Heavy ions and low-x at the LHC

O. Villalobos Baillie
University of Birmingham

Heavy ions and low-x at the LHC

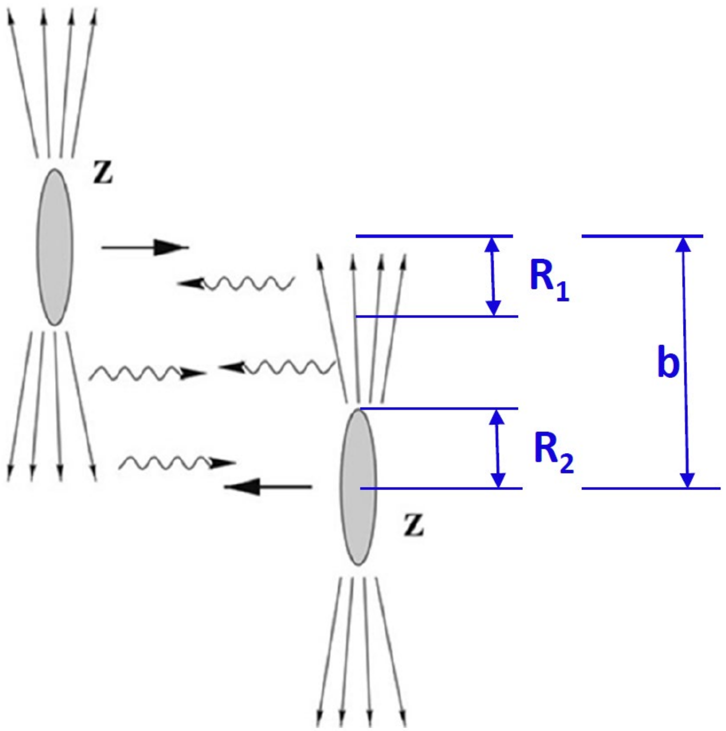
(using Ultra-Peripheral Collisions)

O. Villalobos Baillie
University of Birmingham

Plan of Talk

- Introduction
- Rapidity distributions
- The rapidity ambiguity
- Resolution to give W distributions
- Suppression factors
- t distribution
- Dijet and multijet studies.
- Summary

Introduction to Ultra-Peripheral Collisions

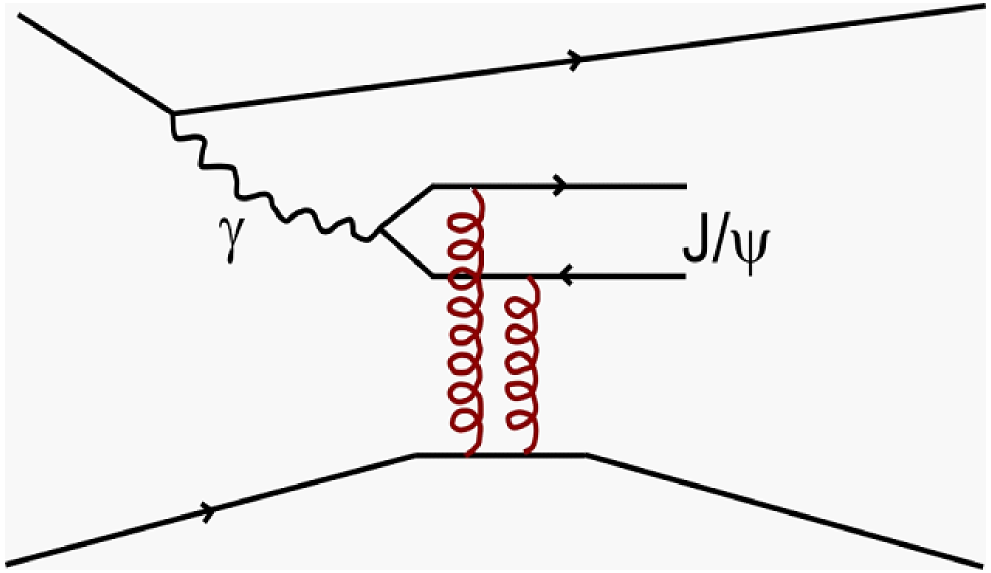


- Geometry:
  - We choose those interactions where the impact parameter is a bit bigger than the sum of the radii, so strong interaction effects are suppressed.
  - Characteristics are
  - Big forward and backward rapidity gaps
  - (usually) low multiplicity

Exclusive Vector Meson Production

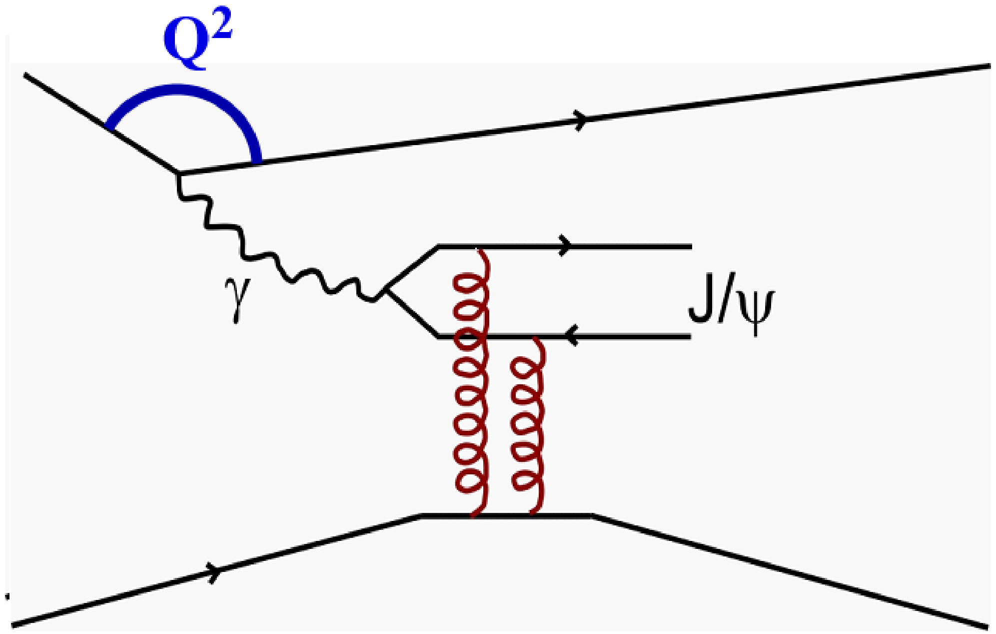
Mainly J/ψ

Kinematics



- A photon is emitted from one of the projectiles (upper vertex), and interacts with two (or more) gluons coming from the other projectile (lower vertex)
- J/ψ sets a hard scale.
- $Q_{\mathrm{scale}}{}^{2} \sim M_{J/\psi}^{2}/4 \sim 2.5\ \mathrm{GeV}^{2}$

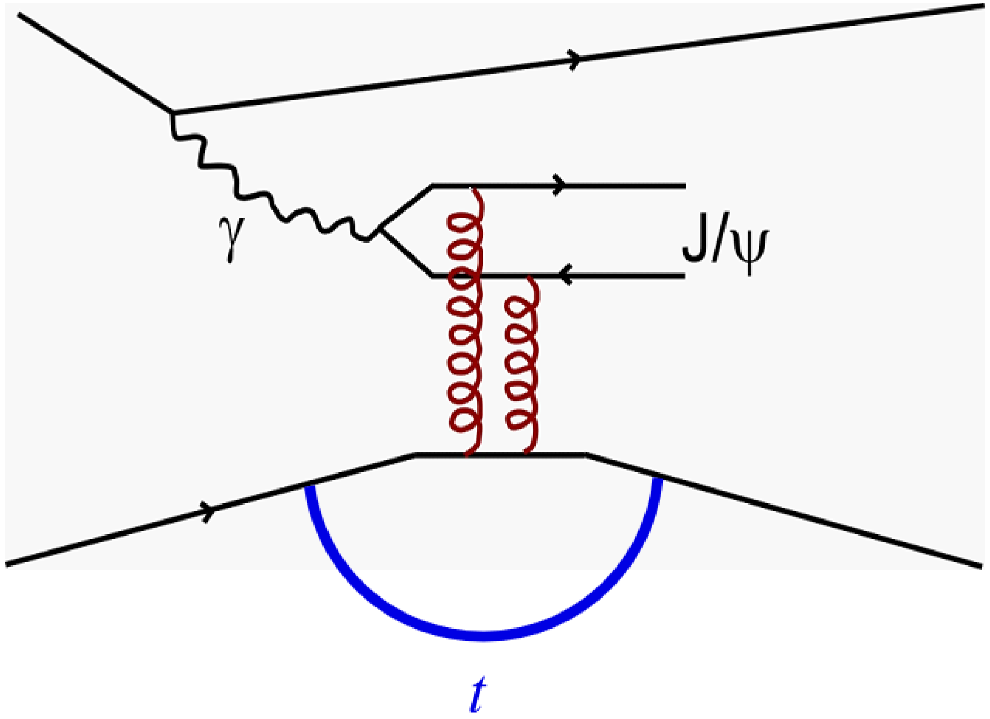
Kinematics



- A photon is emitted from one of the projectiles (upper vertex), and interacts with two (or more) gluons coming from the other projectile (lower vertex)
- The *virtuality* is set by fluctuations in the momentum allowed by the uncertainty principle which are ~1/R, where R is the nuclear radius.

$$Q^2 \sim (\hbar c / R)^2 \sim (25\ \mathrm{MeV})^2$$

Kinematics

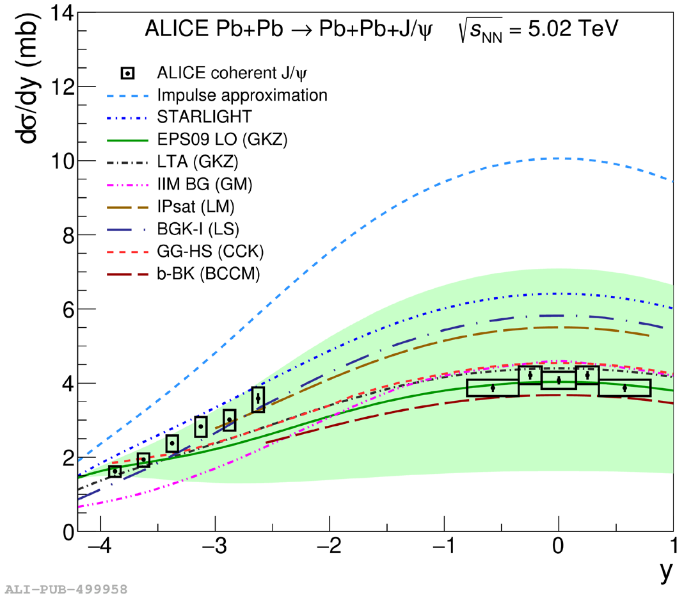


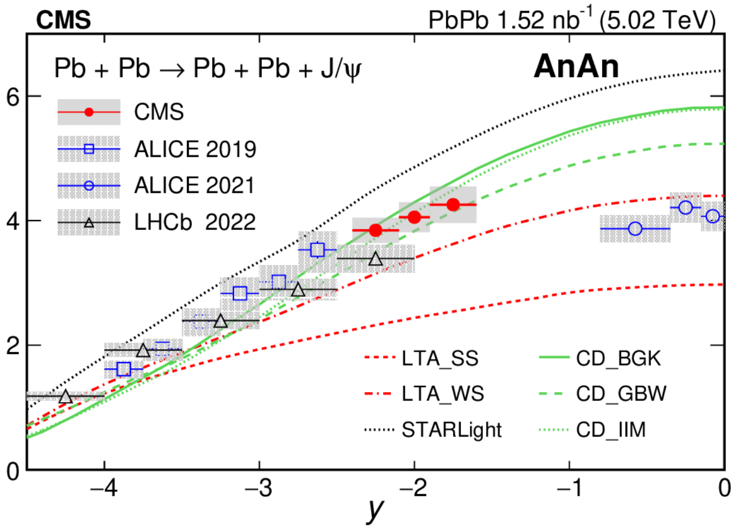
- A photon is emitted from one of the projectiles (upper vertex), and interacts with two (or more) gluons coming from the other projectile (lower vertex)
- The *virtuality* is set by fluctuations in the momentum allowed by the uncertainty principle and are ~1/R, where R is the nuclear radius.

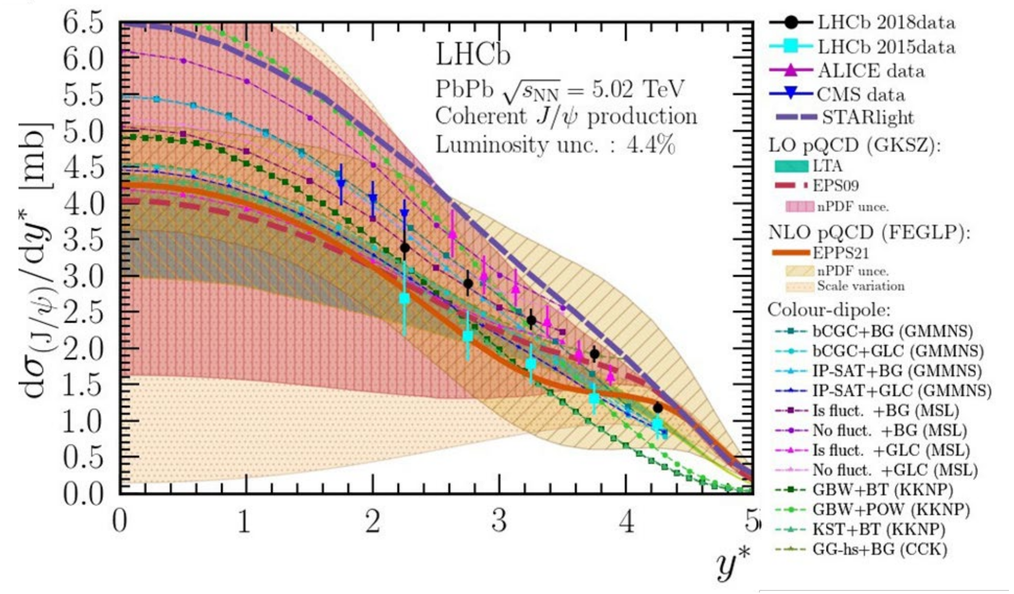
$$Q^2 \sim (\hbar c / R)^2 \sim (25\ \mathrm{MeV})^2$$

