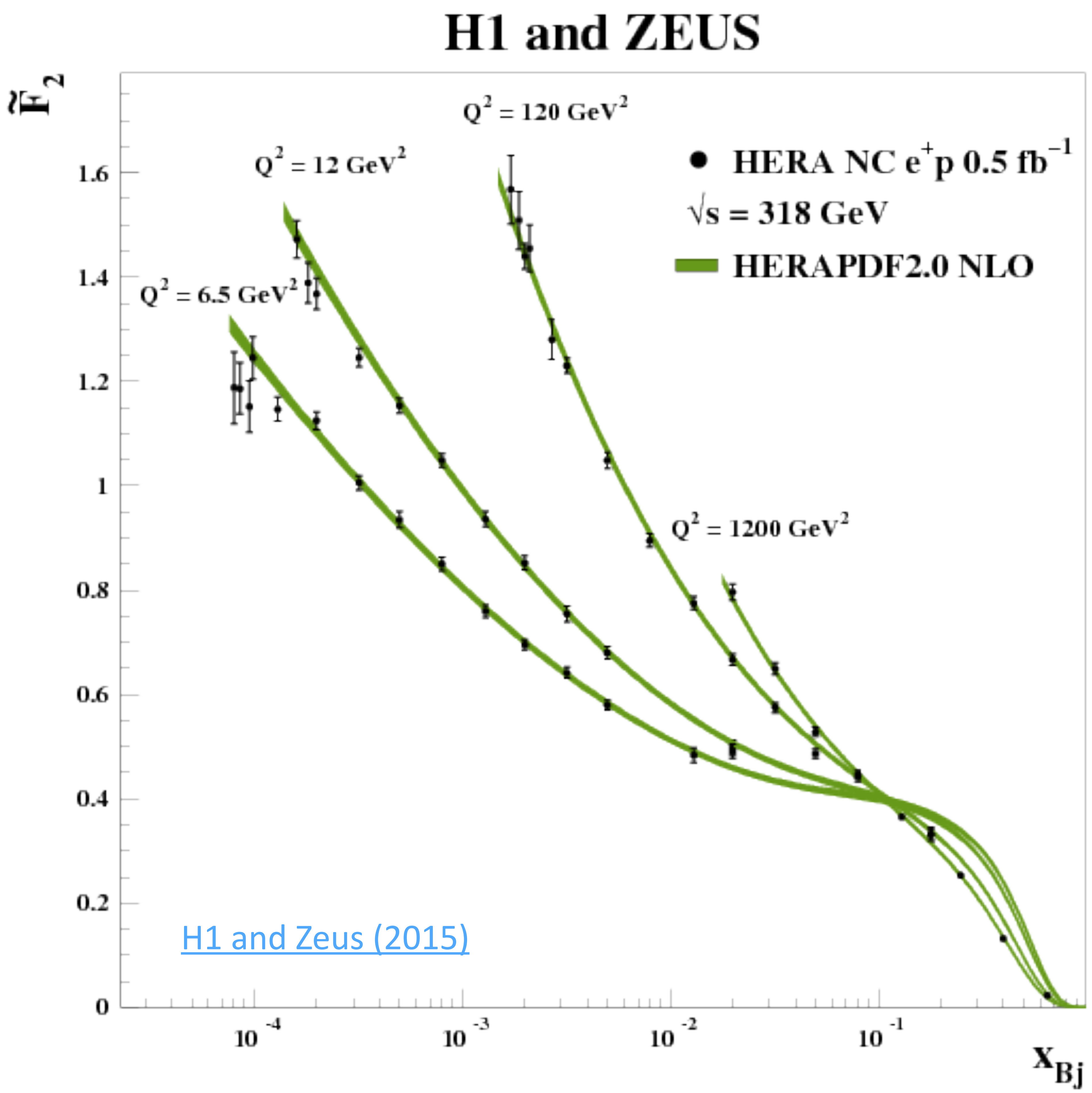
**Mining for gluon saturation at the LHC and future EIC**
**GSI Darmstadt (July 6-10, 2026)**

# Searching for gluon saturation with diffractive photonuclear production of J/ψ with ALICE

**Guillermo Contreras**
**Czech Technical University in Prague**
**(on behalf of the ALICE collaboration)**

# Hadron structure at small x

# The QCD structure of protons




H1 and Zeus (2015)

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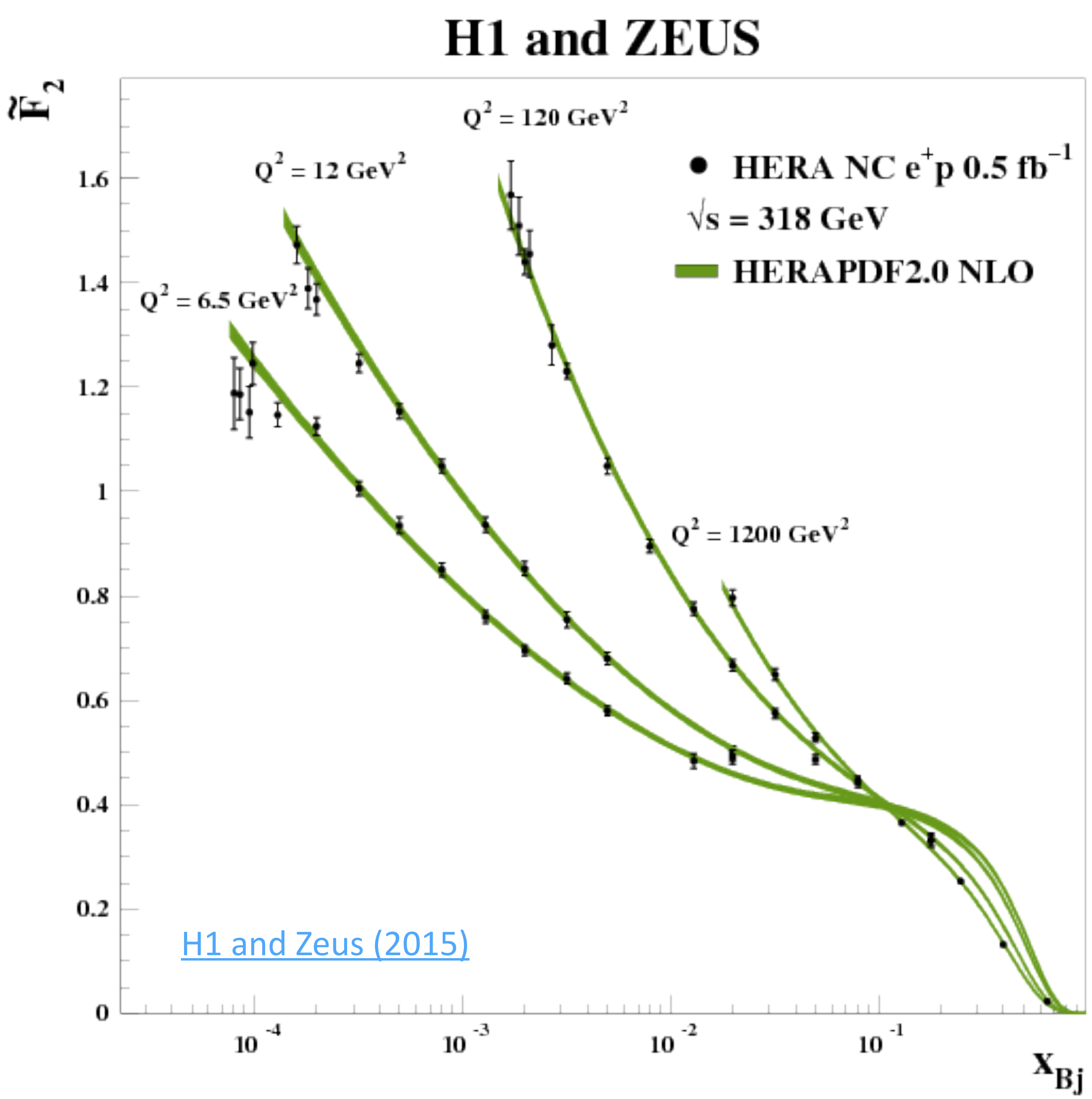


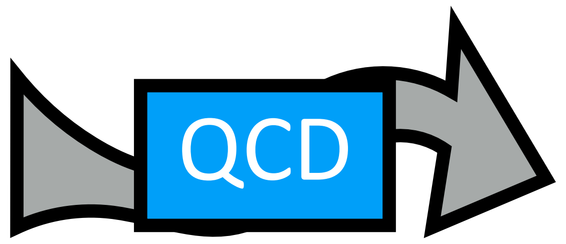


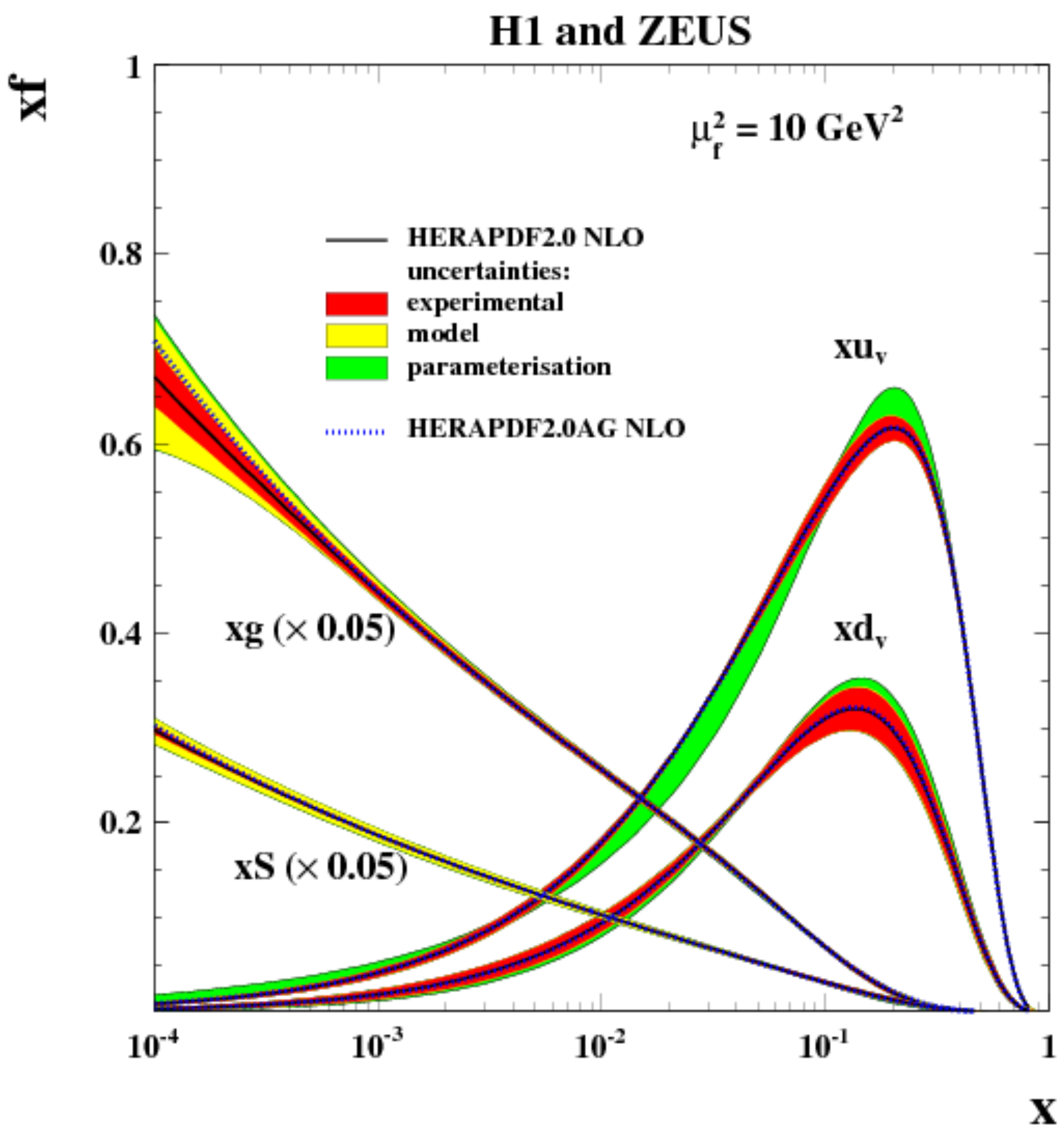


Within pQCD, at small x the proton is mainly made of gluons, whose density grows as a power law with energy

# QCD: gluon saturation at small $x$

Gribov, Levin, Ryskin (1983)
Muller (1989)
Balitsky (1996),
Kovchegov (1999), (2000) ...

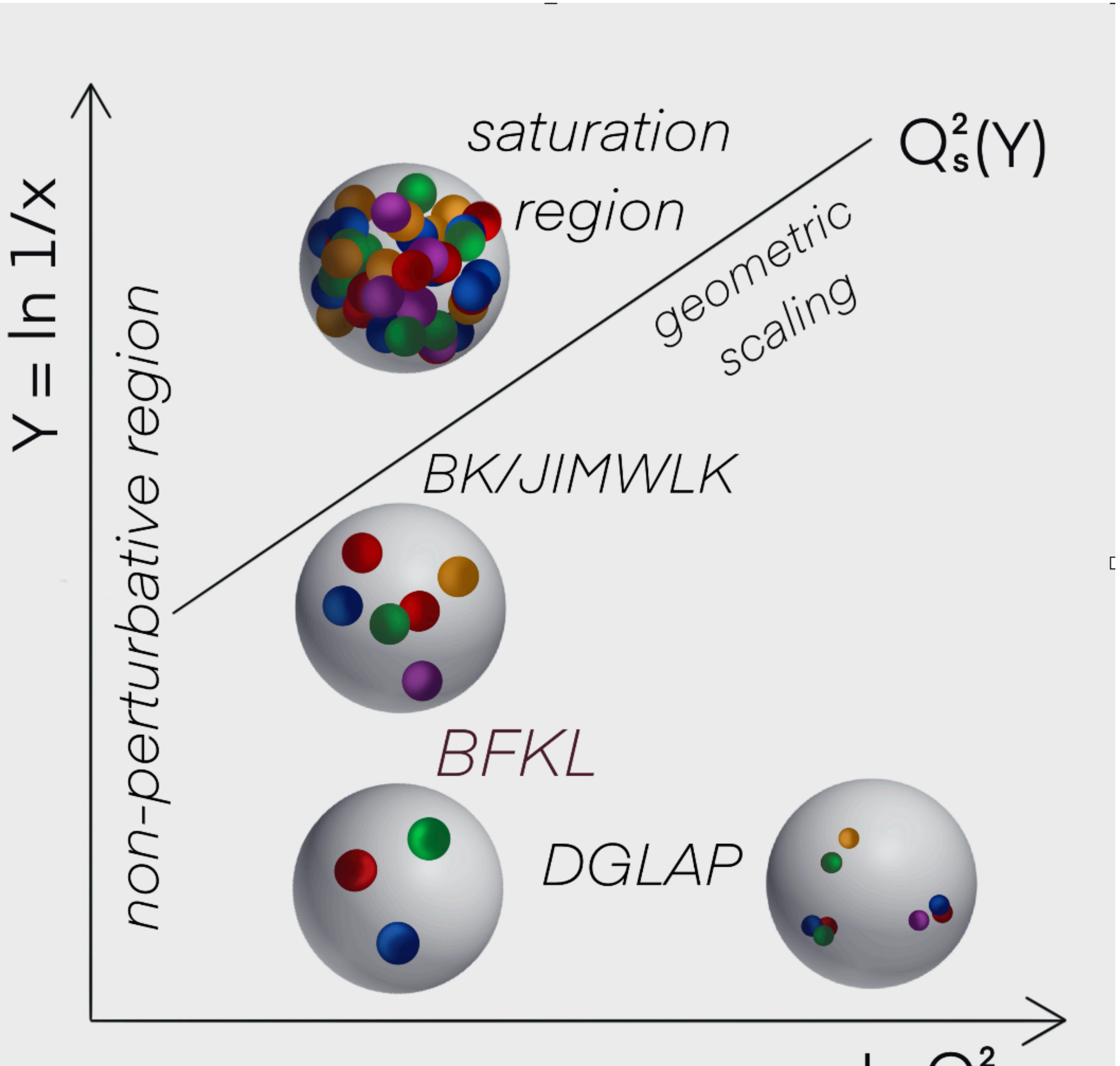


Diagram by Alexandra Ridzikova

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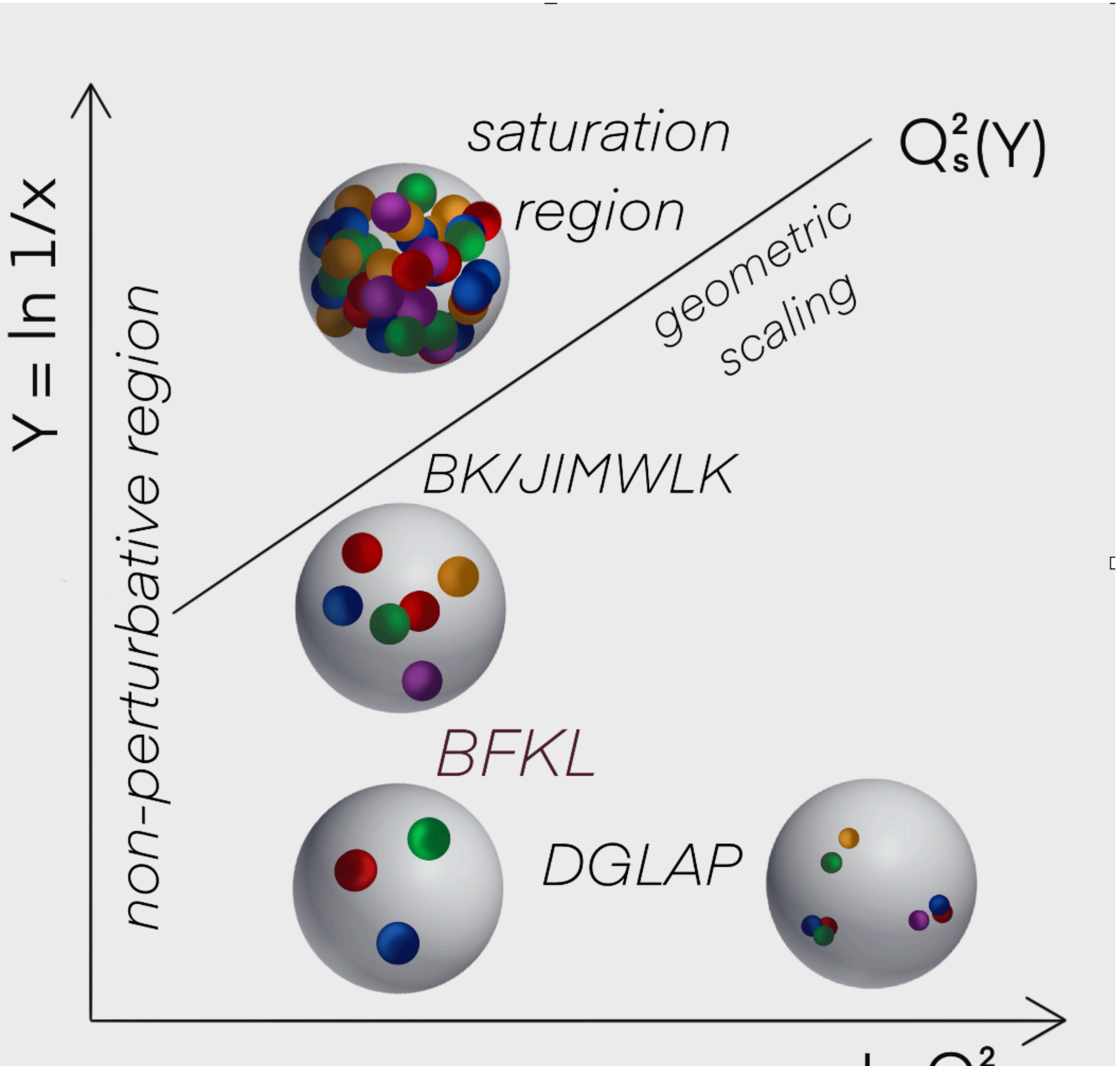
The cross section cannot grow "forever" as a power law without violating basic tenets of QM

In QCD a mechanism to deal with this is to include, besides gluon splitting, also gluon recombination processes

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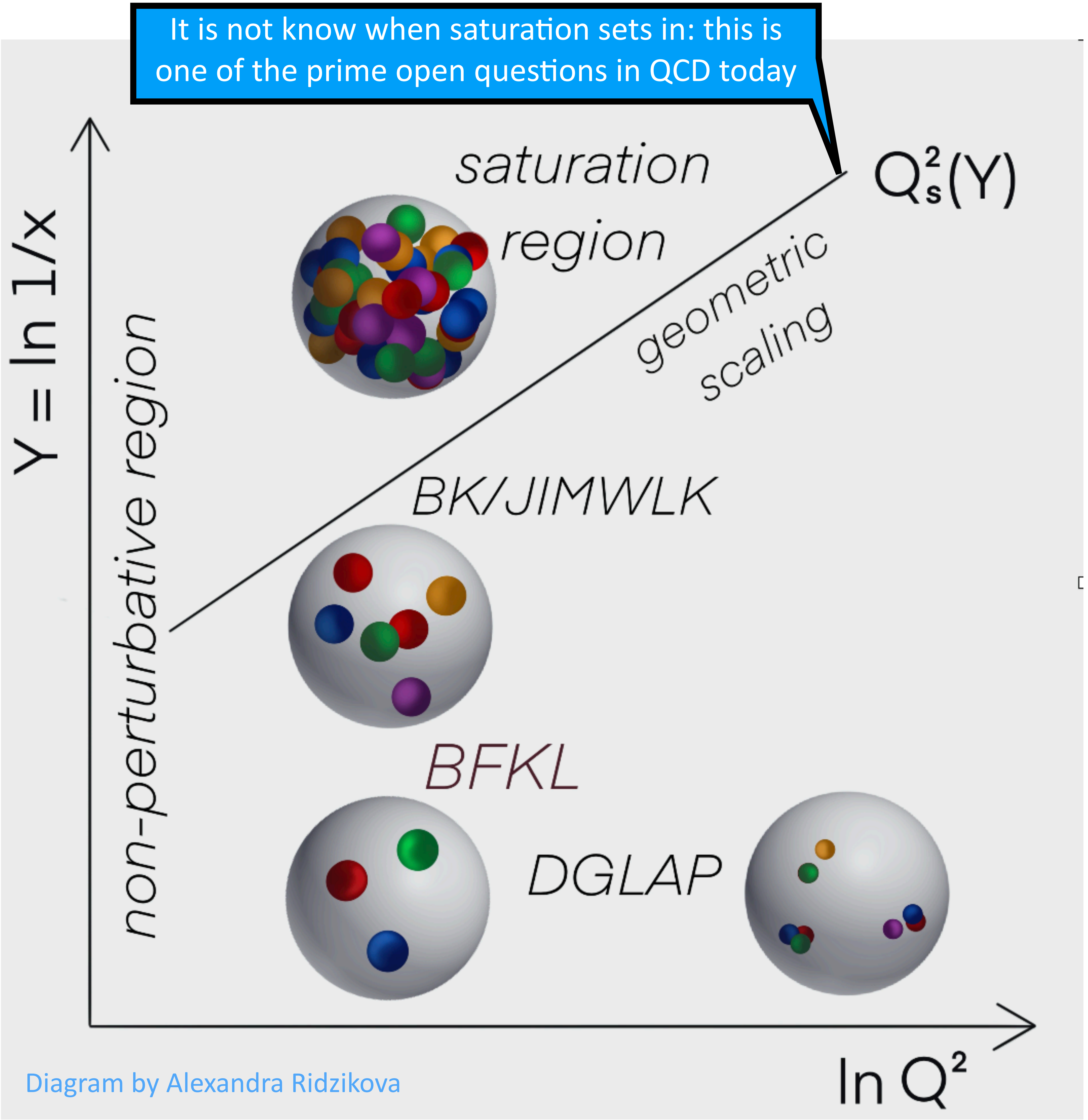
Gluon saturation sets in when the creation and annihilation of gluons reach a dynamic equilibrium



# Diffractive vector meson production and saturation

Ryskin (1993)

To look for saturation, we want a process that is very sensitive to the gluon distribution in hadrons and that can be experimentally studied in a large range of $x$ at a fixed $Q^2$

In QCD, particles interact strongly, without exchanging net colour charges, in processes that are called diffractive. In particular, a photon can interact diffractively to create a vector meson like the J/ψ or ρ or ....

