

Open questions in high energy diffraction: pQCD vs nonperturbative QCD & experimental tools to explore them

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Diffraction in three limits

Nonperturbative/ soft QCD

Leading twist diffraction

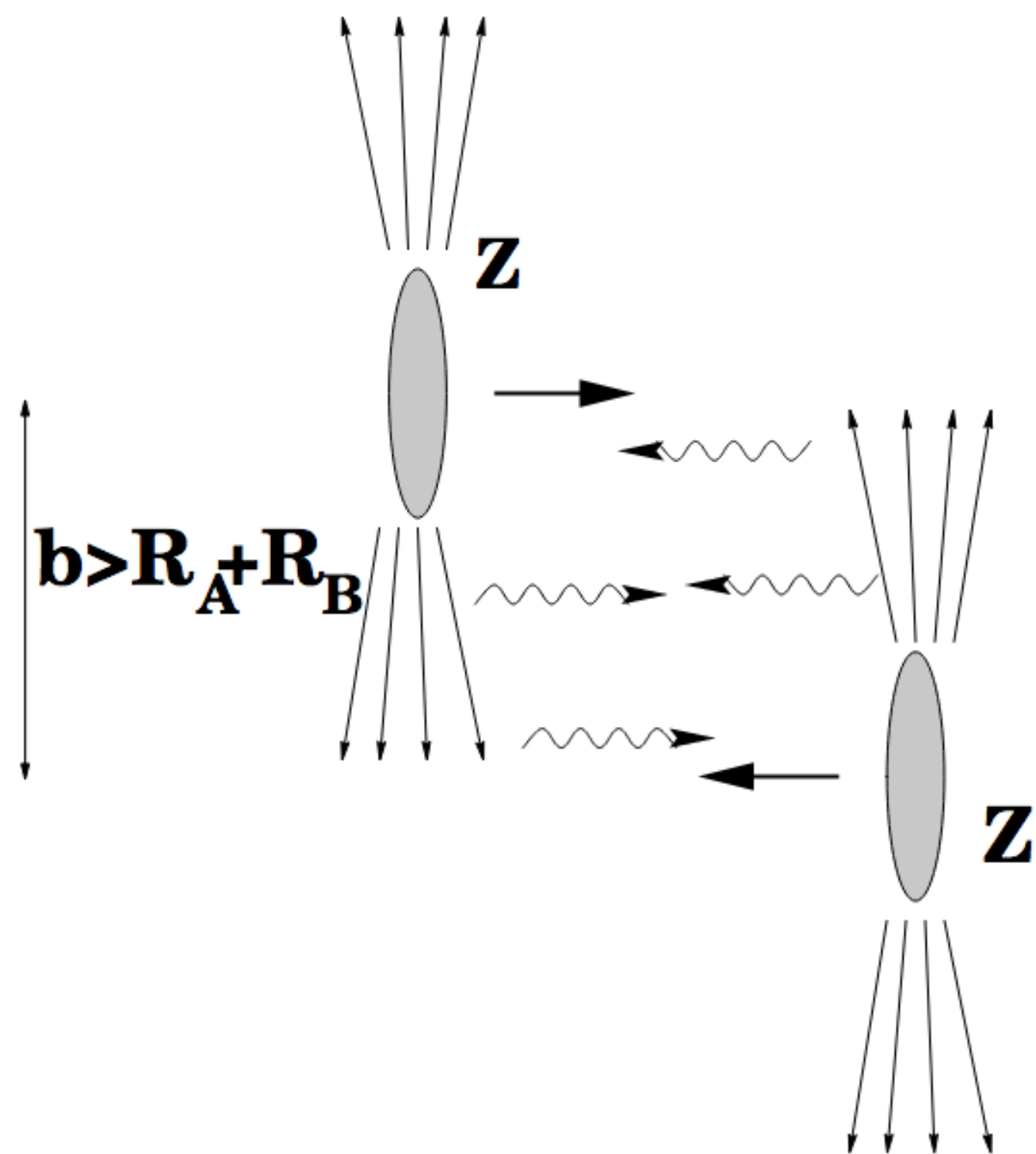
Collisions



BFKL regime: const virtuality & $s \rightarrow \infty$



Current high energy diffraction experimental information: -pp. at FNAL & LHC
DIS - HERA



Schematic diagram of an ultraperipheral (UPC) collision of two ions. The impact parameter, b , is larger than the sum of the two radii, $R_A + R_B$.

Depending on the channel $W_{\gamma N}$ up to 1 TeV can be reached. Hardness of the process can be regulated using different final states.

Next 10 -15 years - the only reasonably direct way to probe small x dynamics at moderate virtualities is study of different UPC at the LHC (pA, AA, pp)

Soft QCD — Universal soft Pomeron ?

$\alpha_{IP}(t) = \alpha_0 + \alpha' t$ **Classical Pomeron - Regge trajectory , hence universal** $A(s, t) \propto s^{\alpha_{IP}(t)}$

$\alpha_0 = 1.08; \alpha' = 0.25 \text{ GeV}^{-2}$ **from pp data**

Cuts = multipomeron exchanges break universality

Puzzle: for ρ - meson photoproduction (most recent data) $\alpha_0 = 1.06; \alpha' = 0.10 \text{ GeV}^{-2}$

Need of special analysis of UPC

The same α' as for J/ψ !!!!!

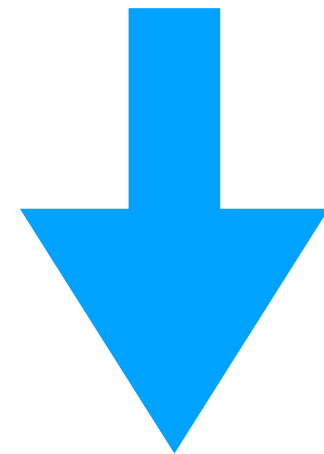
pp - LHC energies: strong deviation from linear Pomeron trajectory fit: $\alpha' = 0.5 \text{ GeV}^{-2}$

ODDERON

Strong evidence for significant C-odd amplitude at high energies,

Is it a Regge trajectory? A perturbative construction?

**Oddeon amplitude in all models has $t=0$ intercept not exceeding 1. Hence
Odderon/ Pomeron should be much larger at $s^{1/2} \sim 30$ GeV than at the LHC**



$\bar{p}p \rightarrow \bar{p}p$ **Data at intermediate energies & joint analysis of fixed and collider data**

Reactions with large odderon contribution in UPC. For example

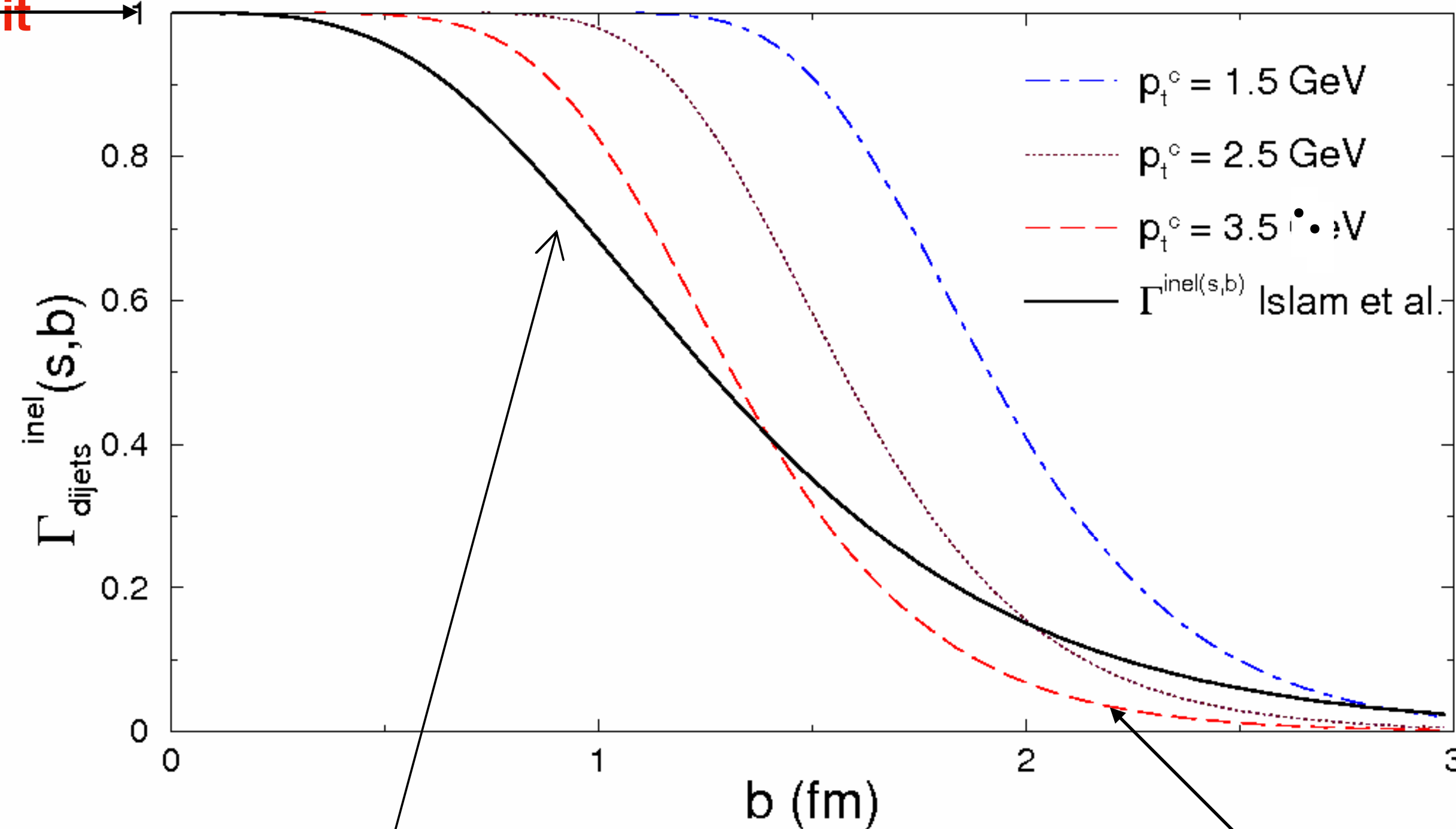
$$AA \rightarrow \chi_c AA$$

S- channel picture of Pomeron, connection to generalized parton distributions and multiparton interactions

