Quarkonium and open charm photoproduction in Pb-Pb collisions

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University of Oslo

Workshop on Advances, Innovations, and Future Perspectives in High Energy Nuclear Physics
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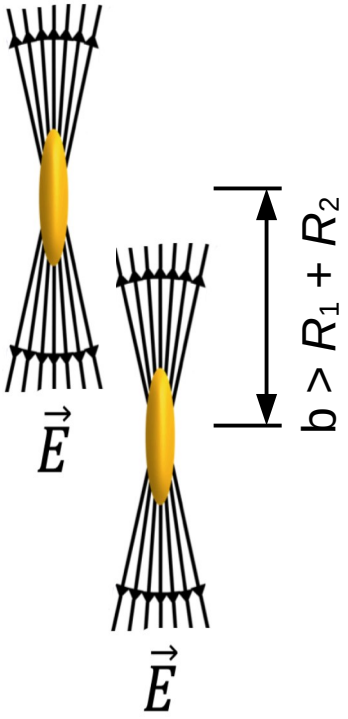
Outline

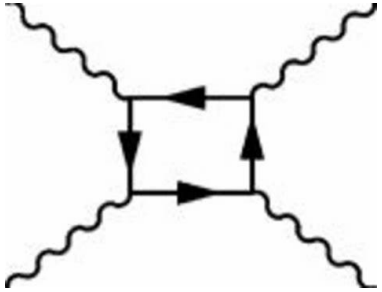
- Introduction
- Exclusive J/ψ photoproduction in UPC
- J/ψ photoproduction in PC
- Open charm and J/ψ photoproduction in single-gap UPC
- Outlook

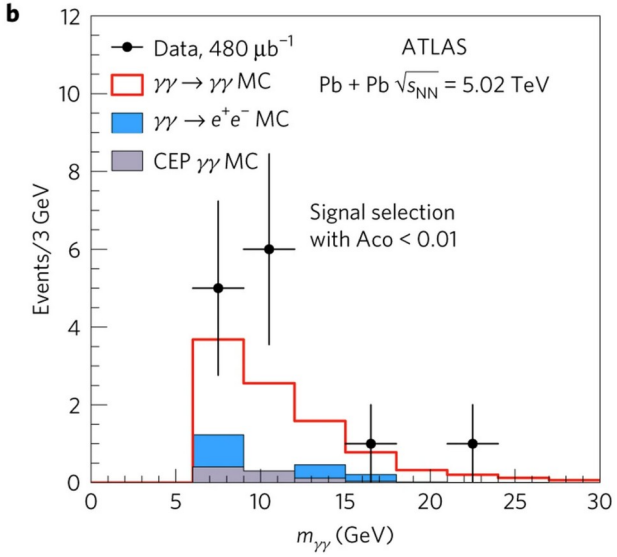
Nuclear electro-magnetic field mediated interactions



- **EM field of nuclei**: beam of quasi-real photons
  - Photons achieve a large boost at the LHC

Nuclear electro-magnetic field mediated interactions

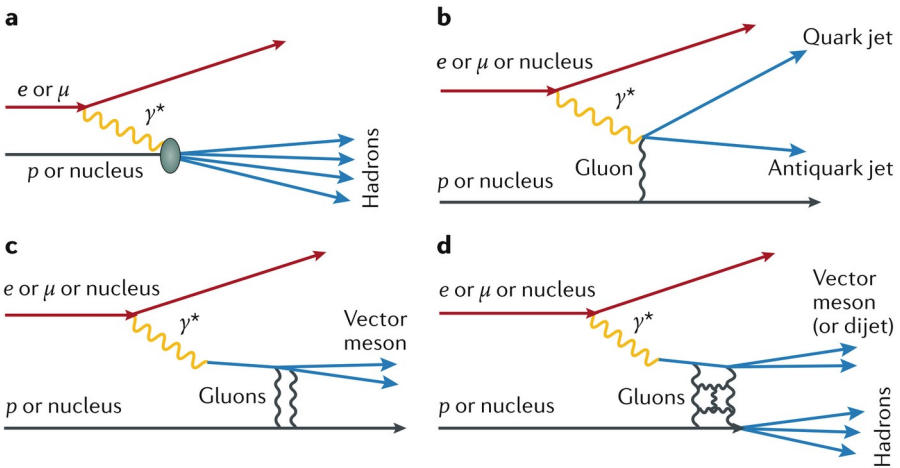




ATLAS, Nature Physics 13 (2017) 852

- **EM field of nuclei**: beam of quasi-real photons
  - Photons achieve a large boost at the LHC
  - Possibility of studying several interactions
    - Photon + photon

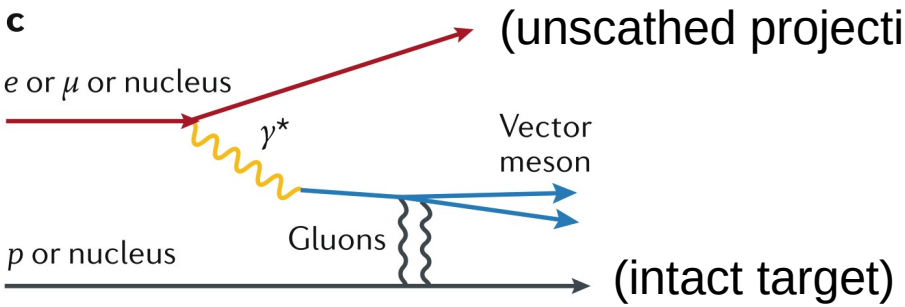
Nuclear electro-magnetic field mediated interactions



S.Klein, H.Mantysaari, Nature Rev. Physics 1 (2019) 662

- **EM field of nuclei**: beam of quasi-real photons
  - Photons achieve a large boost at the LHC
  - Possibility of studying several interactions
    - Photon + photon
    - Photon + nucleus
    - Photon + proton

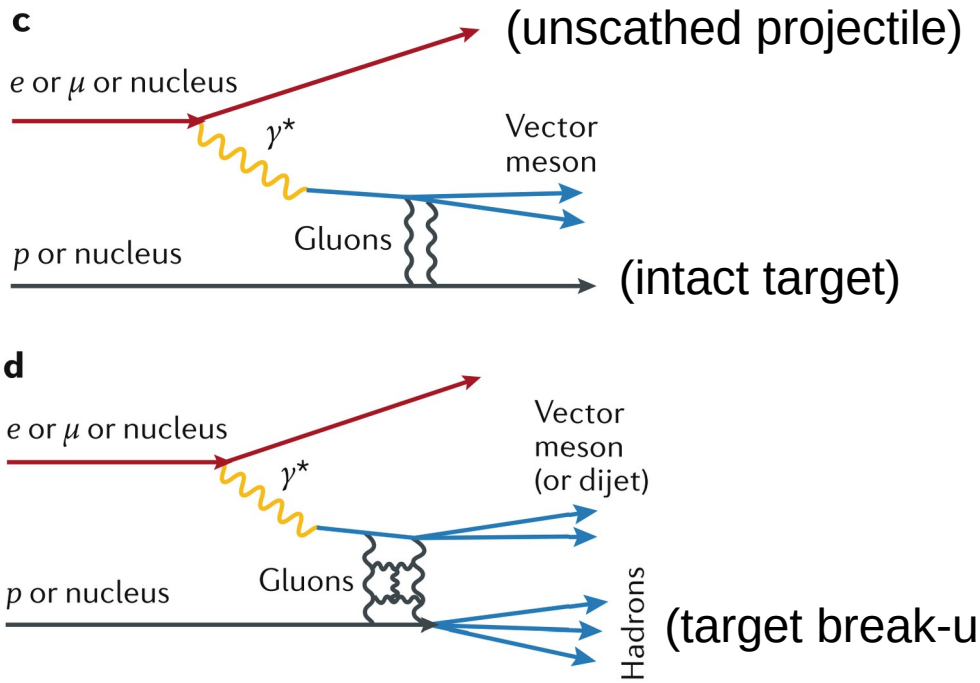
Vector meson photoproduction in UPCs



Coherent photoproduction

- Photon couples to the entire nucleus
- Target nucleus remains intact
- Production of just one vector meson
- $\langle p_T \rangle(\psi) \sim 60$ MeV/c

Vector meson photoproduction in UPCs



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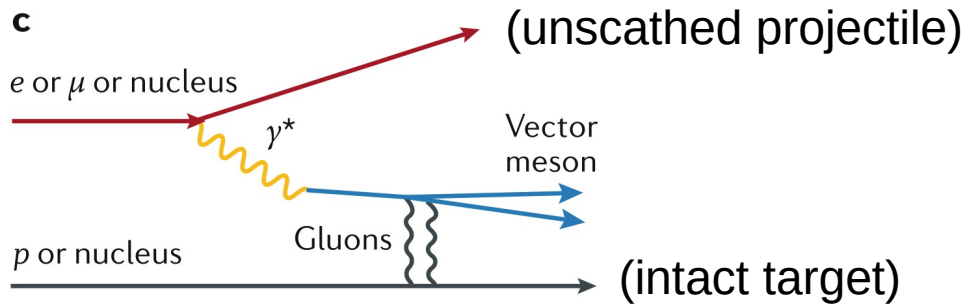
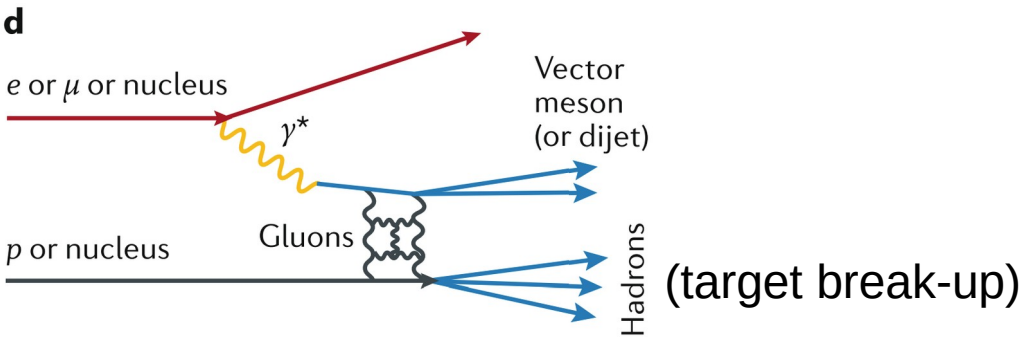
Incoherent photoproduction

- Photon couples to one nucleon
- Target breaks-up → neutron emission measured in ZDCs
- $\langle p_T \rangle(\psi) \sim 500$ MeV/c

Vector meson photoproduction in UPCs

S.Klein, H.Mantysaari, Nature Rev. Physics 1 (2019) 662





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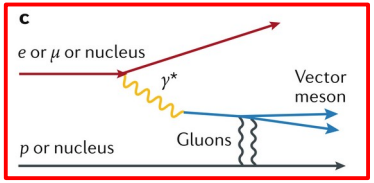
Both processes probe the nuclear parton distributions down to $x \sim 10^{-5}$

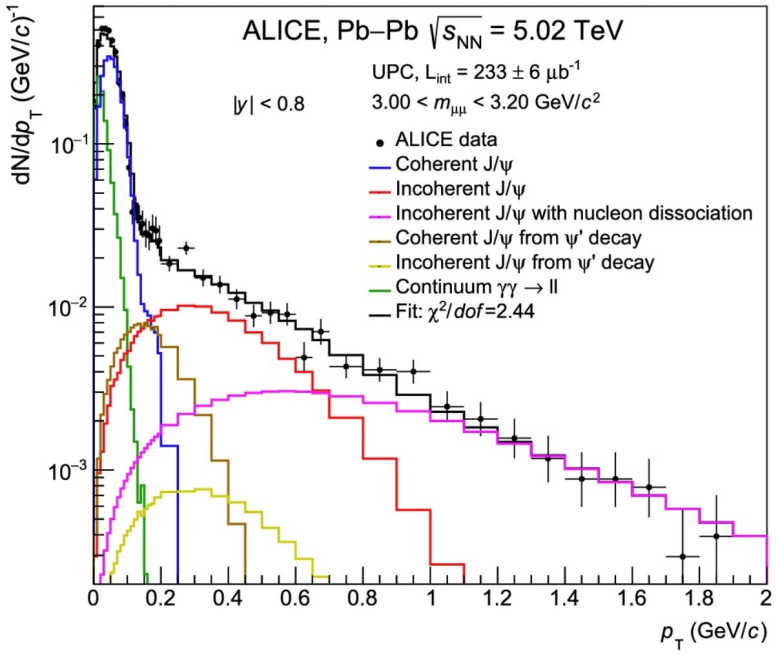
- Coherent: “average” nuclear density
- Incoherent: fluctuations of nucleon/subnucleon gluon density

