FoCal (UPC) program and connections with the EIC

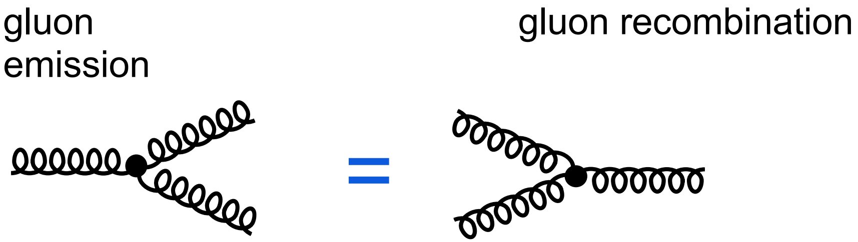
Daniel Tapia Takaki

Color Glass Condensate at the EIC

ECT* Trento, Italy – March 17, 2023

Gluons matter

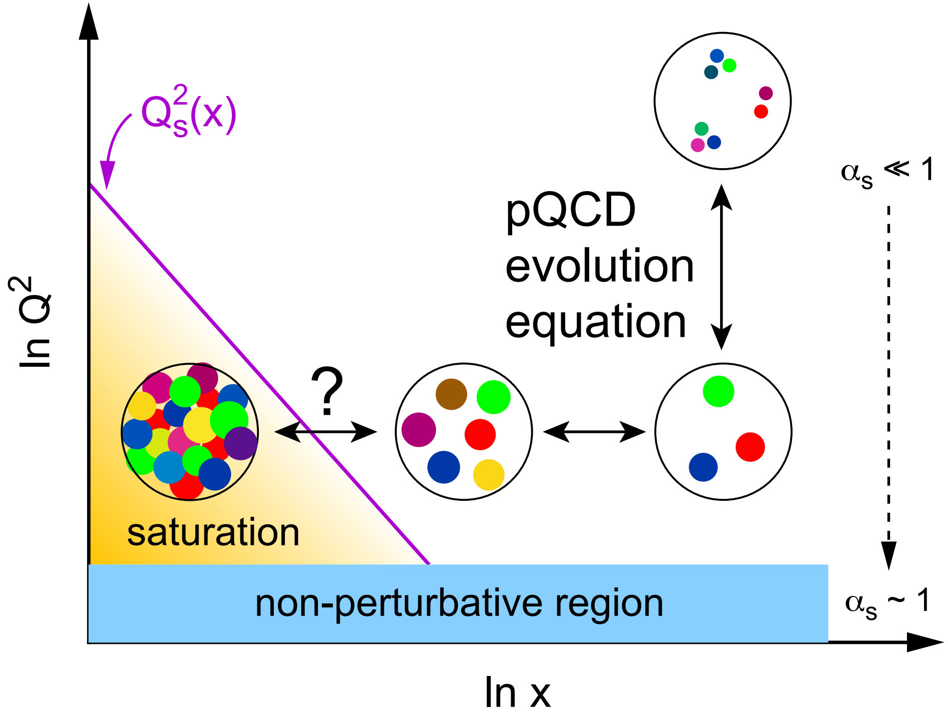
At high energies, or for heavy nuclei at lower energies, gluon saturation is predicted



Dynamical equilibrium of
gluon saturation state reached

- Non-linear QCD evolution equations introduced, but how is gluon saturation triggered?
- Can we determine experimentally the saturation scale (Q_S)?
- Is there a state of matter formed by gluon saturated matter with universal properties?

Evolution of the hadronic structure with Bjorken-x and Q^2



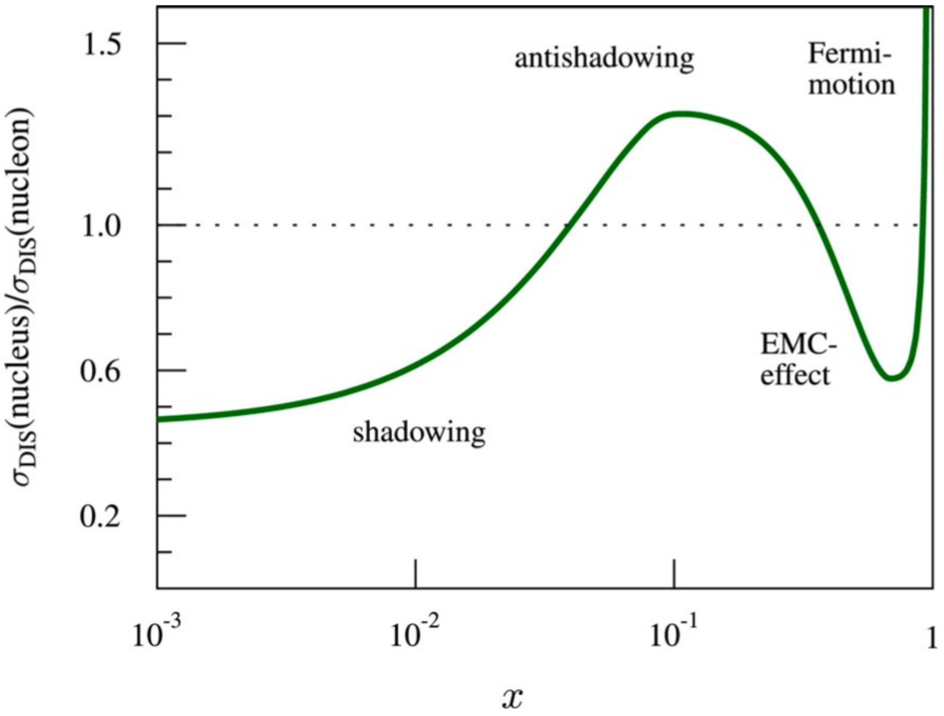
- Experimental observables needed to map out the transition between the dilute and saturation regimes

- For nuclei, the saturation scale is enhanced by a $A^{1/3}$ factor

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

Nuclear shadowing experimentally confirmed, but not fully understood

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$



- Experimental observation that parton distributions are different for protons and nuclei
- What's the mechanism responsible for shadowing? How is gluon saturation related?
- The knowledge of the initial state of nuclei also needed for understanding the QGP evolution

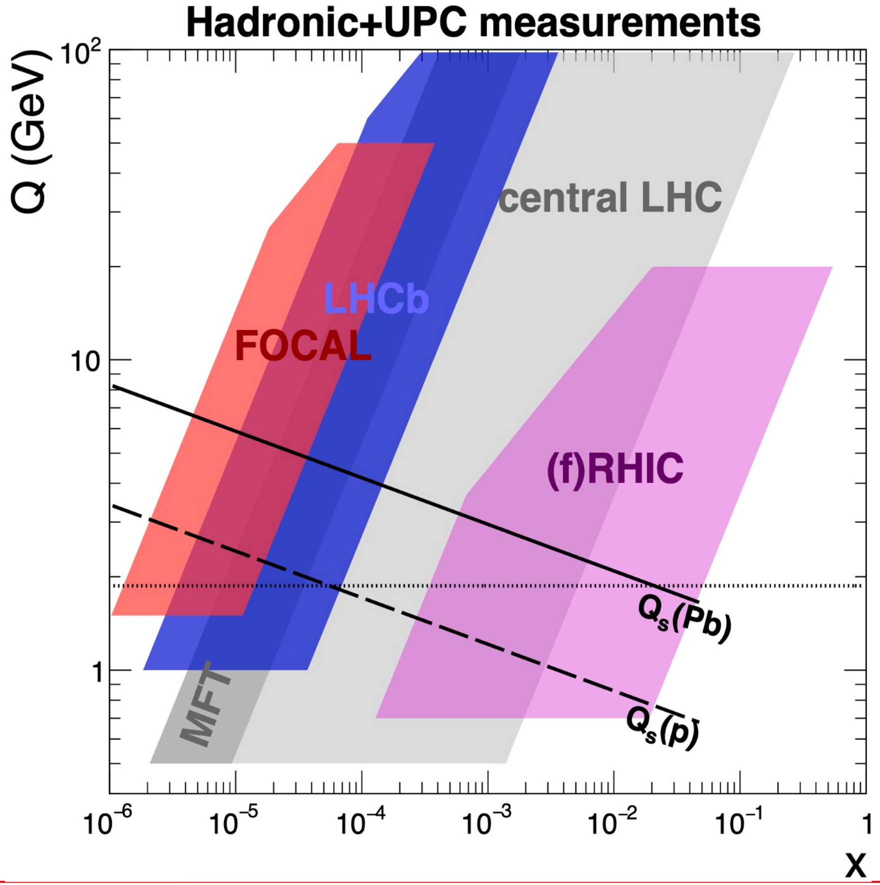
Experimental program

- 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

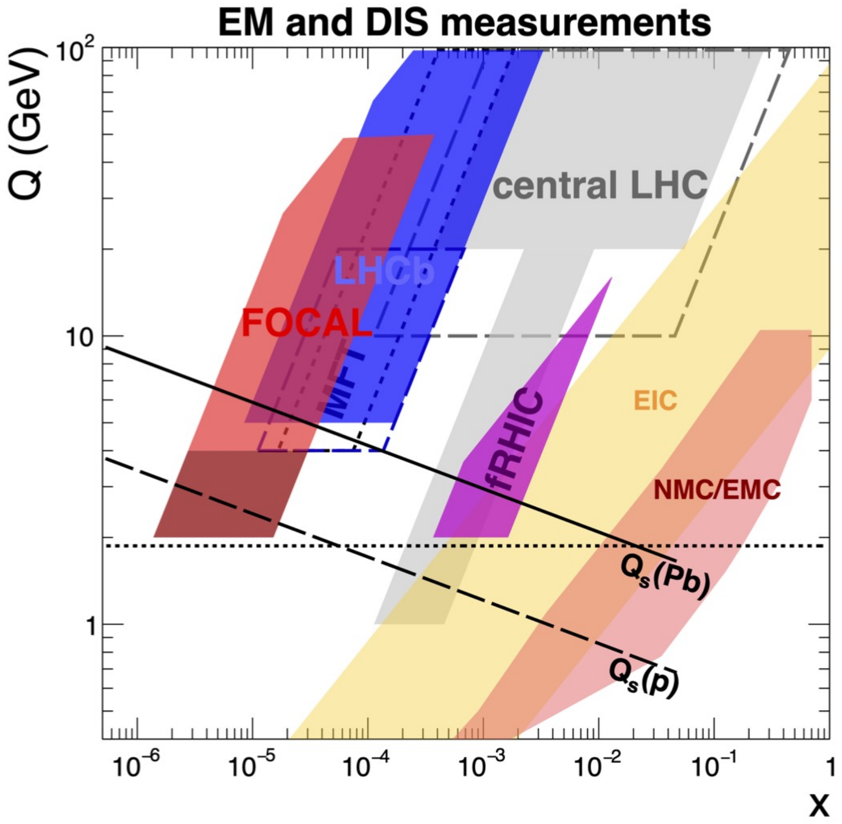
- The LHC explores the high energy domain for both hadronic and photon-induced reactions

