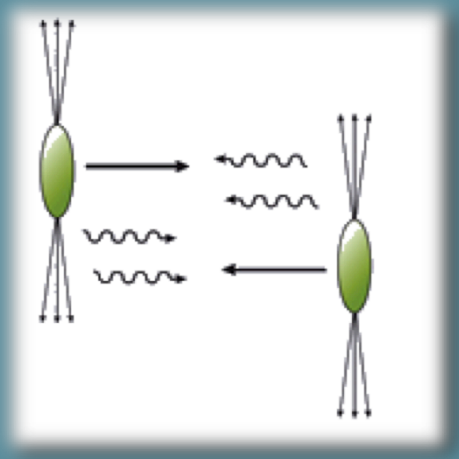


The 2nd International Conference on the Initial Stages in High-Energy Nuclear Collisions

IS2014

December 3rd - 7th
Napa, CA
Embassy Suites Napa Valley

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

D. De Gruttola* for the ALICE Collaboration

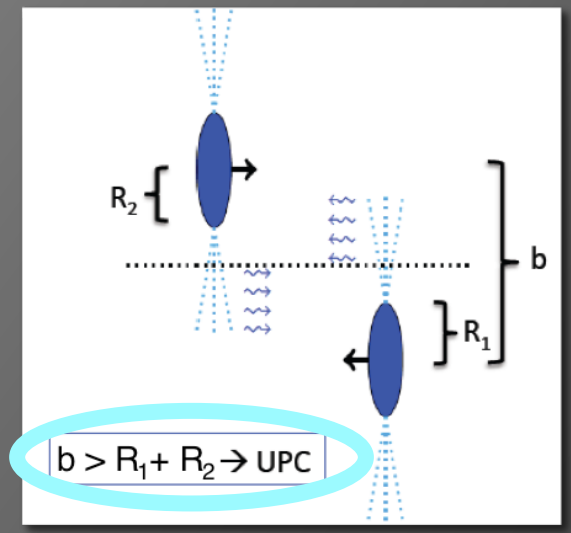
*Centro Fermi Roma and Salerno INFN - Italy

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)
- ✓J/ψ and ψ(2S) cross section (forward and mid-rapidity)
- ✓results and comparison with models (gluon shadowing)
- ✓$\gamma\gamma$ cross section (constraint on QED processes)
- ✓conclusions

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 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:

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

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

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

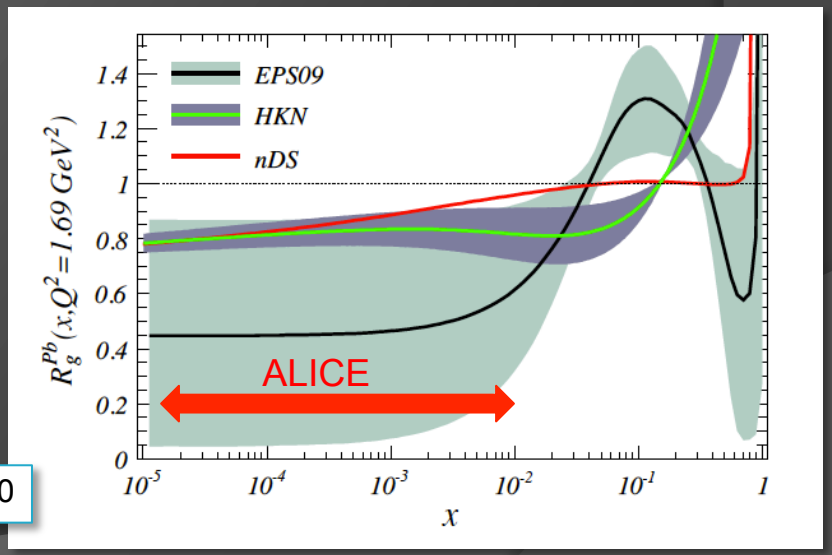
Physics motivation

- ✓ quarkonia 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

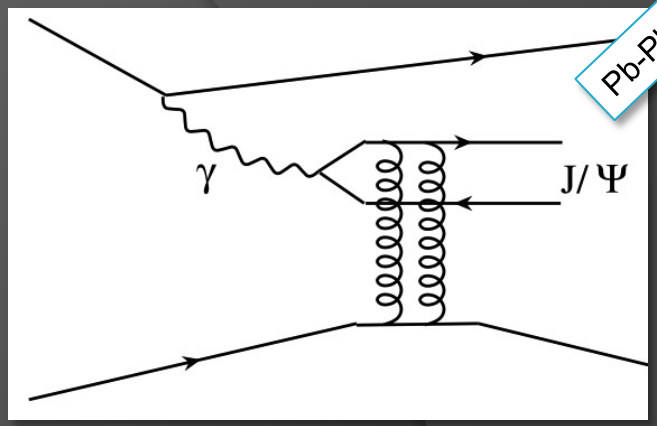
$$R_g^A(x,Q^2) = \frac{G_A(x,Q^2)}{G_p(x,Q^2)}$$



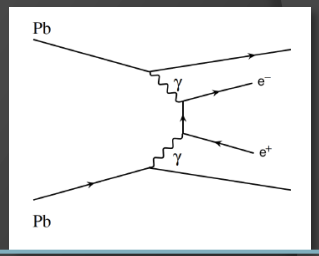
C A Salgado *et al* 2012 *J. Phys. G.: Nucl. Part. Phys.* **39** 015010

Physics motivation

- ✓ coherent vector meson production:
  - ✧ photon couples coherently to all nucleons
  - ✧ $\langle p_T \rangle \sim 1/R_{Pb} \sim 60$ 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



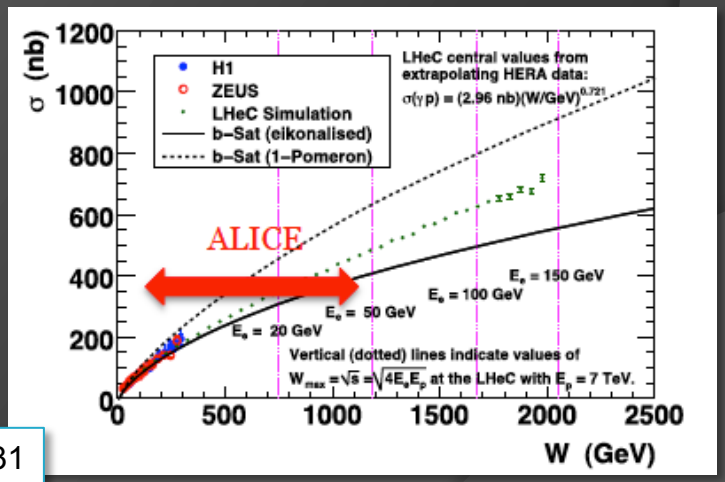
- ✓ an interesting physics case is also γγ interactions to provide informations on QED processes when the vertex $\sqrt{\alpha}$ is replaced by $Z\sqrt{\alpha}$



Pb-Pb

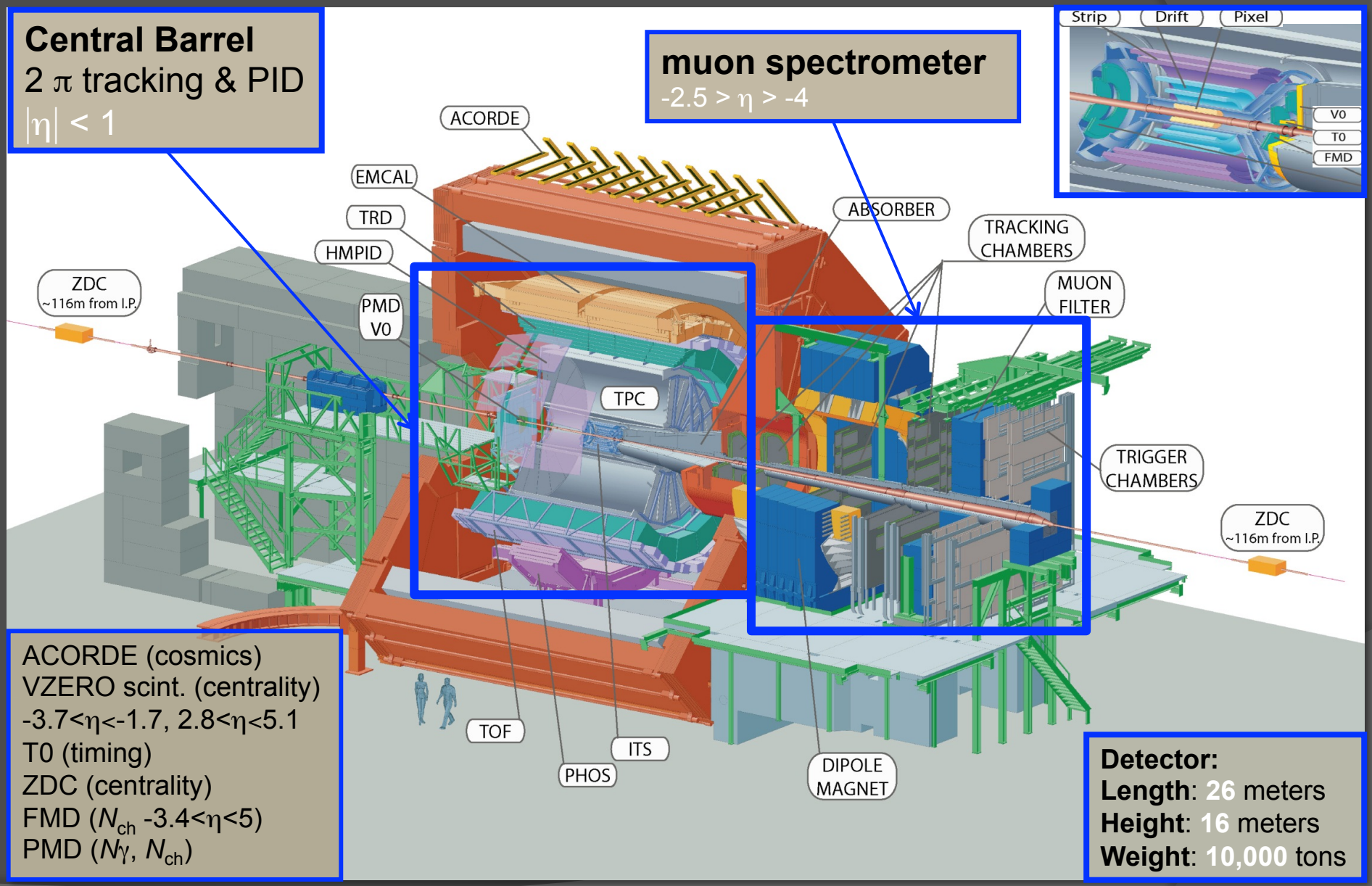
γp cms energy $W_{\gamma p}$ beyond previous experiments (talk by E. Scapparone)