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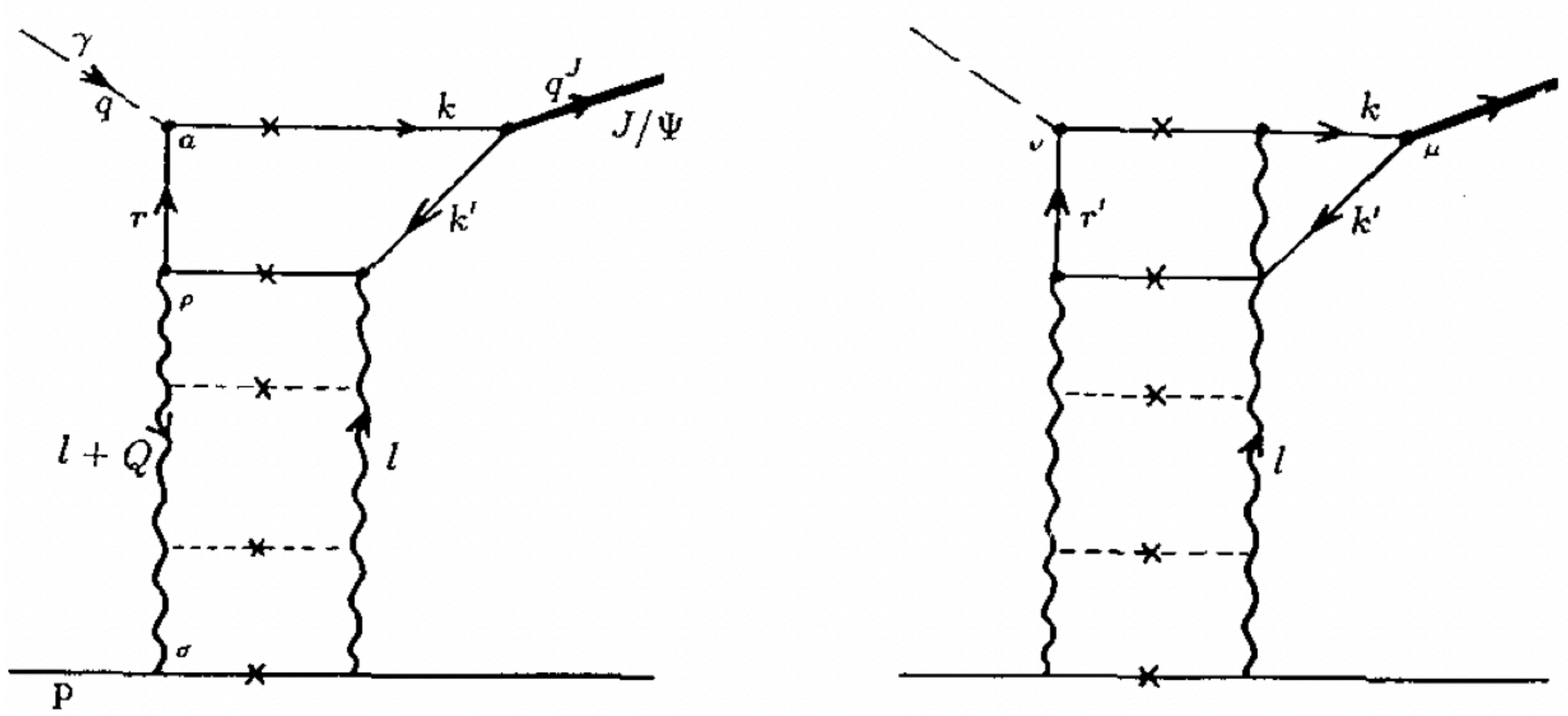

$x = (m^2 + Q^2)/(W^2 + Q^2)$

Note the square!

$$\frac{d\sigma}{dt} \propto \left[xG(x, Q^2)\right]^2$$

gluon distribution

Scale normally taken as $(m^2 + Q^2)/4$

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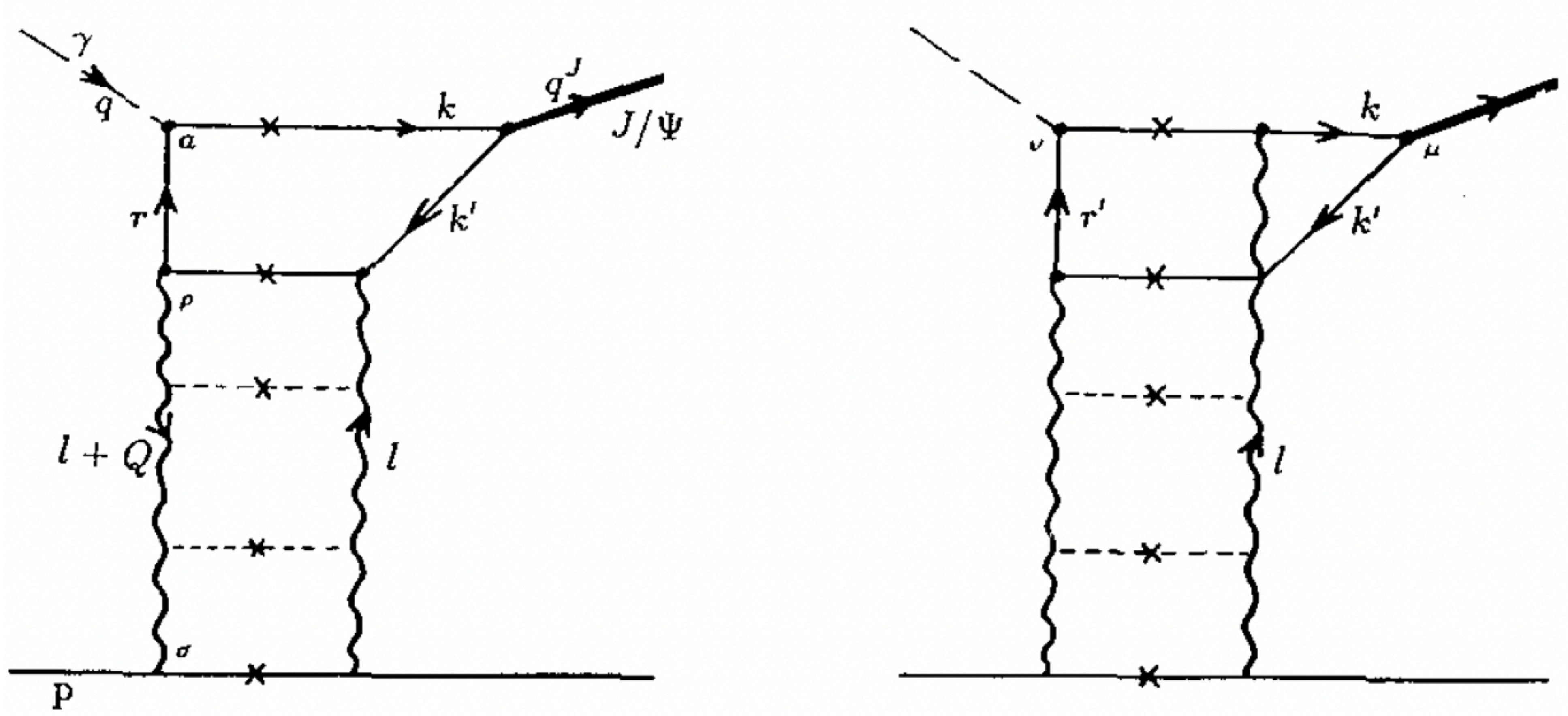


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From the paper:

Thus, the diffractive $J/\Psi$ production provides us with a good chance to find the real position of the saturation boundary and, hence, to answer this question.

# The Good-Walker approach

Good and Walker (1960)
Miettinen and Pumpling (1979)
Mantysaari and Schenke (2016) ...

In diffraction there is no colour exchange:
The incoming hadron can be seen as a superposition of basis states, each of which is absorbed differently

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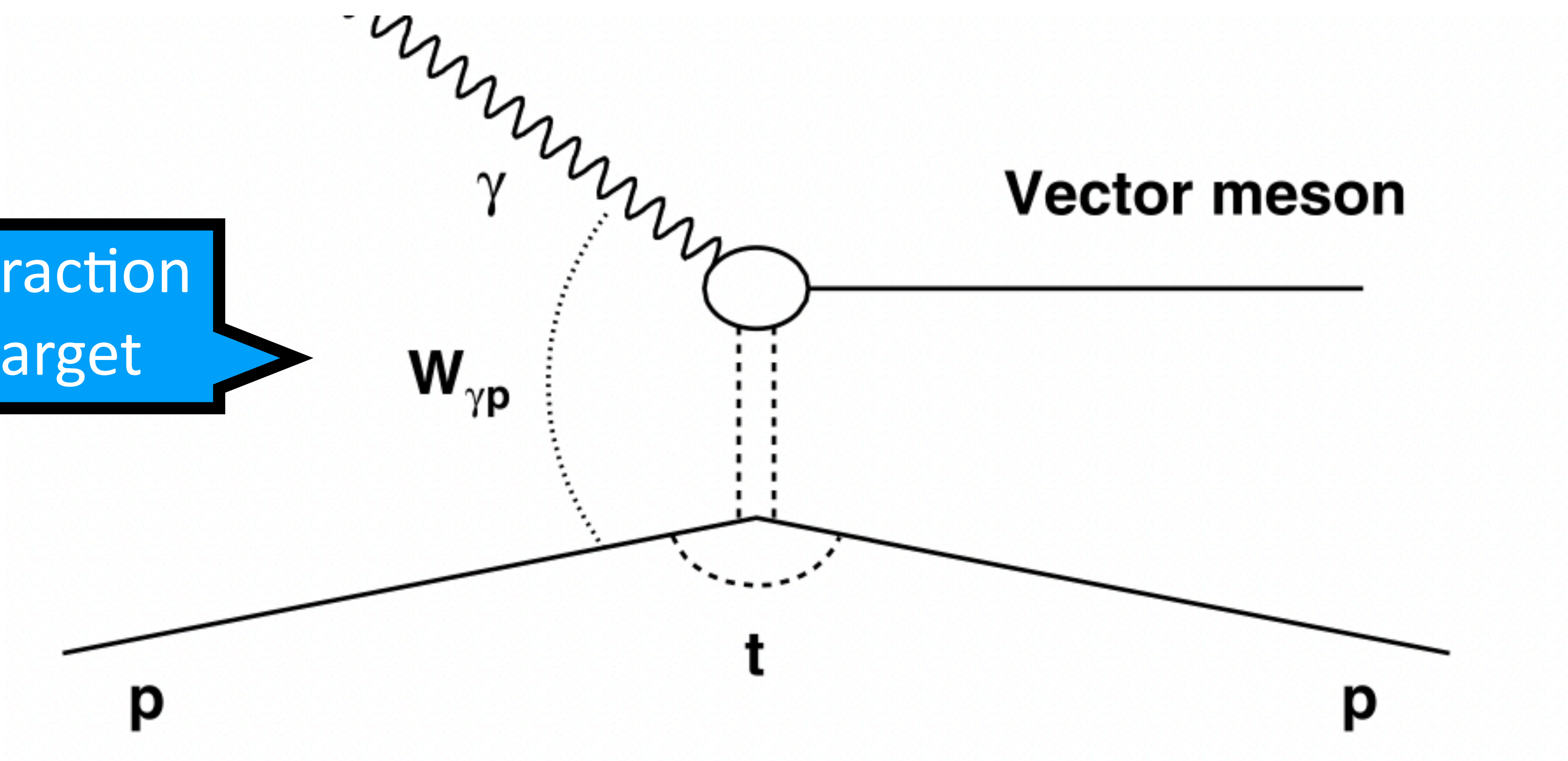
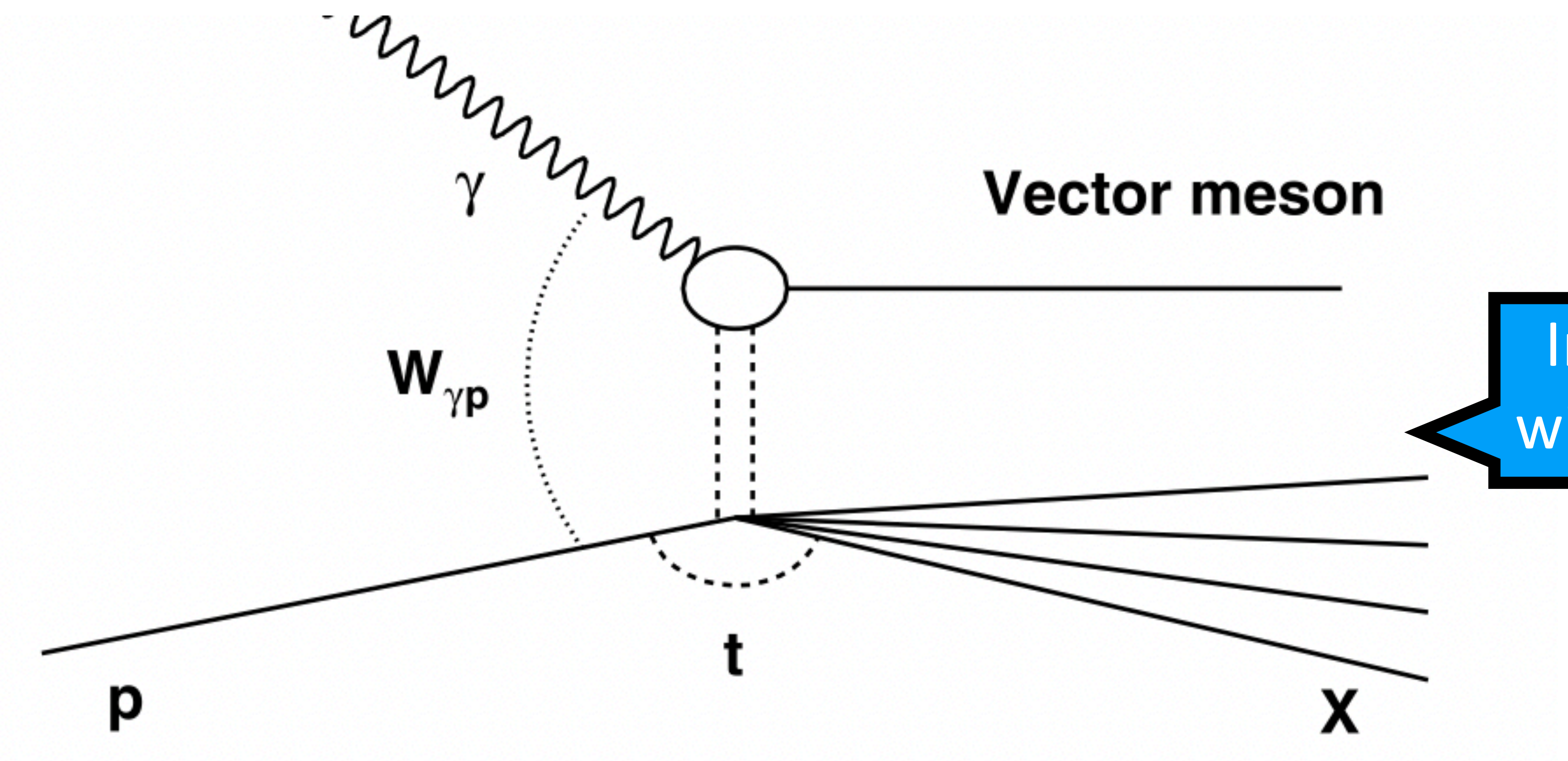
Coherent: interaction with all the target




Incoherent: interaction with a piece of the target

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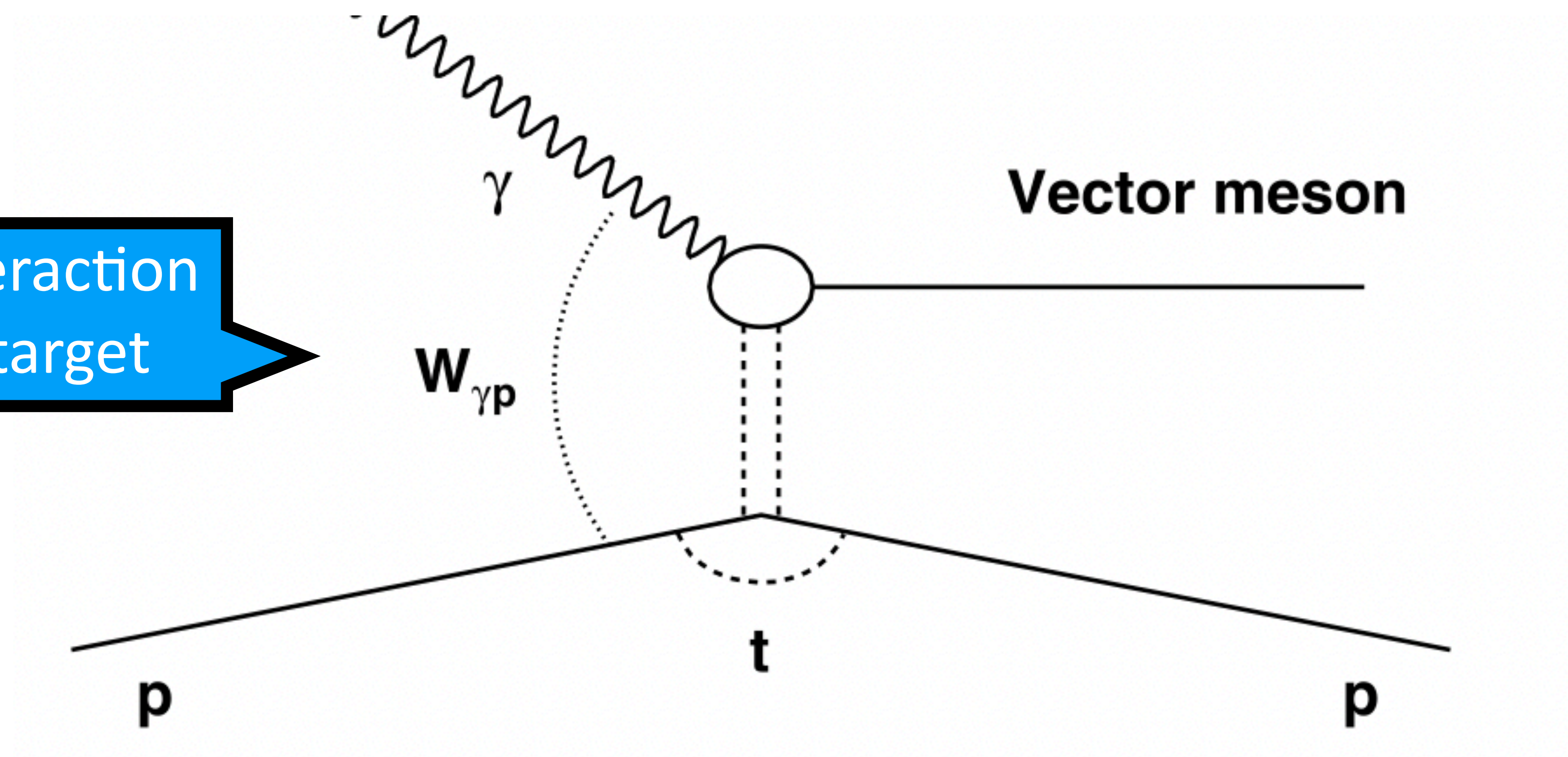
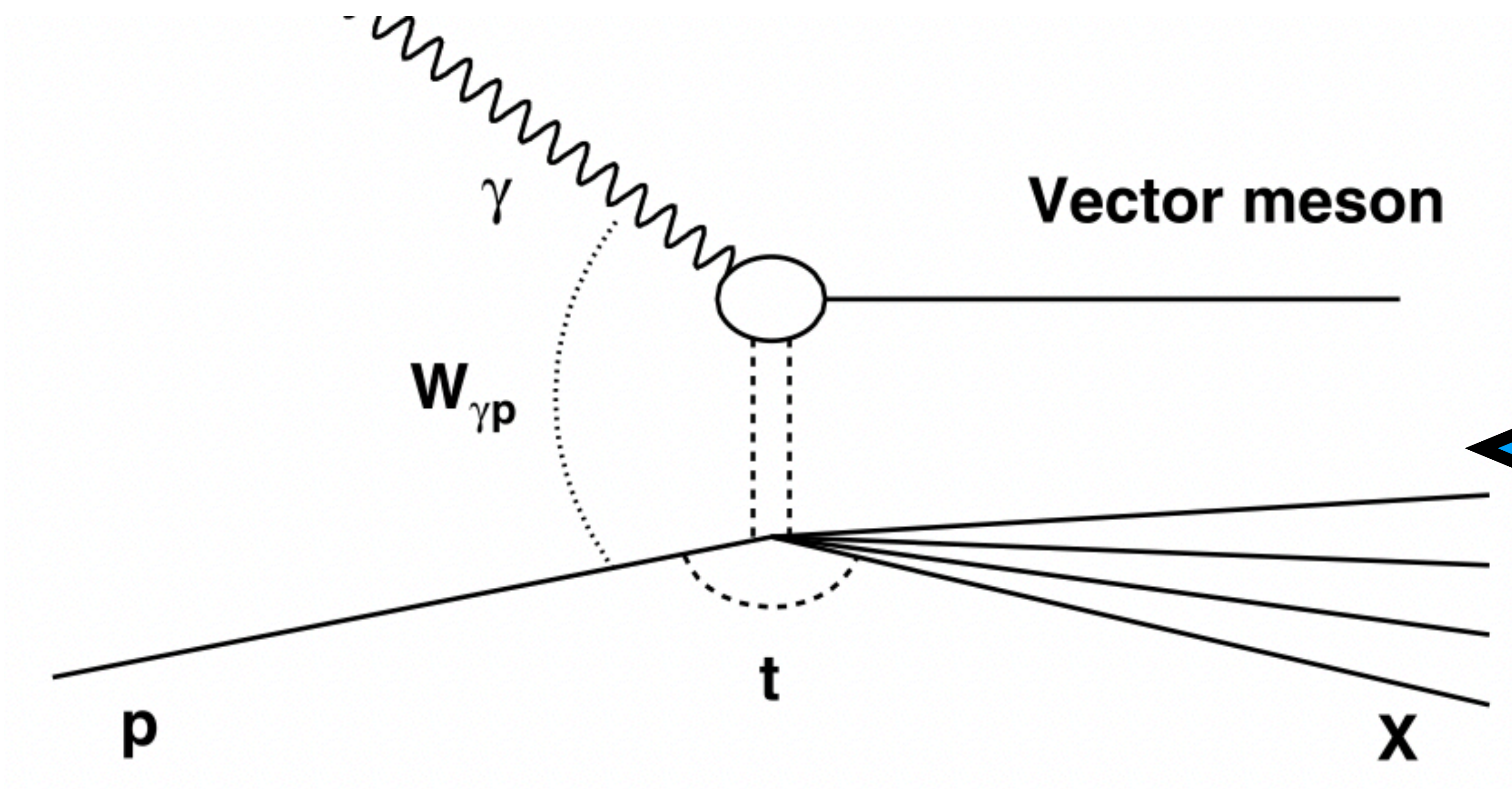