- *t* is the momentum transfer at the lower vertex

Rapidity Distribution





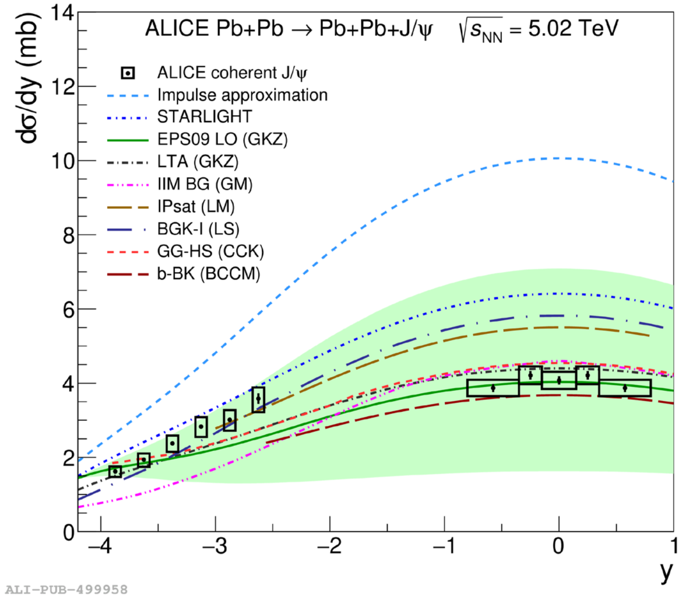


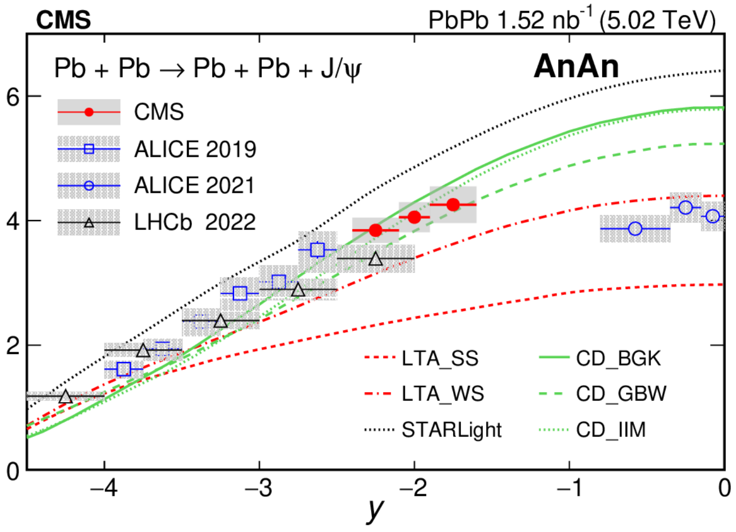
ALICE Eur. Phys. J. C (2021) 81:712

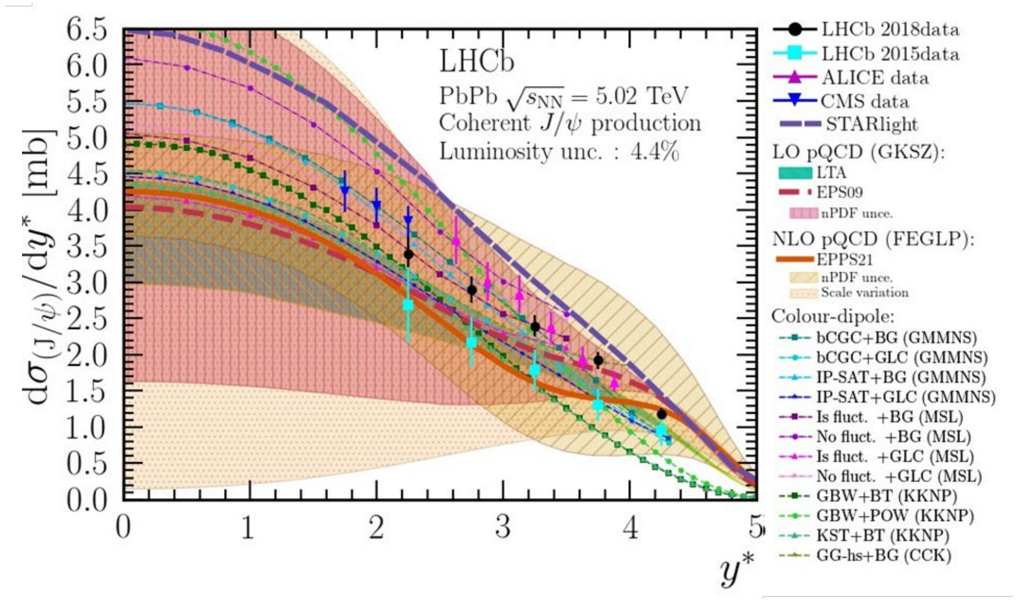
CMS arXiv:2303.16984v1

LHCb JHEP 06 (2023) 146

Rapidity Distribution







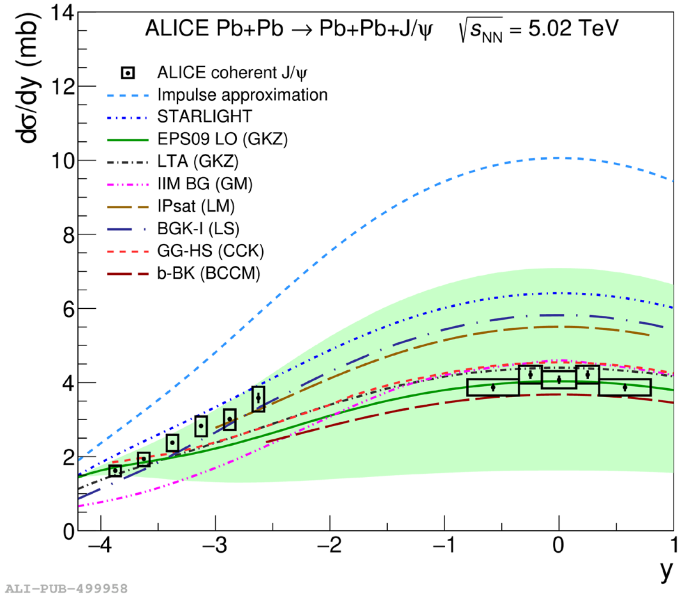
ALICE Eur. Phys. J. C (2021) 81:712

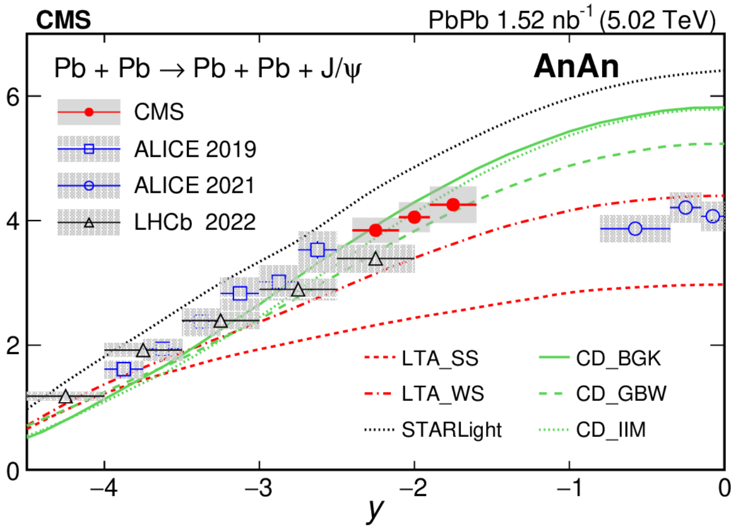
CMS arXiv:2303.16984v1

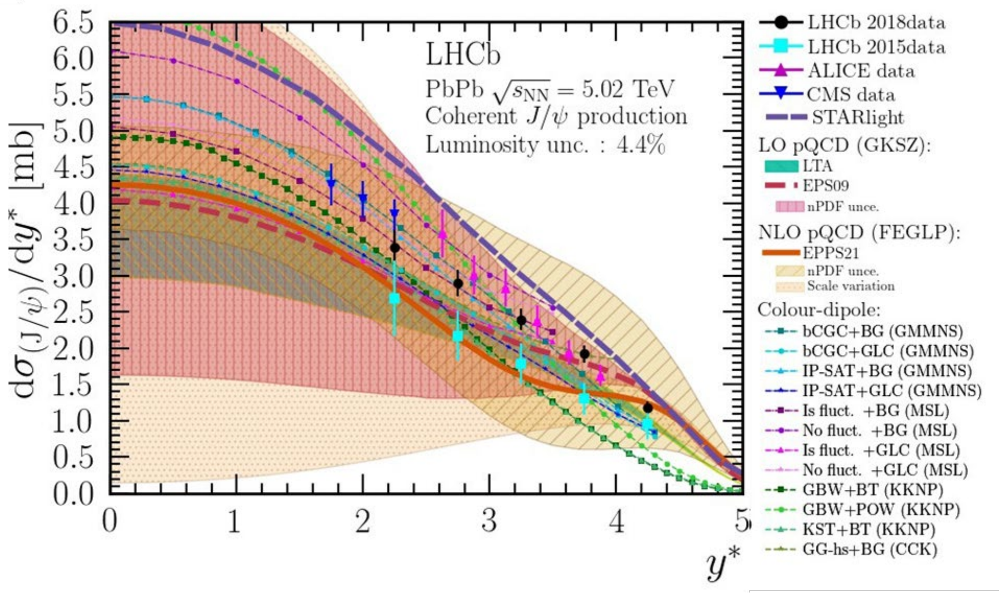
LHCb JHEP 06 (2023) 146

- Main conclusion: models with mild shadowing fit data best
  - P-QCD, CGC, “hot spot” models available. Difficult to predict the data at all rapidities
- Experimental data ALICE-CMS-LHCb converging

Rapidity Distribution



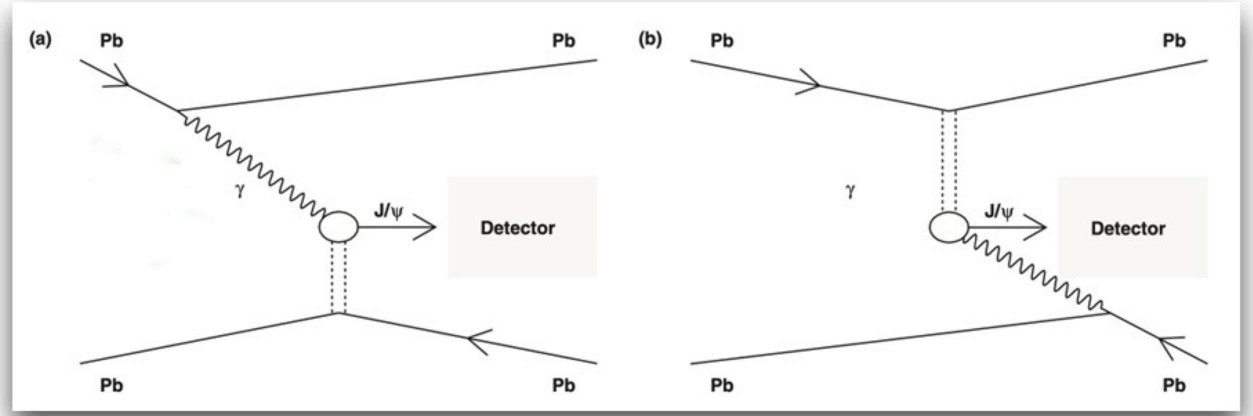




ALICE Eur. Phys. J. C (2021) 81:712

CMS arXiv:2303.16984v1

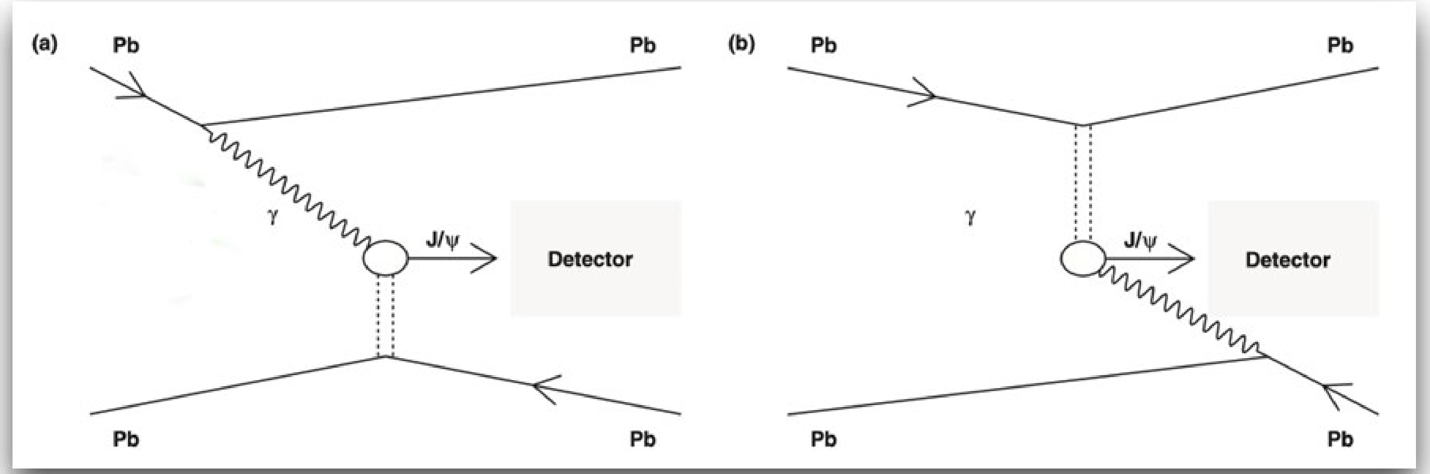
LHCb JHEP 06 (2023) 146



AMBIGUITY PROBLEM

- Each point (except at $y = 0$) gets two contributions, depending on which nucleus emits the photon
- Relative importance depends on rapidity

Rapidity ambiguity

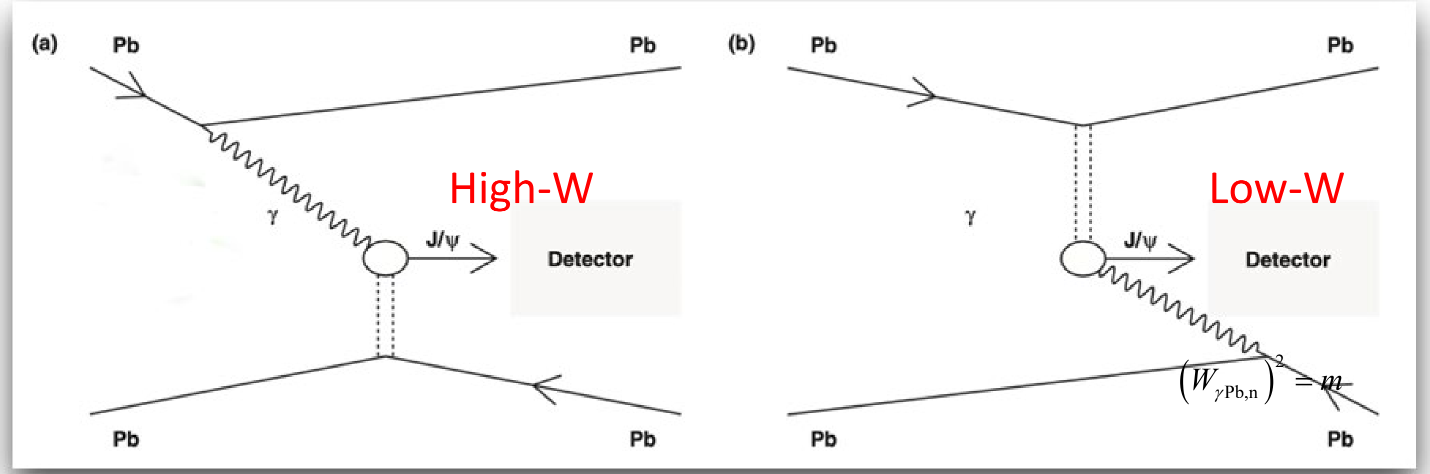


$$\frac{\mathrm{d}\sigma_{\mathrm{PbPb}}}{\mathrm{d}y} = n(y,b)\,\sigma_{\gamma\mathrm{Pb}}(y) + n(-y,b)\,\sigma_{\gamma\mathrm{Pb}}(-y)$$

known unknown unknown

- The PbPb cross section at a given rapidity depends on two photonuclear (γPb) cross sections, depending on which nucleus emits the photon.
- Each photonuclear cross section is multiplied by a flux factor, which depends on *impact parameter*
- A more useful approach is to calculate the flux factor for an impact parameter profile, e.g. for a specific process.
- These flux factors can be obtained from an external programme, such as nOOn or STARlight.

Rapidity ambiguity



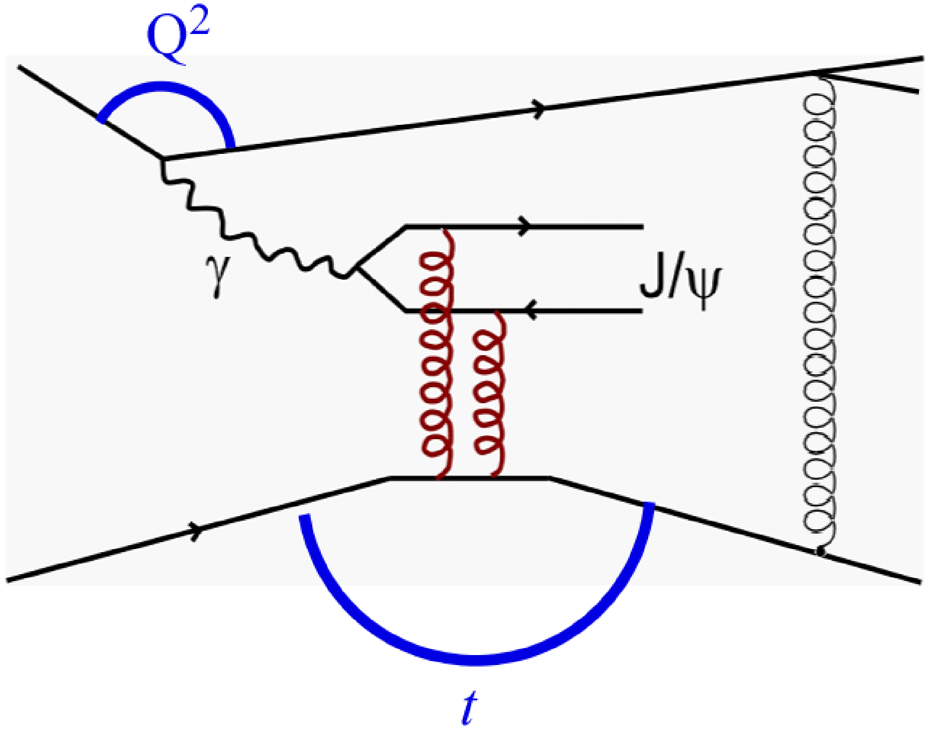
$$\frac{d\sigma_{PbPb}}{dy} = n(y,b)\sigma_{\gamma Pb}(y) + n(-y,b)\sigma_{\gamma Pb}(-y)$$

known unknown unknown

calculable calculable

- KINEMATICS
  - y tells us about W
  - $W_{\gamma Pb}{}^{2} = m\sqrt{s_{NN}}\exp(-y)$
- For identical incoming projectiles, a single rapidity measurement feeds both signs of rapidity.
- We need to be able to disentangle them.
- The fluxes are calculable
- Not possible to calculate the cross sections from a single measurement of dσ/dy.

