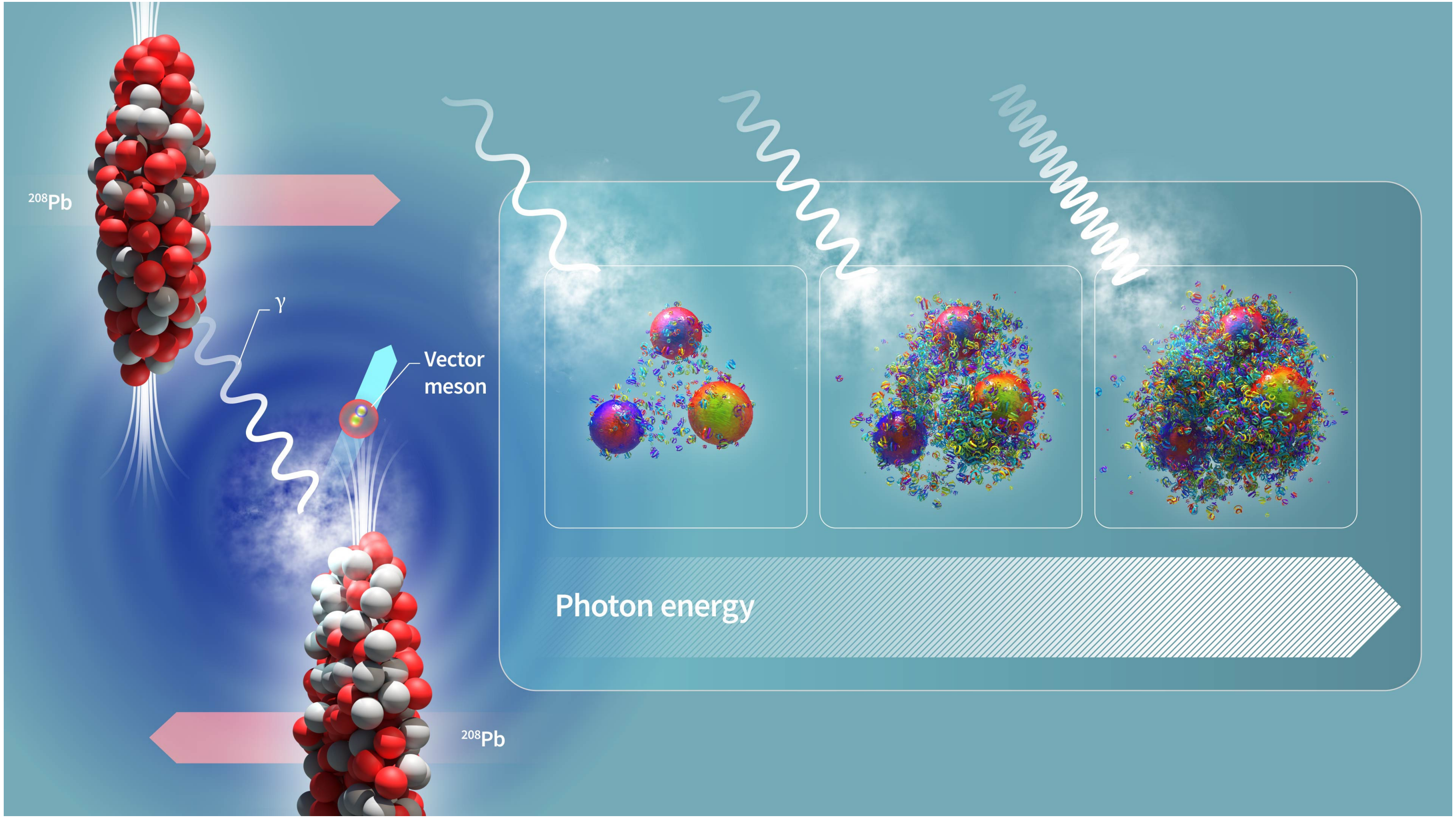
UPC physics in Run 3 and Run 4 with ALICE

Daniel Tapia Takaki

INT Workshop: Heavy-Ion Physics in the EIC era

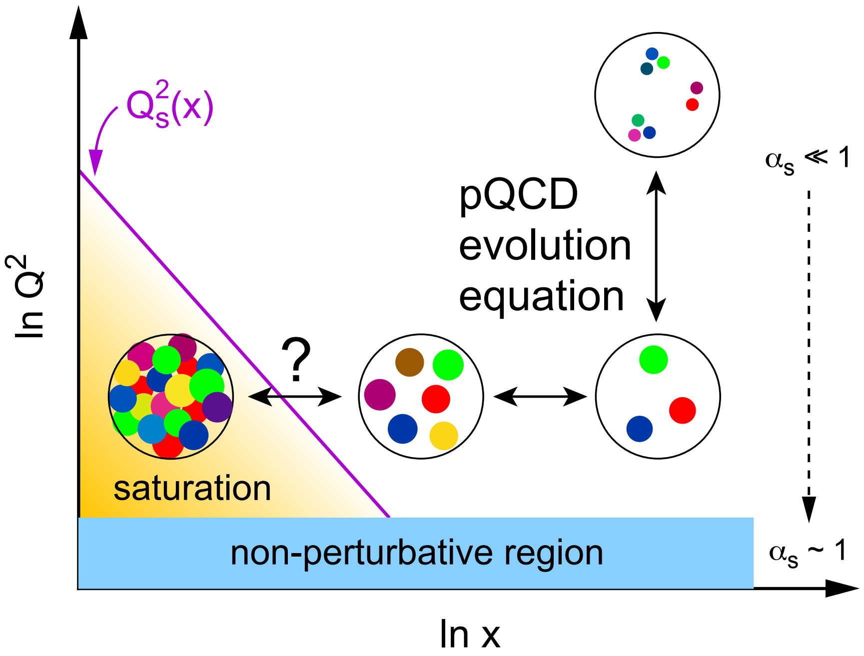
August 19-23, 2024

Ultra peripheral collisions (UPC)



Gluon saturation matters

At high energies, or for heavy nuclei at lower energies, gluon saturation is predicted

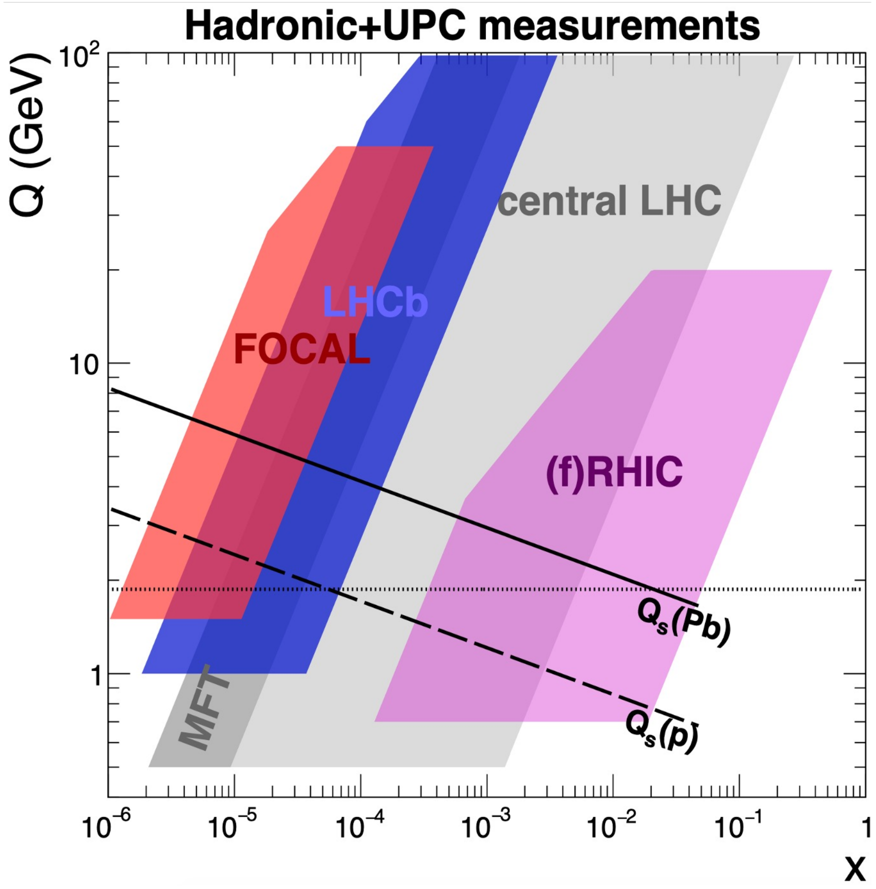


$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

- Non-linear QCD evolution equations introduced, but how is gluon saturation triggered?
- Experimental observables needed to map out the transition between the dilute and saturation regimes. The onset of saturation
- Can we determine experimentally the saturation scale (Q_S)?
- Is there a state of matter formed by gluon saturated matter with universal properties?

Experimental program

- The <u>Electron-Ion Collider</u> will be a dedicated QCD machine with the precision and control capabilities for studying gluon saturation and shadowing in a systematic way like never before.
- The <u>LHC</u> explores the high energy domain for both hadronic and photon-induced reactions
- <u>FoCal</u> at ALICE will explore a unique low-x regime reaching x down to 10^{-6}



The LHC is the Large **Photon** Collider

- **Ultra Peripheral Collisions (UPC)** can explore a wide range of energies using almost real photons

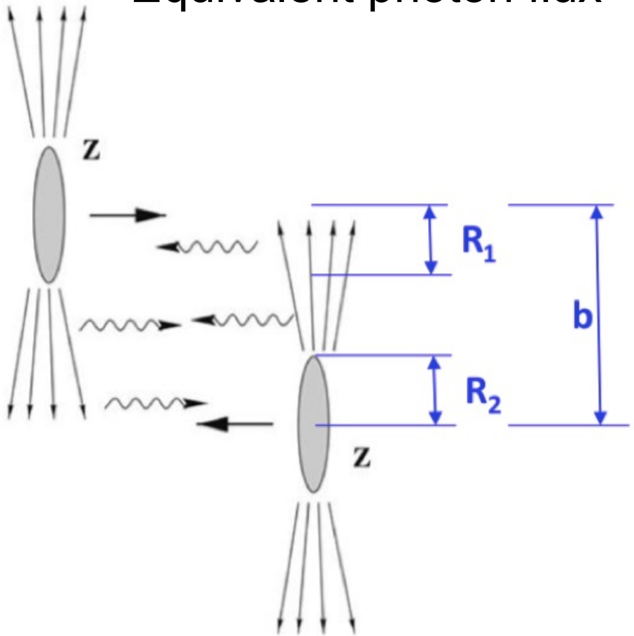
  $k = \gamma M_V \exp(\pm,y)$
  Up to several TeV in γp
  Up to ~ 700 GeV/nucleon in γA
  Up to ~ 150 GeV in $\gamma\gamma$ using UPC PbPb,
  ~ 4 TeV in in $\gamma\gamma$ using UPC pp

- UPCs at the LHC probe the hadronic structure over broad and unique Bjoren *x* region, yet the precision not compatible to DIS machines like the EIC

  $x = M_V/\gamma m_p \exp(\pm,y)$

Interactions mediated by the EM interactions

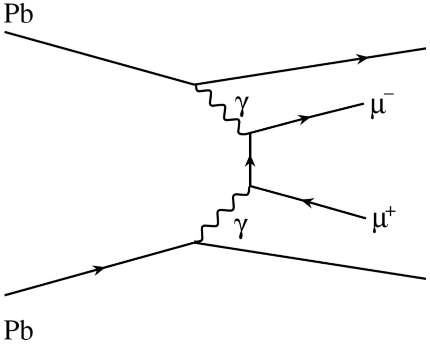
Equivalent photon flux

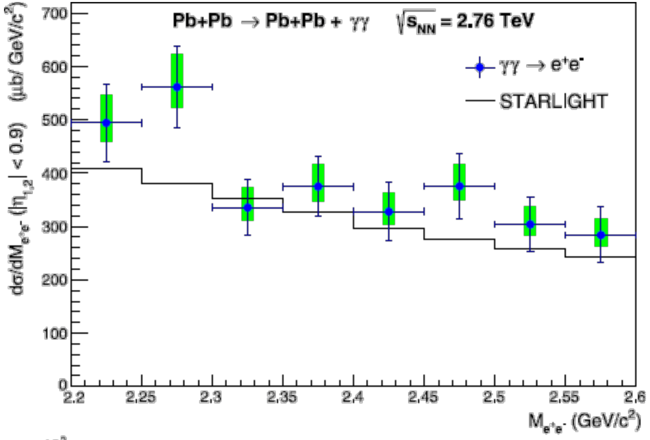


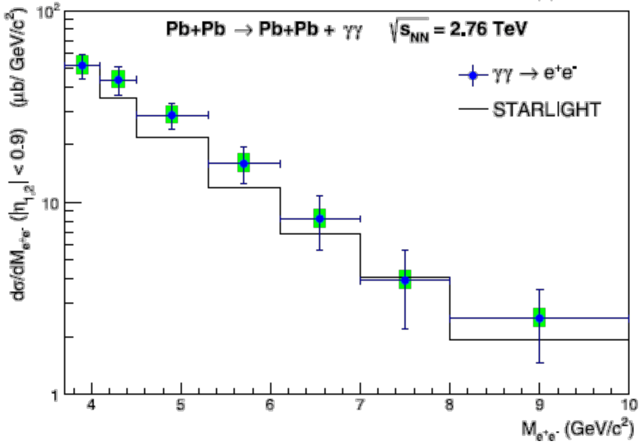
Two-photon interactions in UPC Pb-Pb

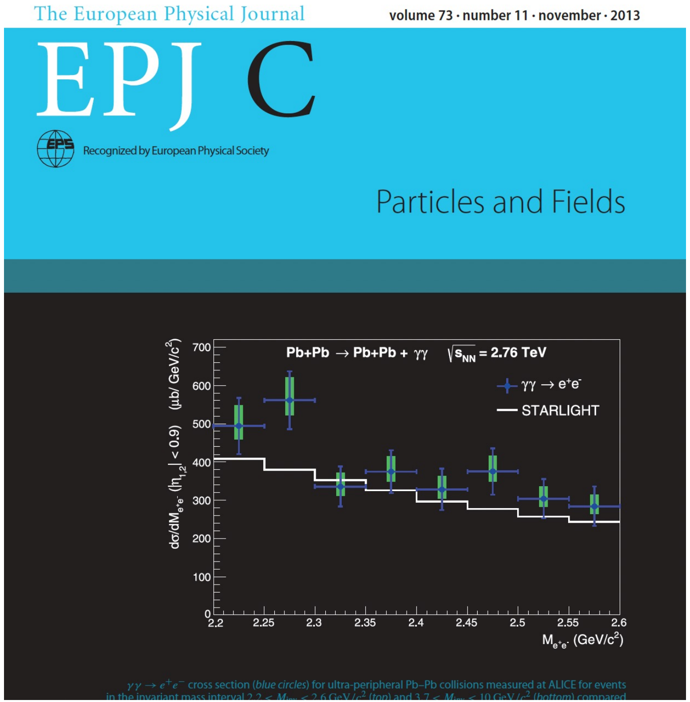
Eur. Phys. J.C 73 (2013) 11, 2617

$$\gamma\gamma \rightarrow e^+e^-$$





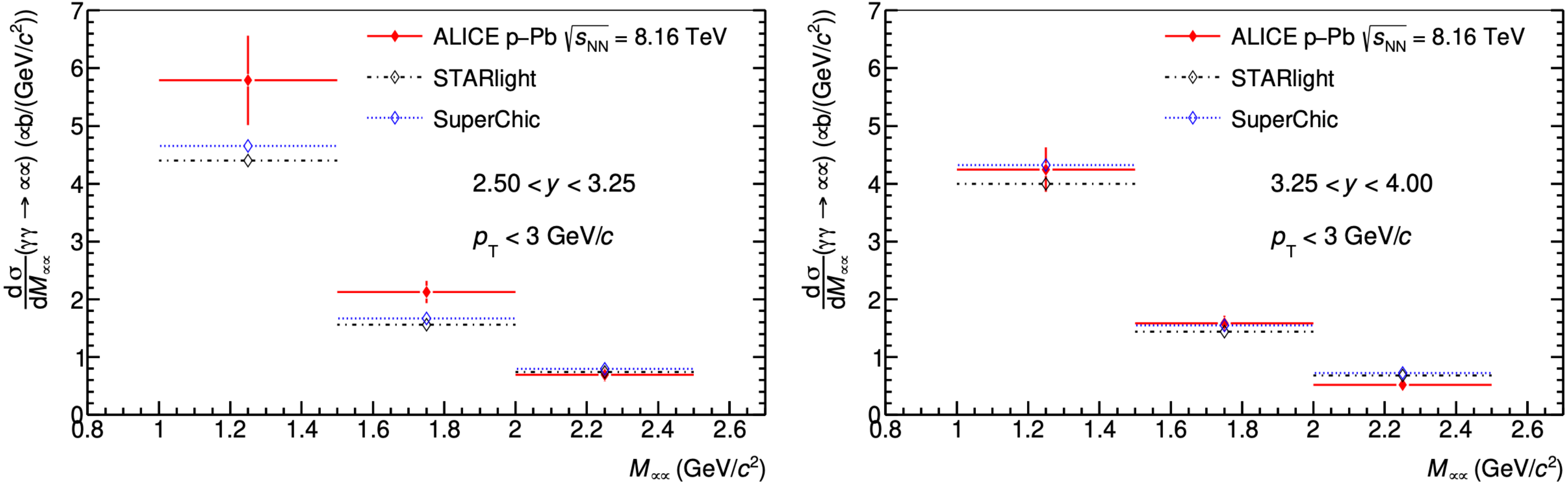




Exclusive dimuons in UPC pPb

Phys. Rev. D 108 (2023) 11, 112004

Two-photon measurements providing tests to the photon flux calculations

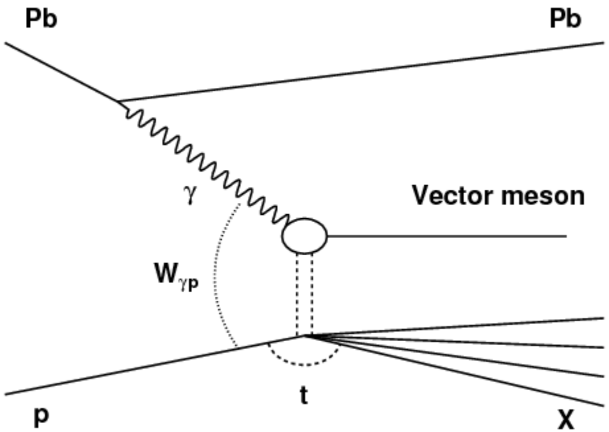


LO QED calculations, but different modeling

- STARLight: point-like charge with radial cutoff
- SuperChic: Charge distributions using form factors

