Ultra-peripheral collisions

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RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

POLISH
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I STAND WITH UKRAINE

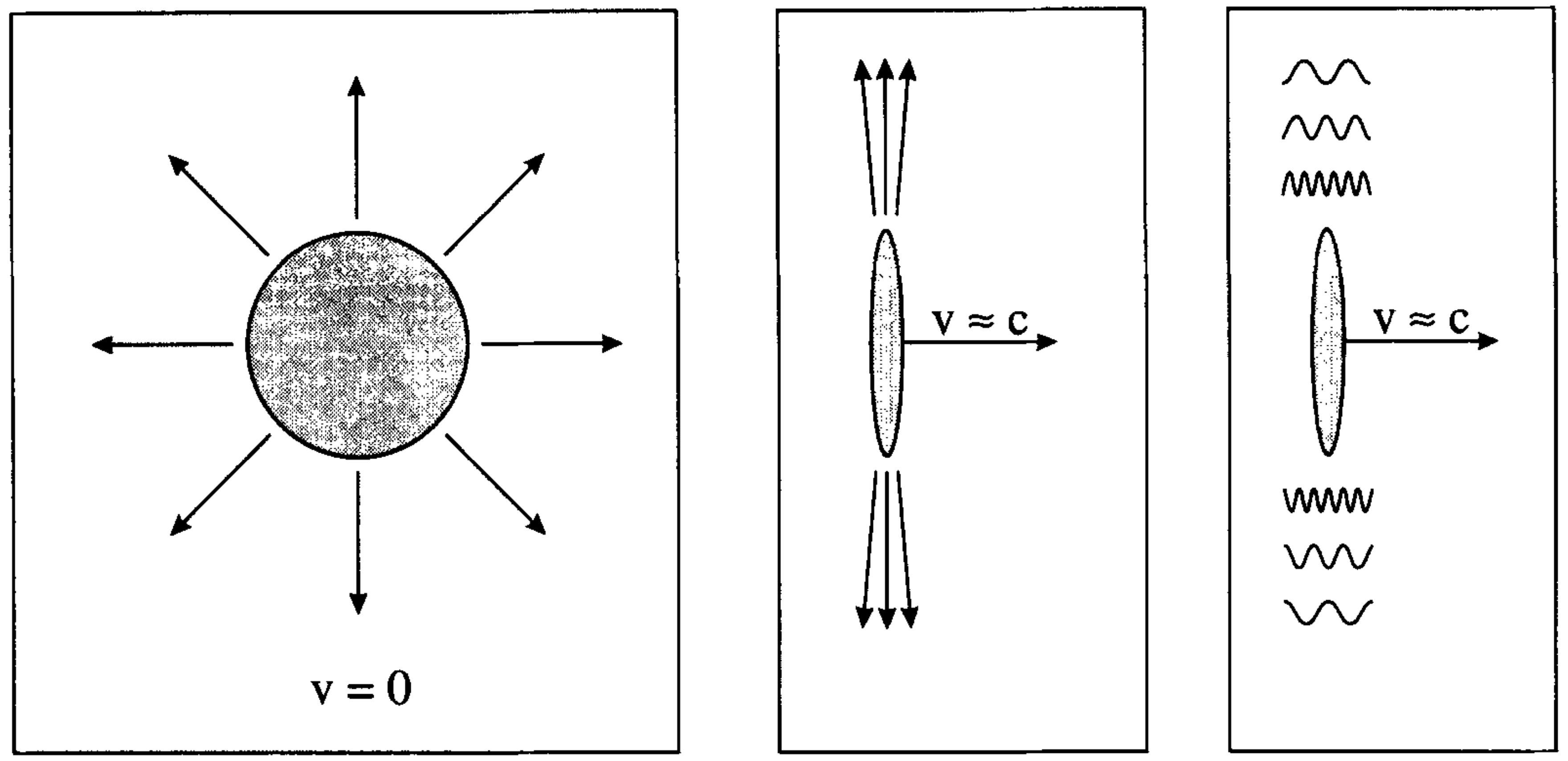
On behalf of the ALICE, ATLAS, CMS, LHCb and MoEDAL collaborations

LHCP 2022

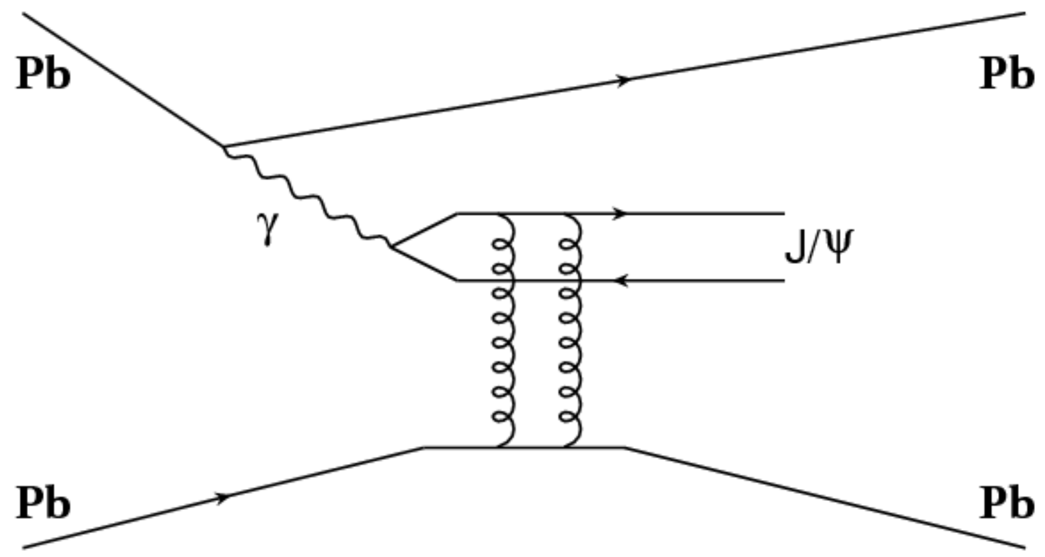
Quasi-real photons from heavy ions

- Boosted nuclei → strong EM fields
- **Coherent** photon flux
  - $\mathbf{E_{max} \lesssim \gamma/R \sim 80\ GeV}$ @LHC (**~3 GeV** @RHIC)
  - **Q ~ 1/R ~ 30 MeV** @ LHC/RHIC
  - Each photon flux scales with ~$\mathbf{Z^2}$

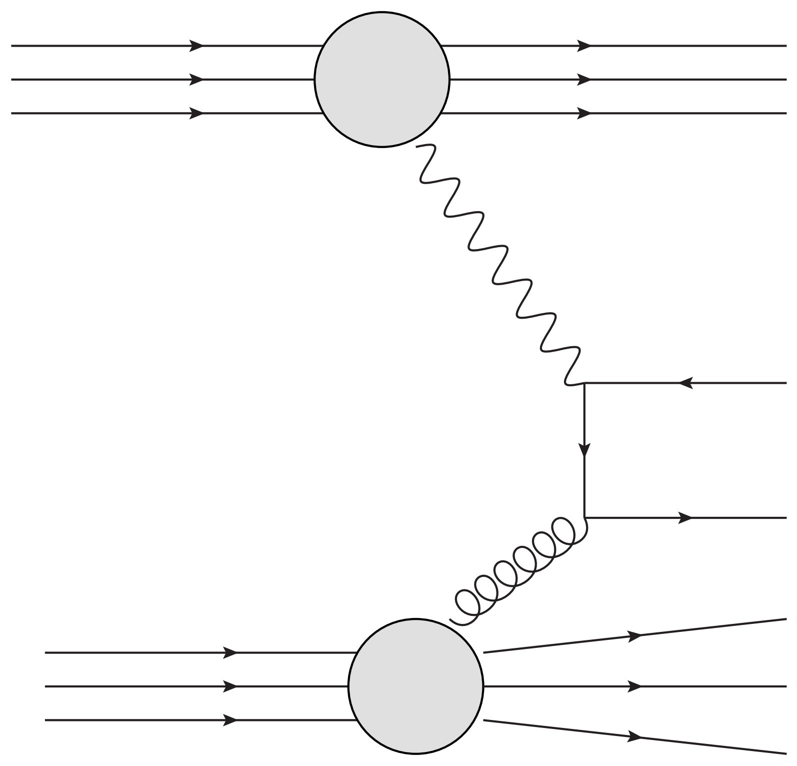
Fermi, Nuovo Cim. 2 (1925) 143-158



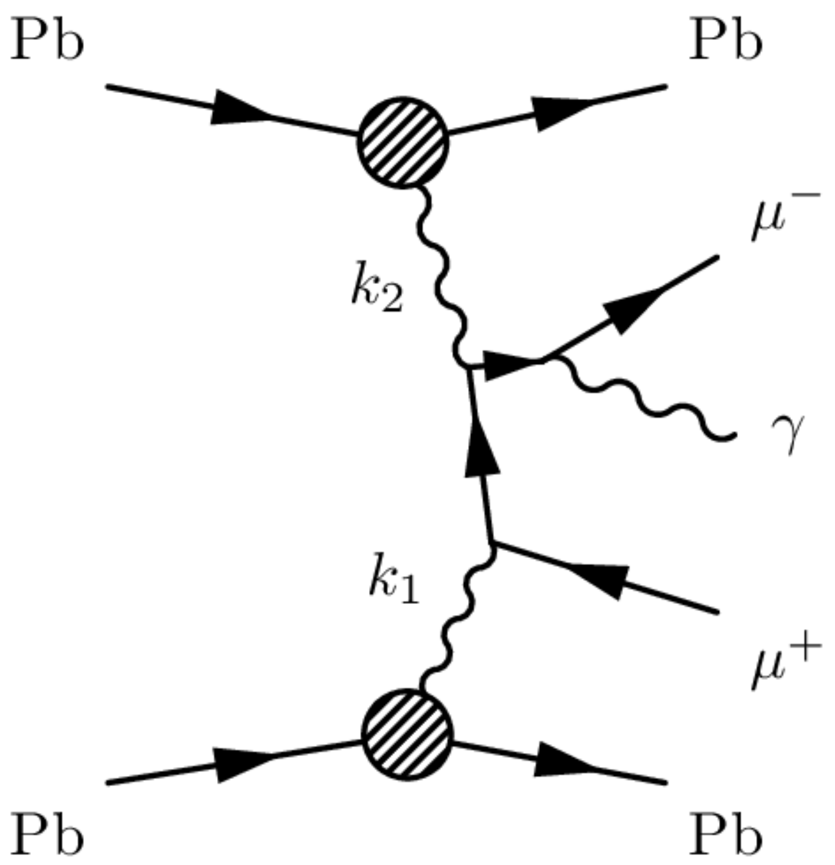
- Various types of interactions possible:



