ALICE results on vector meson photoproduction in ultraperipheral p-Pb and Pb-Pb collisions

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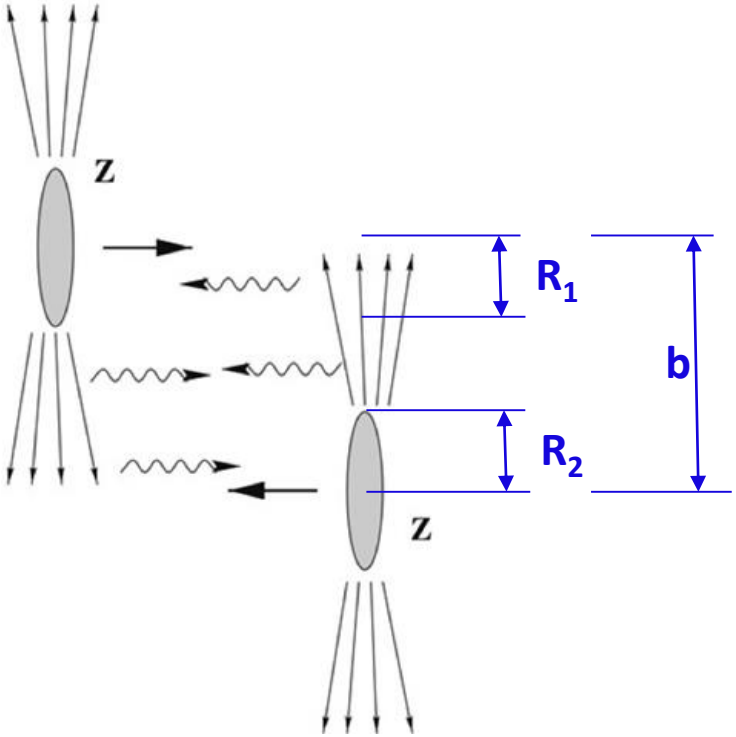
INT workshop INT-17-65W
Probing QCD in Photon-Nucleus Interactions at RHIC and LHC: the path to EIC
Seattle, 13 February 2017

LHC as a γPb 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 γ-induced reactions

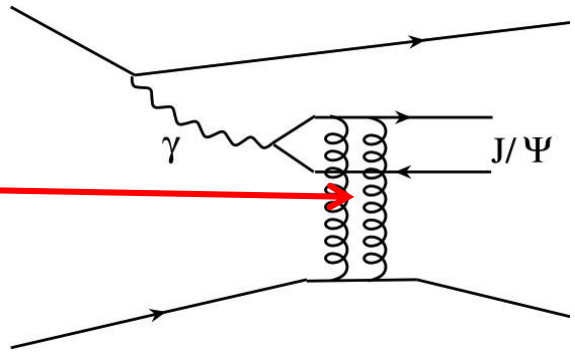
Pb-Pb UPC at LHC can be used to study γ-Pb interactions at higher center-of-mass energies than ever before

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**:

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

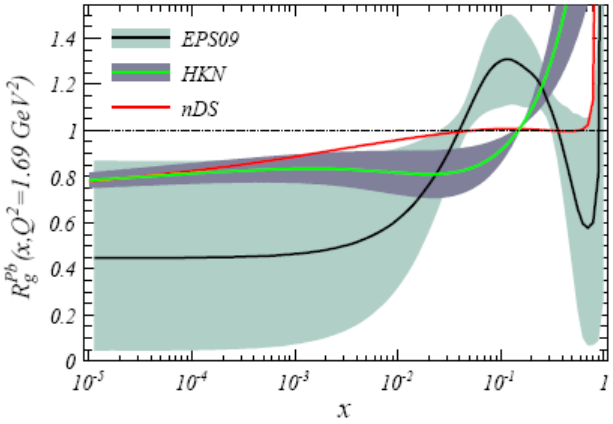


- Mass of J/ψ serves as a hard scale: $Q^2 \sim \frac{M_{J/\psi}^2}{4} \sim 2.5\ \mathrm{GeV}^2$

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

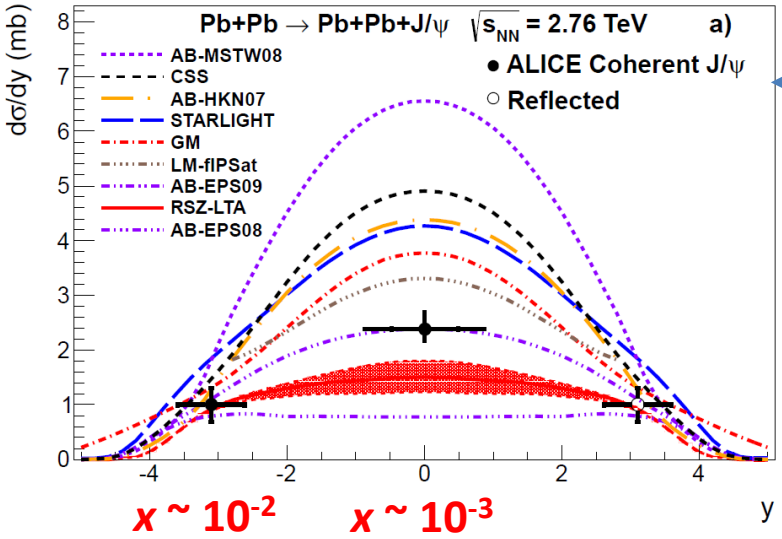
- J/ψ photoproduction in Pb-Pb UPC (lead target): information on **gluon shadowing in nuclei at low x**

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

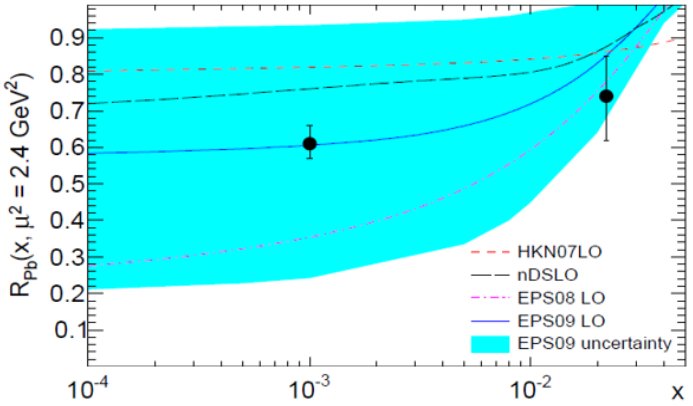


Reminder: results from Run 1

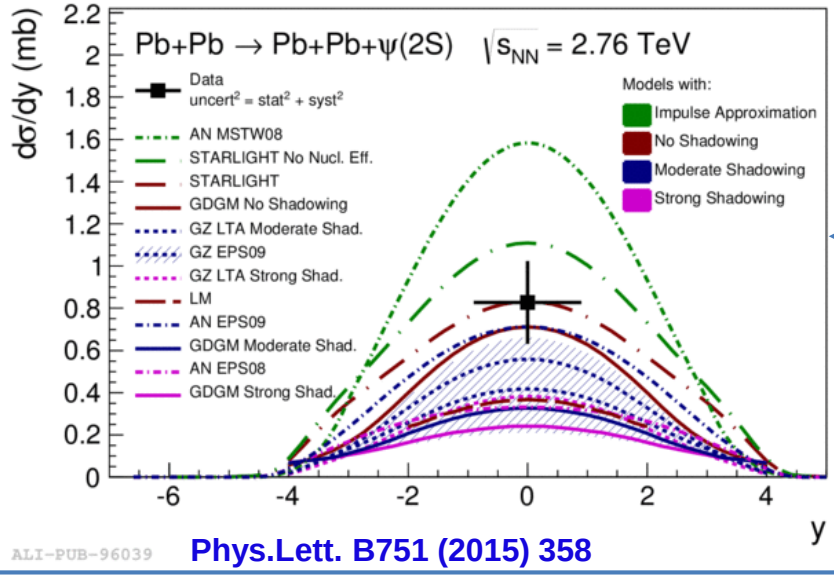
Phys. Lett. B718 (2013) 1273, Eur. Phys. J. C73 (2013) 2617



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



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



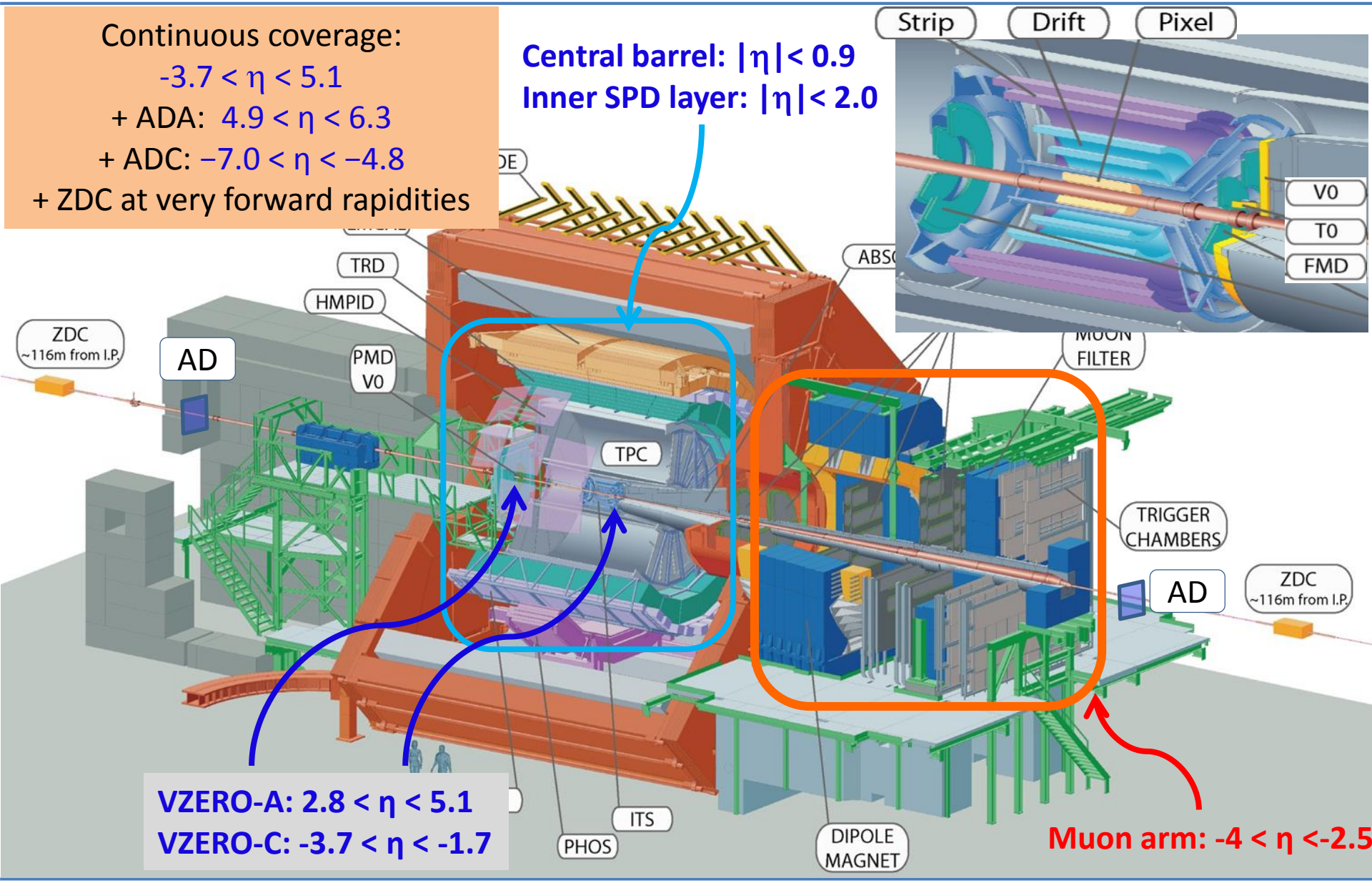
Phys.Lett. B751 (2015) 358

- **ψ':** disfavour models with no nuclear effects and models with strong gluon shadowing
- $\sigma(\psi')/\sigma(J/\psi) \sim 0.34 \pm 0.08$ (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: $|\eta| < 2.0$



