Overview the physics of small-x with ALICE

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Outline

- **Introduction of the gluon saturation**
- **Indications of gluon saturation from existing ALICE data**
- **The ALICE for LHC Run 4: new FoCal and ITS 3 upgrades**
- **Key observables for gluon saturation with FoCal**

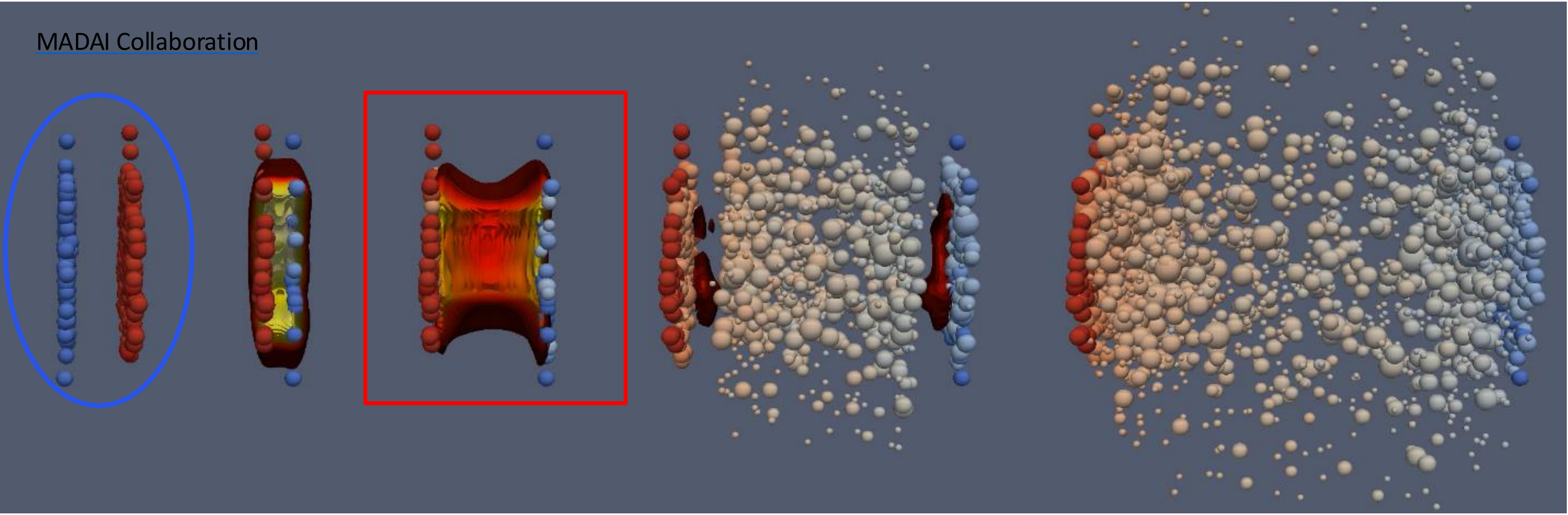
A Large Ion Collider Experiment

- Location: France–Switzerland border
- Circumference: ~27 km
- Main experiments: **ALICE,** ATLAS, CMS, LHCb
- ALICE Collaboration: 38 countries, 165 institutes, 1930 members
- Why do we need such a powerful infrastructure?

Motivation (some 50 years ago)

"It would be **intriguing** to explore **new phenomena** by **distributing** high energy or high nuclear matter over a relatively large volume. , In this way, one could possibly **create abnormal states of nuclear matter**."

Hot and cold QCD Medium in Heavy-Ion Collisions



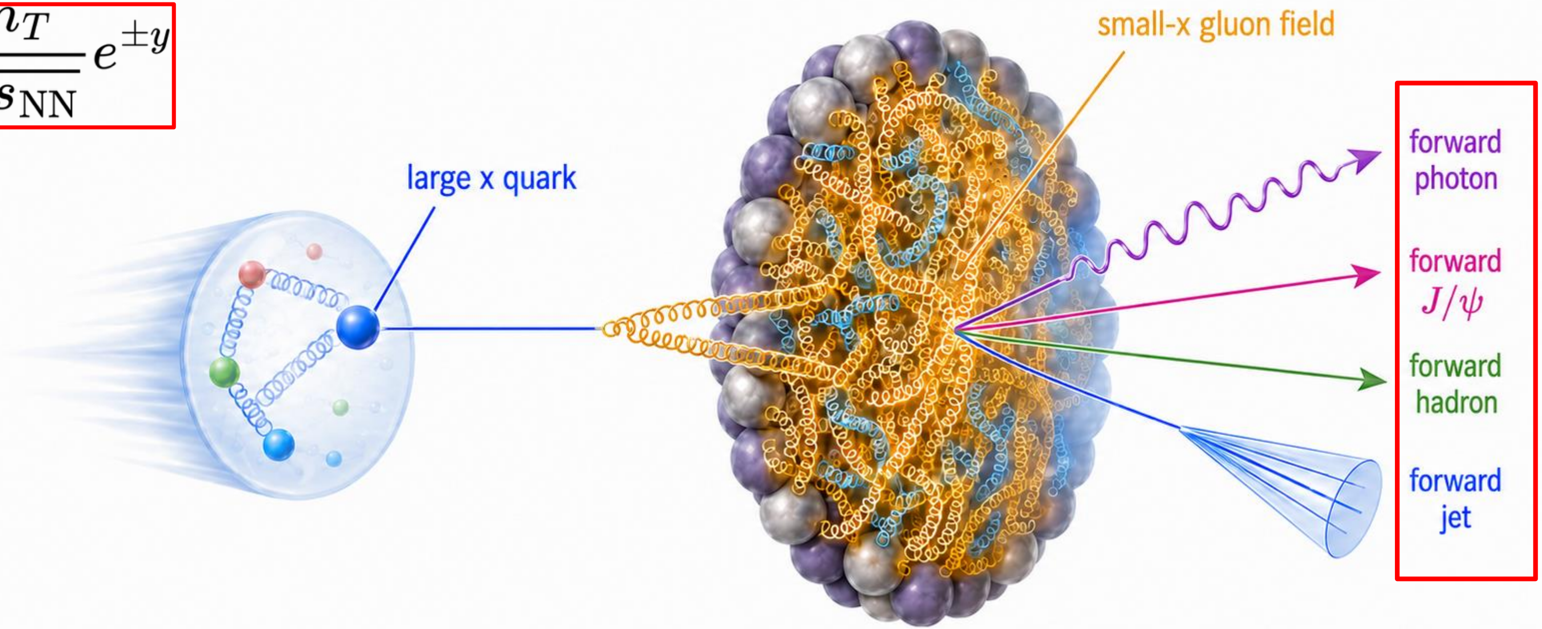
Initial stages
CGC?

quark-gluon plasma (QGP)
fluid dynamic expansion

Final state: hadron scattering

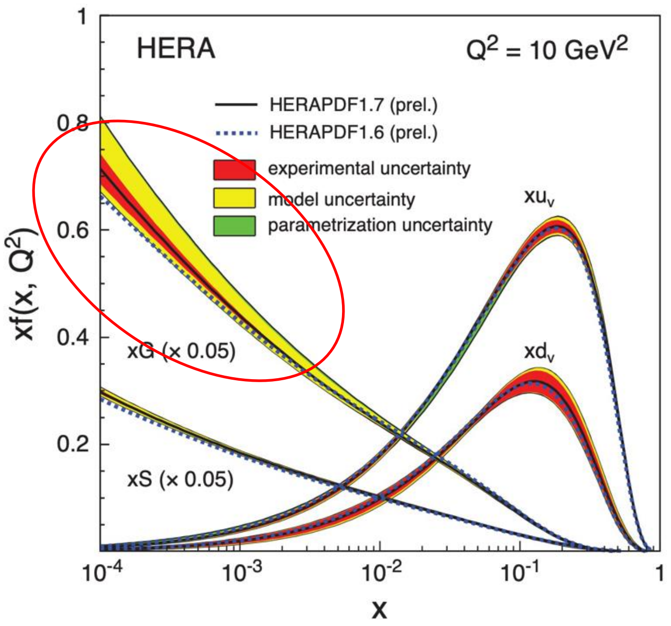
Cold QCD and Small-x Physics

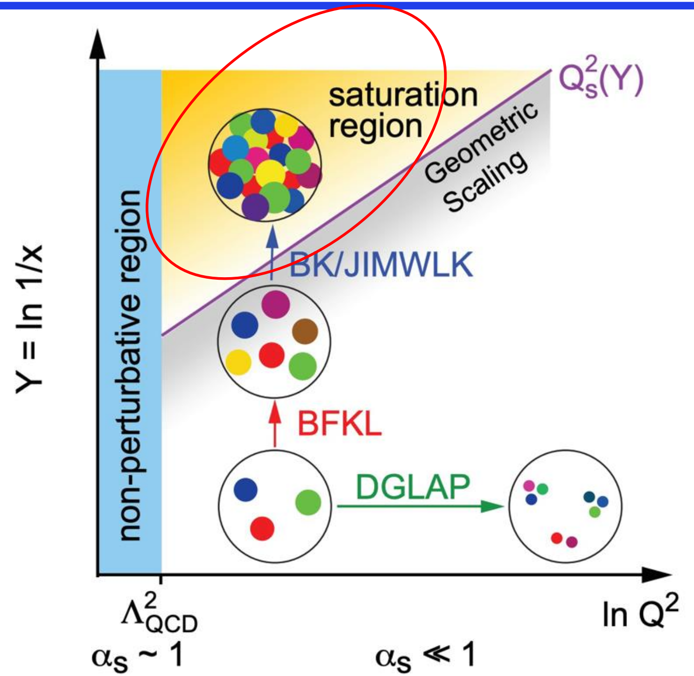
$$x_{1,2} \approx \frac{m_T}{\sqrt{s_{\rm NN}}} e^{\pm y}$$