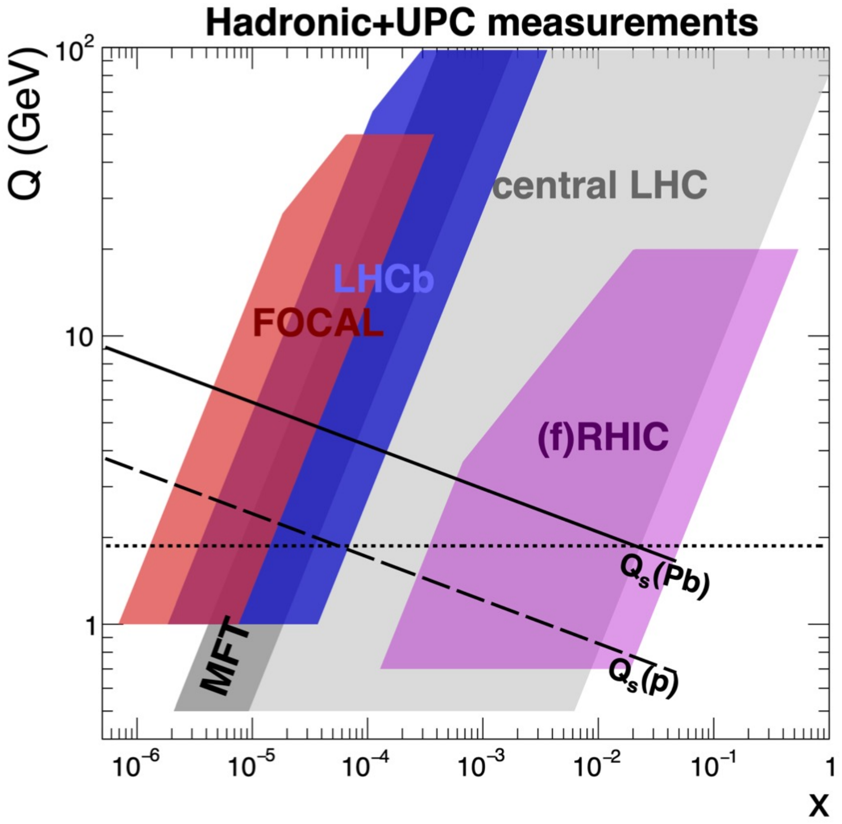
- FoCal at ALICE will explore a unique low-x regime reaching $x \sim 10^{-6}$

