Shedding light on hadron structure with ultra-peripheral collisions

Evgeny Kryshen
(Petersburg Nuclear Physics Institute, Russia)

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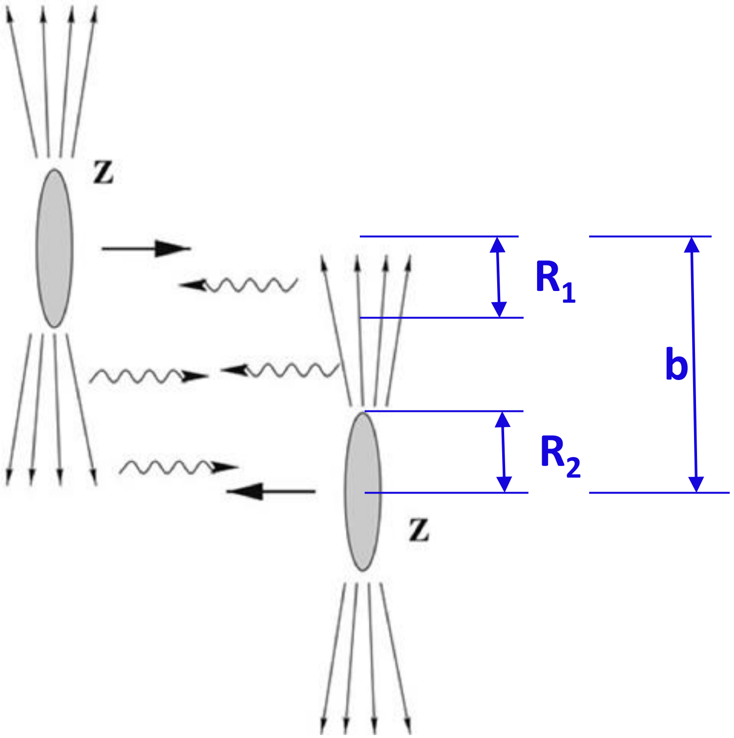
LHC as a $\gamma\gamma$, γp and γPb collider



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)

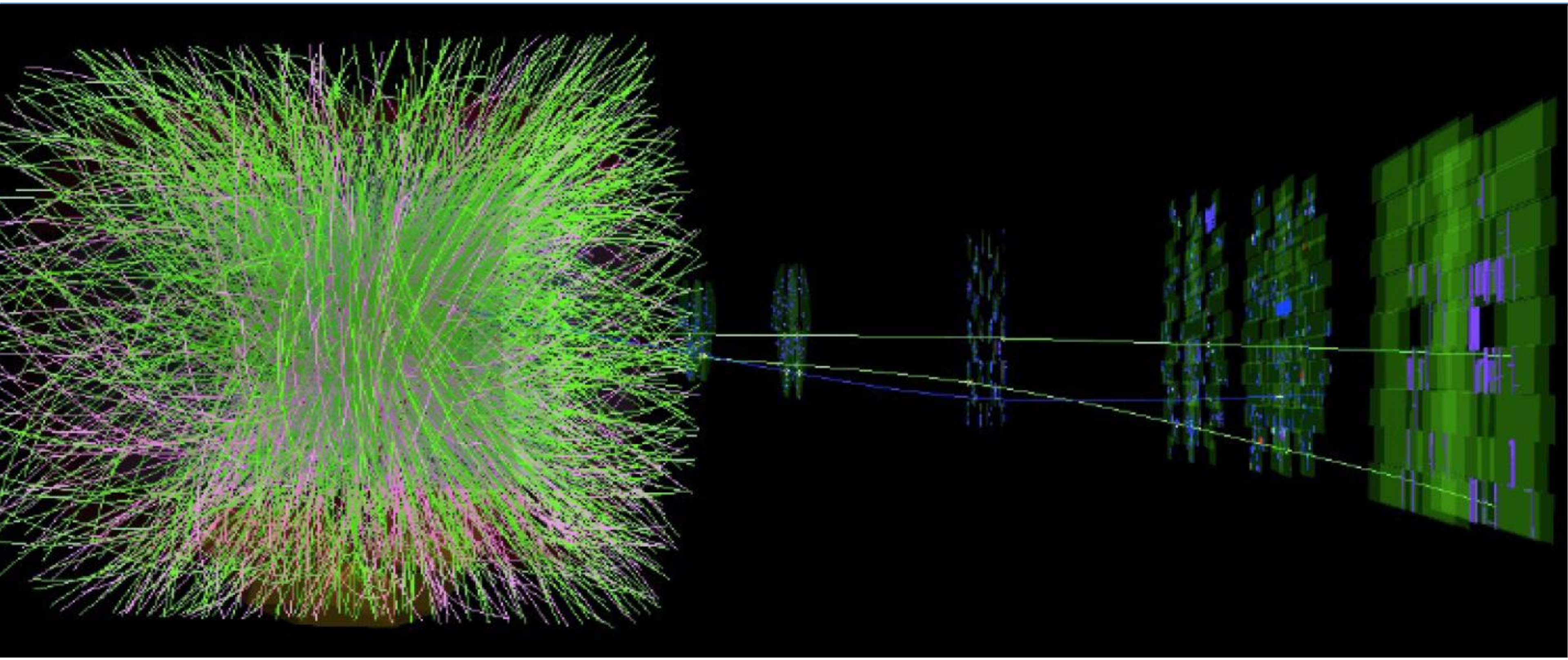
→ flux proportional to Z^2

→ high cross section for γ-induced reactions

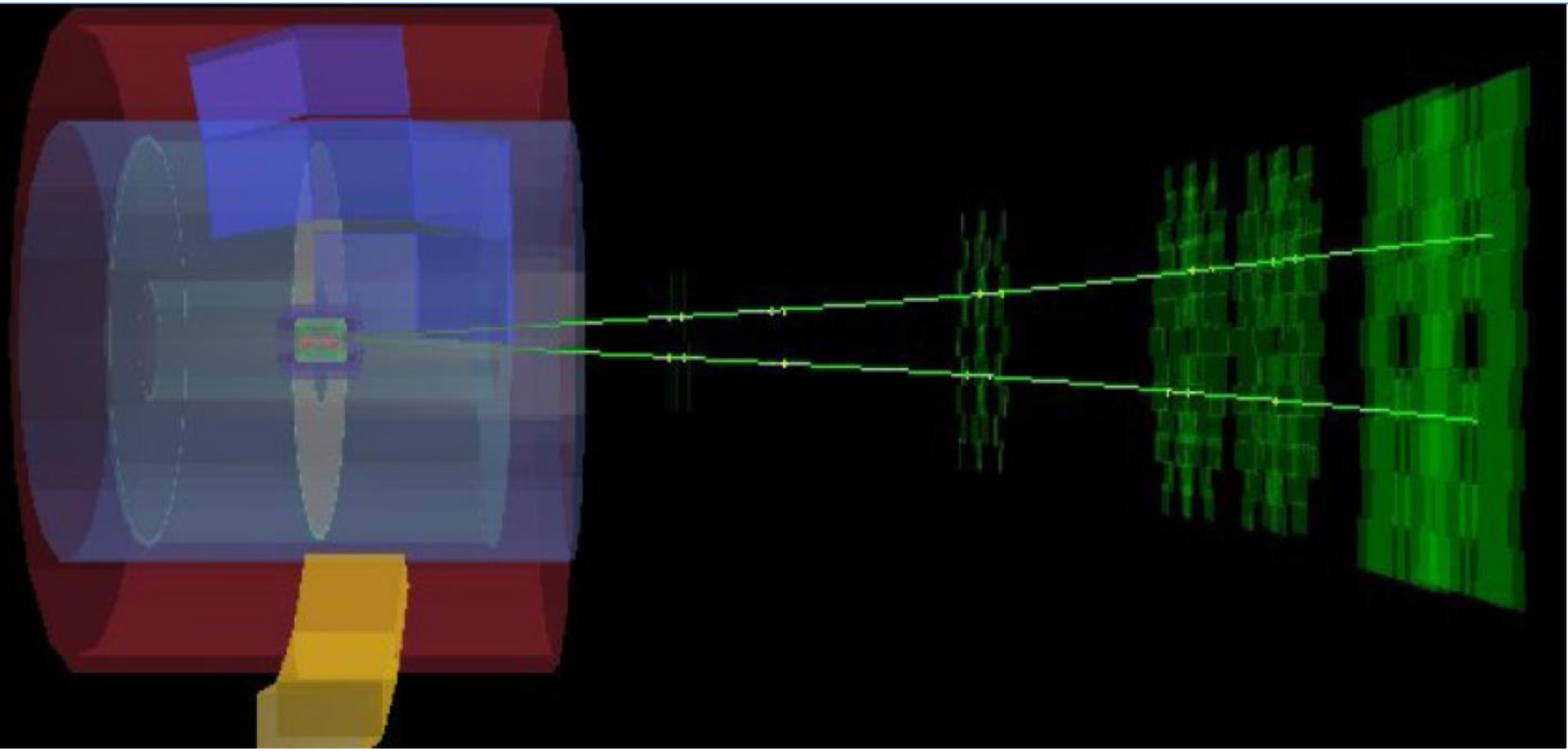
Pb-Pb UPC at LHC can be used to study γ- γ, γ-p, γ-Pb interactions at higher center-of-mass energies than ever before

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

From typical hadronic interaction…

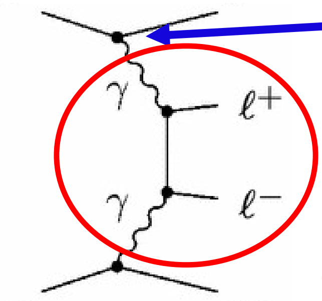


to ultra-peripheral collisions



- Experimental signature: few signal tracks in an otherwise empty detector
- Wide acceptance coverage is important to ensure event emptiness
- Zero degree calorimeters (ZDC) serve to veto hadronic interactions

$\gamma\gamma \rightarrow$ dileptons



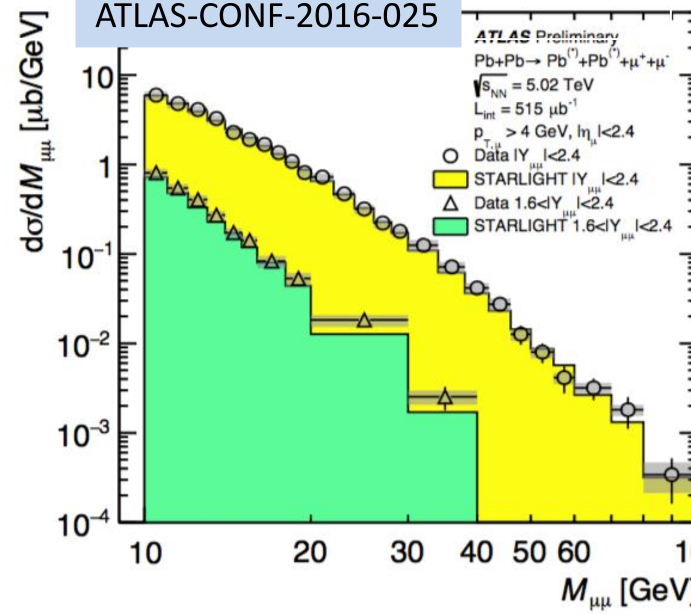
Photon flux proportional to Z^2

$$N_{\gamma/Z}(k) = \frac{2Z^2\alpha_{em}}{\pi}\left[\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}\left(K_1^2(\zeta) - K_0^2(\zeta)\right)\right]$$

$$\zeta = k(2R_A/\gamma_L)$$

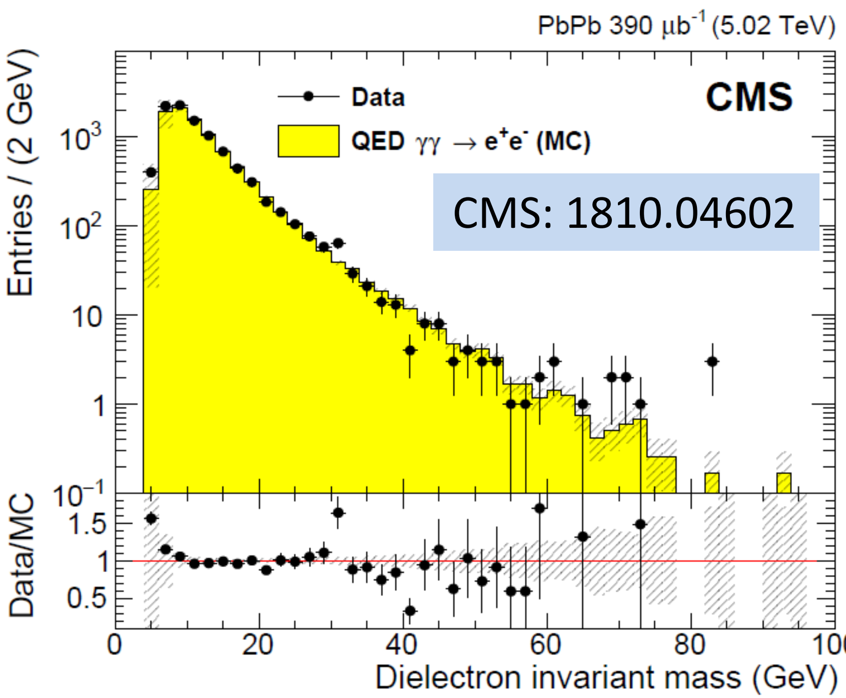
Leading order QED
(Landau & Lifshitz,1934)