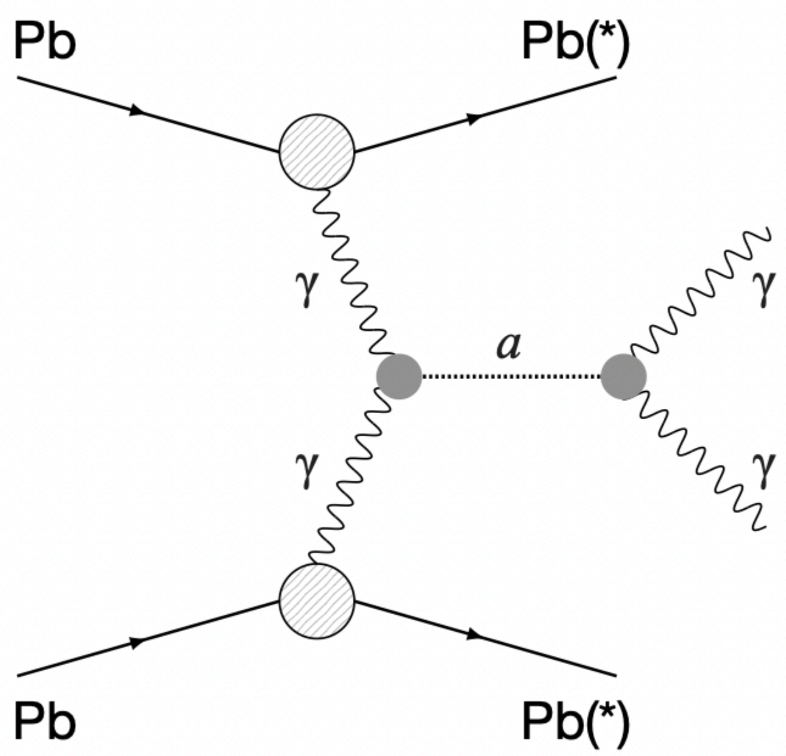
(coherent) **Photo-nuclear**



(Inelastic) **Photo-nuclear**

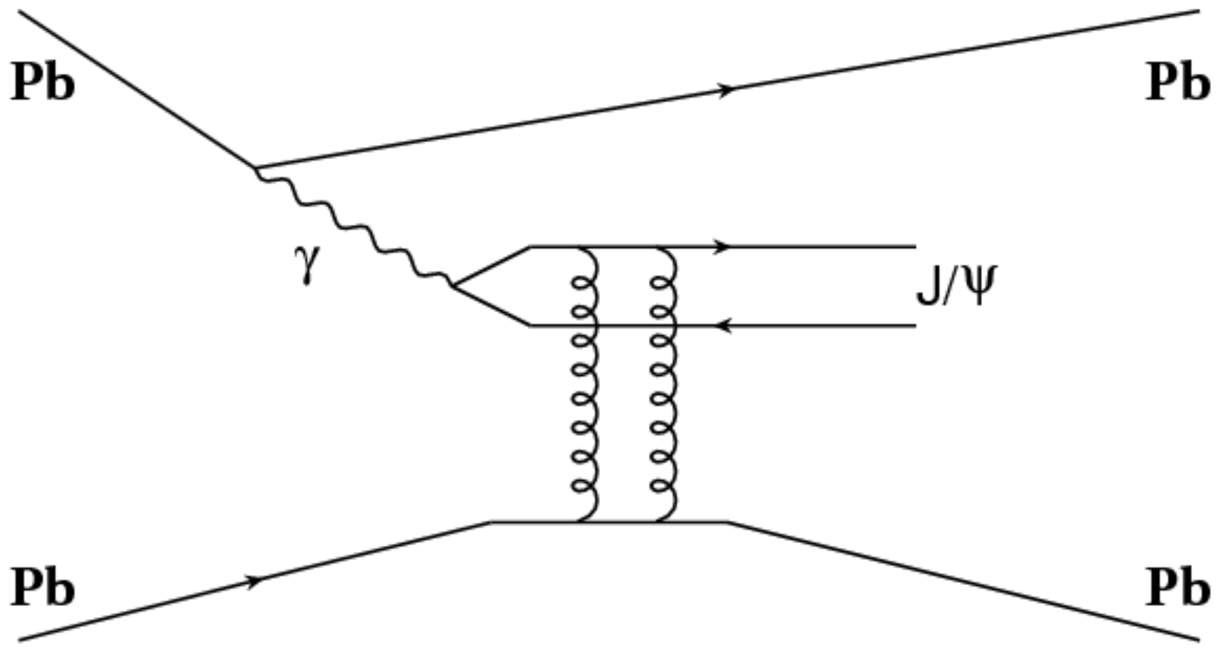


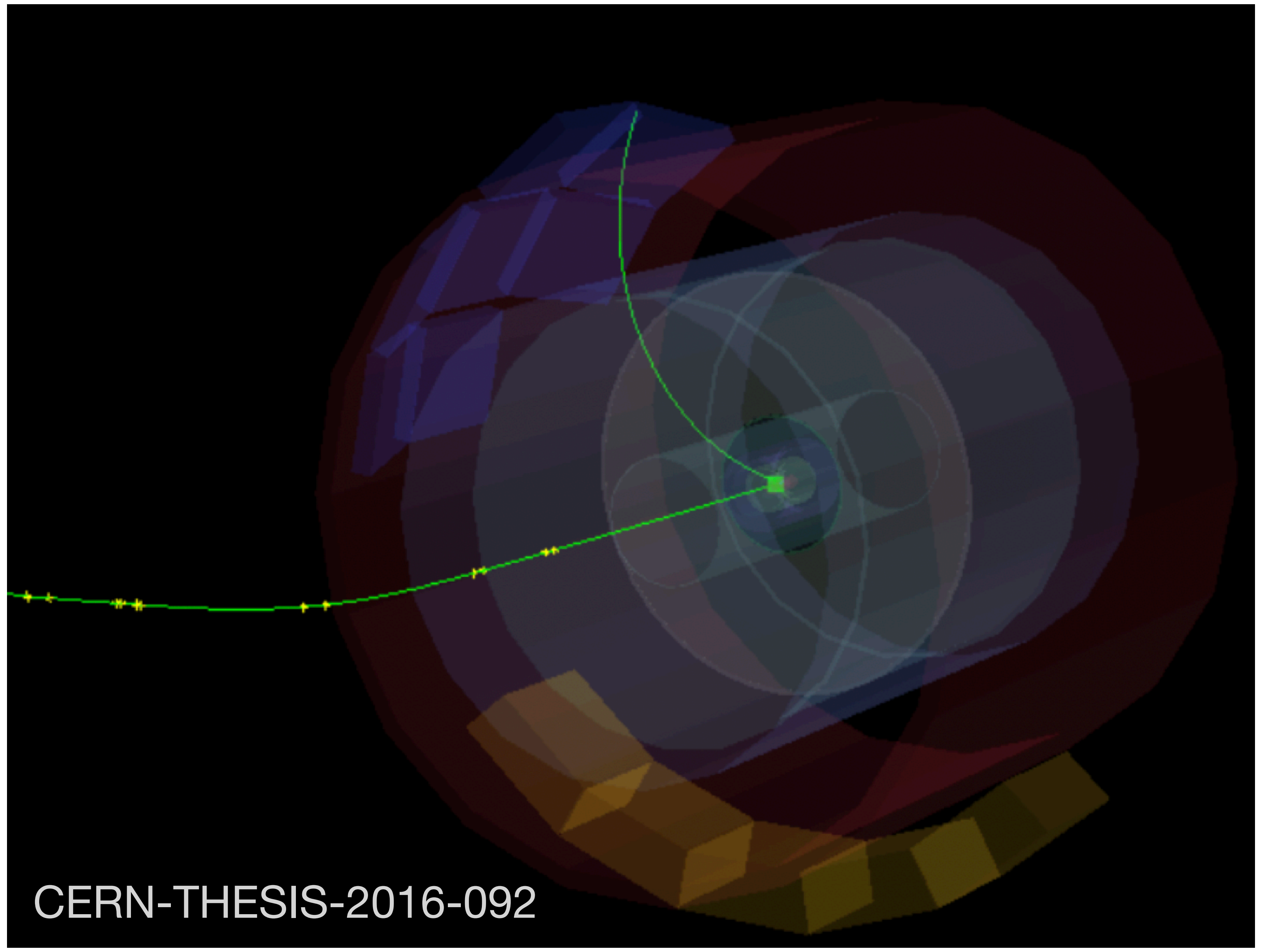
(SM) **Photon-photon**



(BSM) **Photon-photon**

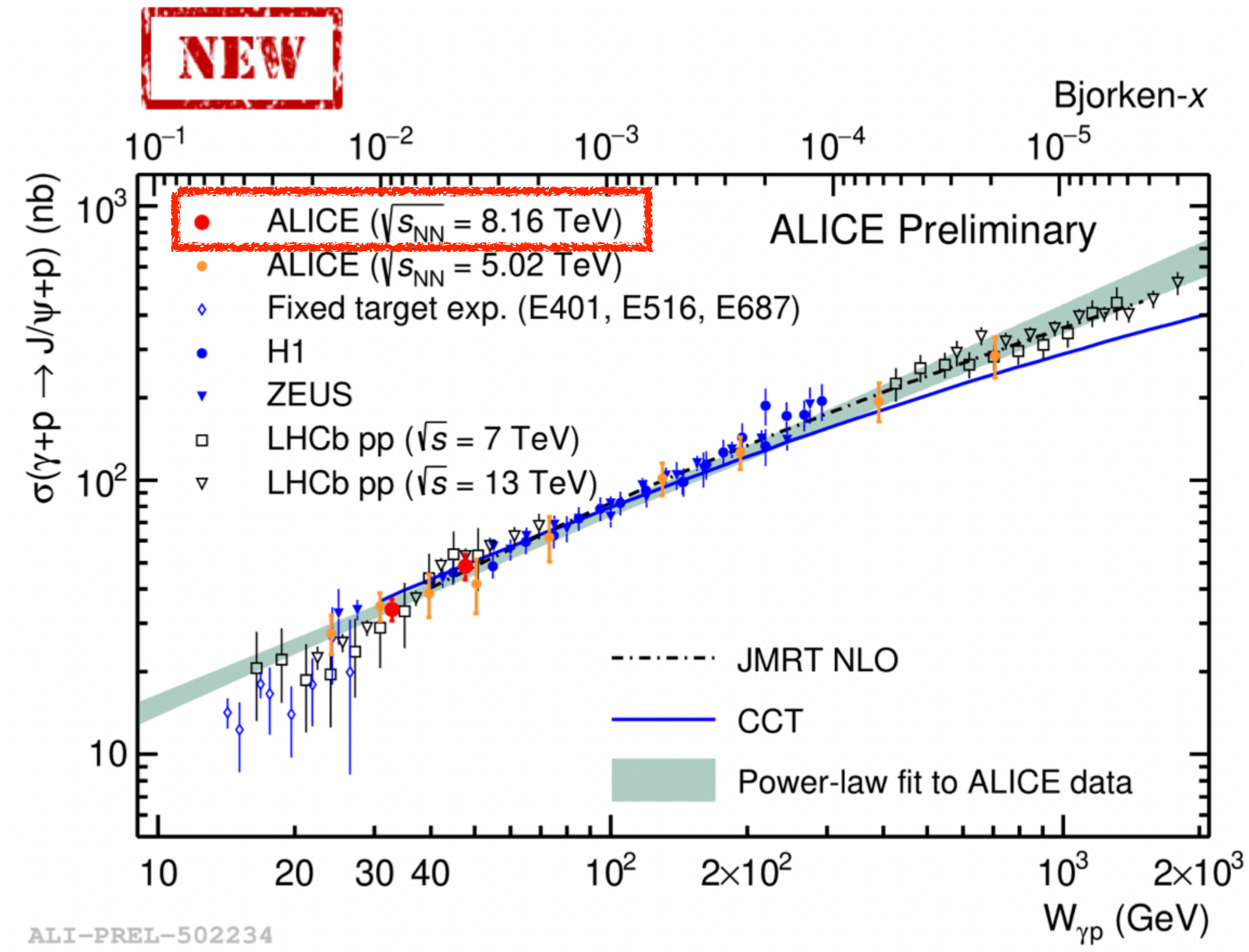
(I) Coherent vector meson production



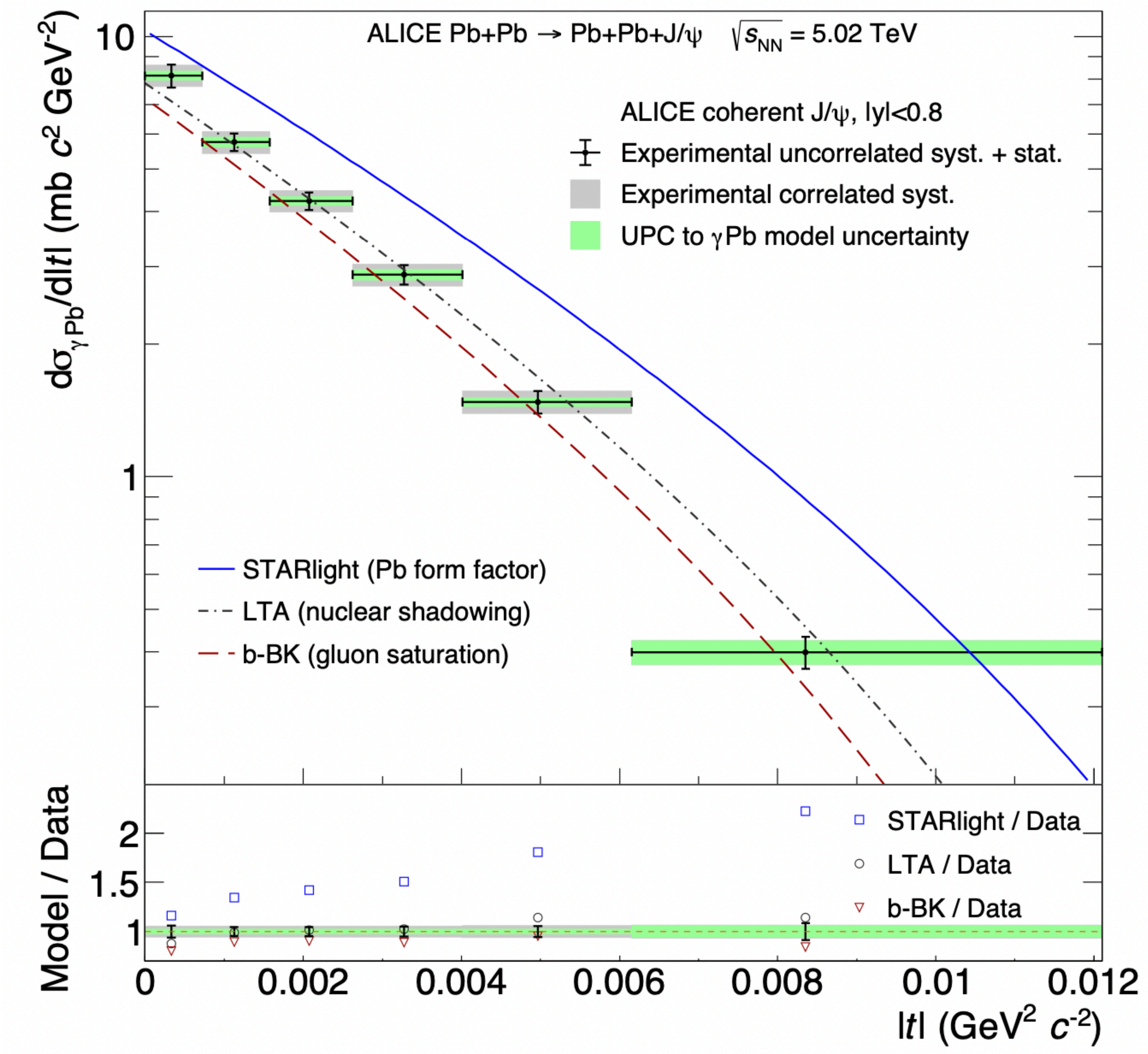


J/ψ photo-production in UPC

- New ALICE measurements in p+Pb and Pb+Pb



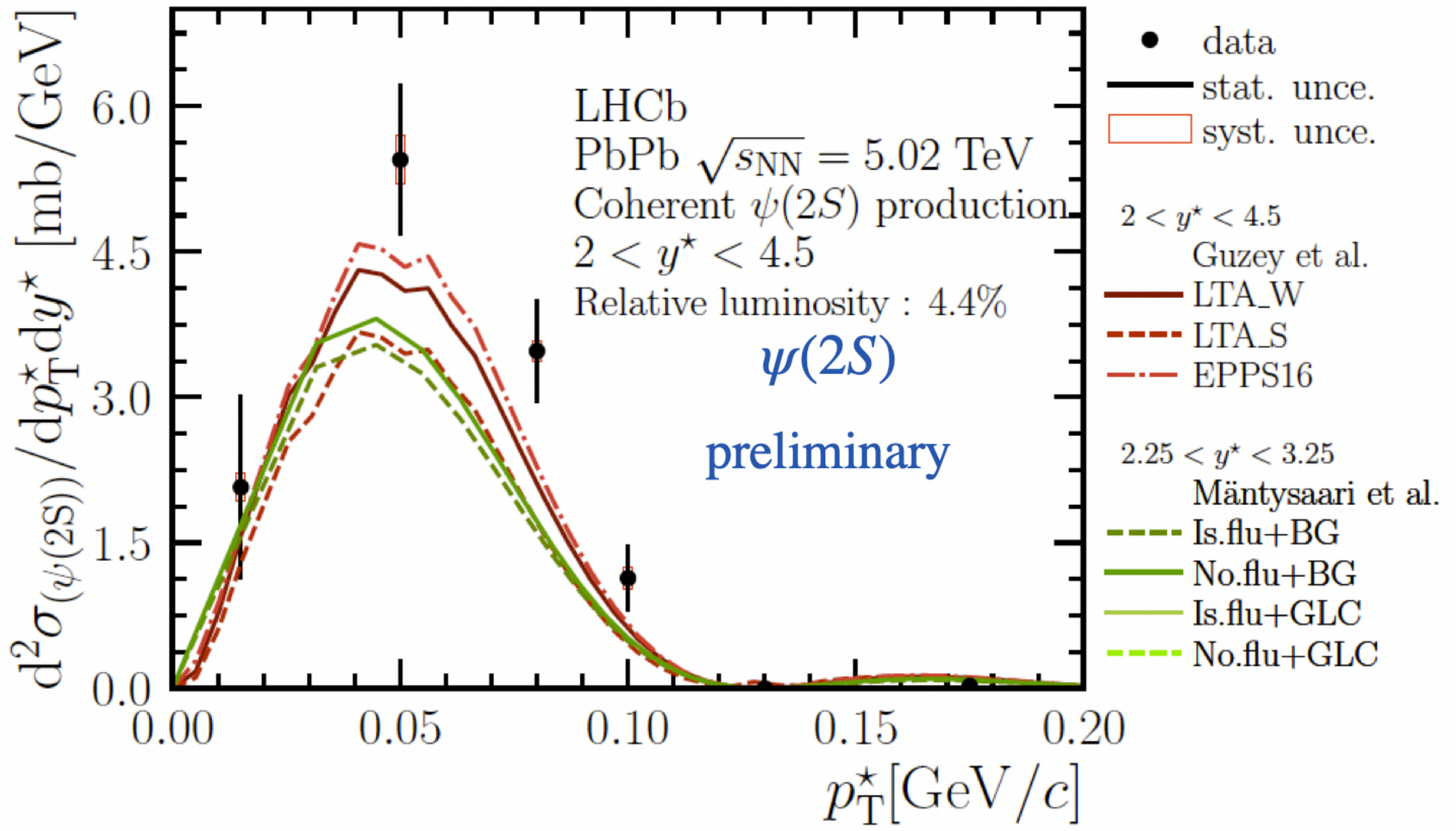
ALICE: PLB 817 (2021) 136280

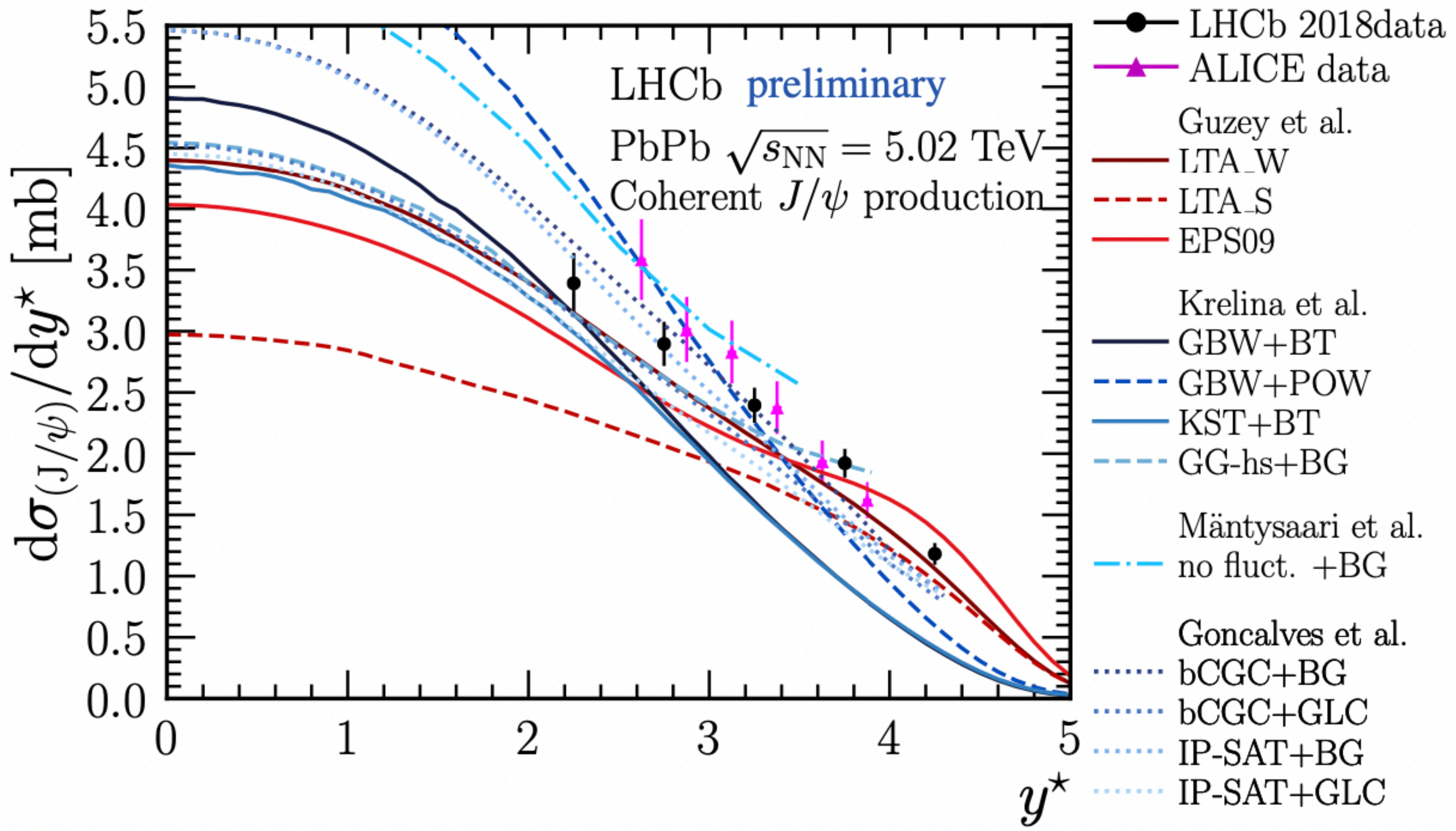


Forward J/ψ and ψ(2S) photo-production in Pb+Pb UPC

LHCb-PAPER-2022-012

- First coherent forward ψ(2S) measurement at the LHC
- J/ψ: new LHCb results is above the older 2015 measurement by 2σ
  - Now compatible with ALICE data



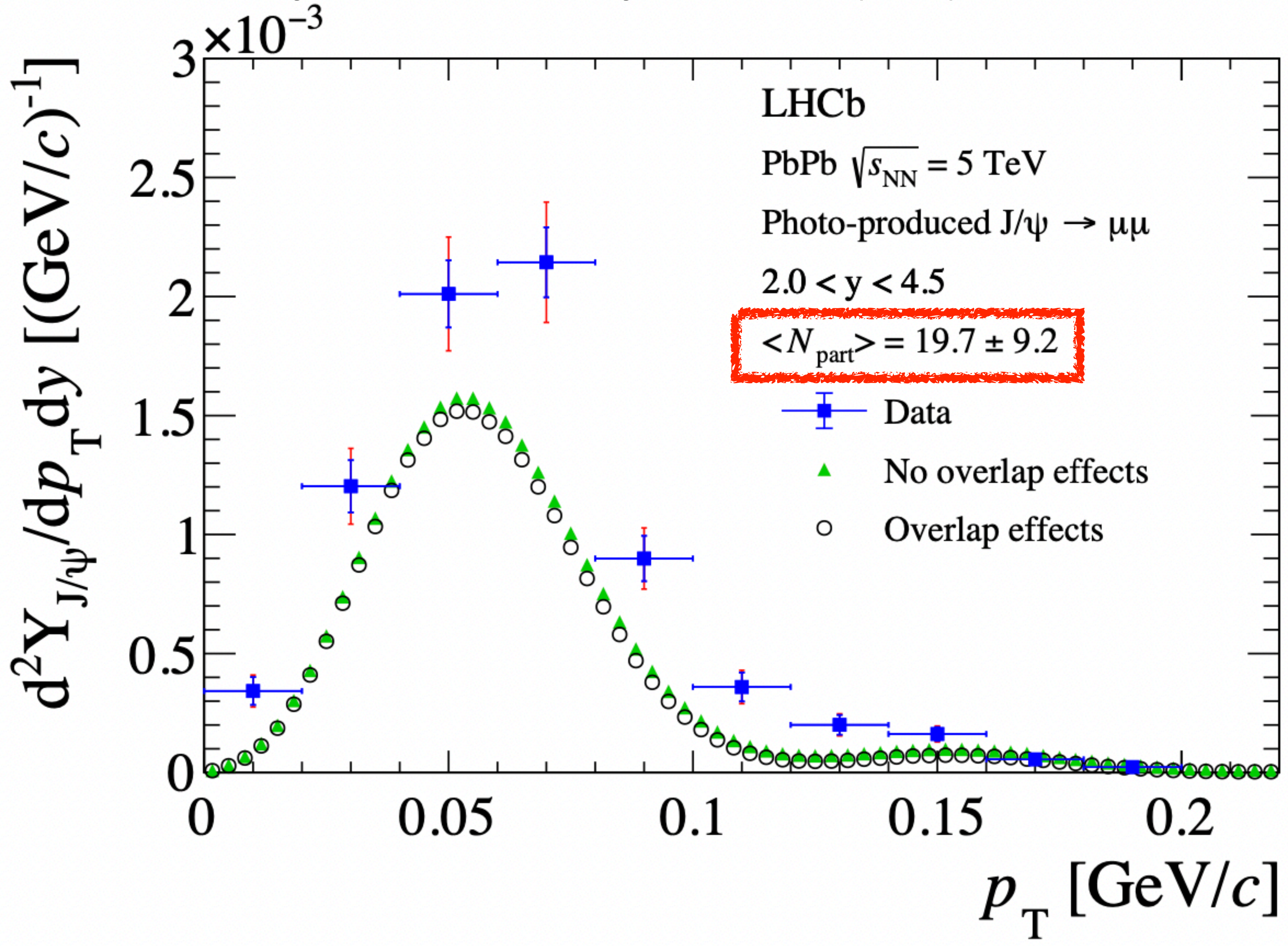


J/ψ photo-production in non-UPC Pb+Pb

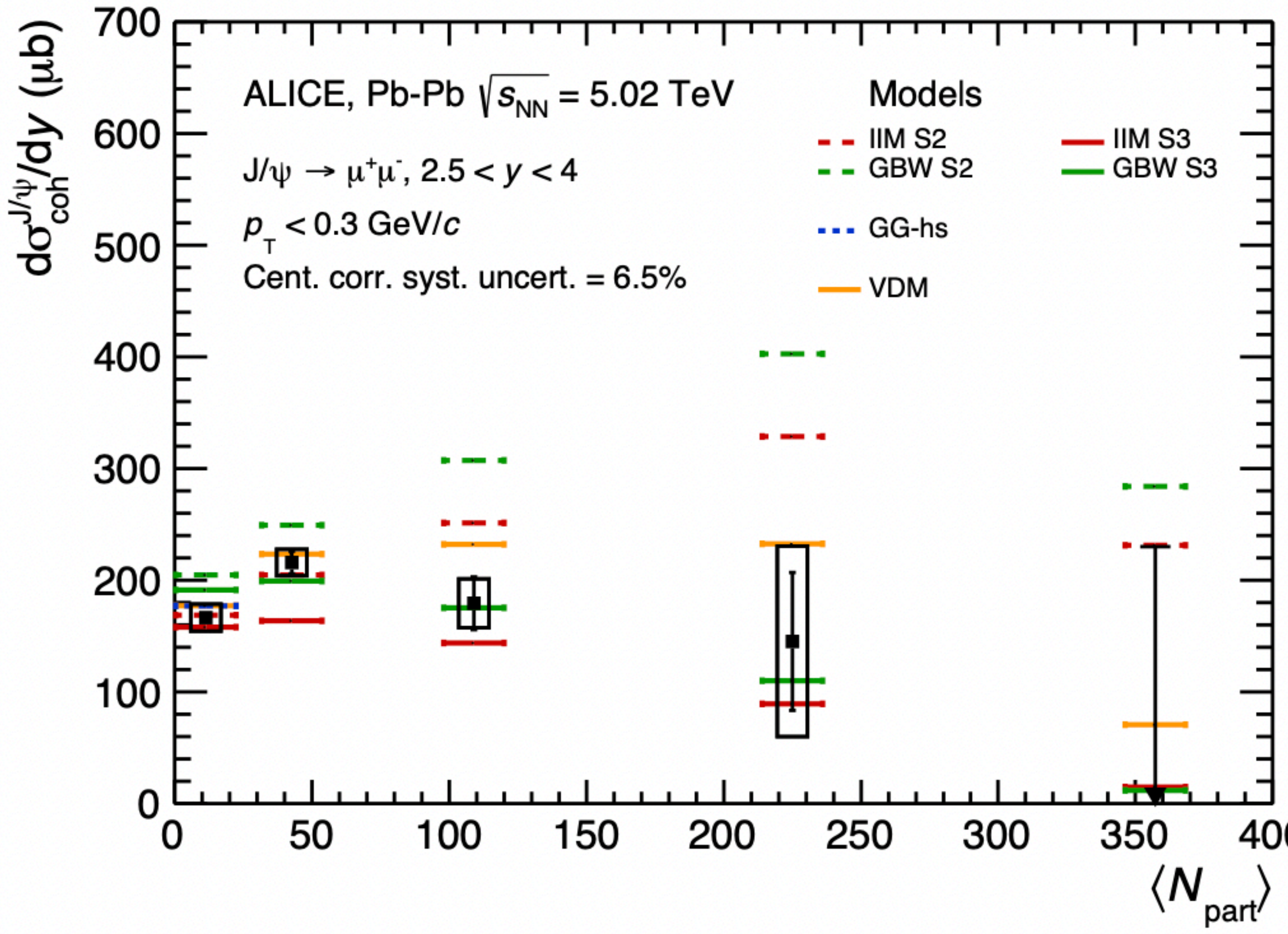
- Measurements use peripheral collisions (ALICE, LHCb), down to the semi-central collisions (ALICE)
  - Results qualitatively described by theory predictions

LHCb: arXiv:2108.02681

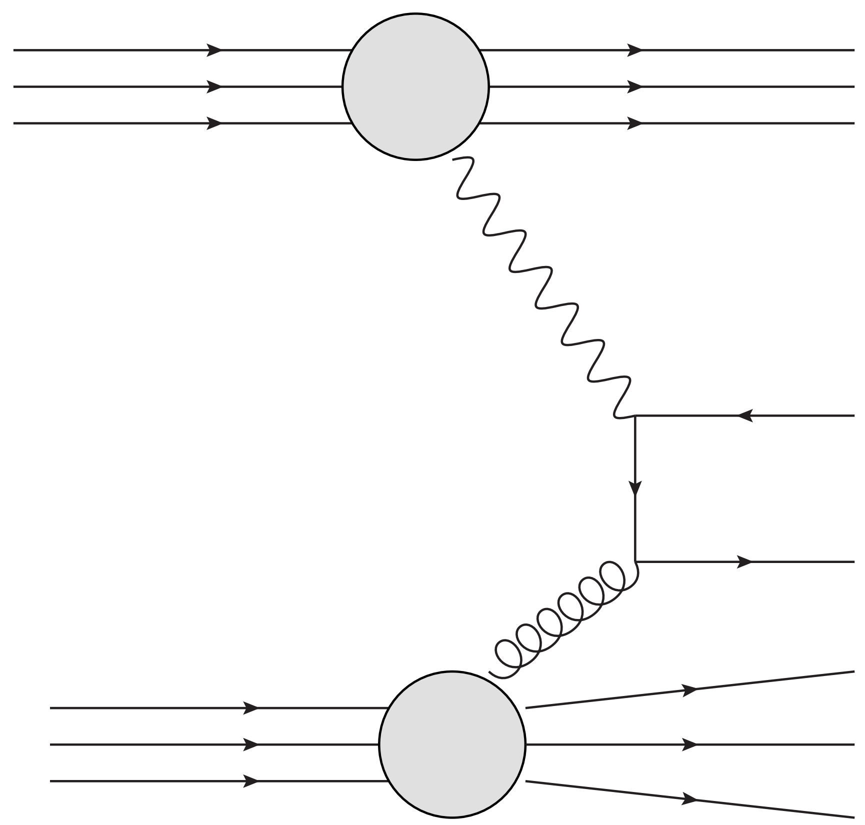
Theory: W. Zha et al., Phys. Rev. C97 (2018) 044910

