Transverse geometry of the hard and soft *pp collisions at the LHC*

Mark Strikman, PSU

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Motivations

Yuri's talk - DPI is example that any observables differential cross section of parton - parton inclusive scattering depend on transverse geometry

Detailed understading of the underlying event is necessary for precision necessary measurements of the hard cross section.

Interplay of soft and hard physics at LHC - constrains on hard physics from soft dynmanics.

Outline

Transverse geometry of high energy pp collisions - implications from studies of generalized parton distributions at HERA - *size matters*

Universality of underlying events at collider energies

High multiplicity - dijet rate correlation

Multijet production and S-channel unitarity

Onset of black disk regime - post -selection - from d -Au at RHIC to LHC

References:

Summary of our studies < 2005

Frankfurt, MS, Weiss, Annu. Rev. Nucl. Part. Sci. 2005. 55:403–65

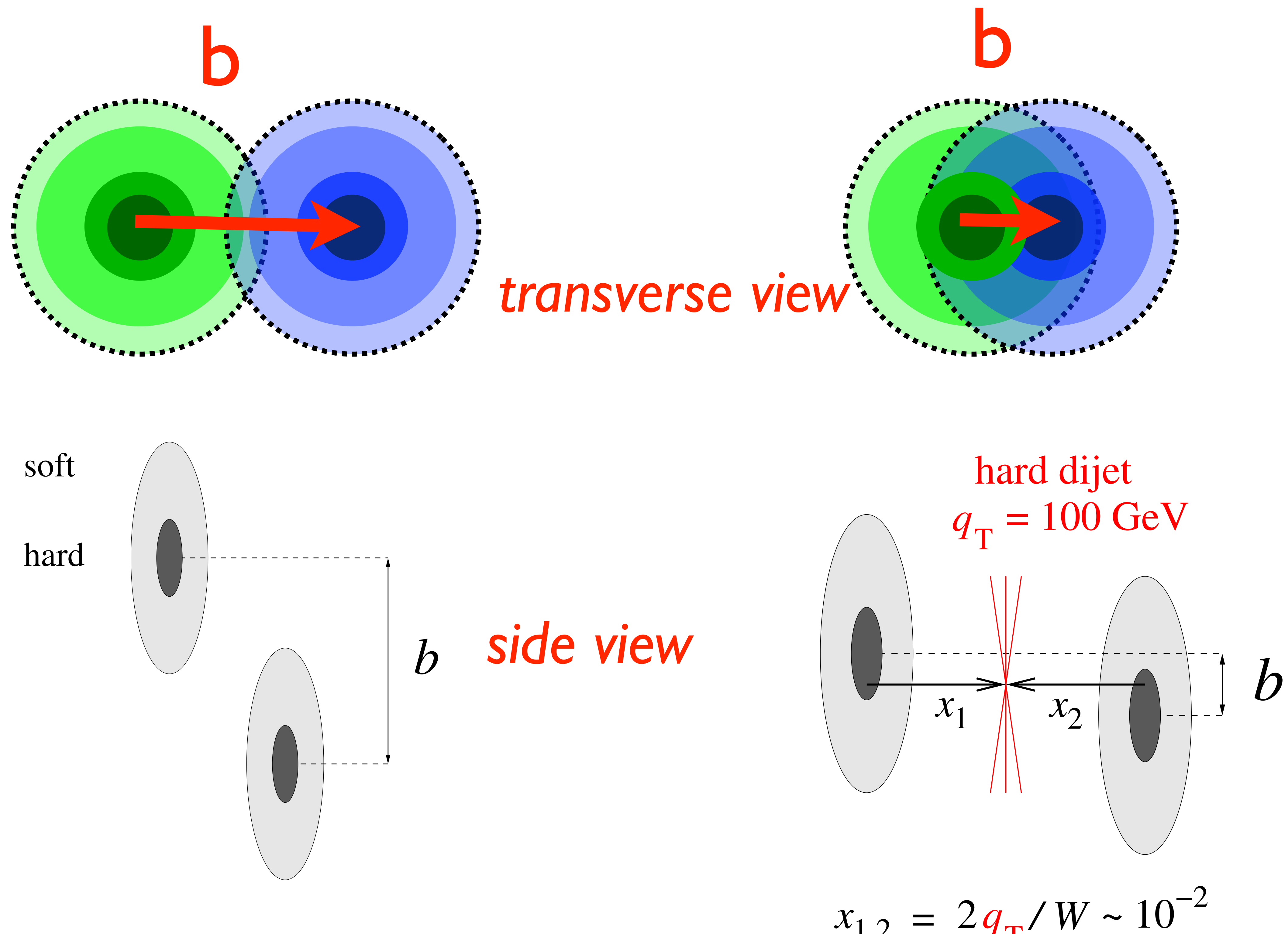
The most recent studies:

MS, W. Vogelsang	**Multiple parton interactions and forward double pion production in pp and dA scattering**
Blok, Dokshitzer, Frankfurt , MS	**list in Yuri's talk**
2010 Frankfurt , Weiss, MS	**Transverse nucleon structure and diagnostics of hard parton-parton processes at LHC**
2011 MS	**Comments on the observation of high multiplicity events at the LHC**
2014 Azarkin, Dremin MS	**Jets in multiparticle production in and beyond geometry of proton-proton collisions at the LHC**

