



Jet production in photon-lead collisions at NLO+PS accuracy

QCD@LHC, 28th Sep 2026, Oxford

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Motivation and outline

The LHC is not only a hadron collider

- Any charged relativistic particle has strongly contracted electro-magnetic field $\Rightarrow$ collinear photons
- This talk will cover the LHC as a **photon collider**
- See large programme on Ultra-Peripheral Collisions, mostly focussing on EW final states
- Based on [[Krauss, PM; 2607.18834](#)] and [[Bothmann, PM; tba, 2026](#)]

Outline

1. Brief introduction to EPA
2. Validation against EW final states
3. Brief introduction to resolved photons
4. Photonuclear jets phenomenology



Equivalent photon approximation

Very brief theory intro

- The photon flux for arbitrary particles can be computed as

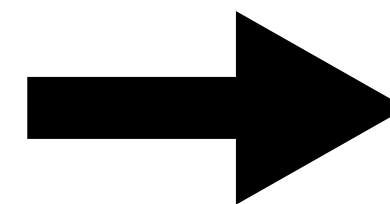
$$\frac{d^3n(x, Q^2, \varphi)}{dx dQ^2 d\varphi} = \frac{\alpha}{2\pi^2} \frac{1}{xQ^2} \left[\frac{x^2}{2} C(Q^2) + \frac{k_{\perp}^2}{Q^2} D(Q^2) \right]$$

with C , D the magnetic and electric form factors

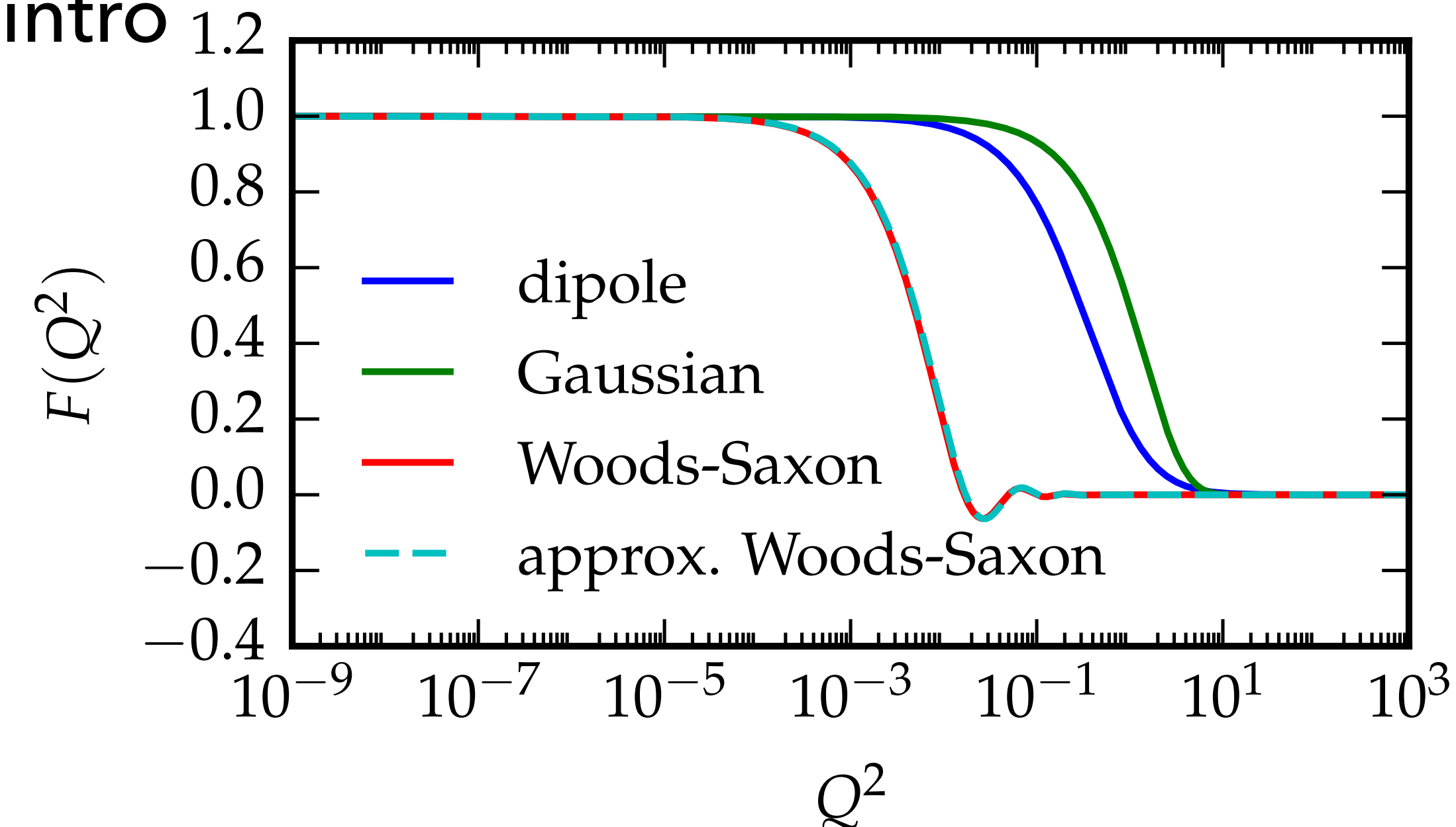
- Neglecting C , inserting form factor for D and Fourier-transforming $Q^2 \approx m^2x^2 + k_{\perp}^2 \Leftrightarrow b_{\gamma}$ we get

$$n(x, b_{\gamma}) = \frac{Z^2\alpha}{\pi^2x} \left| \int_0^{\infty} dk_{\perp} \frac{k_{\perp}^2}{Q^2} F(Q^2) J_1(b_{\gamma}k_{\perp}) \right|^2$$

Highly oscillating Bessel function J_1
This is very hard to solve!



Solution: build a dedicated numerical integrator for convolutions with Bessel functions

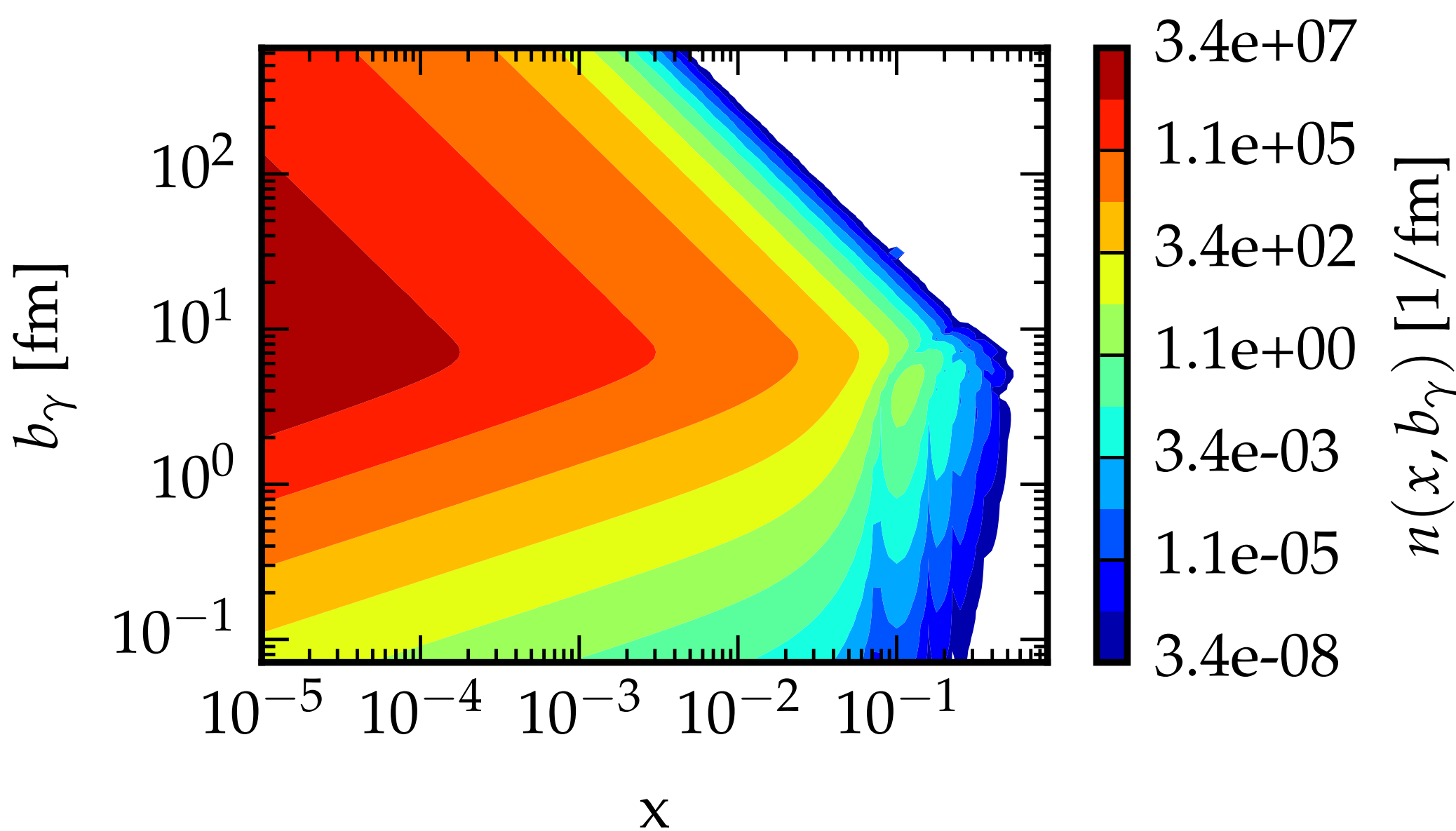




Implemented form factors

Form factor	Application	Evaluation	b -dependent
point-like	Proton, large- b fallback	Analytic	✓
integrated point-like	Proton	Analytic	-
proton	Protons	Analytic	-
proton, approx.	Protons	Analytic	-
dipole	Protons, light ions	Numerical	✓
approx. dipole	Protons, light ions	Numerical	✓
Gaussian	Phenomenological	Numerical	✓
hom.-charged sphere	Phenomenological	Numerical	✓
Woods-Saxon	Heavy ions	Numerical	✓
Woods-Saxon, approx.	Heavy ions	Numerical	✓

