Multiparton/horse interactions (MPI): from pp to pA

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Outline

- Introduction - generalized parton distributions, parton - parton correlations
- MPI in pp scattering - parton parton correlations are necessary
- MPI in pA scattering : *forward dipion production*

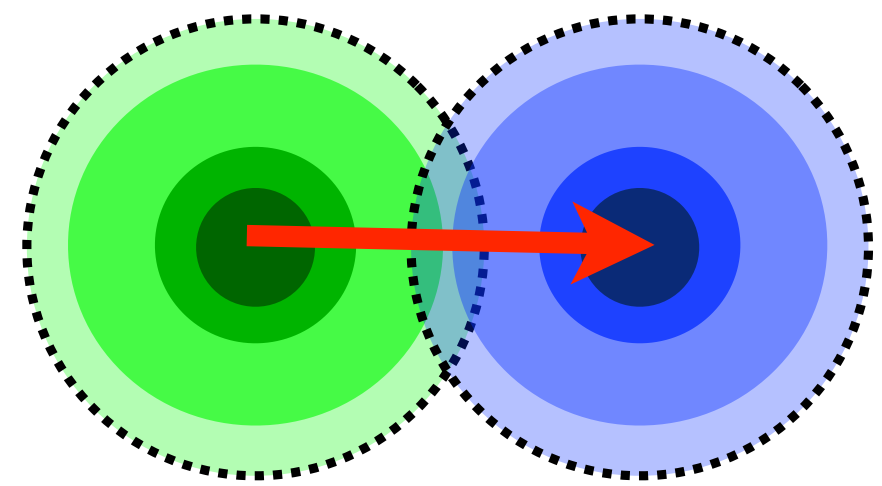
  "MPI - antishadowing effect"

  Small x kinematics

Important characteristic of high energy collisions is the impact parameter of collision. Well defined since angular momentum is conserved and $L = bp$

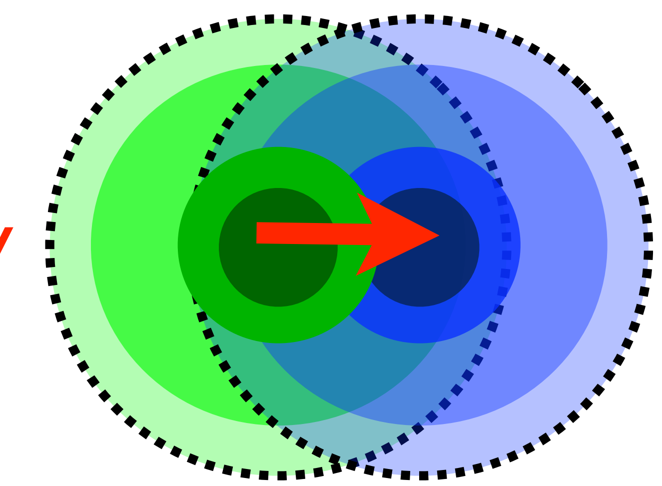
Different intensity of interactions for small and large impact parameters

b

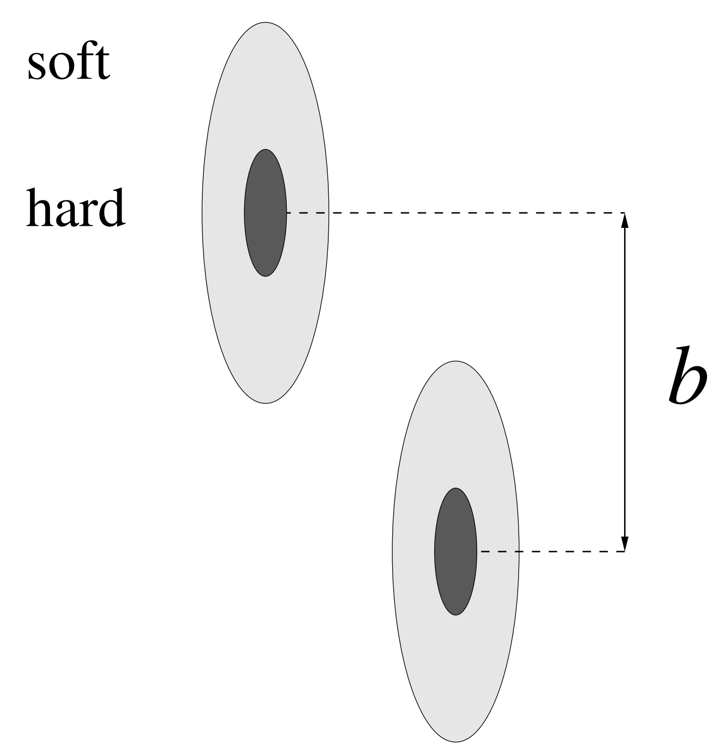


transverse view

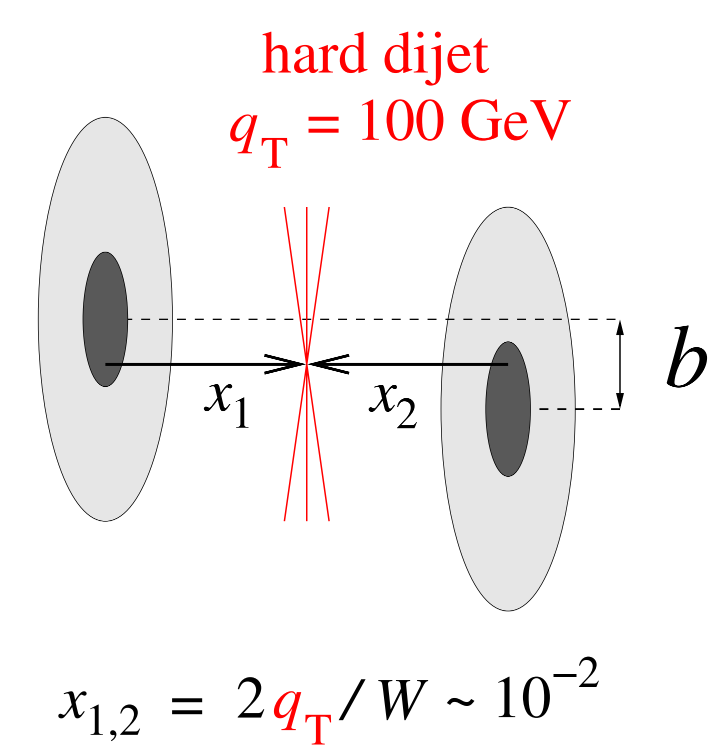
b



Peripheral pp collisions



side view



Central pp collisions

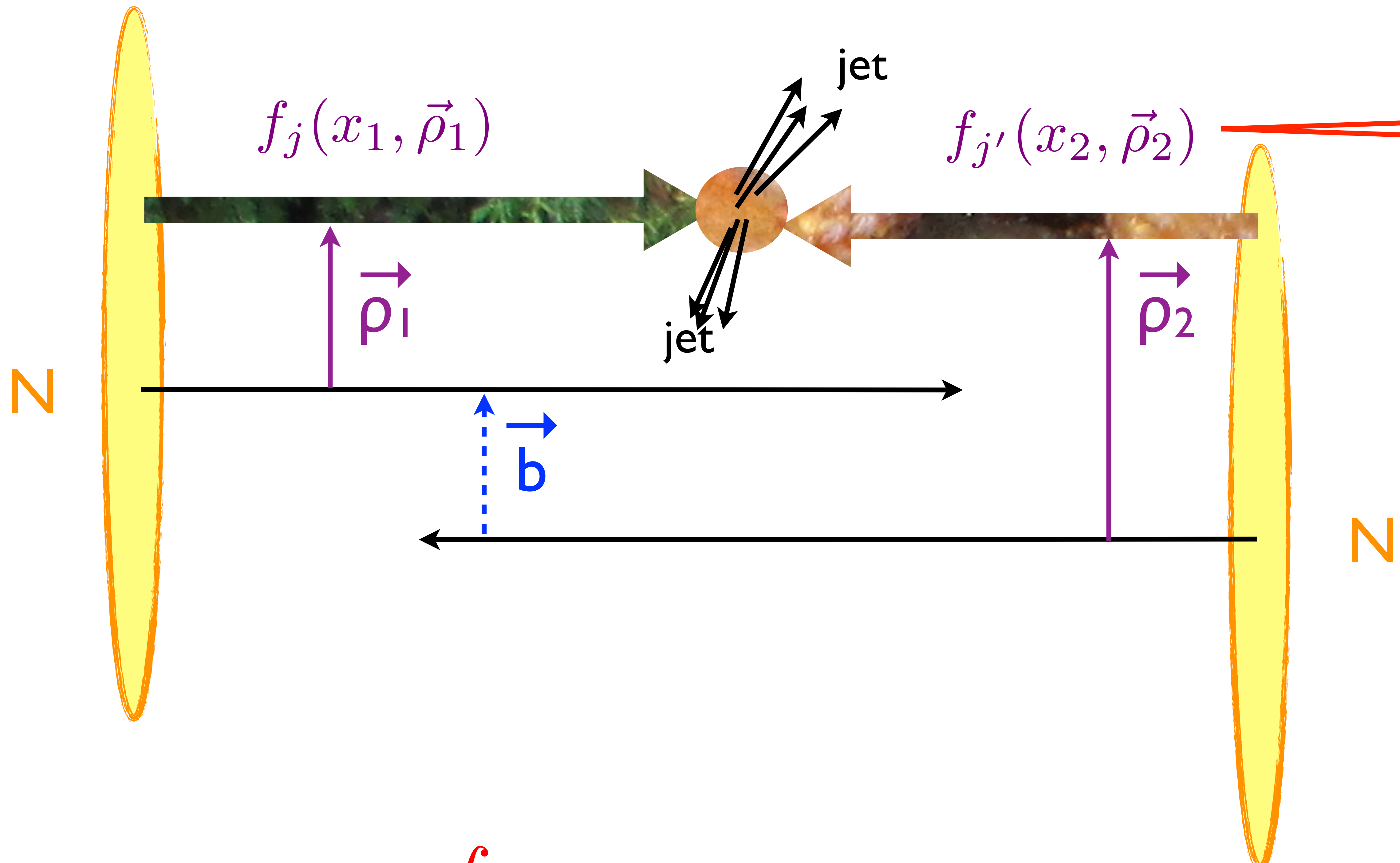
Two scale picture

Small b ➠ large overlap of partons

Large probability of multiparton, soft/hard interactions

Using realistic transverse parton distributions is critical for genuine understanding of final states (underlying events,...) in pp though it does not enter into cross sections of inclusive dijet & inclusive MPI

Geometry of pp collision with production of dijet in the transverse plane



Diagonal Generalized Parton distribution -

For hard collision

$$\vec{\rho}_1 + \vec{b} - \vec{\rho}_2 \propto 1/p_{tjet} \sim 0$$

$$\sigma_h \propto \int d^2b d^2\rho_1 d^2\rho_2 \delta(\rho_1 + b - \rho_2) f_1(x_1, \rho_1) f_2(x_2, \rho_2) \sigma_{2\to 2}$$

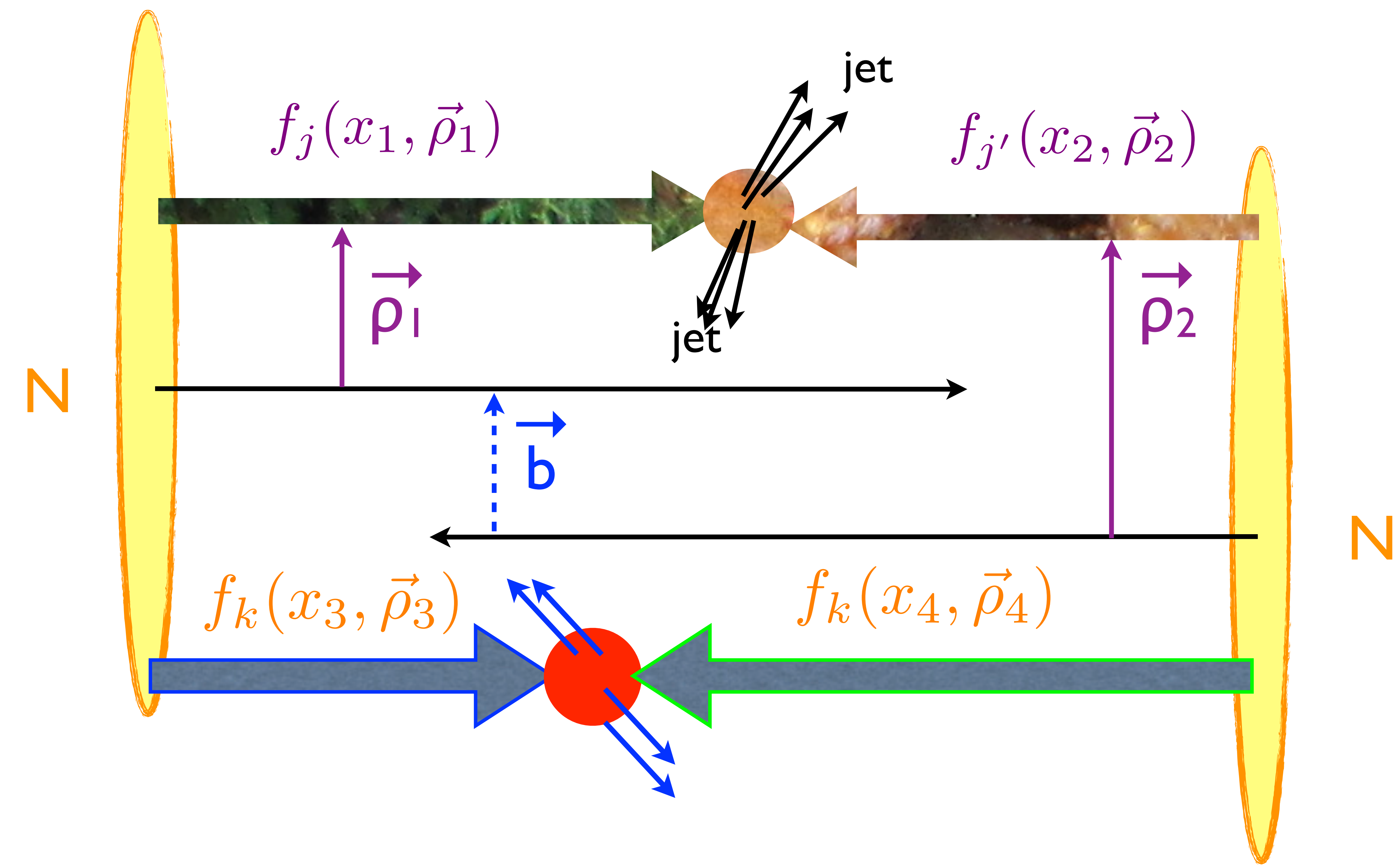
$$= \int d^2\rho_1 d^2\rho_2 f_1(x_1, \rho_1) f_2(x_2, \rho_2) \sigma_{2\to 2} = f_1(x_1) f_2(x_2) \sigma_{2\to 2}$$

For inclusive cross section at high virtuality *transverse structure does not matter* - convolution of parton densities