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

Peripheral pp collisions



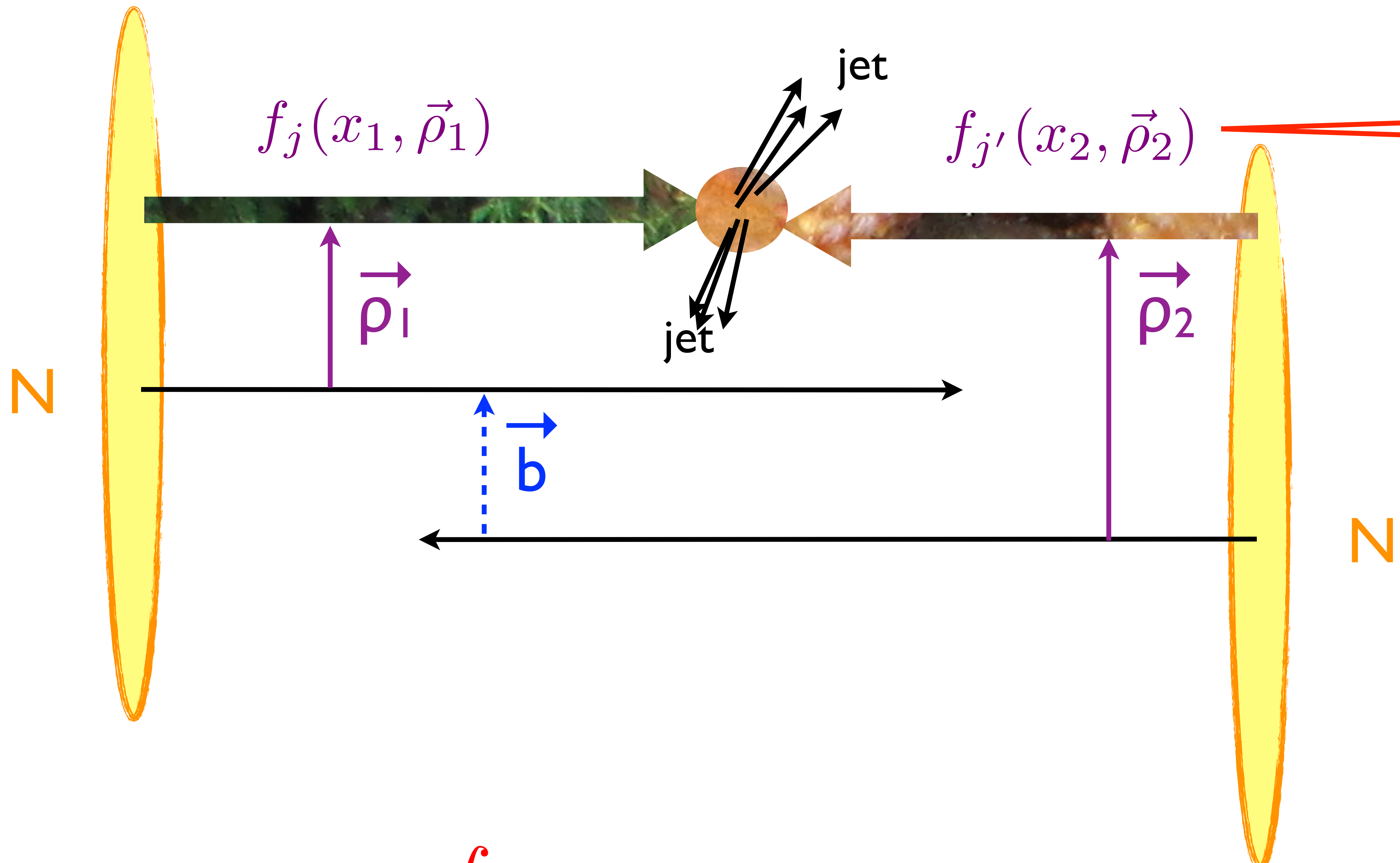
Central pp collisions

Two scale picture

Small b ➡ large overlap of parton densities

Large probability of multiparton, soft/hard interactions

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

In proton-ion, ion-ion collisions collisions at small impact parameters are *strongly different* from the minimal bias events. Is this true also for pp collisions?

Why this is interesting/ important?

- Amplification of the small x effects: in proton - proton collisions a parton with given x_1 resolves partons in another nucleon with $x_2 = 4p_\perp^2/x_1 s$

At Tevatron $x_1 = 0.01, p_\perp = 2GeV/c \Rightarrow x_2 \sim 4 \times 10^{-4}$

At LHC $x_1 = 0.01, p_\perp = 2GeV/c \Rightarrow x_2 \sim 8 \times 10^{-6}$

- Resulting strong difference between the semi-soft component of hadronic final states at LHC &Tevatron in events with production of Z,W, Higgs, SUSY,... and in minimal bias events ➠ structure of underlying events

$\Rightarrow$ ***Necessary to account for new QCD phenomena related to a rapid growth of the gluon fields at small x:*** **parton "1" propagates through the strong gluon field of nucleon "2".**

Hence, accumulation of higher twist effects and possible divergence of the perturbative series.

Impact parameter picture is build into many current MC's of pp collisions at LHC/ Tevatron, cosmic rays at highest energies (GZK) - but <u>does not include so far constrains on the transverse structure of the nucleon originating from HERA studies.</u>

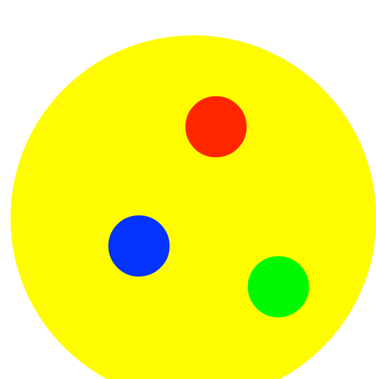
Critical for interpretation of structure of the events with dijets at the colliders, multiple collisions. Multiparton interactions have significant probability at Tevatron and large probability at LHC - *rates scale as 1/(transverse area occupied by partons), depend on the shape of the transverse distribution and on the degree of the overlap.*

First quantitative analysis including information on the transverse structure from HERA -

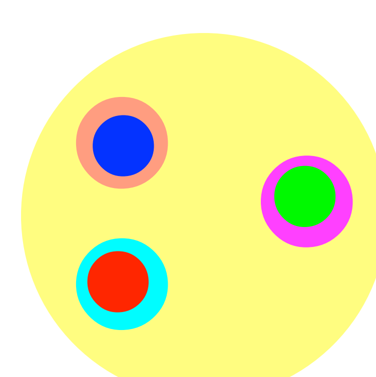
Frankfurt, MS, Weiss, 2003

Goals for colliders - realistic account of the transverse structure of the nucleon, the global structure of the events with Higgs, SUSY,...

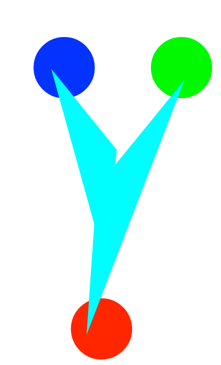
Goals for nucleon structure - probing correlations between quarks, gluons, ...; Distinguish



MIT bag



Constituent quark model with localized gluon fields

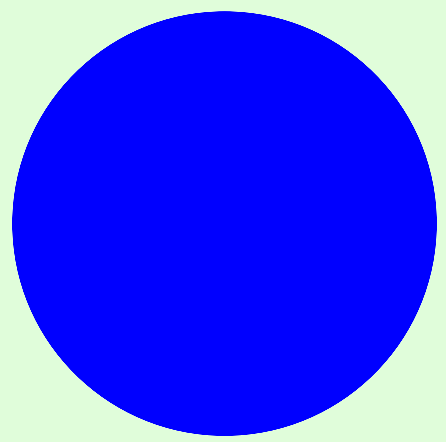


quark - diquark

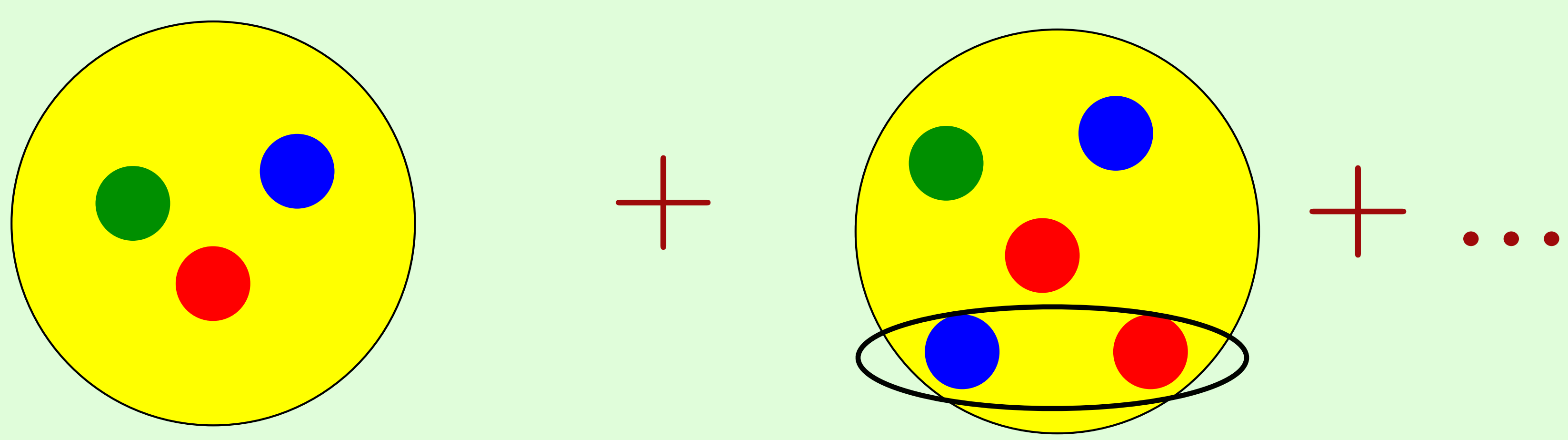
String models

Image of nucleon at different resolutions, q.

