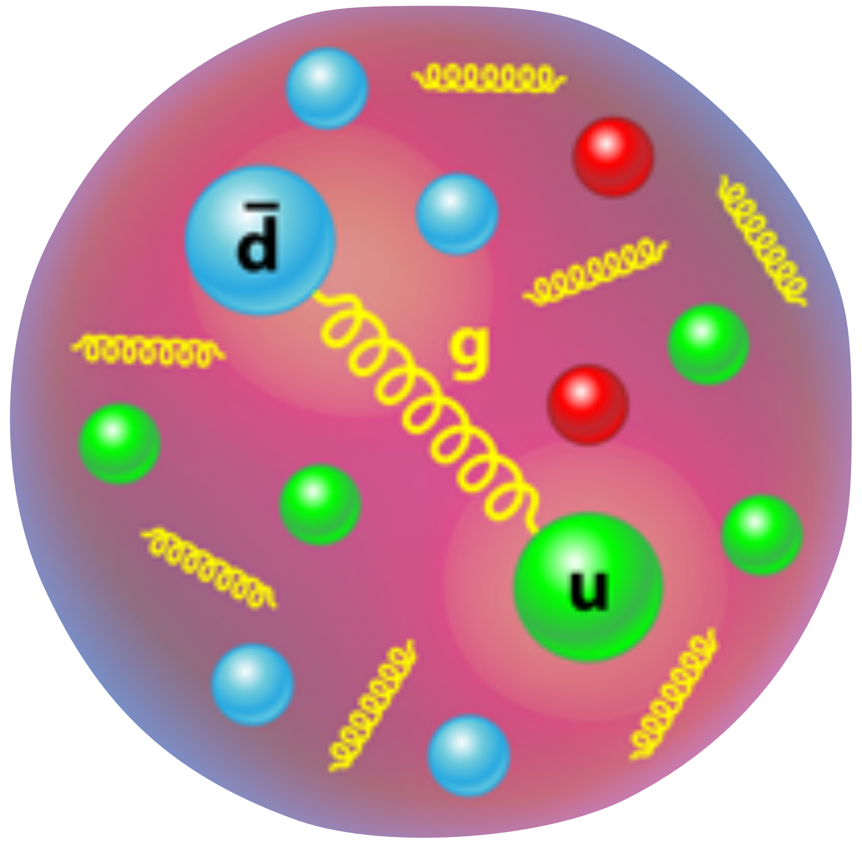


UPC measurements with ALICE

Aude Glaenzer - DPhN / IRFU / CEA-Saclay
supervised by F. Bossu and M. Winn

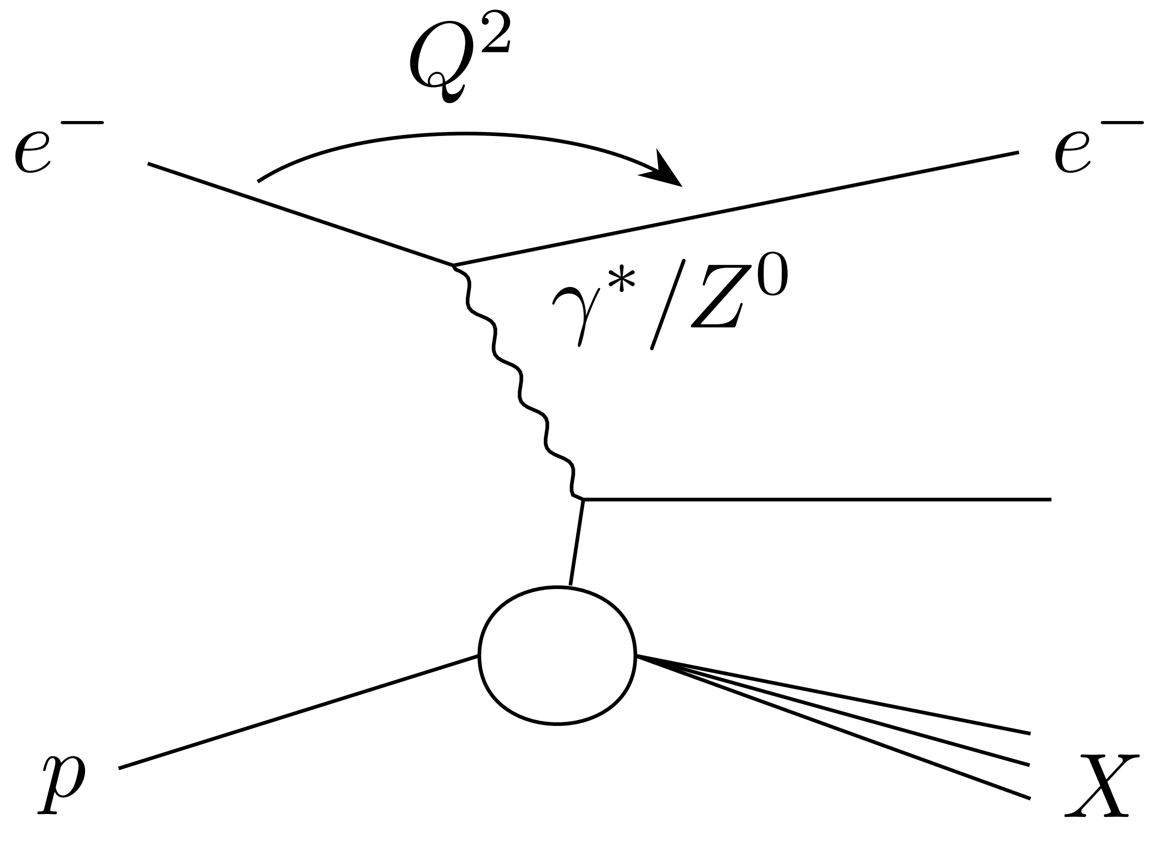
DIS at HERA

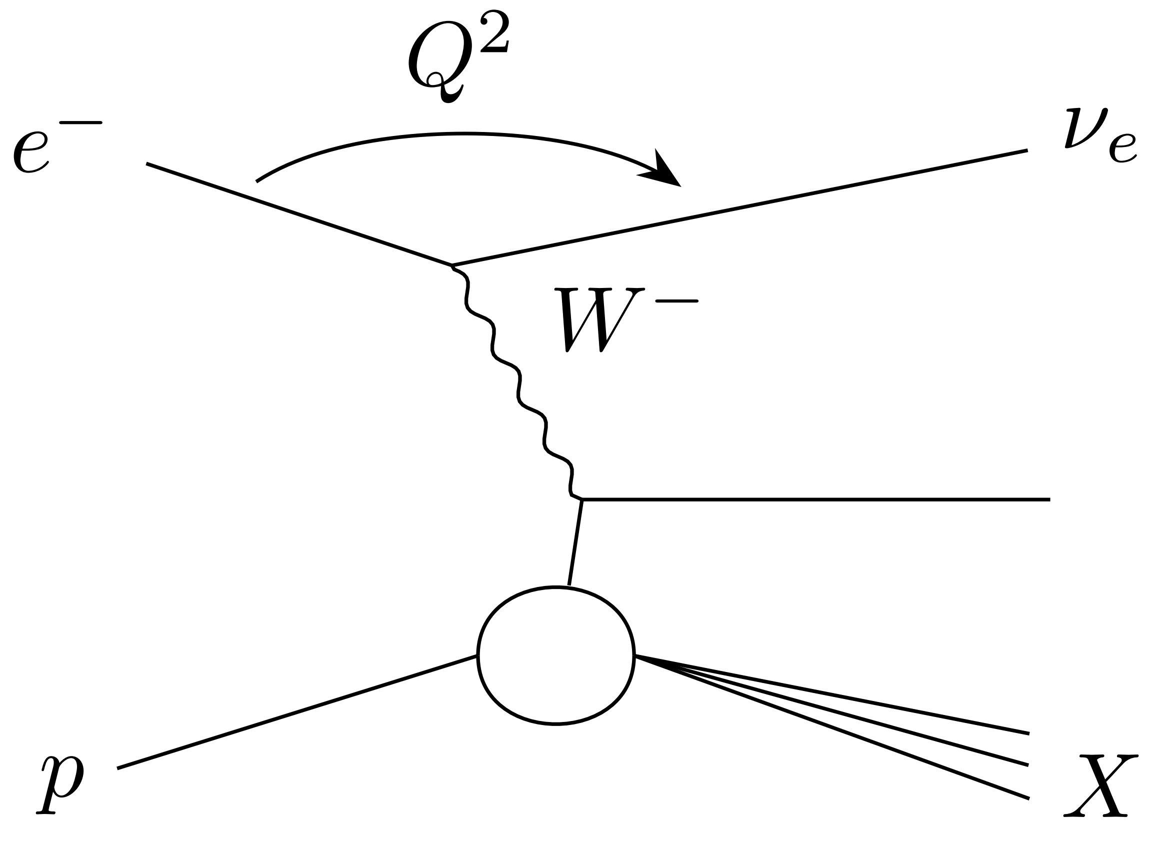
- HERA (Hadron Elektron Ring Anlage) ep collider operated in the years 1992-2007 with center-of-mass energies $\sqrt{s}$ = 225 - 318 GeV
  - HERA I: unpolarized beams
  - HERA II: longitudinally polarised electrons around the interaction points of H1 and ZEUS 4 data sets: $e_R^- p$, $e_L^- p$, $e_R^+ p$, $e_L^+ p$

- DIS: Neutral Current (NC) $ep \to eX$

- DIS: Charged current (CC) $ep \to \nu X$

At LO:





$$\frac{d^2\sigma^\pm_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\tilde{F}_2^\pm \mp Y\_x\tilde{F}_3^\pm - y^2\tilde{F}_L^\pm)$$

$$\frac{d^2\sigma^\pm_{CC}}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)(Y_+W_2^\pm \mp Y\_xW_3^\pm - y^2W_L^\pm)$$

+ data on lepton scattering off the deuteron to separate different quark flavors

Constrains on PDFs from the inclusive cross sections

dominant contribution to the cross section

important at high Q^2

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\boxed{\tilde{F}_2^{\pm}} \mp Y_-\boxed{x\tilde{F}_3^{\pm}} - y^2\boxed{\tilde{F}_L^{\pm}})$$

sizeable only at high y

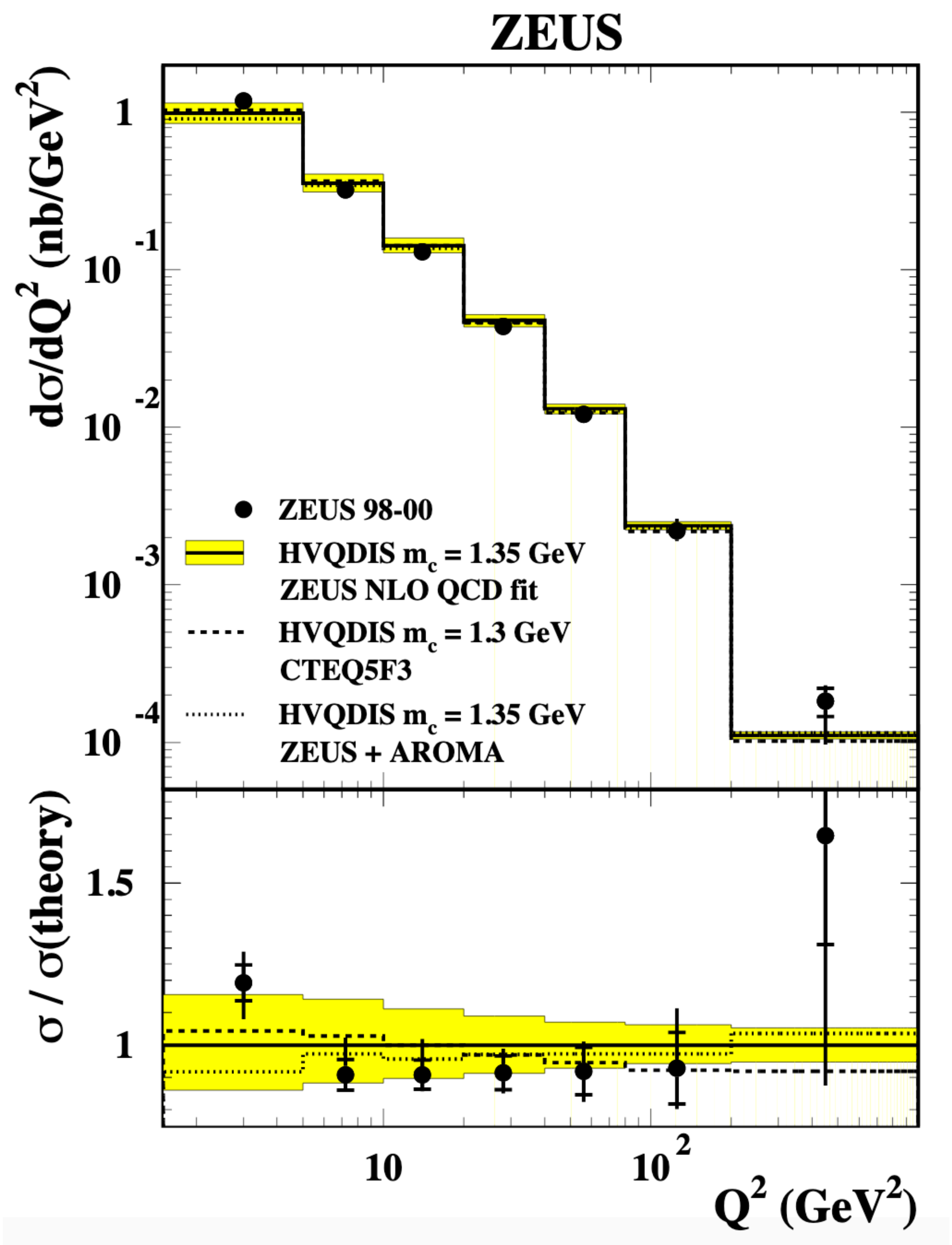
where $Y_{\pm} = 1 \pm (1-y)^2$, $y = \frac{Q^2}{xs}$ (inelasticity) and $\sqrt{s}$ is the center-of-mass energy

- $F_2 = x\sum e_q^2(q+\bar{q})$ for all orders of QCD in the DIS scheme + easily experimentally accessible
- F_2 → scaling violation → measurement of the gluon density

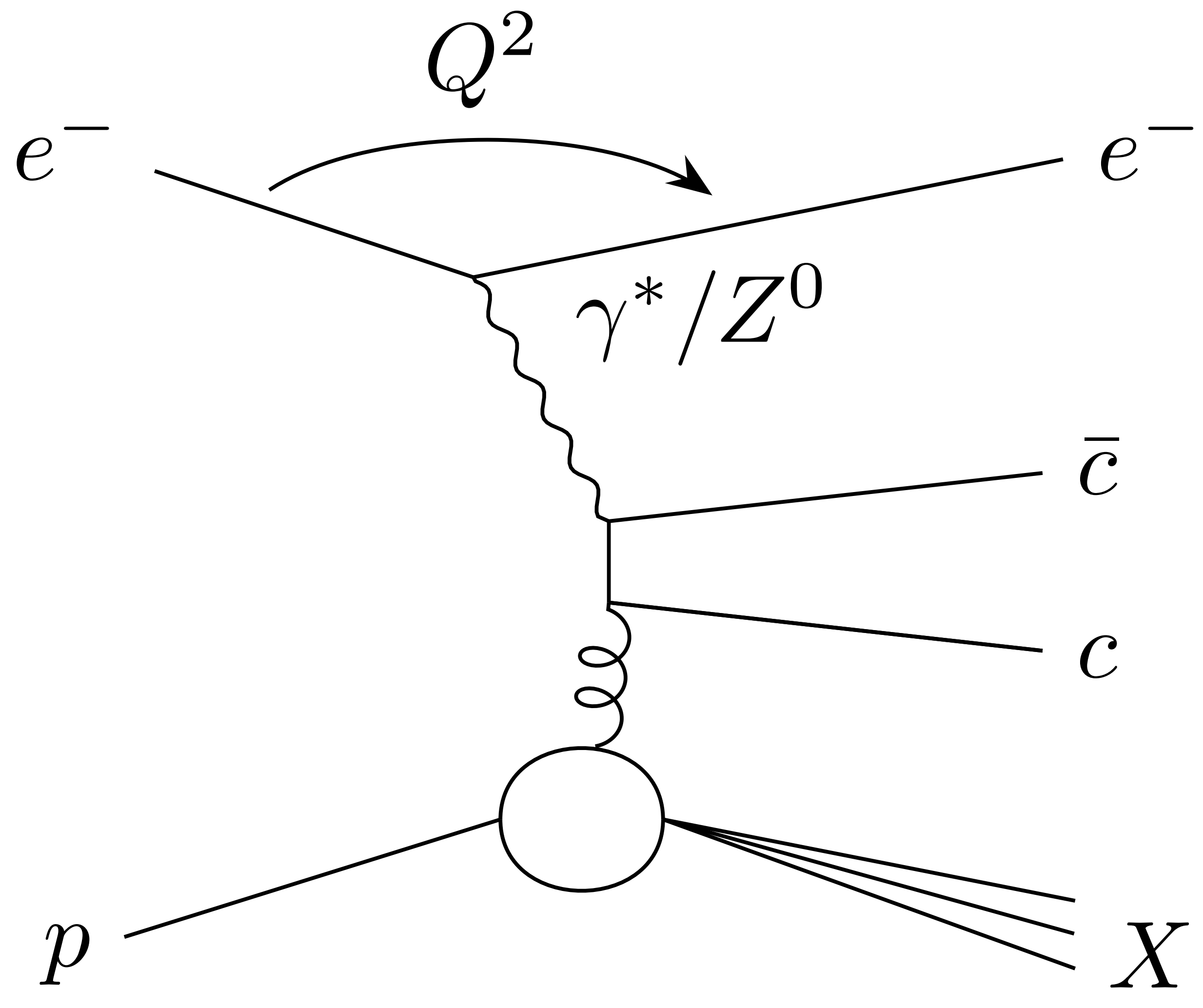
- In the quark parton model in LO, $xF_3 \approx x\sum 2e_q a_q(q-\bar{q})$ (a_e = axial-vector coupling of the quarks to the Z boson)
- xF_3 function measures the valence quark density which is expected to vanish at low x

- In the quark parton model in LO, $F_L \approx 0$ because of helicity conservation for spin 1/2 quarks
- For low x, F_L is mostly determined by the gluon density: in QCD, gluon-emission gives rise to non-vanishing F_L → tool to study gluon density and test pQCD

