Probing Dense Gluon Matter in Ultra-Peripheral Collisions at the LHC and Insights for the EIC

Wei Li
Rice University

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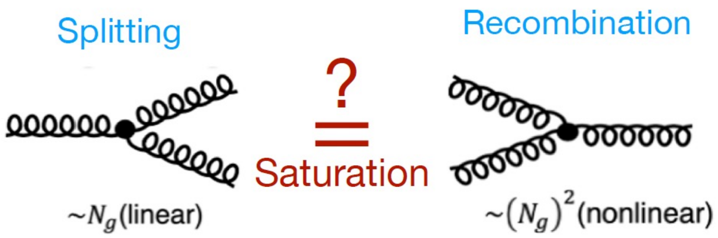
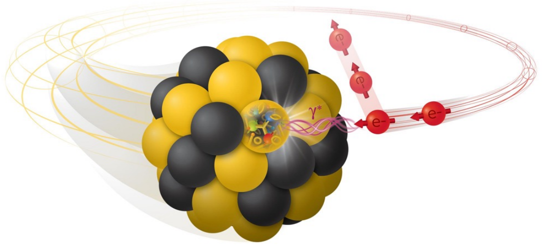
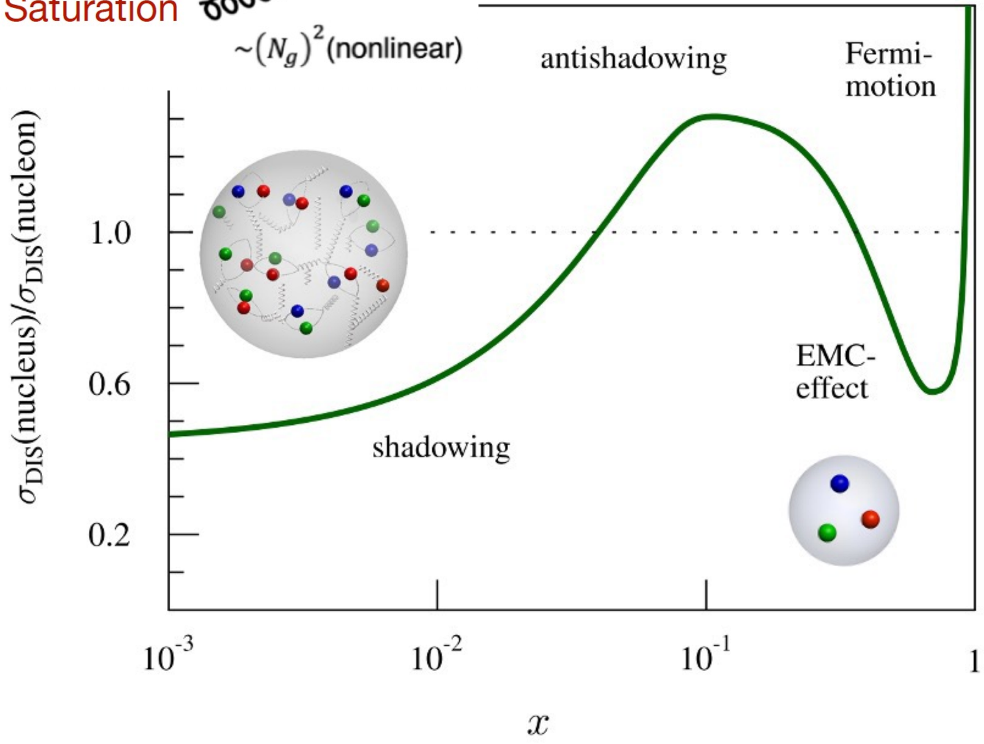
U.S. DEPARTMENT OF ENERGY
Office of Science

Big picture

Onset of nonlinear QCD?

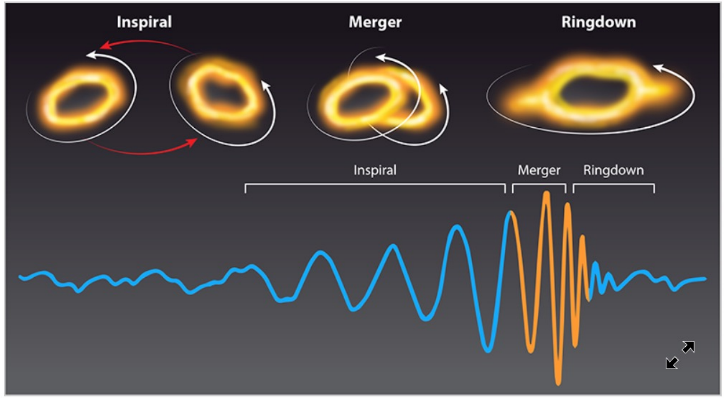






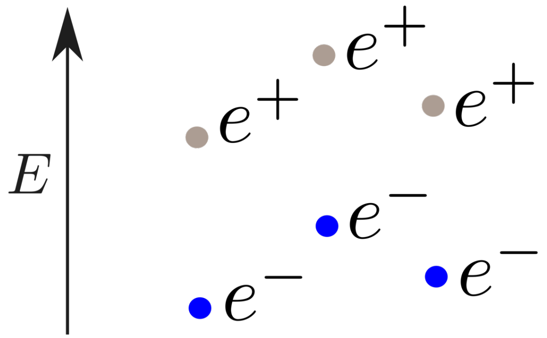
Probing the emergent properties of the strong force in the ultra-dense limit at small x

Nonlinear gravity



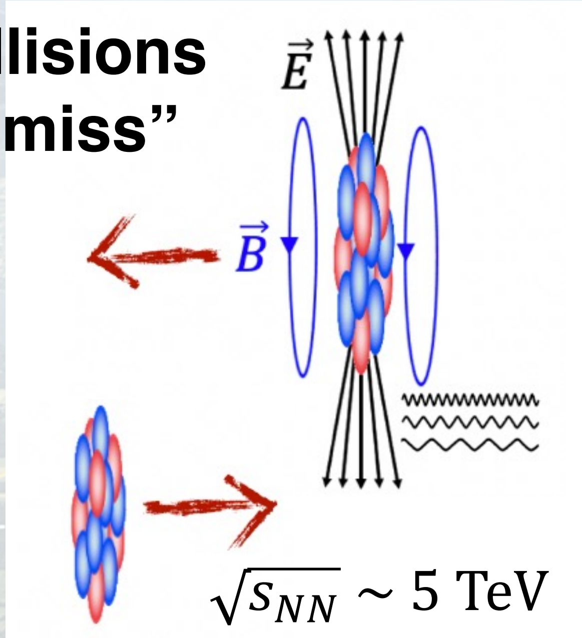
(Top) Kip Thorne; (Bottom) B. P. Abbott *et al.* [8]; adapted by APS/Carin Cain

Nonlinear QED



The LHC as a high-energy photon-ion collider

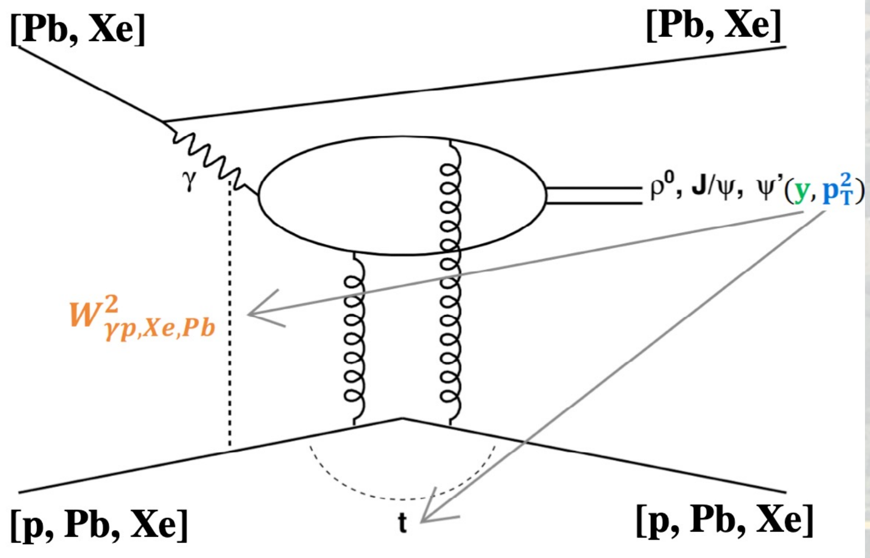
Ultraperipheral collisions (UPCs): two ions "miss"



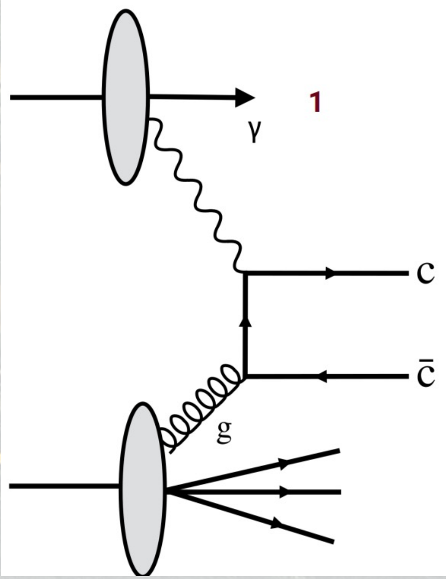
Equivalent Photon Approximation (EPA):

- Photon flux ∝ Z^2
- Quasi-real: $Q^2 \sim 0$, p_T ($\sim\hbar c/R_A$) < 30 MeV
- E_γ^{max} ($\sim\gamma\hbar c/R_A$) ~ 80 GeV

Exclusive:

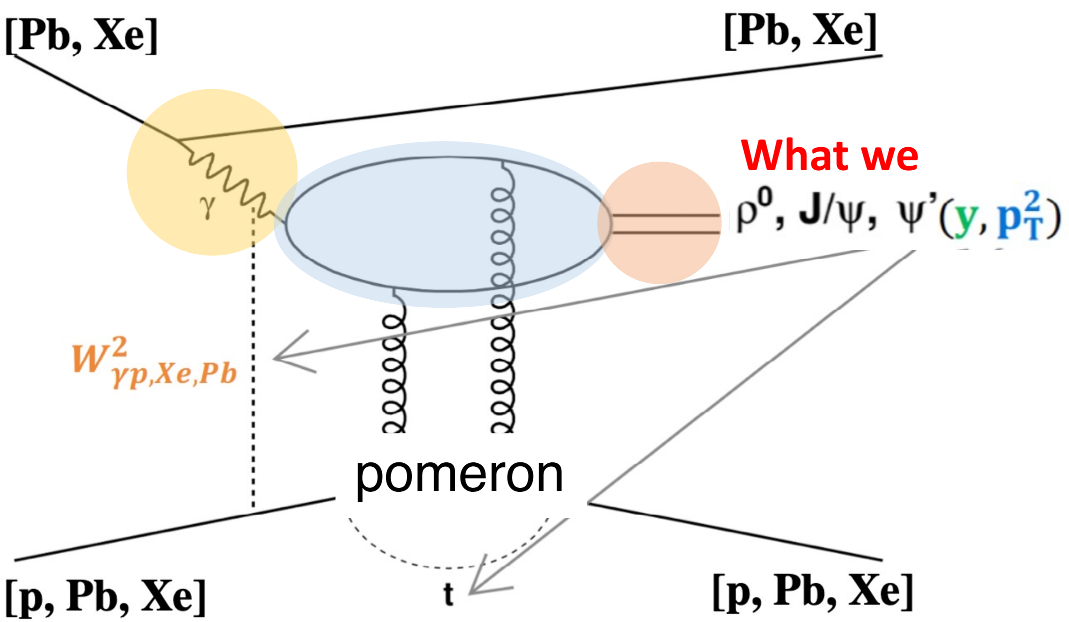


(Semi)-inclusive:



Exclusive vector meson as a probe of the nucleus

Dipole picture



$\sigma \propto \left(xg(x,Q^2)\right)^2$ **at LO pQCD**

- Well-defined kinematics:

$$(\mathrm{y}, p_T^2) \rightarrow (W_{\gamma p}^2, \mathrm{t})$$

$$W^2 = M_{VM}\sqrt{s_{NN}} \cdot e^{\pm y} \qquad x = \frac{M_{VM}}{\sqrt{s_{\mathrm{NN}}}} e^{\mp y}$$

- Low $Q^2 \sim 0$ but heavy quark mass can provide a hard scale for pQCD.

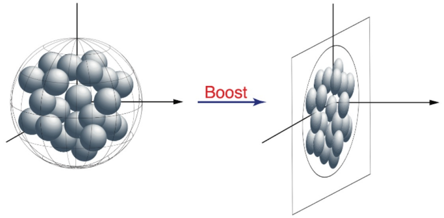
$$Q^2 \sim \frac{Q_0^2 + (m_{VM})^2}{4}, \quad \text{Dipole size: } r_D^2 \sim 1/Q^2$$

- |t|-dist. probes spatial structure (GPDs)

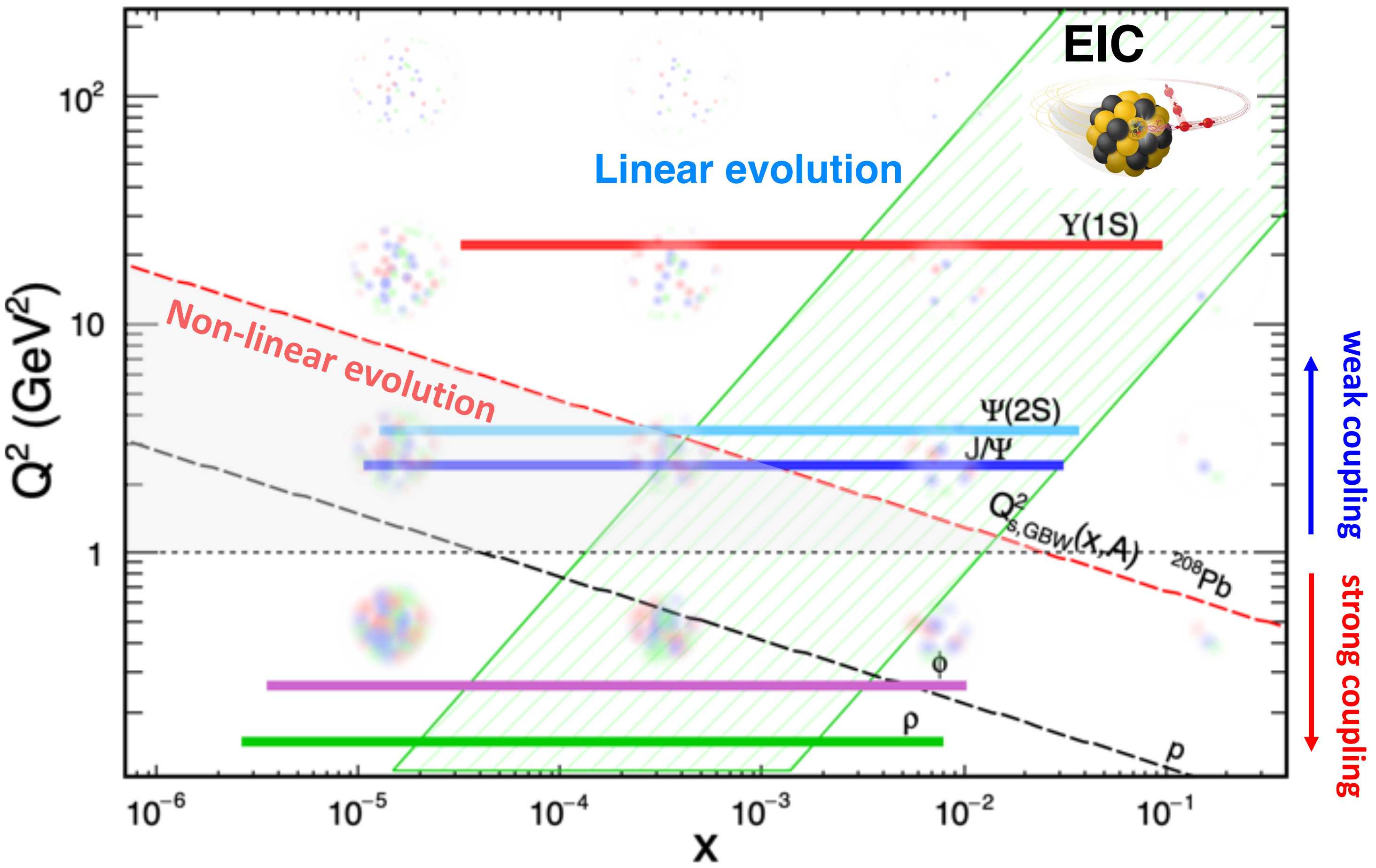
	Gluon field probed	Nucleus target	p_T
Coherent	Average	Ground state	50 MeV
Incoherent	Fluctuations	Excited, often break up	500 MeV

The LHC as a high-energy photon-ion collider

$Q_s^2(A) \sim A^{1/3} Q_s^2(p)$



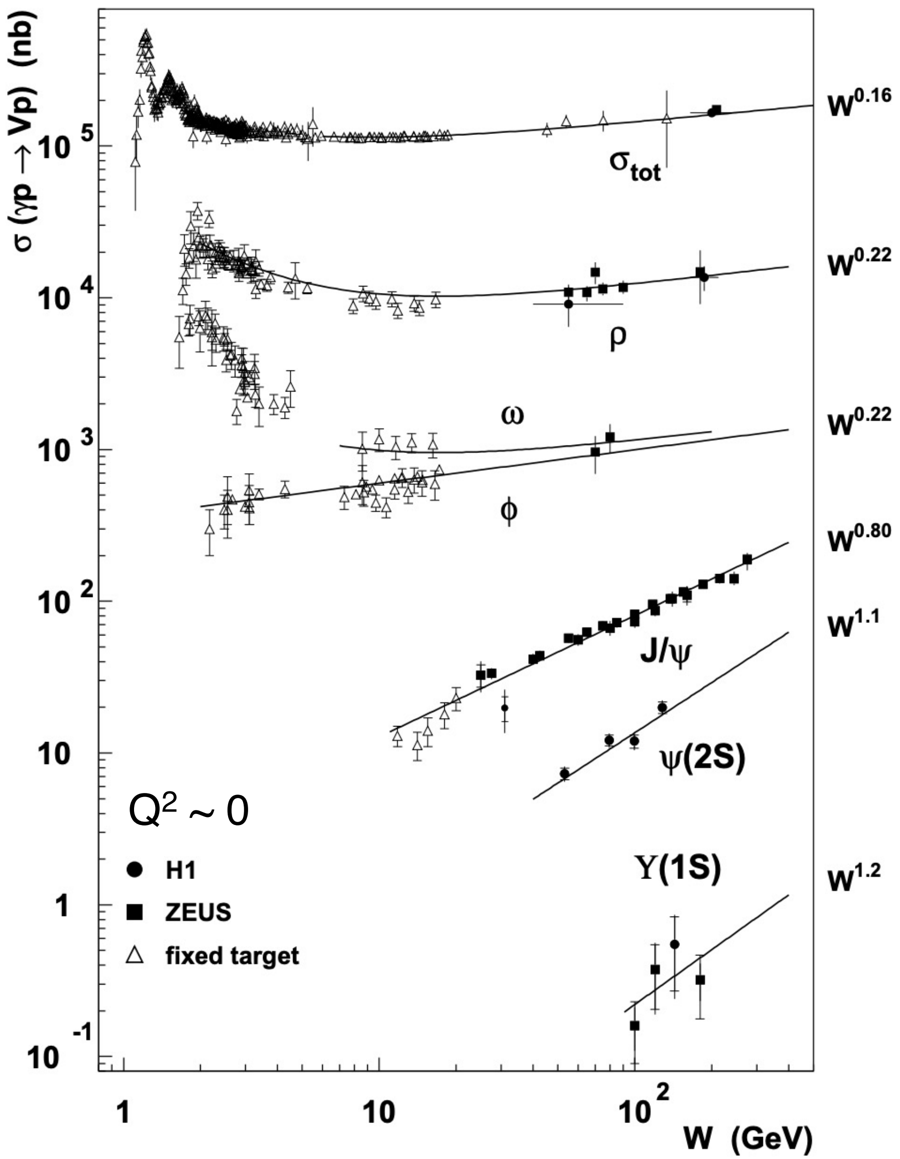
LHC UPC-VM ($|y_{VM}|<4$, $Q^2=\{m_{VM}/2\}^2$)



