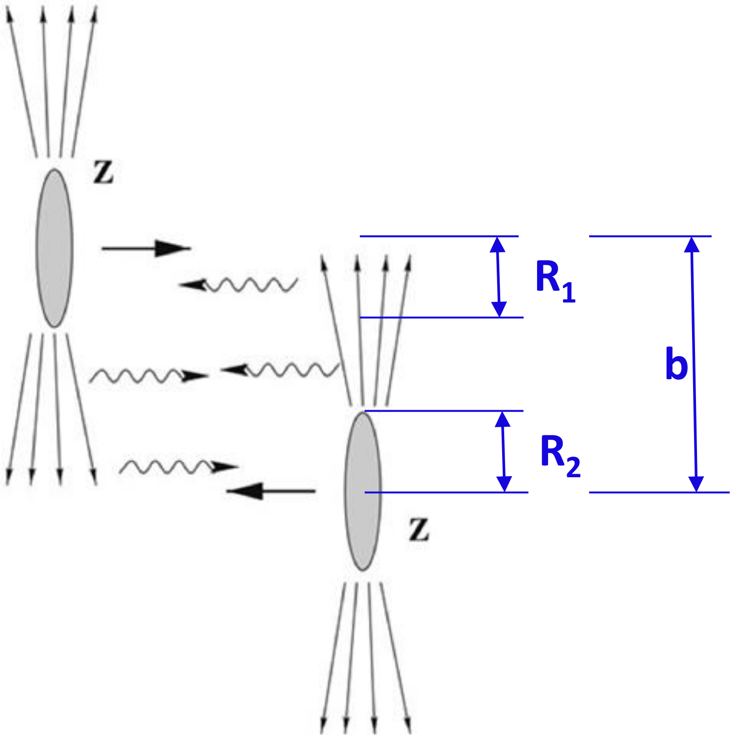
# Photoproduction of heavy vector mesons in ultra-peripheral Pb-Pb collisions

## New results on coherent J/ψ photoproduction in PbPb 2015 data and highlights from p-Pb @ 8 TeV

Evgeny Kryshen
(Petersburg Nuclear Physics Institute, Russia)
for the ALICE collaboration

Quark Matter
Chicago, 7 February 2017

# LHC as a $\gamma$Pb collider




**Ultra-peripheral (UPC) collisions: $b > R_1+R_2$**

→ hadronic interactions strongly suppressed

**High photon flux**

→ well described in Weizsäcker-Williams approximation (quasi-real photons)

→ flux proportional to $Z^2$

→ high cross section for $\gamma$-induced reactions

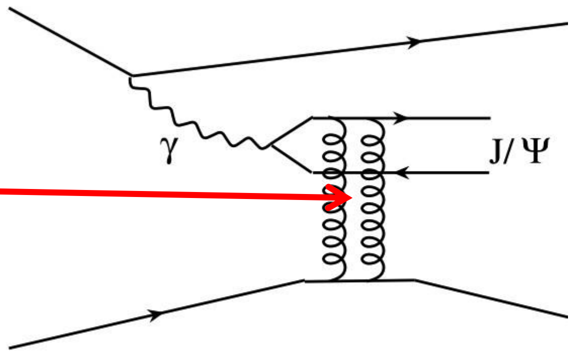
**Pb-Pb UPC at LHC can be used to study $\gamma$-Pb interactions at higher center-of-mass energies than ever before**

**Recent reviews on UPC physics:**
**A.J. Baltz et al, Phys. Rept. 458 (2008) 1**
**J.G. Contreras, J.D. Tapia Takaki. Int.J.Mod.Phys. A30 (2015) 1542012**

# J/ψ photoproduction in UPC

- LO pQCD: coherent J/ψ photoproduction cross section is proportional to the **square of the gluon density in the target**:

$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{\rm em}Q^8}\left[xg_A(x,Q^2)\right]^2$$

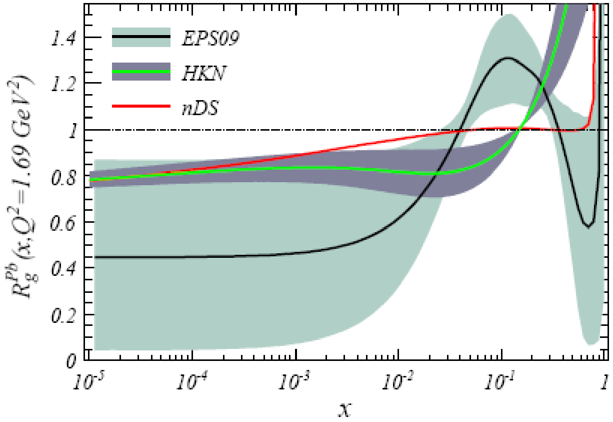



- Mass of J/ψ serves as a hard scale: $Q^2 \sim \frac{M^2_{J/\psi}}{4} \sim 2.5\ \mathrm{GeV}^2$

- Bjorken $x$ ~ $10^{-2}$ – $10^{-5}$ accessible at LHC: $x = \frac{M^2_{J/\psi}}{W^2_{\gamma p}} = \frac{M_{J/\psi}}{2E_p}\exp(\pm y)$

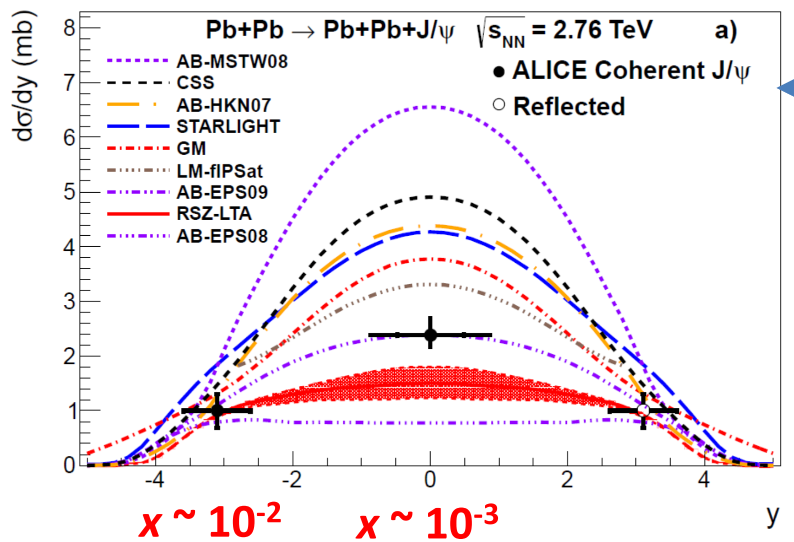
- J/ψ photoproduction in Pb-Pb UPC (lead target): information on **gluon shadowing in nuclei at low $x$**

$$R_g^A(x,Q^2) = \frac{g_A(x,Q^2)}{Ag_p(x,Q^2)}$$ – gluon shadowing factor

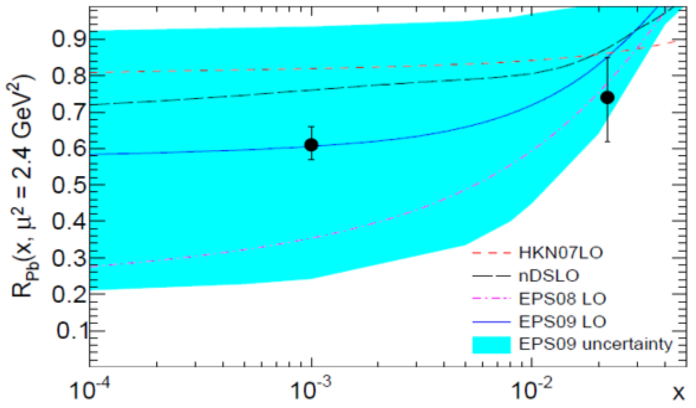


# Reminder: results from Run 1

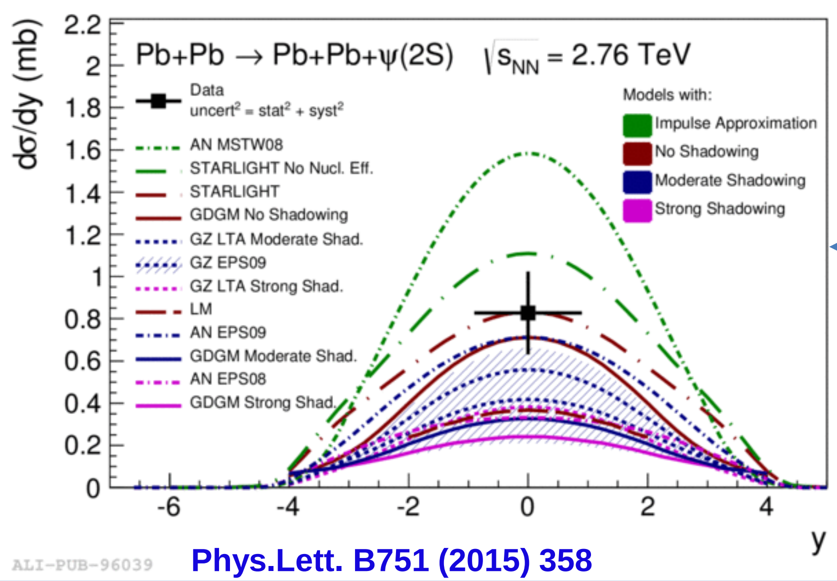
**Phys. Lett. B718 (2013) 1273, Eur. Phys. J. C73 (2013) 2617**




- **J/ψ:** best agreement with models based on EPS09 shadowing (shadowing factor ~0.6 at $x \sim 10^{-3}$, $Q^2 \sim$ 2.4-3 GeV$^2$)




