Exclusive quarkonium production at the LHC

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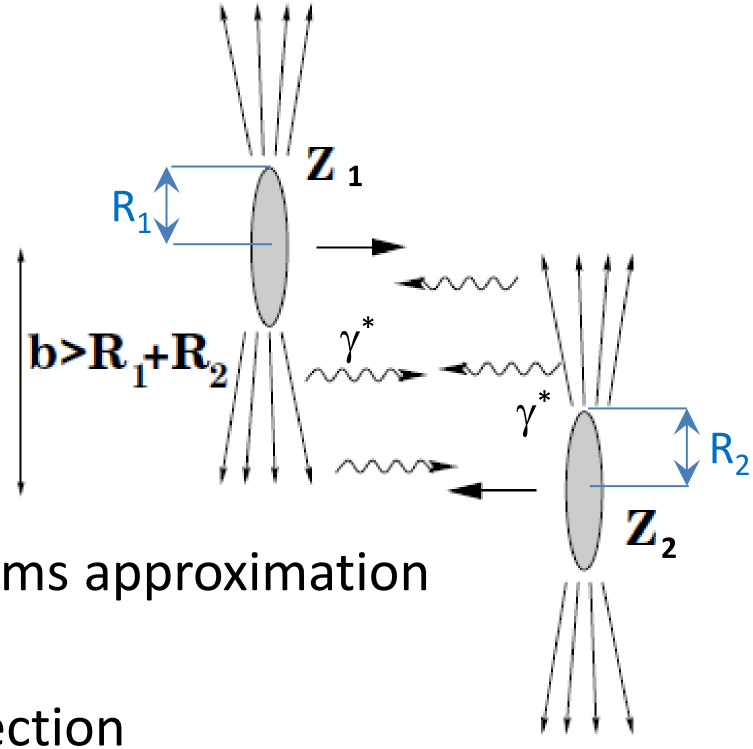
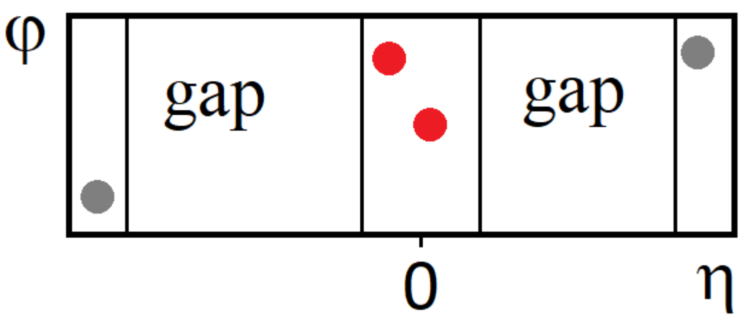
Outline

- Introduction
- Mesurements
  - Coherent and incoherent J/ψ photoproduction in Pb-Pb
  - Coherent ψ(2S) photoproduction in Pb-Pb
  - Exclusive and dissociative J/ψ photoproduction in p-Pb and pp
  - Υ(nS) (n=1,2,3) photoproduction in pp and p-Pb
  - ρ^0 photoproduction in p-Pb, Pb-Pb and Xe-Xe
  - Excited ρ state photoproduction
  - Measurement of nuclear radius and neutron skin
  - Polarization
- Summary

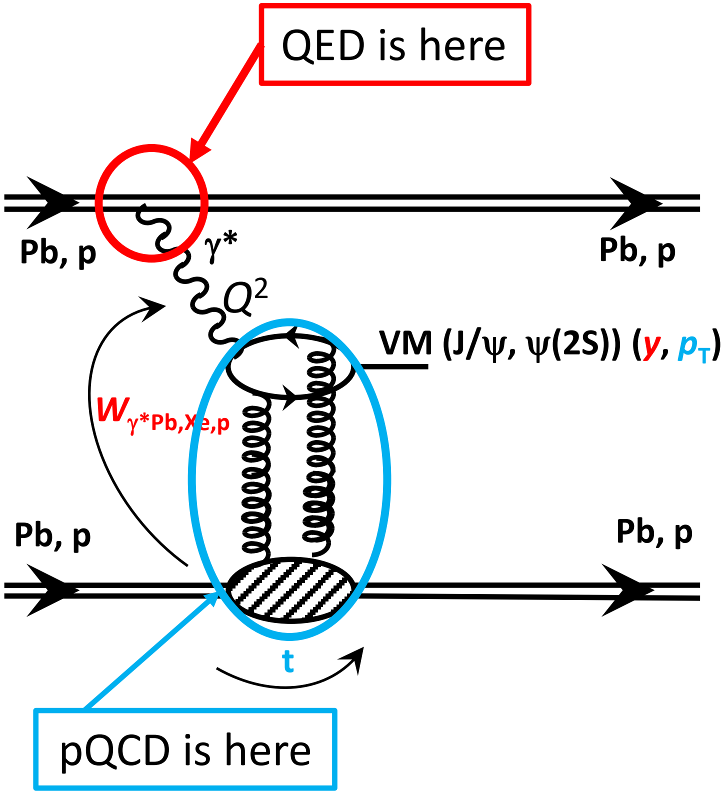
Ultra-peripheral collisions (UPC)



- Impact parameter $b > R_1 + R_2$
  - Hadronic interactions suppressed
- Photon induced reactions:
  - Well described in Weizsäcker-Williams approximation
  - Photon flux $\sim Z^2$ ($Z_{Pb} = 82$)
  - Large γ-induced interaction cross section
- Clear signature:
  - Low detector activity
  - Rapidity gap(s)



Photoproduction and main variables



- Momentum scale $Q^2 \sim M_{VM}{}^2 / 4$
  - Hard scale assured by high mass of J/ψ, ψ′, Υ(nS) meson
  - Semi-hard scale for ρ^0 meson
- Vector Meson (VM) quantum numbers:
  - $J^{PC} = 1^{--}$
- Bjorken-*x:* fraction of longitudinal momentum of proton

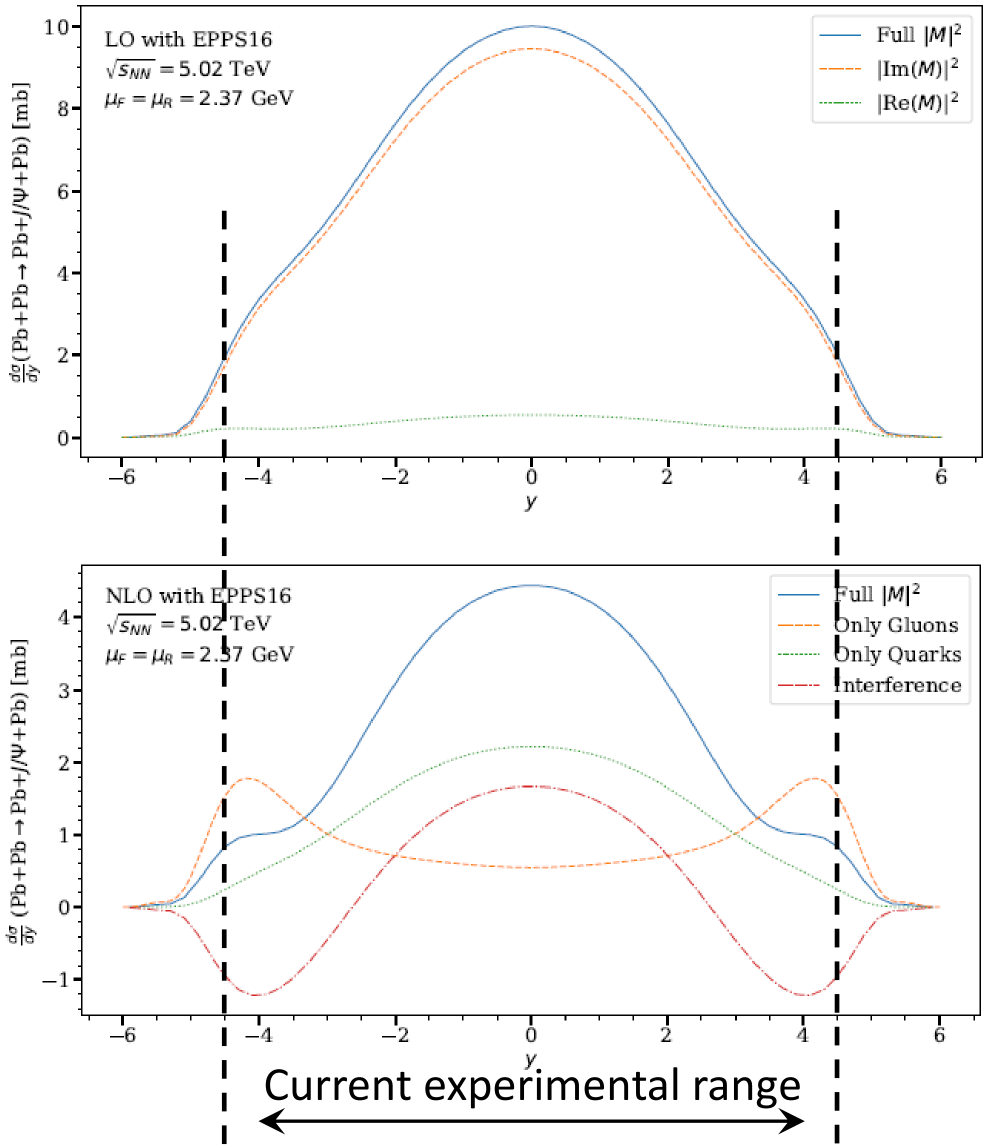
$$x_B = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\pm y}$$

  - ➢ Photoproduction is sensitive to gluon density evolution at low x_B
  - ➢ There are new NLO calculations
- Photon-target centre-of-mass energy

$$W^2_{\gamma^* Pb,p} = 2E_{Pb,p} M_{VM} e^{\mp y}$$

- 4-momentum transfer t
  - Gluon distribution in the transverse plane $|t| \sim p_T{}^2$

J/ψ photoproduction – LO vs NLO



- LO:
  - Gluons
  - Ryskin, Z. Phys. C 57, 89-92 (1993)

$$\frac{d\sigma(\gamma p \to J/\psi p)}{dt} = $$
$$= |F^{2G}{}_N(t)|^2 \frac{\alpha_s{}^2 \Gamma_{ee}{}^J m^3{}_J}{3\alpha_{em}} \pi^3 \left[xG(x,q^2) \frac{2q^2 |q_t{}^J|^2}{(2q^2)^3} \right]^2$$

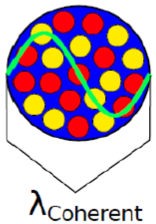
- NLO:
  - Quarks play a role
  - Eskola et al., Phys. Rev. C 106 (2022) no. 3, 035202; arXiv:2210.16048

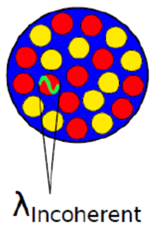
$$\mathcal{M} = \mathcal{M}_G^{\mathrm{LO}} + \mathcal{M}_G^{\mathrm{NLO}} + \mathcal{M}_Q^{\mathrm{NLO}}$$

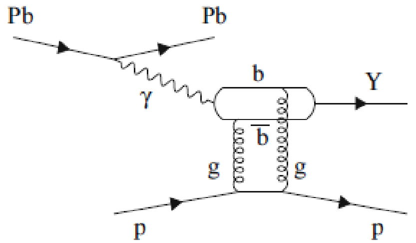
- Differences:
  - Gluons vs quarks
  - Shape
  - Normalization
  - Scale dependence
  - nPDF dependence
- What is the impact of higher order corrections?
- Be carefull with interpretation!

Photoproduction types

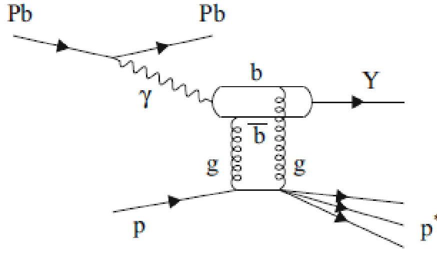
- **Coherent** Vector Meson (VM) photoproduction:
  - Photon couples coherently to all nucleons (whole nucleus)
  - $\langle p_T^{VM} \rangle \sim 1/R_{Pb} \sim 50$ MeV/c
  - Target ion stays intact
- **Incoherent** VM photoproduction:
  - Photon couples to a single nucleon
  - $\langle p_T^{VM} \rangle \sim 1/R_p \sim 400$ MeV/c
  - Target ion breaks, nucleon stays intact
  - Usually accompanied by neutron emission
- **Exclusive** VM photoproduction on target proton:
  - Photon couples to a single proton
  - $\langle p_T^{VM} \rangle \sim 1/R_p \sim 400$ MeV/c
  - Target proton stays intact (similar to coherent) in p-Pb case
- **Dissociative** (or semiexclusive) VM photoproduction:
  – Photon interacts with a single nucleon and excites it
  – $\langle p_T^{VM} \rangle \sim 1$ GeV/c
  – Target nucleon and ion break (in heavy ion collision)
  – Target proton breaks (in p-Pb)





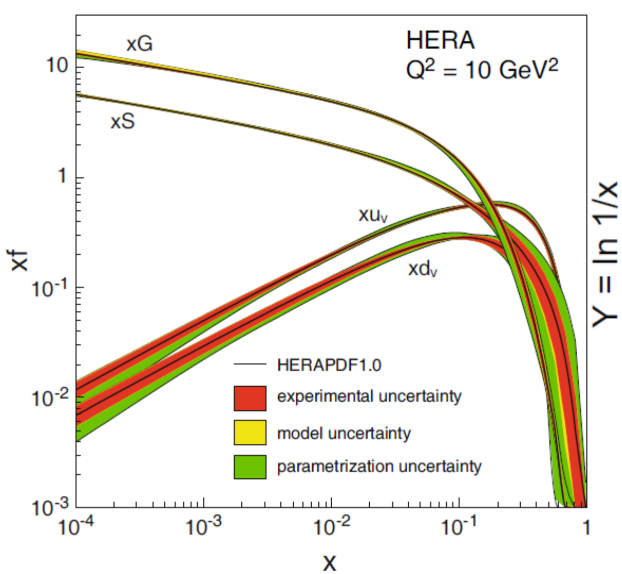


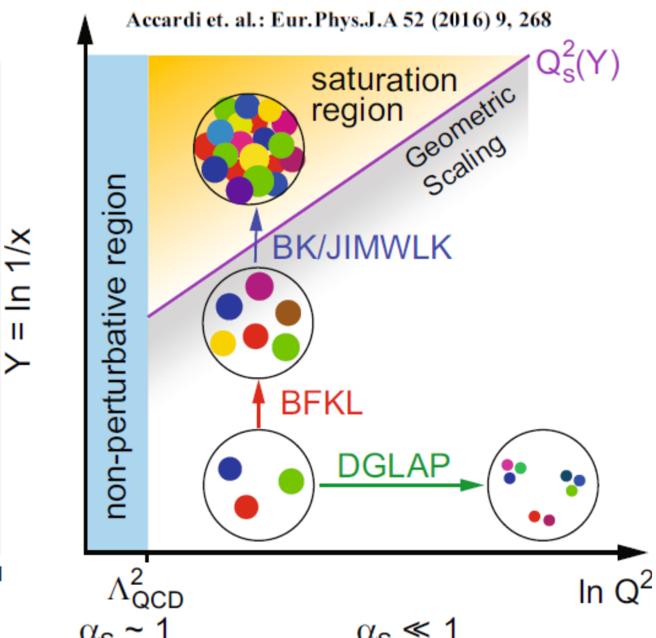
Eur. Phys. J. C (2019) 79:277

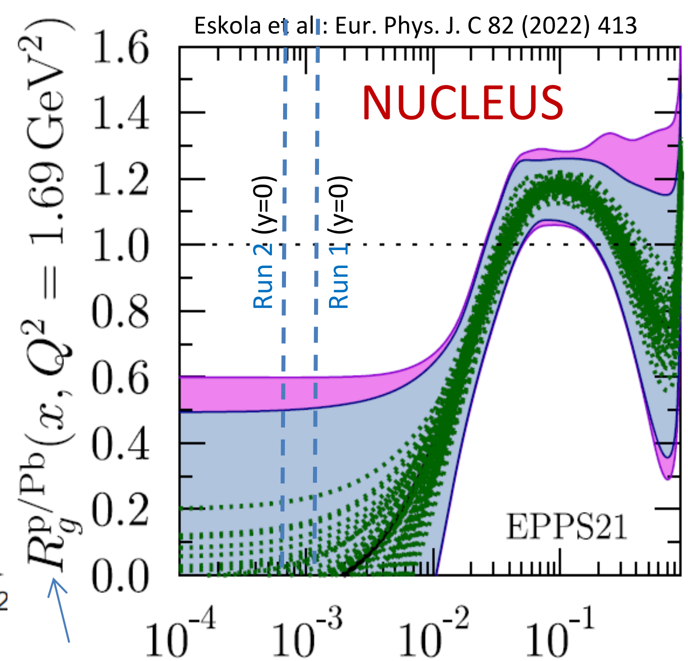


Motivation

- Where is gluon **saturation**?
  - Saturation scale enhanced for nuclei by factor $A^{1/3}$: $(Q_s^A)^2 \approx cQ_0^2\,[A/x]^{1/3}$
- **Coherent** vector meson (ρ^0, J/ψ, $\psi(2S)$,$\Upsilon(nS)$) **photoproduction** particularly sensitive to the **gluon shadowing**
  - Nuclear gluon shadowing factor $R_g^A(x,Q^2)=g_A(x,Q^2)/Ag_p(x,Q^2) < 1$
  - Saturation may contribute to nuclear shadowing
  - Search for saturation at low x_B
- How well do we model **photon flux**?
- Constrain parameters of **models**
- pQCD test

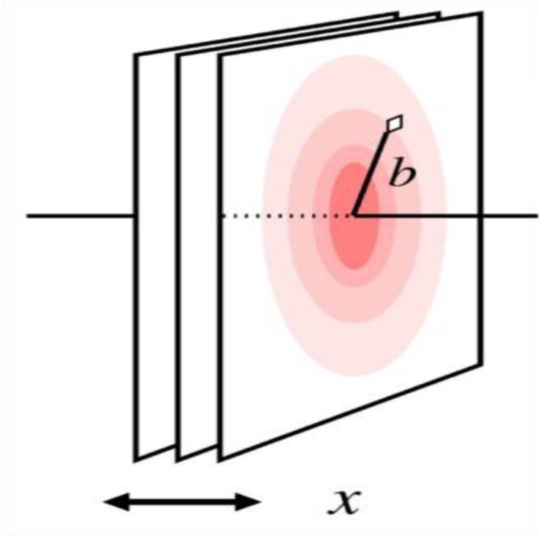






Nuclear gluon shadowing factor

Motivation for t-dependent measurements



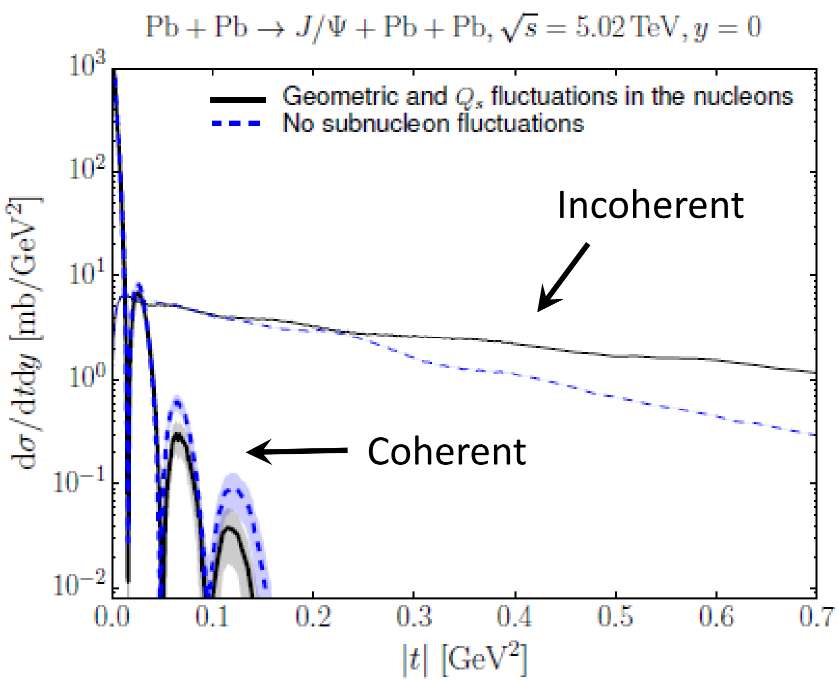
- Gluon density is impact parameter b dependent at given Bjorken-x and Q^2
- b and p_T are Fourier conjugates
- $p_T^2 \approx |t|$ - dependence of the cross section helps to constrain **transverse gluonic structure** at low x_B
- In Good – Walker approach
  - Coherent photoproduction tells about transverse dependence of the gluon shadowing
    - Saturation may contribute to nuclear shadowing
  - Incoherent photoproduction is sensitive to the variance of the spatial gluon distribution (subnucleonic fluctuations)

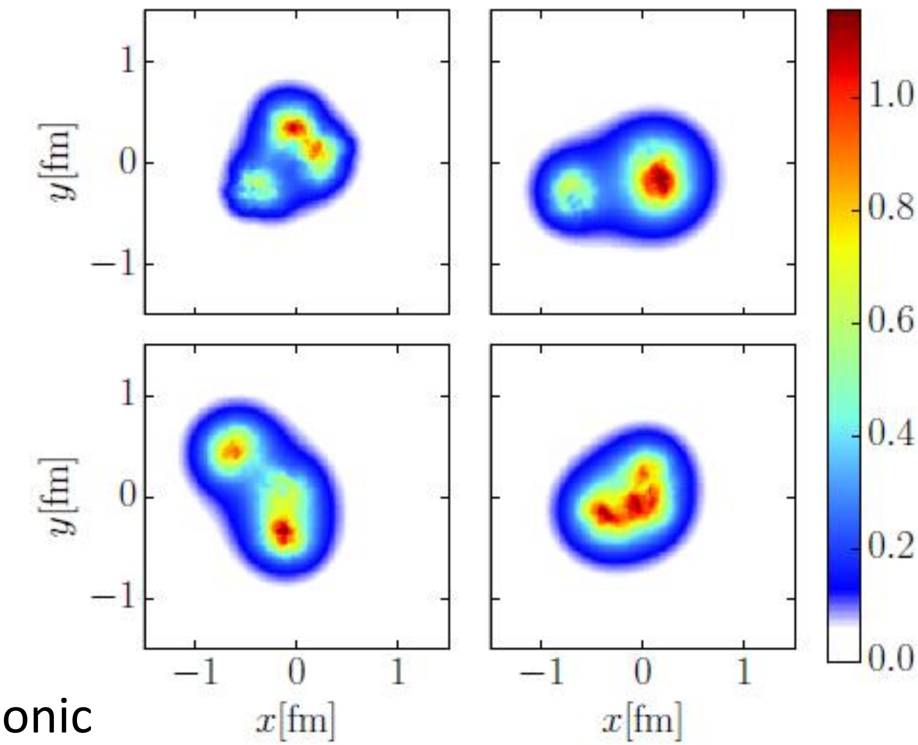
$$\frac{d\sigma^{inc}}{dt} = \frac{{R_g}^2}{16\pi}\left(\langle|A(x,Q^2,\vec{\Delta})|^2\rangle - |\langle A(x,Q^2,\vec{\Delta})\rangle|^2\right)$$

Total Coherent

Motivation – cont.

Mantysaari, Schenke, PLB 772 (2017) 832



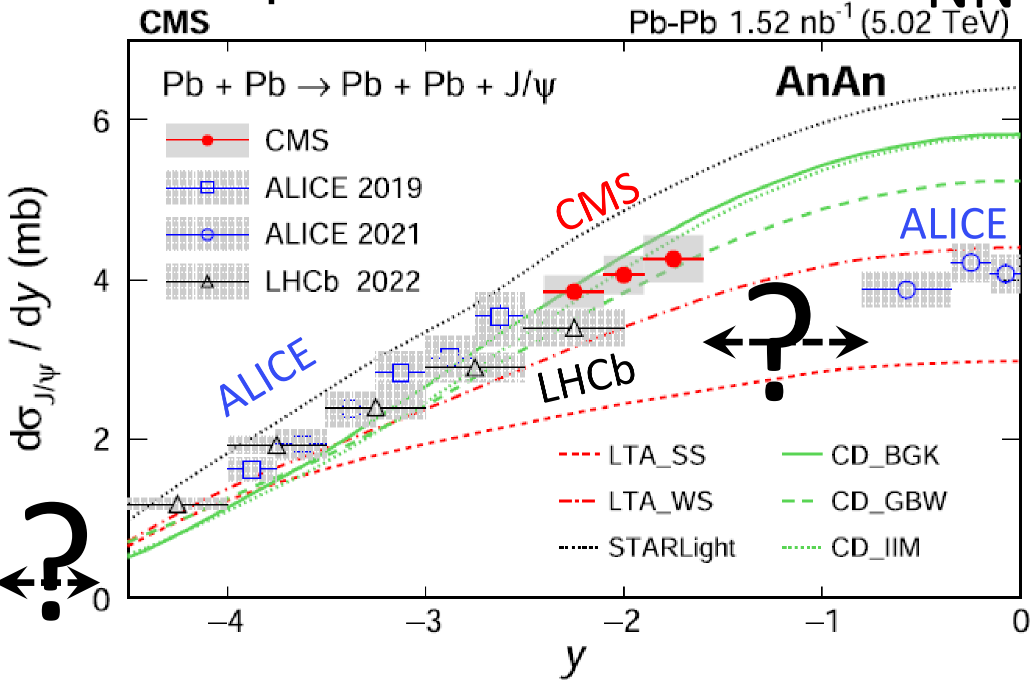


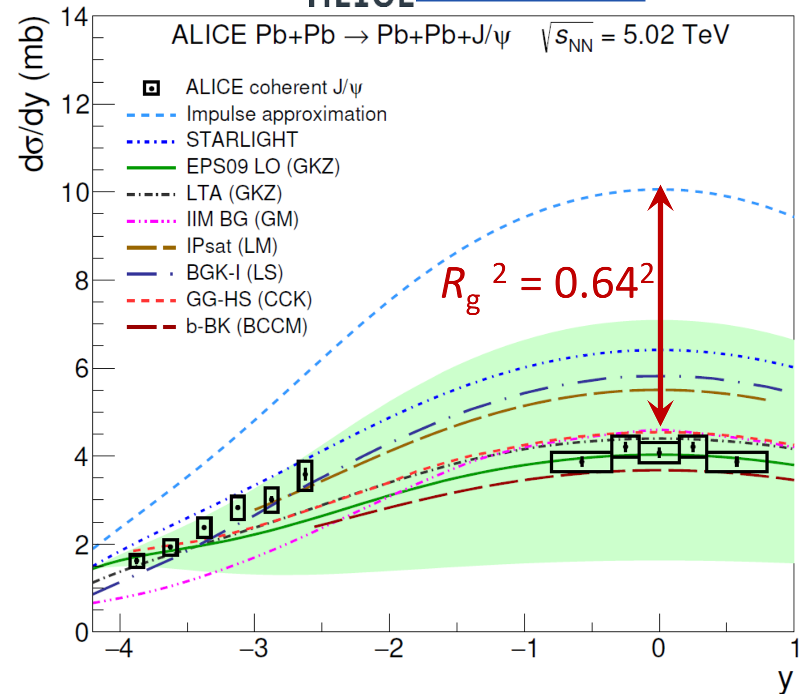
Event by event fluctuations of proton density profile

- Variations in nucleon positions and/or gluonic hot spots → **quantum fluctuations**
- Larger $|t|$ range → scatter of smaller object
- Coherent vs. Incoherent vs. Dissociative J/ψ
  - Access to **different scales**: nucleus, nucleon, hot spots

H. Mantysaari, B. Schenke, PRD 94 (2016) 034042,
J. Cepila, et al., PLB 766, 186 (2017),
S. R. Klein, PRC 107, 055203 (2023).

