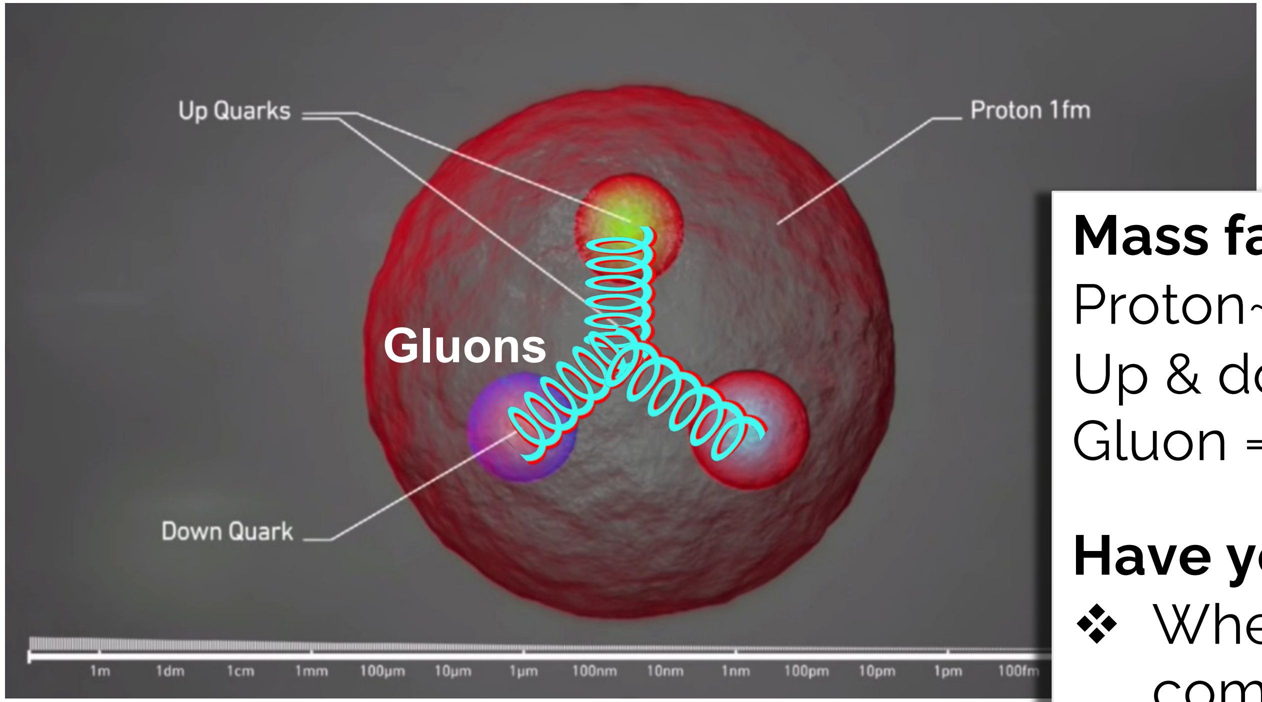
Ultra-peripheral collisions at RHIC and the LHC with Vector Meson

Kong Tu, BNL/SBU

Big question: confinement



Mass fact sheet:

Proton~ 1 GeV/c²

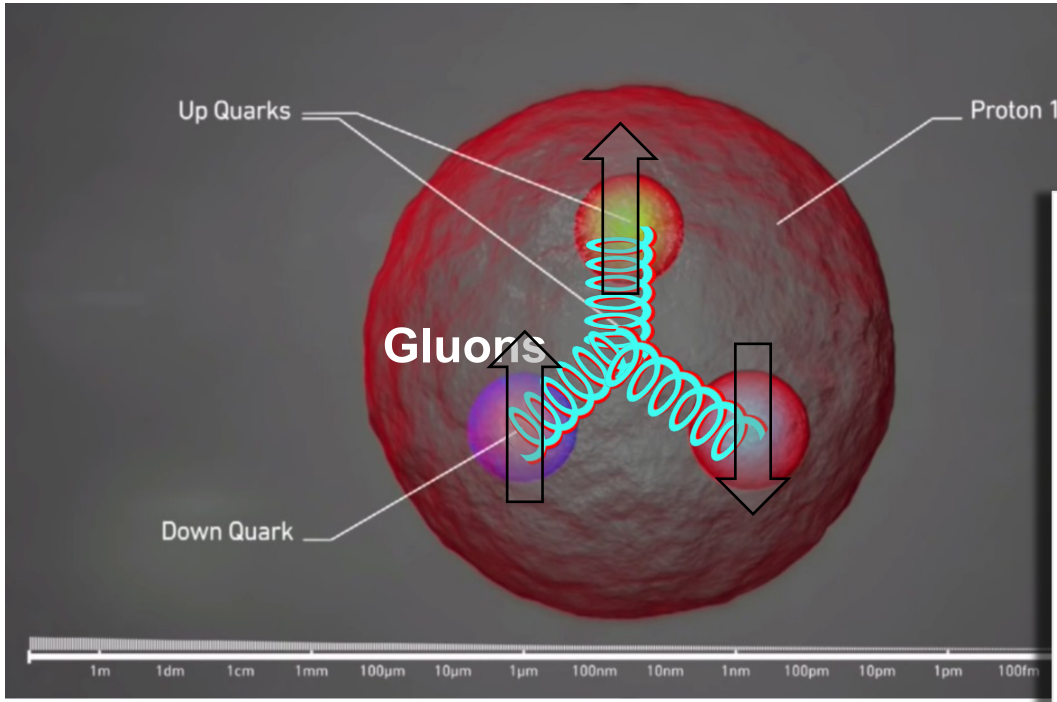
Up & down quarks < 0.005 GeV/c²

Gluon = 0 MeV/c²

Have you wondered?

- Where does > 99% of proton mass come from?

Big question: confinement



Spin decomposition

Quarks only accounts for ~35% of the proton spin.

Have you wondered?

❖ Where does most of proton spin come from?

Mas

Prot

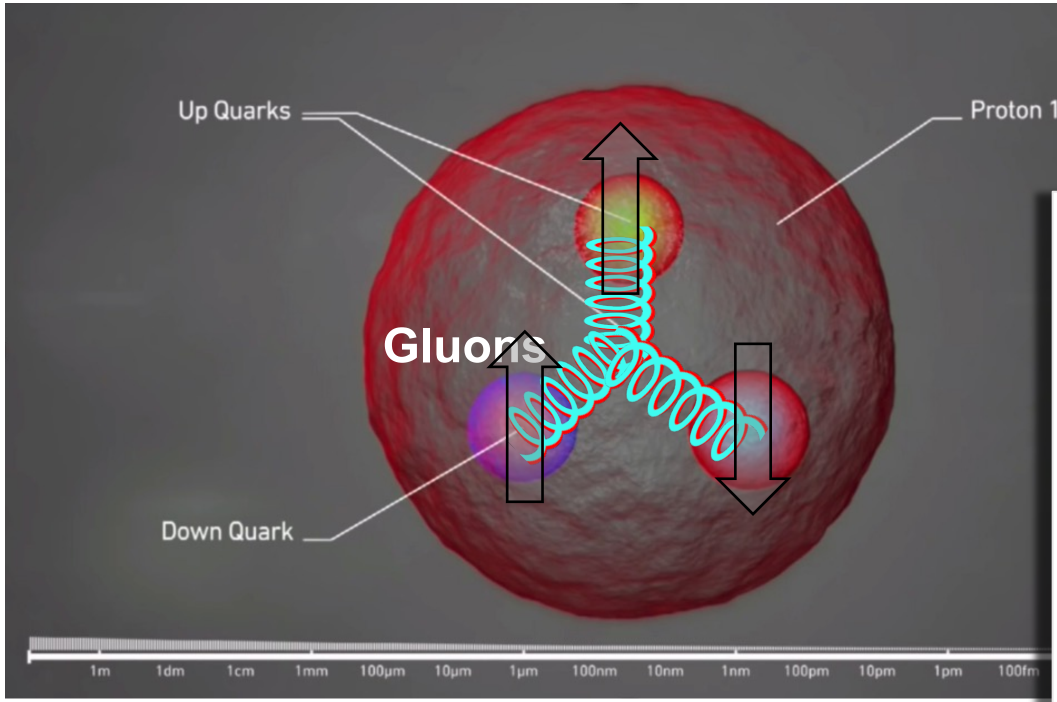
Up &

Gluc

Have you wondered?

❖ Where does > 99% of proton mass come from?

Big question: confinement



Spin decomposition
Quarks only accounts for ~35% of the proton spin.

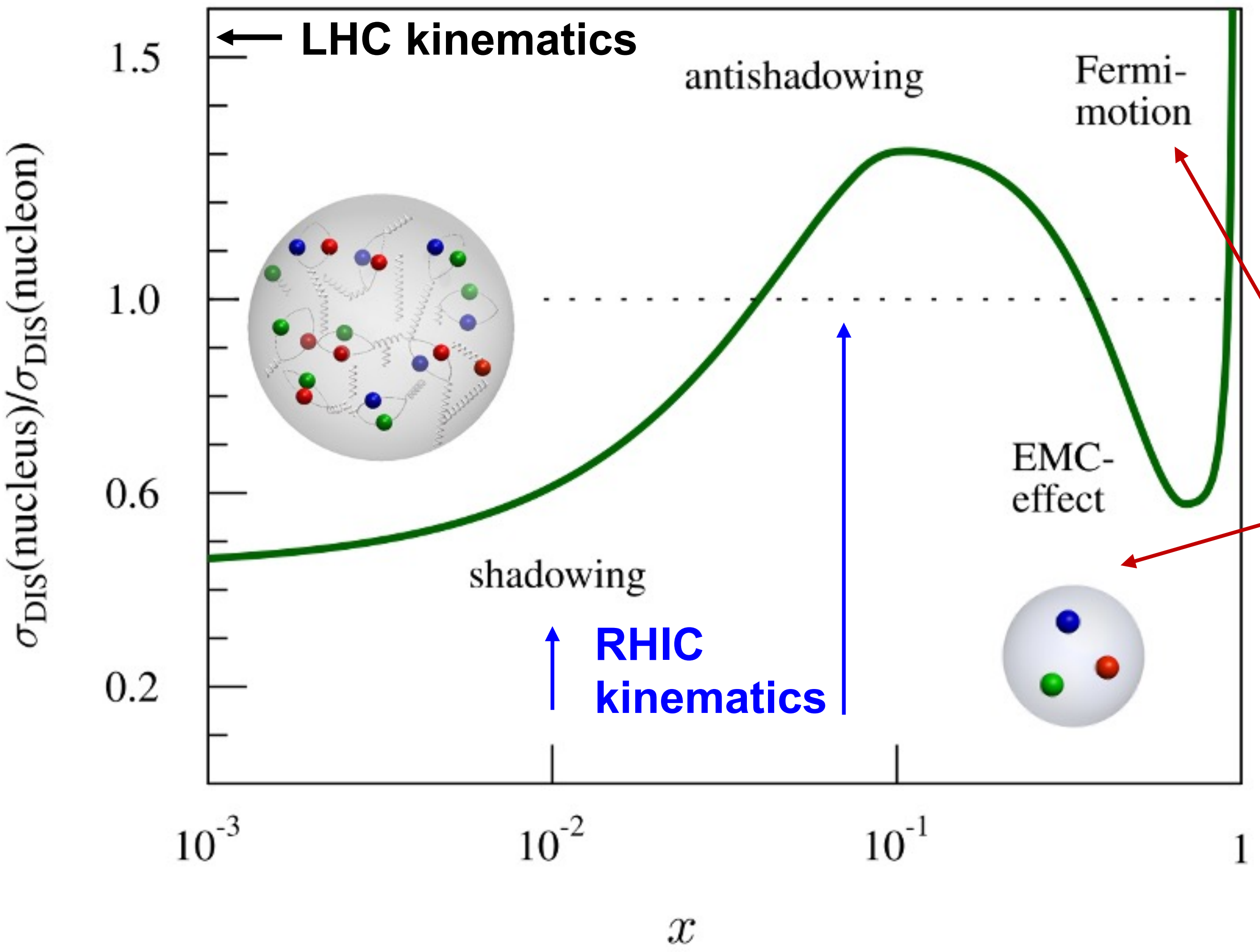
Have you wondered?
❖ Where does most of proton spin come from?

Mas
Prot
Up &
Gluc

Have you wondered?
❖ Where does > 99% of proton mass come from?

Understanding the emergent hadron properties is one of the most compelling and challenging questions in hadronic physics

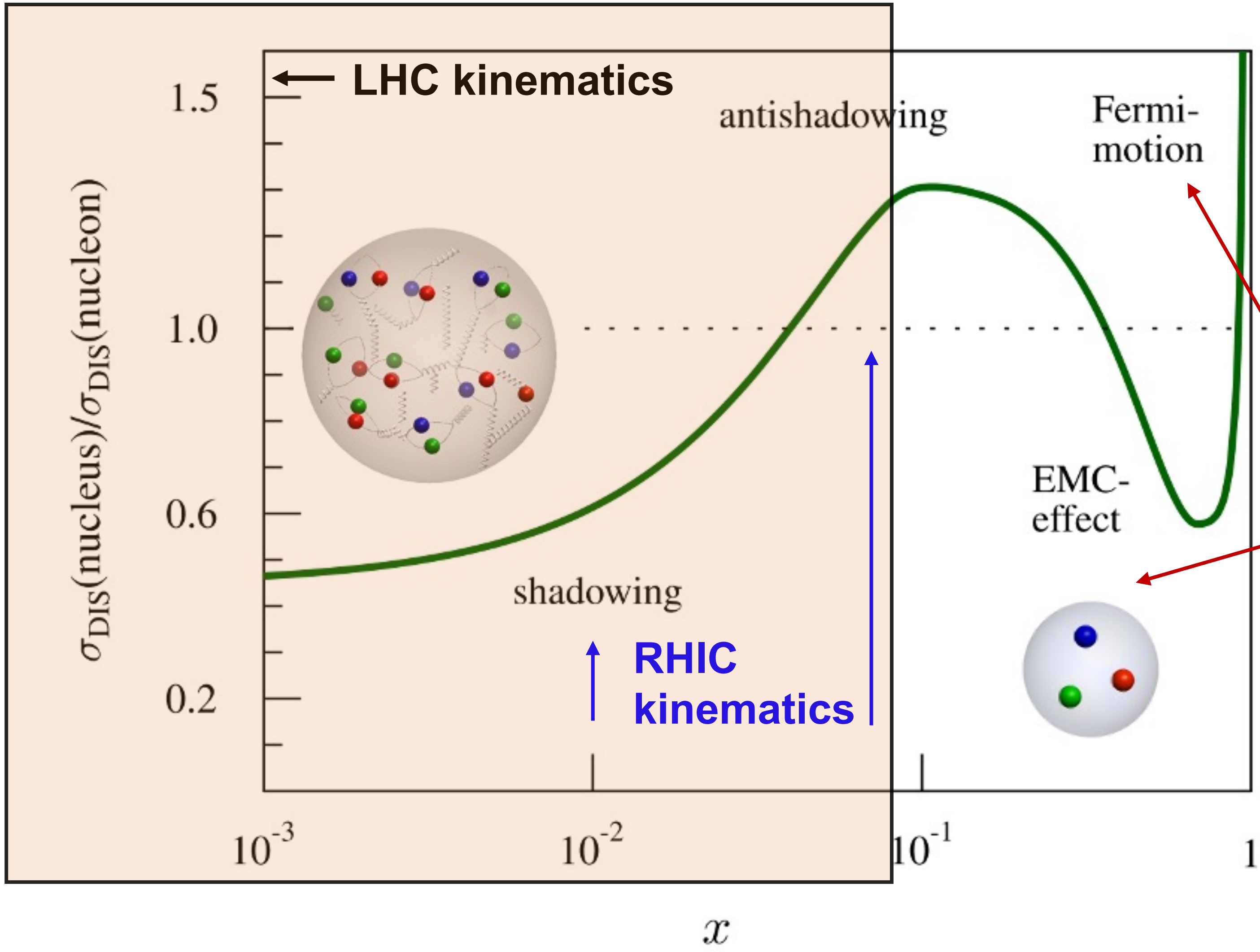
An extended big question – hadron (nucleon) structure in nuclei