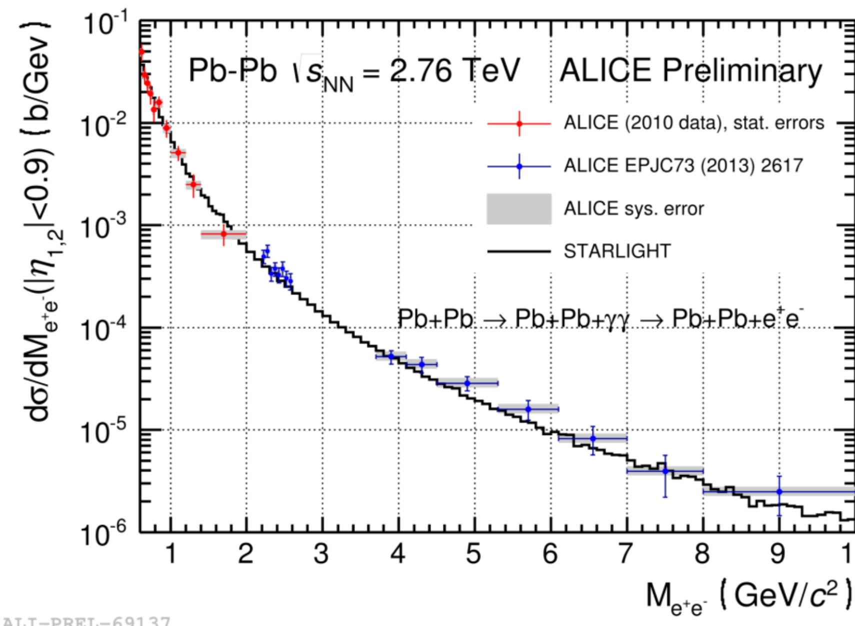
ATLAS-CONF-2016-025



Good agreement between LHC data and LO QED predictions

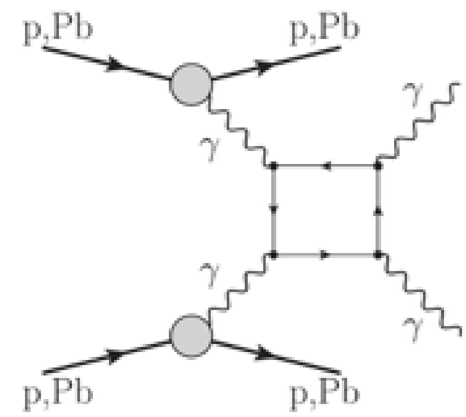
CMS: 1810.04602



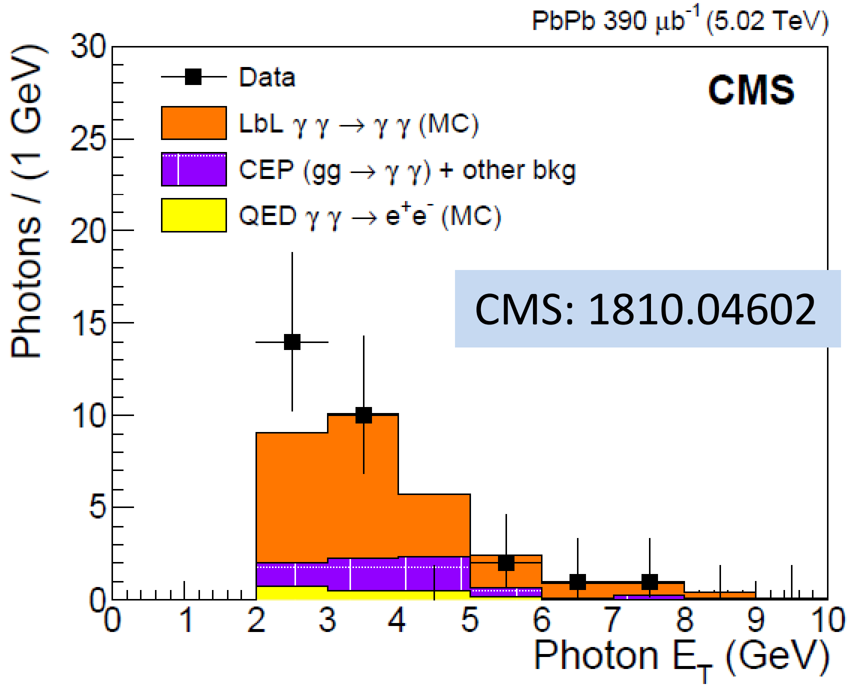


Light-by-light scattering

- Forbidden in classical electrodynamics
- Possible channel to study anomalous gauge couplings and contributions from BSM particles

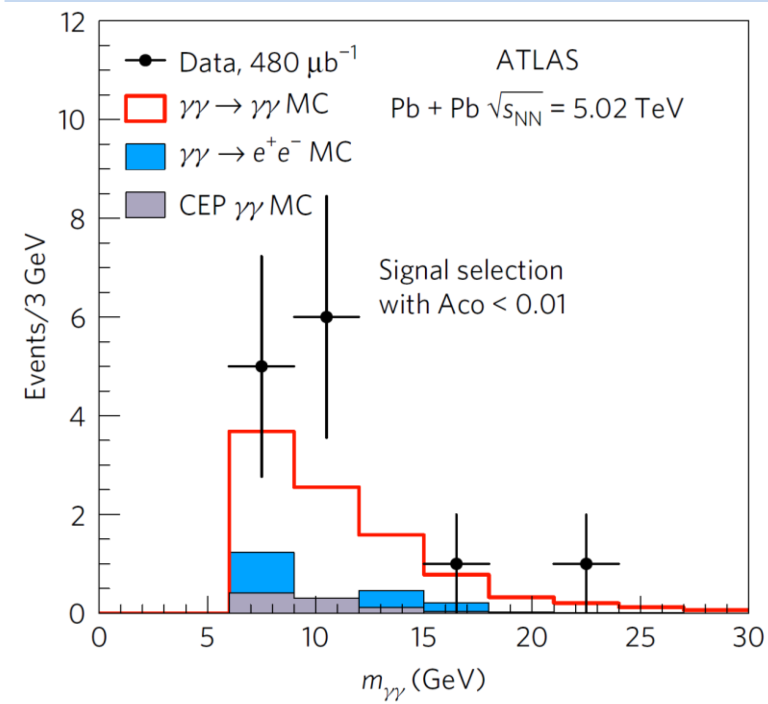


Evidence for light-by-light scattering in UPCs in agreement with SM predictions
4.1σ (CMS) and 4.4σ (ATLAS) significance



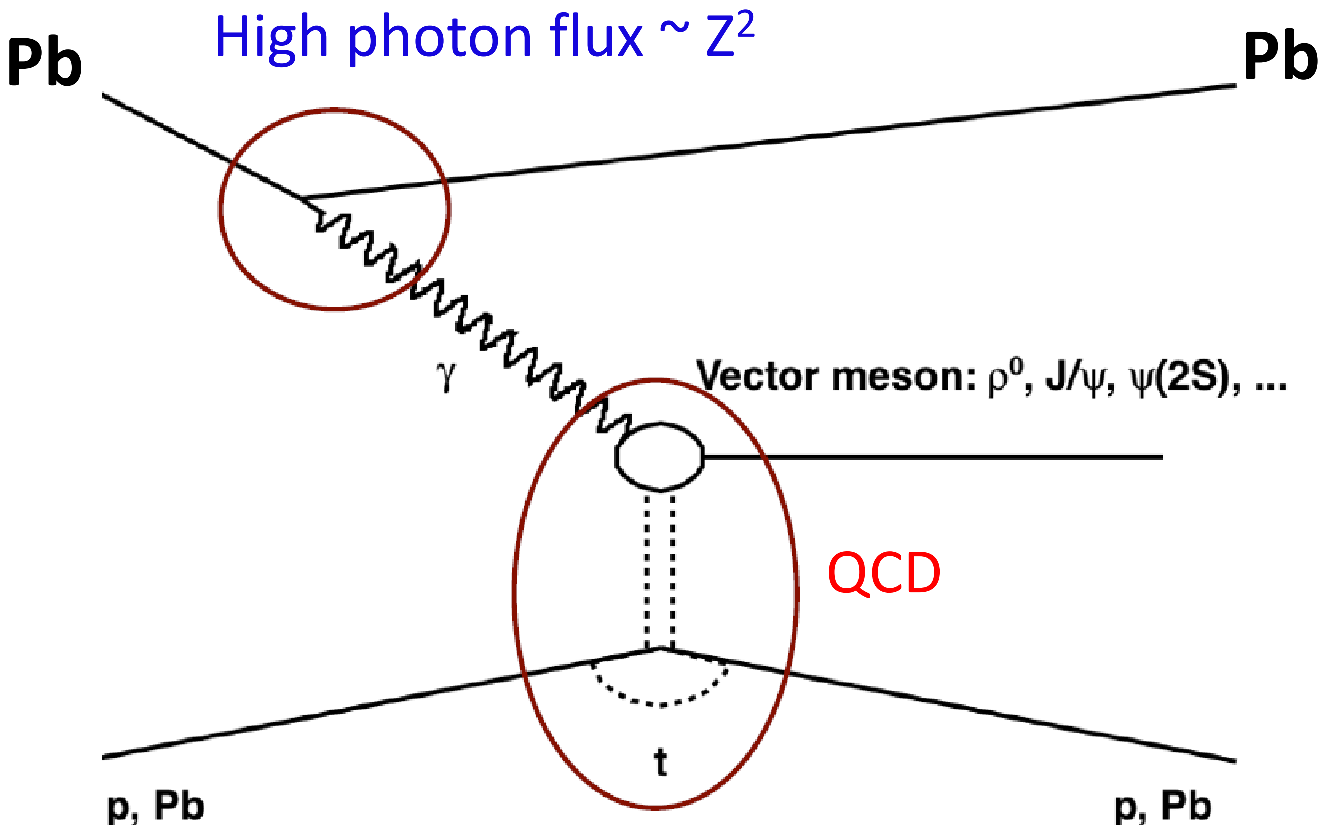
CMS: 1810.04602

ATLAS, Nature Physics 13, 852 (2017)



Best limit on axion-like particles ($\gamma\gamma \to a \to \gamma\gamma$) in 5-50 GeV mass range

Vector meson photoproduction in UPC



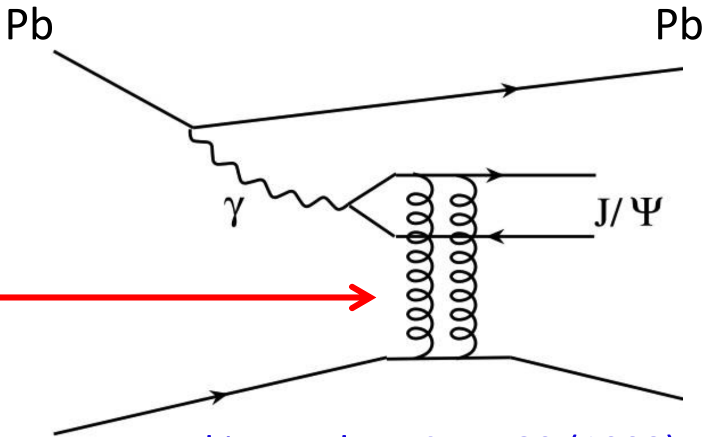
Exclusive vector meson production cross section in UPC can be factorized in two parts:

- QED: photon flux
- QCD: vector meson photoproduction: $\sigma(W_{\gamma p})$

J/ψ photoproduction in UPC

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

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



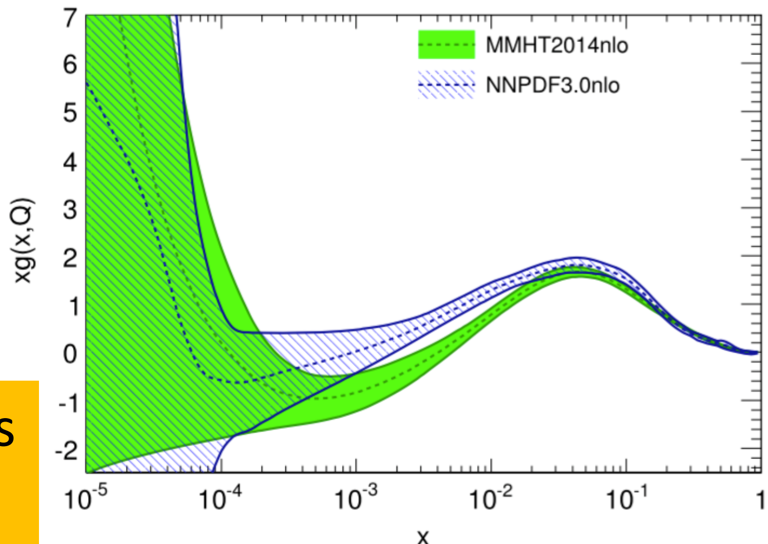
Ryskin: Z. Phys. C 57, 89 (1993)

- J/ψ mass 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:

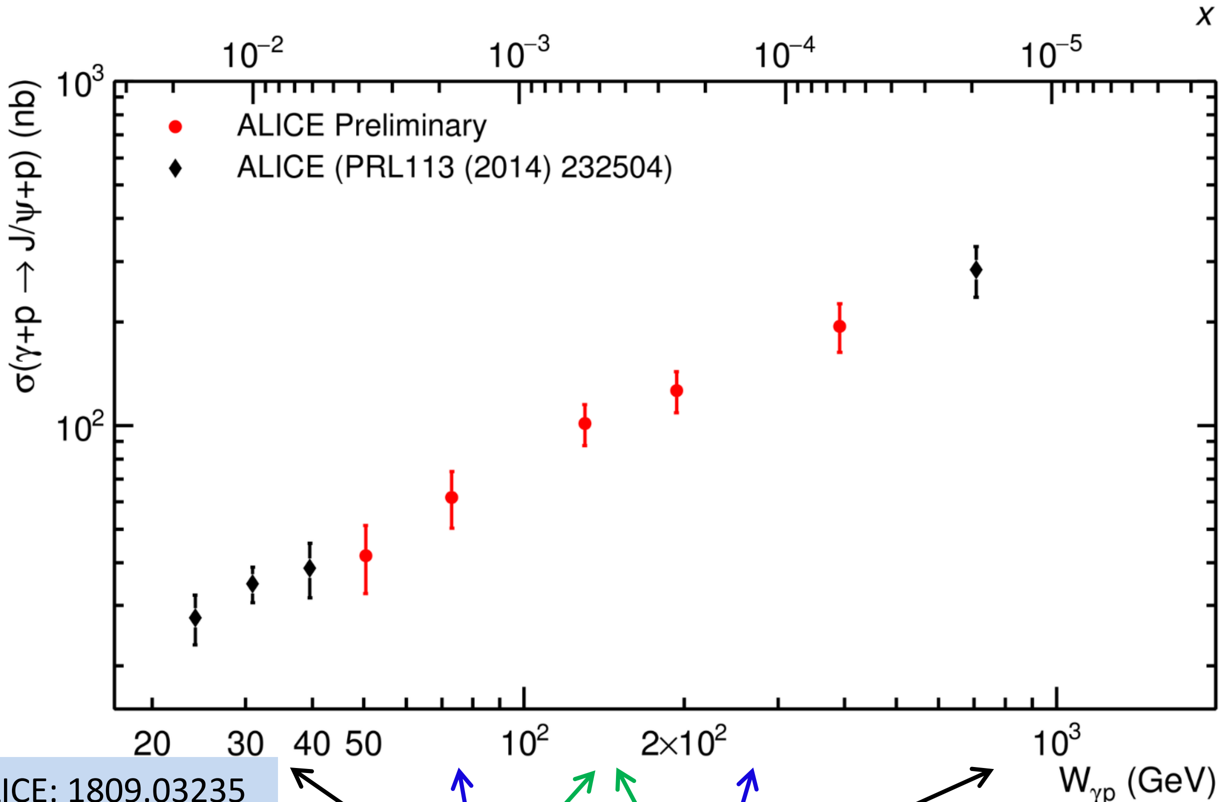
$$x = \frac{M_{J/\psi}^2}{W_{\gamma p}^2} = \frac{M_{J/\psi}}{2E_p}\exp(\pm y)$$



