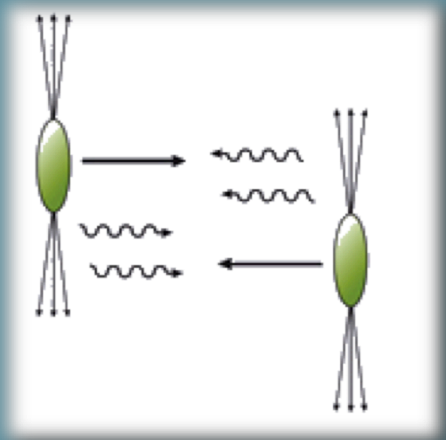


Ultra-peripheral collisions and photoproduction with ALICE at the LHC: results and perspectives

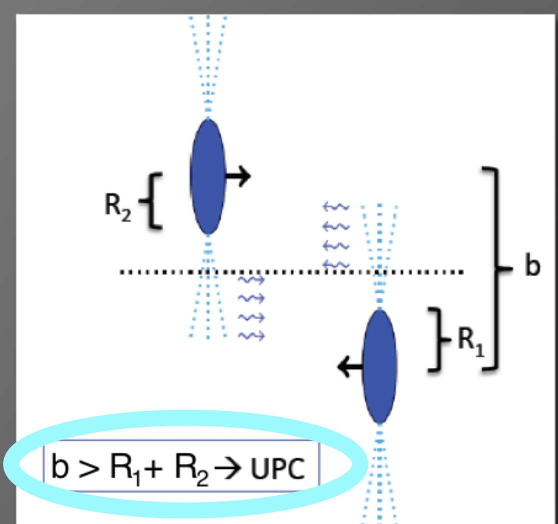
D. De Gruttola* for the ALICE Collaboration
*Centro Fermi Roma and Salerno INFN - Italy

Overview

- ✓LHC as γPb and γp collider (ultra-peripheral collisions)
- ✓physics motivation (gluon distribution in nuclei and nucleons)
- ✓ALICE and UPCs (detector and trigger description)
- ✓results and comparison with models (Pb-Pb and p-Pb)
- ✓conclusions (results and future)

LHC as γPb and γp collider

- ✓ heavy ions are accelerated towards each other at ultra relativistic energies
- ✓ charged particles → accompanied by an electromagnetic field
- ✓ the boosted EM field can be viewed as a beam of quasi-real photons
- ✓ intensity of the photon beam proportional to Z^2
- ✓ photon flux described in Fermi-Weizsäcker-Williams approximation
- ✓ hadronic processes strongly suppressed when $b > R_1+R_2$
- ✓ high σ for γ-induced reactions e.g. vector meson photoproduction



- ✓ virtuality of the photon dependent on the radius of the emitting particle:

$$Q^2 \approx \left(\frac{\hbar c}{R}\right)^2$$

$$\gamma \text{ from p } \rightarrow Q^2 \approx (250\,MeV)^2$$

$$\gamma \text{ from Pb } \rightarrow Q^2 \approx (30\,MeV)^2$$

Physics motivation

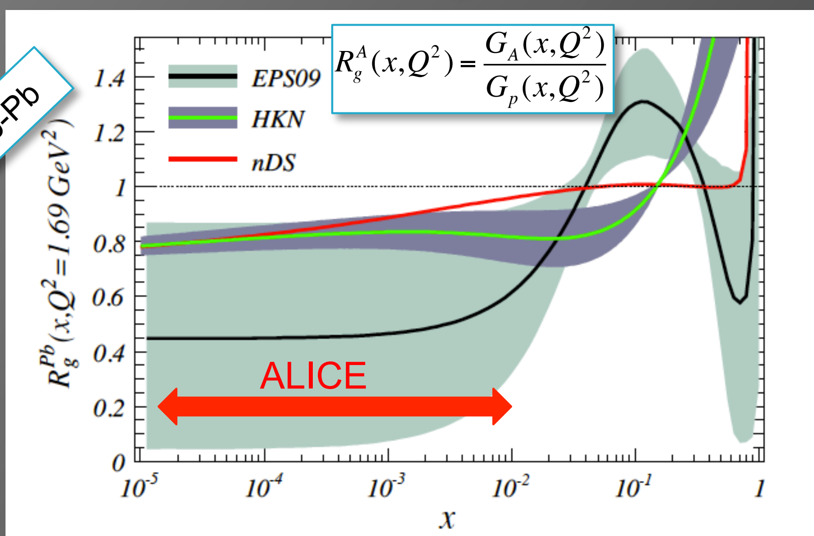
- ✓ quarkonia photoproduction allows one to study the gluon density $G(x,Q^2)$ in the target

$$\left.\frac{d\sigma(\gamma N \to VN)}{dt}\right|_{t=0} \approx \frac{\alpha_s \Gamma_{ee}}{3\alpha_e M_V^5} 16\pi^3 \left(xG(x,Q^2)\right)^2$$

- ✓ Bjorken-x accessible at LHC $x = (M_V/\sqrt{s_{NN}})e^{\pm y} \sim 10^{-2} - 10^{-5}$ (ALICE: $|y|<0.9$; $-3.6<y<2.6$)

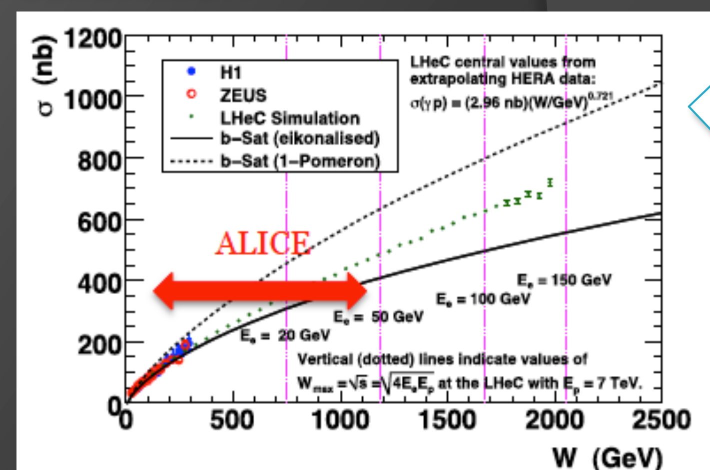
- ✓ vector meson photoproduction as tool to measure nuclear gluon shadowing and saturation

Pb-Pb



C A Salgado *et al* 2012 *J. Phys. G.: Nucl. Part. Phys.* **39** 015010

p-Pb



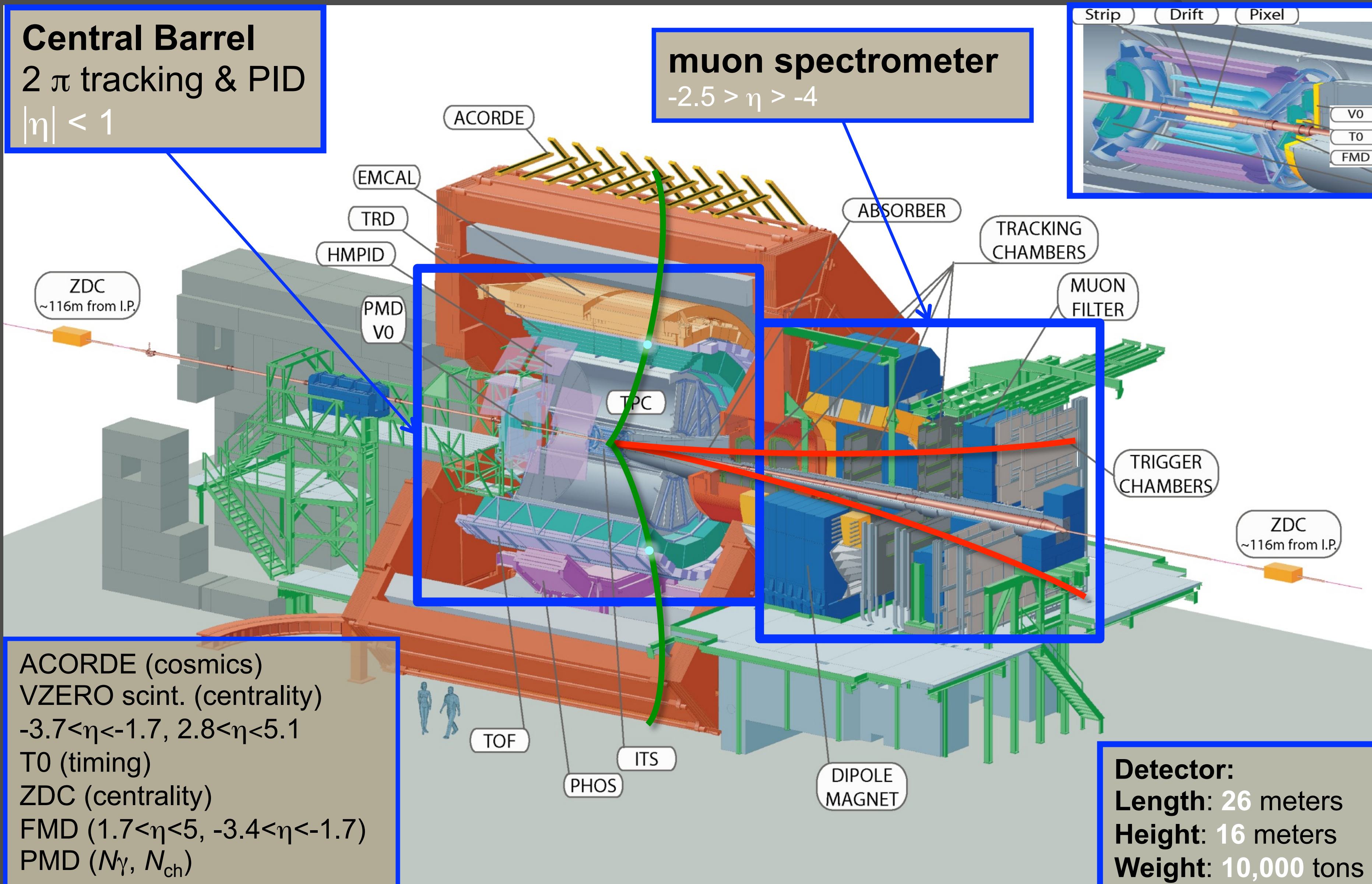
LHeC Study group ArXiv: 1211.4831

γp cms energy $W_{\gamma p}$ beyond previous experiments

ALICE layout (backup for details on the trigger logic)

Central Barrel
2 π tracking & PID
$|\eta| < 1$

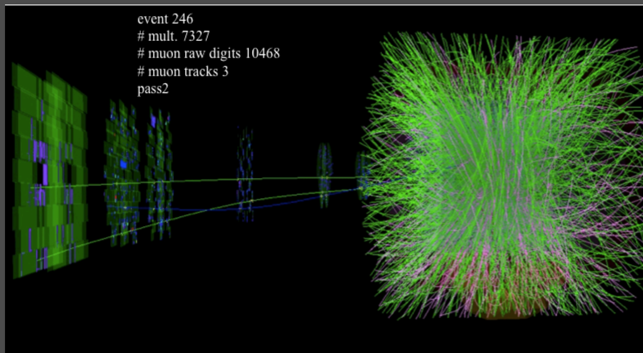
muon spectrometer
$-2.5 > \eta > -4$



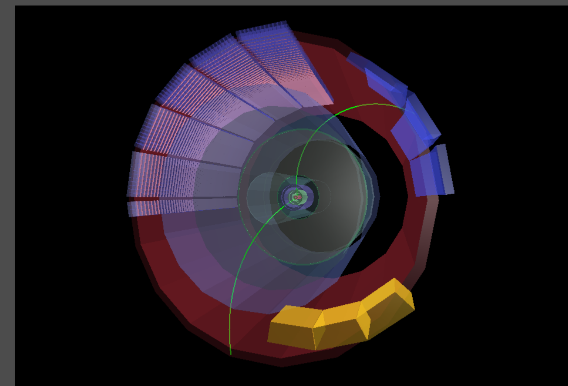
ACORDE (cosmics)
VZERO scint. (centrality)
$-3.7<\eta<-1.7$, $2.8<\eta<5.1$
T0 (timing)
ZDC (centrality)
FMD ($1.7<\eta<5$, $-3.4<\eta<-1.7$)
PMD ($N\gamma$, N_{ch})