- *Is pp interaction at the LHC predominantly black: **No** it is grey*
- *Are pp interactions are predominantly due to minijets? Perhaps.*

Answer sensitive to transverse spread of gluon generalized parton densities

Black limit



$$\sqrt{s} = 14 \text{ TeV}$$

CTEQ 6M gluon pdfs

extrapolated profile function extrapolated profile function from elastic cross section

Also: At large b large contribution to Γ^{inel} is from diffraction where jet production is suppressed

Interface of perturbative and nonperturbative QCD remains a challenge

— exploration of minijet suppression, diffraction with dijet production in pp scattering

$$pp \rightarrow p + \underbrace{dijet + Y}_{M_{\text{diff}}}$$



M_{diff}

$$\sigma = \sigma_{\text{imp. approx}} R_{\text{supp}}$$



$\sim 1/20$ at LHC consistent with s-channel geometry of the process

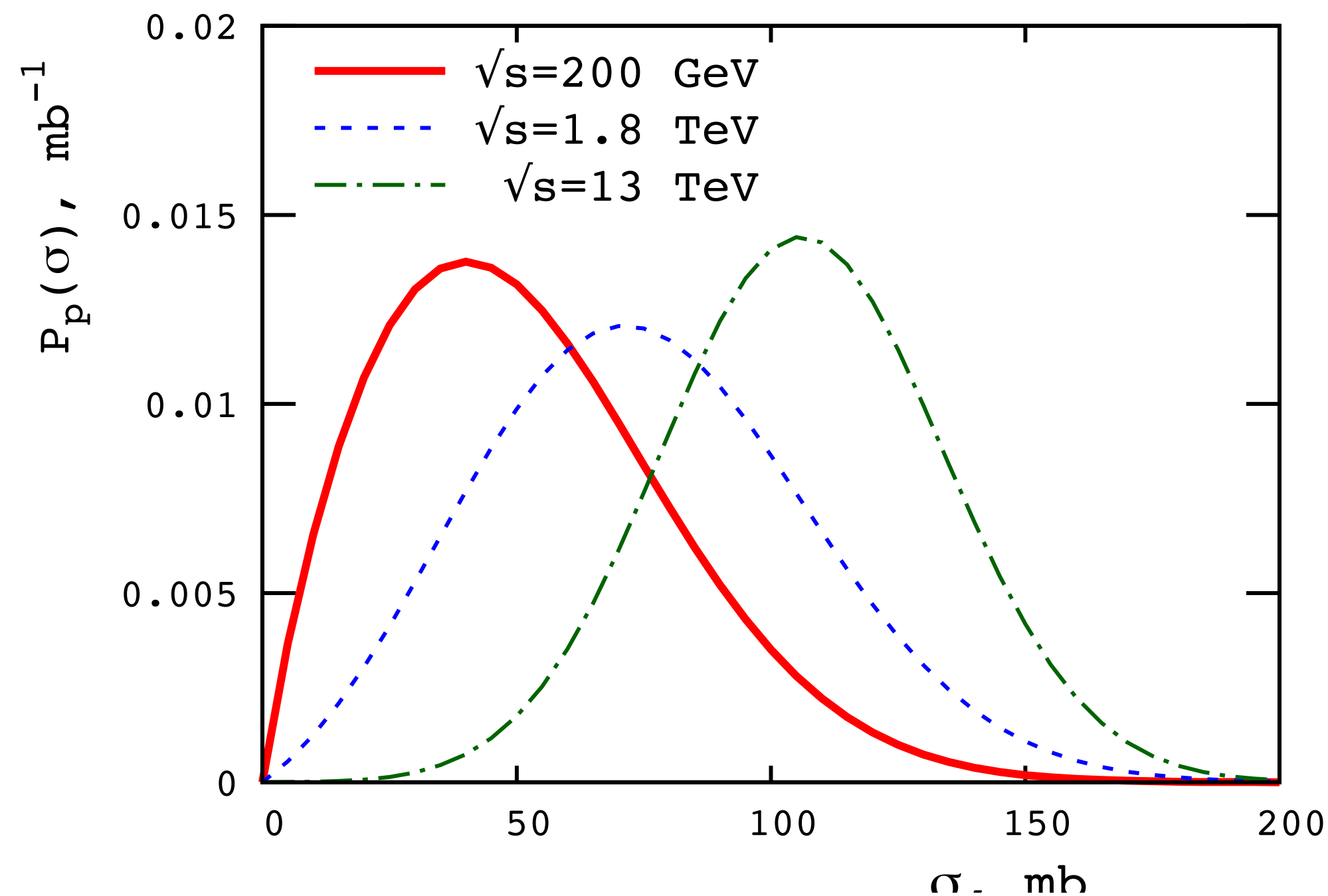
Fluctuations of σ_{pp} may result in x_p dependence of R_{diff} .

- How much does strength of pp interaction fluctuates?

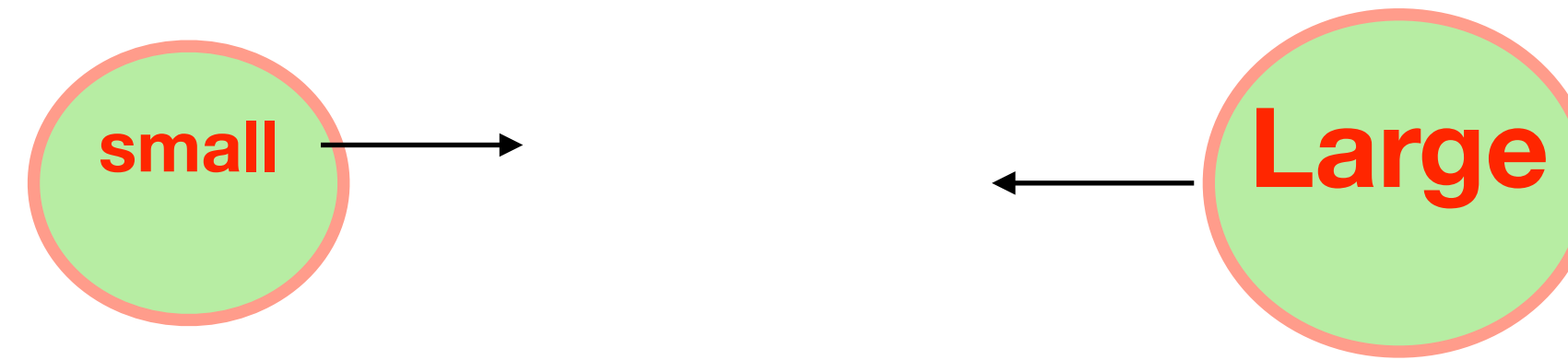
Convenient quantity - $P(\sigma)$ - probability that nucleon interacts with cross section σ

If there were no fluctuations of strength - there would be no inelastic diffraction at $t=0$:

$$\left. \frac{\frac{d\sigma(pp \rightarrow X+p)}{dt}}{\frac{d\sigma(pp \rightarrow p+p)}{dt}} \right|_{t=0} = \frac{\int (\sigma - \sigma_{tot})^2 P(\sigma) d\sigma}{\sigma_{tot}^2} \equiv \omega_\sigma \quad \text{variance}$$



Challenge: to measure ω_σ at LHC
Enters in modeling of pA and AA collisions



cross section of a small dipole off a proton/ nucleus interaction is small, proportional to area of dipole occupied by color, and to gluon density of target and hence grows with decrease of x.

$$\sigma(q\bar{q}T) = \frac{\pi^2}{3} r_{tr}^2 x g_T(x, Q^2 = \lambda/r_t^2) \alpha_s(Q^2)$$

Studies of the diffraction at HERA stimulated derivation of **new QCD factorization theorems**. In difference from derivation in the inclusive case which used closure, main ingredient is the color transparency property of QCD (as reflected in above equation)