$\Downarrow$

However critical for understanding global structure of inelastic events

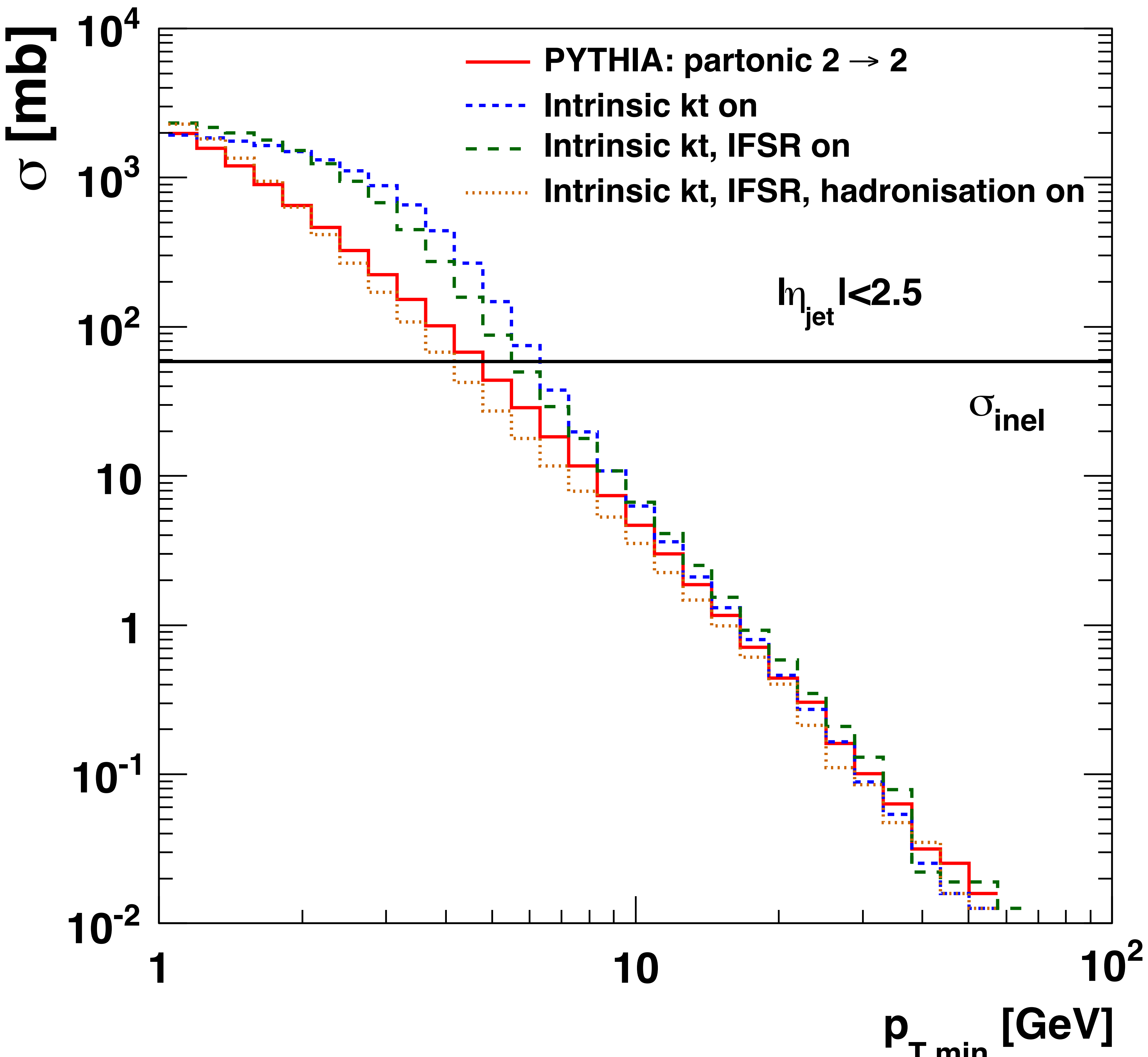
Two pairs of partons can collide in a single collision



Naive geometric picture - two independent parton - parton collisions --- rate depends on the nucleon size only. However this assumes lack of parton - parton correlations. Pairs collide at relative transverse distance ~ 0.5 fm.

If pQCD works at LHC at p_t > 4 GeV/c - a generic inelastic event should contain many minidijets:

jet multiplicity = (inclusive jet σ)/($\sigma_{inel\ (nondiffr)}$ (pp)



A. Grebenyuk et al, 2012

10 dijets with p_t > 4 GeV/c per nondiffractive event !!!

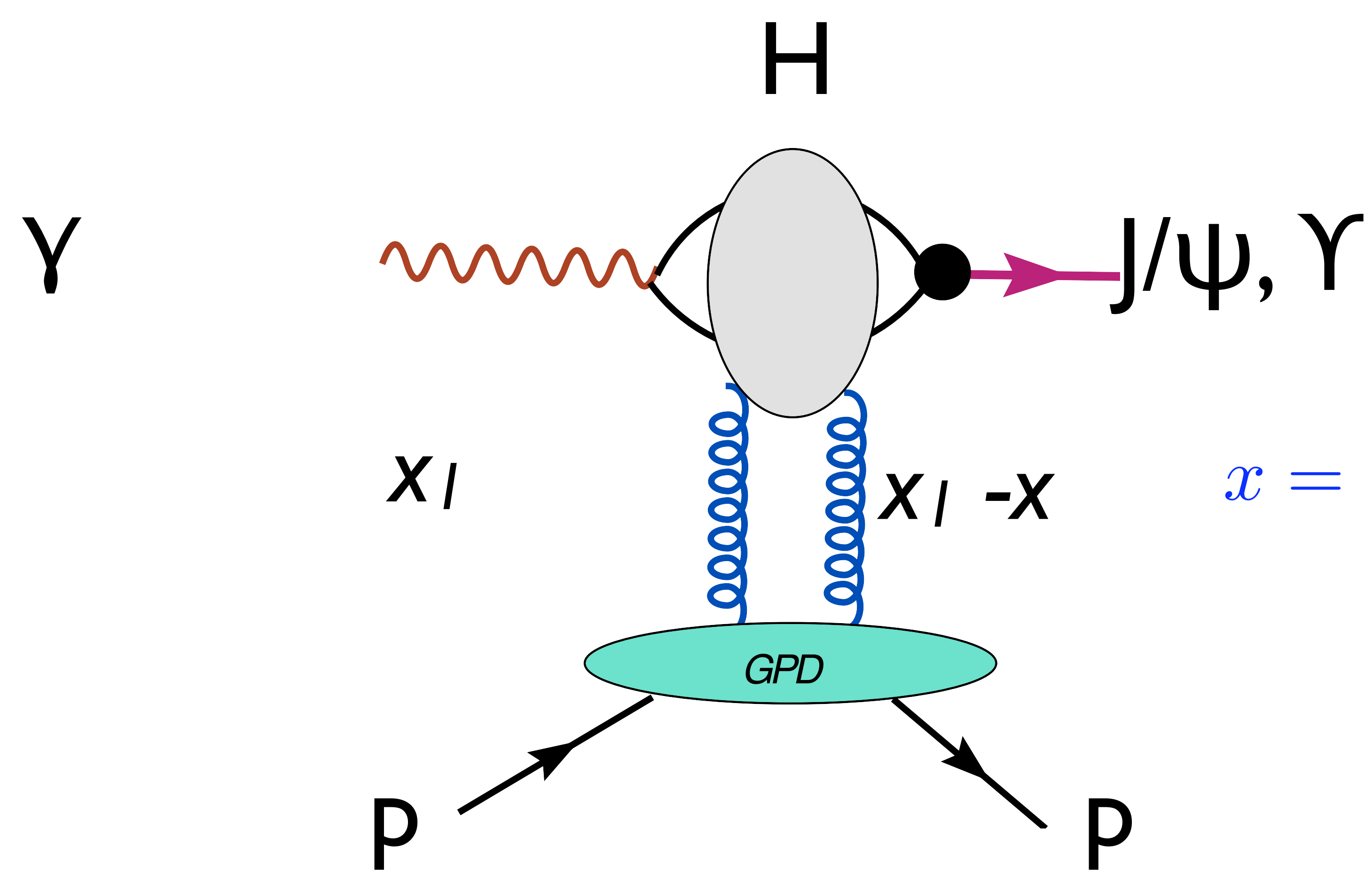
Understanding of MPI is necessary for realistic modeling of pp collisions. *Nuclei - higher local transverse density* $\rightarrow$ enhancement of MPI in pA collisions (MS & Treleani 95 &02) $\rightarrow$ are MPI even more important in pA?

Key question -- how strongly are the parton - parton correlations

$$f(x_1, x_2, \vec{\rho}_1 - \vec{\rho}_2) \stackrel{?}{=} \int d^2\rho_1 d^2\rho_2 \delta(\vec{\rho}_1 - \vec{\rho}_2) f(x_1, \vec{\rho}_1) f(x_2, \vec{\rho}_2)$$

Assumed in all MC models

For gluons transverse spread of partons can be determined form analysis of onium production



$$x = \frac{Q^2 + m_V^2}{W^2}$$

In LT limit $x_l - x << x_l$

however due to DGLAP evolution skewed GPD kinematics for large Q probes diagonal GPD at Q_0 scale

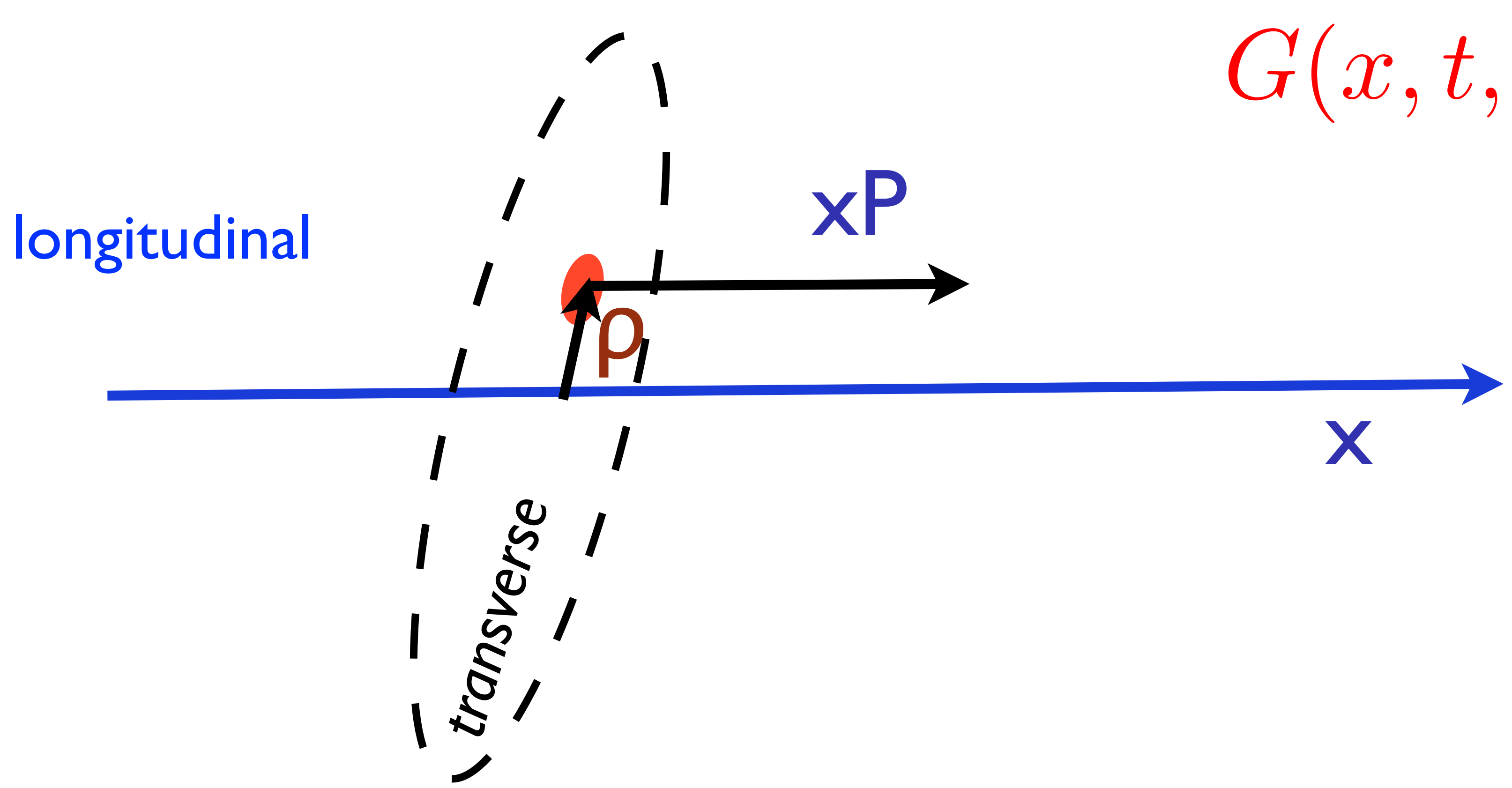
$$A(\gamma^* + p \to \text{"}Onium\text{"} + p) \propto G(x_1, x_1 - x, t)$$

$$G(x, x, t) \equiv G(x, t) = \int d^2\rho e^{-i\vec{\Delta}_\perp \rho} \boxed{G(x, \rho)}$$

transverse spatial distribution of gluons (Q dependent)

$$G(x, t, Q_0^2) = 1/(m_g^2 - t)^2, m_g^2(x = 0.01) \sim 1.1 GeV^2$$

transverse size < e.m. size



$$\int d^2\rho G(x, \rho) = G(x)$$

total gluon density

Experimentally one measures the ratio

$$\frac{\frac{d\sigma(p+\bar{p}\to jet_1+jet_2+jet_3+\gamma)}{d\Omega_{1,2,3,4}}}{\frac{d\sigma(p+\bar{p}\to jet_1+jet_2)}{d\Omega_{1,2}}\cdot\frac{d\sigma(p+\bar{p}\to jet_3+\gamma)}{d\Omega_{3,4}}}=\frac{f(x_1,x_3)f(x_2,x_4)}{\boxed{\sigma_{eff}}f(x_1)f(x_2)f(x_3)f(x_4)}$$

