



# Overview of recent experimental results on ultraperipheral collisions

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# Outline

- Introduction



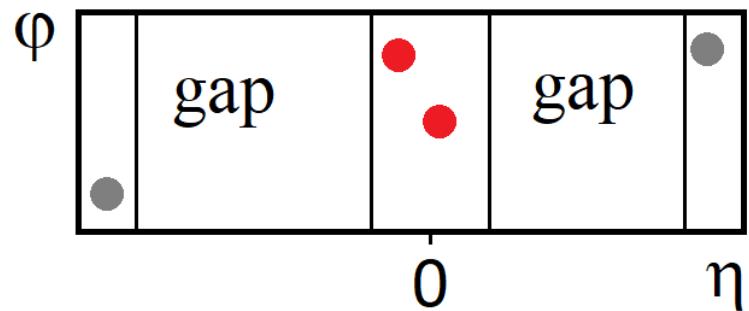
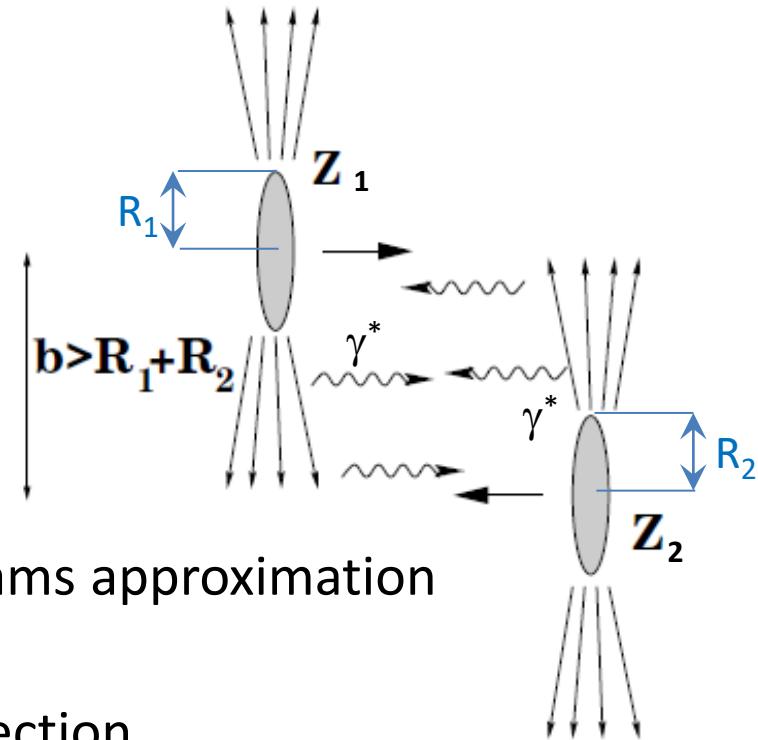
- Measurements

- Coherent J/ $\psi$  photoproduction in Pb-Pb, pp and p-Pb
- Coherent  $\psi(2S)$  photoproduction in Pb-Pb
- Exclusive and dissociative J/ $\psi$  photoproduction in p-Pb
- Y(nS) ( $n=1,2,3$ ) photoproduction in pp and p-Pb
- $\rho^0$  photoproduction in p-Pb, Pb-Pb and Xe-Xe
- Excited  $\rho$  state photoproduction
- Measurement of nuclear radius and neutron skin

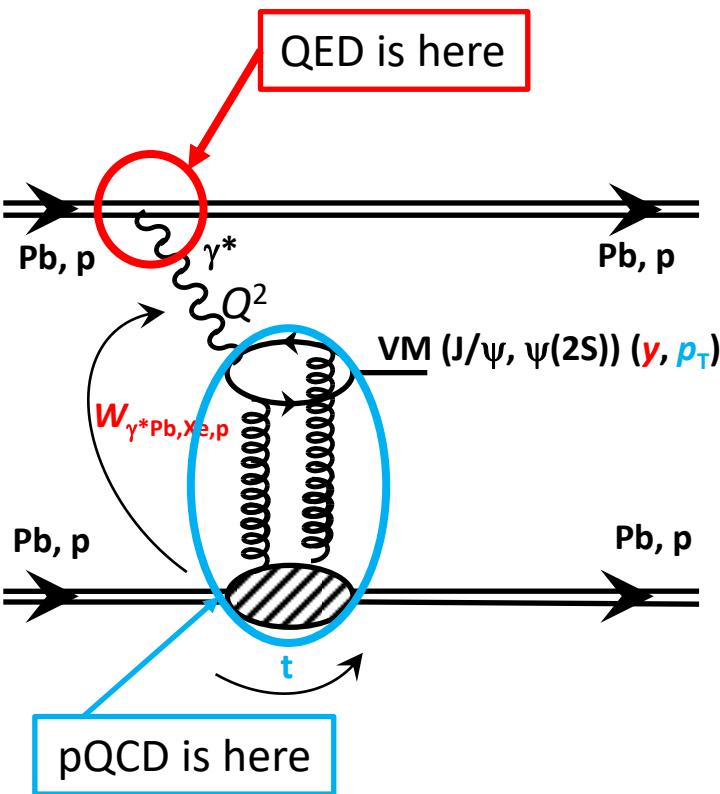
- Summary

# 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  $\sim Z^2$  ( $Z_{\text{Pb}} = 82$ )
  - Large  $\gamma$ -induced interaction cross section
- Clear signature:
  - Low detector activity
  - Rapidity gap(s)

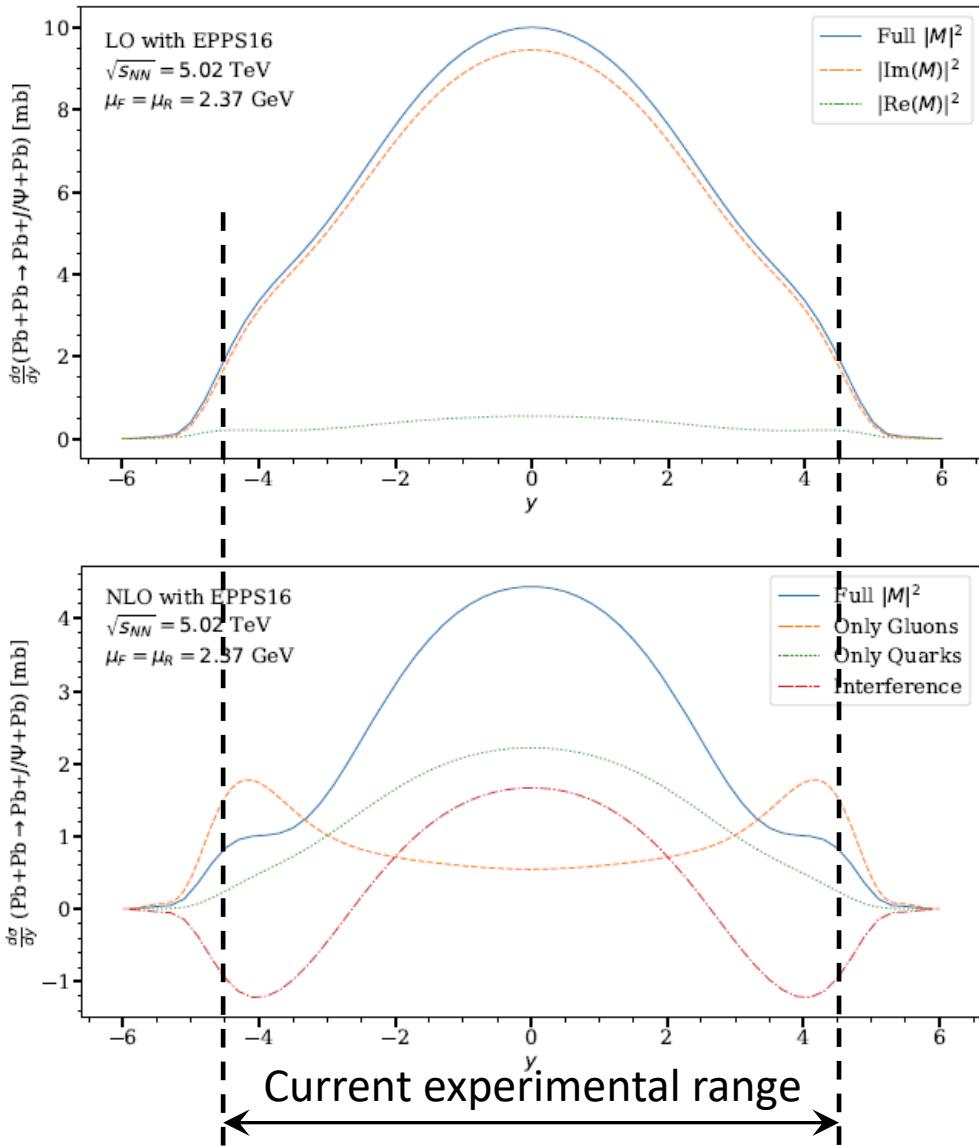


# Photoproduction and main variables



- Photon virtuality  $Q^2 \sim M_{VM}^2 / 4$
- Vector Meson (VM) quantum numbers:
  - $J^{PC} = 1^{--}$
- Bjorken- $x$ : fraction of longitudinal momentum of proton
  - $x_B = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\pm y}$  Warning !!!
  - Photoproduction is sensitive to gluon density evolution at low  $x_B$  Warning !!!
  - There are new NLO calculations
- Photon-target centre-of-mass energy
$$W_{\gamma^* Pb, p}^2 = 2E_{Pb, p} M_{VM} e^{\mp y}$$
- 4-momentum transfer  $t$ 
  - Gluon distribution in the transverse plane  $|t| \sim p_T^2$

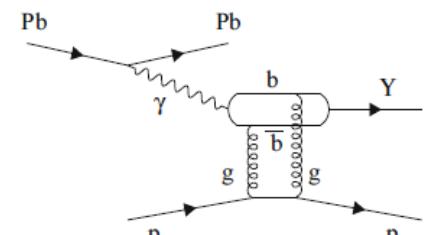
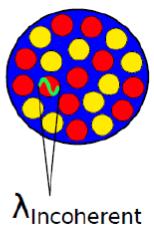
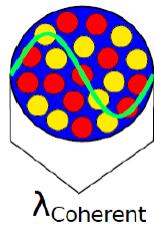
# J/ $\psi$ photoproduction – LO vs NLO



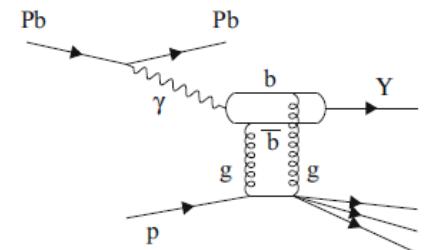
- LO:
  - Gluons
  - Ryskin, Z. Phys. C 57, 89-92 (1993)
$$\frac{d\sigma(\gamma p \rightarrow J/\psi p)}{dt} = |F^{2G}_N(t)|^2 \frac{\alpha_s^2 \Gamma_{ee} J m^3}{3 \alpha_{em}} \pi^3 \left[ x G(x, q^2) \frac{2q^2 |q_t J|^2}{(2q^2)^3} \right]^2$$
- NLO:
  - Quarks play a role
  - Eskola et al., Phys. Rev. C 106 (2022) no. 3, 035202; arXiv:2210.16048
$$\mathcal{M} = \mathcal{M}_G^{\text{LO}} + \mathcal{M}_G^{\text{NLO}} + \mathcal{M}_Q^{\text{NLO}}$$
- Differences:
  - Gluons vs quarks
  - Shape
  - Normalization
  - Scale dependence
  - nPDF dependence
- What is the impact of higher order corrections?
- Be carefull with interpretation!

# $p_T$ signature

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

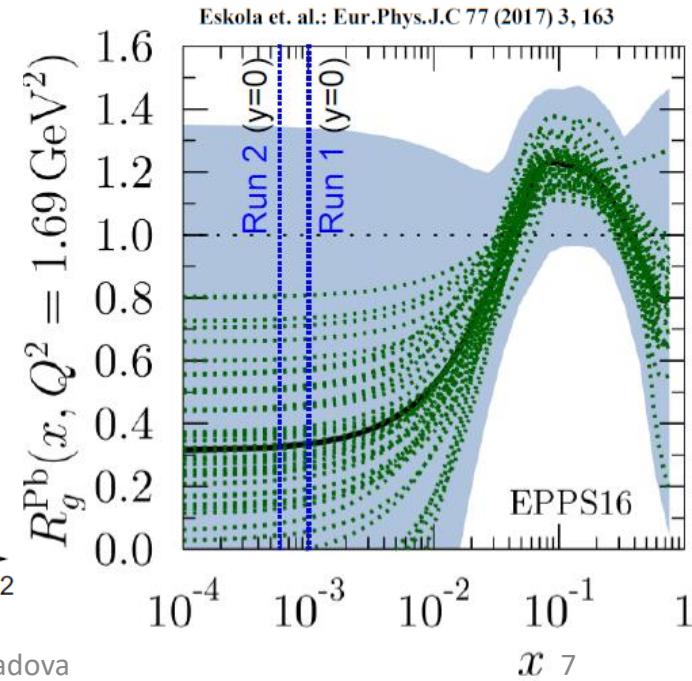
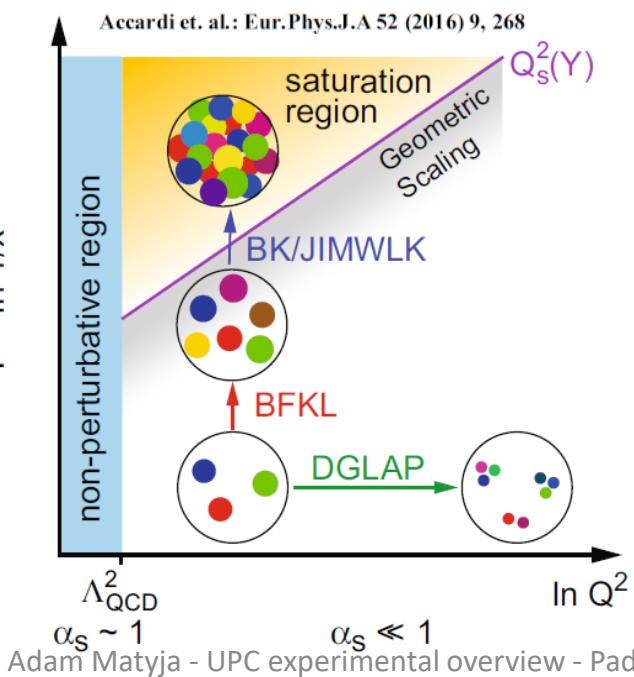
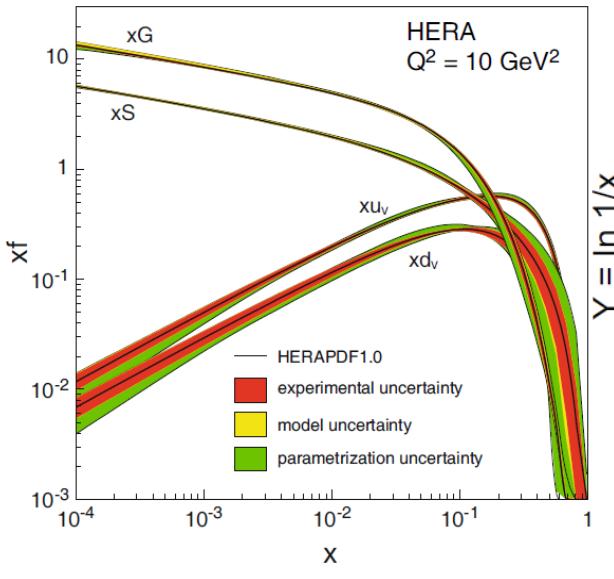


Eur. Phys. J. C (2019) 79:277

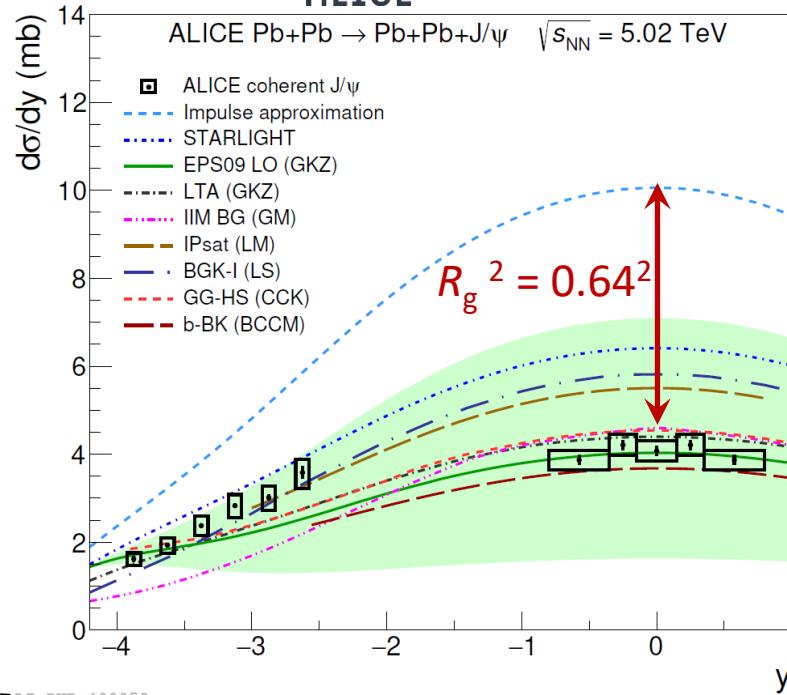
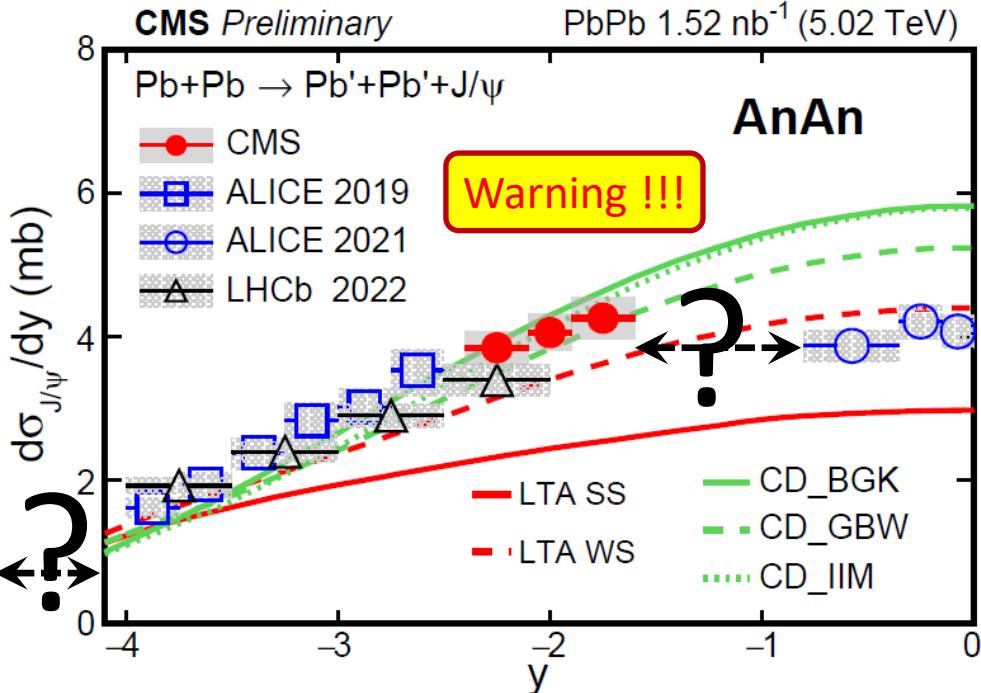


# Motivation

- **Coherent vector meson ( $\rho^0$ ,  $J/\psi$ ,  $\psi(2S)$ ,  $\Upsilon(nS)$ ) 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  $x_B$
- $|t|$ -dependence helps to constrain **transverse gluonic structure** at low  $x_B$
- How well do we model **photon flux**?
- Constrain parameters of **models**
- pQCD test



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



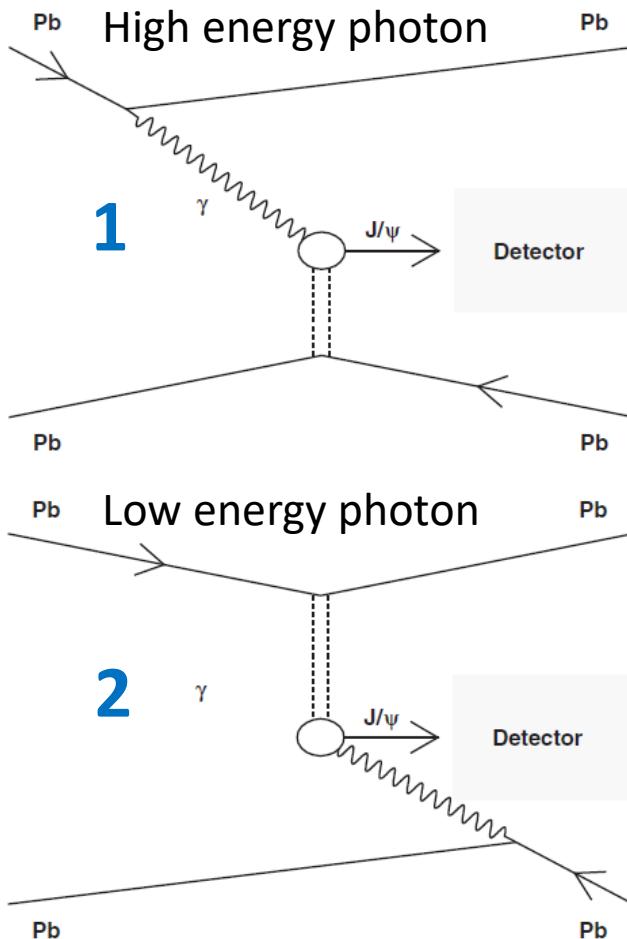
- Forward region (ALICE, CMS, LHCb):  $J/\psi \rightarrow \mu^+\mu^-$
  - Central region (ALICE):  $J/\psi \rightarrow \mu^+\mu^-, e^+e^-$ , pp
  - Nuclear gluon shadowing factor
    - $R_g = 0.64 \pm 0.04$  for  $0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$
  - Compatibility between ALICE, LHCb and 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
- Warning !!!