Vector meson photoproduction in UPC allows one to probe poorly known gluon distributions at low *x*

ALICE: exclusive J/ψ in p-Pb UPC

photons from Pb => proton target

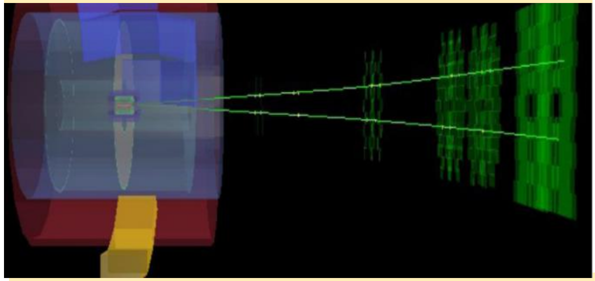


ALICE: 1809.03235

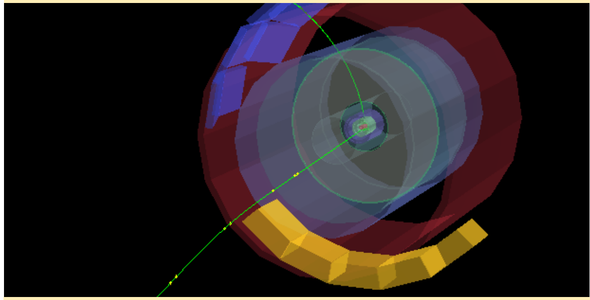
p-Pb

Pb-p

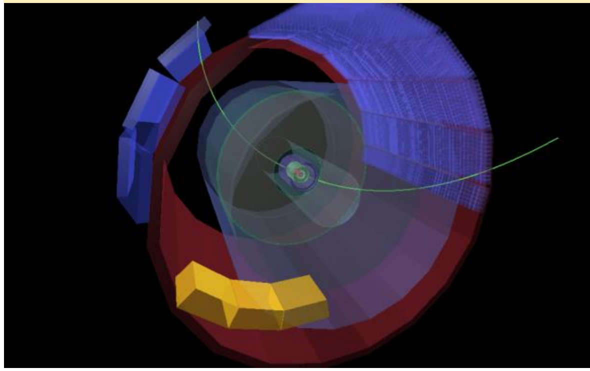
both muons in the muon arm



one muon in the muon arm, the other in the barrel



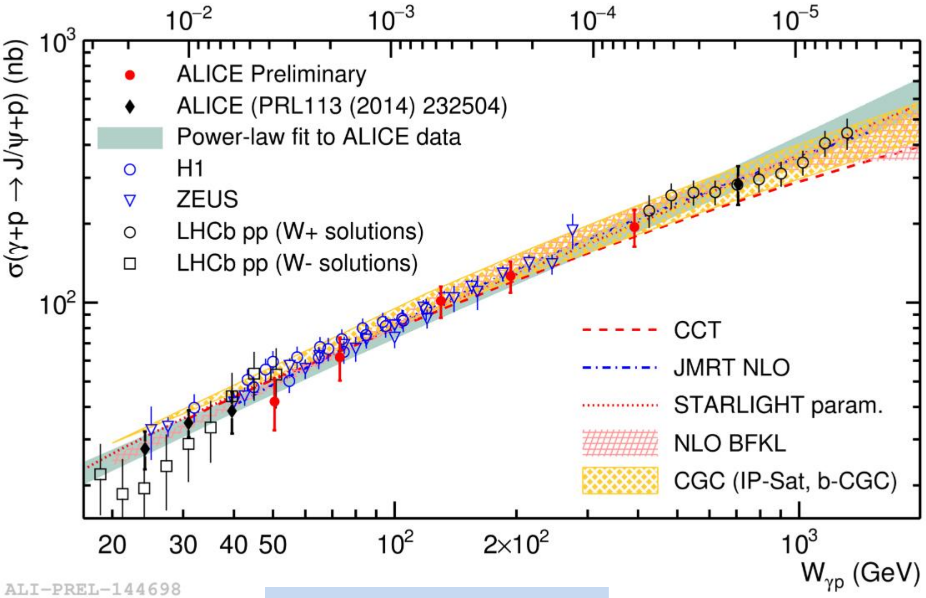
both leptons in the barrel



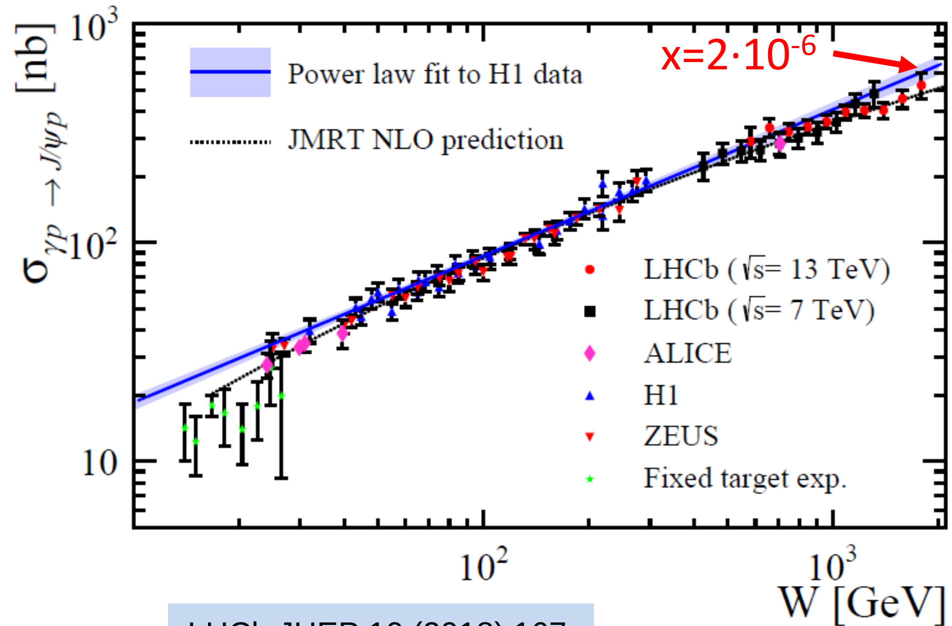
Wide energy range in ALICE extends HERA coverage:

- 2 beam configurations (p-Pb and Pb-p)
- 3 options to measure dilepton J/ψ decays

J/ψ photoproduction off a proton



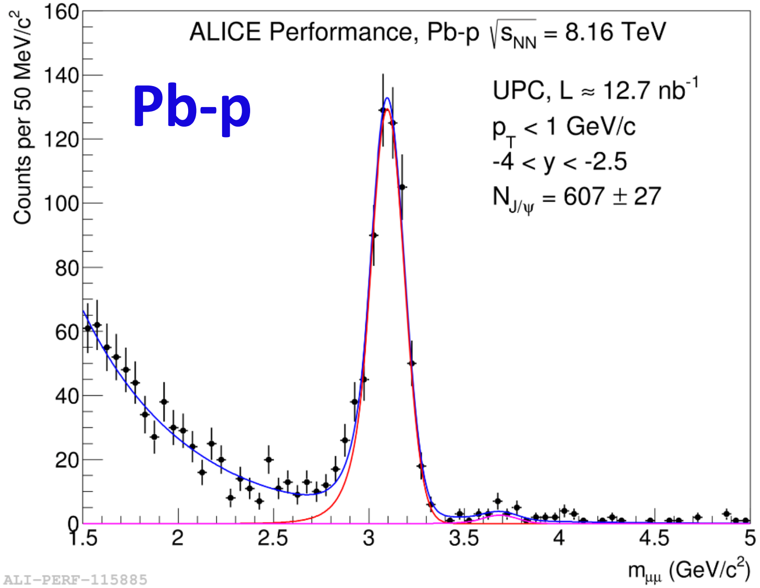
ALICE: 1809.03235

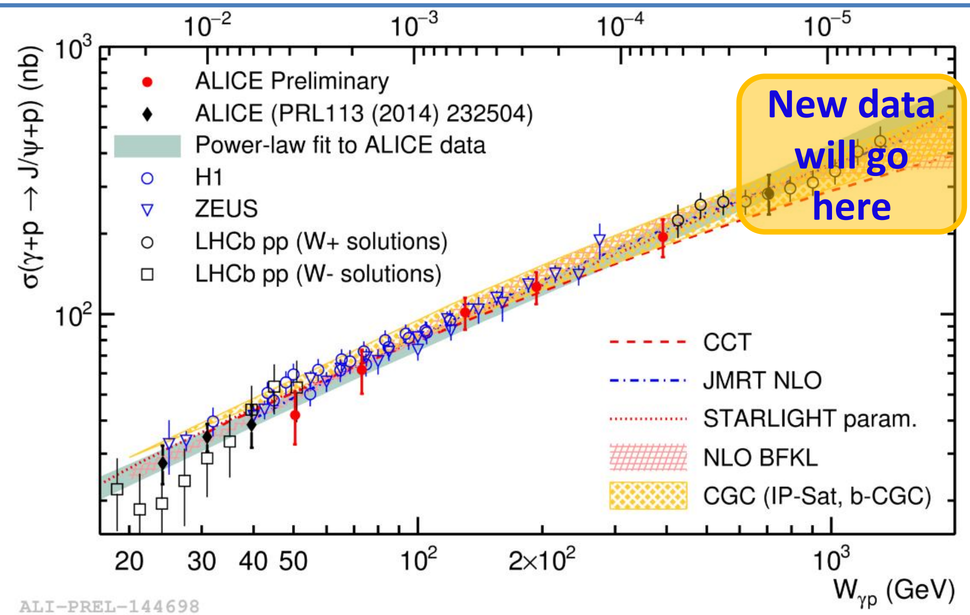


LHCb JHEP 10 (2018) 167

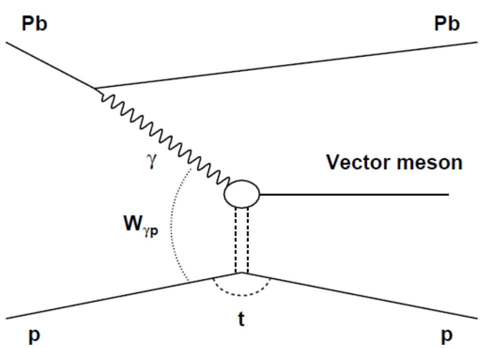
- Nice agreement between HERA in ep, LHCb in pp and ALICE in p-Pb
- Energy dependence well described with a power law fit
  $\rightarrow$ no clear signs of saturation

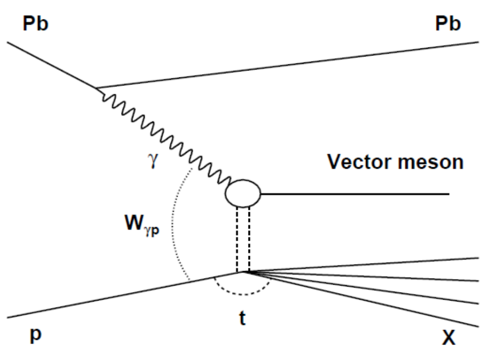
p-Pb @ 8.16 TeV



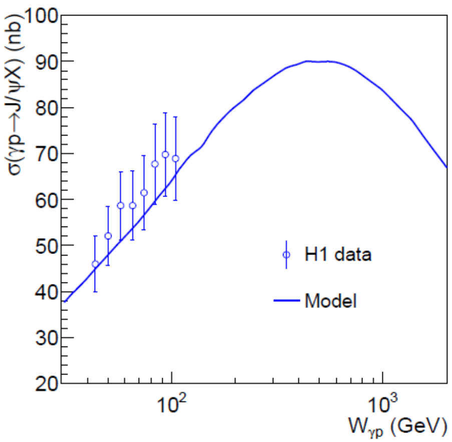


- x10 more stat at high $W_{\gamma p}$ ~ 0.7-1.4 TeV
- Aim to study exclusive and proton-dissociative cross section behaviour at high $W_{\gamma p}$





Predictions for proton-dissociative cross section

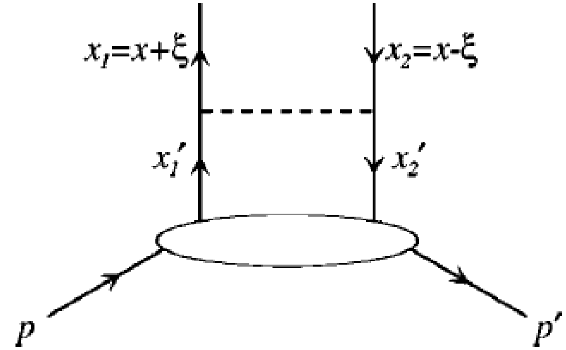


Cepila, Contreras, Takaki: PLB766 (2017) 186

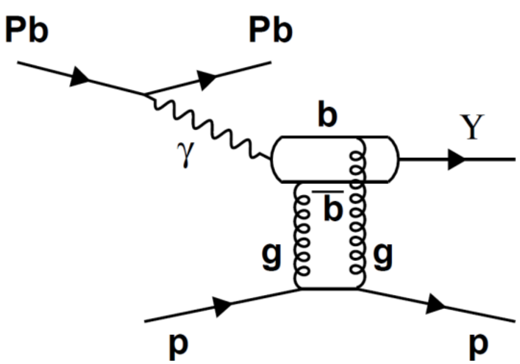
Can we use this data to constrain gluon PDFs?