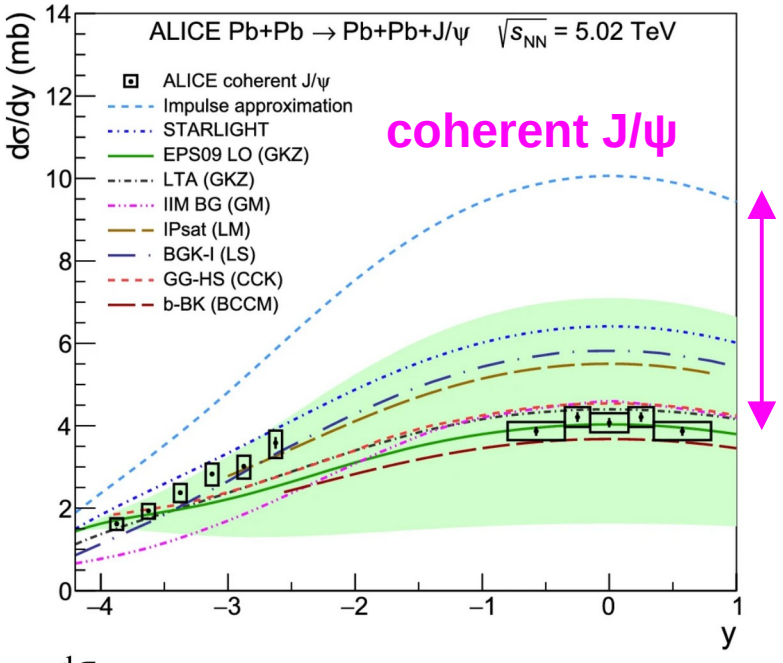
Coherent J/ψ photoproduction in UPCs

coherent



ALICE, EPJC 81 (2021) 712



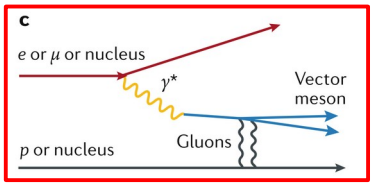


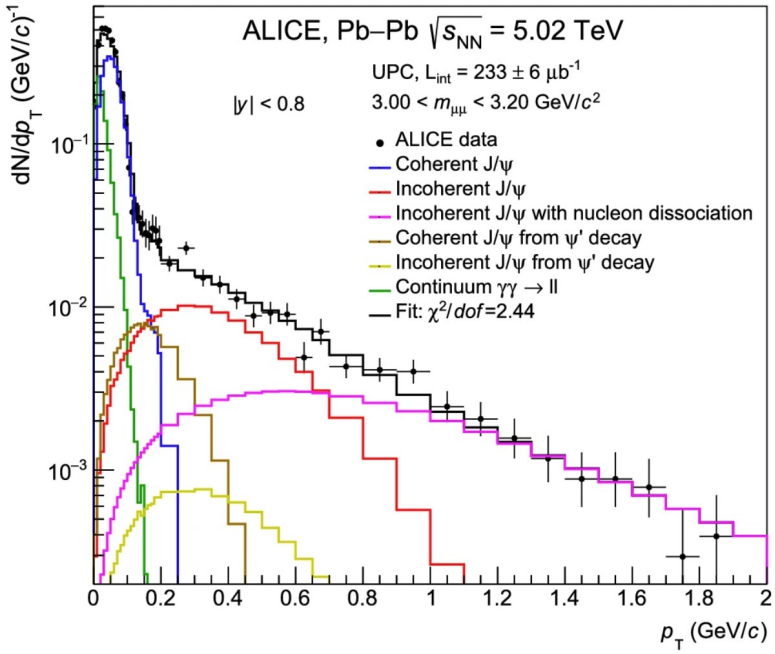
$$\frac{d\sigma_{PbPb}}{dy} = n_\gamma(y,\{b\})\sigma_{\gamma Pb}(y) + n_\gamma(-y,\{b\})\sigma_{\gamma Pb}(-y)$$

- Coherent and incoherent components extracted using template fits
- Midrapidity: coherent J/ψ (x~10^{-3}) compatible with models predicting moderate shadowing
- Forward rapidity: emitter-target ambiguity → folding of low and high-x contributions

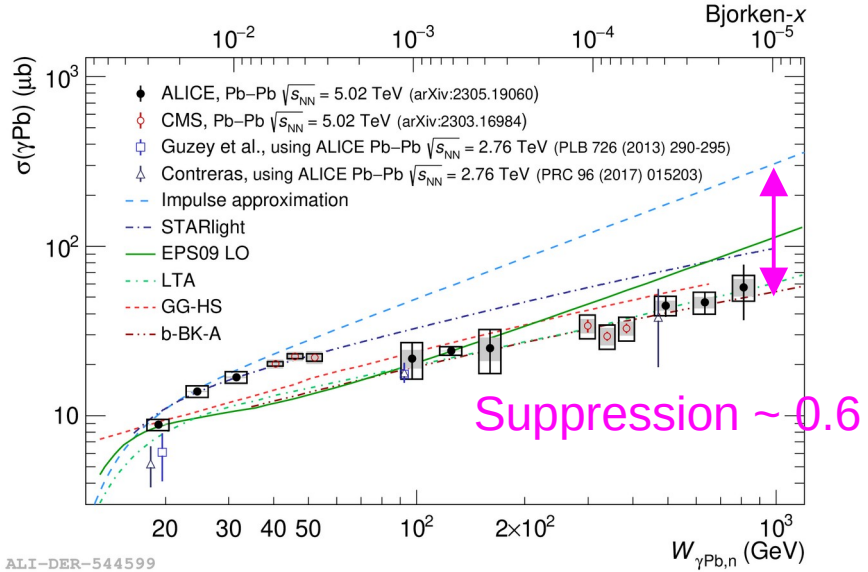
Coherent J/ψ photoproduction in UPCs

coherent





ALICE, JHEP 10 (2023) 119



Suppression ~ 0.6

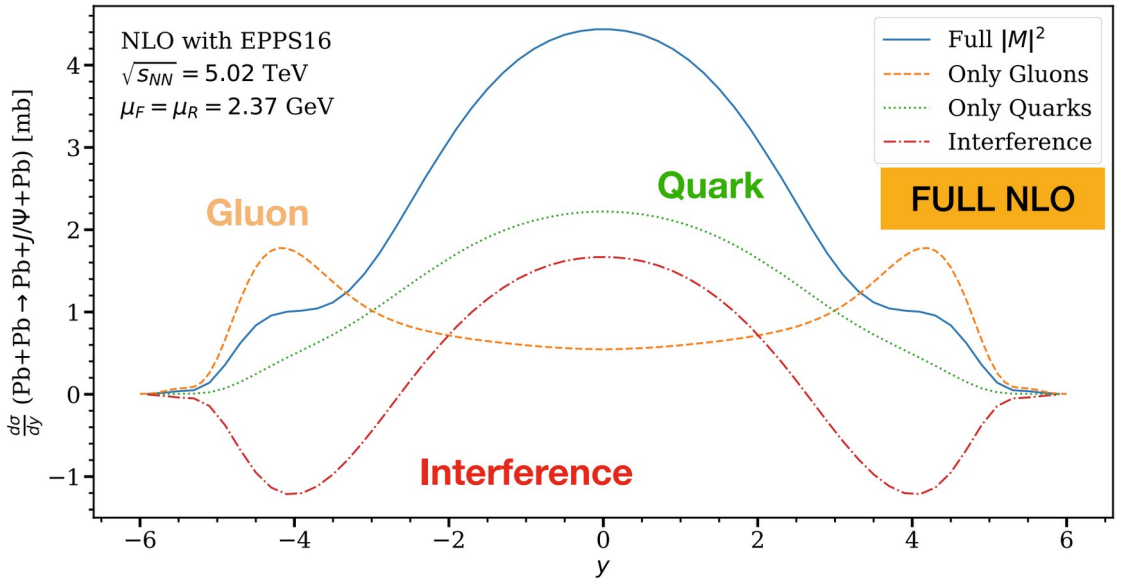
$$\frac{d\sigma_{PbPb}}{dy} = n_\gamma(y,\{b\})\sigma_{\gamma Pb}(y) + n_\gamma(-y,\{b\})\sigma_{\gamma Pb}(-y)$$

See talk by Zhenyu on Sunday

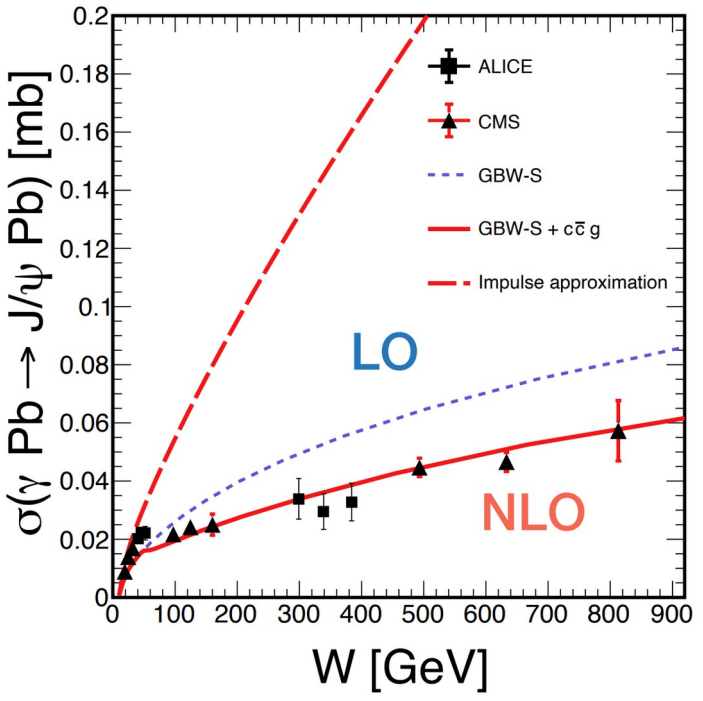
- Emitter-target ambiguity solved using independent measurements in ZDC neutron classes
- High-*x* (low *W*) compatible with IA or Glauber calculations
- Low-*x* (high *W*) better described by models implementing shadowing or saturation

Vector meson photoproduction in UPCs

Eskola et al., PRC 106 (2022) 035202

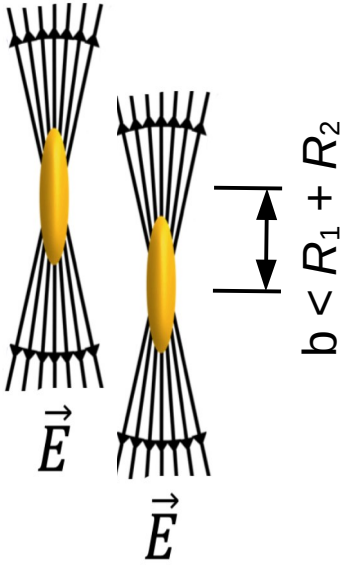


Mantysaari, Penttala, PLB 823 (2021) 136723
Luszczak, Schafer, PLB 856 (2024) 138917



- Full pQCD NLO calculation
  - Different gluon and quark PDF sensitivity wrt LO
- Calculations in the dipole picture using NLO describe well coherent J/ψ data

J/ψ photoproduction in AA collisions with overlap



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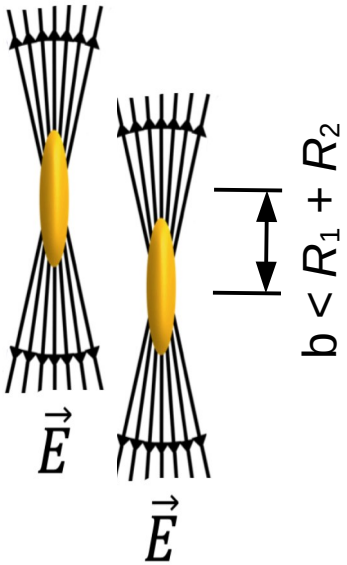
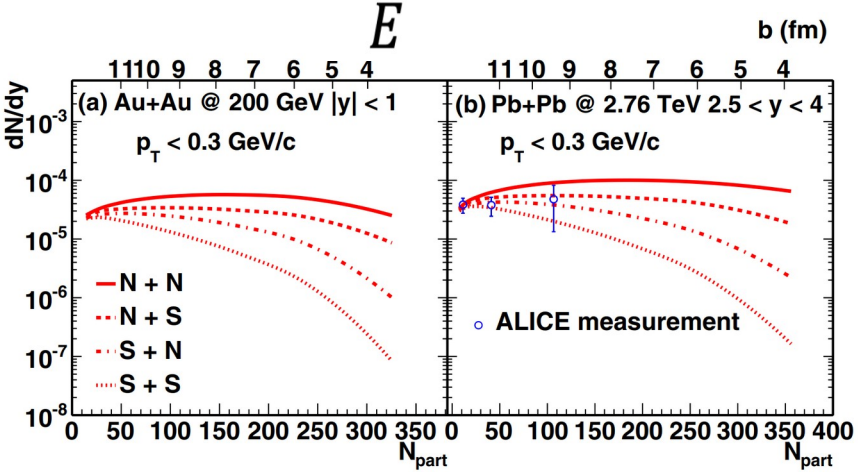
  - Different photon flux
  - Modified photon-nucleus cross-section ?