- **Important to compare e+A DIS with forward p+A and UPC at the LHC**

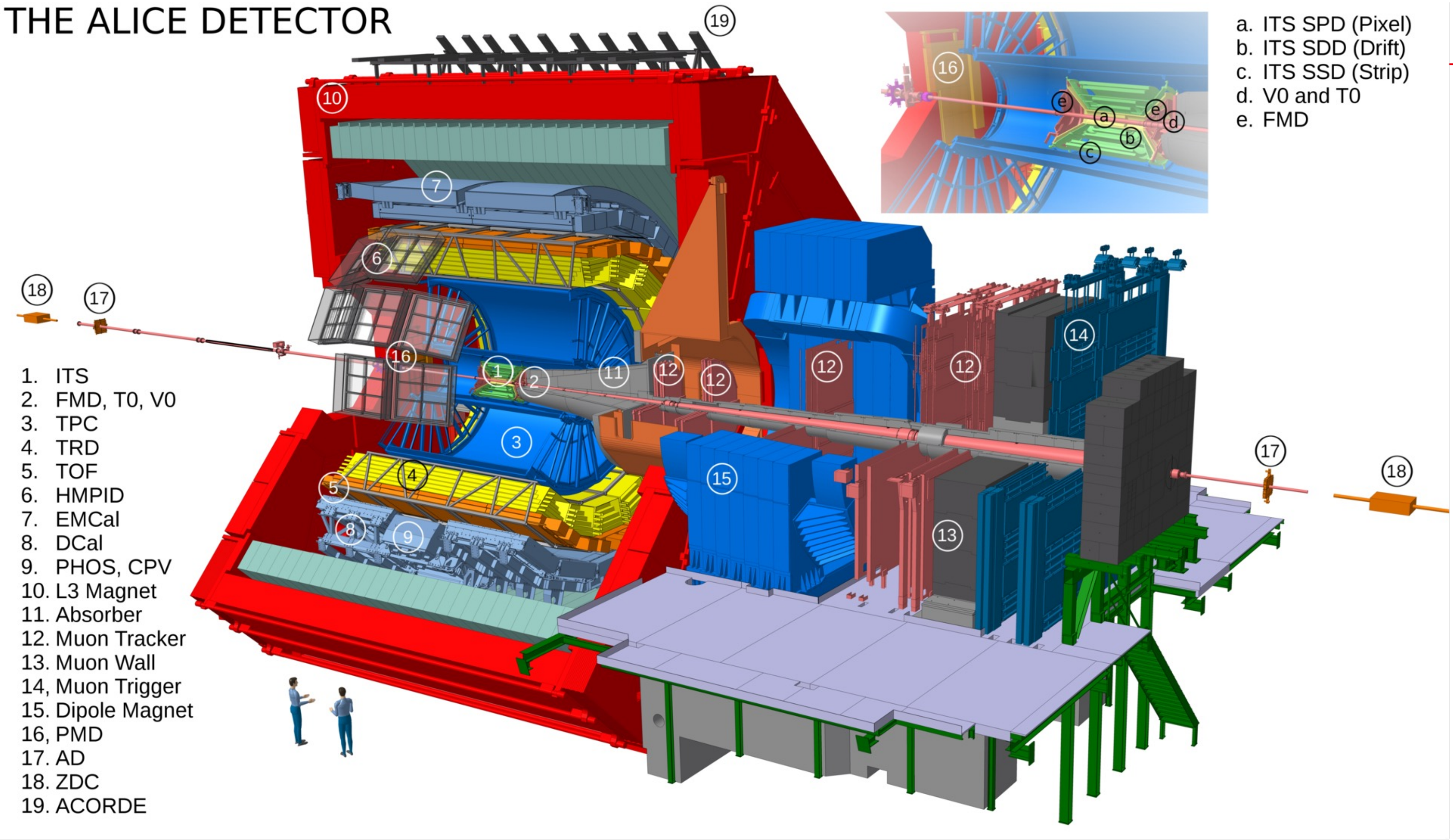


Experimental program

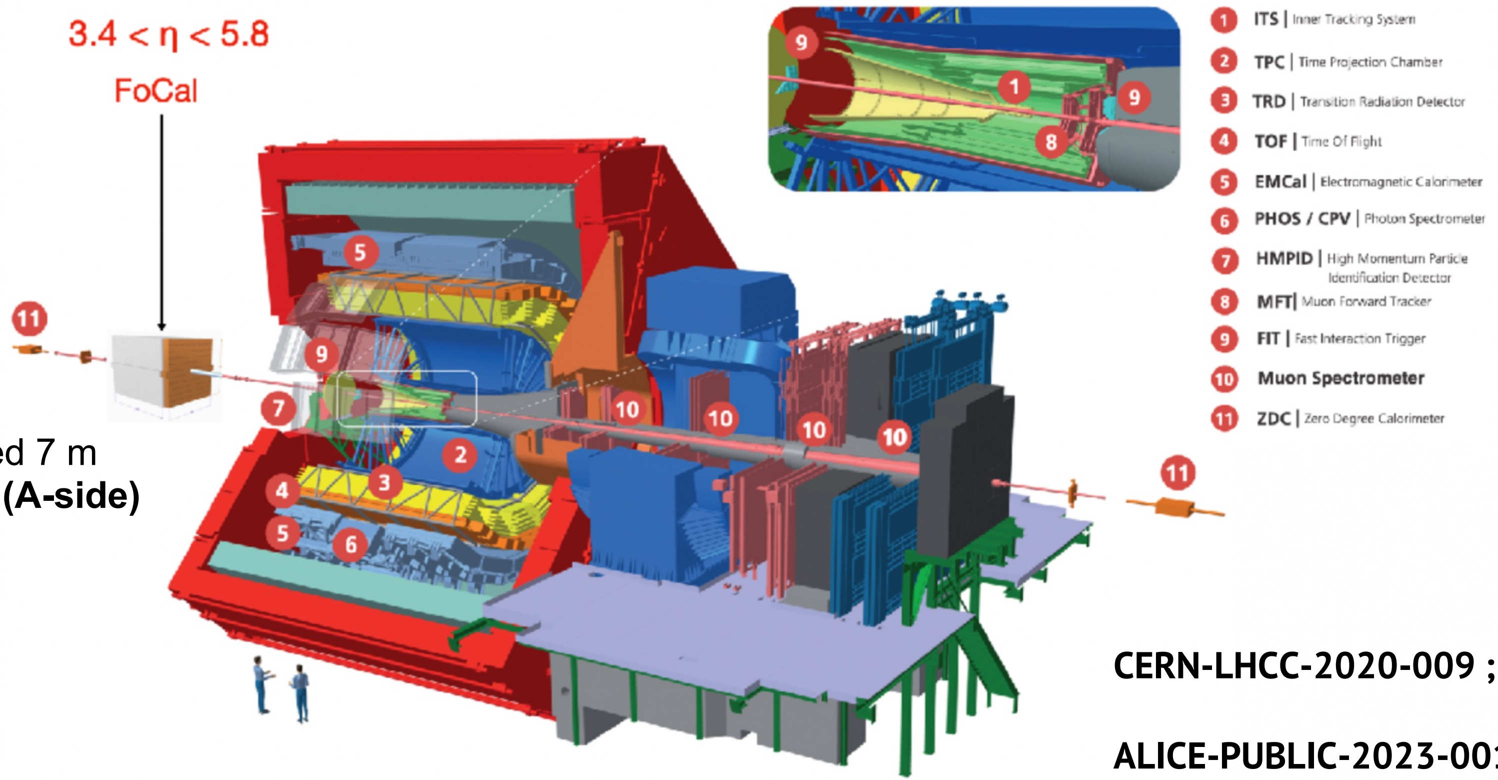




THE ALICE DETECTOR



The ALICE FoCal



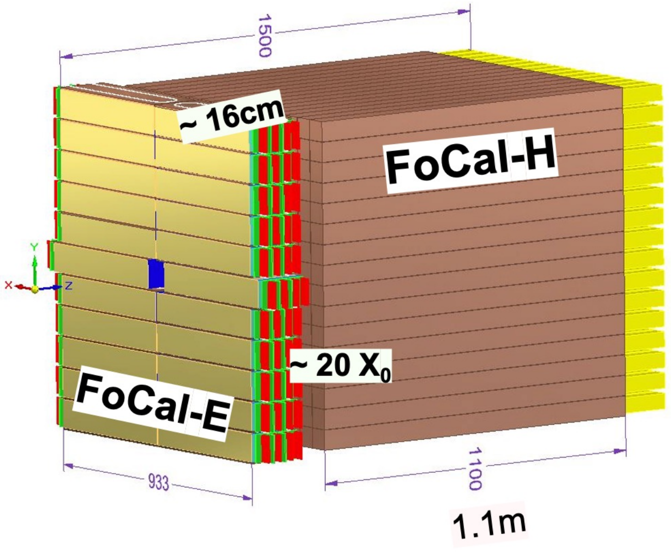
Positioned 7 m
from **IP2 (A-side)**

CERN-LHCC-2020-009 ; LHCC-I-036

ALICE-PUBLIC-2023-001

ALICE Forward Calorimeter (FoCal)

covering **3.4 < η < 5.8**



FoCal-E

| Si+W EM calorimeter (2 subsystems)

| Designed for measurement of direct photons and high p_t neutral pions (Pb-Pb vs pp)

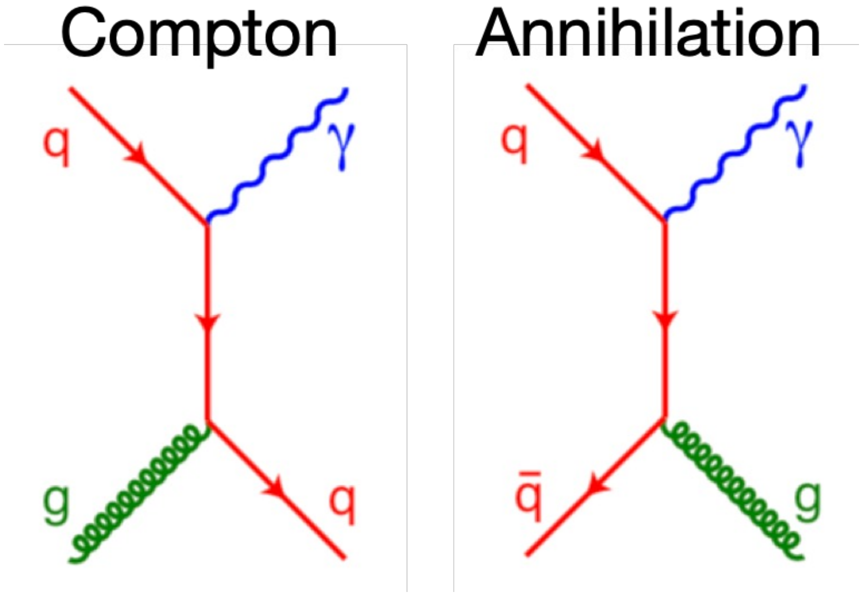
FoCal-H

| Scintillating fibers enclosed in Cu capillary-tubes, readout by SiPMs

| Designed to study the dynamics of hadronic matter and provides good Jet isolation capabilities

FoCal measurements

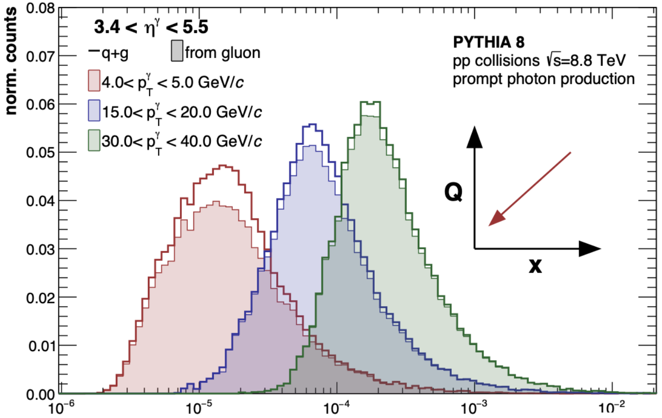
- Prompt and isolated photons (γ)
- Identified π^0 and other neutron particles
- J/ψ and other excited quarkonia states
- W and Z bosons
- Inclusive jets
- Correlations: di-hadron, di-jet, γ+hadron, γ +jet, etc



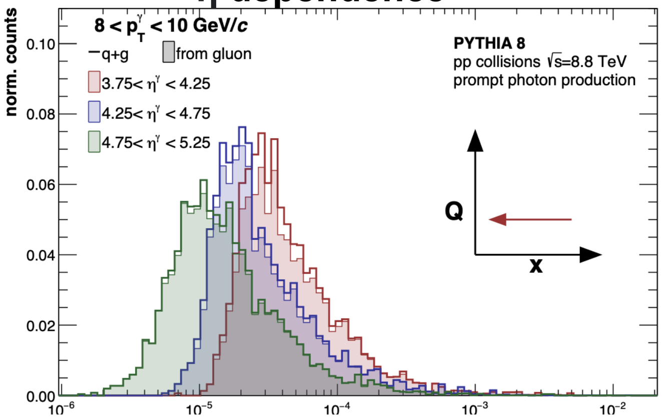
Collision systems:
p+p at 5, 8.8 and 14 TeV
p+Pb at 8.8 TeV; (both p+Pb and Pb+p)

γ in FoCal Kinematics

p_T dependence

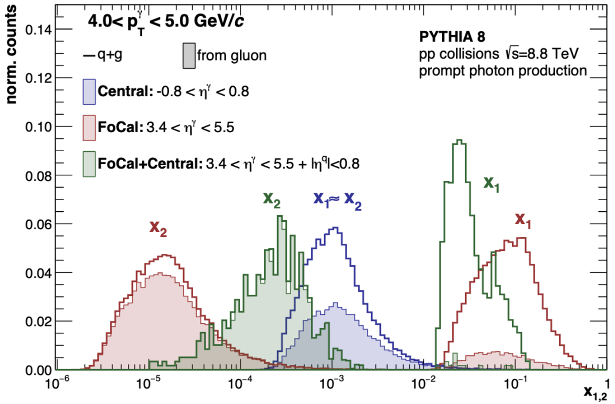


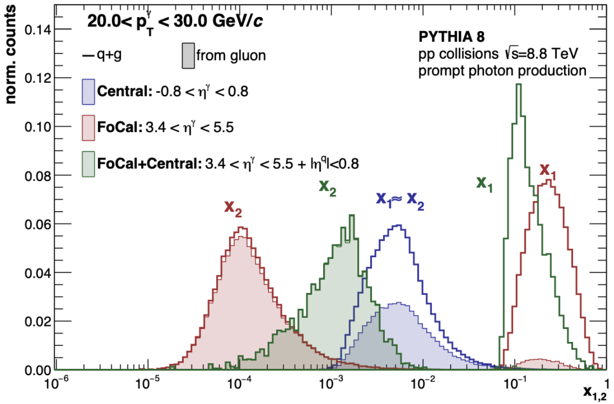
η dependence



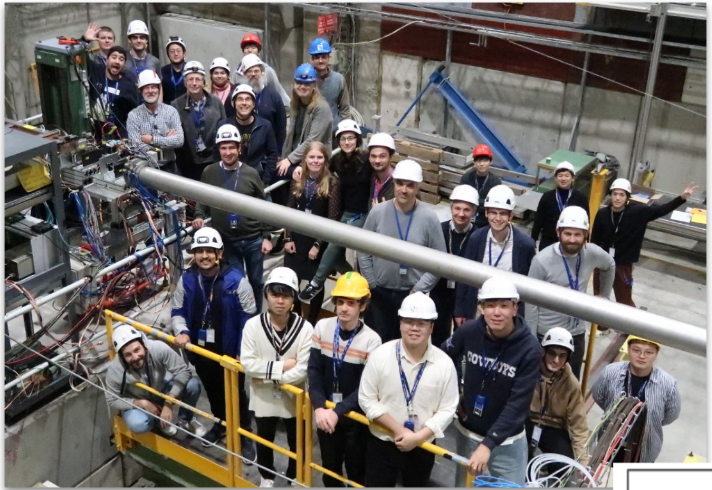
FoCal vs Central

Wide rapidity coverage, complementary with the EIC





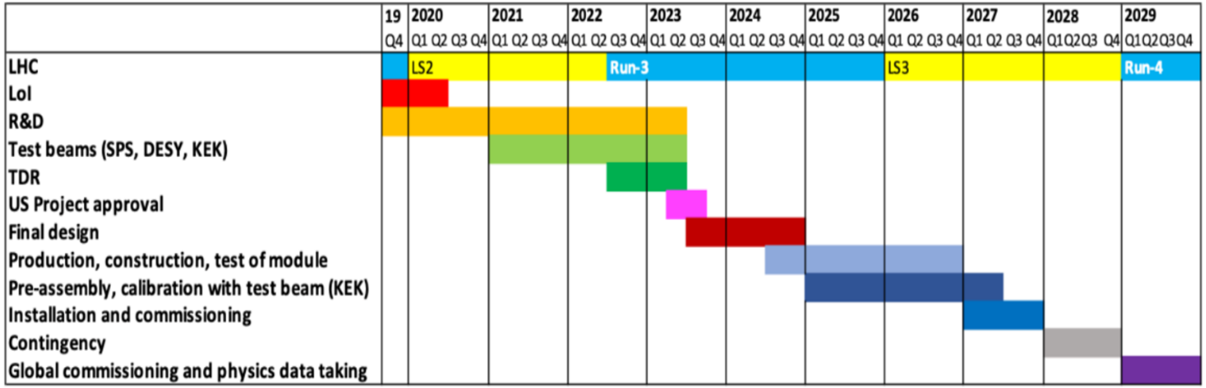
ALICE Forward Calorimeter (FoCal)



