

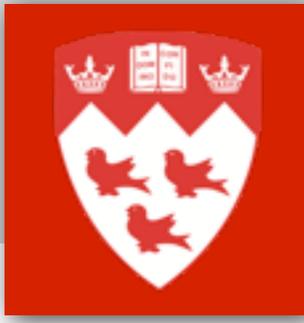


Probing QCD with photons and jets produced in pp collisions with the ATLAS detector

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McGill University

On behalf of the ATLAS Collaboration

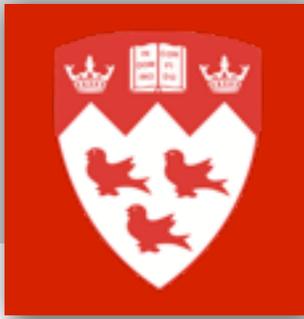
Motivation



Studies of the production of photons and jets in proton-proton collisions at the LHC provide:

- Precision tests of a wide range of Standard Model predictions in new kinematic regimes.
- Constraints on proton PDFs.
- Determination of the strong coupling constant.
- Description of background event kinematics for different searches for new physics.

What we measure?



Measure cross-sections in fiducial volume

$$\sigma_{fid} = \frac{N_{data} - N_{bkg}}{lumi \times C}$$

Corrections for detector inefficiencies

Extrapolate to total phase space

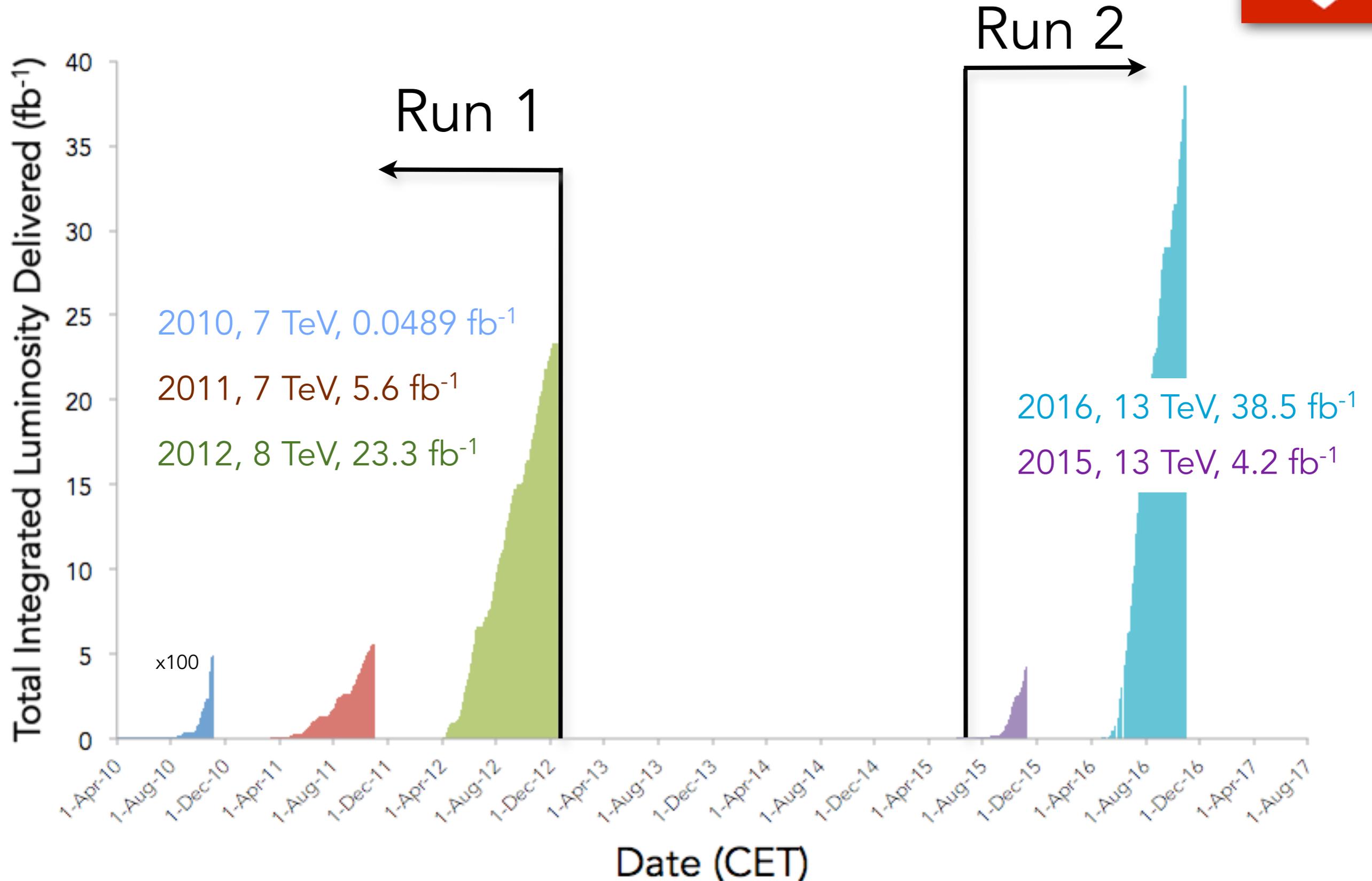
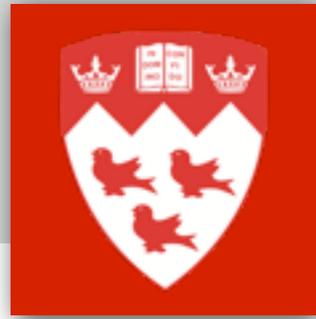
$$\sigma_{tot} = \frac{N_{data} - N_{bkg}}{lumi \times A \times C}$$

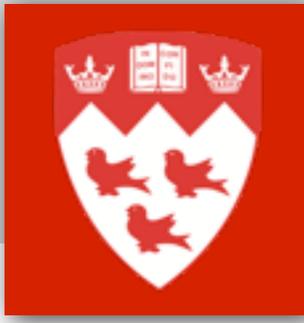
Signal acceptance in fiducial volume

Measure differential cross-sections

- Provide additional kinematic information
- Corrected for detector effects (reported at "particle" level)

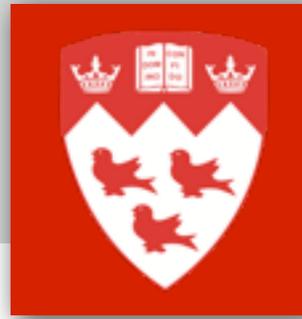
ATLAS data samples





- Inclusive jet production (8 TeV)
[<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-01/>]
- Multi-jet production and determination of strong coupling constant (7 TeV) [Physics Letters B 750 (2015) 427-447]
- Inclusive prompt photon (13 TeV)
[arXiv:1701.06882, submitted to PLB]
- Di-photon production (8 TeV) [arXiv:1704.03839, submitted to PRD]
- Photon+jets (8 TeV) [Nucl.Phys. B918 (2017) 257-316]