Comprehensive set of form factors for protons and nuclei



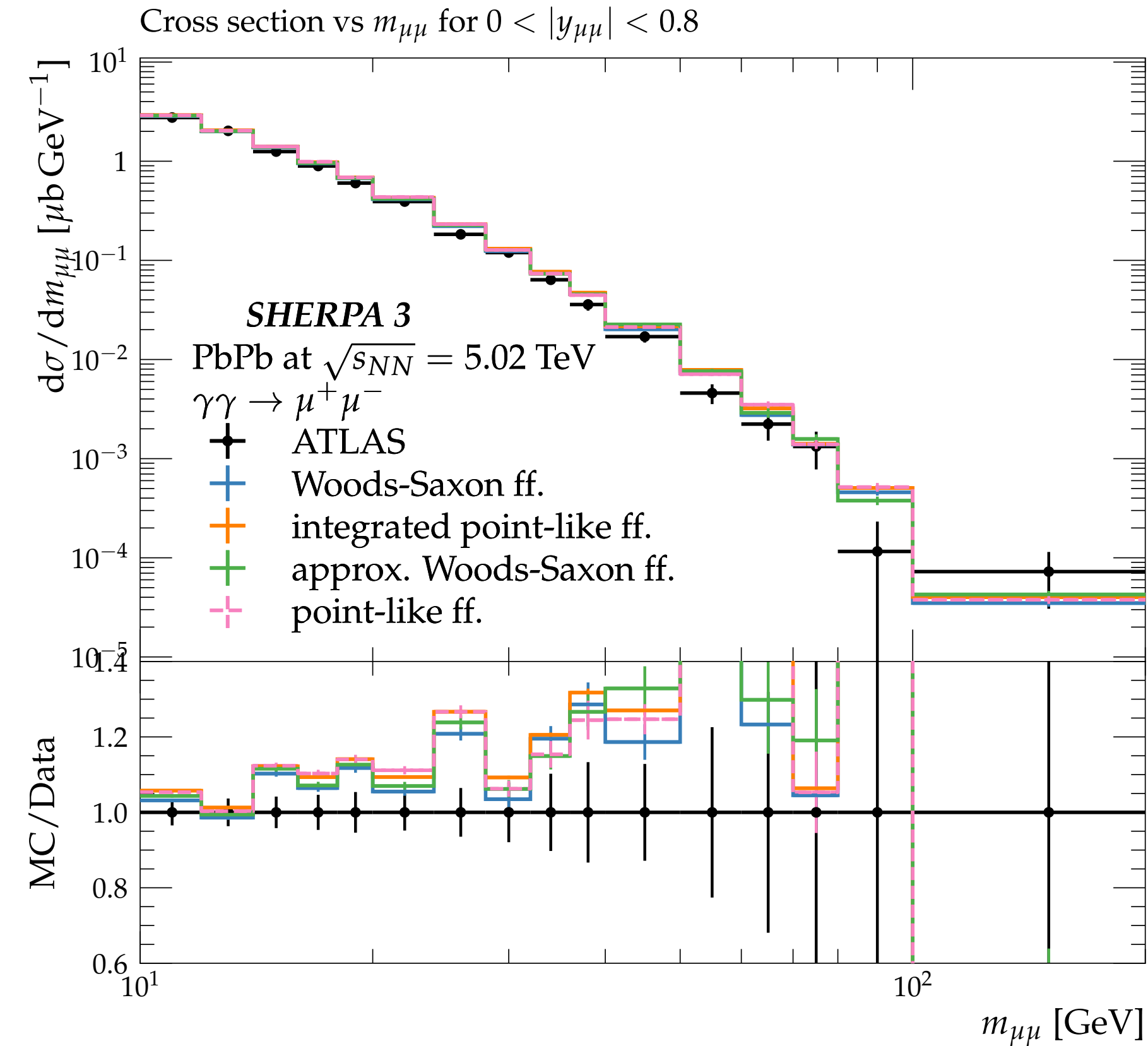
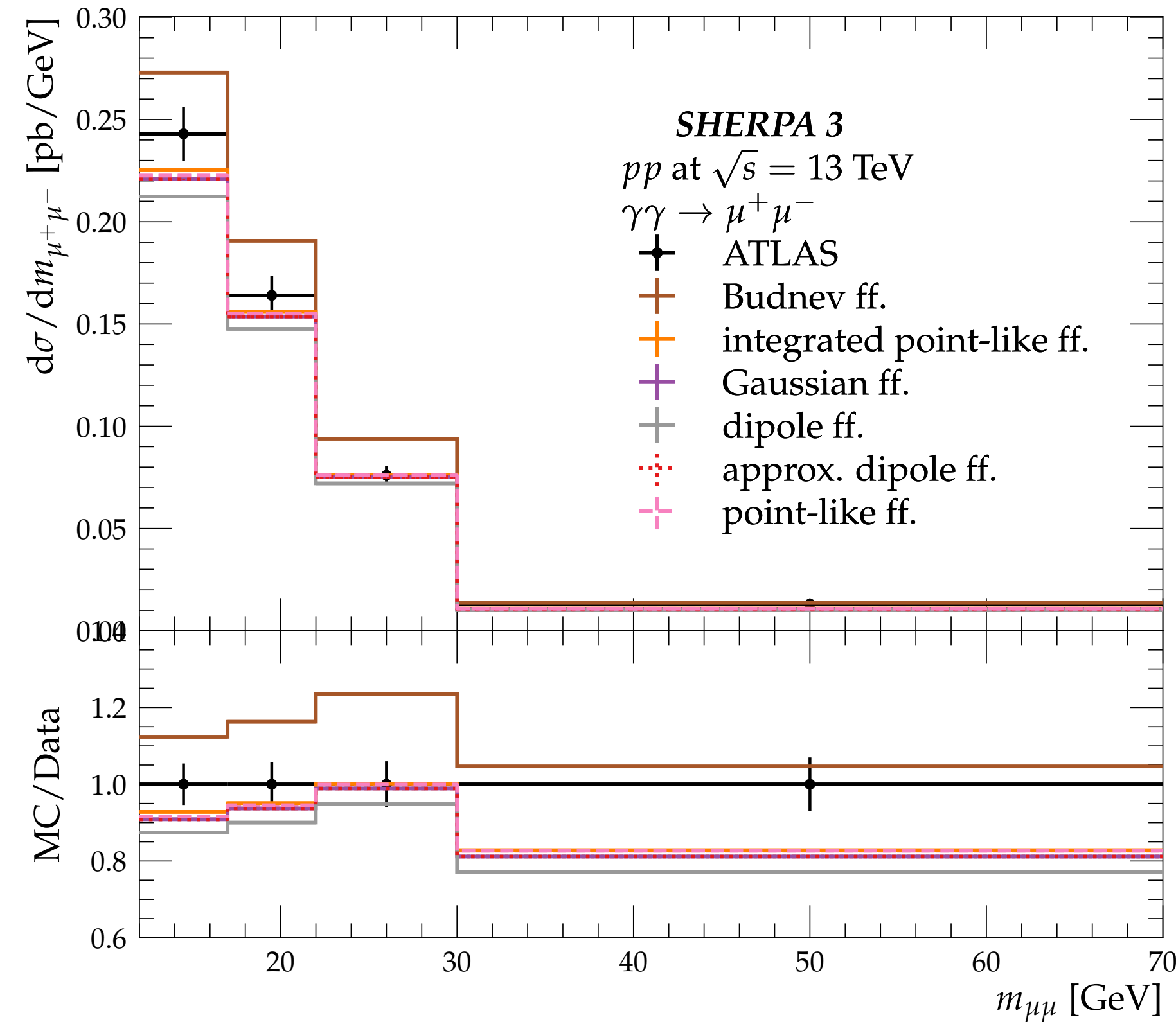
Photon flux $n(x, b_\gamma)$ for Pb-208 using Woods-Saxon



Validation against data

$\gamma\gamma \rightarrow \mu^+\mu^-$ for pp (left) and PbPb (right) beams

- Comparing for various different form factors
- „Budnev“ is an analytical formula keeping the magnetic term, no overlap rejection
- Good agreement, please check [[Krauss, PM; 2607.18834](#)] for more details