Hard Exclusive processes for which factorization is demonstrated

$$\gamma^* + N \rightarrow \gamma + N(\text{baryonic system})$$

D.Muller 94 et al, Radyushkin 96, Ji 96, Collins & Freund 98

$$\pi + T(A, N) \rightarrow jet_1 + jet_2 + T(A, N)$$

Frankfurt, Miller, MS 93 & 03

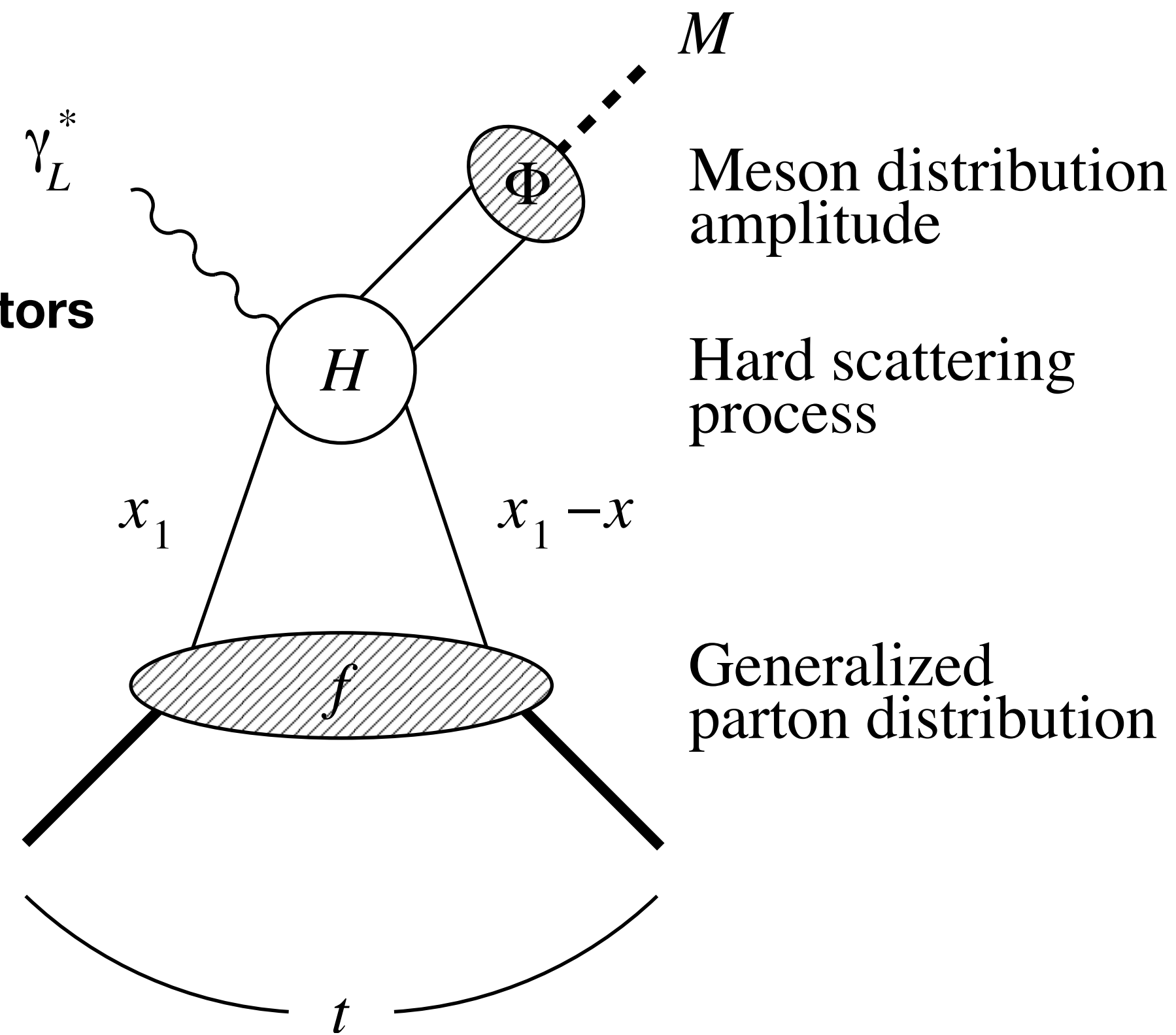
$$\gamma_L^* + N \rightarrow \text{"meson"}(\text{mesons}) + N(\text{baryonic system})$$

Brodsky, Frankfurt, Gunion, Mueller, MS
94- vector mesons, small x

Collins, Frankfurt, MS 97 - general case

provide new effective tools for study of the 3D hadron structure, color transparency and opacity and chiral dynamics as well as transverse dynamics of pp scattering

Amplitude factorizes - convolution of three factors



t-dependence only from GPD's

*transverse spatial
distribution of partons*



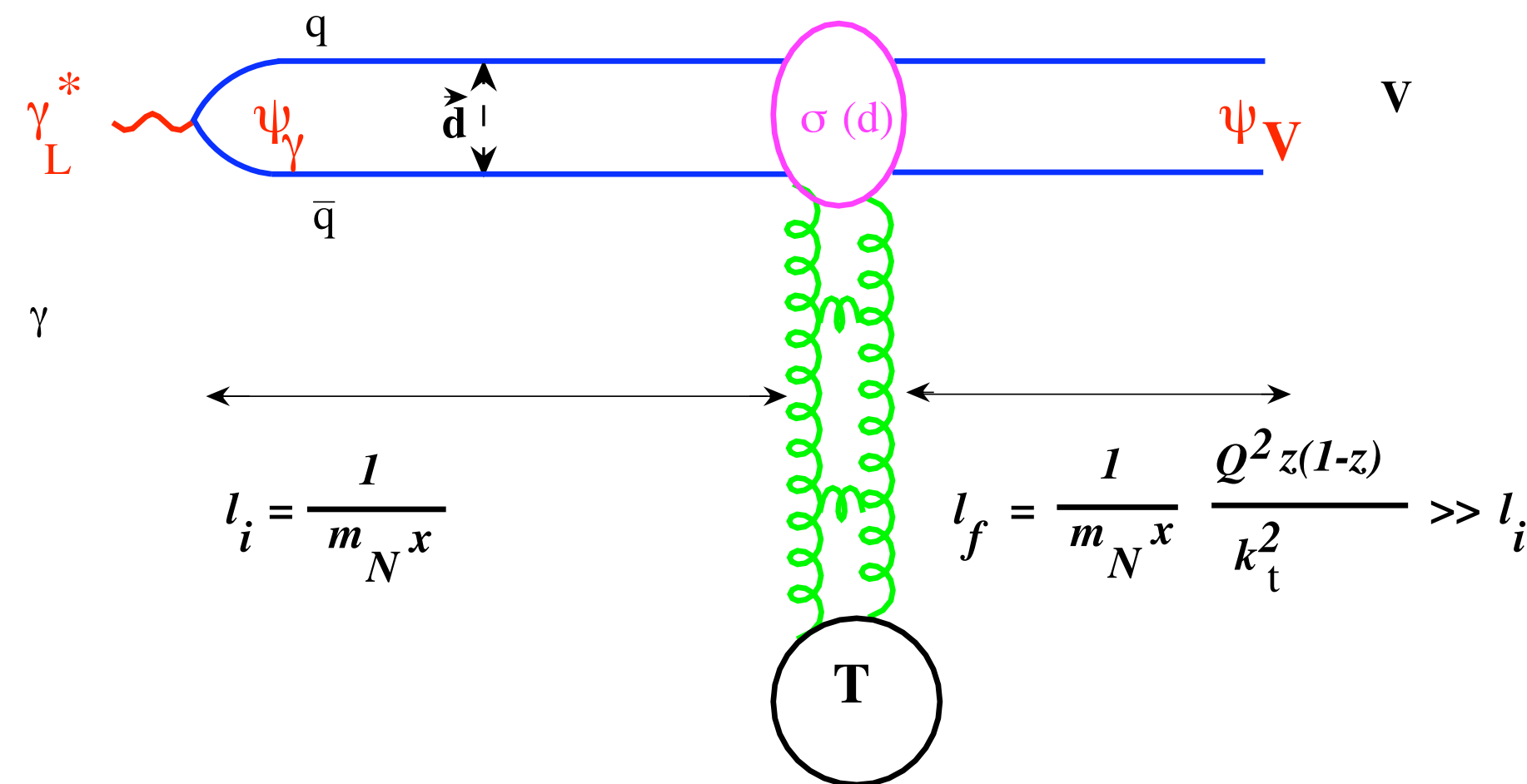
$$f(x, \rho) \equiv \int d^2 \vec{\Delta} e^{i \vec{\Delta} \cdot \vec{\rho}} f(x, x, t), \quad -t = \Delta^2$$

ρ - transverse distance
from the c.m. of proton

$$\rho_{c.m.} = \sum_i \rho_i x_i$$

Vector meson diffractive production: Theory and HERA data

Space-time picture of Vector meson production at small x in the target rest frame



\Rightarrow Similar to the $\pi + T \rightarrow 2jets + T$ process, $A(\gamma_L^* + p \rightarrow V + p)$ at $p_t = 0$ is a convolution of the light-cone wave function of the photon $\Psi_{\gamma^* \rightarrow |q\bar{q}\rangle}$, the amplitude of elastic $q\bar{q}$ - target scattering, $A(q\bar{q}T)$, and the wave function of vector meson, ψ_V : $A = \int d^2d \psi_{\gamma^*}^L(z, d) \sigma(d, s) \psi_V^{q\bar{q}}(z, d)$.

dipole cross section - given by pQCD at small b , can be fixed at large b from matching with soft dynamics to build a model for preasymptotic amplitude

How large are Q^2 are necessary to reach asymptotic regime? for cross section? For t-dependence?

$$\begin{array}{ccc}
 \text{energy denominator} & \frac{1}{Q^2 + \frac{m^2 + k_t^2}{z(1-z)}} & \xrightarrow{\text{operator of interaction}} \left(\frac{1}{Q^2 + \frac{m^2 + k_t^2}{z(1-z)}} \right)^4 \\
 & & \text{m- quark mass} \\
 & \xrightarrow{\quad} & \frac{Q^2}{(\mu^2 + Q^2)^4} \rightarrow \frac{1}{Q^6}
 \end{array}$$

A QCD dipole model of J/ψ production - aims to account more accurately for geometry

$$A(\gamma + p \rightarrow J/\psi + p) = \int d^2d \psi_{\gamma \rightarrow c\bar{c}}(z, d) \sigma_{tot}(c\bar{c}, p) \psi_{J/\psi}(z, d)$$