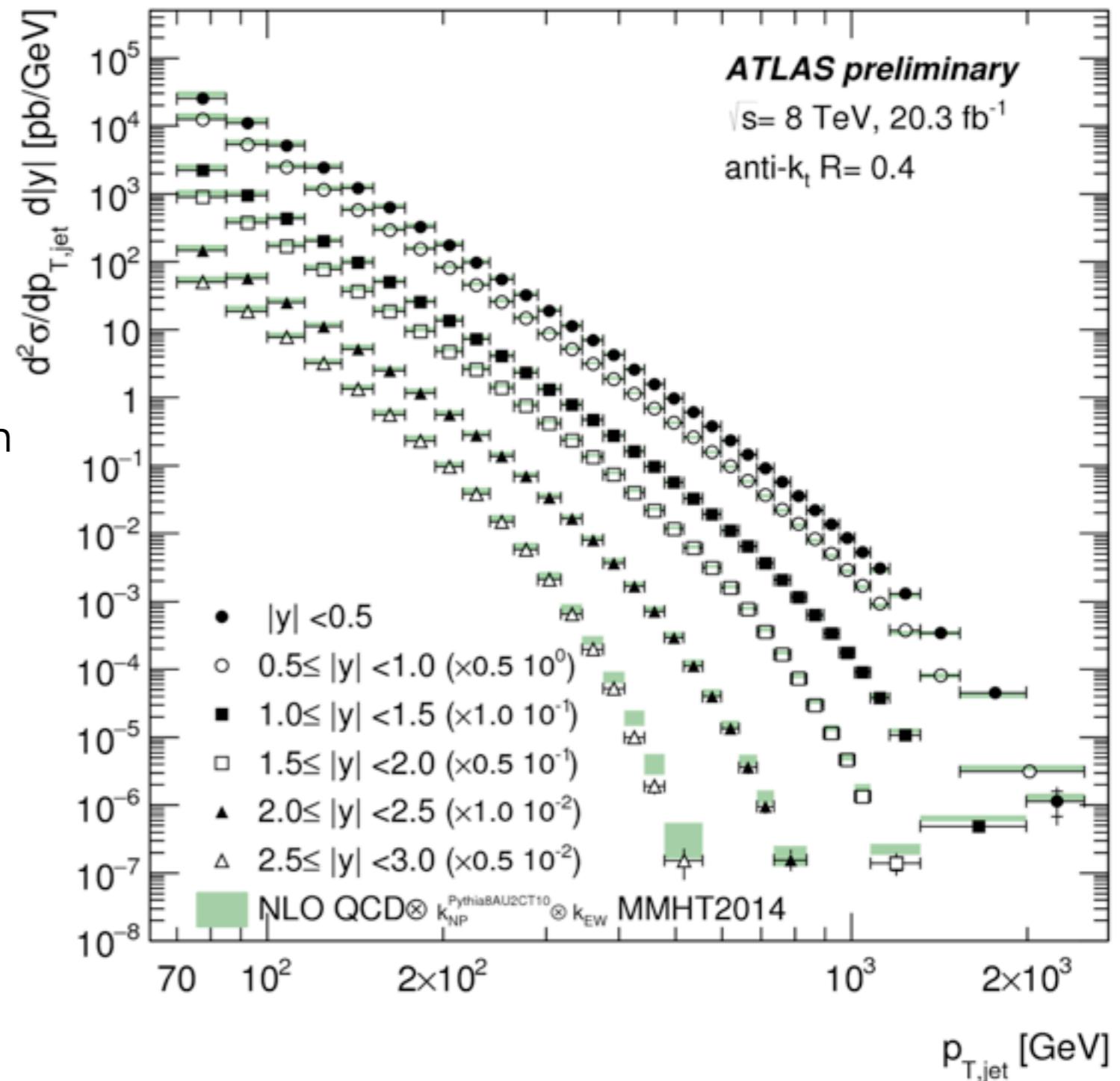
Inclusive jet production



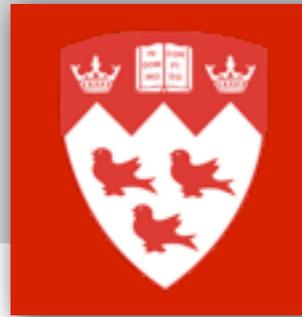
<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-01/>

$$pp \rightarrow \text{jet} + X$$

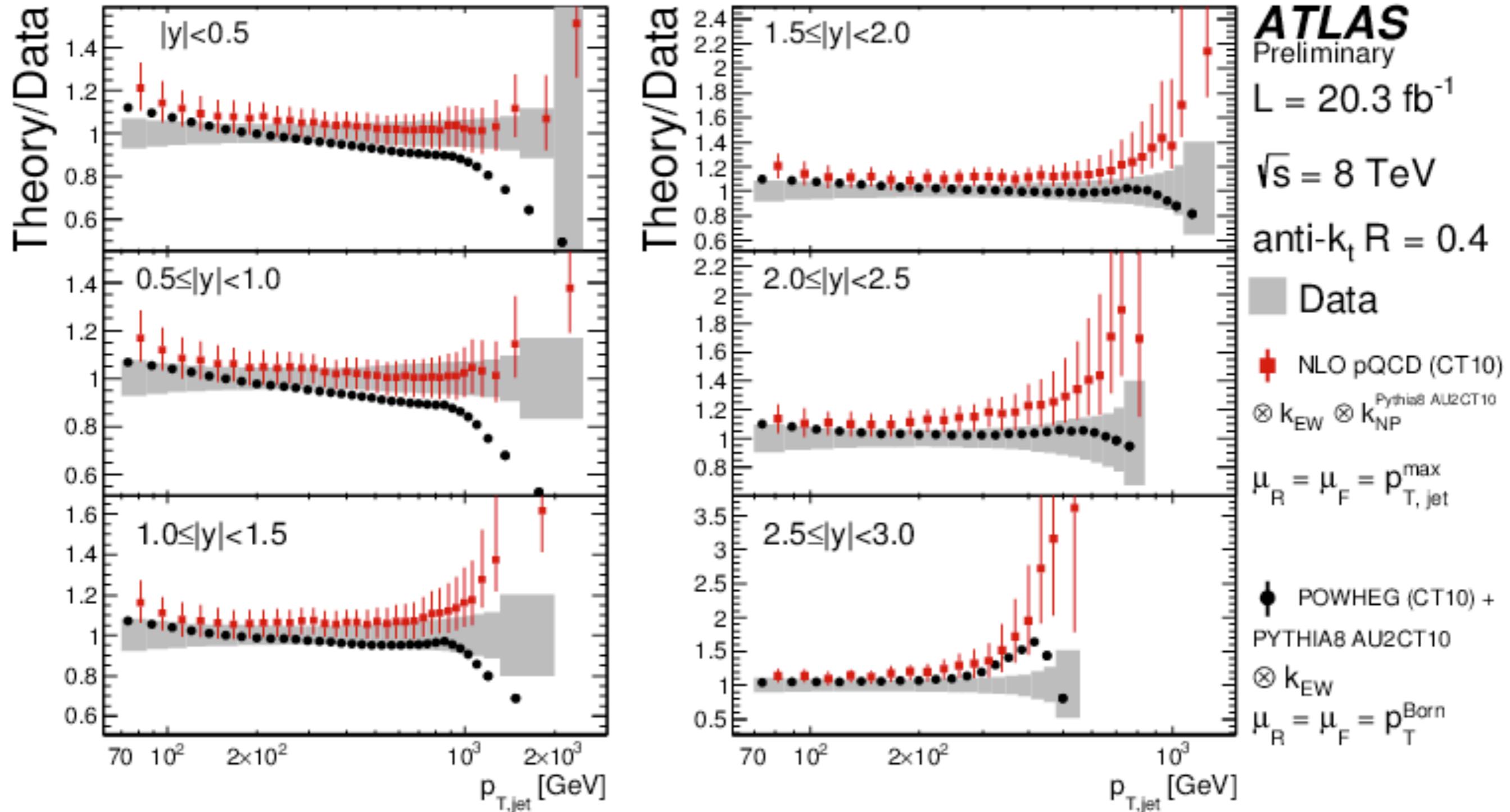
- Doubly-differential jet production cross-section measured at 8 TeV.
- Measurements benefit from increase in integrated luminosity and reduction in jet energy calibration uncertainties.
- Measurements performed with two different jet radius parameters to test the sensitivity to non-perturbative (hadronisation and underlying event) and perturbative (higher-order corrections and parton shower) effects.