From valence quarks to low-x gluons. **Multiple facilities together cover a wide range of kinematic regions.**

Jlab kinematics

An extended big question – hadron (nucleon) structure in nuclei

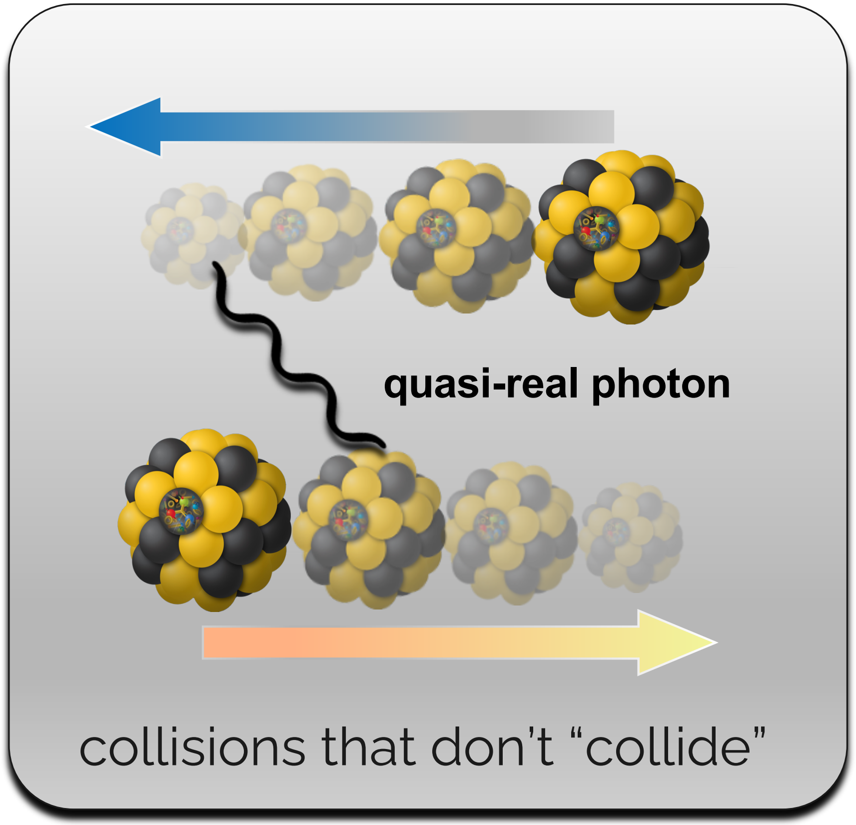


From valence quarks to low-x gluons. **Multiple facilities together cover a wide range of kinematic regions.**

Jlab kinematics

This talk – I will focus on RHIC and LHC kinematics.

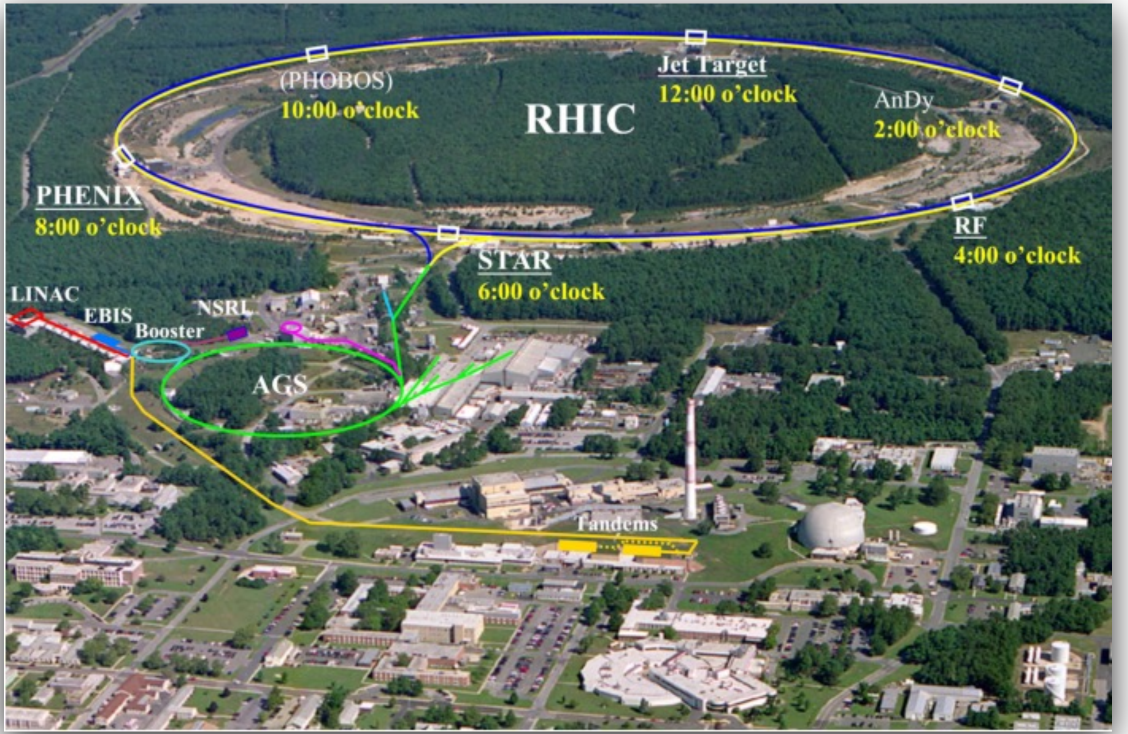
Ultra-peripheral collisions as a tool to understand structure in hadron and nuclei



UPC highlighted features:

- **Large cross section** ← large photon flux
- **Simple configuration.** Photons emitted by nuclei (QED) and enable photon-induced interactions;
- **High energy, low virtuality, transversely polarization of photons**. Photons are quasi-real (Q2 ~ 0) with linearly & transversely polarization;
- **Hard scale** comes from final-states.

Ultra-peripheral collisions as a tool to understand structure in hadron and nuclei

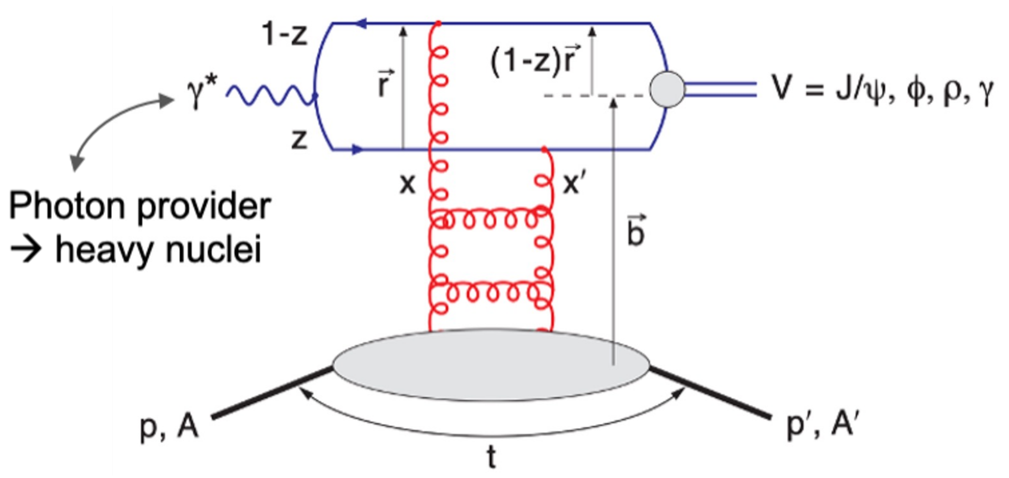


TeV beams based on *p*, O^{16}, Xe^{54}, Pb^{208} U^{238}, Au^{197}, Zr^{96} , Ru^{96}, d^{2} at 200 GeV and *pp* at 510 GeV.

A versatile program with different species, energy, and polarization.

UPCs exclusive VM productions – sensitive to the gluon density and fluctuations.

At Leading Order, 2-gluon exchange

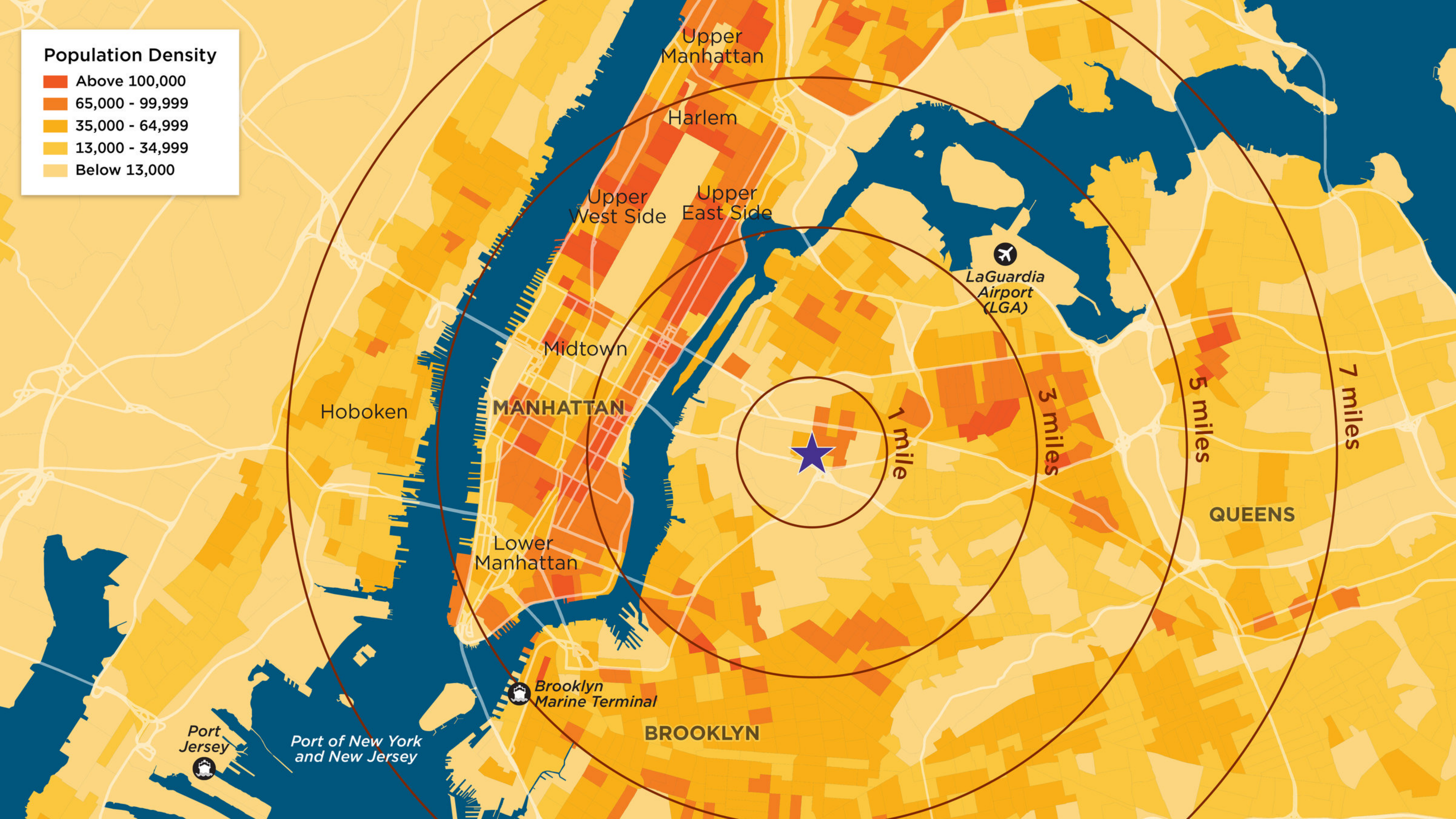


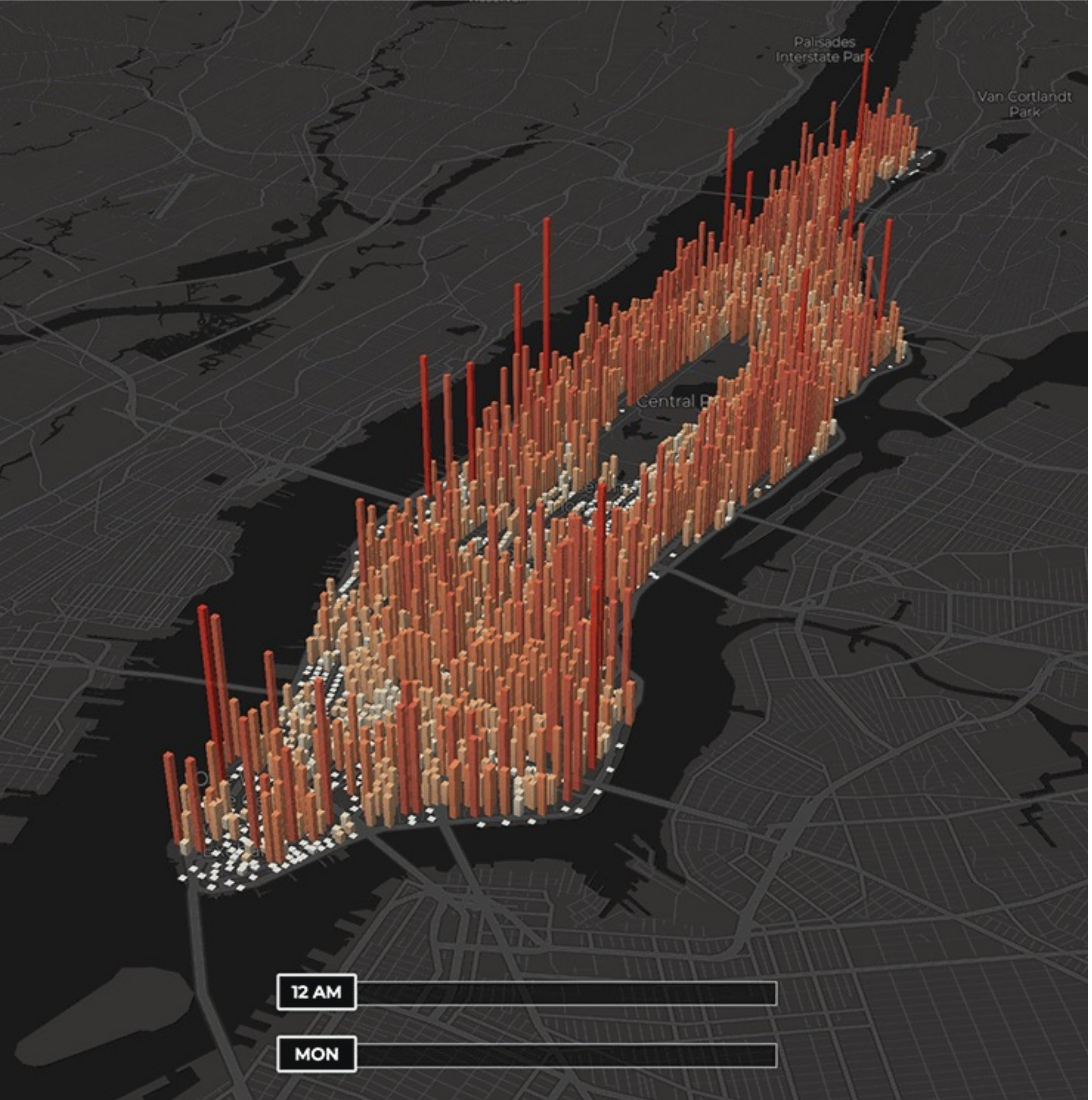
Coherent (target stays intact)	**Incoherent (target breaks up)**
Average nuclear parton density	Event-by-event parton density fluctuations
Momentum transfer (*t*) and transverse spatial position (*b*) are Fourier transforms of each other;	