J/ψ photoproduction in AA collisions with overlap

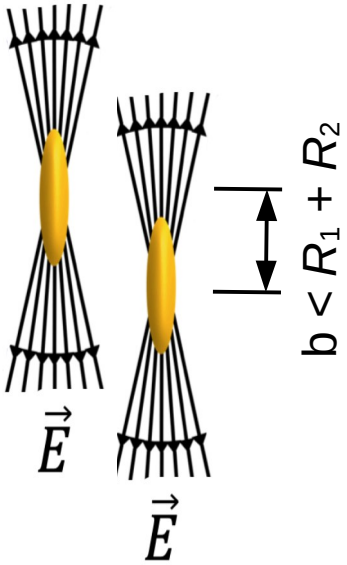


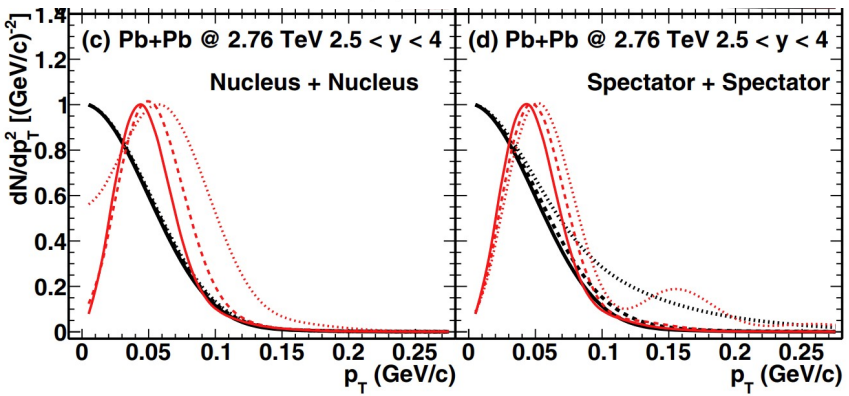


Zha et al., PRC97 (2018) 044910

- Interactions via EM fields occurs in parallel to the hadronic collision
  - Different photon flux
  - Modified photon-nucleus cross-section ?
- Phenomenology of the production cross section ongoing
  - Role of spectator (**S**) and participant (**N**) nucleons
  - Survival of the coherence condition
  - Time ordering of the hadro and photoproduction

J/ψ photoproduction in AA collisions with overlap





Zha et al., PRC97 (2018) 044910

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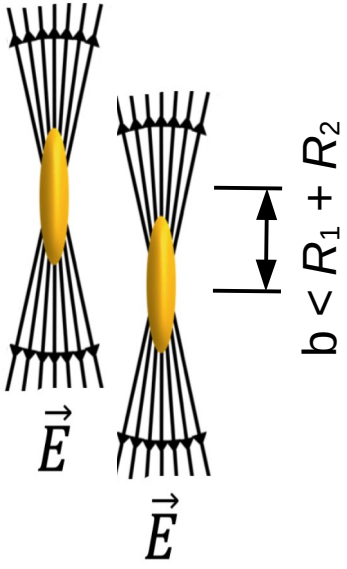
  - Interference due to the emitter-target ambiguity

S.Klein and J.Nystrand, PRL84(2000)11

J/ψ photoproduction in AA collisions with overlap

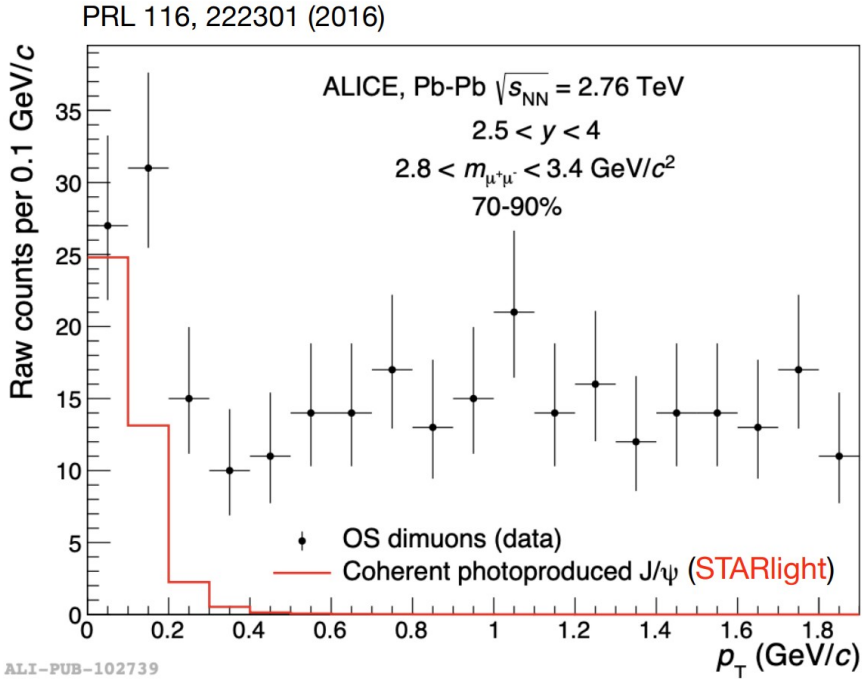


$$\frac{d\sigma_{PbPb}}{dy} = n_\gamma(y,\{b\})\sigma_{\gamma Pb}(y) + n_\gamma(-y,\{b\})\sigma_{\gamma Pb}(-y)$$

- Interactions via EM fields occurs in parallel to the hadronic collision
  - Different photon flux
  - Modified photon-nucleus cross-section ?
- Phenomenology of the production cross section ongoing
  - Role of spectator (**S**) and participant (**N**) nucleons
  - Survival of the coherence condition
  - Time ordering of the hadro and photoproduction
  - Interference due to the emitter-target ambiguity
  - Help solving the emitter-target ambiguity using measurements in different centrality classes

J.G.Contreras, PRC96(2017)015203

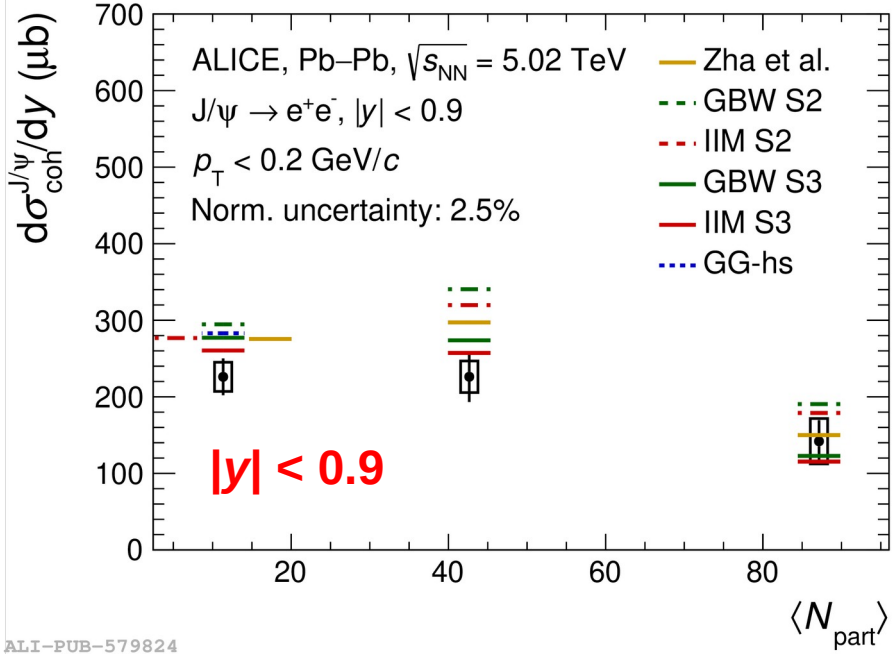
J/ψ photoproduction in AA collisions at $b < R_1+R_2$



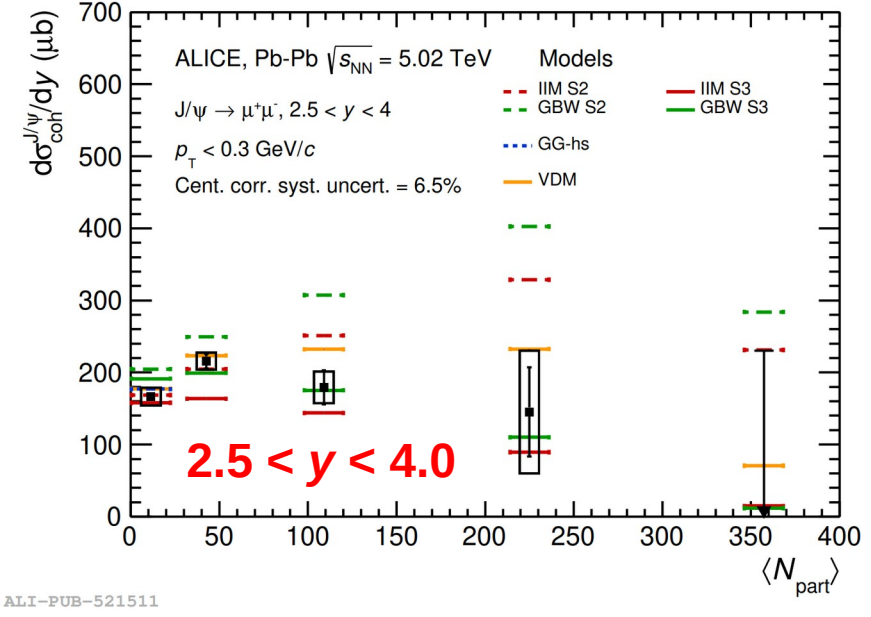
- In Run 1, ALICE reported an excess of J/ψ wrt expectations from hadro-production in peripheral collisions at very low p_T
  - Good agreement with STARLight simulations
  - Similar observation by STAR STAR, PRL 123 (2019) 132302

Coherent photoproduction, data vs models

ALICE, arxiv:2409.11940



VDM: Klusek-Gavenda et al., PLB 790 (2019) 339



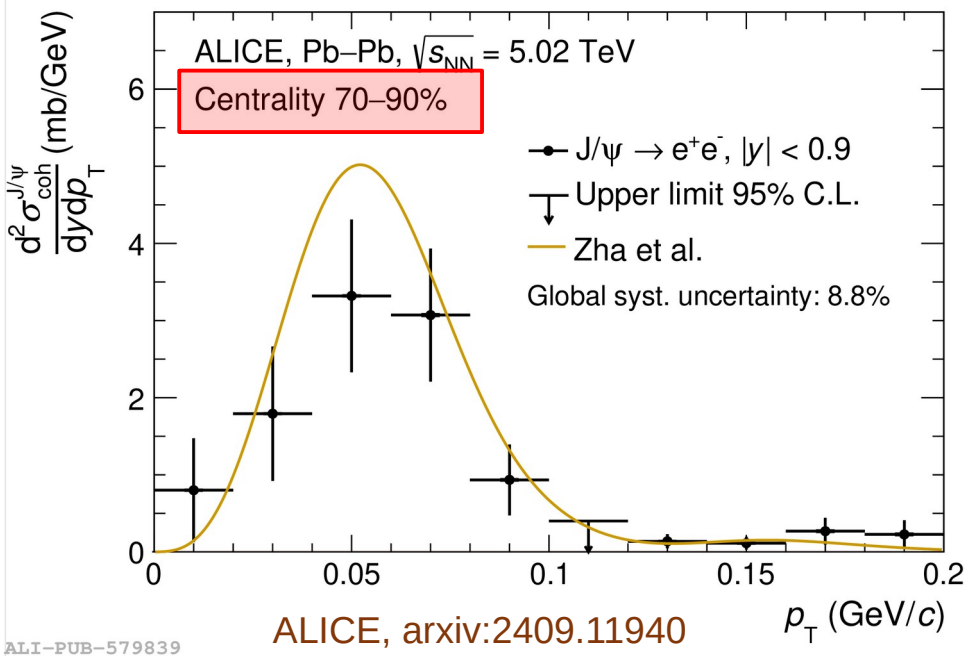
Modifications of photon-flux only:
GBW S2, IIM S2, VDM, GG-hs

Modifications of both photon-flux and σ(γA):
GBW S3, IIM S3, Zha et al.

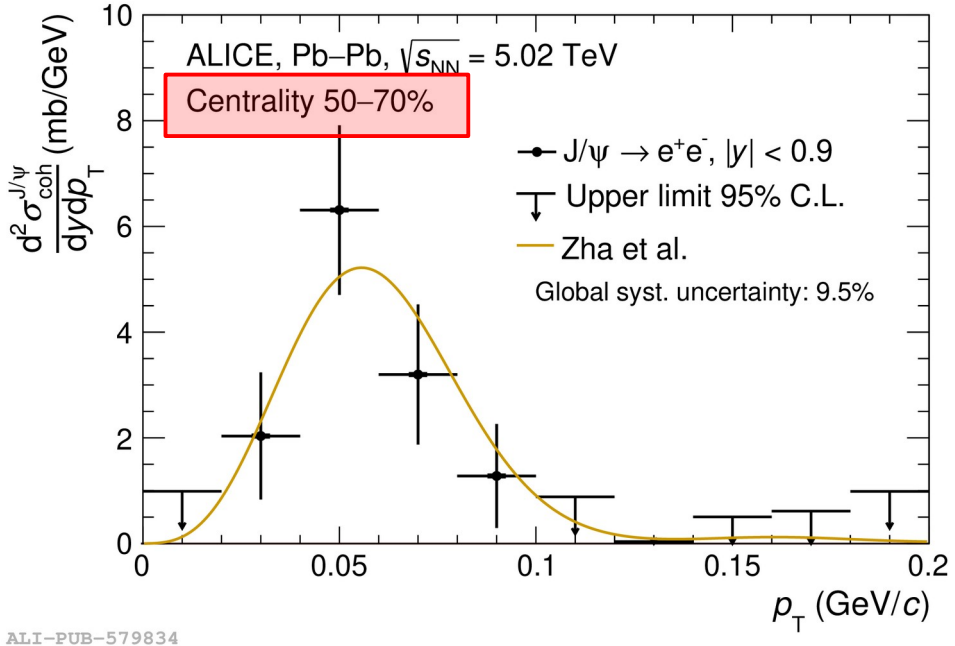
- Data tends to favor models where both the emitted photon flux and photonuclear cross section exclude the participant region
- VDM modifies only the photon flux but still gets a good agreement to data

p_T dependence of J/ψ photoproduction at mid-y

Zha et al., PRC 99 (2019) 061901

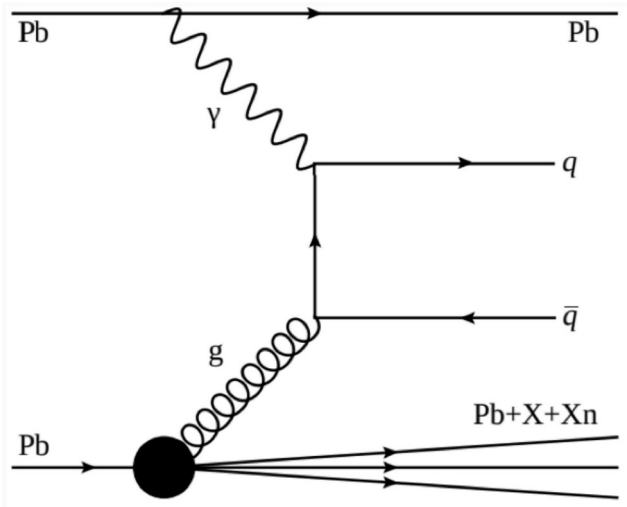


ALICE, arxiv:2409.11940

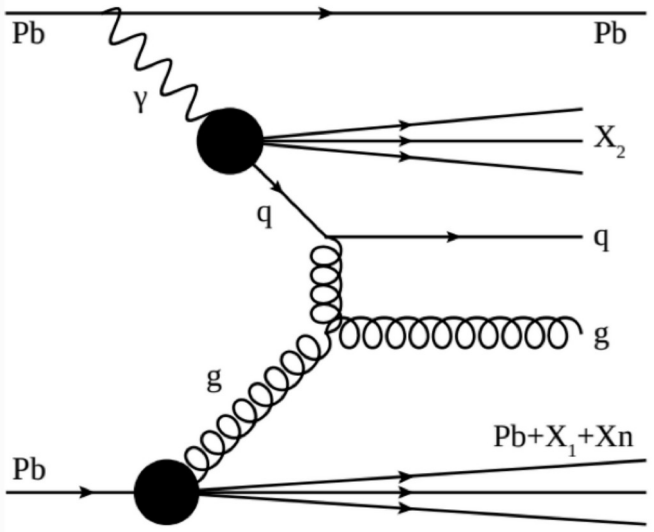


- Model calculations using destructive interference compatible with the data
- Modifications in the differential cross section with centrality still difficult to disentangle with the current datasets at mid-y