R&D studies and beam tests ongoing

Run 4 is currently scheduled for the period 2029–2032

The Technical Design Report (TDR) will be completed this year



The LHC is the Large **Photon** Collider

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

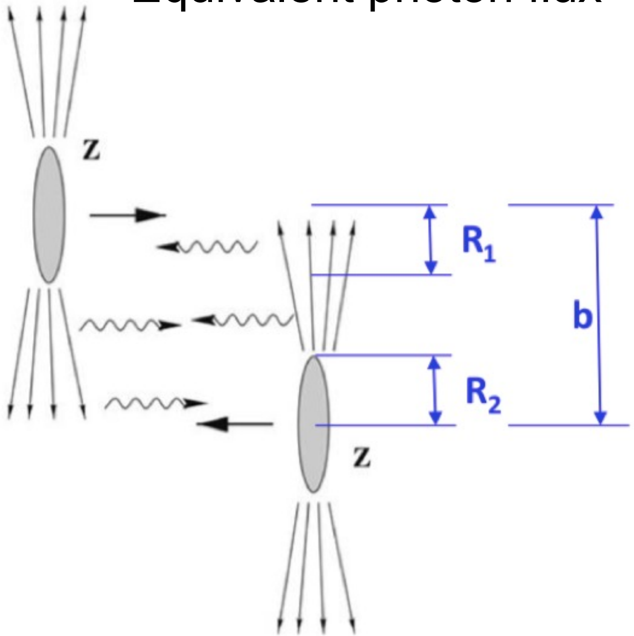
  $k = \gamma M_V \exp(\pm, y)$
  Up to several TeV in γp
  Up to ~ 700 GeV/nucleon in γA
  Up to ~ 150 GeV in $\gamma\gamma$ using UPC PbPb,
  ~ 4 TeV in in $\gamma\gamma$ using UPC pp

- 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

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

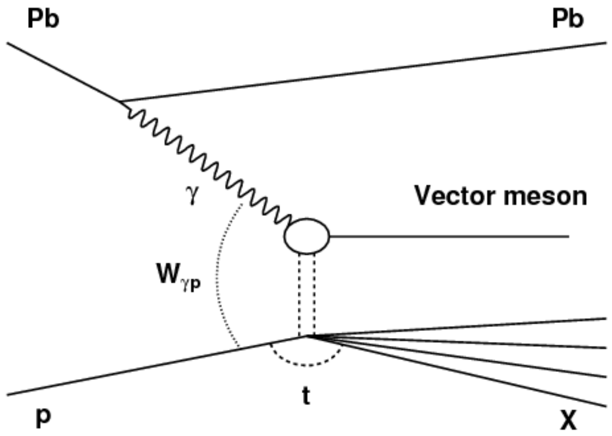
Interactions mediated by the EM interactions

Equivalent photon flux



Vector meson (VM) photoproduction in UPCs

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

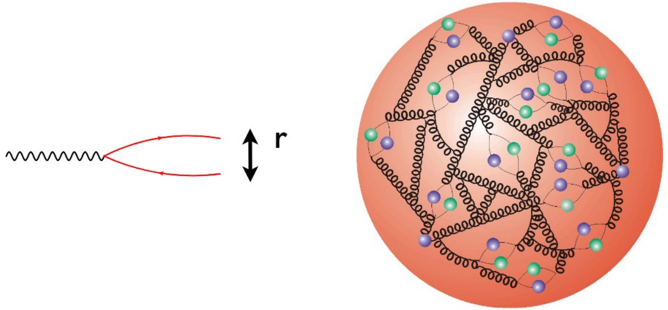


- As in DIS, several reactions are possible in UPCs:

  -Exclusive photoproduction
  -Semi-exclusive photoproduction
  -Inclusive photoproduction

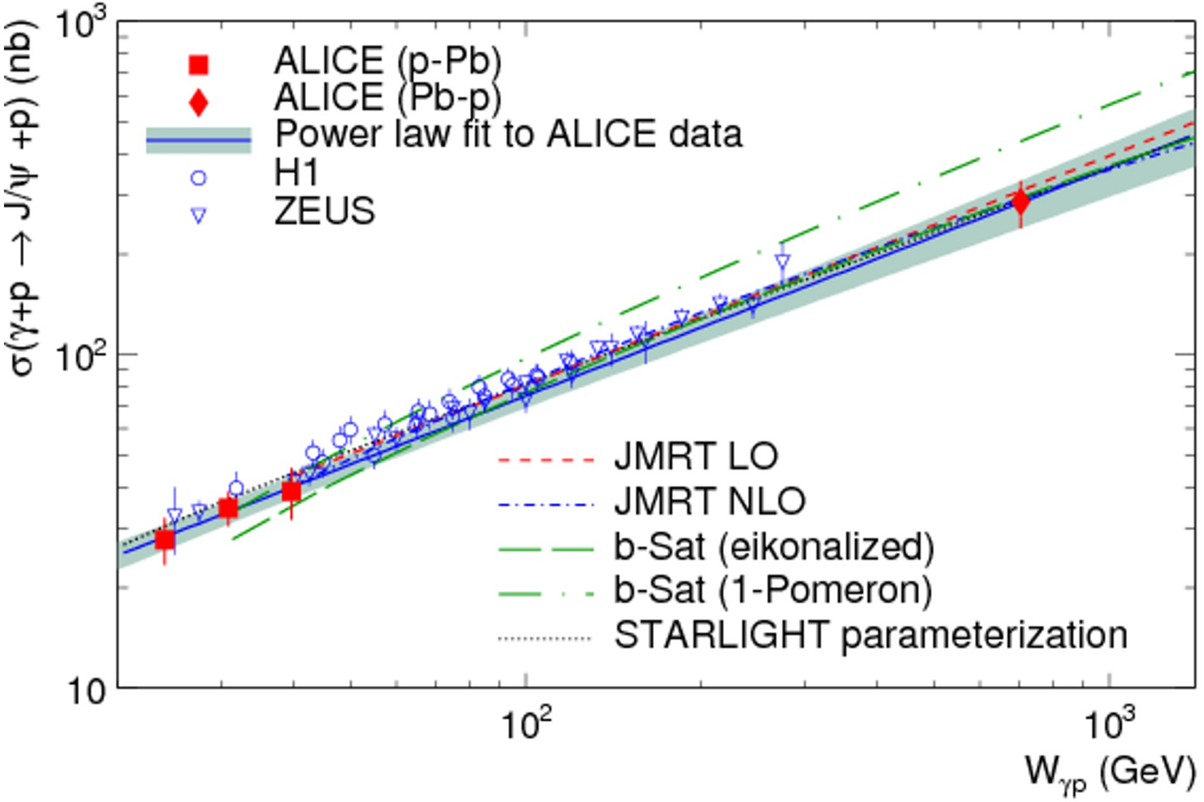
- By studying various VMs, it is possible to study the Q^2 dependence

- 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



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

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

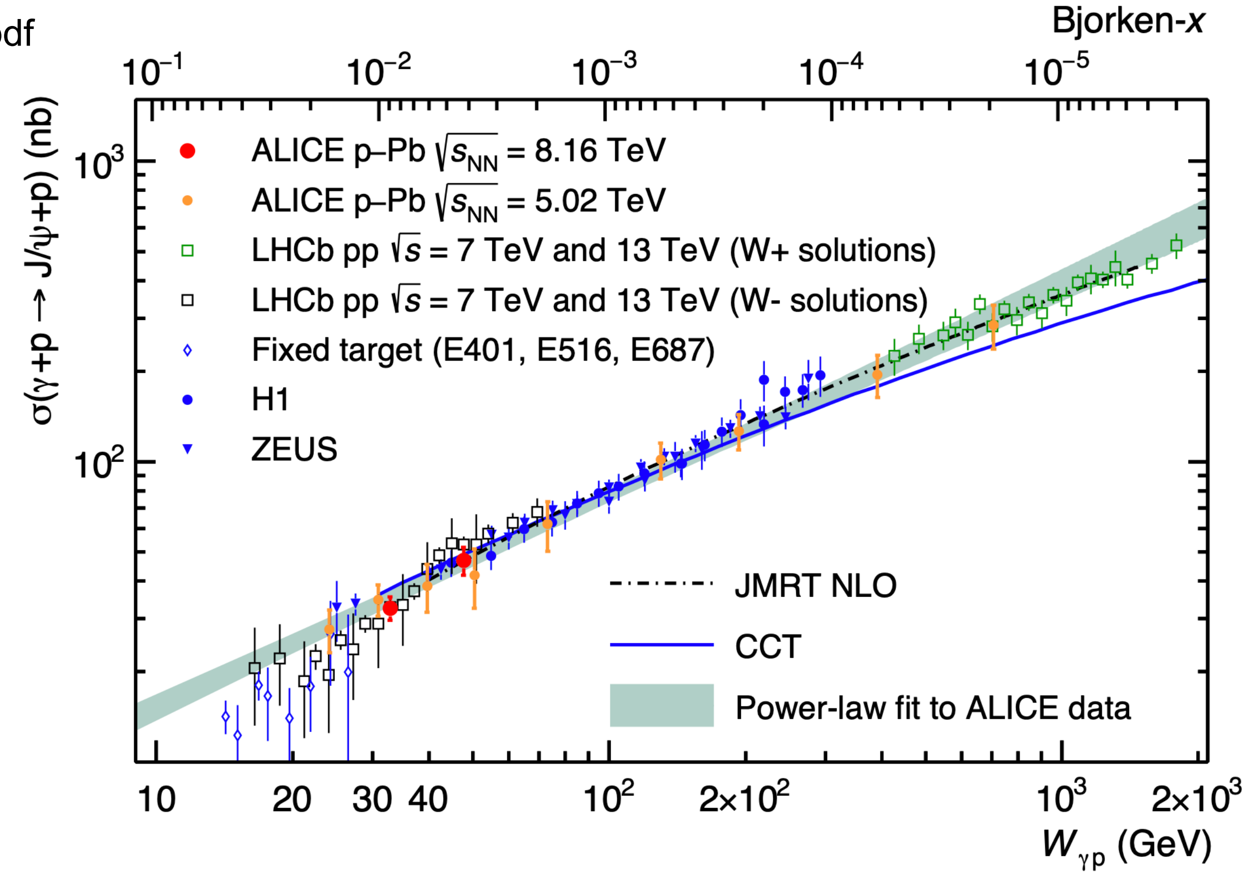


- No change with respect to HERA power-law growth observed at low energies up to 700 GeV
- UPC pPb collisions have no ambiguity on the photon energy