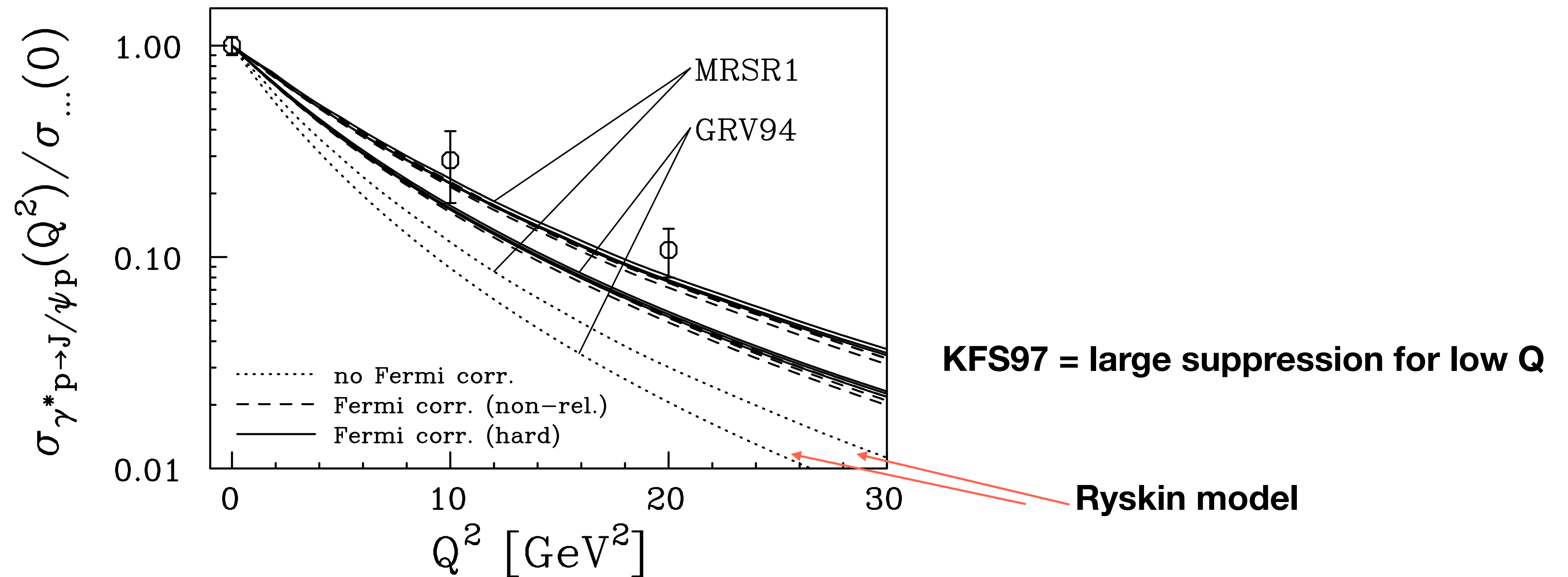
Slow onset of the LT for cross section both for light and heavy mesons

Slow squeezing of dipole size for light mesons, but early dominance of small dipoles for J/ψ

Open questions in exclusive J/psi production

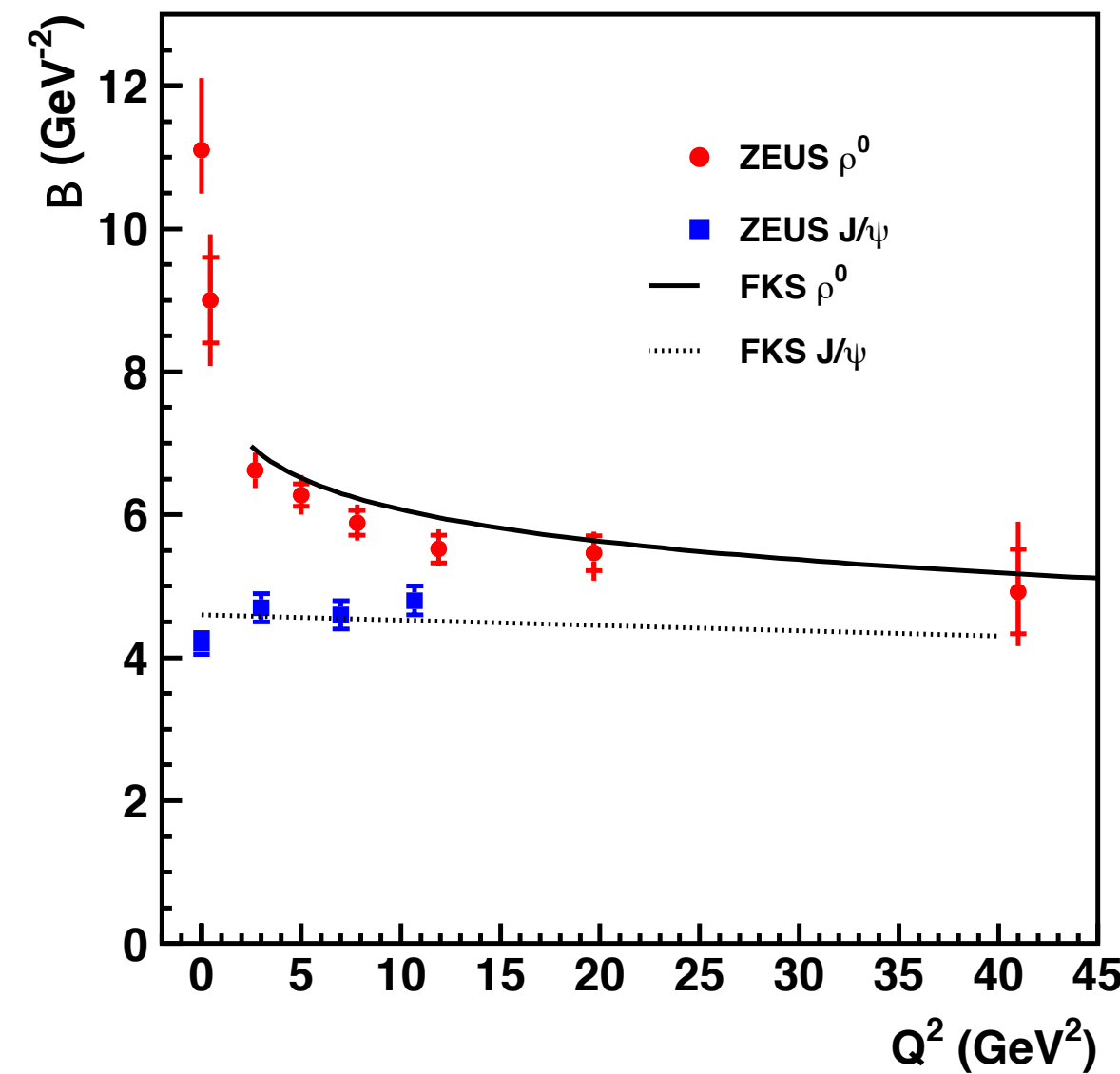
a) How safe it is to neglect Fermi motion of quarks

- Confirmation of the presence of the Fermi suppression factor $T(Q^2)$ in Q^2 dependence of J/ψ production:



- Universal t-slope: process is dominated by the scattering of quark-antiquark pair in a small size configuration - t-dependence is predominantly due to the transverse spread of the gluons in the nucleon - two gluon nucleon form factor/ diagonal gluon GPD $F_g(x,t)$. $d\sigma/dt \propto F_g^2(x,t)$. Onset of universal t-slope regime FKS[Frankfurt,Koepf, MS,97] **early for J/ψ late for ρ**

$$r_T \propto \frac{1}{Q} \left(\frac{1}{m_c} \right) \ll r_N$$



Convergence of the t-slopes, B - $\frac{d\sigma}{dt} = A \exp(Bt)$ ρ-meson electroproduction to the slope of J/ψ photo(electro)production.

⇒ Transverse distribution of gluons GPD) can be extracted from $\gamma + p \rightarrow J/\psi + N$

Correction for finite J/ψ size is ~ 10%.

DIRECTIONS OF FURTHER STUDIES OF GLUON GPDS

Theory: better understanding of finite size corrections for the t-distributions in

(a) photoproduction (UPC) of J/psi & Upsilon down to $x=10^{-4}$.

(b) EIC electroproduction for $x > \text{few } 10^{-3}$ production

Experiment: comparison of the t-dependence of J/psi and Upsilon

Strength of the gluon field should depend on the size of the quark configurations - for small configurations the field is strongly screened - gluon density much smaller than average.

Do we know anything about such fluctuations?