Charm photoproduction in DIS



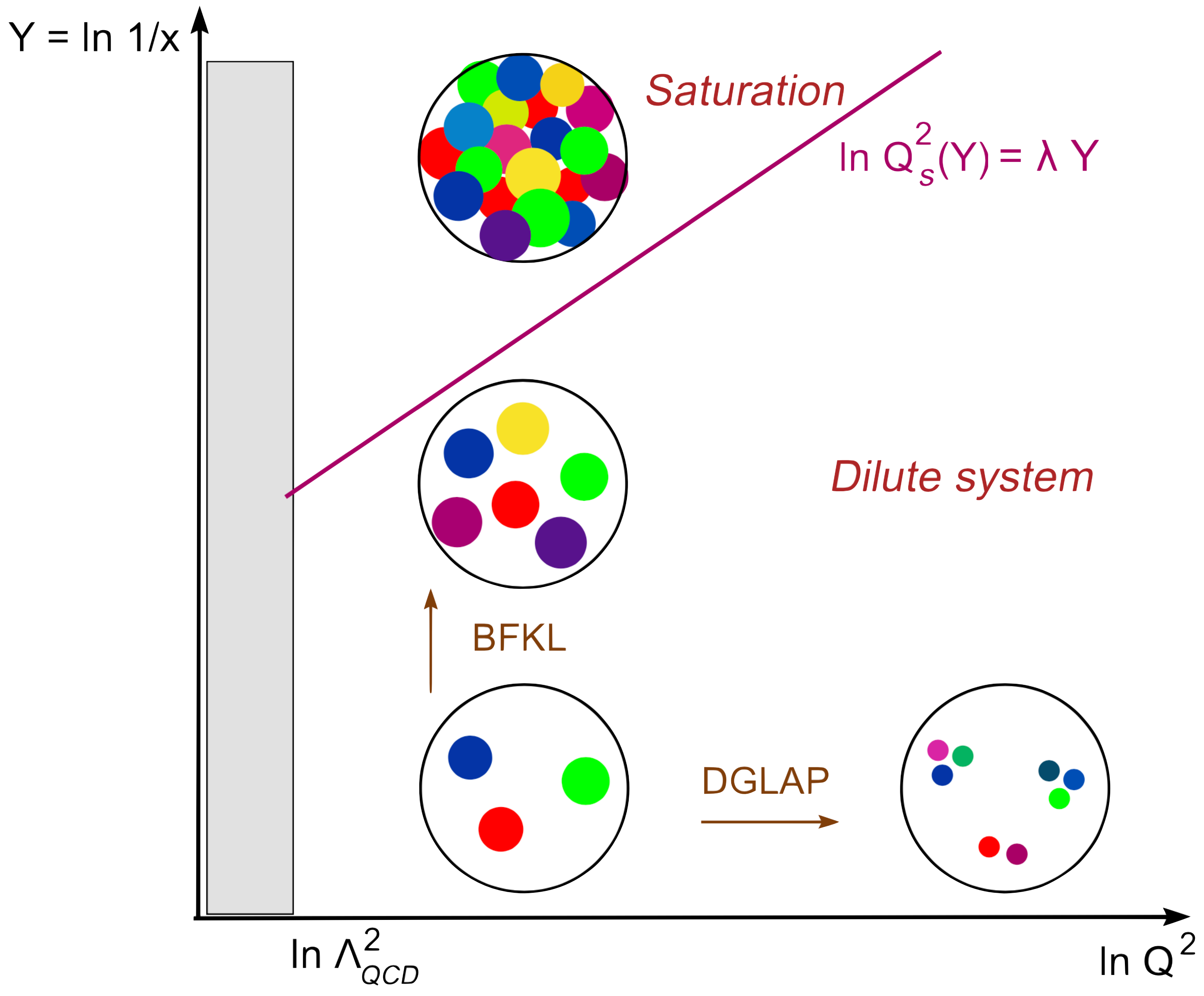
- $m_C > \Lambda_{QCD}$ → pQCD applicable
- Conventional QCD interpretation for $Q^2 \sim m_c^2$ is that charm is determined solely by the gluon density

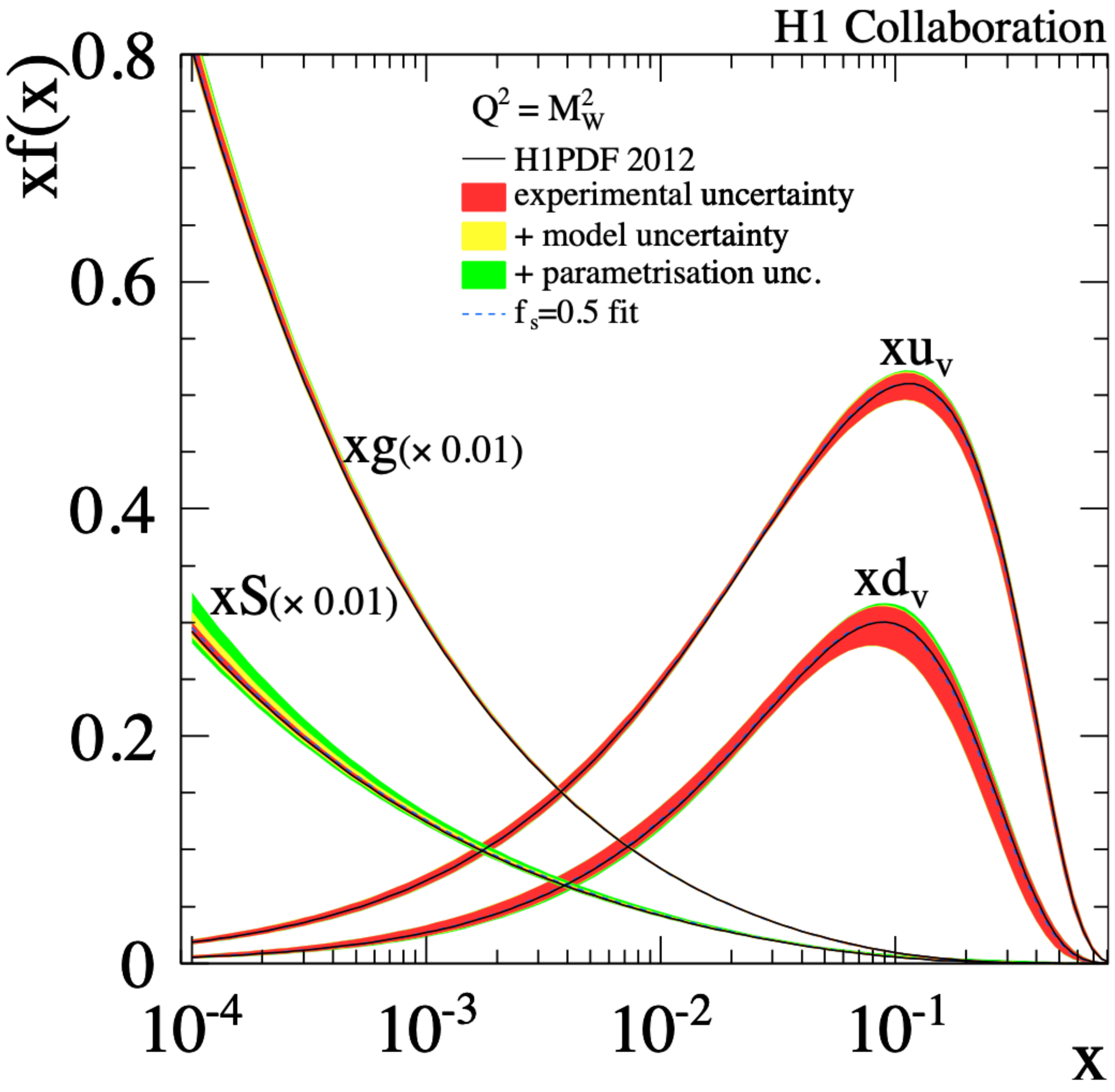


- Production of $D^{*\pm}$ mesons has been measured in DIS at HERA for 1.5 GeV^2 < Q^2 < 1000 GeV^2
- HERA charm and beauty data: constrain m_c, m_b and gluon at low x ($10^{-2} < x < 10^{-4}$)

PDF parametrization

- QCD predictions for the structure functions are obtained by solving the DGLAP evolution equations at NLO (or NNLO)
- Gluon and sea quark distributions rise quickly as their momentum fraction x drops. At small enough x, the growth of the proton parton densities may decrease proportionally with ln(1/x) (saturation at small Bjorken x?)





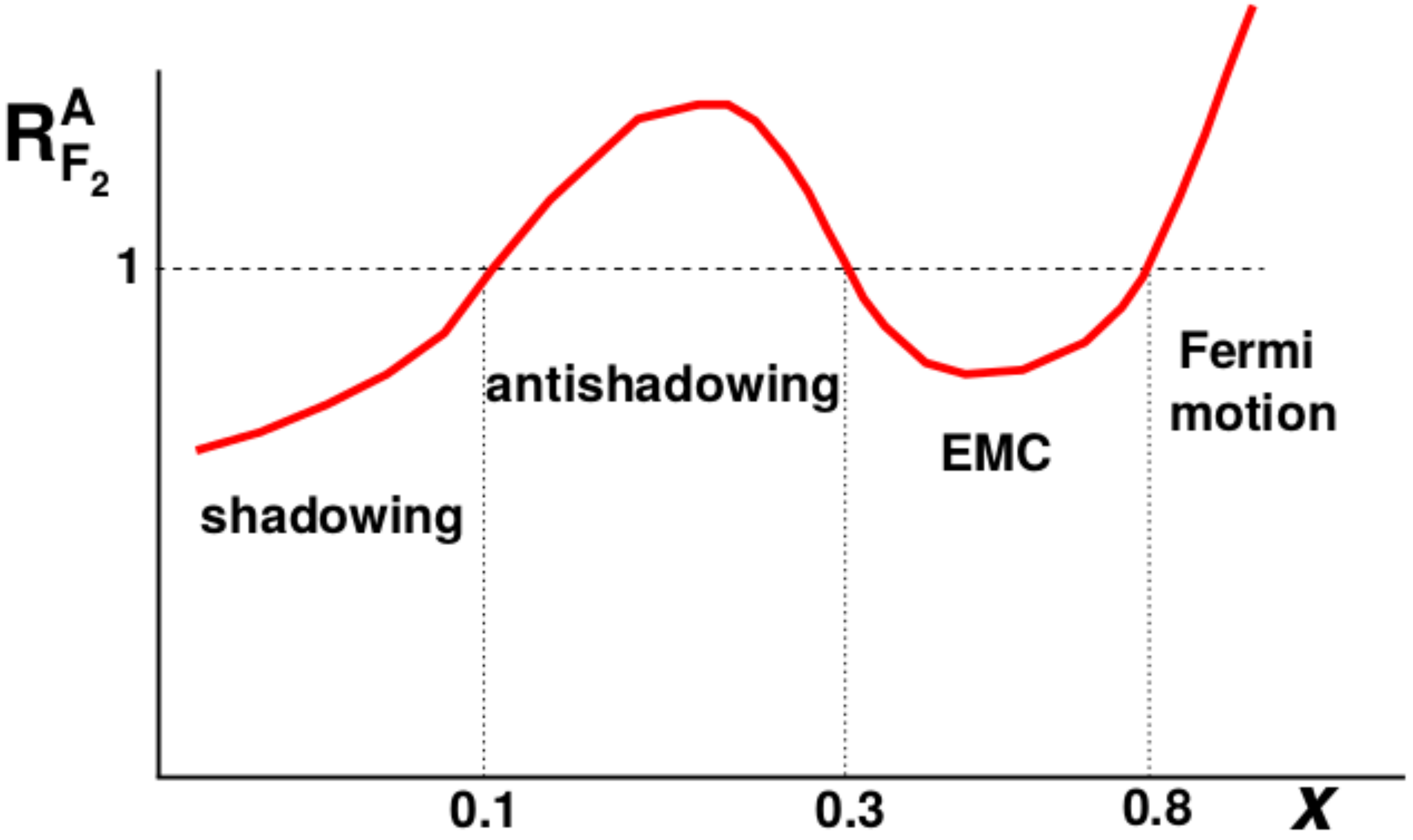
PoS ICHEP2012 (2013) 289 1302.1898 [hep-ex]

After HERA, LHC

- The proton is mainly occupied by gluons for Bjorken $x < 10^{-2}$.
- The increase of the parton densities might be regulated by non-linear effects for squared momentum transfer of the virtual photon of up to Q^2 ~ 4 GeV^2 at the smallest x values studied at HERA, $x \sim 10^{-4}$, such as recombination reactions, e.g.gg→g
- These phenomena are expected to be present already at higher scale in the nucleus.
- In heavy ions at small x, shadowing effects are expected to be observed
- At the LHC, these QCD phenomena should be visible in collisions of both protons and heavy ions.

Shadowing

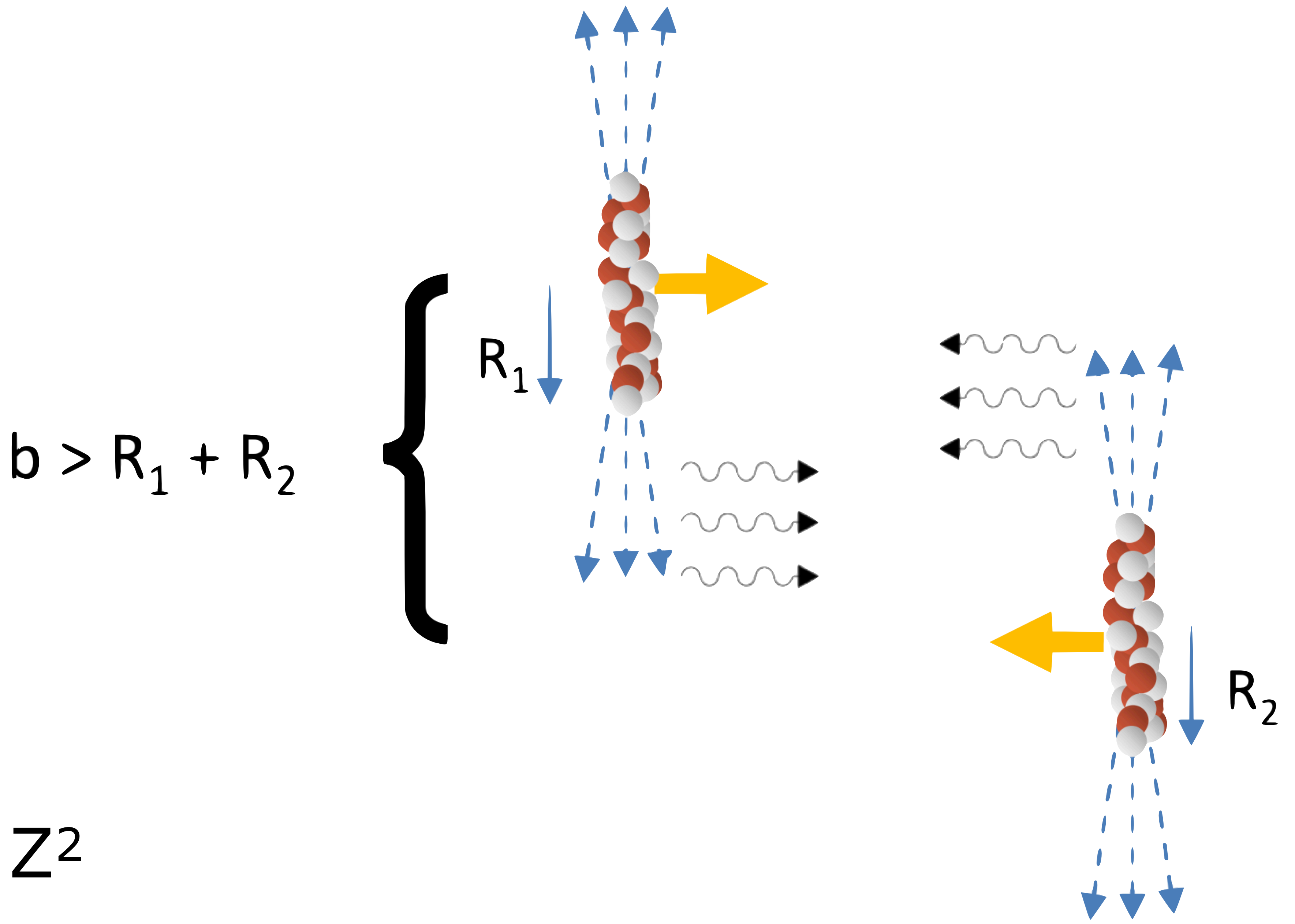
- Nuclear structure functions in nuclei are different from the superposition of those of their constituents nucleons
- The nuclear ratio is defined as the nuclear structure function per nucleon divided by the nucleon structure function $R^A_{F_2}(x,Q^2) = \dfrac{F^A_2(x,Q^2)}{AF^{nucleon}_2(x,Q^2)}$



- For low x values, it implies that the $\gamma*$-nuclei interaction cross section is lower than what one would have expected from scaled up $\gamma*$-nucleon interaction cross section.
- Shadowing effect can be seen as 'multiple scattering' of hadronic components of the virtual photon (arXiv:hep-ph/0604108v2)
- Can be studied in ultra-peripheral collisions at the LHC

What is a UPC = Ultra Peripheral Collision?

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



- The intensity of the photon beam is proportional to Z^2
- In p-Pb UPC, lead-ion is most likely (~95%) the photon source

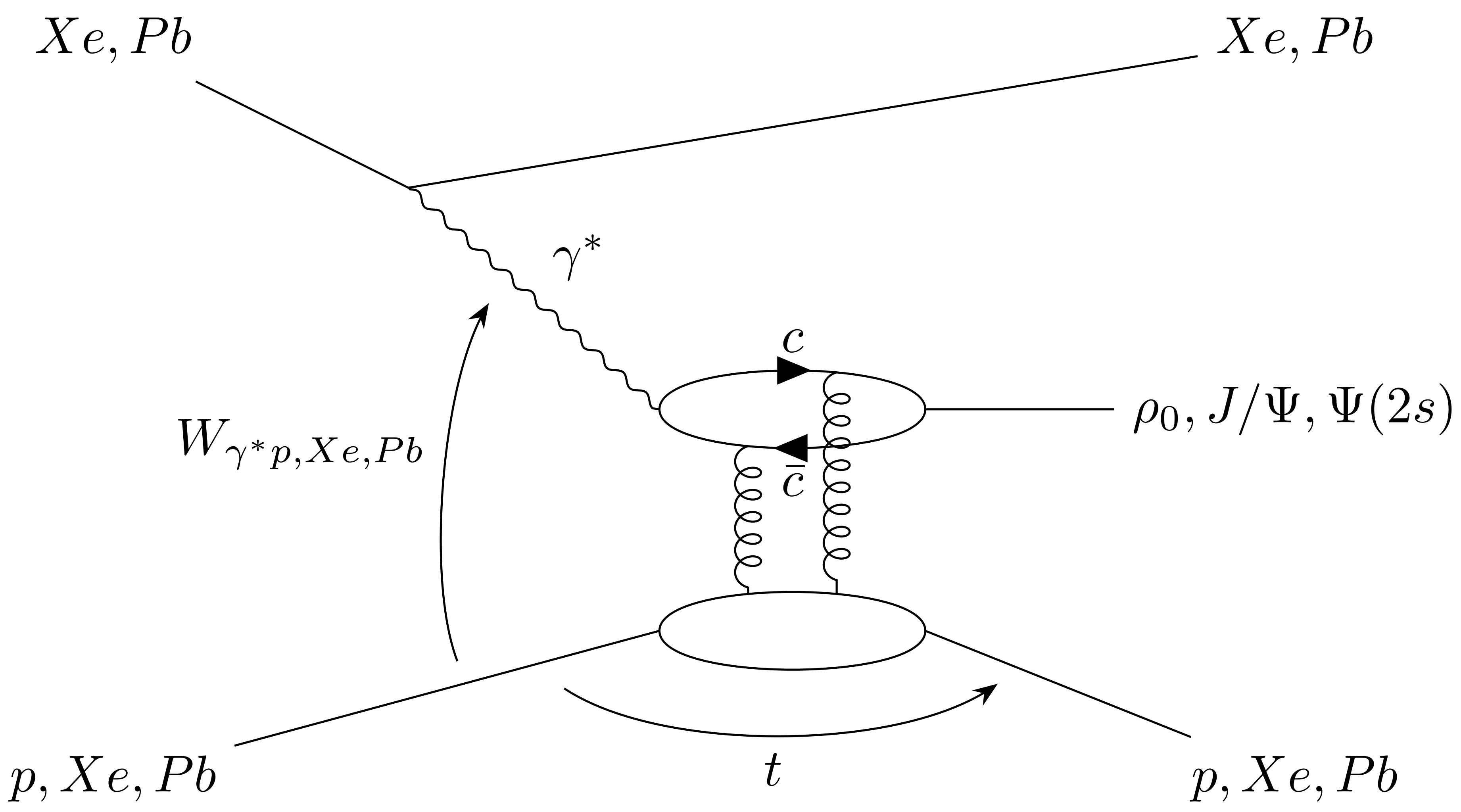
UPCs as a tool to study gluons

- The virtual photon fluctuates in a $q\bar{q}$ dipole
- The virtual photon interacts with the proton and probes its internal structure (probes the event-by-event fluctuations of the proton wave function) via the exchange of 2 gluons
- From this interaction a vector meson (ρ, J/ψ, ψ(2s), …) is produced

- The vector meson then decays to di-leptons
- Provides information on gluon saturation in the proton and shadowing in nuclei at low-x (corresponding to large $W_{\gamma^* p,Xe,Pb}$)
- For small $q\bar{q}$ at leading twist, leading $\ln(1/x)$, $t \to 0$

