Experimental and phenomenological developments in ultra-peripheral collisions

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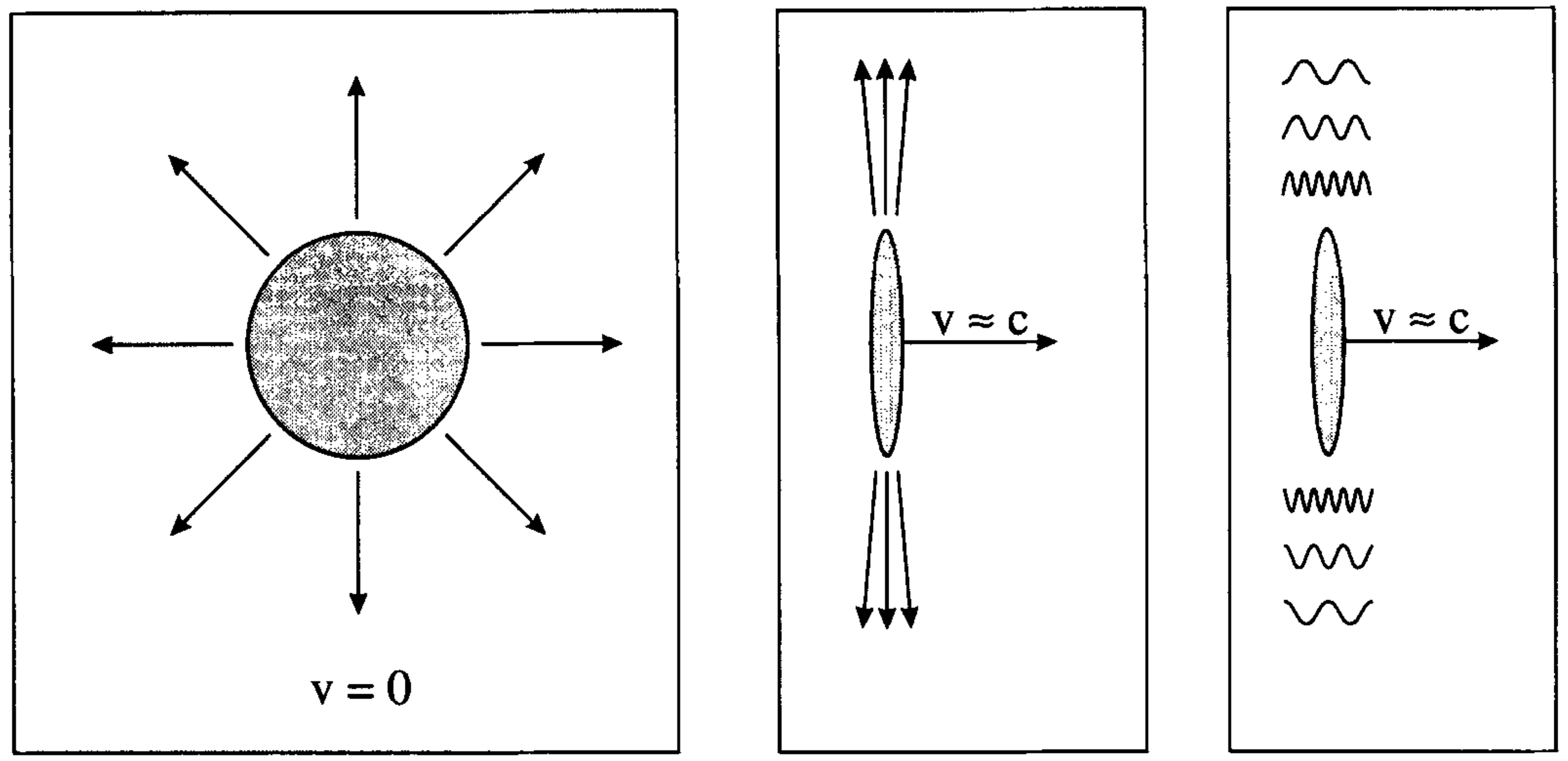
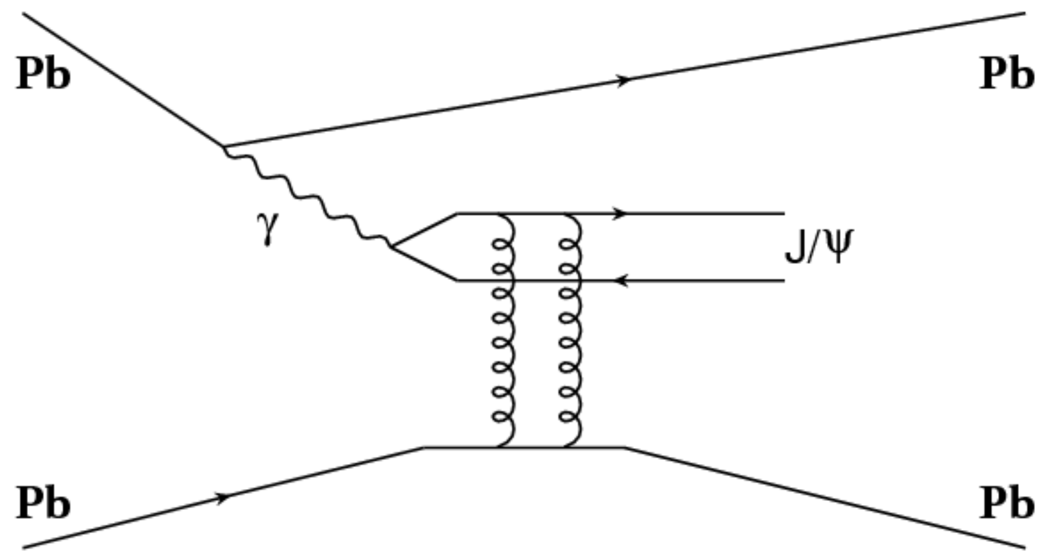
Quark Matter 2022

Quasi-real photons from heavy ions

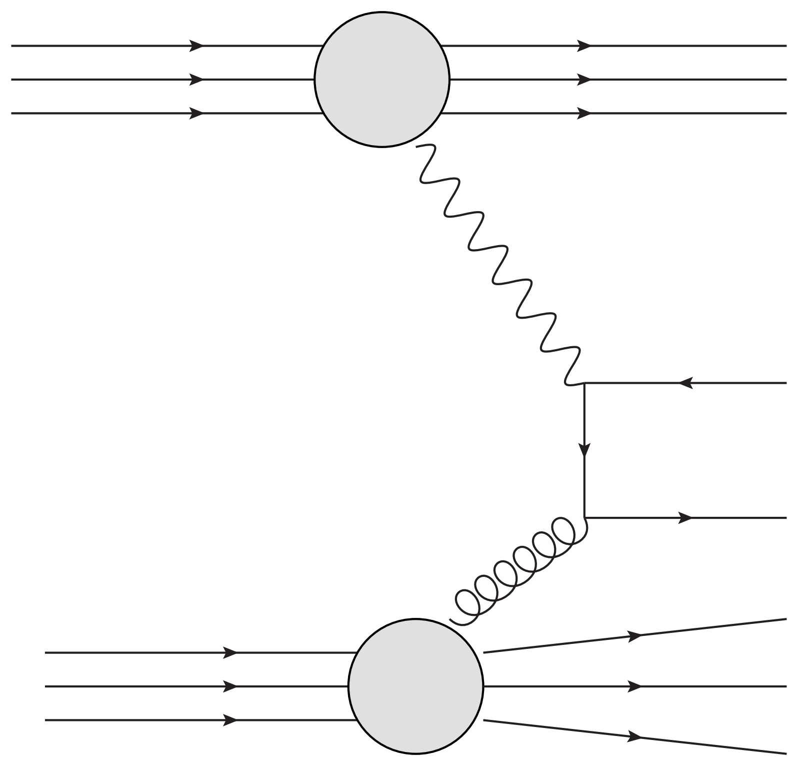
- Boosted nuclei are intense source of quasi-real photons
- **Coherent** photon flux
  - **E_{max} ≲ γ/R ~ 80 GeV** @LHC (**~3 GeV** @RHIC)
  - **Q ~ 1/R ~ 30 MeV** @ LHC/RHIC
  - Each photon flux scales with ~**Z^2**



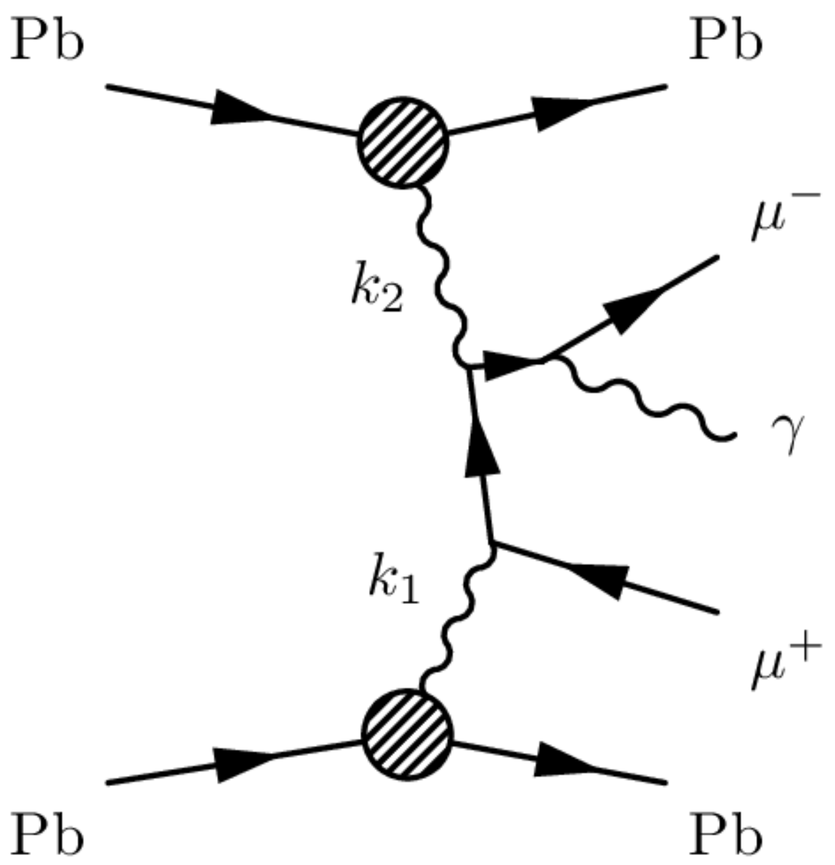
- Various types of interactions possible:



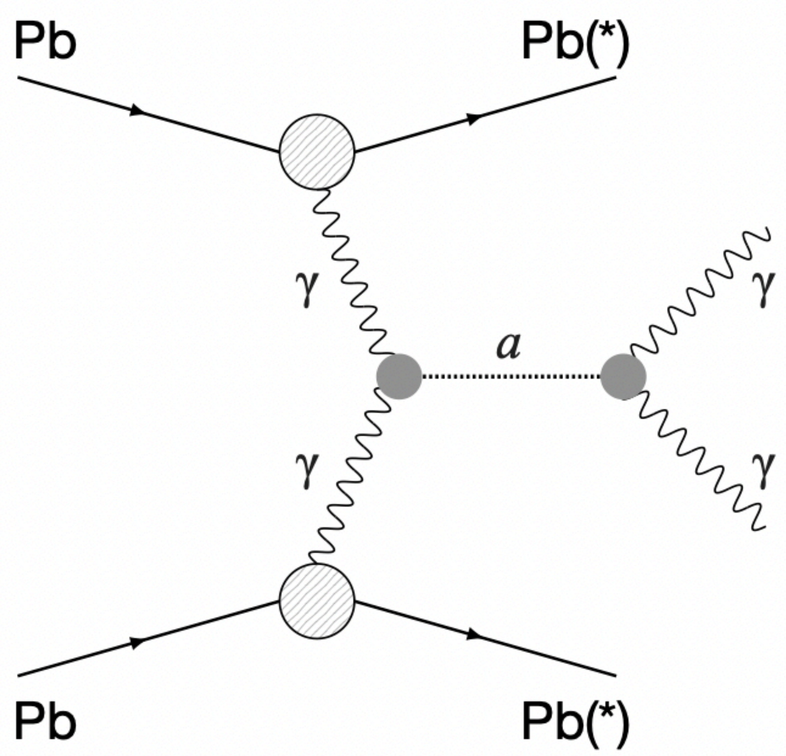
(coherent) **Photo-nuclear**



(Inelastic) **Photo-nuclear**

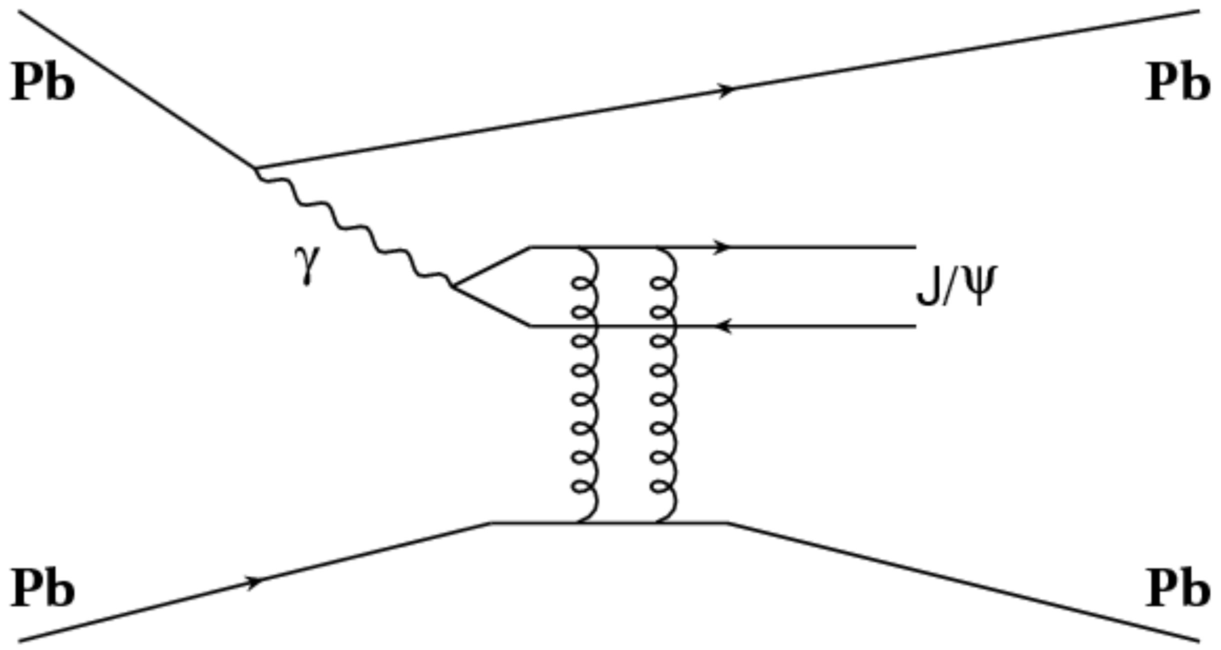


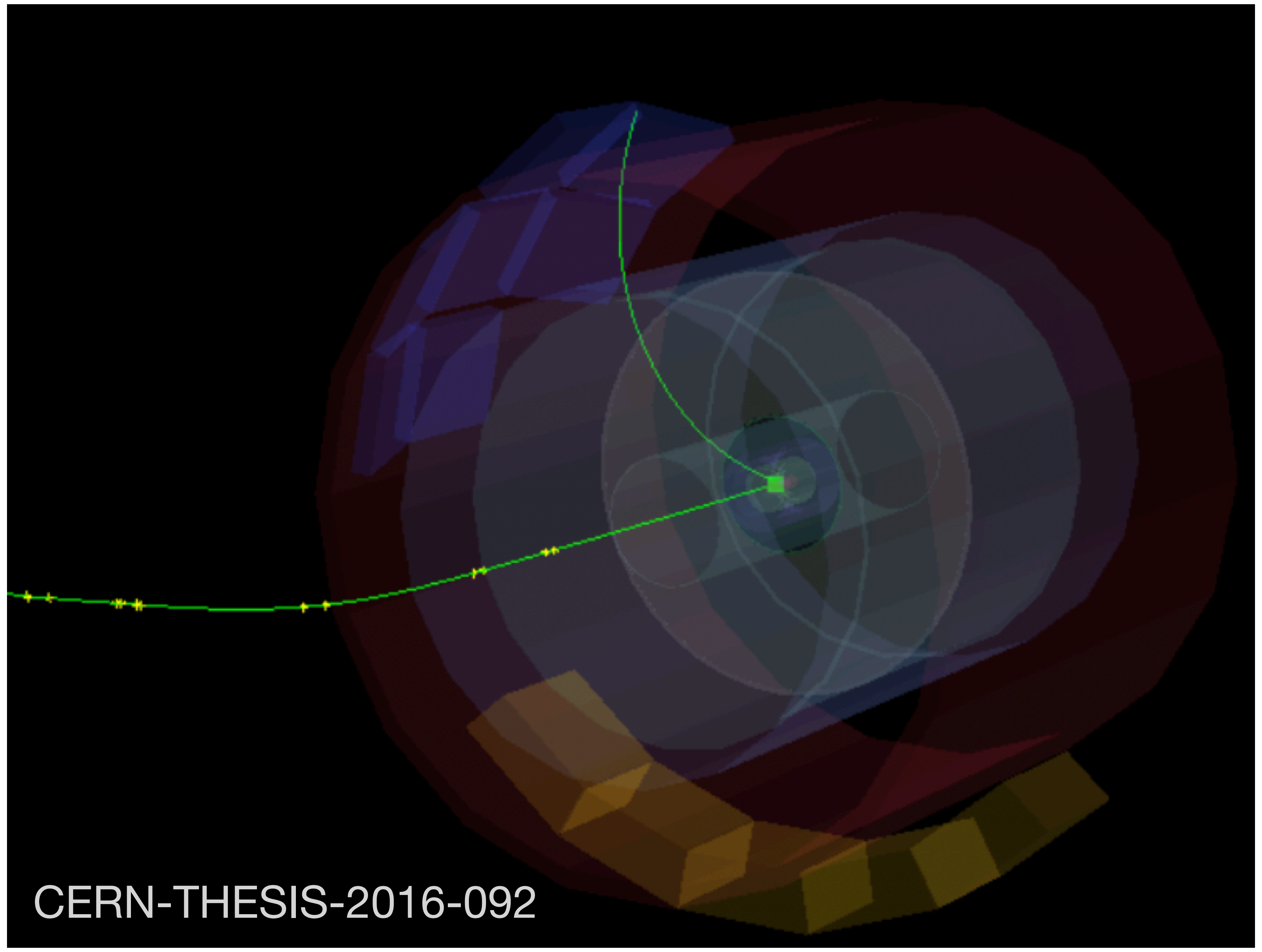
(SM) **Photon-photon**



(BSM) **Photon-photon**

(I) Coherent vector meson production



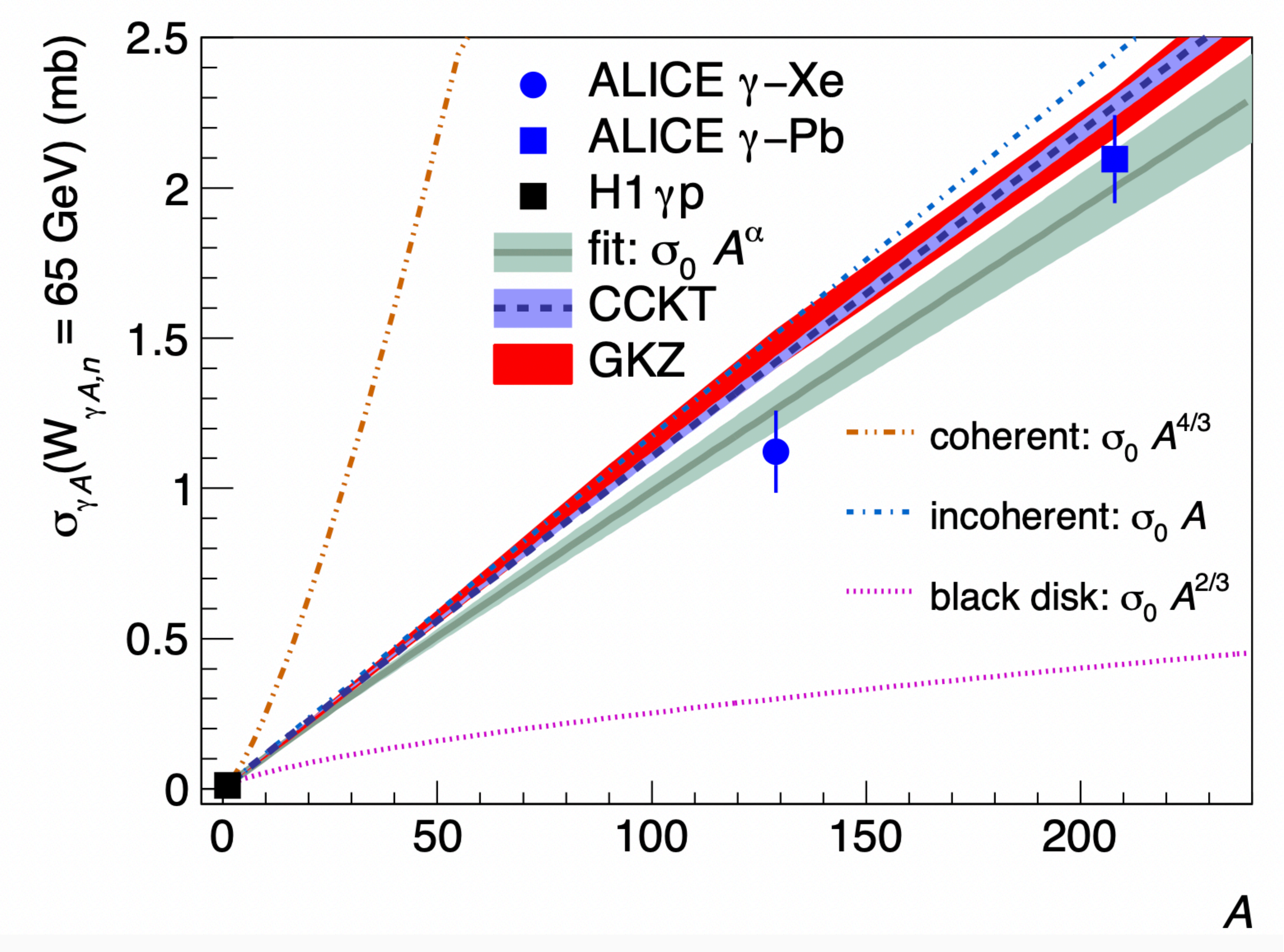


Coherent ρ^0 cross section in UPC

ALICE: PLB 820 (2021) 136481

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

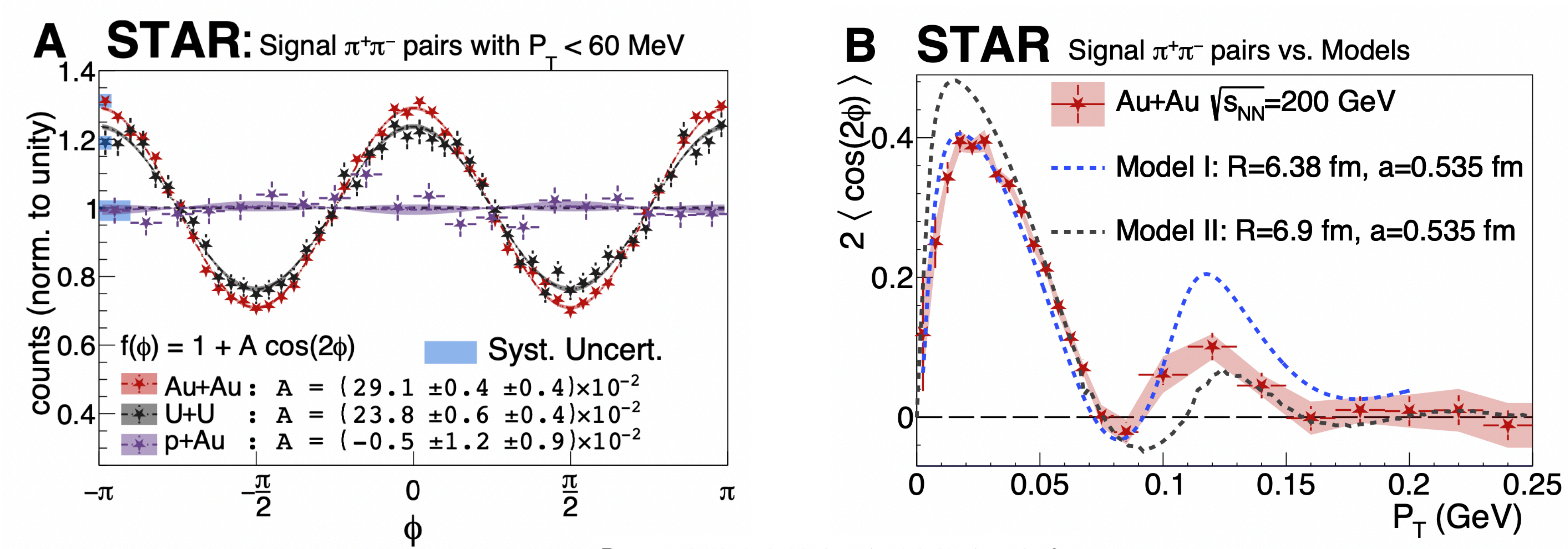
- Power-law fit: $\alpha = 0.96 \pm 0.02$
  - Below coherent -> Shadowing



Nuclear radii using coherent $\rho^0 \to \pi^+\pi^-$

STAR: arXiv:2204.01625

- Spin-induced orbital angular momentum interferometry
  - Precision extraction of strong-interaction radius for Au & U in coherent $\rho^0 \to \pi^+\pi^-$

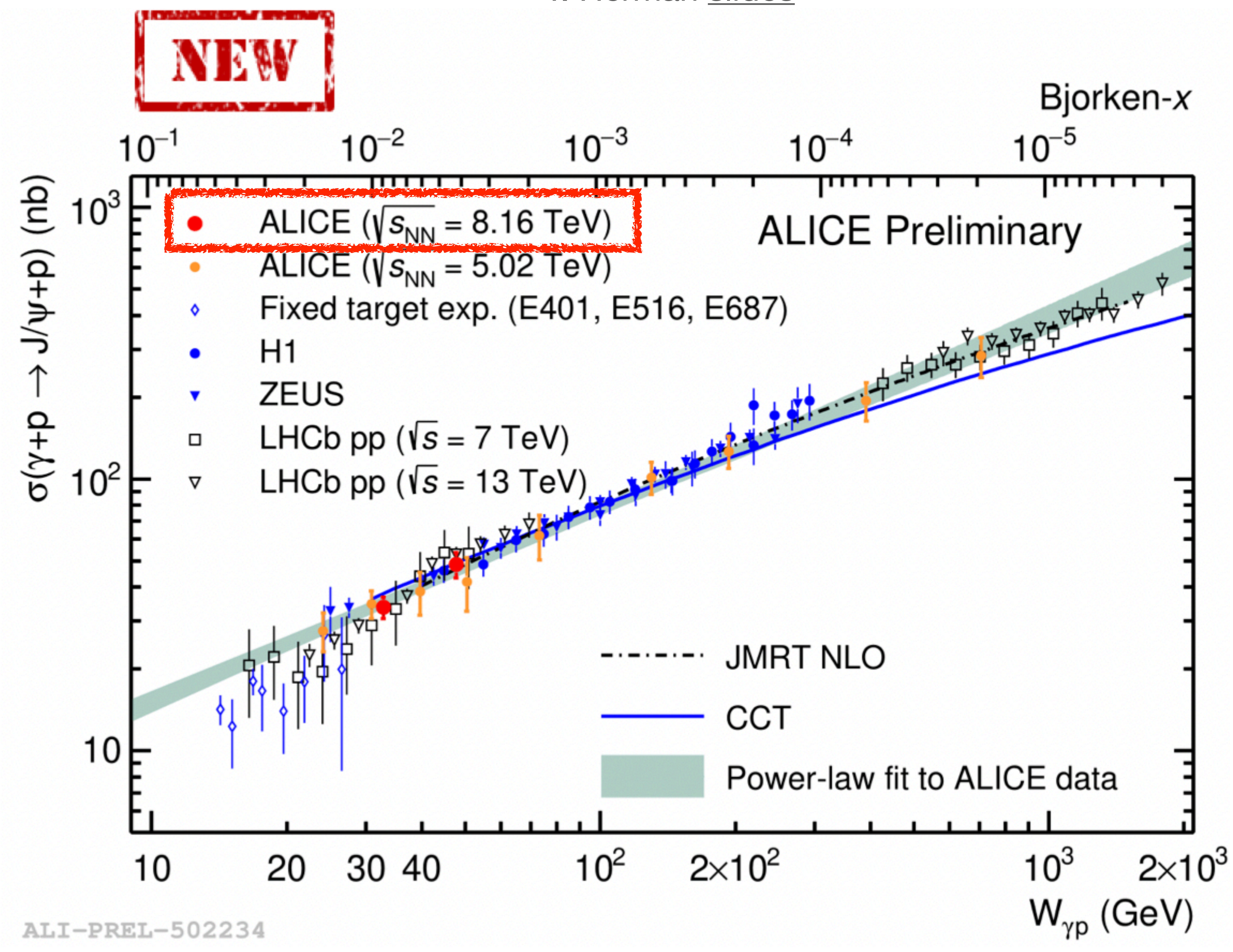


$$R_{\rm Au} = 6.53 \pm 0.03 \text{ (stat.) } \pm 0.05 \text{ (syst.) fm}$$
$$R_{\rm U} = 7.29 \pm 0.06 \text{ (stat.) } \pm 0.05 \text{ (syst.) fm}$$

