Gluons exploration using J/ψ photo-production

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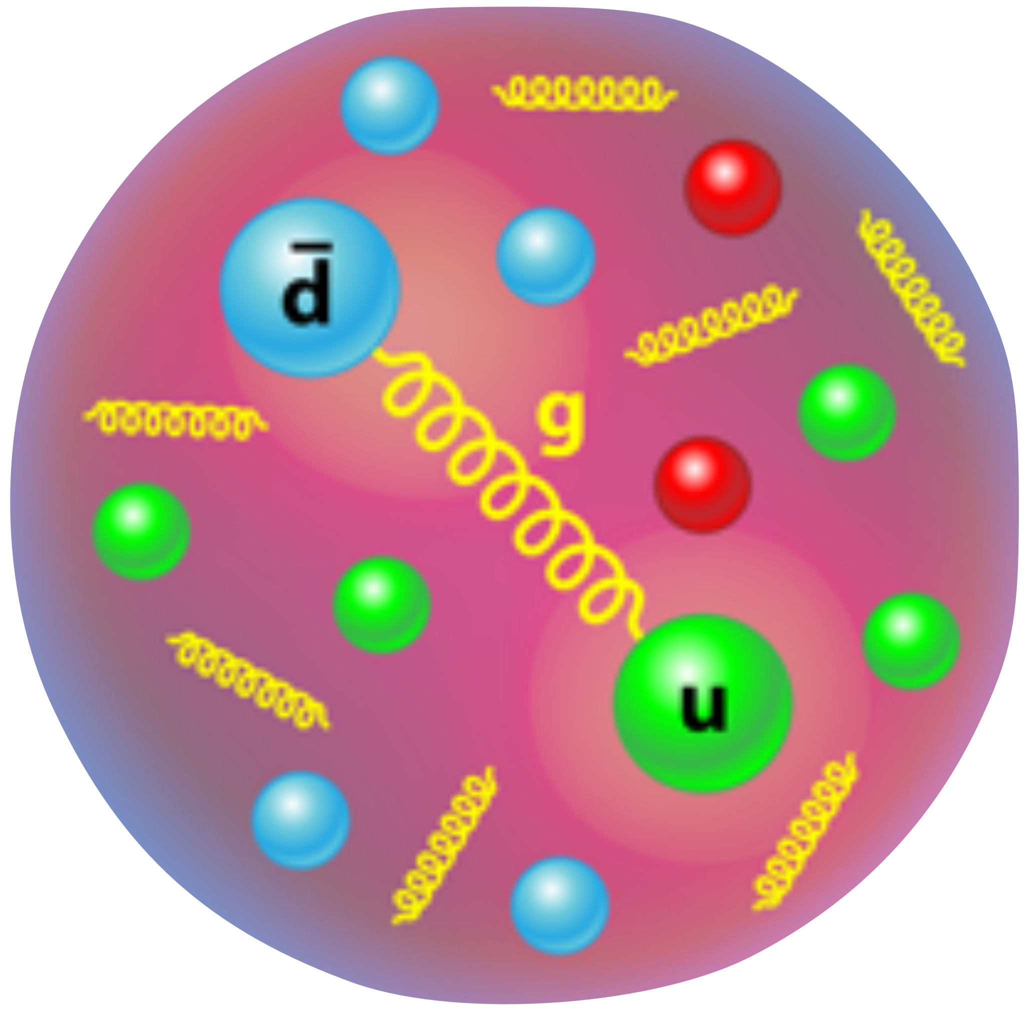


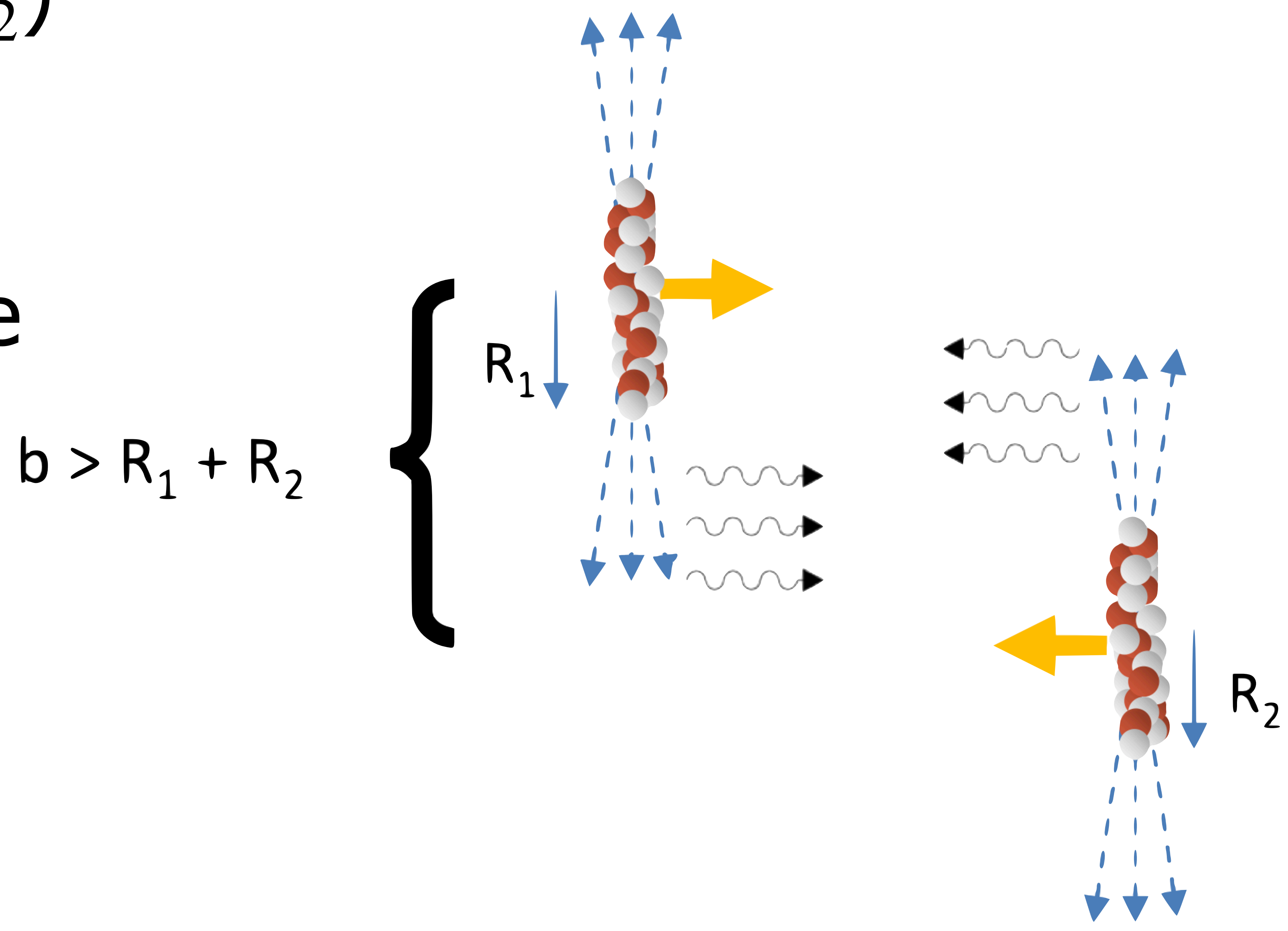
Why is it important to understand the J/ψ?

- J/ψ produced at initial stage of the collision → obtain charm production cross section

- Understanding the average spatial distribution of partons in nuclei: two ways to access the geometric shape and shape fluctuations (https://arxiv.org/pdf/2001.10705.pdf)
    - Look at particle correlations in high multiplicity collisions generated by the (possible) hydrodynamical response to the initial state spatial anisotropies
    - Look at observables that directly probe the event-by-event fluctuations in the target wave function, such as incoherent diffraction in deep inelastic scattering. In addition, one can consider fully elastic scattering processes to obtain more indirect evidence of the proton shape fluctuations.

What is a UPC = Ultra Peripheral Collision?

- Ultrarelativistic system
- Large impact parameter ($b > R_1 + R_2$)
- No nuclear overlap
- Photon induced reactions dominate