LHC – smaller x coverage ⟺ EIC – fully tunable Q^2

Exclusive VM production in γp at HERA

Rev. Mod. Phys. 86 (2014) 1037

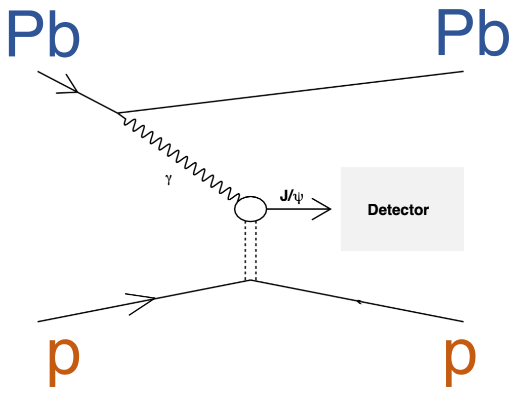


Universality and scaling – power-law growth with W or 1/x

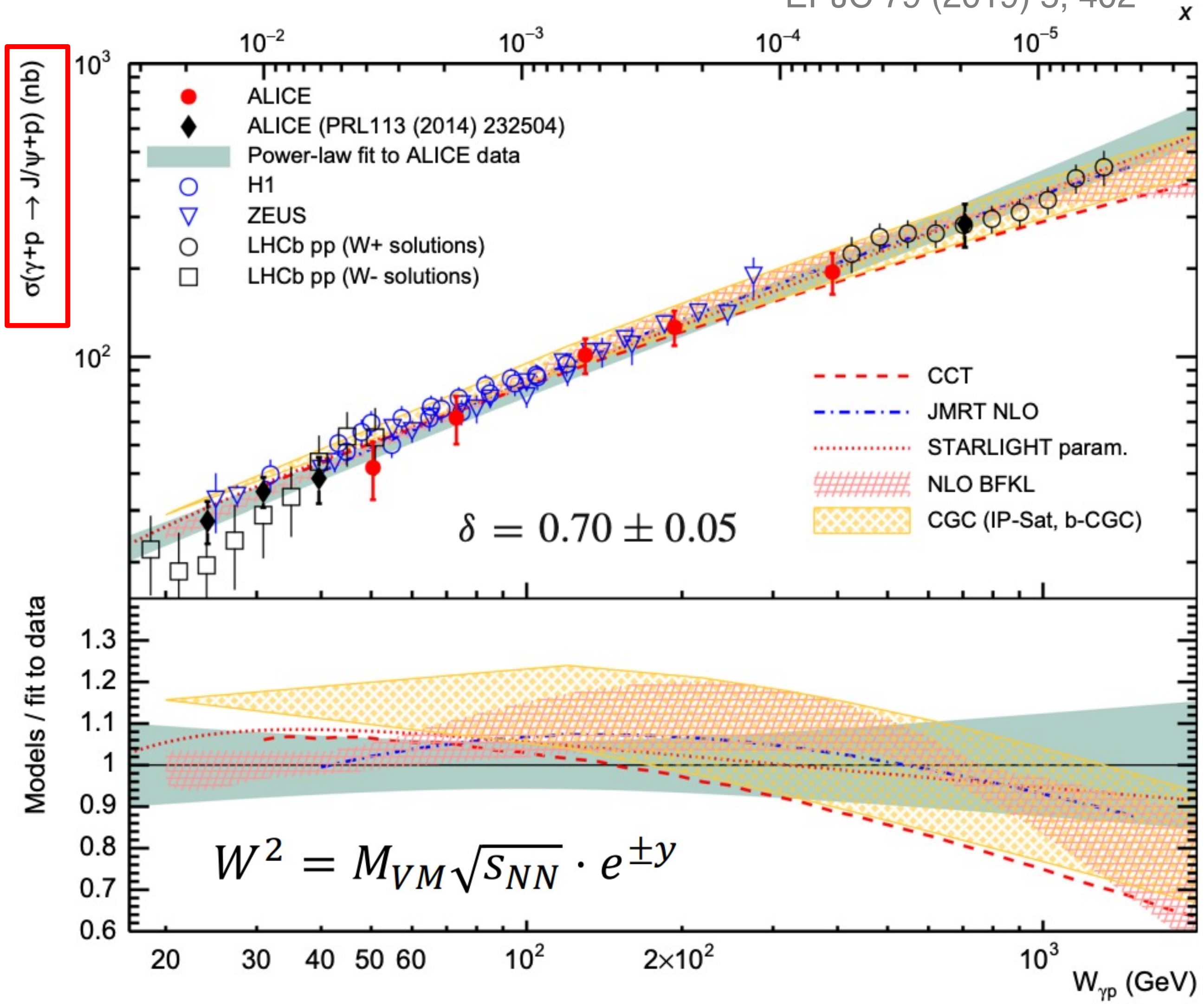
VM mass as a scale of probing the soft to hard QCD transition

- Heavy VM more sensitive to gluons at small x

Exclusive J/ψ in γp at the LHC



EPJC 79 (2019) 5, 402

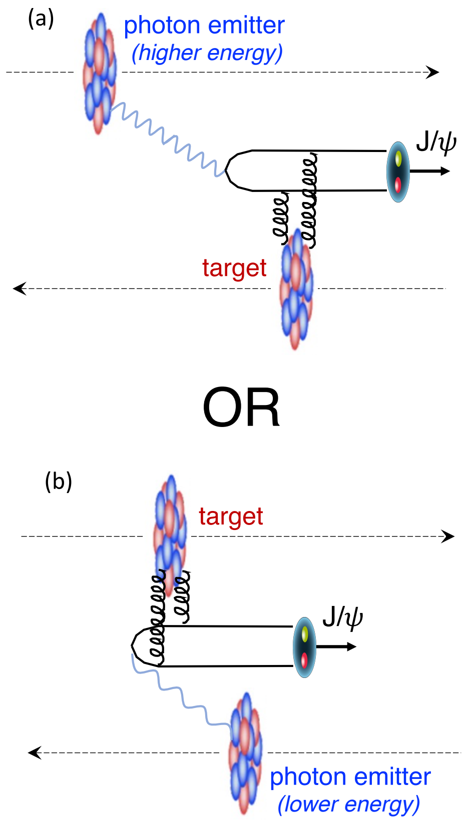


$\boldsymbol{\sigma}(W_{\gamma p})$ follows a universal power-law rise from HERA to the LHC.

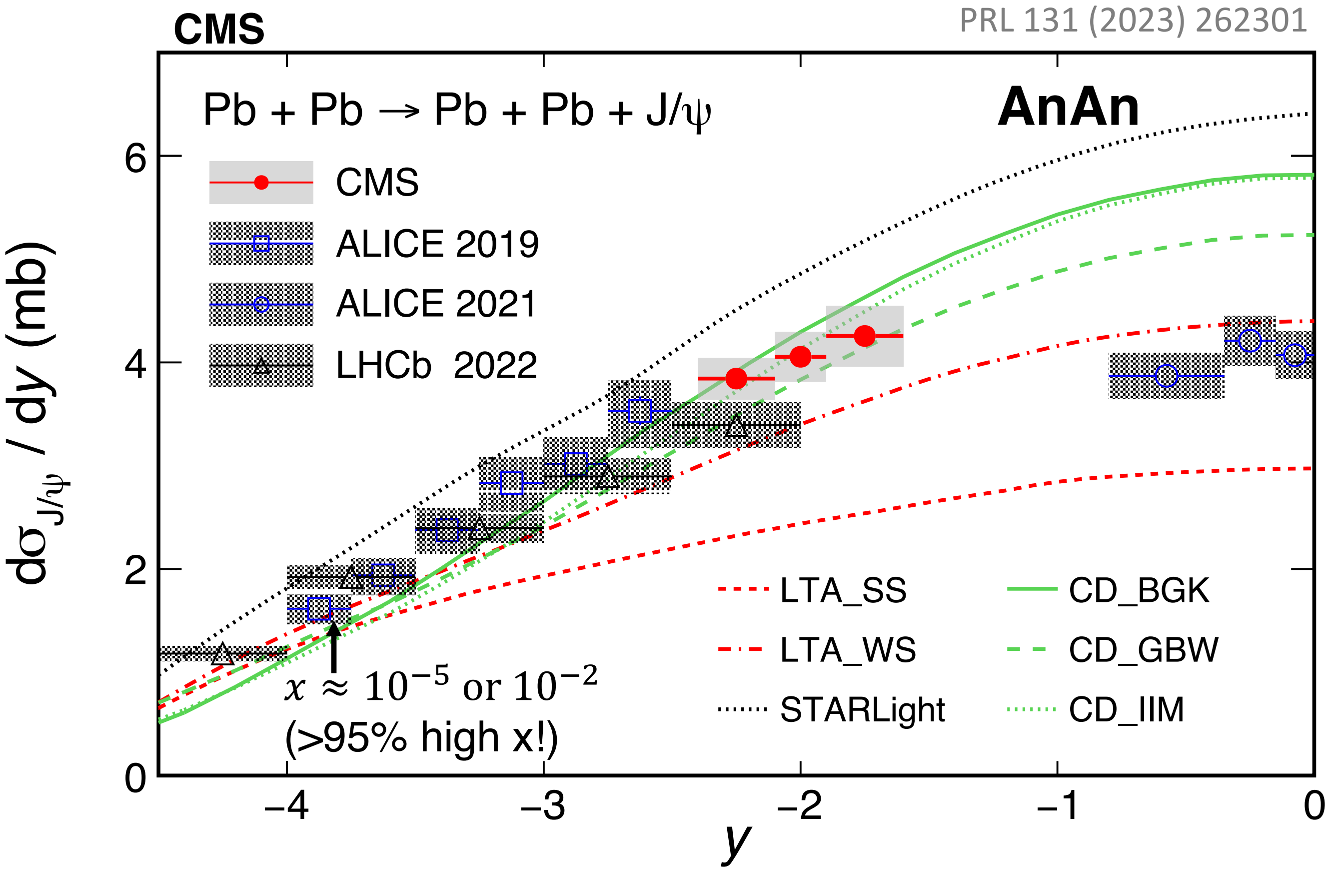
No clear signs of gluon saturation inside a proton to x ~ 10^{-5}!

Exclusive coherent J/ψ in γA

"Two-way ambiguity"



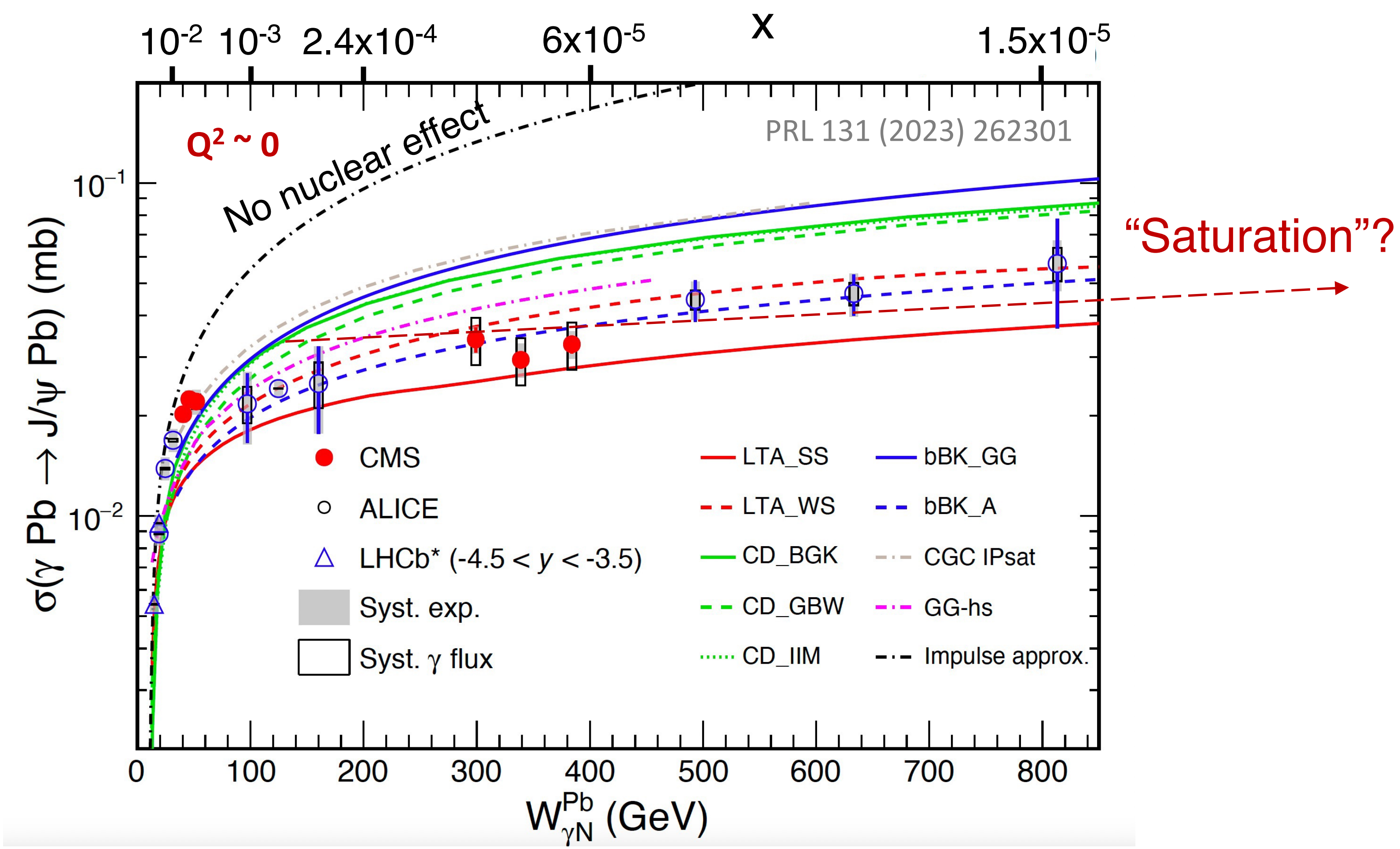
Overcome by IP-dependent study via EMDs



$$\frac{d\sigma_{AA\to AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'}(\omega_1) + N_{\gamma/A}(\omega_2)\cdot\sigma_{\gamma A\to J/\psi A'}(\omega_2)$$

Not sensitive to very small x region

First W dependence of coherent J/ψ in γA

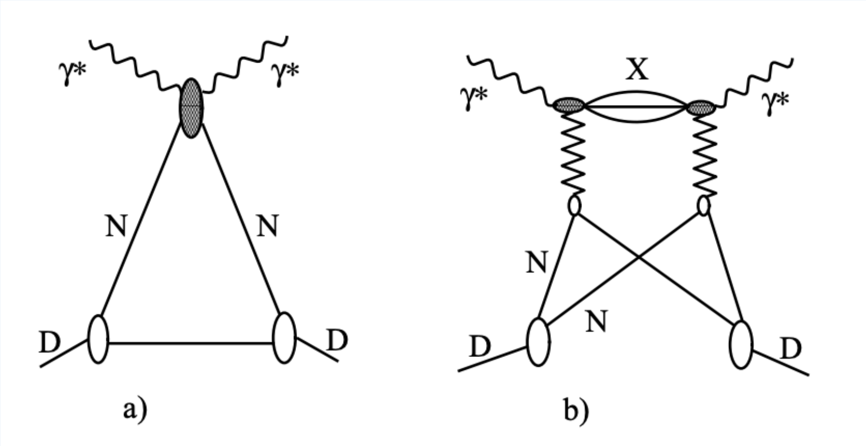


Clear nuclear suppression and indication of xsec saturation at high W!

No theory quantitatively capture the trend: no more power law!