Two main physics goals:

1. Coherent production – **average** nuclear parton density
2. Incoherent production – **E-by-E fluctuations** of nuclear parton density

* Imaging of nuclear parton **spatial** distribution in nuclei. (EIC, see R. Reed's talk)


Population Density
Above 100,000
65,000 - 99,999
35,000 - 64,999
13,000 - 34,999
Below 13,000
Upper Manhattan
Harlem
Upper West Side
Upper East Side
Midtown
MANHATTAN
Hoboken
Lower Manhattan
LaGuardia Airport (LGA)
1 mile
3 miles
5 miles
7 miles
QUEENS
Brooklyn Marine Terminal
BROOKLYN
Port Jersey
Port of New York and New Jersey

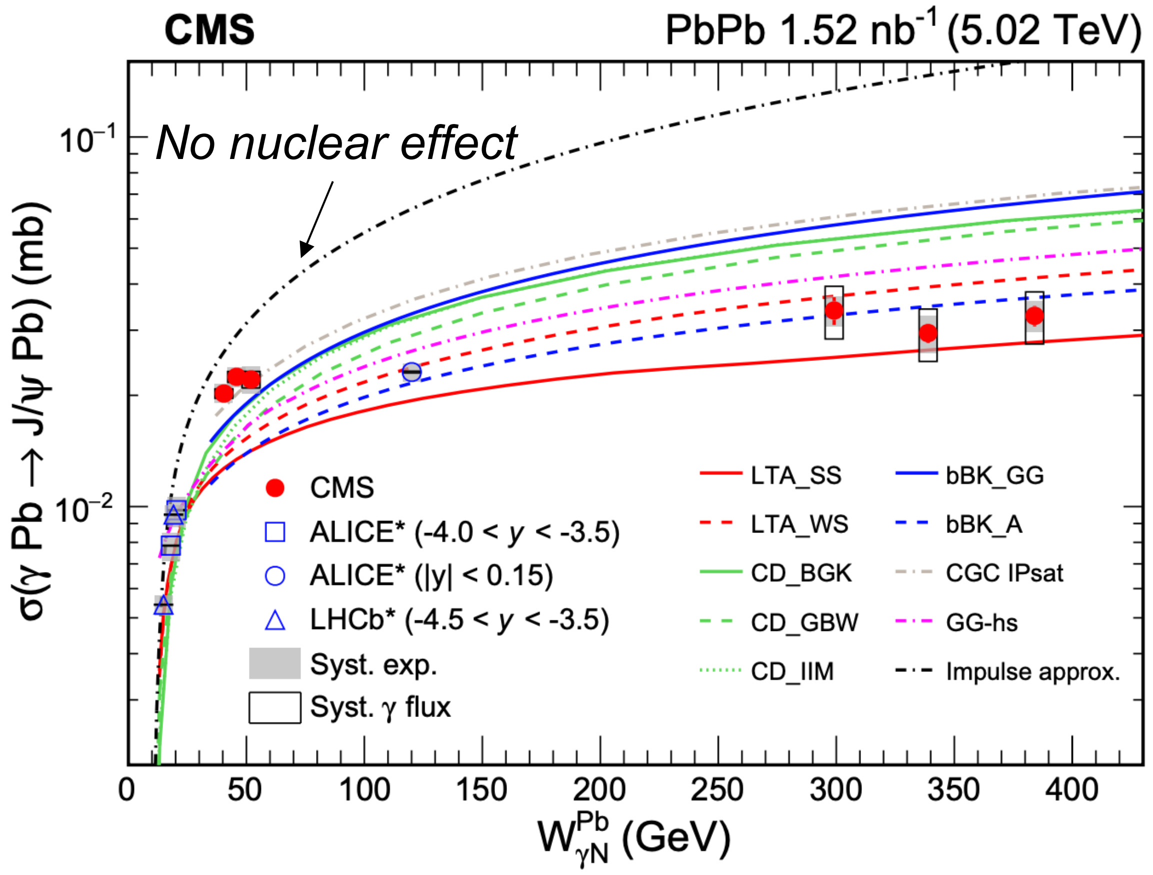


Average density and its **day-by-day, hour-by-hour fluctuation** are two distinct aspects of describing the Manhattan's populations

Together, we have a **full picture of the structure**

Recent UPCs coherent Jpsi highlights

Phys. Rev. Lett. 131 (2023) 26, 262301



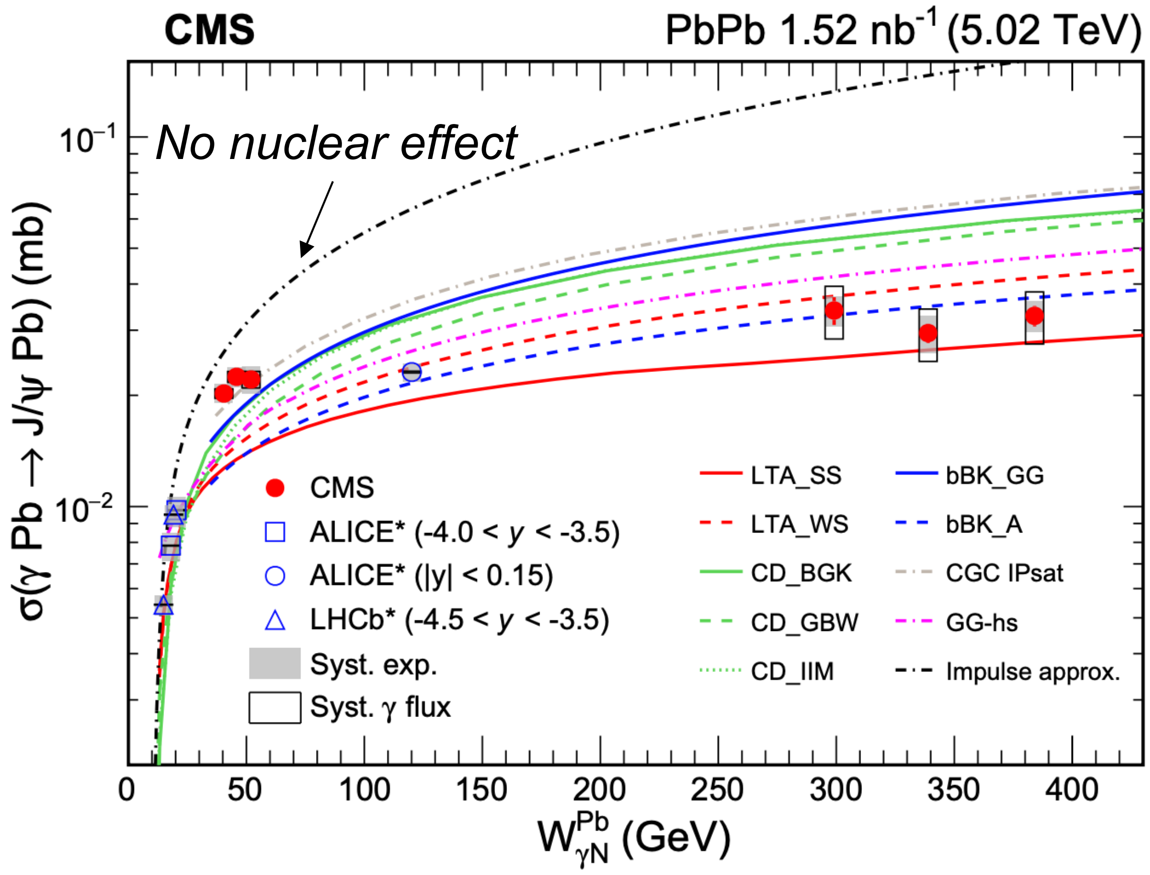
Recent UPCs coherent Jpsi highlights

Phys. Rev. Lett. 131 (2023) 26, 262301

Observation

A significant experimental indication of `**saturation**` of the cross section?

Nevertheless, a clear suppression has been seen.

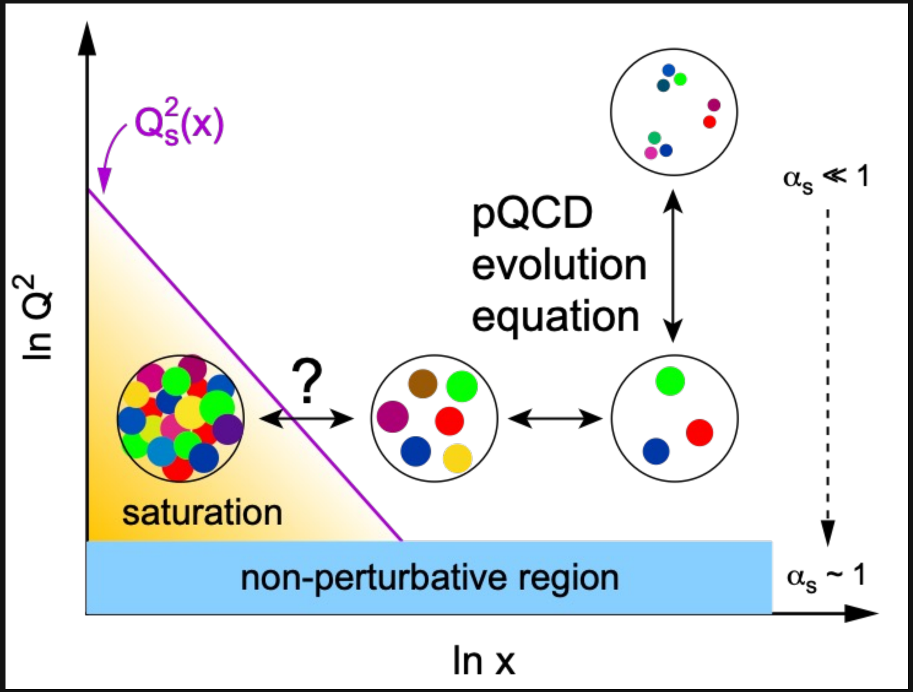


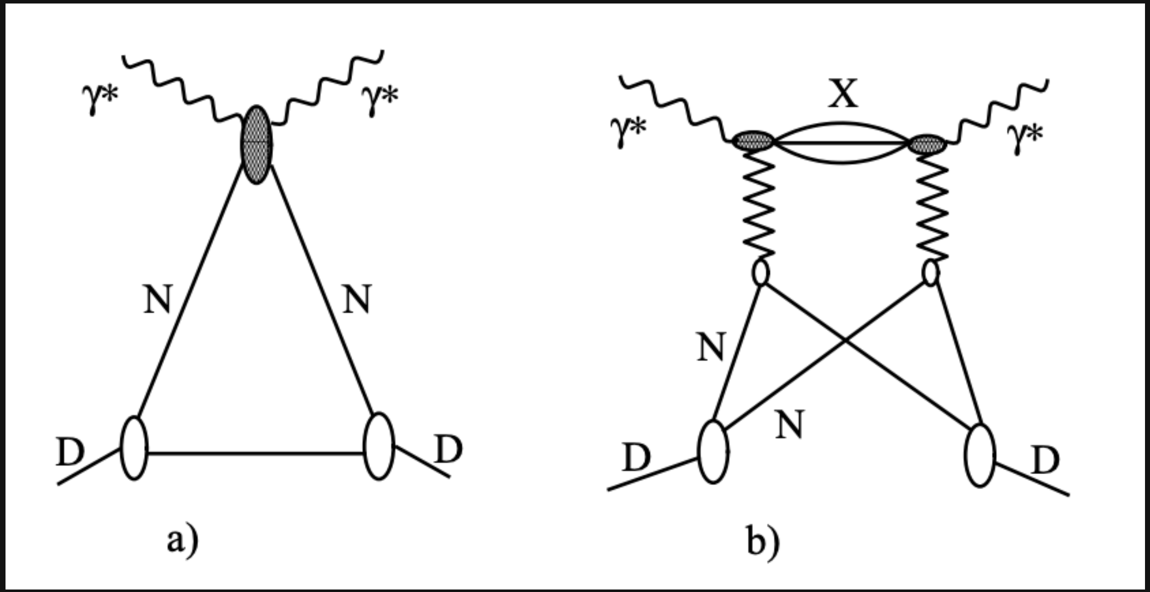
Conclusion

None of the lines (theory) can describe all the data at once.

What else can we conclude?