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

Recent exclusive J/ψ measurements by ALICE using Run 2 (2023)

https://arxiv.org/pdf/2304.12403.pdf



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

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

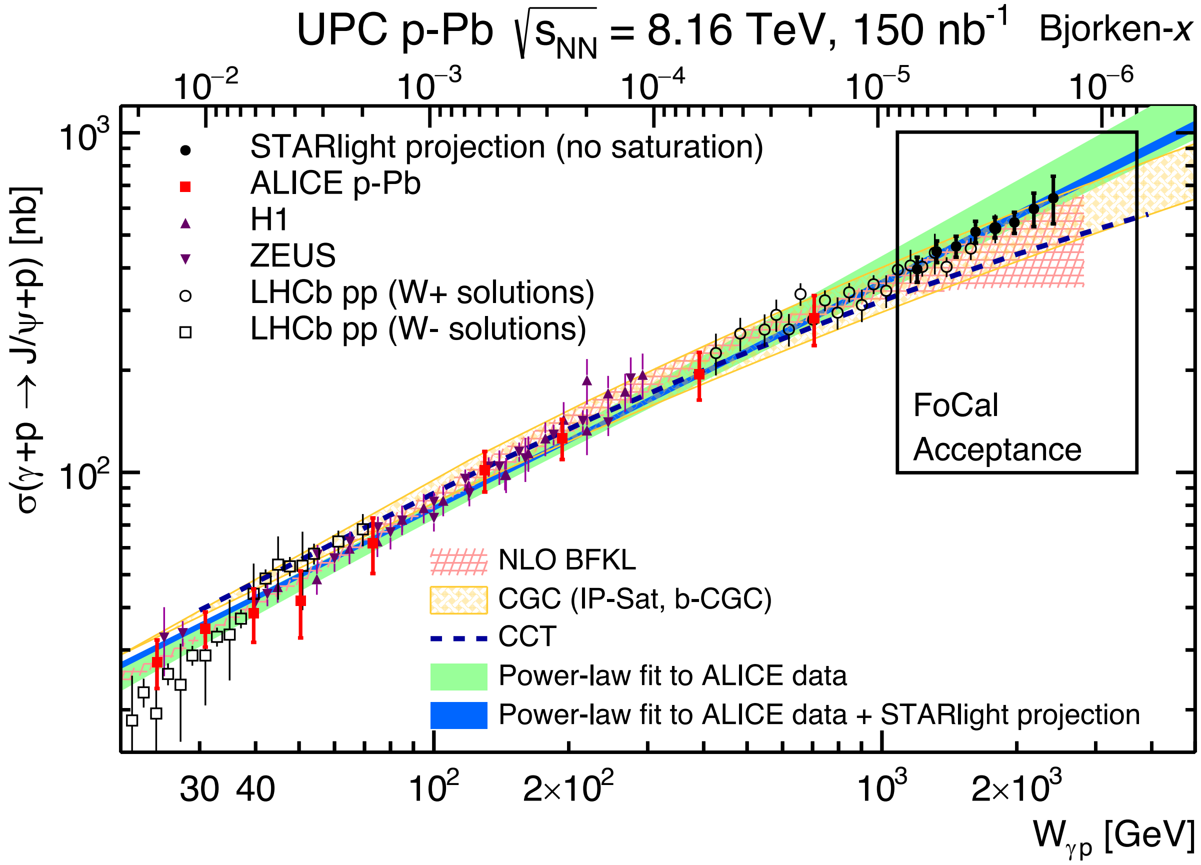
Only UPC asymmetric systems (p-Pb) analyses provide a model independent way of the energy dependence of $\sigma(\gamma p)$

UPC VM projections for FoCal

A. Bylinkin, J. Nystrand and DTT *J. Phys. G: Nucl. Part. Phys.* **50** 055105

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

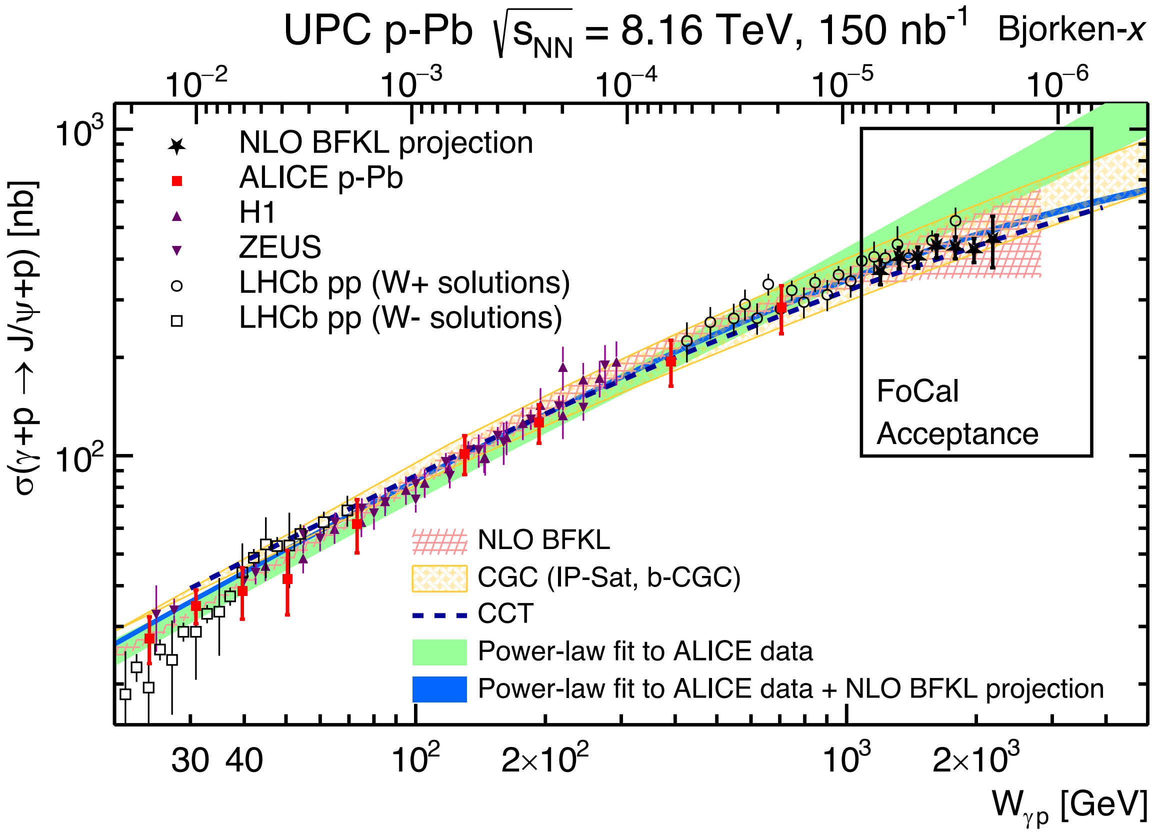


- Deviations from a power-law trend should signal non-linear QCD dynamics
- Here, projections based on STARlight which uses a parametrization based on HERA data

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

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

Projections for exclusive J/ψ off protons

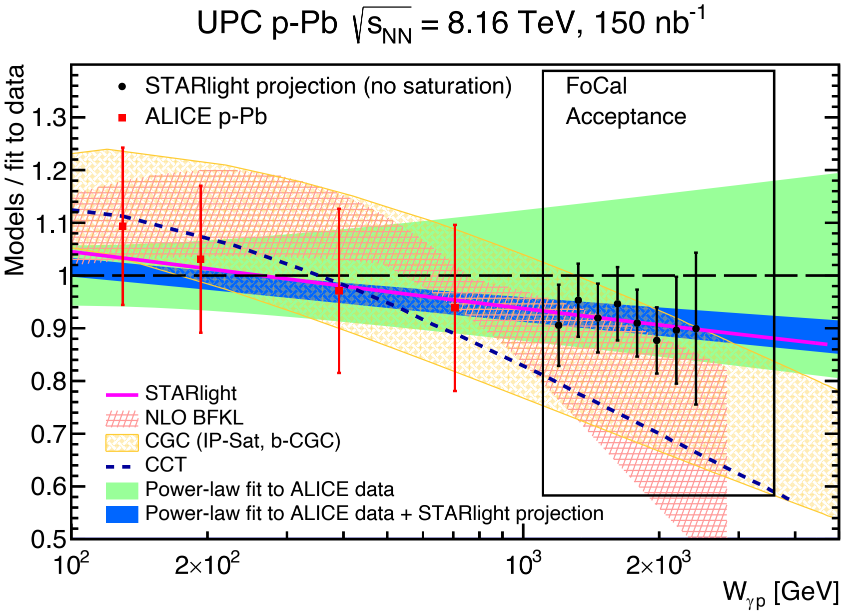


- Projections assuming a broken power-law
- Projected points based on NLO BFKL calculation

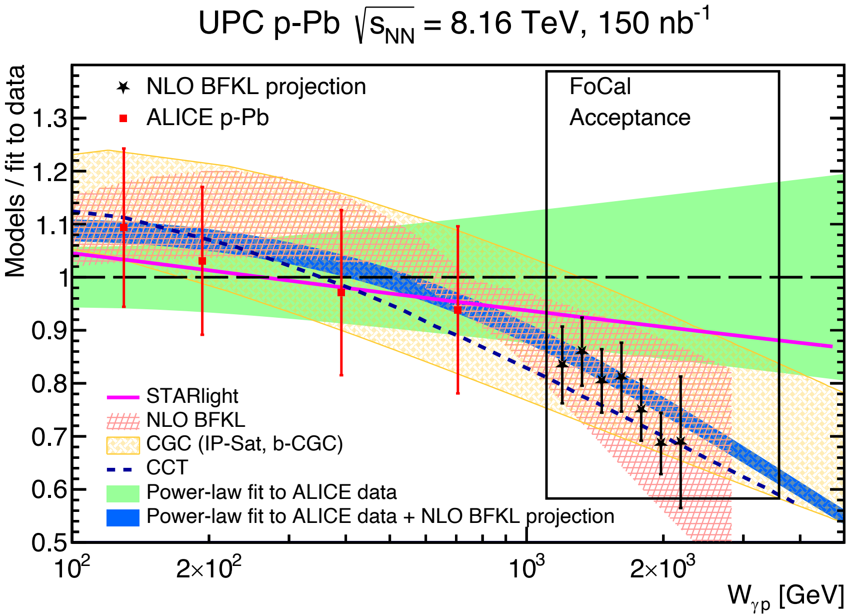
$$\sigma(\gamma p) \approx \frac{\sigma_0}{\frac{1}{W_{\gamma p}^{\delta}} + A}$$