**V. Guzei et al. PLB 726 (2013) 290**



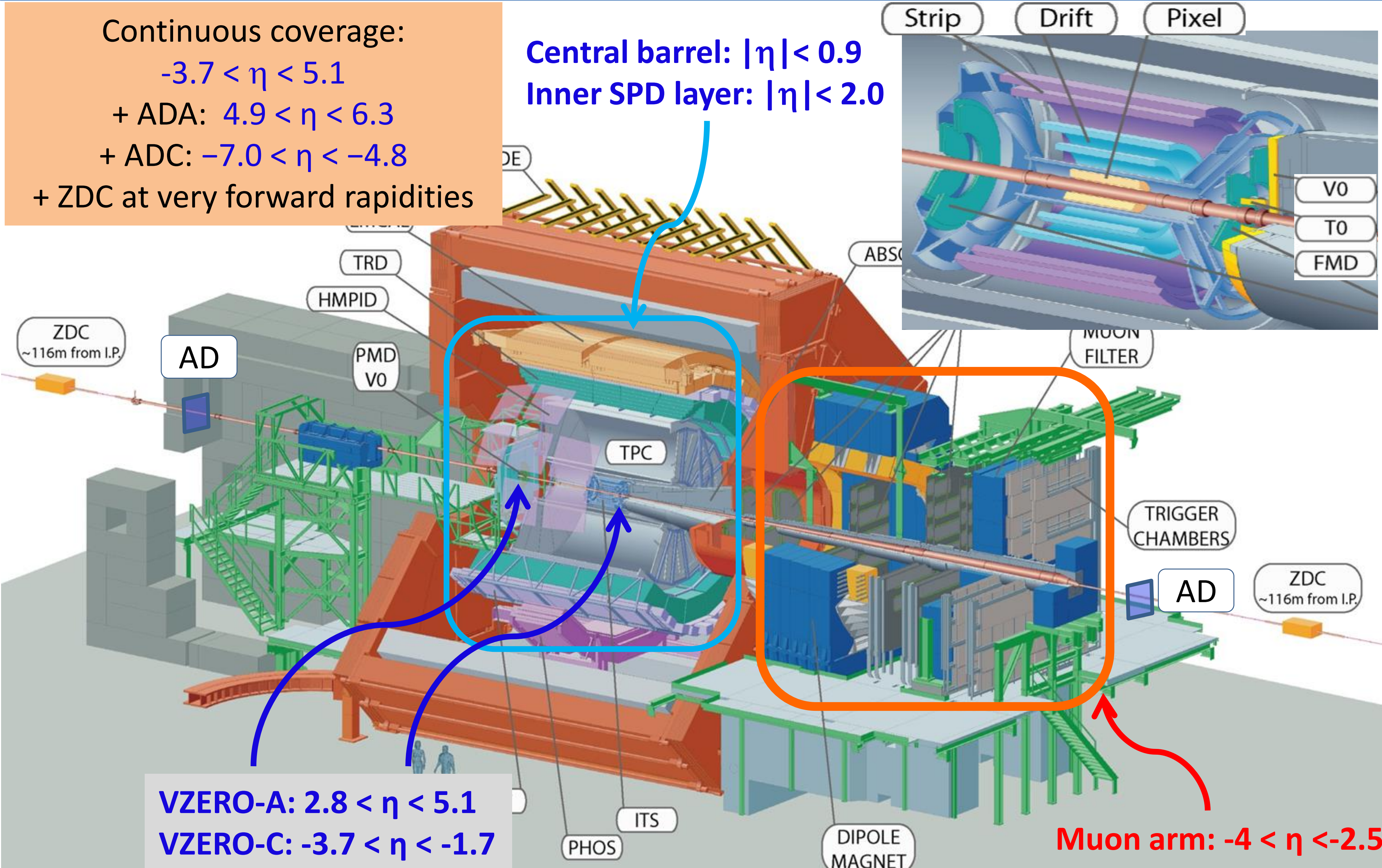

**Phys.Lett. B751 (2015) 358**

- **ψ':** disfavour models with no nuclear effects and models with strong gluon shadowing
- σ(ψ')/σ(J/ψ) ~ 0.34 ± 0.08 (stat+syst) expected < 0.20

# Looking for two tracks in an otherwise empty detector…

Continuous coverage:
$-3.7 < \eta < 5.1$
+ ADA: $4.9 < \eta < 6.3$
+ ADC: $-7.0 < \eta < -4.8$
+ ZDC at very forward rapidities

**Central barrel: $|\eta| < 0.9$**
**Inner SPD layer: $|\eta| < 2.0$**

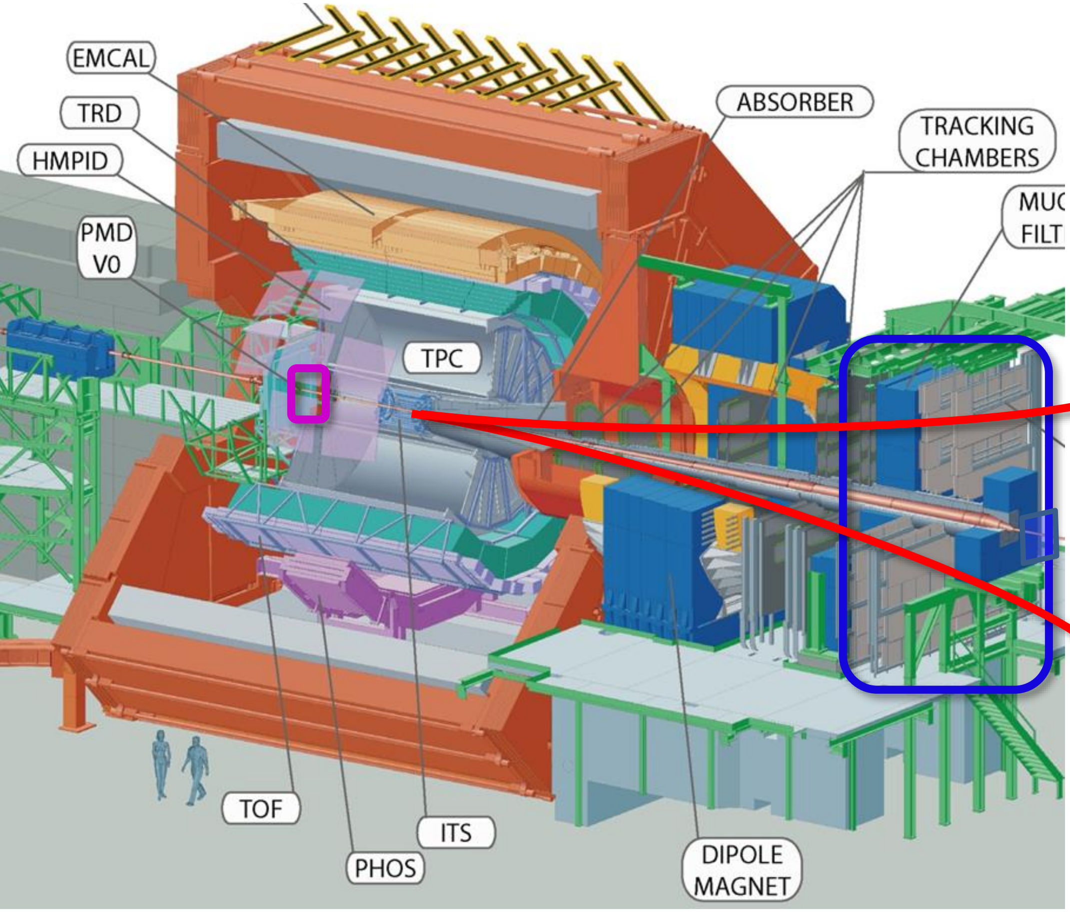


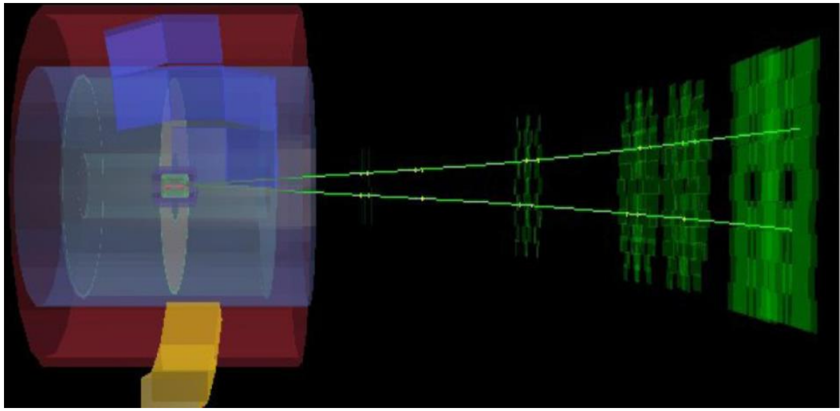

**VZERO-A: $2.8 < \eta < 5.1$**
**VZERO-C: $-3.7 < \eta < -1.7$**

**Muon arm: $-4 < \eta < -2.5$**

# J/ψ at forward rapidity: 2015 data

**UPC forward trigger:**
- 2 unlike-sign tracks with pt>1 GeV/c ($-4 < \eta < -2.5$)
- no hits in **AD-A** ($4.9 < \eta < 6.3$)
- no hits in **AD-C** ($-7.0 < \eta < -4.8$)
- no hits in **VZERO-A** ($2.8 < \eta < 5.1$)



