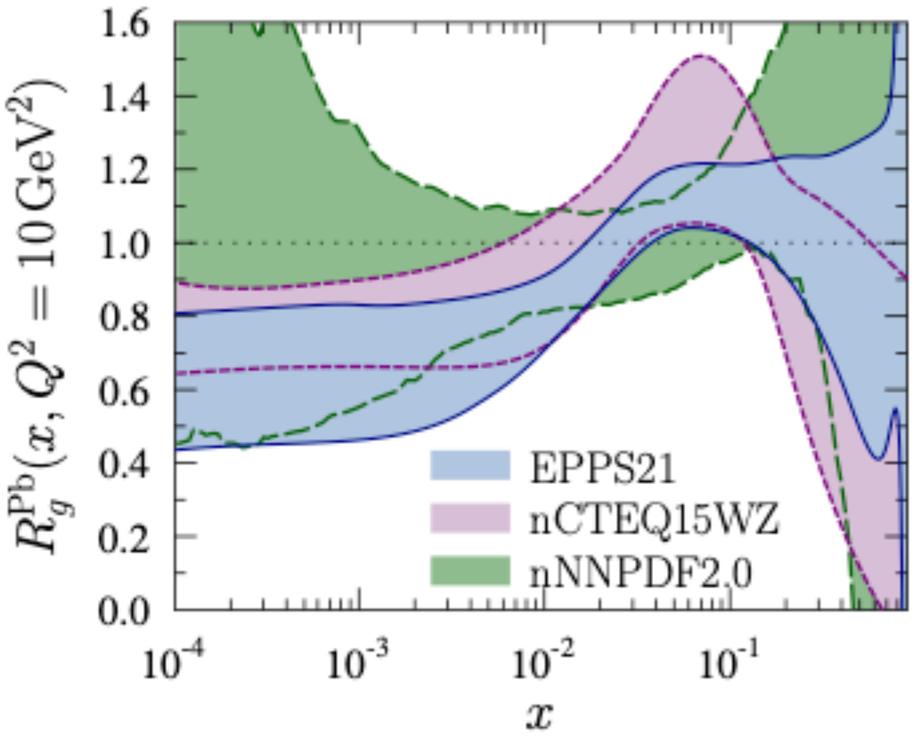
Diffractive Physics from LHC to EIC
probing gluons in nuclei with photoproduction

Minjung Kim
(UC Berkeley / CFNS, Stony Brook U.)

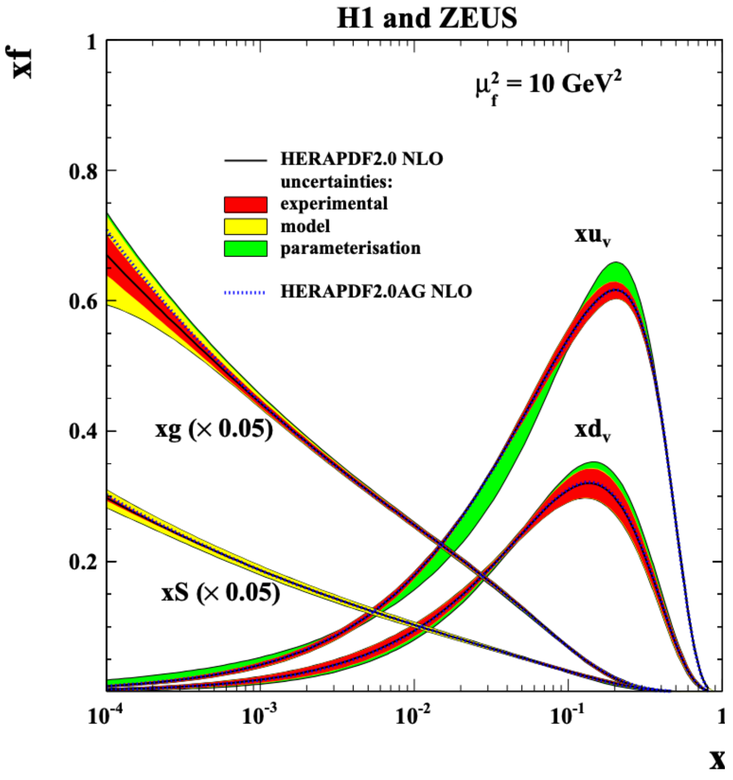
2023 CFNS Postdoc Meet
17. Oct. 2023 (TUE)

Probing gluons in nuclei

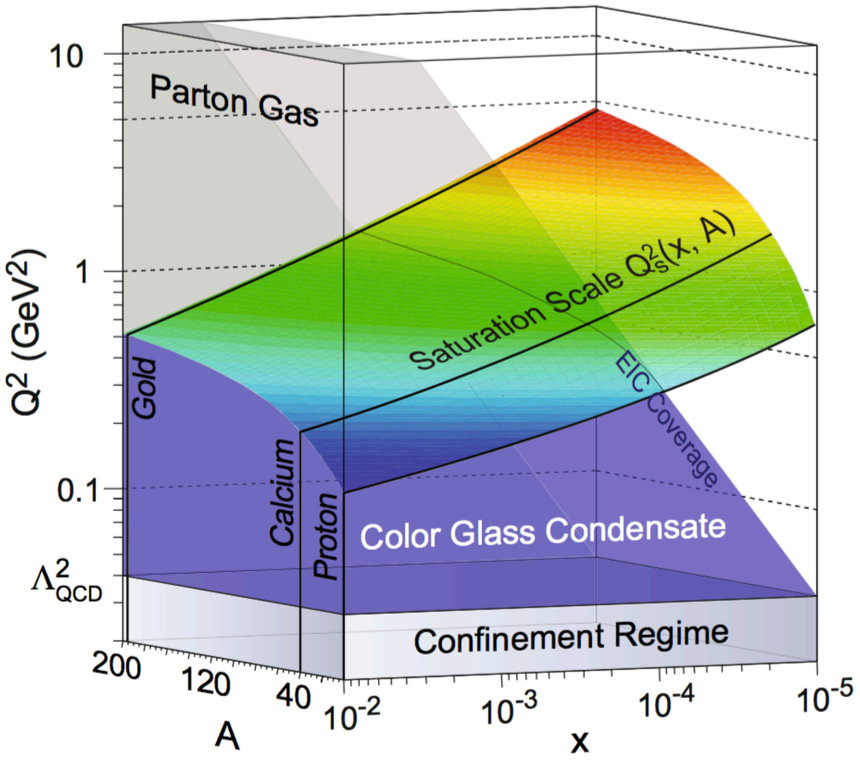
Eskola et al, EPJC 82 (2022) 413



H1 and Zeus, EPCJ 75 (2015) 580



Accardi et al, EPJA 52 (2016) 268



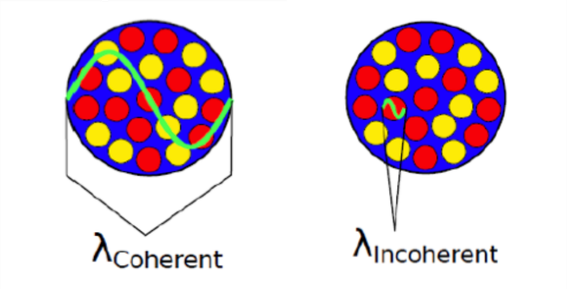
- Nucleus gluon field is not simple superposition of A nucleon fields
- More general question: Where and how does the transition from a dilute parton system to a dense gluon regime state occur?
- Saturation is expected to set at higher x in heavy nuclei!

Ultra-peripheral heavy-ion collisions at the LHC

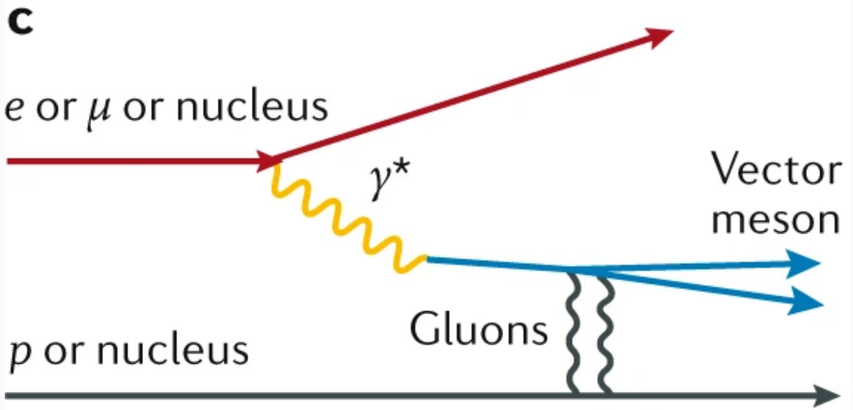
- EM field from ultra-relativistic ions: a beam of quasi real photons (intensity ≈ Z^2)

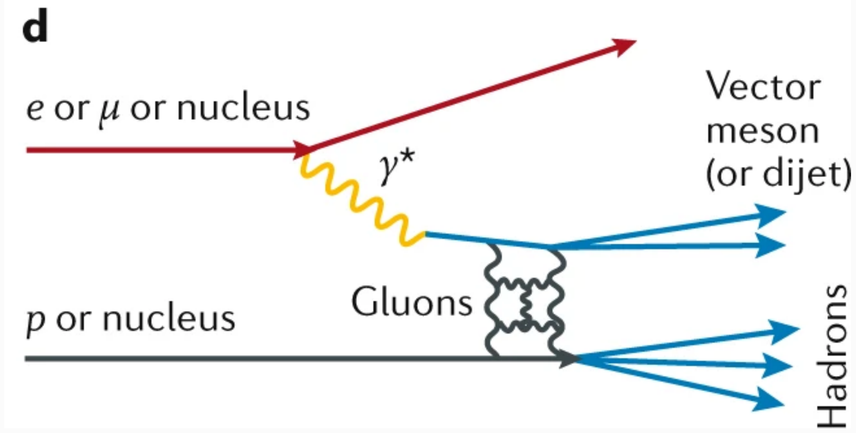
➡Photon energy frontier: up to ~ 500 TeV in target frame at the LHC energies

- Photo-nuclear interaction in ultra-peripheral collisions (UPC): collisions with an impact parameter greater than the sum of the radii of the colliding nuclei, in which hadronic interactions are strongly suppressed
- Lowest-order cross section proportional to the gluon distribution, leading final states such vector meson or dijet
- Coherent and incoherent processes provide complementary informations on gluon density

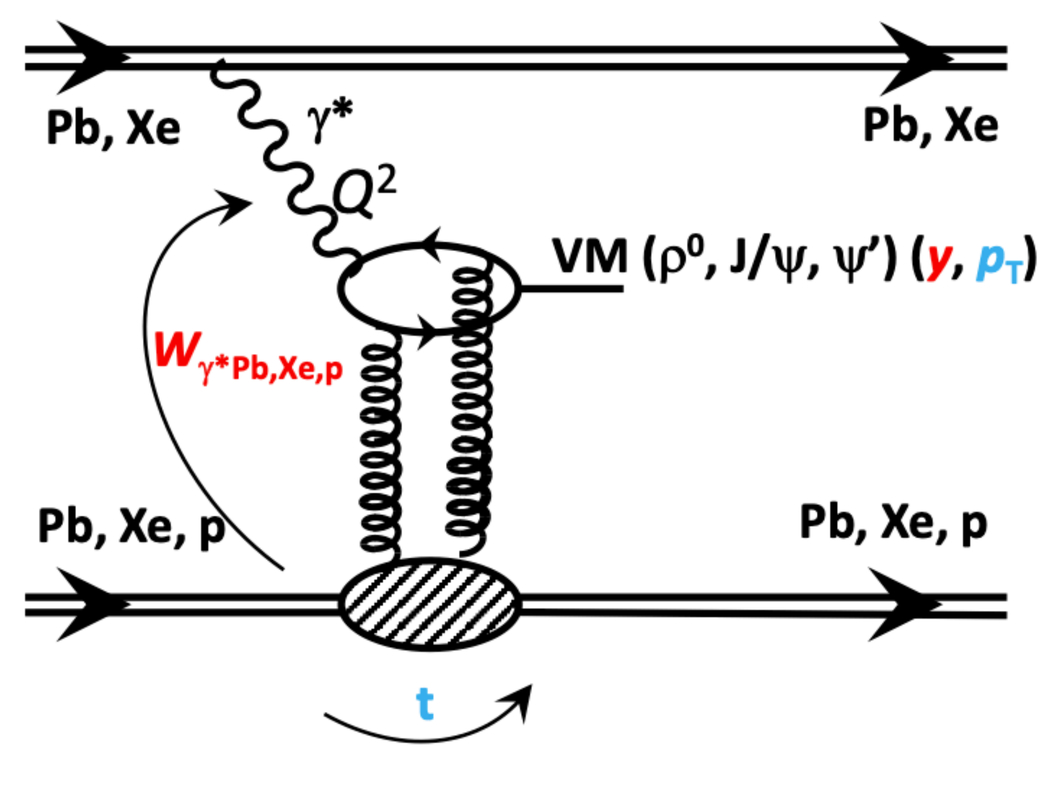


S. Klein, H. Mäntysaari, Nature Reviews Physics 1, 662–674 (2019)





Vector meson photoproduction in UPC

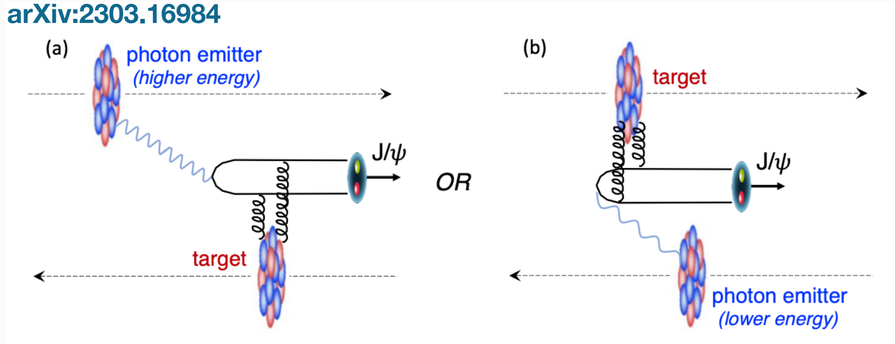


- Photon fluctuates to a $q\bar{q}$ dipole which then elastically scatters off the nucleus, emerging as vector meson having $J^{PC} = 1^{--}$
- Kinematic variables are accessible via measurement:
  - photon virtuality: $Q^2 \sim (M_V/2)^2$
  - Bjorken-x: $x_B = \frac{M_V}{\sqrt{s_{NN}}} e^{\pm y_V}$
  - Photon-target center of mass energy: $W^2_{\gamma-\text{target}} = 2E_{\text{target}} M_V e^{\mp y}$
  - Mandelstam t probing transverse structure of the target: $|t| \approx p_T{}^2$