Digression: Saturation vs Shadowing models





L. Frankfrut,, V. Guzey, M. Strikman (Physics Reports 512 (2012) 255-393)

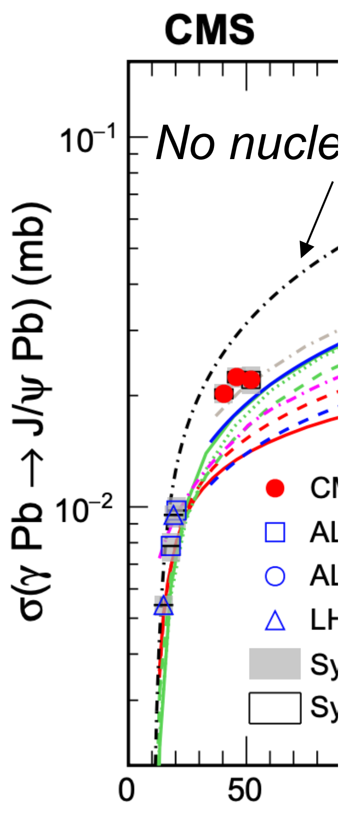
Color Glass Condensate (CGC)
Dipole-target scattering with small-x evolution equation + saturation scale Q_s

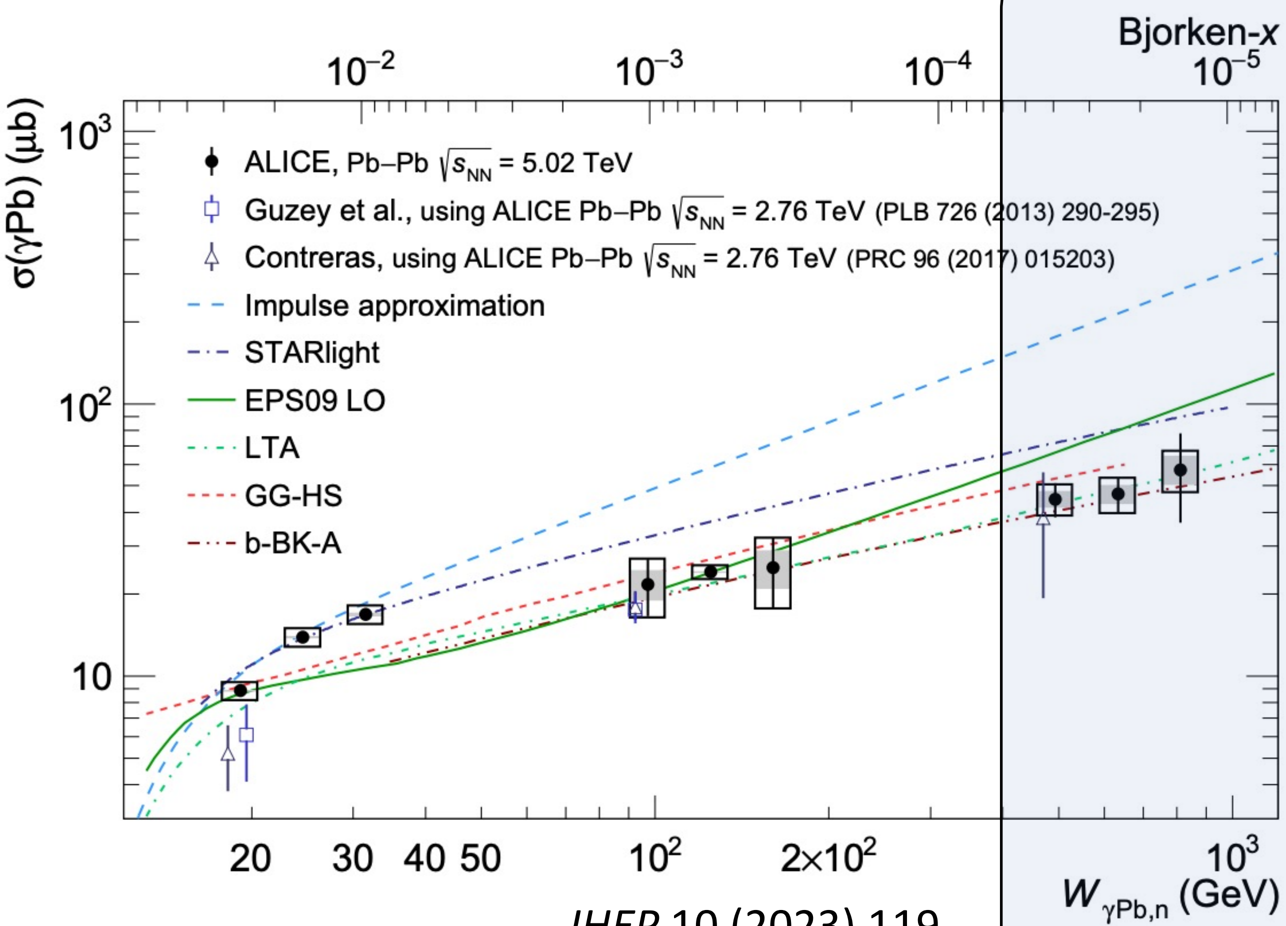
Leading Twist Approximation (LTA)
Combination of Gribov-Glauber theory, QCD factorization, and HERA diffractive data

Recent UPCs coherent Jpsi highlights

- ALICE forward coverage extends the W range even higher. But the same conclusion/question remains.

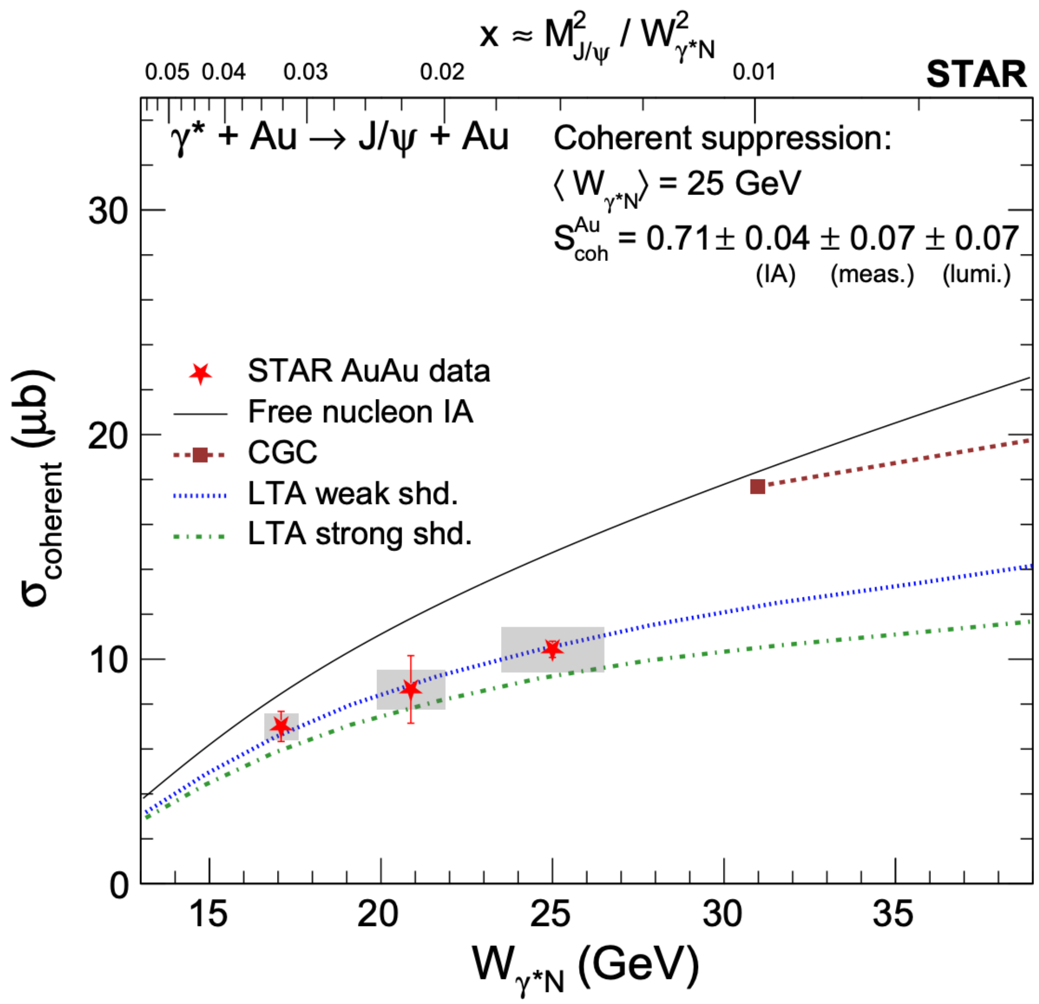
Phys. Rev. Lett. 131 (2023) 26, 262301





JHEP 10 (2023) 119

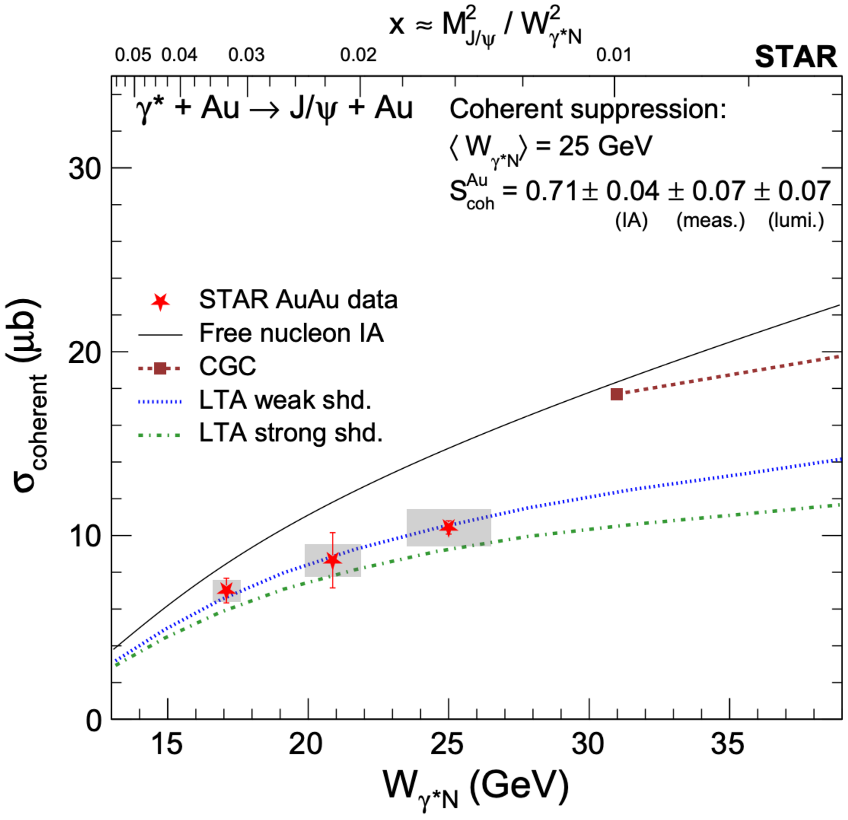
Recent UPCs coherent Jpsi highlights

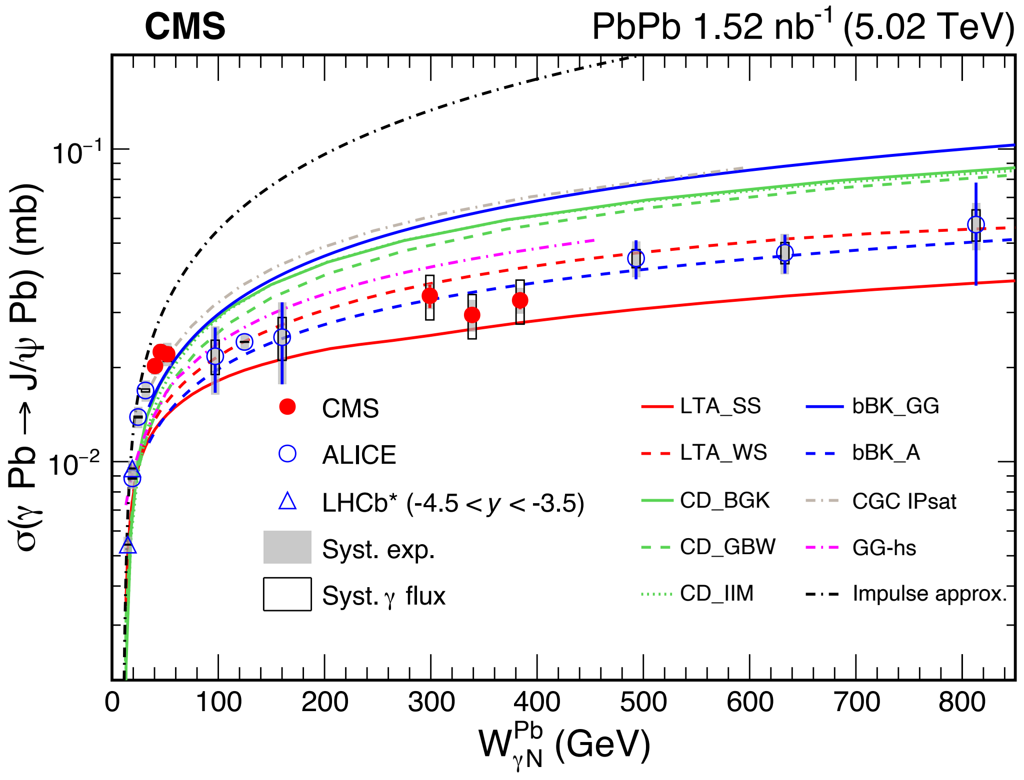


- Strong (30%) suppression seen at x ~ 0.015.
- At lower energies, saturation is NOT a valid picture. The Color Glass Condensate (CGC) calculations can only go down to W~30 GeV.
- CGC still has issues with absolute cross section estimates, while Leading Twist Shadowing (LTA) describes the data well.

Phys. Rev. C 110 (2024) 1, 014911

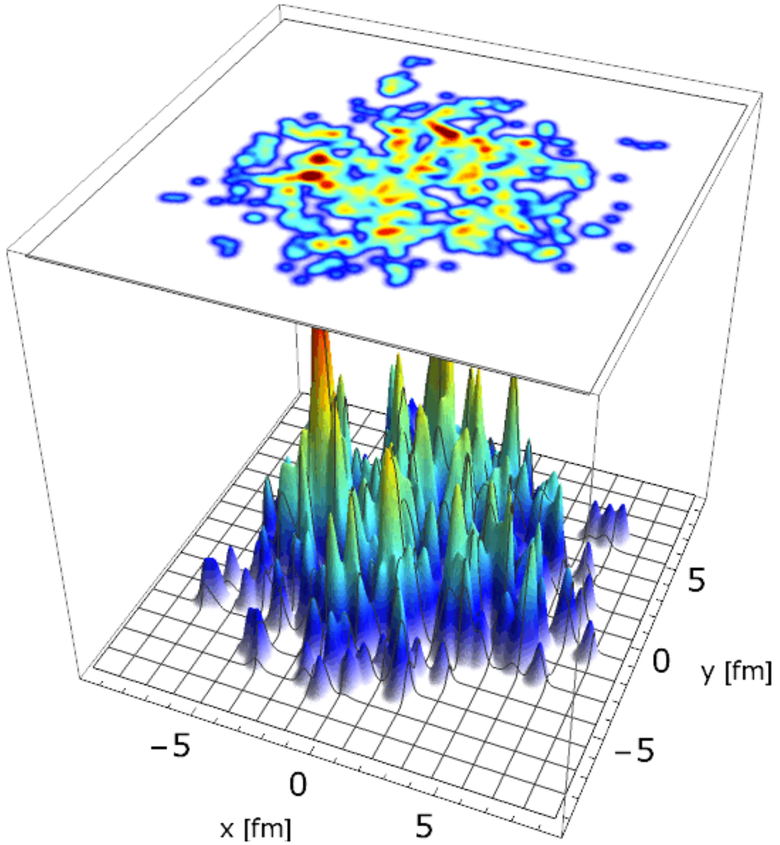
UPCs coherent Jpsi – large nuclear effects





All three experiments (ALICE, CMS, STAR) used the same experimental technique – neutron detection in ZDCs – to reach high and low energies (Eur. Phys. J. C 74, 2942 (2014))

Recent UPCs **incoherent** Jpsi highlights



A reminder:

UPCs Incoherent Jpsi (VMs) production is sensitive to sub-nucleonic fluctuations.