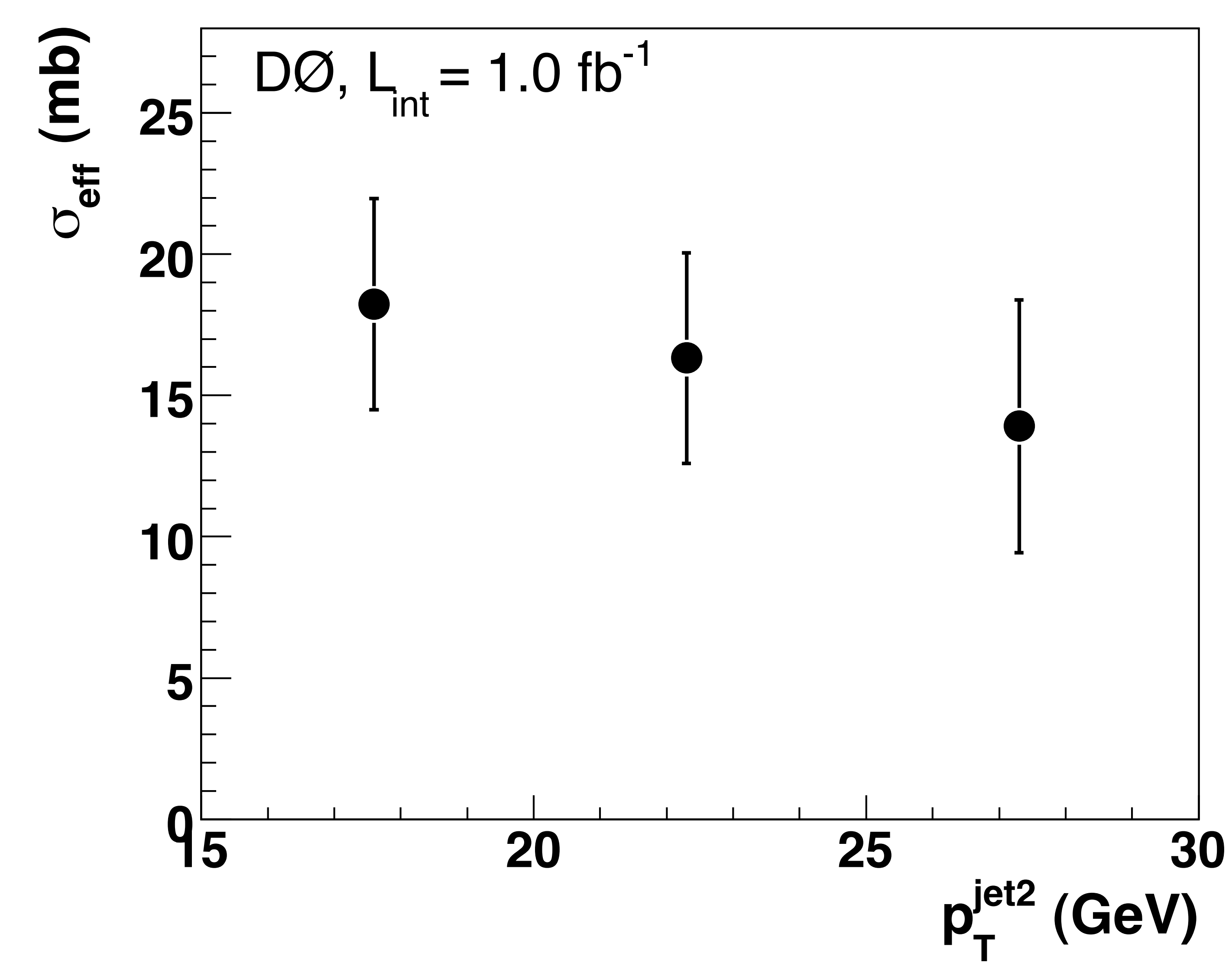
where $f(x_1,x_3),f(x_2,x_4)$ longitudinal light-cone double parton densities and σ_{eff} is ``transverse correlation area". One selects kinematics where 2 →4 (LT two partons into four partons) contribution is small

CDF observed the effect in a restricted x-range: two balanced jets, and jet + photon and found

$$\sigma_{eff}=14.5\pm1.7^{+\ 1.7}_{-\ 2.3}\ mb$$

No dependence of σ_{eff} i on x_i was observed.

A naive expectation (based on r_N=0.8 fm) is σ_{eff} ~ 55 mb indicating high degree of correlations between partons in the nucleon in the transverse plane - next few more technical slides



Similar results from D0.

Challenge to explain the data since in independent parton approximation

$$\sigma_{eff} = \frac{28\pi}{m_g^2} \sim 32 \text{ mb.}$$

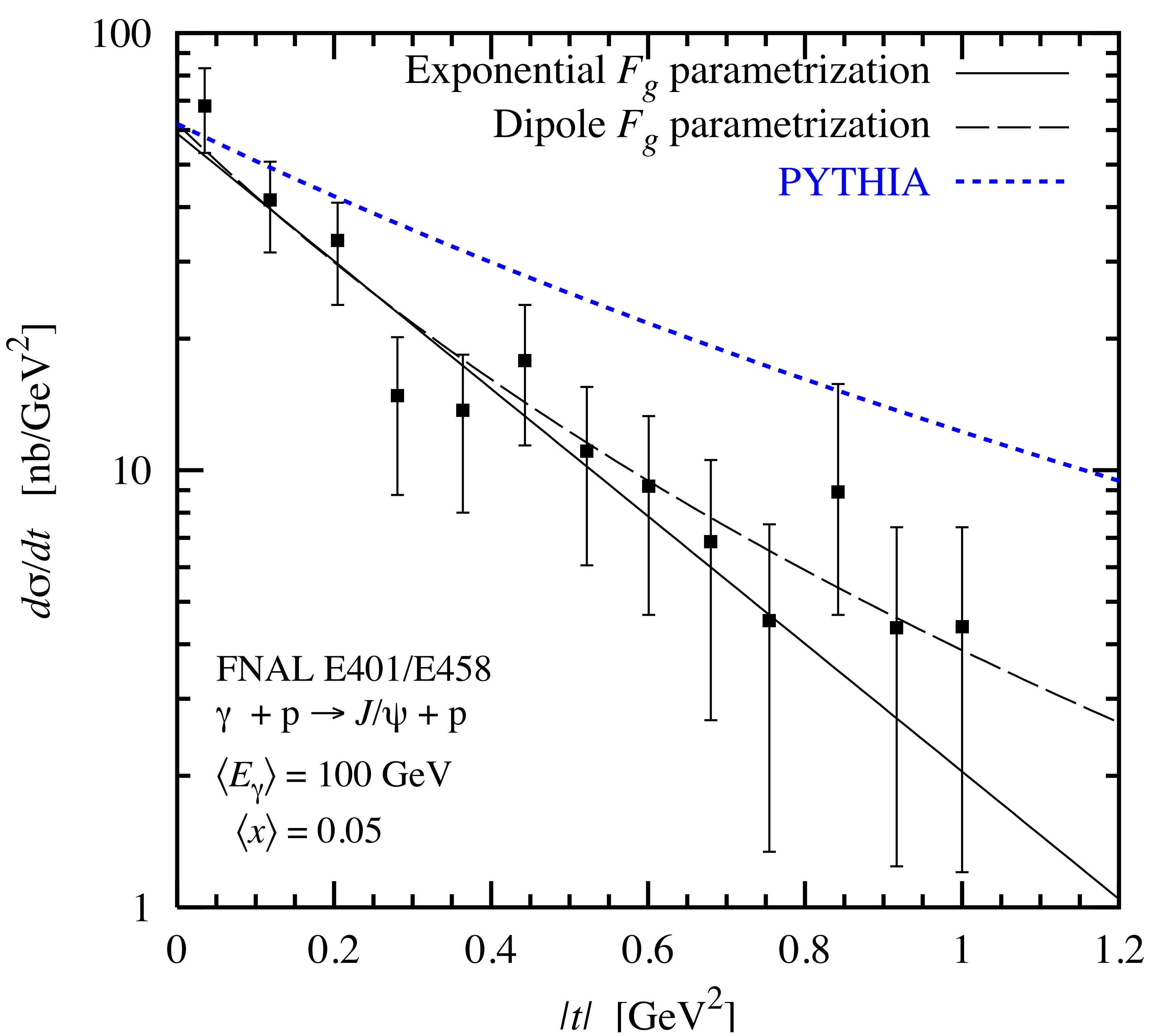
LF, MS, Weiss 03

MPI rate a factor of two smaller than experiment !!!

Realistic model of MPI should include a factor ~2 contribution of correlations

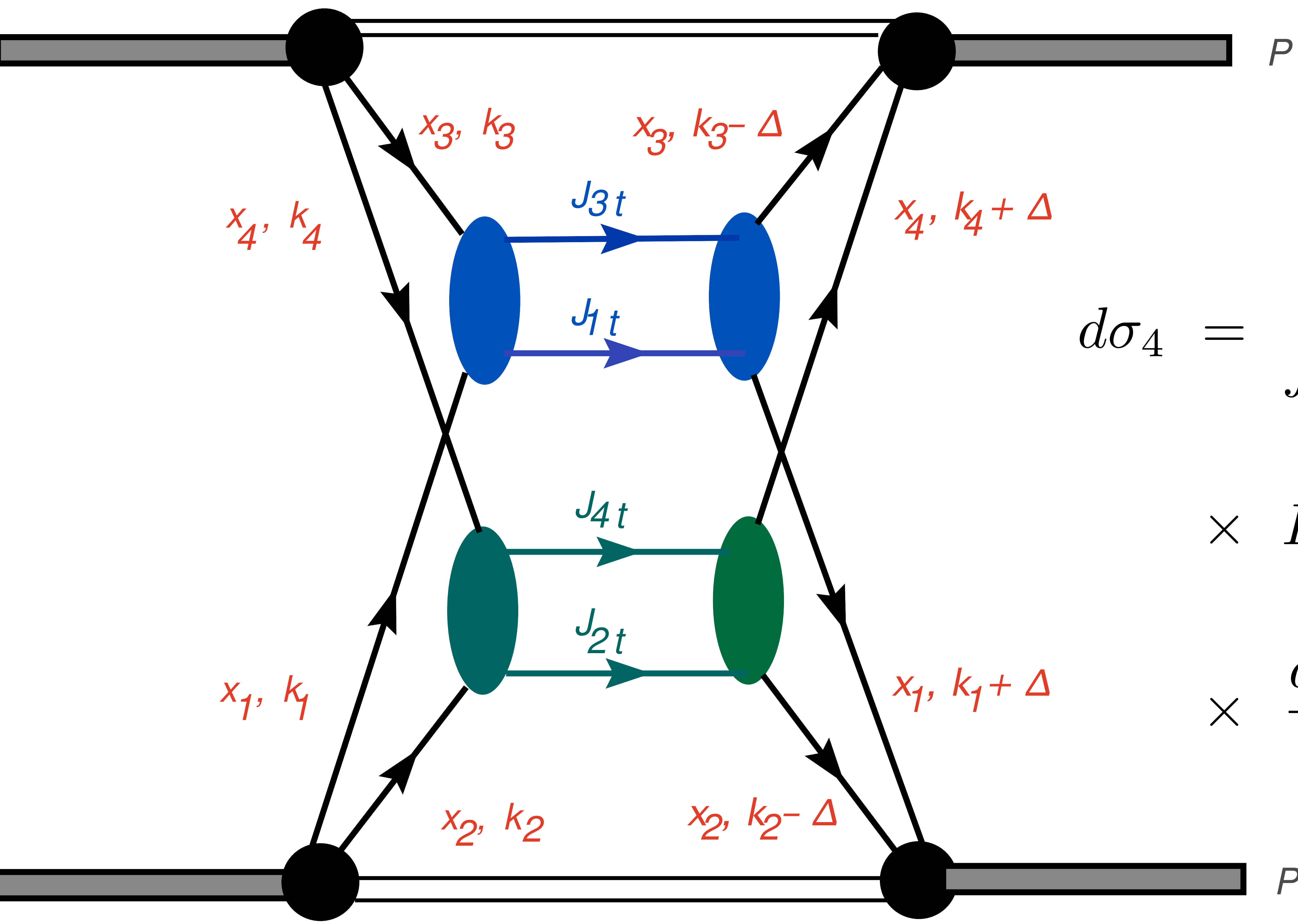
To reproduce σ_{eff} in the independent parton approximation one needs $m_g^2 \sim 2 GeV^2$ (PYTHIA)

area occupied by gluons is at least a factor of two smaller than experiment



$m_g^2 \sim 2$ GeV^2 leads to t -dependence which is too weak to reproduce J/ψ exclusive photoproduction

Blok, Dokshitzer, LF, MS (BDFS) 11-12 derived geometric results from the first principles and developed pQCD theory of MPI. We also discovered new pQCD mechanism of MPI due to pQCD evolution



Δ- transverse disbalence between in and out partons

$$d\sigma_4 = \int \frac{d^2\overrightarrow{\Delta}}{(2\pi)^2} \int dx_1 \int dx_2 \int dx_3 \int dx_4$$

$$\times\ D_a(x_1, x_2, p_1^2, p_2^2, \overrightarrow{\Delta}) D_b(x_3, x_4, p_1^2, p_2^2, -\overrightarrow{\Delta})$$

$$\times\ \frac{d\sigma^{13}}{d\hat{t}_1} \frac{d\sigma^{24}}{d\hat{t}_2} d\hat{t}_1 d\hat{t}_2.$$

D's are double generalized parton distributions

$$\frac{1}{\sigma_{eff}} = \int \frac{d^2\overrightarrow{\Delta}}{(2\pi)^2} \frac{D_a(x_1, x_2, -\overrightarrow{\Delta}) D_b(x_3, x_4, \overrightarrow{\Delta})}{D_a(x_1) D_a(x_2) D_b(x_3) D_b(x_4)},$$

Independent particle approximation which could be reasonable for small x_1, x_2 $\quad D(x_1, x_2, p_1^2, p_2^2, \vec{\Delta}) = G(x_1, p_1^2, \vec{\Delta}) G(x_2, p_2^2, \vec{\Delta})$

one line calculation $\quad F_{2g}(x \sim 0.03, t) = (1 - t/m_g^2)^{-2}, m_g^2 \sim 1.1\, GeV^2$

$$\sigma_{eff} = \frac{28\pi}{m_g^2} \sim 32 \text{ mb.}$$ Practically the same number with exp(Bt) fit.

Hence our result of 03 is pretty stable since $F_{2g}{}^2(\Delta)$ is measured directly.

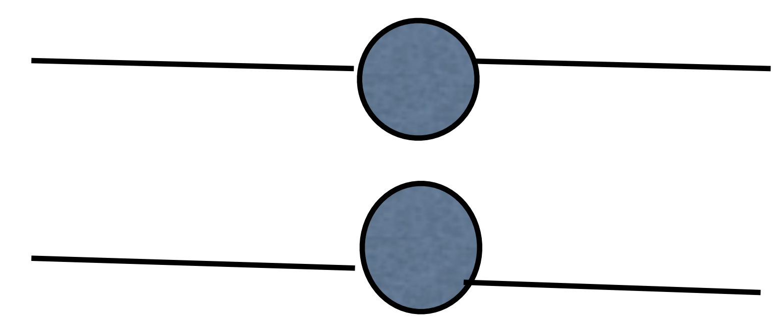
A factor of at least 2 is missing !!!!