$$\frac{d\sigma}{dt} \propto \left| \langle A(x, Q^2, t) \rangle \right|^2$$



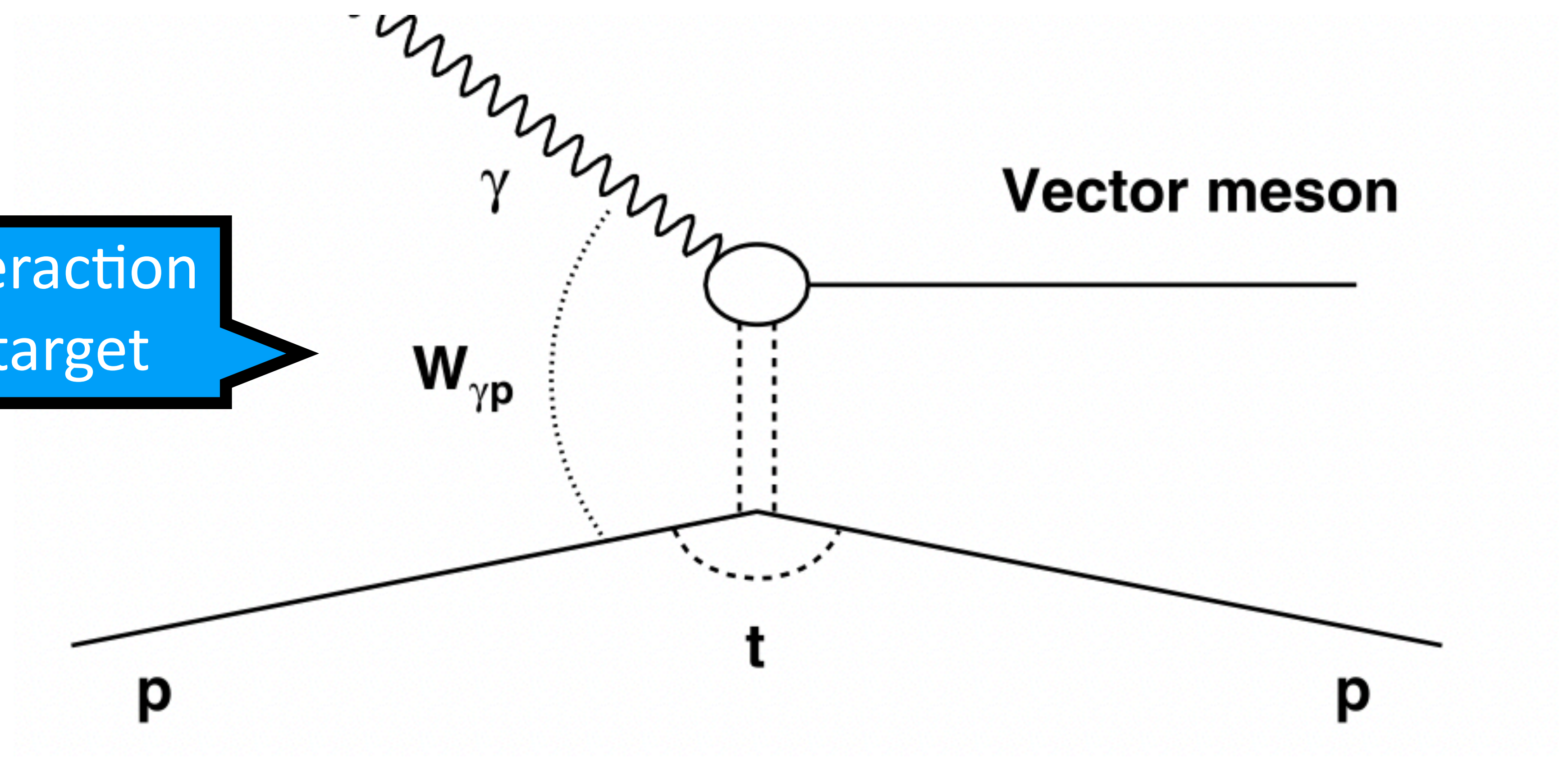

Incoherent: interaction with a piece of the target

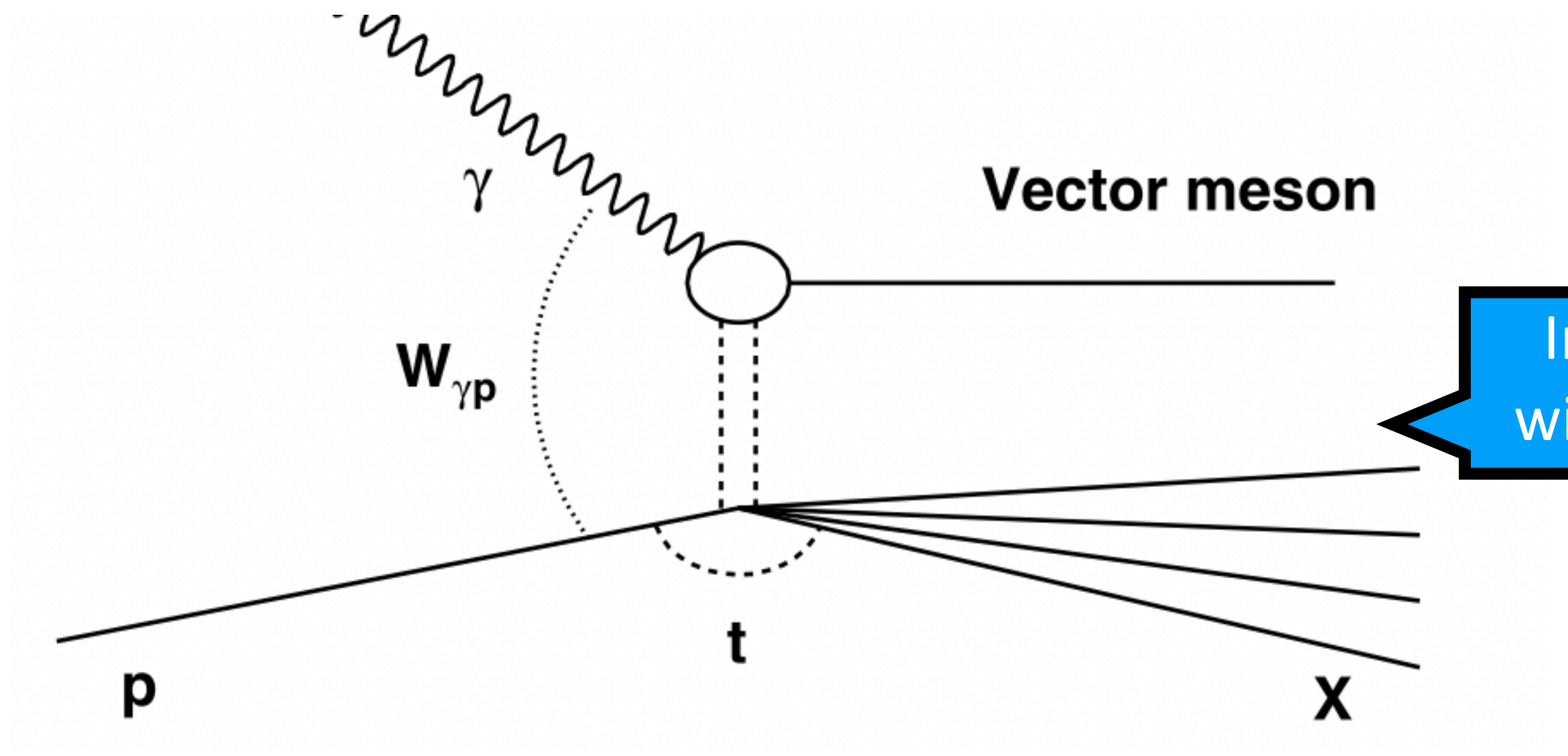
$$\frac{d\sigma}{dt} \propto \left( \langle \left| A(x, Q^2, t) \right|^2 \rangle - \left| \langle A(x, Q^2, t) \rangle \right|^2 \right)$$

In this picture, **coherent** diffractive vector meson production is proportional to the **average** over all colour configurations of the target, while **incoherent** production is proportional to their **variance**

# A window to the gluon field and to its fluctuations

Coherent: interaction with all the target

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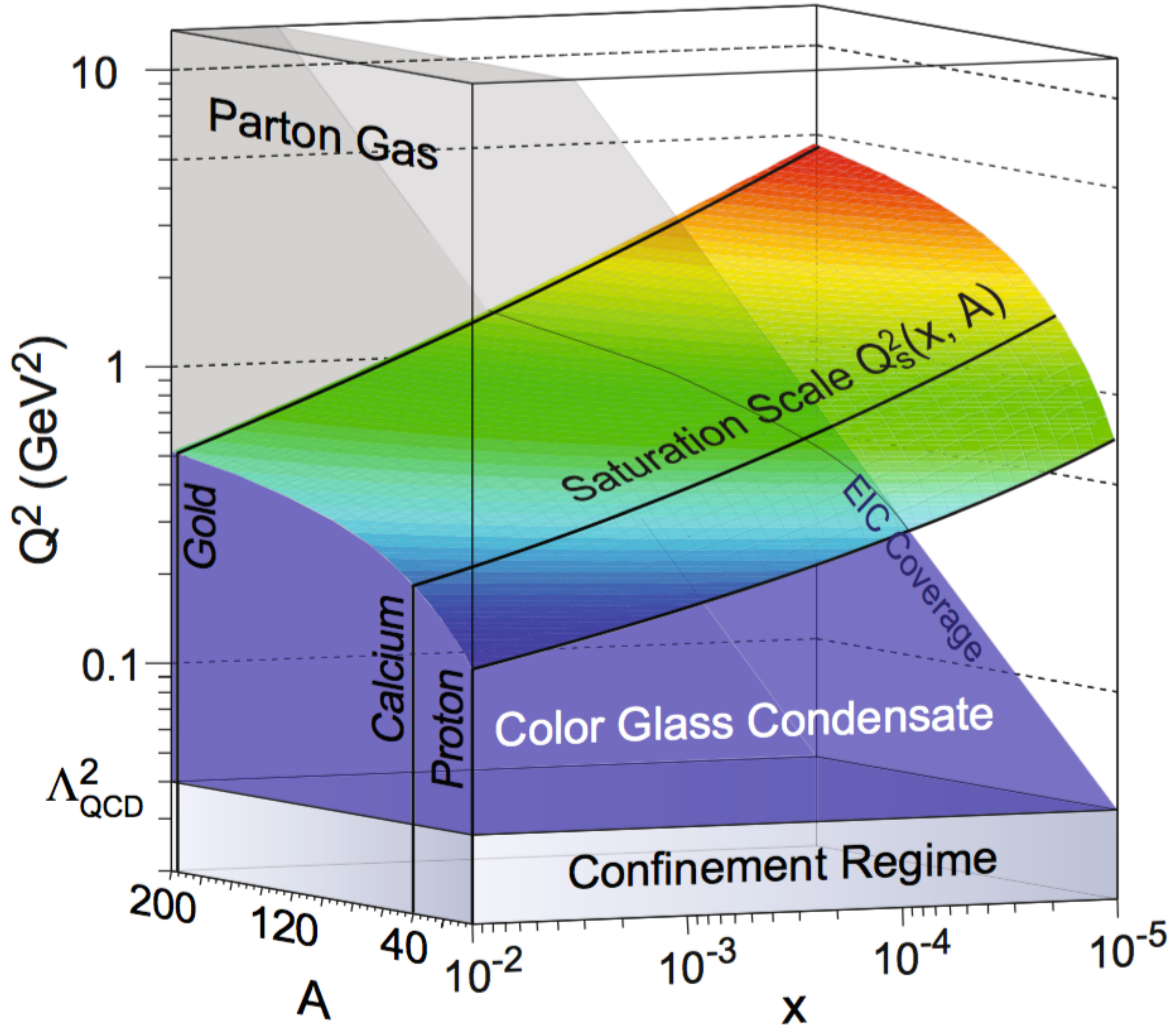
There is no reason to expect that coherent and incoherent vector meson production should have the same signature of gluon saturation → both processes should be studied in detail

# Nuclei as targets

In nuclei, saturation effects are expected to appear at a smaller energy than in p




Accardi et al (2016)

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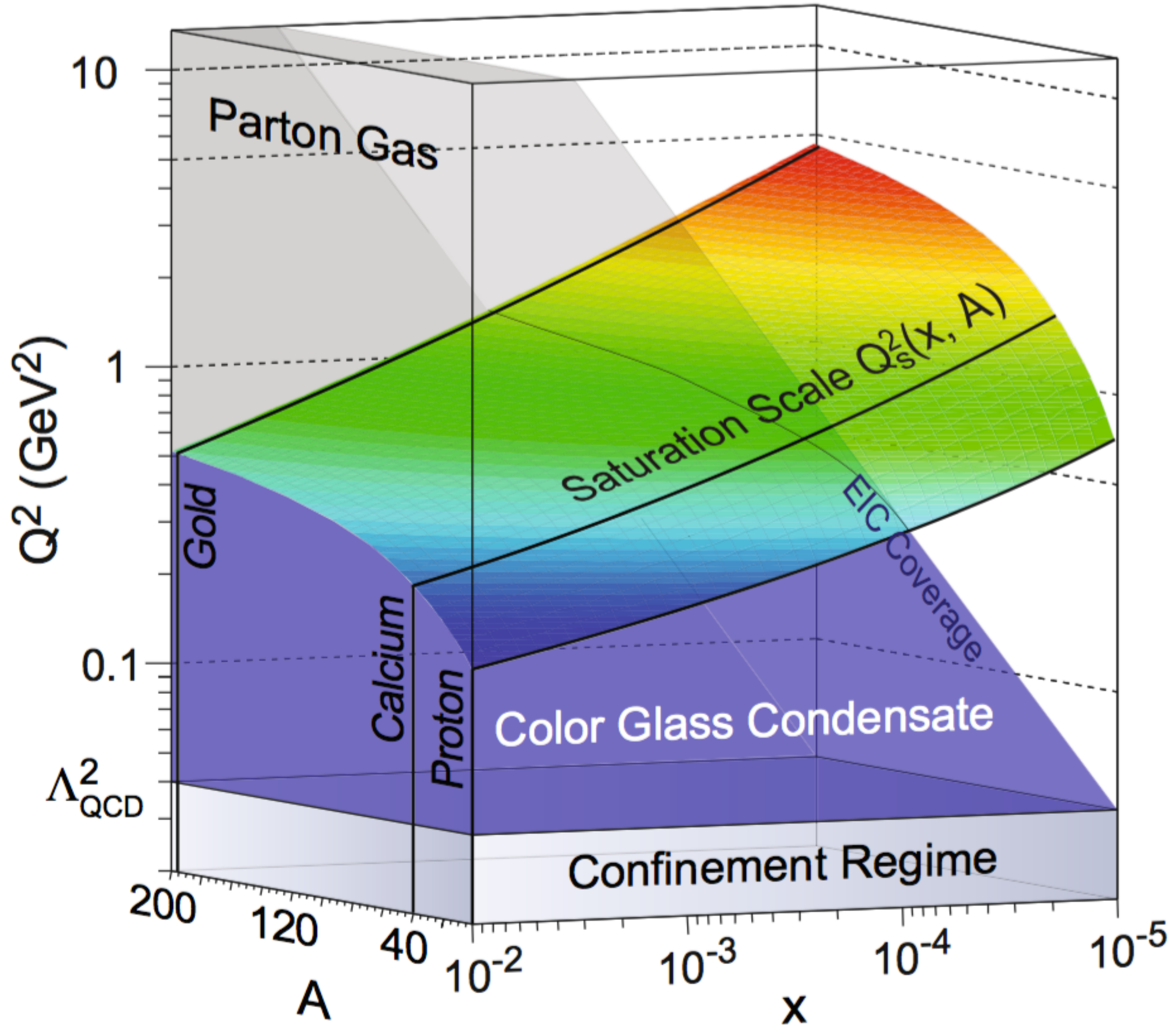


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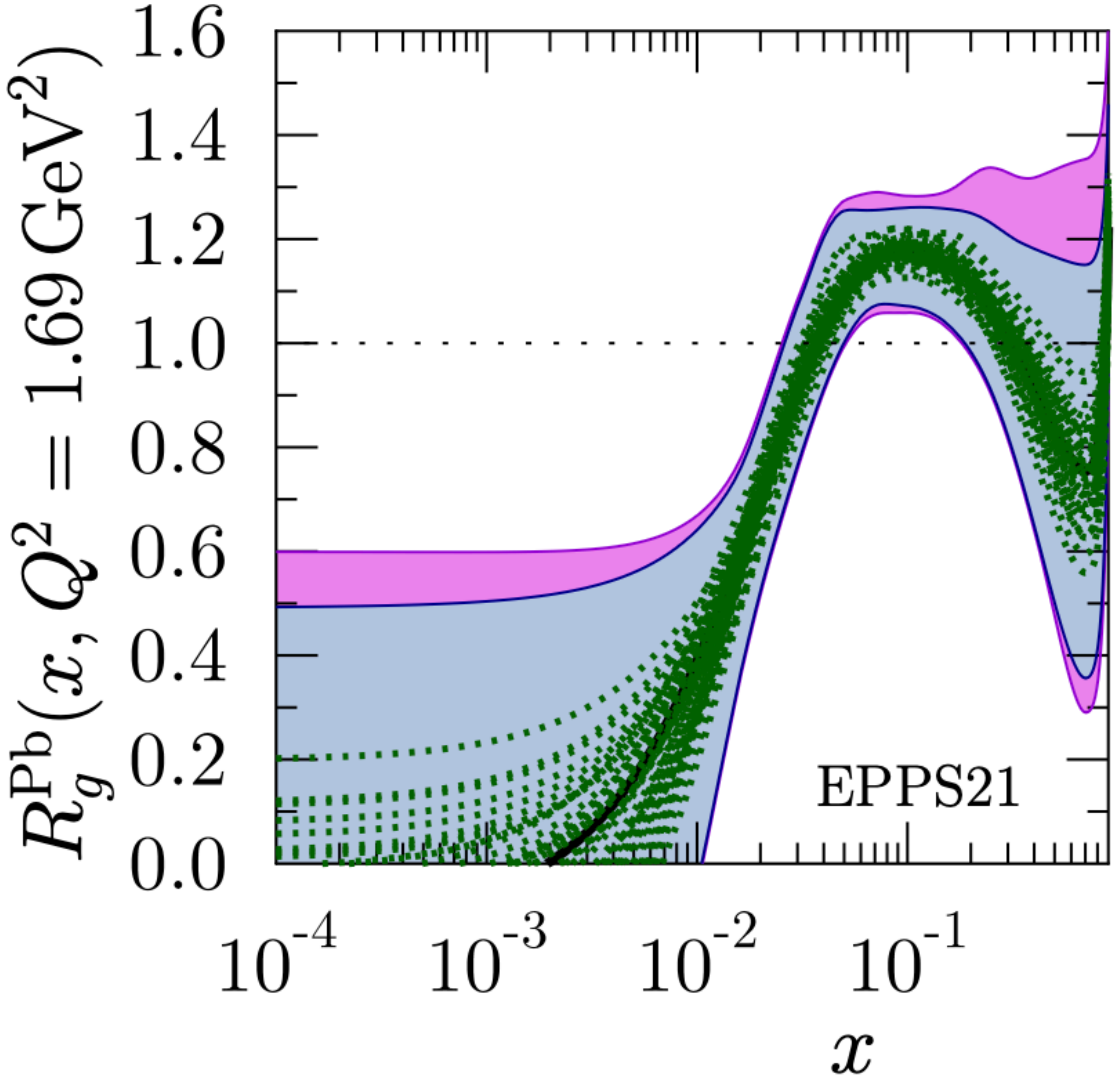
But in nuclei there is also shadowing: the experimental fact that the gluon distribution in nuclei is less than the sum of the gluon distributions of its individual nucleons