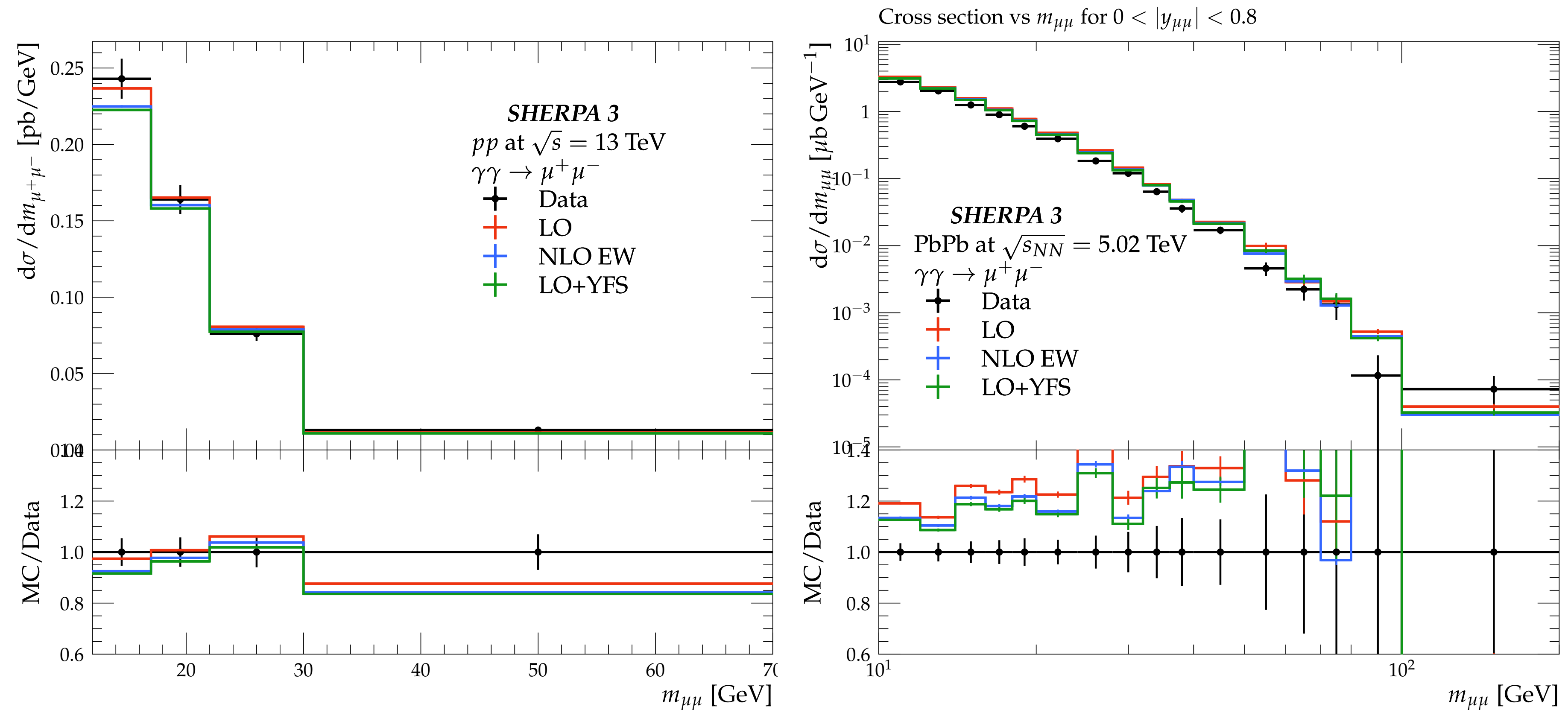




Automated NLO EW and YFS corrections

$\gamma\gamma \rightarrow \mu^+\mu^-$ for pp (left) and PbPb (right) beams

- Two ways to add that radiation: NLO EW (Catani-Seymour dipoles, fixed order) or LO+YFS (soft photons resummed to all orders)
- Generally agree with each other
- Reduce the cross section by about 5%
- Bare leptons, higher-order effects larger in lowest mass bin



Next step in precision would be NLO EW+YFS!

What about jets?



Photon-induced jets

A quick primer

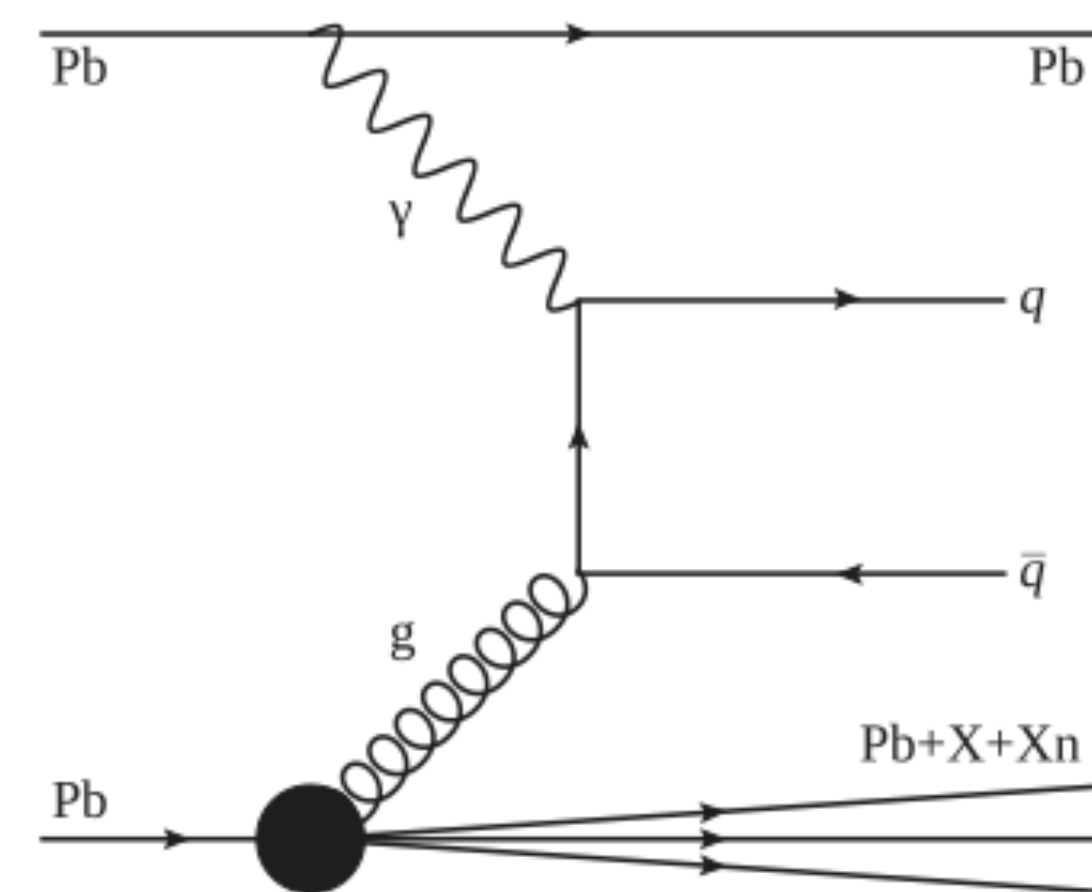
- Earlier colliders, like LEP and HERA, had numerous measurements of such processes

- The photon can undergo a DGLAP-evolution:

$$\frac{\partial f_i^{(\gamma)}(x, \mu)}{\partial \log \mu} = \frac{\alpha_{\text{em}}(\mu)}{2\pi} P_{\gamma i}(x) + \frac{\alpha_S(\mu)}{2\pi} \sum_j \int \frac{dx'}{x'} P_{ji} \left(\frac{x}{x'} \right) f_j^{(\gamma)}(x', \mu)$$