Neutron emission



0n0n	no neutron emission on either side
Xn0n	neutron emission on "A" side
0nXn	neutron emission on "C" side
XnXn	neutron emission on both sides

- Some of the time, an additional photon can be exchanged as a final-state interaction, giving rise to the emission of one or more neutrons.
- The likelihood of this occurring is impact-parameter dependent.
- Different types of neutron emission (no neutrons emitted, neutrons emitted on one side, neutrons emitted on both side) have different impact parameter profiles.
- Measuring them will generate a system of simultaneous equations.

$$\frac{d\sigma_{PbPb}}{dy} = n(y, 0n0n)\sigma_{\gamma Pb}(y) + n(-y, 0n0n)\sigma_{\gamma Pb}(-y)$$

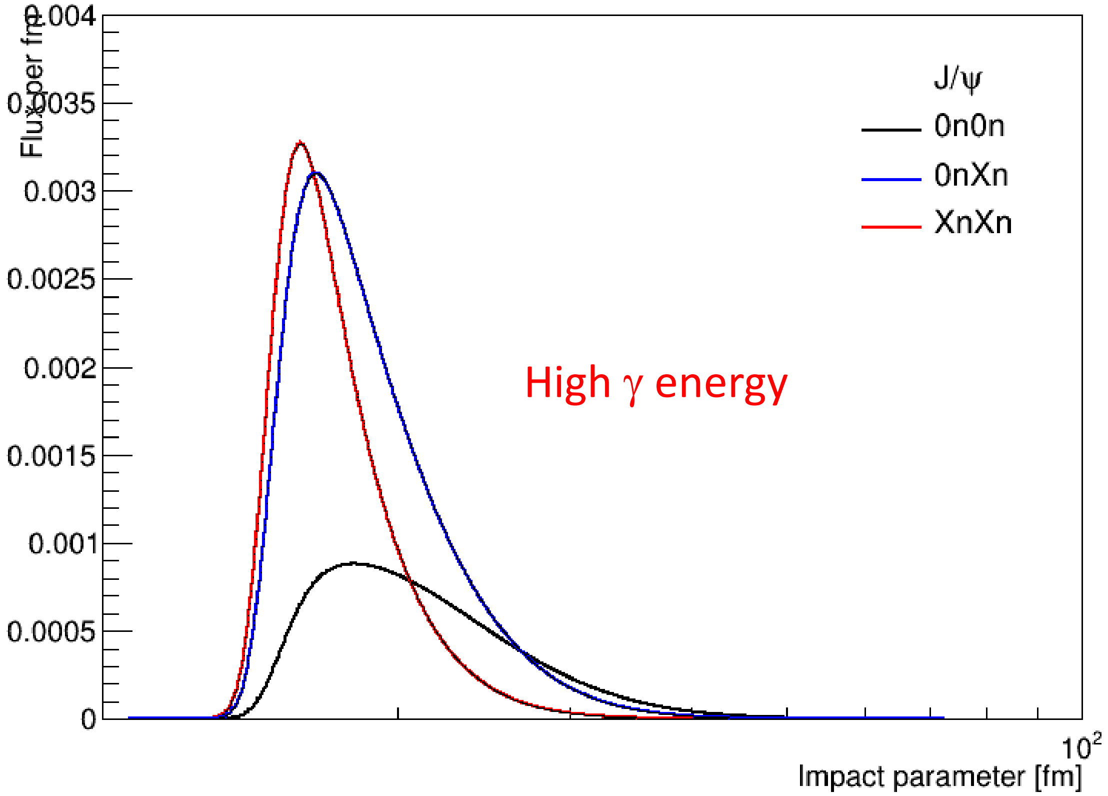
$$\frac{d\sigma_{PbPb}}{dy} = n(y, 0nXn)\sigma_{\gamma Pb}(y) + n(-y, 0nXn)\sigma_{\gamma Pb}(-y)$$

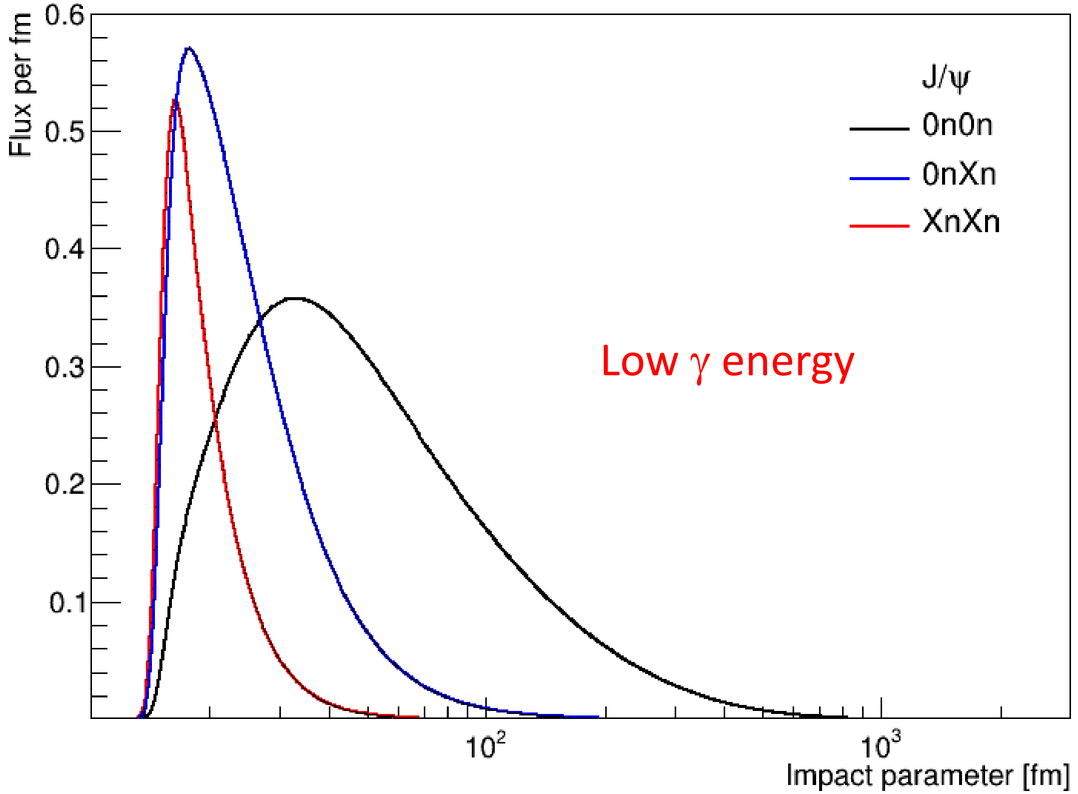
$$\frac{d\sigma_{PbPb}}{dy} = n(y, Xn0n)\sigma_{\gamma Pb}(y) + n(-y, Xn0n)\sigma_{\gamma Pb}(-y)$$

$$\frac{d\sigma_{PbPb}}{dy} = n(y, XnXn)\sigma_{\gamma Pb}(y) + n(-y, XnXn)\sigma_{\gamma Pb}(-y)$$

V. Guzey, E. Kryshen and M. Zhalov, PRC 91 (2016) 05506

Impact parameter flux profiles

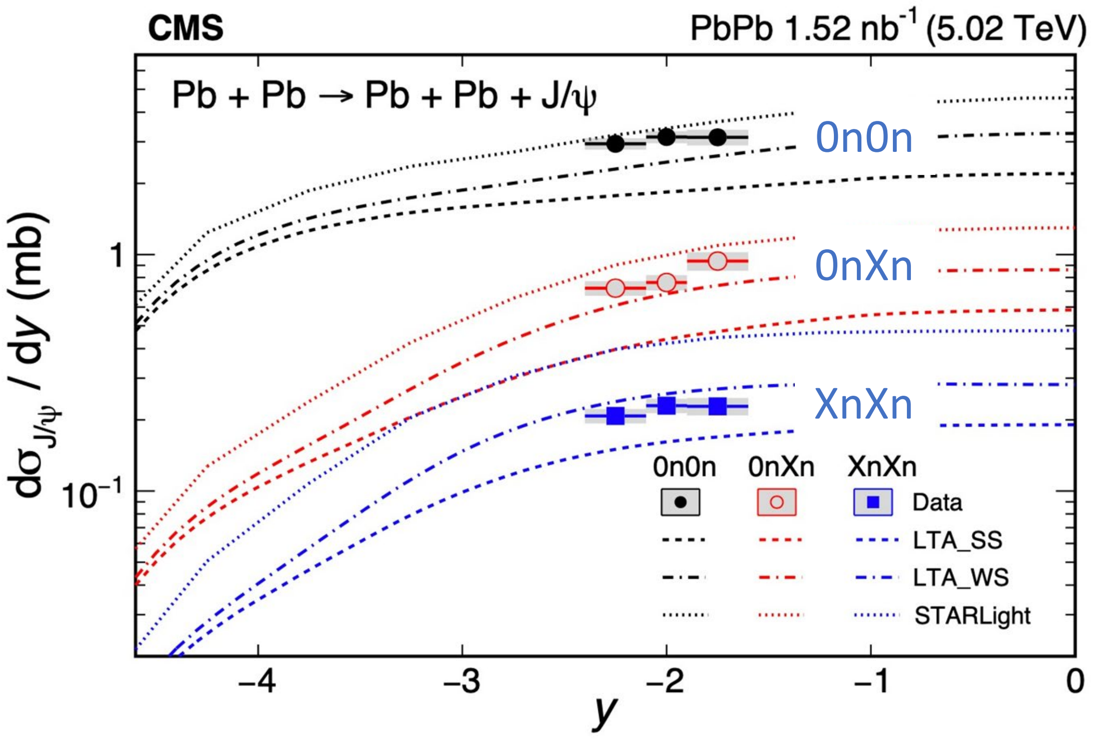




Broz et al., CPC 235 (2020) 107181

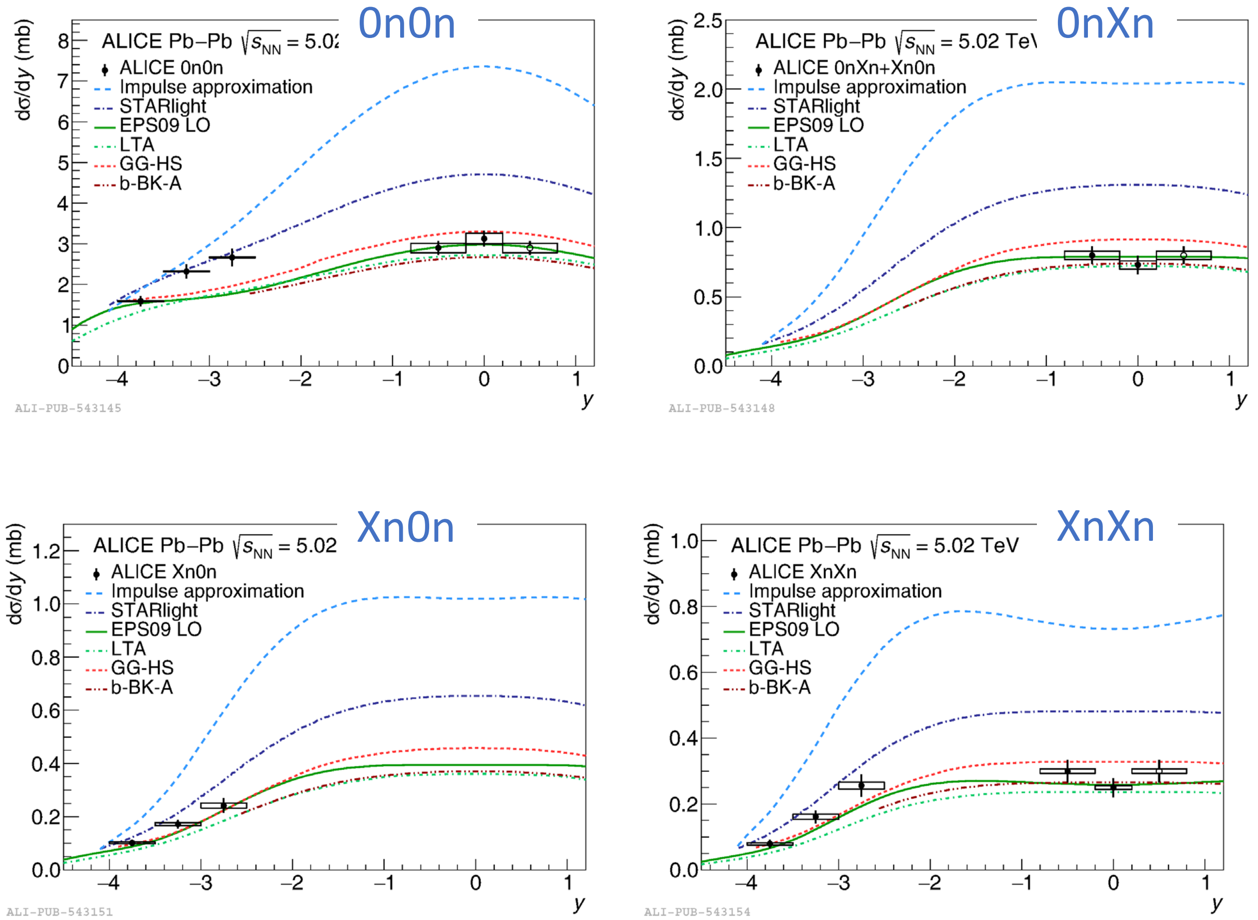
Rapidity distributions, separated by neutron classes

CMS



CMS arXiv:2303.16984v1

ALICE



ALICE arXiv:2305.16090

Put it together

- We can use the impact parameter profiles to calculate an integrated flux
- Using the known differential cross sections in rapidity intervals, we can set up (and solve) the system of simultaneous equations
- The resultant γPb cross sections are listed

Fluxes from nOOn
(M. Broz et al., CPC 235 (2020) 107181)

Table 4: Theoretical input needed to obtain the photonuclear cross section and the nuclear suppression factor. Photon fluxes, see Eq. (1), computed with $\mathbf{n_0^O n}$ for the different neutron classes and rapidity ranges. The last column shows the value of $\sigma^{IA}_{\gamma Pb}$ as computed in Ref. [17].

FLUX FACTORS

y	n_γ(0n0n)	n_γ(0nXn+Xn0n)	n_γ(XnXn)	$\sigma^{IA}_{\gamma Pb}$ (μb)
$3.5 < y < 4$	178.51	18.18	6.34	10
$3 < y < 3.5$	162.99	18.19	6.34	14
$2.5 < y < 3$	147.46	18.19	6.34	19
$0.2 < y < 0.8$	77.88	17.88	6.33	48
$-0.2 < y < 0.2$	62.86	17.47	6.27	58
$-0.8 < y < -0.2$	48.31	16.75	6.18	71
$-3 < y < -2.5$	3.91	4.97	2.78	176
$-3.5 < y < -3$	1.22	2.15	1.42	215
$-4 < y < -3.5$	0.26	0.61	0.48	262

Table 5: Photonuclear cross sections extracted from the UPC measurements using the procedure described in the text. The quoted uncertainties are uncorrelated (unc.), correlated (corr.), caused by migrations across neutron classes (mig.) and by variations of the flux fractions in the different classes (flux frac.). The lines separate the different ranges in $|y|$. Note that two photonuclear cross sections in each rapidity interval are anti-correlated.