J/ψ in Pb-Pb at $\sqrt{s_{NN}} = 5$ TeV





- **Forward** region (ALICE, CMS, LHCb): $J/\psi \to \mu^+\mu^-$
- **Central** region (ALICE): $J/\psi \to \mu^+\mu^-$, e^+e^-, pp

→ Wide rapidity range

- **Nuclear gluon shadowing factor**
  - $R_g = 0.64 \pm 0.04$ for $0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$

ALICE: EPJ C 81 (2021) 712
LHCb: JHEP 07 (2022) 117, JHEP 06 (2023) 146
CMS: PRL 131 (2023) 262301

- **Compatibility** between ALICE, LHCb* and CMS results, but … **tensions** are visible
- **No model describes the full rapidity dependence**
  - Models with nuclear shadowing (EPS09 LO, LTA) or saturation (GG-HS) describe central and very forward data but tensions in semiforward region
  - Other models describe either (semi-)forward or central rapidity region

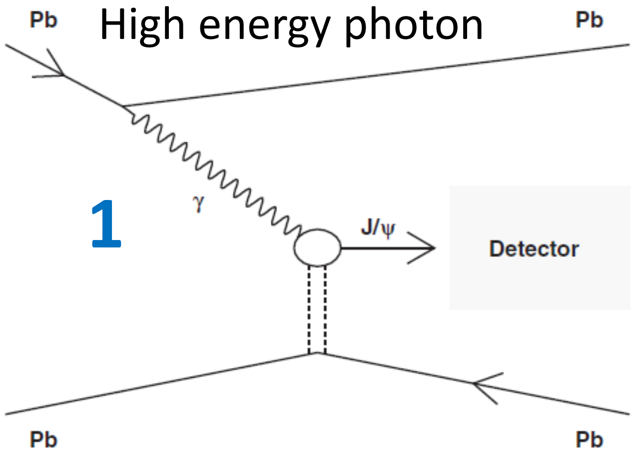
Rapidity dependance: Ambiguity problem

- Two sources ⇒ two values of x_B

ALICE: EPJ C 81 (2021) 712

$$\frac{d\sigma_{AA\rightarrow AA'J/\psi}}{dy} = N(\omega_{\gamma 1})\sigma_{\gamma A}(\omega_{\gamma 1}) + N(\omega_{\gamma 2})\sigma_{\gamma A}(\omega_{\gamma 2})$$

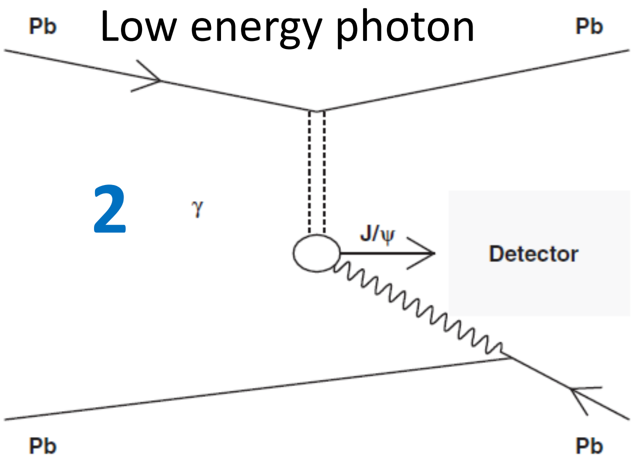
High energy photon



$$\omega_{\gamma 1} = \frac{M_{VM}}{2} e^{+y}$$

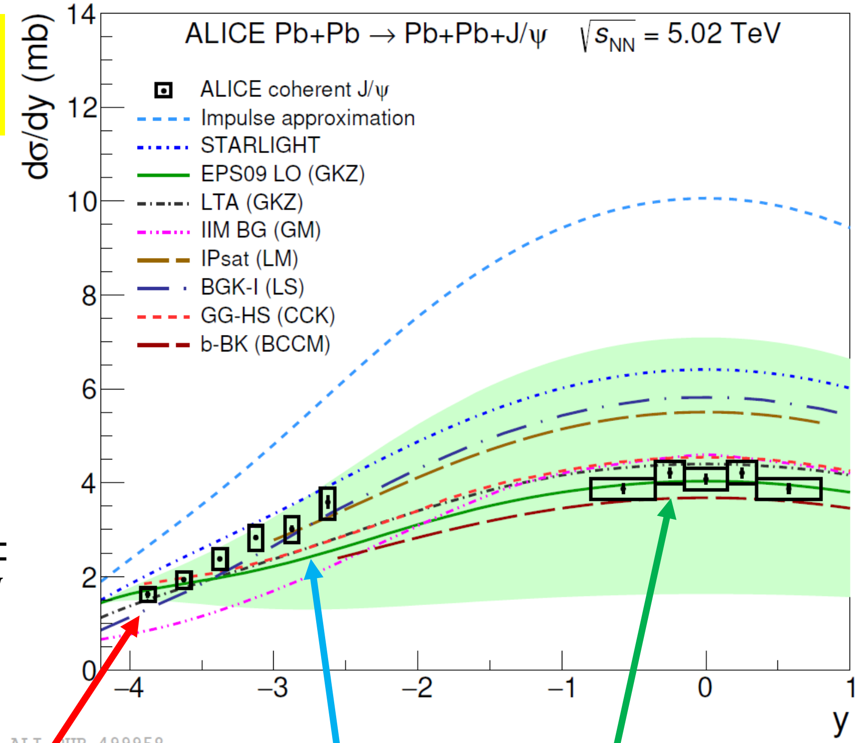
$$x_B = \frac{1}{\omega_{\gamma 1,\gamma 2}} \frac{M^2{}_{VM}}{2\sqrt{s_{NN}}}$$

Low energy photon



$$\omega_{\gamma 2} = \frac{M_{VM}}{2} e^{-y}$$

Contreras, PRC 96, 015203 (2017)



1: 5 % $x_B \sim 1.1 \times 10^{-5}$
2: 95 % $x_B \sim 3.3 \times 10^{-2}$

1: 40 % $x_B \sim 5.1 \times 10^{-4}$
2: 60 % $x_B \sim 0.7 \times 10^{-2}$

50 % each $x_B \sim 10^{-3}$

Solving the ambiguity problem

$$\frac{d\sigma_{AA\rightarrow AA'J/\psi}}{dy} = N(\omega_{\gamma 1})\sigma_{\gamma A}(\omega_{\gamma 1}) + N(\omega_{\gamma 2})\sigma_{\gamma A}(\omega_{\gamma 2})$$

Photon flux

Photon energy

Coherent J/ψ at **midrapidity**

- UPC cross section can be directly linked to photonuclear cross section

Coherent J/ψ at **forward rapidity**

- 95% of the cross section comes from the low energy photon (high x_B gluon)

$$\frac{d\sigma}{dy} = 2N(\omega_{\gamma})\sigma_{\gamma Pb}(\omega_{\gamma})$$

$$\frac{d\sigma}{dy} \cong N(\omega_{\gamma 2})\sigma_{\gamma Pb}(\omega_{\gamma 2})$$

To disentangle both photon contributions we need to measure the same proces in peripheral collisions or with EMD!

Techniques to solve the x_B ambiguity

- Different breakup classes using the neutron ZDC on the A and C side
  - Guzey at al., Eur. Phys. J. C 74 (2014) 7, 2942
  - Photon flux depends on the impact parameter
    - Taken from theory, burdened with uncertainties
  - Solving the linear equations resolves the two-fold ambiguity for VMs at y ≠ 0

$$\frac{d\sigma_{PbPb}}{dy} = \frac{d\sigma_{PbPb}{}^{0N0N}}{dy} + 2\frac{d\sigma_{PbPb}{}^{0NXN}}{dy} + \frac{d\sigma_{PbPb}{}^{XNXN}}{dy}$$

$$\frac{d\sigma_{PbPb}{}^{0N0N}}{dy} = N^{0N0N}(\omega_{\gamma 1}, +y)\sigma_{\gamma Pb}(\omega_{\gamma 1}, +y) + N^{0N0N}(\omega_{\gamma 2}, -y)\sigma_{\gamma Pb}(\omega_{\gamma 2}, -y)$$

$$\frac{d\sigma_{PbPb}{}^{0NXN}}{dy} = N^{0NXN}(\omega_{\gamma 1}, +y)\sigma_{\gamma Pb}(\omega_{\gamma 1}, +y) + N^{0NXN}(\omega_{\gamma 2}, -y)\sigma_{\gamma Pb}(\omega_{\gamma 2}, -y)$$

measured theory extracted

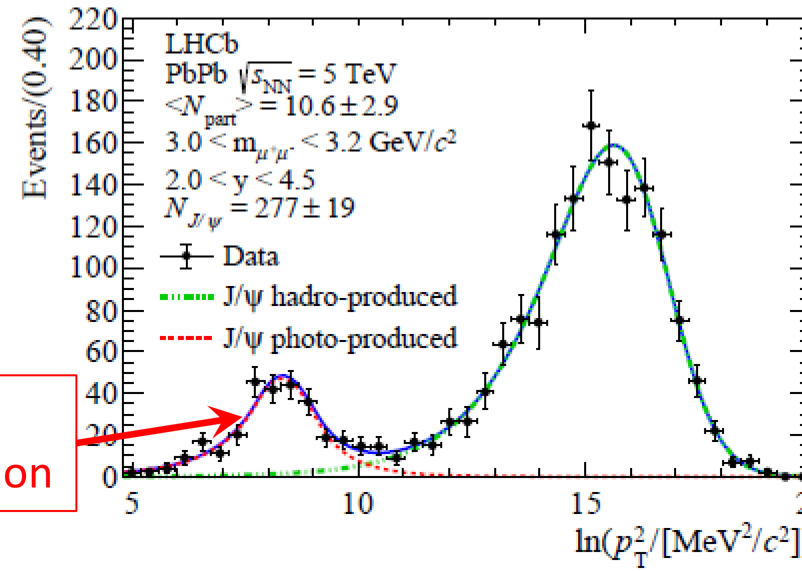
- Simulataneously uses UPC and peripheral classes
  - Contreras, PRC 96 (2017) 015203

$$\frac{d\sigma_{PbPb}{}^{P}}{dy} = N^{P}(\omega_{\gamma 1}, +y)\sigma_{\gamma Pb}(\omega_{\gamma 1}, +y) + N^{P}(\omega_{\gamma 2}, -y)\sigma_{\gamma Pb}(\omega_{\gamma 2}, -y)$$

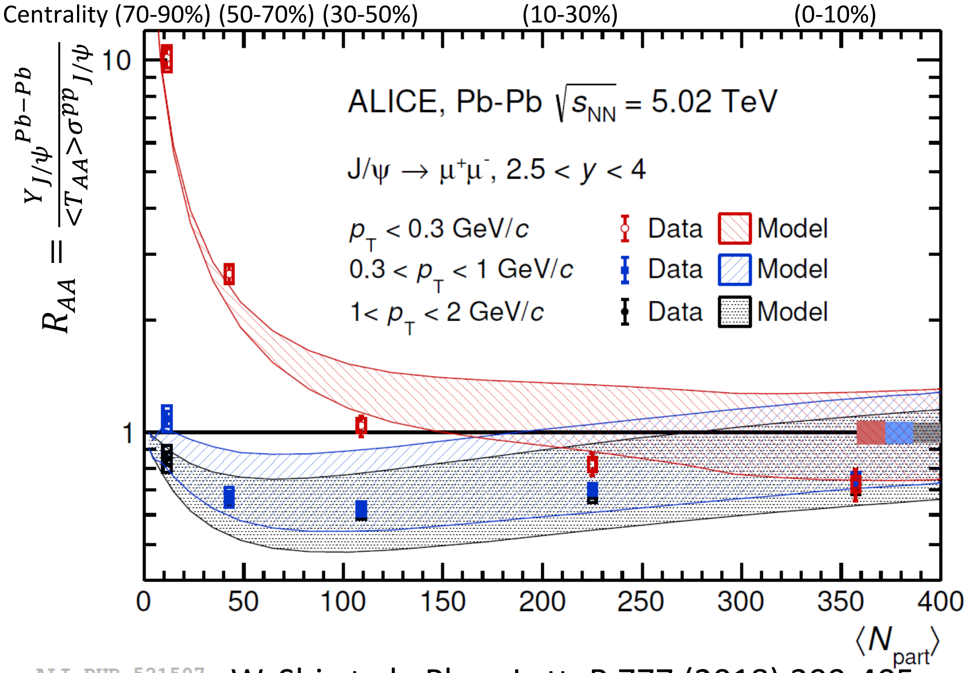
$$\frac{d\sigma_{PbPb}{}^{U}}{dy} = N^{U}(\omega_{\gamma 1}, +y)\sigma_{\gamma Pb}(\omega_{\gamma 1}, +y) + N^{U}(\omega_{\gamma 2}, -y)\sigma_{\gamma Pb}(\omega_{\gamma 2}, -y)$$

Coherent J/ψ in non UPC Pb-Pb

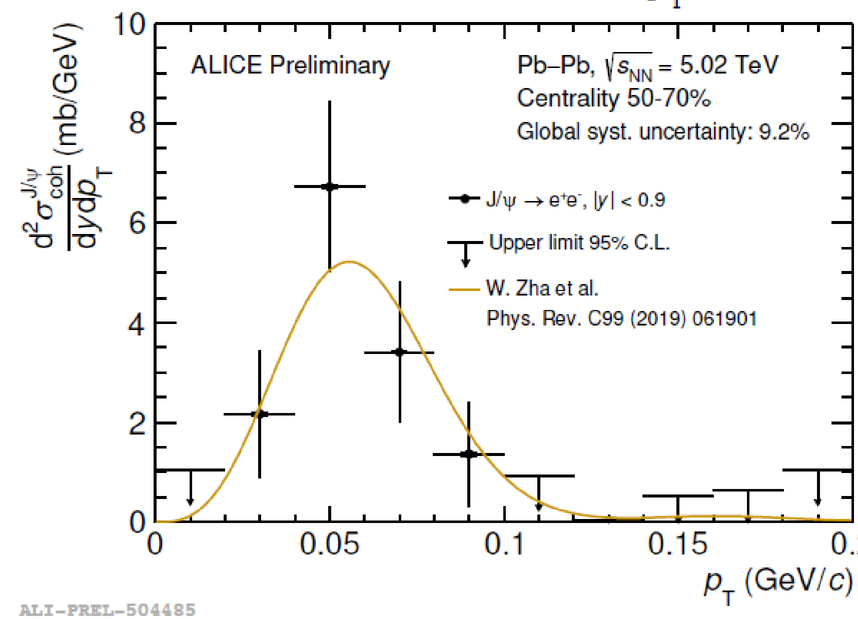
- **Low p_T** (< 0.3 GeV/c) and $\boldsymbol{R_{AA}}$ **excess** (24σ for the peripheral class) explained by photoproduction in **peripheral** collisions
- Hadroproduction dominates in higher p_T intervals
- Good description of R_{AA} by model (W. Shi et al.) with medium effects + photoproduction. QGP effects also considered
- Both **forward** and **central** region
- Is is the same for **other VMs**?



LHCb, PRC105 (2022) L032201



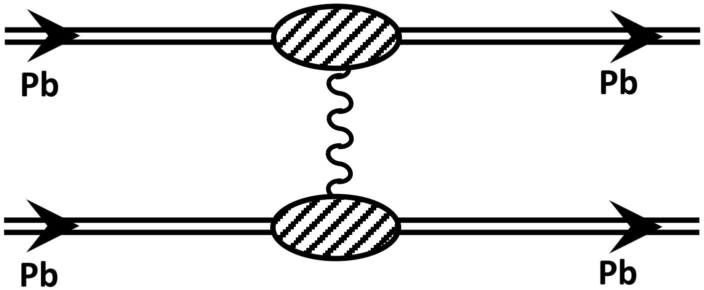
ALICE, arXiv:2204.10684 (2022) → PLB



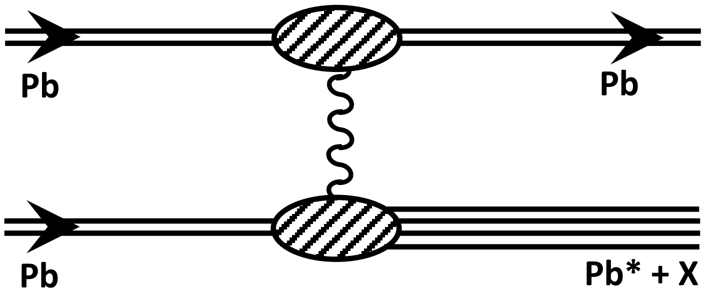
W. Shi et al., Phys. Lett. B 777 (2018) 399-405

Impact parameter dependence

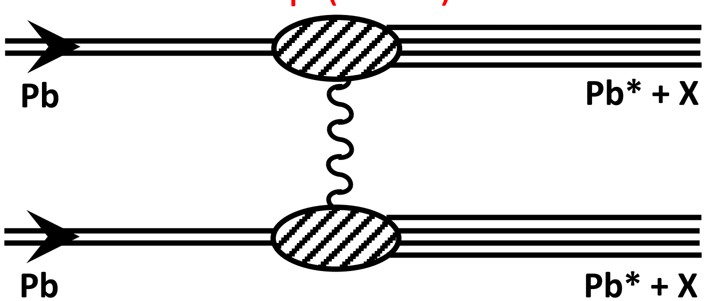
No breakup (0n0n)



Single breakup (Xn0n + 0nXn)



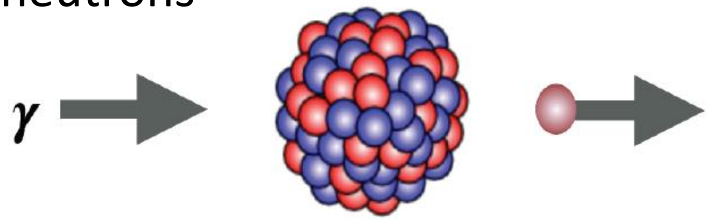
Double breakup (XnXn)

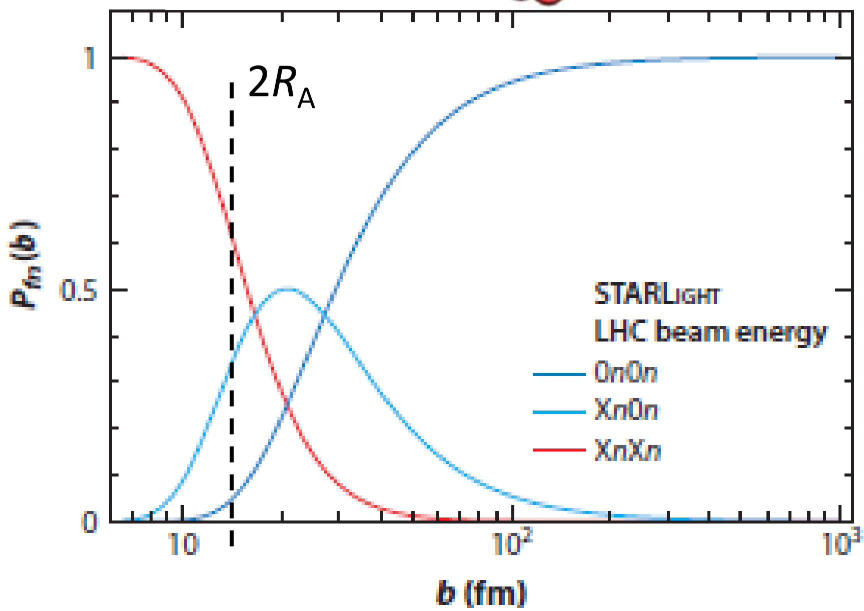


- Excitation of the nuclei possible through the secondary photon exchange

$\Rightarrow$ Giant dipole resonance

All protons vibrating against all neutrons $\rightarrow$ Knocks out neutrons



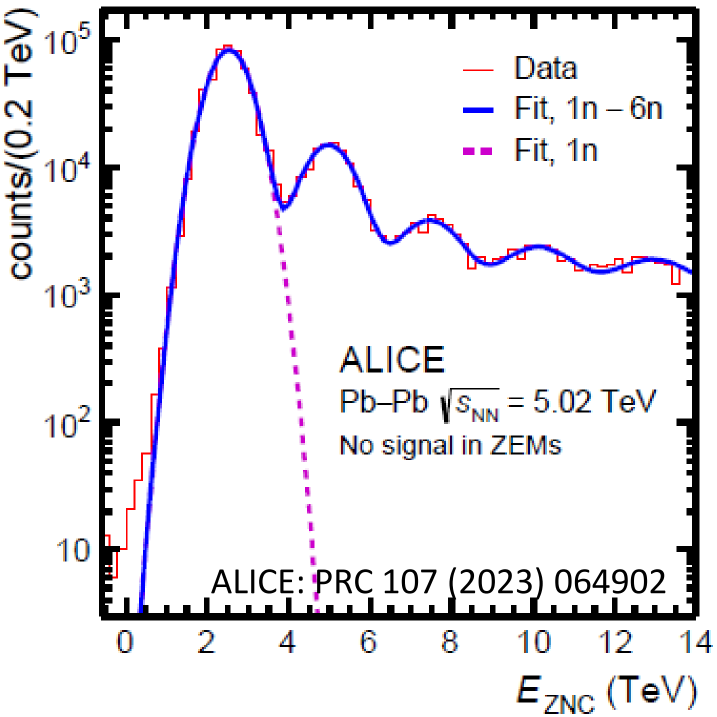


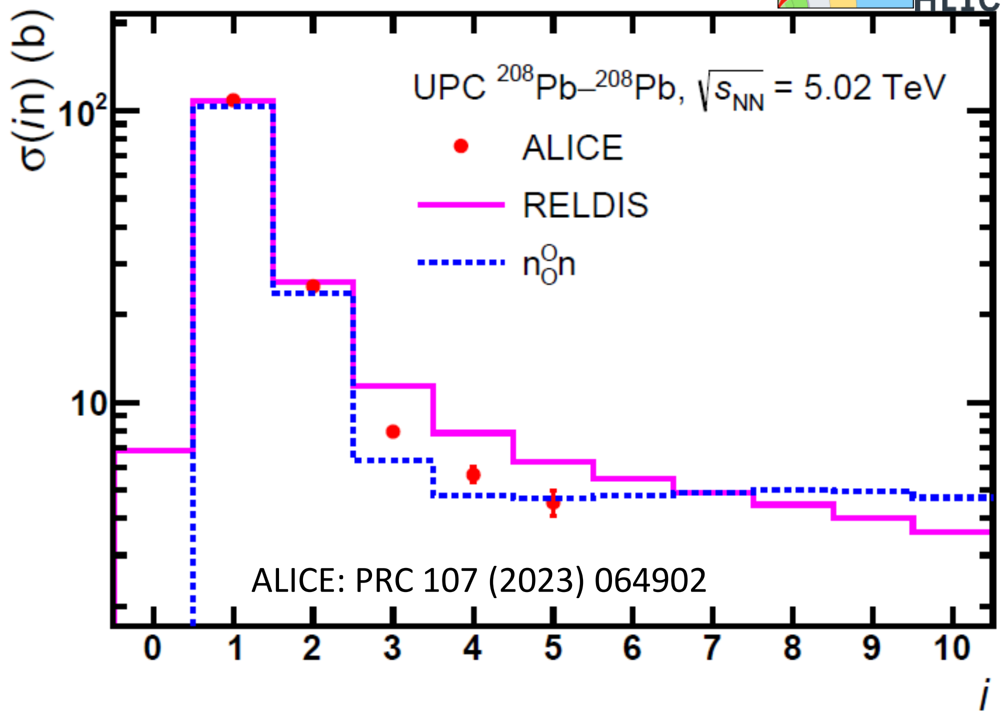
S. Klein, P. Steinberg, Annu. Rev. Nucl. Part. Sci. 70(1), 323 (2020)

UPC event clasifier: 0n0n, 0nXn, XnXn

$\rightarrow$ via electromagnetic dissociation (EMD)

Neutron emission in UPC





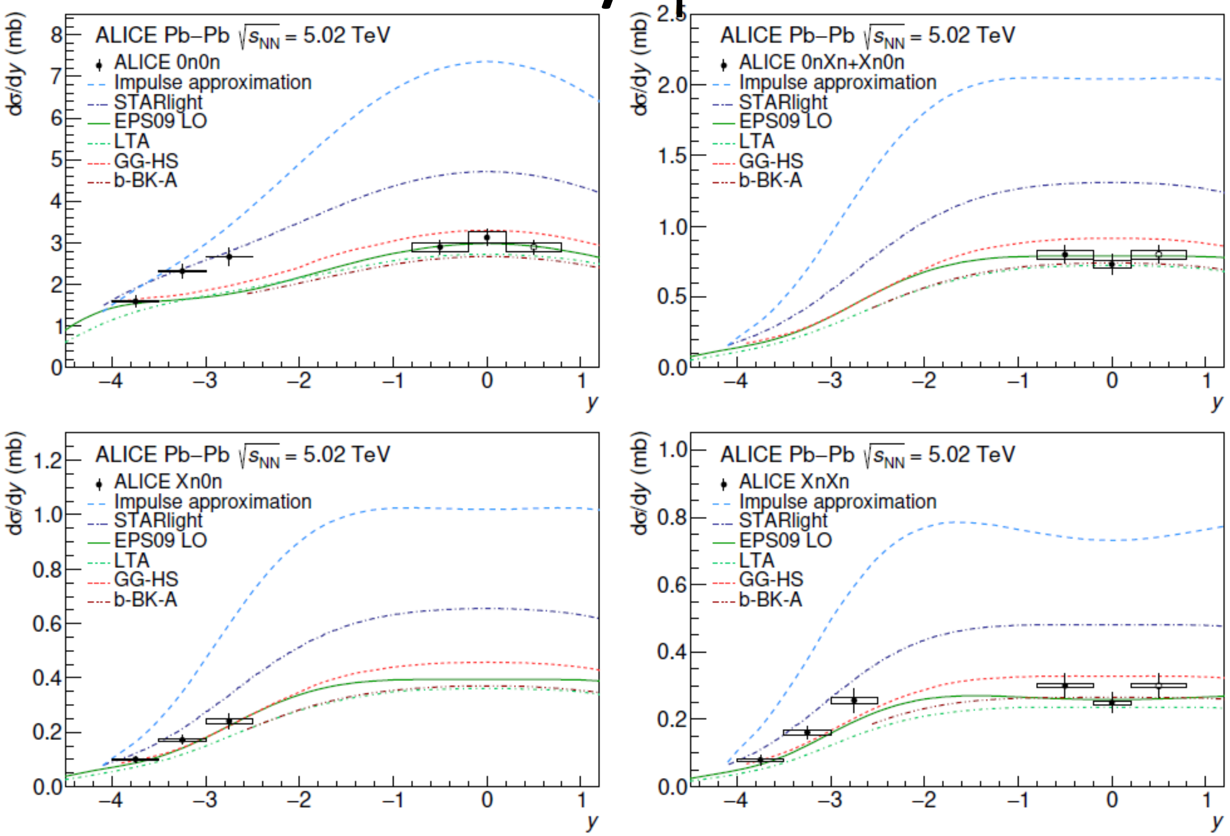
ZN	$\sigma(in)$ (b)	$\sigma^{\text{RELDIS}}(in)$ (b)	$\sigma^{n_O^On}(in)$ (b)
1n	$108.4 \pm 0.1 \pm 3.7$	108.0 ± 5.4	103.7 ± 2.1
2n	$25.0 \pm 0.1 \pm 1.3$	25.9 ± 1.3	23.6 ± 0.5
3n	$7.95 \pm 0.04 \pm 0.23$	11.4 ± 0.6	6.3 ± 0.1
4n	$5.65 \pm 0.03 \pm 0.33$	7.8 ± 0.4	4.8 ± 0.1
5n	$4.54 \pm 0.03 \pm 0.44$	6.3 ± 0.3	4.7 ± 0.1
1n–5n	$151.5 \pm 0.2 \pm 4.6$	159.8 ± 5.6	143.1 ± 2.2

ALICE: PRC 107 (2023) 064902; CMS:PRL 127, 122001 (2021)

- It is huge!
- Up to 5 neutrons
- Hadronic cross section $\sigma_{had} = 7.67 \pm 0.24$ b
- Good description of 1n and 2n emission , but other classes are not so well described

RELDIS: Phys. Part. Nucl. 42 (2011) 215.
N0ON: Comput. Phys. Commun. 253 (2020) 107181.