Inclusive jet production

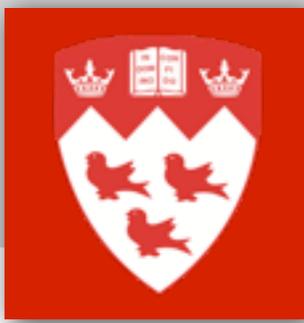


<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-01/>



Multi-jet production

Physics Letters B 750 (2015) 427-447

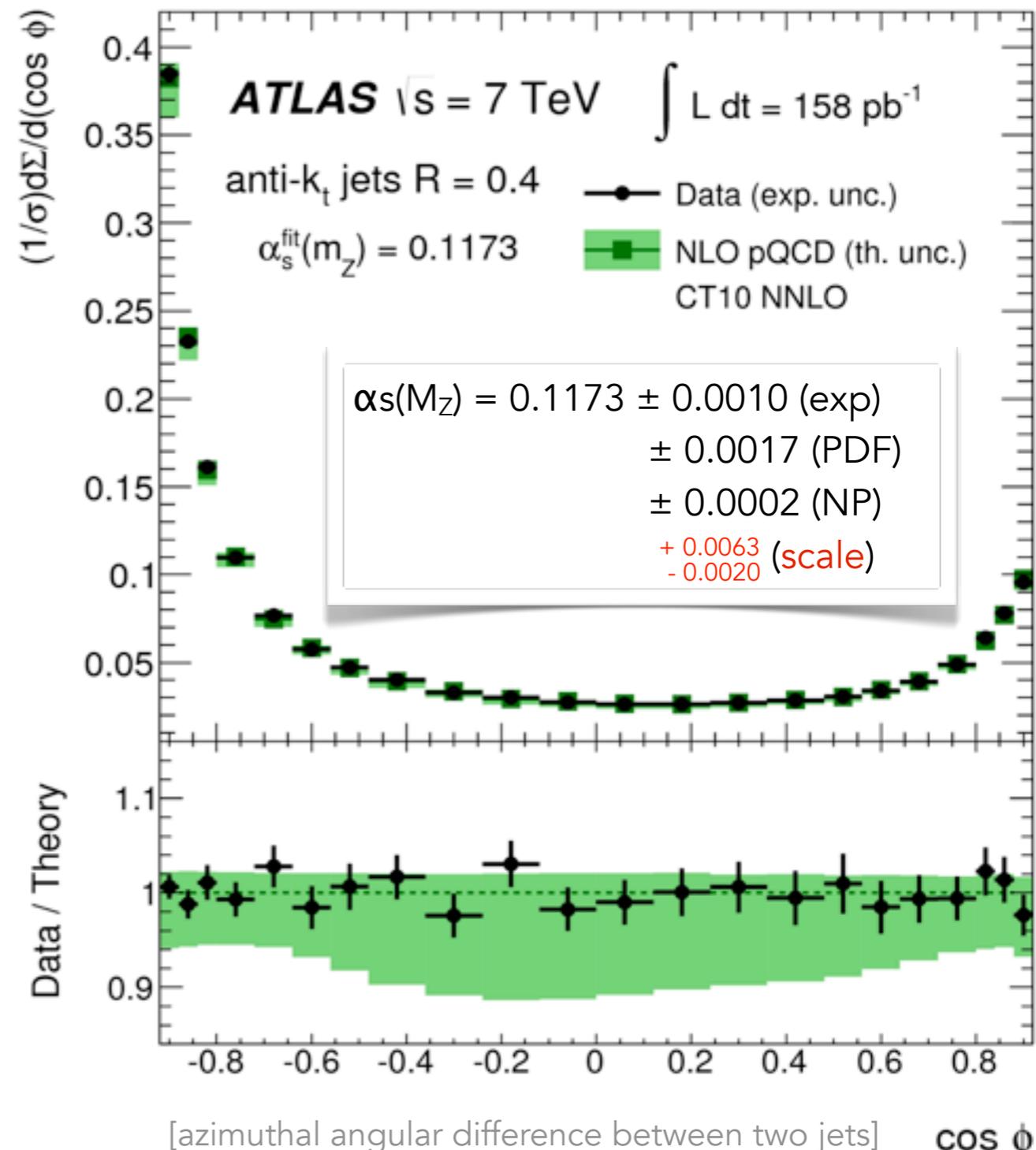


Transverse Energy-Energy correlation function in multi-jet events.

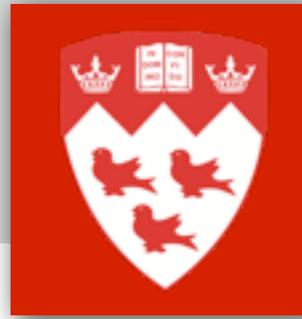
$$\frac{1}{\sigma} \frac{d\Sigma}{d(\cos \phi)} = \frac{1}{\sigma} \sum_{ij} \int \frac{d\sigma}{dx_{Ti} dx_{Tj} d(\cos \phi)} x_{Ti} x_{Tj} dx_{Ti} dx_{Tj},$$

$$\text{where } x_{Ti} = E_{Ti}/E_T \\ \phi = \Delta\varphi_{ij}$$

- By construction, TEEC and ATEEC functions are less affected by experimental effects (e.g. JES, JER, pile-up) than absolute cross-section measurements.
- Determination of α_s obtained from χ^2 fit to NLO predictions.
- Uncertainty dominated by theoretical scale uncertainty.
 - Calculations beyond NLO accuracy are needed for multi-jet production.