Origin of correlations? Perturbative vs non-perturbative. Delicate interplay

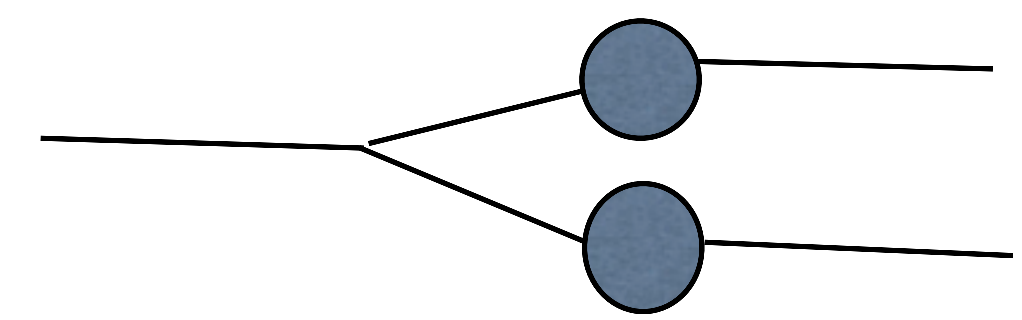
Qualitatively pQCD mechanism is -- parton at Q_0 scale can resolve into two or more partons at higher scale with all partons localized in transverse area $1/Q_0^2$

$$D_h^{1,2}(x_1,x_2,q_1^2,q_2^2;\vec{\Delta}) = {}_{[2]}D_h(x_1,x_2,q_1^2,q_2^2;\vec{\Delta}) + {}_{[1]}D_h(x_1,x_2,q_1^2,q_2^2;\vec{\Delta})$$

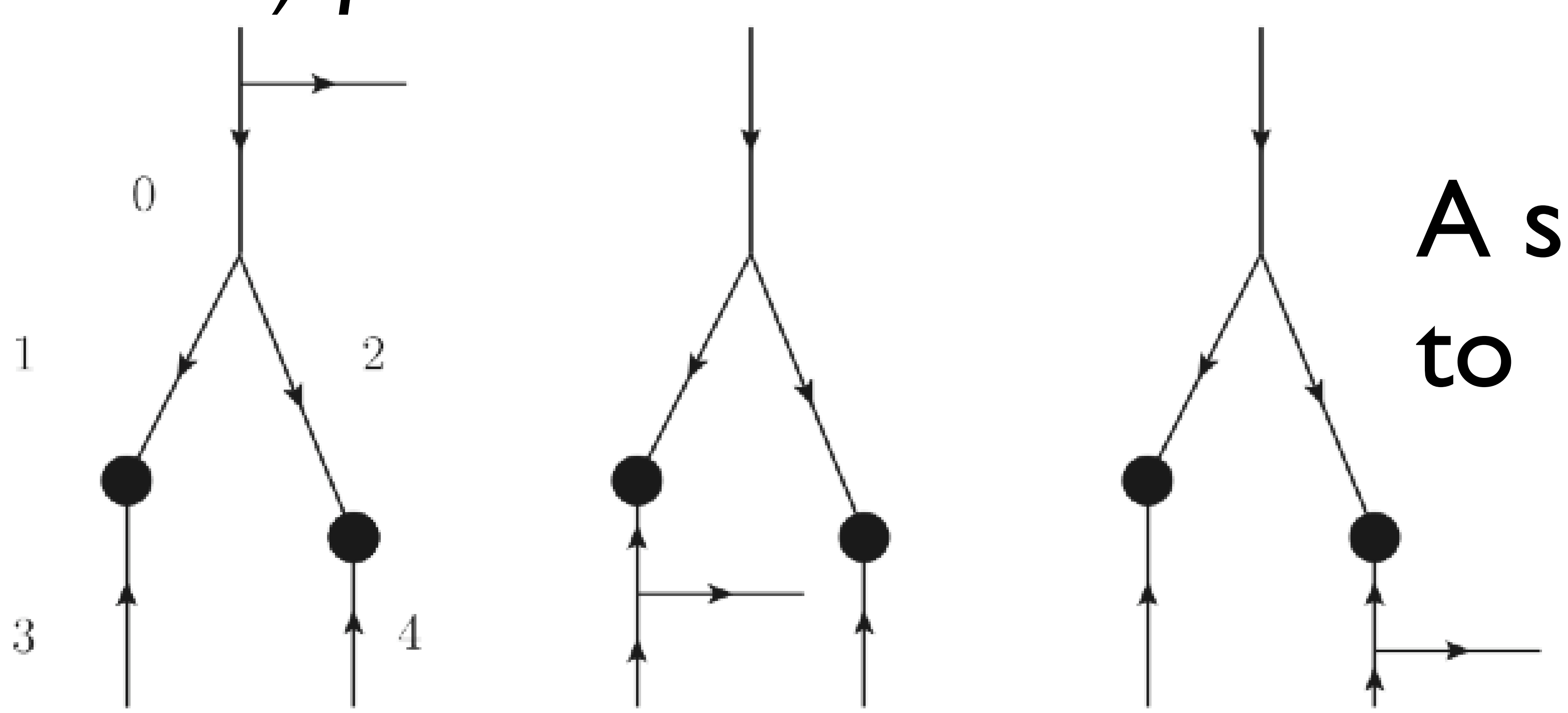
two partons from the wave function



one parton that perturbatively splits into two



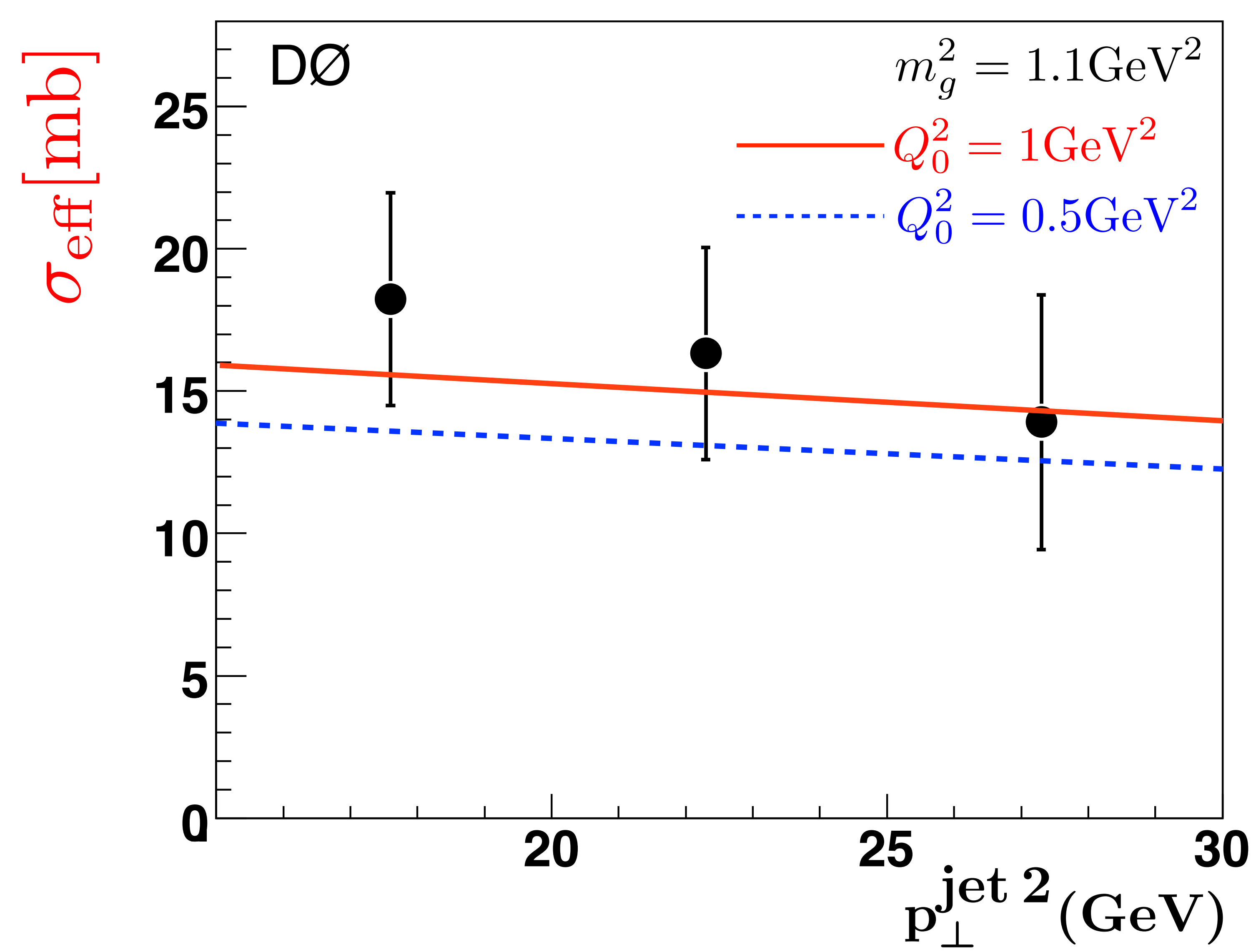
the two contributions do not enter the physical DPI cross section in arithmetic sum, driving one even farther from the familiar factorization picture based on universal(process independent) parton distributions.



A short evolution contributions to $1 \otimes 2$

Geometry and combinatorics enhance $1 \otimes 2$ by a factor of 5

Lengthy eqs & numerical calculations. *Result:* if pQCD evolution starts at low $Q_0 = 0.7 \div 1$ GeV scale we explain a factor of ~2 enhancement $1/\sigma_{eff}$ for large p_t. σ_{eff} grows with decrease of p_t while in MC's it is assumed to be p_t and process independent



$$\sigma_{\mathrm{eff}} = \frac{28\pi}{m_g^2} \cdot \frac{1}{1+R} \simeq \frac{32\,\mathrm{mb}}{1+R}$$

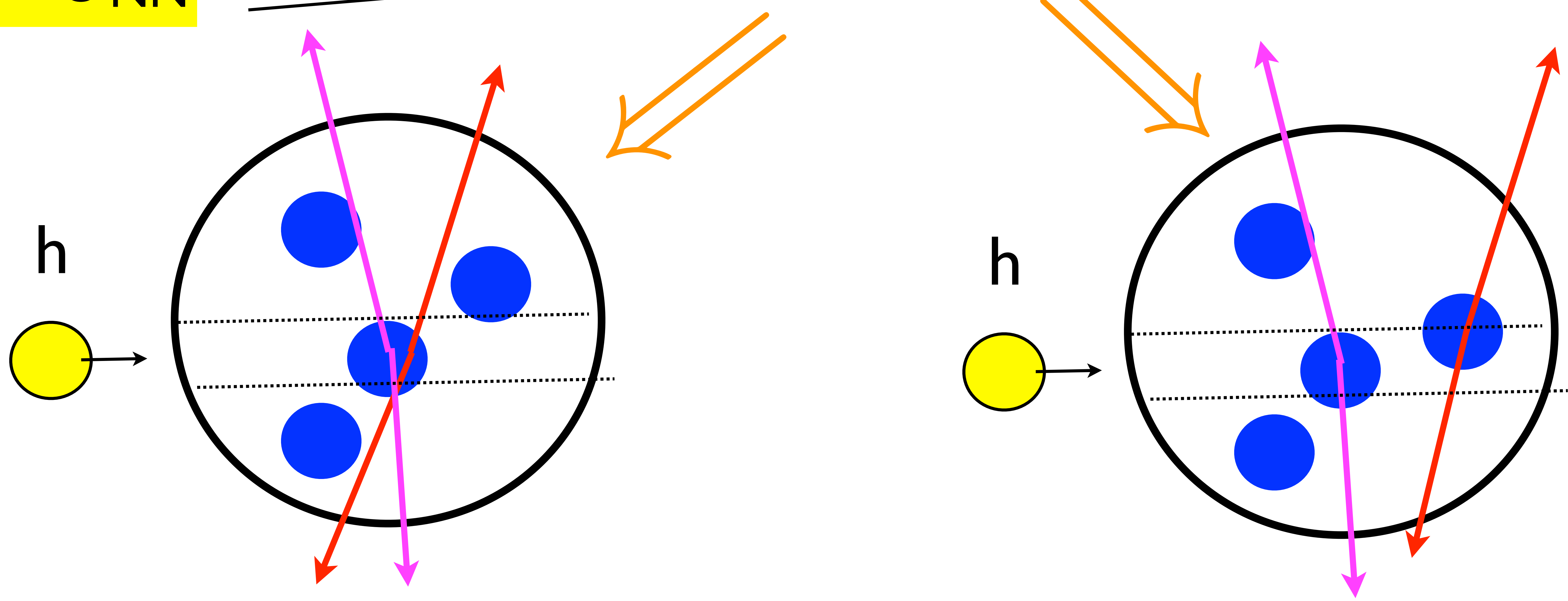
$$R \equiv \frac{\sigma_{1\otimes 2}}{\sigma_{2\otimes 2}} \sim 1$$

MPI in nuclei: probing parton correlations in nucleons and nuclei
+ implications for minijets

MS & Treleani 95 - PRL 2002

$\sigma_1 = \sigma_{NN}$

$$\sigma = \sigma_1 \cdot A + \sigma_2$$



$$R \equiv \frac{\sigma_2}{\sigma_1 \cdot A} \approx \frac{(A-1)}{A^2} \cdot \sigma_{eff} \int T^2(b)\, d^2b \approx 0.68 \cdot \left(\frac{A}{12}\right)^{0.39}\Bigg|_{A\geq 12, \sigma_{eff}\sim 14mb}$$

Nuclear pdf= A*(nucleon pdf)

$$T(b) = \int_{-\infty}^{\infty} dz \rho_A(z,b), \int T(b) d^2b = A.$$

"Antishadowing effect": For A=200, and σ_{eff}=14 mb $\frac{\sigma_{pA}}{A\sigma_{pp}} \approx 3$ linear in σ_{eff} !!

Measurement of R allows to separate longitudinal and transverse correlations of partons as it measures $f(x_1,x_2)/f(x_1)f(x_2)$

First observation of MPI in collisions with nuclei: dAu (pp) $\to 2\ \pi^0$ forward +X

STAR, RHIC

MS & Vogelsang 2010

STAR measured

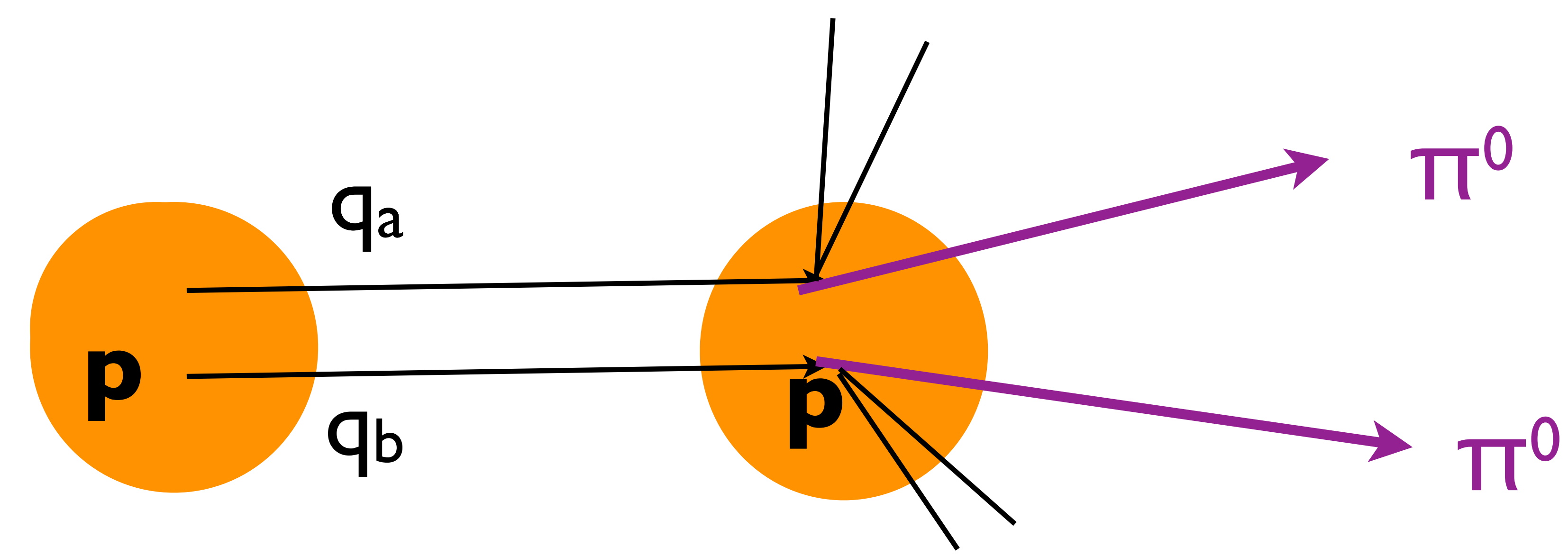
pp $\to \pi^0 + \pi^0 + X$

d-Au $\to \pi^0 + \pi^0 + X$

$\eta_{1,2} \leq 4$ ($x_F \leq 0.5$), $p_T > 1.5$ GeV/c

Trigger for two forward pions selects large x_q larger than the single pion trigger (for which x is also quite large)

In forward kinematics it is possible to observe MPI using just two particles (not 4 jets) !