Detector:
Length: **26** meters
Height: **16** meters
Weight: **10,000** tons

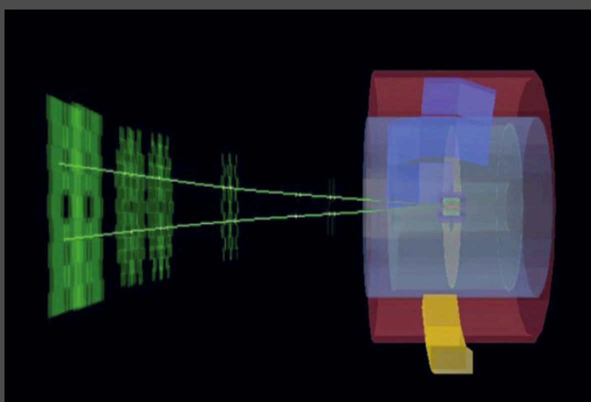
ALICE and Ultra-Peripheral Collisions

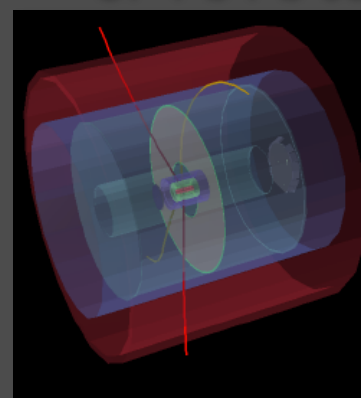


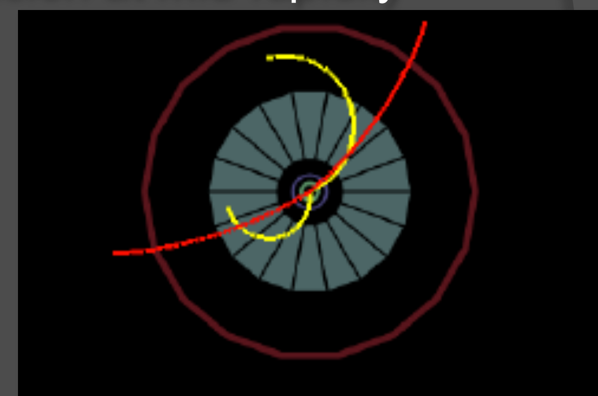
central Pb-Pb collision



UP Pb-Pb collision at mid-rapidity



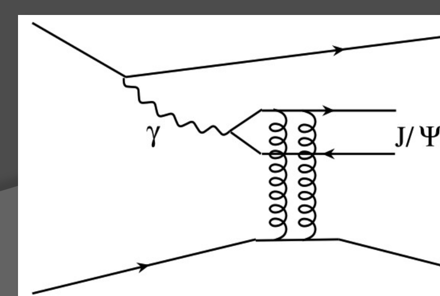




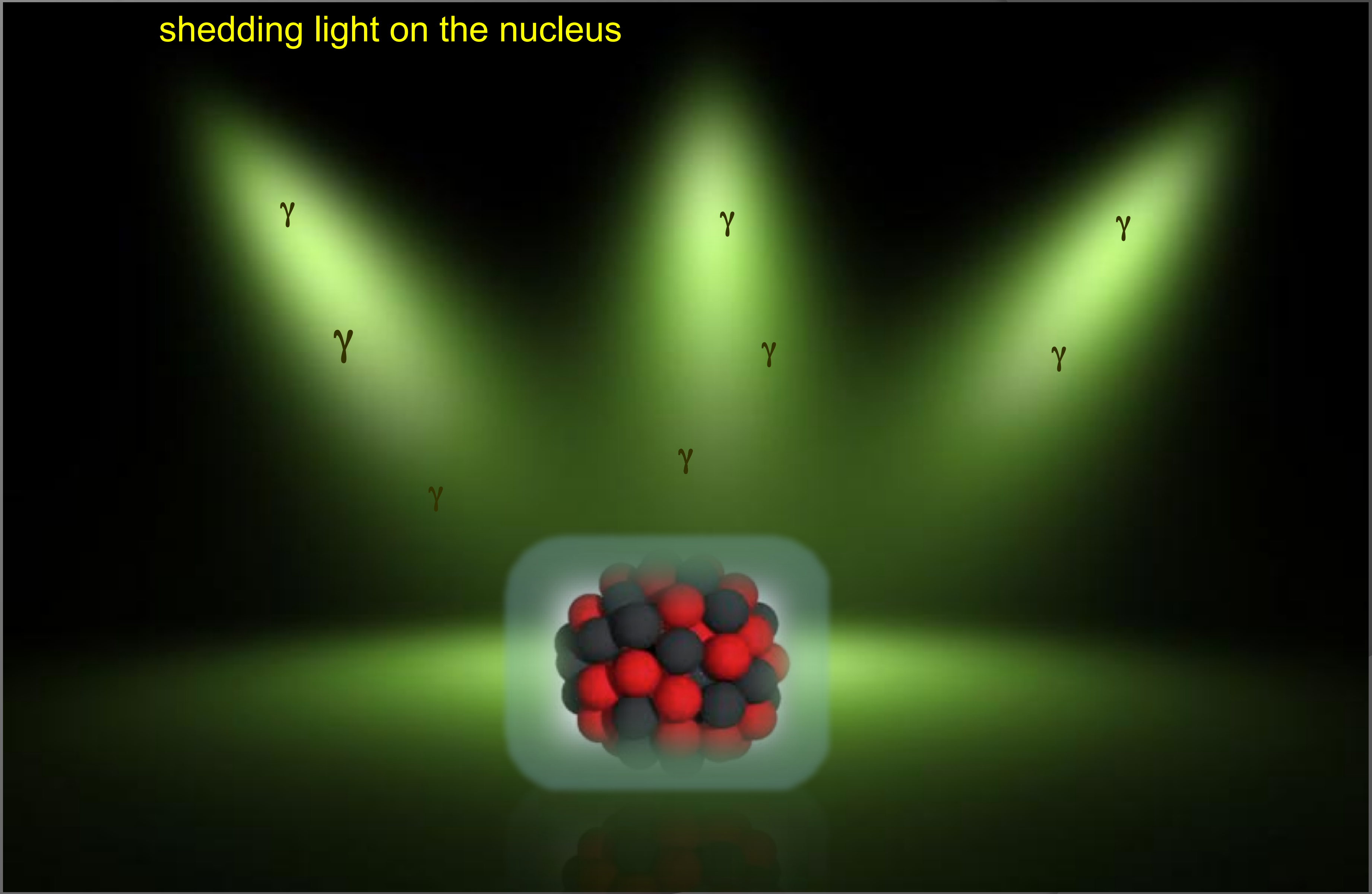
UP Pb-Pb collision at forward rapidity

2 (or 4) tracks in an otherwise empty detector

detailed studies done to understand the noise and the emptiness of the detector



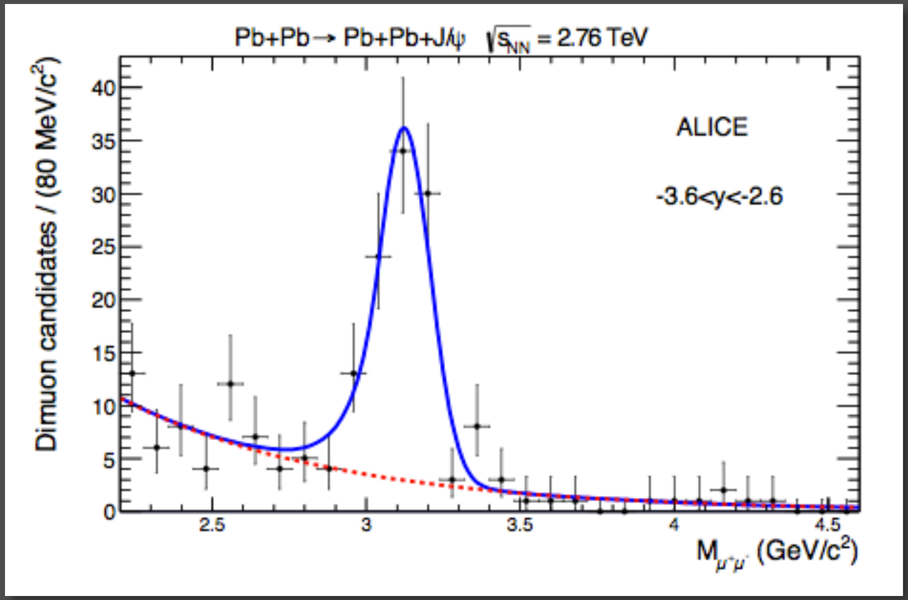
γPb processes (Pb-Pb collisions)

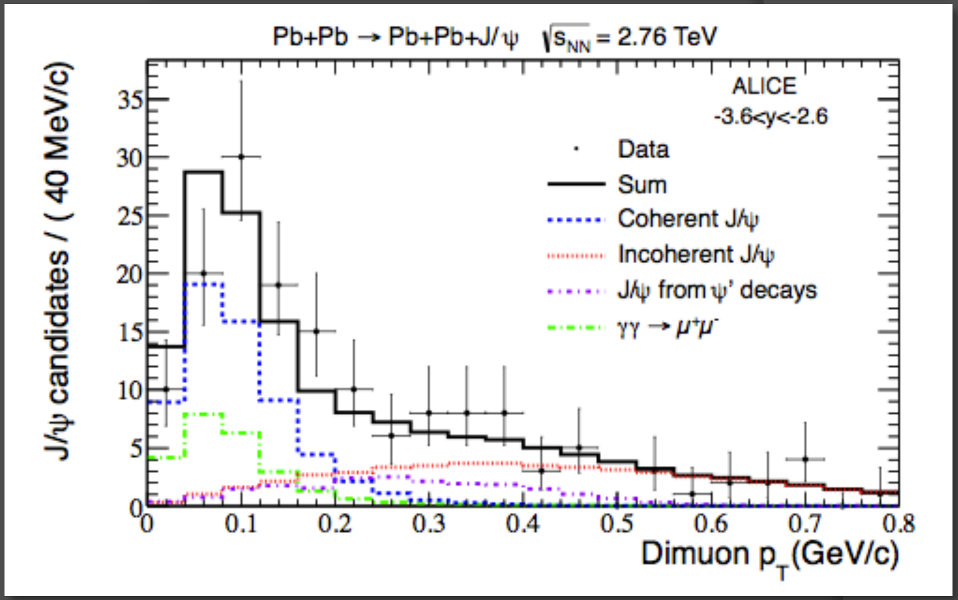


Coherent J/ψ production (forward rapidity)

first measurement of J/ψ photoproduction done at LHC

Phys. Lett. B718 (2013) 1273 -1283





p_T distribution fitted using MC samples representing several components:

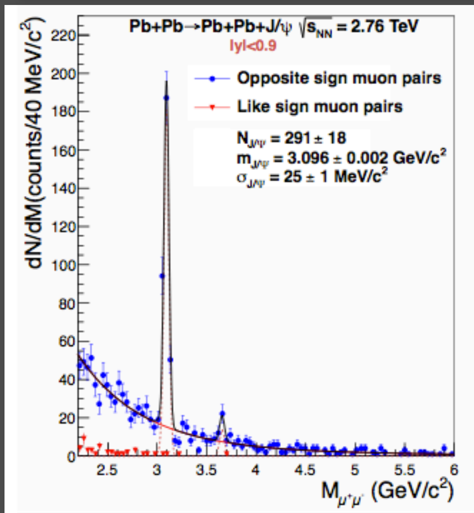
- coherent and incoherent J/ψ
- ψ' feed down
- $\gamma\gamma \rightarrow \mu^+\mu^-$

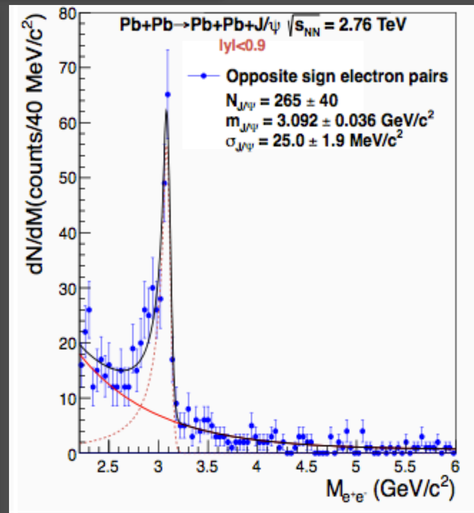
distribution peaked at low momentum as expected from coherent production

J/ψ photoproduction probes the gluon distribution in Pb at x~10^{-2}

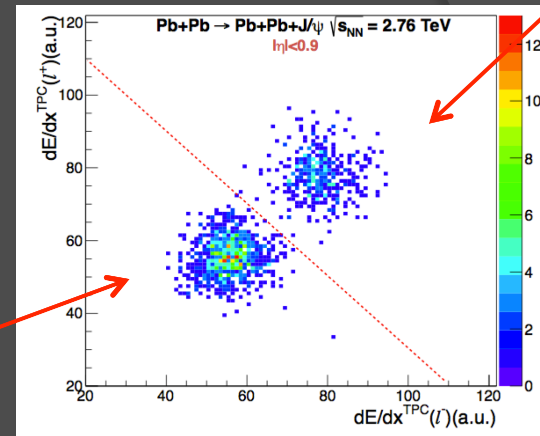
Coherent J/ψ production (mid-rapidity)

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

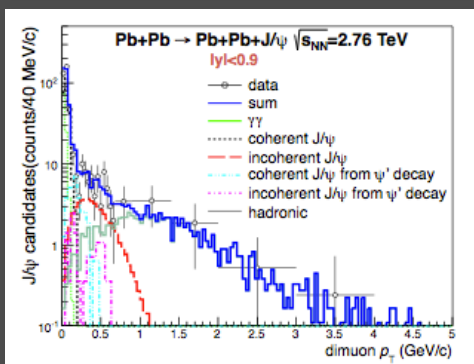


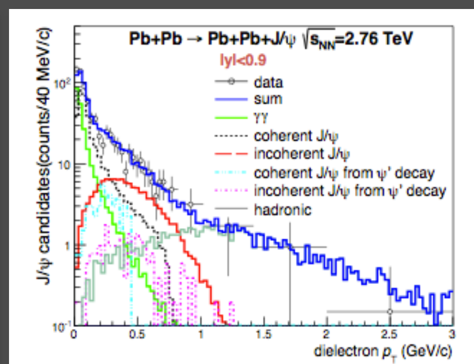


electrons



muons





✓ coherent vector meson production:
- ✧ photon couples coherently to all nucleons
- ✧ $\langle p_T \rangle \sim 1/R_{Pb} \sim 60$ MeV/c
- ✧ no neutron emission in ~80% of cases

✓ incoherent vector meson production:
- ✧ photon couples to a single nucleon
- ✧ $\langle p_T \rangle \sim 1/R_p \sim 500$ MeV/c
- ✧ target nucleus normally breaks up

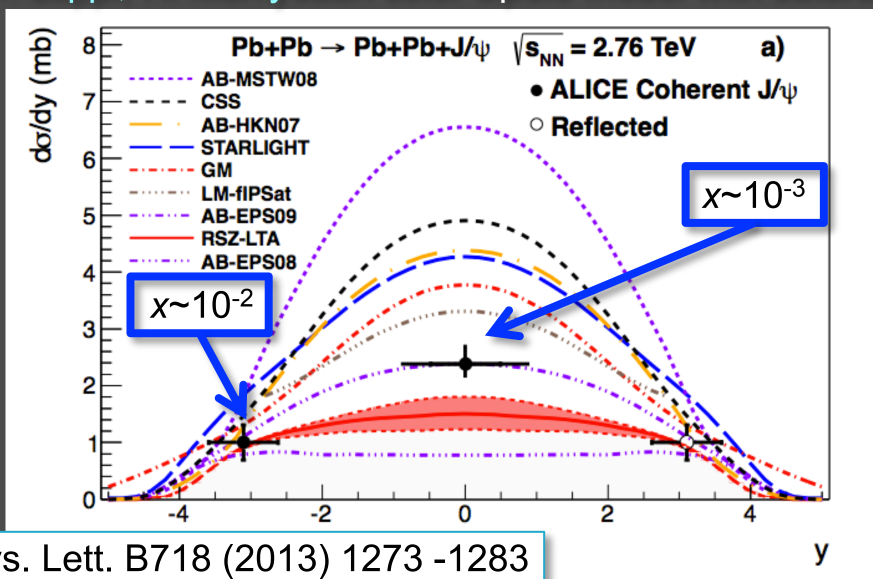
- ✧ coherent and incoherent J/ψ
- ✧ (coherent and incoherent) ψ' feed down
- ✧ $\gamma\gamma \rightarrow \mu^+\mu^-(e^+e^-)$
- ✧ hadronic