Di-jet production in photo-nuclear collisions



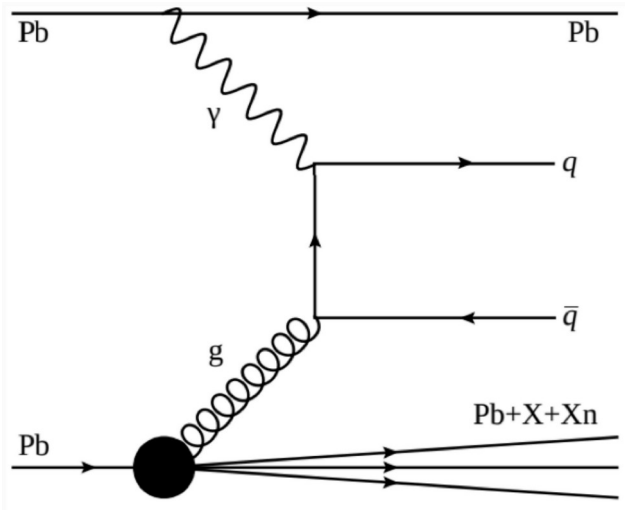
Direct photon scattering



Resolved photon scattering

- One gluon exchange
- Cross sections directly proportional to gluon density in the nucleon or nucleus
- Kinematics of the hard scattering can be determined with a good precision

Di-jet production in photo-nuclear collisions



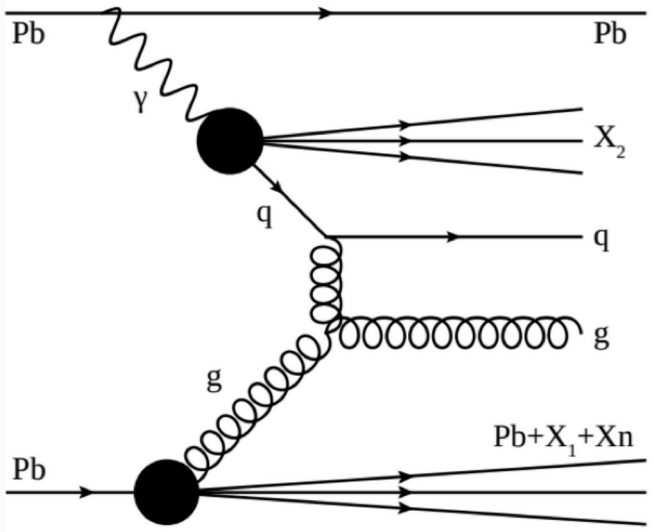
ZDC 0 neutrons

Rapidity gap

di-jets

ZDC neutrons + Nuclear fragmentation

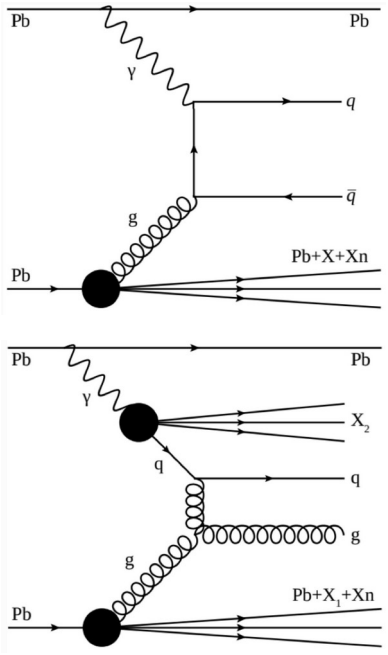
Direct photon scattering



Resolved photon scattering

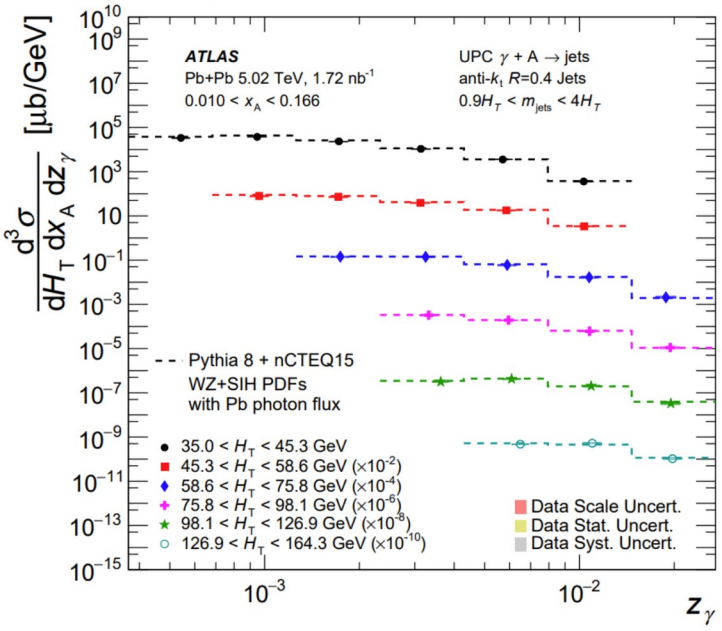
- Events are tagged by using their special topology (“single gap”)
  - Large rapidity gap in particle production
  - No neutrons in the photon direction ZDC
  - Neutron emission in the other ZDC + nuclear fragmentation

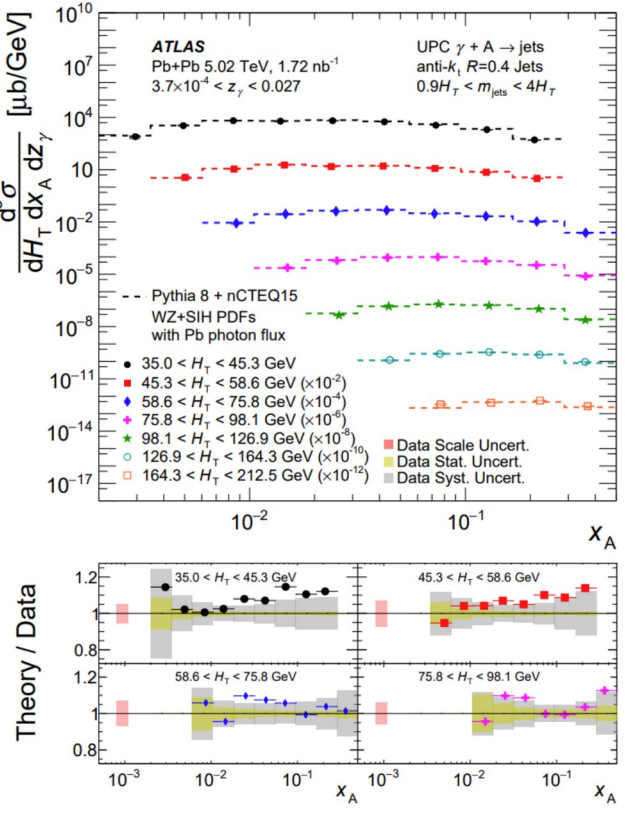
Di-jet production in photo-nuclear collisions



Talk by B.Gilbert, Hard Probes 2024
ATLAS, arxiv: 2409.11060

$$H_T = \sum_i p_T^i \qquad x_A = \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}} \qquad z_\gamma = \frac{M_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}$$

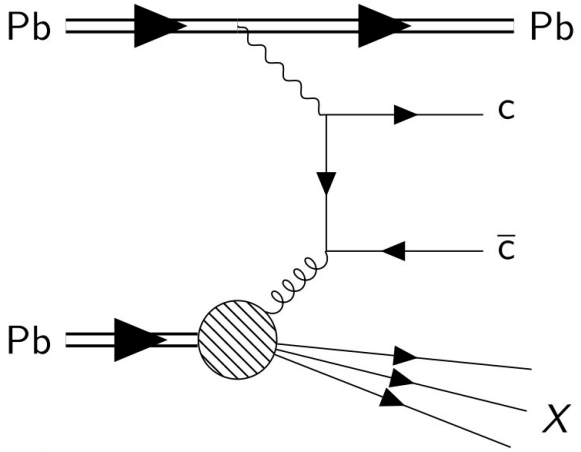


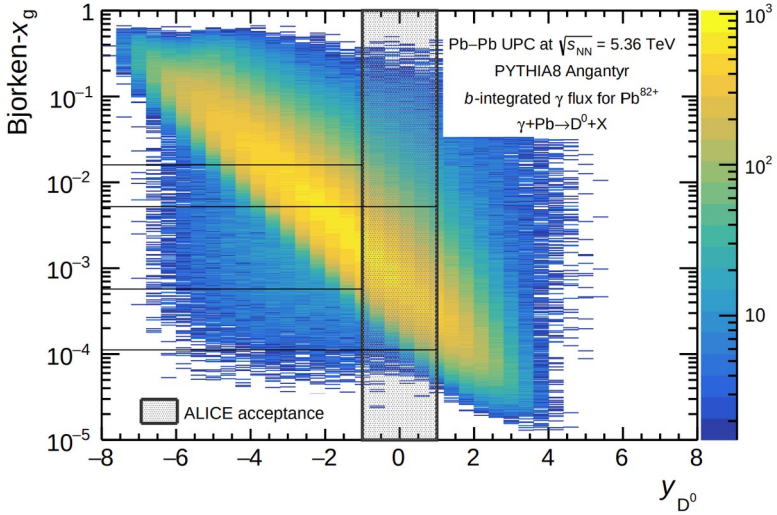


See talk by Qipeng on Sunday

- Recent ATLAS measurement indicates the potential for constraining nuclear PDFs
- Coverage down to x~10^{-3}

Heavy quark pair photoproduction



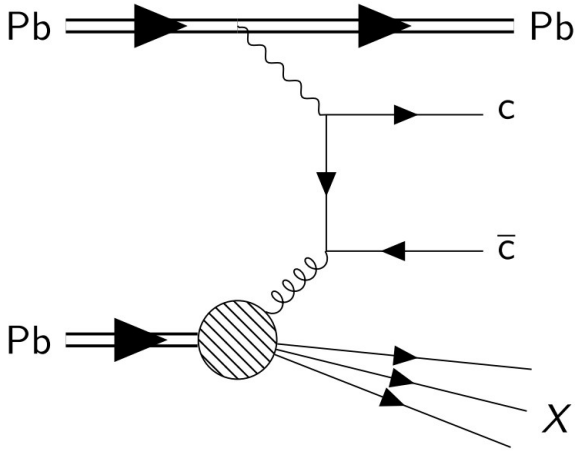


- Pairs of heavy quarks (charm) can be also produced in topologically similar processes
- Large mass of charm quarks → pQCD applicable down to $p_T = 0$
  - Huge cross-section available ~ 2b

S.Klein, J.Nystrand, R.Vogt, PRC 66 (2002) 044906

- Access to gluon PDFs down to x~10^{-4} with ALICE at midrapidity
  - Constrain shadowing and saturation models

Heavy quark pair photoproduction



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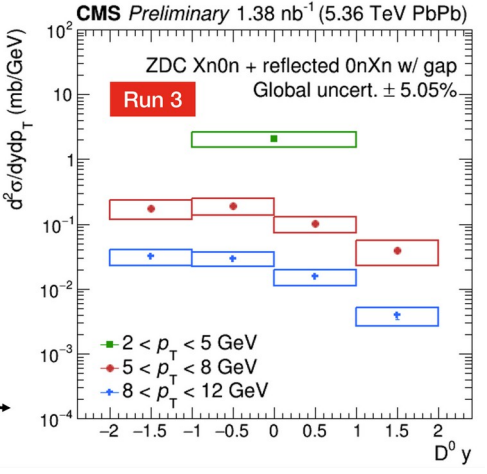
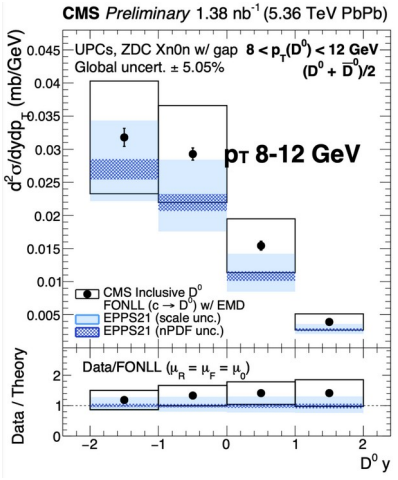
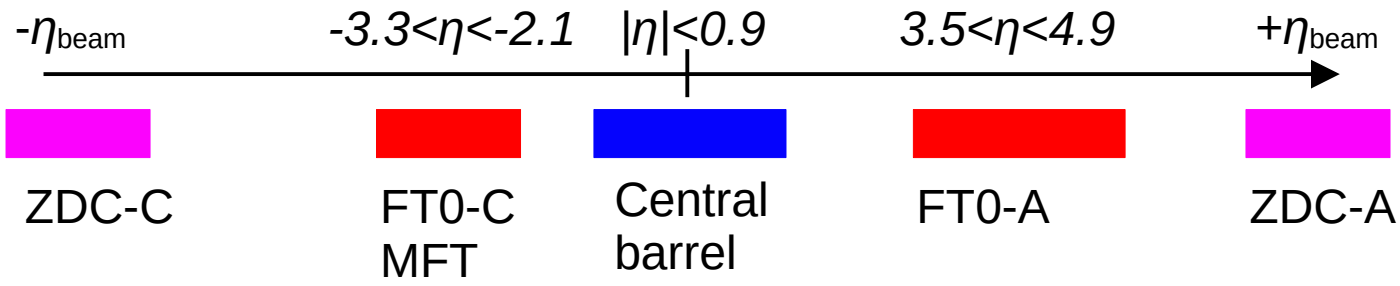