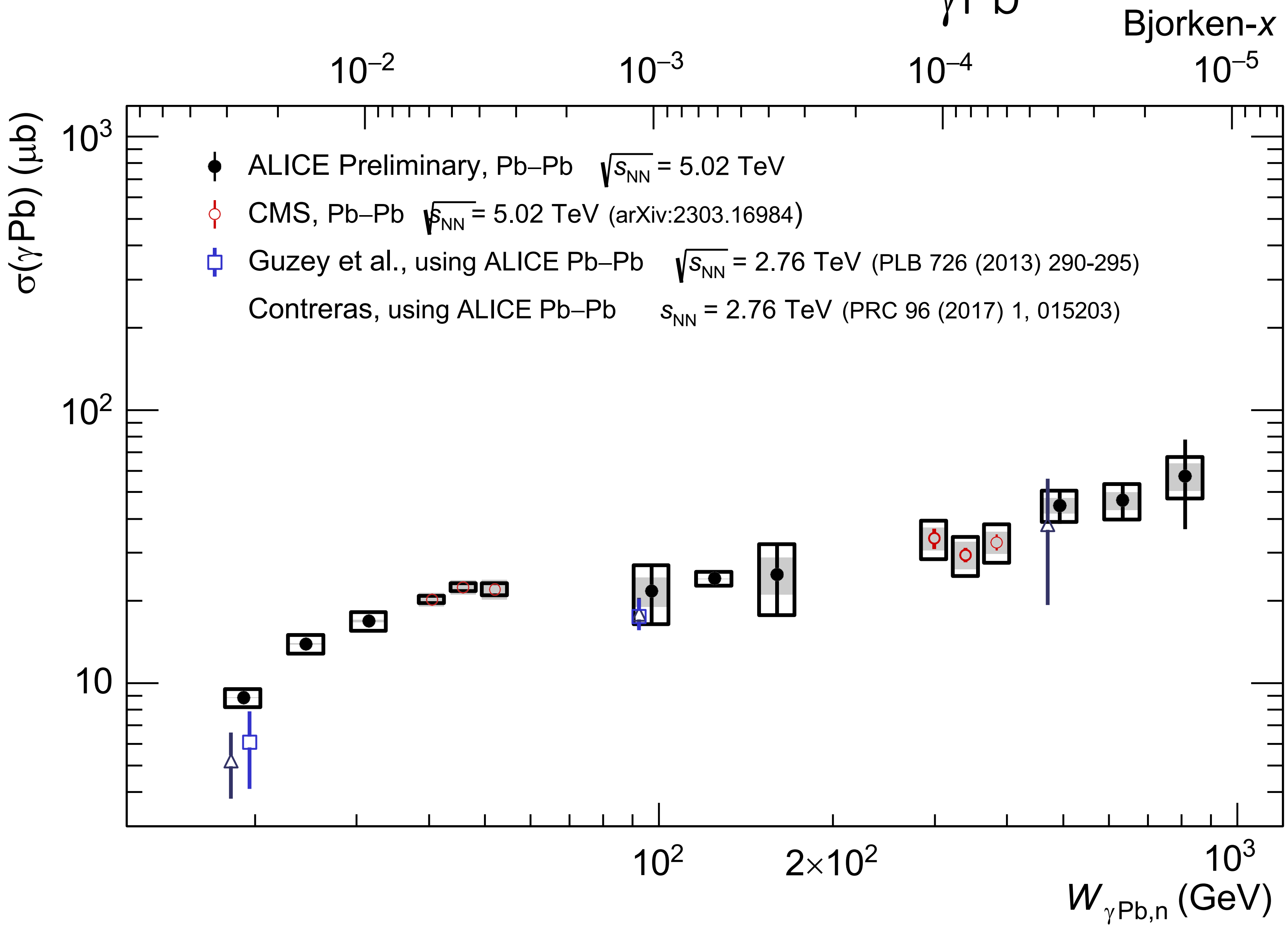
y	$W_{\gamma Pb,n}$ (GeV)	$\sigma_{\gamma Pb}$ (μb)	unc. (μb)	corr. (μb)	mig. (μb)	flux frac. (μb)
$3.5 < y < 4$	19.12	8.84	0.30	0.68	0.02	0.04
$-4 < y < -3.5$	813.05	57.32	20.77	7.57	6.41	6.56
$3 < y < 3.5$	24.55	13.89	0.23	1.08	0.05	0.08
$-3.5 < y < -3$	633.21	46.58	6.61	5.73	3.77	3.63
$2.5 < y < 3$	31.53	16.89	0.59	1.32	0.11	0.18
$-3 < y < -2.5$	493.14	44.68	6.38	5.15	2.73	2.97
$0.2 < y < 0.8$	97.11	21.73	5.12	3.12	4.32	2.73
$-0.8 < y < -0.2$	160.10	25.00	7.33	4.88	5.43	3.91
$-0.2 < y < 0.2$	124.69	24.15	0.69	1.37	0.50	0.06

Rapidity Intervals

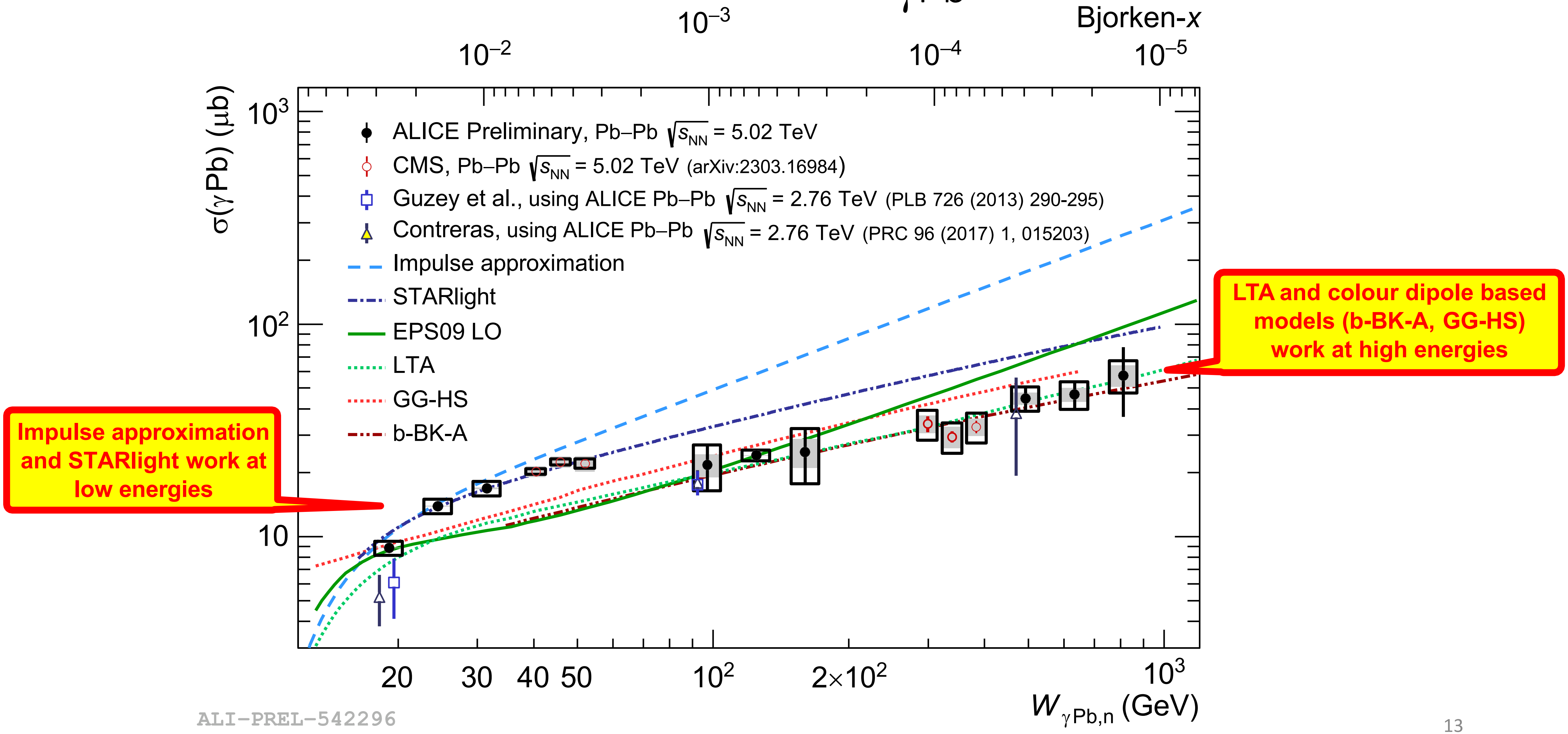
$W_{\gamma Pb}$

Cross sections

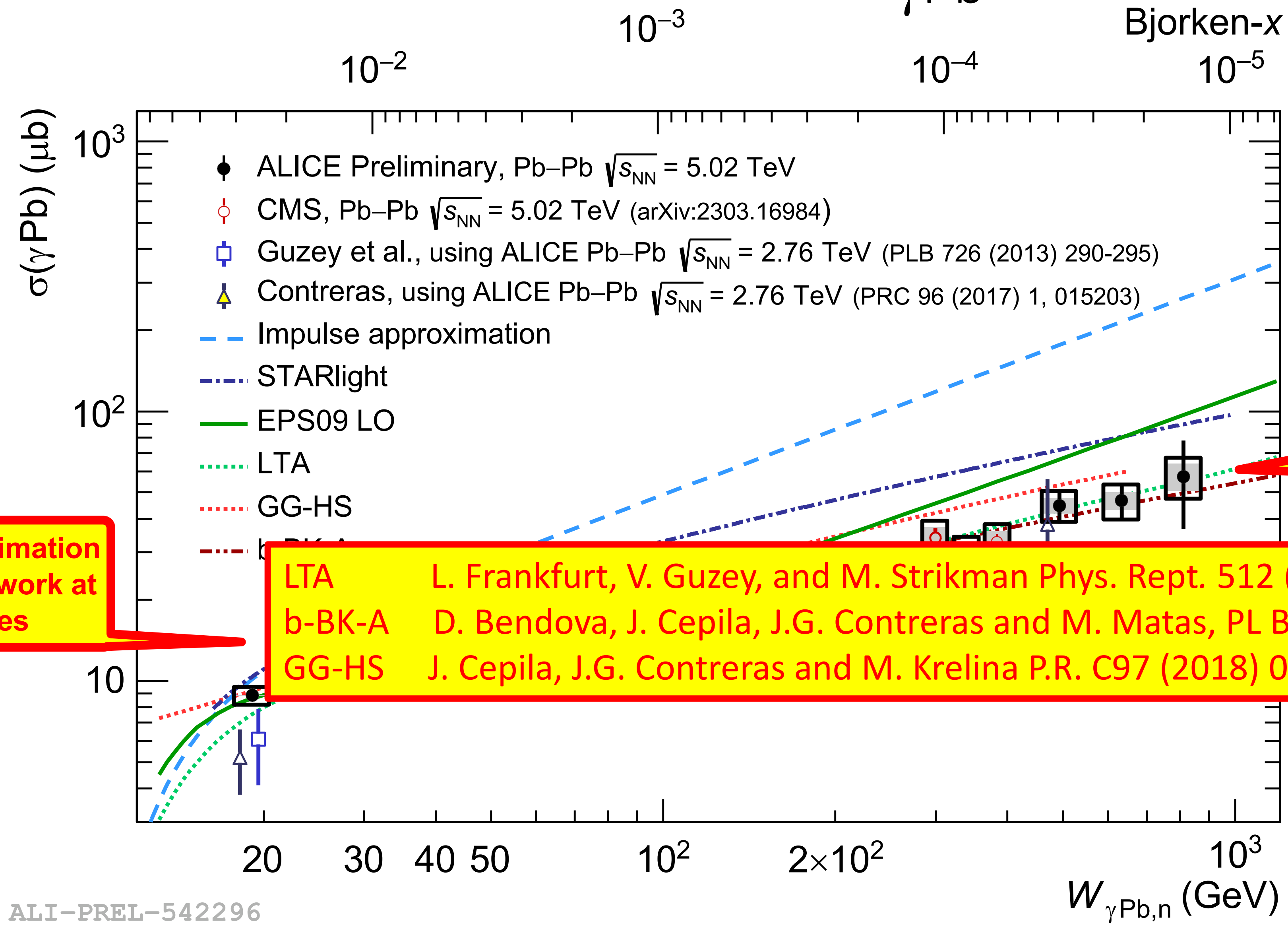
ALICE-CMS cross section vs $W_{\gamma Pb}$



ALICE-CMS cross section vs $W_{\gamma Pb}$



ALICE-CMS cross section vs $W_{\gamma Pb}$



LTA and colour dipole based models (b-BK-A, GG-HS) work at high energies

Impulse approximation and STARlight work at low energies

LTA L. Frankfurt, V. Guzey, and M. Strikman Phys. Rept. 512 (2012) 255
b-BK-A D. Bendova, J. Cepila, J.G. Contreras and M. Matas, PL B817(2021) 136306
GG-HS J. Cepila, J.G. Contreras and M. Krelina P.R. C97 (2018) 024901

Phys. Rept. 512 (2012) 255–393

Digression: pp and pPb

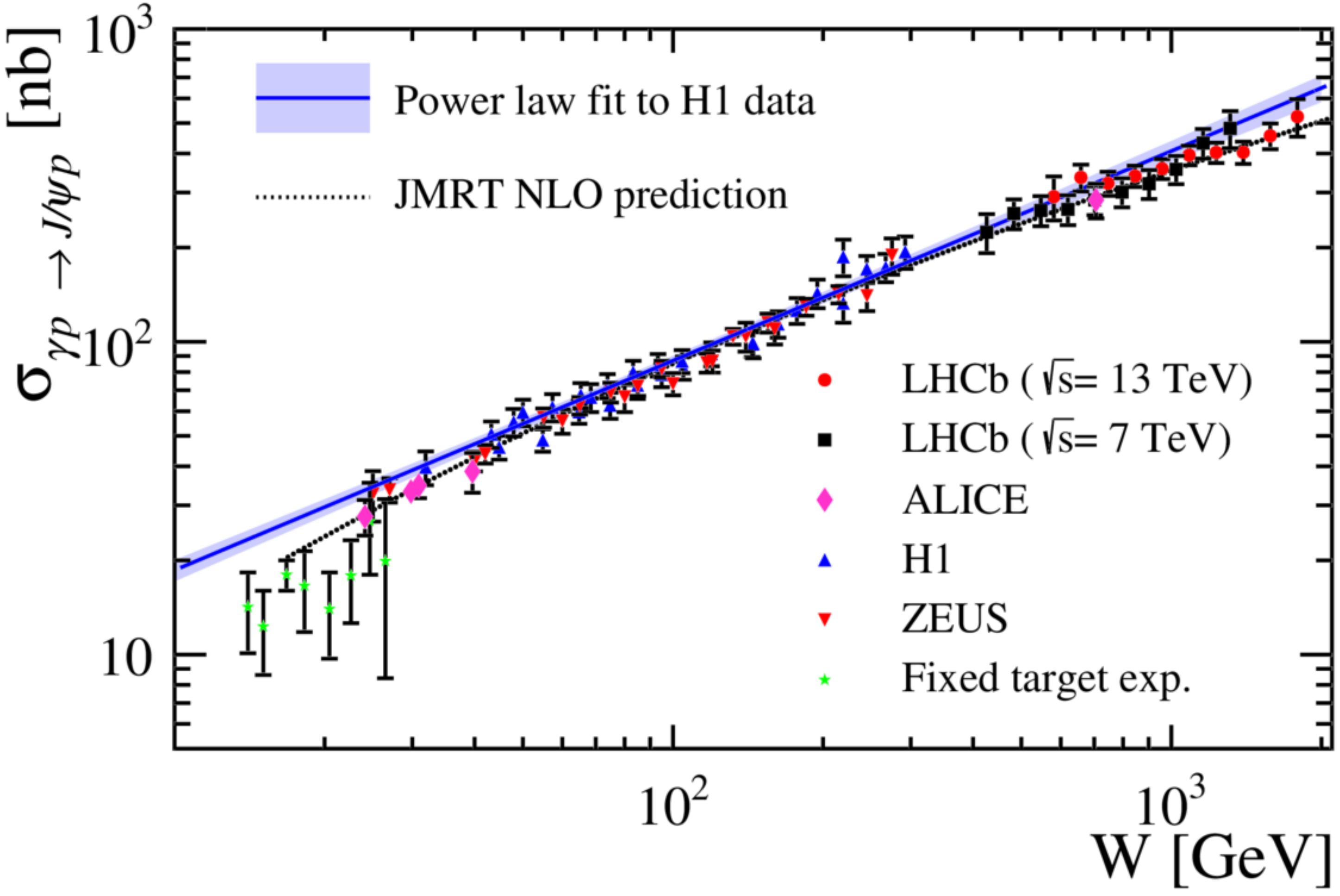
- Essentially the same process takes place in the reactions

  $\text{pp} \to \text{pp J}/\psi$

  $\text{pPb} \to \text{pPb J}/\psi$

  where a proton (Pb nucleus) emits the photon.
- In the pPb reaction, the photon emitter is tagged (“leadshine”).
- The symmetric pp system is subject to the same rapidity ambiguity as we have encountered for PbPb.