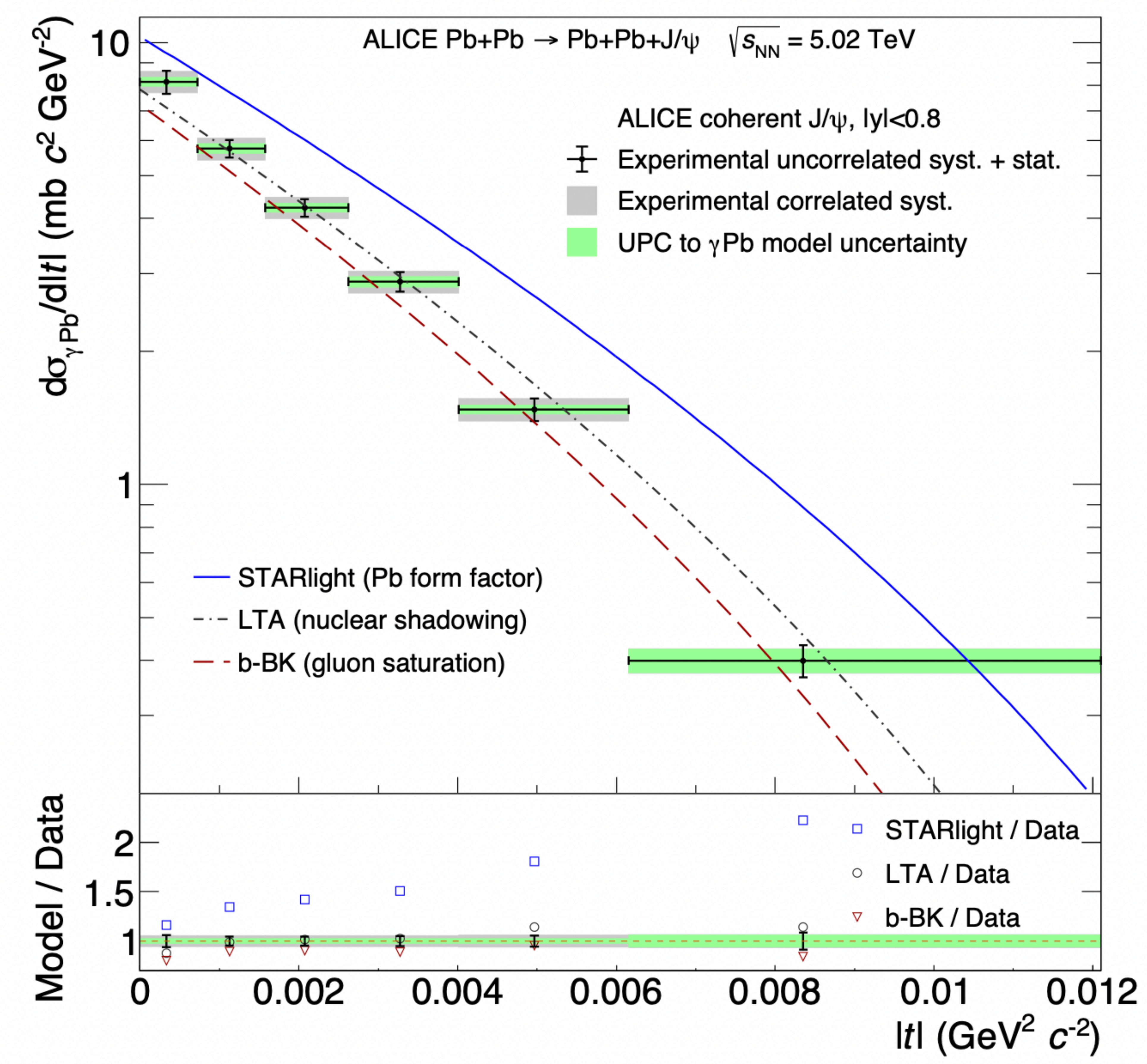
J/ψ photo-production in UPC

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

T. Herman slides



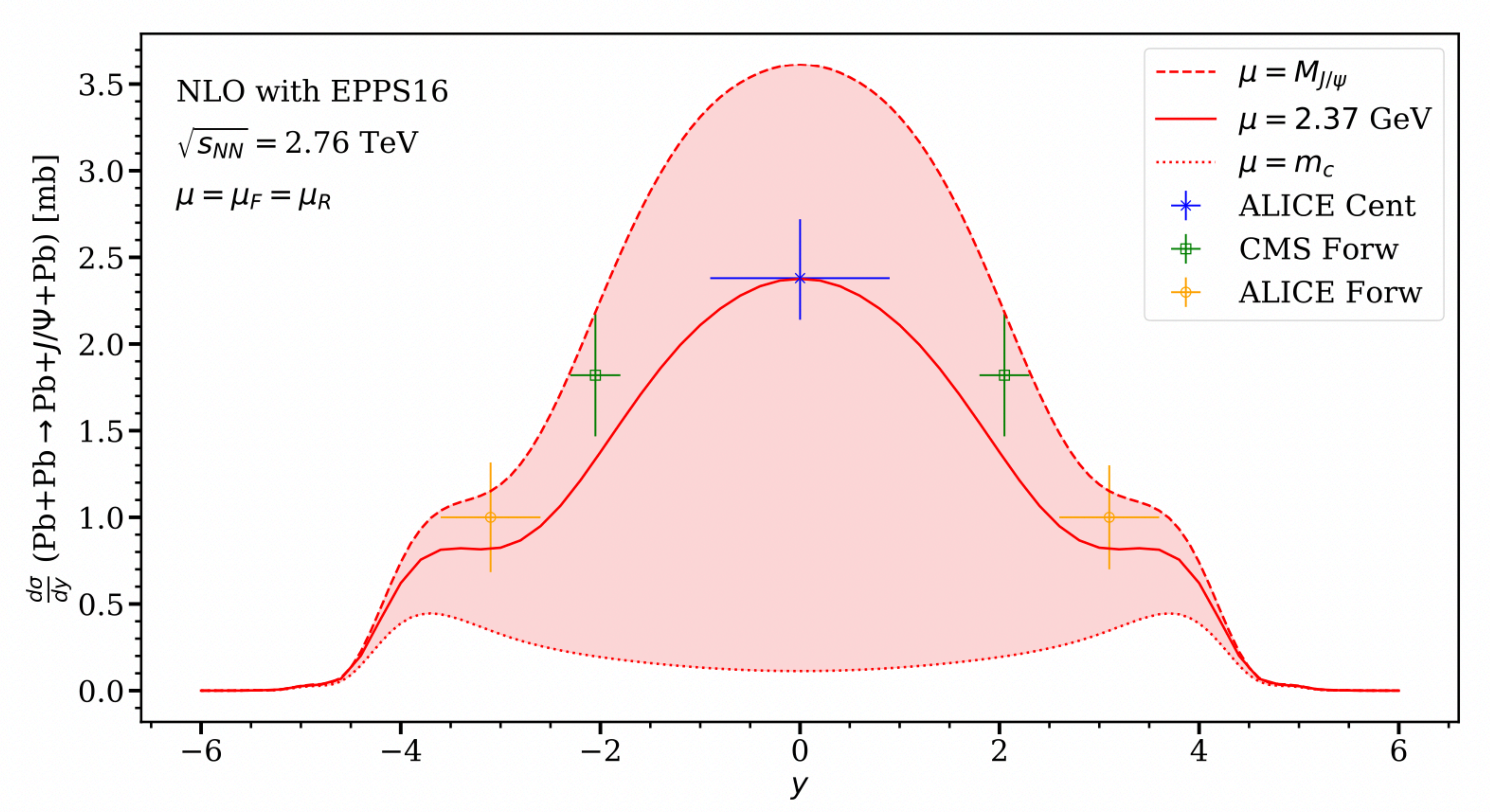
ALICE: PLB 817 (2021) 136280

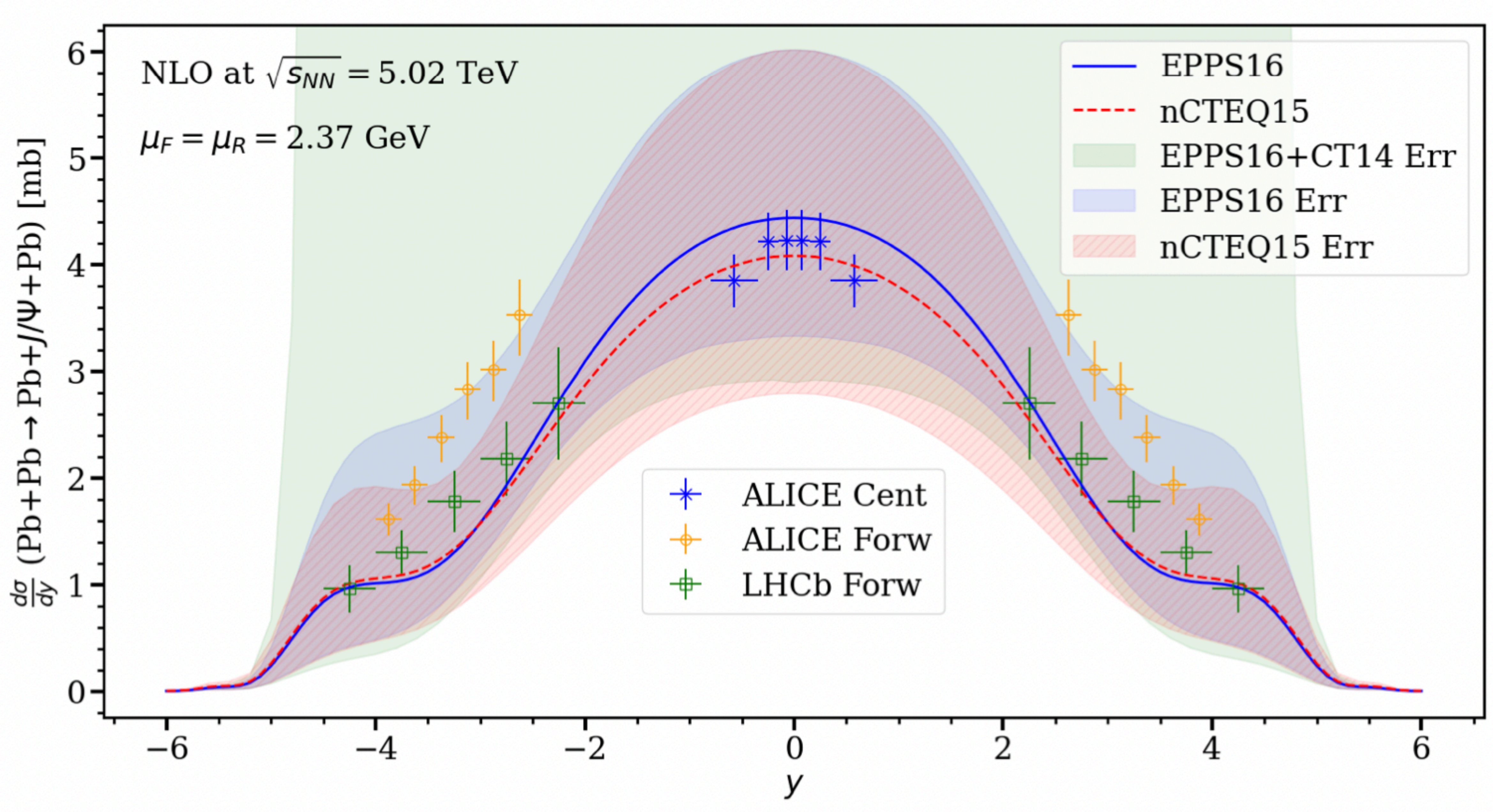


J/ψ photo-production in UPC

Eskola et al., arXiv:2203.11613

- NLO pQCD calculations for A+A are promising!

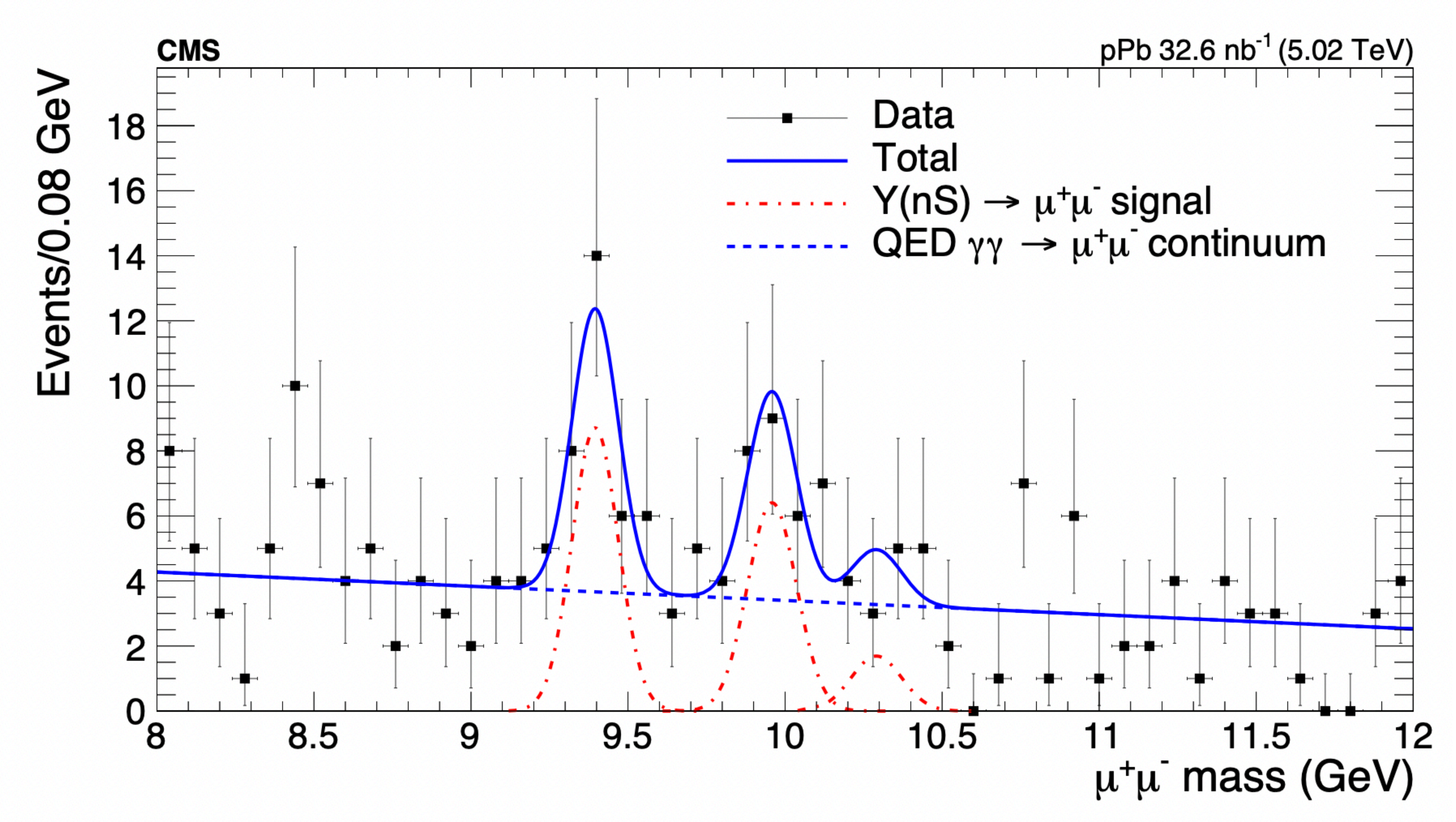


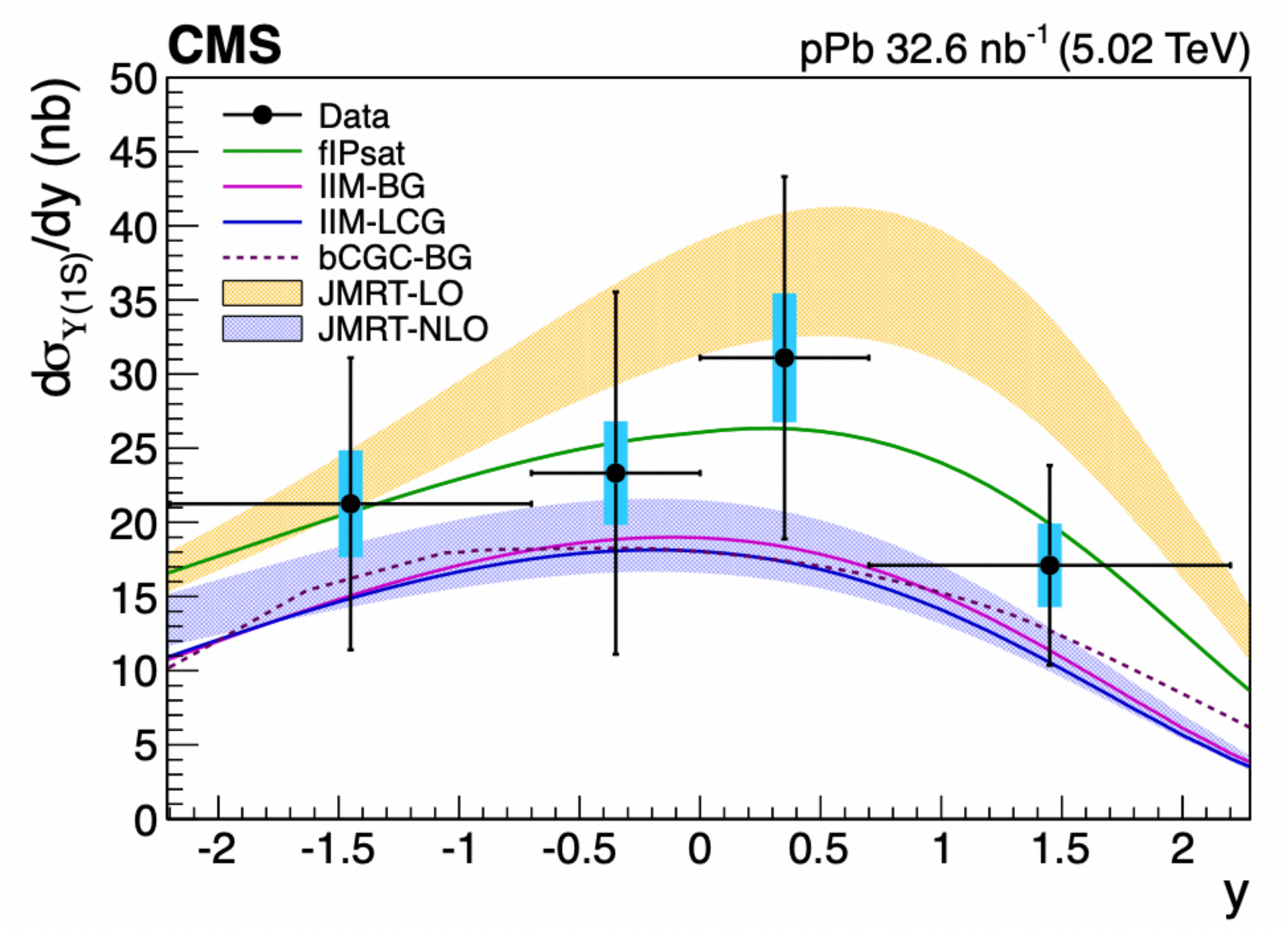


Upsilon photo-production in UPC p+Pb

CMS, EPJC 79 (2019) 277

- Exclusive Upsilon(nS) measured by CMS in γp collisions



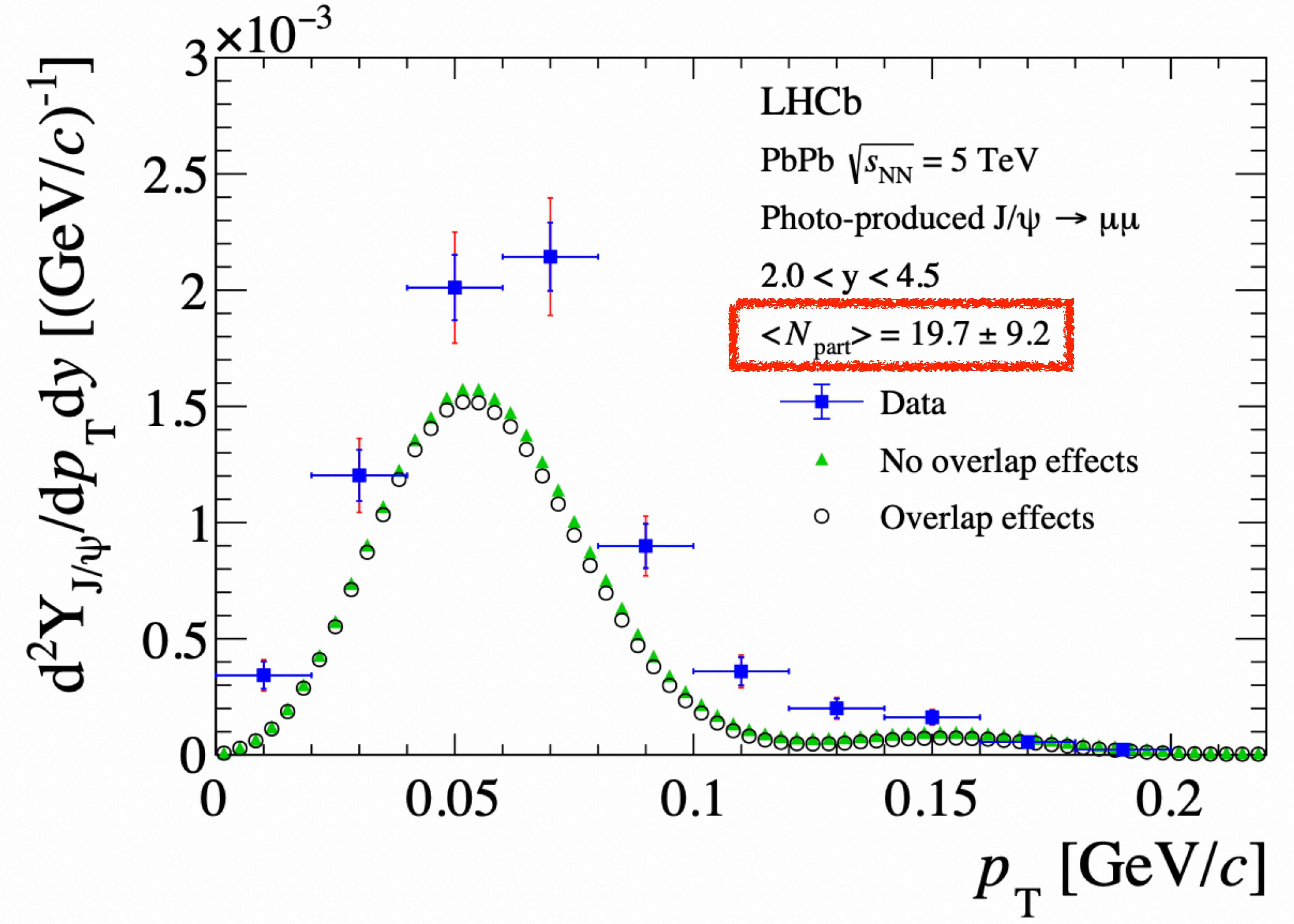


J/ψ photo-production in non-UPC Pb+Pb

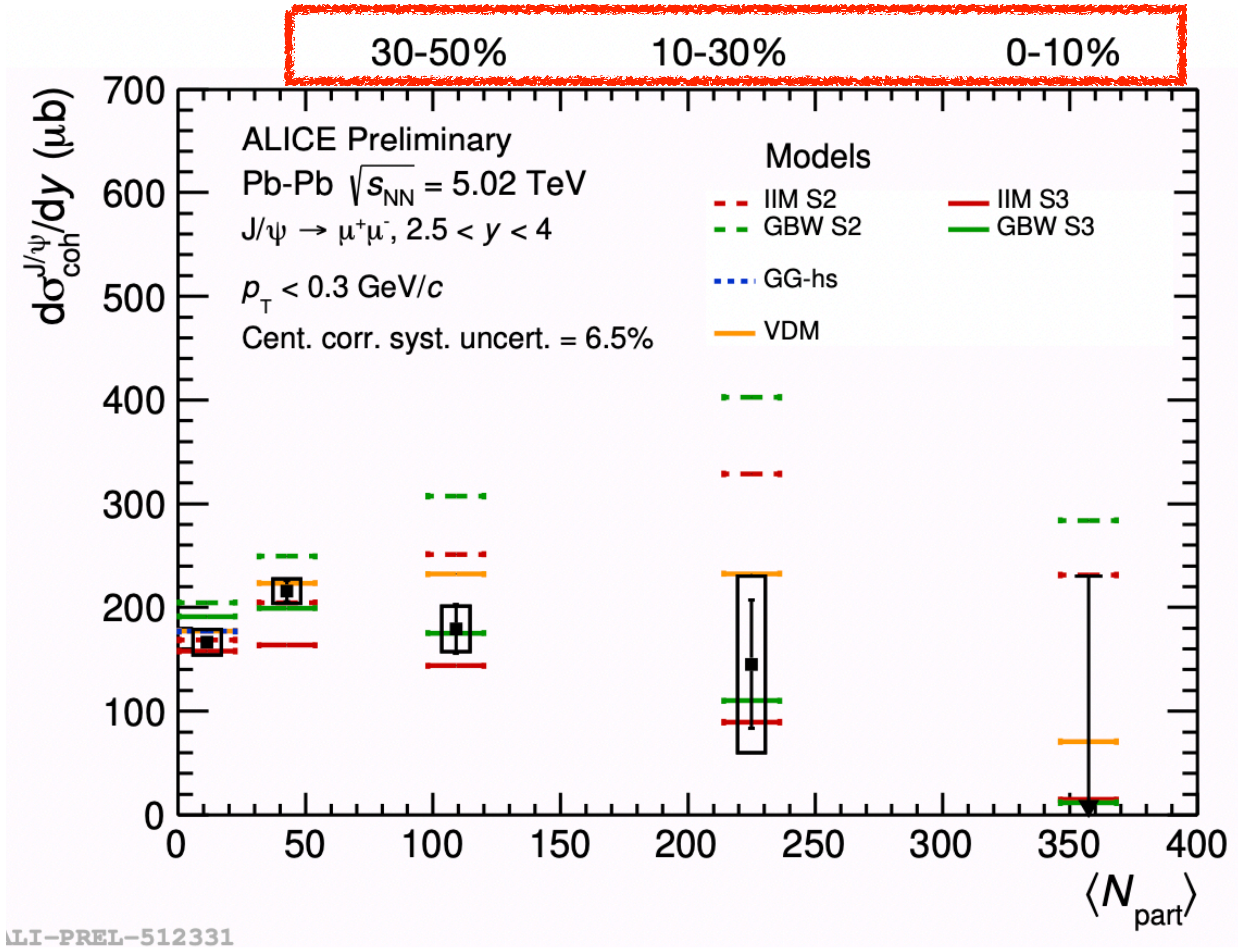
- Measurements use peripheral collisions (ALICE, LHCb), down to semi-central collisions (ALICE)
  - Results qualitatively described by theory predictions

LHCb: arXiv:2108.02681

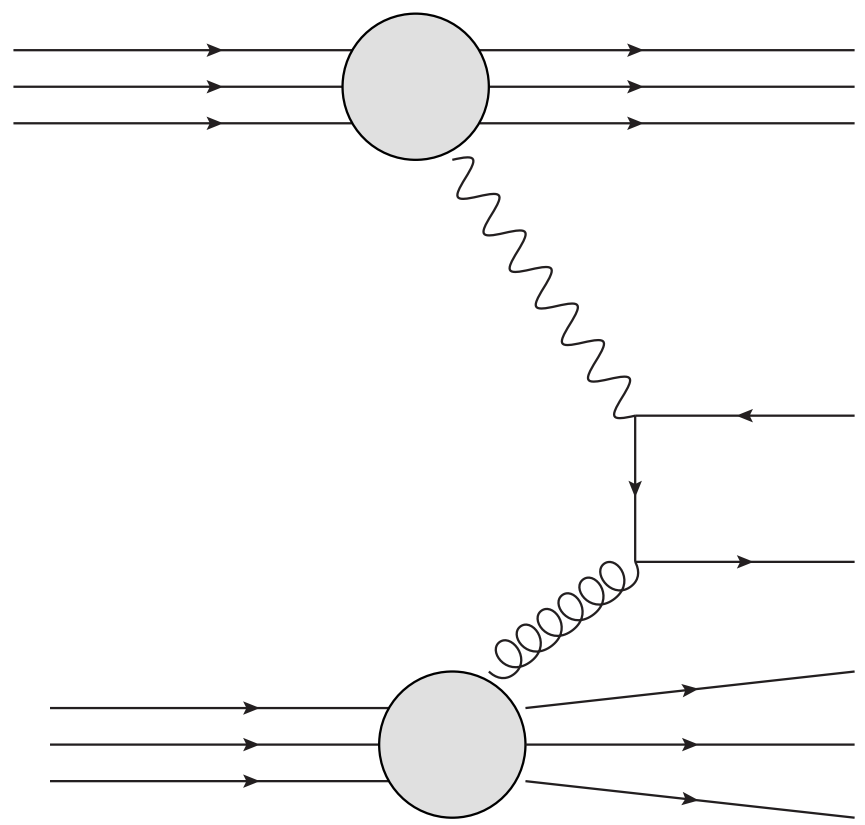
Theory: W. Zha et al., Phys. Rev. C97 (2018) 044910

