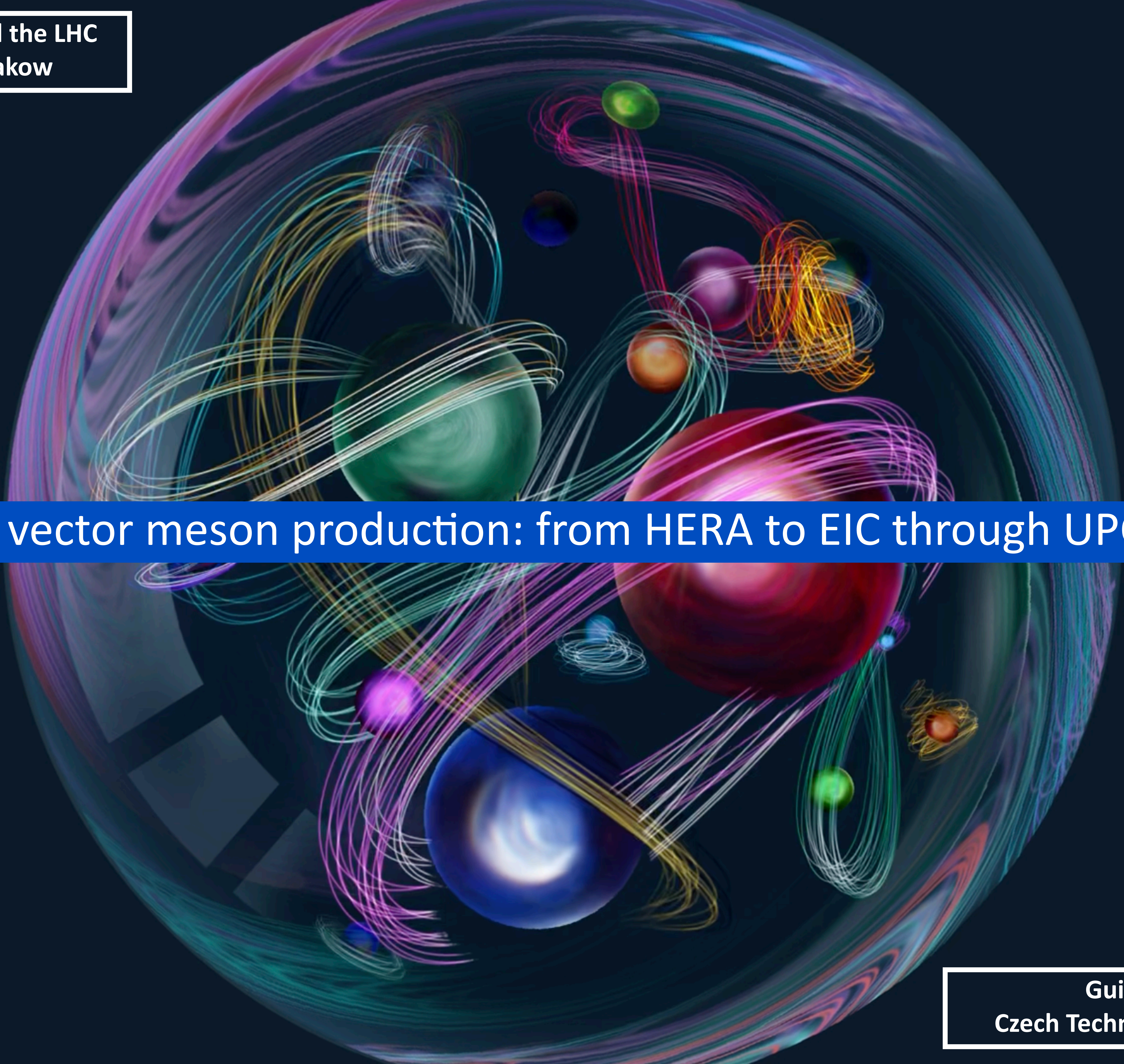
Synergies between the EIC and the LHC
22-24 September 2025, Krakow

Diffractive vector meson production: from HERA to EIC through UPC at LHC

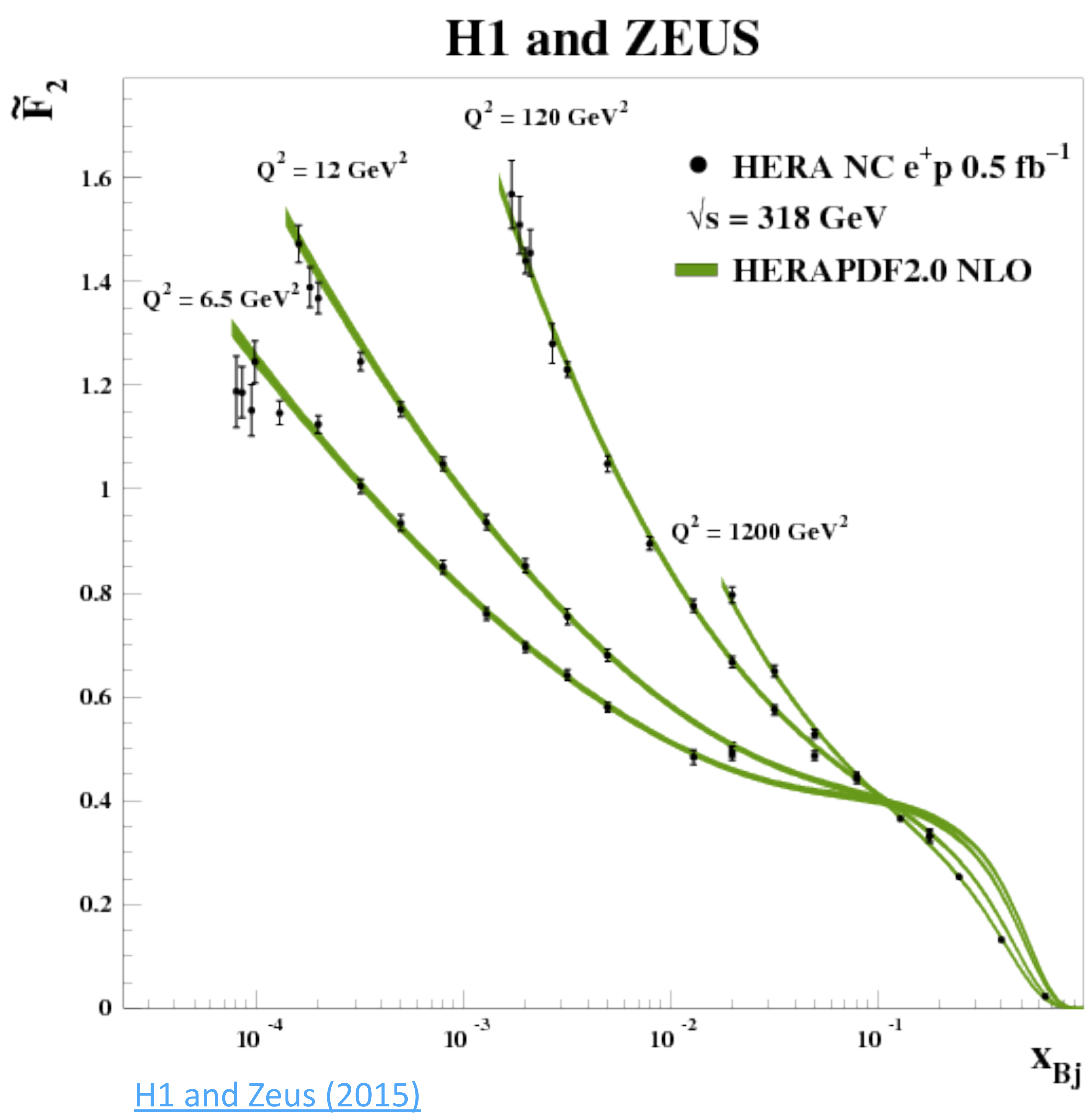


Guillermo Contreras
Czech Technical University in Prague

HERA: proton structure at small x

Guillermo Contreras, CTU in Prague

The behaviour of F_2 at small x



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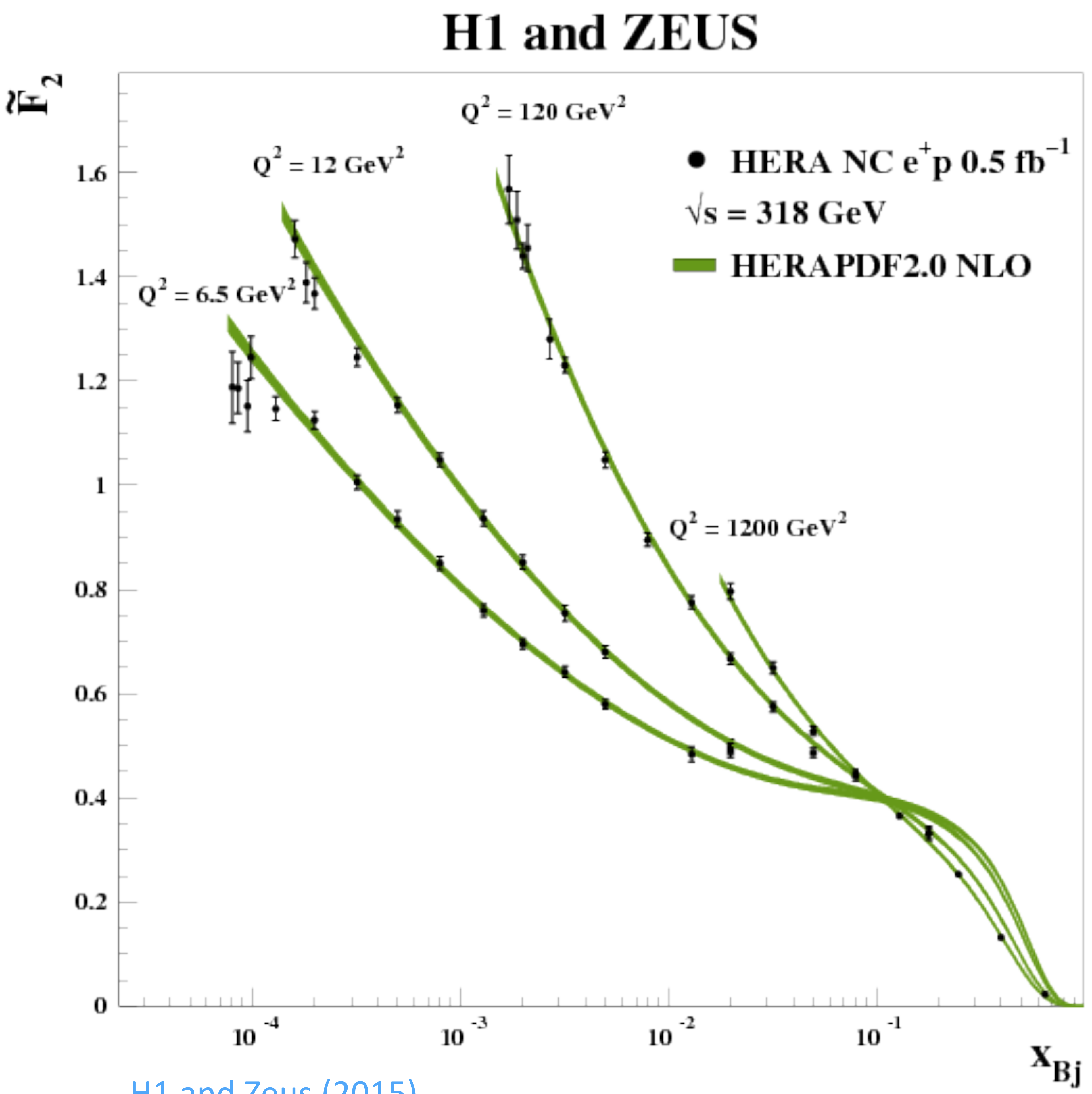

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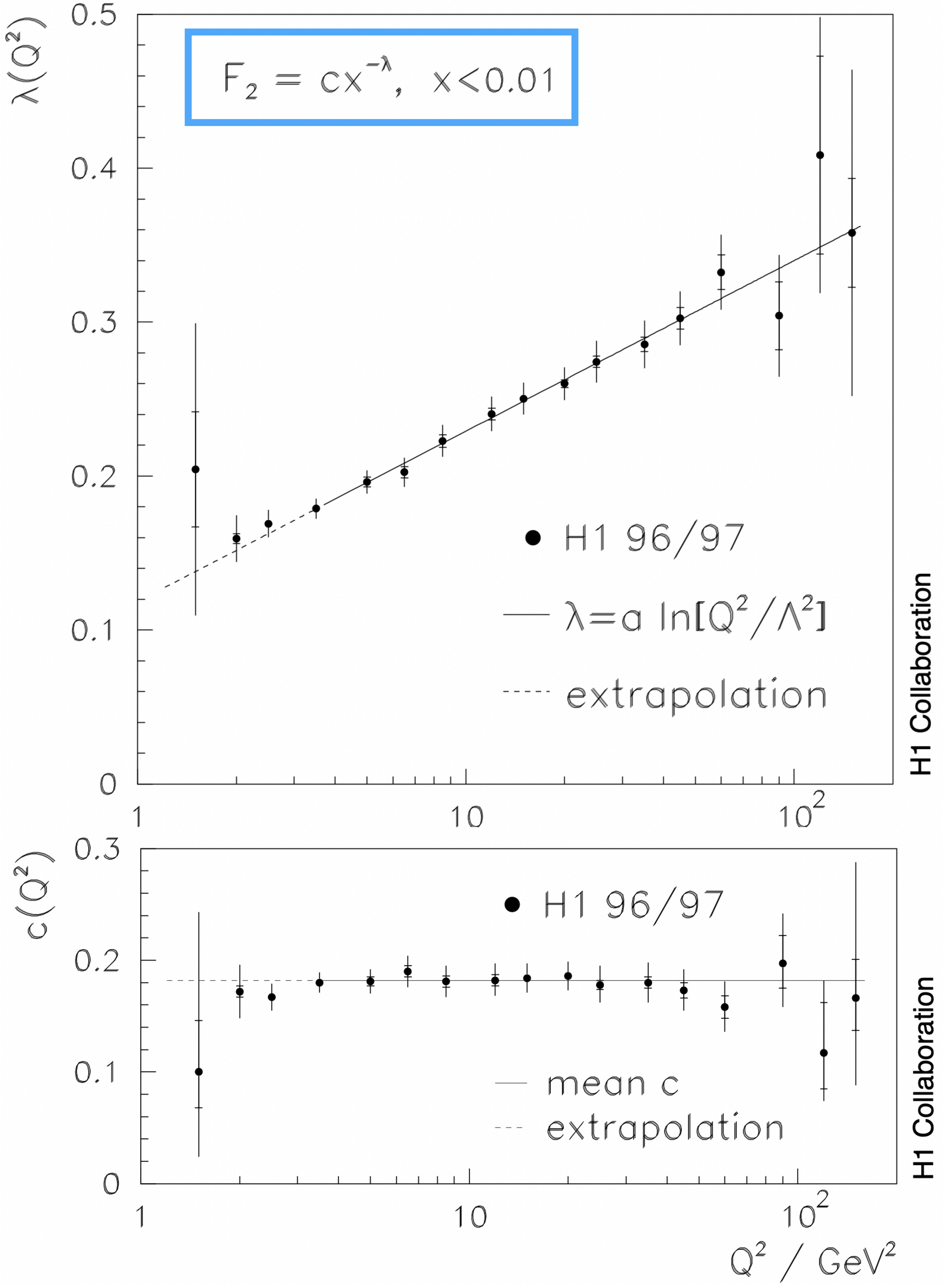

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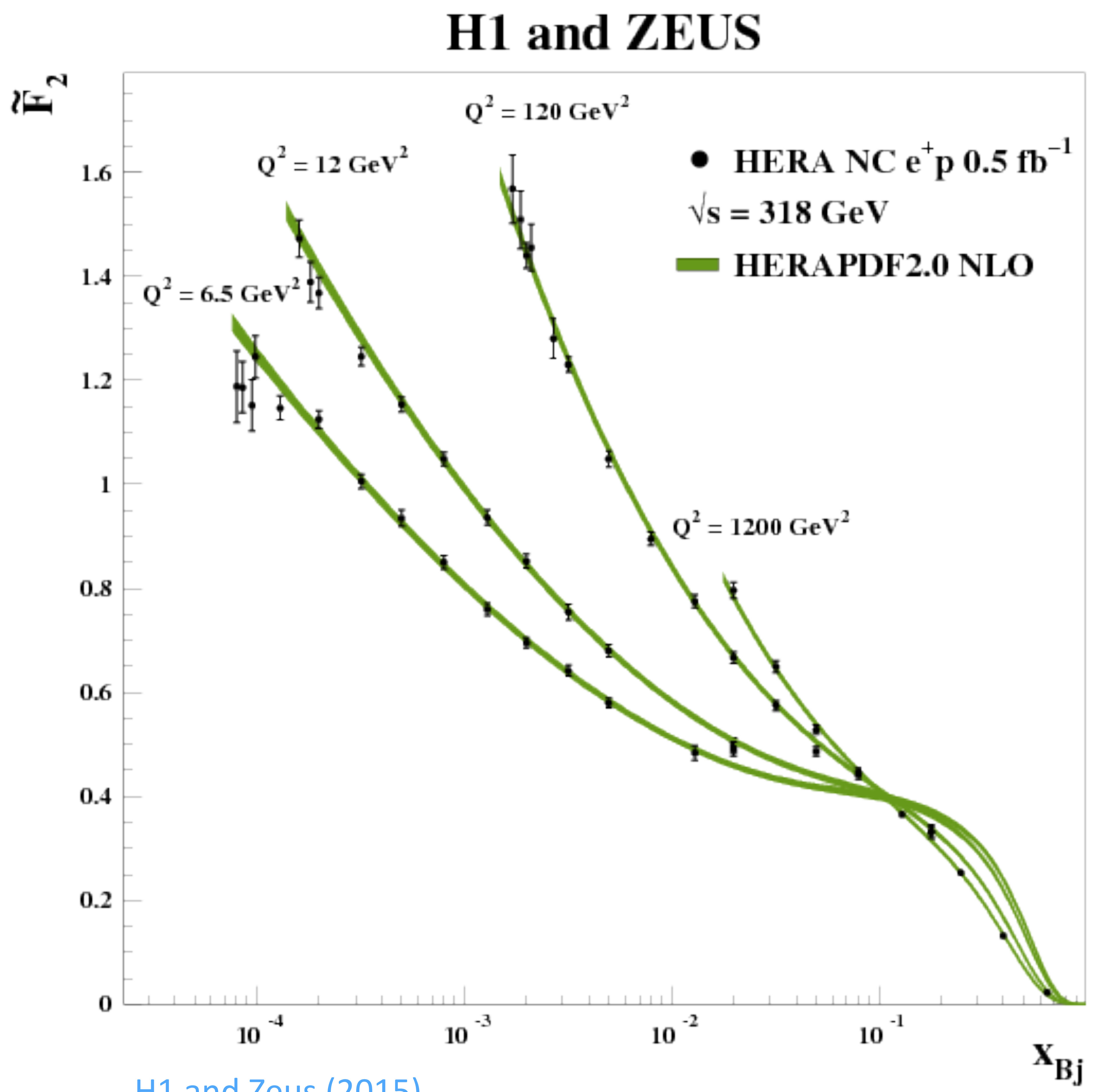
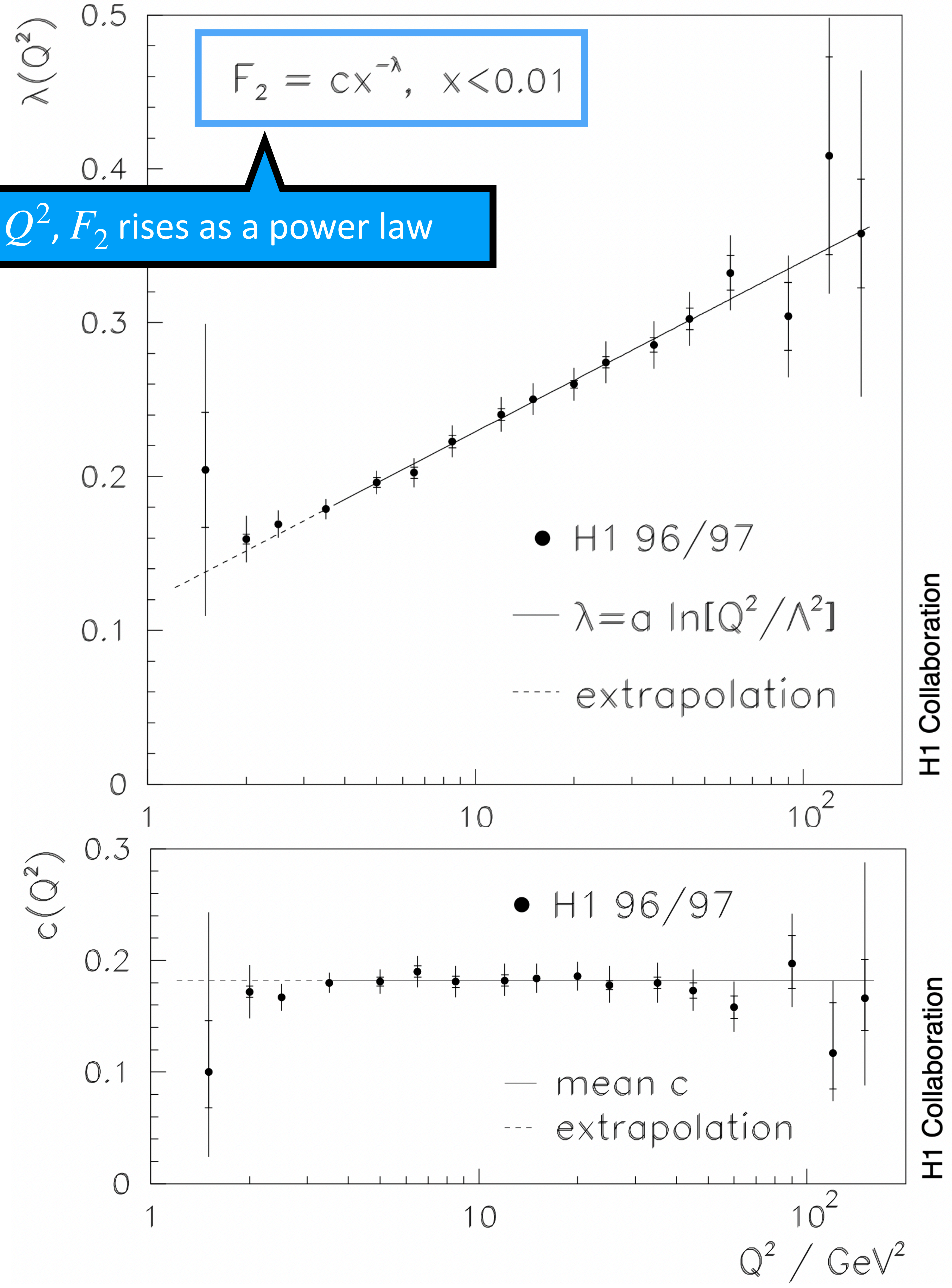


H1 and Zeus (2015)

At small x and fixed Q^2, F_2 rises as a power law



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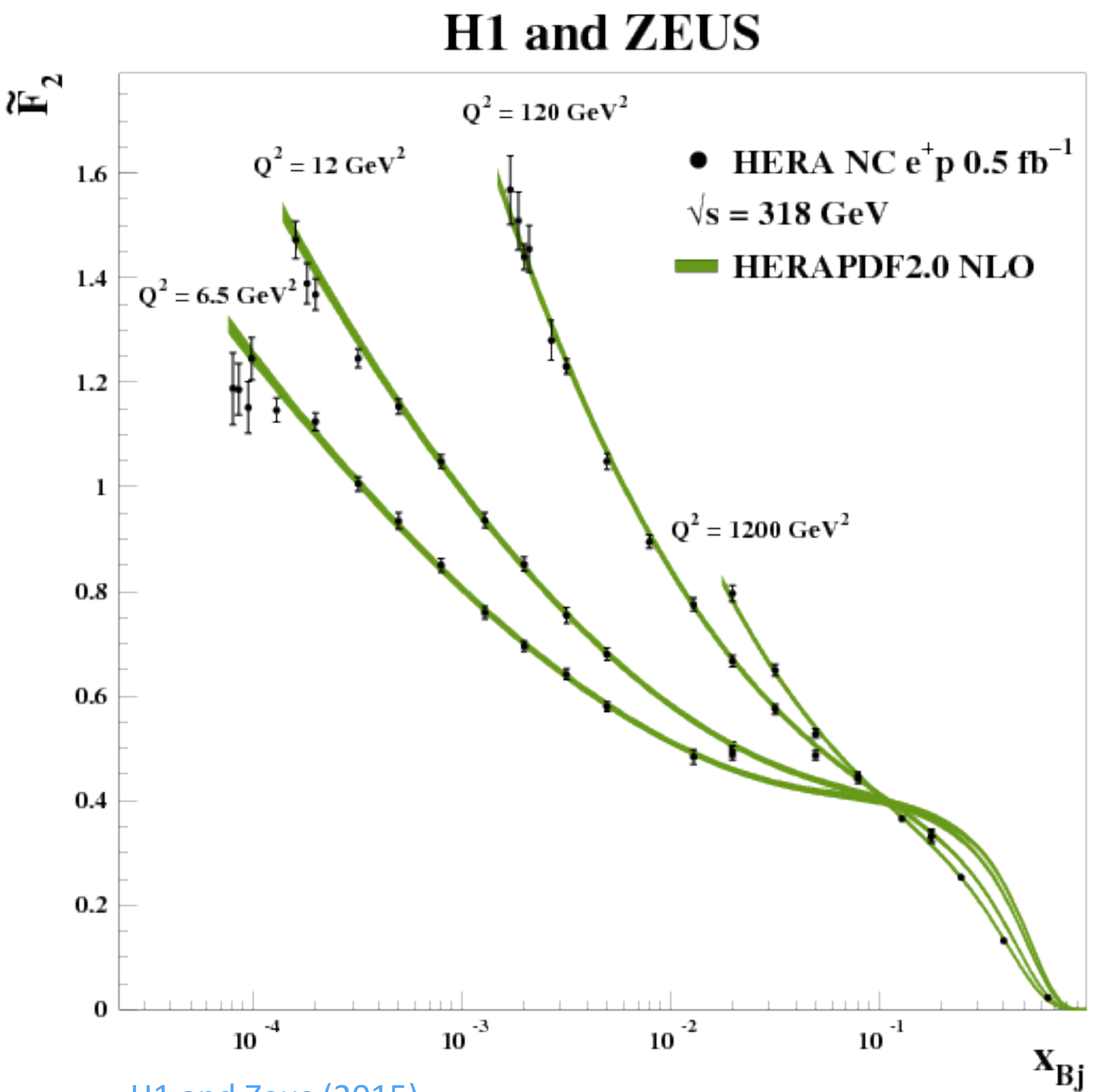

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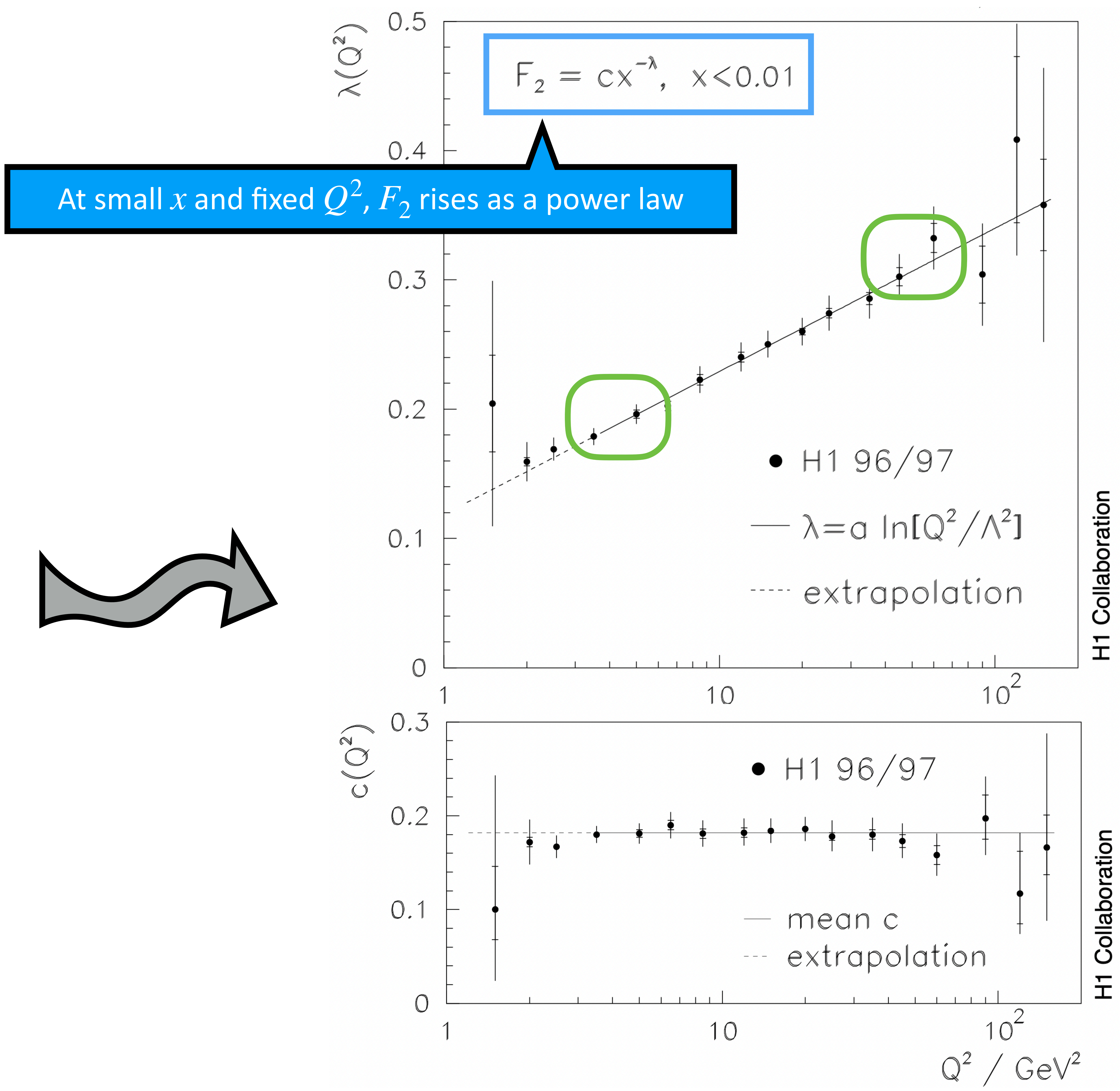

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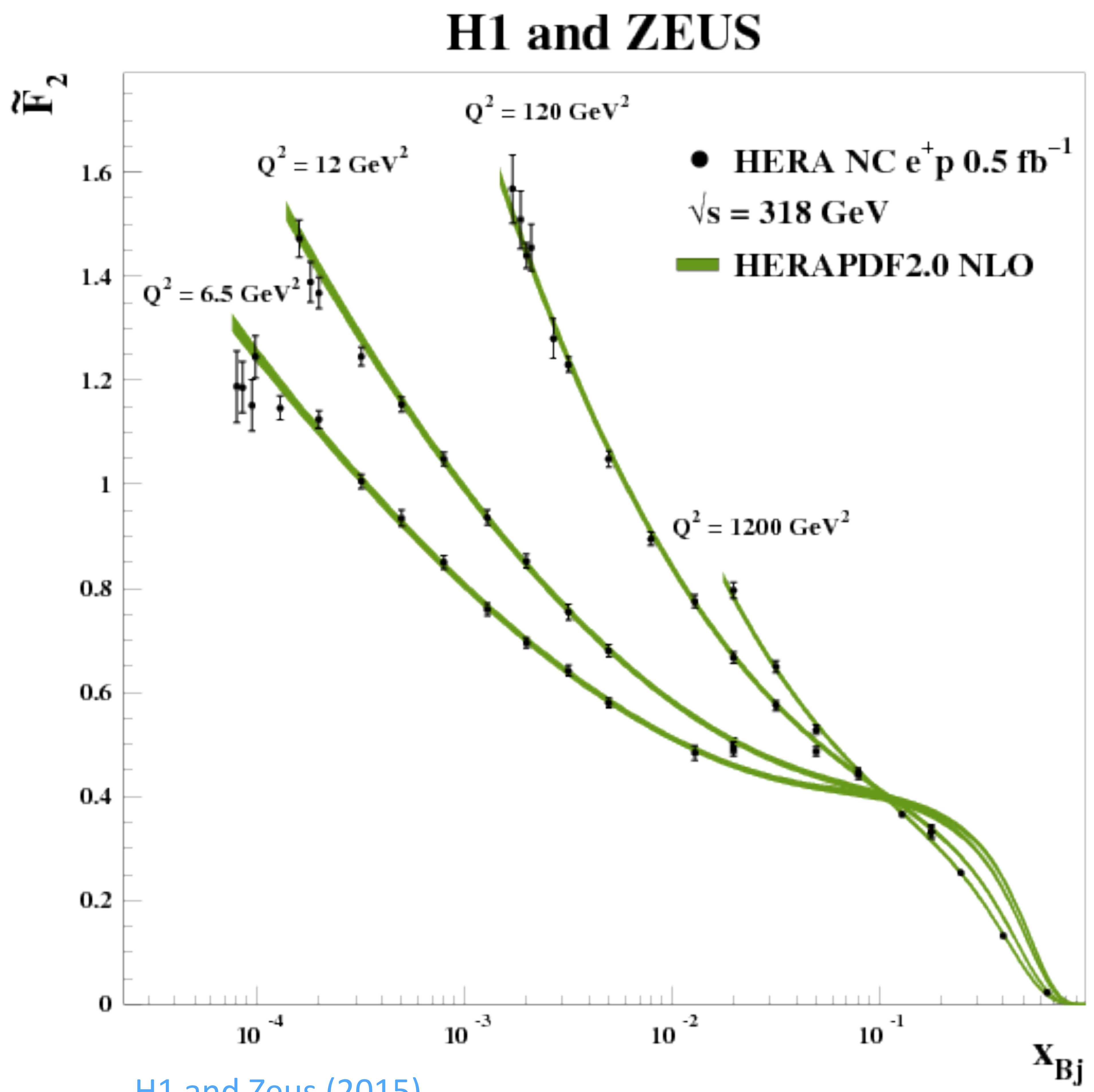