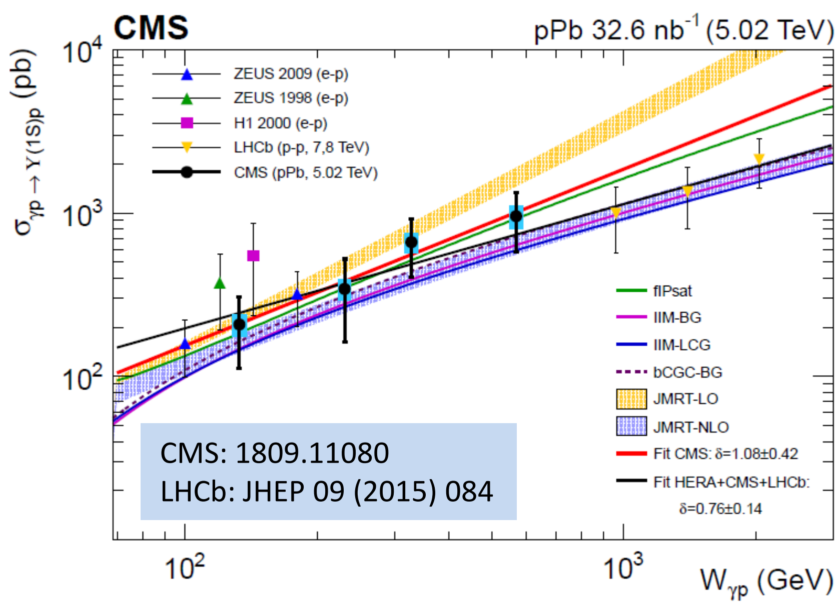
Caveats:

- J/ψ photoproduction probes generalized gluon distributions (two gluons have different x values)
  - Connected with collinear PDFs via Shuvaev transform: PRD 60 (1999) 014015



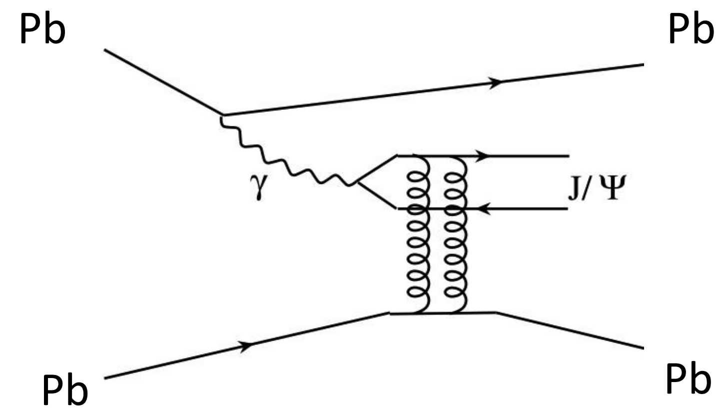
- Scale uncertainty $\mu^2 \sim 2.4\text{-}3\ \mathrm{GeV}^2$ is a reasonable choice
  - Guzey, Zhalov: JHEP 1310 (2013) 207
- Large NLO contributions
  - Υ measurements reveal importance of NLO effects





J/ψ photoproduction on Pb target

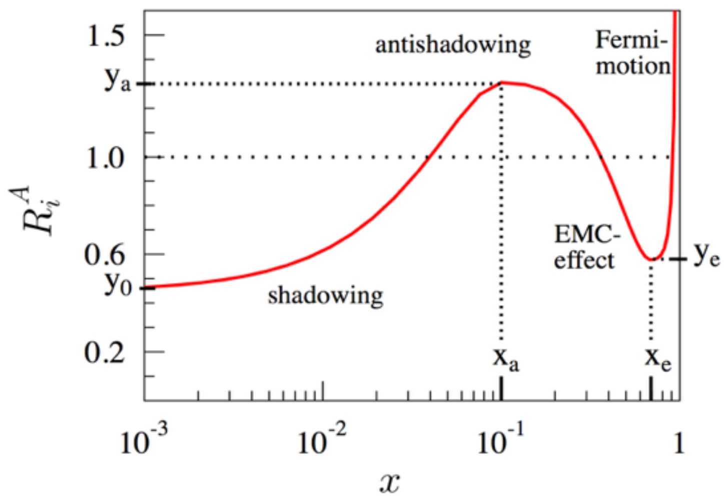
Coherent J/ψ photoproduction cross section is proportional to the **square of the gluon density in nuclei**



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

J/ψ photoproduction in Pb-Pb UPC (lead target) provides 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



Nuclear shadowing = suppression of cross section on a nucleus compared to sum of cross sections on individual nucleons. Explained by destructive interference among amplitudes for interaction with 1, 2 and more nucleons

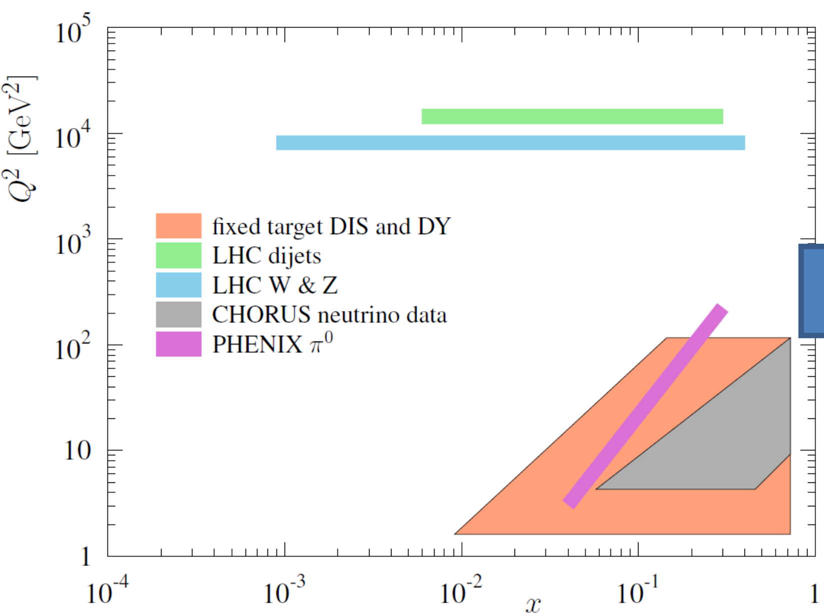
Parton distributions in nuclei (nPDFs)

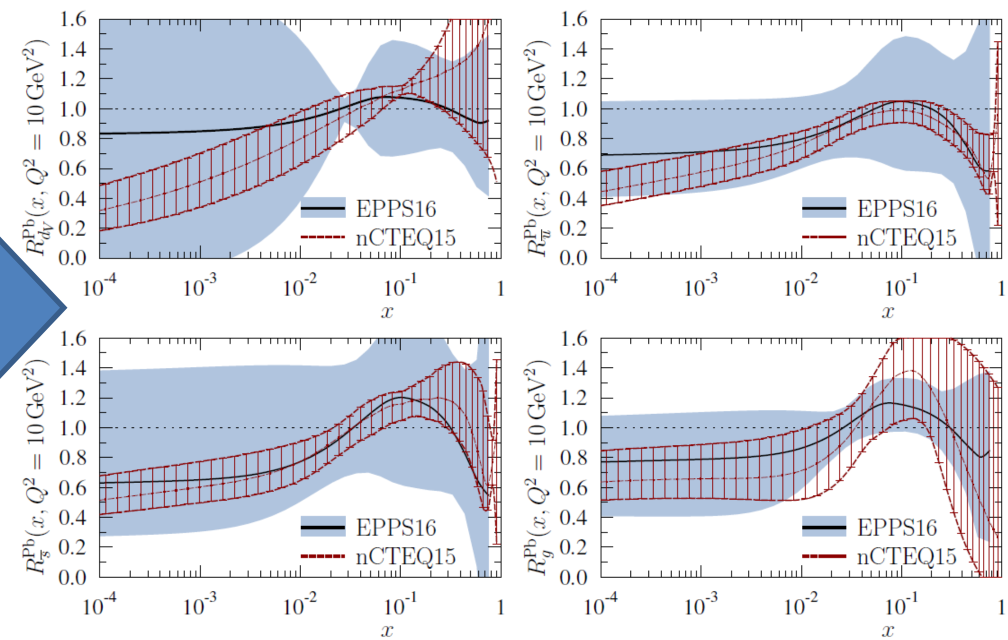
nPDFs are fundamental QCD quantities for the description of DIS, pA, AA collisions

- determine initial state in heavy ion collisions
- required for quantitative estimates for the onset of saturation

Determination of nPDFs:

EPPS16 : EPJ C (2017) 77

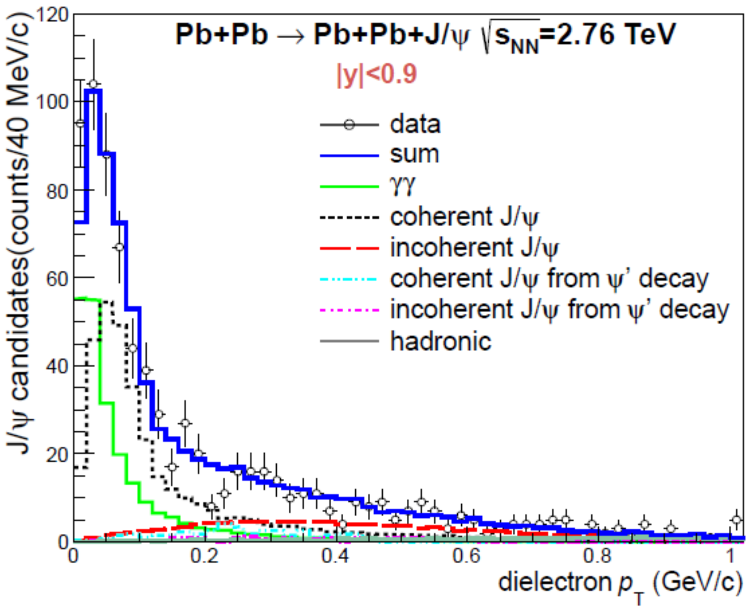




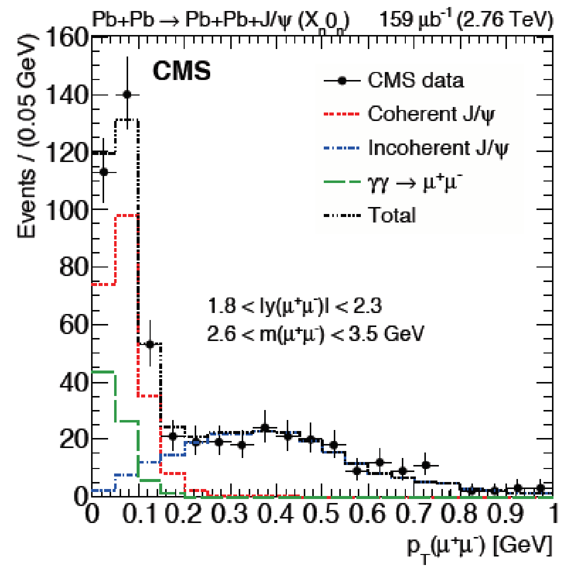
Resulting nPDFs have rather **large uncertainties, especially for small-x gluons** due to:

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

Coherent and incoherent photoproduction



ALICE. Eur. Phys. J. C73 (2013) 2617



CMS: Phys.Lett. B772 (2017) 489-511

Two types of photoproduction processes:

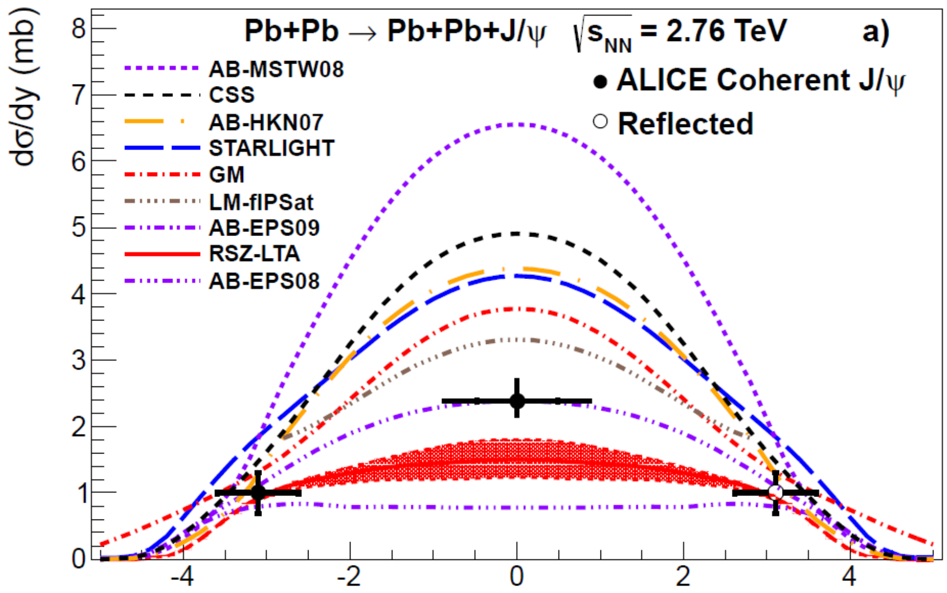
- **Coherent:**
  - photon couples coherently to all nucleons
  - $\langle p_T \rangle \sim 1/R_{Pb} \sim 60$ MeV/c