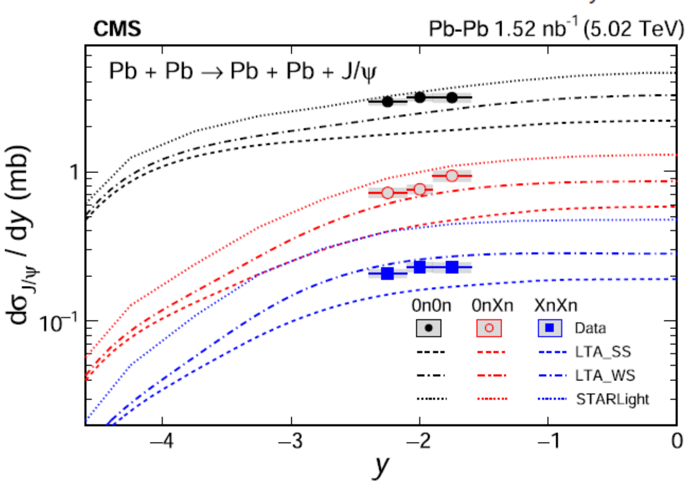
Coherent J/ψ in neutron classes



Corrected for:

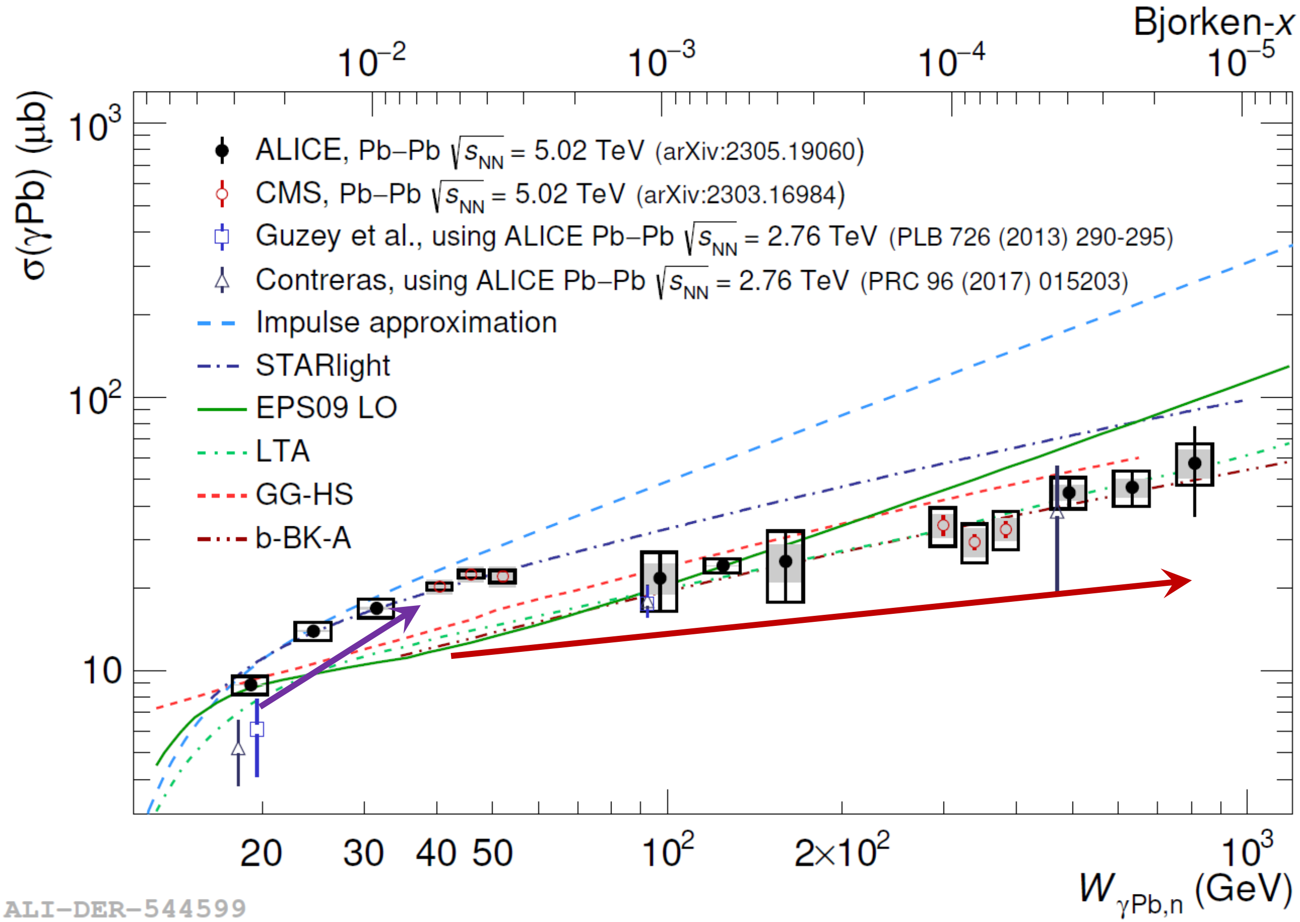
- Event migration among classes
- Neutrons from pile-up
- Charged particle production from dissociation of either nuclei

ALICE: *JHEP* 10 (2023) 119
CMS: PRL 131 (2023) 262301



- 0n0n class has the largest statistics, XnXn – the lowest one
- Complementary measurements from CMS and ALICE
- Sensitivity to test theoretical models
- Good test of photon fluxes

Energy dependence of coherent J/ψ



- **Rise** at low $W_{\gamma Pb,n} \sim$ 15 GeV → ~ 40 GeV

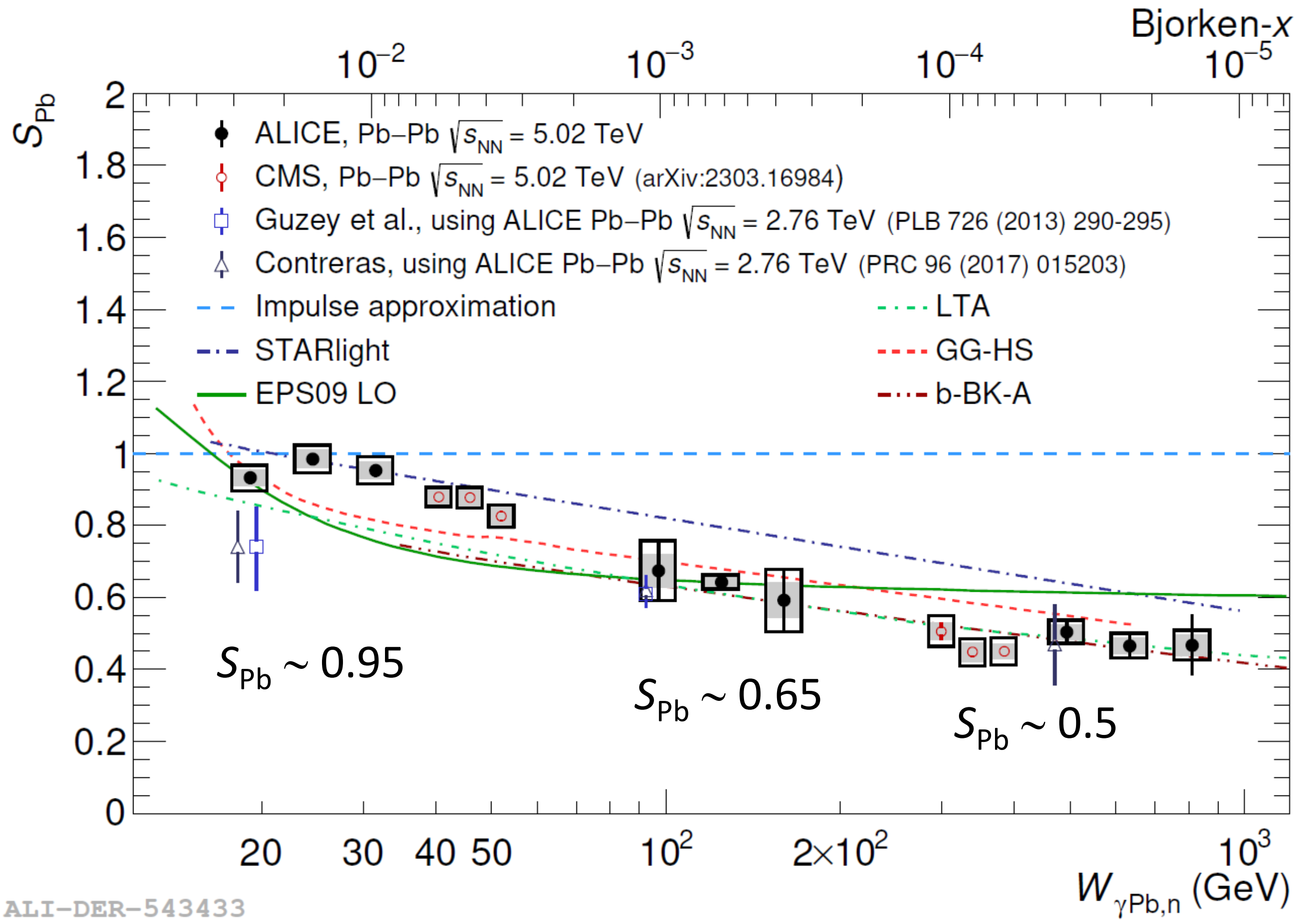
⇒ consistent with fast-growing gluon densities toward lower x_B

- **Flattish** trend from $W_{\gamma N} \sim$ 40 GeV → ~ 800 GeV

- First measurement of the energy dependence of the photonuclear cross section down to $x_B \sim 10^{-5}$
- Or very wide energy range (20 - 800 GeV)
- Consistency between two methods: Run 1 with peripheral collisions and Run 2 data with neutron emission classes
- Good agreement between LHC experiments: CMS and ALICE
- Both saturation and shadowing models are favored at low-x_B

ALICE: *JHEP* 10 (2023) 119
CMS: PRL 131 (2023) 262301

Nuclear suppression factor of coh. J/ψ



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

No model describes the whole energy/Bjorken-x range!

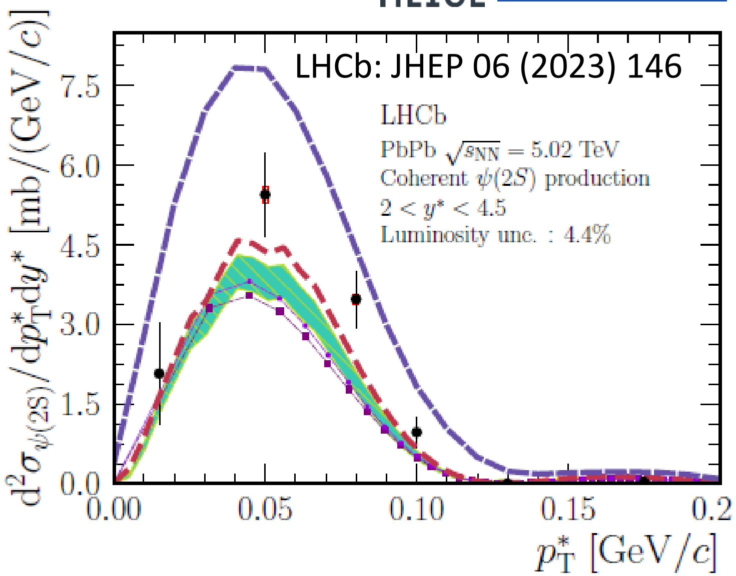
- First measurement of the nuclear suppression factor down to $x_B \sim 1.1 \times 10^{-5}$
- Additional uncertainty from impulse approximation
- Low energy (high x_B):
  - Impulse approximation
  - STARlight
  - $S_{Pb} \sim 0.95$
- High energy (low x_B):
  - data favours both saturation (b-BK-A, GG-HS) and shadowing (LTA) models
  - $S_{Pb} \sim 0.5$

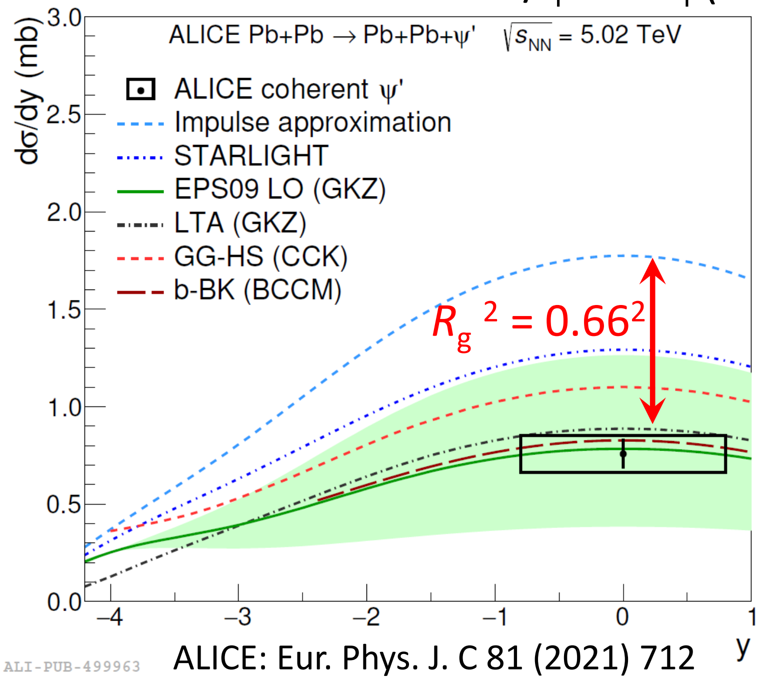
ALICE: *JHEP* 10 (2023) 119
CMS: PRL 131 (2023) 262301

ψ(2S) in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

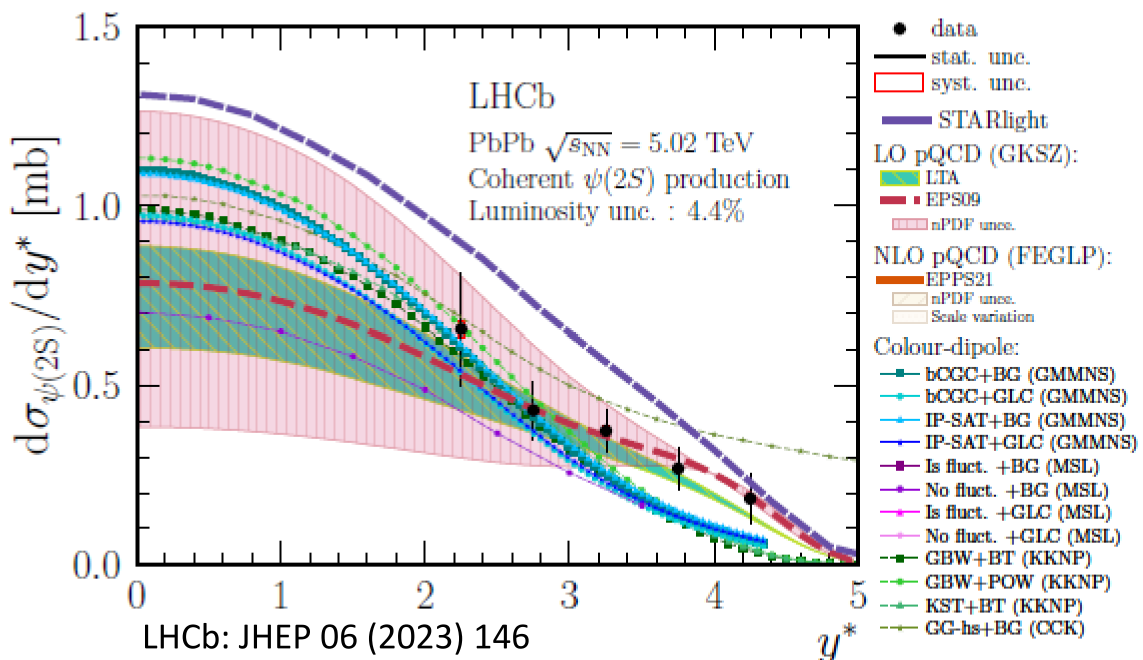
- ALICE: $\psi(2S) \rightarrow \mu^+\mu^-\pi^+\pi^-$, $e^+e^-\pi^+\pi^-$, l^+l^-
- LHCb: $\psi(2S) \rightarrow \mu^+\mu^-$
- **Nuclear gluon shadowing factor**
  - $R_g = 0.66 \pm 0.06$ for $0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$
  - Consistent with J/ψ result
- Good agreement of **models with shadowing** (EPS09 LO, LTA, Guzey et al.)
- Good agreement of ALICE data with model BCCM (with saturation)
- Other models over/under-predict ALICE/LHCb data
- **First measurement** of J/ψ and ψ(2S) p_T spectra @ LHCb

More data points needed!





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



LHCb: JHEP 06 (2023) 146

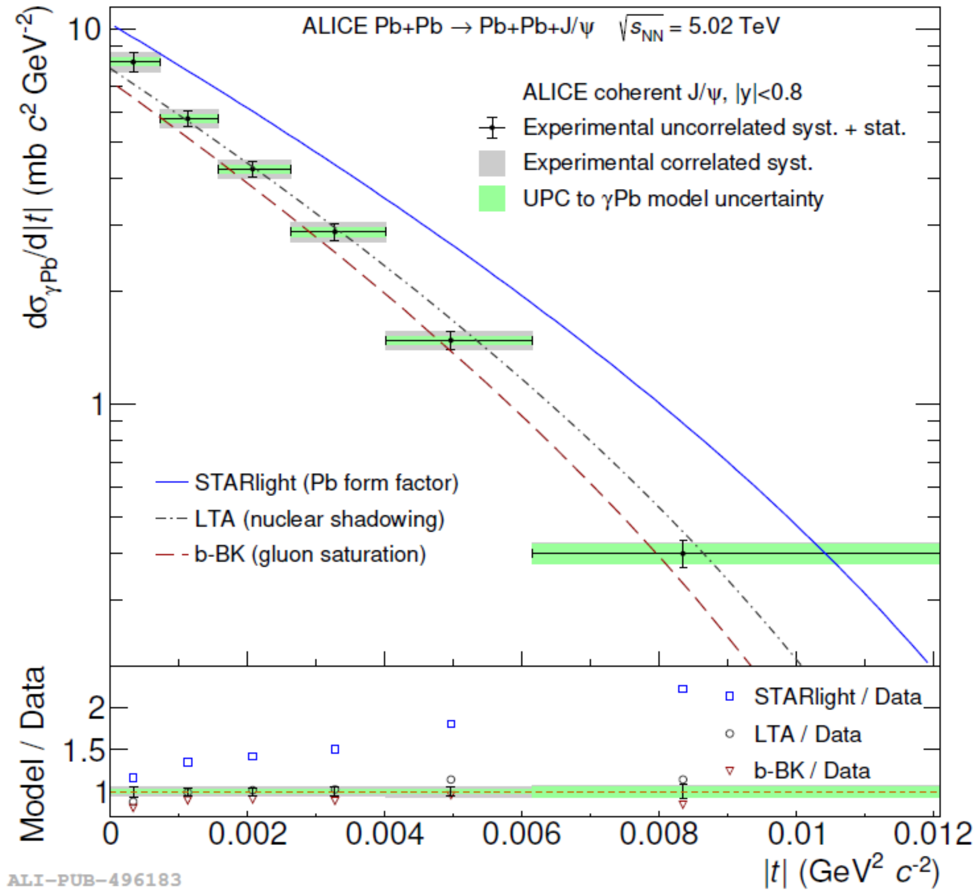
Coherent J/ψ

- **|*t*| dependence** of coherent J/ψ photoproduction is sensitive to the gluon distribution in the transverse plane
- HERA-like precision achieved
- Bayesian and SVD unfolding used to transform $p_T^2 \rightarrow |t|$
- Transition from UPC to photonuclear cross section

$$\left.\frac{d^2\sigma^{coh}_{J/\psi}}{dy\,dp_T^2}\right|_{y=0} = 2n_{\gamma Pb}(y=0)\,\frac{d\sigma_{\gamma Pb}}{d|t|}$$

- Comparison to models:
  - STARlight does not have shadowing, so does not describe shape nor magnitude
  - LTA contains nuclear shadowing – agrees with data
  - b-BK based on gluon saturation – agrees with data

ALICE: PLB 817 (2021) 136280



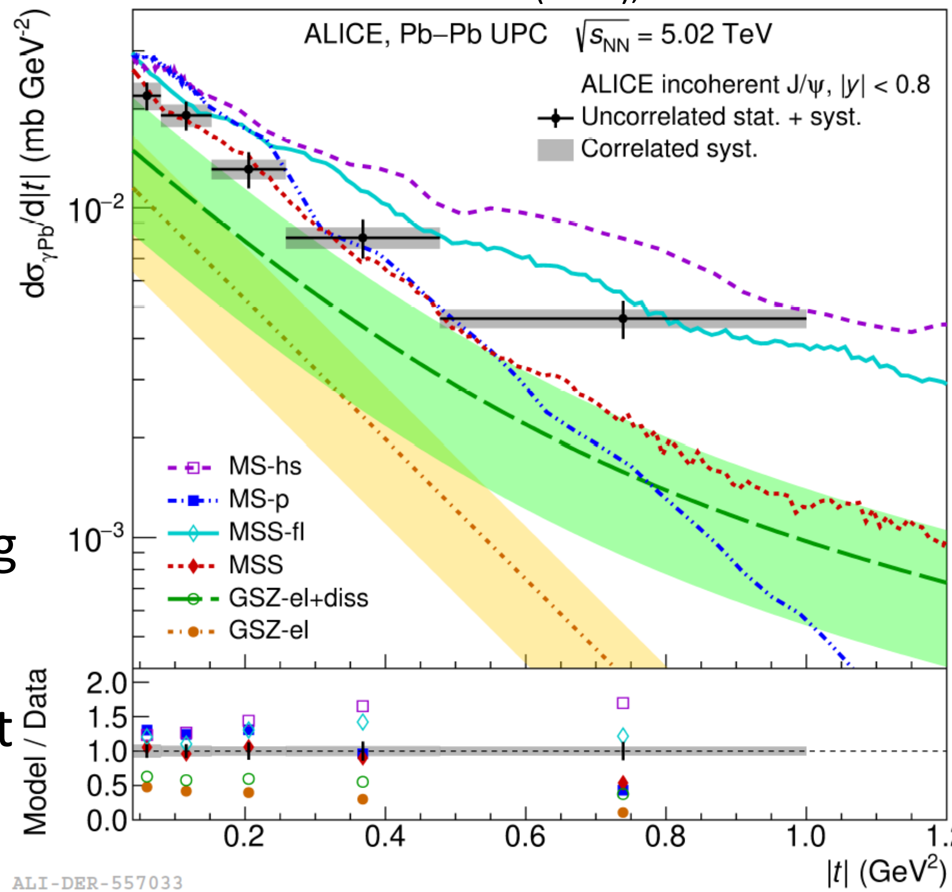
LTA (shadowing): PRC 95 (2) (2017) 025204;
- vector dominance model (VDM) based on perturbative Leading Twist Approximation (LTA) of nuclear shadowing.

b-BK (saturation): arXiv:2006.12980 [hep-ph];
- impact parameter dependent BK computation.

Incoherent J/ψ

- **|*t*| dependence** of the incoherent J/ψ photoproduction is sensitive to the variance of the gluon distribution in the transverse plane
- First measurement which probes **fluctuations** of the gluonic „hot spots" in Pb
- Models fail to predict the normalisation
- Normalization is linked to the scaling from proton to nuclear targets
- (Slope of) data favor models with gluonic subnucleon fluctuations (hot spots in MS-hs, fluctuations MSS-fl and dissociation in GSZ el+dis)

ALICE: arXiv:2305.06169 (2023), submited to PRL



MS (saturation): PLB 772 (2017) 832;
 - Based on IPsat model.
GSZ (shadowing): PRC 99 (2019) 015201;
- VDM based on LTA shadowing including elasic and/or dissociative part
MSS (saturation): PRD 106, 7 (2022) 074019
- Based on JIMWLK equations.

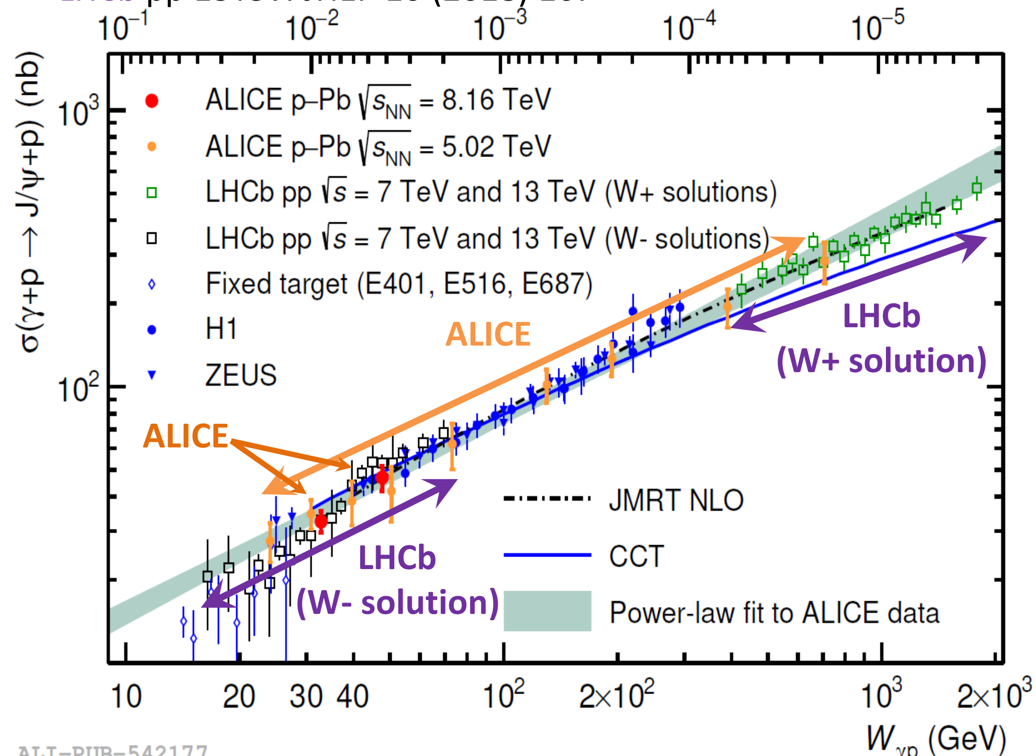
Photonuclear J/ψ cross section

- Gluon distribution at HERA energies follows power law at low x_B
  $\Rightarrow$ similar trend in $W_{\gamma p}$
- **Exclusive J/ψ cross section** at LHC follows HERA trend so far

ALICE: p-Pb at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV
LHCb: pp at $\sqrt{s}$ = 7 and 13 TeV

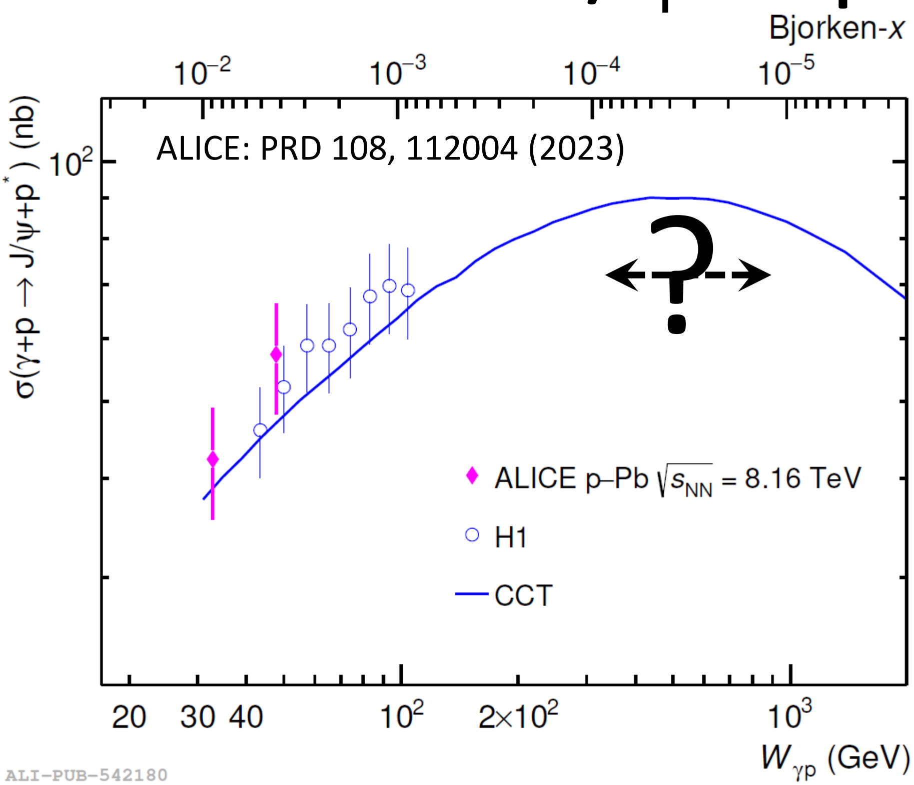
- Power law fit $\sigma \sim W_{\gamma p}{}^{\delta}$
  - H1 data: $\delta = 0.67 \pm 0.03$
  - ALICE data: $\delta = 0.7 \pm 0.04$
  - $\Rightarrow$ agreement LHC and HERA
  - $\Rightarrow$ agreement ALICE and LHCb
- Models show agreement
  - JMRT NLO: based on DGLAP evolution with dominant NLO contribution
    - valid to $x_B \sim 2 \times 10^{-5}$
  - CCT: Saturation in the energy dependent hot spot model
- Probe wide region $x_B \sim 10^{-2}$ - 10^{-6}

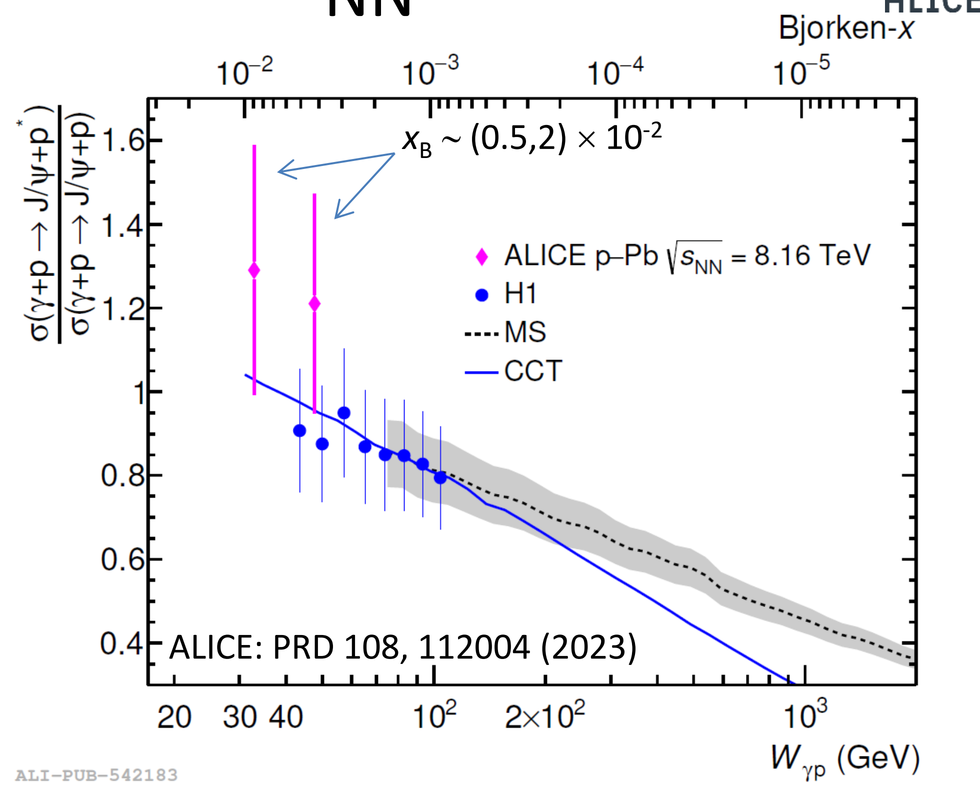
ALICE p-Pb 8.16 TeV: PRD 108, 112004 (2023), (2304.12403)
ALICE p-Pb 5.02TeV: Phys. Rev. Lett. 113 (2014) 232504.
LHCb pp 7TeV: *J. Phys. G: Nucl. Part. Phys.* 41 (2014) 055002;
LHCb pp 13TeV: JHEP 10 (2018) 167



No clear indication of gluon saturation at low x_B

Dissociative J/ψ in p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV





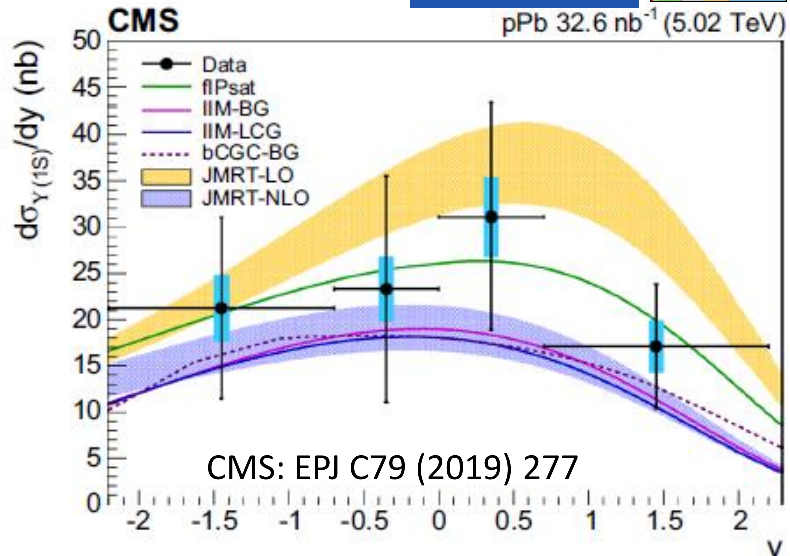
- **First measurement** of the energy dependent **dissociative J/ψ cross section** at the LHC
- Agreement with HERA results
- CCT model with saturation agrees with data
  - Predicted maximum at $W_{\gamma p}$ ~ 500 GeV to be studied in Run 3
- MS model with saturation to be studied in Run 3

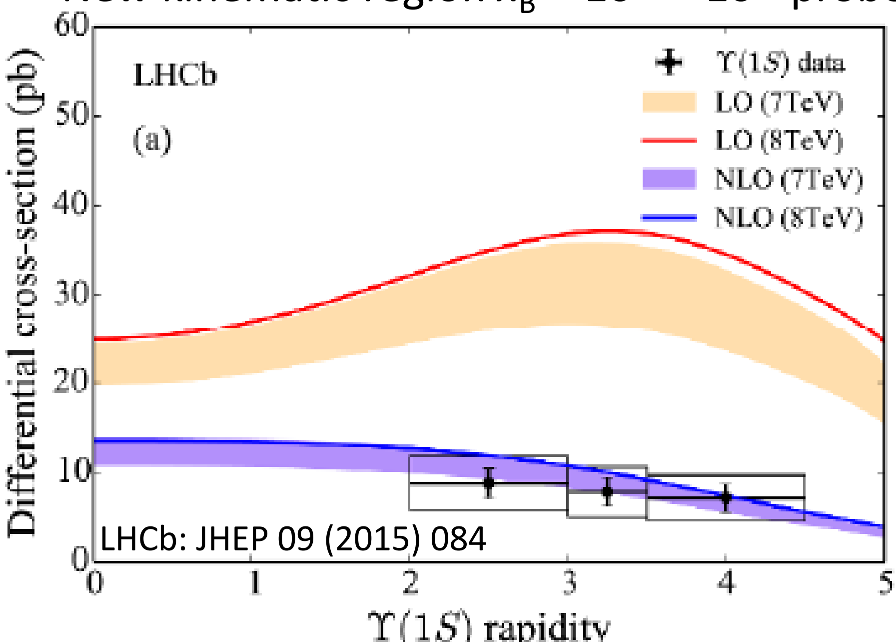
H1: EPJ C73 (2013) 2466.
CCT: PLB 766 (2017) 186;
- colour dipole + energy dependent hot spot model.