Photon two-way ambiguity in UPC

- Ambiguity due to sign in the rapidity of the photon emitter

arXiv:2303.16984



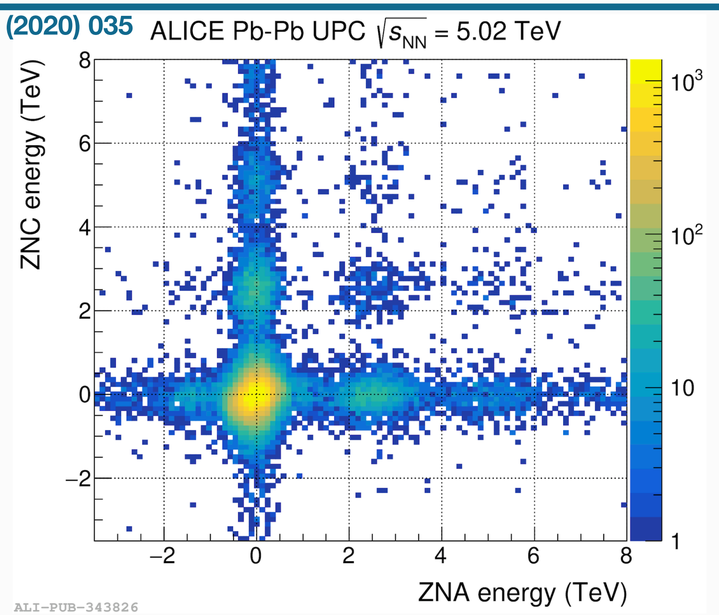
$$x_B = \frac{M_V}{\sqrt{s_{NN}}} e^{\pm y_V}, i.e. y = 3 \rightarrow x \approx 10^{-2} \text{ or } 10^{-5} \text{ for J}/\psi \text{ at LHC energies}$$

- High probability to exchange one or more additional (low energy) photons in a UPC, leading electromagnetic dissociation of ions, to breakup of the nucleus
  ⇒ Neutrons emitted in the forward direction

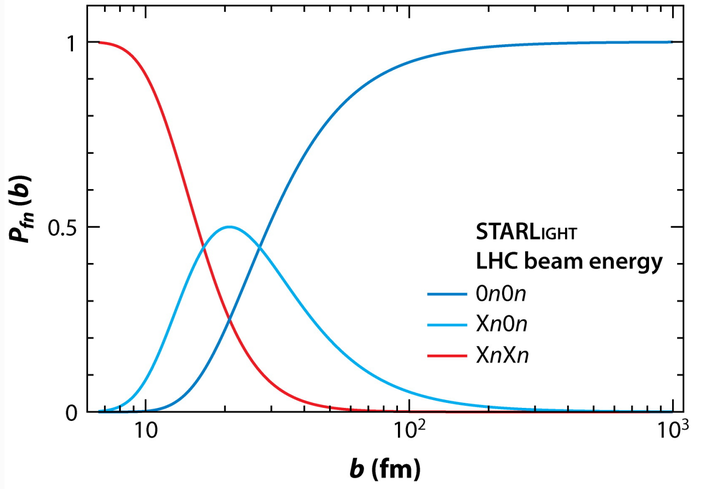
Guzey et al., Eur.Phys.J.C 74 (2014) 7, 2942

- Probability to emit additional photons is assumed to factorize in impact parameter space
  ⇒ ZDC measurements provide impact parameter information for photon flux estimation

ALICE, JHEP 06 (2020) 035



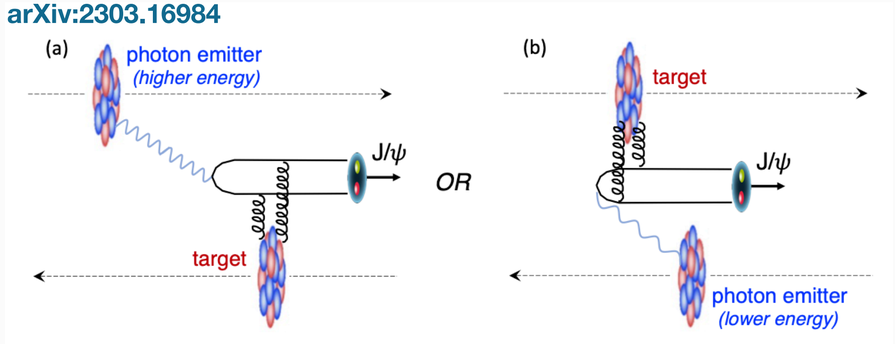
S.Klein, P. Steinberg Annu. Rev. Nucl. Part. Sci, 70 (2020)-323-54



Photon two-way ambiguity in UPC

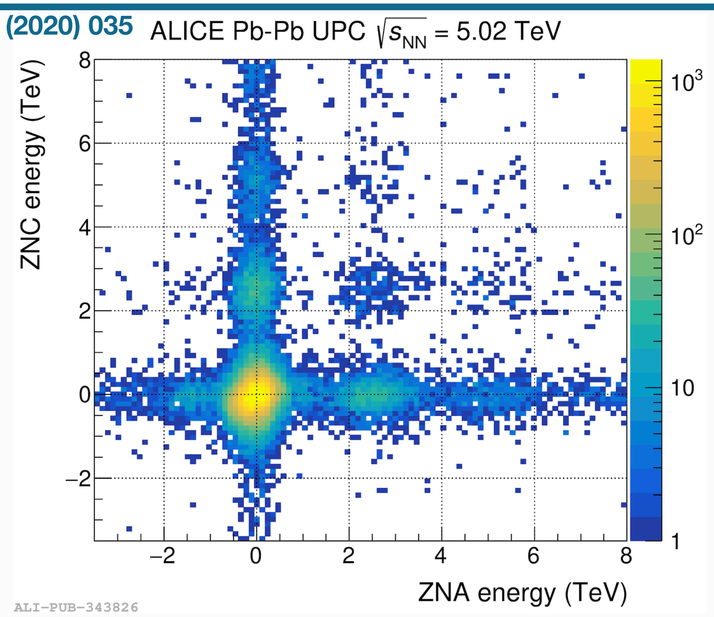
- Ambiguity due to sign in the rapidity of the photon emitter

arXiv:2303.16984



$$x_B = \frac{M_V}{\sqrt{s_{NN}}} e^{\pm y_V}, i.e. y = 3 \rightarrow x \approx 10^{-2} \text{ or } 10^{-5} \text{ for J/}\psi \text{ at LHC energies}$$

ALICE, JHEP 06 (2020) 035



S.Klein, P. Steinberg Annu. Rev. Nucl. Part. Sci. 70 (2020)-323-54

- High probability to exchange one or more additional (low energy) photons in a UPC, leading electromagnetic dissocia… to breakup of the nucleus
  ⇒ Neutrons emitted in the forward direction

Guzey et al., Eur.Phys.J.C 74 (2014) 7, 2942

- Probability to emit additional photons is assumed to… impact parameter space
  ⇒ ZDC measurements provide impact parameter inf… photon flux estimation

$$\frac{d\sigma_{0n0n}}{dy} = n_{0n0n}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{0n0n}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

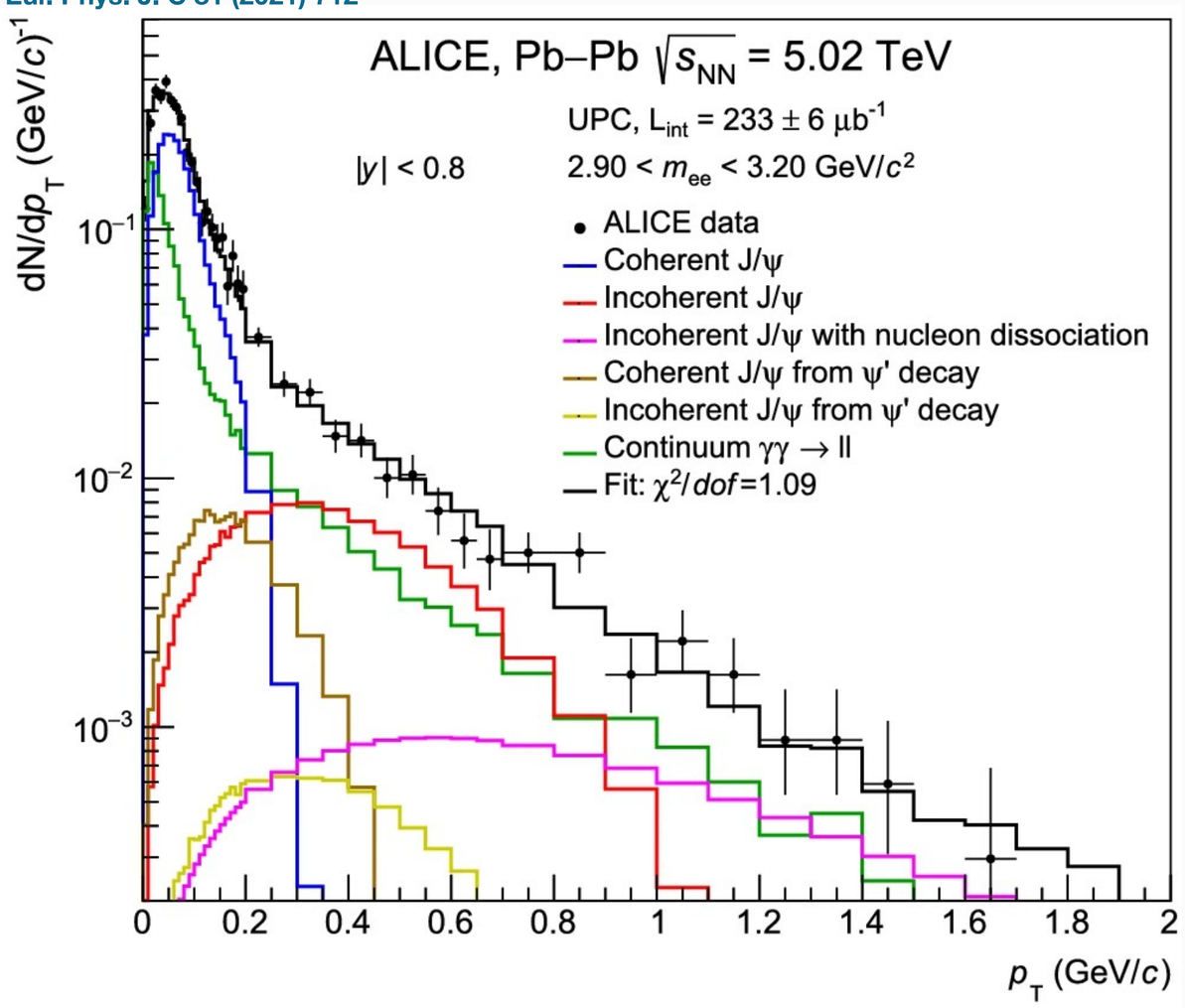
$$\frac{d\sigma_{Xn0n}}{dy} = n_{Xn0n}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{Xn0n}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

$$\frac{d\sigma_{XnXn}}{dy} = n_{XnXn}(k_1)\sigma_{\gamma A}(W_{\gamma p1}) + n_{XnXn}(k_2)\sigma_{\gamma A}(W_{\gamma p2})$$

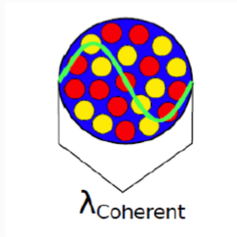
A system of equations which can be solved to extract $\sigma_{\gamma A}(W_1)$ and $\sigma_{\gamma A}(W_2)$

Exclusive photoproduction of J/ψ

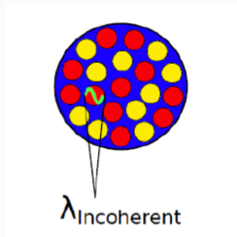
Eur. Phys. J. C 81 (2021) 712



- Good-Walker formalism links coherent and incoherent production to the average nuclear configuration and event-by-event fluctuations respectively



$< p_T > \propto 1/R_{ion} \approx 50$ MeV/c



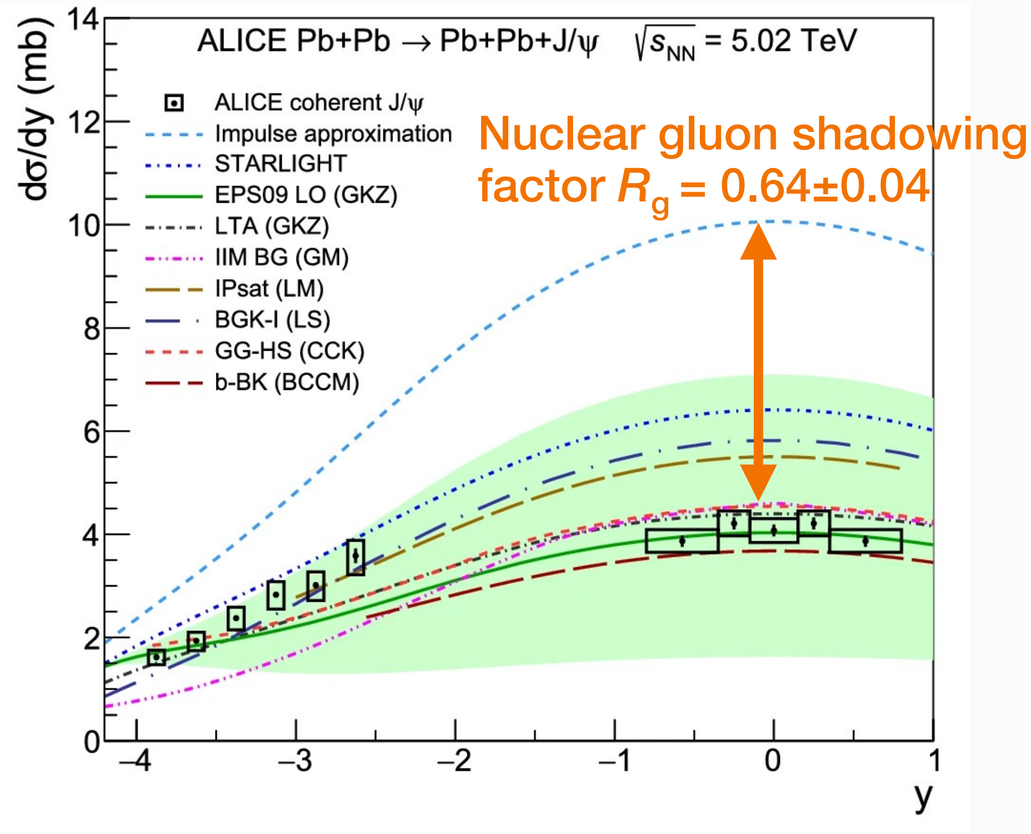
$< p_T > \propto 1/R_{nucleon} \approx 500$ MeV/c