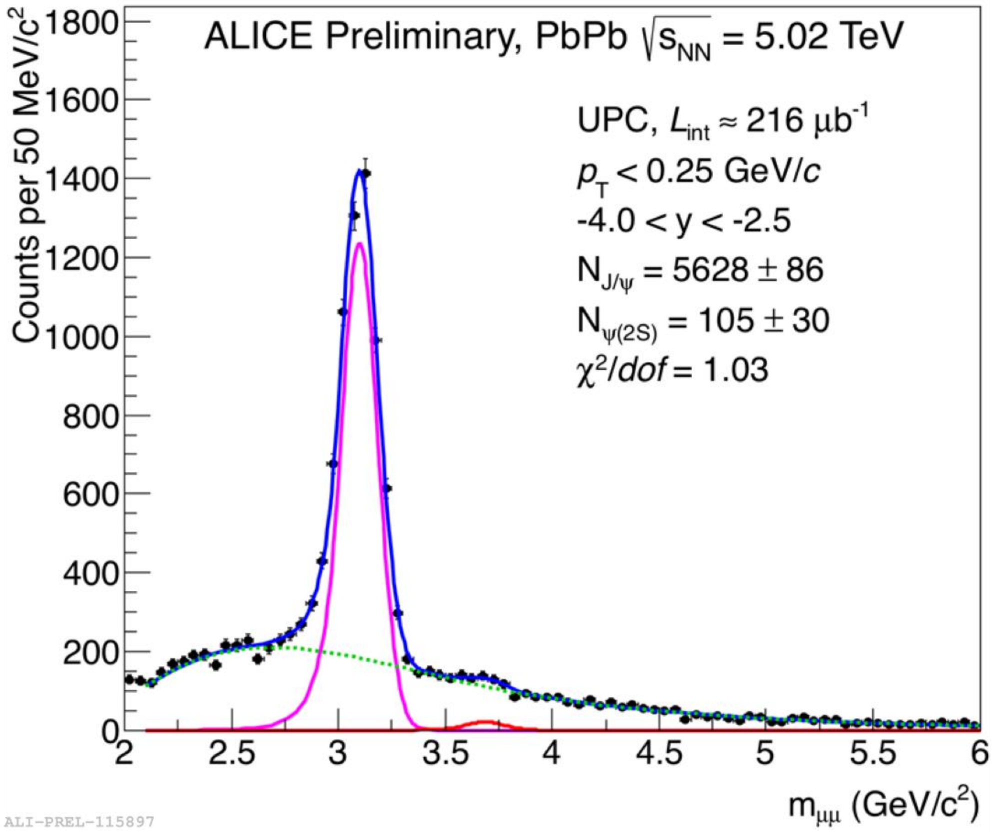



**Pb-Pb integrated luminosity ~ 216 μb$^{-1}$**

**Offline event selection:**
- Vetoes in VZERO in AD
- No SPD tracklets

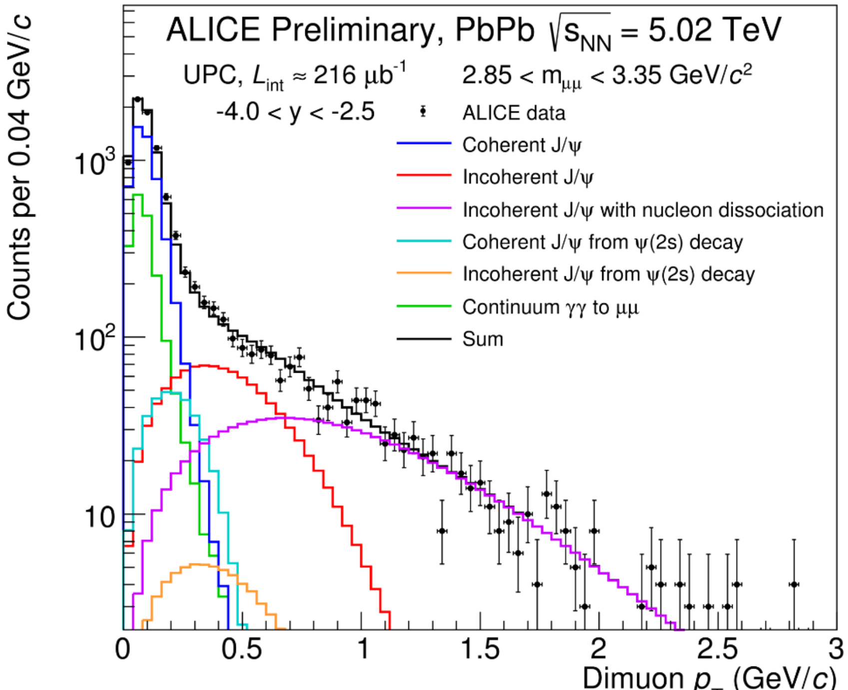
**Track selection:**
- muon tracks: $-4 < \eta < -2.5$
- matching with trigger chambers
- radial position for muons at the end of absorber: $17.5 < R_{abs} < 89.5$ cm
- $p_T$ dependent DCA cut
- opposite sign dimuon

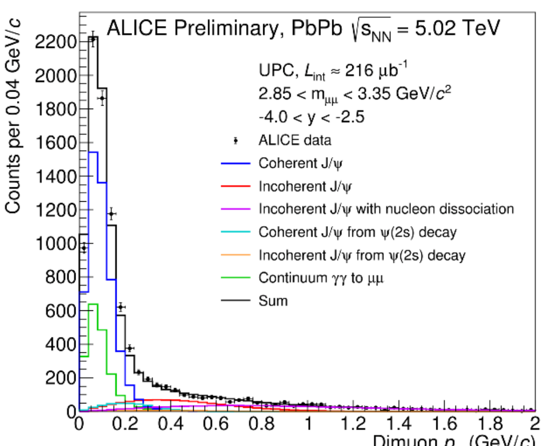
# Invariant mass distribution




- dimuon $p_T < 0.25$ GeV/$c$
- $\psi(2S)$ at 3 sigma significance, $\sigma(\psi(2S))/\sigma(J/\psi)$ ratio close to HERA γp results ($\sigma(2S)/\sigma(1S) = 0.166 \pm 0.011$)
- $J/\psi$ and $\psi(2S)$ fitted to a Crystal Ball
- background (exponent x turn-on polynomial) perfectly described by $\gamma\gamma \rightarrow \mu\mu$ shape from Starlight Monte-Carlo

# $p_T$ distributions

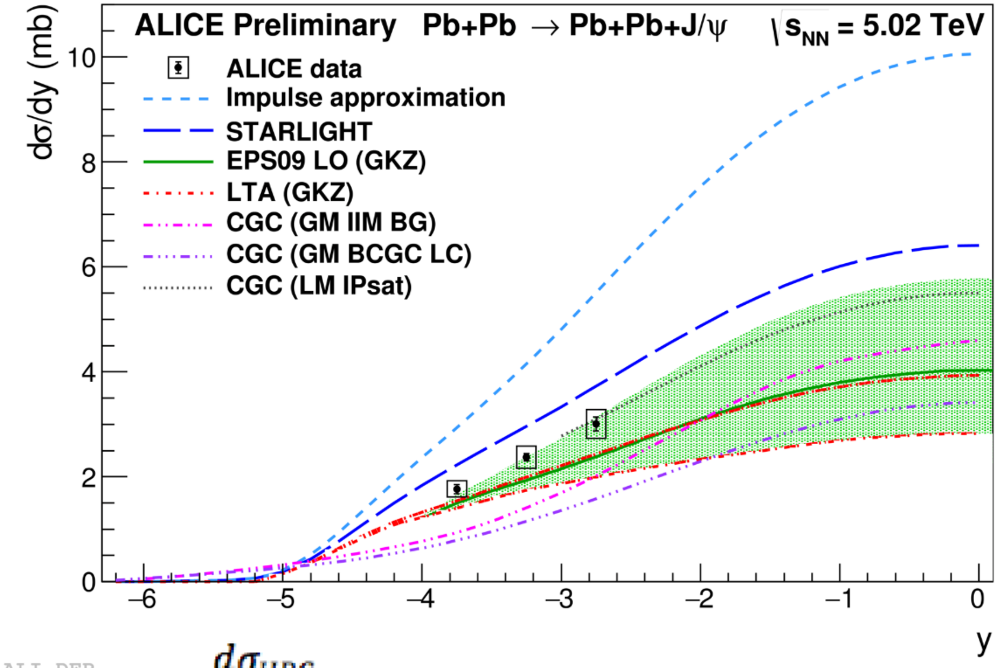



**Contributions (templates from MC):**

- **Coherent J/ψ:**
  - photon couples coherently to all nucleons
  - $\langle p_T \rangle \sim 1/R_{Pb} \sim 60$ MeV/c
- **Incoherent J/ψ:**
  - photon couples to a single nucleon
  - $\langle p_T \rangle \sim 1/R_p \sim 450$ MeV/c
- **Incoherent J/ψ with nucleon dissociation:**
  - shape parameters from HERA
- **J/ψ from coherent and incoherent ψ' decays:** fixed wrt primary J/ψ (~5-6%)
- **γγ →μμ:** fixed integral wrt J/ψ peak (~5%)

# Coherent J/ψ cross section




$$\frac{d\sigma_{UPC}}{dy} = n(\omega_1)\sigma_{\gamma T}(\omega_1) + n(\omega_2)\sigma_{\gamma T}(\omega_2)$$

Low energy (high-x) High energy (low-x)

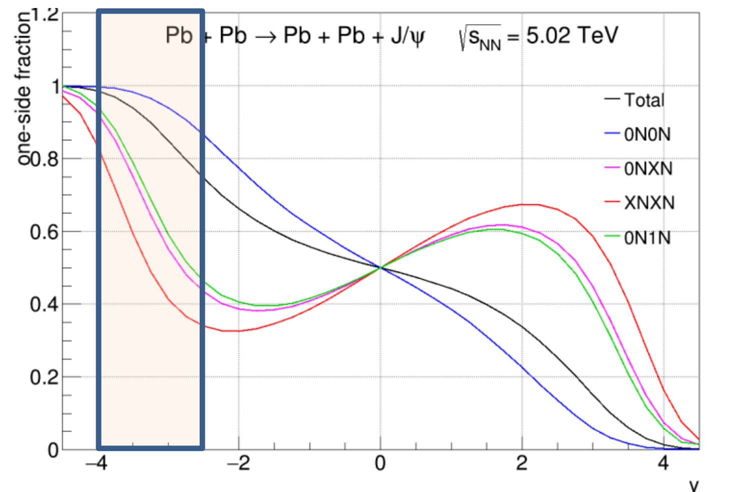
- 90-95% contribution of high-$x$: 0.7-3 x $10^{-2}$
- Back-of-the-envelop calculation (neglect low-$x$): ALICE/Impulse approximation ~ 0.6 => shadowing factor $\sim \sqrt{0.6} \sim 0.8$ (see Phys. Lett. B726 (2013) 290 for details)