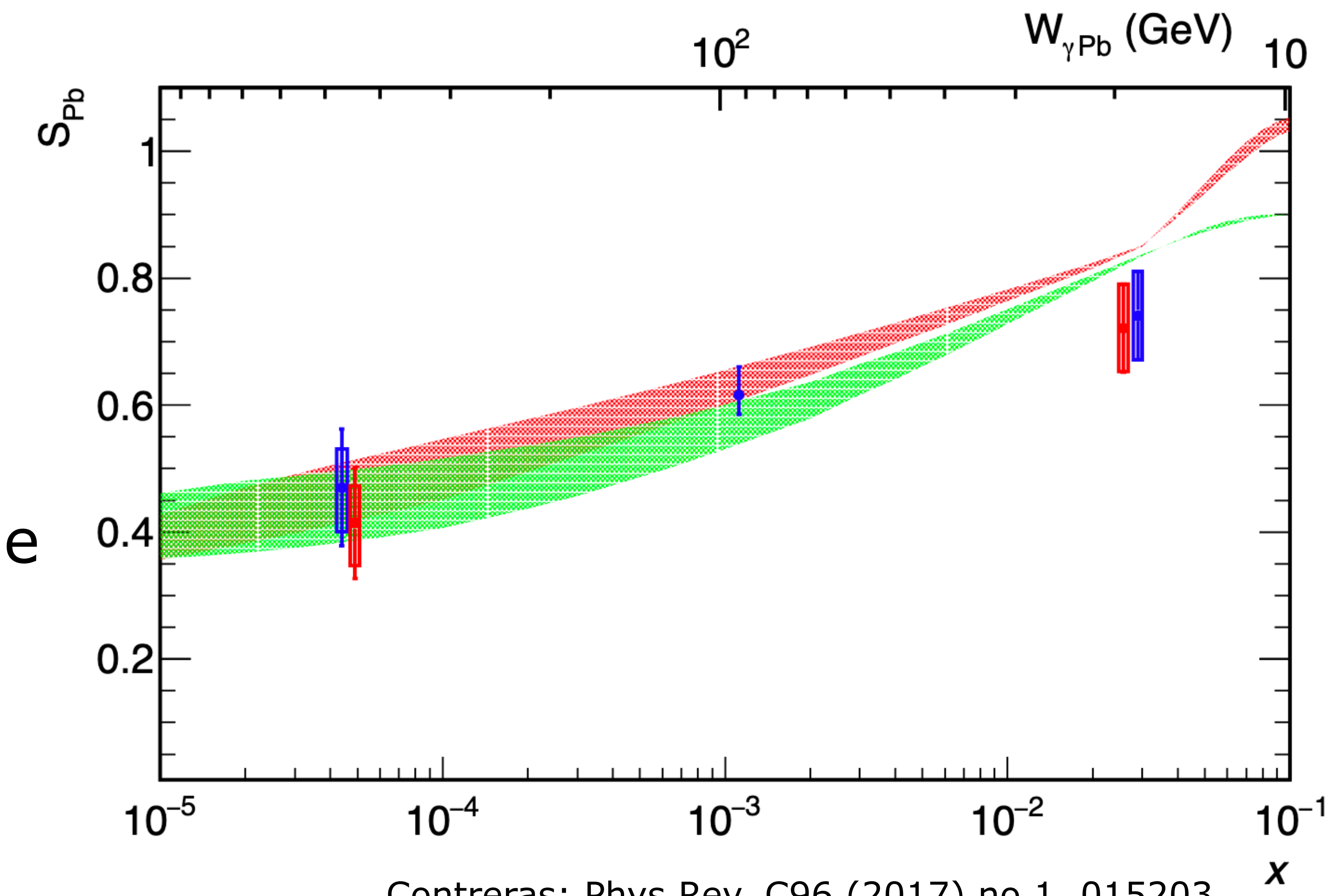
$$\left.\frac{d\sigma_{\gamma^* A\to J/\Psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\Psi}\Gamma_{ee}\pi^3\alpha_S^2(Q^2)}{48\alpha_{em}Q^8}[xg_A(x,Q^2)]^2$$

As discussed yesterday in talk by S. Joosten, GPD probed in this exclusive channel



Pb-Pb UPCs in ALICE (Run 1)

- $S_{Pb}(W_{\gamma p}) = \left[\frac{\sigma^{exp}_{\gamma Pb\to J/\Psi Pb}(W_{\gamma Pb})}{\sigma^{IA}_{\gamma Pb\to J/\Psi Pb}(W_{\gamma Pb})}\right]^{1/2}$
- If no shadowing, $S_{Pb}(W_{\gamma p}) = 1$
- Nuclear suppression factor below 1 indicates nuclear shadowing
- IA = Impulse approximation (all nucleons involved in the scattering, taken from γ-p HERA data) (arXiv:1610.03350v2 [nucl-ex])
- Based on experimental inputs
- Leading Twist Approximation (LTA) with different parameterizations describes data well
- Data reach down to $x \sim 5 \times 10^{-5}$ ($x = M^2_{J/\Psi}/W^2_{\gamma Pb}$)



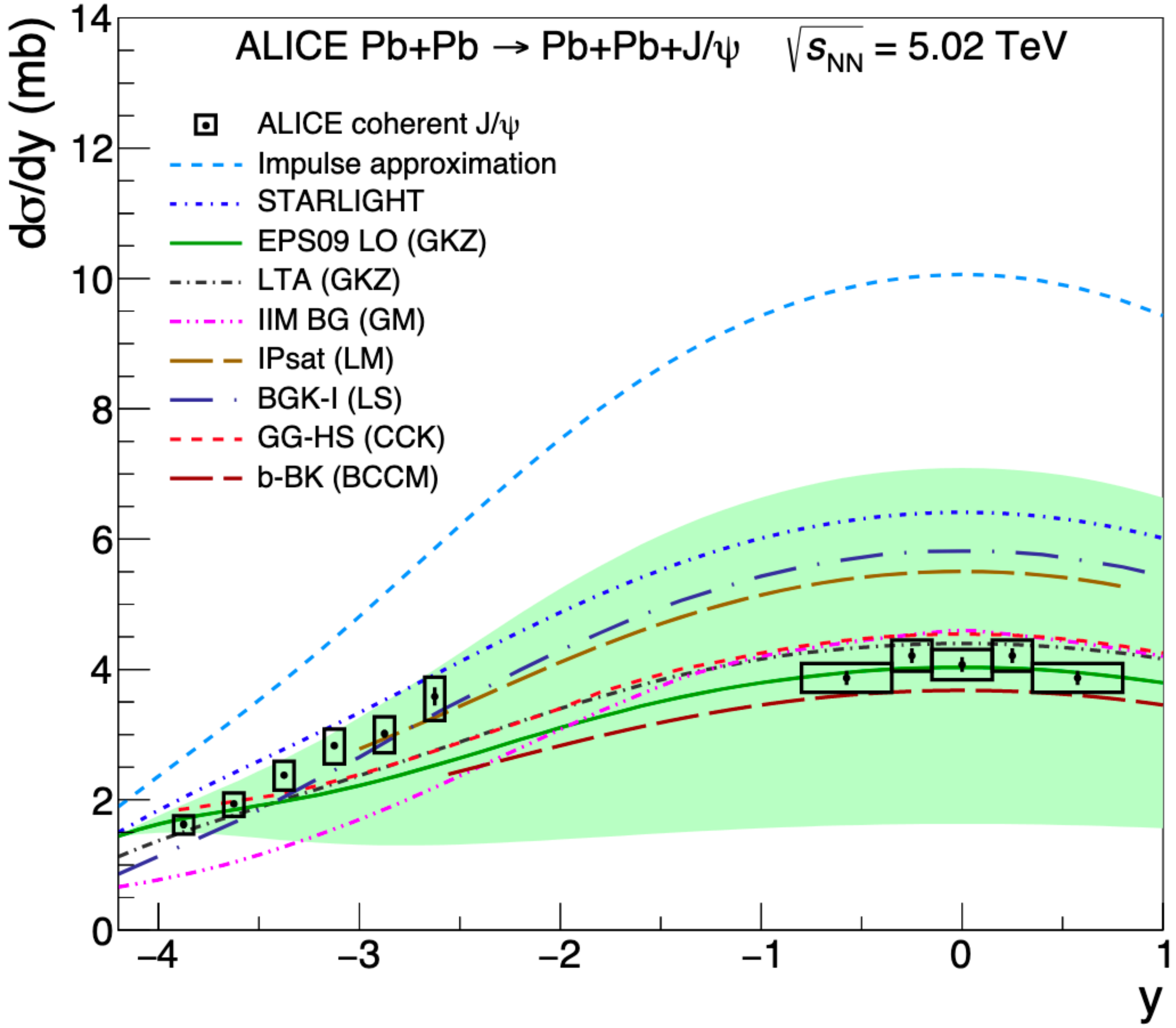
Contreras: Phys.Rev. C96 (2017) no.1, 015203

🟥 prediction of LTA approach using CTEQ6L parton parametrization

🟩 prediction of LTA approach using MNRT07 parton parametrization

Pb–Pb UPCs in ALICE (Run 2)

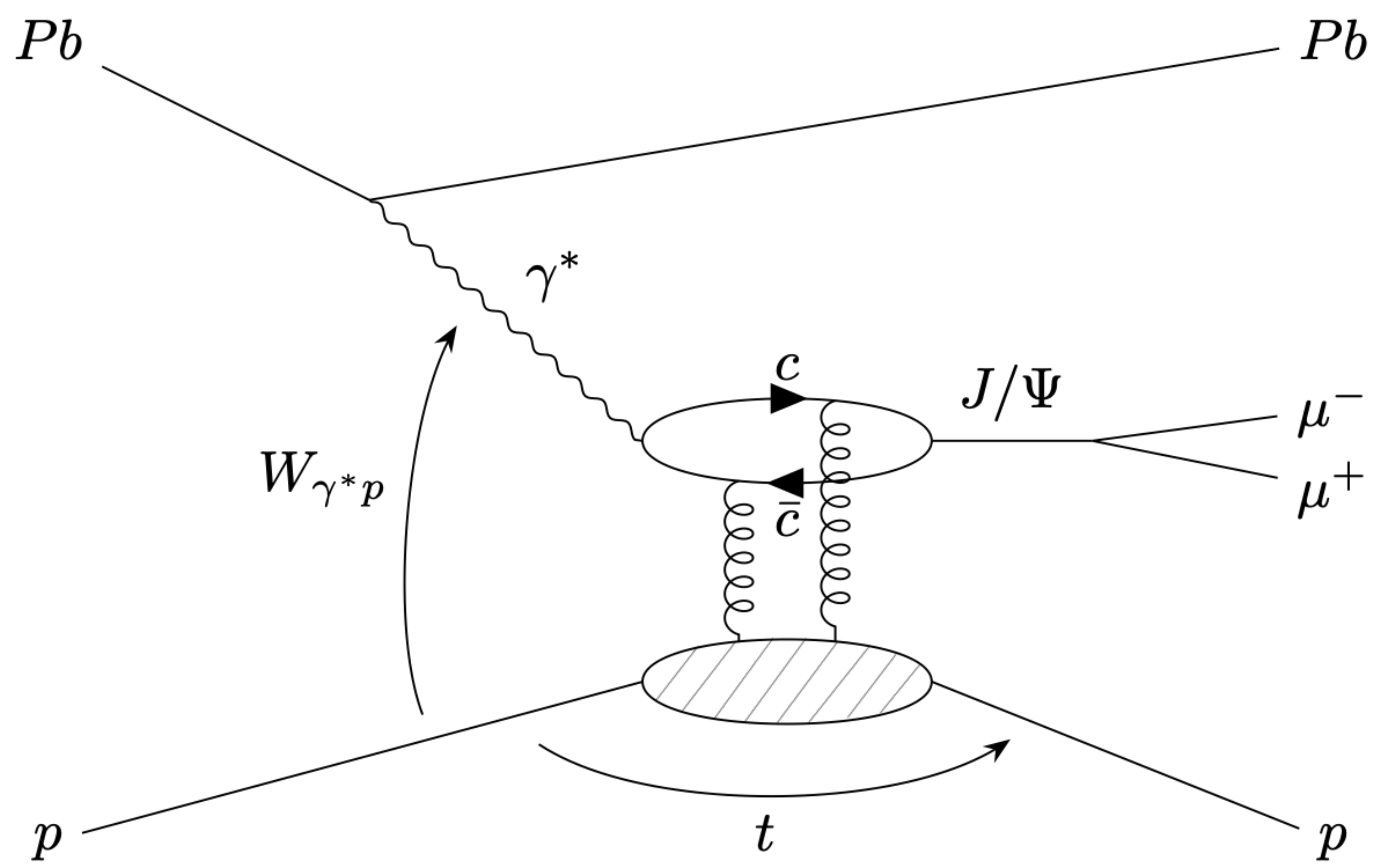
- Rapidity dependence measured
- Comparison of data to the impulse approximation implies $S_{Pb}(x \sim 10^{-3}) = 0.65 \pm 0.03$
- GKZ with EPS09 shadowing and the GG-HS (colour-dipole model with hot spots and including saturation) fit data at central and forward rapidities, but not at semi-forward rapidities (arXiv:2101.04577v1 [nucl-ex])



ALICE: arXiv:2101.04577 [nucl-ex]

J/ψ photoproduction in ALICE (p-Pb Run 2)

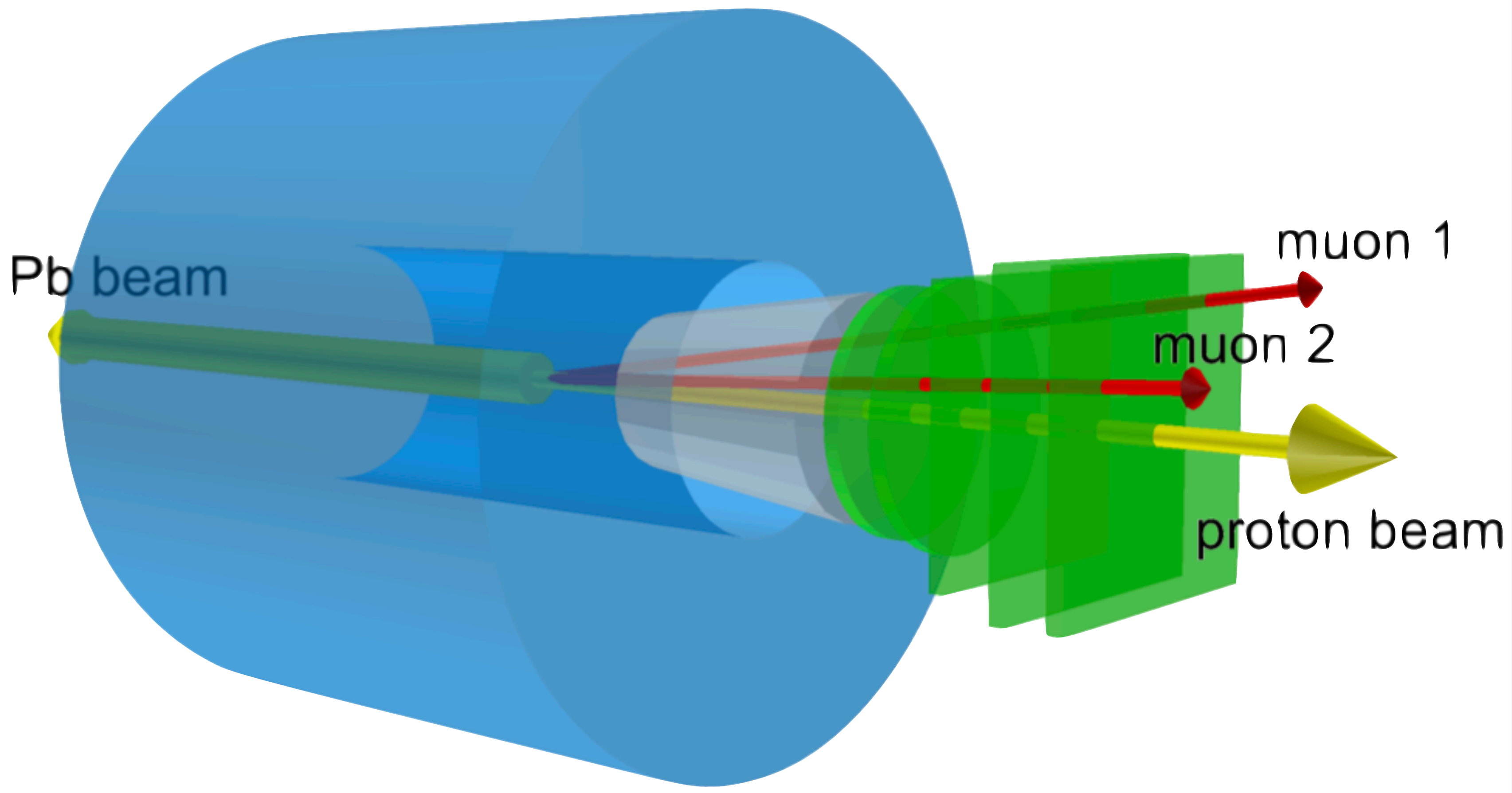
- p-γ^* center-of-mass energy given by $W_{\gamma^* p} = 2E_p\, M_{J/\Psi}\, e^{-y}$ where y is the rapidity of the J/Ψ defined according to the proton beam

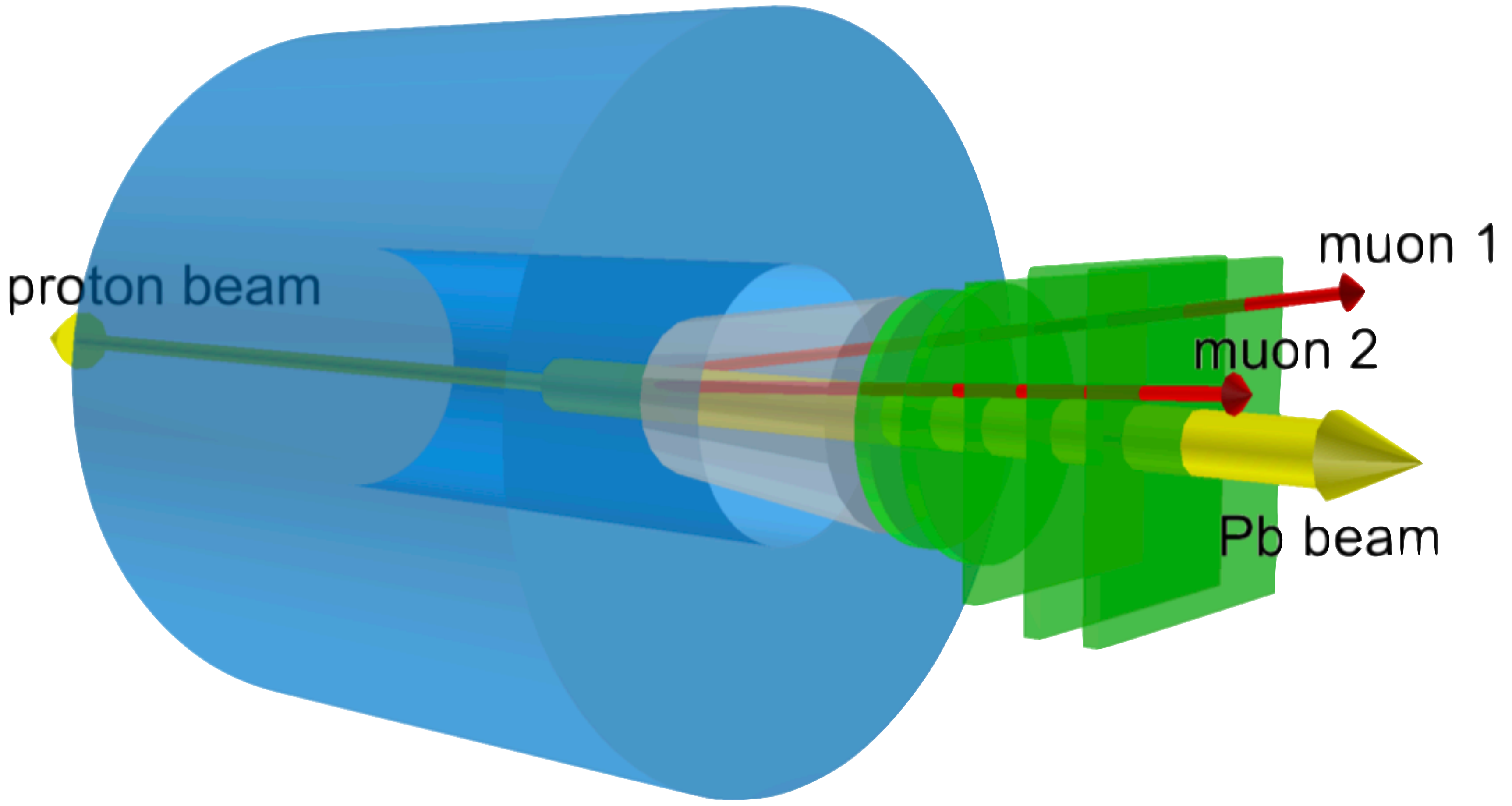


- 2 energy configurations:

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





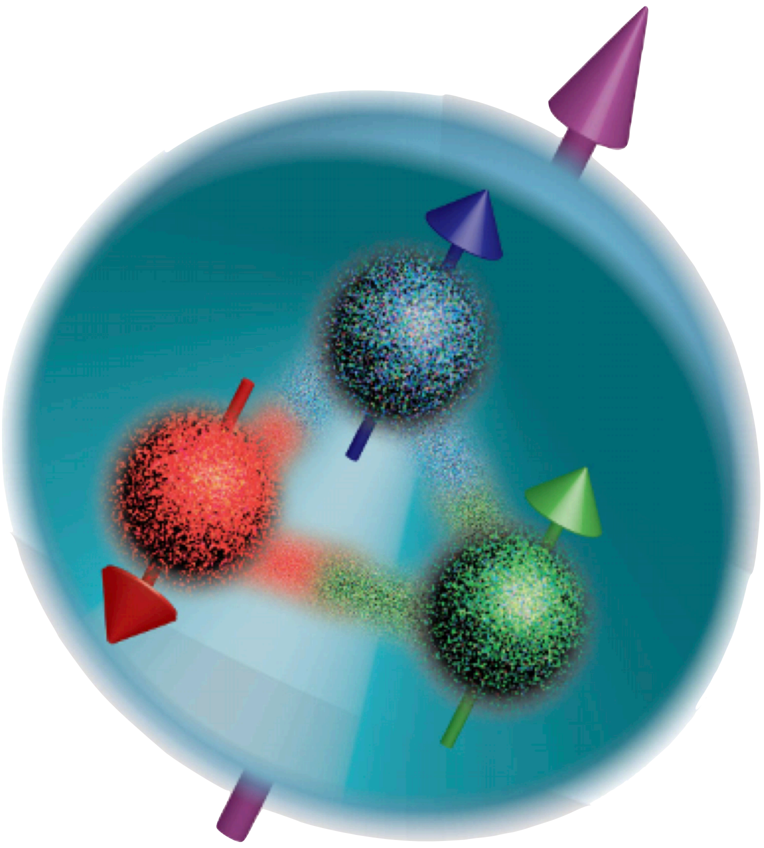
What are we probing?