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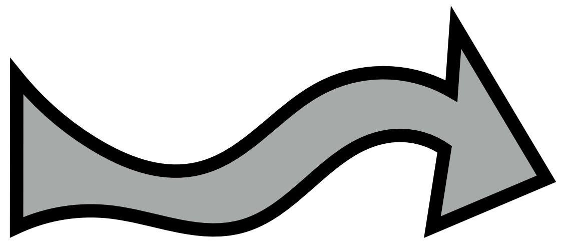

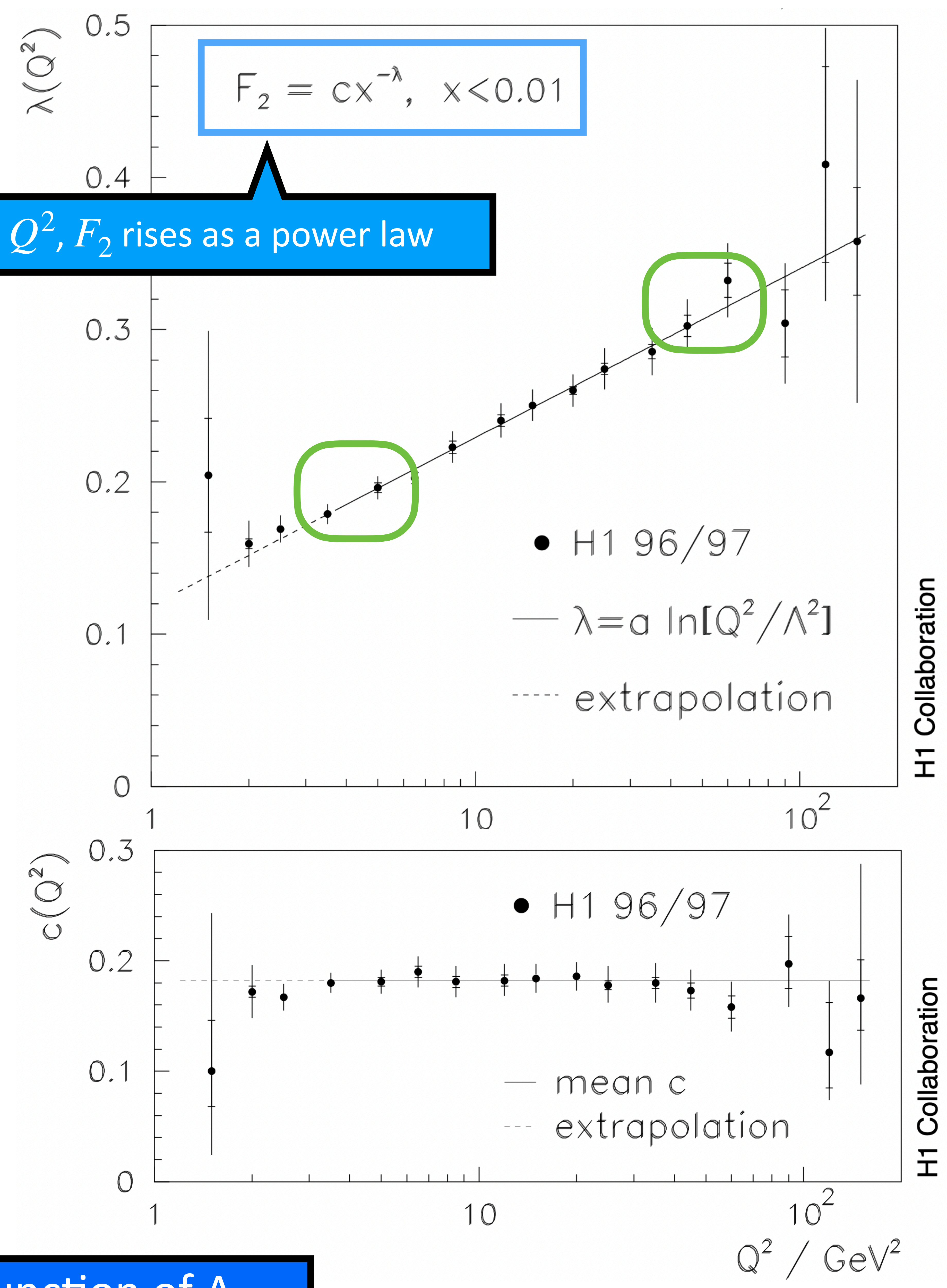

EIC: interesting to see these fits as a function of A

The QCD structure of protons

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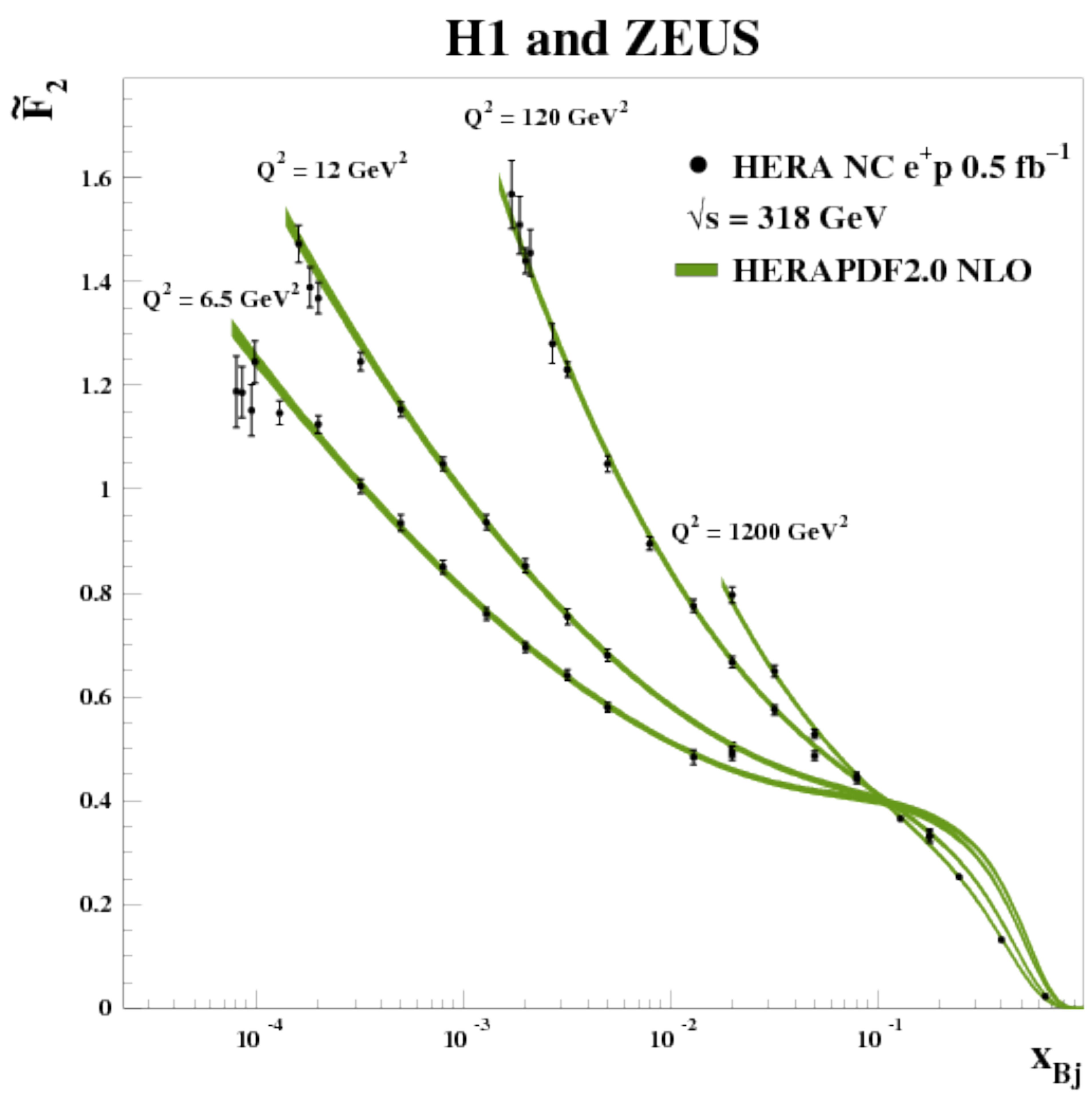
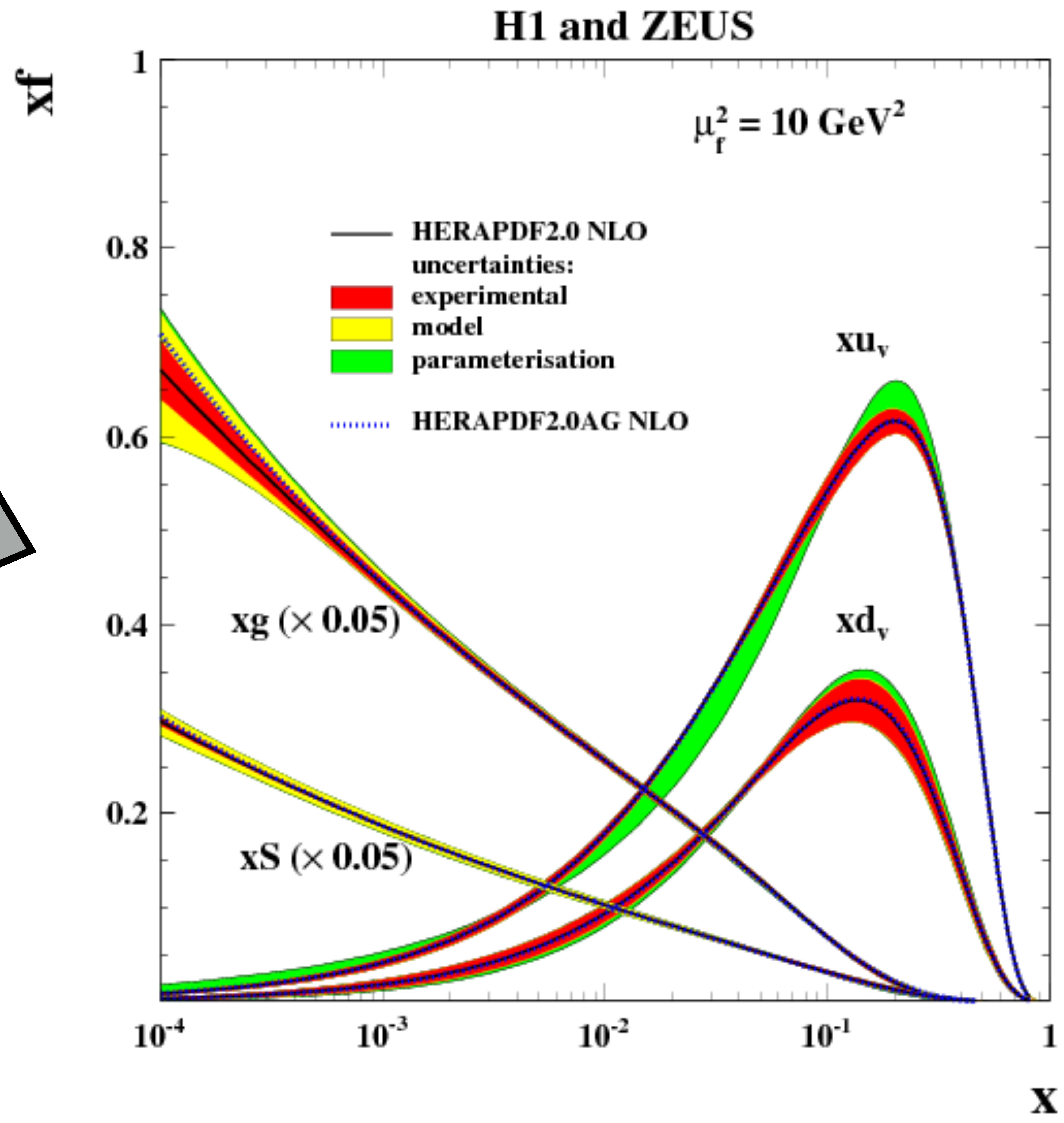


QCD

At small x, the protons are (mainly) made of gluons whose number rises as a power law



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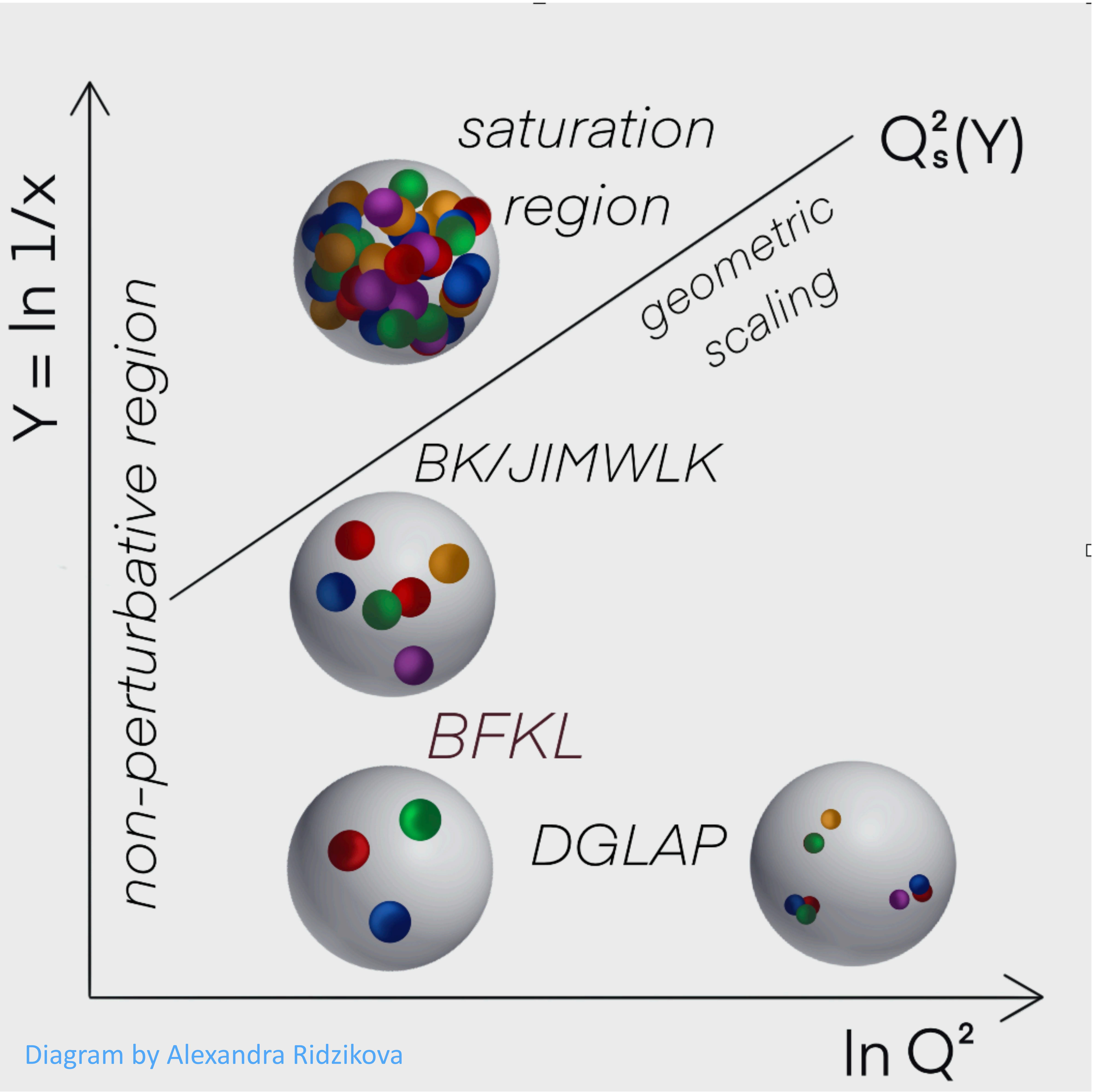

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It is not know when saturation sets in: this is one of the prime open questions in QCD today

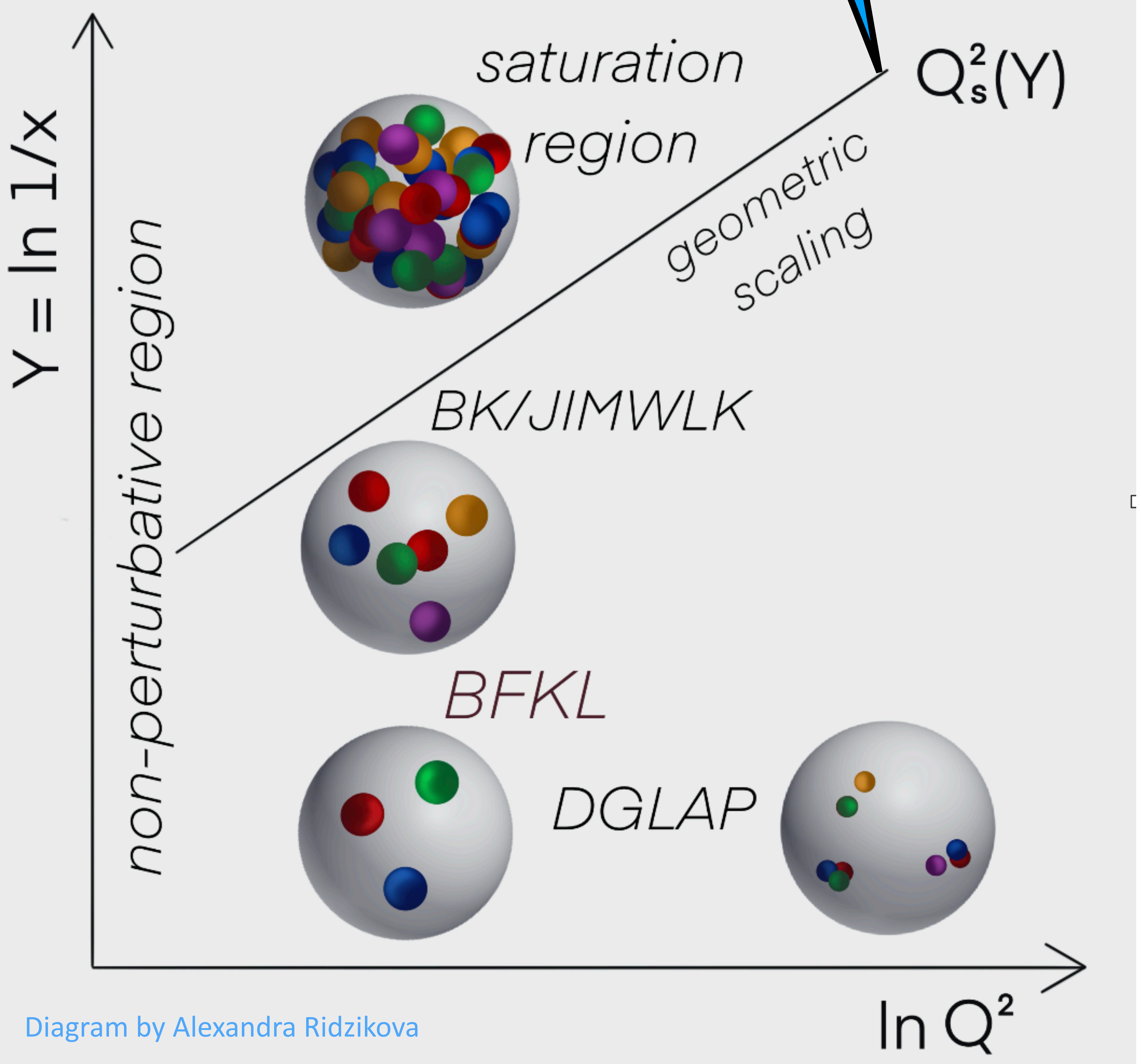

Diagram by Alexandra Ridzikova

Diffractive vector meson production and saturation

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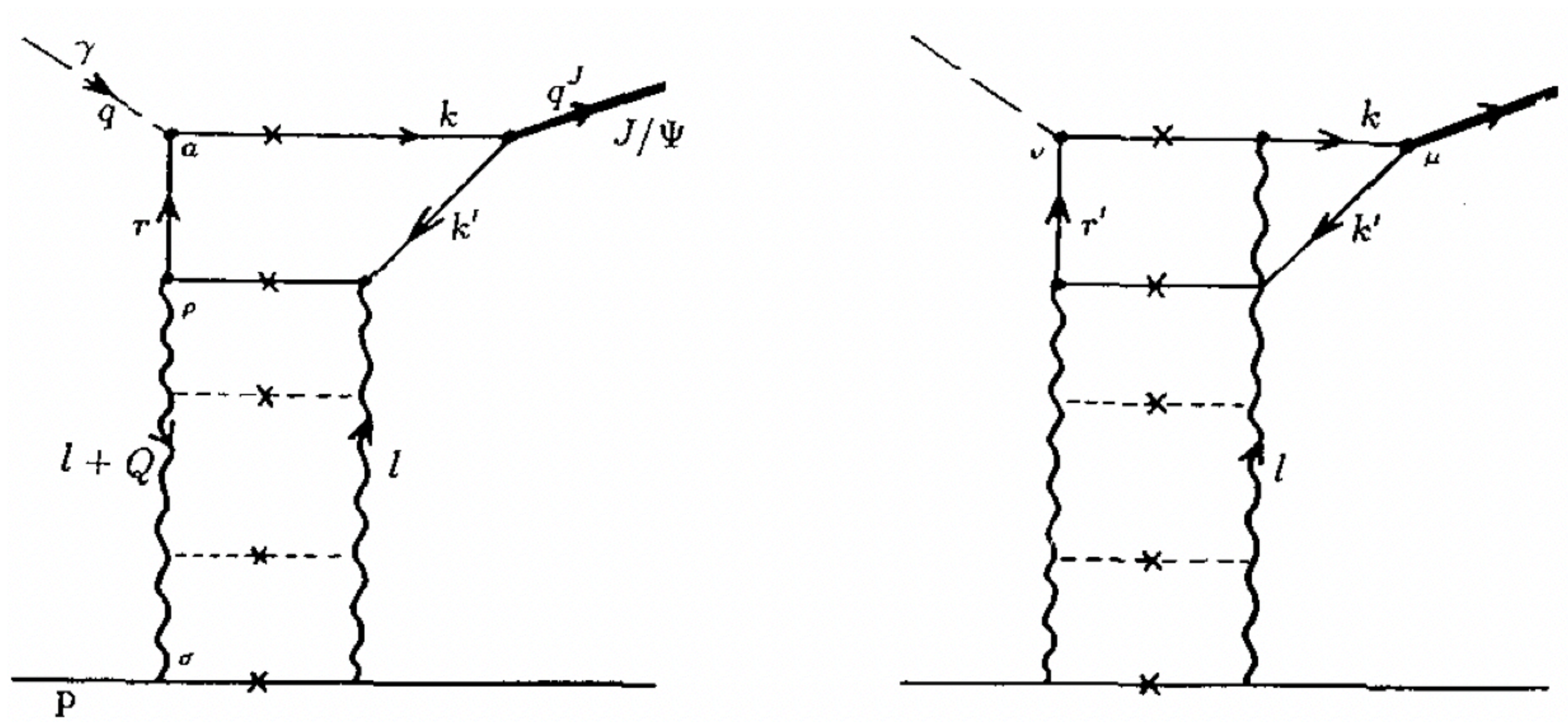

$$\frac{d\sigma}{dt} \propto \left[xG(x,Q^2)\right]^2$$

Note the square!

gluon distribution

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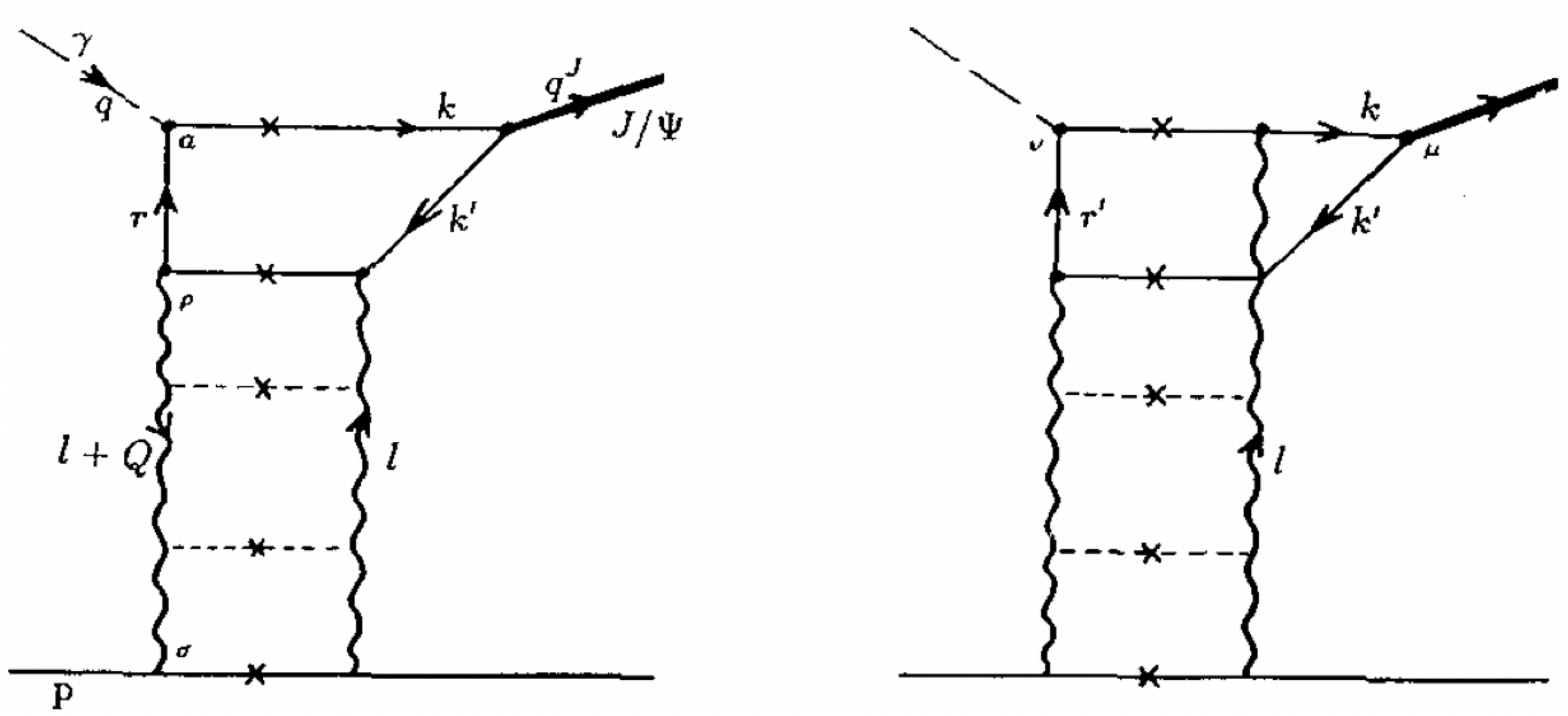

$x = (m^2 + Q^2)/(W^2 + Q^2)$

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gluon distribution

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

m is the vector meson mass
W is the centre – of – mass energy of the photon – proton sytem

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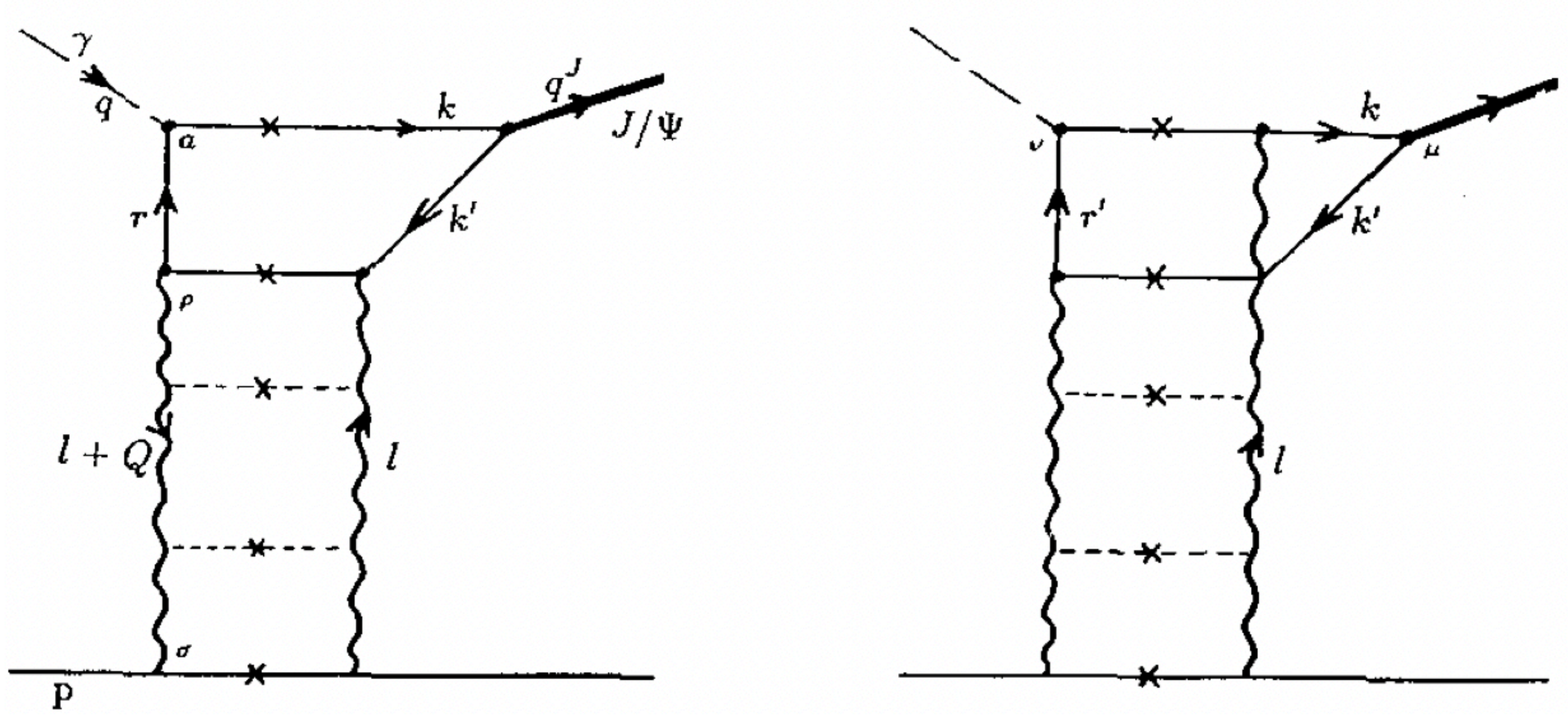

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From the paper:

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

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The Good-Walker approach

Good and Walker (1960)
Miettinen and Pumpling (1979)
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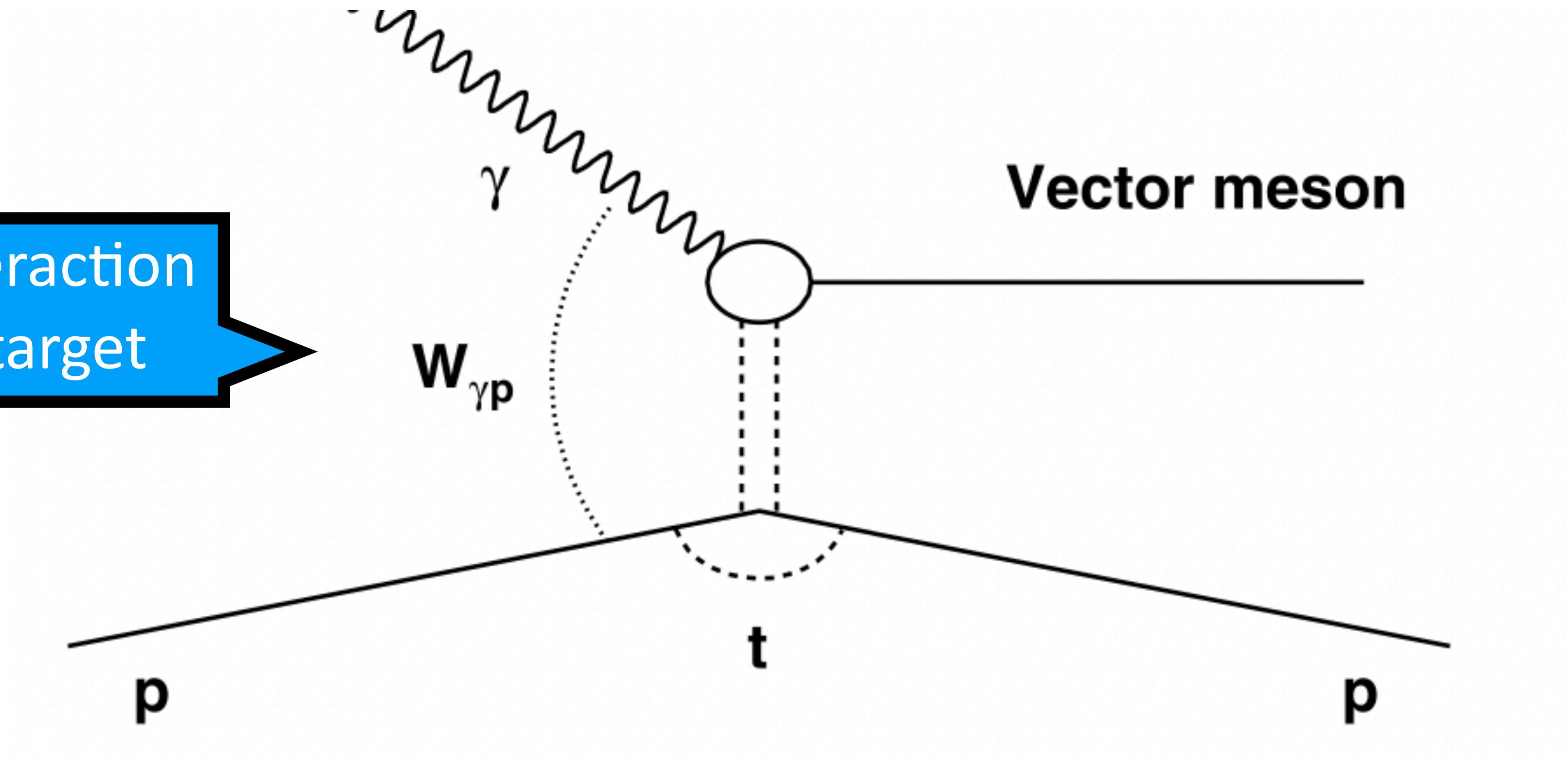
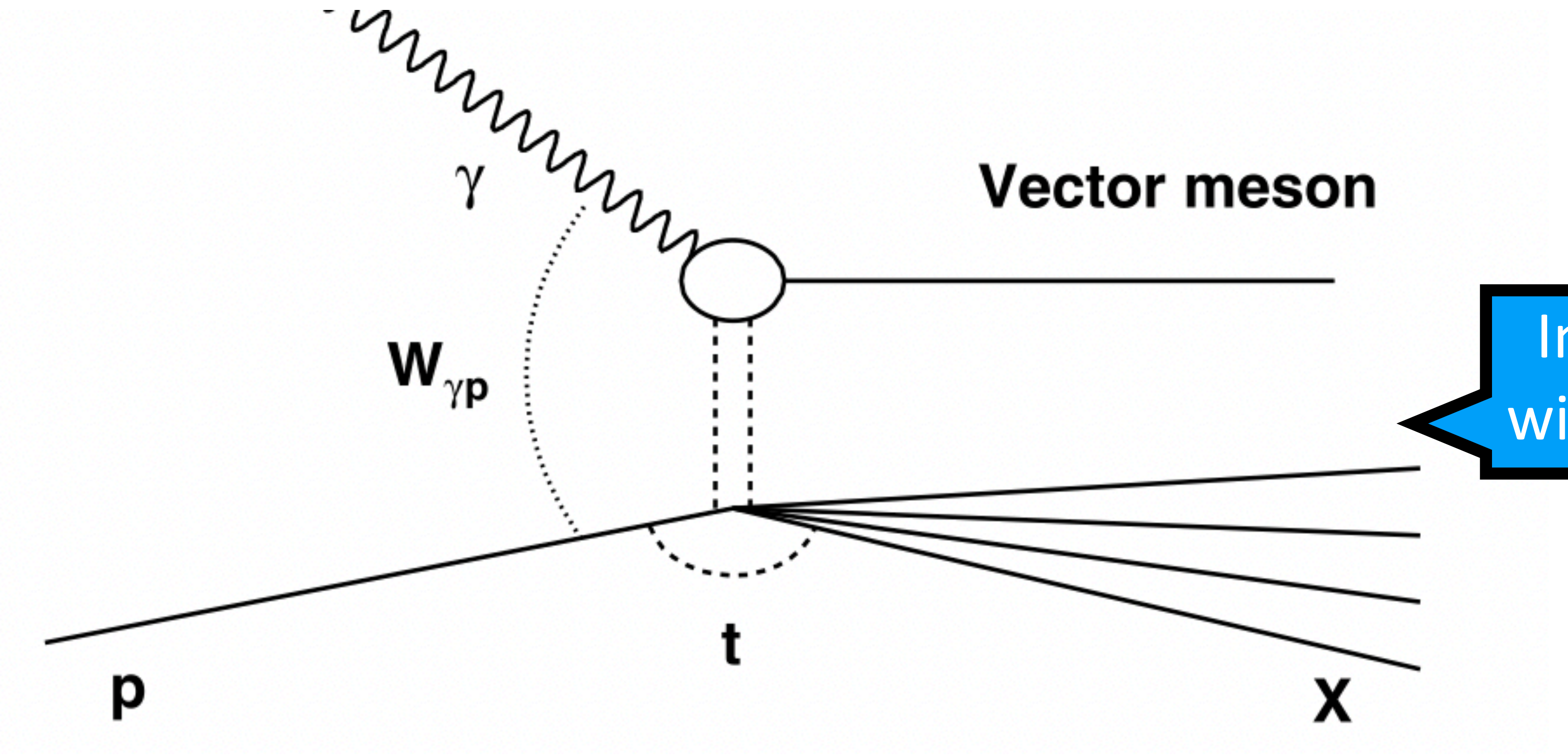
There are two types of diffractive vector meson production

Coherent: interaction with all the target





Incoherent: interaction with a piece of the target

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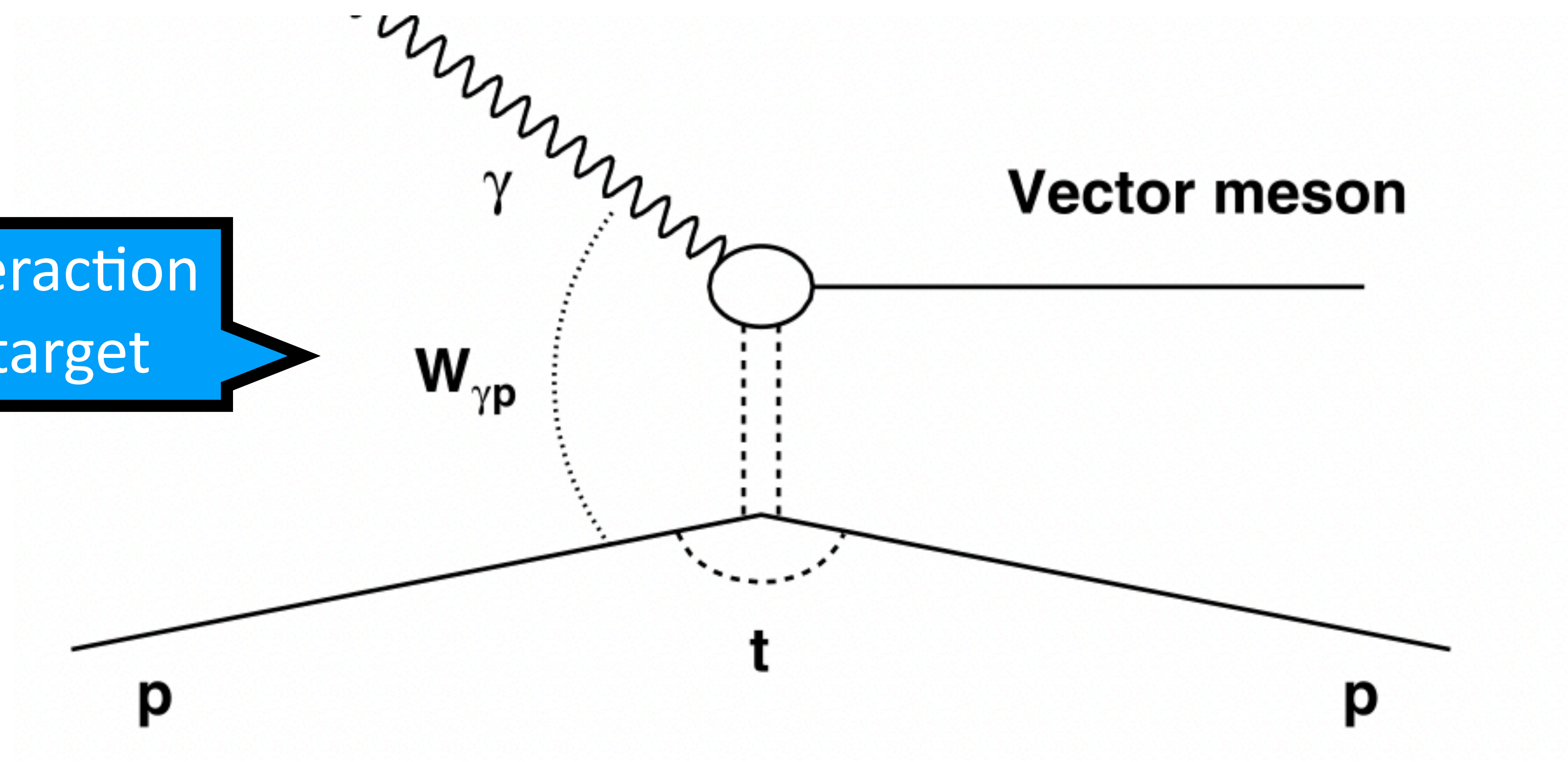

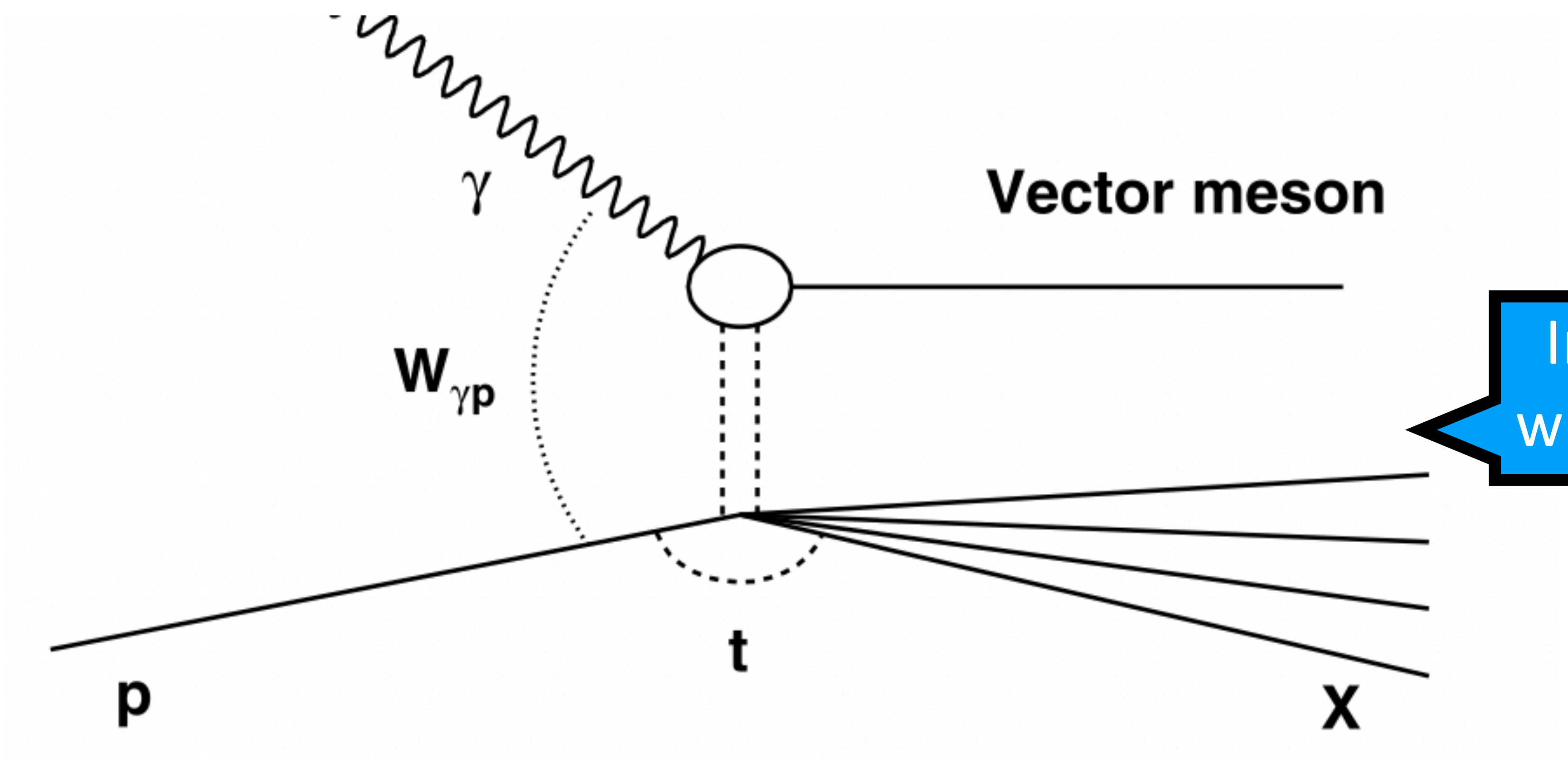

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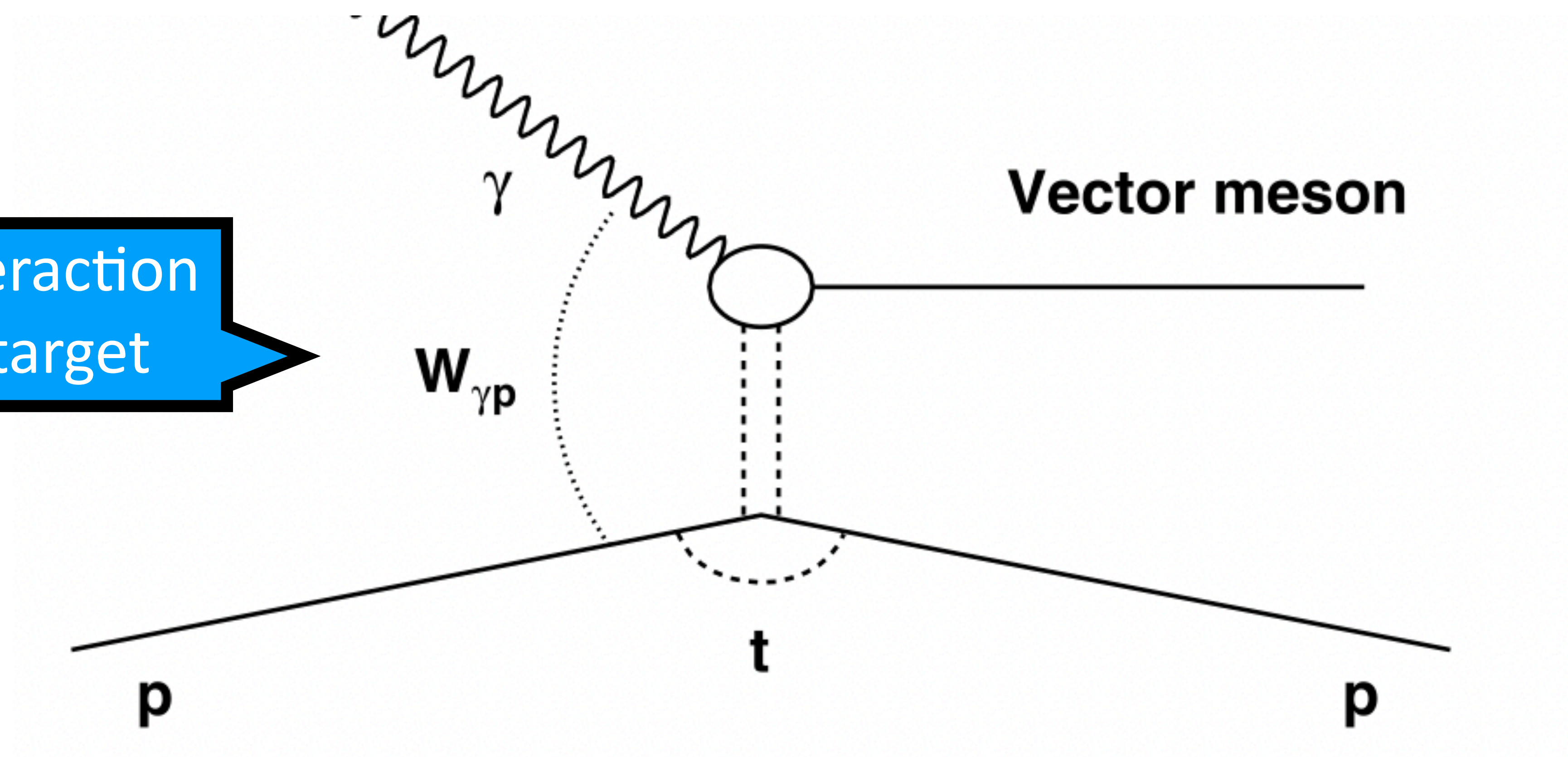

$$\frac{d\sigma}{dt} \propto \left| \left\langle A(x, Q^2, t) \right\rangle \right|^2$$

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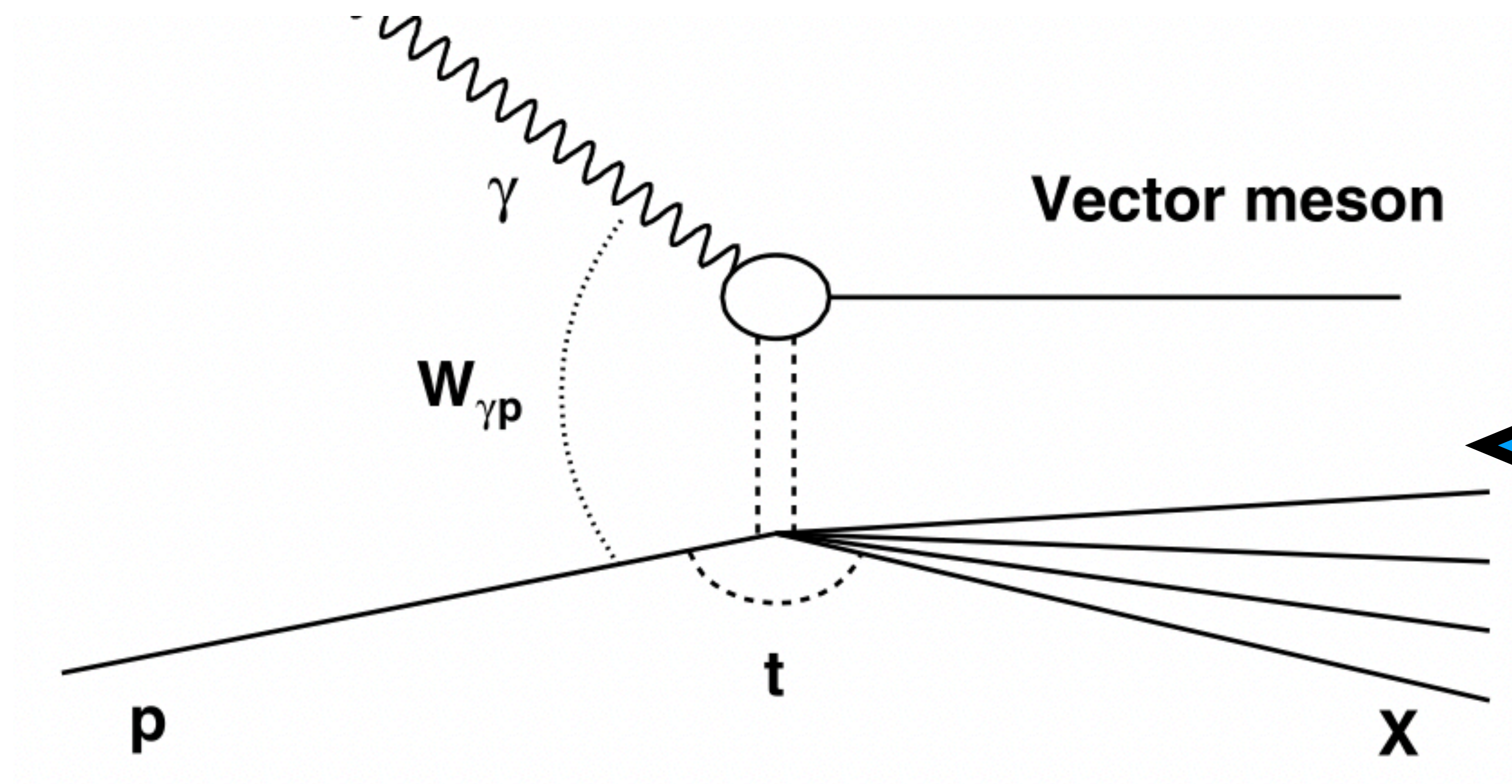
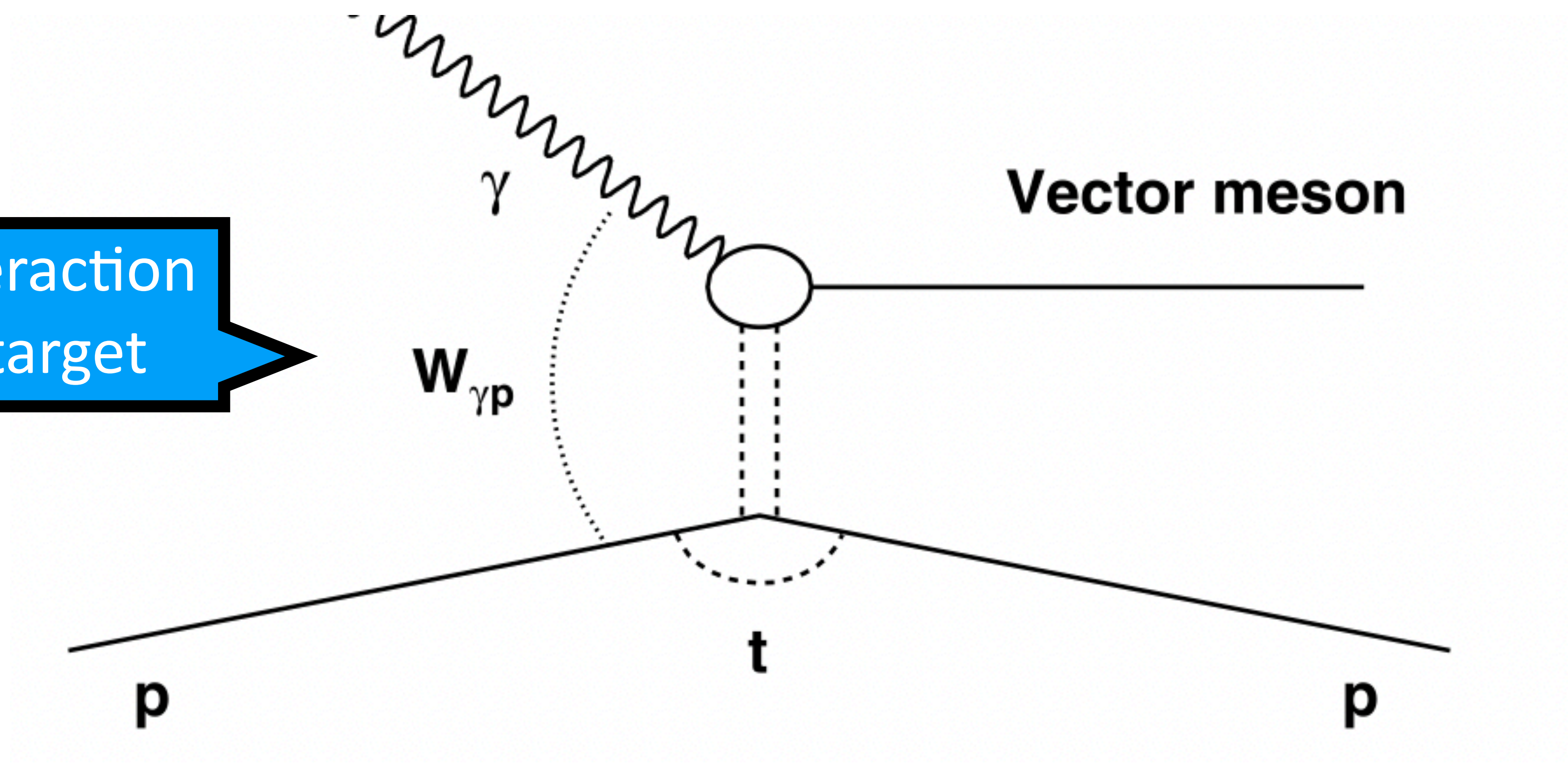


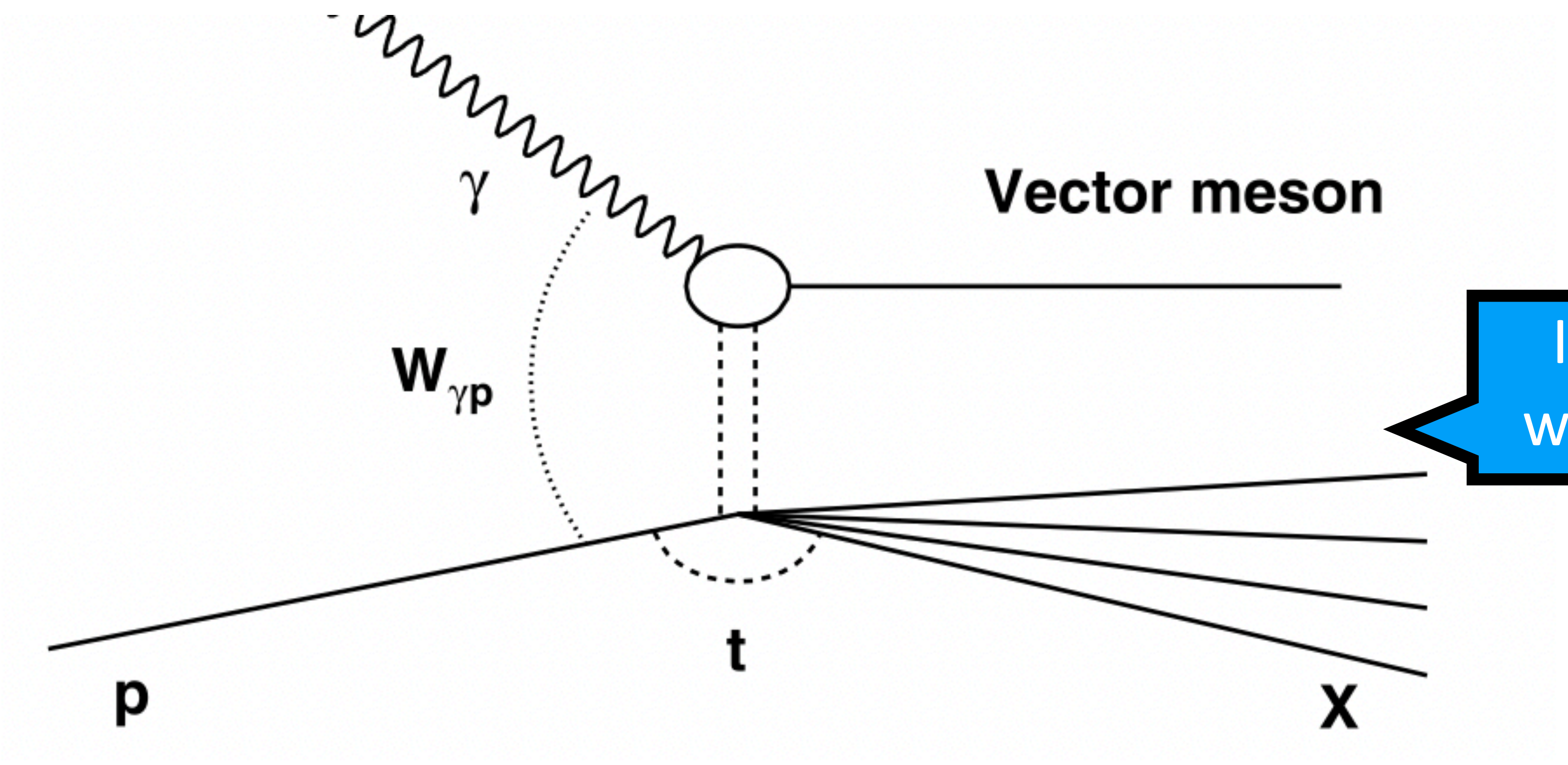
$$\frac{d\sigma}{dt} \propto \left(\left\langle \left| A(x, Q^2, t) \right|^2 \right\rangle - \left| \left\langle A(x, Q^2, t) \right\rangle \right|^2 \right)$$

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**

Diffractive vector meson production and saturation

Coherent: interaction with all the target





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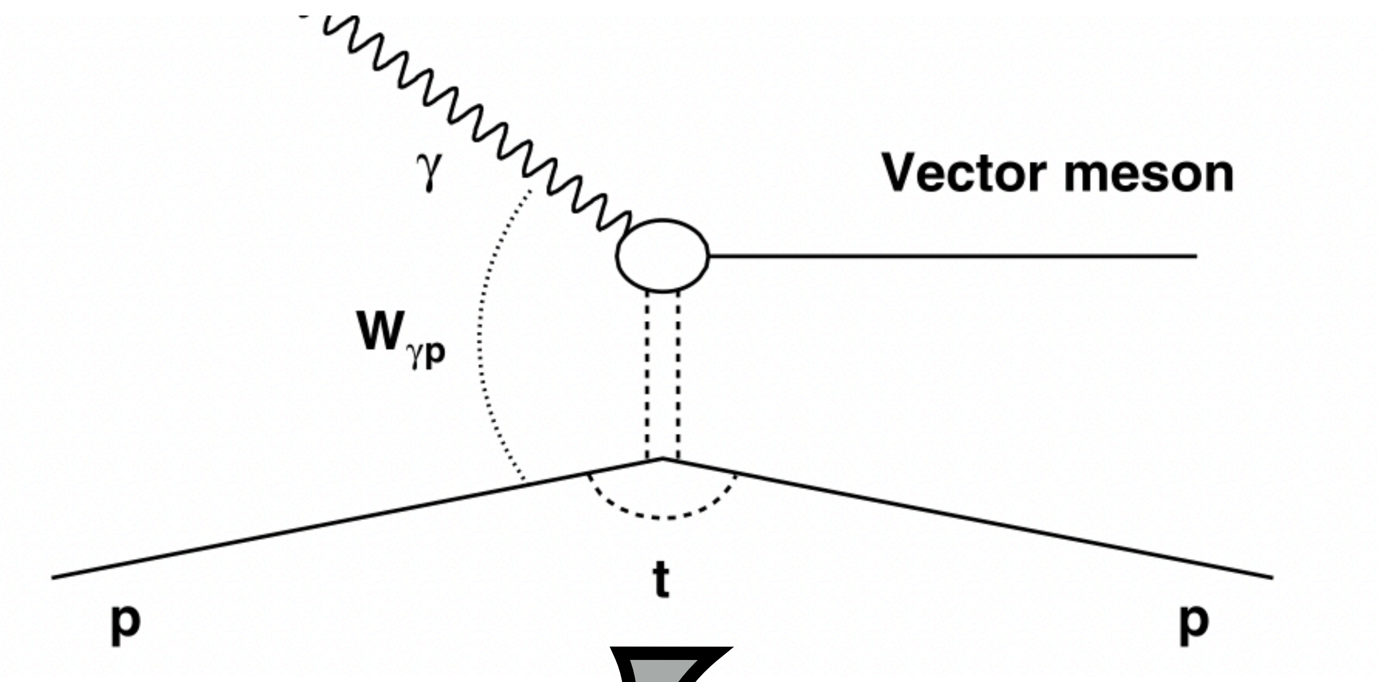
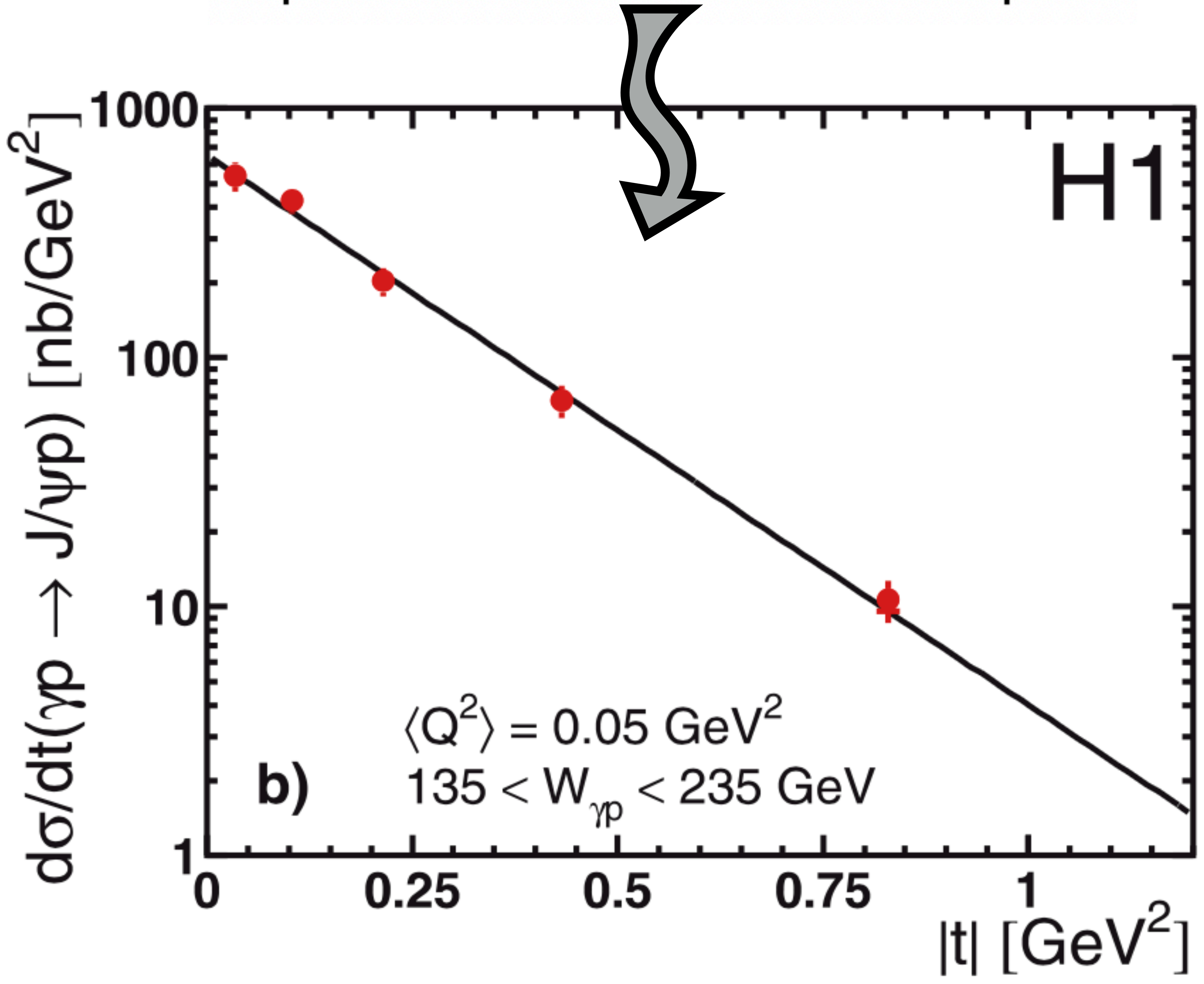
There is no reason to expect that coherent and incoherent vector meson production should have the same signature of gluon saturation → both processes should be studied in detail