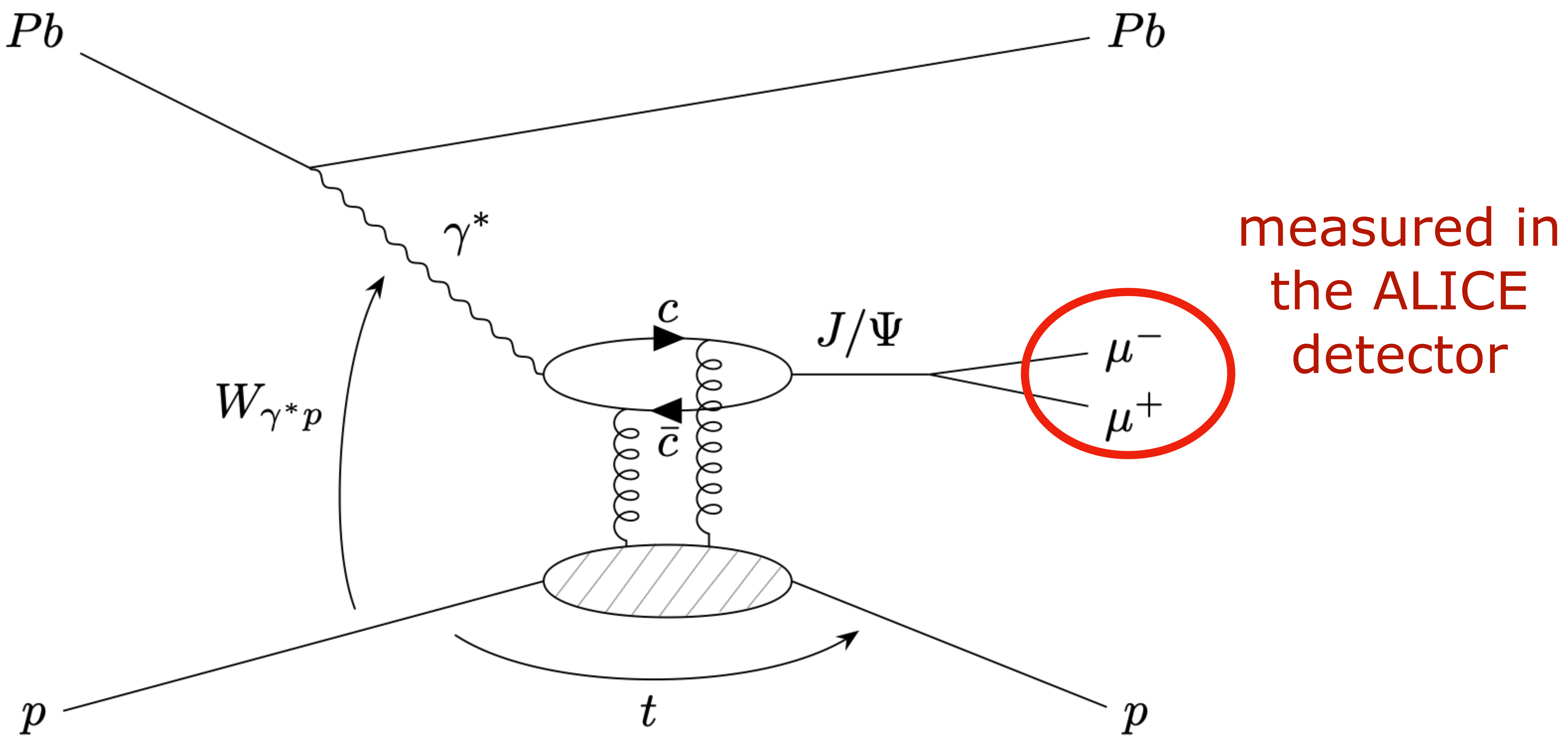


- In p-Pb UPC, lead-ion is most likely (~95%) the photon source

J/ψ photoproduction at high energy

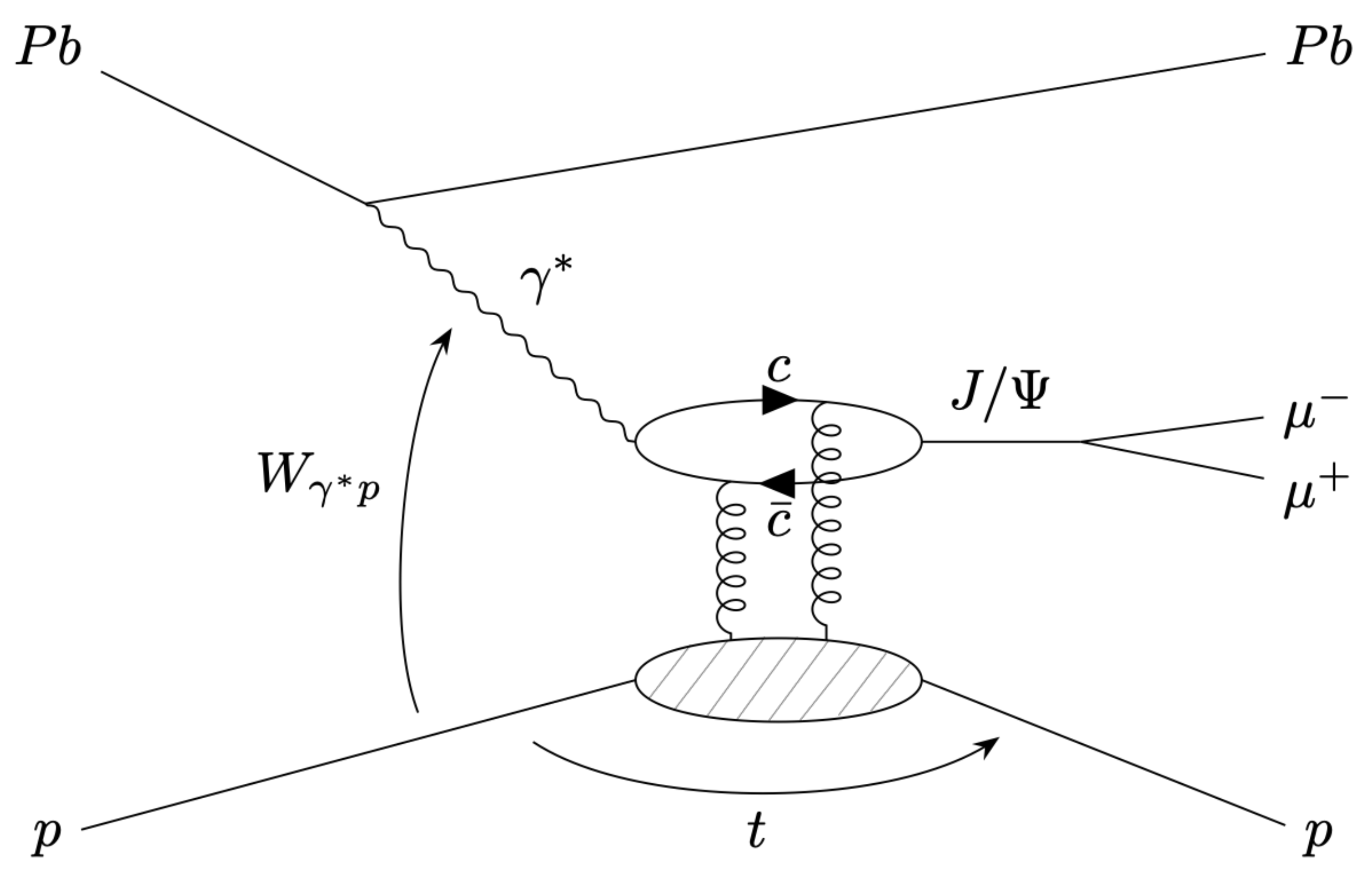
- The virtual photon fluctuates in a $q\bar{q}$ dipole
- The virtual photon interacts with the proton and probes its internal structure via the exchange of 2 gluons
- From this interaction a vector meson (here J/ψ) is produced (LO picture)

- The J/ψ then decays to di-leptons



J/ψ photoproduction in ALICE

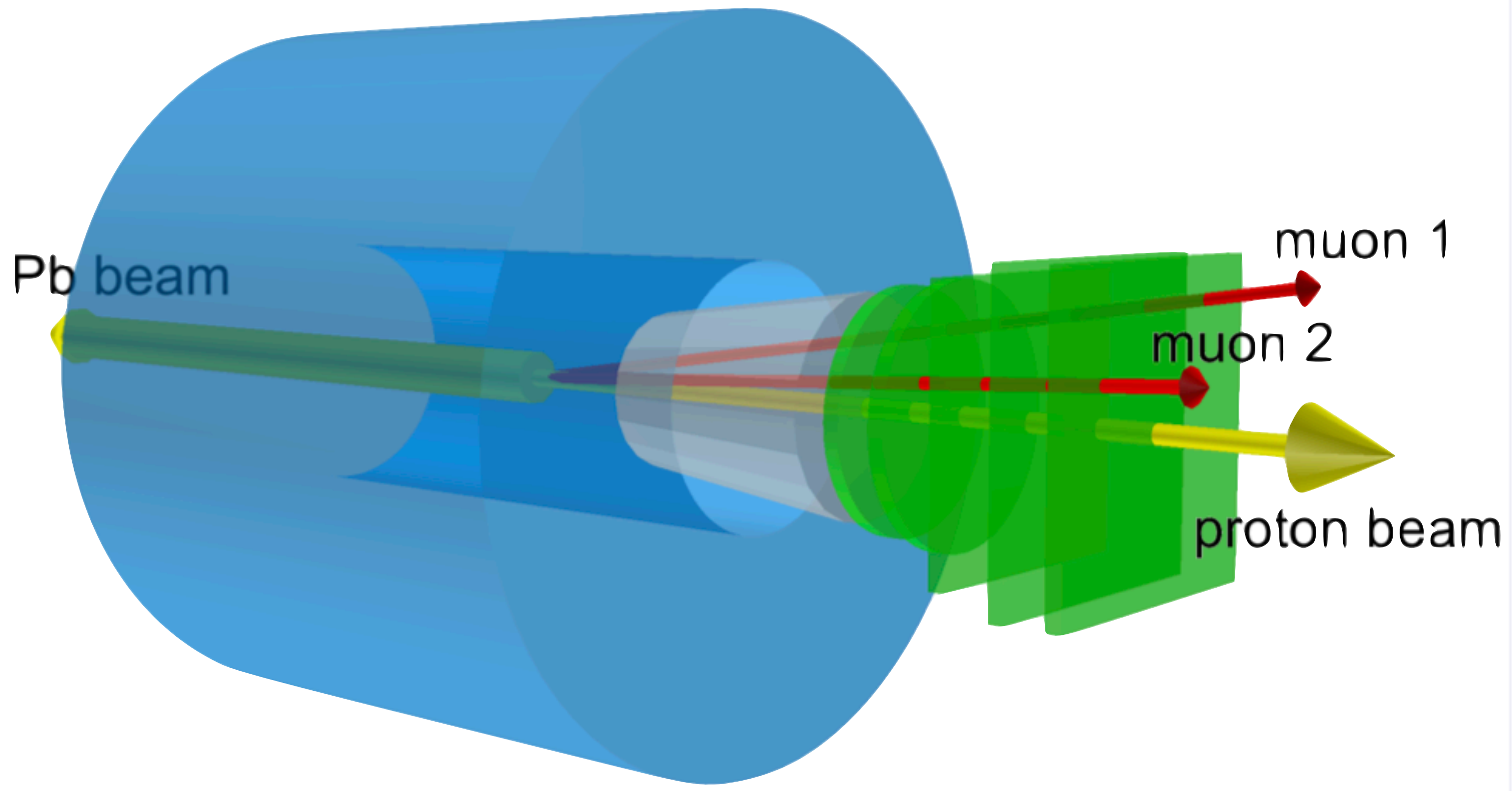
- p-γ^* center-of-mass energy given by $W_{\gamma^* p} = 2E_p\, M_{J/\Psi}\, e^{-y}$ where y is the rapidity of the J/Ψ defined according to the proton beam

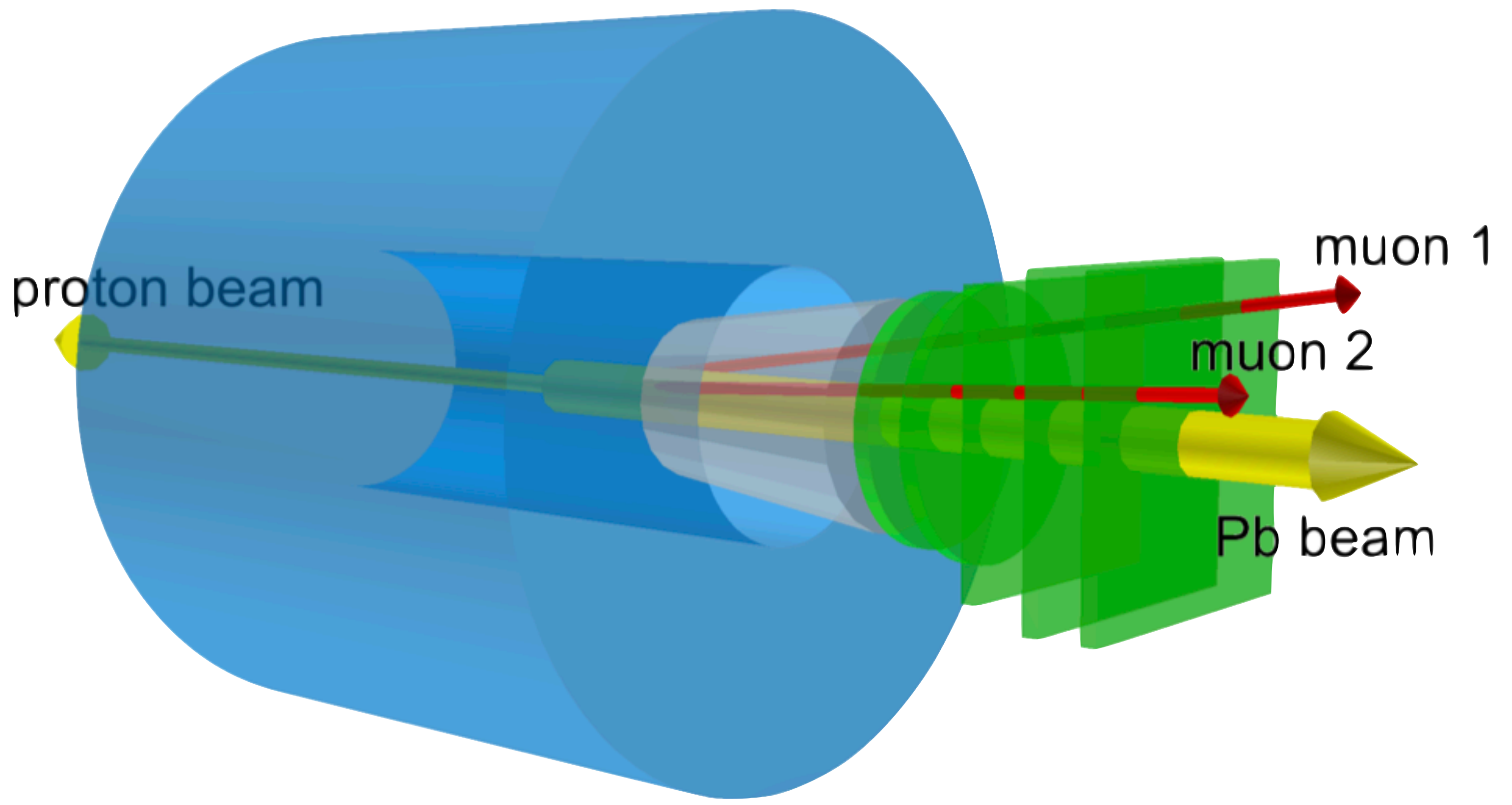


- 2 energy configurations:

the J/ψ goes in the direction of the proton: 27 GeV < $W_{\gamma^* p}$ < 58 GeV

the J/ψ goes in the direction of the Pb ion: 702 GeV < $W_{\gamma^* p}$ < 1486 GeV





What are we probing?

