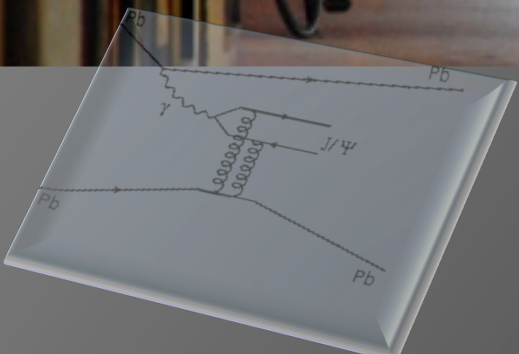


XLIV International Symposium on Multiparticle Dynamics
8 - 12 September 2014 - Bologna, ITALY

Charmonium photoproduction in ultra-peripheral p-Pb and Pb-Pb collisions with ALICE at the LHC

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

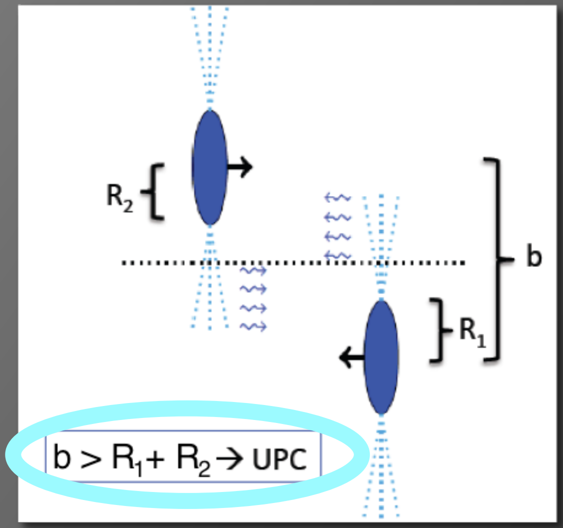
Centro Fermi
Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi
INFN
Istituto Nazionale di Fisica Nucleare
ALICE

Overview

- ✓ LHC as γPb and γp collider (Ultra-peripheral collisions)
- ✓ Physics motivation (gluon distribution in nuclei and nucleons)
- ✓ ALICE and UPC (detector and trigger description)
- ✓ charmonium cross section (forward and mid-rapidity)
- ✓ first results in pA (proton as a target)
- ✓ results and comparison with models (gluon shadowing and saturation)
- ✓ conclusions (achieved results and on going analyses)

LHC as γPb and γp collider

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



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

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

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

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

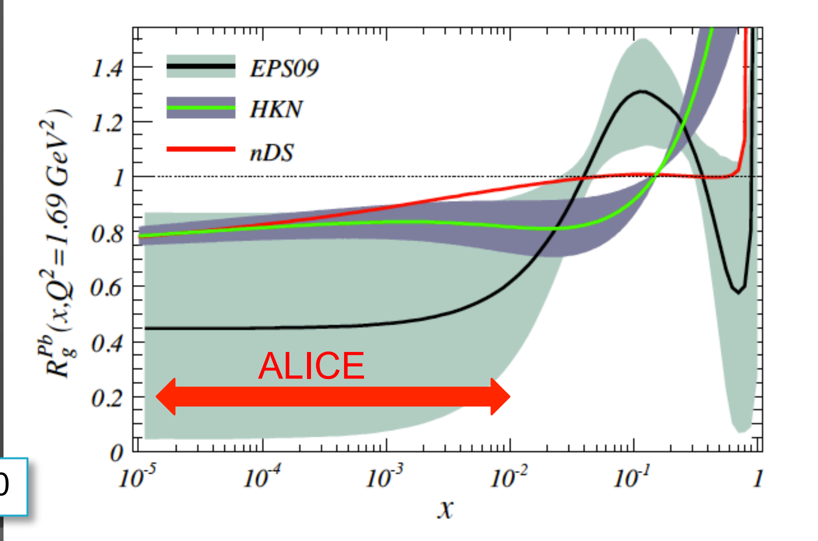
Physics motivation

- ✓ possibility to study non linear effects at low x in the gluon distribution of the target
- ✓ quarkonia photo-production allows to study the gluon density $G(x,Q^2)$ in Pb

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

- ✓ Bjorken-*x* accessible at LHC: $x = (M_V/\sqrt{s_{NN}})\exp(\pm y) \sim 10^{-2} - 10^{-5}$
- ✓ vector meson photo-production as tool to measure nuclear gluon shadowing and saturation

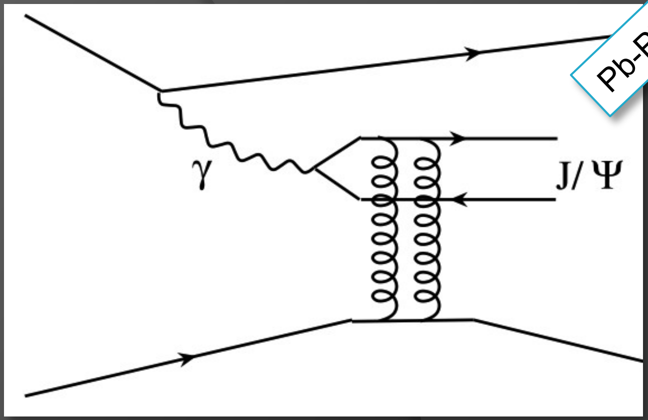
$$R_g^A(x,Q^2) = \frac{G_A(x,Q^2)}{G_p(x,Q^2)}$$



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

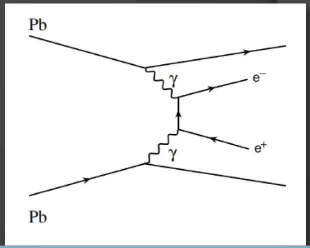
Physics motivation

- ✓ coherent vector meson production:
  - ✧ photon couples coherently to all nucleons
  - ✧ $<p_T> \sim 1/R_{Pb} \sim 60$ MeV/c
  - ✧ no neutron emission in ~80% of cases
- ✓ incoherent vector meson production:
  - ✧ photon couples to a single nucleon
  - ✧ $<p_T> \sim 1/R_p \sim 500$ MeV/c
  - ✧ target nucleus normally breaks up