- How are quarks and gluons distributed inside protons and nuclei (Partonic structure) ?
- At small x, the rapidly increasing gluon density may lead to **nonlinear QCD evolution? and gluon saturation?**

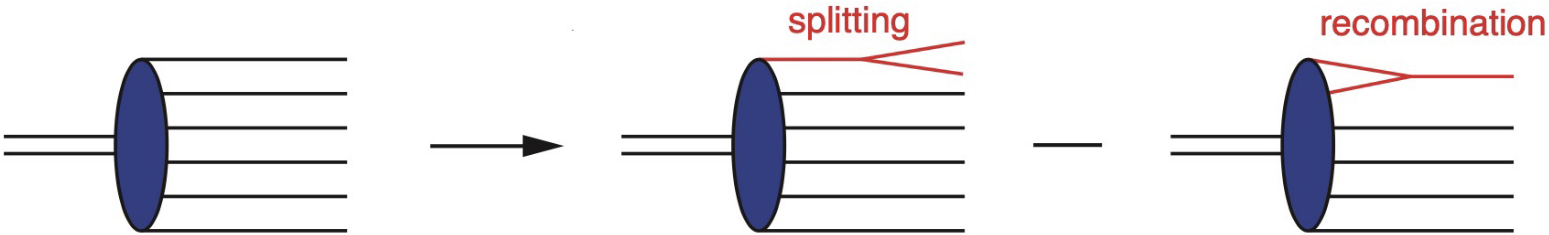
Phase Diagram of Cold QCD





- ➢The growth of the gluon density is **suppressed by nonlinear gluon recombination**.
- ➢Gluon splitting and recombination reach a dynamical balance, leading to gluon saturation.

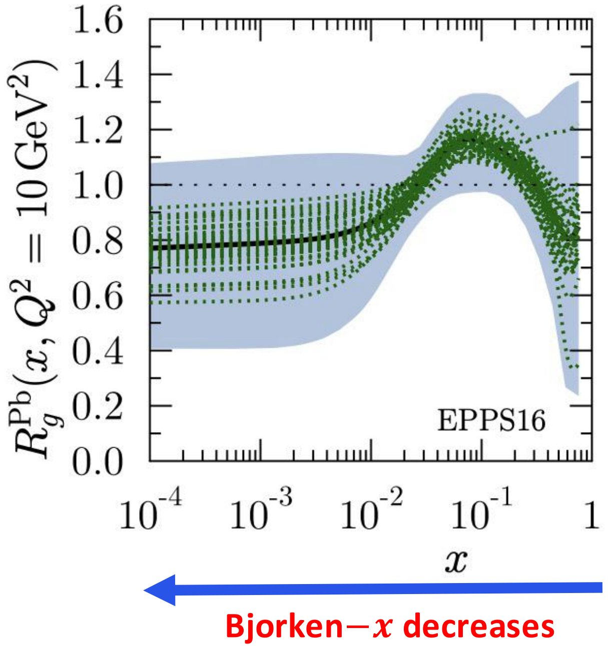
Non-linear QCD evolution



$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x, r_T) - \alpha_s [N(x, r_T)]^2$$

- **Dilute regime:** gluon splitting rapidly increases the gluon density, described by **BFKL linear evolution, g→g+g**
- **Saturation regime:** gluon recombination suppresses further growth, described by **BK (CGC) nonlinear evolution g+g→g** （**indications but not yet confirmed** ）

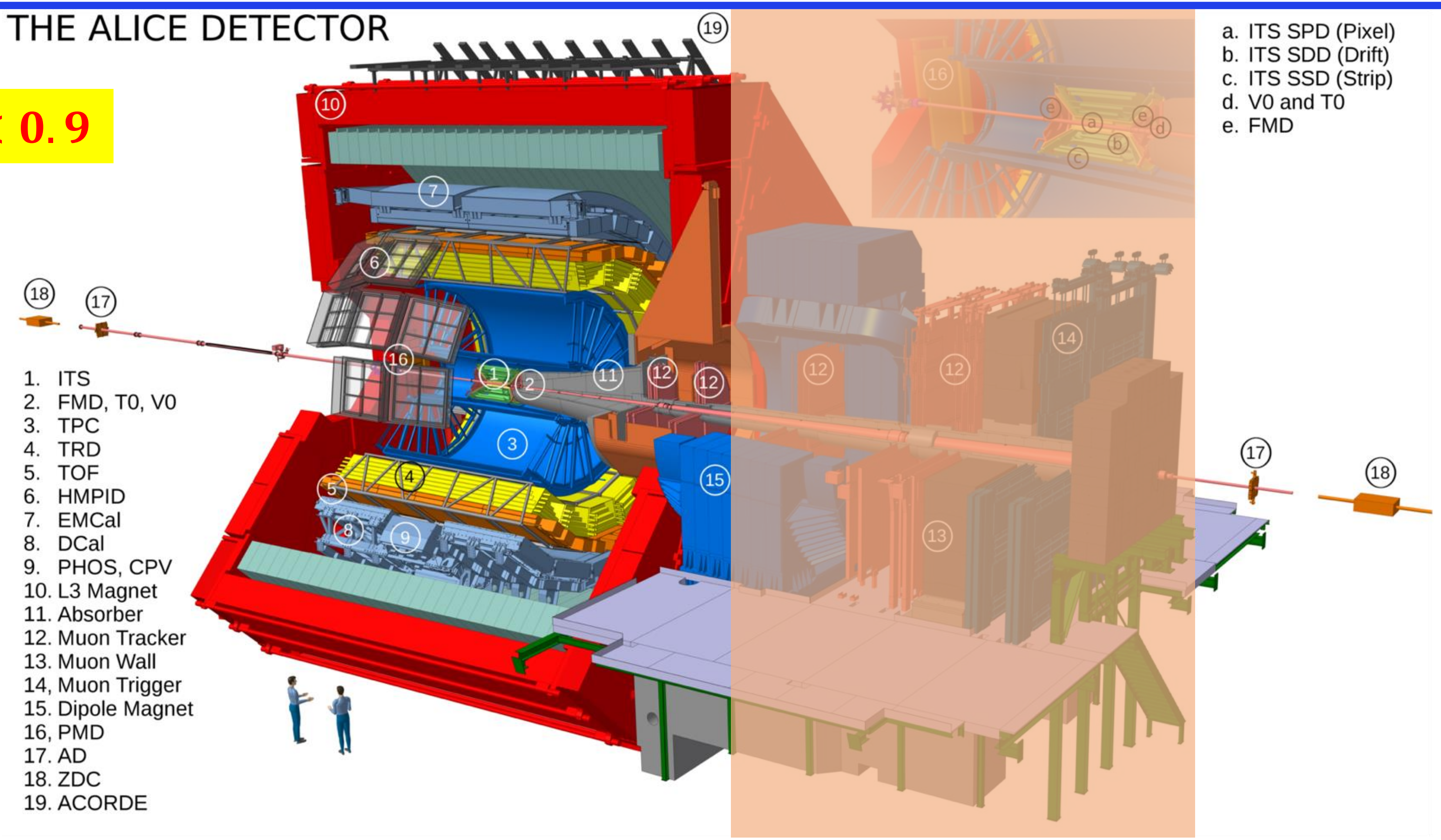
Nuclear gluon distributions at small-x



- ➢ **A strong suppression is observed at small-x, due to nuclear gluon shadowing**
- ➢ Nuclear gluon distributions still have large uncertainty at small-x