The target is probed at the longitudinal momentum fraction (analogous to the Bjorken-x of DIS)

$$x_{\mathbb{P}} \propto W_{\gamma^* p}^{-2}$$

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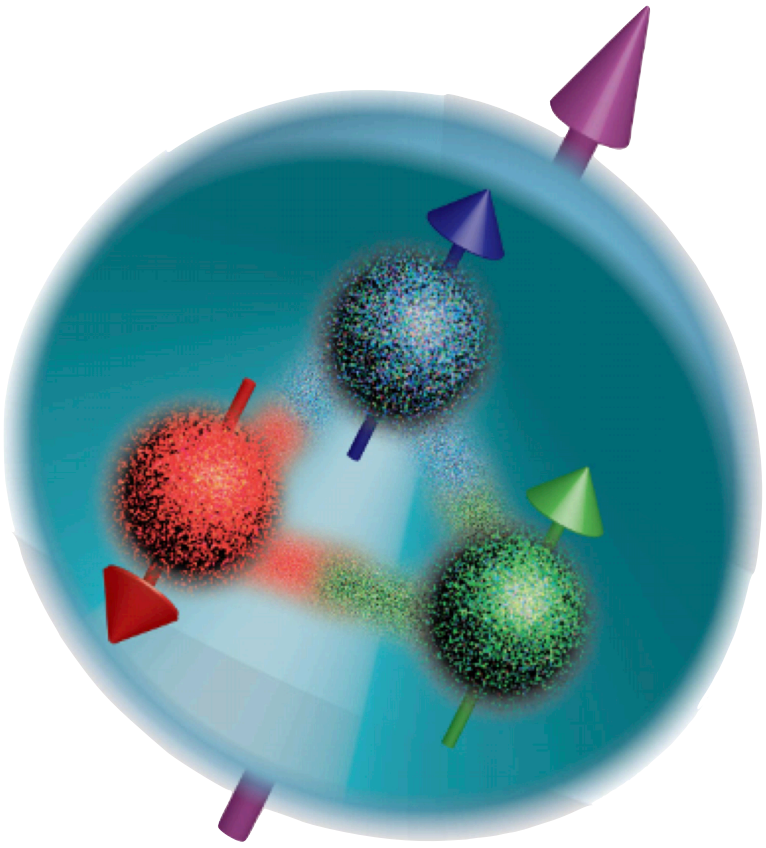

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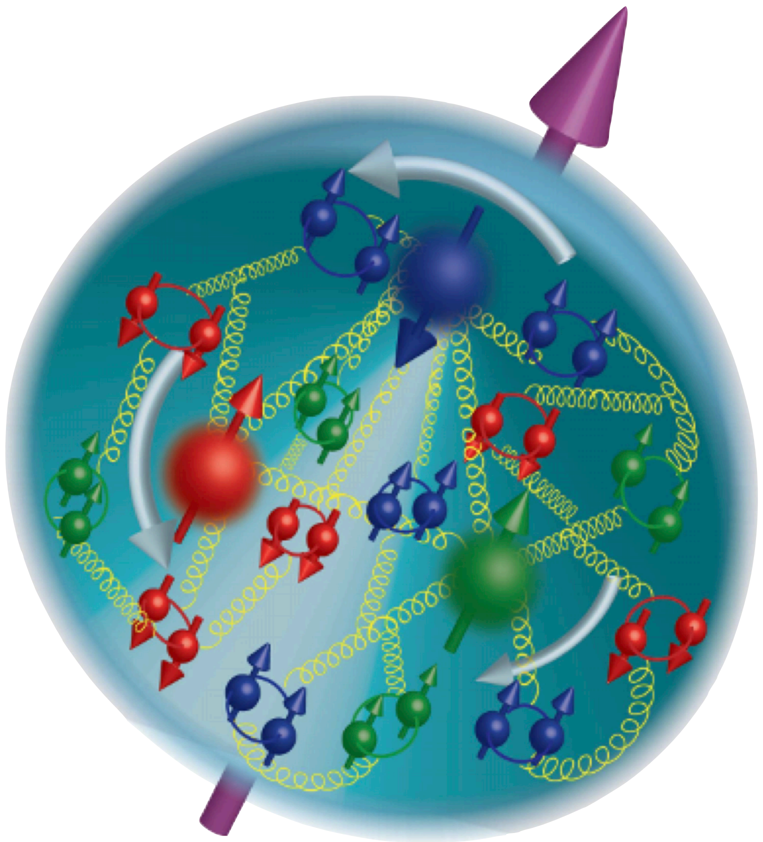


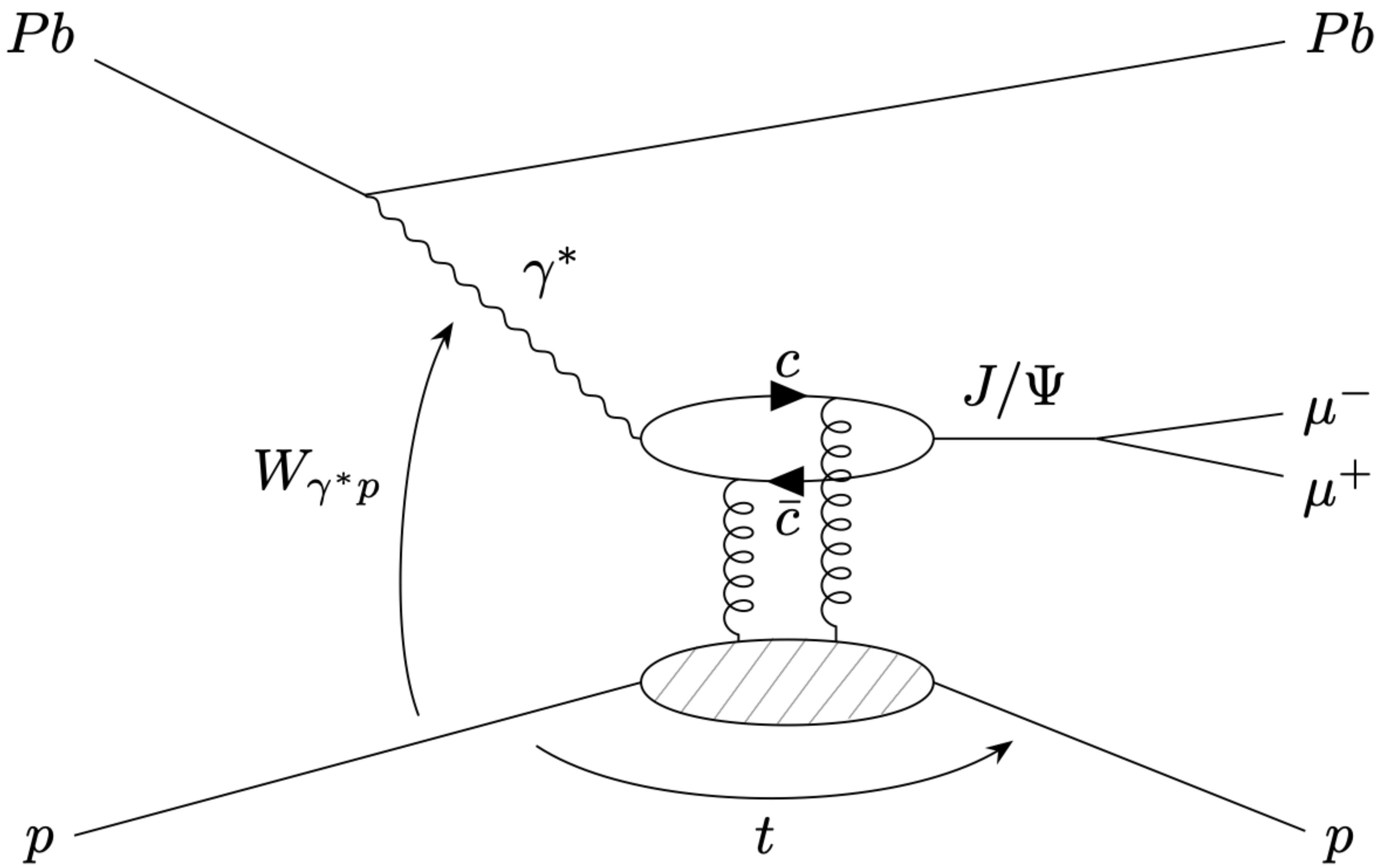
Exclusive J/ψ photoproduction

- In Good-Waker formalism (Heikki Mäntysaari 2020 Rep. Prog. Phys. 83 082201), the proton remains in the same quantum state

$$\frac{d\sigma^{\gamma^* p \to J/\Psi\ p}}{dt} \propto \sum_i |\langle i | A | i \rangle|^2 = |\langle A^{\gamma^* p \to J/\Psi\ p} \rangle|^2$$

Physically: we measure the average structure (configurations) of the proton

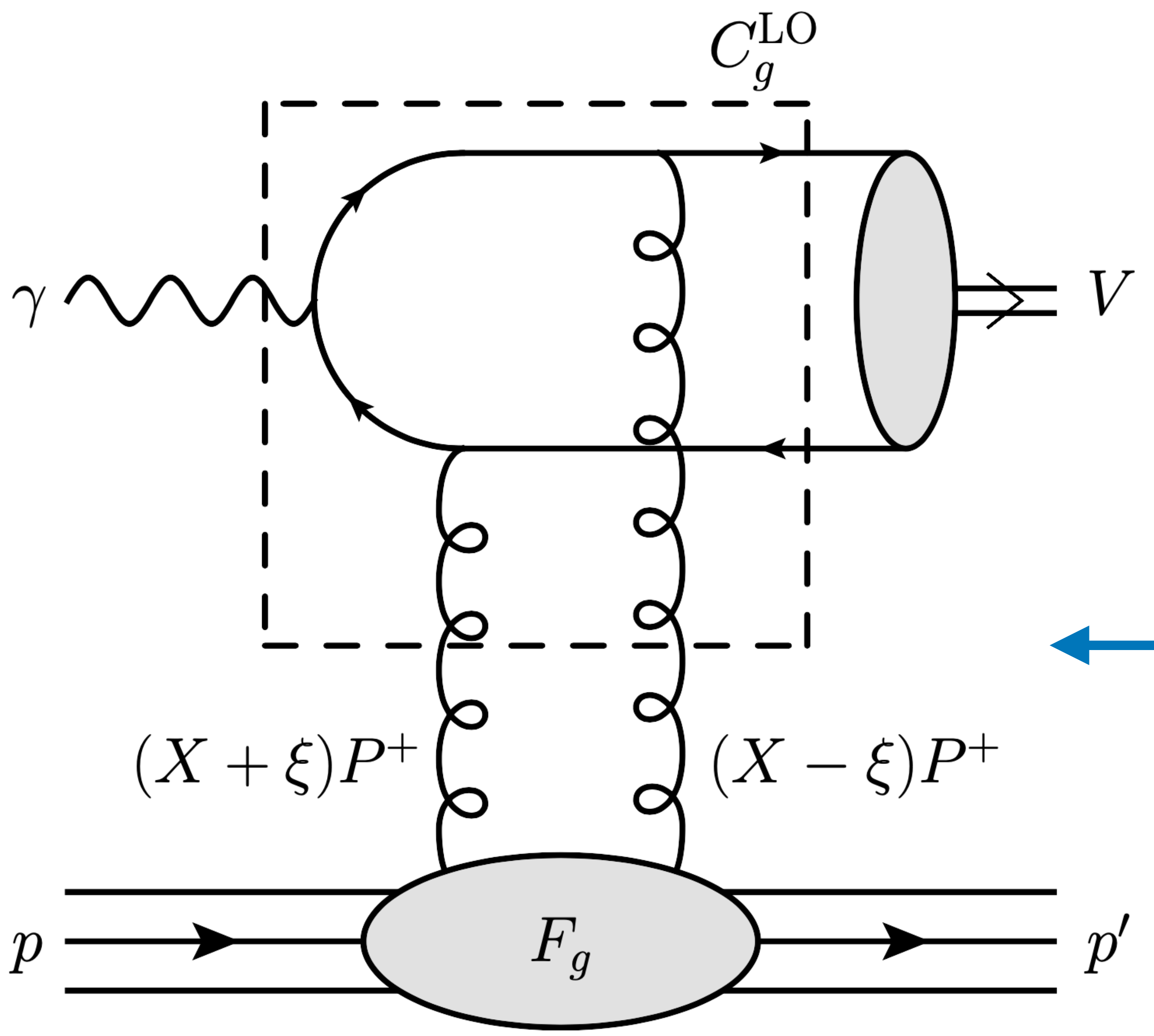
- $\frac{d\sigma}{dt} \propto \exp(-b|t|)$
  - The momentum transfer t is the Fourier conjugate to the impact parameter b
  - The transverse momentum transfer can be used to probe the spatial structure of the target. As such, it becomes possible to study the target structure differentially in the transverse plane (https://arxiv.org/pdf/2006.02830.pdf)