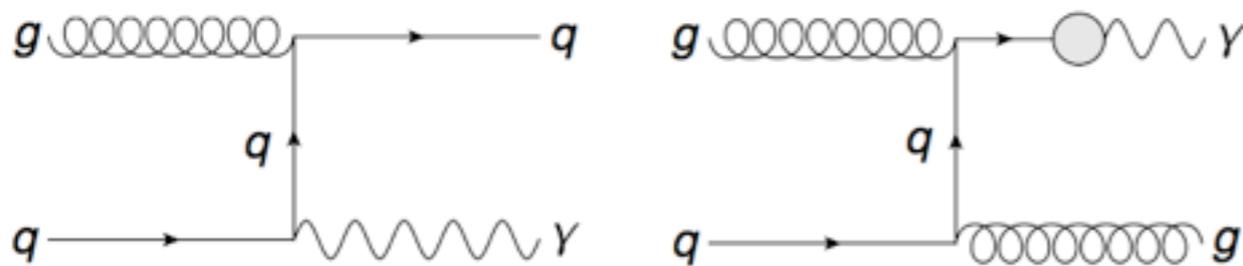


Inclusive photon production

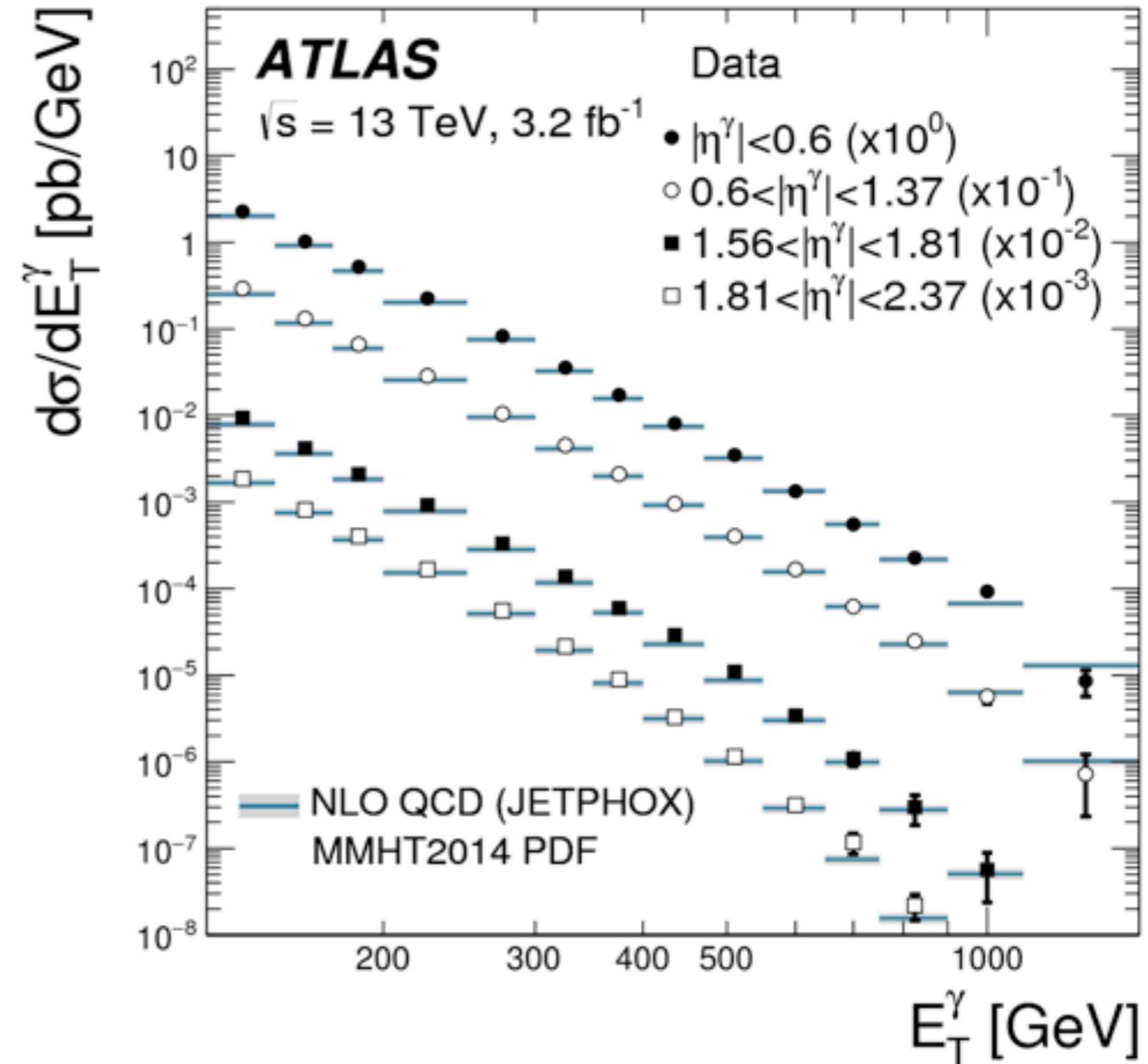


arXiv:1701.06882, submitted to PLB

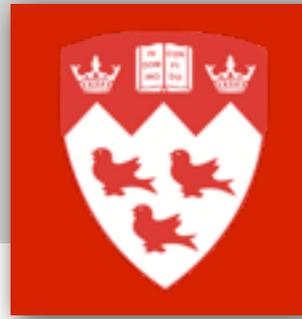
$$pp \rightarrow \gamma + X$$



- Tests of pQCD using colourless probe.
- Sensitivity at LO to gluon density in proton.
- NLO pQCD calculations provide adequate description of measurements; however, test sensitivity limited by theoretical uncertainties associated with missing higher-order terms in pQCD

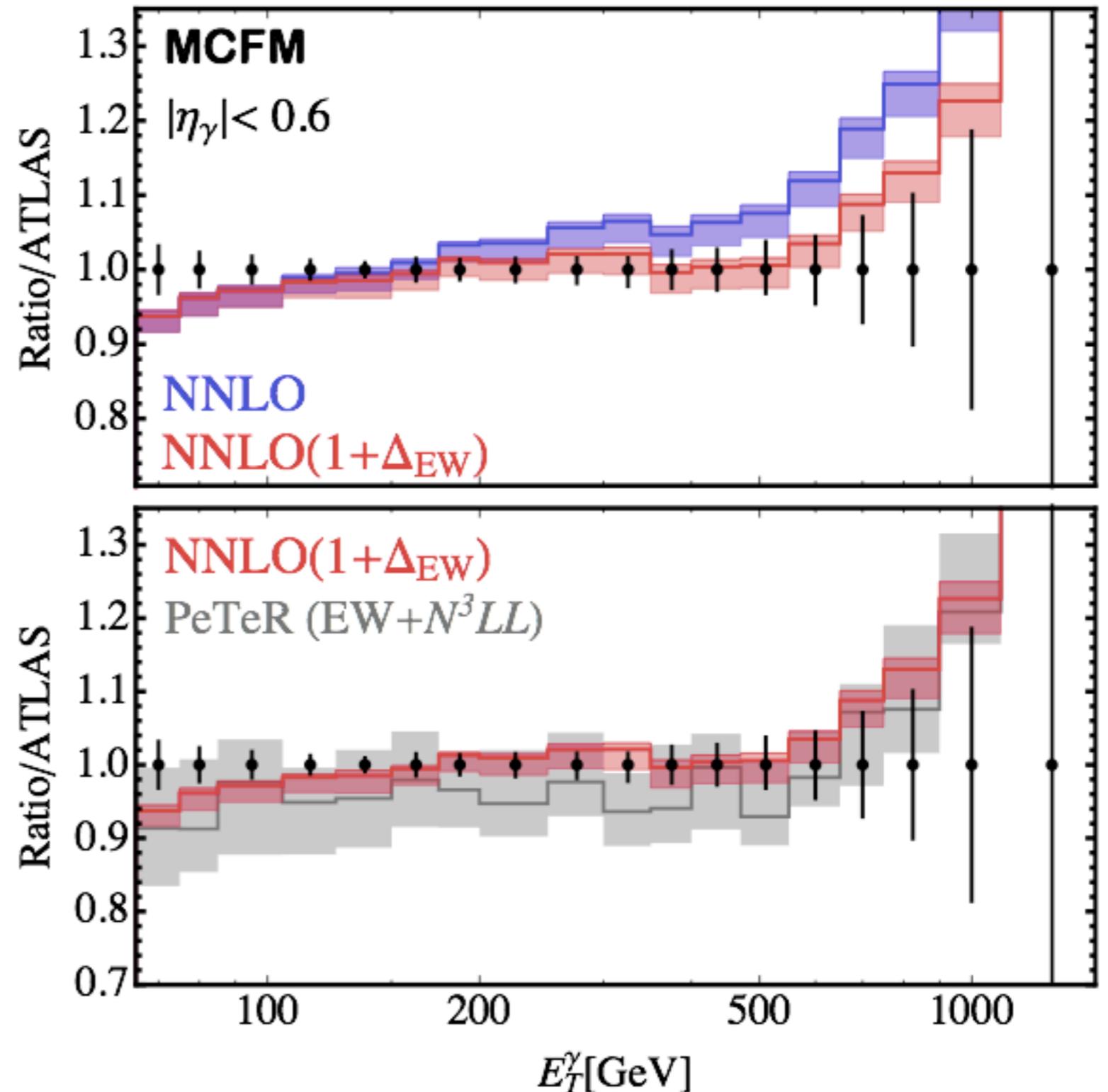


Inclusive photon production

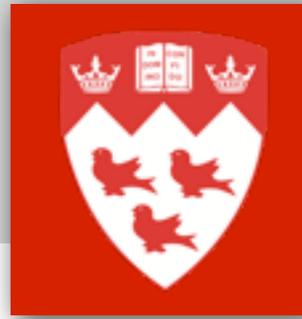


Campbell, Ellis and Williams, arXiv:1612.04333

- Recent NNLO pQCD calculations made available.
- Theoretical uncertainties reduce by a factor of ~ 3 .
- This opens up a new opportunity for precision QCD at LHC.