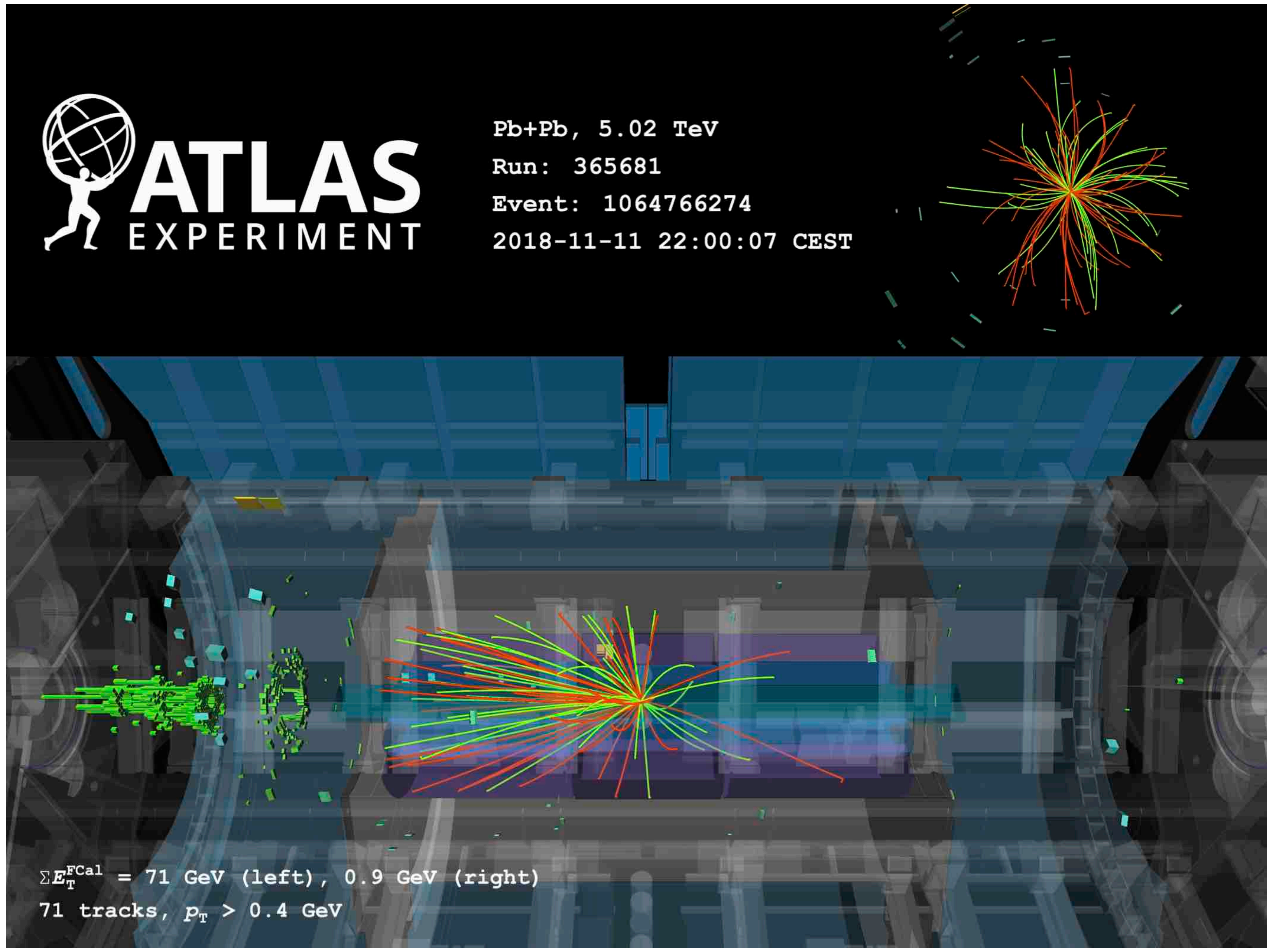


ALICE-PUBLIC-2022-006



(II) Novel measurements involving photo-nuclear interactions

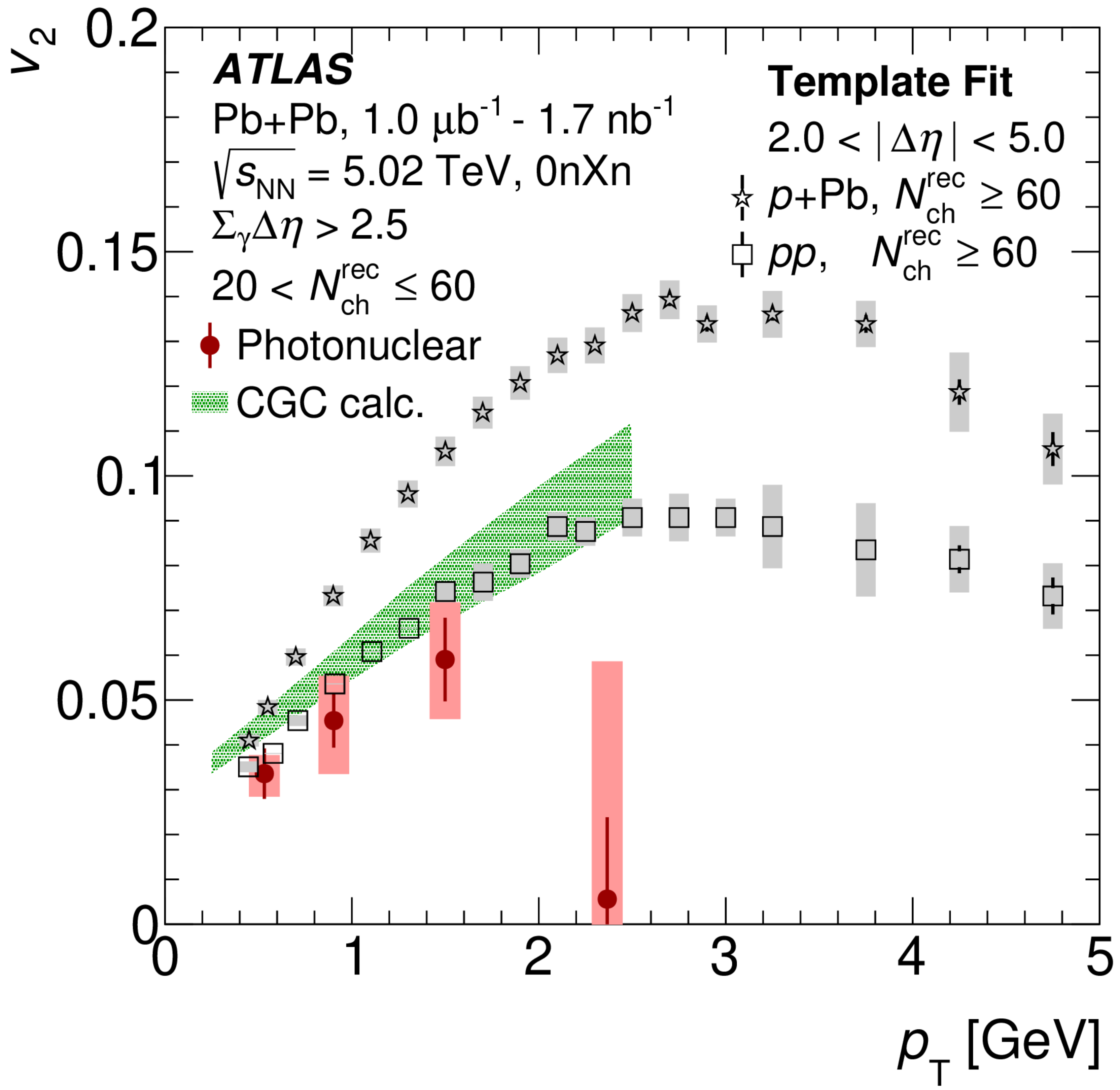


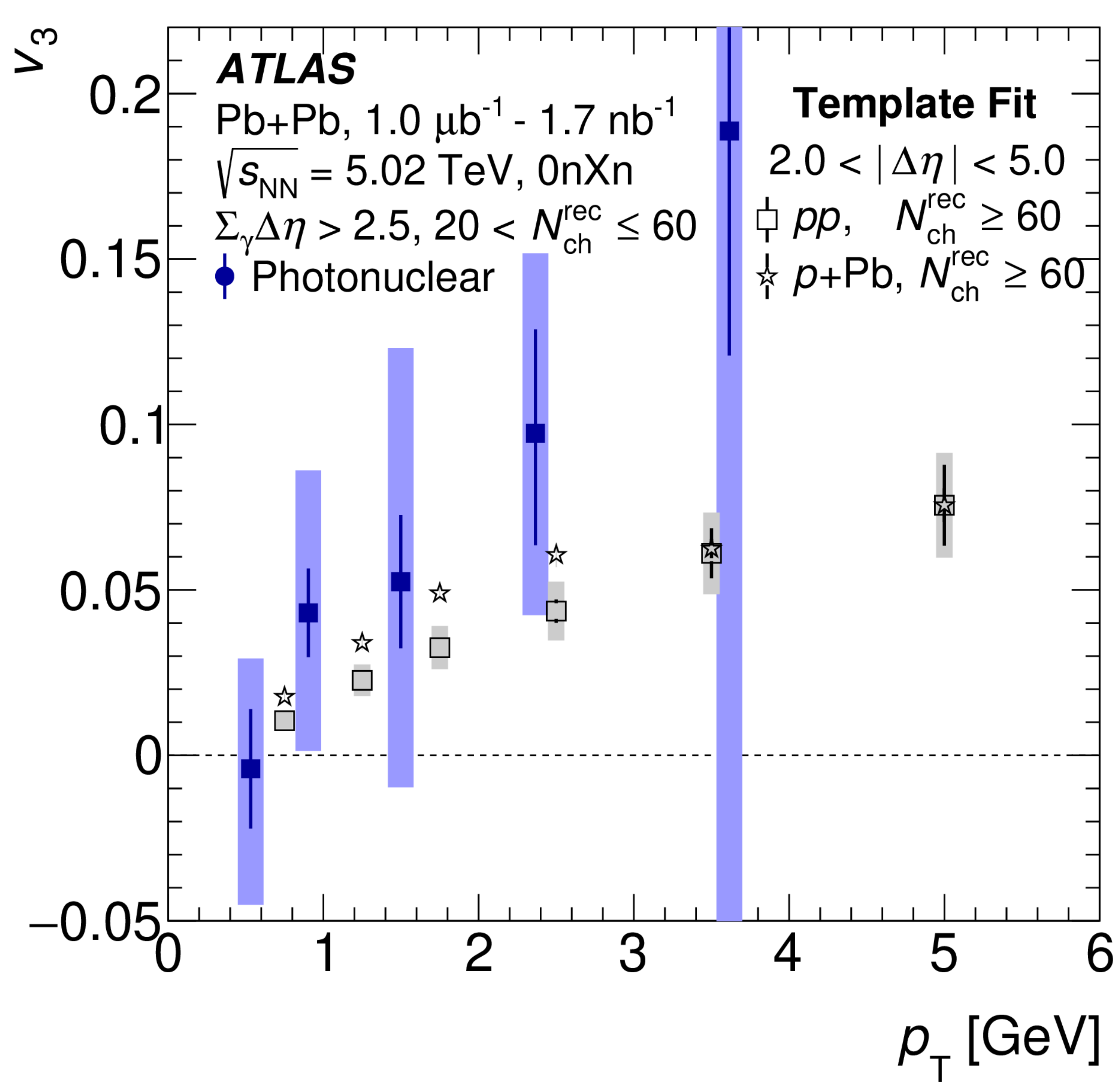


Azimuthal anisotropies in γPb

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



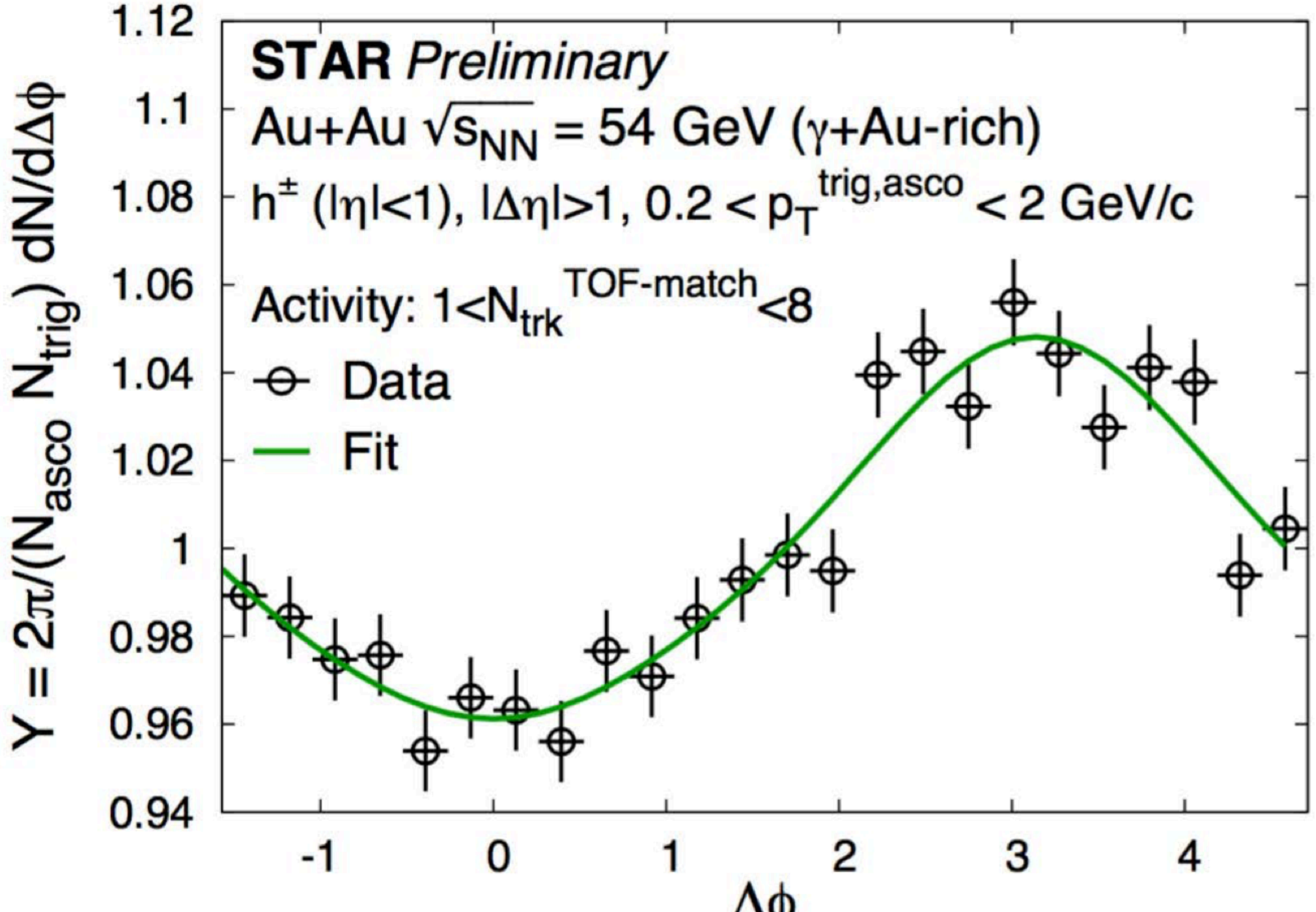


Azimuthal anisotropies in γAu

P. Tribedy slides

T. Liu slides

- Di-hadron correlations studied in photonuclear processes using Au+Au $\sqrt{s_{NN}}$ = 54.4 GeV data @ STAR
  - No signature of collectivity (near side ridge) in the γ+Au,
  - Higher energy and activity events under exploration with STAR forward upgrades

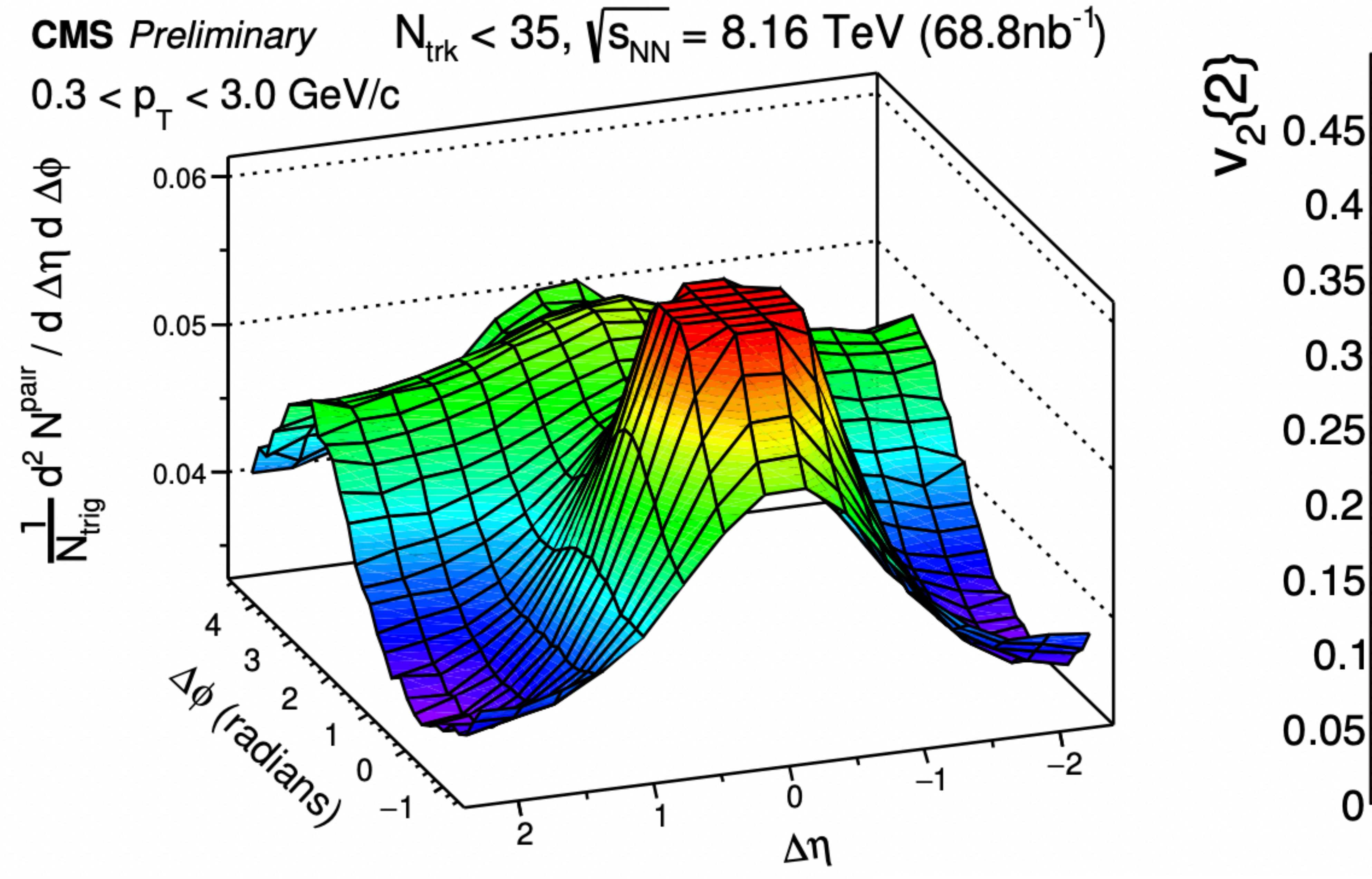


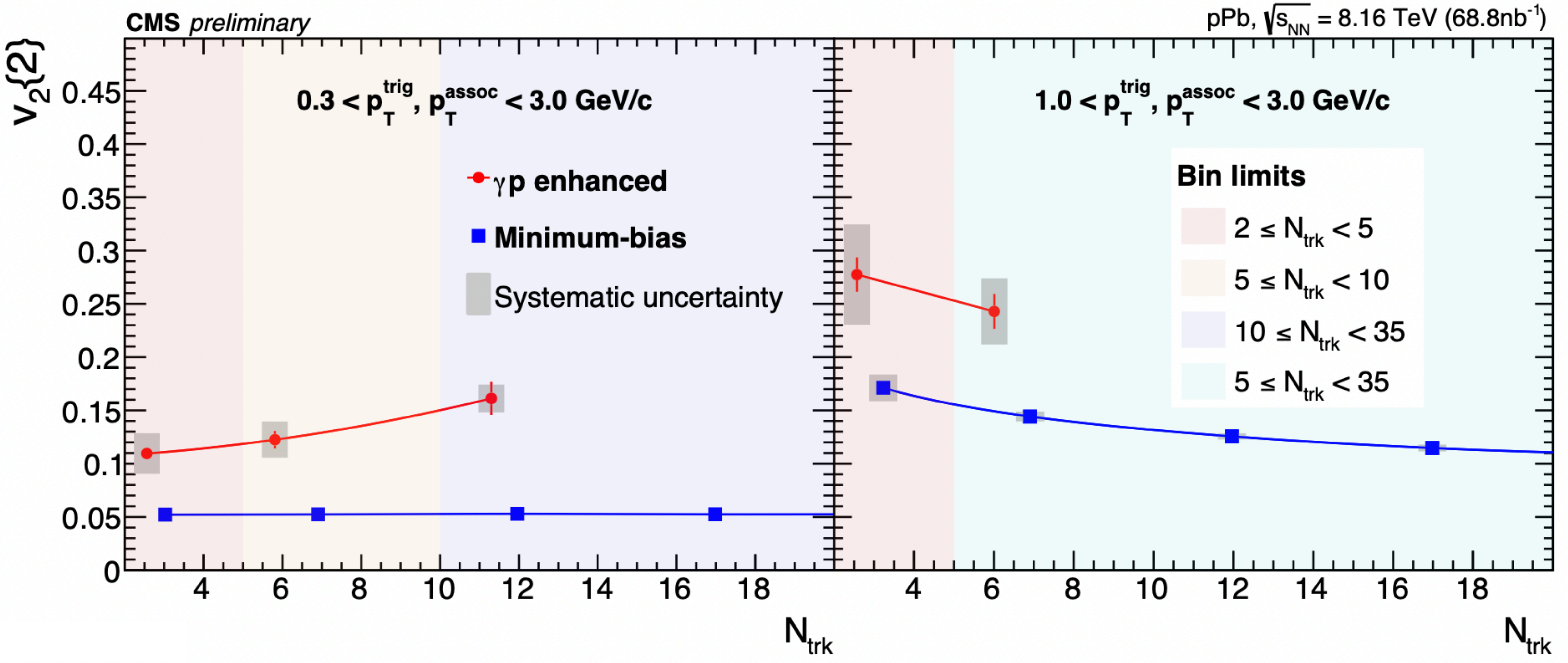
Search for azimuthal anisotropies in γp interactions

CMS-PAS-HIN-18-008

- 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})

γp enhanced



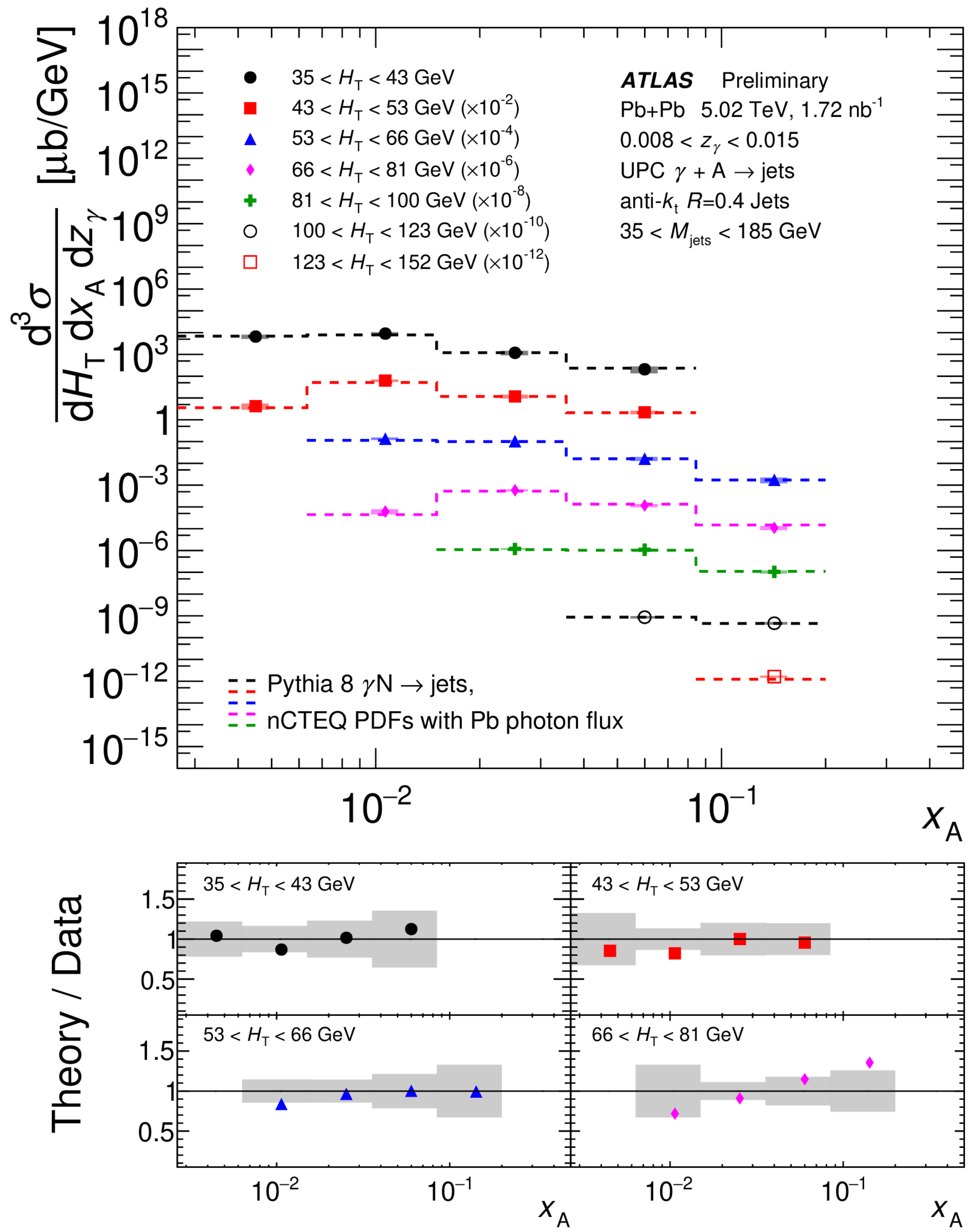


Measurement of photo-nuclear dijet production in Pb+Pb

ATLAS-CONF-2022-021

- Follow-up of the original ATLAS 2015 data (0.5/nb) measurement

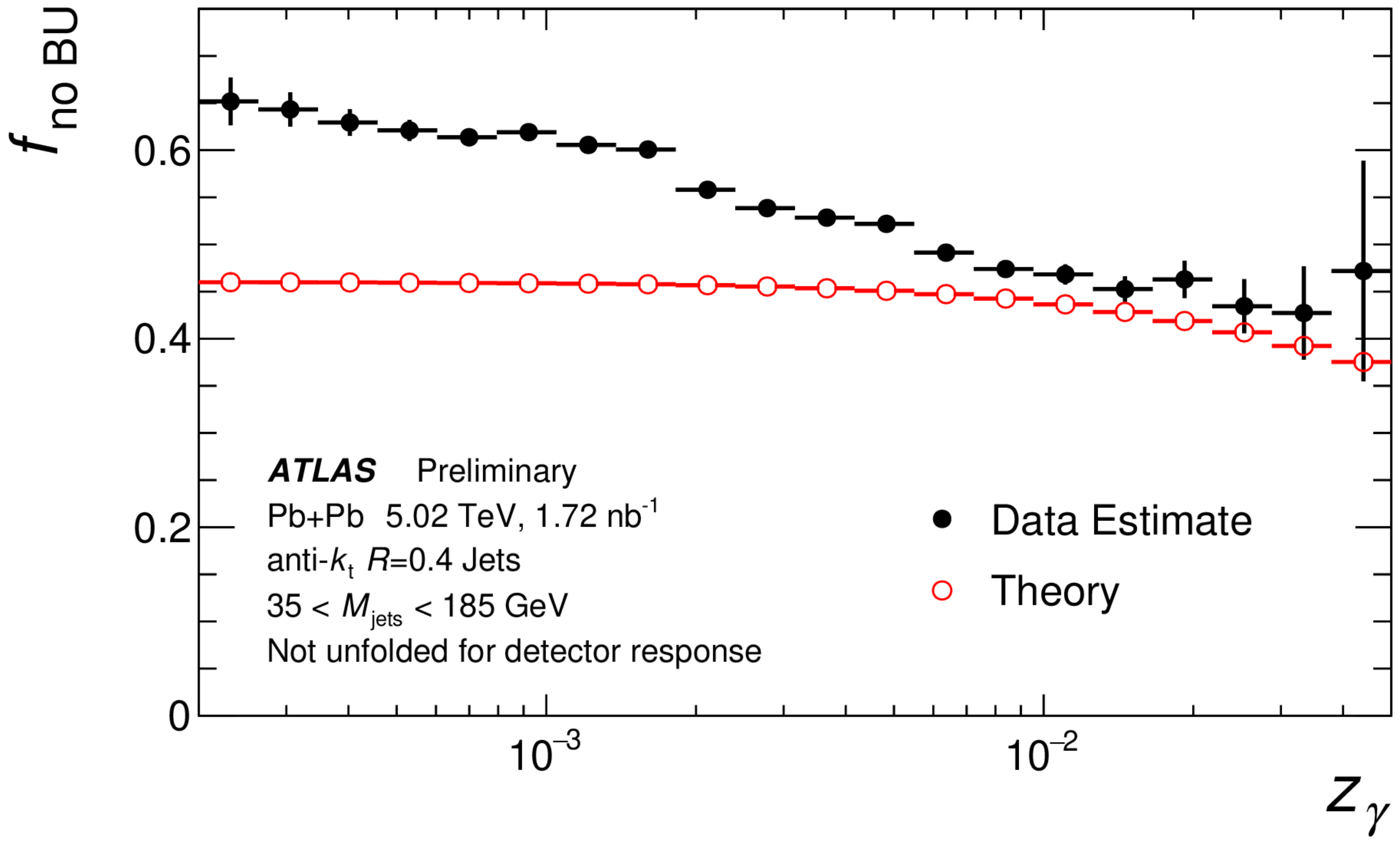
- 2018 Pb+Pb data used (1.7/nb)
- Measurement fully unfolded for detector effects
- Triple-differential cross-sections extracted (x_A, z_y, H_T)
- Comparison to Pythia 8 + nPDFs
- Potential to constrain nPDFs