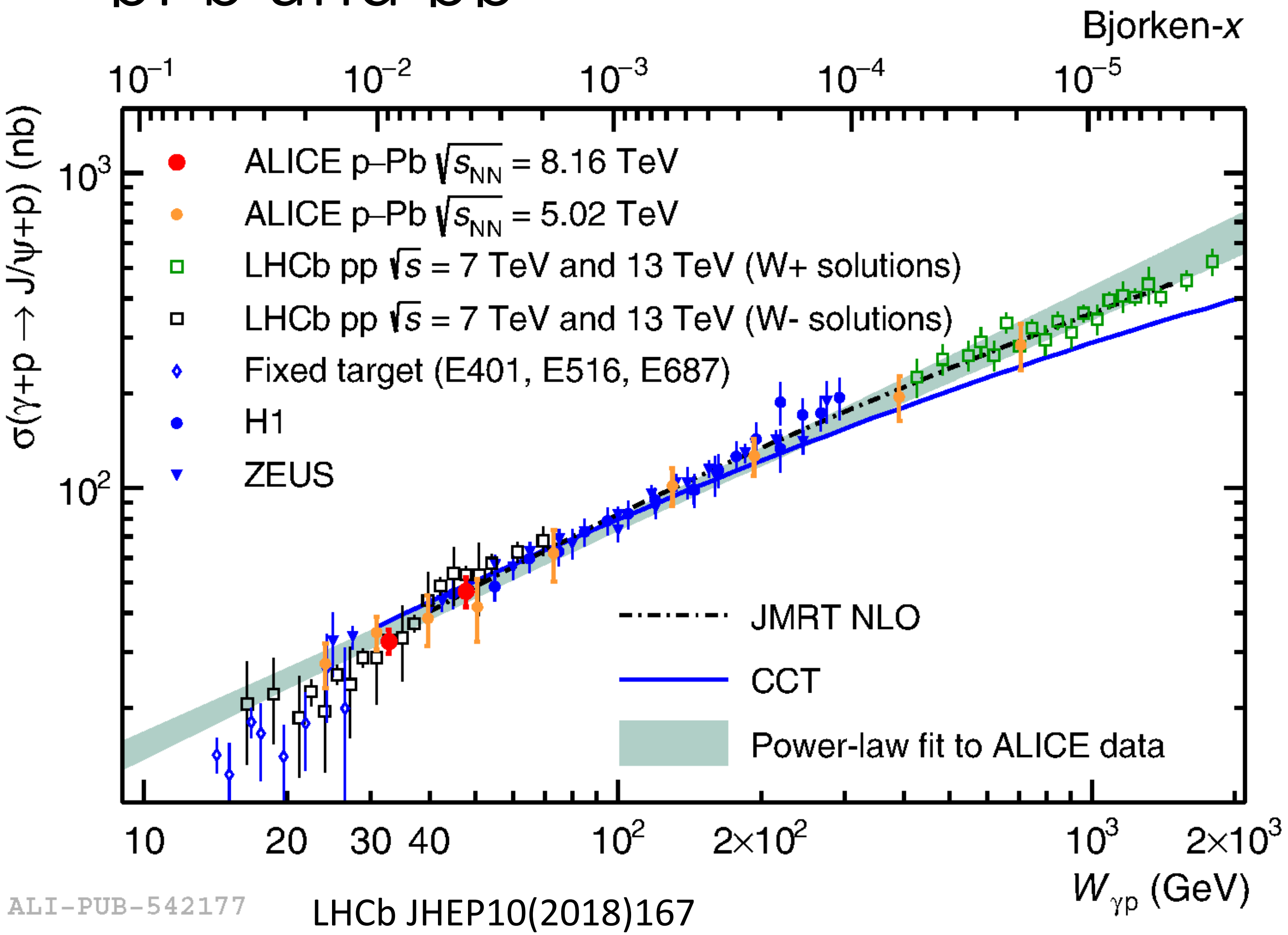
pp results (LHCb)



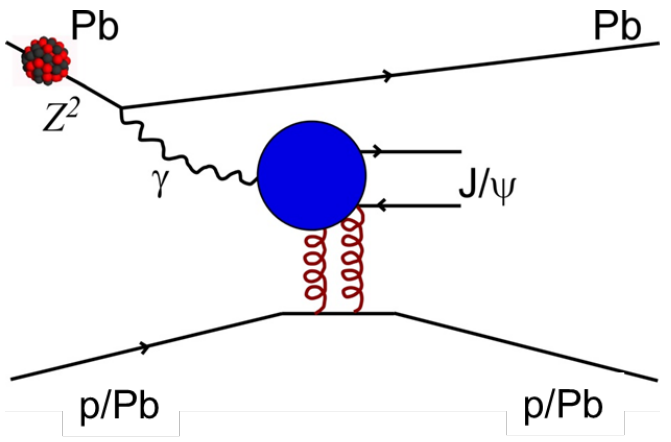
For 13 TeV data, low W points are constrained to lie on HERA line. High W points are free

LHCb JHEP10(2018)167

pPb and pp



LHCb JHEP10(2018)167
ALICE ArXiv:2304.12403



- ALICE uses pPb data to look at the proton.
- Pb is much more likely to be the emitter, resolving the ambiguity
- Power law fits:

$$\sigma = n\left(\frac{W_{\gamma p}}{W_0}\right)^{\delta}$$

$$\delta_{ALICE} = 0.70 \pm 0.04$$

$$\delta_{H1} = 0.69 \pm 0.02$$

$$\delta_{ZEUS} = 0.67 \pm 0.03$$

Back to PbPb

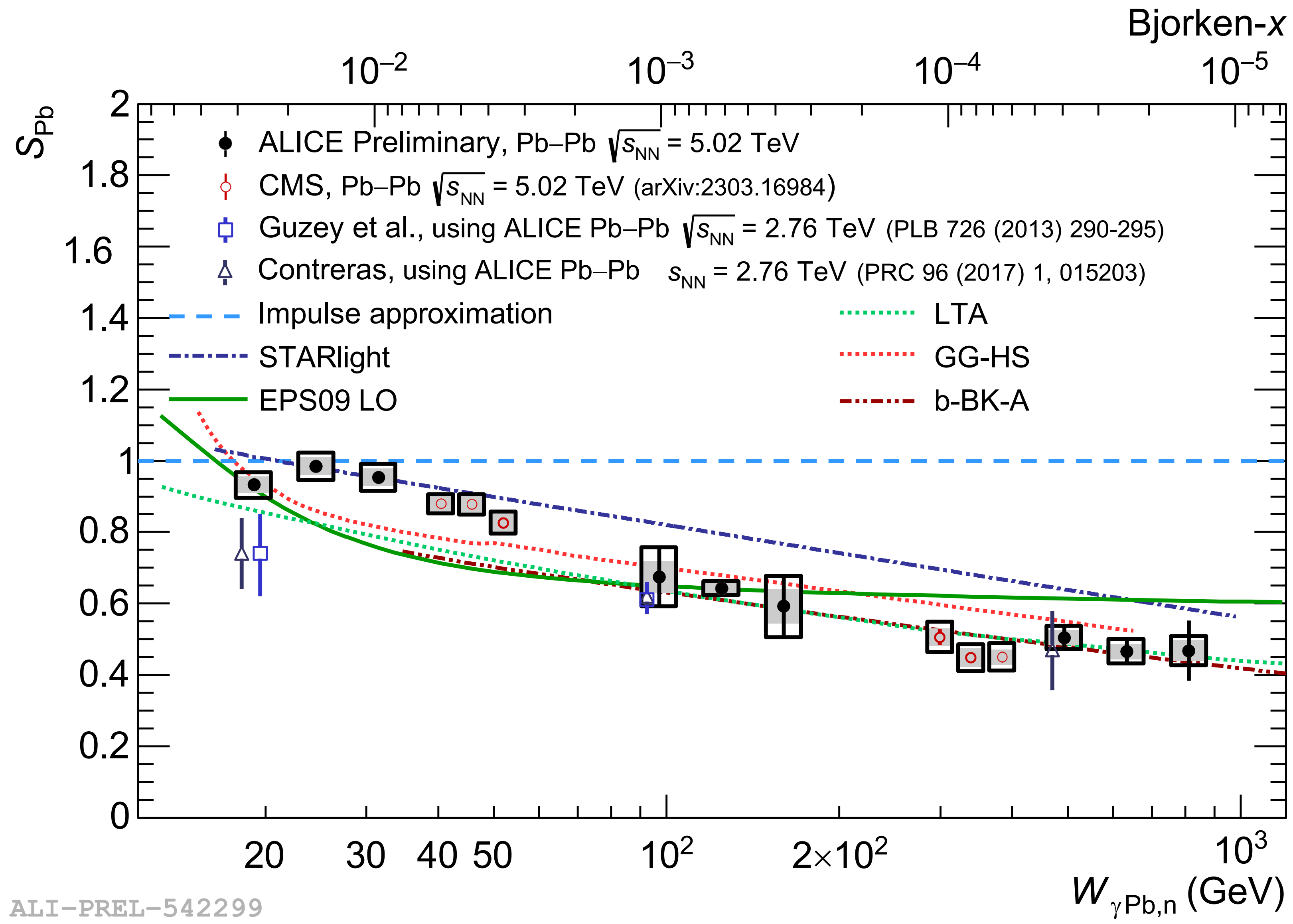
- One of the fundamental questions for ion-ion interactions is to understand how interactions in nuclei are modified with respect to proton-proton
- A powerful tool is to look at suppression factors.
- We define the ratio

$$S_{\mathrm{Pb}} = \sqrt{\frac{\sigma_{\gamma \mathrm{Pb}}}{\sigma_{\gamma \mathrm{Pb}}^{\mathrm{IA}}}}$$

IA Impact Approximation: what happens if there are no nuclear effects

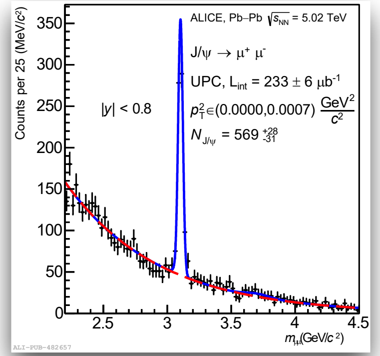
- Allows us to assess the energy dependence.

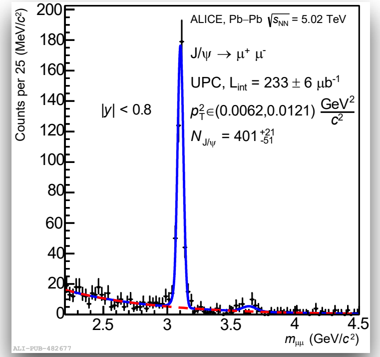
Suppression Factor

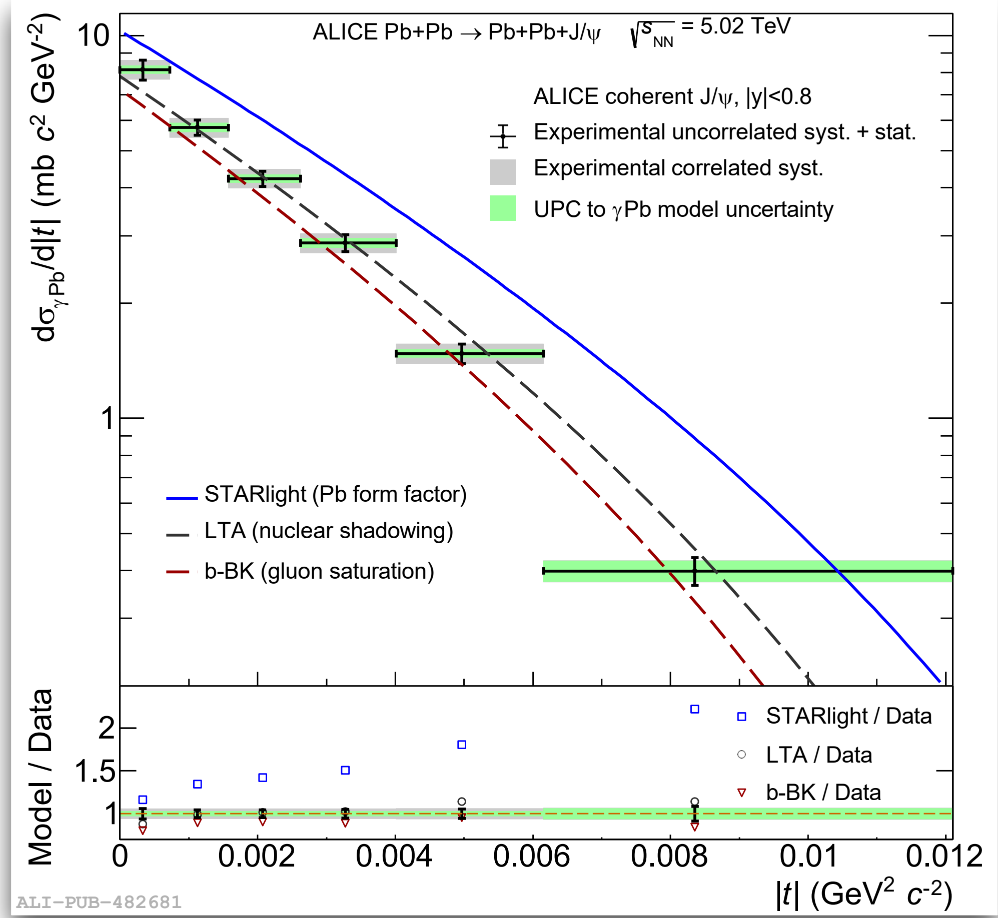


- Little or no suppression at low W
- Possible flattening of suppression curve at highest energies
- Shadowing (LTA) and saturation(b-BK-A) both give quite good descriptions of high-W regime.

t distribution for coherent J/ψ production



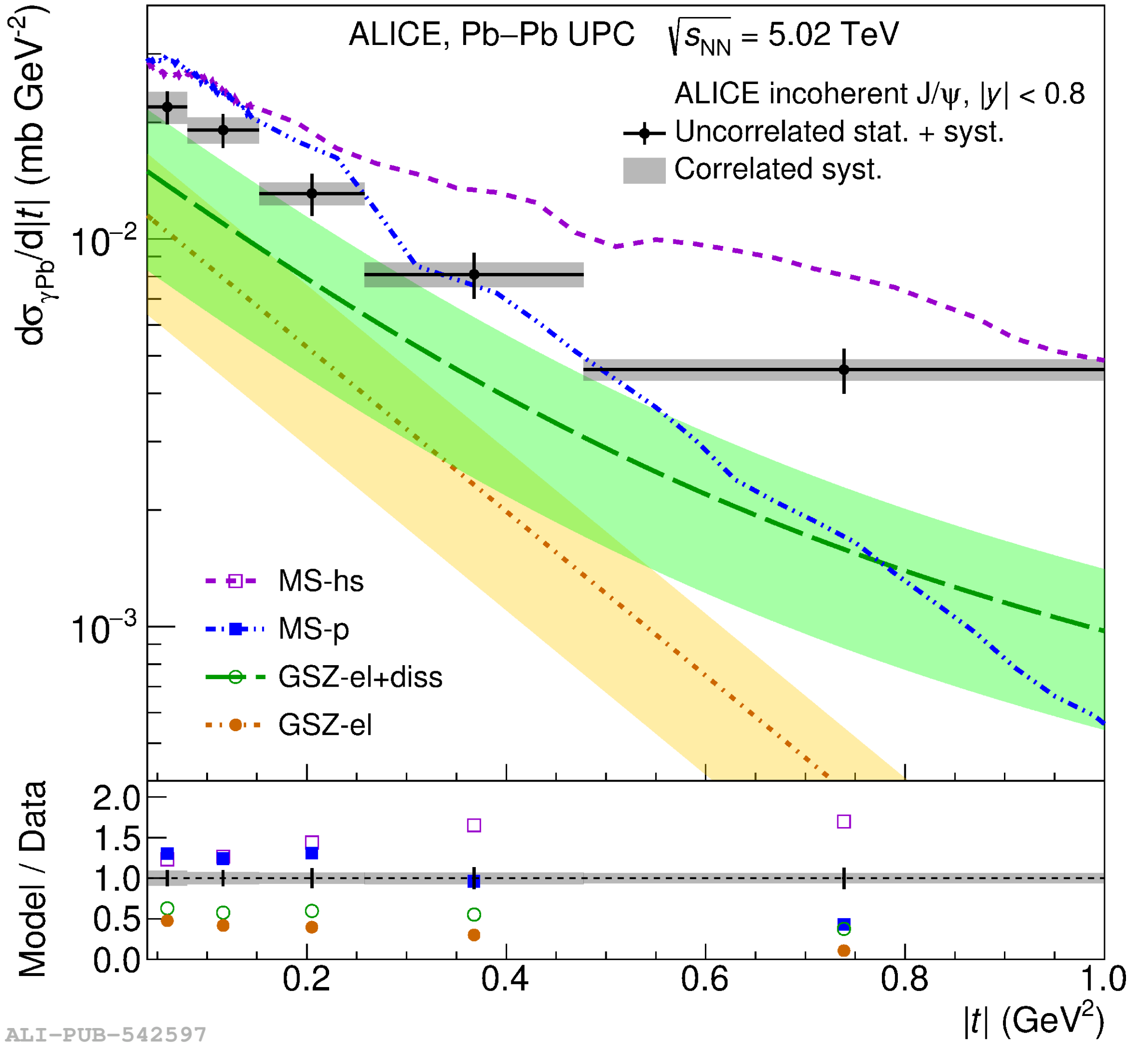




- t related to p_T^2, but necessary to correct for experimental resolution
- $|t|$ related to the transverse size of the target (b and p_T are Fourier conjugates)
- A model based on the form factor does not describe data
- A shadowing based, and a BK computation with impact-parameter dependence, close to data