- **Impulse approximation: no nuclear effects**
- **STARLIGHT: VDM + Glauber,** Klein, Nystrand et al: Comput. Phys. Commun. 212 (2017) 258
- **EPS09 L0 (GKZ): EPS09 shadowing** Guzey, Kryshen, Zhalov, PRC93 (2016) 055206
- **LTA (GKZ): Leading Twist Approximation** Guzey, Kryshen, Zhalov, PRC93 (2016) 055206
- **GM: Color dipole model + IIM/BCGC CGC** Goncalves, Machado et al.: PRC 90 (2014) 015203, JPG 42 (2015) 105001
- **LM IPSat: Color dipole model + IPSat CGC** T. Lappi, H. Mäntysaari, PRC 83 (2011) 065202; 87 (2013) 032201

**Coherent J/ψ cross section in agreement with moderate nuclear gluon shadowing**

# Next…

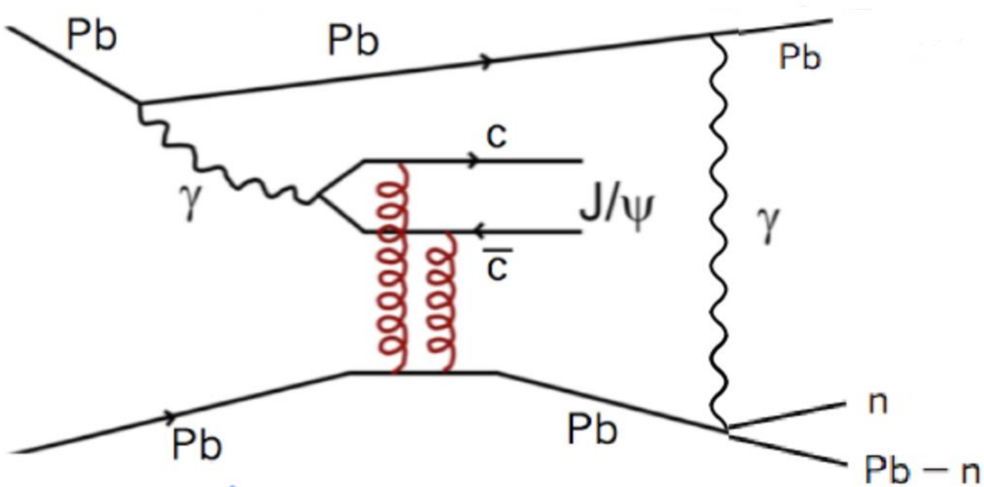
- Study J/ψ photoproduction accompanied by neutron emission (measured with Zero Degree Calorimeters) => access $x$~$10^{-5}$
- J/ψ polarization
- Incoherent cross-section

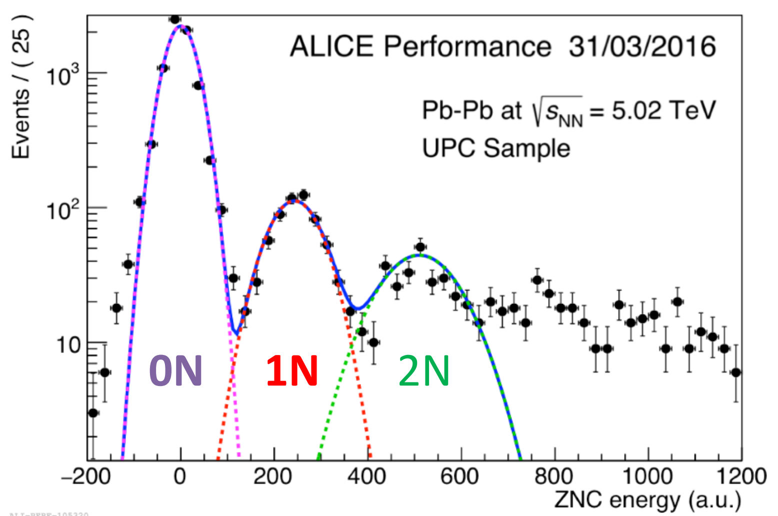



Derived from V. Guzey, EK, M. Zhalov, **PRC93 (2016), 055206**

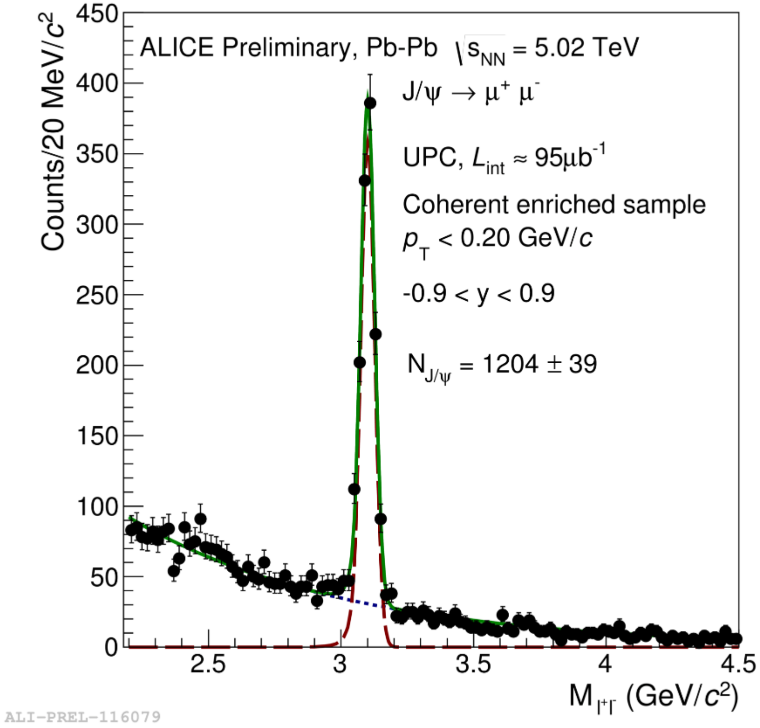
$$\frac{d\sigma_{UPC}}{dy} = n(\omega_1)\sigma_{\gamma T}(\omega_1) + n(\omega_2)\sigma_{\gamma T}(\omega_2)$$

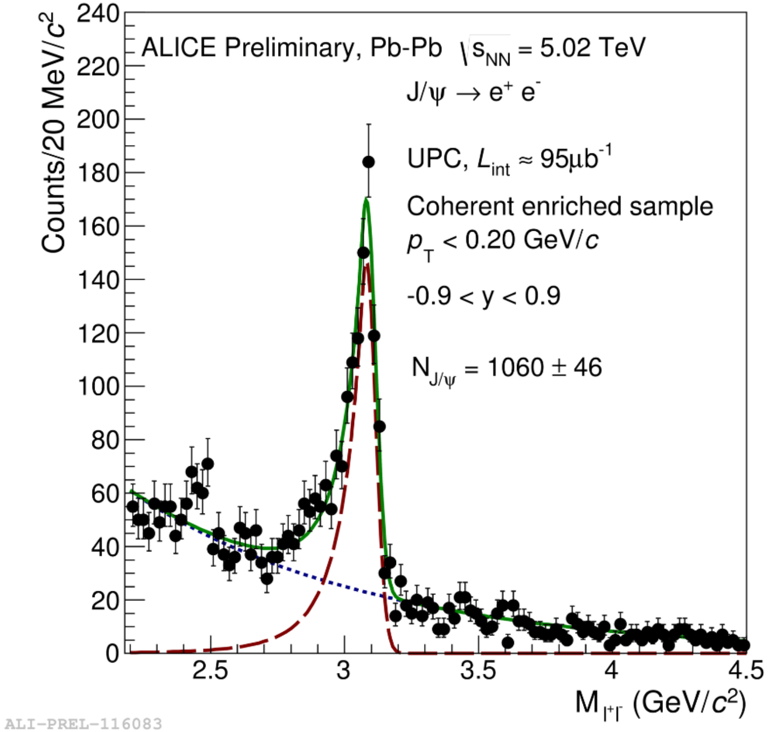
Low energy (high-x) High energy (low-x)