- **Incoherent:**
  - photon couples to a single nucleon
  - $\langle p_T \rangle \sim 1/R_p \sim 450$ MeV/c
  - usually accompanied by neutron emission

- Other contributions: J/ψ from coherent and incoherent ψ' decays and $\gamma\gamma \rightarrow ll$

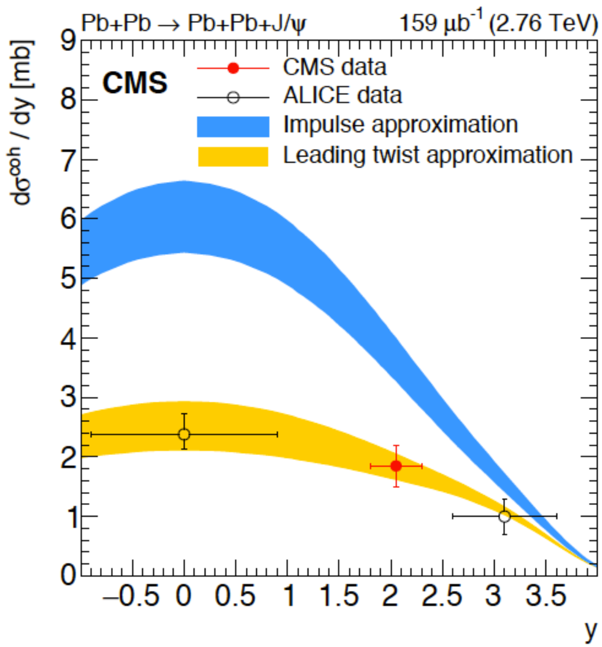
Coherent J/ψ photoproduction: results from Run 1

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



***x* ~ 10^{-2}** ***x* ~ 10^{-3}**

CMS: Phys.Lett. B772 (2017) 489-511



Several competing approaches:

- Empirical shadowing parameterizations: AB, PRC85 (2012) 044904
- Shadowing in leading twist approximation (LTA): RSZ, PLB 710 (2012) 252
- Color dipole model + saturation: GM: PRC84 (2011) 011902, CSS: PRC86 (2012) 014905, LM: PRC87 (2013) 032201

Good agreement with **EPS09 and LTA shadowing**

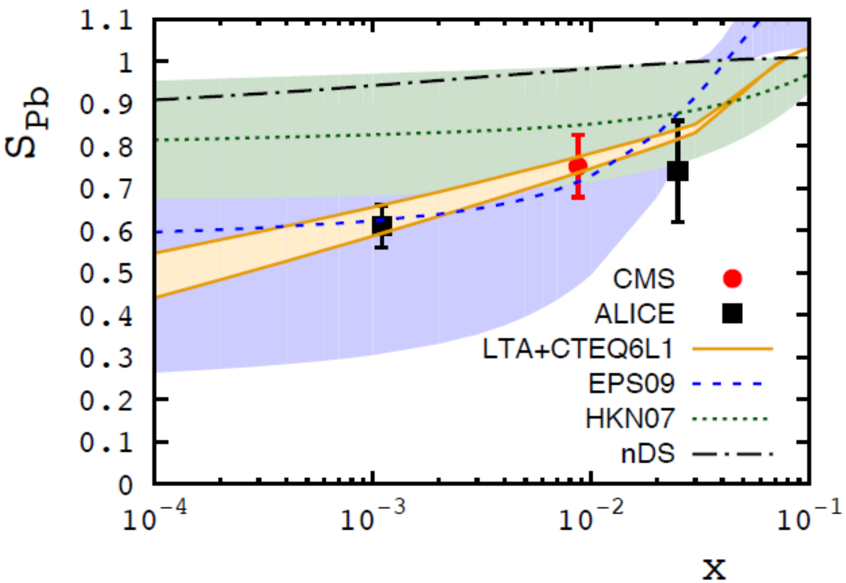
Gluon shadowing from photoproduction data

Nuclear suppression factor:

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

Experimental cross section in Pb-Pb UPC divided by the photon flux

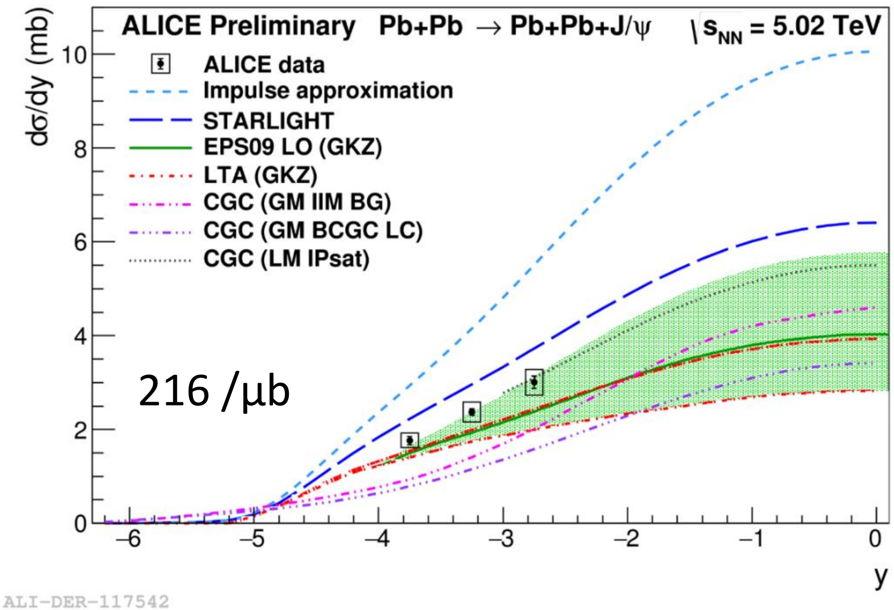
Impulse approximation:
forward photoproduction cross section off proton (HERA) times integral over squared Pb form-factor

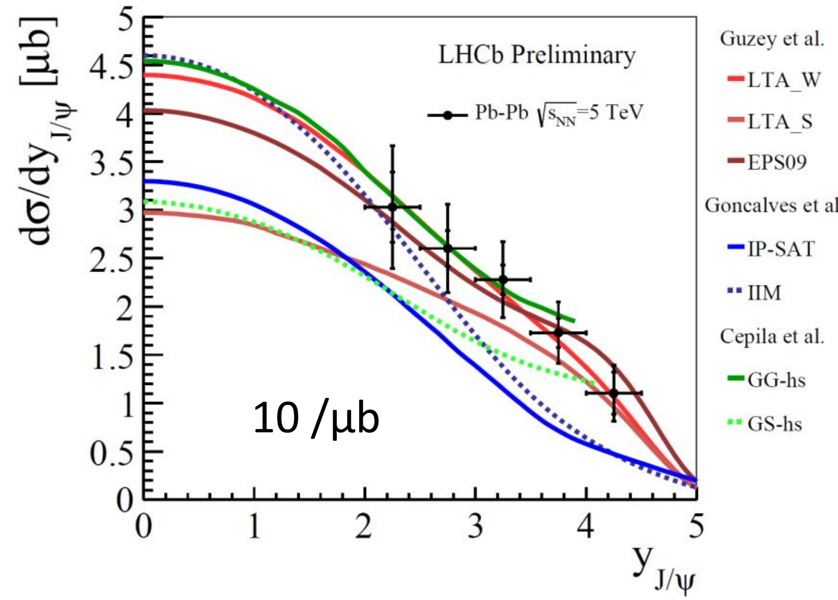


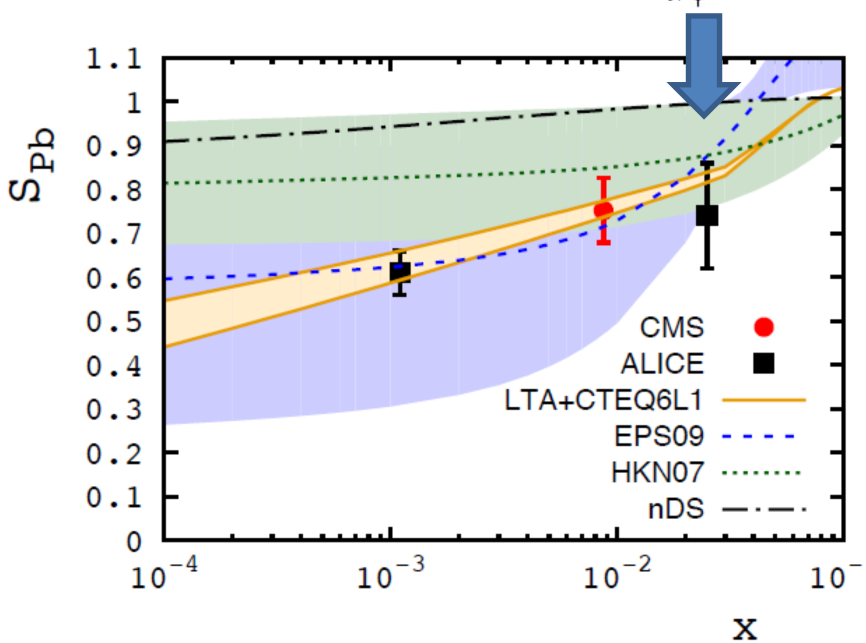
Guzey, EK et al. Phys. Lett. B726 (2013) 290
Guzey, Zhalov JHEP 1310 (2013) 207

- Nuclear suppression factor S gives direct access to $R_g(x,\mu\sim 2.4$ GeV)
- First direct evidence of large gluon nuclear shadowing: $R_g(x,\mu\sim 2.4$ GeV) ~ 0.6
- Many complications (skewness, NLO, scale uncertainty and higher-twist corrections) are likely minimized – S factor can be used in global nPDF fits

First run 2 results (Pb-Pb 2015)





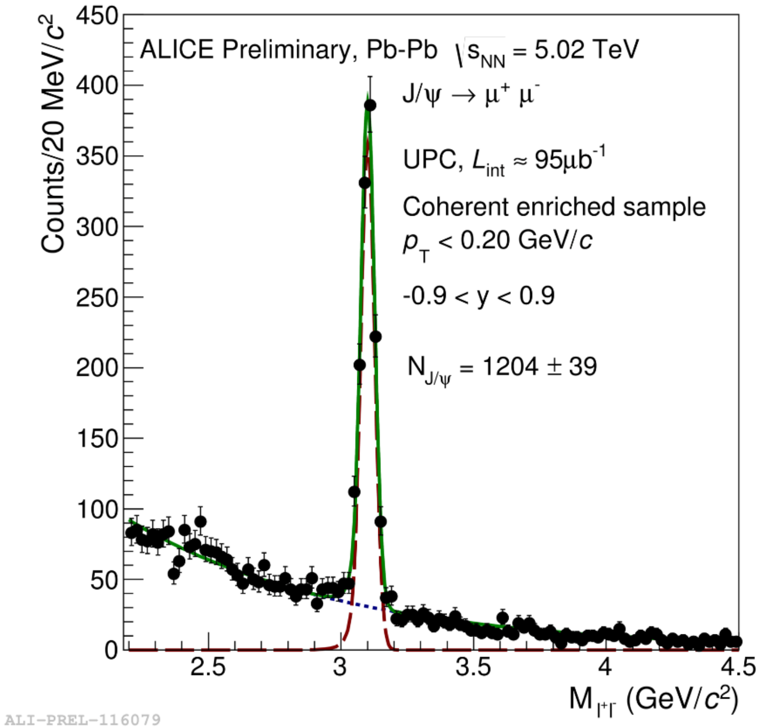


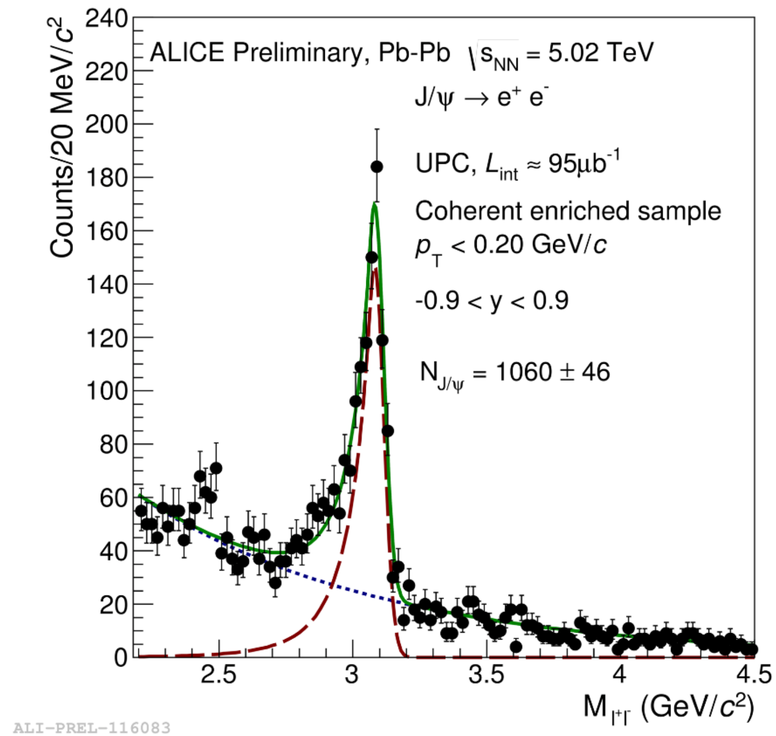
- 90-95% contribution of high-x: 0.7-3 x 10^{-2}
- Back-of-the-envelope calculation (neglect low-x):

