U.S. DEPARTMENT OF ENERGY

Office of Science

Physics results, plans and ideas for UPC p-A physics at ALICE

Daniel Tapia Takaki

Physics with high-luminosity proton-nucleus collisions at the LHC workshop

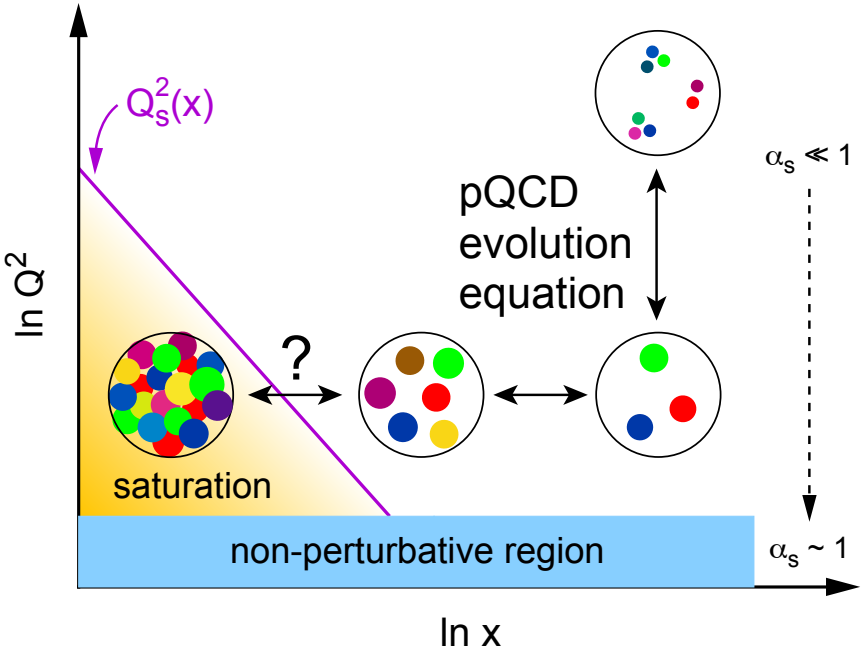
CERN, Geneva

July 4-5, 2024

KU THE UNIVERSITY OF KANSAS

Gluon saturation matters

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

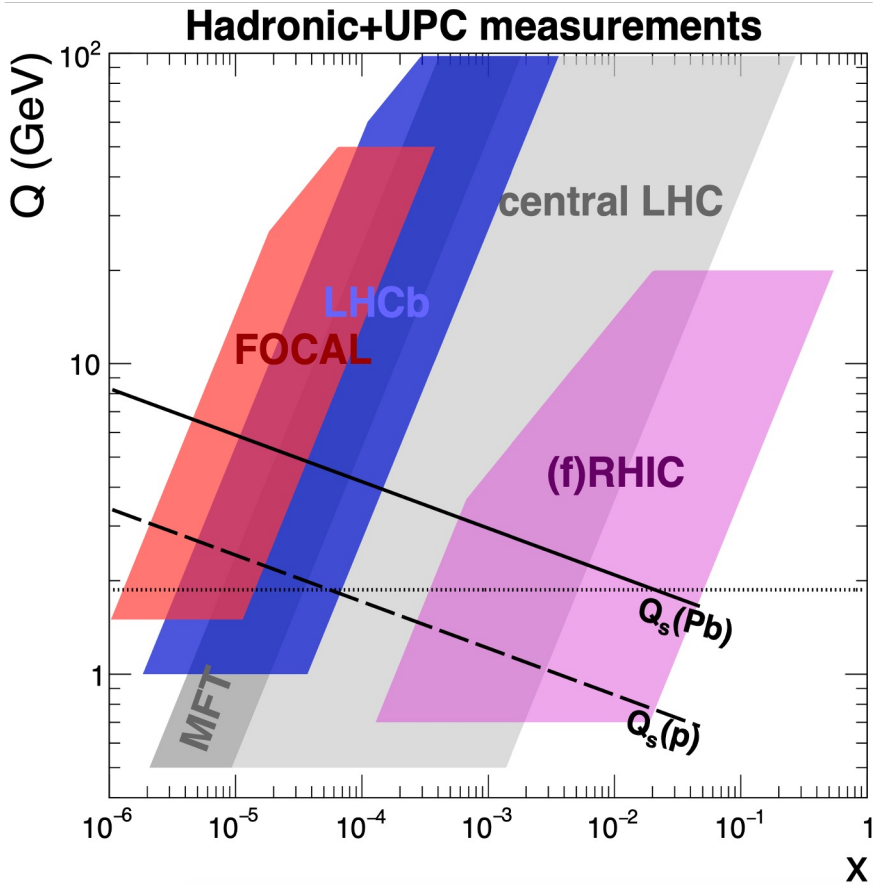


$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

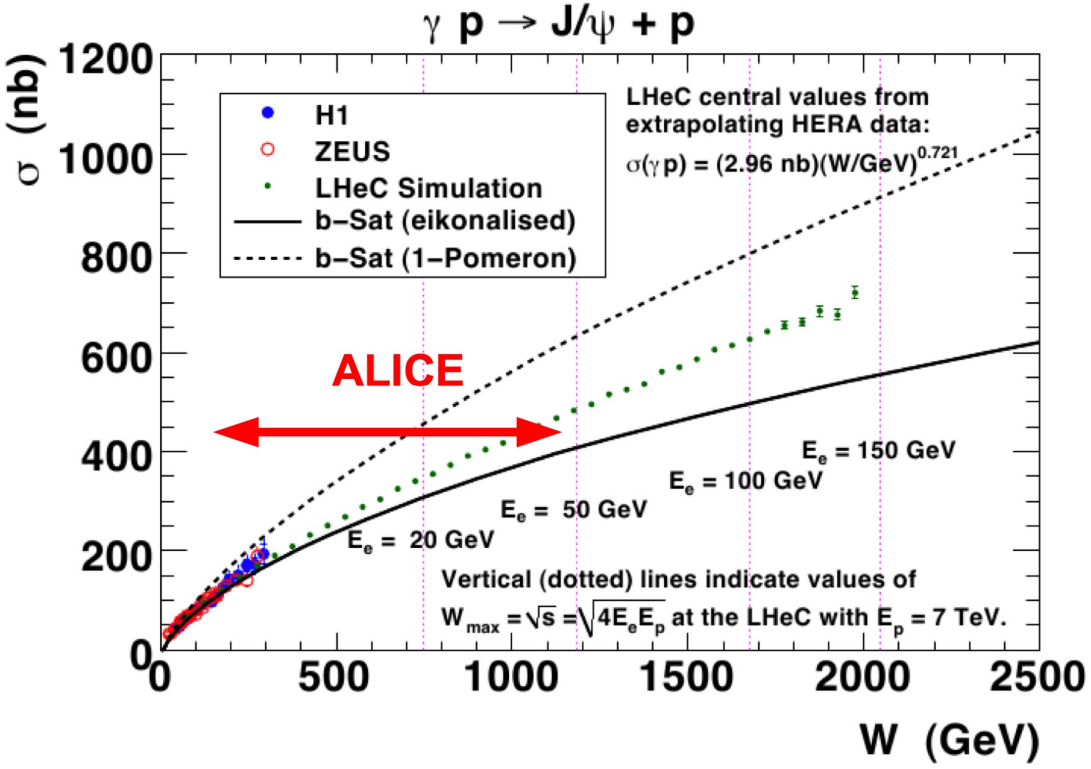
- Non-linear QCD evolution equations introduced, but how is gluon saturation triggered?
- Experimental observables needed to map out the transition between the dilute and saturation regimes. The onset of saturation
- Can we determine experimentally the saturation scale (Q_S)?
- Is there a state of matter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

Experimental program

- The Electron-Ion Collider 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 LHC explores the high energy domain for both hadronic and photon-induced reactions
- FoCal at ALICE will explore a unique low-*x* regime reaching *x* down to 10^{-6}