Vector meson (VM) photoproduction in UPCs

$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$

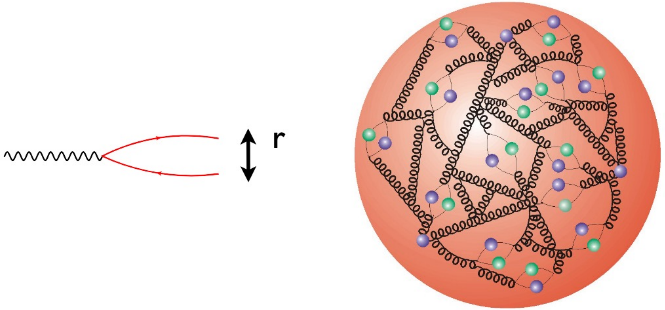


- As in DIS, several reactions are possible in UPCs:

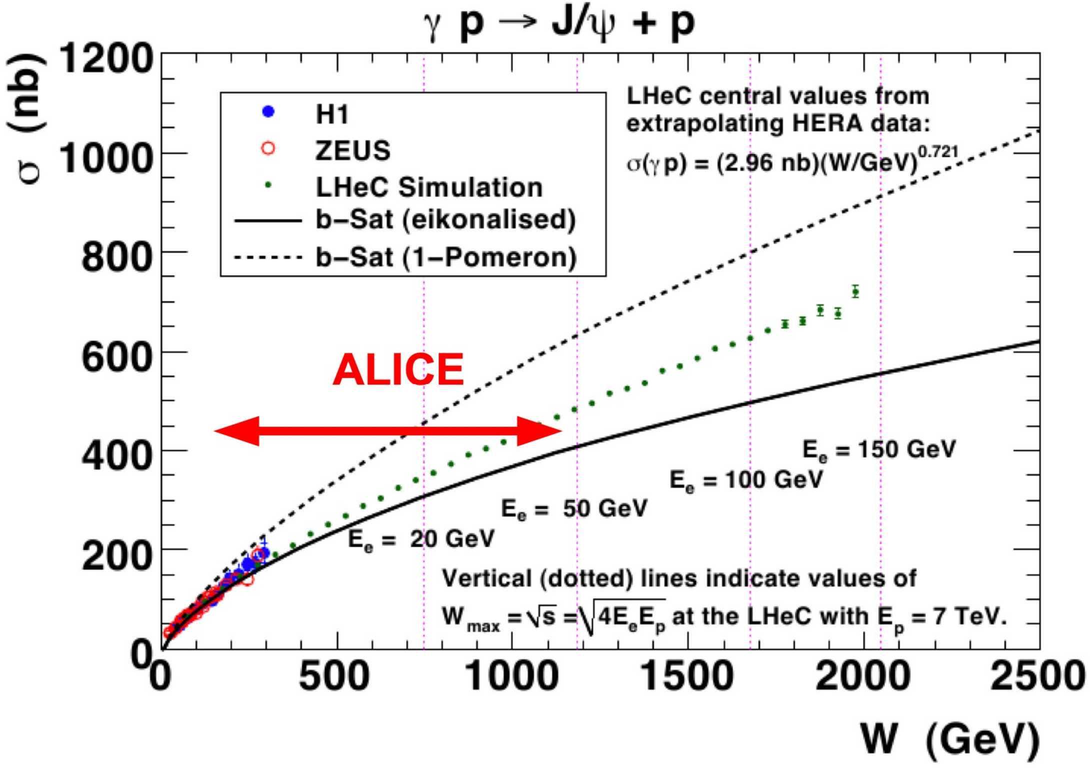
  -Exclusive photoproduction
  -Semi-exclusive photoproduction
  -Inclusive photoproduction

- By studying various VMs, it is possible to study the Q^2 dependence

- In the dipole approach, the light VMs (ϕ, ρ^0) are more sensitive to saturation because of the larger dipole, but pQCD methods not applicable



Predictions pre-LHC data for exclusive J/ψ off protons



- Deviations from the HERA power-law trend predicted as signatures of saturation
- At high energies also possible to distinguish among saturation models

Two-fold ambiguity on the photon direction in symmetric systems

$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$

Symmetric systems (pp, A-A) suffer from the two-fold ambiguity on the photon direction

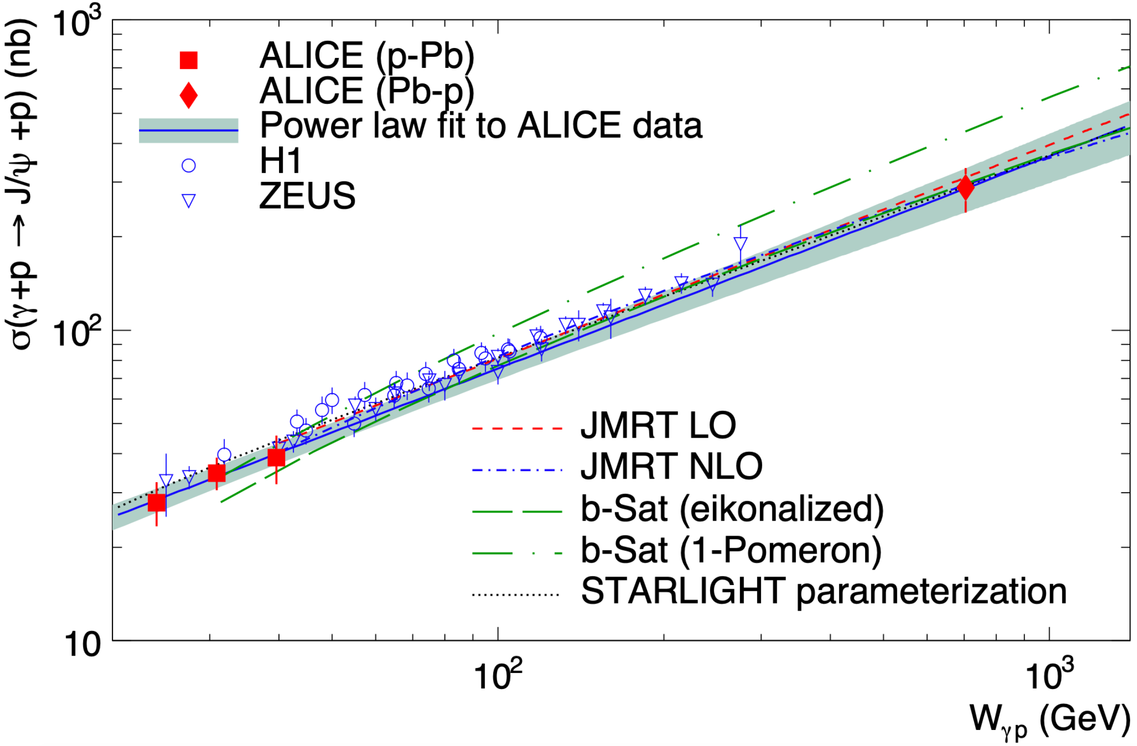
Positive rapidity — Negative rapidity

$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma p, +y) + n(-y)\sigma(\gamma p, -y)$$

Only UPC asymmetric systems (p-Pb) analyses provide a model independent way of the energy dependence of $\sigma(\gamma p)$

Exclusive J/ψ measurements by ALICE using Run 1 (2013)

Phys. Rev. Lett. 113 (2014) 23, 232504



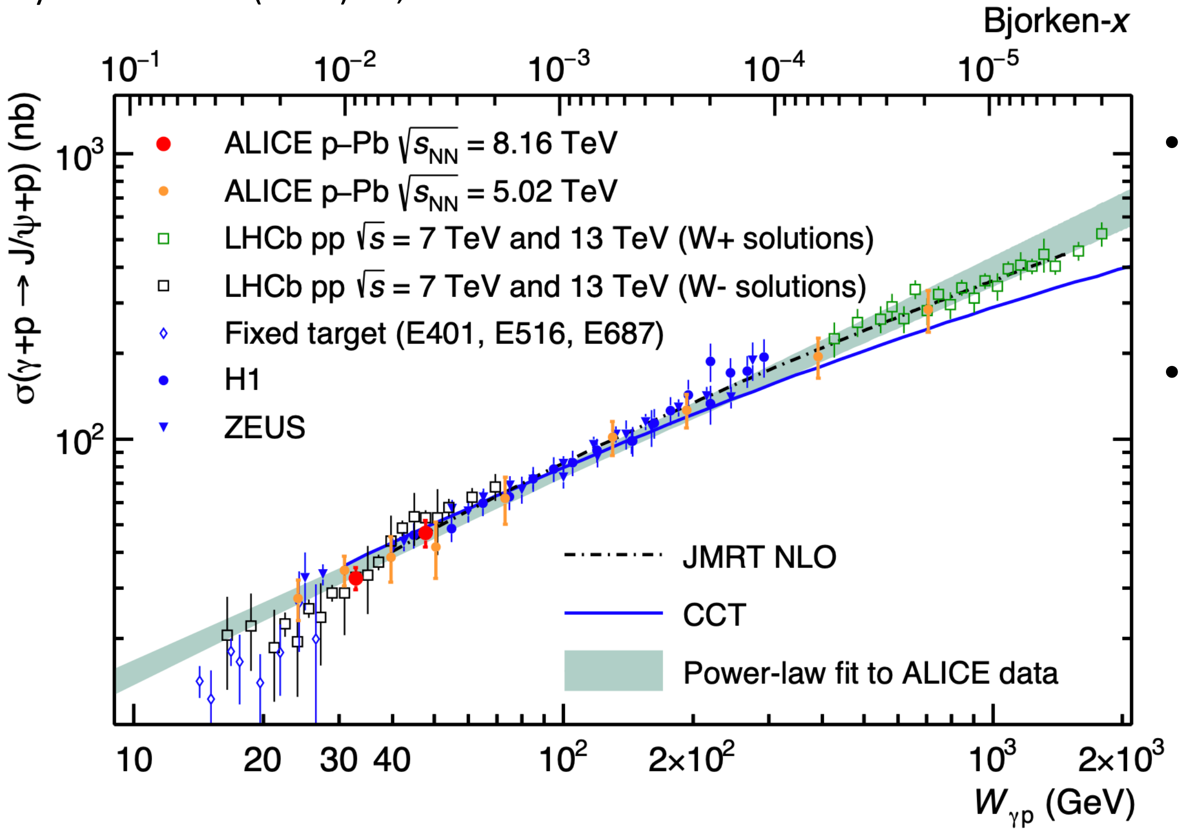
- No change with respect to HERA power-law growth observed at low energies up to 700 GeV

- UPC p-Pb collisions have no ambiguity on the photon energy

$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$

Exclusive J/ψ in UPC p-Pb (2023)

Phys. Rev. D 108 (2023) 11, 112004

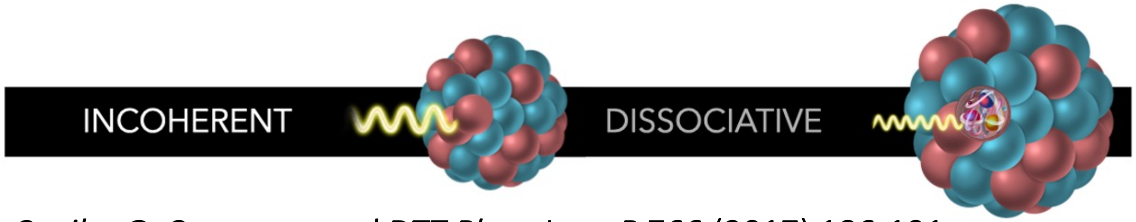


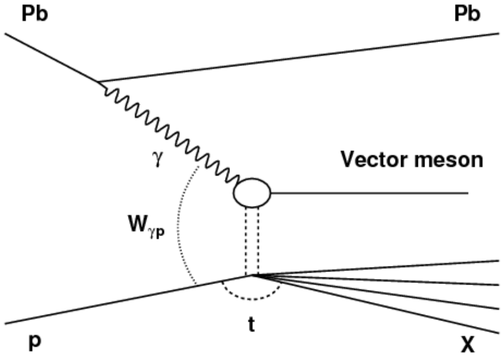
- No change in the behavior observed between HERA and LHC energies
- The highest energy point measured in a model-independent way is only up to 700 GeV in UPC p-Pb by ALICE

Dissociative J/ψ in UPC

See talk by A. Ridzikova at DIS'24
Figures from her

$$\left.\frac{d\sigma^{\gamma^* H \to VH}}{d|t|}\right|_{T,L} = \frac{\left(R_g^{T,L}\right)^2}{16\pi} |\langle \mathcal{A}_{T,L} \rangle|^2$$





J. Cepila, G. Contreras and DTT Phys. Lett. B 766 (2017) 186-191

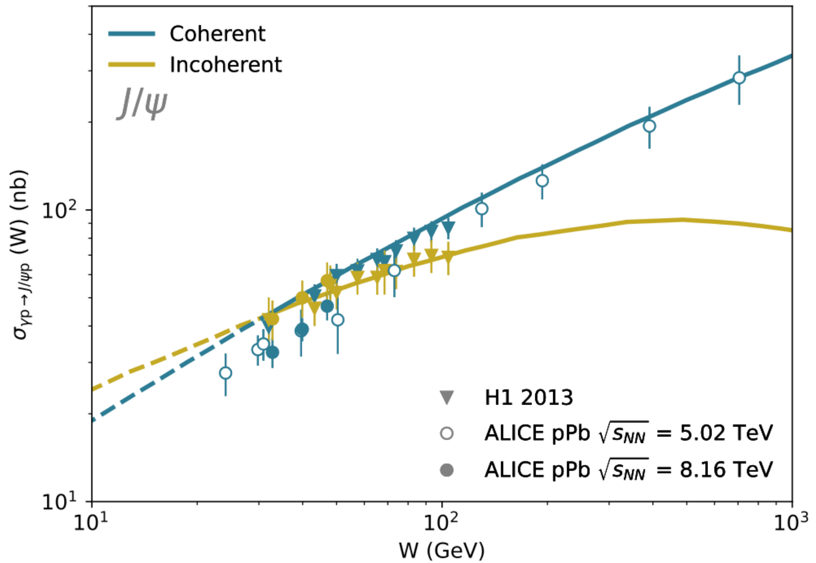
In the hot spot model, the increase in gluon distribution with decreasing Bjorken-*x* is described by the energy-dependent evolution of the number of hot spots

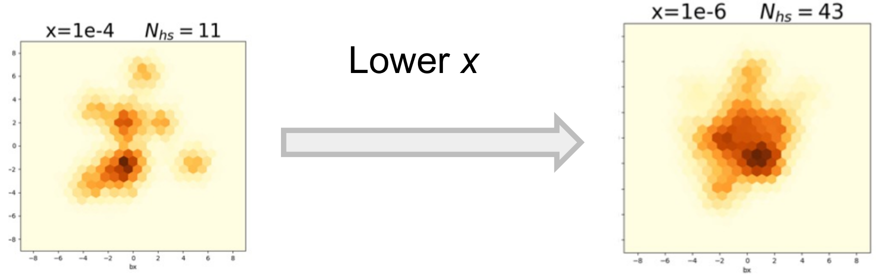
$$\left.\frac{d\sigma^{\gamma^* p \to VY}}{d|t|}\right|_{T,L} = \frac{\left(R_g^{T,L}\right)^2}{16\pi} \left(\langle |\mathcal{A}_{T,L}|^2 \rangle - |\langle \mathcal{A}_{T,L} \rangle|^2 \right)$$

Gluon saturation and dissociative J/ψ in UPC

See talk by A. Ridzikova at DIS'24
Figures from her

Phys. Lett. B 852 (2024) 138613





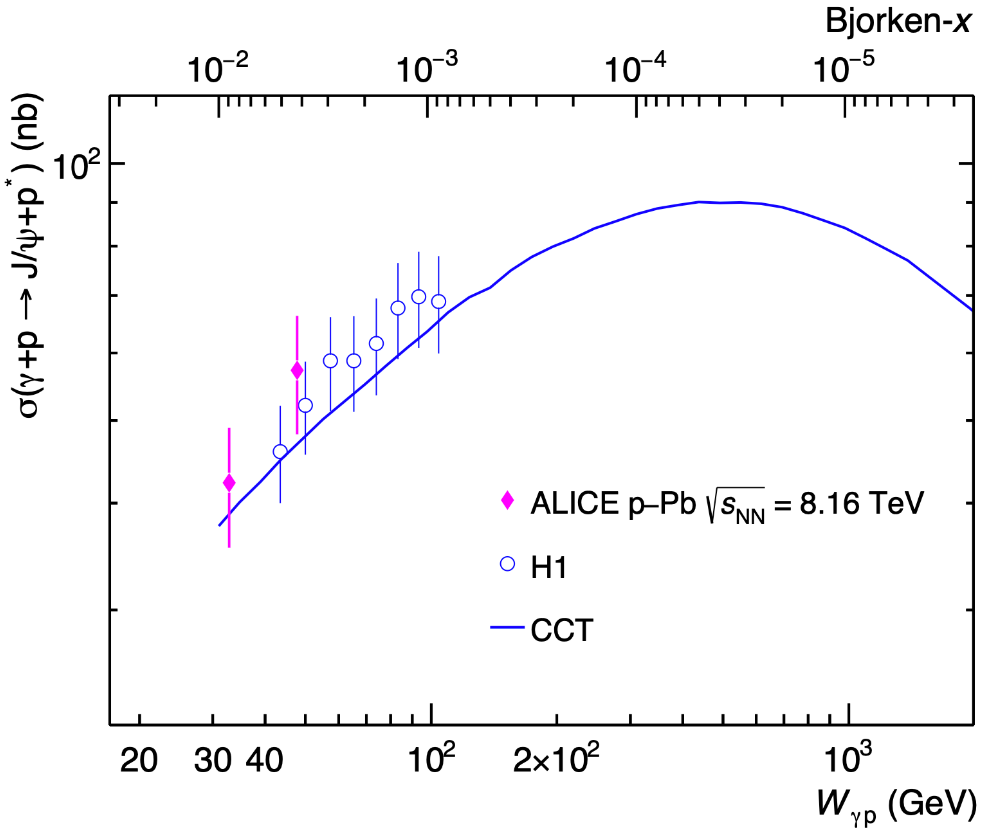
$$\left.\frac{d\sigma^{\gamma^* p \to VY}}{d|t|}\right|_{T,L} = \frac{\left(R_g^{T,L}\right)^2}{16\pi}\left(\langle|\mathcal{A}_{T,L}|^2\rangle - |\langle\mathcal{A}_{T,L}\rangle|^2\right)$$