ALICE: Eur. Phys. J. C 81 (2021) 712  
 LHCb: arXiv:2206.08221 (2022)  
 CMS: PAS HIN-22-002 (2022)

# Rapidity dependance: Ambiguity problem

- Two sources  $\Rightarrow$  two values of  $x_B$

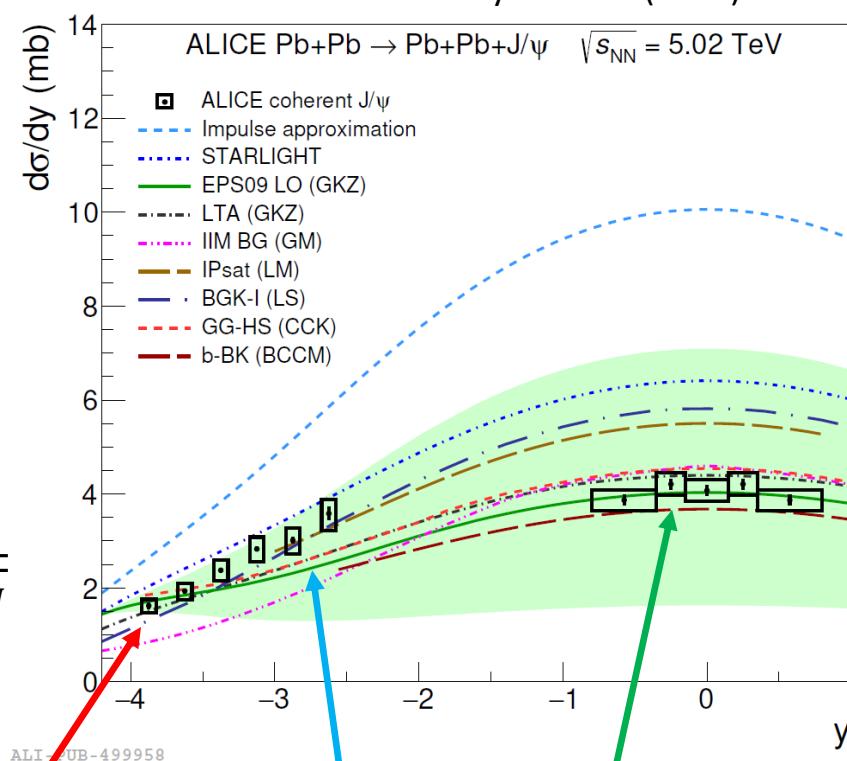
$$\frac{d\sigma_{AA \rightarrow AA' J/\psi}}{dy} = N(\omega_{\gamma 1})\sigma_{\gamma A}(\omega_{\gamma 1}) + N(\omega_{\gamma 2})\sigma_{\gamma A}(\omega_{\gamma 2})$$



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

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

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



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

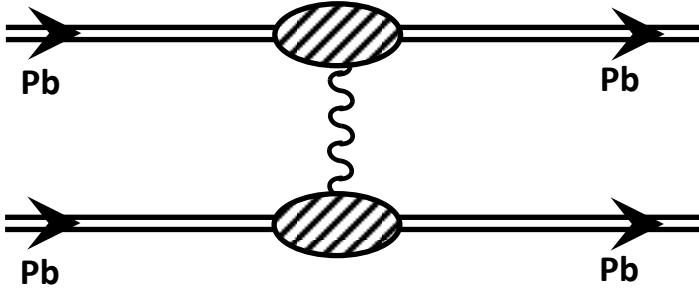
1: 40 %  $x_B \sim 5.1 \times 10^{-4}$   
 2: 60 %  $x_B \sim 0.7 \times 10^{-2}$

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

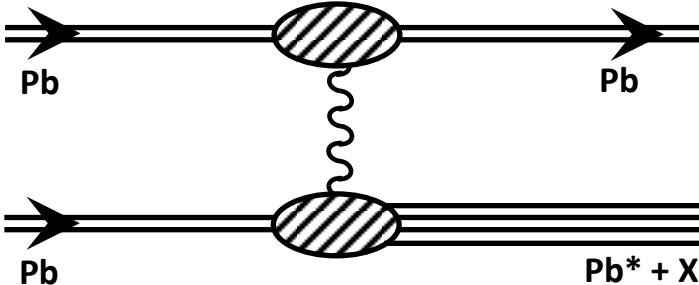
To disentangle both contributions we need to measure the same process with EMD or in peripheral collisions

# Impact parameter dependence

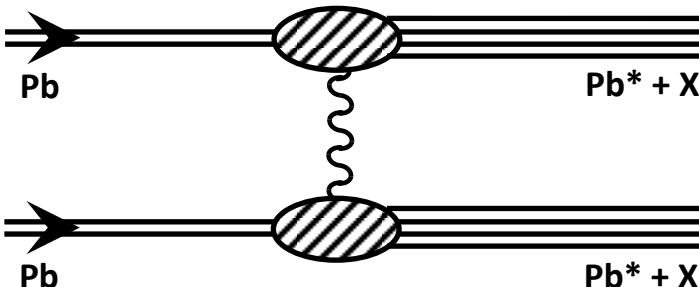
No breakup (0n0n)



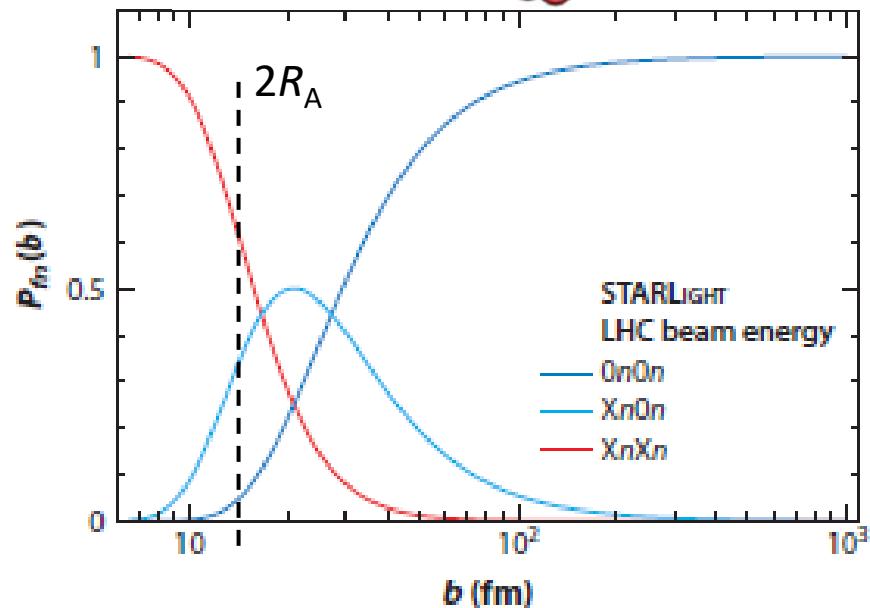
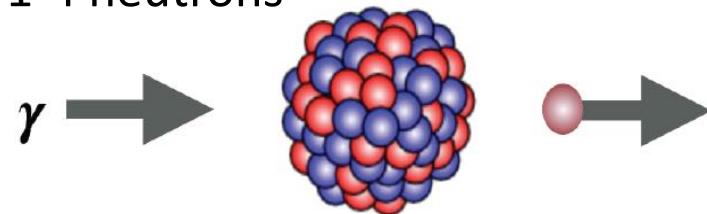
Single breakup ( $Xn0n + 0nXn$ )



Double breakup ( $XnXn$ )



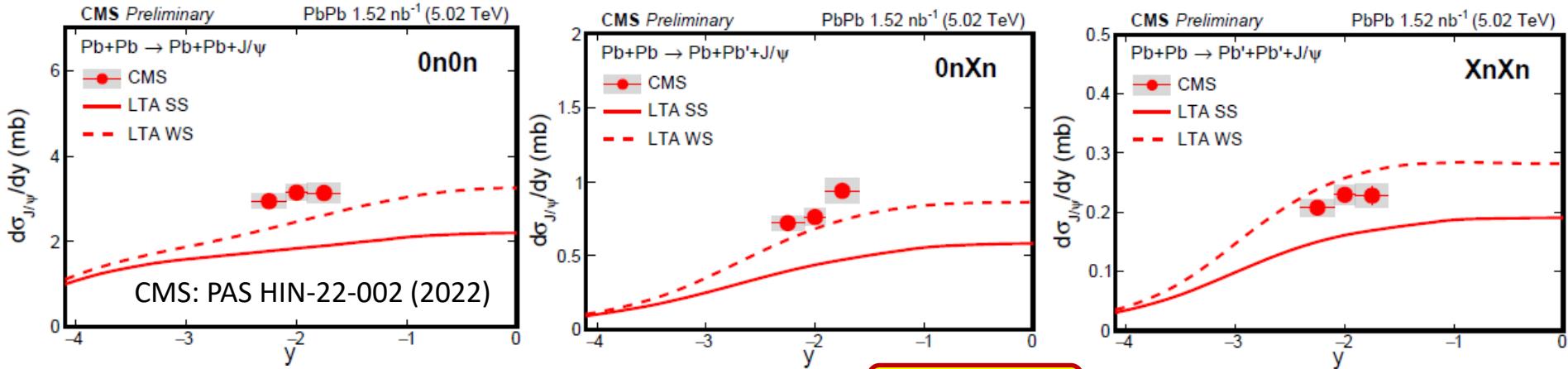
- Excitation of the nuclei possible through the secondary photon exchange  
⇒ Giant dipole resonance
- All protons vibrating against all neutrons → Knocks out 1-4 neutrons



UPC event classifier: 0n0n, 0nXn, XnXn  
→ via electromagnetic dissociation (EMD)

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

# Coherent J/ $\psi$ in nuclear break up classes



- Difficulties in description by theory Warning !!!
- OnOn class has the largest statistics, XnXn – the lowest one
- Cross sections in nuclear breakup classes can be used to calculate photo-nuclear cross sections Guzey et al., EPJC 74 (2014) 2942
  - What is measured is burdened with uncertainties
  - Photon fluxes are taken from theory, but with uncertainties Warning !!!

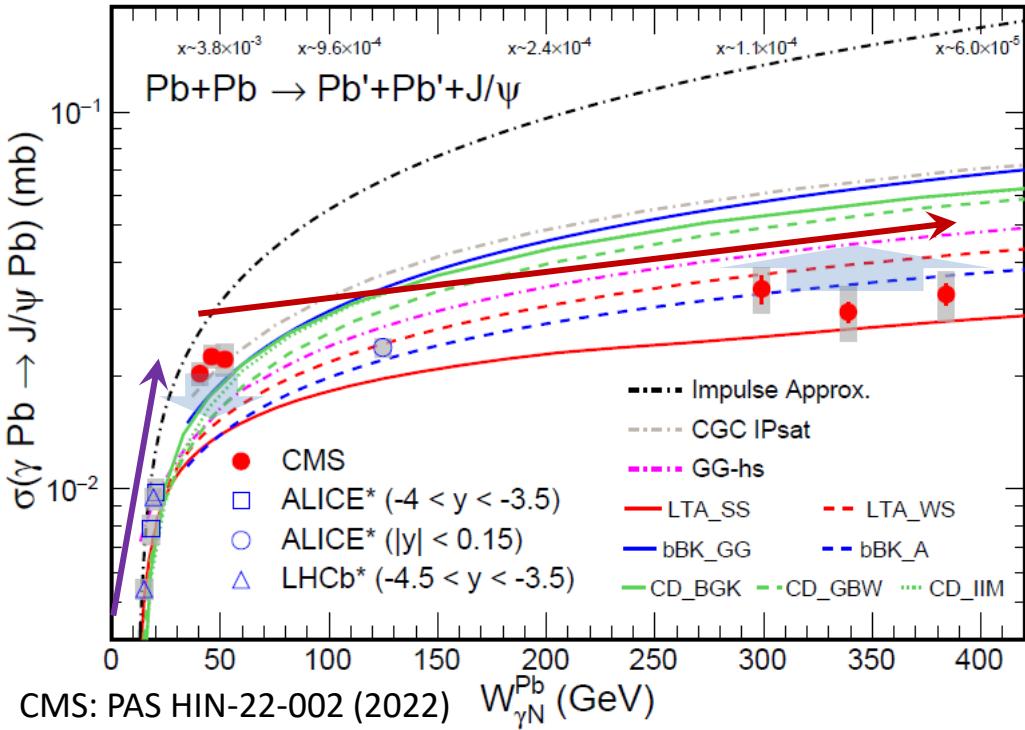
$$\frac{d\sigma^{0n0n}_{AA \rightarrow AA' J/\psi}}{dy} = N^{0n0n}(\omega_{\gamma 1}) \cdot \sigma_{\gamma A}(\omega_{\gamma 1}) + N^{0n0n}(\omega_{\gamma 2}) \cdot \sigma_{\gamma A}(\omega_{\gamma 2})$$

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

# Photo nuclear J/ $\psi$ cross section

CMS Preliminary

PbPb 1.52 nb<sup>-1</sup> (5.02 TeV)



CMS: PAS HIN-22-002 (2022)

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

- ALICE and LHCb data points are averaged over rapidity and only one solution is presented

**Warning !!!**

- Experimental uncertainty is highly correlated across photo-nuclear energy  $W_{\gamma N}$ 
  - Any change (photon fluxes, ...) on one side changes the other side

**Warning !!!**

# Coherent J/ $\psi$ in non UPC Pb-Pb

- Low  $p_T$  ( $< 0.3 \text{ GeV}/c$ ) and  $R_{AA}$  excess 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 it the same for **other VMs?**

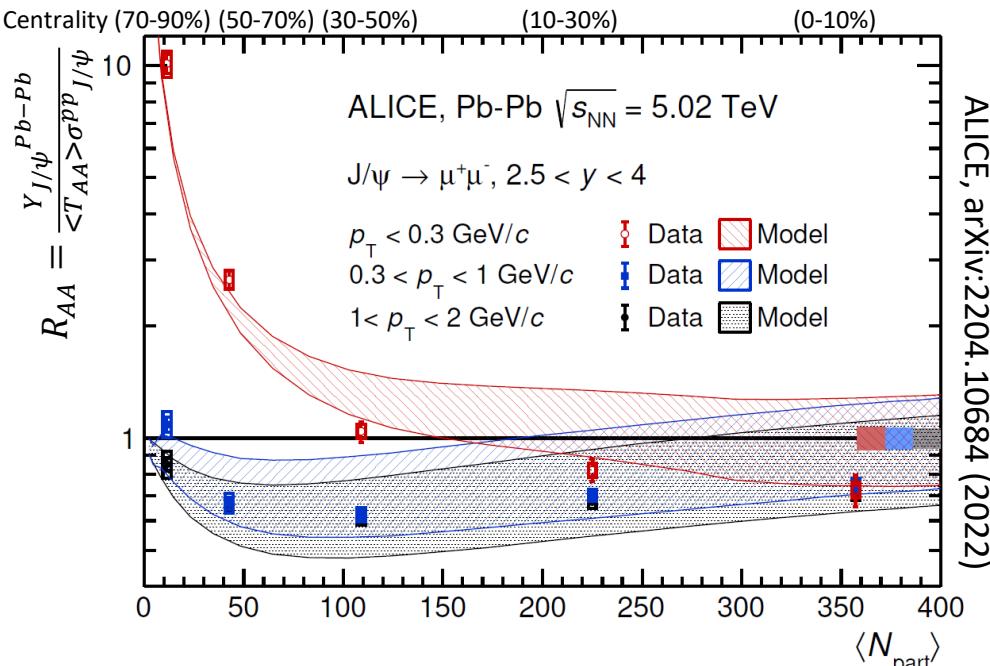
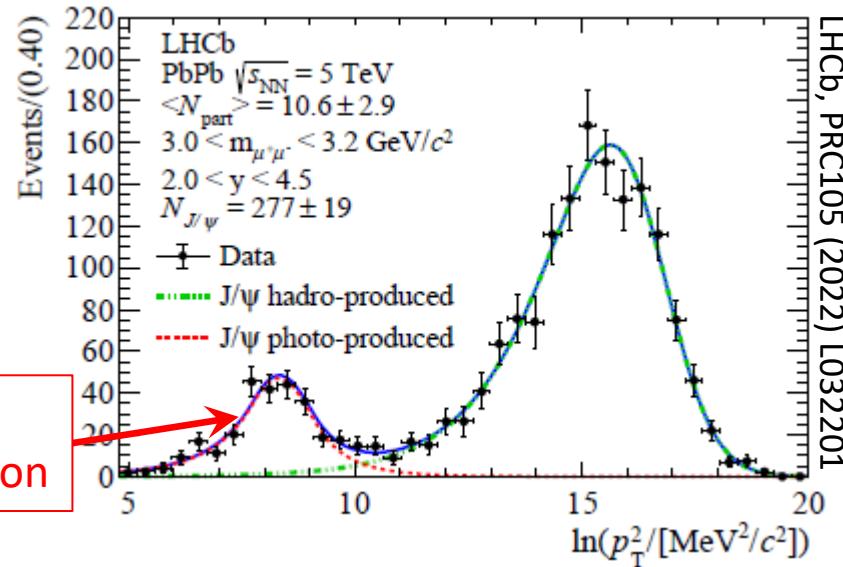
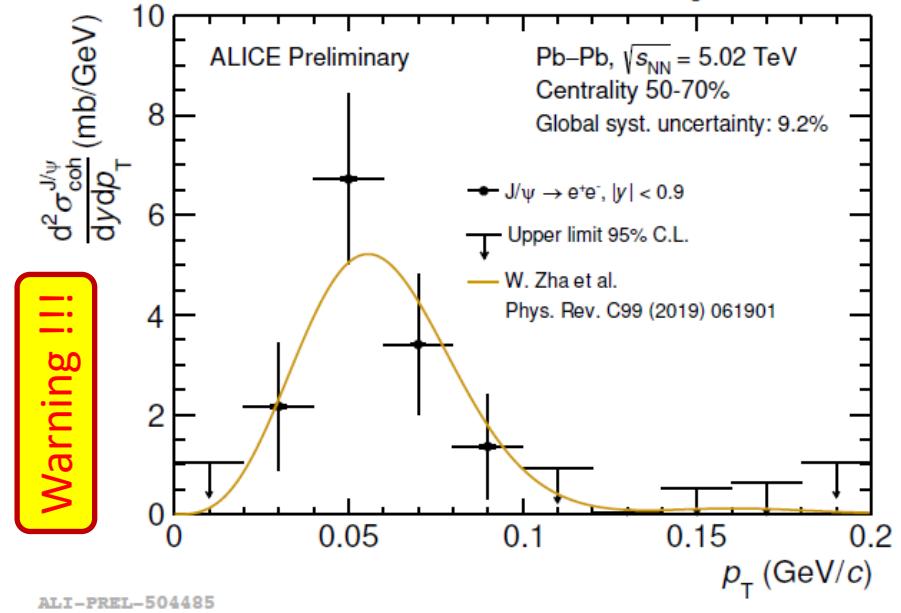


Photo-production



Warning !!!



# $\psi(2S)$ 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  $\text{J}/\psi$  result

- Good agreement of **models with shadowing** (EPS09 LO, LTA, Guzey et al.)

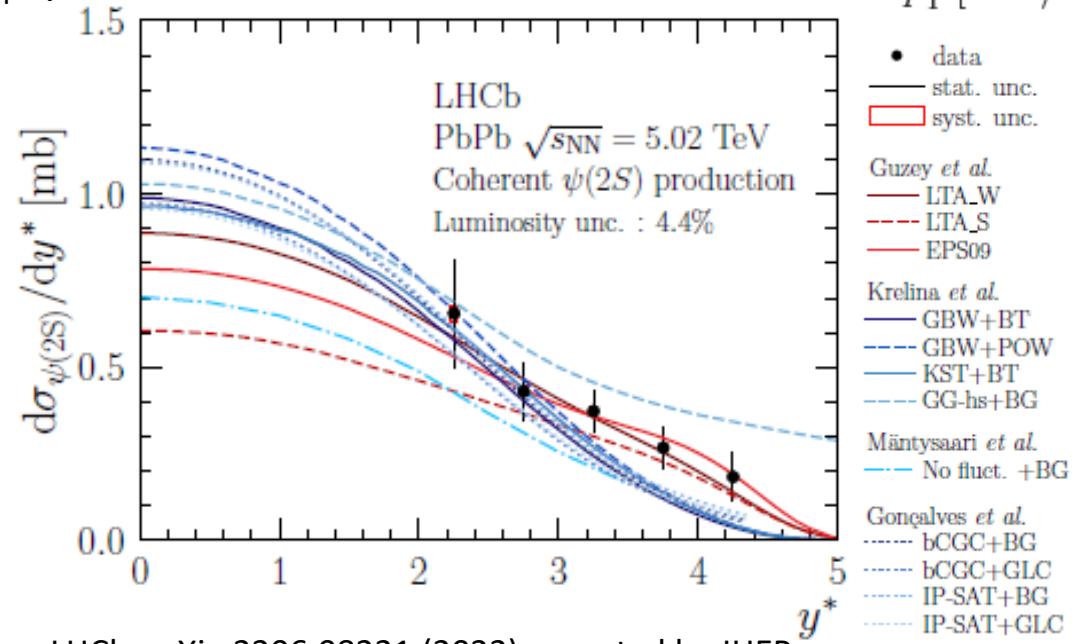
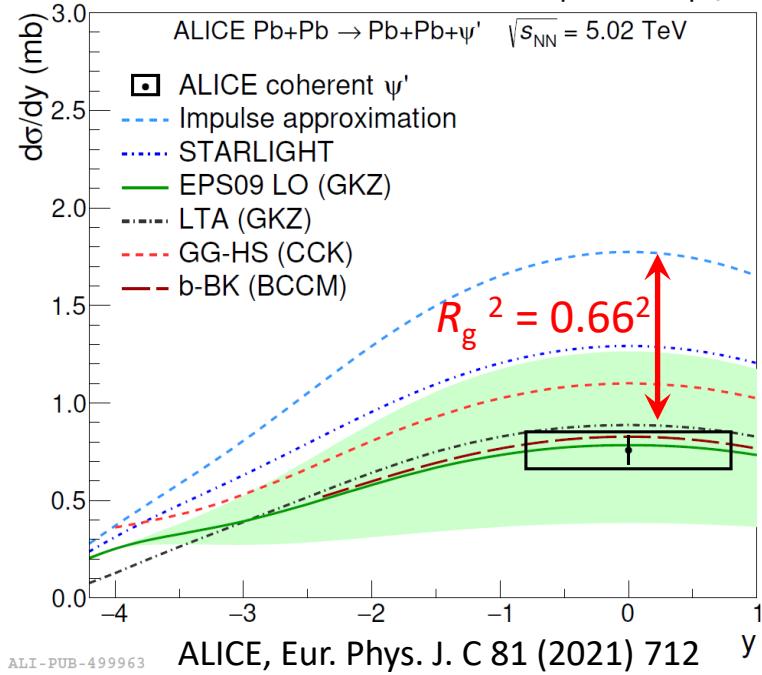
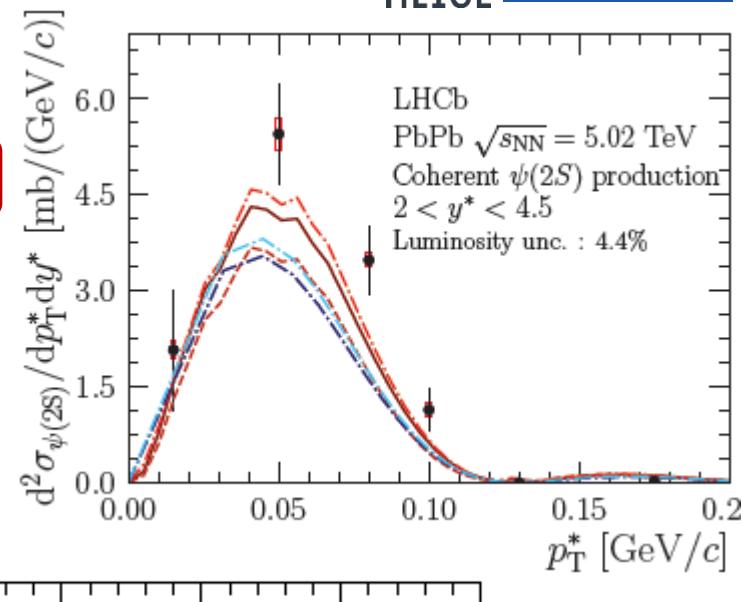
- Good agreement of ALICE data with model BCCM (with saturation)

- Other models over/under-predict ALICE/LHCb data

- First measurement of  $\text{J}/\psi$  and  $\psi(2S)$   $p_T$  spectra @ LHCb**

More data points needed!

Warning !!!