Data/Impulse approximation ~ 0.6

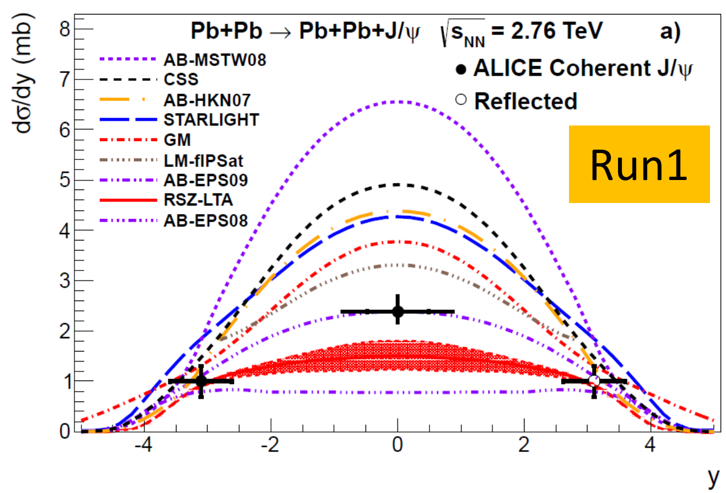
=> shadowing factor $\sim \sqrt{0.6} \sim 0.8$

+ J/ψ in central barrel

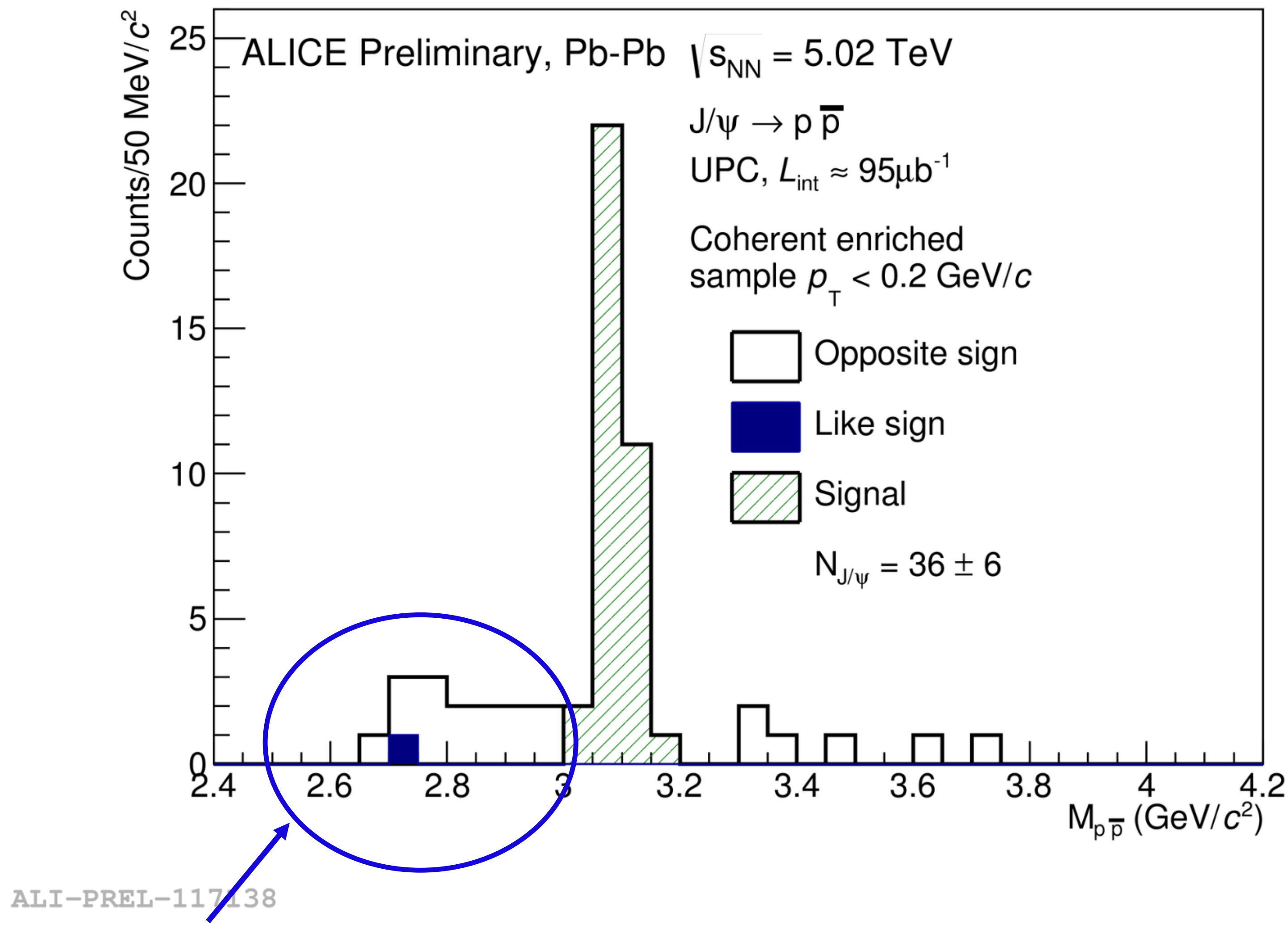




- x4 more statistics wrt Run1
- access to $x \sim 0.5 \times 10^{-3}$

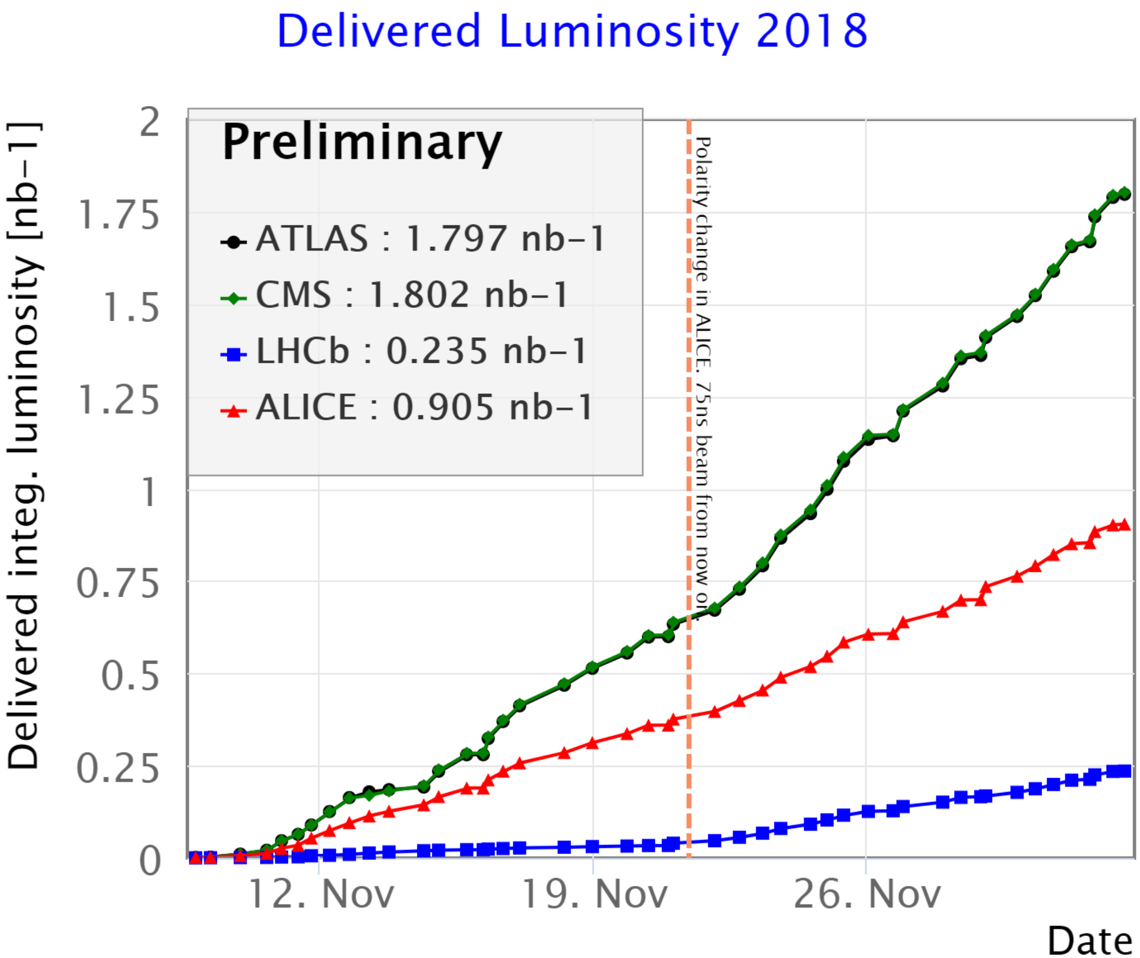


First observation in UPC: J/ψ→ $p\bar{p}$



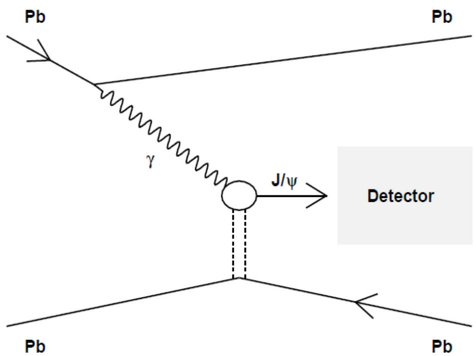
Continuum $\gamma\gamma \to p\bar{p}$ might be also interesting, e.g.
Kłusek-Gawenda, Lebiedowicz, Nachtmann, Szczurek: PRD96 (2017) 094029

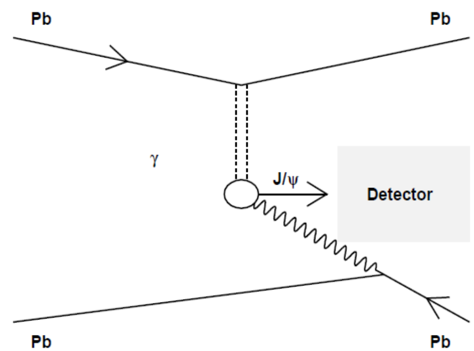
News from Pb-Pb2018



- ATLAS, CMS: 600 /μb (2015) → 1800 /μb (2018)
- ALICE: 216 /μb (2015) → 530 /μb (2018)
- LHCb: 10 /μb (2015) → 235 /μb (2018)

Ultimate goal: access gluon shadowing at x~10^{-5}



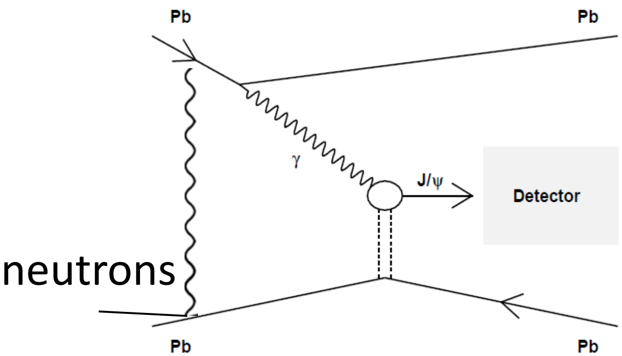


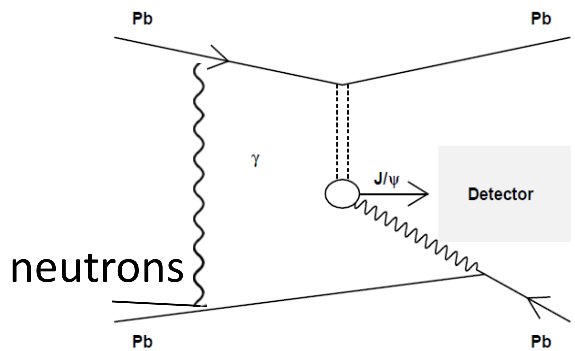
- Two terms in vector meson photoproduction cross section in UPC:

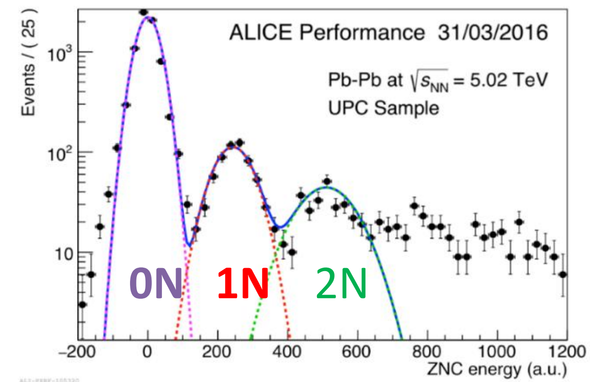
$$\sigma(y) = n(+y)\sigma_{\gamma\mathrm{Pb}}(+y) + n(-y)\sigma_{\gamma\mathrm{Pb}}(-y)$$

low energy photons | **high-x gluons** | **high-energy photons** | **low-x gluons**

Ultimate goal: access gluon shadowing at x~10^{-5}







- Two terms in vector meson photoproduction cross section in UPC:

$$\sigma(y) = \underbrace{n(+y)}_{\text{low energy photons}}\underbrace{\sigma_{\gamma\mathrm{Pb}}(+y)}_{\text{high-x gluons}} + \underbrace{n(-y)}_{\text{high-energy photons}}\underbrace{\sigma_{\gamma\mathrm{Pb}}(-y)}_{\text{low-x gluons}}$$