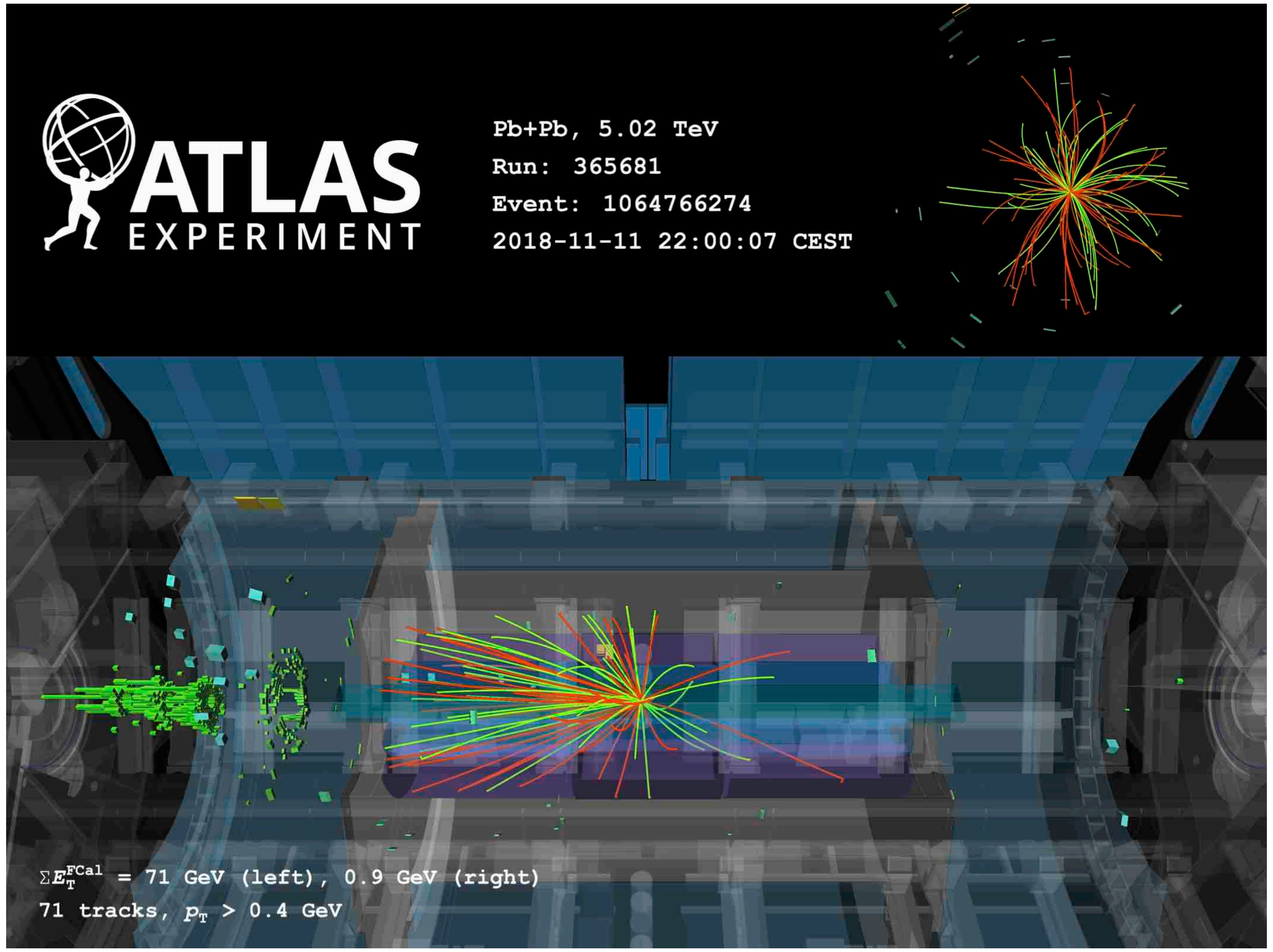


ALICE, arXiv:2204.10684



(II) Novel measurements involving photo-nuclear interactions

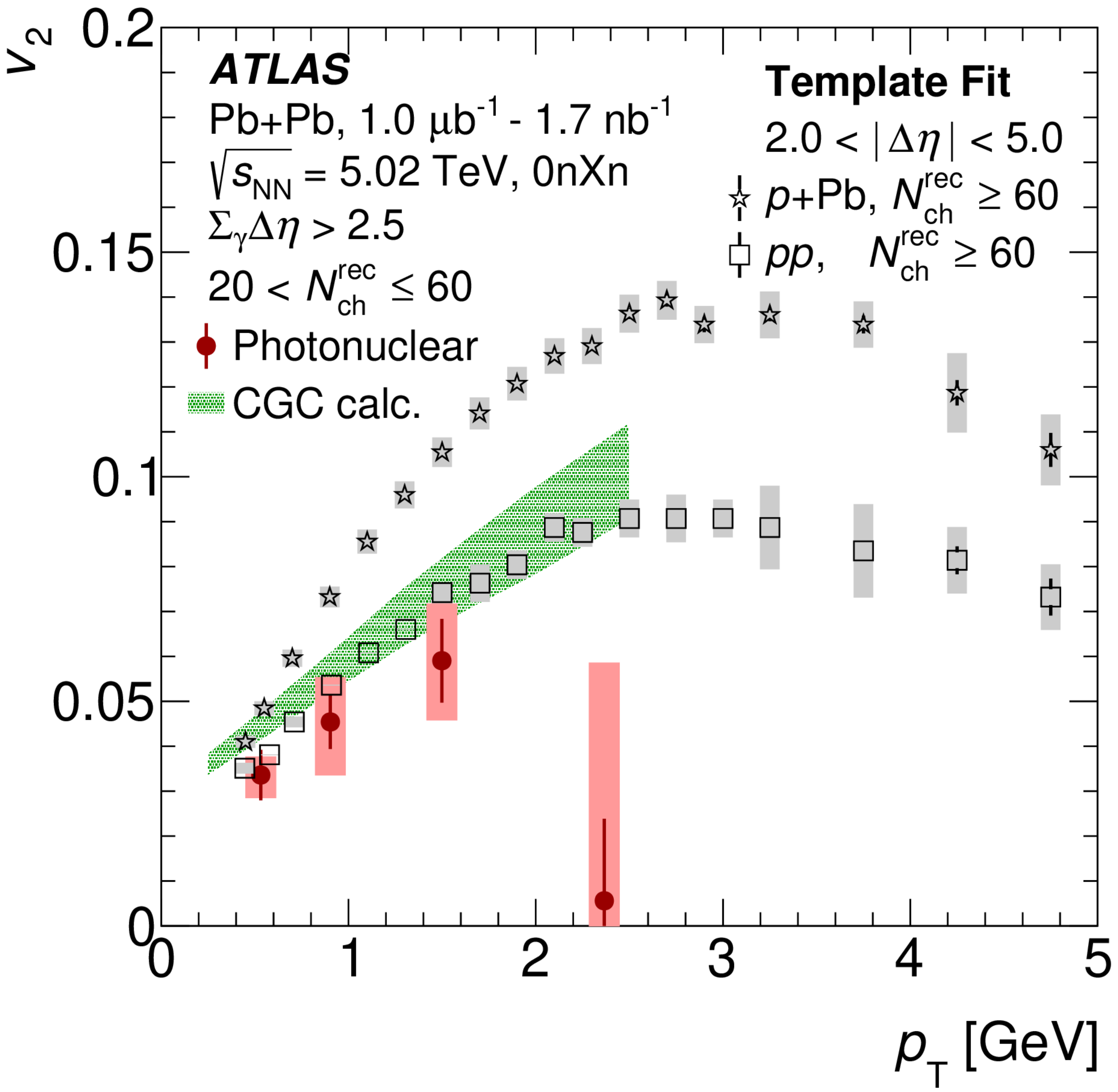


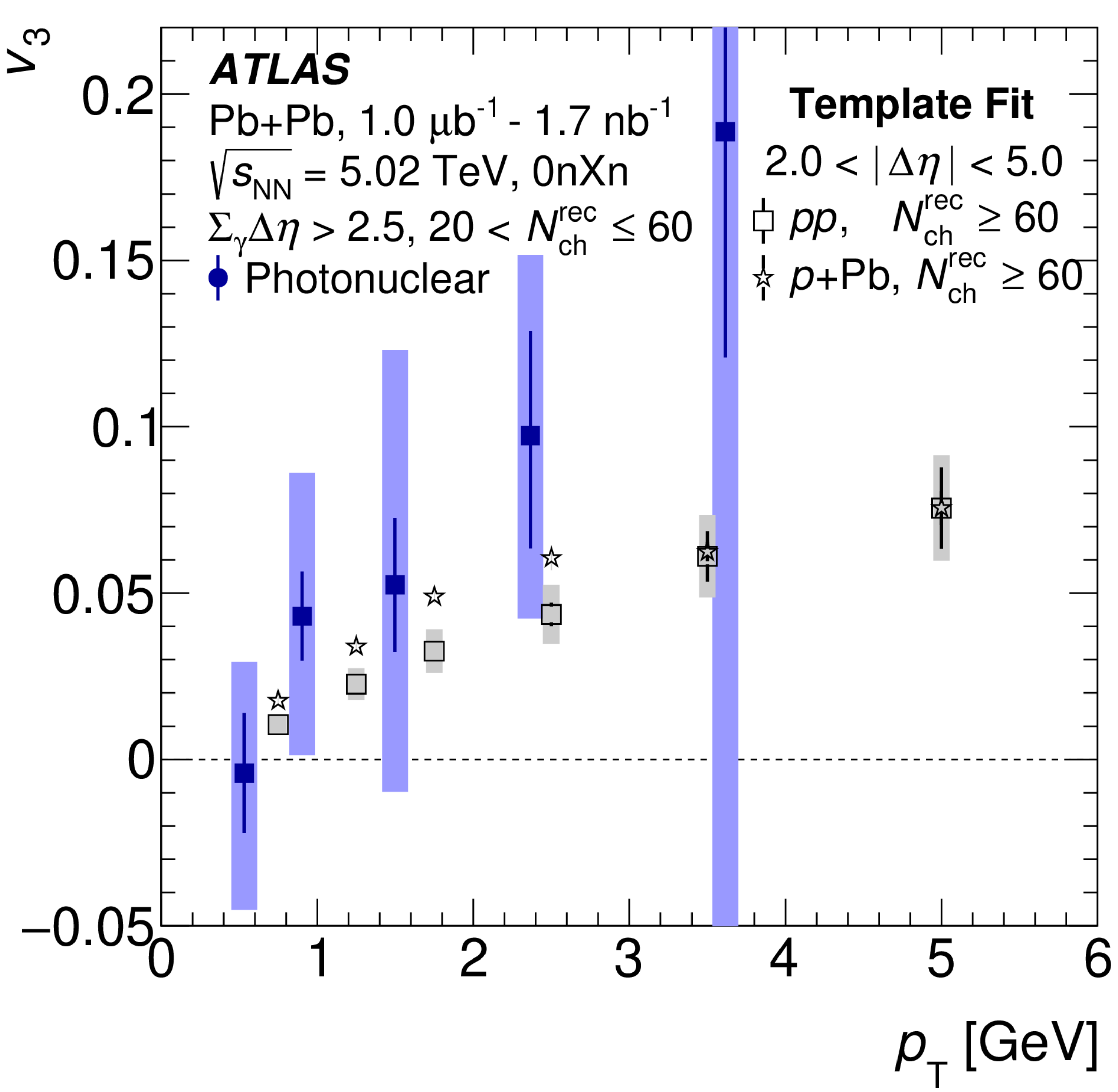


Azimuthal anisotropies in γPb

ATLAS, Phys. Rev. C. 104 (2021) 014903

- Measurement done using photonuclear Pb+Pb UPC events
  - Event selection uses rapidity gaps and “0nXn” forward neutron topology
  - Non-zero v_2 is observed; some hints of non-zero v_3
  - v_2 values are smaller than those in pp and p+Pb

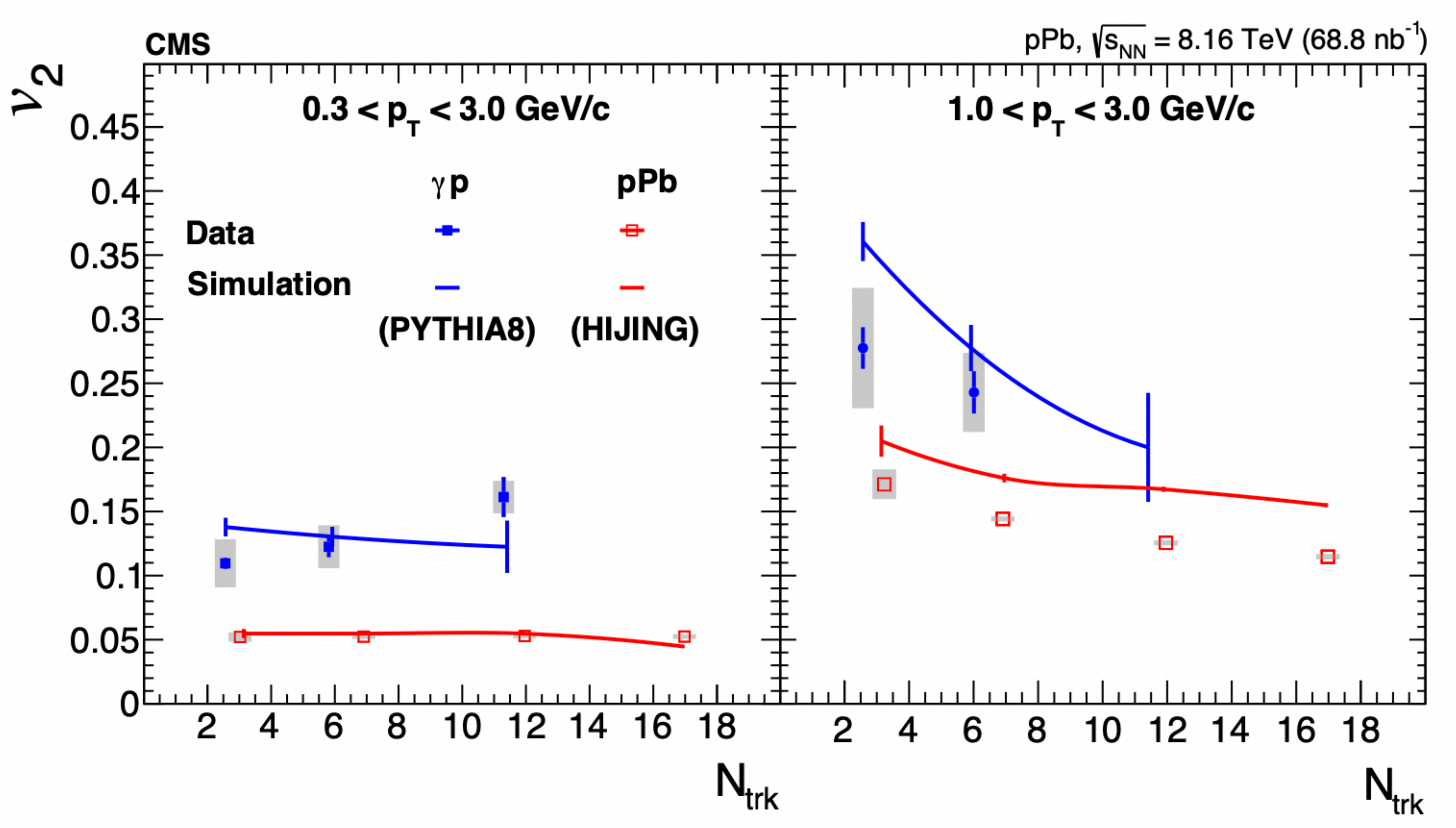




Search for azimuthal anisotropies in γp interactions

CMS, arXiv:2204.13486

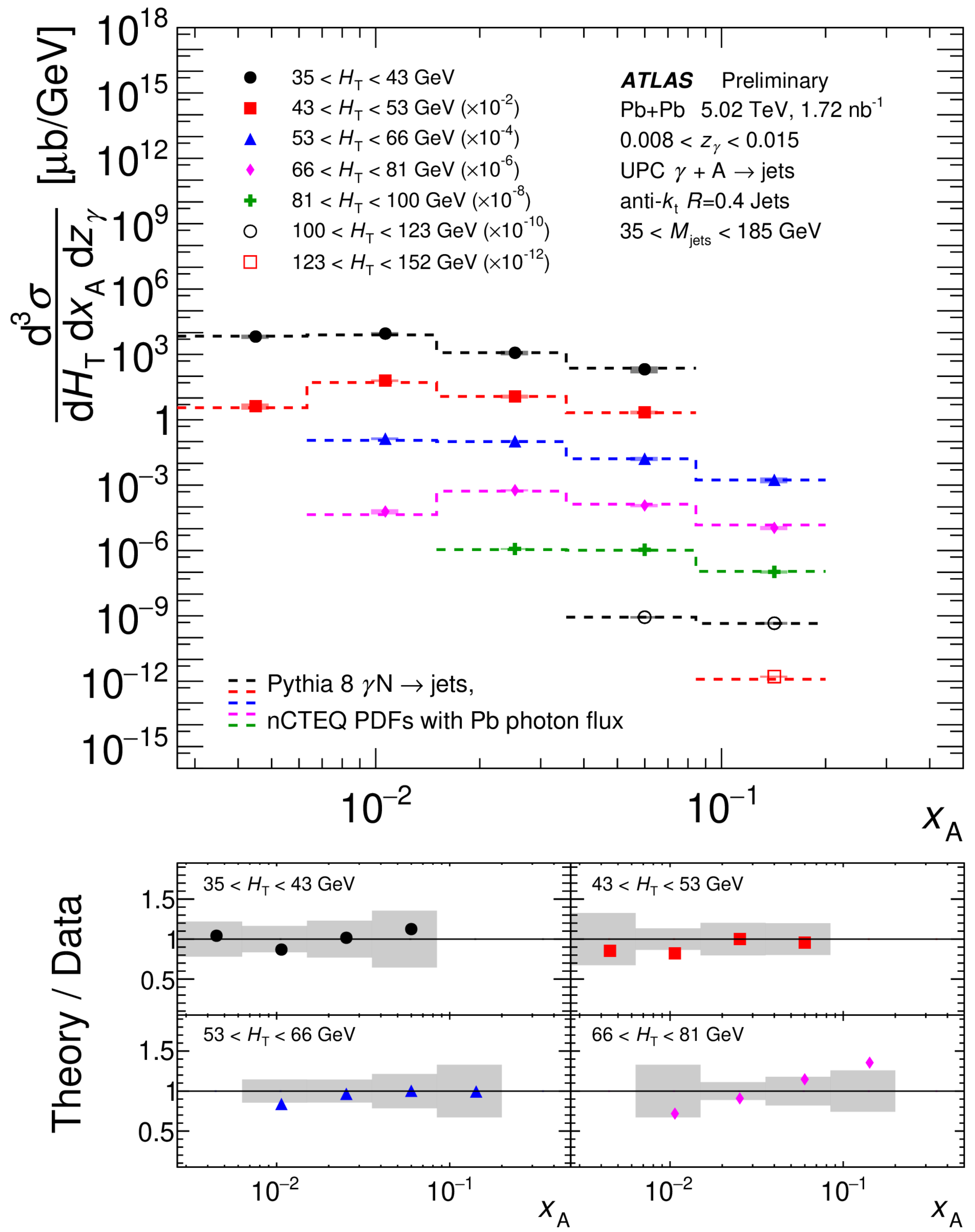
- 2PC measured in γp events (p+Pb data @8.16 TeV)
- v_2 larger for γp-enhanced events than for min-bias events at same multiplicity
  - Likely the effect of jet correlations within γp sample
    (note that no low-multiplicity subtraction is used due to very low-N_{trk})



Measurement of photo-nuclear dijet production in Pb+Pb

ATLAS-CONF-2022-021

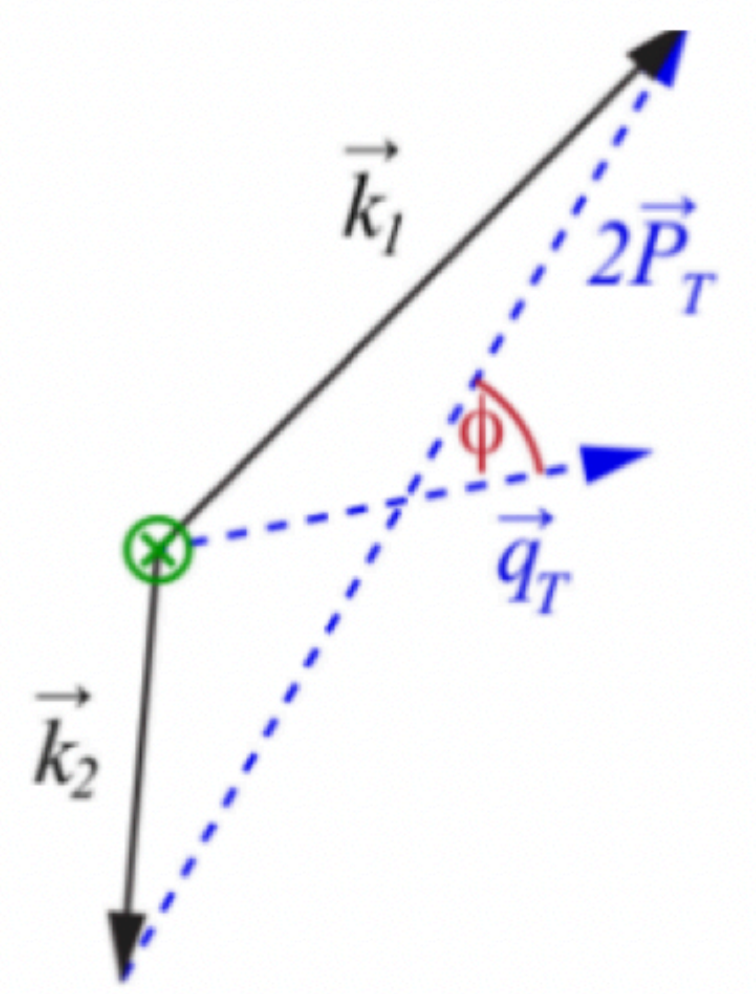
- Follow-up of the original ATLAS 2015 data (0.5/nb) measurement
- 2018 Pb+Pb data used (1.7/nb)
- Measurement fully unfolded for detector effects
- Triple-differential cross-sections extracted (x_A, z_y, H_T)
- Comparison to Pythia 8 + nPDFs
- Potential to constrain nPDFs



Diffractive photo-nuclear dijets in Pb+Pb

CMS, arXiv:2205.00045

- Azimuthal angular decorrelation of dijets (2nd Fourier harmonic)
  - Potentially sensitive to elliptic gluon Wigner distribution

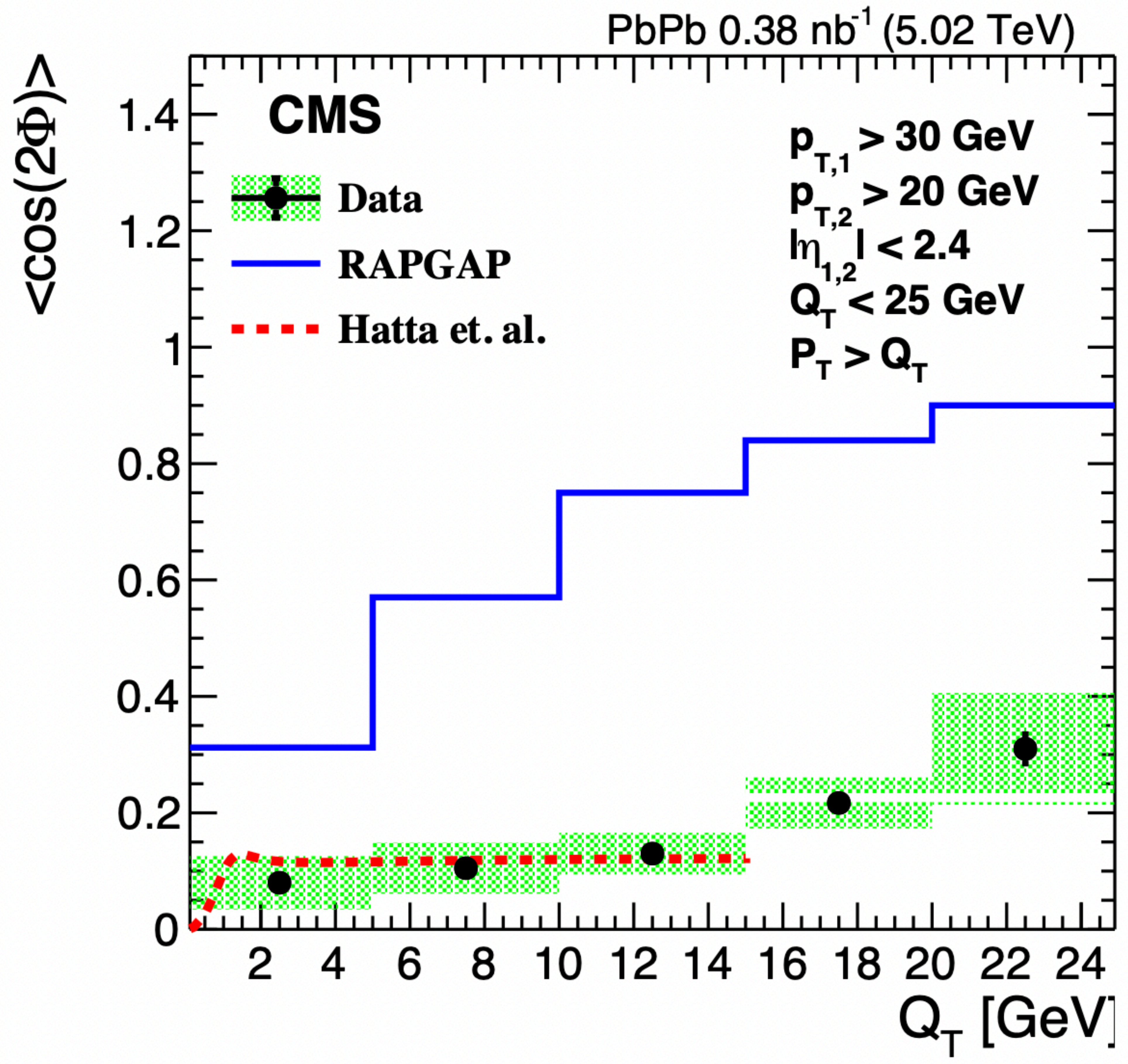


Vector sum of 2 jets:

$$\vec{Q}_T = \vec{k}_1 + \vec{k}_2$$

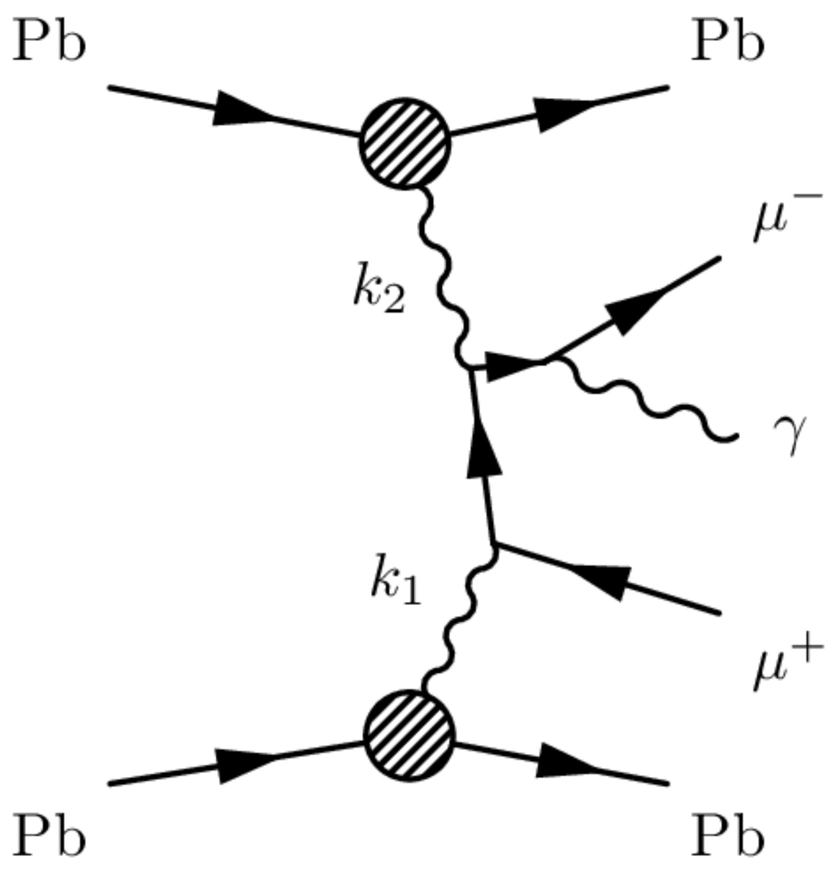
Vector difference of 2 jets

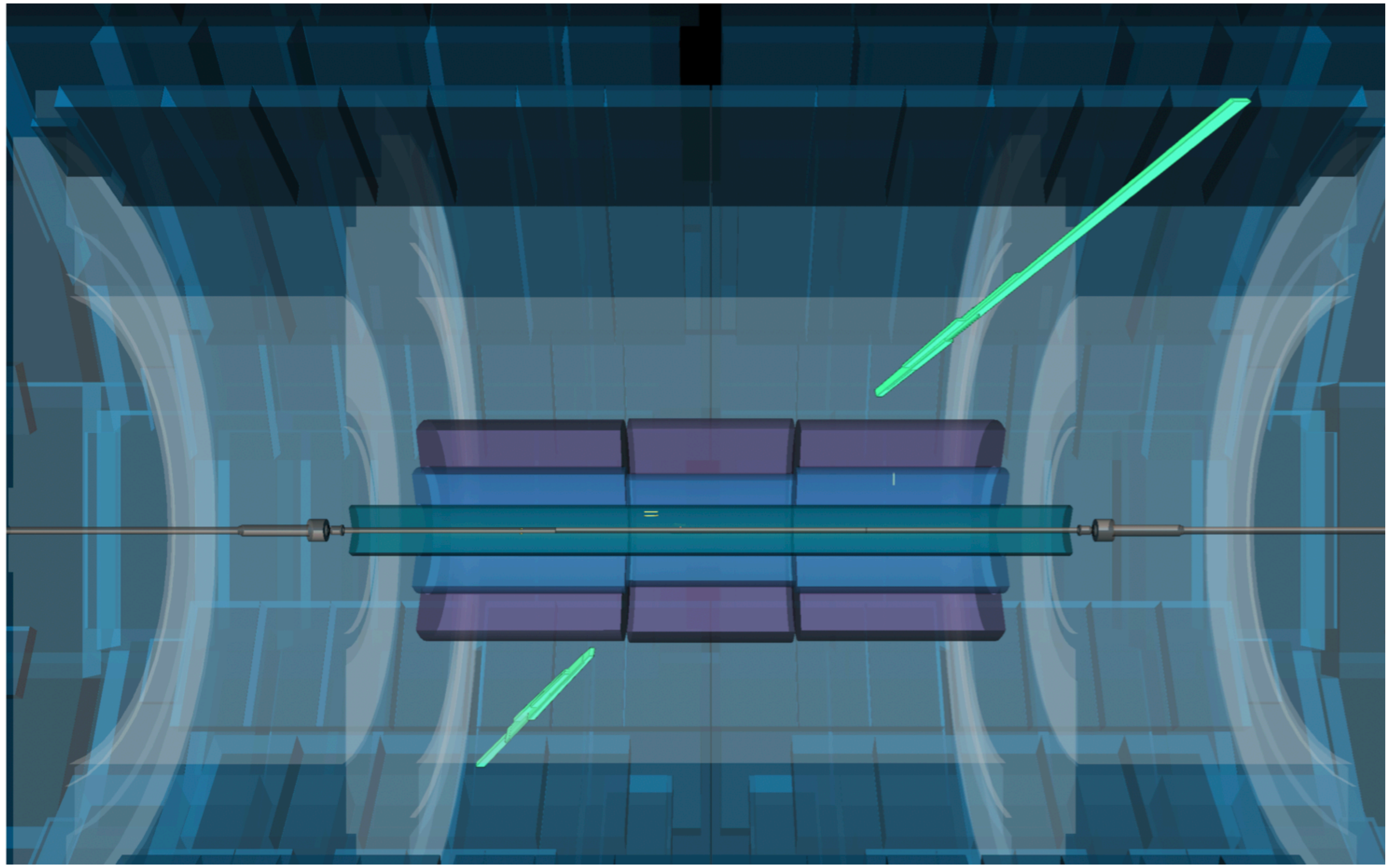
$$\vec{P}_T = \frac{1}{2}(\vec{k}_1 - \vec{k}_2)$$