ALICE, PLB 817(2021) 136280

t distribution for incoherent J/ψ production

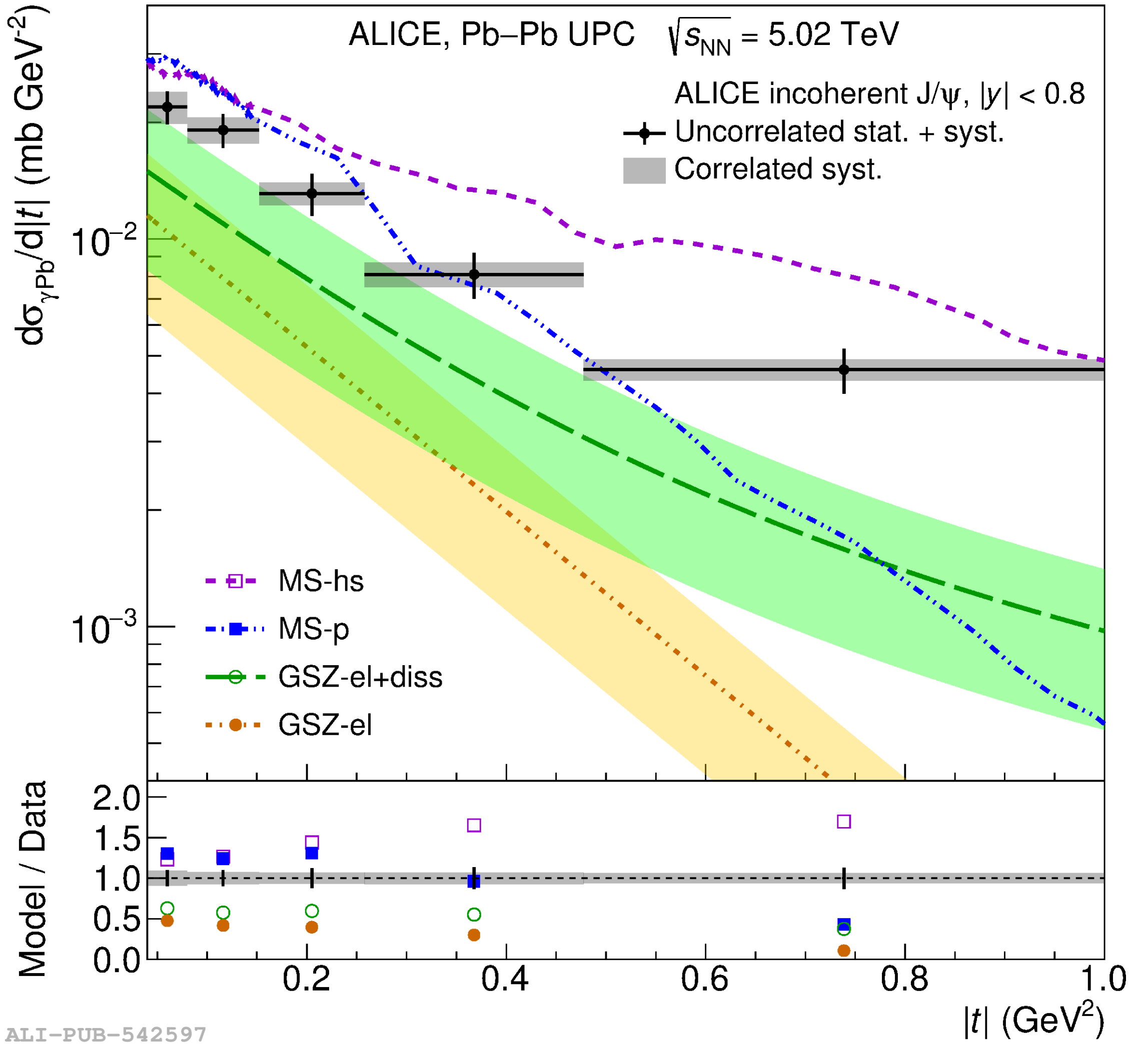


ALICE, arXiv 2305.06169

- |*t*| related to the size of the target: effect of smaller structures appears at larger |*t*|
- Production off nucleons including hot spots (CGC approach)
- Production off nucleons (CGC approach)
- Production off nucleons including dissociation (Shadowing+HERA data)
- Production off nucleons (Shadowing+HERA data)
- Larger |*t*| is sensitive to quantum fluctuations of the colour field at sub-nucleon size scales
- Models including hot spots or dissociation agree better with the slope of data

MS-hs H. Mäntysari and B. Schenke PLB 772 232

t distribution for incoherent J/ψ production

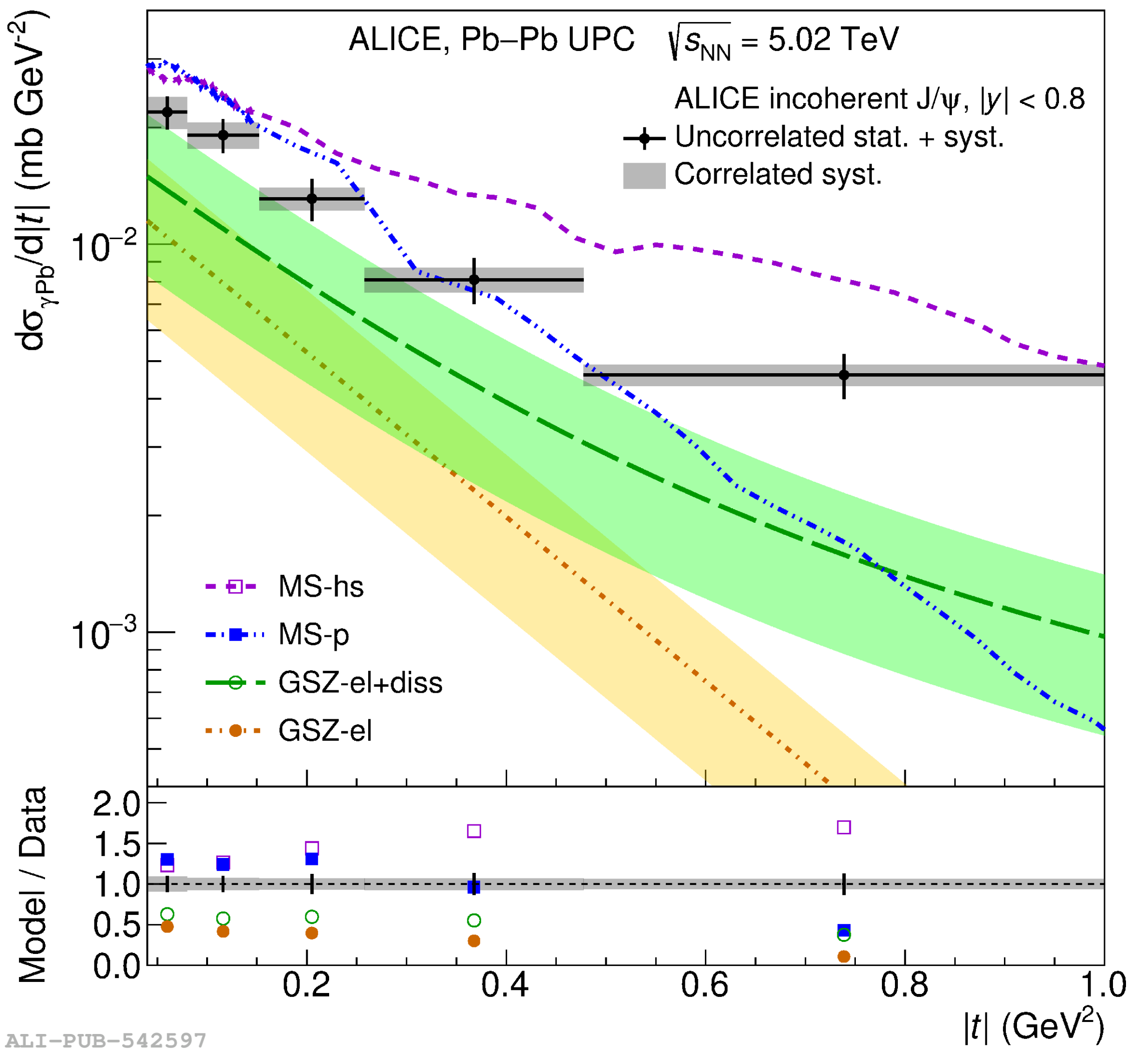


ALICE, arXiv 2305.06169

- |*t*| related to the size of the target: effect of smaller structures appears at larger |*t*|
- Production off nucleons including hot spots (CGC approach)
- Production off nucleons (CGC approach)
- Production off nucleons including dissociation (Shadowing+HERA data)
- Production off nucleons (Shadowing+HERA data)
- Larger |*t*| is sensitive to quantum fluctuations of the colour field at sub-nucleon size scales
- Models including hot spots or dissociation agree better with the slope of data

- MS-hs H. Mäntysari and B. Schenke PLB 772 232

t distribution for incoherent J/ψ production

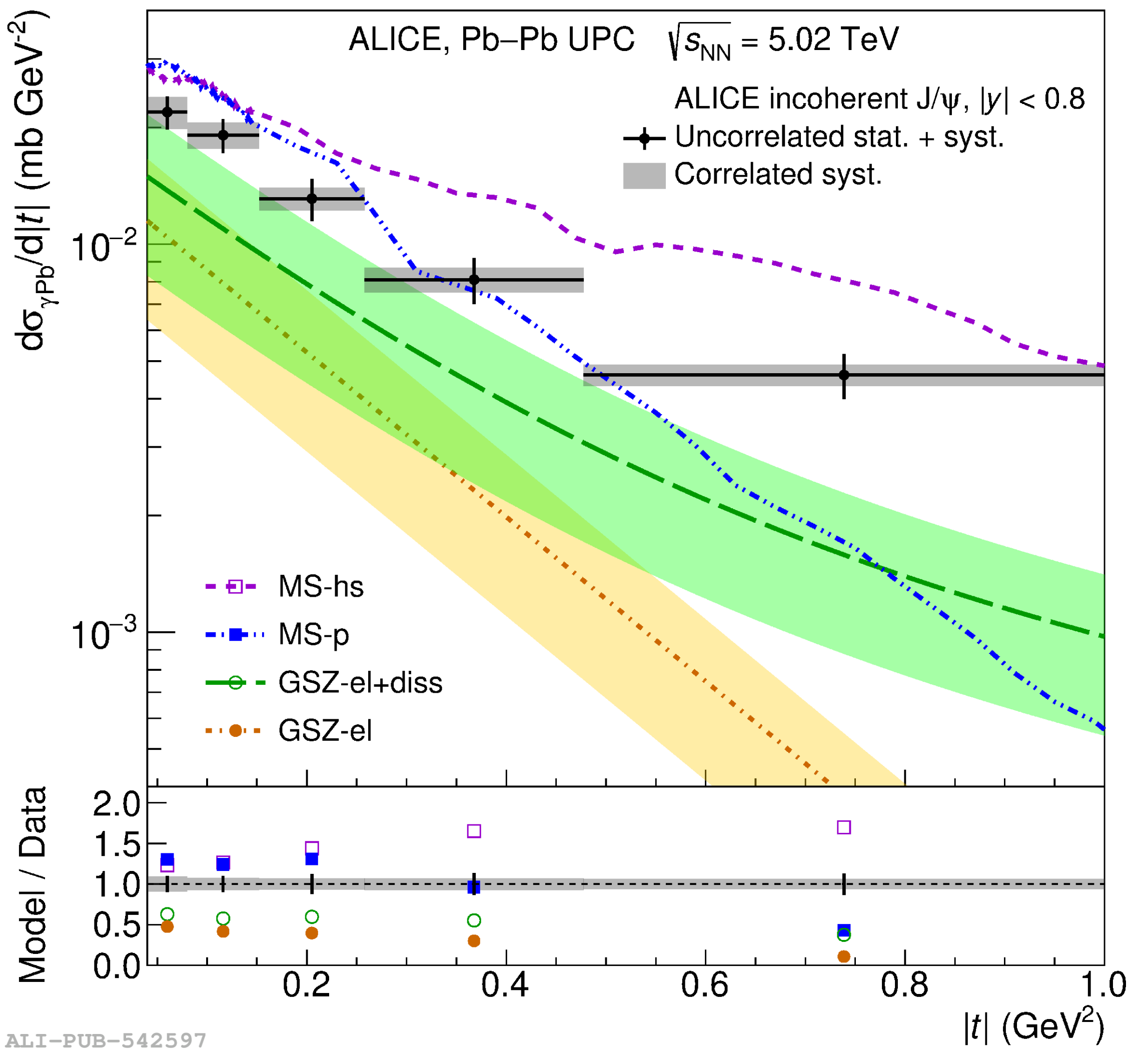


ALICE, arXiv 2305.06169

- $|t|$ related to the size of the target: effect of smaller structures appears at larger $|t|$
- Production off nucleons including hot spots (CGC approach)
- Production off nucleons (CGC approach)
- Production off nucleons including dissociation (Shadowing+HERA data)
- Production off nucleons (Shadowing+HERA data)
- Larger $|t|$ is sensitive to quantum fluctuations of the colour field at sub-nucleon size scales
- Models including hot spots or dissociation agree better with the slope of data

- MS-hs H. Mäntysari and B. Schenke PLB 772 232
- GSZ+el+diss V. Guzey, M. Strikman and M. Zhalov PRC 99 015201

t distribution for incoherent J/ψ production

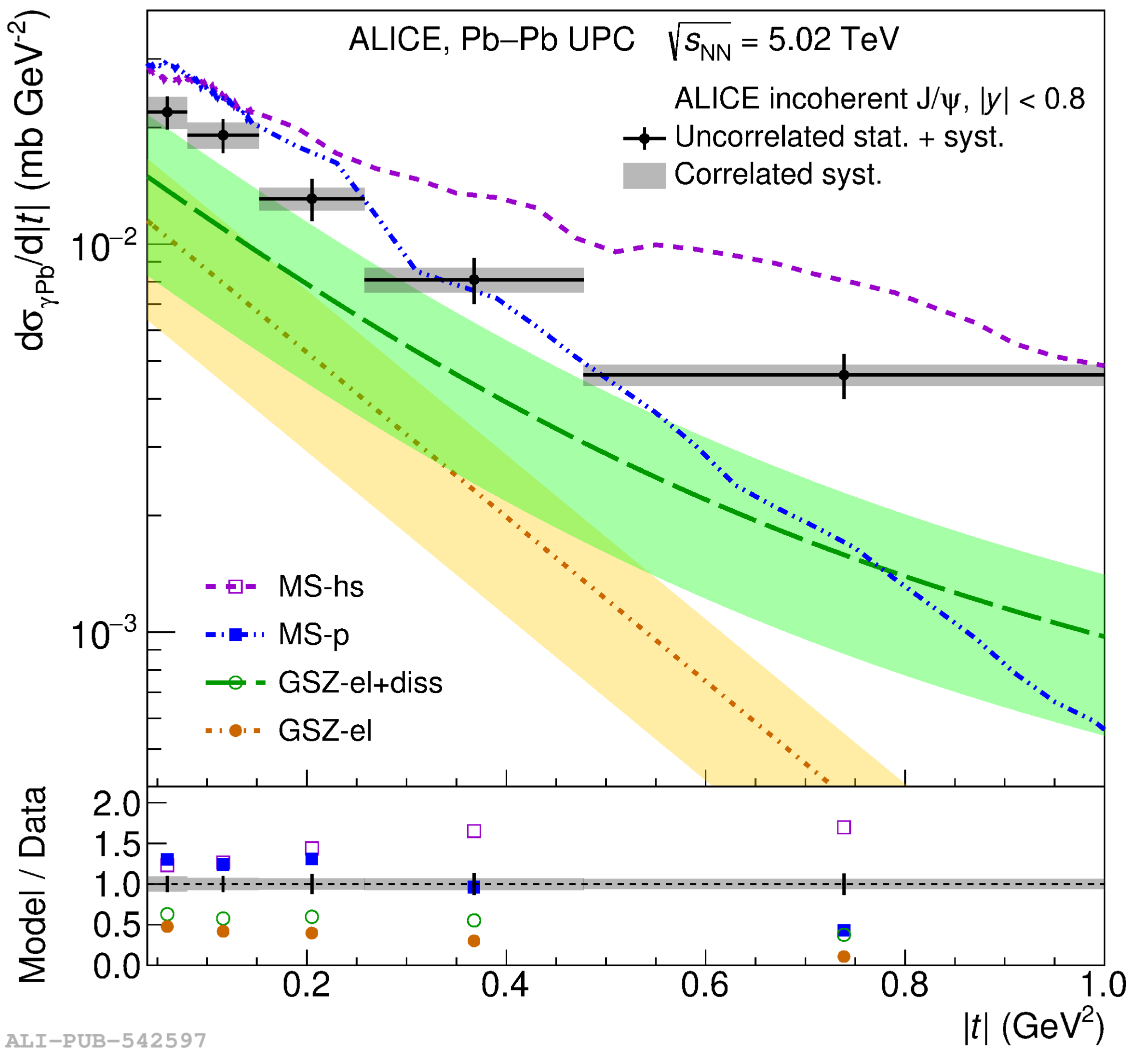


ALICE, arXiv 2305.06169

- |t| related to the size of the target: effect of smaller structures appears at larger |t|
- Production off nucleons including hot spots (CGC approach)
- Production off nucleons (CGC approach)
- Production off nucleons including dissociation (Shadowing+HERA data)
- Production off nucleons (Shadowing+HERA data)
- Larger |t| is sensitive to quantum fluctuations of the colour field at sub-nucleon size scales
- Models including hot spots or dissociation agree better with the slope of data