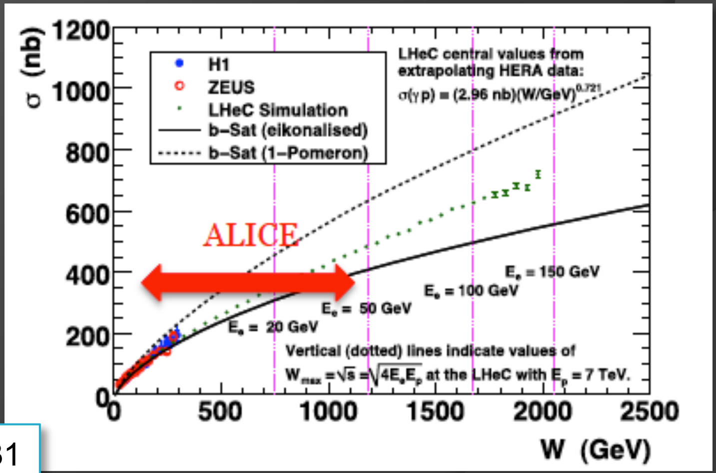
Pb-Pb

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



Pb-Pb

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



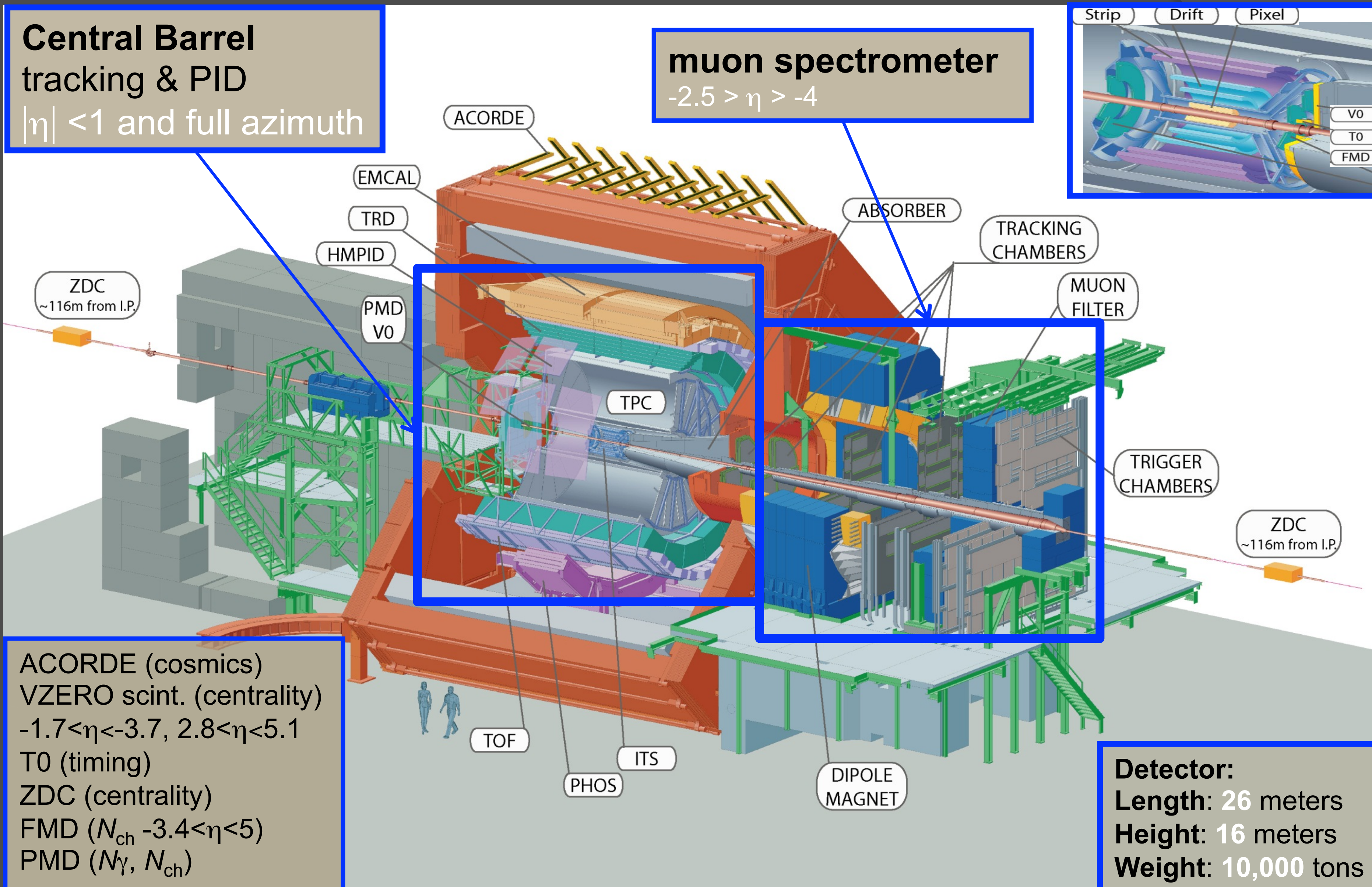
p-Pb

LHeC Study group ArXiv: 1211.4831

ALICE layout

Central Barrel
tracking & PID
$|\eta| < 1$ and full azimuth

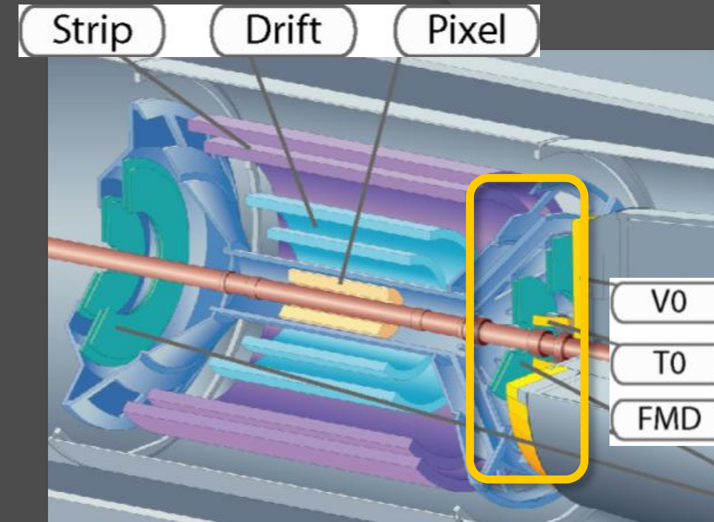
muon spectrometer
$-2.5 > \eta > -4$



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

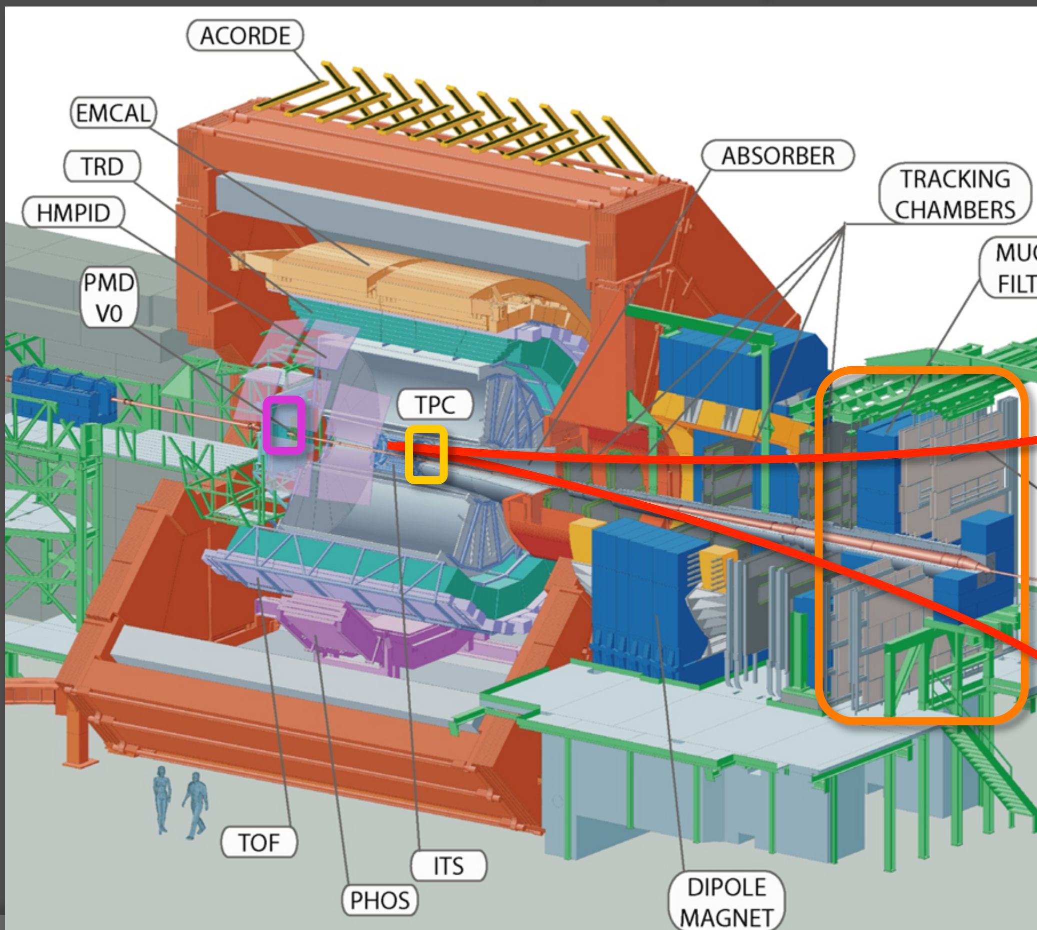
Detector:
Length: **26** meters
Height: **16** meters
Weight: **10,000** tons

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



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 in Pb-Pb~ 55 μb^{-1}

✓ offline event selection:

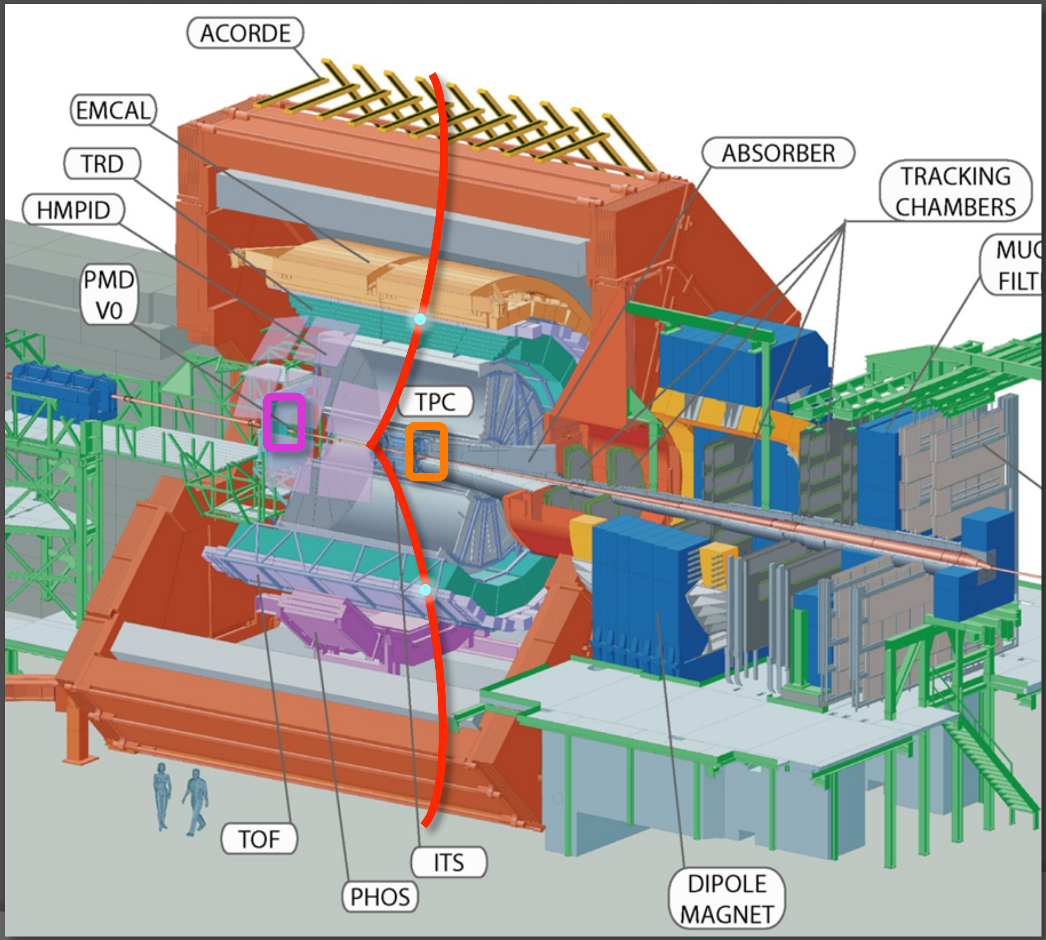
- ✧ beam gas rejection with VZERO
- ✧ hadronic rejection with ZDC and SPD

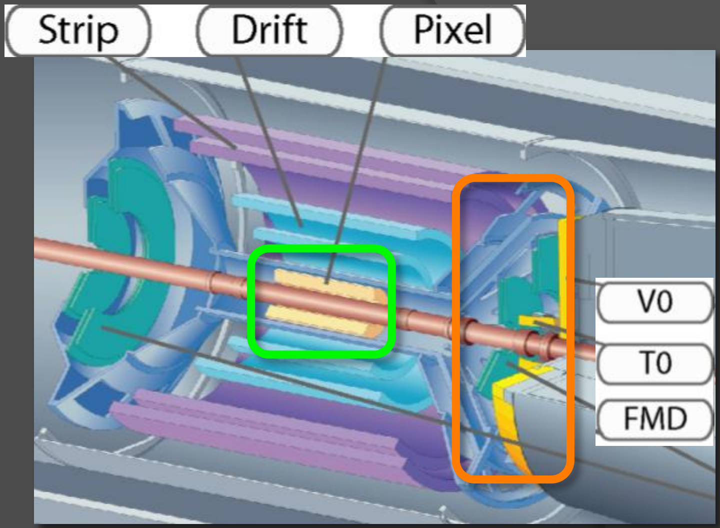
✓ track selection:

- ✧ 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 UPC ($J/\psi \rightarrow \mu^+\mu^-$ 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

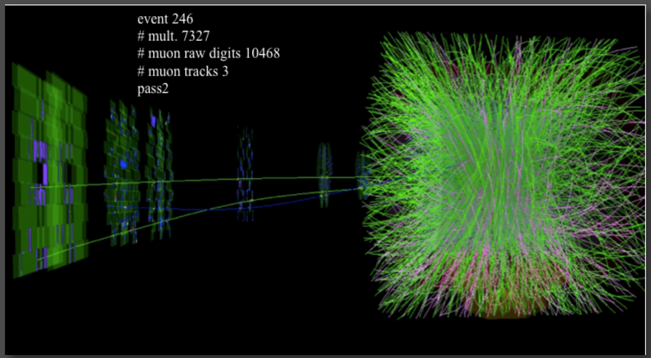




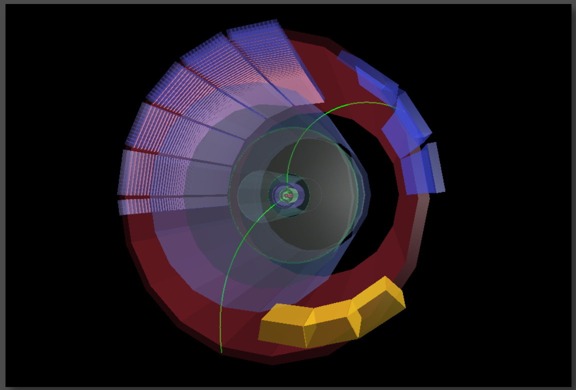
integrated luminosity in Pb-Pb~ 23 μb^{-1}