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

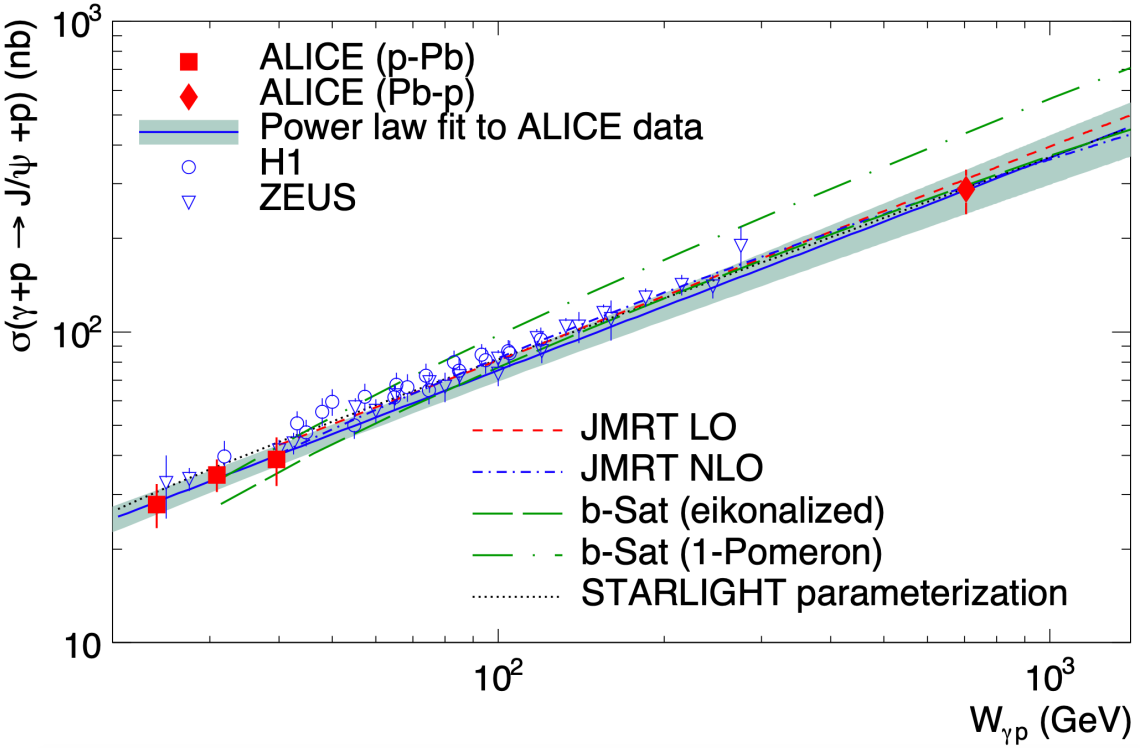
Positive rapidity Negative rapidity

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

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

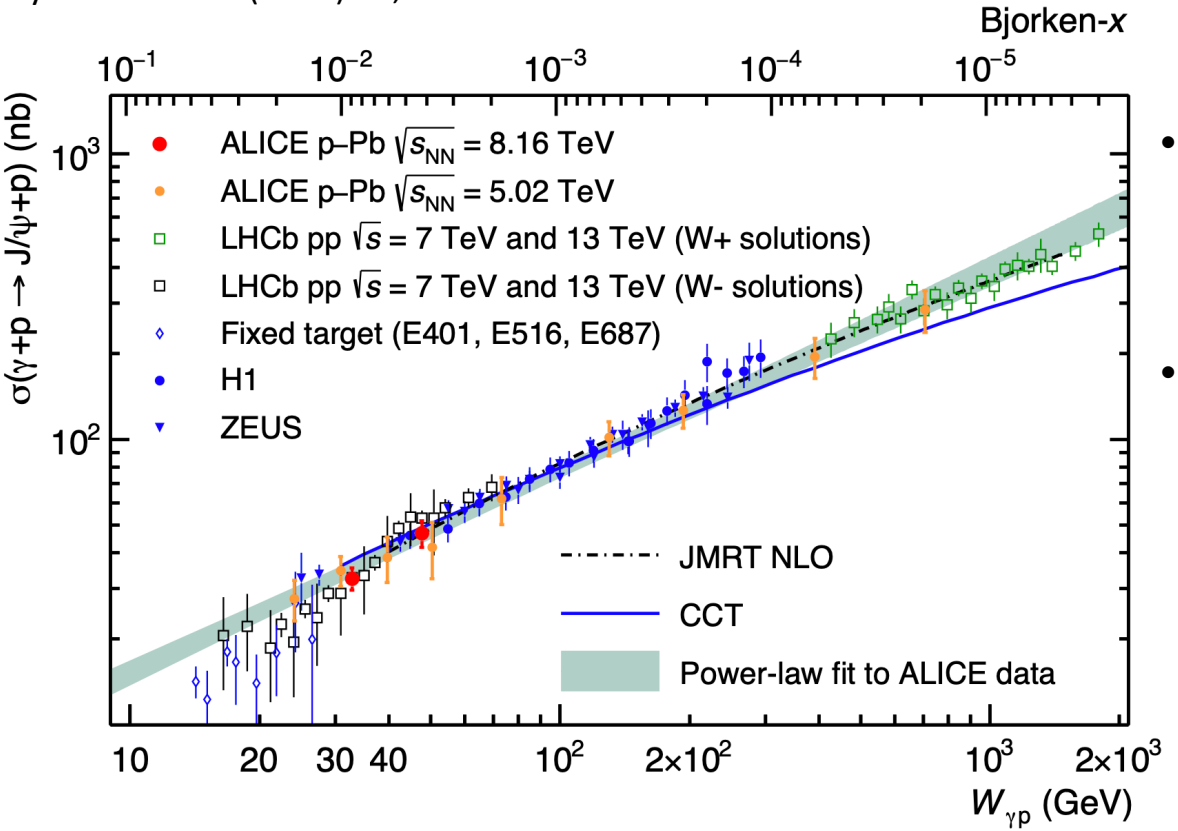


- No change with respect to HERA power-law growth observed at low energies up to 700 GeV
- UPC p-Pb collisions have no ambiguity on the photon energy

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

Exclusive J/ψ in UPC p-Pb (2023)

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

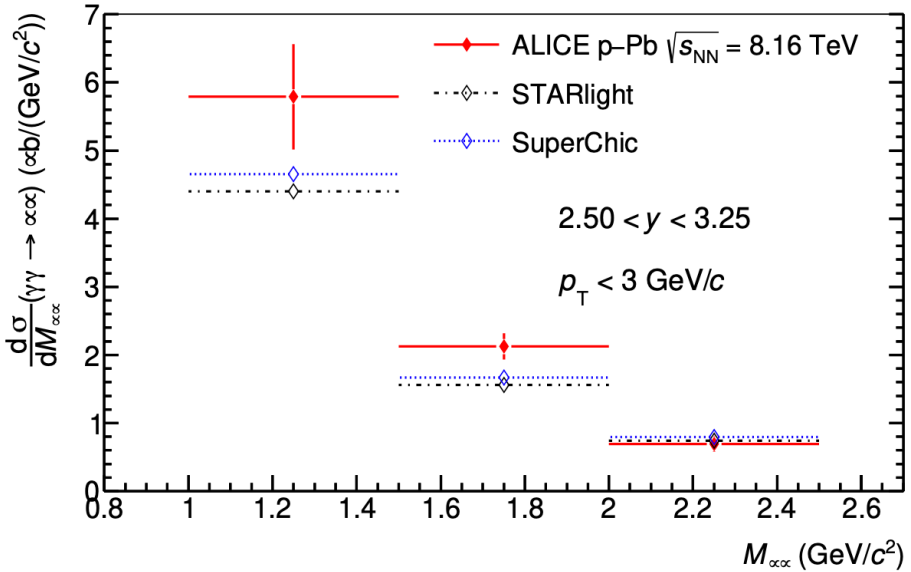


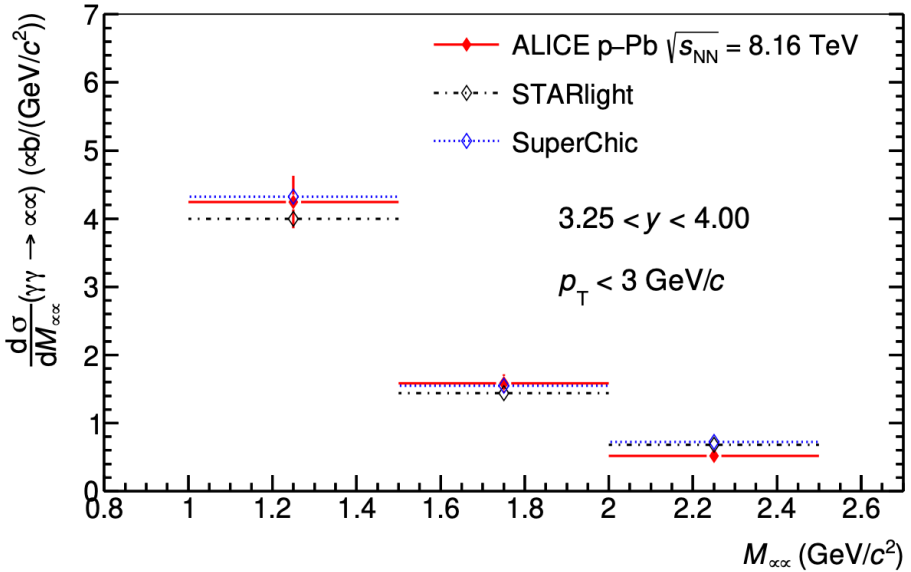
- No change in the behavior observed between HERA and LHC energies
- The highest energy point measured in a model-independent way is only up to 700 GeV in UPC p-Pb by ALICE

Exclusive dimuons in UPC pPb

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

Two-photon measurements providing tests to the photon flux calculations





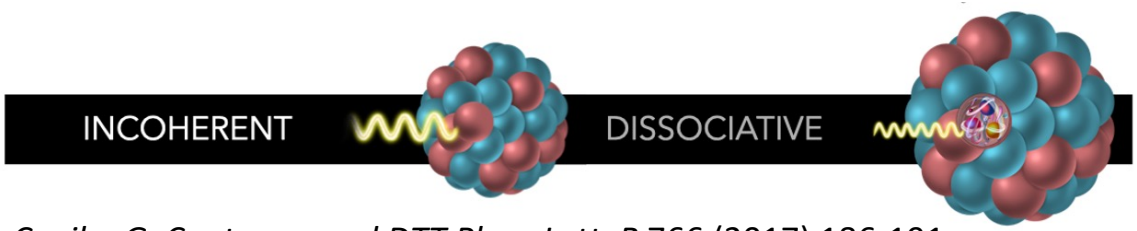
LO QED calculations, but different modeling

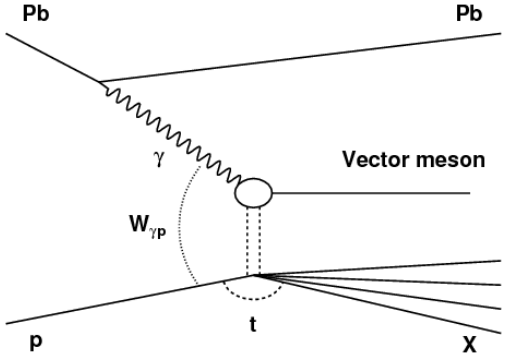
- STARLight: point-like charge with radial cutoff
- SuperChic: Charge distributions using form factors

Dissociative J/ψ in UPC

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

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





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

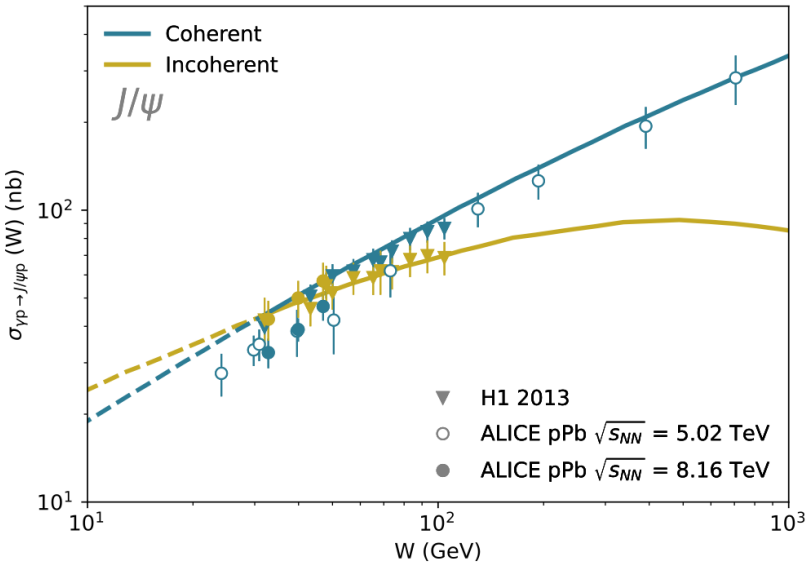
In the hot spot model, the increase in gluon distribution with decreasing Bjorken-*x* is described by the energy-dependent evolution of the number of hot spots

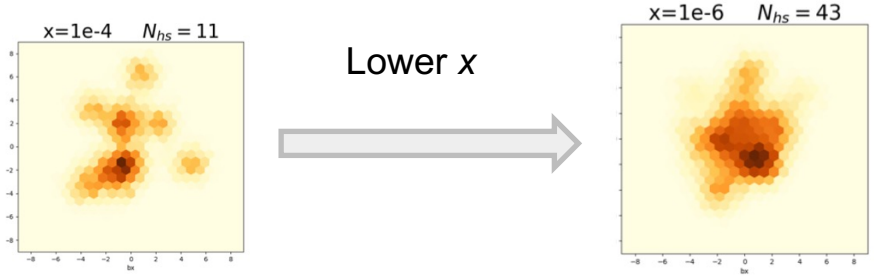
$$\left.\frac{\mathrm{d}\sigma^{\gamma^* p\to \mathrm{VY}}}{\mathrm{d}|t|}\right|_{\mathrm{T,L}} = \frac{\left(R_g^{T,L}\right)^2}{16\pi}\left(\langle|\mathcal{A}_{\mathrm{T,L}}|^2\rangle - |\langle \mathcal{A}_{\mathrm{T,L}}\rangle|^2\right)$$