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

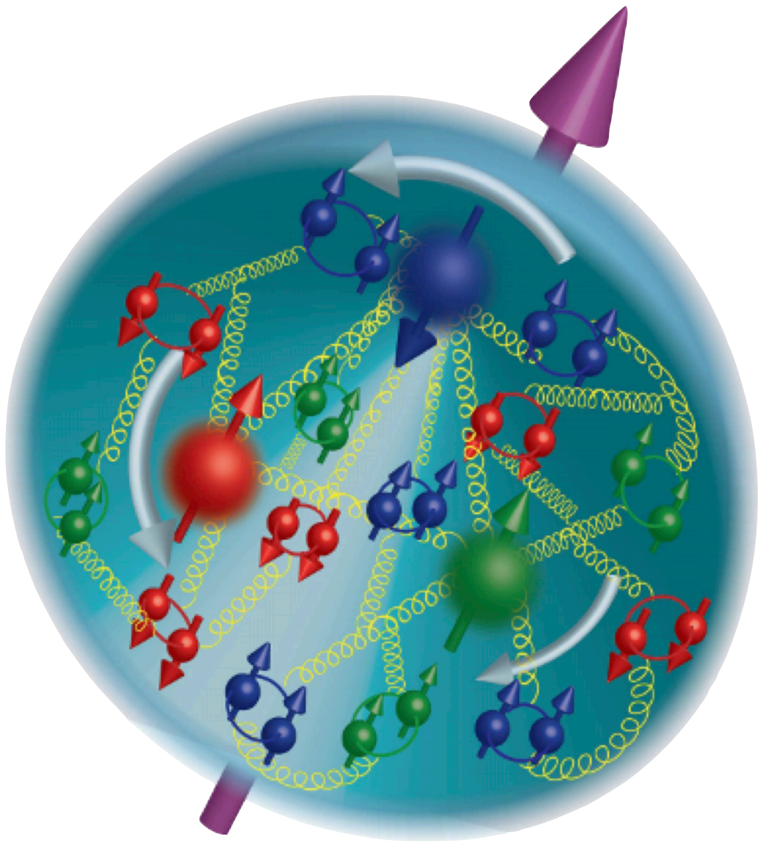
$x_{\mathbb{P}} = \frac{M^2_{J/\Psi} + Q^2 - t}{W^2_{\gamma^* p} + Q^2 - m_p^2}$ where $Q^2 \simeq M^2_{J/\Psi}$ and $t \to 0$, hence $x_{\mathbb{P}} \simeq \frac{2M^2_{J/\Psi}}{W^2_{\gamma^* p}}$

- 2 energy configurations:

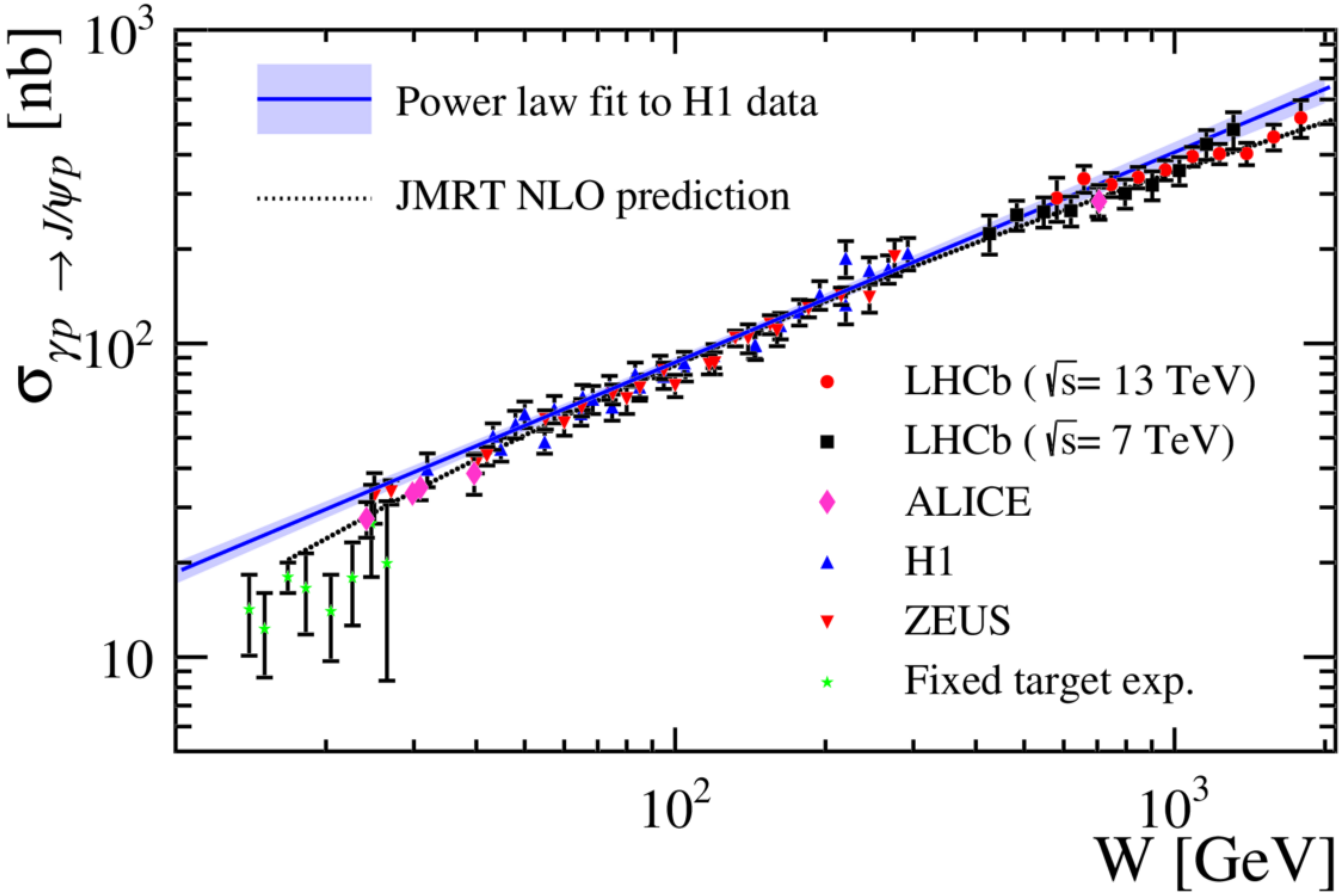
the J/ψ goes in the direction of the proton:
27 GeV < $W_{\gamma^* p}$ < 58 GeV
$5 \times 10^{-3} < x < 2 \times 10^{-2}$



the J/ψ goes in the direction of the Pb ion:
702 GeV < $W_{\gamma^* p}$ < 1486 GeV
$8 \times 10^{-6} < x < 3 \times 10^{-5}$



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))

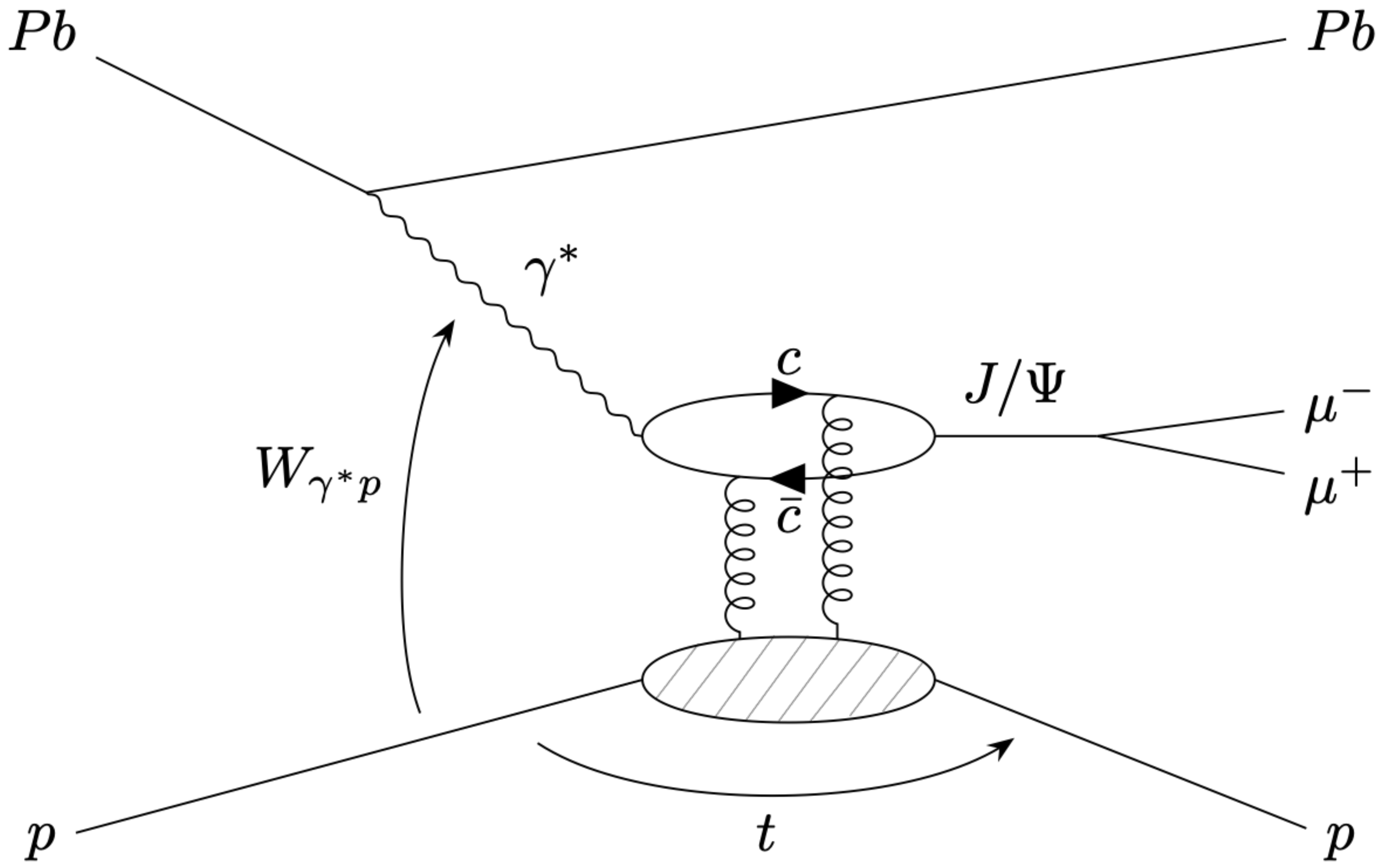
- LHCb studied the same process in p-p collisions (symmetric system : photon emitter identified via HERA data)
- HERA: H1 and ZEUS have measured the cross section of J/ψ photoproduction at energies $W_{\gamma^* p}$ from 20 to 305 GeV
- No change in the behavior of the gluon PDF in the proton is observed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

J/ψ photoproduction

- **exclusive**: the proton remains in the same quantum state

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

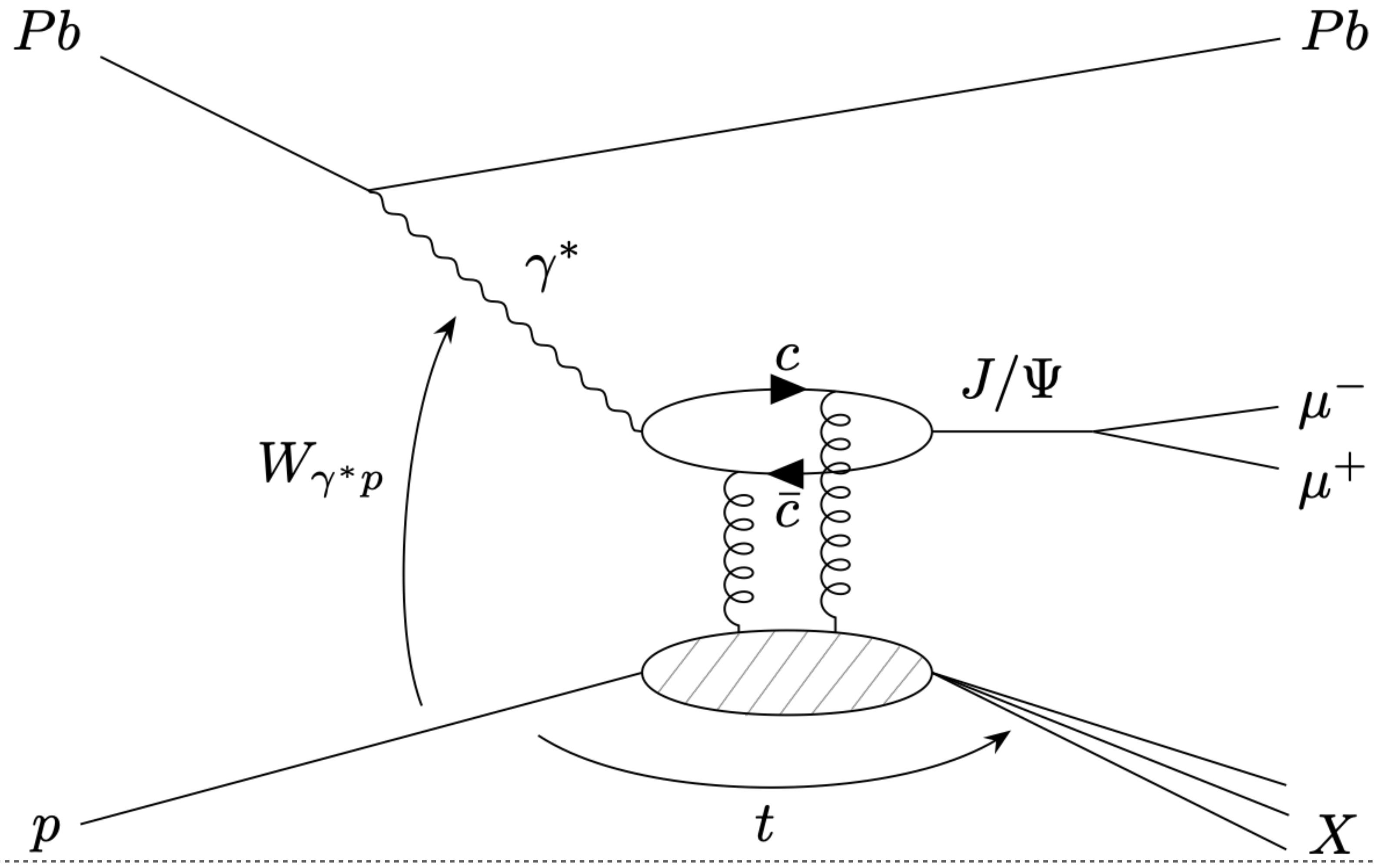
$$\frac{d\sigma^{\gamma^* p \to J/\Psi\ p}}{dt} \propto |\langle A^{\gamma^* p \to J/\Psi\ p} \rangle|^2$$



- **dissociative**: initial and final states are required to be different

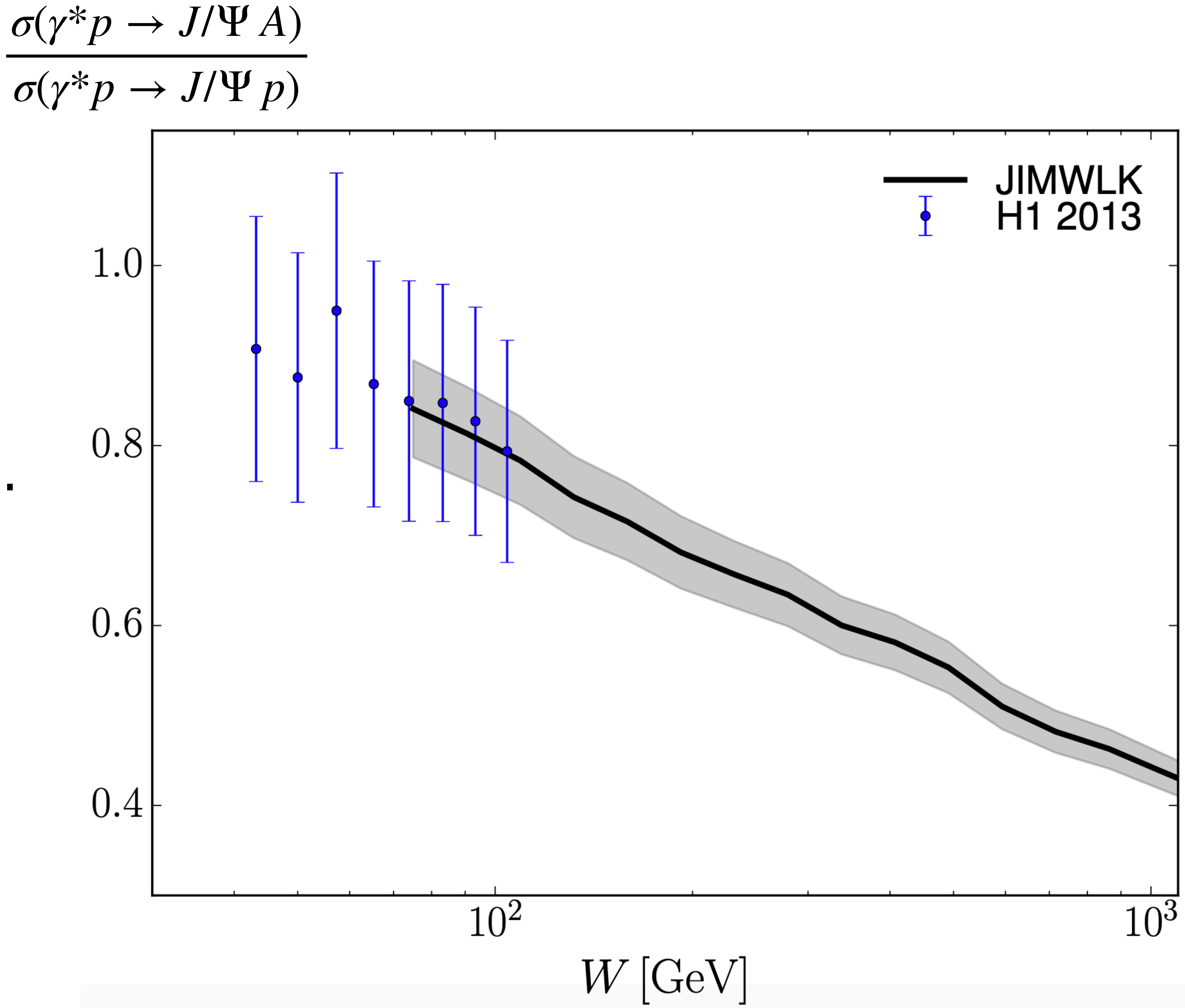
Physically: we measure the fluctuations of the configurations of the proton