- Preliminary results on D^0 mesons by CMS
- Good agreement with FONLL + nPDF

Single-gap event selection in ALICE



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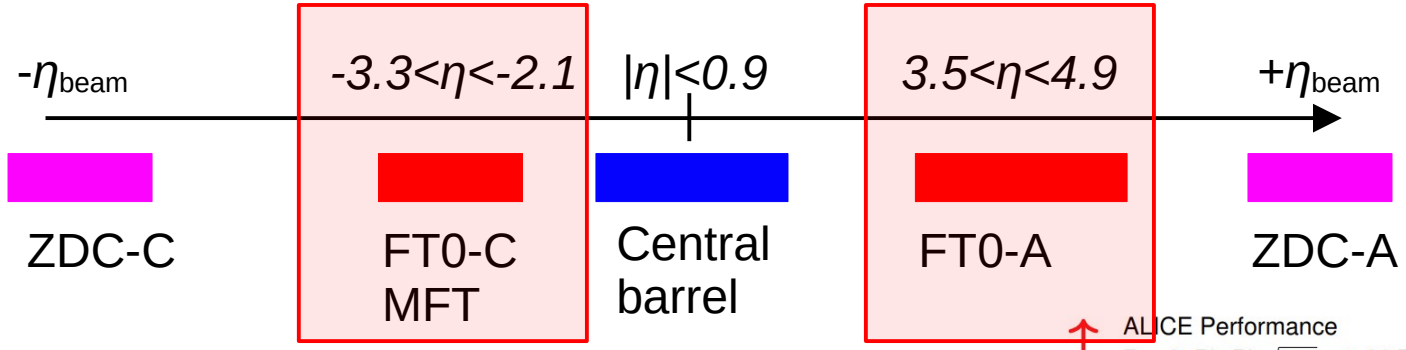
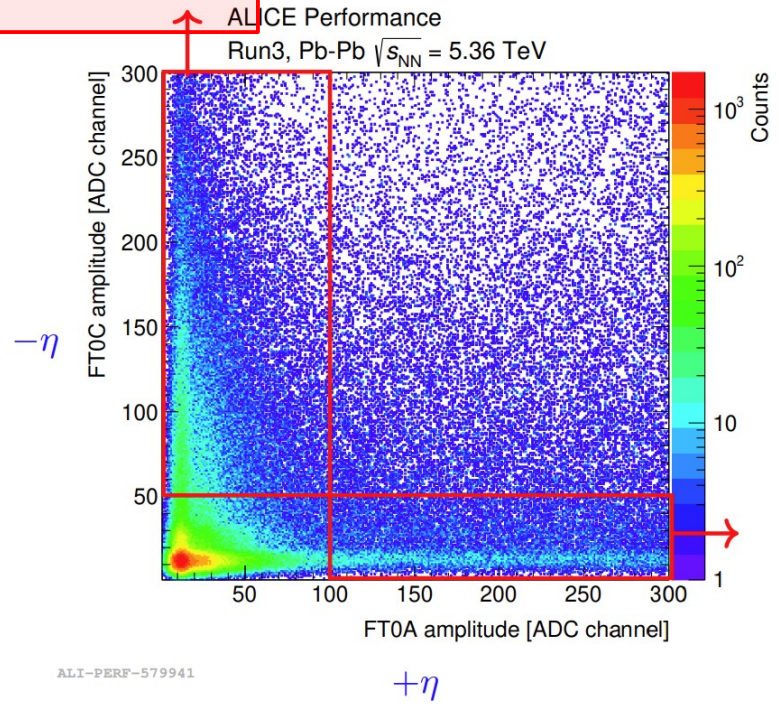


- Event activity η gap configured by requiring **FT0 amplitudes** below threshold on one side and above on the other



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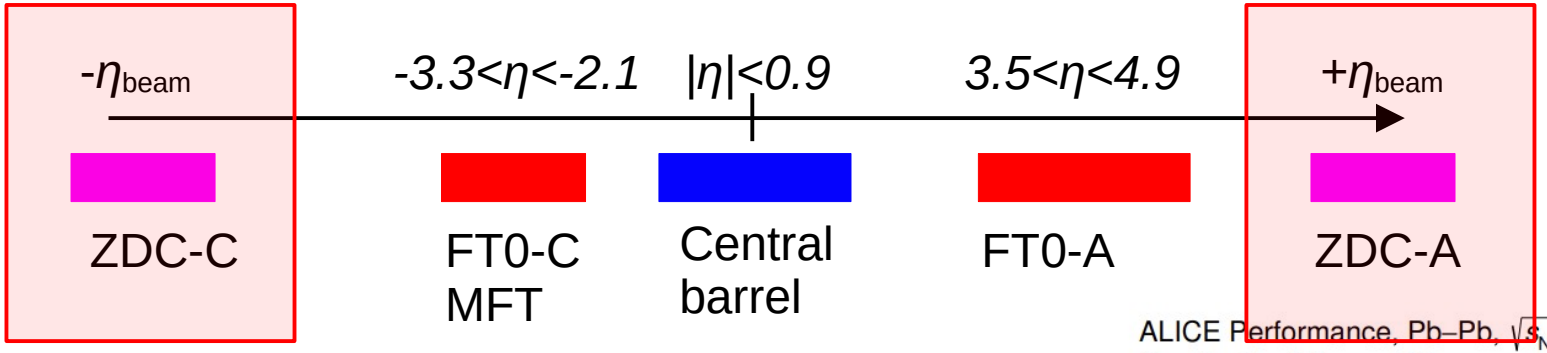
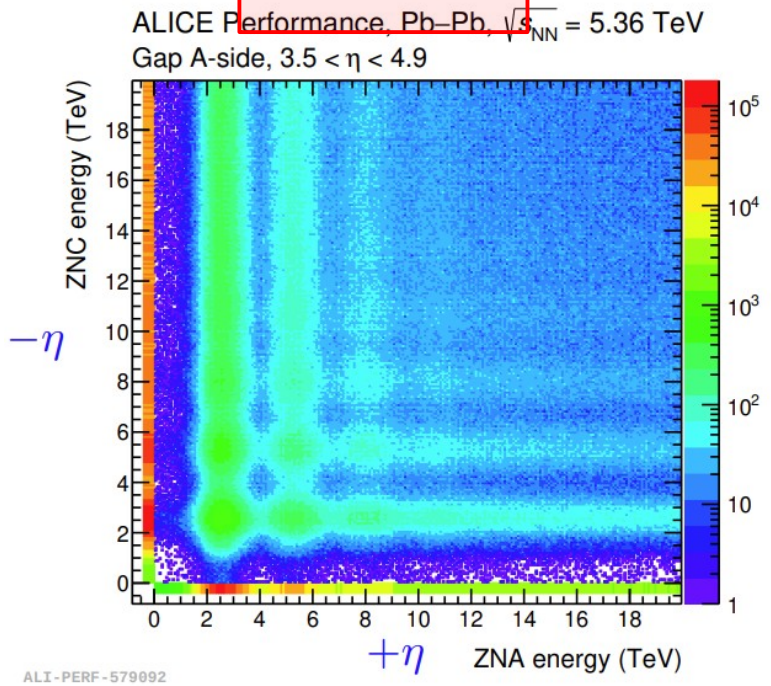
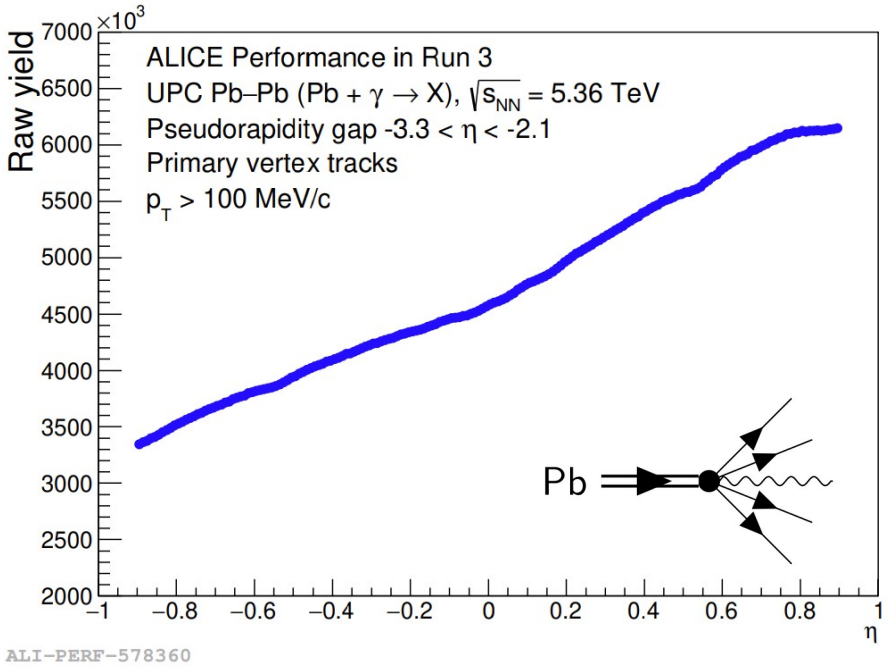
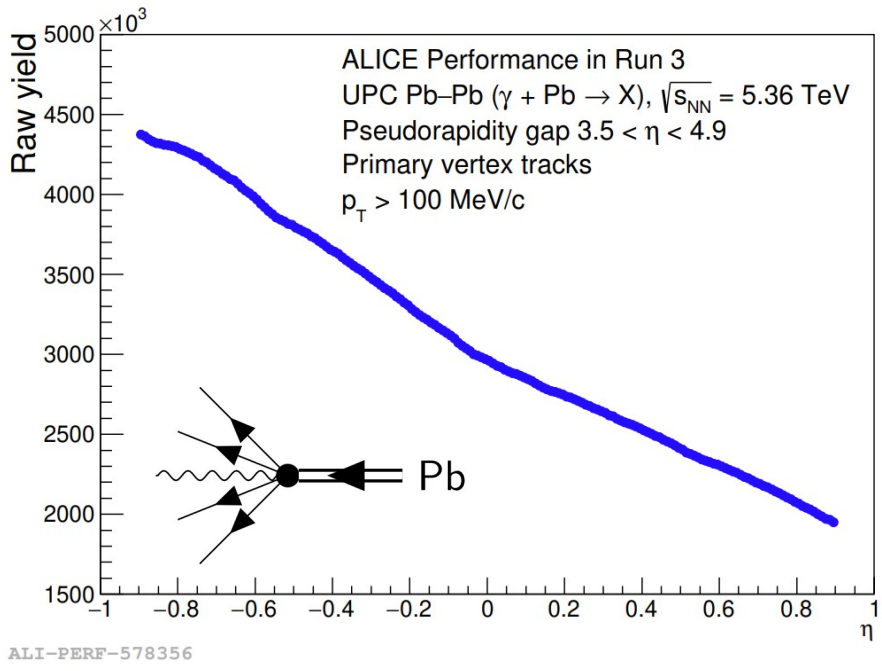


- Event activity η gap configured by requiring **FT0 amplitudes** below threshold on one side and above on the other
- Neutron emission classes can be selected using the **ZDC amplitudes**
  - Individual neutron emissions can be reconstructed up to several neutrons



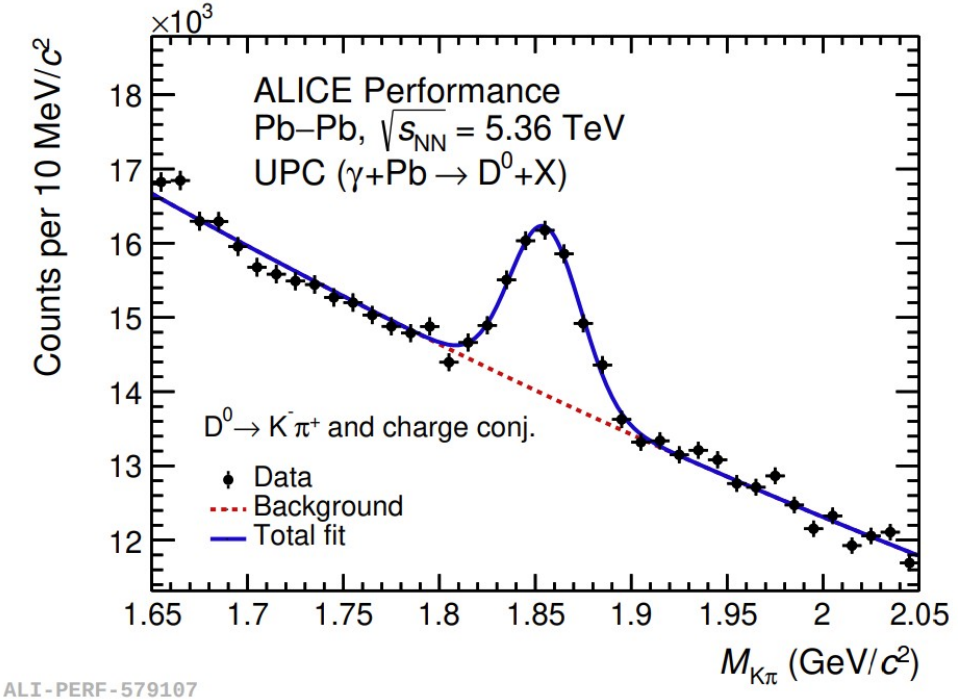
Charged track distributions in single-gap events