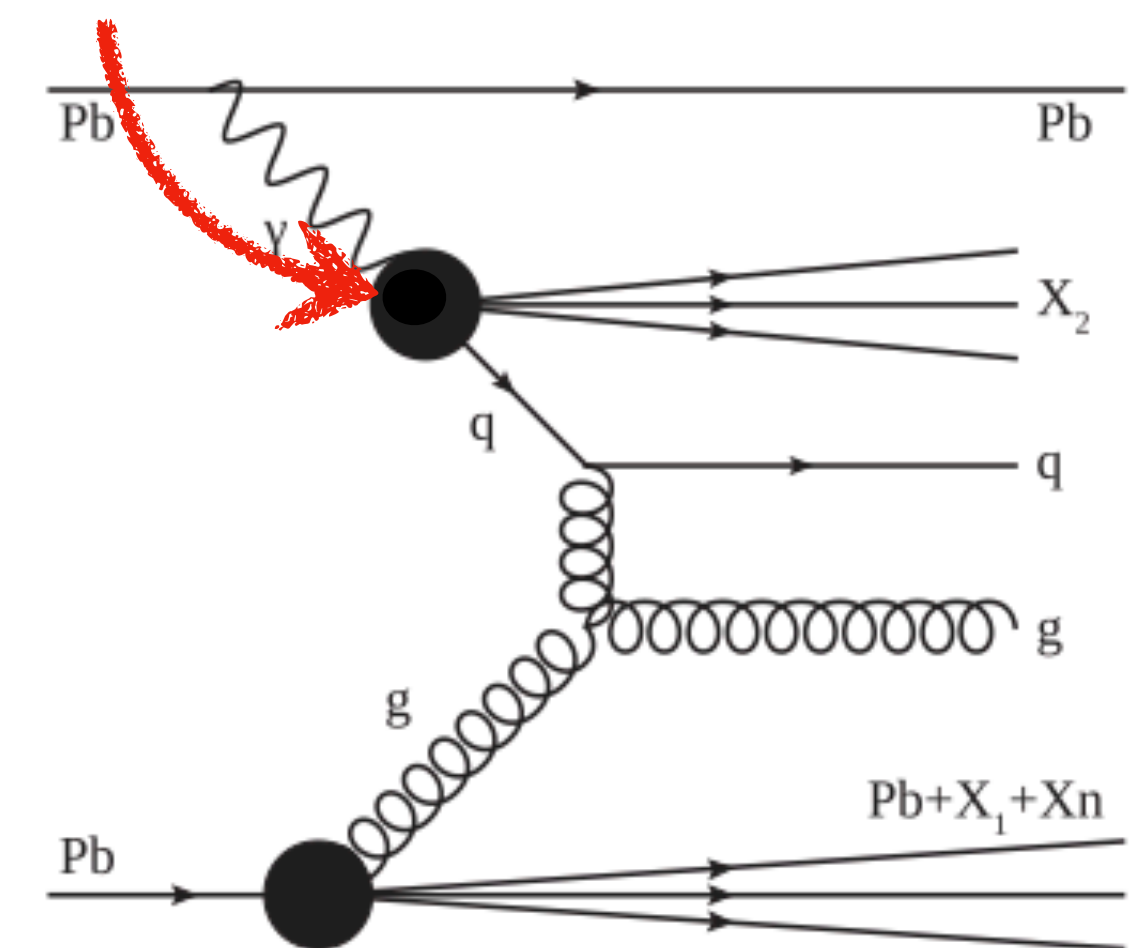
- This gives the notion of **partons inside the photon**
- Got mostly forgotten after shut-downs of LEP and HERA
- see review [[Rev.Mod.Phys. 74 \(2002\) 1221-1282](#)] and recent photon PDF fit [[2606.07189](#)]

„**direct**“ photon interaction



„**resolved**“ photon interaction

This is a photon PDF



Only the sum is physical!



Photonuclear jets @ ATLAS

NLO+PS is work-in-progress

- Triple-differential measurement of jets,

$$\frac{d^3\sigma}{dH_T dy dm_{\text{jets}}} \text{ and } \frac{d^3\sigma}{dH_T dx_A dz_\gamma}$$

This is exceptionally good data for studies of both, nuclear and photon PDFs!

- Measured for $0n$ configurations; we use ATLAS' data-driven rejection of the Xn background
- Phenomenological study using nNNPDF30_nlo_as_0118_A208_Z82 and new VALO10_LO PDFs for the nucleus and photon, first including the photon PDF uncertainty!

PHYSICAL REVIEW D **111**, 052006 (2025)

Measurement of photonuclear jet production in ultraperipheral Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector

G. Aad *et al.*^{*}
(ATLAS Collaboration)

 (Received 18 September 2024; accepted 28 January 2025; published 19 March 2025)

In ultrarelativistic heavy ion collisions at the LHC, each nucleus acts as a source of high-energy real photons that can scatter off the opposing nucleus in ultraperipheral photonuclear ($\gamma + A$) collisions. Hard scattering processes initiated by the photons in such collisions provide a novel method for probing nuclear parton distributions in a kinematic region not easily accessible to other measurements. ATLAS has measured production of dijet and multijet final states in ultraperipheral Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using a dataset recorded in 2018 with an integrated luminosity of 1.72 nb^{-1} . Photonuclear final states are selected by requiring a rapidity gap in the photon direction; this selects events where one of the outgoing nuclei remains intact. Jets are reconstructed using the anti- k_t algorithm with radius parameter, $R = 0.4$. Triple-differential cross sections, unfolded for detector response, are measured and presented using two sets of kinematic variables. The first set consists of the total transverse momentum (H_T), rapidity, and mass of the jet system. The second set uses H_T and particle-level nuclear and photon parton momentum fractions, x_A and z_γ , respectively. The results are compared with leading-order perturbative QCD calculations of photonuclear jet production cross sections, where all leading order predictions using existing fits fall below the data in the shadowing region. More detailed theoretical comparisons will allow these results to strongly constrain nuclear parton distributions, and these data provide results from the LHC directly comparable to early physics results at the planned Electron-Ion Collider.

DOI: [10.1103/PhysRevD.111.052006](https://doi.org/10.1103/PhysRevD.111.052006)

I. INTRODUCTION

Studies of hard-scattering processes are a crucial component of the ultrarelativistic heavy-ion physics programs at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider. Such studies will soon reach or, in some cases, have already reached [1–3] a level of precision

Recent advances in the methods used to perform global fits to nuclear PDFs [9] and extensions to next-to-next-to-leading-order (NNLO) [10] in perturbative QCD, combined with the inclusion [3,11–13] of recent data from the LHC and experiments at Jefferson Laboratory, have significantly reduced uncertainties in the extracted nuclear PDFs.



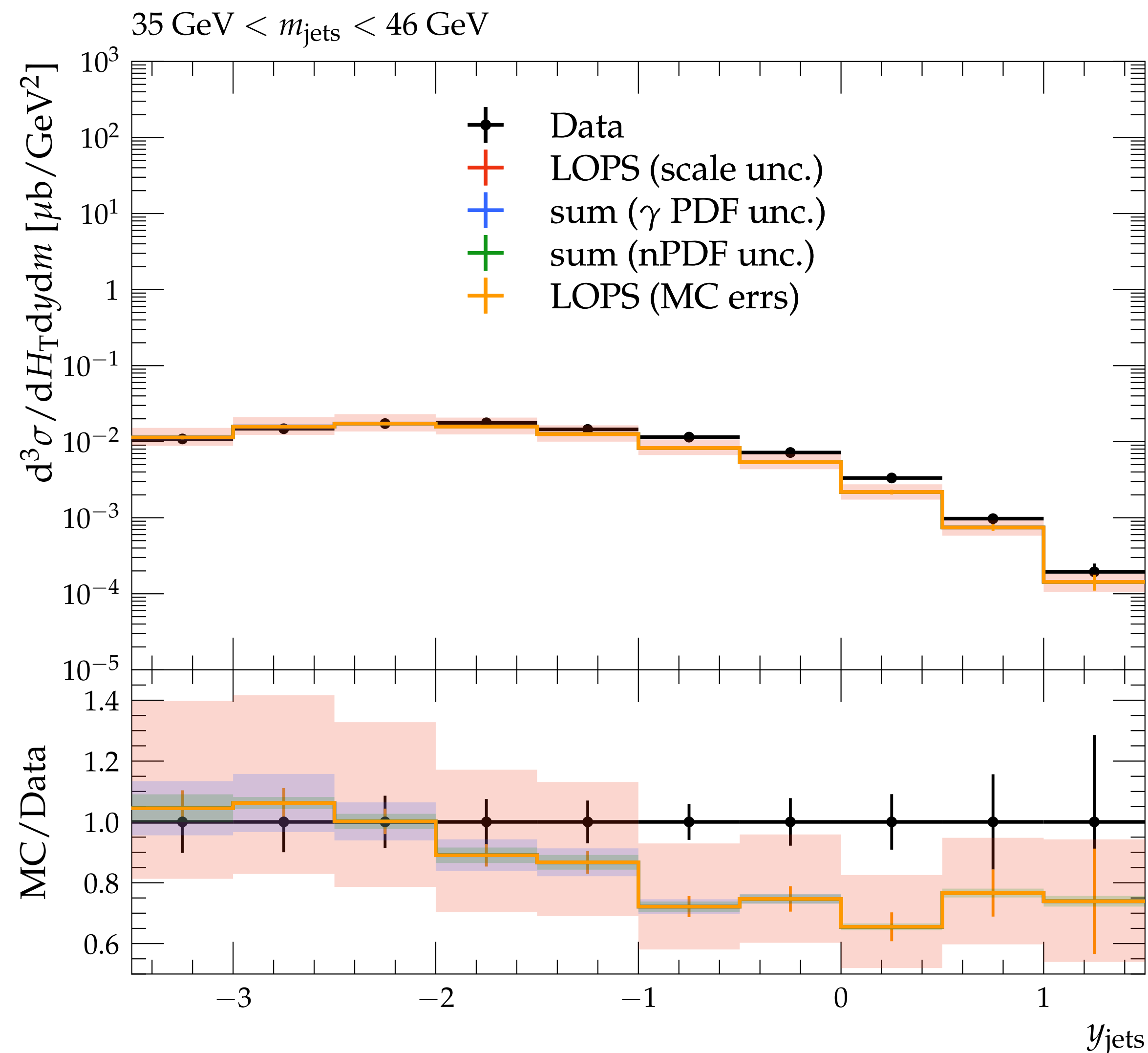
Comparison to data

Preliminary LO+PS calculation

Three sources of uncertainty:

- Scale uncertainties, still dominant at LO
 - nuclear PDF
 - **photon PDF**
- Interestingly, nuclear and photon PDF seem to be poorly constrained in the **same phase space**

Expectation/Hope: with NLO, photon PDF will be limiting factor in some regions
⇒ high constraining power for PDF extractions