HERA: diffractive vector meson production

Coherent vector meson production: Mandelstam-t dependence

H1 (2006)





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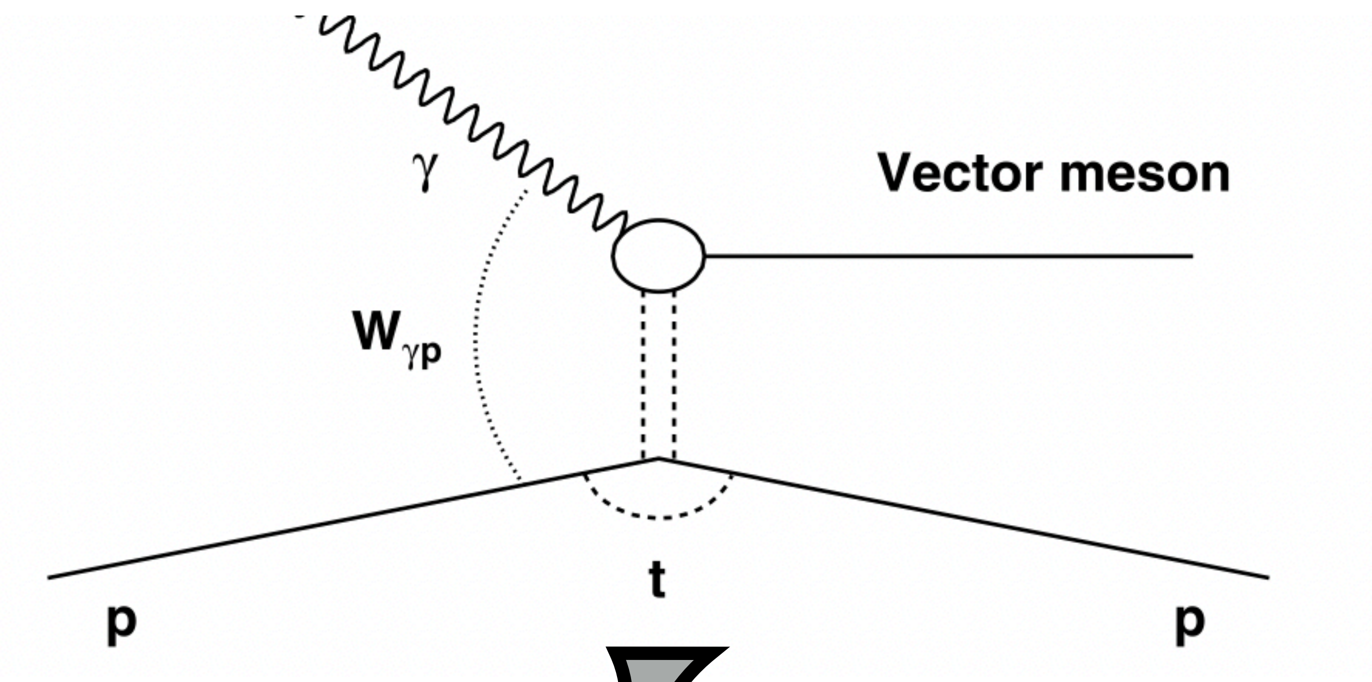

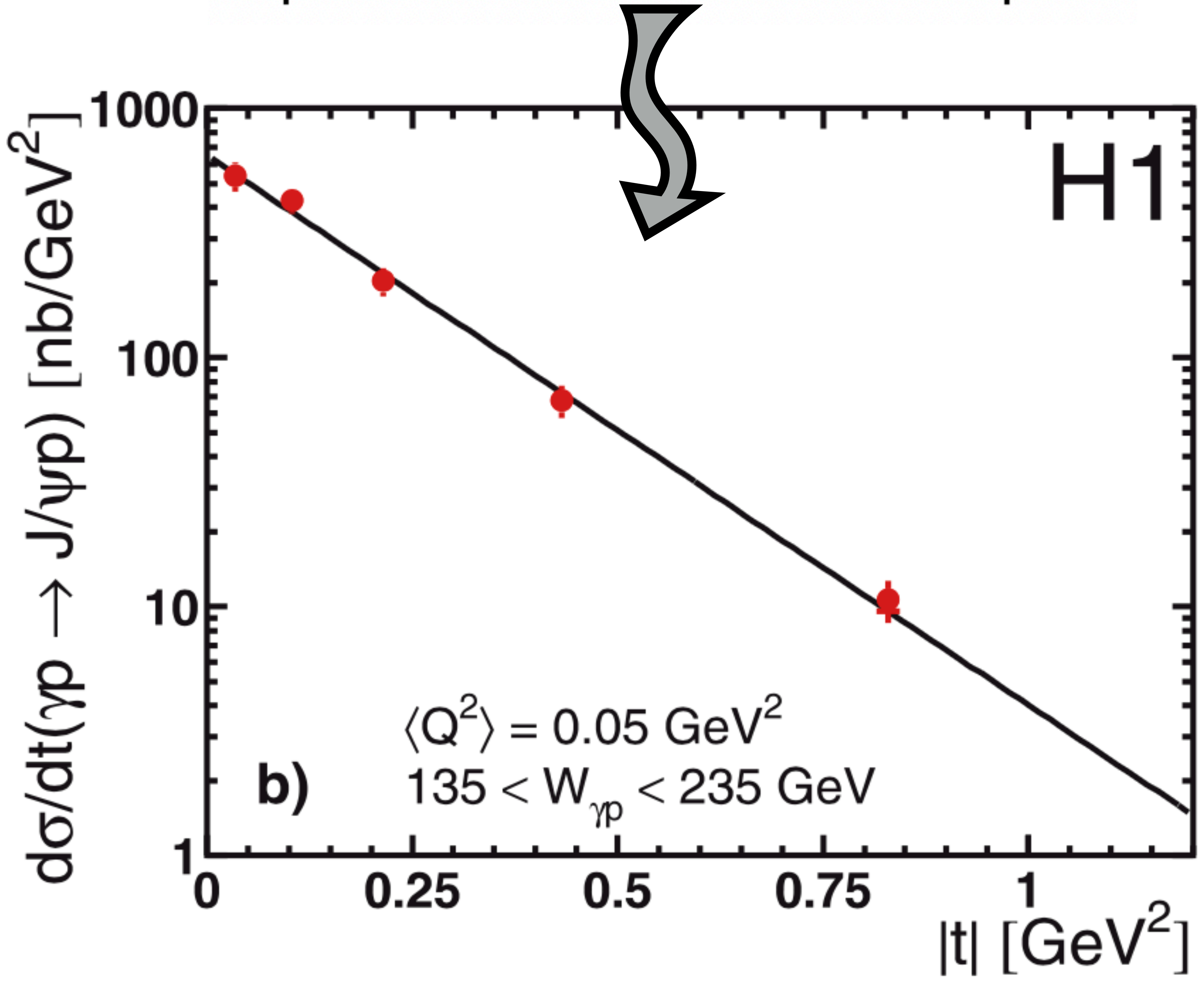

Mandelstam-t is related, through a Fourier transform, with the impact-parameter plane

Data are well described by an exponential (of slope b) which implies a gaussian distribution in the impact-parameter plane

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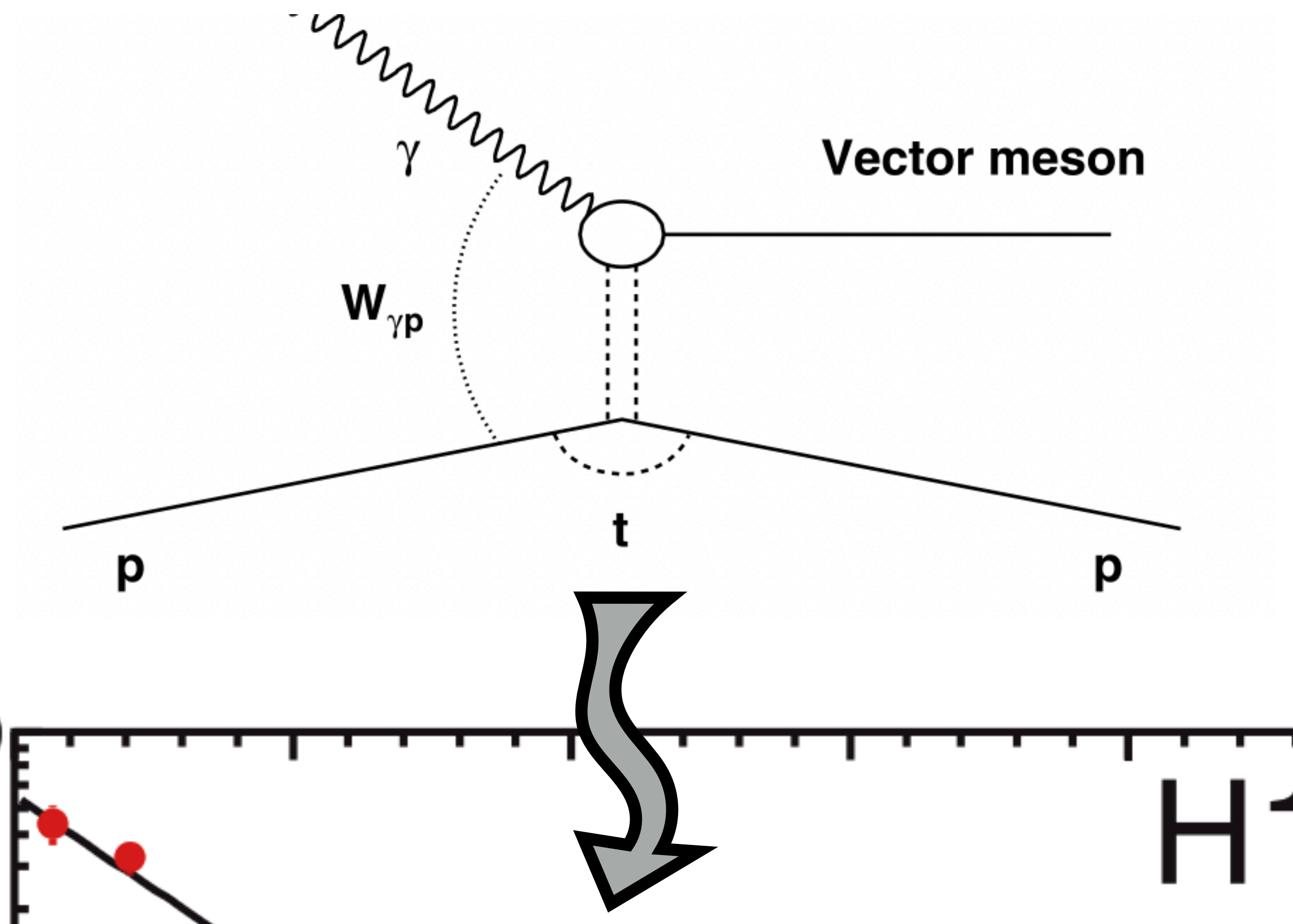

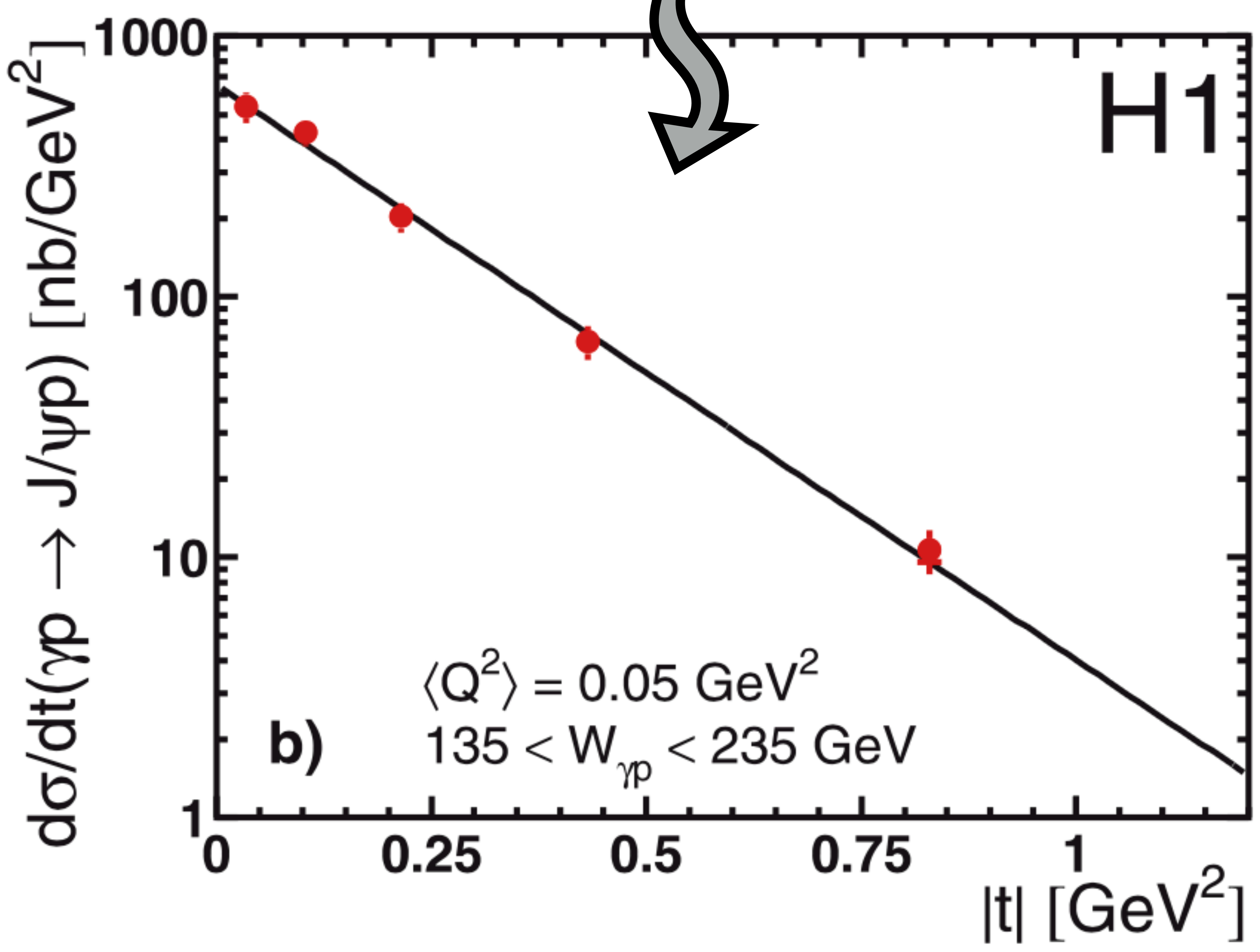

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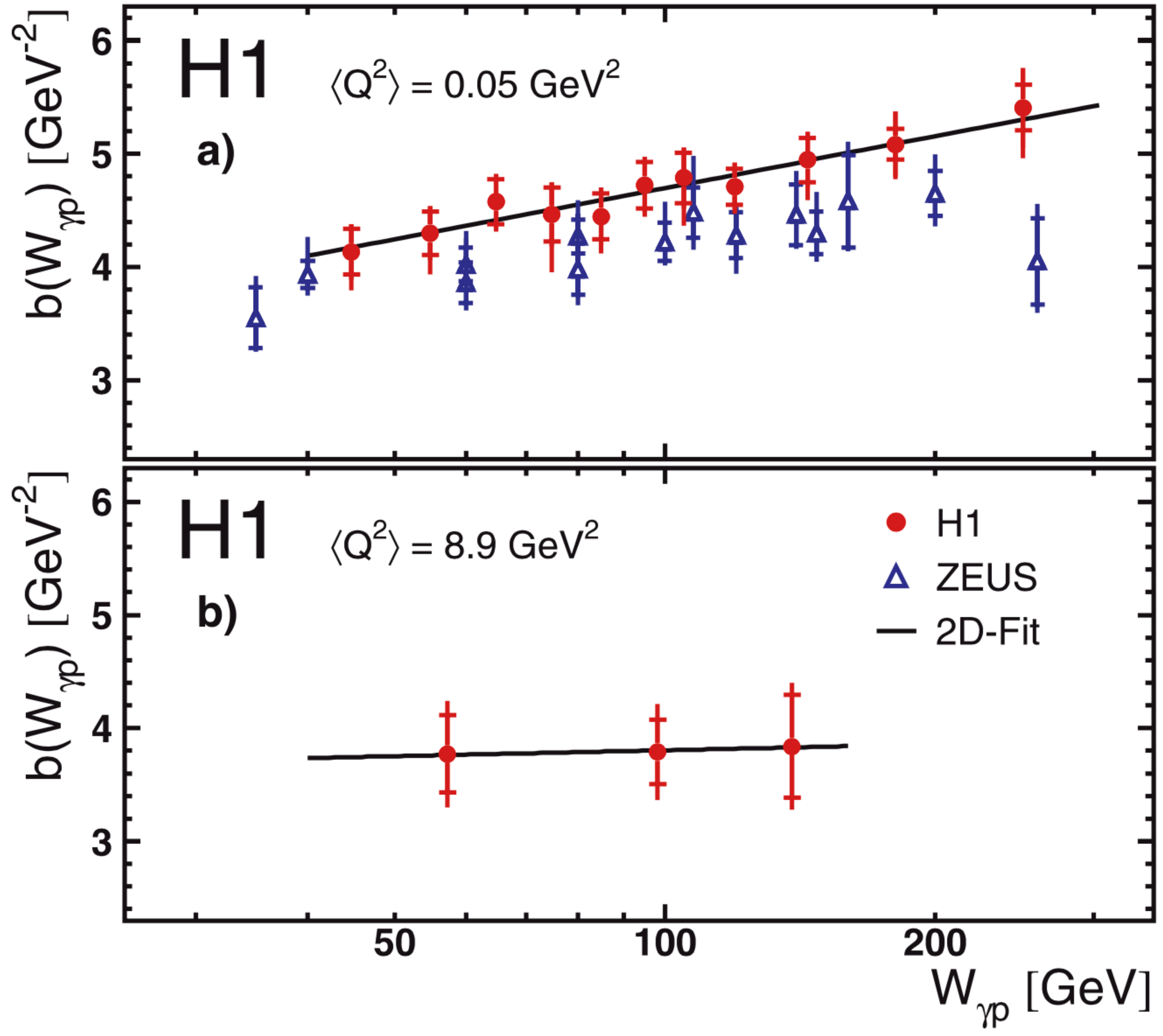
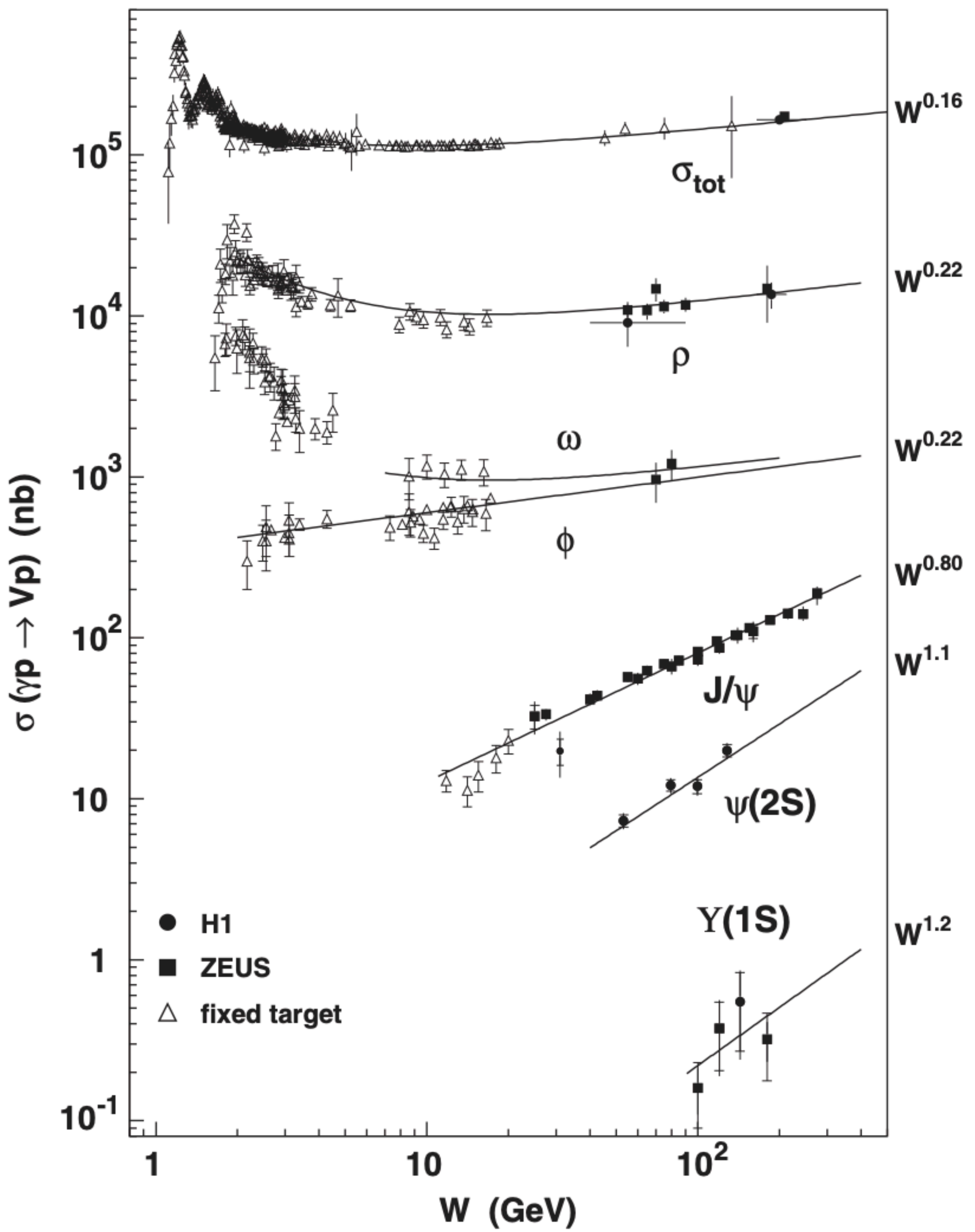
In photo-production, the inferred size of the target grows logarithmically with energy



Coherent vector meson production: Mass and energy dependence

The energy dependence of coherent vector-meson photo-production has been studied extensively up to 200 GeV for vector mesons with masses from below 1 GeV/c^2 to 9.46 GeV/c^2

Newman and Wing (2014)



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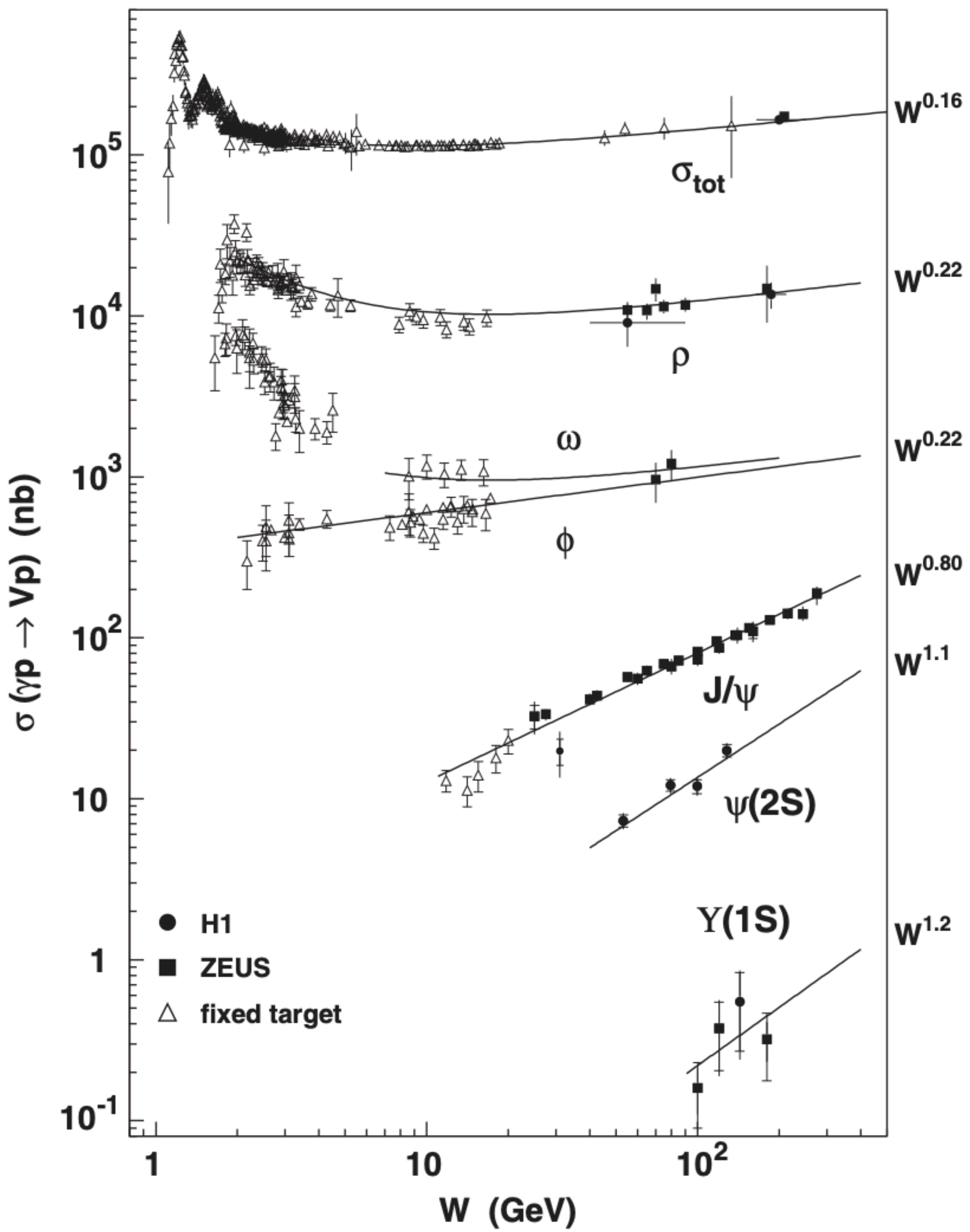

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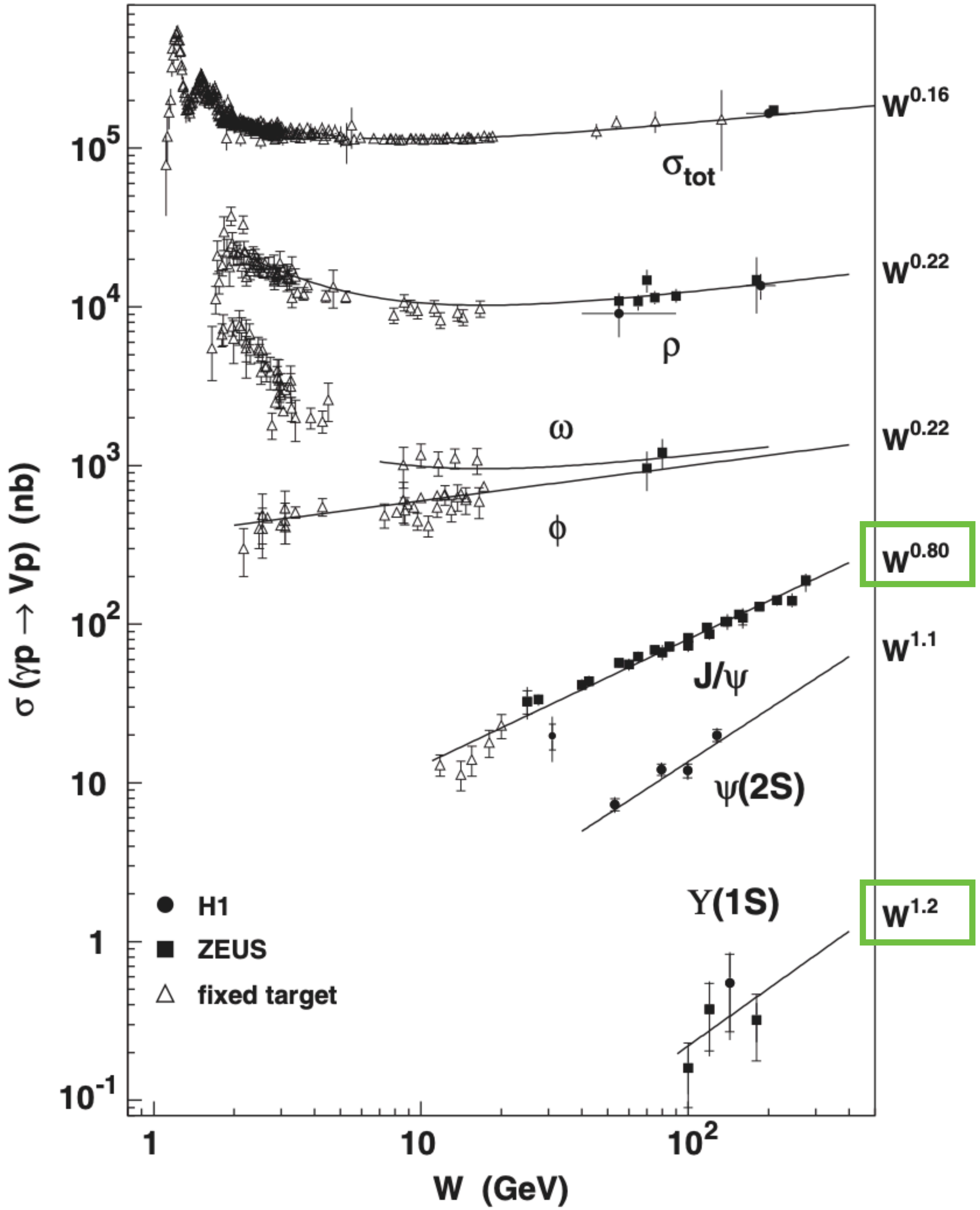