(more details in the backup)

p_T < 200 (300) MeV/c and < 6 neutrons emitted by nuclei to separate coherent from incoherent samples

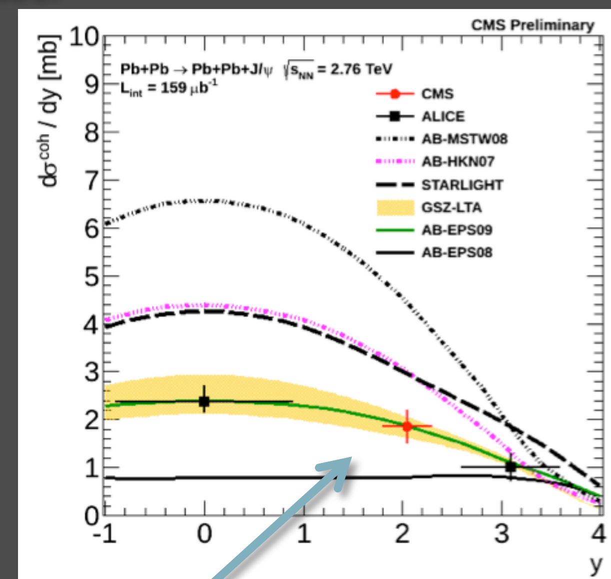
Results and comparison with models

- ✓ AB: Adeluyi and Bertulani, PRC85 (2012) 044904 LO pQCD + K-factor + nuclear PDFs
- ✓ CSS: Cisek, Szczurek, Schäfer PRC86 (2012) 014905 color dipole model with unintegrated gluon
- ✓ STARLIGHT: Klein, Nystrand PRC60 (1999) 01493 classical Glauber model + fit to HERA data
- ✓ GM: Goncalves, Machado, PRC84 (2011) 011902 color dipole model with CGC-like saturation
- ✓ RSZ: Rebyakova, Strikman, Zhalov, PLB 710 (2012) 252 LO pQCD amplitude for two gluon exchange (gluon density incorporates shadowing computed in leading twist approximation)
- ✓ T. Lappi, H. Mäntysaari color dipole model with saturation + Glauber



Phys. Lett. B718 (2013) 1273 -1283

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



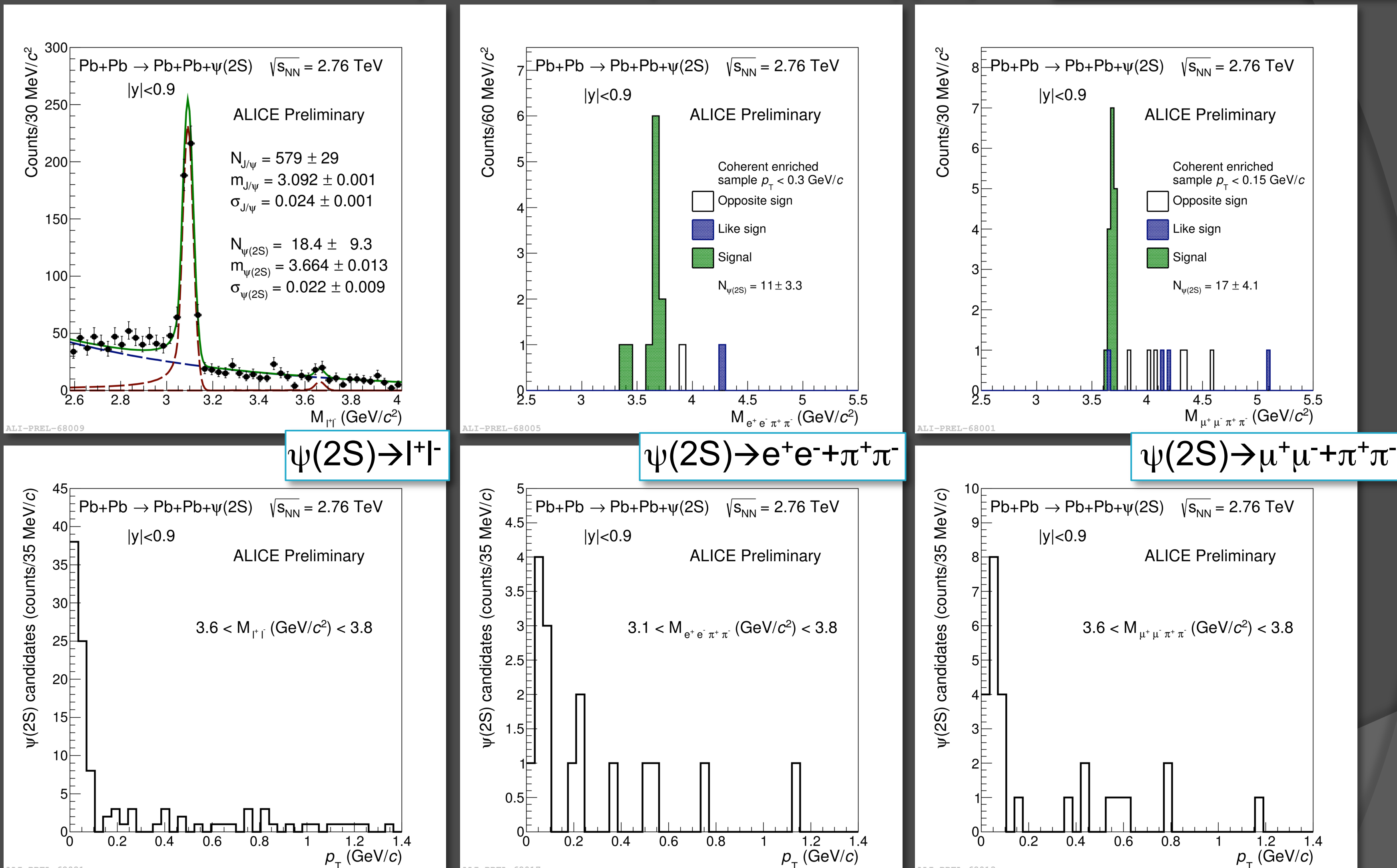
ALICE provided the first direct experimental evidence for moderate *nuclear gluon shadowing* (good agreement with calculation using the EPS09 nuclear gluon prediction)

CMS results (not corrected for ψ(2S) feed-down (~10%)) consistent with ALICE

Coherent ψ(2S) production (mid-rapidity)

first exclusive photonuclear production of ψ(2S)

ALICE arXiv 1508.05076



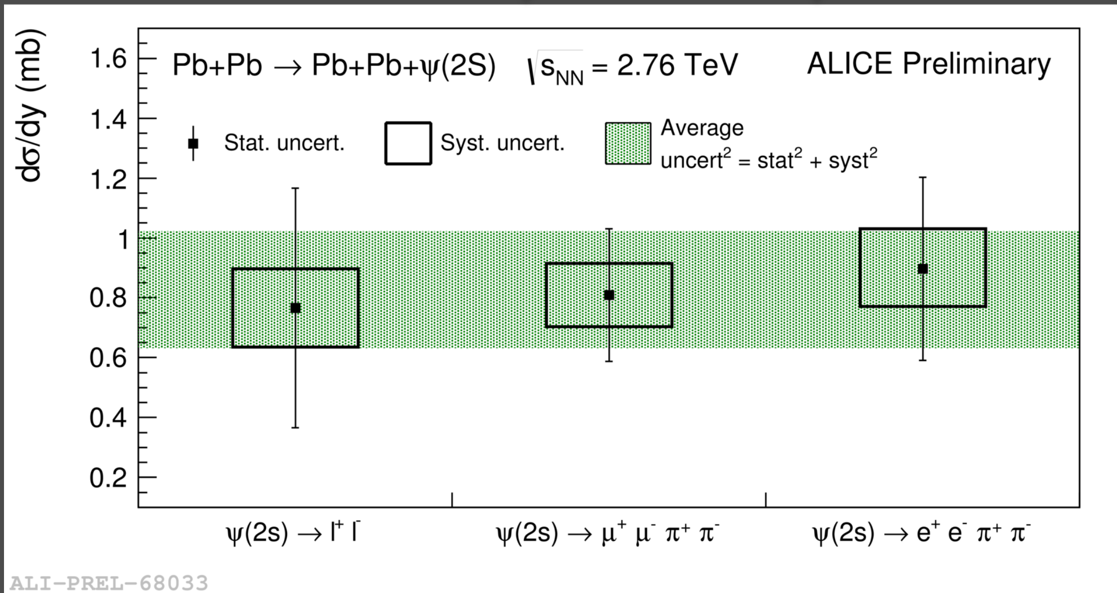
✓ clear coherent contribution at very low p_T

✓ moderate number of candidates in 4-lepton channels, but very clear signal

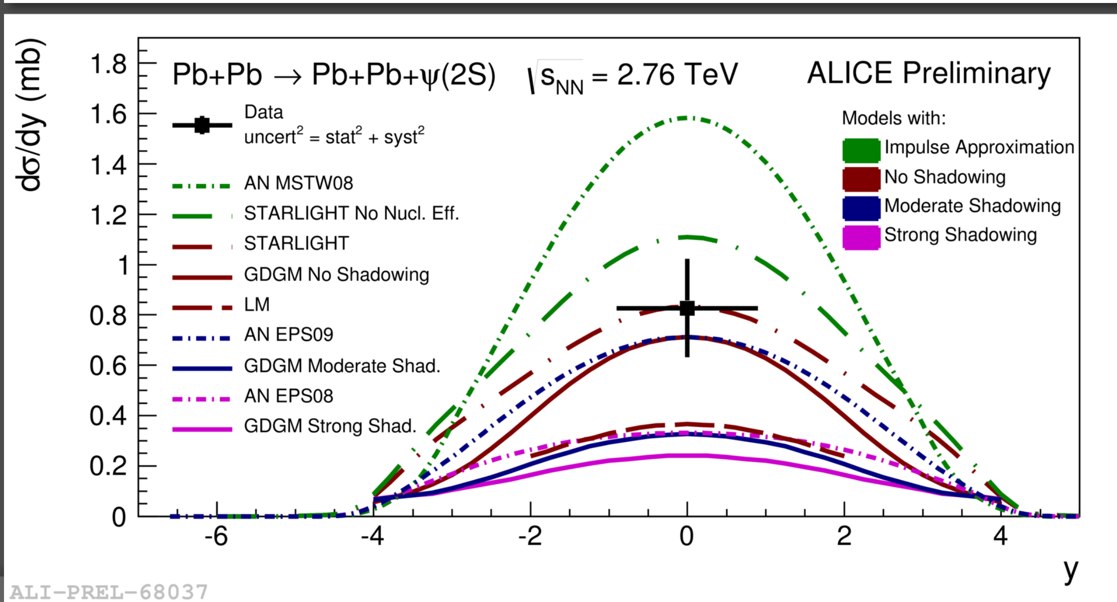
Coherent ψ(2S) cross section

first exclusive photonuclear production of ψ(2S)

ALICE arXiv 1508.05076



$$\frac{d\sigma}{dy} = 0.83 \pm 0.19 \text{ (stat+syst) mb}$$

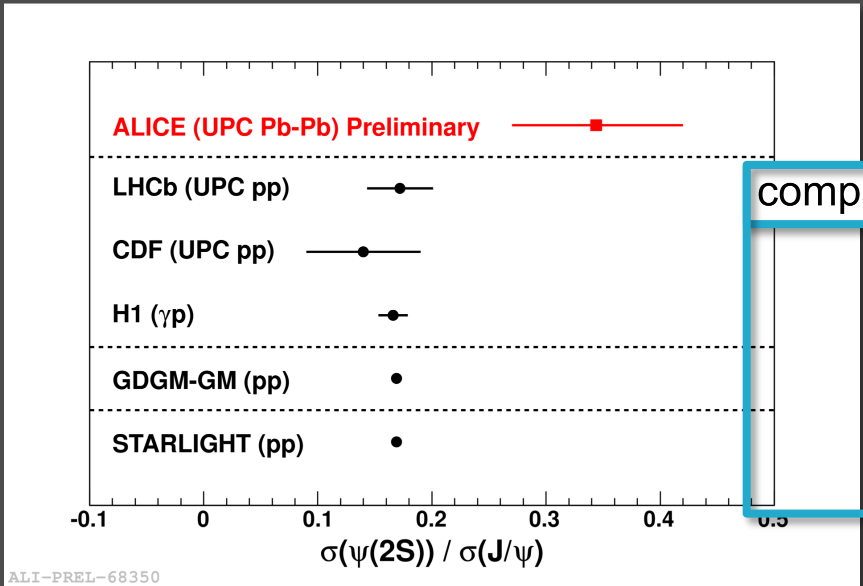


- ✓ data disfavor models using impulse approximation and strong nuclear shadowing
- ✓ difficult to give a preference between models with mild shadowing (EPS09) or Glauber nuclear treatment (STARLIGHT, GDGM, LM)

ψ'/ψ ratio

✓ many sources of systematic uncertainties cancel in the measured ratio

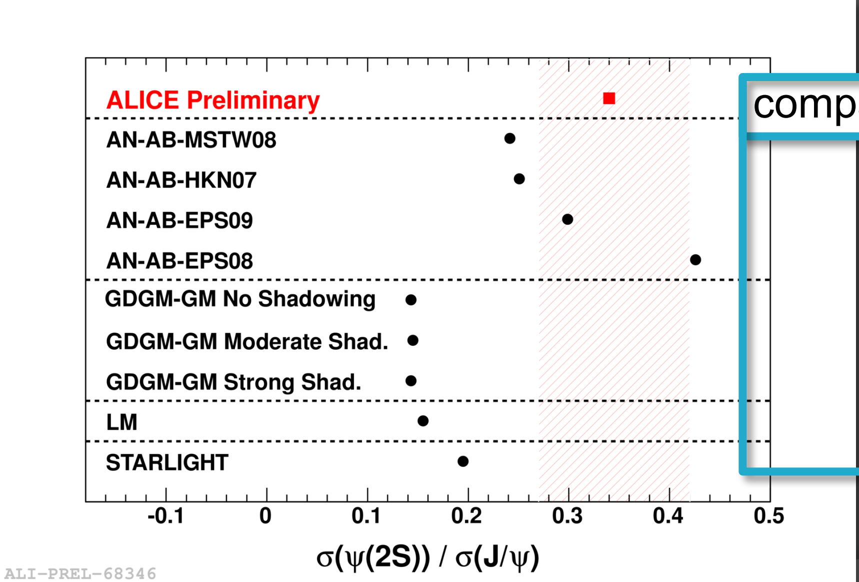
✓ $R[\sigma(\psi(2S))/\sigma(J/\psi)] = 0.34^{+0.08}_{-0.07}$ (stat+syst)



comparison with pp/γp data and models

✓ change of R from pp to Pb-Pb may indicate that nuclear effects affect 1S and 2S states differently