In the hot spot model, the increase of large hot spots within the proton reaches a point of significant overlap, and the resulting uniformity reduces both the variance and the dissociative cross section

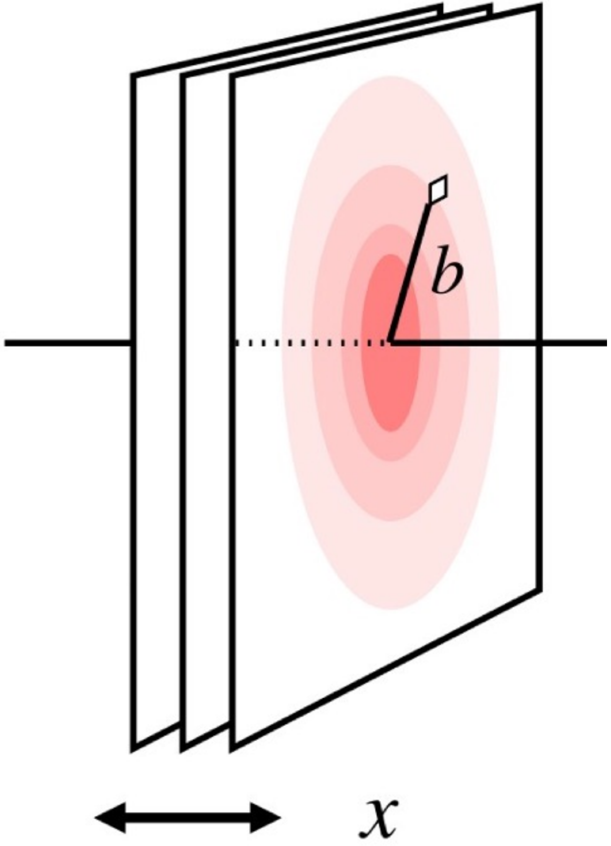
Phys. Lett. B 766 (2017) 186-191

Dissociative J/ψ in UPC pPb

Phys. Rev. D 108 (2023) 11, 112004



Transverse profile of the target

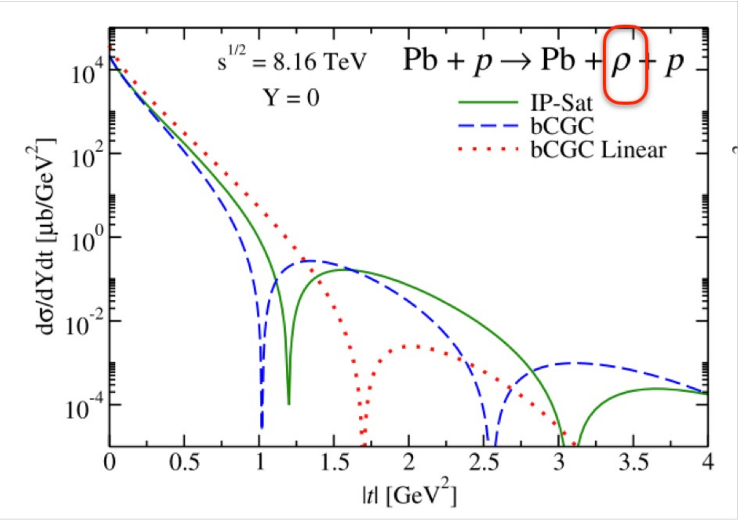


UPCs can probe the transverse profile of the target!

Appearance and location of diffractive dips can be signatures of gluon saturation

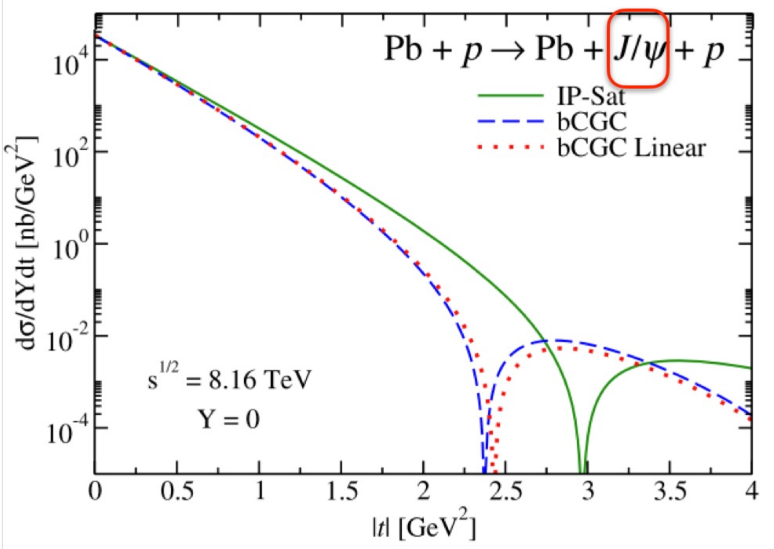
Transverse profile of the target

V. Goncalves, et al.
Phys. Lett. B791 (2019) 299-304



Signature of gluon saturation

Study of ρ^0 is very promising since diffractive dips expected at lower t values



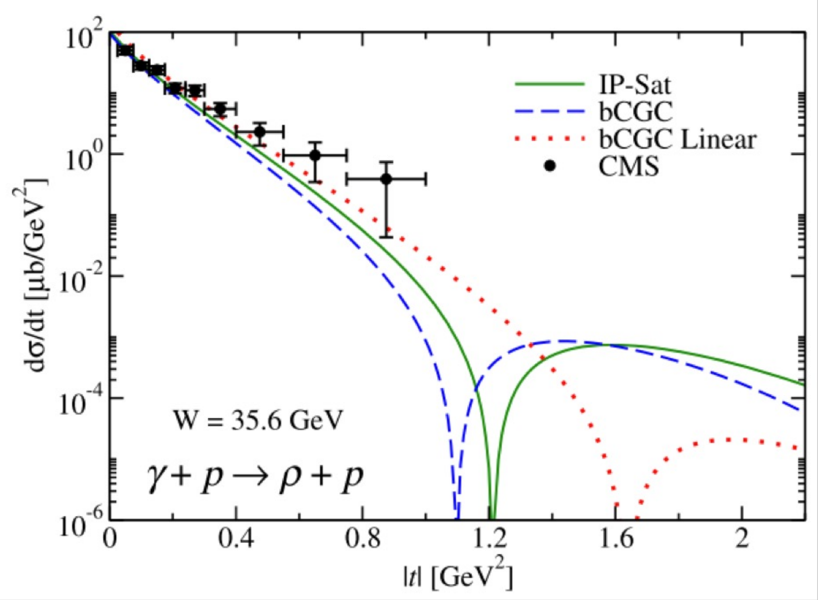
Location of the Diffractive dips:
Different for IP-Sat and bCGC

Energy dependence of the t-distribution: onset of gluon saturation

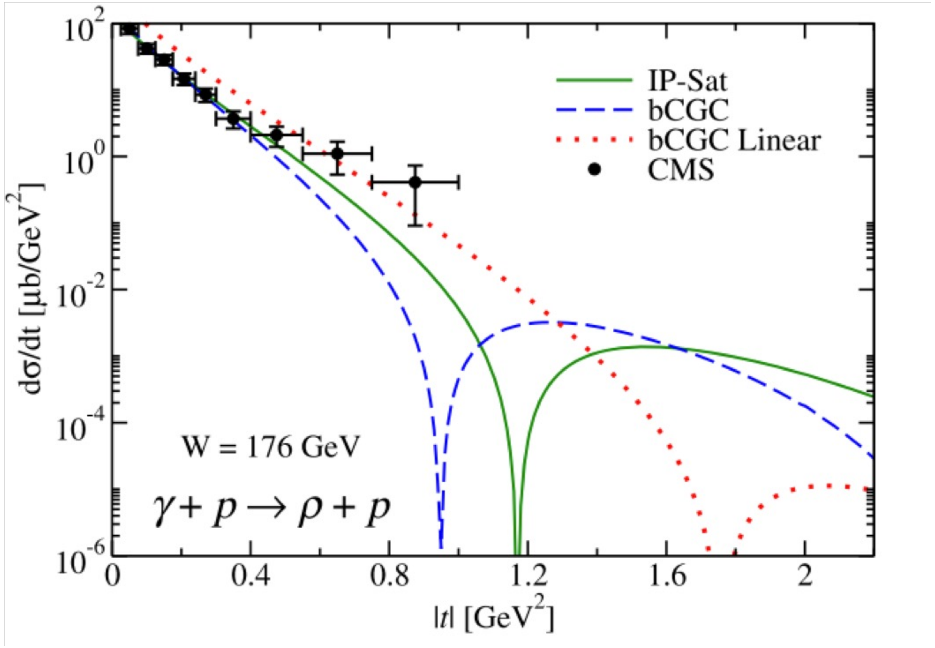
t-dependence measurement of UPC ρ^0

V. Goncalves, et al.
Phys. Lett. B791 (2019) 299-304

36 Gev

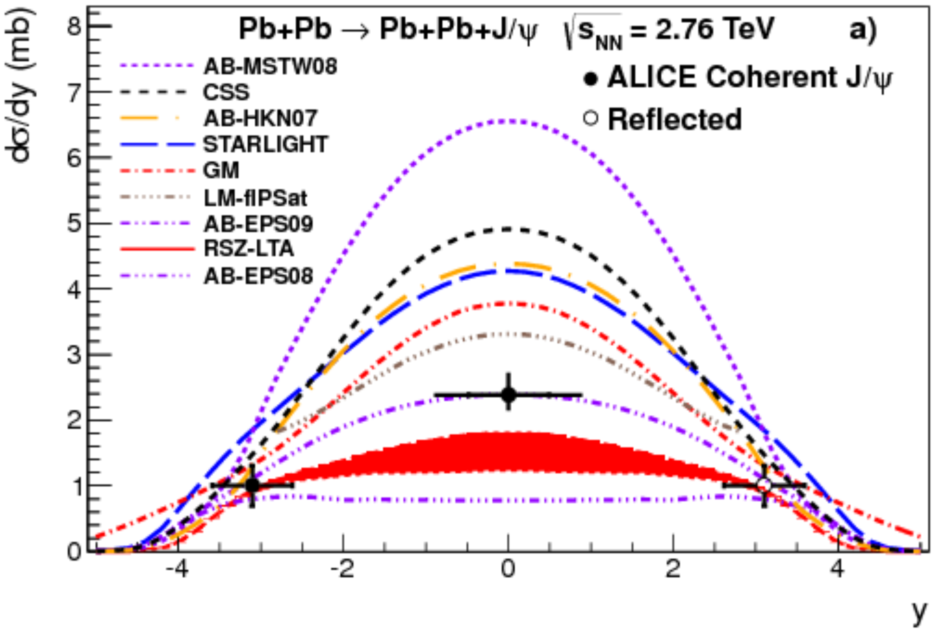


176 Gev

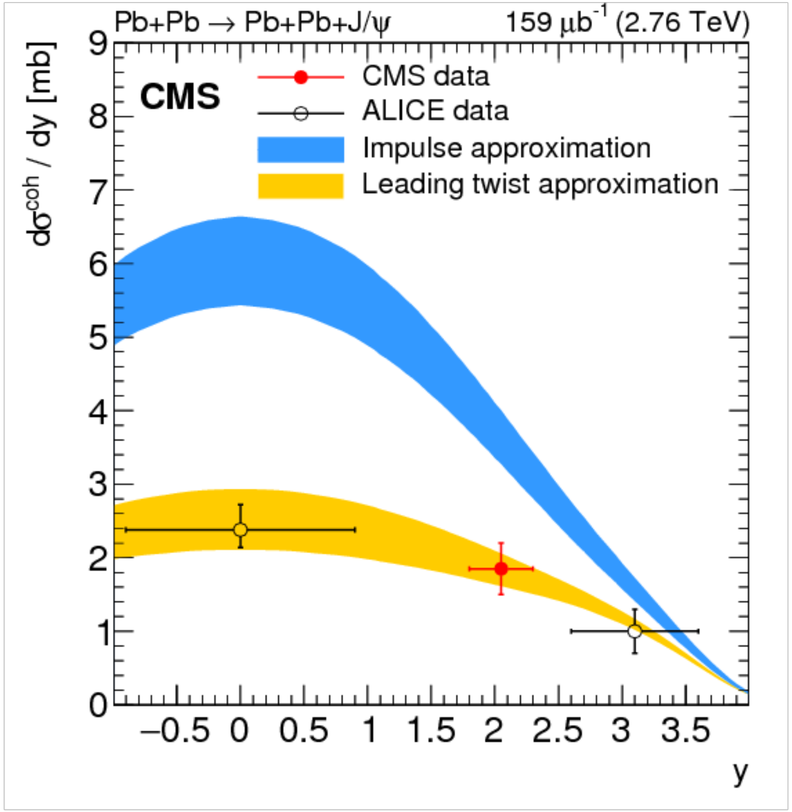


Coherent J/ψ in UPC Pb-Pb

Eur. Phys. J. C 73 (2013) 11, 2617



Phys. Lett. B 772 (2017) 489-511



Coherent J/ψ in UPC Pb-Pb

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

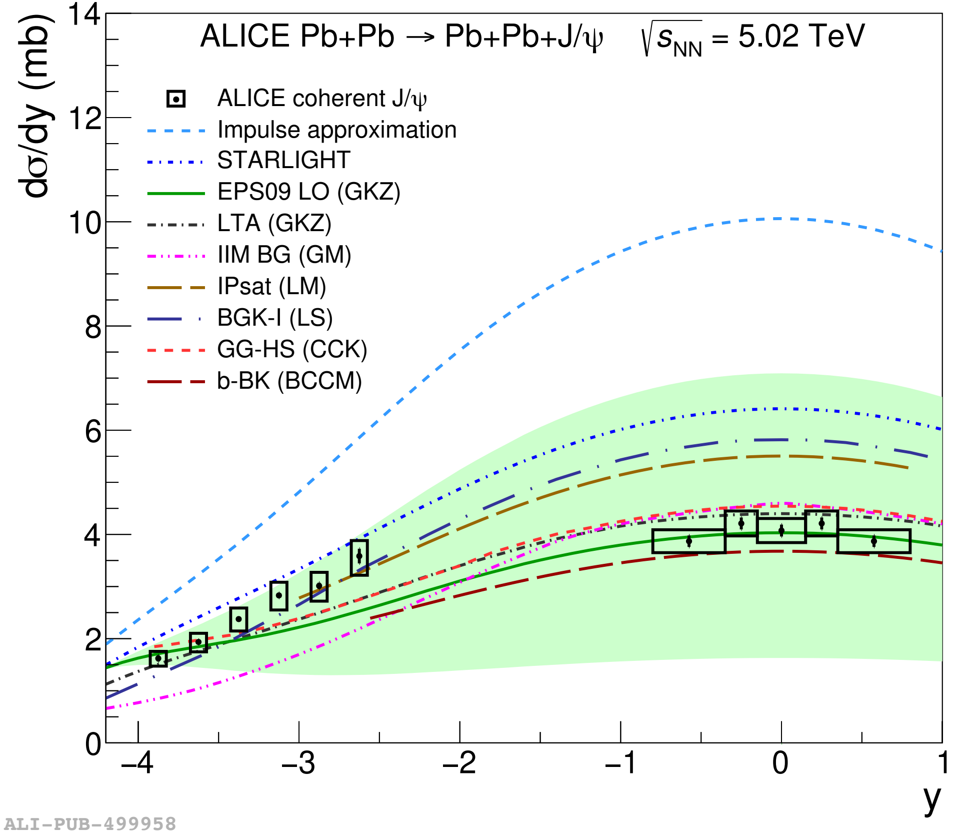
- Confirmation of nuclear shadowing with Run 2 data

- No model can describe the rapidity dependence

$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$

Mid-rapidity x ~10^{-3}

Forward rapidity 95% at x ~ 10^{-2}
5% at x ~ 10^{-5}

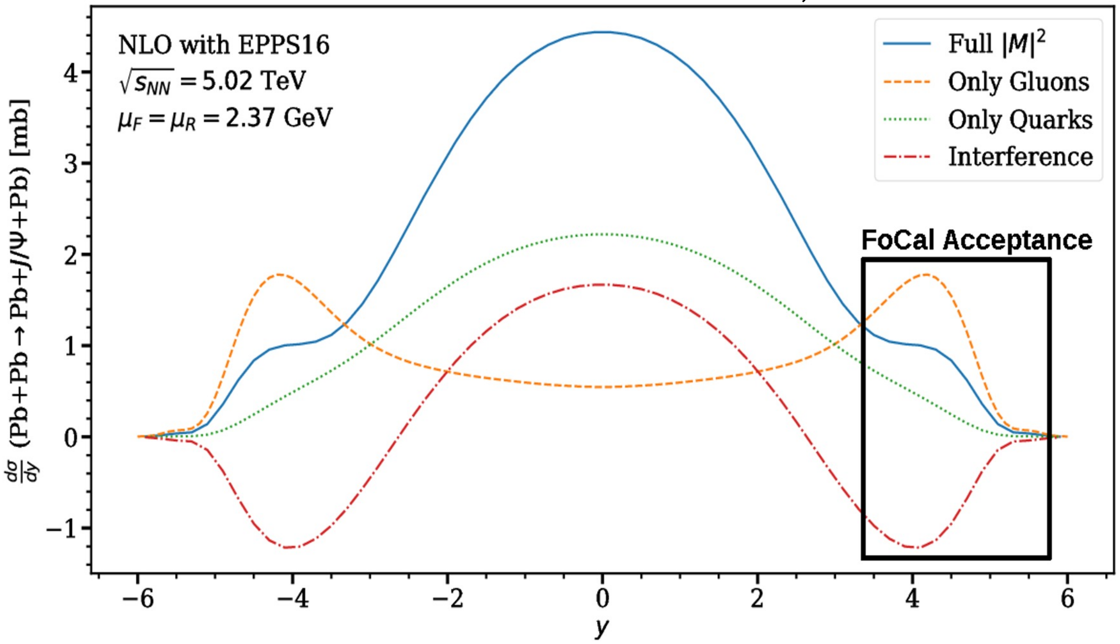


Projections for VMs in γPb

Recent NLO calculations indicate importance of quark contribution and large scale uncertainties