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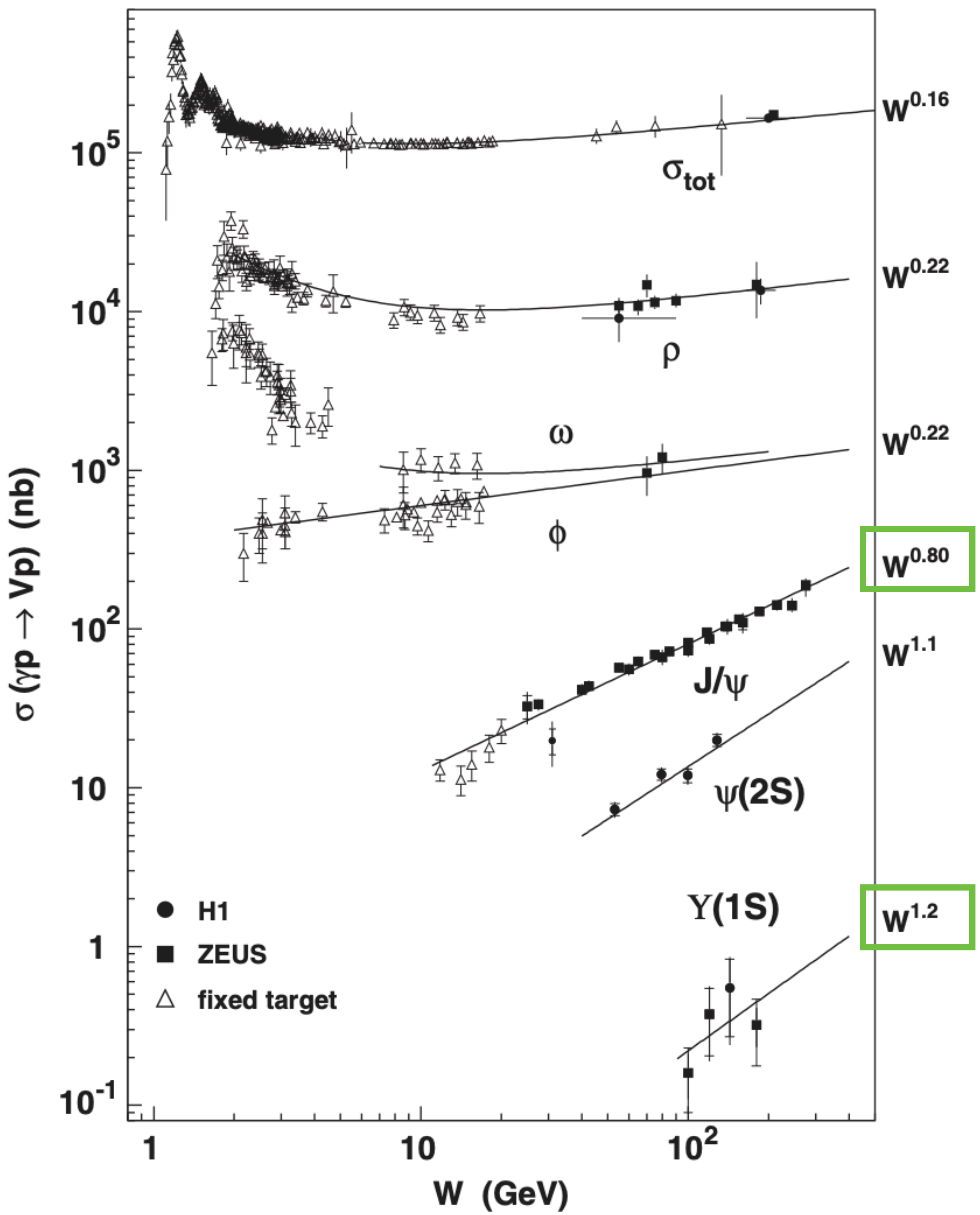

Incoherent vector meson production

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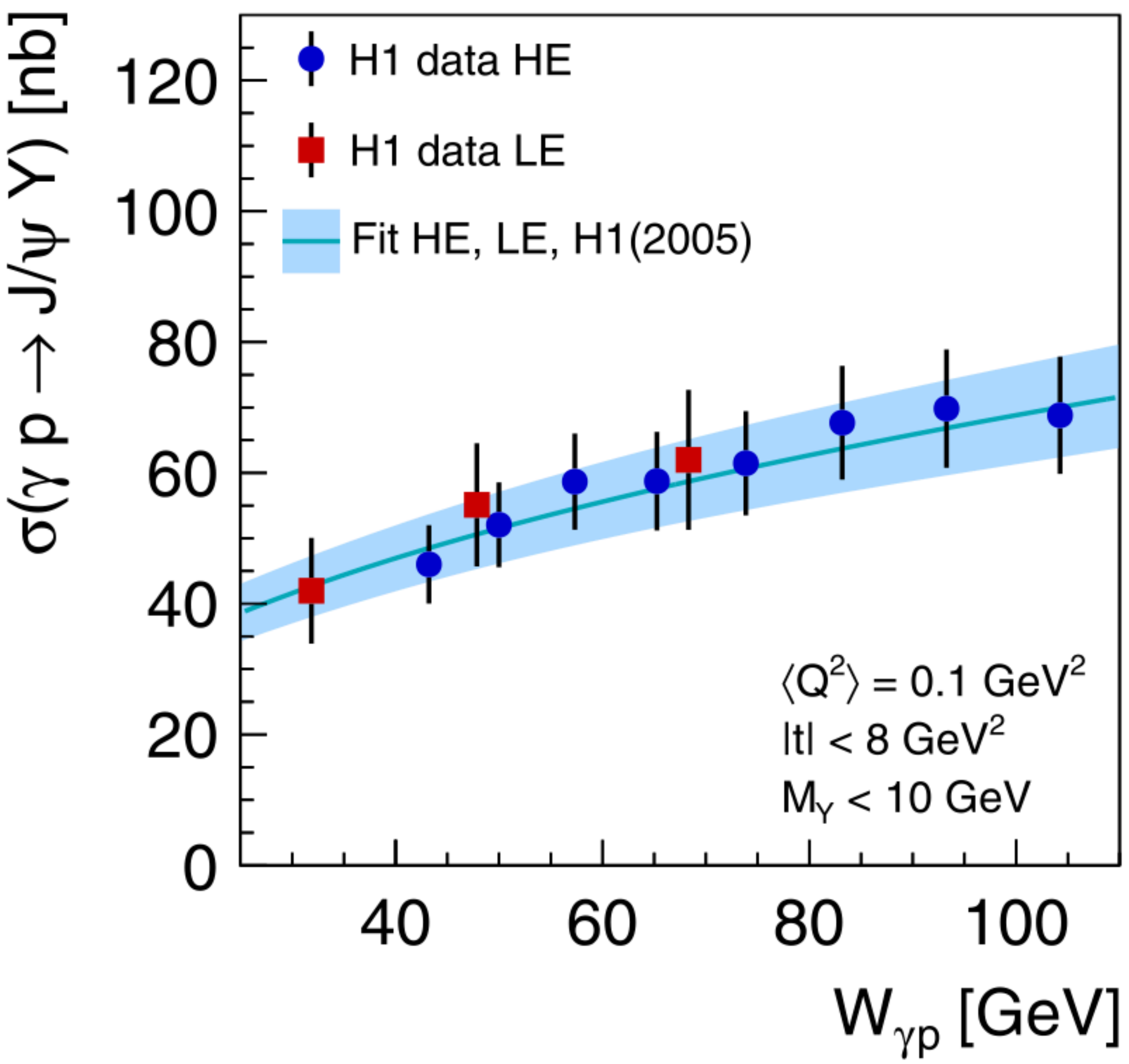

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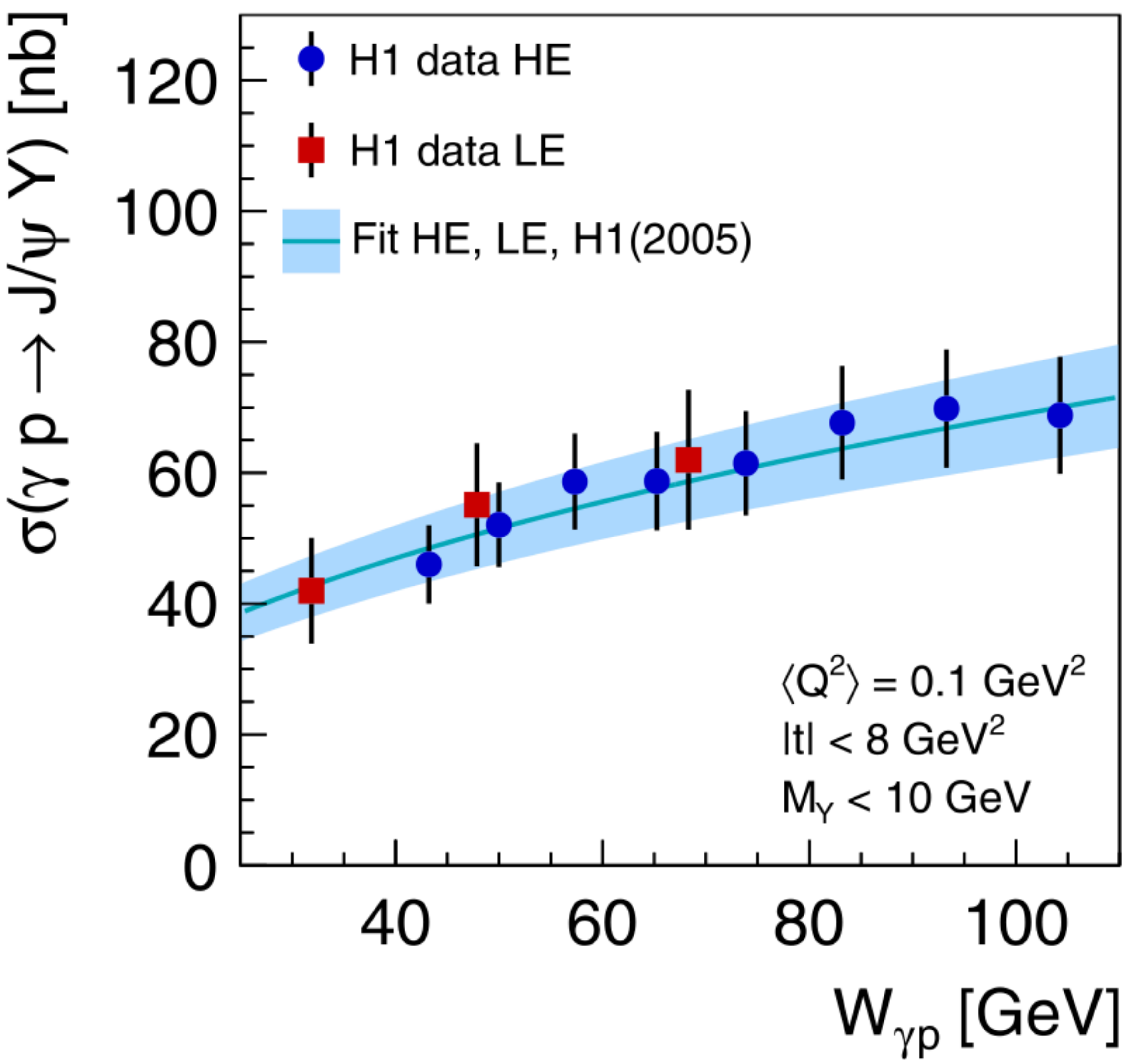

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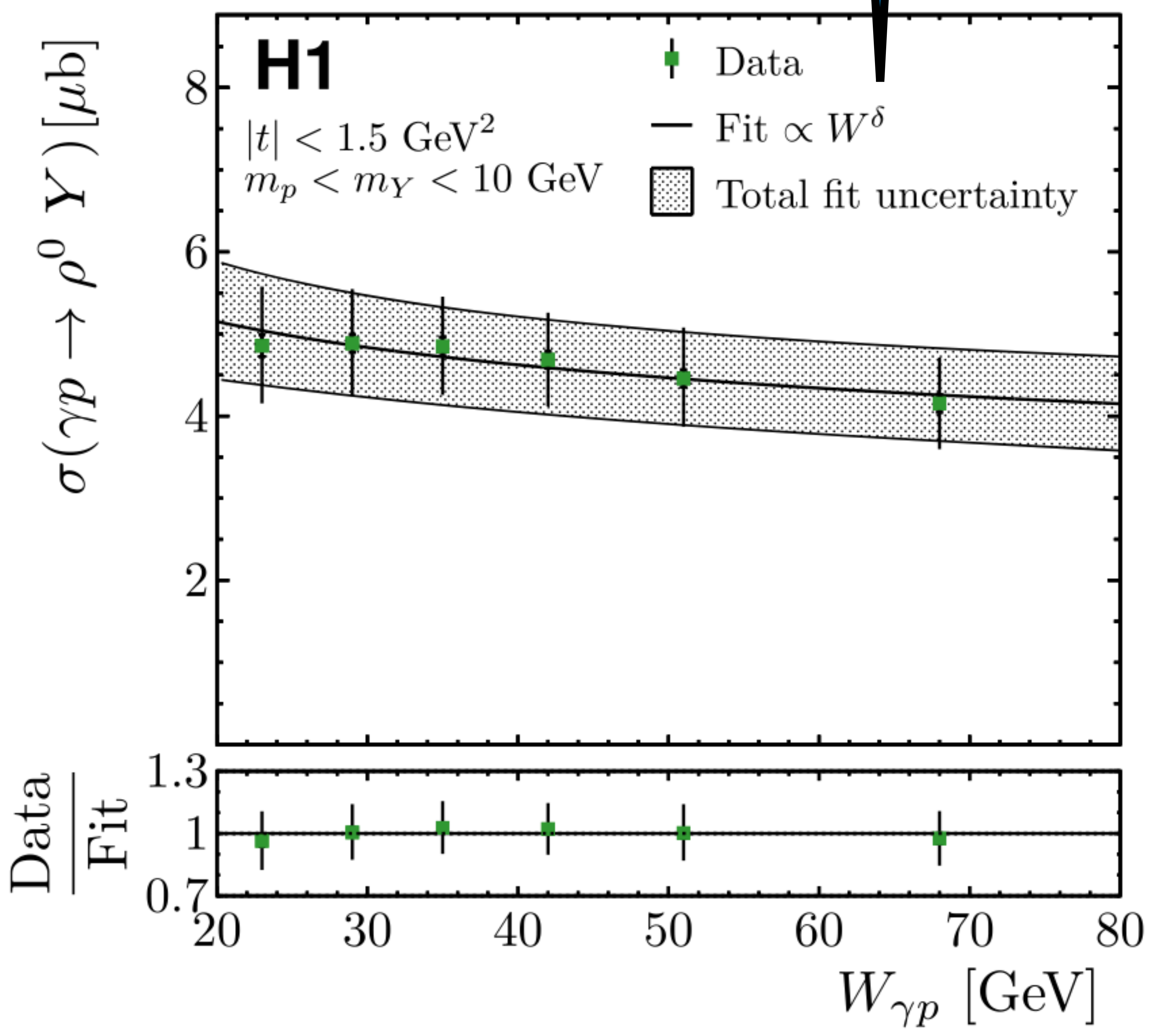
$\delta = -0.156 \pm 0.026^{+0.081}_{-0.079}$

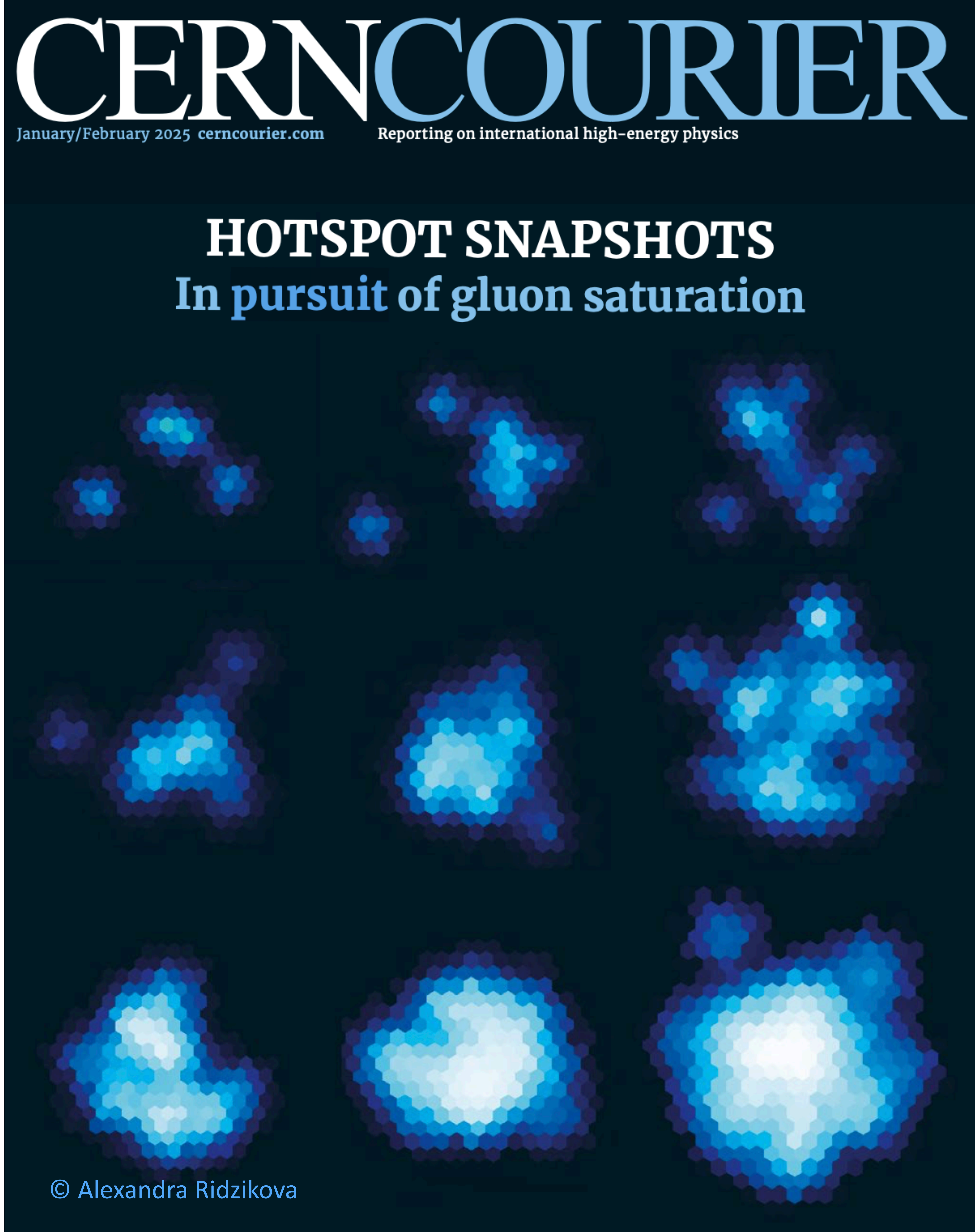
H1 (2020)



... while for ρ it seems to ***decrease*** with energy

CERN Courier (2025)

The energy-dependent hotspot model



The energy-dependent hotspot model

Cepila, JGC, Tapia Takaki (2017)

Assume that the proton is made of hotspots distributed randomly in impact parameter:

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

The positions of the hot spots are obtained e-by-e from a Gaussian distribution representing the proton

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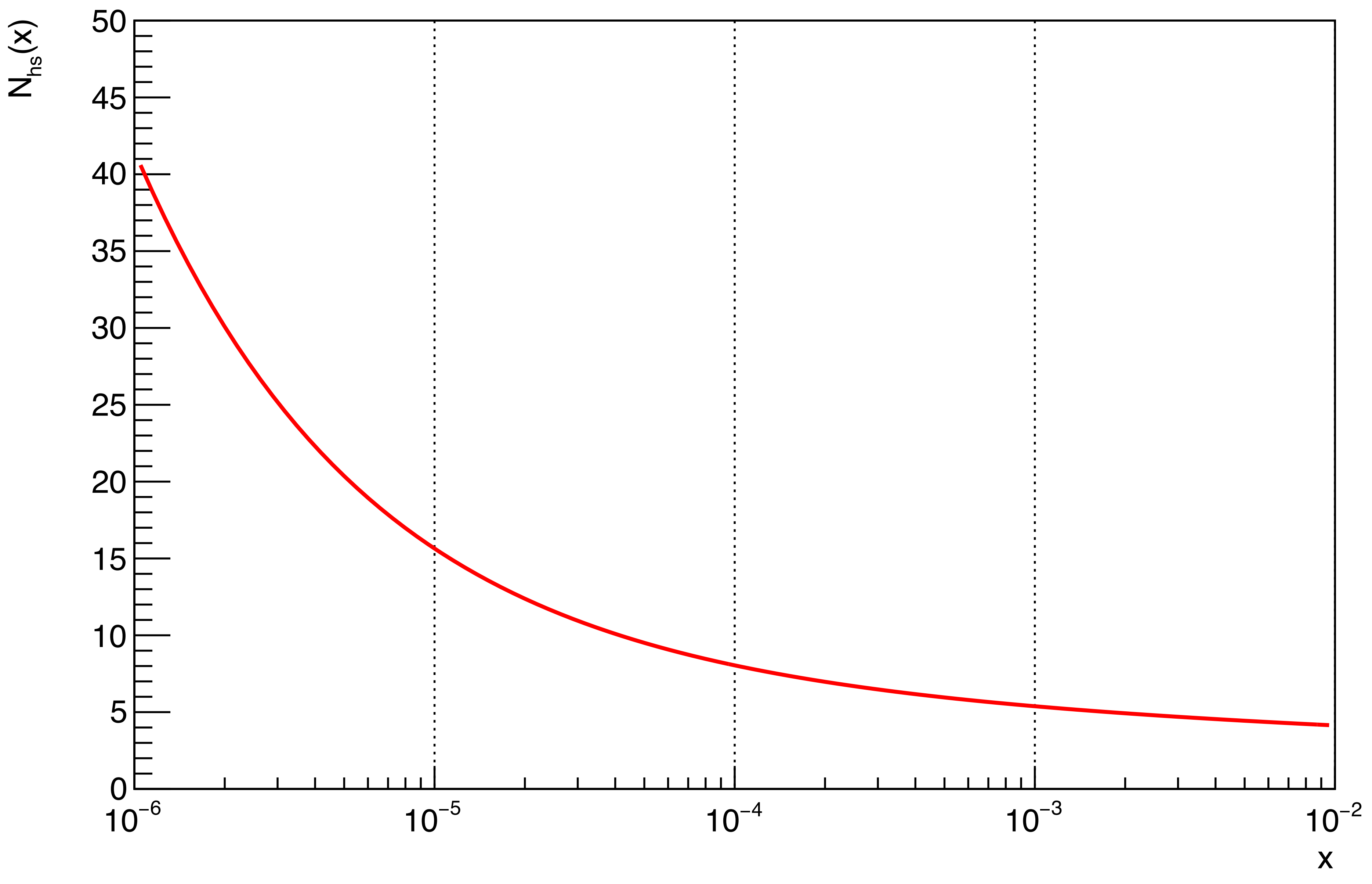

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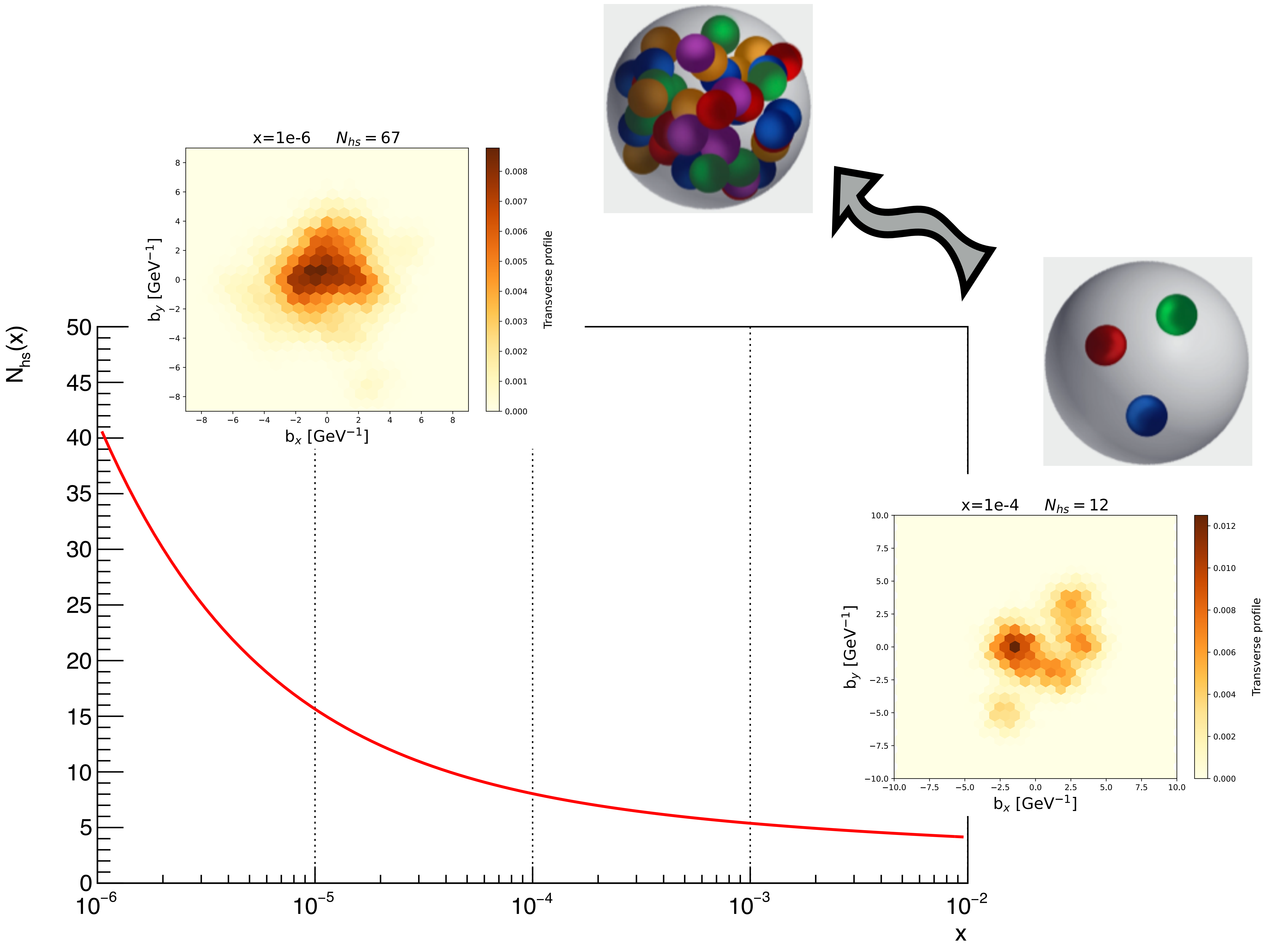

Cepila, JGC, Matas, Ridzikova (2024)

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Cepila, JGC, Tapia Takaki (2017)

Assume that the proton is made of hotspots distributed randomly in impact parameter:

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

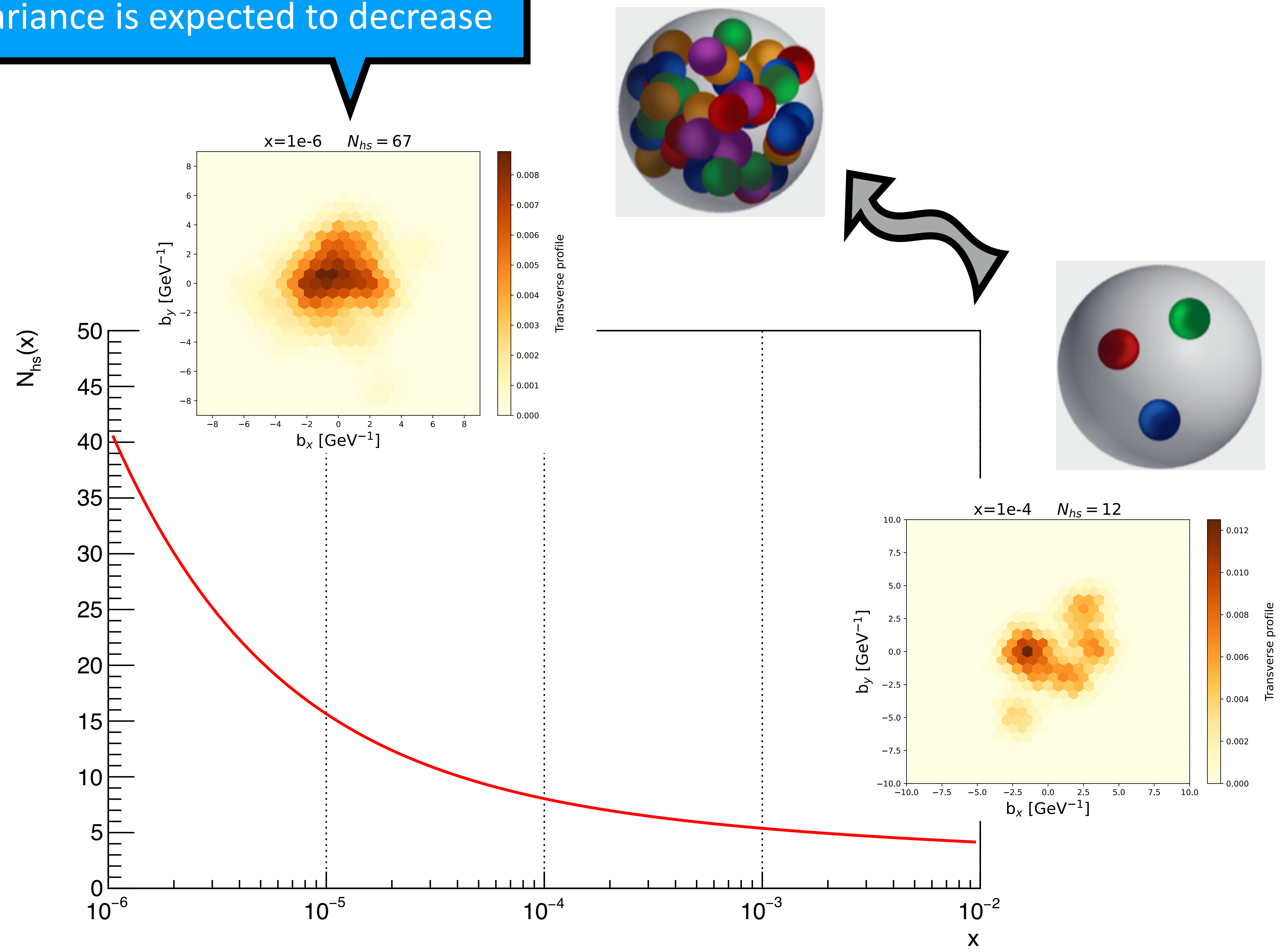
The positions of the hot spots are obtained e-by-e from a Gaussian distribution representing the proton

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

The hot spots have a Gaussian shape in impact parameter

Assume that the number of hotspots grows with energy to mimic what is expected in QCD

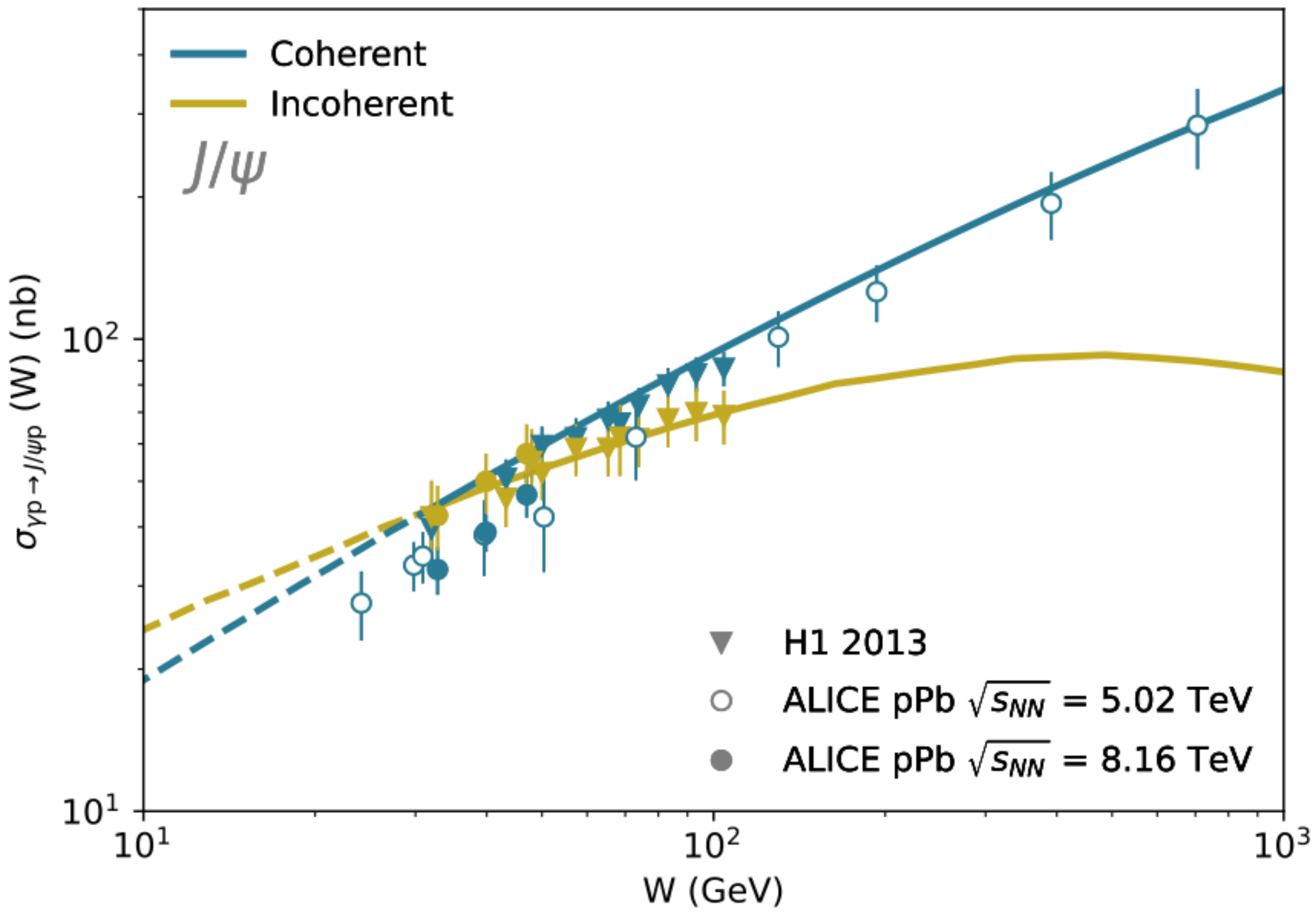
All configurations resemble each other, the variance is expected to decrease