EPPS21 (2022)

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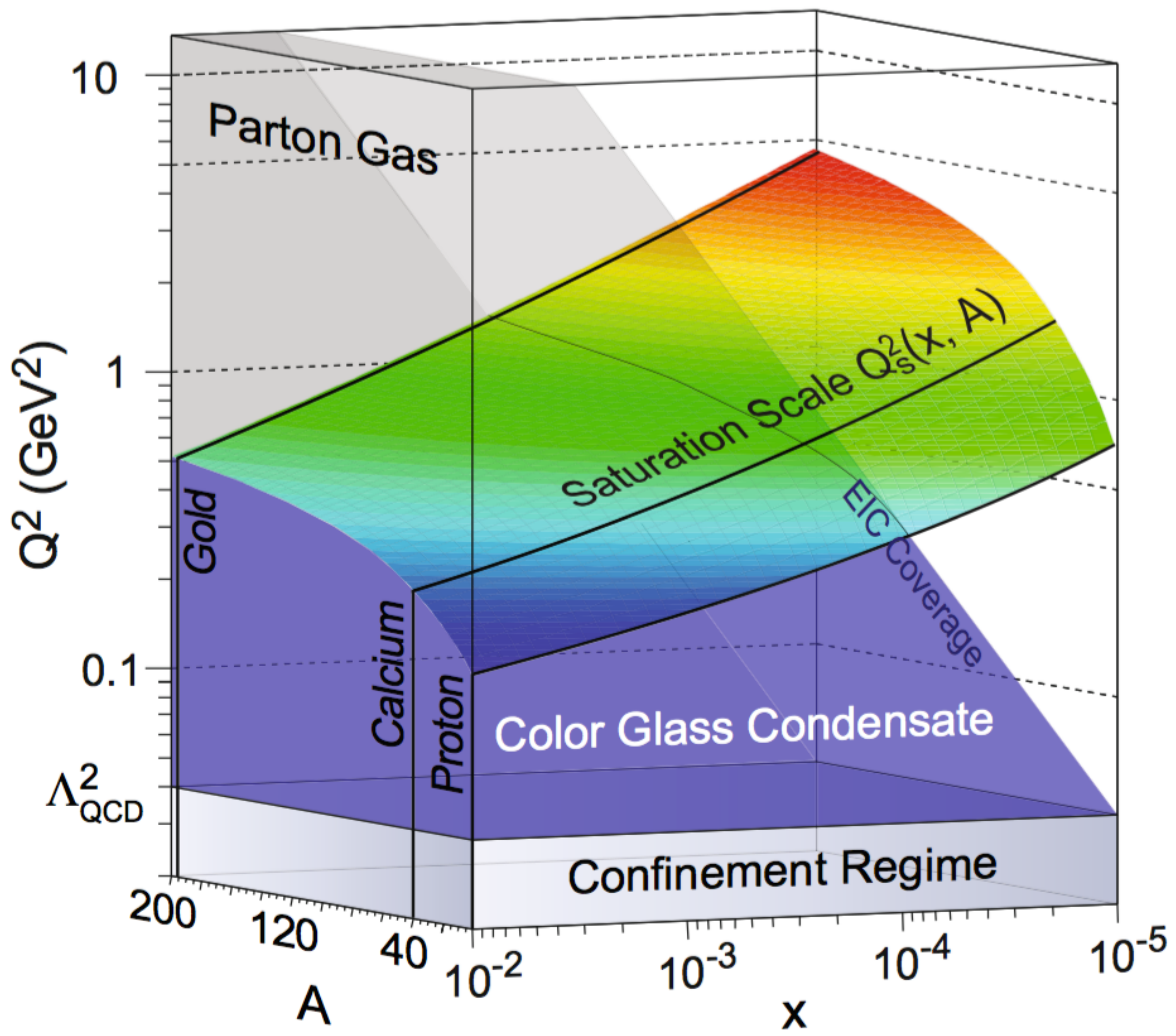


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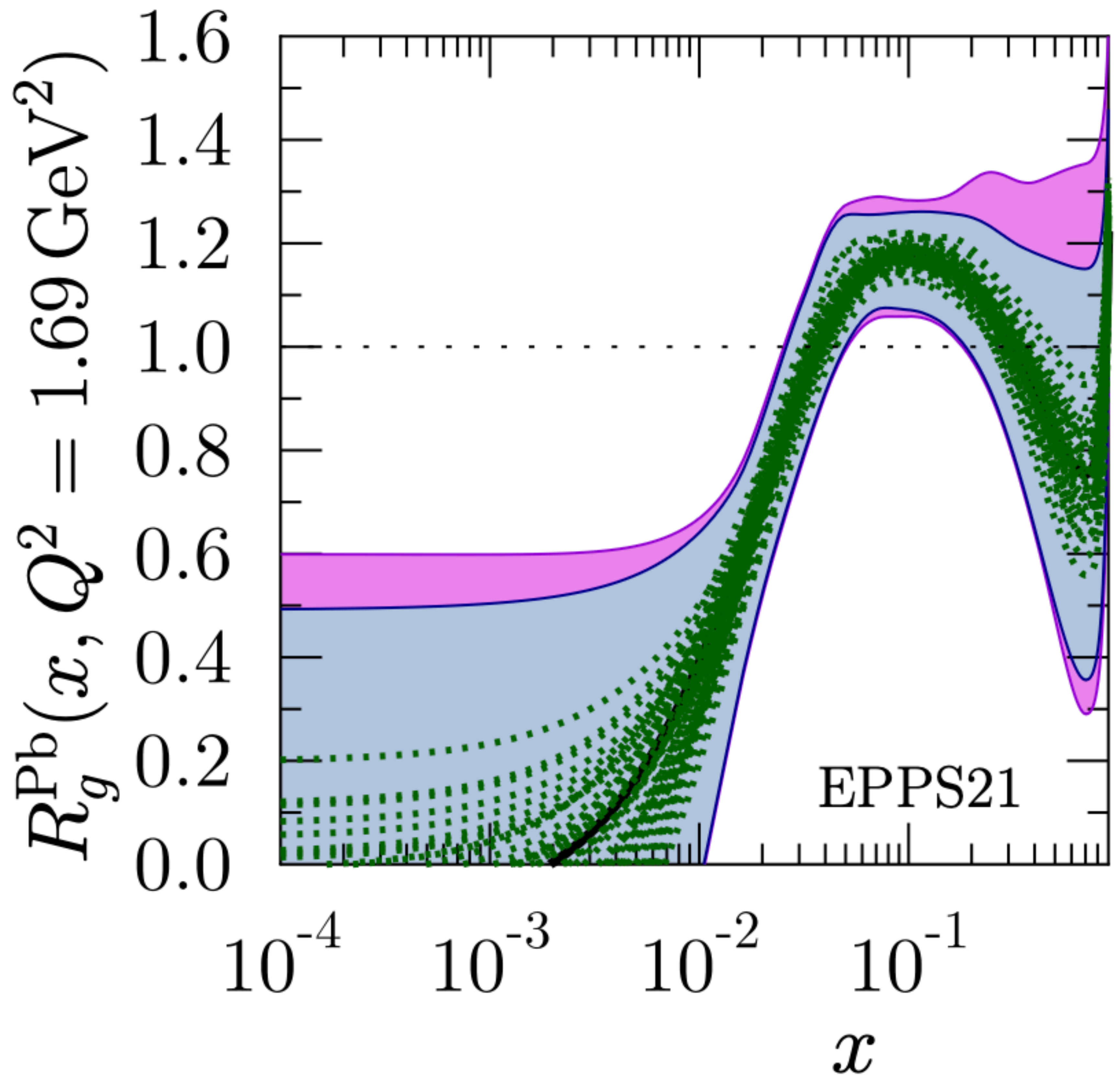



EPPS21 (2022)

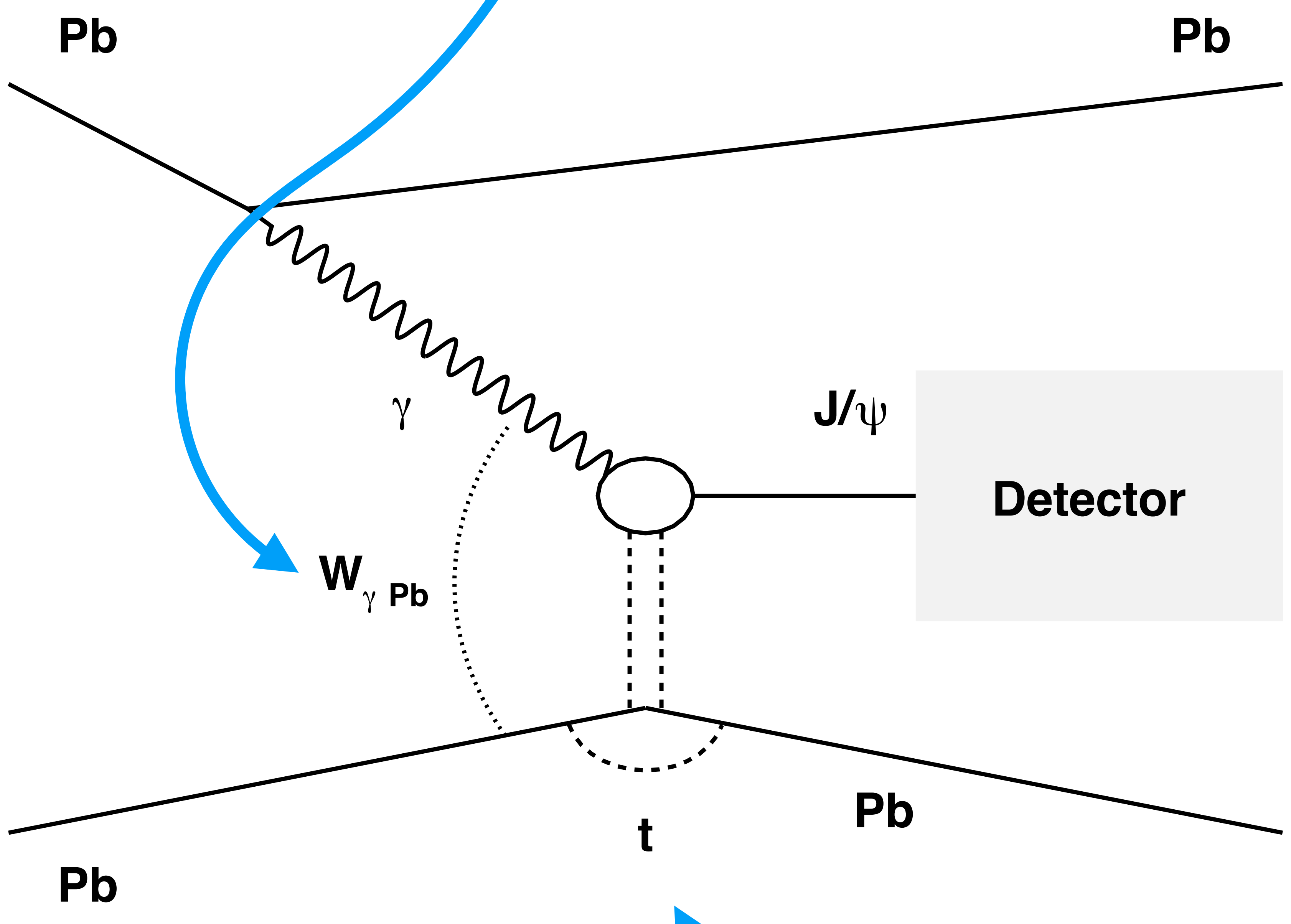
The relation between saturation and shadowing and how to disentangle their effects is an open problem

# Diffractive $J/\psi$ production in ALICE

# Kinematics

Energy dependence from the rapidity of the vector meson

$$W^2 = m\sqrt{s_{\mathrm{NN}}}\,\exp^{-y}$$




Mandelstam t dependence from the transverse momentum of the vector meson:

$$-t = p_{\perp}^{2}$$



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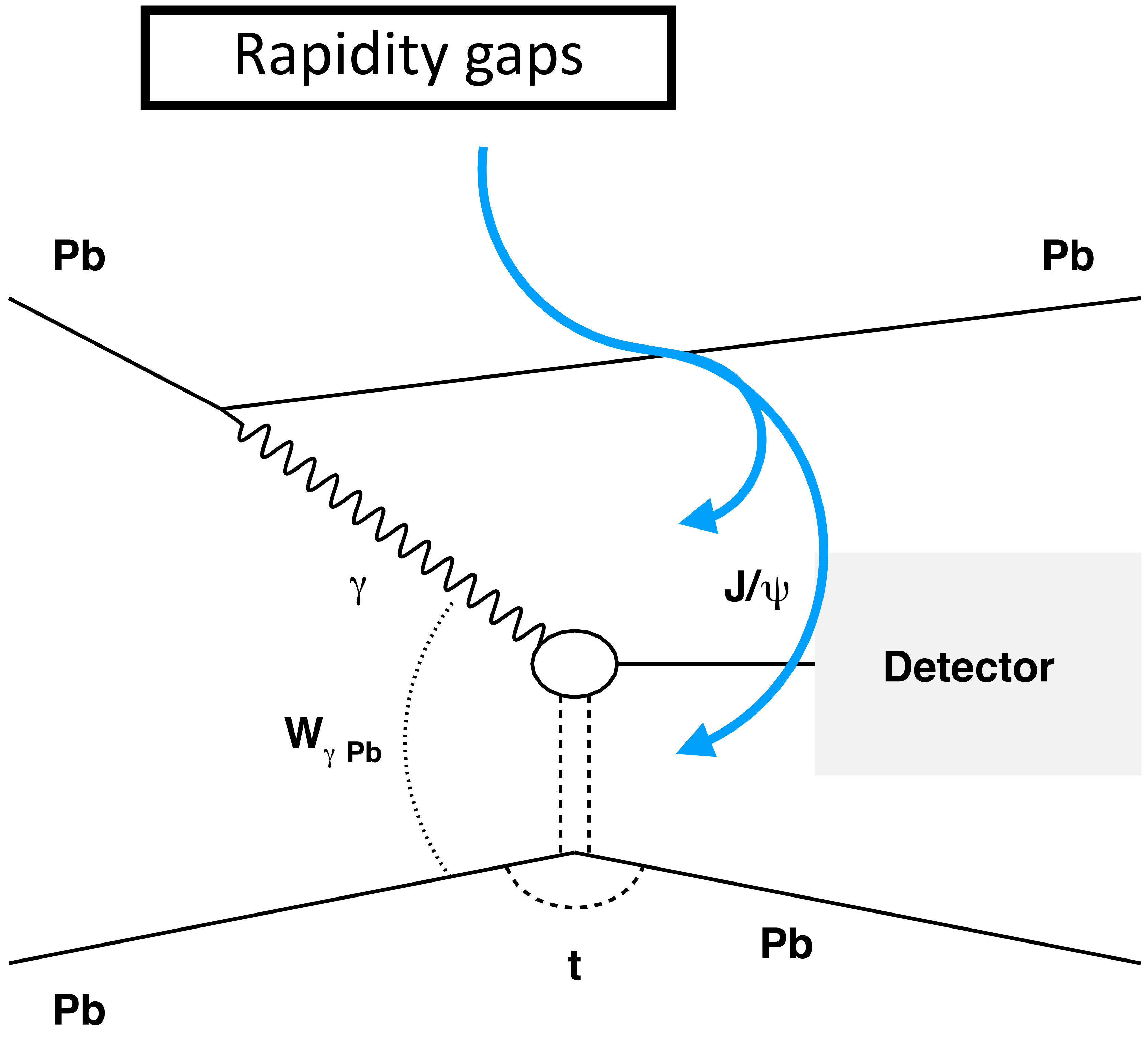
# Signatures