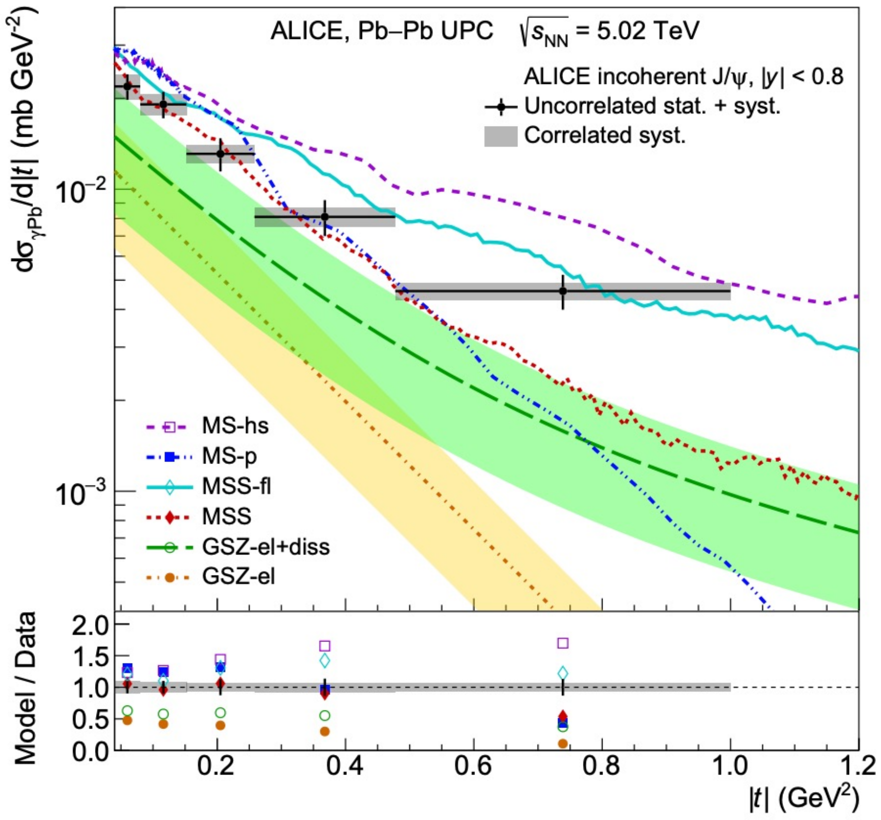
“Hint” of sub-nucleonic fluctuations?

Qualitative expectation: fluctuation → enhancement of incoherent cross section, esp higher t.

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

“Hint” of sub-nucleonic fluctuations?

Qualitative expectation: fluctuation → enhancement of incoherent cross section, esp higher t.



ALICE shines light into the nucleus to probe its structure

New ALICE results shed light on the nature of gluonic matter at the LHC

14 JULY, 2023 | By ALICE collaboration

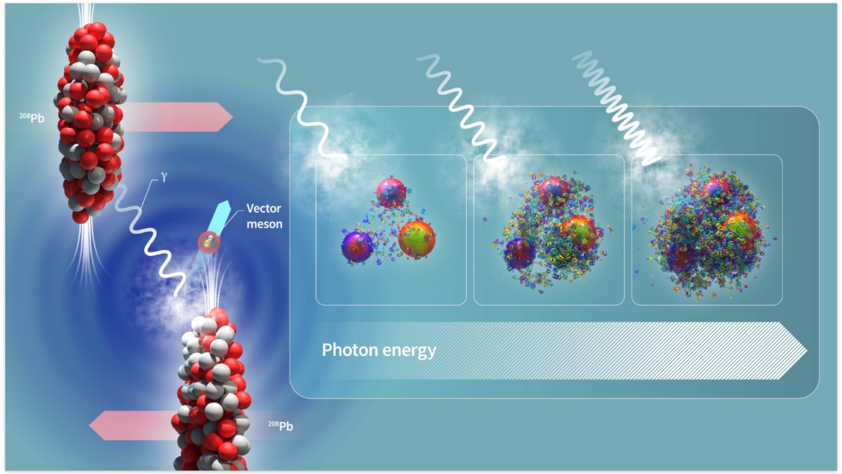
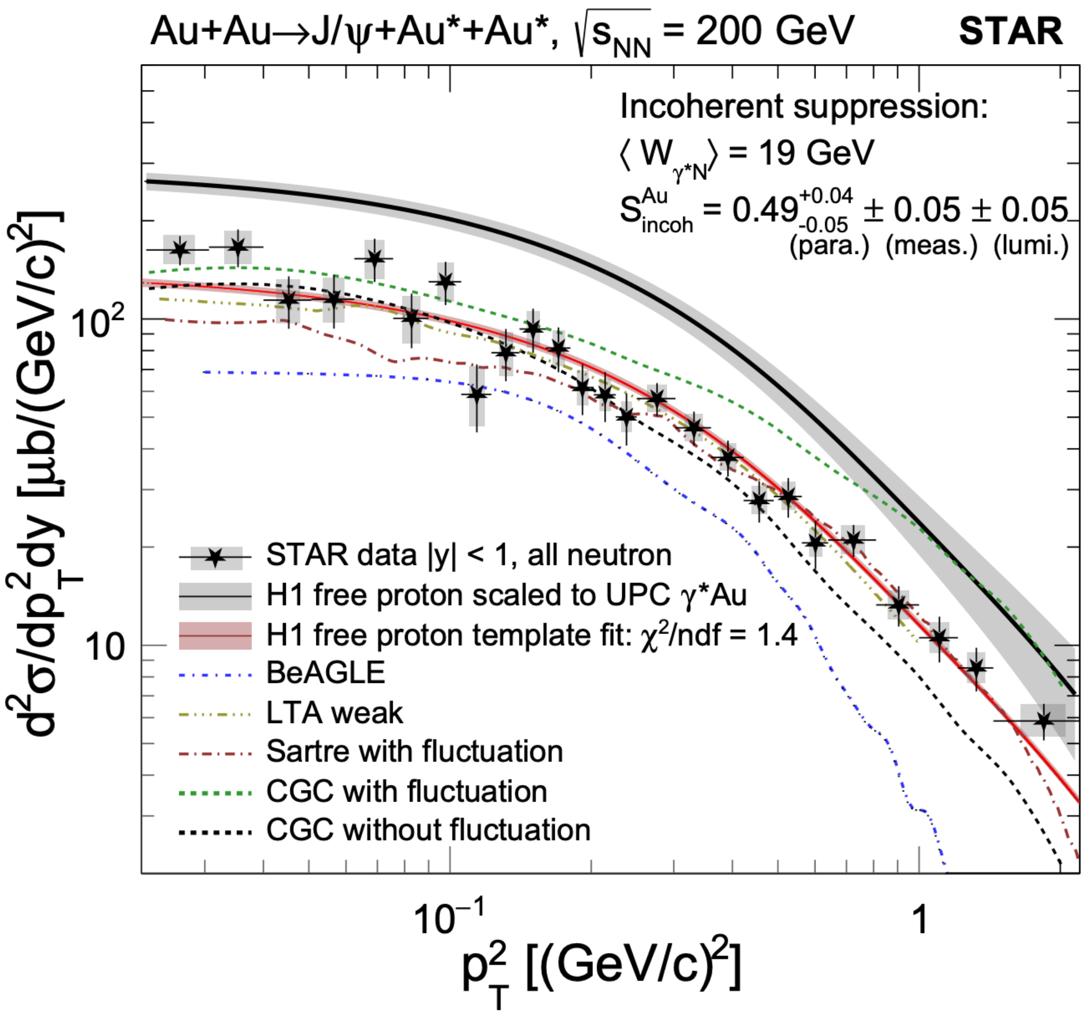


Illustration of an ultra-peripheral collision where the two lead ion beams at the LHC pass by close to each other without colliding. Photons emitted from one beam strike the other, producing electromagnetic interactions. The structure of the gluonic matter in the nucleus gets further exposed when probed by higher energy photons. (Image: CERN)

Model with the fluctuation describes the shape of the momentum transfer well, but so does the shadowing model.

STAR: extending to higher *t*

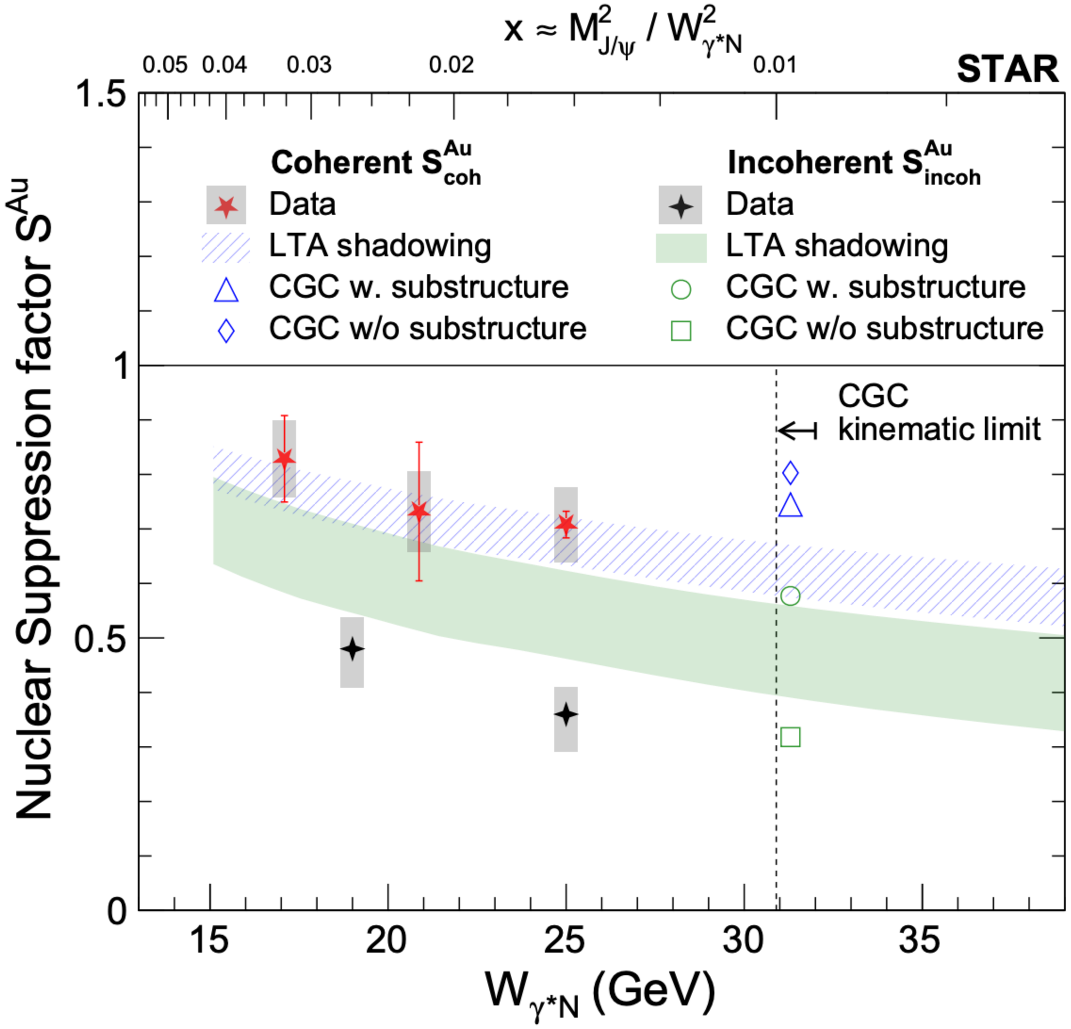


Observation:

- Consistent data with ALICE, but extended coverage.
- Energy is significantly lower! So, certainly, this shape of t isn't a unique signature of high energy (low-x) dynamics.
- Can't conclude that it directly supports the fluctuation model or not. But what it can say: **the free proton and bound nucleon have the same degree of fluctuation (or not!).**

Phys. Rev. C 110 (2024) 1, 014911

t-integrated incoherent Jpsi cross section

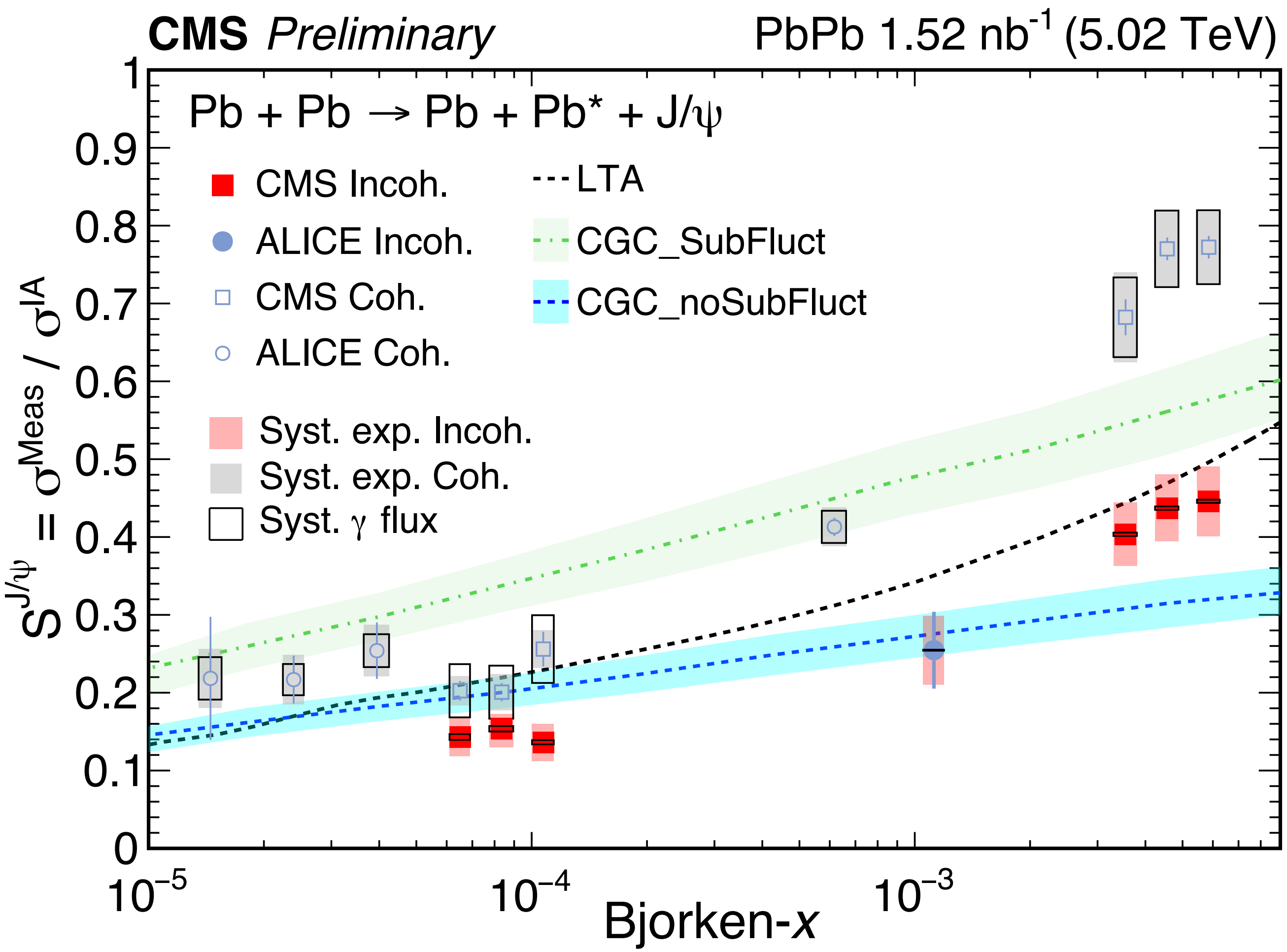


Observation:

- Large suppression has been observed, which is twice as large as the coherent counterparts.
- **Again, inconclusive if additional fluctuation can be seen on top of free protons.**

Phys. Rev. Lett. 133 (2024) 5, 052301

CMS: extending to lower x



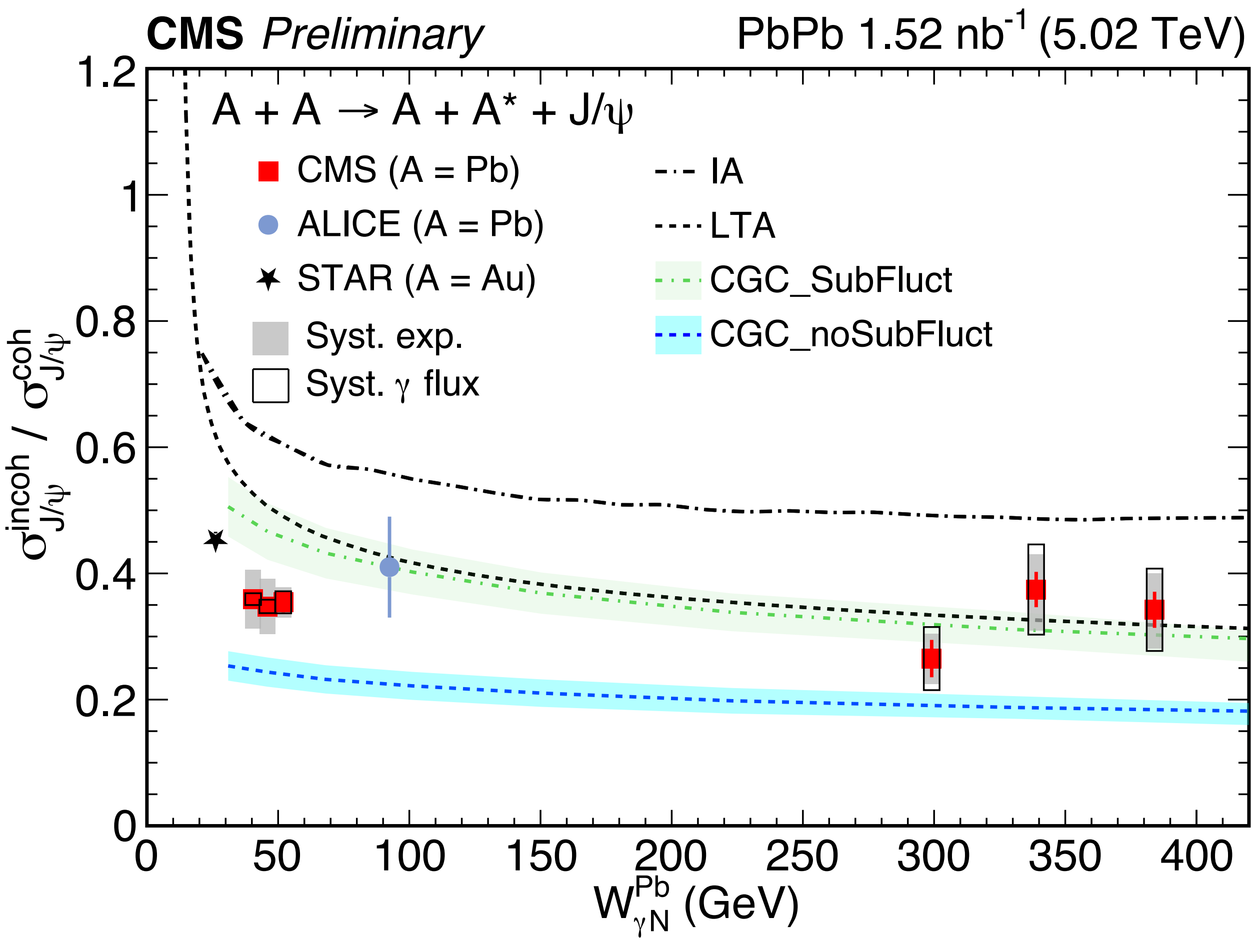
(see X. Wang's talk in the afternoon)

Observation:

- Stronger suppression at lower-x but the x-dependence is much weaker than coherent's.
- **This suppression at lower x again supports model without additional fluctuation.**

arXiv:2503.08903

Incoherent to coherent ratio



Interpretation becomes harder:

This ratio supports additional sub-nucleonic fluctuation!

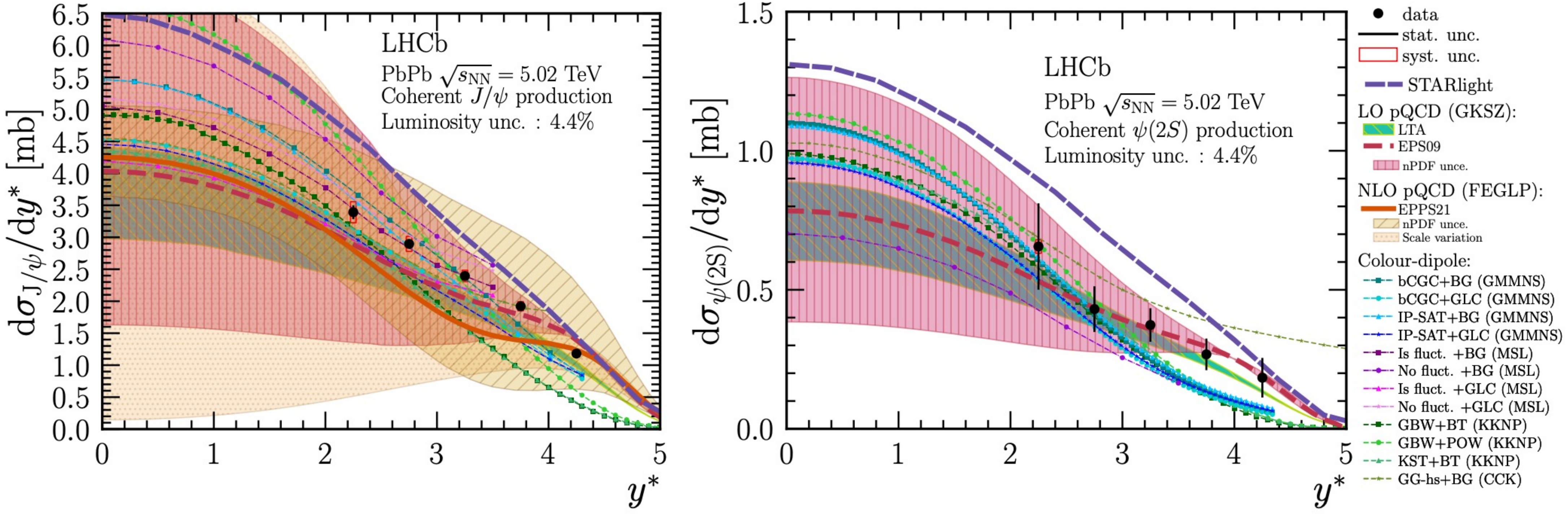
Could be due to the cancellation in normalization issue in CGC?

arXiv:2503.08903

A similar but new techniques were developed to reach higher W, see X. Wang's talk later

Challenge: **saturation**-based models vs **shadowing**-based models, and others.

JHEP 06 (2023) 146

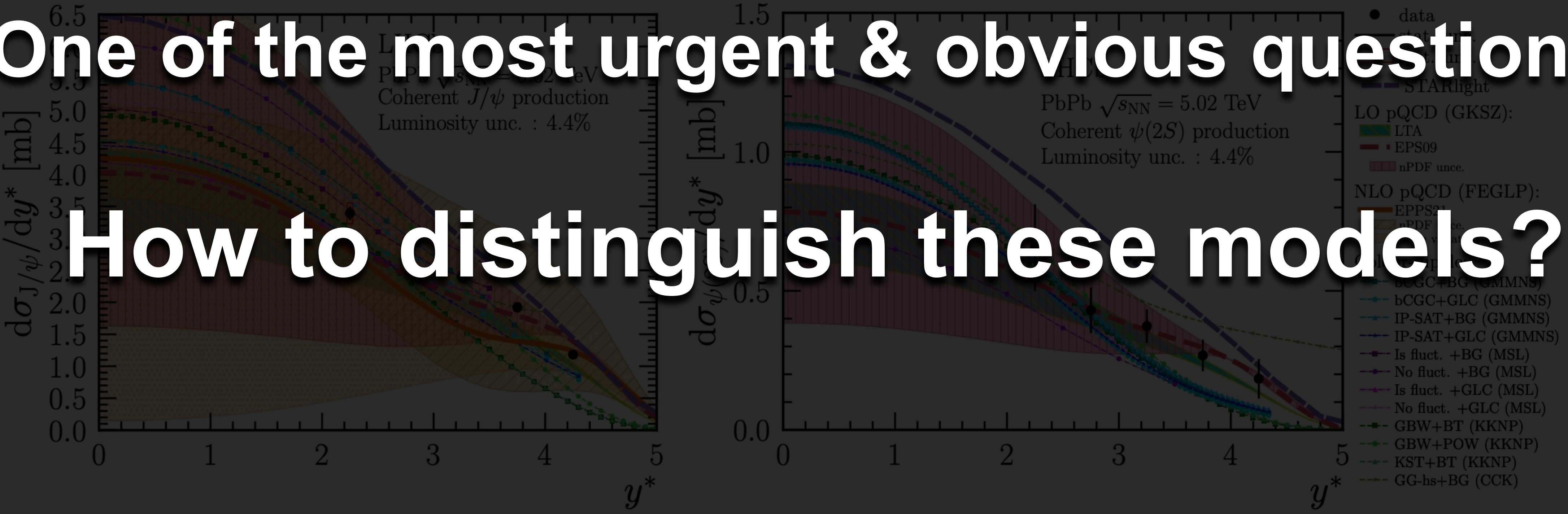


The current data precision, including ALICE, CMS, LHCb, STAR, is clearly not the bottleneck of this problem

Challenge: **saturation**-based models vs **shadowing**-based models, and others.

One of the most urgent & obvious questions:

How to distinguish these models?

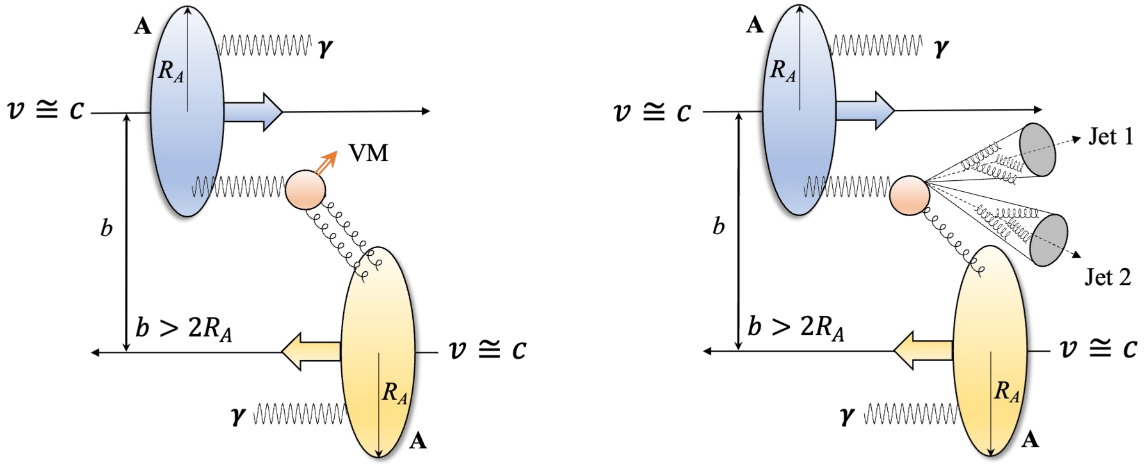


The current data precision, including ALICE, CMS, LHCb, STAR, is clearly not the bottleneck of this problem

Y. V. Kovchegov, H. Sun, ***ZT*** *(Phys. Rev. D* 109 (2024) 9, 094028)

New experimental proposal – double ratio

$$R_{\mathrm{UPC}} = \frac{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2 \mathrm{p_T} \right)\right]_{\gamma \mathrm{A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2 \mathrm{p_T} \right)\right]_{\gamma \mathrm{p}}}$$



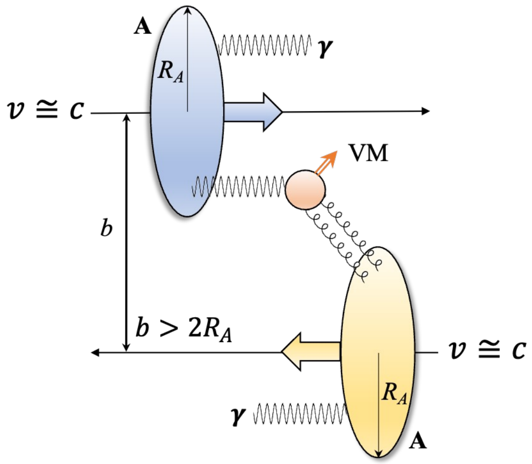
Vector Meson photoproduction

Jet photoproduction

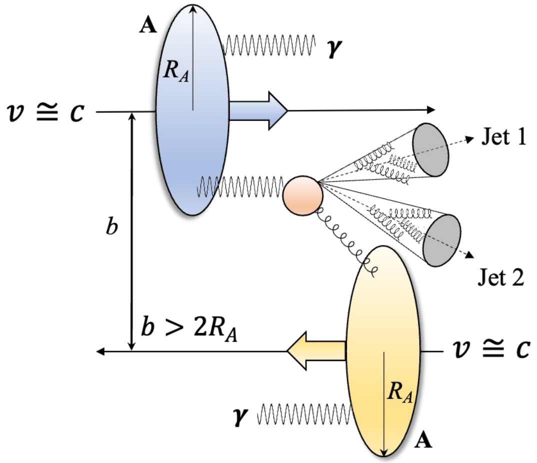
*Y. V. Kovchegov, H. Sun, **ZT** (Phys. Rev. D* 109 (2024) 9, 094028)