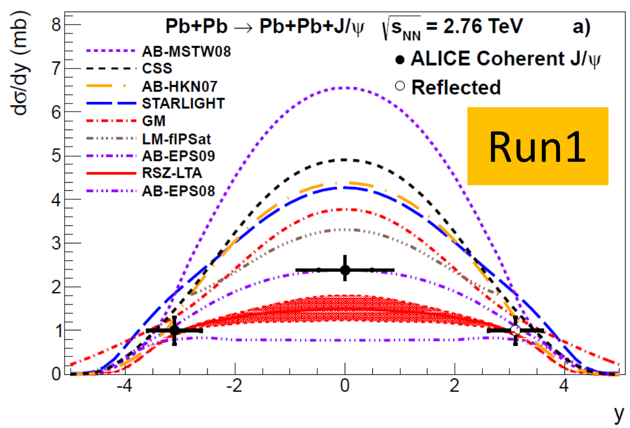



# + J/ψ in central barrel

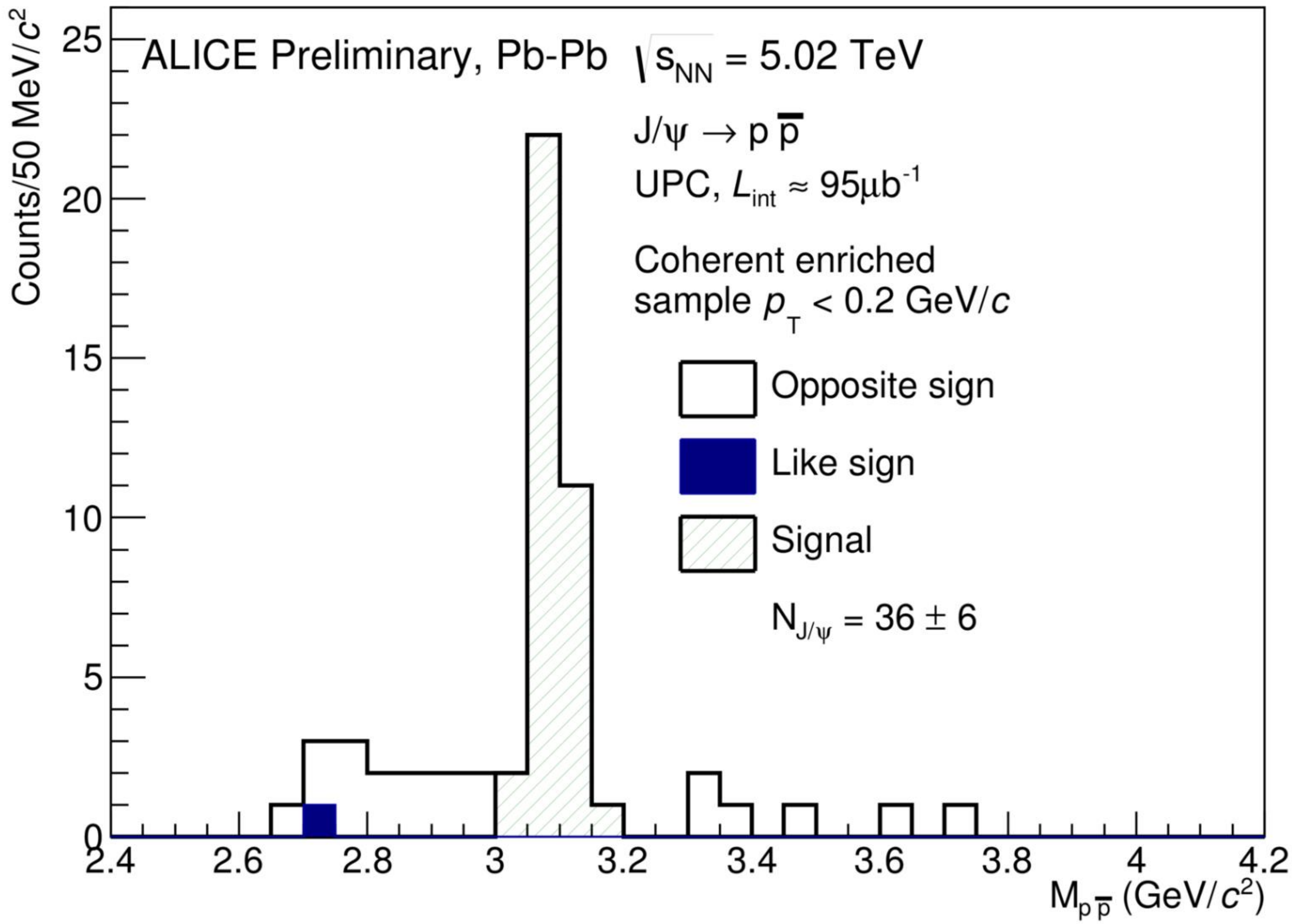



- x4 more statistics wrt Run1
- access to $x \sim 0.5 \times 10^{-3}$

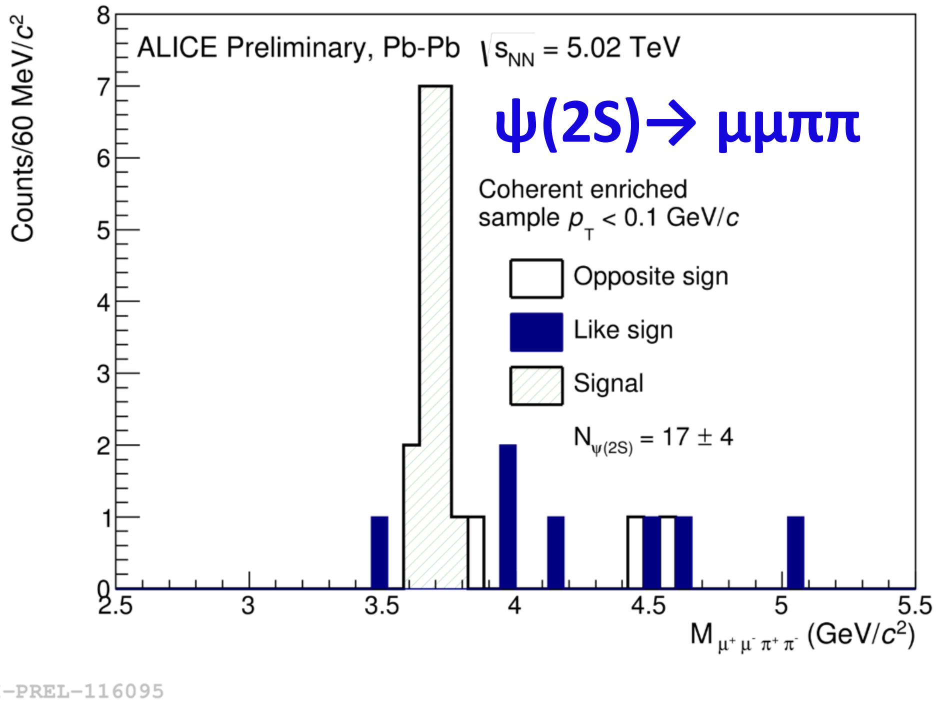


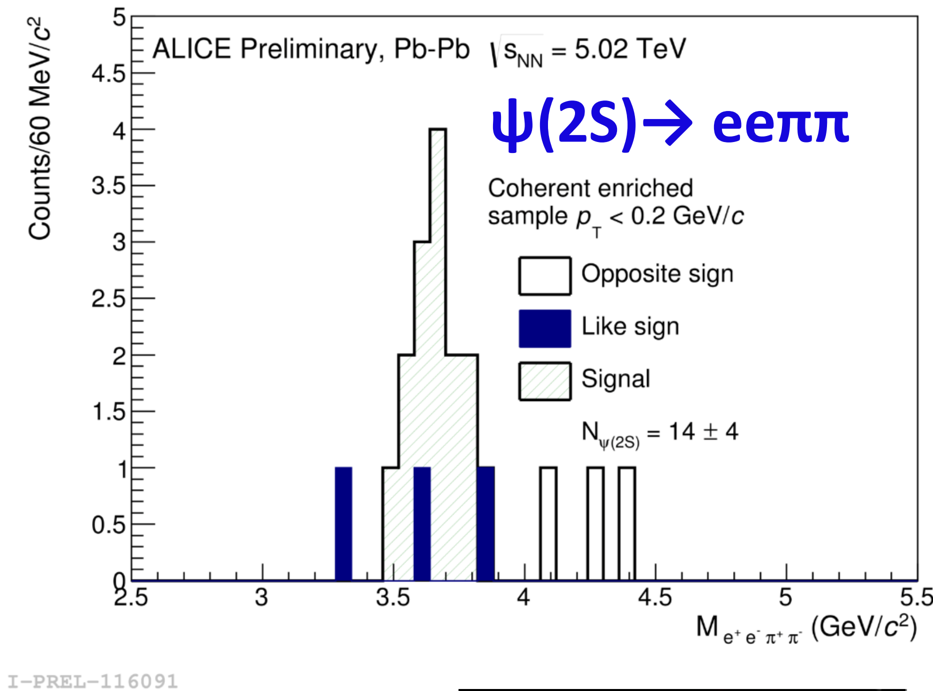
# First observation in UPC: J/ψ→ $p\bar{p}$