p-Pb



LHeC Study group ArXiv: 1211.4831

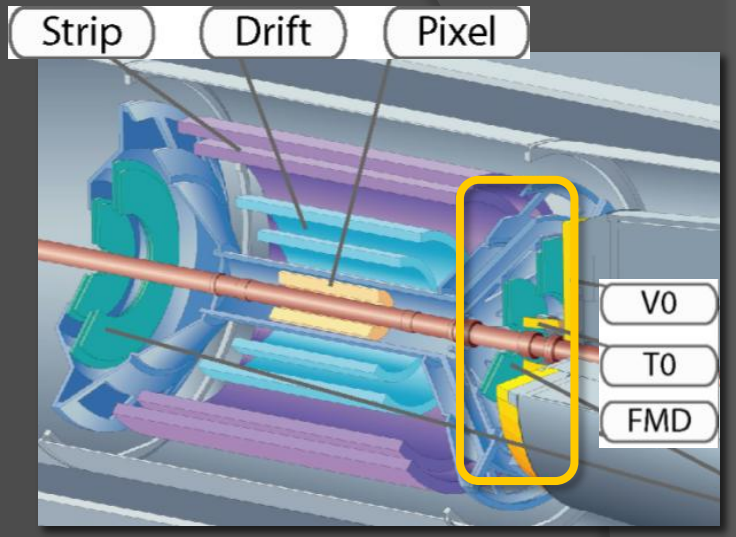
ALICE layout

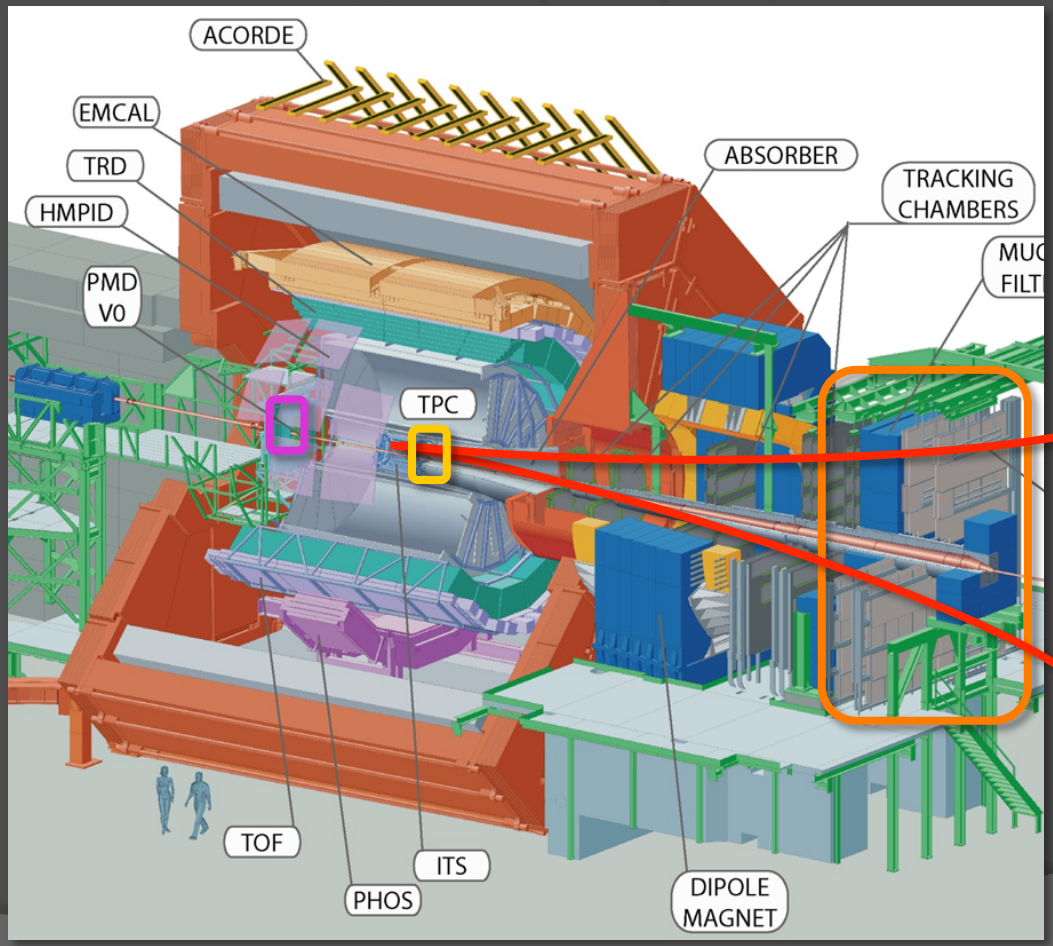


ALICE and UPCs ($J/\psi \rightarrow \mu^+\mu^-$)

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

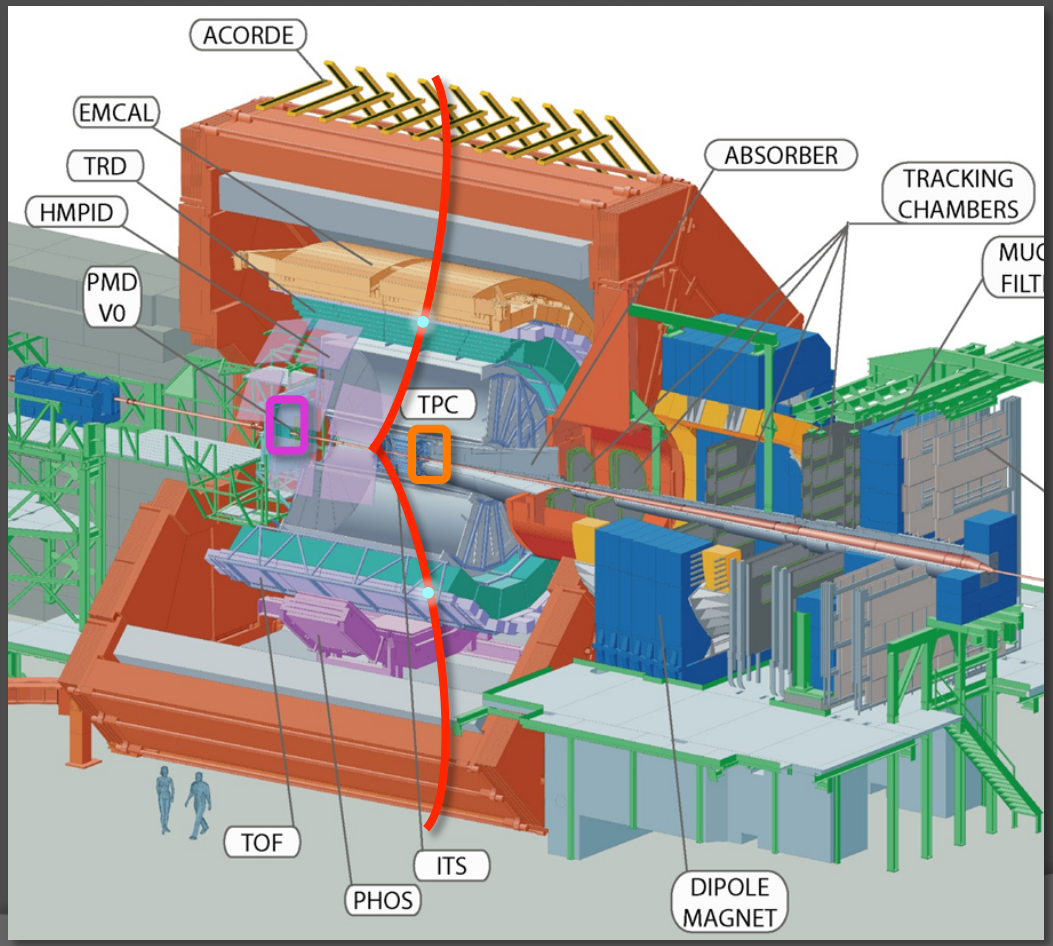
✓ track selection:

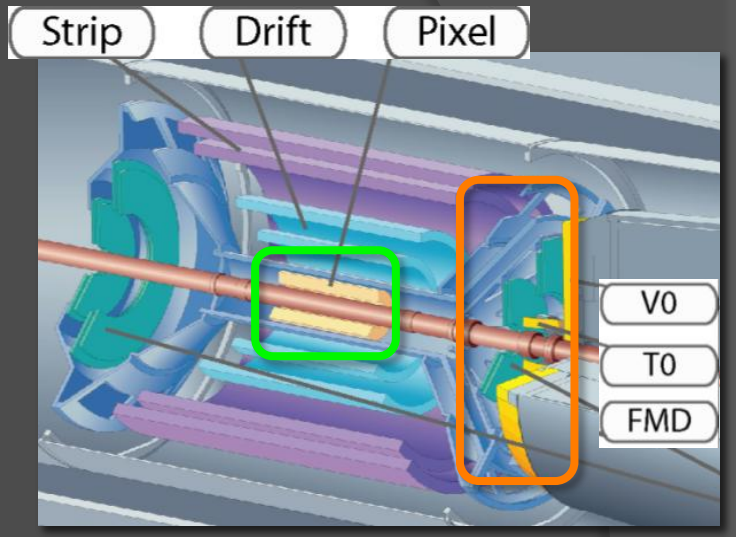
- ✧ muon tracks: $-3.7 < \eta < -2.5$
- ✧ matching with the trigger
- ✧ radial position for muons at the end of absorber: $17.5 < R_{abs} < 89.5$ cm
- ✧ p_T dependent DCA cut
- ✧ opposite sign dimuon: $-3.6 < y < -2.6$