Yes - MS + LF + C.Weiss,
D.Treliani PRL 08

Consider $\gamma_L^* + p \rightarrow V + X$ for $Q^2 > \text{few GeV}^2$

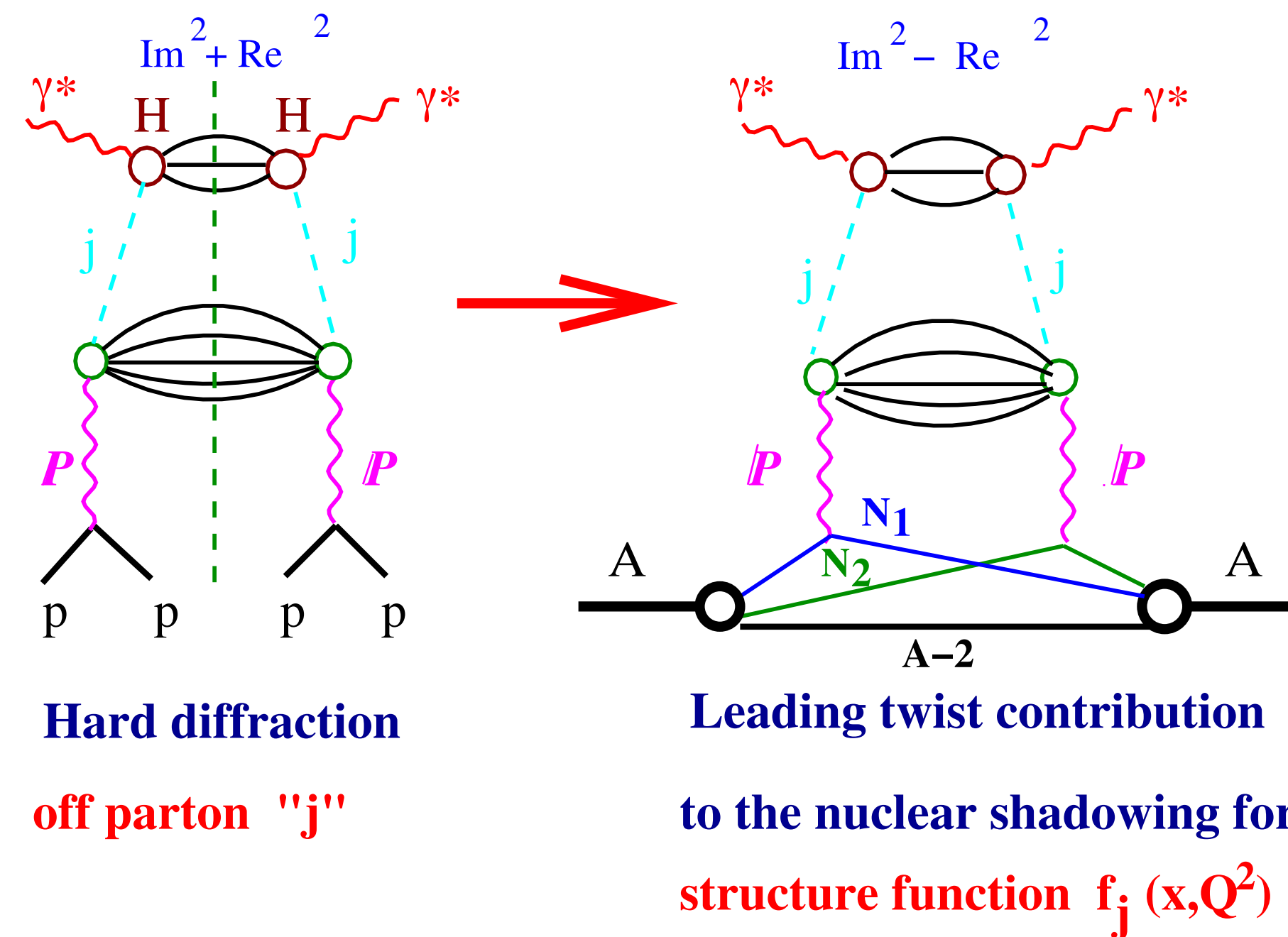
In this limit the QCD factorization theorem (BFGMS03, CFS07) for these processes is applicable

$$\omega_g \equiv \frac{\langle G^2 \rangle - \langle G \rangle^2}{\langle G \rangle^2} = \frac{d\sigma_{\gamma^*+p \rightarrow VM+X}}{dt} \bigg/ \frac{d\sigma_{\gamma^*+p \rightarrow VM+p}}{dt} \bigg|_{t=0}.$$

Comparable fluctuations to soft regime

Indications that ω_g drops with decrease of x at $x < 10^{-3}$

Deep connection between diffraction in DIS (diffractive pdfs $f_j^D(\frac{x}{x_P}, Q^2, x_P, t)$) and nuclear shadowing for nuclear pdf

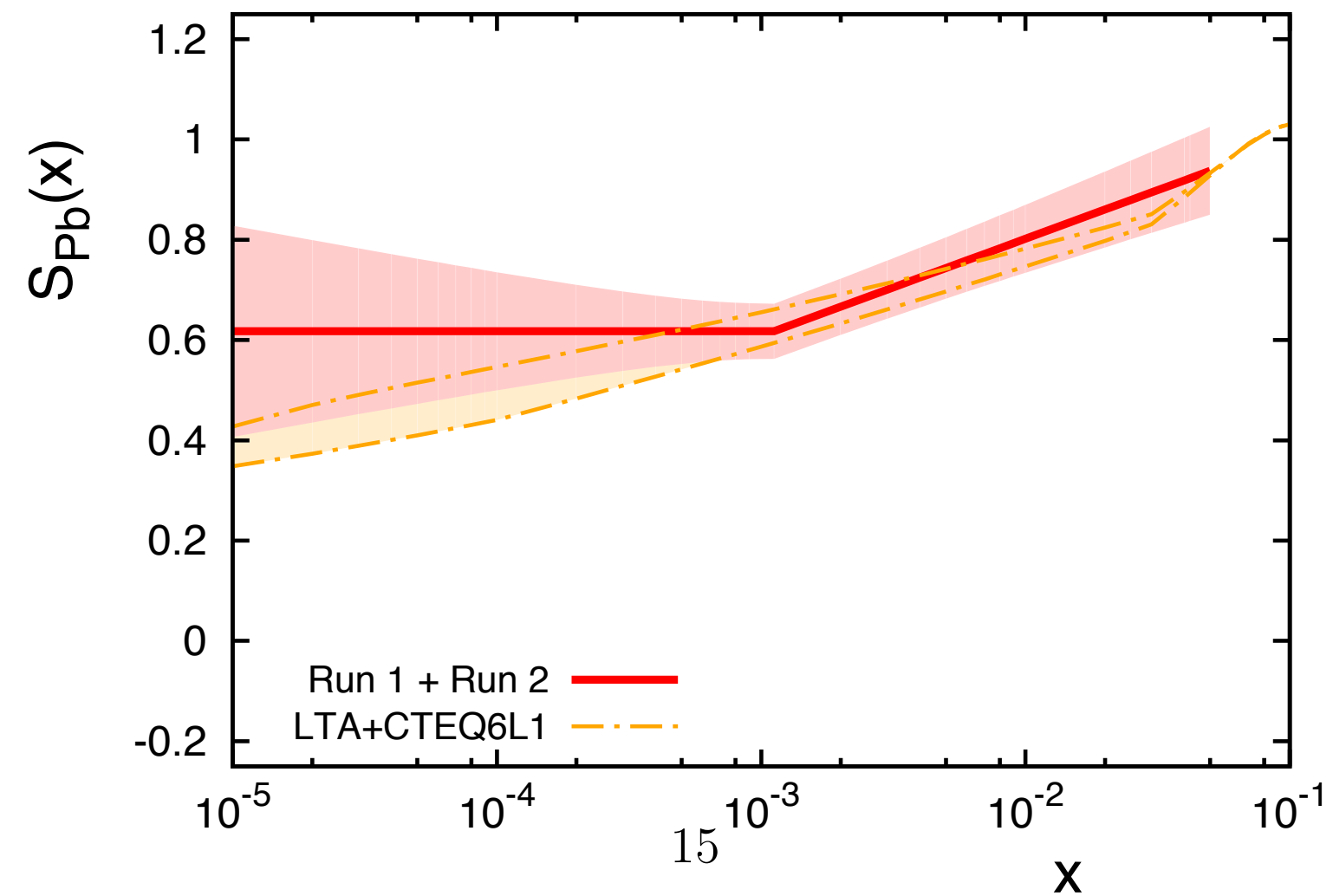
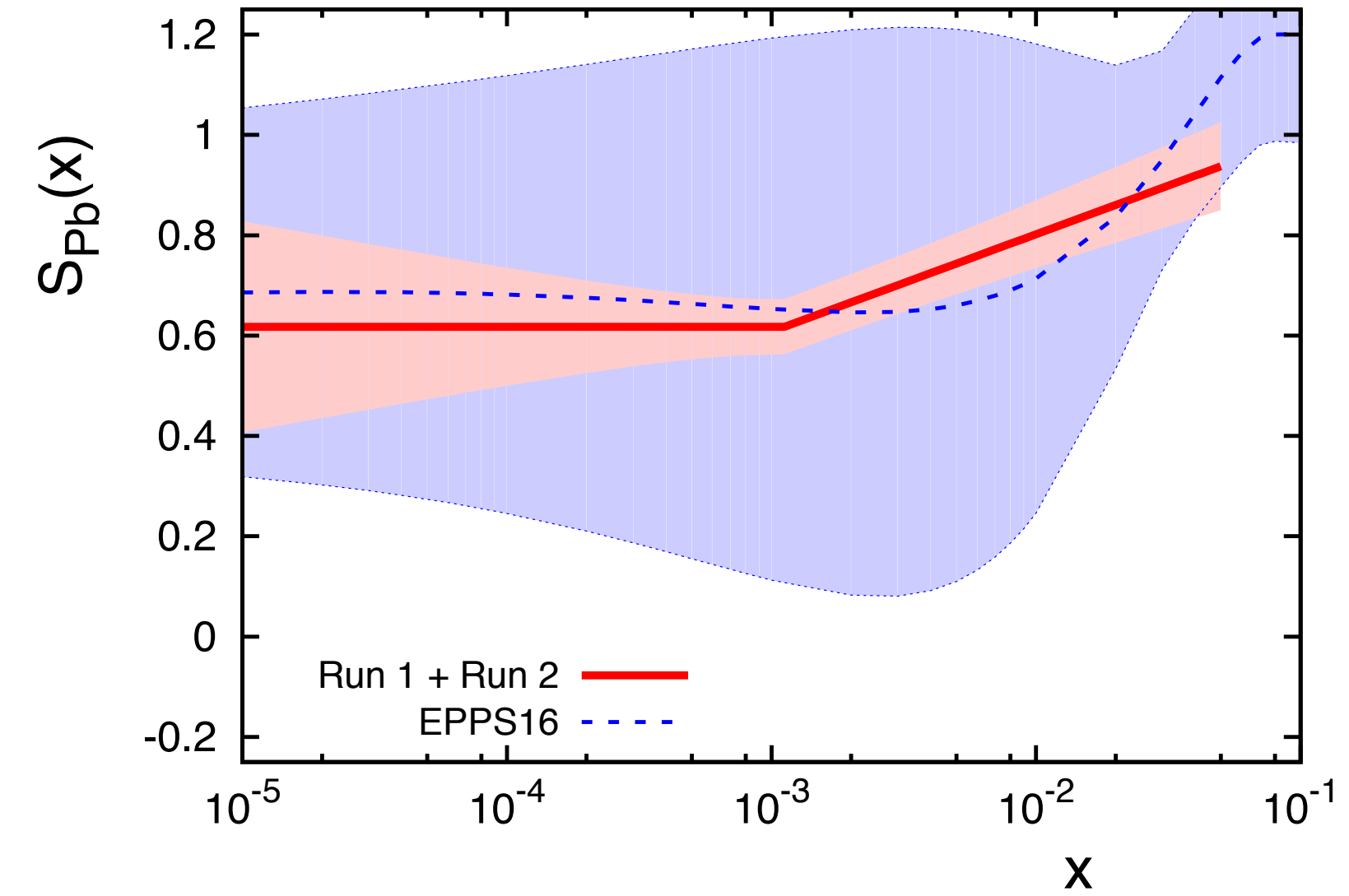
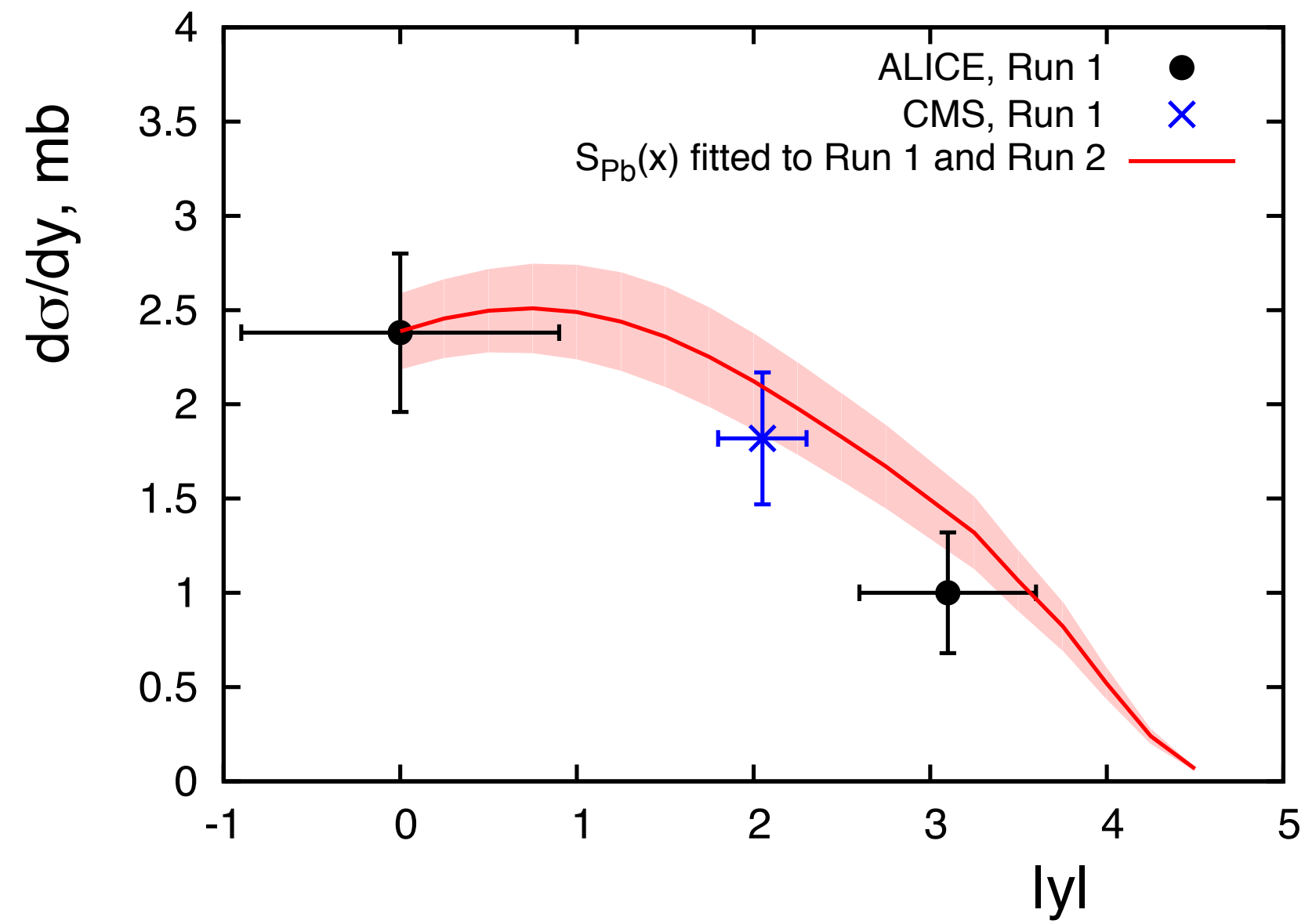