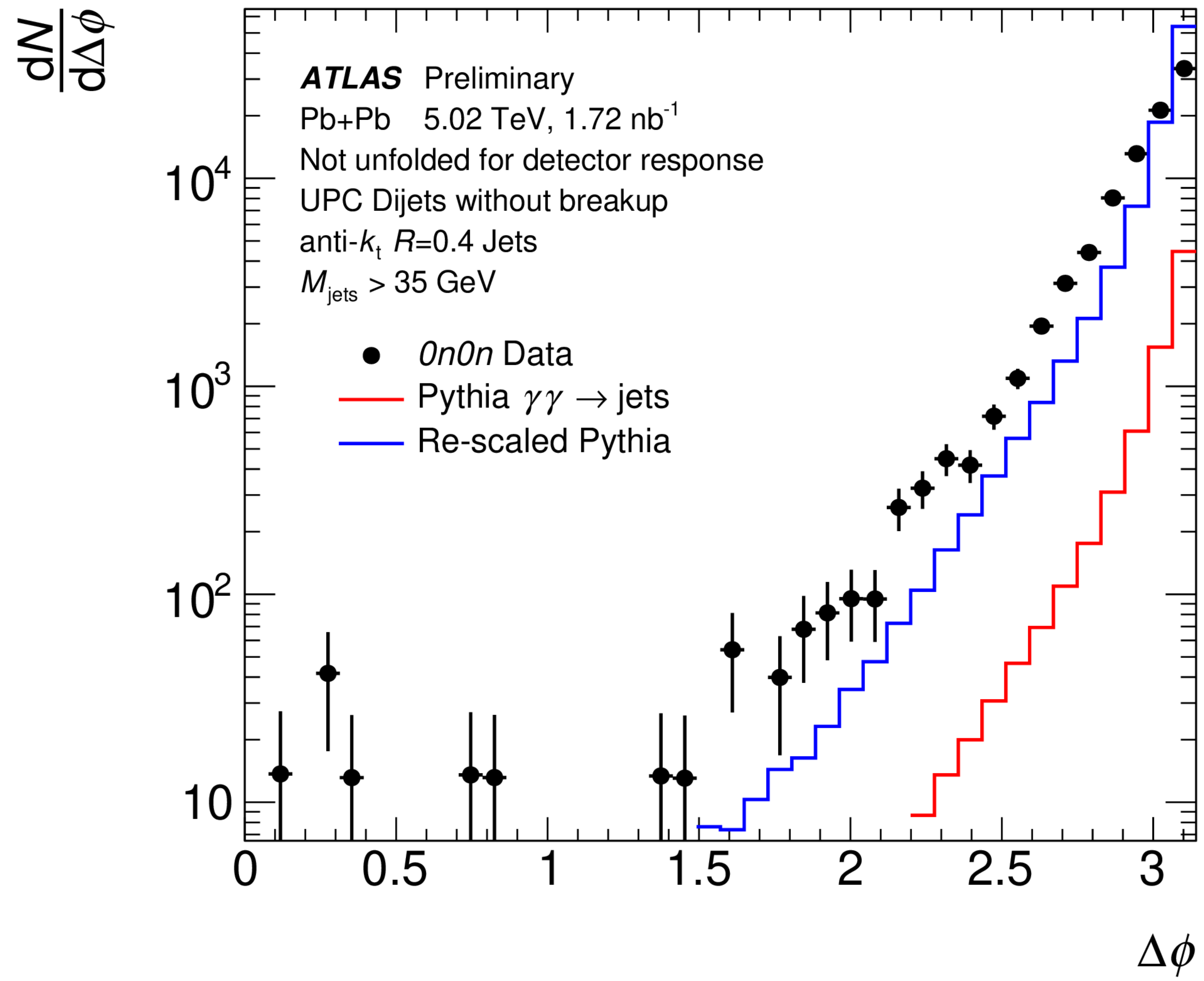


Measurement of photo-nuclear dijet production in Pb+Pb

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



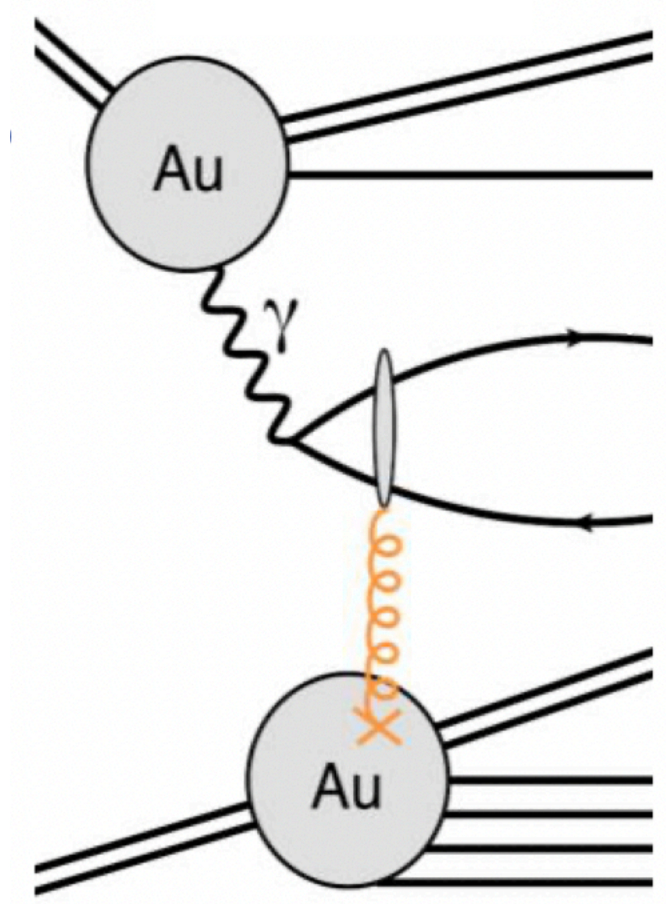


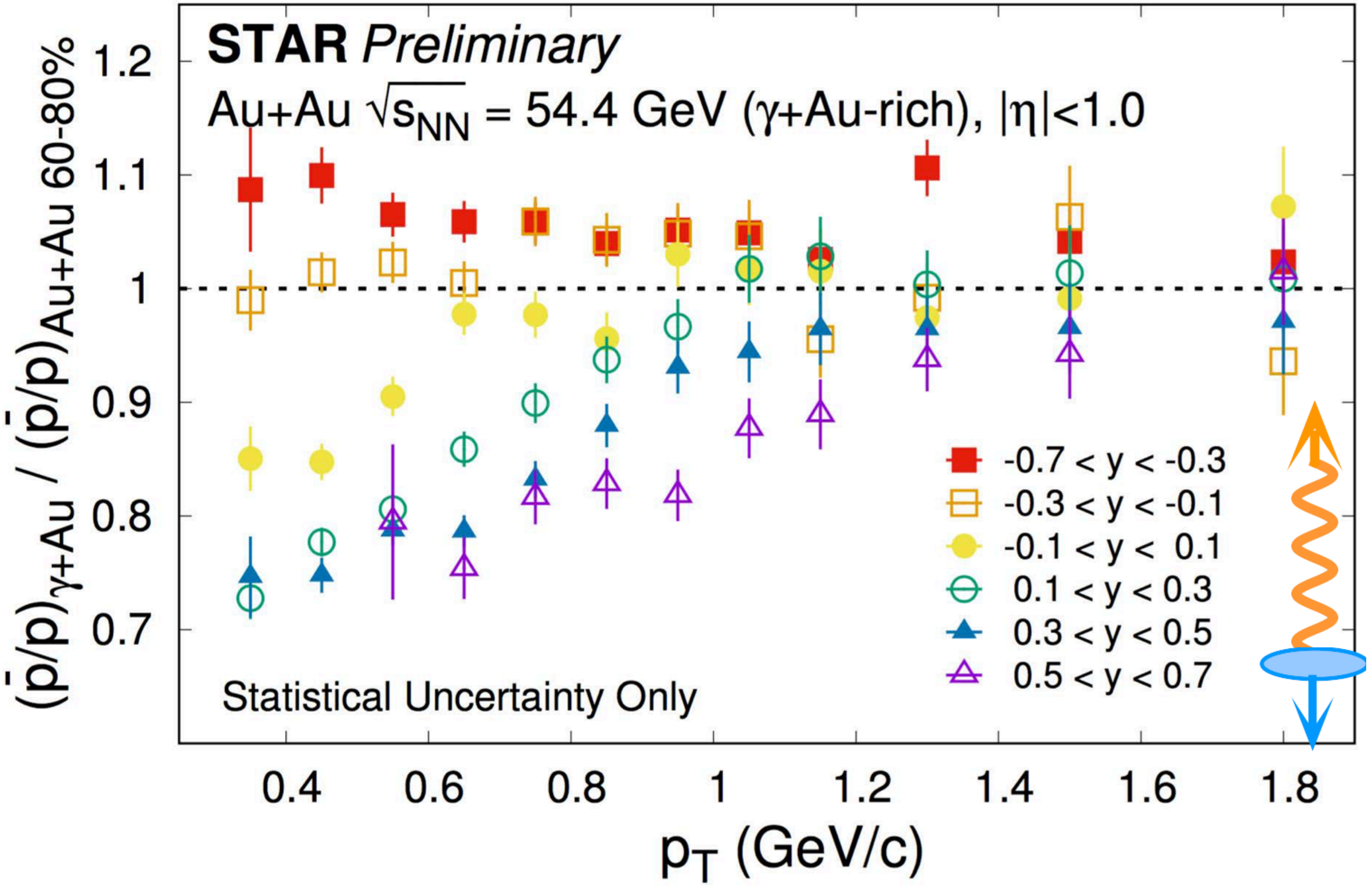
New insights on baryon stopping

P. Tribedy slides

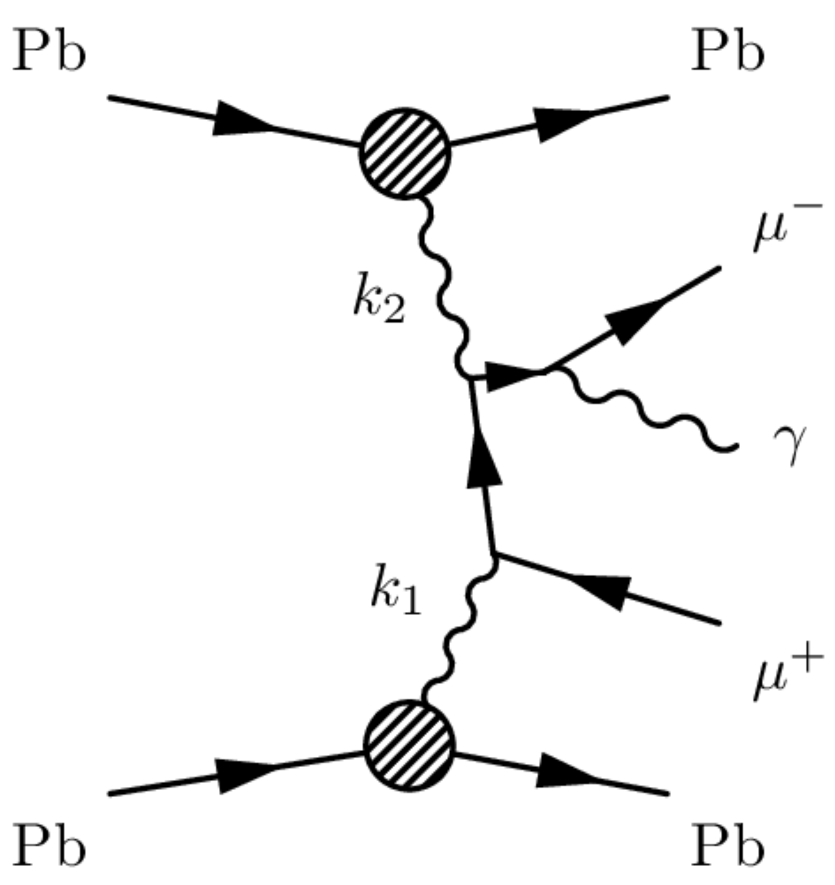
N. Lewis poster

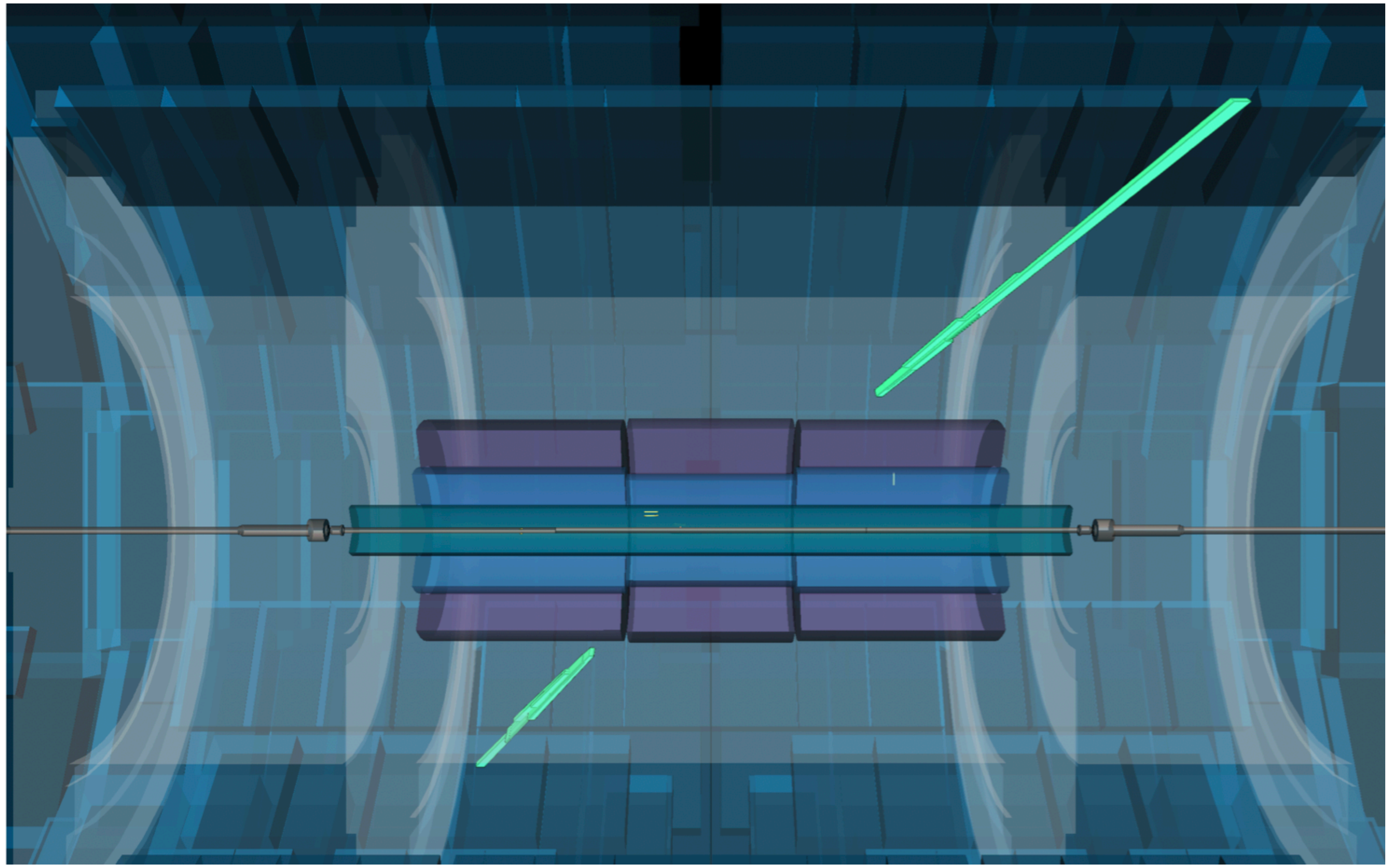
- First look at photonuclear events @STAR: stronger rapidity dependent stopping in γ+Au ≫ Au+Au





(III) SM photon-photon interactions





Progress in MC generators

Harland-Lang et al., EPJC 79 (2019) 1, 39
EPJC 80 (2020) 10, 925

Burmasov et al., arXiv:2111.11383 [hep-ph]

Broz et al., Comput.Phys.Commun. 253 (2020) 107181

- **SuperChic 3+**
  - Simulates variety of QCD-induced and photon-induced exclusive reactions
  - Also handles loop-induced processes (LbyL) and variety of BSM models (ALPs, monopoles, etc.)
  - refined treatment of the photon flux and nuclear overlap
  - Polarization effects taken into account
- **UPCgen**
  - Focus on yy->ll production
  - refined treatment of photon fluxes
  - photon polarization effects included
  - Can set arbitrary values of the lepton anomalous magnetic moment (useful in the studies of tau g-2)
- **Noon**
  - Generates extra neutrons from EM dissociation in UPC
  - Can be interfaced to other MC generators

Eur. Phys. J. C (2019) 79:39
https://doi.org/10.1140/epjc/s10052-018-6530-5
THE EUROPEAN PHYSICAL JOURNAL C
CrossMark
Regular Article - Theoretical Physics

Exclusive LHC physics with heavy ions: SuperChic 3

L. A. Harland-Lang[1,a], V. A. Khoze[2,3], M. G. Ryskin[3]
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[2] Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, UK
[3] Petersburg Nuclear Physics Institute, NRC Kurchatov Institute, Gatchina, St. Petersburg 188300, Russia

Upcgen: a Monte Carlo simulation program for dilepton pair production in ultra-peripheral collisions of heavy ions

Nazar Burmasov[a,*], Evgeny Kryshen[a], Paul Bühler[b], Roman Lavicka[b]
[a] *Petersburg Nuclear Physics Institute named by B.P.Konstantinov of National Research Center «Kurchatov Institute», 1 mkr. Orlova roshcha, 188300 Gatchina, Russia*
[b] *Stefan Meyer Institute for Subatomic Physics, Kegelgasse 27, 1030 Vienna, Austria*

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Computer Physics Communications
Volume 253, August 2020, 107181

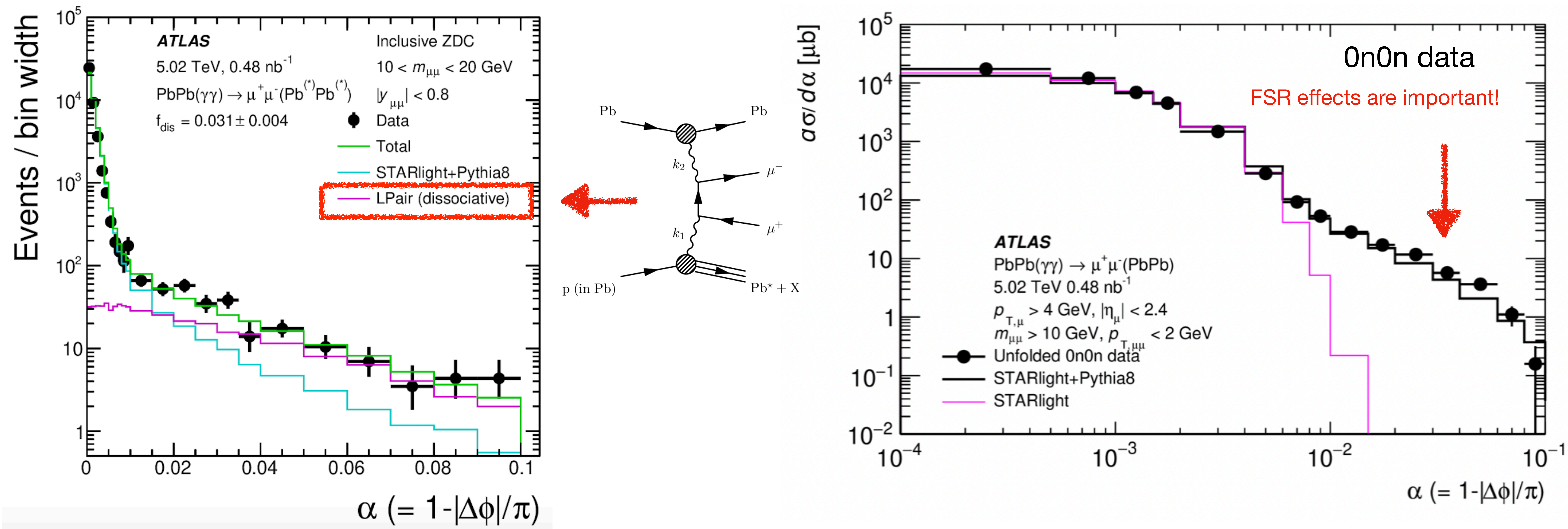
A generator of forward neutrons for ultra-peripheral collisions: $\mathbf{n_O^O n}$ ☆, ☆☆