Rest frame.



resolution 1 fm, q < 300 MeV/c

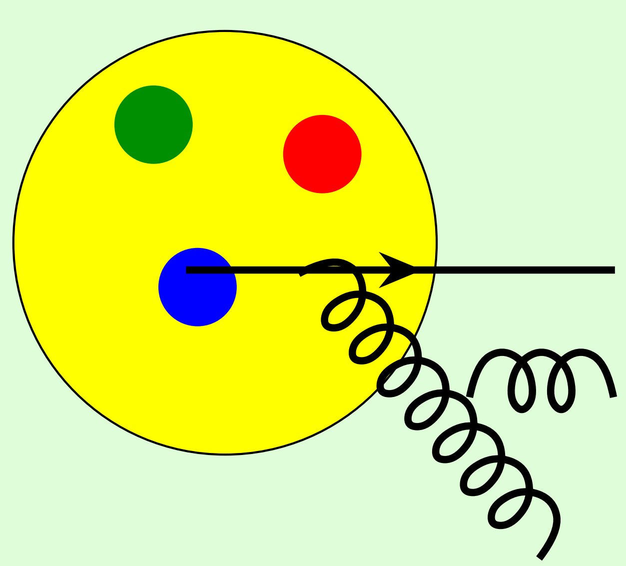


$q\bar{q}$ $pair$ in π

resolution 1/3 fm

1000 > q > 300 MeV/c

Constituent quarks, pions (picture inspired by chiral QCD)



q > 1000 MeV/c

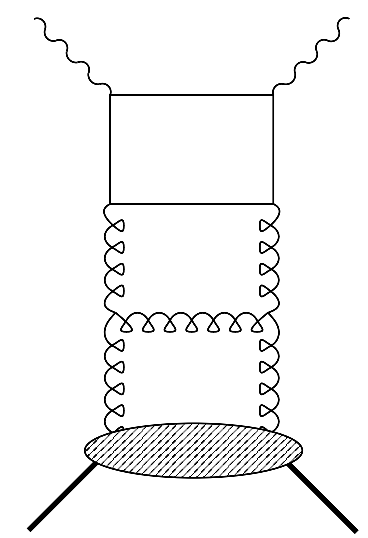
pQCD evolution

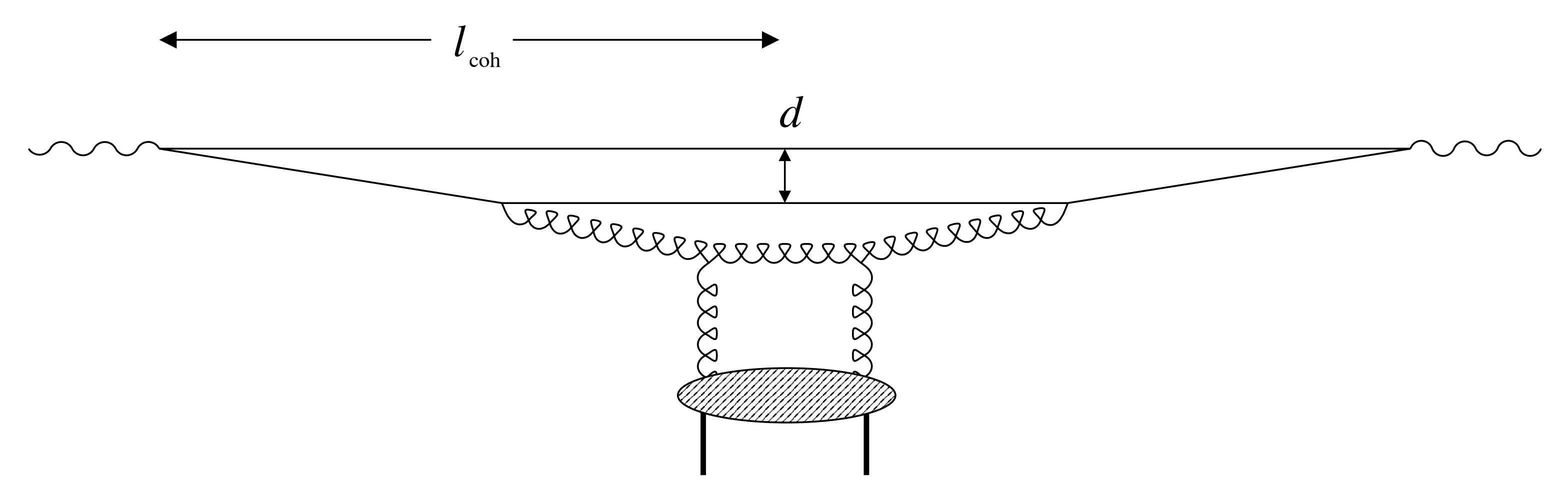
Note: This is image averaged over sizes of quark-gluon configurations in nucleon

Image of nucleon at different resolution scales q.

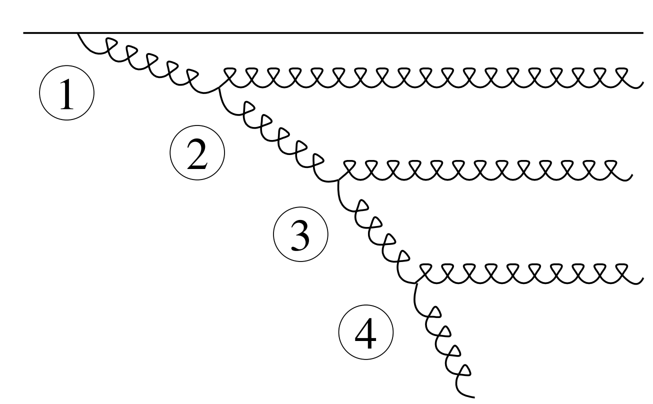
Fast frame.

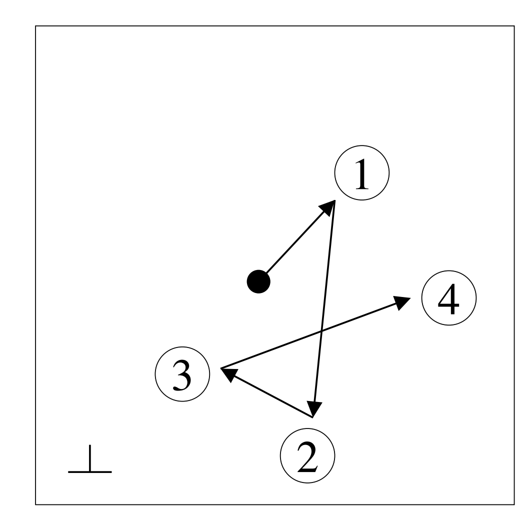
Energy dependence of the transverse size of small x partons.