The FoCal region is gluon dominated

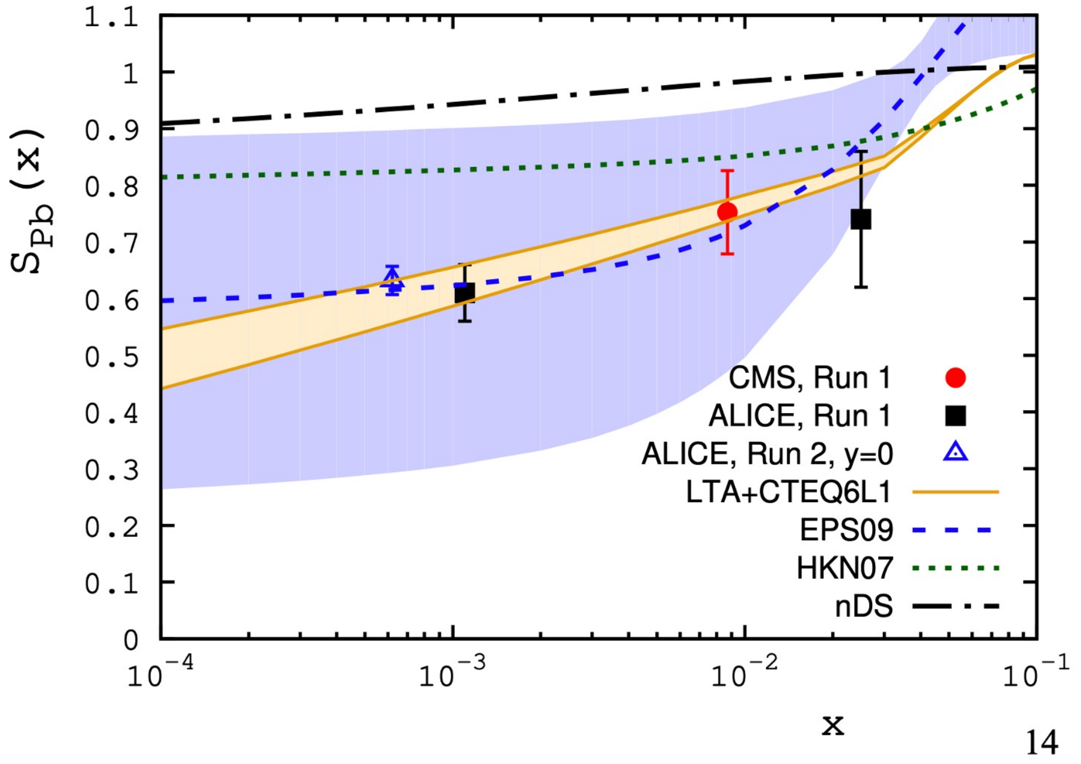
K. Eskola et al., arXiv:2203.11613



- At LO predicted to be proportial to the square of the gluon density (Z. Ryskin Phys. C 57, 89 (1993), but several caveats
- UPC J/ψ also described by Generalized Parton Distributions (GPDs), with some theory considerations

Nuclear suppression factor for UPC J/ψ: Comparing γPb to γp

V. Guzey et al. PLB 726 (2013)



An experimental definition, which can be linked to PDFs at LO

$$S_{Pb}(x) = \sqrt{\frac{\sigma_{\gamma A \to J/\psi A}(W_{\gamma p})}{\sigma^{\mathrm{IA}}_{\gamma A \to J/\psi A}(W_{\gamma p})}} = \kappa_{A/N} \frac{x g_A(x, \mu^2)}{A x g_N(x, \mu^2)}$$

Run 1 data from ALICE was the first at indicating nuclear gluon shadowing at x ~ 10^{-3}

Large scale NLO uncertainties should cancel in the $S_{Pb}(x)$ ratio

ALICE results at y=0 have no ambiguity on the photon energy

Two-fold ambiguity on the photon direction in symmetric systems

$$W^2_{\gamma p} = 2E_p M_{J/\psi} e^{\pm y}$$

Symmetric systems (pp, A-A) suffer from the two-fold ambiguity on the photon direction

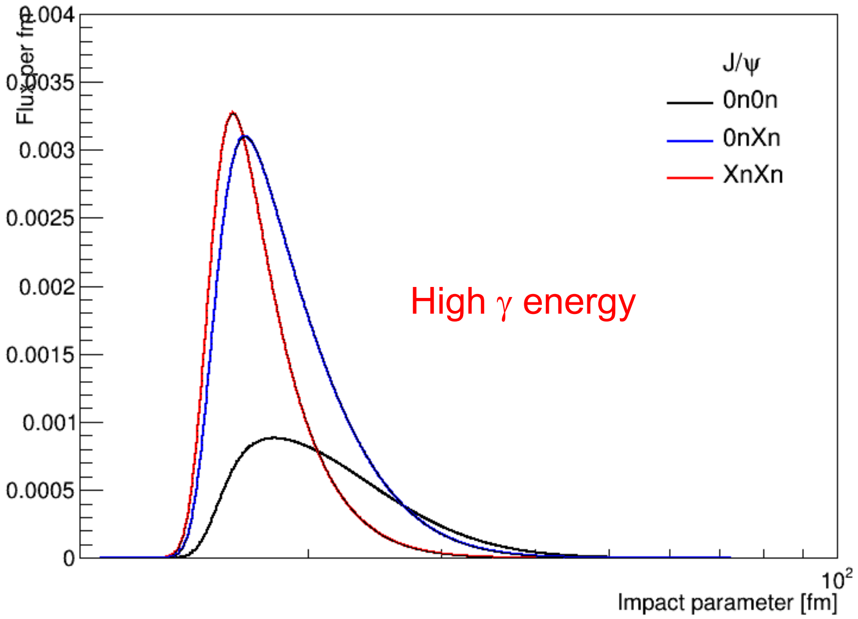
Positive rapidity | Negative rapidity

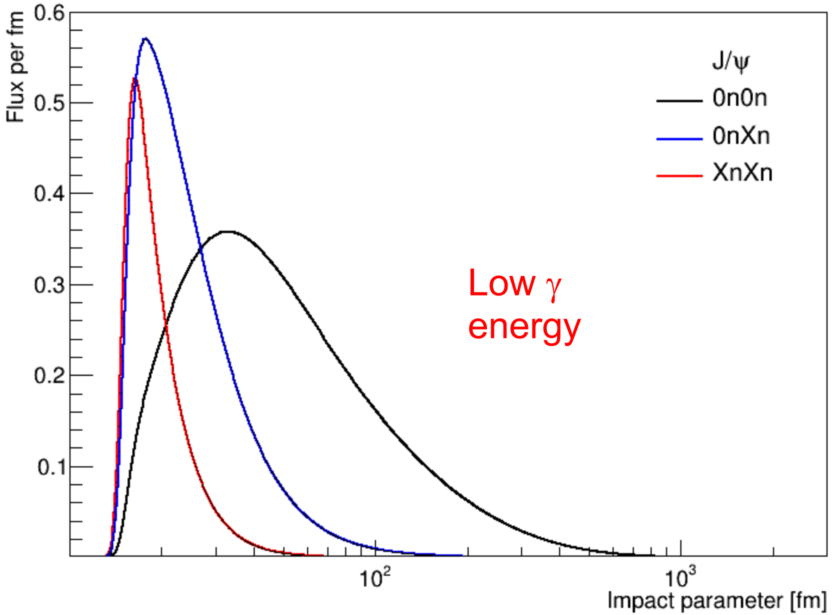
$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma p, +y) + n(-y)\sigma(\gamma p, -y)$$

Analyses of UPC asymmetric systems (p-Pb) provide a model independent way to study the energy dependence of $\sigma(\gamma p)$

Impact parameter flux profile

Broz, Contreras and DTT, CPC 235 (2020) 107181





Neutron-dependence of coherent J/ψ in UPC Pb-Pb

The photon flux (n) depends on the impact parameter

Decomposed in terms of neutron configurations emitted in the forward region

$$\frac{d\sigma}{dy} = \frac{d\sigma(\mathrm{0n0n})}{dy} + 2\frac{d\sigma(\mathrm{0nXn})}{dy} + \frac{d\sigma(\mathrm{XnXn})}{dy}$$

Solving the linear equations resolves the two-fold ambiguity for VMs at y ≠ 0

Positive rapidity

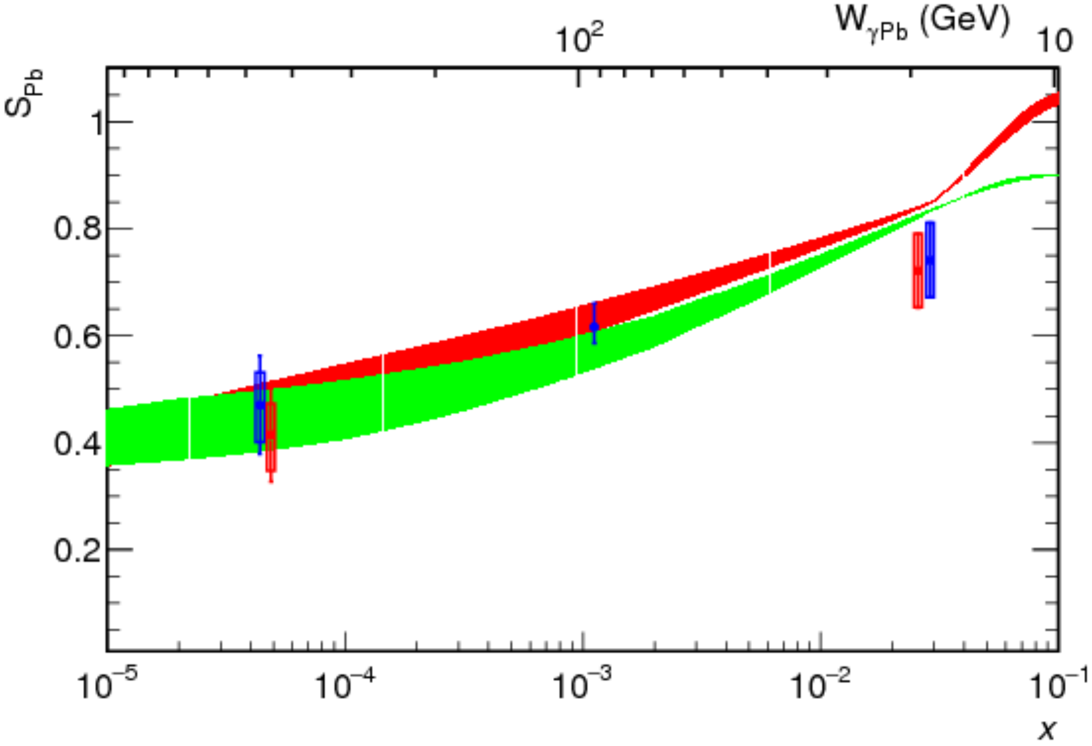
Negative rapidity

$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma \mathrm{p}, +\mathrm{y}) + \mathrm{n}(-\mathrm{y})\sigma(\gamma \mathrm{p}, -\mathrm{y})$$

Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942

Nuclear suppression factor for peripheral (not UPC) J/ψ

J.G. Contreras, *Phys. Rev .C* 96 (2017) 1, 015203



Run 1 data from ALICE observed Coherent-like J/ψ from peripheral hadronic PbPb events. Process later confirmed by STAR

The photon flux depends on the impact parameter, these peripheral J/ψ explore γP energies beyond coherent J/ψ at the same y interval at the same cms energy

Sensitivity to x ~ 10^{-5}

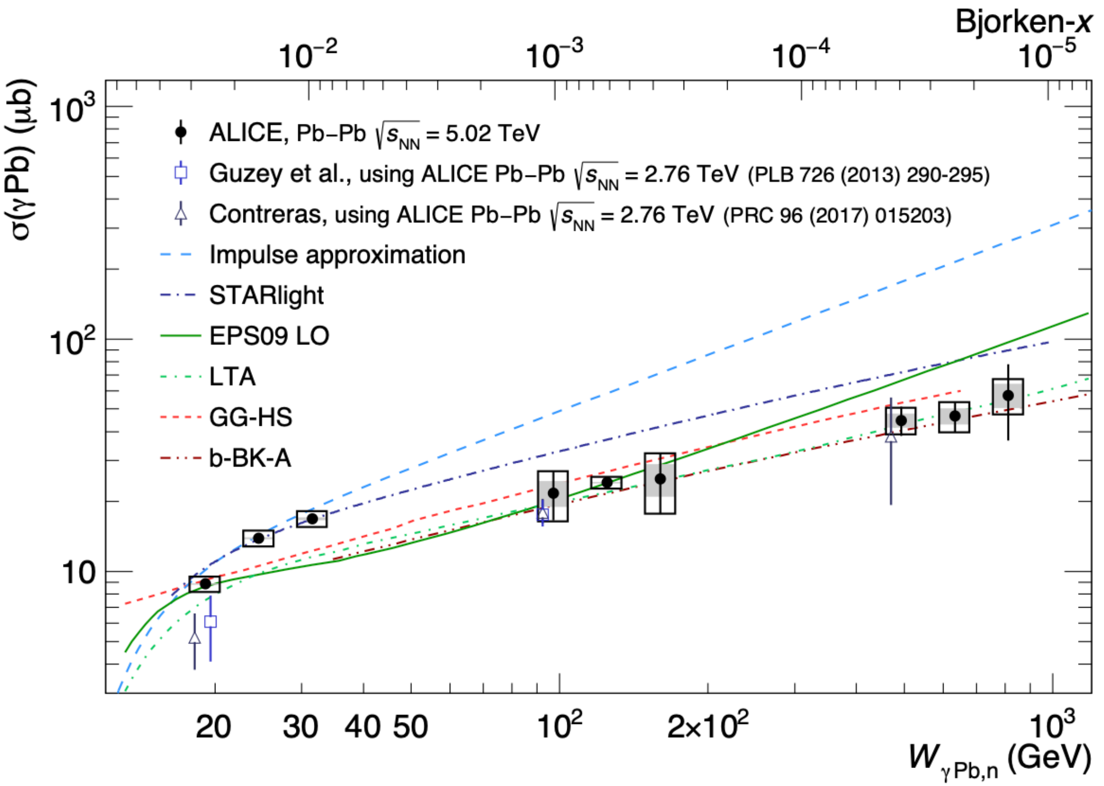
Energy dependence of coherent J/ψ in γPb – ALICE Run 1 and Run 2 data

JHEP 10 (2023) 119

Confirmed Run 1 results.
At low x, both shadowing and saturation models describe the data

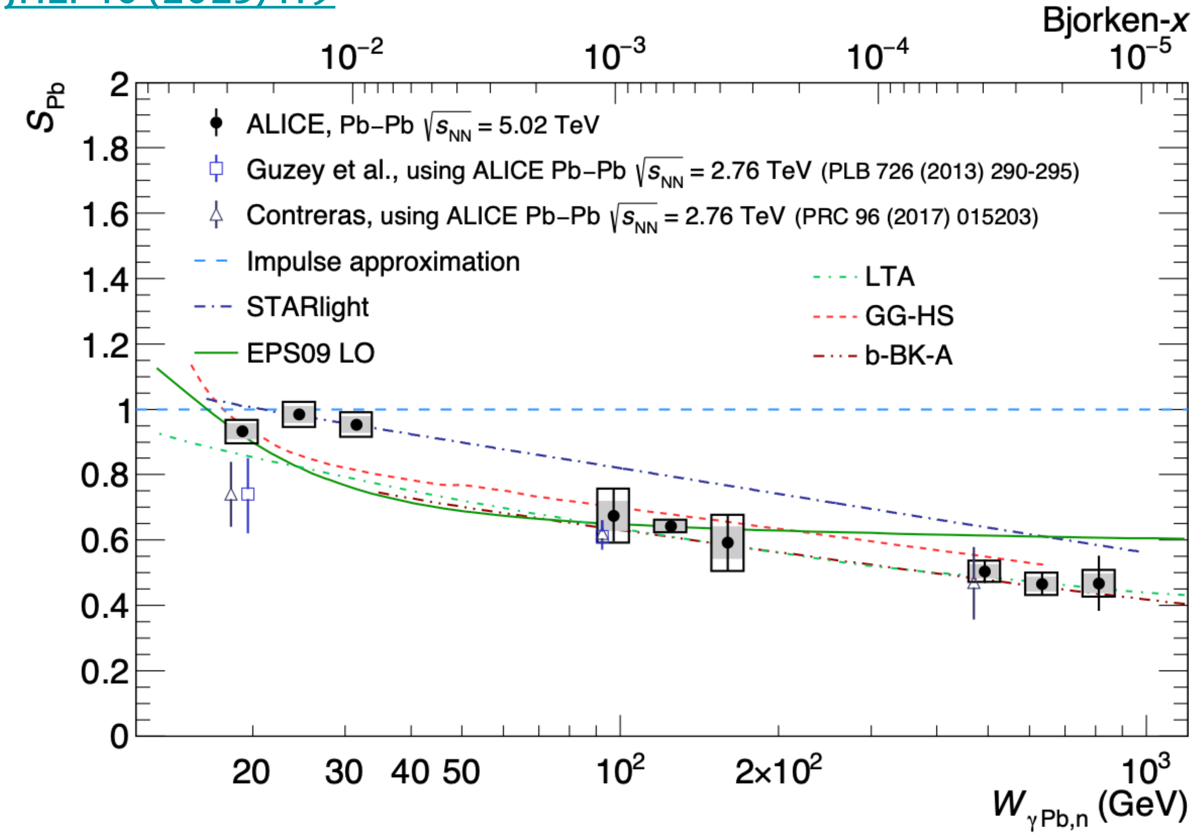
Energy dependence across the whole range not described by models

In a single experiment exploring (20,800) GeV in $W_{\gamma Pb}$ and x from 10^{-2} to 10^{-5}