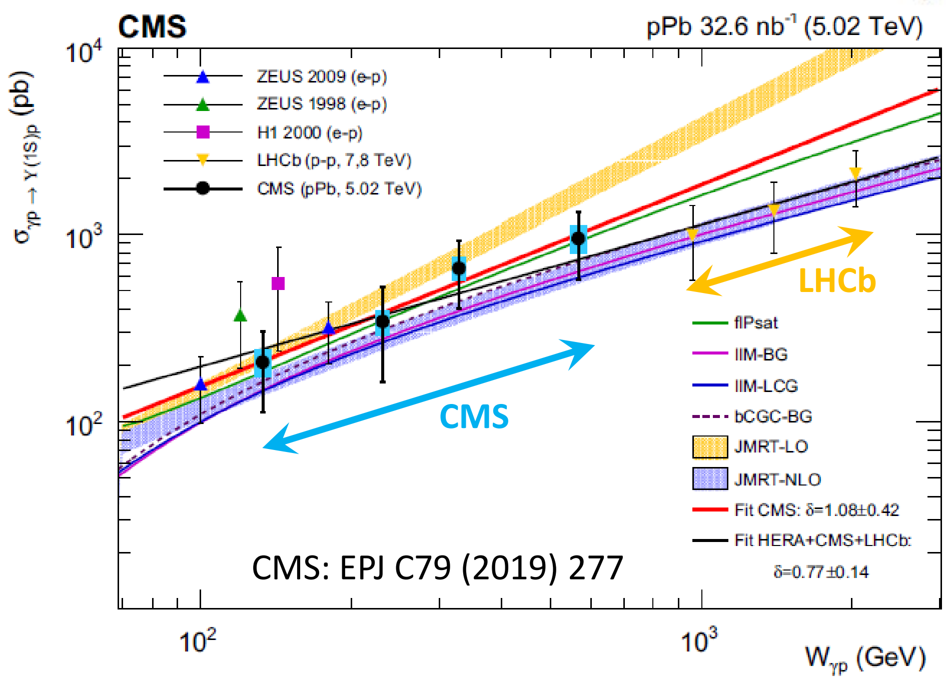
MS: PRD 98 (2018) 034013;
- perturbative JIMWLK + constrains from fits to H1 data.

Υ(nS) in p-Pb and pp

- $\Upsilon(nS) \rightarrow \mu^+\mu^-$
- **Cross section** measured in central (CMS) and forward (LHCb) region
- **NLO** calculations **favored** by LHCb data
- **Saturation** models consistent with CMS and LHCb
- Fit to CMS: $\delta = 1.08 \pm 0.42$
  - $\Rightarrow$ Consistent with ZEUS: $\delta = 1.2 \pm 0.8$
  - $\Rightarrow$ Consistent with ZEUS+H1+CMS: $\delta = 0.99 \pm 0.27$
- Fit to HERA+CMS+LHCb: $\delta = 0.77 \pm 0.14$
  - $\Rightarrow$ Consistent with J/ψ data
- New kinematic region $x_B \sim 10^{-5} - 10^{-2}$ probed

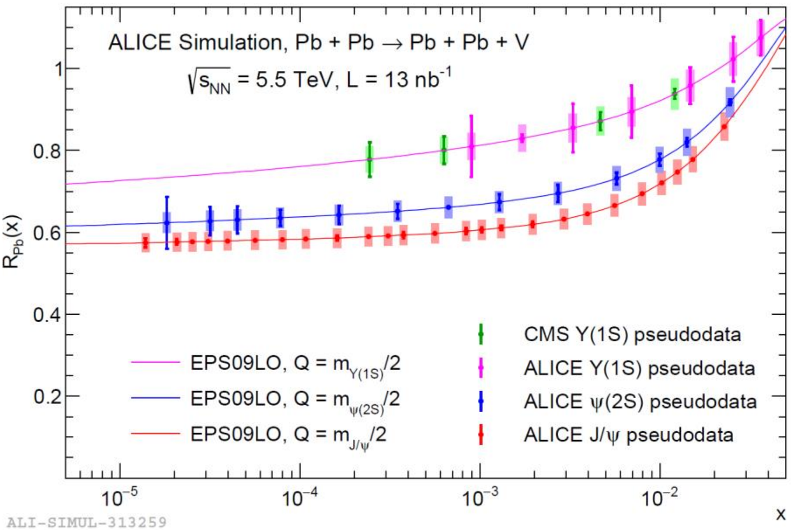


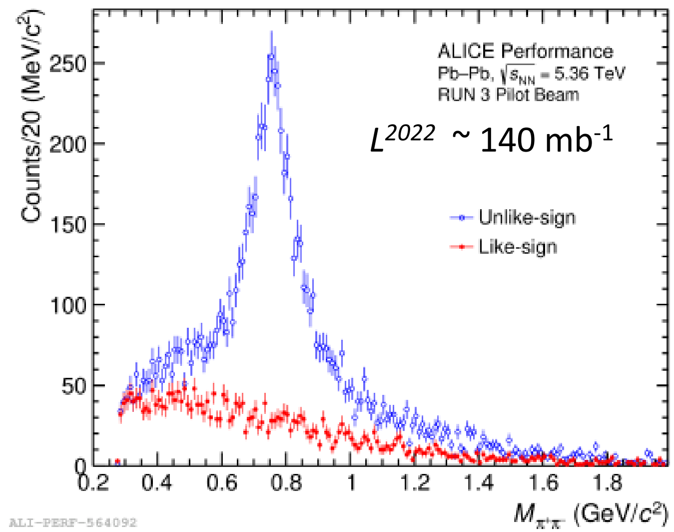




Future measurements in Run 3 and 4

- Address **gluon shadowing in nuclei** at low x_B
- Constrain gluon distribution in **transverse plane**
- Allow for **scale dependence** of gluon shadowing studies with different meson species





A. Khatun @ UPC 2023: International workshop on the physics of Ultra Peripheral Collisions, Playa del Carmel, 15/12/2023

CERN Yellow Rep.Monogr. 7 (2019) 1159 PbPb $L_{Pb\text{-}Pb}$= 13/nb

Meson	σ	All Total	$\|y\| < 0.9$ Total	$\|y\| < 2.4$ Total	$2.5 < y < 4.0$ Total l	$2 < y < 5$ Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$Y(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

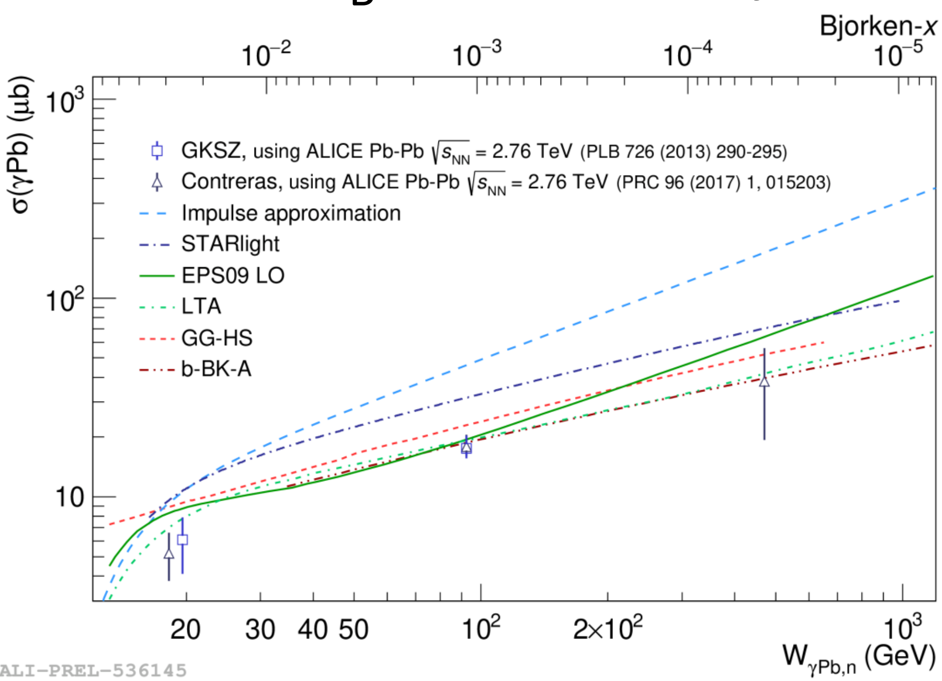
Summary

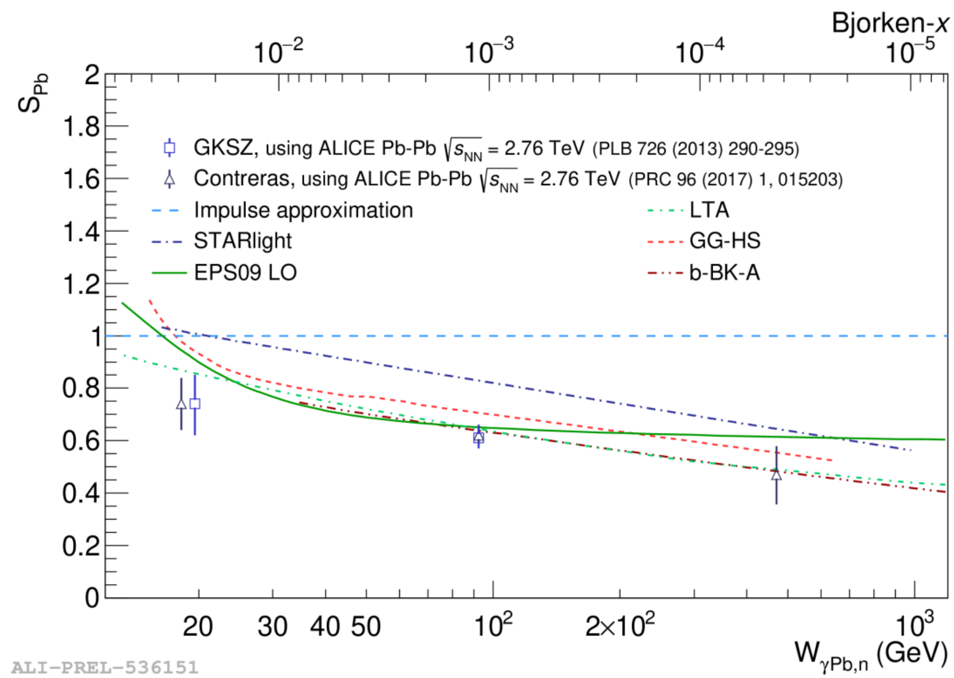
- Nuclear gluon structure probed with J/ψ and ψ(2S) at $x_B \sim 10^{-2} - 10^{-5}$
  - Measurements signal large nuclear gluon shadowing effects
    - $R_g \sim 0.65$ at $x_B \sim 10^{-3}$
    - $R_g \sim 0.5$ at $x_B \sim 10^{-5}$
- Proton gluon structure probed with J/ψ and Υ(nS) at $x_B \sim 10^{-2} - 10^{-5}$
  - More (and precise) data needed to discriminate between models
- We probed fluctuations at sub-nucleon scale for the first time in $|t|$-dependence c.s.
- Photoproduction measured towards more central collisions
- Data **strongly challenges** theory
  - Models with shadowing or saturation describe data the best
  - No model currently describe the rapidity dependence and $|t|$ dependence
- We are limited by statistics and looking forward for Run 3 and beyond results

Backup

Energy dependence in coherent J/ψ

- Compilation of published results based on ALICE Run 1 data compared to current model calculations
  - Sensitivity to $x_B \sim 10^{-4}$
  - Low x_B described by shadowing and saturation models



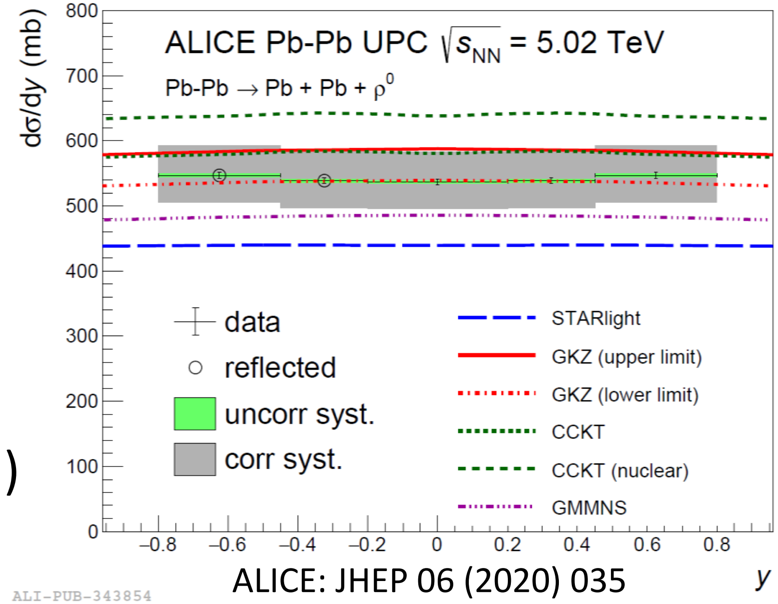


EPS09 LO: PRC 93 (2016) 055206 + JHEP 04 (2009) 065
LTA: PRC 93 (2016) 055206 + Phys. Rept. 512 (2012) 255

GG-HS: PRC97 (2018) 024901
b-BK-A: PLB 817 (2021) 136306

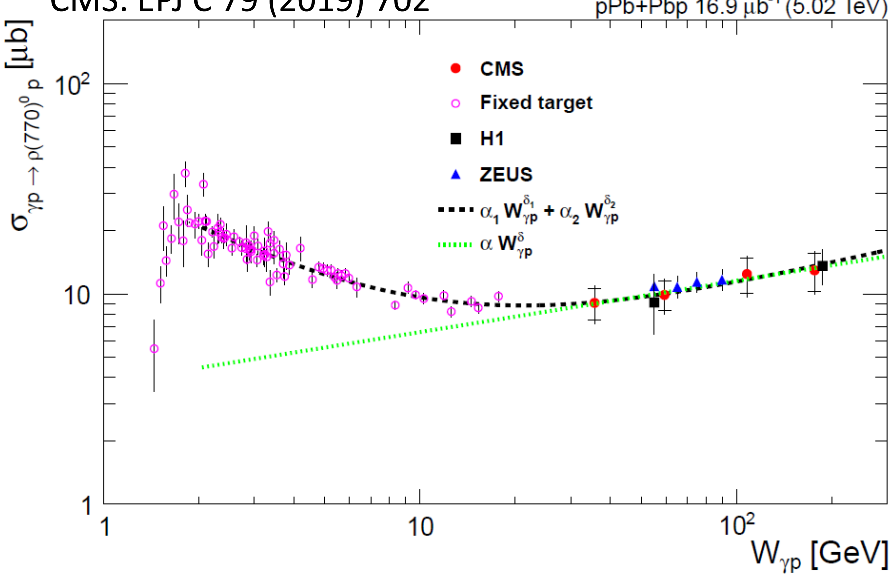
ρ^0 photoproduction

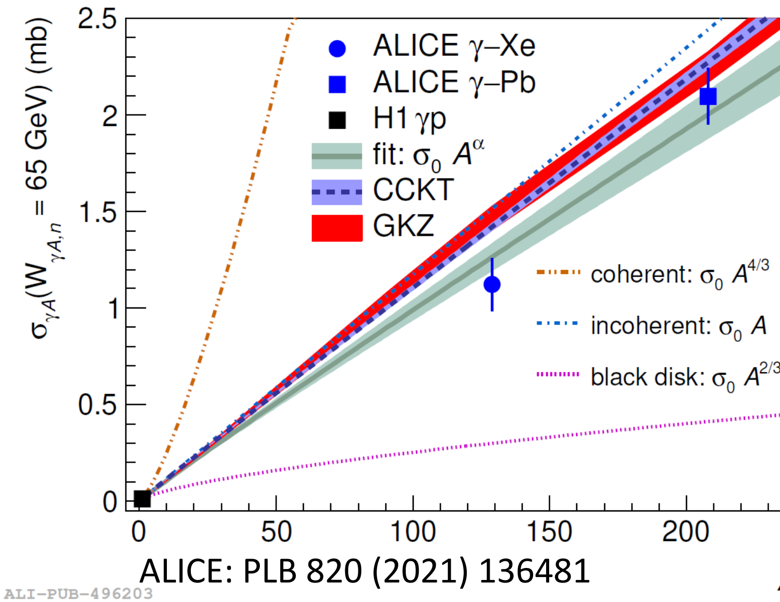
- **Large cross section** (~550 mb) described by models
- Measurement in nuclear **breakup classes** (0n0n, 0nXn, XnXn) to distinguish *b* dependence
- $\sigma(\gamma A \to \rho^0 A) \sim A^{\alpha}$ with a slope $\alpha = 0.96 \pm 0.02^{sy}$
  - $\Rightarrow$ Signals important **shadowing effect**
- Far away from Black Disk Limit
- Why not to validate with other elements (O,Kr,...)
- Good **agreement** of **CMS** data with **HERA**
  - No ambiguity in energy in p-Pb collisons



ALICE: JHEP 06 (2020) 035

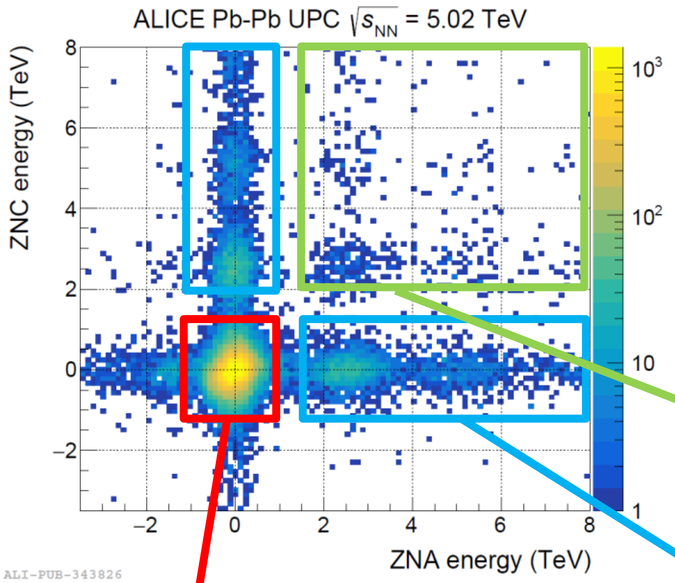
CMS: EPJ C 79 (2019) 702





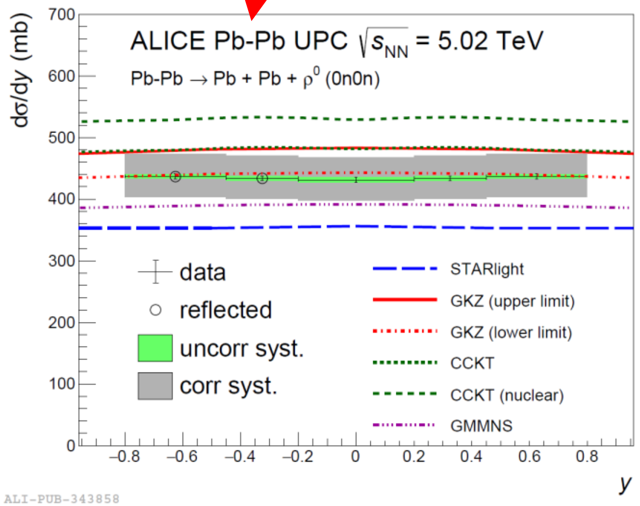
ALICE: PLB 820 (2021) 136481

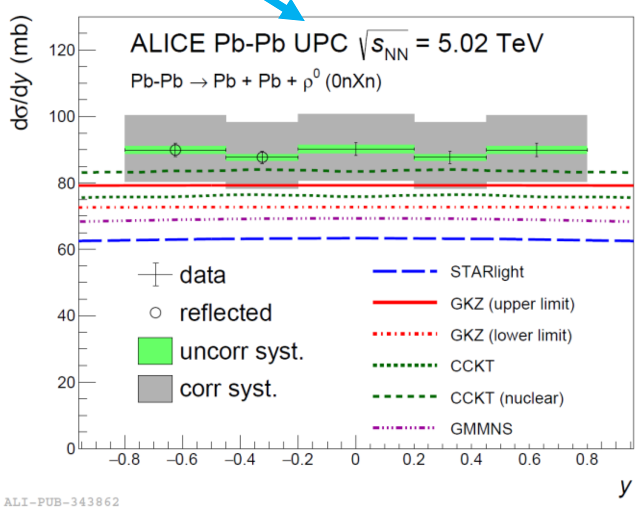
ρ^0 in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

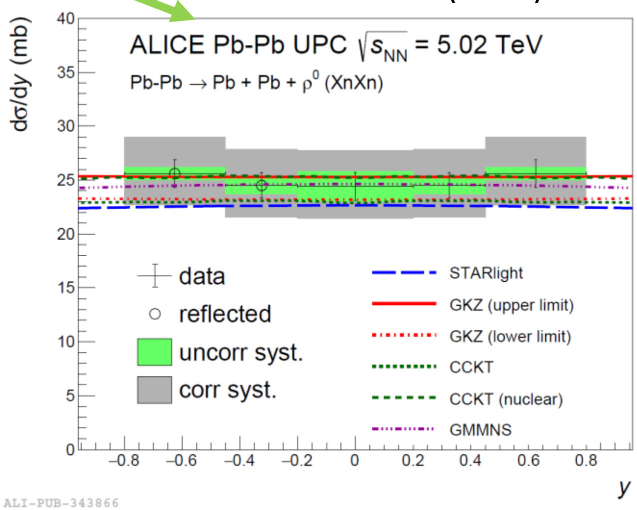


- Impact parameter dependence via ZDC selection in 3 classes: 0n0n, 0nXn, XnXn
- Comparisons with models
  - GKZ (nuclear shadowing) gives the best description
  - CCKT (saturation) is slightly worse
  - STARlight and GMMNS (saturation) underestimate
  - Worst description for 0nXn class
- Test of photon flux description

ALICE: JHEP 06 (2020) 035

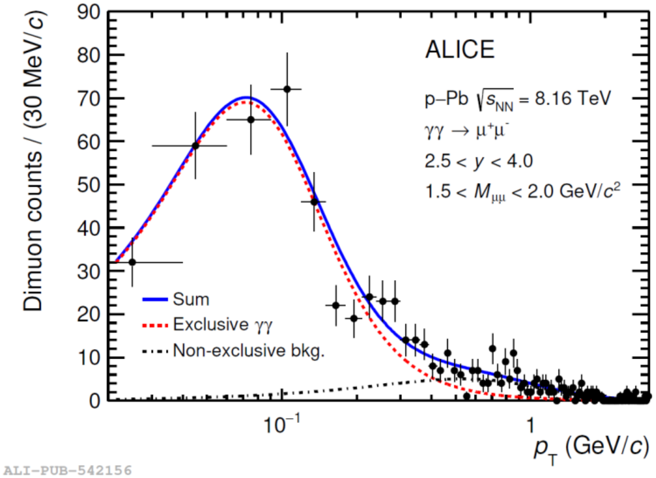




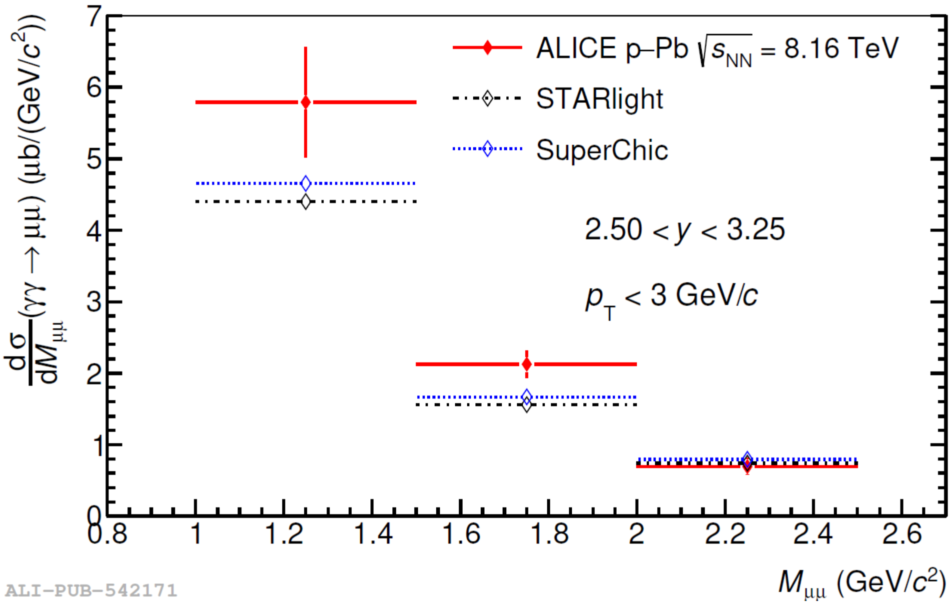


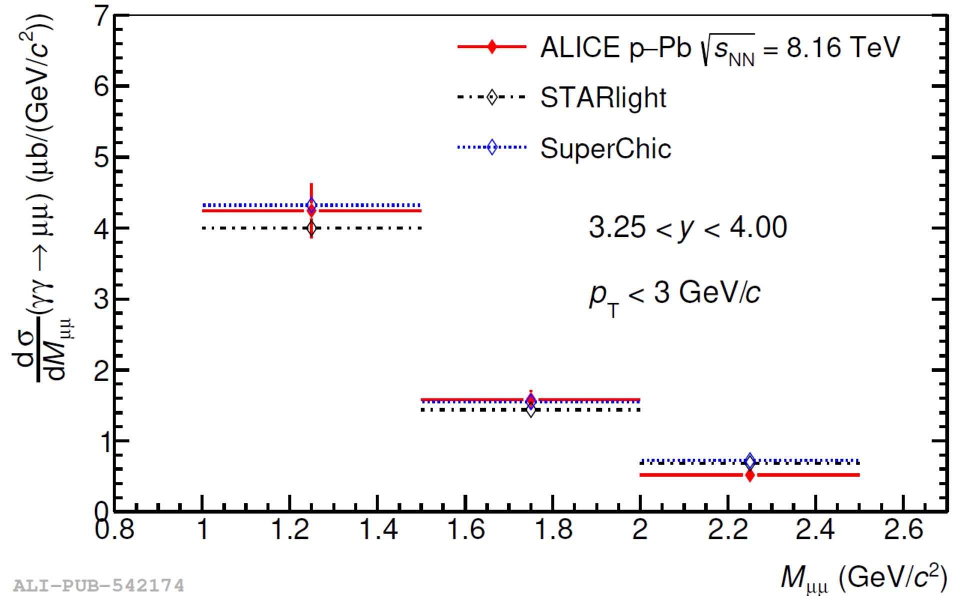
$\gamma\gamma \rightarrow \mu\mu$ in p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV

- **$\gamma\gamma \rightarrow \mu\mu$ cross section**
- Good agreement of simulation and data
- Comparison with STARlight and SuperChic (both LO QED, no FSR) shows slight excess in data, but still agreement within 3σ
- Important background for other UPC processes
- Constrains theoretical models



arXiv:2304.12403, submitted to PRD



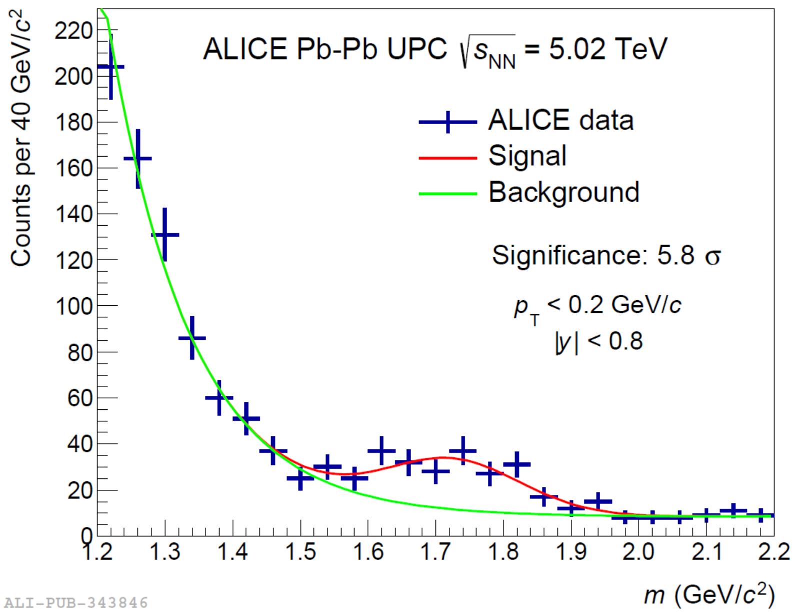


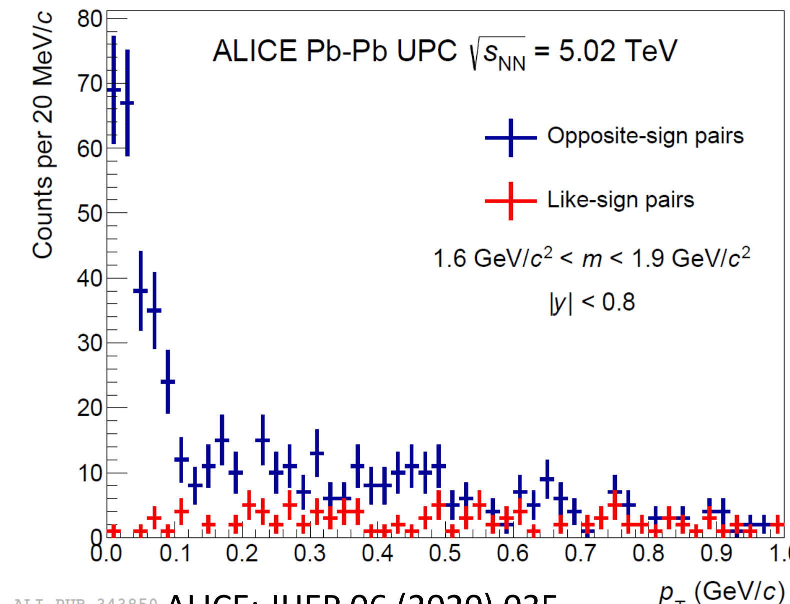
STARlight 2.2.0: Comput. Phys. Commun. 212 (2017) 258.
SuperChic 4.15: EPJC80 (2020) 925.