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



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

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

Summary and outlook

- HERA unveiled the structure of the proton down to x ~ 10^{-4}
- Non-linear effects are expected to be seen both in protons for smaller x (saturation) as well as shadowing in nuclei
- In ALICE
    - in Pb-Pb collisions, data is consistent with shadowing effects in the Pb nucleus
    - in p-Pb collisions, saturation has not been found in Run 1 data, but is expected to 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

DIS @ HERA

F_2

dominant contribution to the cross section

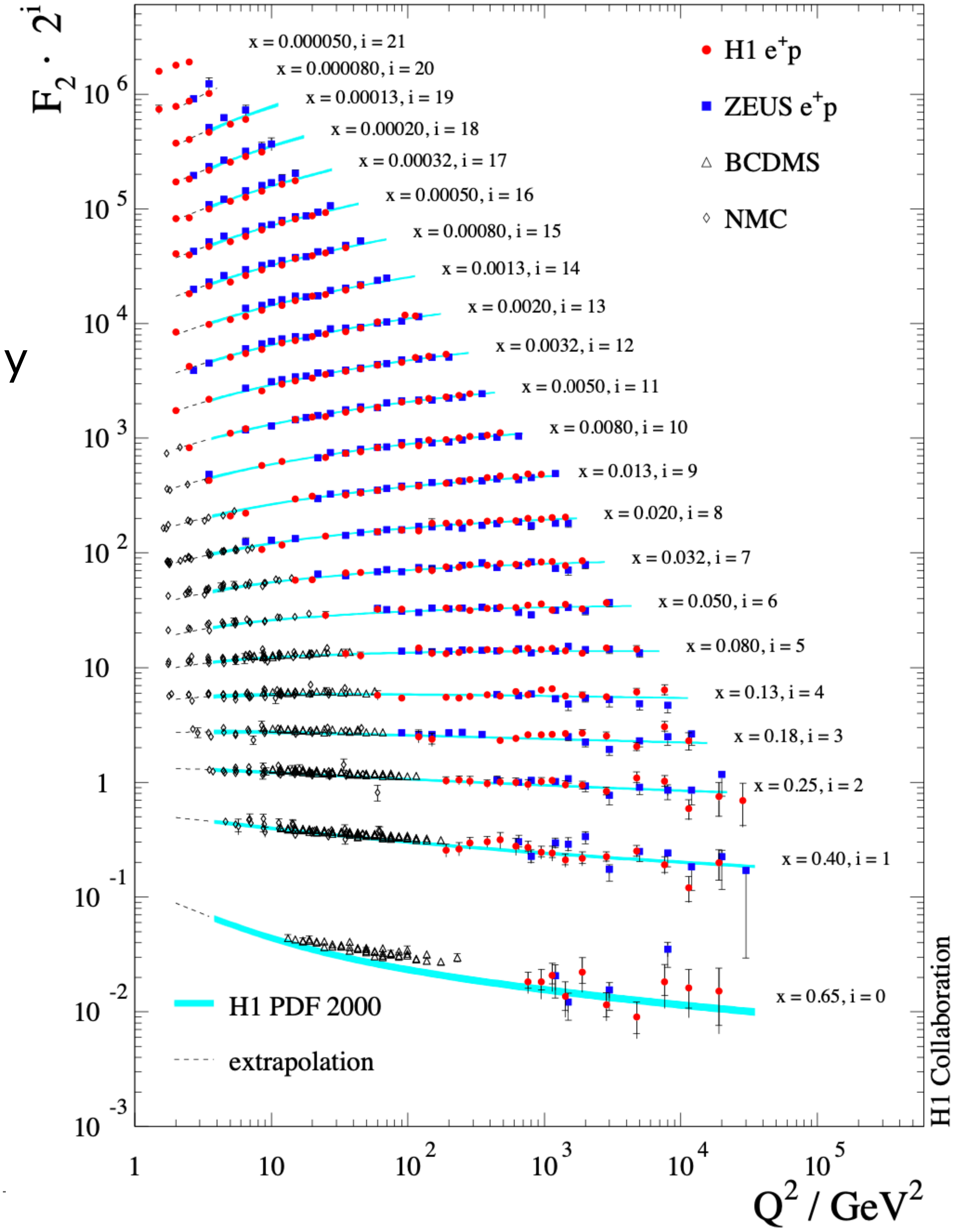
important at high Q^2

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\boxed{\tilde{F}_2^{\pm}} \mp Y_-\boxed{x\tilde{F}_3^{\pm}} - y^2\boxed{\tilde{F}_L^{\pm}})$$

sizeable only at high y

where $Y_{\pm} = 1 \pm (1-y)^2$, $y = \dfrac{Q^2}{xs}$ (inelasticity) and $\sqrt{s}$ is the center-of-mass energy

- $\tilde{F}_2$ = combination of F_2 and $F_2^{\gamma Z}$ (interference term)
- $F_2 = x\sum e_q^2(q+\bar{q})$ for all orders of QCD in the DIS scheme + easily experimentally accessible
- Gluon density can be extracted from fits to F_2 along lines of constant x $g(x,Q^2) \sim \dfrac{dF_2(x,Q^2)}{d\ln(Q^2)}$
- F_2 increasing at lower x → increasing gluon desnity
- F_2 → scaling violation → measurement of the gluon density



xF_3

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+ \overset{\text{dominant contribution to the cross section}}{\enclose{circle}{\tilde{F}^{\pm}_2}} \mp Y_- \overset{\text{important at high } Q^2}{\enclose{circle}{x\tilde{F}^{\pm}_3}} - y^2 \enclose{circle}{\tilde{F}^{\pm}_L}) \quad \text{sizeable only at high } y$$

where $Y_{\pm} = 1 \pm (1-y)^2$, $y = \frac{Q^2}{xs}$ (inelasticity) and $\sqrt{s}$ is the center-of-mass energy

- In the quark parton model in LO, $xF_3 \approx x \sum 2e_q a_q (q - \bar{q})$ (ae = axial-vector coupling of the quarks to the Z boson)
- xF_3 arises from gamma-Z interference, can be accessed by measuring charge asymmetry at high Q2
- xF_3 function measures the valence quark density which is expected to vanish at low x (q qbar difference)

Measurement of longitudinal structure function F_L

dominant contribution to the cross section

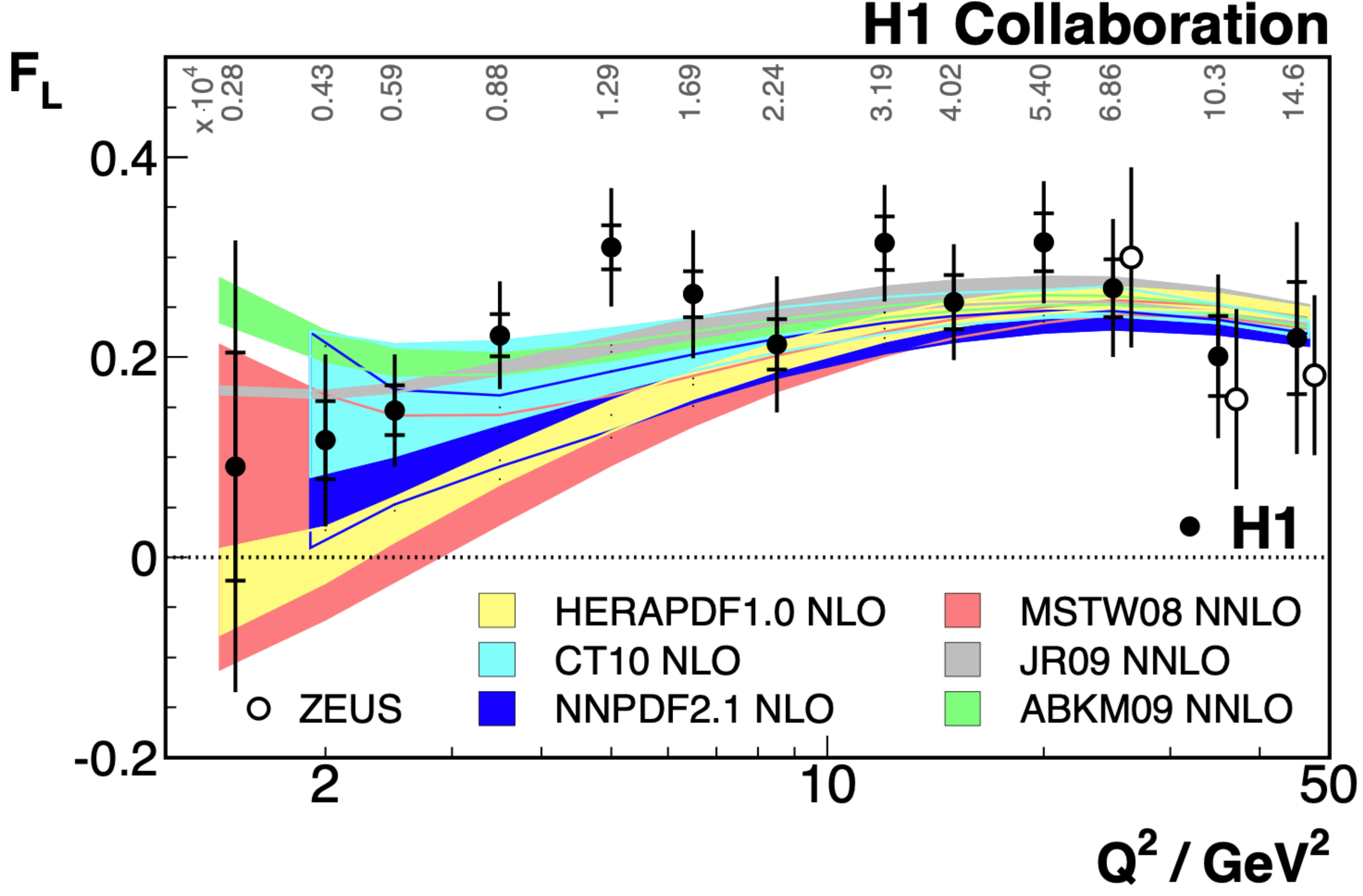
important at high Q^2

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\boxed{\tilde{F}^{\pm}_2} \mp Y_-\boxed{x\tilde{F}^{\pm}_3} - y^2\boxed{\tilde{F}^{\pm}_L})$$

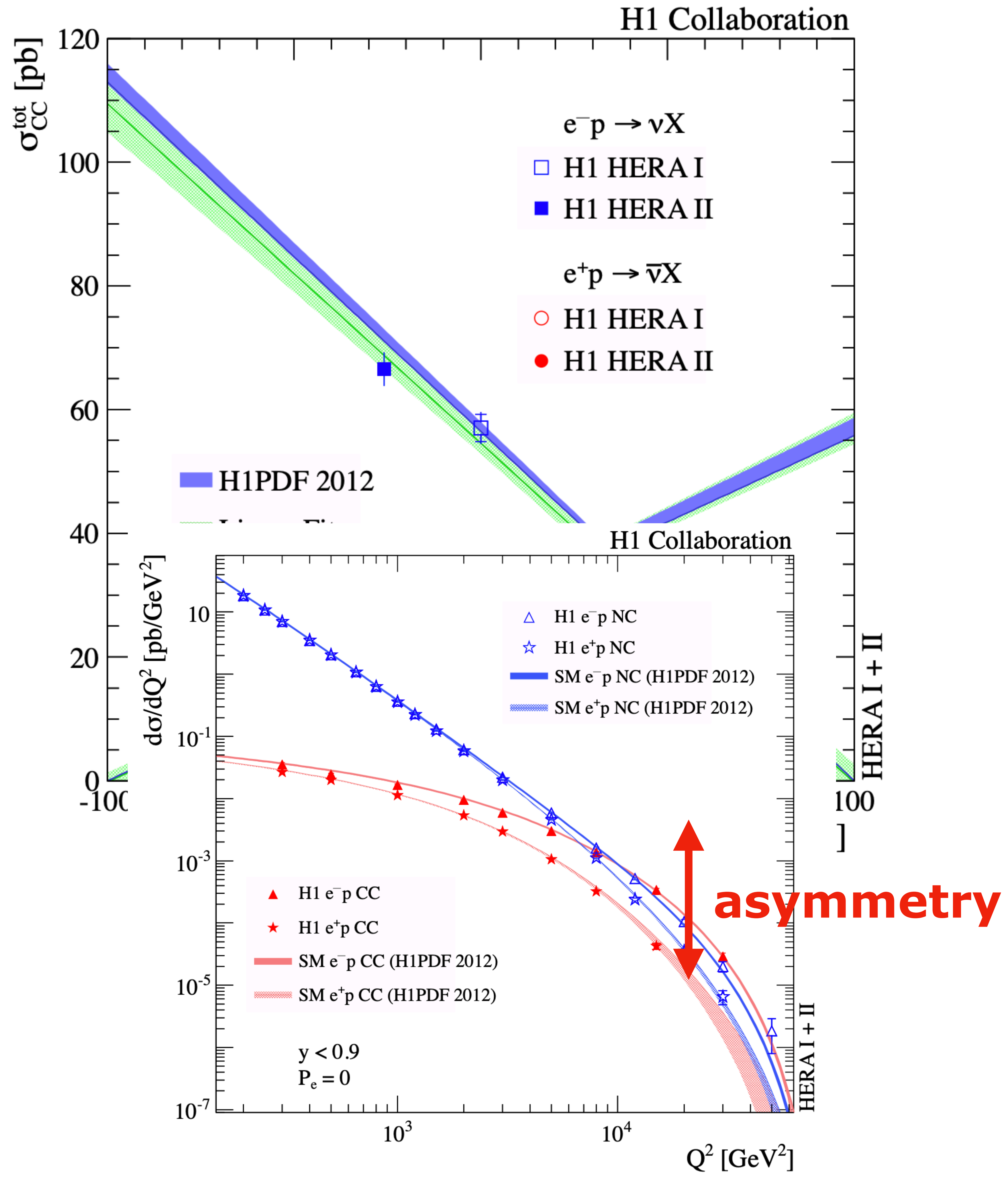
sizeable only at high y

where $Y_{\pm} = 1 \pm (1-y)^2$, $y = \frac{Q^2}{xs}$ (inelasticity) and $\sqrt{s}$ is the center-of-mass energy

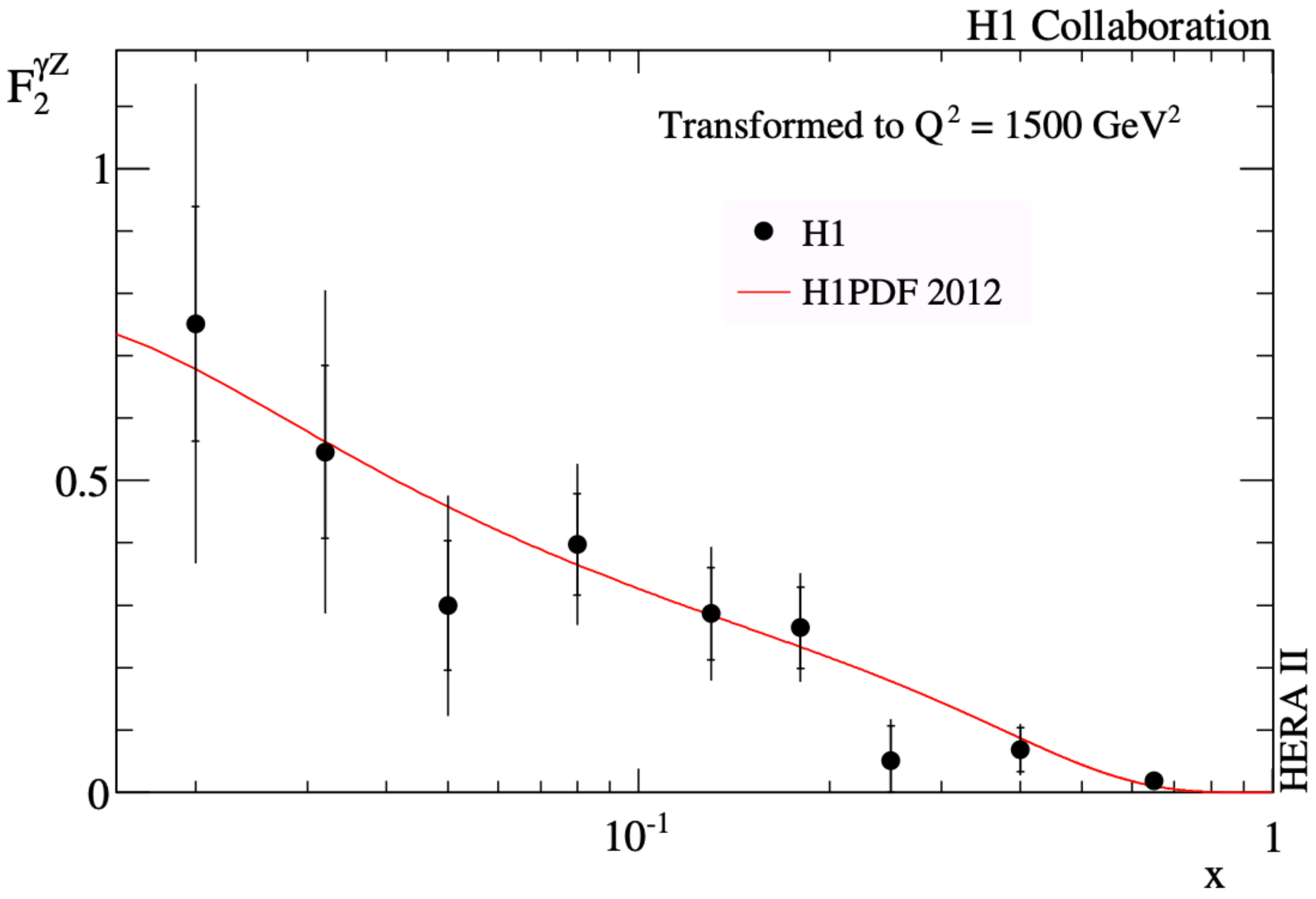
- In the quark parton model in LO, $F_L \approx 0$ because of helicity conservation for spin 1/2 quarks
- In QCD, gluon-emission gives rise to non-vanishing F_L → tool to study gluon density and test pQCD
- For low x, F_L is mostly determined by the gluon density g(x)
- Using inclusive DIS NC cross sections
- @ high y, for a fixed CME, the measured DIS cross section cannot be unambiguously decomposed into its F2 and FL contributions → can be achieved by comparing the cross section measured using different CME
- Ep = 920 GeV, 2.5 GeV^2 < Q^2 < 90 GeV^2,
- Ep = 575 GeV and Ep = 460 GeV, 1.5 GeV^2 < Q^2 < 90 GeV^2, integrated lumi 5.9 pb^{-1} and 12.2 pb^{-1}.
- Data combined with HERA I results to cover 0.2 GeV^2 < Q^2 < 150 GeV^2, 5 x 10^{-6} < x < 0.15 and 0.005 < y < 0.85