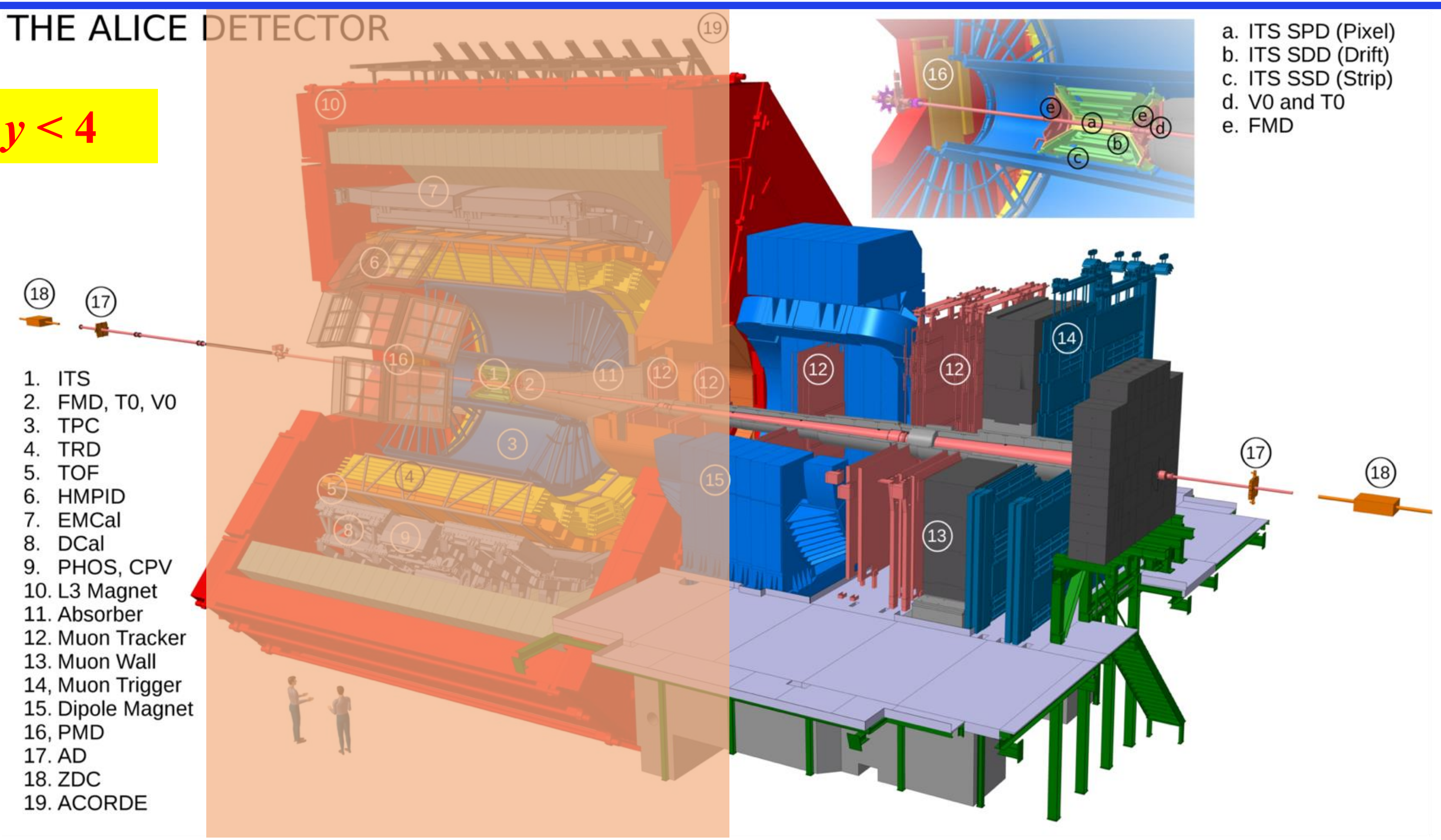
Introduction to ALICE detector

$|y| < 0.9$



Introduction to ALICE detector

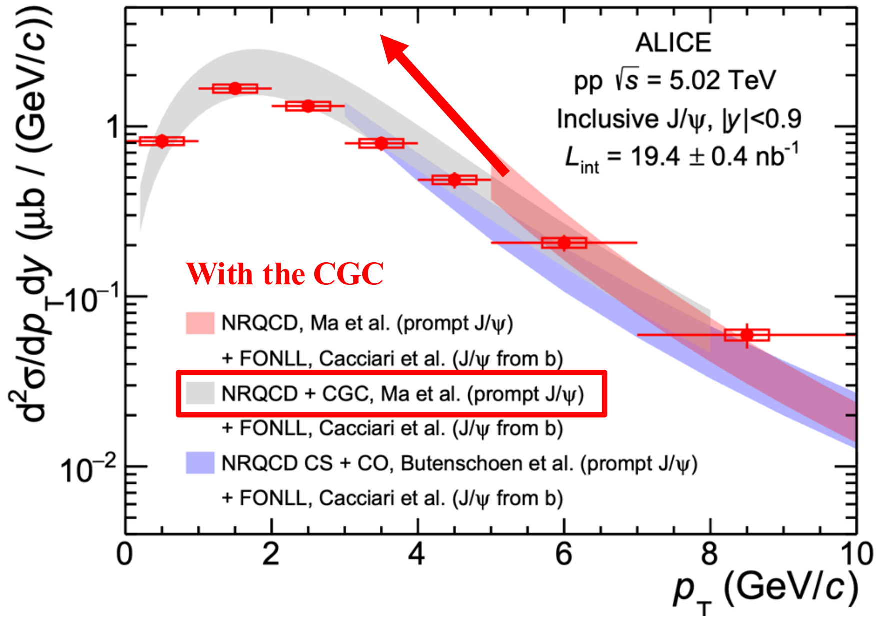
$2.5 < y < 4$



Gluon saturation improves the NRQCD

$$d\sigma_{AB\to J/\psi+X} = \sum_{i,j,n}\int dx_1 dx_2 f_{i/A}(x_1,\mu_F) f_{j/B}(x_2,\mu_F) d\hat{\sigma}_{ij\to c\bar{c}[n]+X}\left\langle \mathcal{O}_n^{J/\psi}\right\rangle$$

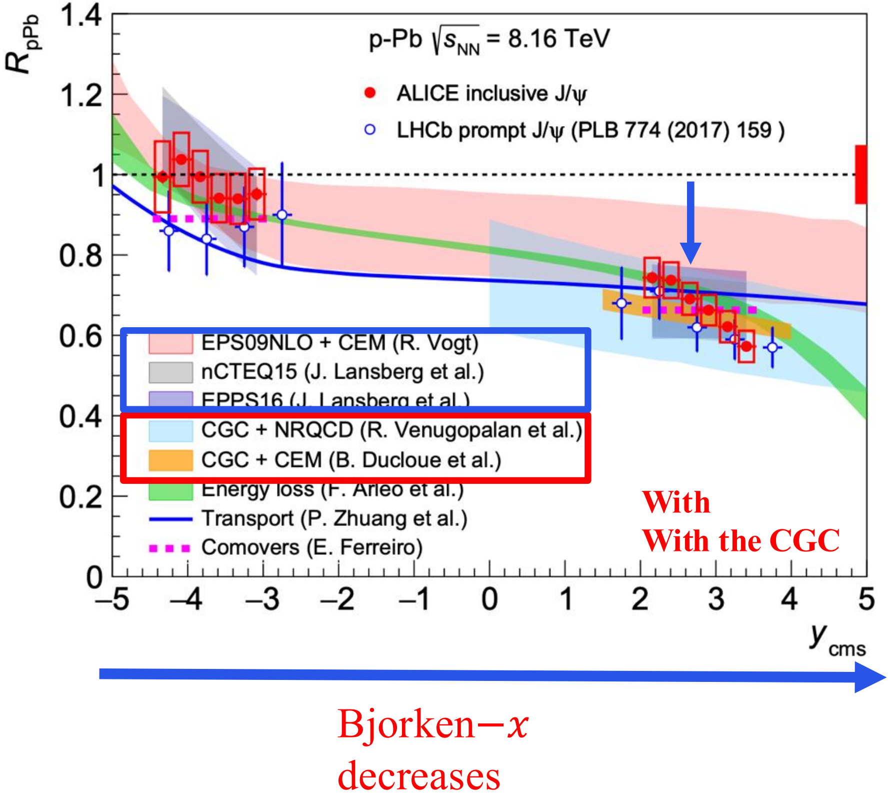
PDFs ⊗ partonic production ⊗ NRQCD hadronization



- **J/ψ mesons are predominantly produced via gluon fusion** and are therefore sensitive to the gluon density gluon.
- NRQCD alone overpredicts the J/ψ yield at pT, incorporating **CGC effects accounts for gluon saturation** and improves agreement with the measured yields.

ALICE, JHEP 10 (2019) 084

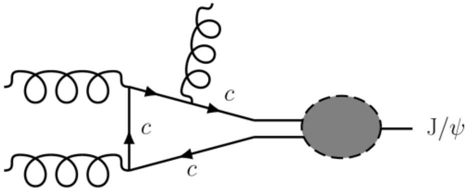
J/ψ suppression is consistent with gluon saturation

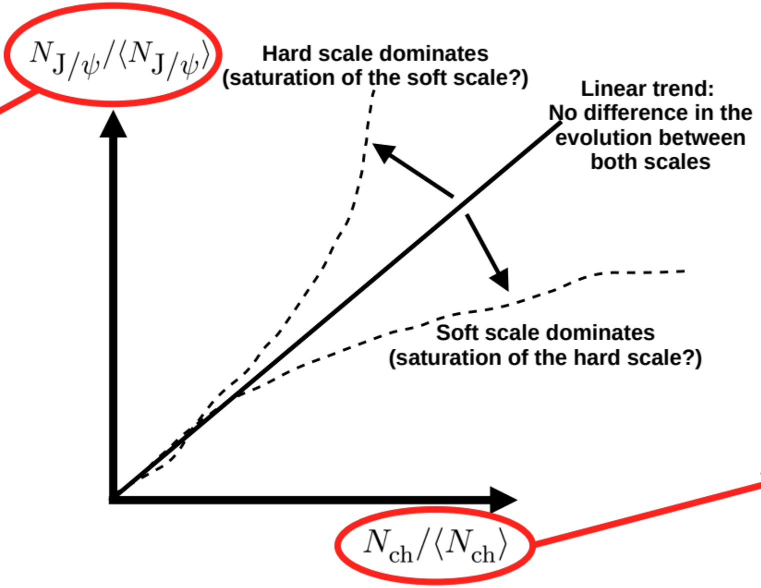


- Toward forward rapidity, the Bjorken-x probed in the Pb nucleus decreases, entering the **small-x region**.
- **CGC-based calculations**, combined with NRQCD or CEM, reproduce the observed suppression, indicating significant gluon-saturation effects.