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





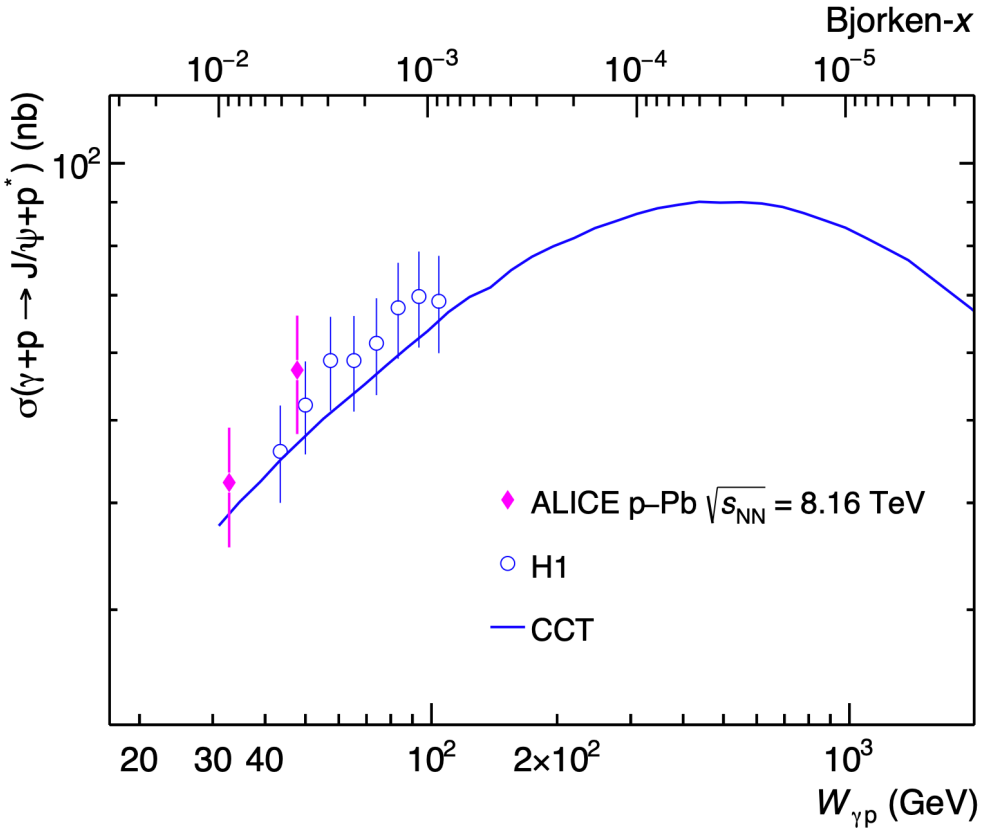
$$\left.\frac{\mathrm{d}\sigma^{\gamma^* p \to \mathrm{V}Y}}{\mathrm{d}|t|}\right|_{\mathrm{T,L}} = \frac{\left(R_g^{T,L}\right)^2}{16\pi}\left(\langle|\mathcal{A}_{\mathrm{T,L}}|^2\rangle - |\langle\mathcal{A}_{\mathrm{T,L}}\rangle|^2\right)$$

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

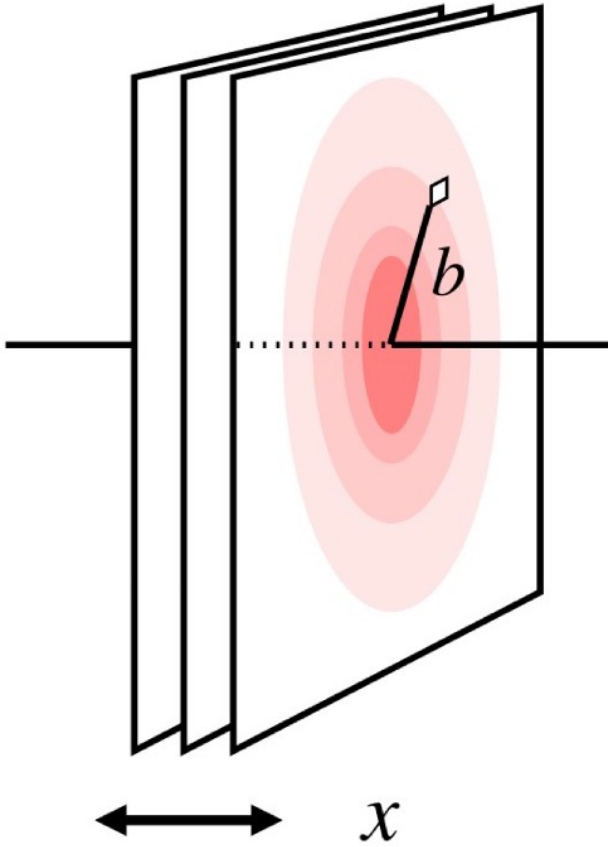
Phys. Lett. B 766 (2017) 186-191

Dissociative J/ψ in UPC pPb

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



Transverse profile of the target

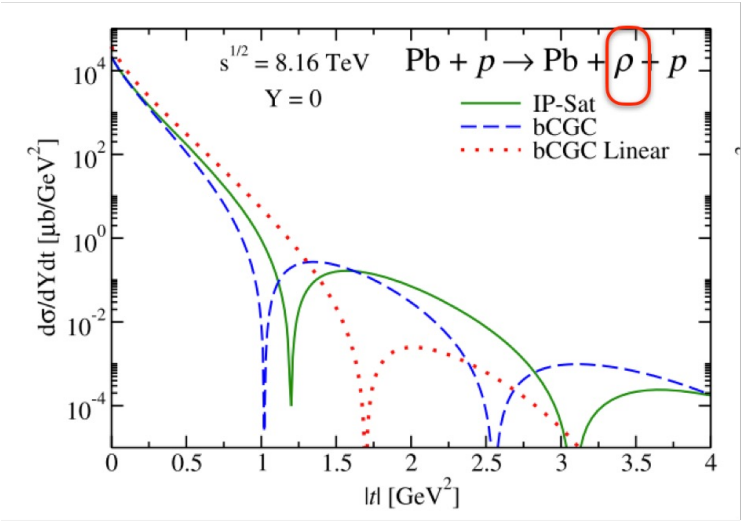


UPCs can probe the transverse profile of the target!

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

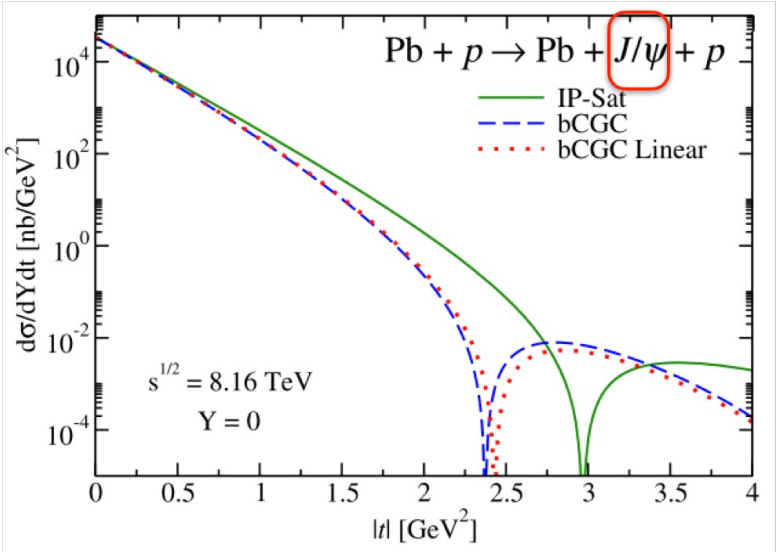


Location of the Diffractive dips:
Different for IP-Sat and bCGC

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

Signature of gluon saturation

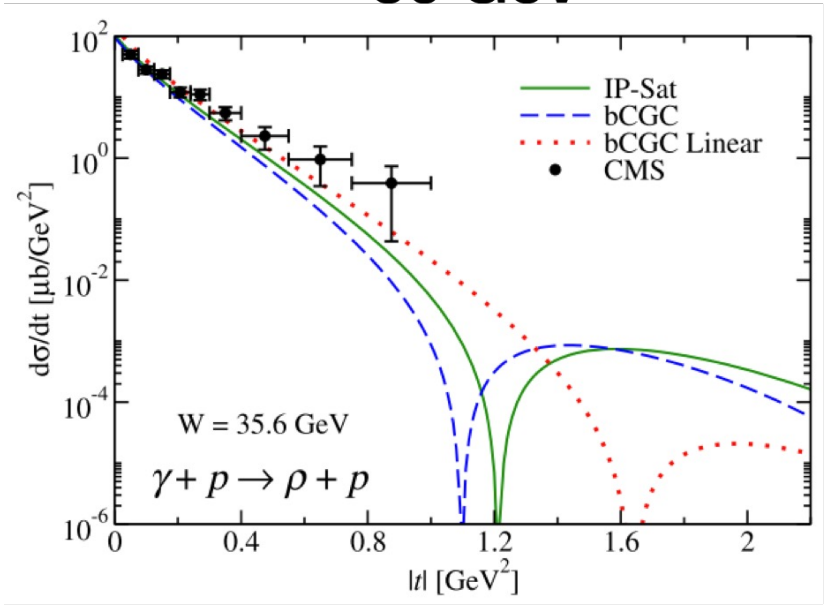
Study of ρ^0 is very promising since diffractive dips expected at lower t values