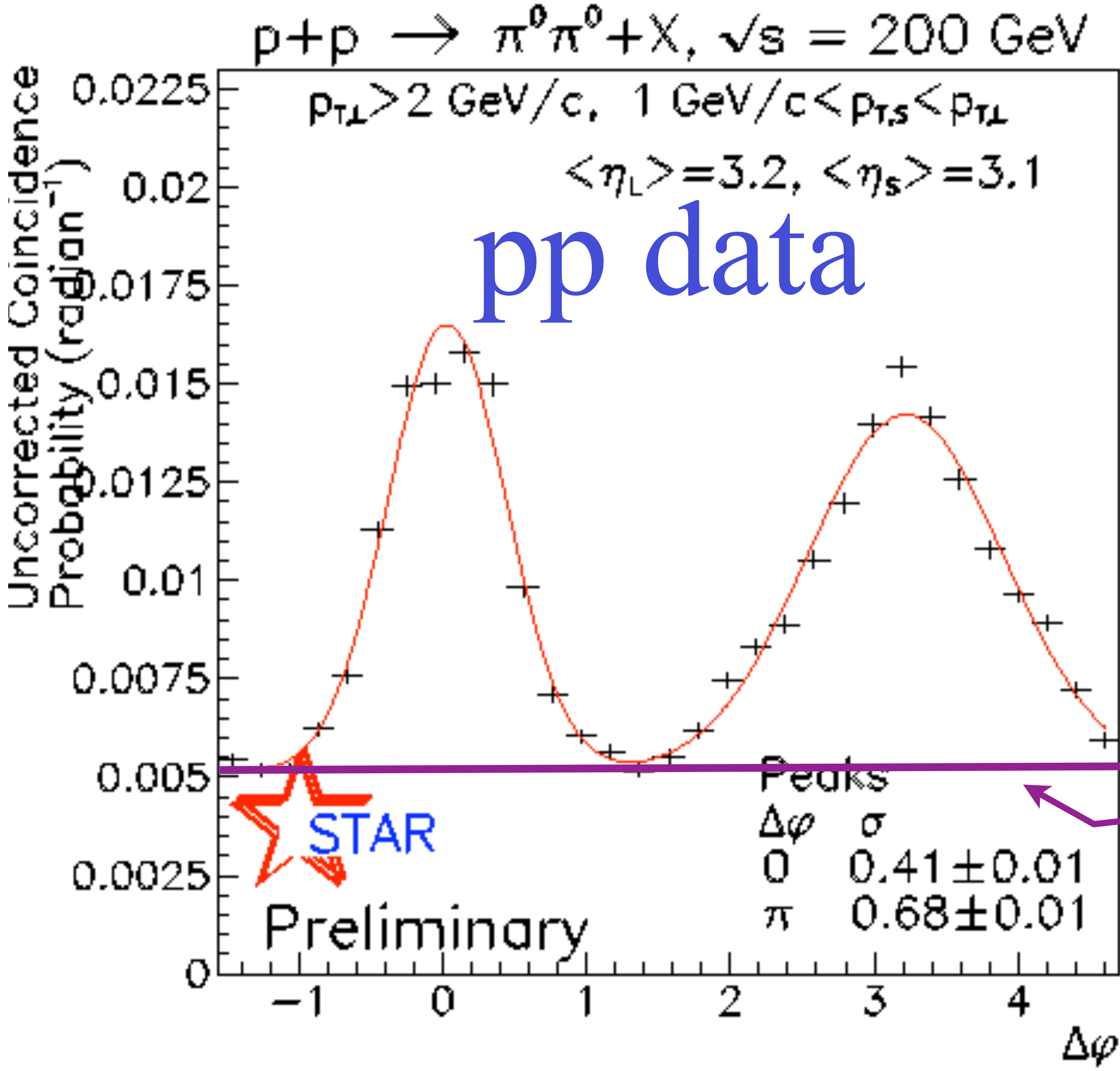


$$\frac{d^4\sigma_{\text{double}}}{dp_{T,1}d\eta_1 dp_{T,2}d\eta_2} = \frac{1}{\pi R_{\text{int}}^2} \sum_{abc\,a'b'c'} \int dx_a dx_b dz_c dx_{a'} dx_{b'} dz_{c'}\; f^p_{aa'}(x_a, x_{a'}) f^p_b(x_b) f^p_{b'}(x_{b'})$$

$$\times \quad \frac{d^2\hat{\sigma}^{ab\to cX}}{dp_{T,1}d\eta_1} \frac{d^2\hat{\sigma}^{a'b'\to c'X'}}{dp_{T,2}d\eta_2} D_c^{\pi^0}(z_c)\, D_{c'}^{\pi^0}(z_{c'})\,.$$

$$f^p_{qq'}(x_q, x_{q'}) = \frac{1}{2}\left[f^p_q(x_q) \times \phi\left(\frac{x_{q'}}{1-x_q}\right) + (q \leftrightarrow q')\right]$$

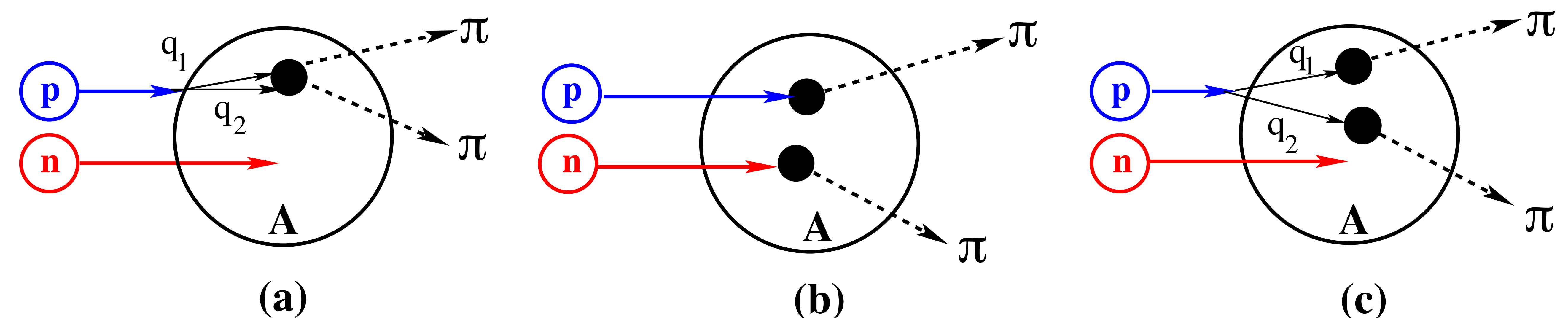
$$\phi(\xi) = \frac{c}{\sqrt{\xi}}(1-\xi)^n$$



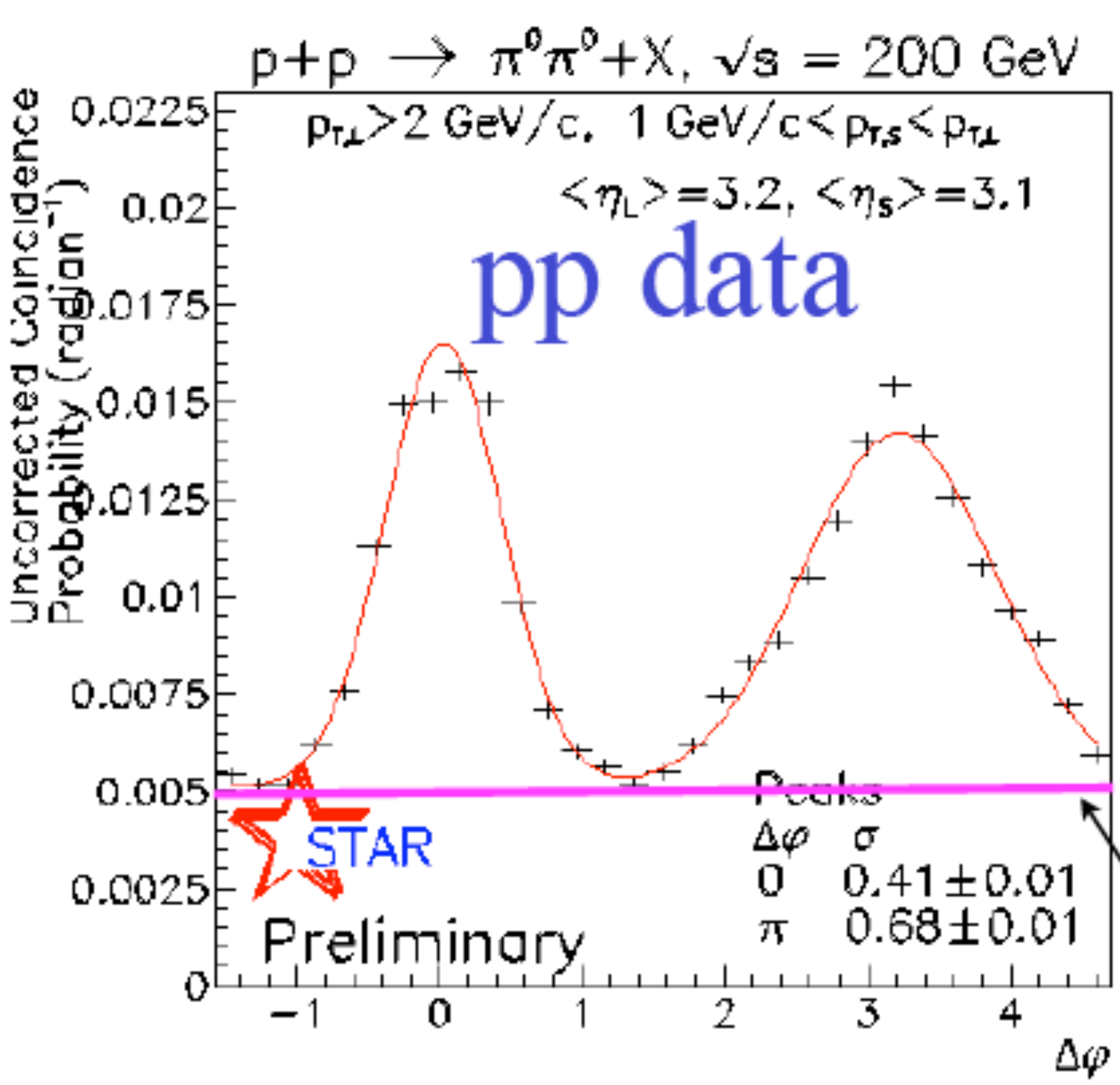
pedestal = MPI?

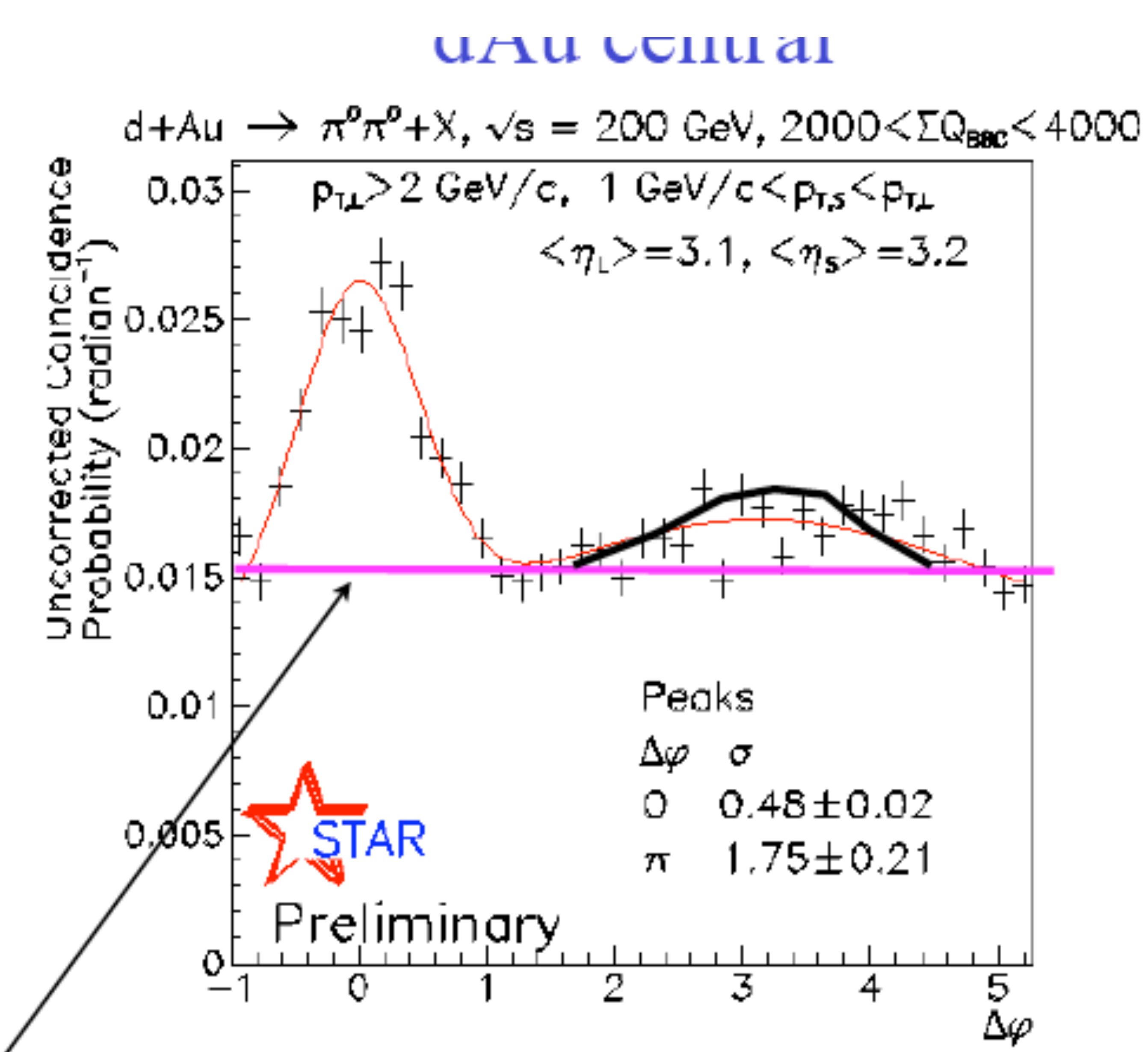
We estimated: pedestal/away peak ~ 2 ; consistent with the data

CHECK: much larger pedestal in dA



Accounting for effecting energy losses effect and LT gluon shadowing reduces (4→4)/ (2→2) ratio - still Δφ independent pedestal in dA is 2.5 ÷ 4 times larger in pp. We also find suppression of Δφ =180° peak by a factor ~ four





1 : 3

pedestal

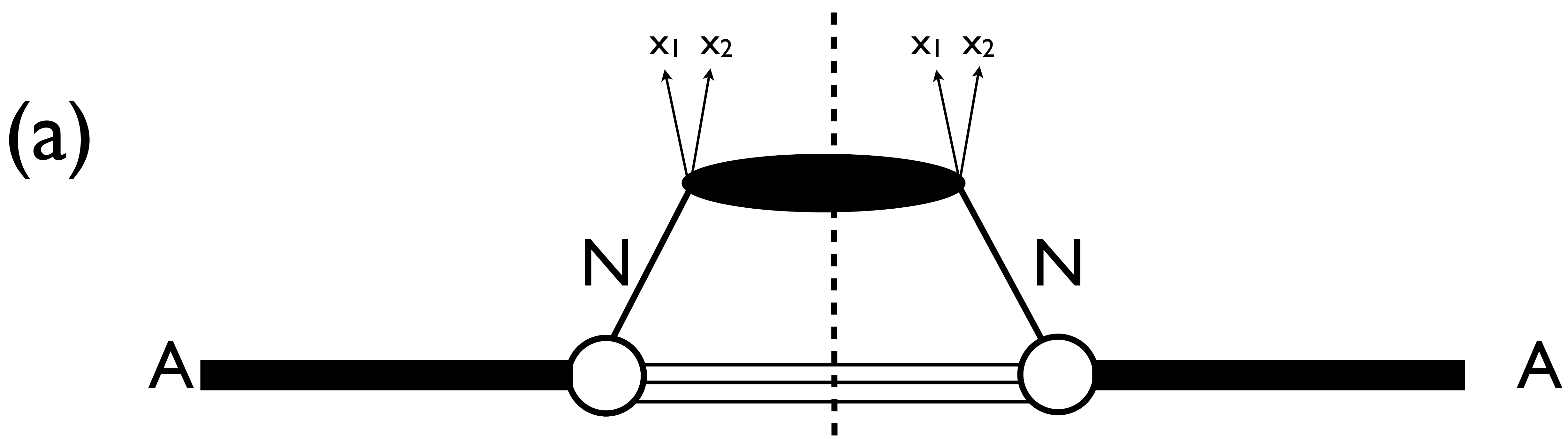
Black curve is the pp data peak above pedestal for φ ~π scaled down by a factor of 4

pQCD theory of MPI in pA

MS & Treleani treatment of pA was based on partonic model. In QCD in addition to 4 ⊗4 there is an important 3 ⊗ 4 contribution - need to perform a new analysis, to calculate $_2$GPD of nuclei, estimate uncertainties of the nuclear effects.