S. Klein, Phys. Rev. C 107, 055203

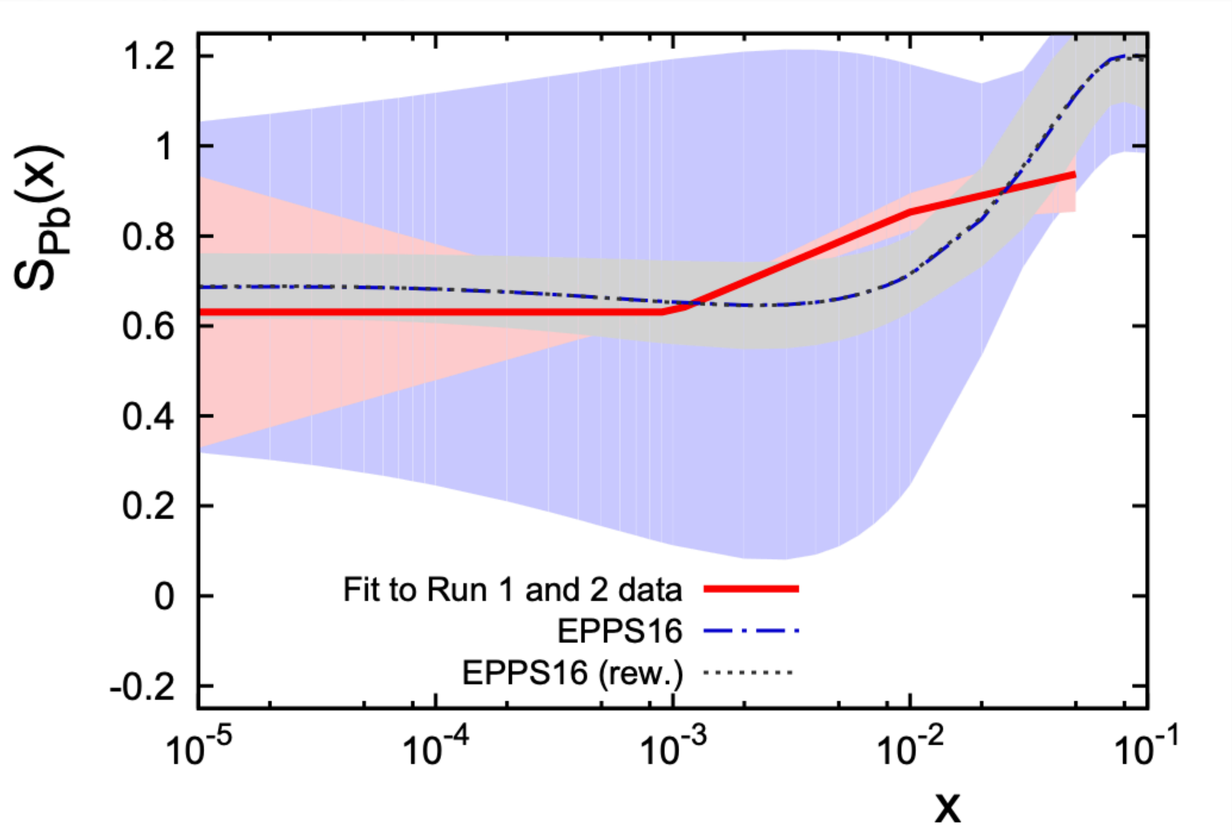
- Caveat: UPCs and eA collisions may involve multiple photons; other possible sub-reactions or different time-scale,…
  ⇒ Interpretation of incoherent production is not trivial!

Coherent J/ψ photoproduction constraining gluon density

Eur. Phys. J. C 81 (2021) 712

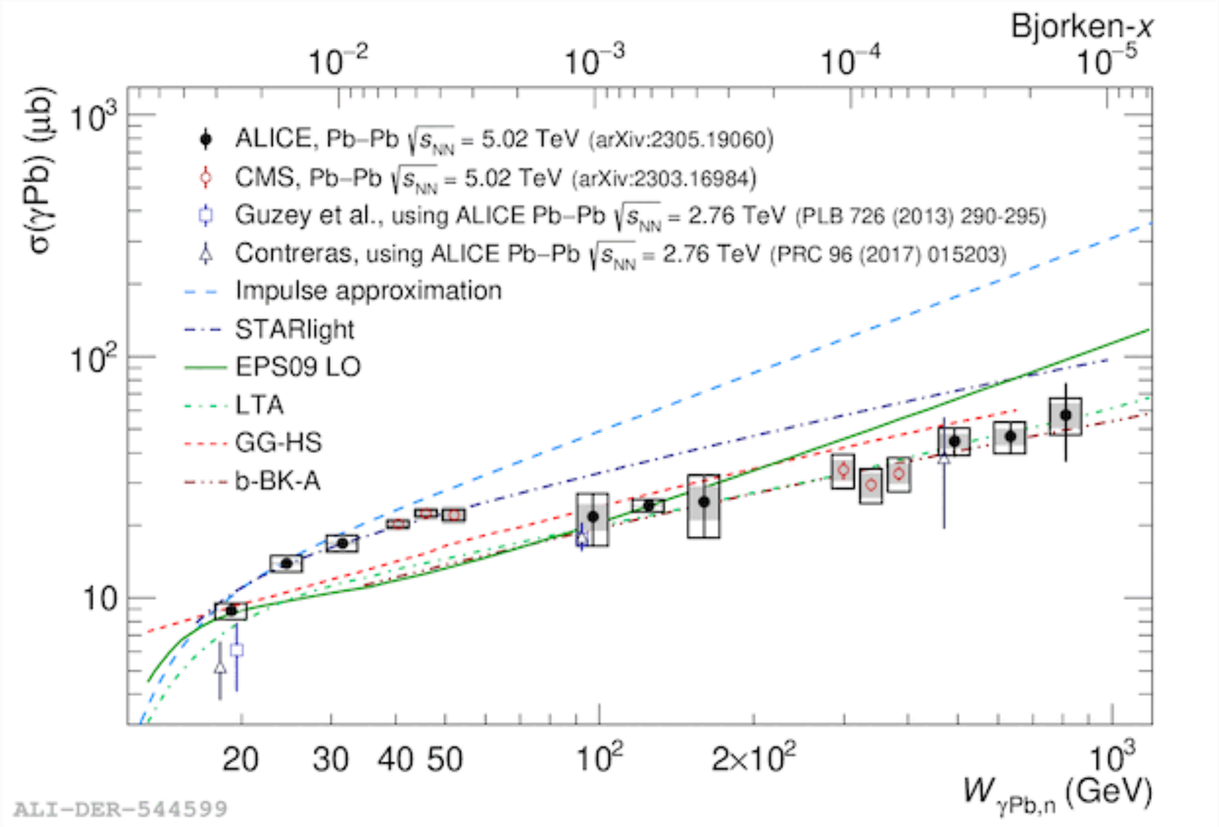


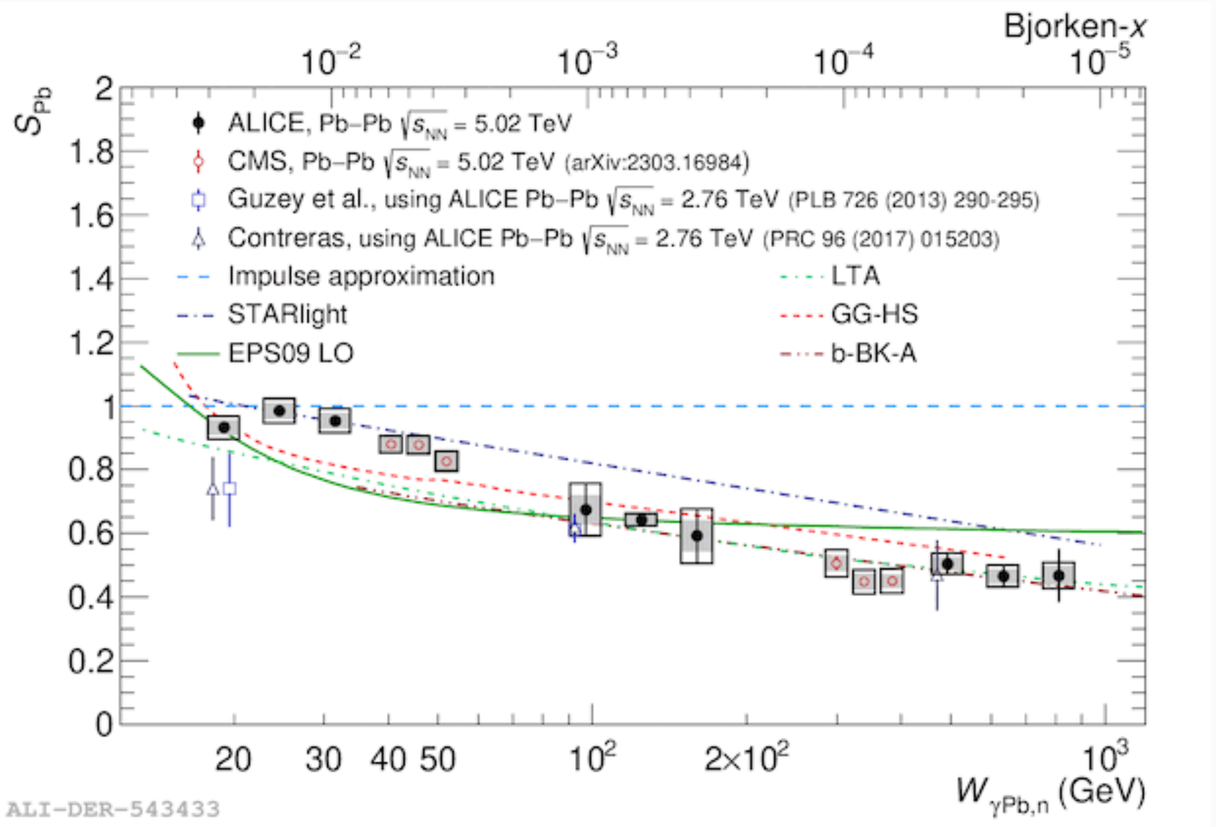
Guzey et al. Phys.Lett.B 816 (2021) 136202



- Midrapidity: $x \in (0.3, 1.4) \times 10^{-3}$, compatible with models predicting moderate shadowing
- 2-fold photon directional ambiguity in forward rapidity:
  $x \in (1.1,5.1) \times 10^{-5}$ or $x \in (0.7,3.3) \times 10^{-2}$

Energy/Bjorken-x dependence coherent J/ψ photoproduction

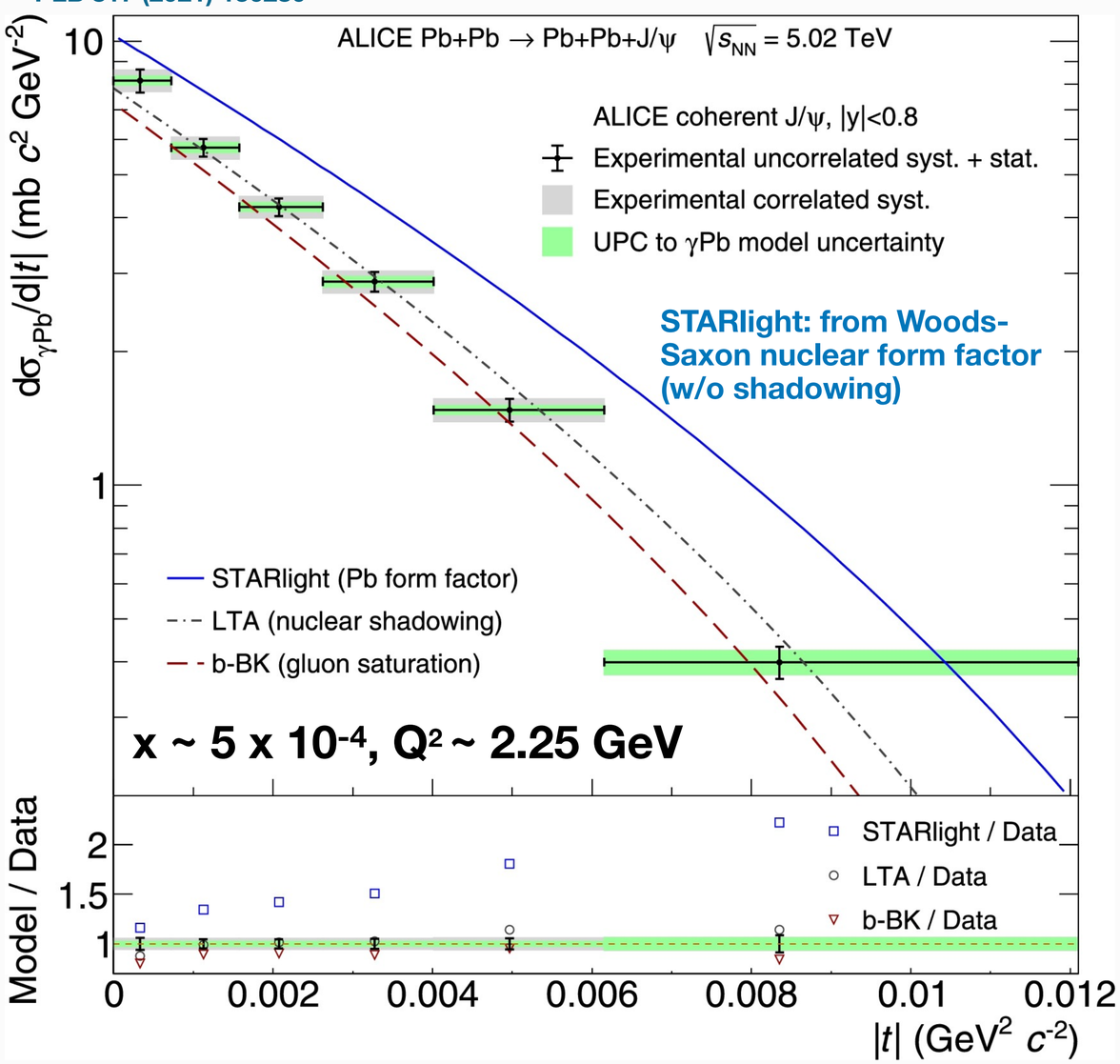




- Complementary measurements of ALICE and CMS in wide energy (Bjorken-x) range
- While impulse approximation and STARlight work at low energies, shadowing and saturation based models describe suppression at high energies

ltl-dependent coherent J/ψ in UPCs

PLB 817 (2021) 136280



- The square of the momentum transferred to the target nucleus is related through a two-dimensional Fourier transform to the gluon distribution in the plane transverse to the interaction
(b and t are Fourier conjugates)
- The lowest-order pQCD coherent vector meson photoproduction:

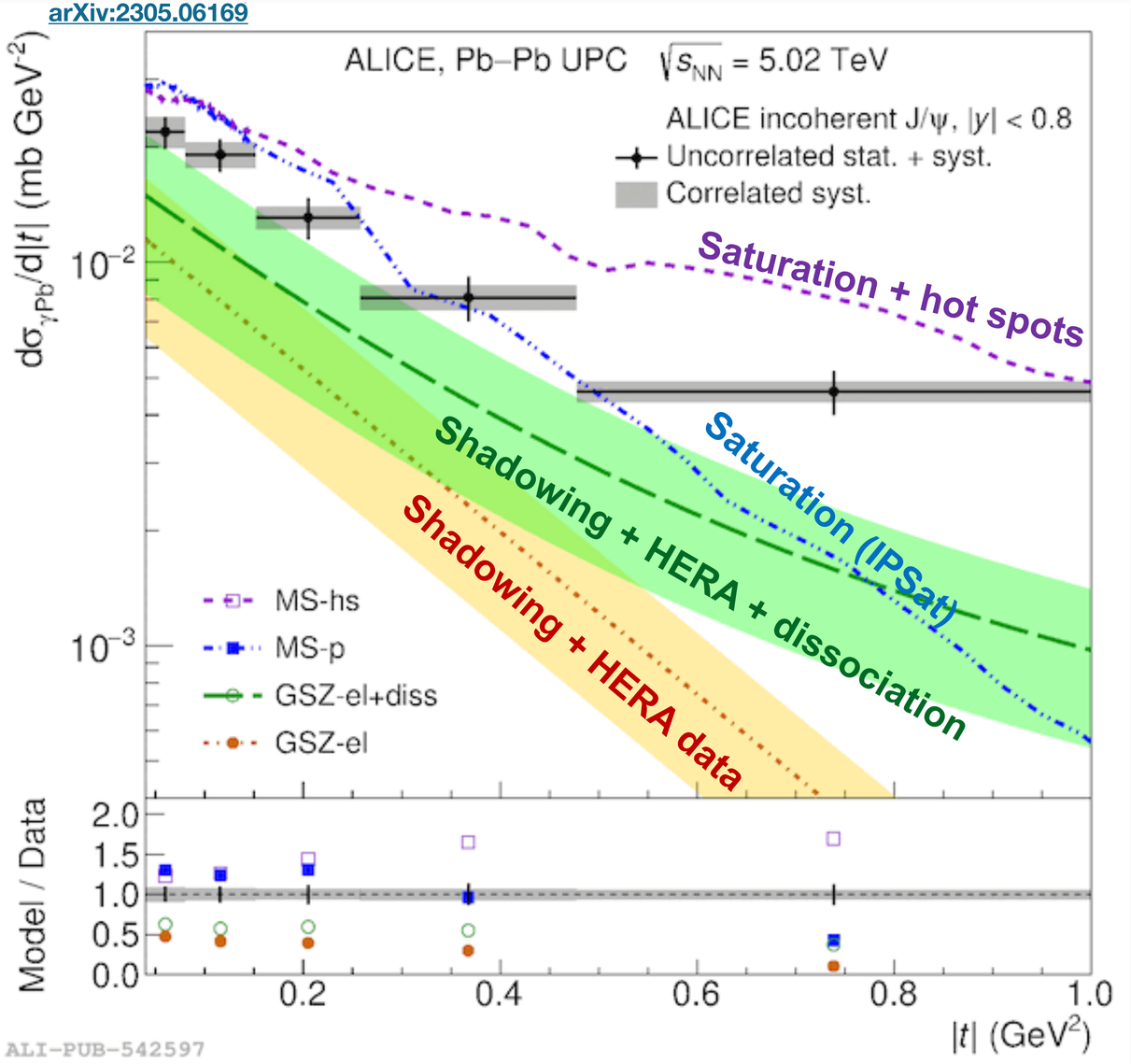
$$\frac{d\sigma_{coh}}{dt} = \frac{\pi^3 \alpha_s^2 M^3 \Gamma_{V\to e^+ + e^-}}{3\alpha_{em}} \left[\frac{1}{(2q^2)^2} xg(x,q^2)\right]^2 F_N^{2g}(t)^2$$

Phenomenological two-gluon form factor describing gluon distribution of nucleus in transverse plane

- Falls off more steeply than the Woods-Saxon nuclear form factor; consistent with dipole model calculations that include nuclear shadowing and/or gluon saturation

ltl-dependent incoherent J/ψ in UPCs

arXiv:2305.06169



- Models including gluonic subnucleon fluctuations (hot spots or dissociation) agree better with the slope of the measurement
- First measurement of its kind ever
  ⇒ complementary measurements needed

J/ψ photoproduction: updates from theory

- pQCD calculation with shadowing:
  - at LO: only gluon contributes
  - at NLO: quark and additional internal gluon
- Considerable scale dependence
- Difficult to reproduce rapidity dependence in measurements

Gyzey et al. arXiv:2303.12630

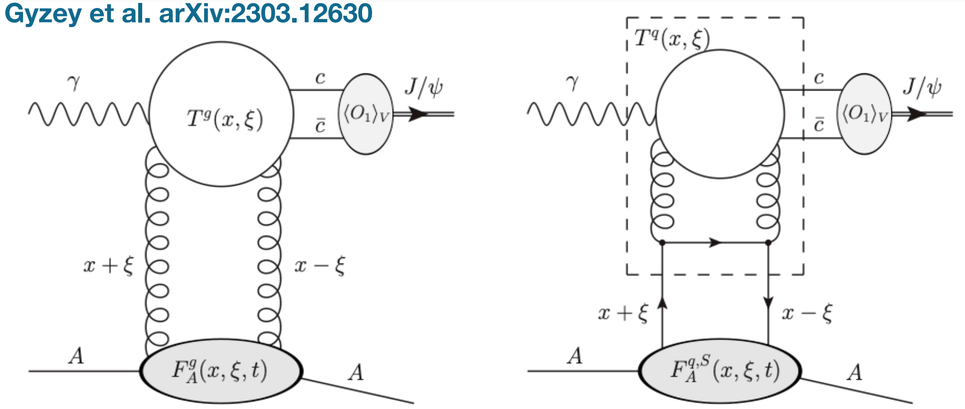
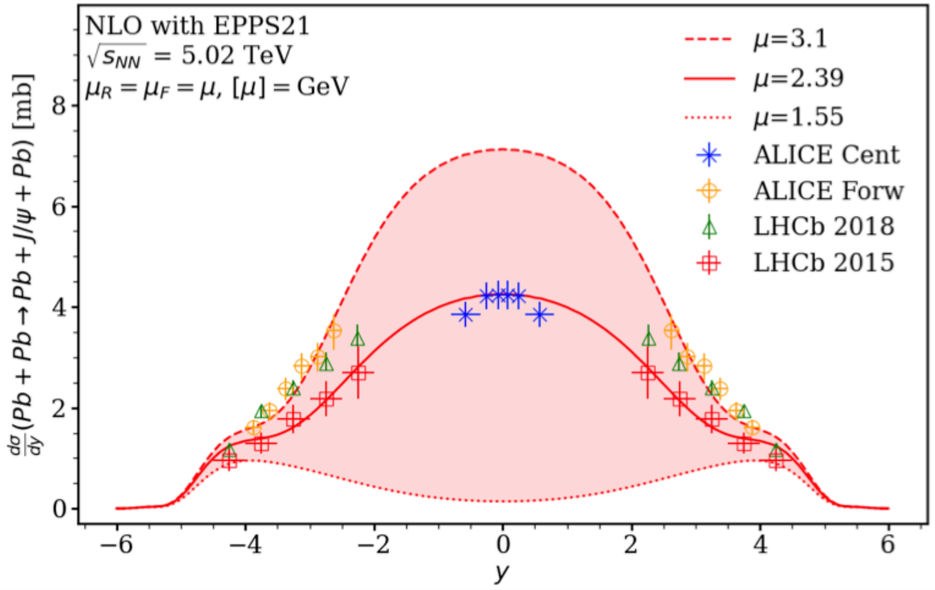


Fig. 1. Graphical representation of the $\gamma + A \to J/\psi + A$ amplitude in NLO pQCD: gluon (left) and quark (right) contributions.



J/ψ photoproduction: updates from theory

- pQCD calculation with shadowing:
  - at LO: only gluon contributes
  - at NLO: quark and additional internal gluon
- Considerable scale dependence
- Difficult to reproduce rapidity dependence in measurements
- Large contribution of quarks (and additional interference); LO and NLO gluon amplitudes tend to cancel

Gyzey et al. arXiv:2303.12630

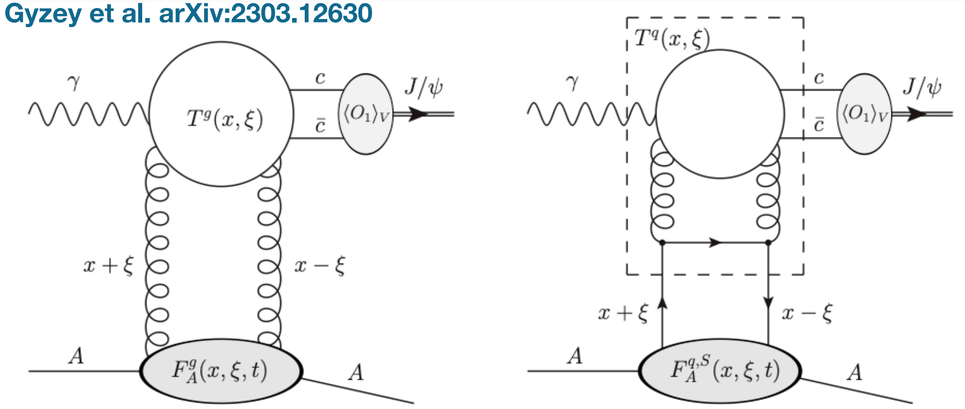
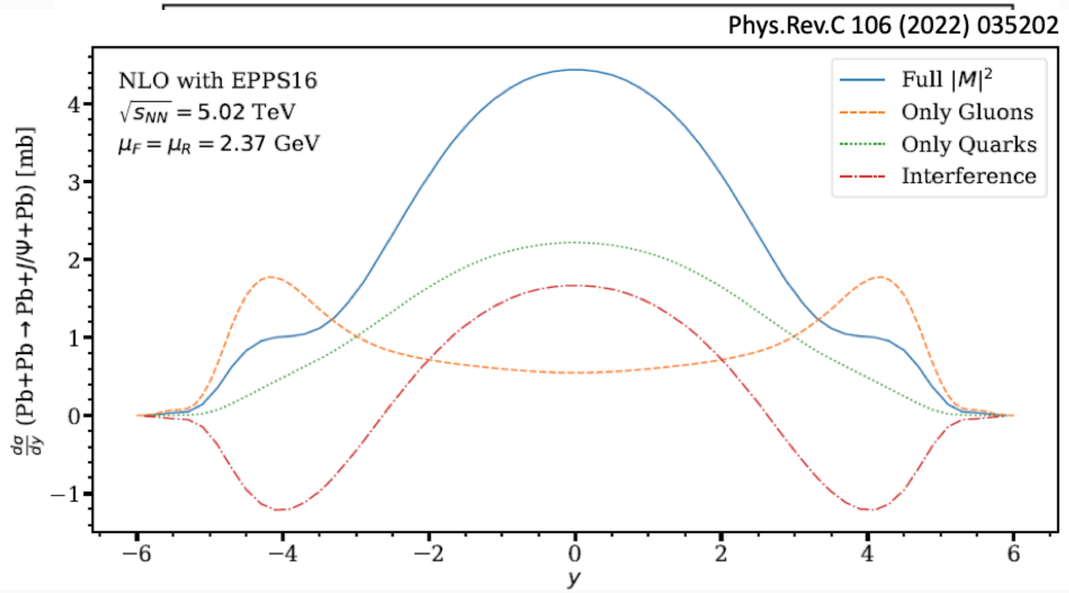


Fig. 1. Graphical representation of the $\gamma + A \to J/\psi + A$ amplitude in NLO pQCD: gluon (left) and quark (right) contributions.

Phys.Rev.C 106 (2022) 035202



J/ψ photoproduction: updates from theory

- pQCD calculation with shadowing:
  - at LO: only gluon contributes
  - at NLO: quark and additional internal gluon
- Considerable scale dependence
- Difficult to reproduce rapidity dependence in measurements
- Large contribution of quarks (and additional interference); LO and NLO gluon amplitudes tend to cancel
- Dipole picutre: inclusion of higher qqg Fock states by introducing 3—body dipole cross section and wave function better describes the measurements