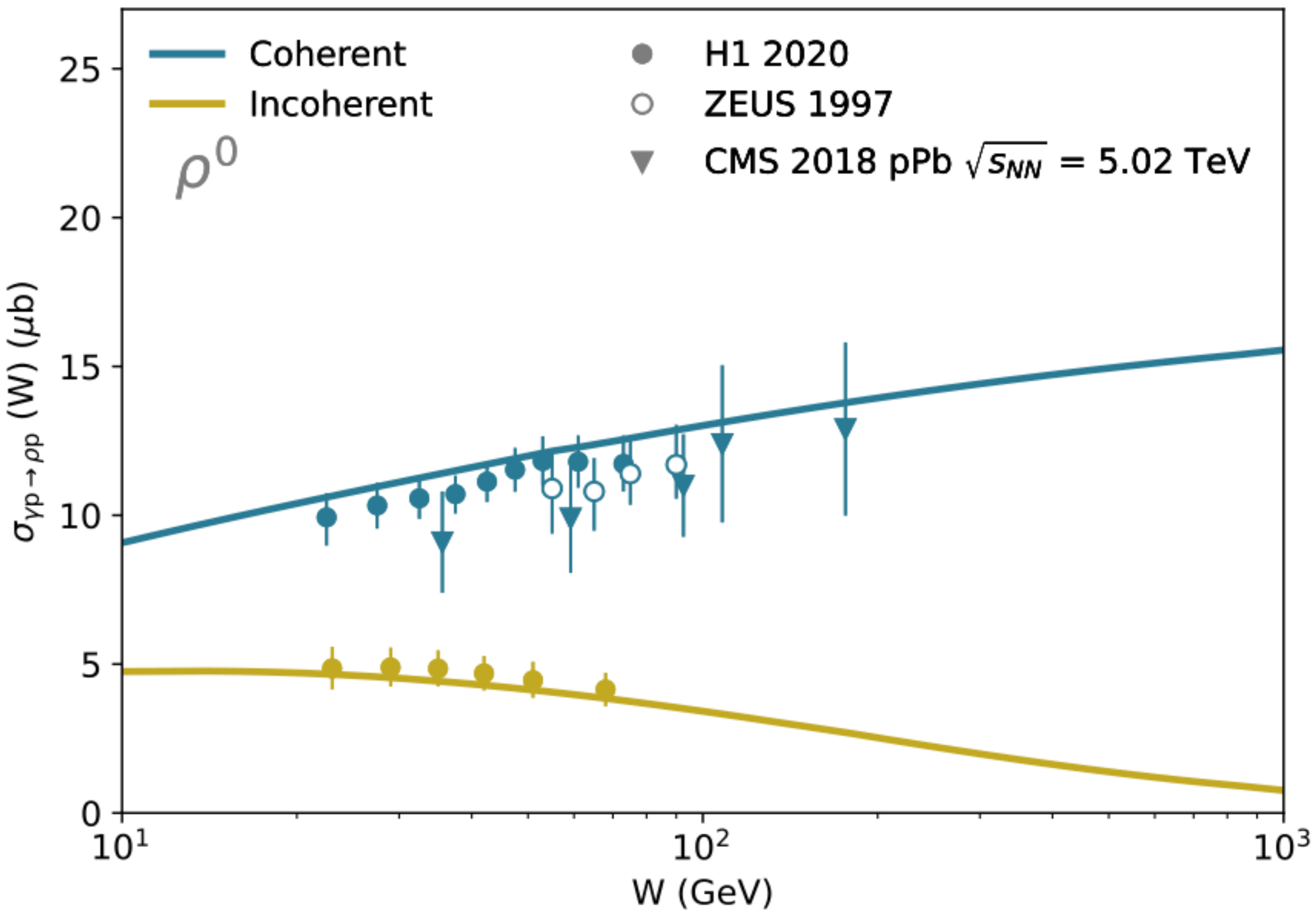


Cepila, JGC, Matas, Ridzikova (2024)

Comparison to data

Cepila, JGC, Matas, Ridzikova (2024)





HERA, and LHC, data for coherent and incoherent J/ψ and ρ production reasonably well described

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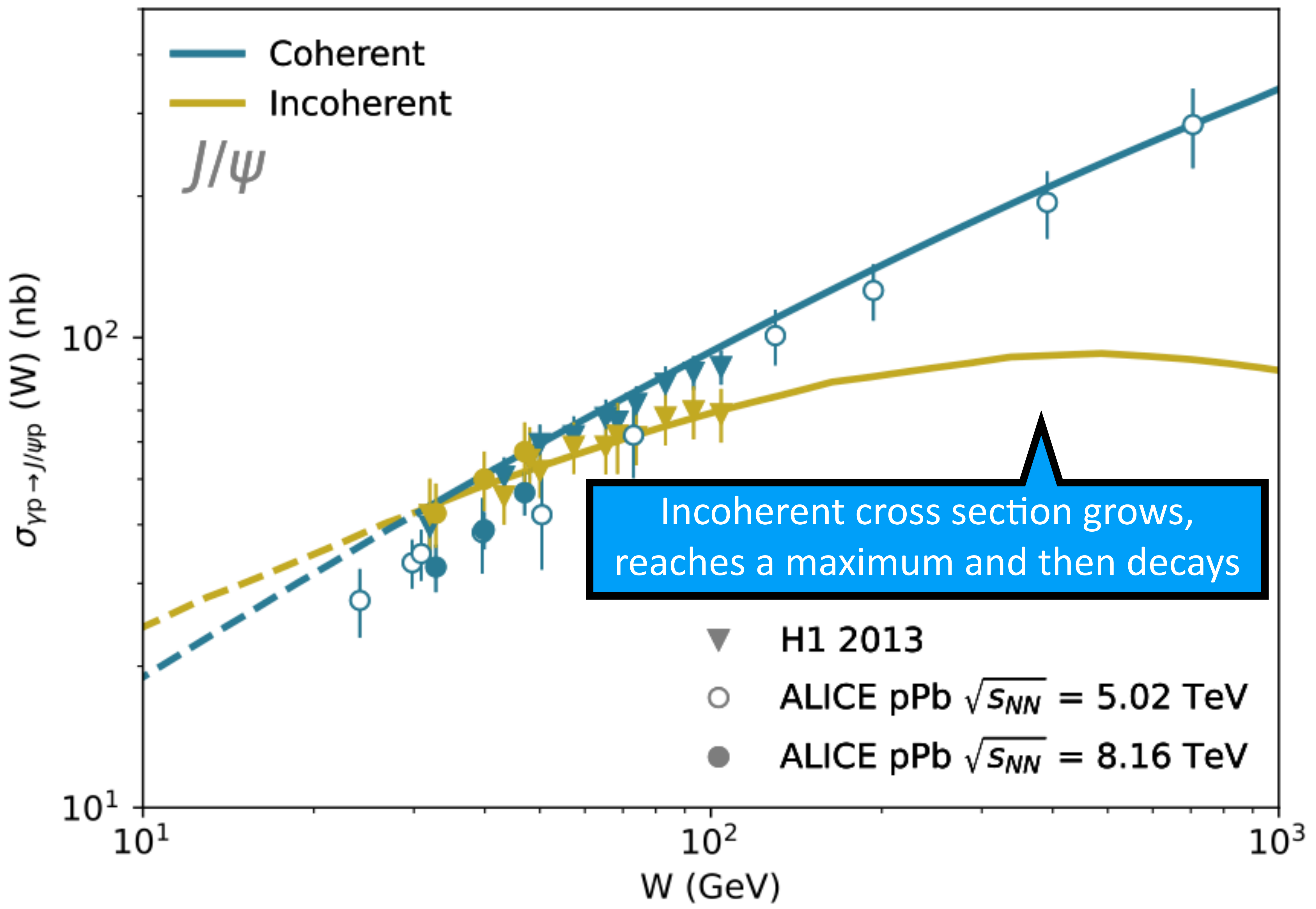
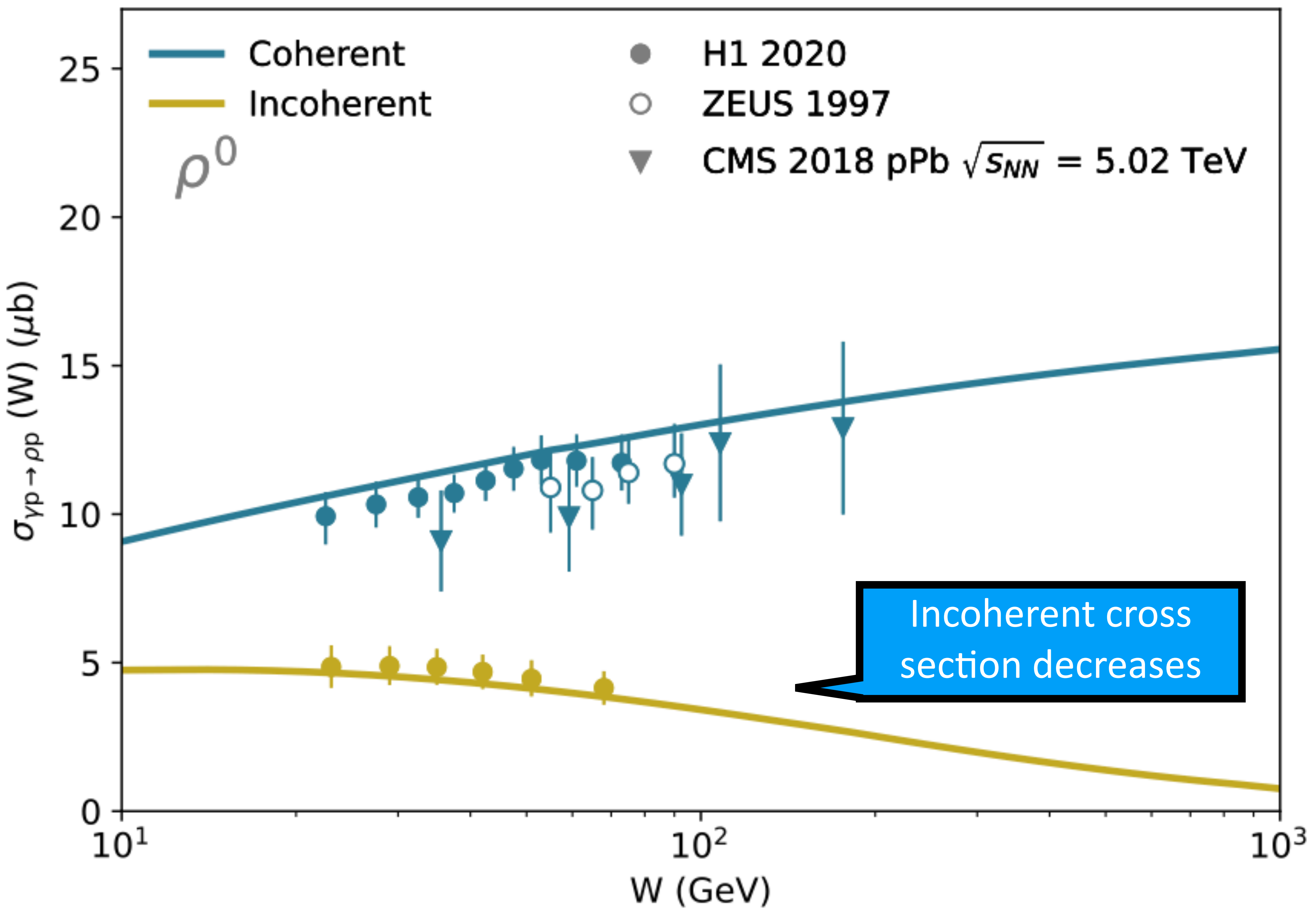


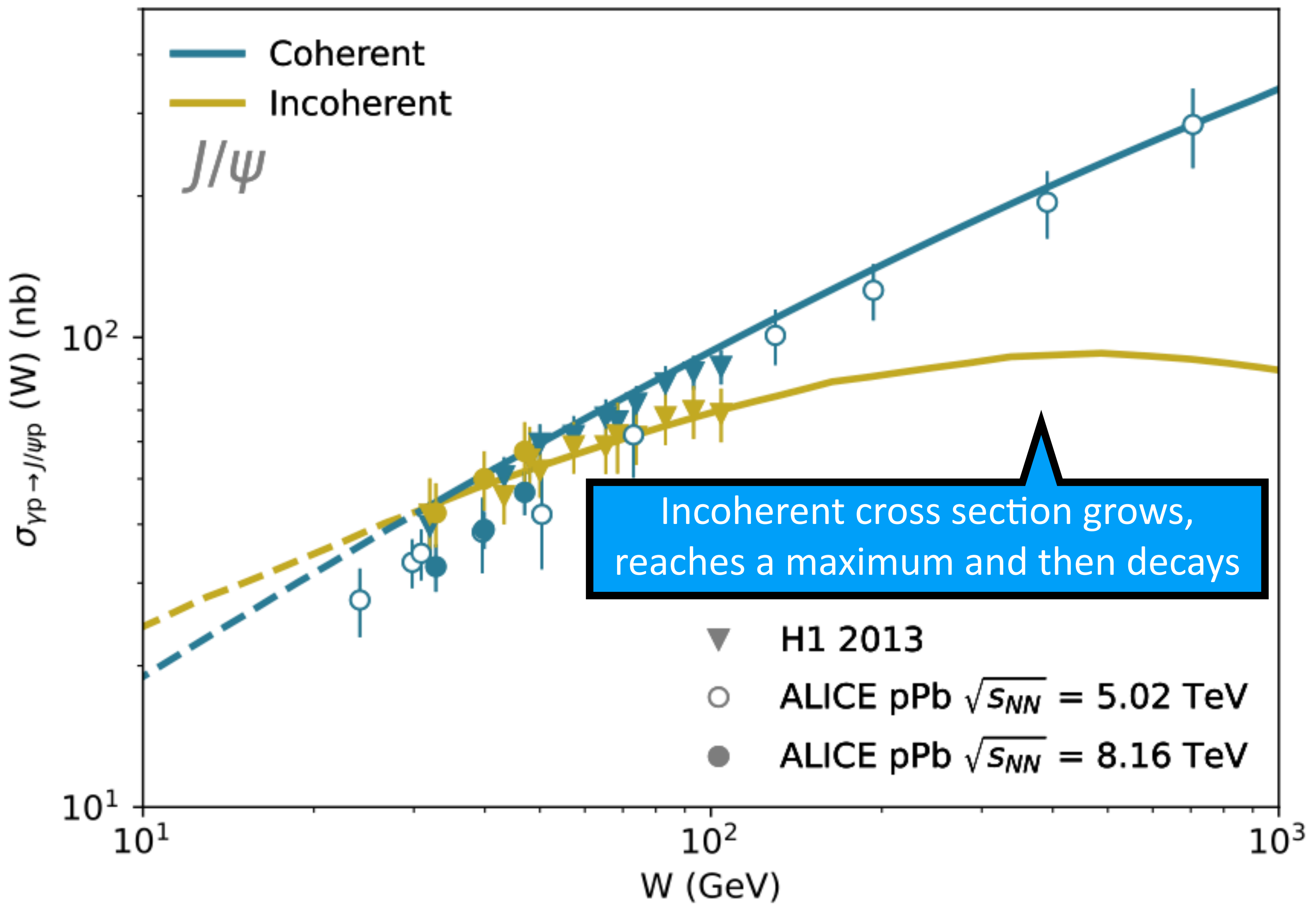


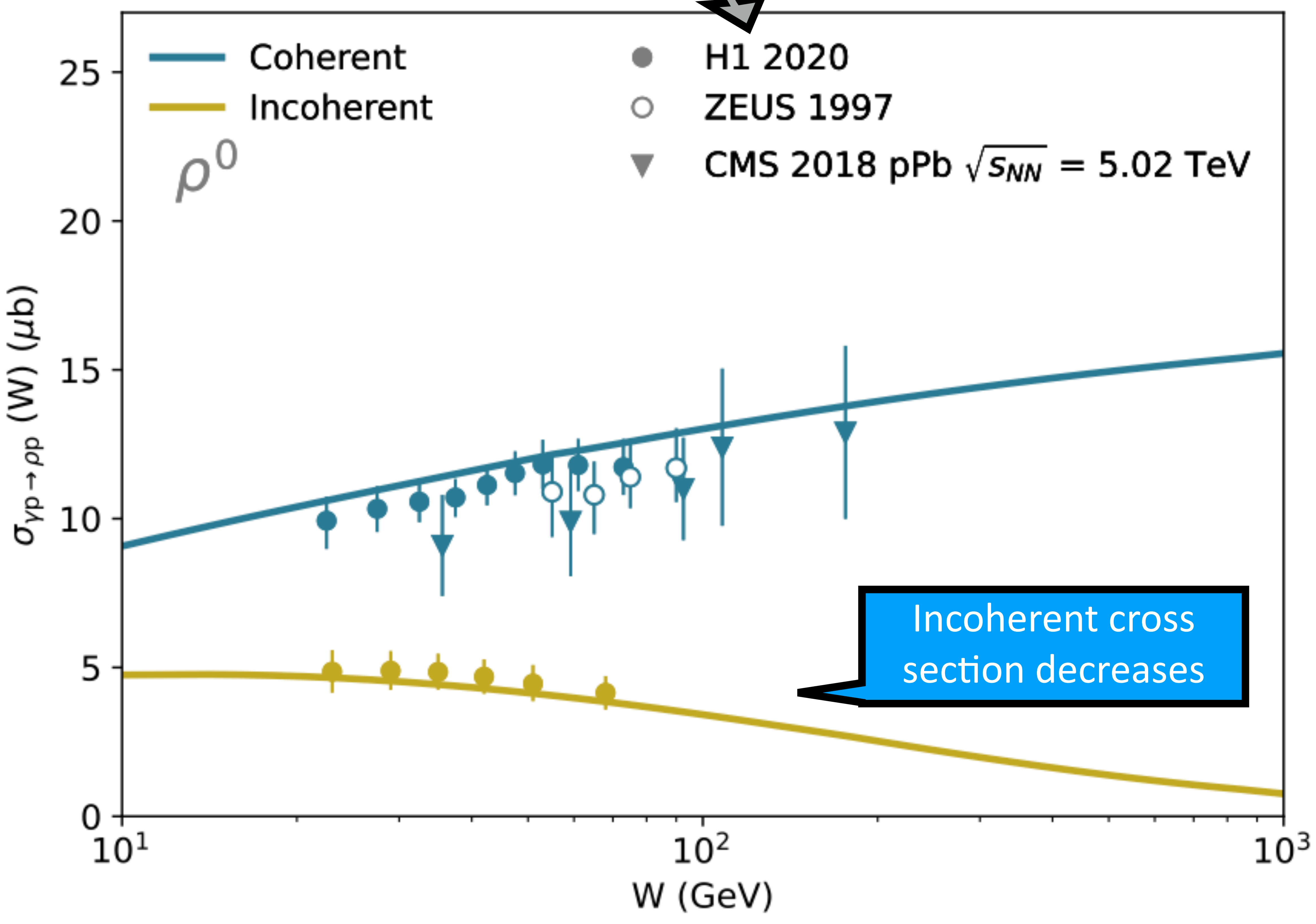
HERA, and LHC, data for coherent and incoherent J/ψ and ρ production reasonably well described

Comparison to data

H1: caveats both from the experimental (phase space) and phenomenological side (non perturbative scale)

Cepila, JGC, Matas, Ridzikova (2024)





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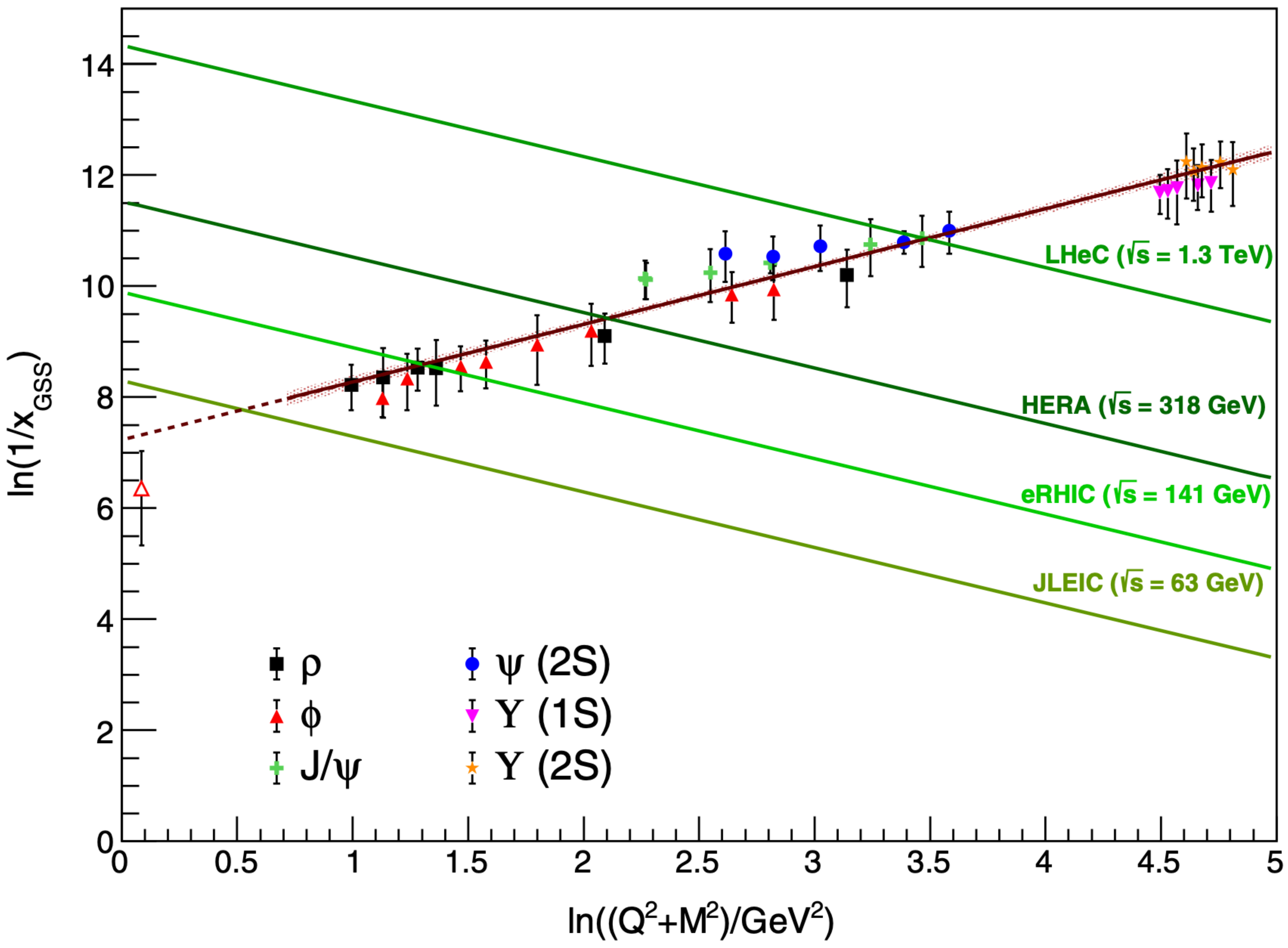
Position of maxima

Bendova, Cepila, JGC (2019)

The position of the maximum in the (scale, x) plane changes logarithmically according to this model



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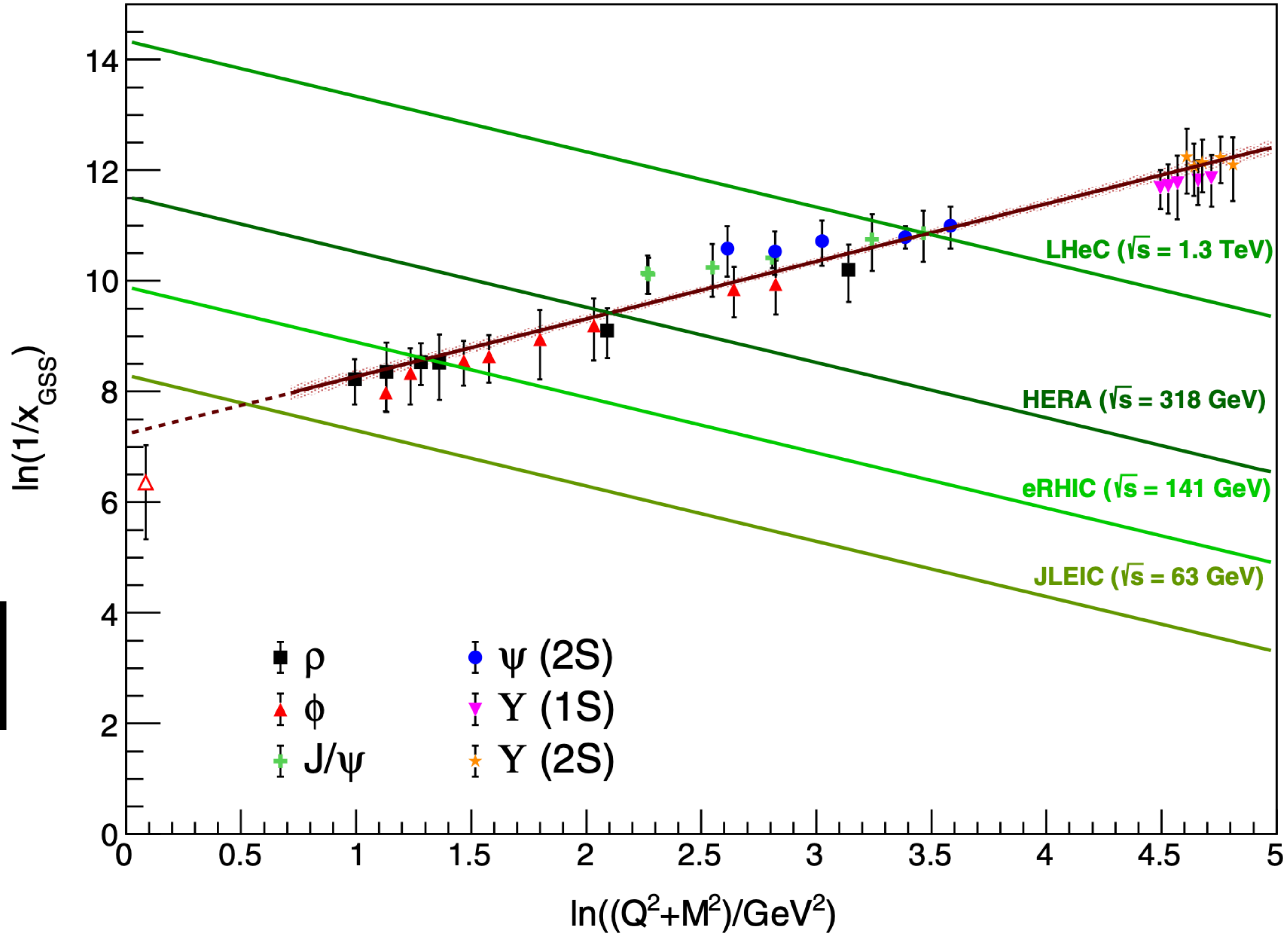
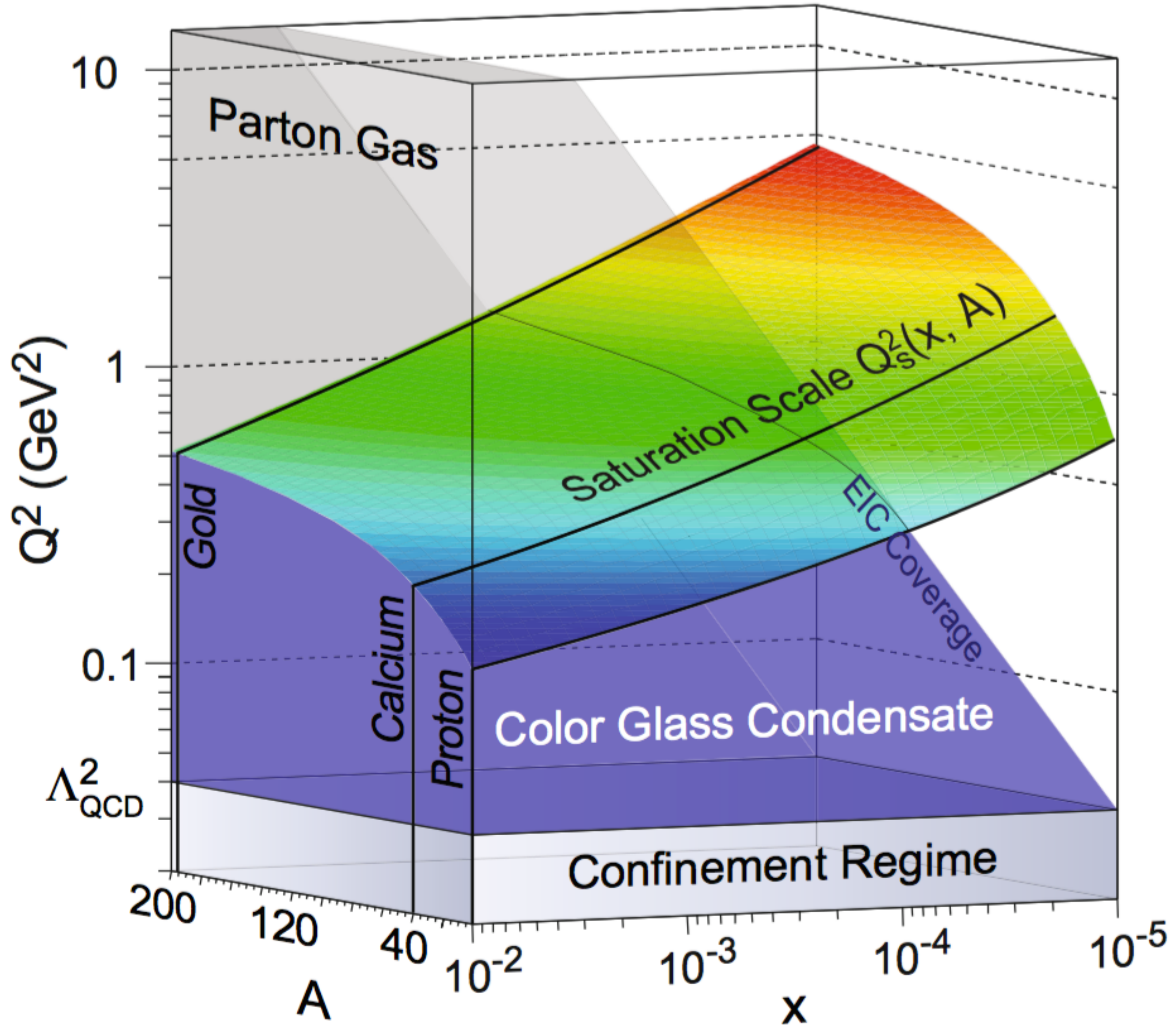


EIC will be able to do these measurements with high precision and adding the nuclear mass dependence