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



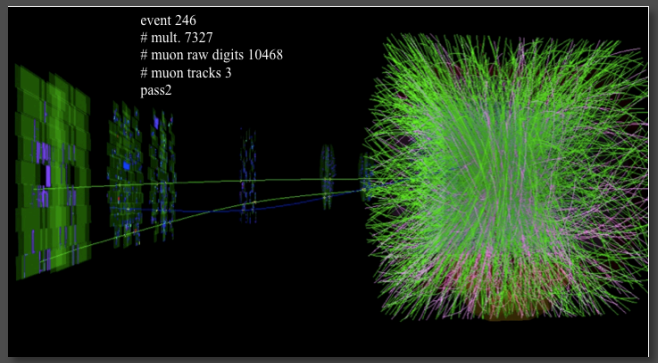


integrated luminosity ~ 23 μb^{-1}

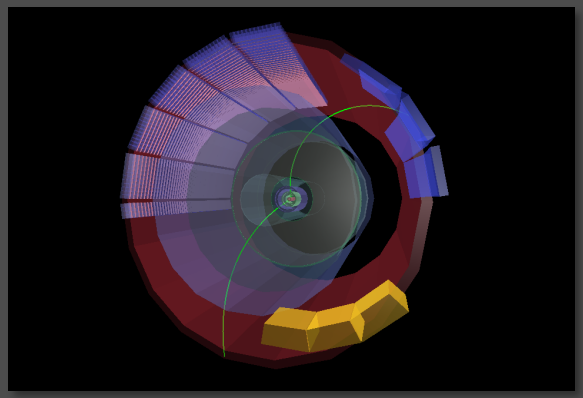
✓ offline event selection:

- 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

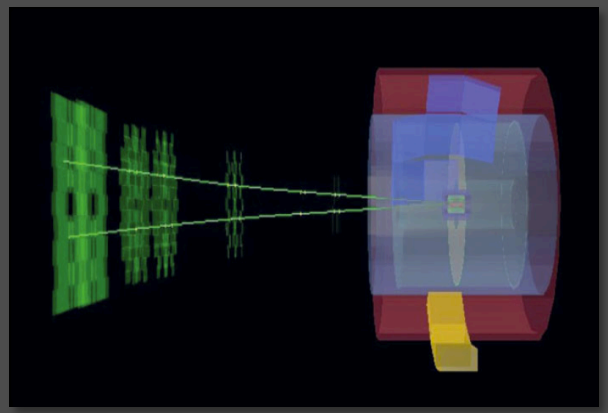
ALICE and Ultra-Peripheral Collisions



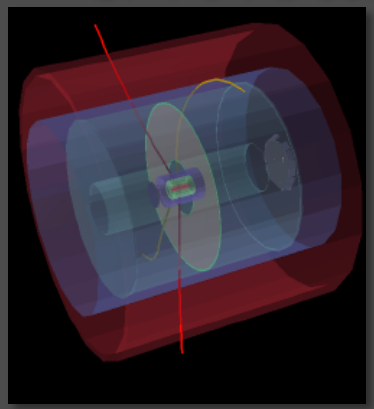
central Pb-Pb collision

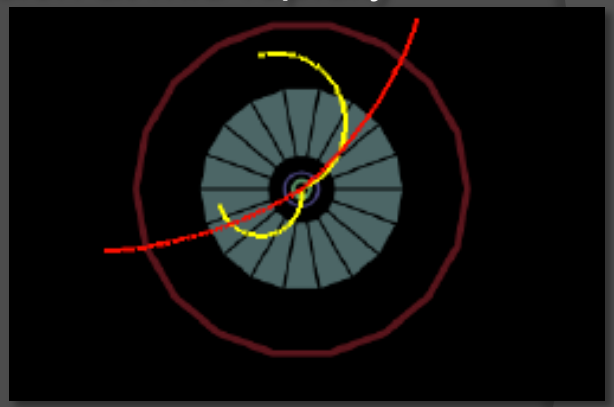


UP Pb-Pb collision at mid-rapidity



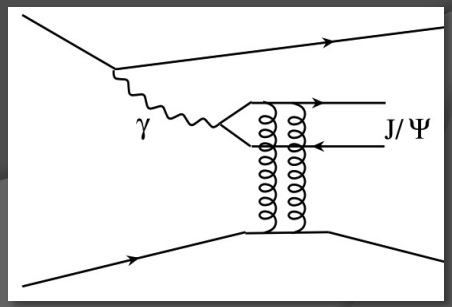
UP Pb-Pb collision at forward rapidity



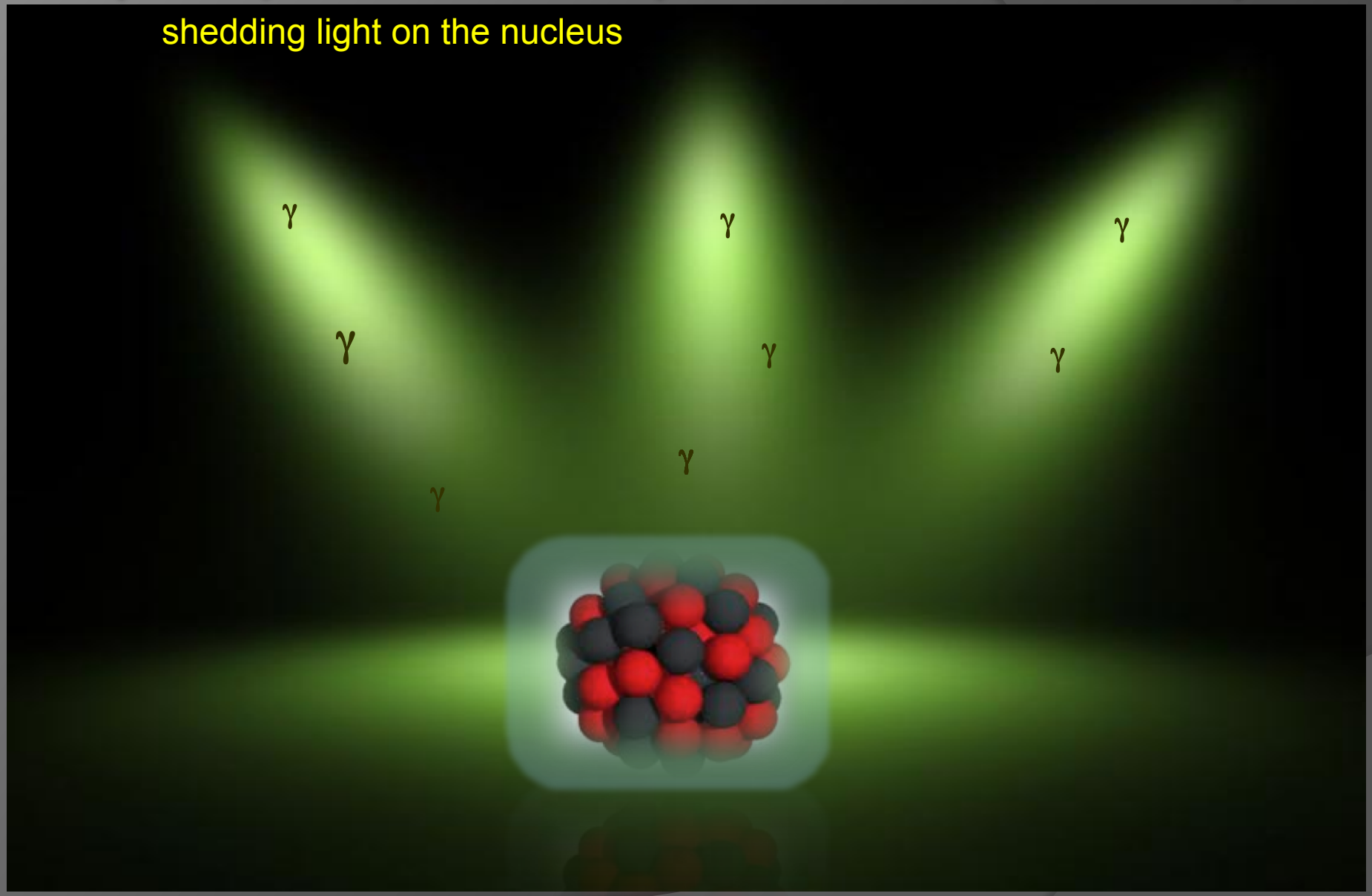


2 (or 4) tracks in an otherwise empty detector

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



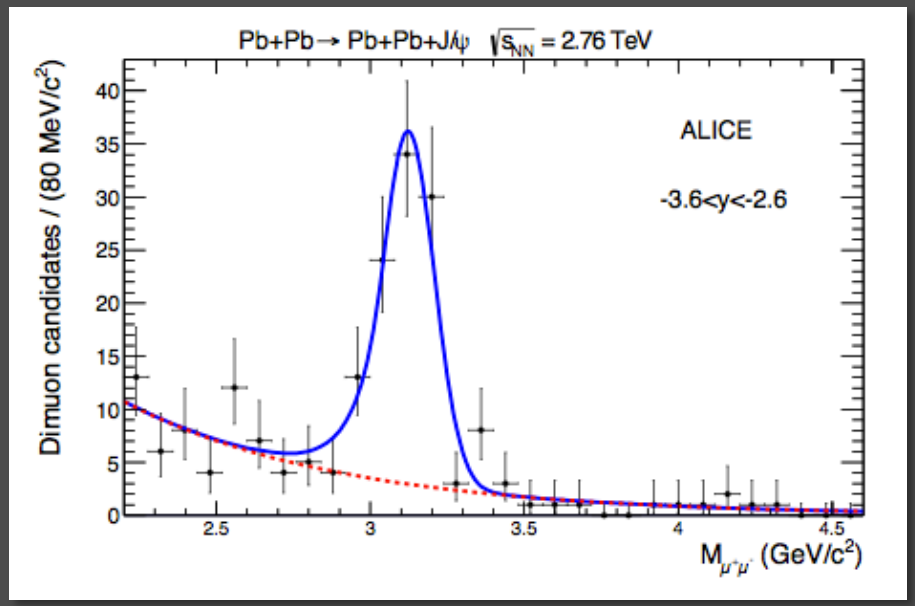
γPb processes (Pb-Pb collisions)