ρ′ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

- Resonance-like structure $M^{\pi\pi} \sim 1.7$ GeV/c^2
  - Significance of 4.5 σ
  - Seen also by STAR, ZEUS, H1
  - Most probably $\rho_3(1690)$ with angular momentum J = 3
  - More data from Run3 + Run4 needed

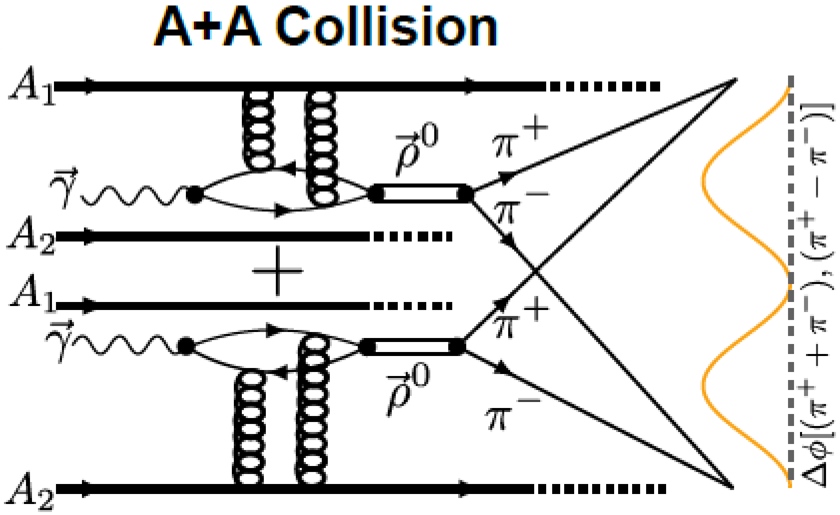
$$\frac{dN_{\pi\pi}}{dm} = P_1 \cdot \exp(-P_2 \cdot (m - 1.2\,\mathrm{GeV}/c^2)) + P_3 + P_4 \cdot \exp(-(m - M_x)^2/\Gamma_x^2)$$



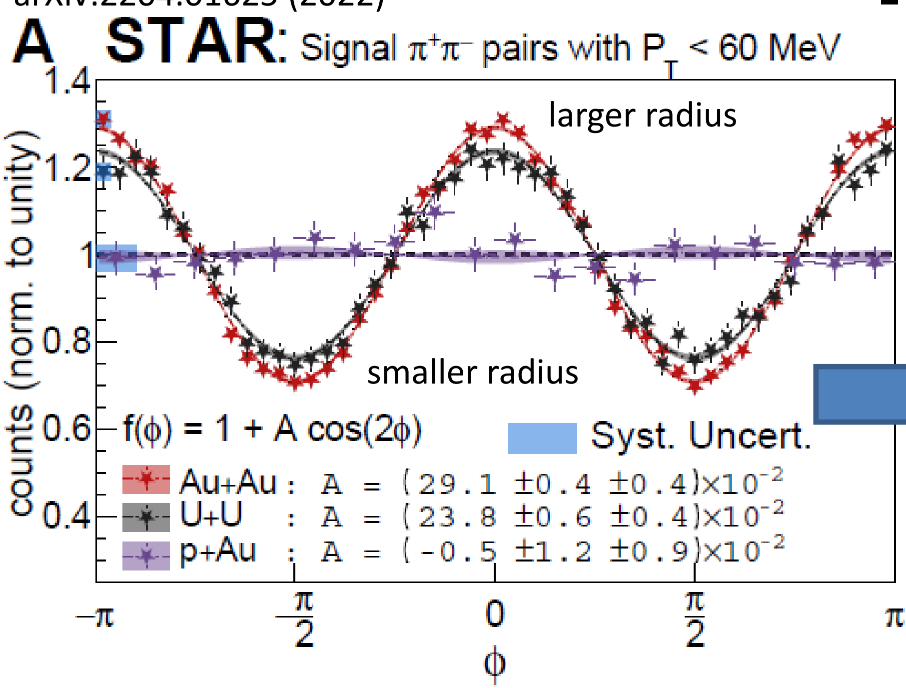


ALICE: JHEP 06 (2020) 035

Nuclear radius and neutron skin



arXiv:2204.01625 (2022)



- One ρ^0 produced, but interference of two contributions to the amplitude
- Eistein-Podolsky-Rosen (EPR) paradox
  - ρ^0 wave functions are created at a distance of <b> ~ 20 fm apart
  - ρ^0 lifetime is ~ 1 fm
- If photons are linearly polarized ⇒ $\cos 2\phi$ asymmetry exists
- Interference effect is sensitive to the nuclear geometry (gluon distribution)
  ⇒ difference between ^{197}Au and ^{238}U
  ⇒ significance 4.3 σ
  ⇒ A ~ 0 for p – Au collisions

Radius (which is 1 fm too large):
- R_{Au} = 6.53 ± 0.06 fm
- R_U = 7.29 ± 0.08 fm

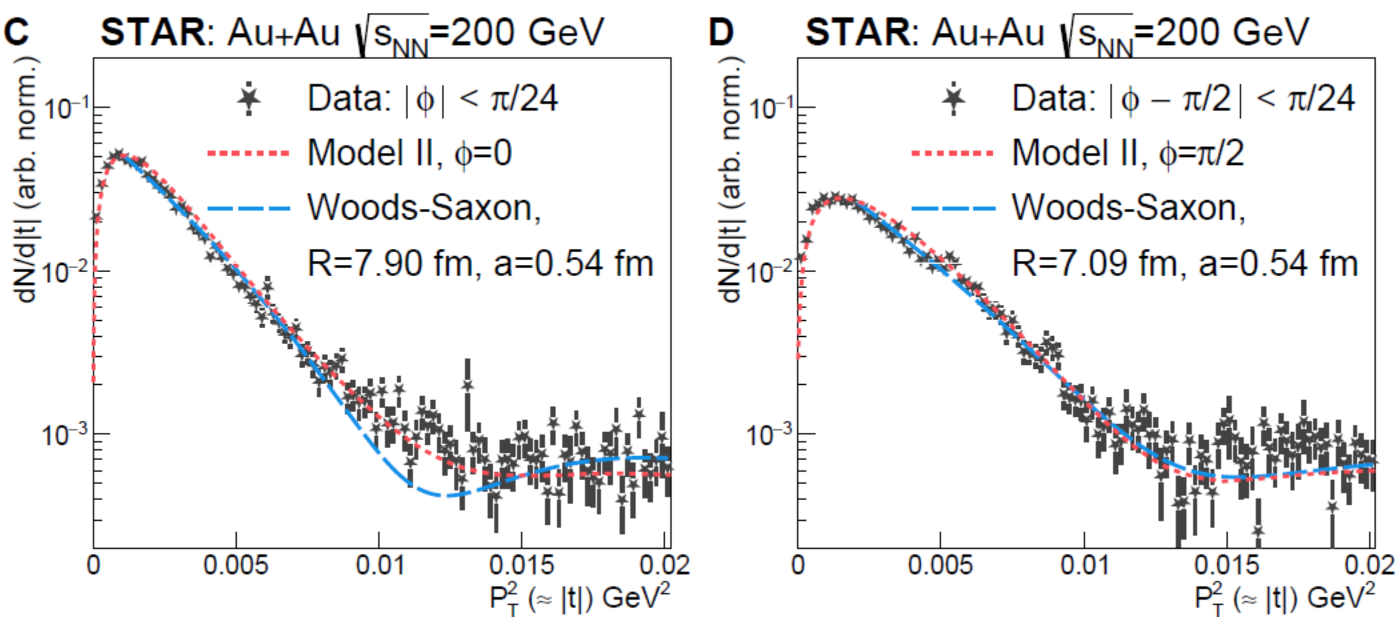
Precision neutron skin measurements:
- $S_{Au} = 0.17 \pm 0.03^{stat} \pm 0.08^{syst}$ fm
- $S_U = 0.44 \pm 0.05^{stat} \pm 0.08^{syst}$ fm

What are values for Pb?

- Extracted radius appeared to be too large for 1 fm
- Extracted radius is for the case of maximum interference ($\phi \sim 0$) is larger than case with minimum interference ($\phi \sim \pi/2$)

$$\rho_A(r;R,a) = \frac{\rho_0}{1+\exp[(r-R)/a]}$$

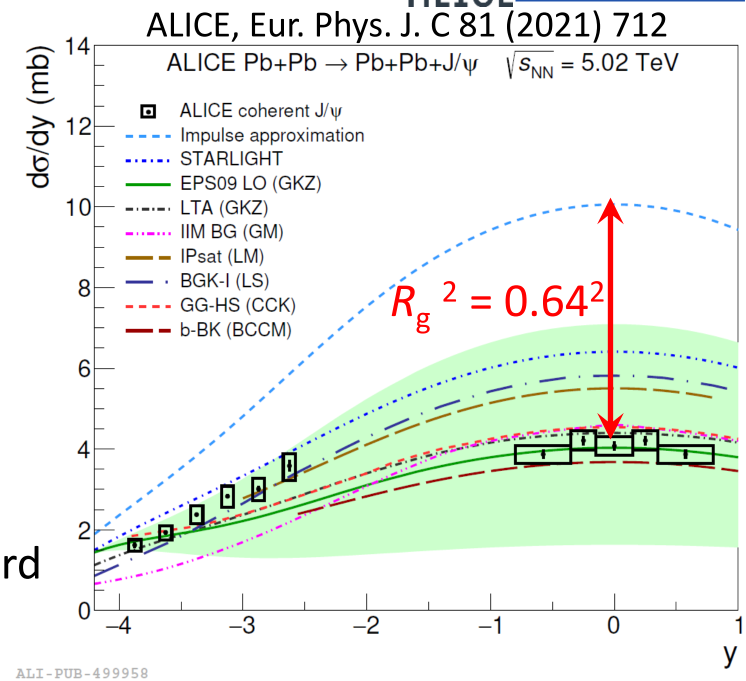
R – nuclear radius
a – surface thickness
$\rho_0 = 3A/(4\pi R^3)$ - normalization



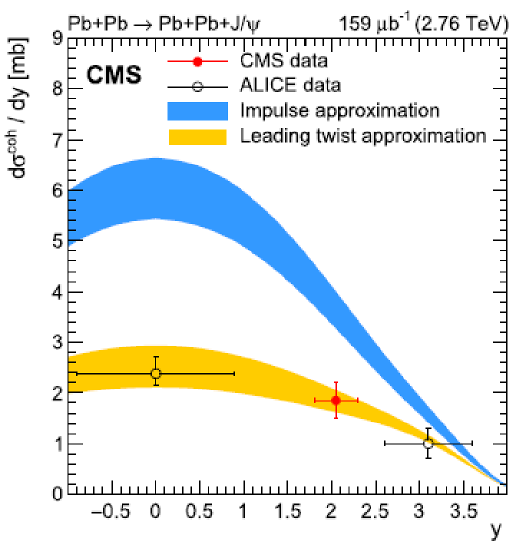
J/ψ in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76/5 TeV

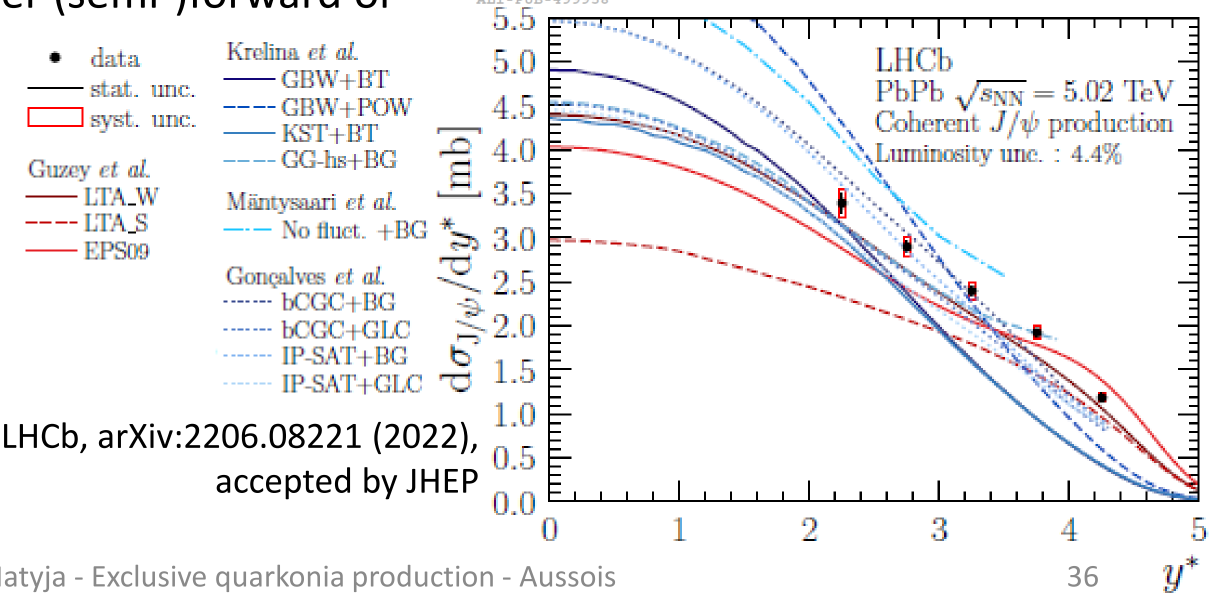
- **Forward** region (ALICE, CMS, LHCb):
  - $J/\psi \rightarrow \mu^+\mu^-$
- **Central** region (ALICE):
  - $J/\psi \rightarrow \mu^+\mu^-$, e^+e^-, $p\bar{p}$
- **Nuclear gluon shadowing factor**
  $R_g = 0.64 \pm 0.04$ for $0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$
- **Compatibility** between LHCb and ALICE results
- No model describes the full rapidity dependence
  - Models with nuclear shadowing (EPS09 LO, LTA) or saturation (GG-HS) describe central and very forward data but tensions in semiforward region
  - Other models describe either (semi-)forward or central rapidity region

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



ALICE, Phys. Lett. B 718 (2013) 1273
ALICE, Eur. Phys. J. C 73 (2013) 2617
CMS, PLB 772 (2017) 489

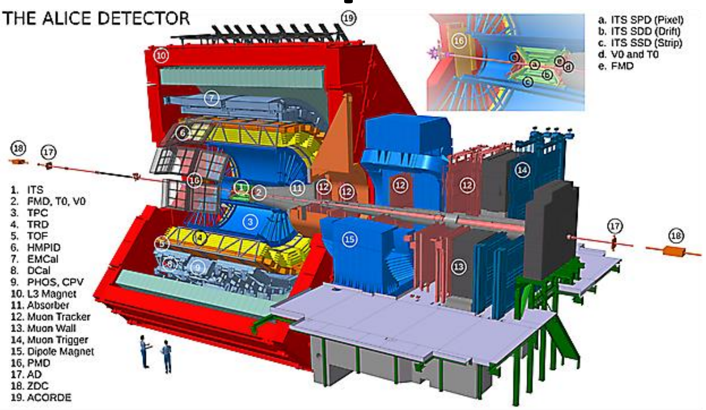


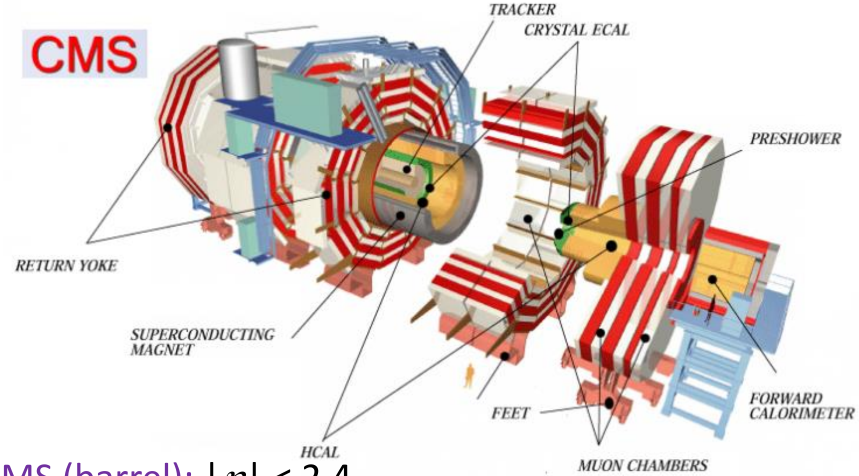


LHCb, arXiv:2206.08221 (2022), accepted by JHEP

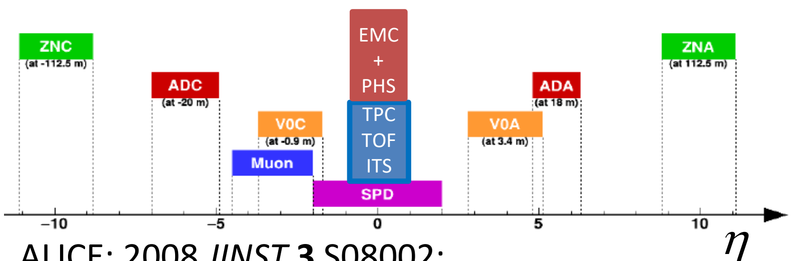
Experimental apparatus

CMS: JINST 3 S08004 (2008);
JINST 16 P05008 (2021)
ZDC: AIPConf.Proc.867:258-265,2006





- ALICE Barrel: $|\eta| < 0.9$,
- Muon Arm: $-4 < \eta < -2.5$
- ALICE Diffractive detecors: ZDC, AD, V0

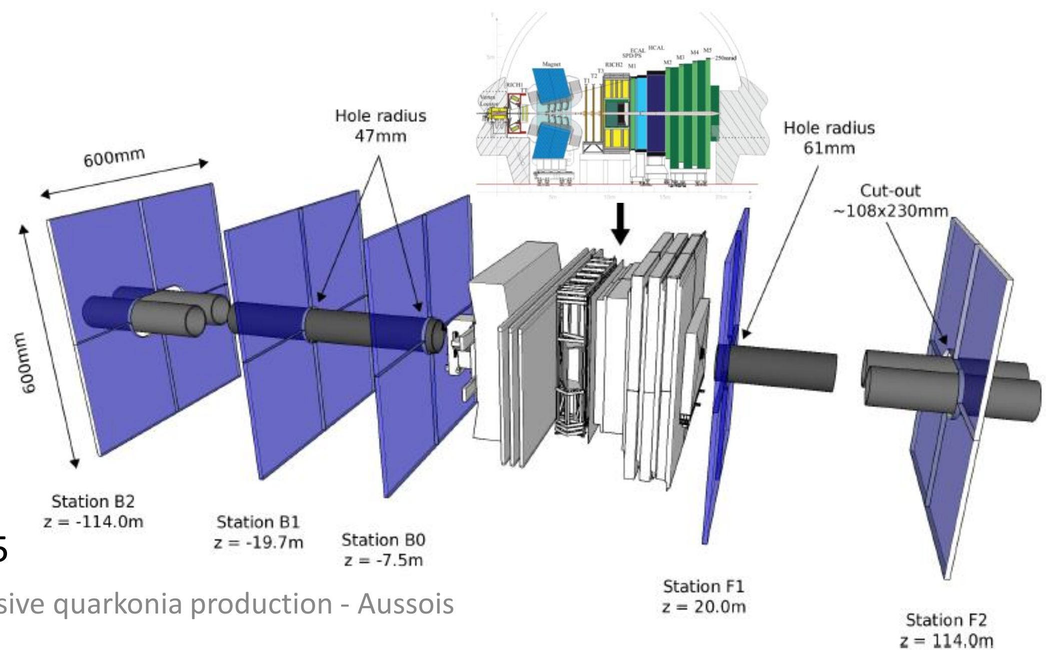


ALICE: 2008 *JINST* **3** S08002;
Int. J. Mod. Phys. A29 (2014) 1430044

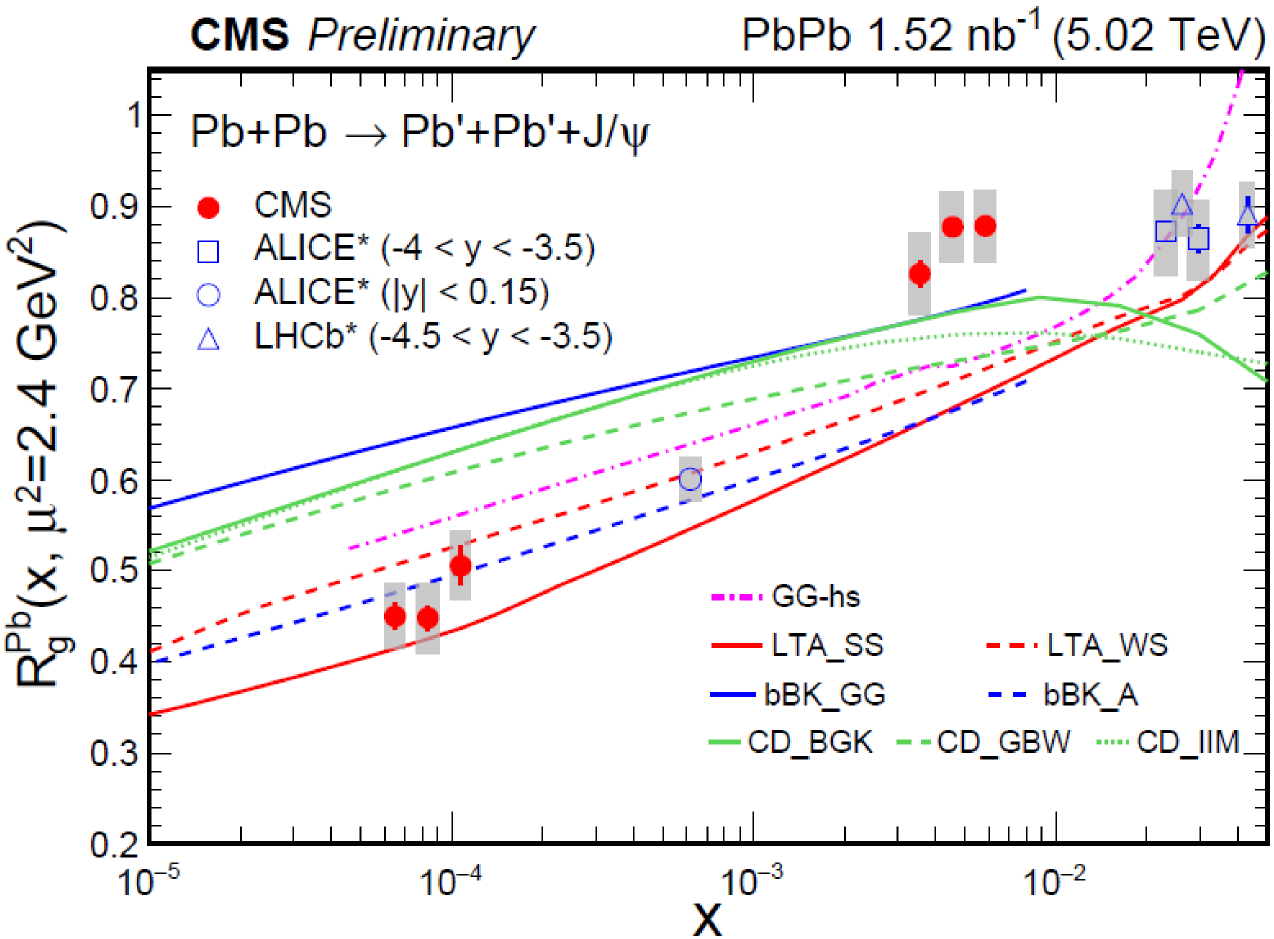
- CMS (barrel): $|\eta| < 2.4$
- Hadron forward calorimeters: $2.9 < |\eta| < 5.2$
- ZDC: $|\eta| > 8.3$

LHCb: 2008 JINST 3 S08005;
Int. J. Mod. Phys. A30 (2015) 1530022.
HeRSCheL: JINST 13 (2018) P04017.