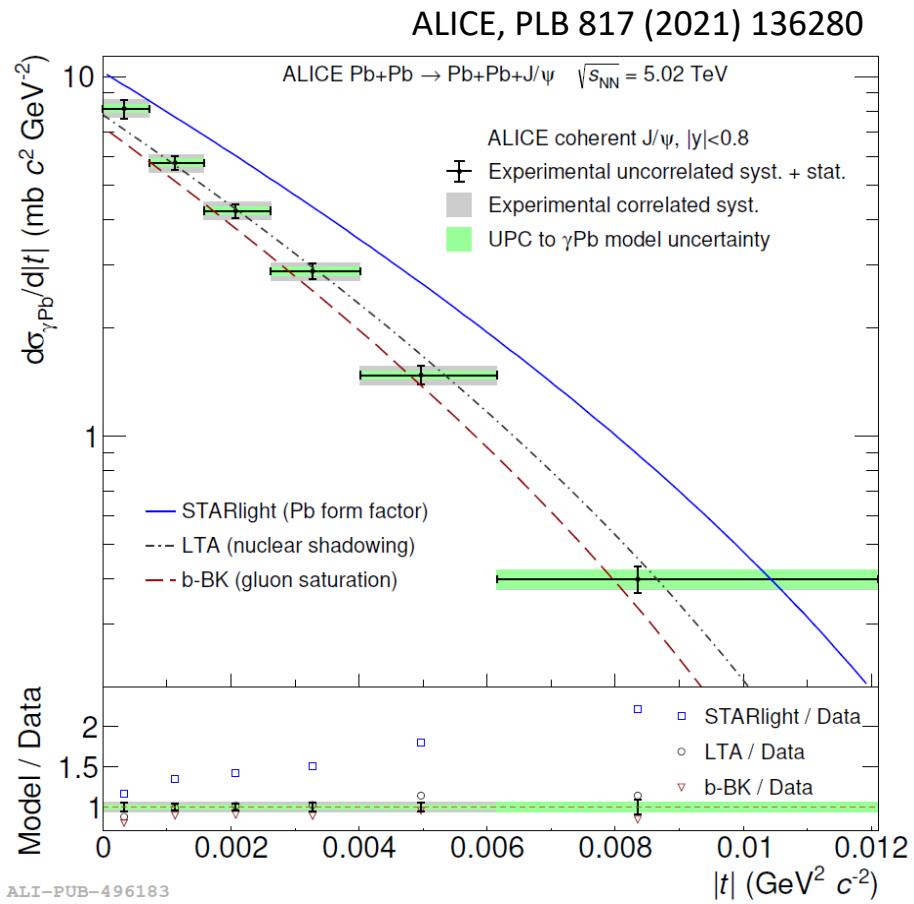
# J/ $\psi$ in Pb-Pb at $\sqrt{s}_{NN} = 5.02$ TeV

- Central region
  - $J/\psi \rightarrow \mu^+ \mu^-$
- $|t|$  dependence** is sensitive to spatial gluon distribution
- Bayesian and SVD unfolding used to transform  $p_T^2 \rightarrow |t|$
- Transition from UPC to photonuclear cross section

$$\frac{d^2\sigma_{J/\psi}^{coh}}{dydp_T^2} \Big|_{y=0} = 2n_{\gamma Pb}(y=0) \frac{d\sigma_{\gamma Pb}}{d|t|}$$

Photon flux

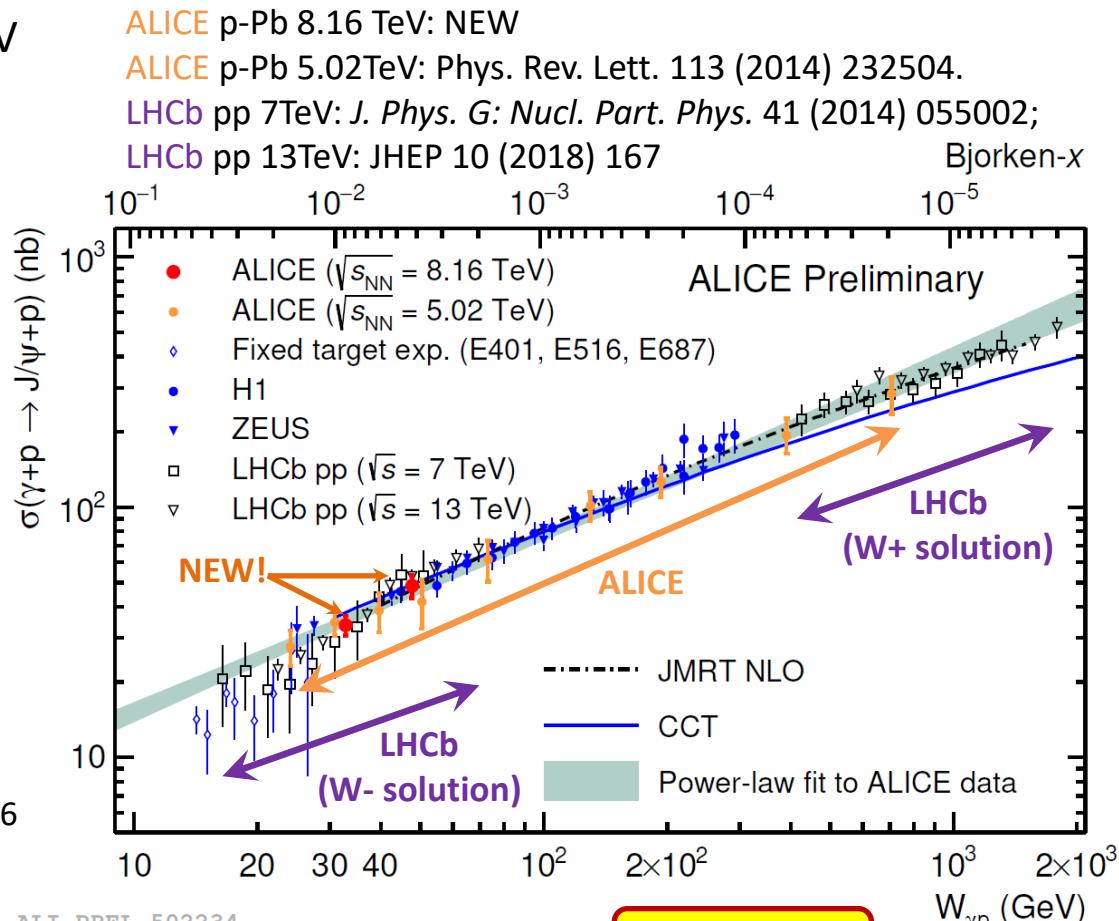
- Comparison to models:
    - STARlight does not contain explicitly shadowing – do not describe shape nor magnitude
    - LTA contains nuclear shadowing – agrees with data
    - b-BK based on gluon saturation – agrees with data
- ⇒ Reflects effects of QCD dynamics at small  $x_B \sim 10^{-3}$



# Photonuclear J/ $\psi$ cross section

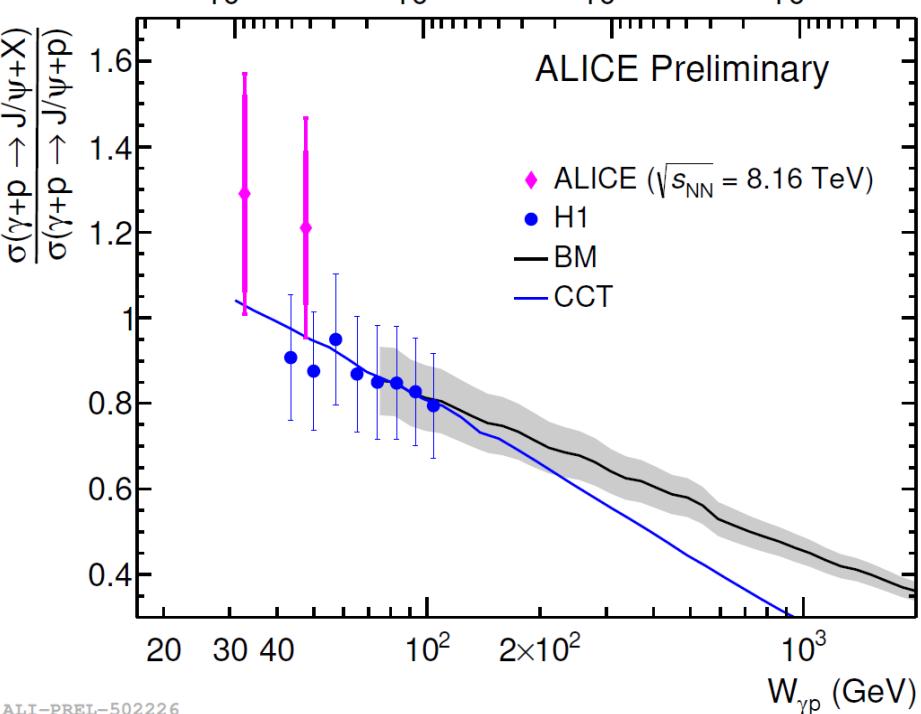
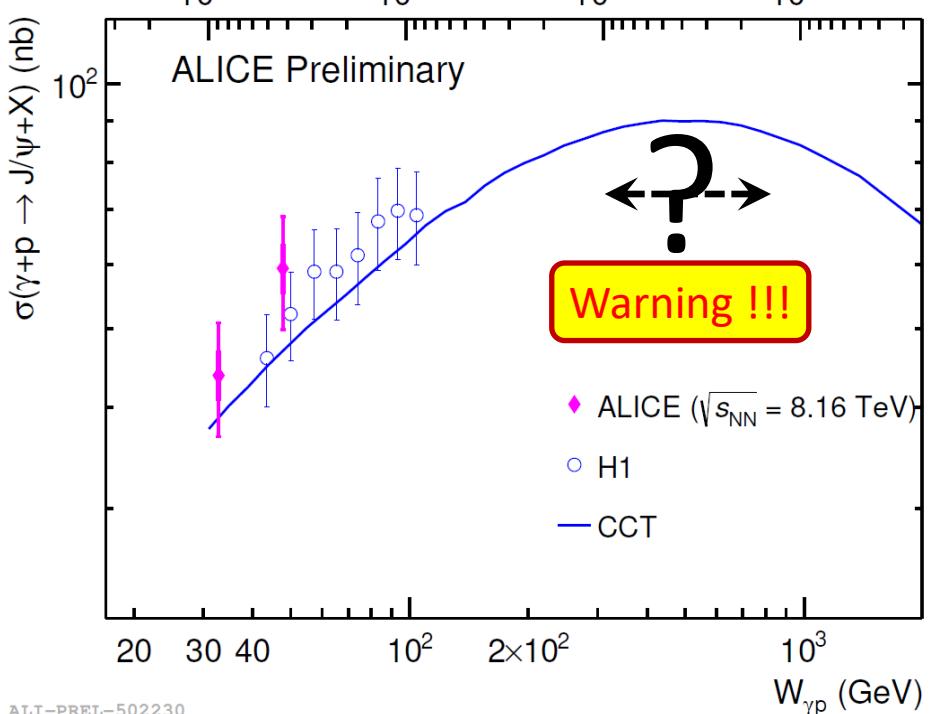


- Gluon distribution at HERA energies follows power law at low  $x_B$   
 $\Rightarrow$  similar trend in  $W_{\gamma p}$
- Exclusive J/ $\psi$  cross section** at LHC follows HERA trend so far
- ALICE: p-Pb at  $\sqrt{s_{NN}} = 5.02$  and 8.16 TeV  
LHCb: pp at  $\sqrt{s} = 7$  and 13 TeV
- Power law 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 an energy dependent hot spot model
- Probe wide region  $x_B \sim 10^{-2} - 10^{-6}$



No clear indication of gluon saturation at low  $x_B$

# Dissociative J/ $\psi$ in p-Pb at $\sqrt{s}_{NN} = 8.16$ TeV

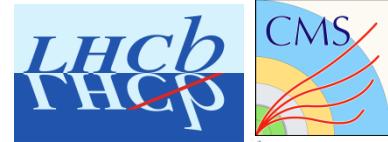


ALI-PREL-502230

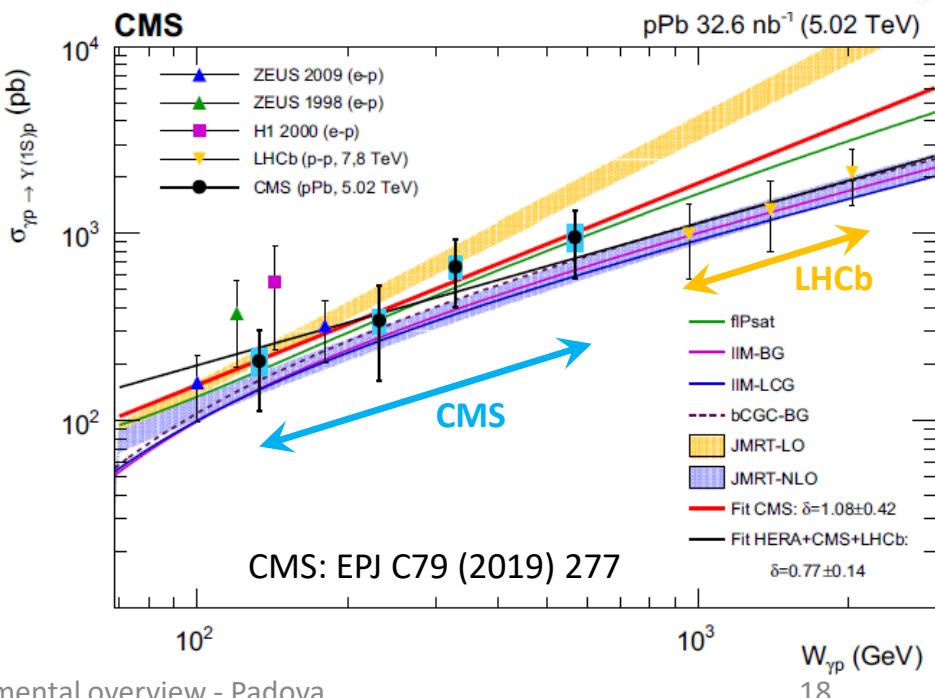
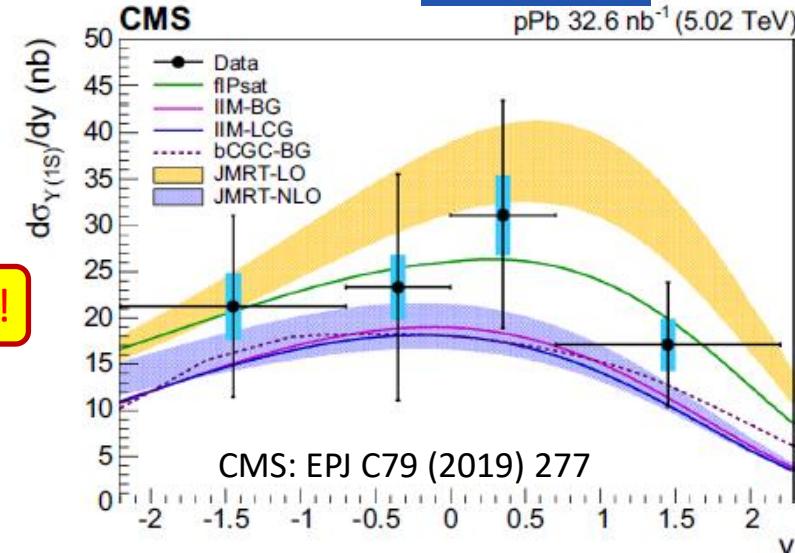
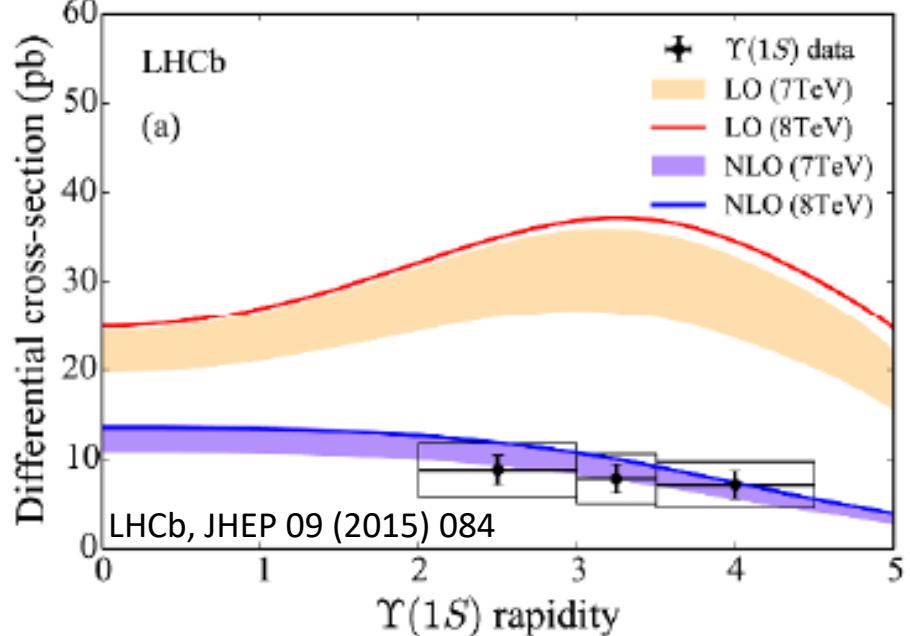
ALI-PREL-50226

- First measurement of the dissociative cross section at the LHC
- Energy dependent dissociative J/ $\psi$  cross section ( $x_B \sim (0.5, 2) \times 10^{-2}$ )
- Agreement with HERA results
- CCT model with saturation agrees with data
  - Predicted maximum at  $W_{\gamma p} \sim 500$  GeV to be checked in Run 3
- BM: perturbative JIMWLK evolution with parameters constrained to H1 data to be checked in Run 3

# $\Upsilon(nS)$ in p-Pb and pp

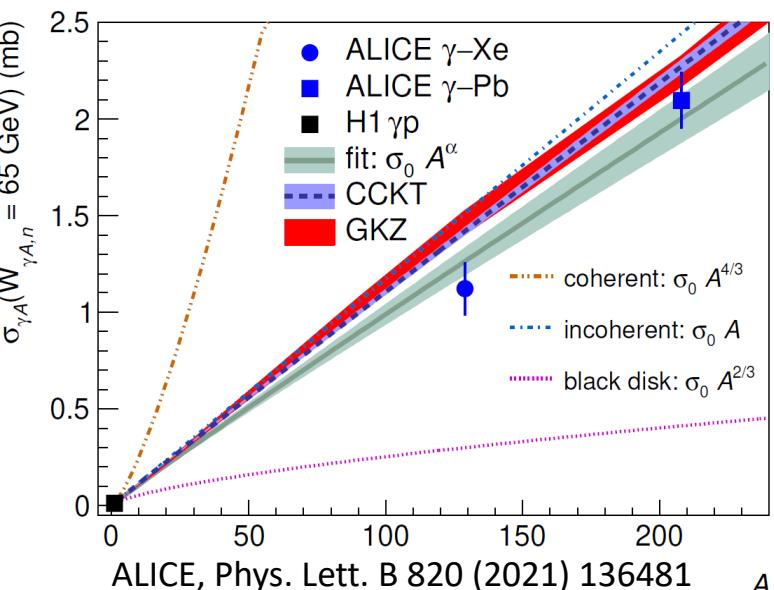
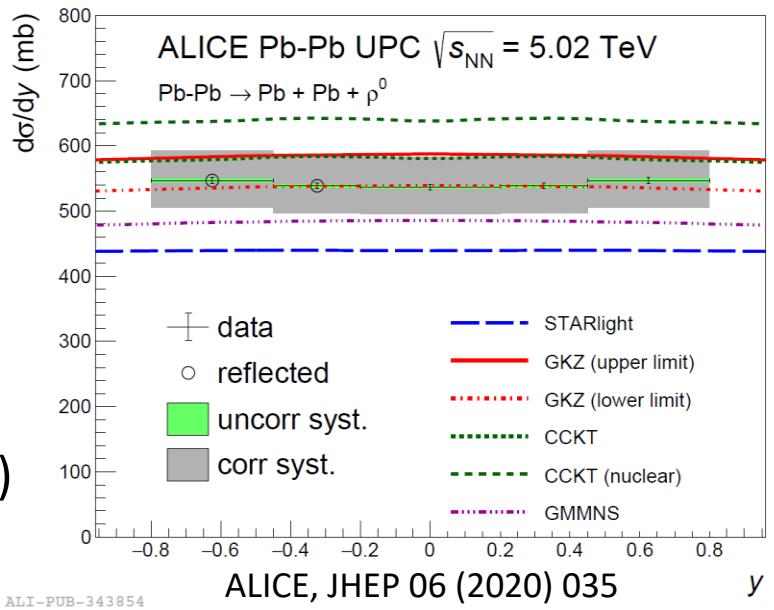
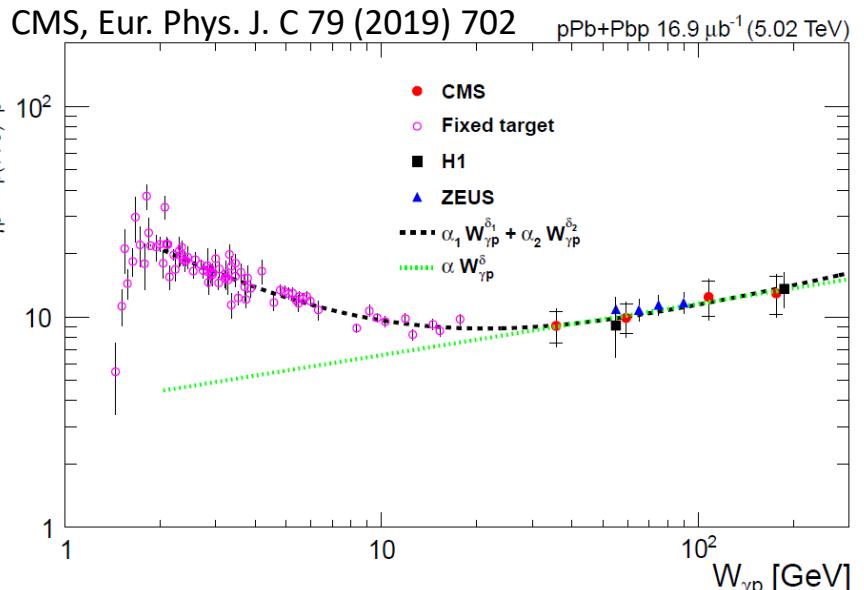


- $\Upsilon(nS) \rightarrow \mu^+ \mu^-$
- **Cross section** measured in central (CMS) and forward (LHCb) region
- **NLO** calculations **favored** by LHCb data
- **Saturation** models consistent with CMS and LHCb
- Fit to CMS:  $\delta = 1.08 \pm 0.42$
- Warning !!!
- ⇒ Consistent with ZEUS:  $\delta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

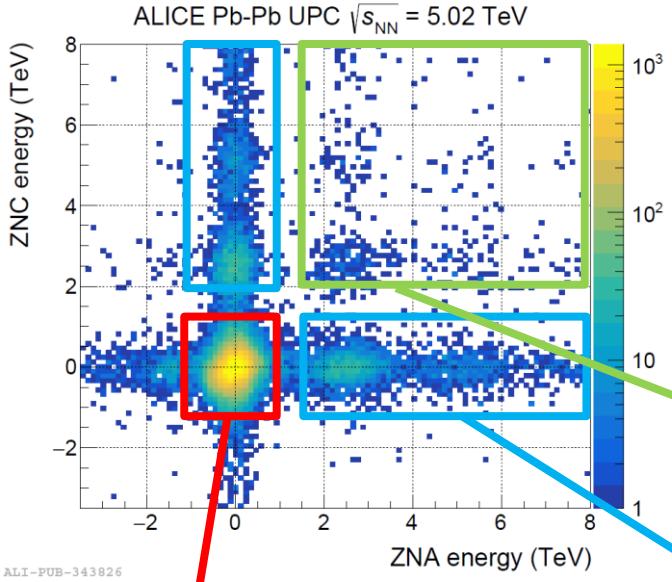


# $\rho^0$ photoproduction

- Large cross section ( $\sim 550$  mb) described by models
- Measurement in nuclear **breakup classes** (0n0n, OnXn, XnXn) to distinguish  $b$  dependence
- $\sigma(\gamma A \rightarrow \rho^0 A) \sim A^\alpha$  with a slope  
 $\alpha = 0.96 \pm 0.02^{\text{sy}}$   
 $\Rightarrow$  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 collisions