New experimental proposal – double ratio

$$R_{\mathrm{UPC}} = \frac{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2 \mathrm{p_T}\right)\right]_{\gamma \mathrm{A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2 \mathrm{p_T}\right)\right]_{\gamma \mathrm{p}}}$$



Vector Meson photoproduction

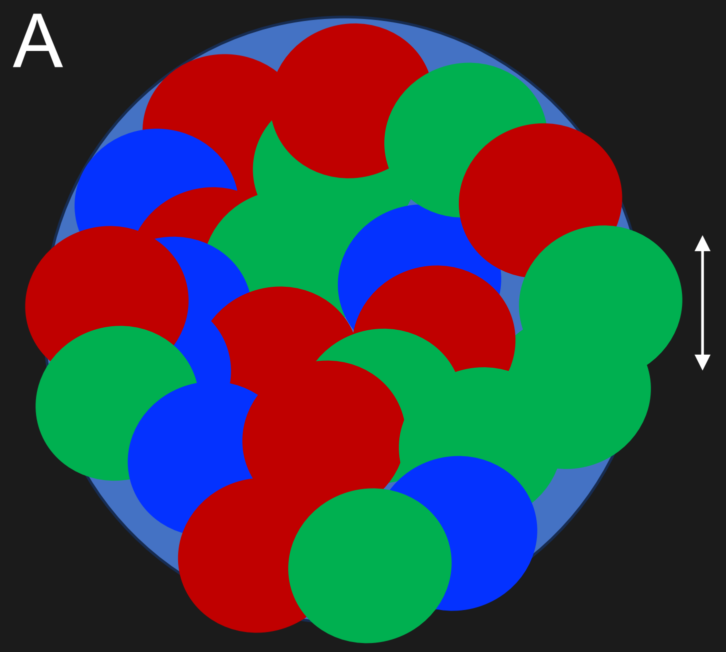


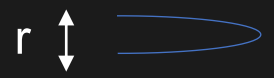
Jet photoproduction

Distinct expectation:

- Saturation: diffractive J/ψ is less suppressed than inclusive jet/*h* production.
- Shadowing: diffractive J/ψ is more suppressed than inclusive jet/*h* production

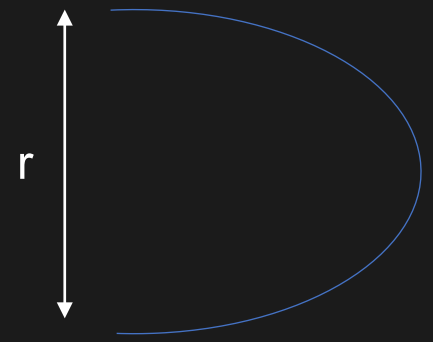
Two knobs to turn: the target and the probe





Non-saturation

$1/Q_s$ vs r = dipole size



Saturation

High energy

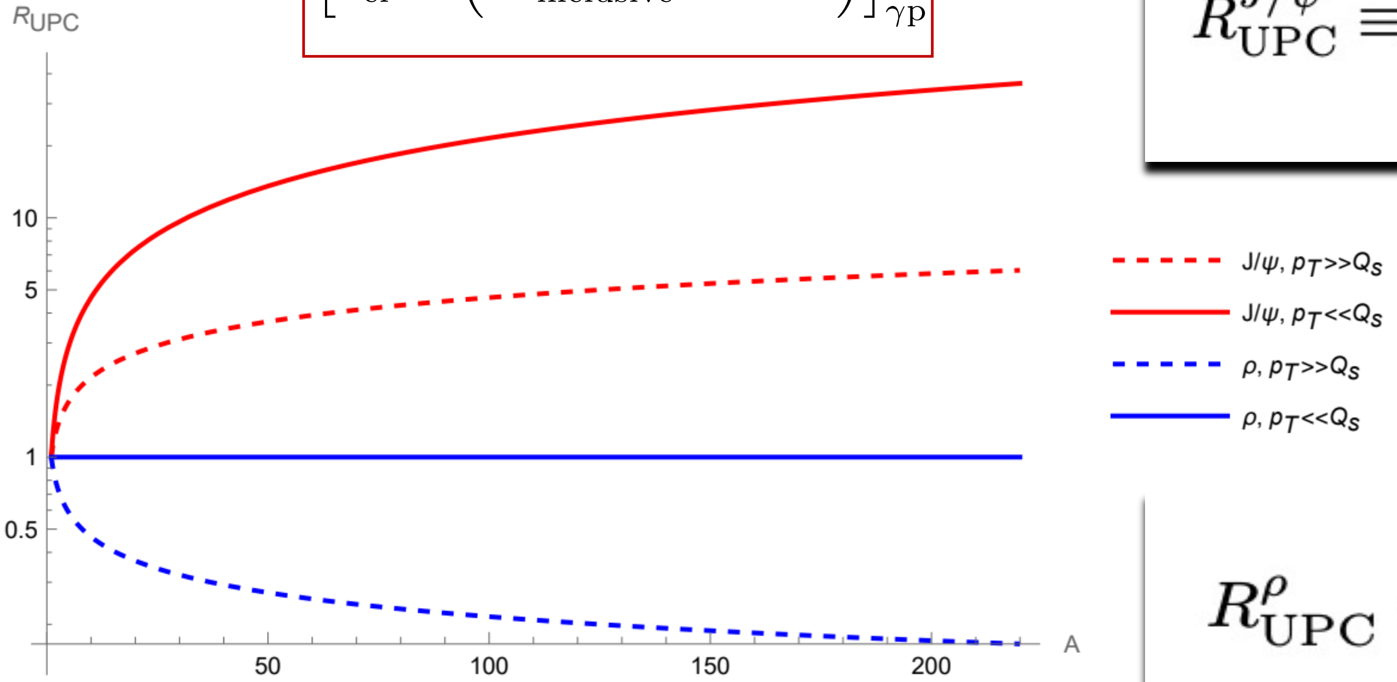
$Q_s^2 \sim (A/x)^{1/3}$

Target

Probe

CGC: A-scaling for J/ψ and ρ meson

$$R_{\mathrm{UPC}} = \frac{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2\mathrm{p_T}\right)\right]_{\gamma \mathrm{A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2\mathrm{p_T}\right)\right]_{\gamma \mathrm{p}}}$$



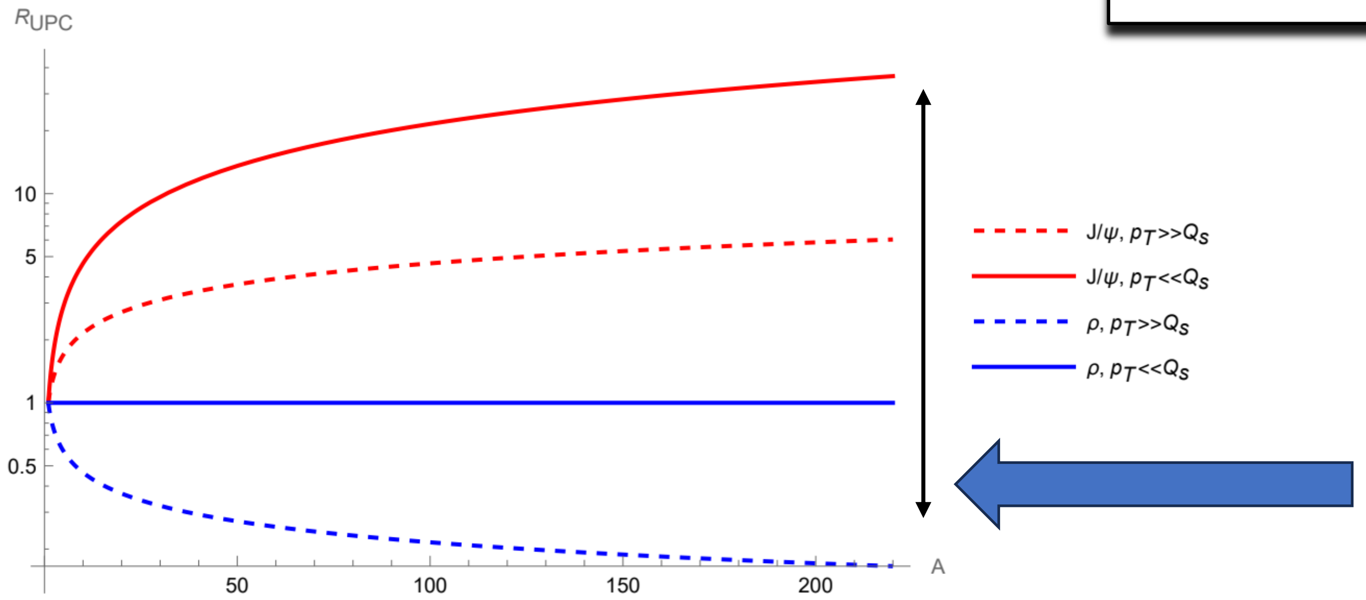
$$R_{\mathrm{UPC}}^{J/\psi} \equiv \frac{R_1^{J/\psi}(\mathrm{A})}{R_1^{J/\psi}(p)} = \begin{cases} A^{\frac{1}{3}}, & p_T \gg Q_s, \\ A^{\frac{2}{3}}, & p_T \ll Q_s. \end{cases}$$

$$R_{\mathrm{UPC}}^{\rho} = \begin{cases} A^{-\frac{1}{3}}, & p_T \gg Q_s, \\ A^0 = 1, & p_T \ll Q_s. \end{cases}$$

Shadowing model prediction for R_{UPC}?

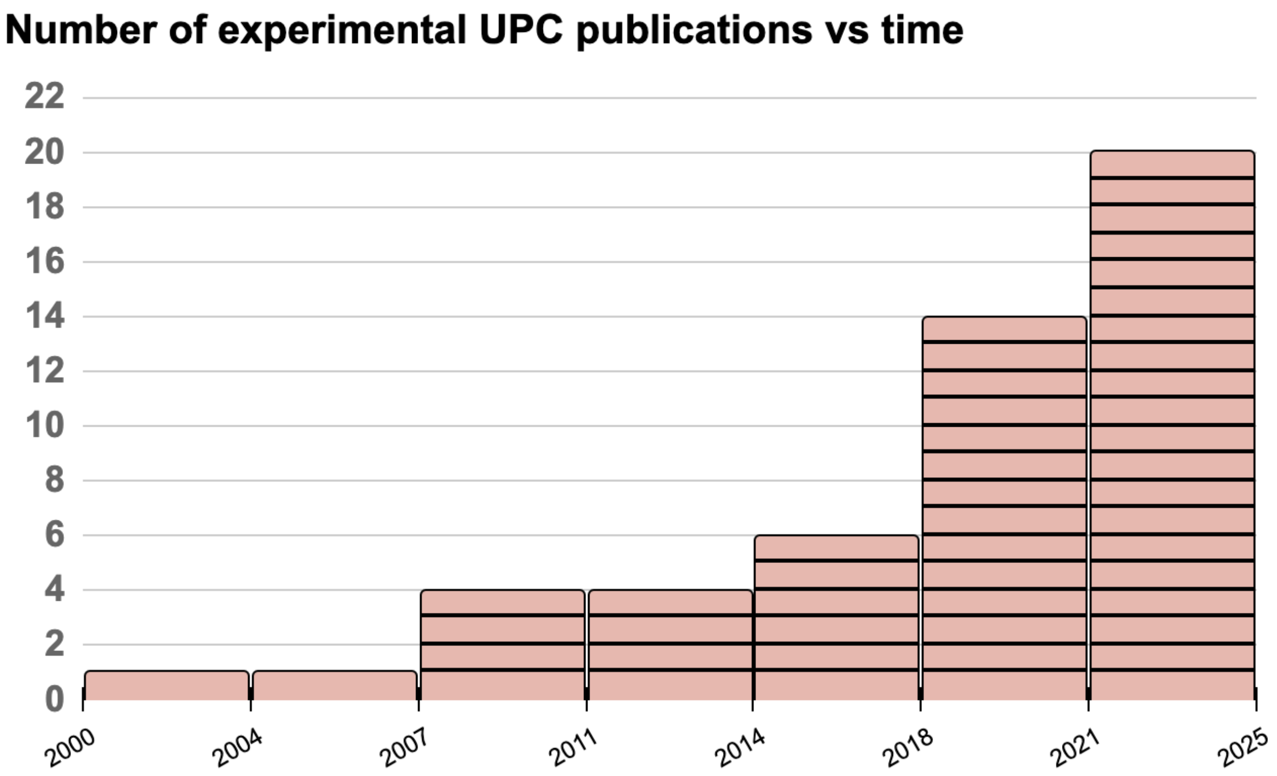
$$R_{\mathrm{UPC}} = \frac{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2 \mathrm{p_T}\right)\right]_{\gamma \mathrm{A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2 \mathrm{p_T}\right)\right]_{\gamma \mathrm{p}}}$$

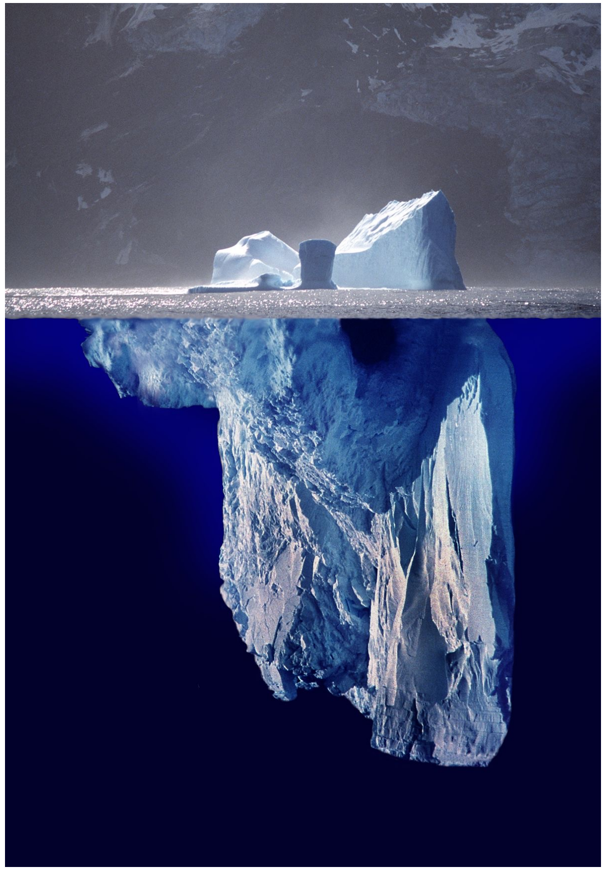
Claim: this double ratio may provide the maximal separation between the two models



My naïve expectation would be somewhere here but need proper calculations.