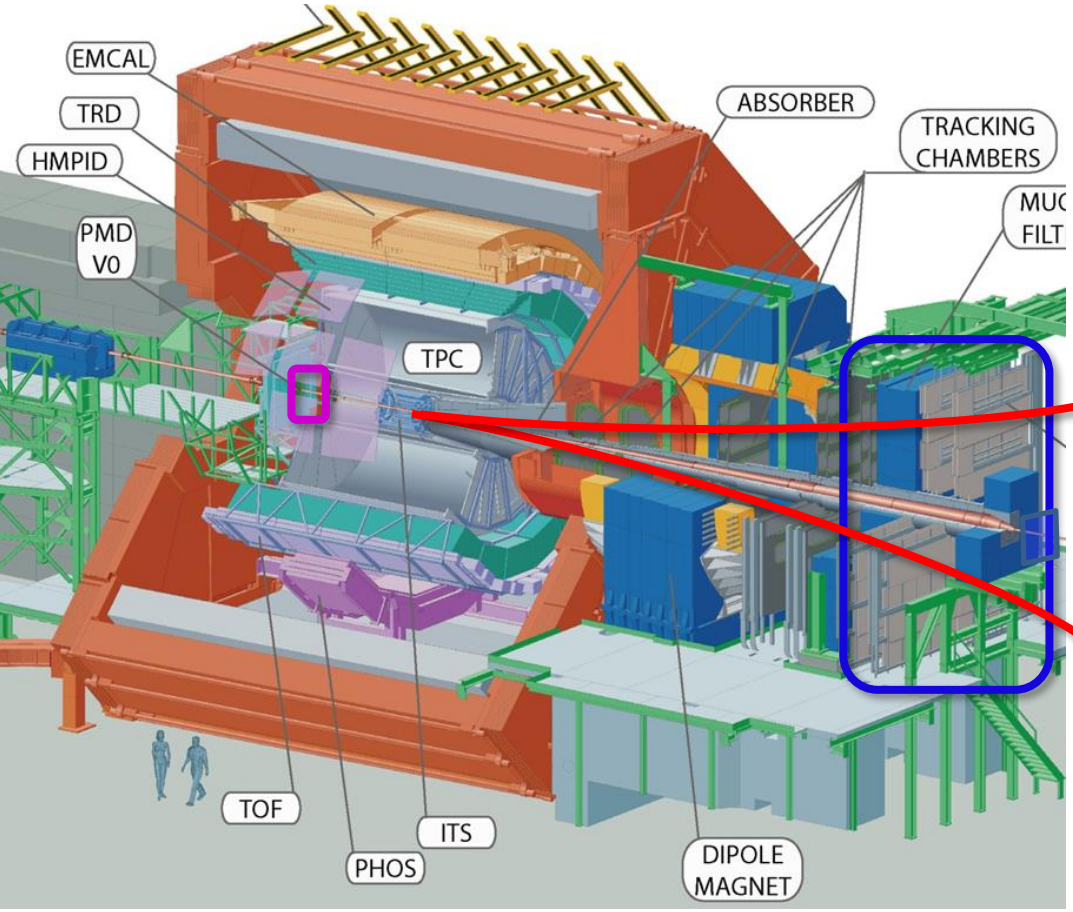
VZERO-A: $2.8 < \eta < 5.1$
VZERO-C: $-3.7 < \eta < -1.7$

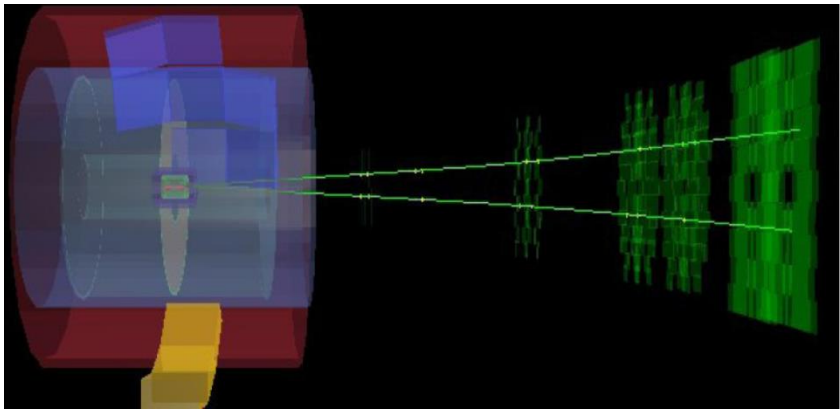
Muon arm: $-4 < \eta < -2.5$

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}

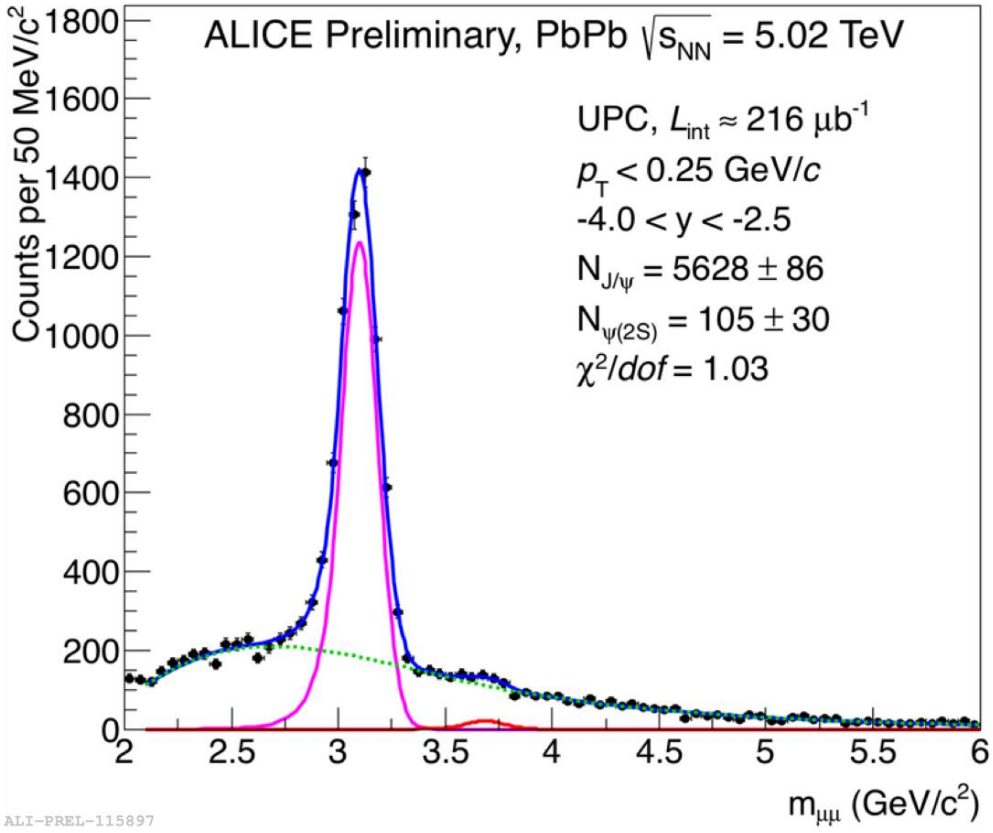
Offline event selection:

- 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

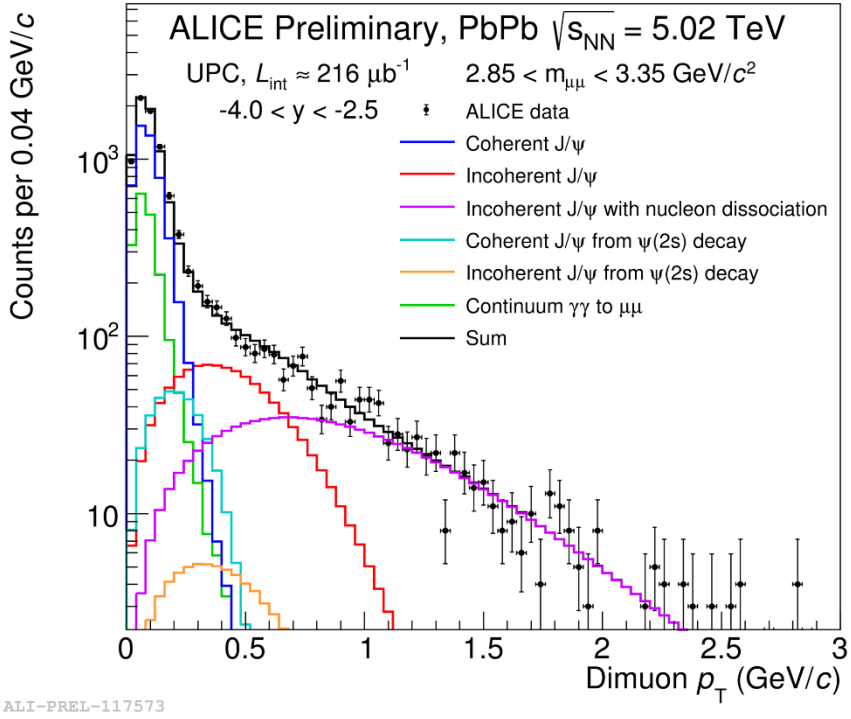
Invariant mass distribution

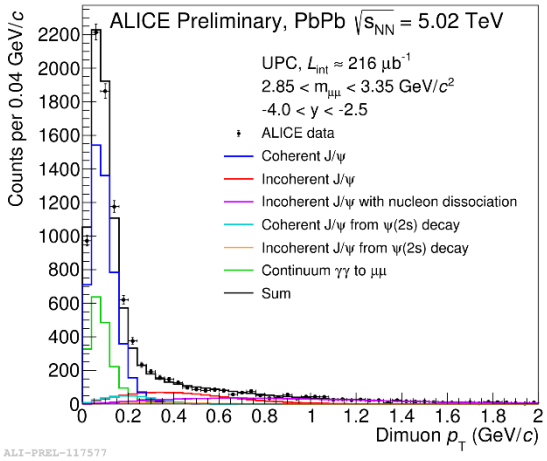


NEW

- dimuon $p_T < 0.25$ GeV/c
- ψ(2S) at 3 sigma significance, σ(ψ(2S))/σ(J/ψ) ratio close to HERA γp results (σ(2S)/σ(1S) = 0.166 ± 0.011)
- J/ψ and ψ(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