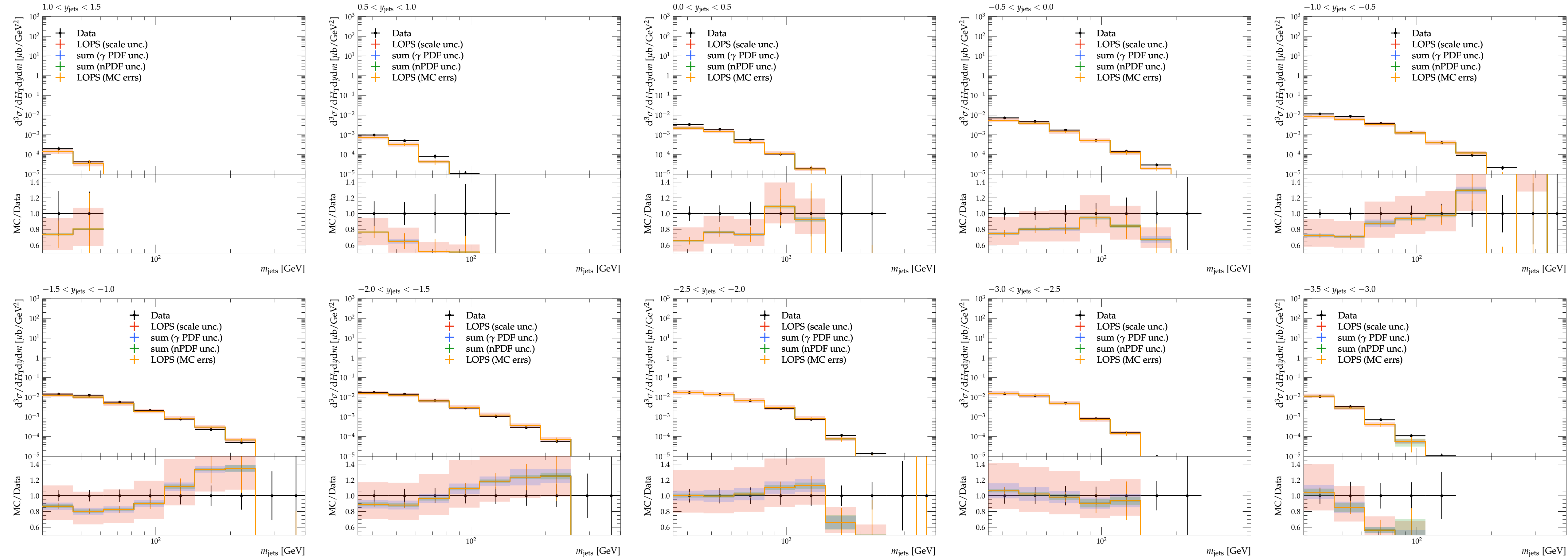




Good agreement across wide range

Preliminary LO calculation

Forward