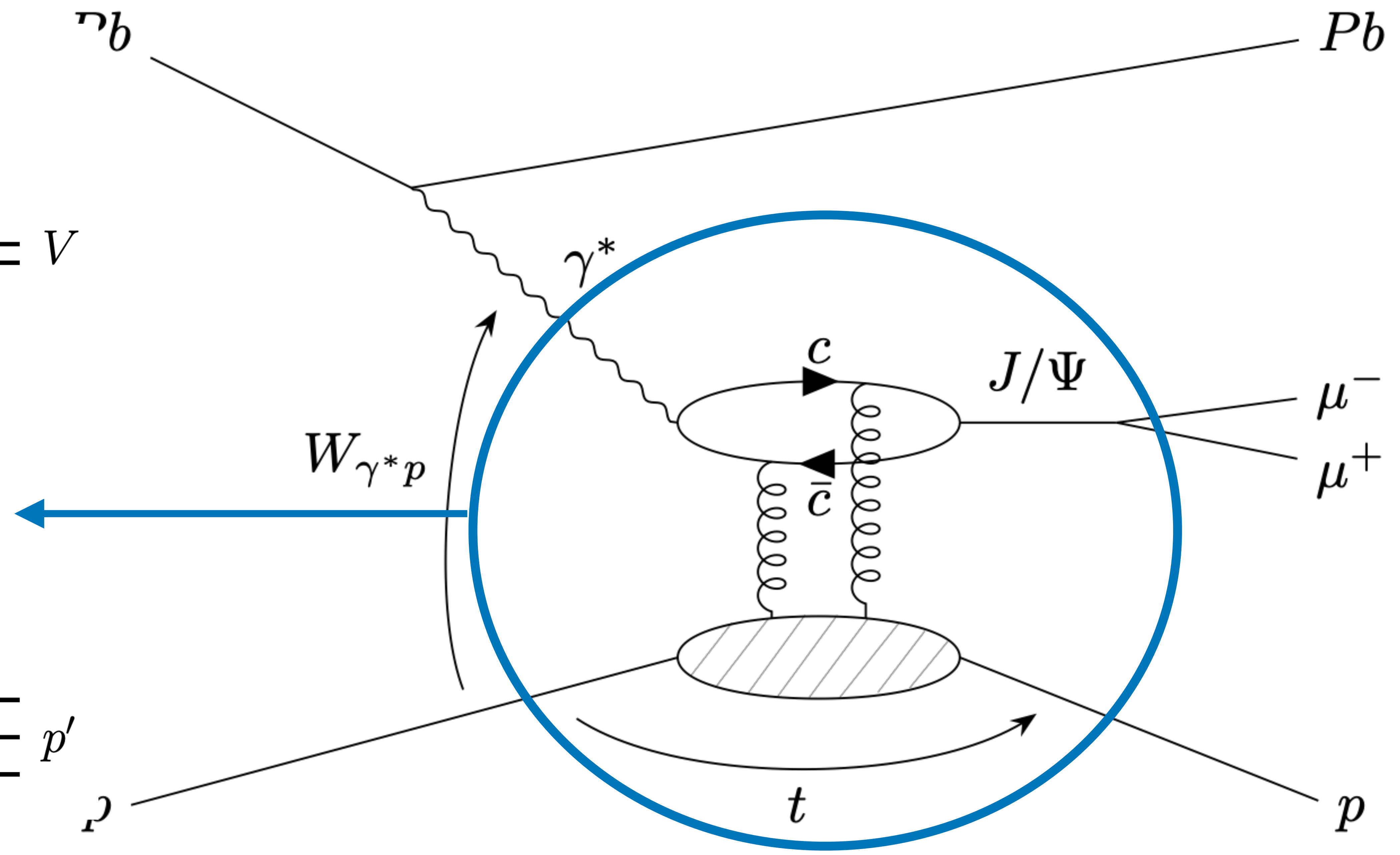


Exclusive J/ψ photoproduction

- At LO, the GPD function $F_g(X,\xi)$ accounts for the fact that the momenta of the 'left' and 'right' partons carry different proton momentum fractions $X + \xi$ and $X - \xi$ respectively.

(https://arxiv.org/pdf/1908.08398.pdf)





- The Shuvaev transform: as ξ → 0 (and at t = 0),

GPD $F_g(X, \xi)$ → PDF(x = X +ξ)

relevant values of X in the convolution of the GPD with the coefficient function are of the order of ξ

→ we probe the gluon PDF for x ~ 2ξ

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\Psi\ p)\Big|_{t=0} \propto [xg(x,Q^2)]^2$$

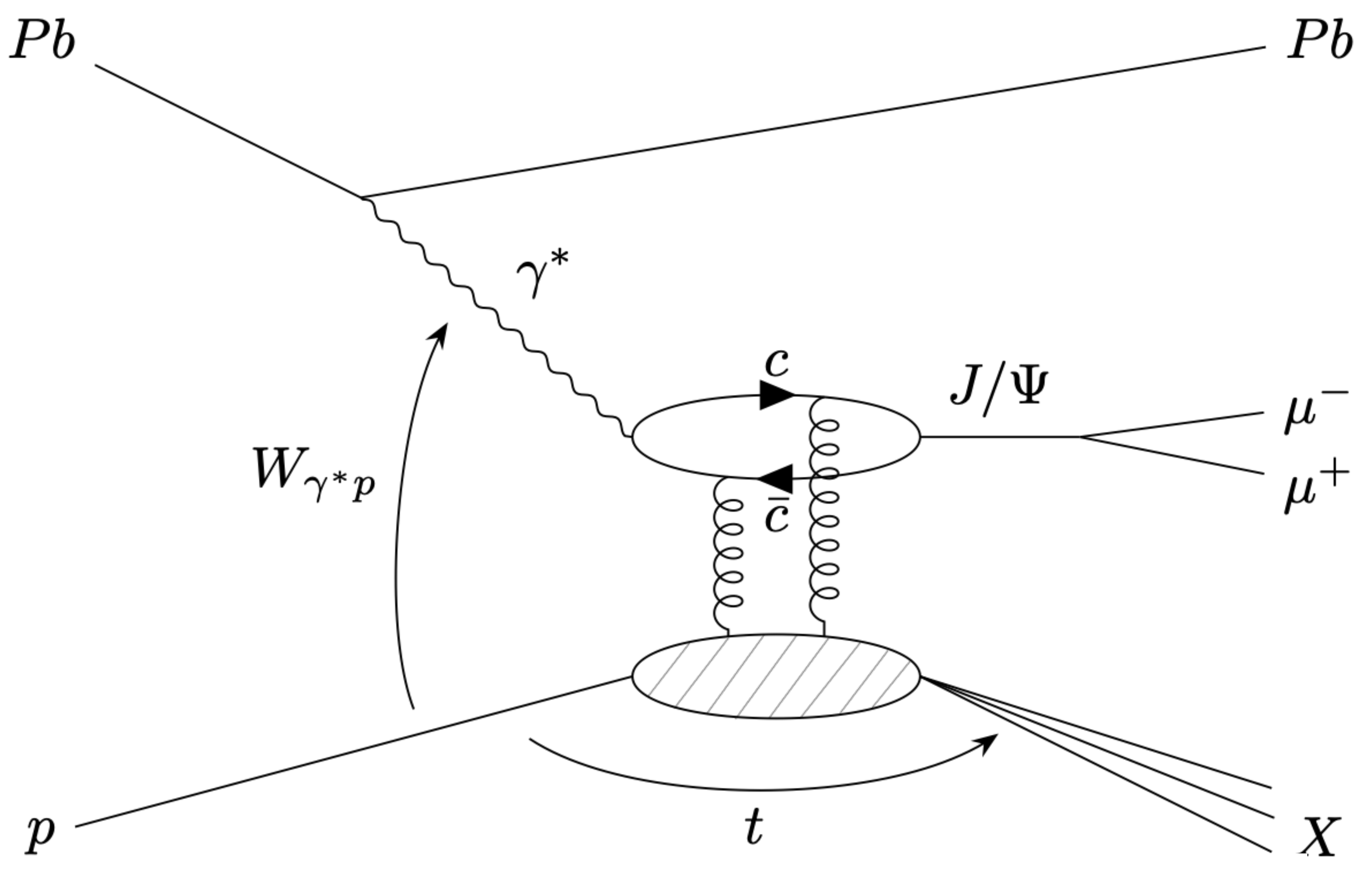
Inclusive J/ψ photoproduction

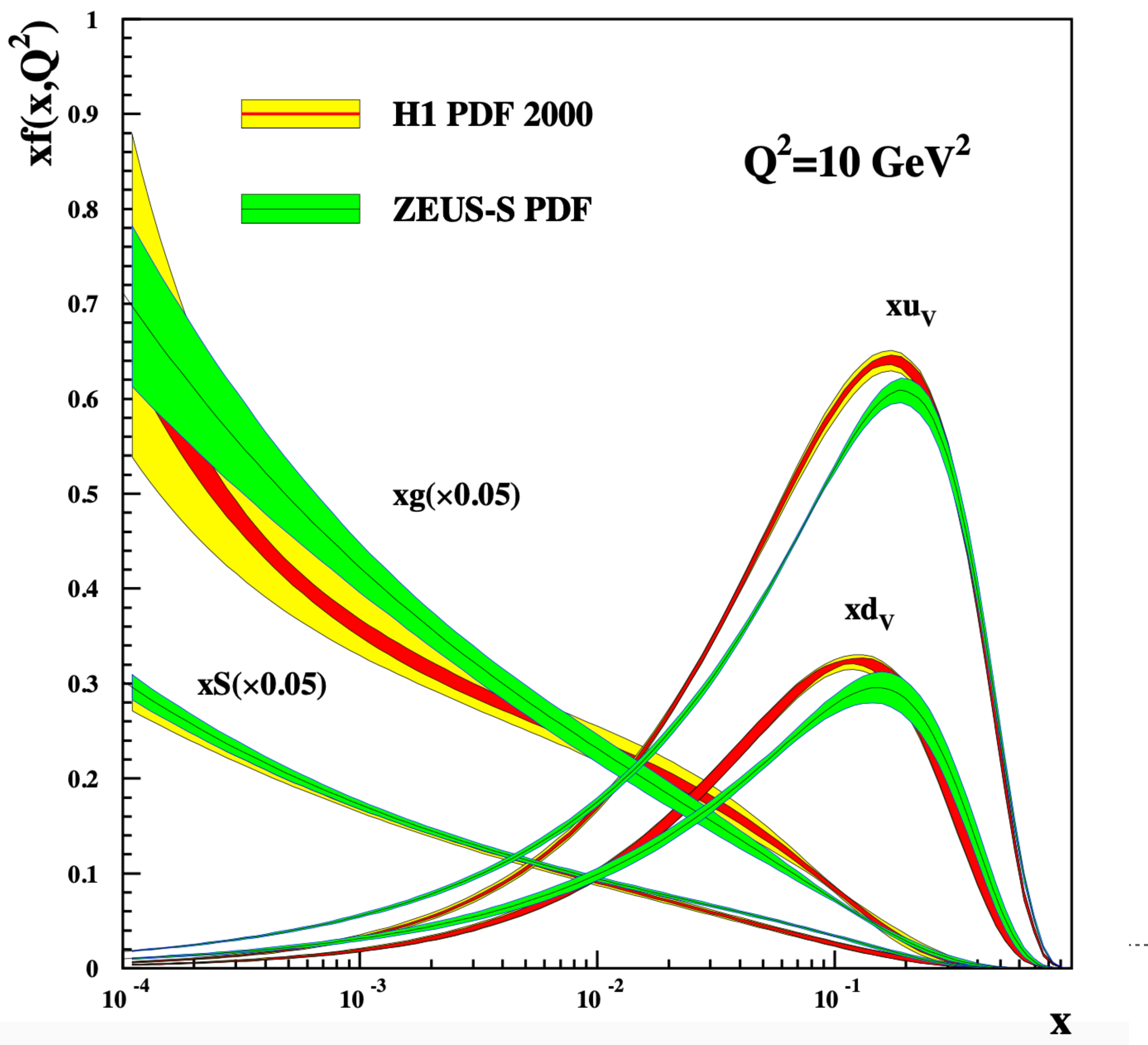
- In Good-Waker formalism (Heikki Mäntysaari 2020 Rep. Prog. Phys. 83 082201), initial and final states are required to be different