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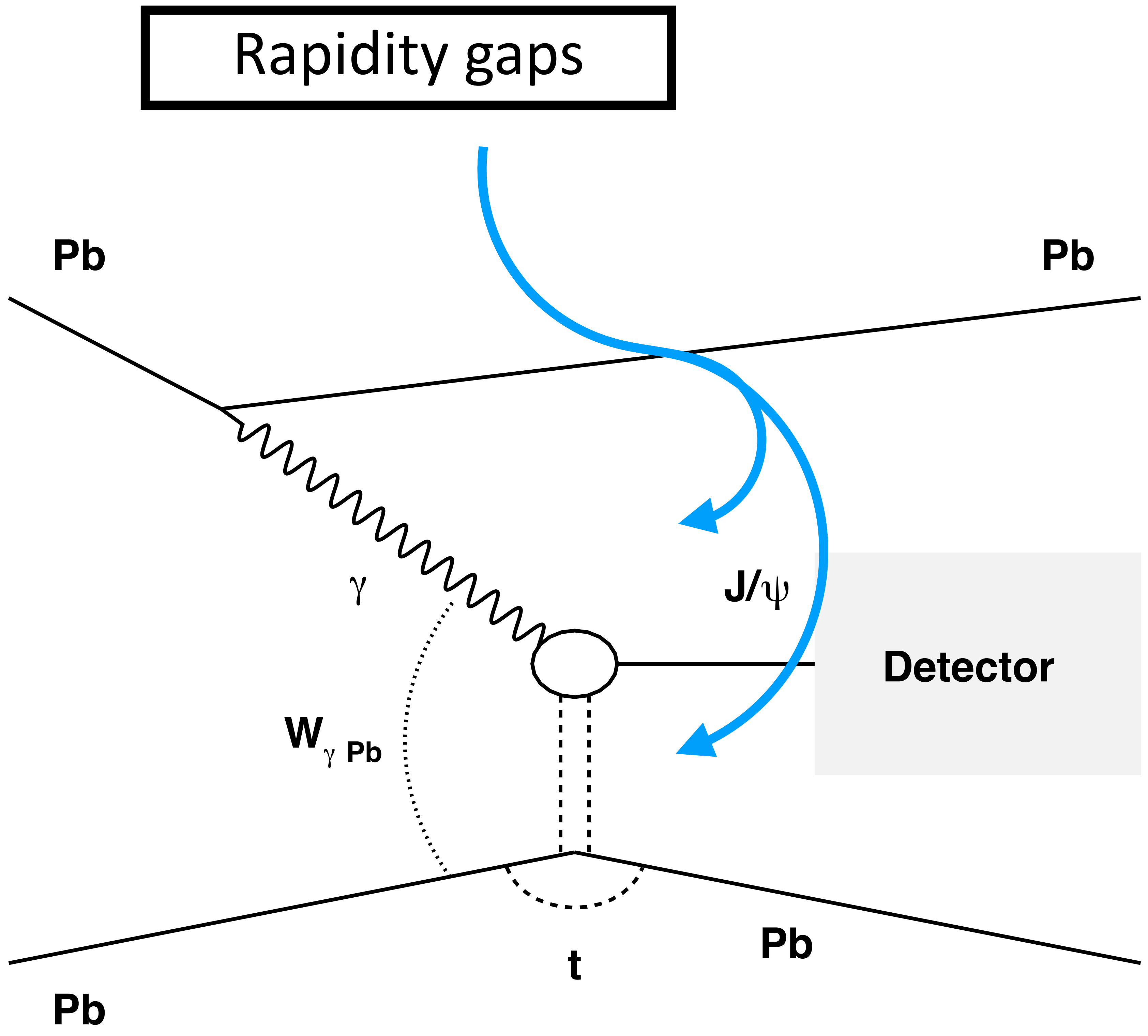
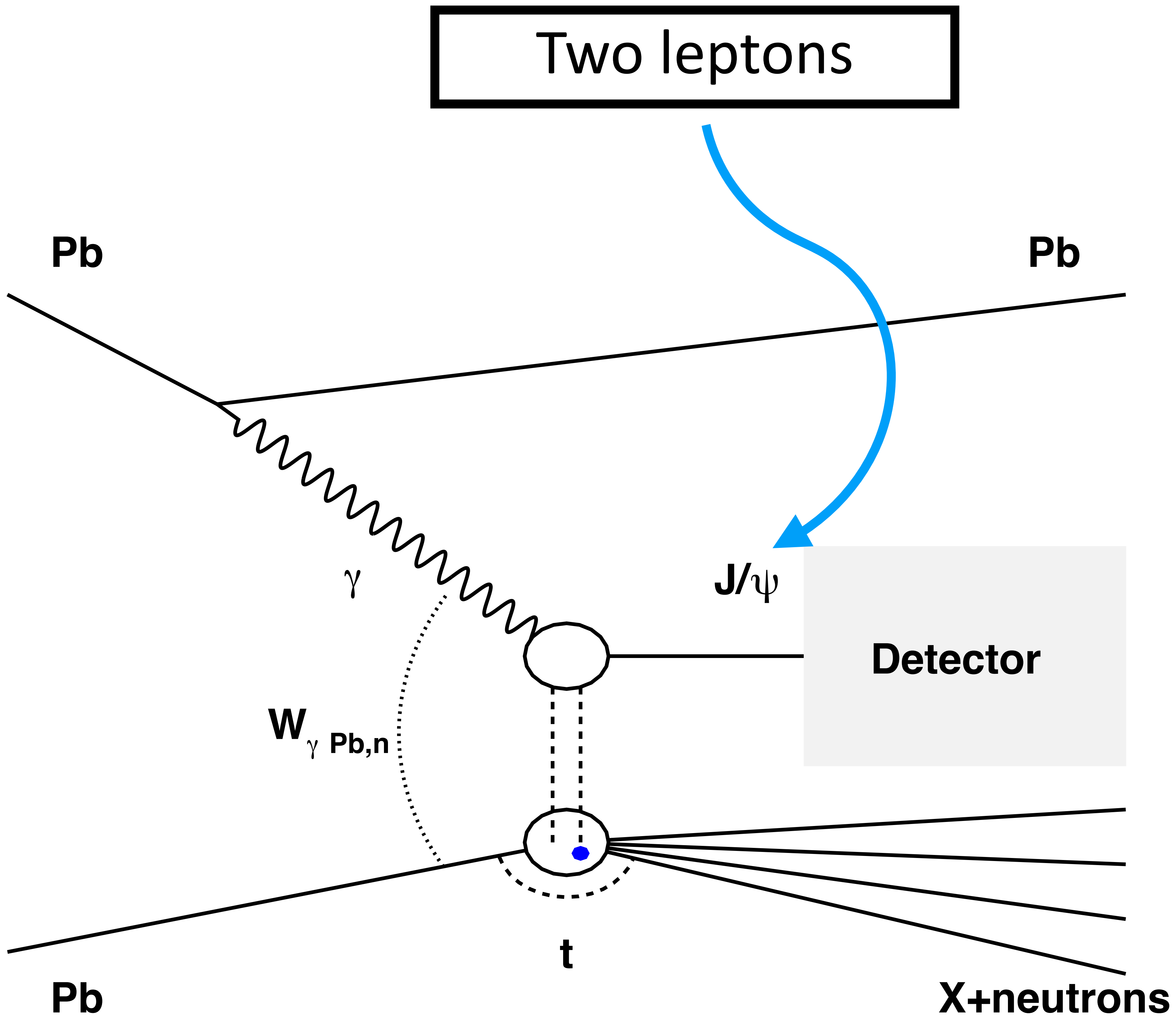
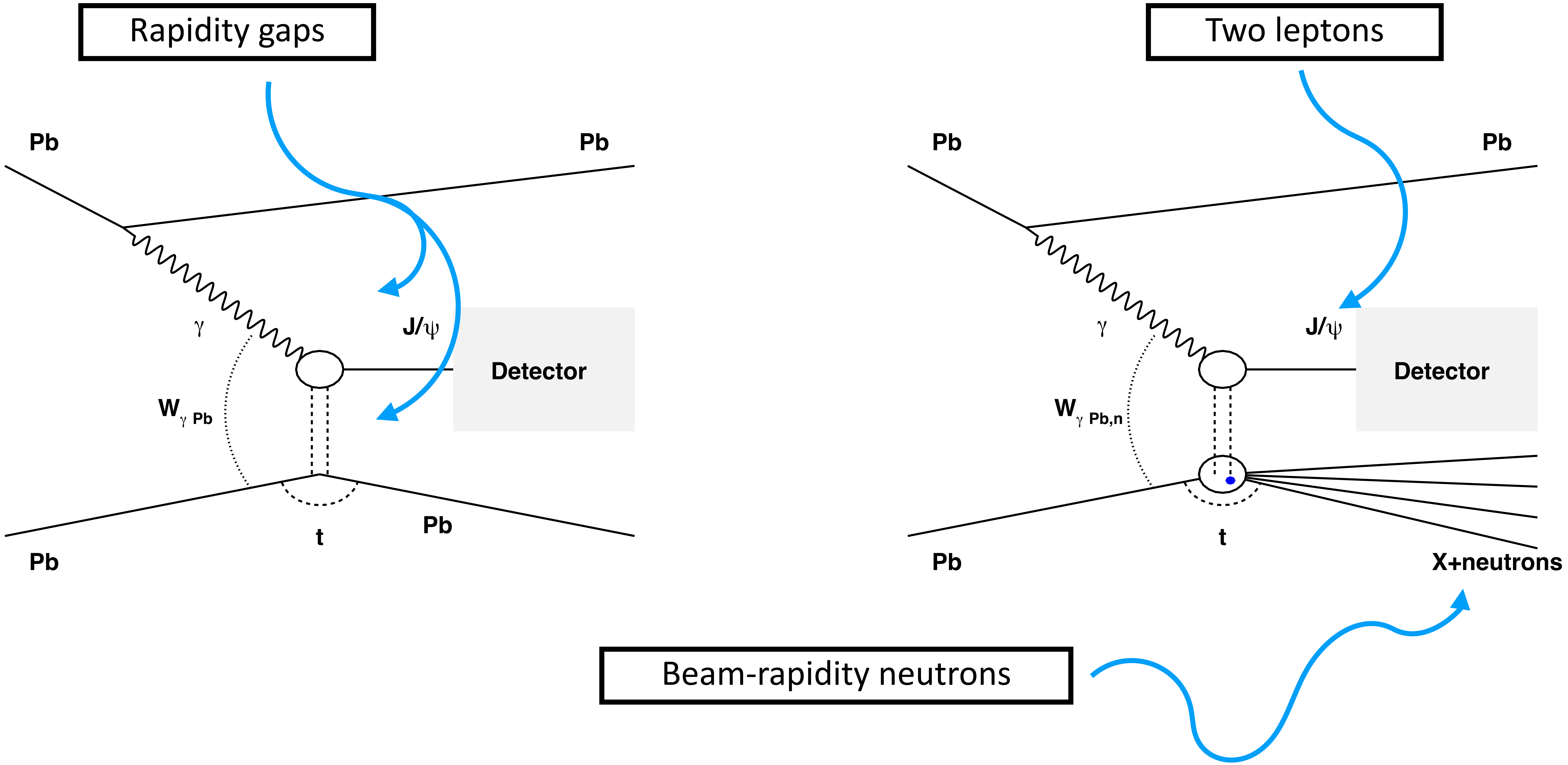


Rapidity gaps
Pb
Pb
γ
J/ψ
Detector
W γ Pb
t
Pb
Pb

Two leptons
Pb
Pb
γ
J/ψ
Detector
W γ Pb,n
t
Pb
X+neutrons

# Signatures



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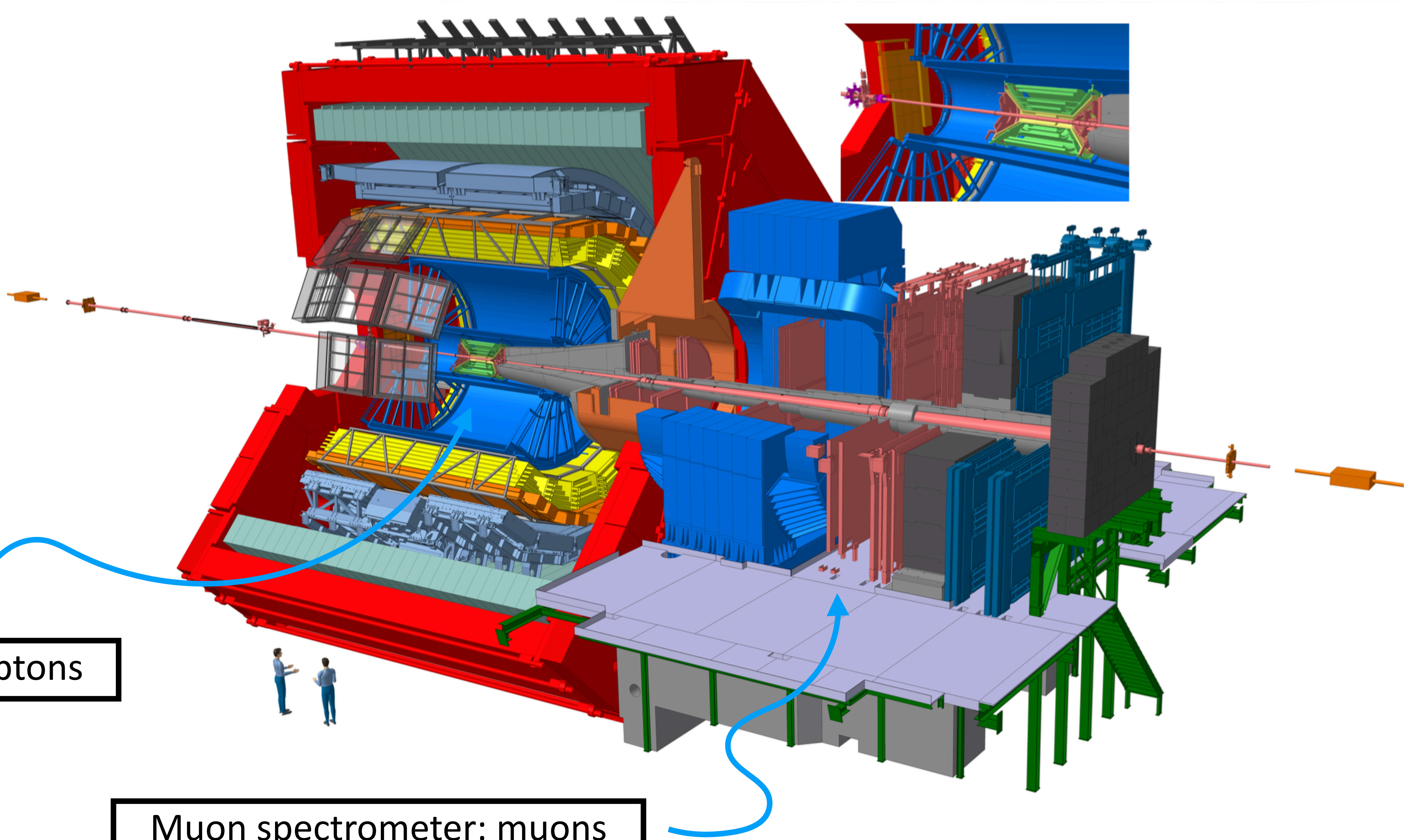
# Signatures as seen by ALICE



ITS+TPC: leptons

Muon spectrometer: muons

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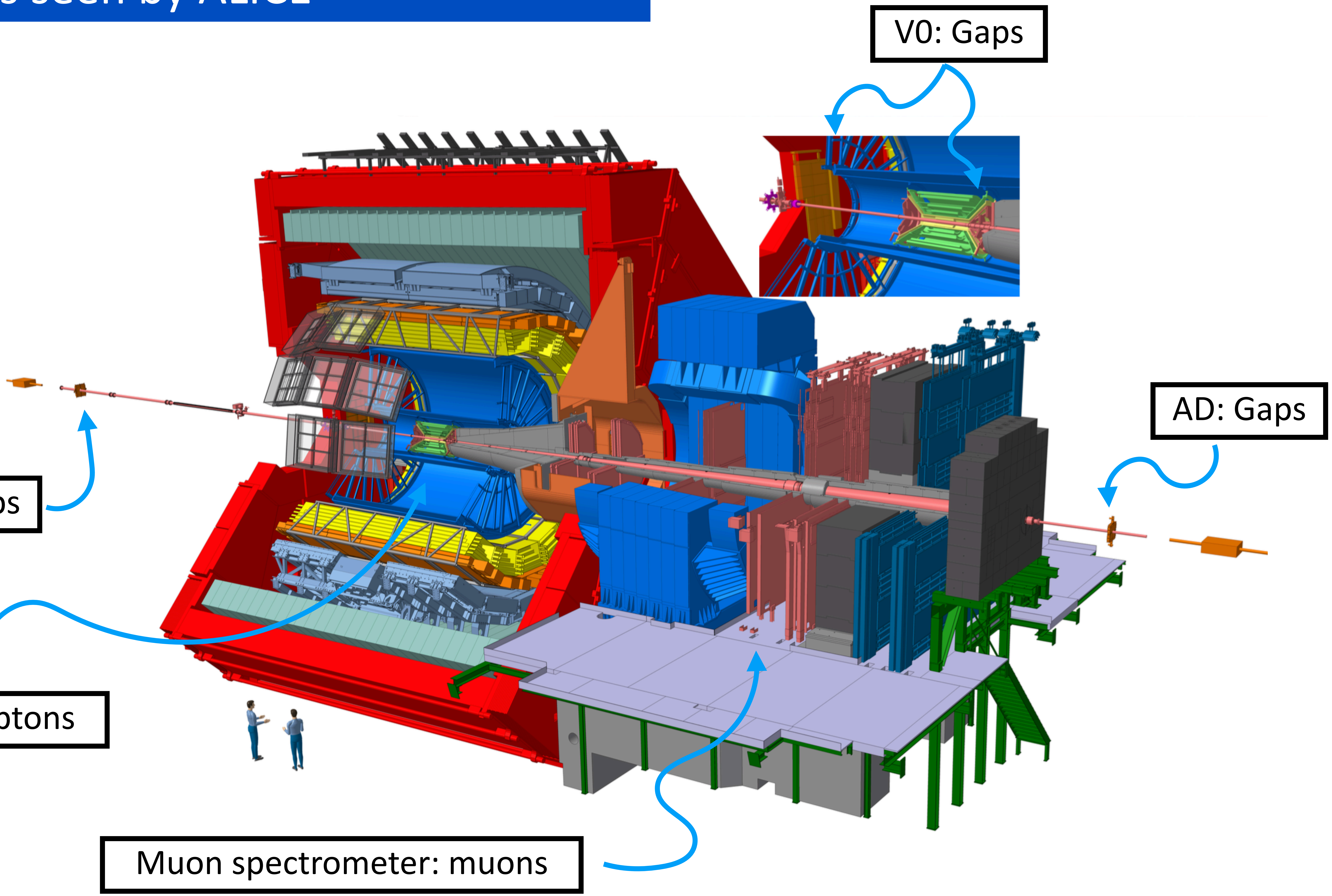




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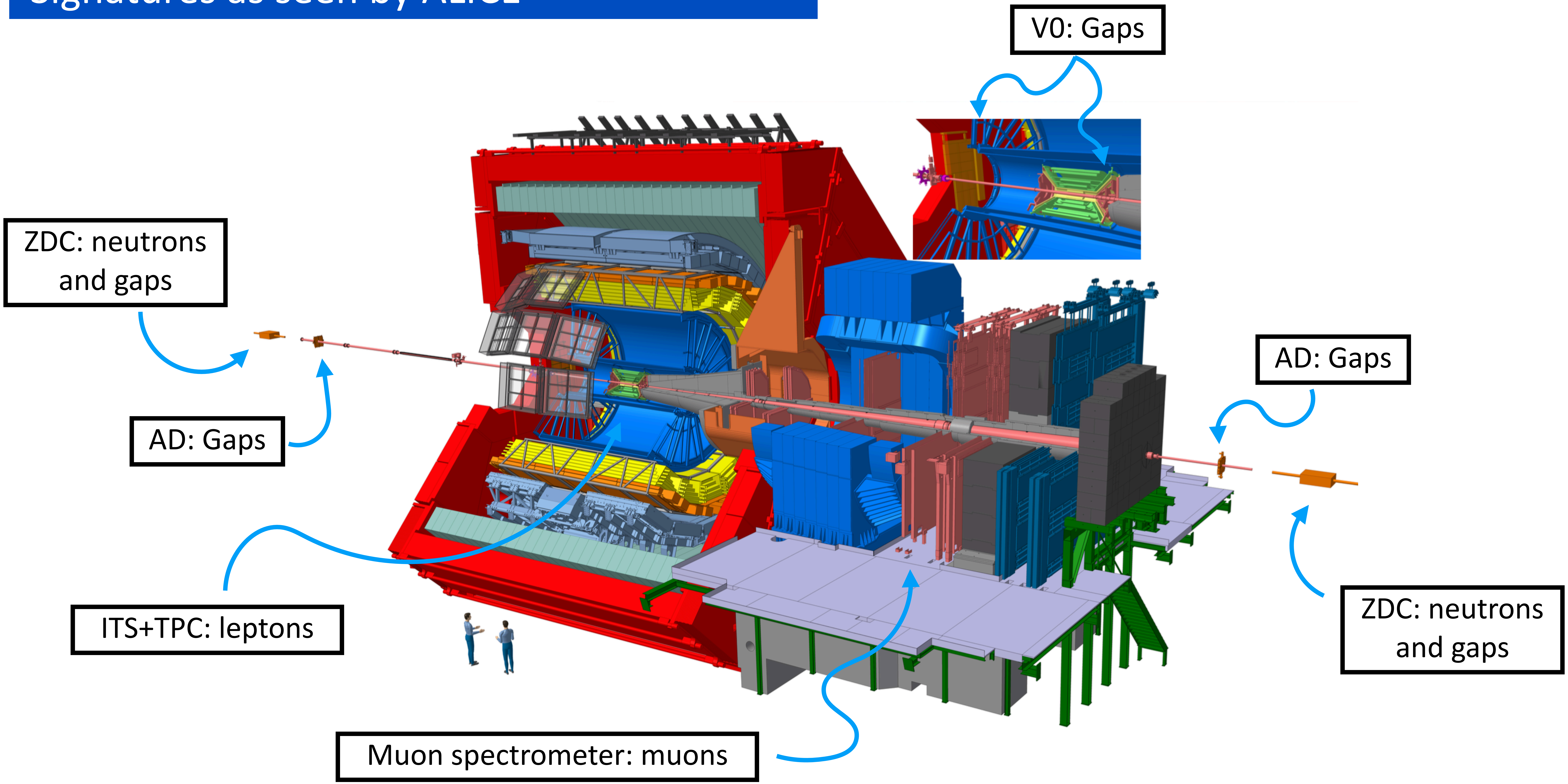
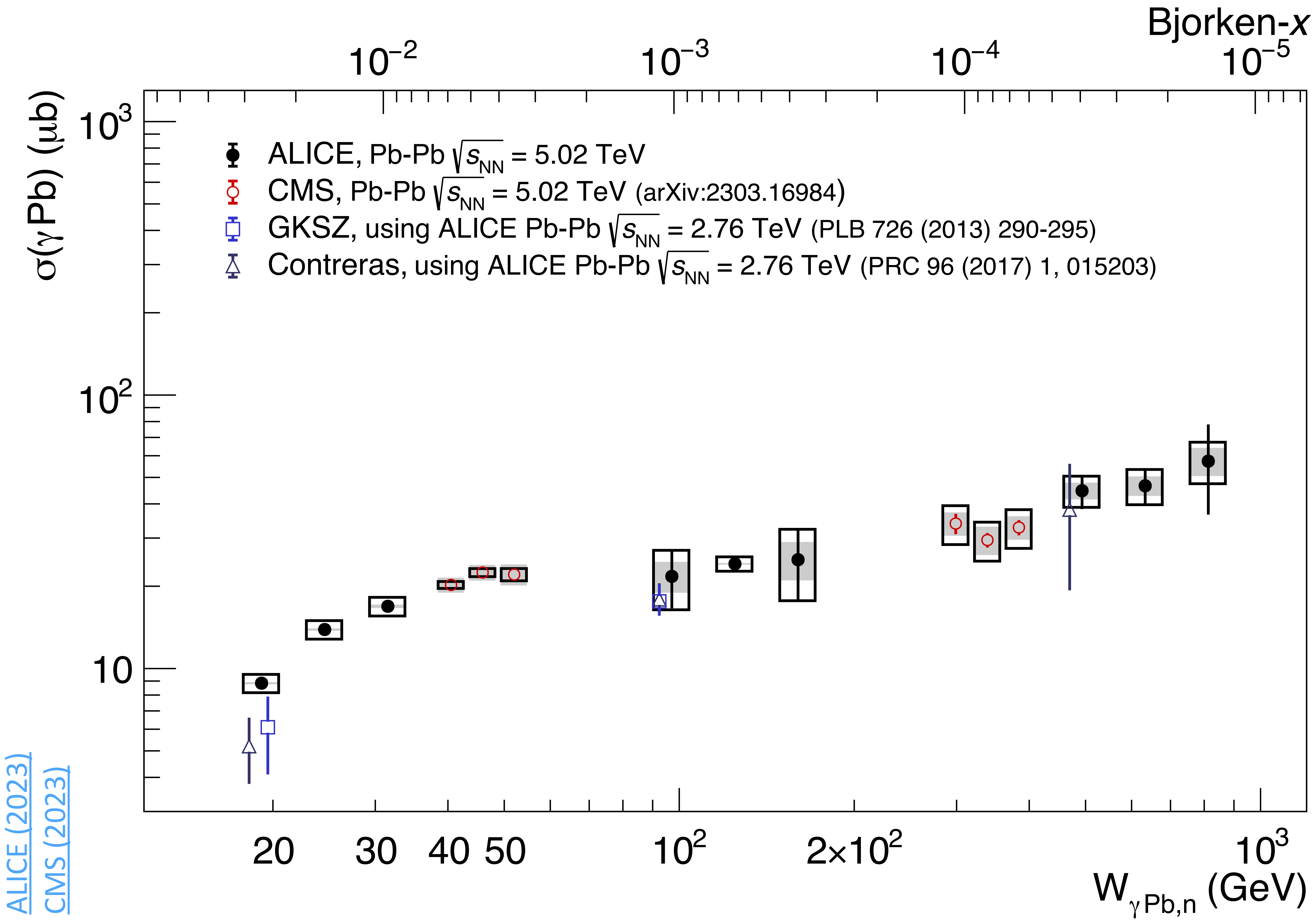


# Coherent J/ψ production: data




ALICE (2023)
CMS (2023)

