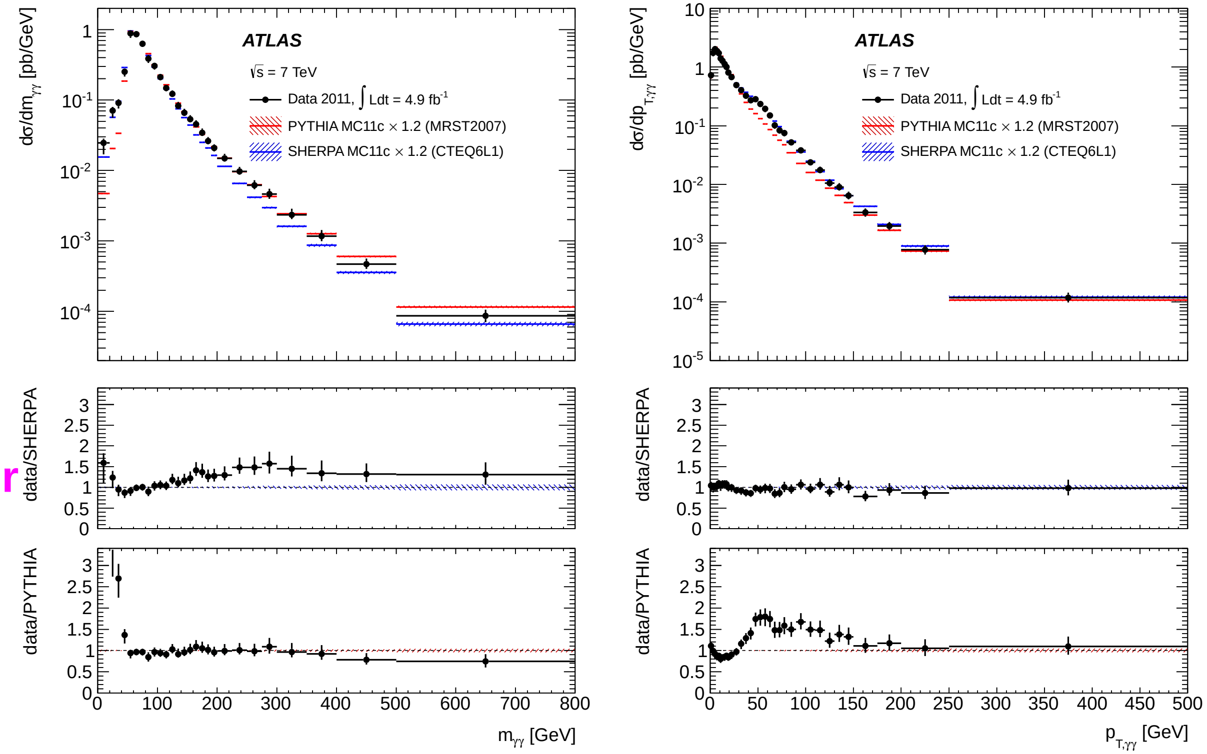
Isolated photon pairs: understanding the QCD background

$pp \to \gamma\gamma + X$: 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 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