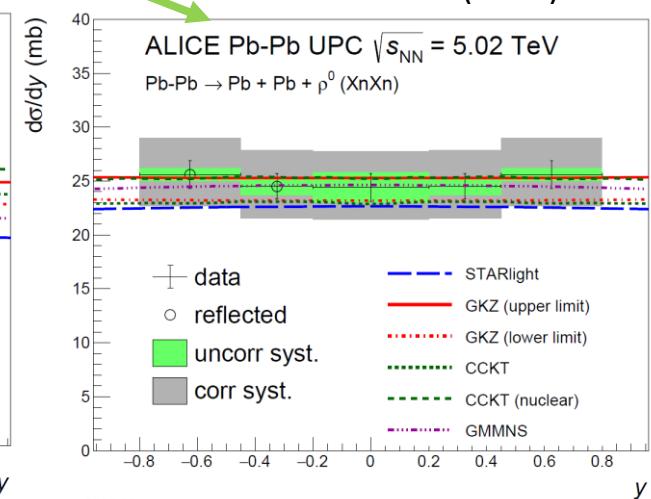
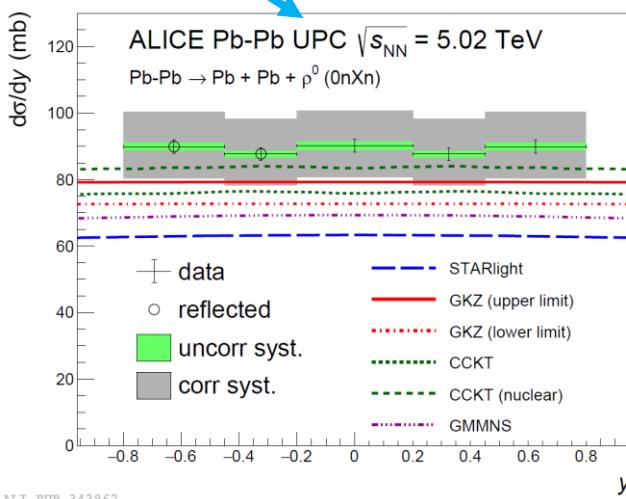
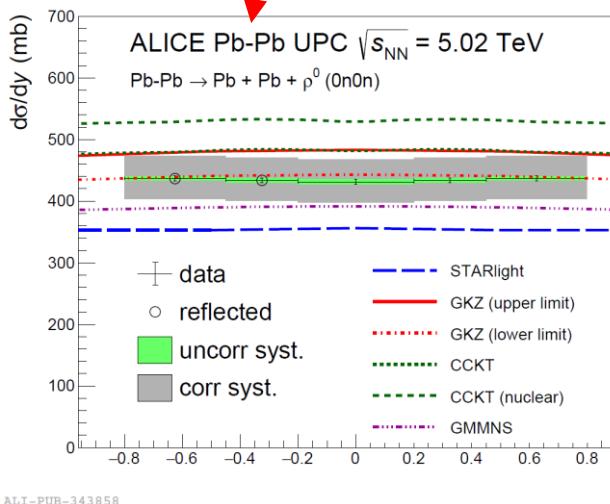


# $\rho^0$ in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV



- Impact parameter dependence via ZDC selection in 3 classes: On0n, OnXn, XnXn
- Comparisons with models
  - GKZ (nuclear shadowing) gives the best description
  - CCKT (saturation) is slightly worse
  - STARlight and GMMNS (saturation) underestimate
  - Worst description for OnXn class
- Test of photon flux description

**Warning !!!**



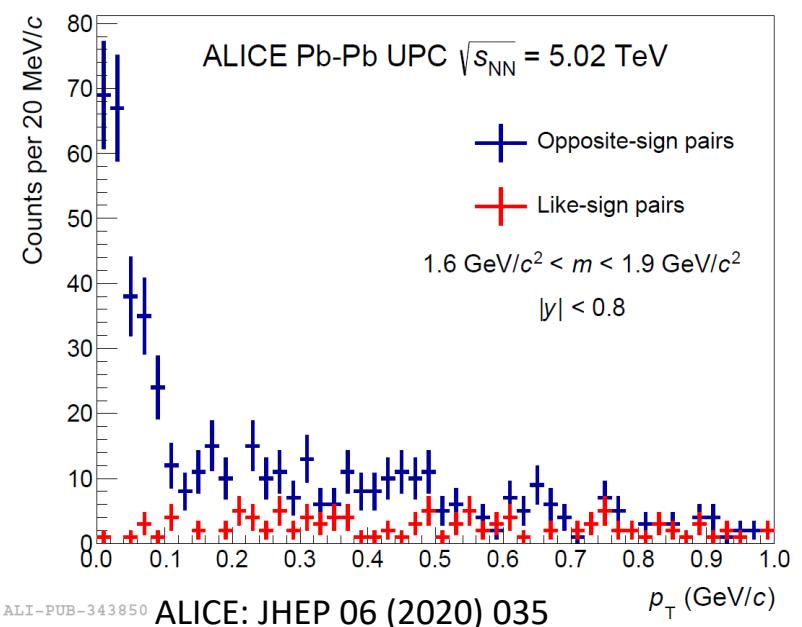
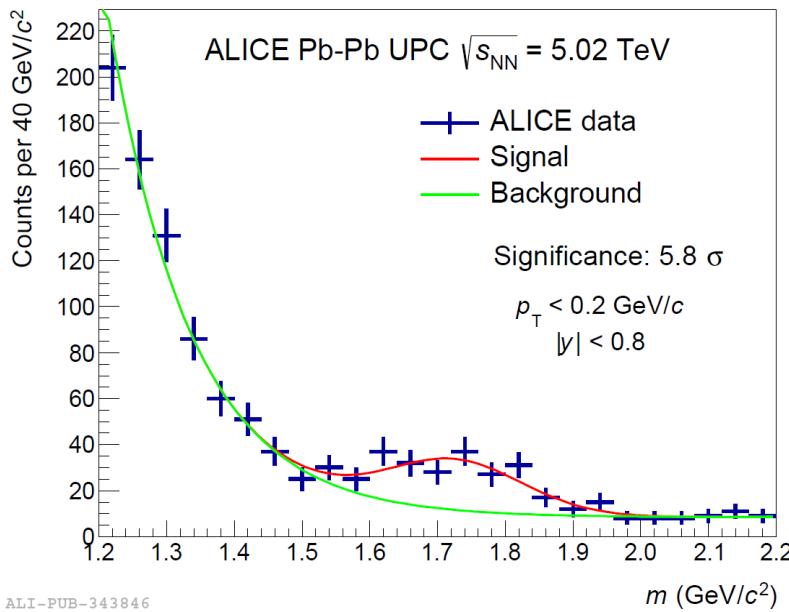
# $\rho'$ in Pb-Pb at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

- Resonance-like structure  $M^{\pi\pi} \sim 1.7 \text{ GeV}/c^2$

- Significance of  $4.5 \sigma$
- Seen also by STAR, ZEUS, H1
- Most probably  $\rho_3(1690)$  with angular momentum  $J = 3$
- More data from Run3 + Run4 needed Warning !!!



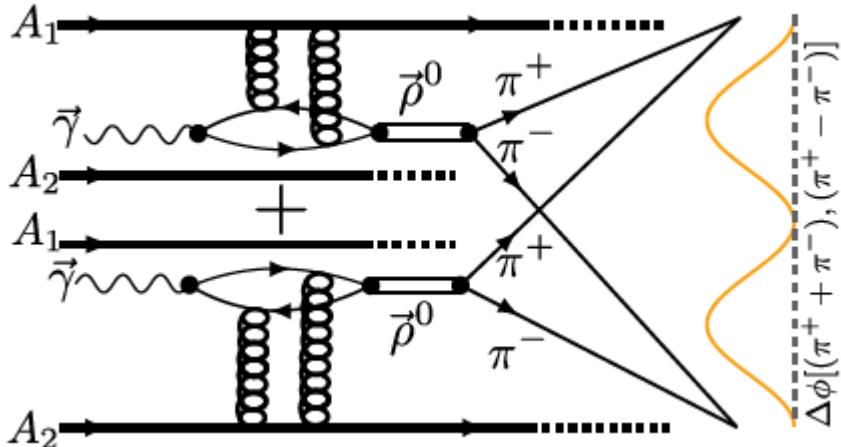
$$\frac{dN_{\pi\pi}}{dm} = P_1 \cdot \exp(-P_2 \cdot (m - 1.2 \text{ GeV}/c^2)) + P_3 + P_4 \cdot \exp(-(m - M_x)^2/\Gamma_x^2)$$



# Nuclear radius and neutron skin

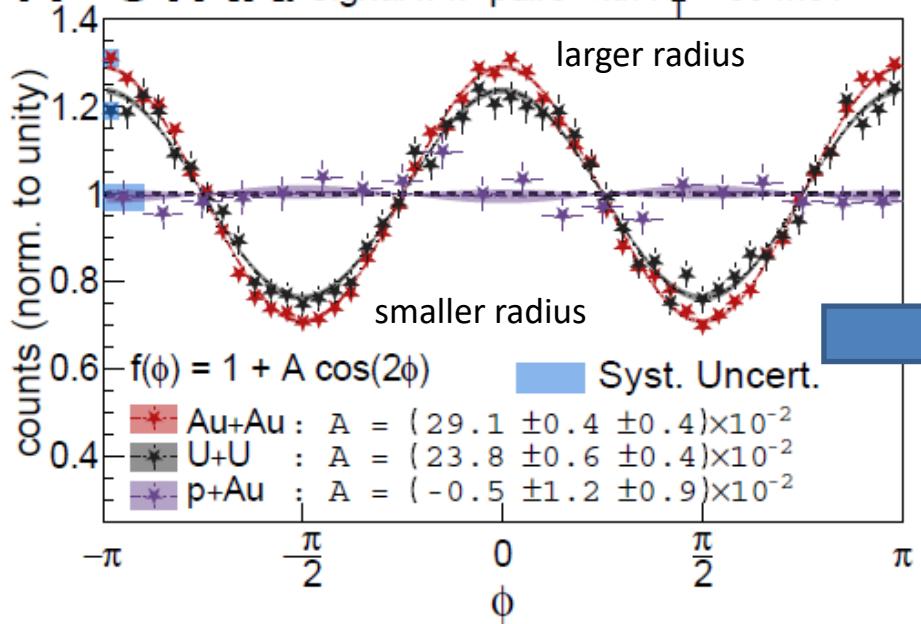


## A+A Collision



arXiv:2204.01625 (2022)

## A STAR: Signal $\pi^+\pi^-$ pairs with $P_T < 60$ MeV



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

Radius (which is 1 fm too large):

$$\begin{aligned} - R_{\text{Au}} &= 6.53 \pm 0.06 \text{ fm} \\ - R_{\text{U}} &= 7.29 \pm 0.08 \text{ fm} \end{aligned}$$

Precision neutron skin measurements:

$$\begin{aligned} - S_{\text{Au}} &= 0.17 \pm 0.03^{\text{stat}} \pm 0.08^{\text{syst}} \text{ fm} \\ - S_{\text{U}} &= 0.44 \pm 0.05^{\text{stat}} \pm 0.08^{\text{syst}} \text{ fm} \end{aligned}$$

What are values for Pb?

Warning !!!

# Summary

- Nuclear gluon structure probed with  $\rho^0$ ,  $J/\psi$  and  $\psi(2S)$  at  $x_B \sim 10^{-3} - 10^{-5}$ 
  - Measurements signal large nuclear gluon shadowing effects  $R_g \sim 0.65$  at  $x_B \sim 10^{-3}$
  - Models with shadowing or saturation describe data the best
  - No model currently describe the rapidity dependence
- Proton gluon structure probed with  $\rho^0$ ,  $J/\psi$  and  $\Upsilon(nS)$  at  $x_B \sim 10^{-2} - 10^{-5}$ 
  - More (and precise) data needed to discriminate between models
- Photoproduction measured towards more central collisions
- Nuclear radius and skin measured for Au and U
- We are limited by statistics and looking forward for Run 3 and beyond results

# Backup

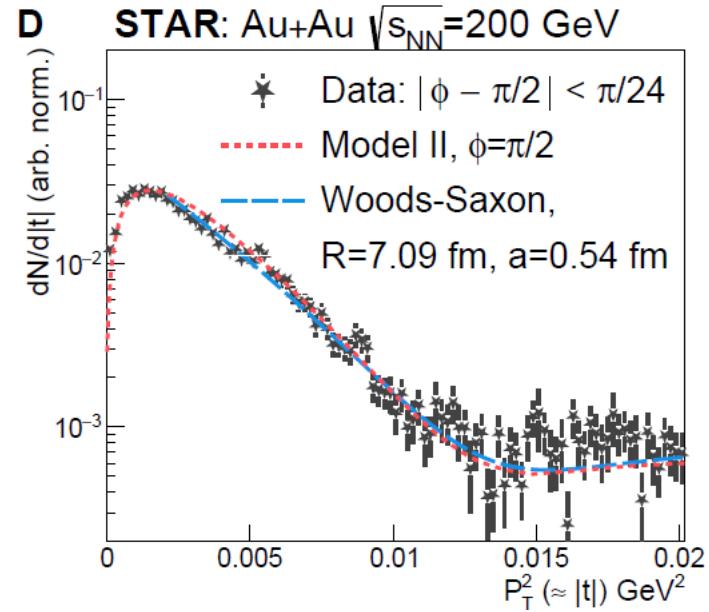
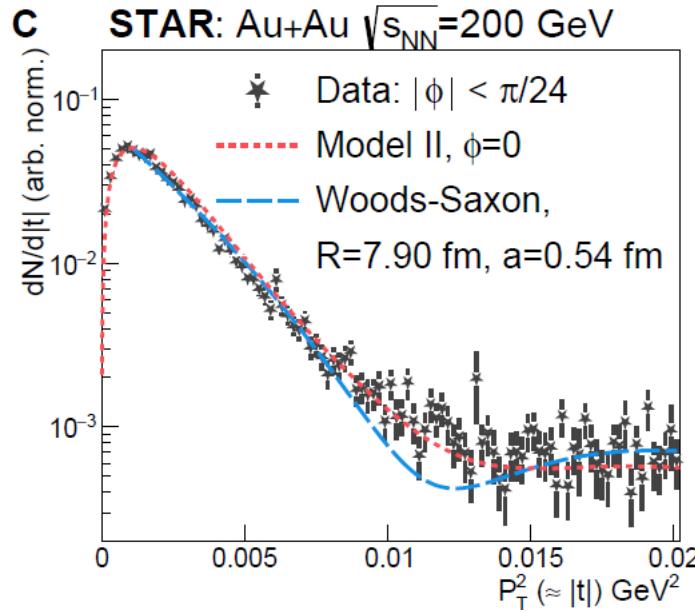
- Extracted radius appeared to be too large for 1 fm
- Extracted radius is for the case of maximum interference ( $\phi \sim 0$ ) is larger than case with minimum interference ( $\phi \sim \pi/2$ )

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

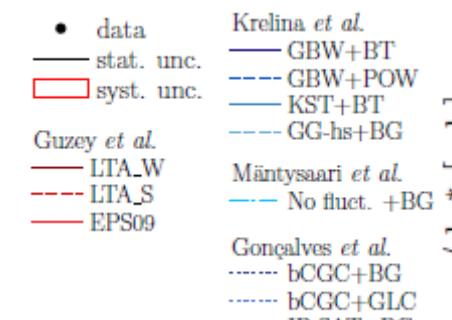
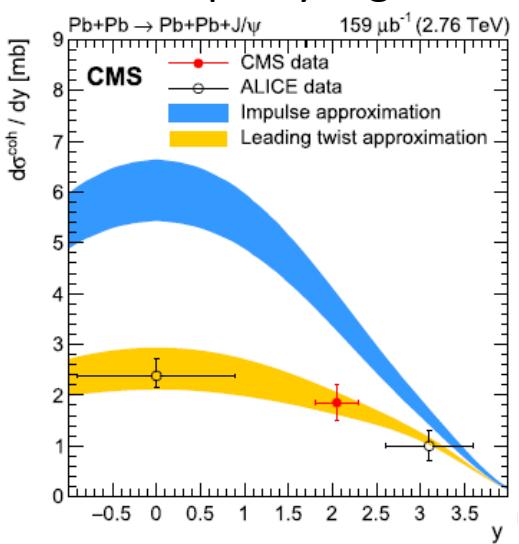
R – nuclear radius

a – surface thickness

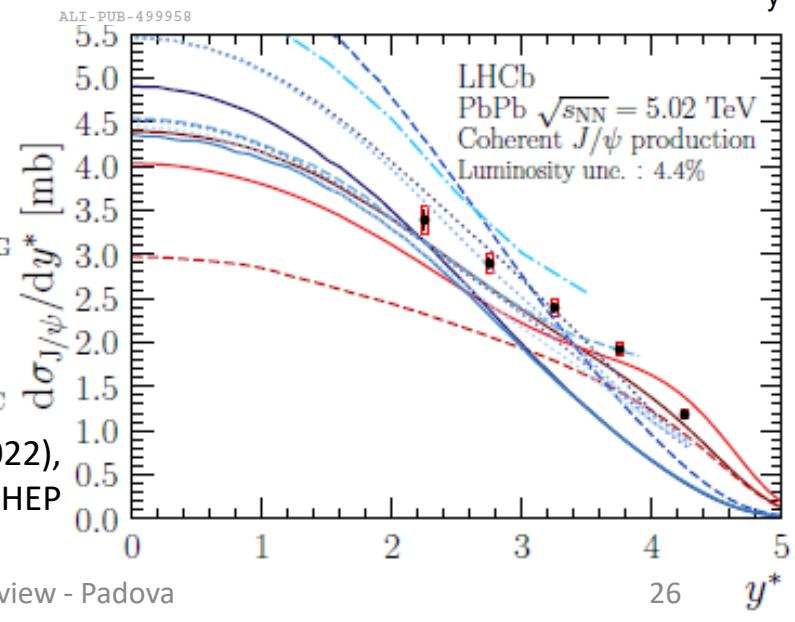
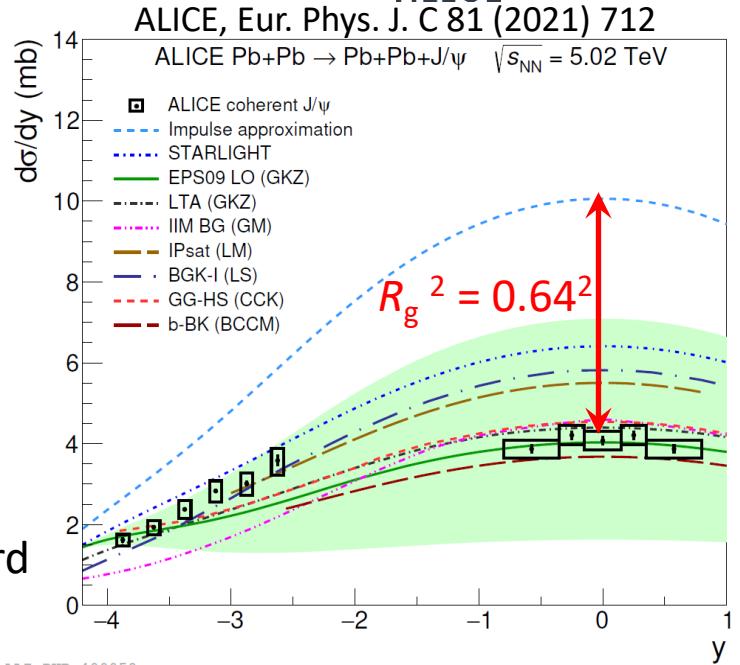
$\rho_0 = 3A/(4\pi R^3)$  - normalization



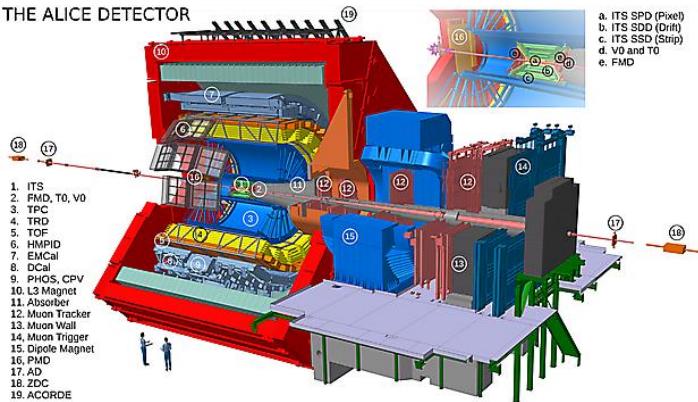
- **Forward region (ALICE, CMS, LHCb):**
  - $J/\psi \rightarrow \mu^+ \mu^-$
- **Central region (ALICE):**
  - $J/\psi \rightarrow \mu^+ \mu^-, e^+ e^-, pp$
- **Nuclear gluon shadowing factor**  
 $R_g = 0.64 \pm 0.04$  for  $0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$
- **Compatibility** between 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



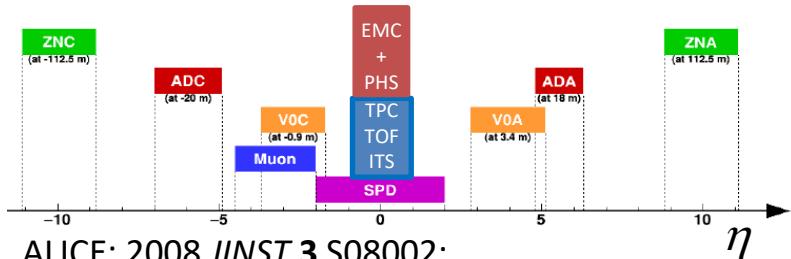
LHCb, arXiv:2206.08221 (2022),  
accepted by JHEP



# Experimental apparatus



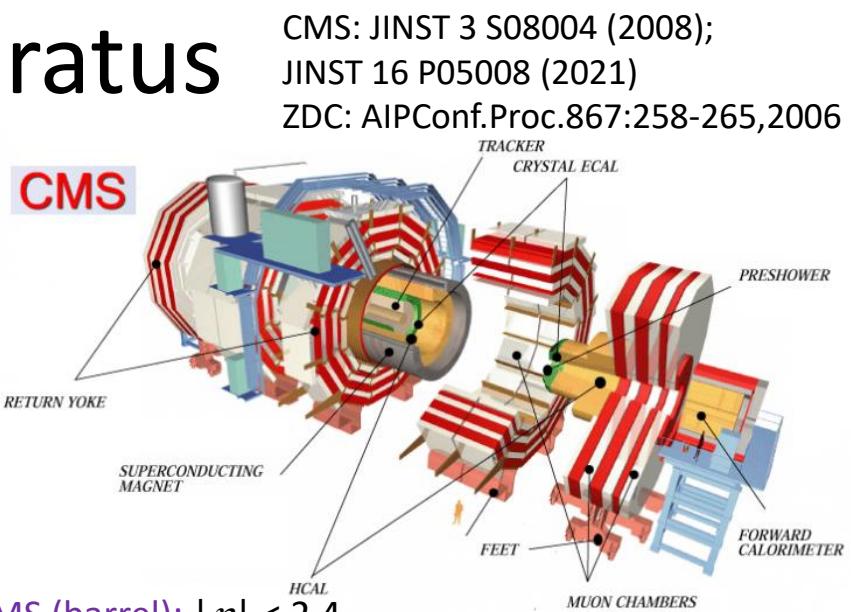
- **ALICE Barrel:**  $|\eta| < 0.9$ ,
- **Muon Arm:**  $-4 < \eta < -2.5$
- **ALICE Diffractive detectors:** ZDC, AD, VO