A. Łuszczak, W. Schäfer, arXiv:2108.06788

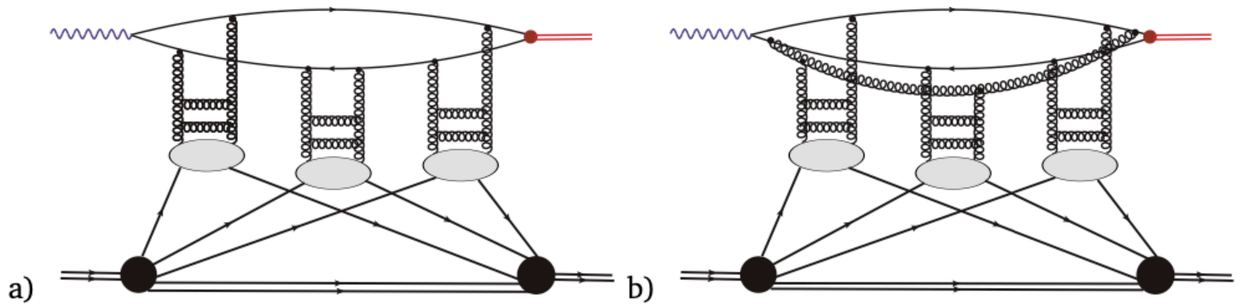
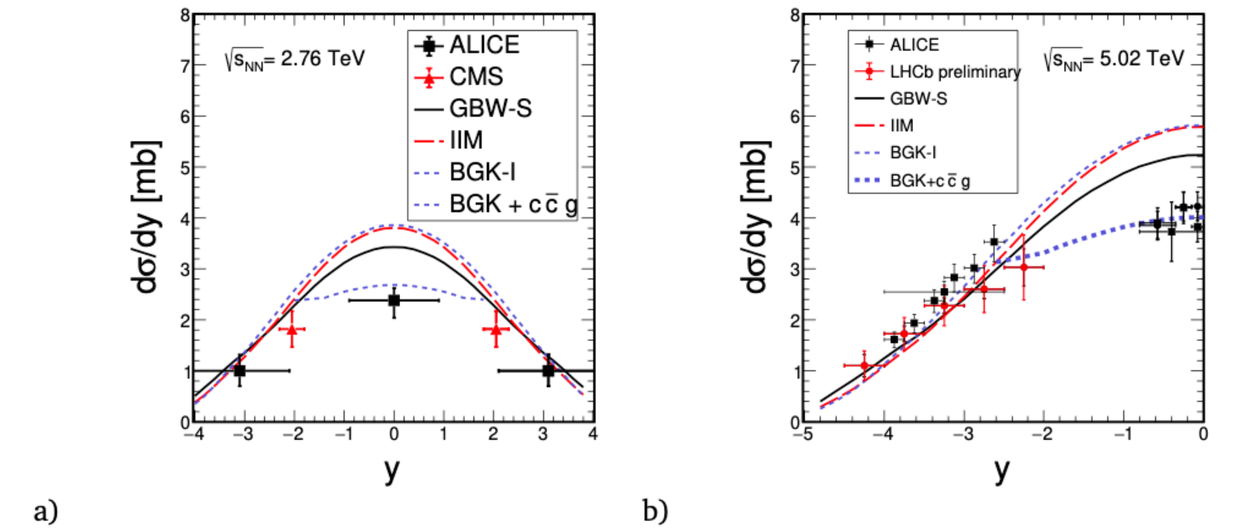
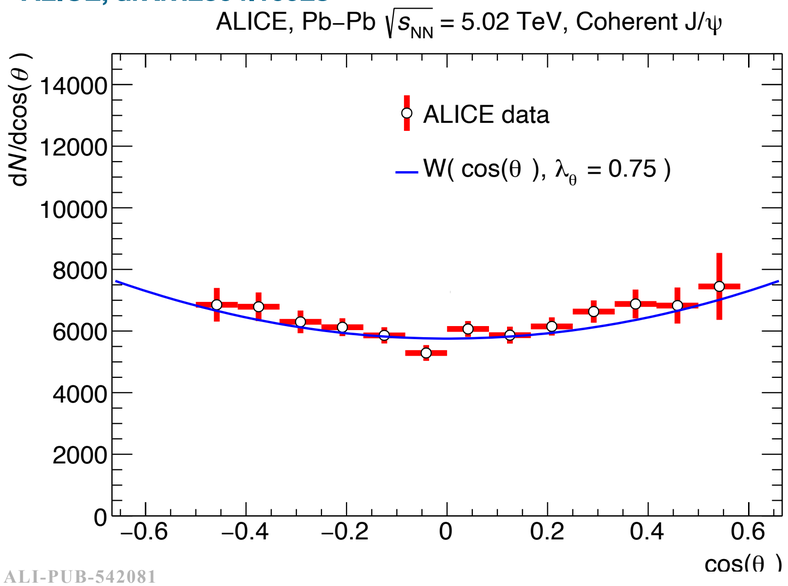


Figure 1: Coherent photoproduction of a vector meson in which the nucleus stays in its ground state.

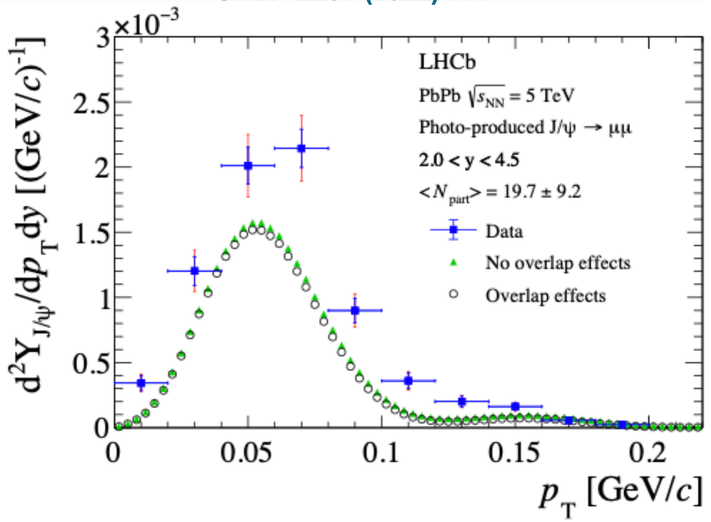


Photon-induced processes not covered today……

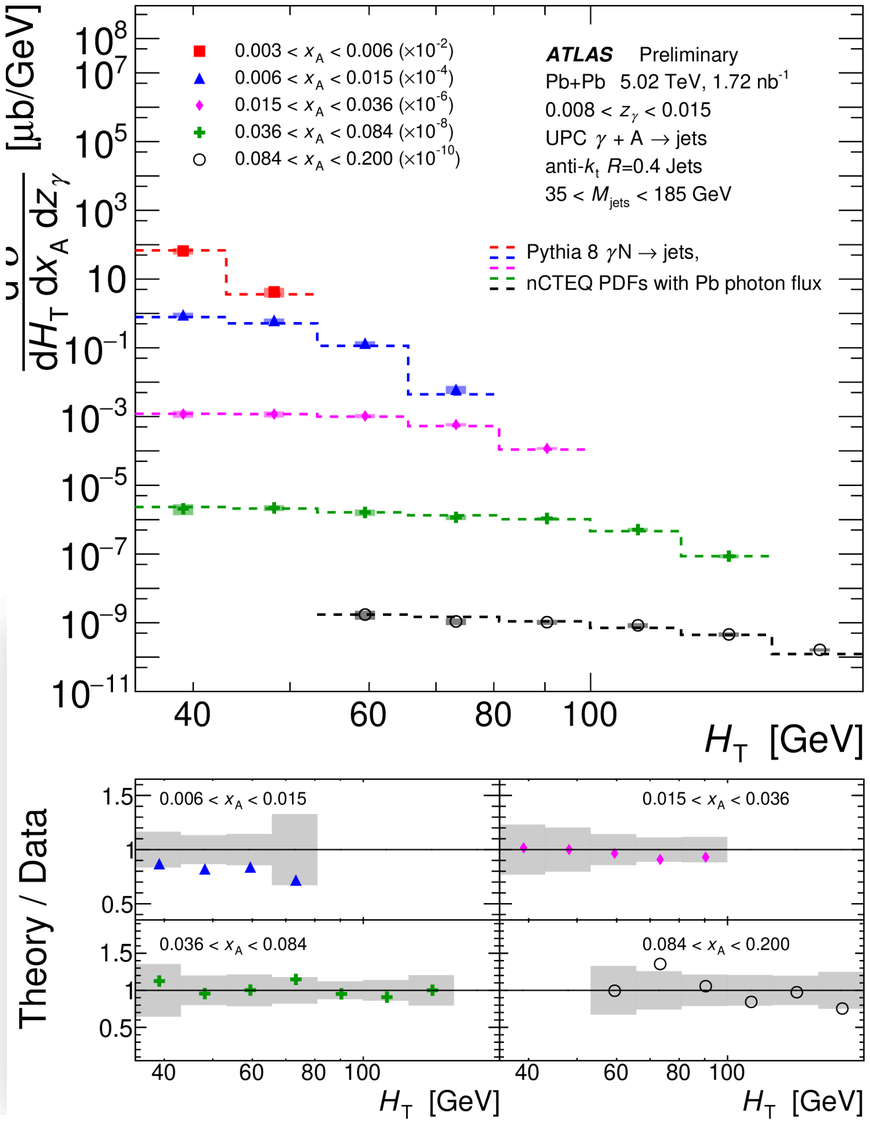
ALICE, arXiv:2304.10928



JHEP 2207 (2022) 117

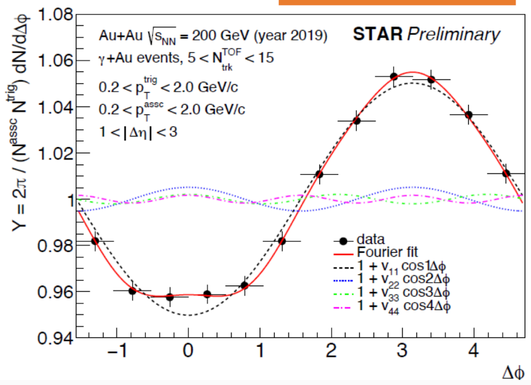


http://cds.cern.ch/record/2806461/files/ATLAS-CONF-2022-021.pdf

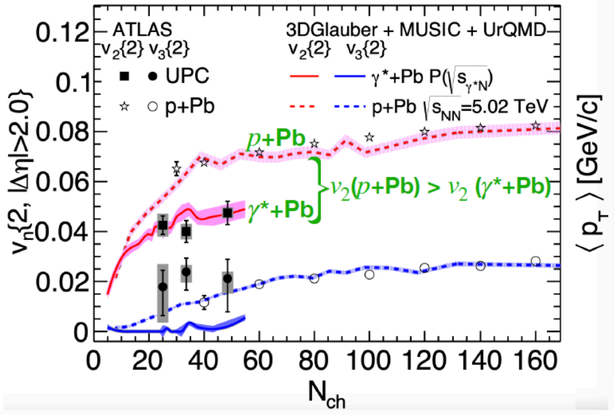


QGP-like signatures in UPC?

Shengli Huang (STAR)



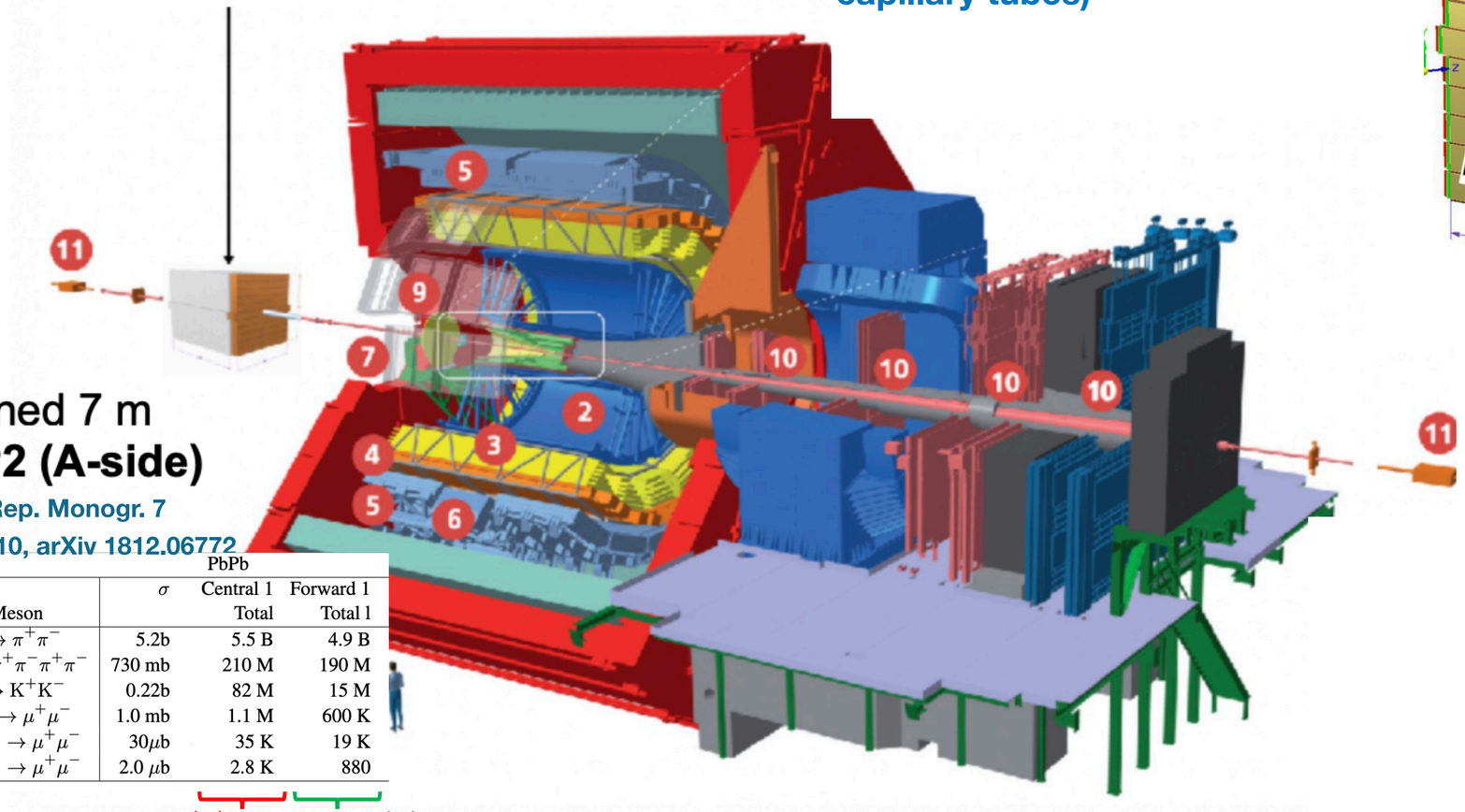
Sruthy Jyothi Das (ATLAS)



FOCAL: a Forward Calorimeter in ALICE (Run 4)

3.4 < η < 5.8
FOCAL

FOCAL-E (Si-W EM calorimeter)
FOCAL-H (Scintillating fibers in Cu capillary tubes)



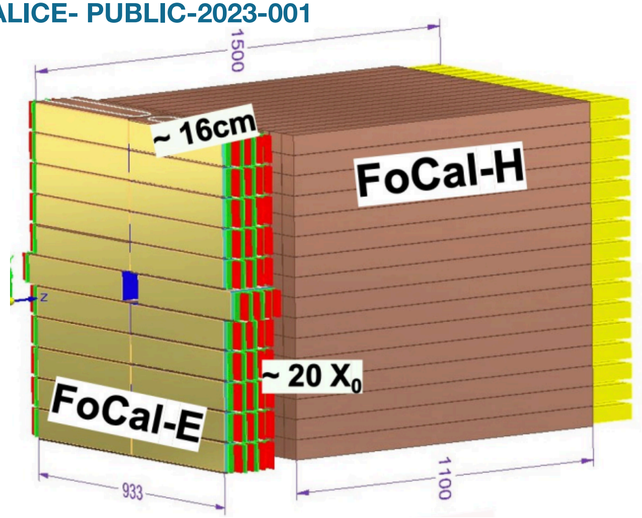
Positioned 7 m from **IP2 (A-side)**

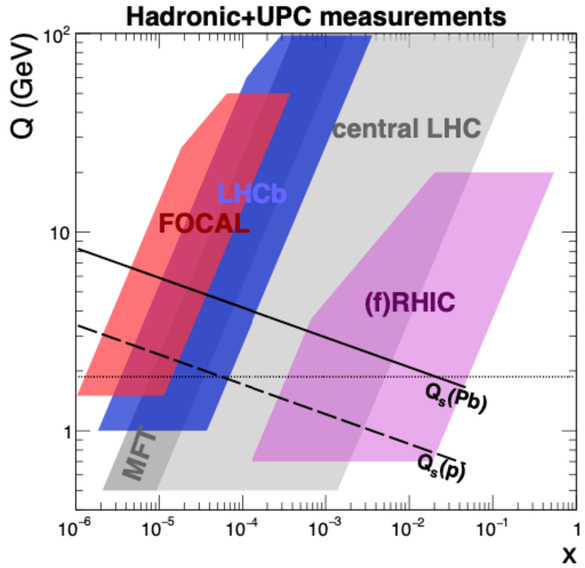
CERN Yellow Rep. Monogr. 7 (2019) 1159-1410, arXiv 1812.06772