✓ 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

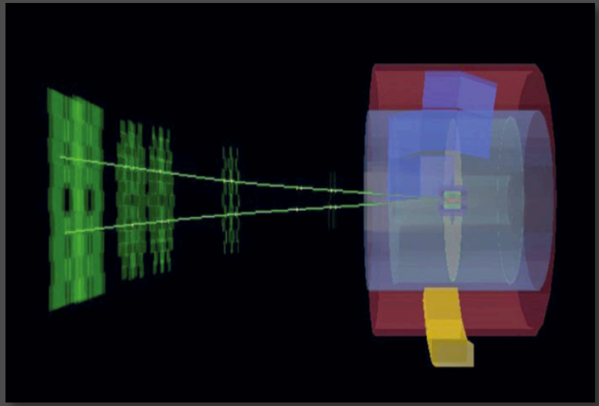
ALICE and Ultra-Peripheral Collisions



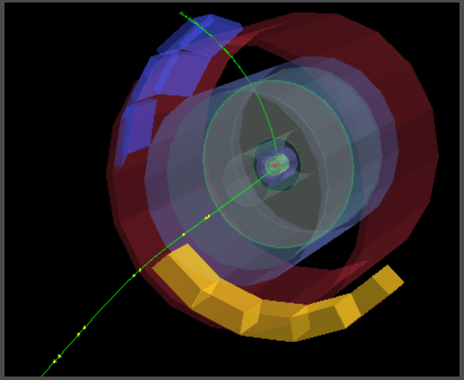
central Pb-Pb collision



UP Pb-Pb collision at mid-rapidity



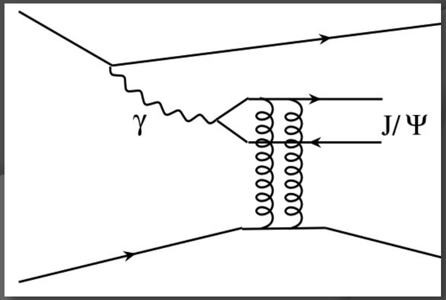
UP Pb-Pb collision at forward rapidity



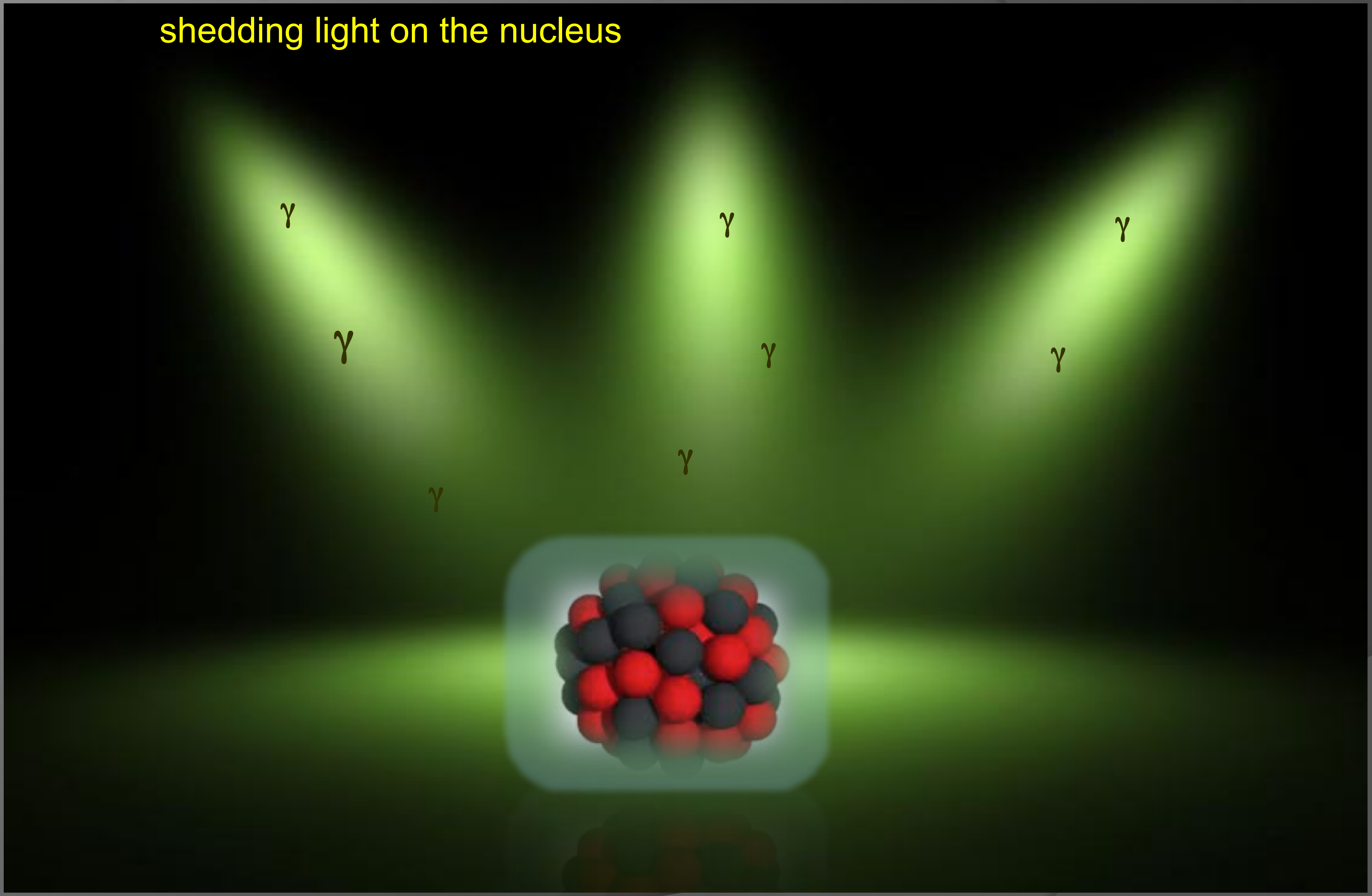
UP p-Pb collision at semi-forward rapidity

2 (or 4) tracks in an otherwise empty detector

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

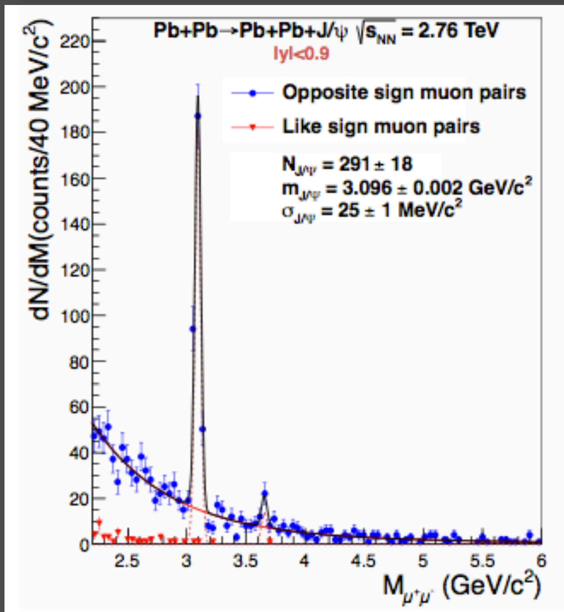


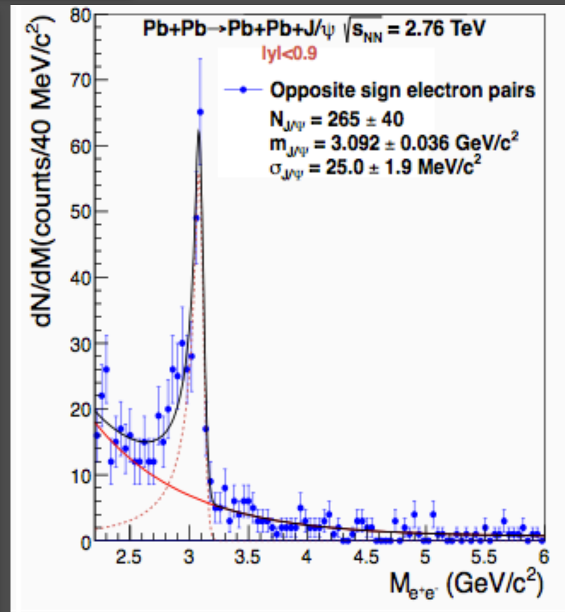
γPb processes (Pb-Pb collisions)



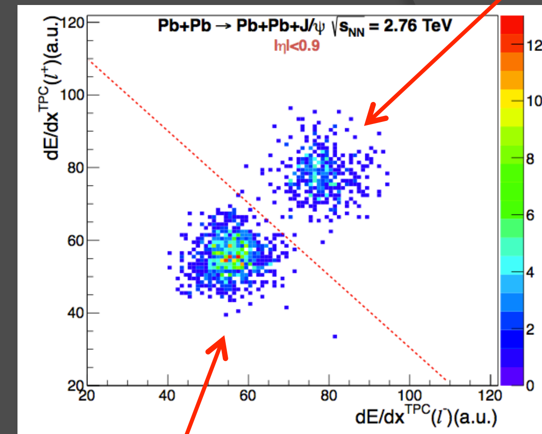
J/ψ measurements at mid-rapidity

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

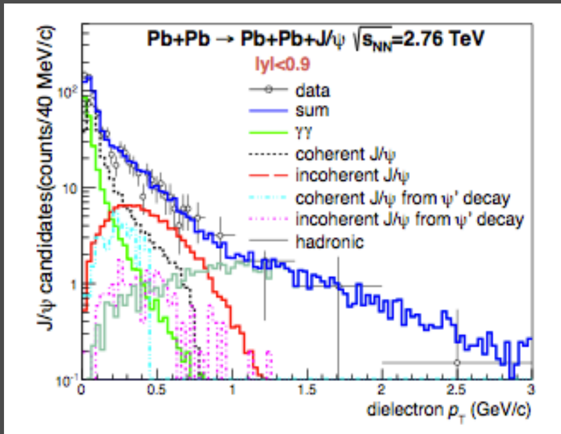


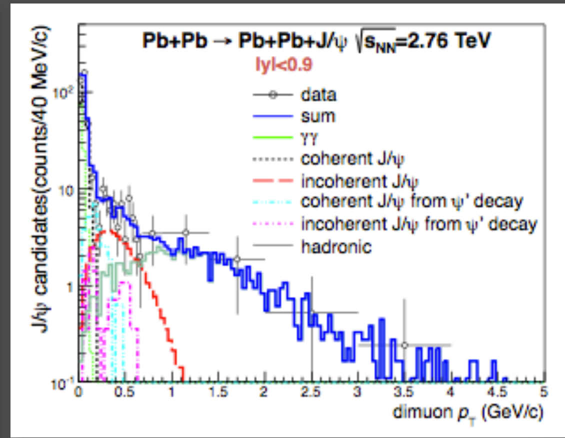


electrons



muons





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

(more details in the backup)

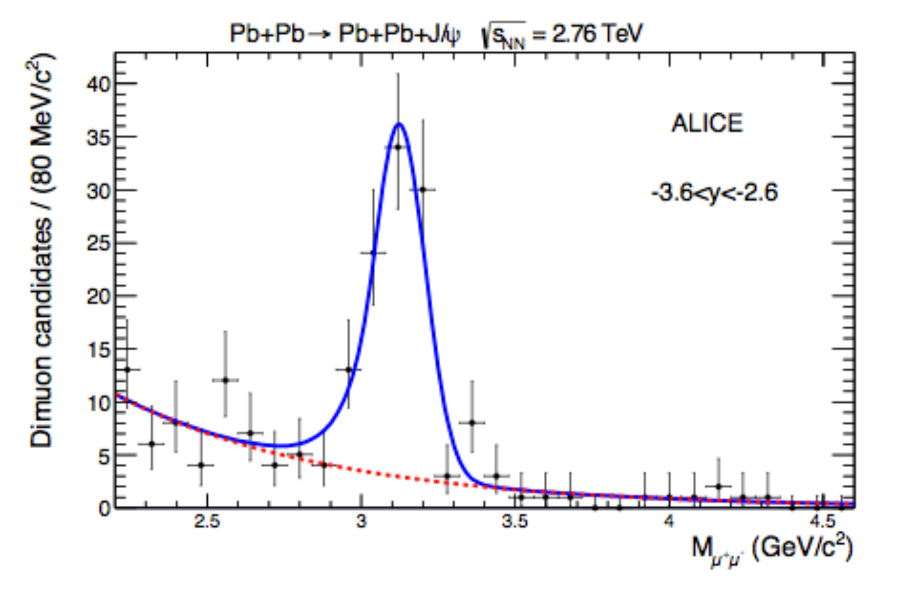
coherent enriched sample
p_T < 200 (300) MeV/c

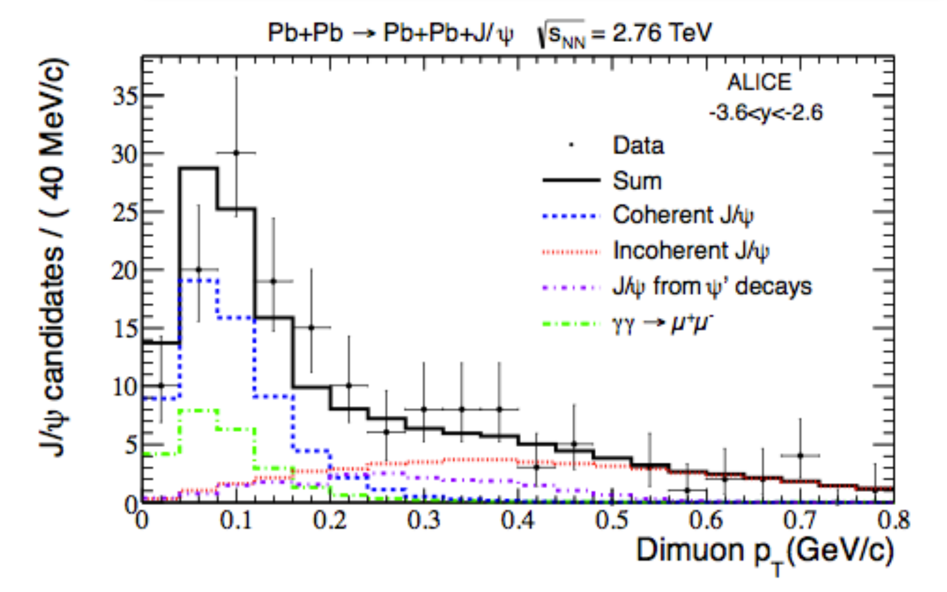
J/ψ photo-production probes the gluon distribution in Pb at $x \sim 10^{-3}$