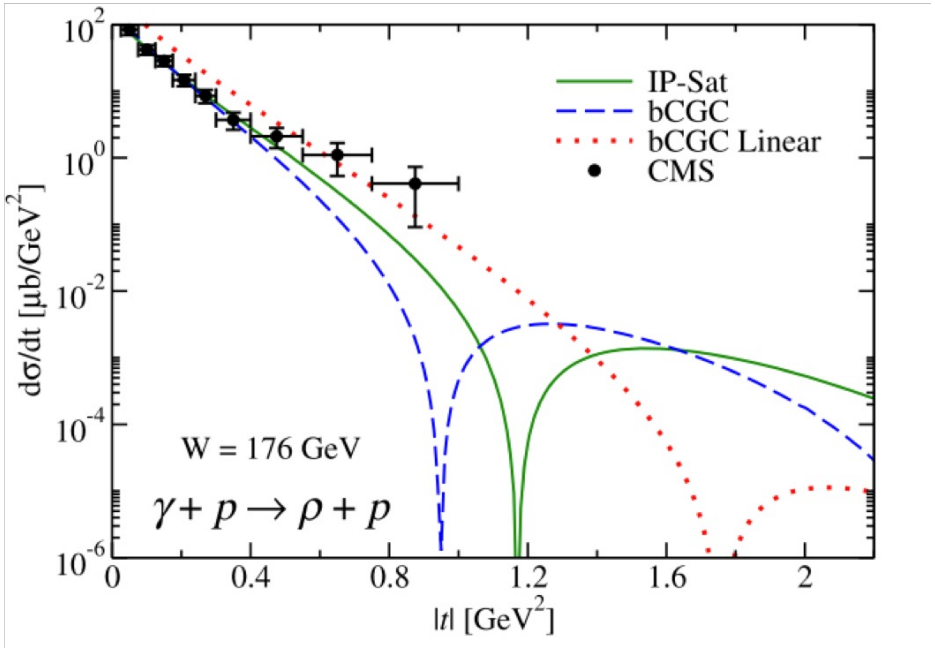
t-dependence measurement of UPC ρ^0

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

36 Gev



176 Gev

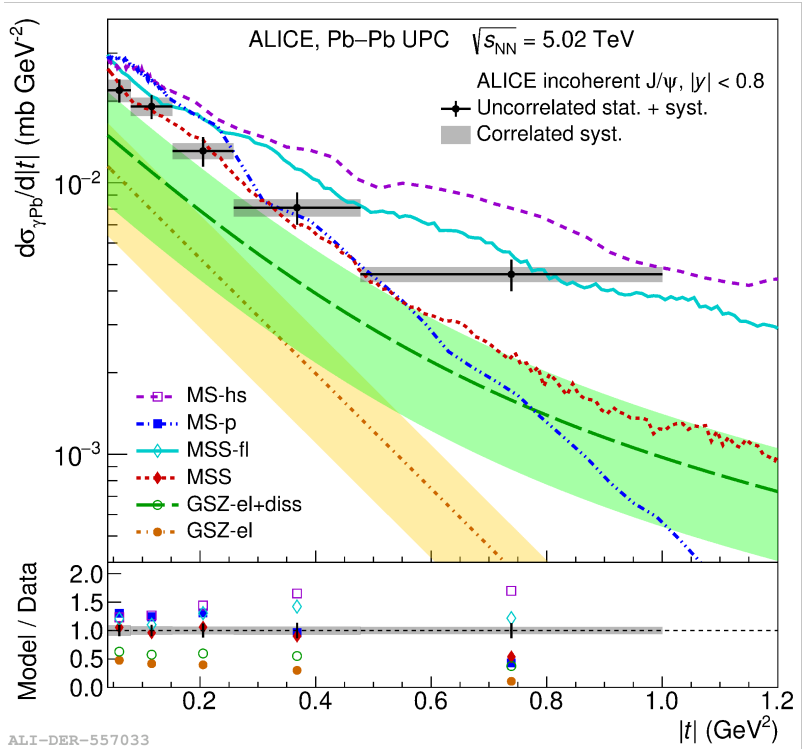


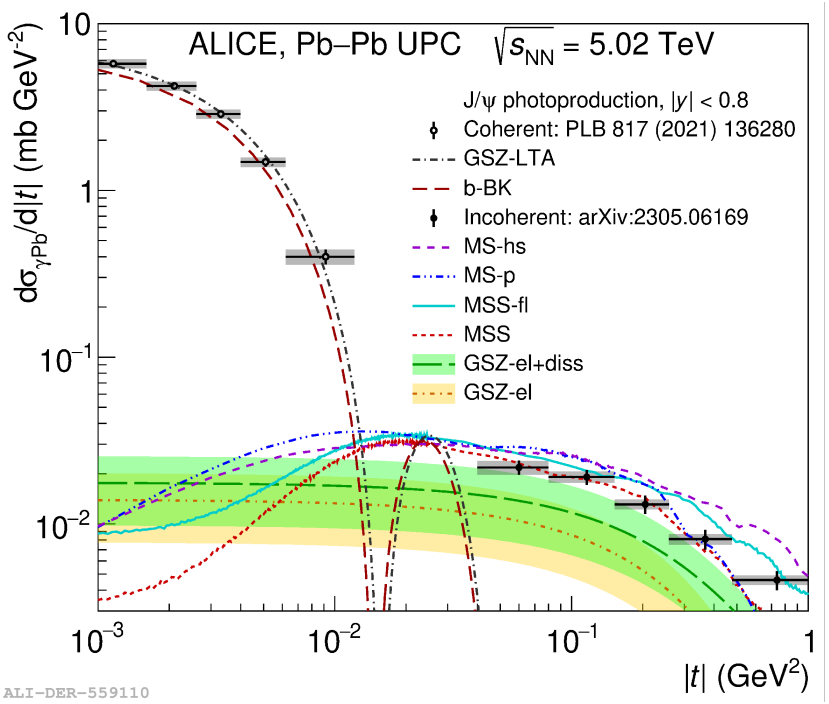
t-dependence of coherent and incoherent J/ψ in UPC Pb-Pb

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

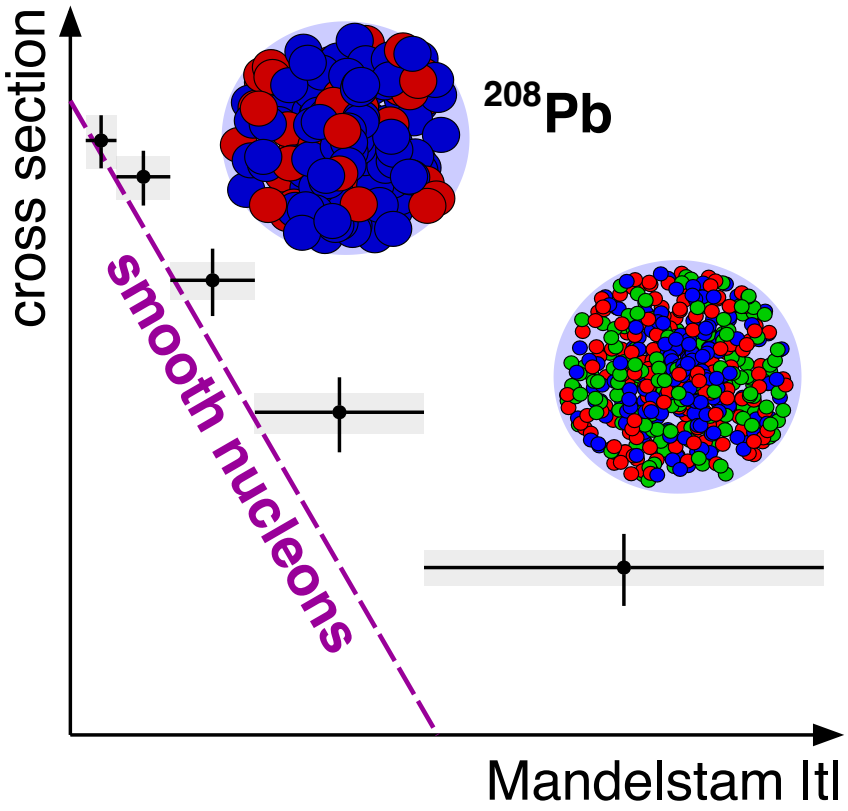
Phys.Rev.Lett. 132 (2024) 16, 162302

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





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

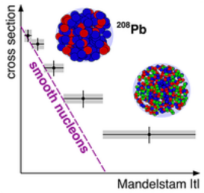


Editors' Suggestion

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

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

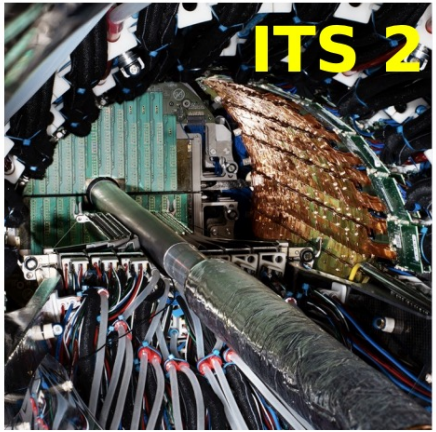
Phys. Rev. Lett. **132**, 162302 (2024) – Published 19 April 2024

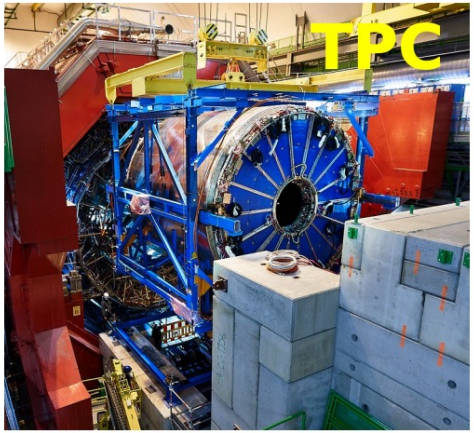


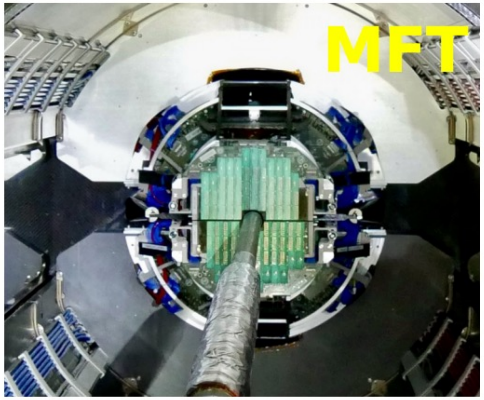
The first experimental measurement of the incoherent photonuclear production of J/ψ in ultraperipheral heavy-ion collisions is better explained by the presence of subnuclear quantum fluctuations of the gluon field.

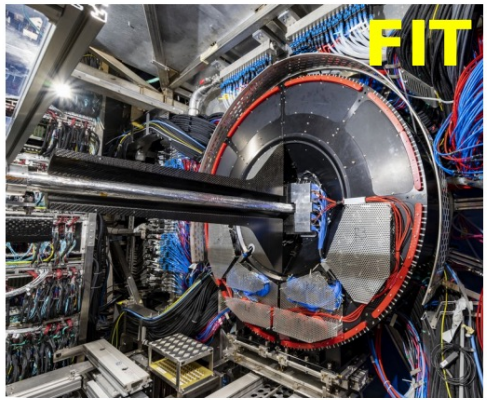
Show Abstract +

ALICE in Run 3: A major upgrade



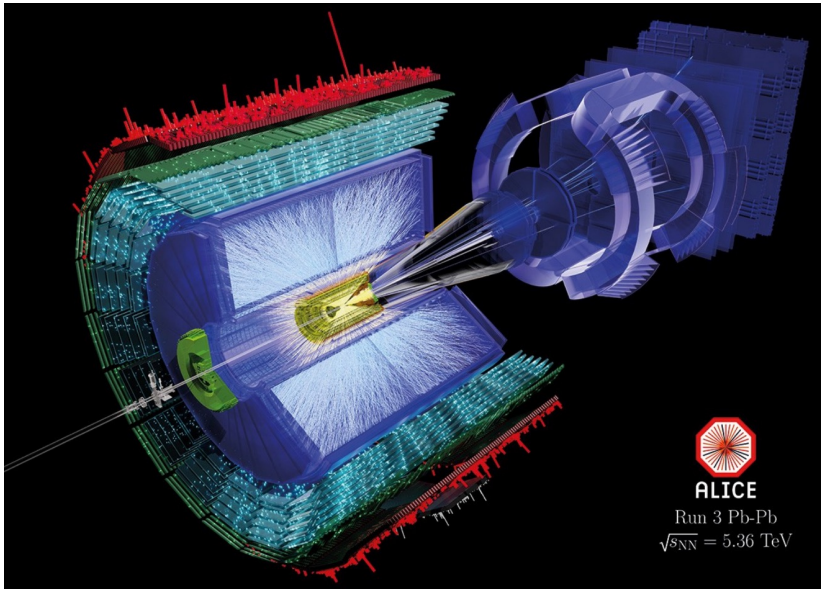


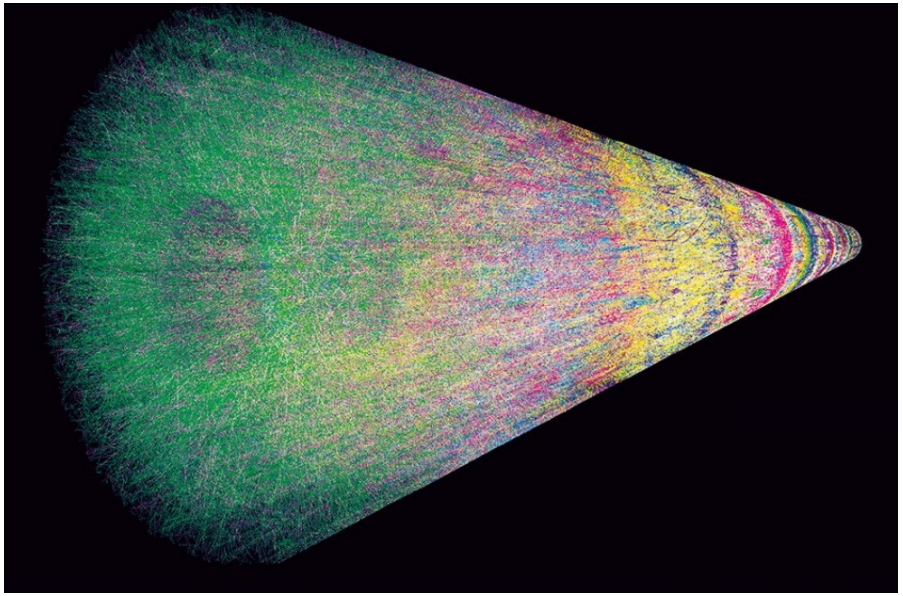




- 50 times increase in the readout rate
- 3 to 6x improvement in pointing resolution
- Secondary vertexing for forward muons