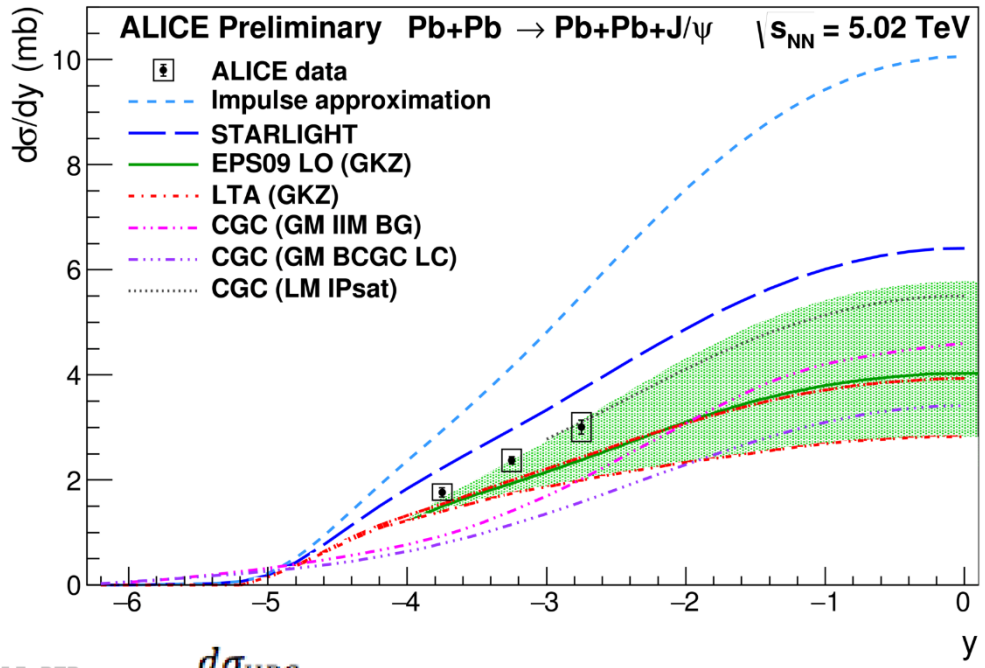
NEW

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

NEW



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

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

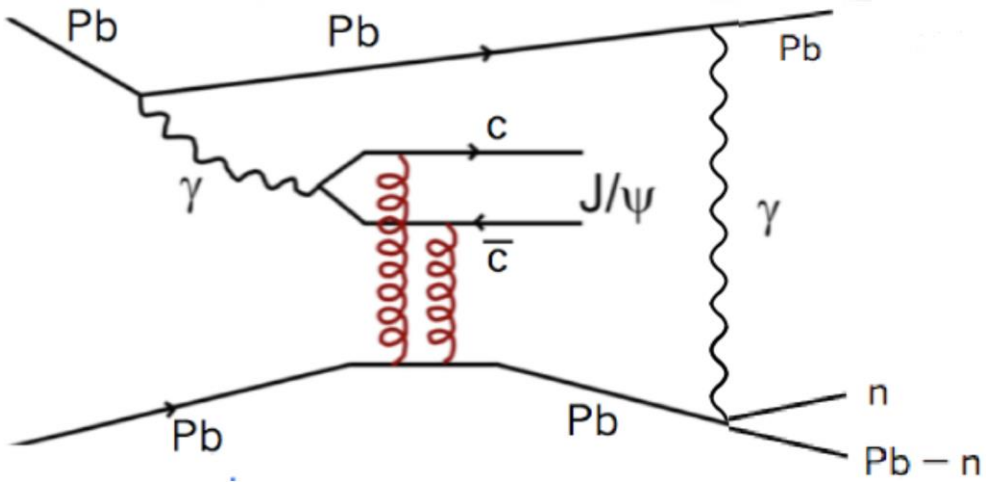
Coherent J/ψ cross section in agreement with moderate nuclear gluon shadowing

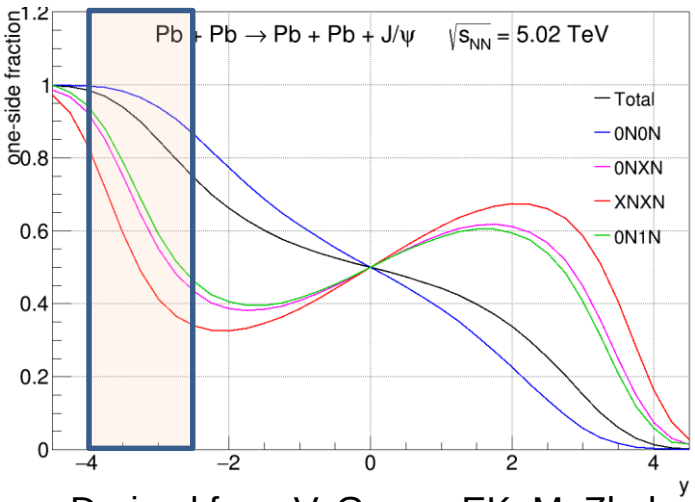
Next…

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

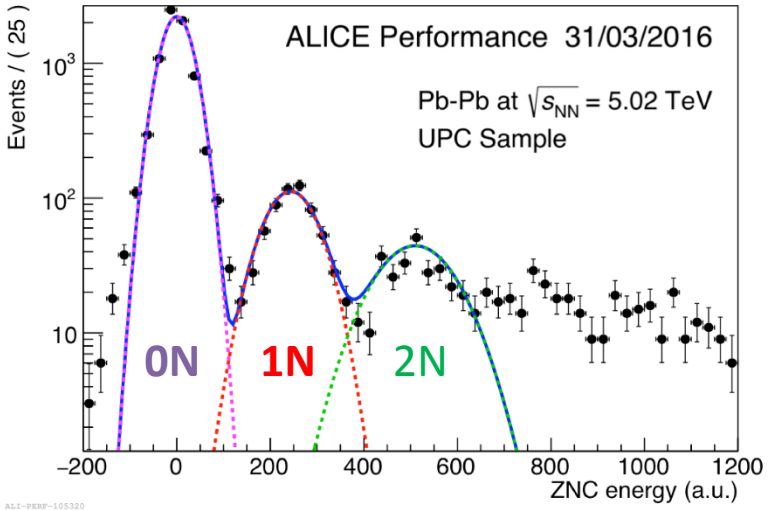
$$\frac{d\sigma_{UPC}}{dy} = n(\omega_1)\sigma_{\gamma T}(\omega_1) + n(\omega_2)\sigma_{\gamma T}(\omega_2)$$