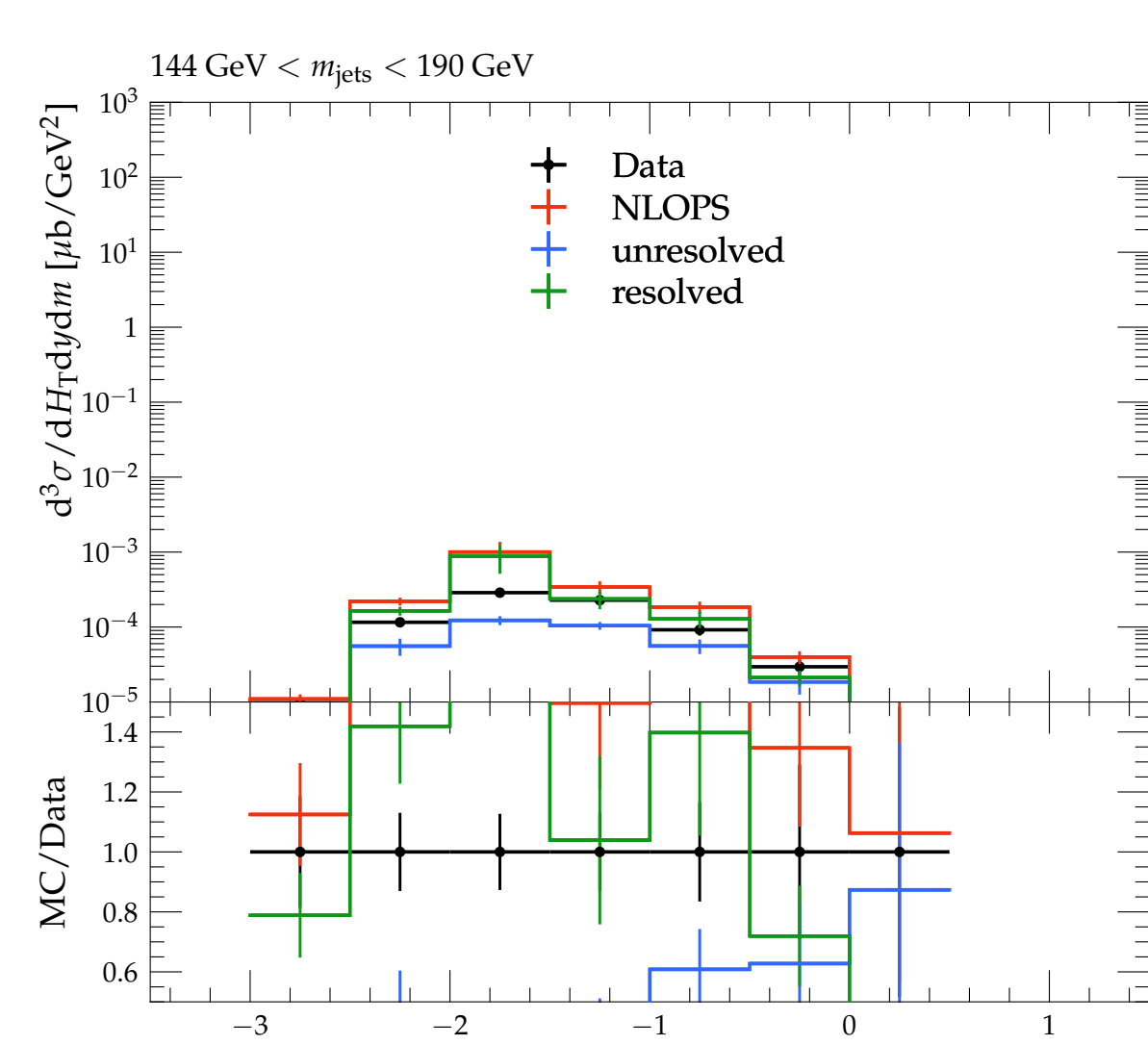
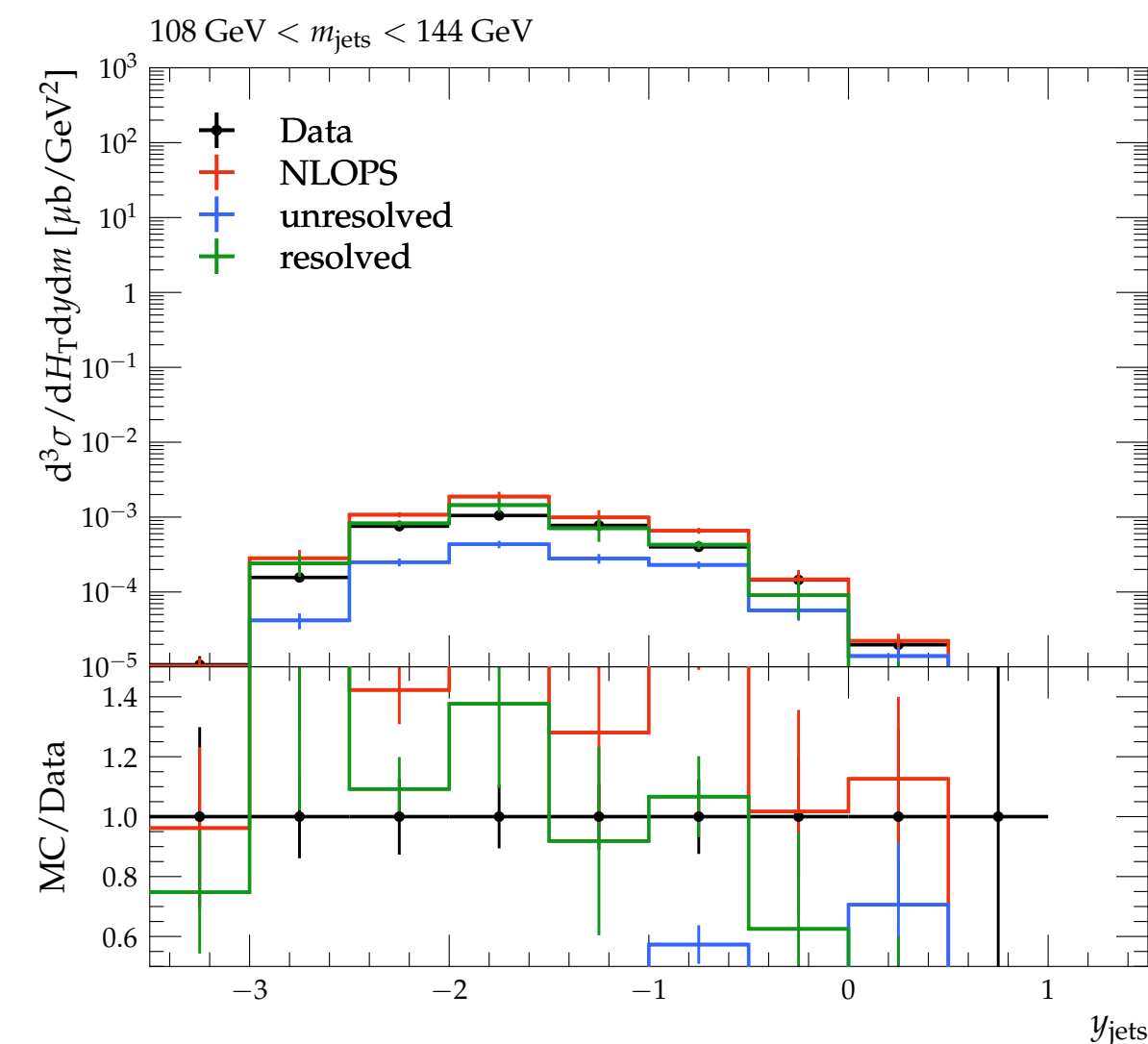
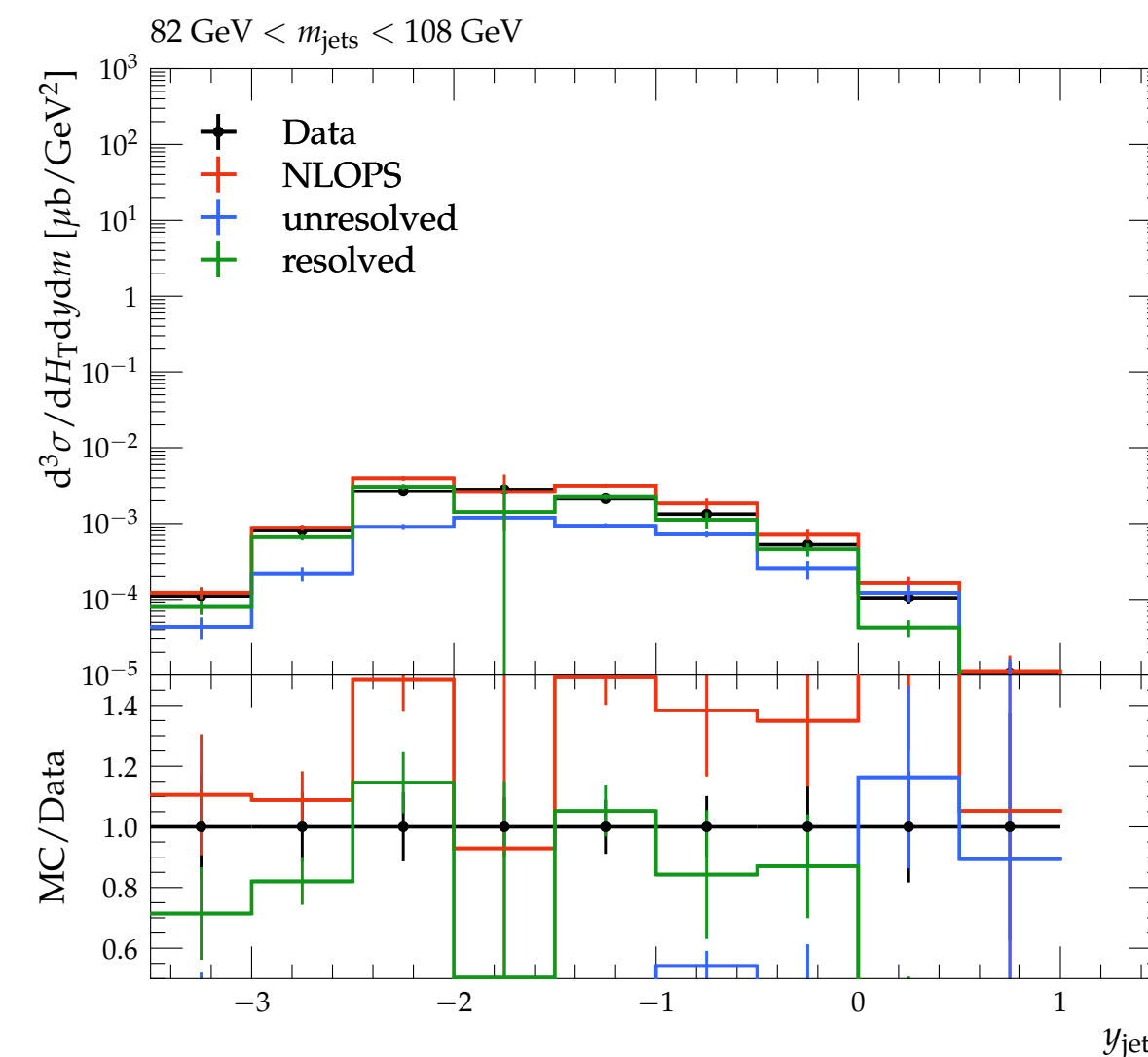