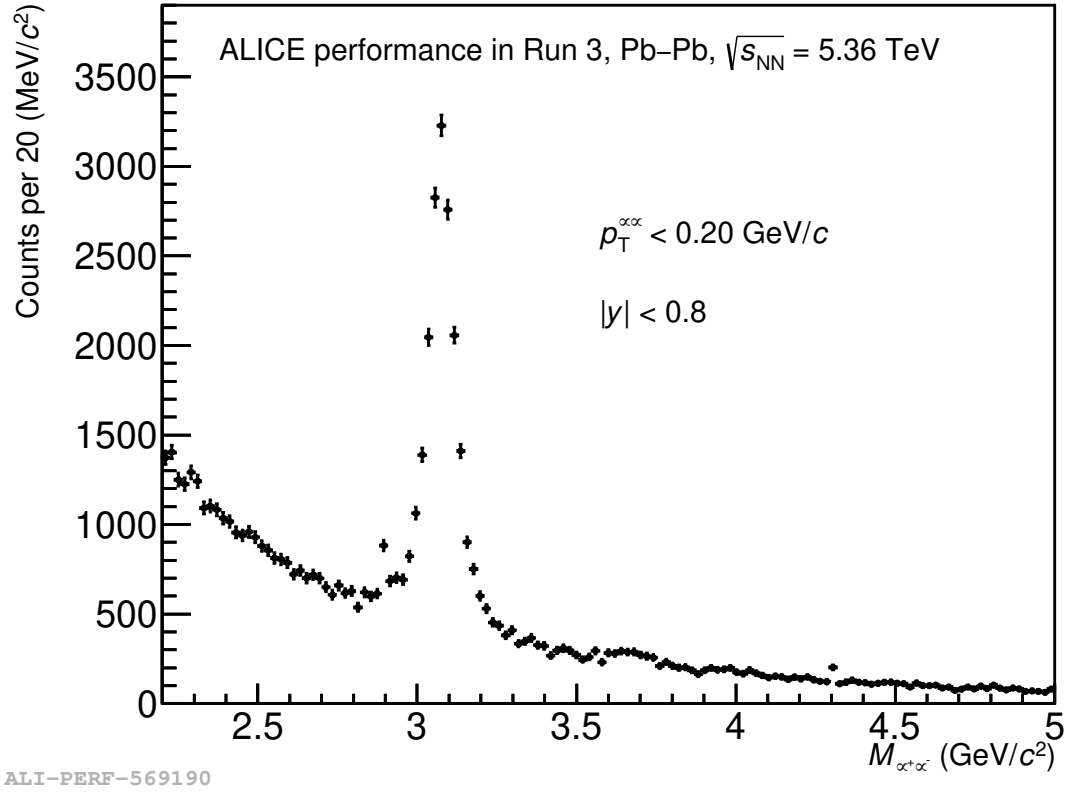
ALICE in Run 3: Trigger-less mode





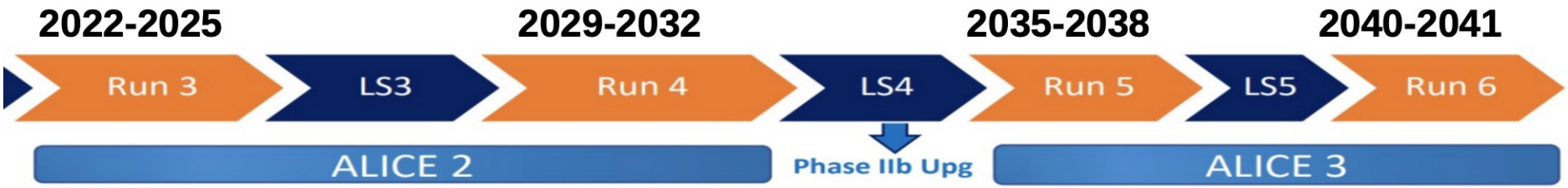
2 μs time frame of Pb-Pb collisions at a 50 kHz interaction rate in the TPC

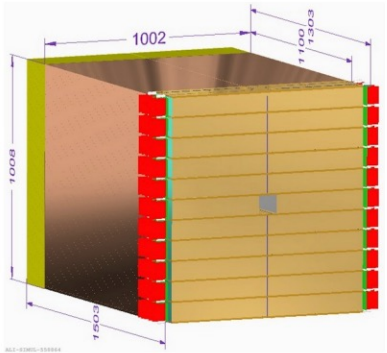
Great performance for reconstructing UPC vector mesons

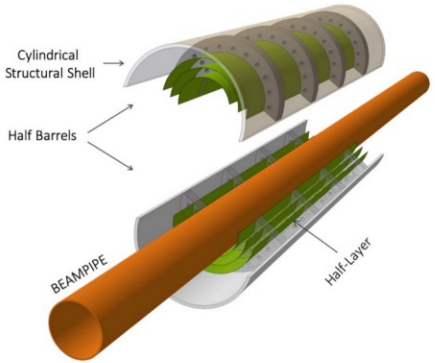


- The trigger-less mode will enable to develop further the UPC physics program in ALICE from Run 3
- New processes, including inelastic UPC events will be possible

ALICE timeline





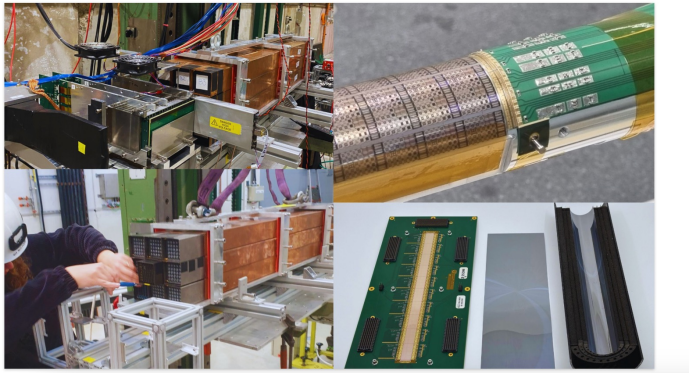


FoCal and ITS3

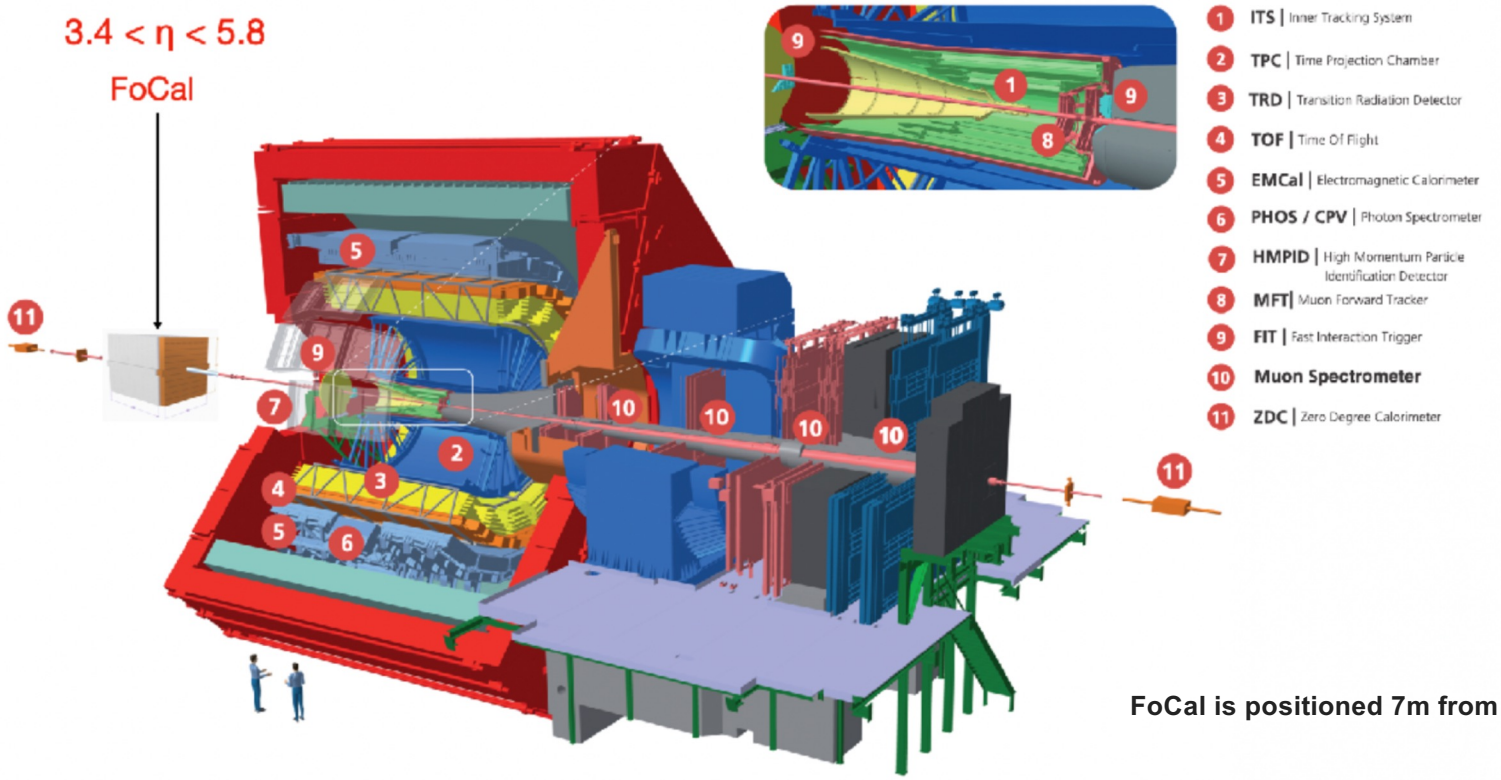
ALICE gets the green light for new subdetectors