Predicted correctly shadowing for J/ψ in UPG: $\gamma A \rightarrow J/\psi A$ New LHC data allow to go below $y=0$, $x=m_{J/\psi}/2E_N$

Coherent UPC probably would remain the best source of information for gluon shadowing $g_A(x, \mu)/g_p(x, \mu)$ at small x for a long time, Impact for interpretation of pA, AA collisions

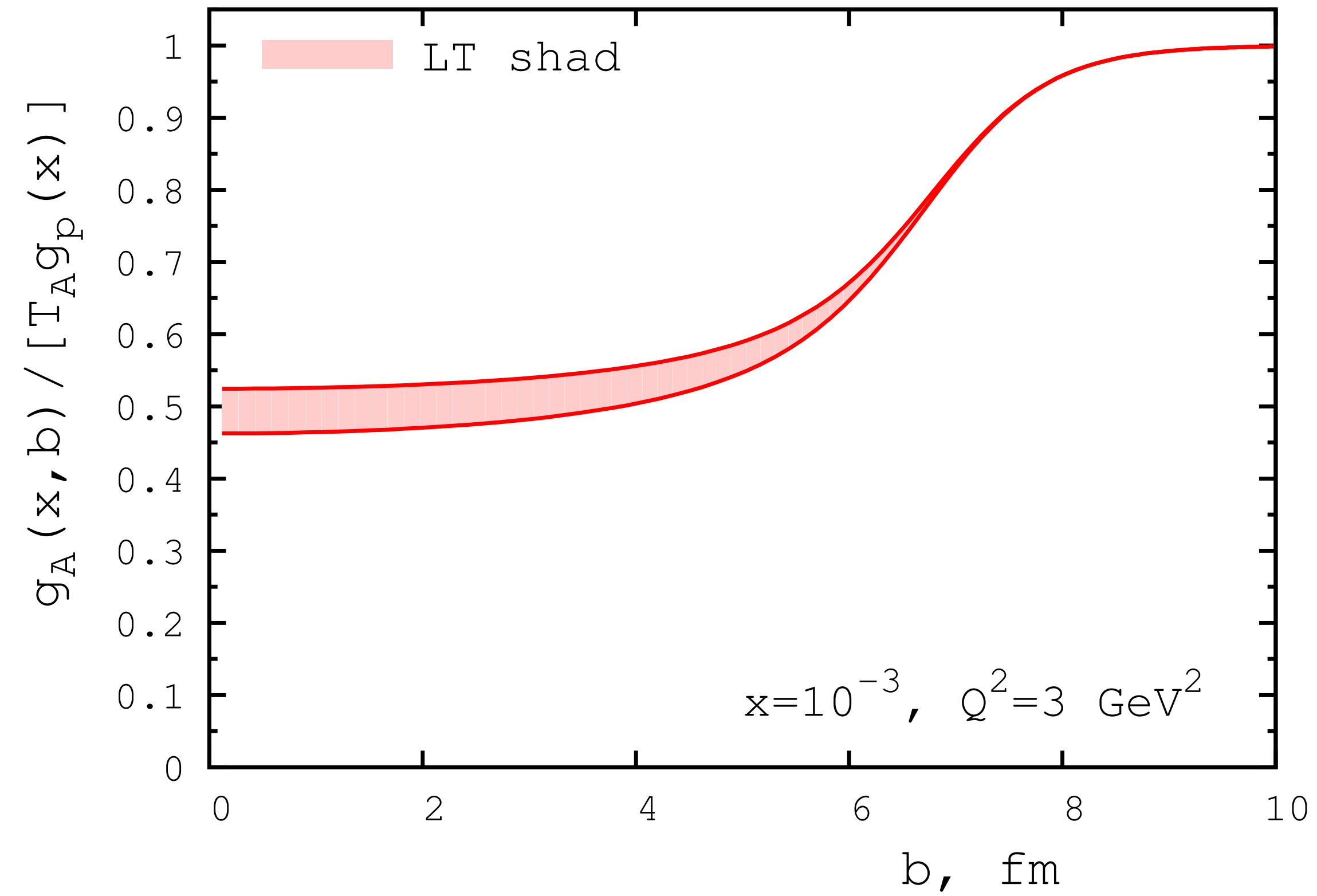
$$S_{Pb}(x) = \sqrt{\frac{\sigma_{\gamma A \rightarrow J/\psi A}(W_{\gamma p})}{\sigma_{\gamma A \rightarrow J/\psi A}^{\text{IA}}(W_{\gamma p})}} = g_A(x, \mu)/g_p(x, \mu) \quad \odot$$

Theoretical challenge - higher twist corrections for the relation \odot are probably small