LHC: diffractive vector meson production

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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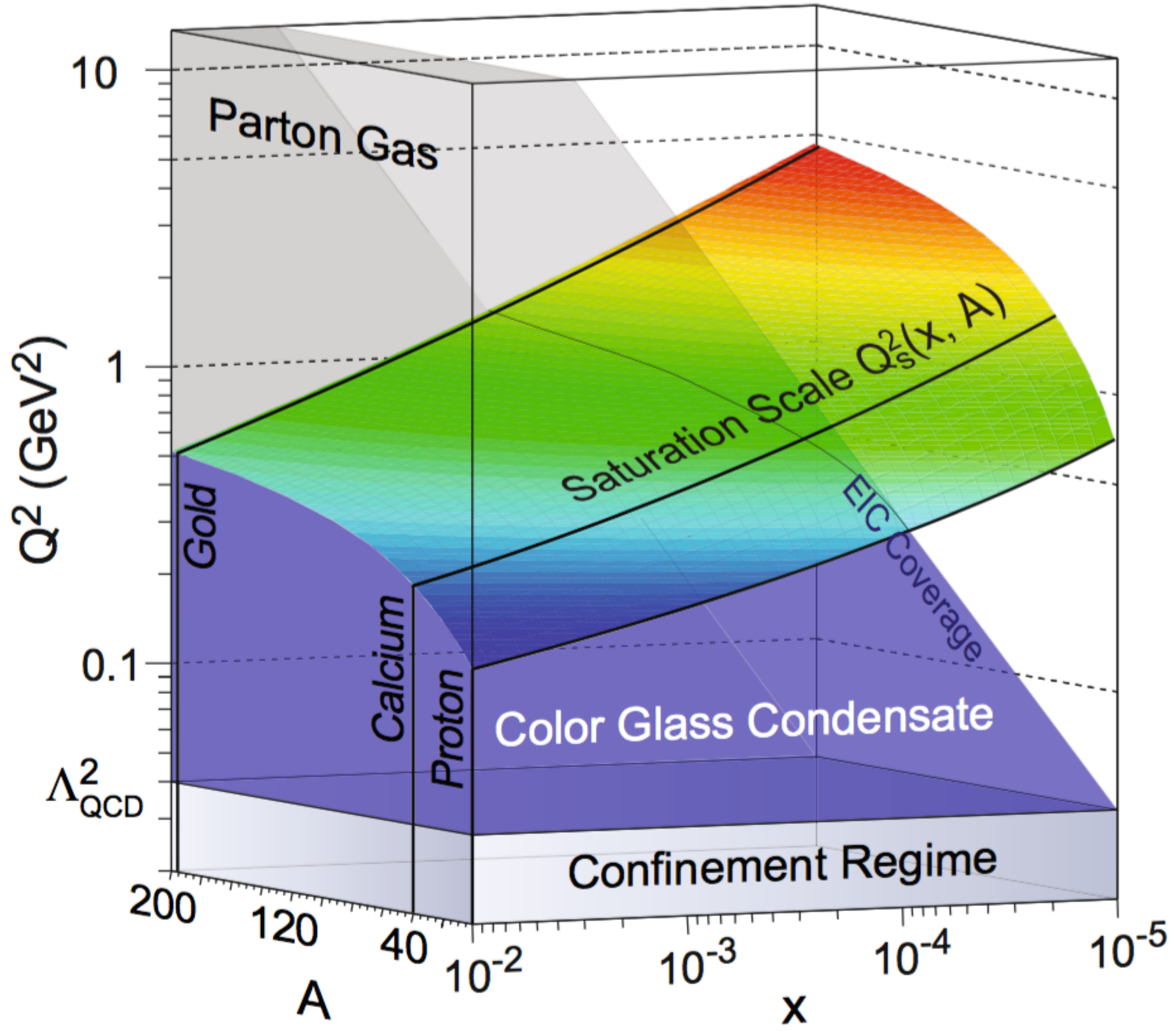
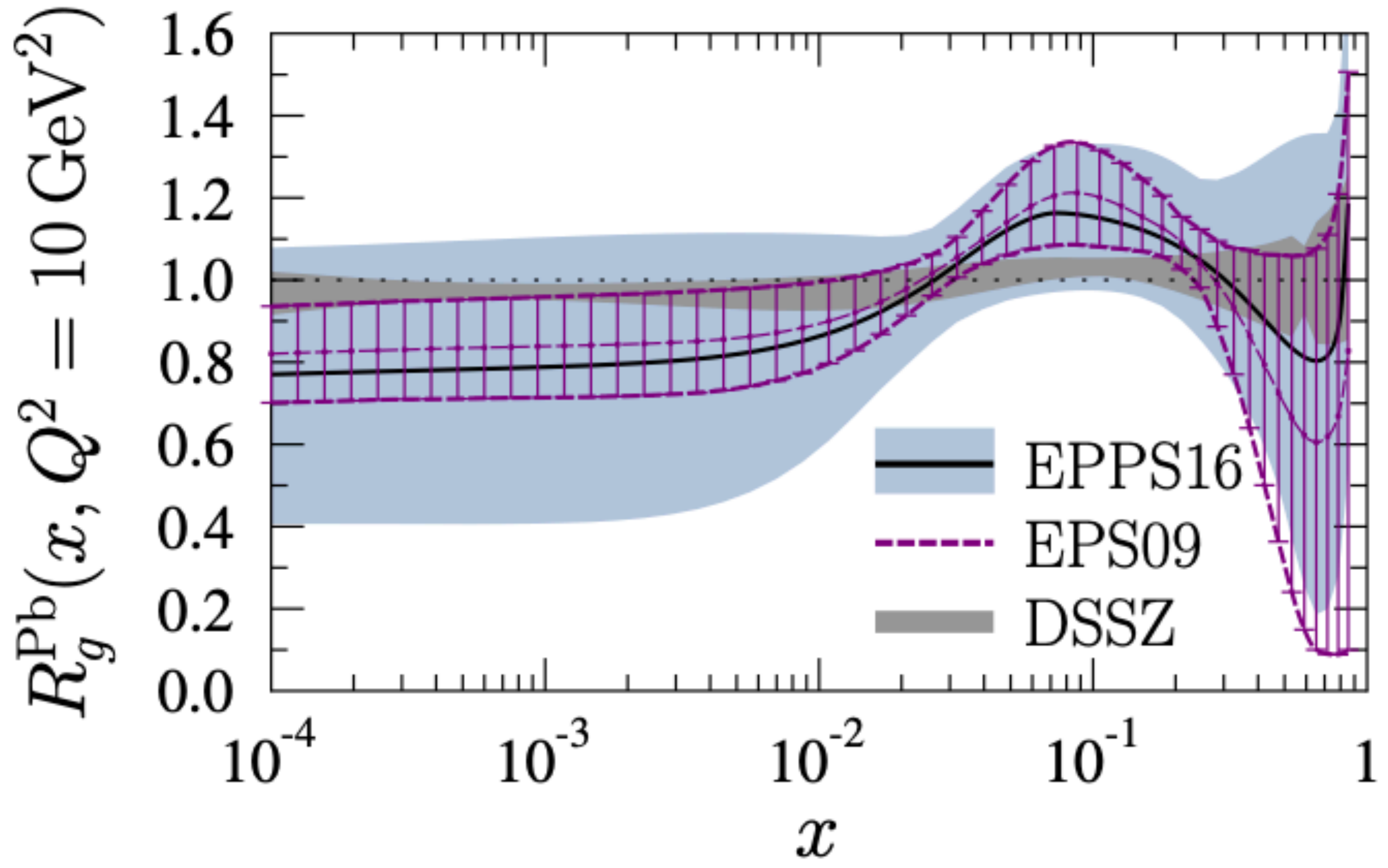


Accardi et al (2016)

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

EPPS16 (2017)



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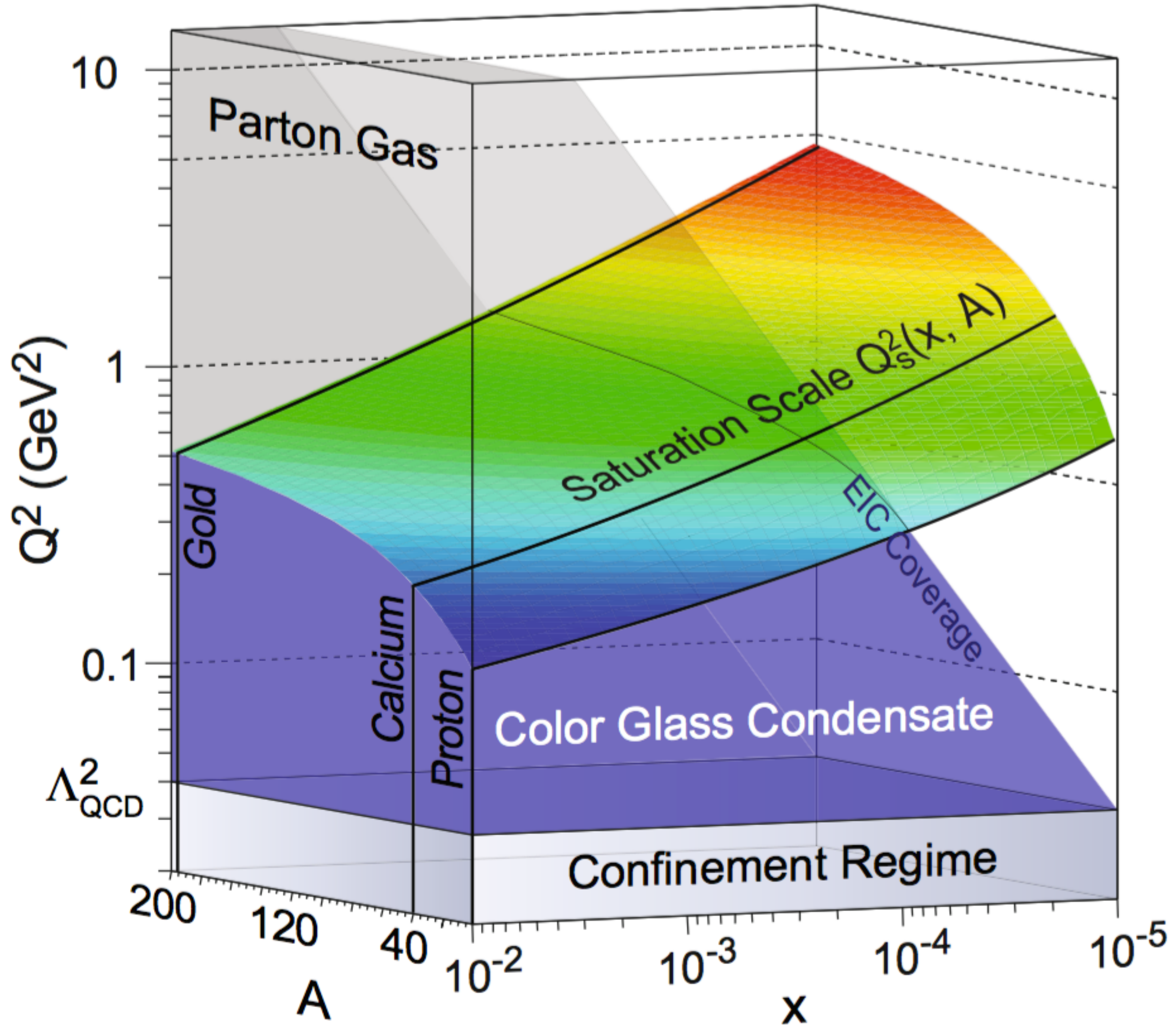

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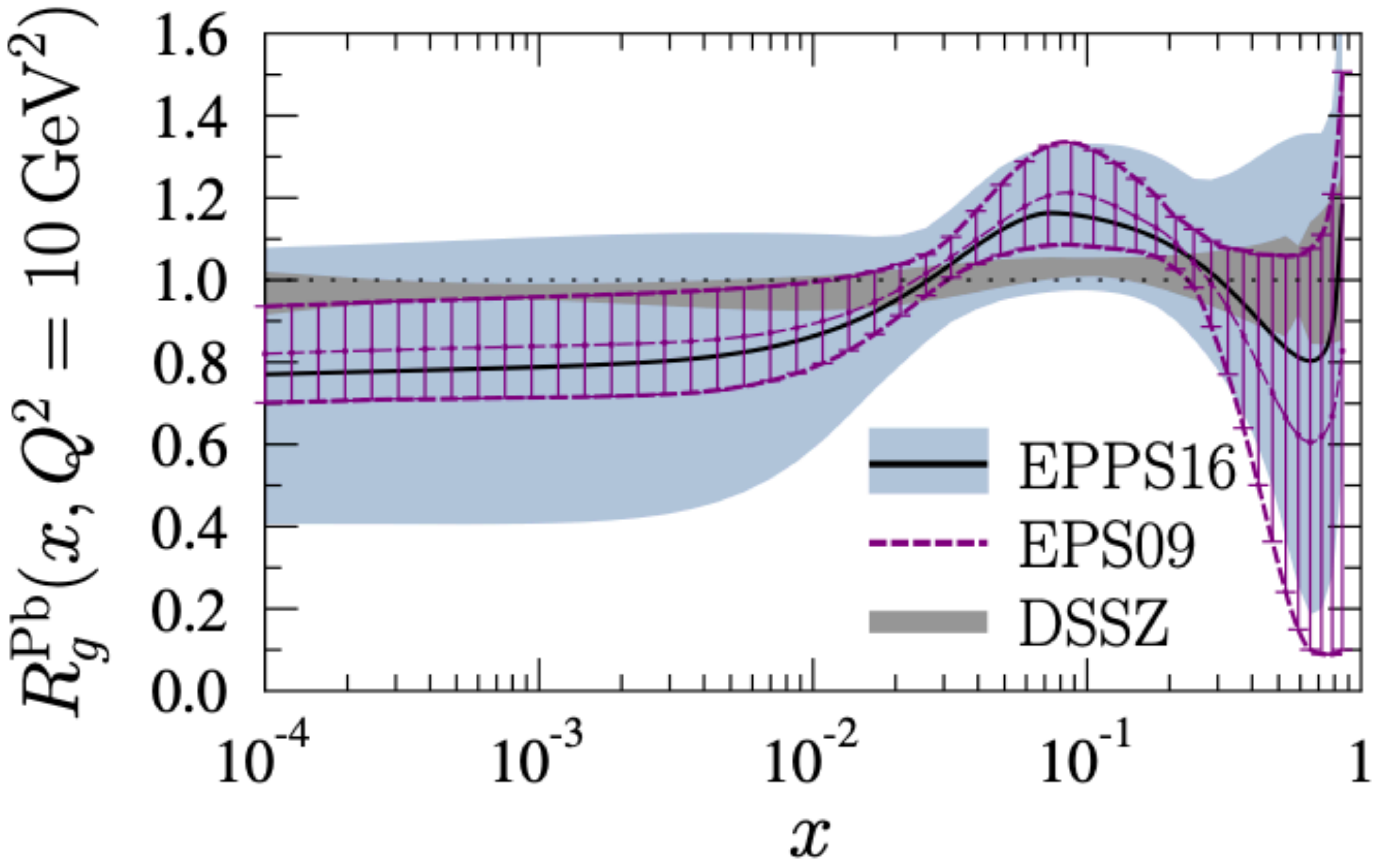
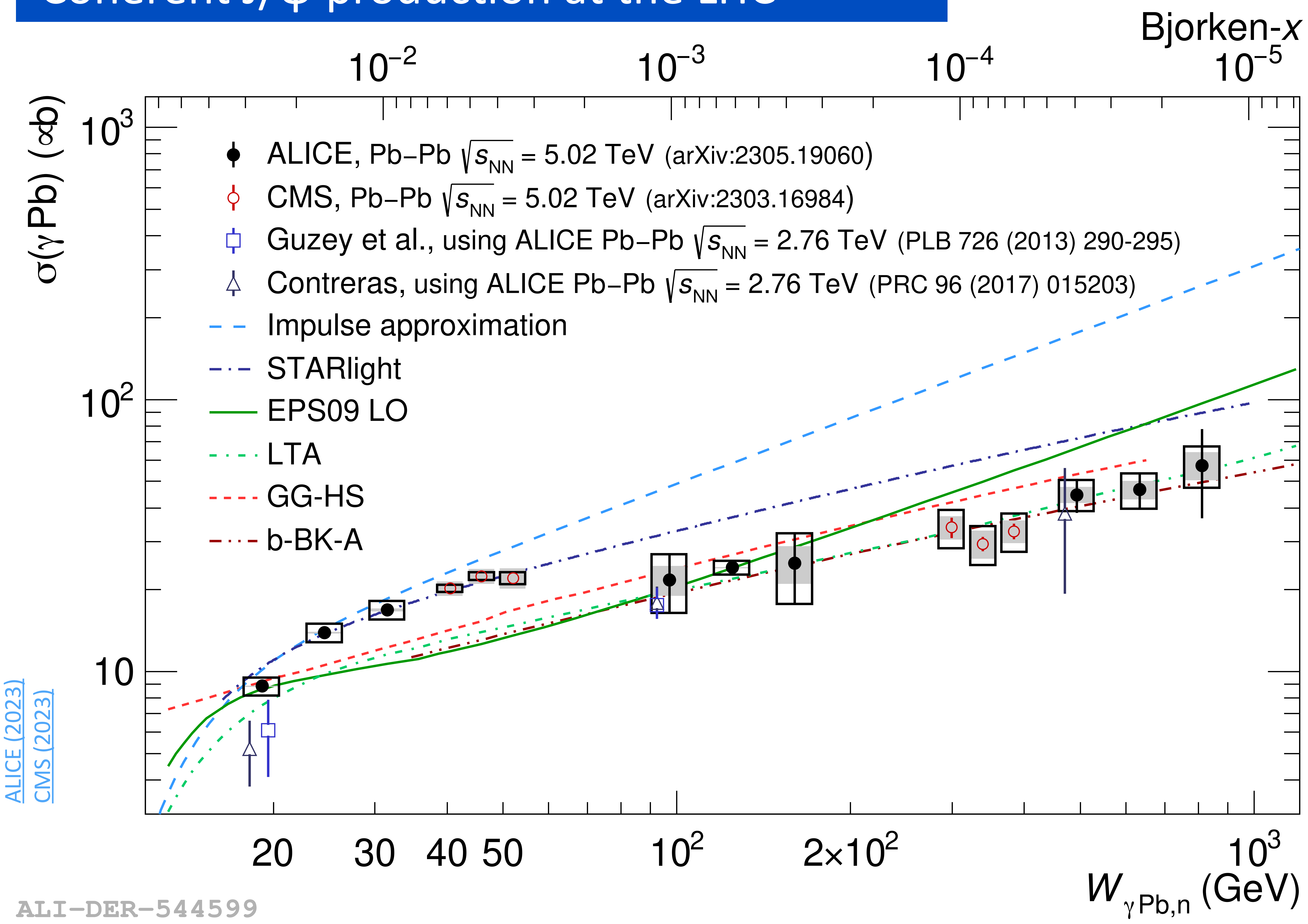


The relation between saturation and shadowing and how to disentangle their effects is an open problem

Coherent J/ψ production at the LHC



Bjorken-x dependence measured across three orders of magnitude!

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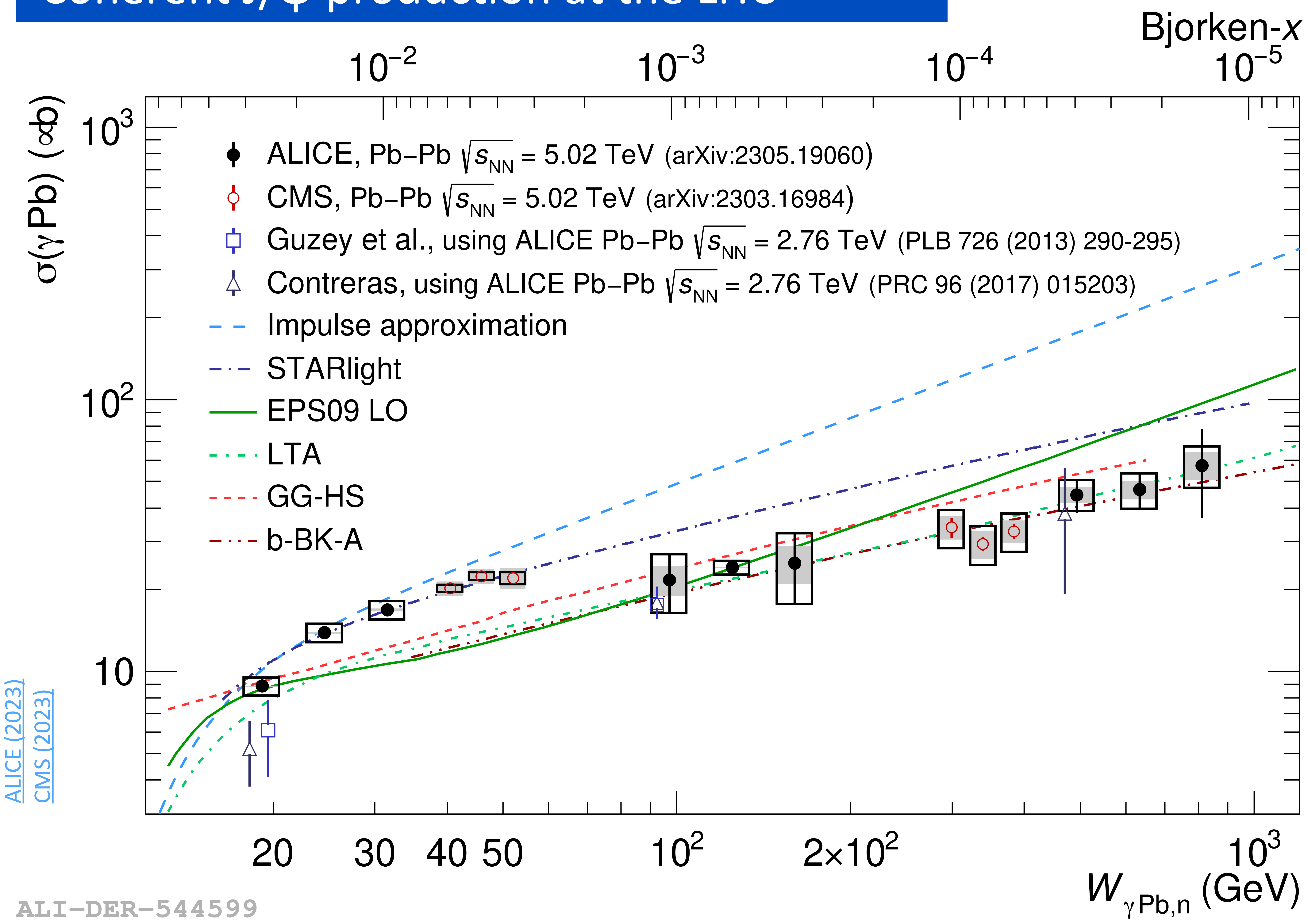

ALICE (2023)
CMS (2023)

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Impulse approximation does not work at small x

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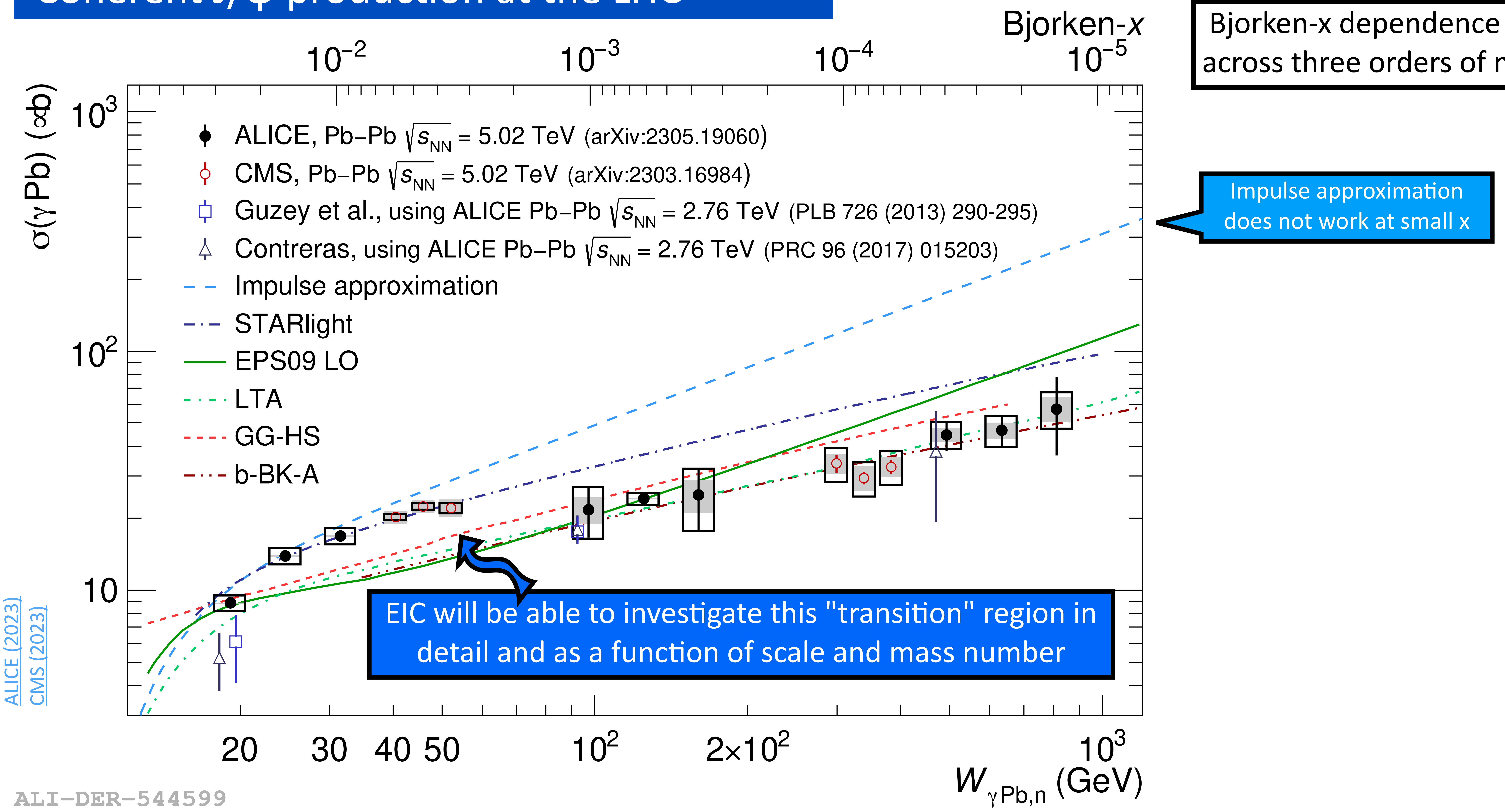
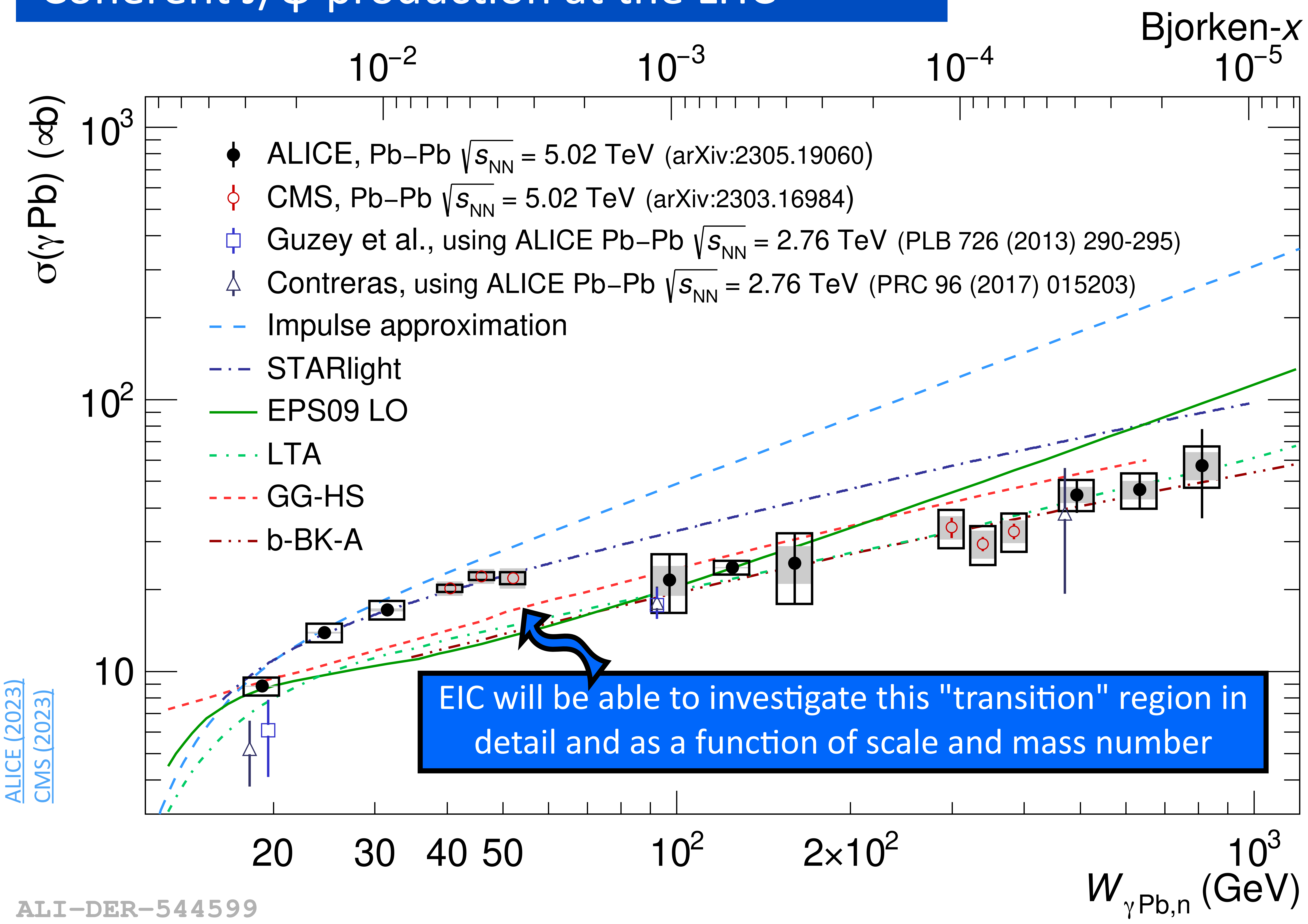


Guillermo Contreras, CTU in Prague

Coherent J/ψ production at the LHC



EIC will be able to investigate this "transition" region in detail and as a function of scale and mass number

Bjorken-x dependence measured across three orders of magnitude!

Impulse approximation does not work at small x

Above 100 GeV, saturation- and shadowing-based models provide a good description of data

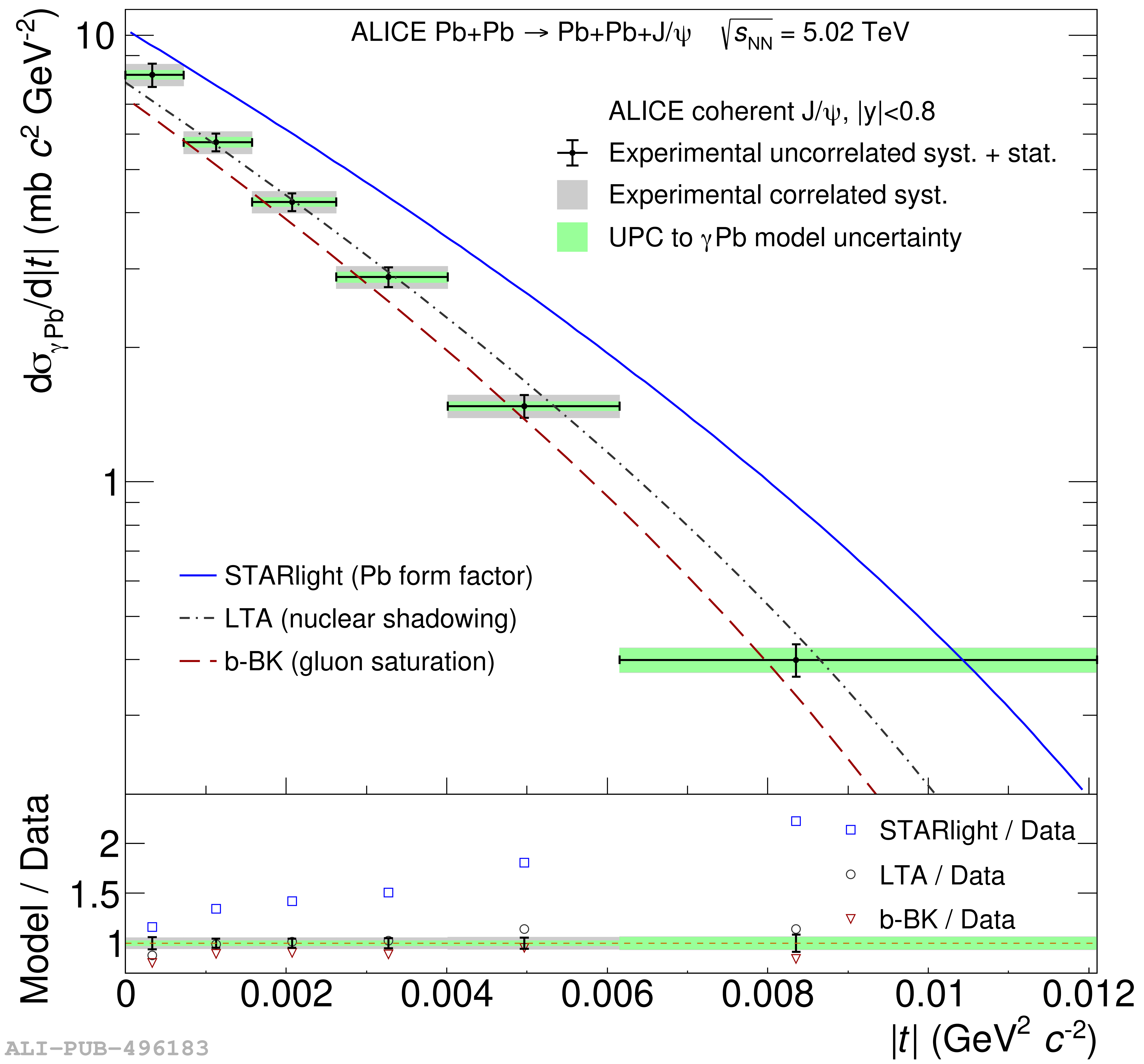
Other observables are needed to pin down saturation

Guillermo Contreras, CTU in Prague

Coherent J/ψ production at the LHC

ALICE (2021)