UPCs is booming – and still present a lot of opportunities





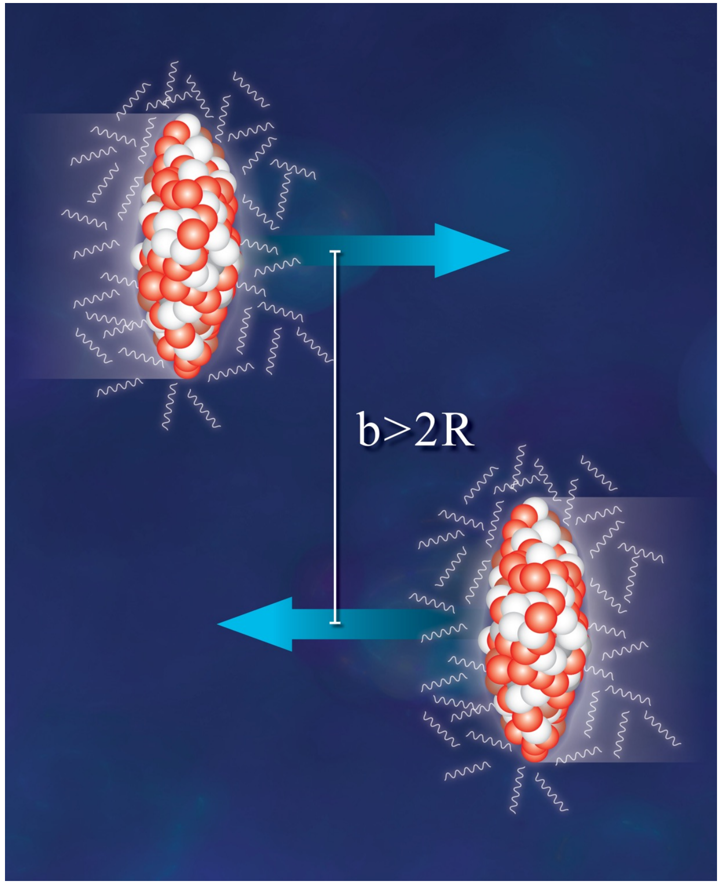
Exclusive

Semi- or inclusive

Most of these publications are **exclusive reactions** – VM (rho, Jpsi, Psi(2s)), ee,, pipi, 4pi, KK, mumu, photon-photon)

Outlook to (DIS, QM, UPC) 2025 meetings

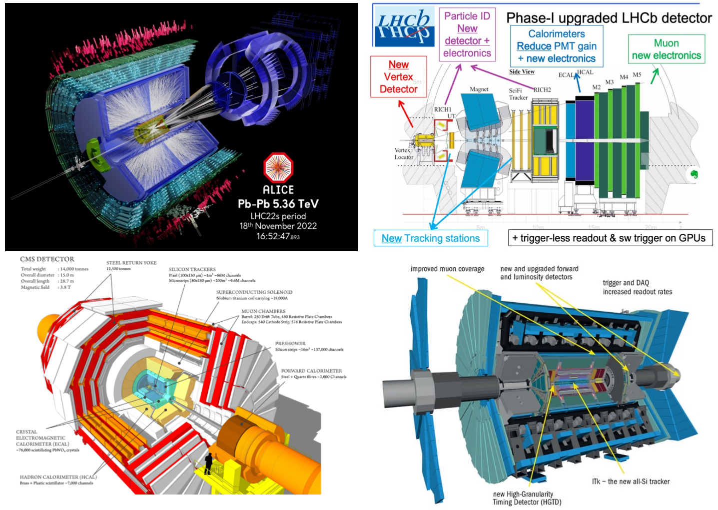
- Semi-inclusive UPCs with heavy-flavor, see G. Michele. (CMS) and T. Boettcher's (LHCb) talk
- Entanglement Enabled Intensity Interferometry (E^2I^2) with VMs, A.Ikbal's talk (STAR)
- Exclusive/semi-inclusive (di)jets productions (CMS, ATLAS)
- Exclusive phi meson photoproduction – Mass/scale dependence; (STAR, CMS, LHCb)
- …
- …*given how fast this topic is evolving, I may not catch all the (internal) developments.*

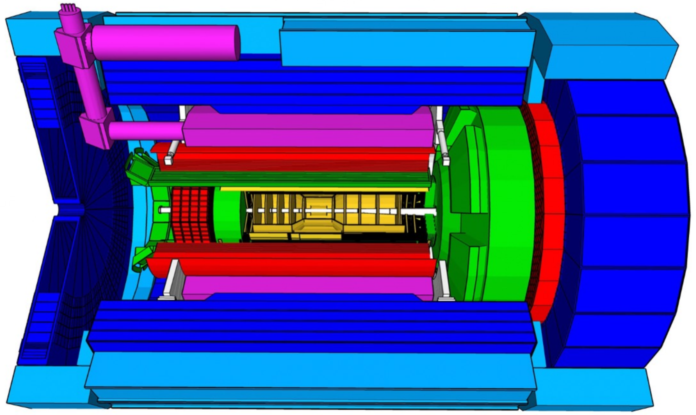


Summary and future

- Large amount of data on VMs (Jpsi, phi) in UPCs, both **coherent and incoherent**. Data precision is not the bottleneck to our understanding.
- Many models can describe part of the data – while understanding the entire phase space is the **current challenge.**
- Need more **sensitive/new probes, e.g., R_{UPC},** to distinguish models. (Shadowing vs Saturation)
- UPCs are great training grounds for transitioning to the **Electron-Ion Collider** AND have higher energy reach at the LHC.

LHC Run 3 & 4





EIC ePIC

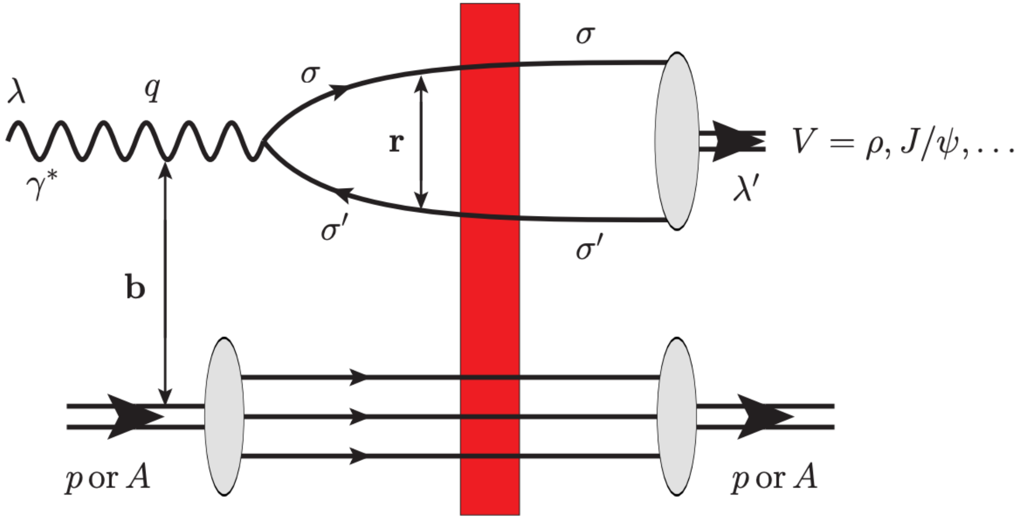
Backup

CGC: calculating the double ratio

$$R_{\mathrm{UPC}} = \frac{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2\mathrm{p_T}\right)\right]_{\gamma\mathrm{A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2\mathrm{p_T}\right)\right]_{\gamma\mathrm{p}}}$$

CGC: calculating the double ratio – Vector Meson (VM)

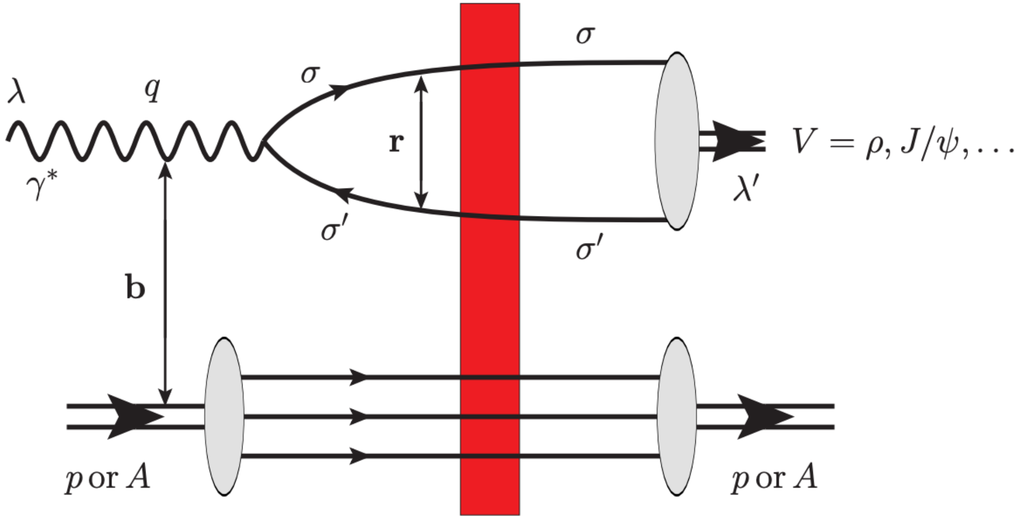
$$R_{\mathrm{UPC}} = \frac{\boxed{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}}\right.}/\left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}}/\mathrm{d}^2\mathrm{p_T}\right)\Big]_{\gamma\mathrm{A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}}/\left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}}/\mathrm{d}^2\mathrm{p_T}\right)\right]_{\gamma\mathrm{p}}}$$



Standard CGC framework, dipole amplitude from BK/JIMWLK, GGM/MV model for initial condition, etc.

CGC: A-scaling for J/ψ and ρ meson

$$R_{\mathrm{UPC}} = \frac{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2 \mathrm{p_T}\right)\right]_{\gamma \mathrm{A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2 \mathrm{p_T}\right)\right]_{\gamma \mathrm{p}}}$$



Standard CGC framework, dipole amplitude from BK/JIMWLK, GGM/MV model for initial condition, etc

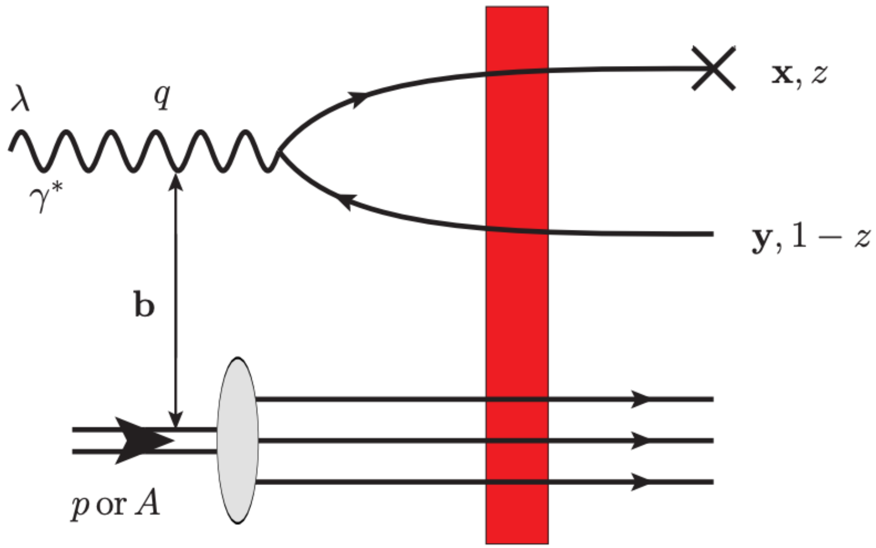
$$\sigma_{\mathrm{el}}^{\gamma^* \mathrm{A} \to V \mathrm{A}} \propto \begin{cases} A^{4/3}, & \text{outside the saturation region,} \\ A^{2/3}, & \text{inside the saturation region.} \end{cases}$$

J/ψ

ρ

CGC: calculating the double ratio – inclusive quark

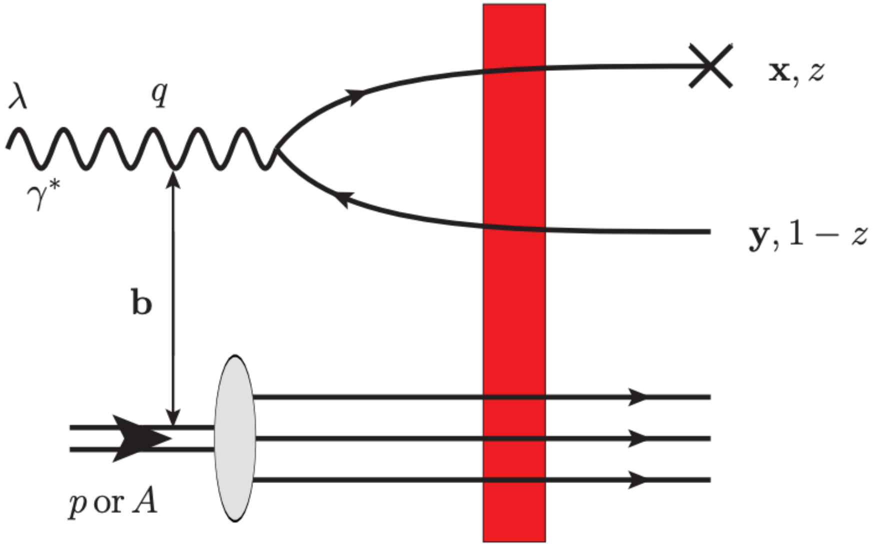
$$R_{\mathrm{UPC}} = \frac{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \boxed{\left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2\mathrm{p_T}\right)}\right]_{\gamma\mathrm{A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2\mathrm{p_T}\right)\right]_{\gamma\mathrm{p}}}$$



Similar calculations, except quark-antiquark pair doesn't become VM, target breaks up so no color-singlet, etc. **"X" is the measured parton.**

CGC: calculating the double ratio – inclusive quark

$$R_{\mathrm{UPC}} = \frac{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \boxed{\left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2\mathrm{p_T}\right)}\right]_{\gamma\mathrm{A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{hadron/jet}} / \mathrm{d}^2\mathrm{p_T}\right)\right]_{\gamma\mathrm{p}}}$$



Similar calculations, except quark-antiquark pair doesn't become VM, target breaks up so no color-singlet, etc. **"X" is the measured parton.**

$$\frac{d\sigma}{d^2p_T} \propto \begin{cases} A, & p_T \gg Q_s, \\ A^{2/3}, & p_T \ll Q_s. \end{cases}$$