QT is the proxy for recoil momentum of Pb target

(III) SM photon-photon interactions

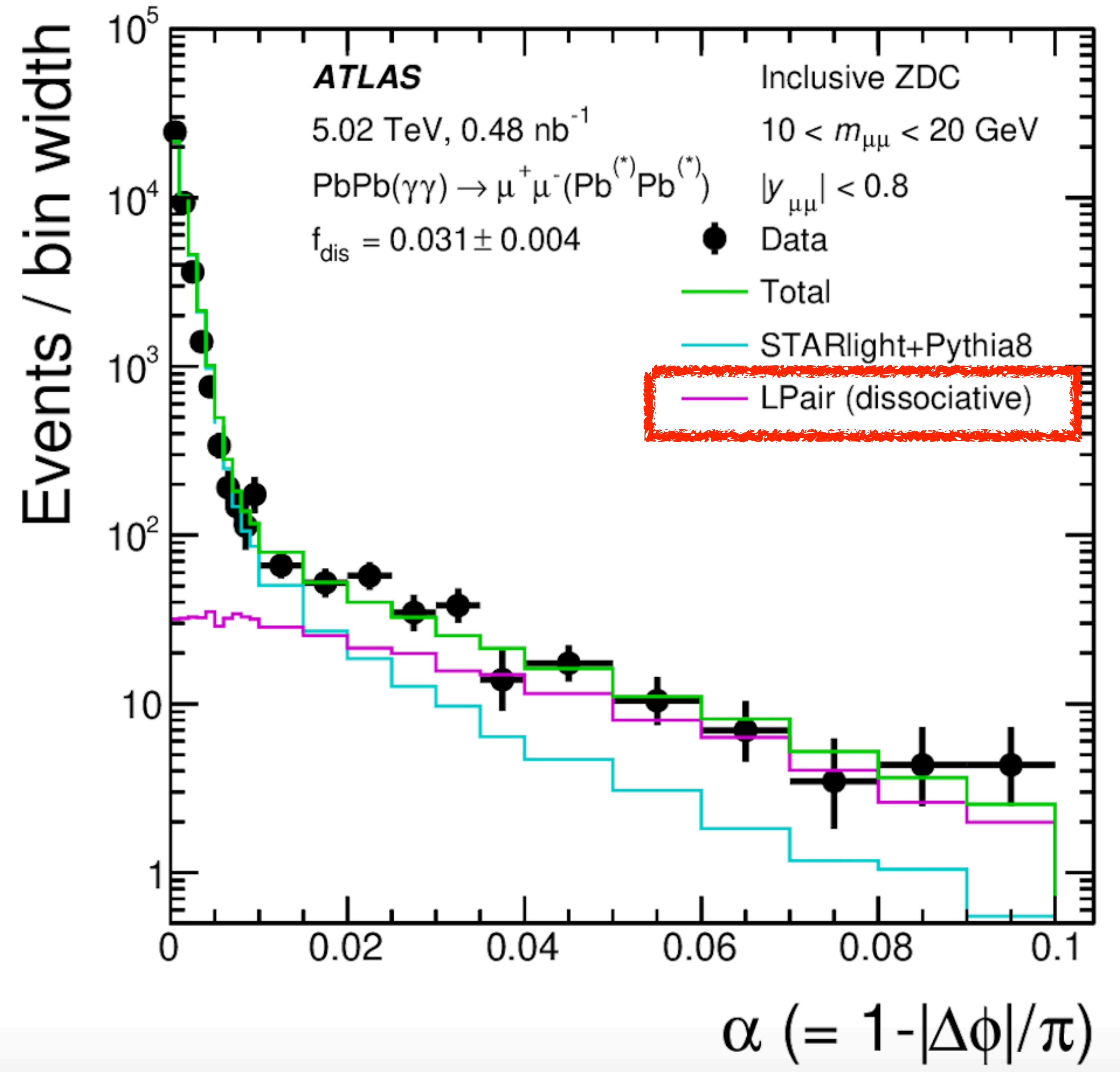


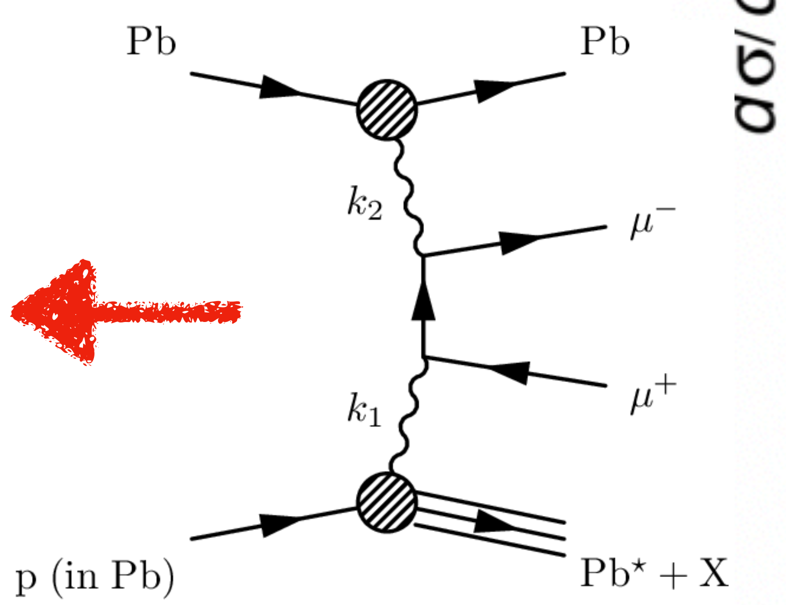


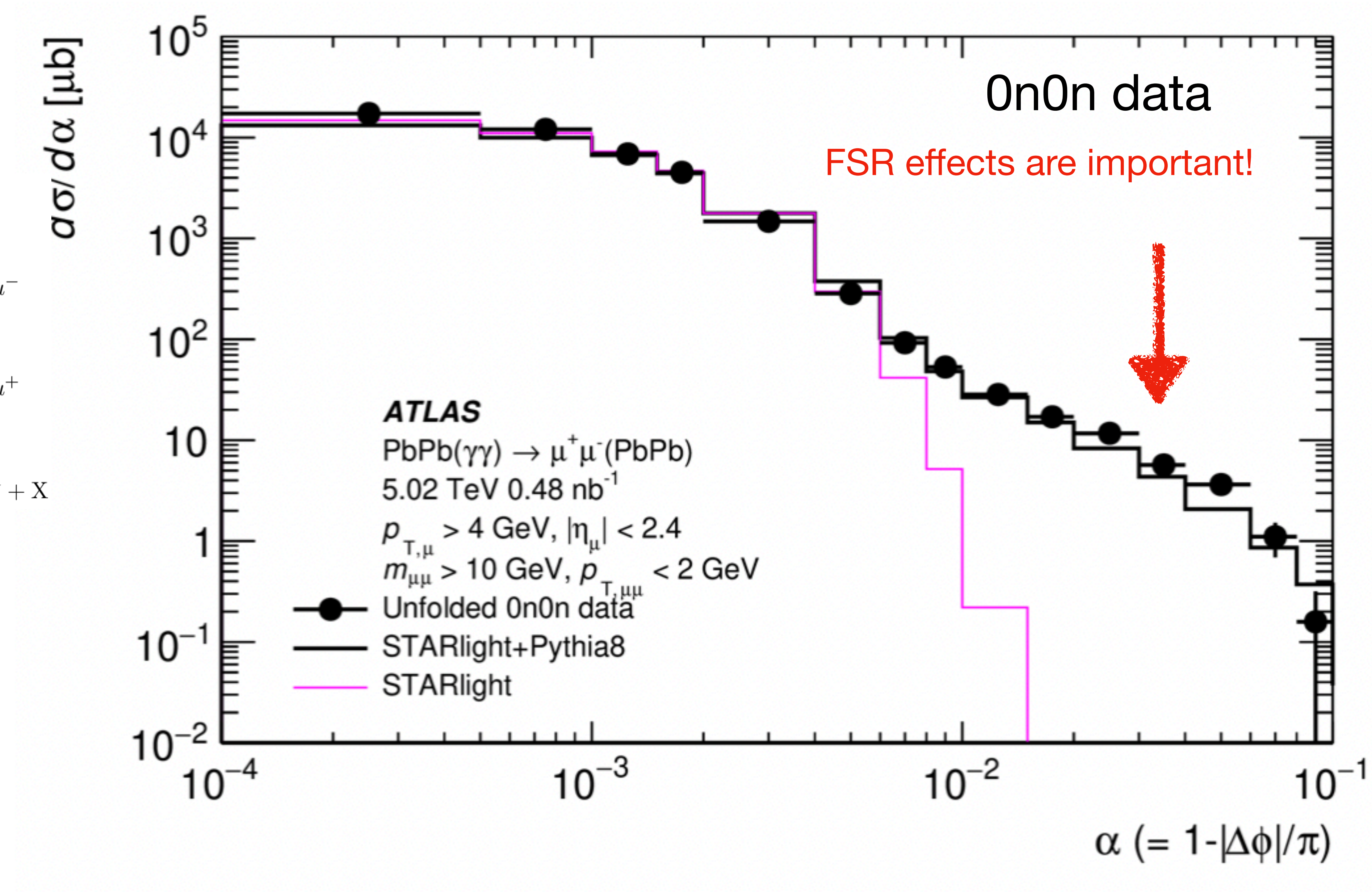
γγ→μμ production in Pb+Pb UPC

ATLAS, Phys. Rev. C 104 (2021) 024906

- Abundant rate → precision test of QED and initial photon flux modeling
- Comprehensive measurement of cross sections in dimuon mass, rapidity, cos(theta), acoplanarity





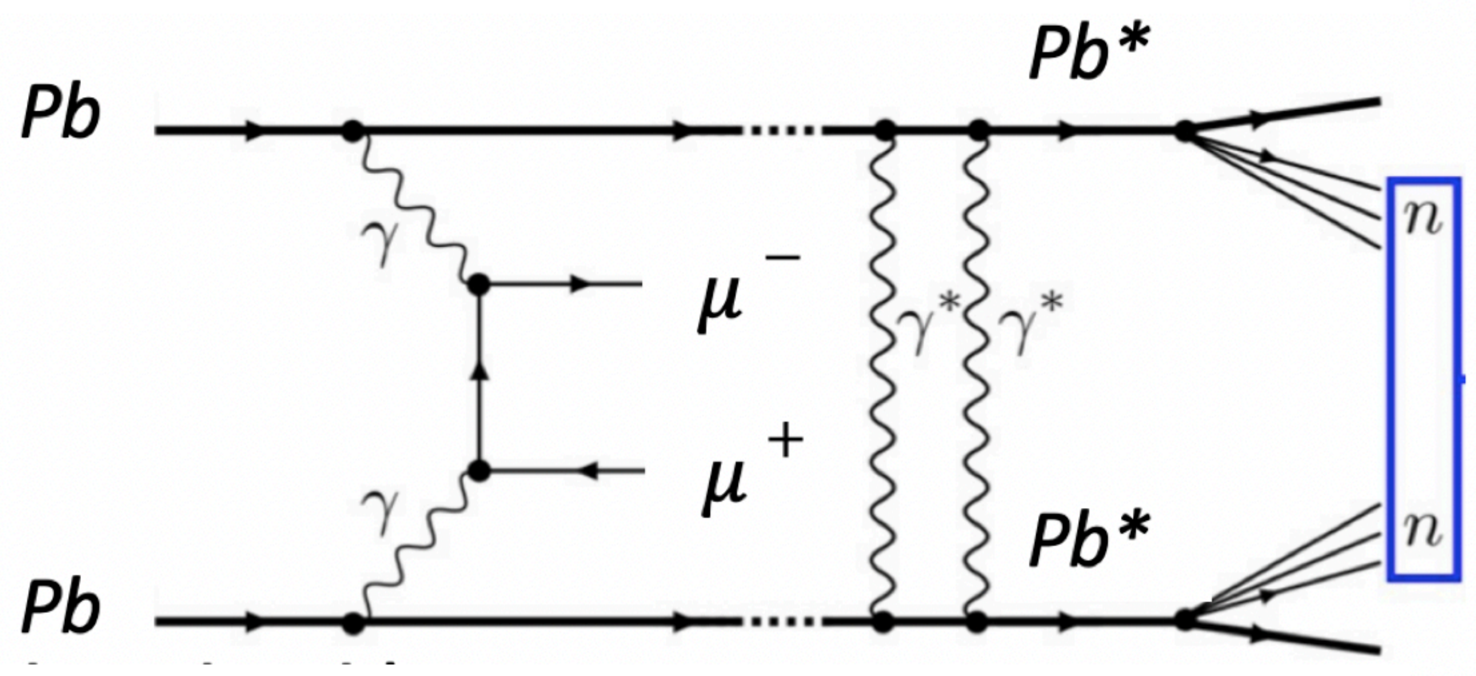


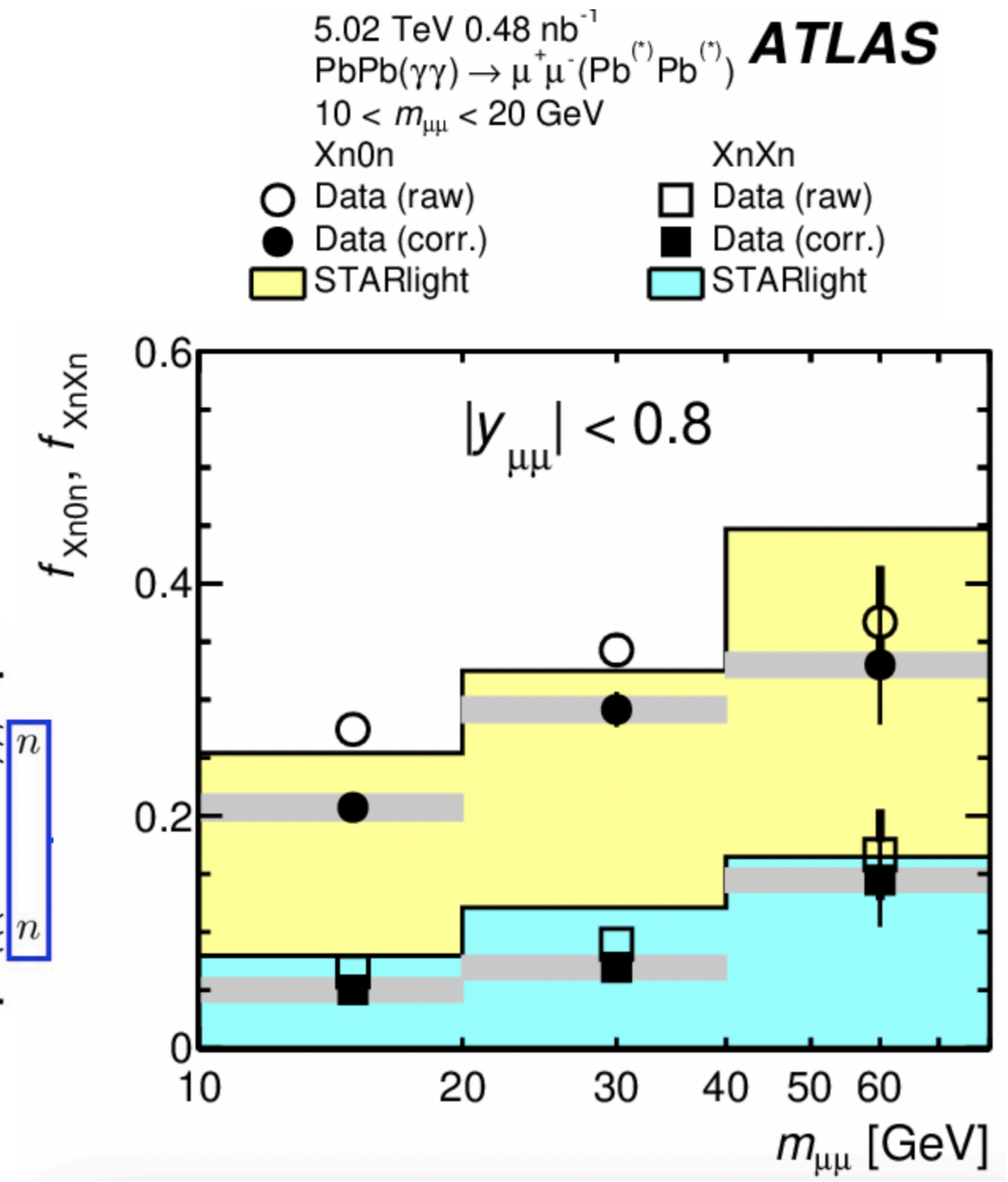
γγ→μμ production in Pb+Pb UPC

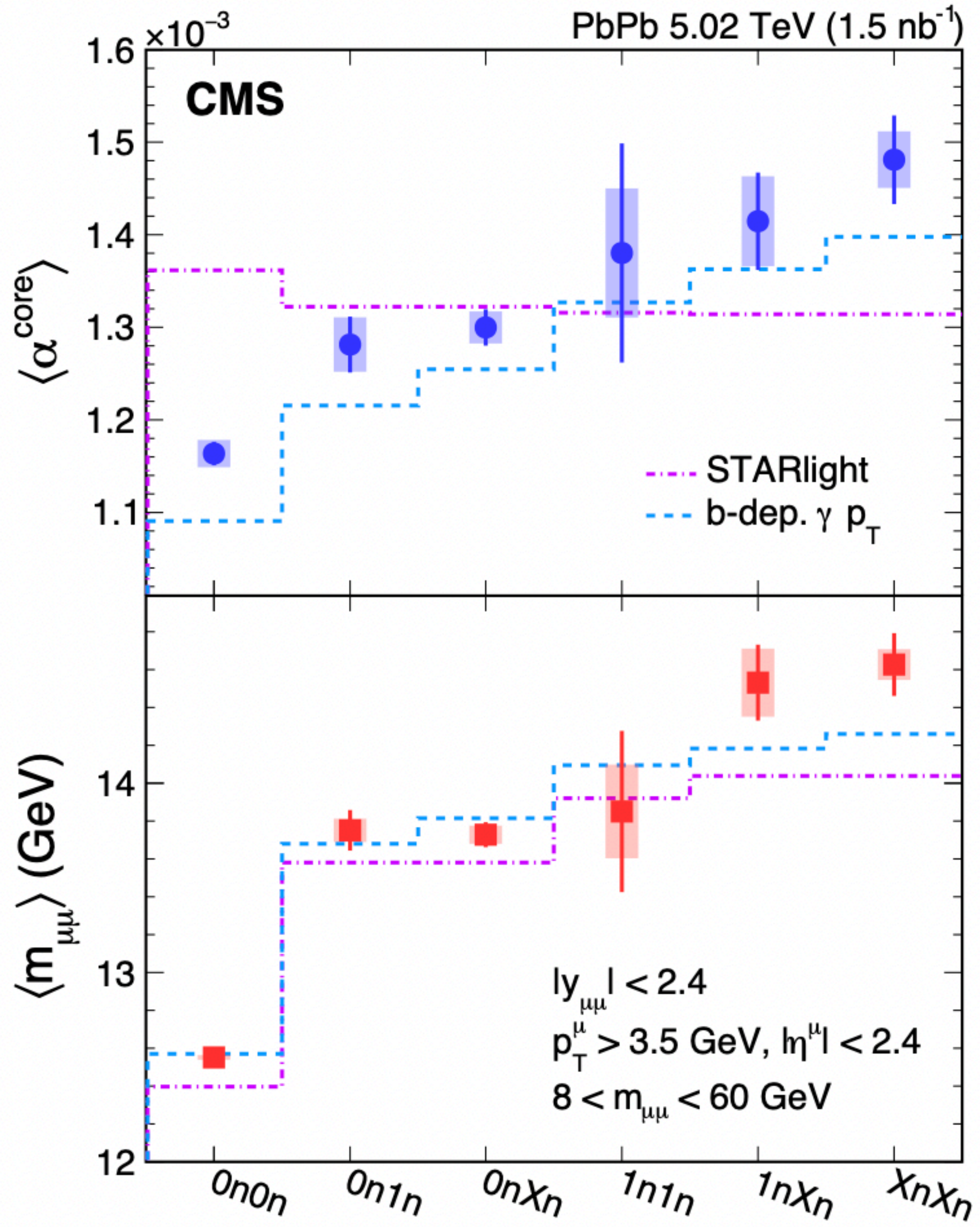
ATLAS, Phys. Rev. C 104 (2021) 024906

CMS, PRL 127, 122001 (2021)

- Measuring properties of events with singe and mutual EM dissociation
  → indirect probe of Pb+Pb impact parameter in γγ interactions



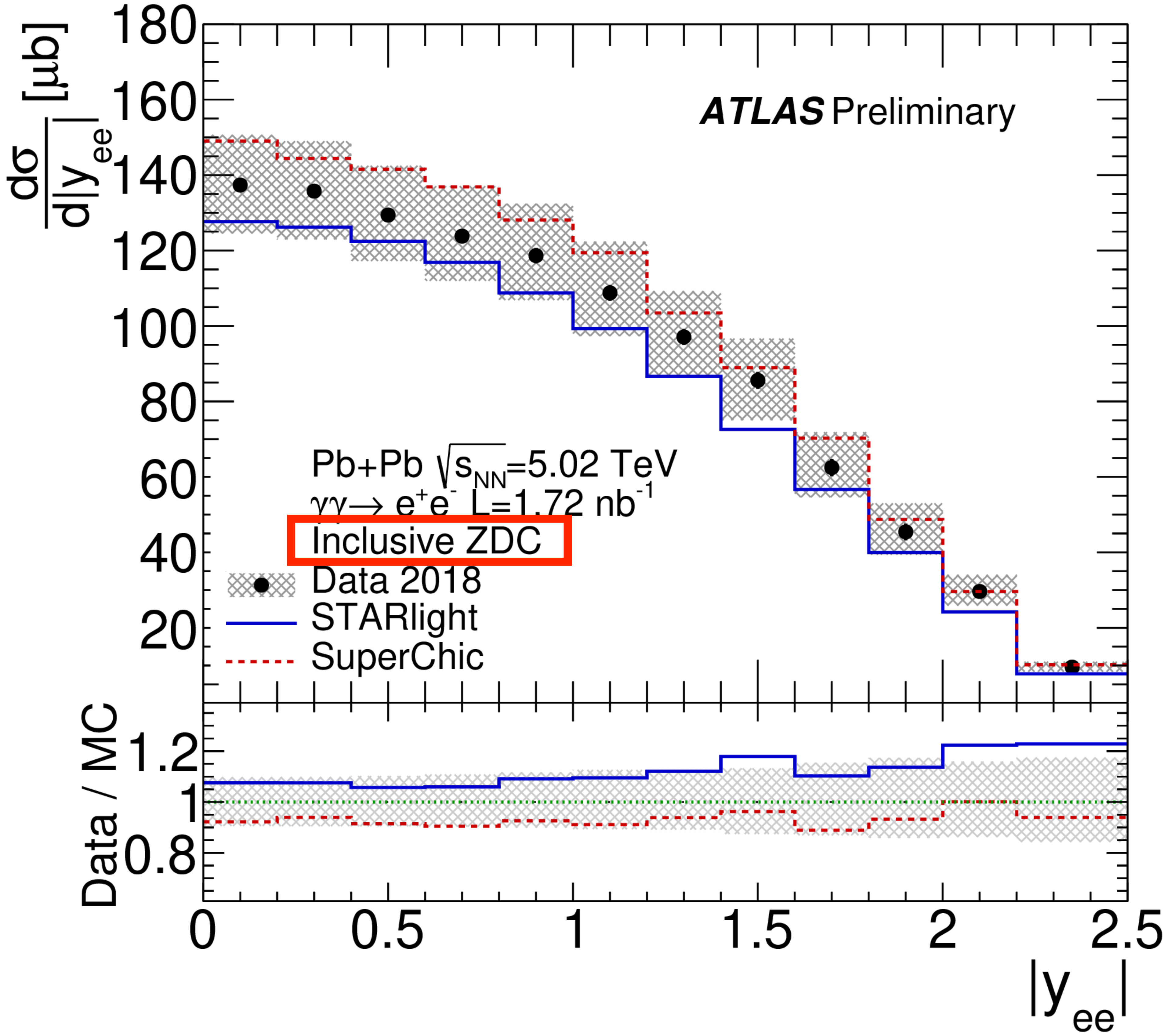


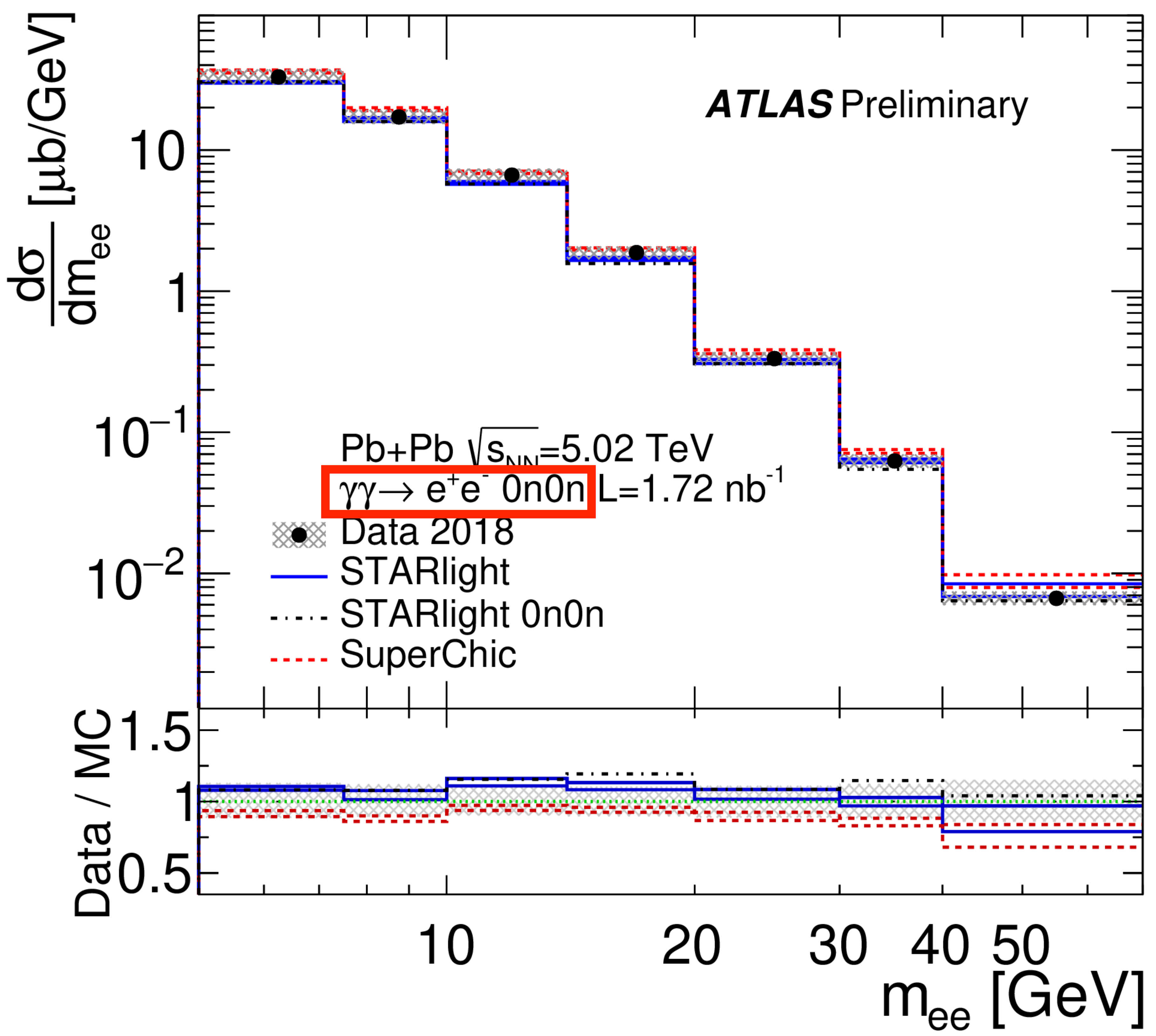


γγ→ee production in Pb+Pb UPC

ATLAS-CONF-2022-025

- Similar techniques as in ATLAS μμ UPC measurement but notable advances
  - Higher statistics from 2018 data
  - Extended fiducial region