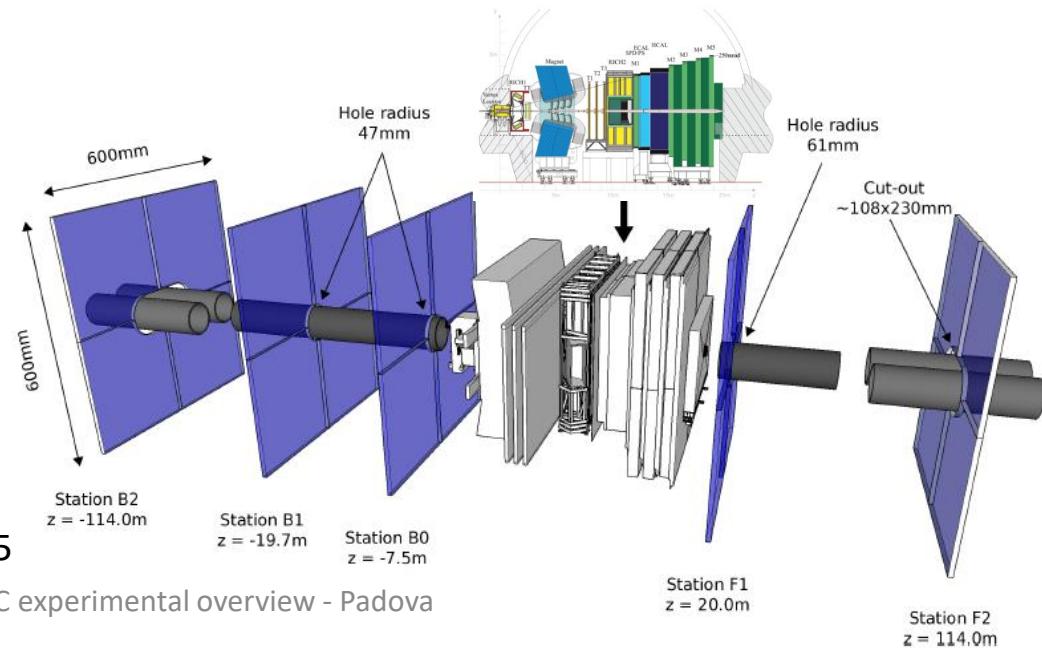
ALICE: 2008 JINST 3 S08002;  
Int. J. Mod. Phys. A29 (2014) 1430044

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

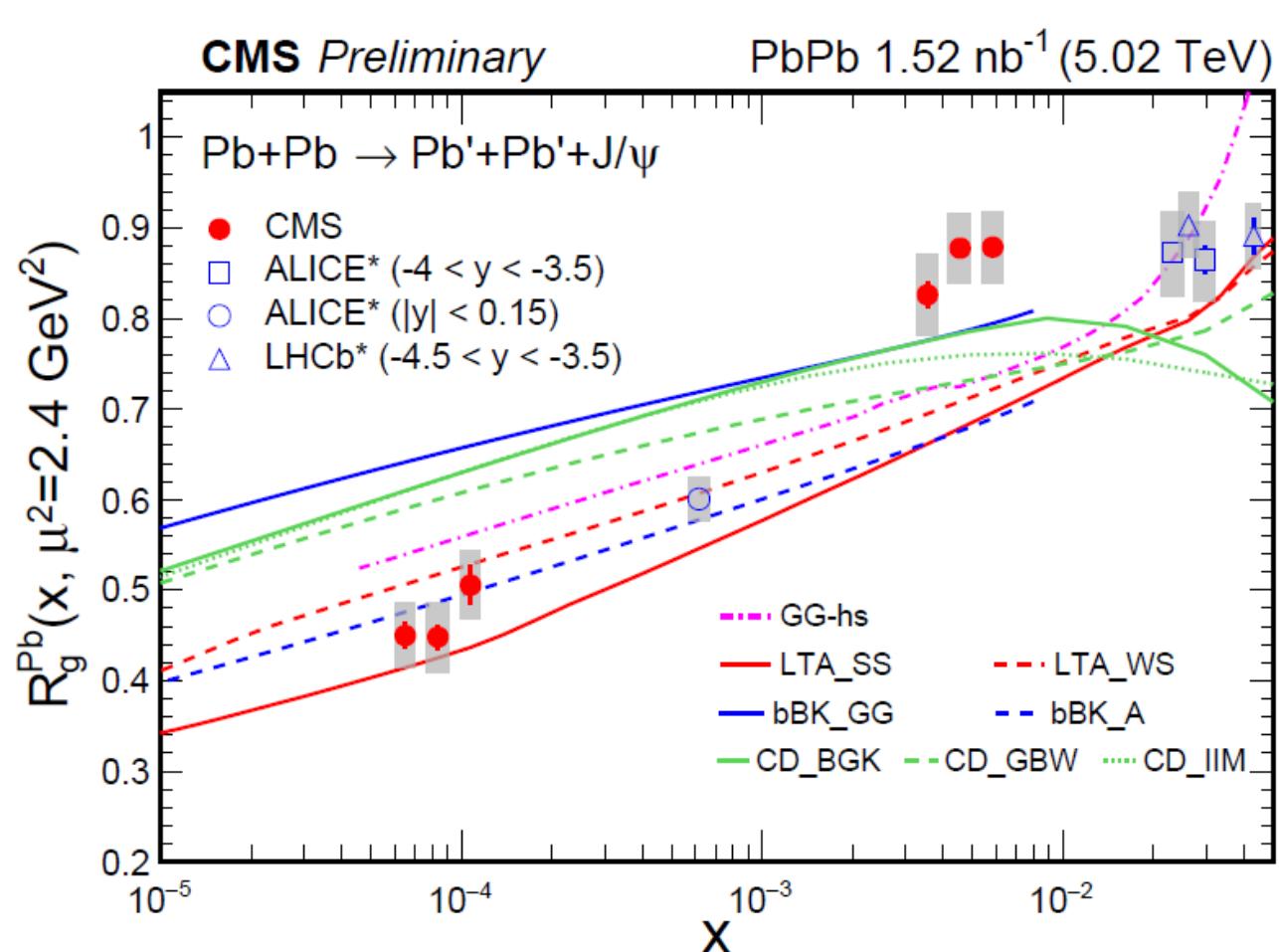
- **LHCb (forward region):**  $2 < \eta < 5$
- **LHCb HERSCHEL:**  $5 < |\eta| < 10$
- **VELO (backward region):**  $-3.5 < \eta < -1.5$



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



# Nuclear gluon suppression factor

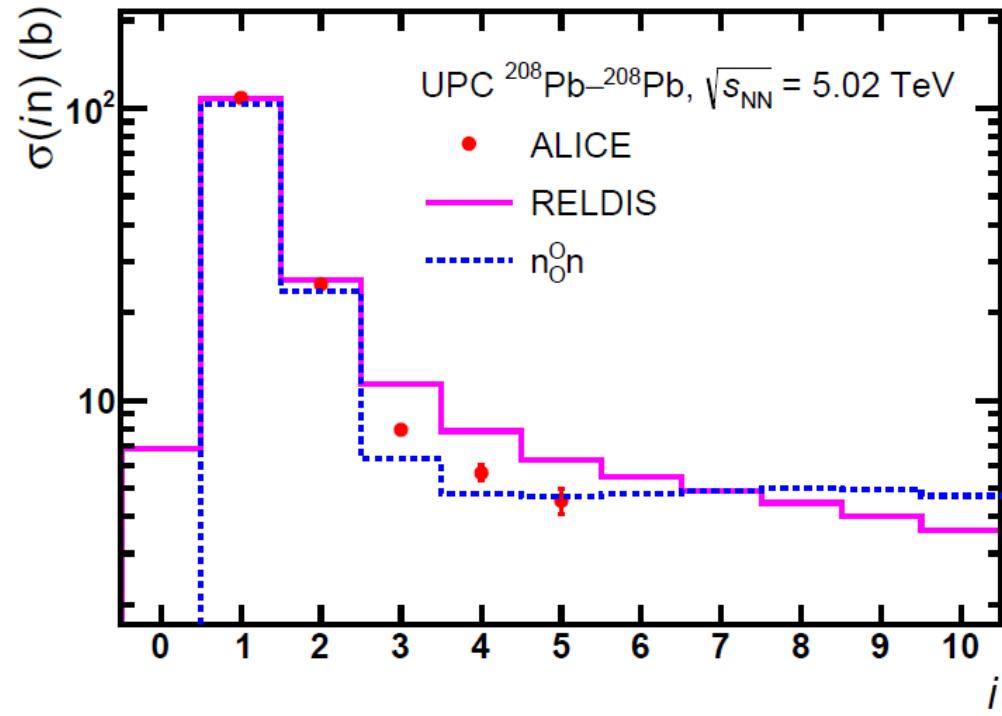
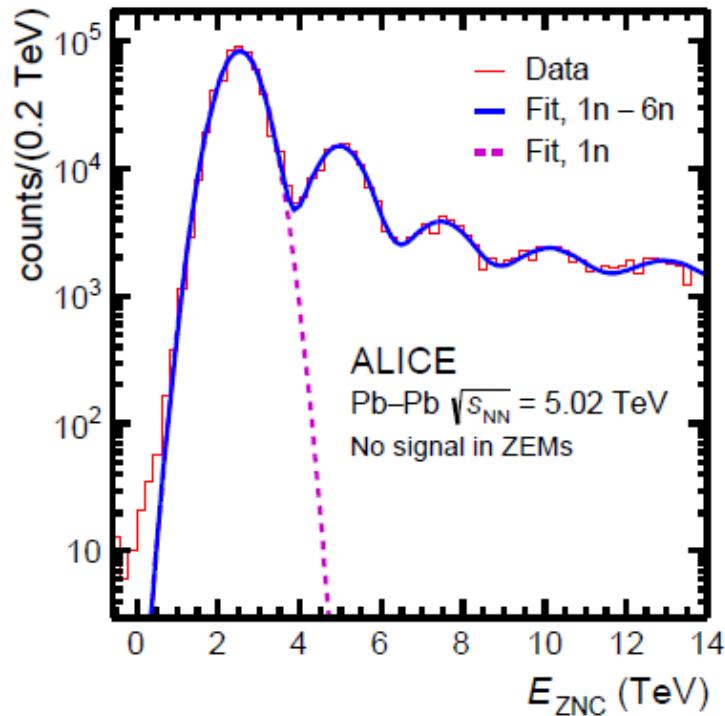


$$R_{g}^{\text{Pb}} = \sqrt{\frac{\sigma_{\gamma A \rightarrow J/\psi A}^{\text{exp}}}{\sigma_{\gamma A \rightarrow J/\psi A}^{\text{IA}}}}$$

- $R_{g}^{\text{Pb}}$  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

CMS: PAS HIN-22-002 (2022)

# Neutron emission in UPC



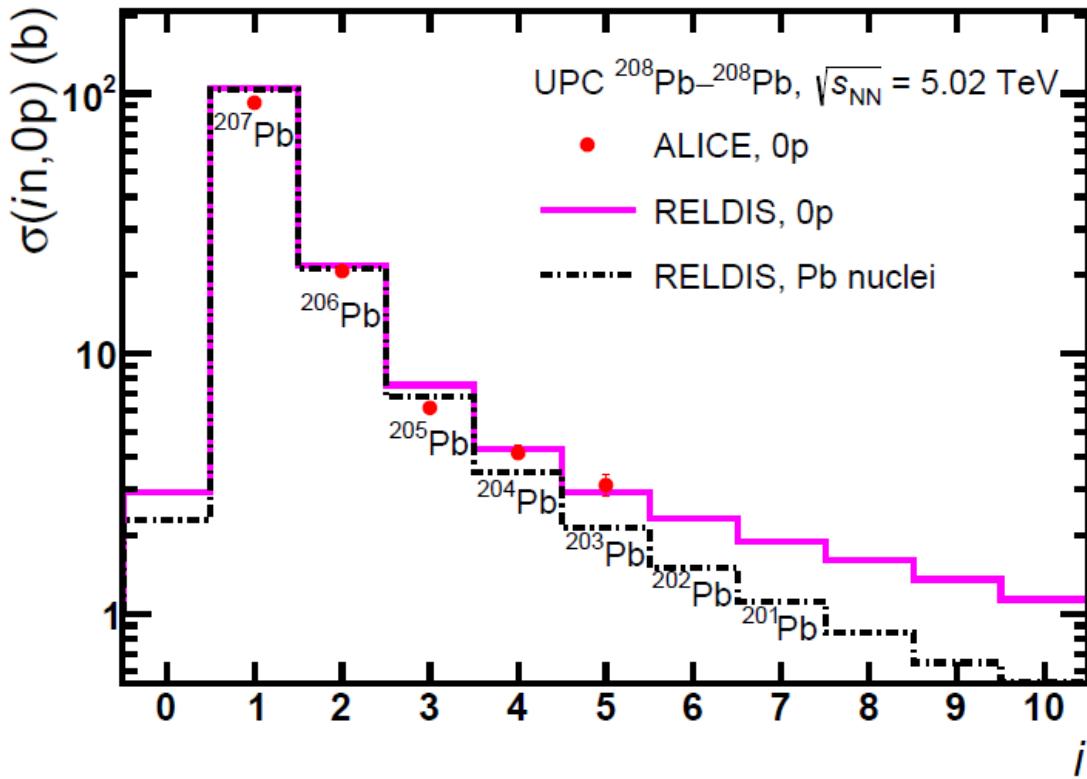
ZN	$\sigma(i/n)$ (b)	$\sigma^{\text{RELDIS}}(in)$ (b)	$\sigma^{n_0^0 n}(in)$ (b)
1n	$108.4 \pm 0.1 \pm 3.7$	$108.0 \pm 5.4$	$103.7 \pm 2.1$
2n	$25.0 \pm 0.1 \pm 1.3$	$25.9 \pm 1.3$	$23.6 \pm 0.5$
3n	$7.95 \pm 0.04 \pm 0.23$	$11.4 \pm 0.6$	$6.3 \pm 0.1$
4n	$5.65 \pm 0.03 \pm 0.33$	$7.8 \pm 0.4$	$4.8 \pm 0.1$
5n	$4.54 \pm 0.03 \pm 0.44$	$6.3 \pm 0.3$	$4.7 \pm 0.1$
1n–5n	$151.5 \pm 0.2 \pm 4.6$	$159.8 \pm 5.6$	$143.1 \pm 2.2$

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

RELDIS: Phys. Part. Nucl. 42 (2011) 215.

N00N: Comput. Phys. Commun. 253 (2020) 107181.

# Neutron emission classes with 0p



# Articles

## ALICE

- Coherent J/ $\psi$  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/ $\psi$  photoproduction off protons in ultra-peripheral p-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, Phys. Rev. Lett. 113 (2014) 232504.
- Coherent J/ $\psi$  photoproduction at forward rapidity in ultra-peripheral Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, Phys. Lett. B798 (2019) 134926.
- Coherent J/ $\psi$  and  $\psi'$  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/ $\psi$  photonuclear production, PLB 817 (2021) 136280.
- Energy dependence of exclusive J/ $\psi$  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/ $\psi$  from peripheral to central Pb-Pb collisions at 5.02 TeV, arXiv:2204.10684 (2022).
- Coherent photoproduction of  $\rho^0$  vector mesons in ultra-peripheral Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, JHEP 06 (2020) 035.
- First measurement of coherent  $\rho^0$  photoproduction in ultra-peripheral Xe-Xe collisions at  $\sqrt{s_{NN}} = 5.44$  TeV, Phys. Lett. B 820 (2021) 136481.

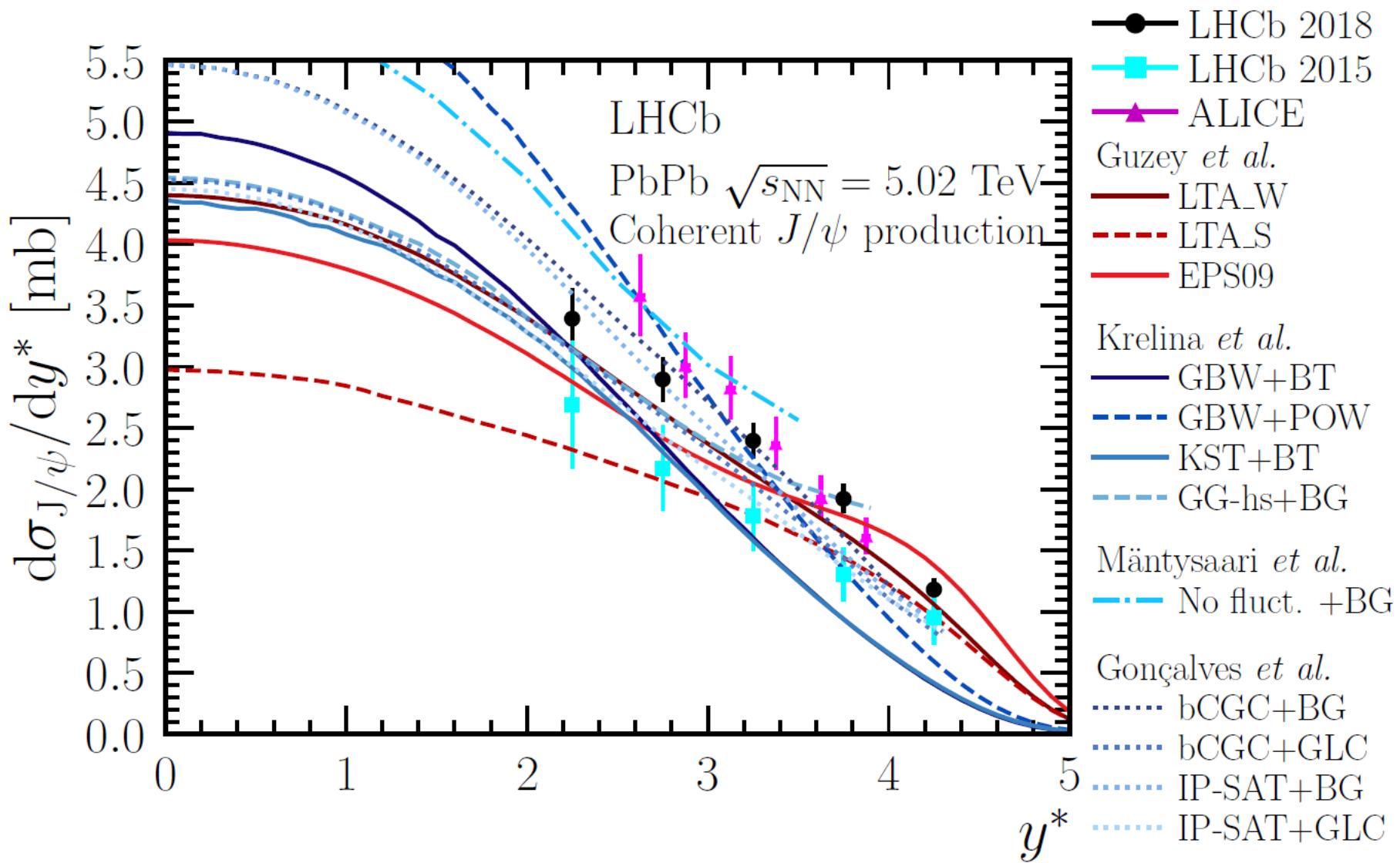
## CMS

- Coherent J/ $\psi$  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  $\Upsilon$  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/ $\psi$  and  $\psi(2S)$  production cross-sections in pp collisions at  $\sqrt{s} = 7$  TeV, J. Phys. G 41 (2014) 055002.
- Measurement of the exclusive  $\Upsilon$  production cross-section in pp collisions at  $\sqrt{s} = 7$  TeV and 8TeV, JHEP 09 (2015) 084.
- Central exclusive production of J/ $\psi$  and  $\psi(2S)$  mesons in pp collisions at  $\sqrt{s} = 13$  TeV, JHEP 10 (2018) 167.
- Study of coherent J/ $\psi$  production in lead-lead collisions at  $\sqrt{s_{NN}} = 5$ TeV, 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/ $\psi$  photo-production in Pb-Pb peripheral collisions at  $\sqrt{s_{NN}} = 5$ TeV, Phys. Rev. C105 (2022) L032201.

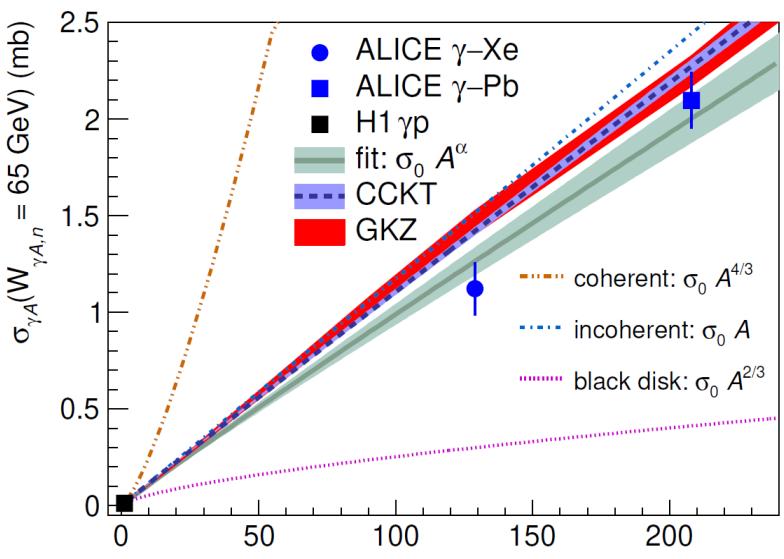
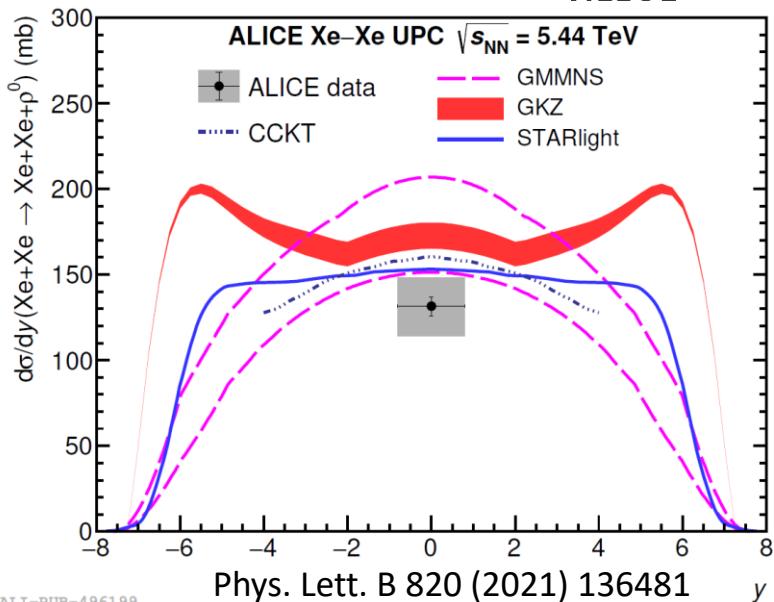
# Comparison LHCb/ALICE – Pb-Pb @ 5 TeV



# $\rho^0$ in Xe-Xe at $\sqrt{s}_{\text{NN}} = 5.44 \text{ TeV}$



- $d\sigma/dy = 131.5 \pm 5.6^{\text{st}} +17.5_{-16.9}^{\text{sy}} \text{ mb}$
- All models relatively close to data
  
- $W_{\gamma A, n} = 65 \text{ GeV}$
- $\sigma(\gamma A \rightarrow \rho^0 A) \sim A^\alpha$  with a slope  $\alpha = 0.96 \pm 0.02^{\text{sy}}$ 
  - ⇒ 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)