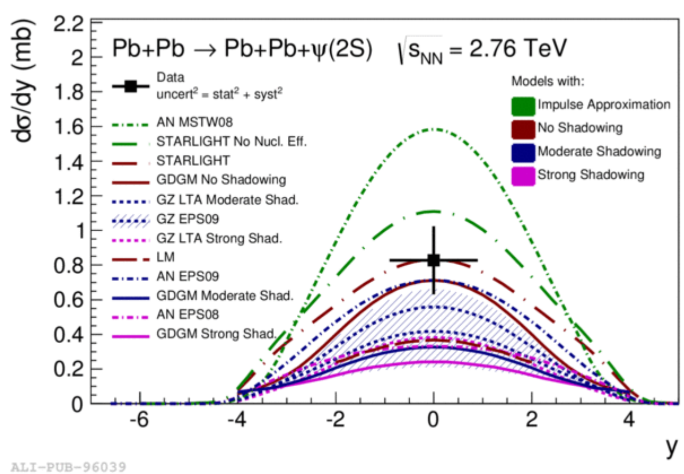

ALI-PREL-117138

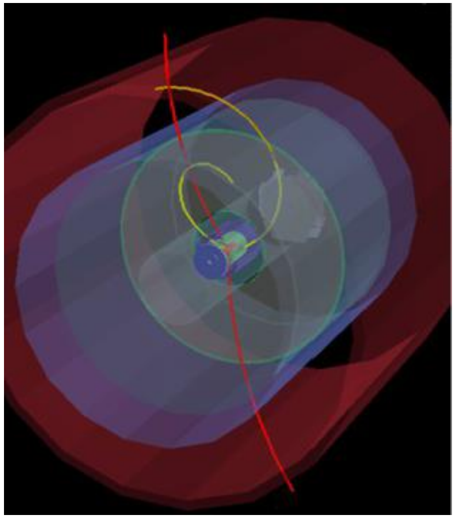
# + ψ(2S) → J/ψππ



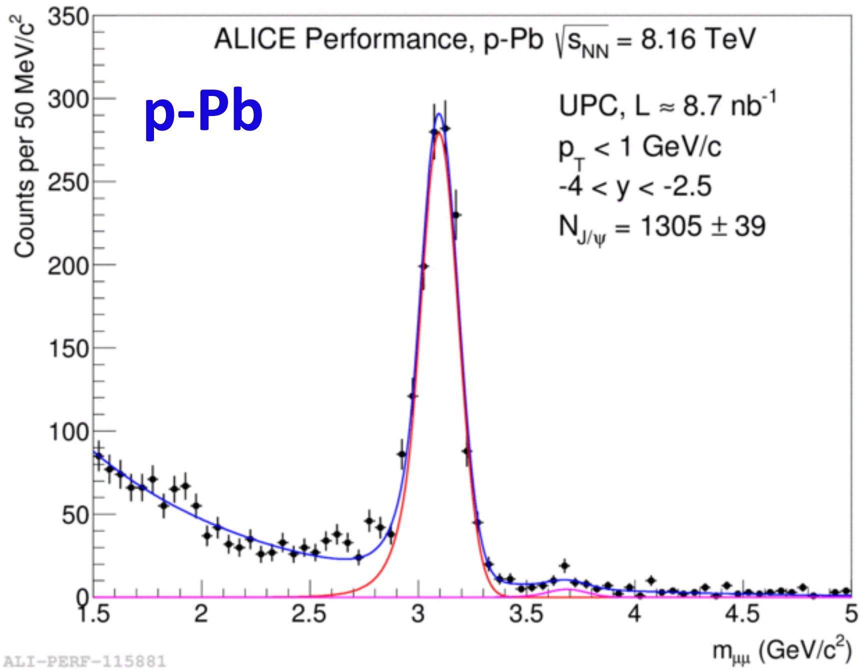



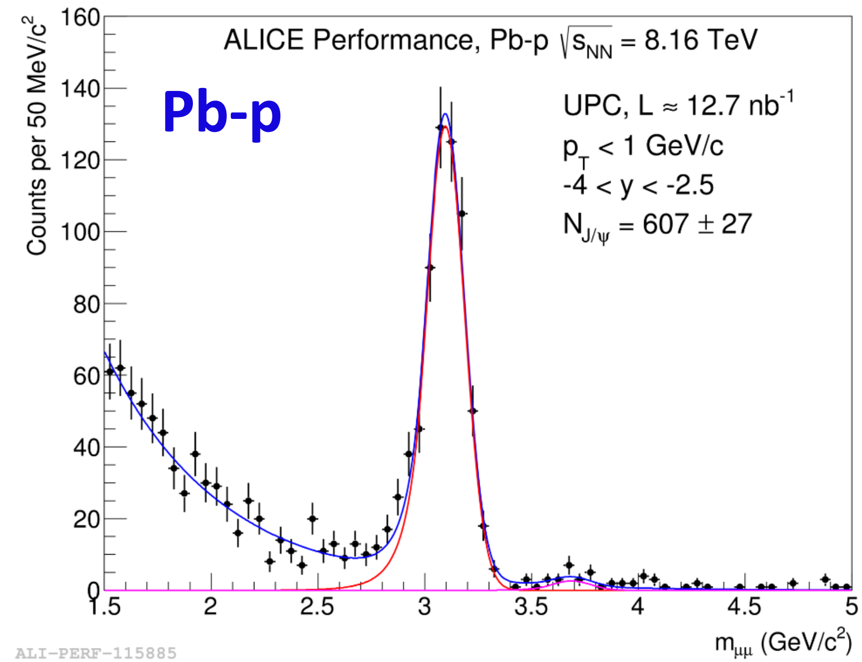

**Run 1**



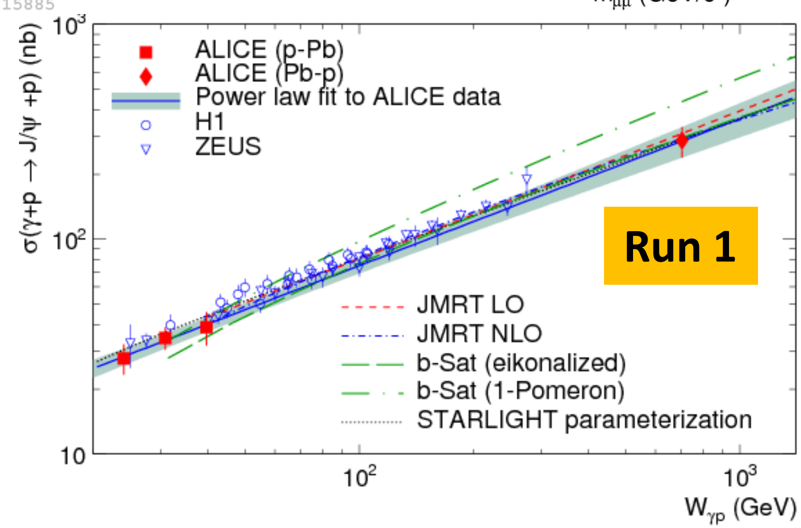



# p-Pb @ 8 TeV




- x10 more stat at high $W_{\gamma p}$ ~ 0.7-1.4 TeV
- search for gluon saturation effects in p at low $x$~$10^{-5}$
- study proton-dissociative cross section behaviour at high $W_{\gamma p}$




PRL 113 (2014) 232504

# Summary and outlook

- Coherent J/ψ photoproduction cross section at forward rapidity in Pb-Pb at 5 TeV in agreement with moderate nuclear gluon shadowing

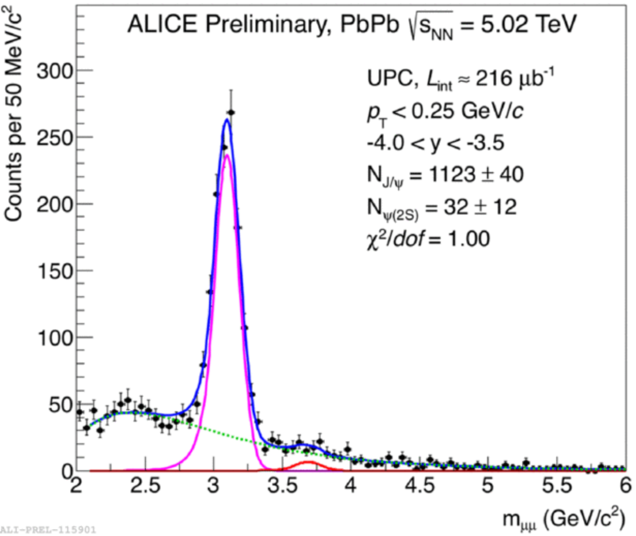
- More results from Run2 expected soon:
  - Incoherent J/ψ, ZDC-differential studies, J/ψ polarization at forward rapidity
  - J/ψ and ψ(2S) photoproduction in Pb-Pb at central rapidity
  - J/ψ photoproduction in p-Pb

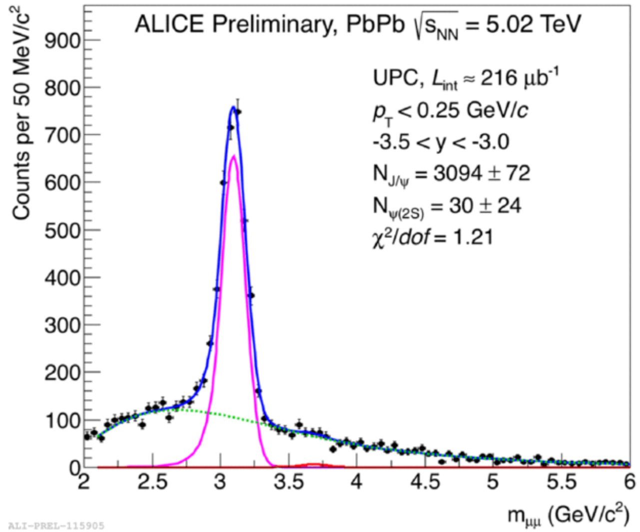
→ Poster on ρ photoproduction in Pb-Pb Run2 data by David Horak

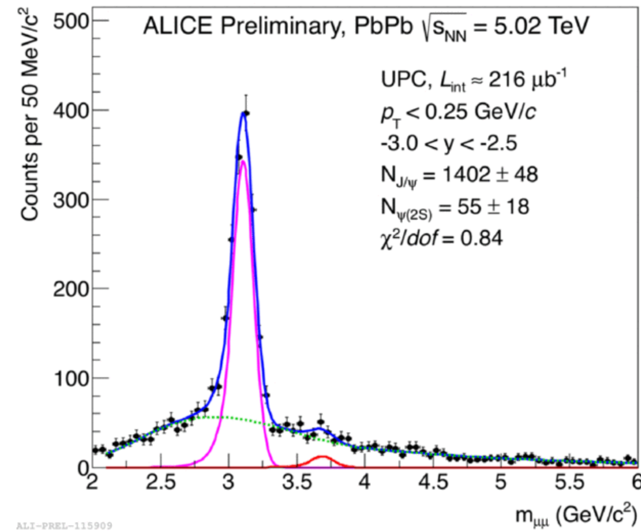
BACKUP

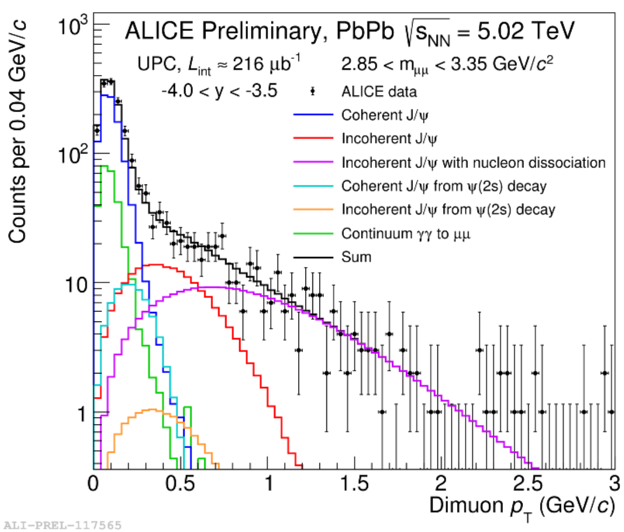
# Invariant mass and pt fits in rapidity bins