J/ψ measurements (coherent at forward rapidity)

first measurement of J/ψ photo-production done at LHC

Phys. Lett. B718 (2013) 1273 -1283





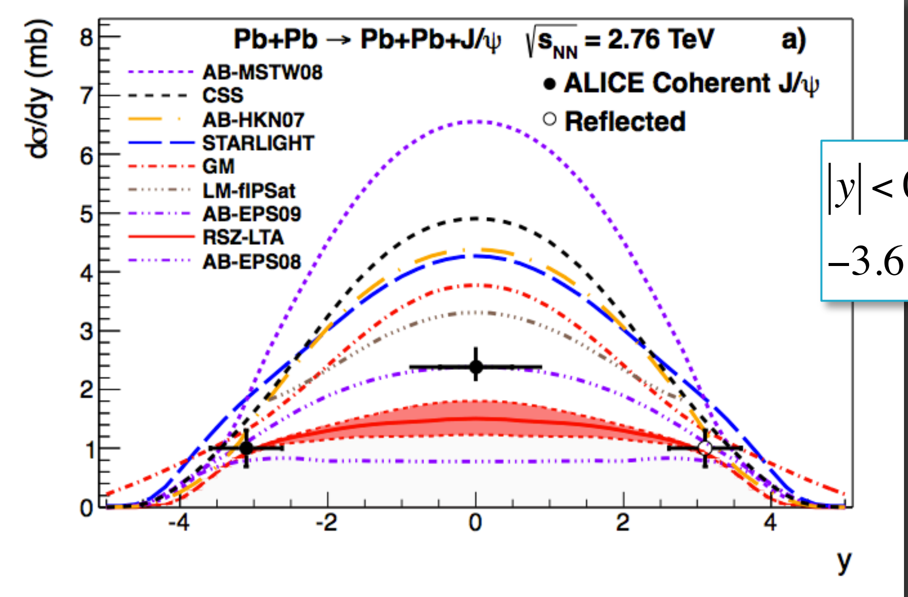
p_T distribution fitted using MC samples representing several components:

- 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 photo-production probes the gluon distribution in Pb at $x \sim 10^{-2}$

Results and comparison with models



Phys. Lett. B718 (2013) 1273 -1283

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

$$|y| < 0.9 \quad \rightarrow d\sigma^{coh}_{J/\psi} / dy = 2.38^{+0.34}_{-0.24}(stat + syst) \text{ mb}$$

$$-3.6 < y < -2.6 \rightarrow d\sigma^{coh}_{J/\psi} / dy = 1.00 \pm 0.18(stat)^{+0.24}_{-0.26}(syst) \text{ mb}$$

data are closer to models incorporating nuclear gluon shadowing

✓ AB: Adeluyi and Bertulani, PRC85 (2012) 044904
these models use LO pQCD scaled by an effective constant to correct for missing contributions
MSTW08 assumes no nuclear effects, EPS08/09 incorporate nuclear effects according to different parametrizations

✓ CSS: Cisek, Szczurek, Sch.fer PRC86 (2012) 014905
color dipole model based on unintegrated gluon distribution of the proton

measured cross section in good agreement with the calculation using the EPS09 nuclear gluon fit

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

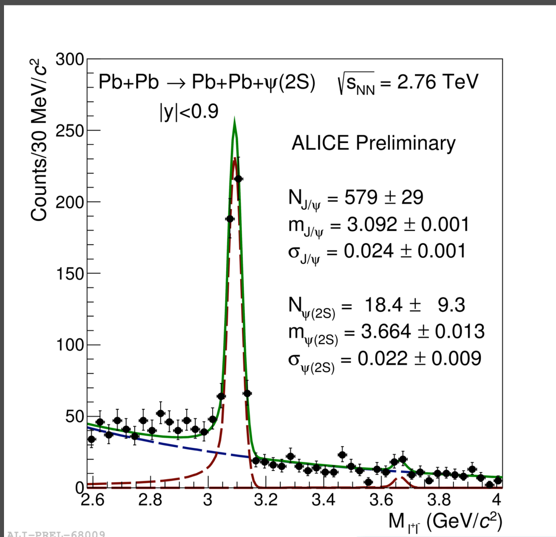
✓ GM: Goncalves, Machado, PRC84 (2011) 011902
color dipole model, where the dipole nucleon cross section is from the IIM saturation model

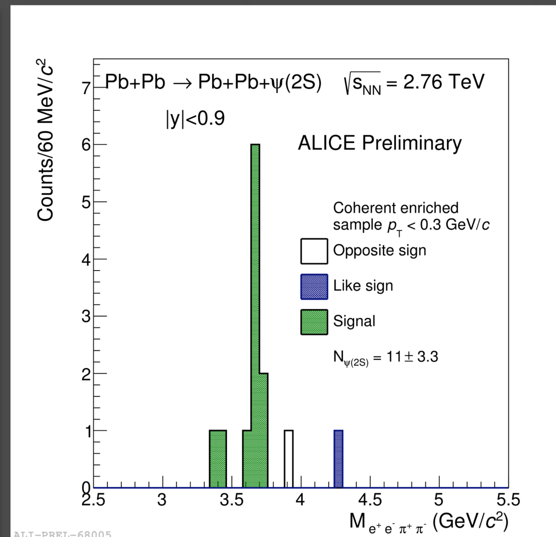
- ✓ no nuclear effects: AB-MSTW08
- ✓ Glauber approach: STARLIGHT, GM, CSS, LM
- ✓ partonic models: RSZ-LTA, AB-EPS08,09, AB-HKN07

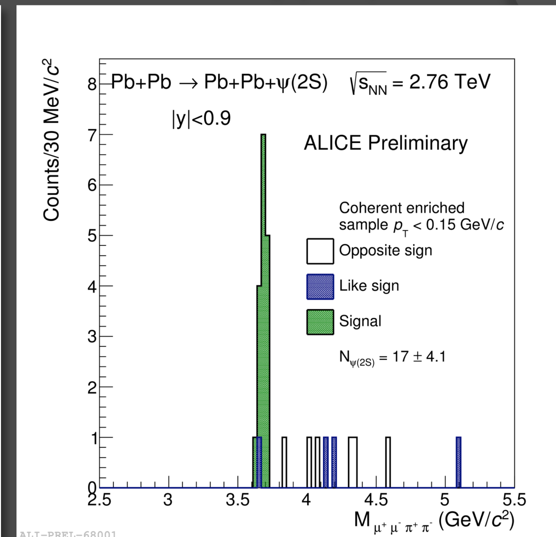
✓ RSZ: Rebyakova, Strikman, Zhalov, PLB 710 (2012) 252
based on LO pQCD amplitude for two gluon exchange where the gluon density Incorporates shadowing computed in leading twist approximation

$\psi(2S)$ measurements (mid-rapidity)