✓ models predict the ratio for pp correctly



comparison with Pb-Pb models

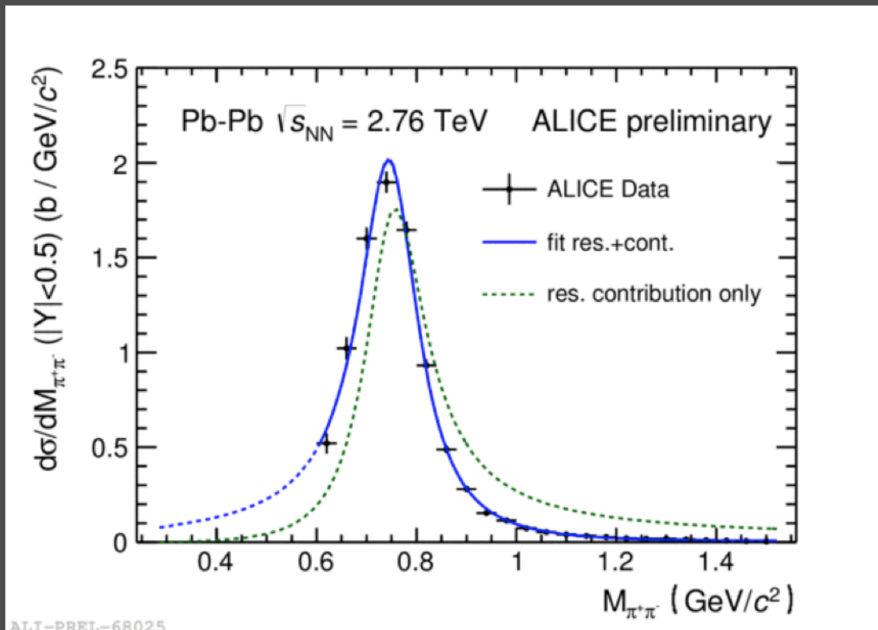
✓ the same models that reproduced correctly the pp ratio, fail in describing the Pb-Pb ratio

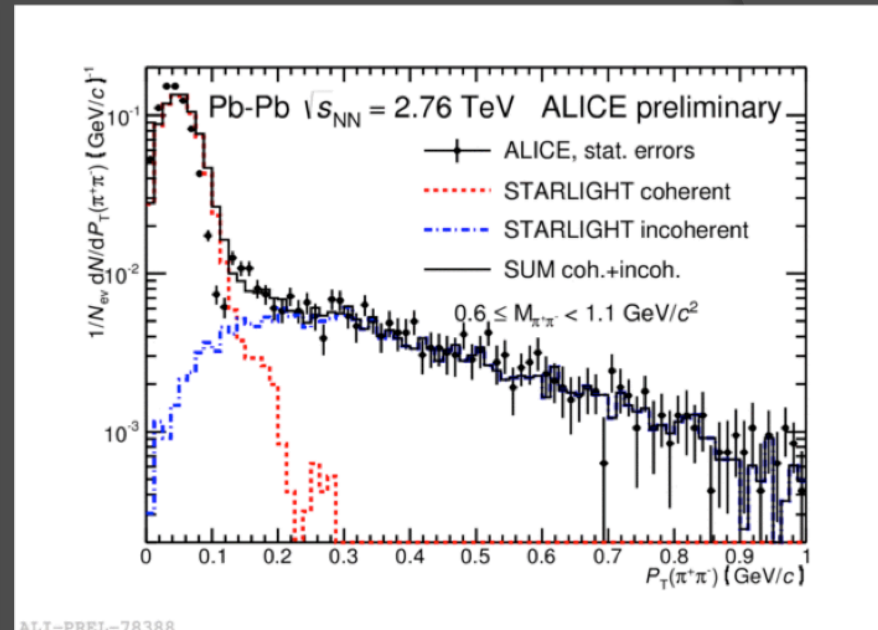
✓ the AN EPS09 model describes in a satisfactory way this ratio (although it assumes the same wave function for J/ψ and ψ(2S))

Coherent ρ^0 production

Pb+Pb → Pb+Pb+$\pi^+\pi^-$

ALICE arXiv 1503.09177 - accepted by JHEP





fit to Breit-Wigner resonance
+ continuum term (Söding 1966)

p_T < 150 MeV/c to reject incoherent contribution

$$\frac{d\sigma}{dM_{\pi\pi}} = \left| A \frac{\sqrt{M_{\pi\pi} M_{\rho^0} \Gamma(M_{\pi\pi})}}{M_{\pi\pi}^2 - M_{\rho^0}^2 + i M_{\rho^0} \Gamma(M_{\pi\pi})} + B \right|^2$$

$$\Gamma(m_{\pi\pi}) = \Gamma_{\rho^0} \frac{m_{\rho^0}}{m_{\pi\pi}} \left(\frac{m_{\pi\pi}^2 - 4m_\pi^2}{m_{\rho^0}^2 - 4m_\pi^2} \right)^{3/2}$$

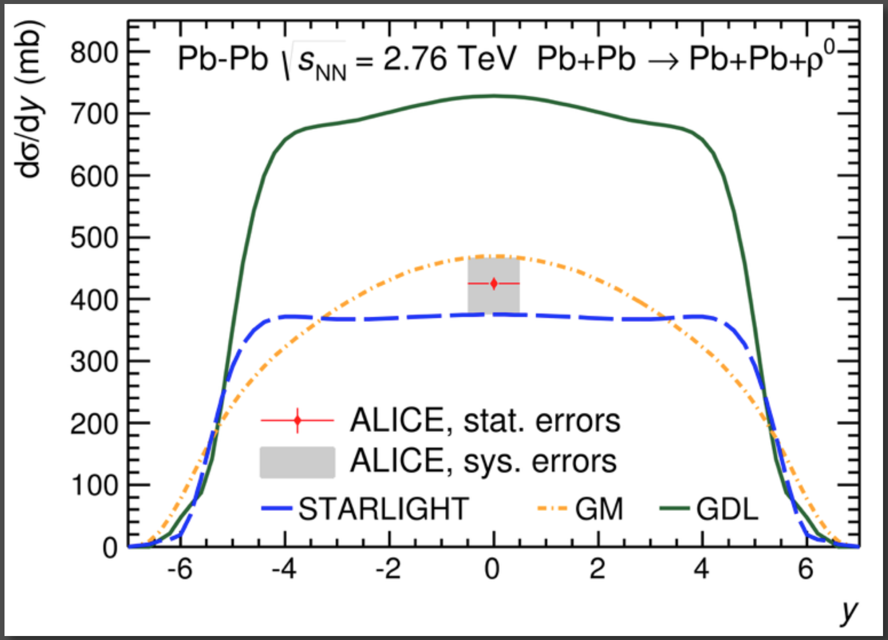
M_ρ = 761.6 ± 2.3 (stat)$^{+6.1}_{-3.0}$(syst) MeV/c^2 (PDG 769 - 775 MeV/c^2)

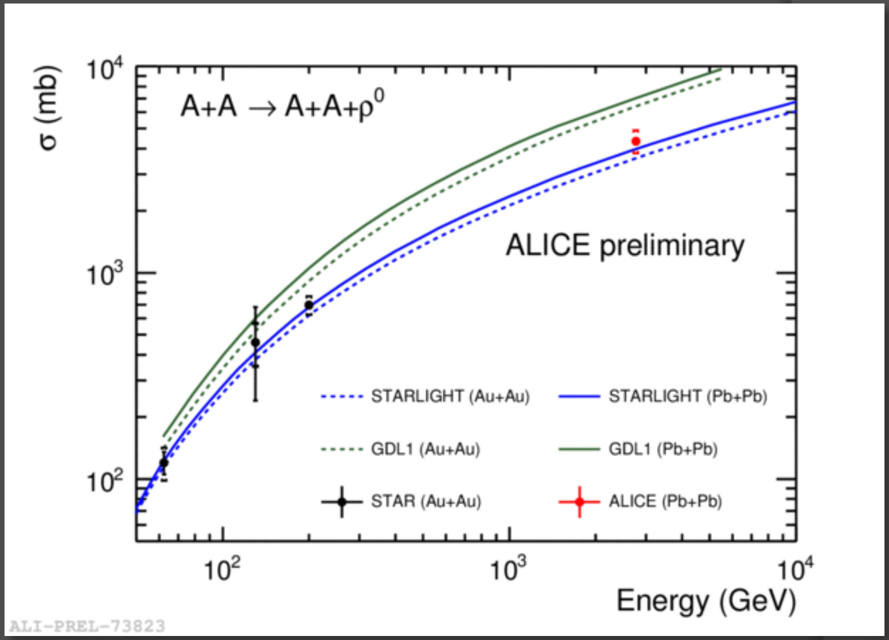
Γ = 150.2 ± 5.5 (stat)$^{+12.0}_{-5.6}$(syst) MeV/c^2 (PDG 148 – 152 MeV/c^2)

|B/A| = 0.50 ± 0.04 (stat)$^{+0.10}_{-0.04}$ (syst) (GeV/c^2)$^{1/2}$

Coherent ρ^0 production

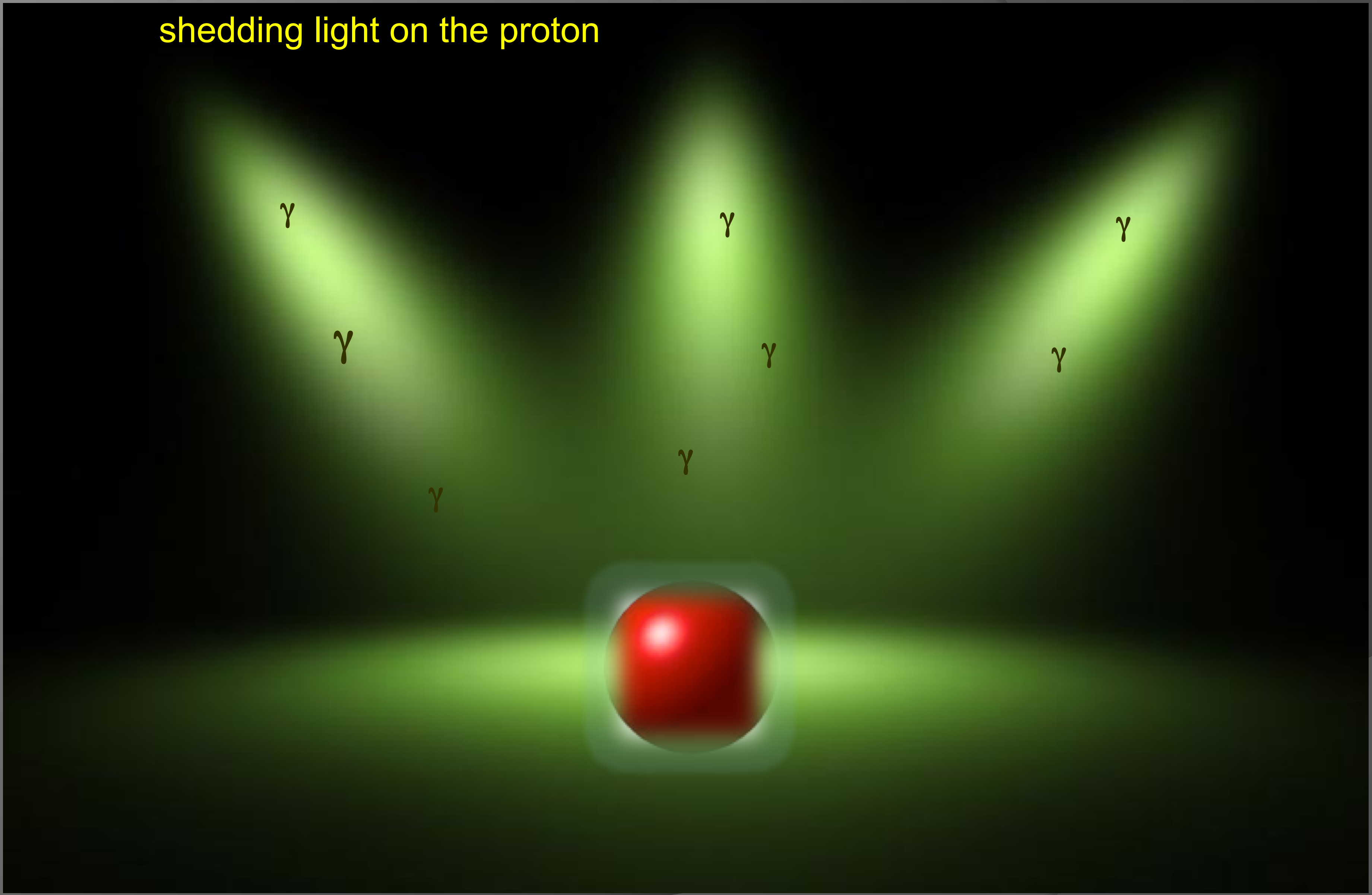
- ✓ GM: V.P. Goncalves, M.V.T. Machado color dipole model with CGC-like saturation
- ✓ GDL: L. Frankfurt, M. Strikman, M. Zhalov QM Glauber + DL fit to HERA data
- ✓ STARLIGHT: Klein, Nystrand PRC60 (1999) 01493 classical Glauber model + fit to HERA data