(a) (b)





(c) longitudinal momentum transverse coordinate

$$R^2(n) \approx \frac{n}{k_{t0}^2}$$

Random walk in b-space (Gribov 70). *(Drunken sailor walk)*

Length of the random walk $\propto$ rapidity, y as each step a change in rapidity of few units.

$$n \propto y \implies R^2 = R_0^2 + cy \equiv R_0^2 + c' \ln s$$

Implications:

(a) The transverse size of the soft wee parton cloud should logarithmically grow with energy.

(b) Logarithmic increase of the t-slope of the elastic hadron-hadron scattering amplitude with energy:

$$f(t) \propto \exp(Bt/2), \quad B(s) = B_0 + 2\alpha' \ln(s/s_0)$$

$$\alpha' \propto 1/k_{t0}^2$$

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

Hard Exclusive processes

$$\gamma^* + N \to \gamma + N(baryonic\, system)$$

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

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

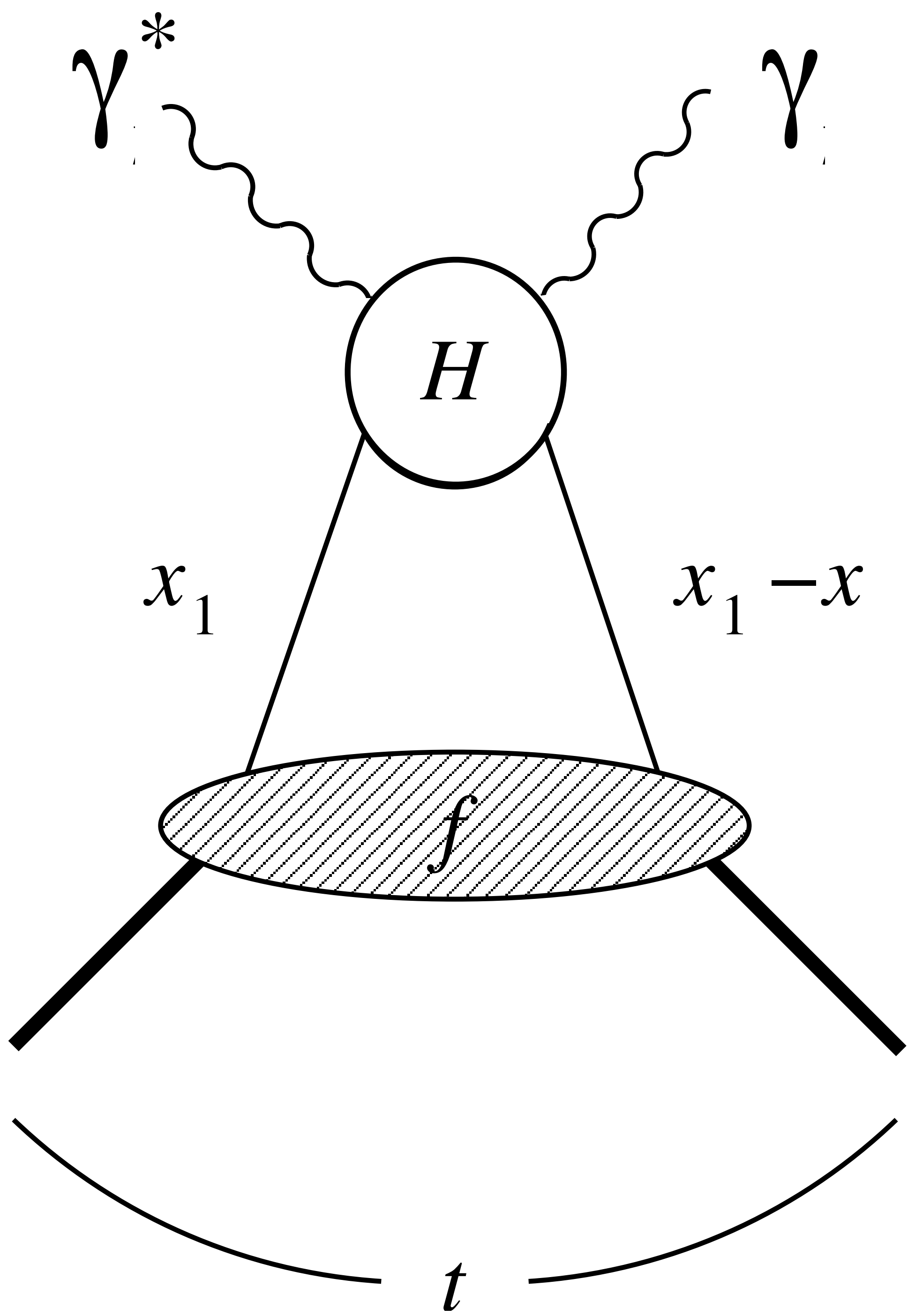
Frankfurt, Miller, MS 93 & 03

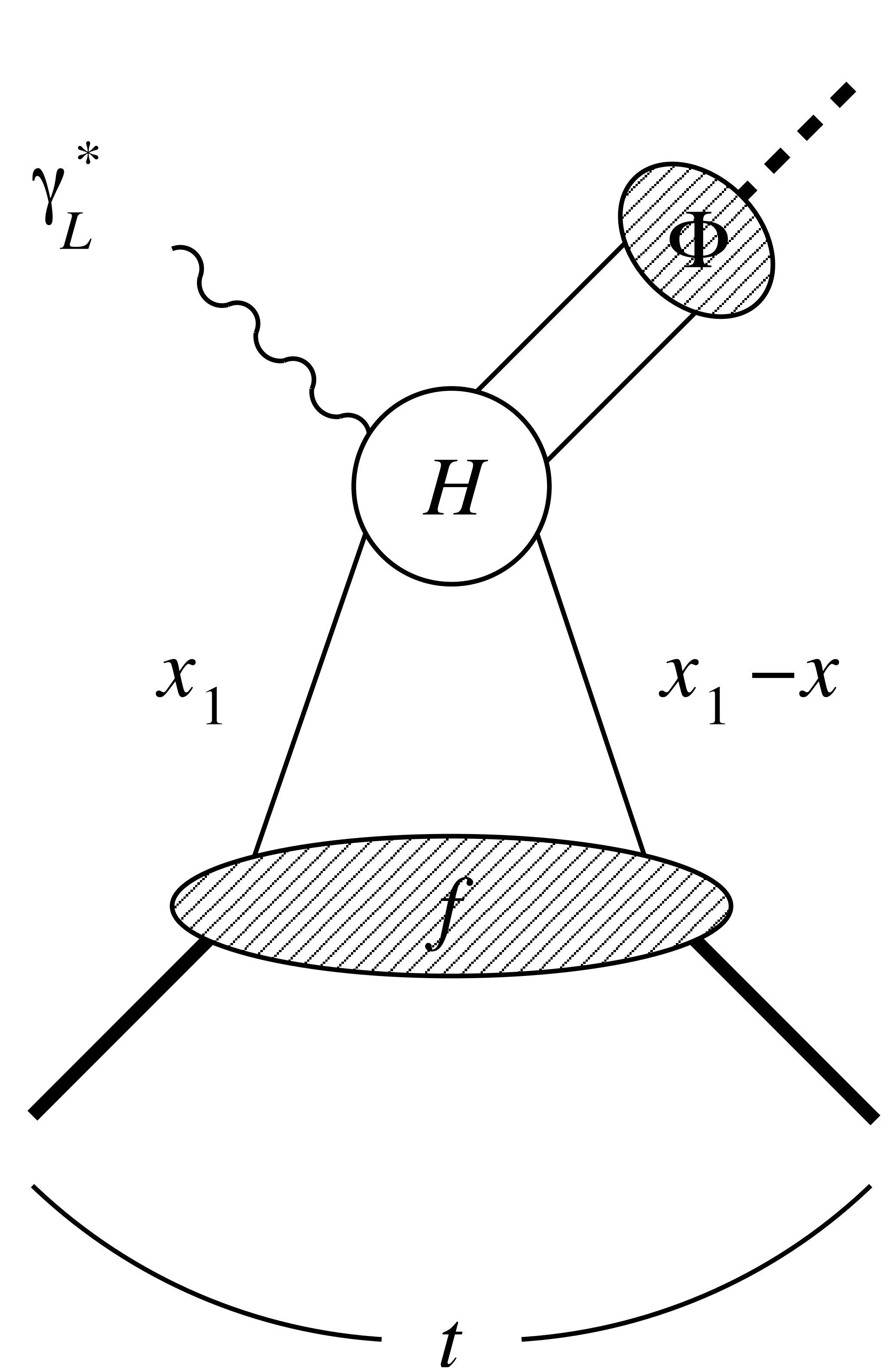
$$\gamma_L^* + N \to "meson"(mesons) + N(baryonic\, system)$$