- σ_{CC}^{tot} measured for Q^2 > 400 GeV^2, y < 0.9 —> **data consistent with the absence of right-handed weak charged currents**
  - In LO, $\tilde{\sigma}_{CC}^{e^+p}$ and $\tilde{\sigma}_{CC}^{e^-p}$ are sensitive to different quark densities: $\tilde{\sigma}_{CC}^{e^+p} \approx x[\bar{u}+\bar{c}] + (1-y)^2 x[d+s]$ and $\tilde{\sigma}_{CC}^{e^-p} \approx x[u+c] + (1-y)^2 x[\bar{d}+\bar{s}]$
- $\frac{d\sigma_{CC,NC}}{dQ^2}$ measured for 200 GeV^2 < Q^2 < 50 000 GeV^2, y < 0.9
  - $\frac{d\sigma_{NC}}{dQ^2} \propto 1/Q^4$ and $\frac{d\sigma_{CC}}{dQ^2} \propto [M_W^2/(Q^2+M_W^2)]^2$
  - illustrate unified behavior of the electromagnetic and weak interactions in DIS
  - asymmetry provides a direct measure of parity violation in NC DIS



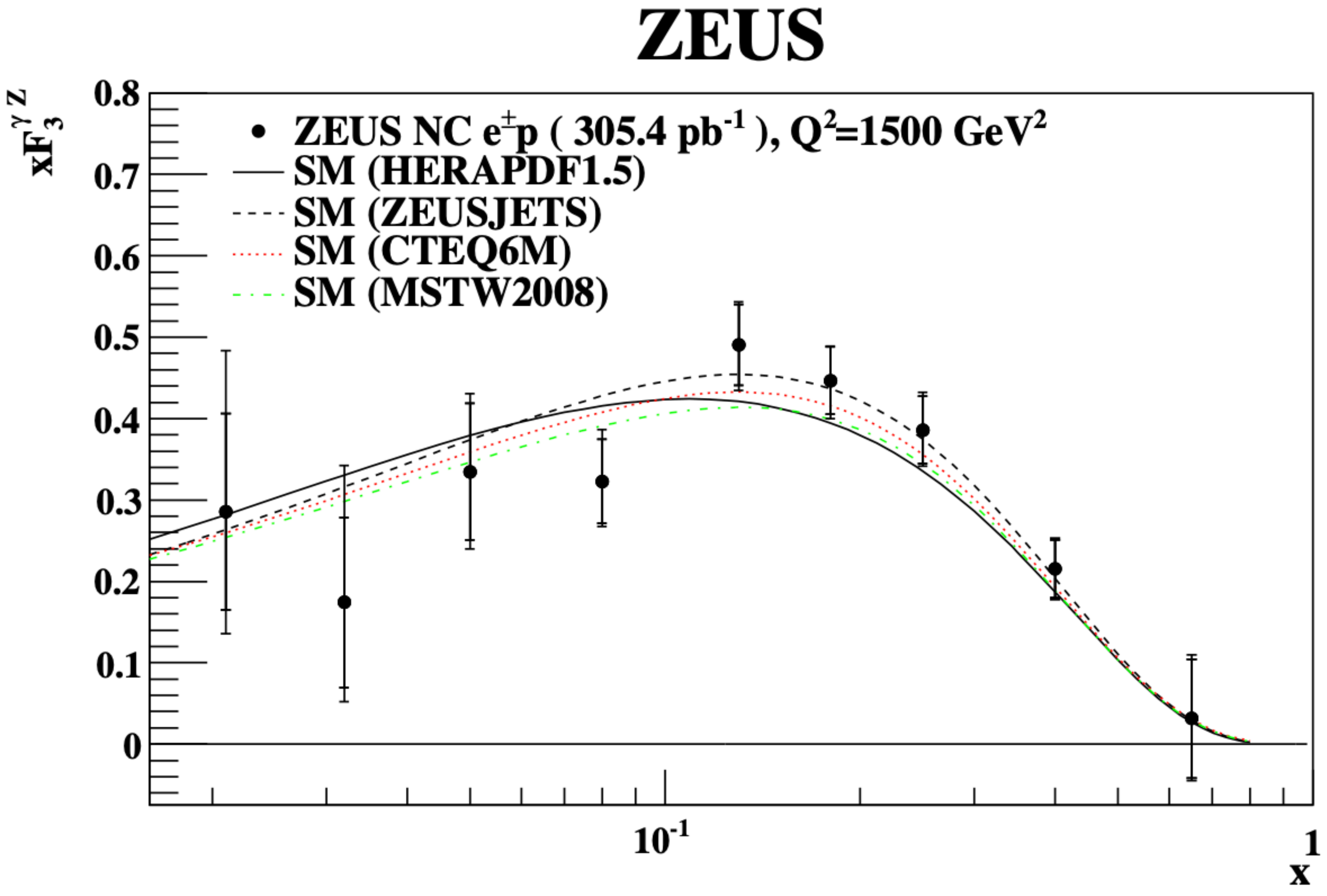
- $\frac{d^2\sigma_{CC,NC}}{dxdQ^2}$ measured
  - $\frac{d^2\sigma_{NC}}{dxdQ^2}$ for 120 GeV² < Q^2 < 50 000 GeV² and 0.002 < x < 0.65
  - $\frac{d^2\sigma_{CC}}{dxdQ^2}$ for 300 GeV² < Q^2 < 30 000 GeV² and 0.008 < x < 0.4
  - + special measurement a high y: 0.63 < y < 0.9 and 60 < Q^2 < 800 GeV² where the left and right handed polarized data sets are combined to measure unpolarized NC cross sections for e− p and e+ p as in this region the sensitivity to the polarization is small → improved measurement of $xF_3^{\gamma Z}$
  - first determination of $F_2^{\gamma Z}$



F. Aaron et al. [H1 Collaboration], JHEP 1209 (2012) 061

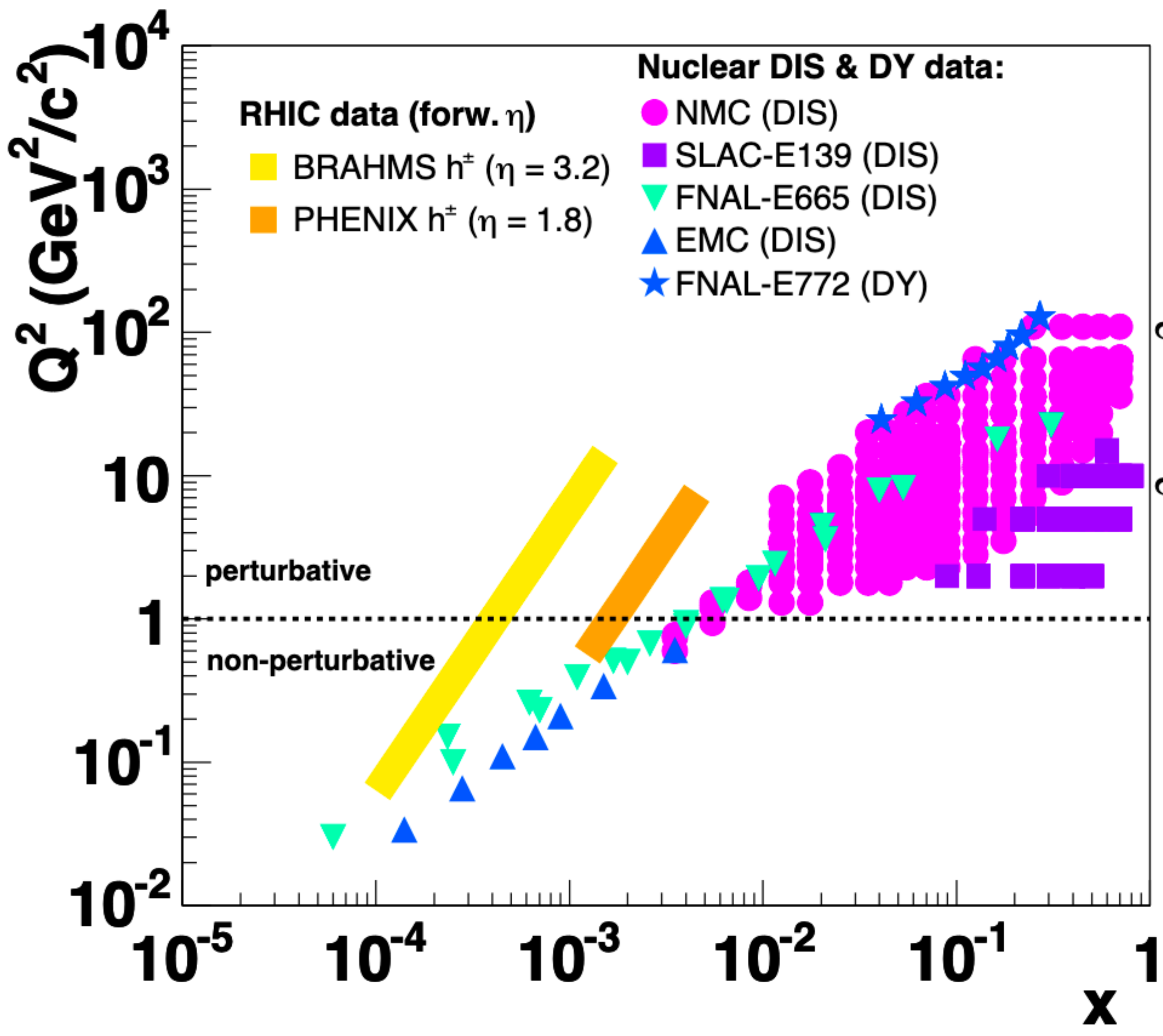
ZEUS: NC cross section measurements

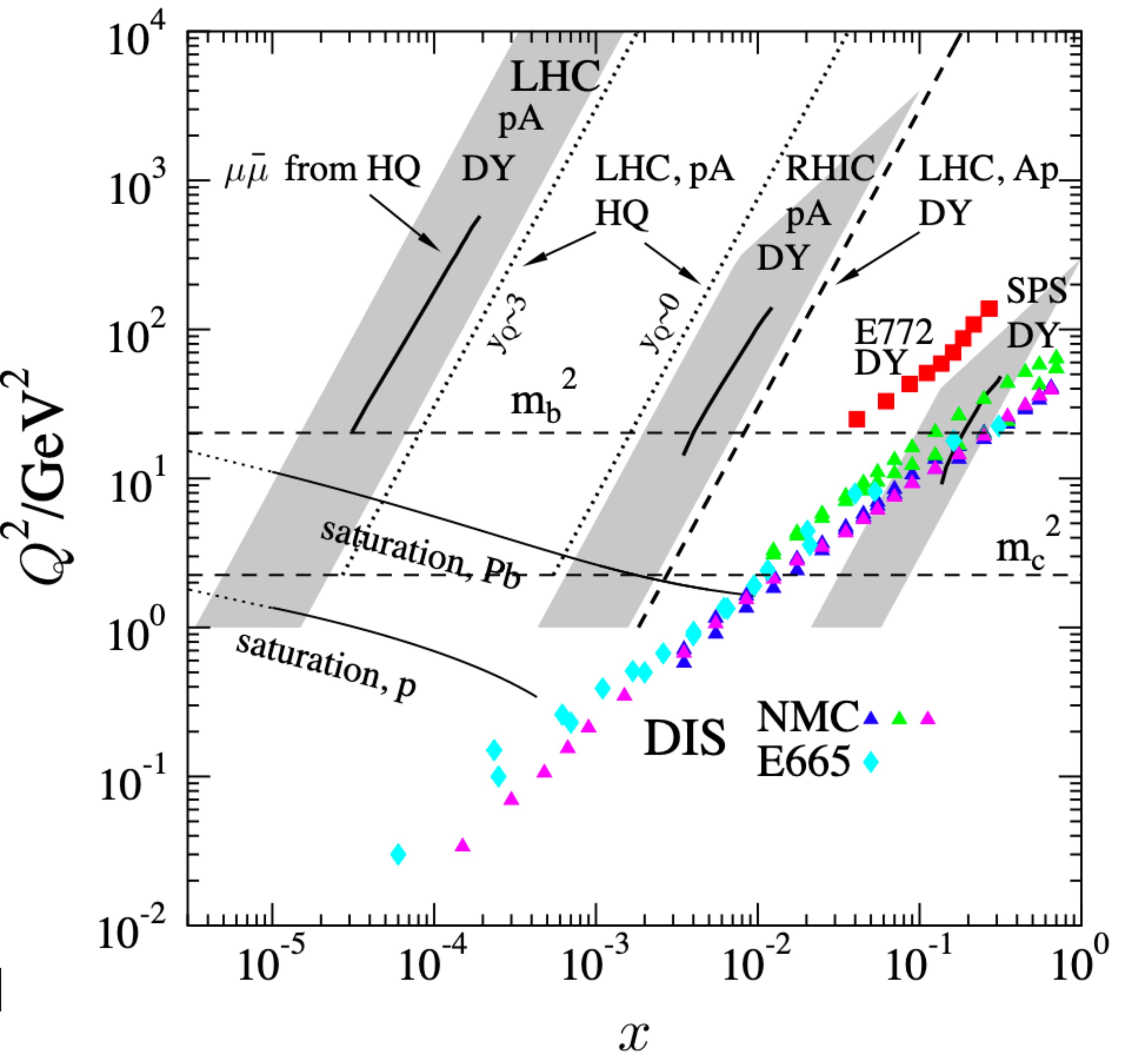
- The ZEUS collaboration has published the measurement of the NC cross sections for e+p data collected in 2006-2007 years . Together with the single and double differential NC cross sections, the structure functions $\tilde{F}_3$ and $\tilde{F}_3^{\gamma Z}$ were determined. This is the final ZEUS measurement of the inclusive cross sections from the HERA II period.



ALICE

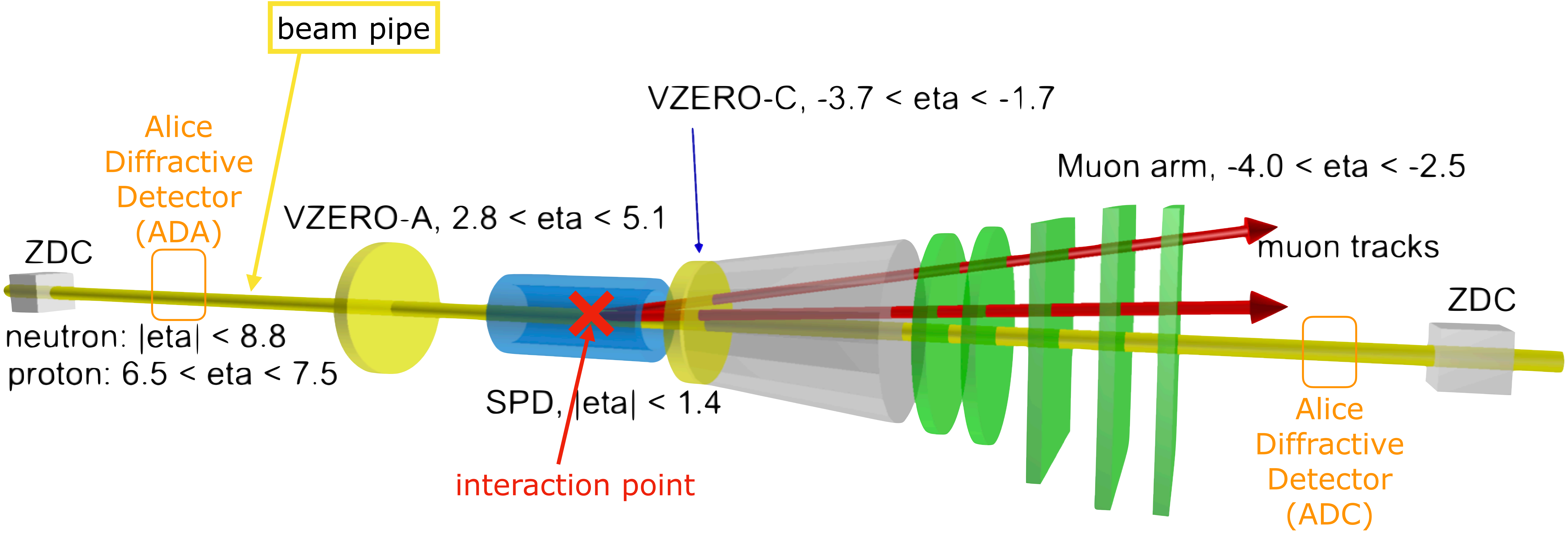
Shadowing





- shadowing increases with decreasing x
- shadowing increases with the mass number of the nucleus
- shadowing decreases with increasing Q^2
- existing experimental data do not allow a determination of the dependence of shadowing on the centrality of the collision

Selection of data



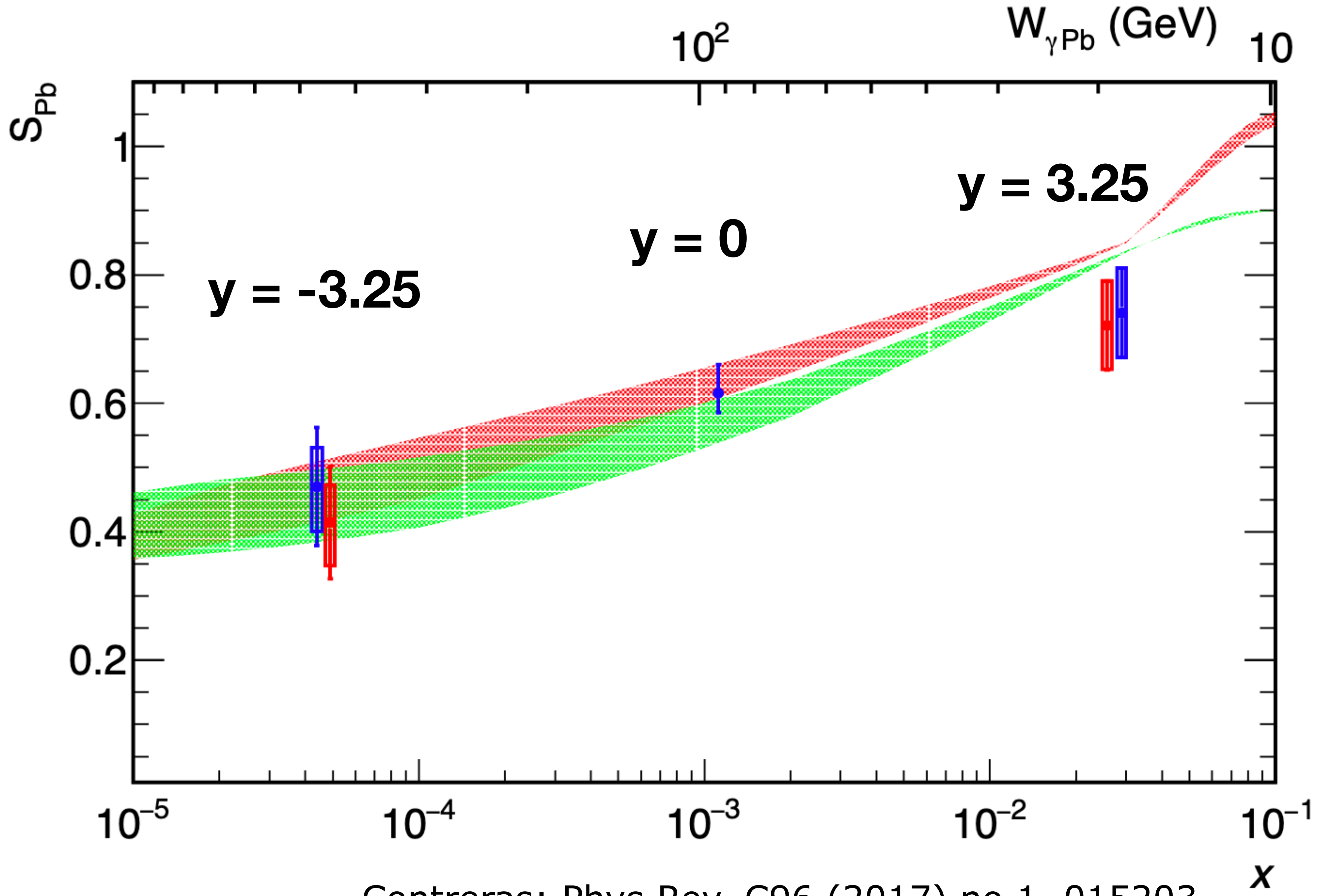
- ZDC = Zero Degree Calorimeter
- SPD = Silicon Pixel Detector
- VZERO = scintillator arrays