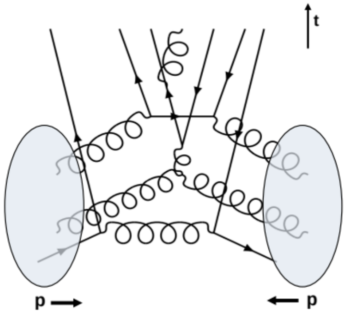
J/ψ versus multiplicity probe the gluon saturation

J/ψ yield (normalised to its mean value) increases with $N_{MPI_{\text{hard}}}$

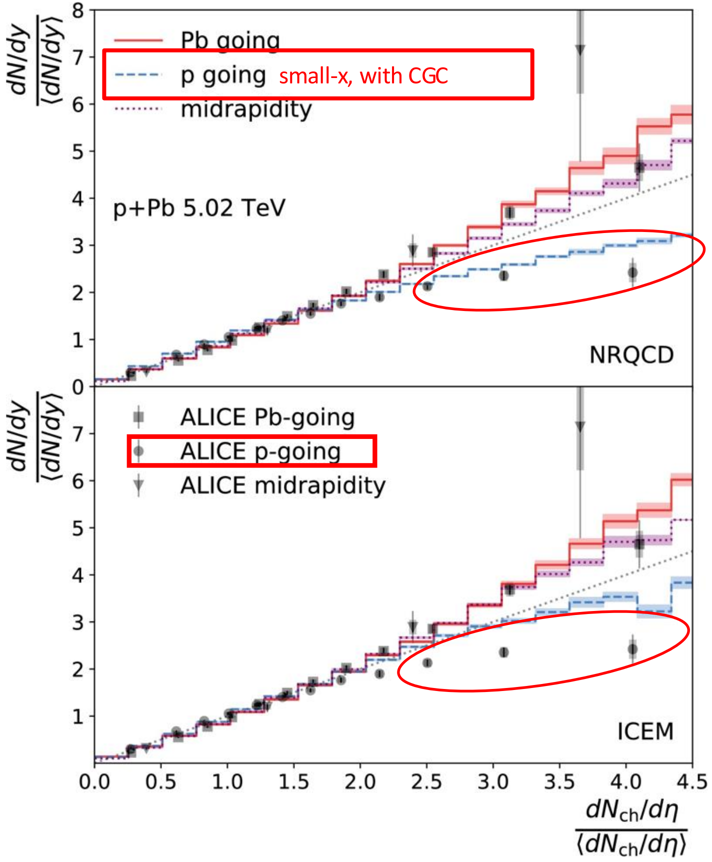




Charged-particle multiplicity (normalized to its mean value) increases with N_{MPI}



In p-Pb collisions: with the gluon saturation



- Different Bjorken-x regions are probed in the Pb nucleus:

  $x_{Pb} \sim 10^{-5}$ *in the p−going direction,*

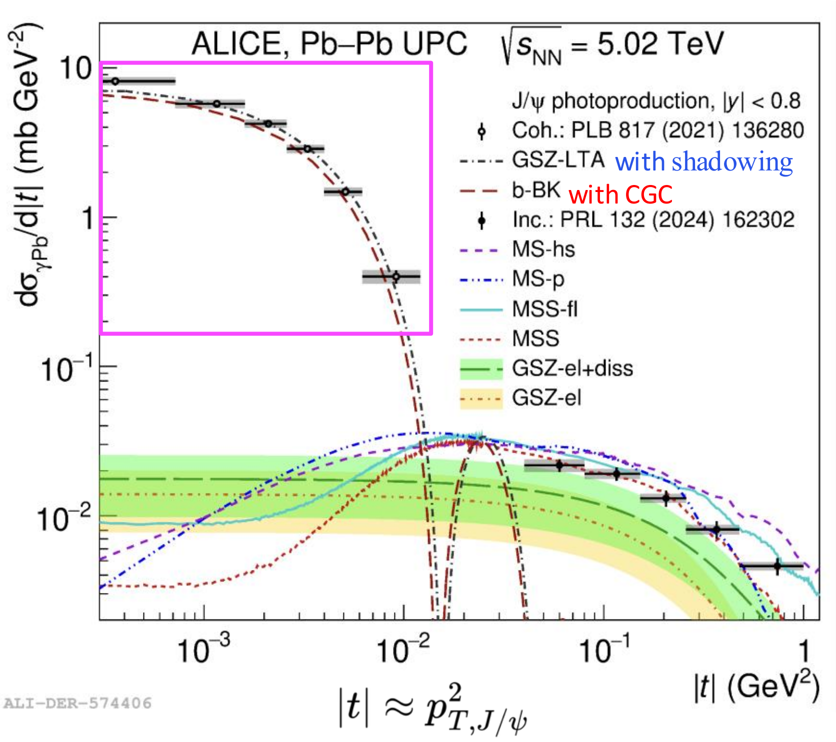
  $x_{Pb} \sim 10^{-2}$ *in the Pb−going direction*.

- CGC calculations including gluon saturation reproduce the observed trends at forward and backward rapidity

F. Salazar et al, Phys. Lett. B 827 (2022) 136952.

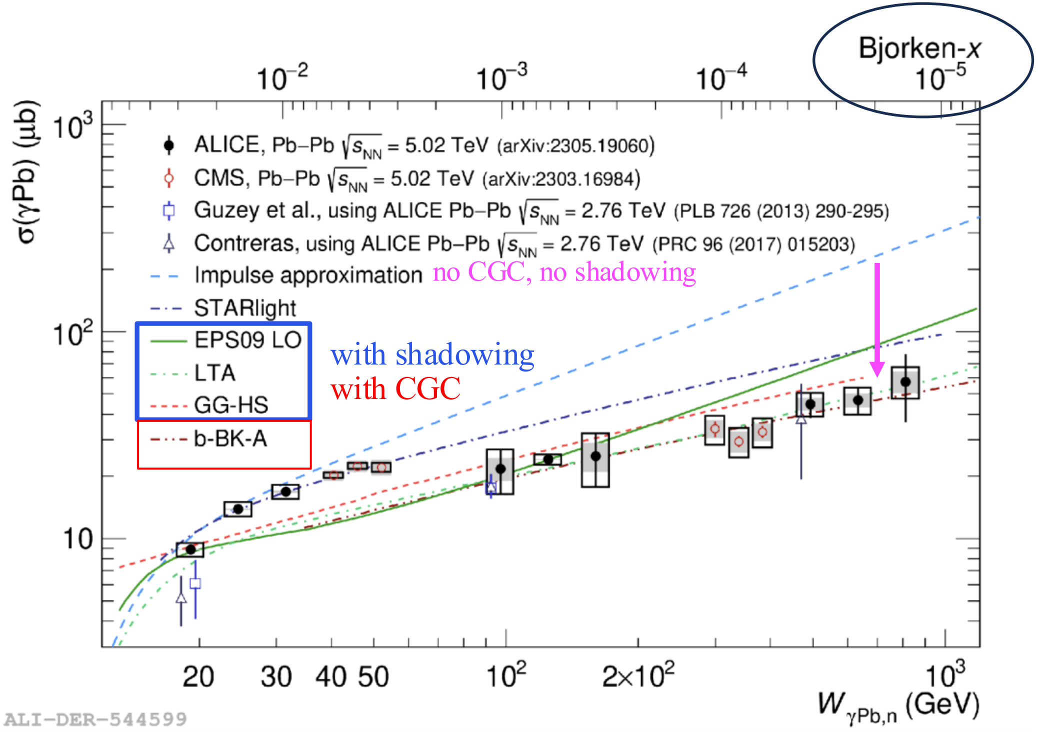
J/ψ Photoproduction in UPCs

PLB 817 (2021) 136280 PRL 132 (2024) 162302



- Coherent and incoherent J/ψ photoproduction provide complementary information on the average gluon density and its fluctuations
- Coherent J/ψ production can be described by models incorporating **nuclear shadowing or gluon saturation**
- How can the effects of nuclear shadowing and gluon saturation be disentangled?