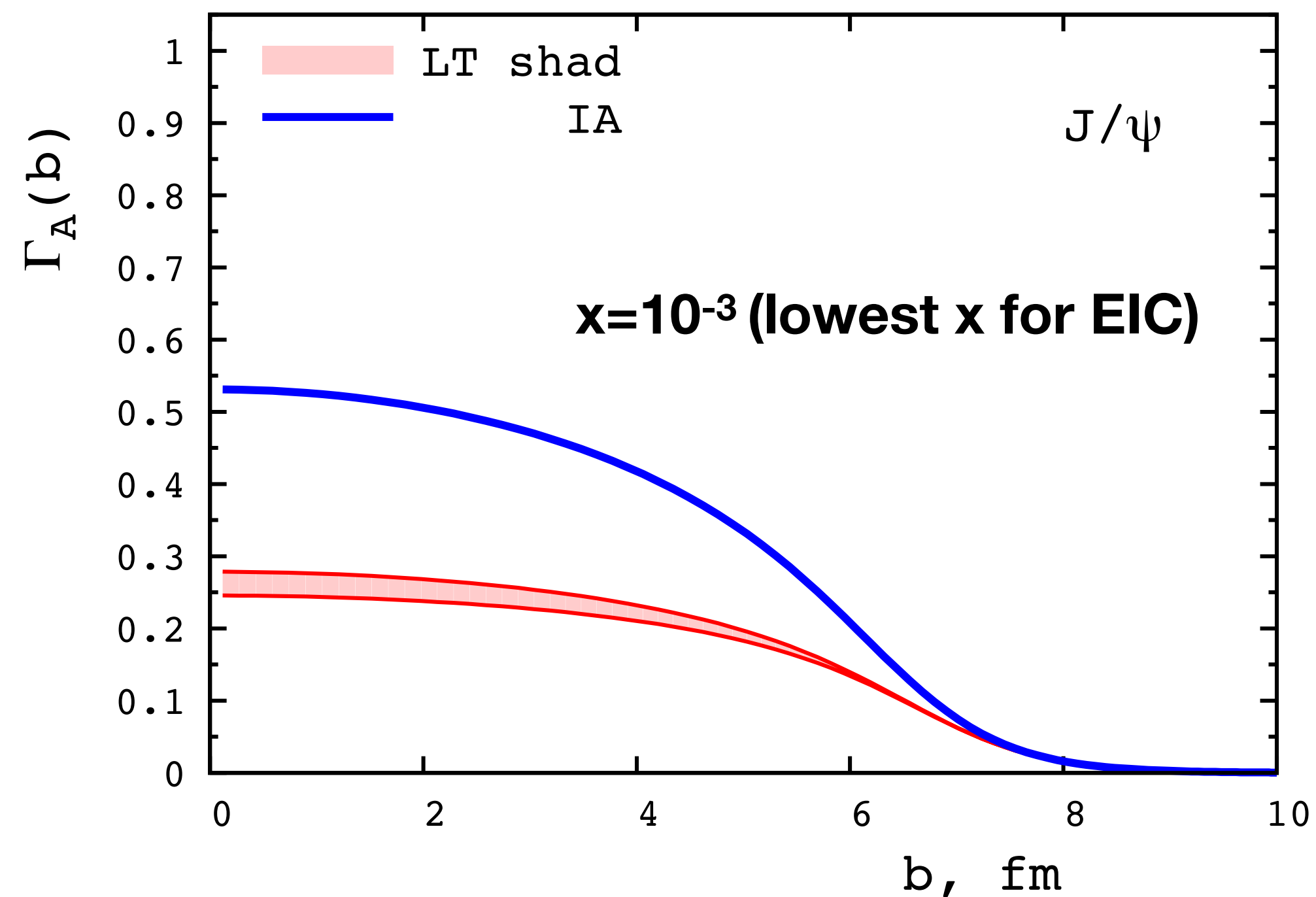


Our prediction (orange dashed dot) for $x=10^{-4}$ is bit below the range. Necessary to figure out the reasons for discrepancy between LHCb and ALICE & study impact parameter dependence of the J/ψ yield

we also predicted increase of t -dependence of coherent J/ψ production as compared to impulse approximation



Leading twist gluon shadowing in impact parameter space for coherent J/ψ photoproduction on Pb as a function of $|\vec{b}|$.



The scattering amplitude in impact parameter space $\Gamma_A(b)$ for coherent J/ψ photoproduction on Pb as a function of $|b|$.

Gluon shadowing changes regime of interaction for $x \sim 10^{-3}$ and small b from close to black (probability to interact inelastically) $1 - (1 - \Gamma)^2 = 0.77$ to grey $1 - (1 - \Gamma)^2 = 0.45$

To reach the black limit $x \sim 10^{-5}$ is necessary. About the same for scattering off protons

—> UPC at the LHC & eA collider like LHeC

BFKL regime: const virtuality & $s \rightarrow \infty$



Perturbative Pomeron: what is the energy dependence of cross section in the vacuum channel ?

Problem for the study - two large parameters $\ln Q^2$, and $\ln 1/x$.

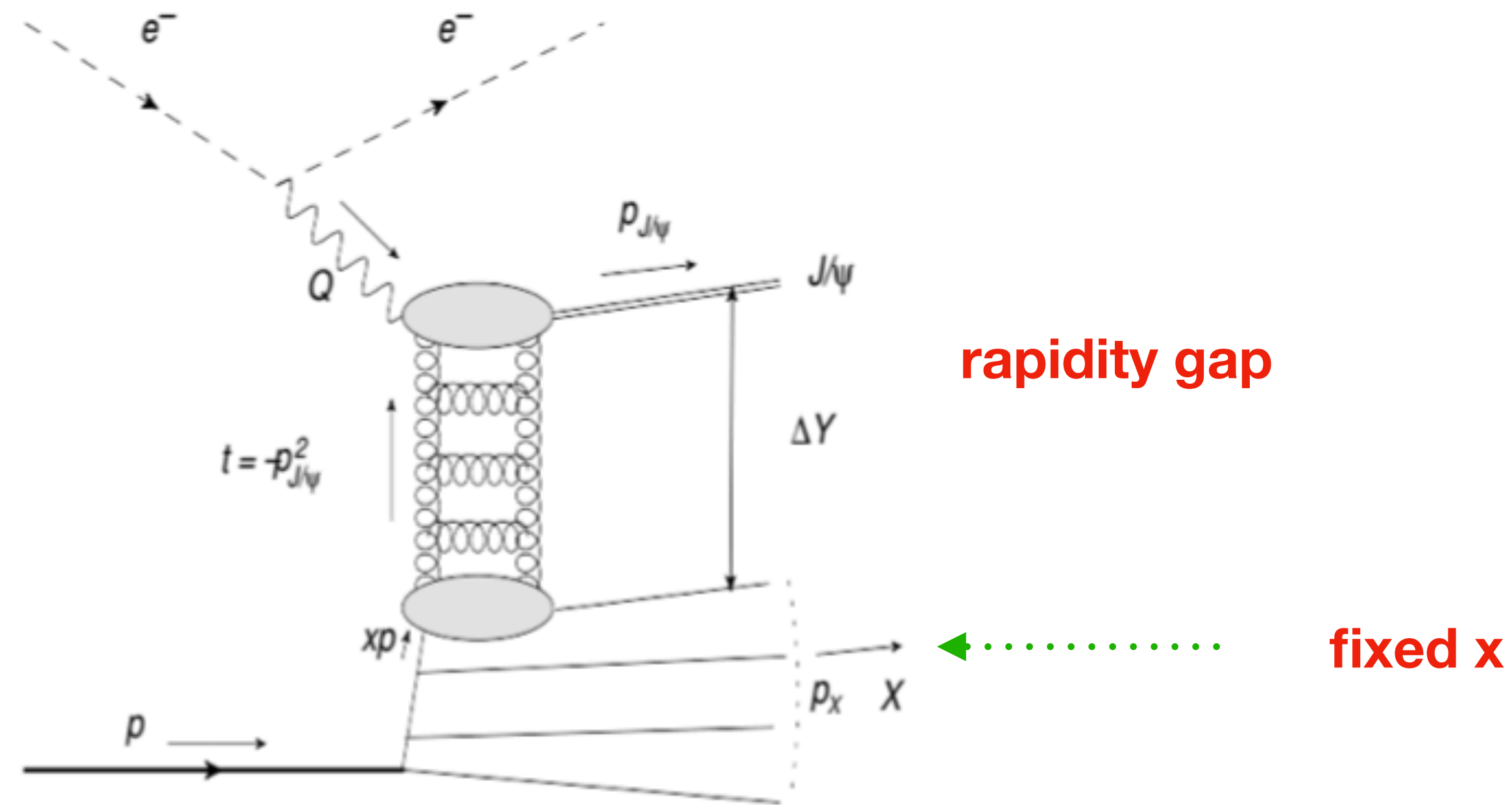
DIS - both parameters enter (DGLAP); BFKL - only $\ln 1/x$ (scattering of two small dipoles)

BFKL elastic amplitude $f(s) = (s/s_0)^{1+\omega_P}$

leading log $\omega_P \sim 0.5 \div 0.8$, NLO ~ 0.1 , resummation ~ 0.25

Main reason for small values of ω_P is energy conservation

Promising direction: Rapidity gaps at large t for J/ψ production - squeezing from both ends. Can be measured in UPC (pA) if good acceptance in proton fragmentation region



The choice of large t ensures several important simplifications:

* *the parton ladder mediating quasielastic scattering is attached to the projectile via two gluons.*

** *attachment of the ladder to two different partons of the target is strongly suppressed.*

*** *small transverse size $d_{q\bar{q}} \propto 1/\sqrt{-t} \sim 0.15\text{fm}$ for J/ψ for $-t \sim m_{J/\psi}^2$*

$$\frac{d\sigma_{\gamma+p \rightarrow V+X}}{dt d\tilde{x}} = \frac{d\sigma_{\gamma+quark \rightarrow V+quark}}{dt} \left[\frac{81}{16} g_p(\tilde{x}, t) + \sum_i (q_p^i(\tilde{x}, t) + \bar{q}_p^i(\tilde{x}, t)) \right]$$