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



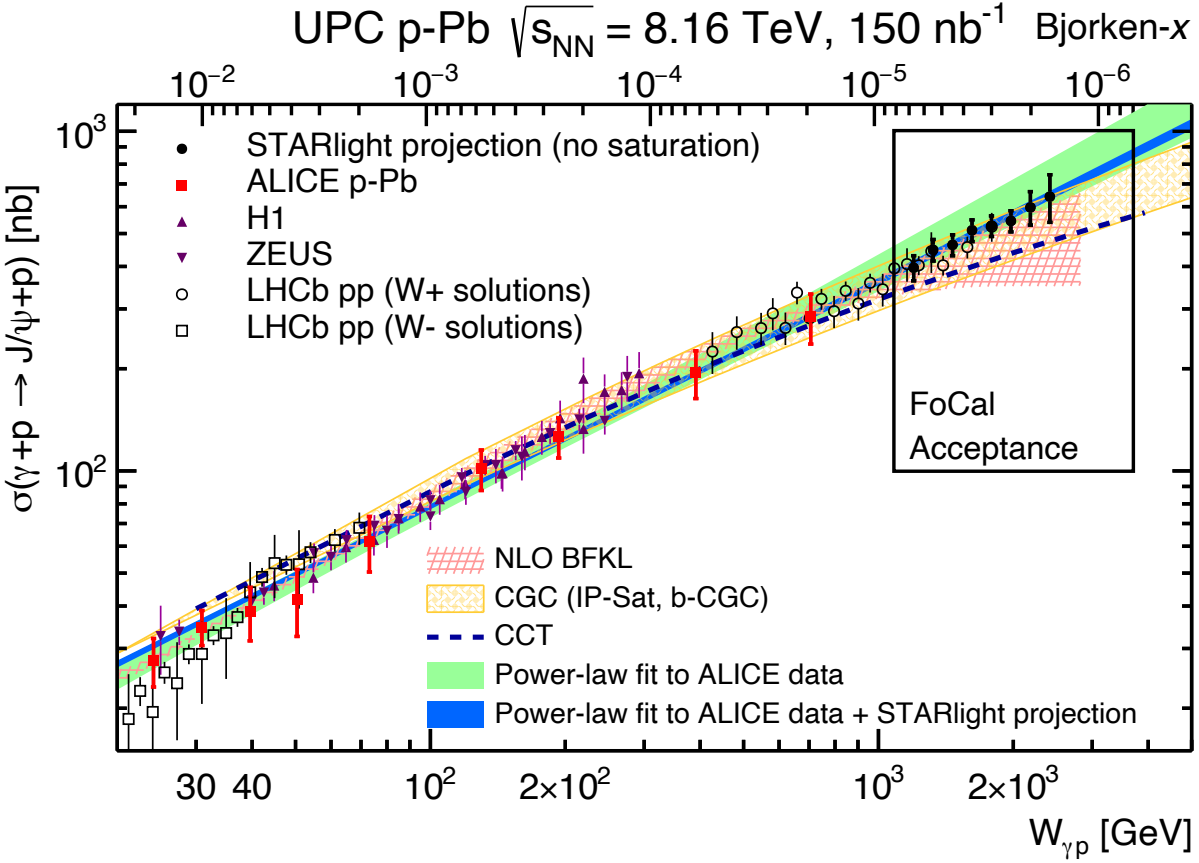
FoCal is positioned 7m from IP2 (A-side)

UPC VM projections for FoCal

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

VM	$\sigma(\mathrm{p}+\mathrm{Pb}\to\mathrm{p}+\mathrm{Pb}+\mathrm{VM})$	$\sigma(3.4\leq\eta_{1,2}\leq5.8)$ 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

Projections for exclusive J/ψ off protons

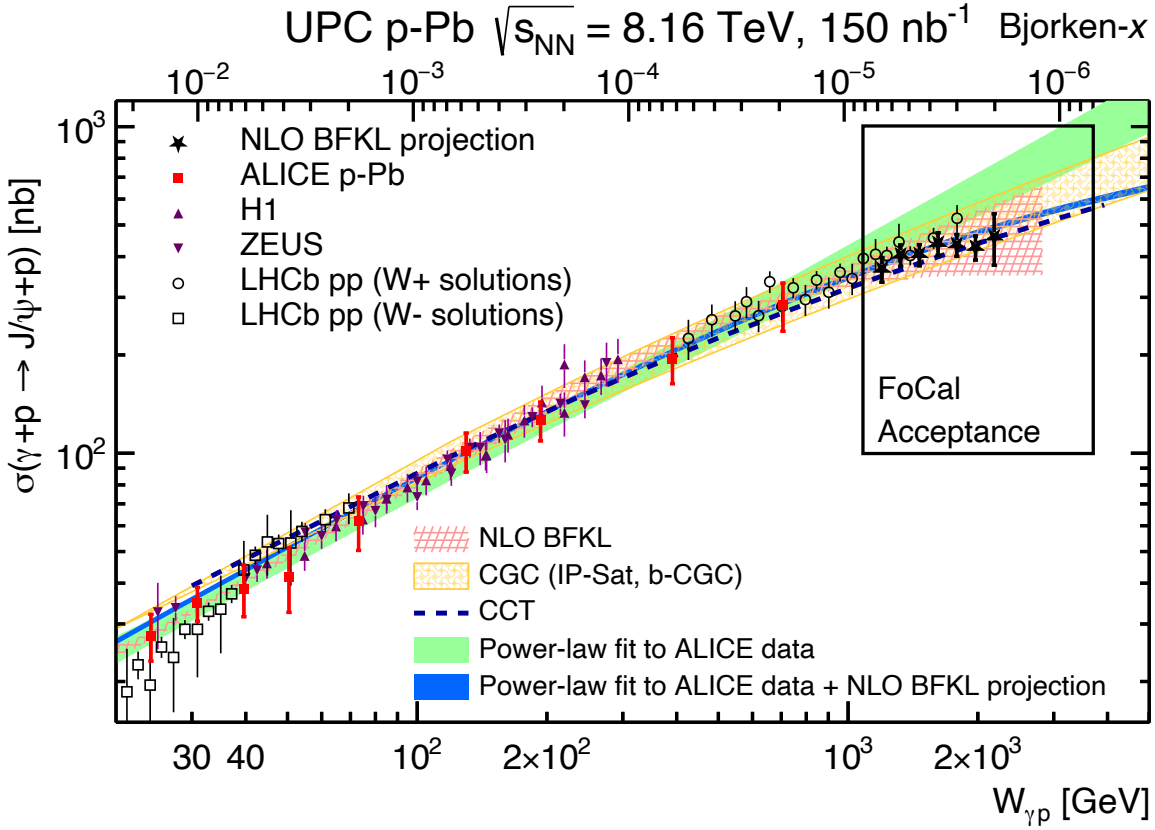


- Deviations from a power-law trend should signal non-linear QCD dynamics
- Here, projections based on STARlight which uses a parametrization based on HERA data

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

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

Projections for exclusive J/ψ off protons

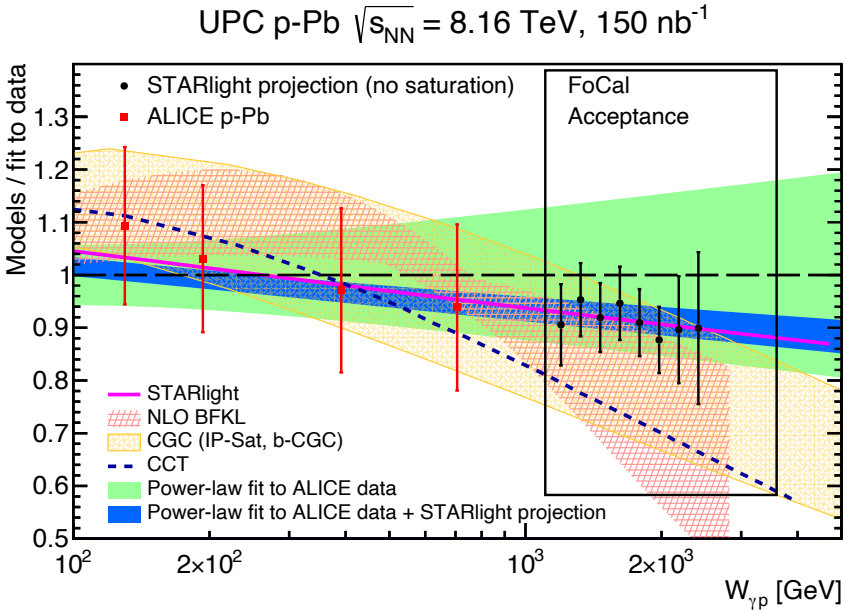


- Projections assuming a broken power-law
- Projected points based on NLO BFKL calculation

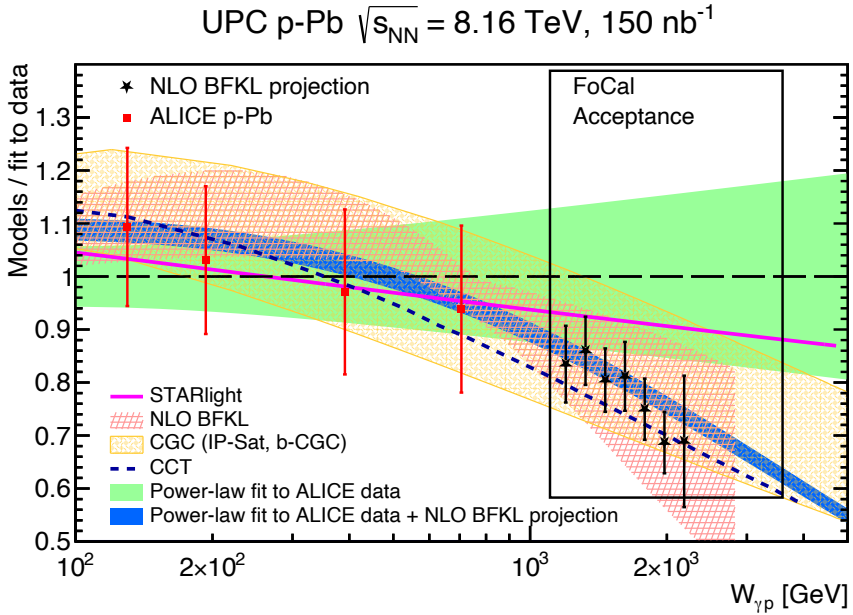
$$\sigma(\gamma p) \approx \frac{\sigma_0}{\frac{1}{W_{\gamma p}^{\delta}} + A}$$

Projections for exclusive J/ψ off protons

Power-law behavior (STARlight)