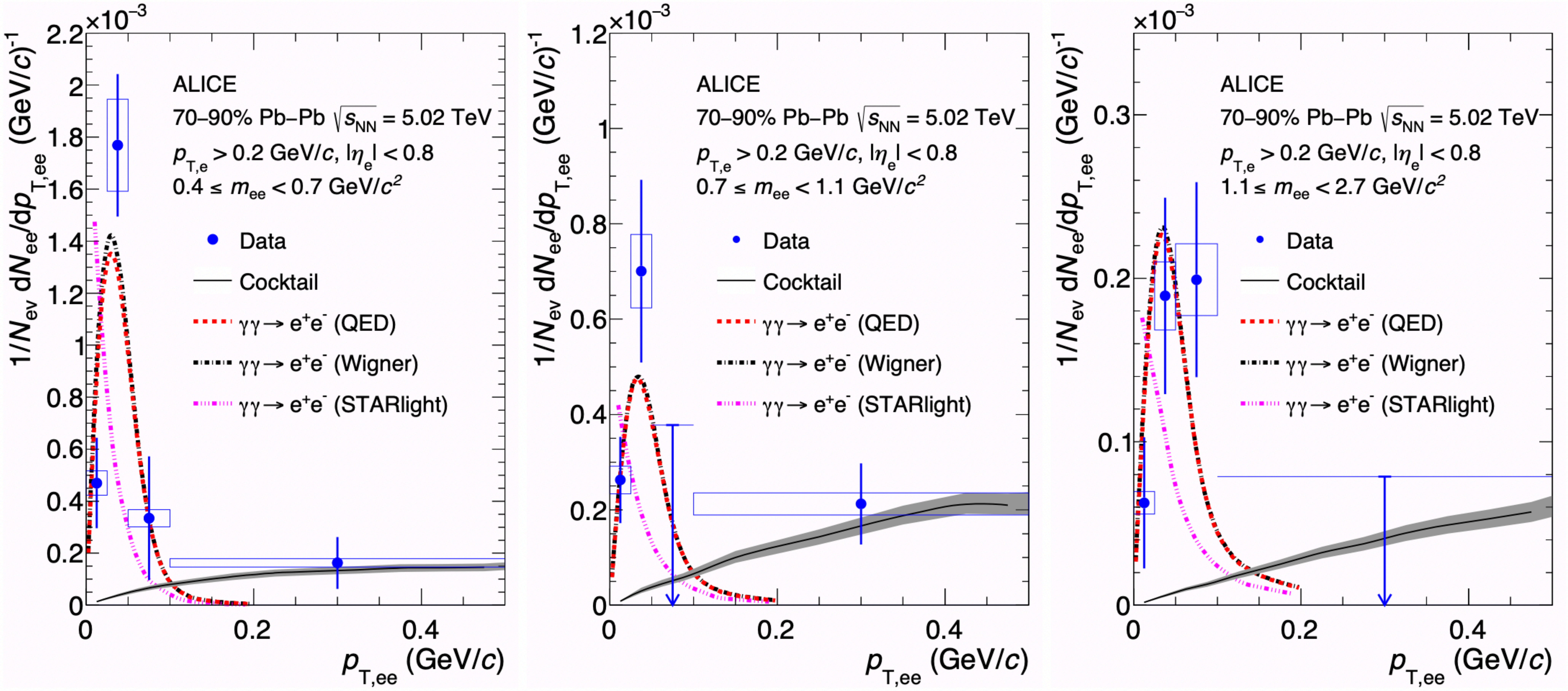




γγ→ee production in non-UPC events

ALICE, arXiv:2204.11732

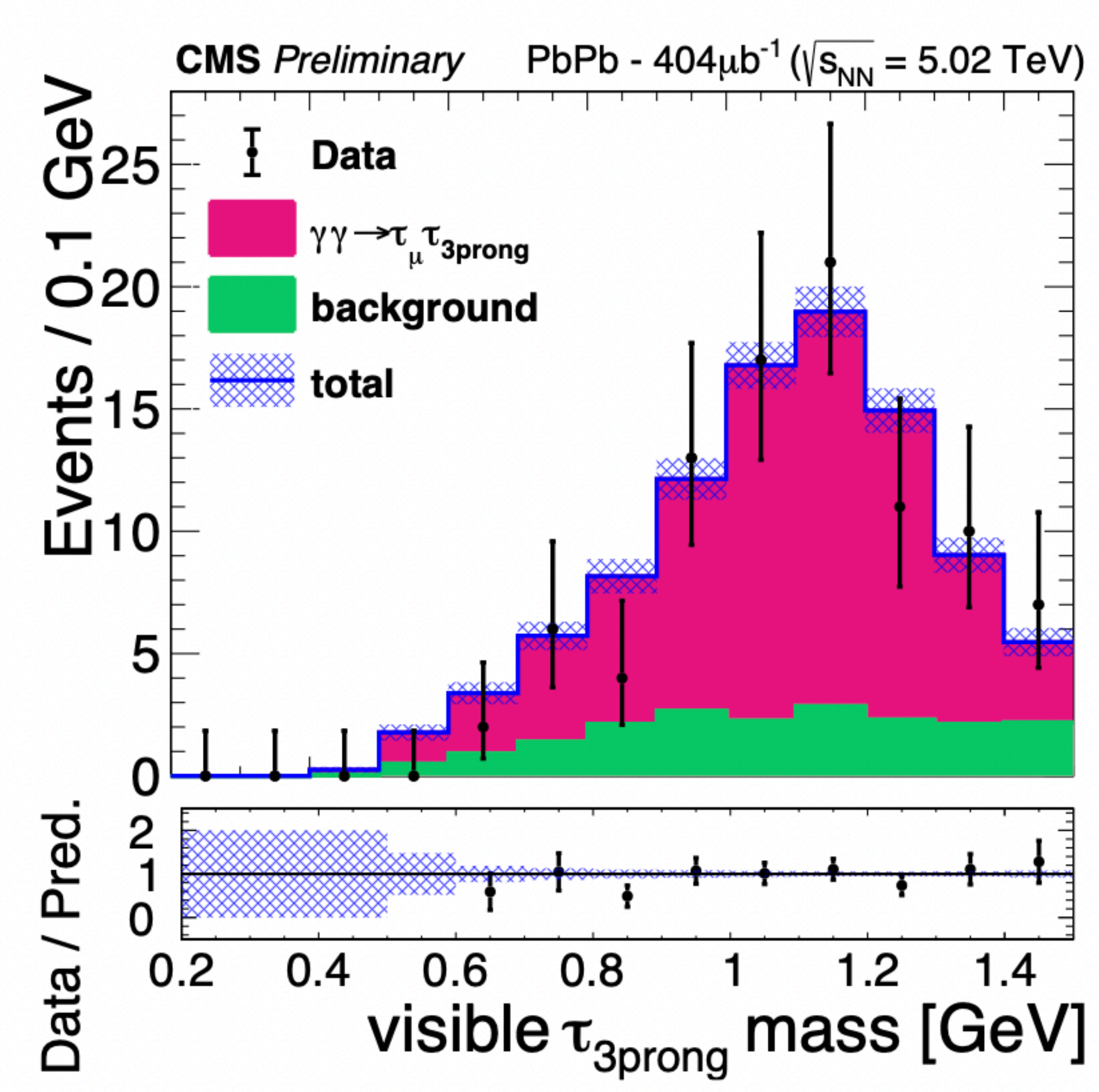
- ALICE exploits low-mass γγ→ee production in (semi-)peripheral collisions

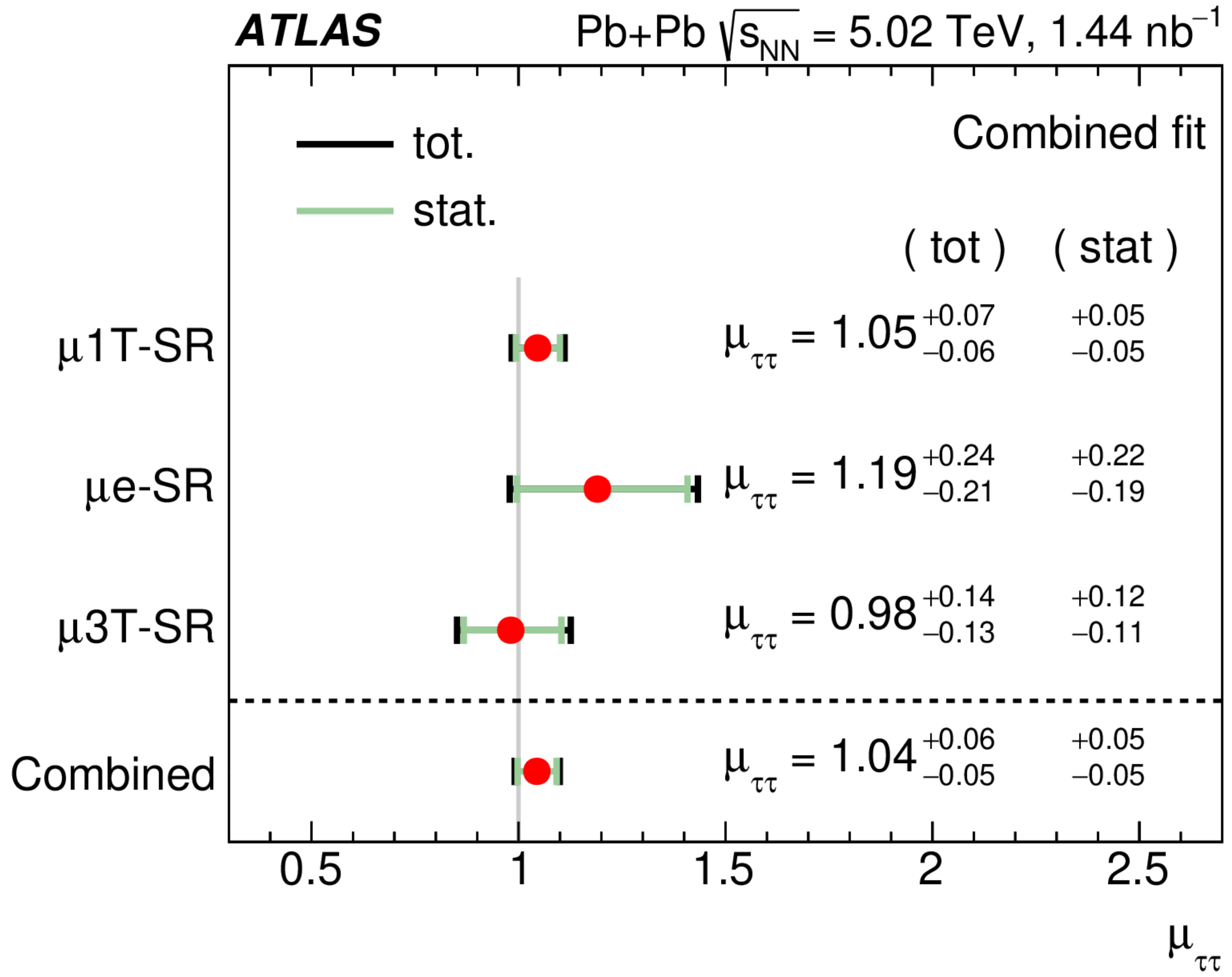


ATLAS: arXiv:2204.13478
CMS: CMS-PAS-HIN-21-009

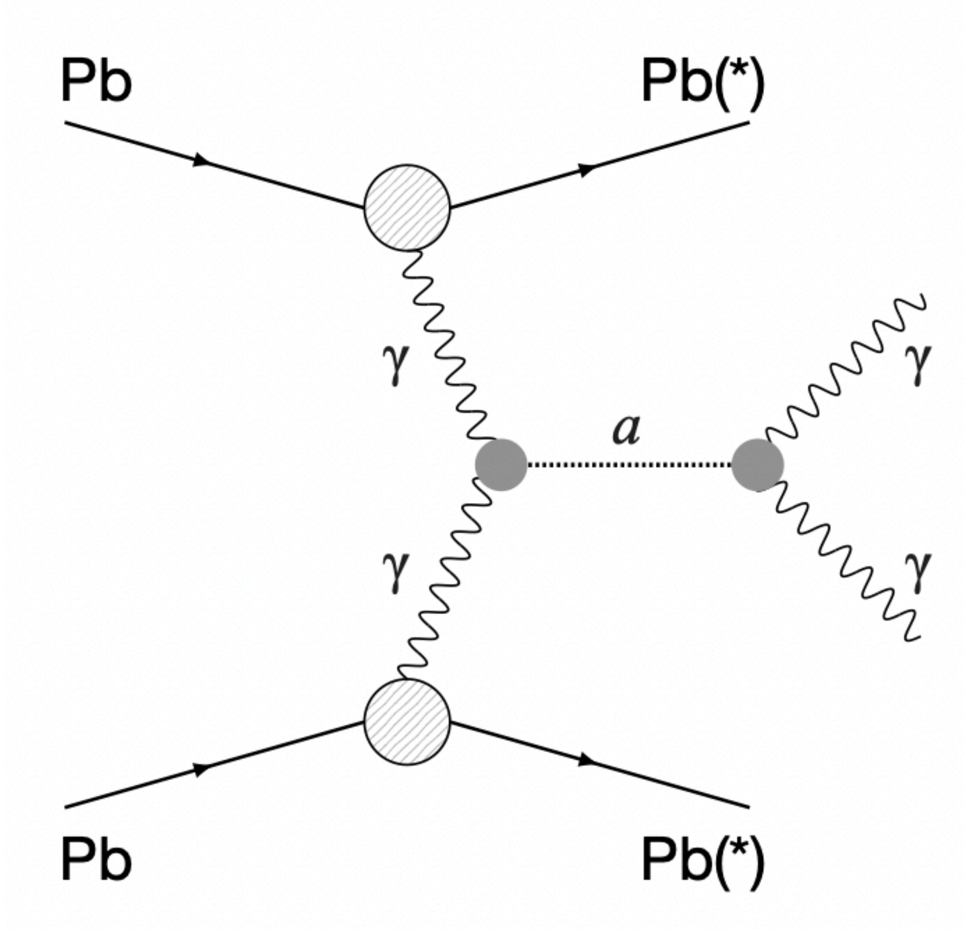
$\gamma\gamma \rightarrow \tau\tau$ production in Pb+Pb UPC

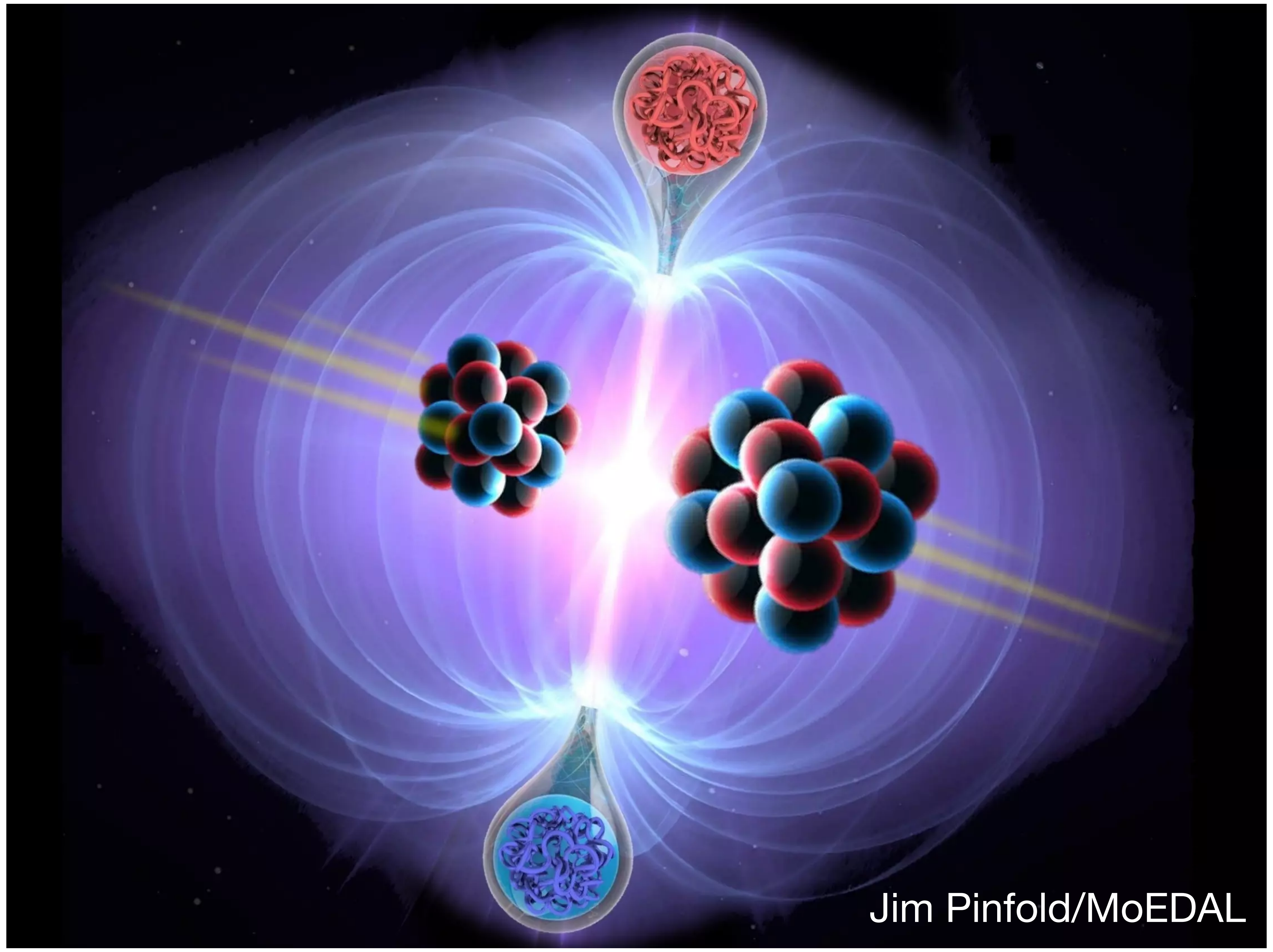
- $\gamma\gamma \rightarrow \tau\tau$ process observed for the first time in hadron collisions
  - Targeting **μ+3prong** decays (CMS) or **μ+3prong**, **μ+1prong** and **μ+e** (ATLAS)
  - CMS: fiducial cross section measured with 16% rel. precision (2015 data)
  - ATLAS: signal strength measured with **5%** rel. precision (2018 data)





(III) BSM photon-photon interactions





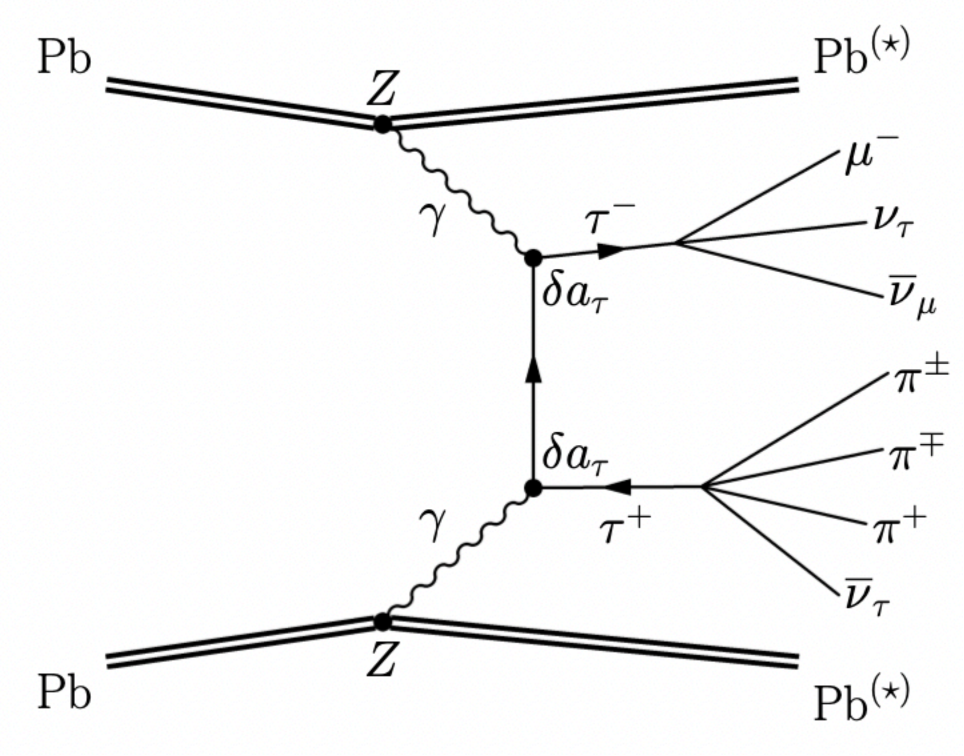
Tau anomalous magnetic moment

- **a_{tau} = (g_{tau}-2)/2** poorly constrained experimentally; can be sensitive to BSM
- Interest in measuring a_{tau} at the LHC revisited recently

ELSEVIER
Physics Letters B
Volume 271, Issues 1–2, 14 November 1991, Pages 256-260

The possibility of using a large heavy-ion collider for measuring the electromagnetic properties of the tau lepton ☆

F. del Aguila [a, b], F. Cornet [c, b], J.I. Illana [b]



ELSEVIER
Physics Letters B
Volume 809, 10 October 2020, 135682

Anomalous electromagnetic moments of τ lepton in $\gamma\gamma \to \tau^+\tau^-$ reaction in Pb+Pb collisions at the LHC

Mateusz Dyndał [a], Mariola Kłusek-Gawenda [b], Antoni Szczurek [b, 1], Matthias Schott [c]

PHYSICAL REVIEW D **102,** 113008 (2020)

New physics and tau $g-2$ using LHC heavy ion collisions

Lydia Beresford[1,*] and Jesse Liu[1,2,†]
[1]*Department of Physics, University of Oxford, Oxford OX1 3RH, United Kingdom*
[2]*Department of Physics, University of Chicago, Chicago, Illinois 60637, USA*

(Received 1 November 2019; revised 5 April 2020; accepted 16 November 2020; published 22 December 2020)

The anomalous magnetic moment of the tau lepton $a_\tau = (g_\tau - 2)/2$ strikingly evades measurement but is highly sensitive to new physics such as compositeness or supersymmetry. We propose using ultraperipheral heavy ion collisions at the LHC to probe modified magnetic δa_τ and electric dipole moments δd_τ. We design a suite of analyses with signatures comprising one electron/muon plus track(s), leveraging the exceptionally clean photon fusion $\gamma\gamma \to \tau\tau$ events to reconstruct both leptonic and hadronic tau decays sensitive to $\delta a_\tau, \delta d_\tau$. Assuming 10% systematic uncertainties, the current 2 nb^{-1} lead-lead dataset could already provide constraints of $-0.0080 < a_\tau < 0.0046$ at 68% C.L. This surpasses 15-year-old lepton collider precision by a factor of 3 while opening novel avenues to new physics.