Coherent J/ψ photoproduction

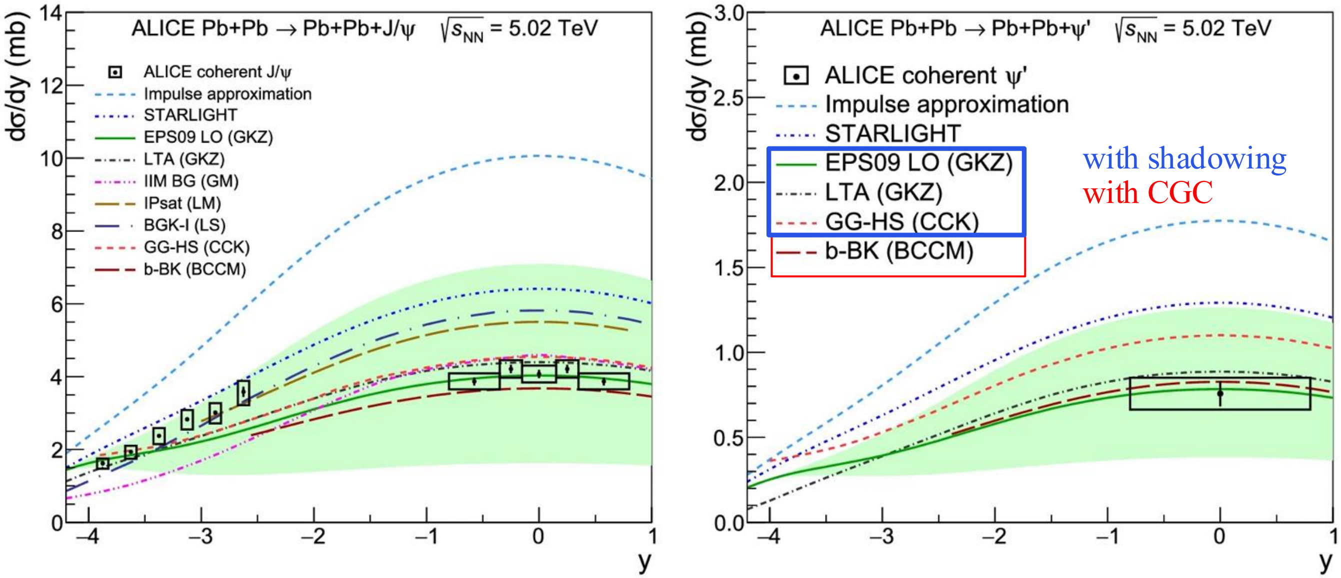


ALICE, JHEP 10 (2023)119

$$x \downarrow \Rightarrow g(x) \uparrow \Rightarrow \sigma(\gamma\mathrm{Pb} \to J/\psi\mathrm{Pb}) \uparrow$$

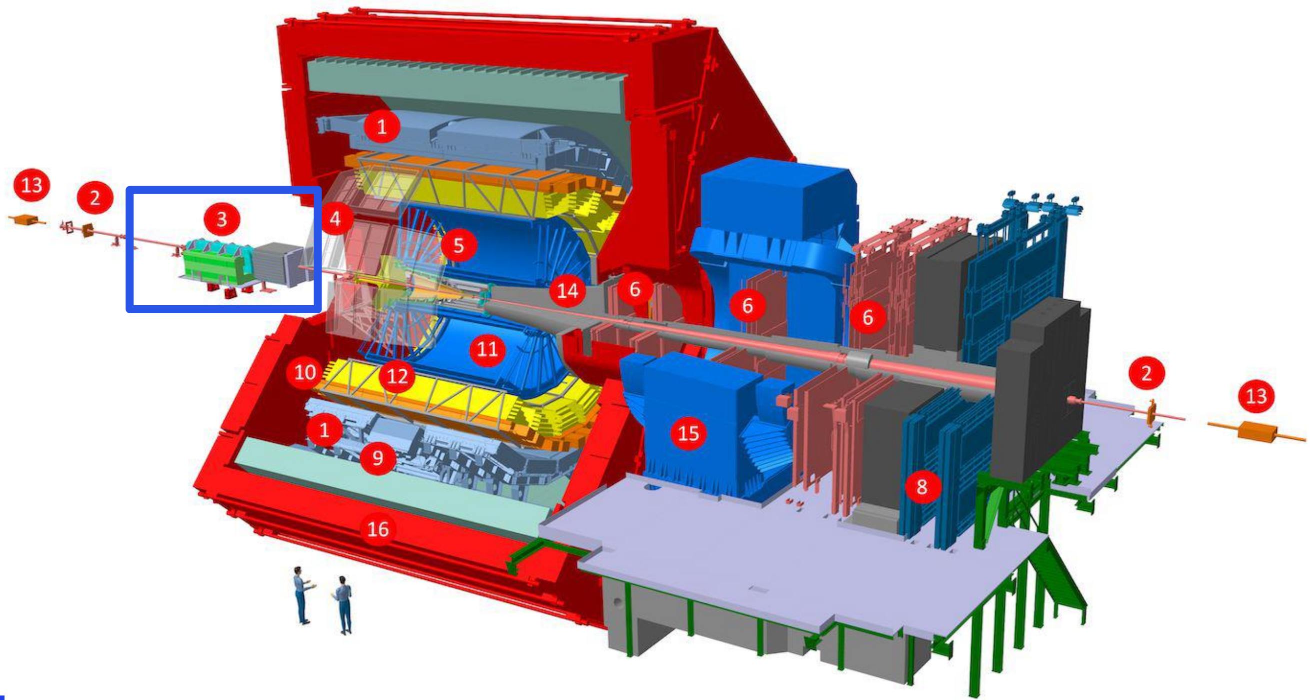
- A strong suppression is observed in the small-*x* region, possibly due to **gluon saturation and/or nuclear shadowing**
- No single model describes the cross section over the full Bjorken-*x* range.

Coherent J/ψ and ψ(2S) photoproduction



- Models including nuclear shadowing, or gluon saturation provide a better description of the data
- More precise measurements are needed to disentangle nuclear shadowing from gluon saturation