Nuclear suppression factor – ALICE Run 1 and Run 2 data

JHEP 10 (2023) 119

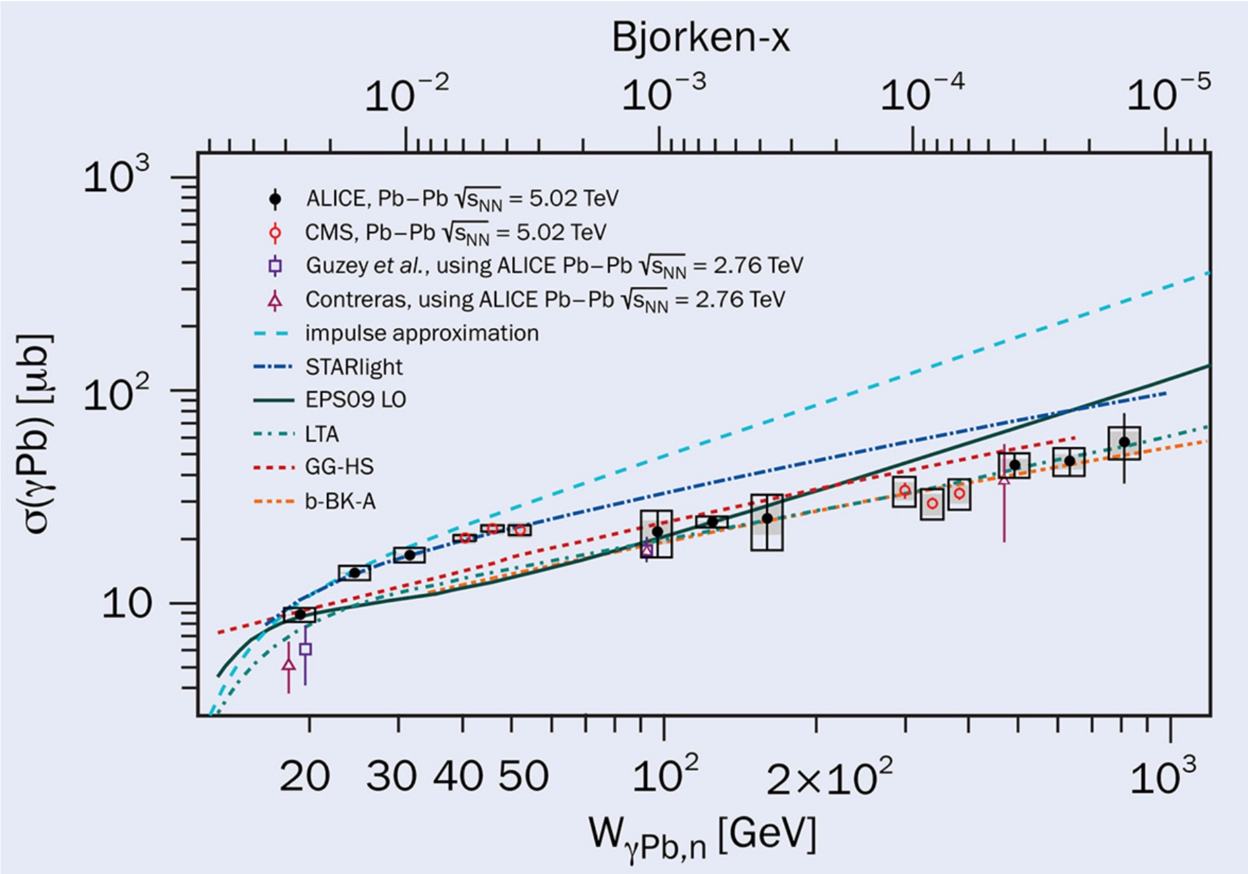


At low x, both shadowing and saturation models describe the data

Confirmation that peripheral hadronic events can be used to extract the energy dependence. Already explored down to $x = 4.4 \times 10^{-5}$ using Run 1 data

With the neutron-dependent analysis using Run 2 data, down to $x = 1.1 \times 10^{-5}$, Run 2

Energy dependence of coherent J/ψ in γPb



JHEP 10 (2023) 119

Both gluon saturation and shadowing describe the data at high energies

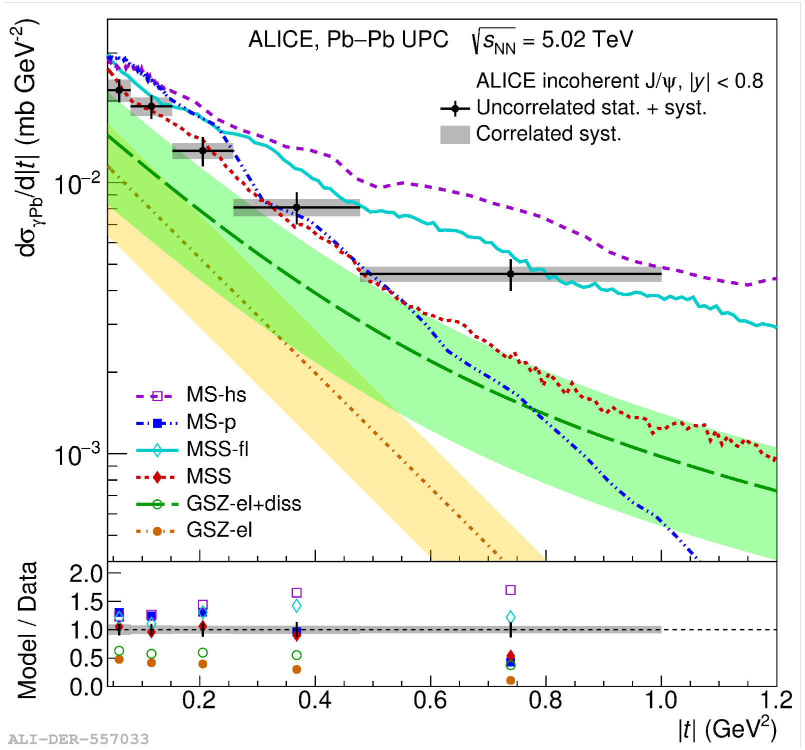
At low energies the data cannot be described by these models

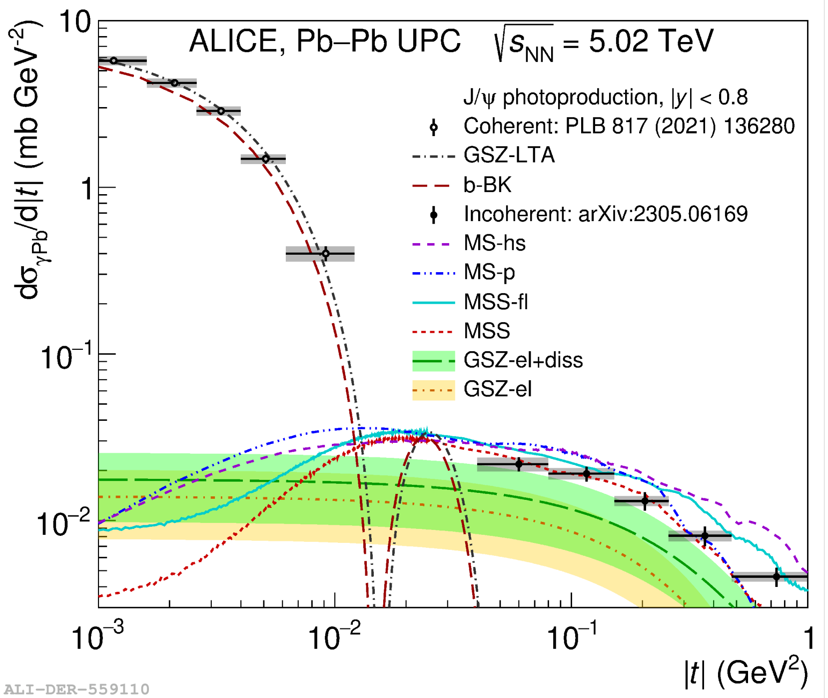
t-dependence of coherent and incoherent J/ψ in UPC Pb-Pb

First measurement of the |t|-dependence of incoherent J/ψ photonuclear production

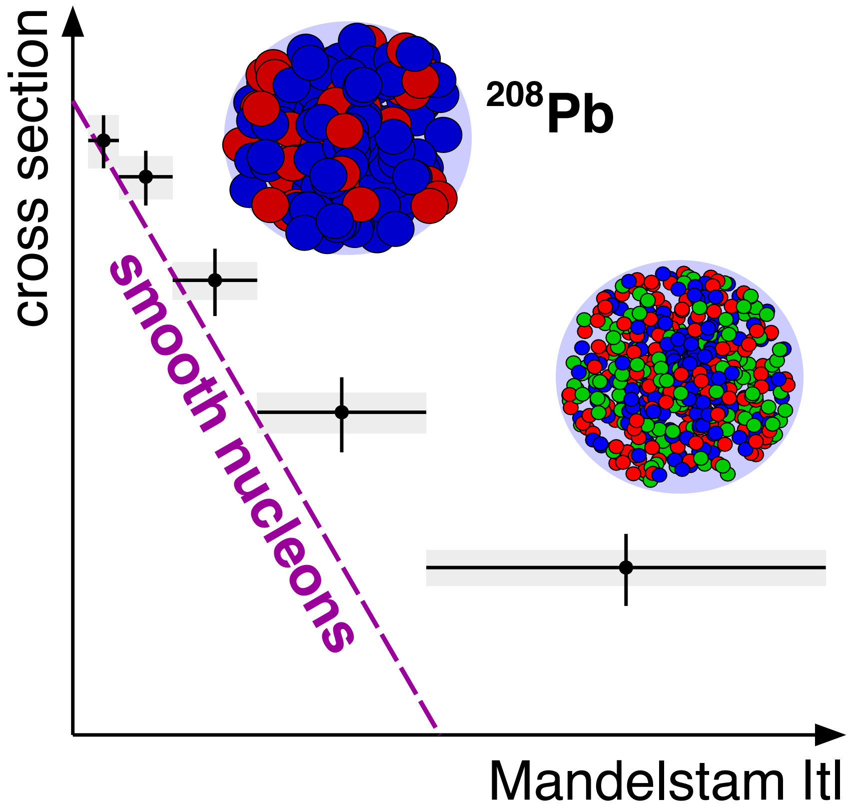
Phys.Rev.Lett. 132 (2024) 16, 162302

Probing for gluonic ”hot spots” in Pb using UPCs for the first time!





t-dependence of incoherent J/ψ in UPC Pb-Pb

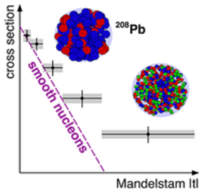


Editors' Suggestion

First Measurement of the |t| Dependence of Incoherent J/ψ Photonuclear Production

S. Acharya *et al.* (ALICE Collaboration)

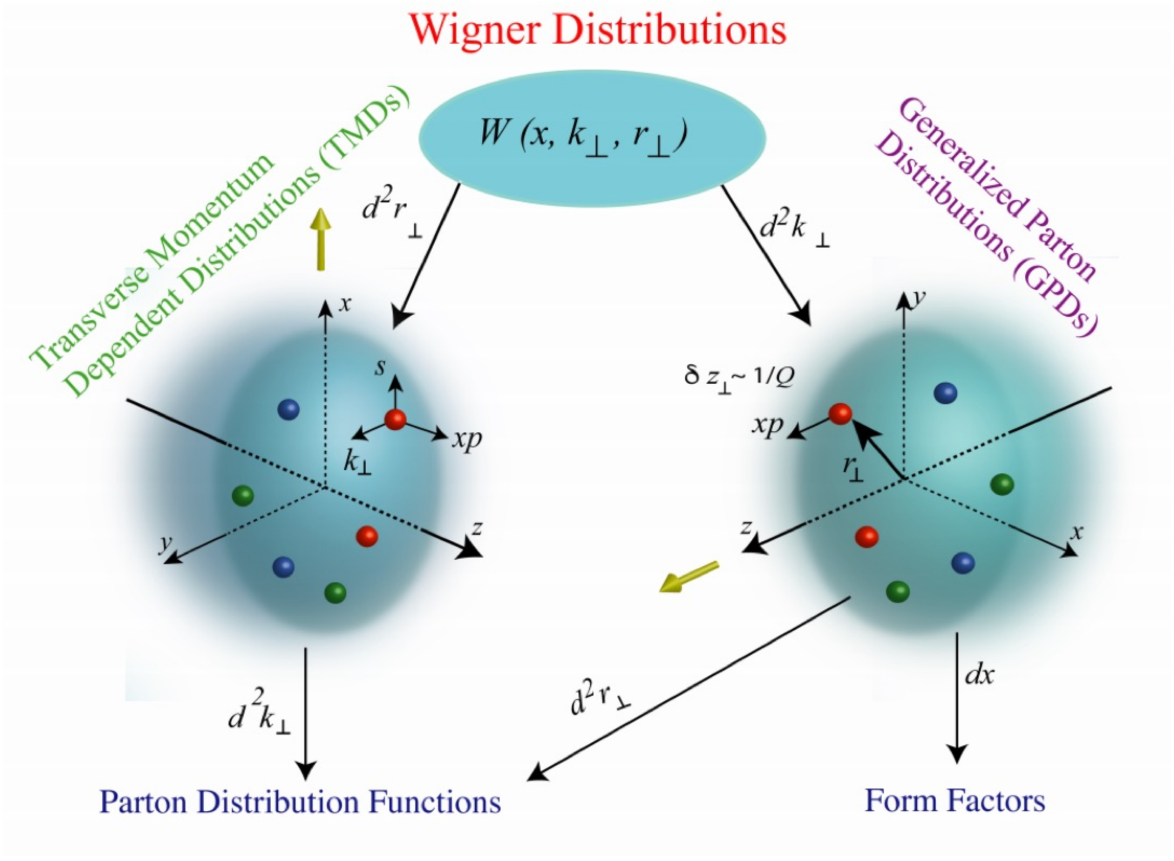
Phys. Rev. Lett. **132**, 162302 (2024) – Published 19 April 2024



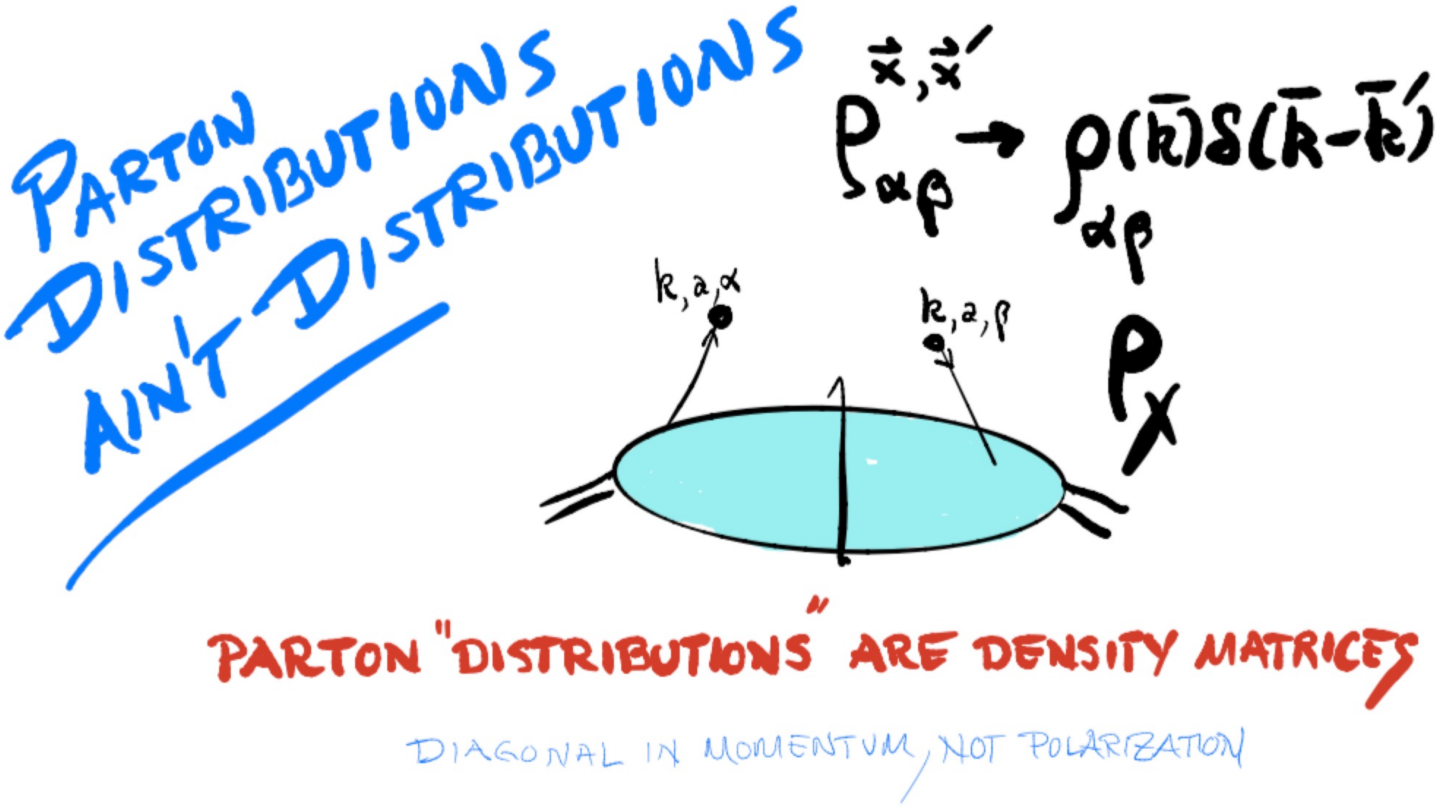
The first experimental measurement of the incoherent photonuclear production of J/ψ in ultraperipheral heavy-ion collisions is better explained by the presence of subnuclear quantum fluctuations of the gluon field.