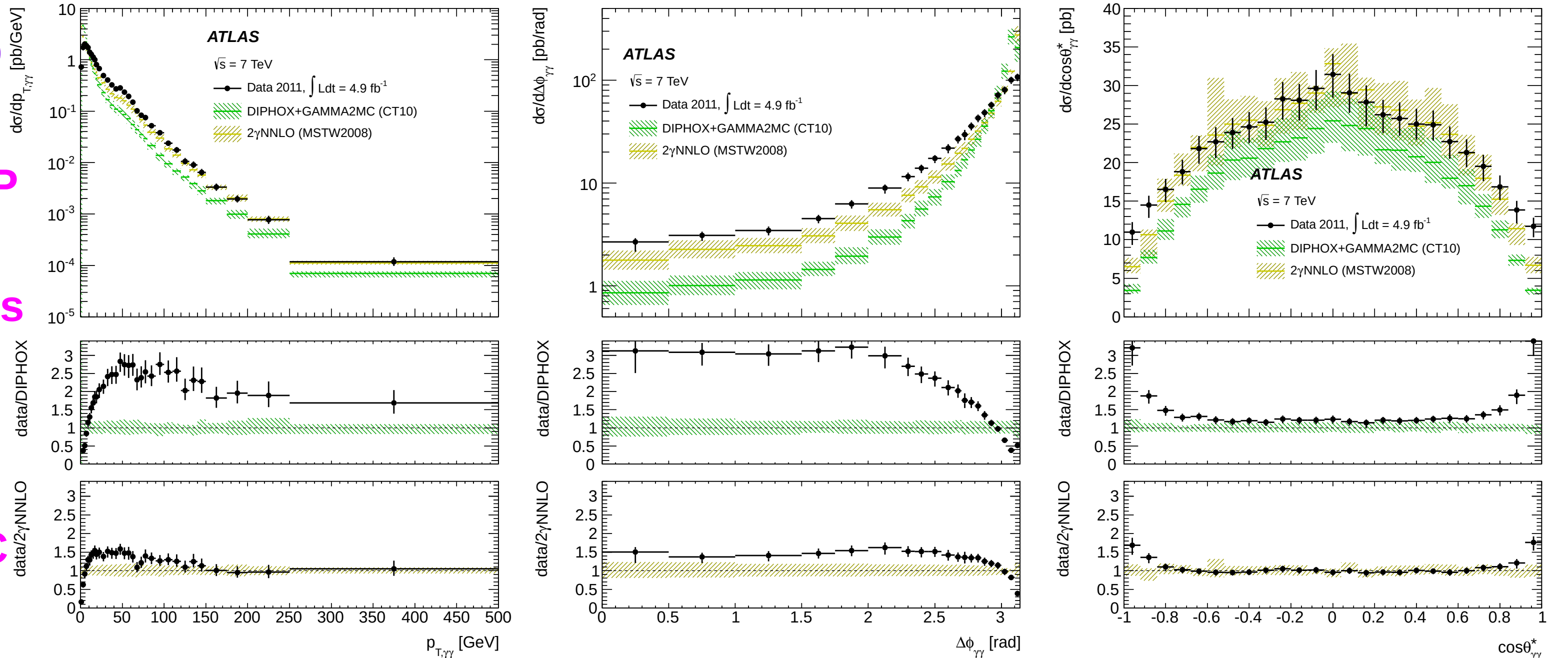
JHEP 01 (2013) 086

Isolated photon pairs: understanding the QCD background

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

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

- Comparison to HO predictions
  - → 2γNNLO: NNLO DP
  - → DIPHOX: NLO DP and F contributions with NNNLO calculation to box diagram $gg \to \gamma\gamma$ using GAMMA2MC



→ DIPHOX+GAMMA2MC: fails to describe the data for $\Delta\phi_{\gamma\gamma} \sim \pi$ and low $p_{T,\gamma\gamma}$ due importance of soft-gluon resummation in this region and underestimates the data everywhere else due to missing higher orders

→ 2γNNLO: is closest to the data, but still below the data in regions where the fragmentation contribution is more significant

- Sensitivity to higher orders:

  ⇒ improved calculations are needed to understand fully diphoton production

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Conclusions

- **QCD@LHC:**
  - ∗ **Charged-particle event shapes**
    $\Rightarrow$ **possibility to tune further the MC models for the soft underlying event**
  - ∗ **W+2-jet production**
    $\Rightarrow$ **measurement of multiparton interactions**
  - ∗ **Inclusive-jet cross sections**
    $\Rightarrow$ **tests of pQCD and determination of pPDFs**
  - ∗ **Multijet cross sections**
    $\Rightarrow$ **tests of pQCD and determination of α_s**
  - ∗ **Inclusive-photon production**
    $\Rightarrow$ **tests of pQCD and possibility to constrain further the pPDFs**
  - ∗ **Photon+jet production**
    $\Rightarrow$ **tests of QCD dynamics**
  - ∗ **Diphoton production**
    $\Rightarrow$ **understanding of photon-pair production via QCD (irreducible background to $H \rightarrow \gamma\gamma$)**

Back-up slides

Event shapes

- **The sphericity describes the event energy flow based on the momentum tensor**