Nuclear Shadowing vs Gluon Saturation

Leading-twist approximation (LTA)

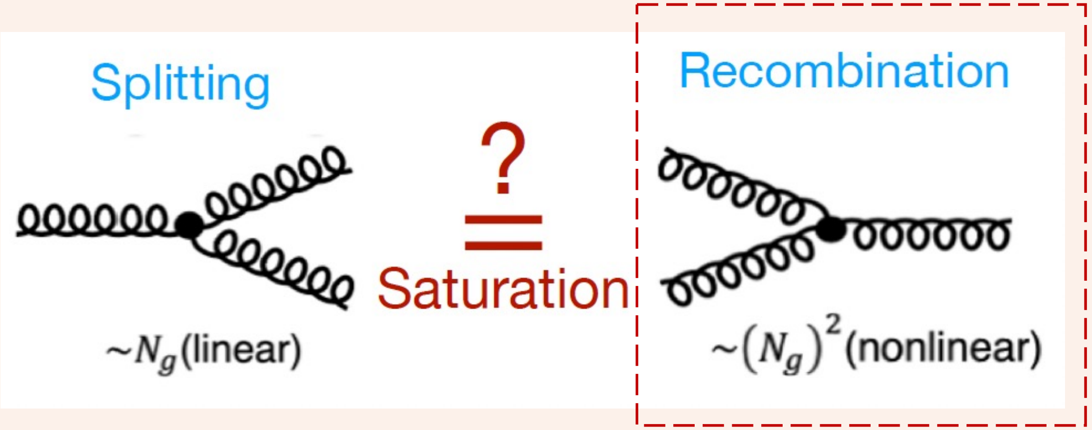


L. Frankfrut,, V. Guzey, M. Strikman (Physics Reports 512 (2012) 255)

Gribov-Glauber + Collinear factorization (DGLAP)

Multi-nucleon interference – absent in γp

Gluon saturation (all-twist inclusive)



Color glass condensate (CGC)

Non-linear evolution (BK, JIMWLK) + sat. scale Q_s

Multi-gluon interference – also occur in γp; valid and dominant at small x

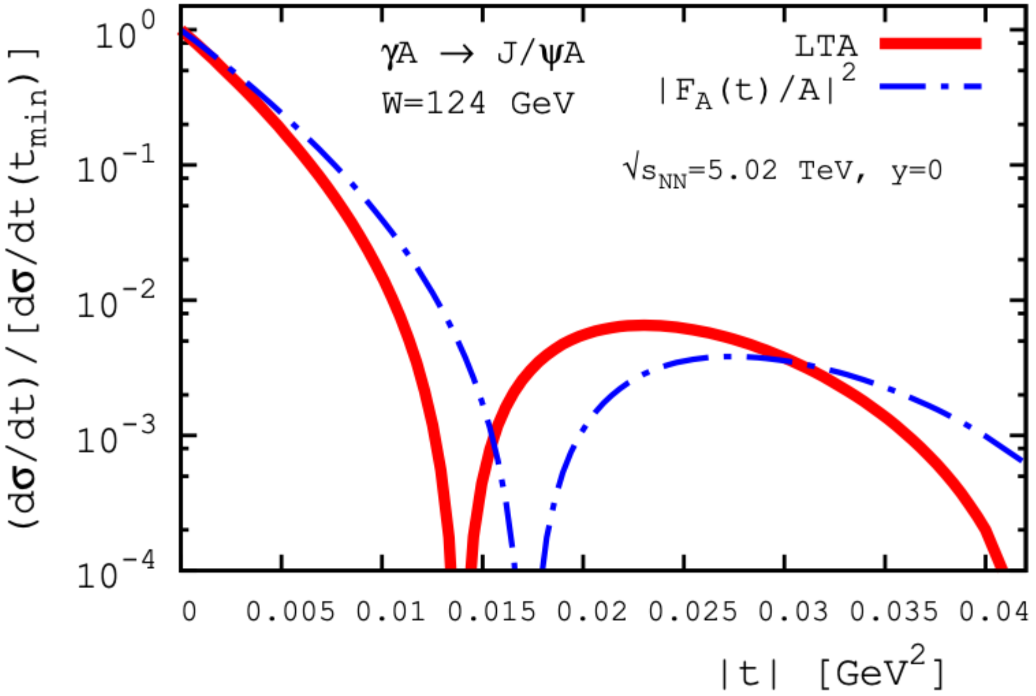
Both are formulated within the perturbative (weakly coupled) framework **and have dependence on model parameters**

Nuclear Shadowing vs Gluon Saturation

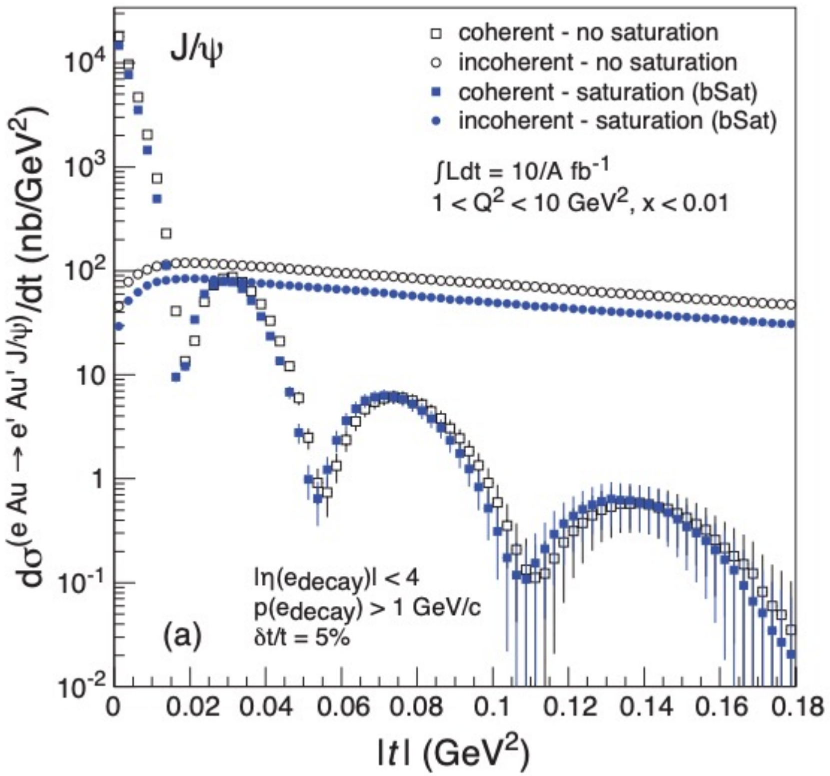
Leading-twist approximation (LTA)

Gluon saturation (all-twist inclusive)

PRC 95, 025204 (2017)



PRC 87 (2013) 2, 024913

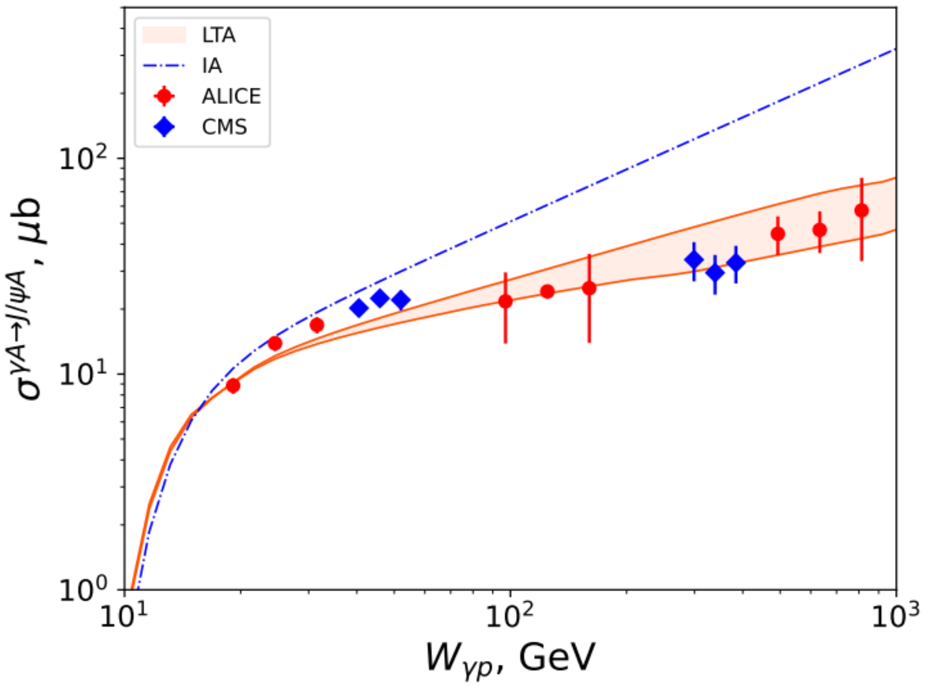


They often predict qualitatively the same nuclear modification effects

Latest attempts to fit the data

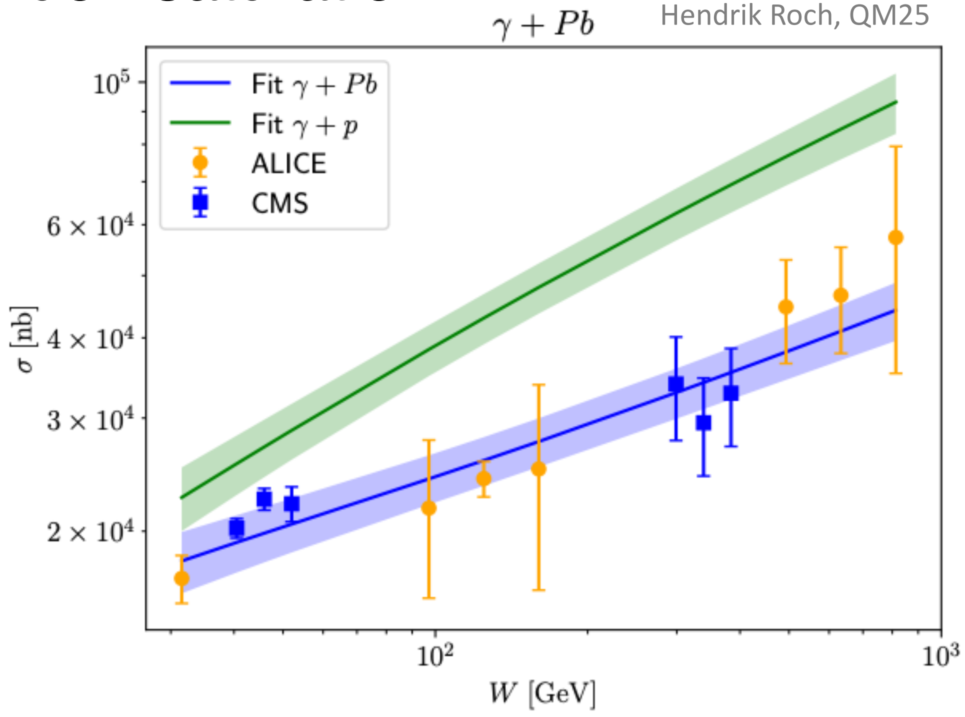
LTA shadowing

Guzey, Strikman, arXiv:2404.17476



Gluon saturation

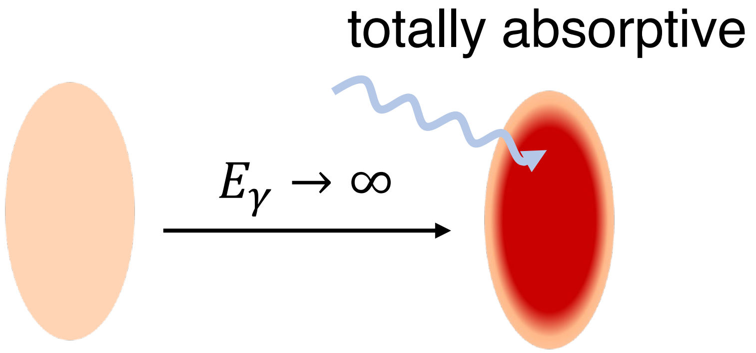
Hendrik Roch, QM25



- Both can find a parameter space to fit the data
- Theoretical uncertainties derived

Important to test its predicative power for future measurements

Black disk limit (BDL)

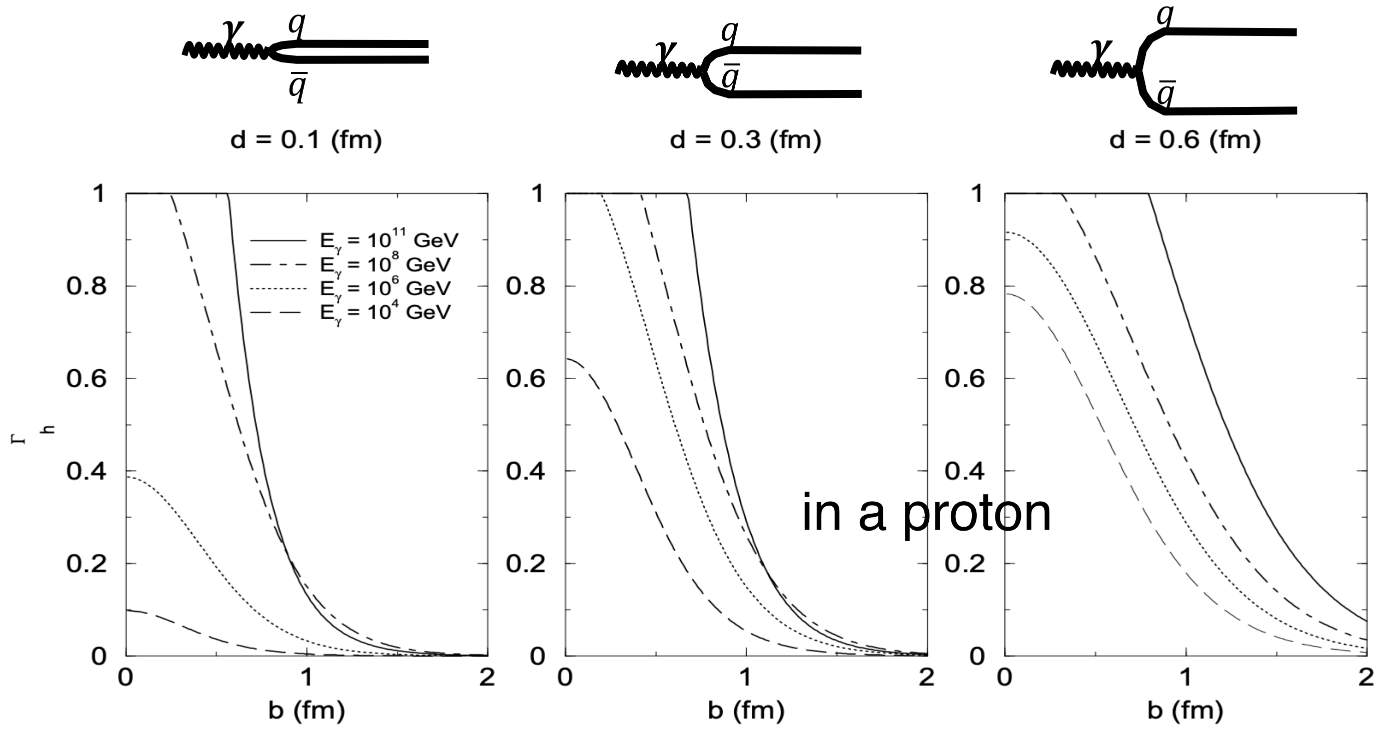


$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

– "Black Disk Limit (BDL)"

$\sigma_{coh} \to$ const.

$\sigma_{incoh} \to 0$



T.C. Rogers M.I. Strikman, arXiv:hep-ph/0512311

Physics Reports 512 (2012) 255

Weakly coupled: moderate r ~ $1/Q_s$, nonlinear but perturbative

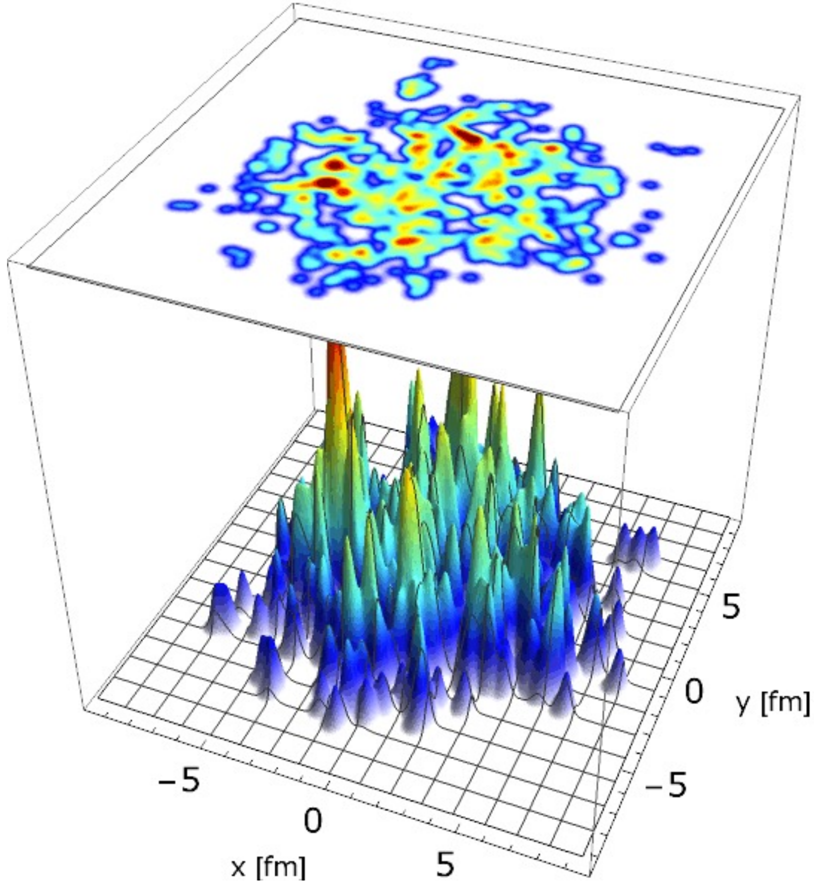
Strongly coupled: large r >> $1/Q_s$, nonperturbative absorption

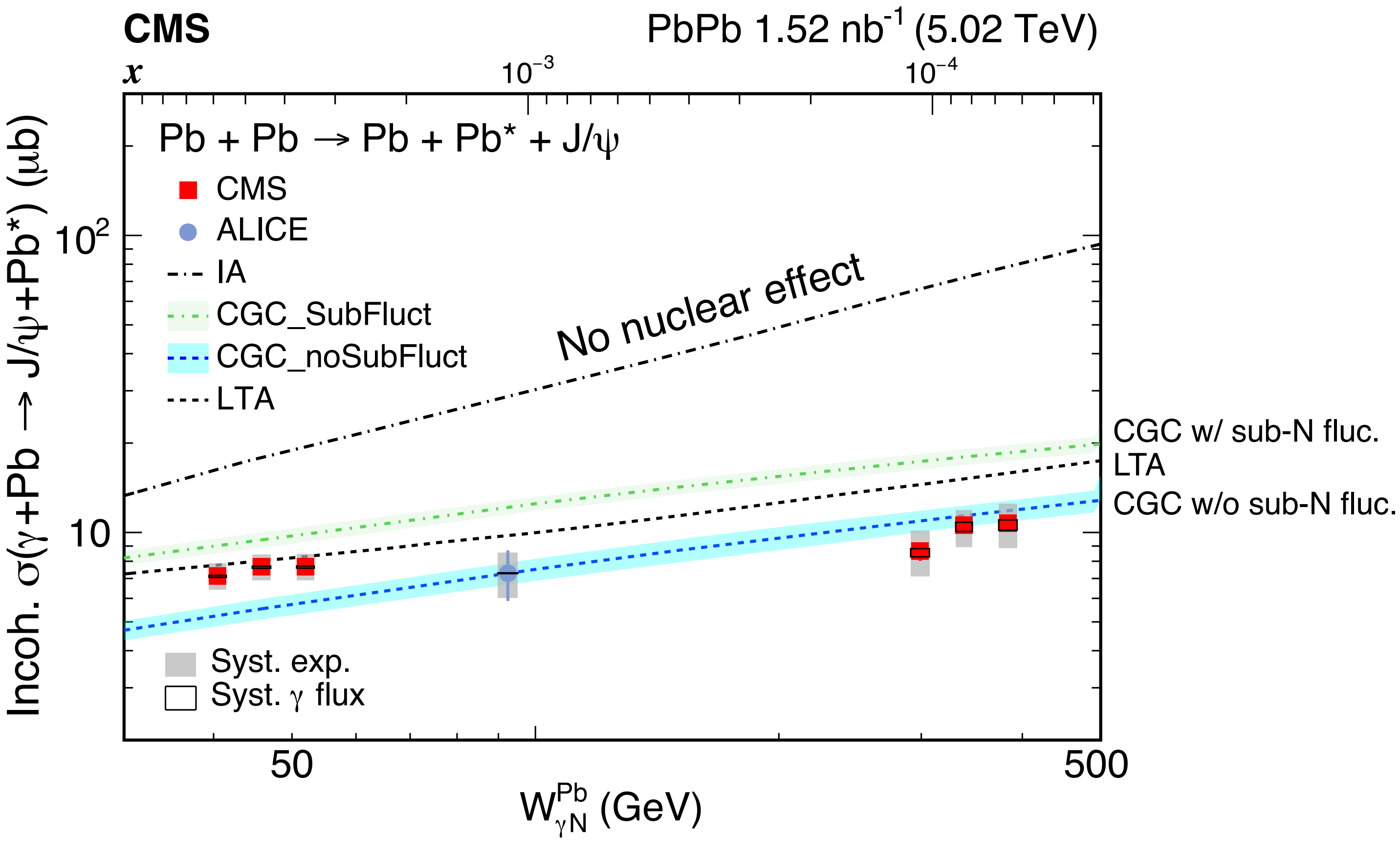
→ **BDL**

– New theoretical tools needed!