- Neutron-differential cross sections may help to decouple low-x and high-x cross sections:

measured

known fluxes

no neutrons: $\boxed{\sigma_{0\mathrm{N}0\mathrm{N}}(y)} = \boxed{n_{0\mathrm{N}0\mathrm{N}}(+y)}\sigma_{\gamma\mathrm{Pb}}(+y) + \boxed{n_{0\mathrm{N}0\mathrm{N}}(-y)}\sigma_{\gamma\mathrm{Pb}}(-y),$

neutrons on one side: $\boxed{\sigma_{0\mathrm{NXN}}(y)} = \boxed{n_{0\mathrm{NXN}}(+y)}\sigma_{\gamma\mathrm{Pb}}(+y) + \boxed{n_{0\mathrm{NXN}}(-y)}\sigma_{\gamma\mathrm{Pb}}(-y)$

unknown photoproduction cross sections

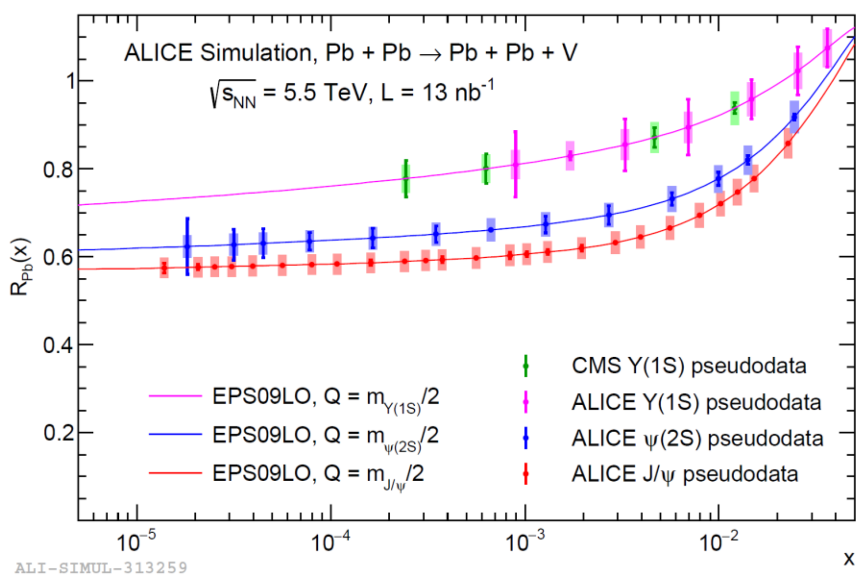
Effective flux in J/ψ photoproduction is modified in presence of additional photon exchange

Run3-4 projections (Pb-Pb)

- Expected statistics in Run 3-4 (13 /nb):

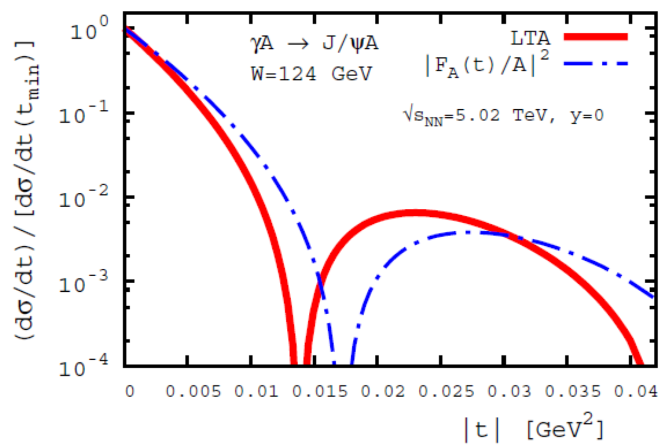
Yellow report on Run3-4: 1812.06772

PbPb							
Meson	σ	All Total	Central ALICE	Central CMS, ATLAS	Forward ALICE	Forward LHCb
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	2.5 mb	32 M	3.0 M	15 M	1.2 M	3.3 M
$\psi' \to \mu^+\mu^-$	64μb	830 K	82 K	410 K	31 K	79 K
$\Upsilon(1S) \to \mu^+\mu^-$	2.6 μb	33 K	4.0 K	20K	880	2.0 K



$$x = \frac{m_V}{\sqrt{s_{NN}}} \exp(-y) \qquad R_{Pb}(x) = \left(\frac{\sigma_{\gamma Pb}(x)}{\sigma_{IA}(x)}\right)^{1/2},$$

Main goals for Run3-4:
- access to gluon shadowing at low x
- probe gluon distribution in transverse plane



Guzey, Strikman, Zhalov PRC95 (2017) 025204

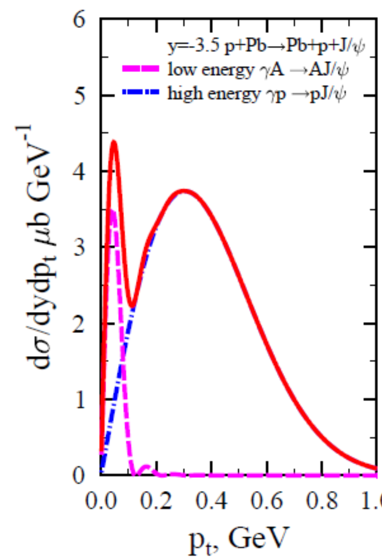
Run3-4 projections (p-Pb)

- Expected statistics in Run 3-4 (2/nb):

Yellow report on Run3-4: 1812.06772

pPb - lead shine, γp								
Meson	σ	A Tot	Central ALICE	Central CMS, ATLAS	Forward ALICE	Forward LHCb	Backwarc ALICE	Backward LHCb
$\rho \to \pi^+\pi^-$	35 mb	70 B	3.9 B	15 B	2.0 B	5.5 B	850 M	2.0 B
$\phi \to K^+K^-$	870 μb	1.7 B	65 M	290 M	22 M	120 M	9.7 M	52 M
$J/\psi \to \mu^+\mu^-$	6.2 μb	12 M	1.0 M	5.2 M	260 K	800 K	180 K	430 K
$\psi(2S) \to \mu^+\mu^-$	134 nb	270 K	22 K	110 K	6.0 K	18 K	3.2 K	7.7 K
$\Upsilon(1S) \to \mu^+\mu^-$	5.74 nb	11 K	1.1 K	5.4 K	310	880	41	100

pPb - proton shine, γA								
Meson	σ	A Tot	Central ALICE	Central CMS, ATLAS	Forward ALICE	Forward LHCb	Backwarc ALICE	Backward LHCb
$\rho \to \pi^+\pi^-$	531 μb	1.1 B	83 M	360 M	20 M	44 M	56 M	150 M
$\phi \to K^+K^-$	23 μb	46 M	1.3 M	8.0 M	120 K	1.7 M	210 K	3.9 M
$J/\psi \to \mu^+\mu^-$	333 nb	670 K	55 K	290 K	14K	36 K	15 K	41 K
$\psi(2S) \to \mu^+\mu^-$	8.9 nb	18 K	1.5 K	7.9 K	380	990	380	1.0 K
$\Upsilon(1S) \to \mu^+\mu^-$	0.43 nb	860	93	460	14	34	14	30



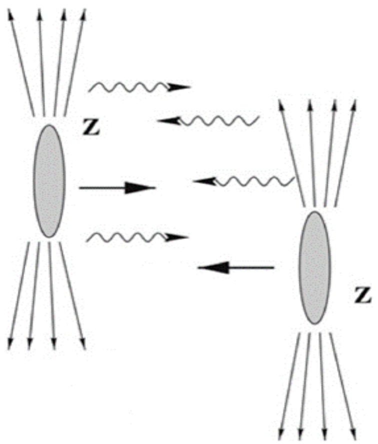
Guzey, Zhalov:
JHEP 1402 (2014) 046

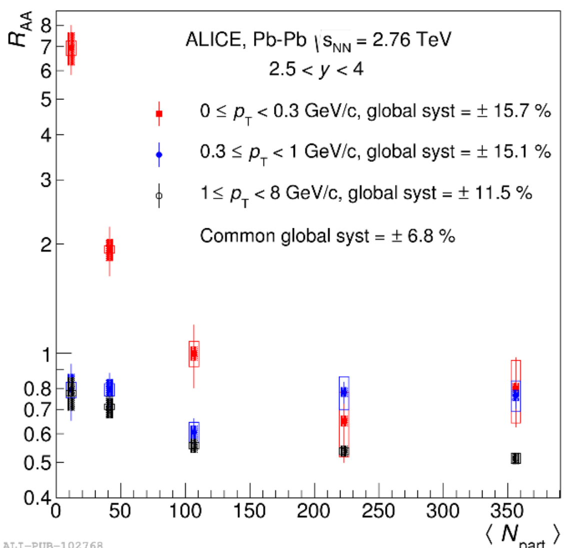
Main goals:

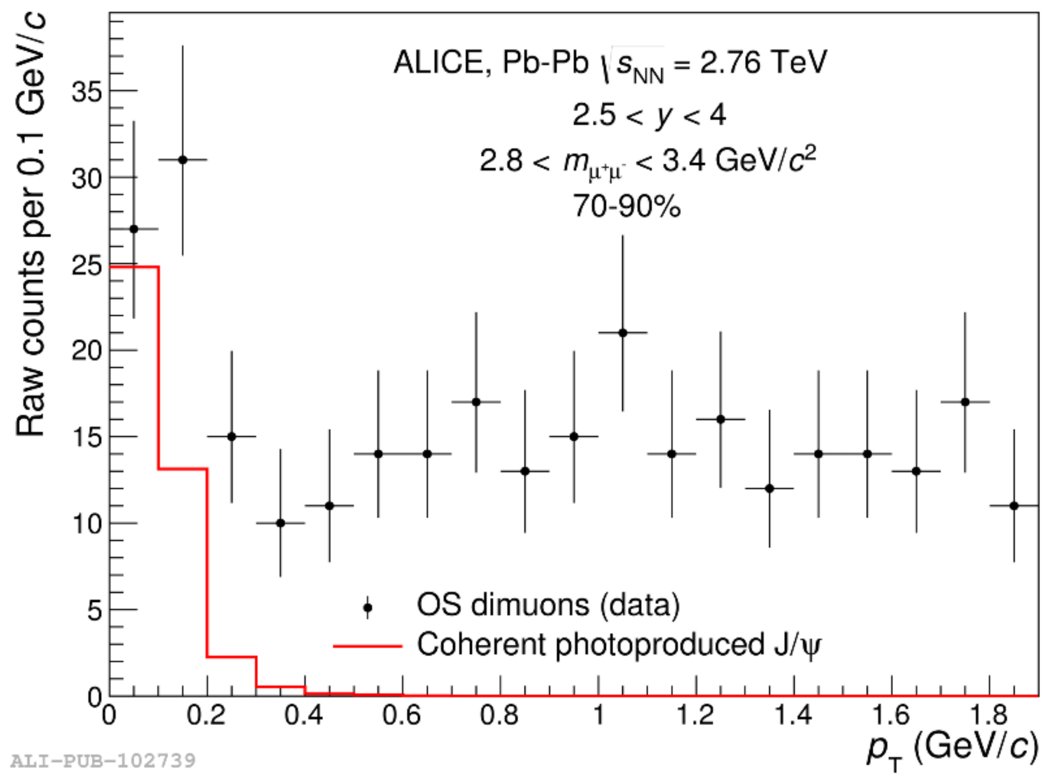
- Precision measurements on vector meson photoproduction off proton
- Access gluon shadowing at 10^{-5} with proton-shine gamma off lead

Coherent J/ψ in hadronic collisions?

ALICE: PRL 116 (2016) 222301



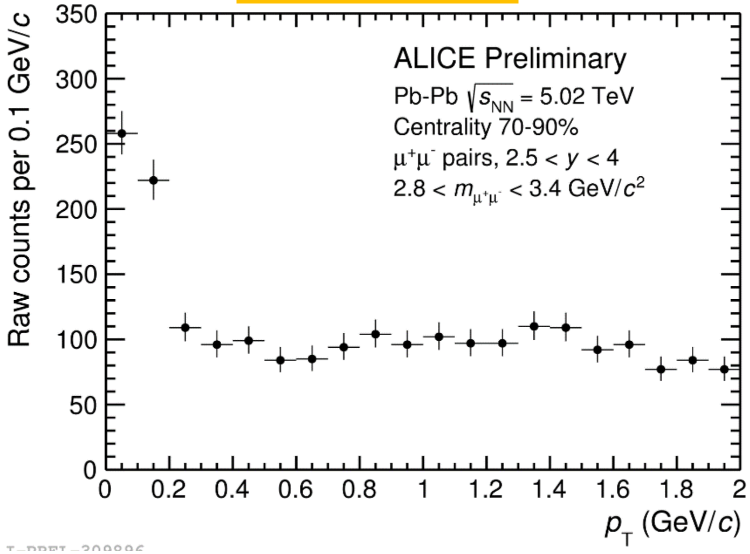




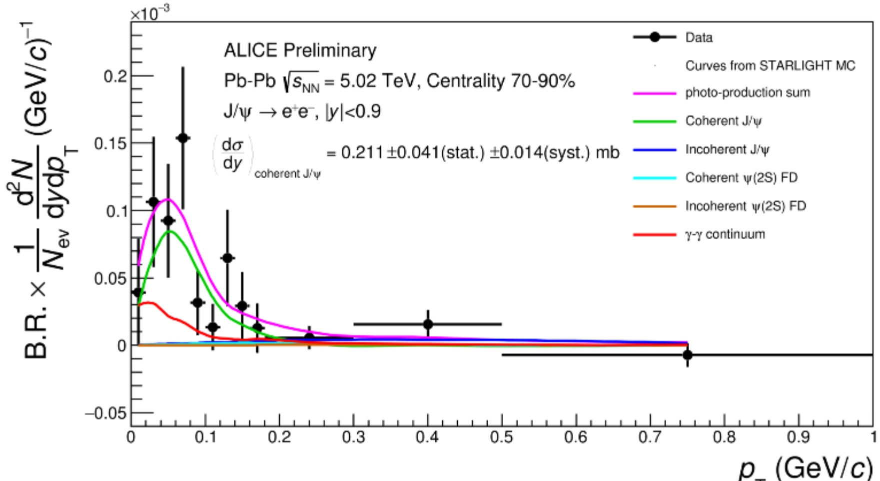
- Data shows an excess of J/ψ at low p_T < 200 MeV/c (R_{AA} ~ 7)
- Possible interpretation: coherent photoproduction on nuclear fragments