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



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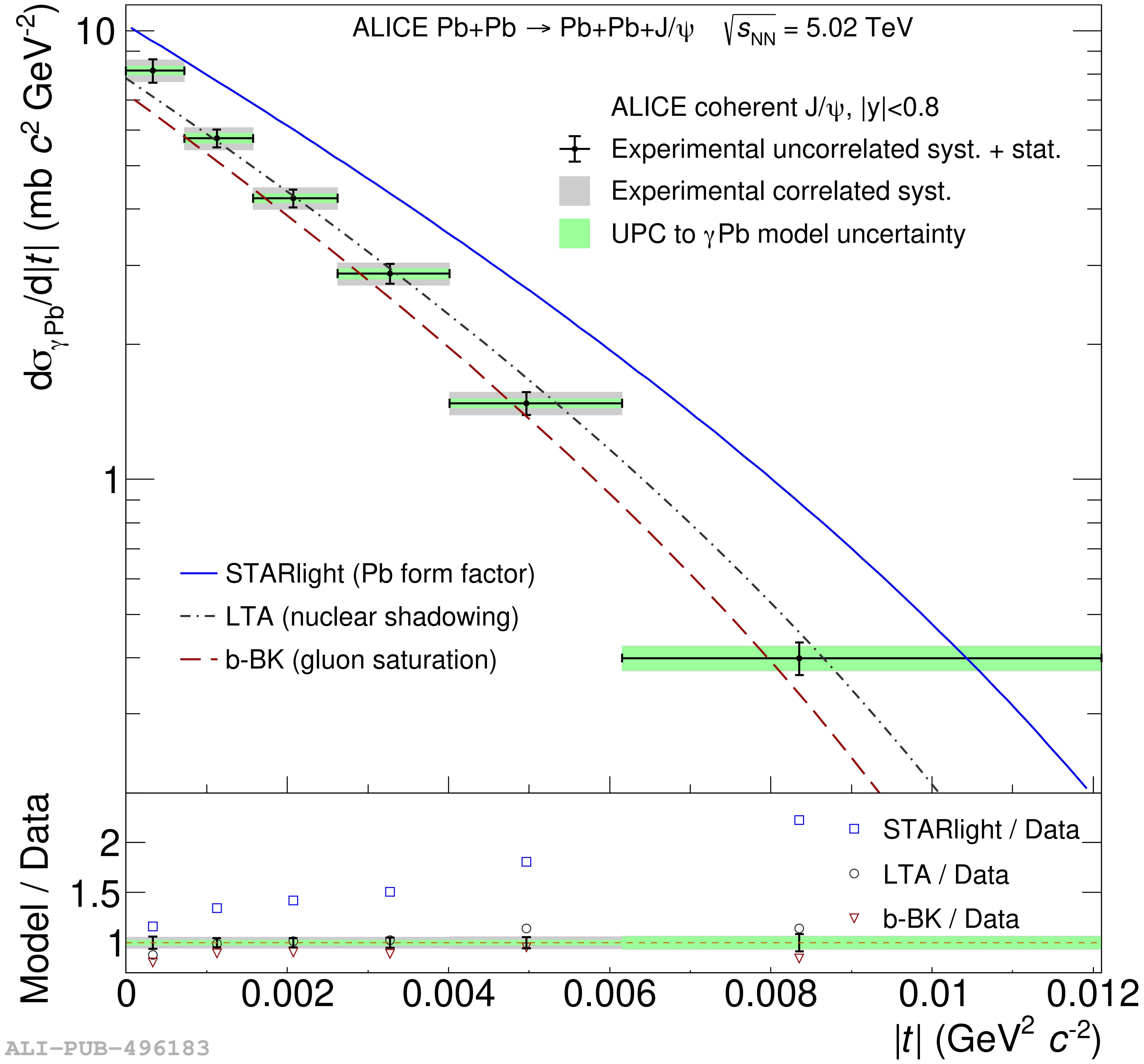

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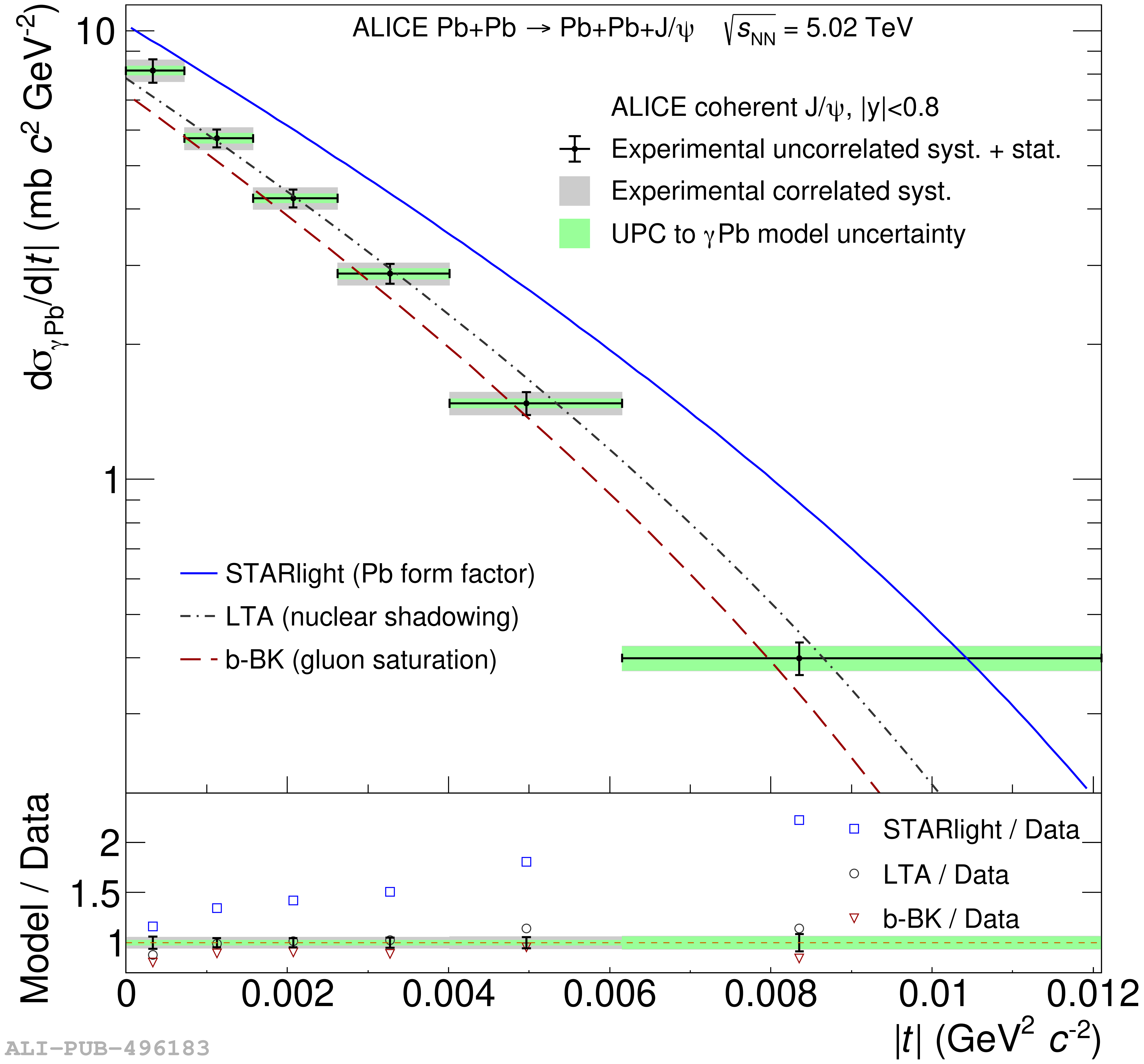

Incoherent J/ψ production at the LHC

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Diffractive incoherent photonuclear production at large Mandelstam-t looks like a good place to look for saturation

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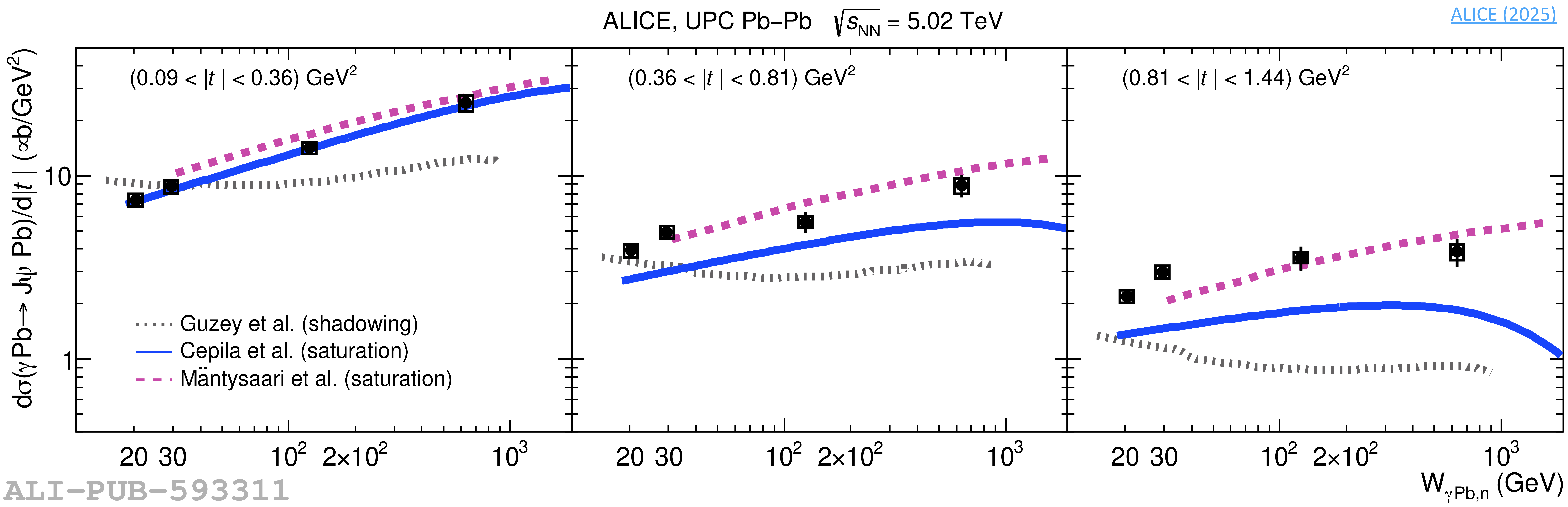

Bjorken-x dependence measured in a large energy range for different Mandelstam-t ranges

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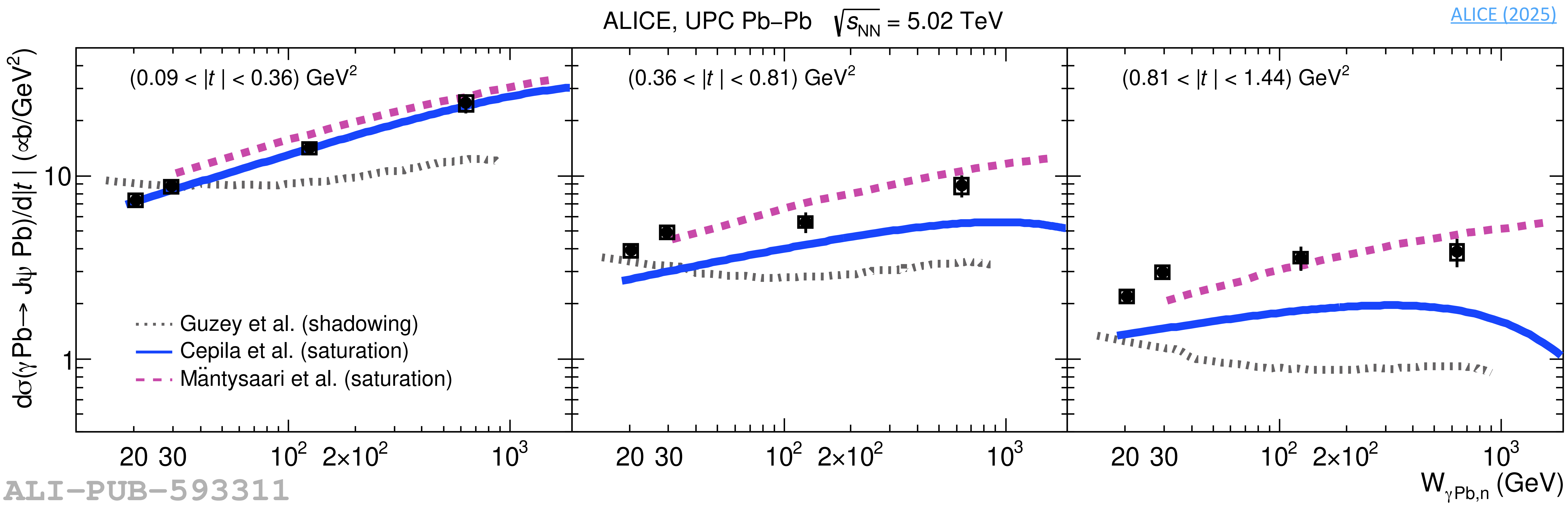


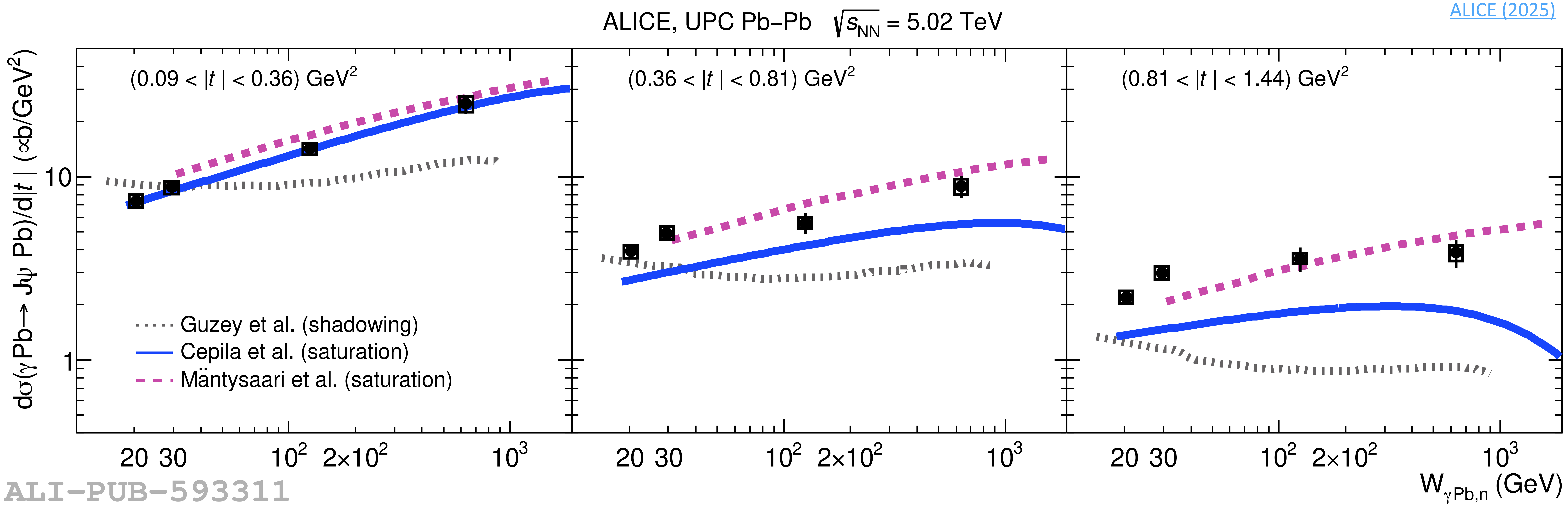
Bjorken-x dependence measured in a large energy range for different Mandelstam-t ranges

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

Incoherent J/ψ production at the LHC

This shadowing model (that described all other measurements) seems to have problems to follow the measured trends

ALICE (2025)



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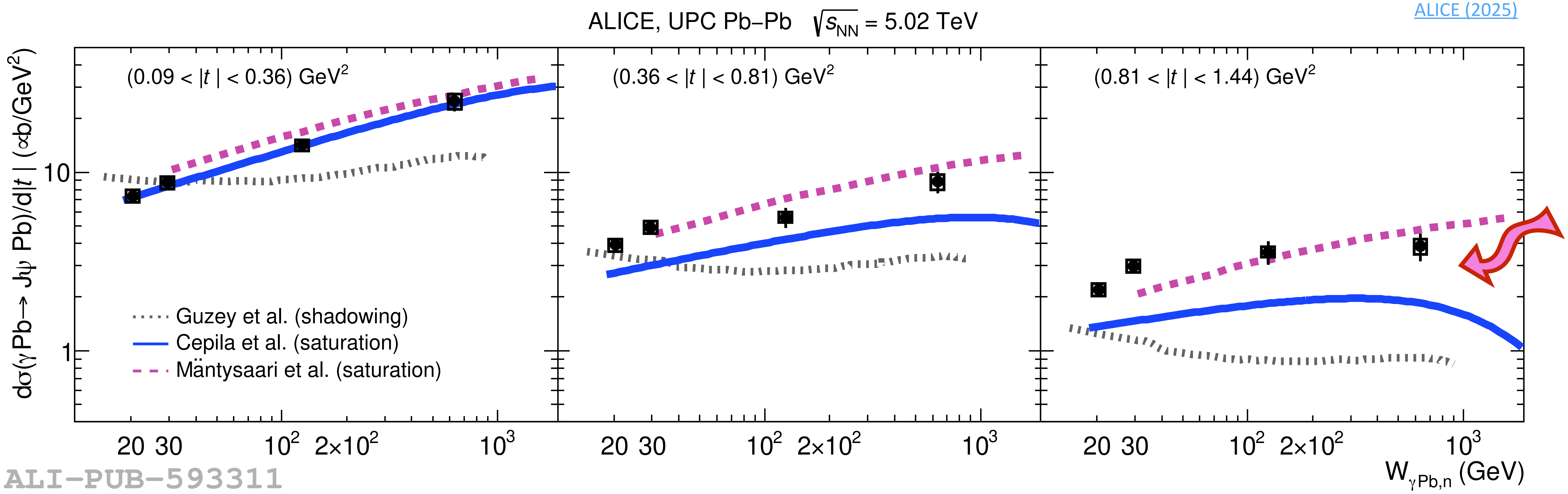

Two saturation-based models differ in the predicted behaviour at high energies and high Mandelstam-t: data cannot (yet?) decide if the cross section starts to decrease

LHC: nuclear shape?

LHC: nuclear shape?

EIC will be an ideal place to study this in detail

OO predictions

Cepila, JGC, Matas, Ridzikova (2025)

In July 2025, LHC provided pO, OO, and Ne-Ne collisions

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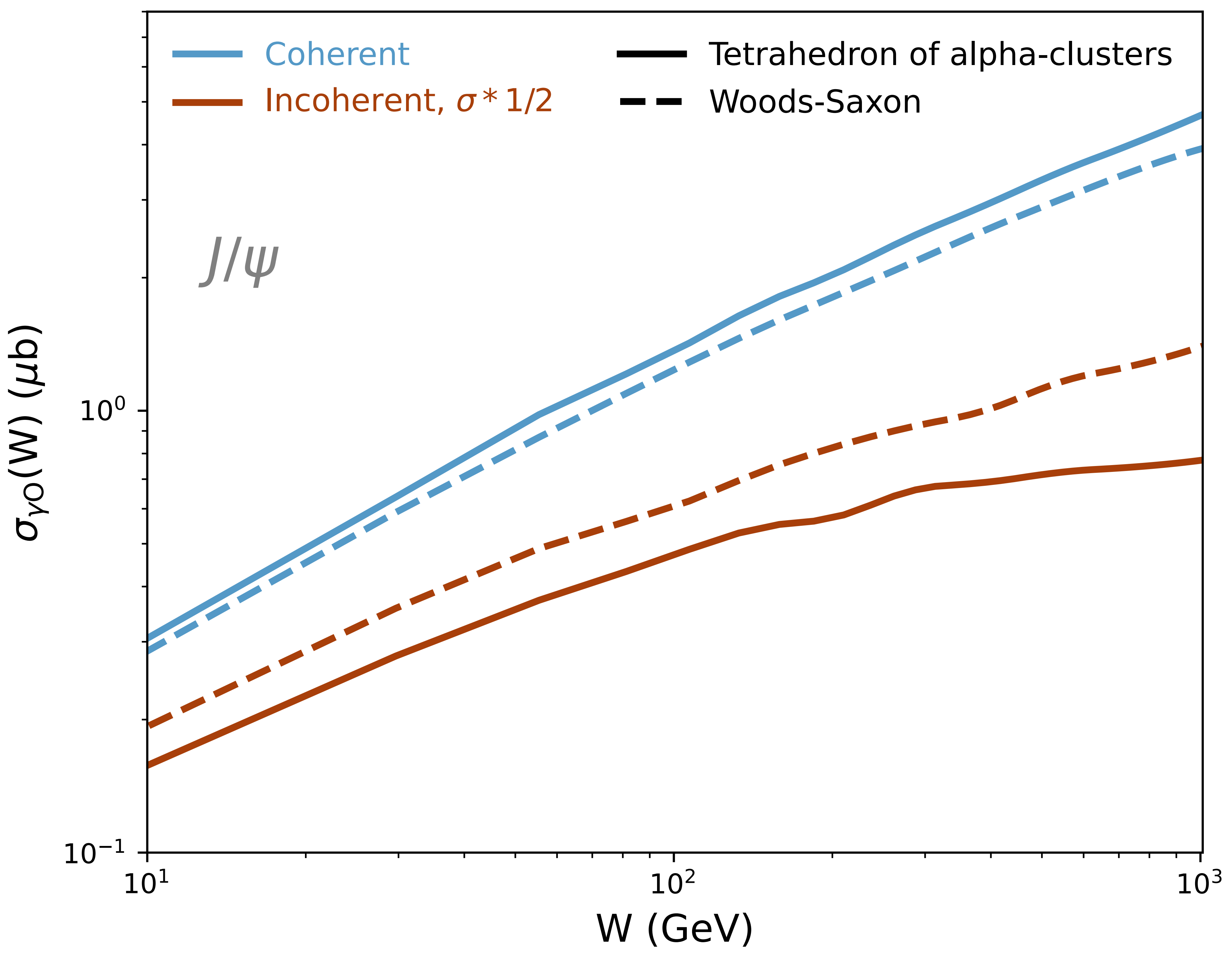

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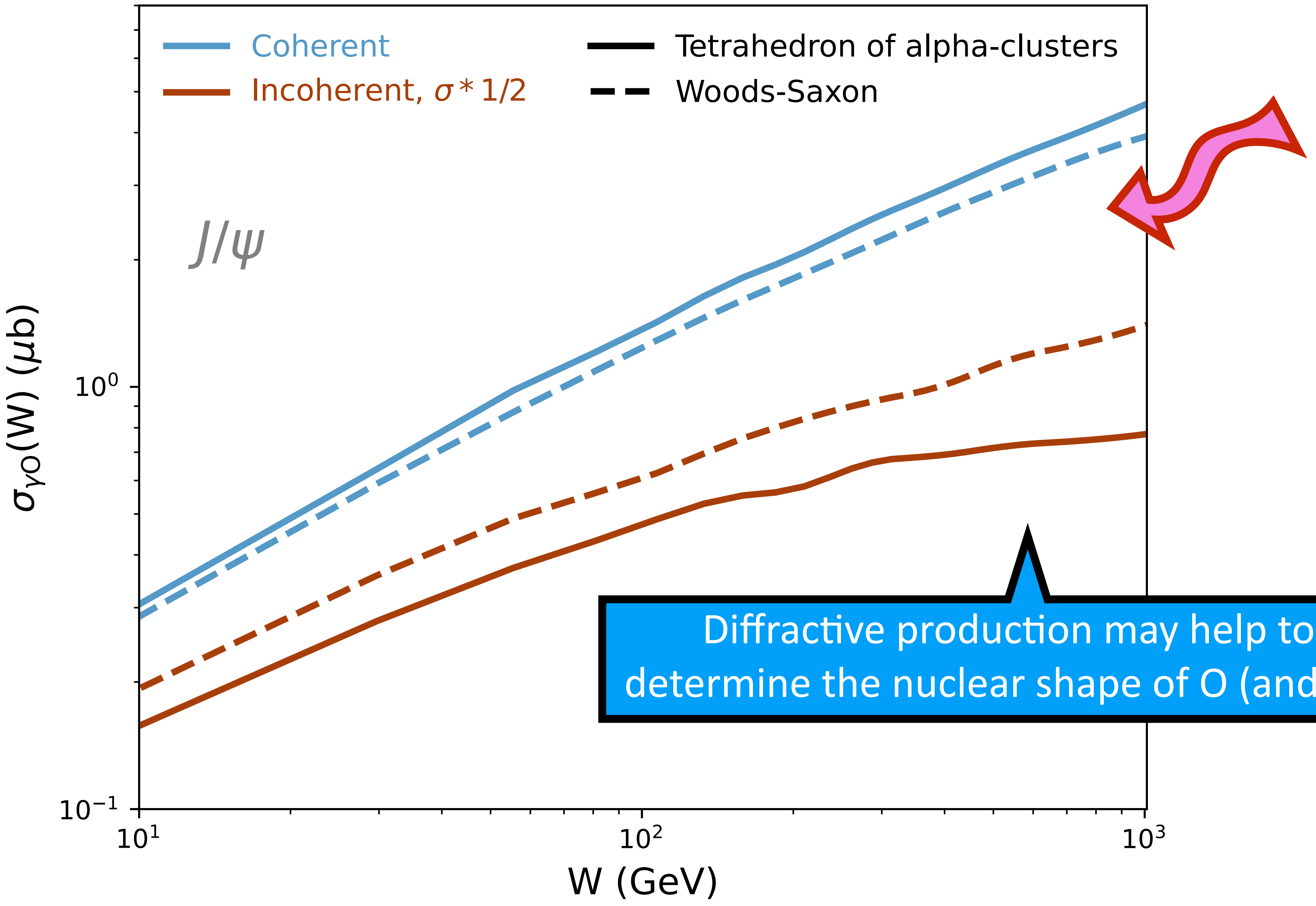

Diffractive production may help to determine the nuclear shape of O (and Ne)

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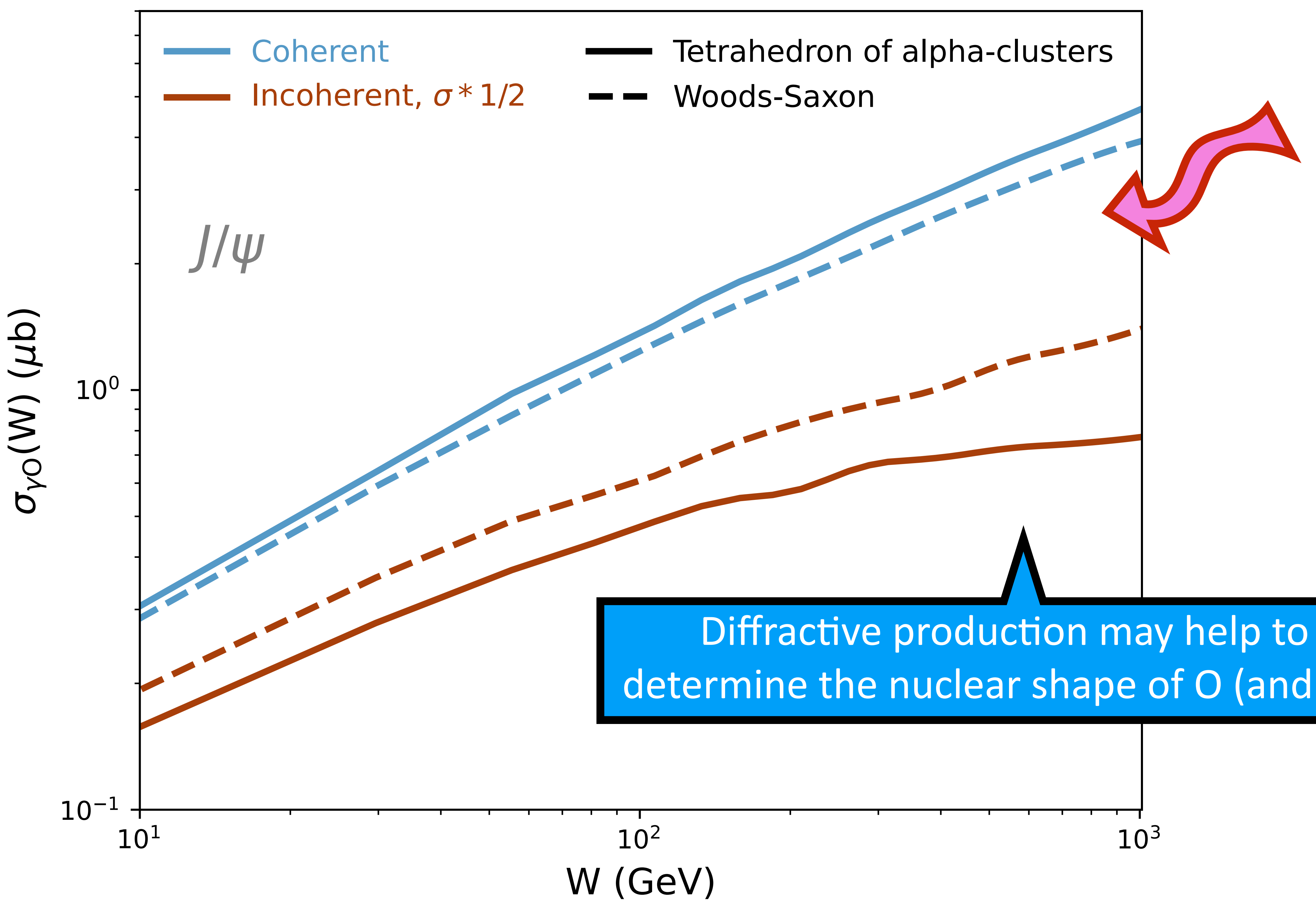

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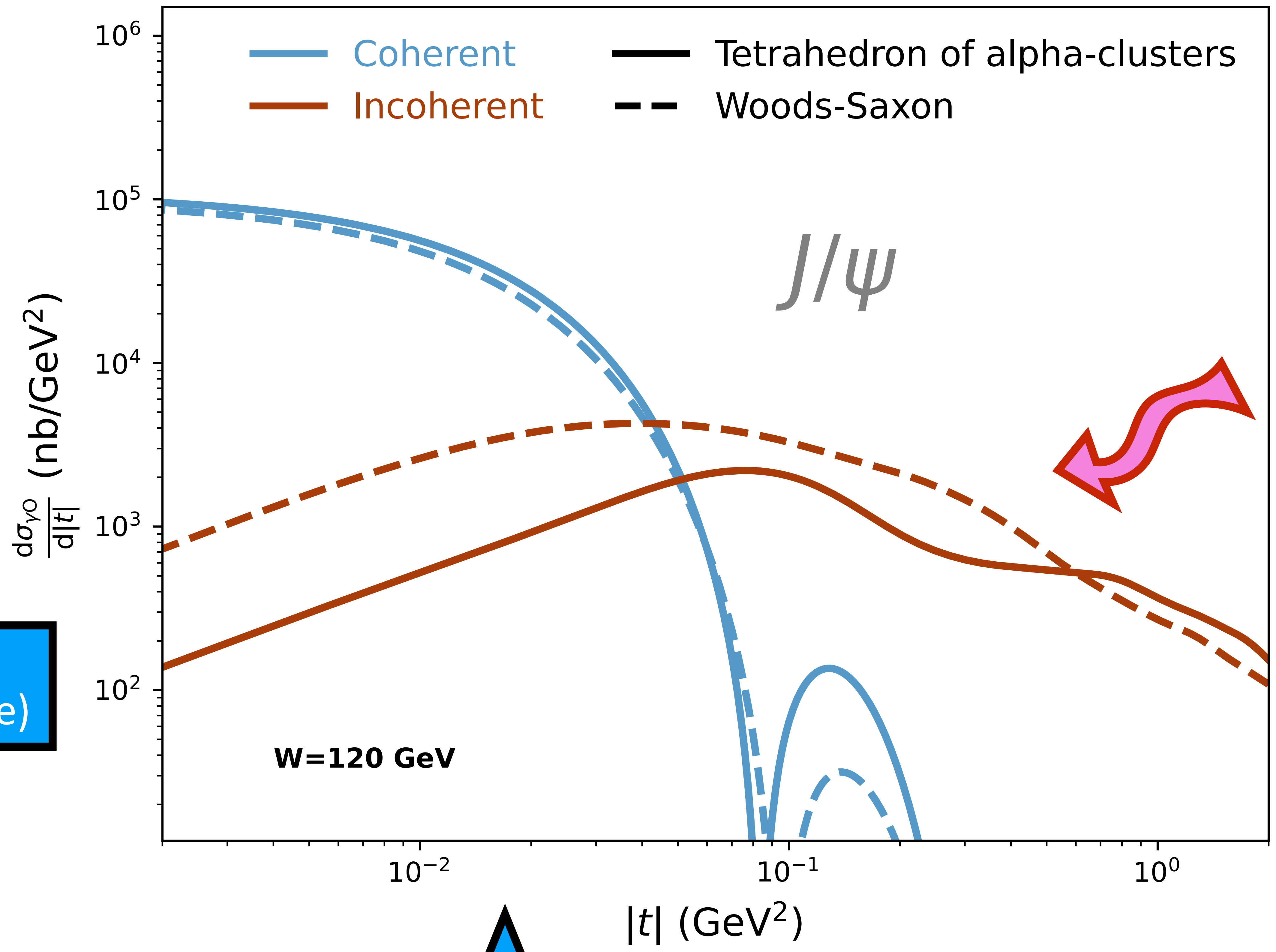

The dependence on Mandelstam-t of incoherent cross section is sensitive to saturation and nuclear shape

EIC: some potential lessons

From HERA to EIC through UPC at LHC

A rich trove of results from HERA, including technical aspects.

Many students at EIC will be too young to be aware of these measurements: do not let these results be forgotten

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Saturation will be established by consistency between many different measurements and the QCD evolution of the observables

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LHC was not designed nor operated to perform this type of measurements; nonetheless, current results, which were not contemplated when the LHC was planned, have HERA like precision

Encourage students to look for new ways to look for saturation (and/or other phenomena) even if the machine/detector was not designed for it

Summary

Phenomenology

- Incoherent vector meson production offers a window to fluctuations of the gluon field
- It also provides, within the Good-Walker approach, a striking signature for saturation

Experiment

- LHC results are reaching HERA like precision and cover a variety of observables
- HERA+LHC/RHIC are a rich testing ground for new ideas and methods for EIC

Guillermo Contreras, CTU in Prague