Blok, MS ,Weidemann 2012

Summary

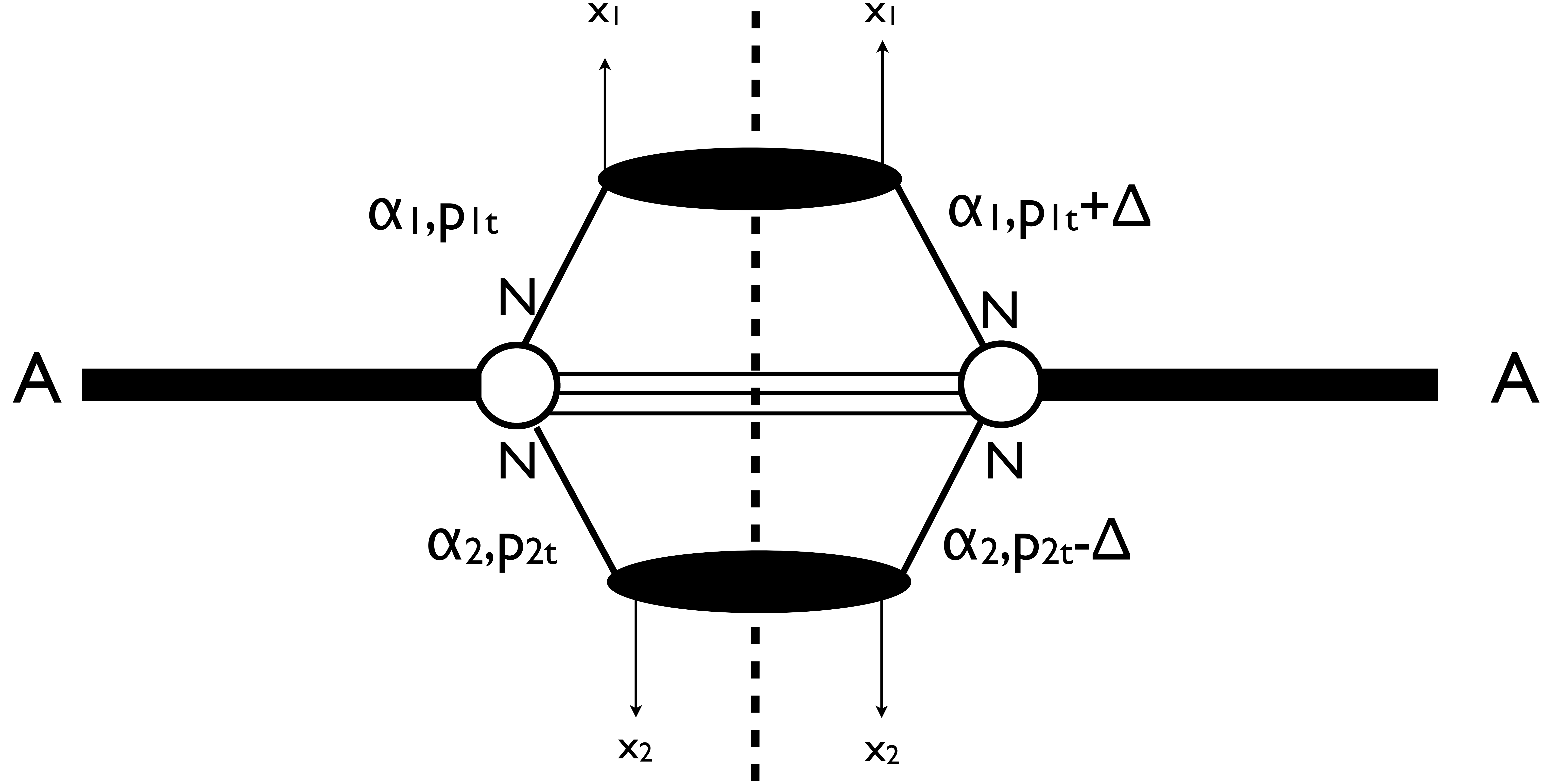


Impulse approximation - two partons (or one parton in the case of 3 ⊗ 4) are taken from the same nucleon. For x> 0.03 when no shadowing effects are

$$G_A^{1N}(x_1, x_2, \vec{\Delta}) = A\, G^{1N}(x_1, x_2, \vec{\Delta}) \left(1 + O\left(\int (\alpha - 1)^2 \rho_A^N(\alpha, p_t) \frac{d\alpha}{\alpha} d^2 p_t\right)\right)$$

light-cone nucleon density matrix

Double nucleon interaction: diagonal case



$$G_A^{2N}(x_1, x_2, \vec{\Delta}) \;=\; A(A-1)\int \frac{1}{\alpha_1\alpha_2}\prod_{i=1}^{i=A}\frac{d\alpha_i d^2 p_{ti}}{\alpha_i}\,\delta\left(\sum_i \alpha_i - A\right)\,\delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right)\,\psi_A^*(\alpha_1, \alpha_2, p_{t1}, .$$

$$\times\psi_A(\alpha_1, \alpha_2, p_{t1} + \vec{\Delta}, p_{t2} - \vec{\Delta}, ...)G_N(x_1/\alpha_1, |\vec{\Delta}|)G_N(x_2/\alpha_2, |\vec{\Delta}|).$$

$$G_A^{2N}(x_1,x_2,\vec{\Delta}) = A(A-1)G_N(x_1,|\vec{\Delta}|)G_N(x_2,|\vec{\Delta}|)\ F_A^{\rm double}(\vec{\Delta},-\vec{\Delta}),$$

$$F_A^{\rm double}(\vec{\Delta},-\vec{\Delta}) = \int \prod_{i=1}^{i=A}\frac{d\alpha_i d^2p_{ti}}{\alpha_i}\,\delta\left(\sum_i \alpha_i - A\right)\,\delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right)\psi_A^*(\alpha_1,\alpha_2,p_{t1},p_{t2},....)$$
$$\times\psi_A(\alpha_1,\alpha_2,p_{t1}+\vec{\Delta},p_{t2}-\vec{\Delta},....)\,.$$

Here $F_A^{\rm double}(\Delta,-\Delta)$ is the double nucleon nuclear form factor which is the same as in the Glauber model.

$$F_A^{NR\ \rm double}(\vec{\Delta},-\vec{\Delta}) = \int\left(\prod_{i=1}^{i=A} d^3p_i\right)\psi_A^*(p_1,p_2,...)\psi_A(p_1+\vec{\Delta},p_2-\vec{\Delta},p_3,...)\delta^{(3)}\left(\sum_{i=1}^{A}p_i\right)$$

$$F_A^{\rm double}(\vec{\Delta},-\vec{\Delta}) \simeq \left|\int d^3r\,\frac{1}{A}\rho_A(r)\ \exp\left[i\vec{\Delta}\cdot\vec{r}\right]\right|^2 = F_A(\vec{\Delta})^2$$

$$F_A^{\rm double}(\vec{\Delta},-\vec{\Delta}) \simeq \left|\int d^3r\,\frac{1}{A}\rho_A(r)\ \exp\left[i\vec{\Delta}\cdot\vec{r}\right]\right|^2 = F_A(\vec{\Delta})^2 \ \approx \exp\left[-\frac{1}{3}\Delta^2 R_A^2\right]$$

Derived expressions allow very compact calculations both for heavy and light nuclei

Since $<\Delta^2> r_N^2 << 1$

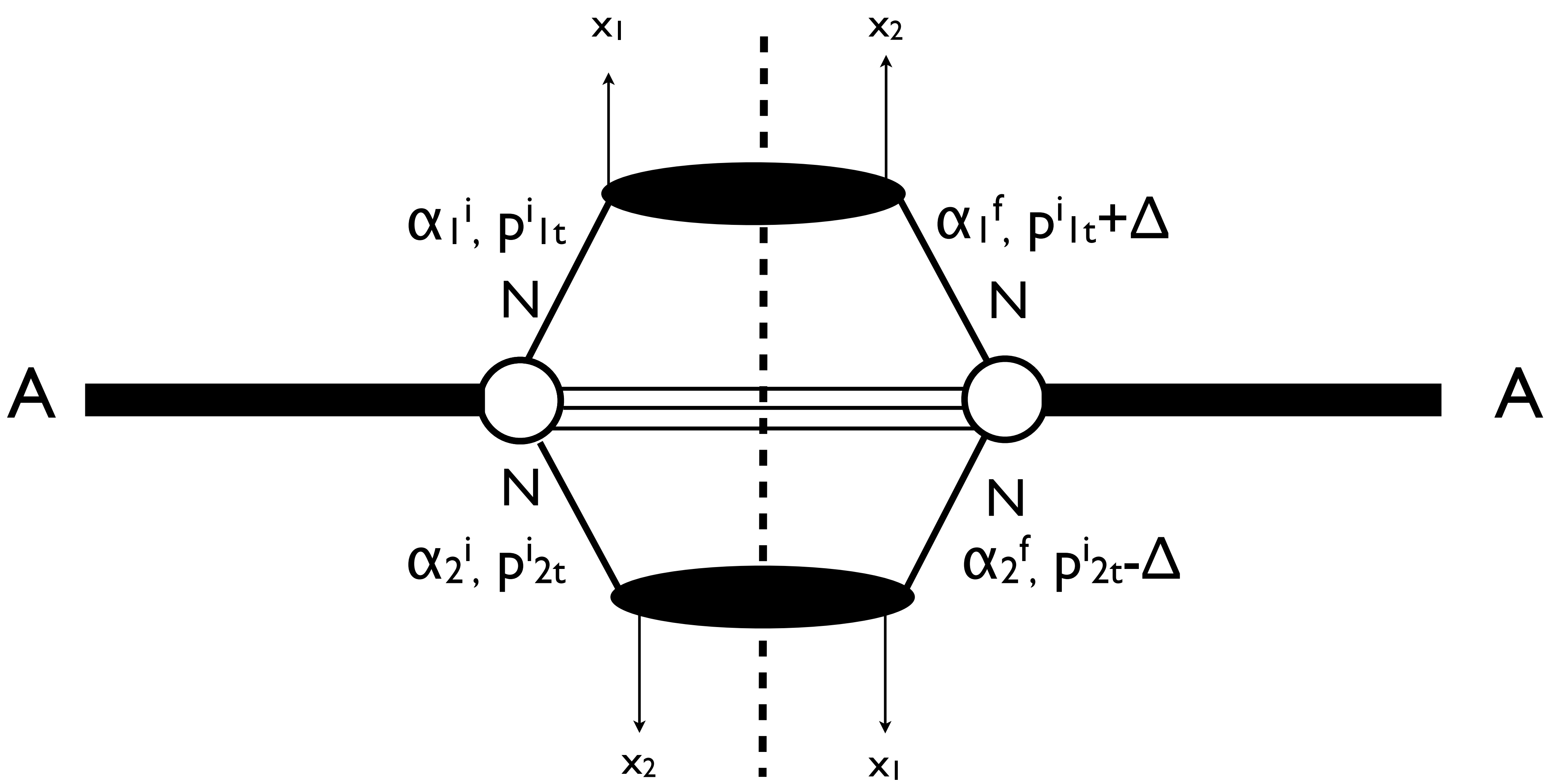
$$G_A^{2N}(x_1, x_2, \vec{\Delta}) \to f_N(x_1)\, f_N(x_2)\ F_A^{\mathrm{double}}(\vec{\Delta}, -\vec{\Delta})$$

$$\frac{\sigma_4(x_1', x_2', x_1, x_2)}{d\hat{t}_1 d\hat{t}_2} = \frac{f_p(x_1', x_2')}{f_p(x_1') f_p(x_2')} \frac{d\sigma_{2\mathrm{jet}}(x_1', x_1)}{d\hat{t}_1} \frac{d\sigma_{2\mathrm{jet}}(x_2', x_2)}{d\hat{t}_2} \frac{(A-1)}{A} \underbrace{\int T^2(b) d^2 b}_{\propto A^{4/3}}$$

measures longitudinal correlations

~ 1.2 in pQCD calculation of BDFS for 4 jets

Other contributions, accuracy of approximations



Schematic presentation of an interference contribution to the nucleus ${}_2$GPD in which the two patrons of momentum fractions x_1 and x_2 are drawn from two different nucleons in the amplitude, but in which the assignment between partons and active nucleons is swapped in the complex conjugate amplitude.

issue emphasized by Treleani and Calucci for light nuclei

Our conclusions:

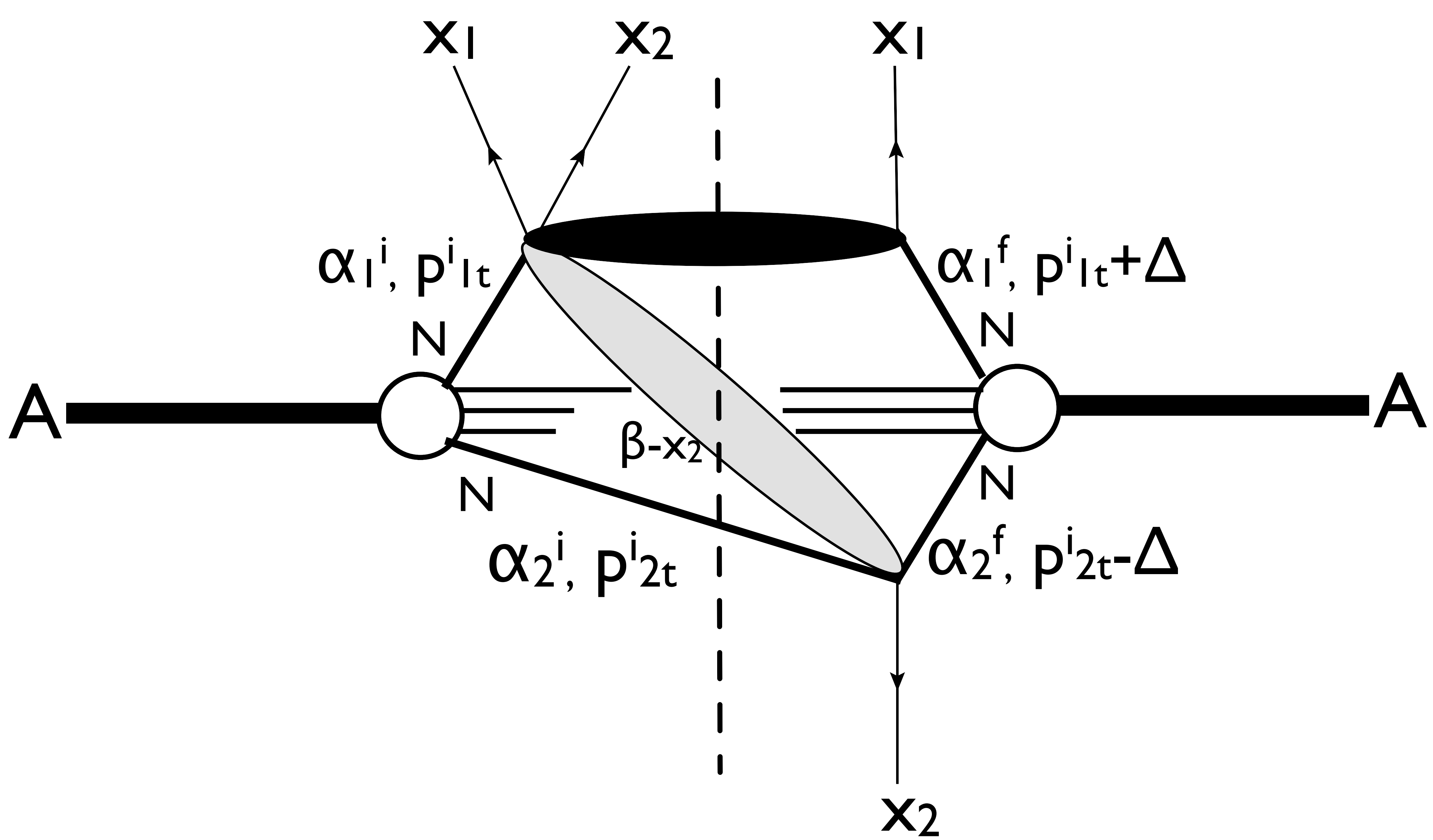
(a) longitudinal form factor kills interference for $|x_1-x_2| > 0.03$:

Suppression factor $\exp(-(x_1 - x_2)^2 m_N^2 \cdot R_A^2/3)$

(b) if $|x_1 - x_2| < 0.03$, $x_1 > 0.05$, finite Ioffe time allows interference only between nearby nucleons -- no $A^{4/3}$ term. Probably the same scale EMC effect for these x.

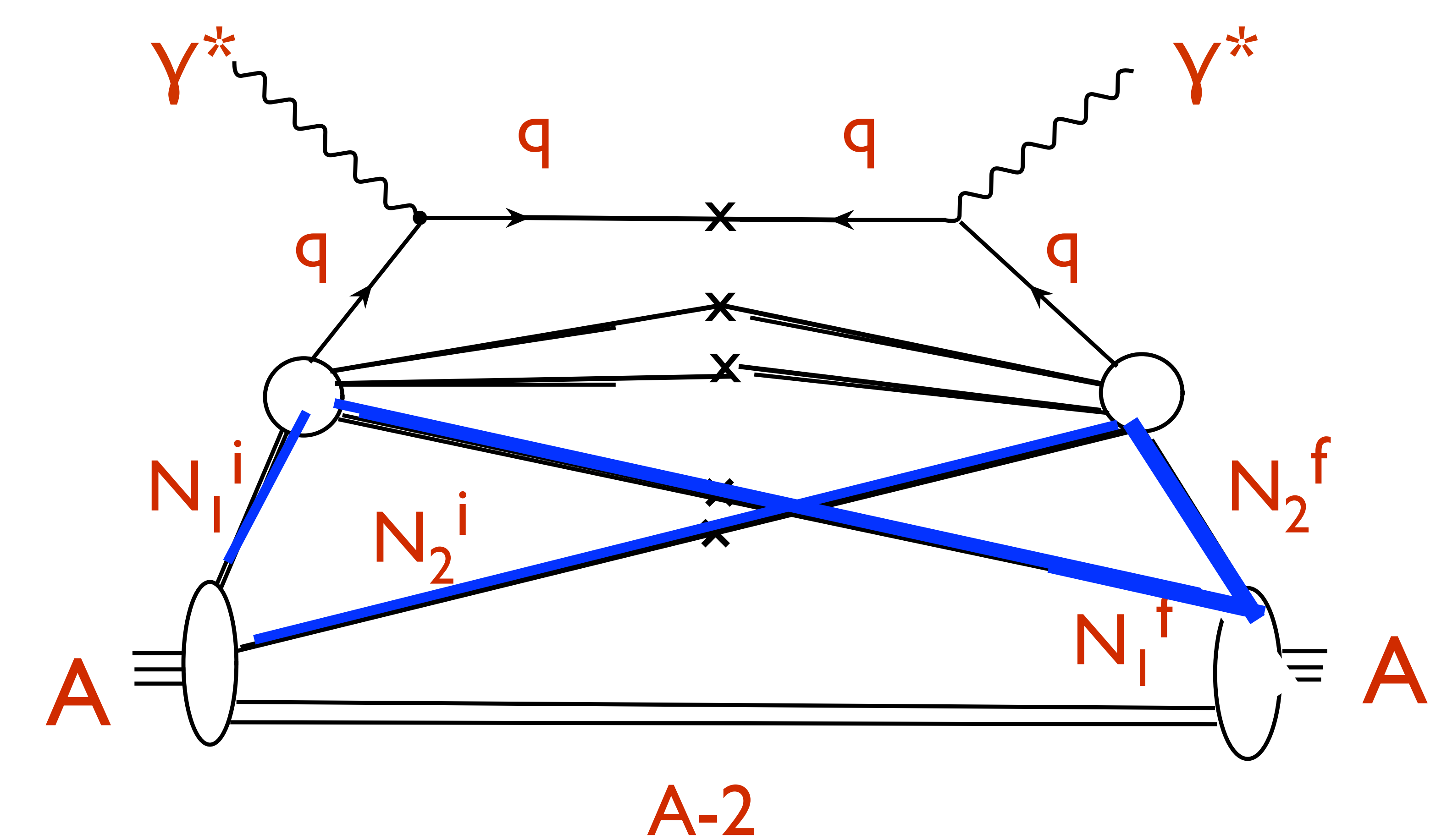
(c) For resolution scale Q - all radiated partons have to be included in the exchange - otherwise very strong suppression

(d) $x_1 < 0.01, x_2 > 0.03$



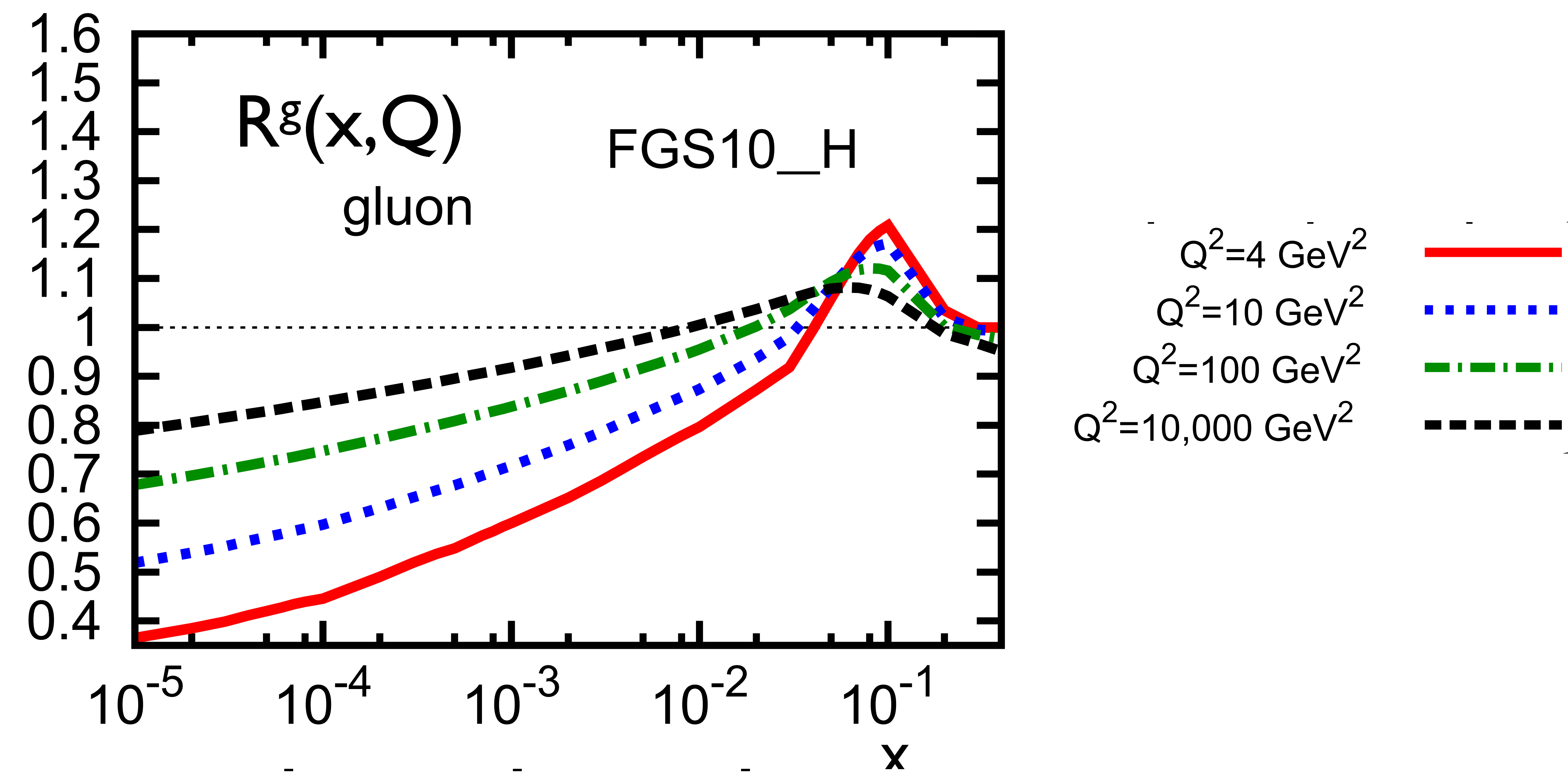
Interference of interactions with one and two nucleons

Subdiagram for x_1 parton is = first diagrams for nuclear shadowing in the theory of leading twist shadowing (Guzey, LF, MS 98 -12)

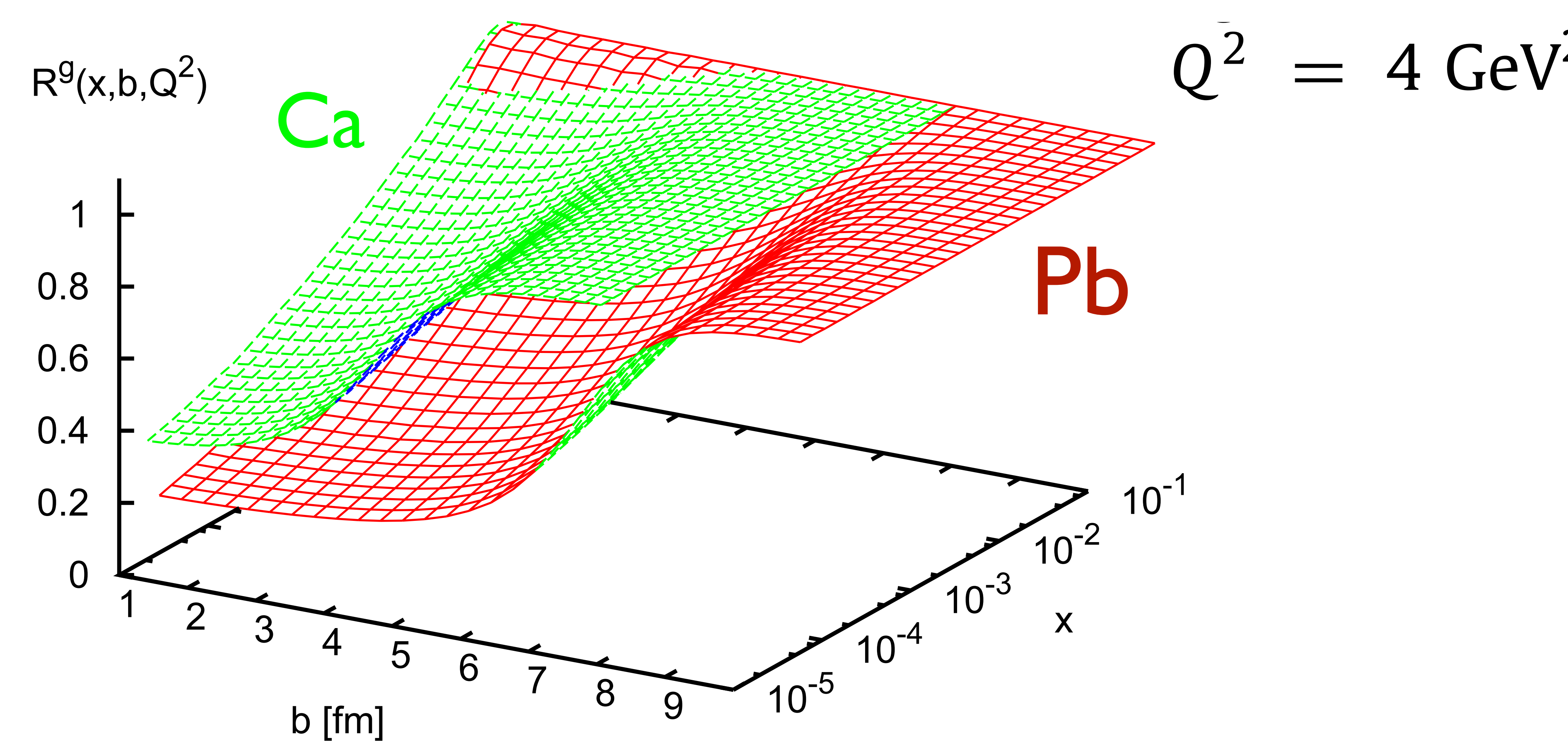


Prediction of the LT theory of nuclear shadowing based on factorization theorem for diffraction and AGK

Strong reduction of nuclear shadowing at fixed x due to the DGLAP flow of partons from larger x