Coherent J/ψ in hadronic collisions: news from Run2

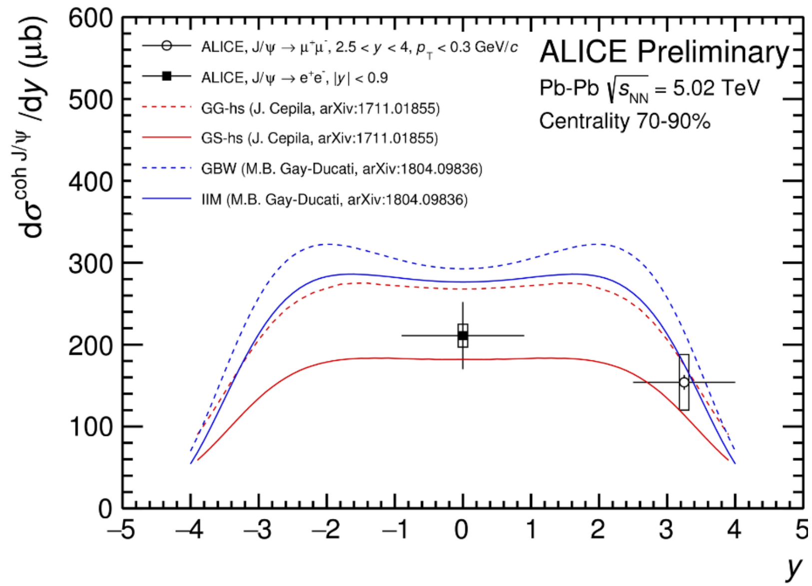
Forward J/ψ



Central barrel J/ψ



ALI-PREL-148057



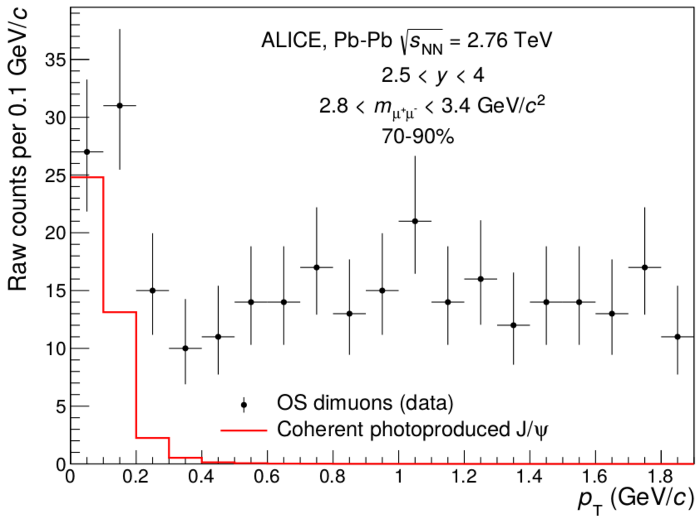
ALI-PREL-309948

Theoretical challenge:

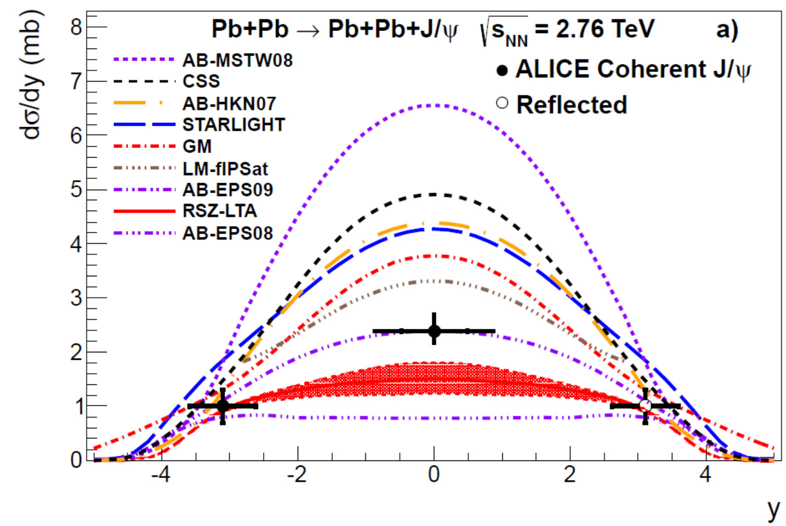
- How can the coherence condition survive when both nuclei are broken by hadronic interaction?
- Do only spectator nucleons participate to the coherence?

Low-x gluons with coherent J/ψ in hadronic collisions?

J/ψ in peripheral collisions (b<2R)

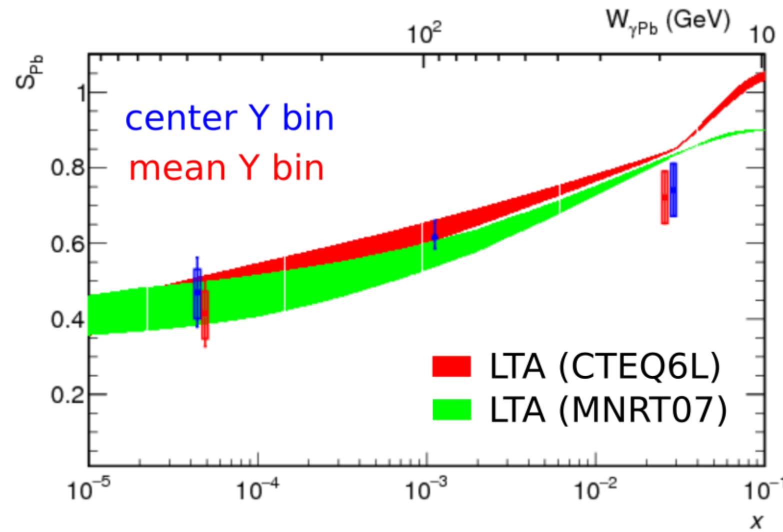


J/ψ in ultra-peripheral collisions (b>2R)



$$\sigma_{\gamma\mathrm{Pb}}(-y) = \left(n_\gamma^P(y) \frac{d\sigma^U_{\mathrm{PbPb}}}{dy} - n_\gamma^U(y) \frac{d\sigma^P_{\mathrm{PbPb}}}{dy} \right) / F(y)$$

$$\sigma_{\gamma\mathrm{Pb}}(y) = \left(n_\gamma^U(-y) \frac{d\sigma^P_{\mathrm{PbPb}}}{dy} - n_\gamma^P(-y) \frac{d\sigma^U_{\mathrm{PbPb}}}{dy} \right) / F(y)$$



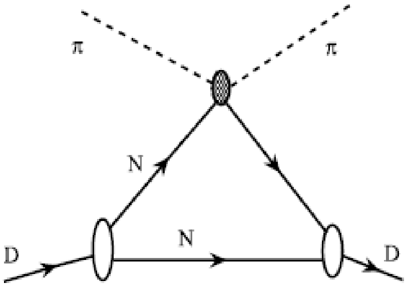
G. Contreras, PRC96 (2017) 015203

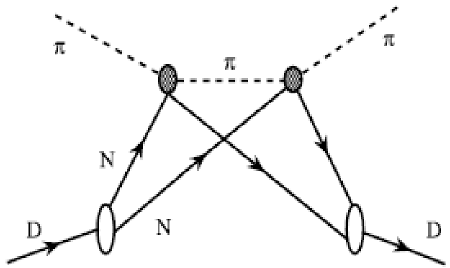
Summary

- Continuum $\gamma\gamma \rightarrow l^+l^-$ cross sections consistent with LO predictions
  - Validate photon fluxes obtained with EPA
- Photoproduction of vector mesons in UPC at LHC allows one to study gluon distributions at unprecedently high energies
- Coherent J/ψ photoproduction cross sections in UPC shows direct evidence of large gluon shadowing $R(x=10^{-3}) \sim 0.6$
- Unexpected discoveries: coherent J/ψ in hadronic events
- Expect lots of high precision data on photoproduction of vector mesons in UPC in Run3-4

On nuclear shadowing

Glauber shadowing (modeling of several consequent interactions):

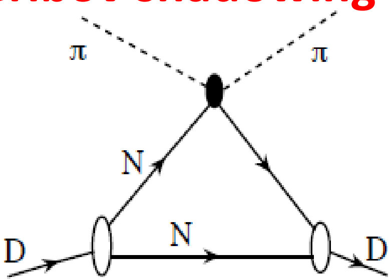


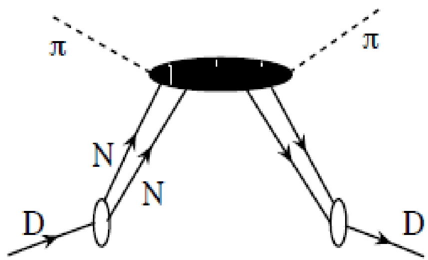


$$\sigma_{\rm tot}^{\pi D} = 2\,\sigma_{\rm tot}^{\pi N} - \frac{(\sigma_{\rm tot}^{\pi N})^2}{4\pi}\left\langle \frac{1}{r^2}\right\rangle_D$$

shadowing = destructive interference between single and multiple interactions

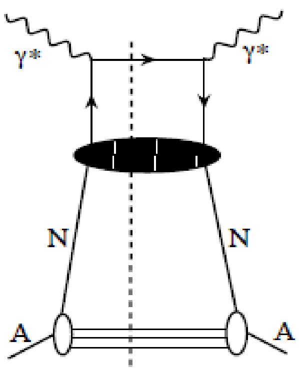
Gribov shadowing (coherent interaction via intermediate diffractive states):

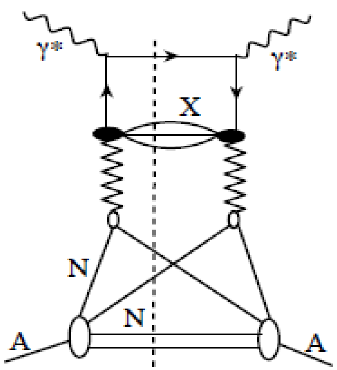




$$\sigma_{\rm tot}^{\pi D} = 2\sigma_{\rm tot}^{\pi N} - 2\int d\vec{k}^2 \rho\left(4\vec{k}^2\right)\frac{d\sigma_{\rm diff}^{\pi N}(\vec{k})}{d\vec{k}^2}$$

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





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

shadowing is expressed via diffractive PDFs

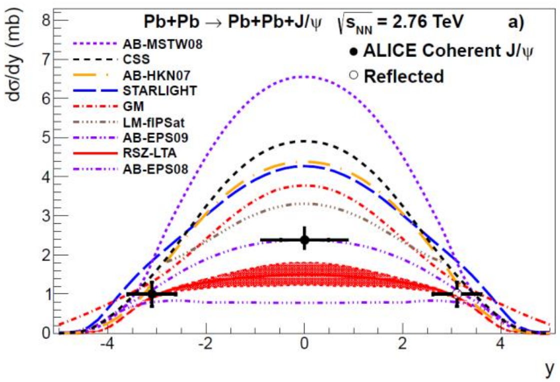
Photoproduction cross-section from ALICE data

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

ALICE measurement:

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

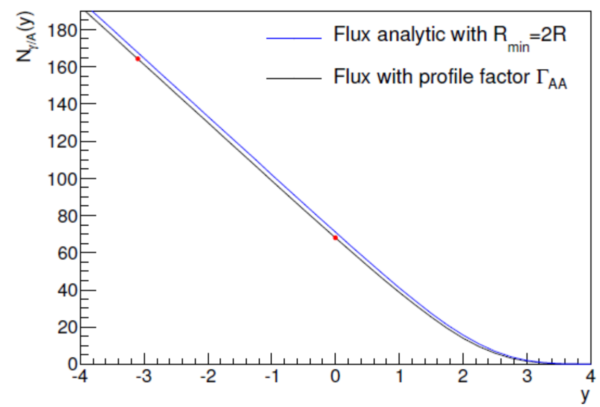
$$\frac{\sigma_{AA\to AAJ/\psi}(-3.6<y<-2.6)}{\Delta y} = 1.00 \pm 0.18(\mathrm{stat})^{+0.23}_{-0.26}(\mathrm{syst})\ \mathrm{mb}$$



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:

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

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

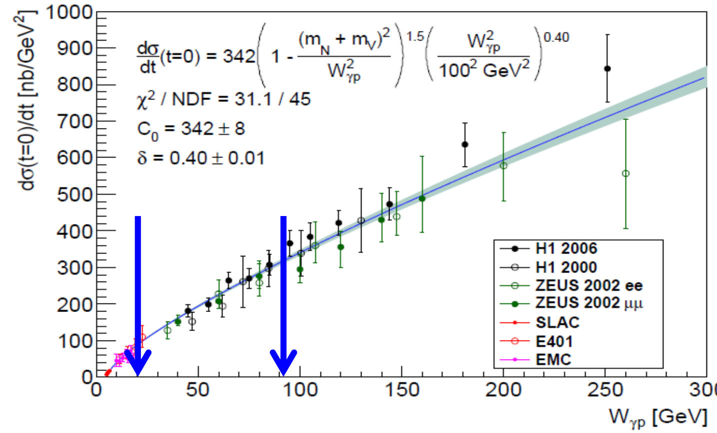
Photoproduction cross-section in the Impulse Approximation

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

Forward J/psi photoproduction cross section:

$$\frac{d\sigma_{\gamma p\to J/\psi p}(19.6\text{ GeV},t=0)}{dt} = 86.9\pm1.8\text{ nb}/\text{GeV}^2$$

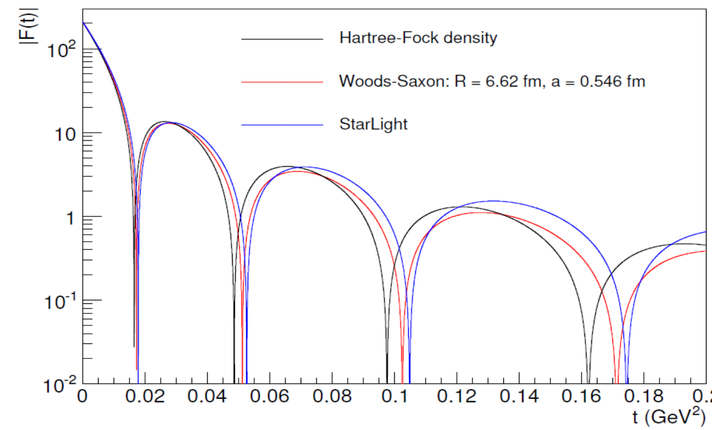
$$\frac{d\sigma_{\gamma p\to J/\psi p}(92.4\text{ GeV},t=0)}{dt} = 319.8\pm7.1\text{ nb}/\text{GeV}^2$$



Integral over squared form factor:

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

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



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

J/psi photoproduction on nucleus in Impulse Approximation:

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

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

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:

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

$$\div$$

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

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

$$\Downarrow$$

- Nuclear suppression factor:

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

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