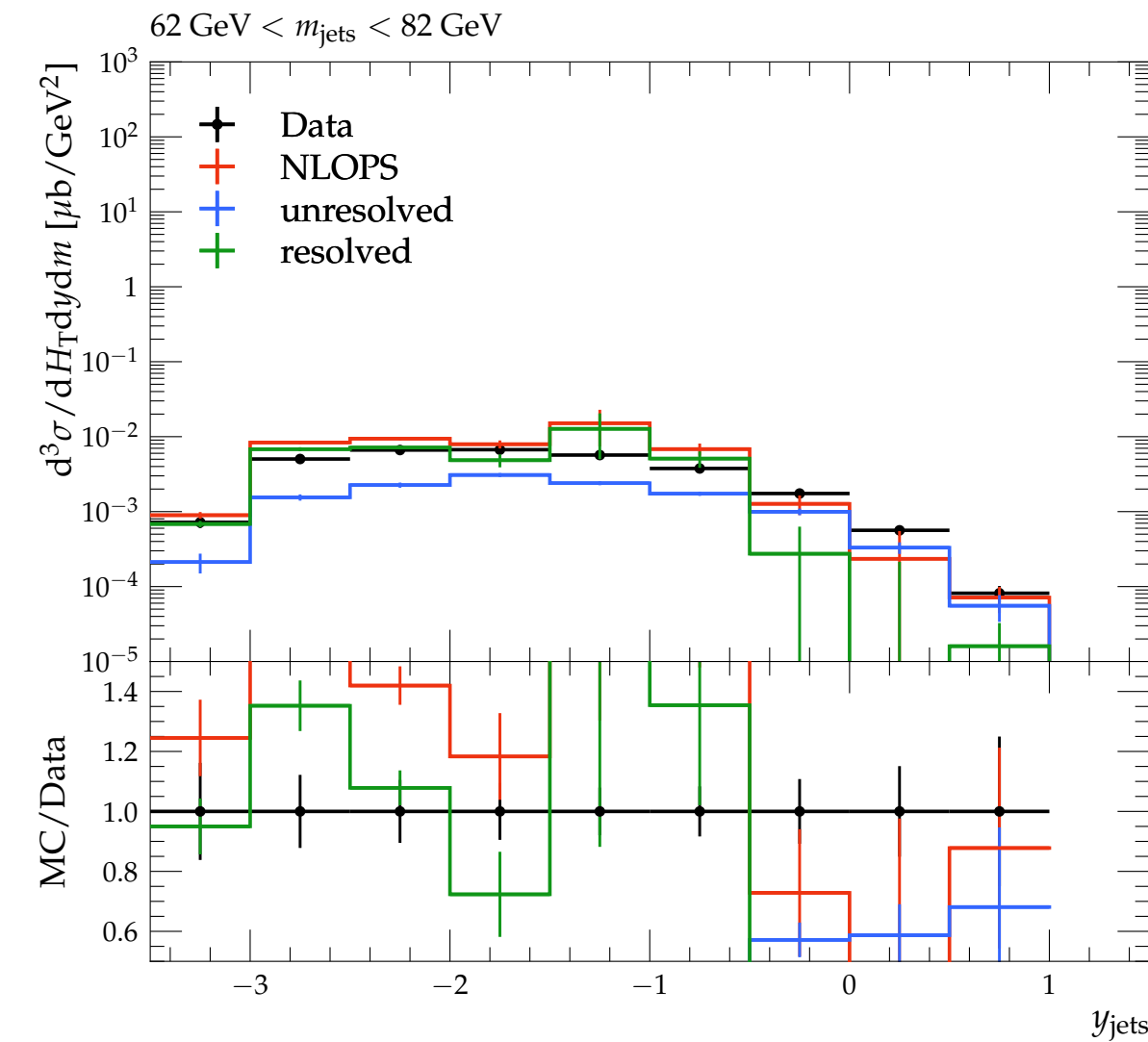
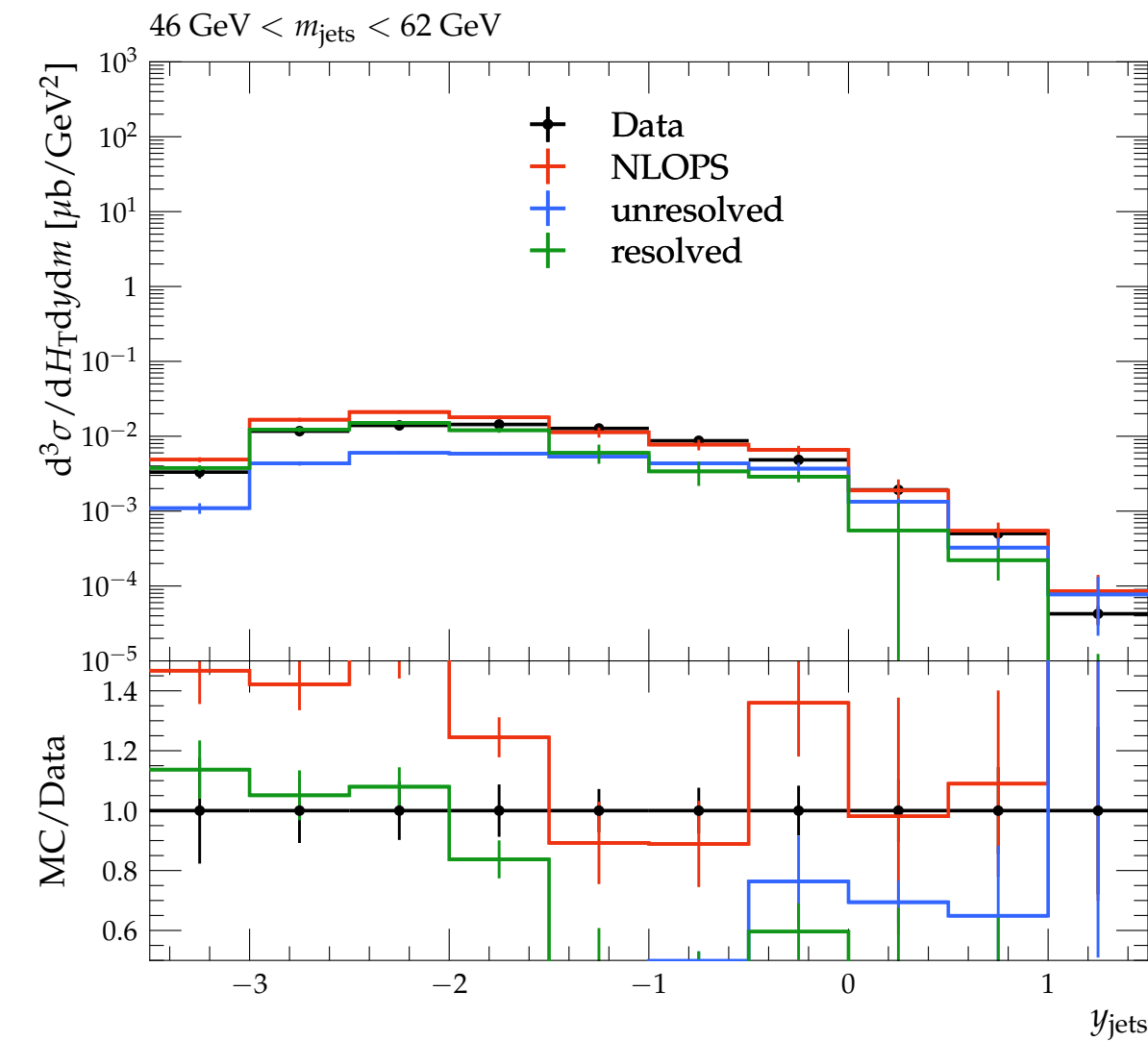
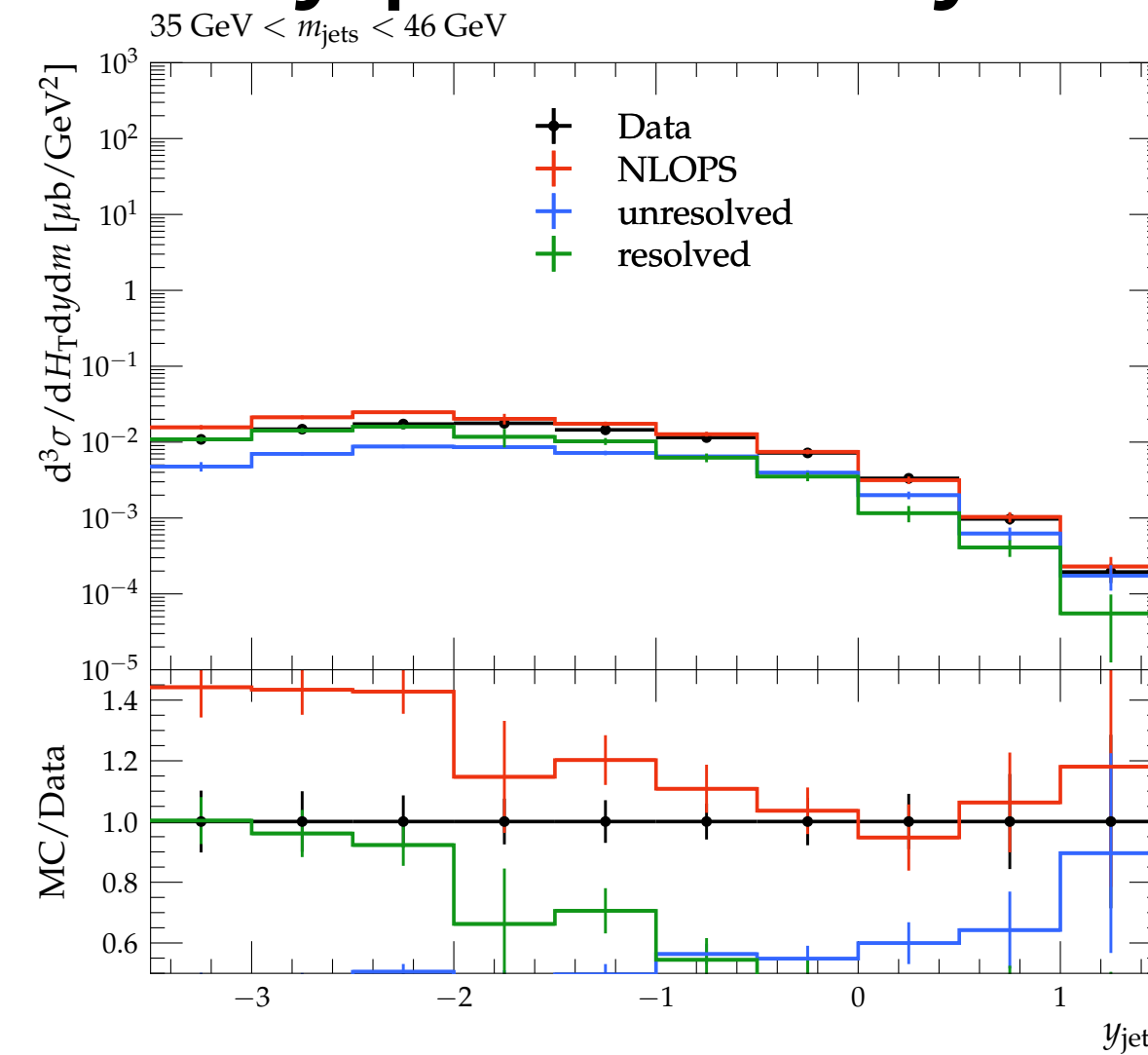
Backward