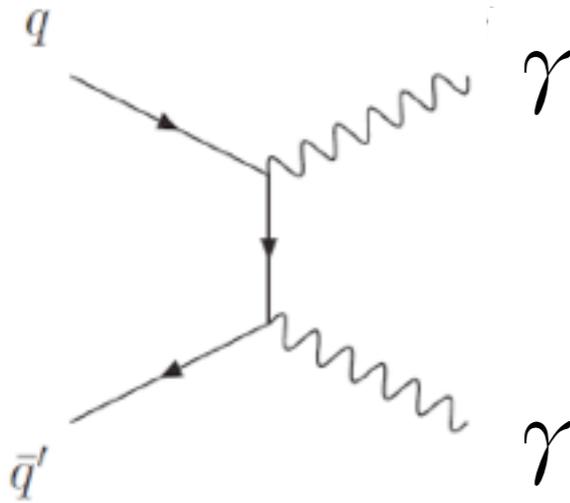


Di-photon production

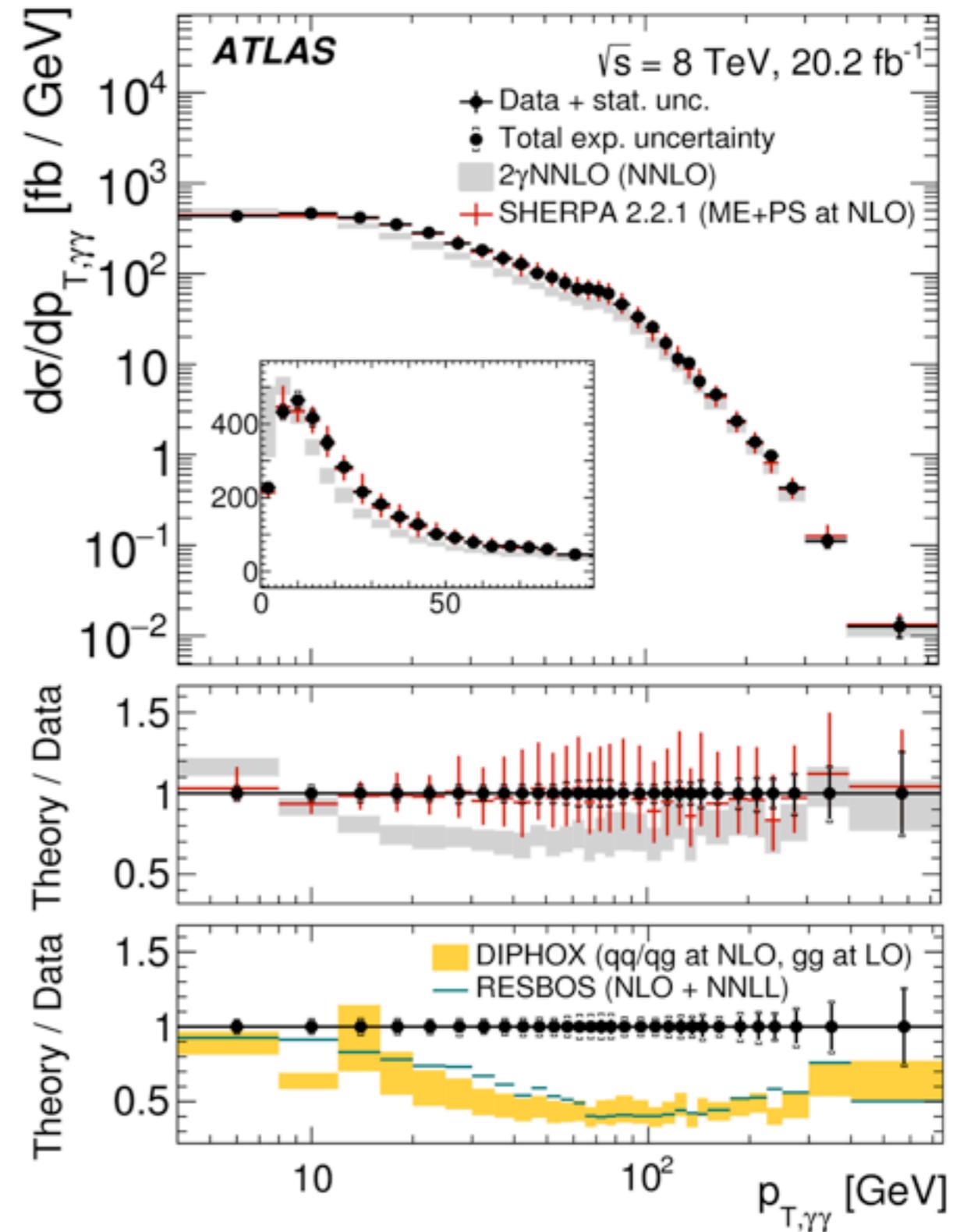


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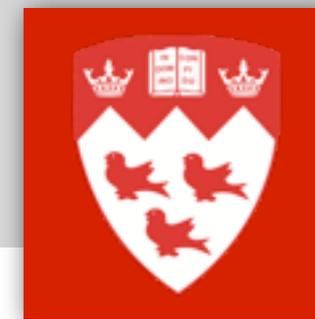
$$pp \rightarrow \gamma + \gamma + X$$



- Cross-section at 8 TeV measured differentially as function of 6 kinematic observables.
- Systematic uncertainties reduced by up to factor of 2 compared to measurements at 7 TeV, due to improvements in background estimation
 - Despite higher pile-up conditions

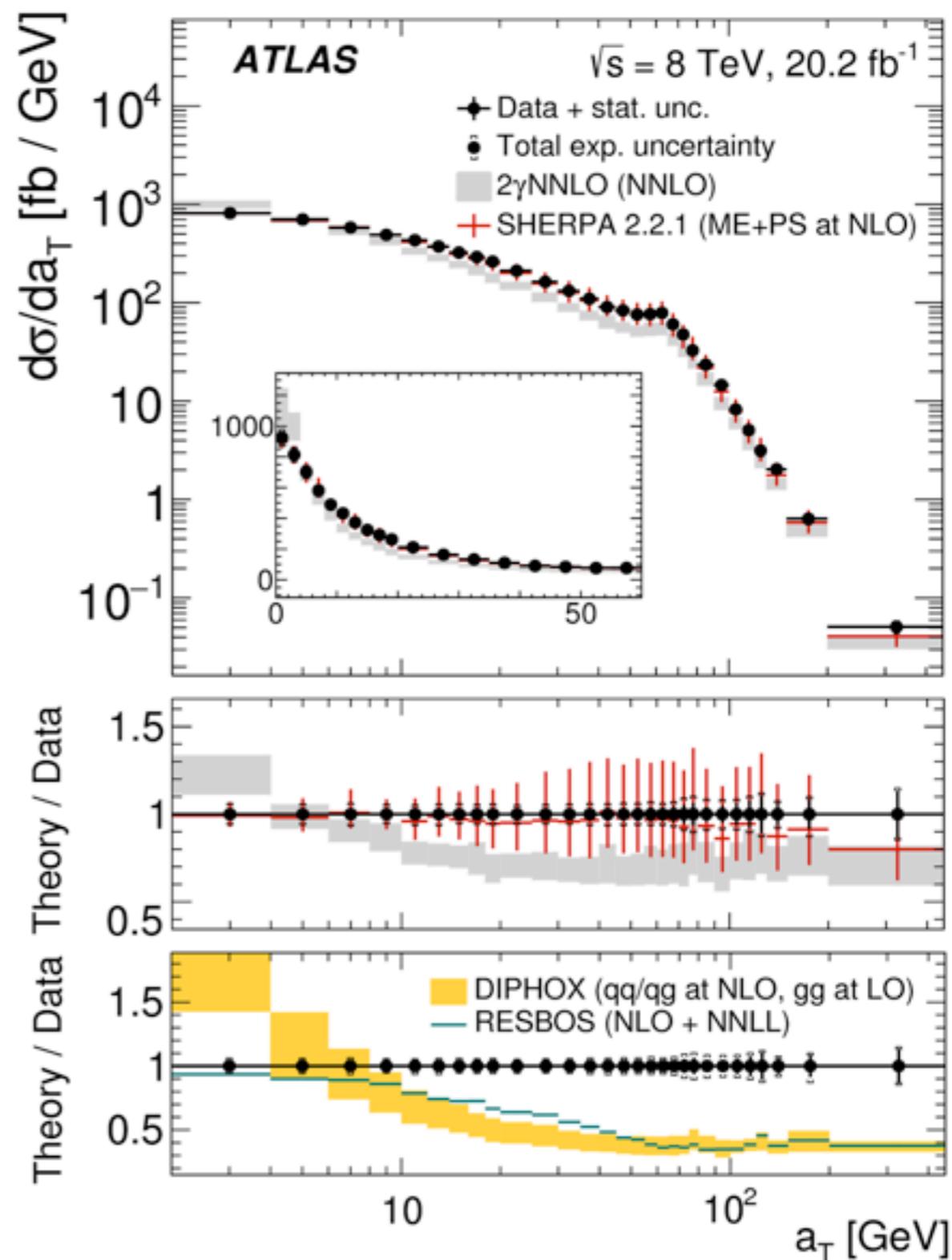
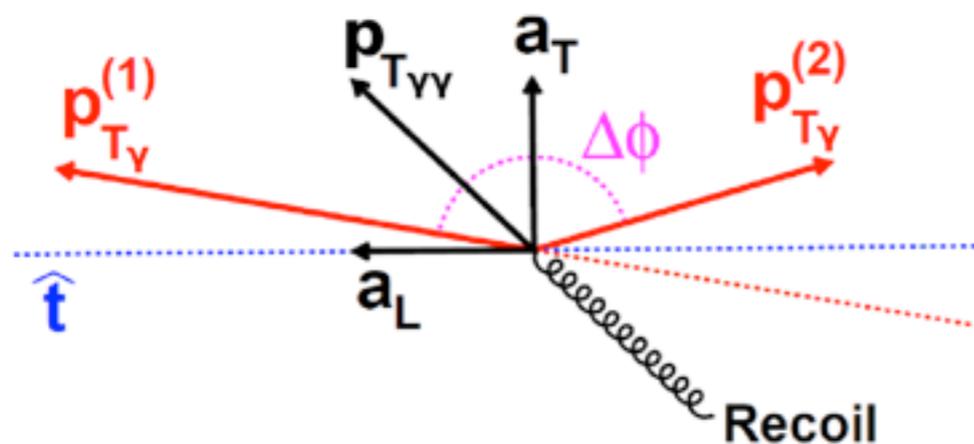