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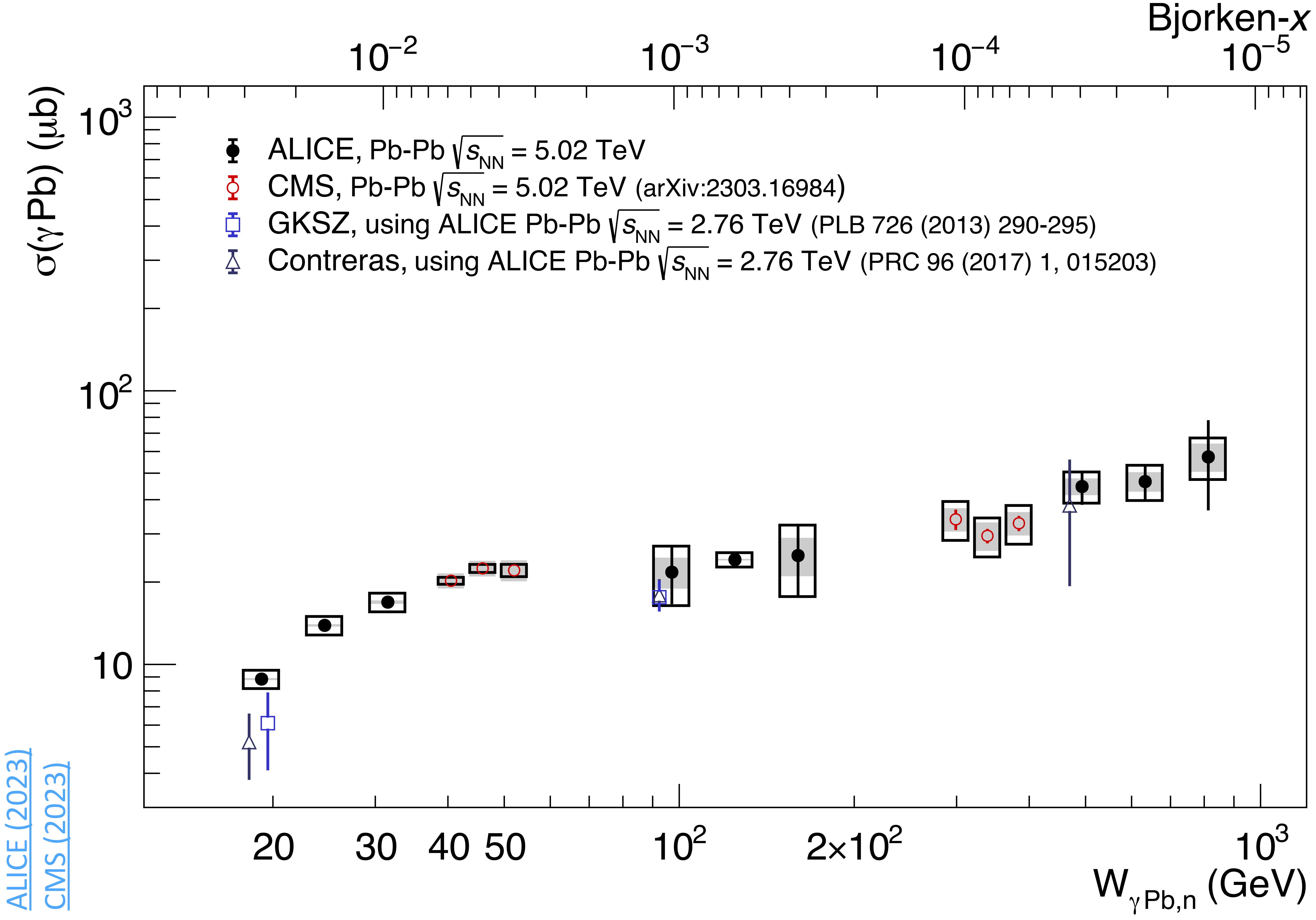


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ALICE data from Run 1 agree with those from Run 2

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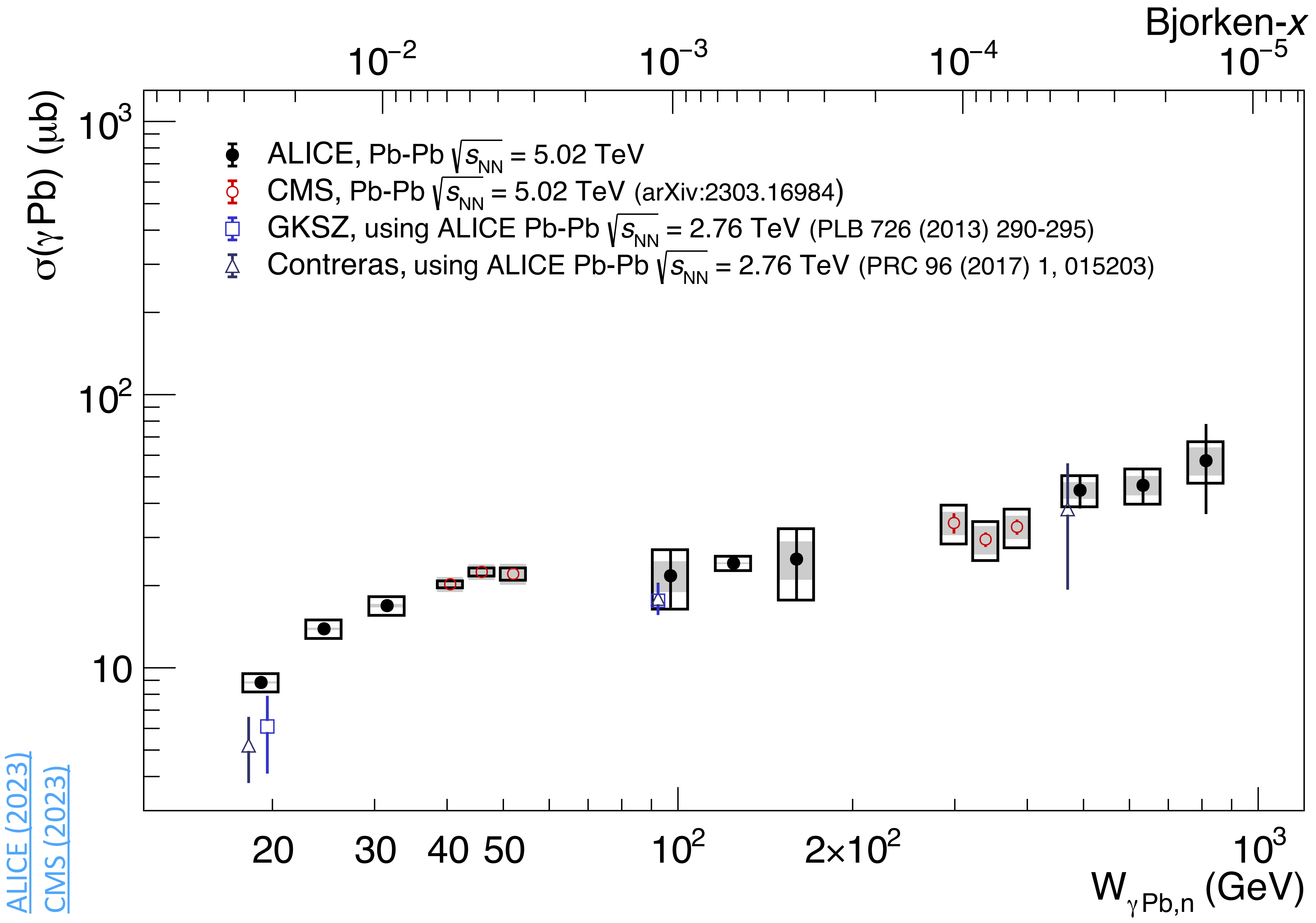


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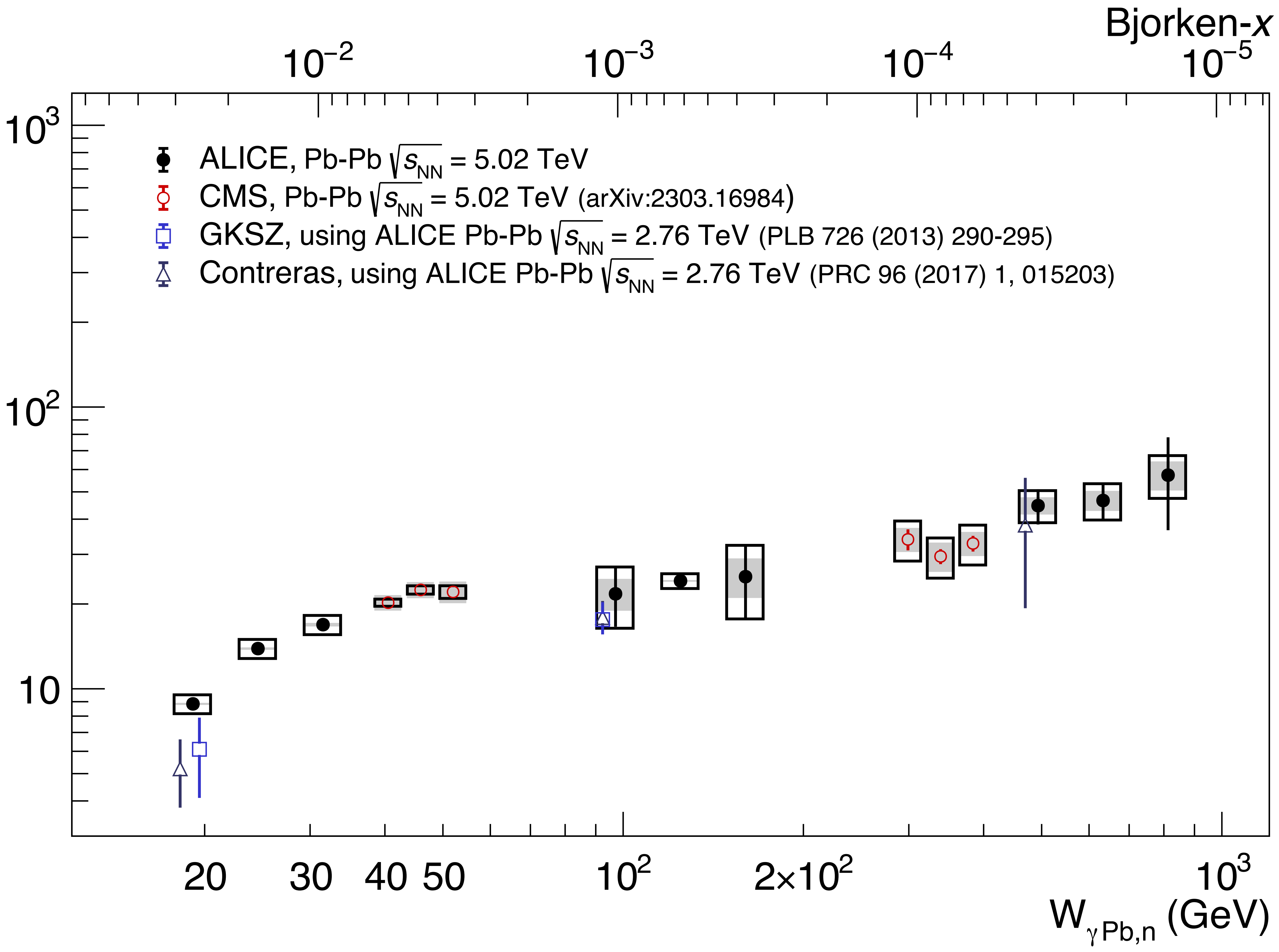



ALICE (2023)

CMS (2023)

ALICE data from Run 1 agree with those from Run 2

ALICE and CMS data agree and complement each other

Bjorken-x dependence measured across three orders of magnitude!

# Coherent J/ψ production: IA

Impulse approximation: nucleus as a collection of nucleons neglecting all nuclear effects except coherence

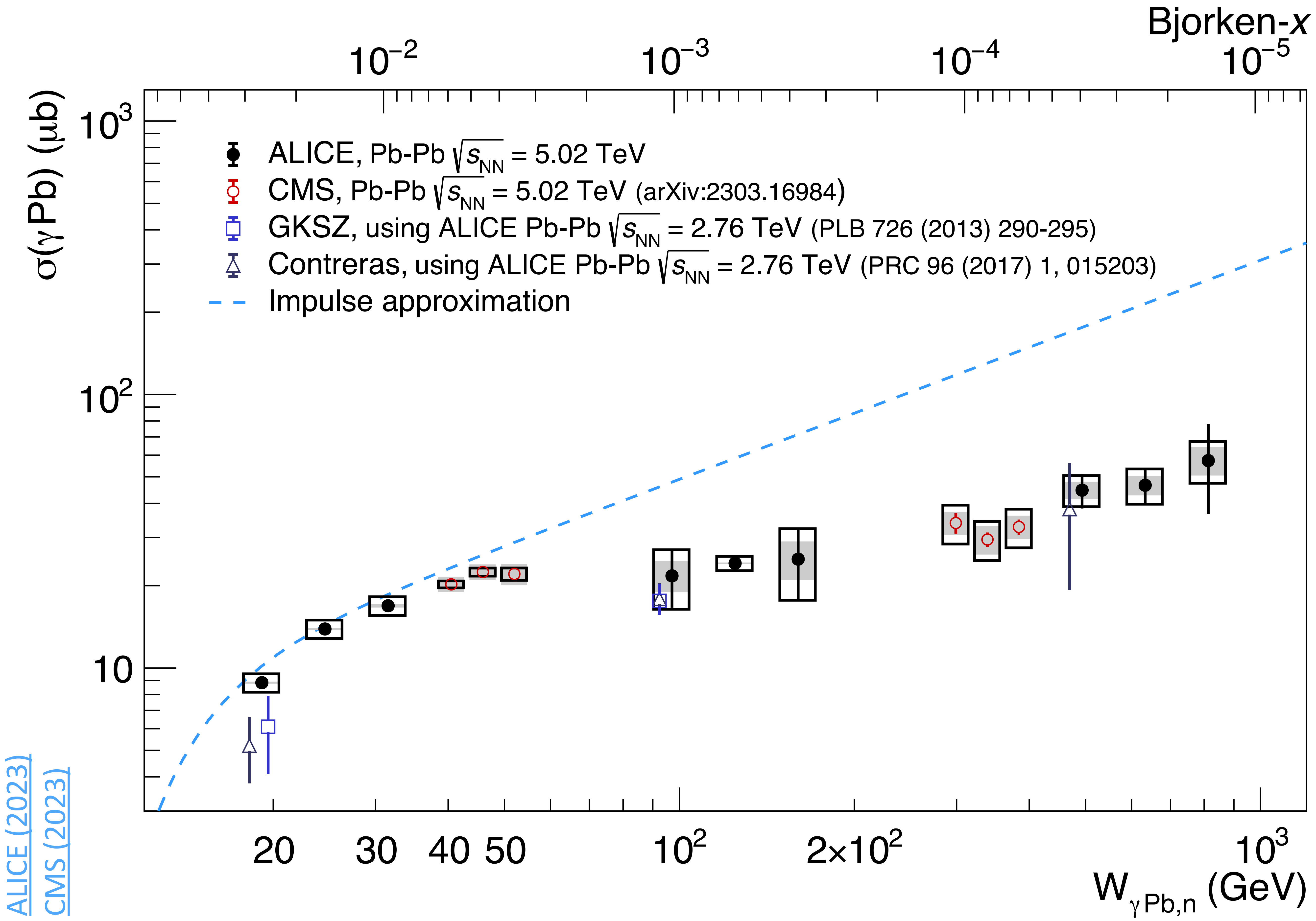
From HERA data

$$\sigma^{\mathrm{IA}}_{\gamma A\rightarrow J/\psi A}(W_{\gamma\mathrm{p}}) = \frac{d\sigma^{\mathrm{pQCD}}_{\gamma\mathrm{p}\rightarrow J/\psi\mathrm{p}}(W_{\gamma\mathrm{p}}, t=0)}{dt}\Phi_A(t_{\mathrm{min}})$$

$$\Phi_A(t_{\mathrm{min}}) = \int_{-\infty}^{t_{\mathrm{min}}} dt \left| F_A(t) \right|^2$$

Nuclear form factor

# Coherent J/ψ production: IA

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$$\Phi_A(t_{min}) = \int_{-\infty}^{t_{min}} dt \left|F_A(t)\right|^2$$

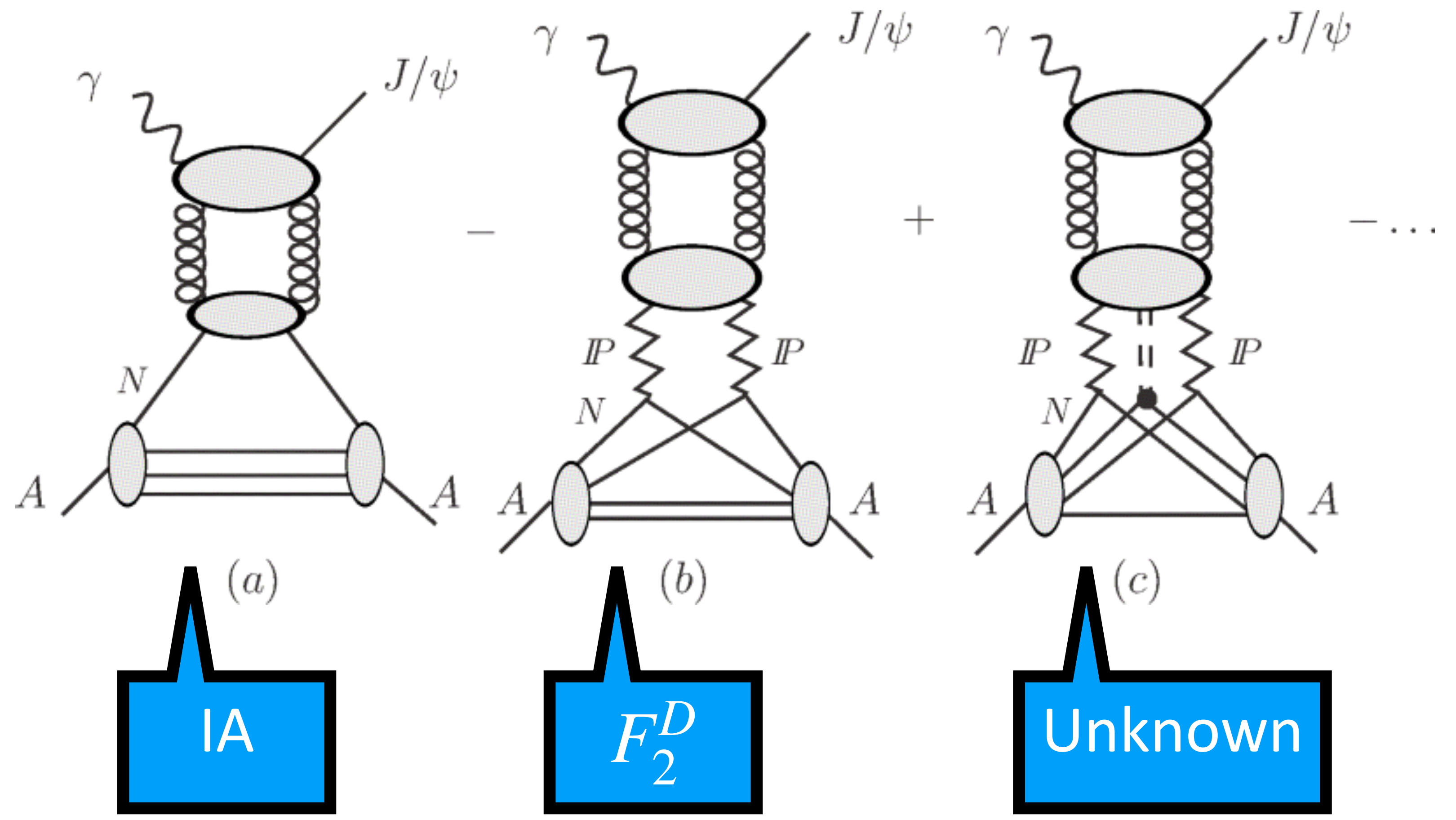
Nuclear form factor

Impulse approximation does not describe data at small x → nuclear effects are important in this regime

# Coherent J/ψ production: LTA

Guzey et al (2014)

LTA (leading twist approximation)
shadowing from absorption corrections
from multiple scattering



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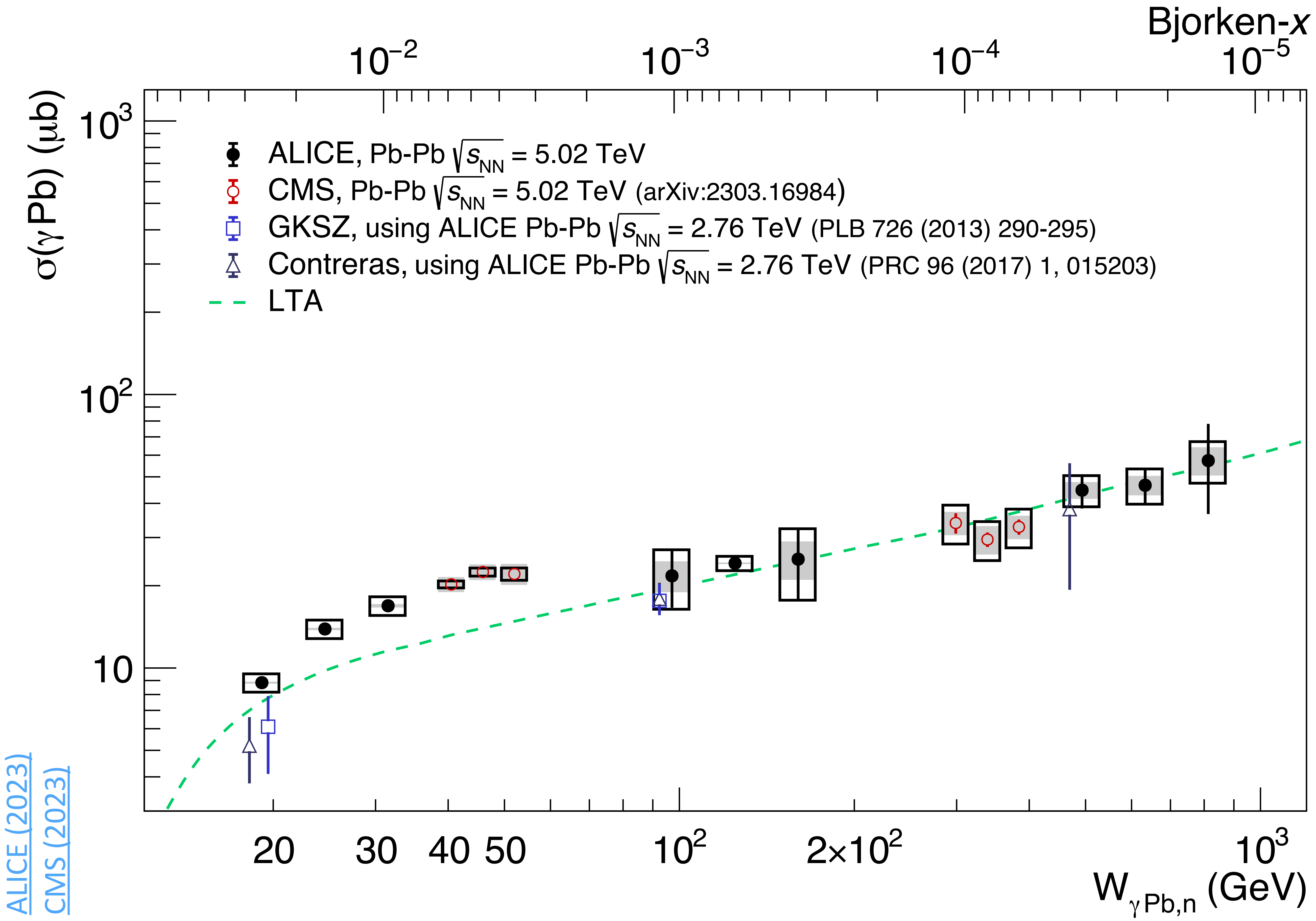