Meson	σ	PbPb Central 1 Total	PbPb Forward 1 Total 1
$\rho \to \pi^+\pi^-$	5.2b	5.5 B	4.9 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	210 M	190 M
$\phi \to K^+K^-$	0.22b	82 M	15 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	1.1 M	600 K
$\psi(2S) \to \mu^+\mu^-$	30μb	35 K	19 K
$\Upsilon(1S) \to \mu^+\mu^-$	2.0 μb	2.8 K	880

$|y| < 0.9$ $2.5 < |y| < 4$

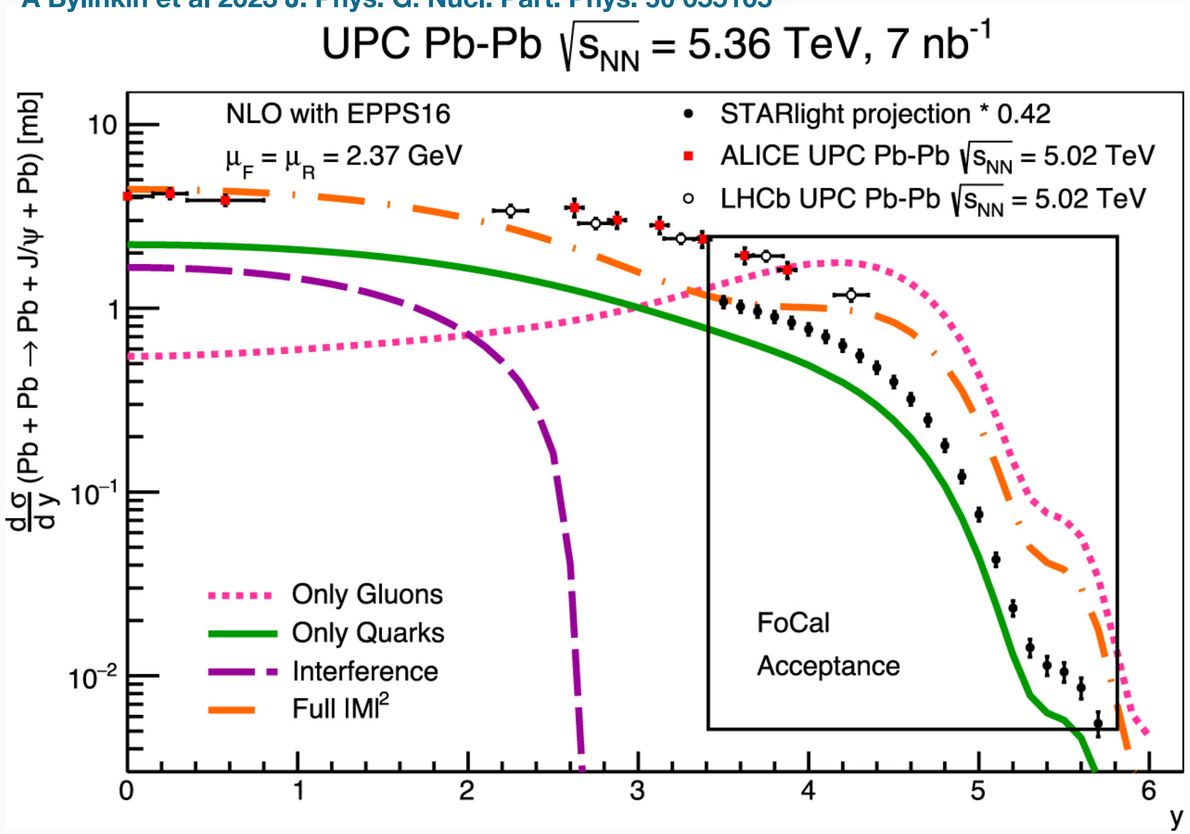
ALICE- PUBLIC-2023-001

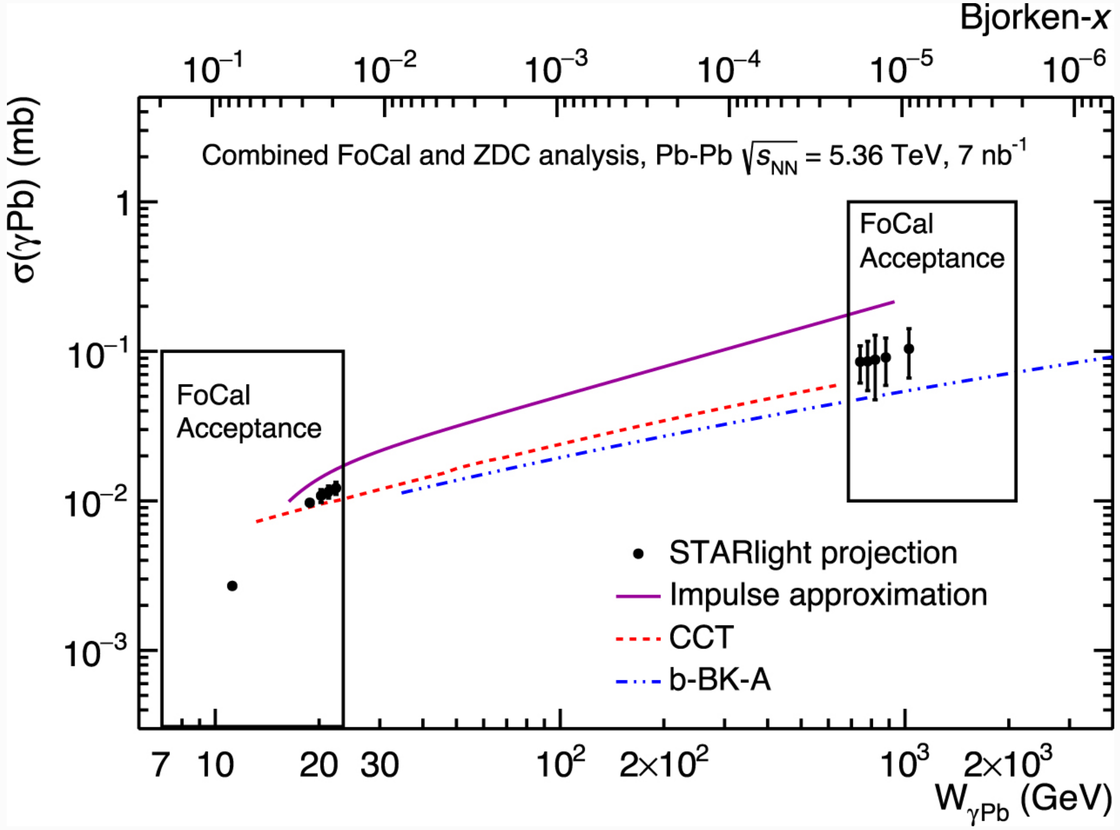




J/ψ photoproduction with FOCAL

A Bylinkin et al 2023 J. Phys. G: Nucl. Part. Phys. 50 055105

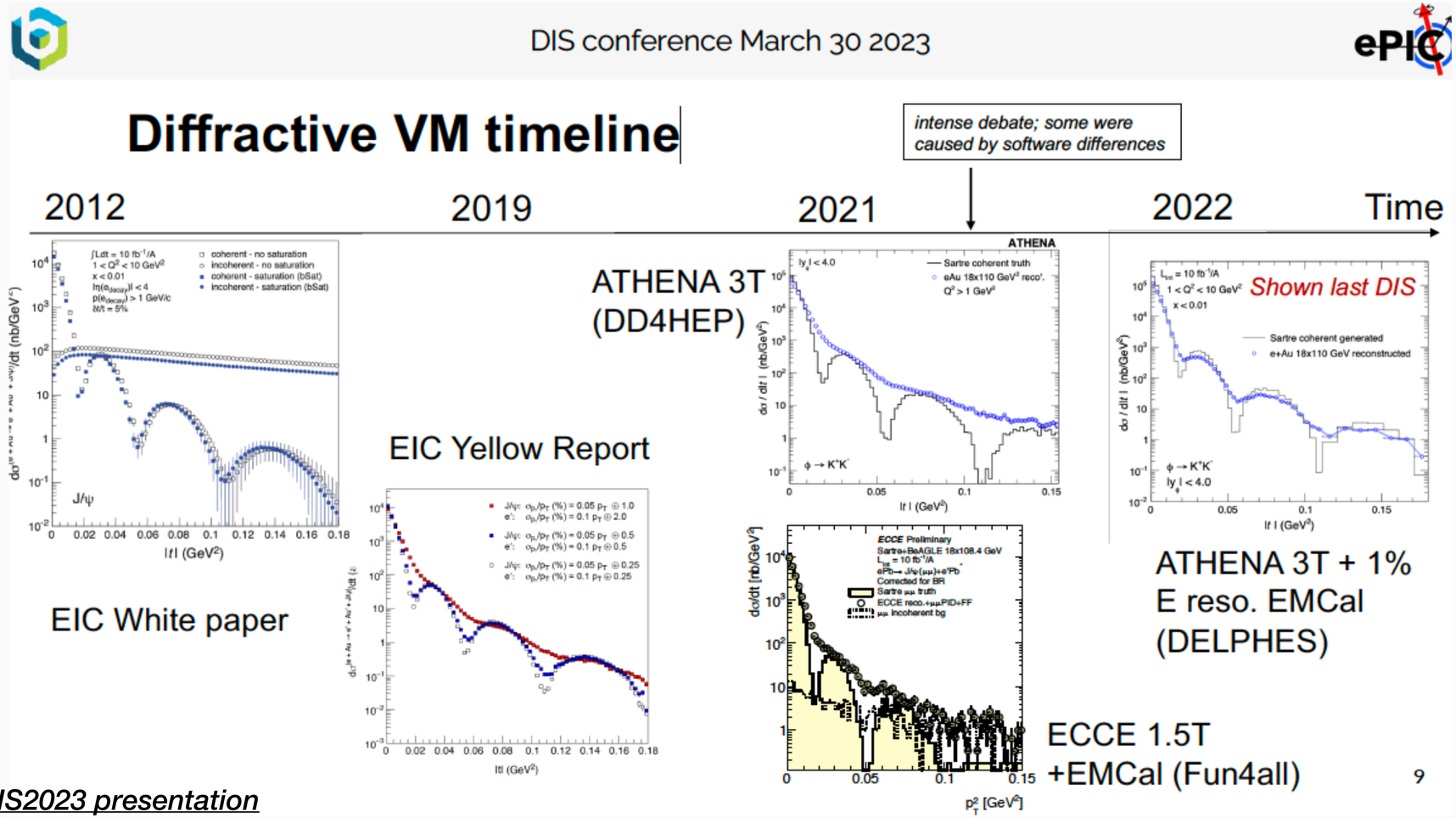




- Extend the range for J/ψ reconstruction to 3.4 < η< 5.8
- Corresponding to $W_{\gamma p} > 1$ TeV and $x < 10^{-5}$

Photoproduction at EIC with the EPIC detector

- Wide range of photon Q2 with high luminosity and optimized detector for precision measurement



★ *From Kong Tu's DIS2023 presentation*

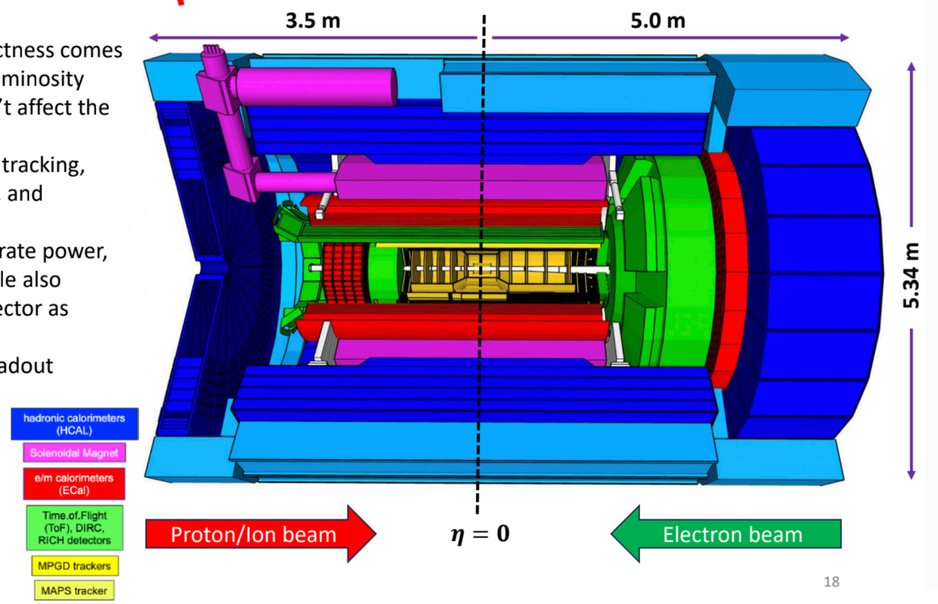
Photoproduction with the EPIC detector

- Full simulation chain, from generator to reconstructed objects, is ready with
  - EPIC geometry
    (updated time to time for the latest design)
  - Reconstruction algorithms
    (inc. tracking, clustering,…)
- Photoproductions of various vector mesons are studied under diverse conditions
  - Acceptance and kinematic limitation
  - Separation of coherent/incoherent contribution
  - ……