Pb-Pb UPCs in ALICE (Run 1)

- $S_{Pb}(W_{\gamma p}) = \left[\frac{\sigma^{exp}_{\gamma Pb\rightarrow J/\Psi Pb}(W_{\gamma Pb})}{\sigma^{IA}_{\gamma Pb\rightarrow J/\Psi Pb}(W_{\gamma Pb})}\right]^{1/2}$
- If no shadowing, $S_{Pb}(W_{\gamma p}) = 1$
- Nuclear suppression factor below 1 indicates nuclear shadowing
- IA = Impulse approximation (all nucleons involved in the scattering, taken from γ-p HERA data) (arXiv:1610.03350v2 [nucl-ex])
- IA defined as $\sigma^{IA}_{\gamma Pb}(W_{\gamma Pb}) = \frac{d\sigma_{\gamma p}(W_{\gamma p} = W_{\gamma Pb}, t=0)}{dt}\Phi_{Pb}(|t|_{min})$

where $d\sigma_{\gamma p}/dt$ at $t = 0$ si extracted from data on exclusive J/ψ photoproduction off protons at a photon-proton center-of-mass energy $W_{\gamma p}$ according to the fit presented in [Phys. Lett.B726, 290 (2013)], t is the square of the momentum transferred in the target vertex and the form factor $F_{WS}(t)$ is used to compute

$$\Phi_{Pb}(|t|_{min}) = \int_{|t|_{min}}^{\infty} d|t||F_{WS}(t)|^2$$

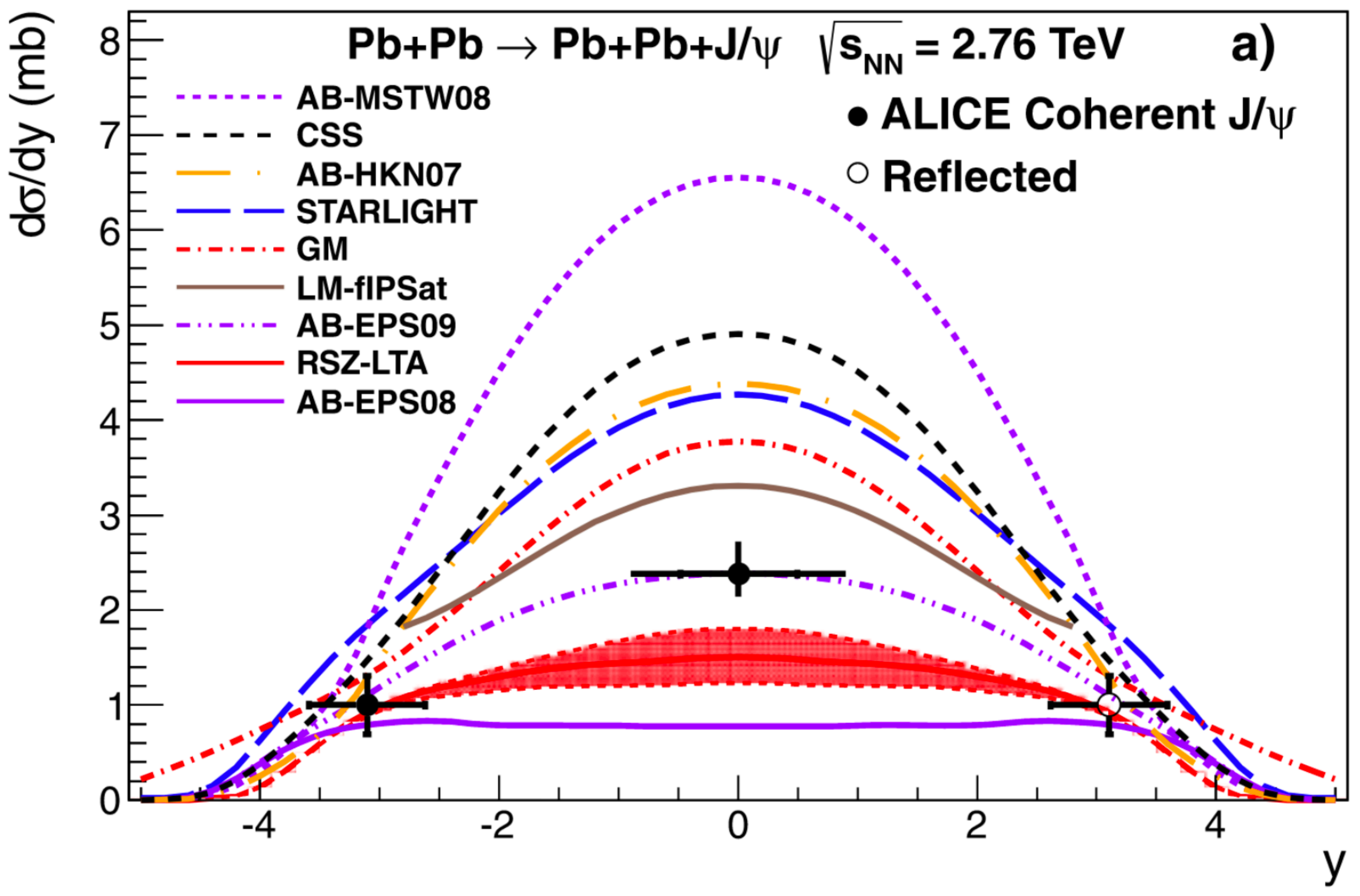


Contreras: Phys.Rev. C96 (2017) no.1, 015203

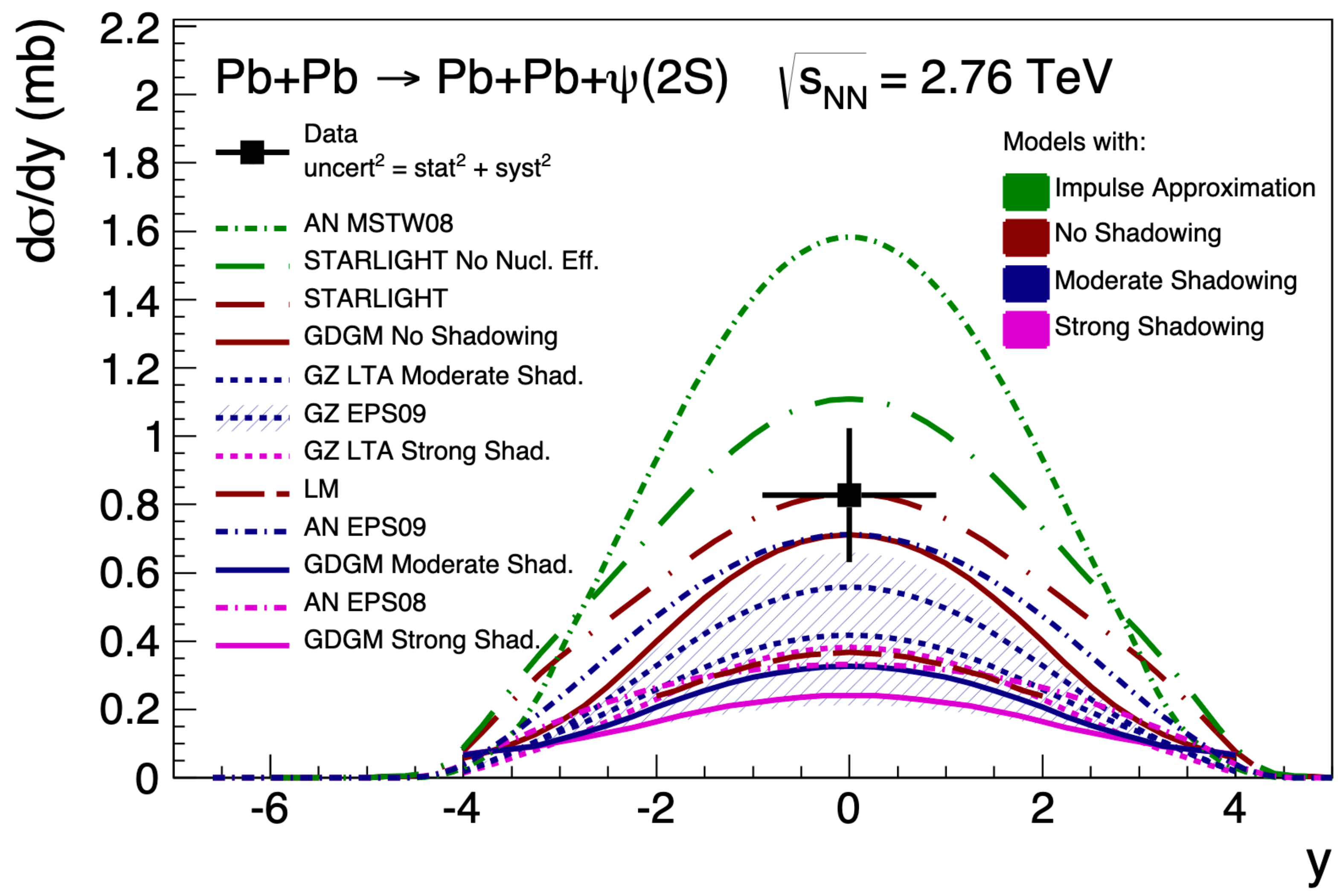
🟥 prediction of LTA approach using CTEQ6L parton parametrization

🟩 prediction of LTA approach using MNRT07 parton parametrization

Pb–Pb UPCs in ALICE (Run 1)



ALICE: Eur.Phys.J. C73 (2013) no.11, 2617

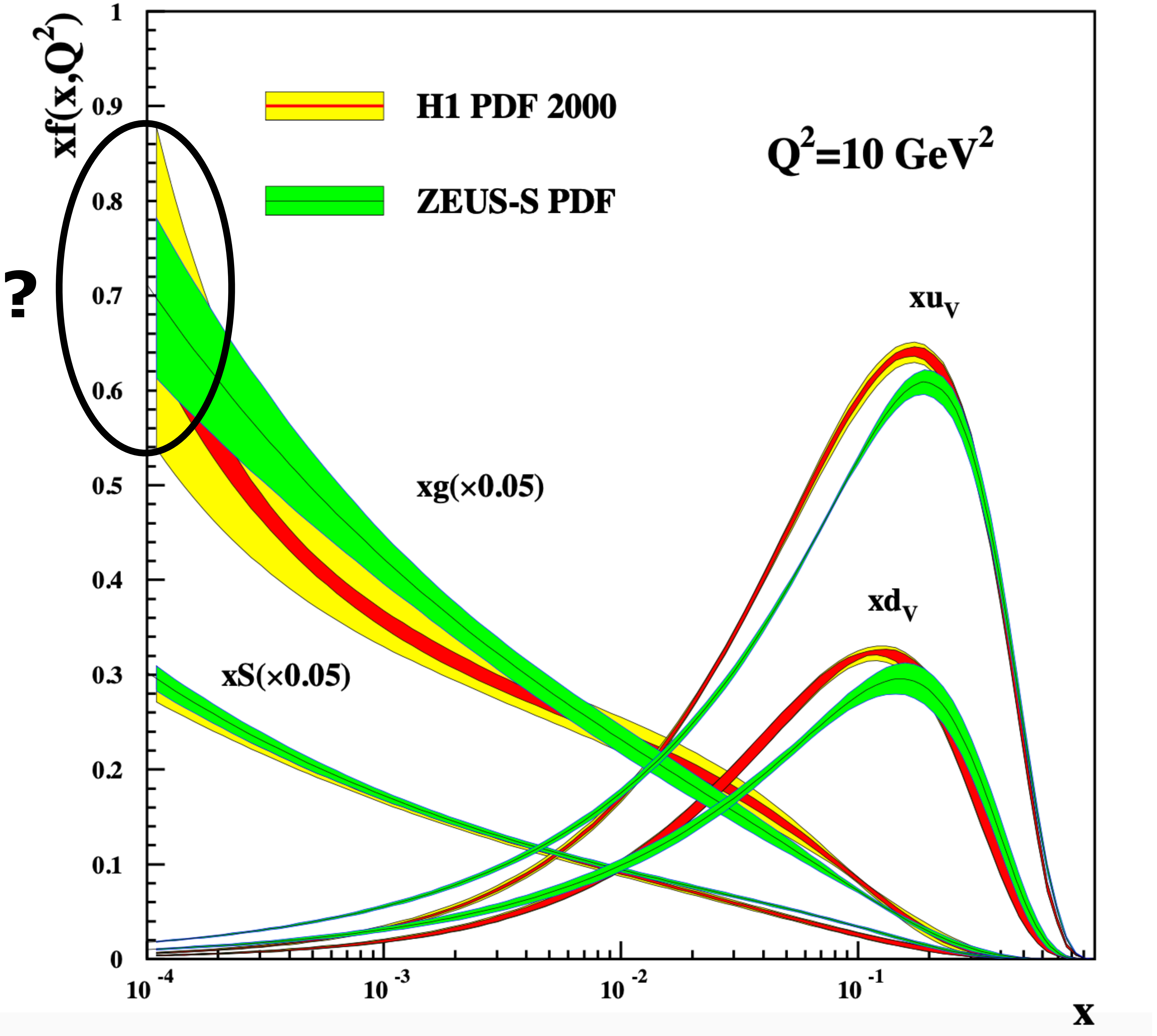


ALICE: Phys.Lett. B 751 (2015) 358-370

- Coherent J/ψ cross sections were measured in the forward and the central rapidity region
- Coherent ψ(2s)cross section was measured in the central rapidity region
- Large spread of predictions before the measurement
- Data favour moderate nuclear shadowing models at central rapidity.
- ALICE measurement supports calculations which include a moderate shadowing of gluons in nuclei. Models with all nucleons involved in the scattering (Impulse Approximation) and those with a strong shadowing are disfavored.

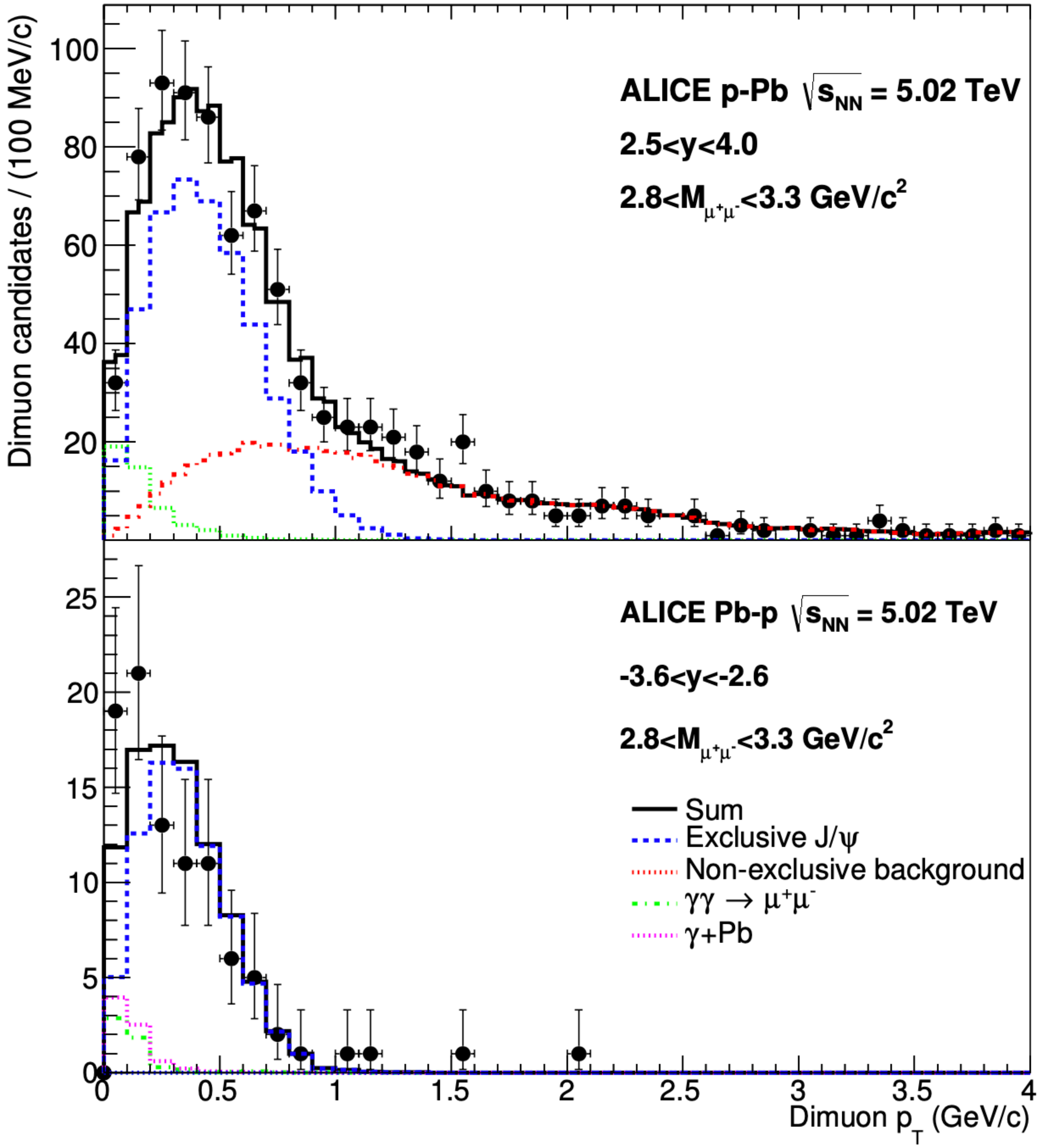
Saturation

- 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



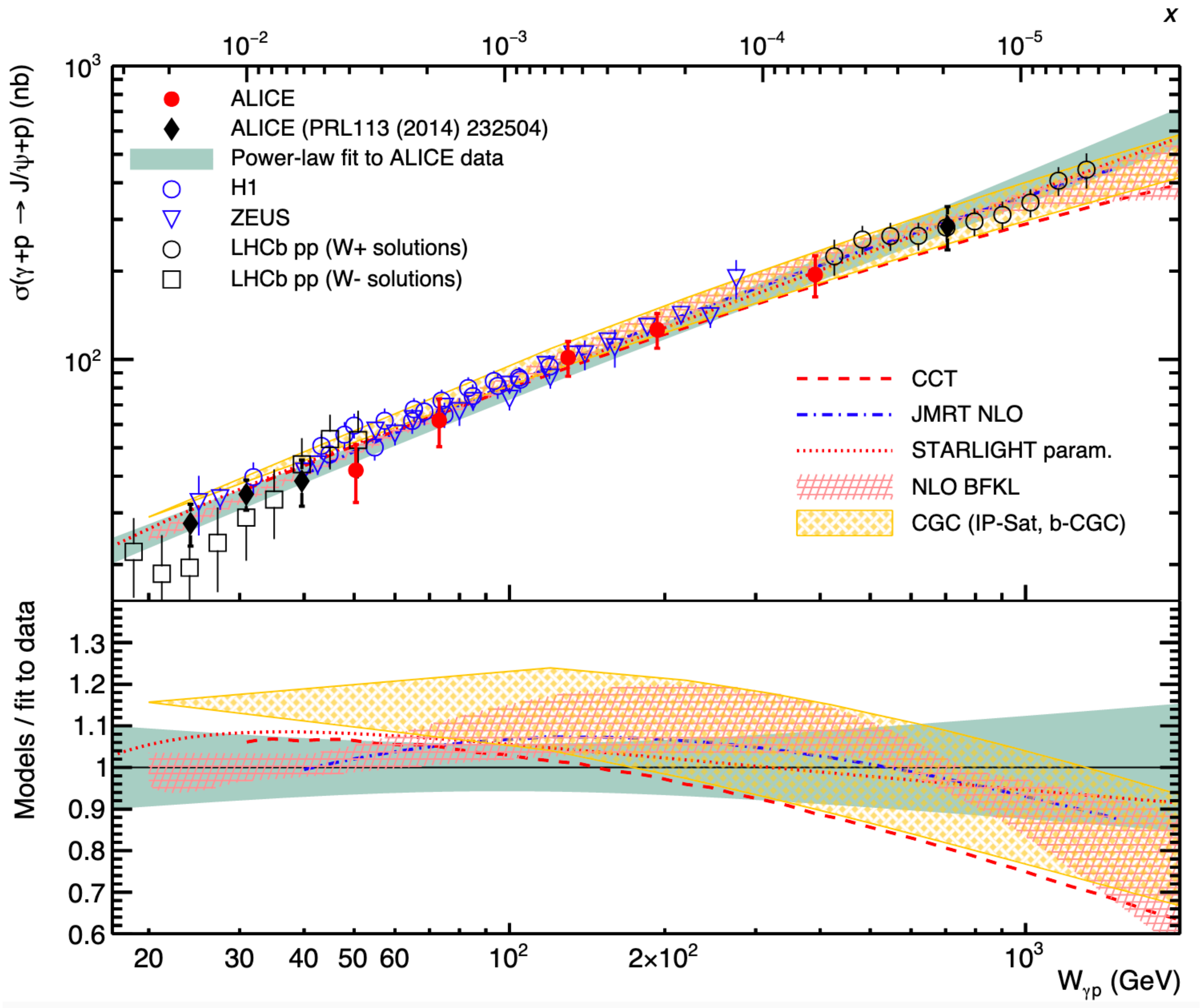
ref: L.V. Gribov, E.M. Levin, and M.G. Ryskin, Phys. Rept. 100 (1983) 1.