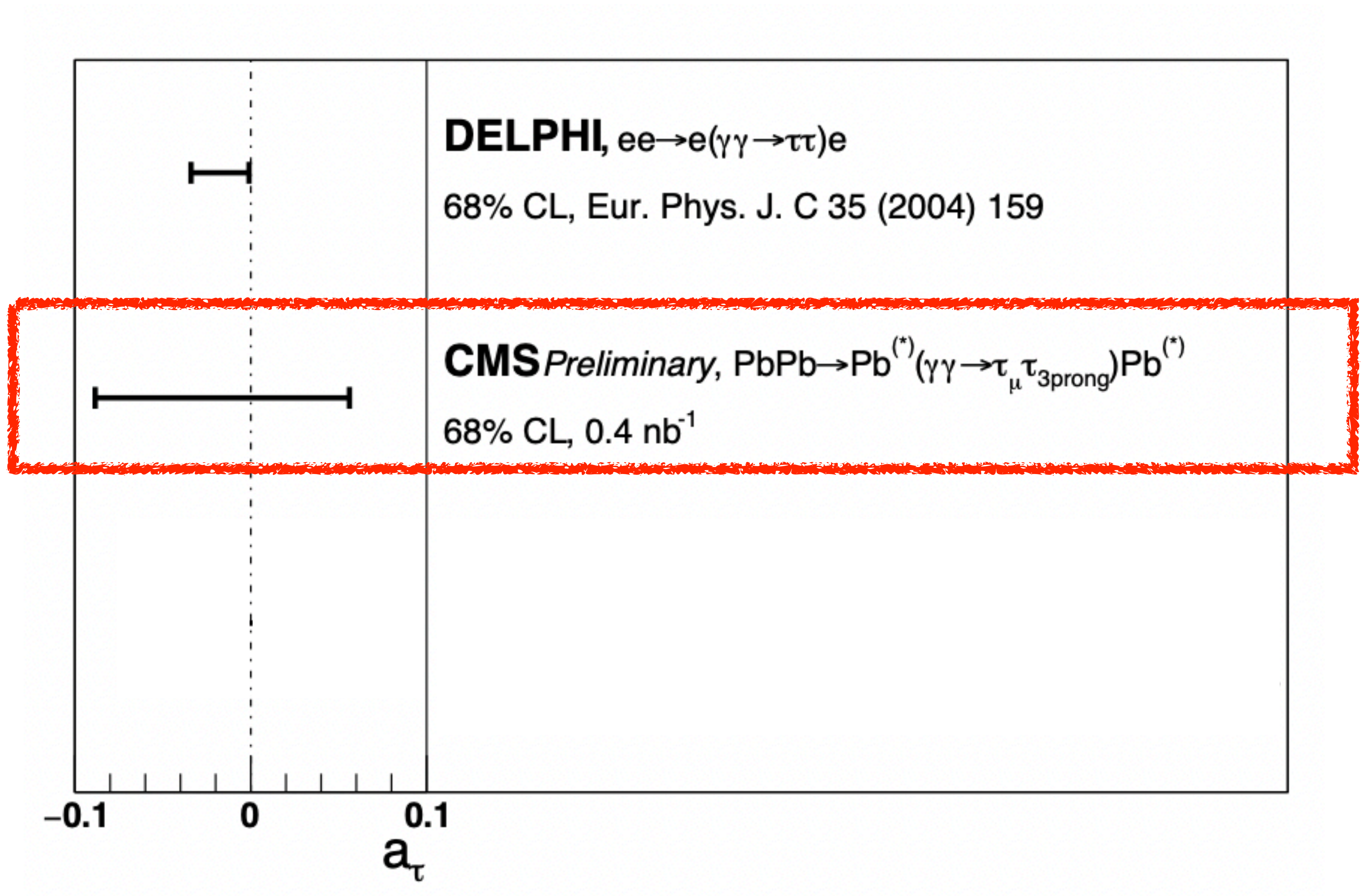
DOI: 10.1103/PhysRevD.102.113008

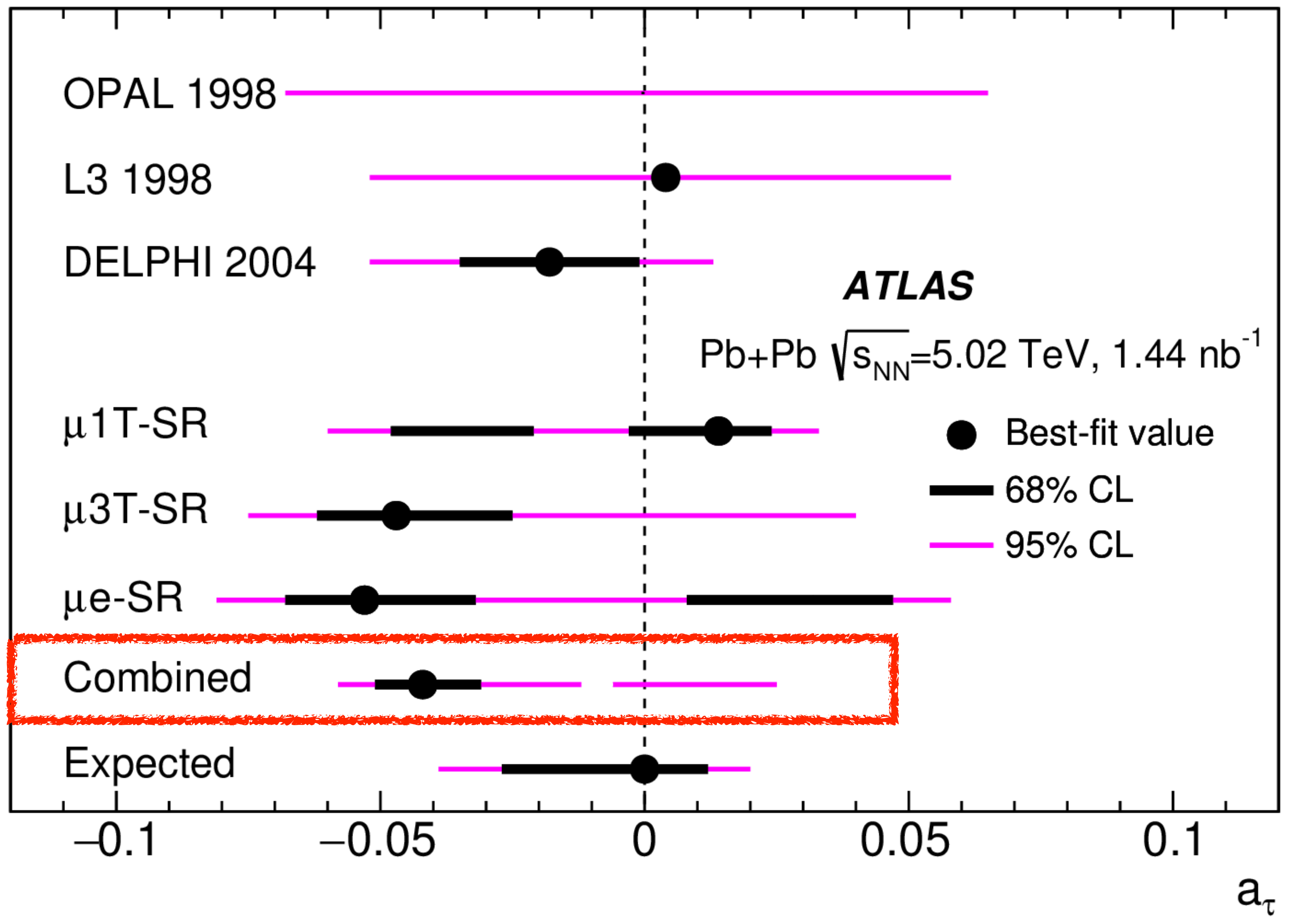
Constraints on tau anomalous magnetic moment

ATLAS: arXiv:2204.13478

CMS: CMS-PAS-HIN-21-009

- Both ATLAS and CMS provide their first constraints on a_{tau}
- ATLAS precision (stat.-dominated) competitive with DELPHI@LEP (PDG) limits
  - Excellent prospects for LHC Run 3 & beyond



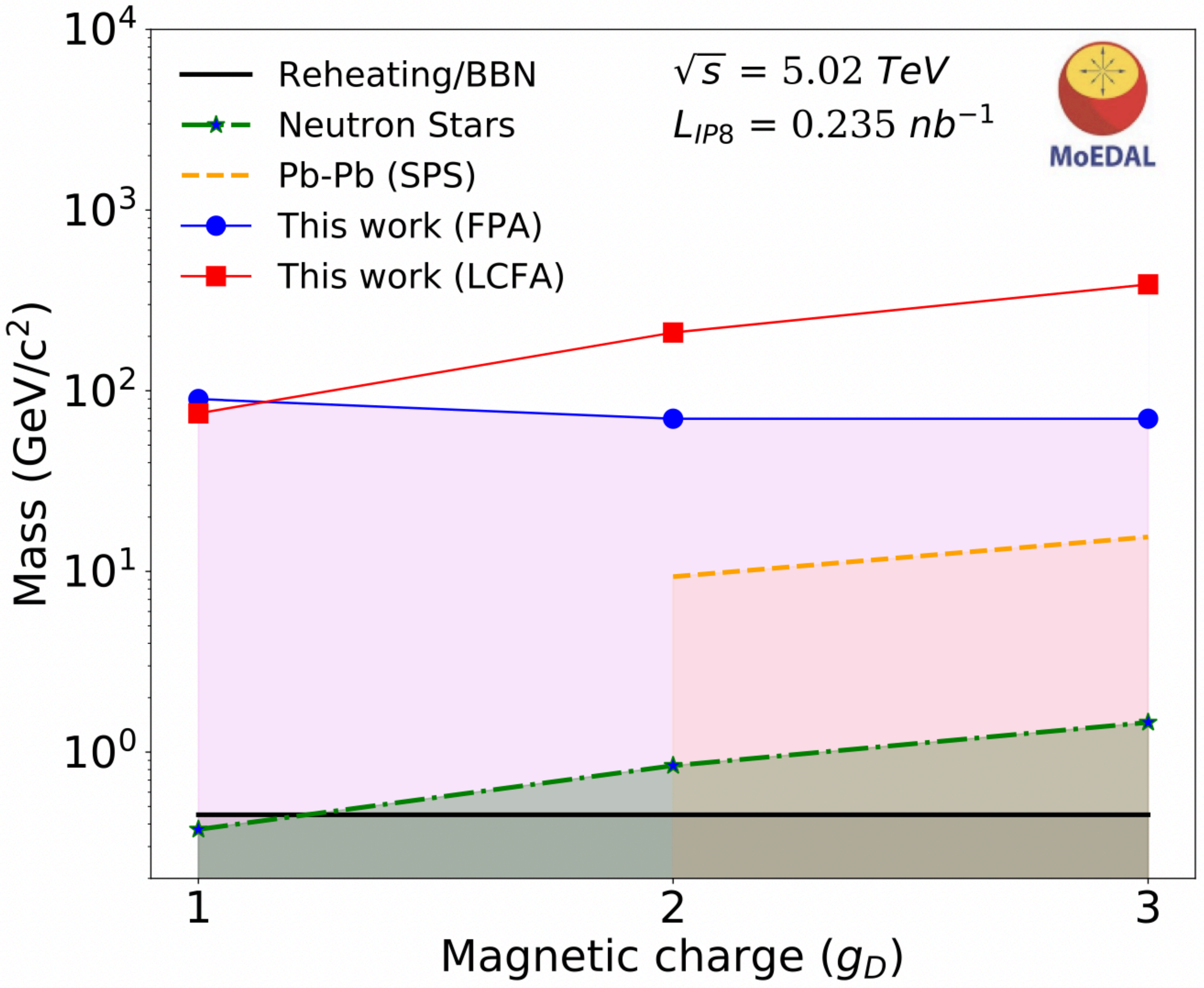


Magnetic monopoles via the Schwinger production

MoEDAL, Nature 602 (2022) 7895, 63-67

- Recent MoEDAL search
  - Exposure of Monopole Trapping Detector in 0.235 nb^{-1} of Pb+Pb in 2018
  - Limits on monopoles of charge **1 – 3 g_D** and masses up to **75 GeV**

- First direct search sensitive to monopoles that are not point-like, based on non-perturbative calculation of monopole production cross section



Summary

- Rich physics programme of ultraperipheral collisions at the LHC

- Coherent vector meson photo-production
  - Abundant rate, down to the most central collisions!

- Interesting opportunities to further explore photo-nuclear interactions
  - Unique environment to test the collective phenomena in small systems
  - dijet production -> potential to constrain nPDFs, small-x gluon tomography
  - …

- HI ultraperipheral collisions are excellent QED and BSM laboratories
  - Tau g-2 constrained using LHC UPC data with precision compatible with LEP (PDG)
  - Clean way to search for BSM particles that couple to photons

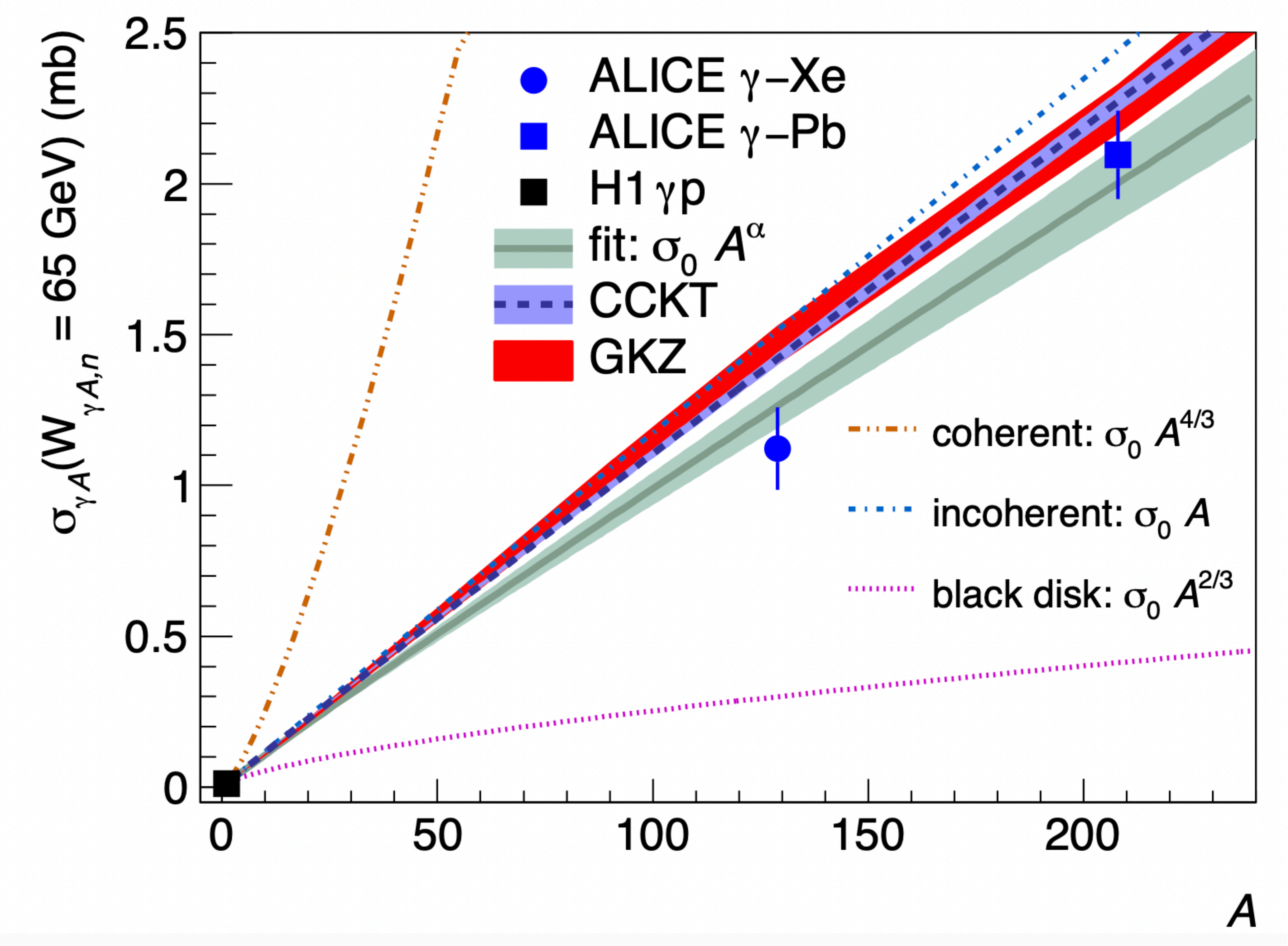
Backup

Coherent ρ^0 cross section in UPC

ALICE: PLB 820 (2021) 136481

- Measurement with Pb and Xe collisions -> **study of the A dependence**

- Power-law fit: $\alpha = 0.96 \pm 0.02$
  - Below coherent -> Shadowing



Azimuthal anisotropies in γPb

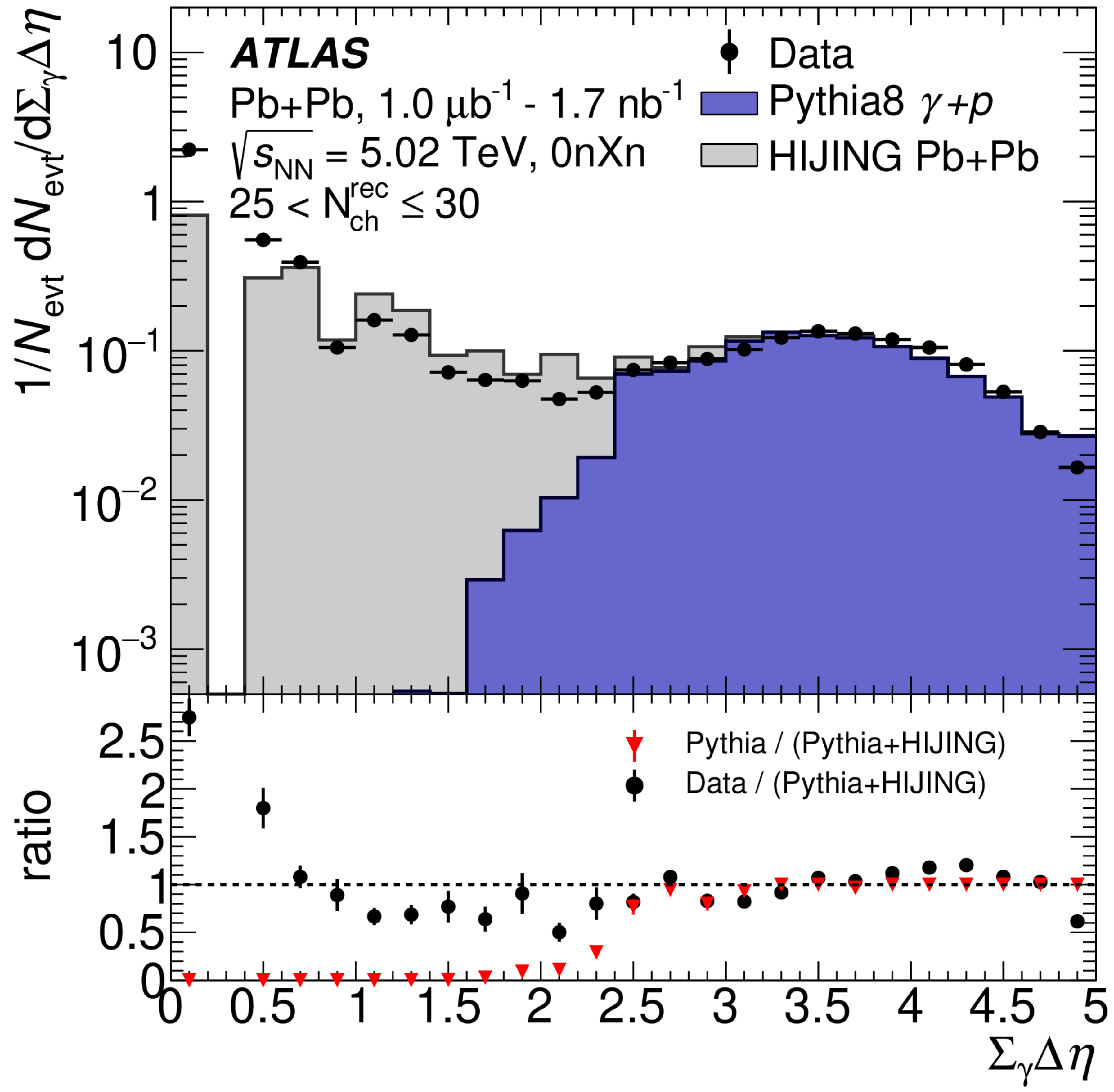
ATLAS, Phys. Rev. C. 104 (2021) 014903

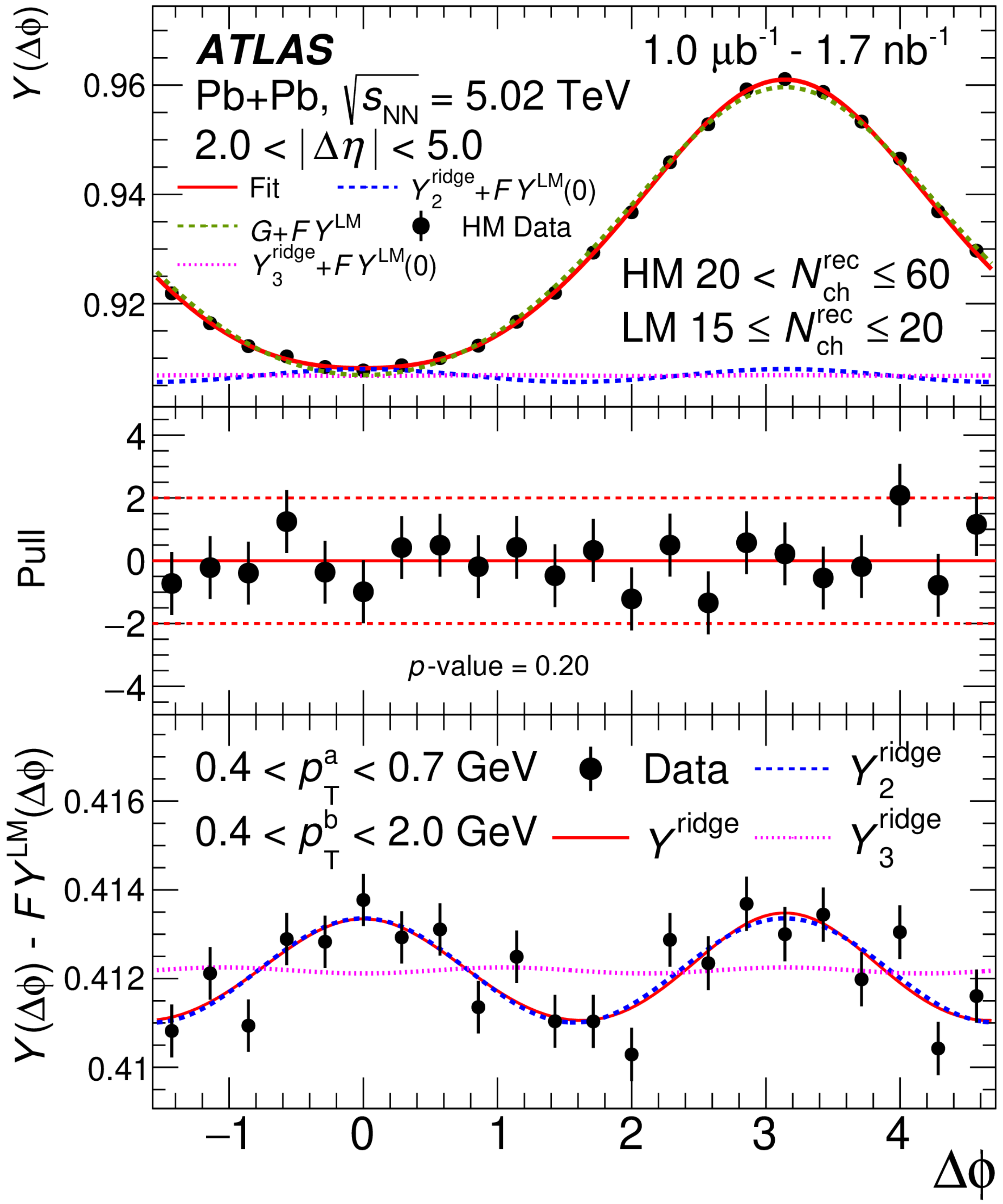
- Measurement done using photonuclear Pb+Pb UPC events

correlation function in LM events

$$Y^{\mathrm{HM}}(\Delta\phi) = FY^{\mathrm{LM}}(\Delta\phi) + G\left\{1 + 2\sum_{n=2}^{4} v_{n,n}\cos(n\Delta\phi)\right\}$$
$$= FY^{\mathrm{LM}}(\Delta\phi) + Y^{\mathrm{ridge}}(\Delta\phi). \quad (1)$$