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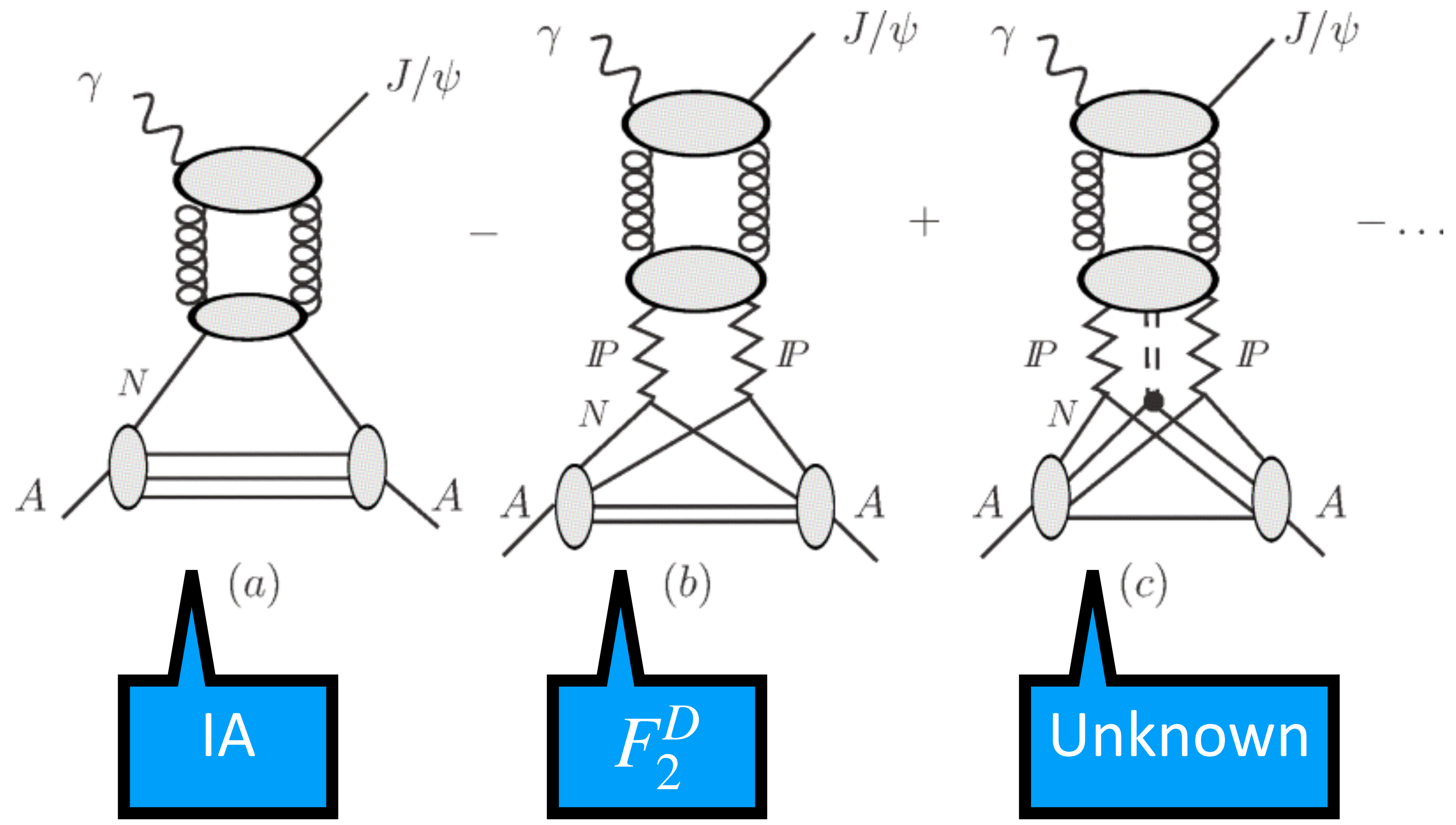
LTA (leading twist approximation) shadowing from absorption corrections from multiple scattering




Modelling the unknown contributions yield strong and weak shadowing predictions (differing by a large amount), their average describes the small x data

# Coherent J/ψ production: HS

See Saša's talk for more details

Cepila, JGC, Tapia-Takaki (2017)

Energy dependent hotspot model: saturation based with nucleons made of hotspots whose positions change event by event

$$T_{\rm p}(\vec{b}) = \frac{1}{N_{\rm hs}} \sum_{i=1}^{N_{\rm hs}} T_{\rm hs}\left(\vec{b} - \vec{b}_i\right)$$

$$T_{\rm hs}(\vec{b} - \vec{b}_i) = \frac{1}{2\pi B_{\rm hs}} \exp\left(-\frac{\left(\vec{b} - \vec{b}_i\right)^2}{2B_{\rm hs}}\right)$$

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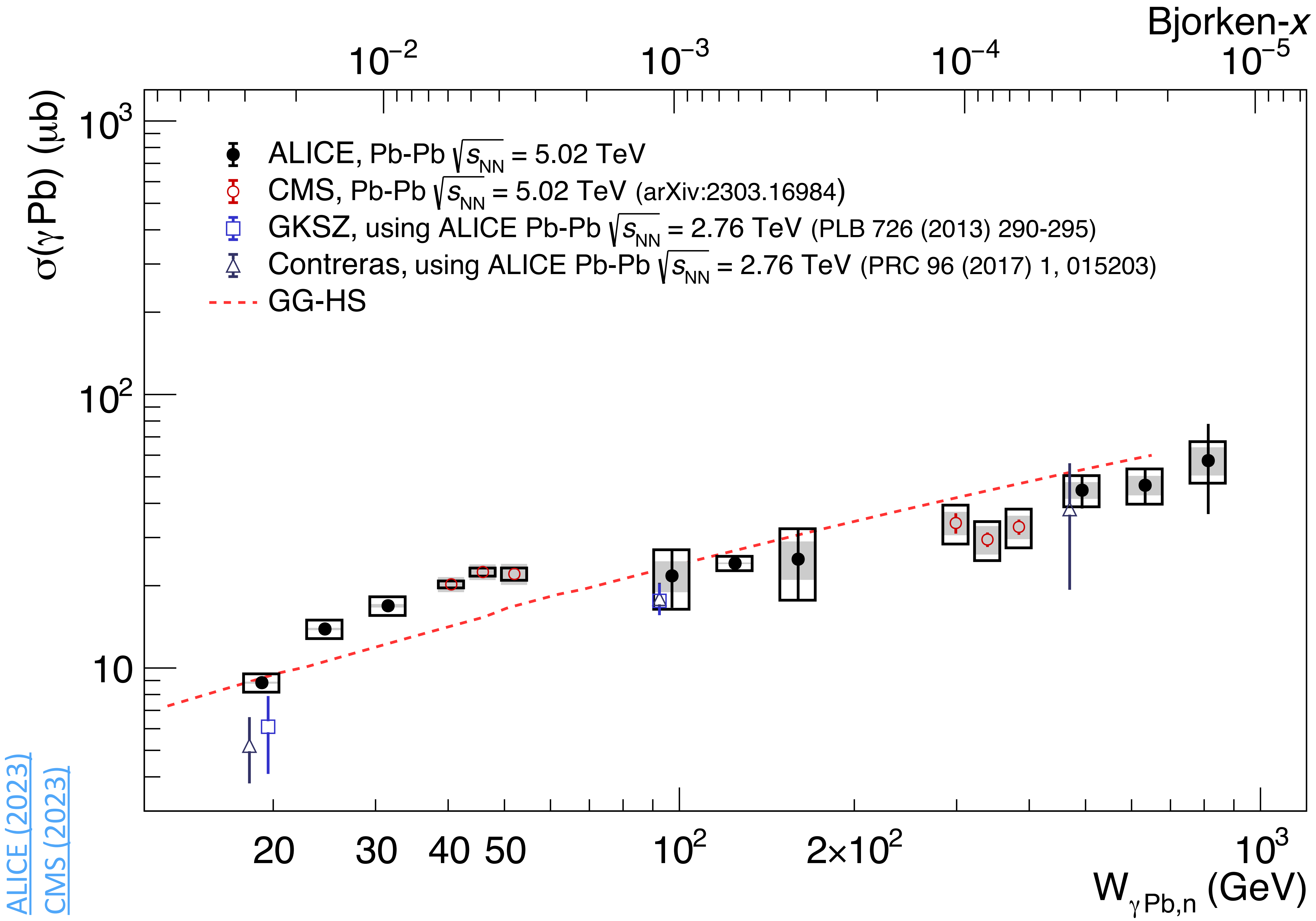


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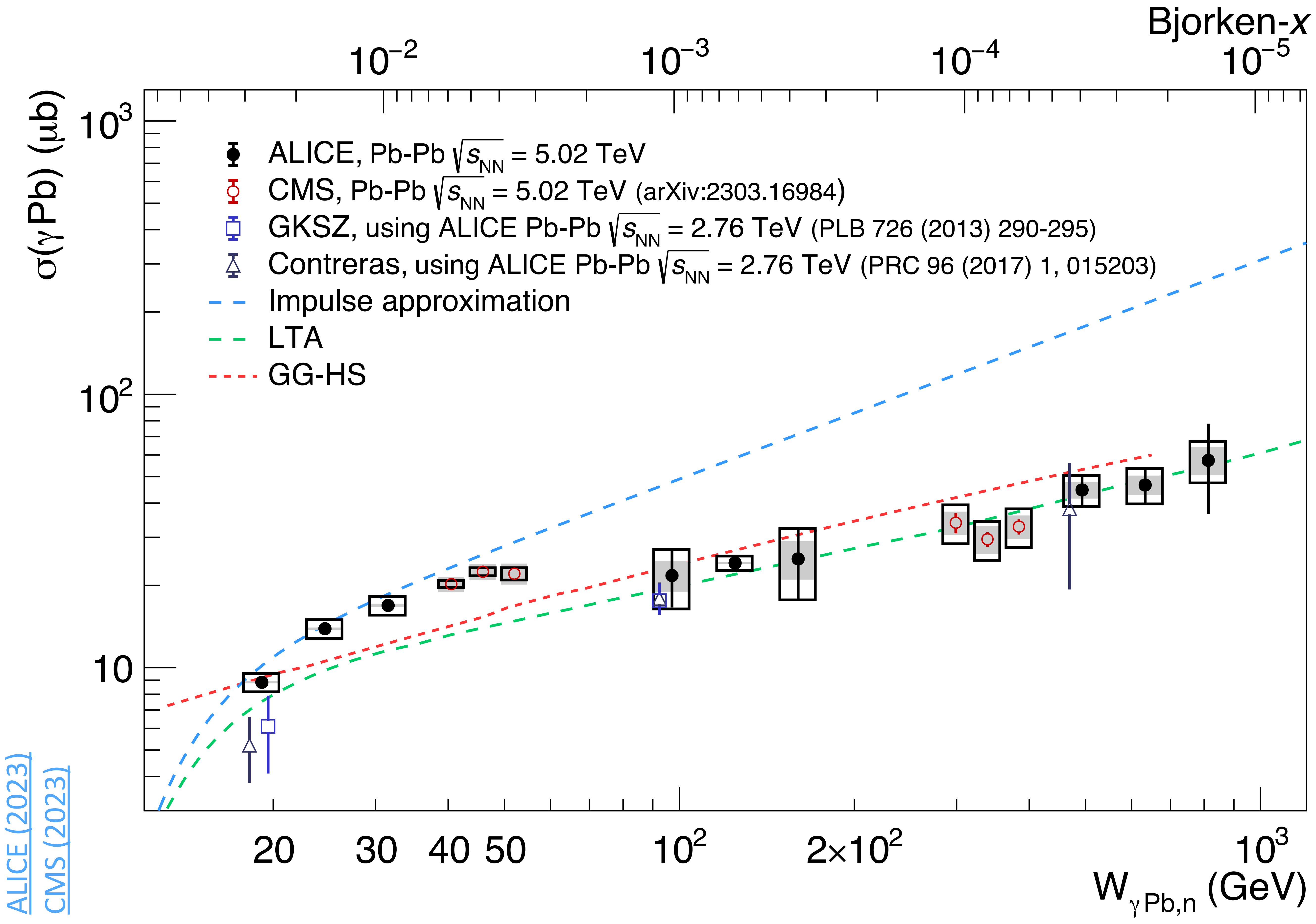
Uses the colour-dipole model. Other models based on this approach and including saturation through CGC or BK yield similar results: good description at small x

# Coherent J/ψ production: the full picture




ALICE (2023)
CMS (2023)

No model describe all the data

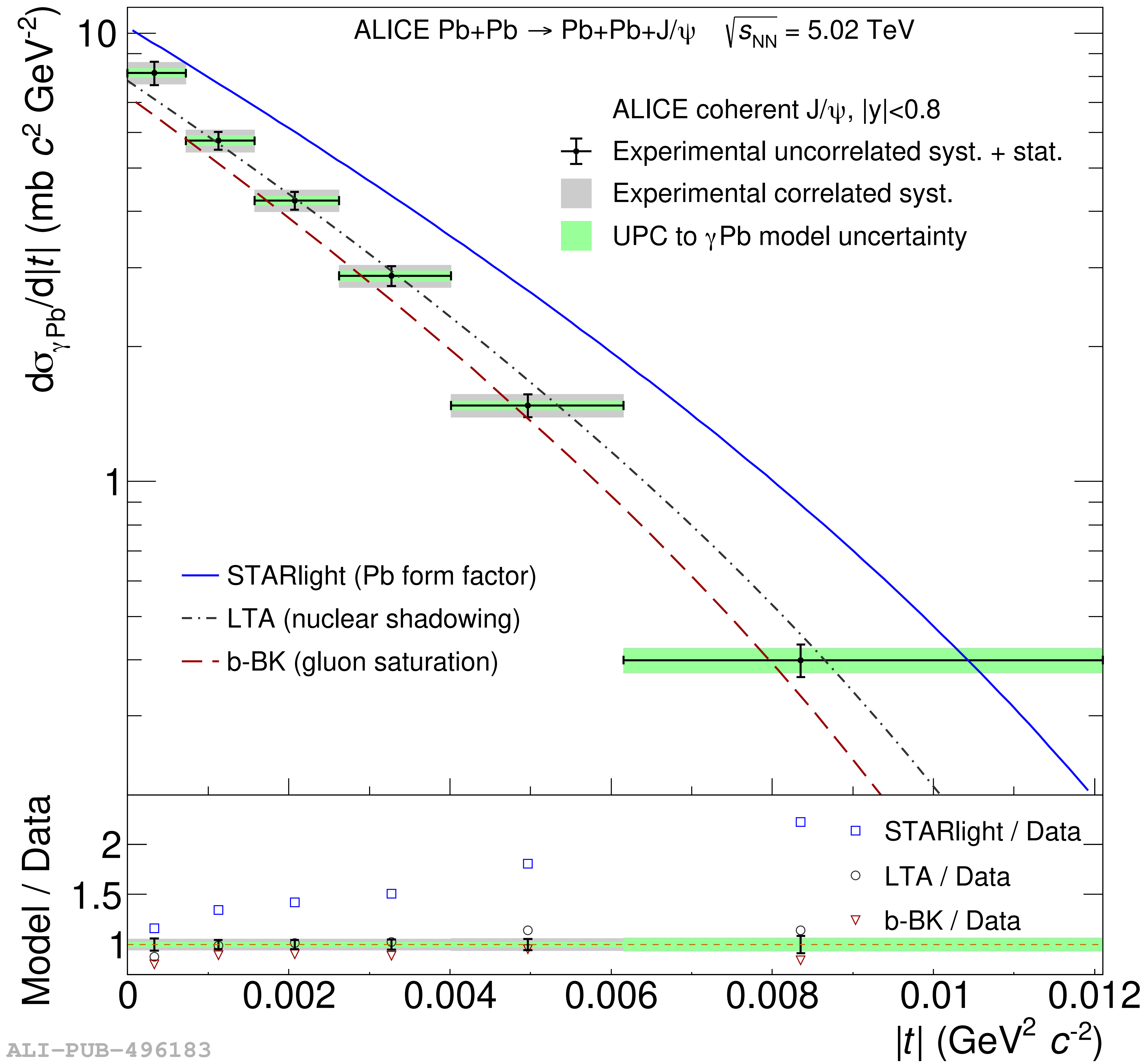
Nuclear effects important at small x

Shadowing and saturation based predictions are similar at small x

This observable on its own is not enough to find saturation

# Coherent J/ψ production: gluons in the transverse plane

ALICE (2021)



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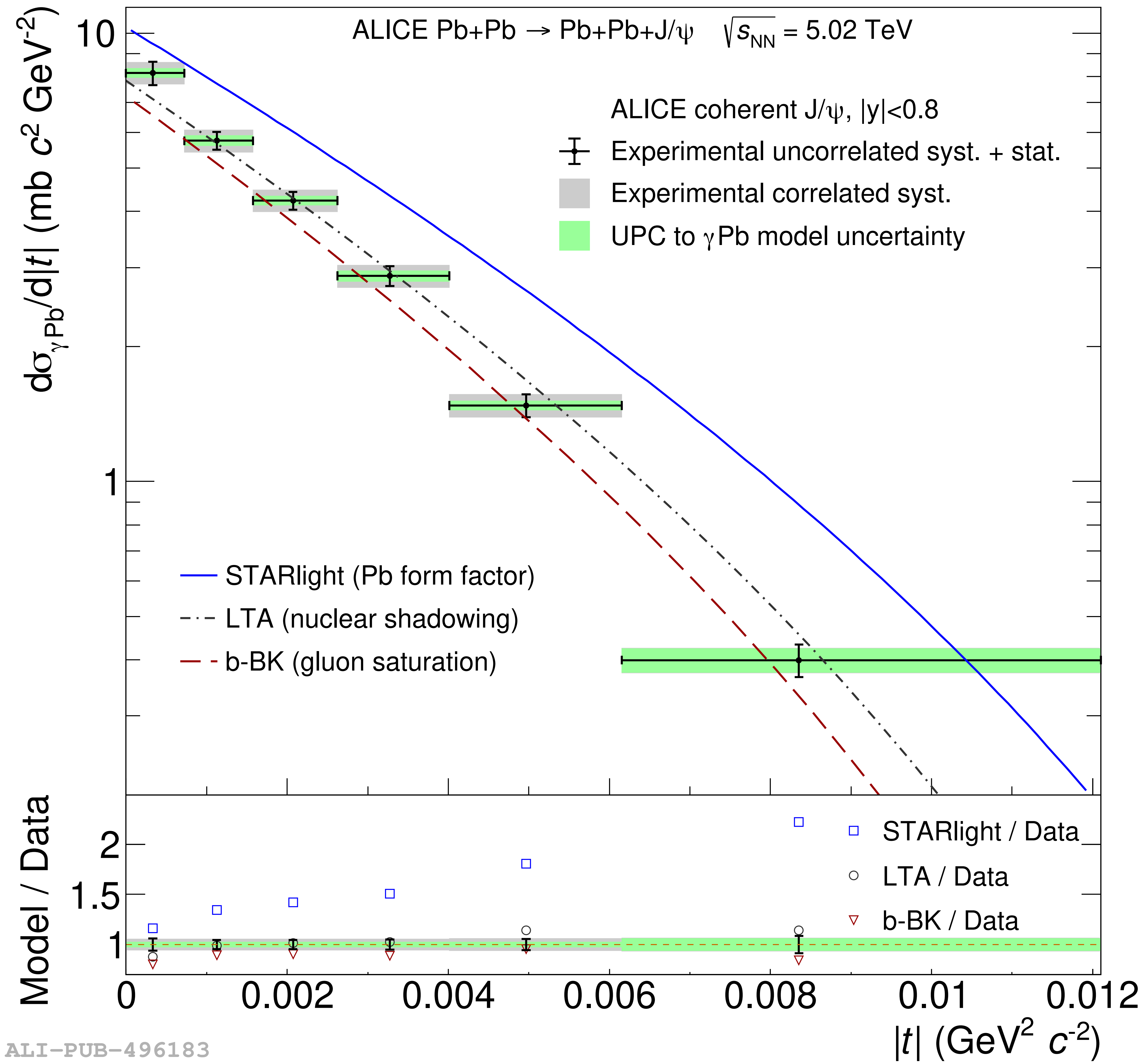


Transverse momentum and impact parameter are Fourier conjugate variables → Mandelstam-t dependence is sensitive to the gluon distribution in impact parameter