Projections for exclusive J/ψ off protons

Power-law behavior (STARlight)

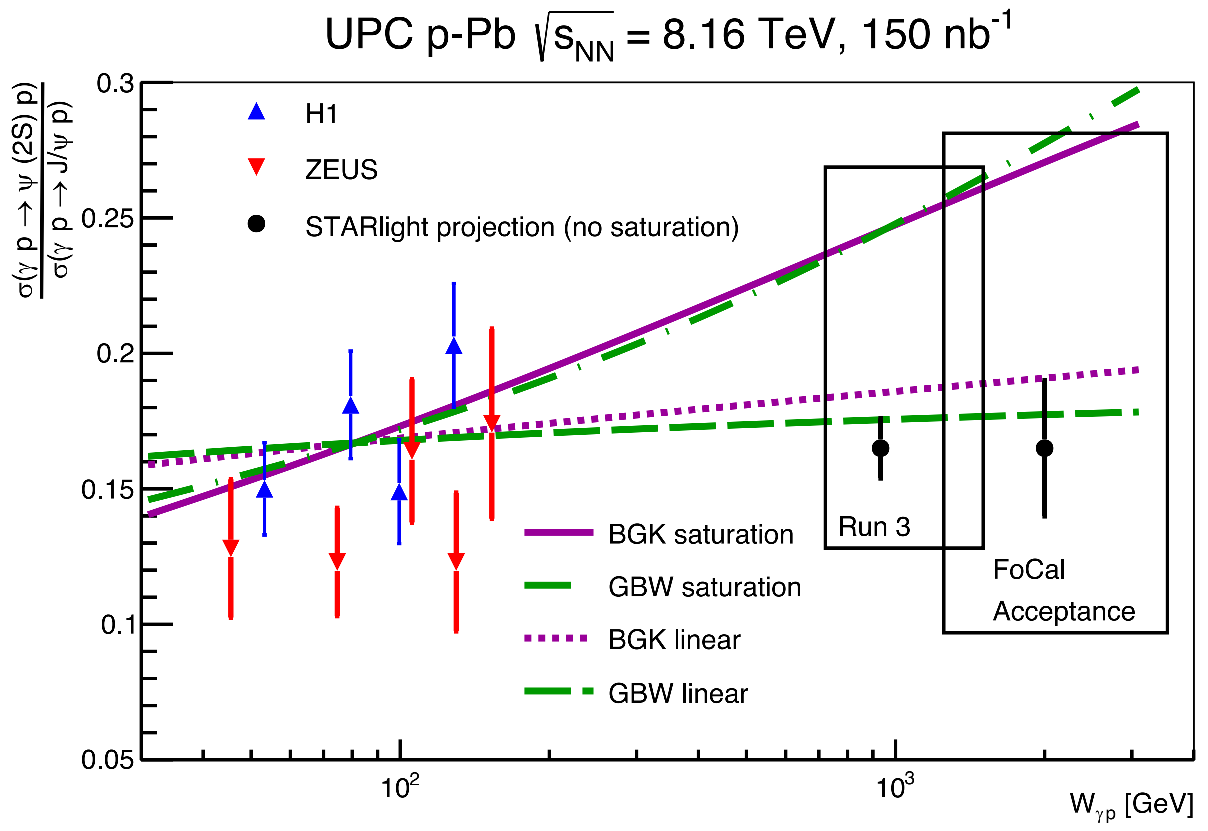


Broken power-law behavior (NLO BFKL)



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

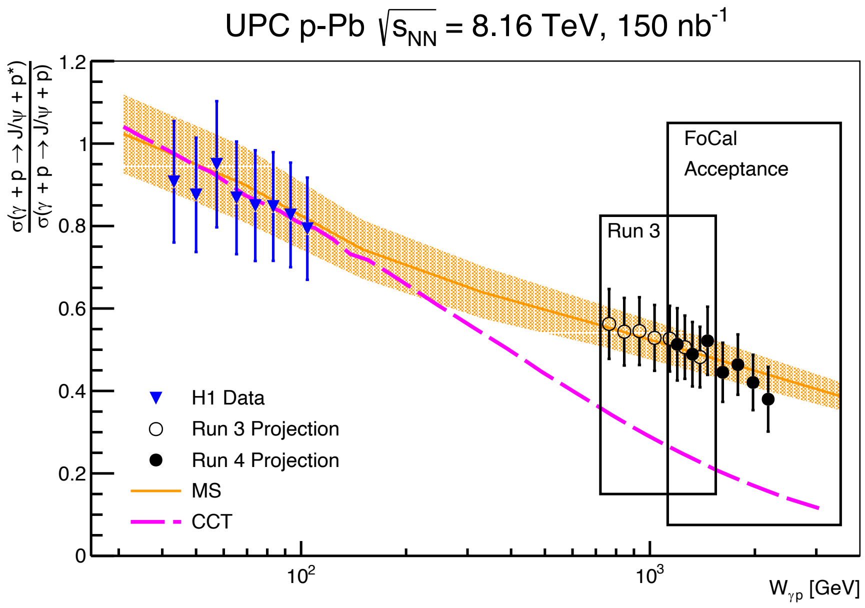
Projections for exclusive ψ(2S) and J/ψ cross section ratio in γp



- 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

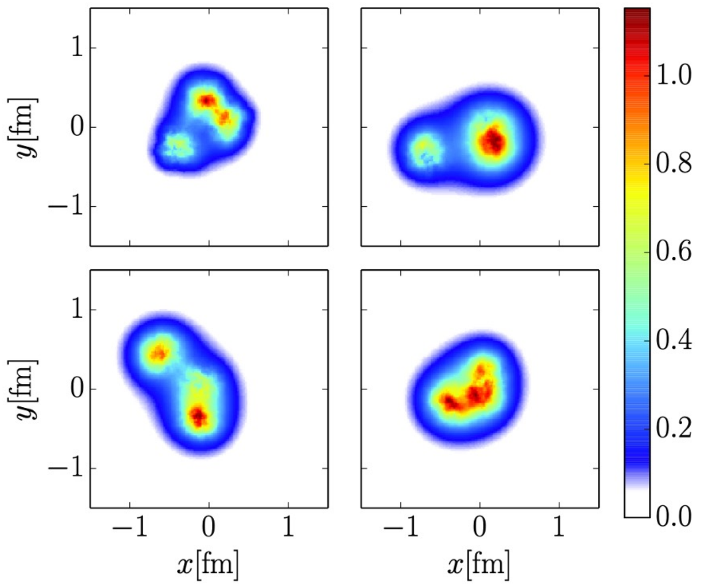
Projections for dissociative J/ψ cross section ratio in γp

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



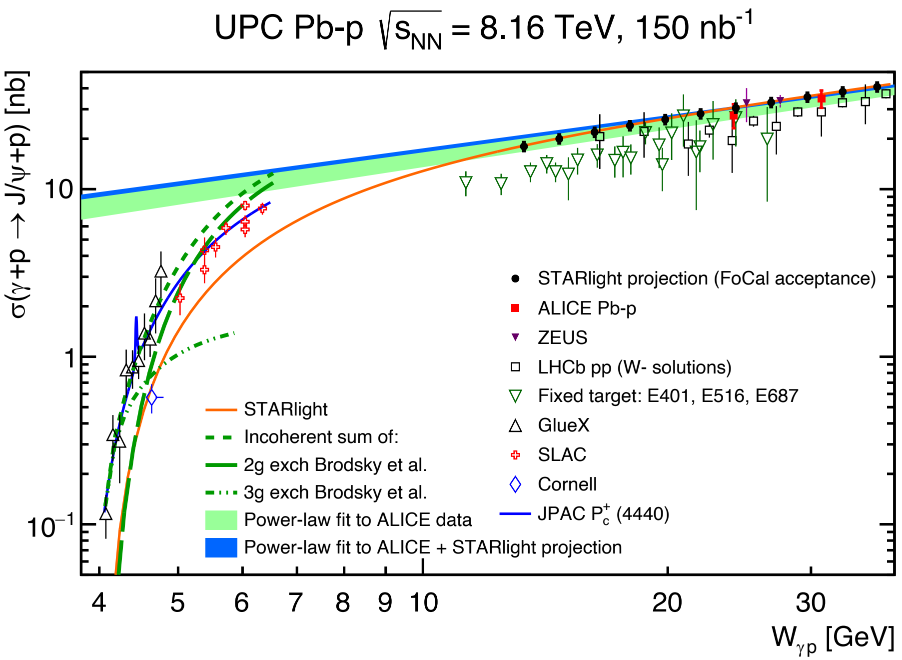
Mantysaari and Schenk, PRD 94, 034042 (2016)

S. Klein arXiv:2301.014018

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

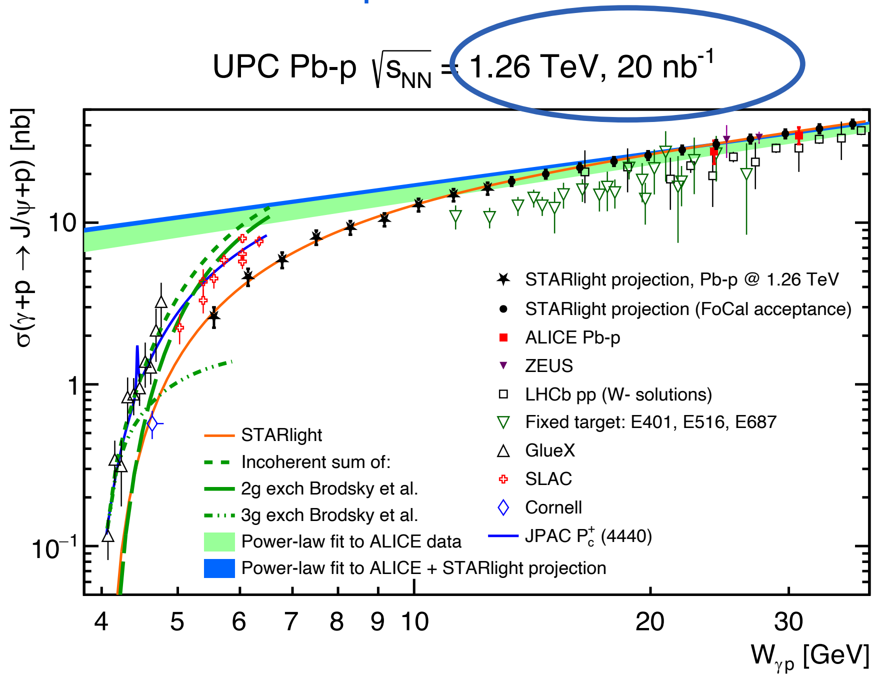
$$\frac{d\sigma(\gamma p \to J/\psi Y)}{dt} = \frac{R_g^2}{16\pi}\left(\left\langle\left|A(x,Q^2,\vec{\Delta})\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})\right\rangle\right|^2\right)$$