first exclusive photonuclear production of $\psi(2S)$



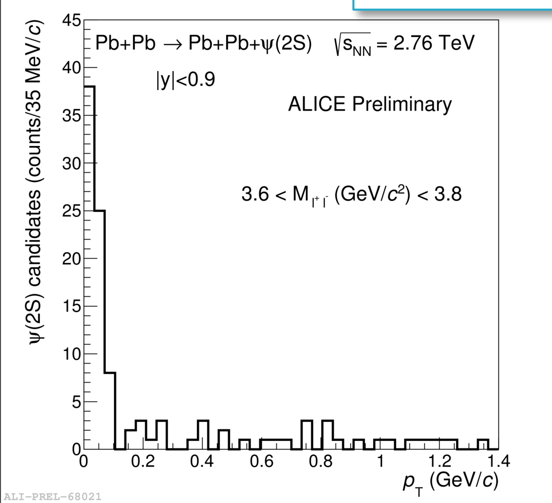


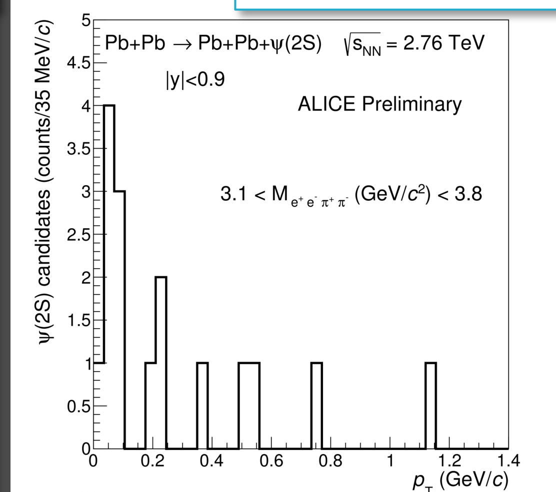


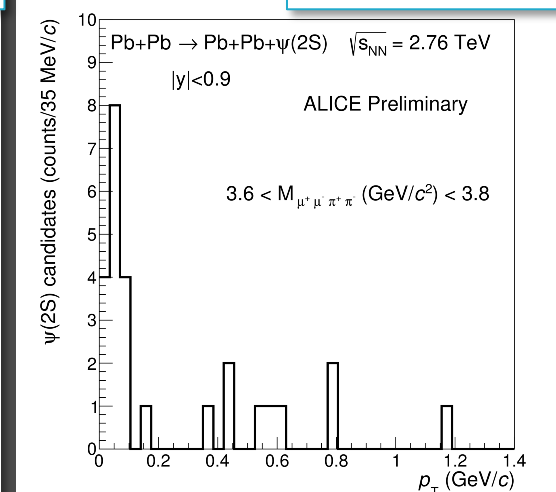
$\psi(2S) \rightarrow l^+l^-$

$\psi(2S) \rightarrow e^+e^- + \pi^+\pi^-$

$\psi(2S) \rightarrow \mu^+\mu^- + \pi^+\pi^-$



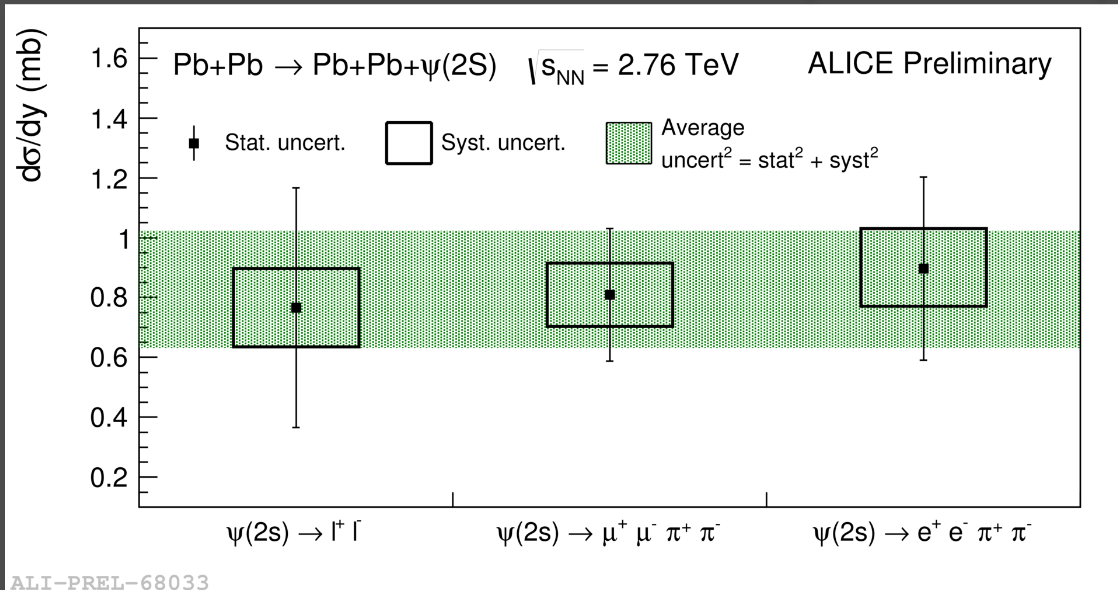




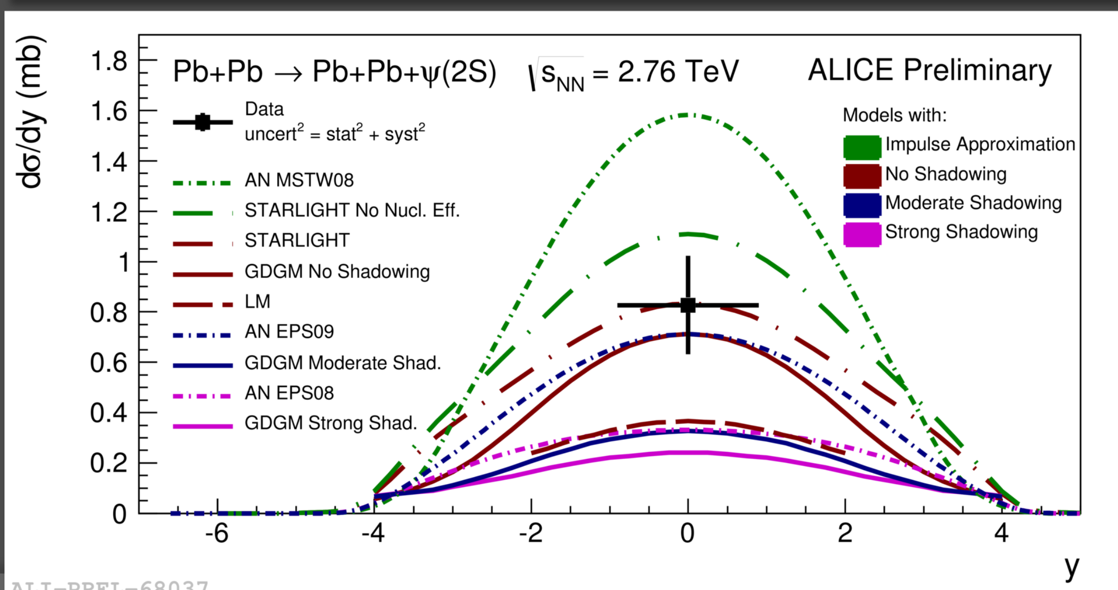
- ✓ clear coherent contribution at very low p_T
- ✓ moderate number of candidates in 4-lepton channels, but very clear signal

ψ(2S)/ψ ratio

first exclusive photonuclear production of ψ(2S)

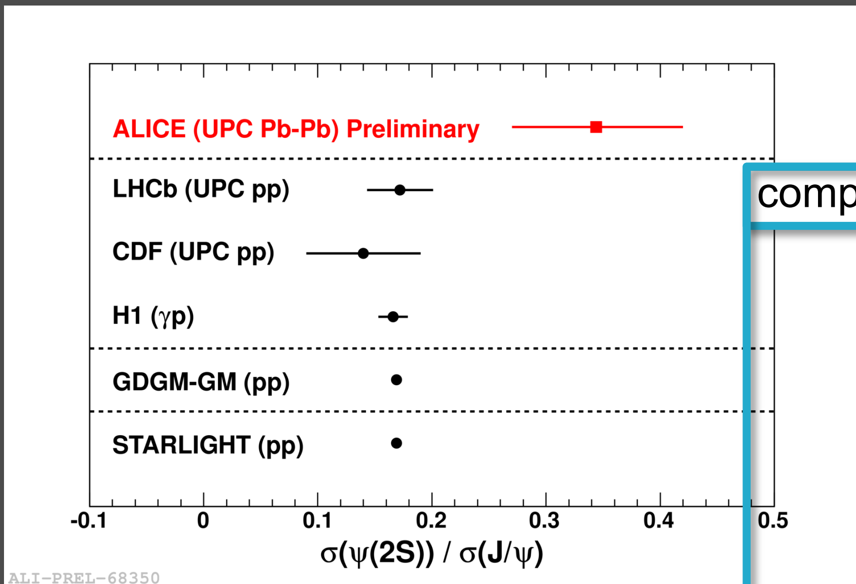


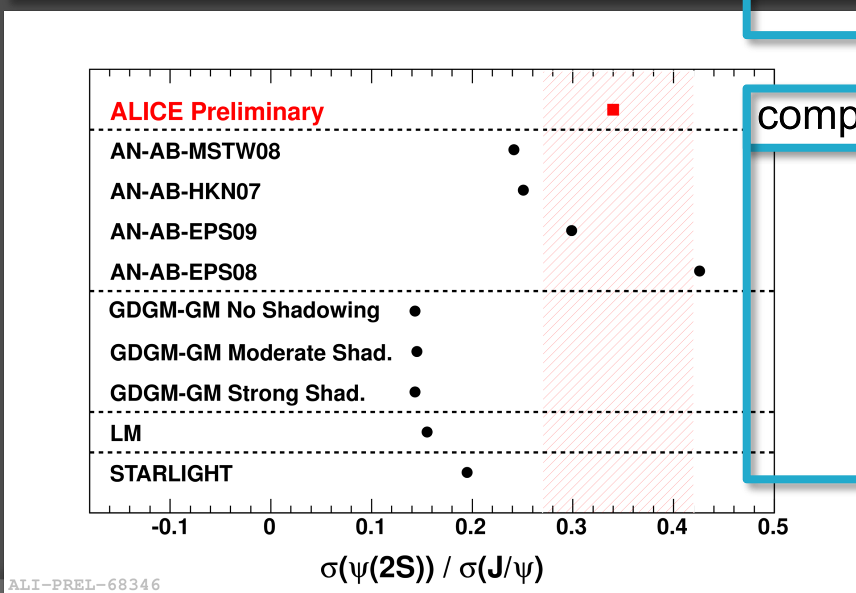
$$\frac{d\sigma}{dy} = 0.83 \pm 0.19 \text{ (stat+syst) mb}$$



- ✓ 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(2S)/ψ ratio





- ✓ many sources of systematic uncertainties will cancel in the measured ratio
- ✓ $R[\sigma(\psi(2S))/\sigma(J/\psi)] = 0.34^{+0.08}_{-0.07}$ (stat+syst)

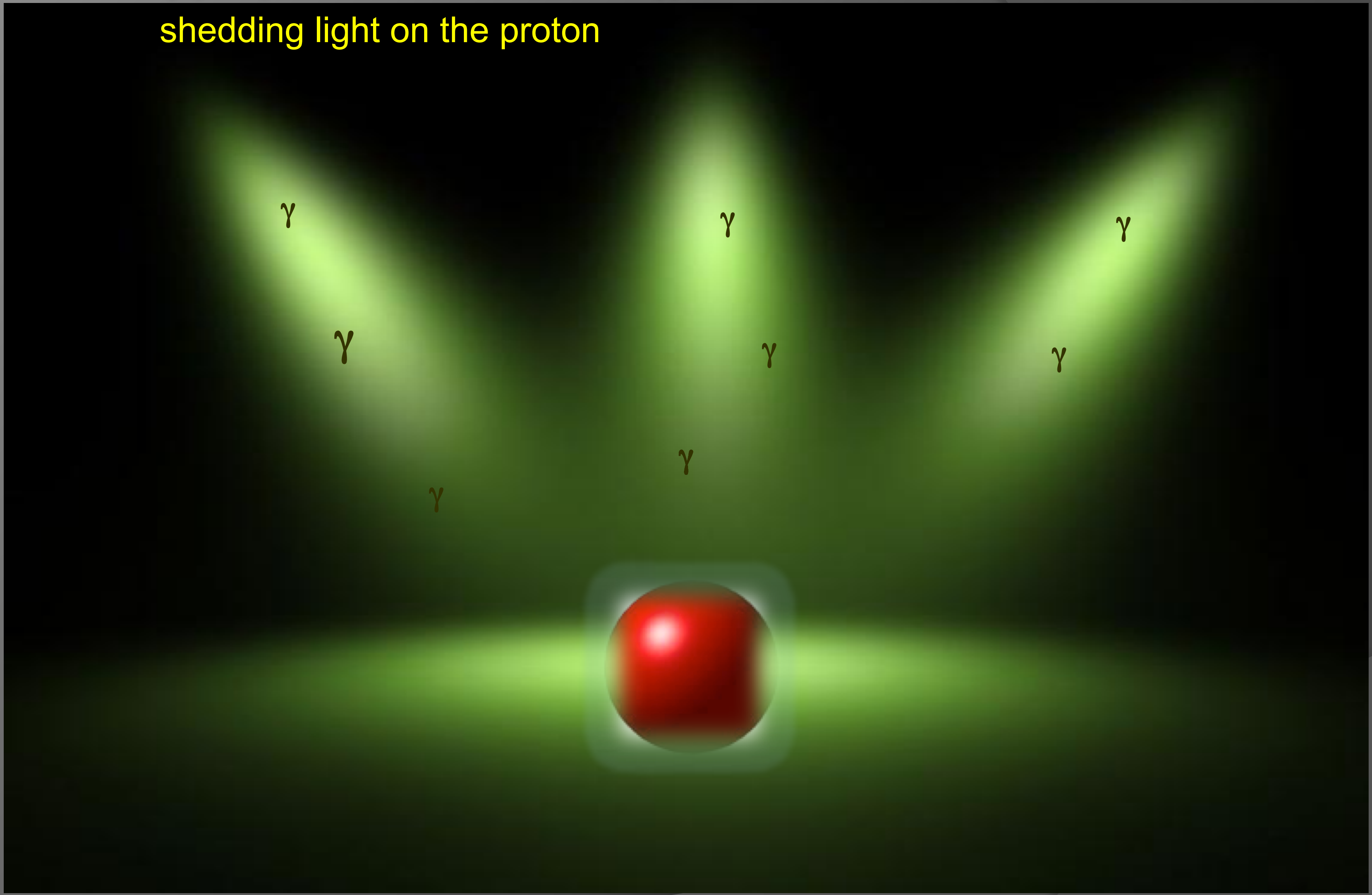
comparison with pp data and models

- ✓ 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 reproduce correctly the pp ratio, fail in describing the Pb-Pb ratio
- ✓ the AN EPS09 model, although it assumes a ψ(2S) wave function identical to the J/ψ one, describes in a satisfactory way this ratio

γp processes (p-Pb collisions)



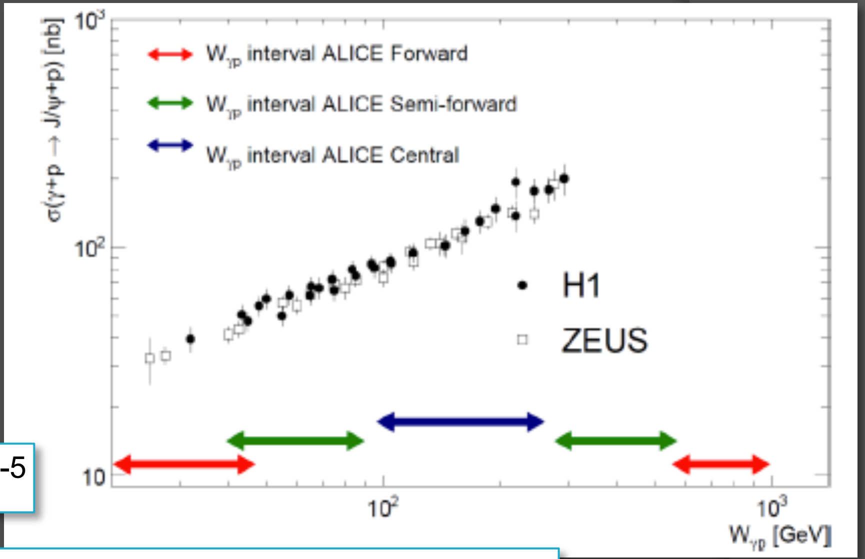
ALICE Physics potential in p-A

J/ψ photoproduction dominated by γ+p process

p-Pb: proton moves towards the muon arm
Pb-p: Pb-nucleus moves towards the muon arm

accessible kinematics regions:

p-Pb forward	$21<W_{\gamma p}<45$ GeV
p-Pb semi-forward	$45<W_{\gamma p}<82$ GeV
mid-rapidity	$100<W_{\gamma p}<250$ GeV
Pb-p semi-forward	$300<W_{\gamma p}<550$ GeV
Pb-p forward	$550<W_{\gamma p}<1160$ GeV