The FoCal detector at the ALICE experiment



1 **EMCAL |** Electromagnetic Calorimeter

2 **FIT |** Fast Interaction Trigger

3 **FoCal |** Forward Calorimeter

4 **HMPID|** High Momentum Particle Identification Detector

5 **ITS|** Inner Tracking System

6 **MCH|** Muon Tracking Chambers

7 **MFT|** Muon Forward Tracker

8 **MID|** Muon Identifier

9 **PHOS/CPV|** Photon Spectrometer

10 **TOF|** Time Of Flight

11 **TPC|** Time Projection Chamber

12 **TRD|** Transition Radiation Detector

13 **ZDC|** Zero Degree Calorimeter

14 **Absorber**

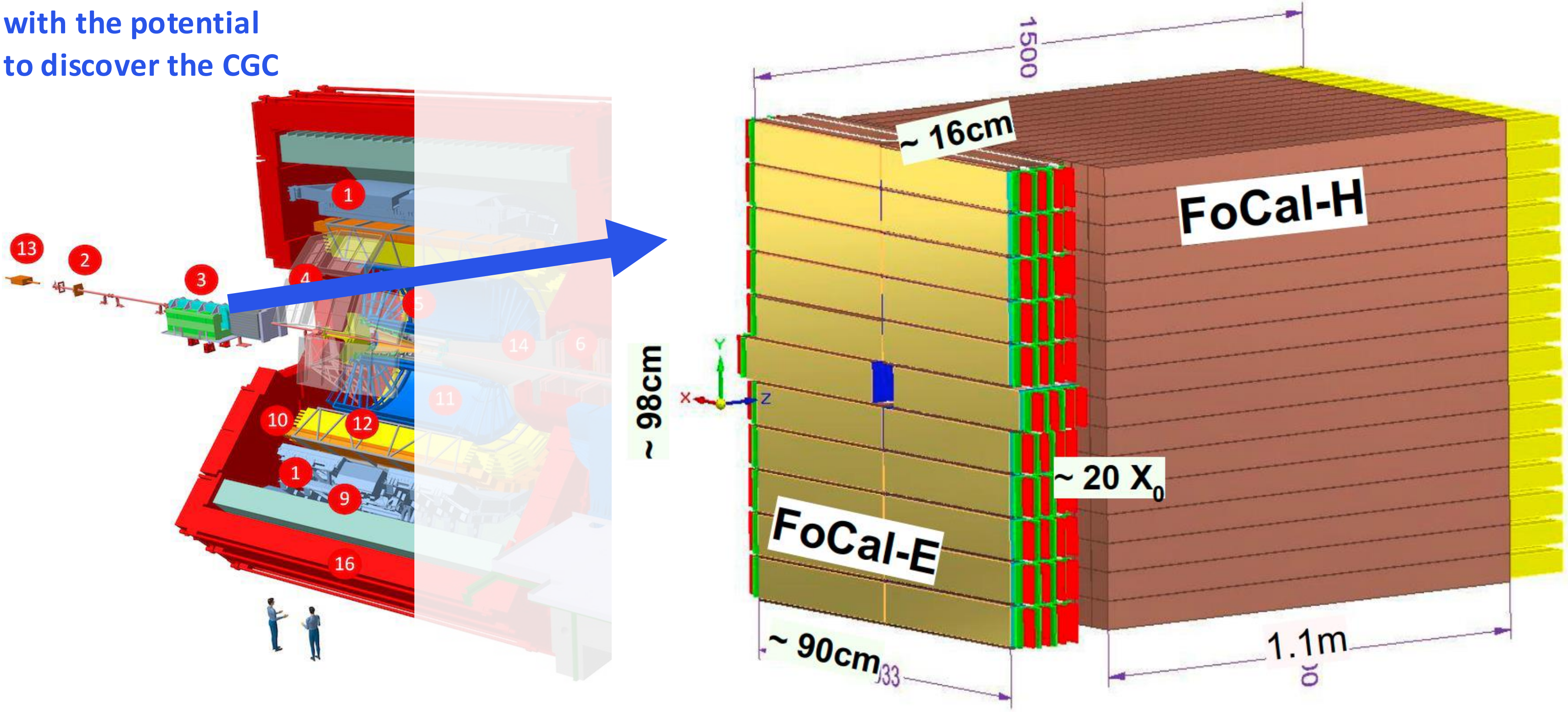
15 **Dipole Magnet**

16 **L3 Magnet**

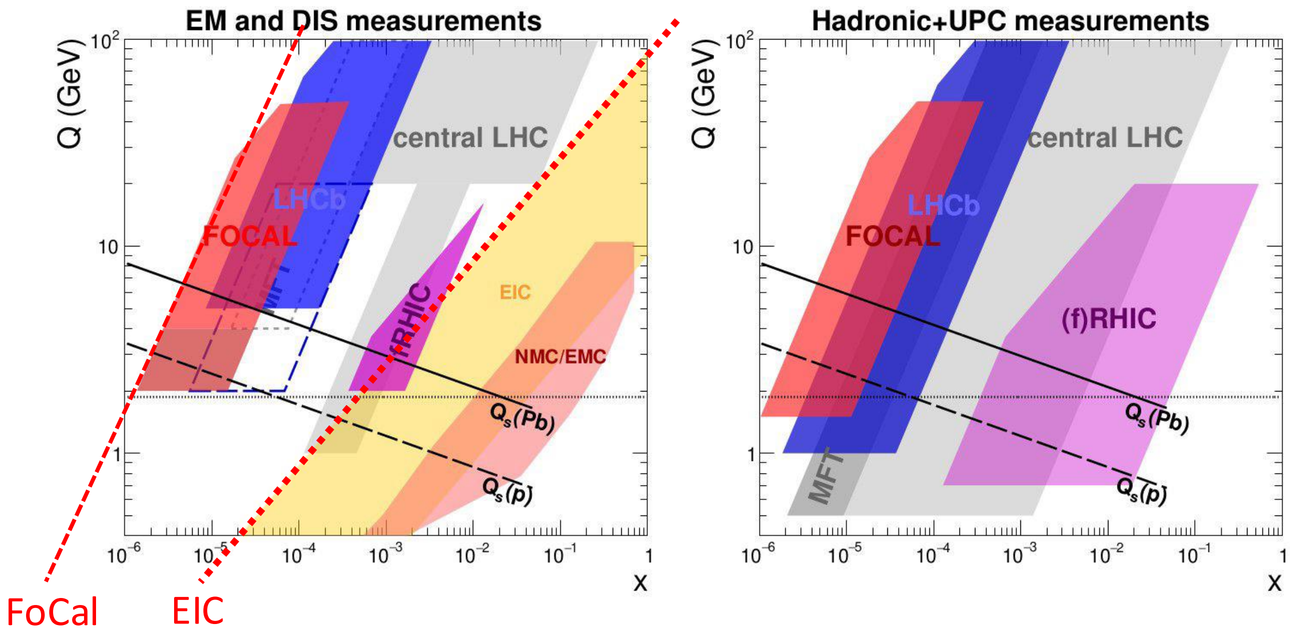
The FoCal detector at the ALICE experiment

$3.2 < y < 5.8$

with the potential
to discover the CGC

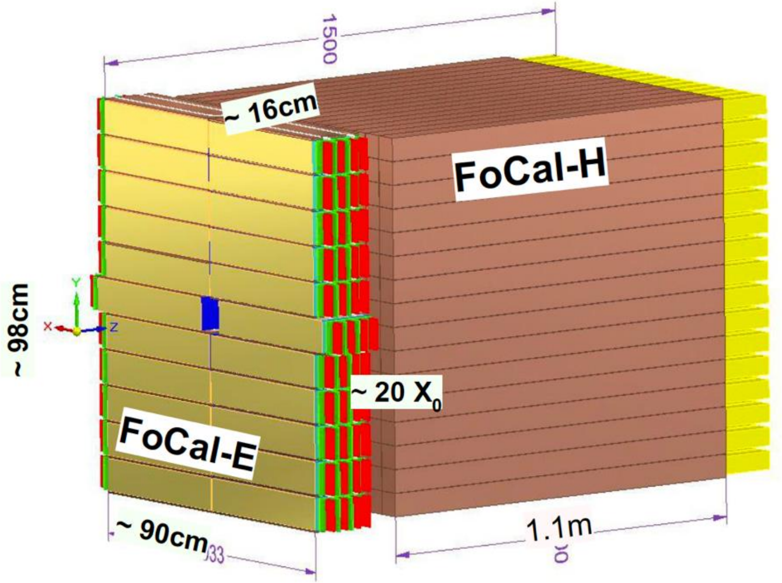


Kinematic reach of small-x measurements



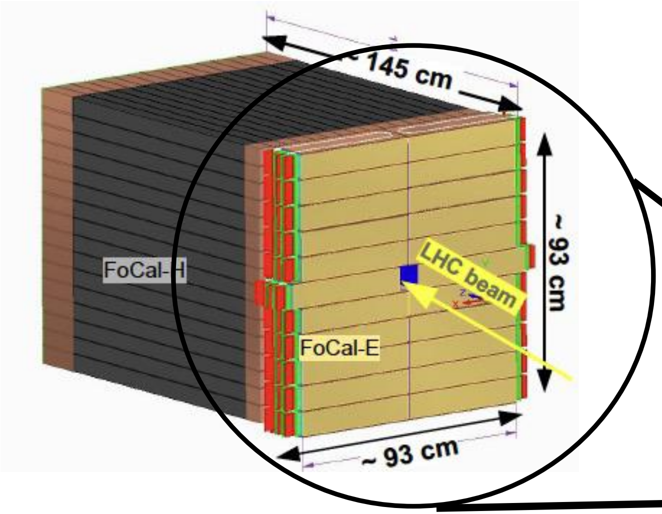
FoCal **extends the experimentally** accessible Q-x kinematic domain and complements current and future facilities, such as the EIC, enabling high-precision studies of the evolution of gluon saturation effects.

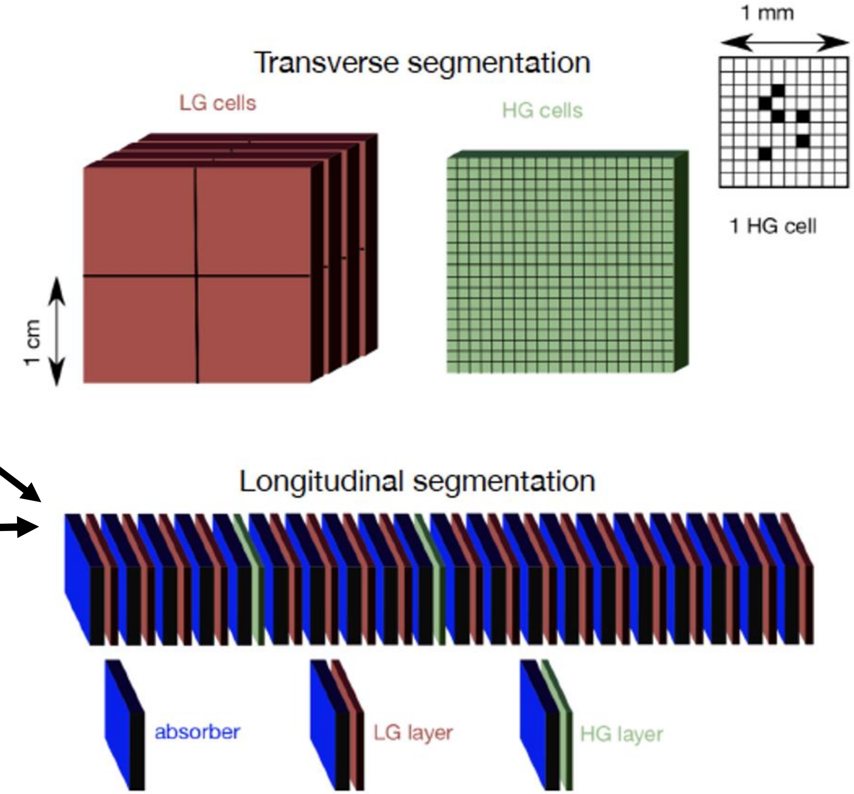
FoCal in perspective future measurements



- Study of saturation requires to study evolution of observables over large range in x at low Q^2
- Forward LHC: **significantly lower-x**
- **Testing QCD universality**: does saturation provide a coherent description of all observables, and is therefore a universal description of the high gluon density regime?