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



Near-threshold production motivated by spectroscopy, pentaquarks, etc

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



Projections for VMs in γPb

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

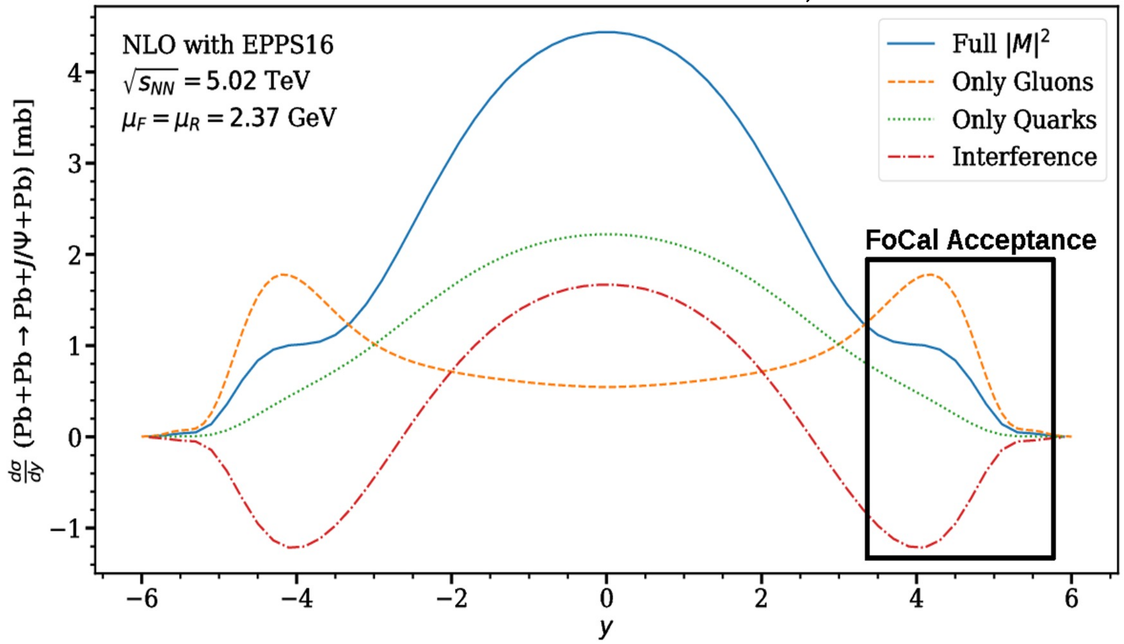
VM	$\sigma(\text{Pb}+\text{Pb}\rightarrow\text{Pb}+\text{Pb}+\text{VM})$	$\sigma(3.4 \leq \eta_{1,2} \leq 5.8)$	Yield
ρ^0	5.0 b	20 μb	140,000
ϕ	440 mb	10 μb	70,000
J/ψ	39 mb	53 μb	370,000
$\psi(2S)$	7.5 mb	1.1 μb	7,500
$\Upsilon(1S)$	94 μb	5.0 nb	35

Projections for VMs in γPb

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

The FoCal region is gluon dominated

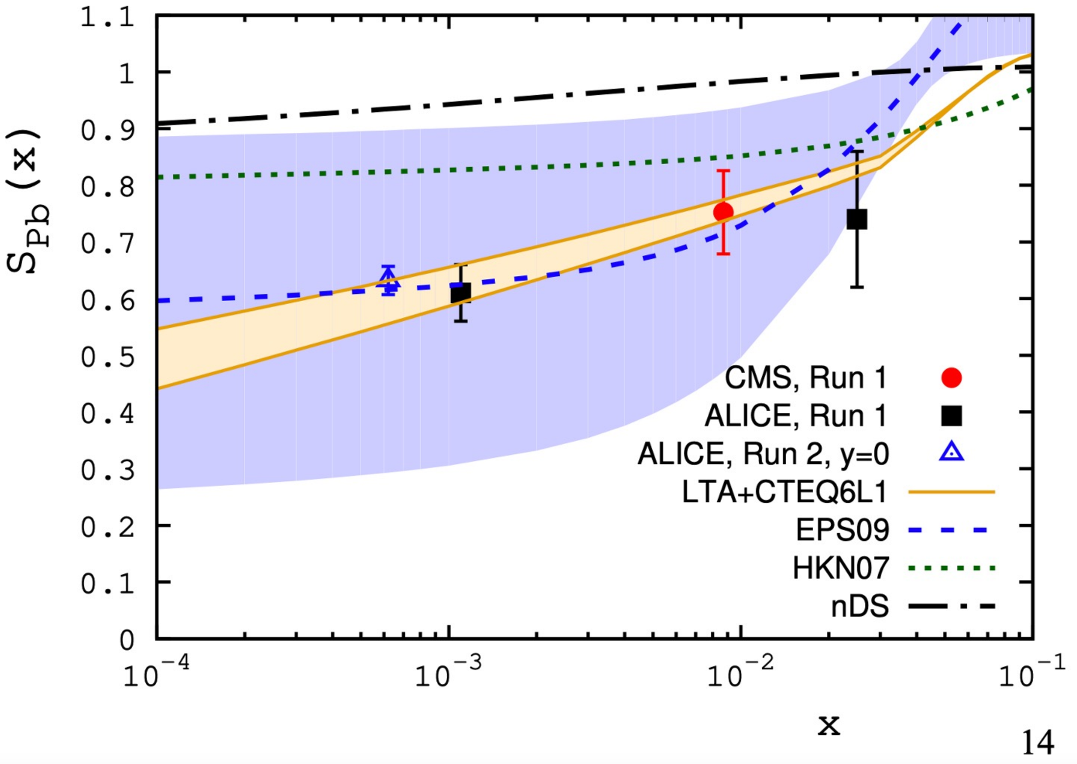
K. Eskola et al., arXiv:2203.11613



- 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

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

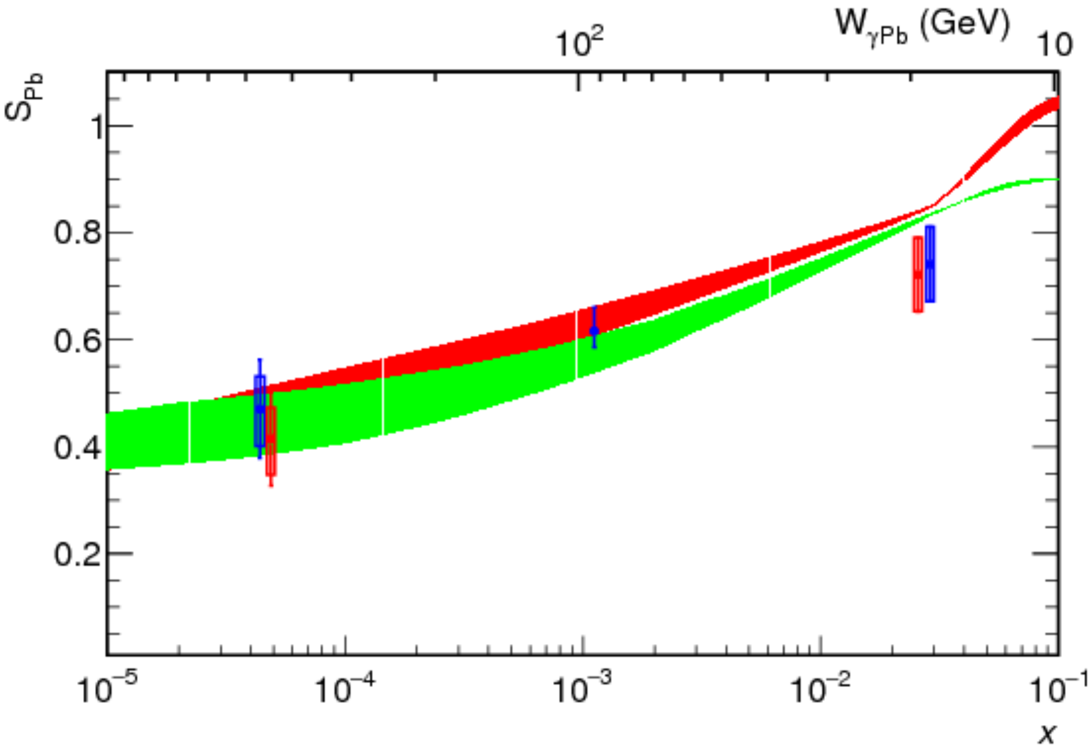
Run 1 data from ALICE was the first at indicating nuclear gluon shadowing at x ~ 10^{-3}