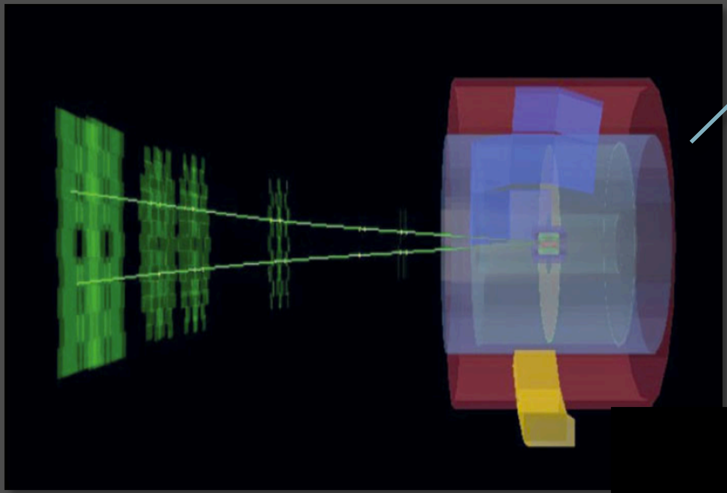


- ✓ surprising agreement with STARLIGHT
- ✓ why the GDL model fails? (it includes the elastic part of the total cross section, neglected by STARLIGHT - see arXiv 1506.07150)

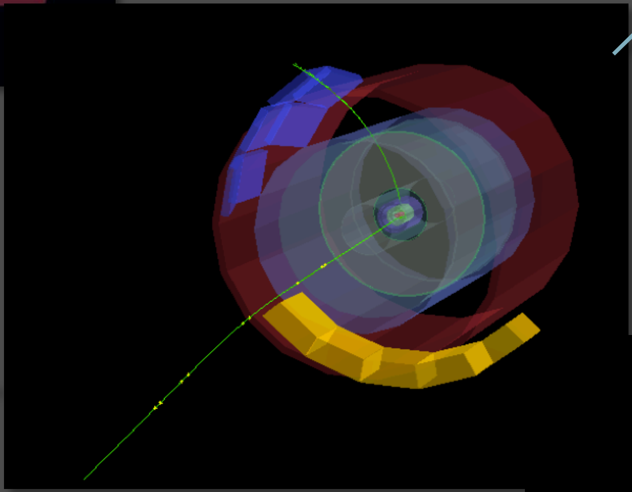
γp processes (p-Pb collisions)



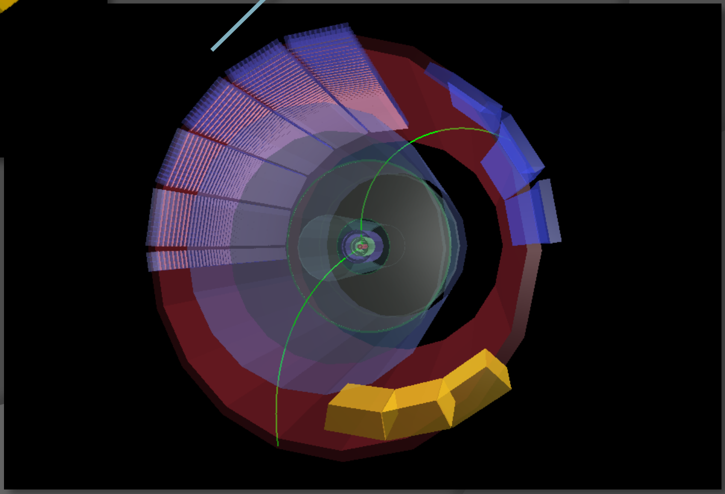
UPC in p-Pb at ALICE



forward rapidity (J/ψ → $\mu^+\mu^-$)



semi-forward rapidity (J/ψ → $\mu^+\mu^-$)



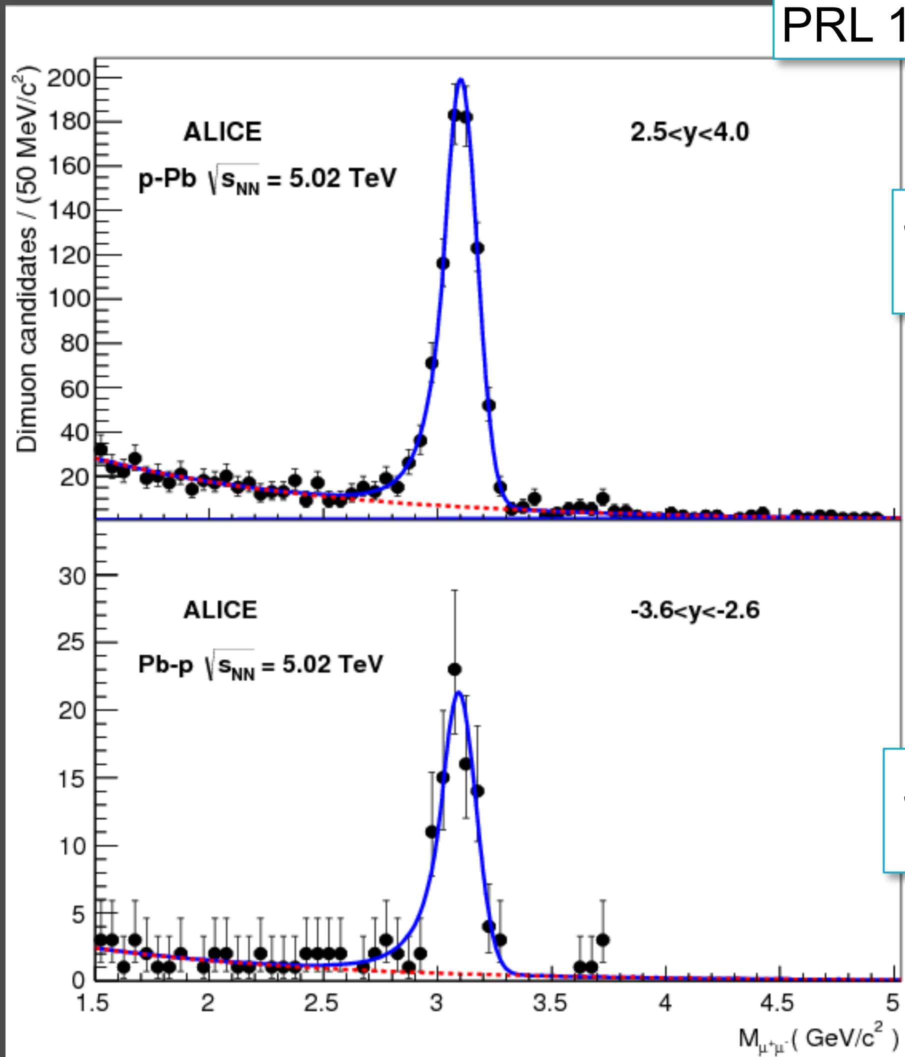
mid-rapidity (J/ψ → $\mu^+\mu^-$ and J/ψ → e^+e^-)

trigger logic:

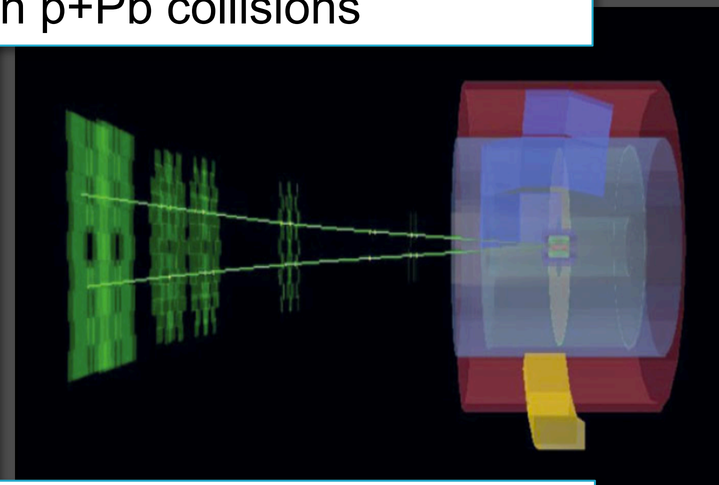
- ✓ similar to Pb-Pb case for forward and mid-rapidities, but improved purity
- ✓ semi-forward
  - ✧ V0A and V0C (≥5 cells) vetoed
  - ✧ SPD multiplicity (≥ 7 outer chips) vetoed
  - ✧ single muon with p_T>0.5GeV/c
  - ✧ SPD (≥ 1 chips)

J/ψ in p-Pb and Pb-p

PRL 113 (2014) 23, 232504



$J/\psi \rightarrow \mu^+\mu^-$ at forward rapidity in p+Pb collisions



$J/\psi \rightarrow \mu^+\mu^-$ at forward rapidity in Pb+p collisions

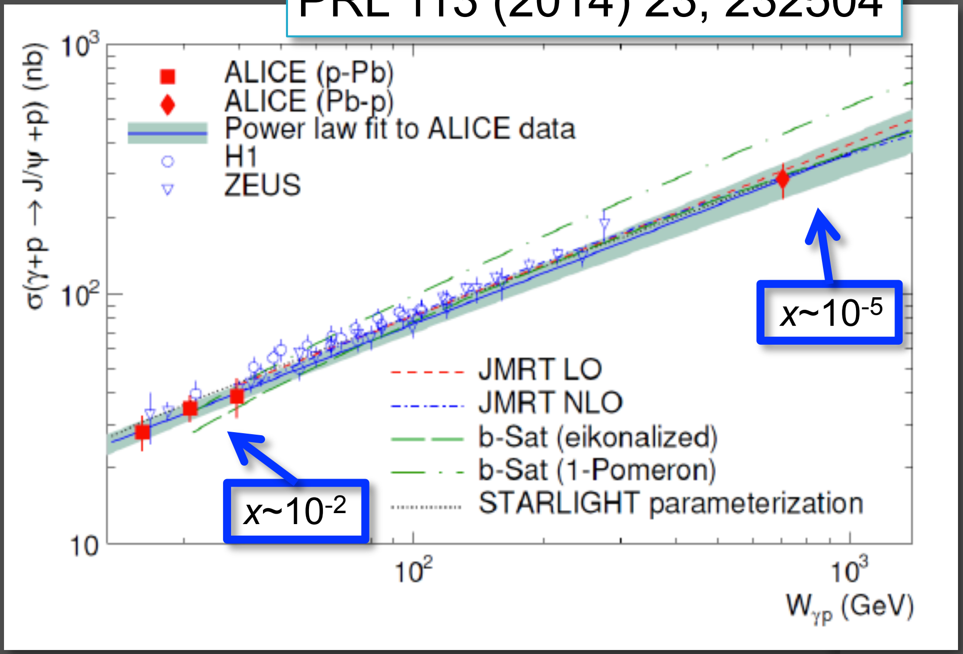
clean signal and very small background

photoproduction in p-Pb dominated by γp interactions (> 95% of the cases)
→ <u>photon source is known</u> → rapidity of the J/ψ measures $W_{\gamma p}$

Measured γp cross sections in p-Pb

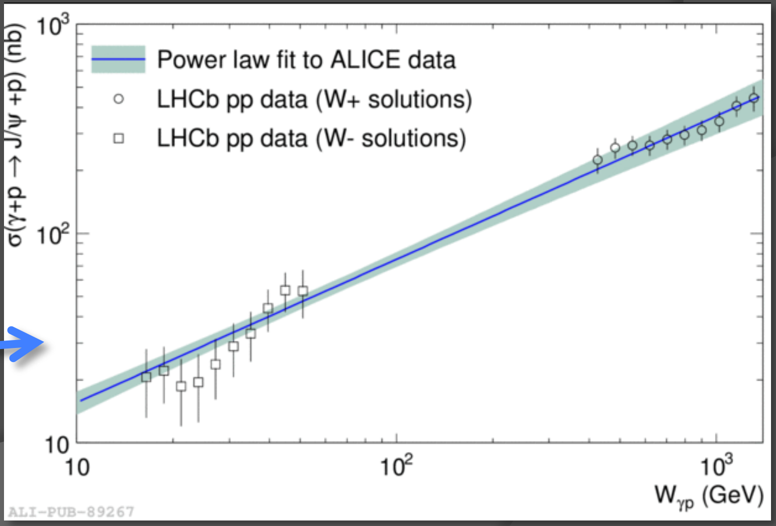
- ✓ first direct γp measurement at the LHC
- ✓ ALICE data reaches more than twice the largest energy reached at HERA
- ✓ ALICE data are compatible with a power law with exponent 0.67±0.06
- ✓ exponent is compatible with those from H1 (0.67±0.03) and ZEUS (0.69±0.02±0.03)
- ✓ HERA and ALICE cross section points stay on the same power law

PRL 113 (2014) 23, 232504



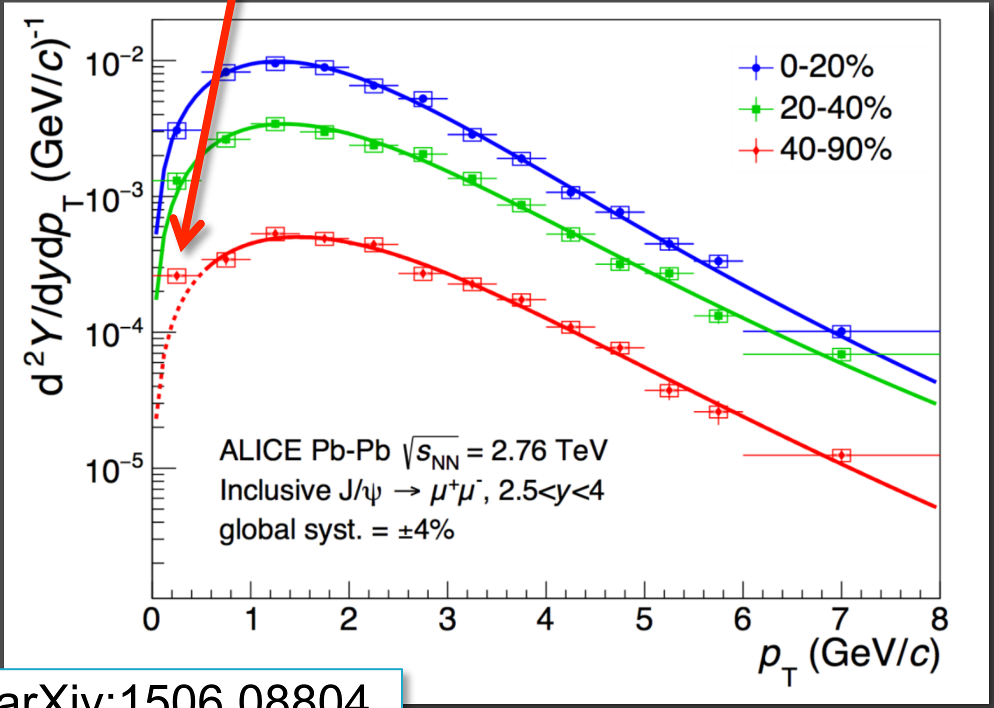
the most straightforward interpretation is that **no change** in the behavior of the **gluon PDF** in the proton manifests itself between **HERA and LHC**