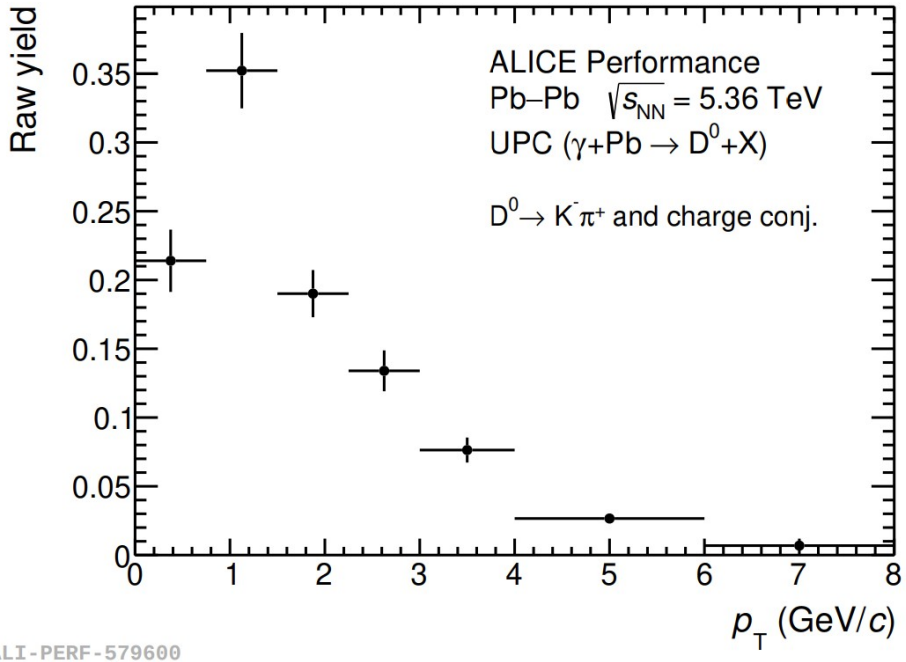


- Asymmetric pseudo-rapidity distributions for charged particles in the barrel
  - Expected in single-gap events

$D^0 + \overline{D^0}$ measurement in ALICE



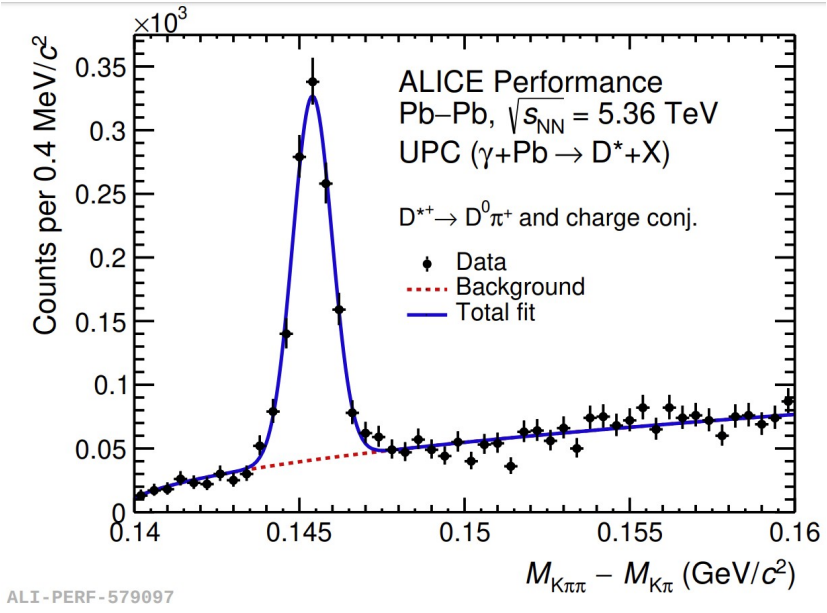
ALI-PERF-579107

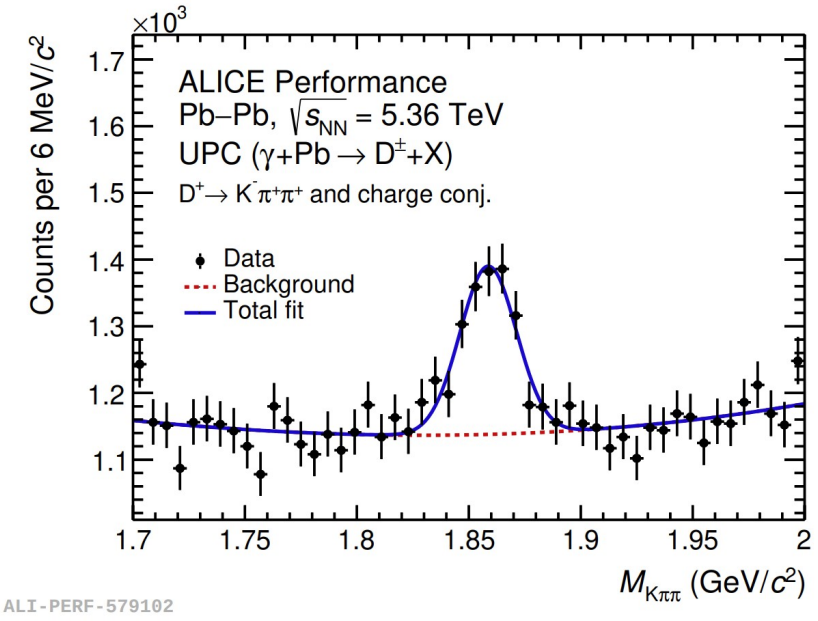


ALI-PERF-579600

- Very good performance of D^0 signal in Kπ decay channel
- Coverage down to $p_T = 0$

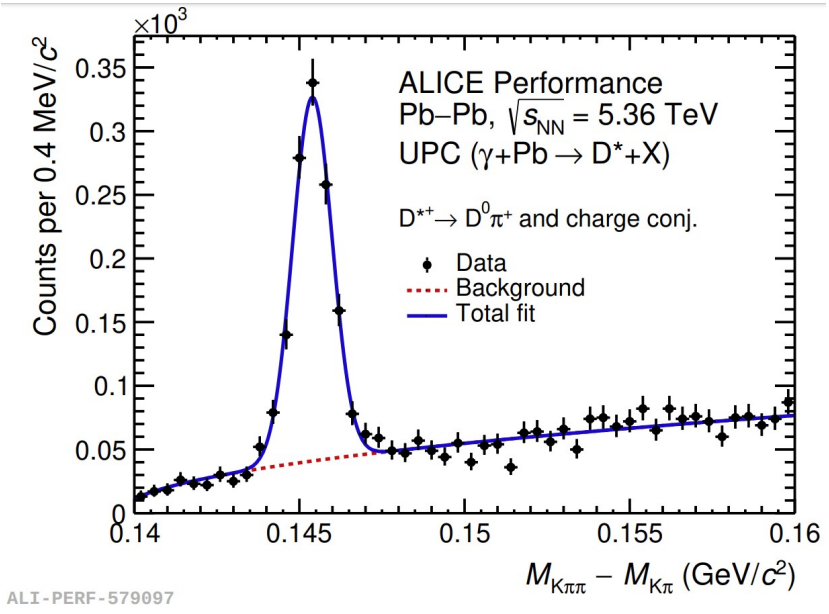
Reconstruction performance for $D^{*+/-}$, $D^{+/-}$

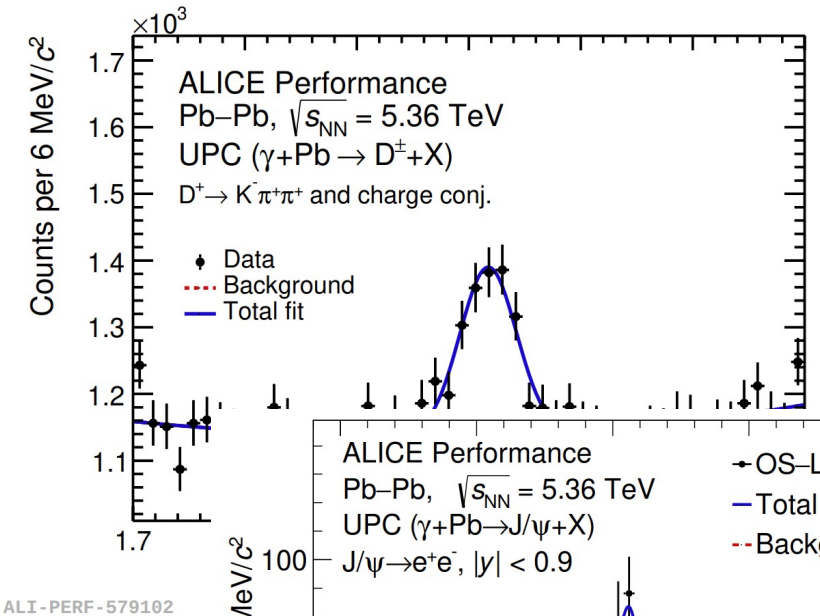


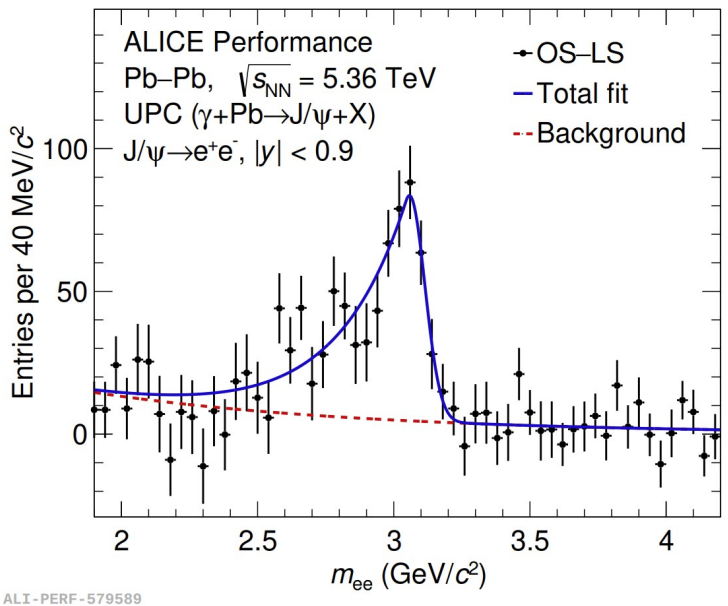


- Reconstruction of higher mass open-charm: $D^{*+/-}$, $D^{+/-}$

Reconstruction performance for $D^{*+/-}$, $D^{+/-}$ and J/ψ



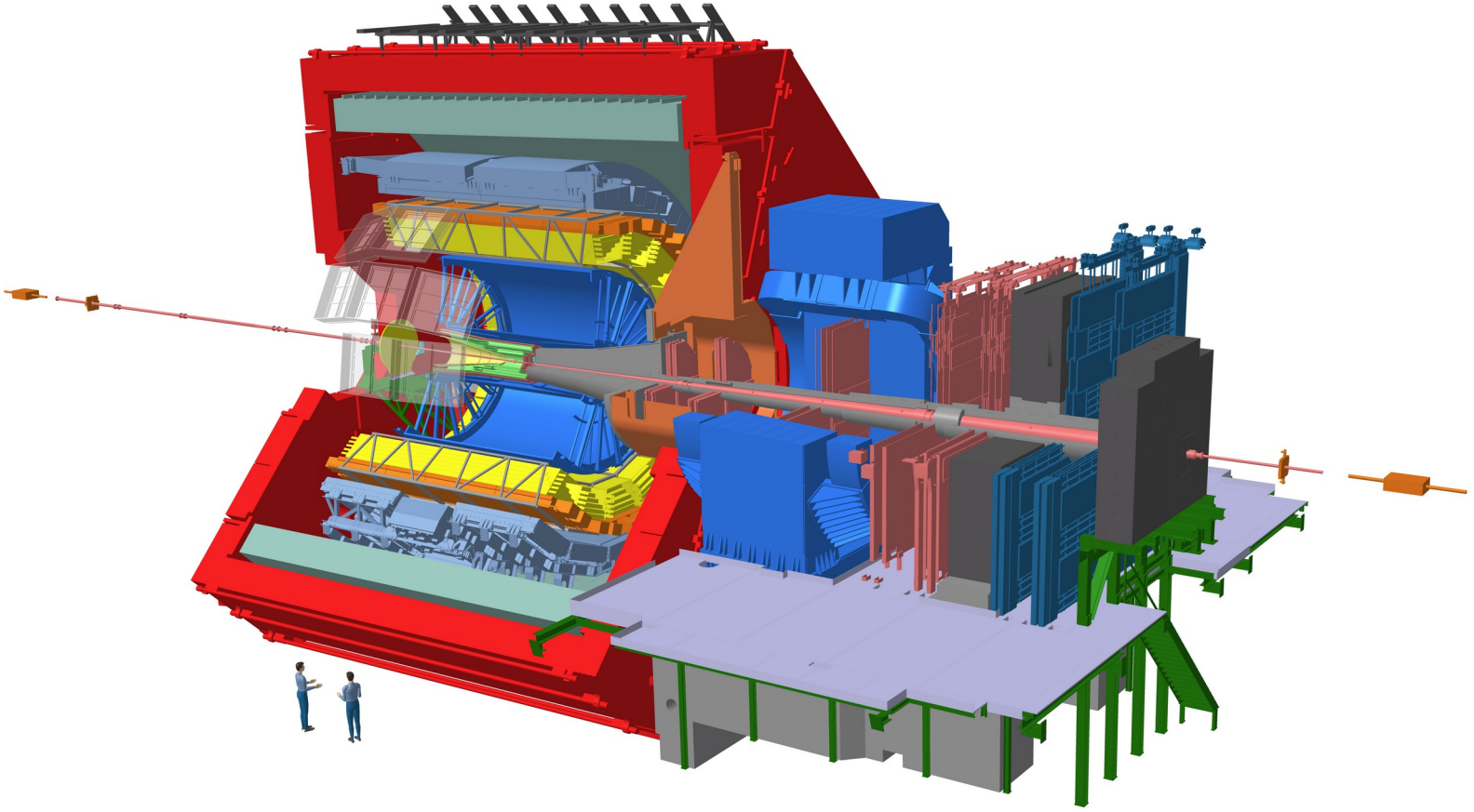




- Reconstruction of higher mass open-charm: $D^{*+/-}$, $D^{+/-}$ and J/ψ in the e^+e^- channel