M. Broz [a], J.G. Contreras [a], J.D. Tapia Takaki [b]

$\gamma\gamma \to \mu\mu$ production in Pb+Pb UPC

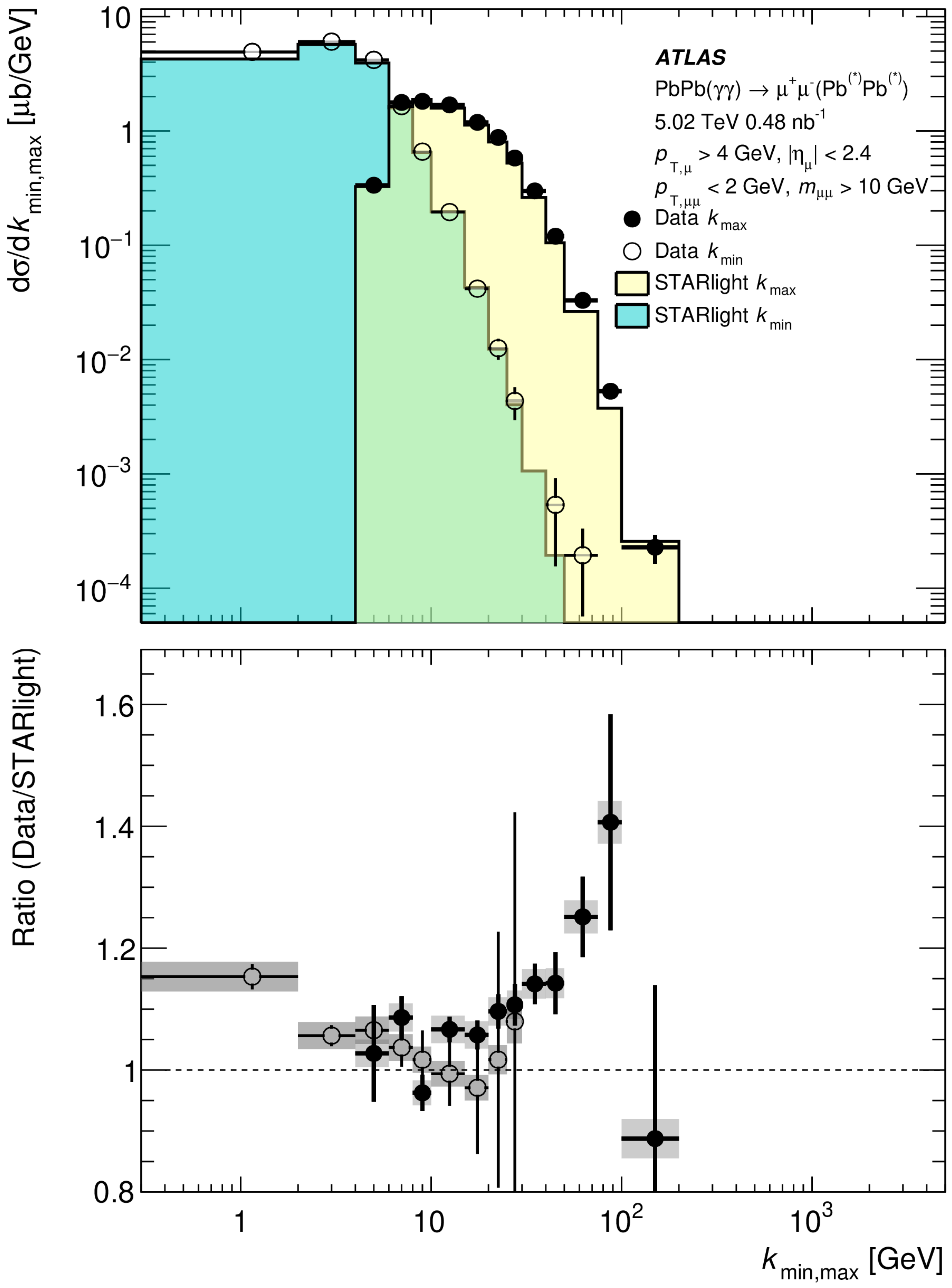
ATLAS, Phys. Rev. C 104 (2021) 024906

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

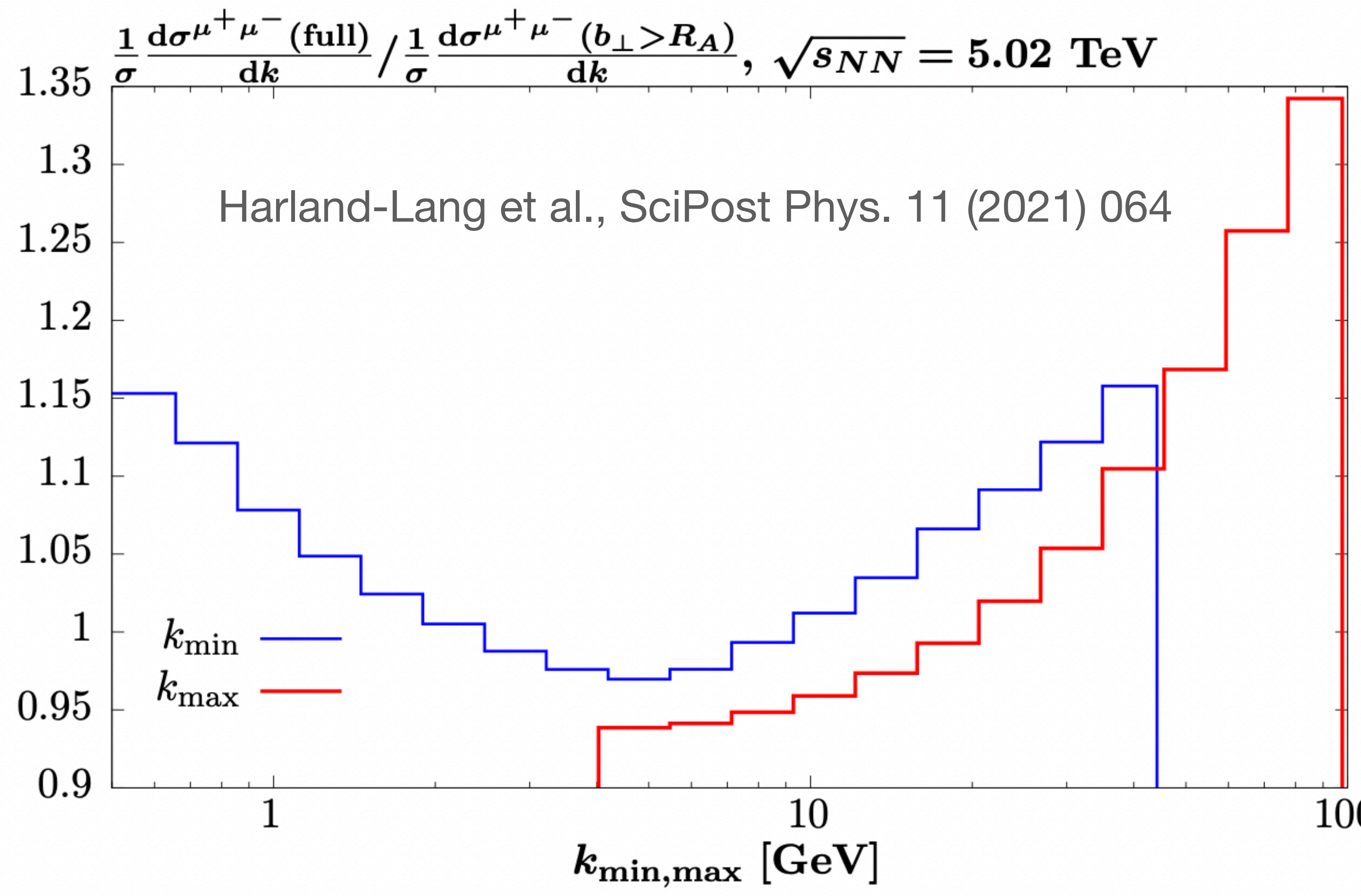


γγ→μμ production in Pb+Pb UPC

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



- 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

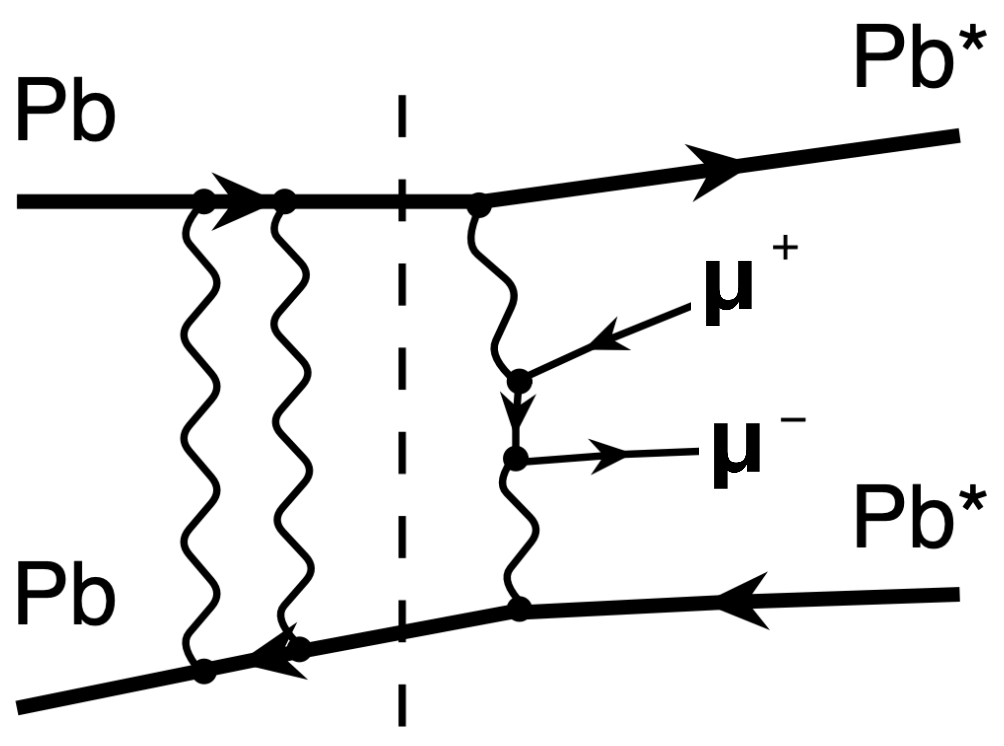


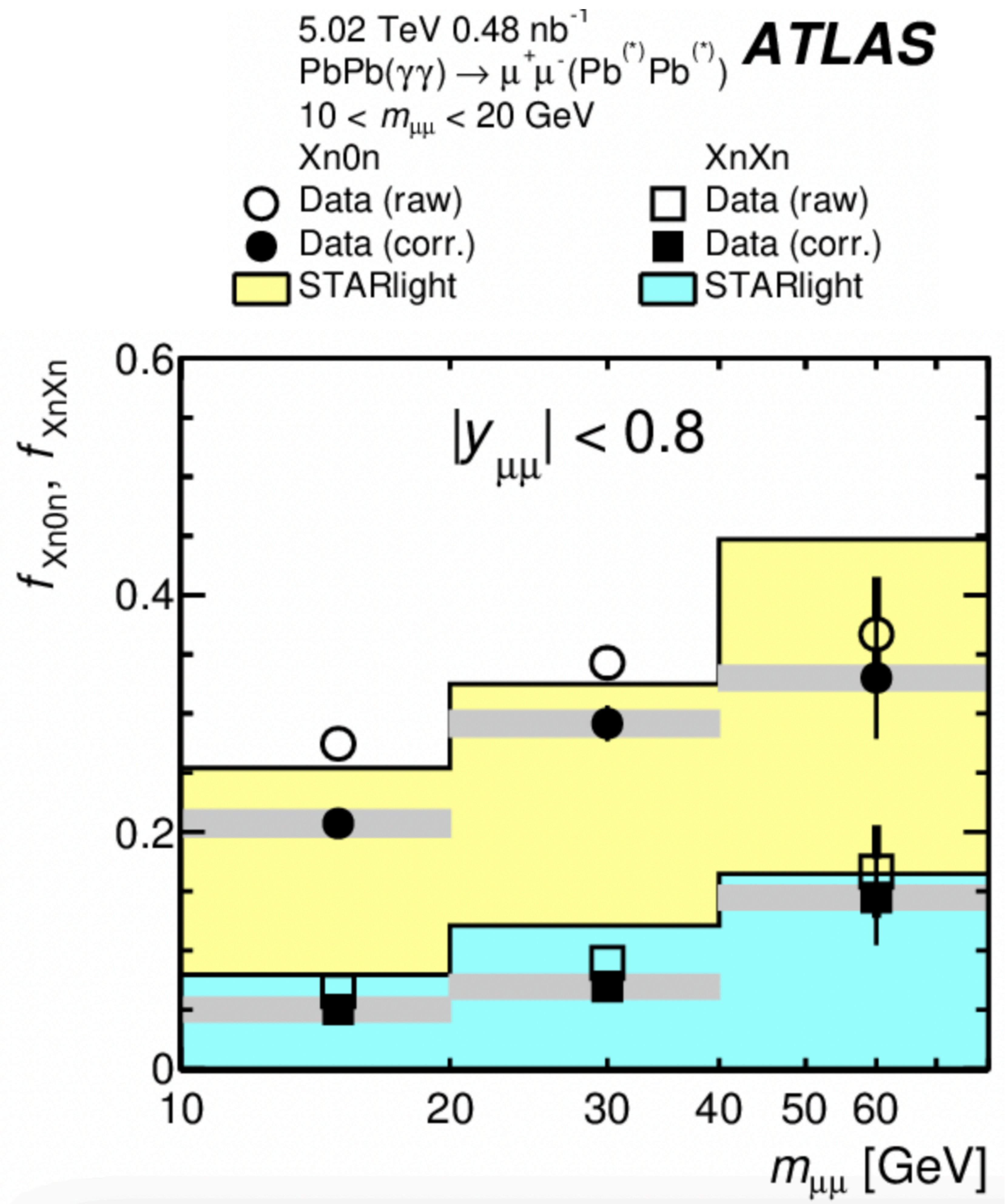
γγ→μμ production in Pb+Pb UPC

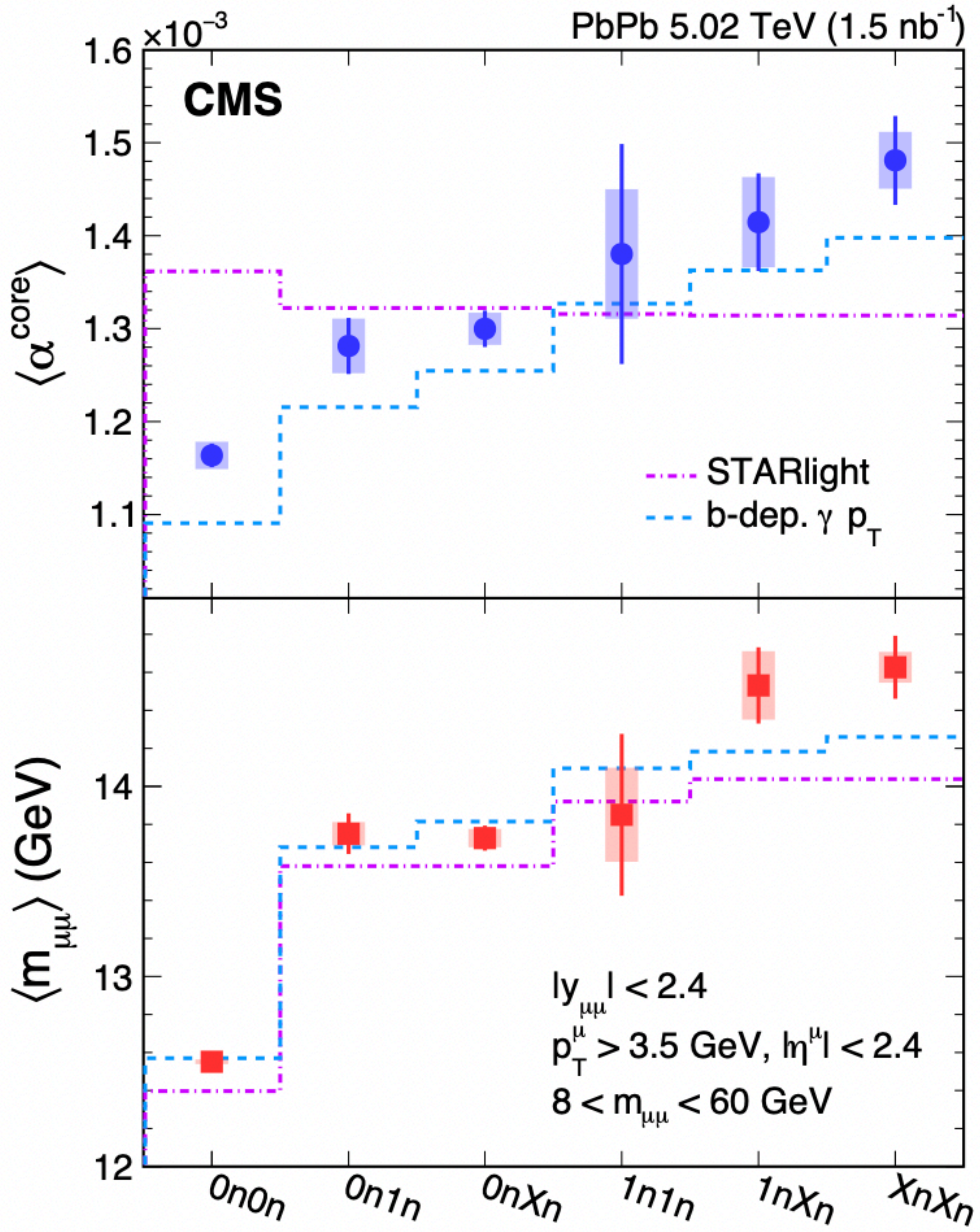
ATLAS, Phys. Rev. C 104 (2021) 024906

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

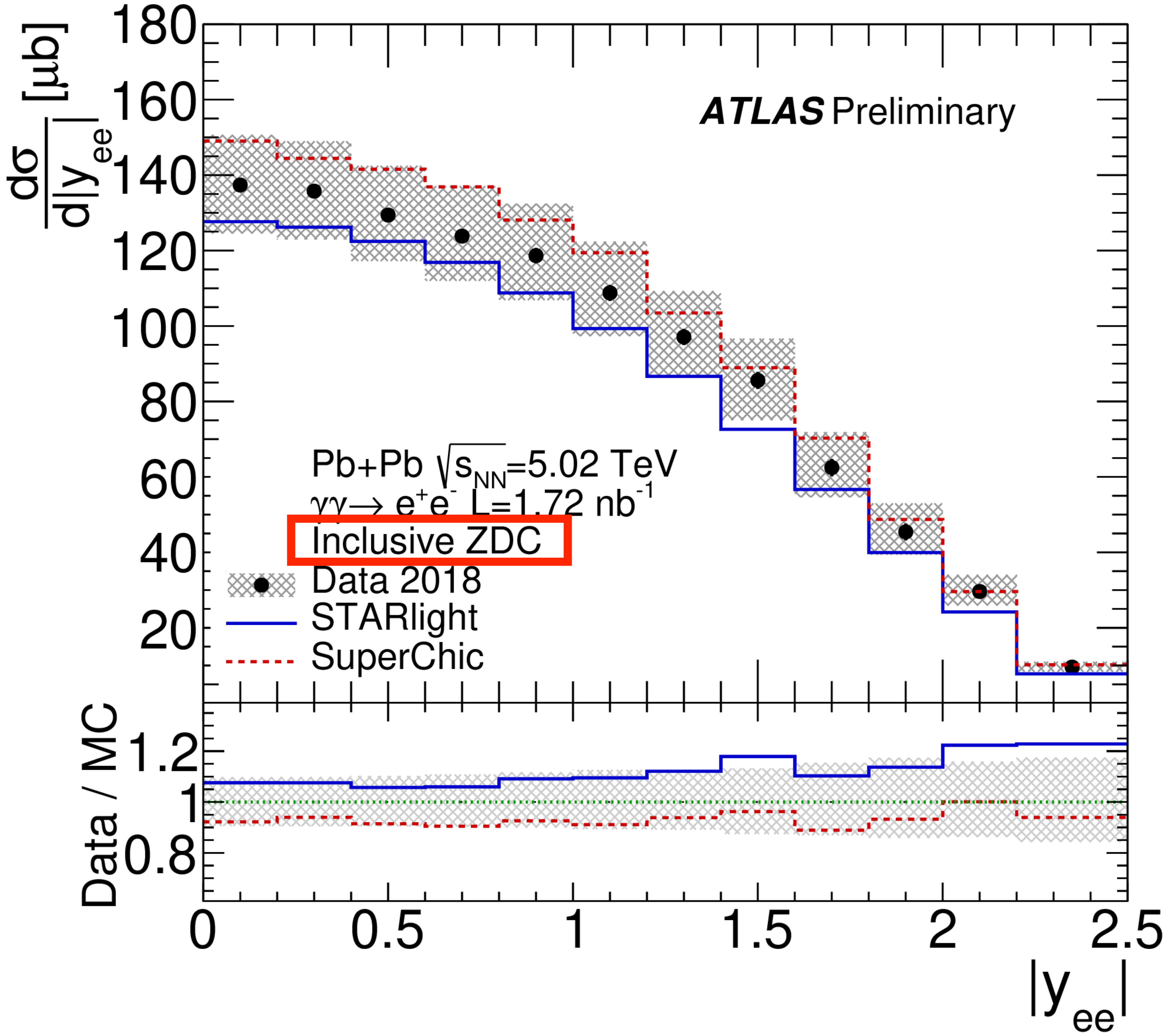


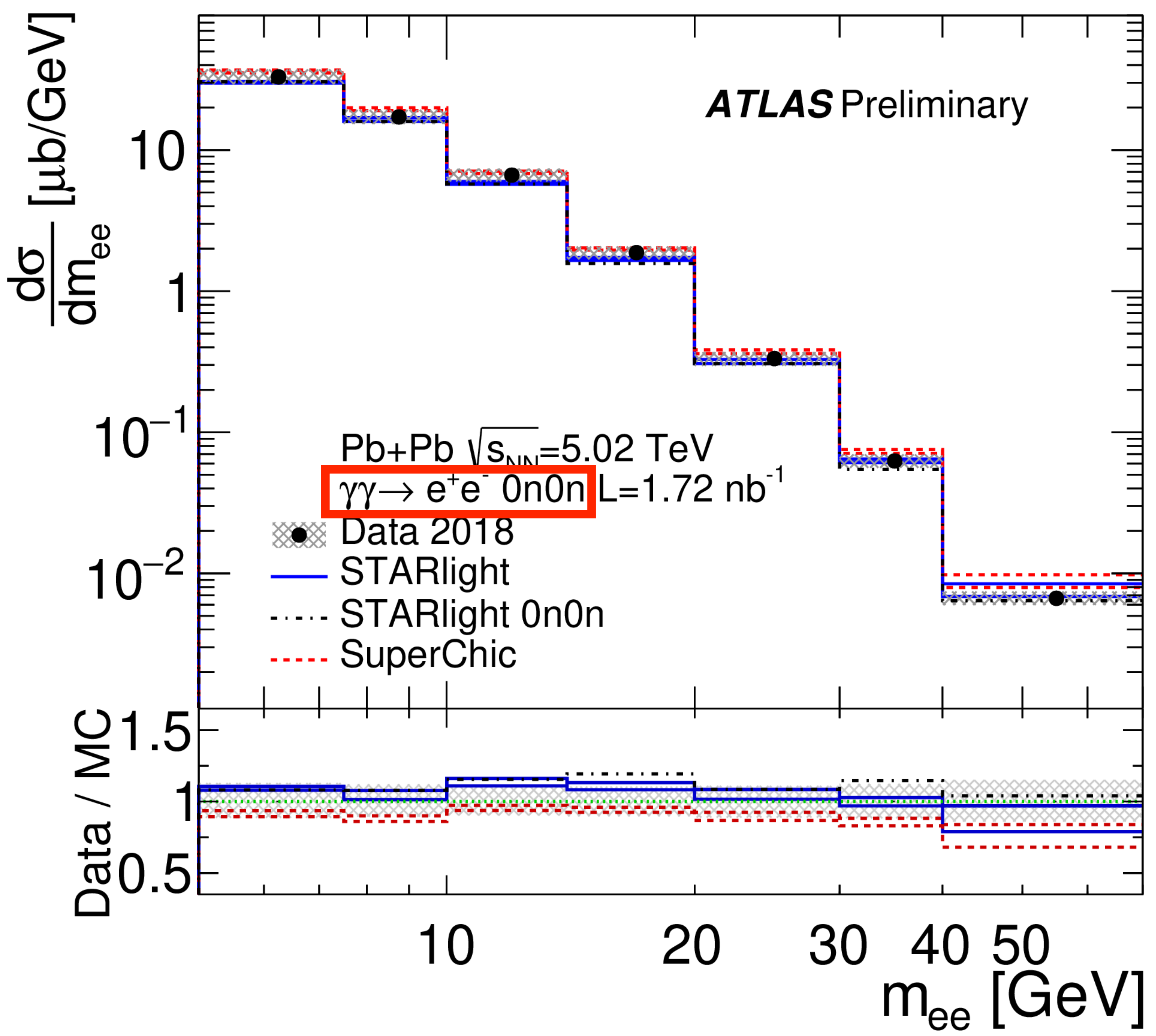




γγ→ee production in Pb+Pb UPC

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

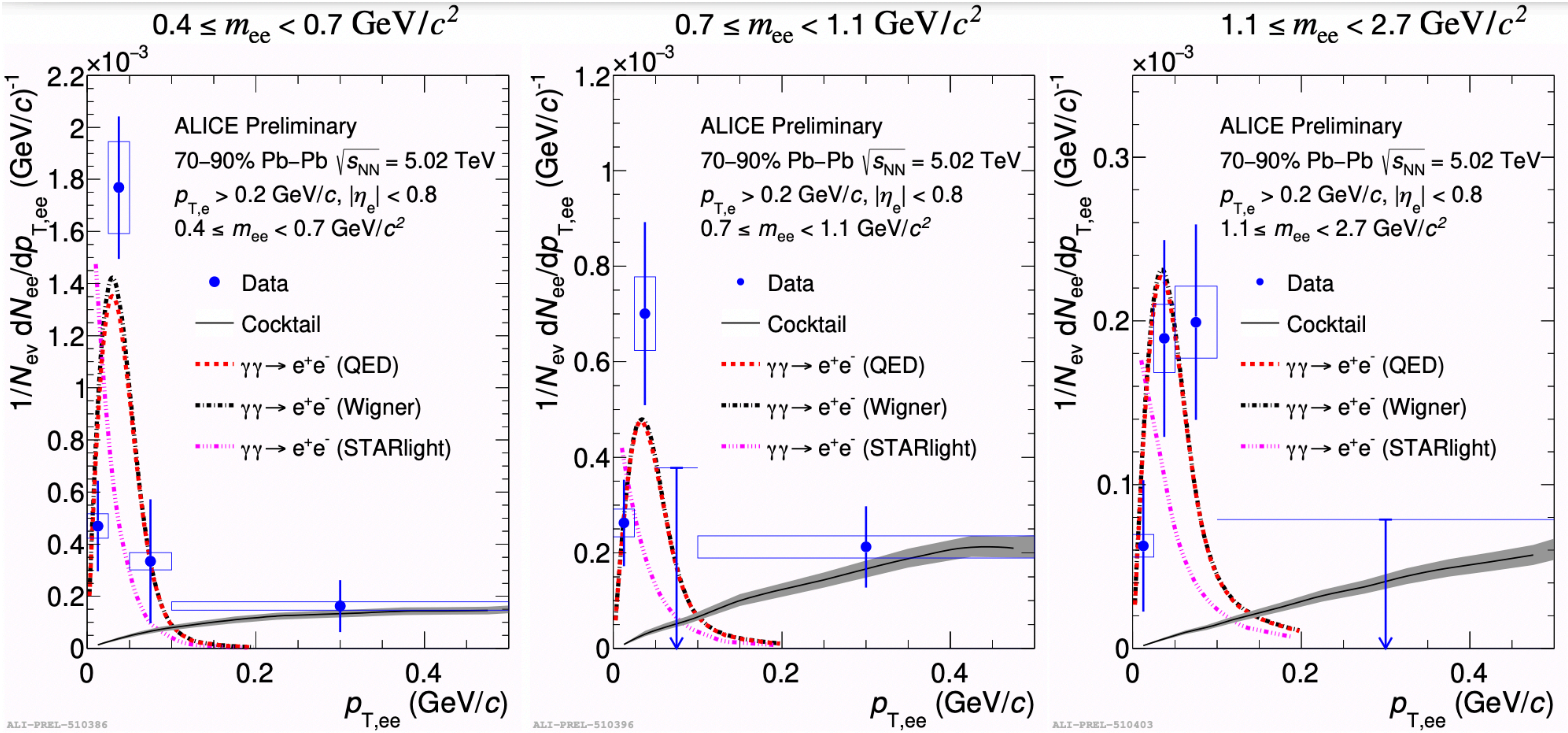




γγ→ll production in non-UPC events

A. Neagu slides

- **ALICE** & STAR exploit low-mass γγ→ll production in peripheral collisions



$\gamma\gamma \rightarrow e^+e^-$ (QED)
W.Zha et al.
PLB 800 (2020) 135089
EPJA 57 (2021) 10, 299

$\gamma\gamma \rightarrow e^+e^-$ (Wigner)
M. Klusek-Gawenda et al.
PLB 814 (2021) 136114

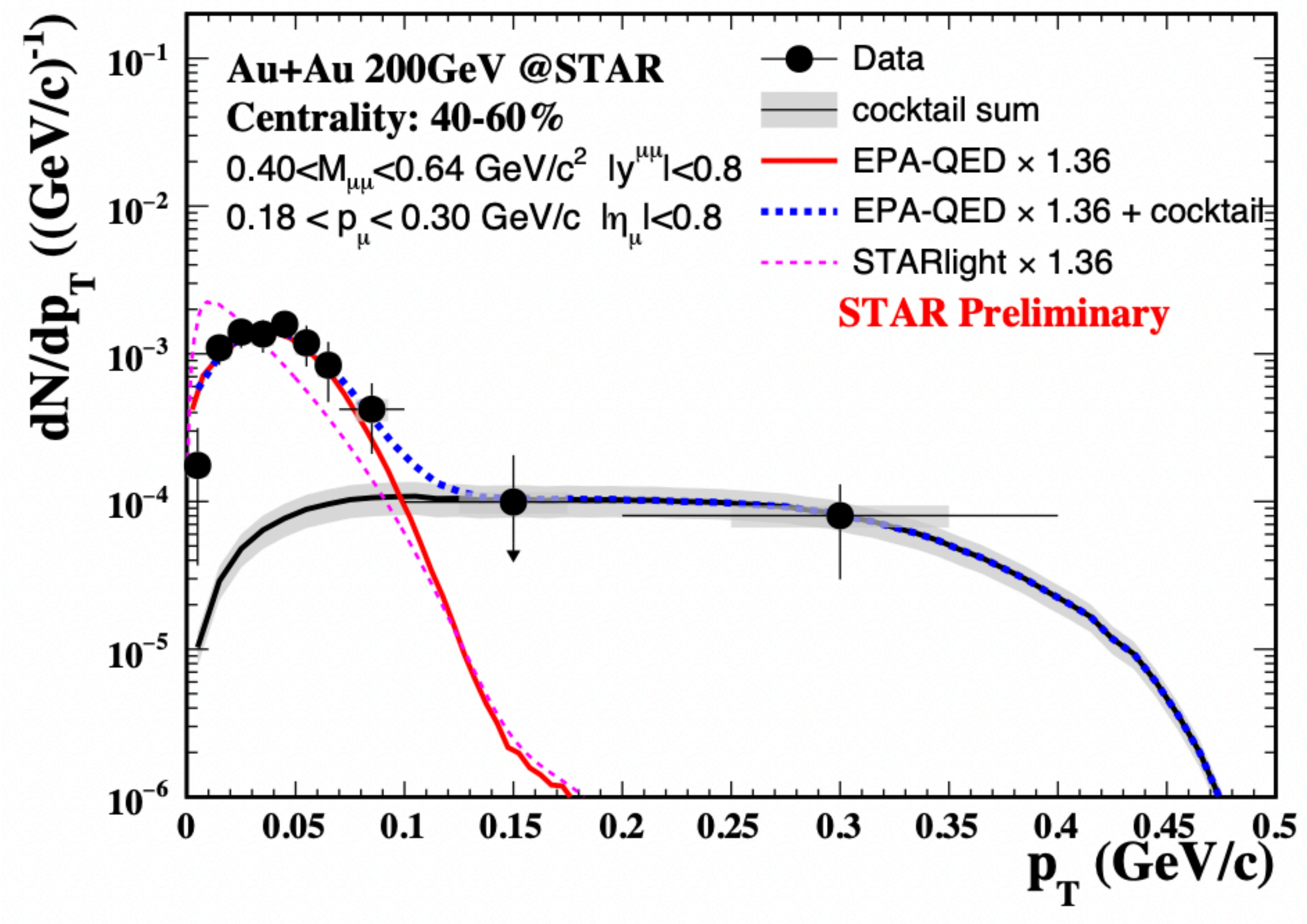
$\gamma\gamma \rightarrow e^+e^-$ (Starlight)
S. Klein et al.
PRC 97 (2018) 5, 054903
CPC 212 (2017) 258-268

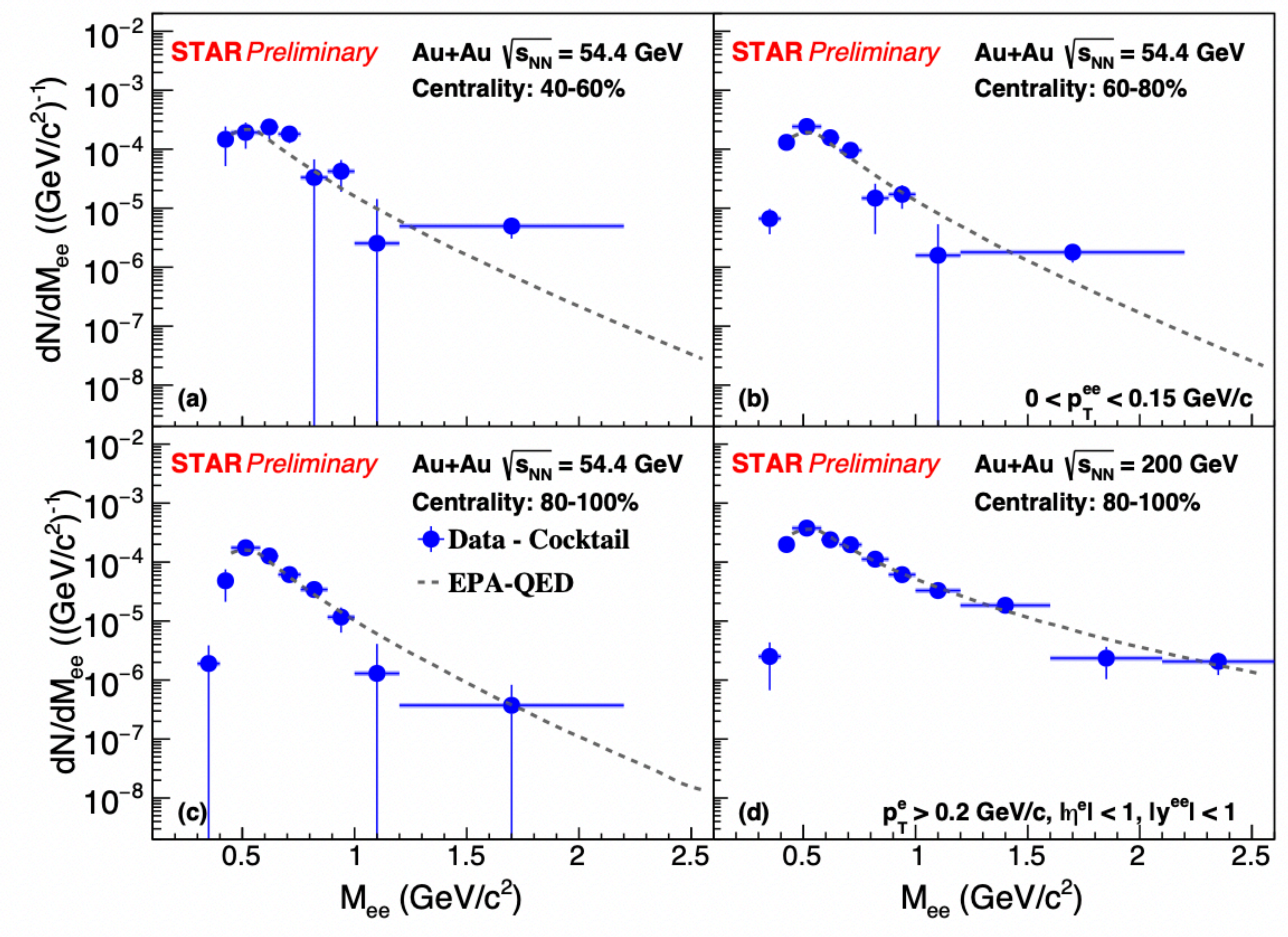
ALICE-PUBLIC-2022-007

γγ→ll production in non-UPC events

X. Wang slides

- ALICE & **STAR** exploit low-mass γγ→ll production in peripheral collisions

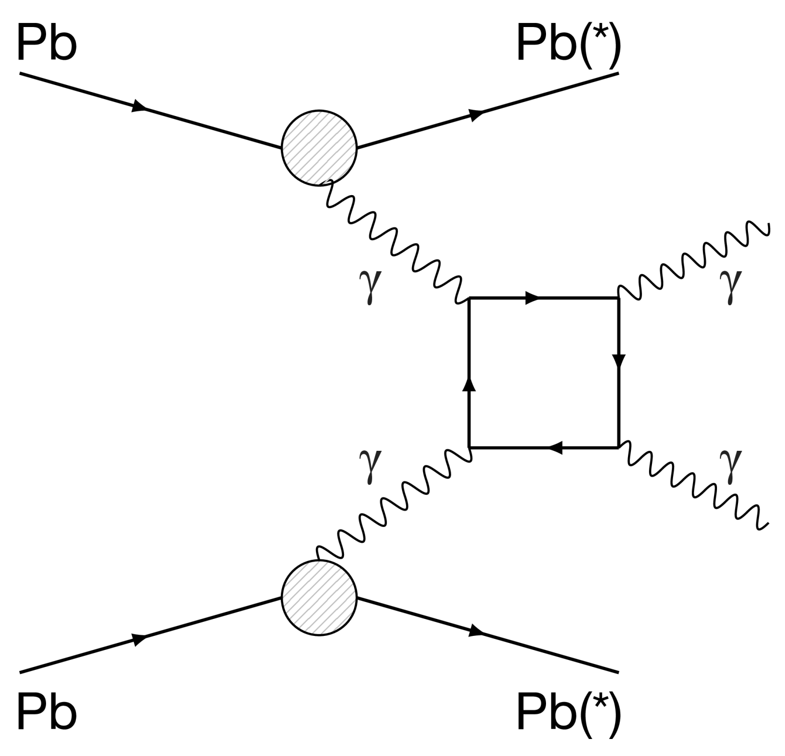


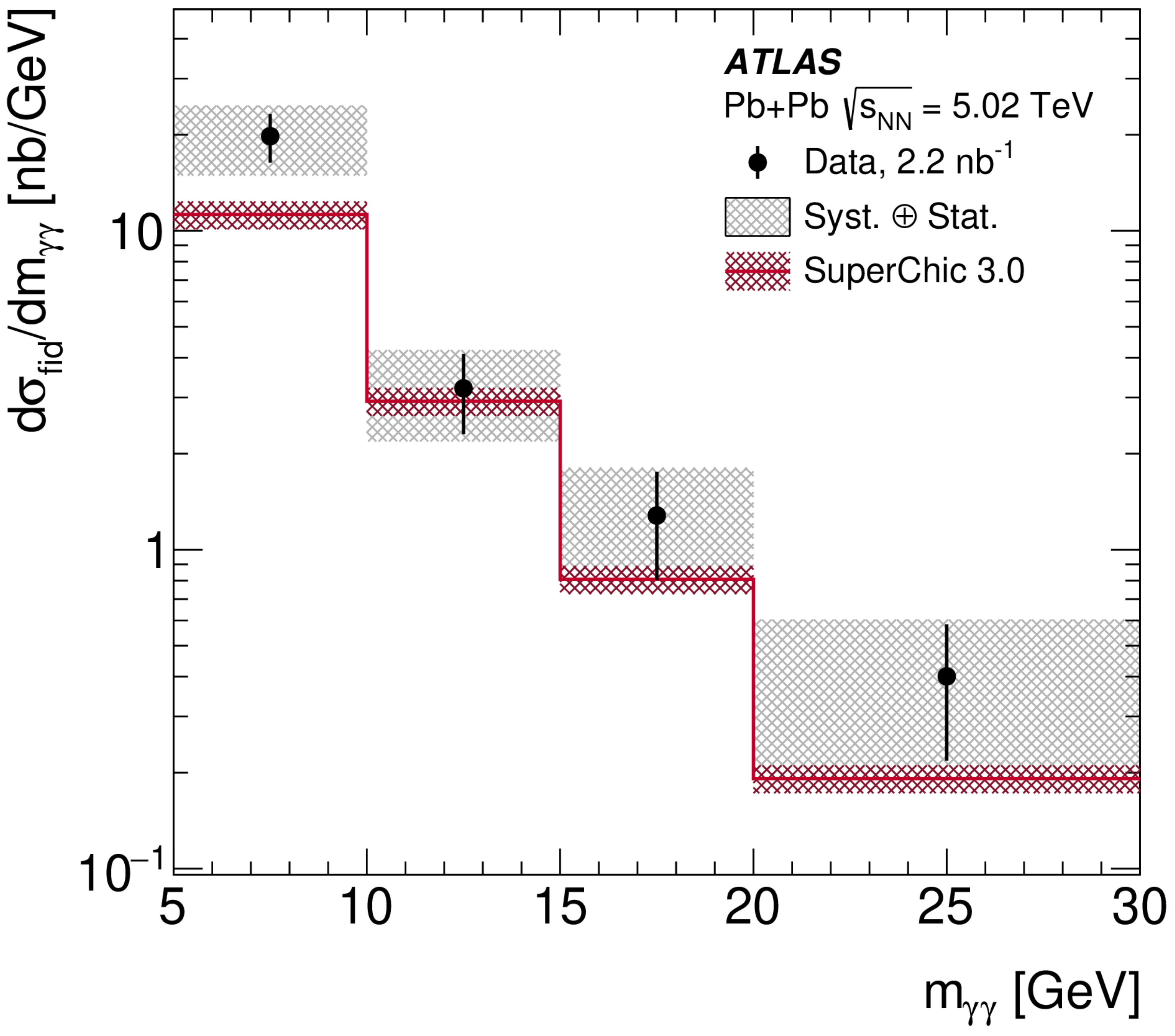


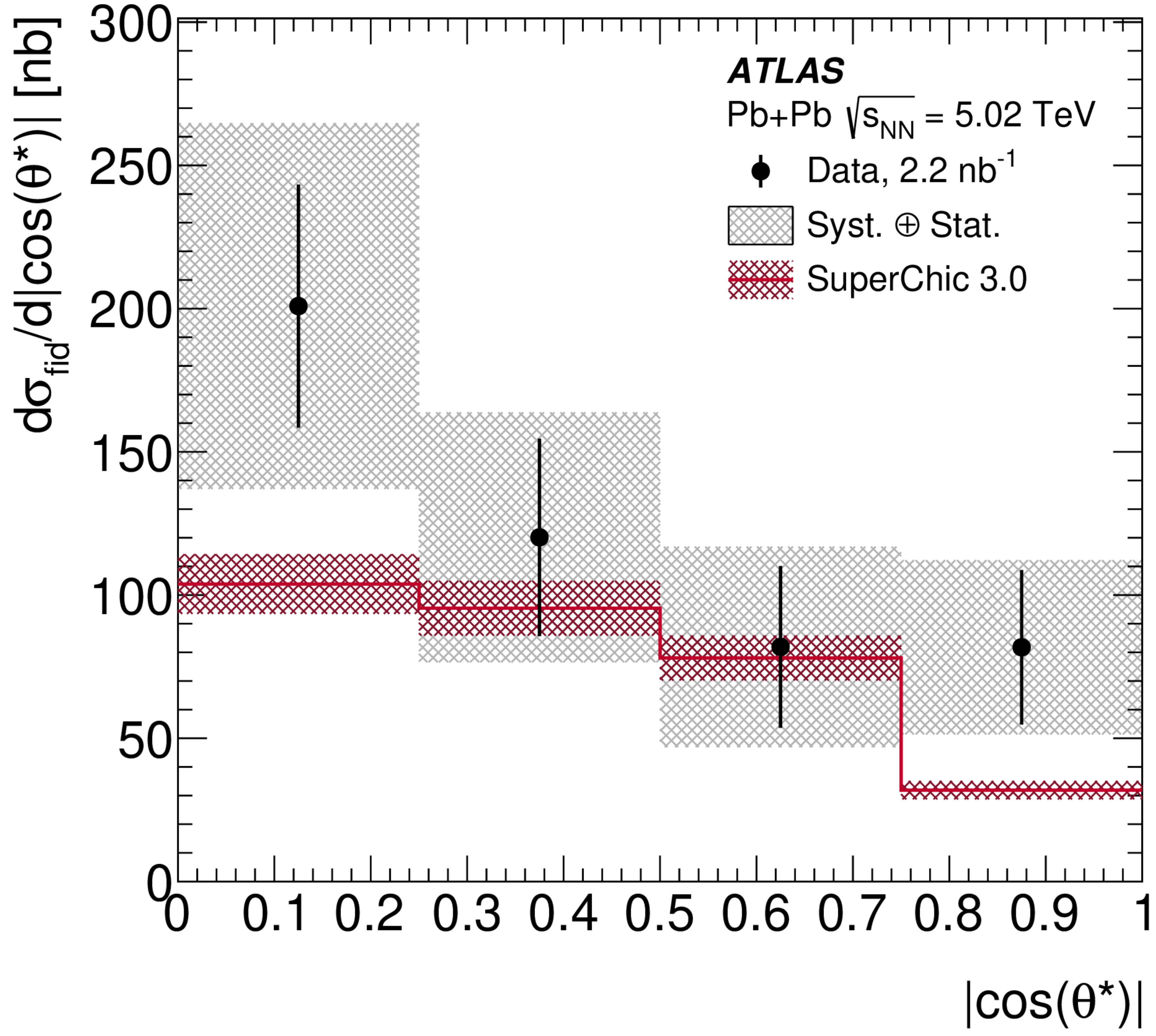
Measurement of light-by-light scattering