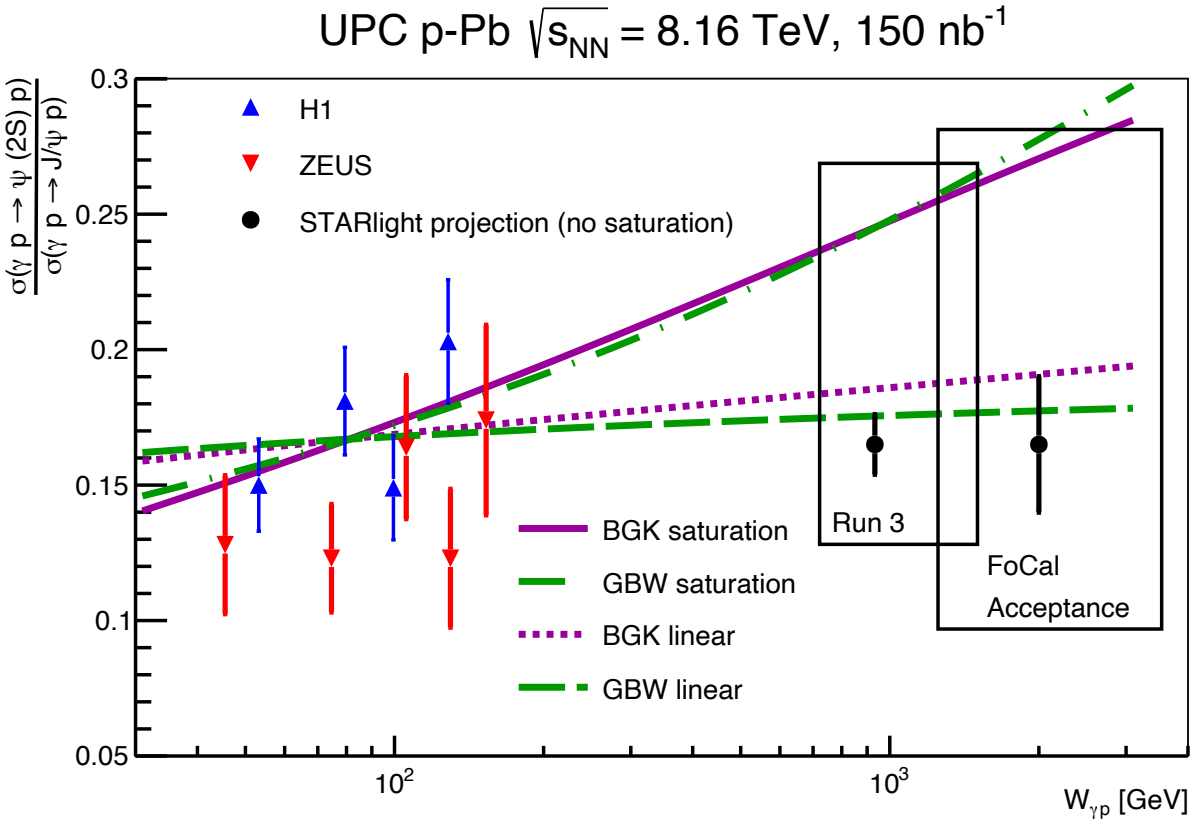


Broken power-law behavior (NLO BFKL)



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

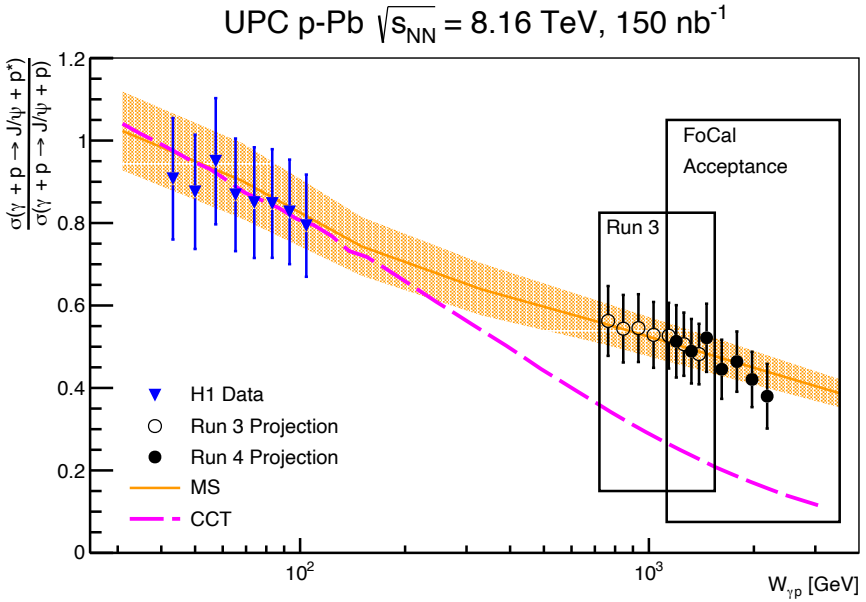
Projections for exclusive $\psi(2S)$ and J/ψ cross section ratio in γp



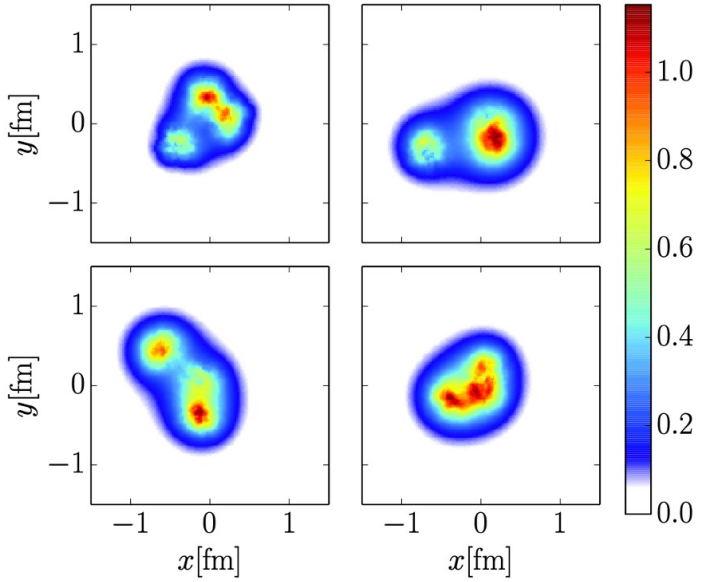
- Different wave functions and dipole sizes evolution result in great sensitivity to non-linear QCD effects
- No sensitivity at HERA, but expected at the LHC
- Projections here based on STARlight

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

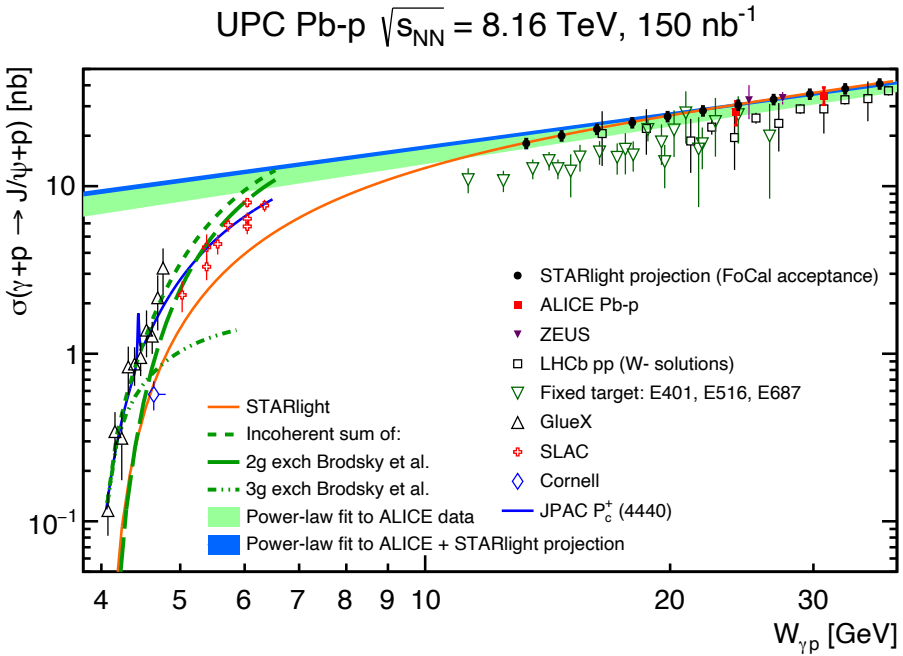


Mantysaari and Schenk, PRD 94, 034042 (2016)
S. Klein arXiv:2301.014018

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

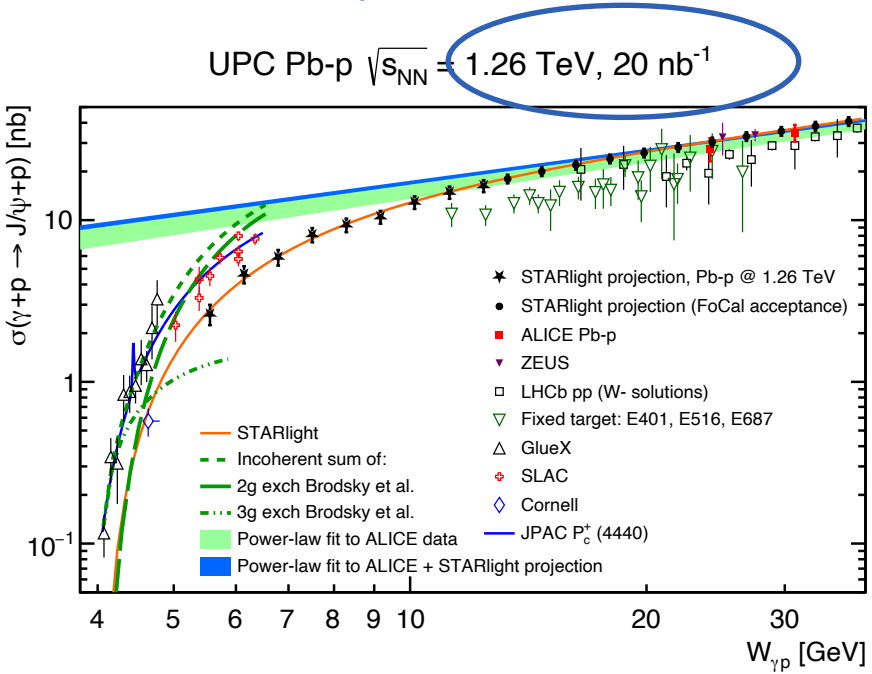
$$\frac{d\sigma(\gamma p \to \mathrm{J}/\psi Y)}{dt} = \frac{R_g^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})\right\rangle\right|^2\right)$$

Idea: Near threshold and intermediate energies for exclusive J/ψ in γp



Near-threshold production motivated by pentaquarks and exotic theory mechanisms

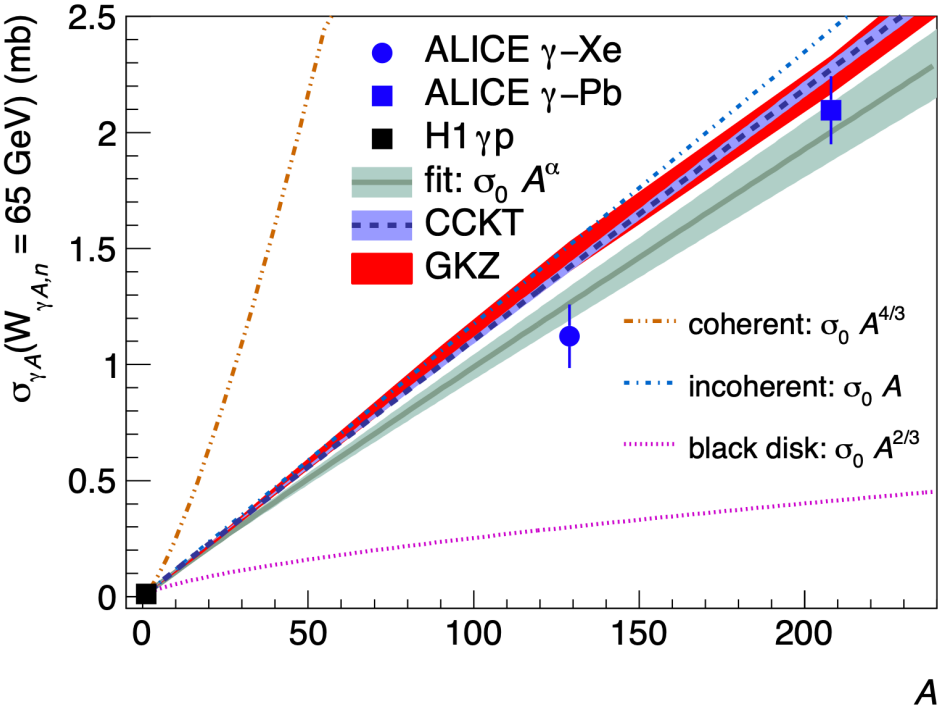
A special pPb run could be requested to explore near threshold production



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!