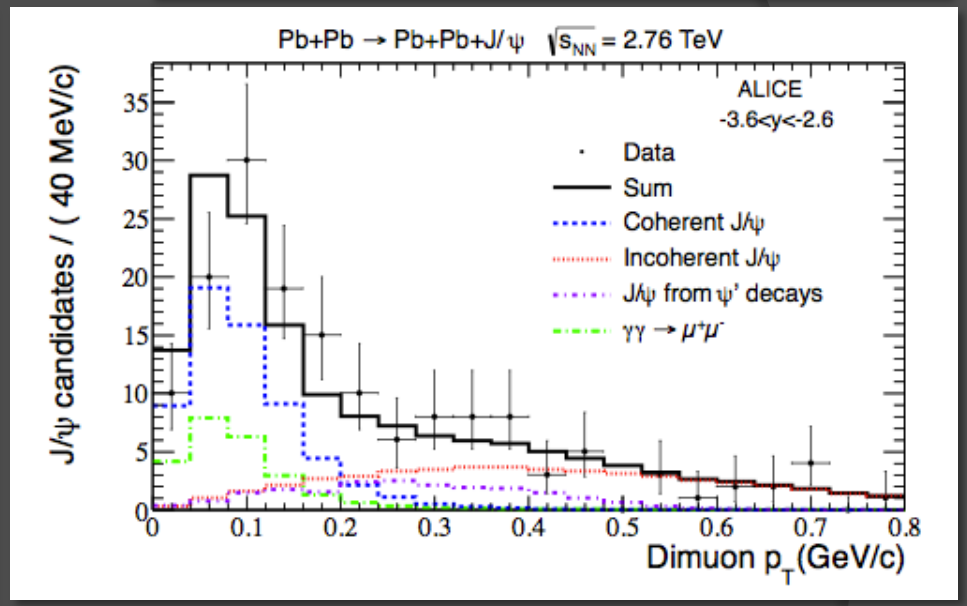


J/ψ measurement (coherent at forward rapidity)

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
- ✧ $\gamma\gamma \rightarrow \mu^+\mu^-$

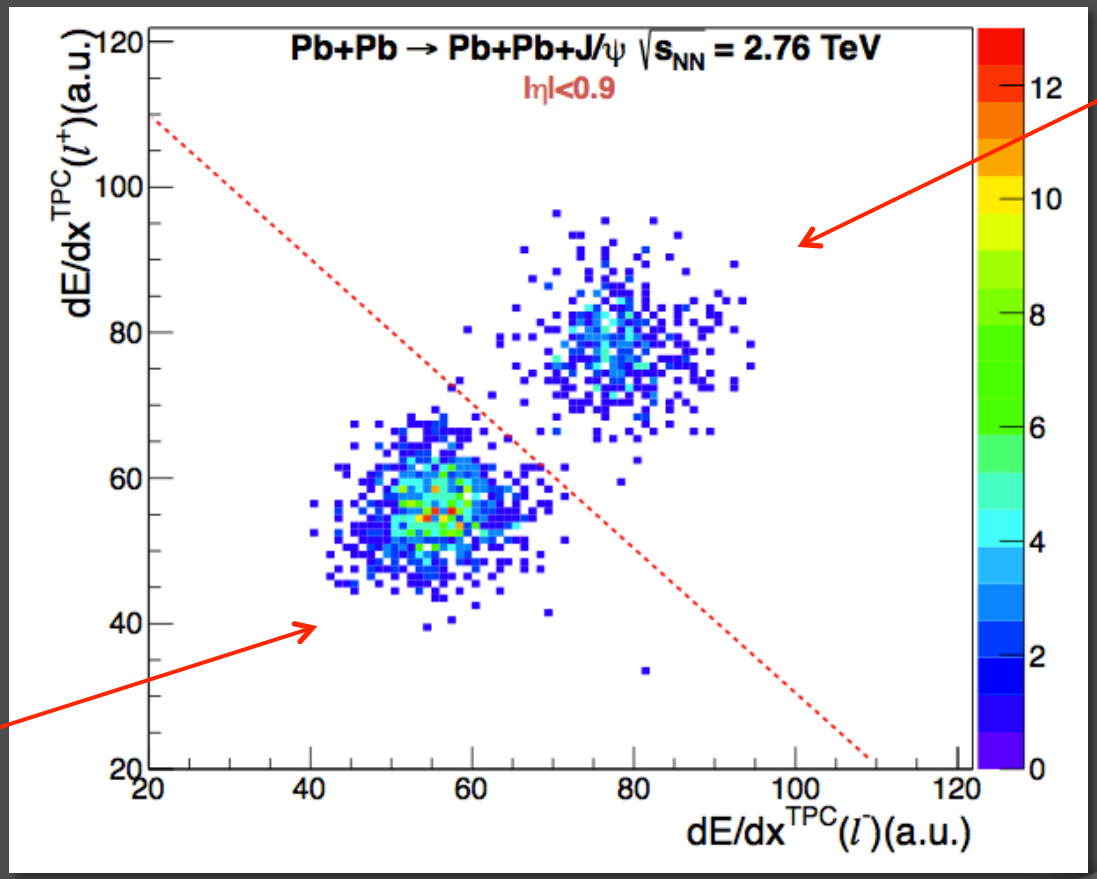
distribution peaked at low momentum as expected from coherent production

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

J/ψ measurement (mid-rapidity)

✧ Eur. J. Phys. C73, 2617 (2013)

electrons



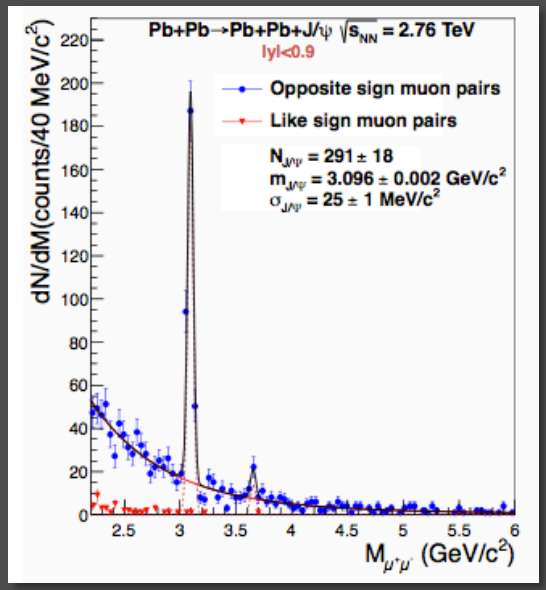
muons

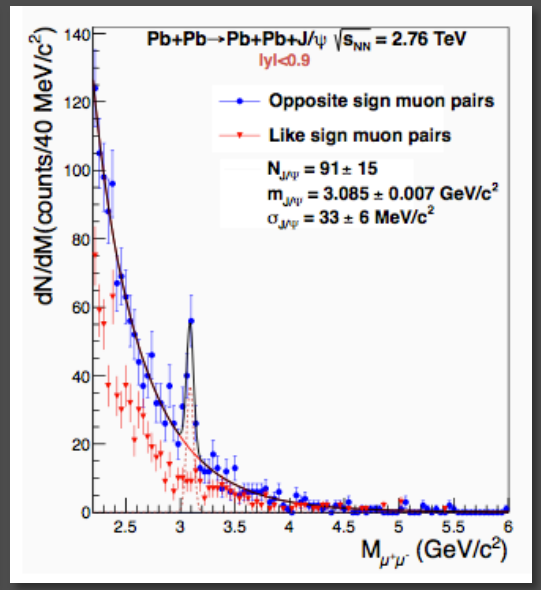
decay channels separation by looking at the dE/dx in TPC

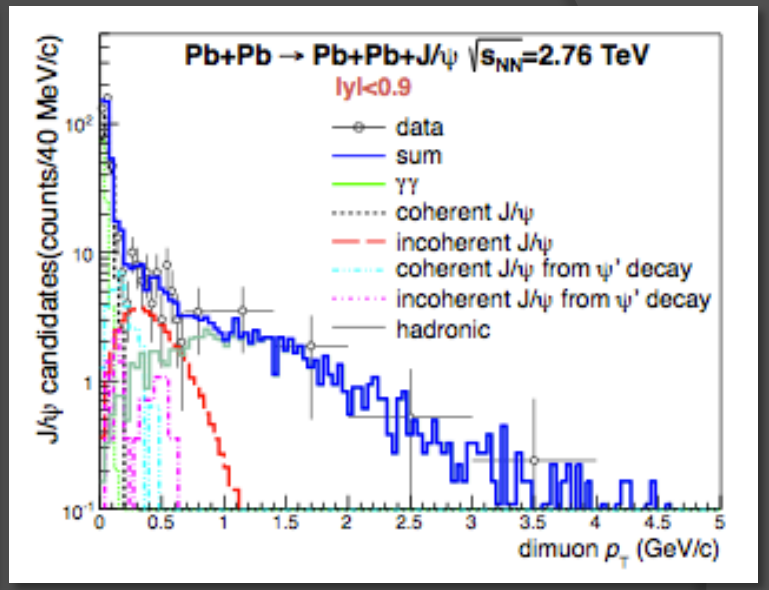
J/ψ measurement (coherent and incoherent at mid-rapidity)

dimuon channel

✧ Eur. J. Phys. C73, 2617 (2013)







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

p_T < 200 MeV/c and < 6 neutrons emitted by nuclei to separate coherent from incoherent production

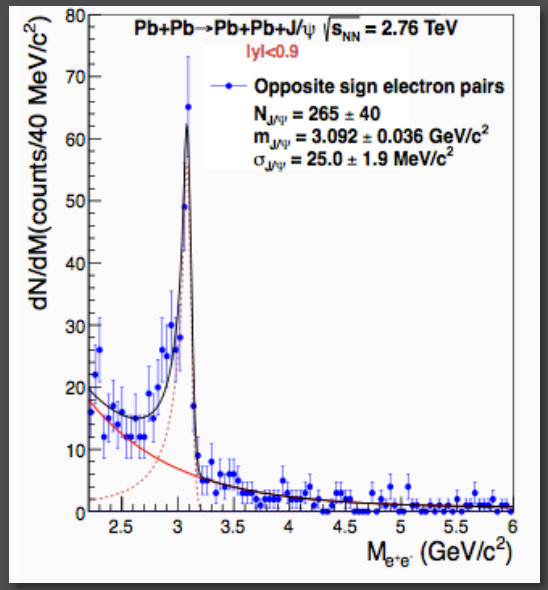
distribution peaked at low momentum as expected from coherent production

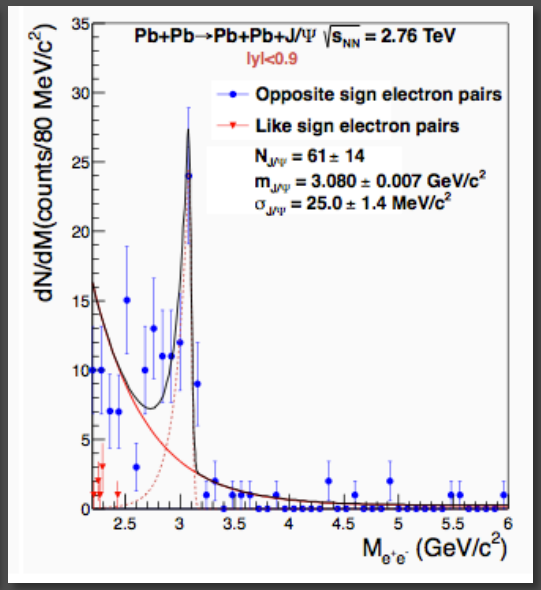
- J/ψ photo-production probes the gluon distribution in Pb at $x \sim 10^{-3}$
- incoherent processes provide further constraints on the different models