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





Meson distribution amplitude

Hard scattering process

Generalized parton distribution

Baryo-baryonic

t-dependence only from GPD's

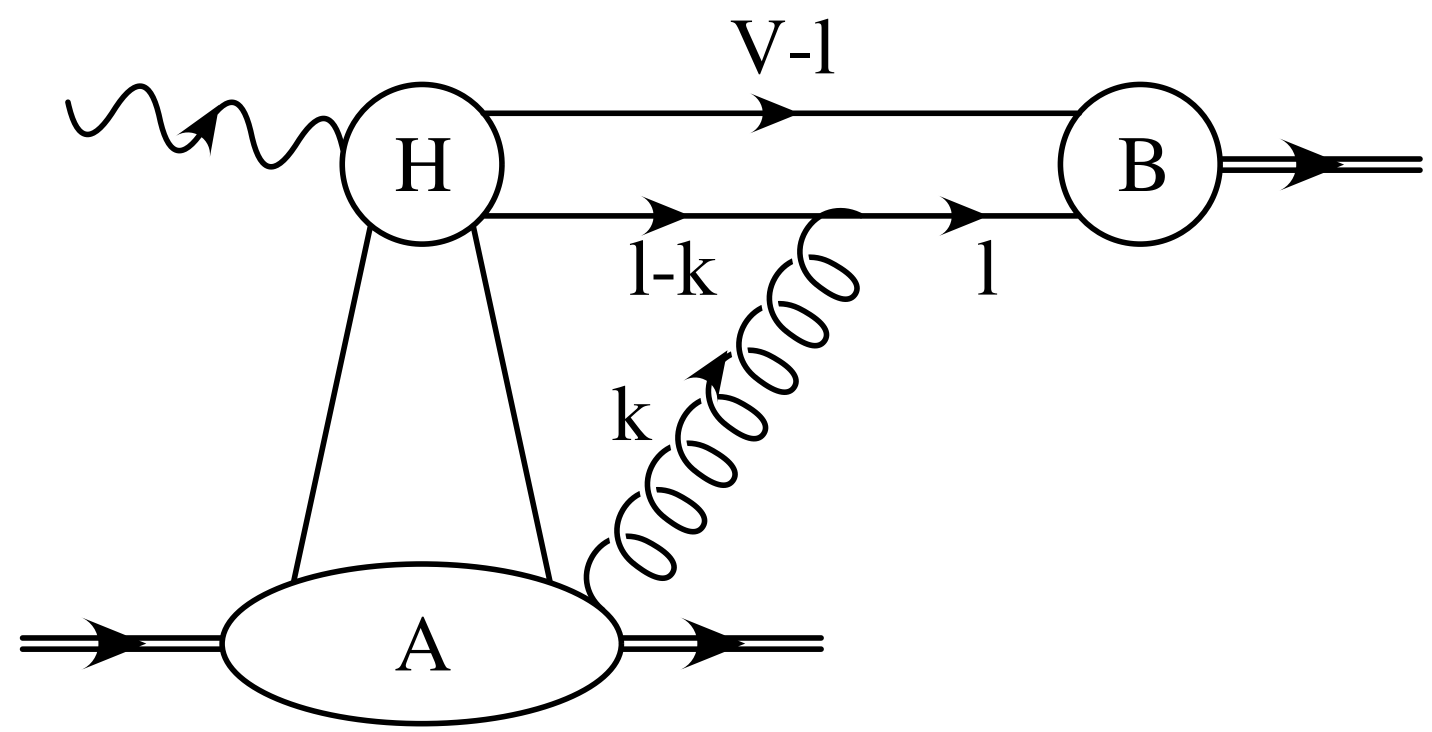
transverse spatial distribution of partons - - - - →

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

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

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

Diagrams like:



where an extra gluon is exchanged between the hard blocks are suppressed by a factor $\frac{1}{Q^2}$. —Very lengthy proof - CFS

Qualitatively - due to color screening/transparency - small transverse size of γ_L^* selects small size (point-like) configurations in meson.

Best seen in the Breit frame

Before the interaction

N

⇛ (p,p)

γ^*

O (0, q)

After photon absorption: for $m^2_{\text{meson system}}$= const, m^2_{baryon}=const, x=const, $Q^2 \to \infty$

Meson system	Baryon system
⇚ fast left movers	fast right movers ⇛

No soft interactions between left and right movers is possible provided the meson system has a small size. Insured by the choice of γ^*_L

For γ^*_T nonperturbative contribution is suppressed only by $\ln Q^2$ similar to $F_{2N}(x,Q^2)$