First W dependence of incoherent J/ψ in γA

Probe gluon field fluctuations



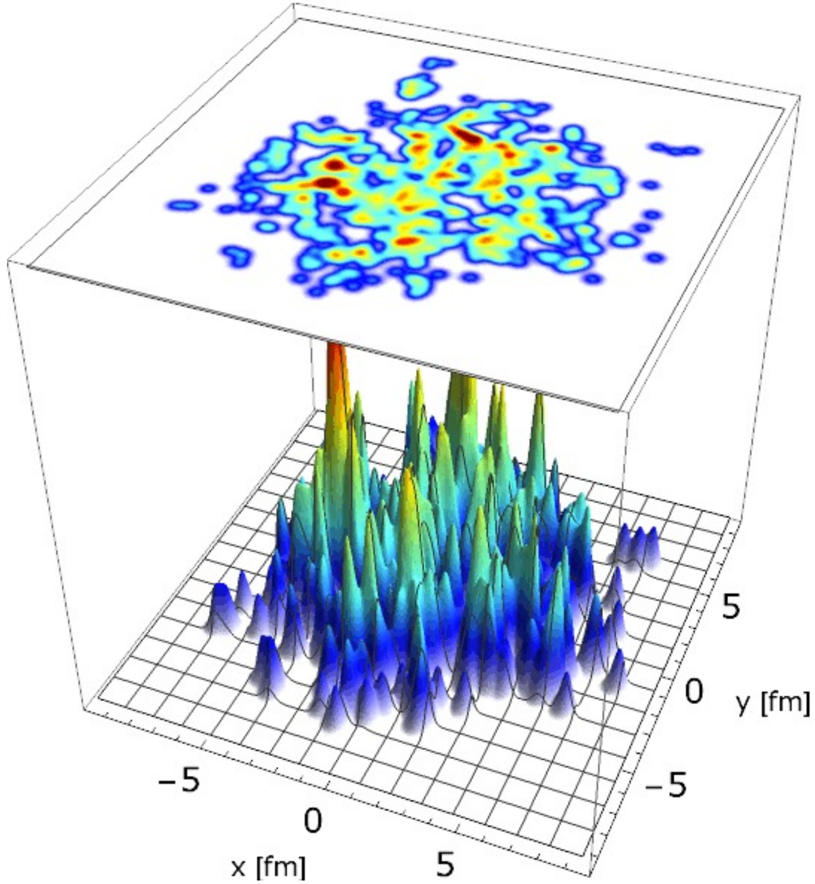


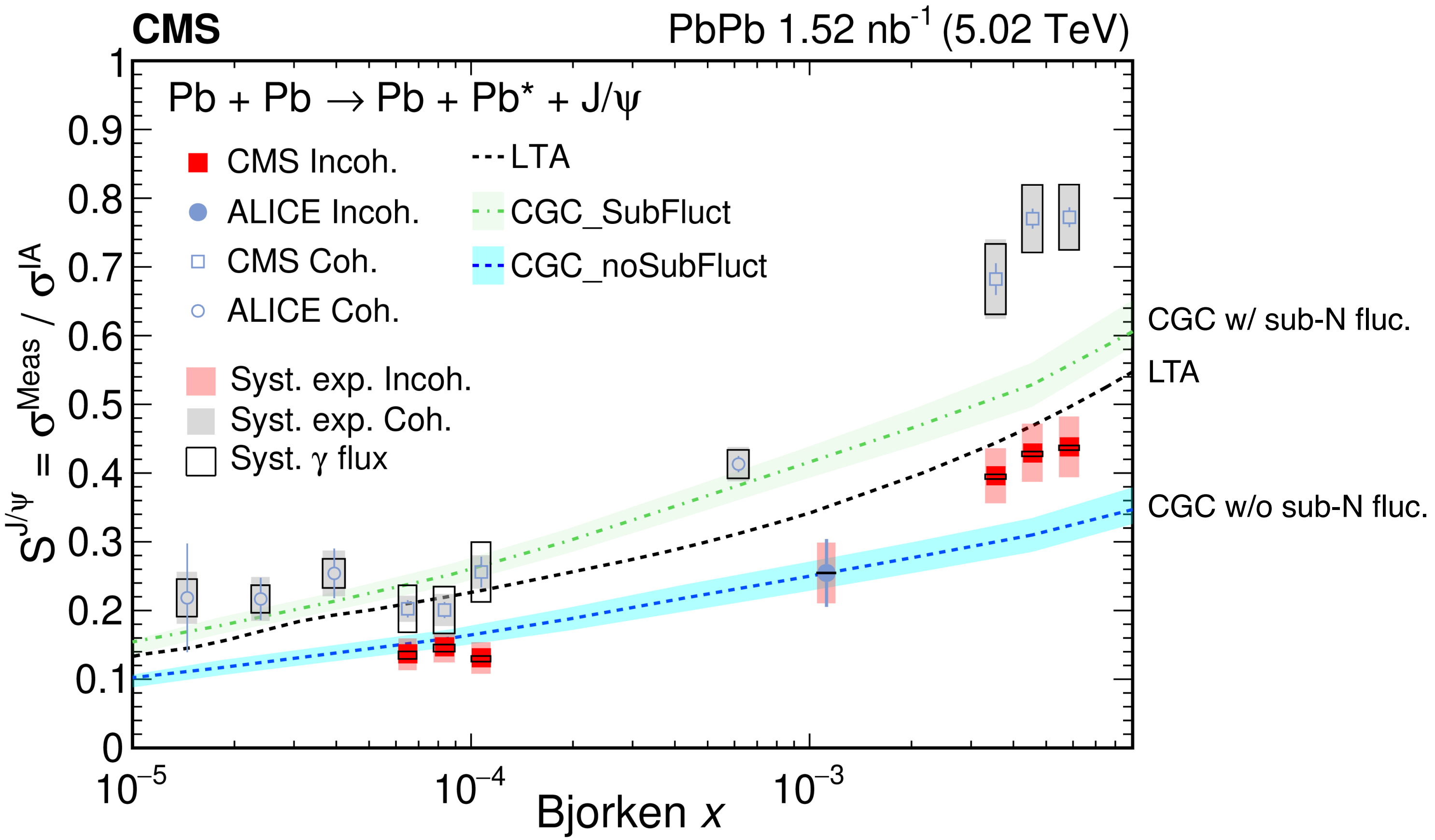
Stronger W-dep. suppression than model predicts

Far from the full BDL (otherwise, incoh. disappears)

First W dependence of incoherent J/ψ in γA

Probe gluon field fluctuations





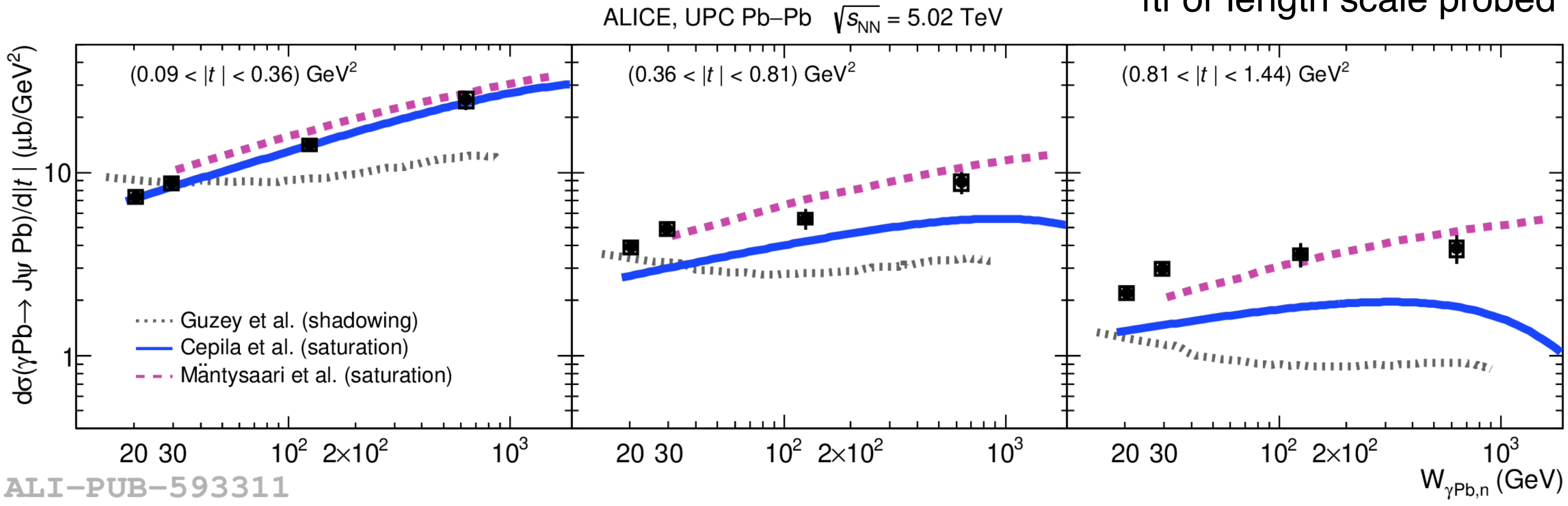
Stronger nuclear suppression for incoh. than coh.

S ~ 0.1 for x < 10^{-4}

First W dependence of incoherent J/ψ in γA

Nucleonic → *Partonic*

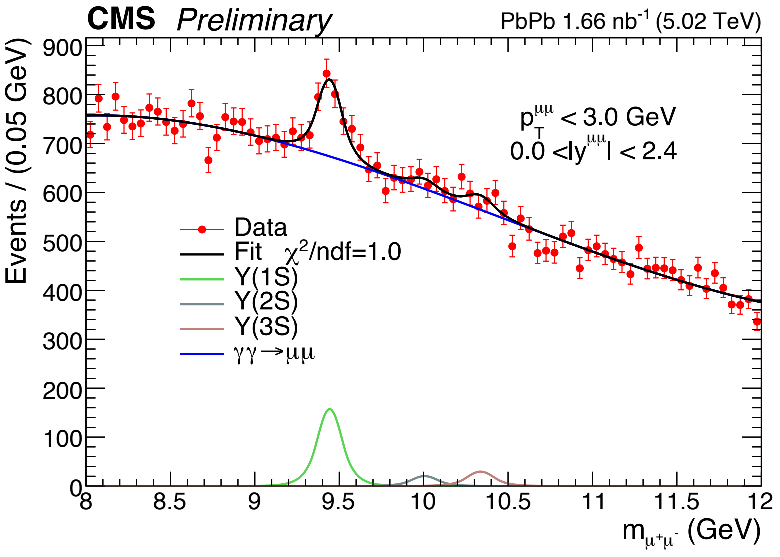
|t| or length scale probed



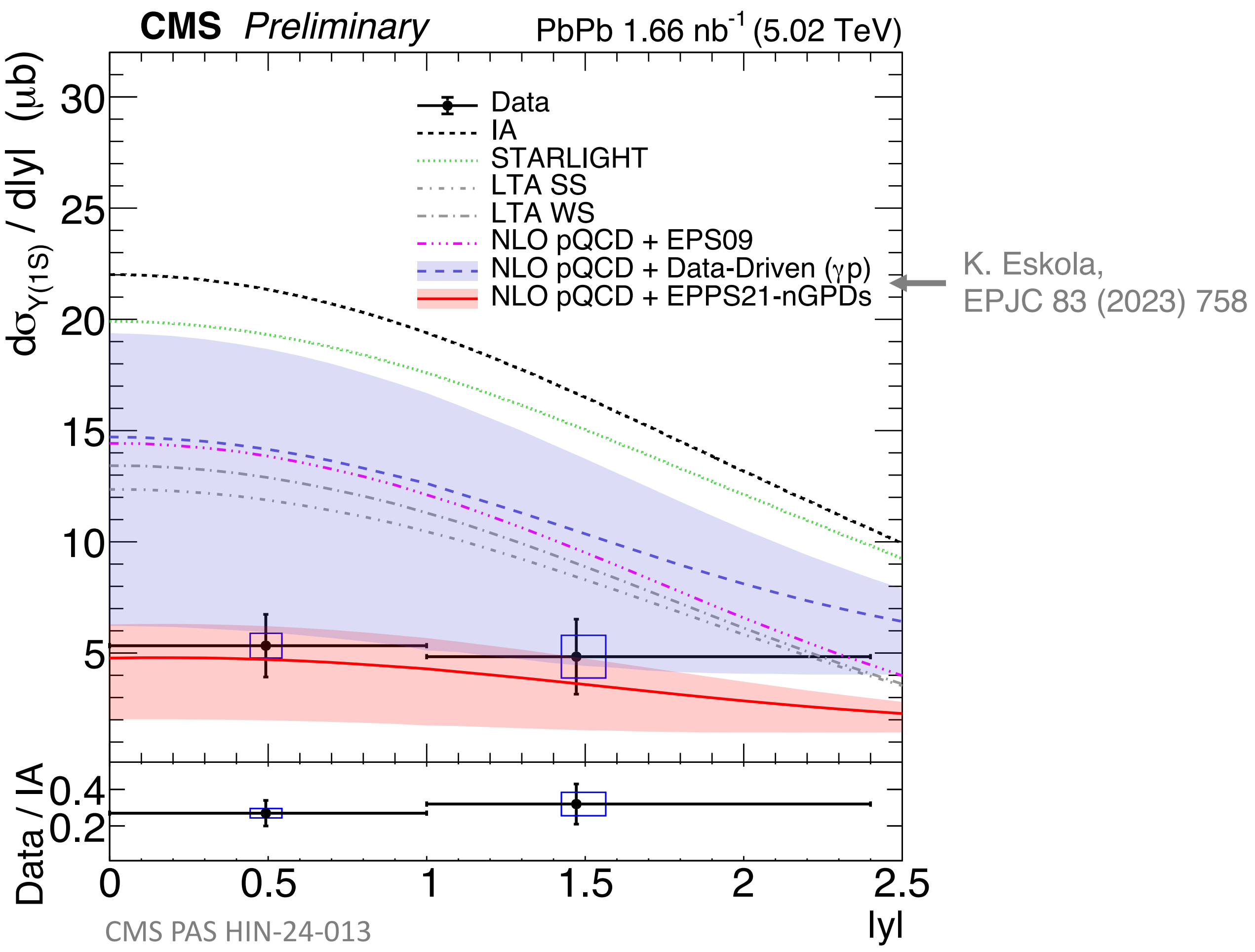
Flattening in W for larger |t| → stronger suppression of small-scale fluctuations

Zooming into harder scale – ϒ(nS)

Safely in the linear regime
($Q^2 \sim 20\ GeV^2$)



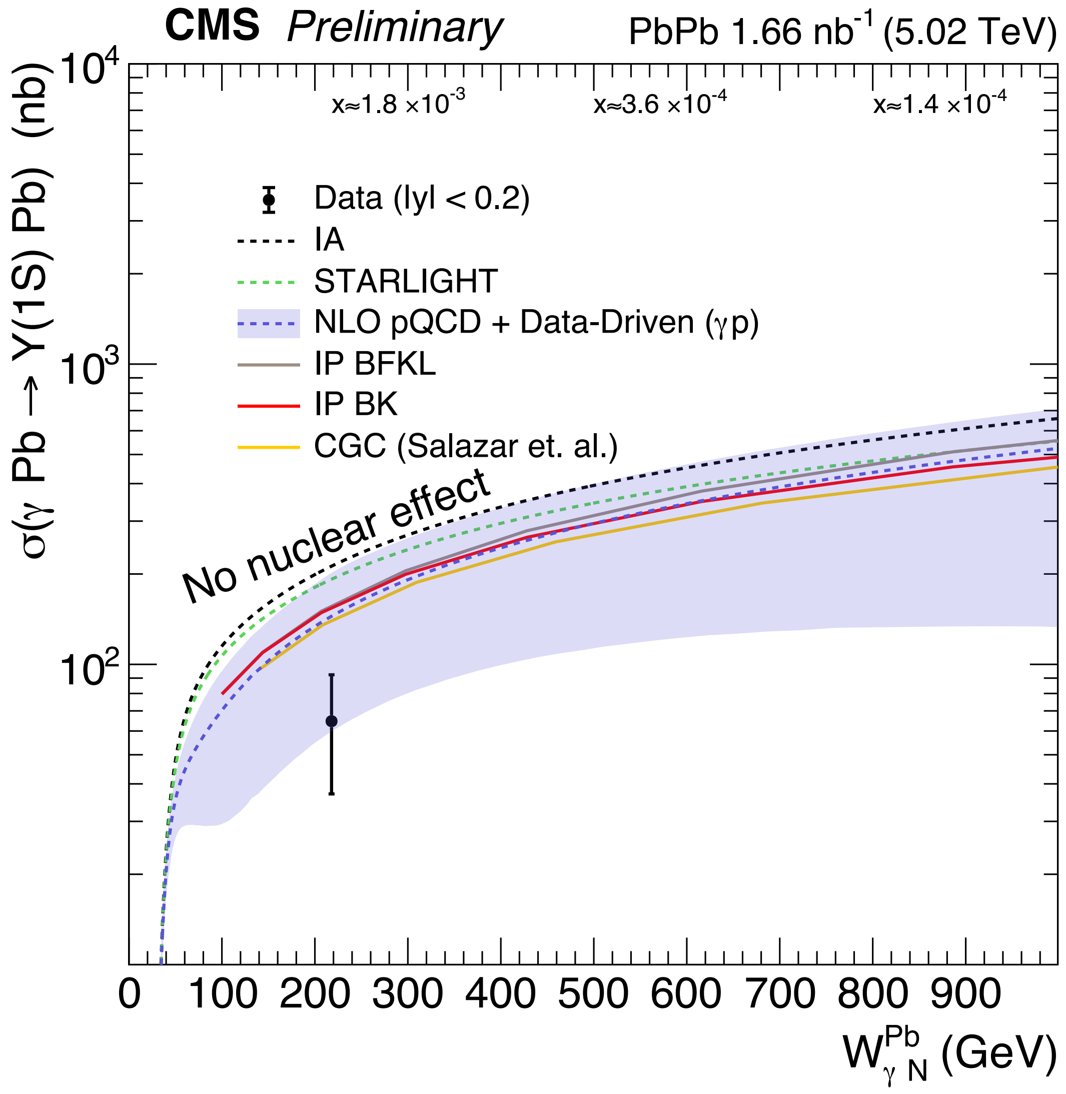
QED BKG is a challenge



Surprisingly large suppression: **S ~ 0.2-0.4 !?**

Best described by EPPS21 nPDF + nGPD

Zooming into harder scale – ϒ(nS)