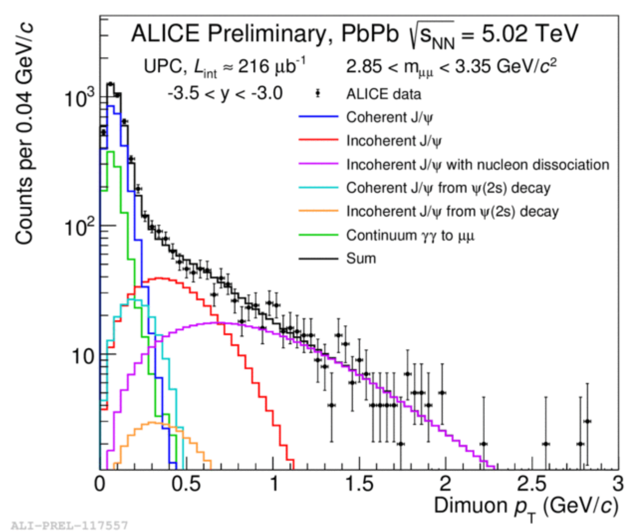
- Cross sections extracted in 3 rapidity bins (-4.0,-3.5,-3.0,-2.5)

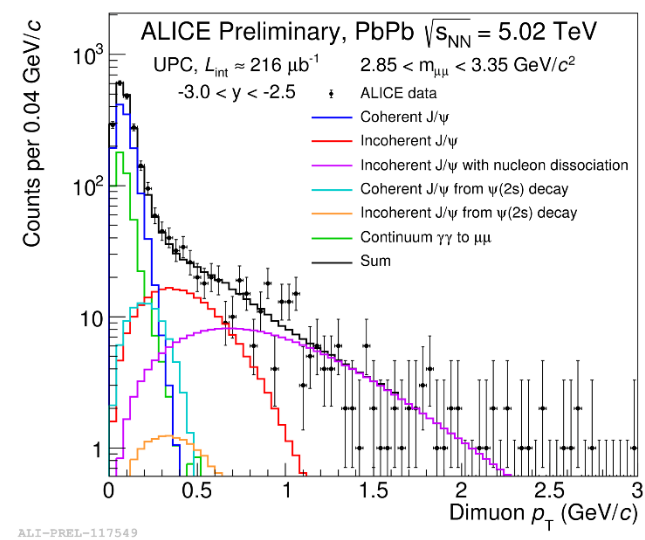


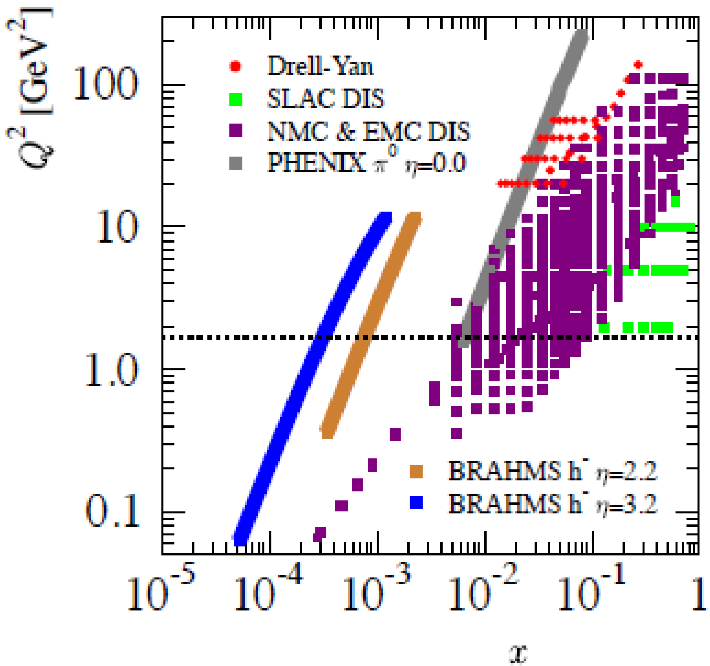



# Parton distributions in nuclei (nPDFs)

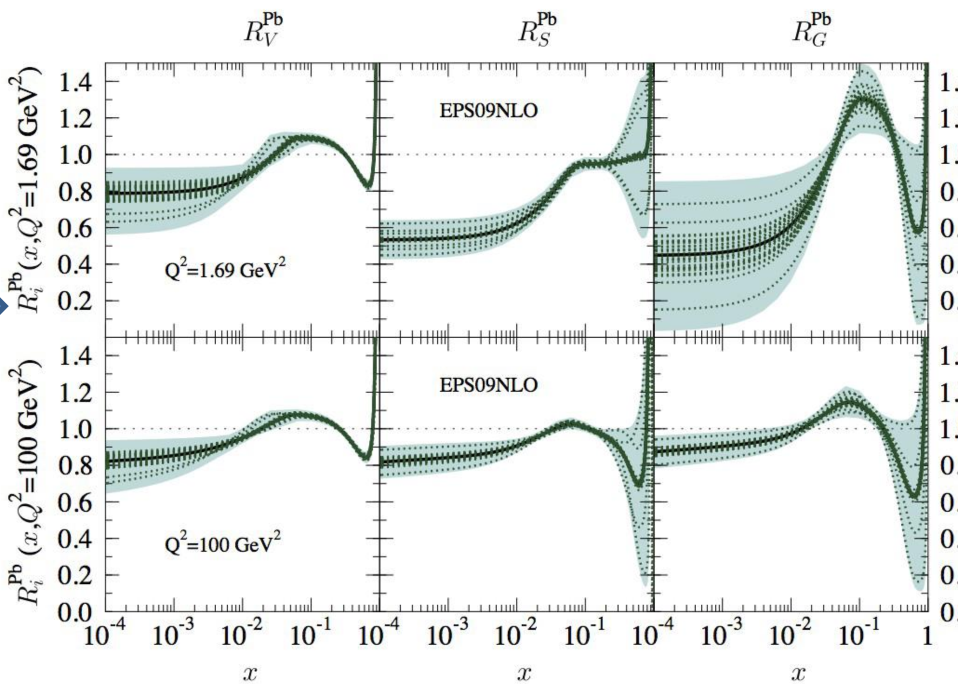
**nPDFs are fundamental QCD quantities** for the description of DIS, pA, AA collisions

- determine initial state in heavy ion collisions (main motivation for p-Pb runs)
- required for quantitative estimates for the onset of saturation

**Determination of nPDFs:**




C. Salgado et al. JHEP 0904:065,2009

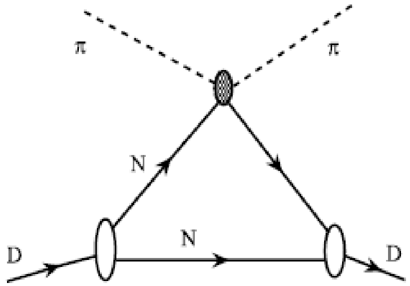


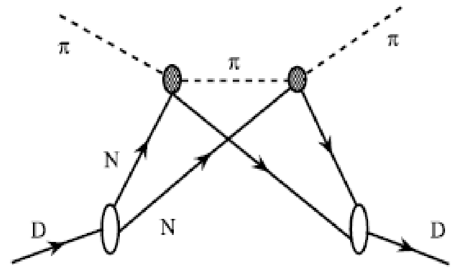

Resulting nPDFs have rather **large uncertainties, especially for small-x gluons** due to:

- Limited kinematics
- Indirect extraction of gluons via $Q^2$ evolution

# On nuclear shadowing

**Glauber shadowing (modeling of several consequent interactions):**

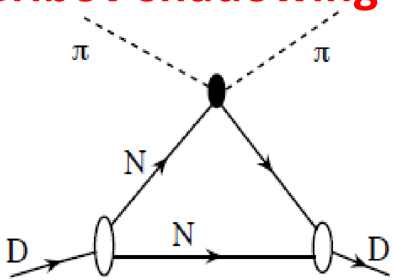


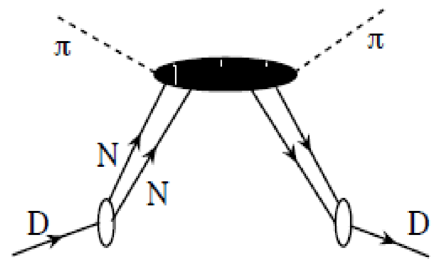




$$\sigma_{\rm tot}^{\pi D} = 2\,\sigma_{\rm tot}^{\pi N} - \frac{(\sigma_{\rm tot}^{\pi N})^2}{4\pi} \left\langle \frac{1}{r^2} \right\rangle_D$$

**shadowing = destructive interference between single and multiple interactions**

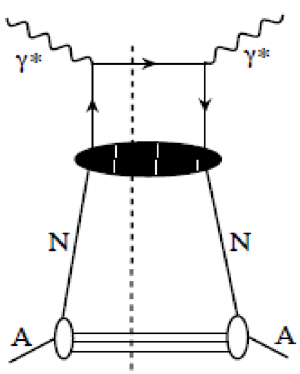
**Gribov shadowing (coherent interaction via intermediate diffractive states):**