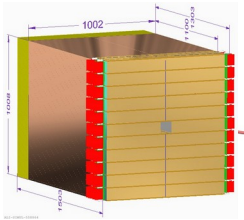
Outlook

The ALICE detector (Run 3 setup)

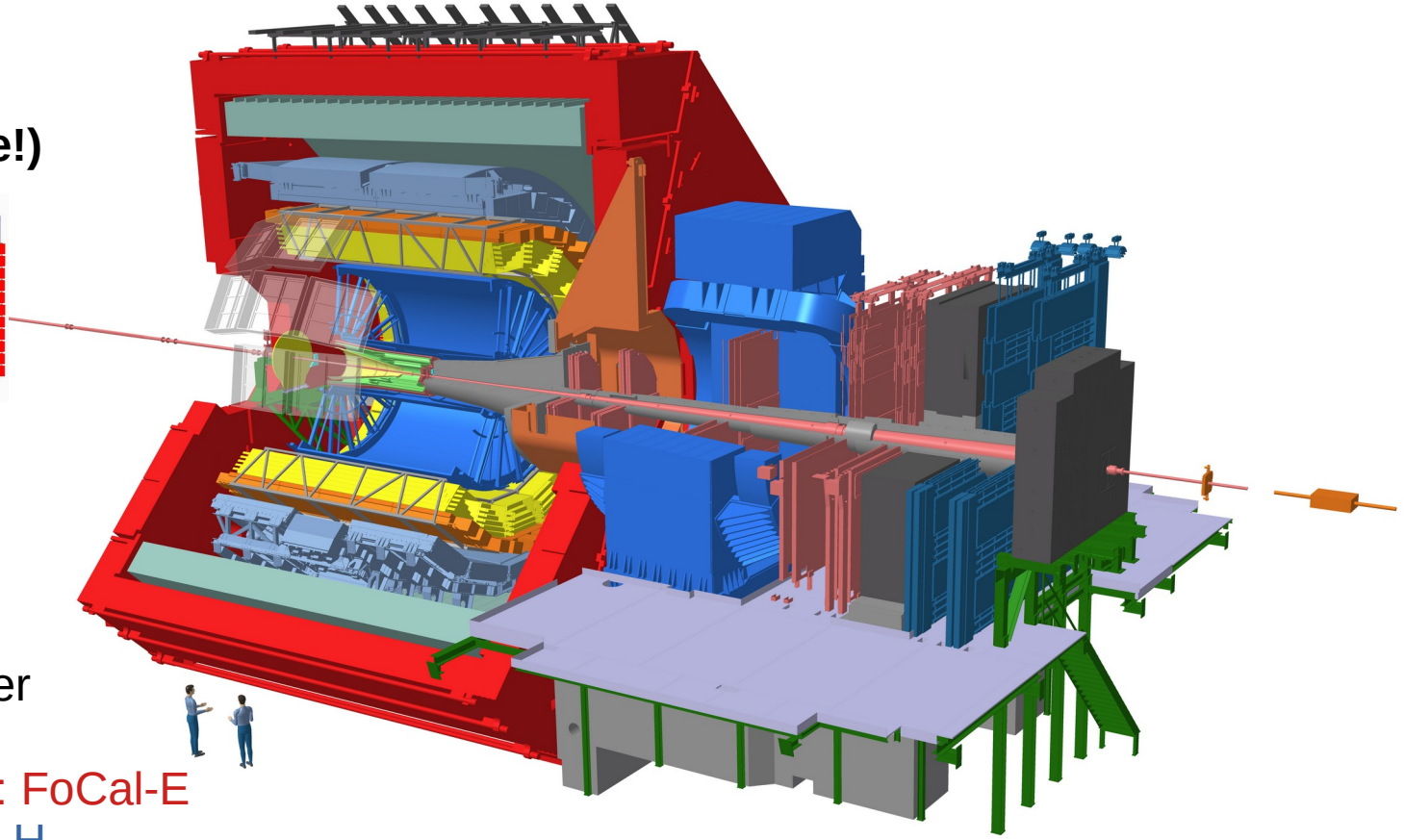


The ALICE detector + FoCal in Run 4

(not to scale!)



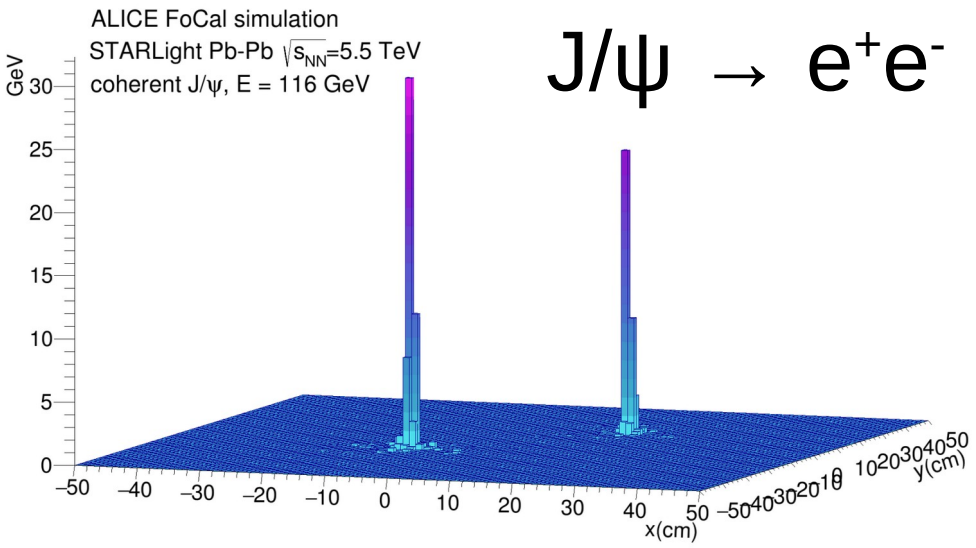
FoCal
3.2 < η < 5.8



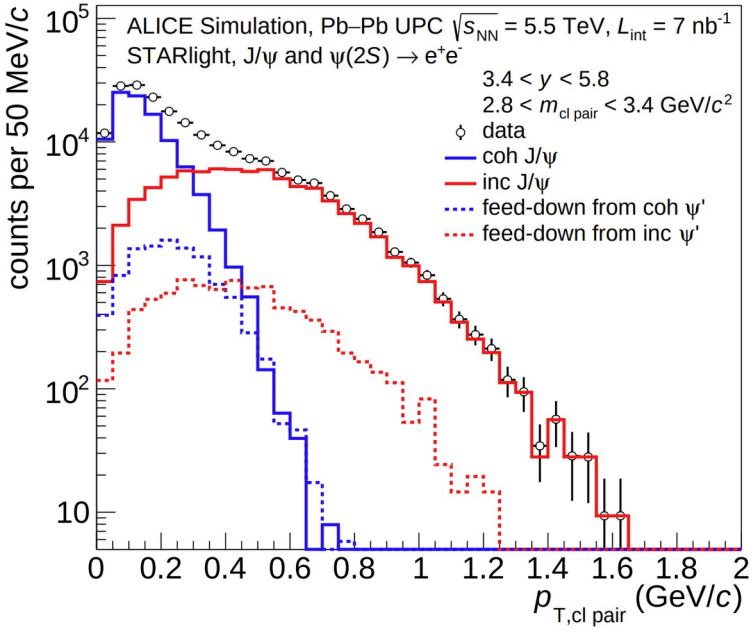
- Forward calorimeter (3.2<η<5.8)
  - Electromagnetic: FoCal-E
  - Hadronic: FoCal-H

FoCal Technical Design Report

J/ψ and ψ(2S) reconstruction in Pb-Pb



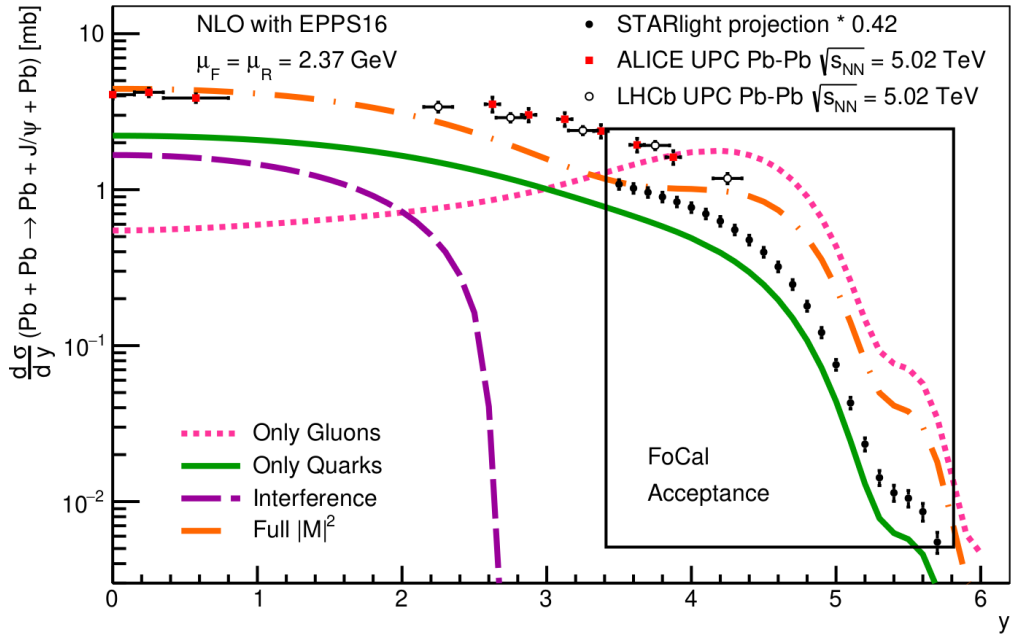
$J/\psi \rightarrow e^+e^-$



- Ground and excited charmonium states can be separated
- Coherent and incoherent components can be extracted from the p_T distribution
- Very large photoproduced quarkonia sample expected to be measured with FoCal

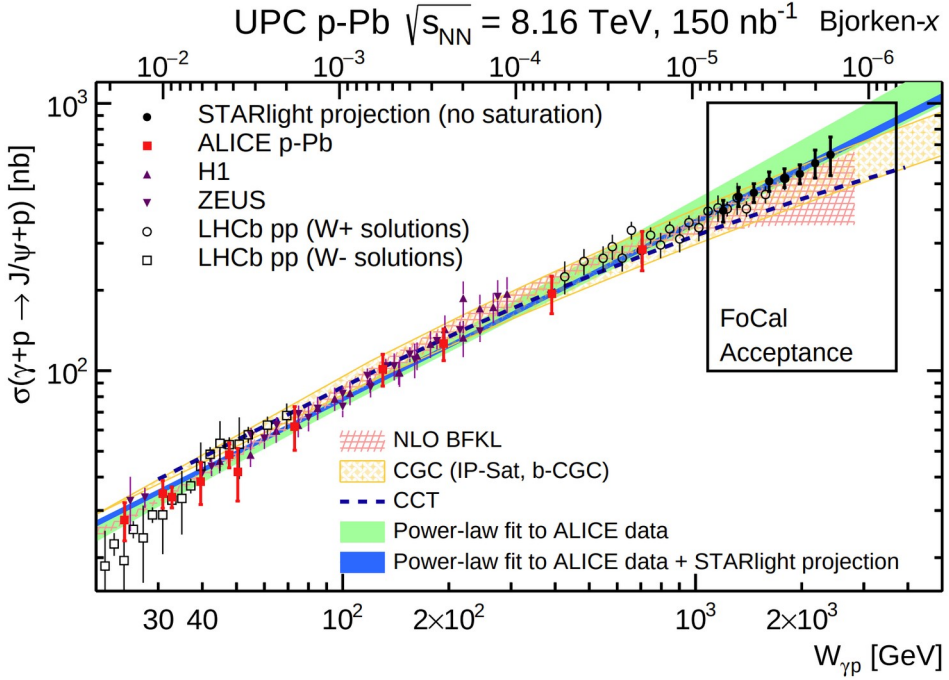
Coherent J/ψ photoproduction in Pb-Pb UPC

Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107



- Extension of the measurement to *y*~5.5 with very good stat. uncertainties
- Interference between quark and gluon contributions largest in the FoCal acceptance *Flett, Jones, Martin, Ryskin and Teubner, arXiv:1908.08398*

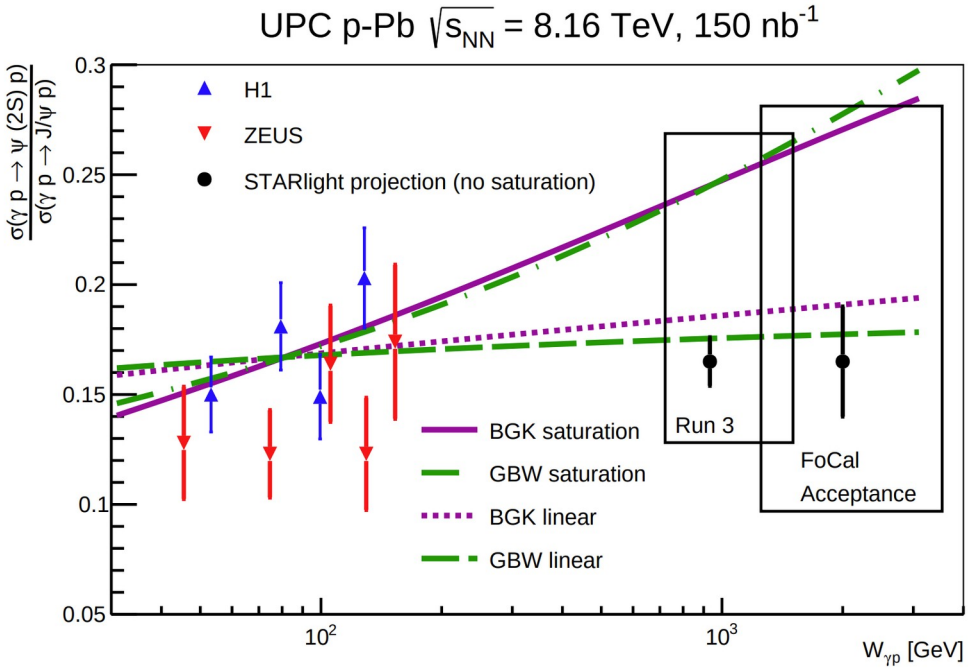
Photoproduction off protons σ(γ+p) at high-*W*