Di-photon production

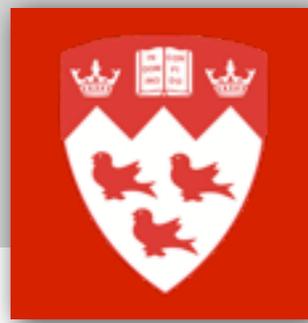


arXiv:1704.03839, submitted to PRD

- Measurements as function of all 6 observables are well-described by SHERPA (ME+PS at NLO).
- Specific regions of phase space particularly sensitive to soft gluons emissions.
 - Low a_T region well described by parton shower (SHERPA) or inclusion of soft-gluon resummation (RESBOS)
- In some regions, disagreements of up to x2 between NLO and data.
 - Inclusion of NNLO corrections not sufficient to reproduce the measurements.

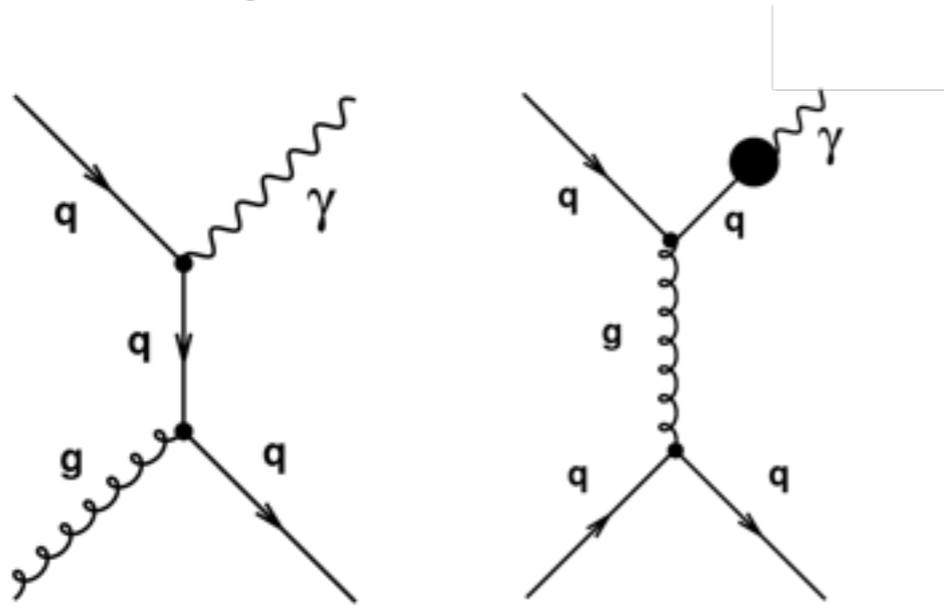


Photon + jets production

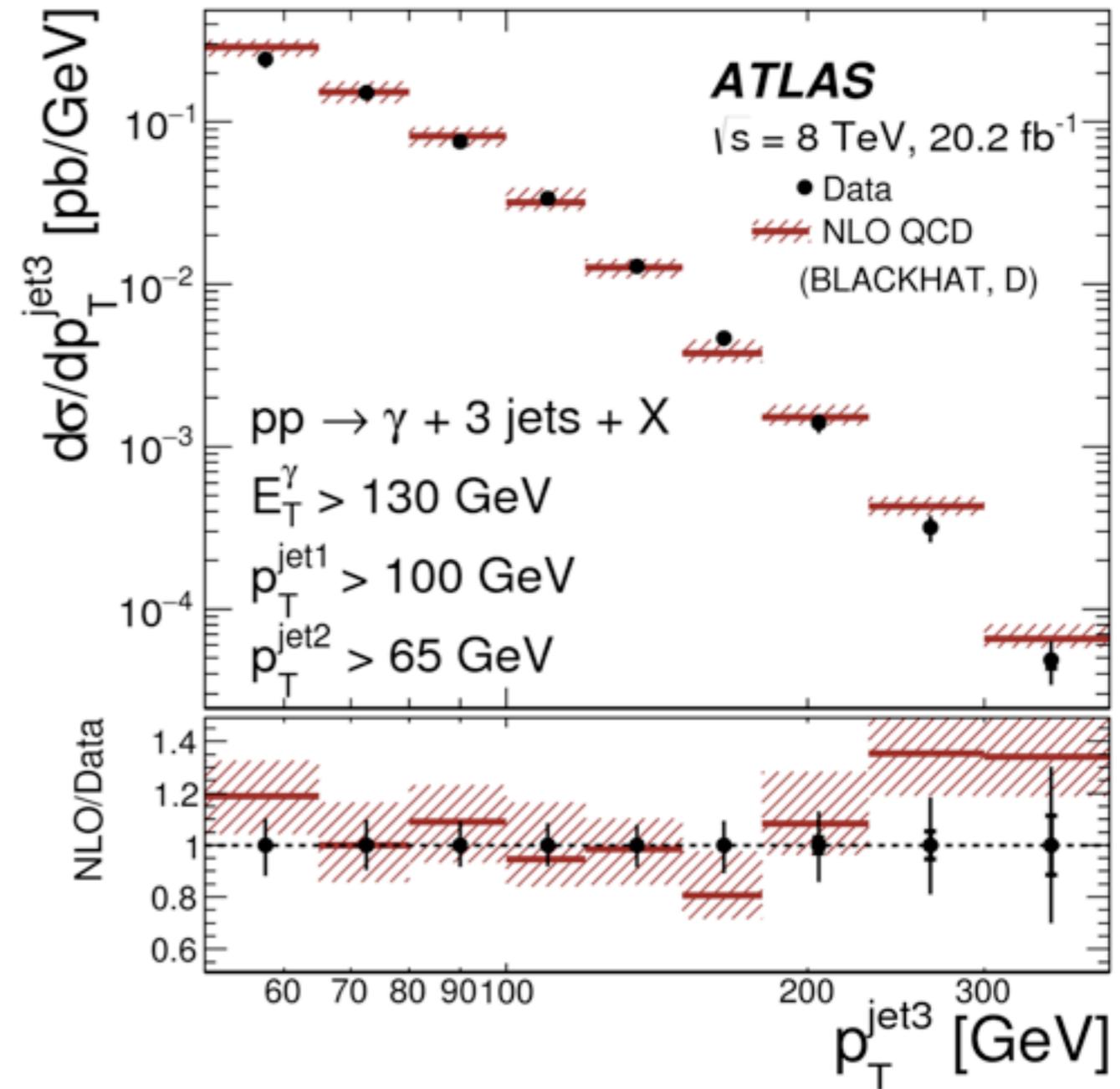


$$pp \rightarrow \gamma + \text{jets} + X$$

Nucl.Phys. B918 (2017) 257-316



- Study of the dynamics of $\gamma + \geq 1,2,3$ jets production.
- Differential cross-sections measured as function of several kinematic variables.
- NLO calculations provide good description of measurements.