- LHCb (forward region): $2 < \eta < 5$
- LHCb HERSCHEL: $5 < |\eta| < 10$
- VELO (backward region): $-3.5 < \eta < -1.5$



Nuclear gluon suppression factor

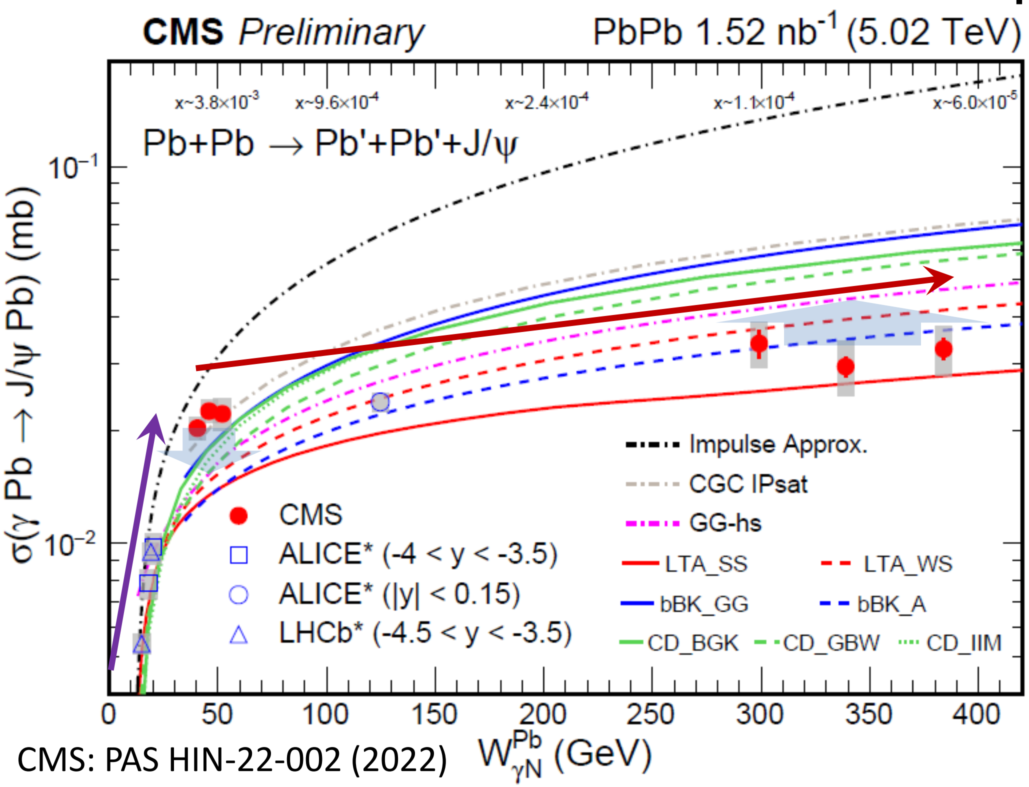


CMS: PAS HIN-22-002 (2022)

$$R^{Pb}{}_g = \sqrt{\frac{\sigma^{exp}{}_{\gamma A \to J/\psi A}}{\sigma^{IA}{}_{\gamma A \to J/\psi A}}}$$

- $R^{Pb}{}_g$ represents gluon suppression at LO
- IA – Impulse approximation – no effects except coherence
- Flat behavior at large $x_B > 10^{-3}$
- Drop towards lower x_B values
- No model describes data

Photo nuclear J/ψ cross section

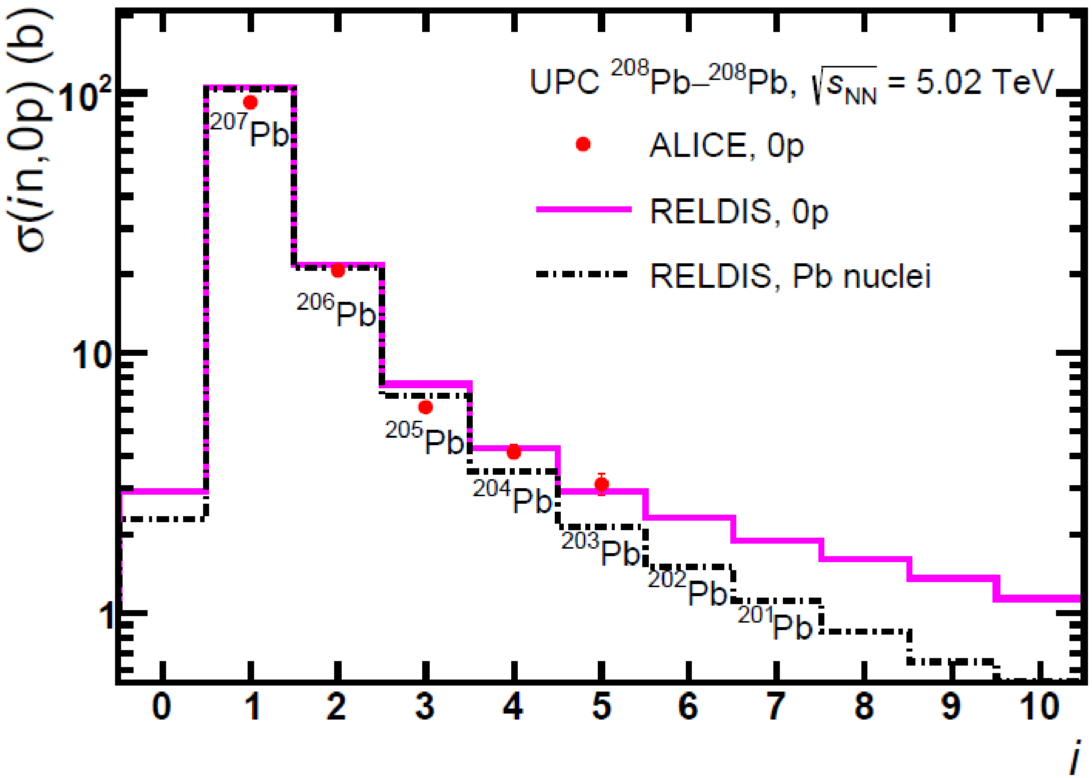


CMS: PAS HIN-22-002 (2022)

- ALICE and LHCb data points are averaged over rapidity and only one solution is presented
- Experimental uncertainty is highly correlated across photo-nuclear energy $W_{\gamma N}$
  - Any change (photon fluxes, …) on one side changes the other side

- Access low $x_B \sim 10^{-4} - 10^{-5}$ range without rising the collision energy
- Strong rise at low $W_{\gamma N} \sim 15$ GeV $\rightarrow \sim 40$ GeV
  $\Rightarrow$ consistent with fast-growing gluon densities toward low x_B
- Flattish trend from $W_{\gamma N} \sim 40$ GeV $\rightarrow \sim 400$ GeV
  $\Rightarrow$ slow rise with a slope $(2.98 \pm 0.42^{stat} \pm 1.06^{syst}) \times 10^{-5}$ mb/GeV
- No model describes full data range

Neitron emission classes with 0p

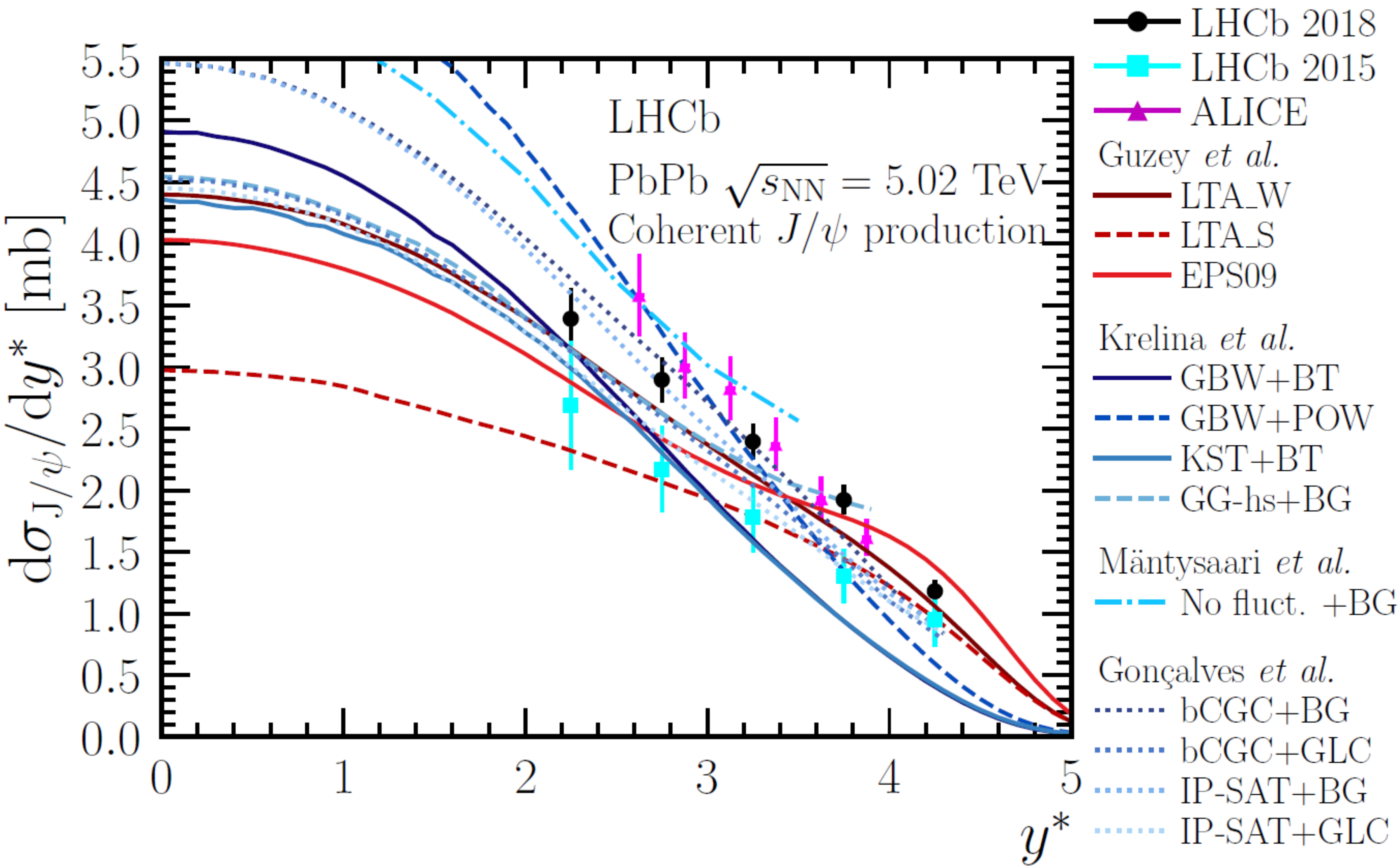


ALICE, arXiv:2209.04250v1 (2022)

Articles

- ALICE
  - Coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B718 (2013) 1273.
  - Charmonium and e + e − pair photoproduction at mid-rapidity in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Eur. Phys. J. C73, 2617 (2013).
  - Exclusive J/ψ photoproduction off protons in ultra-peripheral p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02TeV, Phys. Rev. Lett. 113 (2014) 232504.
  - Coherent J/ψ photoproduction at forward rapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys.Lett. B798 (2019) 134926.
  - Coherent J/ψ and ψ′ photoproduction at midrapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Eur. Phys. J. C 81 (2021) 712.
  - First measurement of the |t|-dependence of coherent J/ψ photonuclear production, PLB 817 (2021) 136280.
  - Energy dependence of exclusive J/ψ photoproduction off protons in ultra-peripheral p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Eur. Phys. J. C (2019) 79: 402.
  - Photoproduction of low-p_T J/ψ from peripheral to central Pb-Pb collisons at 5.02 TeV, arXiv:2204.10684 (2022).
  - Coherent photoproduction of ρ^0 vector mesons in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, JHEP 06 (2020) 035.
  - First measurement of coherent ρ^0 photoproduction in ultra-peripheral Xe-Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV, Phys. Lett. B 820 (2021) 136481.
- CMS
  - Coherent J/ψ photoproduction in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}}$=2.76 TeV with the CMS experiment, Physics Letters B772 (2017) 489–511.
  - Measurement of exclusive ϒ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Eur. Phys. J. C (2019) 79:277.
  - Measurement of exclusive $\rho(770)^0$ photoproduction in ultraperipheral pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Eur. Phys. J. C 79, 702 (2019).
- LHCb
  - Updated measurements of exclusive J/ψ and ψ(2S) production cross-sections in pp collisions at $\sqrt{s}$ = 7 TeV, J. Phys. G 41 (2014) 055002.
  - Measurement of the exclusive ϒ production cross-section in pp collisions at $\sqrt{s}$ = 7 TeV and 8TeV, JHEP 09 (2015) 084.
  - Central exclusive production of J/ψ and ψ(2S) mesons in pp collisions at $\sqrt{s}$ = 13 TeV, JHEP 10 (2018) 167.
  - Study of coherent J/ψ production in lead-lead collisions at $\sqrt{s_{NN}}$ = 5TeV, arXiv:2107.03223v1 [hep-ex] (2021).
  - Study of the coherent charmonium production in ultra-peripheral lead-lead collisions, arXiv:2206.08221 [hep-ex] (2022).
  - J/ψ photo-production in Pb-Pb peripheral collisions at $\sqrt{s_{NN}}$ = 5TeV, Phys. Rev. C105 (2022) L032201.

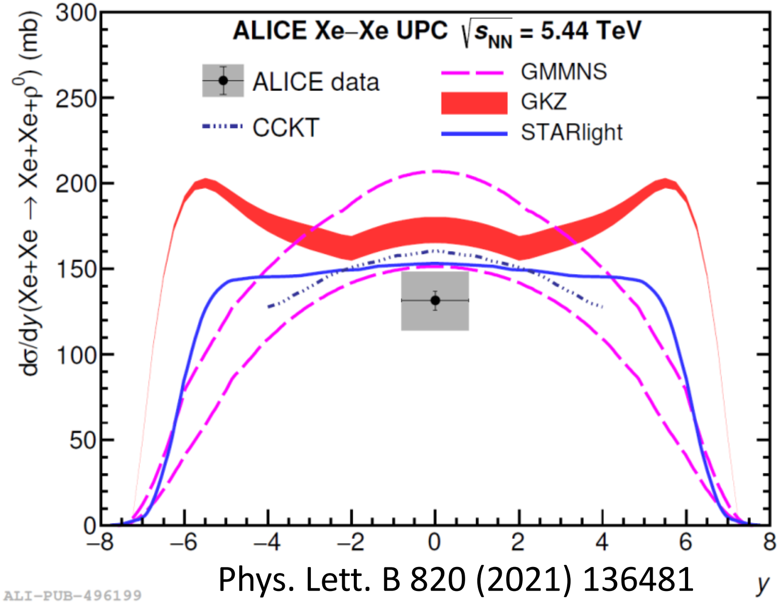
Comparison LHCb/ALICE – Pb-Pb @ 5 TeV



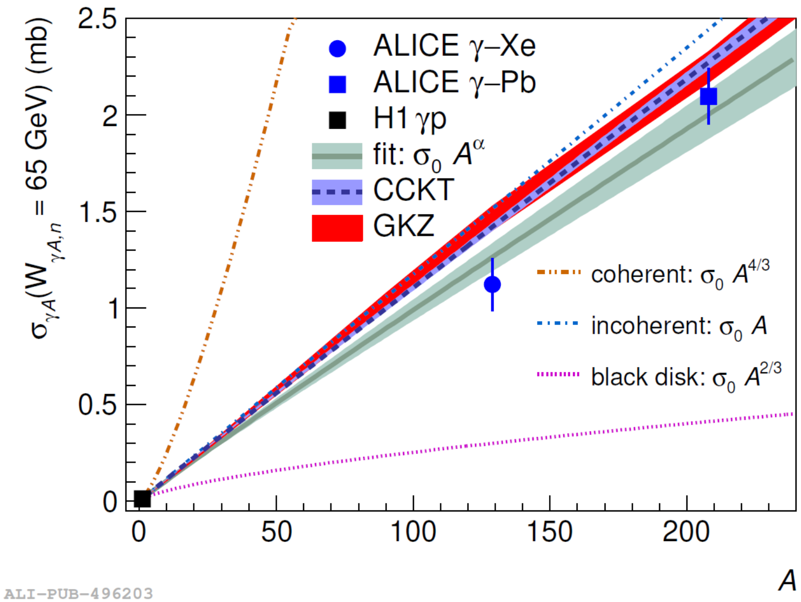
ρ^0 in Xe-Xe at $\sqrt{s_{NN}}$ = 5.44 TeV

- $d\sigma/dy = 131.5 \pm 5.6^{st}\,{}^{+17.5}_{-16.9}{}^{sy}$ mb
- All models relatively close to data

- $W_{\gamma A,n}$ = 65 GeV
- $\sigma(\gamma A \rightarrow \rho^0 A) \sim A^{\alpha}$ with a slope $\alpha = 0.96 \pm 0.02^{sy}$
  - $\Rightarrow$ Signals important shadowing effect
  - – Far from black disk limit
  - – Slope close to 1 by coincidence
- Fair description of data by models CCKT (saturation) and GKZ (shadowing)



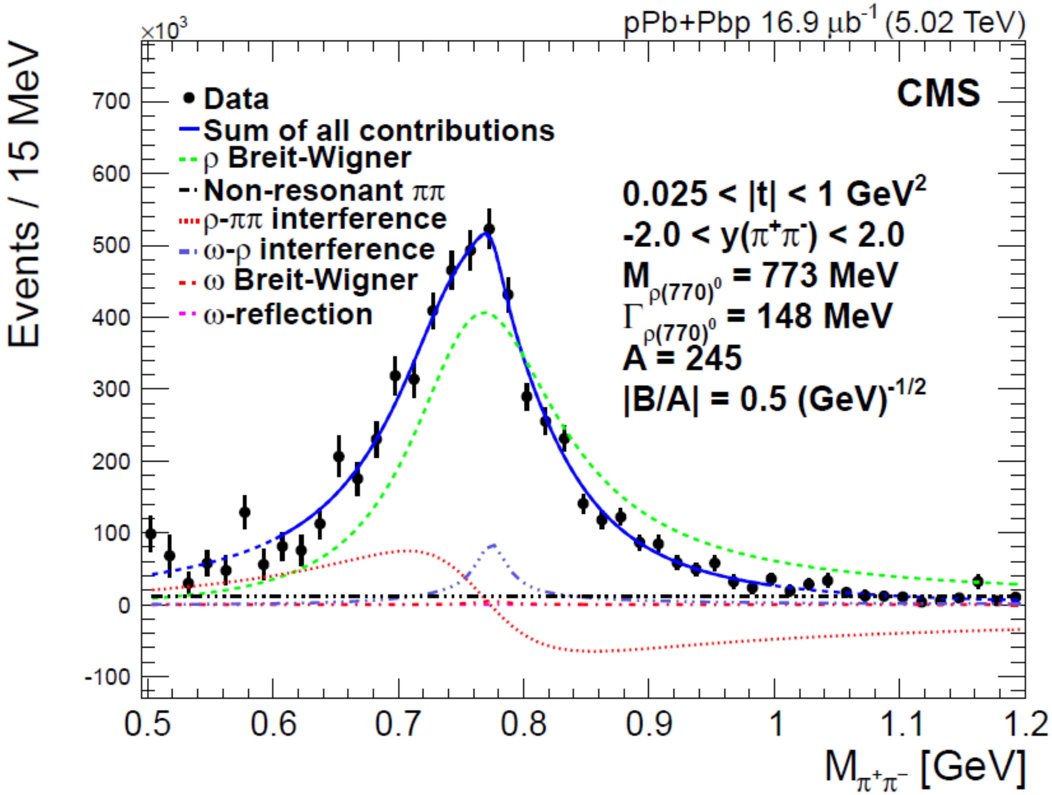
Phys. Lett. B 820 (2021) 136481



ρ^0 @5TeV in Pb-Pb, CMS

$$\frac{dN_{\pi^+\pi^-}}{dM_{\pi^+\pi^-}} = \left| A \frac{\sqrt{M_{\pi^+\pi^-} M_{\rho(770)} \Gamma_{\rho(770)}}}{M^2_{\pi^+\pi^-} - M^2_{\rho(770)^0} + i M_{\rho(770)^0} \Gamma_{\rho(770)}} + B + C e^{i\phi_\omega} \frac{\sqrt{M_{\pi^+\pi^-} M_{\omega(783)} \Gamma_{\omega(783)\to\pi\pi}}}{M^2_{\pi^+\pi^-} - M^2_{\omega(783)} + i M_{\omega(783)^0} \Gamma_{\omega(783)}} \right|^2$$

$$\Gamma_{\rho(770)} = \Gamma_0 \frac{M_{\rho(770)^0}}{M_{\pi^+\pi^-}} \left[\frac{M^2_{\pi^+\pi^-} - 4m^2_{\pi^\pm}}{M^2_{\rho(770)^0} - 4m^2_{\pi^\pm}} \right]^{\frac{3}{2}} \qquad \Gamma_{\omega(783)} = \Gamma_0 \frac{M_{\omega(783)}}{M_{\pi^+\pi^-}} \left[\frac{M^2_{\pi^+\pi^-} - 9m^2_{\pi^\pm}}{M^2_{\omega(783)} - 9m^2_{\pi^\pm}} \right]^{\frac{3}{2}}$$

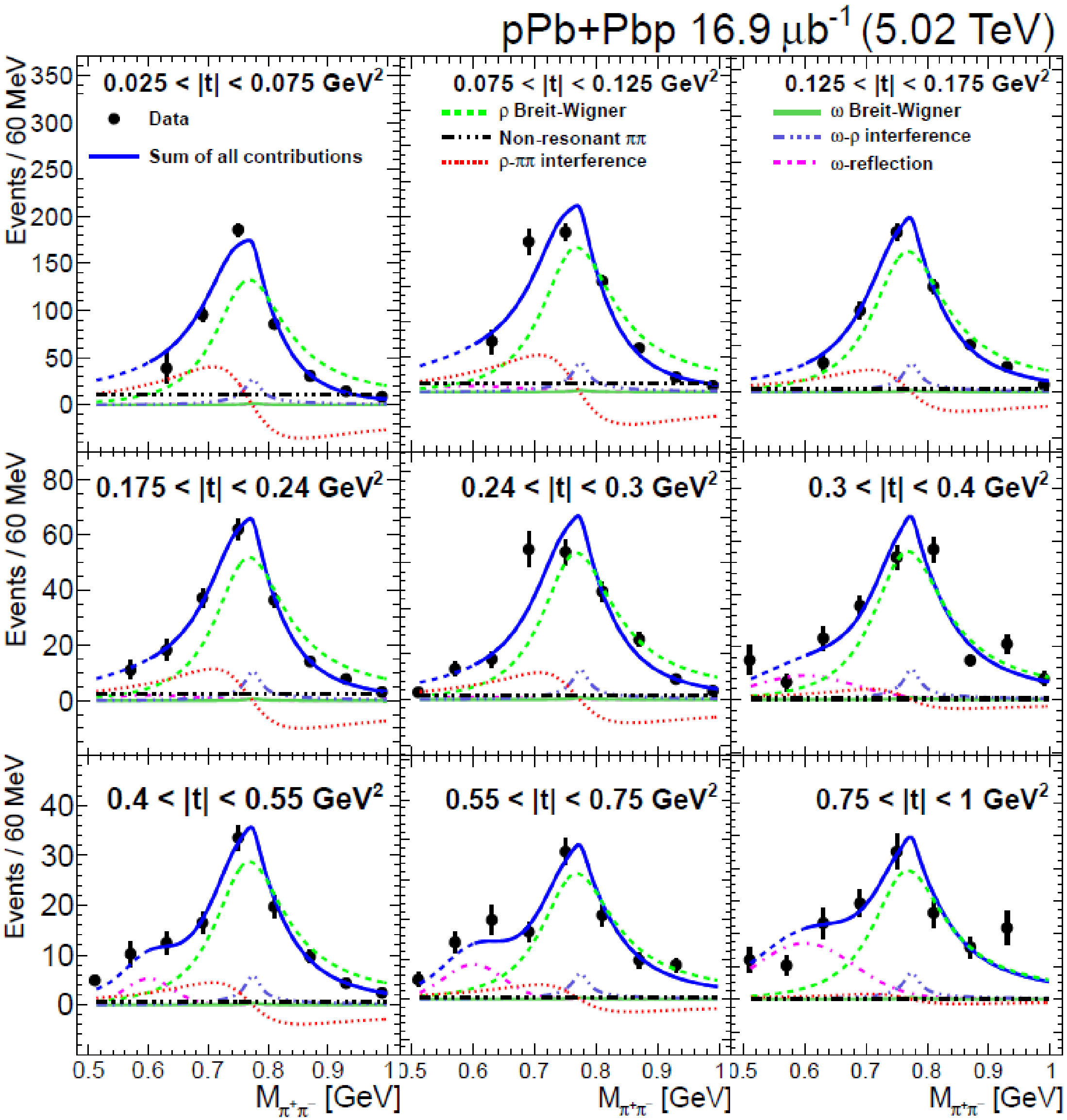


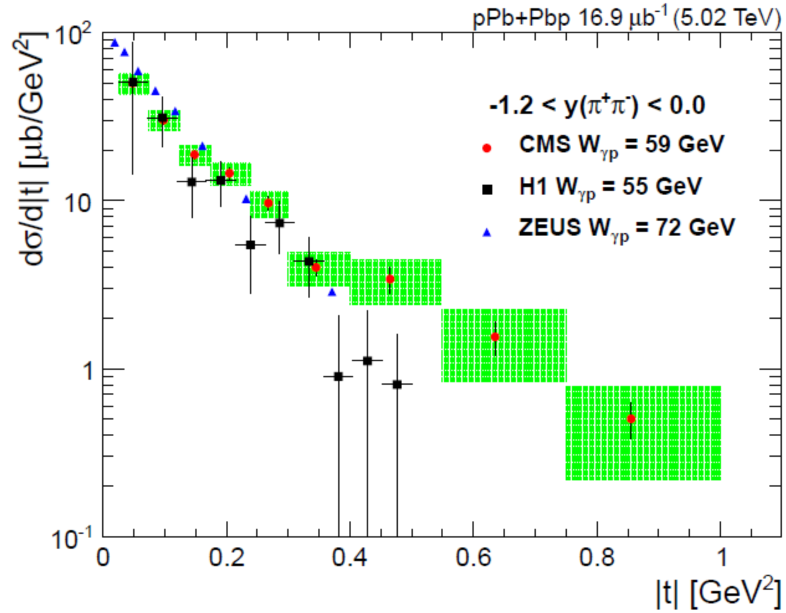
$$\frac{d\sigma}{dy} = \frac{N^{exc}_{\rho(770)^0}}{\mathcal{B}(\rho(770)^0 \to \pi^+\pi^-) L \Delta y},$$

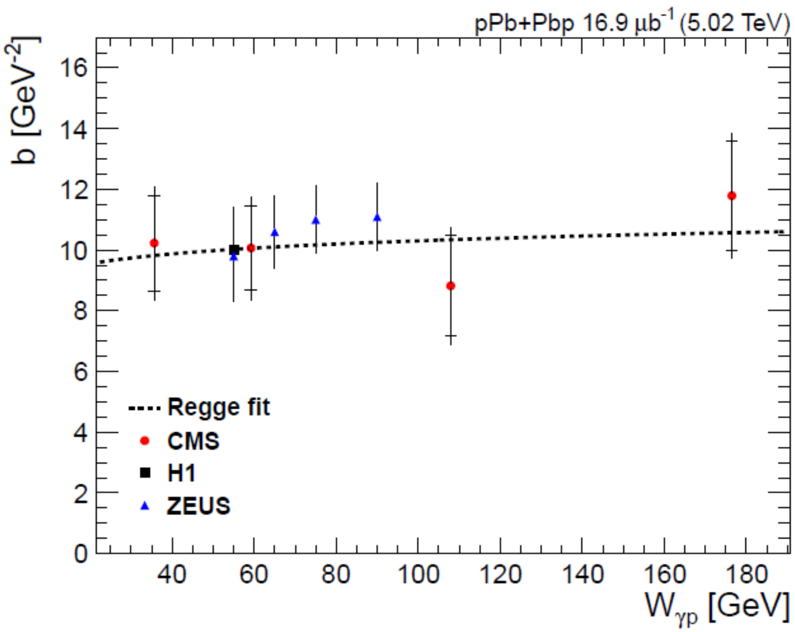
$$\frac{d\sigma}{dy}(pPb \to pPb\rho(770)^0) = k \frac{dn}{dk} \sigma(\gamma p \to \rho(770)^0 p)$$