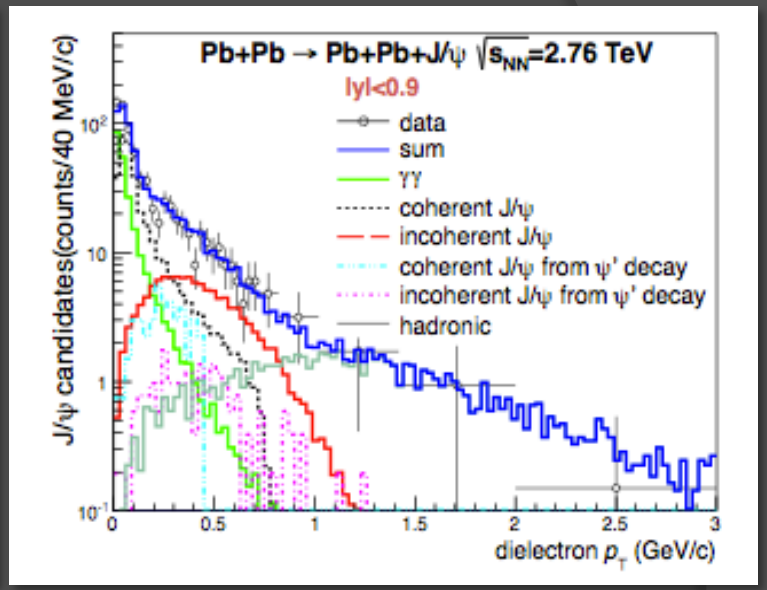
J/ψ measurement (coherent and incoherent at mid-rapidity)

dielectron channel

✧ Eur. J. Phys. C73, 2617 (2013)







p_T distribution fitted using MC samples representing several components:

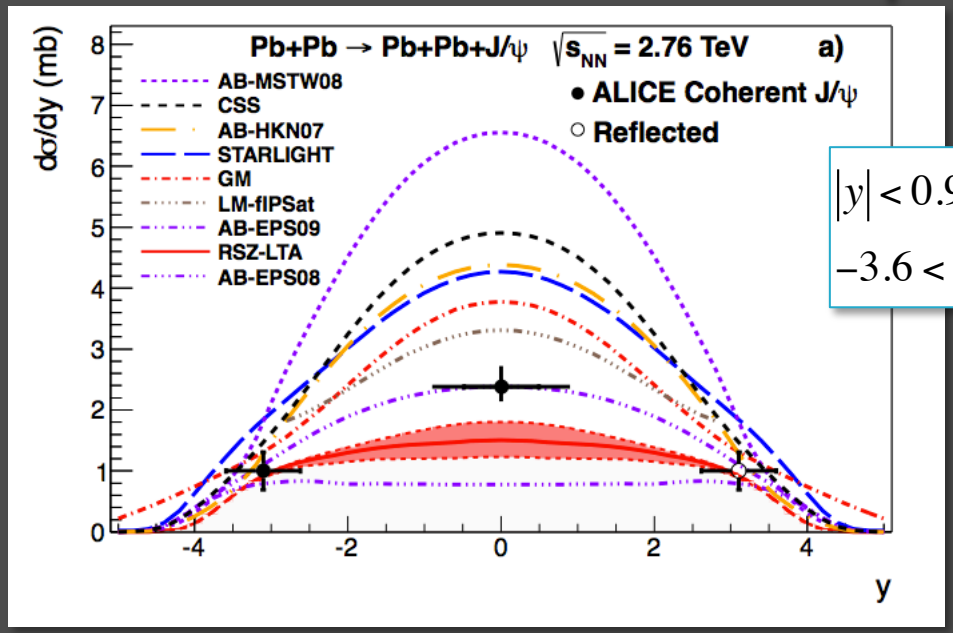
- ✧ coherent and incoherent J/ψ
- ✧ (coherent and incoherent) ψ' feed down
- ✧ $\gamma\gamma \rightarrow e^+e^-$
- ✧ hadronic

p_T < 300 MeV/c and < 6 neutrons emitted by nuclei to separate coherent from incoherent production

distribution peaked at low momentum as expected from coherent production

- ○ J/ψ photo-production probes the gluon distribution in Pb at $x \sim 10^{-3}$
- ○ incoherent processes provide further constraints on the different models

Results and comparison with models



Phys. Lett. B718 (2013) 1273 -1283

✧ Eur. J. Phys. C73, 2617 (2013)

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

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

data are closer to models incorporating nuclear gluon shadowing

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

✓ 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

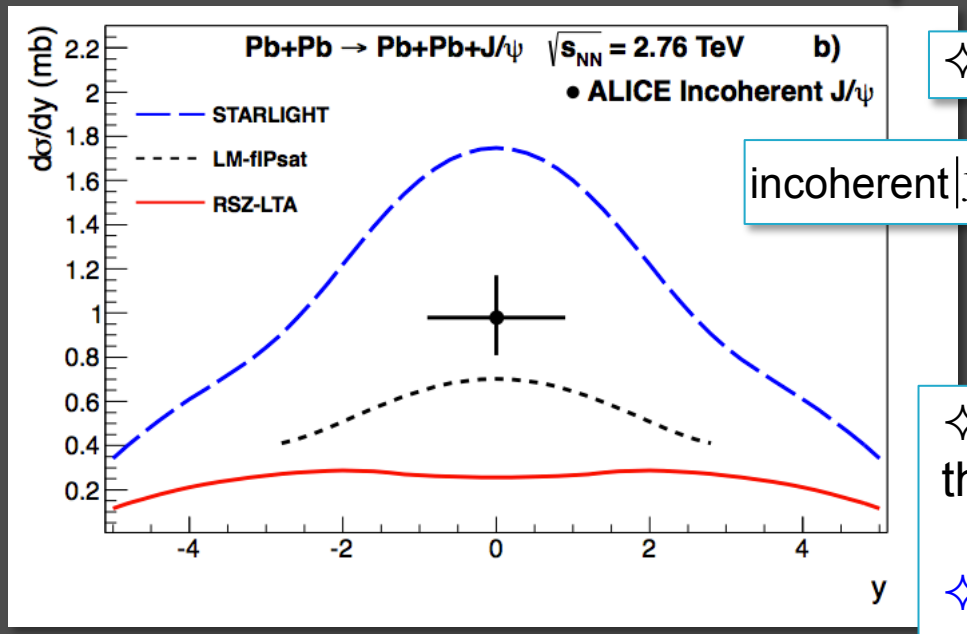
✓ CSS: Cisek, Szczurek, Sch.fer PRC86 (2012) 014905
color dipole model based on unintegrated gluon distribution of the proton

✓ 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

✓ 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

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

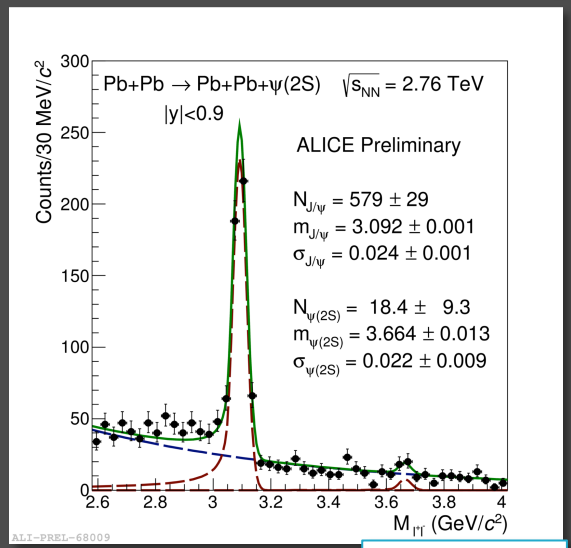
✓ RSZ: Rebyakova, Strikman, Zhalov, PLB 710 (2012) 252
based on LO pQCD amplitude for two gluon exchange where the gluon density incorporates shadowing computed in leading twist approximation

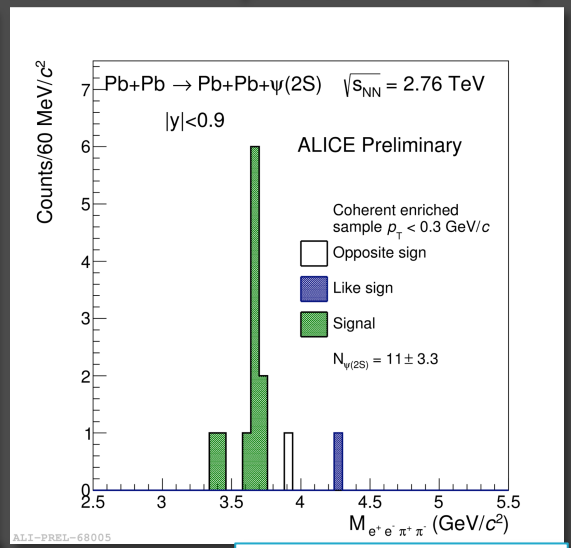
✓ LM: Lappi, Mantysaari, PRC87 (2013) 032201
color dipole model based with Glauber approach and a saturation prescription

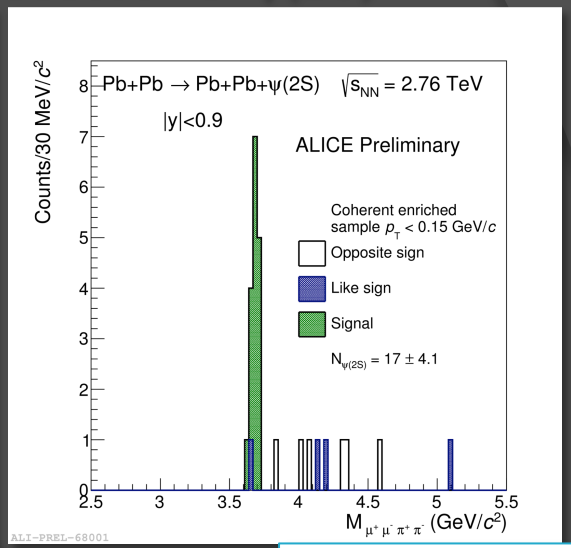
incoherent processes provide further constraints on the treatment of the nuclear modifications implemented in the different models

ψ(2S) measurements (mid-rapidity)