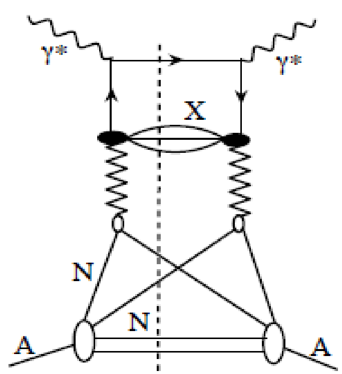



$$\sigma_{\rm tot}^{\pi D} = 2\sigma_{\rm tot}^{\pi N} - 2\int d\vec{k}^2 \rho\left(4\vec{k}^2\right) \frac{d\sigma_{\rm diff}^{\pi N}(\vec{k})}{d\vec{k}^2}$$

**Leading twist shadowing (generalization of Gribov shadowing to the parton level):**




$$xf_{j/A}^{(b)}(x,Q^2) = -8\pi A(A-1)\Re e\frac{(1-i\eta)^2}{1+\eta^2}\int_x^{0.1} dx_{\mathbb{P}}\beta f_j^{D(4)}(\beta,Q^2,x_{\mathbb{P}},t_{\rm min})$$
$$\times \int d^2\vec{b}\int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2\, \rho_A(\vec{b},z_1)\rho_A(\vec{b},z_2)e^{i(z_1-z_2)x_{\mathbb{P}}m_N}.$$

shadowing is expressed via diffractive PDFs

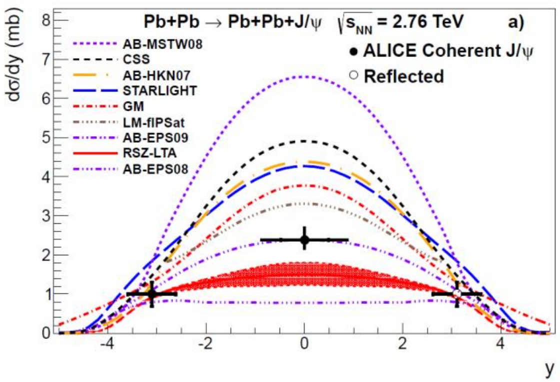
# Photoproduction cross-section from ALICE data

V. Guzei, E. Kryshen, M. Strikman, M. Zhalov. Phys. Lett. B726 (2013) 290

## ALICE measurement:

$$\frac{\sigma_{AA\to AAJ/\psi}(|y|<0.9)}{\Delta y} = 2.33 \pm 0.13(\mathrm{stat}) \pm 0.23(\mathrm{syst})\ \mathrm{mb}$$

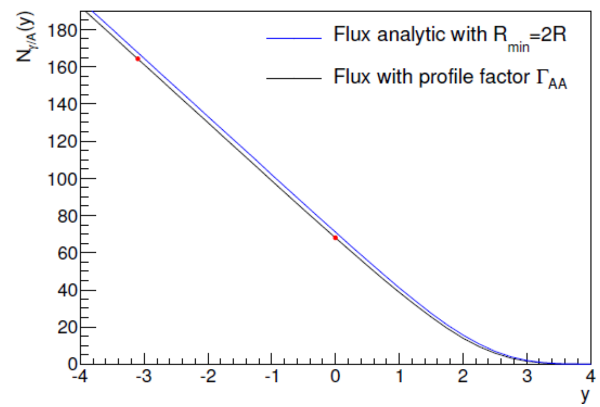
$$\frac{\sigma_{AA\to AAJ/\psi}(-3.6<y<-2.6)}{\Delta y} = 1.00 \pm 0.18(\mathrm{stat})^{+0.23}_{-0.26}(\mathrm{syst})\ \mathrm{mb}$$




## Photon flux:

$$N_{\gamma/Pb}(y=-3.1) = 163.9 \pm 8.2$$

$$N_{\gamma/Pb}(y=0) = 67.7 \pm 3.4$$




## J/ψ photoproduction cross section from ALICE data:

$$\sigma_{\gamma Pb\to PbJ/\psi}(W_{\gamma p}=19.6\,\mathrm{GeV}) = 6.1^{+1.8}_{-2.0}\ \mu\mathrm{b}$$

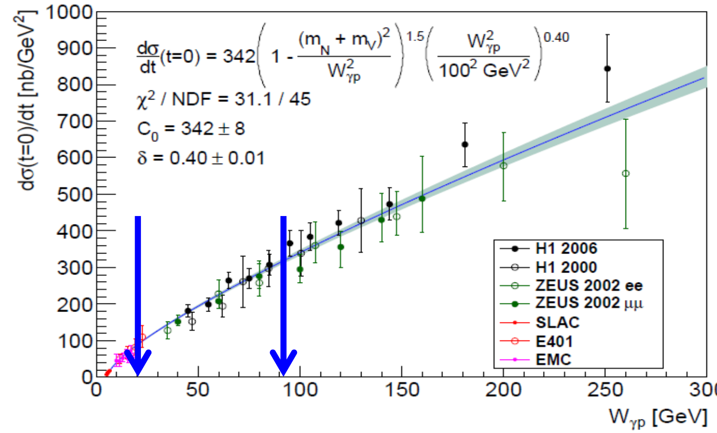
$$\sigma'_{\gamma Pb\to PbJ/\psi}(W_{\gamma p}=92.4\,\mathrm{GeV}) = 17.2 \pm 2.1\ \mu\mathrm{b}$$

# Photoproduction cross-section in the Impulse Approximation

V. Guzei, E. Kryshen, M. Strikman, M. Zhalov. Phys. Lett. B726 (2013) 290

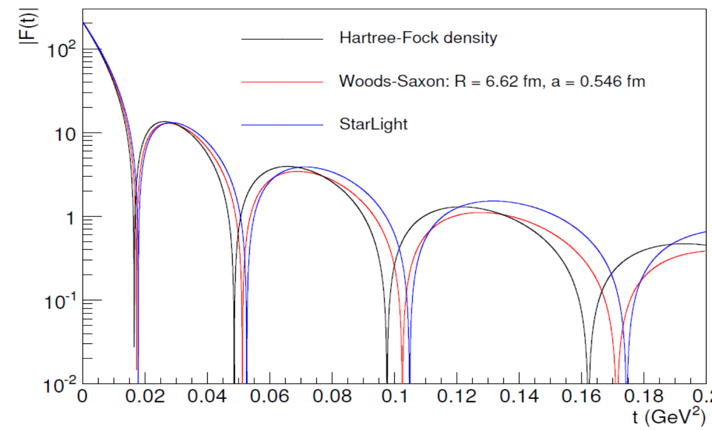
Forward J/psi photoproduction cross section:

$$\frac{d\sigma_{\gamma p\to J/\psi p}(19.6\text{ GeV}, t=0)}{dt} = 86.9 \pm 1.8\text{ nb/GeV}^2$$
$$\frac{d\sigma_{\gamma p\to J/\psi p}(92.4\text{ GeV}, t=0)}{dt} = 319.8 \pm 7.1\text{ nb/GeV}^2$$




Integral over squared form factor:

$$\Phi_{WS}(W_{\gamma p} = 19.6\text{ GeV}) = 127.2\text{ GeV}^2$$
$$\Phi_{WS}(W_{\gamma p} = 92.4\text{ GeV}) = 149.2\text{ GeV}^2$$




J/psi photoproduction on nucleus in Impulse Approximation:

$$\Phi(t_{min}) = \int_{t_{min}}^{\infty} dt\,|F_A(t)|^2$$

$$\sigma^{IA}_{\gamma Pb\to PbJ/\psi}(W_{\gamma p} = 19.6\text{GeV}) = 11.1 \pm 0.6\ \mu\text{b}$$
$$\sigma^{IA}_{\gamma Pb\to PbJ/\psi}(W_{\gamma p} = 92.4\text{GeV}) = 47.7 \pm 2.6\ \mu\text{b}$$

# Estimation of the nuclear suppression factor

V. Guzei, E. Kryshen, M. Strikman, M. Zhalov. Phys. Lett. B726 (2013) 290

- J/psi photoproduction cross section measured by ALICE:

$$\sigma_{\gamma Pb \to PbJ/\psi}(W_{\gamma p} = 19.6\,\text{GeV}) = 6.1^{+1.8}_{-2.0}\ \mu\text{b}$$
$$\sigma_{\gamma Pb \to PbJ/\psi}(W_{\gamma p} = 92.4\,\text{GeV}) = 17.2 \pm 2.1\ \mu\text{b}$$

÷

- J/psi photoproduction cross section in the Impulse Approximation:

$$\sigma^{IA}_{\gamma Pb \to PbJ/\psi}(W_{\gamma p} = 19.6\,\text{GeV}) = 11.1 \pm 0.6\ \mu\text{b}$$
$$\sigma^{IA}_{\gamma Pb \to PbJ/\psi}(W_{\gamma p} = 92.4\,\text{GeV}) = 47.7 \pm 2.6\ \mu\text{b}$$

- Nuclear suppression factor:

$$S(W_{\gamma p}) \equiv \left[ \frac{\sigma_{\gamma \text{Pb} \to J/\psi \text{Pb}}(W_{\gamma p})}{\sigma^{\text{IA}}_{\gamma \text{Pb} \to J/\psi \text{Pb}}(W_{\gamma p})} \right]^{1/2}$$

$$S(W_{\gamma p} = 19.6\ \text{GeV}) = 0.74^{+0.11}_{-0.12}$$
$$S(W_{\gamma p} = 92.4\ \text{GeV}) = 0.61^{+0.05}_{-0.04}$$