FoCal-E detector

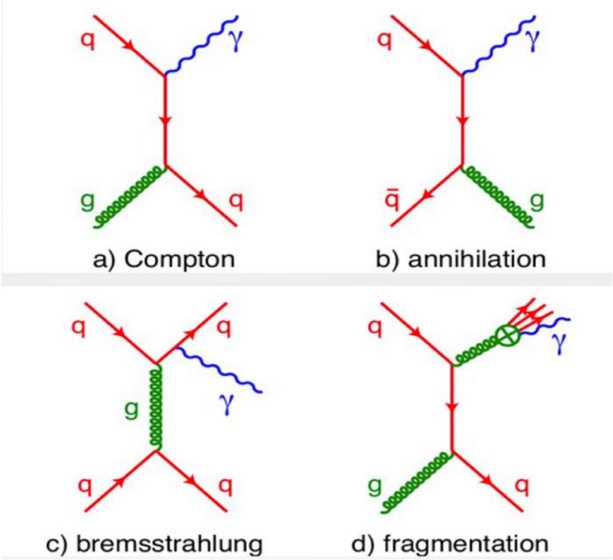


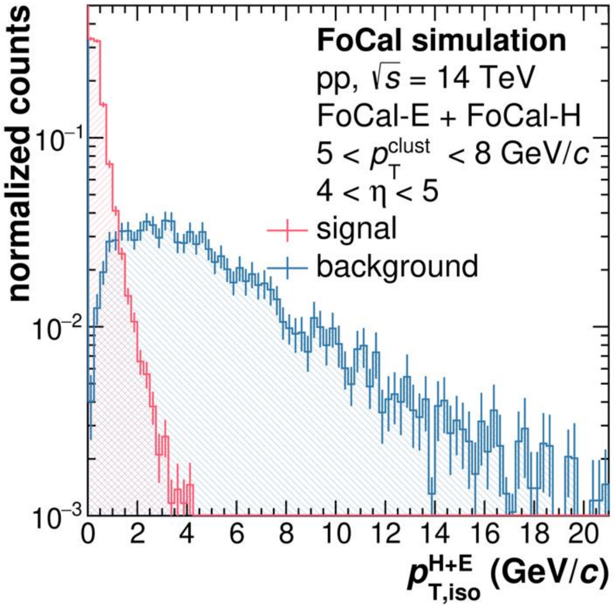


FoCal-E:

- W absorber: 20 layers ~ 20 X0
- Si sensor:
  18 low-granularity pad layers
  2 high-granularity pixel layers (30 x30 μm^2)

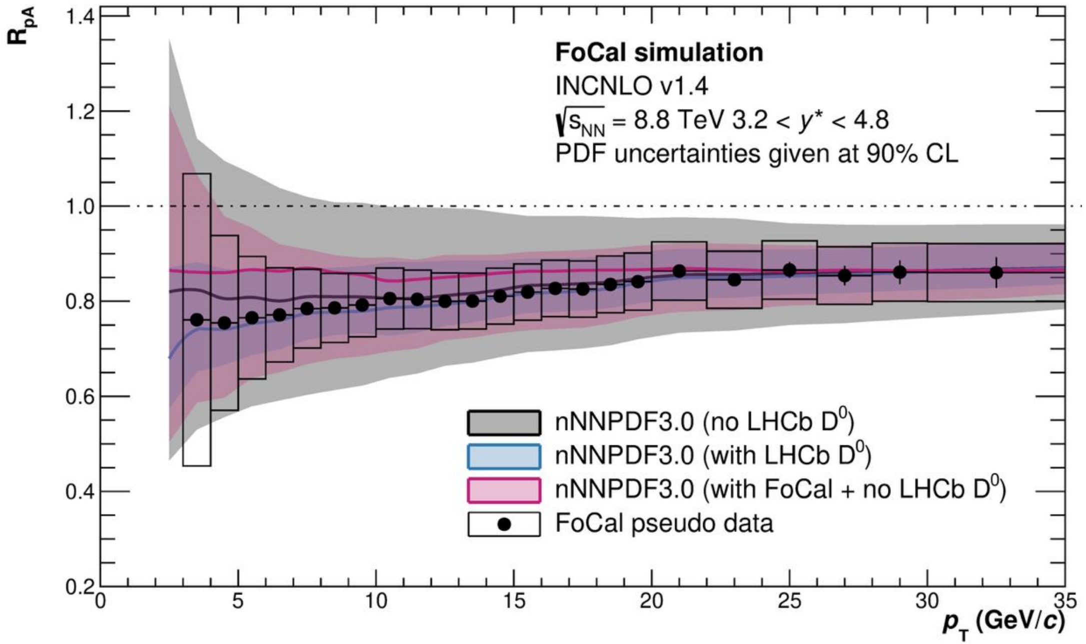
Prompt photons





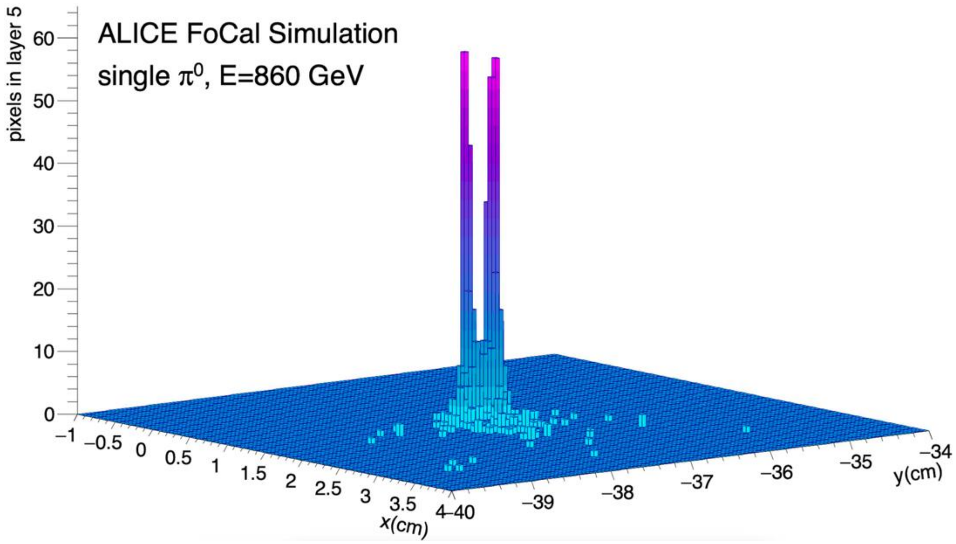
- Prompt photons: $qg \rightarrow \gamma q$, no final-state interaction → clean gluon probe
- Colourless and does not undergo strong final-state interactions, provides a relatively clean reference for the initial hard scattering

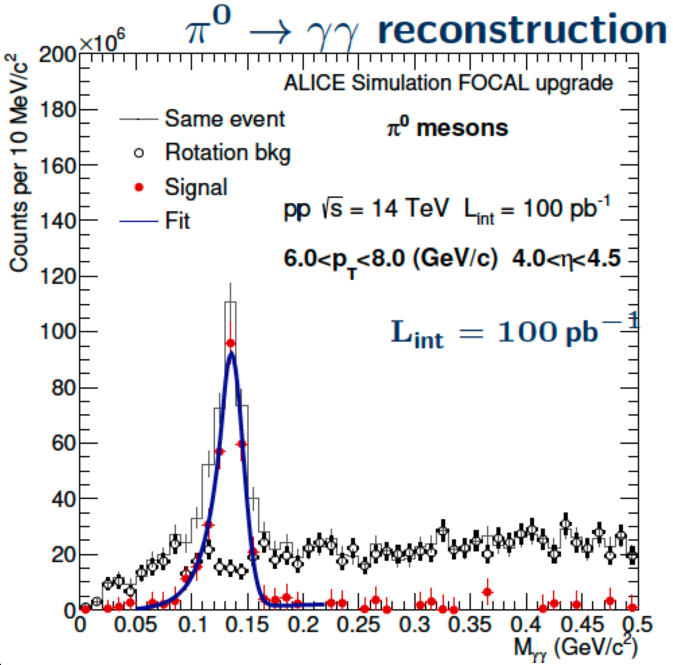
Prompt photons to constrain nPDF



- FoCal pseudo-data reduce nNNPDF3.0 uncertainties (≈ LHCb *D* mesons) , forward photons provide strong nPDF constraints
- Get rid of the final-state effect

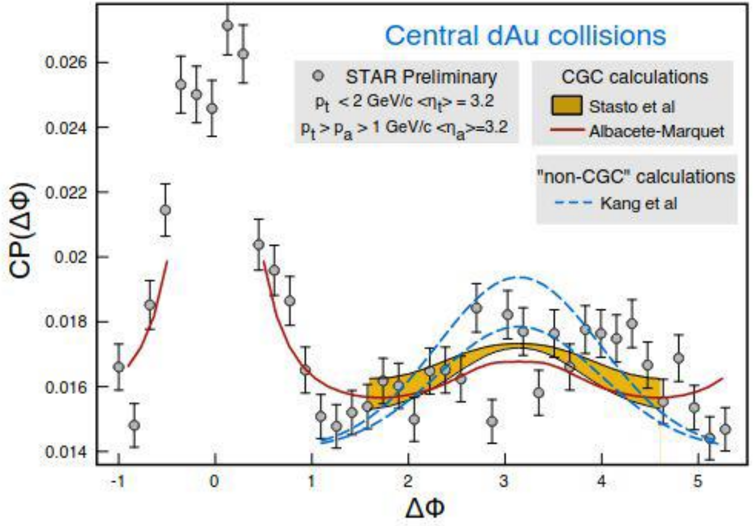
FoCal performance: π^0 and η mesons

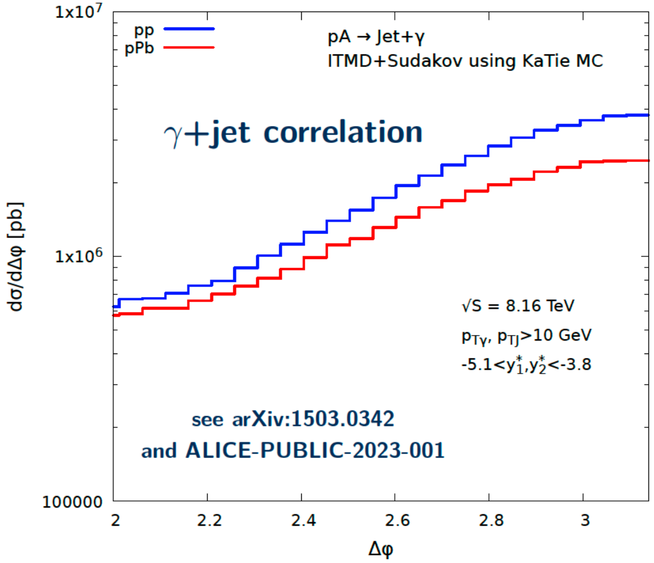




- GEANT simulations confirm FoCal capability for π^0, η, ω reconstruction
- Run 4 luminosity enables measurements up to ~ 2 TeV over wide rapidity range
- High granularity pixel layers achieve ~80% efficiency with <5 mm photon separation