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

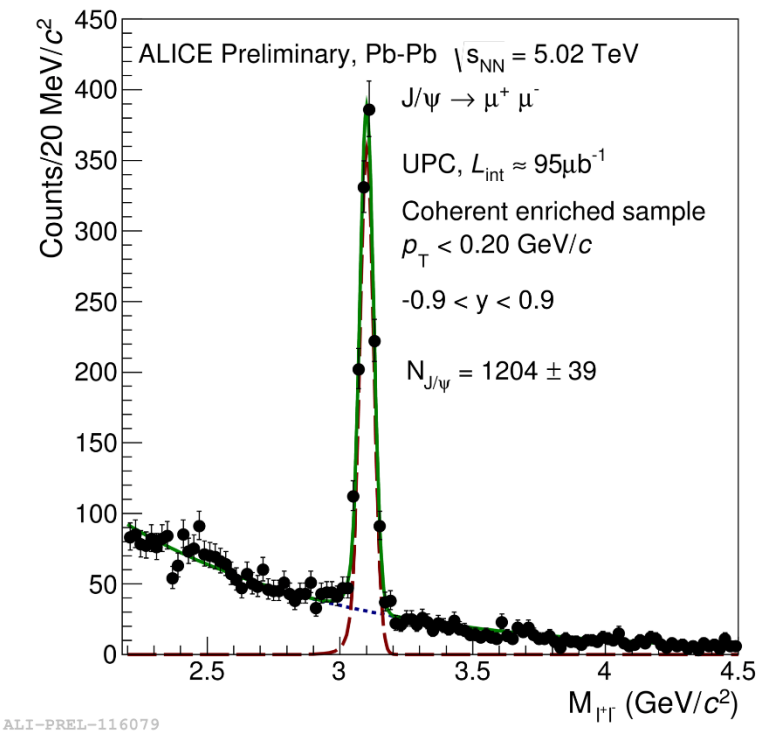


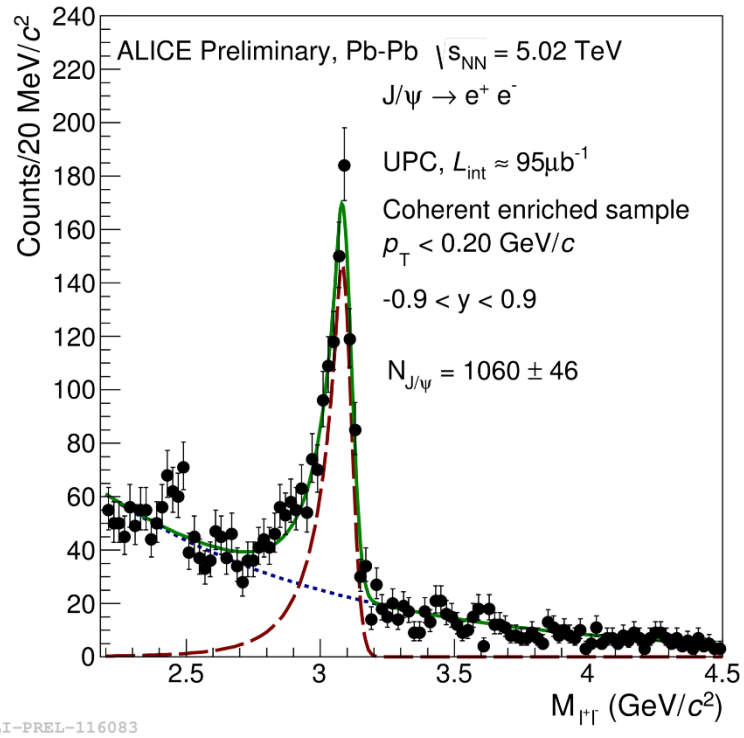


Derived from V. Guzey, EK, M. Zhalov, **PRC93 (2016), 055206**

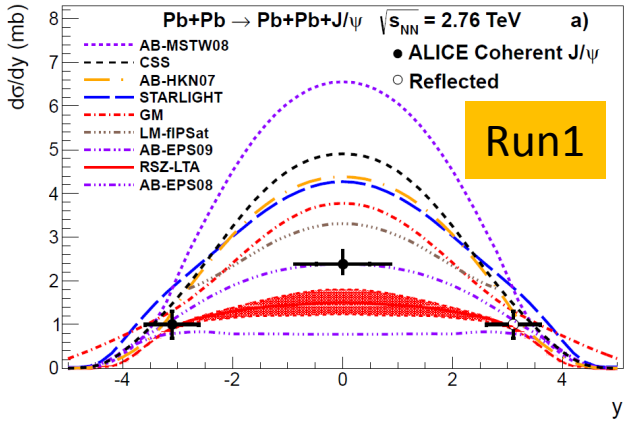


+ J/ψ in central barrel

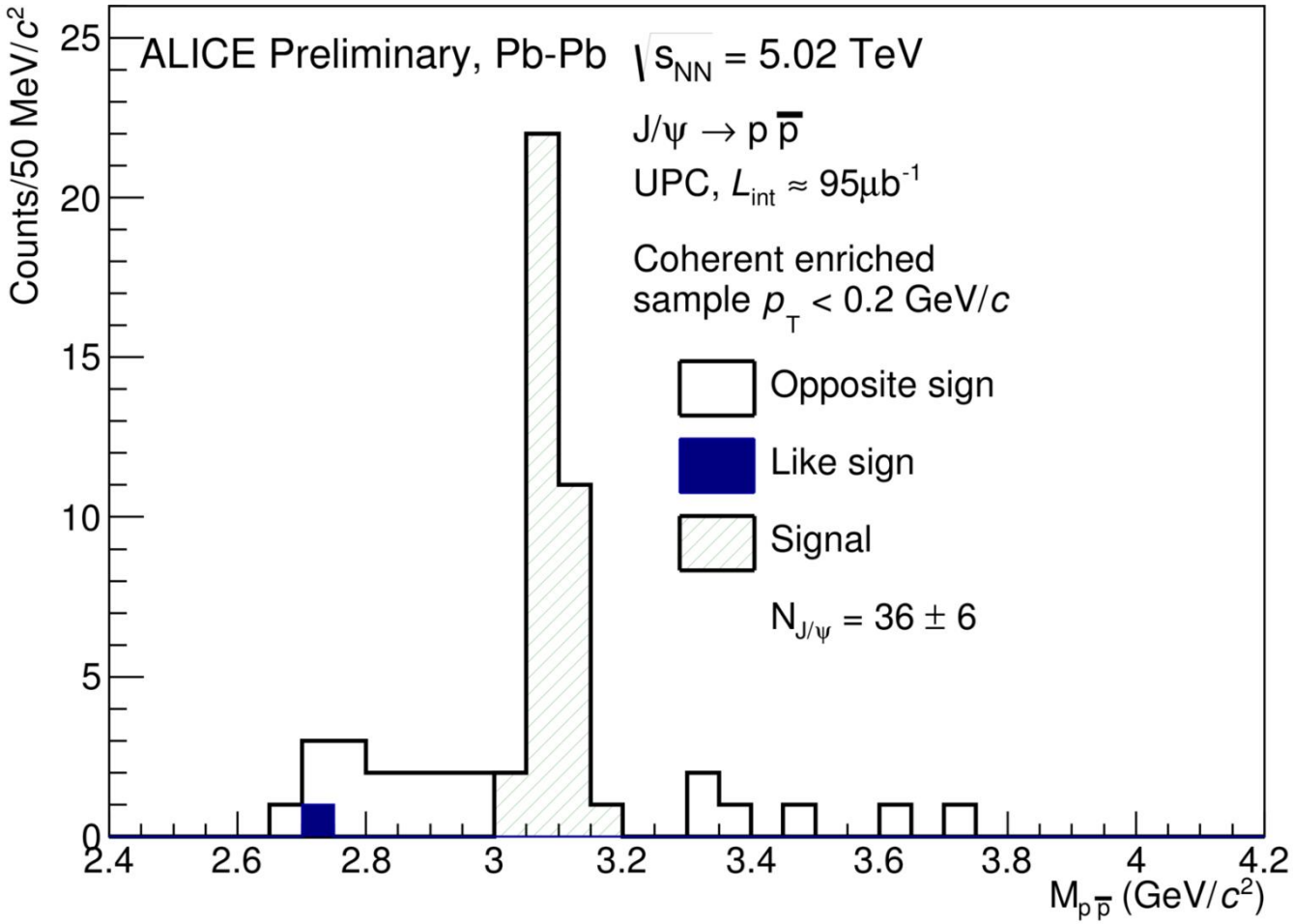




- x4 more statistics wrt Run1
- access to x ~ 0.5 x 10^{-3}

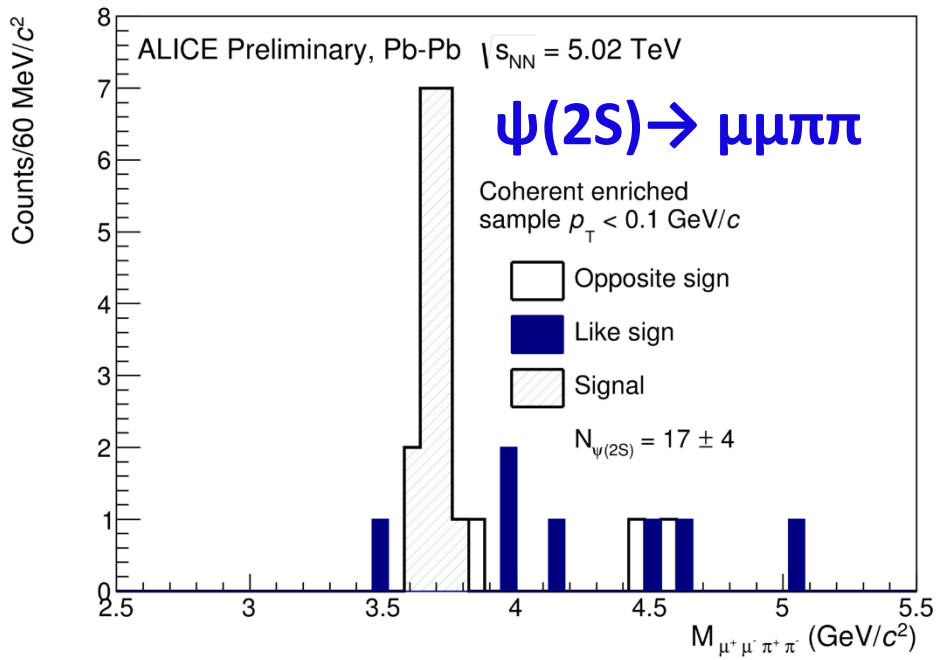


First observation in UPC: J/ψ→ $p\bar{p}$

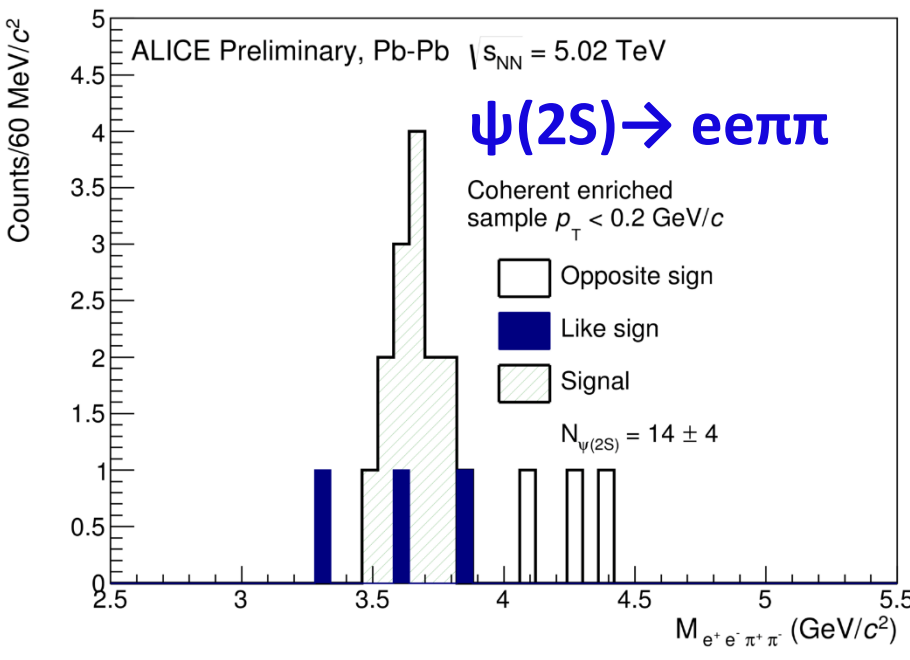


ALI-PREL-117138

+ ψ(2S) → J/ψππ

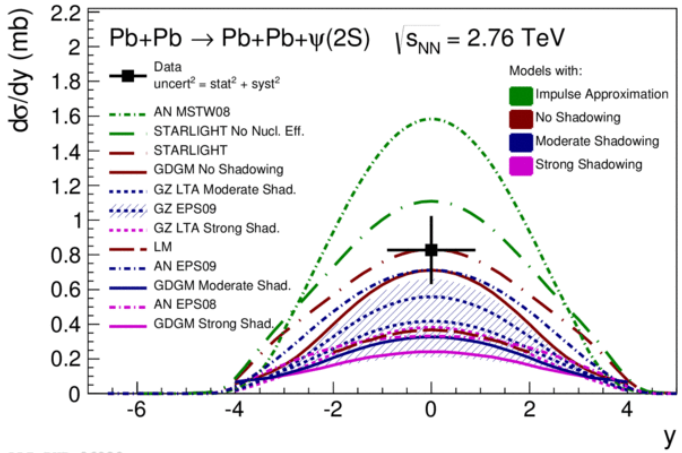


ALI-PREL-116095

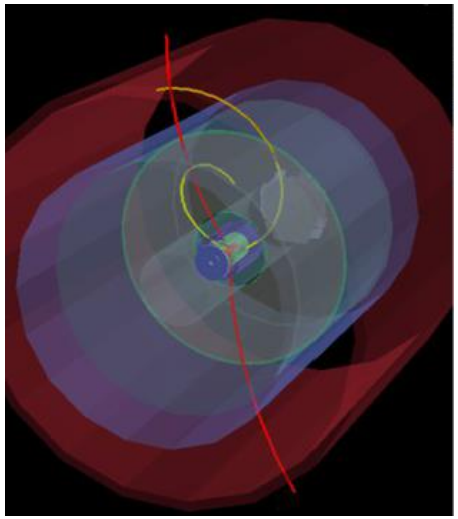


I-PREL-116091

Run 1



ALI-PUB-96039



J/ψ in ultraperipheral p-Pb collisions

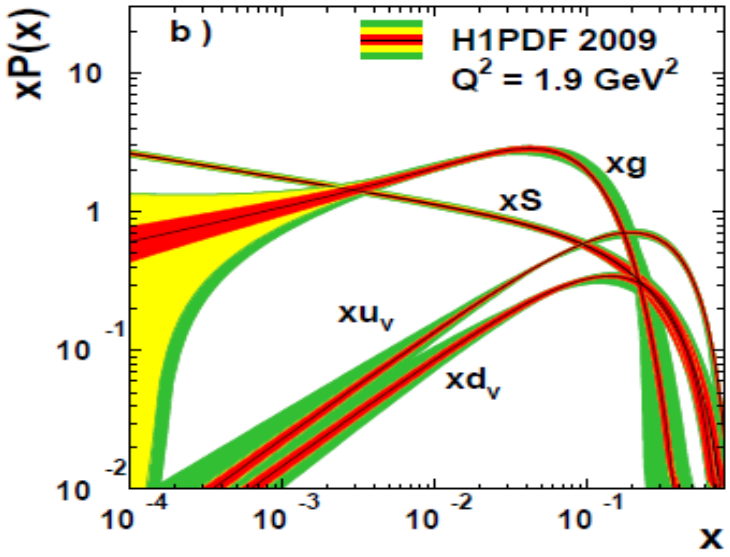
J/ψ photoproduction off proton

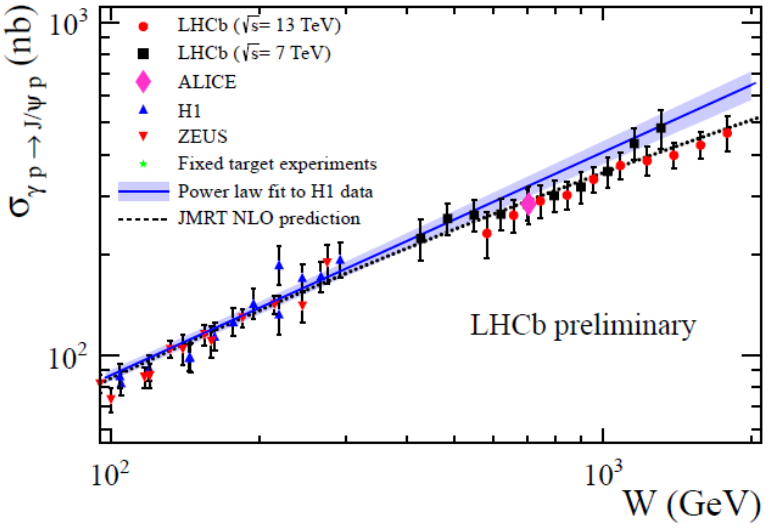
$$\left.\frac{d\sigma_{\gamma p\to pJ/\psi}}{dt}\right|_{t=0} = \frac{M_{J/\psi}^3\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{\rm em}Q^8}\left[xg_p(x,Q^2)\right]^2$$

- J/ψ photoproduction off proton allows one to probe poorly known **gluon distribution in the proton at low x** and search for **saturation effects**

- HERA: J/ψ photoproduction in *ep* (*x* down to 10^{-4})
  - Consistent with power law (no hint for saturation)
  - Data was used to extract gluon PDFs (MNRT, JMRT)

- LHCb: exclusive J/ψ in *pp* @ 7, 13 TeV
  - forward rapidity (x~10^{-2} + x~10^{-5})
  - photon emitter unknown -assumed power law to separate low and high-energy contributions

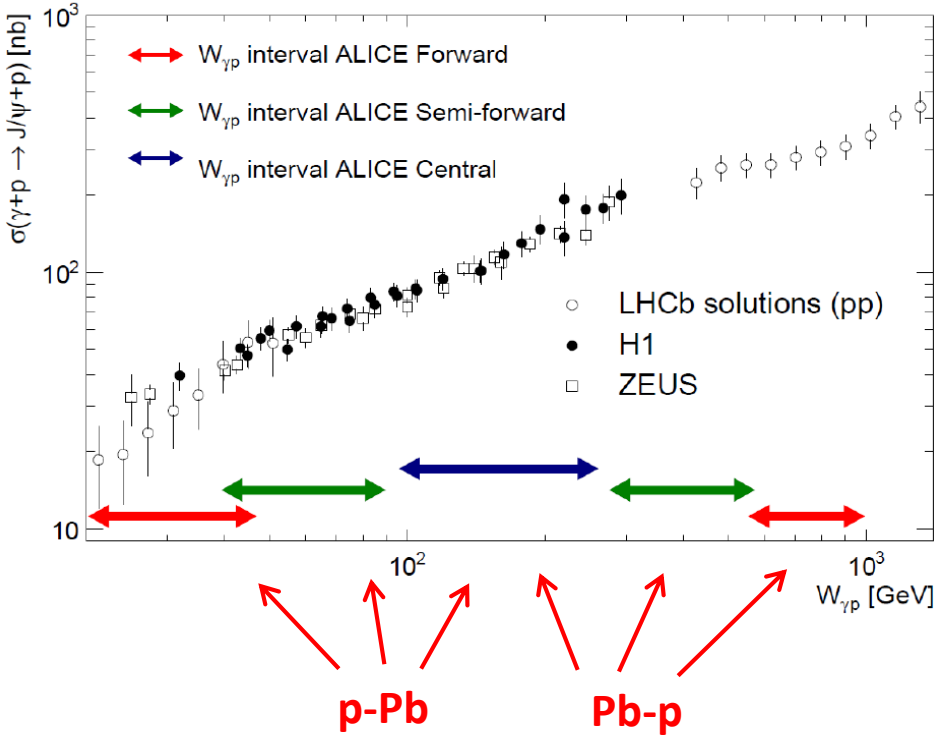




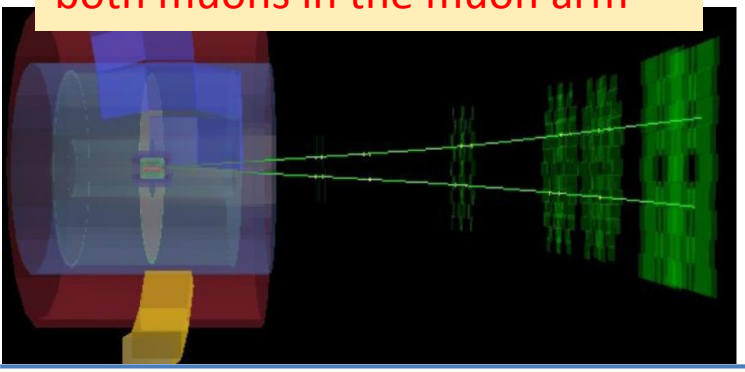
p-Pb UPC with ALICE

Advantage of p-Pb collisions wrt pp:

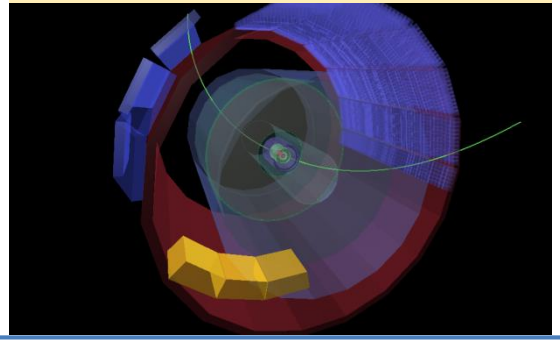
- Large photon flux from Pb
- Photon source is known
  → no assumption required to separate low and high energy contributions
- Hadronic contribution can be strongly suppressed by ensuring Pb nuclei are intact (no signal in ZDC)
- Contamination from central exclusive χ_c production negligible



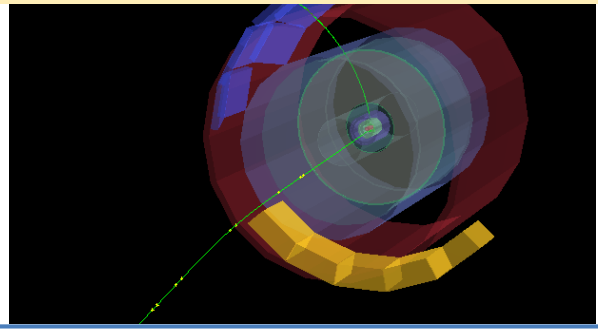
both muons in the muon arm



both leptons in the barrel



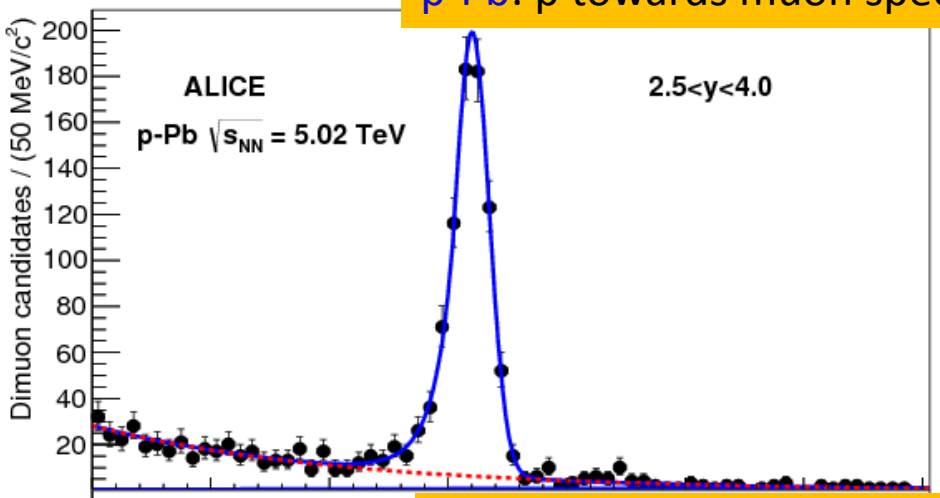
one muon in the muon arm, second in the barrel

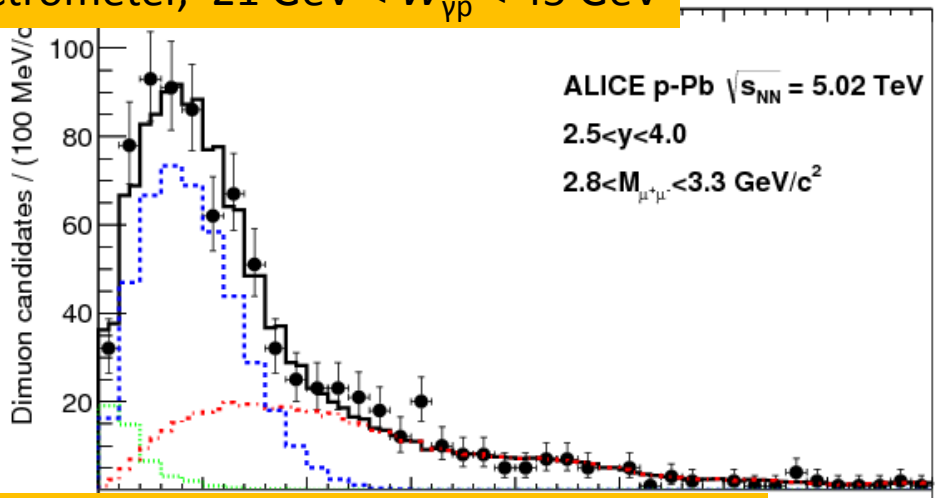


Results on forward p-Pb and Pb-p collisions

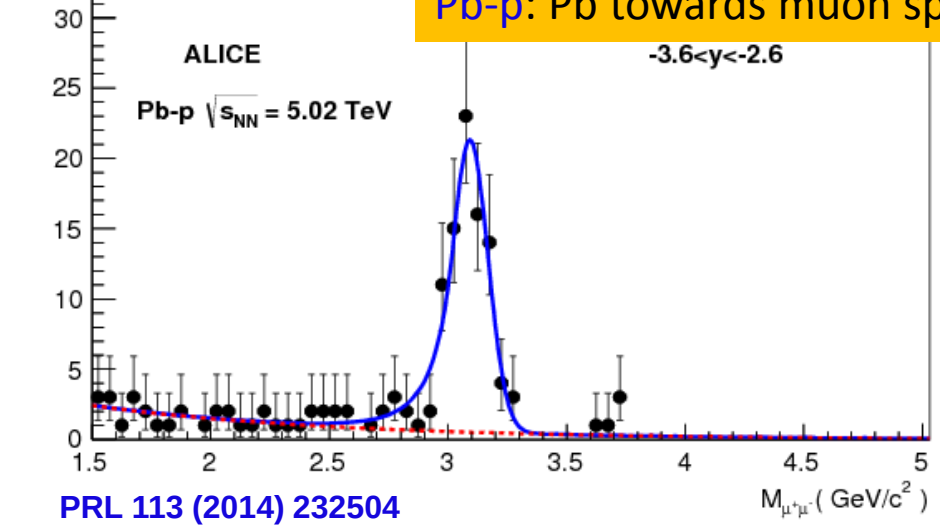
- Using p_T-templates to extract contribution of exclusive J/ψ

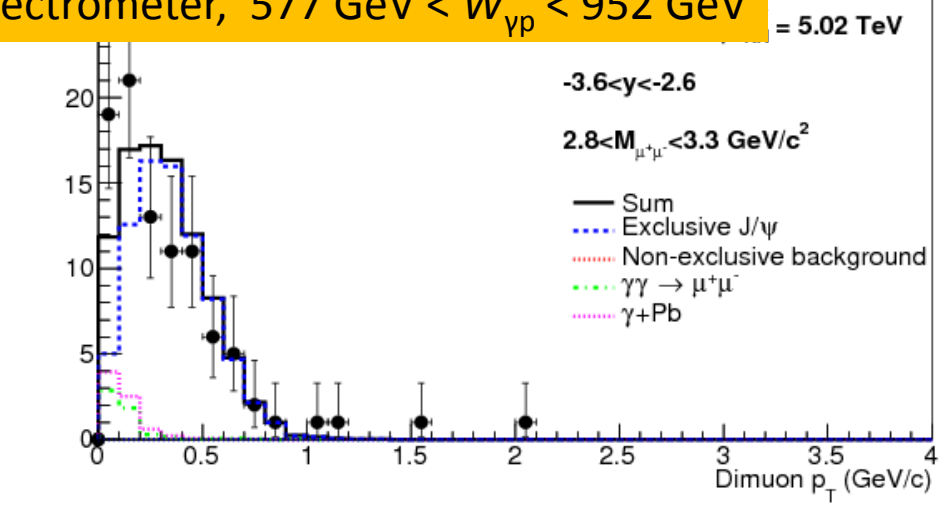
p-Pb: p towards muon spectrometer, 21 GeV < $W_{\gamma p}$ < 45 GeV





Pb-p: Pb towards muon spectrometer, 577 GeV < $W_{\gamma p}$ < 952 GeV

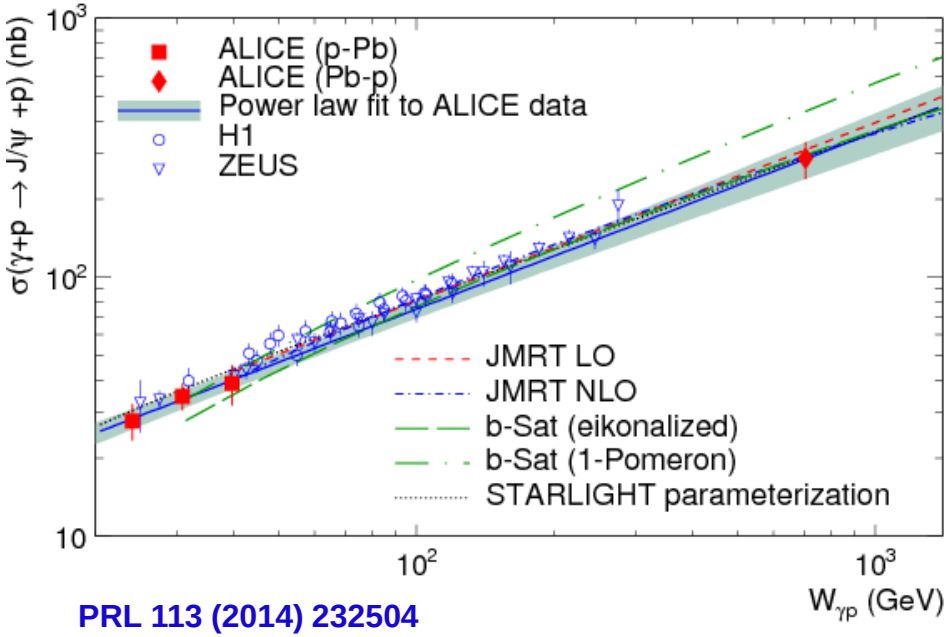




PRL 113 (2014) 232504

Tests of power law dependence

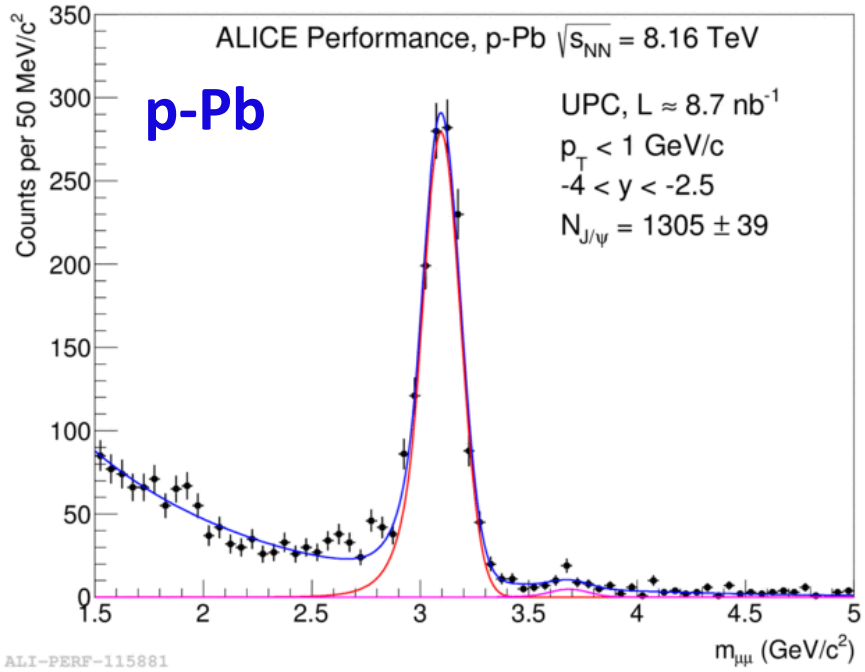
- Results compatible with predictions based on fits to HERA data
- Power law exponent from ALICE data alone: $\delta = 0.67 \pm 0.06$
- Exponent compatible with HERA:
  - H1: $\delta = 0.67 \pm 0.03$
  - ZEUS: $\delta = 0.69 \pm 0.02 \pm 0.03$
- LHCb solutions consistent with the power-law fit obtained from ALICE results