- ✓ going to higher p-Pb centre of mass energies would be important for this measurement
  - ✓ solutions extracted from LHCb pp measurement consistent with the power-law fit obtained from ALICE results



Excess of very low-p_T J/ψ in peripheral Pb-Pb collisions

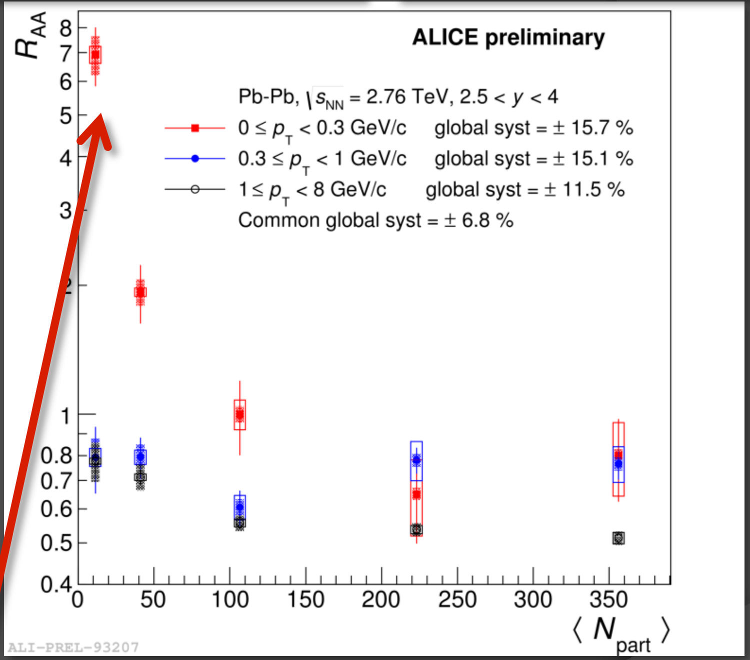
clear excess at very low p_T in peripheral Pb-Pb collisions with respect to hadronic production expectations



arXiv:1506.08804

$$R_{AA} = \frac{N_{AA}^{J/\psi}}{\langle N_{coll} \rangle N_{pp}^{J/\psi}}$$

= 1 → No medium effect
< 1 → Suppression
> 1 → Enhancement

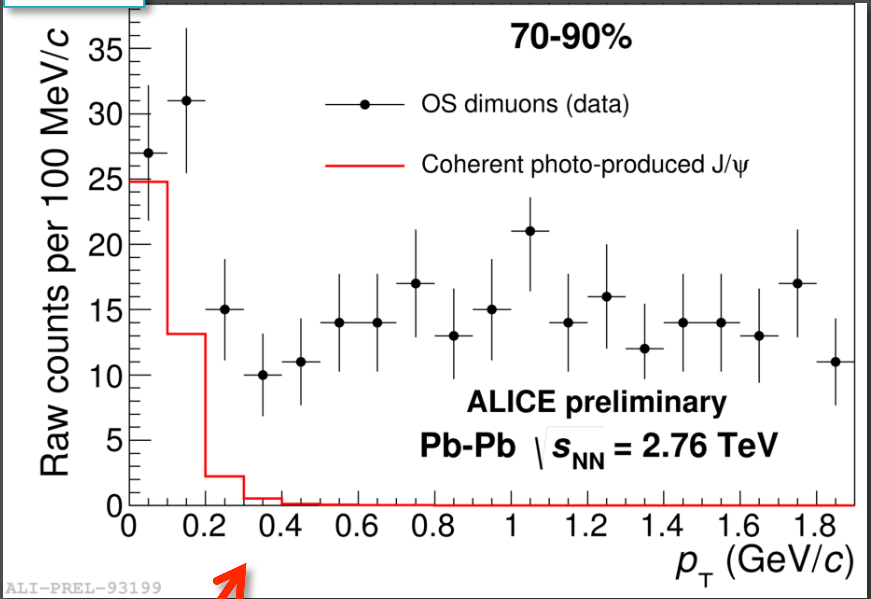


enhancement of J/ψ R_{AA} in most peripheral collisions for p_T < 0.3 GeV/c

Plausible explanation

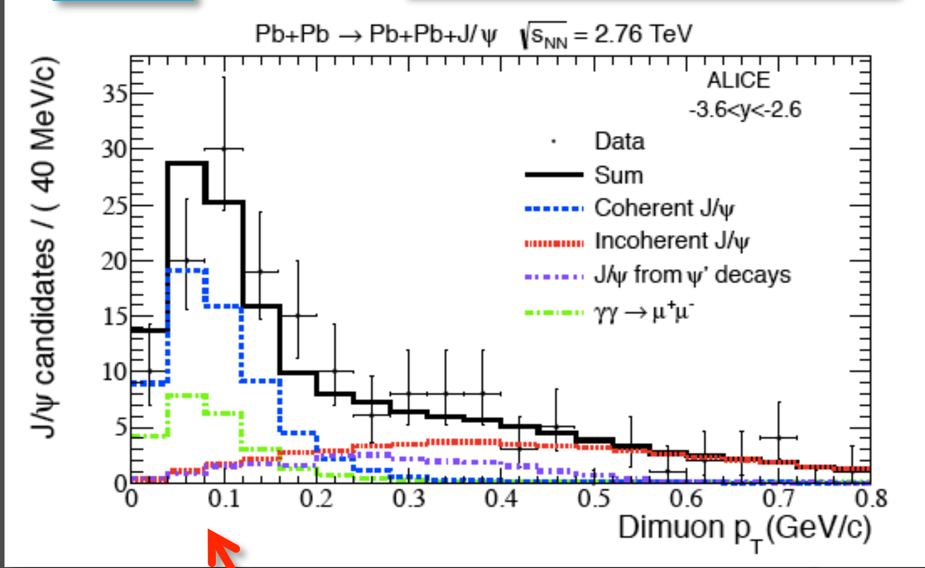
remarkably similar to J/ψ photoproduction in ultra-peripheral collisions (b>2R)

b<2R



b>2R

PLB 718 (2013) 1273



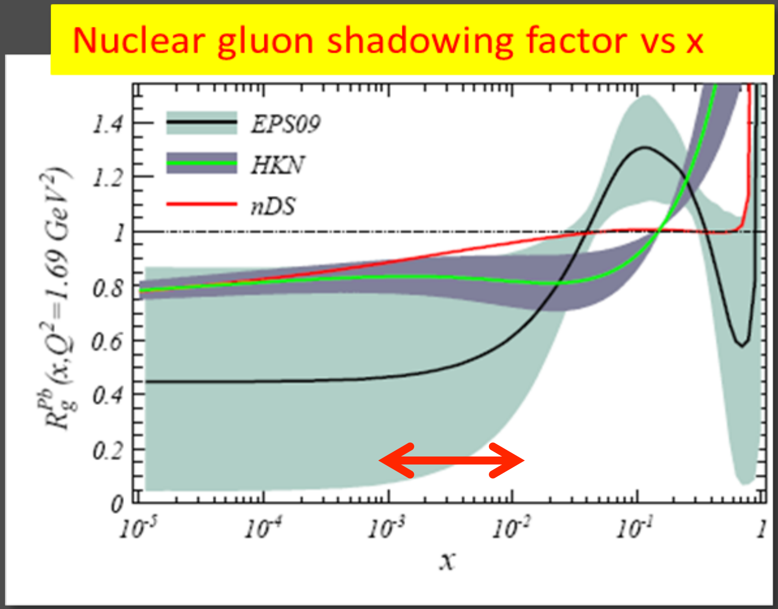
p_T distribution of photoproduced J/ψ in UPC

p_T distribution of photoproduced (?) J/ψ in peripheral PbPb collisions

- ✓ coherent photoproduction at b < 2R is a possible explanation for the observed excess
- ✓ possible signature to probe the charmonium color screening dissociation in the QGP at LHC energies

lack of theory calculations for J/ψ photoproduction at b<2R

Future (I)



$$\left.\frac{d\sigma(\gamma N \to VN)}{dt}\right|_{t=0} \approx \frac{\alpha_s \Gamma_{ee}}{3\alpha_e M_V^5} 16\pi^3 \left(xG(x,Q^2)\right)^2$$

✓ uncertainties in the plot of the nuclear gluon shadowing factor vs *x:*
this was the motivation to study vector meson photoproduction in A-A systems (slide 4)

it's time to use these results to constrain G(*x*,Q^2)

✓ exclusive vector mesons

- ✧ higher collision energy
- ✧ increased statistics
- ✧ new species

⇒

- ✧ better constraints on gluon distribution
- ✧ wider range of *x* and scale Q^2 ($\sim M_V^2$) probed

✓ meson spectroscopy (e.g. excited vector meson states, searches for exclusive production of glueball states)

✓ high precision measurements of $\gamma\gamma \to e^+e^-$ to study QED with strong field

Future (II)

✓ inclusive photoproduction of heavy quarks and jets

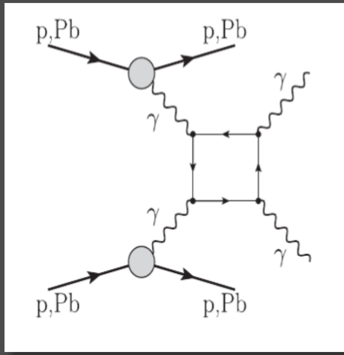
✧ photoproduction of $c\bar{c}$ through photo-gluon fusion ($\sigma \approx 1$ b in Pb+Pb collisions at the LHC (Klein, Nystrand, Vogt, Phys. Rev. C 66 (2002) 044906))

✧ photonuclear jet or dijet production (γ+parton → jet or dijet (Strikman, Vogt, White, PRL 96 (2006) 082001) challenging measurement for ALICE)

✧ advantage → processes with exchange of a single gluon (possibility to go to NLO)

✧ drawback → linear dependence on the gluon density → smaller sensitivity

✓ electroweak final states



$\gamma\gamma \to \gamma\gamma$

✧ in the SM this box diagram involves quarks, W, etc → extra contributions from new heavy charged particles and/or super symmetric partners of SM particles? (PRL 111, 080405 (2013))

✧ σ depends on the $M\gamma\gamma$ threshold (if $M_{\gamma\gamma}$>5 GeV → σ~30-40 nb)

✧ with 1 nb^{-1} at $\sqrt{s_{NN}}$=5.5 TeV → N ~ 30-40 events

✧ N~20 events in CMS/ATLAS, 5-10 events in ALICE

Run3 is required for a large statistics, but we can start at Run2

Future (III)

✓ excess of very low p_T J/ψ in PbPb collisions

✧ measurement in the dielectron channel at mid-rapidity with data from Run 2 at LHC

✧ improve precision of the measurement in the dimuon decay channel

✧ ALICE upgrade at high rate (50kHz):

- L_{int} = 10nb^{-1} until 2026
- J/ψ very low p_T excess can be studied in most central collisions
- open the possibility to study the excess polarization to confirm the mechanism at play

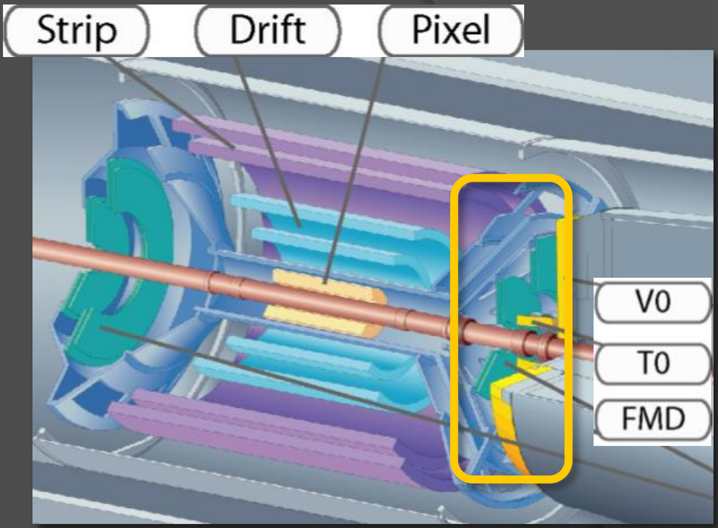
Conclusions

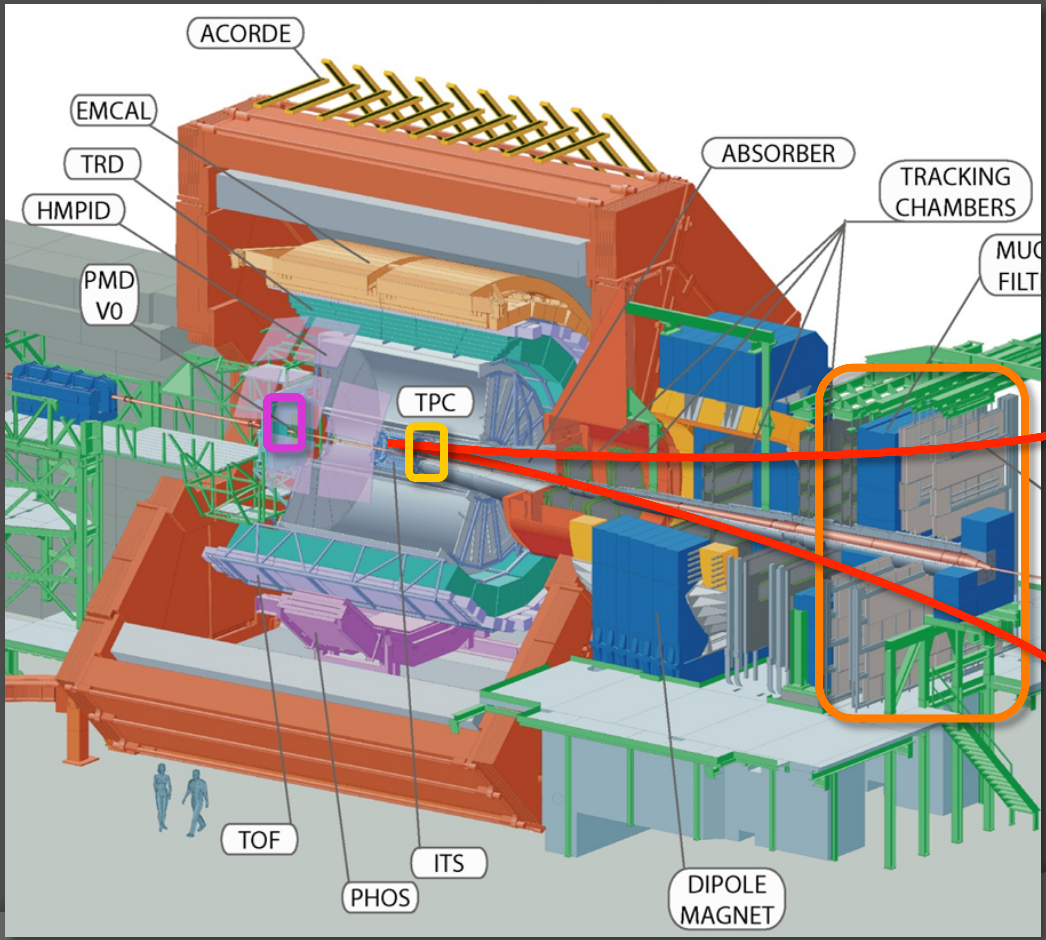
- ✓ first two heavy-ion runs (Run1) at LHC have produced a multitude of results on UPC, most of them from ALICE
- ✓ cross section for the J/ψ and ψ(2S) found to be in agreement with models with moderate nuclear gluon shadowing (EPS09). The ψ(2S) measurements still suffer from low statistics but are consistent with the J/ψ results
- ✓ detailed predictions in general, but ρ and ψ(2S) require more theoretical work for their interpretation
- ✓ nice measurements came → it's time to use them into the global fits
- ✓ Run2 will be a great step forward in UPC for pp, p-Pb and Pb-Pb collisions
- ✓ UPC physics has the potential to search for new physics and go beyond standard QED and QCD studies
- ✓ coherent J/ψ photoproduction at *b*<2R as a possible signature to probe the charmonium color screening dissociation in the QGP at LHC energies

back-up

ALICE and UPCs ($J/\psi \rightarrow \mu^+\mu^-$)