Good agreement across wide range

Very preliminary NLO+PS calculation

- Looking at (scheme-dependent) direct/resolved split; here in $\overline{\text{MS}}$ scheme
- Overshooting due to LO photon PDF
- Confirms that backward direction is sensitive to resolved photon interactions
- Combined fit of photon and nuclear PDF could be necessary?

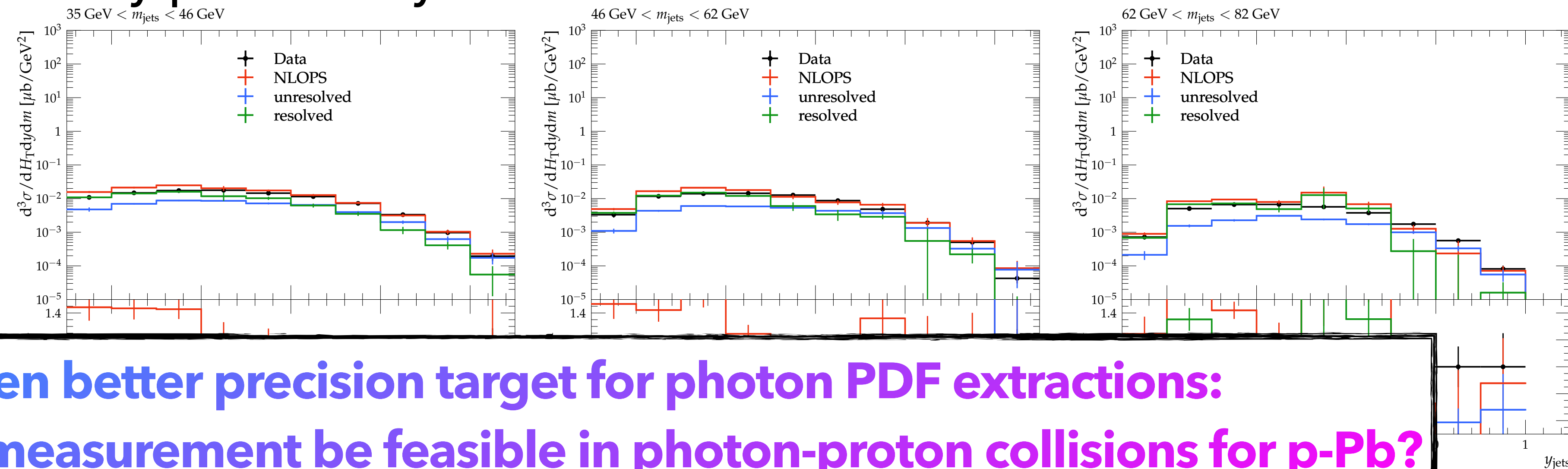




Good agreement across wide range

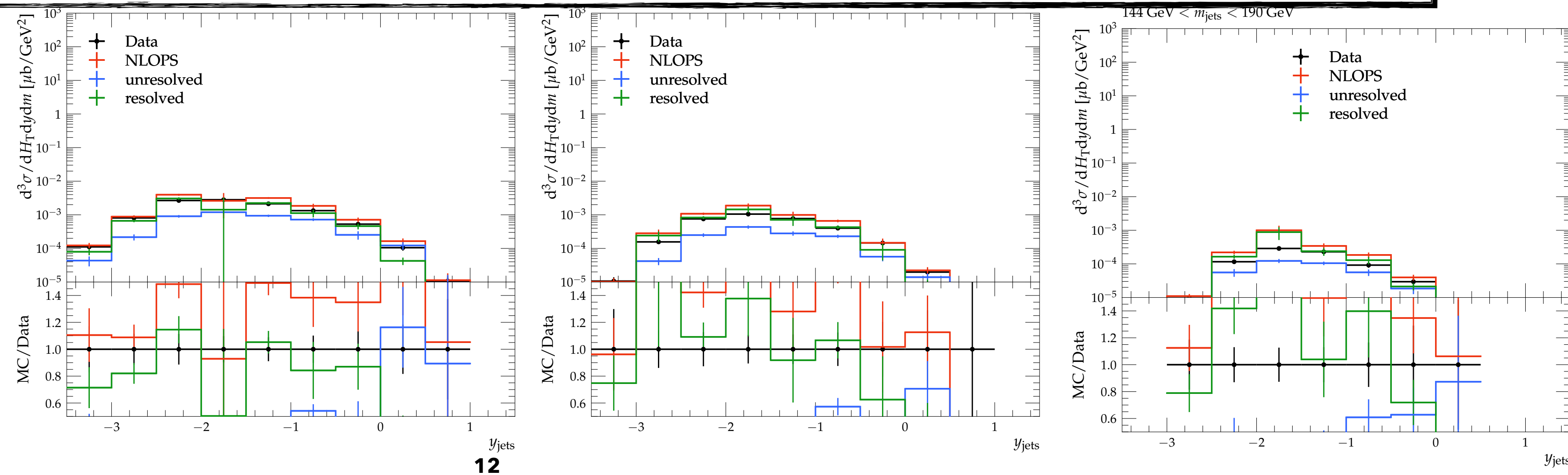
Very preliminary NLO+PS calculation

- Looking at (scheme-dependent) direct/resolved split; here in $\overline{\text{MS}}$ scheme
- Overshooting due to LO photon PDF
- Confirm direction resolved photon interactions
- Combined fit of photon and nuclear PDF could be necessary?



An even better precision target for photon PDF extractions:

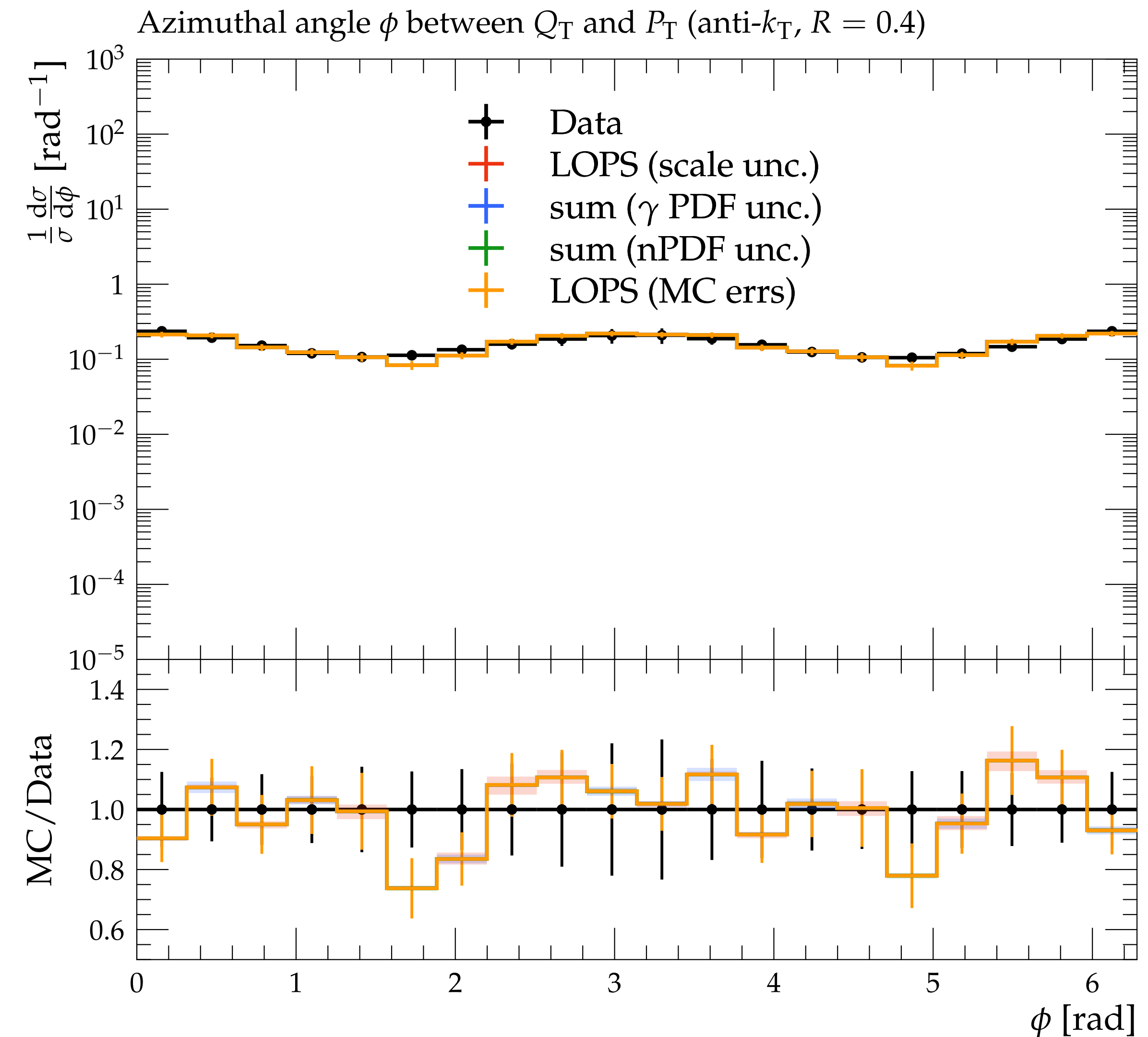
Would such a measurement be feasible in photon-proton collisions for p-Pb?





Comparing to data

- Comparing against CMS data as well; it's especially sensitive to IS effects
- Azimuthal angle is well-described
- more pheno is on the way



PHYSICAL REVIEW LETTERS **131**, 051901 (2023)

Azimuthal Correlations within Exclusive Dijets with Large Momentum Transfer in Photon-Lead Collisions

A. Tumasyan *et al.**
(CMS Collaboration)

(Received 29 April 2022; revised 11 November 2022; accepted 15 February 2023; published 1 August 2023)

The structure of nucleons is multidimensional and depends on the transverse momenta, spatial geometry, and polarization of the constituent partons. Such a structure can be studied using high-energy photons produced in ultraperipheral heavy-ion collisions. The first measurement of the azimuthal angular correlations of exclusively produced events with two jets in photon-lead interactions at large momentum transfer is presented, a process that is considered to be sensitive to the underlying nuclear gluon polarization. This study uses a data sample of ultraperipheral lead-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV, corresponding to an integrated luminosity of 0.38 nb^{-1} , collected with the CMS experiment at the LHC. The measured second harmonic of the correlation between the sum and difference of the two jet transverse momentum vectors is found to be positive, and rising, as the dijet transverse momentum increases. A well-tuned model that has been successful at describing a wide range of proton scattering data from the HERA experiments fails to describe the observed correlations, suggesting the presence of gluon polarization effects.

DOI: [10.1103/PhysRevLett.131.051901](https://doi.org/10.1103/PhysRevLett.131.051901)



Summary

EPA

- Comprehensive implementation of photon fluxes for protons and nuclei
- Complete treatment of impact parameter dependence, automated NLO EW and QCD, and YFS corrections
- Validation using $\gamma\gamma \rightarrow \mu\mu$ data

Photonuclear jets

- first phenomenology with LO+PS, comparing to ATLAS and CMS data
- first NLO+PS calculation

To be released with Sherpa v3.1 (still this year, hopefully)