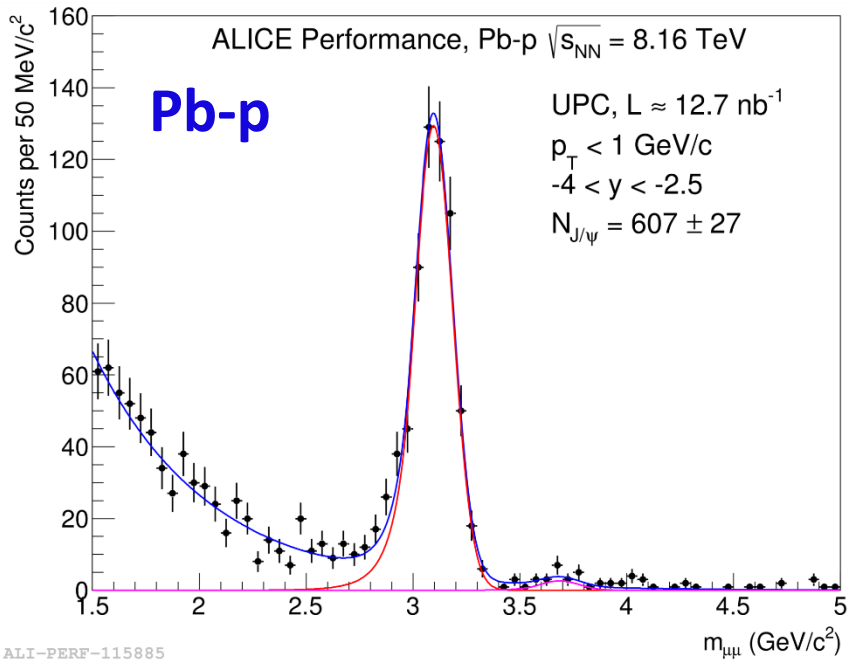


PRL 113 (2014) 232504

No significant change in the gluon density behaviour between HERA and LHC energies

p-Pb @ 8 TeV



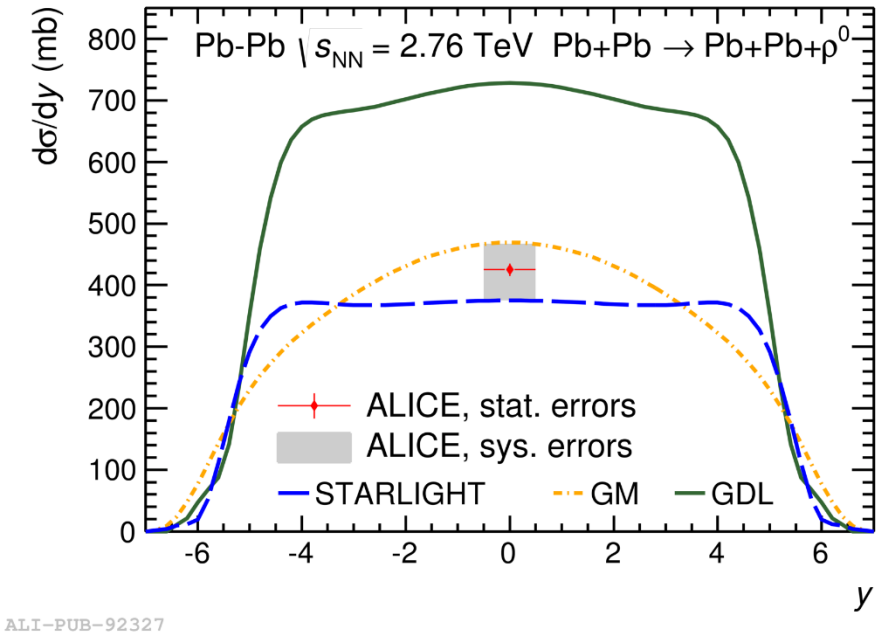


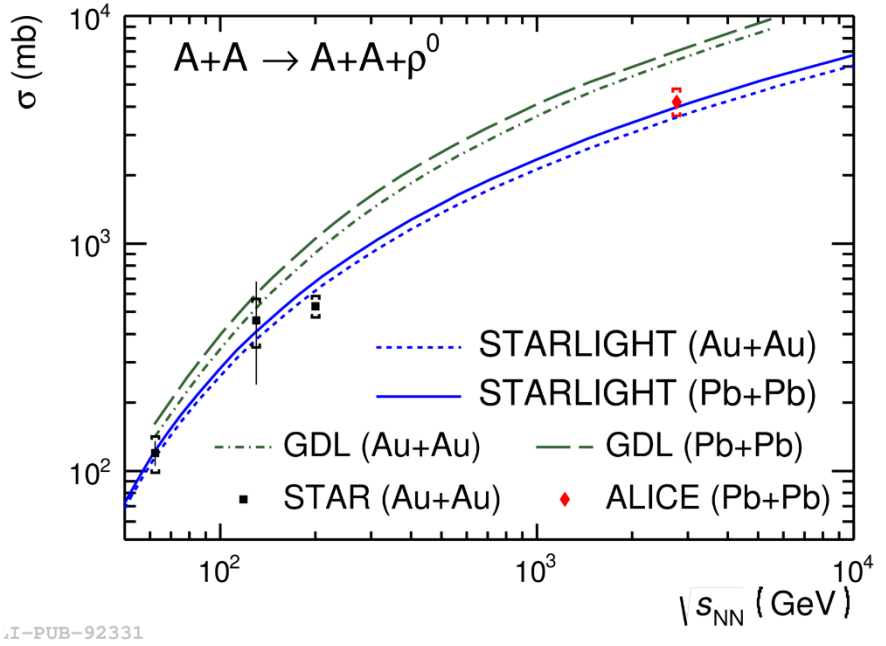
- x10 more stat at high $W_{\gamma p}$ ~ 0.7-1.4 TeV
- search for gluon saturation effects in p at low x~10^{-5}
- study proton-dissociative cross section behaviour at high $W_{\gamma p}$

ρ^0 photoproduction in ultraperipheral Pb-Pb collisions

ρ^0 photoproduction in Pb-Pb @ 2.76 TeV

JHEP 1509 (2015) 095





GDL: Frankfurt, Strikman, Zhalov [Phys. Lett. B 537 (2002) 51; Phys. Rev. C 67(2003) 034901]

- Vector Meson Dominance Model + Glauber approach.
- $\sigma_{\rho N}$ from Donnachie-Landshoff model.

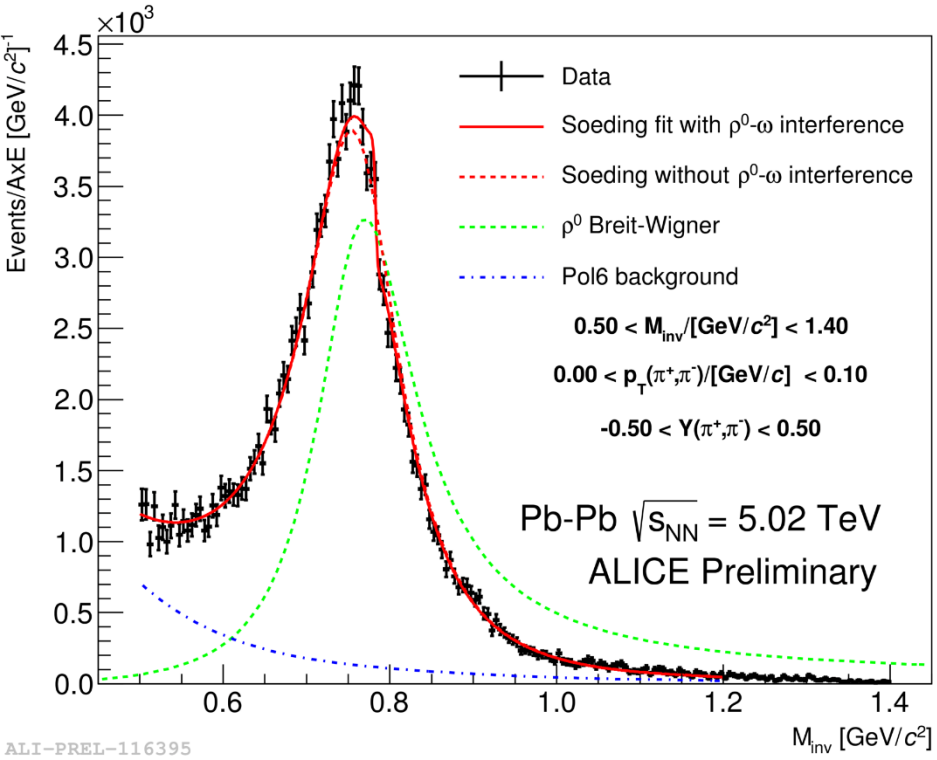
GM: Gonçalves, Machado [Phys. Rev. C 84 (2011) 011902]

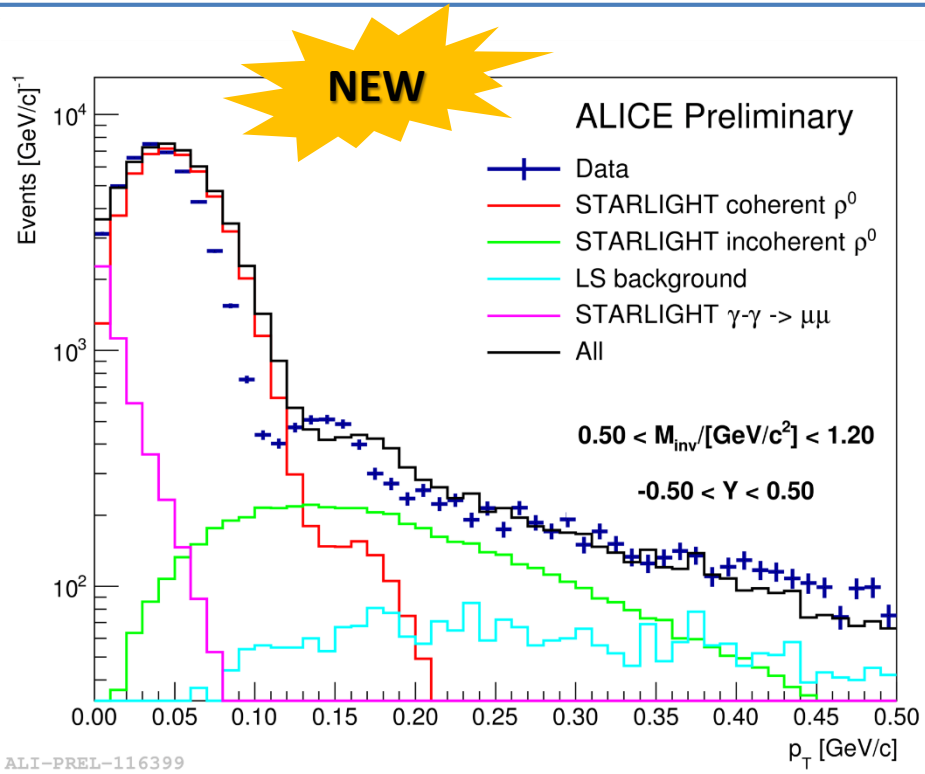
- Based on the color dipole model in combination with saturation from a CGC-IIM model.