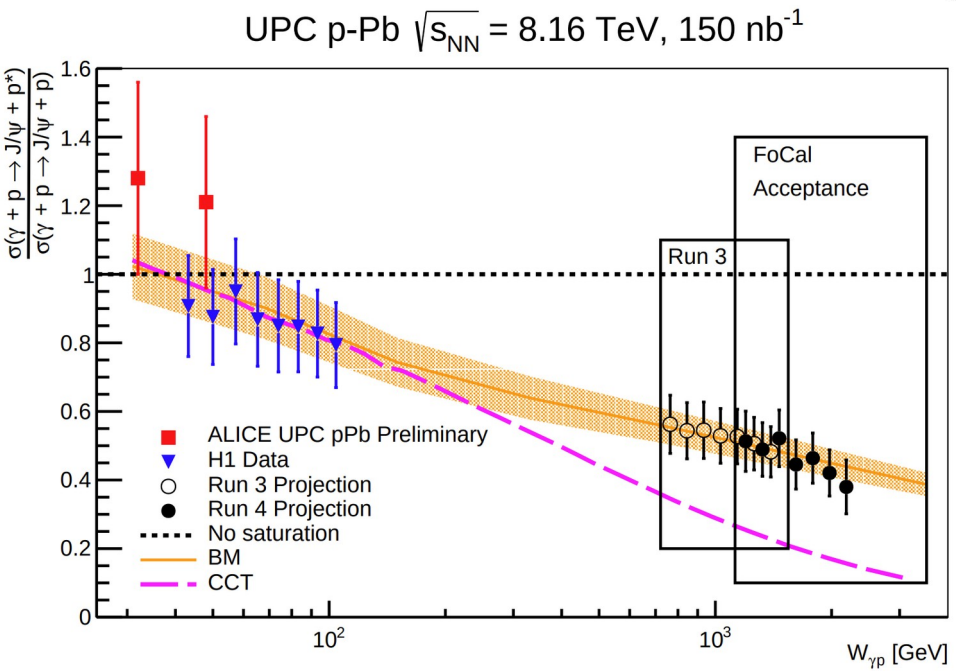


- FoCal extends coverage in $W_{\gamma p}$ up to about 2 TeV and nearly as low as $x \sim 10^{-6}$
- Large lever arm for discriminating linear vs saturation scenarios

Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107

Saturation model constrains with p-Pb UPC data





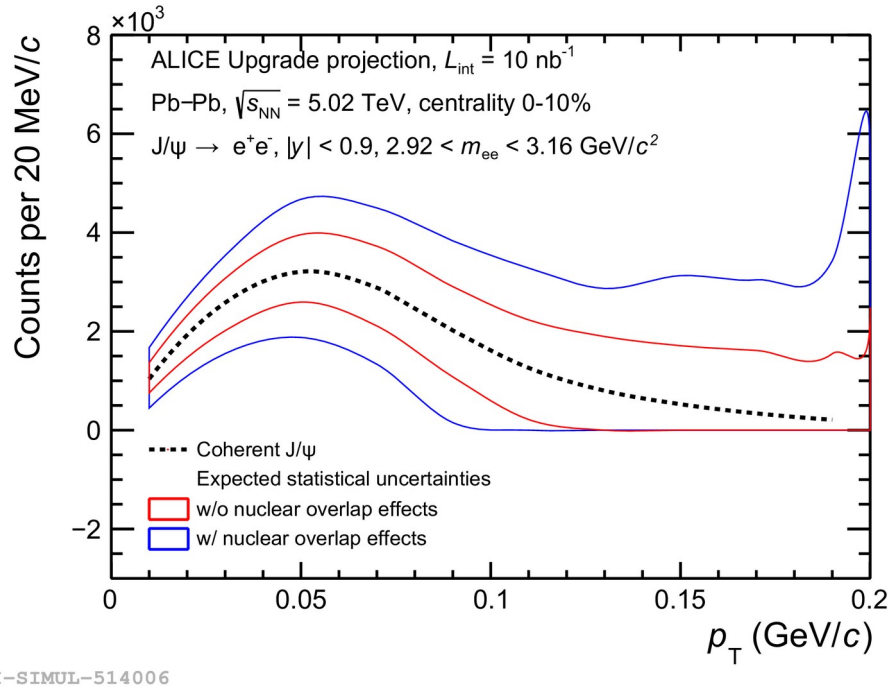
Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107

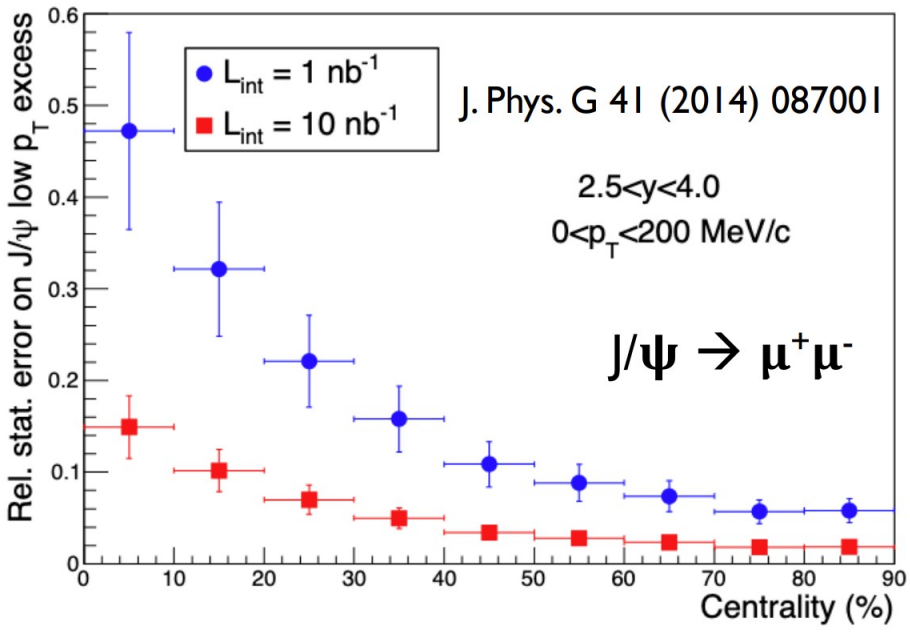
- Very good discrimination power between linear vs saturation models:
  - Coherent production ratio of ψ(2S) / J/ψ
  - Ratio of dissociative / exclusive production

Summary

- Exclusive J/ψ photoproduction differential measurements in UPCs constrain gluon (and quark) distributions in nuclei
  - Models implementing shadowing or saturation tend to agree with data at low-*x*, but not in detail
  - New calculations at NLO suggest large differences with LO and seem to explain coherent J/ψ
- Progress in measurements of coherent J/ψ photoproduction in peripheral collisions
  - Model calculations seem to favour the scenario in which both the photon flux and photo-nuclear cross-section need to exclude the participant region
    - Possible new probe of QGP ?
- Big progress in measurements of single-gap UPC events
  - Di-jets: ATLAS
  - Open charm and quarkonia: ALICE and CMS
- ALICE outlook:
  - large increase in datasets during Run-3 and 4
  - FoCal upgrade will extend kinematic reach for exclusive production down to $x \sim 10^{-6}$

Projections for Run 3 and Run 4

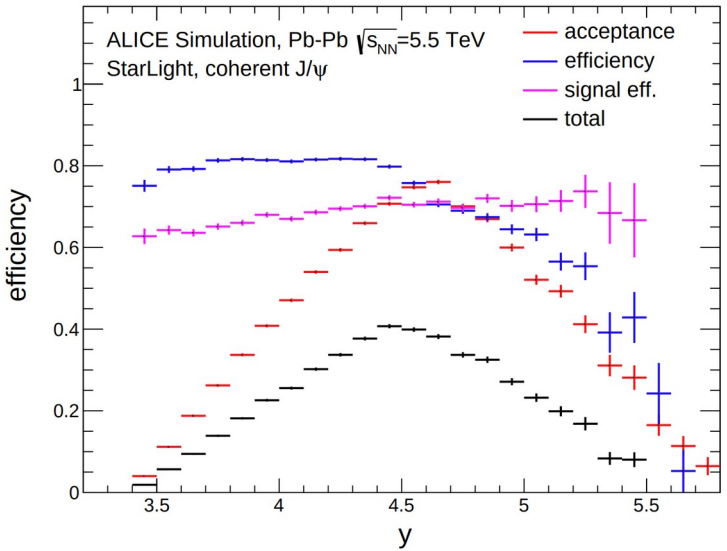




ALI-SIMUL-514006

- Expected integrated luminosity in Pb–Pb: ~10 nb^{-1} at both mid and fwd-*y*
- In central collisions (0-10%), expected significance of coherent yields of 5-10
- Below 10% centrality:
  - Precise measurements of p_T spectrum, azimuthal correlations, polarization

Vector meson photo-production in UPC



- High efficiency (~80%) for J/ψ measurement in e^+e^-
- Coverage up to *y*~5.5

Pb-Pb @ 5.36 TeV, L = 7/nb

VM	$\sigma(\mathrm{Pb+Pb\to Pb+Pb+VM})$	$\sigma(3.4 \le \eta_{1,2} \le 5.8)$	Yield
ρ^0	5.0 b	20 μb	140,000
ϕ	440 mb	10 μb	70,000
J/ψ	39 mb	53 μb	370,000
$\psi(2S)$	7.5 mb	1.1 μb	7,500
$\Upsilon(1S)$	94 μb	5.0 nb	35

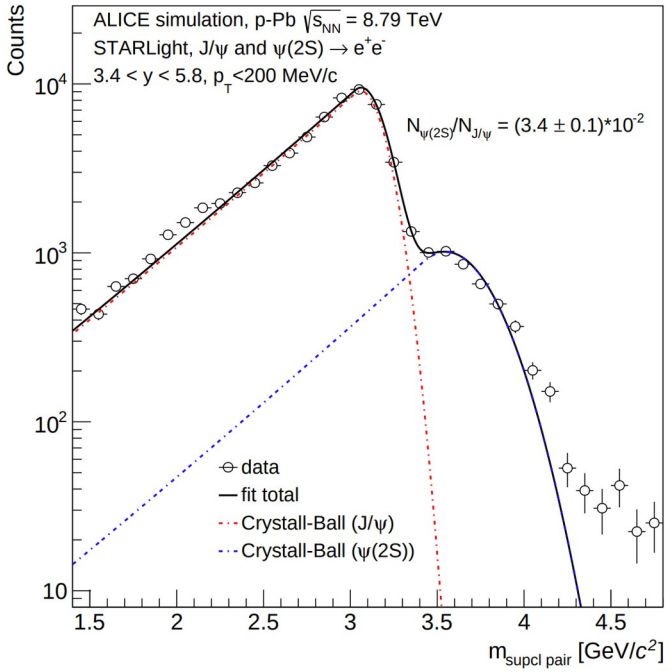
p-Pb, Pb-p @ 8.8 TeV, L = 150/nb

VM	$\sigma(\mathrm{p+Pb\to p+Pb+VM})$	$\sigma(3.4 \le \eta_{1,2} \le 5.8)$ p $\to$ FoCal	Yield p $\to$ FoCal
ρ^0	35 mb	140 nb	21,000
ϕ	1.7 mb	51 nb	7,700
J/ψ	98 μb	400 nb	60,000
$\psi(2S)$	16 μb	8.9 nb	1,300
$\Upsilon(1S)$	220 nb	0.38 nb	60
		Pb $\to$ FoCal	Pb $\to$ FoCal
ρ^0	35 mb	17 nb	2,600
ϕ	1.7 mb	5.3 nb	800
J/ψ	98 μb	36 nb	5,400
$\psi(2S)$	16 μb	0.53 nb	80
$\Upsilon(1S)$	220 nb	0.67 pb	~ 0

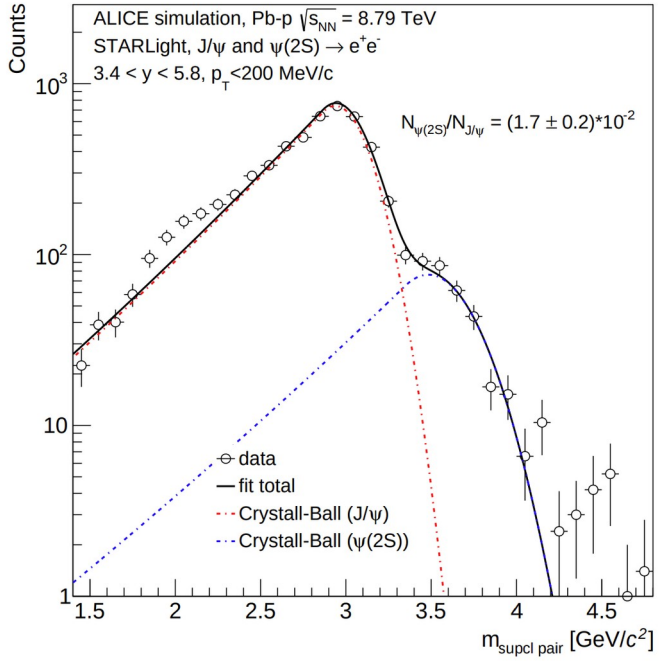
Bylinkin, Nystrand, Tapia Takaki, arXiv:2211.16107

J/ψ and ψ' reconstruction in p-Pb and Pb-p

p-Pb (low-$W_{\gamma p}$)



Pb-p (high-$W_{\gamma p}$)



- Simulation studies done with realistic expectations of quarkonia yields
- ψ(2S)/J/ψ ratio expected to be measured with about **3%** and **12%** statistical uncertainty in **p-Pb (low-*W*)** and **Pb-p (high-*W*)**, respectively