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



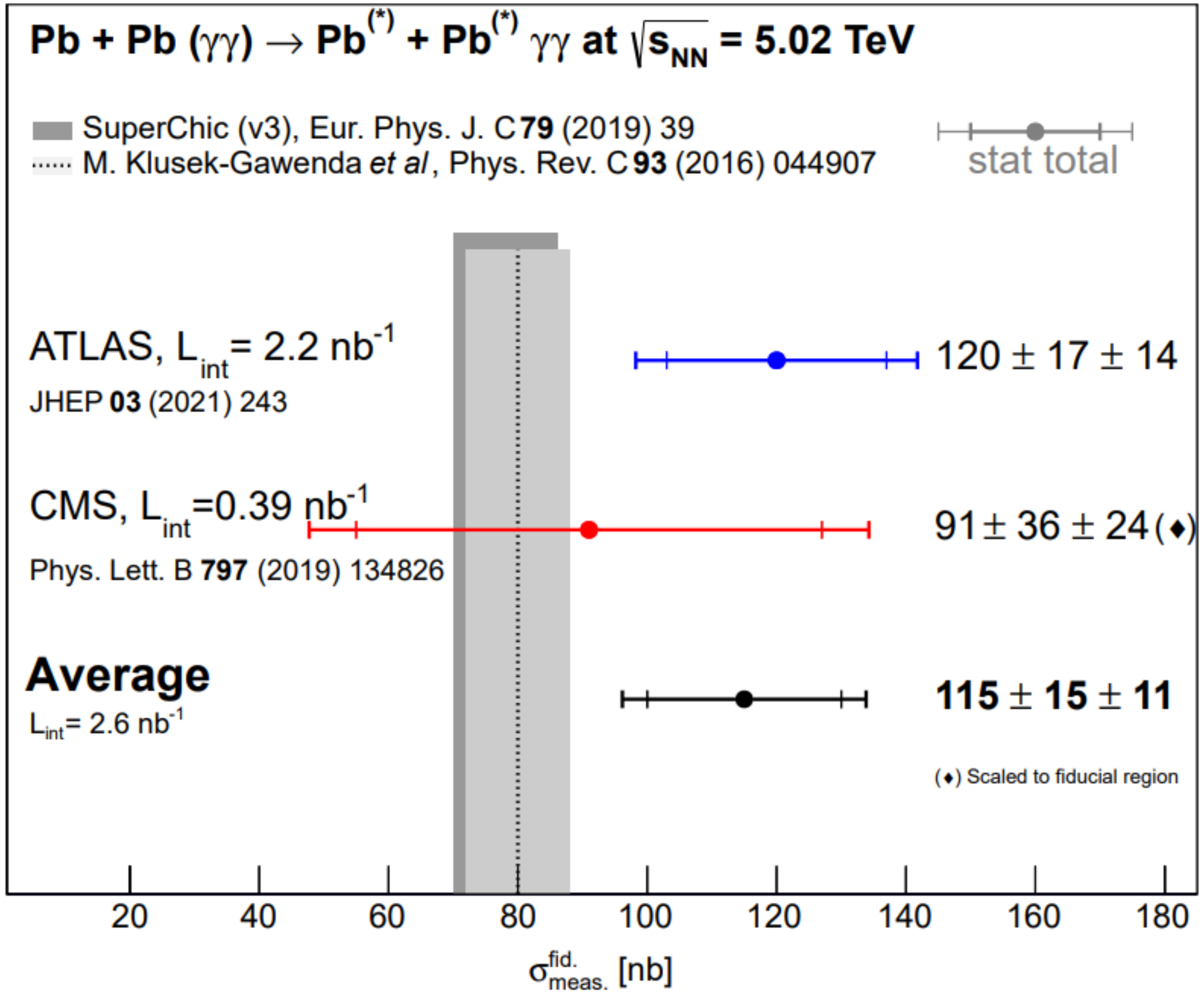




Measurement of light-by-light scattering

Krintiras et al., arXiv:2204.02845

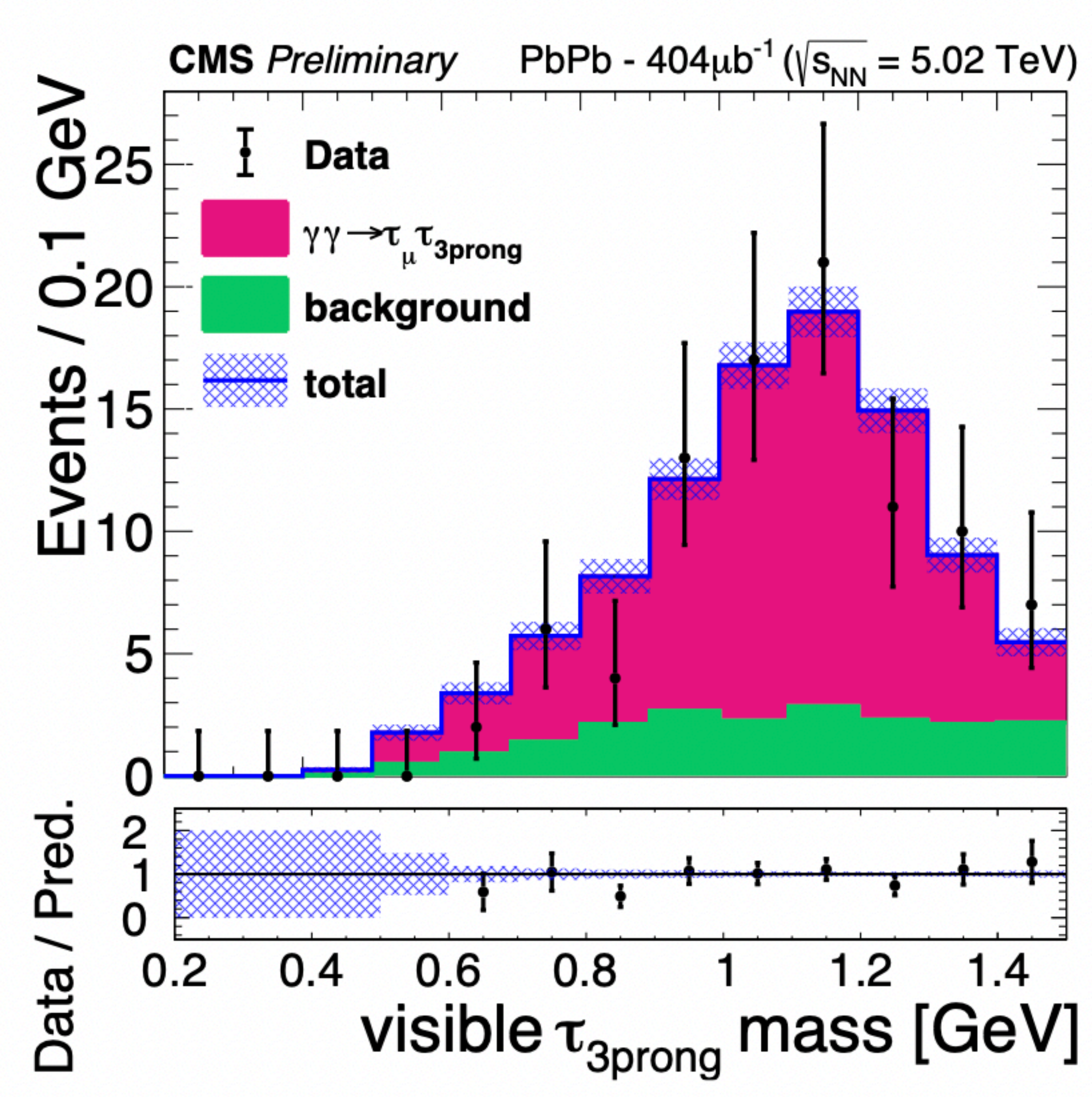
- Combining ATLAS+CMS measurements in a “common” fiducial phase-space

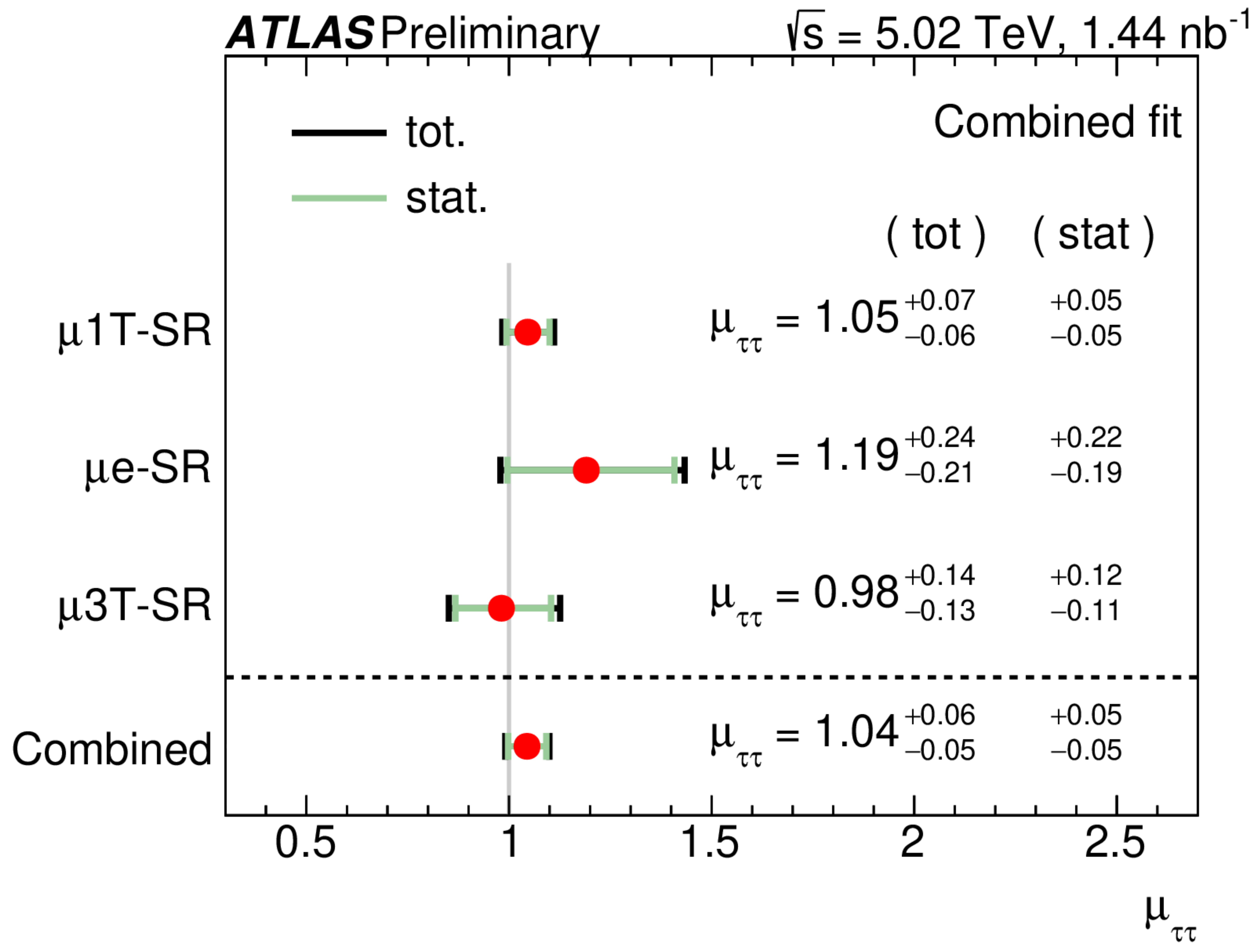


ATLAS: CERN-EP-2022-079
CMS: CMS-PAS-HIN-21-009

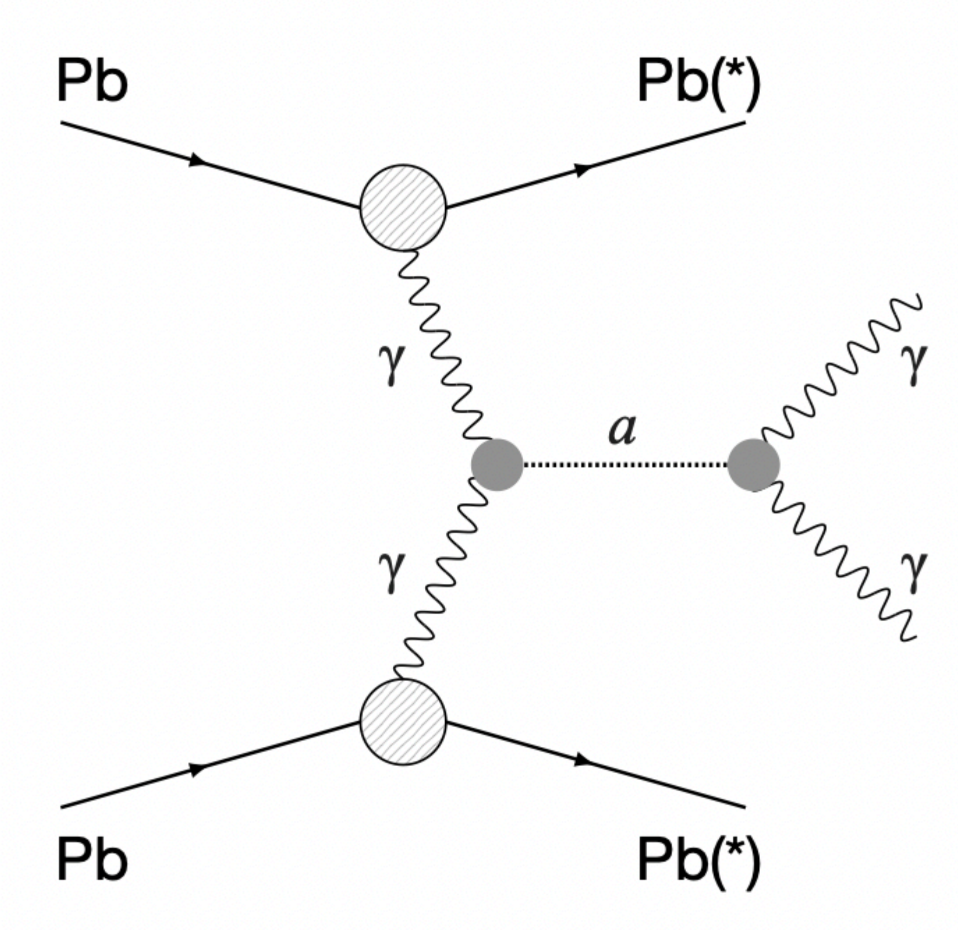
$\gamma\gamma \rightarrow \tau\,\tau$ production in Pb+Pb UPC

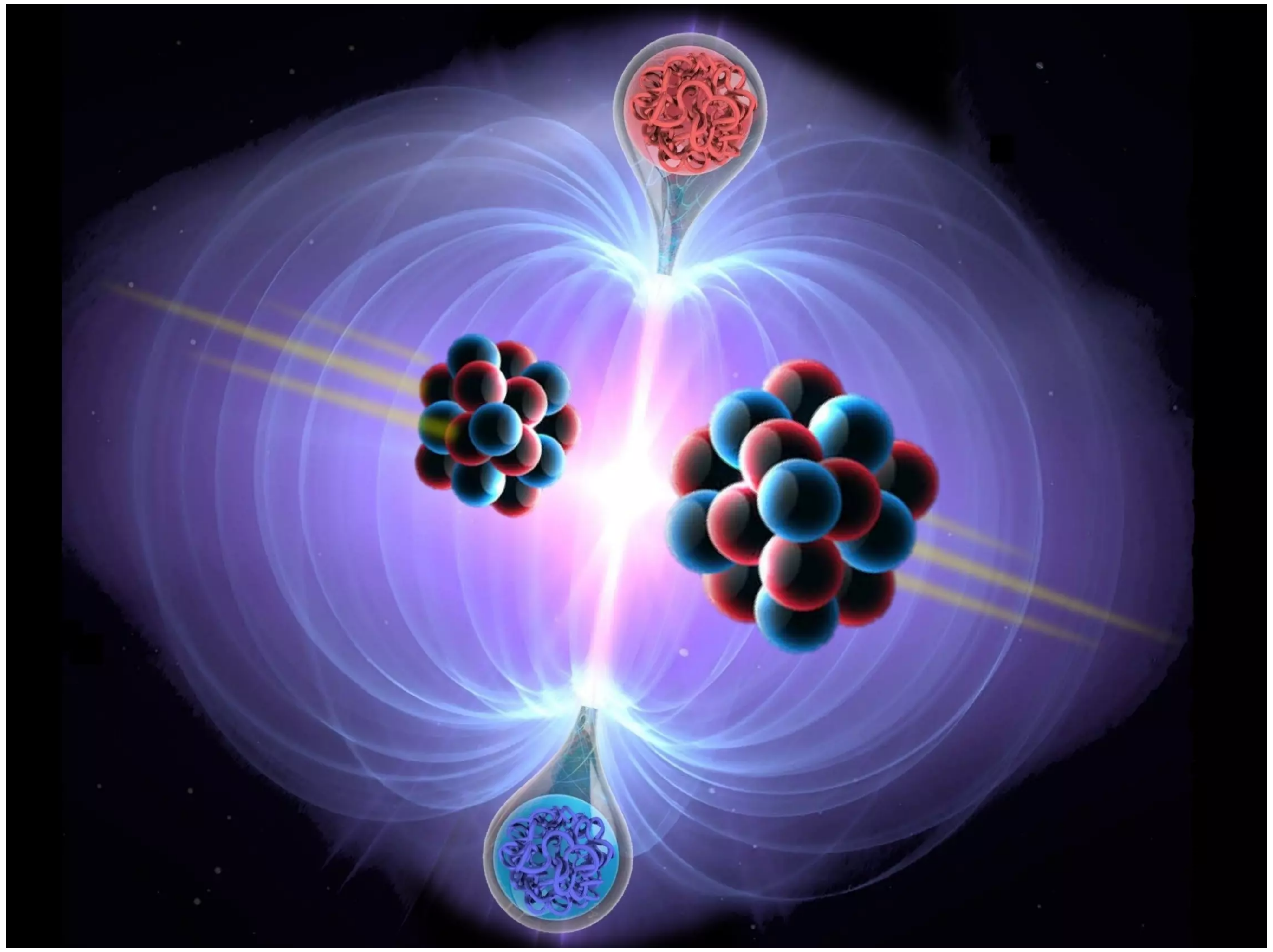
- $\gamma\gamma \rightarrow \tau\,\tau$ production observed for the first time in hadron collisions
  - Targeting mu+3prong decays (CMS) or mu+3prong, mu+1prong and mu+e (ATLAS)
  - CMS: fiducial cross section measured with 16% rel. precision (2015 data)
  - ATLAS: signal strength measured with **5%**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





(III) BSM photon-photon interactions





Constraints on 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

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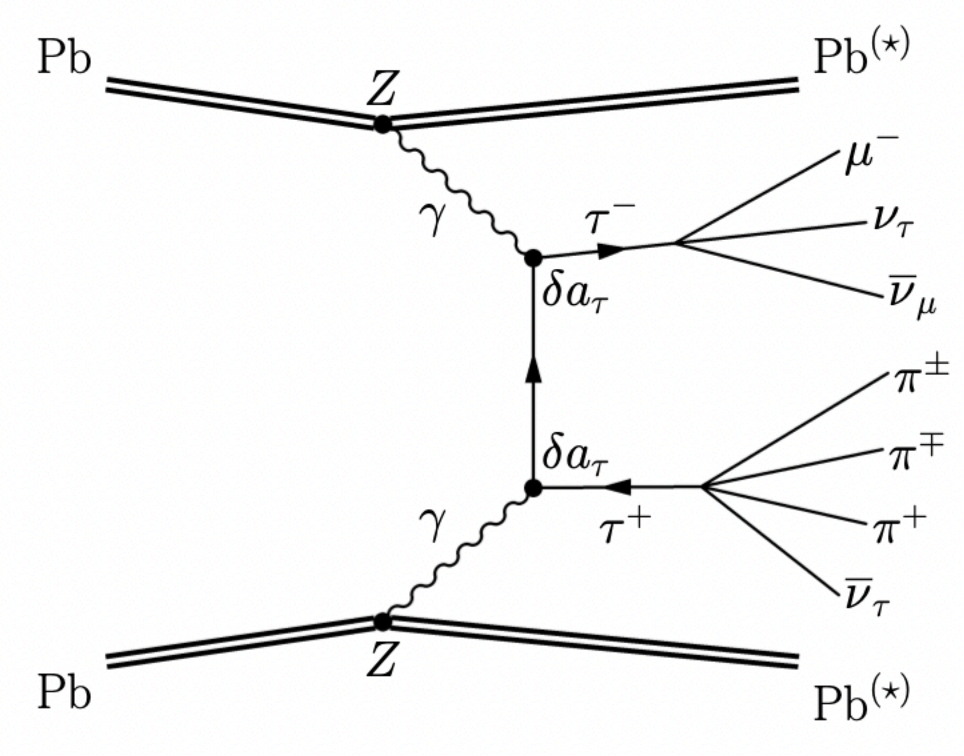
Physics Letters B
Volume 271, Issues 1–2, 14 November 1991, Pages 256-260

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

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

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

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

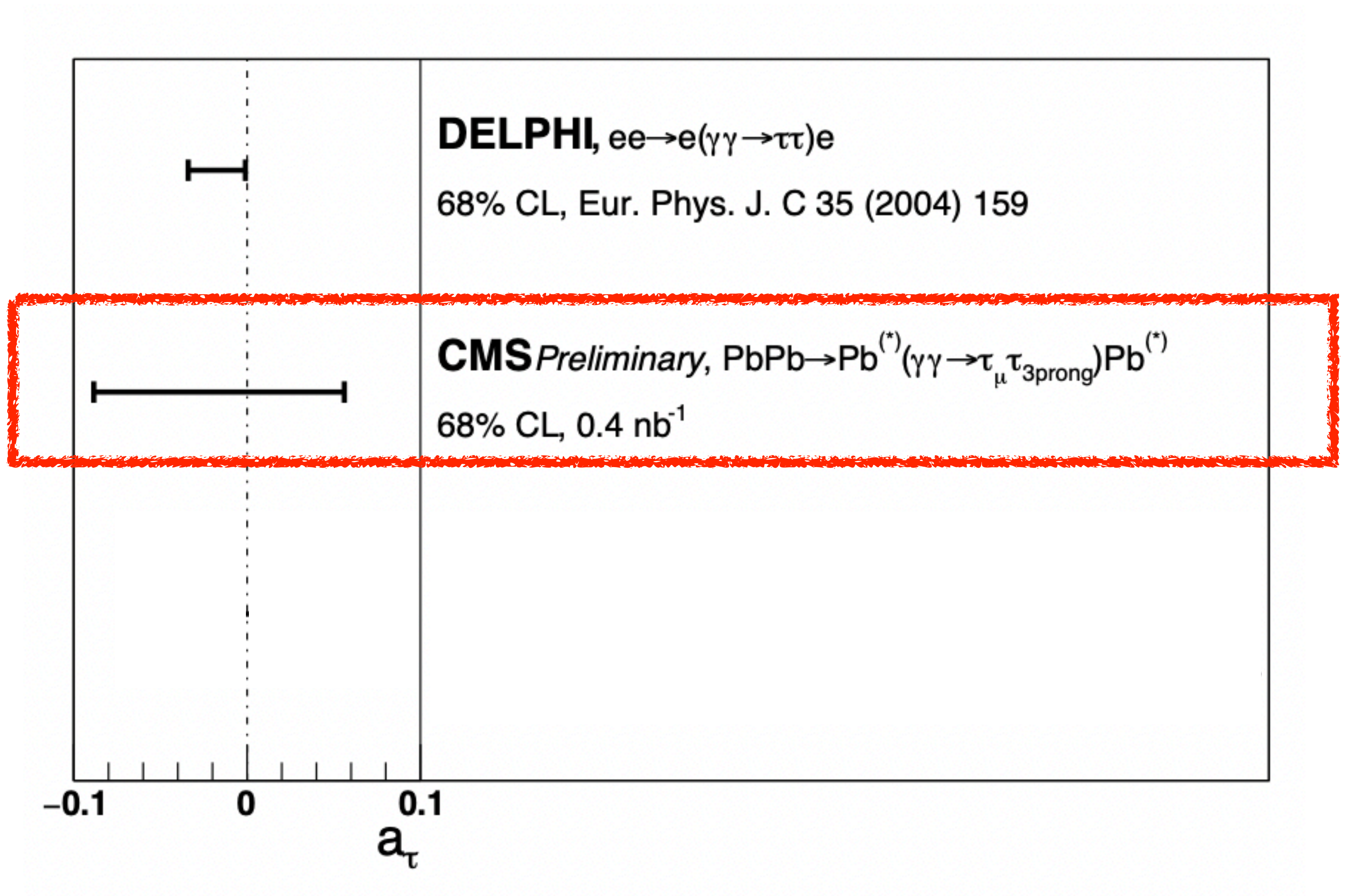
The anomalous magnetic moment of the tau lepton $a_\tau = (g_\tau - 2)/2$ strikingly evades measurement but is highly sensitive to new physics such as compositeness or supersymmetry. We propose using ultraperipheral heavy ion collisions at the LHC to probe modified magnetic δa_τ and electric dipole moments 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.