flow coefficients

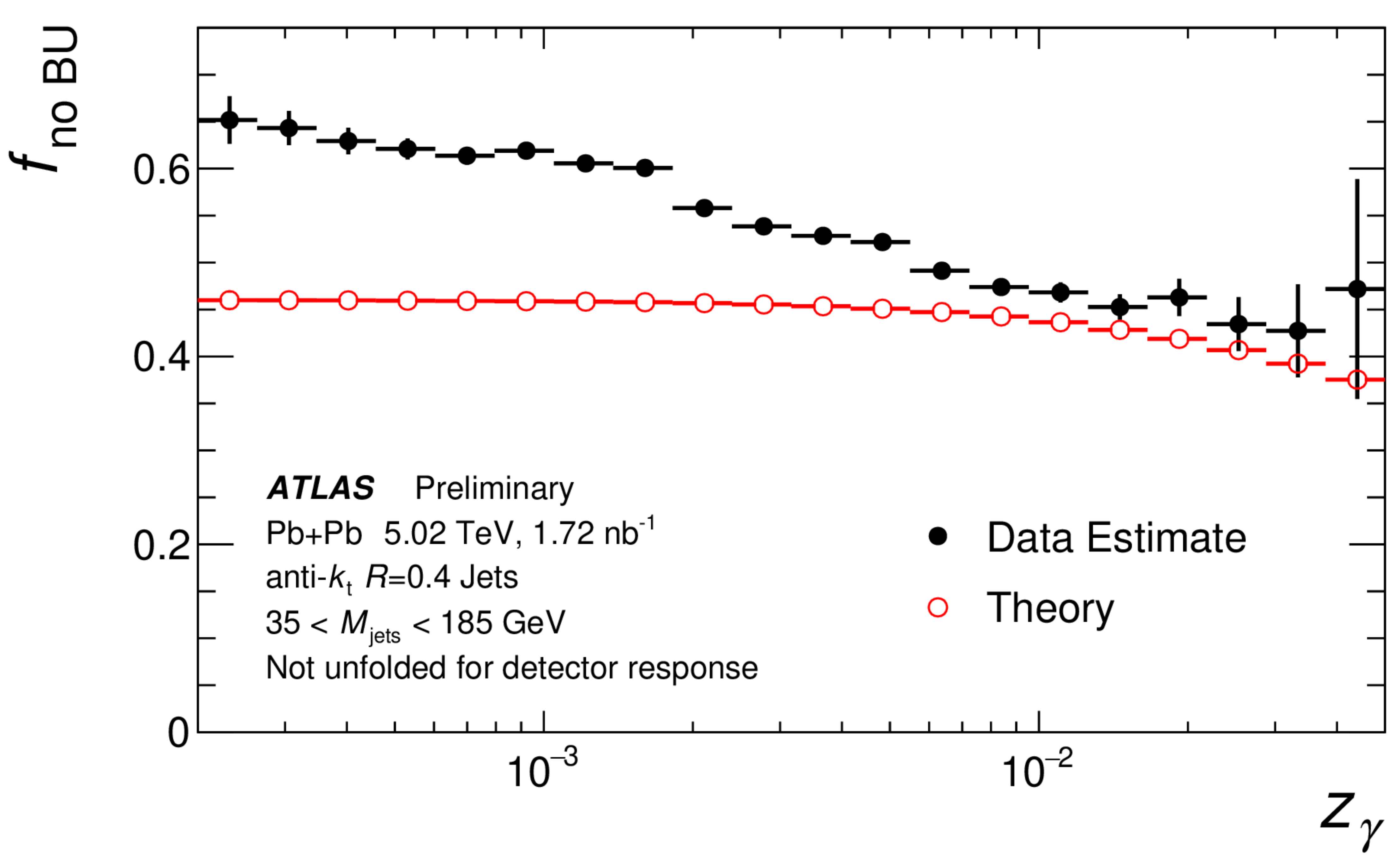


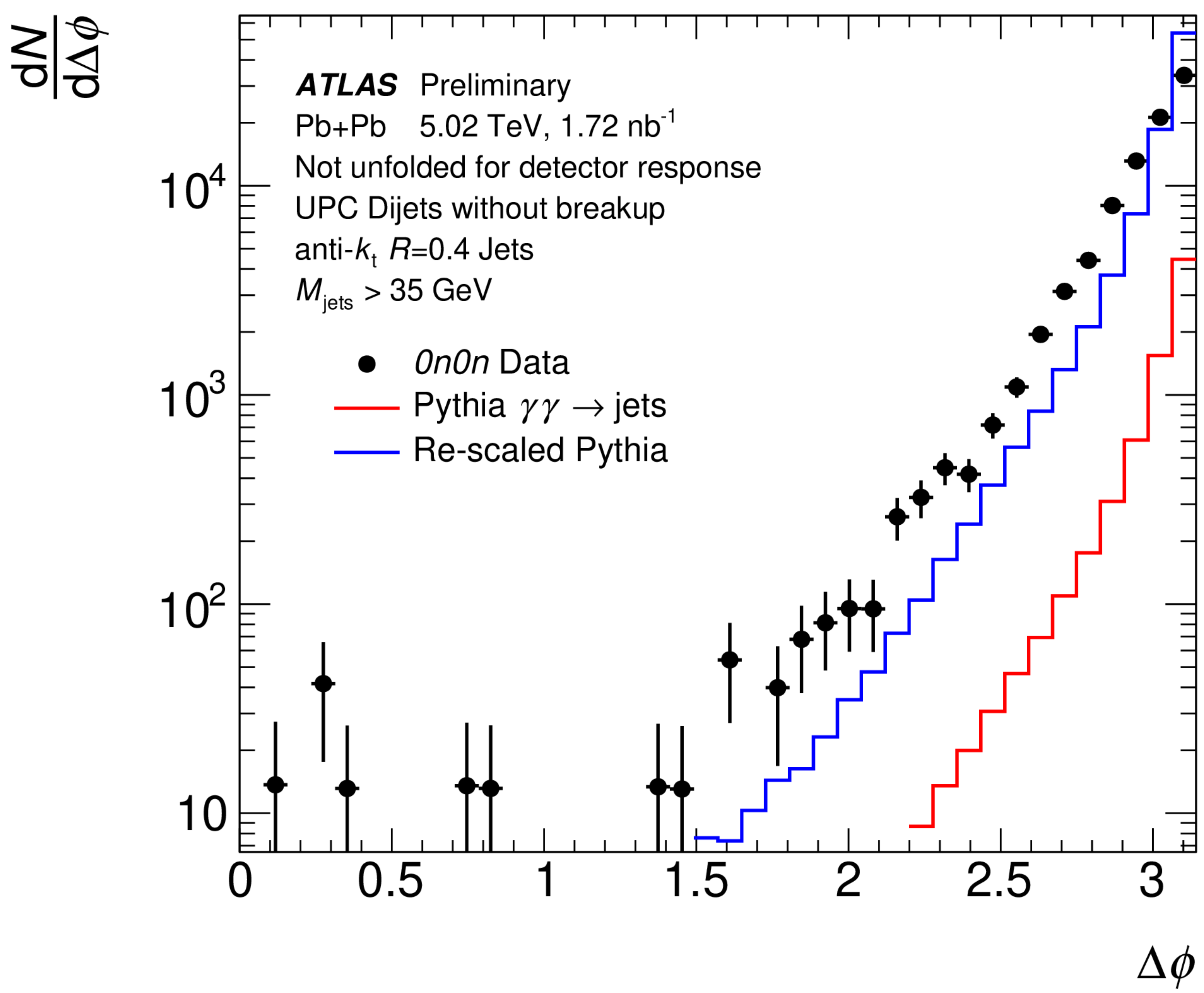


Measurement of photo-nuclear dijet production in Pb+Pb

ATLAS-CONF-2022-021

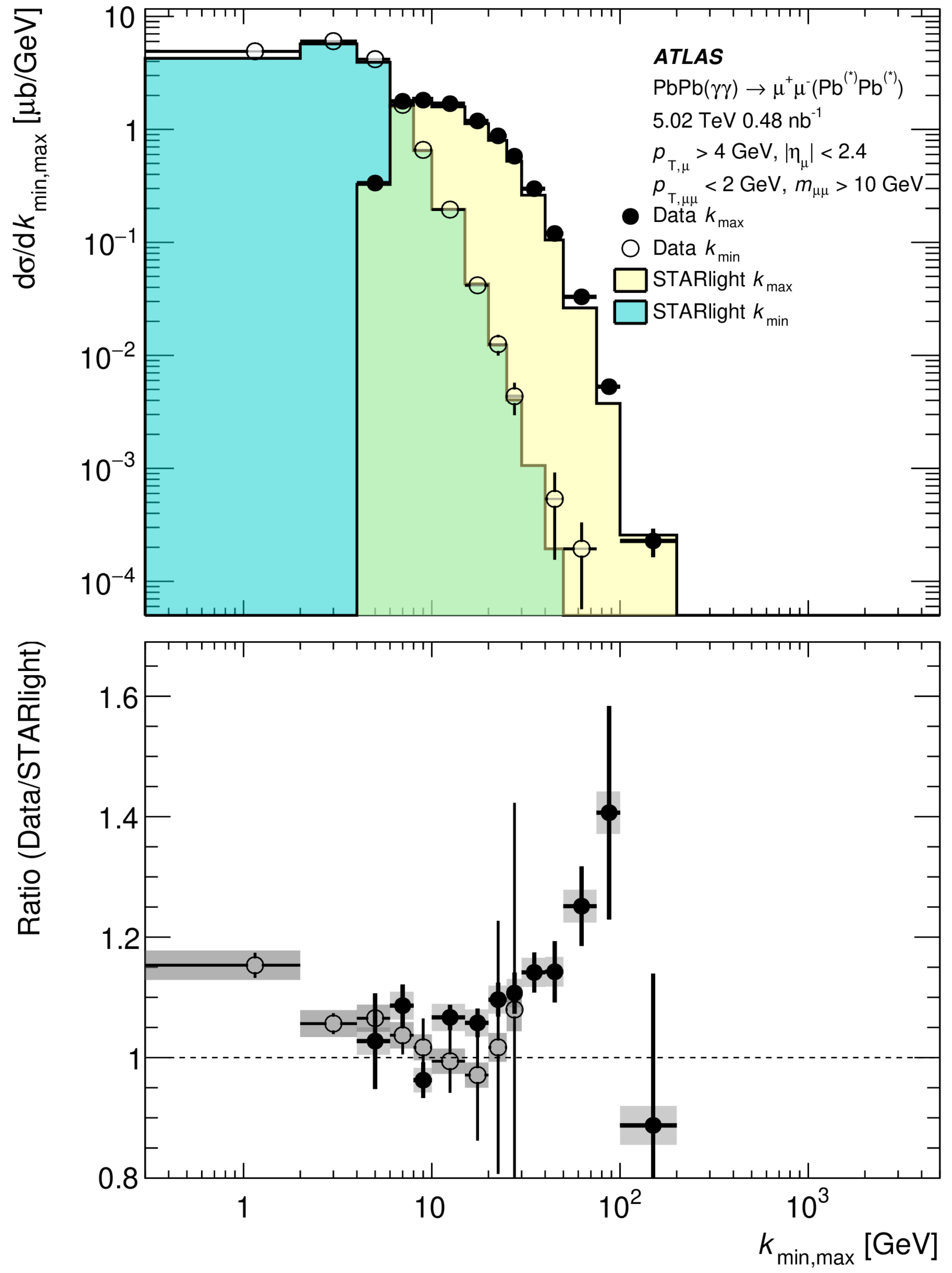
- "No-breakup" fraction is measured by comparing 0nXn and XnXn topologies
  - Provides valuable input for theory calculations
- Observation of exclusive dijet events (0n0n "no-breakup" topology)
  - Likely a mixture of diffractive + photon-photon production mechanisms



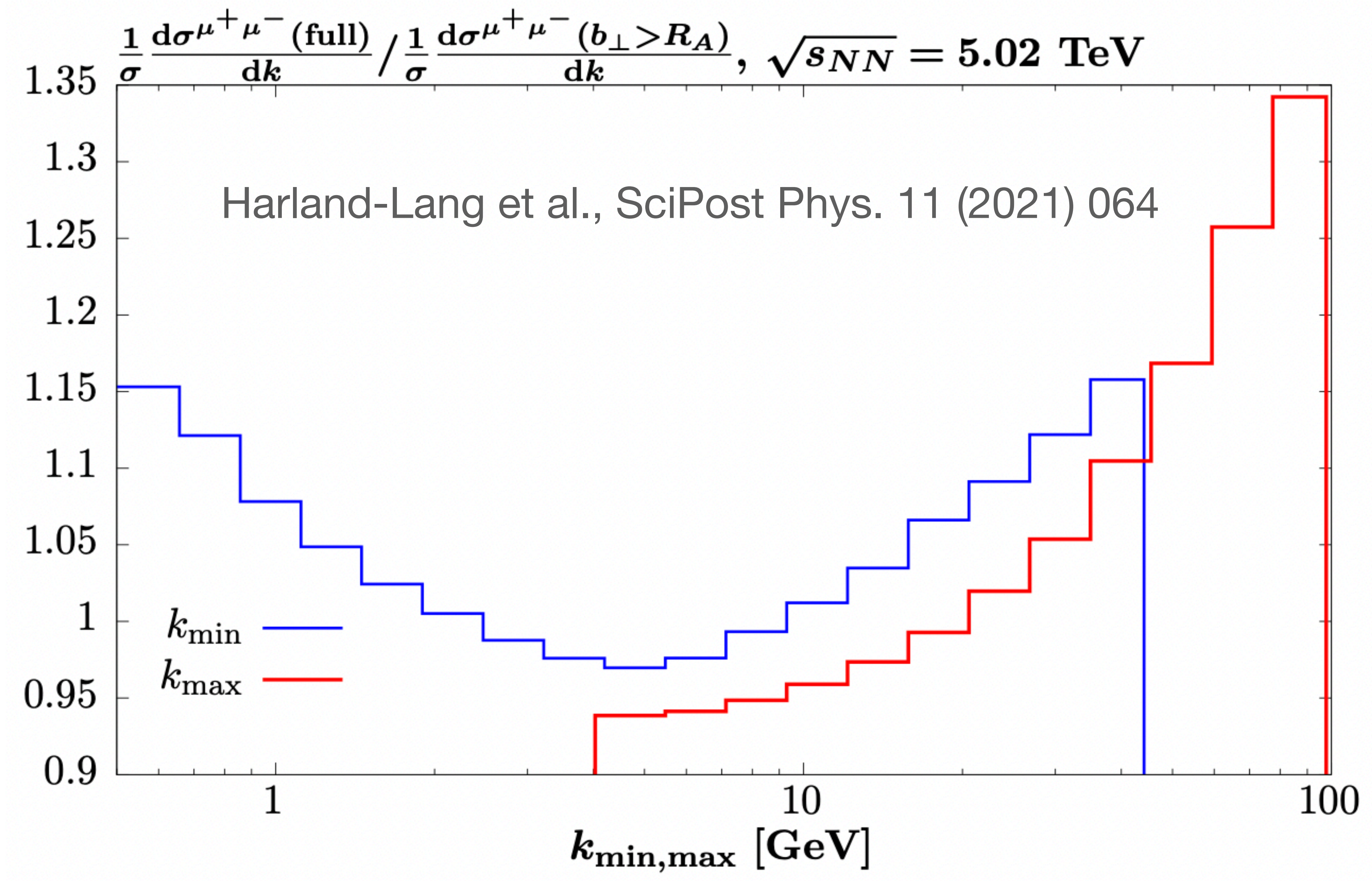


γγ→μμ production in Pb+Pb UPC

ATLAS, Phys. Rev. C 104 (2021) 024906



- μμ mass and rapidity directly relates to the energy distribution of initial photons
  - Confirming issues with (simplified) photon flux modeling in STARlight
  - SuperChic3 implementation largely resolves the issue



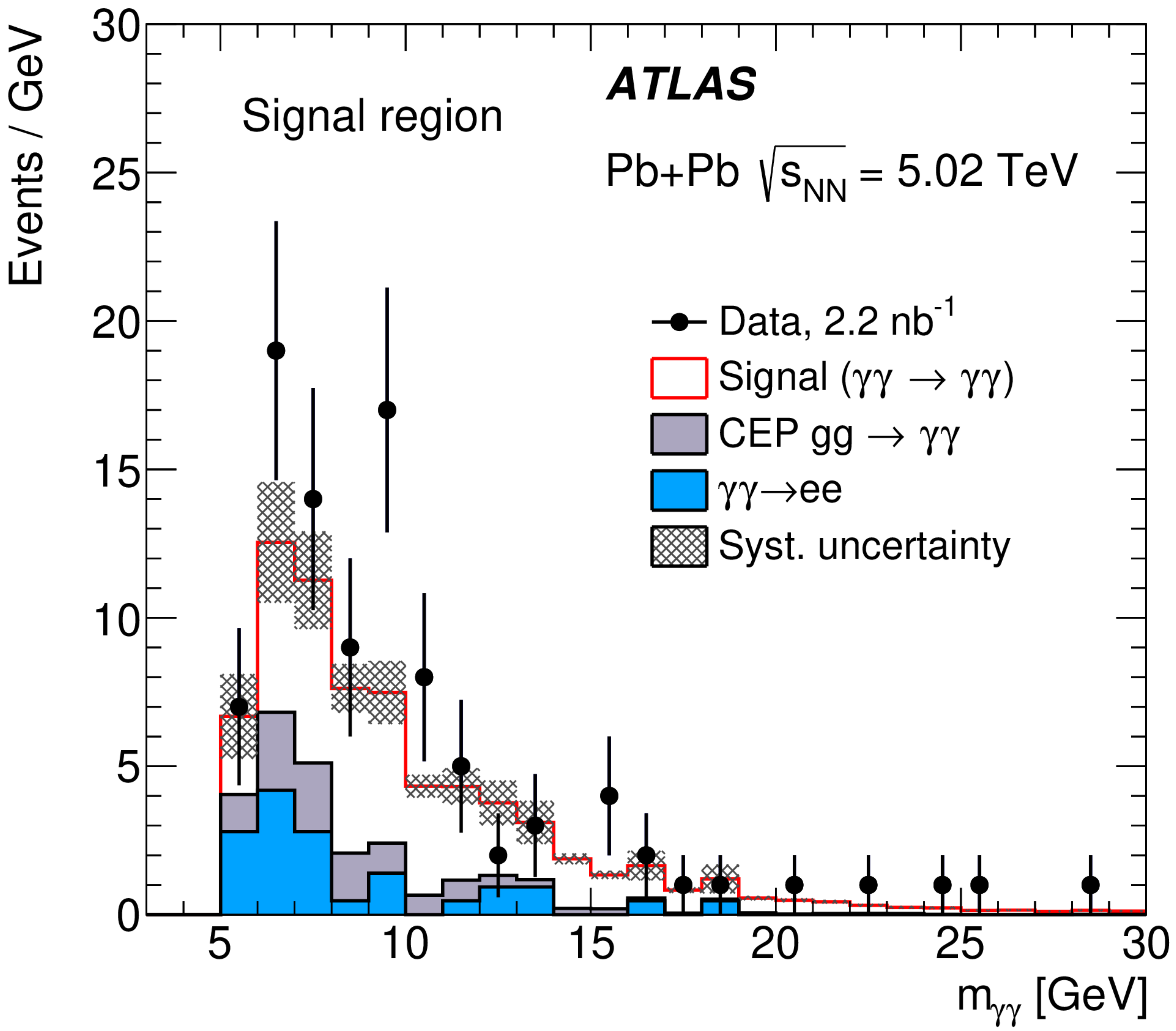
Search for axion-like particles in γγ interactions

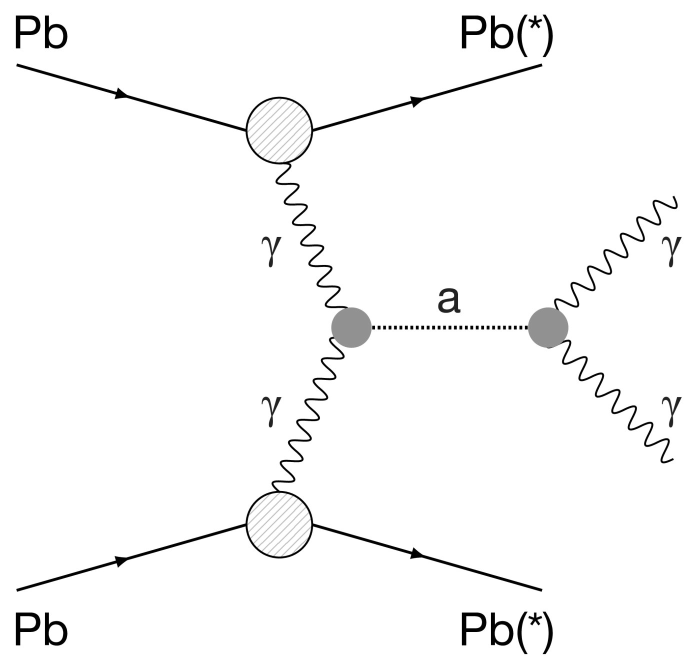
- Light-by-light scattering process signature (γγ→γγ) used to search for ALPs in Pb+Pb collisions
- ATLAS and CMS provide the most stringent limits to date on ALPs for masses in the range **5-100 GeV**

Original idea:
Knapen et al., PRL 118 (2017) 17, 171801

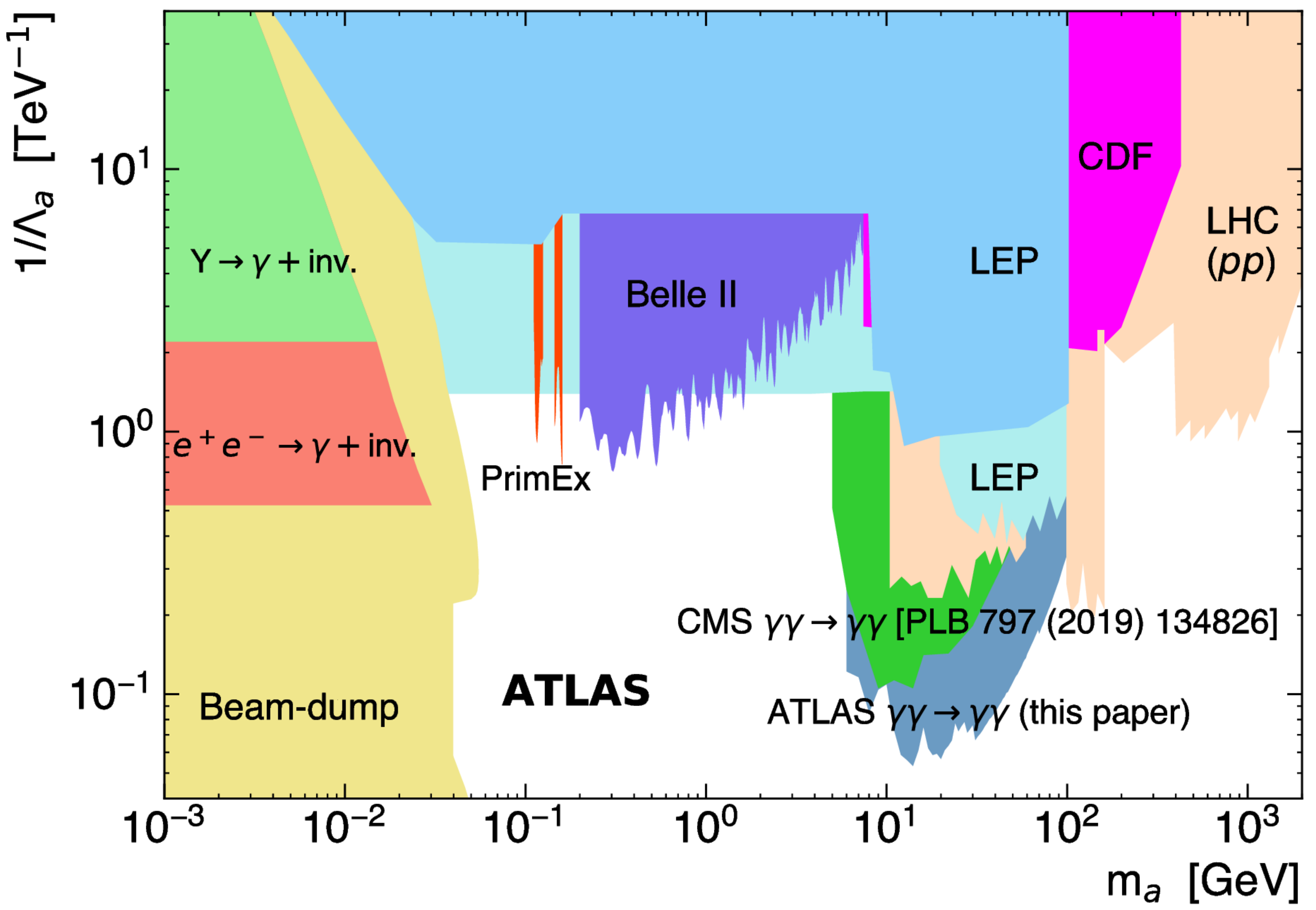
CMS: Phys. Lett. B 797 (2019) 134826

ATLAS: JHEP 03 (2021) 243





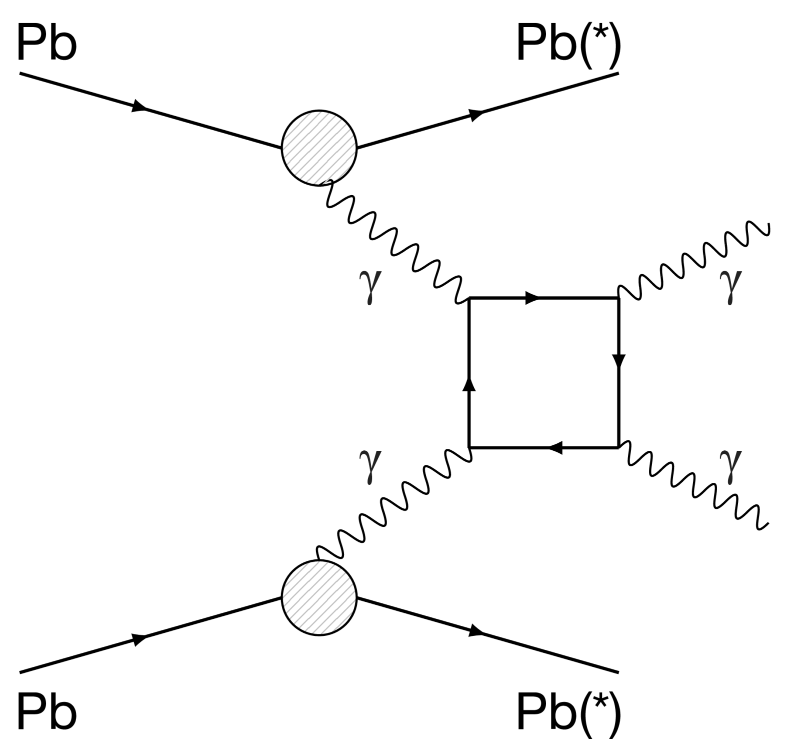
Existing constraints from JHEP 12 (2017) 044