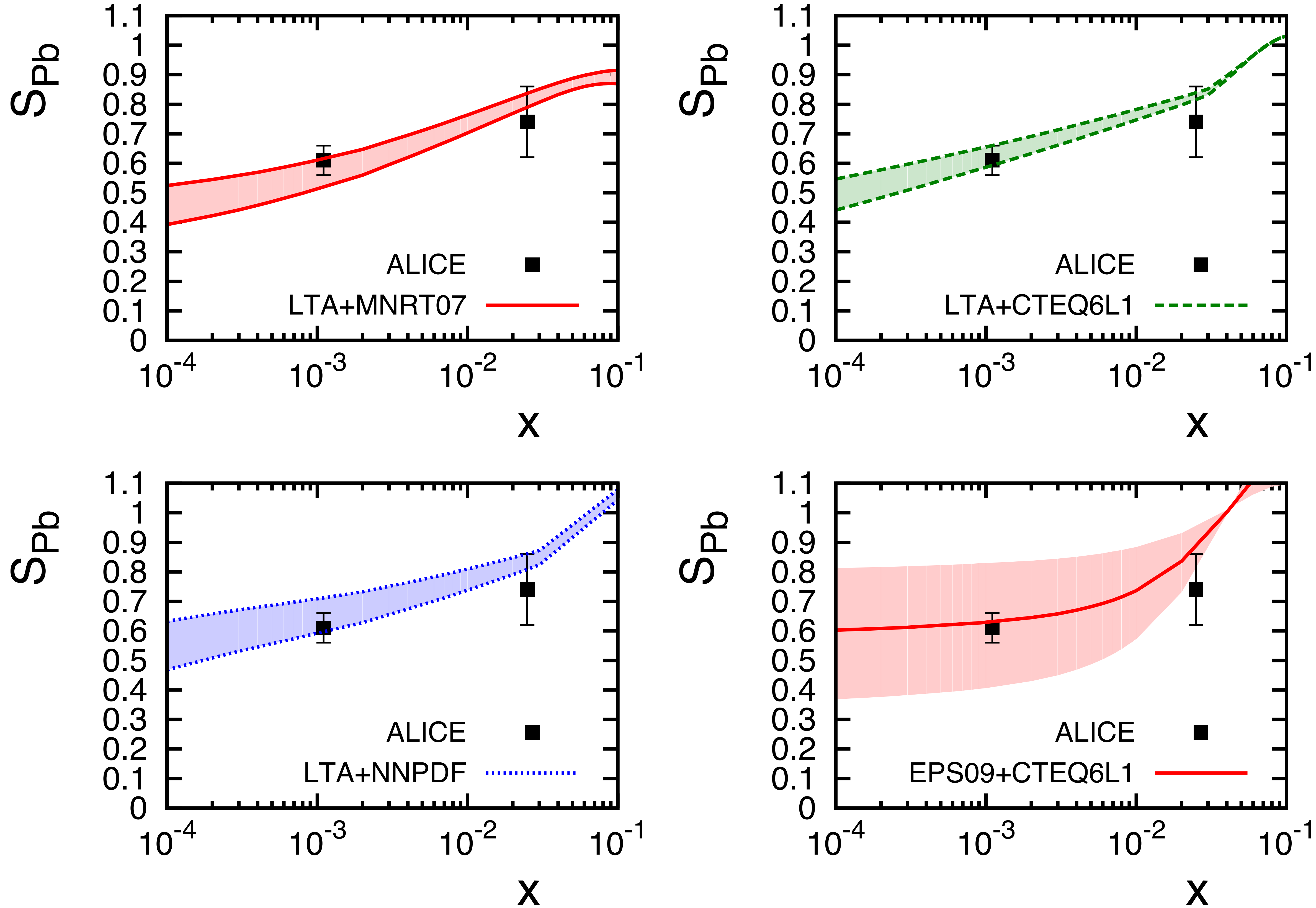


Spatial dependence of nuclear modification of gluon generalized pdfs in Ca and Pb



Strong suppression of coherent J/ψ production observed by ALICE (next talk) confirms our prediction of significant gluon shadowing on the $Q^2 \sim 3$ GeV^2

$$S_{Pb} = \left[\frac{\sigma(\gamma A \to J/\psi + A)}{\sigma_{imp.approx.}(\gamma A \to J/\psi + A)}\right]^{1/2} = \frac{g_A(x,Q^2)}{g_N(x,Q^2)}$$

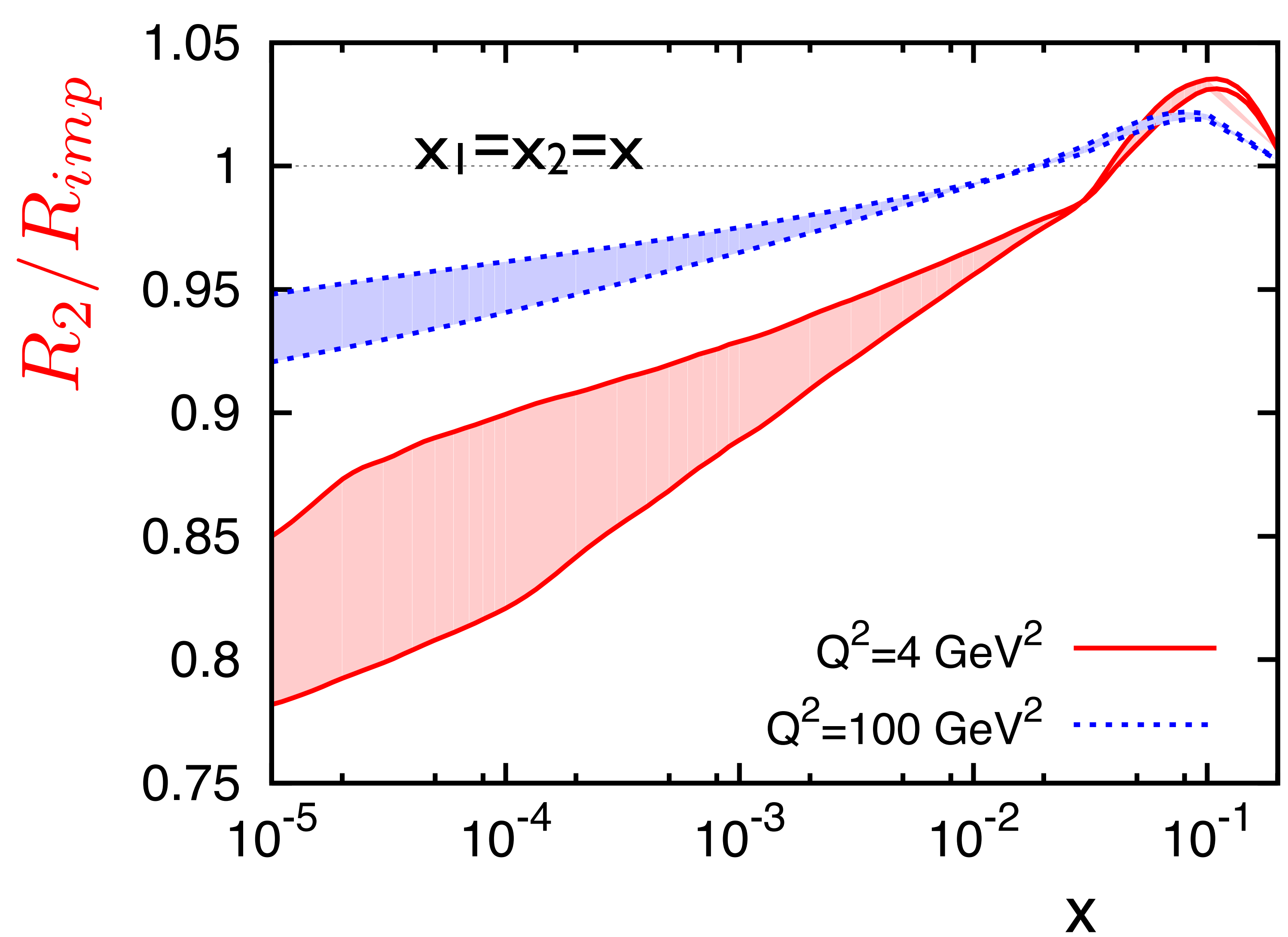


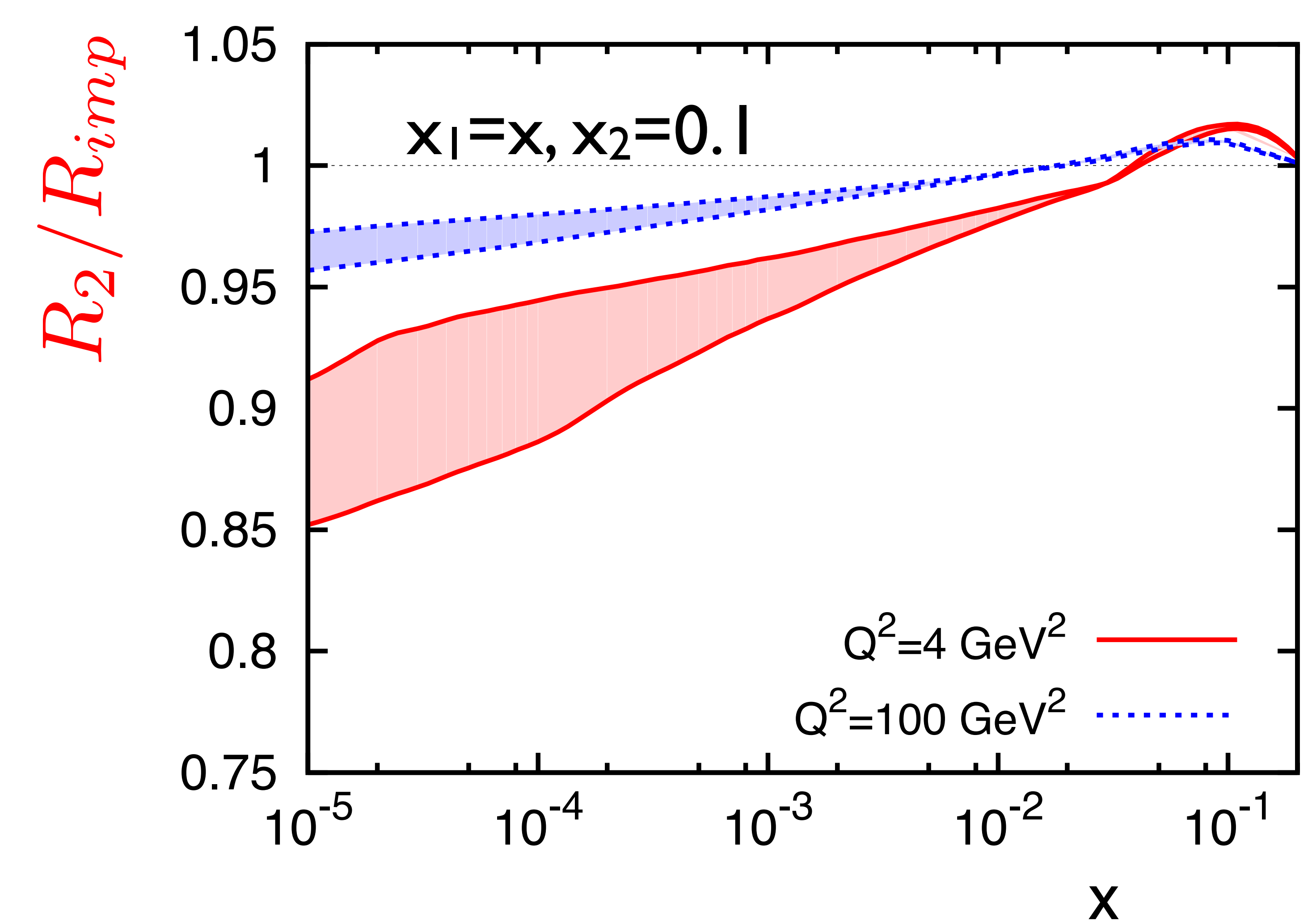
Points - experimental values of S extracted by Guzey et al (arXiv:1305.1724) from the ALICE data; Curves - analysis with determination of Q -scale by Guzey and Zhalov arXiv:1307.6689

Shadowing modifies

Impulse approx term by $R_{imp} = R^g(x_1, Q_1^2)\, R^g(x_2, Q_2^2)$

Double scattering term by $$R_2 = \frac{\int d^2b [R^g(x_1, b) \cdot R^g(x_2, b) T(b)^2}{\int d^2b [R^g(x_1) \cdot T(b)] \int d^2b [R^g(x_2) \cdot T(b)]}$$





Suppression of "double" scattering term relative to impulse term due to shadowing effects is modest but somewhat larger when both x's are small

Conclusions

- p QCD leads to a strong growth of parton - parton correlation contribution to MPI

- In the 4 jet LHC kinematics MPI vs LT 2→ 4 processes are enhanced in pA by a factor of 3 as compared to pp case.

  Will allow to test MPI analyses done of pp done at LHC (D'Enterria)

- Nuclear shadowing strongly reduces minijet MPI in pA (a factor of ~3 for central pA with $x_1 \sim x_2 \sim 10^{-3}$ and $p_t = 3$ GeV/c) --- D - mesons at LHCb?

- dA forward dipion production - strong evidence for MPI - data explained if MPI is combined with post selection effect of effective energy losses. In the future pp and pA data may allow *measurement of leading quark - quark correlations* in pp scattering at RHIC

Suplementary slides

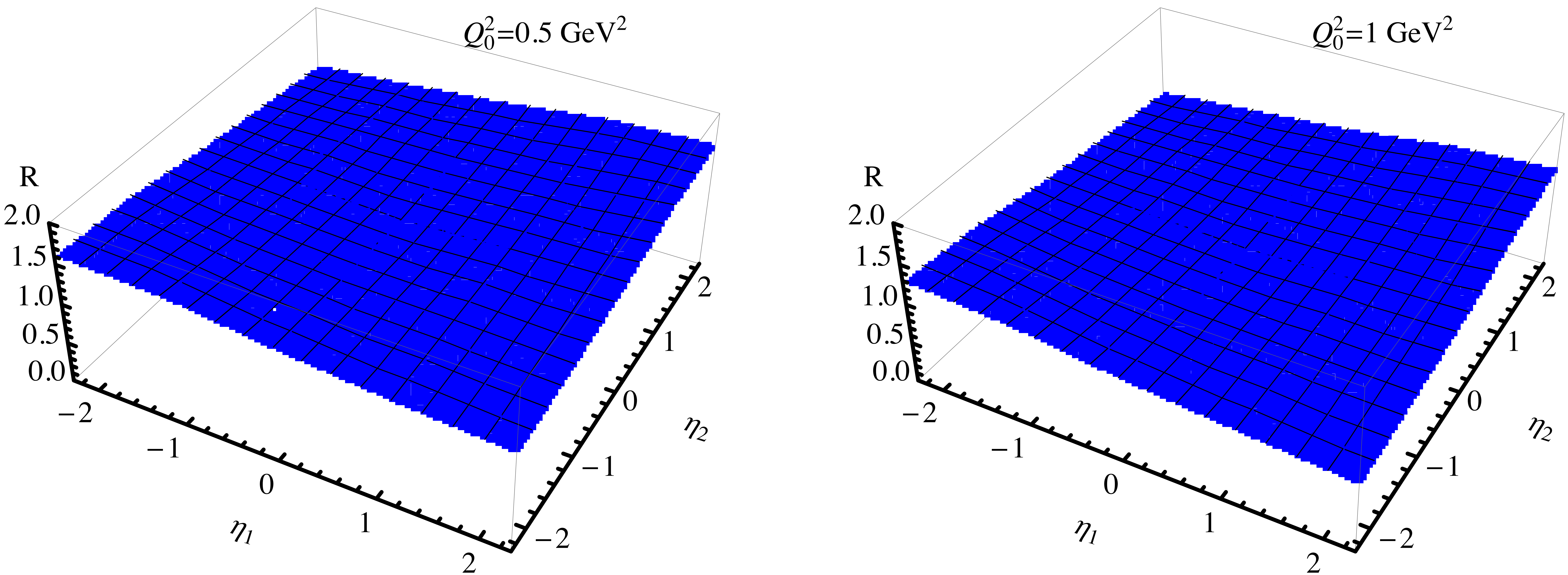


FIG. 6: Rapidity dependence of the R factor for two pairs of $p_\perp = 50\,\mathrm{GeV}$ jets produced in gluon-gluon collisions

wavy lines stand for diffractive hard interactions "Pomerons", H_i's are hard probes,
colored bloks are diffractive states which include the parton involved in the hard interaction