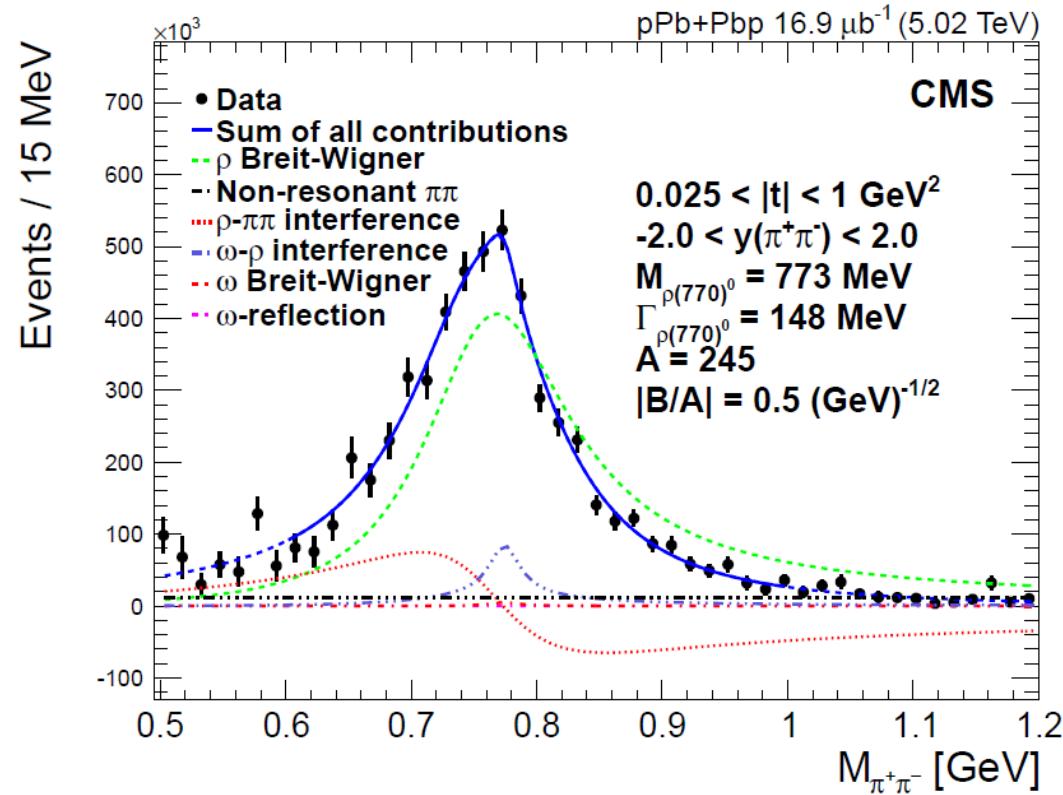


# $\rho^0$ @5TeV in Pb-Pb, CMS

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

$$\Gamma_{\rho(770)} = \Gamma_0 \frac{M_{\rho(770)^0}}{M_{\pi^+\pi^-}} \left[ \frac{M_{\pi^+\pi^-}^2 - 4m_{\pi^\pm}^2}{M_{\rho(770)^0}^2 - 4m_{\pi^\pm}^2} \right]^{\frac{3}{2}}$$

$$\Gamma_{\omega(783)} = \Gamma_0 \frac{M_{\omega(783)}}{M_{\pi^+\pi^-}} \left[ \frac{M_{\pi^+\pi^-}^2 - 9m_{\pi^\pm}^2}{M_{\omega(783)}^2 - 9m_{\pi^\pm}^2} \right]^{\frac{3}{2}}$$

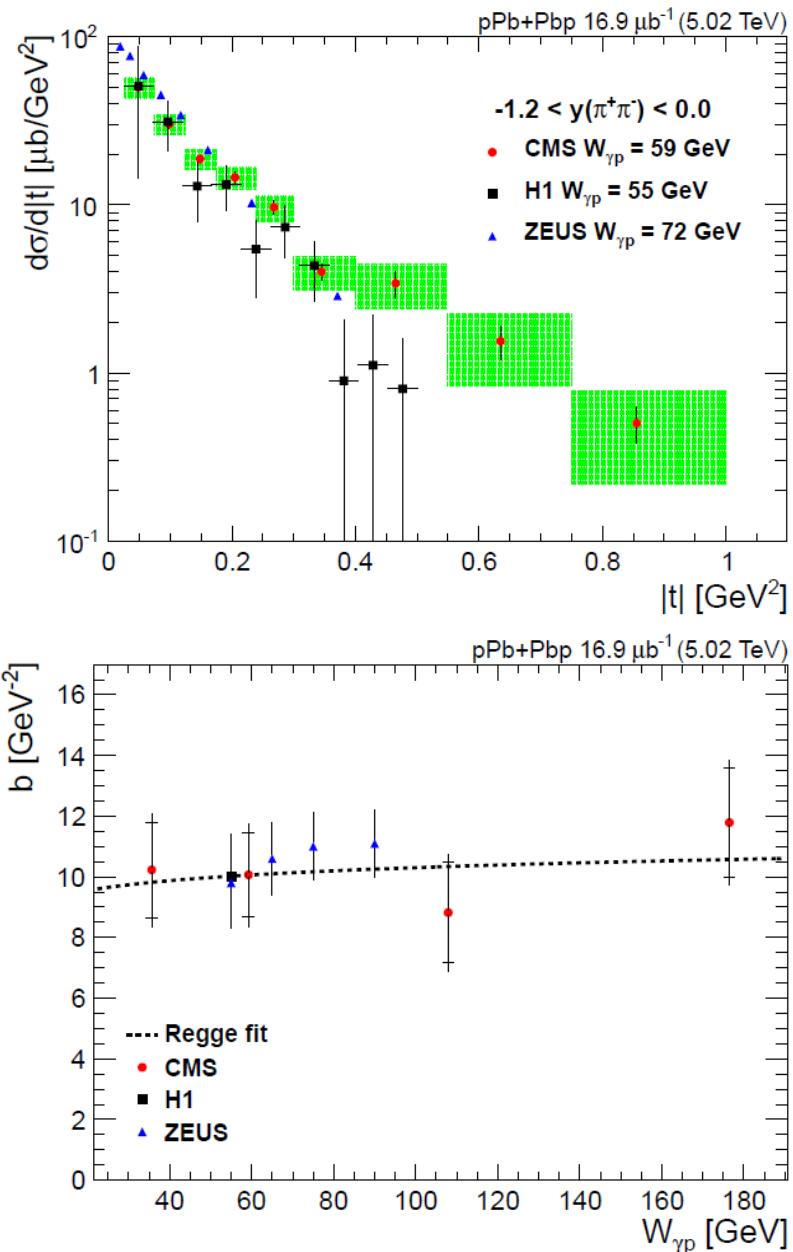
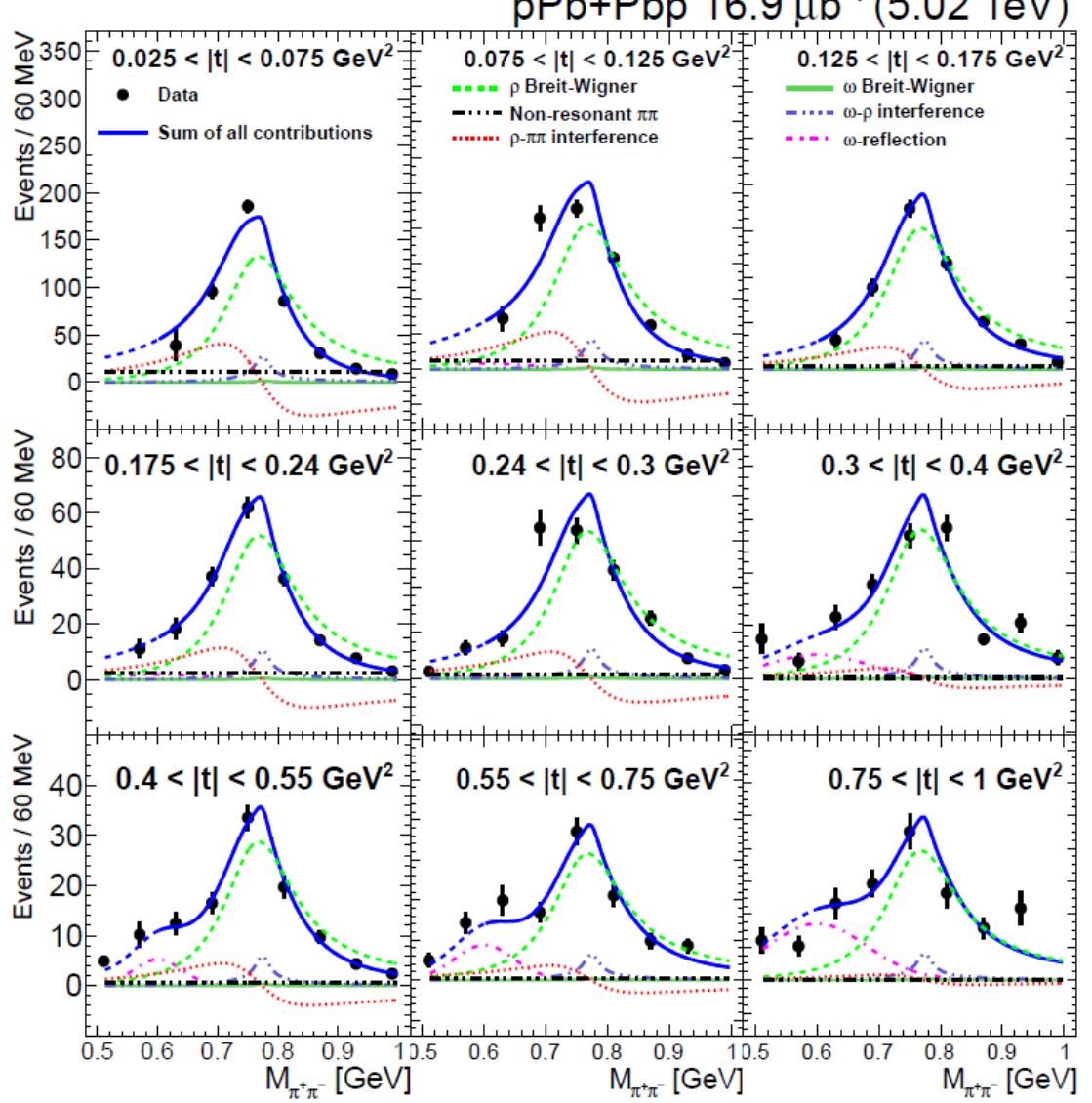


$$\frac{d\sigma}{dy} = \frac{N_{\rho(770)^0}^{\text{exc}}}{\mathcal{B}(\rho(770)^0 \rightarrow \pi^+\pi^-) L \Delta y},$$

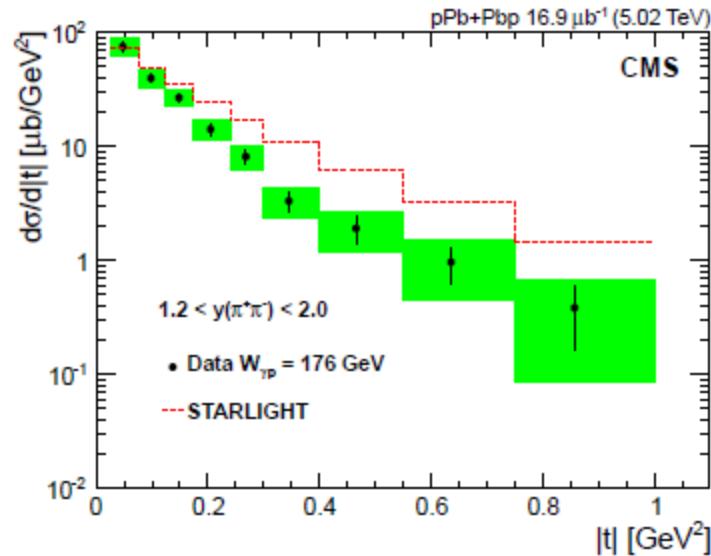
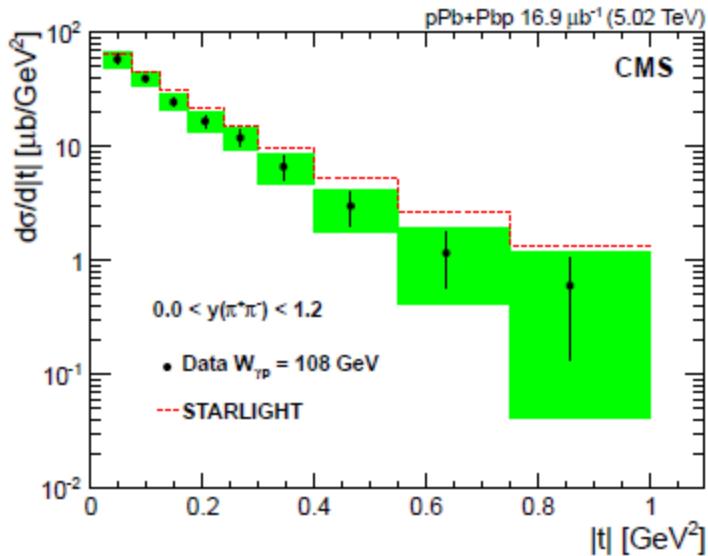
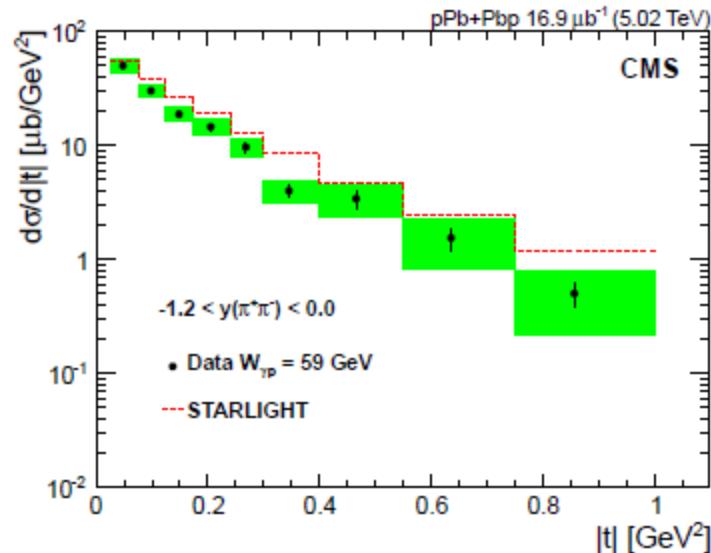
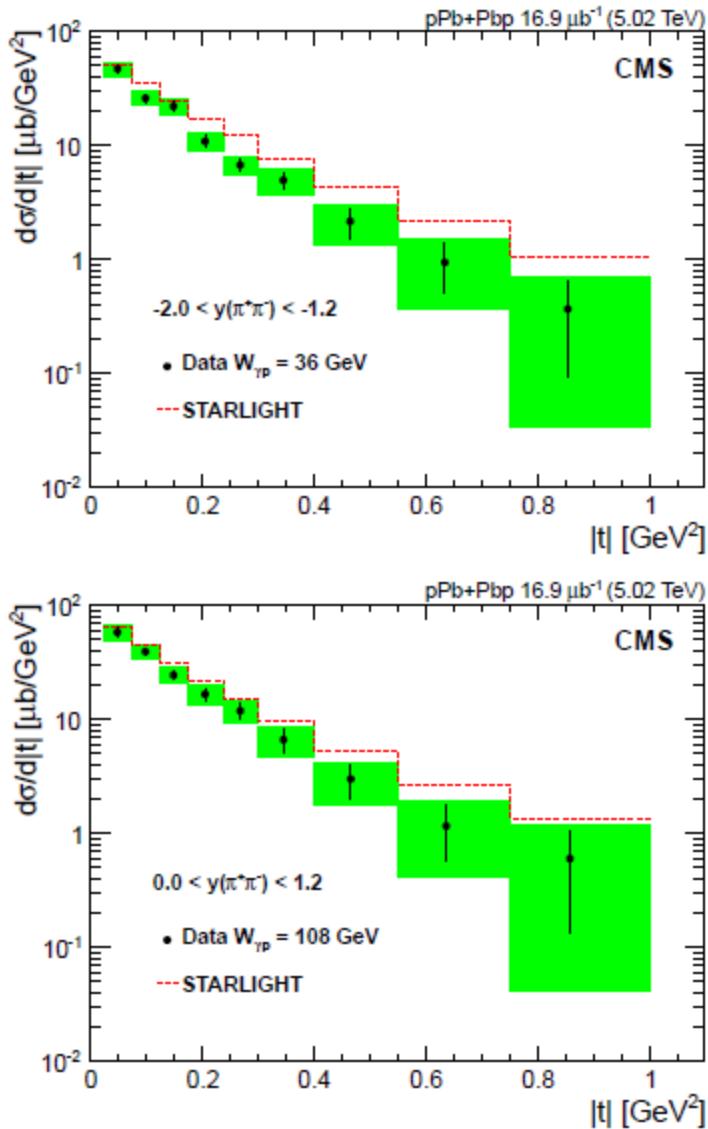
$$\frac{d\sigma}{dy}(p\text{Pb} \rightarrow p\text{Pb}\rho(770)^0) = k \frac{dn}{dk} \sigma(\gamma p \rightarrow \rho(770)^0 p)$$

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

# $\rho^0$ @5TeV in Pb-Pb, CMS

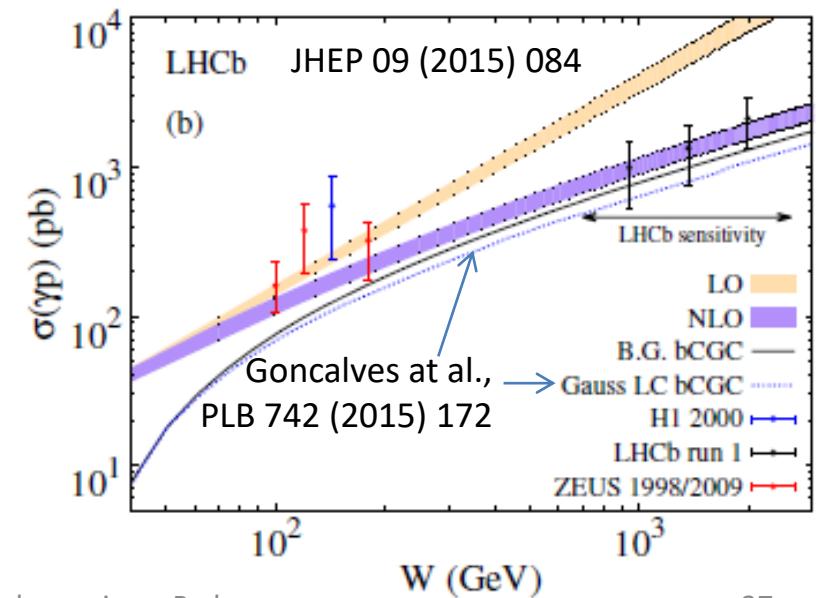
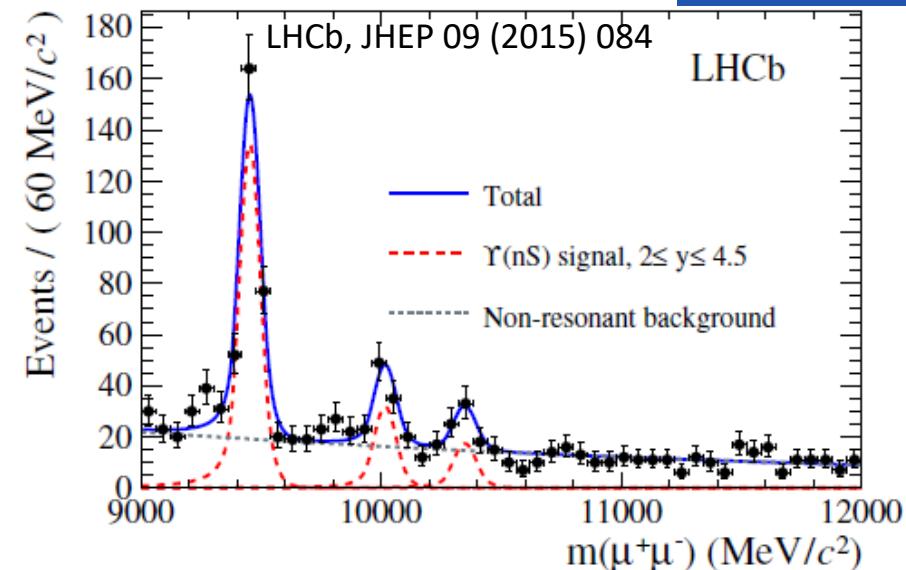
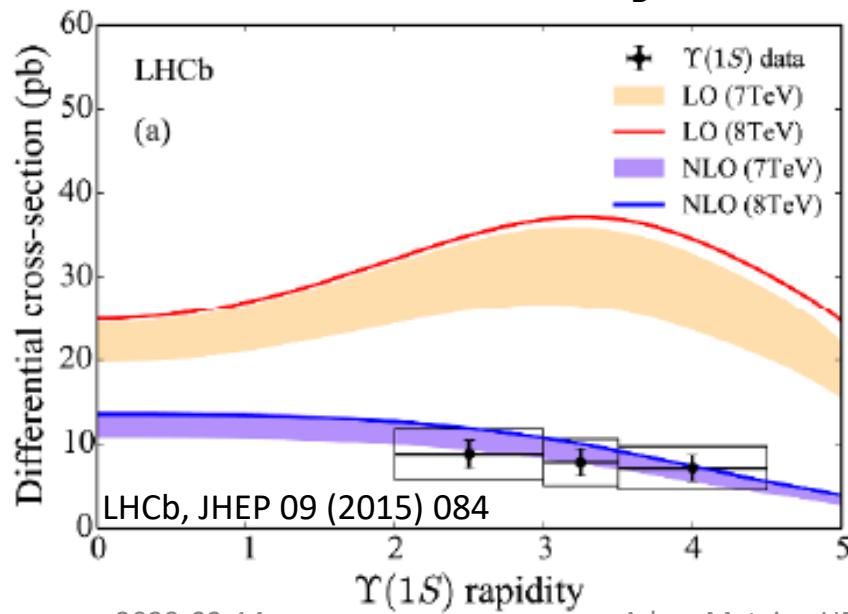