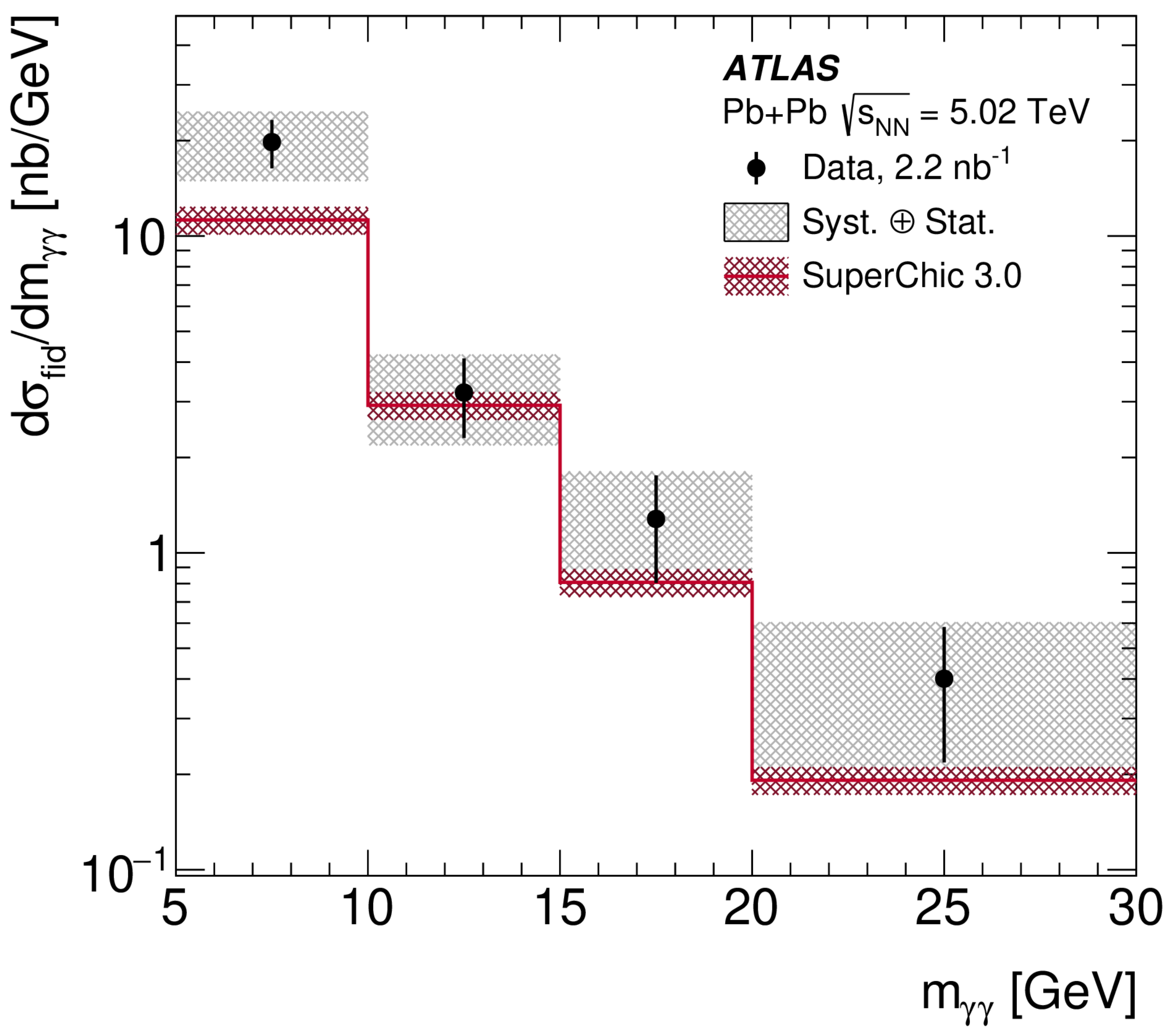


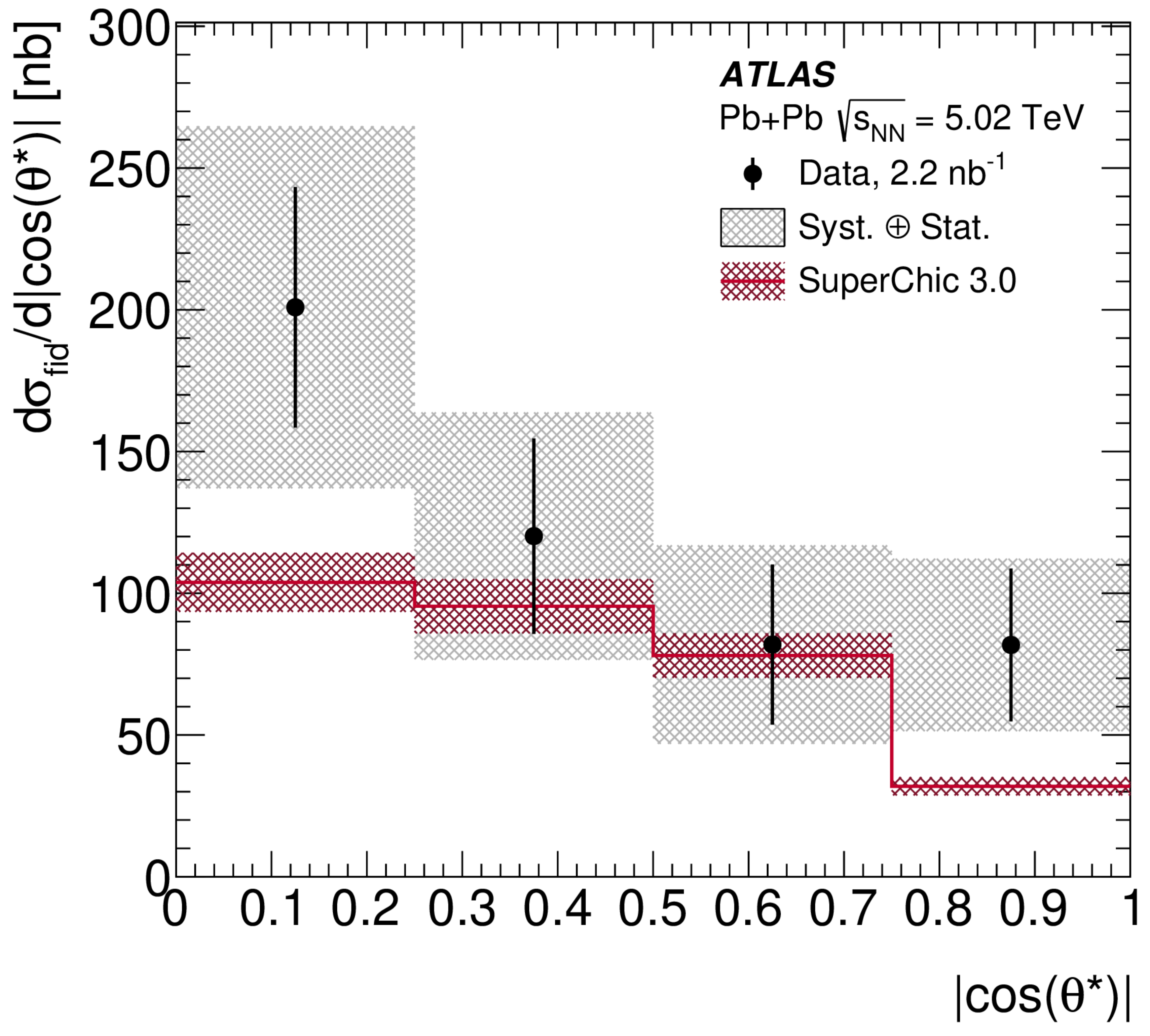
Measurement of light-by-light scattering

ATLAS: JHEP 03 (2021) 243

- Initial CMS/ATLAS evidence/observation for SM γγ→γγ loop process transformed into a more in-depth measurement
  - Measurement of fiducial integrated and differential cross sections

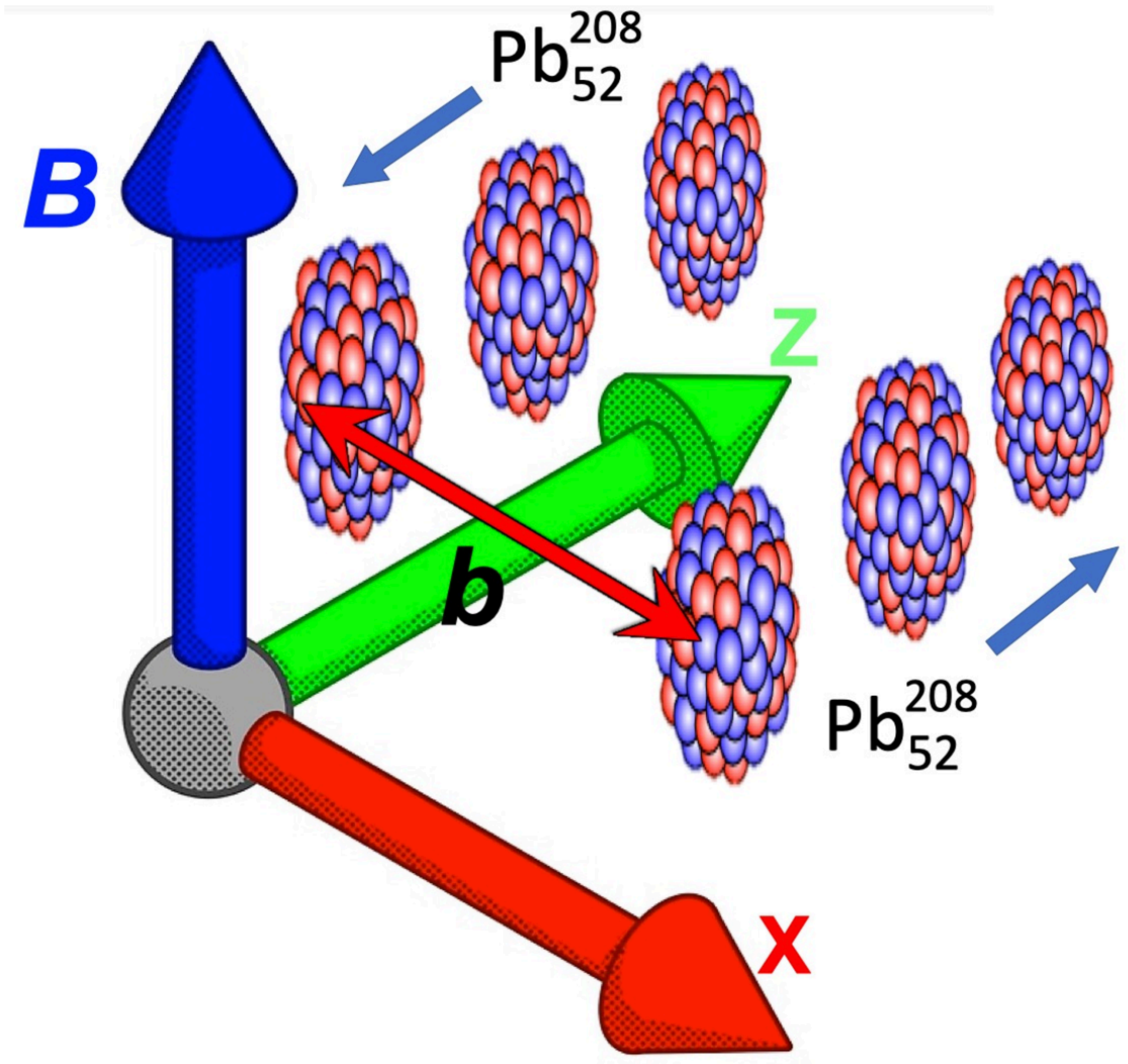






Magnetic monopoles via the Schwinger production

- Schwinger mechanism originally described spontaneous creation of e+e- pairs in presence of an extremely strong electric field
  - Same mechanism can work for monopole pairs in the presence of strong magnetic fields
  - **The strongest fields are generated in ultraperipheral collisions (b~2R)**
  - Advantages over pp monopole searches:
    - Calculations use semiclassical techniques → do not suffer from non-perturbative nature of coupling
    - no exponential suppression ($e^{-4/\alpha} \sim= 10^{-238}$) for finite-sized monopoles*



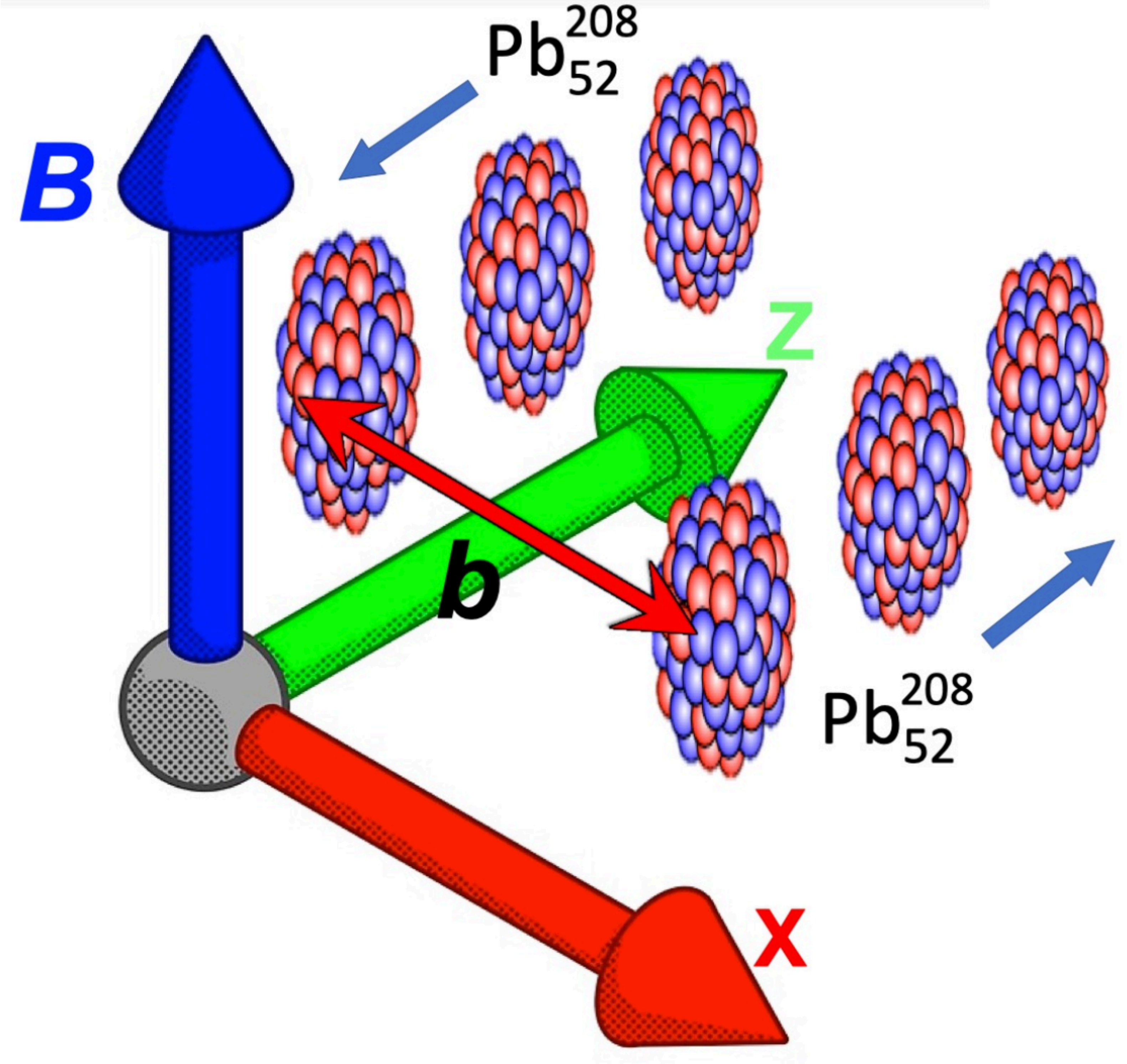
Gould et al., PRD 100, 015041 (2019), PRD 104, 015033 (2021)

Ho & Rajantie, PRD 101, 055003 (2020), PRD 103 (2021) 11, 115033

* Drukier, Nussinov, Phys. Rev. Lett. 49, 102 (1982)

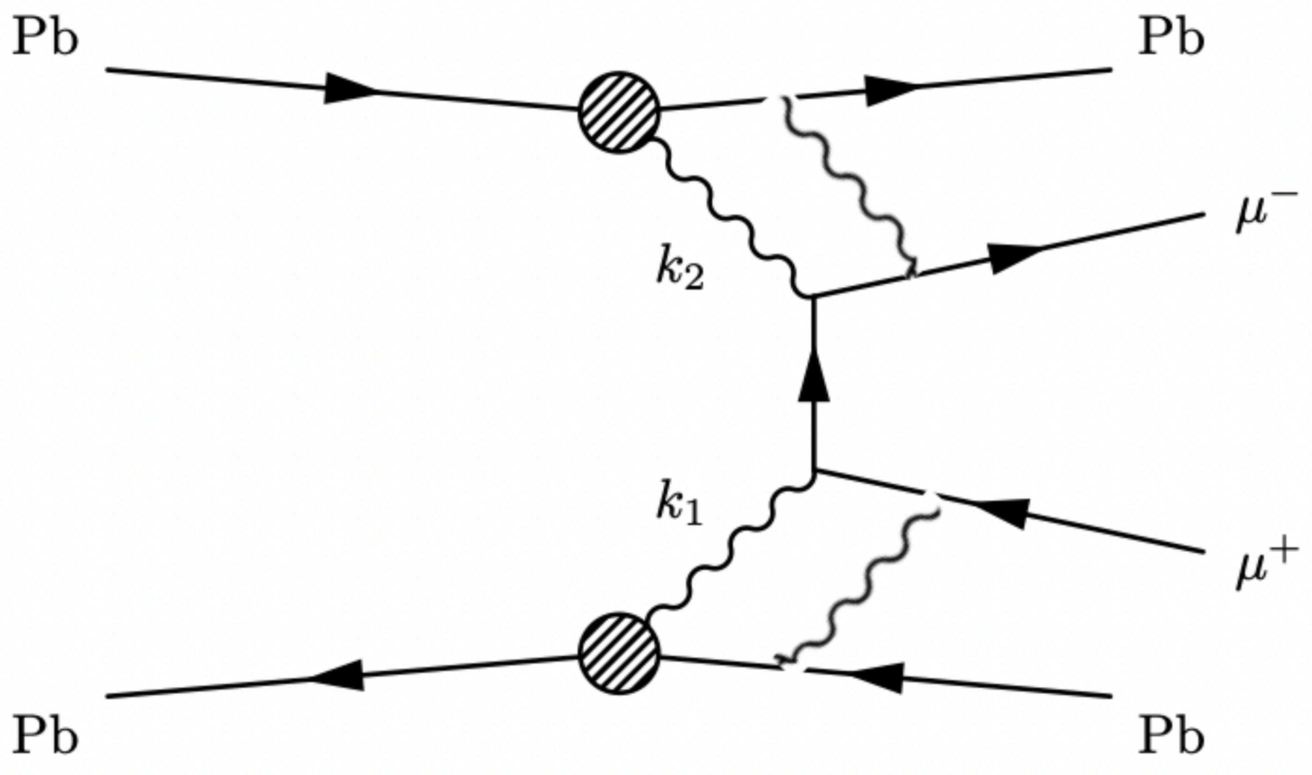
Magnetic monopoles via the Schwinger production

- Two approximations to the magnetic monopole cross-section calculations
  - **FPA (free-particle approximation):**
    space-time dependence of EM field of HI is treated exactly,
    but MM self-interactions are neglected
    (MM self-interactions enhance expected cross sections)
  - **LCFA (locally constant field approximation):**
    space-time dependence of EM field is neglected,
    but MM self-interactions are treated exactly
    (space-time dependence of EM field enhances expected cross sections)
  - Complementary approaches (with uncorrelated uncertainties) leading to conservative results

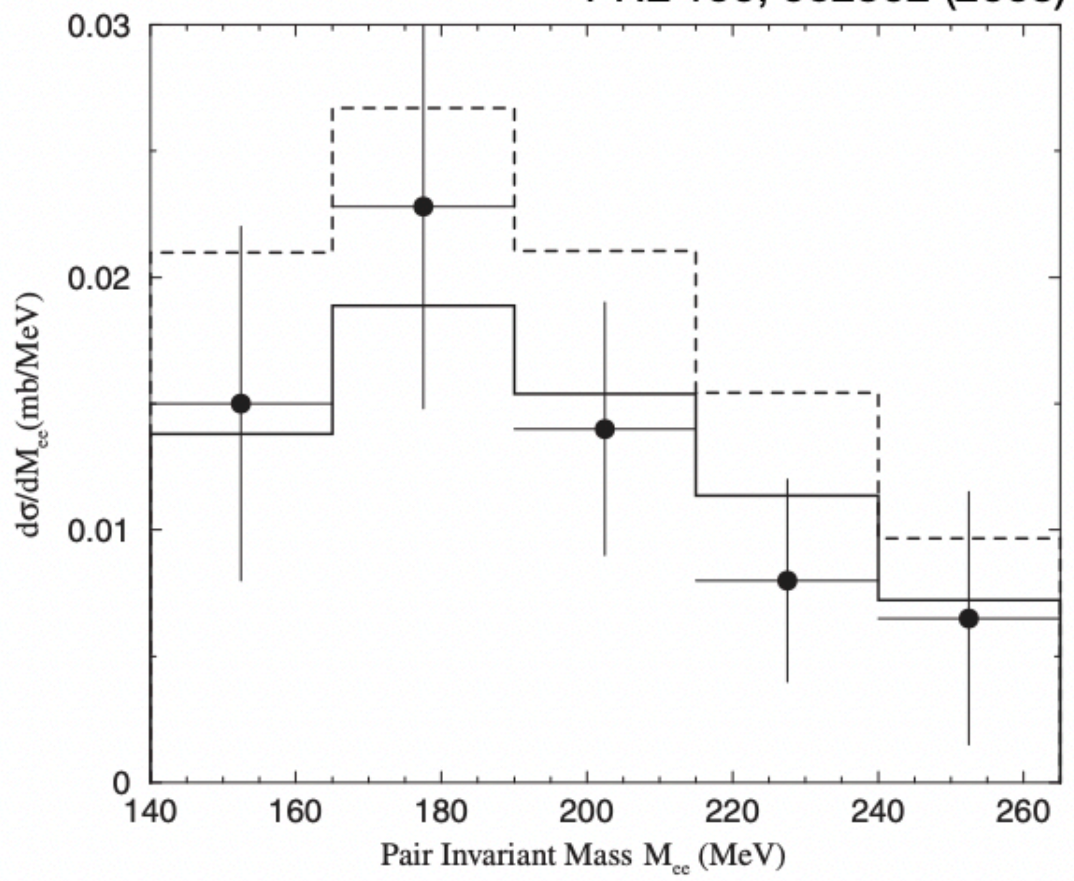


Higher order contributions

From P. Steinberg



PRL 100, 062302 (2008)



Baltz, 2008
~20% reduction in cross sections at low e+e- masses

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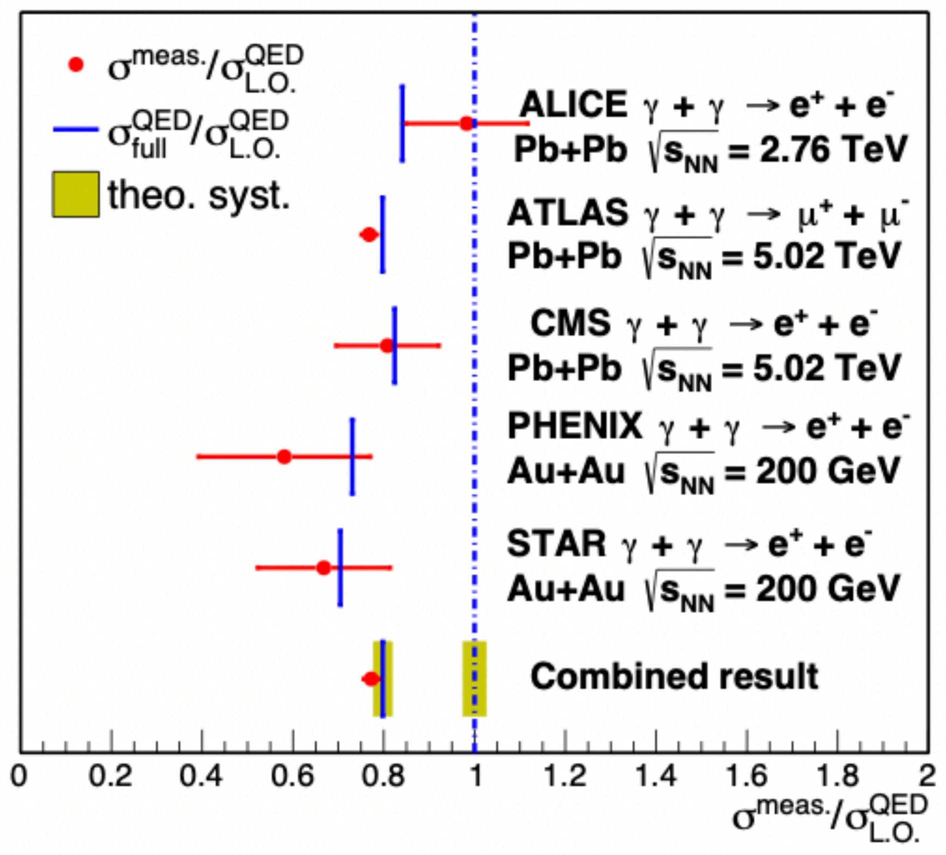

Tang & Zha, 2021
large reductions in all kinematic regions going from LO to HO

HO Coulomb corrections not included in either STARlight or SuperChic:
These corrections qualitatively lower the cross sections,
perhaps up to 20% (e.g. Tang & Zha) compensating for the increase!

However, some disagreement between groups on just how much:
some authors predict impact on muons should be negligible.

May be important for correct fluxes: **watch this space**!