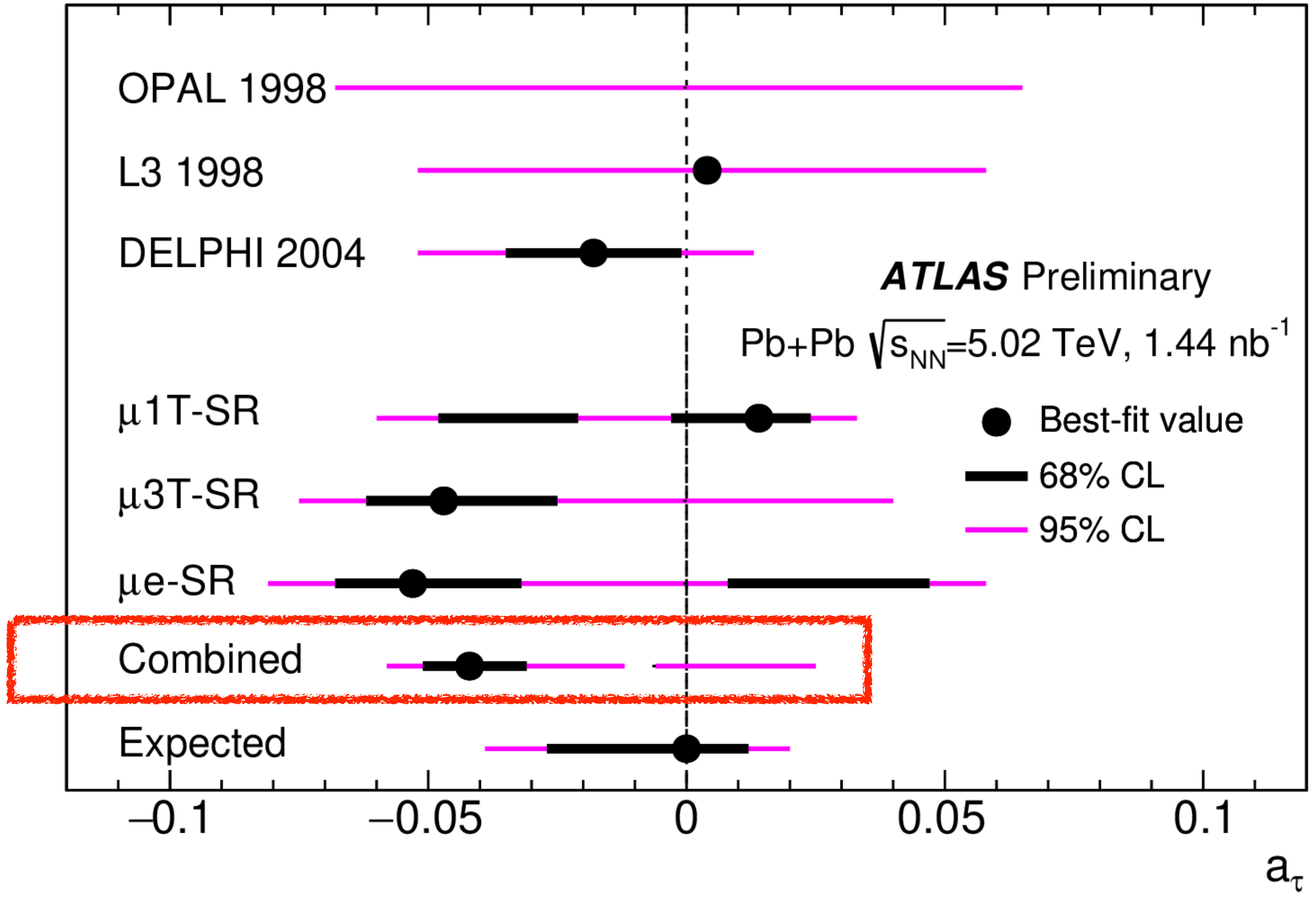
DOI: 10.1103/PhysRevD.102.113008

Constraints on tau anomalous magnetic moment

ATLAS: CERN-EP-2022-079
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





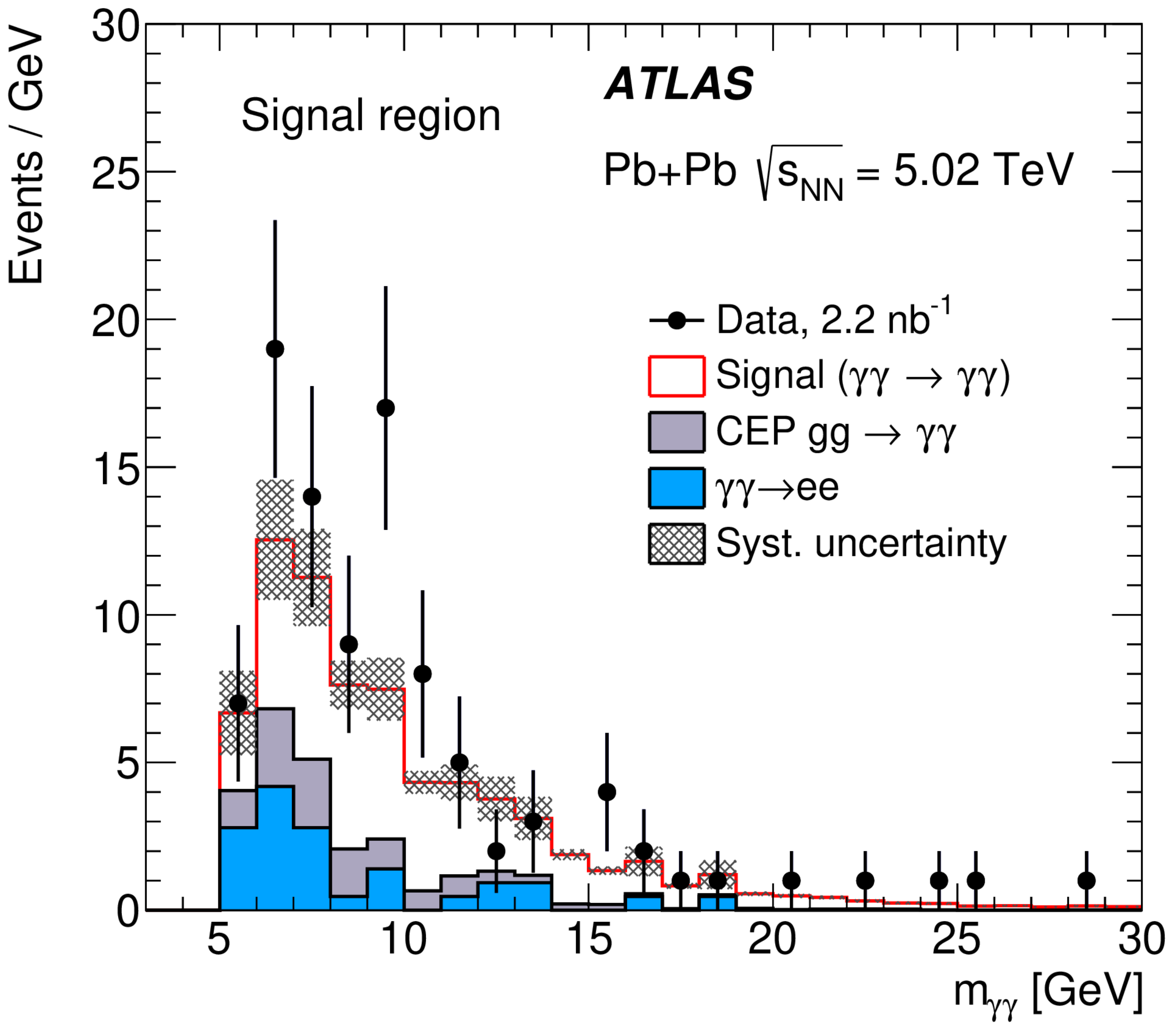
Search for axion-like particles in γγ interactions

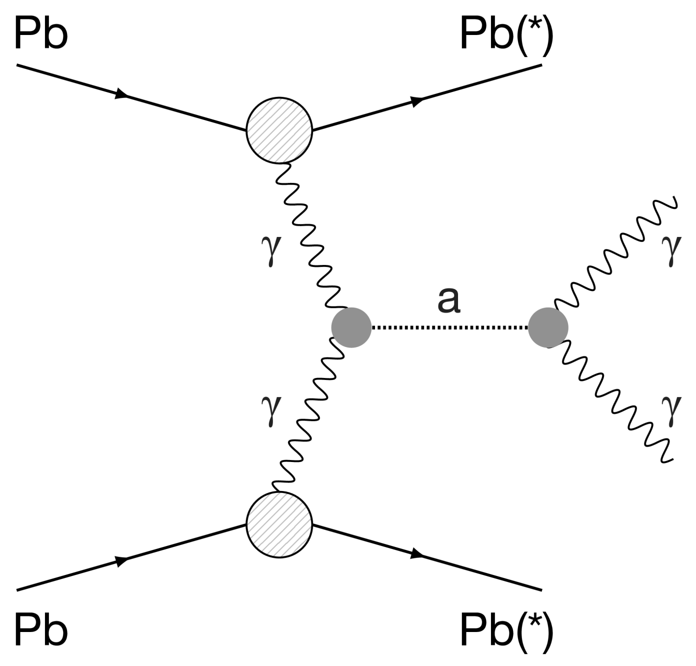
- Light-by-light scattering process signature (γγ→γγ) used to search for ALPs in Pb+Pb collisions
- ATLAS and CMS provide the most stringent limits to date on ALPs for masses in the range 5-100 GeV

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

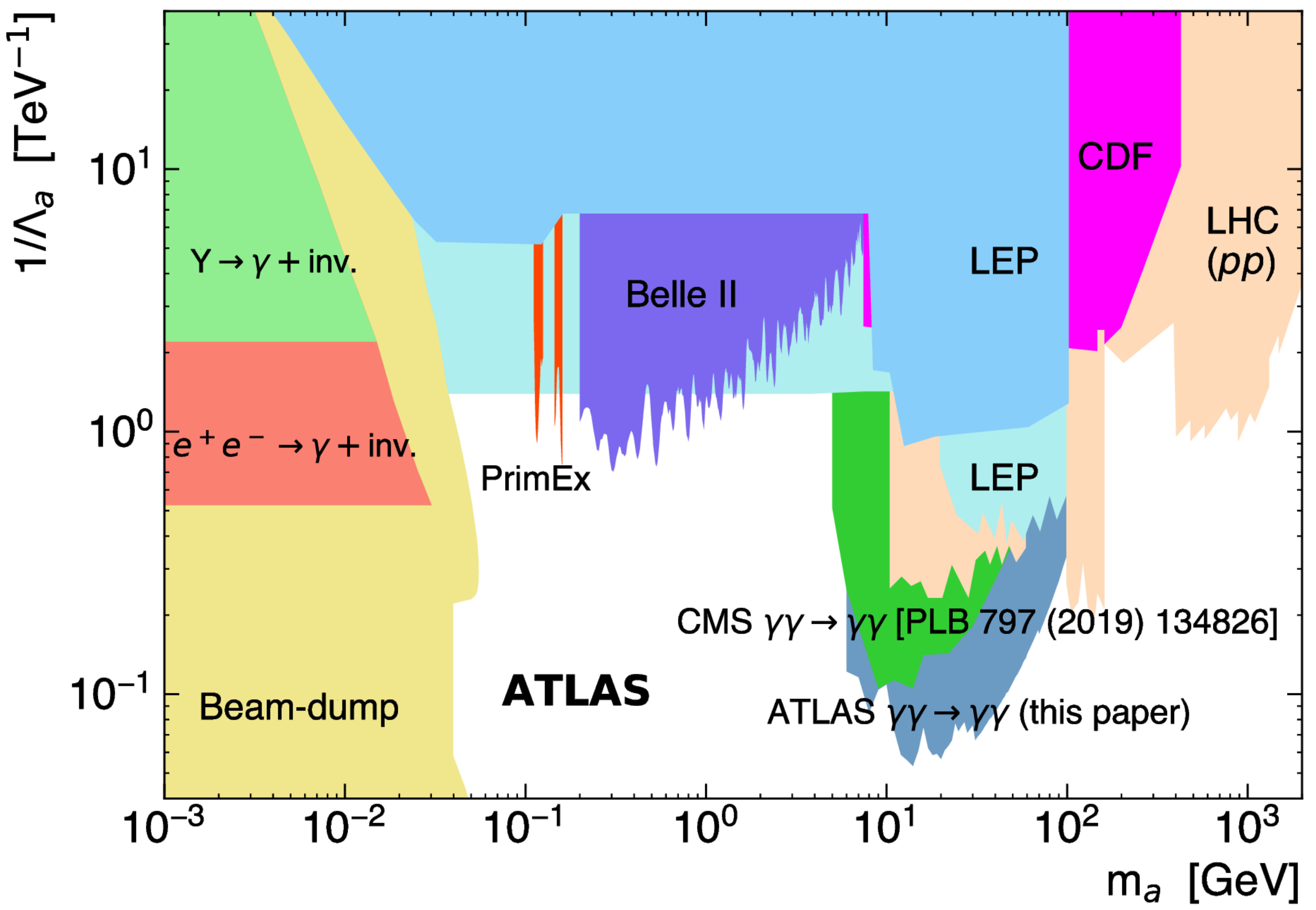
CMS: Phys. Lett. B 797 (2019) 134826

ATLAS: JHEP 03 (2021) 243



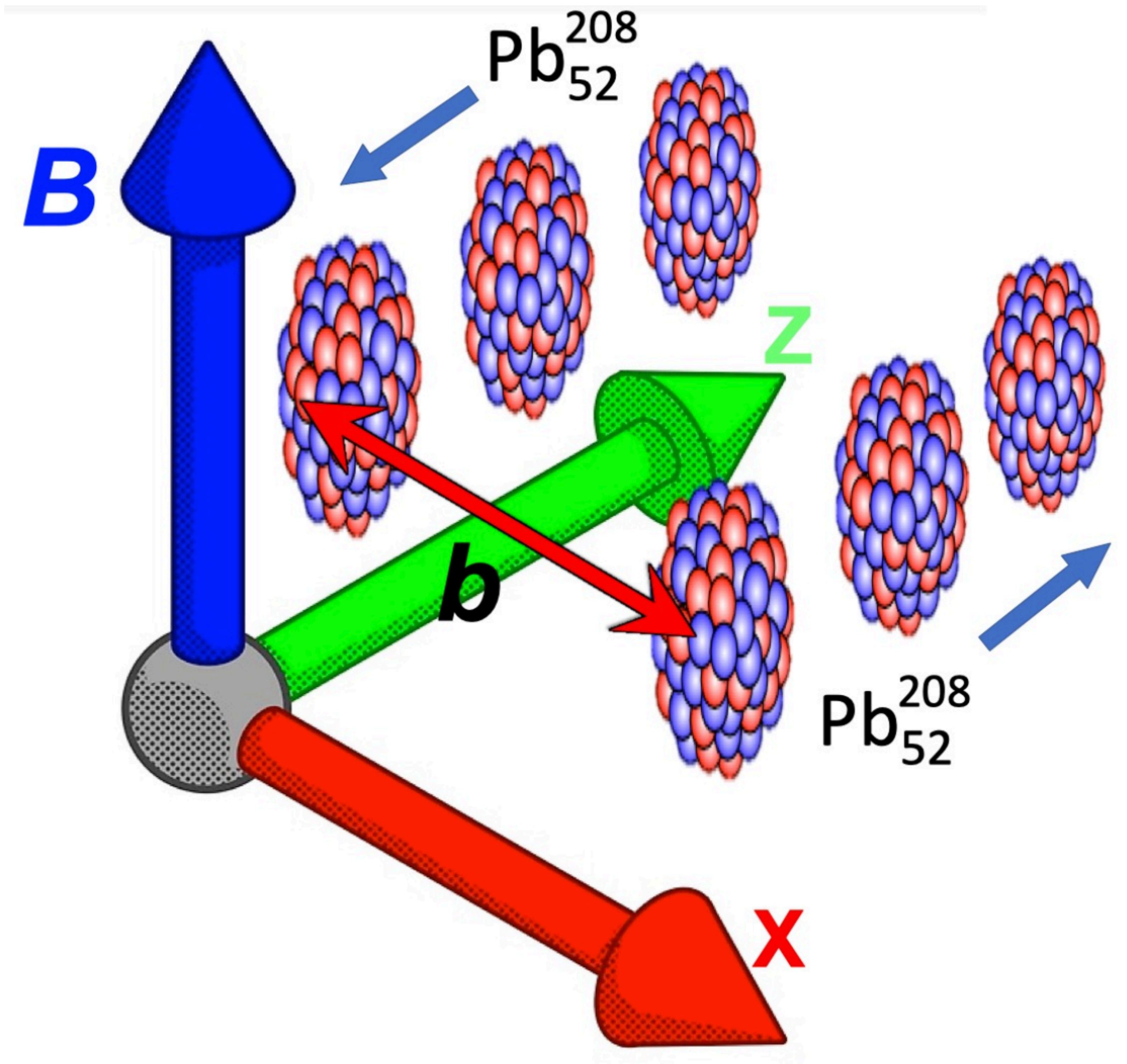


Existing constraints from JHEP 12 (2017) 044



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

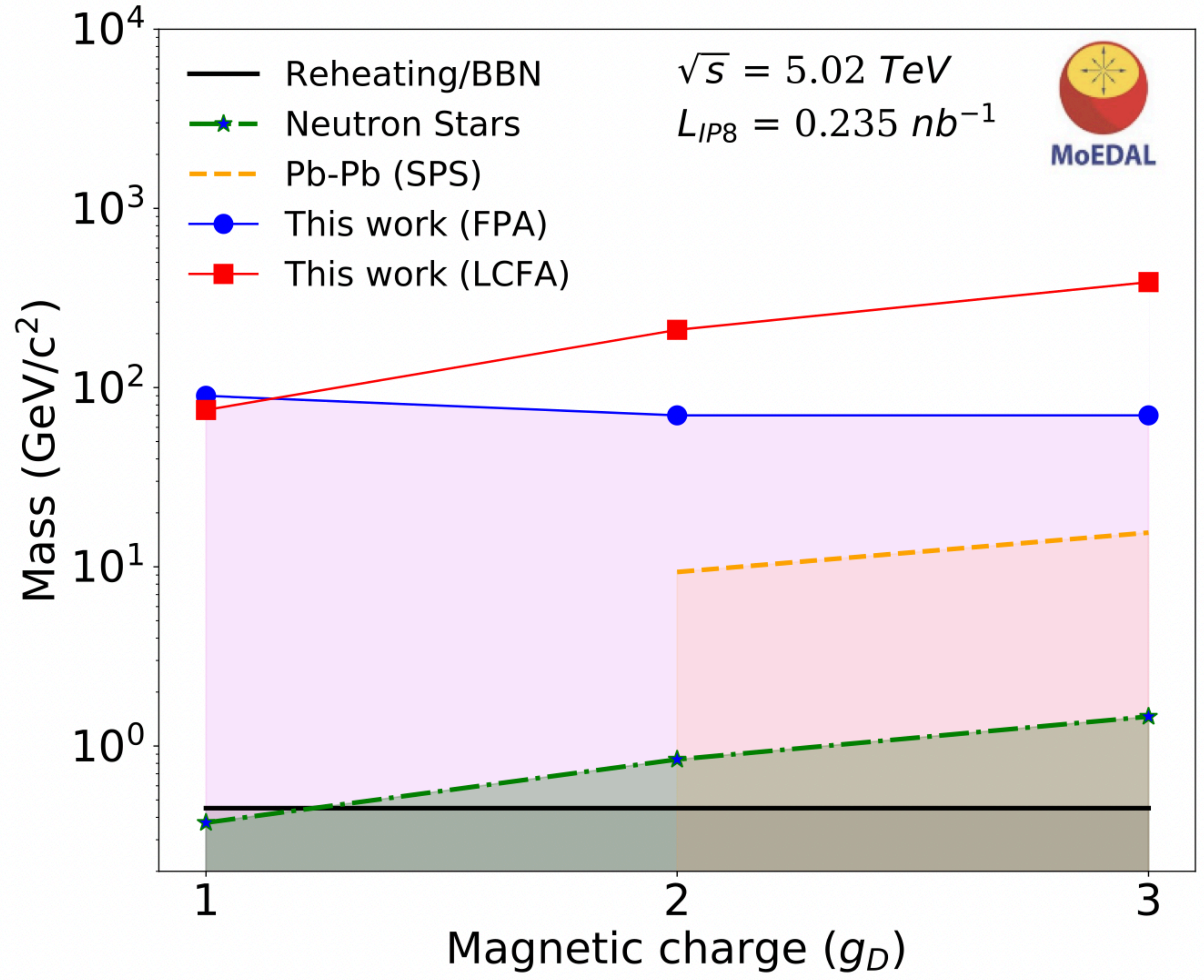
* Drukier, Nussinov, Phys. Rev. Lett. 49, 102 (1982)

Magnetic monopoles via the Schwinger production

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



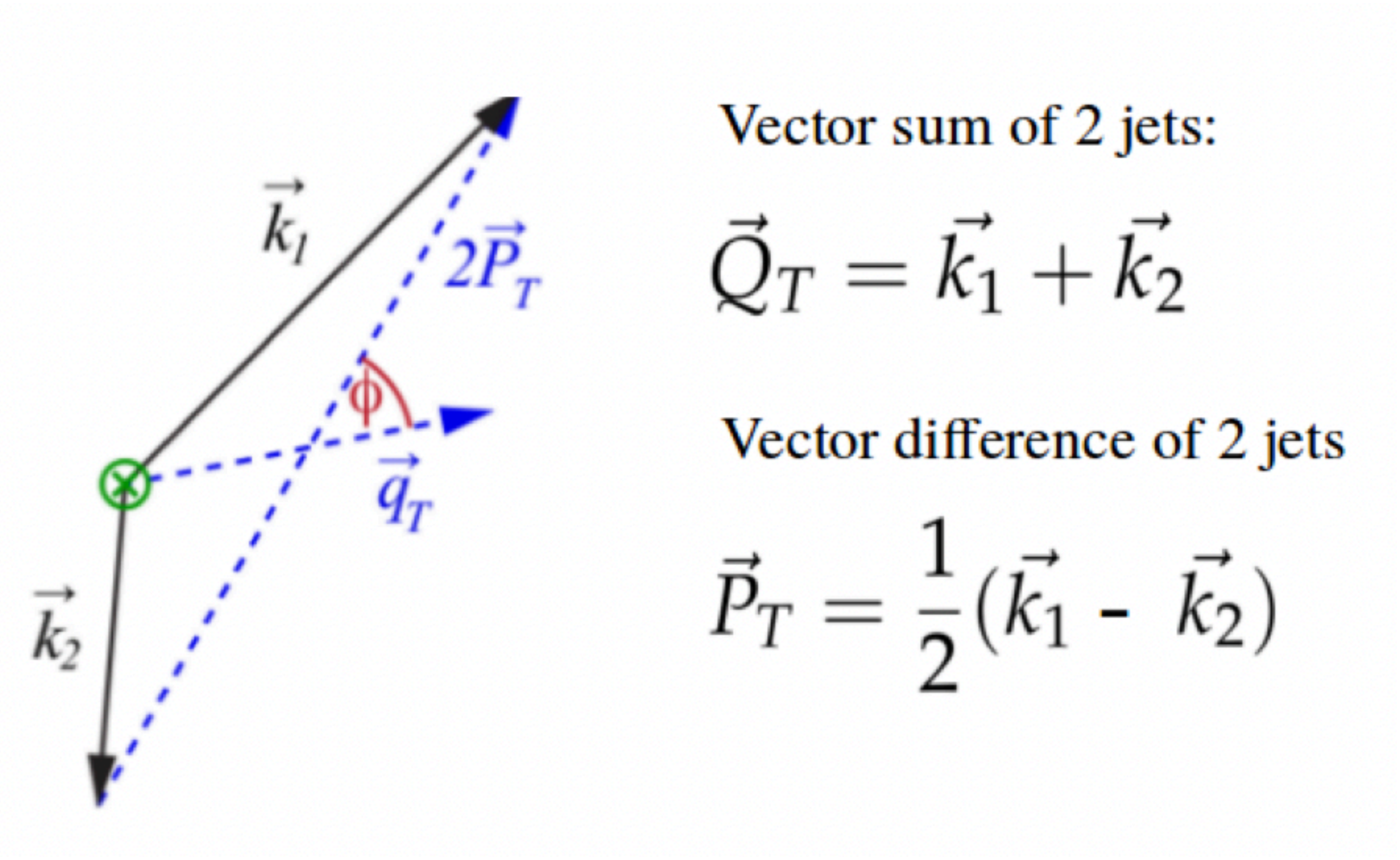
Summary

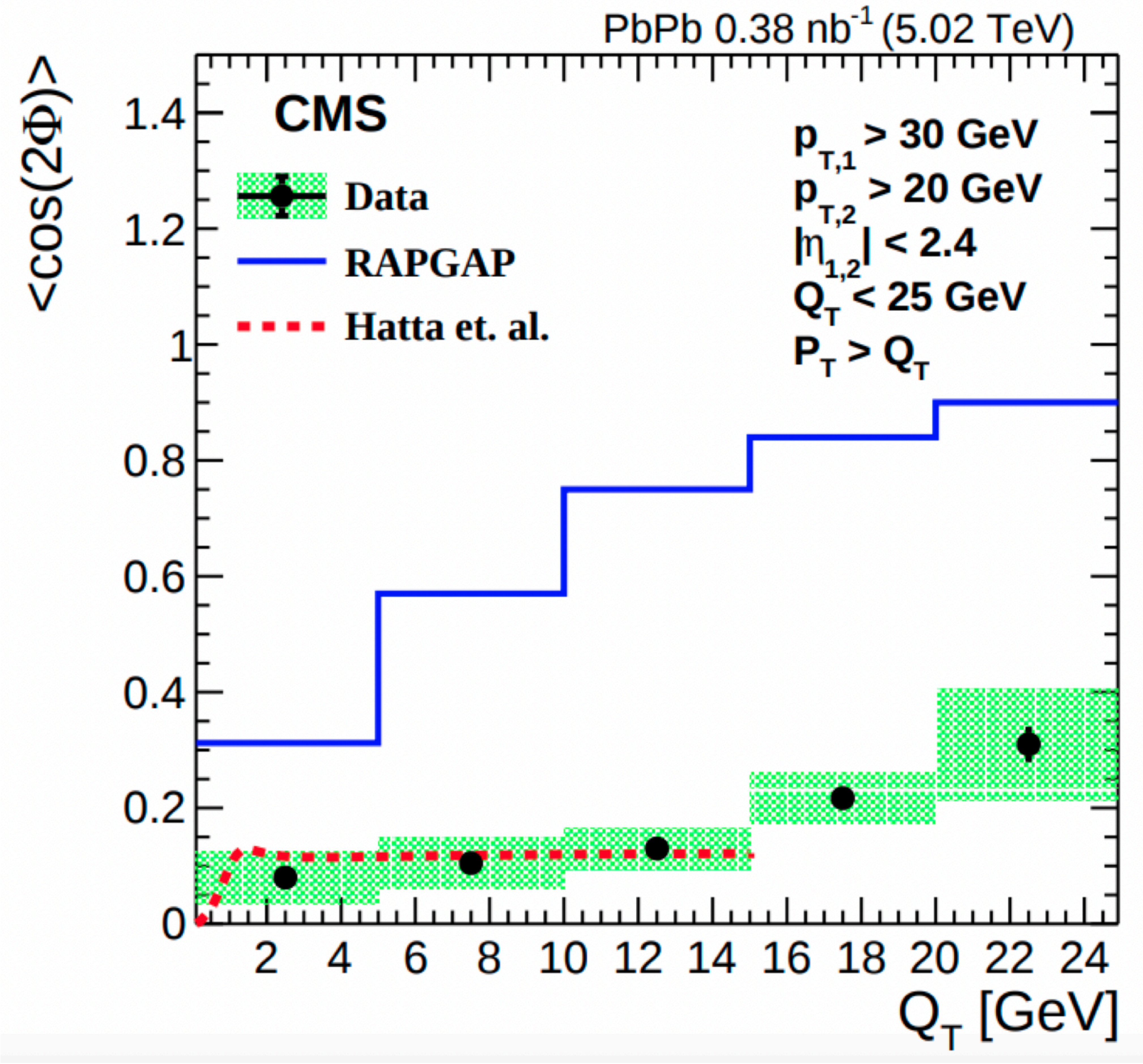
- Rich physics programme of UPC collisions at hadron colliders
- Coherent VM production
  - Abundant rate, down to the most central collisions!
  - Precision extraction of nuclear radii possible
- Interesting opportunities to further explore photo-nuclear interactions
  - Unique environment to test the collective phenomena in small systems
  - dijet production -> potential to constrain nPDFs, small-x gluon tomography
  - …
- HI UPC 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
- Good progress in theory/pheno calculations
  - Further developments crucial to understand the measurements better!