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

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

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}

Neutron-dependence of coherent J/ψ in γPb

The photon flux (n) depends on the impact parameter

Decomposed in terms of neutron configurations emitted in the forward region

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

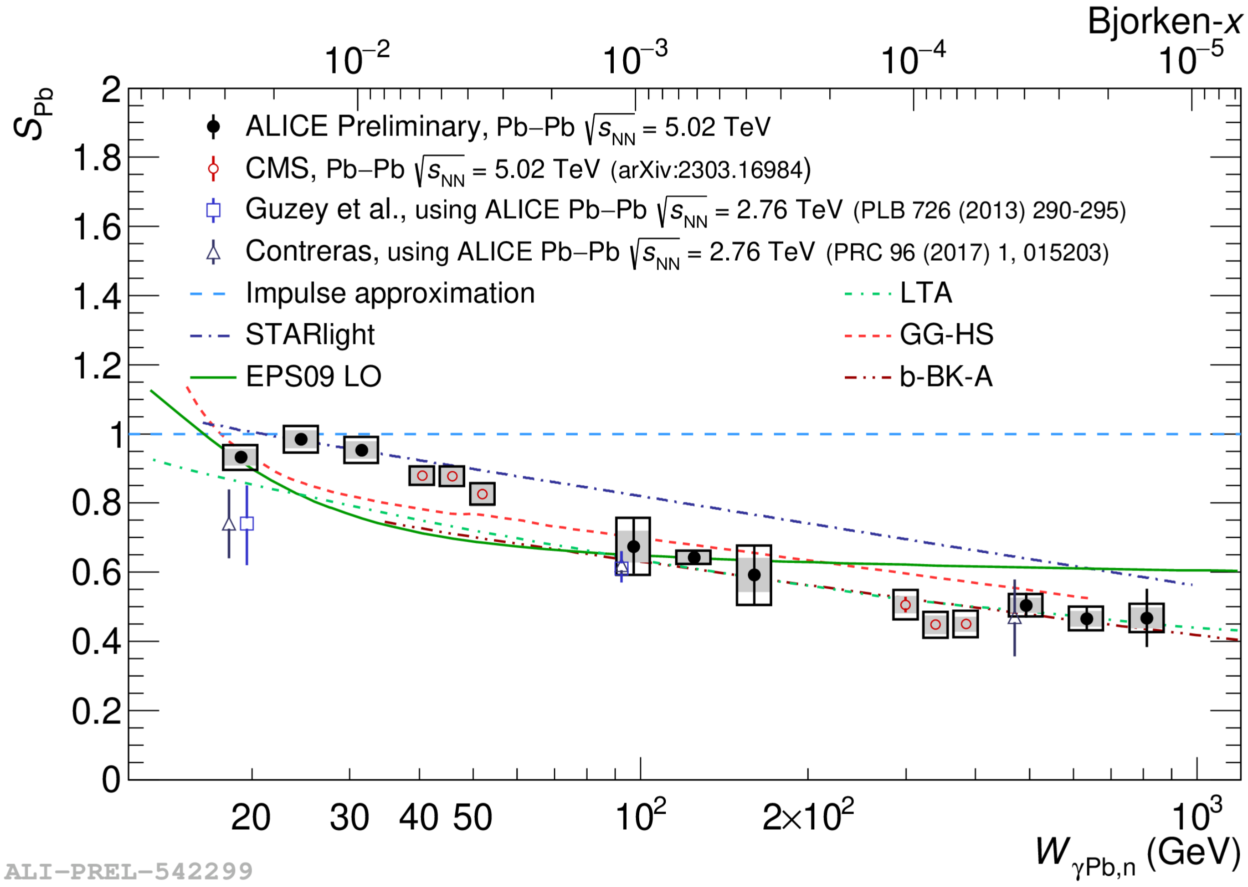
Solving the linear equations resolves the two-photon ambiguity for VMs at y ≠ 0

Positive rapidity

Negative rapidity

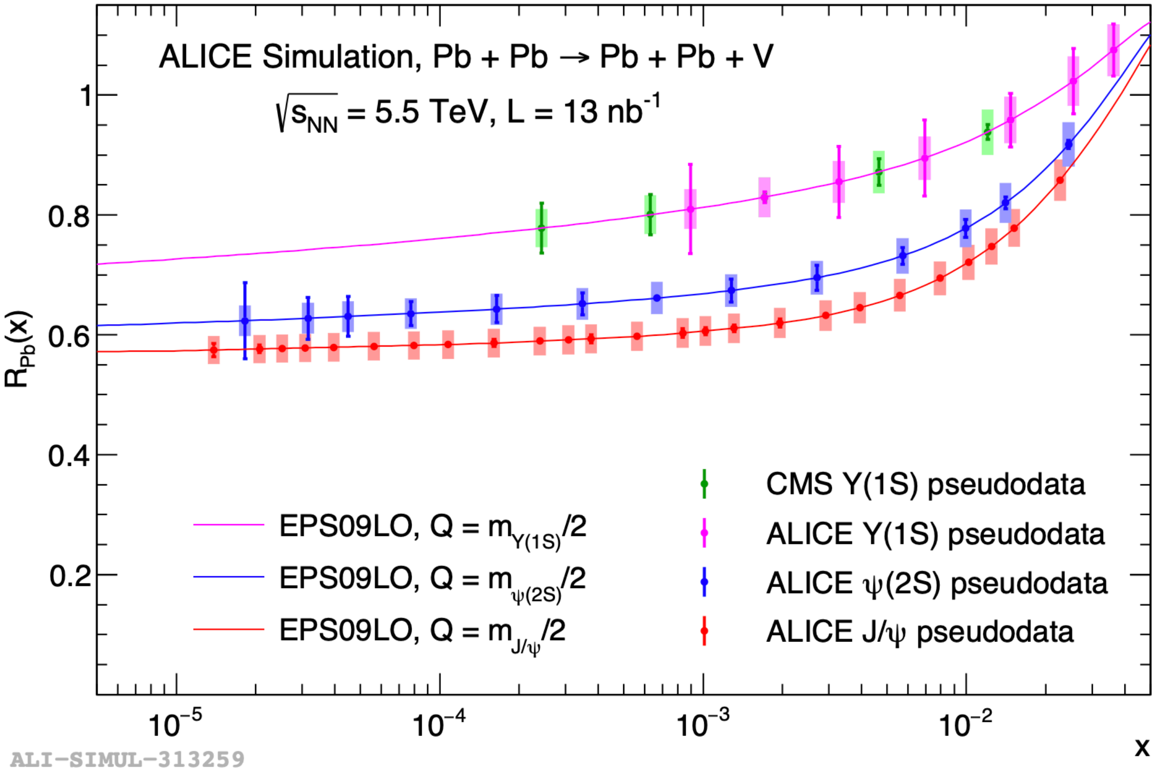
$$\frac{d\sigma}{dy} = n(+y)\sigma(\gamma\mathrm{p}, +\mathrm{y}) + \mathrm{n}(-\mathrm{y})\sigma(\gamma\mathrm{p}, -\mathrm{y})$$

Run 1 and Run 2 results – latest results



Projections for Run 3+4 – without FoCal

Z. Citron et al. CERN Yellow Rep.Monogr. 7 (2019) 1159-1410



- Projections consider neutrons-dependence analysis for VMs at $y \neq 0$
- Analysis combined Run 3+4 statistics, important precision expected, while FoCal will explore further down in *x* where the gluon contribution is dominant

Neutron-dependence of coherent J/ψ in γPb

Decomposed in terms of neutron configurations emitted in the forward region

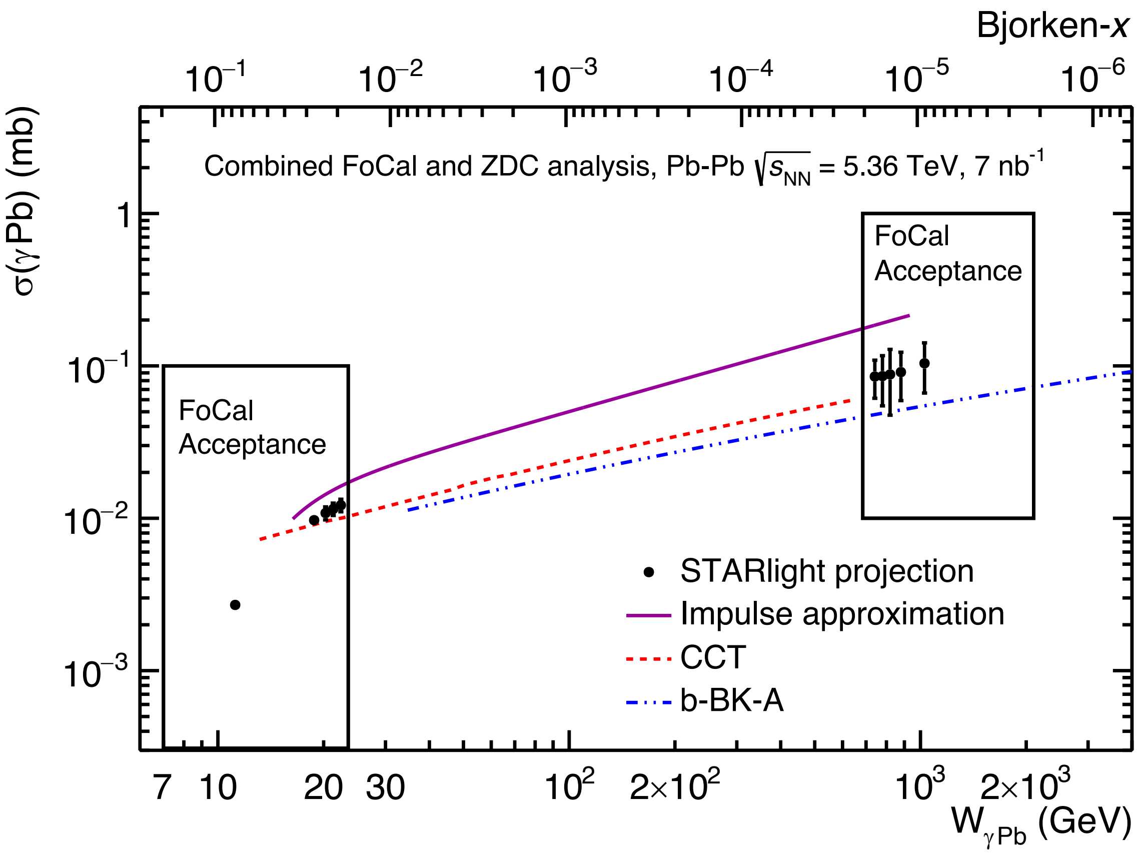
$$\frac{d\sigma}{dy} = \frac{d\sigma(\mathrm{0n0n})}{dy} + 2\frac{d\sigma(\mathrm{0nXn})}{dy} + \frac{d\sigma(\mathrm{XnXn})}{dy}$$

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* ~ 10^{-6} in Pb thanks to FoCal

Summary

- FoCal will enable a unique physics program at the LHC, complementary to the EIC

- The LHC is the energy frontier collider for photon-induced processes using Ultra Peripheral Collisions

- Strong research program in UPCs for probing the hadronic structure at high energies. New measurements and instrumentation in the forward region needed

- FoCal will explore the Bjorken *x* region of a few 10^{-6} for proton and nuclei using UPC VMs, potential to observe deviations of non-linear QCD effects at high energies via comprehensive physics program.
- Examples of other UPC analyses not discussed:
  - Momentum-transfer (t) dependence of VMs
  - Inclusive photoproduction, angular correlations
  - Dijet photoproduction, two-photon process

More about FoCal

- CERN-LHCC-2020-009 ; LHCC-I-036
  https://cds.cern.ch/record/2719928?ln=es

- ALICE-PUBLIC-2023-001
  https://cds.cern.ch/record/2858858

- A. Bylinkin, J. Nystrand and DTT J. Phys. G: Nucl. Part. Phys. 50 055105