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2}$$

where $\alpha, \beta = x, y, z$ components of the momentum of particle i

- **The sphericity of the event is defined in terms of the two smallest eigenvalues of this tensor, λ_2 and λ_3: $S = \frac{3}{2}(\lambda_2 + \lambda_3$**

- **The transverse sphericity is defined in terms of the transverse components only**

$$S^{xy} = \sum_i \frac{1}{|\vec{p}_{T,i}|^2} \begin{bmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{x,i}p_{y,i} & p_{y,i}^2 \end{bmatrix}$$

and $S_\perp = \frac{2\lambda_2^{xy}}{\lambda_1^{xy}+\lambda_2^{xy}}$, where $\lambda_2^{xy} < \lambda_1^{xy}$ are the two eigenvalues of S^{xy}

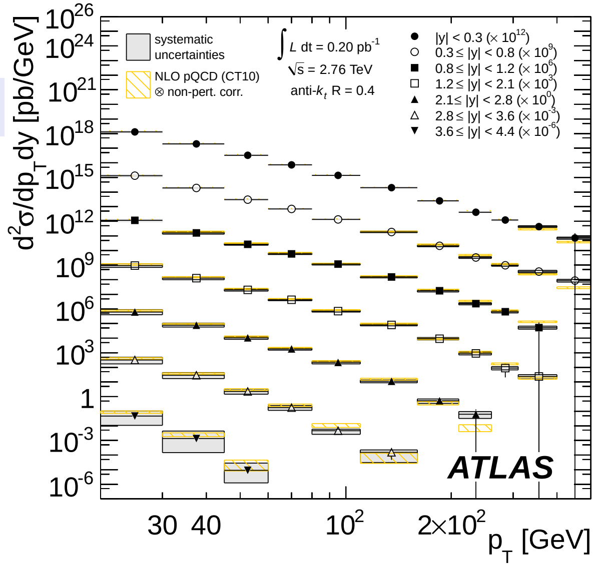
Inclusive-jet cross sections at $\sqrt{s} = 2.76$ TeV

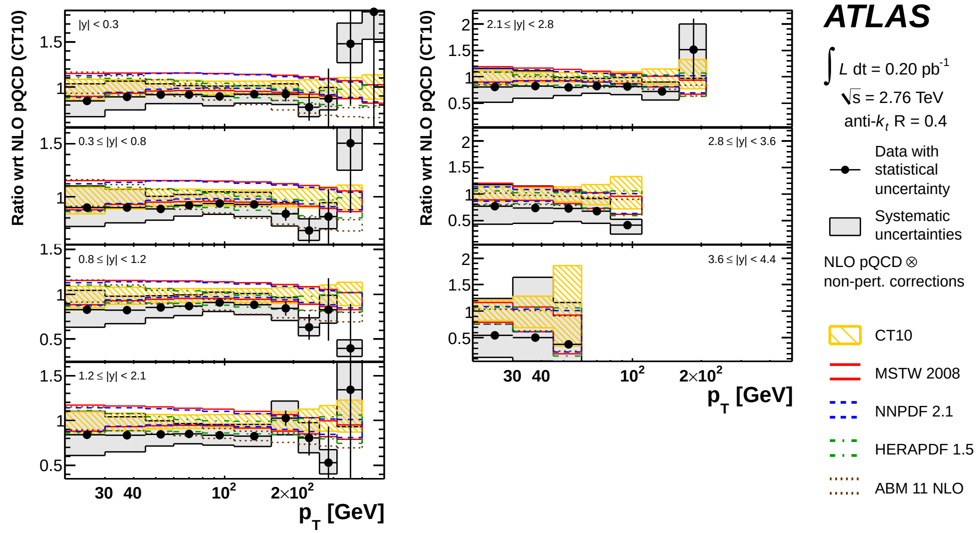
$pp \longrightarrow \text{jet} + X$: inclusive-jet cross sections

$\mathcal{L} = 0.2$ pb^{-1}

- Jet search: anti-k_T algorithm with $R = 0.4$ and $R = 0.6$
- Jets with $20 < p_T^{\text{jet}} < 430$ GeV and $|y^{\text{jet}}| < 4.4$
- Centre-of-mass energy: $\sqrt{s} = 2.76$ TeV