Large unexpected nuclear suppression:

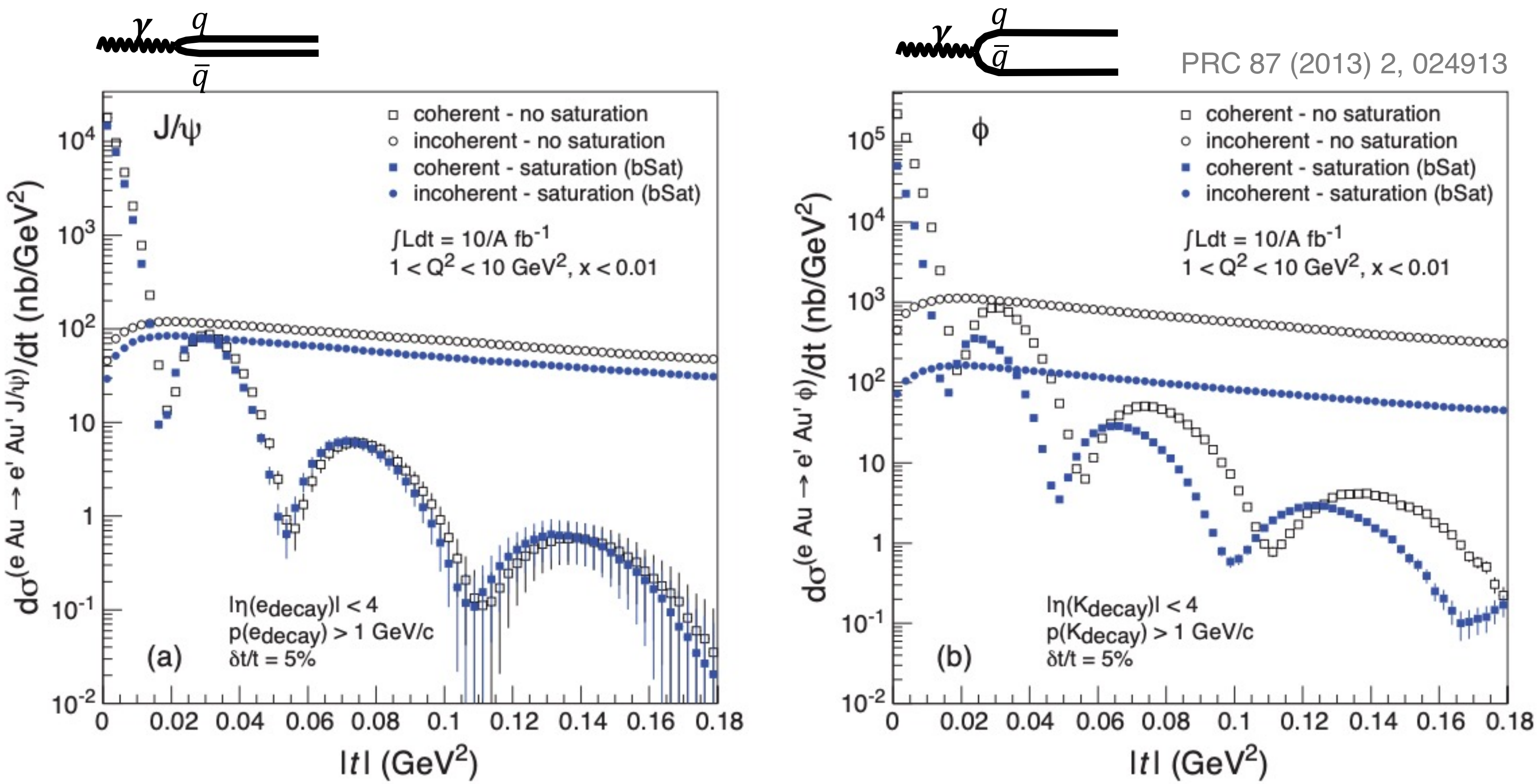
S ~ 0.25 at Q^2 ~ 20 GeV^2 and x ~ 10^{-3}!?

Measurements to be improved:

- ~ 4x statistics by end 2025
- W dependence

Zooming out to lighter scales – ρ, ϕ

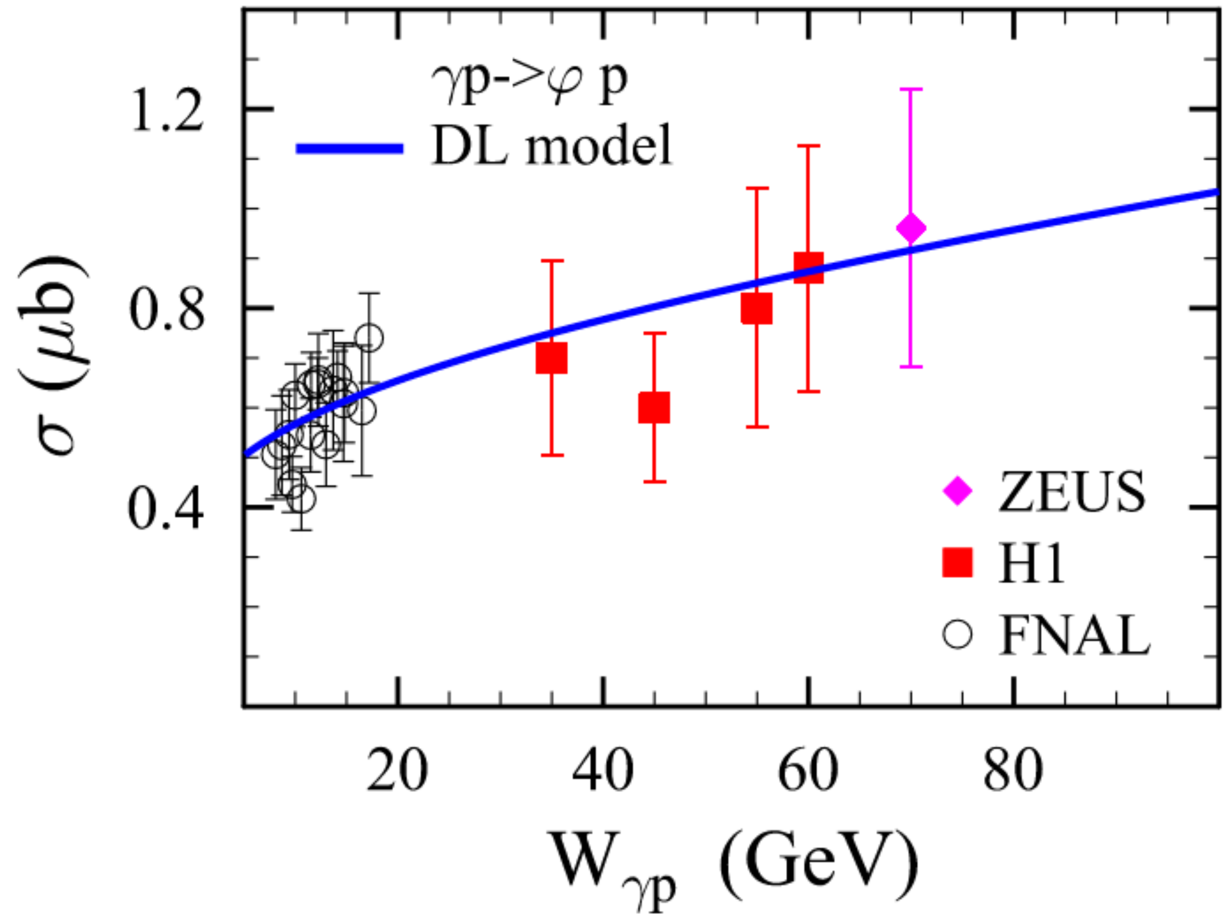
Dipole size for J/ψ too small? e.g., $Q^2 \sim Q_0^2 + (m_{VM})^2$



ϕ mass near the boundary of weak and strong coupling
→ More sensitive to saturation?

Exclusive ϕ in γp

PRC 93, 055206 (2016)



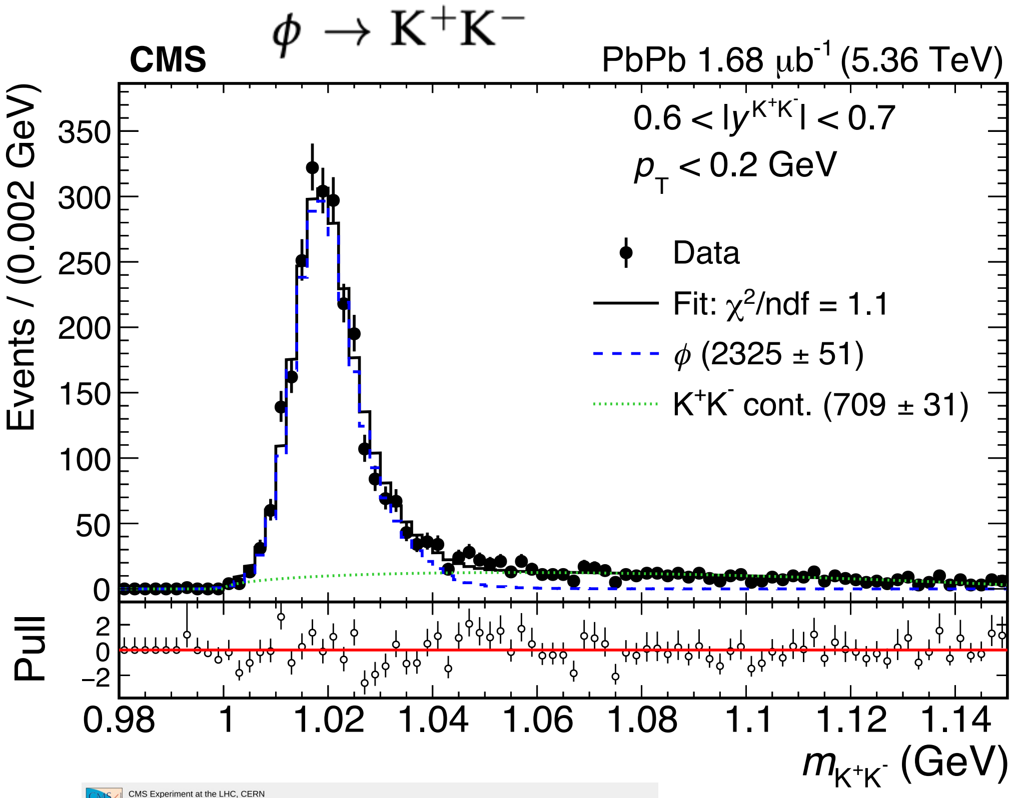
Not very well measured even in γp

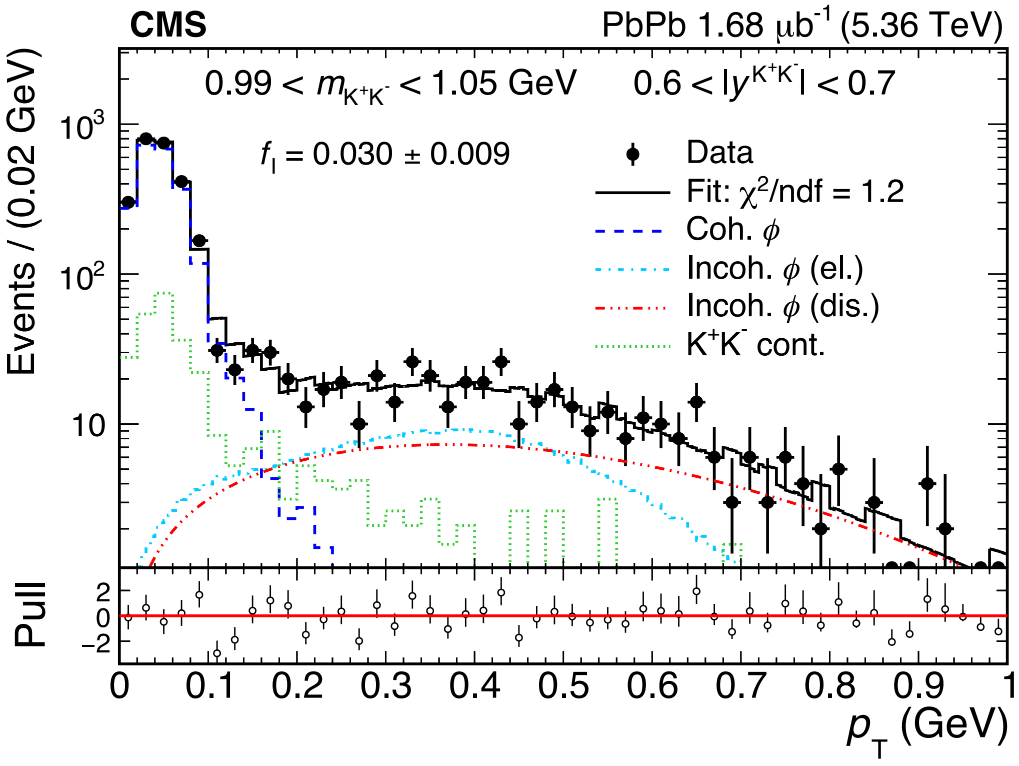
- Difficult to measure due to soft kaon daughters ($p_T \sim 100$ MeV)

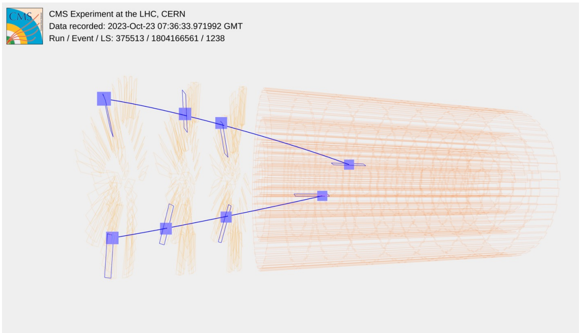
Being used for input to γA models
→ large uncertainties

First LHC measurements (pO, pPb) expected soon

First observation of exclusive ϕ in γA



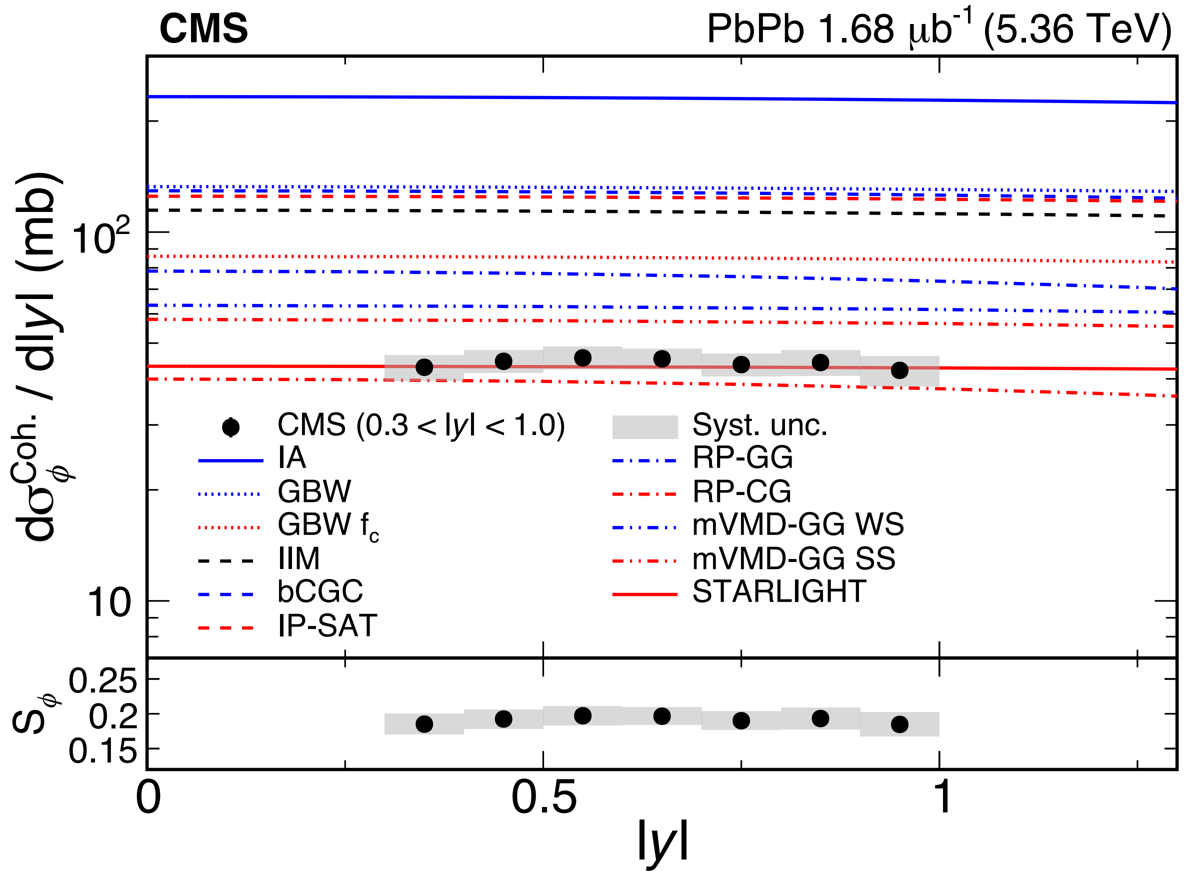




Require a Pb radius of **~ 8.67 fm** (instead of typically 6.67 fm) to describe the coherent p_T width!

First observation of exclusive ϕ in γA

Coherent ϕ cross section



Strong nuclear suppression:

S ~ 0.2 at x ~10^{-4}

All perturbative approaches seem to fail

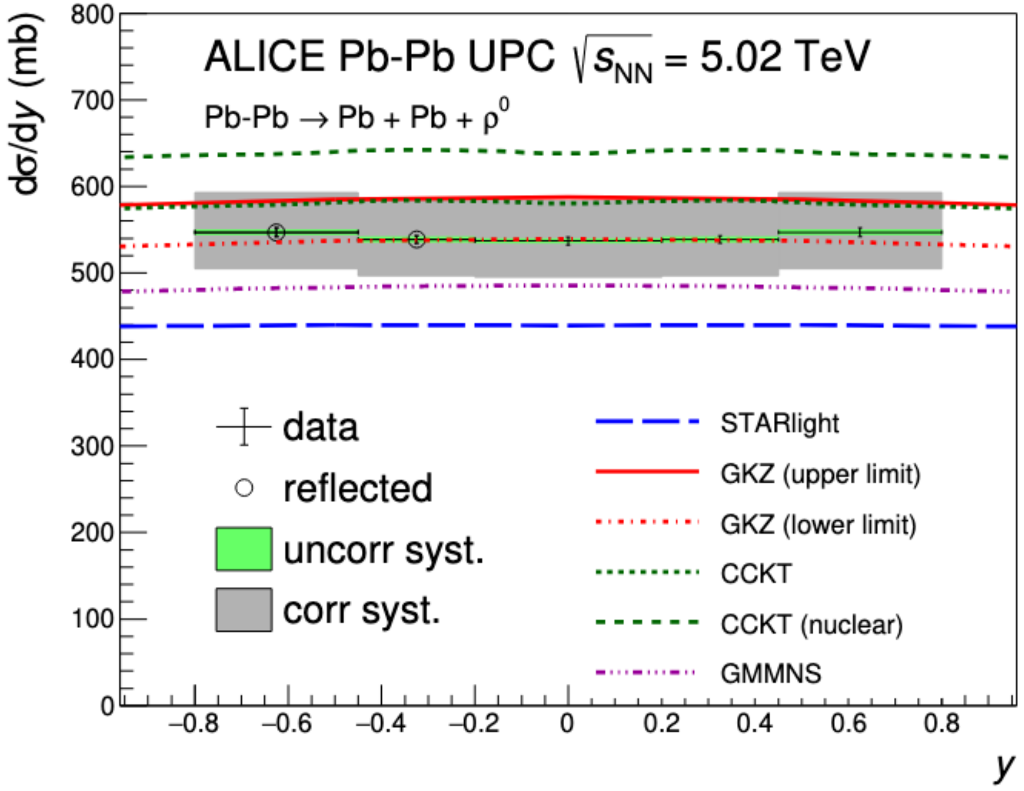
STARLight gives the best description

Full W dependence to come!