STARLIGHT: Klein, Nystrand [Phys. Rev. C 60 (1999) 014903, http://starlight.hepforge.org/]

- Glauber model neglecting the elastic part of total cross section.
- Uses experimental data on $\sigma_{\rho N}$ cross section.

ρ^0 photoproduction in Pb-Pb @ 5 TeV

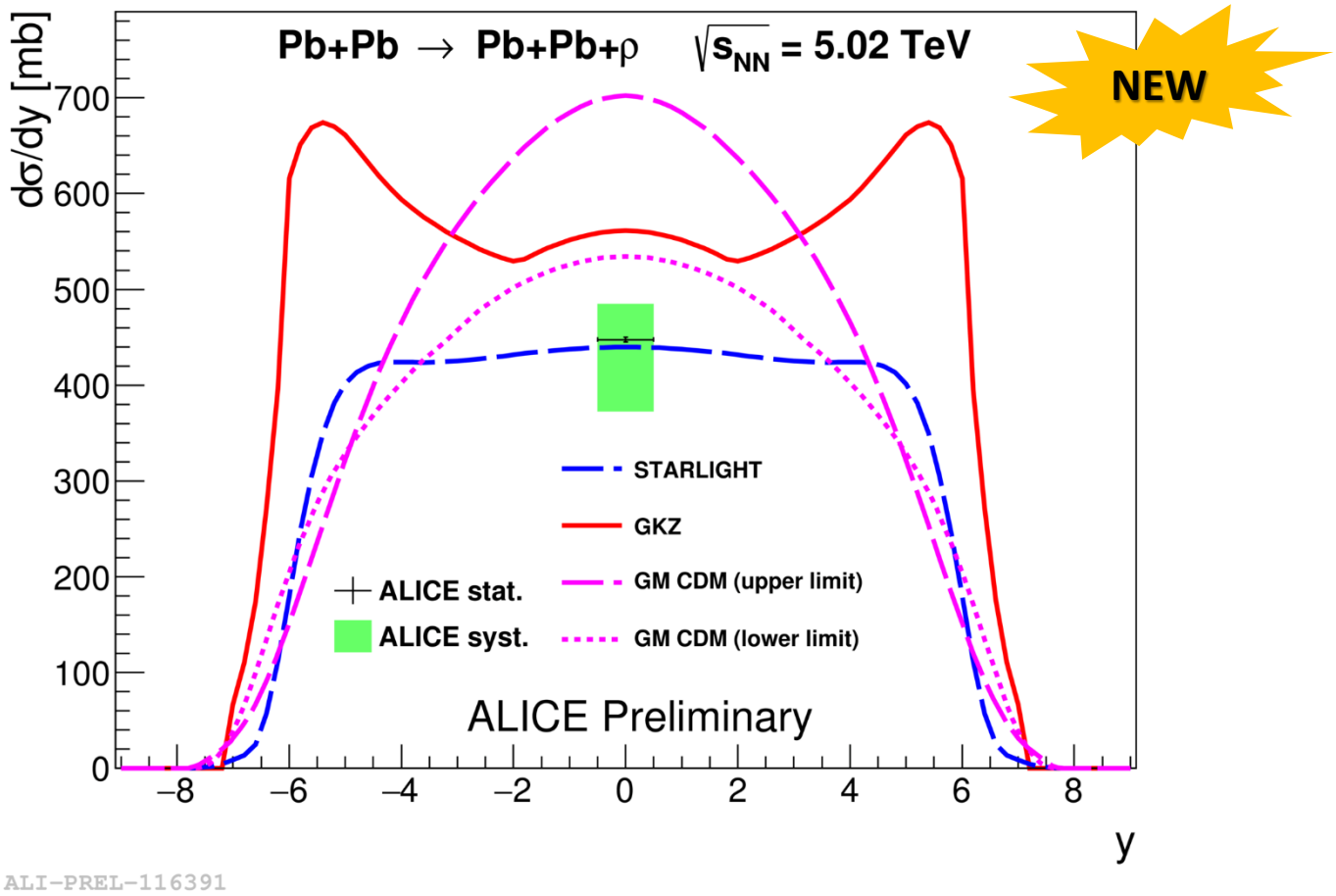




$$\frac{d\sigma}{dm_{\pi\pi}} = |A \cdot BW + B + C \cdot e^{i\phi} \cdot BW|^2 + N \cdot \mathrm{pol6}$$

- Second diffractive peak clearly visible
- Coherent p_T distribution from STARLIGHT significantly wider than data
  => access impact-parameter dependent shadowing effects (e.g. Guzey, Strikman, Zhalov: arxiv:1611.05471)

Coherent ρ^0 cross section at 5 TeV



- **STARLIGHT: VDM + Glauber.** Klein, Nystrand et al: Comput. Phys. Commun. 212 (2017) 258
- **GKZ: Gribov-Glauber shadowing.** Guzey et al, PLB752 (2016) 51**,** PRC93 (2016) 055206
- **GM CDM**. Gonçalves, Machado et al, PRC80 (2009), 054901, PRC91 (2015) 025203

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

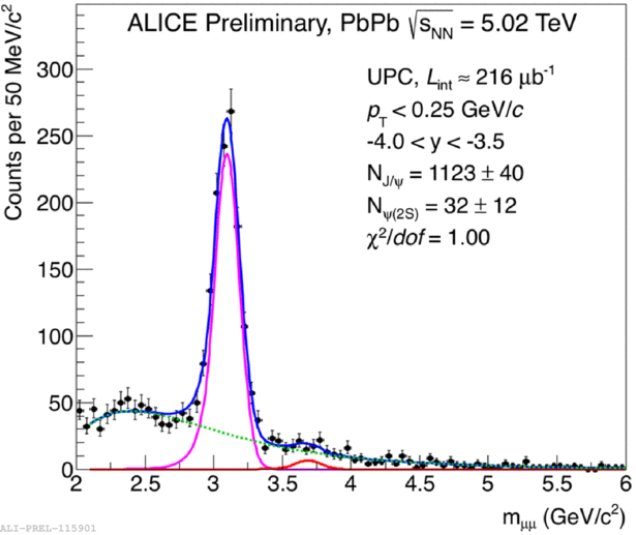
- ρ photoproduction cross section compatible with STARLIGHT but still below Gribov-Glauber shadowing predictions and CDM

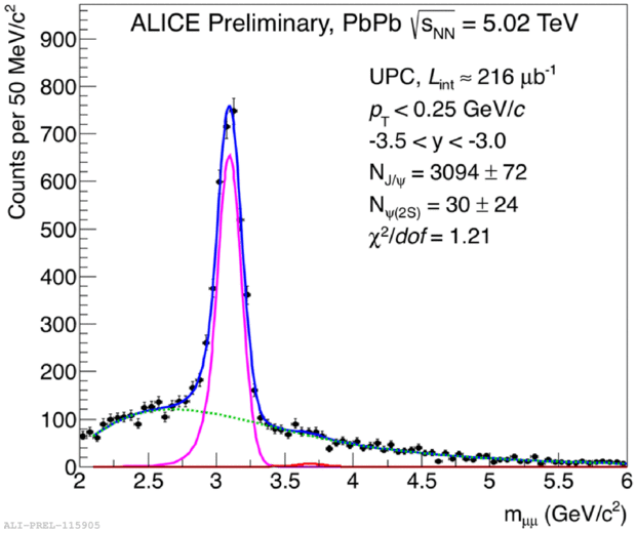
- More results from Run2 expected soon:
  - Incoherent J/ψ, ZDC-differential studies, J/ψ polarization at forward rapidity
  - J/ψ and ψ(2S) photoproduction in Pb-Pb at central rapidity
  - J/ψ photoproduction in p-Pb

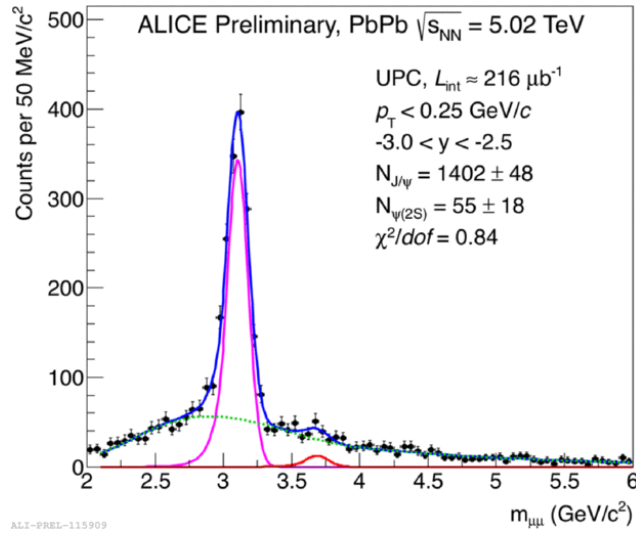
BACKUP

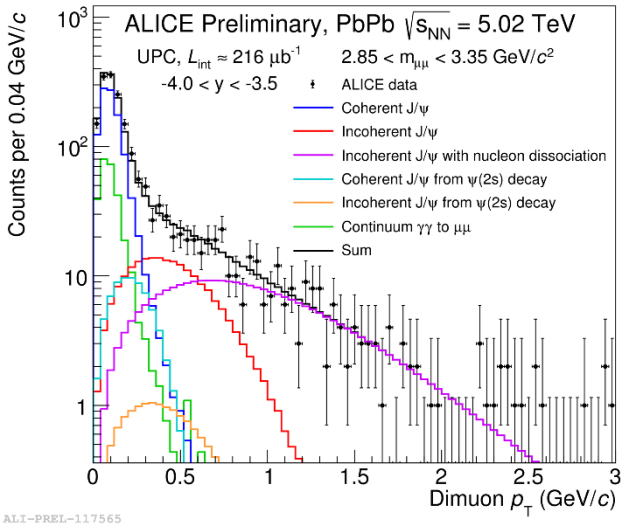
Invariant mass and pt fits in rapidity bins

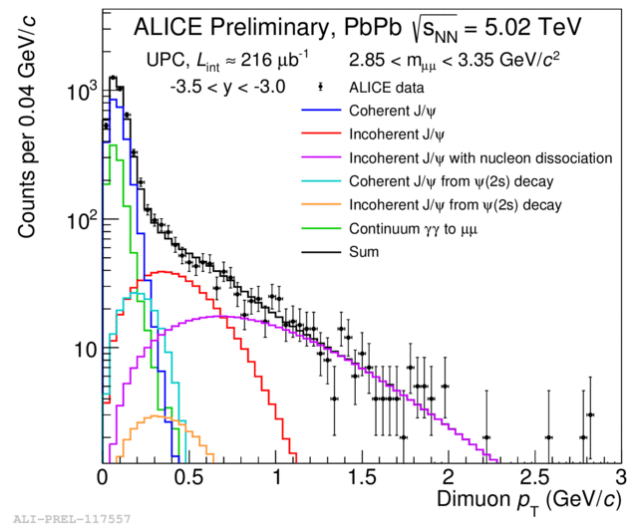
- Cross sections extracted in 3 rapidity bins (-4.0,-3.5,-3.0,-2.5)