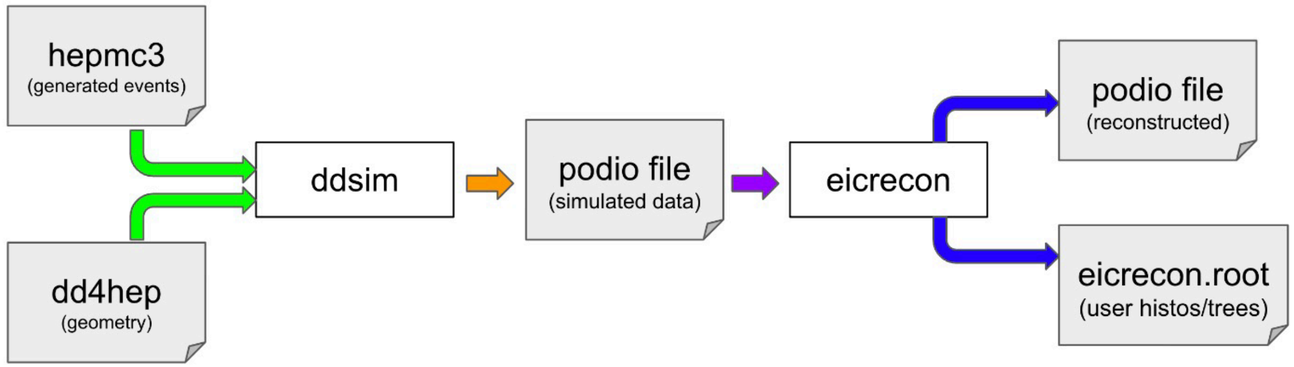
★ *From Barak's SPIN 2023 presentation*

ePIC detector design

- Detector is ~9m long – compactness comes from IR design allowing high luminosity
- Solenoidal field – magnet won't affect the electron beam
- Combines > 16 subsystems for tracking, vertexing, PID, EM calorimetry, and hadronic calorimetry
- Substantial challenges to integrate power, cooling, and data services, while also maintaining as hermetic a detector as possible
- Detector will use streaming-readout approach

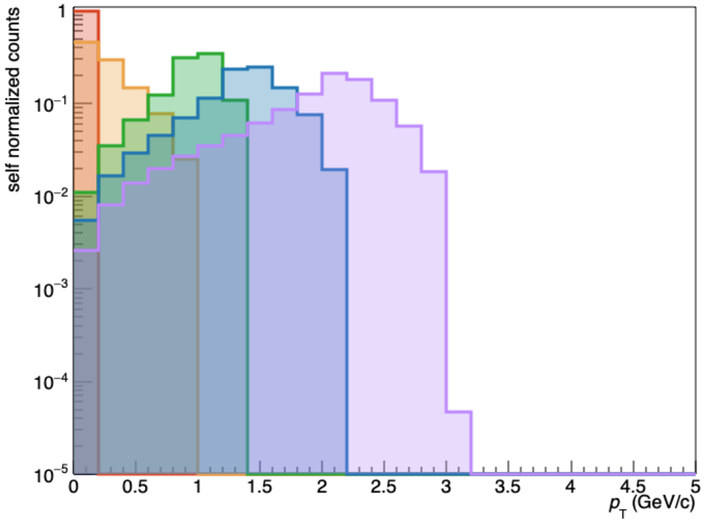


9/28/2023 18

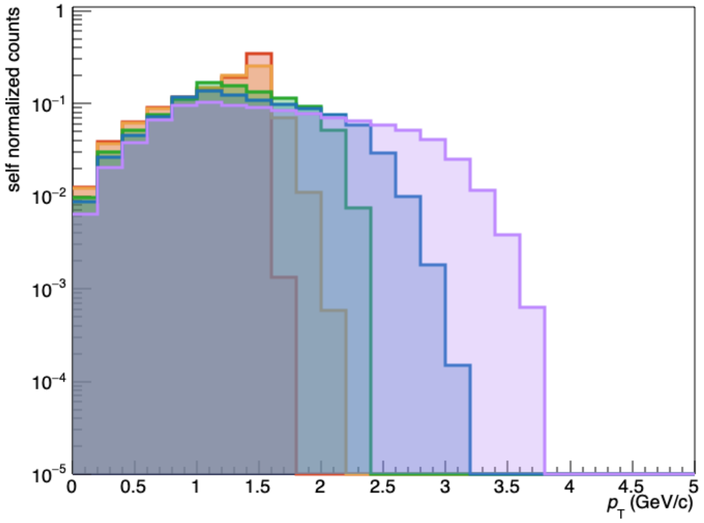


Acceptance of final state particles for J/ψ photoproduction

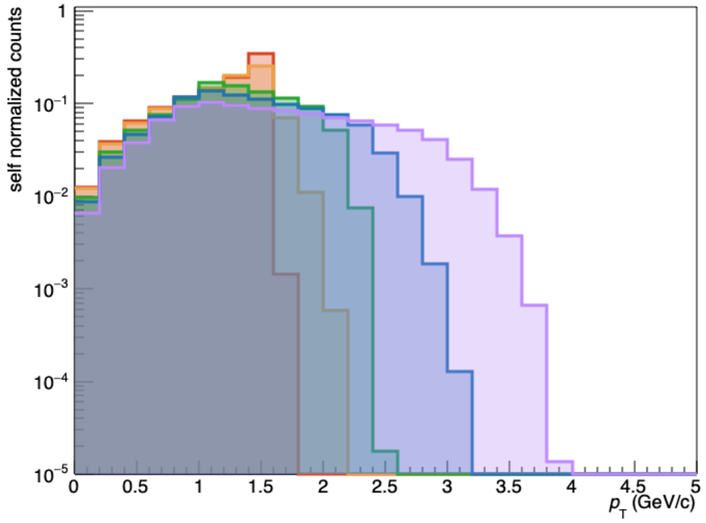
Scattered electron



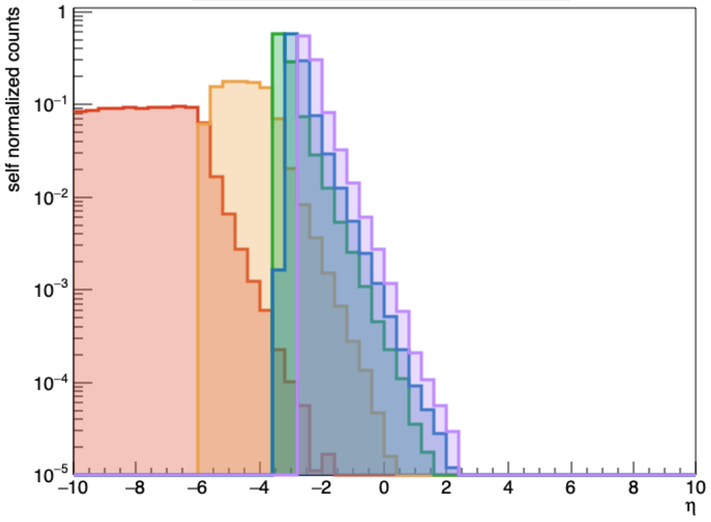
Decayed electron



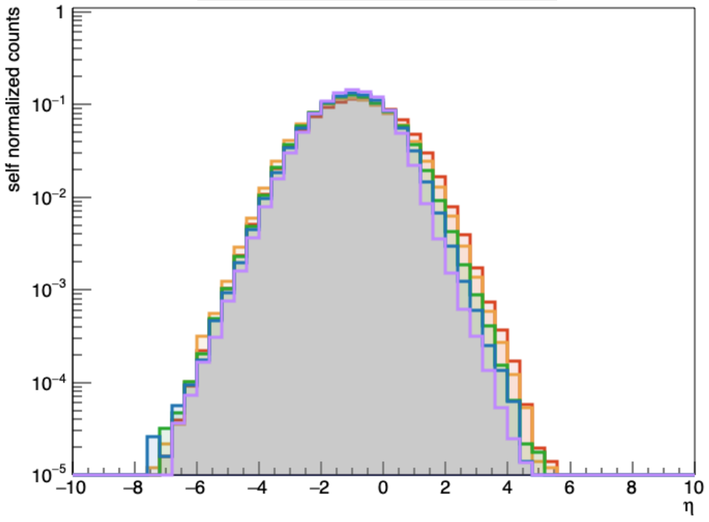
Decayed positron



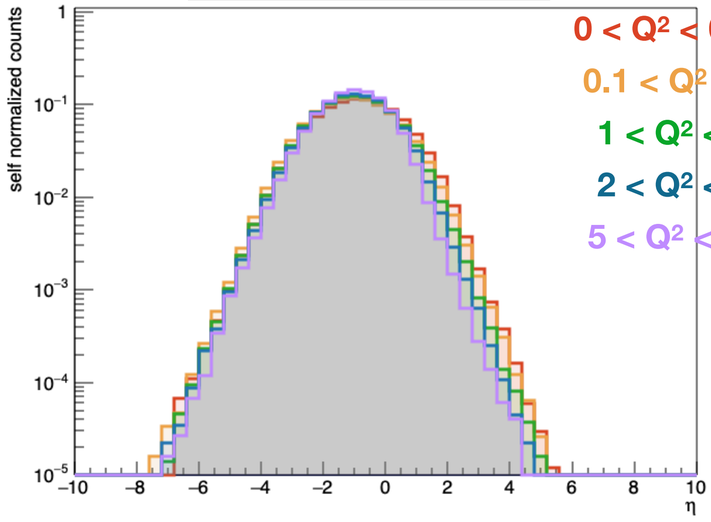
Scattered electron



Decayed electron

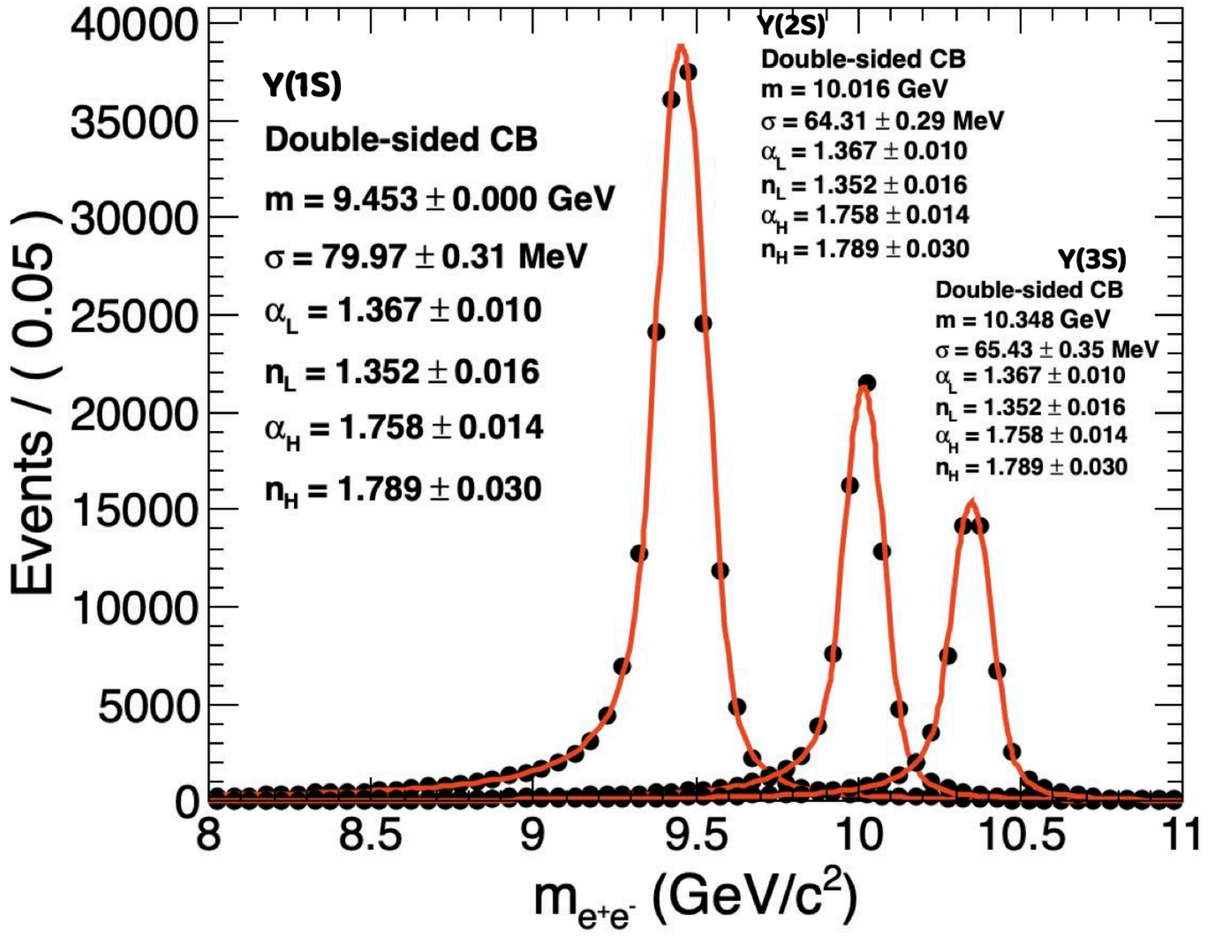


Decayed positron



First look of Υ(nS) photoproduction

★ *Collaborate with Saeahram @ UC Davis*



- Used the ratio for the yields
  1 : 0.45 : 0.33
  from the STARlight paper

- Fitted with the DSCB(Double-Sided Crystal Ball) function with the constraints on the mean and tail parameter values of Υ(2S) and Υ(3S).