Show Abstract +

Beyond the 1-Dimensional picture



A new point of view

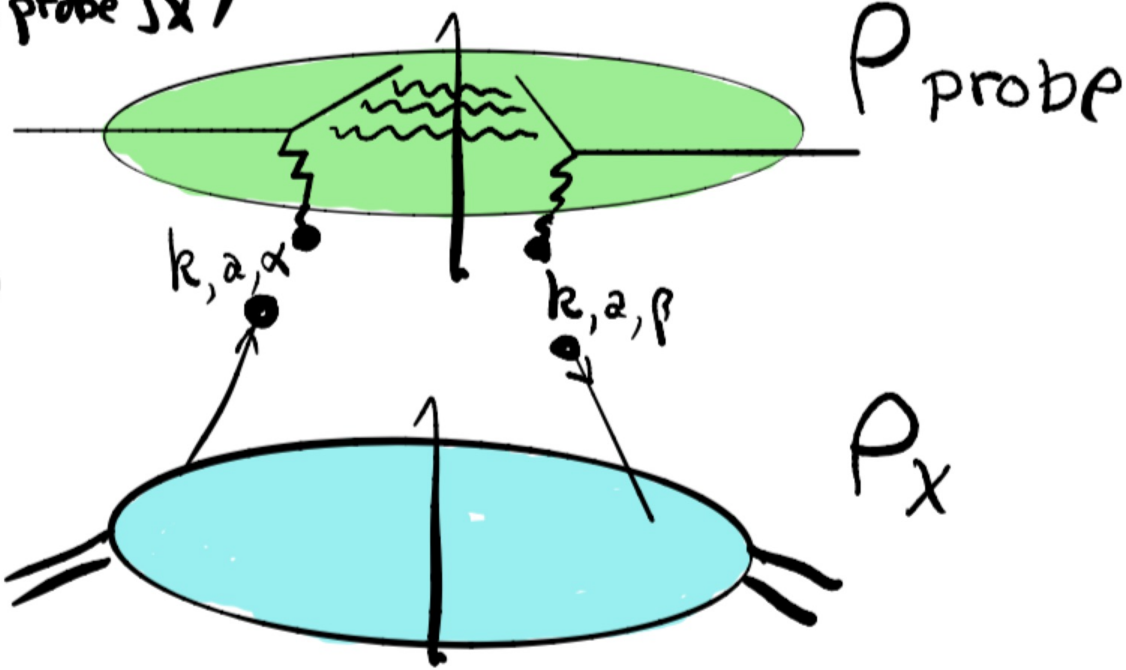


A new point of view

EVERY CROSS SECTION

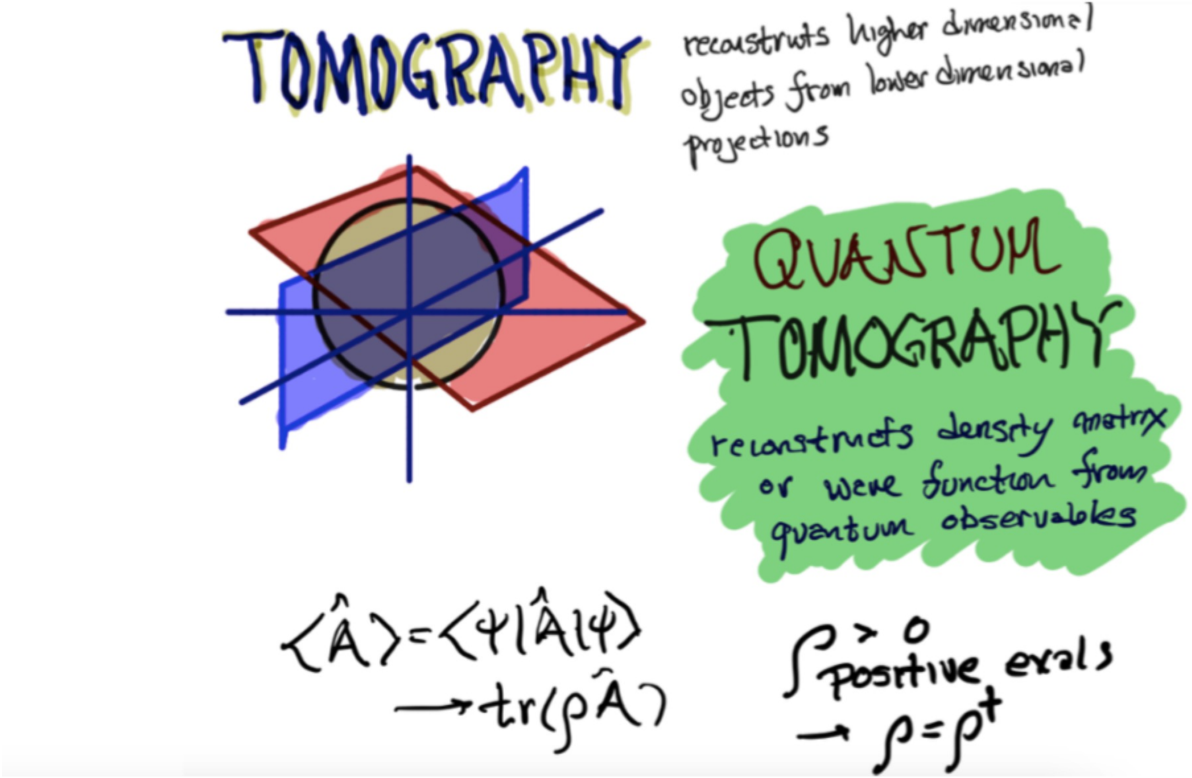
$$d\sigma = \mathrm{tr}(\rho_{probe}\,\rho_X)$$

DIS

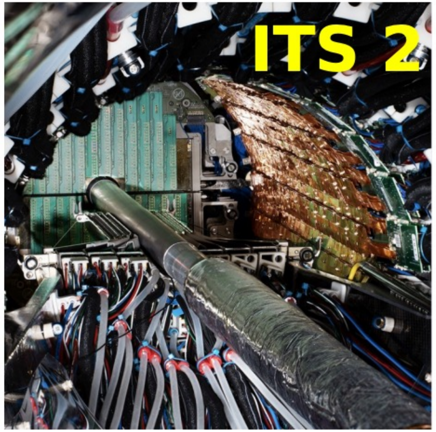


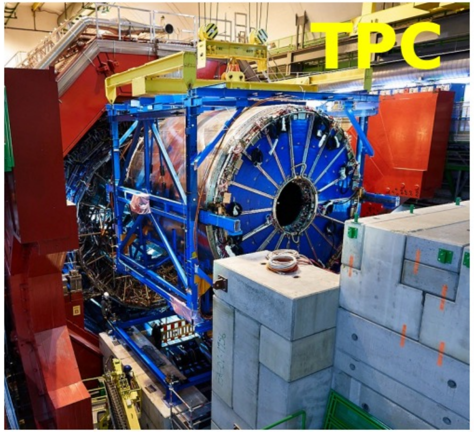
A new point of view

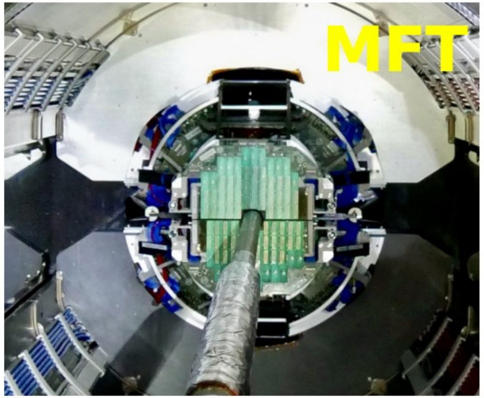
Martens, Ralston, Tapia Takaki Eur. Phys. J. C78, 5, 2018

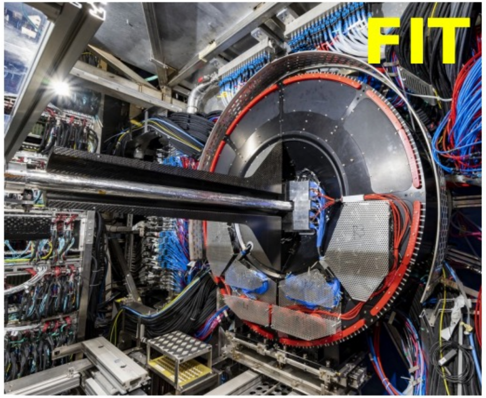


ALICE in Run 3: A major upgrade



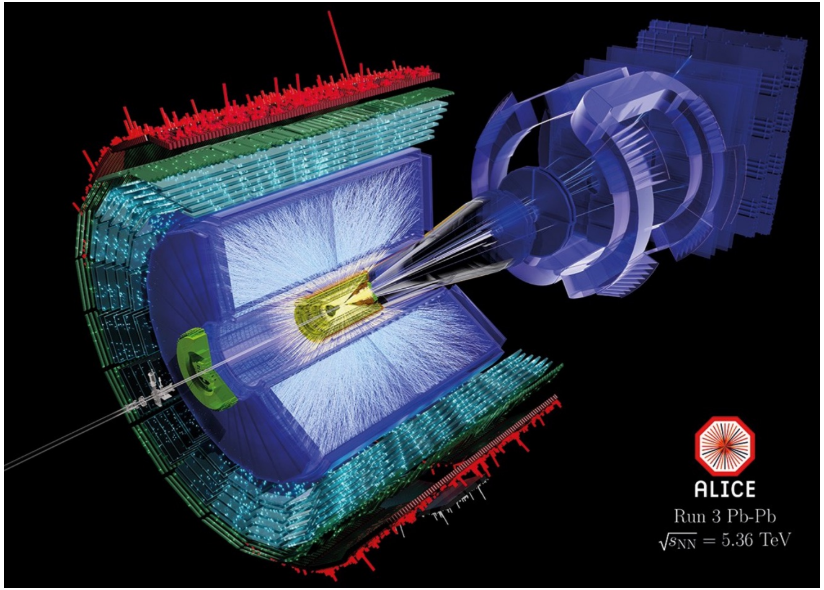


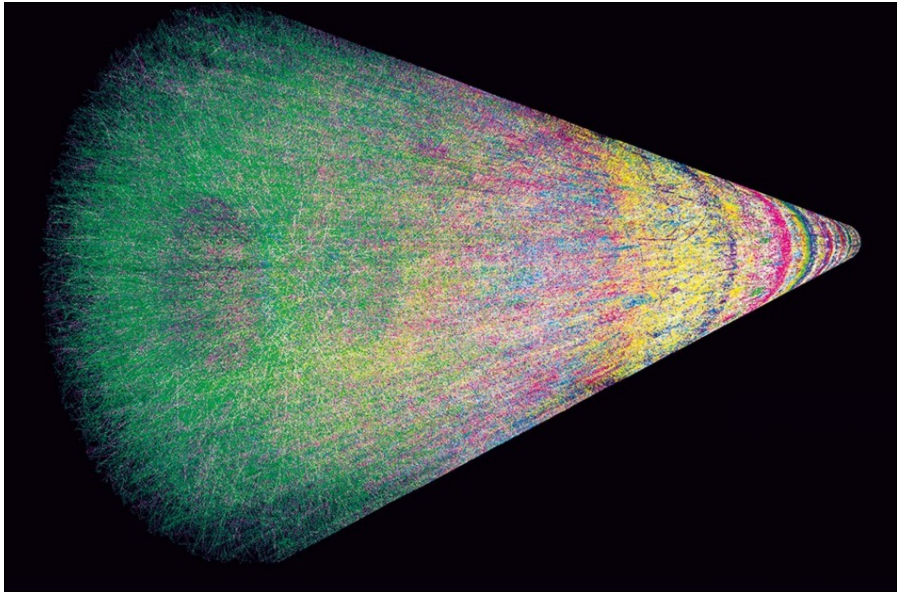




- 50 times increase in the readout rate
- 3 to 6x improvement in pointing resolution
- Secondary vertexing for forward muons

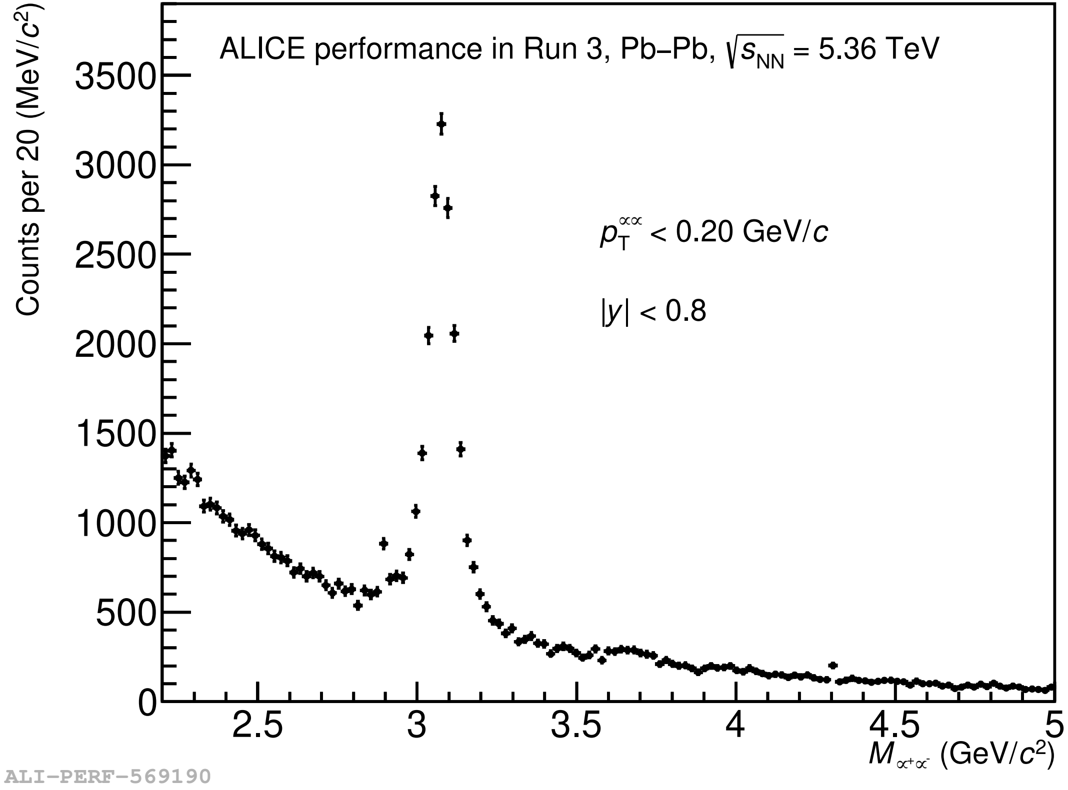
ALICE in Run 3: Trigger-less mode





2 μs time frame of Pb-Pb collisions at a 50 kHz interaction rate in the TPC

Great performance for reconstructing UPC vector mesons



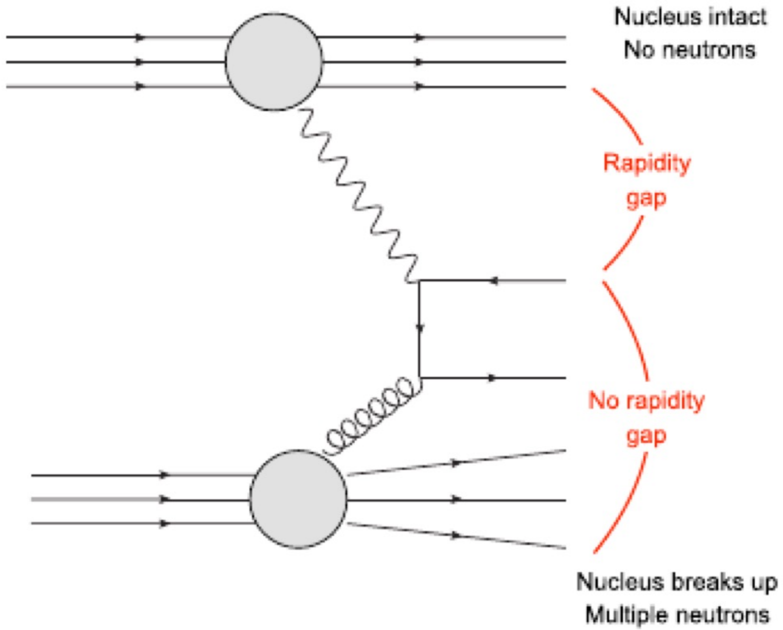
- The trigger-less mode will enable to develop further the UPC physics program in ALICE from Run 3
- New processes, including inelastic UPC events will be possible

Run 3 data analysis: Inelastic γ+Pb -> X events

Experimental signatures for inelastic photonuclear interactions:

1) There is a rapidity gap on the side of the photon-emitting nucleus → main experimental signature

2) The photon energy << beam energy → particle production is shifted in rapidity to the side of the target nucleus



Phys. Rev C 66 (2002) 044906

Total cross sections in Pb+Pb @ √s = 5.5 TeV

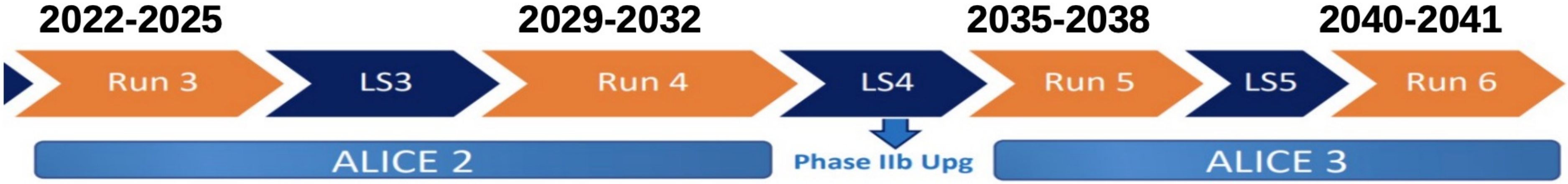
σ(Pb+Pb → Pb+ccbar+X) = 2b

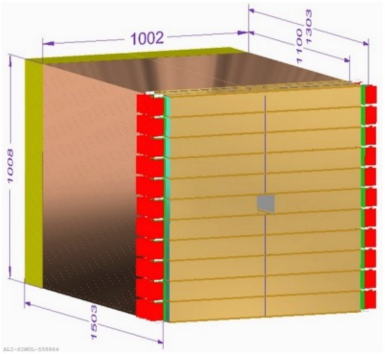
σ(Pb+Pb → Pb + bbbar +X) = 830 μb

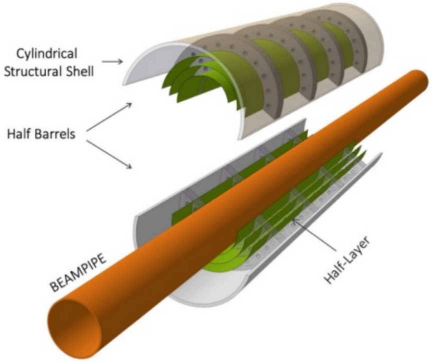
Direct production: a bare photon interacts with a parton in the target

Resolved production: the photon fluctuates to vector meson which interacts inelastically with the target

ALICE timeline





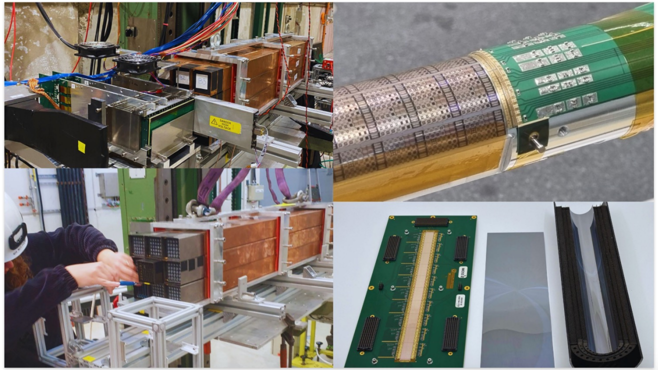


FoCal and ITS3

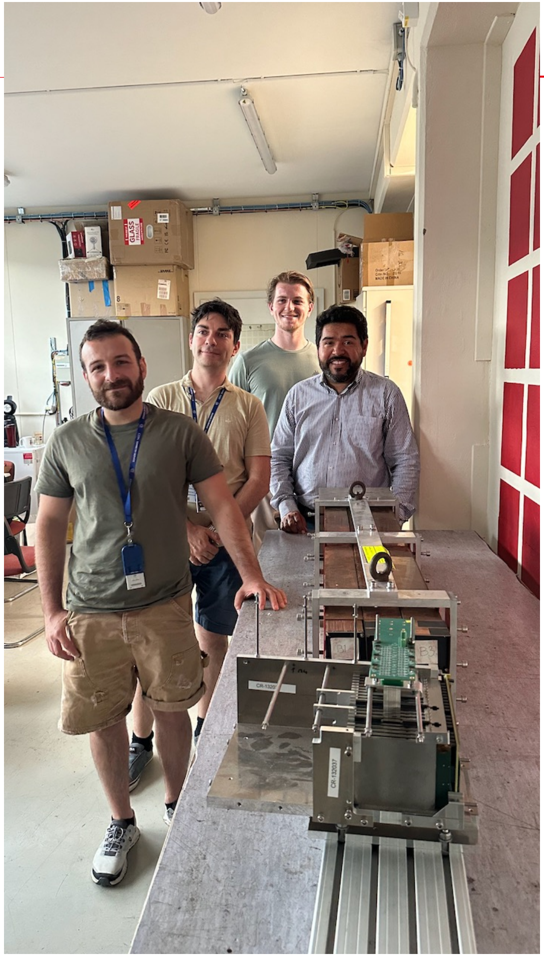
ALICE gets the green light for new subdetectors