# $\rho^0$ @5TeV in Pb-Pb, CMS



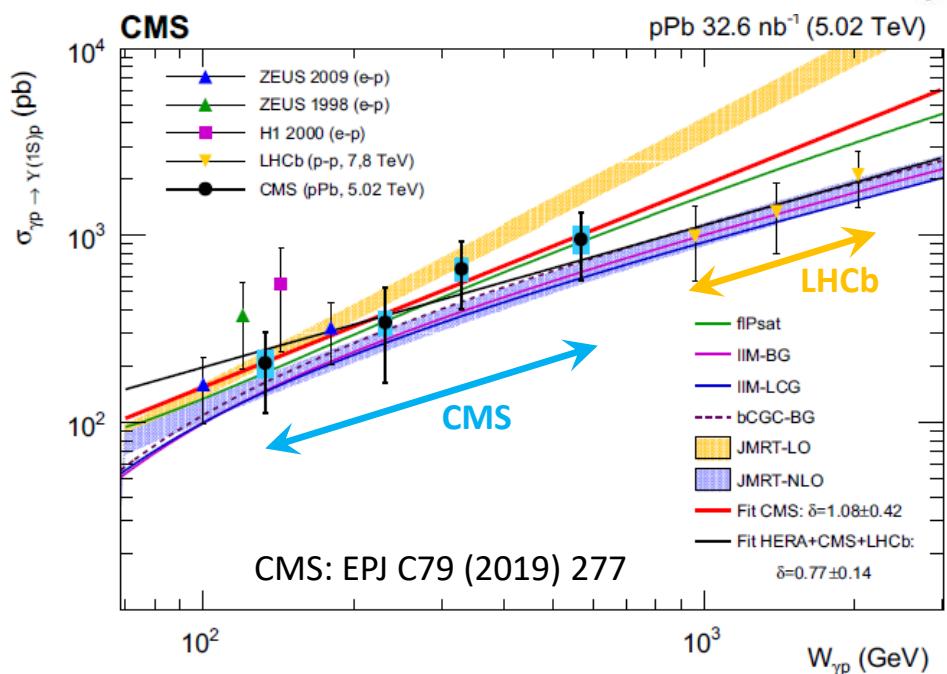
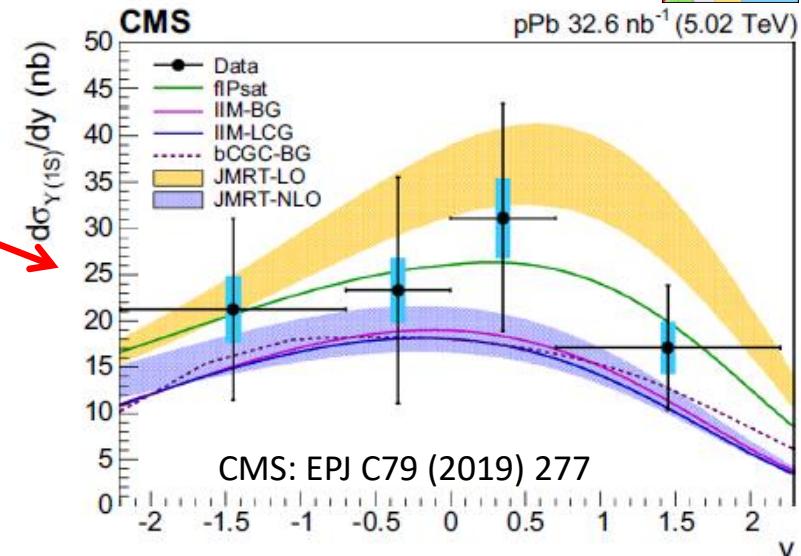
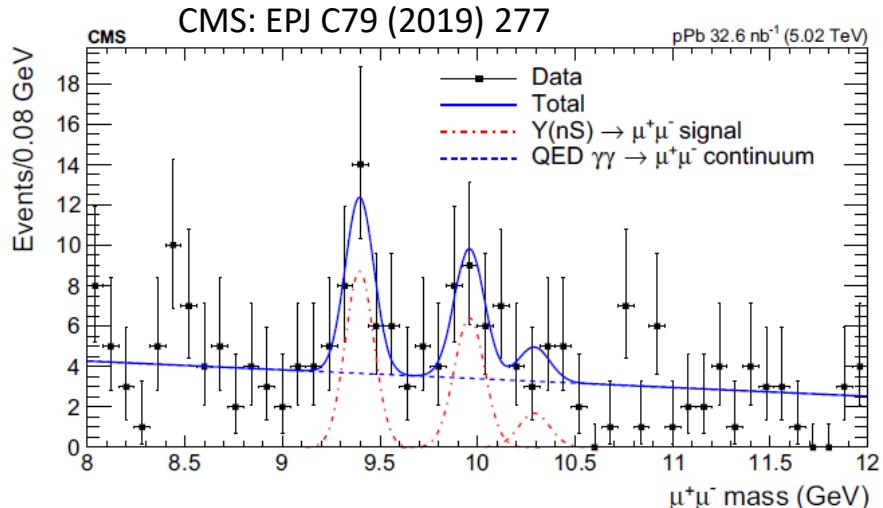
# $\Upsilon(nS)$ in pp at $\sqrt{s} = 7, 8$ TeV

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



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

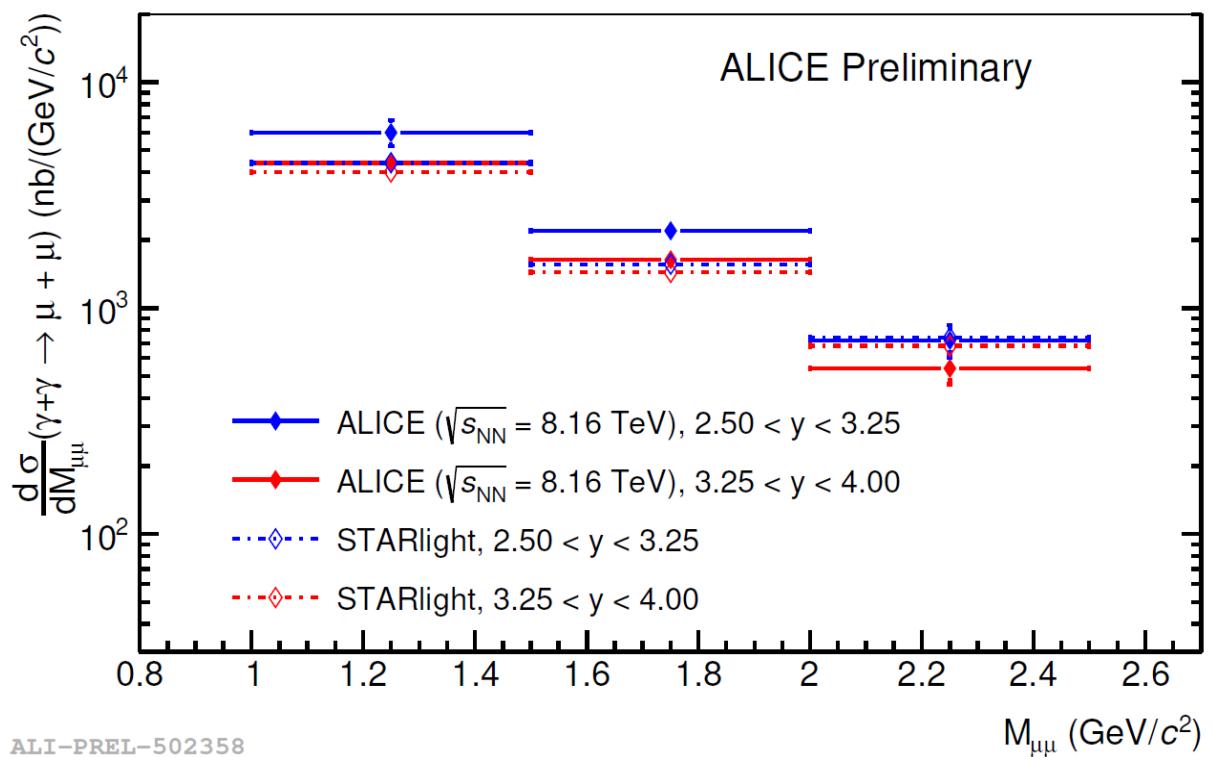
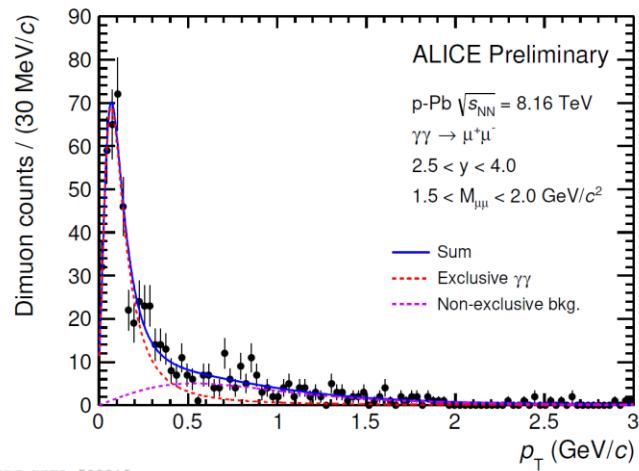
- $\Upsilon(nS) \rightarrow \mu^+ \mu^-$
- **Cross section** extracted from ratios and inclusive  $\Upsilon(nS)$  treatment
- Theory calculations (LO and NLO) and saturation models consistent with CMS data
- Fit to CMS:  $\delta = 1.08 \pm 0.42$ 
  - ⇒ Consistent with ZEUS:  $\delta = 1.2 \pm 0.8$
 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



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

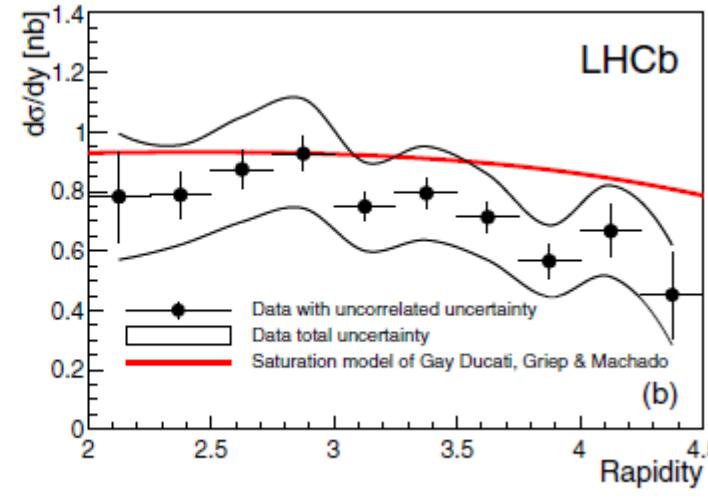
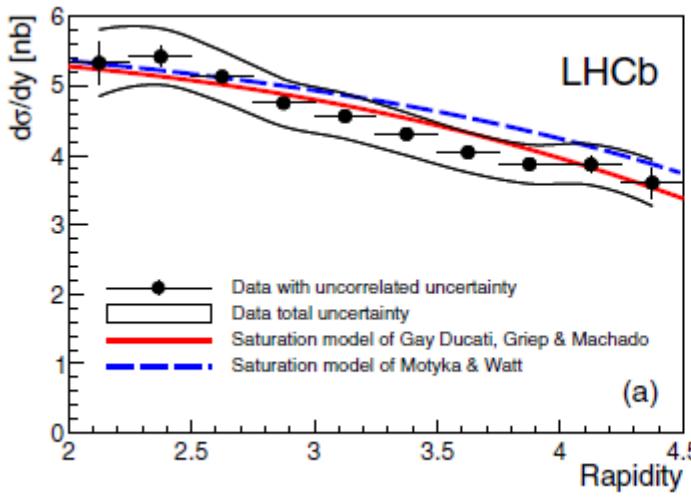
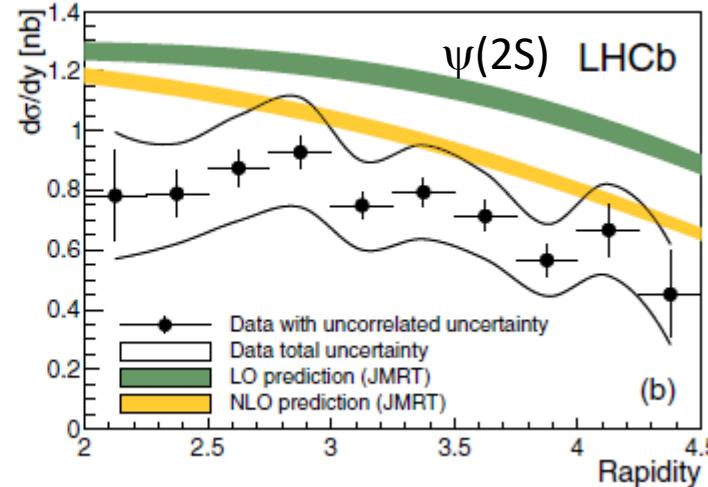
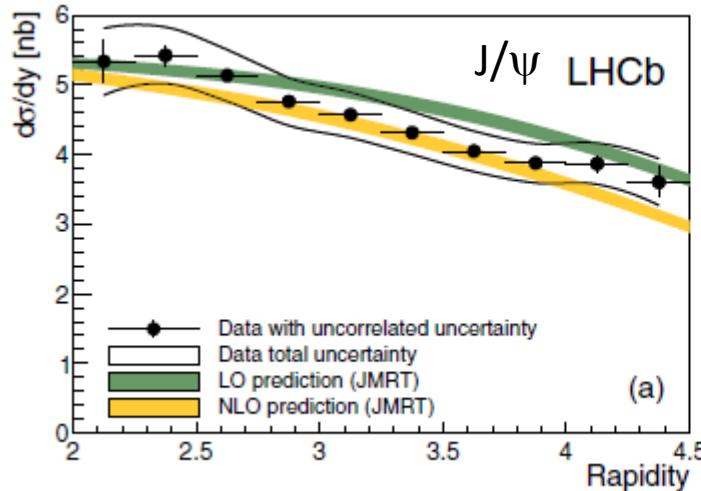


- $\gamma\gamma \rightarrow \mu\mu$  cross section
- Good agreement of simulation and data
- Comparison with STARlight (LO QED, no FSR) shows slight excess in data
- Important background for other UPC processes
- Constrain theoretical models



# $J/\psi, \psi(2S)$ in pp@7 TeV

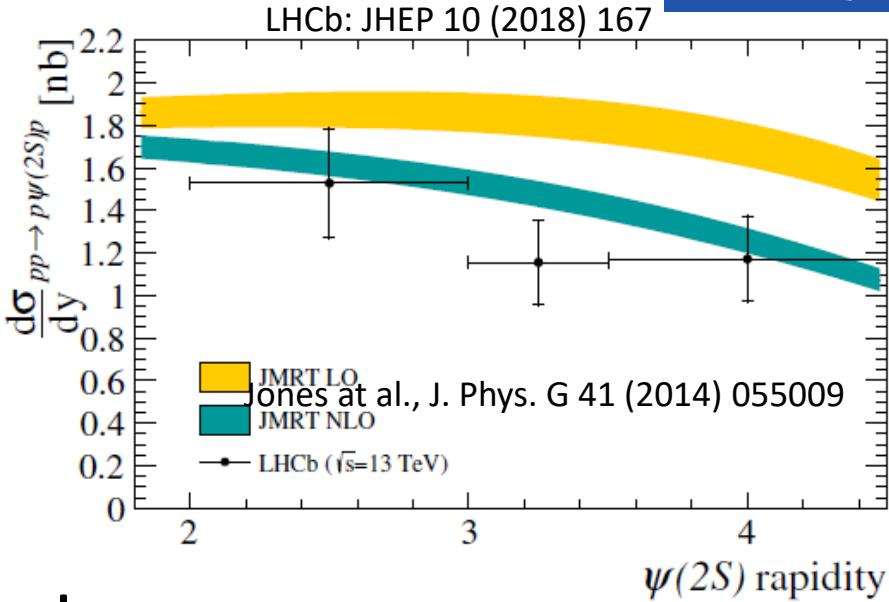
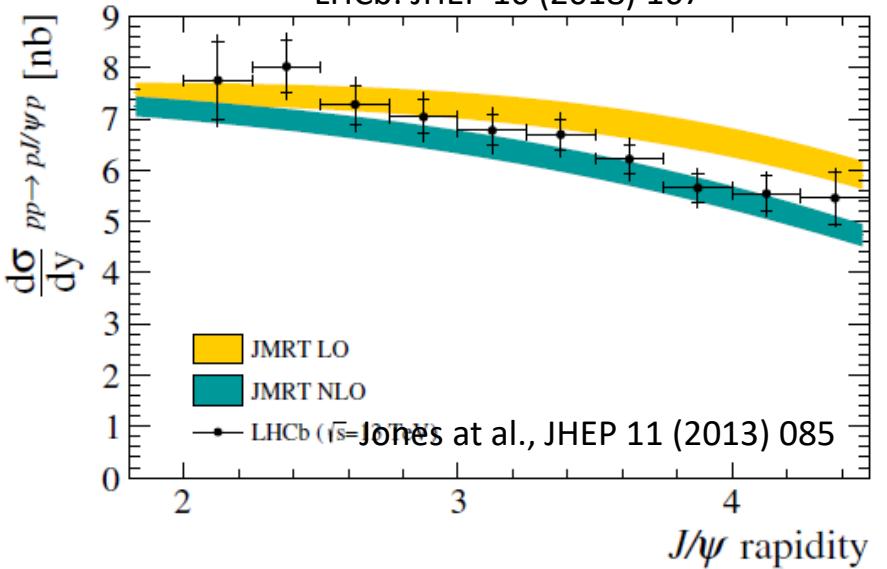
LHCb: J. Phys. G: Nucl. Part. Phys. **41** (2014) 055002



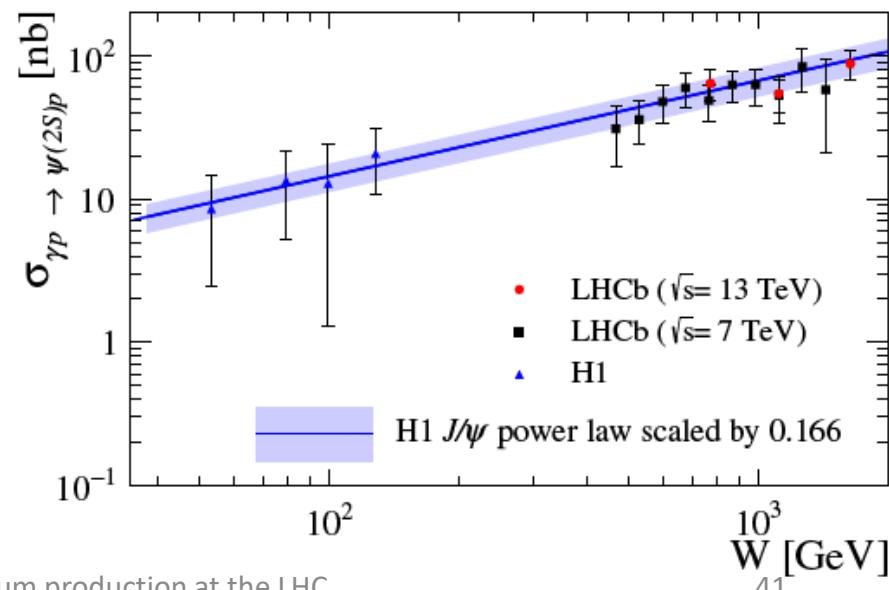
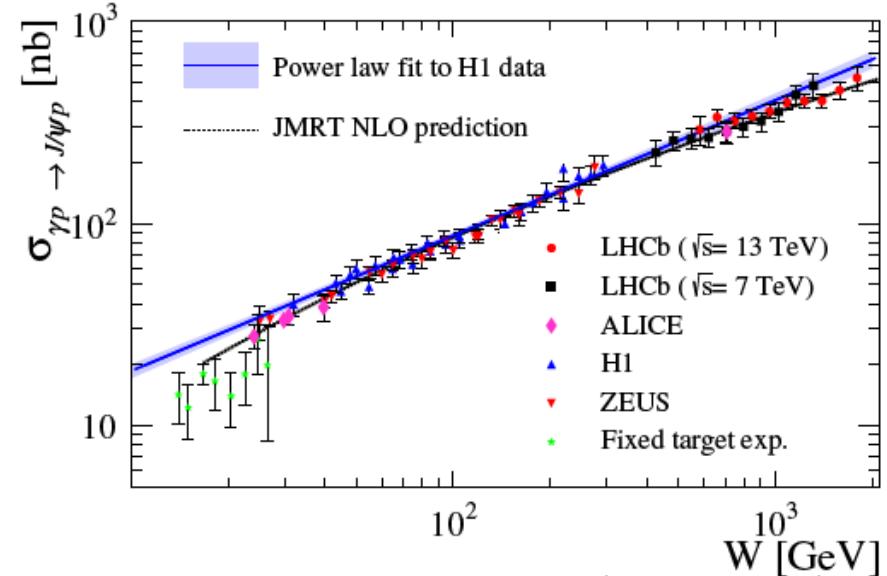
# $J/\psi, \psi(2S)$ in pp@13 TeV

LHCb  
JHEP

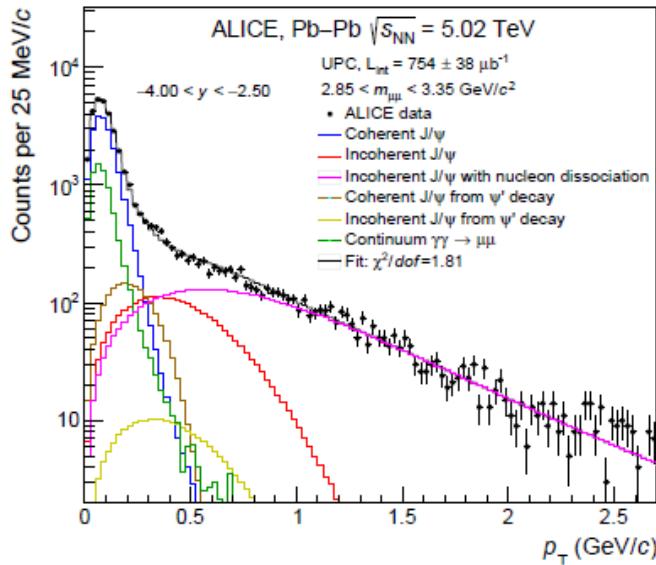
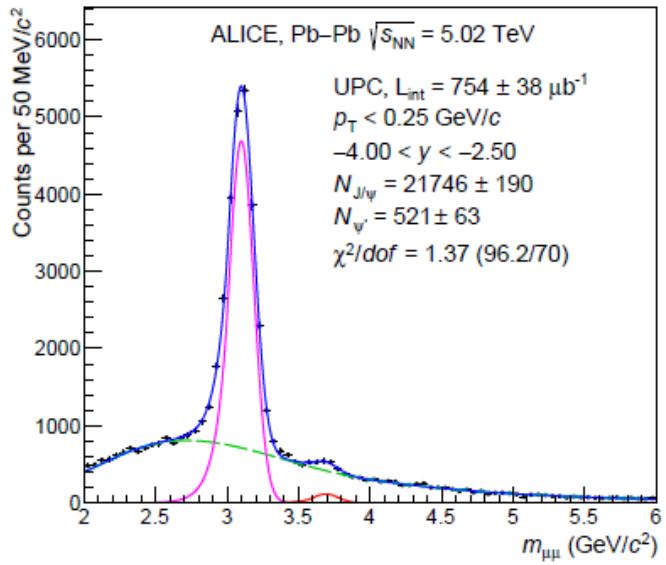
LHCb: JHEP 10 (2018) 167