$$\frac{d\sigma^{\gamma^* p\to J/\Psi\ X}}{dt} \propto \sum_i \sum_{f\neq i} |\langle f|A|i\rangle|^2 = \sum_i \sum_f \langle i|A^*|f\rangle\langle f|A|i\rangle - \sum_i \langle i|A^*|i\rangle\langle i|A|i\rangle$$
$$= \sum_i \langle i|A^*A|i\rangle - \sum_i |\langle i|A|i\rangle|^2$$
$$= \langle|A^{\gamma^* p\to J/\Psi\ p}|^2\rangle - |\langle A^{\gamma^* p\to J/\Psi\ p}\rangle|^2$$

Physically: we measure the fluctuations of the configurations of the proton

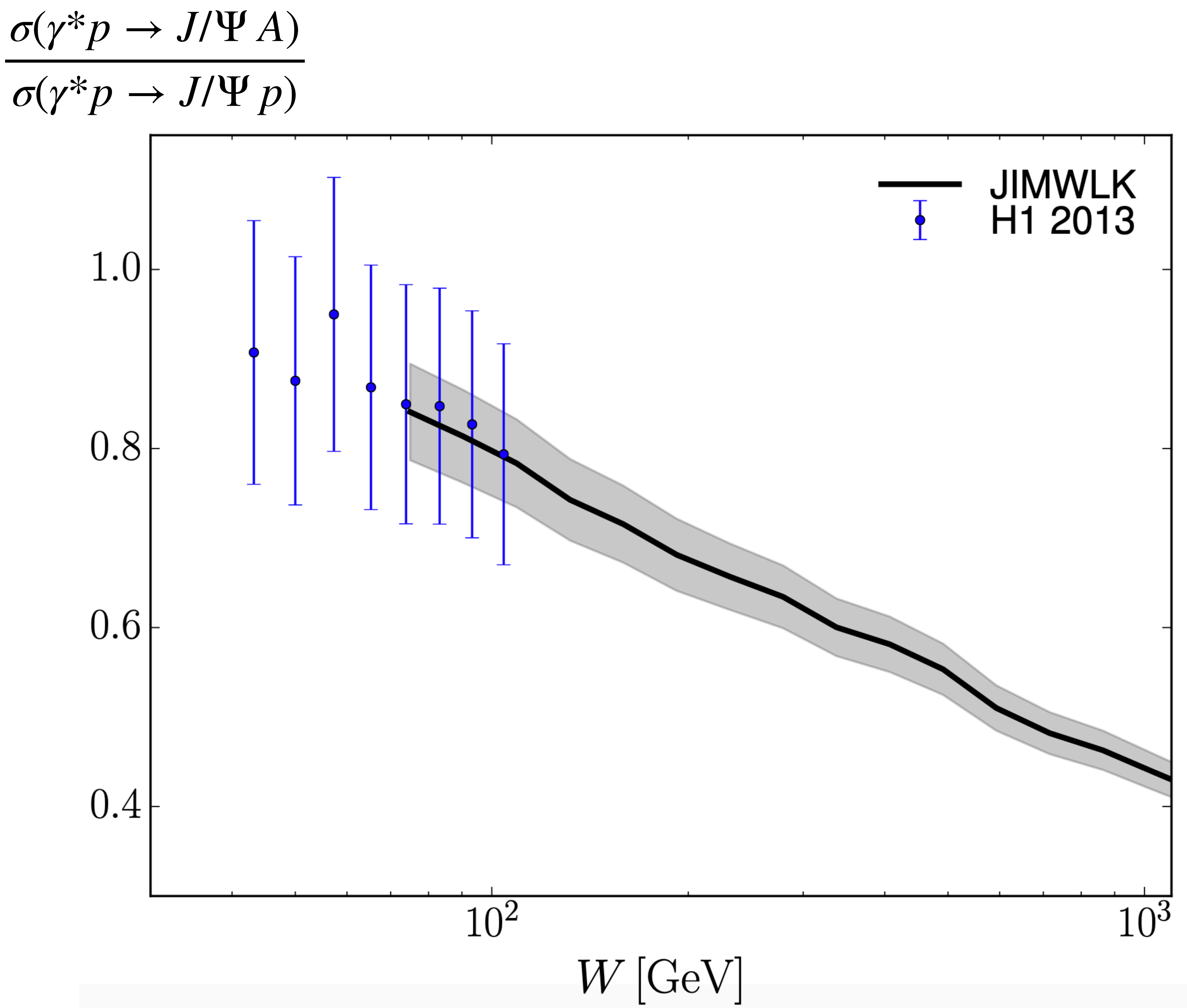
- The parton density increases with decreasing momentum fraction x
  - Saturation at low x?





Saturation

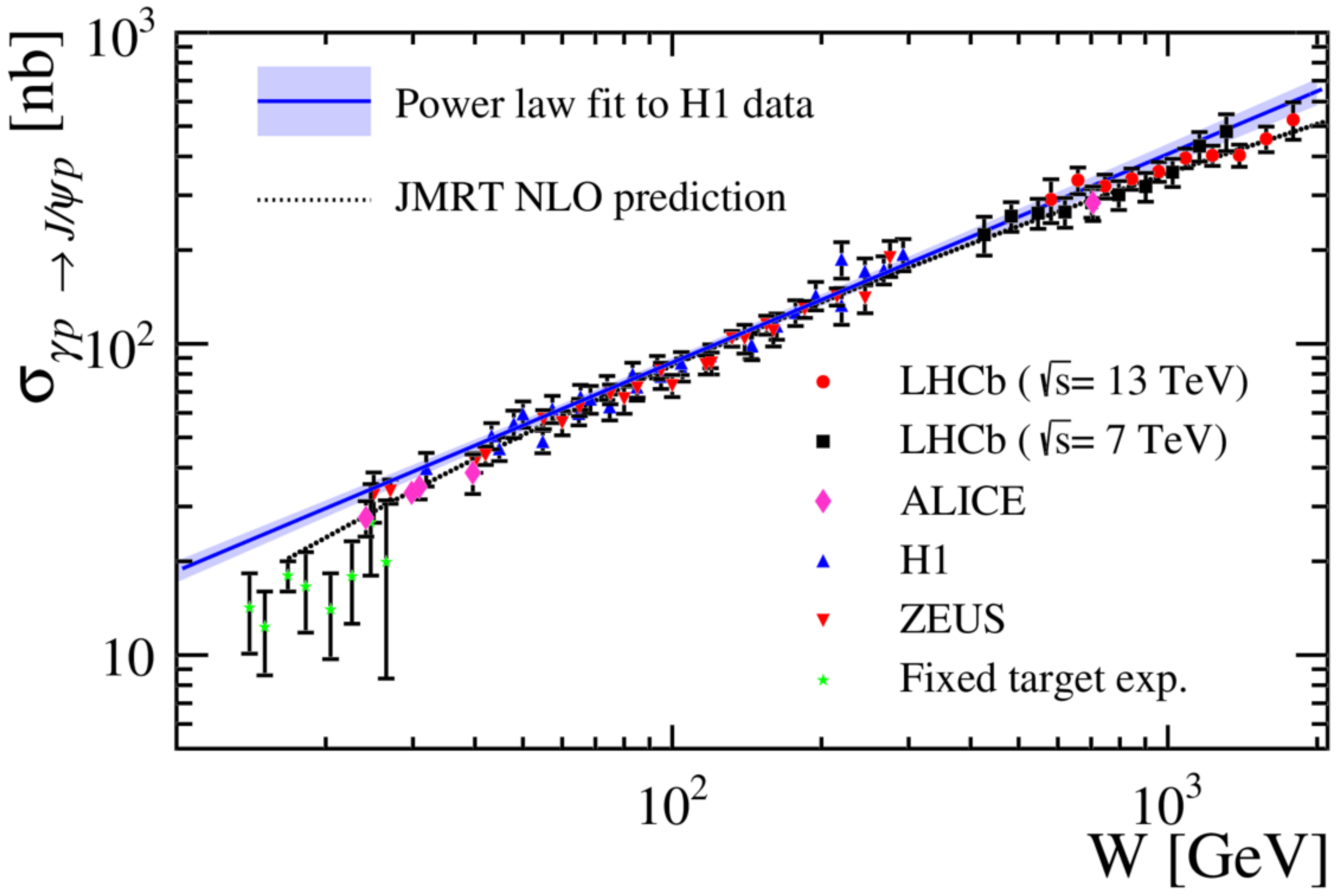
- Black disk limit: area where the number of gluons stops increasing, fluctuations of the proton configurations are suppressed
- When the gluon occupation number is large enough, there are important non–linear effects. These non–linearities can manifest themselves both as
  - gluon recombination (compensates gluon radiation)
  - or as multiple interactions with an external projectile



source : Heikki Mäntysaari 2020 Rep. Prog. Phys. 83 082201

ref: L.V. Gribov, E.M. Levin, and M.G. Ryskin, Phys. Rept. 100 (1983) 1.