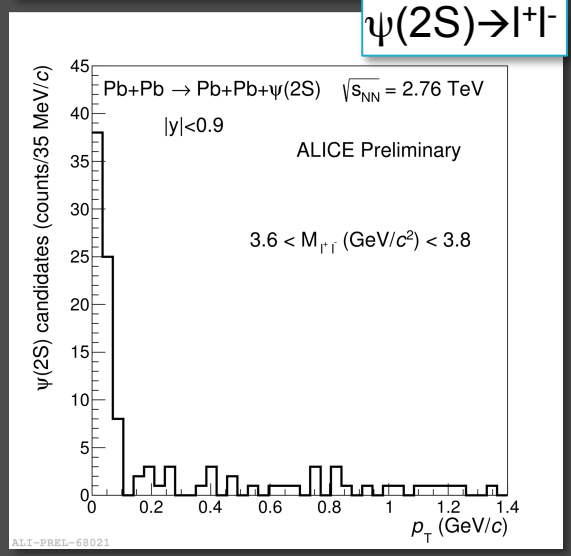
first exclusive photonuclear production of ψ(2S)



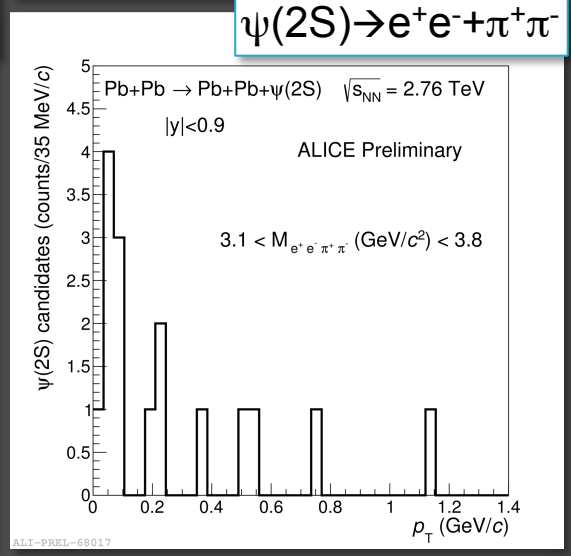




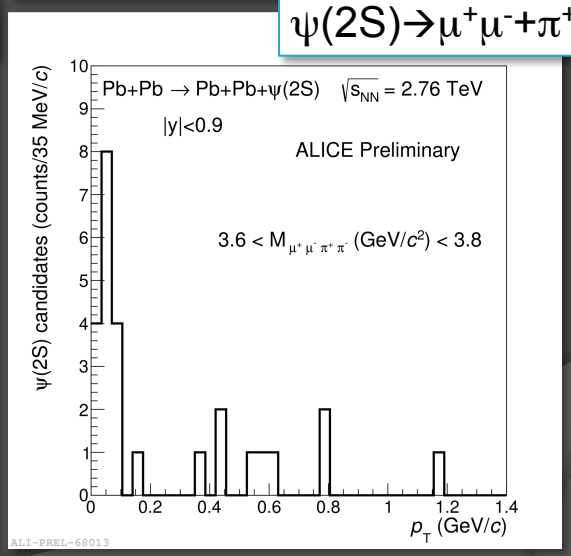
ψ(2S)→l⁺l⁻



ψ(2S)→e⁺e⁻+π⁺π⁻



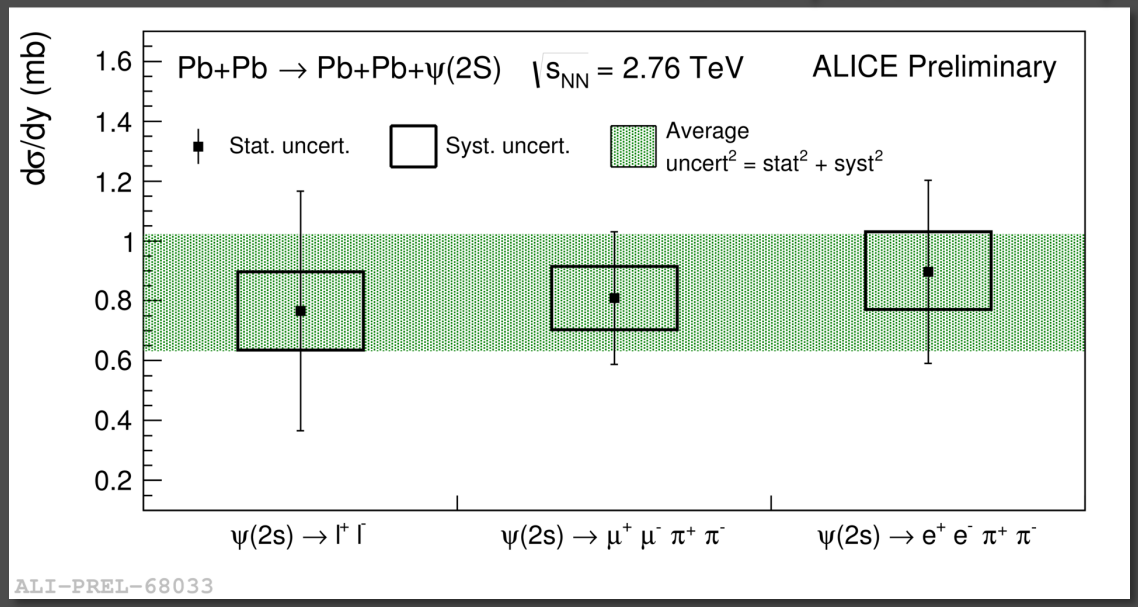
ψ(2S)→μ⁺μ⁻+π⁺π⁻



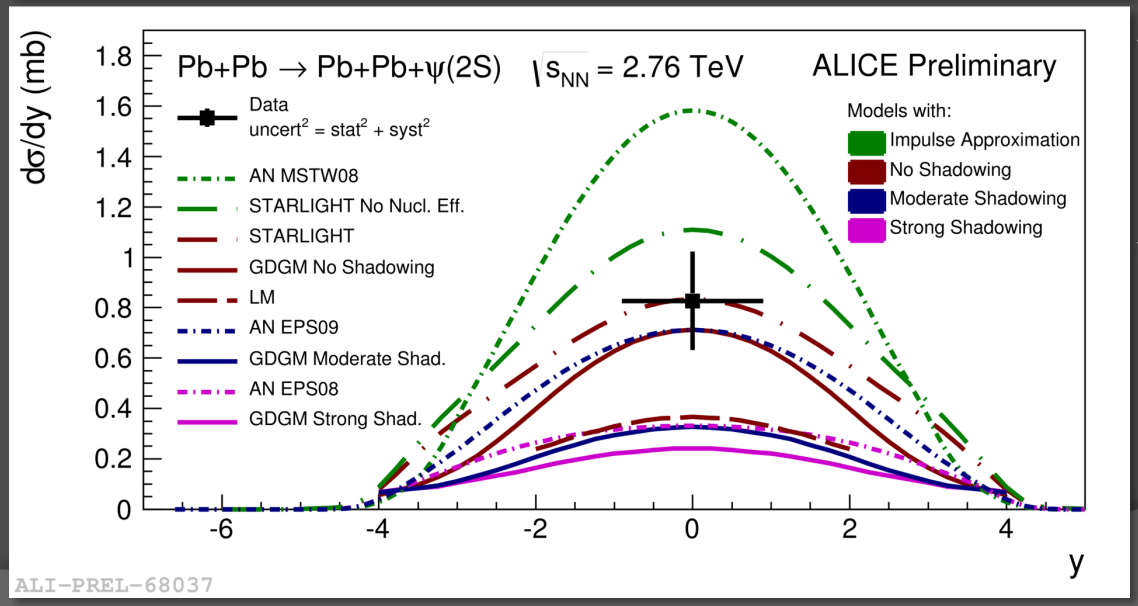
- ✓ clear coherent contribution at very low p_T
- ✓ moderate number of candidates in 4-lepton channels, but very clear signal

ψ'/ψ ratio

first exclusive photonuclear production of ψ(2S)

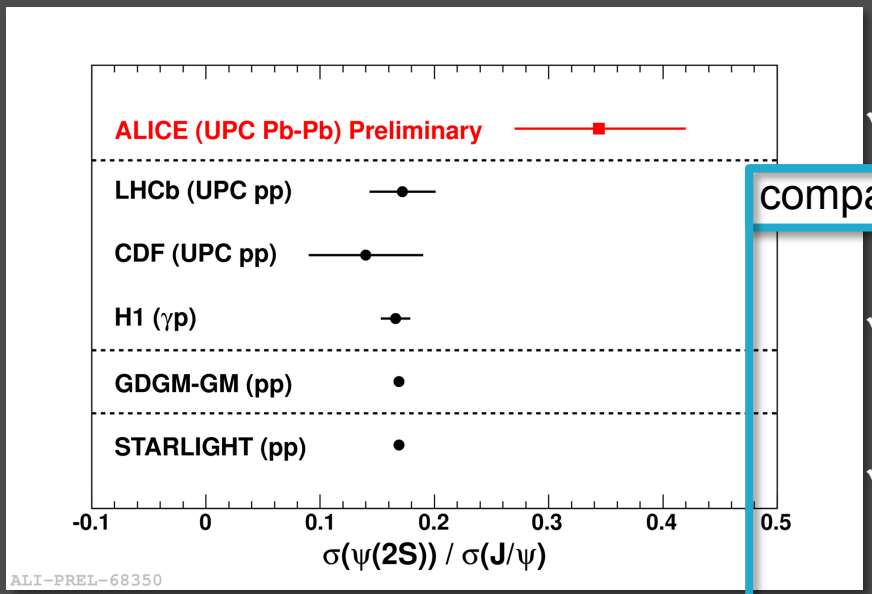


$$\frac{d\sigma}{dy} = 0.83 \pm 0.19 \text{ (stat+syst) mb}$$



- ✓ 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)