$R = 0.4$





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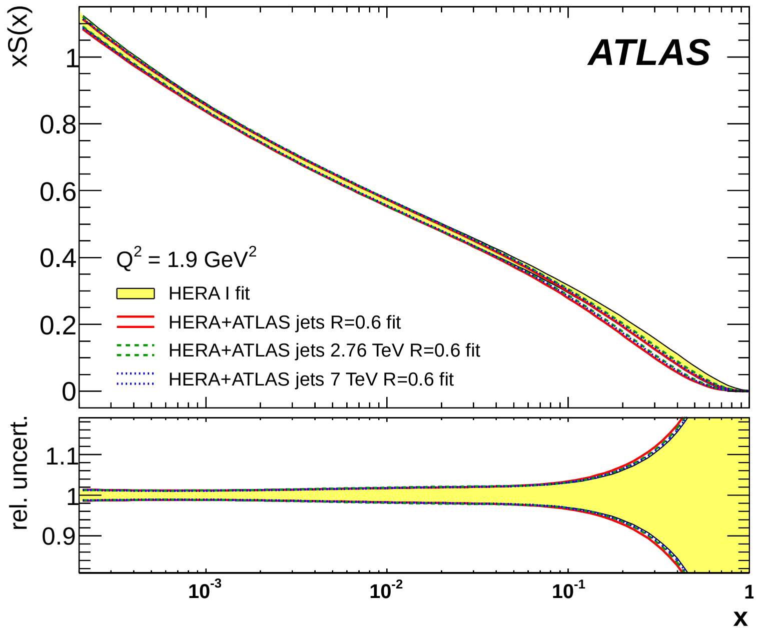
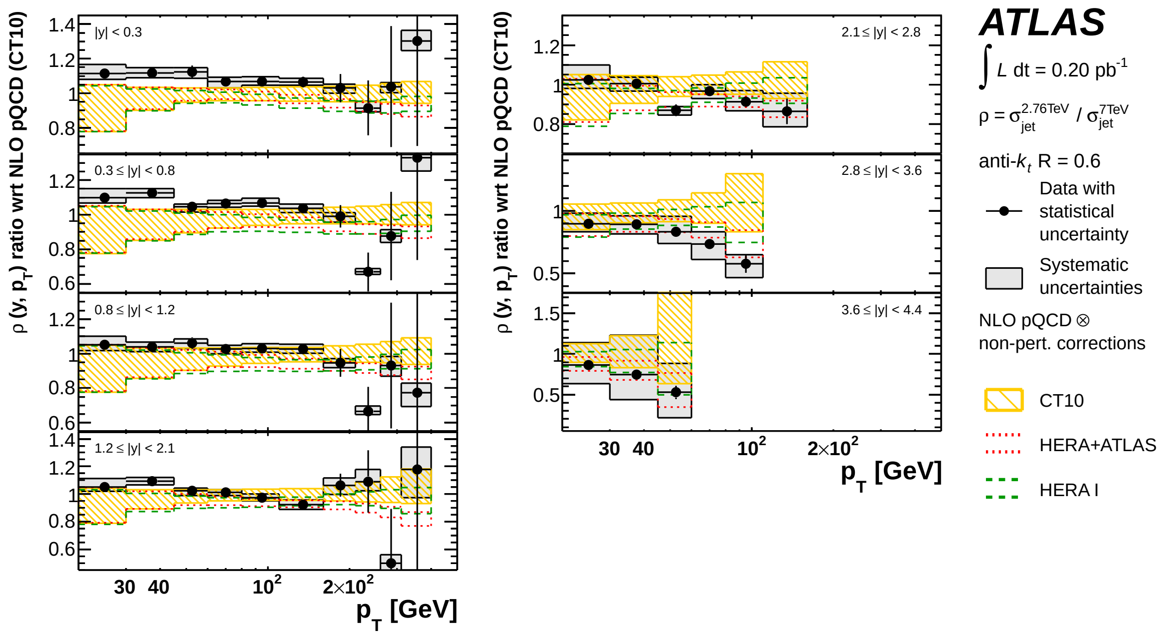
Inclusive-jet cross sections: determining the proton PDFs