CERN's dedicated heavy-ion physics experiment, ALICE, is upgrading its Inner Tracking System and adding a forward calorimeter for the next phase of the LHC upgrade

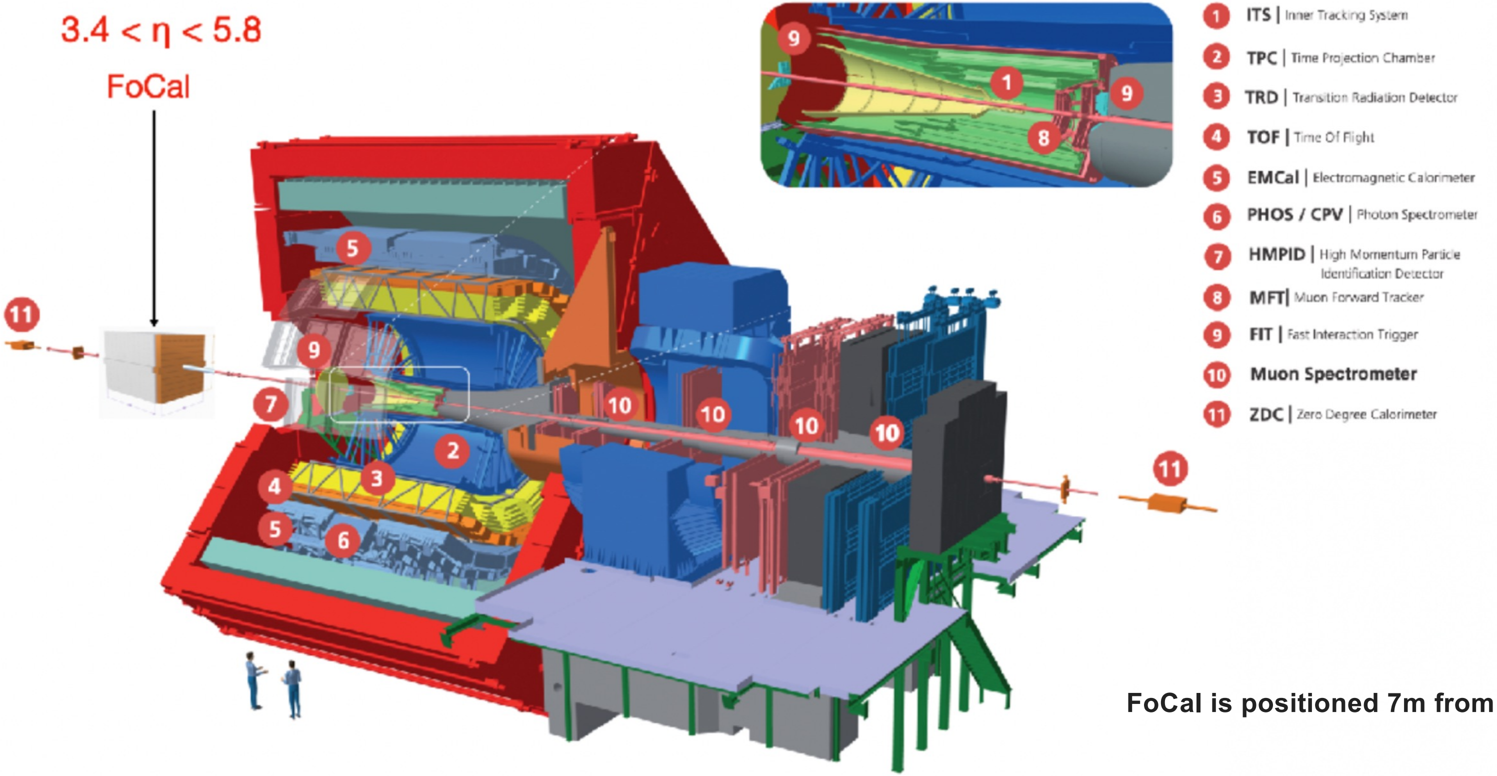
25 APRIL, 2024 | By ALICE collaboration



The ALICE FoCal project for Run 4



The ALICE FoCal project for Run 4



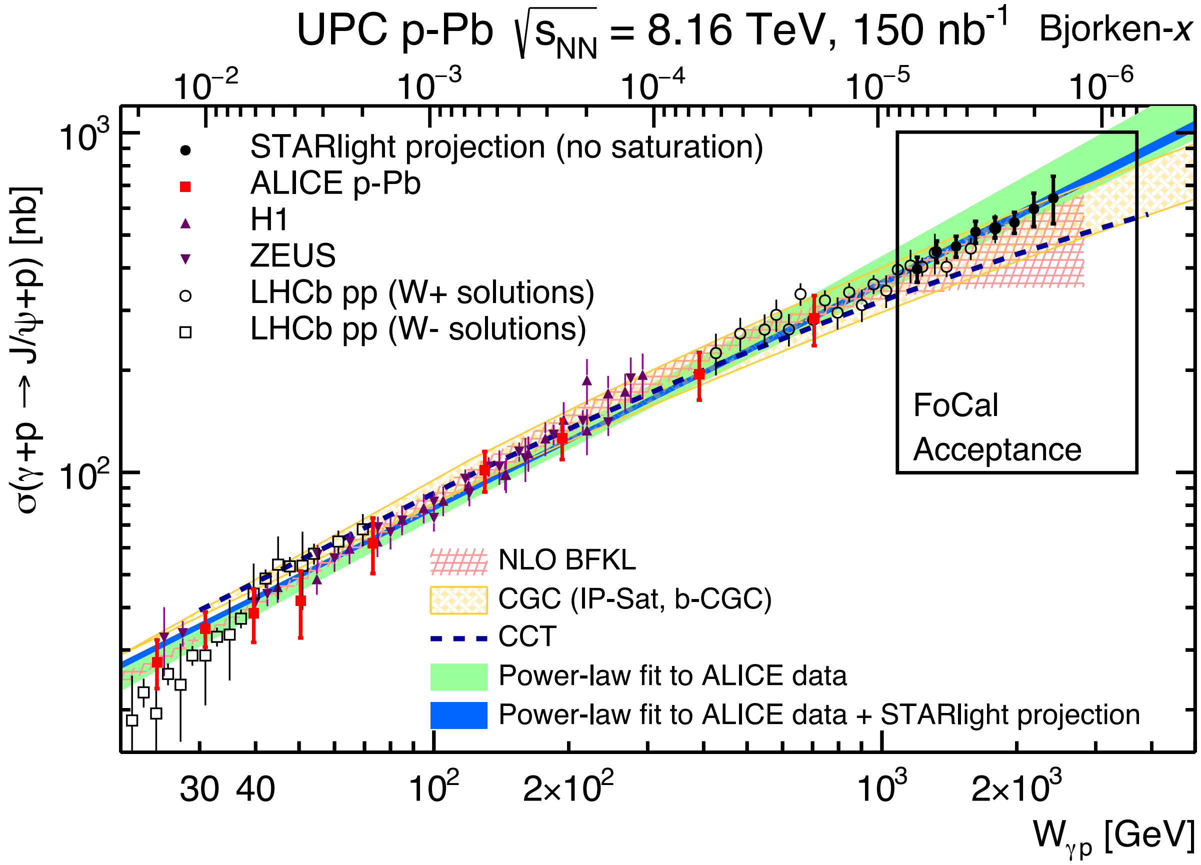
FoCal is positioned 7m from IP2 (A-side)

UPC VM projections for FoCal

A. Bylinkin, J. Nystrand and DTT *J. Phys. G* 50 (2023) 055105, 5

VM	$\sigma(\mathrm{p}+\mathrm{Pb} \to \mathrm{p}+\mathrm{Pb}+\mathrm{VM})$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$	Yield
		$\mathrm{p} \to$ FoCal	$\mathrm{p} \to$ 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
		$\mathrm{Pb} \to$ FoCal	$\mathrm{Pb} \to$ 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

Projections for exclusive J/ψ off protons

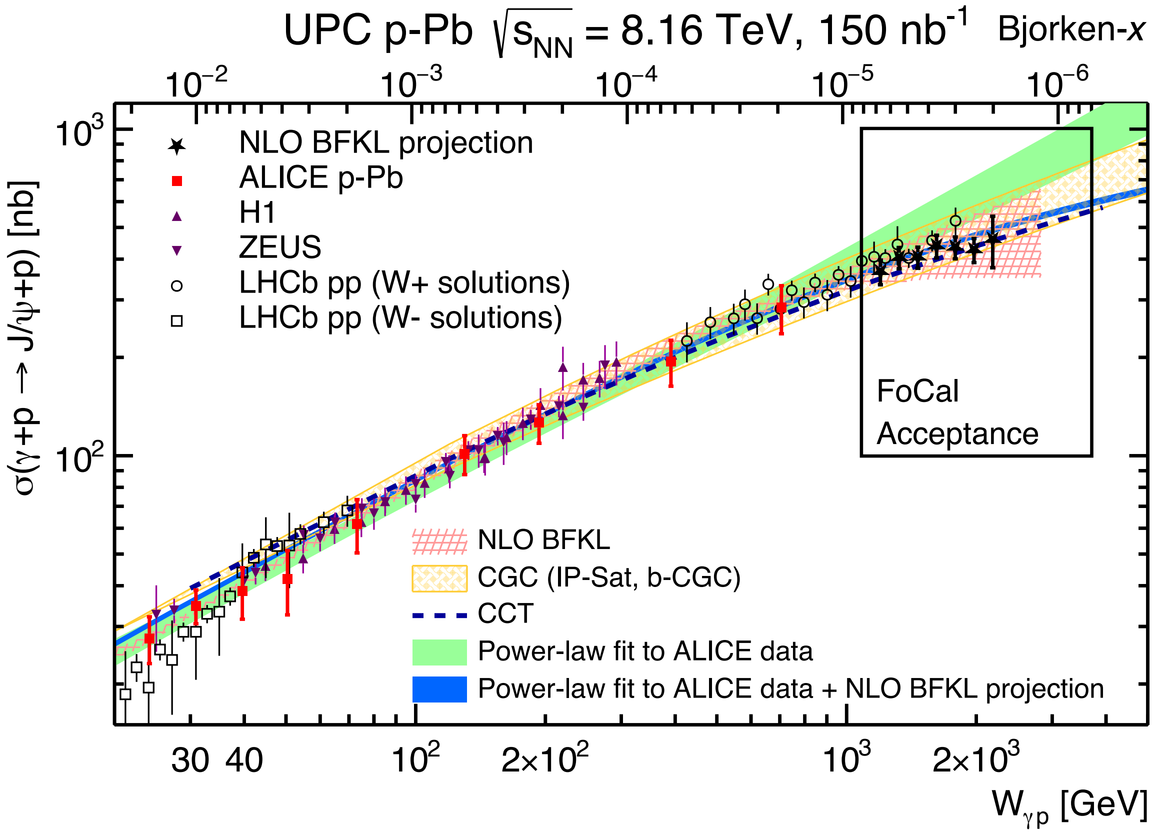


- Deviations from a power-law trend should signal non-linear QCD dynamics
- Here, projections based on STARlight which uses a parametrization based on HERA data

$$\sigma_0(W_{\gamma p}/W_0)^{\delta}$$

- For all figures, 60% efficiency. Conservative assumption after acceptance selection

Projections for exclusive J/ψ off protons

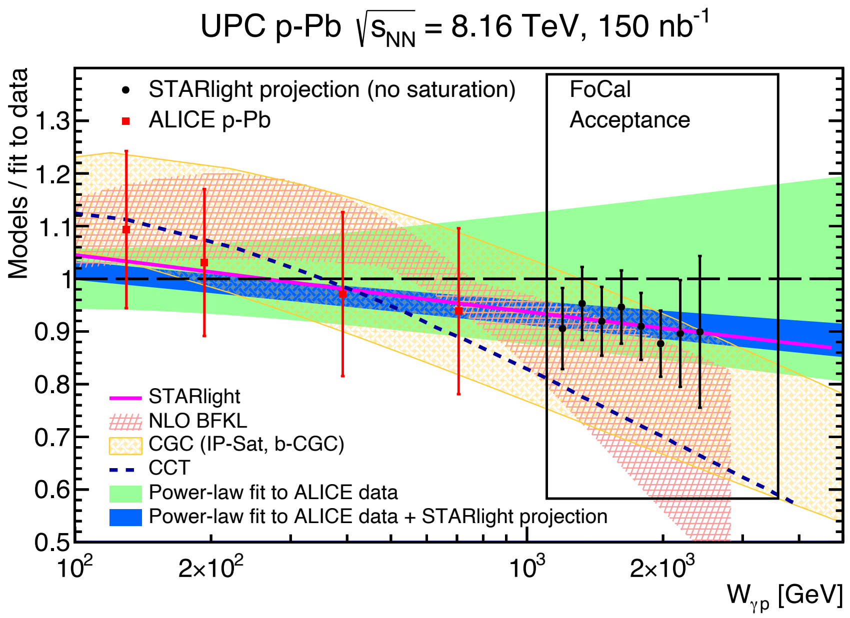


- Projections assuming a broken power-law
- Projected points based on NLO BFKL calculation

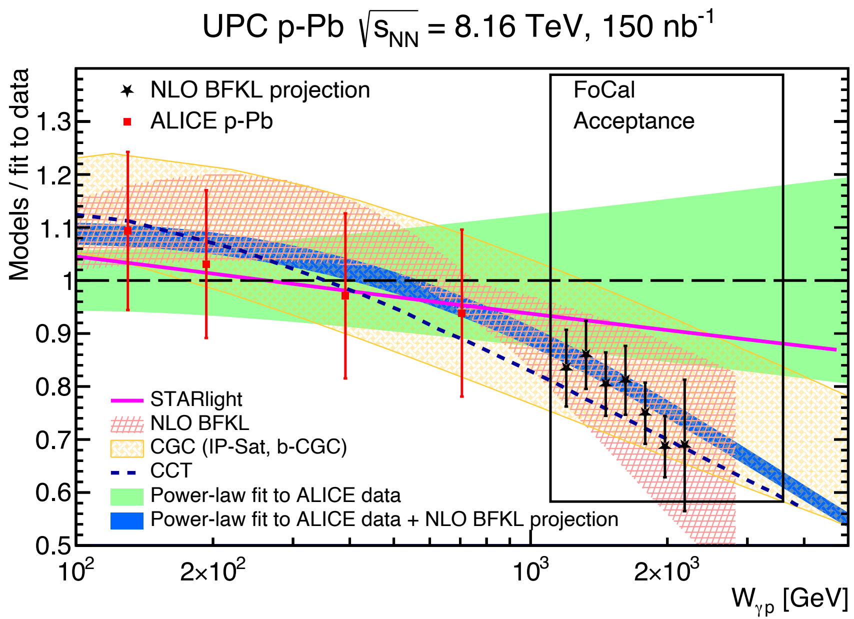
$$\sigma(\gamma p) \approx \frac{\sigma_0}{\frac{1}{W_{\gamma p}^{\delta}} + A}$$

Projections for exclusive J/ψ off protons

Power-law behavior (STARlight)

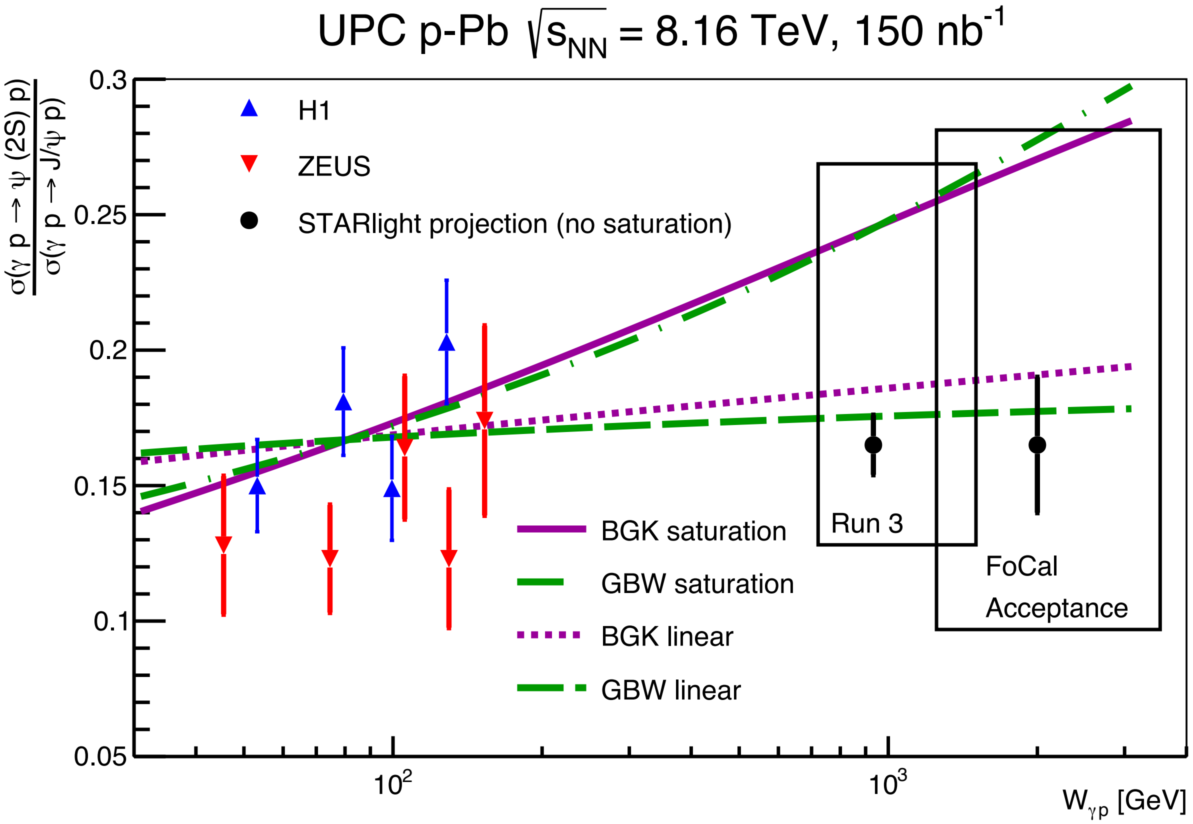


Broken power-law behavior (NLO BFKL)