UPC forward trigger
- ✧ single muon trigger with $p_T > 1$ GeV/c ($-4<\eta<-2.5$)
- ✧ hit in VZERO-C ($-3.7<\eta<-1.7$)
- ✧ no hits in VZERO-A ($2.8<\eta<5.1$)



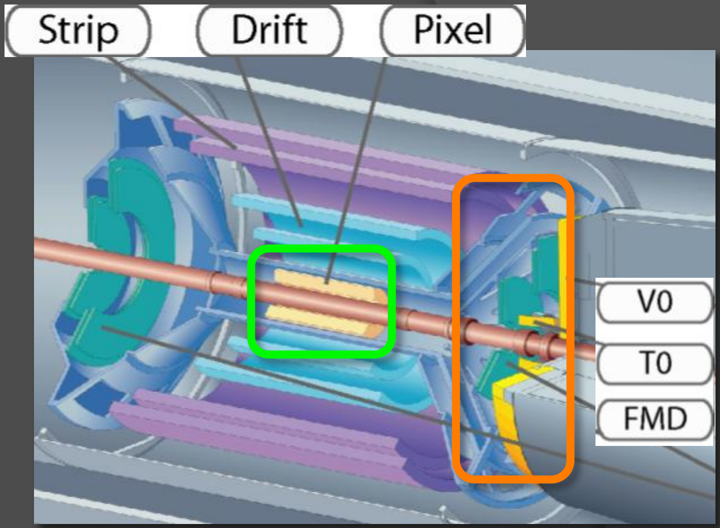


integrated luminosity ~ 55 μb^{-1}

✓ offline event selection:
- ✧ beam gas rejection with VZERO
- ✧ hadronic rejection with ZDC and SPD

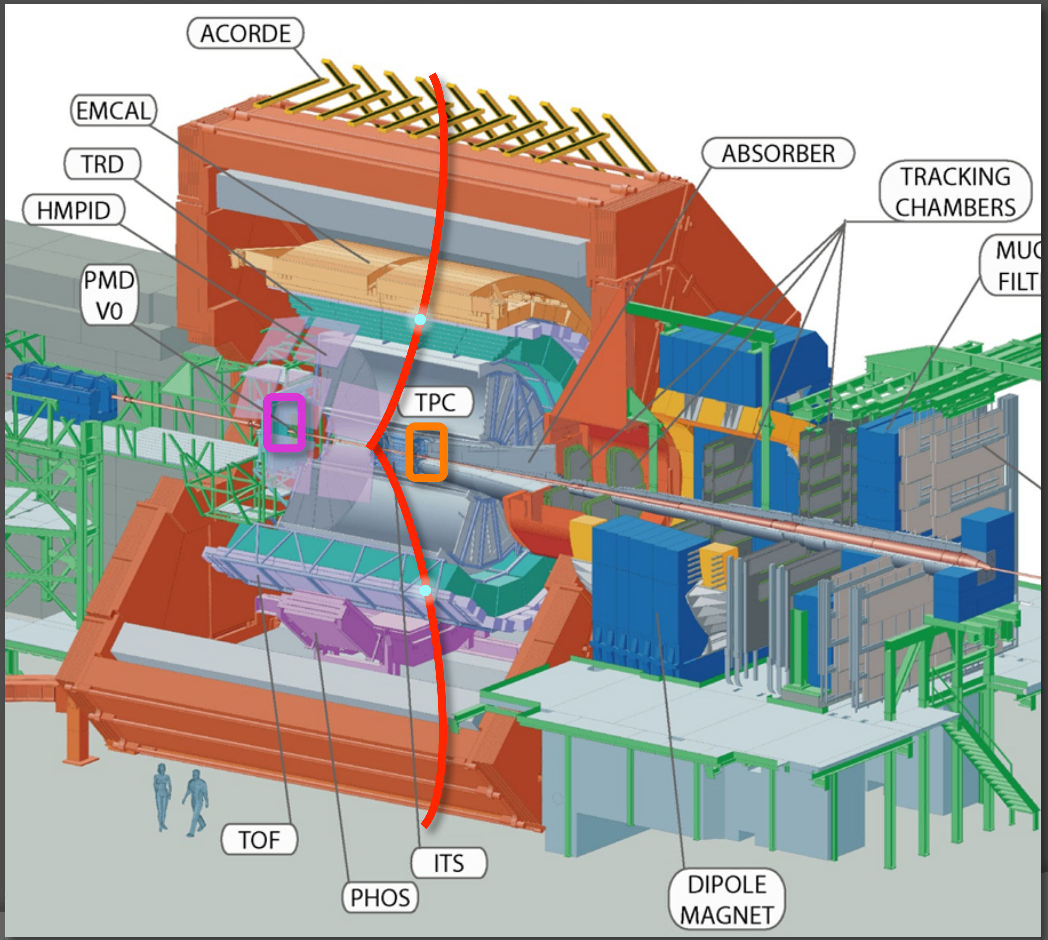
✓ track selection:
- ✧ muon tracks: $-3.7 < \eta < -2.5$
- ✧ matching with the trigger
- ✧ radial position for muons at the end of absorber: $17.5 < R_{abs} < 89.5$ cm
- ✧ p_T dependent DCA cut
- ✧ opposite sign dimuon: $-3.6 < y < -2.6$

ALICE and UPCs ($J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$)



UPC mid-rapidity trigger

- ✧ ≥ 2 hits in SPD
- ✧ 2≤ TOF hits ≤6 and back-to-back topology
- ✧ veto on VZERO-C and VZERO-A

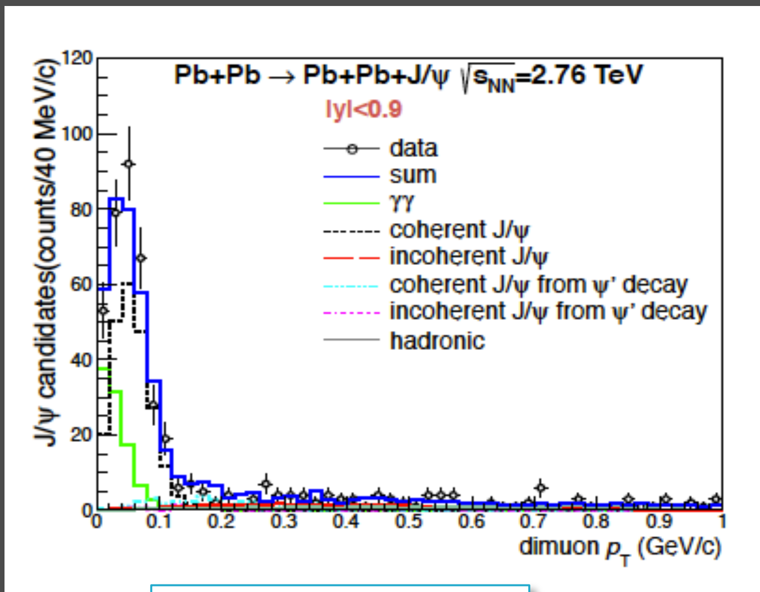


integrated luminosity ~ 23 μb^{-1}

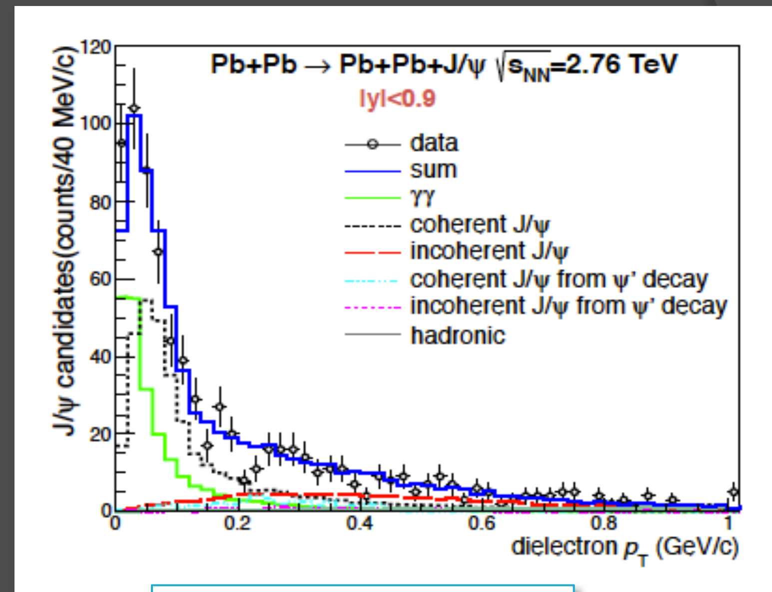
✓ offline event selection:

- ✧ rejection with VZERO and FMD
- ✧ primary vertex
- ✧ max (p_{T1}, p_{T2}) > 1 GeV/c
- ✧ dE/dx consistent with e/μ
- ✧ opposite sign tracks
- ✧ ZDC cut on number of neutrons emitted in coherent events

J/ψ p_T distributions (linear scale)



dimuon channel



dielectron channel

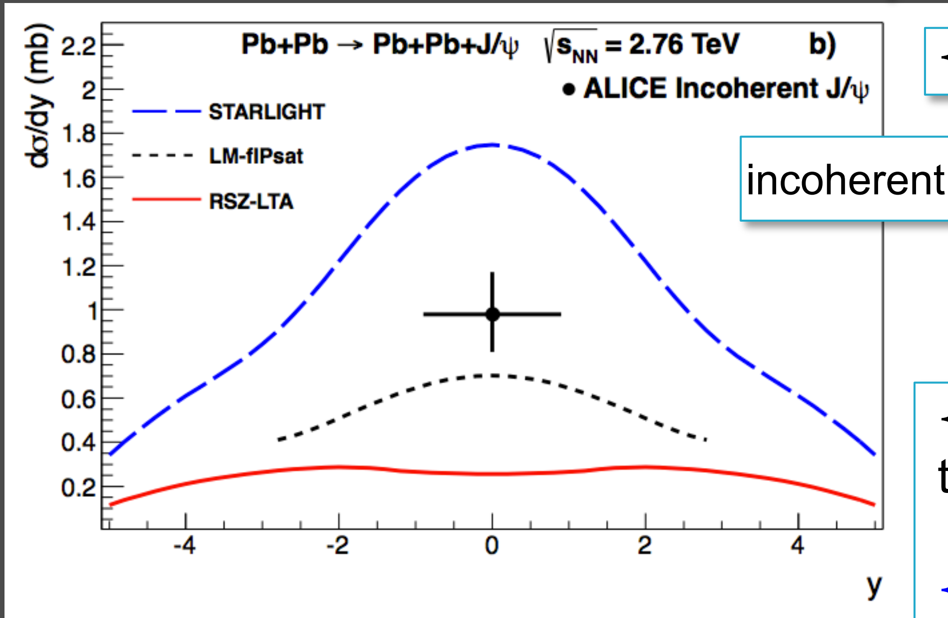
p_T distribution fitted using MC samples representing several components:

- coherent and incoherent J/ψ
- (coherent and incoherent) ψ' feed down
- $\gamma\gamma \rightarrow \mu^+\mu^-$
- hadronic

$$N^{\text{coh}}_{J/\psi} = \frac{N_{\text{yield}}}{1 + f_I + f_D}$$

distribution peaked at low momentum as expected from coherent production

Results and comparison with models



✧ Eur. J. Phys. C73, 2617 (2013)

incoherent $|y| < 0.9 \rightarrow d\sigma^{inc}_{J/\psi} / dy = 0.98^{+0.19}_{-0.17}(stat + syst)$ mb

✧ none of the three existing models predicts the incoherent cross section correctly

✧ STARLIGHT predicts a correct incoherent-to-coherent ratio (0.41)
✧ ALICE measurement $0.41^{+0.10}_{-0.08}(stat + syst)$