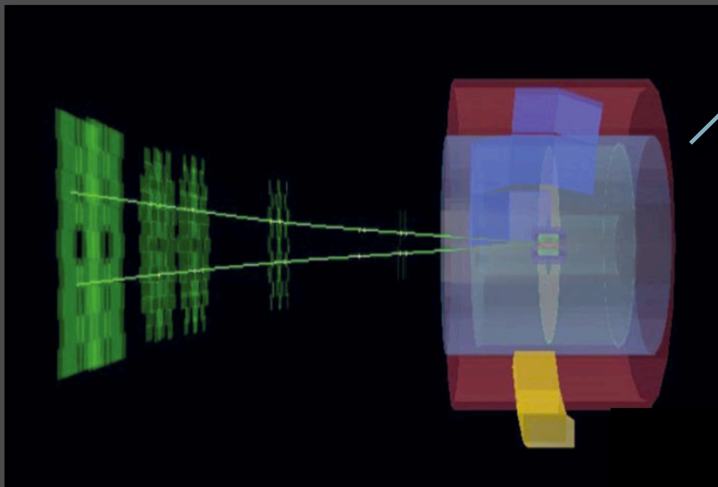


possibility to study gluon PDFs in proton up to $x \sim 10^{-5}$

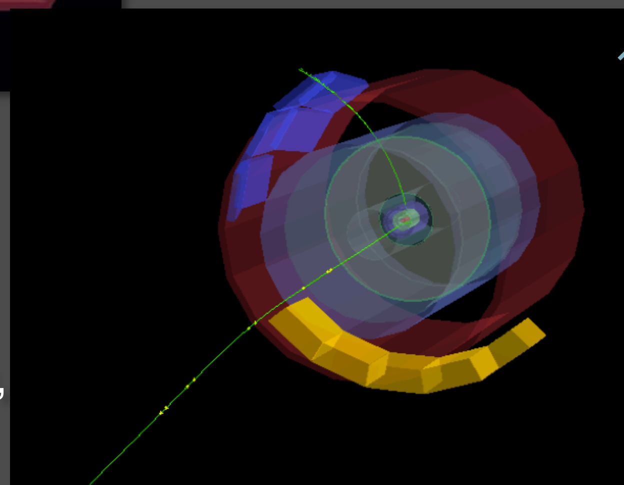
H1: A. Aktas et al. Eur.Phys. J.C46:585-603,2006 ZEUS: S. Chekanov et al., Nucl. Phys. B695 (2004) 3

- ✓ measuring the charmonium rapidity w.r.t. the direction of the target, the energy in the photon target system can be determined
- ✓ the source of the photon is known (big advantage w.r.t. pp and Pb-Pb)

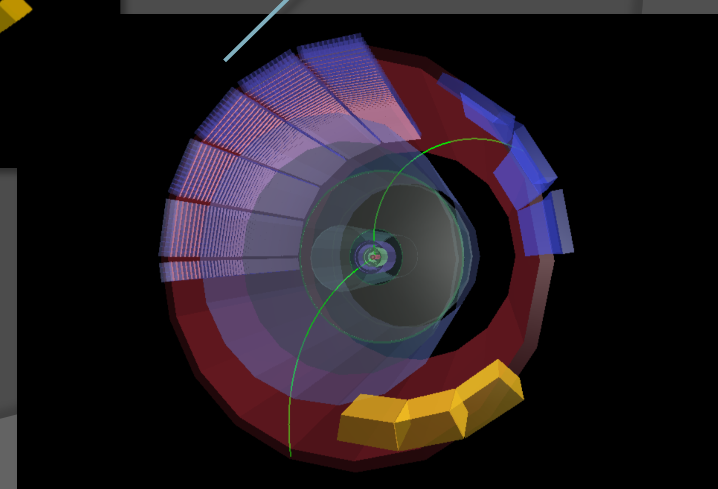
UPCs in pA



forward rapidity ($J/\psi \rightarrow \mu^+\mu^-$)



semi-forward rapidity ($J/\psi \rightarrow \mu^+\mu^-$)

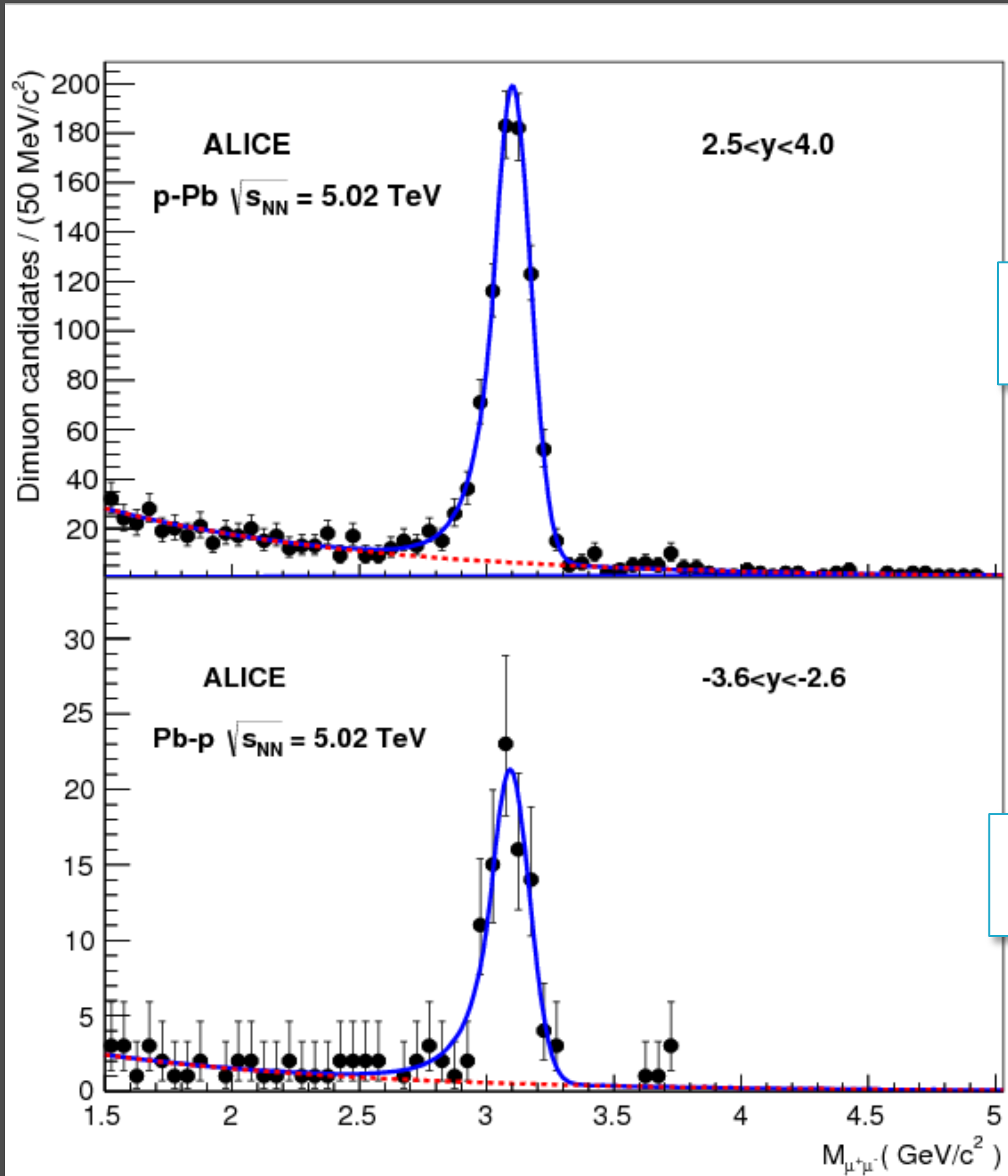


mid-rapidity ($J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$)

trigger logic:

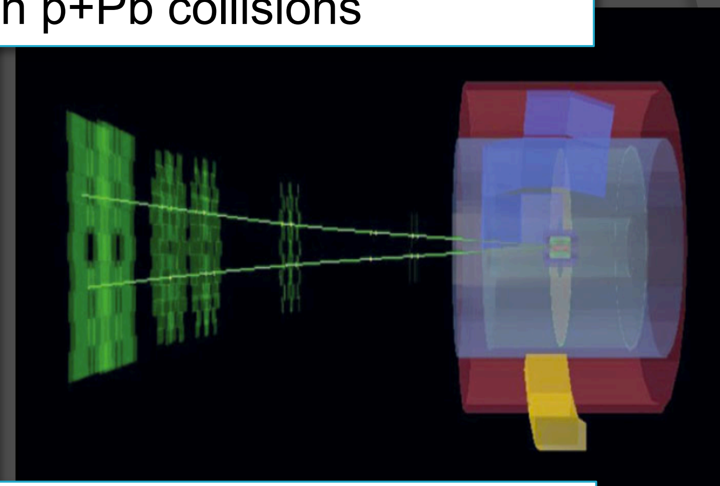
- ✓ similar to Pb-Pb case for forward and mid-rapidities, but improved purity
- ✓ semi-forward
  - ✧ V0A and V0C (≥5 cells) vetoed
  - ✧ SPD multiplicity (≥ 7 outer chips) vetoed
  - ✧ single muon with p_T>0.5GeV/c
  - ✧ SPD (≥ 1 chips)

J/ψ in p-Pb and Pb-p



arXiv 1406.7819

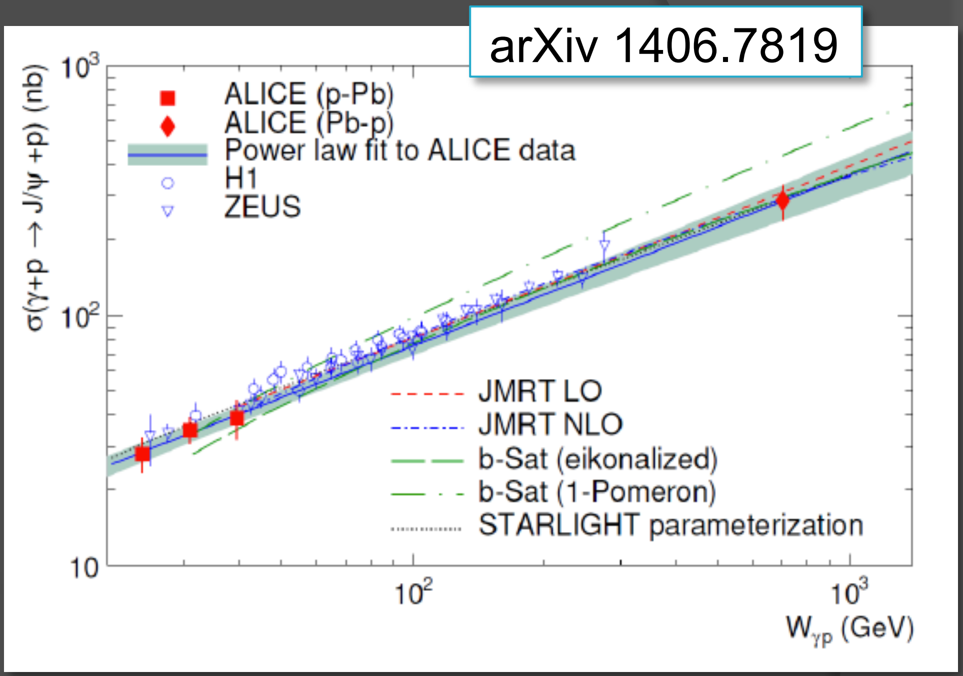
$J/\psi \rightarrow \mu^+\mu^-$ at forward rapidity in p+Pb collisions



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

Measured γp cross sections in p-Pb

- ✓ first direct γp measurement at the LHC
- ✓ 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)
- ✓ LHCb solutions consistent with the power-law fit obtained from ALICE results



- ✓ JMRT: LO model based on a power law; NLO model includes the expected main NLO contributions
- ✓ b-Sat (eikonalised) includes b-dependent saturation effects based on a CGC inspired model
- ✓ HERA and ALICE cross section points stay on the same power law
- ✓ the most straightforward interpretation is that no change in the behavior of the gluon PDF in the proton manifests itself between HERA and LHC