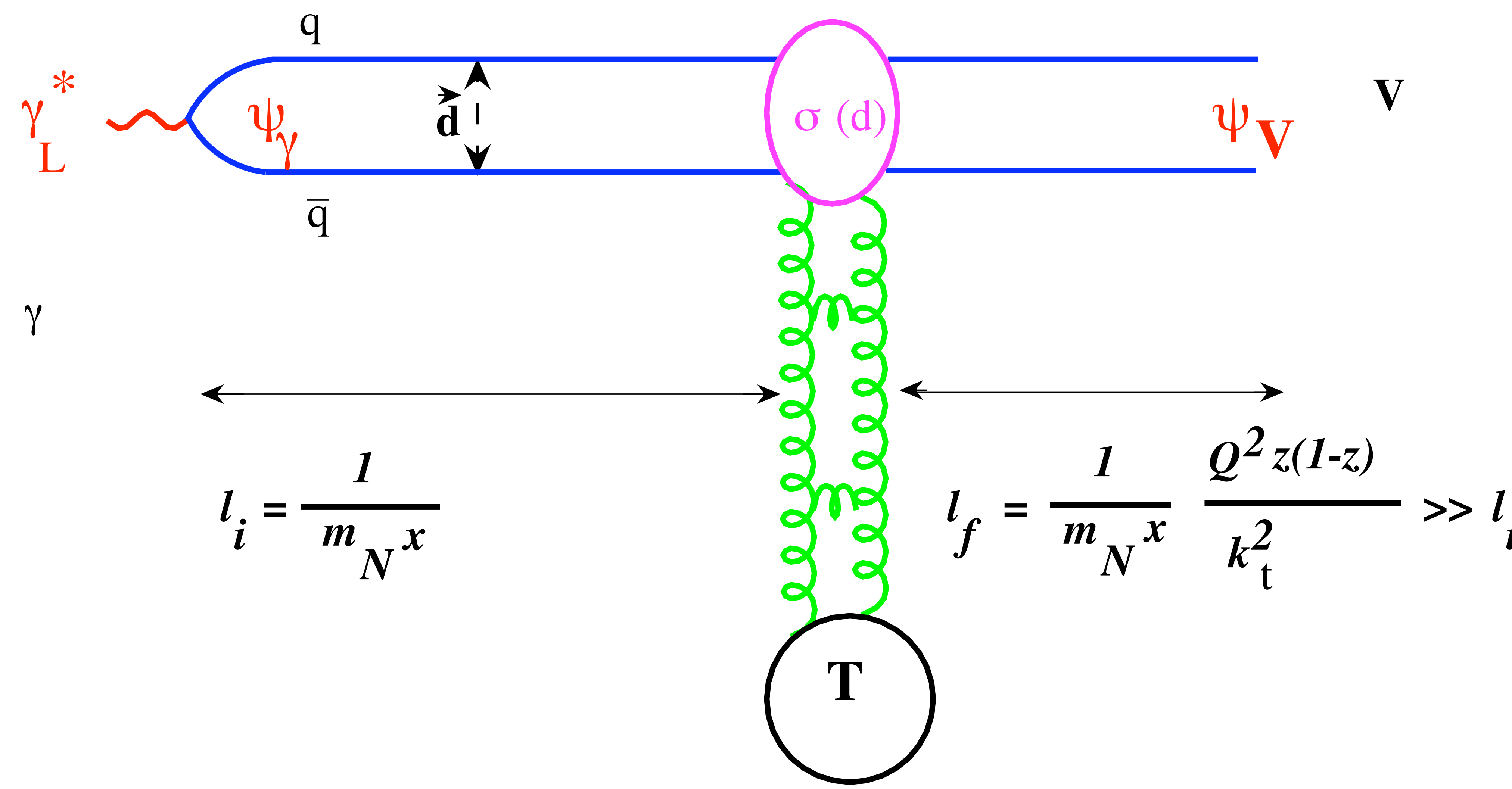
Signature differences between VM production with γ^*_T and γ^*_L are

- larger t-slope for " γ^*_T
- increase of $\sigma_{L/}\ \sigma_T$ with W at mixed Q^2

Difficult measurements - H1 sees some evidence for a slighter larger σ_T t-slope, ZEUS does not.

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

The leading twist parameter free answer is BFGMS94

$$\left.\frac{d\sigma^L_{\gamma^* N\to VN}}{dt}\right|_{t=0} =$$

$$\frac{12\pi^3\Gamma_{V\to e^+e^-} M_V \alpha_s^2(Q)\eta_V^2 \left|\left(1+i\frac{\pi}{2}\frac{d}{d\ln x}\right) xG_T(x,Q^2)\right|^2}{\alpha_{EM} Q^6 N_c^2}$$

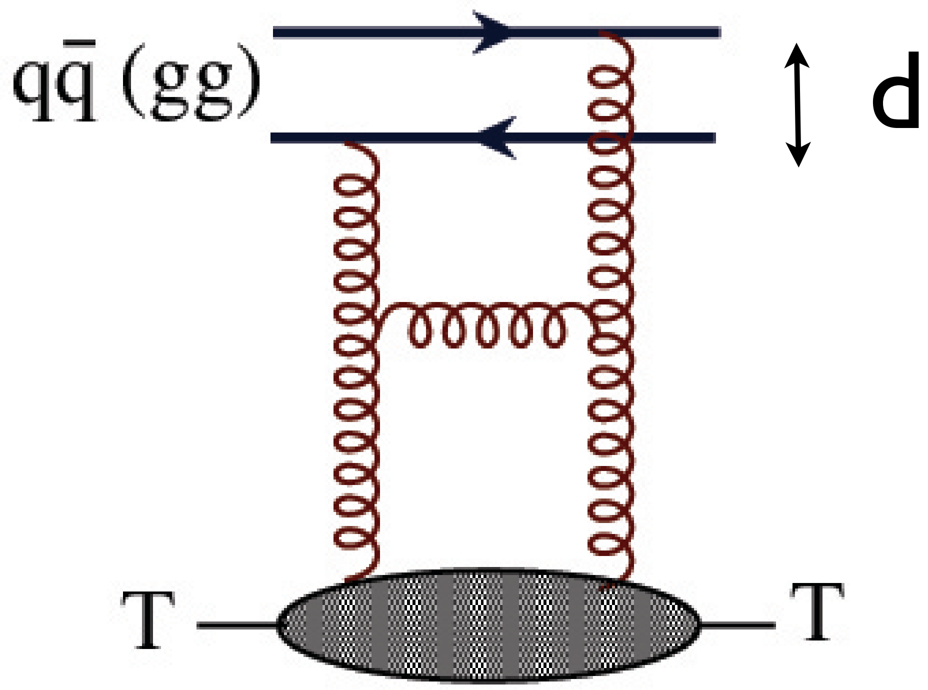
. *Here,* $\Gamma_{V\to e^+e^-}$ *is the decay width of* $V \to e^+e^-$;

$$\eta_V \equiv \frac{1}{2}\frac{\int \frac{dz\, d^2k_t}{z(1-z)}\Phi_V(z,k_t)}{\int dz\, d^2k_t\, \Phi_V(z,k_t)} \to 3 \;|_{Q^2\to\infty}$$

Note: In the leading twist d=0 in $\psi_V(z,d)$. *Finite* b *effects in the meson wave function is one of the major sources of the higher twist effects.*

Interaction of fast particles in QCD is expected to differ qualitatively from soft dynamics

Consider first "small dipole - hadron" cross section



$$\sigma_{inel}^{dipole-T}(x,d) = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x, \lambda/d^2)$$

F^2 Casimir operator of color SU(3)