➢ Flat in y indicates flat in W or BDL?

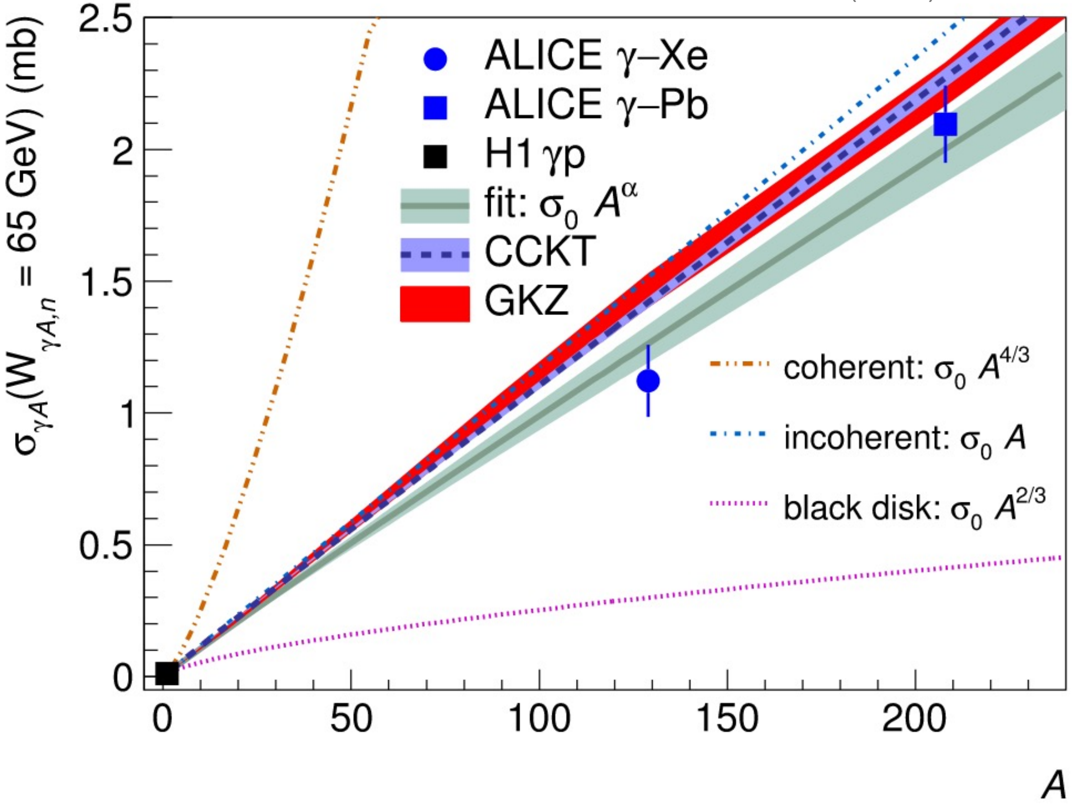
Exclusive ρ in γA

JHEP 06 (2020) 035



Full W dependence to come soon!

PLB 820 (2021) 136481



ρ at x ~ 10^{-4} still far from BDL, despite of large dipole size. Why?

A brief summary so far

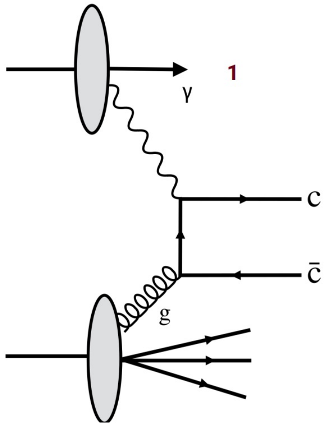
Modifications of gluons in the Pb nucleus

	x	ϕ	J/ψ		Υ**(1S)**
		coherent	coherent	incoherent	coherent
$S \equiv \frac{\sigma^{\gamma A}}{\sigma^{IA}}$	10^{-2}		0.8	0.4	
	10^{-3}		0.4	0.2	0.25
	10^{-4}	0.2	0.2	0.1	
	10^{-5}		0.2		

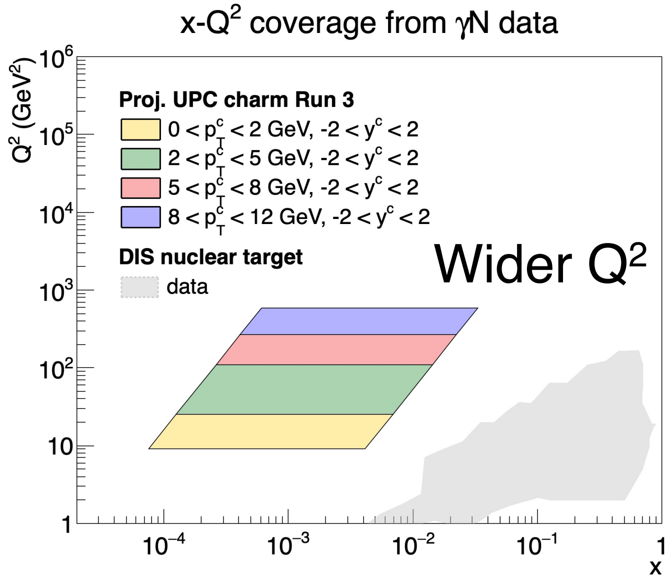
Neither linear nor nonlinear evolution models fully describe the data

An exciting comprehensive program ahead!

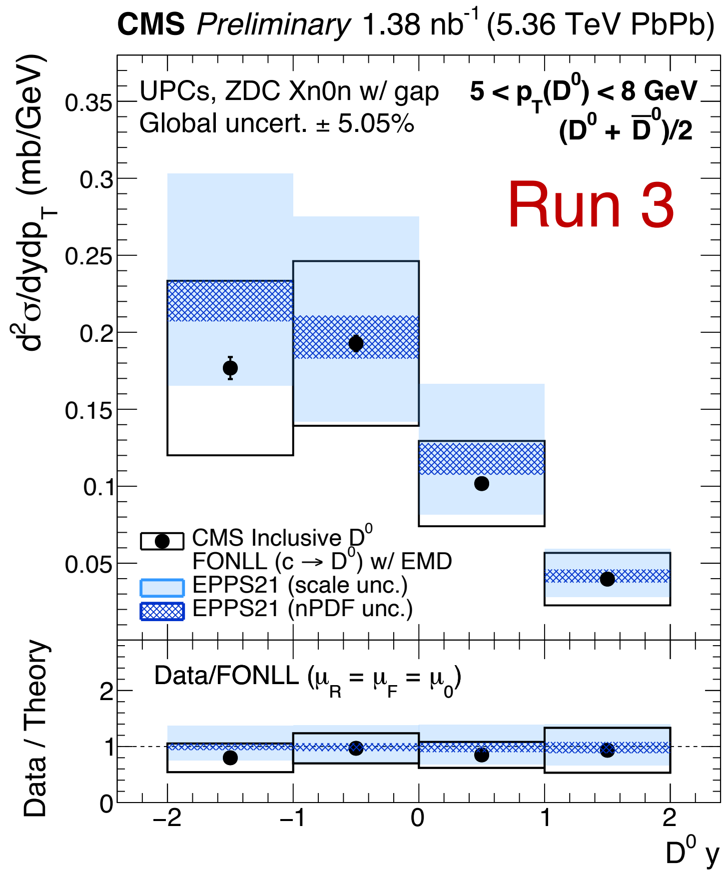
Semi-inclusive UPCs

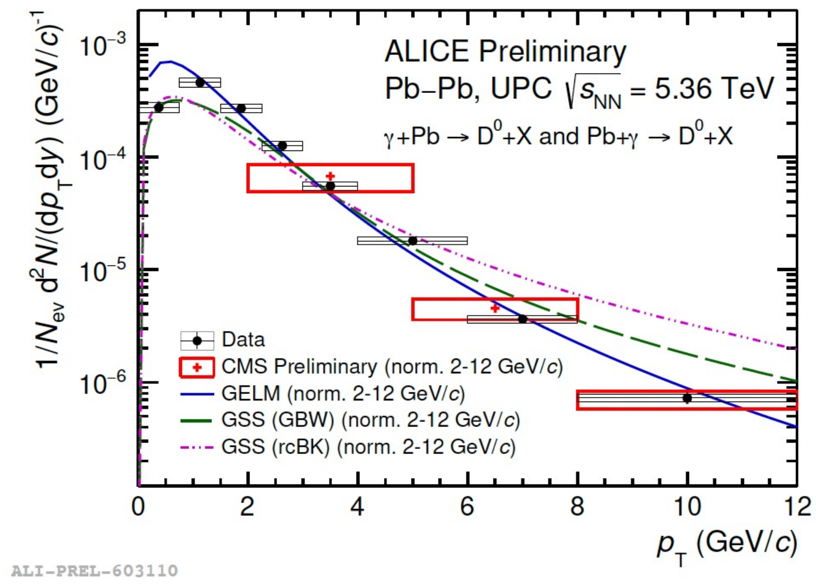


Semi-inclusive photonuclear



First open heavy flavors in UPCs





New and clean constraints on nuclear PDF

Sensitivity to saturation effects?

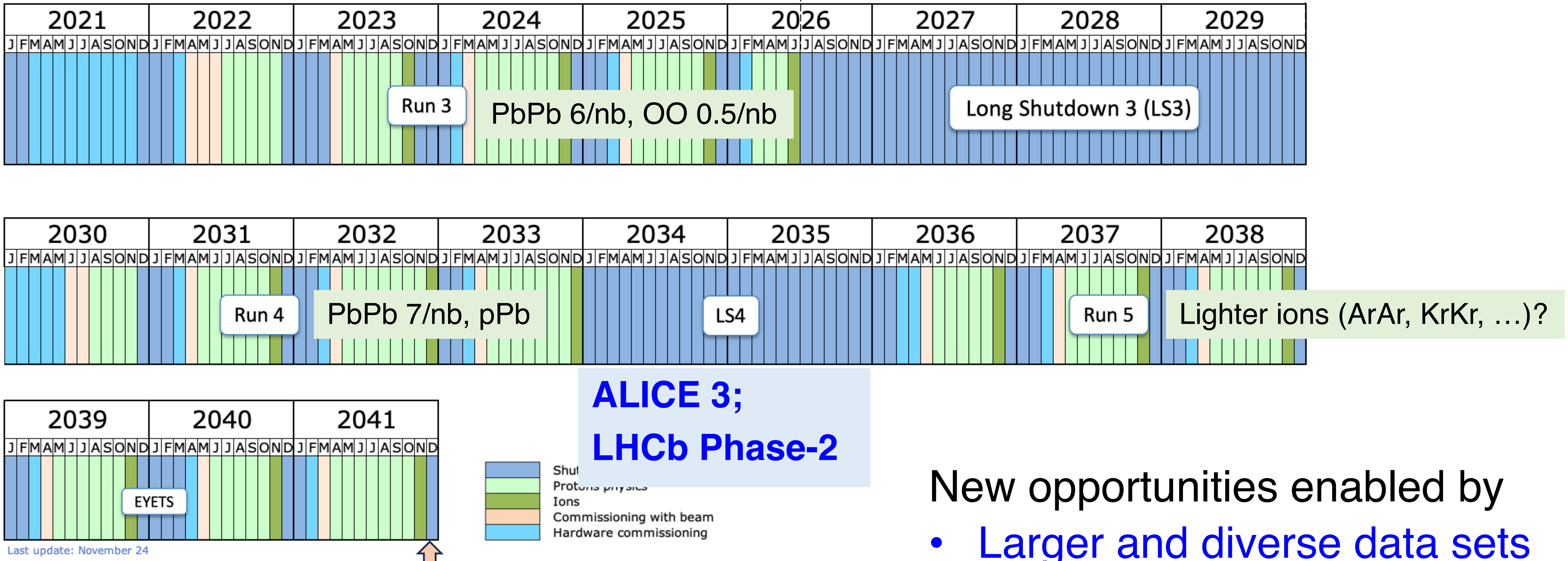
Future LHC program

Run 2:
PbPb: 2/nb
pPb: 0.18/pb

Run 3 well underway

ATLAS/CMS Phase-2;
ALICE ITS3, FoCal

HL-LHC →



ALICE 3;
LHCb Phase-2

Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning

pp 3000 fb^{-1}

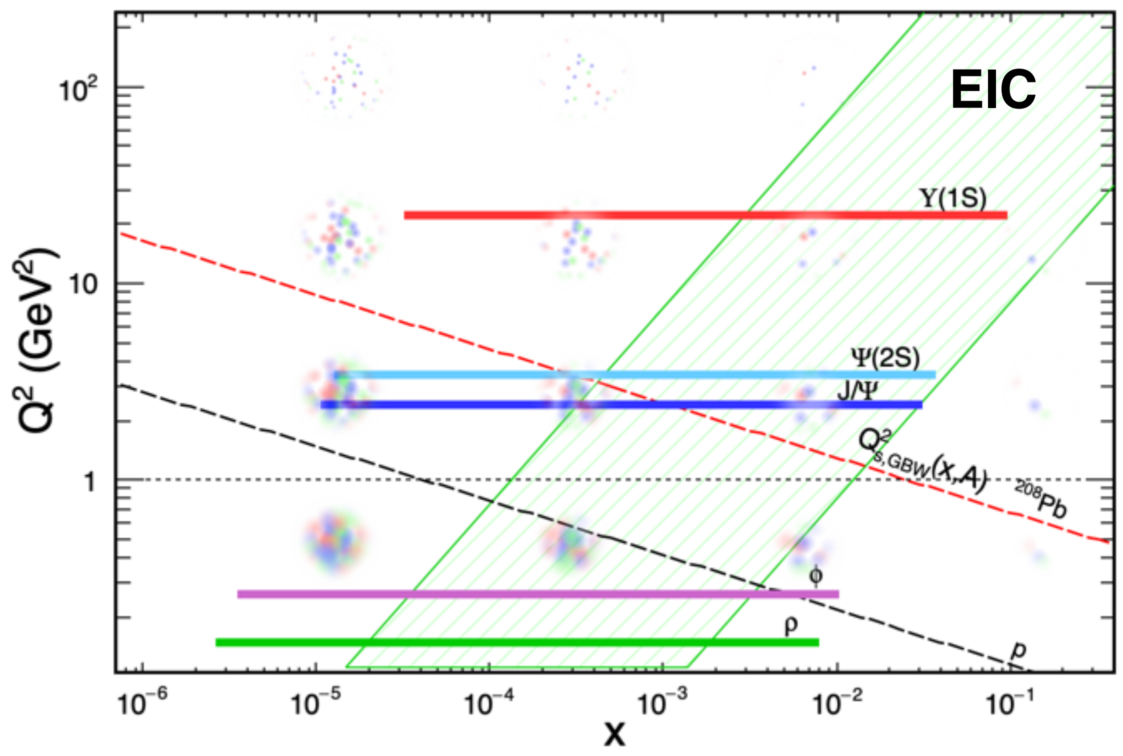
New opportunities enabled by

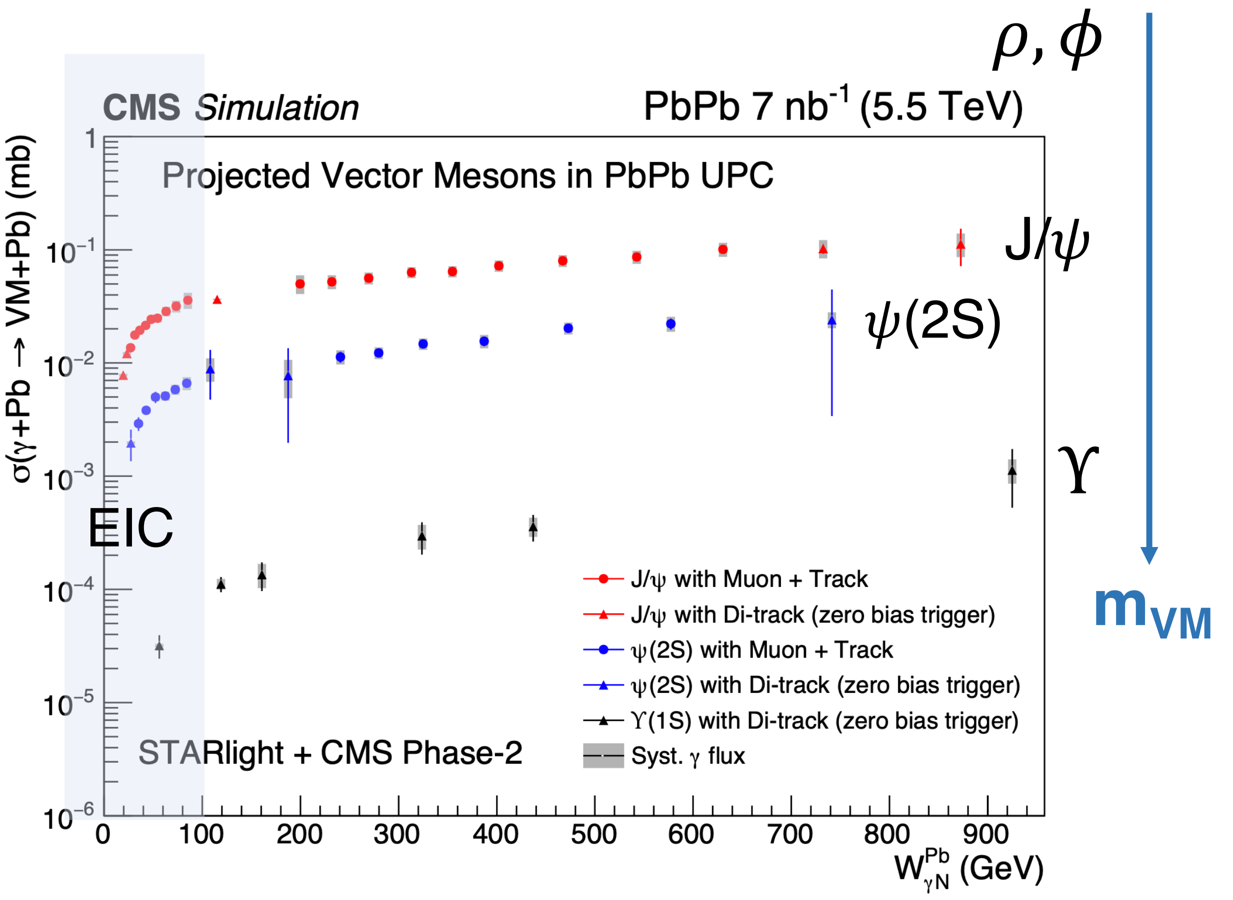
- Larger and diverse data sets
- **Detector upgrades!**