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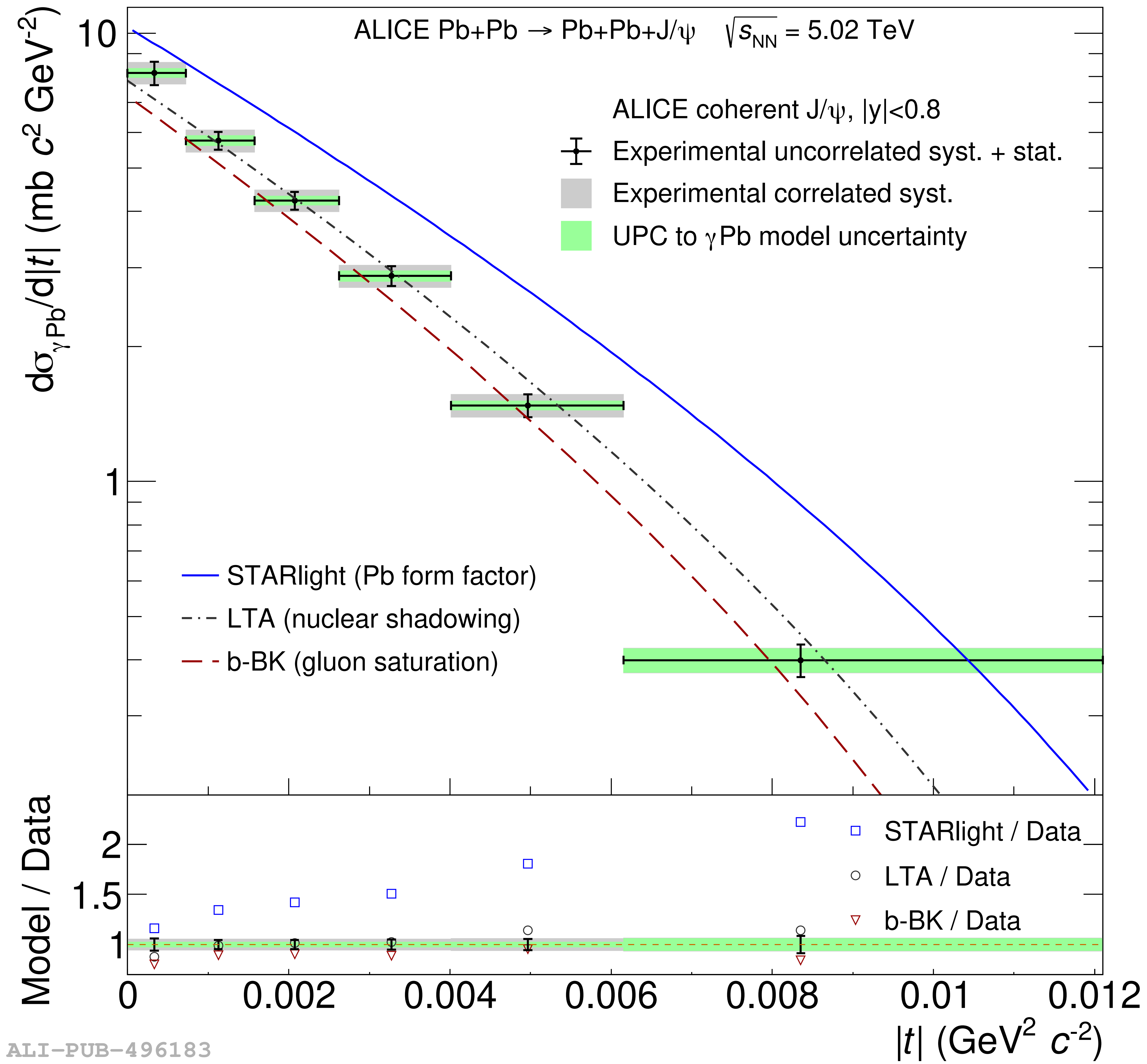


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Mandelstam-t dependence measured with HERA-like precision down to zero momentum transfer

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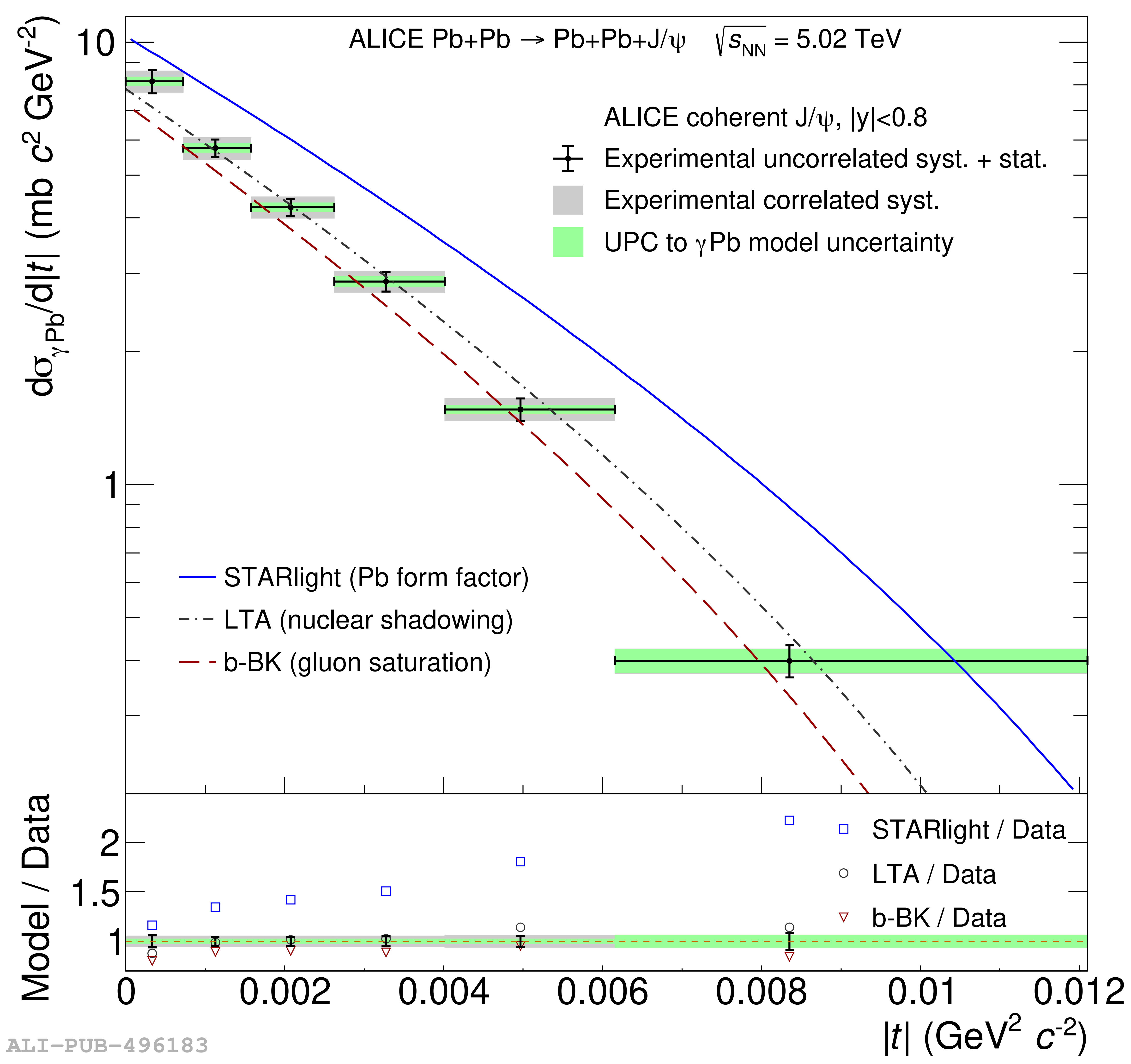


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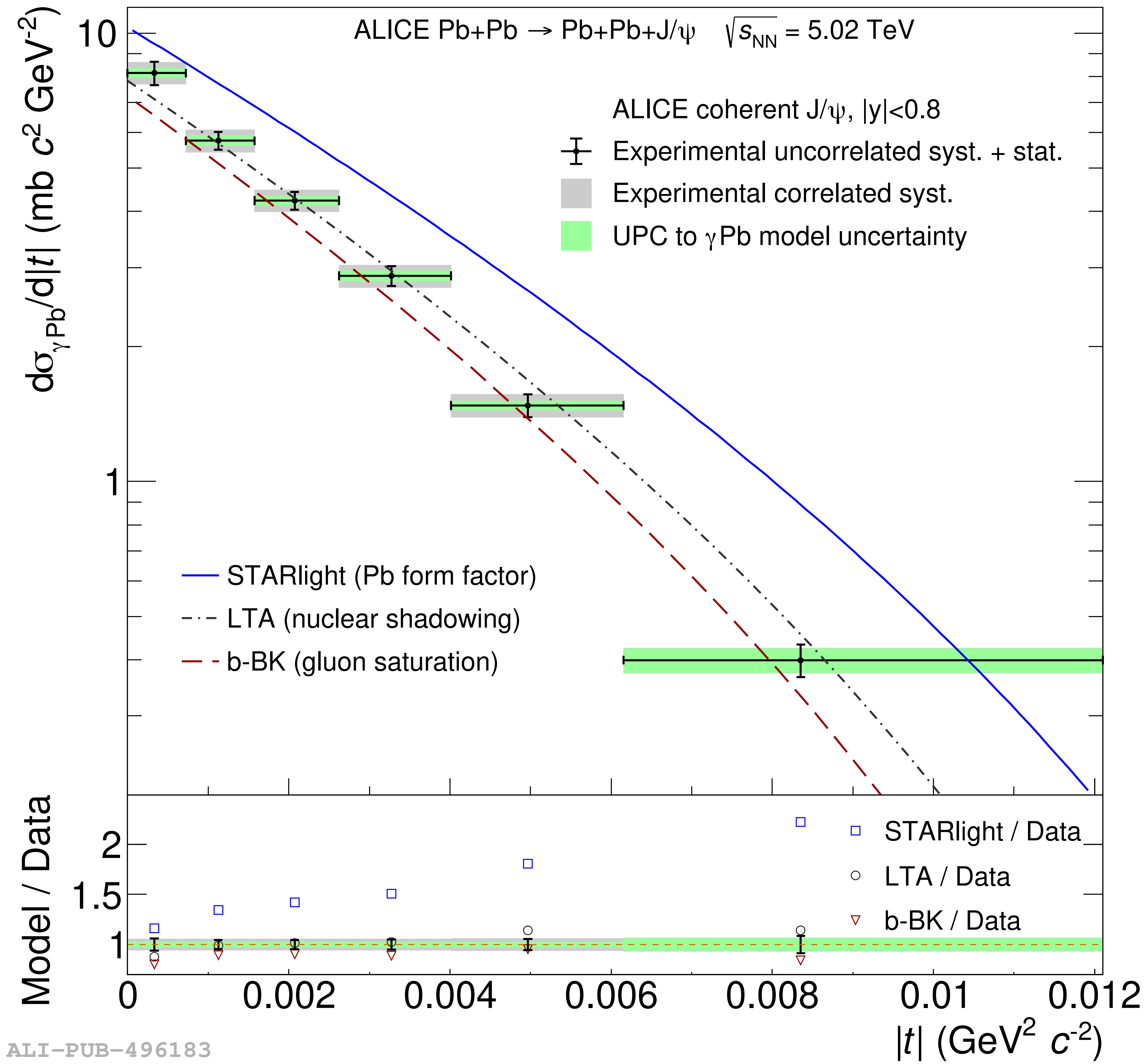


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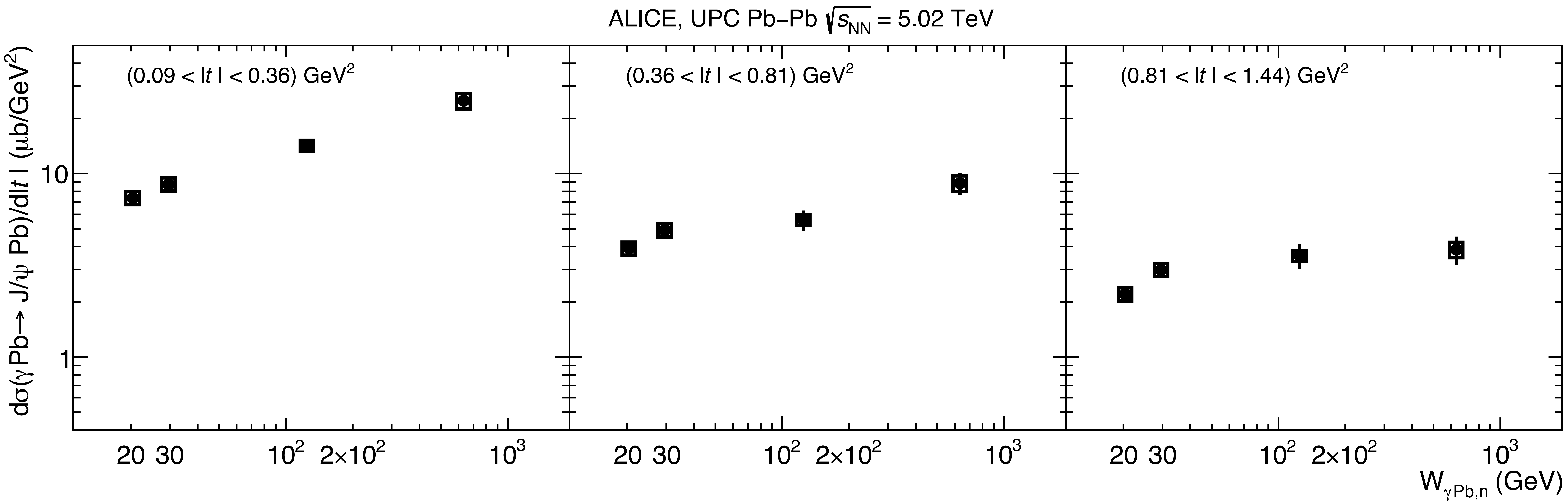
Saturation- and shadowing-based models provide a good description of data → exploit fluctuations

# Multi-differential incoherent J/ψ: data

ALICE (2025)




Bjorken-x dependence measured in a large energy range for different Mandelstam-t ranges

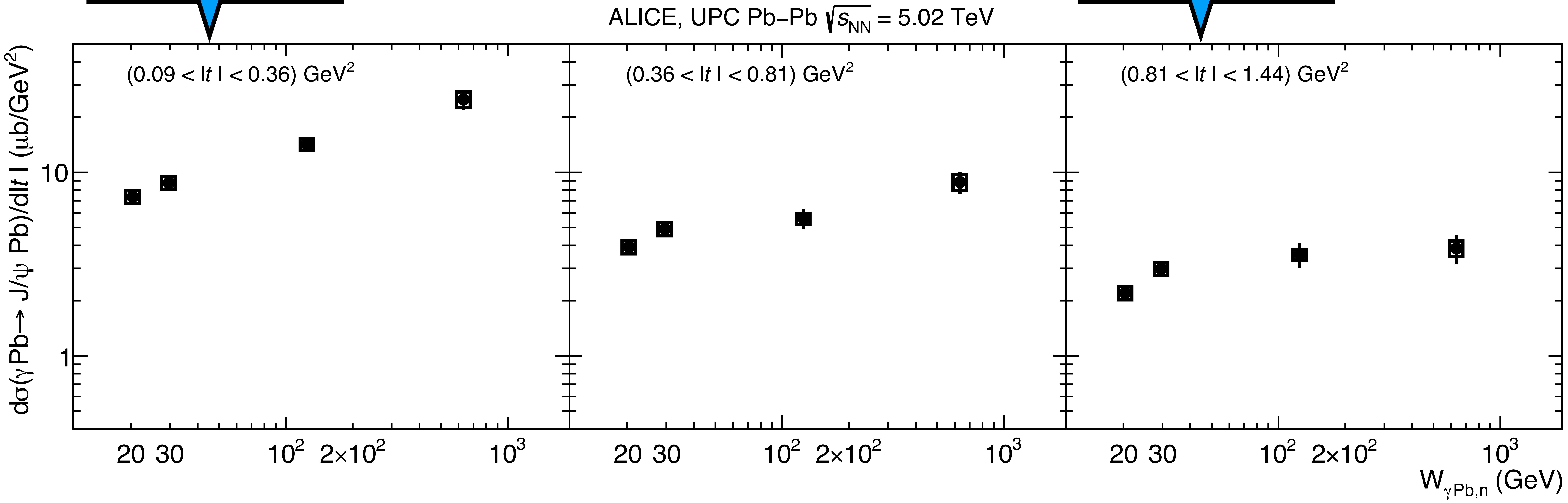
The rate of grow with energy decreases as Mandelstam-t increases

# Multi-differential incoherent J/ψ: data

Sensitive to fluctuations at large scales

Sensitive to fluctuations at small scales

ALICE (2025)

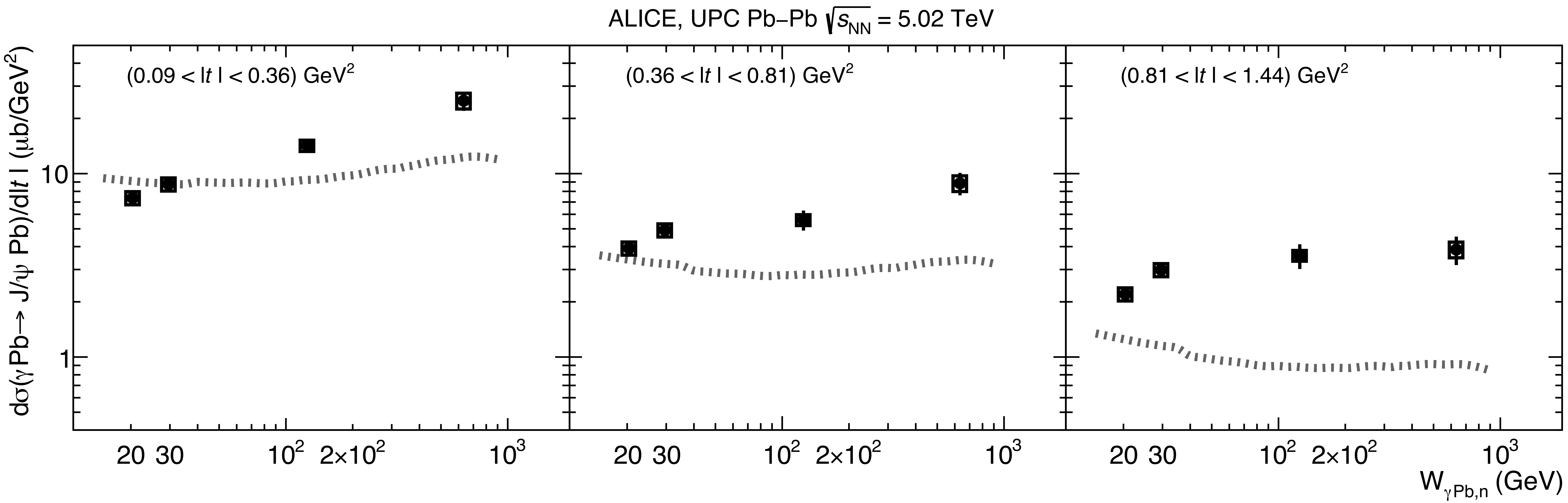



Bjorken-x dependence measured in a large energy range for different Mandelstam-t ranges

The rate of grow with energy decreases as Mandelstam-t increases

# Multi-differential incoherent J/ψ: LTA

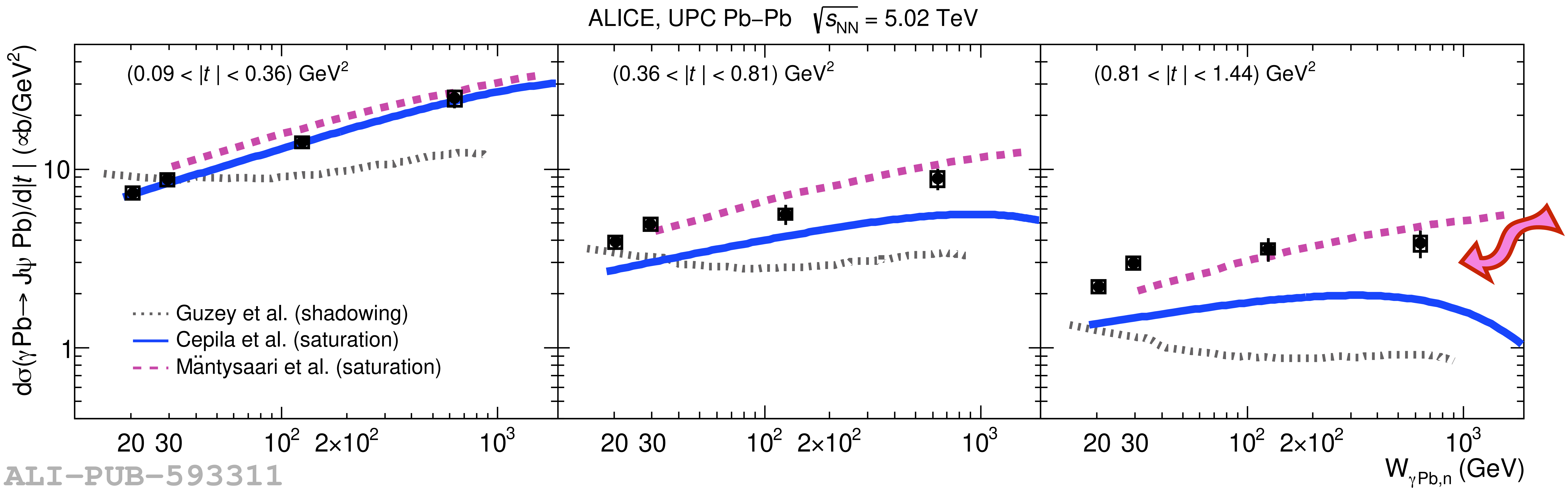
ALICE (2025)




The LTA model that describes coherent data seems to be disfavoured by this measurement

# Multi-differential incoherent J/ψ: the full picture

ALICE (2025)




Two saturation-based models differ in the predicted behaviour at high energies and high Mandelstam-t:
data cannot (yet?) decide if the cross section starts to decrease

# Summary and outlook

Due to its sensitivity to the gluon field, diffractive photonuclear J/ψ production is a good tool to search for saturation

Within the Good-Walker approach this process give access to the average and the variance of the gluon distribution

LHC results are reaching HERA like precision over a large kinematic range in Bjorken-x and Mandelstam-t

Disentangling the contributions of shadowing from those of saturation will require simultaneous multi-differential measurements of different observables

ALICE has already recorded much more data during LHC Run 3 so these measurements should be feasible in the near future