Looking for gluon saturation at LHC: previous measurements

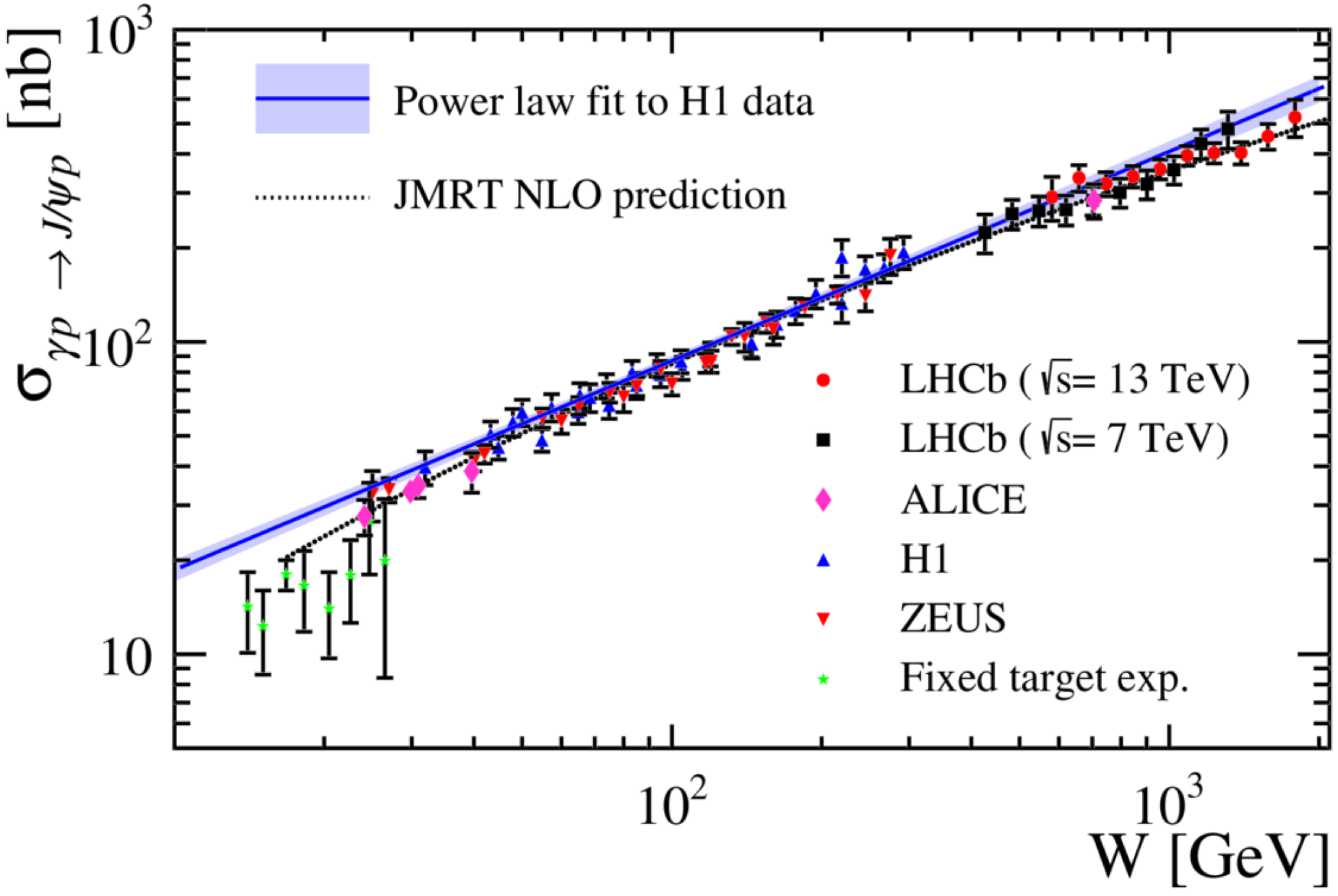


- Power-law fit $\sigma \sim W^{\delta}_{\gamma^* p}$
- Fit to ALICE data (Run 1) alone: δ = 0.68 ± 0.06 → no deviation from a power law is observed up to about 700 GeV

(ZEUS: δ = 0.69 ± 0.02 (stat) ± 0.03 (syst), H1: δ = 0.67 ± 0.03 (stat + syst))

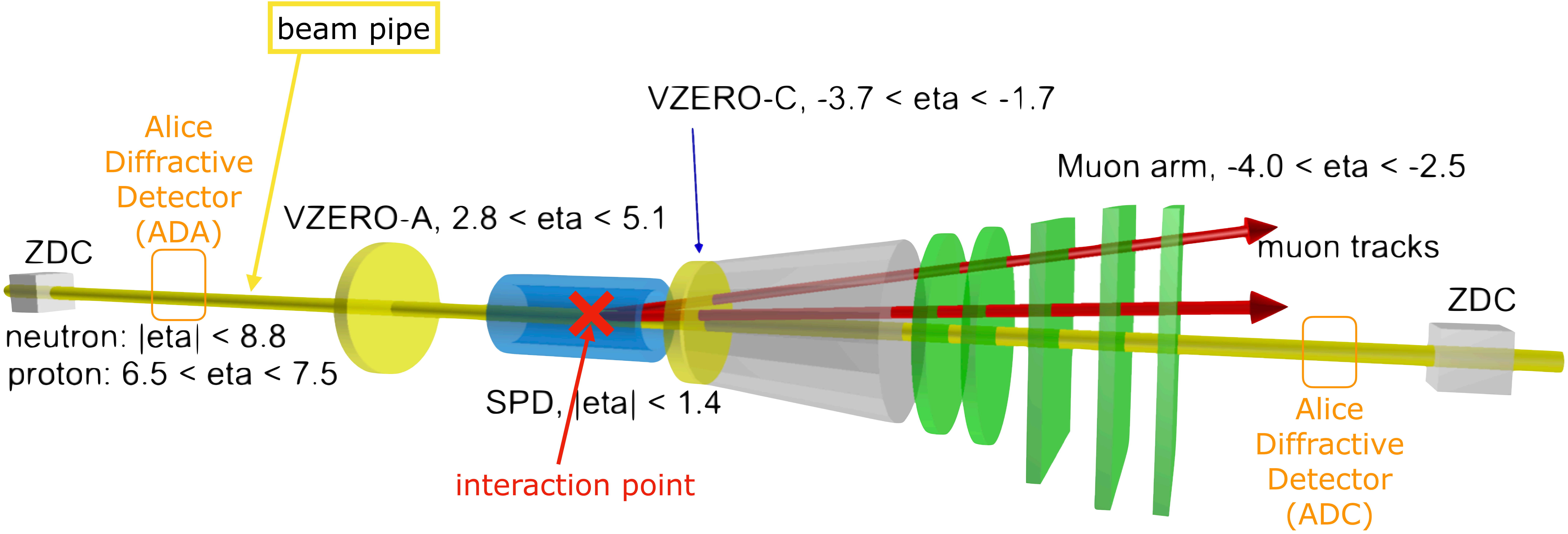
- LHCb studied the same process in p-p collisions (symmetric system : photon emitter identified via HERA data)
- HERA: H1 and ZEUS have measured the cross section of J/ψ photoproduction at energies $W_{\gamma^* p}$ from 20 to 305 GeV
- No change in the behavior of the gluon PDF in the proton is observed between HERA and LHC energies

So what’s new?



- In this analysis (2016 data), the CM energy in the p-Pb system is $\sqrt{s}$ = 8.16 TeV (5 TeV in 2013), allowing to reach up to $W_{\gamma^* p}$ = 1500 GeV
- Luminosity went from 3.9 nb^{-1} in p-Pb (4.5 nb^{-1} in Pb-p) in 2013 to 7.6 nb^{-1} in p-Pb (11.9 nb^{-1} in Pb-p) in 2016
- Inclusive J/ψ contribution in UPCs has not been studied in ALICE yet
- Different kinematic regime: $x \sim 8 \times 10^{-6}$ ($x \sim 4 \times 10^{-5}$ with 2013 data, gluon PDFs probed at $x \sim 10^{-4}$ at HERA)

Selection of data

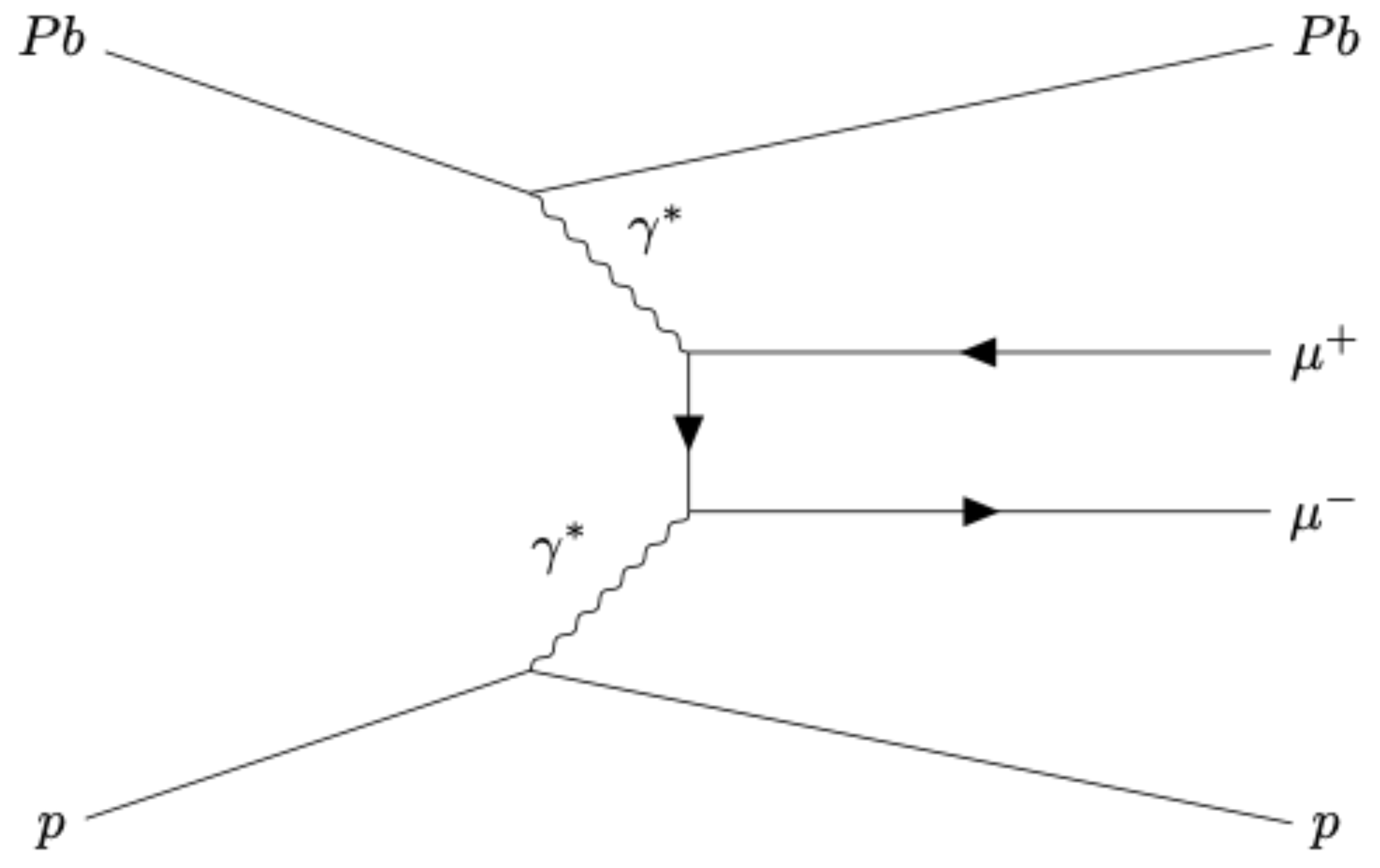


- ZDC = Zero Degree Calorimeter
- SPD = Silicon Pixel Detector
- VZERO = scintillator arrays