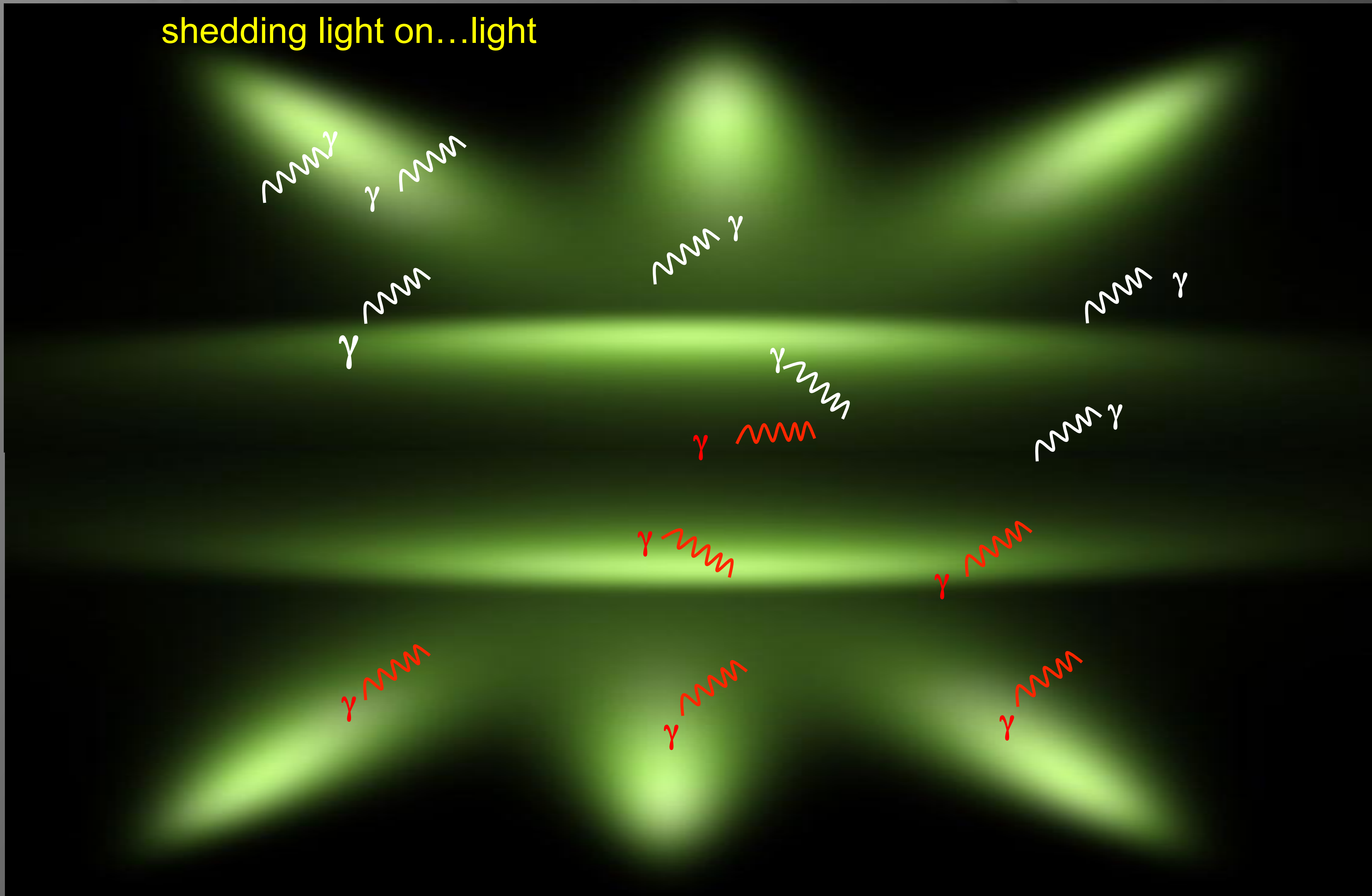
✓ STARLIGHT: Klein, Nystrand PRC60 (1999) 01493
GVDM coupled to a Glauber approach and using HERA data to fix the γp cross section

✓ RSZ: Rebyakova, Strikman, Zhalov, PLB 710 (2012) 252
based on LO pQCD amplitude for two gluon exchange where the gluon density incorporates shadowing computed in leading twist approximation

✓ LM: Lappi, Mantysaari, PRC87 (2013) 032201
color dipole model based with Glauber approach and a saturation prescription

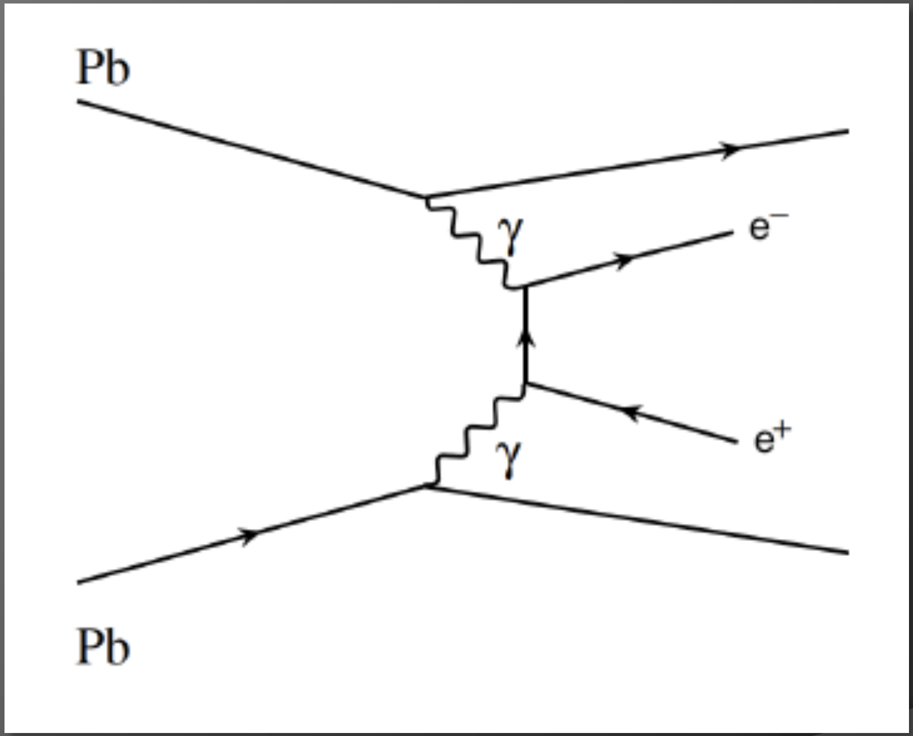
incoherent processes provide further constraints on the treatment of the nuclear modifications implemented in the different models

γγ processes (Pb-Pb collisions)



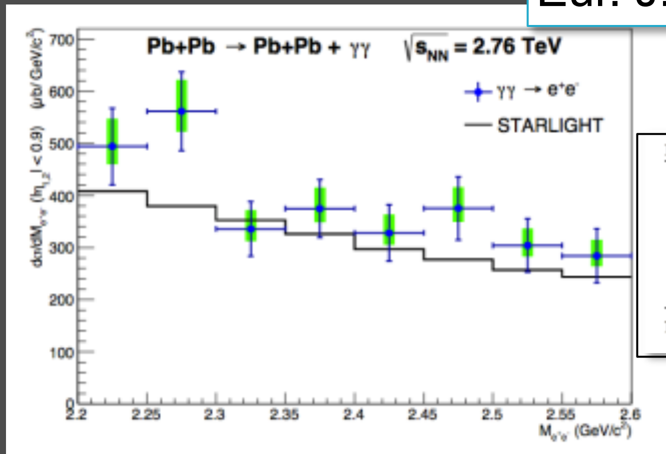
Processes in Pb+Pb

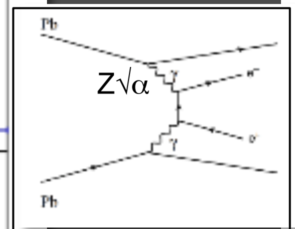
✓ an interesting physics case is also γγ interactions to provide informations on QED processes when the vertex $\sqrt{\alpha}$ is replaced by $Z\sqrt{\alpha}$

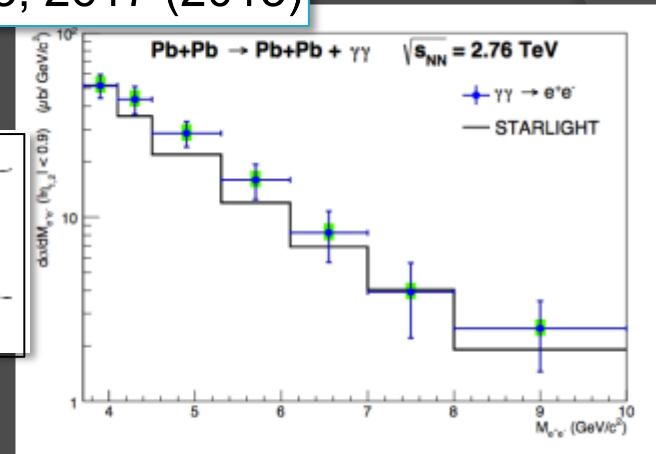


γγ cross section

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







✓ the γγ cross section measurement provides important constraints on QED calculations when the vertex $\sqrt{\alpha}$ has to be replaced by $Z\sqrt{\alpha}$

✓ due to the large Pb charge, giving $Z\sqrt{\alpha} \sim 0.6$, the inclusion of higher order terms is not straightforward → the models* including higher order terms predict a reduction of the cross section up to 30%

ALICE measurements			
✧ [2.2,2.6] GeV/c² →	$\sigma_{\gamma\gamma}^{e^+e^-} = 154 \pm 11(stat)^{+16.6}_{-10.8}(syst)\ \mu b$	precision 12%
✧ [3.7,10] GeV/c² →	$\sigma_{\gamma\gamma}^{e^+e^-} = 91 \pm 10(stat)^{+10.9}_{-8.0}(syst)\ \mu b$	precision 16%

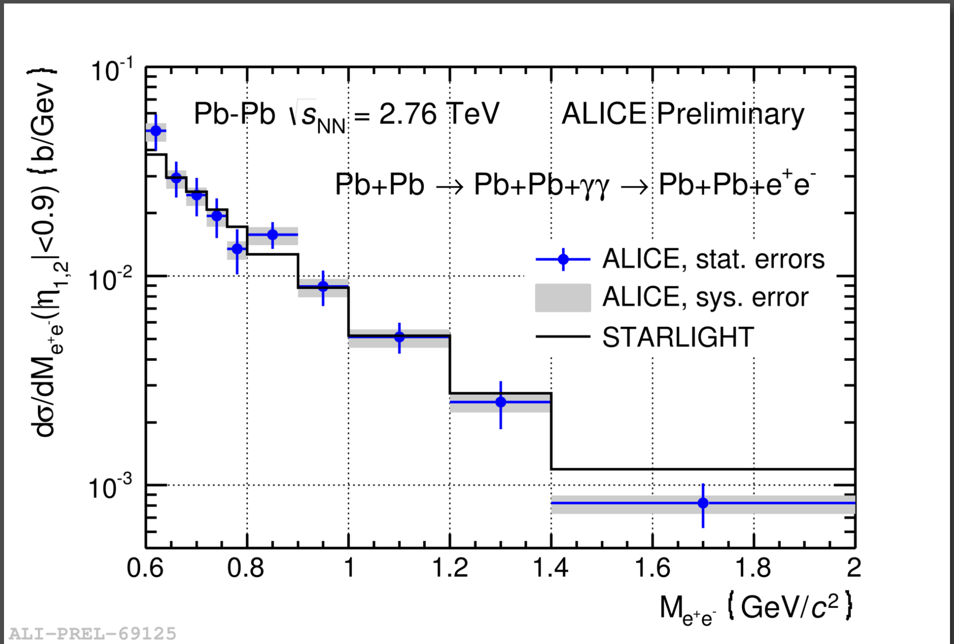
✓ the measured values for the γγ cross sections are 20% above but fully compatible within 1.0 σ and 1.5 σ with the STARLIGHT (LO) prediction for the low and high invariant mass intervals (128 μb and 77 μb)

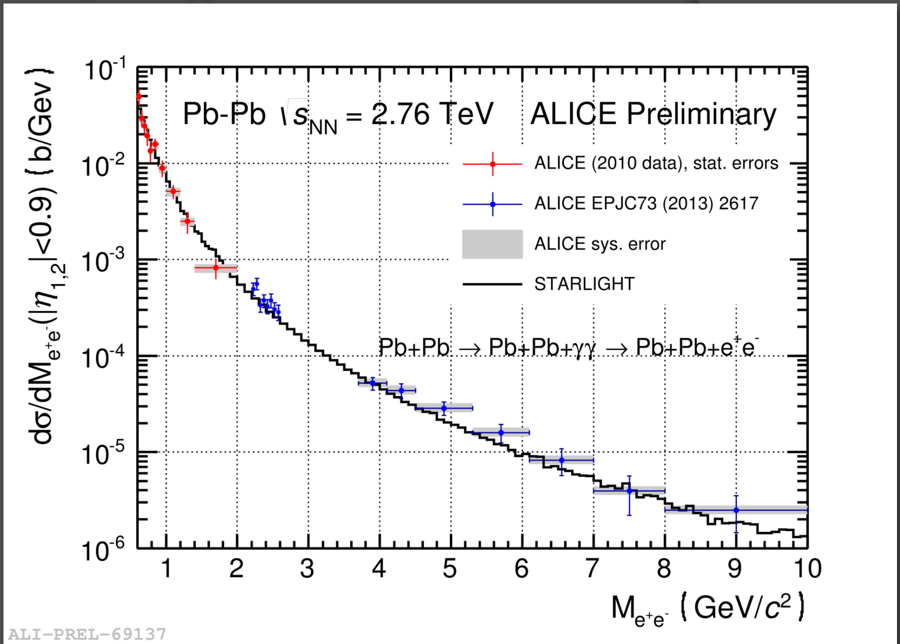
→ the models predicting a strong contribution of higher-order terms (not included in STARLIGHT) are not favored

*Baltz Phys. *Review 80 2009 034-901*

γγ cross section

using 2010 Pb-Pb data this measurement can be extended down to M_{ee} = 0.6 GeV/c^2 and the results can be combined to cover the range M_{ee} = 0.6 - 10 GeV/c^2





$\sigma(\lvert\eta_{1,2}\rvert \leq 0.9)$	data	STARLIGHT
($0.6 \leq M_{ee} \leq 2.0$ GeV/c^2)	9.8 ± 0.6(stat) +0.9/-1.2(syst) mb	9.7 mb
($2.2 \leq M_{ee} \leq 2.6$ GeV/c^2)	154 ± 11(stat) +17/-11(syst) μb	128 μb
($3.7 \leq M_{ee} \leq 10.0$ GeV/c^2)	91 ± 10(stat) +11/-8(syst) μb	77 μb

γγ cross section

transverse momentum distribution well described by the Monte Carlo (STARLIGHT)