$$k = (1/2) M_{\rho(770)^0} \exp\left(-y_{\rho(770)^0}\right)$$

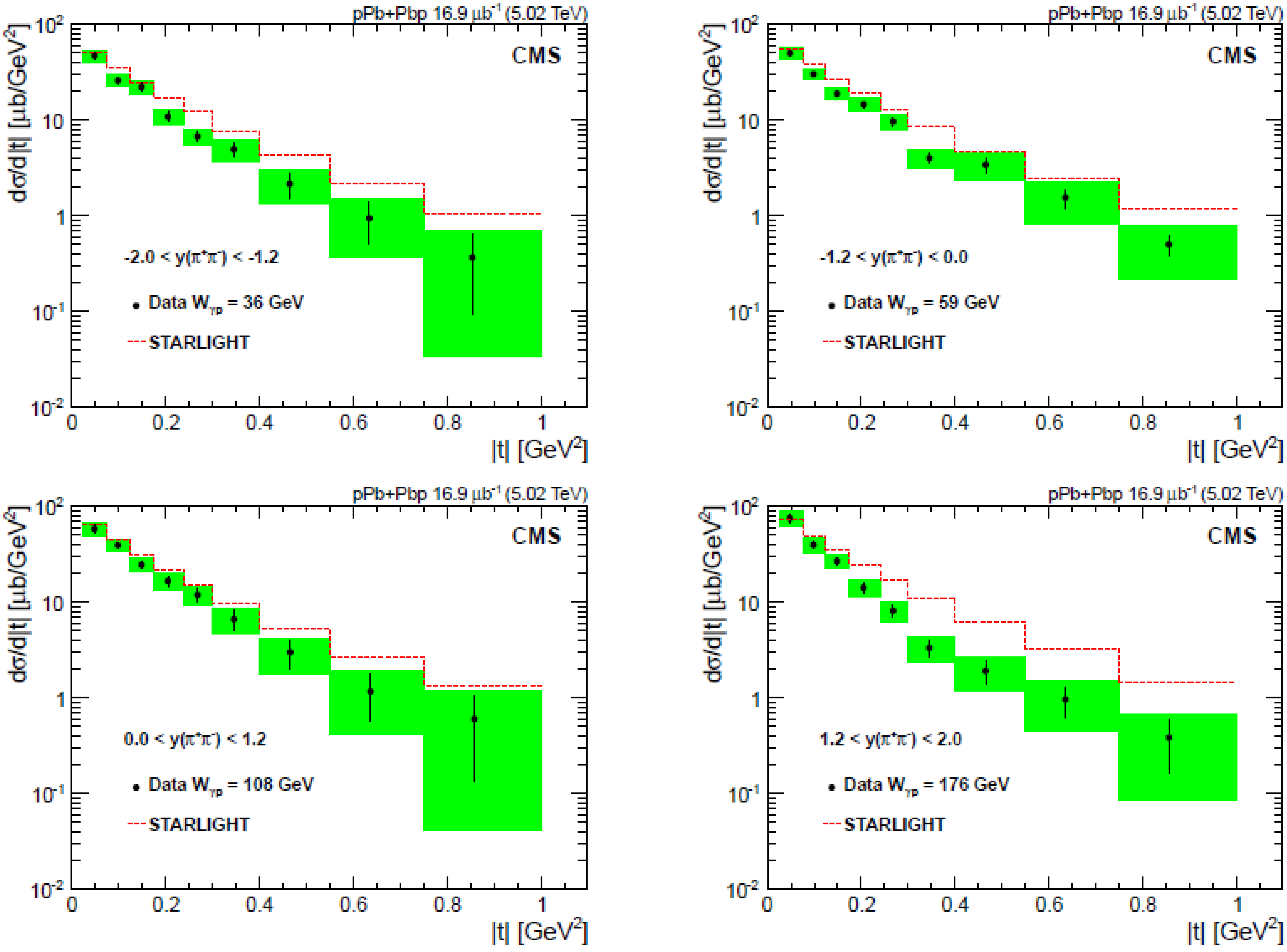
ρ^0 @5TeV in Pb-Pb, CMS





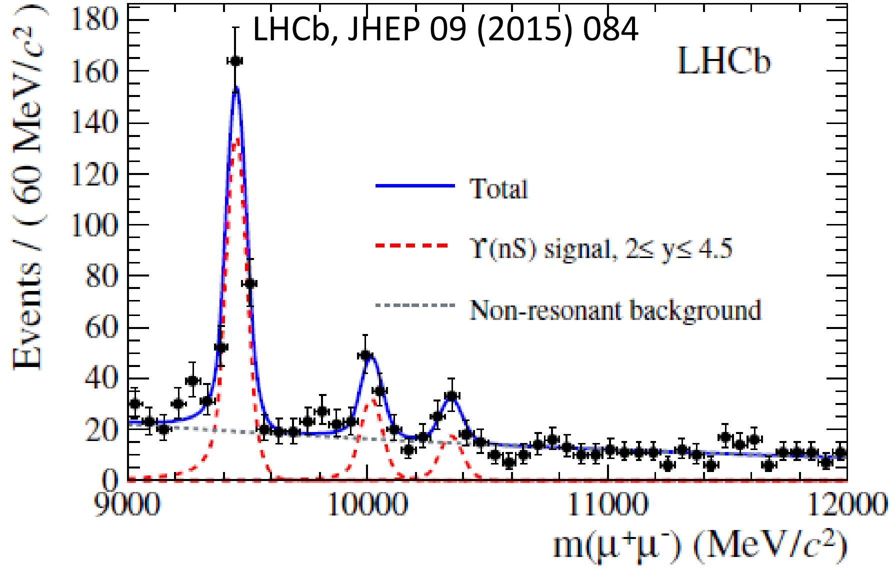


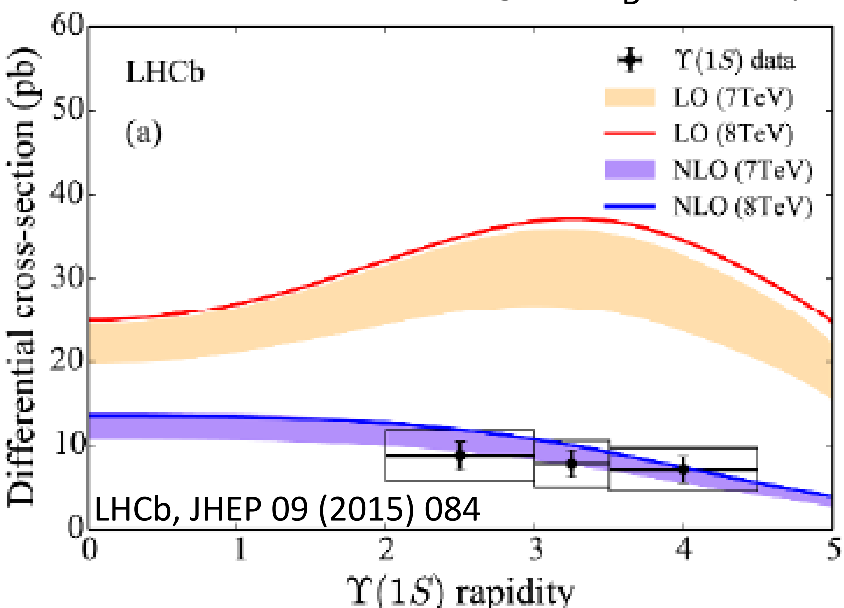
ρ^0 @5TeV in Pb-Pb, CMS

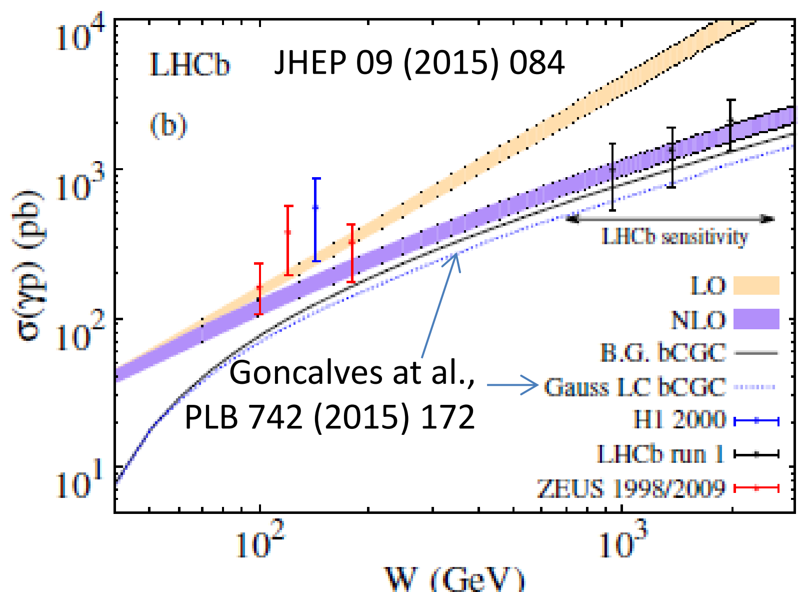


Υ(nS) in pp at $\sqrt{s}$ = 7, 8 TeV

- $\Upsilon(nS) \to \mu^+\mu^-$
  - Feed down ($\chi_b \to \Upsilon\gamma$) corrected
- **Cross section** in the LHCb acceptance:
  - $\sigma(pp \to p\Upsilon(1S)p) = 9 \pm 2.1 \pm 1.7$ pb
  - $\sigma(pp \to p\Upsilon(2S)p) = 1.3 \pm 0.8 \pm 0.3$ pb
  - $\sigma(pp \to p\Upsilon(3S)p) = <3.4$ pb at 95% cl.
- Good agreement of geometry corrected σ(Υ(1S)) and σ(γp) with NLO calculations (Jones at al., JHEP 11 (2013) 085)
- Saturation model (bCGC) relatively close
- New kinematic region $x_B \sim 10^{-5}$ probed

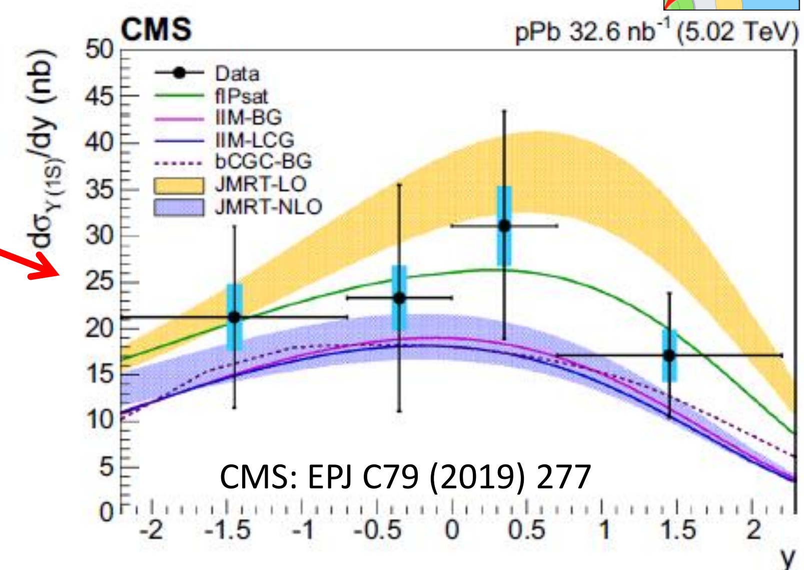




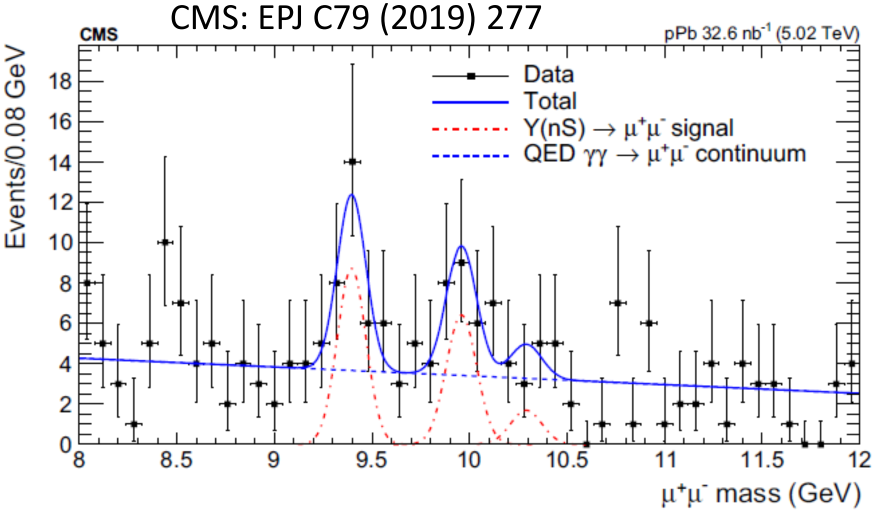


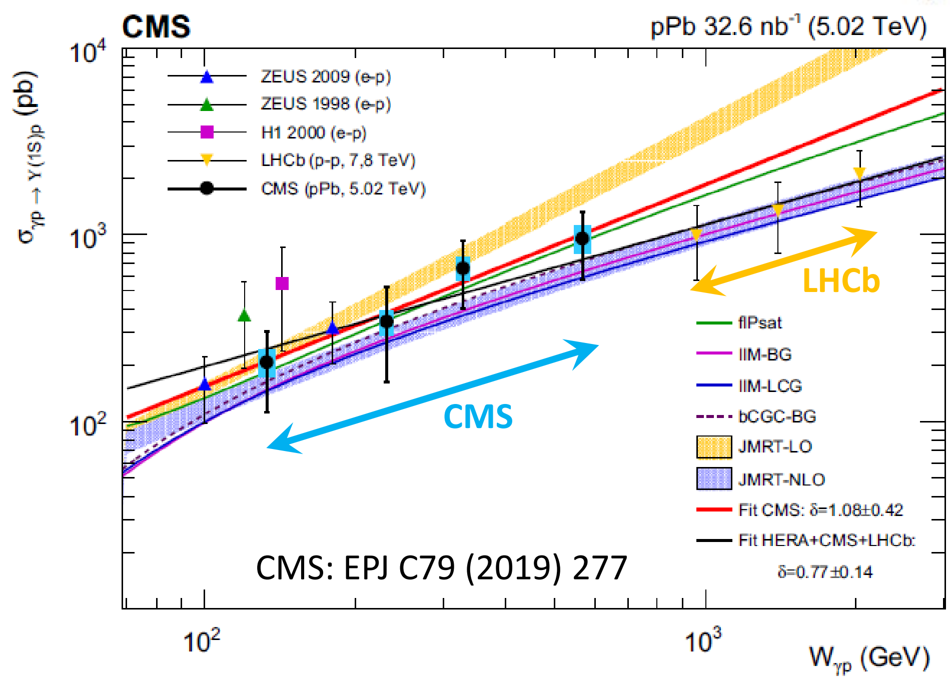
Υ(nS) in p-Pb at $\sqrt{s}$ = 5.02 TeV

- $\Upsilon(nS) \to \mu^+\mu^-$
- **Cross section** extracted from ratios and inclusive Υ(nS) treatment
- Theory calculations (LO and NLO) and saturation models consistent with CMS data
- Fit to CMS: $\delta = 1.08 \pm 0.42$
  - $\Rightarrow$ Consistent with ZEUS: $\delta = 1.2 \pm 0.8$
  - $\Rightarrow$ Consistent with ZEUS+H1+CMS: $\delta = 0.99 \pm 0.27$
- Fit to HERA+CMS+LHCb: $\delta = 0.77 \pm 0.14$
  - $\Rightarrow$ Consistent with J/ψ data
- JMRT LO disfavored
- New kinematic region $x_B \sim 10^{-4} - 10^{-2}$ probed which interconnects HERA and LHCb data



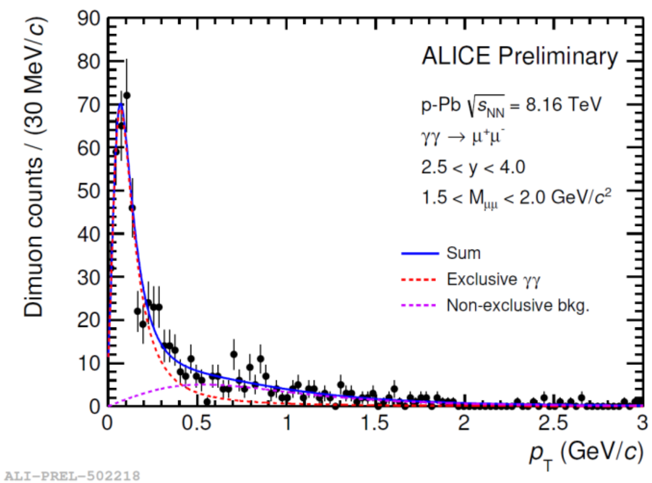
CMS: EPJ C79 (2019) 277

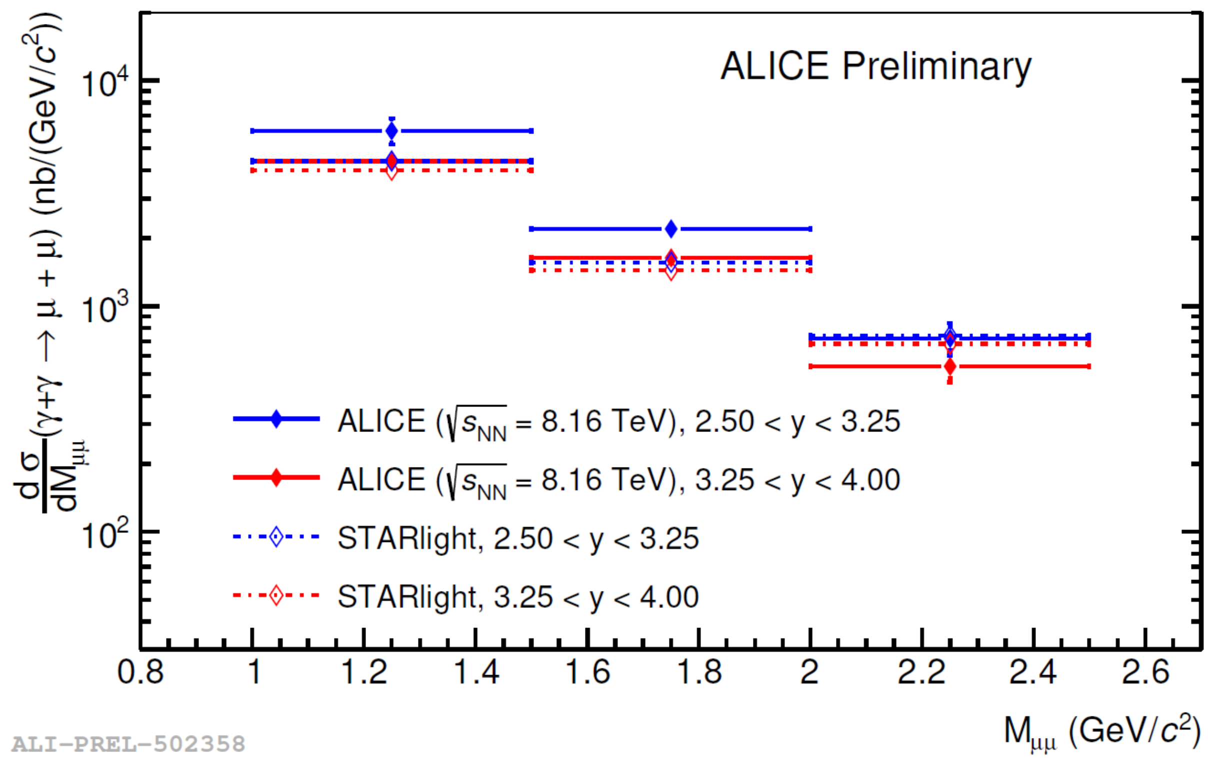




$\gamma\gamma \rightarrow \mu\mu$ in p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV

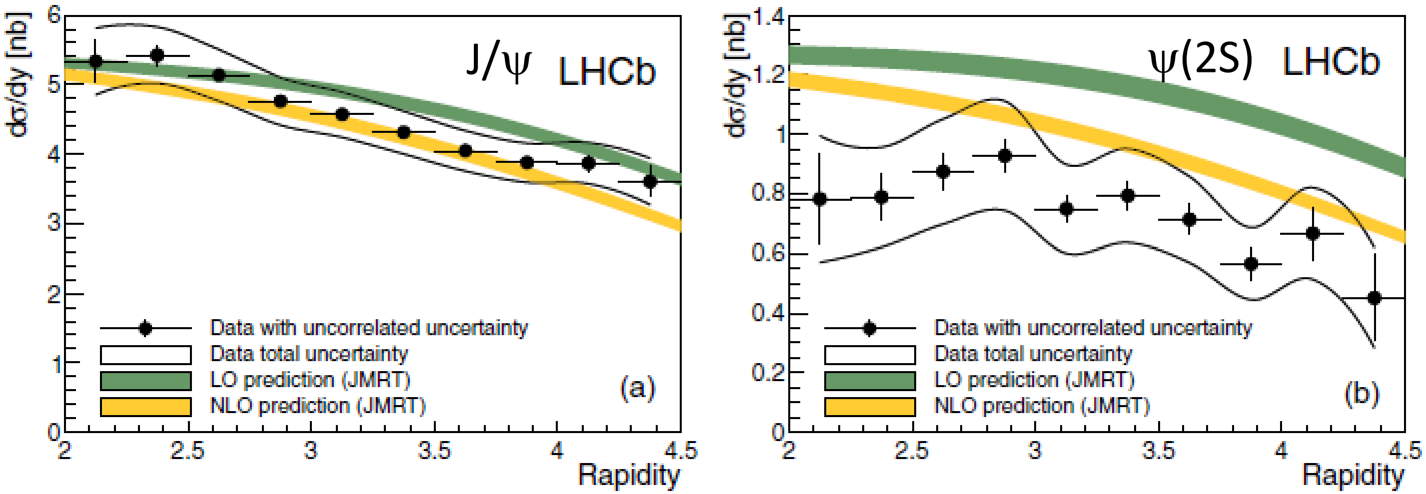
- **$\gamma\gamma \rightarrow \mu\mu$ cross section**
- Good agreement of simulation and data
- Comparison with STARlight (LO QED, no FSR) shows slight excess in data
- Important background for other UPC processes
- Constrain theoretical models

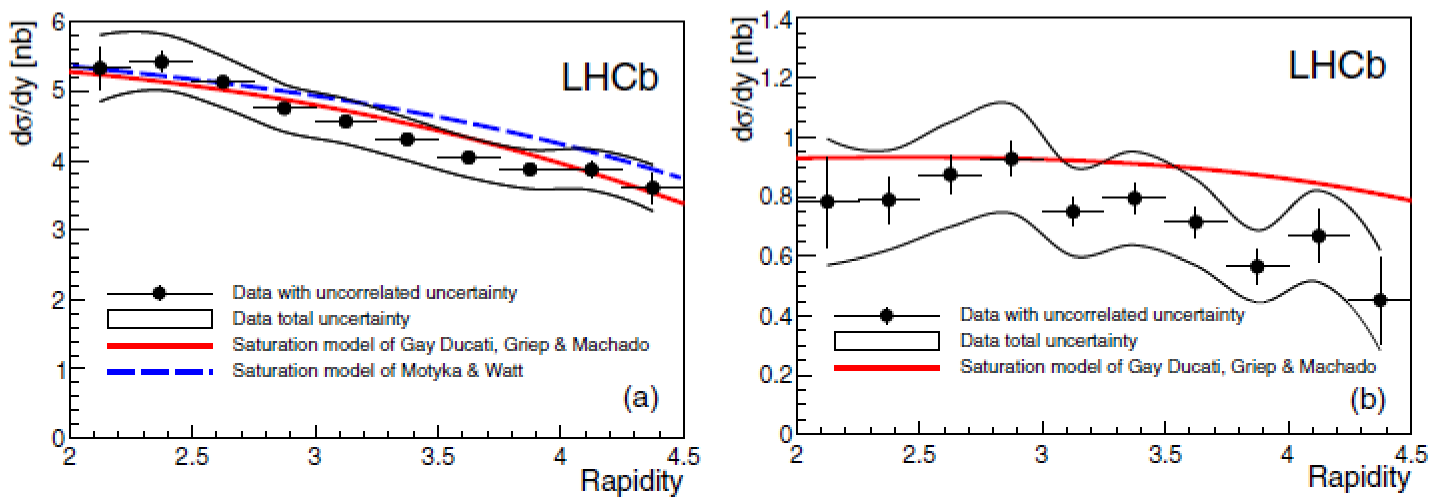




J/ψ, ψ(2S) in pp@7 TeV

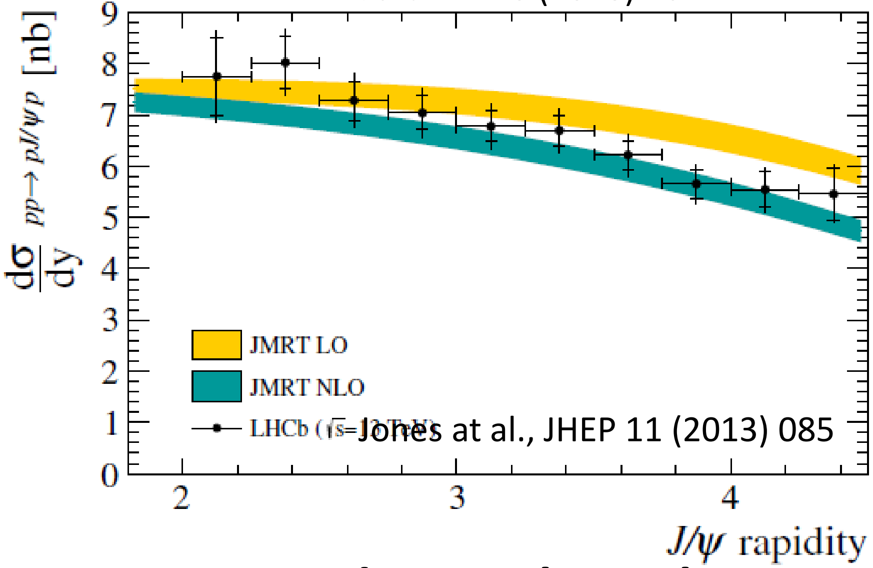
LHCb:J. Phys. G: Nucl. Part. Phys. **41** (2014) 055002