Additional slides

Projections for VMs in γPb

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

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

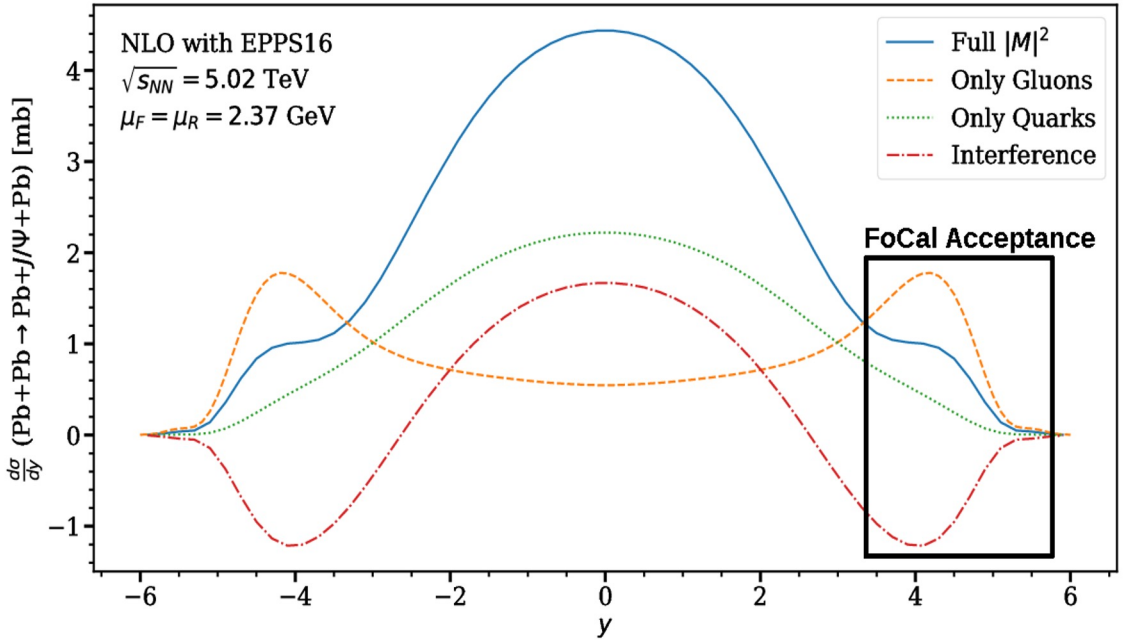
VM	$\sigma(\mathrm{Pb}+\mathrm{Pb}\to\mathrm{Pb}+\mathrm{Pb}+\mathrm{VM})$	$\sigma(3.4\leq\eta_{1,2}\leq5.8)$	Yield
ρ^0	5.0 b	20 μb	140,000
ϕ	440 mb	10 μb	70,000
J/ψ	39 mb	53 μb	370,000
$\psi(2S)$	7.5 mb	1.1 μb	7,500
$\Upsilon(1S)$	94 μb	5.0 nb	35

Projections for VMs in γPb

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

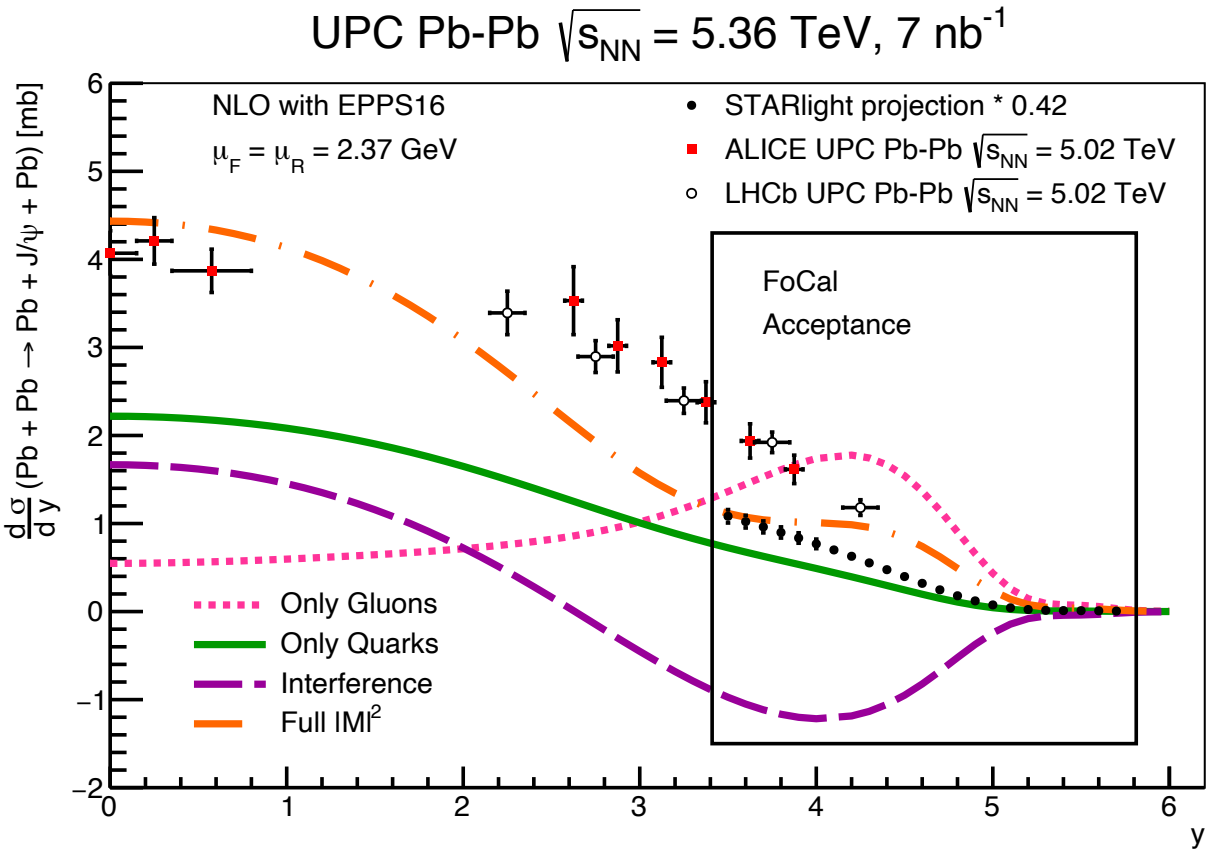
The FoCal region is gluon dominated

K. Eskola et al., *Phys. Rev. C* 106 (2022) 3, 035202



- 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

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

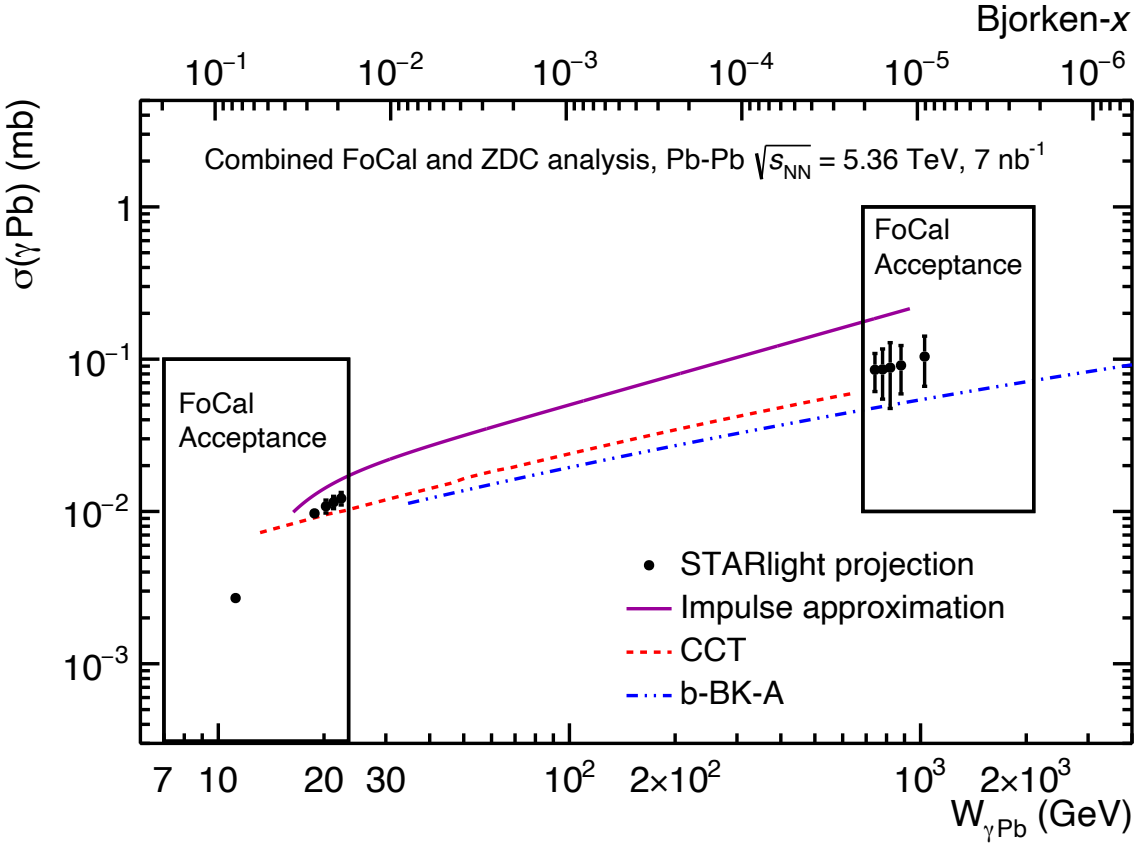
$$\frac{d\sigma}{dy} = \frac{d\sigma(\mathrm{0n0n})}{dy} + 2\frac{d\sigma(\mathrm{0nXn})}{dy} + \frac{d\sigma(\mathrm{XnXn})}{dy}$$

Neutron configuration	$\sigma(\mathrm{Pb+Pb \to J/\psi + Pb + Pb})$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$	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