Signal reconstruction

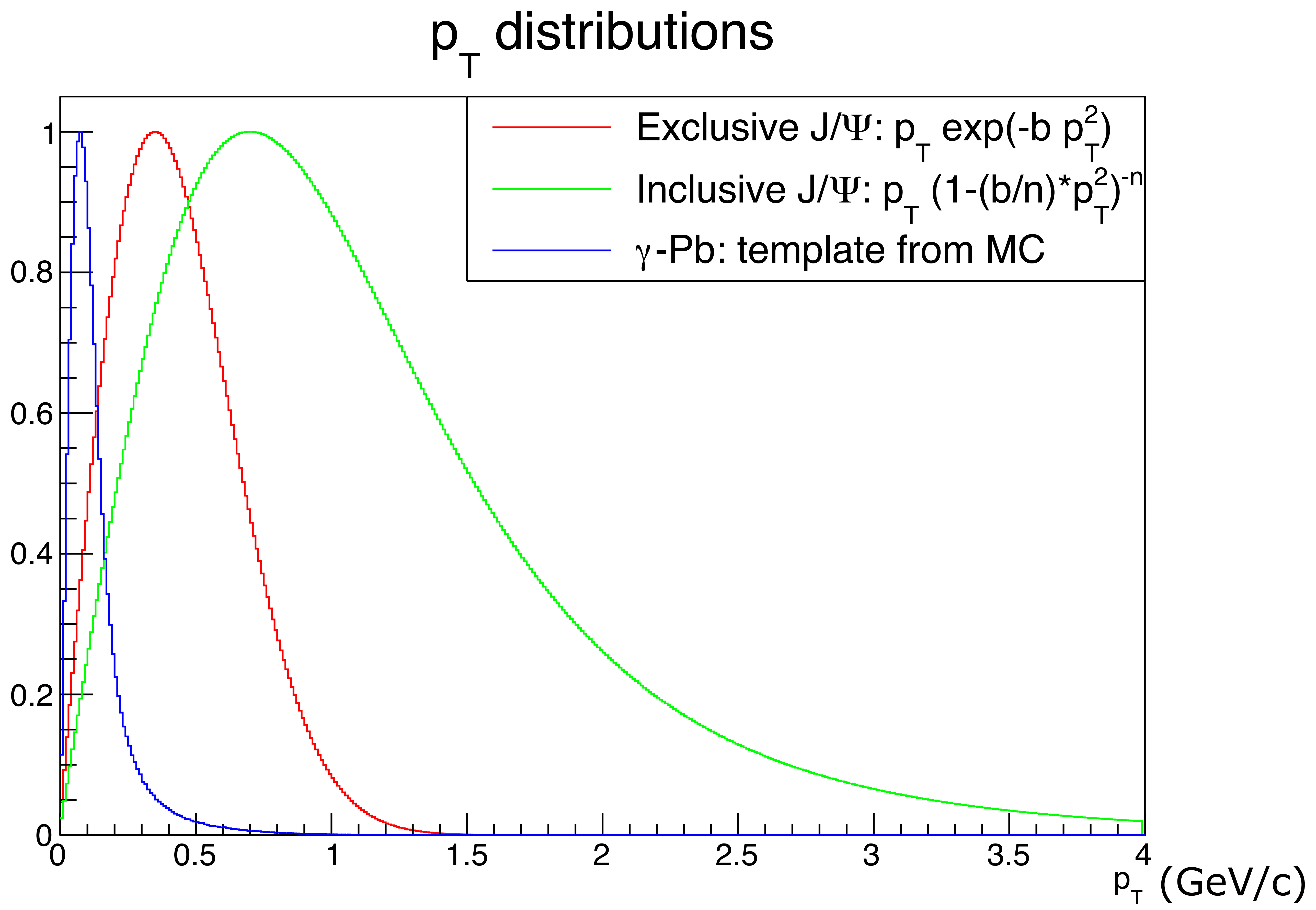
- Signal reconstructed from dimuon pairs
- Mass fit with a Crystal Ball ($J/\Psi \to \mu^-\mu^+$) and an exponential function (dimuon continuum, $\gamma\gamma \to \mu^-\mu^+$)

dimuon continuum:



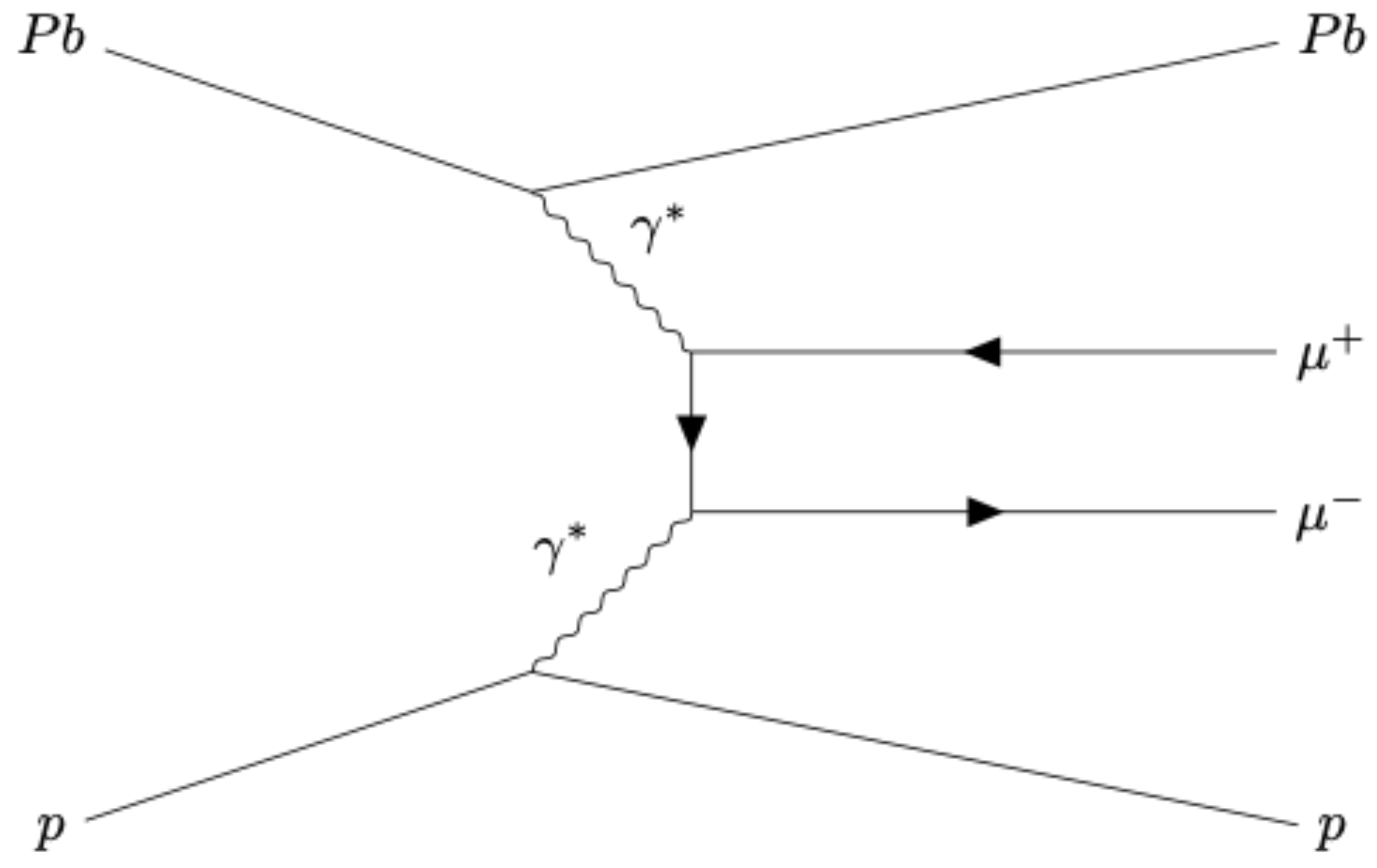
Different contributions in J/ψ peak

- The different contributions in the J/ψ peak can be discriminated because of their different p_T distribution



Dimuon continuum measurement

- First precise measurement of the exclusive $\gamma\gamma \rightarrow \mu\mu$ in ALICE
- Measurement in the invariant mass range 1.0 GeV/ $c^2 < M_{\mu\mu} < 2.5$ GeV/c^2, where J/ψs are absent.
- A high precision measurement of this process serves the purpose of fixing the rates of other UPC processes
- Might also improve the predictions for e.g. light-by-light scattering
- In future works, the feasibility of time-like-Compton scattering could be investigated as well



Summary and outlook

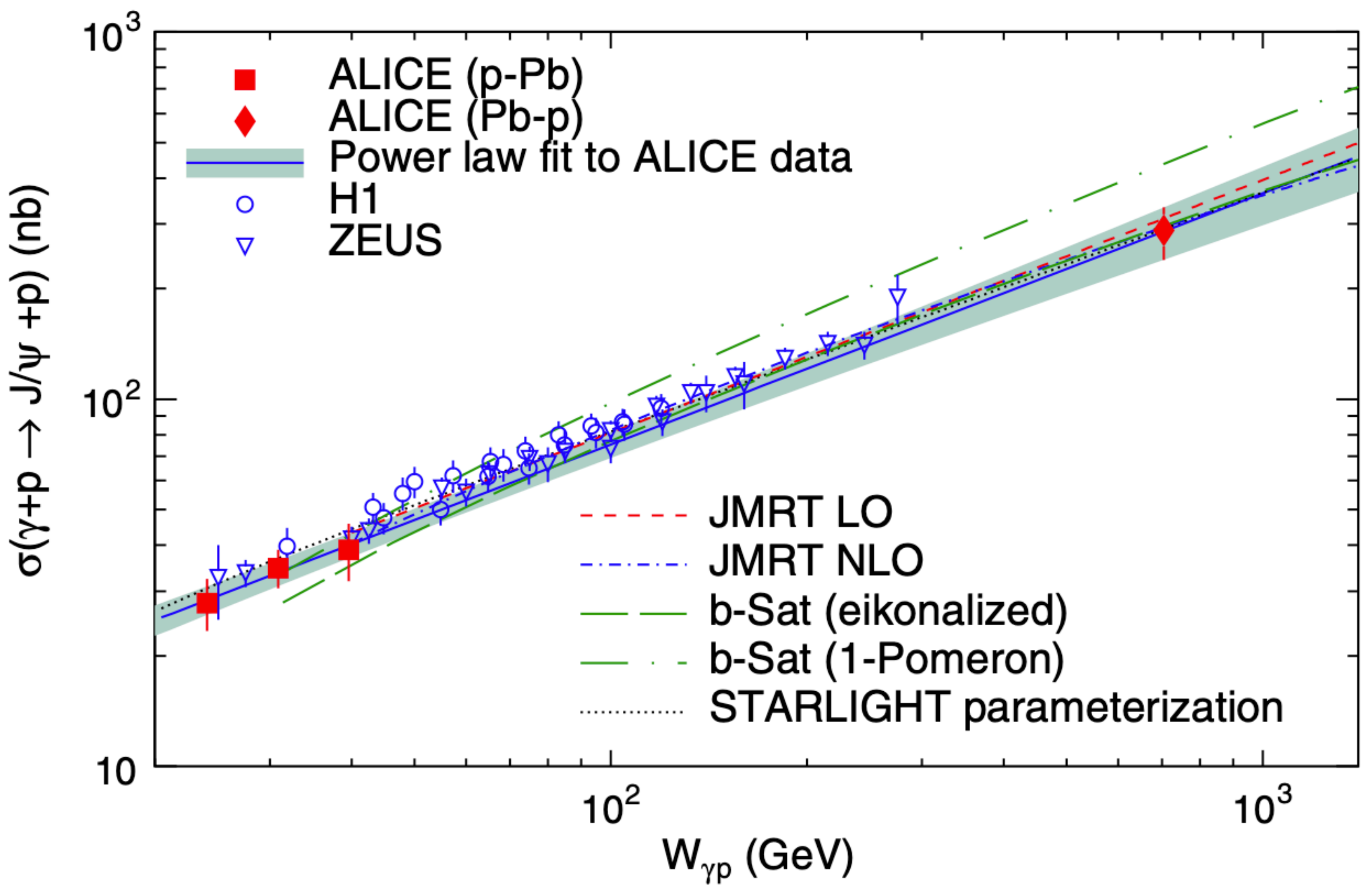
- HERA unveiled the structure of the proton down to x ~ 10^{-4}
- Non-linear effects could be seen in protons for smaller x (saturation)
- In ALICE p-Pb data in Run 1:
  - saturation has not been found, will it be visible in Run 2 data?
- ALICE p-Pb data in Run 2:
  - luminosity increased from 3.9 nb-1 in p-Pb (4.5 nb^{-1} in Pb-p) in 2013 to 7.6 nb^{-1} in p-Pb (11.9 nb^{-1} in Pb-p) in 2016
  - increased energy $W_{\gamma^* p}$ ~ 1500 GeV (~ 900 GeV in 2013), corresponding to x ~ 8 × 10^{-6} (x ~ 3 × 10^{-5} in 2013)
  - ongoing analysis