Future LHC program: **Run 3&4 (2025-2035)**

Comprehensive scans in a broad range of **x (<10^{-5})** and Q^2 (**m_{VM}**)

LHC UPC-VM ($|y_{VM}|<4$, $Q^2=[m_{VM}/2]^2$)

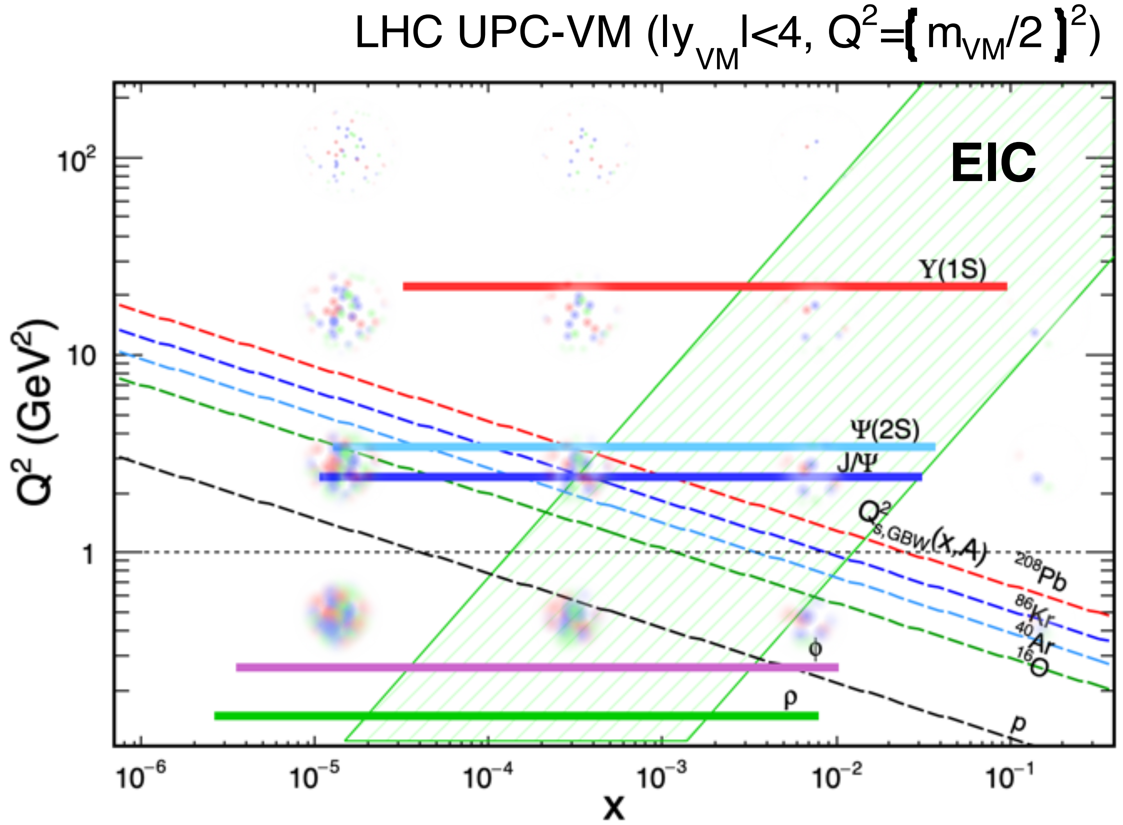




Critical tests of theoretical predictions before EIC starts

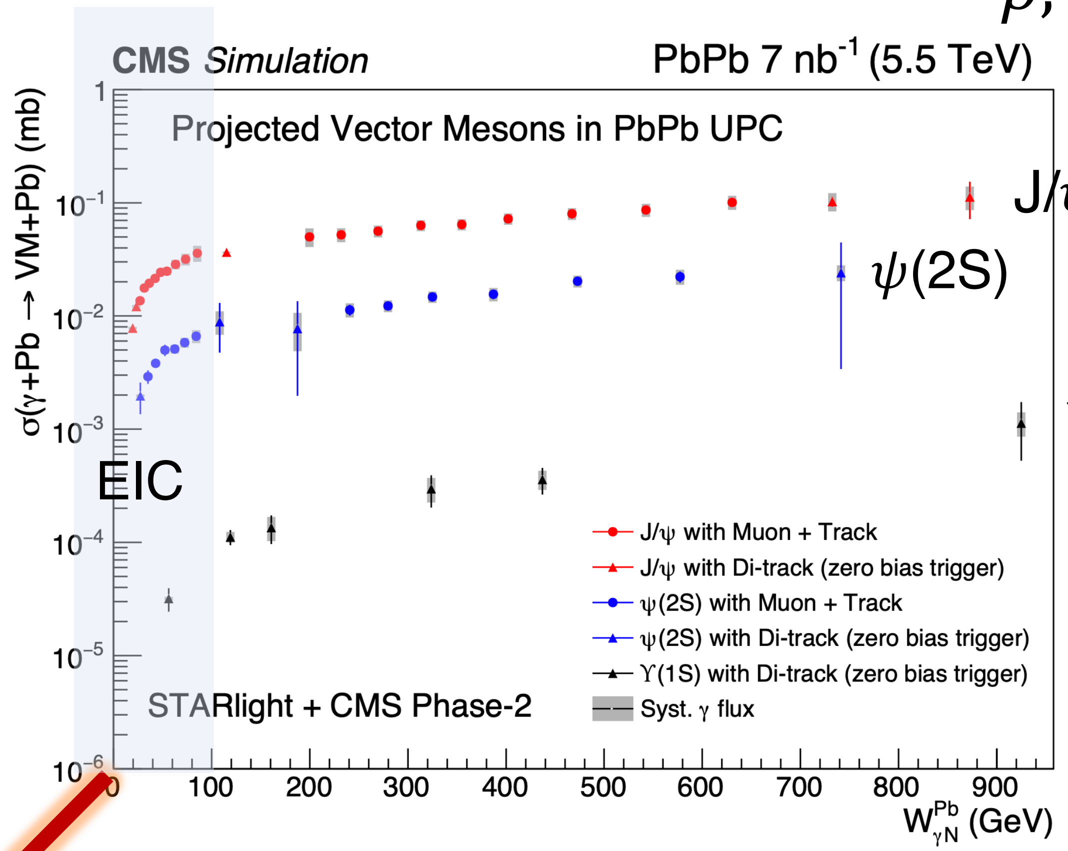
Future LHC program: **Run 5 (2035+)**

Light ion scans (O, Ar, Kr)?



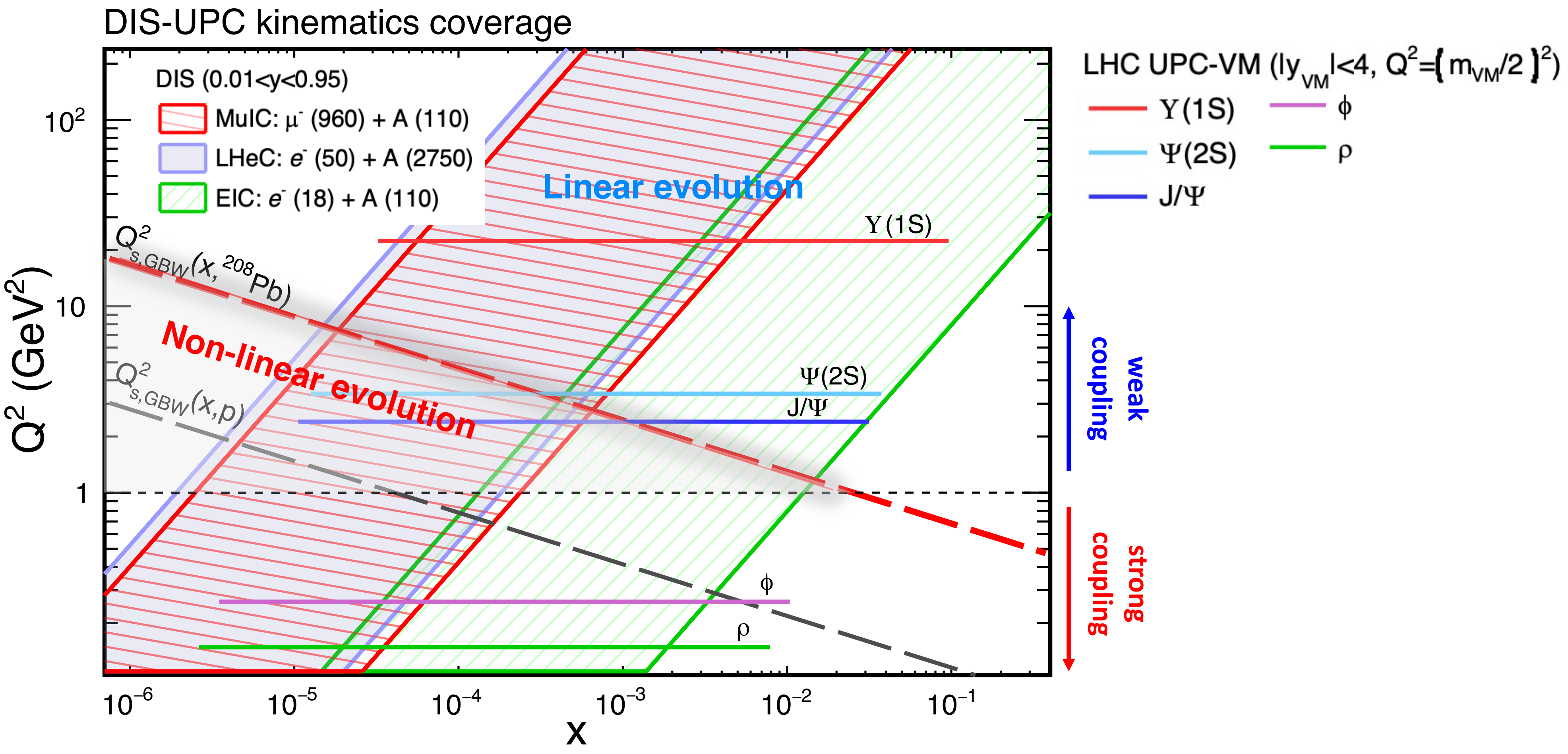
[Luminosity estimate (R. Bruce)]

Comprehensive scans in **x**, Q^2 (**m_{VM}**) and ***A* (one species per month)**



OO test run in July 2025

The ultimate QCD frontier: **2045+**



A TeV-scale DIS machine will provide unmatched access to the non-linear, high-density regime of QCD.

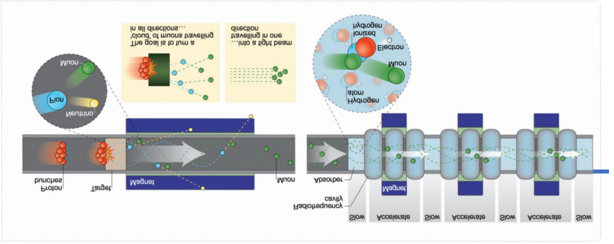
The ultimate QCD frontier: **2045+**

An "upgrade" of EIC by replacing e by μ beam
(potentially cost effective and affordable)

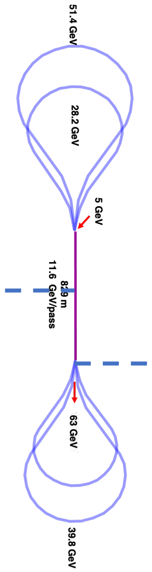
Final acceleration to TeV:
Fast-ramping magnets

Initial acceleration:
Recirculating Linacs (RLA)

Muon production & cooling

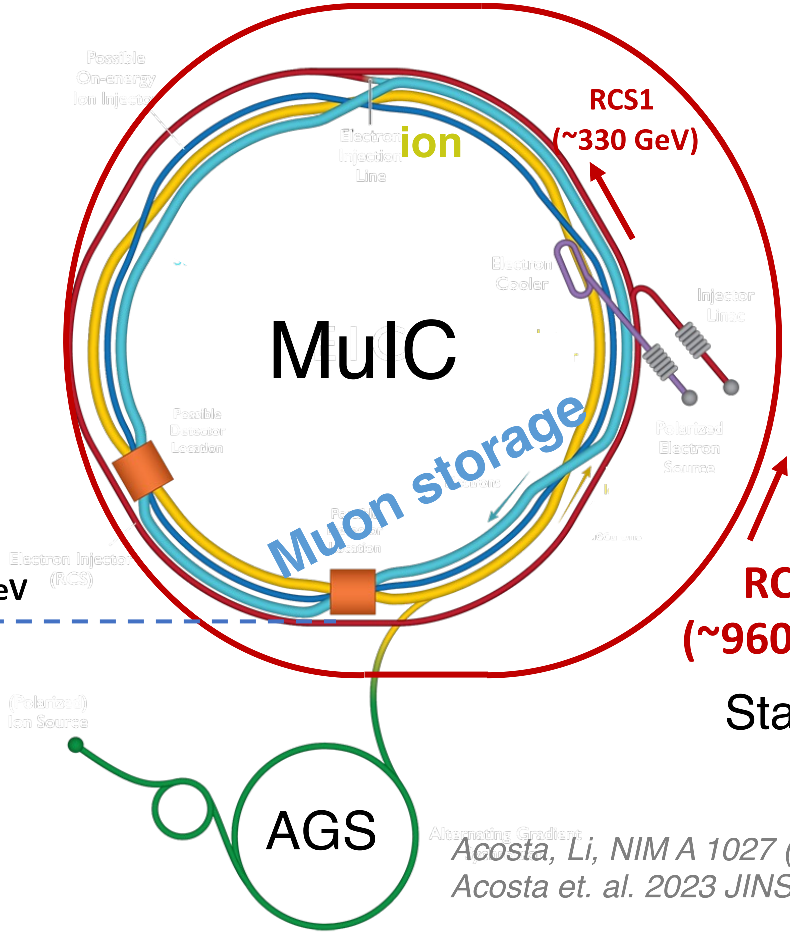


few GeV



~100 GeV

Stage 0



RCS2
(~960 GeV)

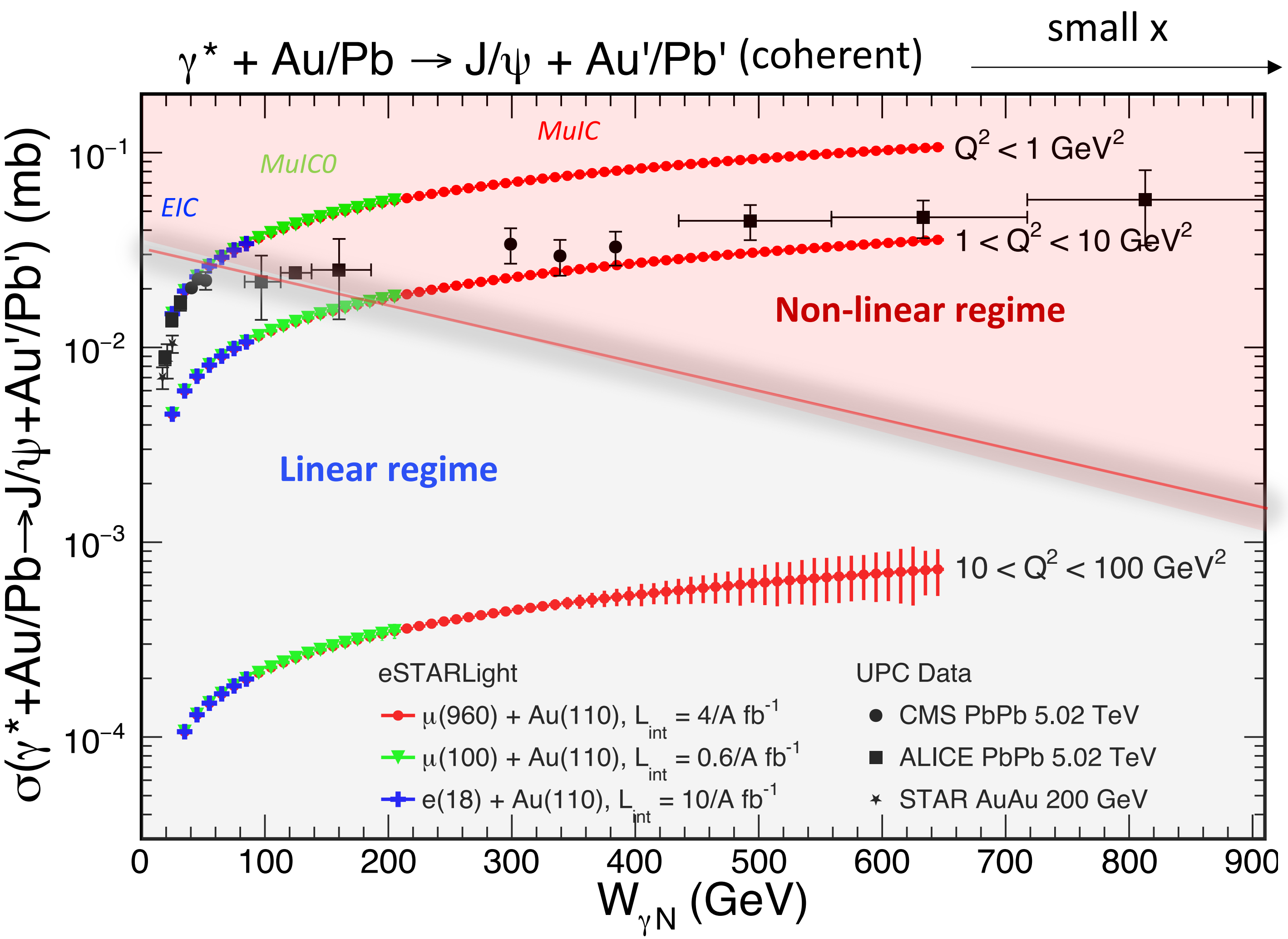
Stage 1

Stage 0: 100 (μ) + 110 (Au)
Stage 1: 960 (μ) + 110 (Au)

Acosta, Li, NIM A 1027 (2022) 166334
Acosta et. al. 2023 JINST 18 P09025

Strong synergies with the HEP community (Muon shot!)