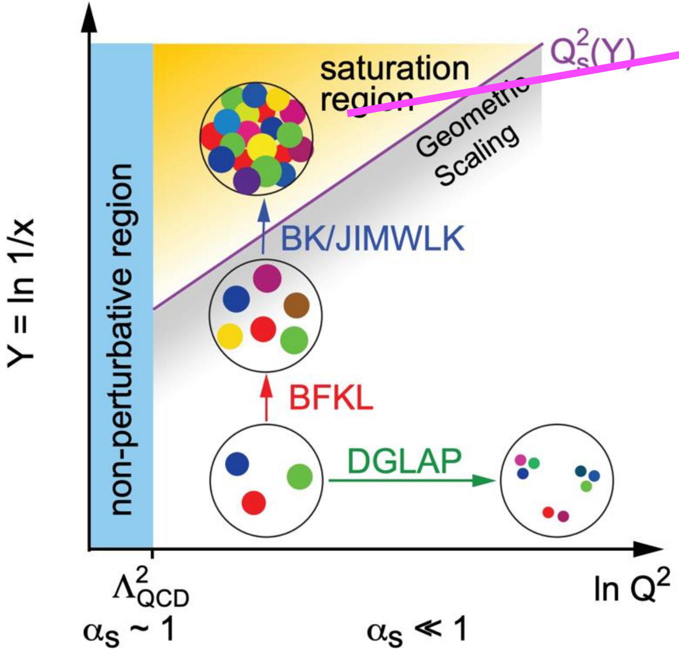
Measurement of isolated γ–hadron and γ–jet correlations

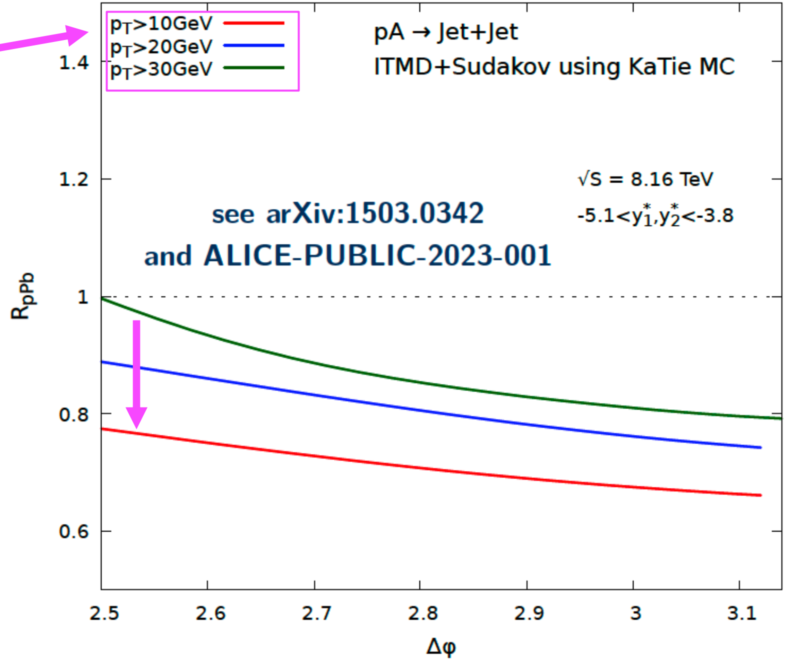




- ➢ Azimuthal correlation of the γ–jets, γ–hadron correlation can access to the low-x gluon dynamics
- ➢ Expectation of yield suppression and de-correlation due to saturation effects

Measurement of the jet at forward rapidity

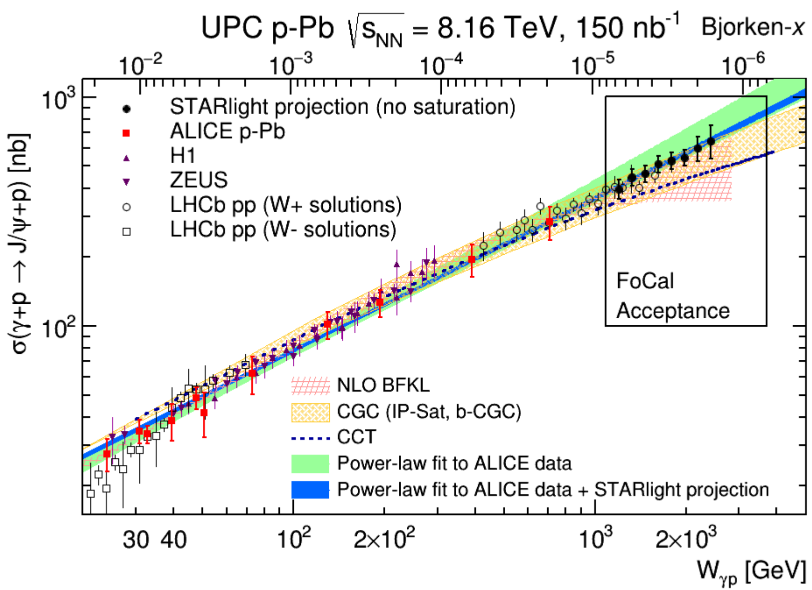




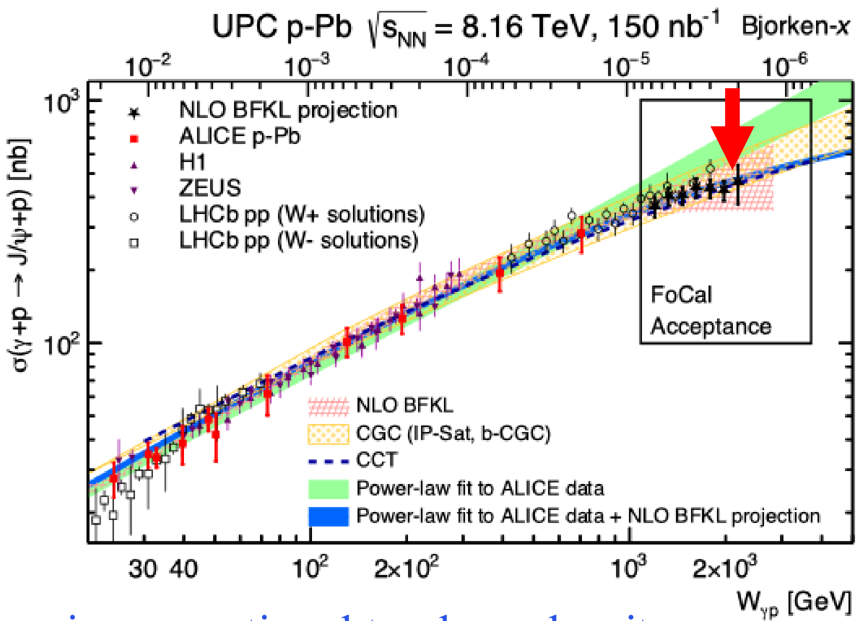
- Dijet azimuthal correlations and momentum imbalance **are sensitive to low-*x* gluon densities**.
- Yield suppression and decorrelation are expected due to **saturation effects.**

Vector meson photo-production in UPC

Without saturation



With saturation



- Photo-production cross section of vector mesons in proportional to gluon density
- Deviation from power-law growth of cross section with increasing Wp expected due to **saturation effects**

The timeline of ALICE FoCal

- ALICE Run 3 with the major detector upgrades and successful data taking from 2022 to 2026
- During LS3(2026-2028), the ITS will undergo further upgrades, while new FoCal detector will be installed and commissioned
- Run 4 data taking is expected from 2029 to 2032 (pp/pA/AA)

- **FoCal Physics**

  Probes the very small-$x \sim 10^{-6}$
- **Key Observables**
  - Prompt photons
  - π^0 and η mesons
  - Jets and γ–jet correlations
  - J/ψ and ψ(2S)
  - Particle correlations
  - **New observables**?

LHC LS2	LHC RUN 3	LHC LS3	LHC RUN 4	LHC LS4	LHC RUN 5 and RUN 6
2019-2021	2022-2026	2026-2028	2029-2032	2032-2034	2035-2041

Summary and outlook

- The **Color Glass Condensate (CGC)** is a novel state of high-density gluonic matter expected at very small Bjorken-x.
- Existing measurements provide indications of **gluon saturation**, but not yet experimental confirmed.
- **ALICE FoCal** will significantly extend the small-x (10^{-6}) reach and has the potential to reveal nonlinear QCD evolution, gluon saturation, and possible signatures of the CGC

Thanks