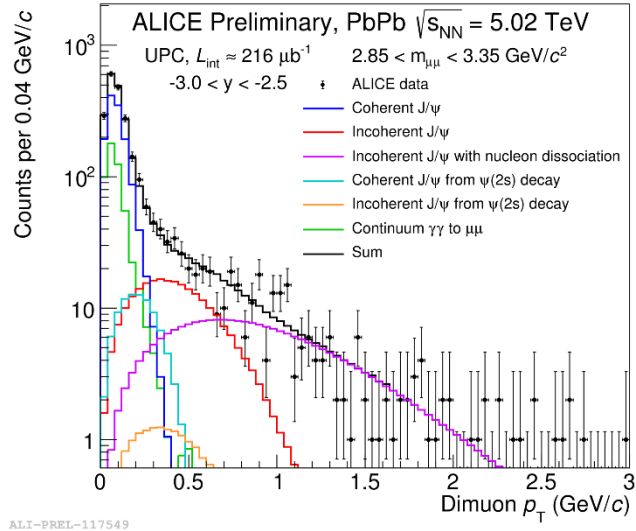












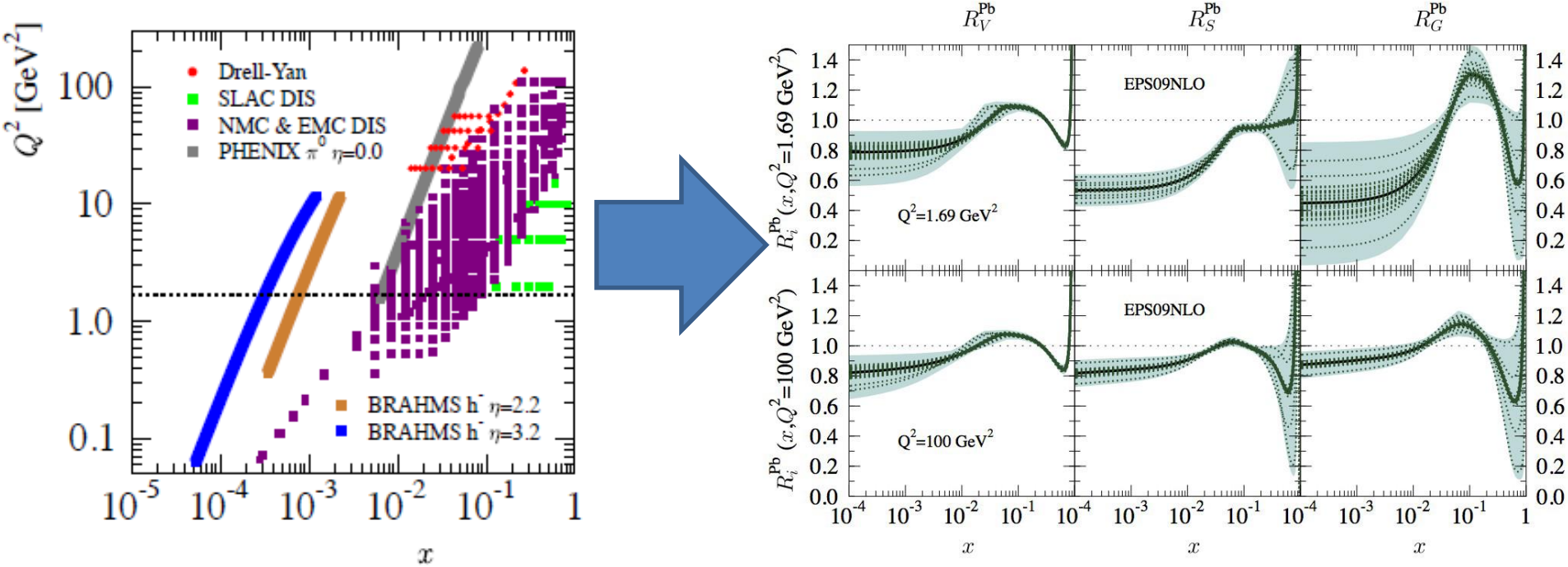
Parton distributions in nuclei (nPDFs)

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

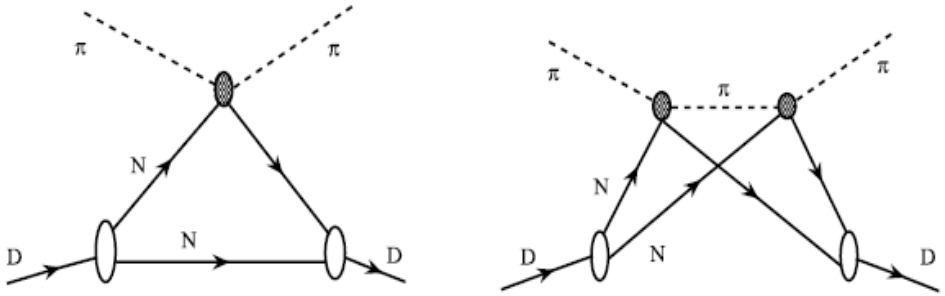


Resulting nPDFs have rather **large uncertainties, especially for small-x gluons** due to:

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

On nuclear shadowing

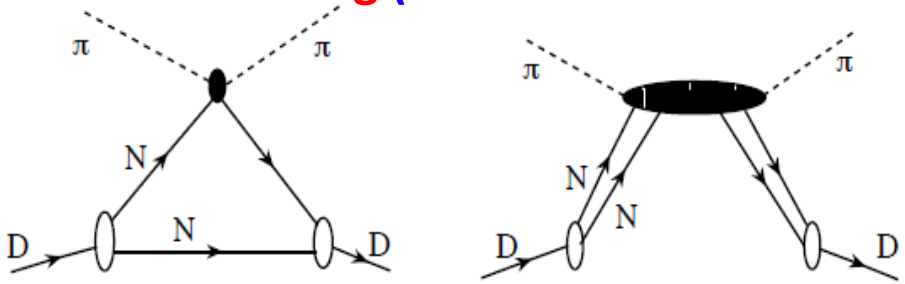
Glauber shadowing (modeling of several consequent interactions):



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

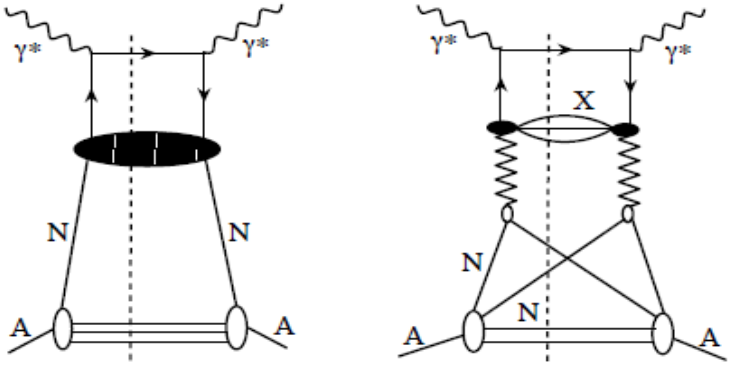
shadowing = destructive interference between single and multiple interactions

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

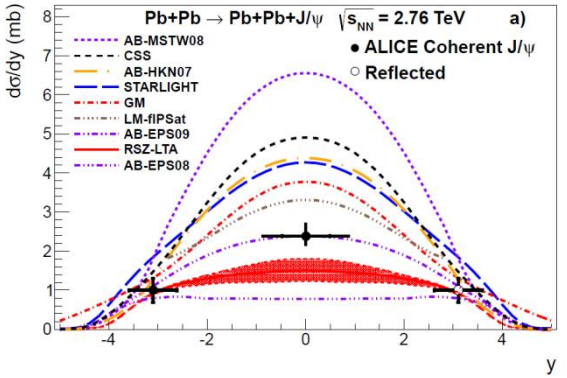
Photoproduction cross-section from ALICE data

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

ALICE measurement:

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

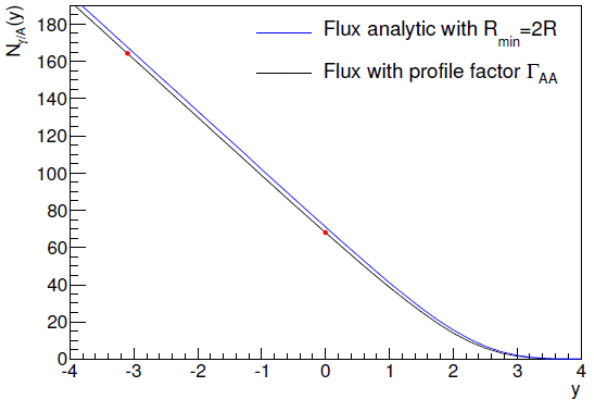
$$\frac{\sigma_{AA\to AAJ/\psi}(-3.6<y<-2.6)}{\Delta y} = 1.00 \pm 0.18(\text{stat})^{+0.23}_{-0.26}(\text{syst}) \text{ mb}$$



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:

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

$$\sigma_{\gamma Pb\to PbJ/\psi}(W_{\gamma p}=92.4\,\text{GeV}) = 17.2 \pm 2.1\ \mu\text{b}$$

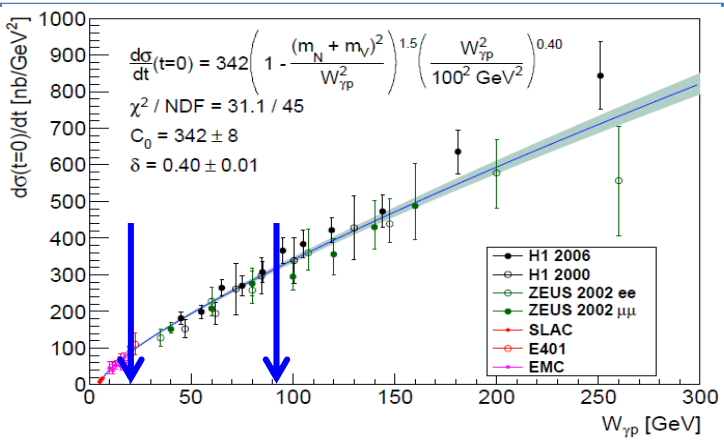
Photoproduction cross-section in the Impulse Approximation

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

Forward J/psi photoproduction cross section:

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

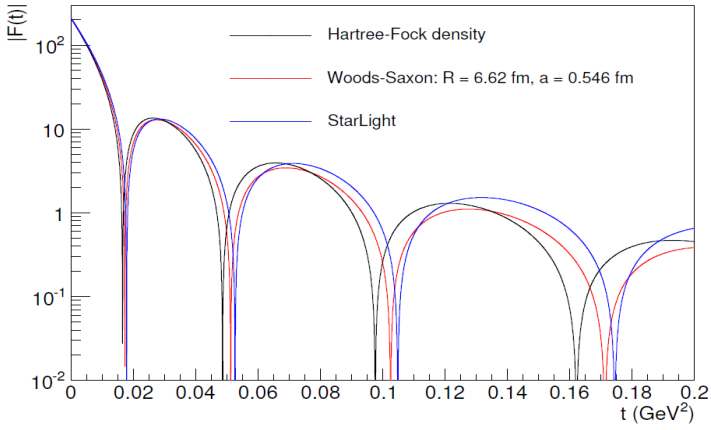
$$\frac{d\sigma_{\gamma p\to J/\psi p}(92.4\ \mathrm{GeV}, t=0)}{dt} = 319.8 \pm 7.1\ \mathrm{nb/GeV^2}$$



Integral over squared form factor:

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

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



J/psi photoproduction on nucleus in Impulse Approximation:

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

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

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

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:

$$\sigma_{\gamma Pb\to PbJ/\psi}(W_{\gamma p}=19.6\,\mathrm{GeV}) = 6.1^{+1.8}_{-2.0}\ \mu\mathrm{b}$$
$$\sigma_{\gamma Pb\to PbJ/\psi}(W_{\gamma p}=92.4\,\mathrm{GeV}) = 17.2\pm2.1\ \mu\mathrm{b}$$

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

$$\sigma^{\mathrm{IA}}_{\gamma Pb\to PbJ/\psi}(W_{\gamma p}=19.6\,\mathrm{GeV}) = 11.1\pm0.6\ \mu\mathrm{b}$$
$$\sigma^{\mathrm{IA}}_{\gamma Pb\to PbJ/\psi}(W_{\gamma p}=92.4\,\mathrm{GeV}) = 47.7\pm2.6\ \mu\mathrm{b}$$

- Nuclear suppression factor:

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

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