- MS-hs H. Mäntysari and B. Schenke PLB 772 232
- GSZ+el+diss V. Guzey, M. Strikman and M. Zhalov PRC 99 015201

t distribution for incoherent J/ψ production



ALICE, arXiv 2305.06169

- $|t|$ related to the size of the target: effect of smaller structures appears at larger $|t|$
- Production off nucleons including hot spots (CGC approach)
- Production off nucleons (CGC approach)
- Production off nucleons including dissociation (Shadowing+HERA data)
- Production off nucleons (Shadowing+HERA data)
- Larger $|t|$ is sensitive to quantum fluctuations of the colour field at sub-nucleon size scales
- Models including hot spots or dissociation agree better with the slope of data

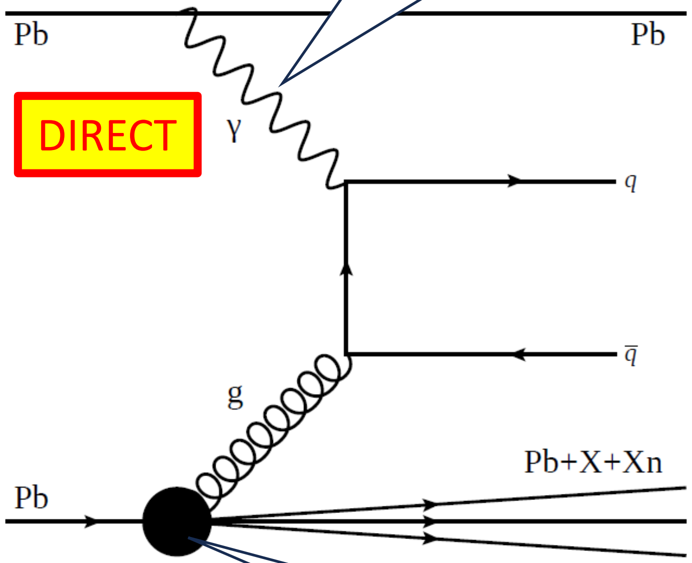
- MS-hs H. Mäntysari and B. Schenke PLB 772 232
- GSZ+el+diss V. Guzey, M. Strikman and M. Zhalov PRC 99 015201

Jet studies

Jet Production ATLAS multijets

Rapidity gap on photon emission side

DIRECT

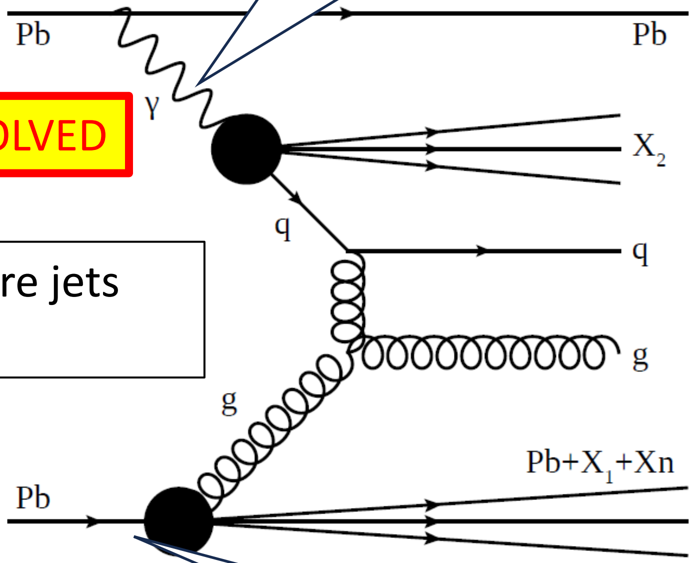


Nucleus that emits gluon breaks up

Two or more jets produced

Rapidity gap on photon emission side

RESOLVED



Nucleus that emits gluon breaks up

ATLAS-CONF-2022-021

Jet Production

3 Variables

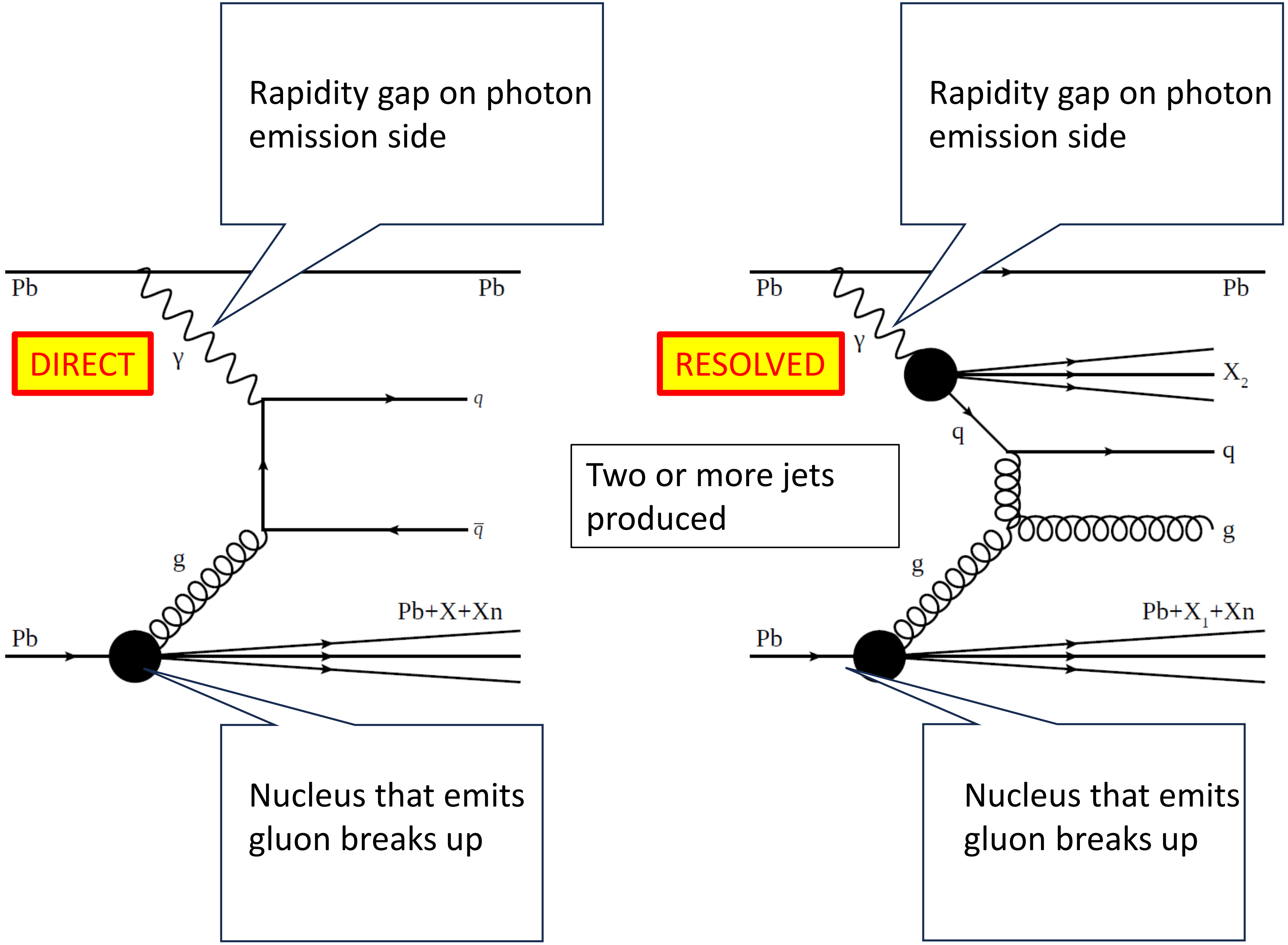
$$H_T = \sum_i p_{Ti}$$

$$x_A = \frac{M_{\mathrm{jets}}}{\sqrt{s_{\mathrm{NN}}}} e^{-y_{\mathrm{jets}}}$$

$$z_\gamma = \frac{M_{\mathrm{jets}}}{\sqrt{s_{\mathrm{NN}}}} e^{+y_{\mathrm{jets}}}$$

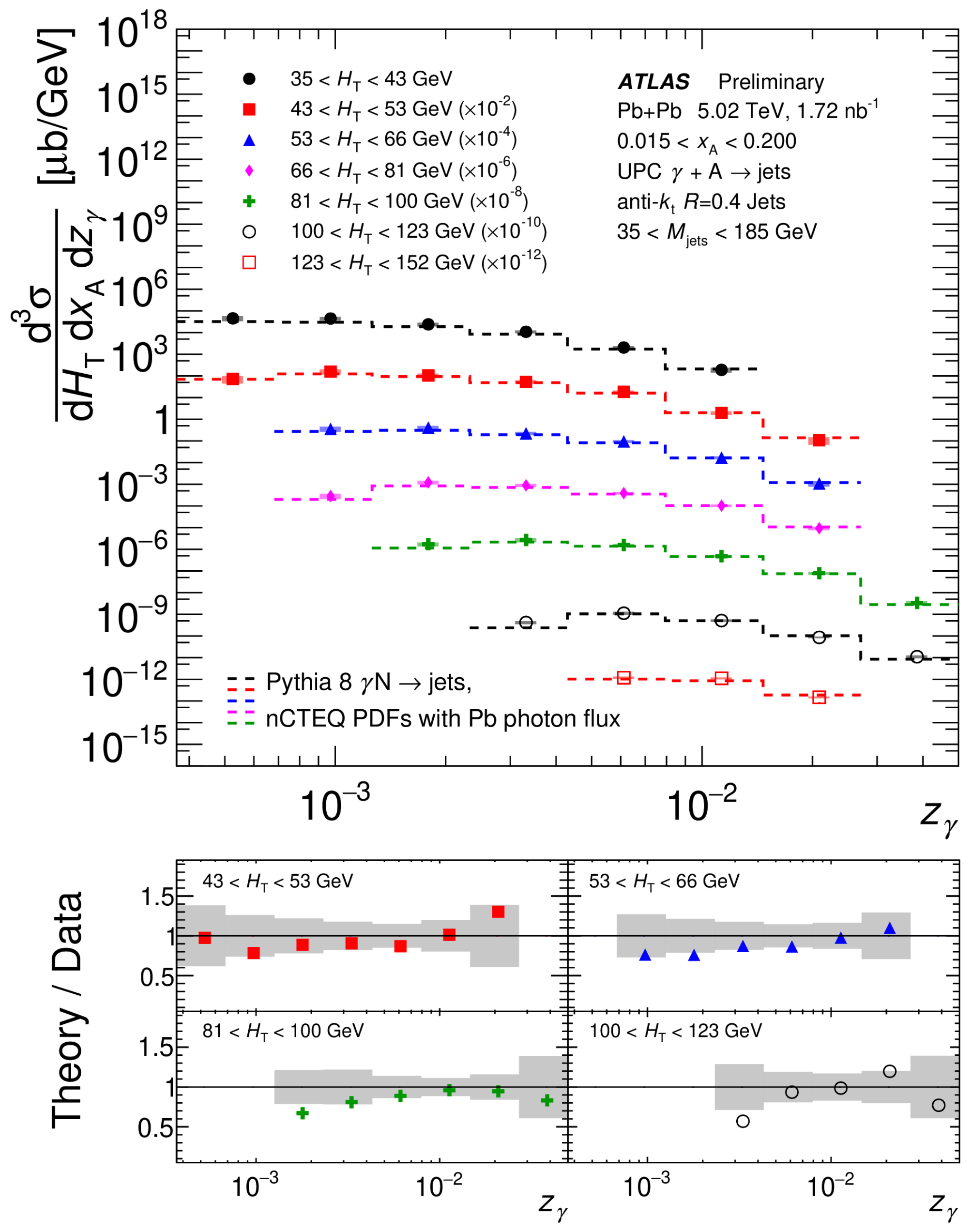
x_A, are z_γ fractions of beam momentum on nucleus and photon sides.

ATLAS-CONF-2022-021



z_γ dependence

Theory uses PYTHIA 8 with NCTEQ PDFs and STARlight photon fluxes

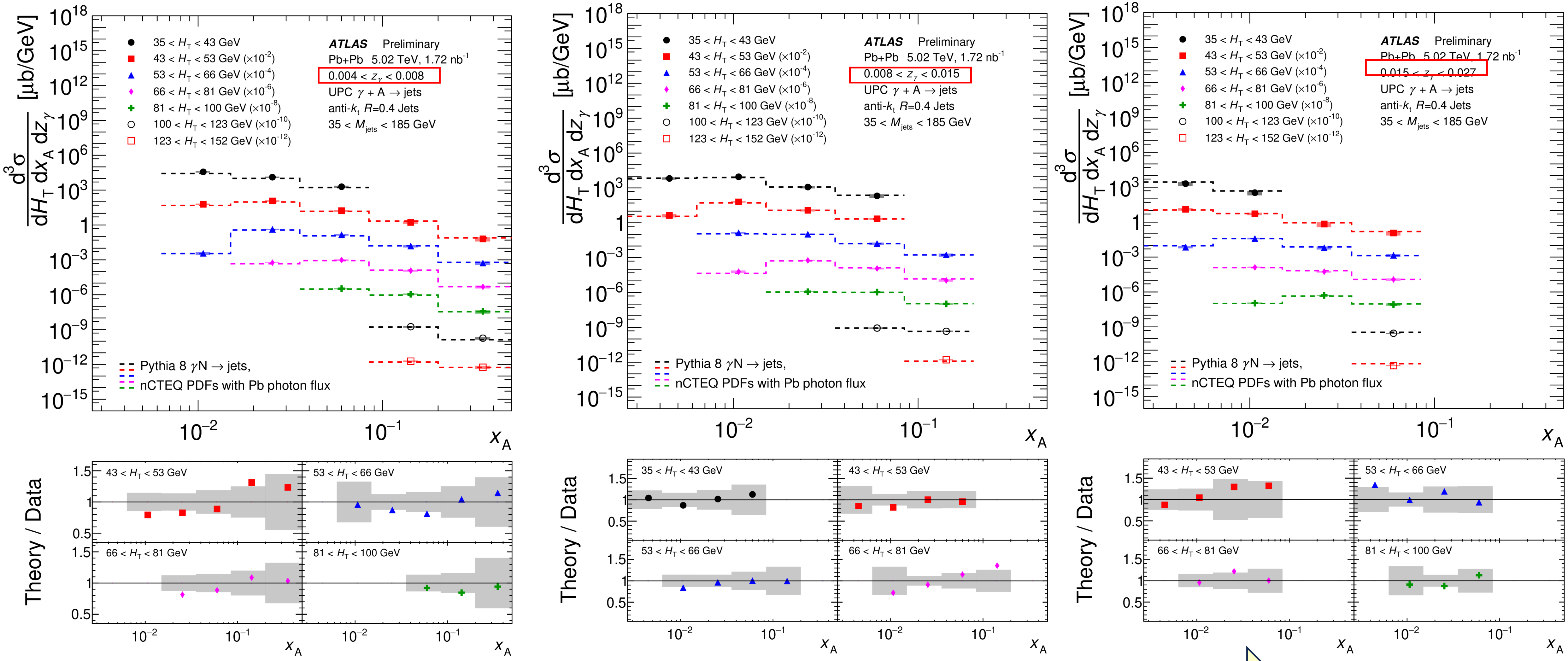


- Triple differential cross section, plotted against different variables
- Different hard scales (H_T)
- Good description for all photon energies