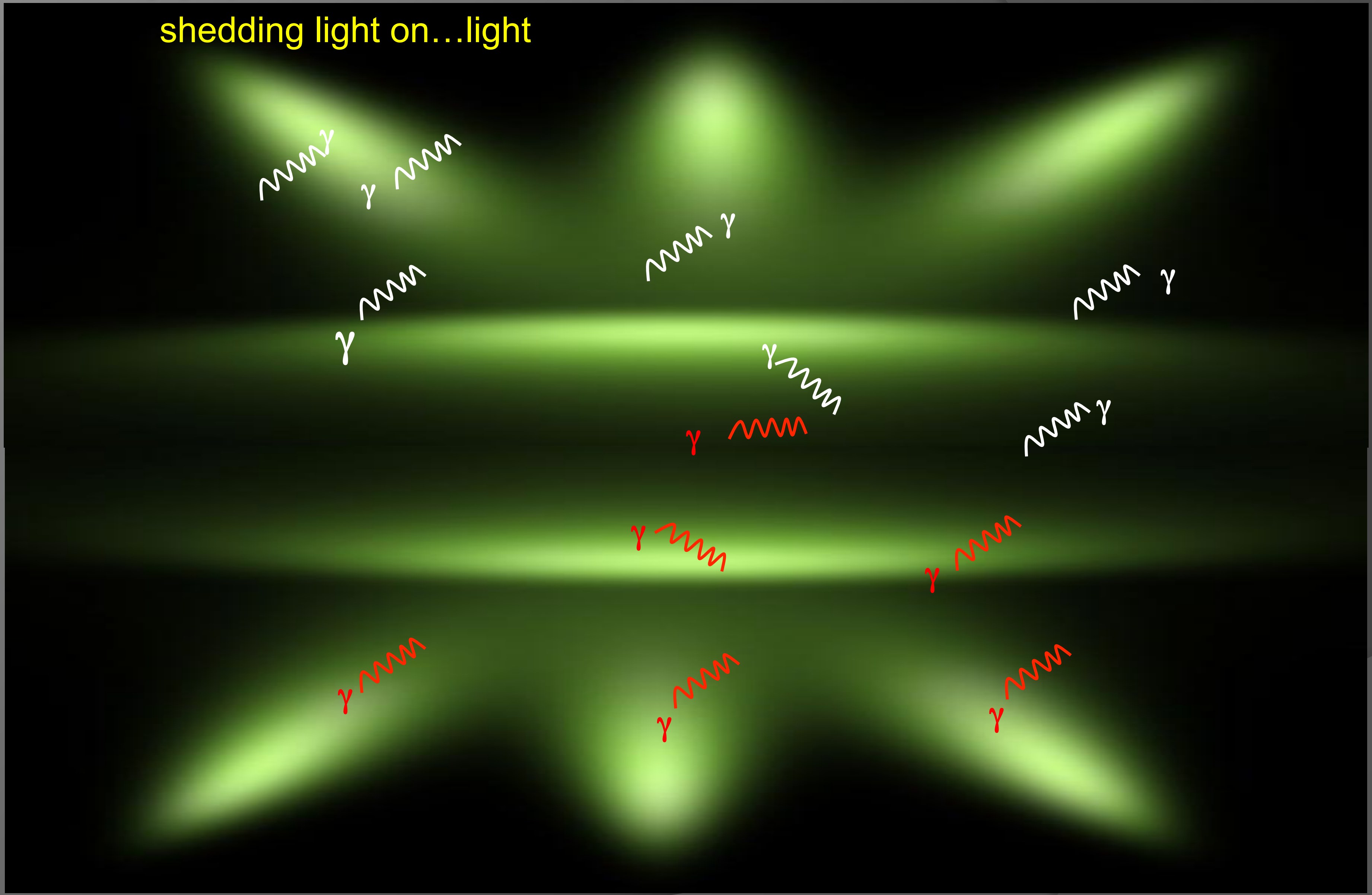
Conclusions

LHC as γPb, γp and $\gamma\gamma$ collider to study:

- ✓ (Pb-Pb) measurement of exclusive vector meson (J/ψ) cross sections to investigate the gluon distribution in the nuclei
- ✓ (Pb-Pb) results agree with EPS09 gluon distribution, favoring the presence of gluon shadowing
- ✓ (Pb-Pb) ψ(2S) vector meson photoproduction measured
- ✓ (p-Pb and Pb-p) no change in the behavior of the gluon PDF in the proton manifests itself between HERA and LHC(p-Pb)
- ✓ two ALICE papers:
  - ✧ Phys. Lett. B718 (2013) 1273-1283
  - ✧ Eur. J. Phys. C73, 2617 (2013)
- ✓ other three ALICE papers in preparation

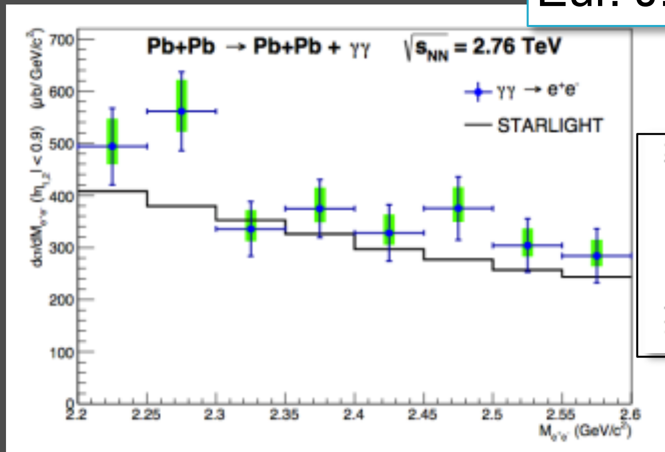
back up

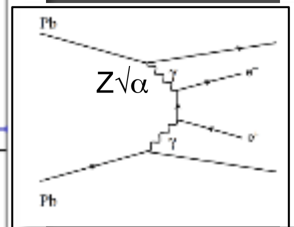
γγ processes (Pb-Pb collisions)

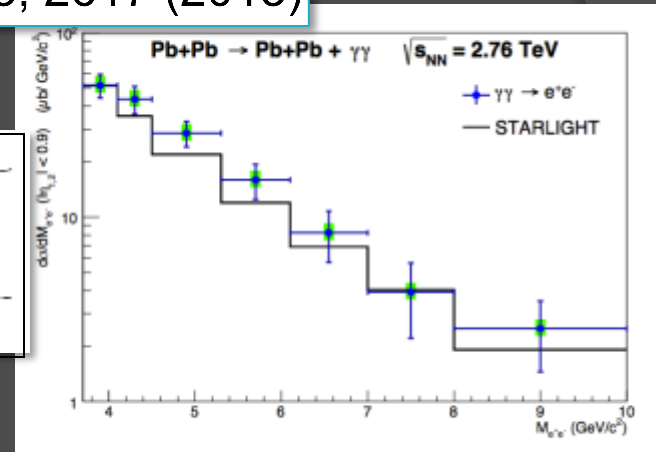


γγ cross section

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







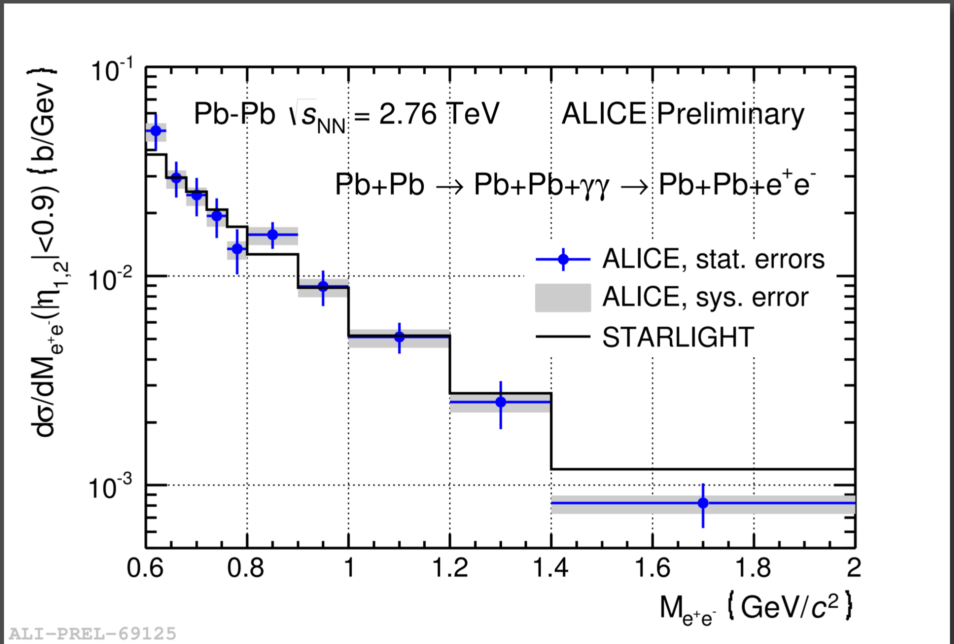
- ✓ the γγ cross section measurement provides important constraints on QED calculations when the vertex √α has to be replaced by Z√α
- ✓ due to the large Pb charge, giving Z√α ~ 0.6, the inclusion of higher order terms is not straightforward → the models* including higher order terms predict a reduction of the cross section up to 30%
  - ✧ [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)

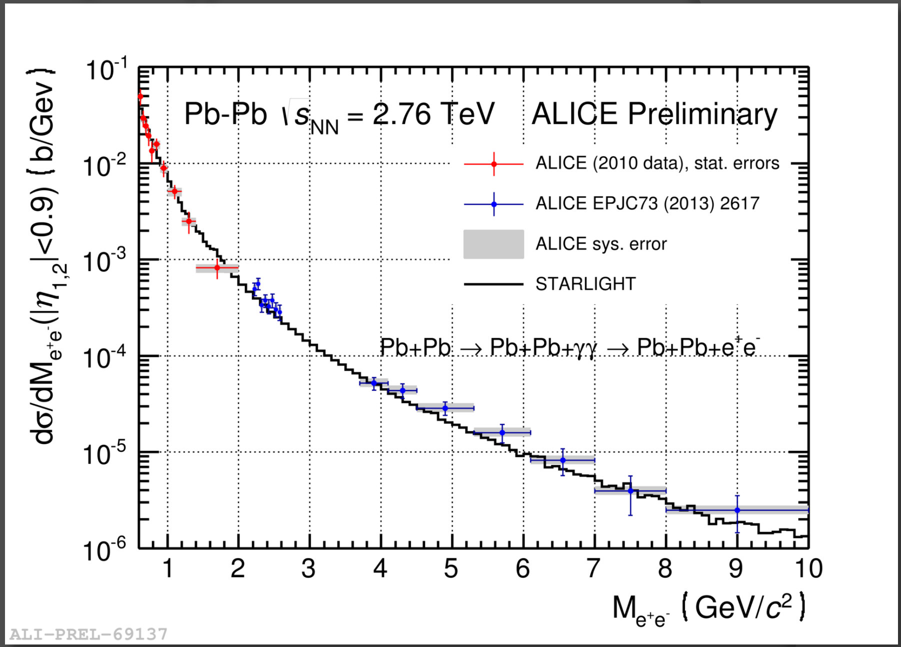
→ the models predicting a strong contribution of higher-order terms (not included in STARLIGHT) are not favored