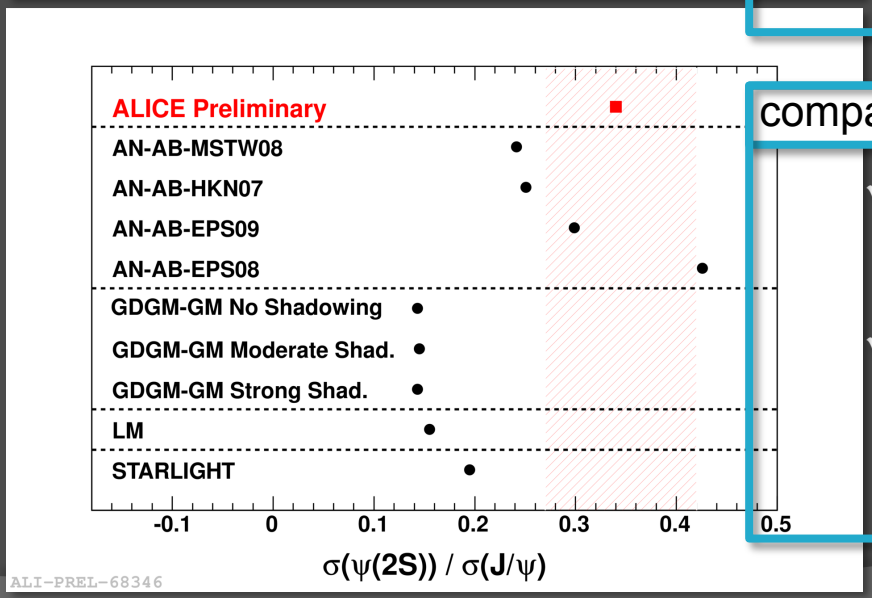
ψ'/ψ ratio



- ✓ 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

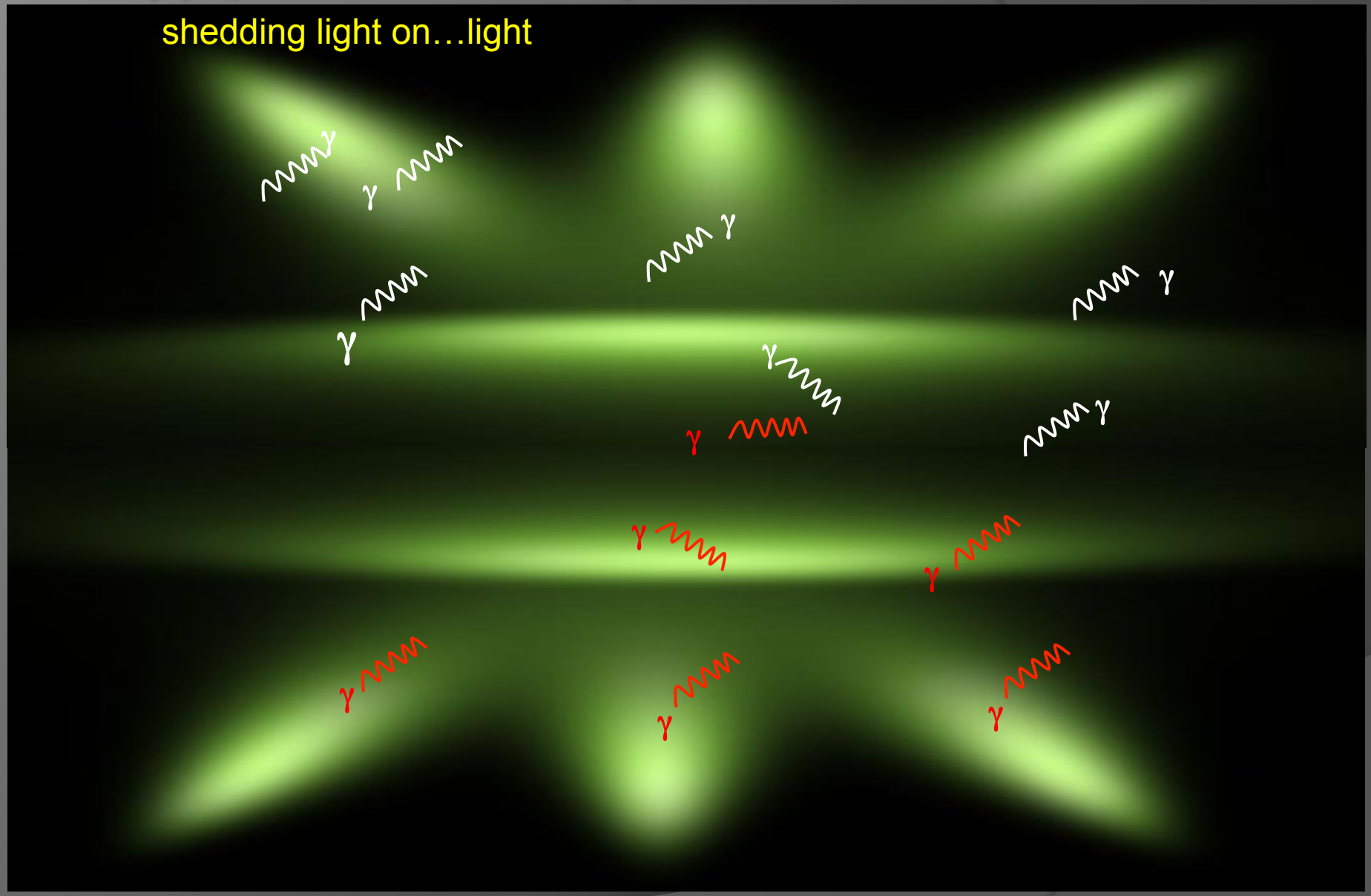
- ✓ change of R from pp to Pb-Pb may indicate that nuclear effects affect 1S and 2S states differently
- ✓ models predict the ratio for pp correctly



comparison with Pb-Pb models

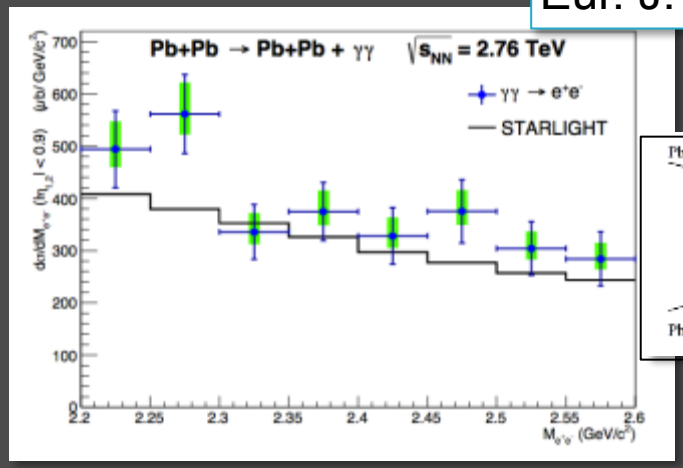
- ✓ the same models that reproduced correctly the pp ratio, fail in describing the Pb-Pb ratio
- ✓ the AN EPS09 model describes in a satisfactory way this ratio (although it assumes the same functional form for J/ψ and ψ(2S))

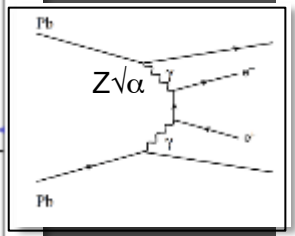
γγ processes (Pb-Pb collisions)

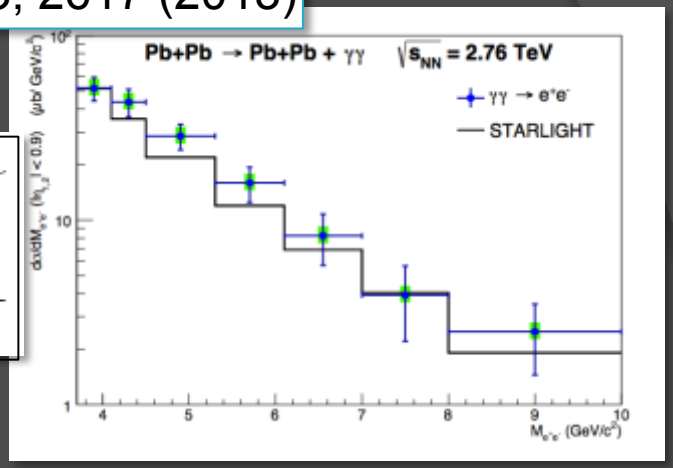


γγ cross section

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







- ✓ the γγ cross section measurement provides important constraints on QED calculations when the vertex $\sqrt{\alpha}$ 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%

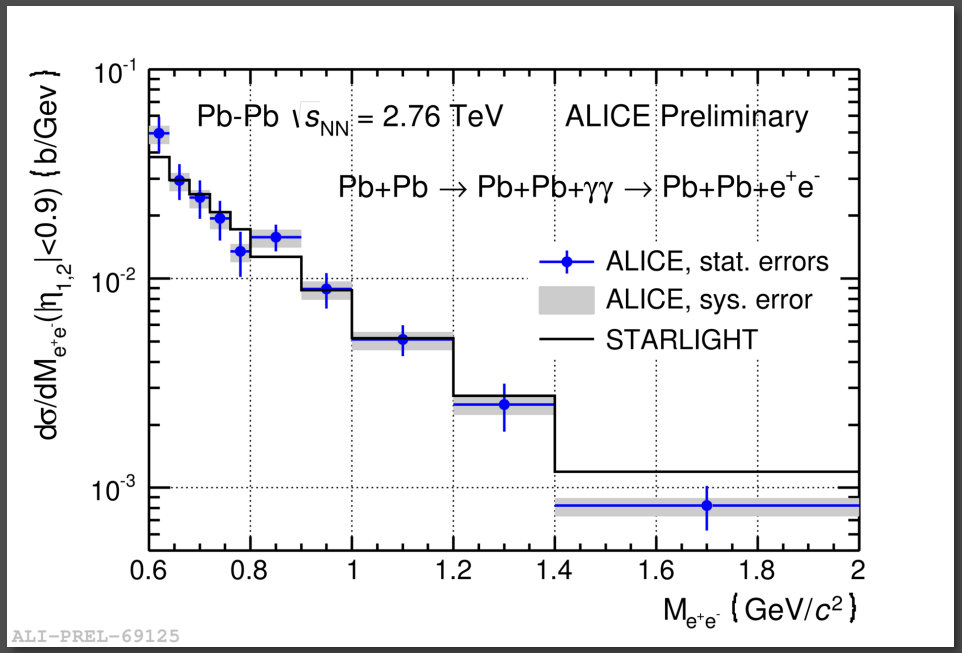
- ✓ the measured values for the γγ cross sections are 20% above but fully compatible within 1.0 σ and 1.5 σ with the STARLIGHT (LO) prediction for the low and high invariant mass intervals (128 μb and 77 μb)