ATLAS-CONF-2022-021

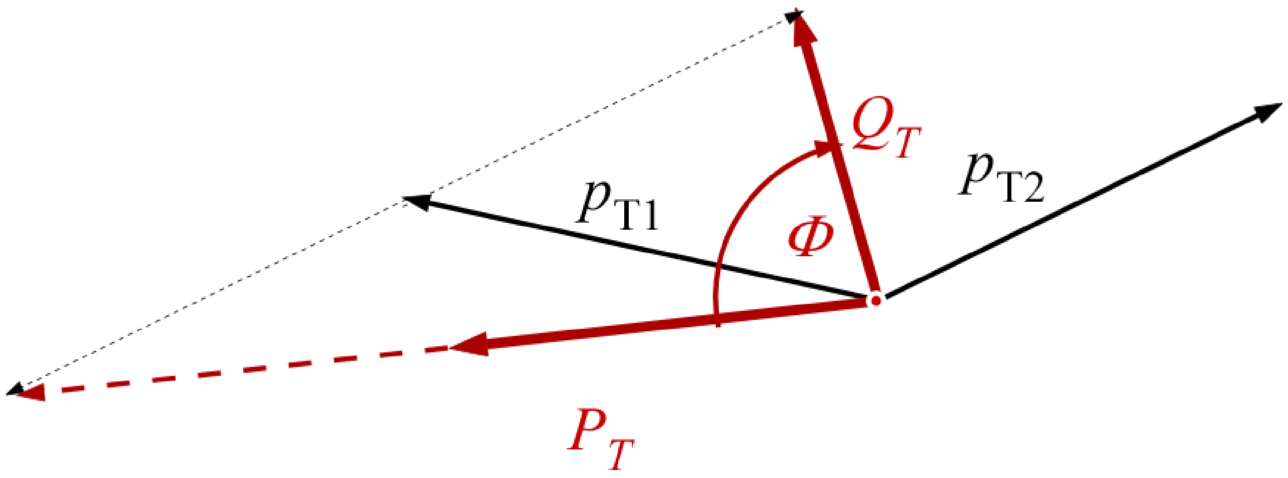
x_A dependence

ATLAS-CONF-2022-021



photon energy increases

CMS dijet azimuthal correlations



- CMS considers dijets with transverse momenta p_{T1} and p_{T2}

$$P_T = \frac{(p_{T1} - p_{T2})}{2}$$

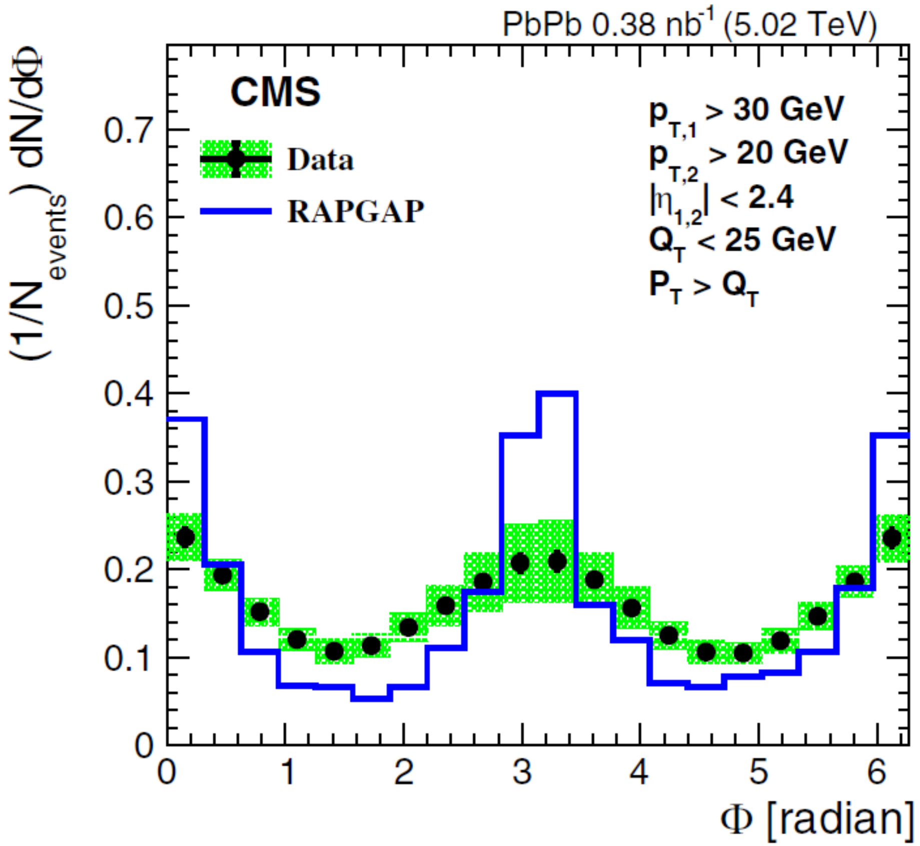
$$Q_T = (p_{T1} + p_{T2})$$

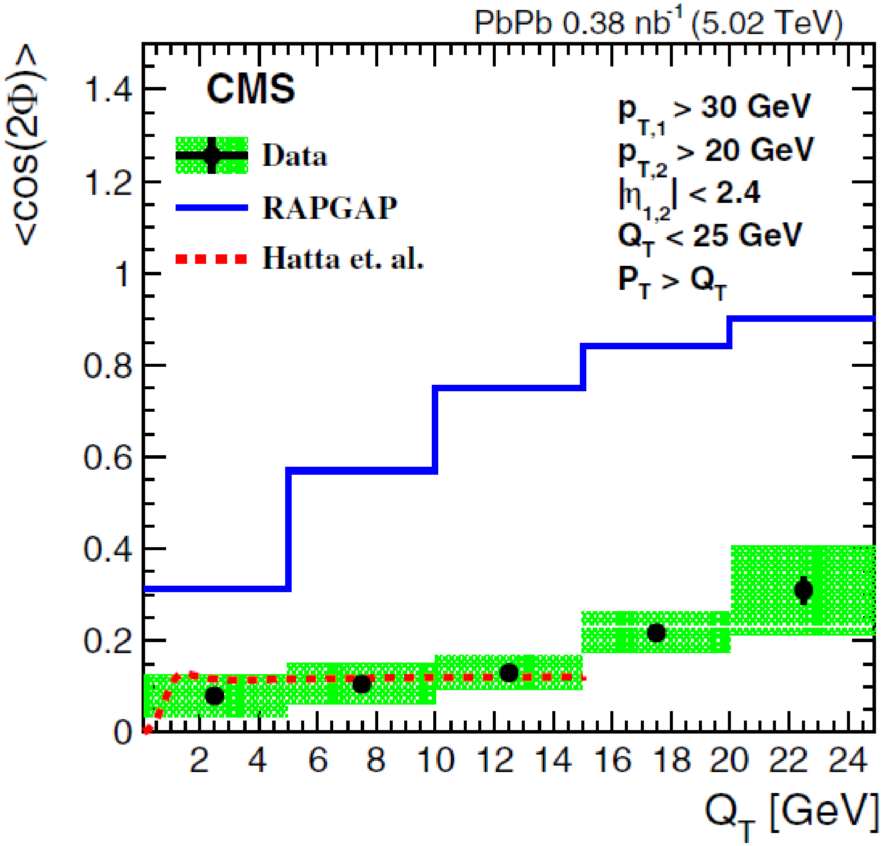
$$P_T . Q_T = |P_T||Q_T| \cos\Phi$$

CMS PRL131 051901 2023

Φ distribution

CMS PRL131 051901 2023





$\langle\cos(2\Phi)\rangle$ rises with Q_T and effect is overestimated by RAPGAP

Such increase in azimuthal asymmetry has been associated with gluon saturation

(*See e.g. A. Van Hameren* et al., *Phys. Lett. B795 511)*

Summary

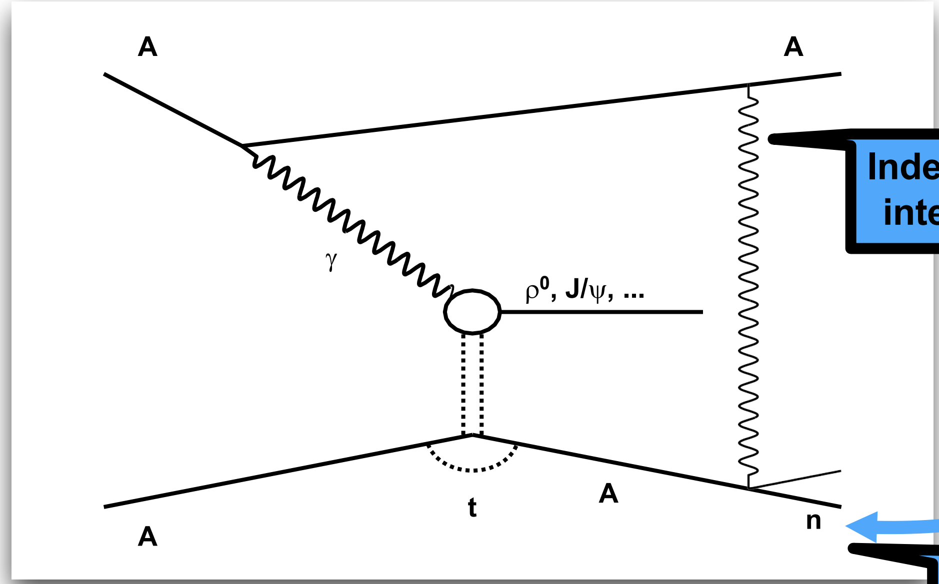
- Many UPC studies now exist, from all the LHC collaborations
- Vector meson production, particularly the J/ψ, is the most developed probe.
- Similar studies can be done with other vector mesons (ρ,ϕ, $\psi(2S)$, Υ) The heavier probes, in particular, give different hard mass scales
- Studies reveal quite significant shadowing effects as *x* decreases, which are yet to be understood.
- ATLAS and CMS have initiated studies into UPC jets. Characterisation is as yet not fully developed, but this is a promising new probe.

Backup

Ambiguity problem: use EMD

Guzey, Strikman, Zhalov, EPJ C74 (2014) 2942

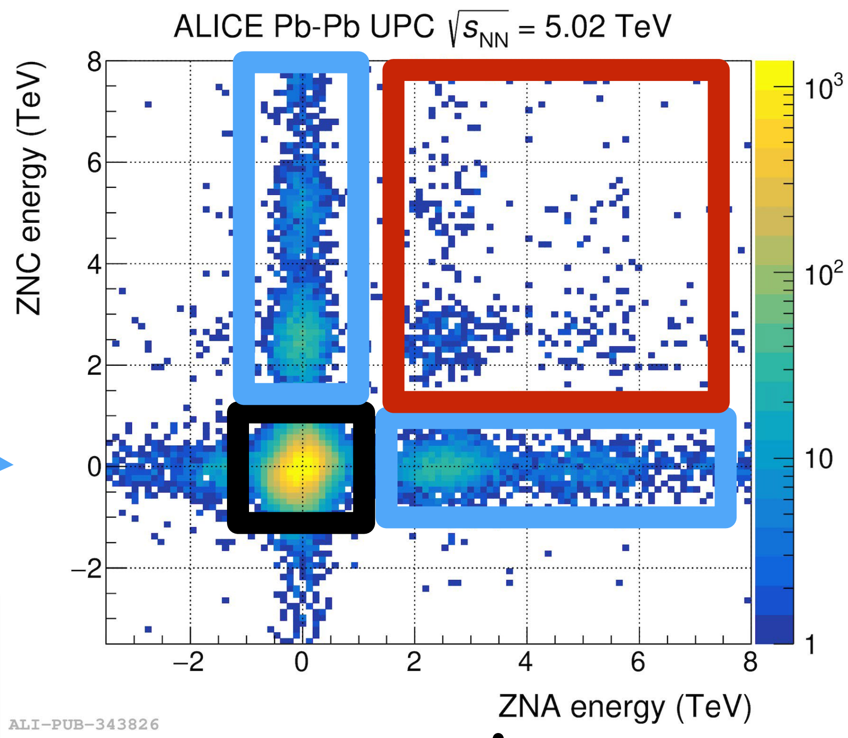
Electromagnetic dissociation of nuclei



Independent interaction

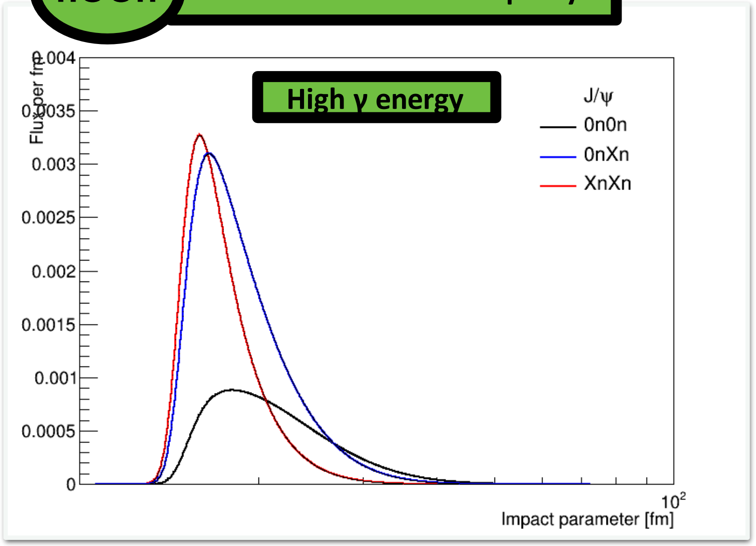
ZDC

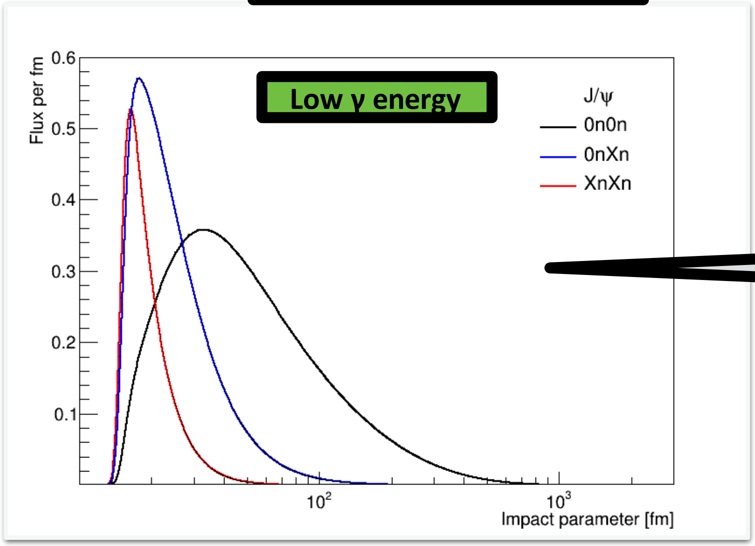
neutrons are emitted along the beamline



ALICE, JHEP 06 (2020) 035

nOOn **Photon fluxes at fwd rapidity:**



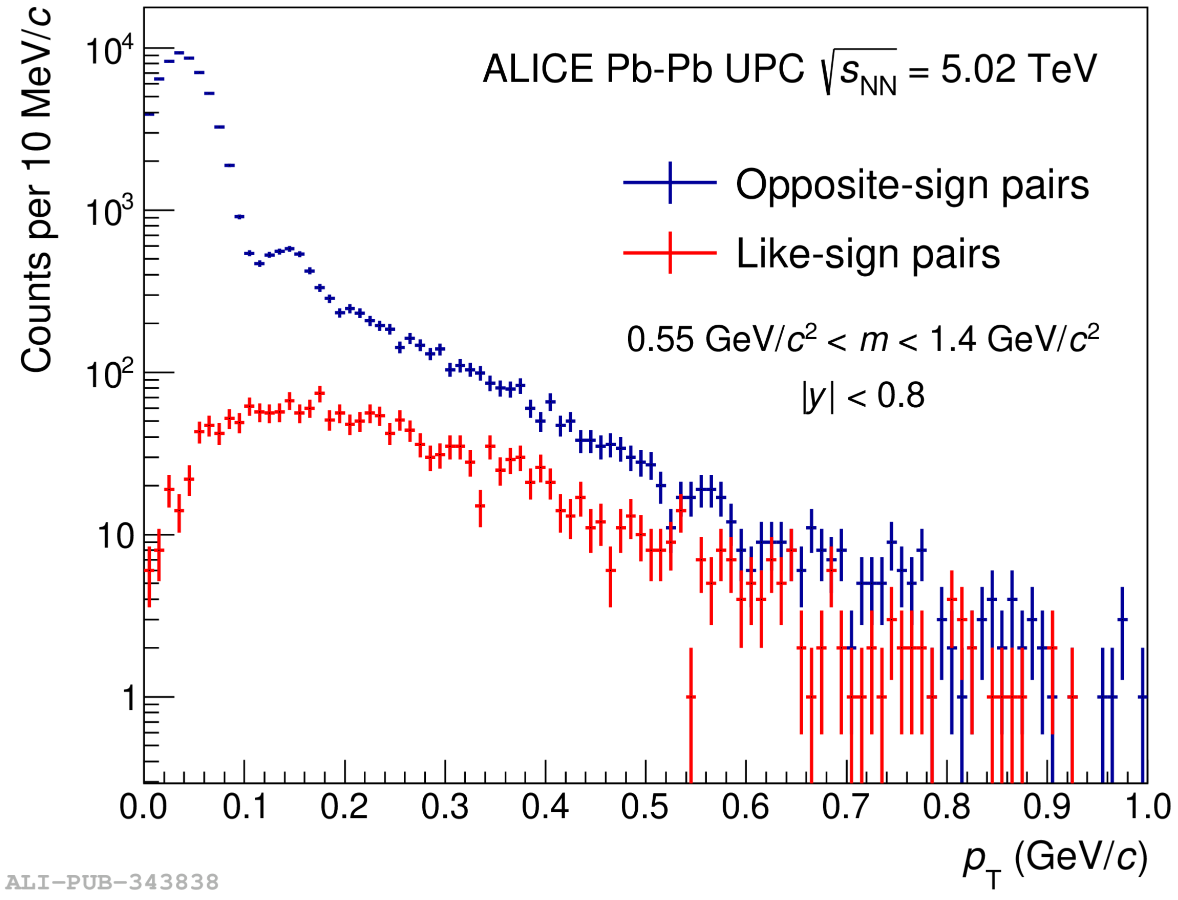


0n0n: no EMD neutron (large b)
0nXn: single EMD (medium b)
XnXn: mutual EMD (smaller b)

Three independent measurements at the same rapidity, but different impact parameters

Broz et al., CPC 235 (2020) 107181

ρ^0 diffractive dip



"… a diffraction dip is clearly seen in the transverse momentum distribution…"

ALICE JHEP06 (2020) 35