- $m_{YnS} = m_{Y1S} * \frac{PDGmass_{nS}}{PDGmass_{1S}}$

- Resolution of each peak:
  σ_{1S} = 79.97 ± 0.31 MeV
  σ_{2S} = 64.31 ± 0.29 MeV → need to investigate further
  σ_{3S} = 65.43 ± 0.35 MeV

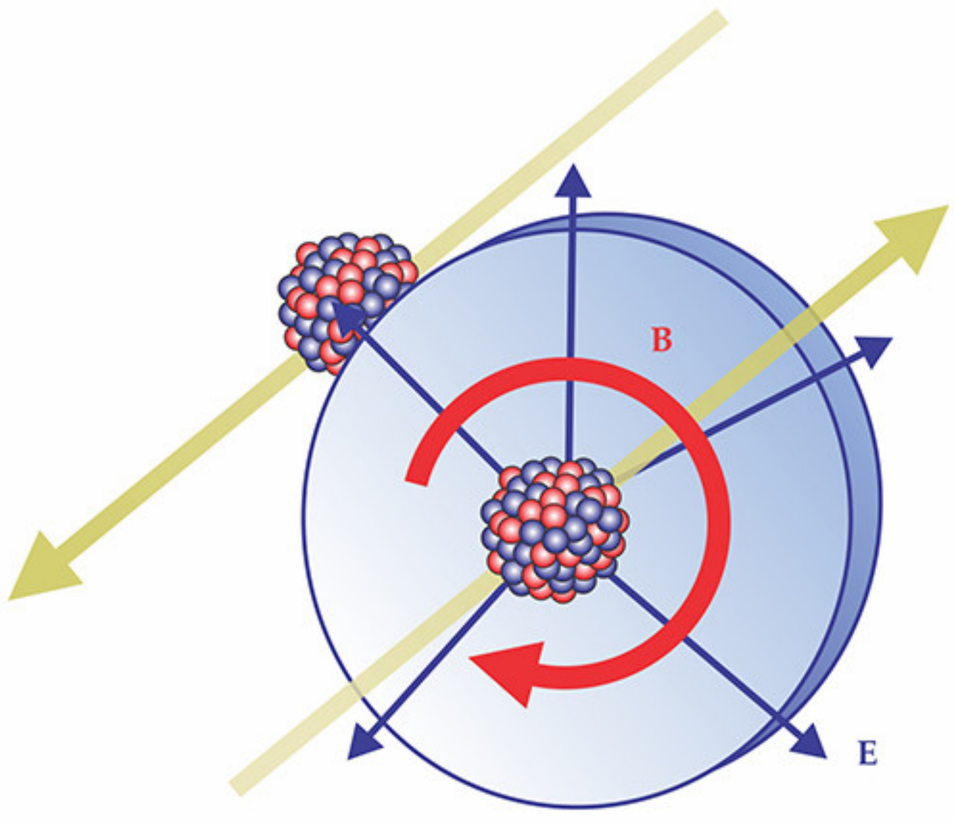
Summary and outlook

- Photoproduction measurements at the LHC provide valuable inputs for studying the nuclear structure at high energies (small Bjorken-x), dense gluon system
- LHC Run 3 Pb-Pb data taking campaign is coming soon. Run 4 with ALICE FoCAL will extend kinematic coverage of down to $x < 10^{-5}$
- Full simulation chain, from generator to reconstructed objects, is ready for EPIC: various studies of photoproduction and diffractive physics are ongoing! ⇒ stay tuned!
- EIC and UPCs (at the RHIC and LHC) are complementary, respectively providing precision measurements for different photon Q^2 and probes of low x gluons

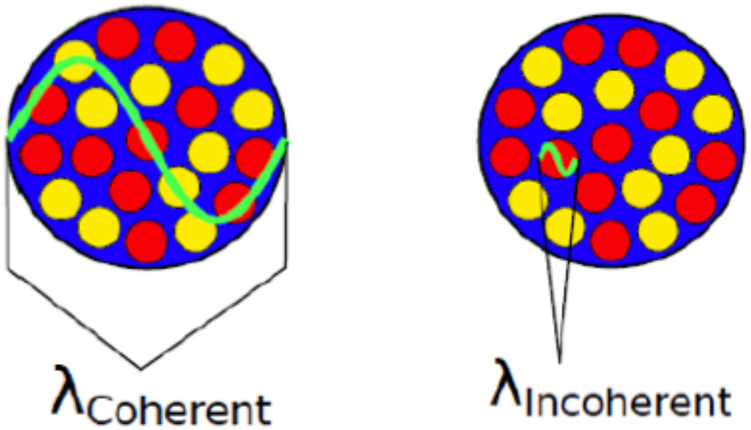
Backup

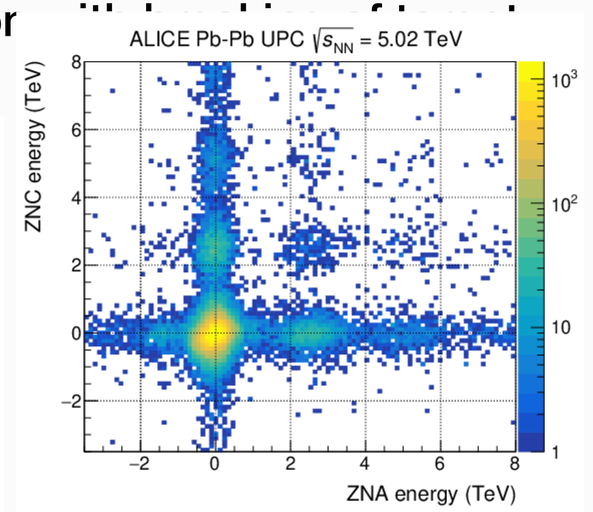
Ultra-peripheral heavy-ion collisions at the LHC: Photon energy frontier

S. Klein, J. Nystrand, Physics Today 70, 10, 40 (2017)



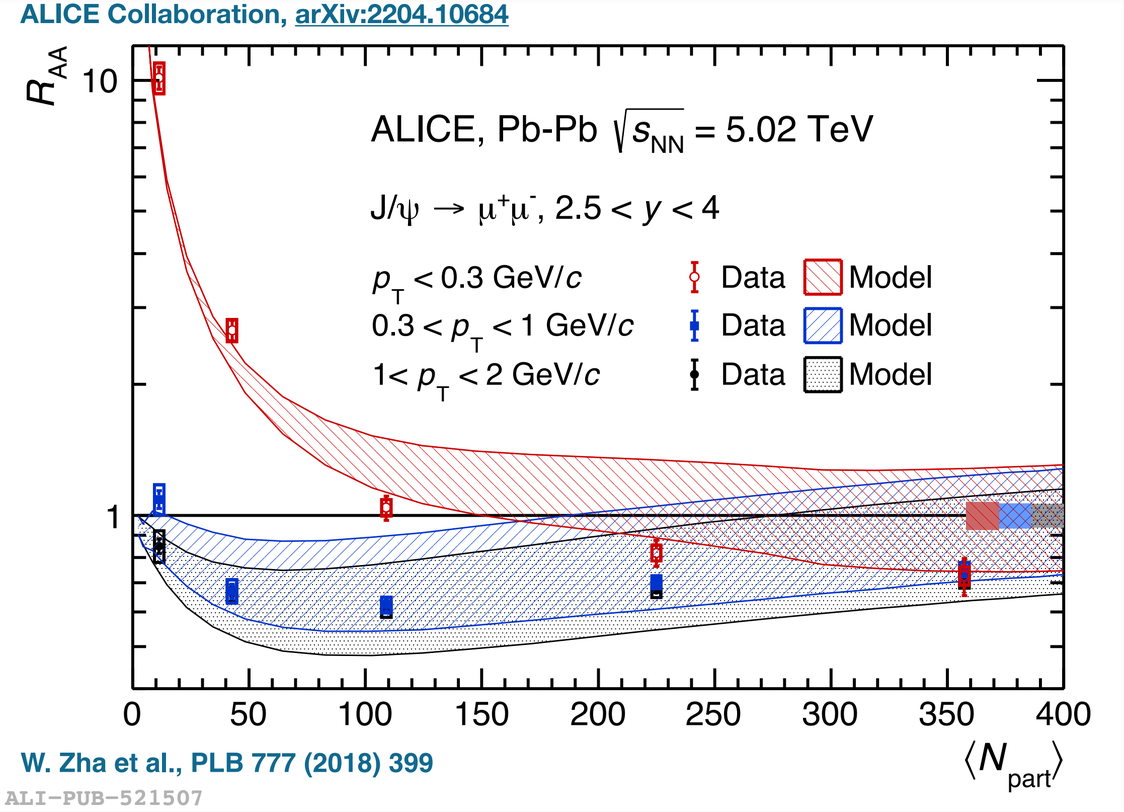
- EM field of ultra-relativistic ions → a beam of quasi real photons (intensity ≈ Z^2)
- Photon energy frontier: up to ~ 500 TeV in target frame at the LHC energies
- Photons can then fluctuate into a hadronic object or a colour dipole
- Ultra-Peripheral Collision (UPC): b > 2R
  →hadronic interactions are strongly suppressed
- Coherent (Incoherent) photoproduction: photon couples to all nucleons in whole nucleus (a single nucleon or ion)





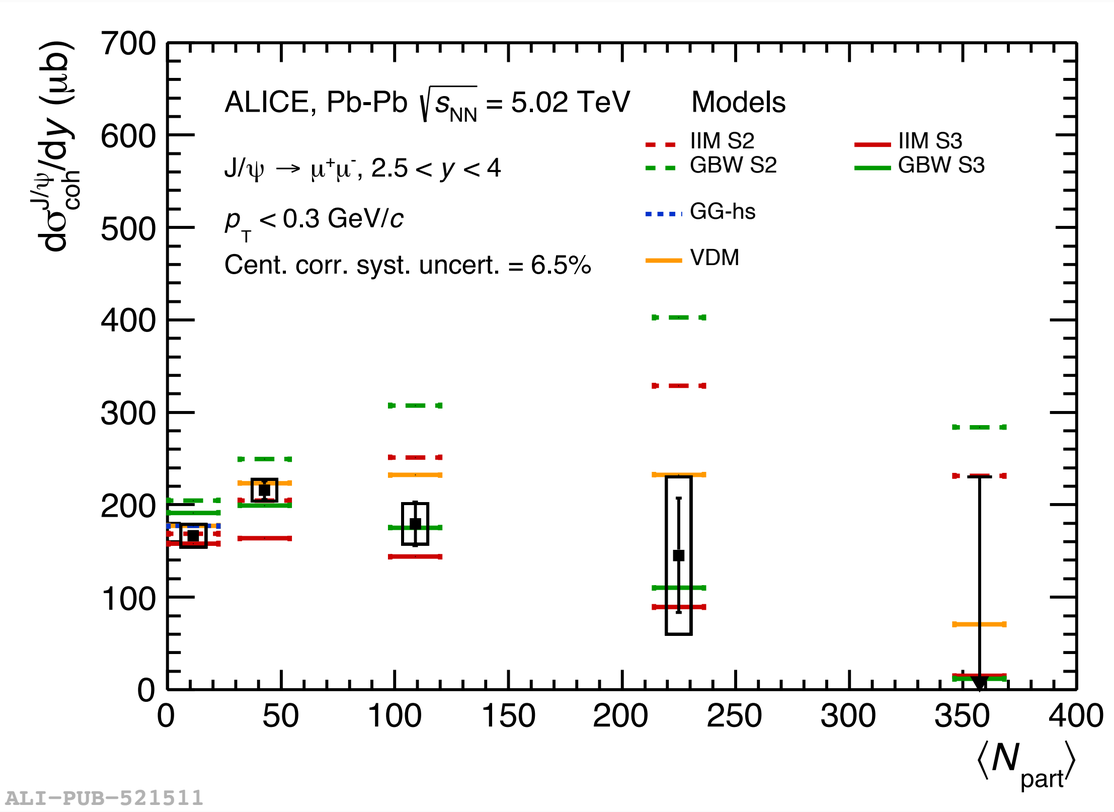
Coherent J/ψ photoproduction in Pb-Pb collisions

ALICE Collaboration, arXiv:2204.10684



W. Zha et al., PLB 777 (2018) 399

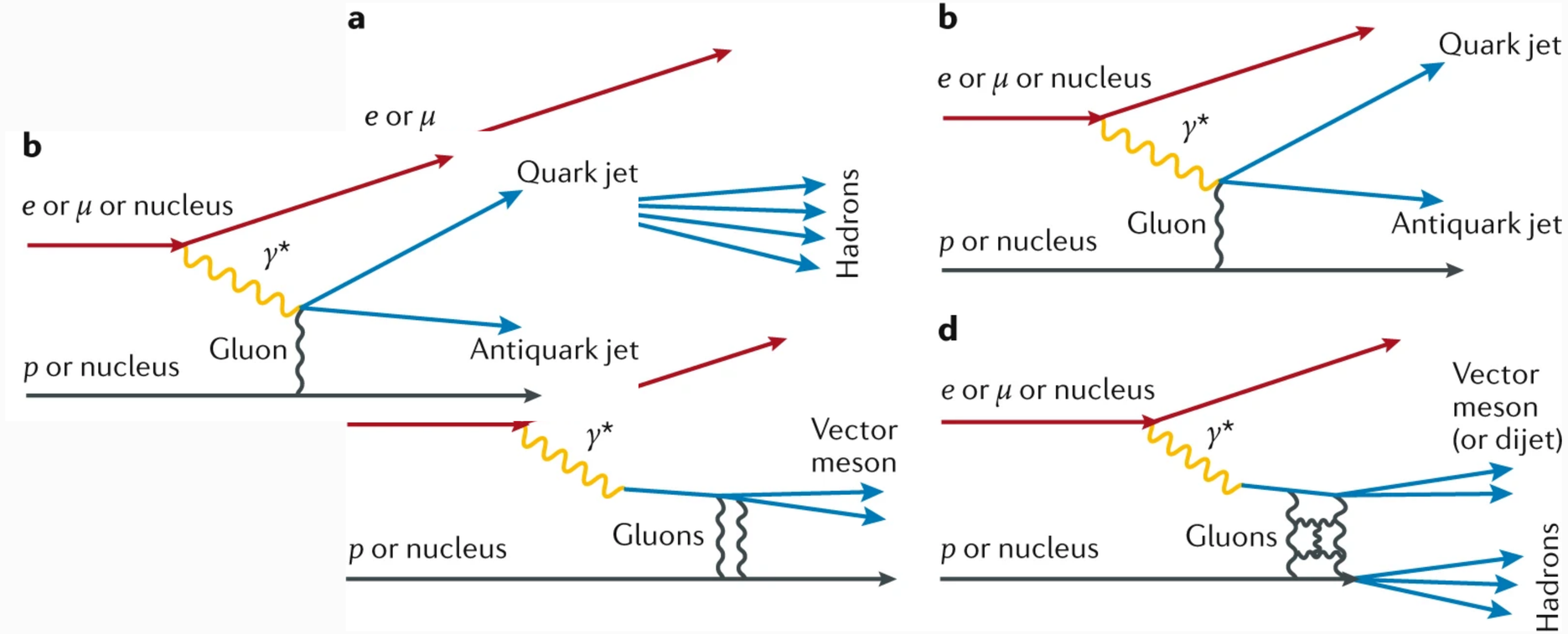
ALI-PUB-521507



ALI-PUB-521511

first ALICE measurement: PRL 116 (2016) 222301

- Low p_T J/ψ (p_T < 0.3 GeV/c) large excess → coherent J/ψ photoproduction in Pb-Pb collisions
- UPC based model including overlap effect qualitatively describes the trend of data in peripheral collisions J. G. Contreras, PRC 96 (2017) 015203


a
e or μ
Quark jet
Hadrons
b
e or μ or nucleus
γ*
Gluon
Antiquark jet
p or nucleus
γ*
Vector
meson
Gluons
p or nucleus
b
e or μ or nucleus
Quark jet
γ*
Gluon
Antiquark jet
p or nucleus
d
e or μ or nucleus
Vector
meson
(or dijet)
γ*
Gluons
p or nucleus
Hadrons

J/ψ photoproduction - NLO