$\exp(2\omega_p \Delta Y)$

resummation predicts a huge effect - between $\Delta Y = 2$ and $\Delta Y = 4$ σ is expected to increase by a factor of 3 !!!

if EIC would have a detector with fine acceptance in the nucleon fragmentation region. At LHC much larger ΔY can be reached \rightarrow even larger effect

Another new direction is production of two vector mesons in ultra peripheral heavy ion collisions

$$\gamma + \gamma \rightarrow J/\psi + J/\psi.$$

vs

$$\gamma + \gamma \rightarrow J/\psi + \rho$$

$$\gamma + \gamma \rightarrow \rho + \rho$$

Conclusions

- ❖ High energy diffraction have a tremendous potential for probing high energy QCD dynamics in soft and hard regimes in the ways complementary to inelastic processes.
- ❖ UPC at the LHC have the best potential for probing small x dynamics in the next decade. Additional information from pp & pA collisions at the LHC using improved forward acceptance of the LHC detectors.
- ❖ These studies may provide initial answers to a number of questions which would be to addressed at EIC. **Complementarity:** LHC = higher energy, lower statistics, higher minimal resolution (virtuality) scale. EIC - high precision, wide range of virtualities, but lower energy range hardly compensated by use of nuclear beams,

Supplementary slides

why heavy nucleus did not help significantly?

Where is $A^{1/3}$ factor?

nucleus is much more dilute than proton + gluon shadowing

$$\frac{Q_{sA}^2}{Q_{sN}^2} = A \frac{R_{gN}^2}{R_A^2} \frac{g_A(x, Q^2)}{A g_N(x, Q^2)}$$

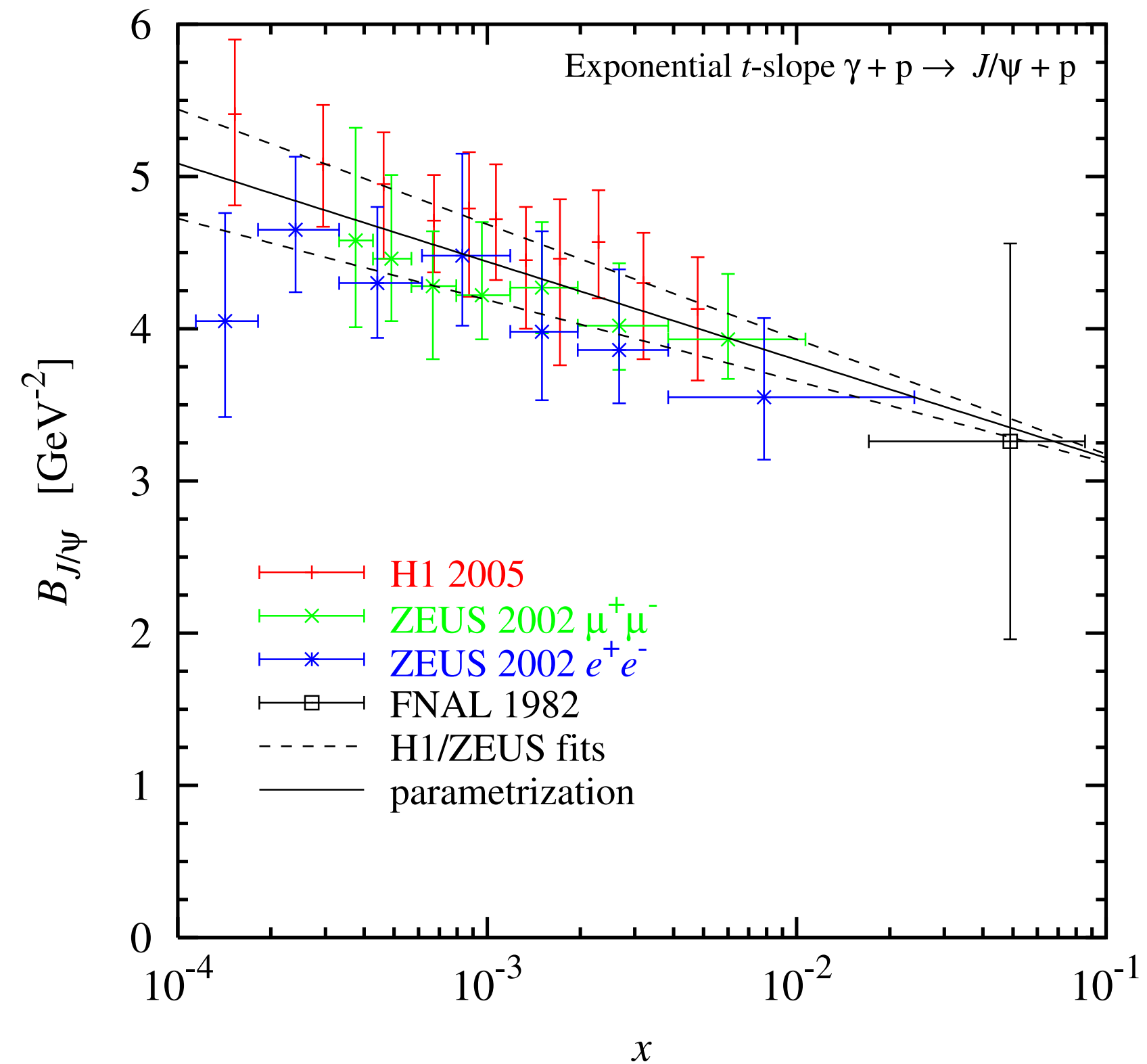
$$R_{gN}^2(x = 10^{-3}) = 0.6 \text{ fm}^2$$

$$Q_{sA}^2(b = 0)/Q_{sN}^2 = T_A(b = 0) \cdot S_A(x, b = 0) \cdot 2R_{gN}^2 = 1.2$$

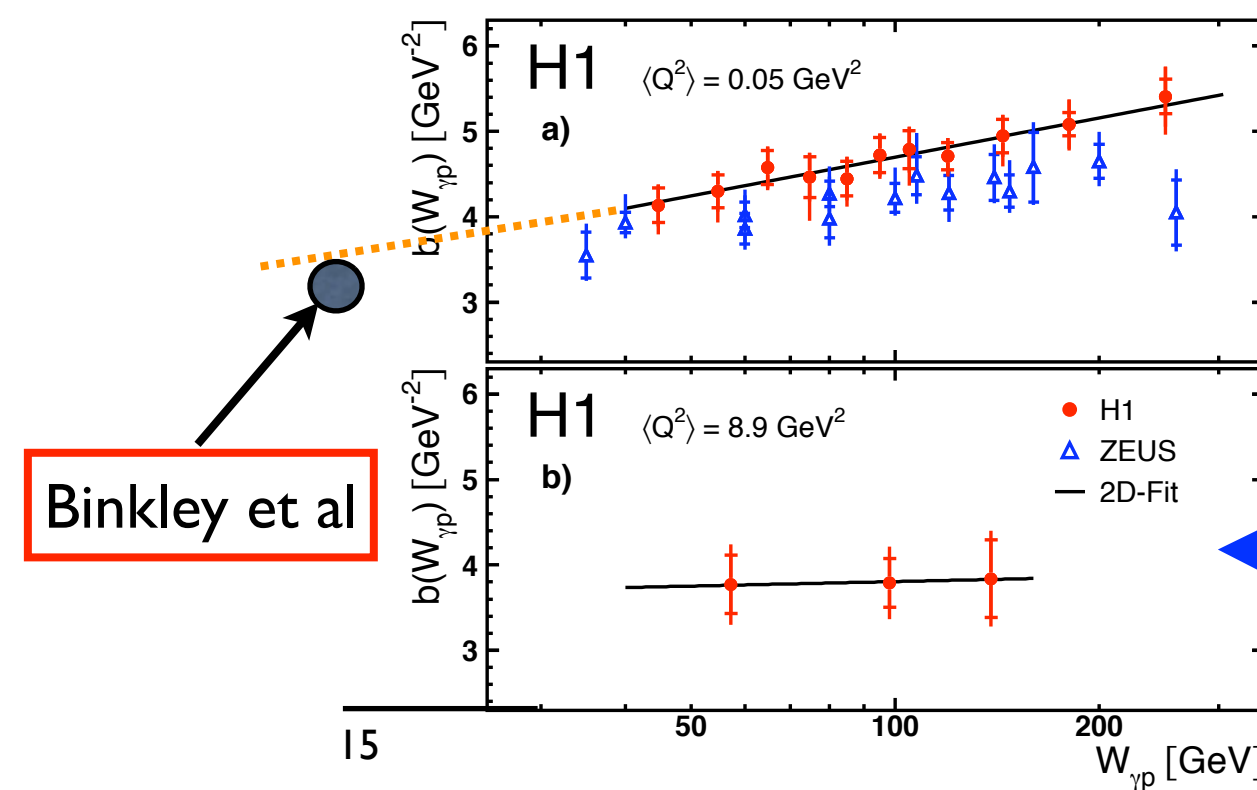
A~200

compare: $Q_{\text{sat}}^2 = 1 \text{ GeV}^2$ for proton at $x=10^{-4}$ (Jamal Jalilian-Marian 2021)

J/ψ elastic photo and electro production



$$B = B(W_0) + 2\alpha' \ln(W^2/W_0^2)$$



α' consistent with zero but there is a tension between different data sets!!!

t -slope for J/ψ especially at $Q^2=9 \text{ GeV}^2$ is systematically lower than for DVCS -
 transverse *quark distribution* is somewhat wider