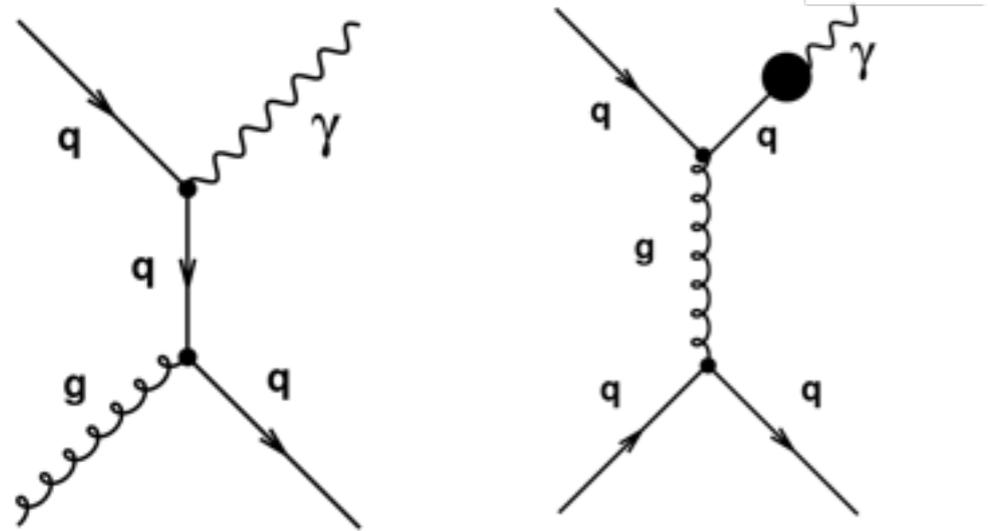


Photon + jets production



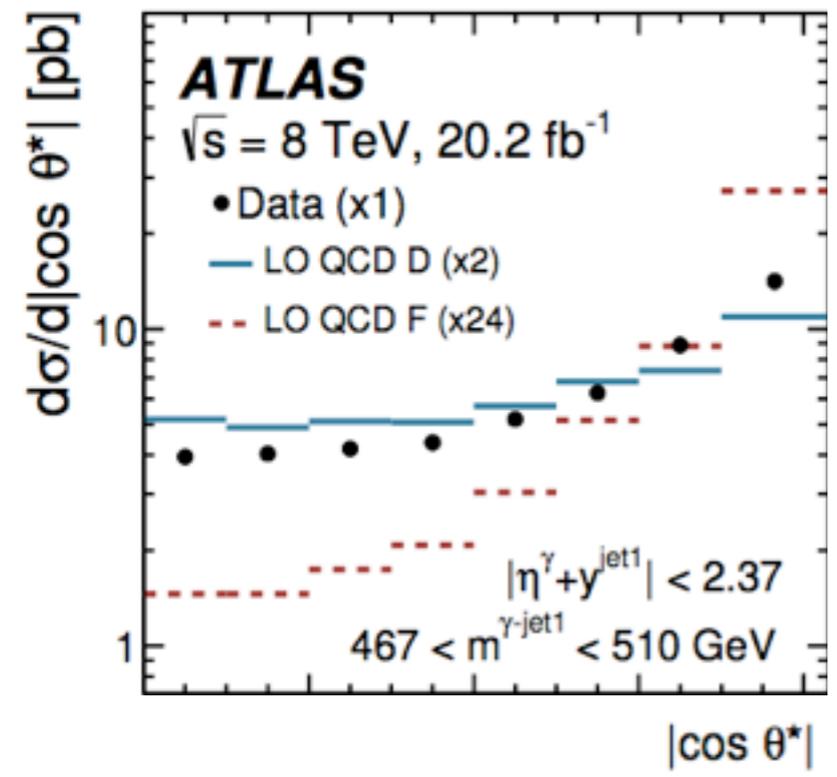
Nucl.Phys. B918 (2017) 257-316

$$pp \rightarrow \gamma + \text{jets} + X$$

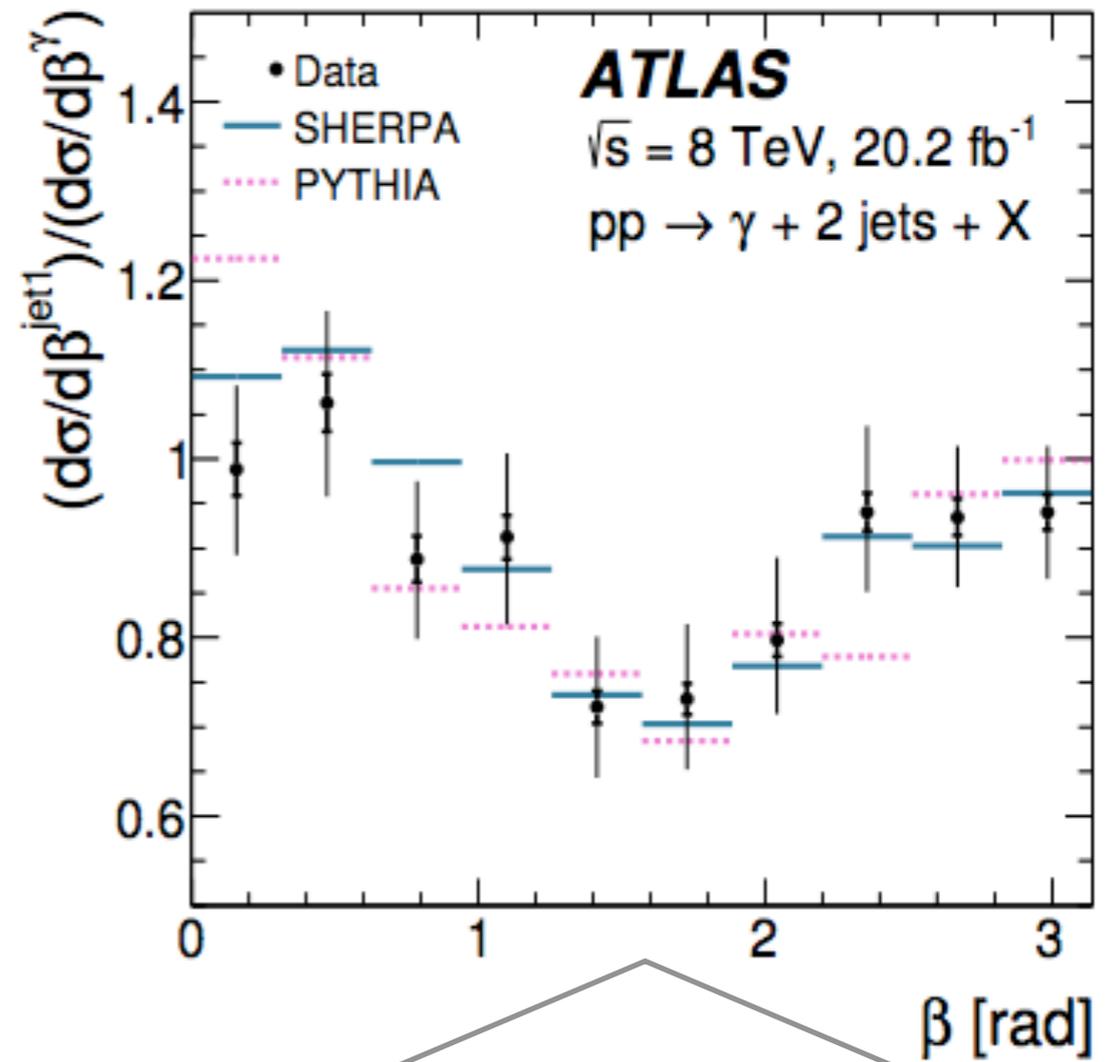


$$(1 - |\cos \theta^*|)^{-1}$$

$$(1 - |\cos \theta^*|)^{-2}$$

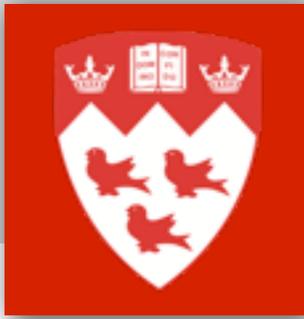


Quark exchange diagrams observed to dominate.



Patterns of QCD radiation around the photon observed to be different than those around the leading jet.

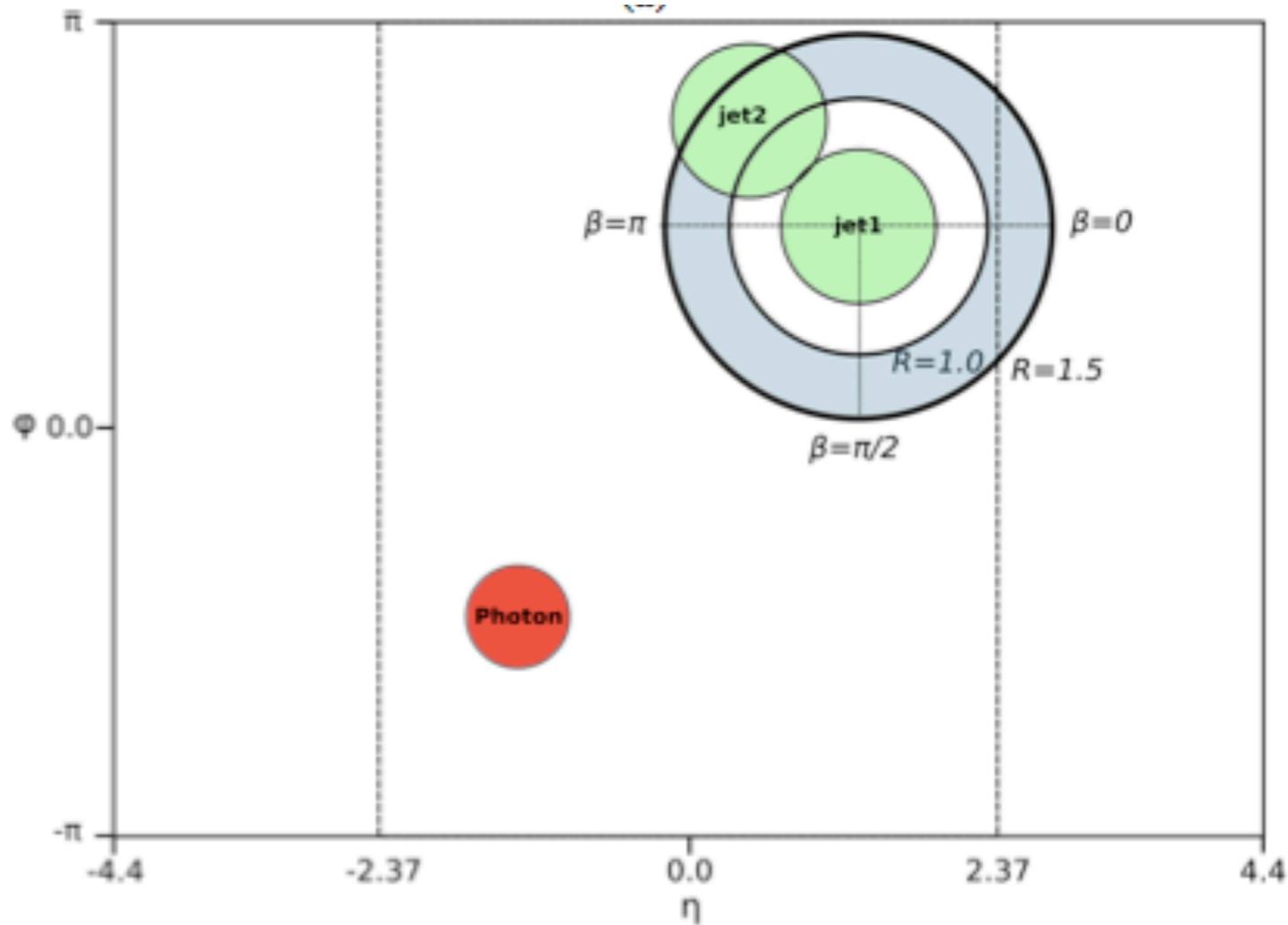
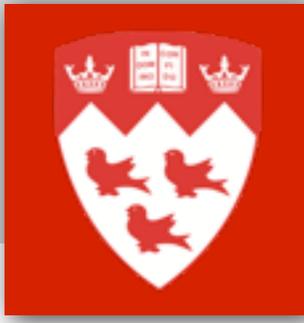
Summary



- Large data samples, well-understood detector performance and effective pile-up mitigation techniques make it possible to perform precision measurements of known Standard Model processes.
- Study of photons and jets production in pp collisions provides stringent tests of QCD.