Baym, Blattel, F&S 93

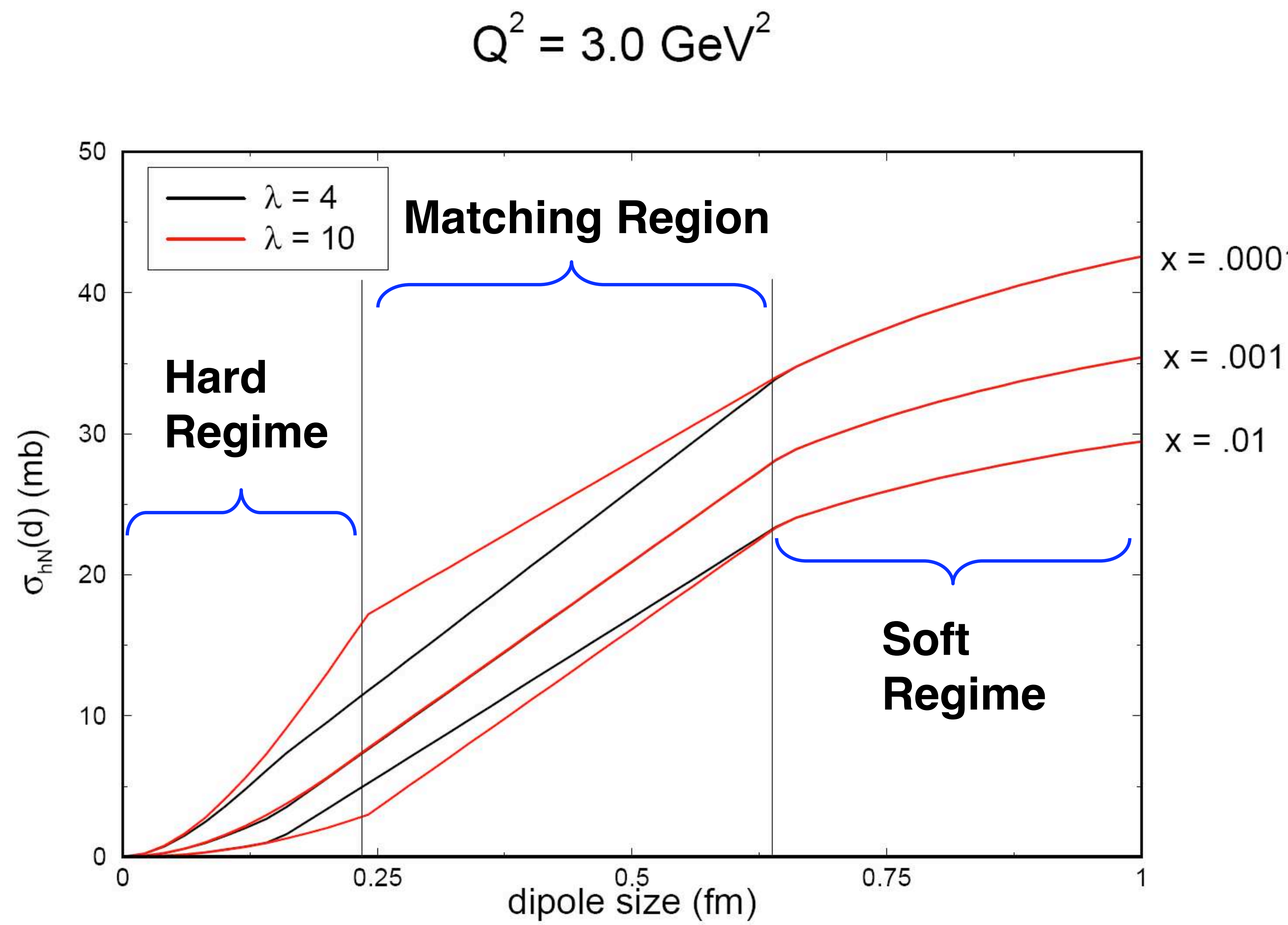
F^2 (quark) =4/3 F^2 (gluon)=3

$$\sigma(d, x_N) = \frac{\pi^2}{3}\alpha_s(Q^2_{eff}) d^2 \left[x_N G_N(x_N, Q^2_{eff}) \boxed{+ 2/3 x_N S_N(x_N, Q^2_{eff})}\right] \longleftarrow$$

Important at E_{dipole} < 10 GeV

Comment: This simple picture is valid only in LO. NLO would require introducing mixing of different components. Also, in more accurate expression there is an integral over x, and an extra term due to quark exchanges. However the general pattern is now tested and works.

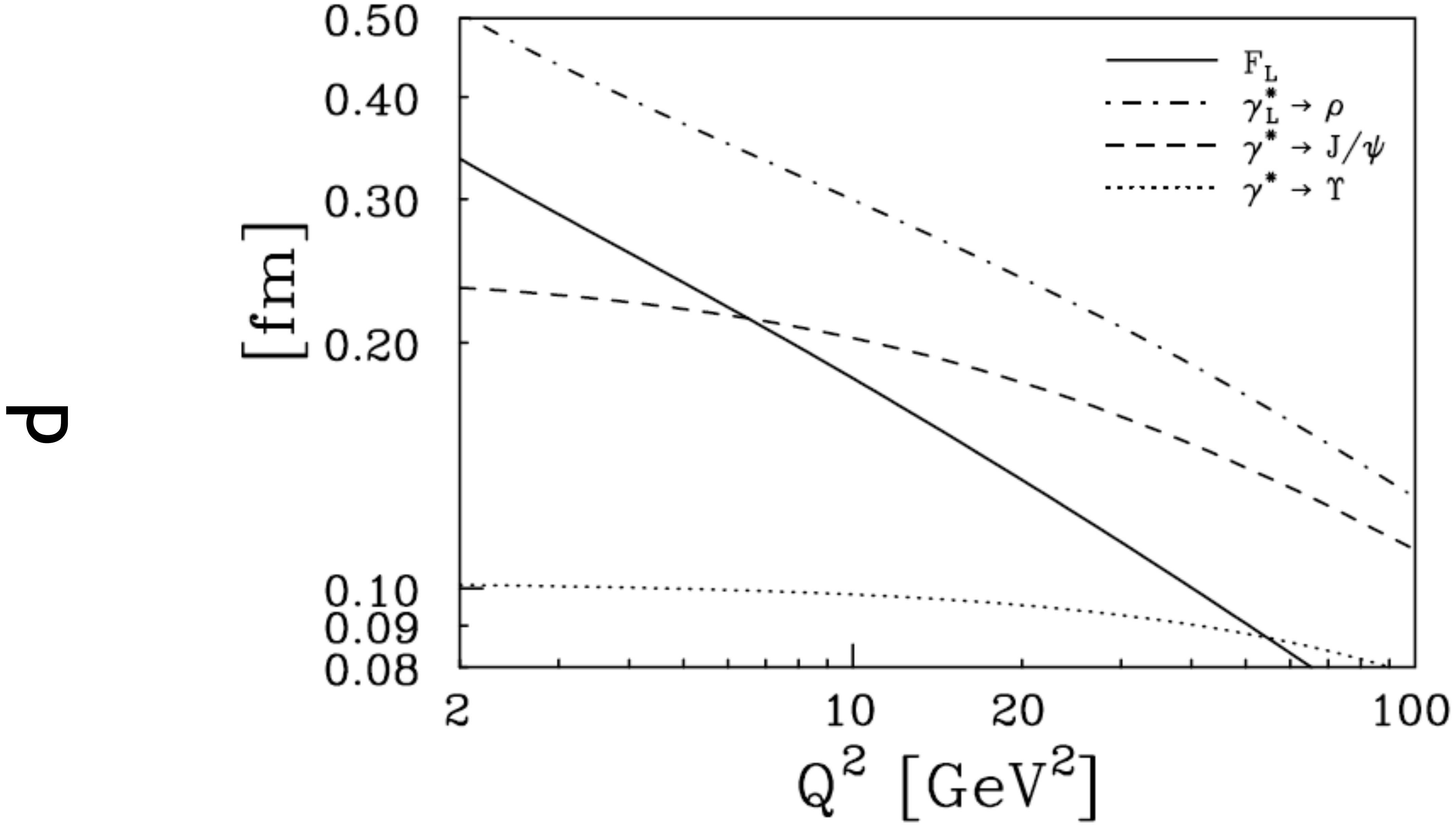
HERA data confirm a fast increase of the cross sections of interaction small dipoles with energy predicted by pQCD due to $xG_N \propto x^{-\omega(Q)}$, $\omega \in 0.2 \div 0.4$