Backup

Diffractive photo-nuclear dijets in Pb+Pb

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

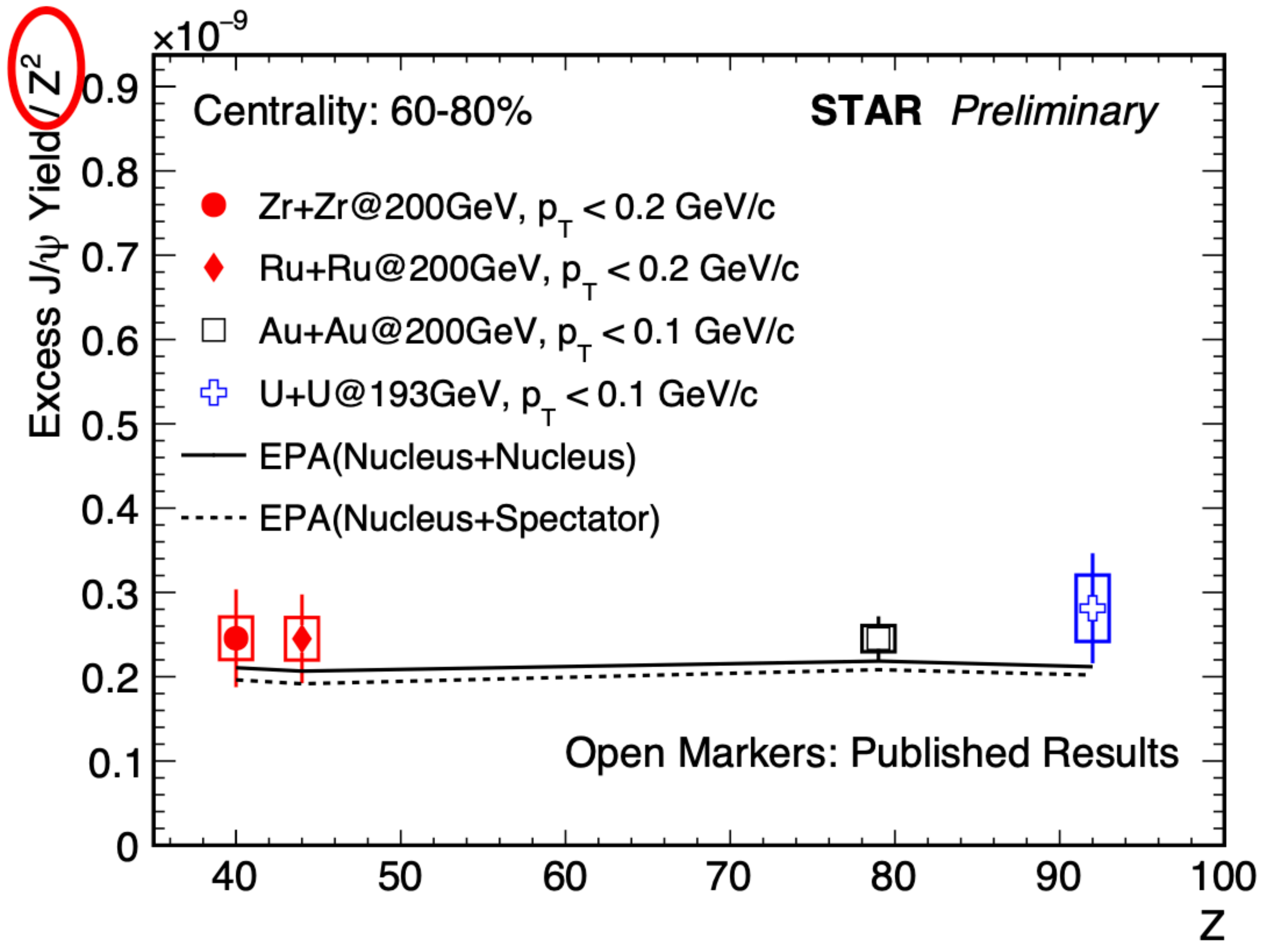




QT is the proxy for recoil momentum of Pb target

J/ψ photo-production in non-UPC: Collision Species Dependence

- Coherent J/ψ measurements in Ru+Ru, Zr+Zr, Au+Au and U+U at STAR
- Yields seem to be independent of form factor and impact parameter

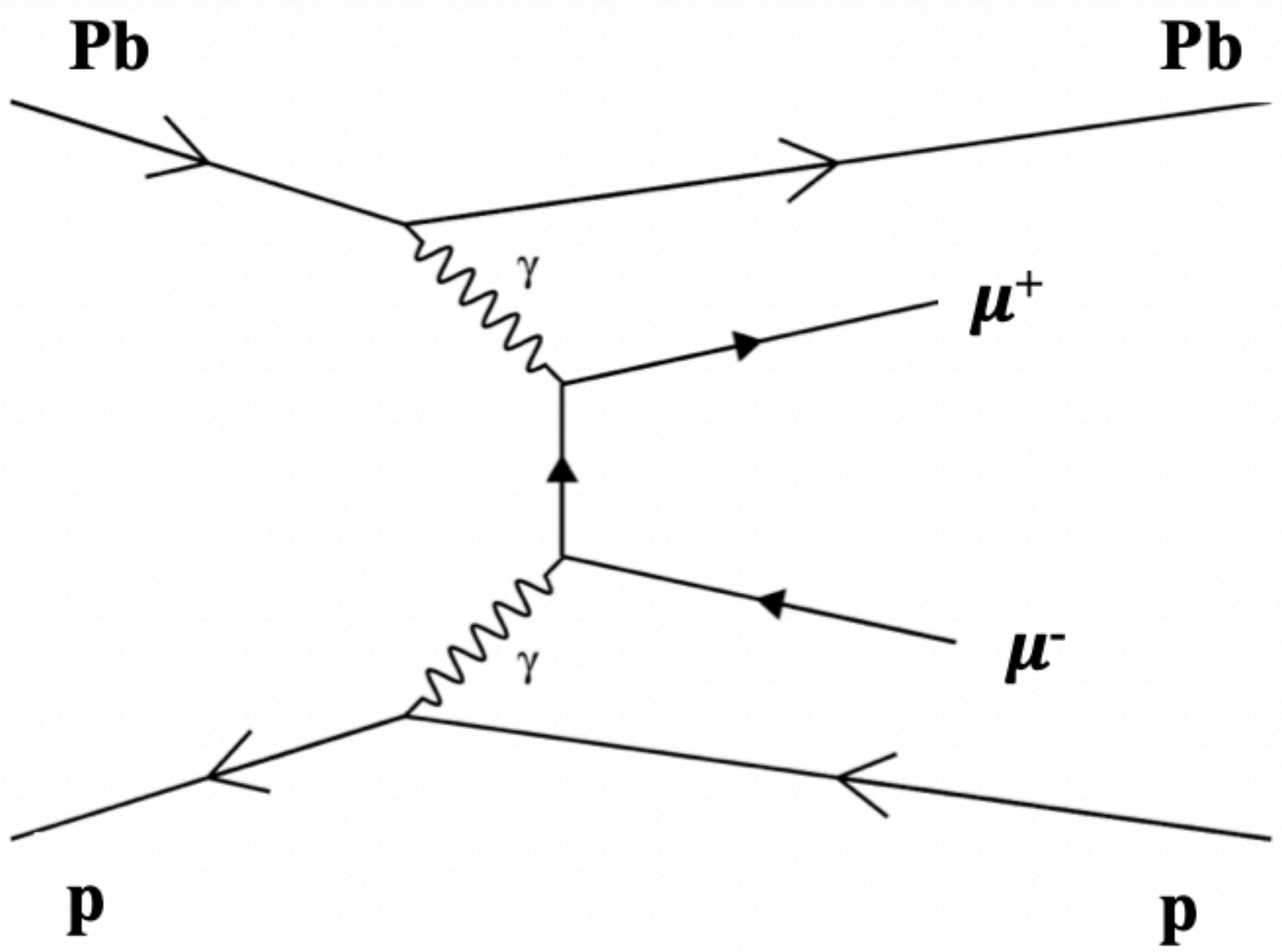


$\gamma\gamma \rightarrow \mu\mu$ cross section

- $\gamma\gamma \rightarrow \mu\mu$ cross section in the **low mass** region!
- STARlight:
  - LO QED without final-state radiation or other NLO effects
  - No interactions within the radius of the targets

→ **Slight excess in data agreement within 3 sigma**

- Can be used to improve current models
  - **Fix background** for VM or jet **photoproduction**
  - Improve predictions for **light-by-light scattering**



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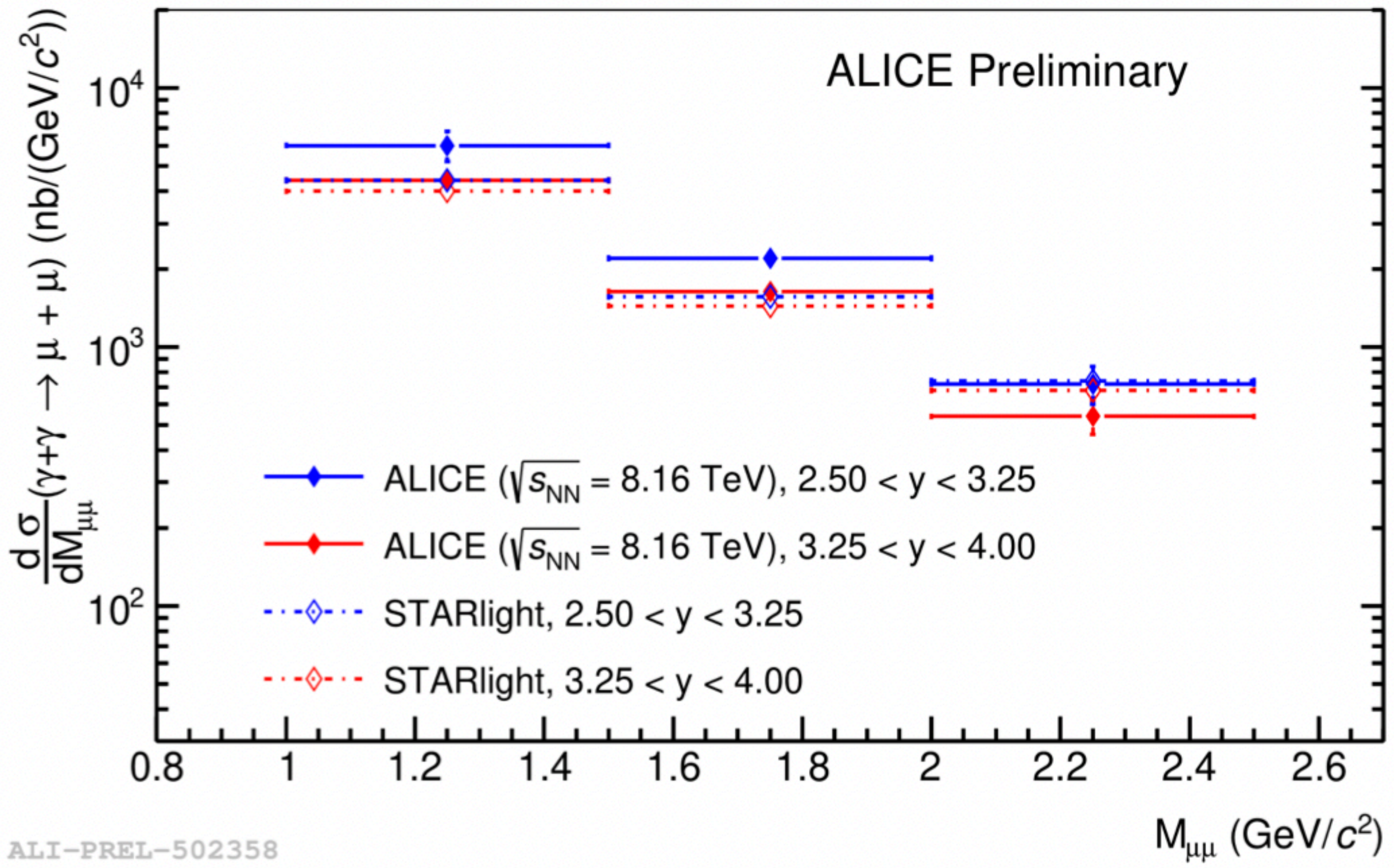


Azimuthal anisotropies in γPb

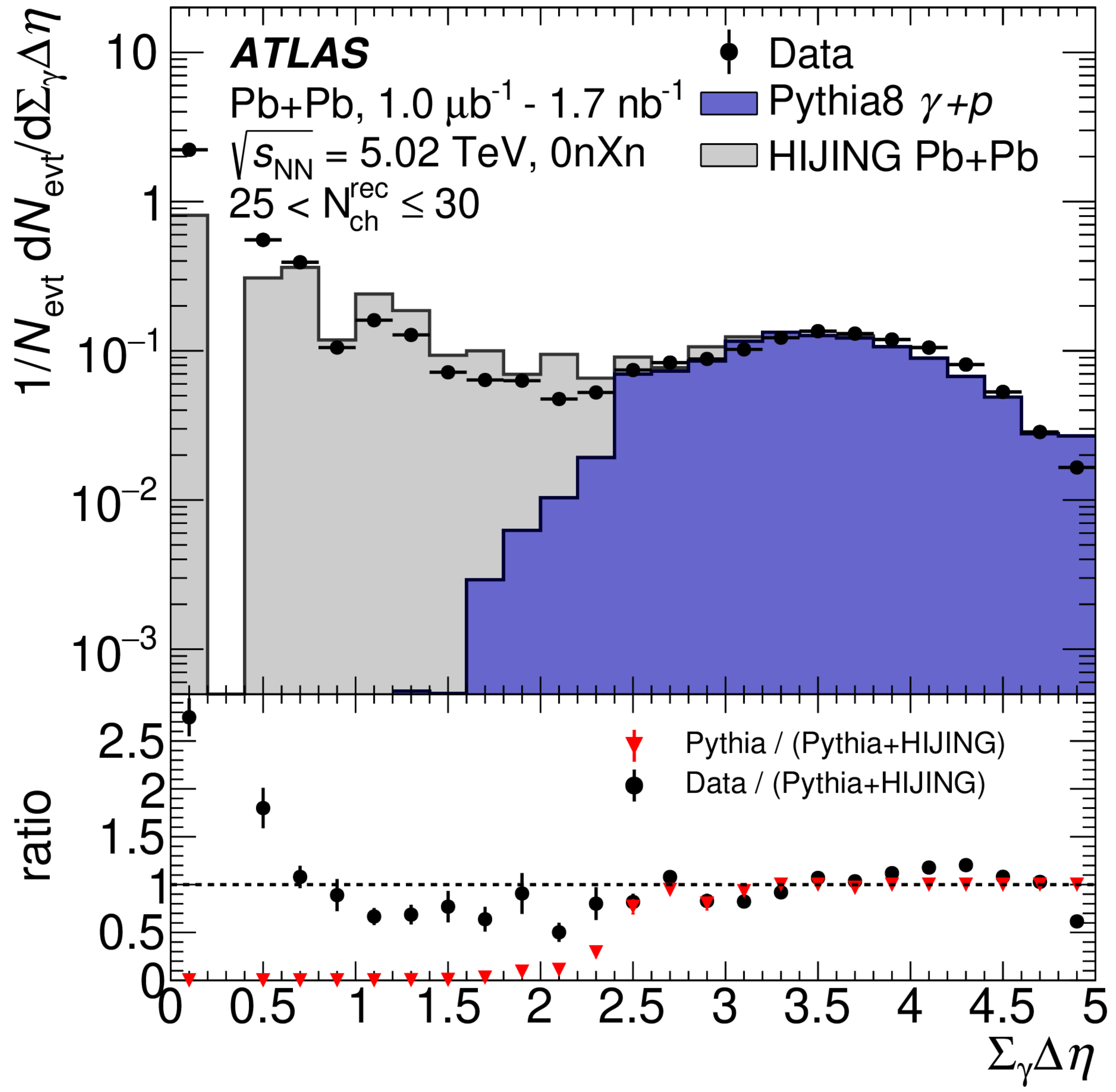
ATLAS, Phys. Rev. C. 104 (2021) 014903

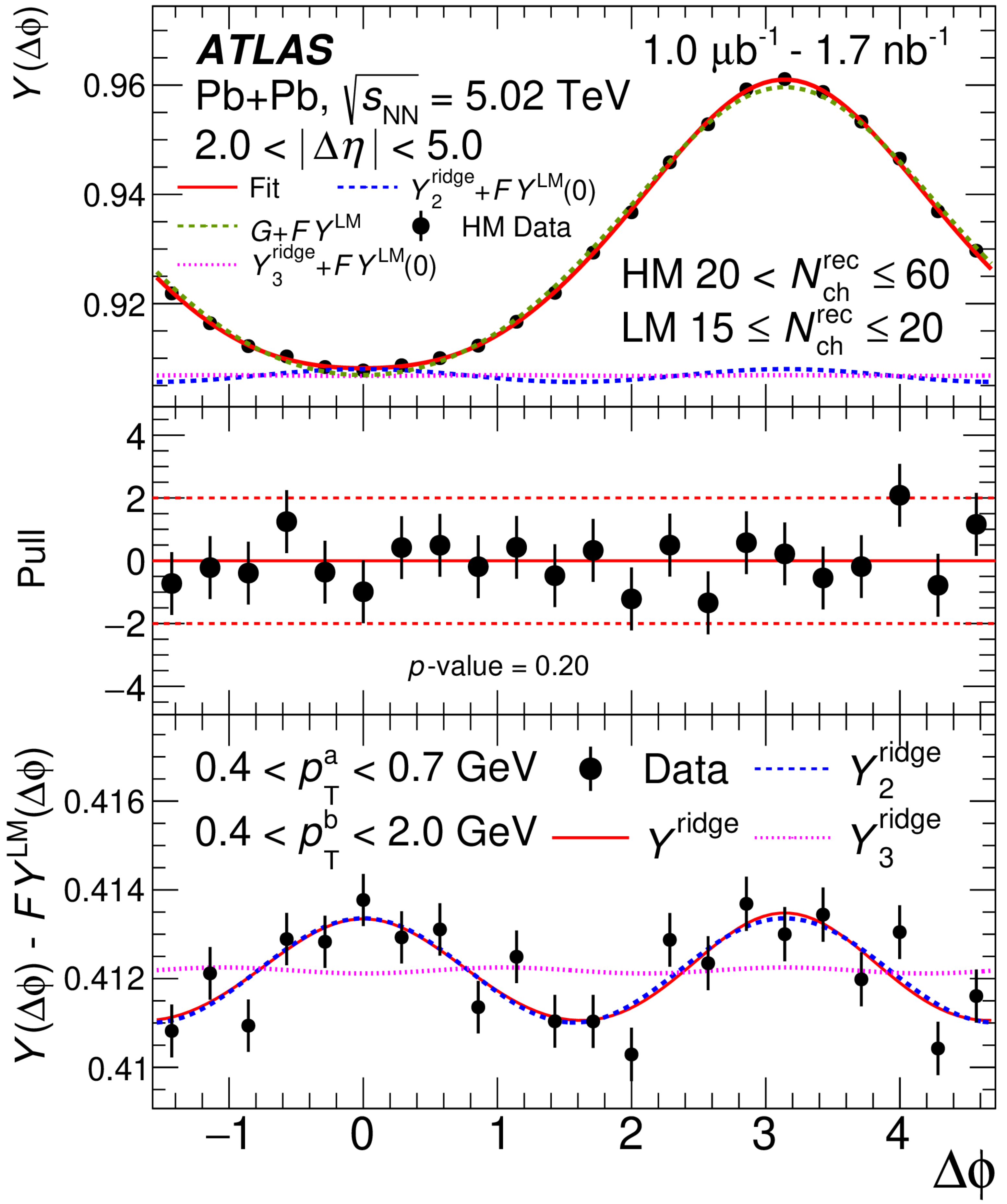
- Measurement done using photonuclear Pb+Pb UPC events

correlation function in LM events

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

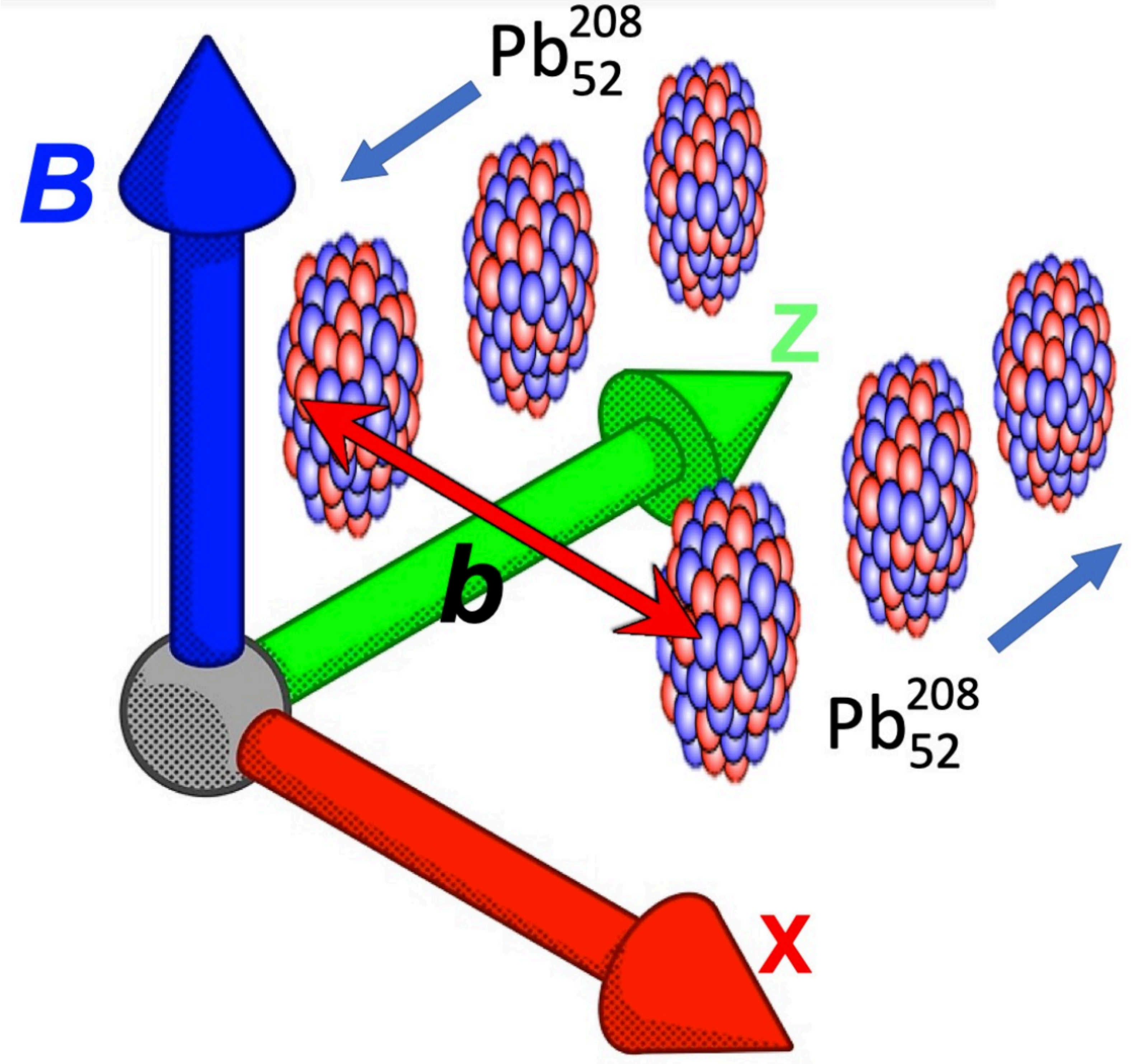
flow coefficients





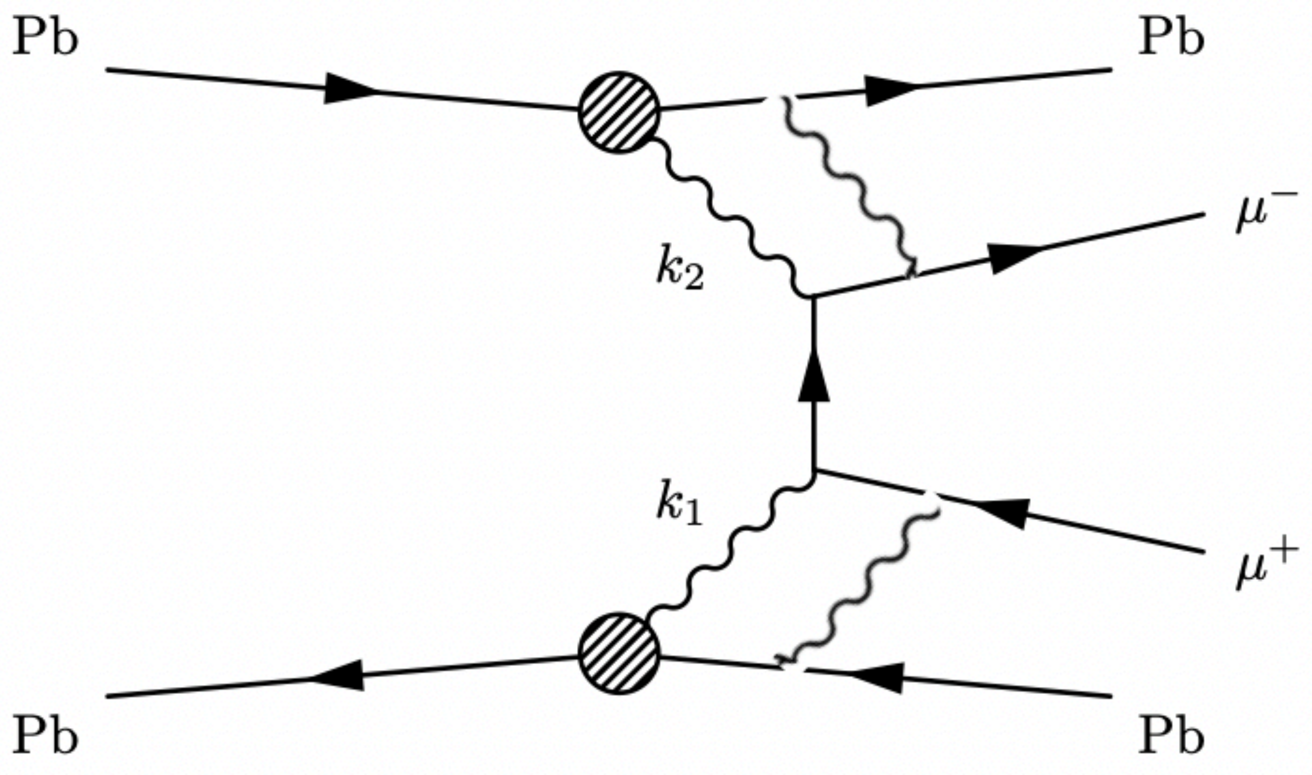
Magnetic monopoles via the Schwinger production

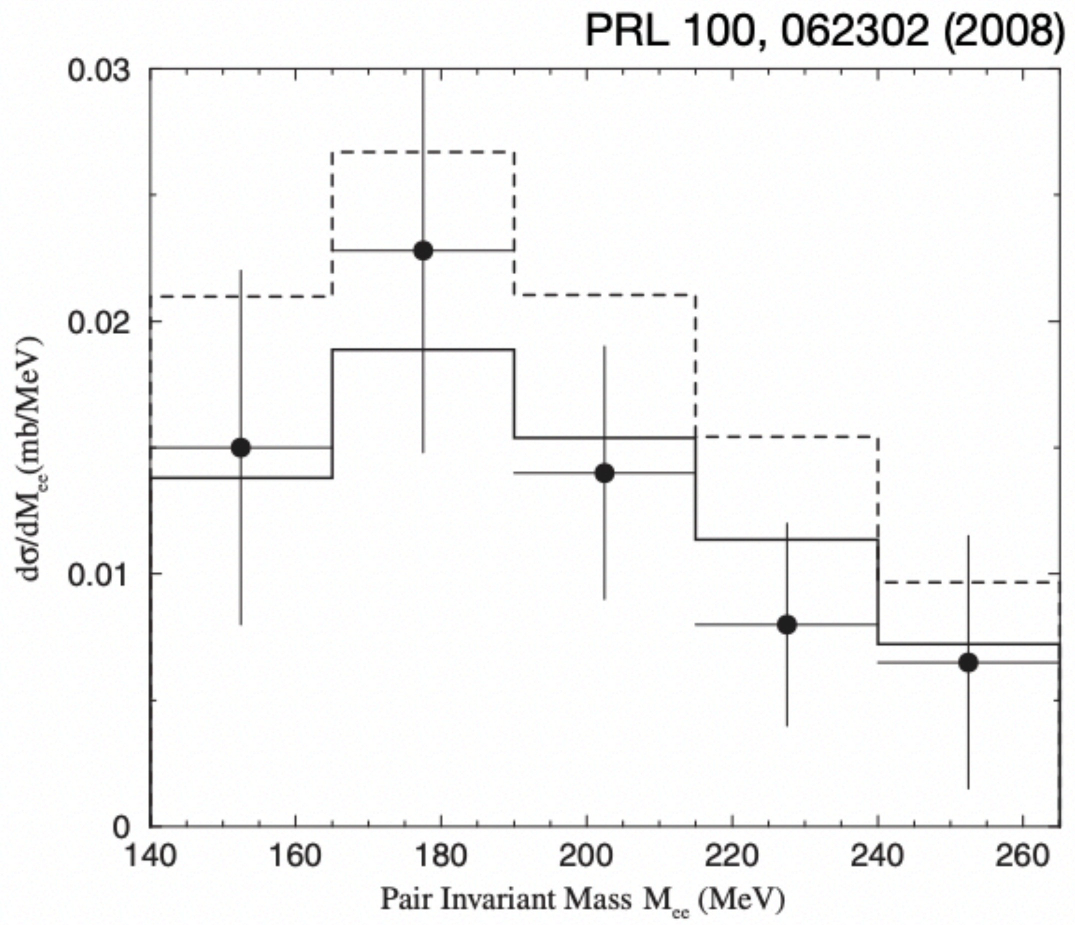
- Two approximations to the magnetic monopole cross-section calculations
  - **FPA (free-particle approximation):**
    space-time dependence of EM field of HI is treated exactly,
    but MM self-interactions are neglected
    (MM self-interactions enhance expected cross sections)
  - **LCFA (locally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



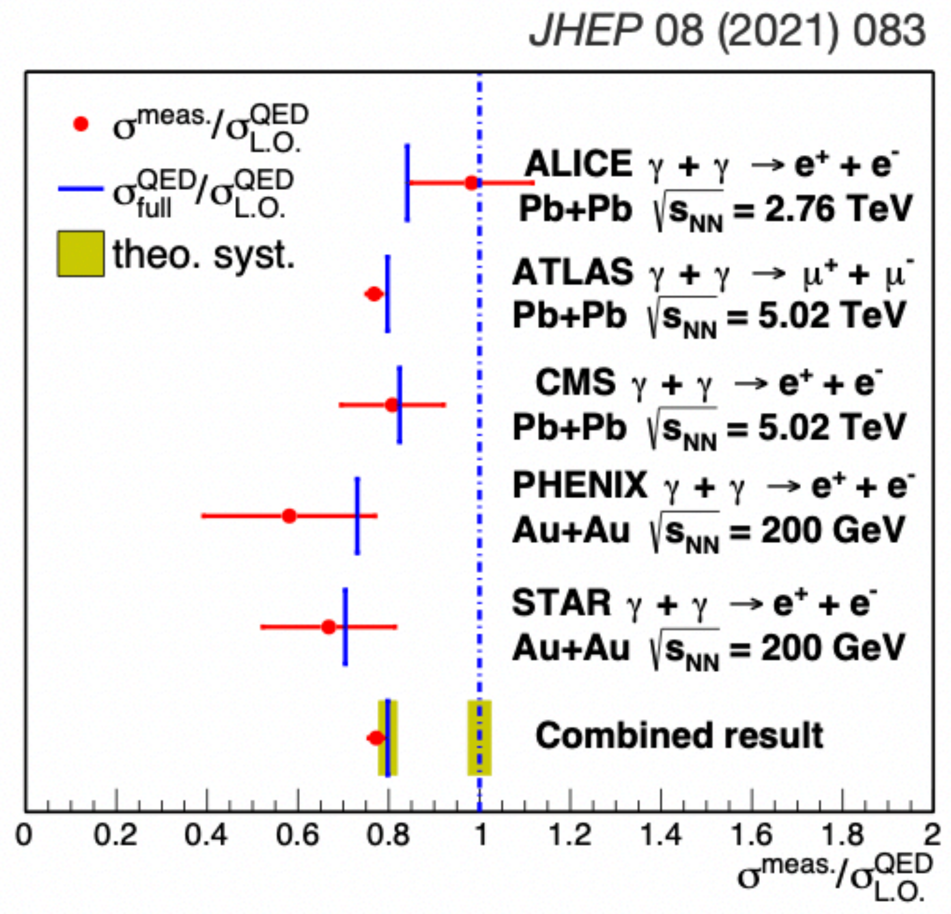
From P. Steinberg

Higher order contributions





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



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**!