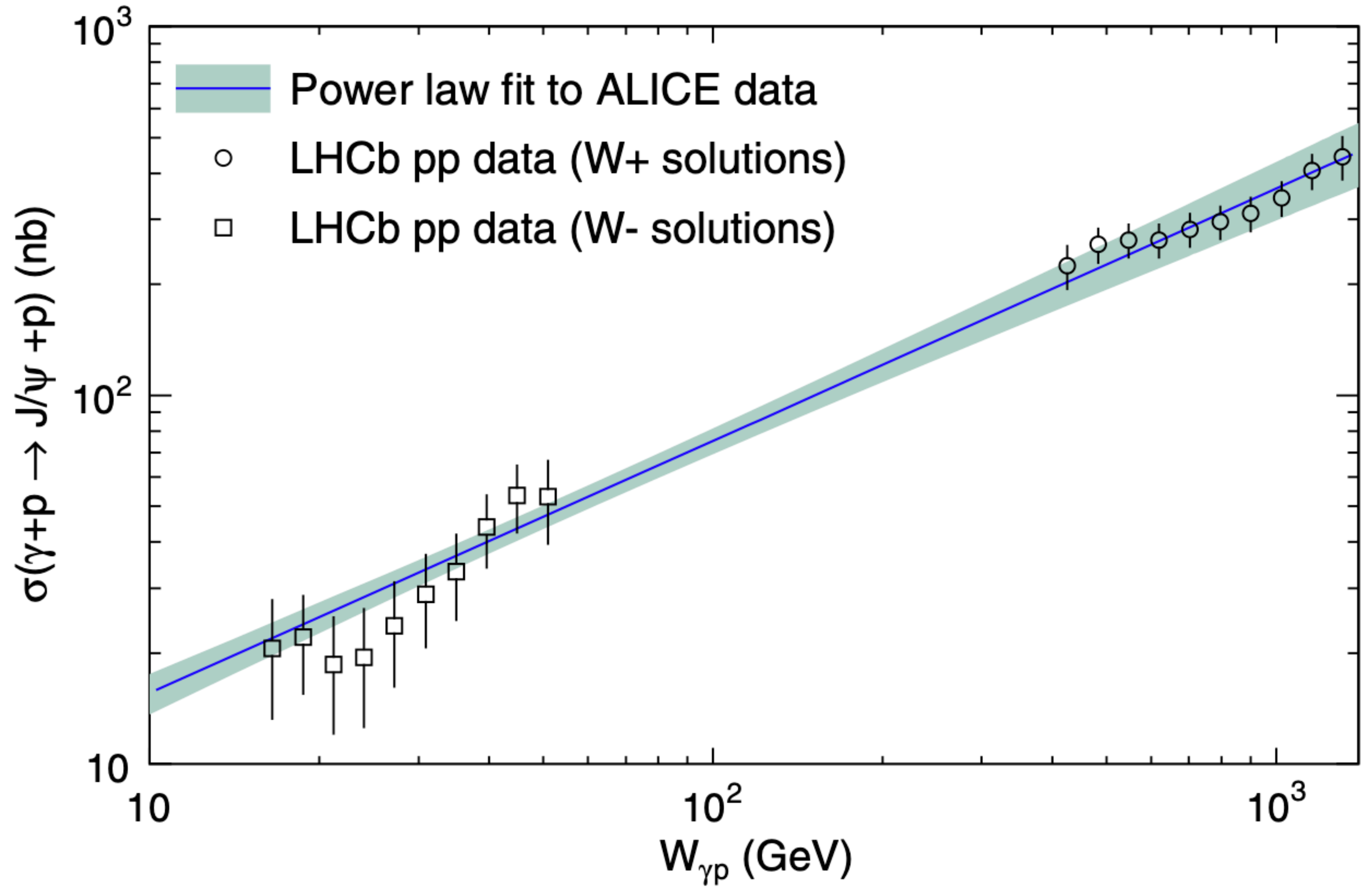
Thank you for your attention!

Back up ALICE

Has this measurement been done before?

- HERA: H1 and ZEUS have measured the cross section of J/ψ photoproduction at energies $W_{\gamma^* p}$ from 20 to 305 GeV
  - Results are inconclusive regarding the question of gluon saturation: data can be described with or without it
- @LHC, LHCb studied the same process in p-p collisions (symmetric system : impossible to identify the photon emitter)
- @LHC, ALICE studied this in 2013 in p-Pb collisions for $W_{\gamma^* p}$ up to 700 GeV





from PRL 113 (2014), 232504

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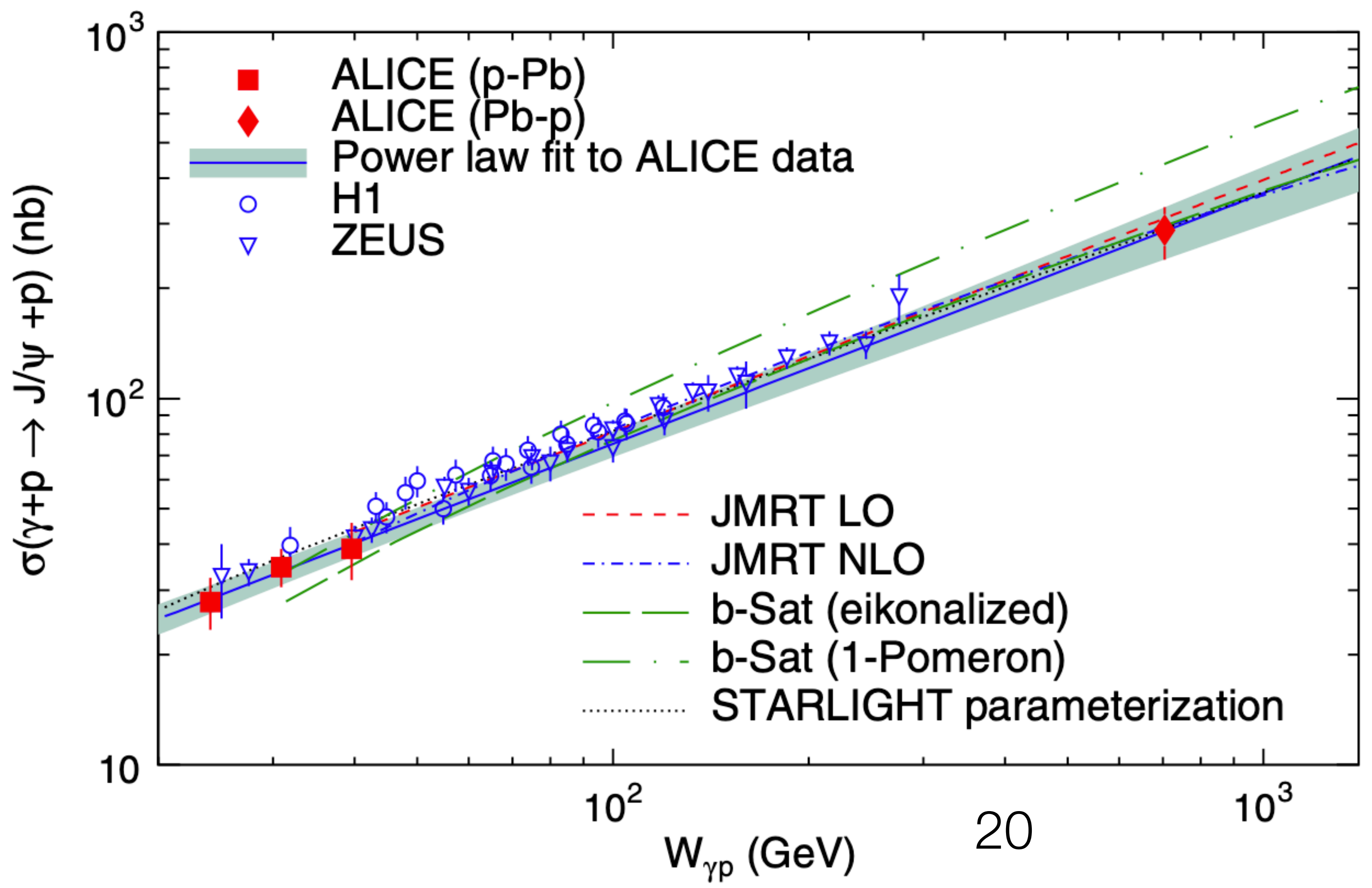
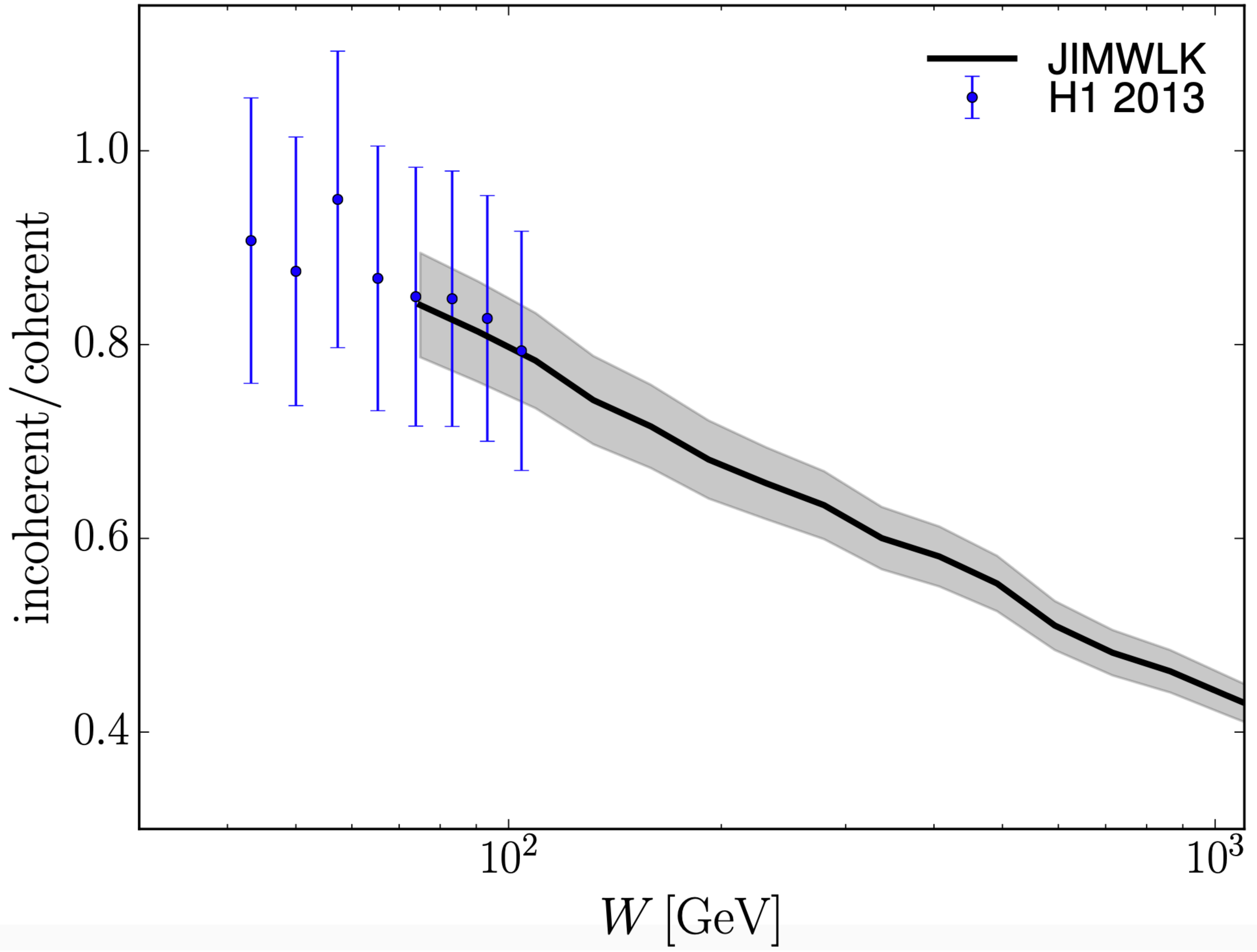


JIMWLK equation

- Development of a new approach to high–energy evolution in QCD, which is genuinely non–linear, and which culminated in the effective theory for the Color Glass Condensate (CGC). This new approach consists in a Wilsonian renormalization group analysis in which gluons are integrated out in layers of longitudinal momenta and in the presence of the strong color fields radiated by the gluons integrated out in the previous steps. The emission of new quantum gluons at each evolution step modifies the sources for the classical fields, and the non–linear effects induced by the latter provide the necessary feedback from the high–density environment on the evolution. **The central result of this analysis is a functional evolution equation, the JIMWLK equation, which describes the simultaneous evolution of all the n–point correlation functions of the classical fields (which mix with each under evolution because of the non–linear effects)**.
- In the limit where the classical fields are weak, which corresponds to relatively low energies, the non–linear effects can be neglected and then the JIMWLK equation reduces to the BFKL evolution.



source : arXiv:2001.10705v1

H.M, B. Schenke, 1806.06783

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