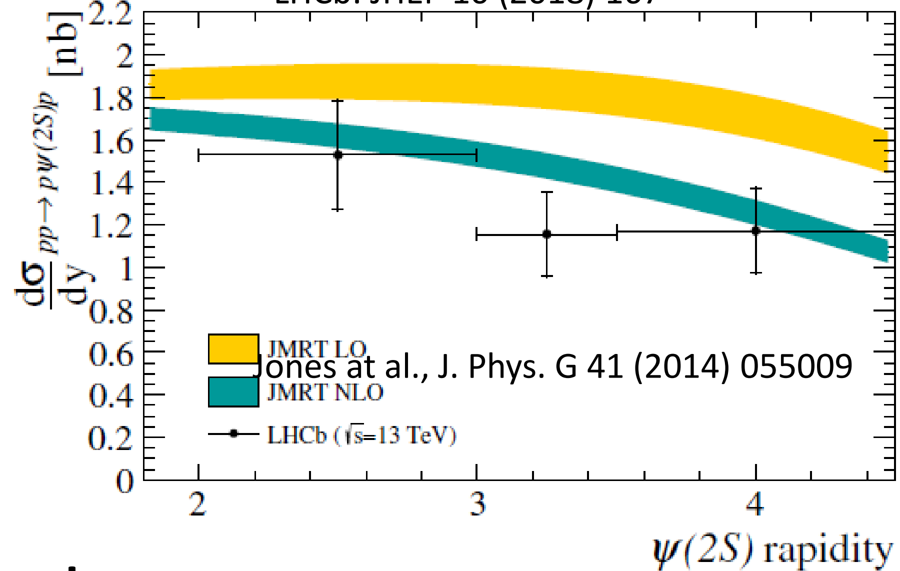


J/ψ, ψ(2S) in pp@13 TeV

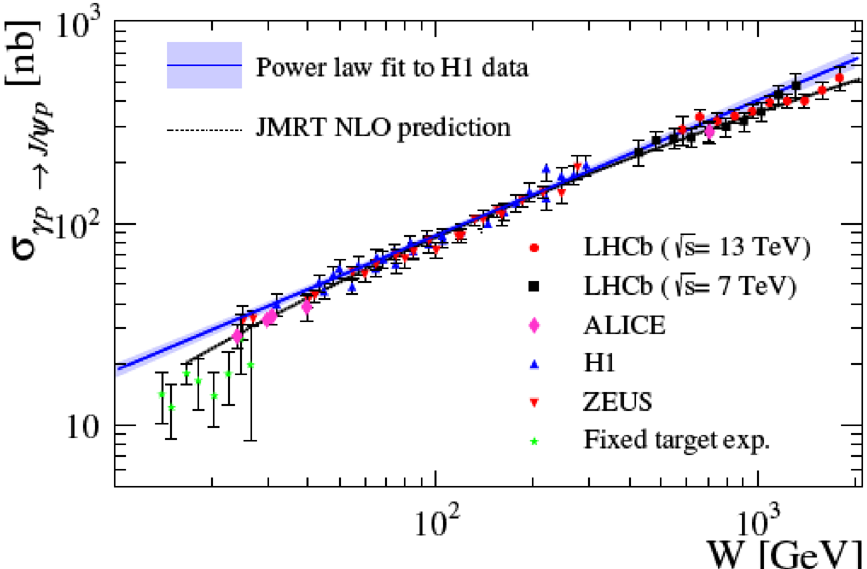
LHCb: JHEP 10 (2018) 167

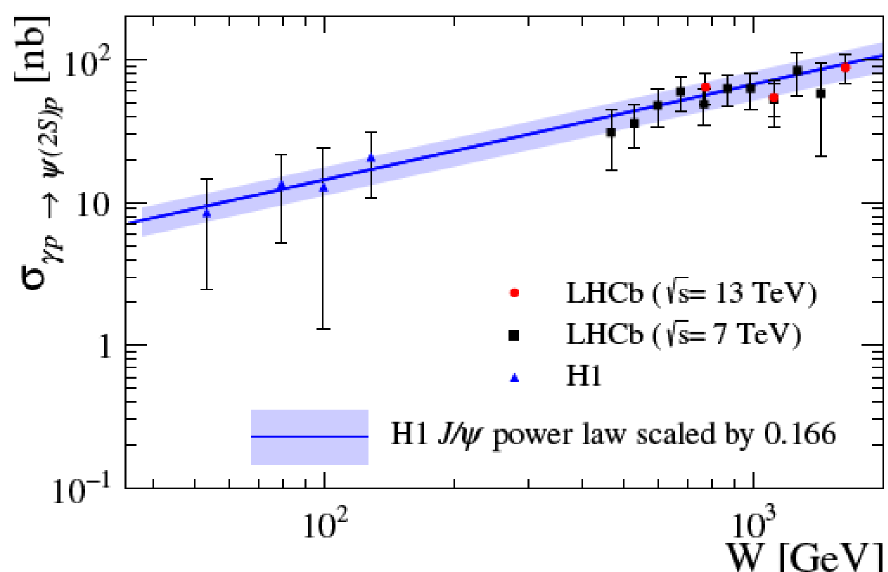


LHCb: JHEP 10 (2018) 167

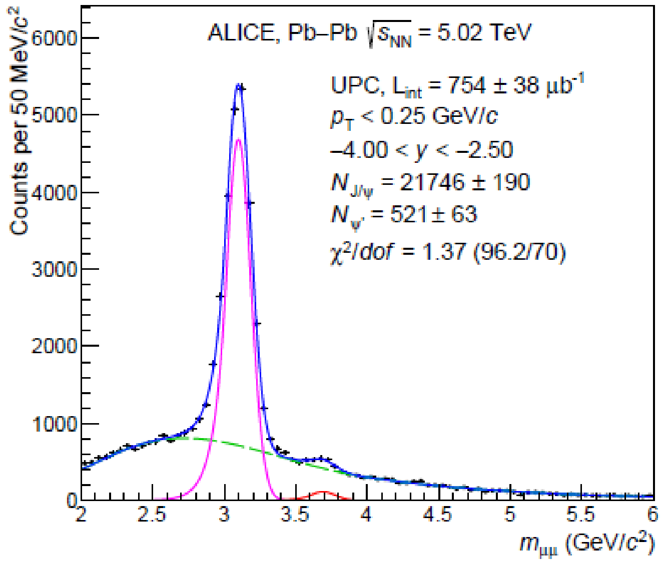


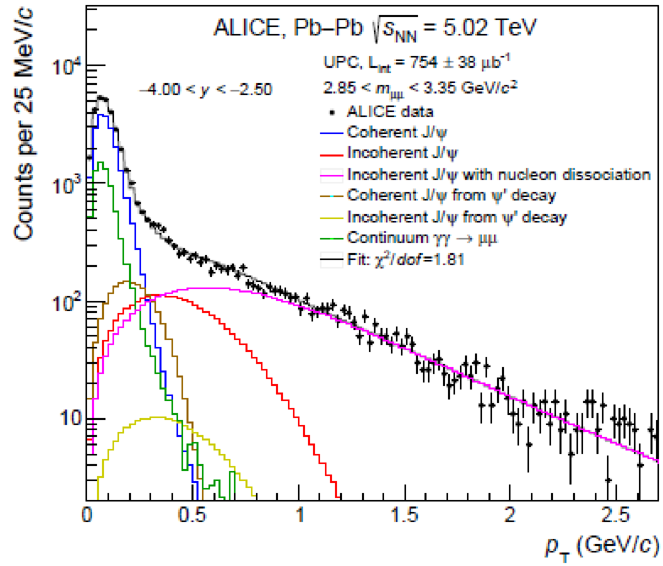
- NLO describes better the data



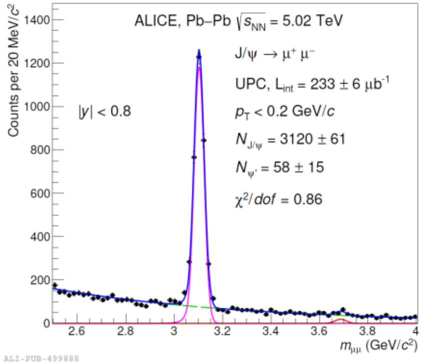


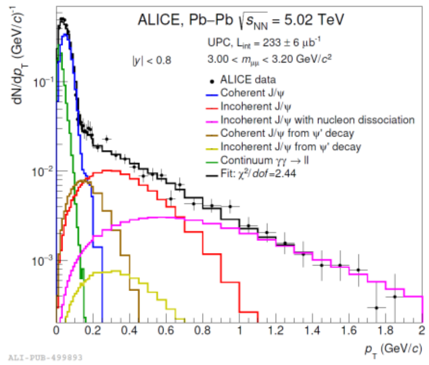
ALICE J/ψ in Pb-Pb – forward

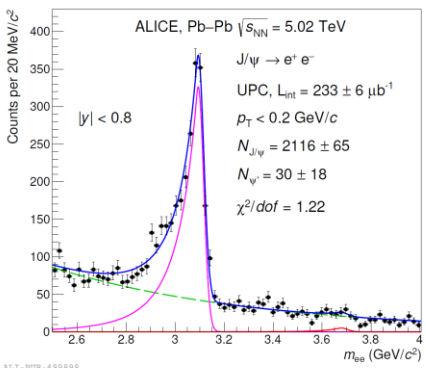


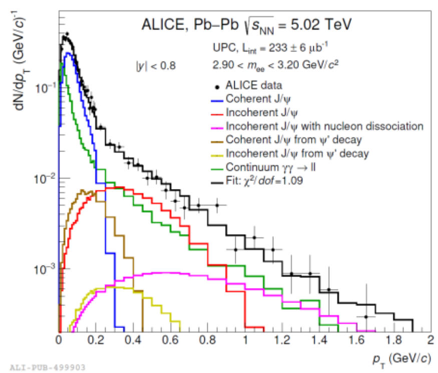


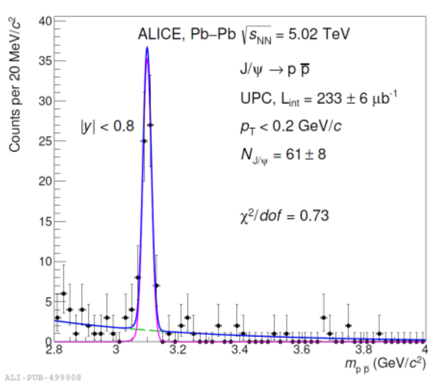
ALICE J/ψ in Pb-Pb – central barrel

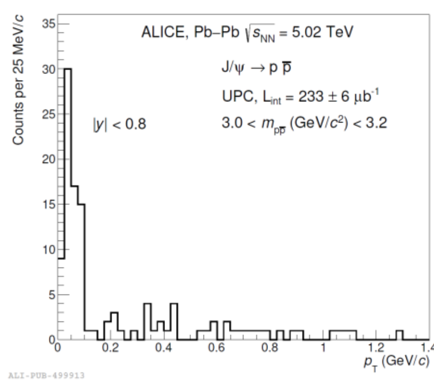


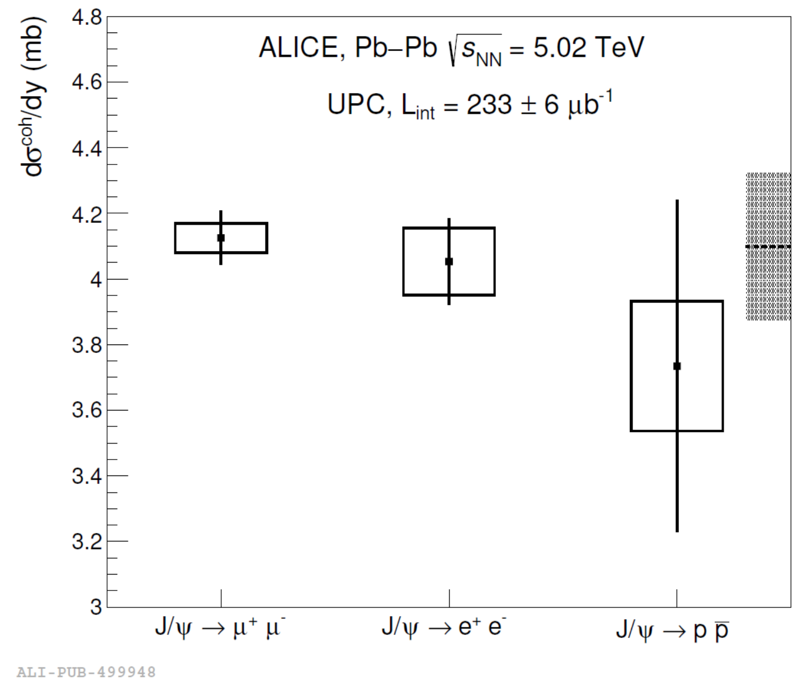




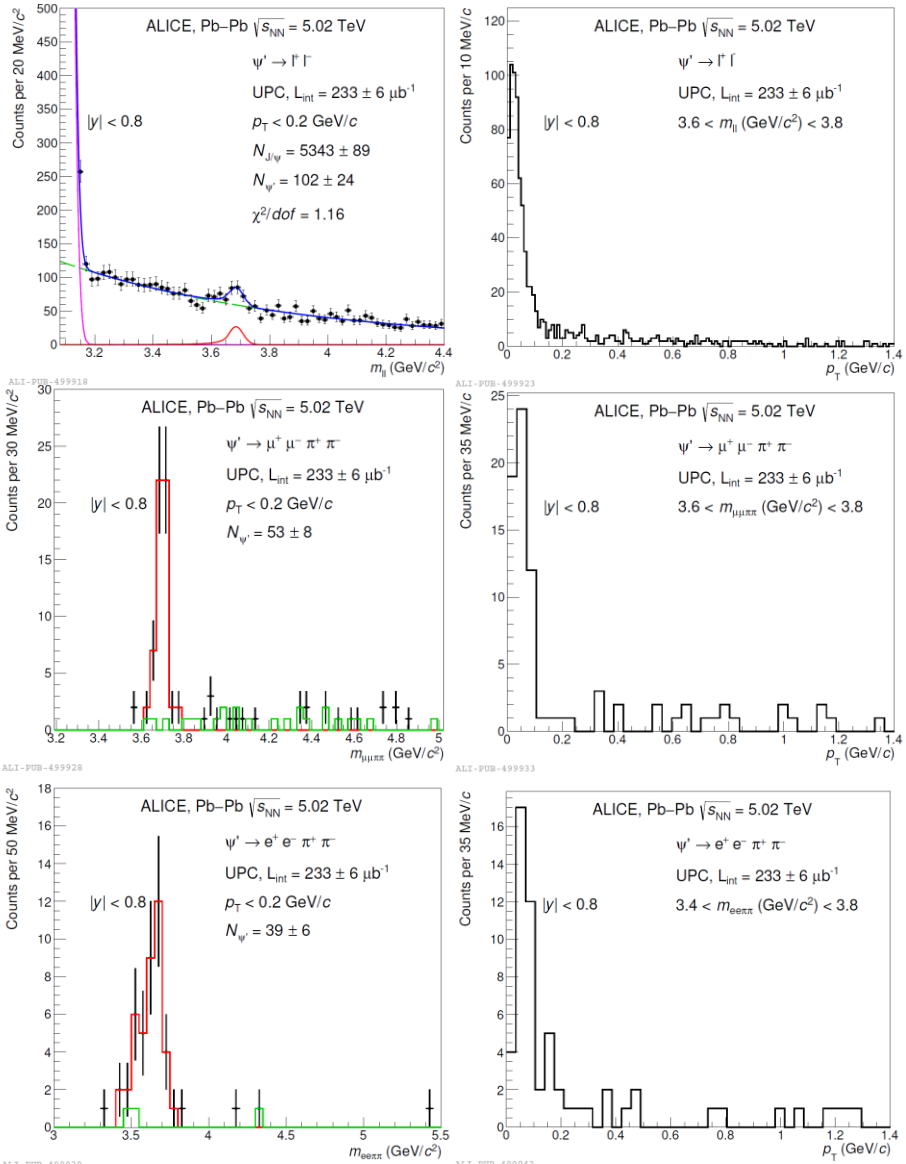


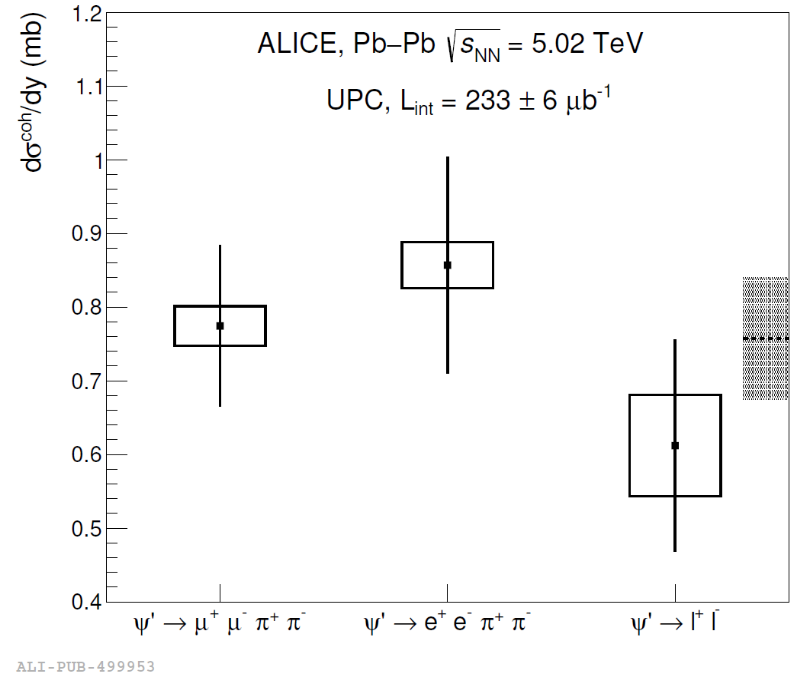




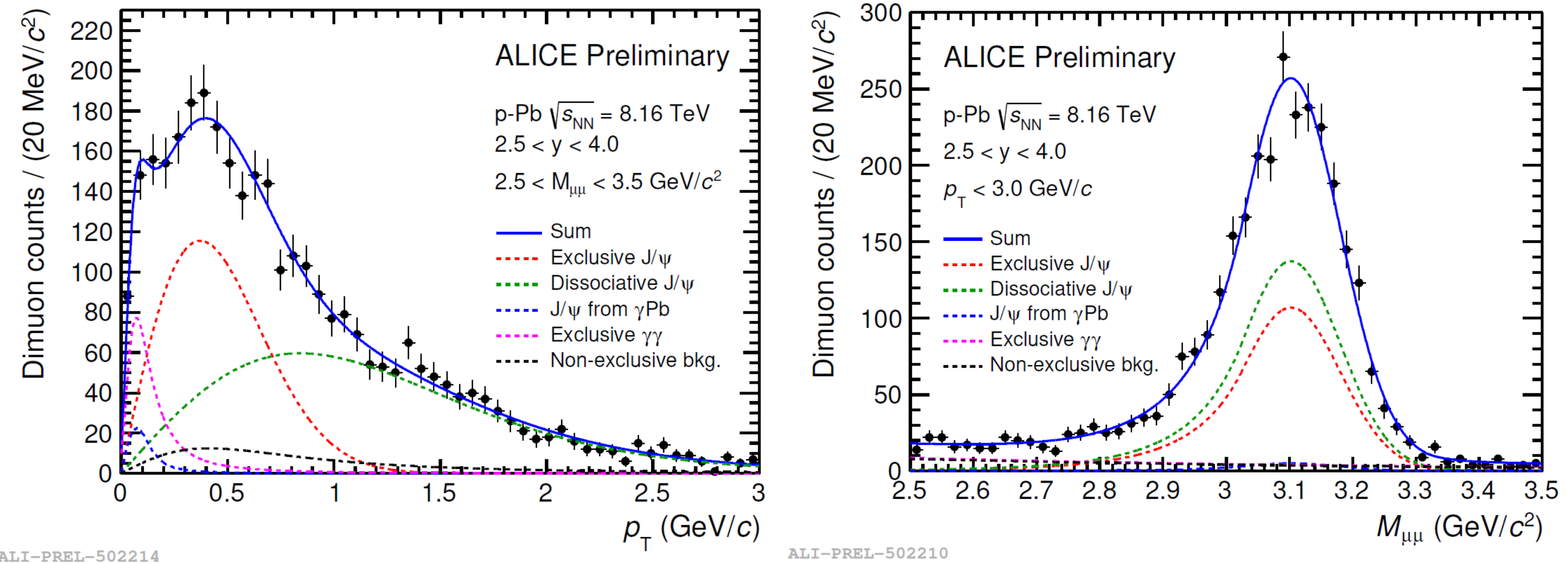


ALICE ψ’ in Pb-Pb – central barrel





ALICE Exclusive J/ψ in p-Pb



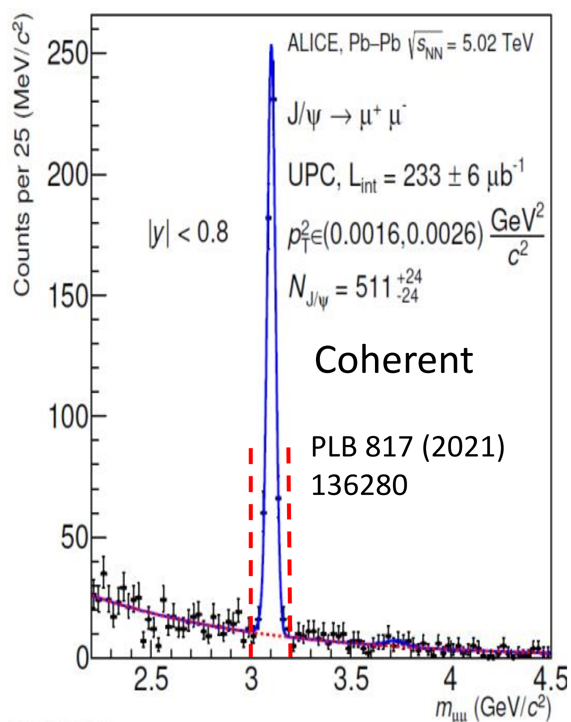
J/ψ in UPC Pb-Pb

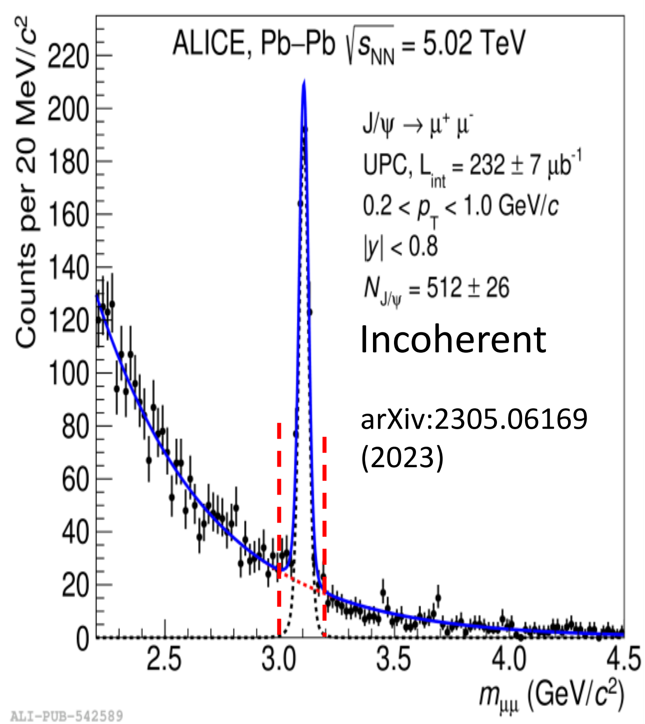
- Central rapidity region $|y^{J/\psi}| < 0.8$ which corresponds to $x_B \sim 10^{-3}$
- Very clear $J/\psi \to \mu^+\mu^-$ signal
- Corrections from p_T distribution
- Bayesian (and SVD) unfolding in coherent analysis
  - To account for p_T migrations
  - To transform $p_T^2 \to |t|$
- Transition from UPC to photonuclear cross section

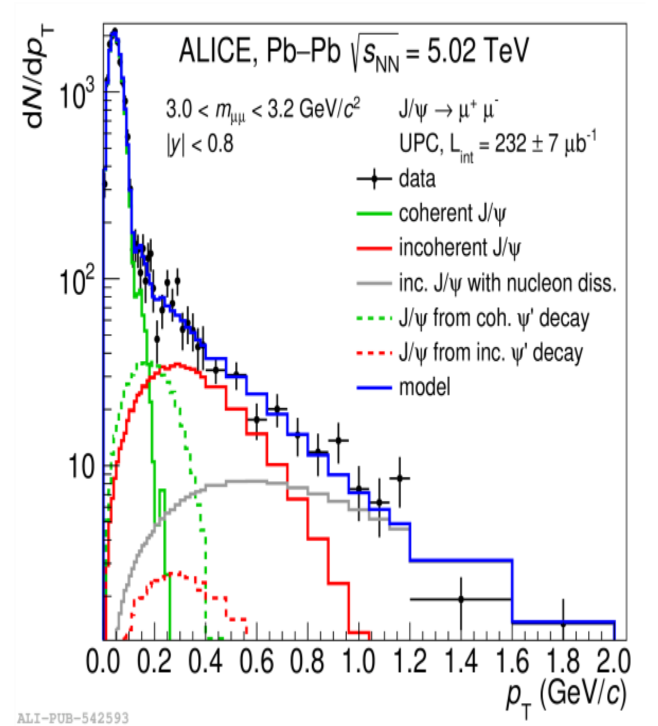
What we want to extract

Photon flux

$$\left.\frac{d^2\sigma^{coh/incoh}_{J/\psi}}{dy\,dp_T^2}\right|_{y=0} = 2n_{\gamma Pb}(y=0)\frac{d\sigma_{\gamma Pb}}{d|t|}$$



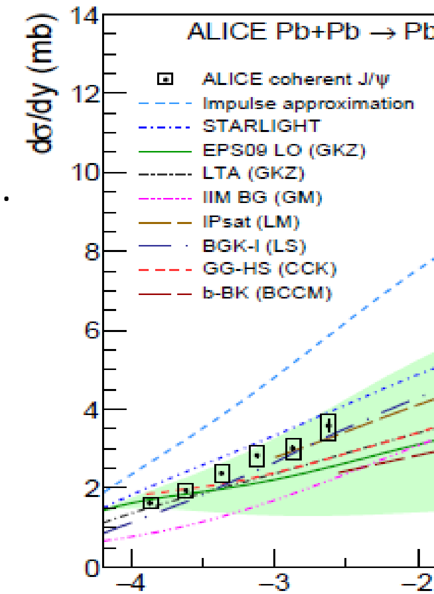




Models

- **Black disk limit:**
  - Frankfurt, Strikman, Zhalov, *Phys. Lett.* B537 (2002) 51–61.
  - total cross section of the interaction is equal to 2π R_A^2.
- **STARlight:**
  - Klein, Nystrand, Seger, Gorbunov, Butterworth, Comput. Phys. Commun. 212 (2017) 258–268; Klein and Nystrand, Phys. Rev. C 60 (1999) 014903.
  - Based on a phenomenological description of the exclusive production of VM off nucleons, the optical theorem, and a Glauber-like eikonal formalism, does not take into account the elastic part of the elementary VM–nucleon cross section.
  - Includes multiple scattering, **no gluon shadowing**.
- **GKZ (Guzey, Kryshen and Zhalov):**
  - Guzey, Kryshen, Zhalov, Phys. Rev. C93 (2016) 055206; Frankfurt, Guzey, Strikman, Zhalov, Phys. Lett. B752 (2016) 51–58.
  - Based on a modified **vector dominance model**, in which the hadronic fluctuations of the photon interact with the nucleons in the nucleus according to the Gribov-Glauber model of **nuclear shadowing**
- **GMMNS (Goncalves, Machado, Morerira, Navarra and dos Santos):**
  - Gonçalves, Machado, Moreira, Navarra, dos Santos, Phys. Rev. D96 (2017) 094027; Iancu, Itakura, Munier, Phys. Lett. B590 (2004) 199–208,
  - Based on the Iancu-Itakura-Munier (IIM) implementation of **gluon saturation** within the **colour dipole model** coupled to a boosted-Gaussian description of the wave function of the vector meson.
- **CCKT (Cepila, Contreras, Krelina and Tapia):**
  - Cepila, Contreras, Tapia Takaki, Phys. Lett. B766 (2017) 186–191; Cepila, Contreras, Krelina, Tapia Takaki, Nucl. Phys. B934 (2018) 330–340; N. Armesto, Eur. Phys. J. C26 (2002) 35–43
  - Based on the **colour dipole model** with the structure of the nucleon in the transverse plane described by so-called **hot spots**, regions of high gluonic density, whose number increases with increasing energy. The nuclear effects are implemented along the ideas of the Glauber model. Version without hot spots (named *nuclear*) and including them.
  - Indicates **gluon saturation**.

Models



- **Impulse approximation:**
  - Exclusive photoproduction off protons, neglects all nuclear effects but coherence.
  - Based on STARlight.
- **EPS09 LO:**
  - GKZ model with parameterization of **nuclear shadowing** data.
  - Eskola, Paukkunen, Salgado, JHEP 04 (2009) 065.
- **LTA:**
  - GKZ model based on Leading Twist Approximation of **nuclear shadowing**.
  - Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255–393.
- **IIM BG, IPsat, BGK-I:**
  - **Color dipole** approach coupled to the Color Glass Condensate (CGC) formalism with different assumptions on the dipole-proton scattering amplitudę.
  - **IIM BG:** Gonçalves, Moreira, Navarra, Phys. Rev. C 90 (2014) 015203; dos Santos, Machado, J. Phys. G 42 no. 10, (2015) 105001. (saturation)
  - **IPsat:** Lappi, Mäntysaari, Phys. Rev. C 83 (2011) 065202; Lappi, Mäntysaari, Phys. Rev. C 87 (2013) 032201. (saturation)
  - **BGK-I:** A. Łuszczak, Schäfer, Phys. Rev. C 99 no. 4, (2019) 044905. (shadowing)
- **GG-HS**:
  - CCK **color dipol model** with **hot spots** nucleon structure with Glauber-Gribov formalism
  - Cepila, Contreras, Krelina, Phys. Rev. C 97 no. 2, (2018) 024901; Cepila, Contreras, Tapia Takaki, Phys. Lett. B766 (2017) 186–191.
- **b-BK:**
  - Bendova, Cepila, Contreras, Matas (BCCM) model based on the **color dipole** approach coupled to the impact-parameter dependent Balitsky-Kovchegov equation with initial conditions based on the Woods-Saxon shape of the Pb nucleus.
  - Bendova, Cepila, Contreras, Matas, Physics Letters B 817 (2021) 136306.

Models

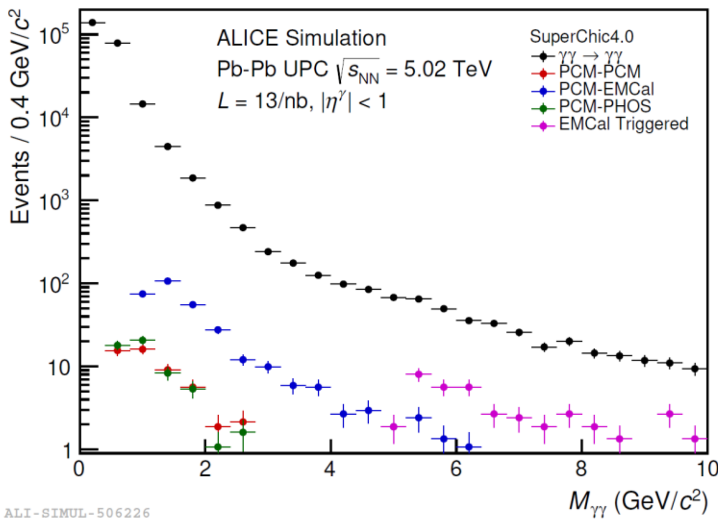
- **Guzey at al.**
  - **Look at GKZ**
- **Krelina et al**.
  - Cepila, Contreras, Krelina, Phys. Rev. C97 (2018) 024901; Kopeliovich, Krelina, Nemchik, Potashnikova, arXiv:2008.05116
  - variations of the colour-dipole model based on CGC theory.
  - GBW + BT: Golec-Biernat-Wusthof (GBW) model include light-front colour dipoles; Buchmuller-Tye (BT) potentials which describe data for proton-electron generation of charmonium.
  - GWB + POW: GWB model and power-like (POW) potentials which describe data for proton-electron generation of charmonium.
  - KST + BT: Kopeliovich-Schafer-Tarasov (KST) model include light-front colour dipoles and Buchmuller-Tye (BT) potentials
  - GG-hs +BG look at **GG-HS model**, boosted-Gaussian (BG) vector wave function; meson mainly consists of a quark-anti-quark pair, and the spin and polarization are the same as that of the photon.
- **Mantysaari et al**.
  - H. Mantysaari and B. Schenke, Phys. Lett. B772 (2017) 832; Lappi and H. Mantysaari, PoS DIS2014 (2014) 069,
  - (No fluct. +BG) the cross-section is calculated using the colour-dipole model, including a subnucleon scale uctuation based on CGC theory.
- **Goncalves et al**.
  - Goncalves et al., Phys. Rev. D96 (2017) 094027; Goncalves and Machado, Eur. Phys. J. C40 (2005) 519,
  - depend on the dipole-hadron scattering amplitude and vector-meson wave function.
  - bCGC+BG: The impact-parameter-CGC (bCGC) model: dipole-hadron scattering amplitude given by the solution of the Balitsky-Fadin-Kuraev-Lipatov (BFKL) equation and the Balitski-Kovchegov (BK)equation + impact parameter dependence on the saturation scale. Assumption of boosted-Gaussian (BG) vector wave function
  - bCGC+GLC: bCGC with Gauss-LC (GLC) vector wave function
  - IP-SAT+BG: the impact-parameter saturation (IP-SAT) model where dipole-hadron scattering amplitude depends on a gluon distribution evolved through the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi equation
  - IP-SAT+GLC: the impact-parameter saturation (IP-SAT) model with Gauss-LC (GLC) vector wave function

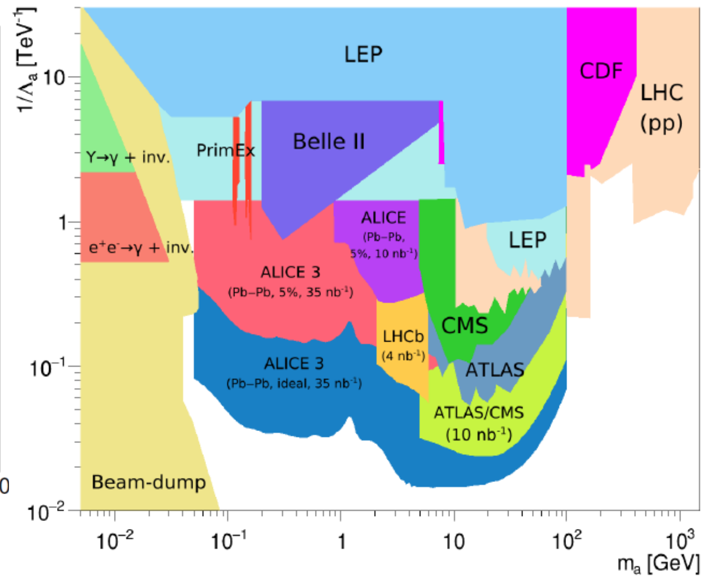
Models

- noon:
  - Broz, Contreras, Tapia Takaki, “A generator of forward neutrons for ultra-peripheral collisions: nOOn”, Comput. Phys. Commun. (2020) 107181.
- JMRT NLO:
  - next-to-leading-order calculations
  - Jones, Martin, Ryskin, Teubner, J. Phys. G 44 no. 3, (2017) 03LT01; JHEP 11 (2013) 085.
- BM:
  - Perturbative JIMWLK evolution based on HERA data
  - Mantysaari, Schenke, Phys. Rev. D 98 no. 3, (2018) 034013

ALICE in future runs (3, 4 and beyond)

- Precise and new vector meson photoproduction
- Light-by-light scattering

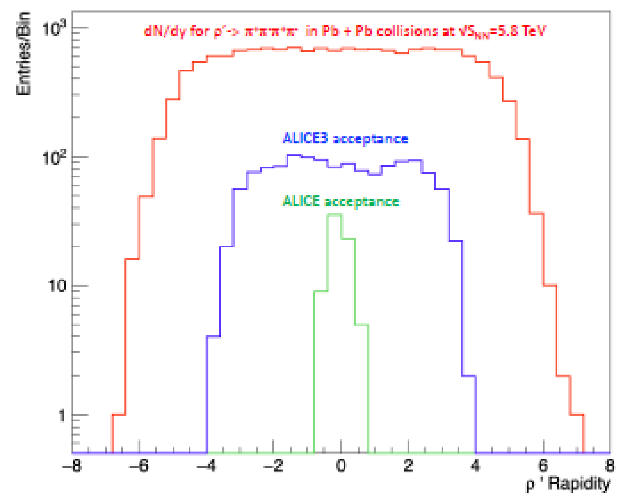




ALICE3 LOI: CERN-LHCC-2022-009 / LHCC-I-038

CERN Yellow Rep.Monogr. 7 (2019) 1159

Meson, channel	$\sigma^{Pb\text{-}Pb}$	N^{Tot}	$N^{\|\eta\| < 0.9}$	$N^{-4 < \eta < -2.5}$
$\rho^0 \to \pi^+ \pi^-$	5.2 b	68×10^9	5.5×10^9	-
$\rho' \to \pi^+ \pi^- \pi^+ \pi^-$	730 mb	9.5×10^9	210×10^6	-
$\phi \to K^+ K^-$	0.22 b	2.9×10^9	82×10^6	-
$J/\psi \to \mu^+ \mu^-$	1.0 mb	14×10^6	1.1×10^6	600×10^3
$\psi(2S) \to \mu^+ \mu^-$	30 μb	400×10^3	35×10^3	19×10^3
$\Upsilon(1S) \to \mu^+ \mu^-$	2.0 μb	26×10^3	2.8×10^3	880



$L^{Pb\text{-}Pb}$ = 13/nb