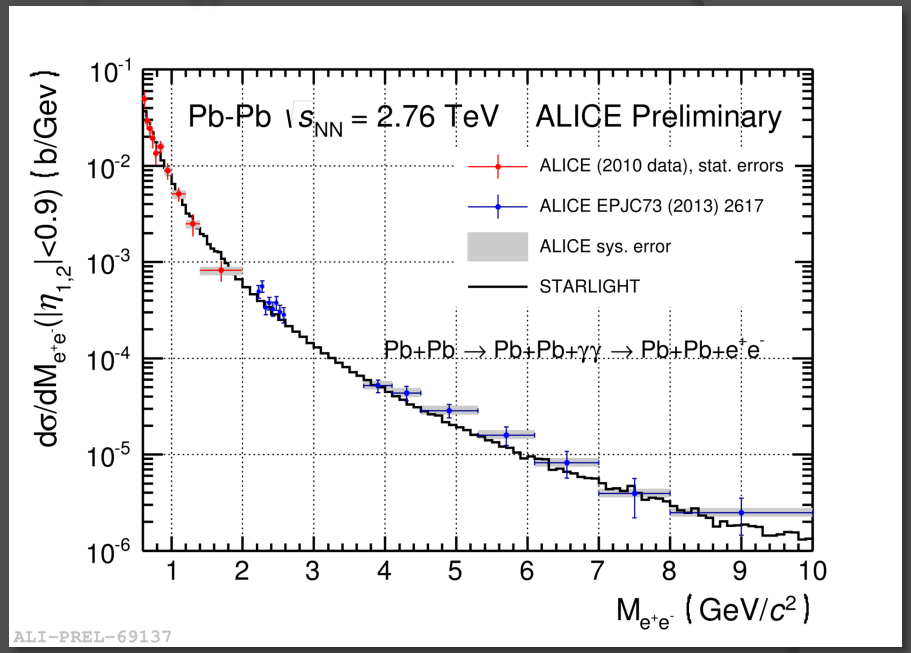
→ the models predicting a strong contribution of higher-order terms (not included in STARLIGHT) are not favored

*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

Conclusions

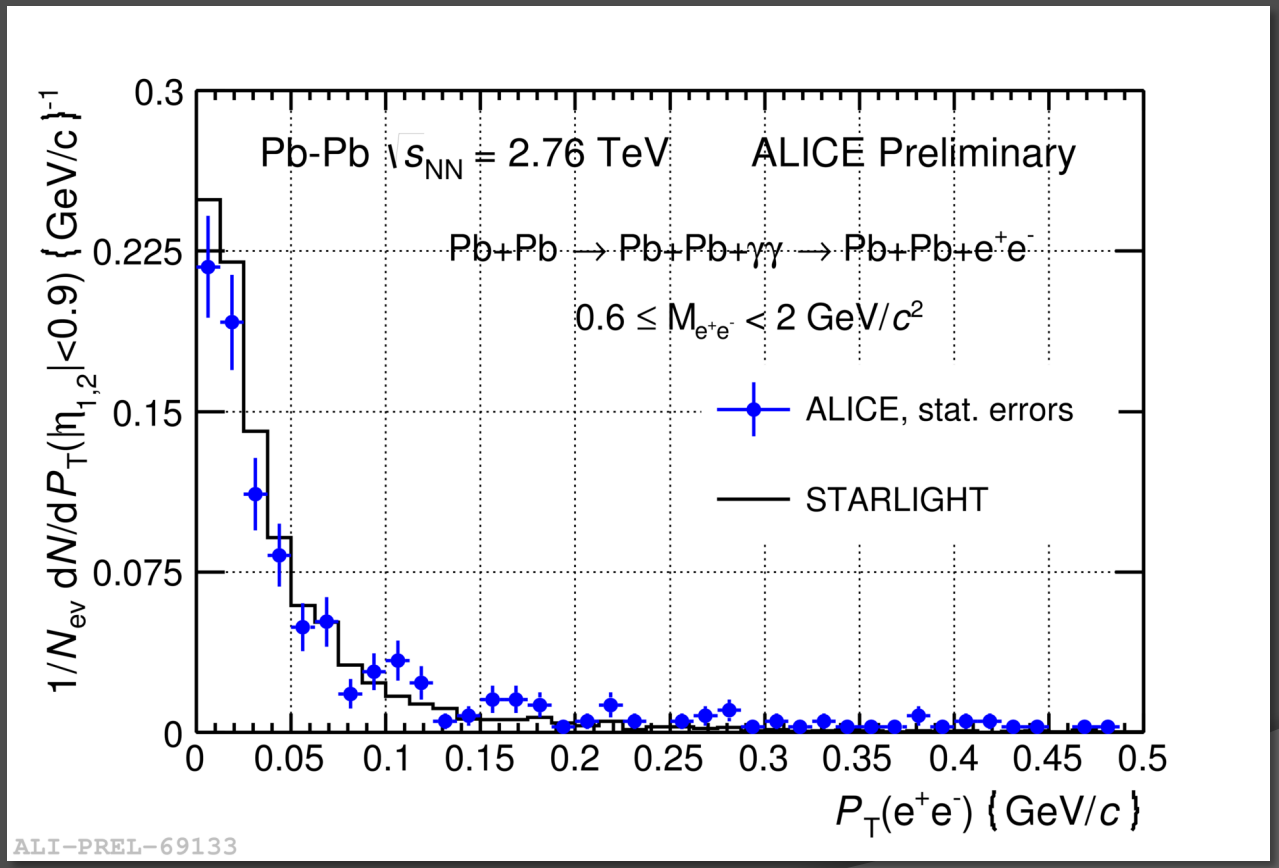
LHC as γPb, γp and $\gamma\gamma$ collider to study:

- ✓ (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' vector meson photoproduction measured
- ✓ (Pb-Pb) $\gamma\gamma$ cross section to set constraint on QED processes
- ✓ three ALICE papers:
  - ✧ Phys. Lett. B718 (2013) 1273-1283 (J/ψ at forward rapidity)
  - ✧ Eur. J. Phys. C73, 2617 (2013) (J/ψ and $\gamma\gamma$ at mid-rapidity)
  - ✧ arxiv:1406.7819, accepted for publication in PRL (p-Pb - talk by E. Scapparone)

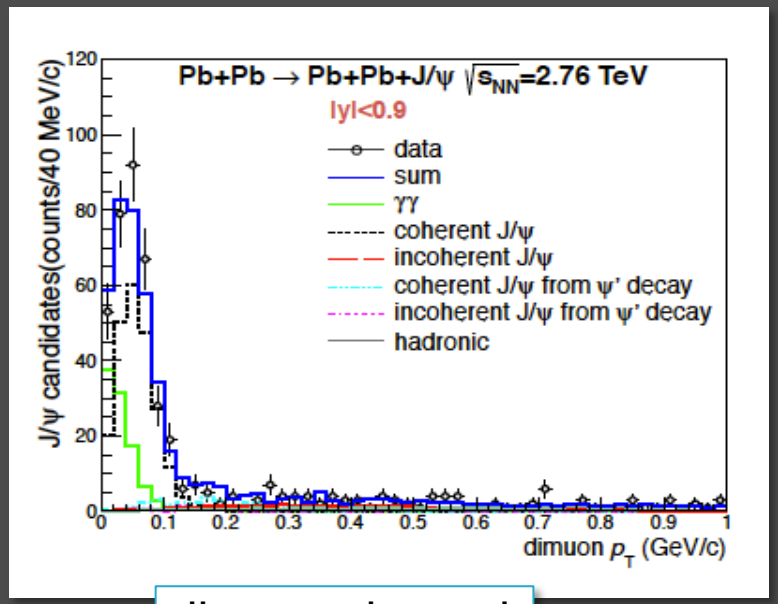
back-up

γγ cross section

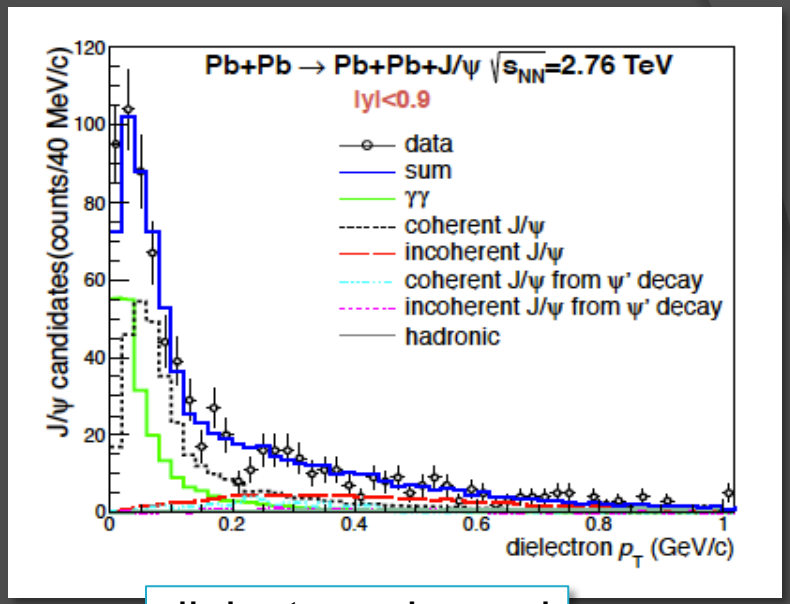
transverse momentum distribution well described by the Monte Carlo (STARLIGHT)



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

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

distribution peaked at low momentum as expected from coherent production

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

- ✓ fraction f_D of J/Ψ coming from the decay of $\psi' \rightarrow J/\Psi$ + 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:

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

see table in the next slide for the results

Feed down (ψ' → J/Ψ + anything)

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

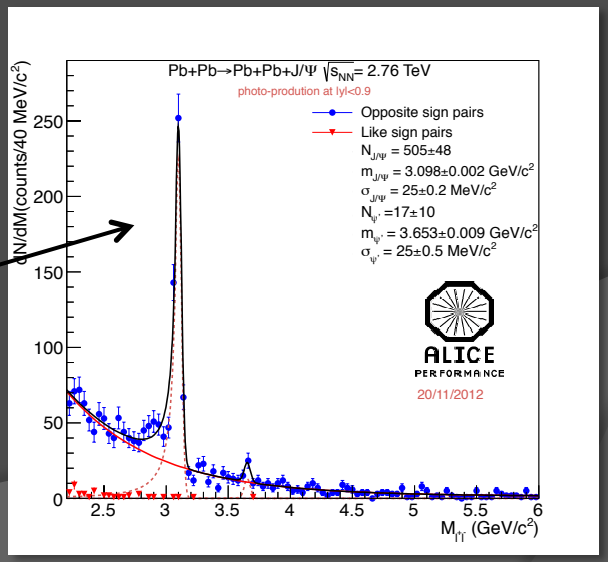
due to the limited statistics the two decay channels were combined:

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

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

→ 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