The ultimate QCD frontier: **2045+**



Assume 10% of L_{peak}

Implementation in two stages

If you do small-x calculations, don't stop at EIC kinematics! Dream Big!

Summary

- **The LHC as a photon-ion collider** provides strong synergy with the EIC in exploring **small-x QCD** and the dynamics of **dense gluon matter**.

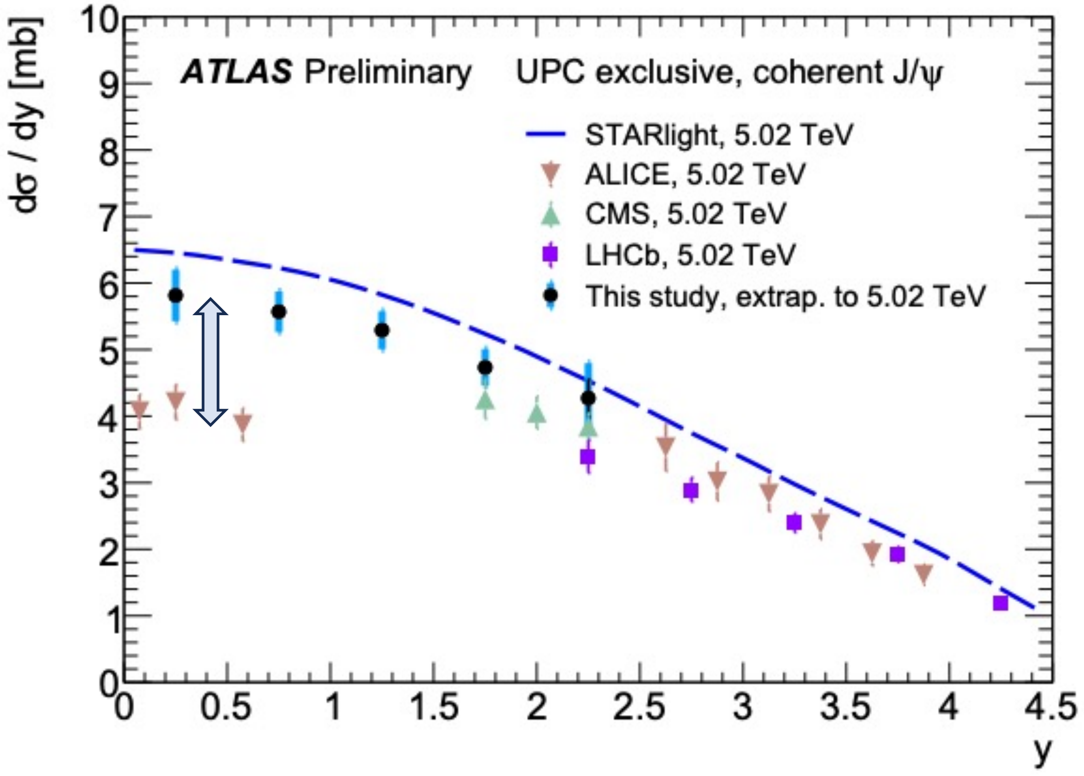
- **Significant gluon modification** in dense environments are observed via **photon-induced VM production** across a range of energy (mass) scales.

- The **future LHC UPC program** will offer precision tests of theoretical frameworks that underpin the **EIC's small-x** physics goals.

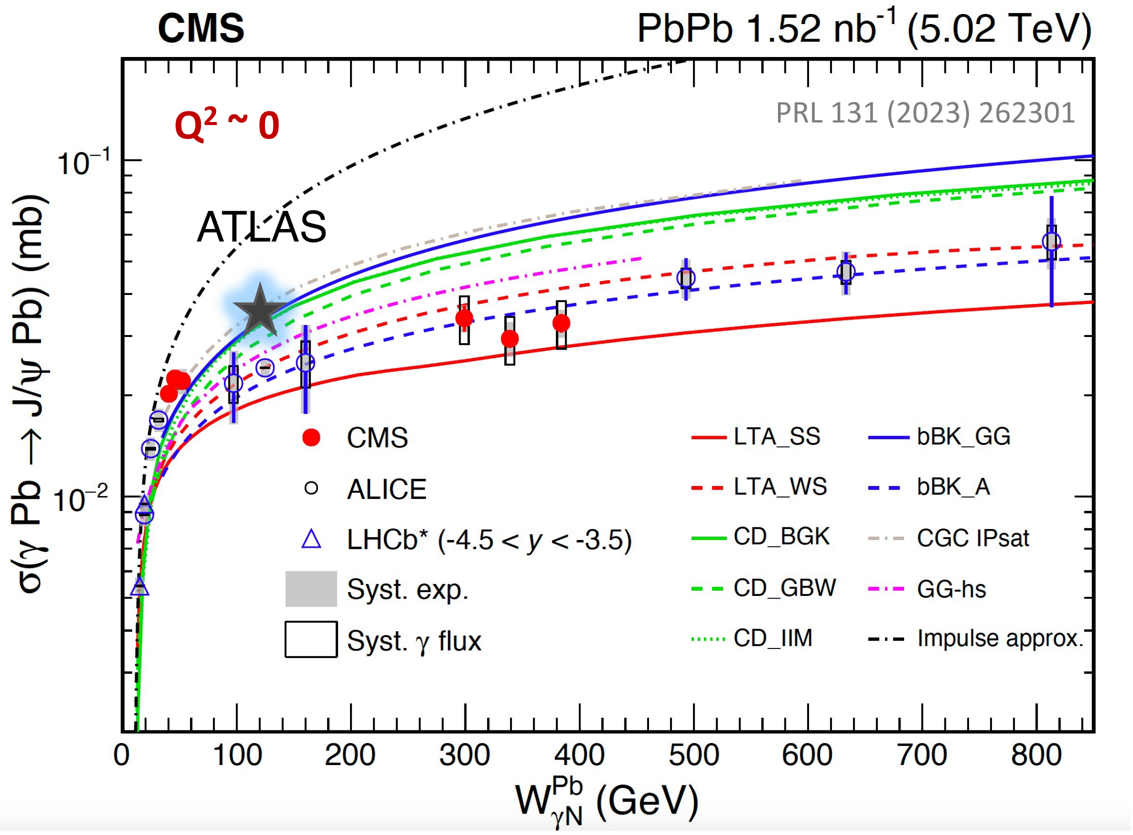
- A **TeV-scale lepton-ion collider** (e.g., a muon-ion collider) would be the ultimate dream and push toward the **ultimate QCD frontier.**

Backups

A recent experimental discrepancy!?



40% discrepancy between ALICE and ATLAS at midrapidity



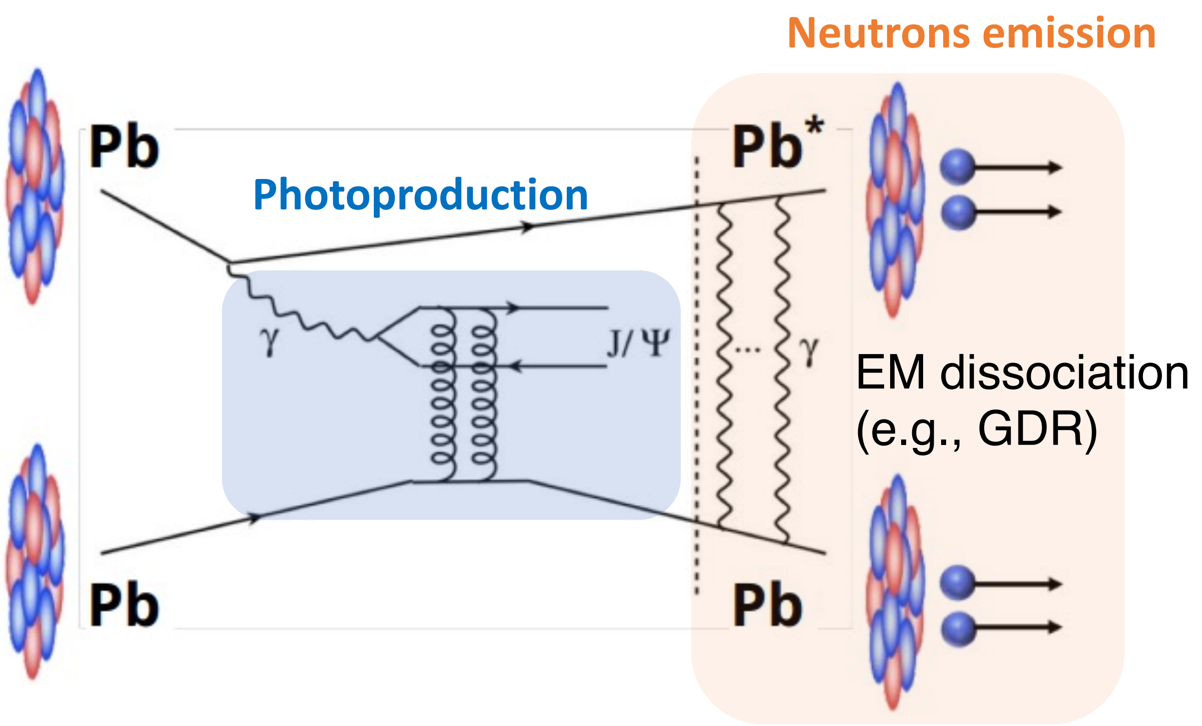
ATLAS agrees better with CGC IPsat but incompatible with CMS and ALICE

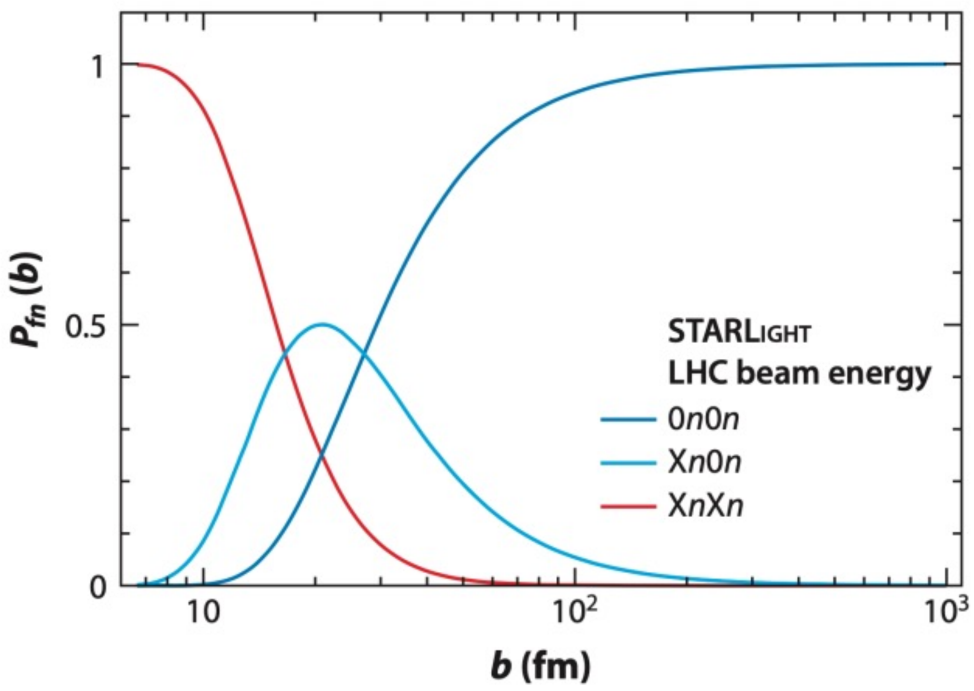
Don't jump on it yet! Stay tuned for CMS midrapidity results

A Solution To The "Two-way Ambiguity"

Proposed by Guzey et al., EPJC 74 (2014) 2942

Control the impact parameter or "centrality" of UPCs via forward neutron multiplicity





Spencer Klein & PAS, Ann Rev Nucl Part Sci Vol. 70:323-354

Nucleus excitation probability:

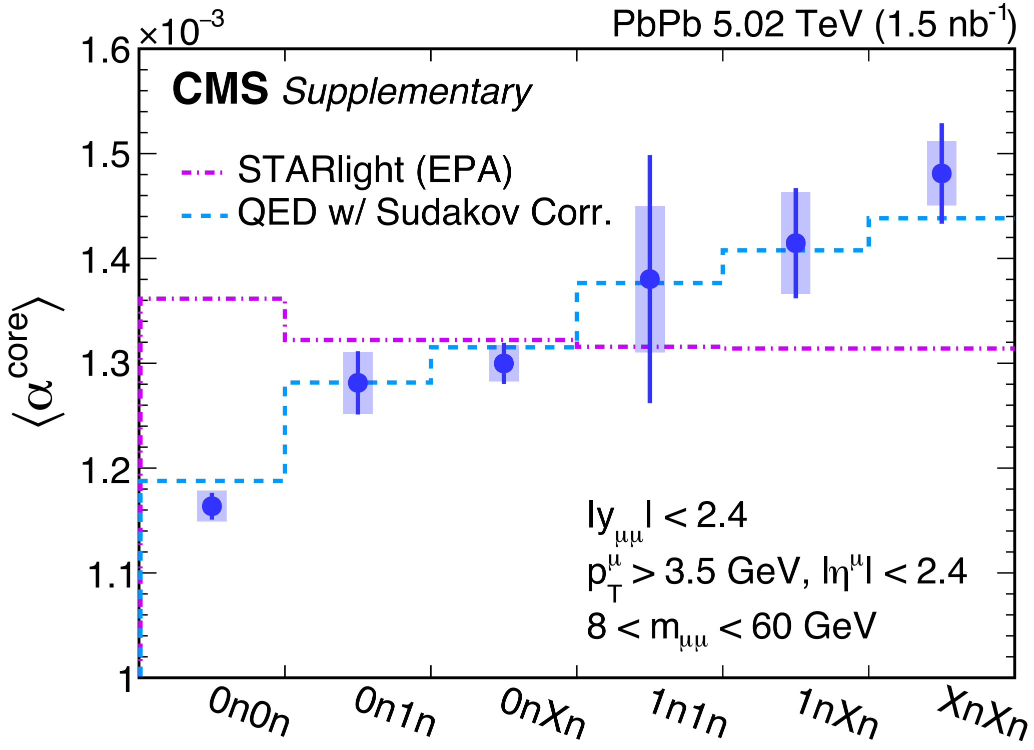
$$P_i(b) \propto 1/b^2$$

- Analogous to centrality:
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$

A Solution To The "Two-way Ambiguity"

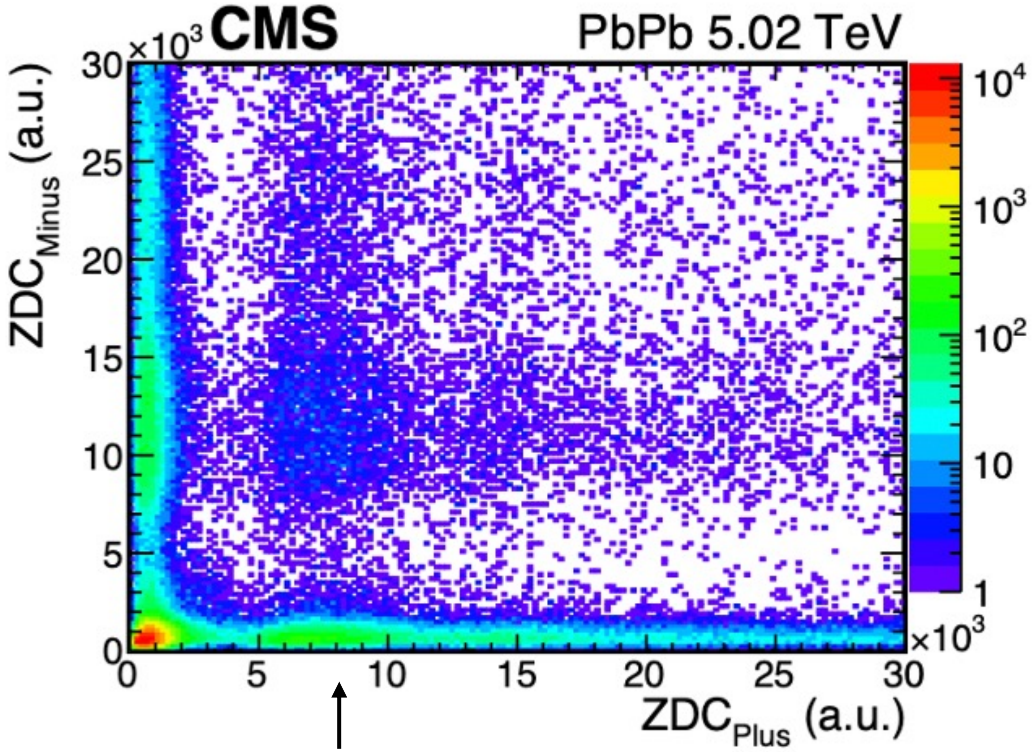
Control the impact parameter or "centrality" of UPCs via forward neutron multiplicity

Dimuon acoplanarity from $\gamma\gamma \rightarrow \mu^+\mu^-$



PRL 127 (2021) 12, 122001

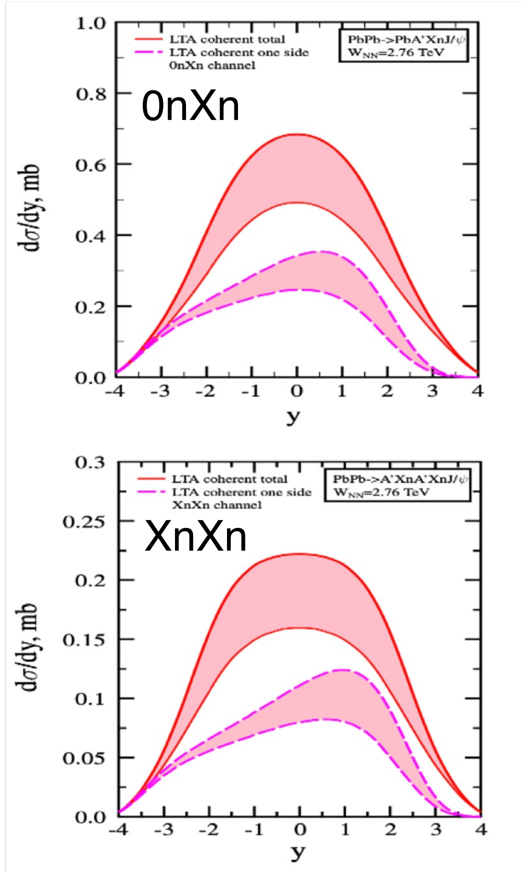
Energy distribution of ZDC+ vs ZDC-



Single neutron peak

A Solution To The "Two-way Ambiguity"

For each J/ψ |y| bin,



Guzey et al., EPJC 74 (2014) 2942

What is measured | Photon flux from theory | What we want

$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{XnXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

⇓

Solve for $\sigma_{\gamma A\to J/\psi A'}(w_1)$ and $\sigma_{\gamma A\to J/\psi A'}(w_2)$

⇓

$\sigma_{\gamma A\to J/\psi A'}(W^{Pb}_{\gamma N}$ or $x)$, probing $x \sim 10^{-4} - 10^{-5}$ gluons in nuclei!