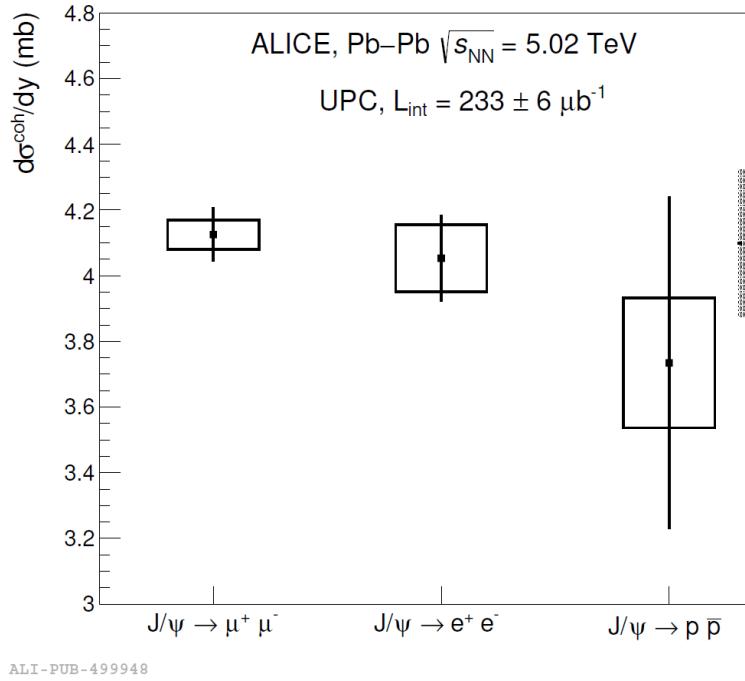
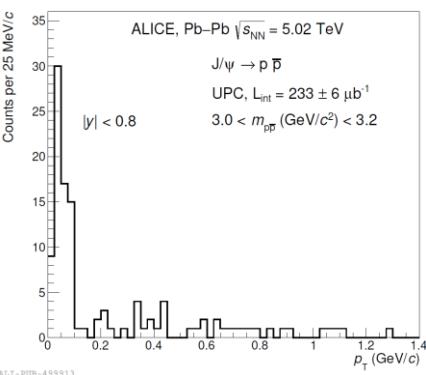
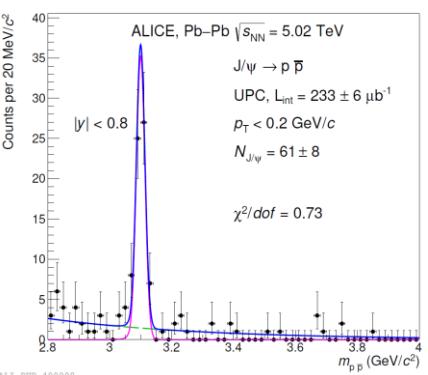
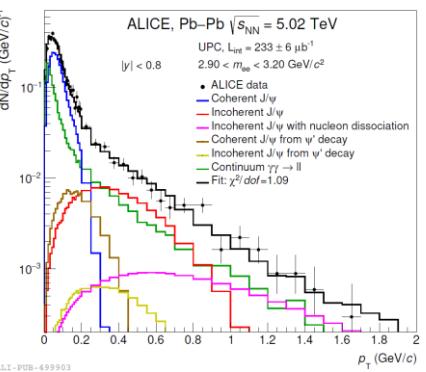
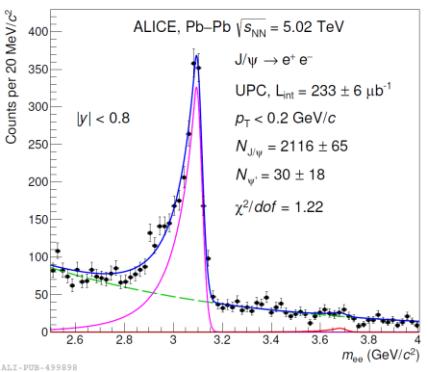
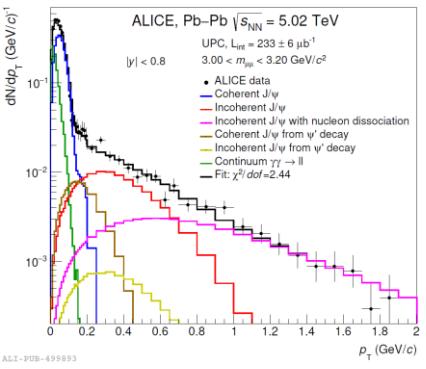
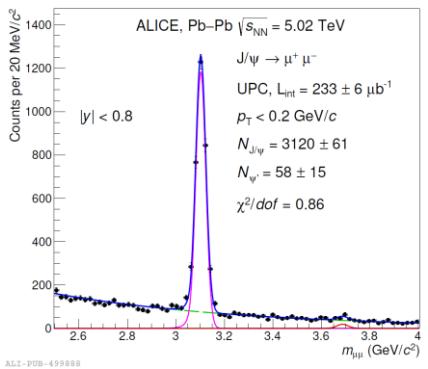
- NLO describes better the data



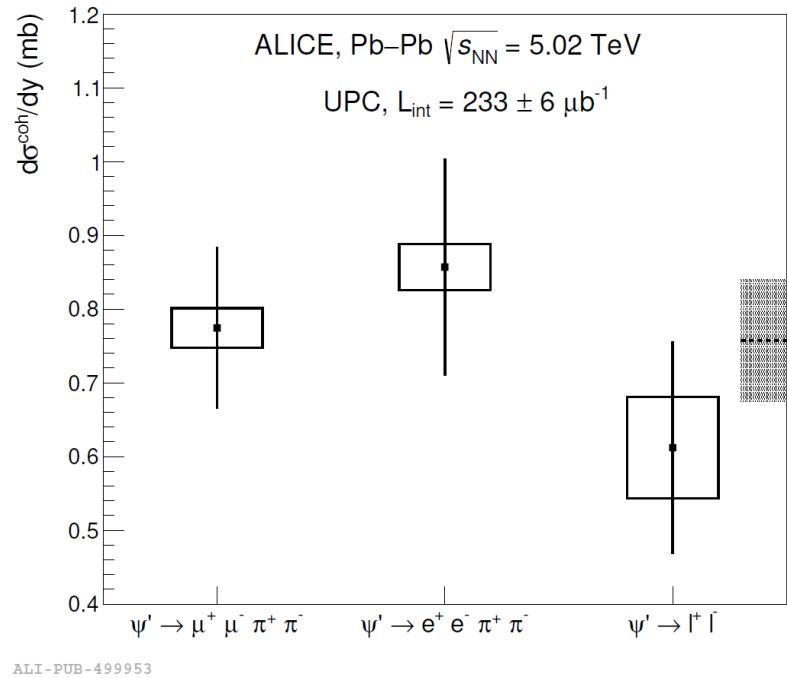
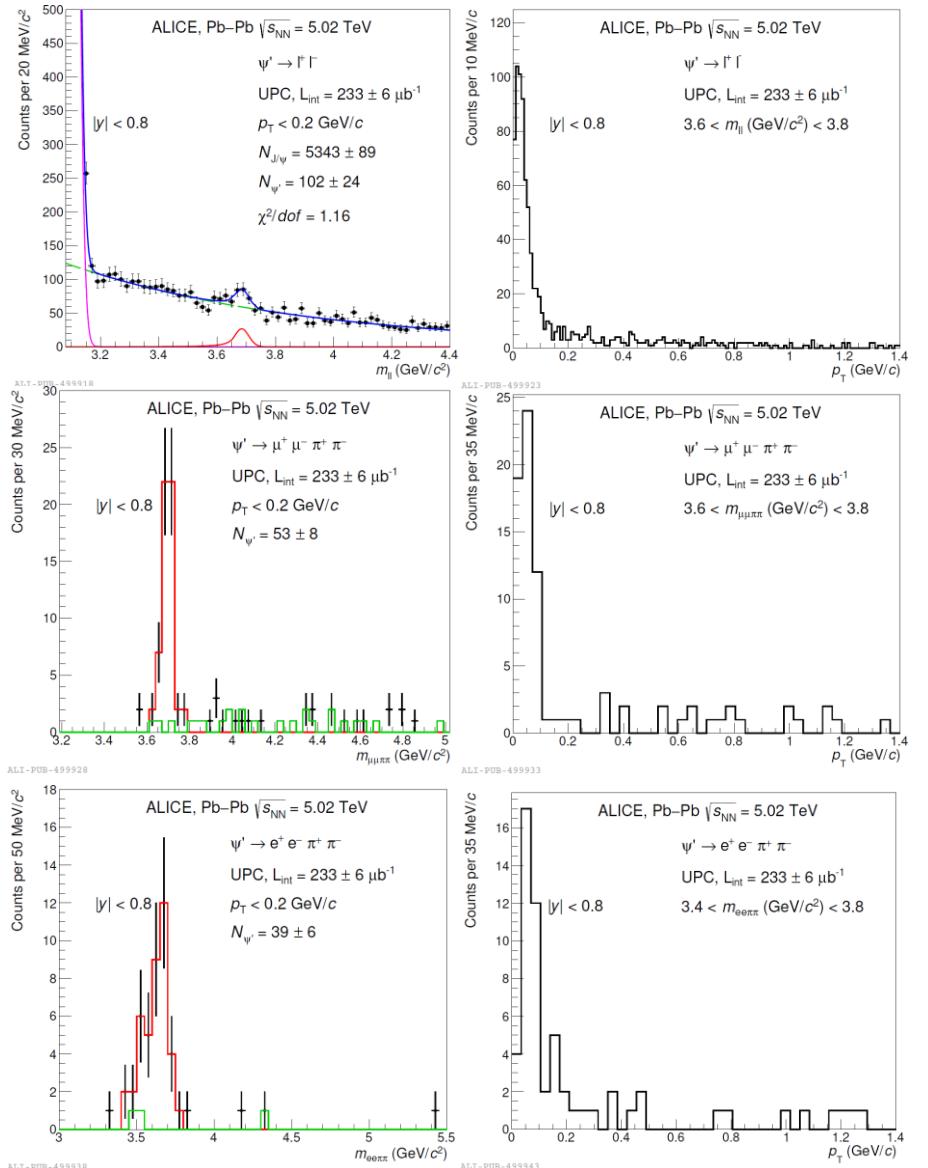
# ALICE J/ $\psi$ in Pb-Pb – forward



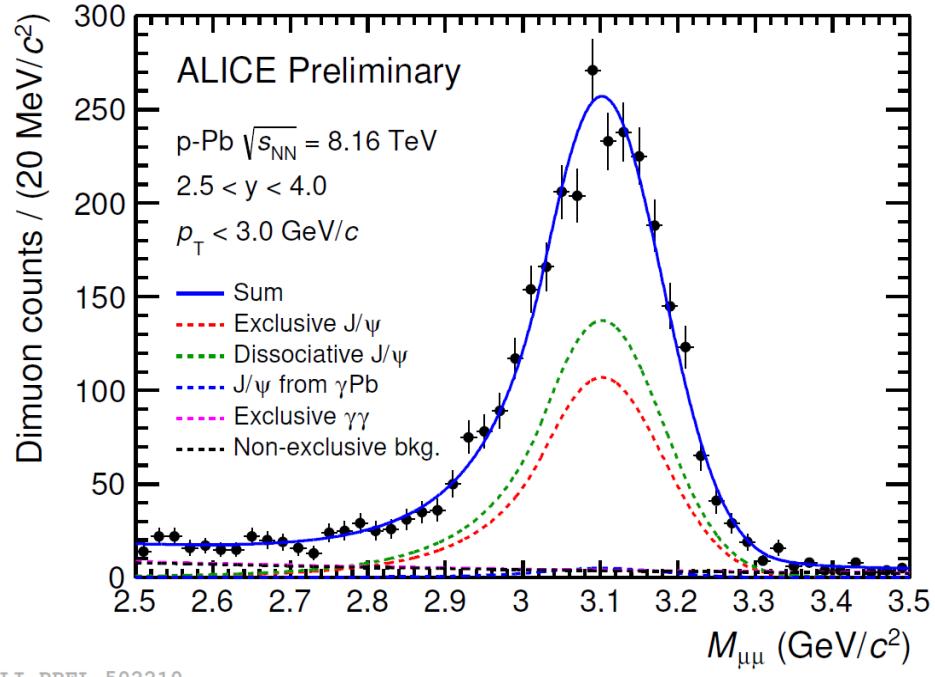
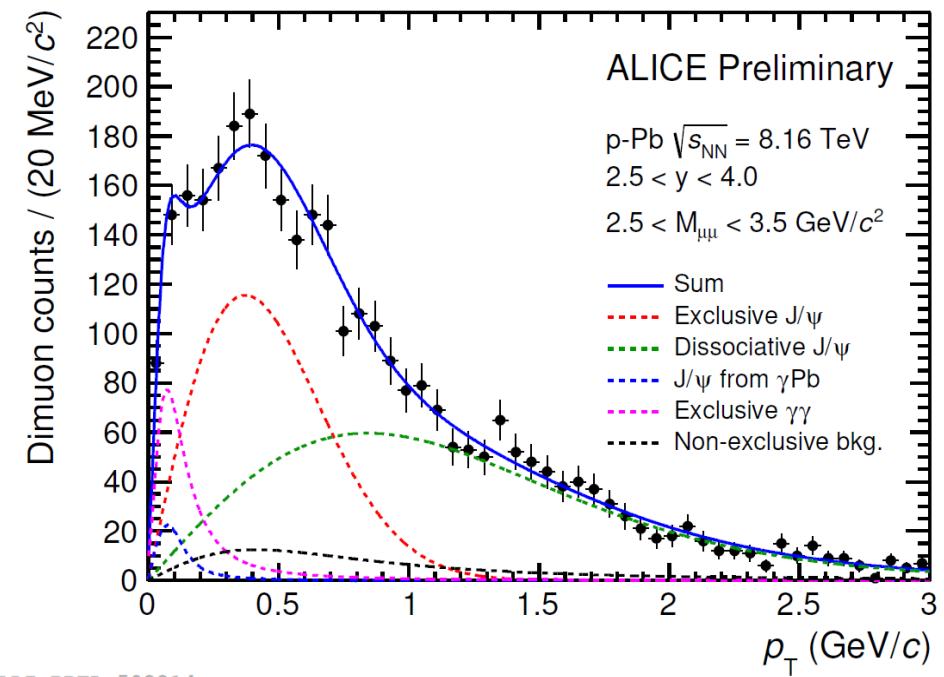
# ALICE J/ $\psi$ in Pb-Pb – central barrel



# ALICE $\psi'$ in Pb-Pb – central barrel



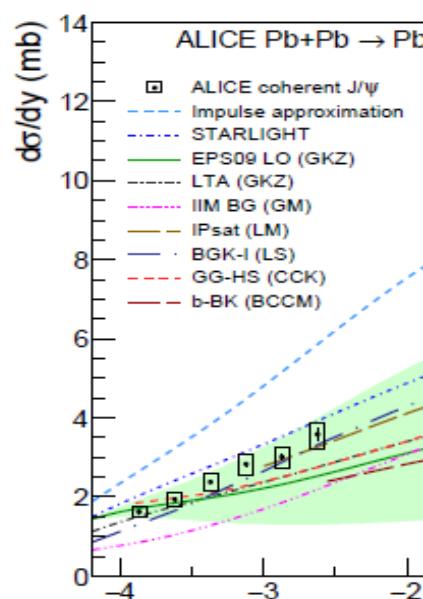
# ALICE Exclusive J/ $\psi$ in p-Pb



# Models

- **Black disk limit:**
  - Frankfurt, Strikman, Zhalov, *Phys. Lett.* B537 (2002) 51–61.
  - total cross section of the interaction is equal to  $2\pi R_A^2$ .
- **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. C* 93 (2016) 055206; Frankfurt, Guzey, Strikman, Zhalov, *Phys. Lett. B* 752 (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. D* 96 (2017) 094027; Iancu, Itakura, Munier, *Phys. Lett. B* 590 (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. B* 766 (2017) 186–191; Cepila, Contreras, Krelina, Tapia Takaki, *Nucl. Phys. B* 934 (2018) 330–340; N. Armesto, *Eur. Phys. J. C* 26 (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 amplitude.
  - **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 dipole 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

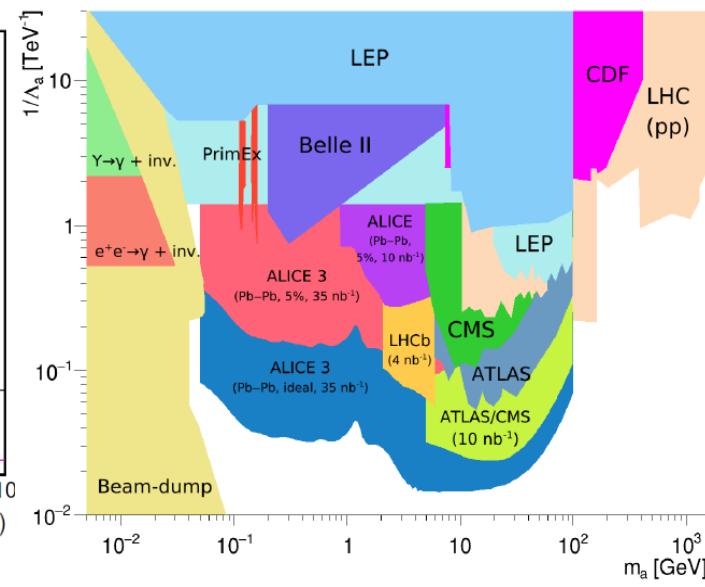
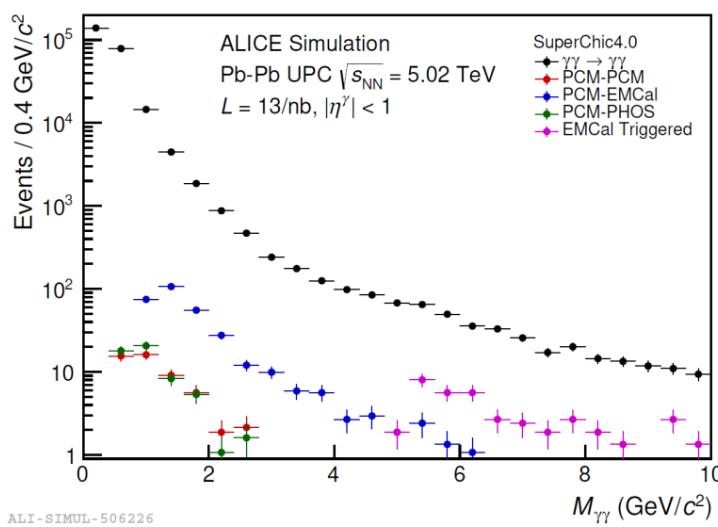
- **Guzey et al.**
  - Look at GKZ
- **Krelina et al.**
  - Cepila, Contreras, Krelina, Phys. Rev. C97 (2018) 024901; Kopeliovich, Krelina, Nemchik, Potashnikova, arXiv:2008.05116
  - variations of the **colour-dipole model** based on CGC theory.
  - GBW + BT: Golec-Biernat-Wusthof (GBW) model include 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 fluctuation 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)

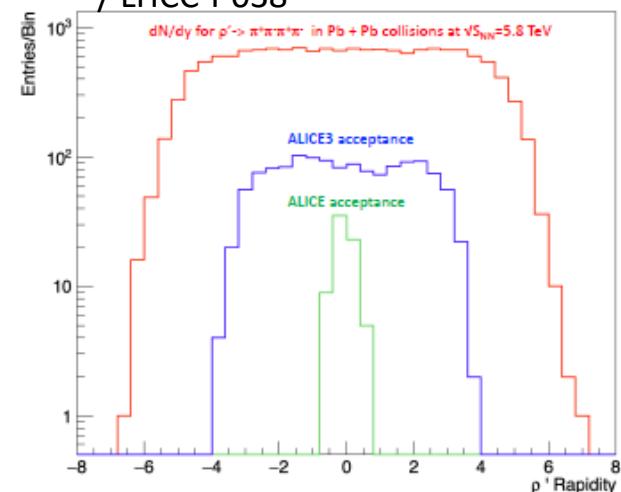
- Precise and new vector meson photoproduction
- Light-by-light scattering



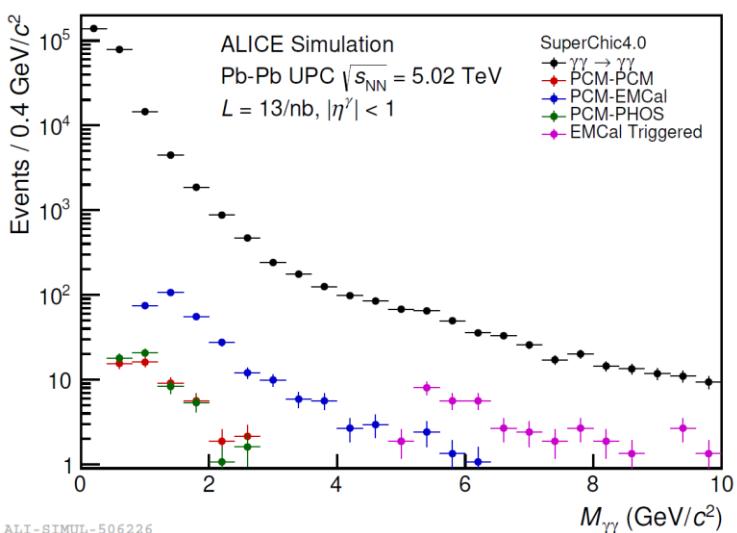
CERN Yellow Rep. Monogr. 7 (2019) 1159

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

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

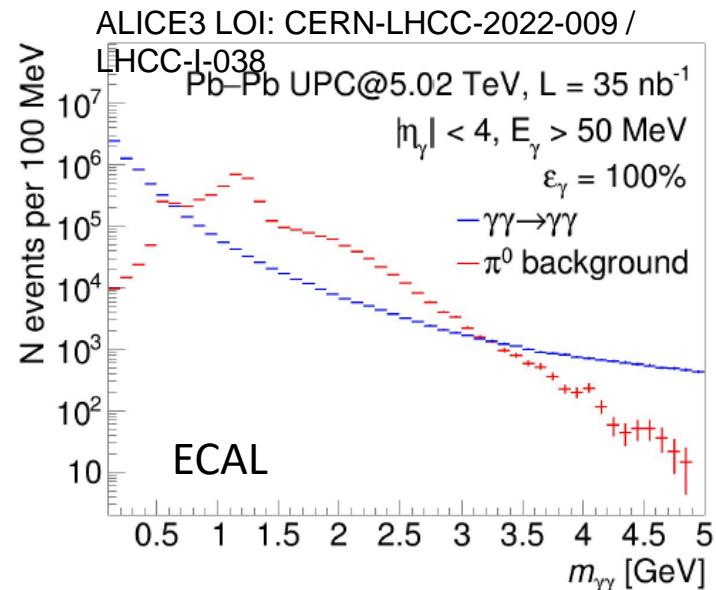


# Feasibility studies for ALICE 2 and 3



$$A_S = \left| \frac{|\vec{p}_T(1)| - |\vec{p}_T(2)|}{|\vec{p}_T(1)| + |\vec{p}_T(2)|} \right|$$

Background  
reduction with  
 $A_S$  variable



## Considered topologies in Run 3 and 4

Both  $\gamma$ 's reconstructed with Photon Conversion

Method (PCM) from  $e^+e^-$  pairs

- $p_T^{\gamma, \text{PCM}} > 0.1 \text{ GeV}/c$

One  $\gamma$  via PCM, other in EMCal acceptance

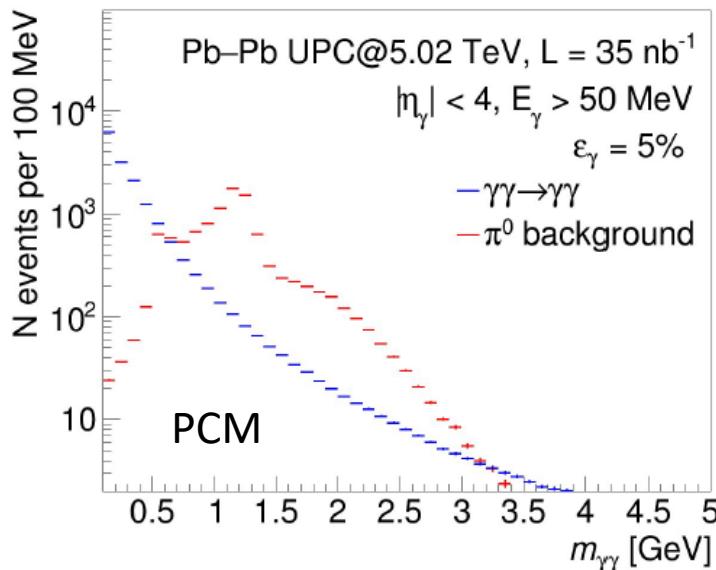
- $p_T^{\gamma, \text{EMCal}} > 0.5 \text{ GeV}/c$
- $p_T^{\gamma, \text{PCM}} > 0.1 \text{ GeV}/c$

One  $\gamma$  via PCM, other in PHOS acceptance

- $p_T^{\gamma, \text{PHOS}} > 0.3 \text{ GeV}/c$
- $p_T^{\gamma, \text{PCM}} > 0.1 \text{ GeV}/c$

Both  $\gamma$ 's in EMCal acceptance, one triggered

- $p_T^{\gamma, \text{EMCal}} > 0.5 \text{ GeV}/c$
- $p_T^{\gamma, \text{EMCal triggered}} > 2.5 \text{ GeV}/c$



# $\tau$ anomalous magnetic moment

- Anomalous magnetic moment:
  - $a_\tau^{\text{exp}} = -0.018(17)$  (DELPHI, EPJC 35 (2004) 159)
  - $a_\tau^{\text{SM}} = 0.00117721(5)$  (S. Eidelman and M. Passera, Mod. Phys. Lett. A 22, 159 (2007))
- Cross section and  $\tau$  kinematics sensitive to  $a_\tau$ 
  - L. Beresford and J. Liu, PRD 102 (2020) 113008
  - M. Dyndał et al., PLB 809 (2020) 135682
  - Burmasov et al., arXiv:2203.00990 (2022)