FoCal measurement would be sufficient to observe a deviation from a power law behavior, if exists

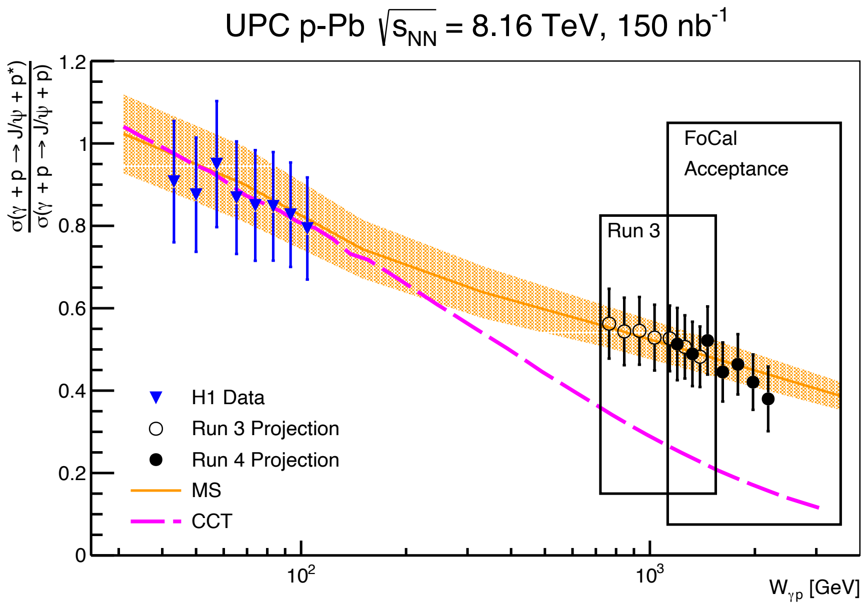
Projections for exclusive ψ(2S) and J/ψ cross section ratio in γp



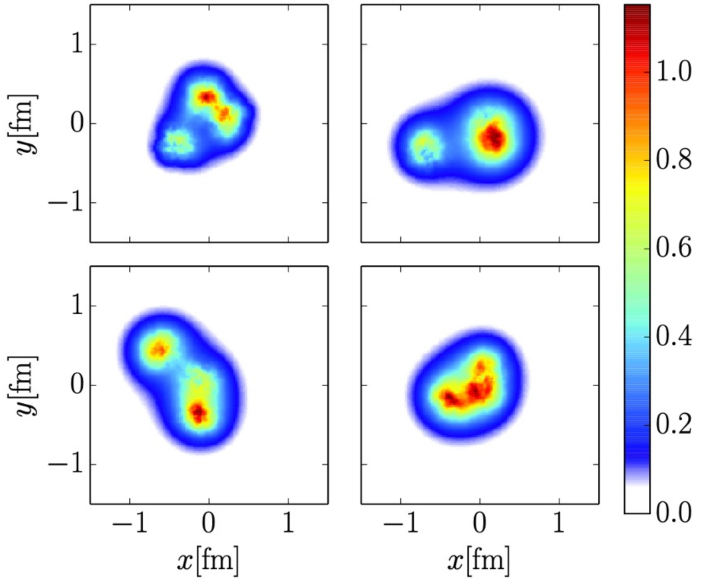
- Different wave functions and dipole sizes evolution result in great sensitivity to non-linear QCD effects
- No sensitivity at HERA, but expected at the LHC
- Projections here based on STARlight

Projections for dissociative J/ψ cross section ratio in γp

J. Cepilia, J.G. Contreras and DTT
Phys. Lett.B 766 (2017) 186-191



Projections here based on the MS model
Event-by-event fluctuations

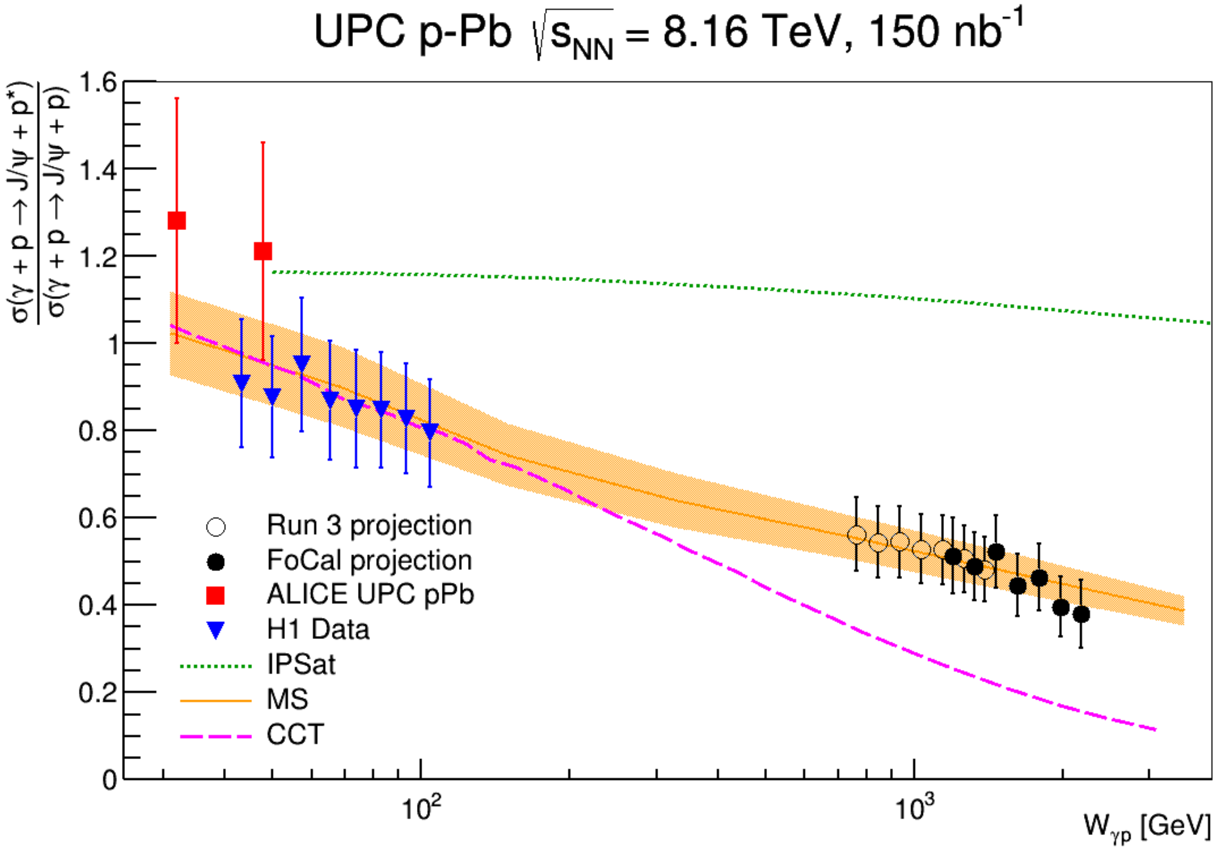


Mantysaari and Schenk, PRD 94, 034042 (2016)
S. Klein arXiv:2301.014018

In the Good-Walker approach, sensitive to subnucleonic fluctuations of the gluon density

$$\frac{d\sigma(\gamma p \rightarrow J/\psi Y)}{dt} = \frac{R_g^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})\right\rangle\right|^2\right)$$

Projections for dissociative J/ψ cross section ratio in γp



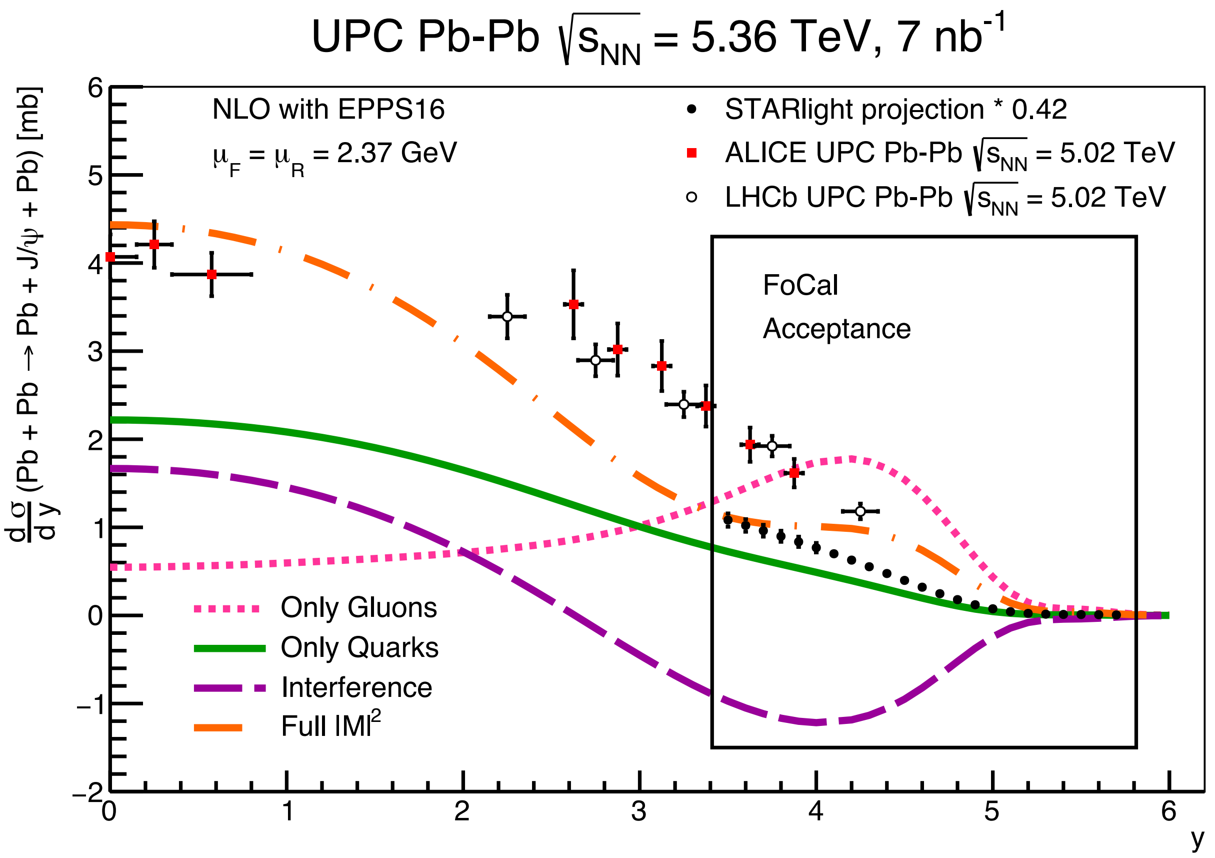
Projections for VMs in γPb

$$\mathcal{L} = 7.0\ \text{nb}^{-1}$$

A. Bylinkin, J. Nystrand and DTT *J.Phys.G* 50 (2023) 055105, 5

VM	$\sigma(\text{Pb}+\text{Pb}\to\text{Pb}+\text{Pb}+\text{VM})$	$\sigma(3.4 \le \eta_{1,2} \le 5.8)$	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

Projections for coherent J/ψ cross section ratio in γPb



- FoCal acceptance dominated by gluons and sensitivity to the form factor
- Projections here based on STARlight

Neutron-dependence of coherent J/ψ in γPb

Decomposed in terms of neutron configurations emitted in the forward region

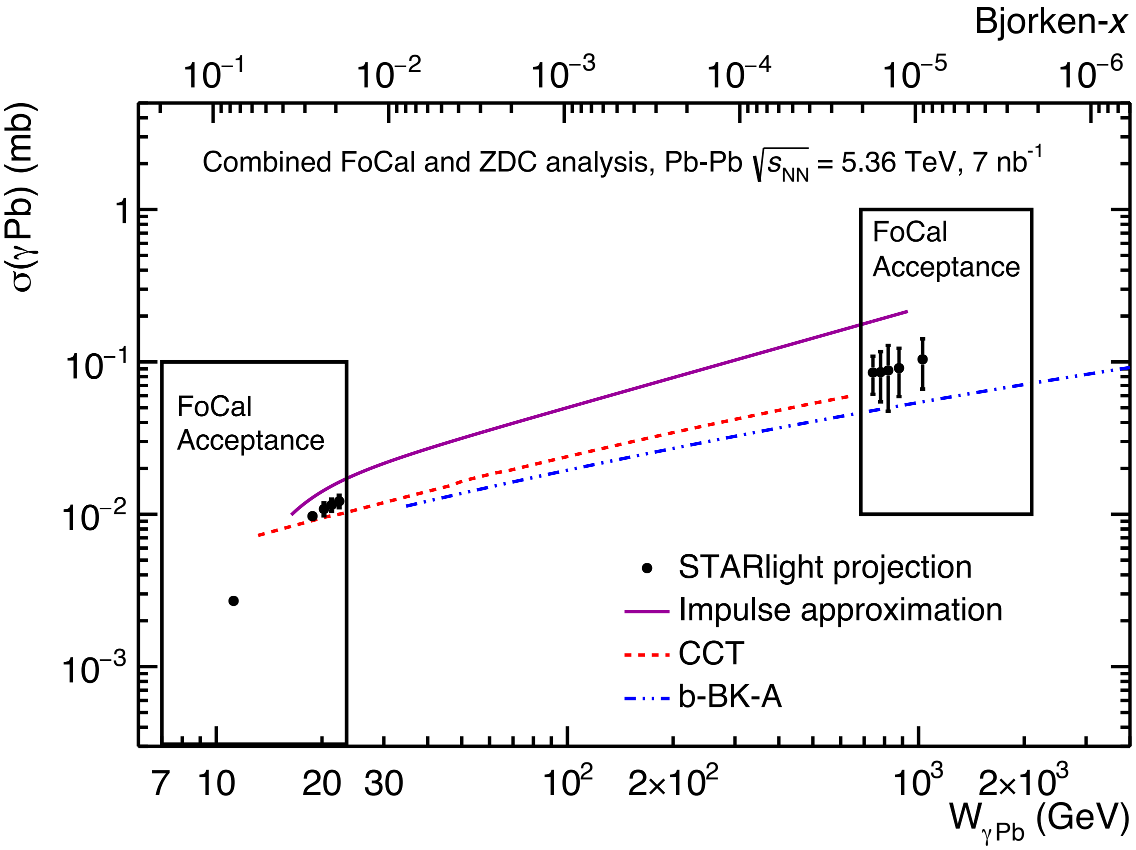
$$\frac{d\sigma}{dy} = \frac{d\sigma(\mathrm{0n0n})}{dy} + 2\frac{d\sigma(\mathrm{0nXn})}{dy} + \frac{d\sigma(\mathrm{XnXn})}{dy}$$

Neutron configuration	$\sigma(\mathrm{Pb+Pb} \to \mathrm{J}/\psi + \mathrm{Pb} + \mathrm{Pb})$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$	Yield
0n0n	28.8 mb	47 μb	329,000
0nXn + Xn0n	7.3 mb	5.0 μb	35,000
XnXn	3.0 mb	2.0 μb	14,000

Solving the linear equations resolves the two-photon ambiguity for VMs at y ≠ 0

$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma\mathrm{p}, +\mathrm{y}) + \mathrm{n}(-\mathrm{y})\sigma(\gamma\mathrm{p}, -\mathrm{y})$$

Projections for Neutron-dependence of coherent J/ψ in γPb



- Neutrons measured with Zero Degree Calorimeters
- Projections based on STARlight
- ALICE will be the only detector capable of explore $x \sim 10^{-6}$ in Pb thanks to FoCal

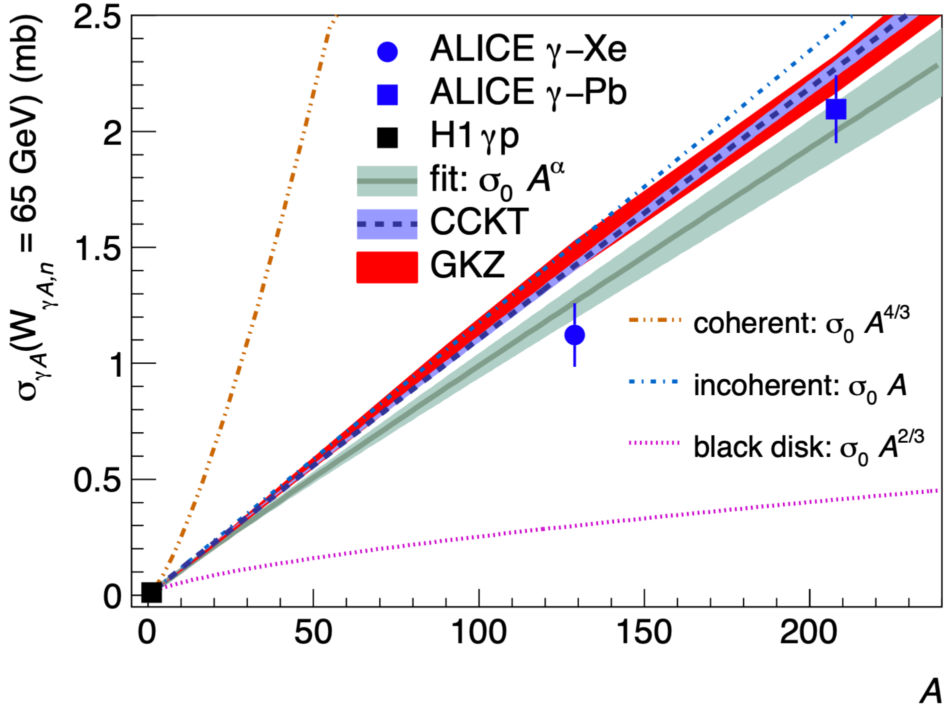
Ideas for the UPC O-O program

- With sufficient luminosity, it would be possible to study the A-dependence of UPC J/ψ for p, O and Pb

- Possible to do the A-dependence for UPC ρ^0 for p, O, Xe and Pb

- The probability for Coulomb excitation in coincidence with vector meson production in O-O is small. So, unlikely to be able to extract r0 photonuclear cross section using 0nXn and XnXn fragmentation

Phys. Lett. B 820 (2021) 136481



Thanks!