$pp \longrightarrow \text{jet} + \text{X}$: inclusive-jet cross sections





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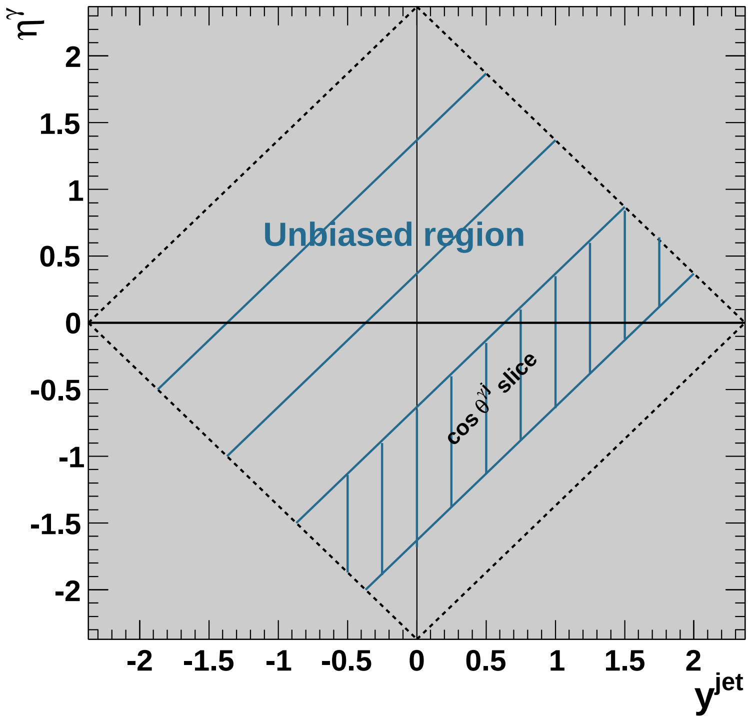
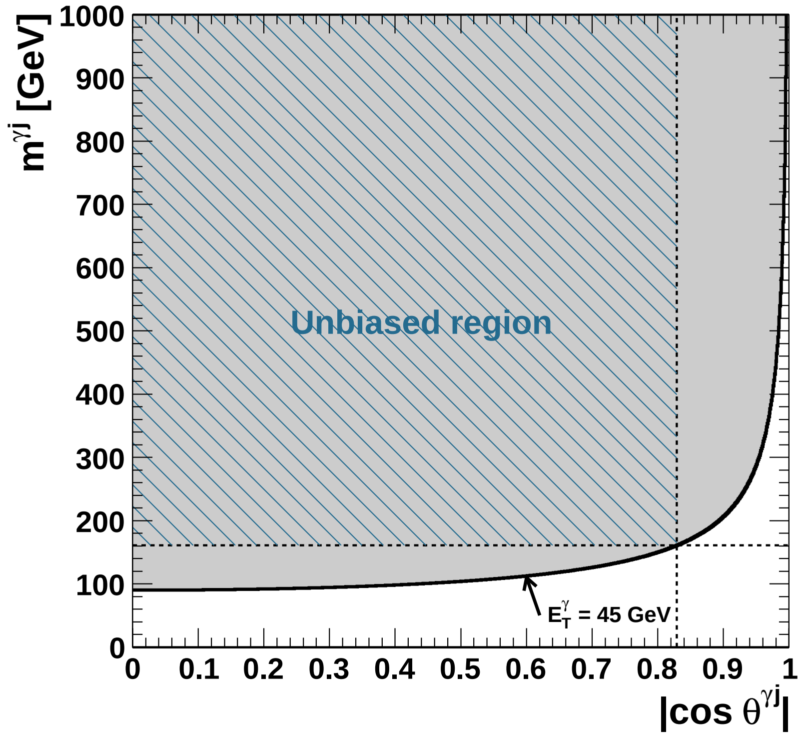
Isolated photons in association with jets

$pp \rightarrow \gamma + \text{jet} + \text{X}$: **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:**
  $\rightarrow$ $|\eta^{\gamma} + y^{\text{jet}}| < 2.37$, $|\cos\theta^{\gamma j}| < 0.83$ 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 $\eta^{\gamma} + y^{\text{jet}}$ 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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