 - Calculations beyond NLO needed to reduce theoretical scale uncertainties.
- Measurements can be used to set constraints on proton PDFs and extract a value of α_s .

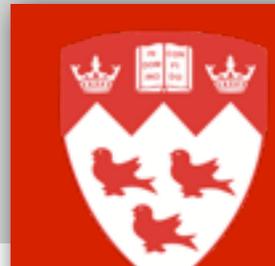
Backup

Photon+jet production



$$\beta^{\text{jet1}} = \tan^{-1} \frac{|\phi^{\text{jet2}} - \phi^{\text{jet1}}|}{\text{sign}(\eta^{\text{jet1}}) \cdot (\eta^{\text{jet2}} - \eta^{\text{jet1}})}$$

TEEC and ATEEC



$$\frac{1}{\sigma} \frac{d\Sigma}{d(\cos \phi)} = \frac{1}{\sigma} \sum_{ij} \int \frac{d\sigma}{dx_{Ti} dx_{Tj} d(\cos \phi)} x_{Ti} x_{Tj} dx_{Ti} dx_{Tj},$$

$$\frac{1}{\sigma} \frac{d\Sigma^{\text{asym}}}{d(\cos \phi)} \equiv \frac{1}{\sigma} \frac{d\Sigma}{d(\cos \phi)} \Big|_{\phi} - \frac{1}{\sigma} \frac{d\Sigma}{d(\cos \phi)} \Big|_{\pi-\phi}$$