p–Pb collisions at ALICE (Run 1)



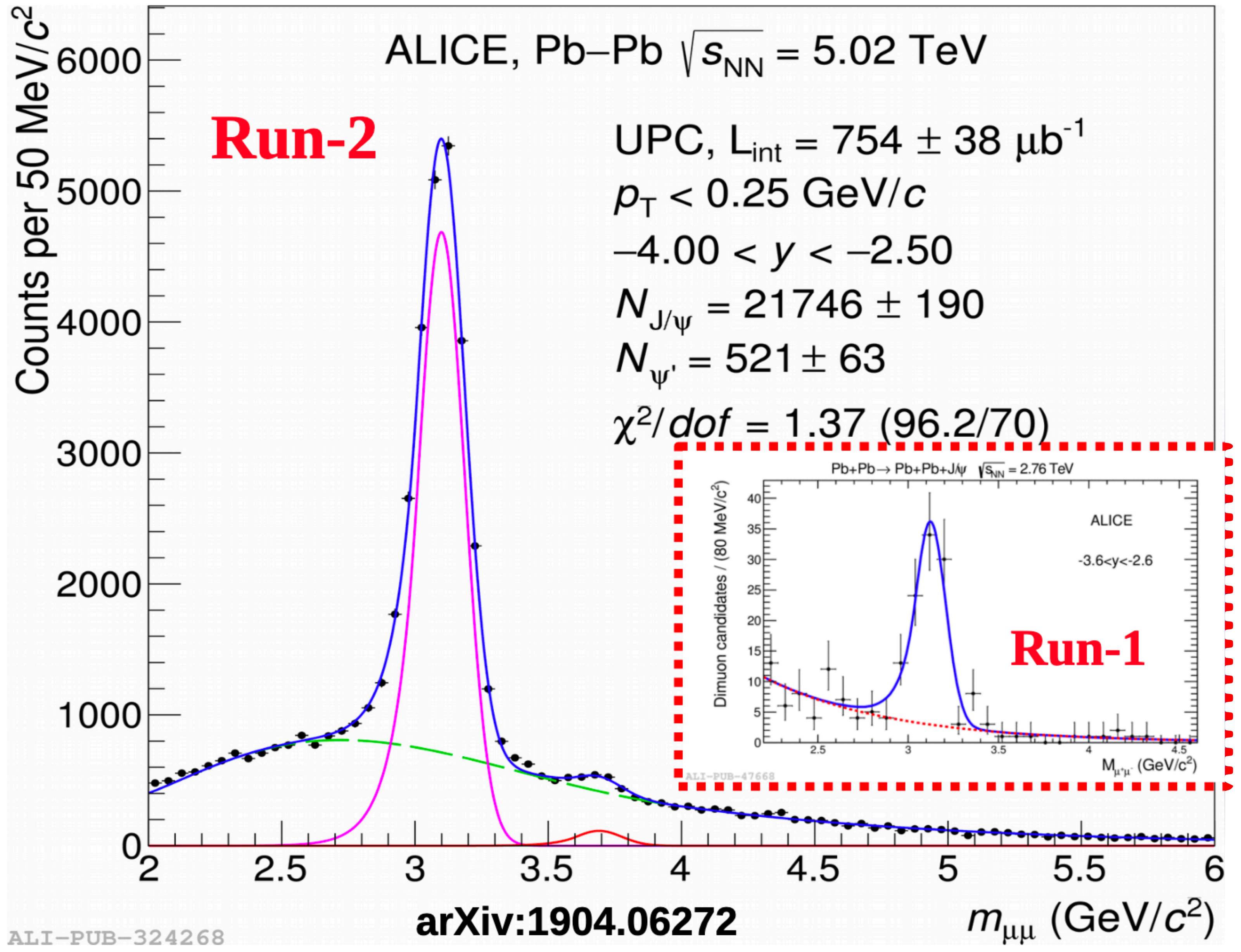
p–Pb collisions at ALICE (Run 1)

- Measurement in a single experiment from 20 GeV to 700 GeV corresponding to 3 orders of magnitude in x from 10−2 to 10−5. $x = \frac{M^2_{J/\Psi}}{W^2_{\gamma p}}$
- N(Wγp/90)δ
- Exponent value δ=(0.70±0.05).
- Exponent value compatible with previous ALICE data.
- Exponent value compatible with HERA measurements as well.
- Agreement with various models and LHCb solutions.



ALICE: Eur.Phys.J. C79 (2019), 402

Pb–Pb UPCs in ALICE (Run 2)

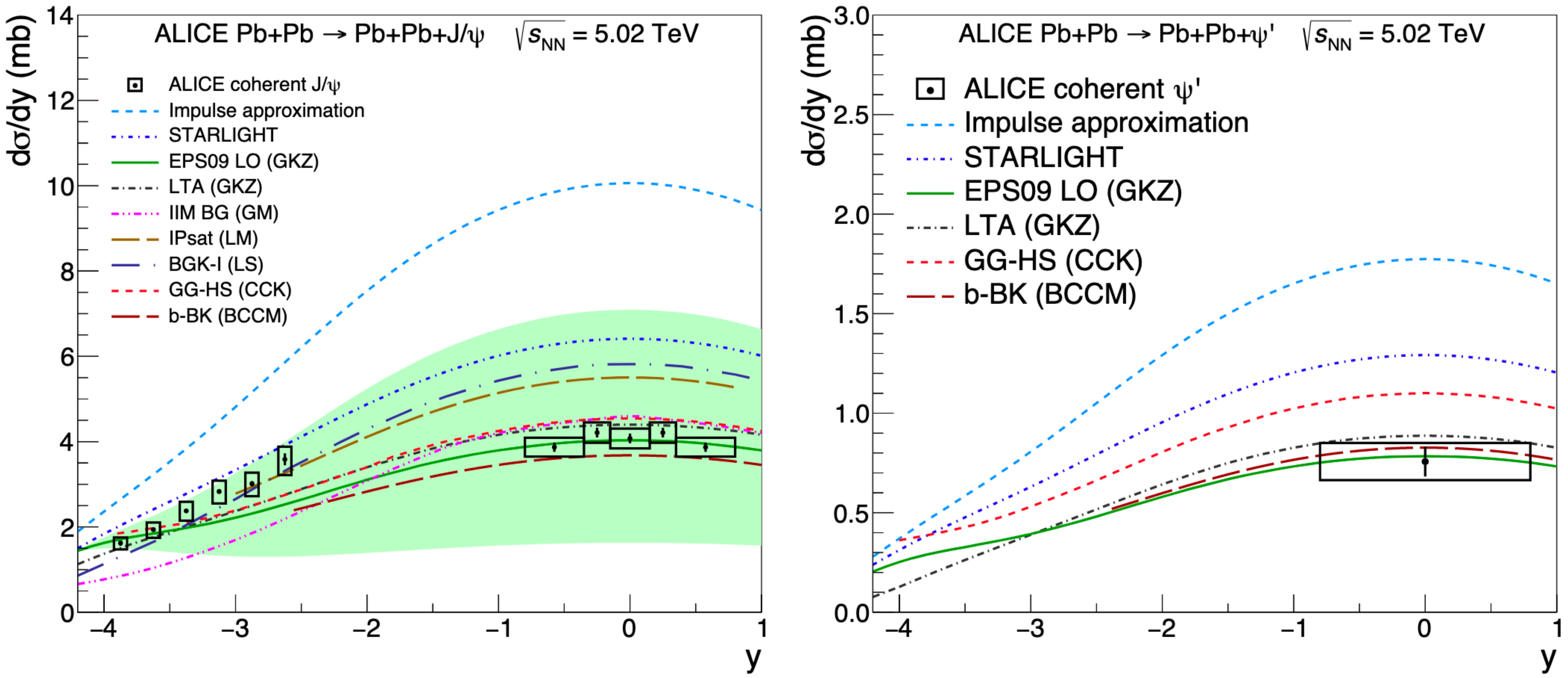


arXiv:1904.06272

- Increased LHC Run-2 Pb-Pb luminosity (∫L > 700 μb−1) together with larger J/ψ photoproduction cross section and more efficient event triggering provides ~200 times larger J/ψ yield as compared to the Run-1 data. Forward AD detector, installed for Run-2 and included into the trigger suppresses background from peripheral heavy-ion collisions. It provides a cleaner sample than was possible in the Run 1 data.

Pb–Pb UPCs in ALICE (Run 2)

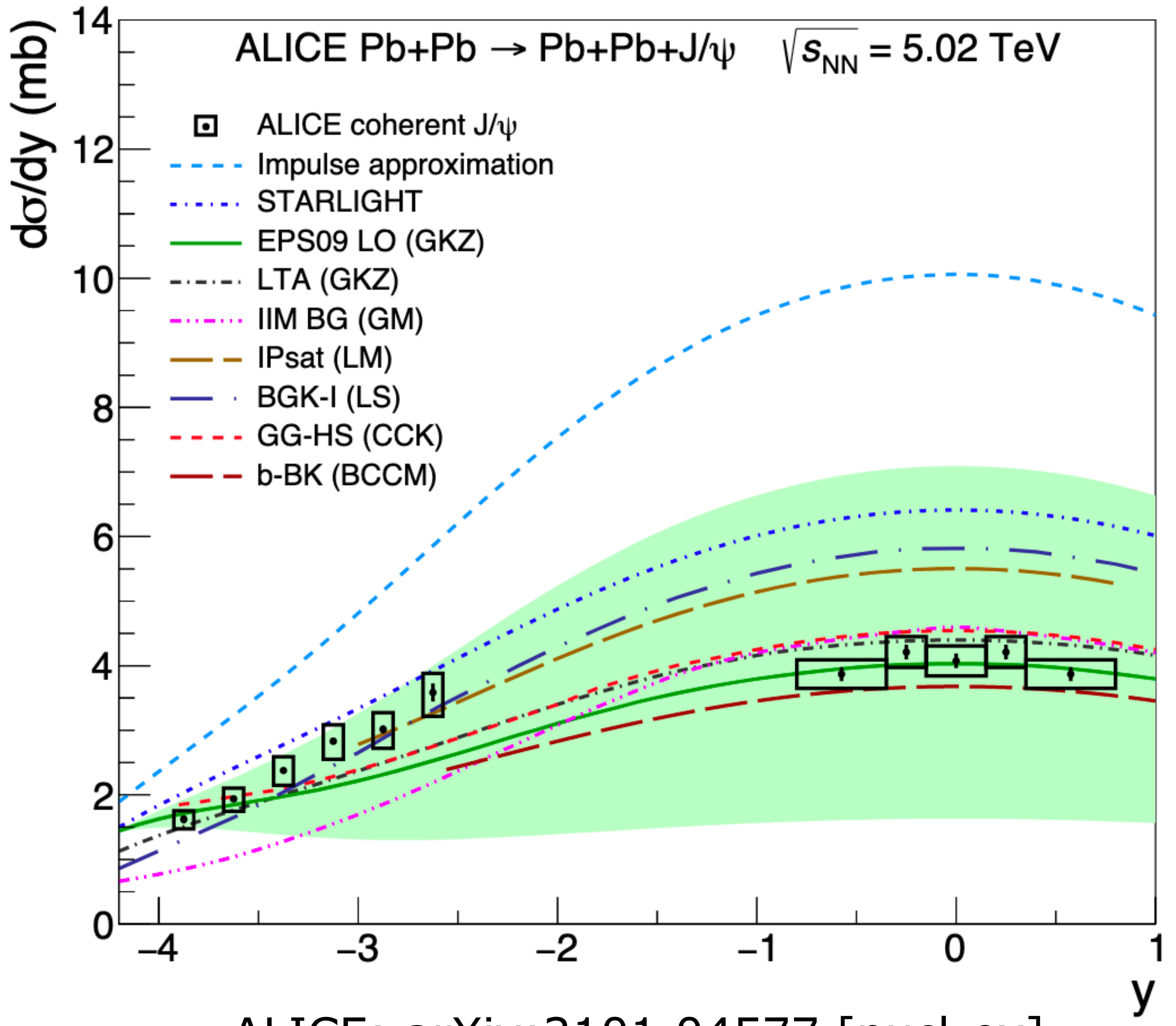
- New midrapidity points.
- Large integrated luminosity allowed to measure the rapidity dependence.
- Comparison of data to the impulse approximation implies SPb(x~10−3) = 0.65±0.03.
- GKZ with EPS09 shadowing andthe GG-HS (colour-dipole model with hot spots and including saturation) fitdata at central and forward rapidities,but not at semi-forward rapidities.
- Supports results from J/ψ. Extraction of ψ′/J/ψ compatible with:
  - Previous ALICE measurement at fwdy,ALICE: Phys.Lett. B 798 (2019) 134926
  - H1 measurement in ep collisions,H1: Phys.Lett. B 541 (2002) 251-264
  - LHCb measurement in pp collisions, LHCb: JHEP 10 (2018) 167
  - GKZ predictions in the leading twist approximation (LTA) or shadowing with EPS09.Guzeyet. al.: Phys. Rev. C 93 no. 5, (2016) 055206



ALICE: arXiv:2101.04577 [nucl-ex]

Pb–Pb UPCs in ALICE (Run 2)

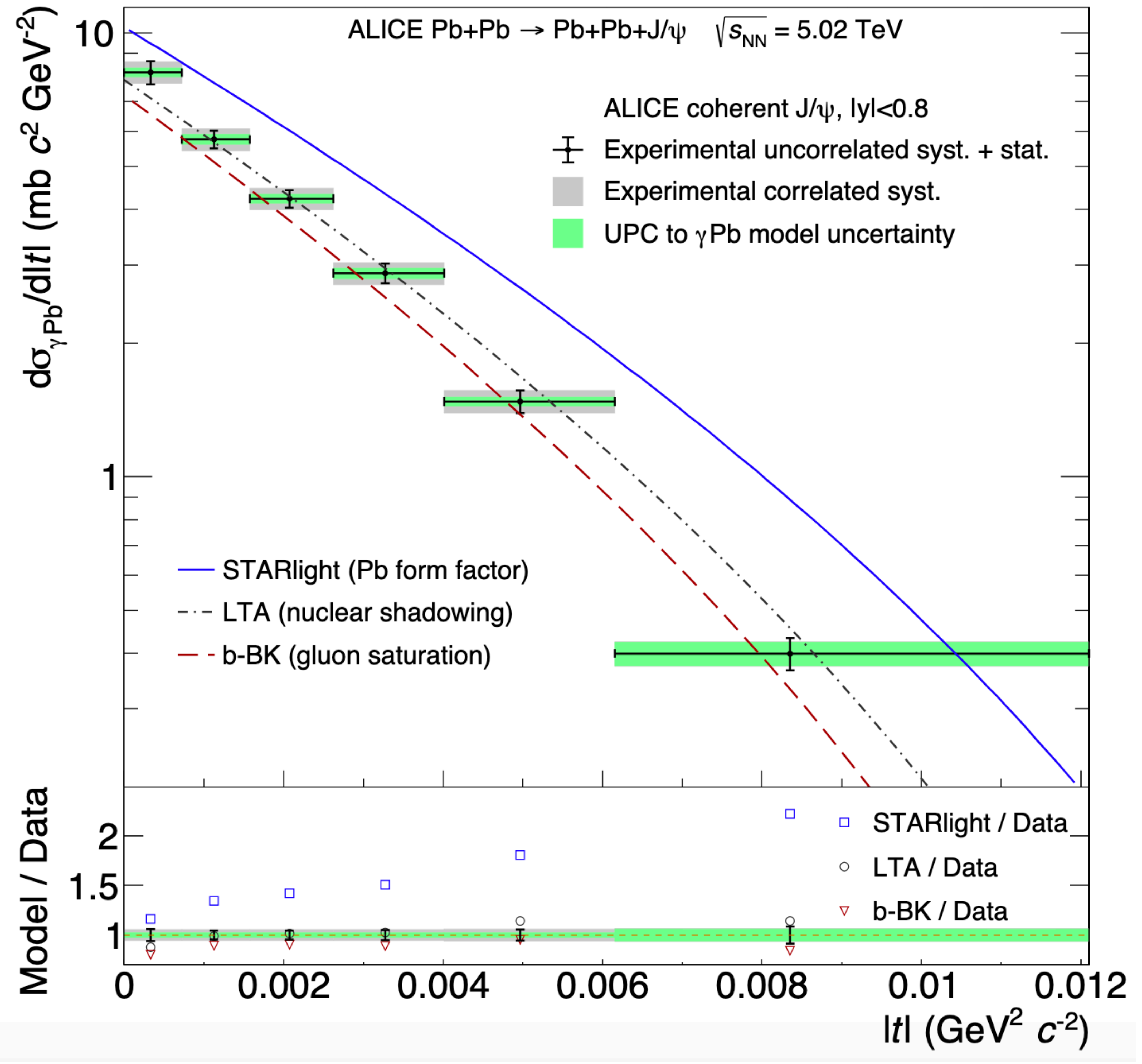
- GKZ with EPS09 shadowing and the GG-HS (colour-dipole model with hot spots and including saturation) fit data at central and forward rapidities, but not at semi-forward rapidities (arXiv:2101.04577v1 [nucl-ex])
- Models:
  - IA (impulse approximation), taken from STARlight: based on data from exclusive J/ψ photoproduction off protons, neglects all nuclear effects except for the coherence. It takes into account multiple interactions within the nucleus but not the gluon shadowing corrections.
  - GKZ: 2 calculations, one based on the EPS09 LO parametrization of the available nuclear shadowing data and the other on the leading twist approximation (LTA) of nuclear shadowing based on the combination of the Gribov-Glauber theory and the diffractive PDFs from HERA.
  - CCK: based on the color dipole model with the structure of the nucleon in the transverse plane described by the so-called hot spots, regions of high gluonic density. Nuclear effects are implemented (energy-dependent hot-spot model with the standard Glauber-Gribov formalism (GG-HS)).
  - BCCM: based on the color dipole approach coupled to the solutions of the impact-parameter dependent Balitsky-Kovchegov equation with initial conditions based on the Woods-Saxon shape of the Pb nucleus.
  - + predictions for J/ψ within the color dipole approach coupled to the Color Glass Condensate (CGC) formalism with different assumptions on the dipole-proton scattering amplitude.



ALICE: arXiv:2101.04577 [nucl-ex]

Pb–Pb UPCs in ALICE (Run 2)

- First measurement ever of the|t|-dependence of J/ψ photonuclear production.
- |t|-dependence related by a 2D Fourier transform to the distribution of gluons in the impact-parameter plane.
- Comparison of data to the Pb form factor prediction implies existence of QCD dynamical effects.
- Models incorporating nuclear shadowing according to LTA or gluon saturation from the impact-parameter dependent Balitsky-Kovchegov (b-BK) describe well the data



ALICE: arXiv:2101.04623 [nucl-ex