*Baltz P*hys. 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

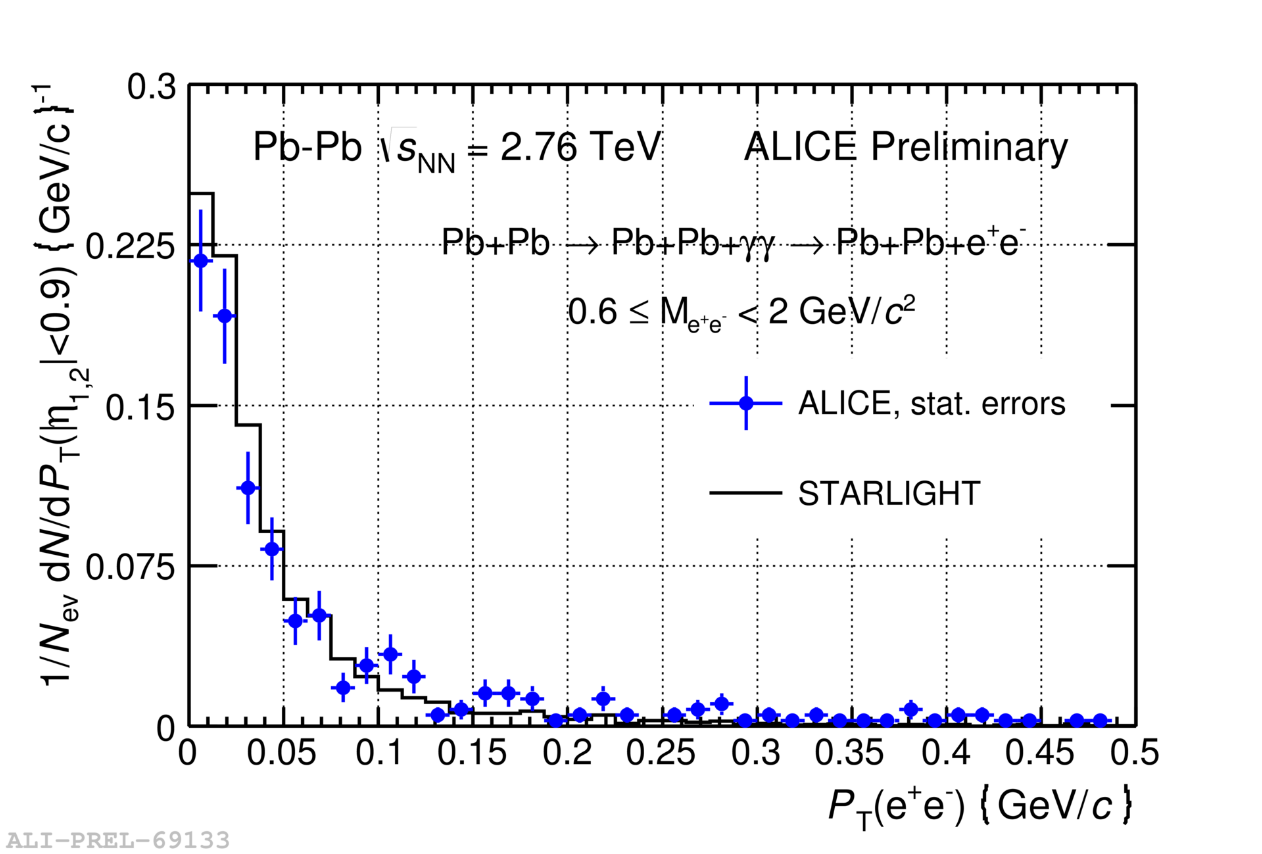




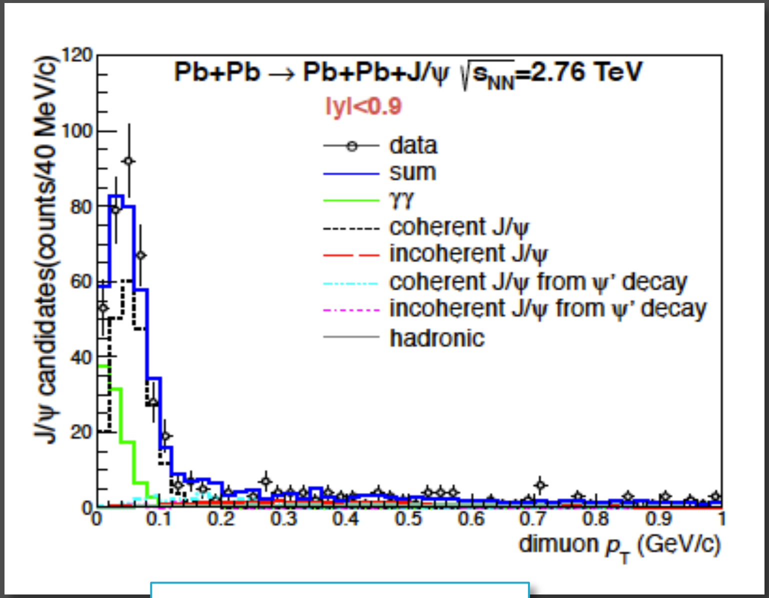
$\sigma(\|\eta_{1,2}\| \leq 0.9)$	data	STARLIGHT
(0.6 ≤ M_{ee} ≤ 2.0 GeV/c^2)	9.8 ± 0.6(stat) +0.9/-1.2(syst) mb	9.7 mb
(2.2 ≤ M_{ee} ≤ 2.6 GeV/c^2)	154 ± 11(stat) +17/-11(syst) μb	128 μb
(3.7 ≤ M_{ee} ≤ 10.0 GeV/c^2)	91 ± 10(stat) +11/-8(syst) μb	77 μb

γγ cross section

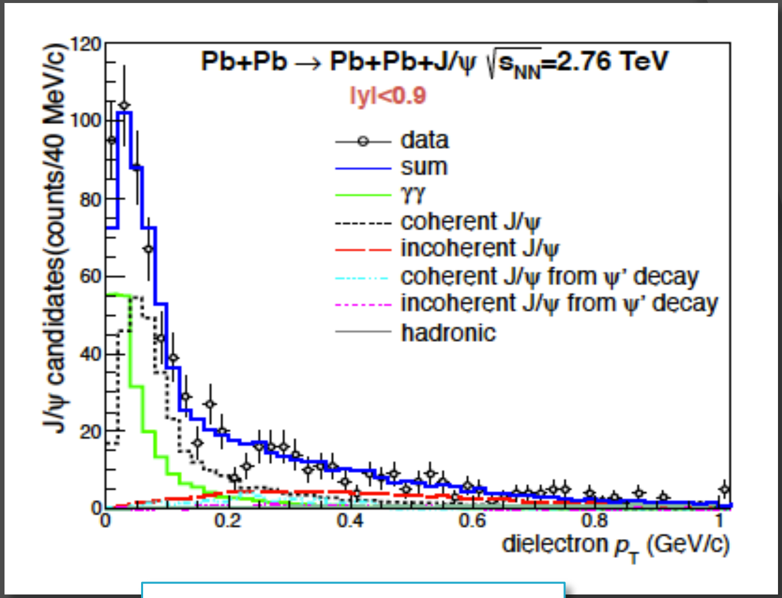
transverse momentum distribution well described by the Monte Carlo (STARLIGHT)



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

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

distribution peaked at low momentum as expected from coherent production

Feed down (ψ' → J/Ψ + anything)

- ✓ fraction f_D of J/Ψ coming from the decay of ψ'→ J/Ψ + anything estimated by simulating a sample of coherently produced ψ' with STARLIGHT, using PYTHIA to simulate their decay into J/Ψ

- ✓ contribution from incoherent ψ' expected to be negligible for the enriched coherent J/Ψ samples → not considered

- ✓ ψ' polarization can be shared between J/Ψ and the other daughters → ψ' decay simulated assuming no polarization, full transverse and full longitudinal polarization for the J/Ψ

for a given polarization P:

$$f_D^P = \frac{\sigma_{\psi'} \cdot BR(\psi' \to J/\psi + \text{anything}) \cdot (\text{Acc} \times \varepsilon)^P_{\psi' \to J/\psi}}{\sigma_{J/\psi} \cdot (\text{Acc} \times \varepsilon)_{J/\psi}}$$

see table in the next slide for the results

Feed down ($\psi' \rightarrow J/\Psi$ + anything)

alternatively the ratio ψ' over J/Ψ, used to compute the feed-down f_D, can be extracted from the data

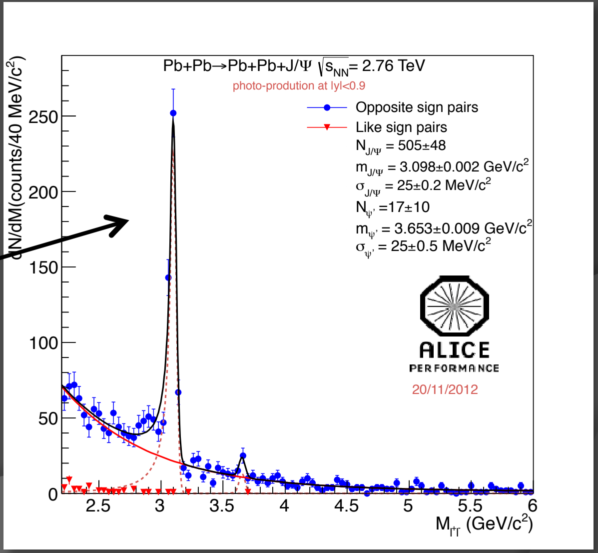
due to the limited statistics the two decay channels were combined:

$N_{\psi'} = 17 \pm 10$ and $N_{J/\psi} = 505 \pm 48$

$$f_D^P = \frac{N_{\psi'} \cdot BR(J/\psi \rightarrow l^+l^-) \cdot BR(\psi' \rightarrow J/\psi + \text{anything}) \cdot (\text{Acc} \times \varepsilon)^P_{\psi' \rightarrow J/\psi}}{N_{J/\psi} \cdot BR(\psi' \rightarrow l^+l^-)(\text{Acc} \times \varepsilon)^P_{\psi' \rightarrow l^+l^-}}$$

→ f_D ranges from 11.0±6.5% for transverse ψ' polarization to 15±9% for longitudinal ψ' polarization

the average of these estimates is $f_D = 0.10^{+0.05}_{-0.06}$

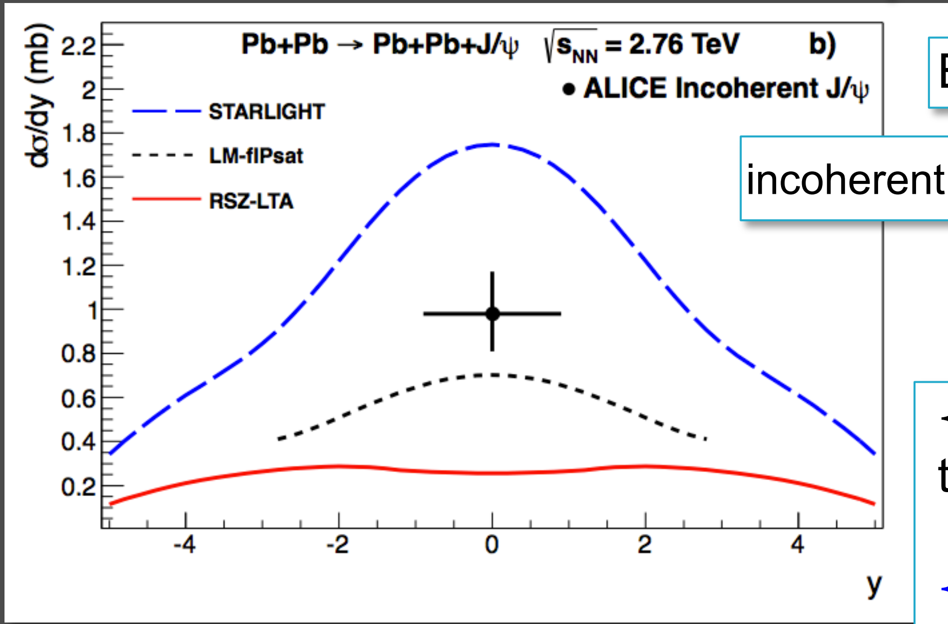


invariant mass distribution for combined dimuon and dielectron channels

Fit procedure

- ✓ exponential for underlying continuum (systematics evaluated using polynomial)
- ✓ Crystall Ball (exp+gauss) to extract the J/Ψ signal
- ✓ tail CB parameters (α and n) left free for the coherent sample (systematics evaluated fixing the paramters) and fixed to MC values for the incoherent one
- ✓ incoherent dimuons fitted also using a polynomial to take into account the combinatorial background, as constrained to the LS pair spectrum
- ✓ fit also constrained to a MC cocktail (J/Ψ + $\gamma\gamma$)

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

the ratio $\sigma_{inc}/\sigma_{coh}$ provides further constraints on the treatment of the nuclear modifications implemented in the different models