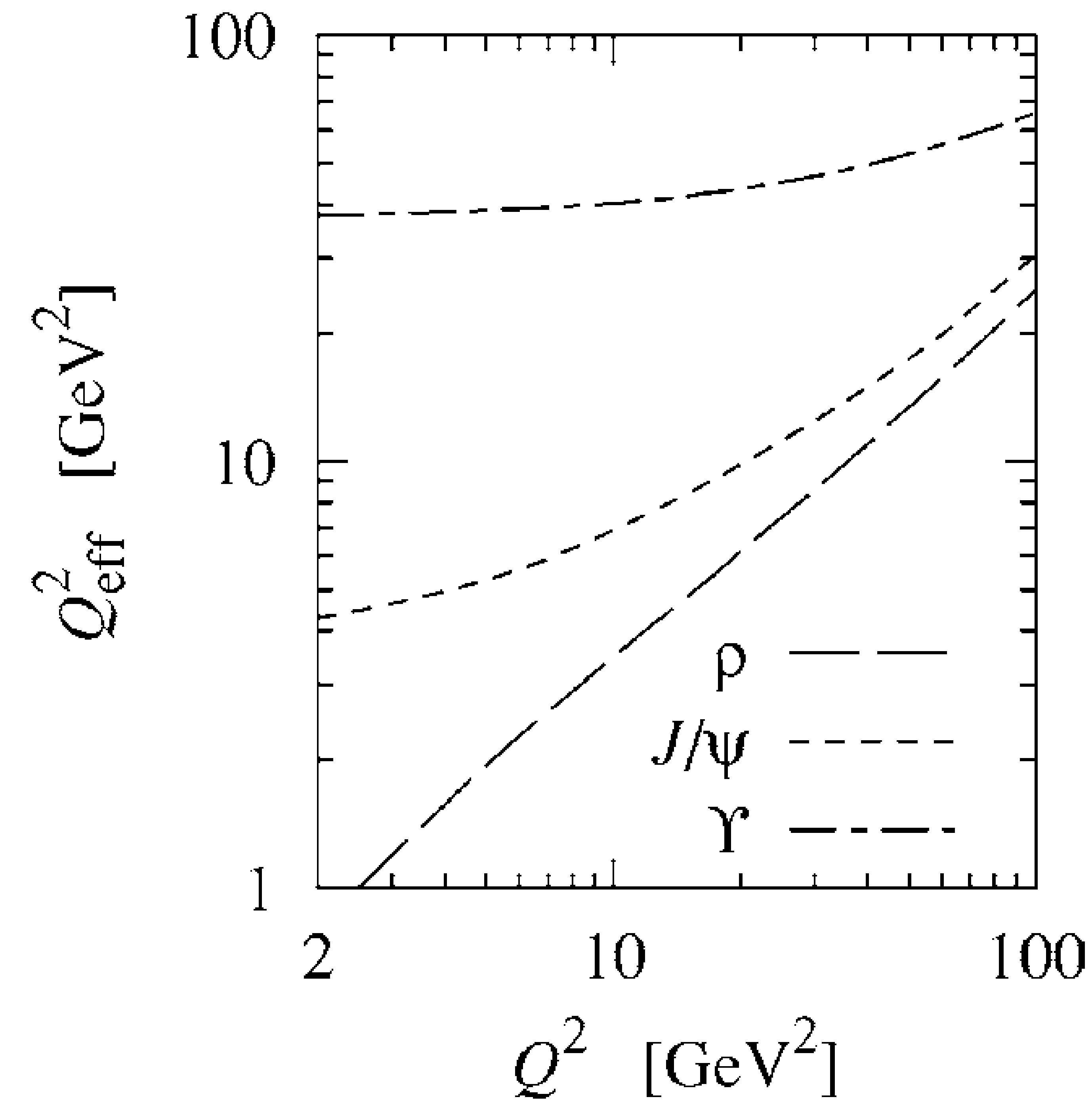


The interaction cross-section, $\hat{\sigma}$ for CTEQ4L, $x = 0.01, 0.001, 0.0001$, $\lambda = 4, 10$. Based on pQCD expression for $\hat{\sigma}$ at small d_t, soft dynamics at large b, and smooth interpolation. Provides a good description of F_{2p} at HERA and J/ψ photoproduction.

Provided a reasonable prediction for σ_L

Frankfurt, Guzey, McDermott, MS 2000-2001

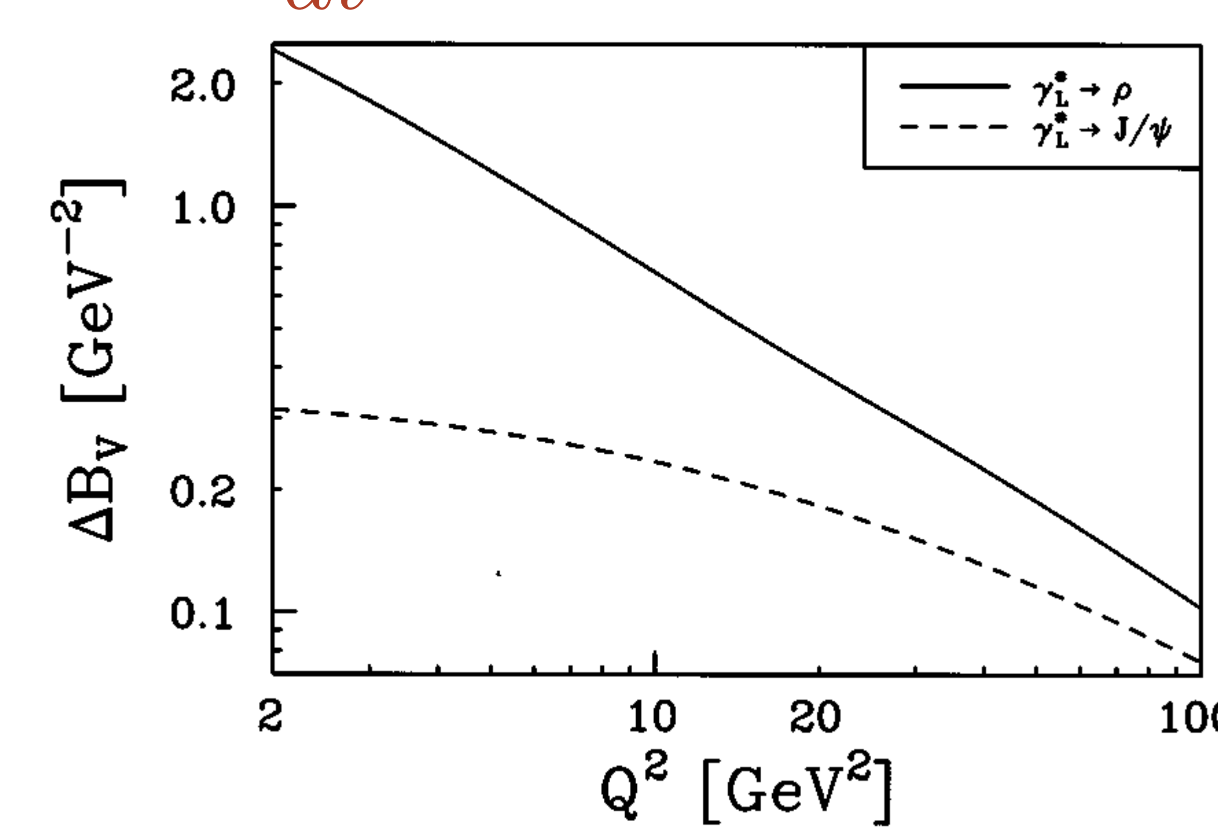




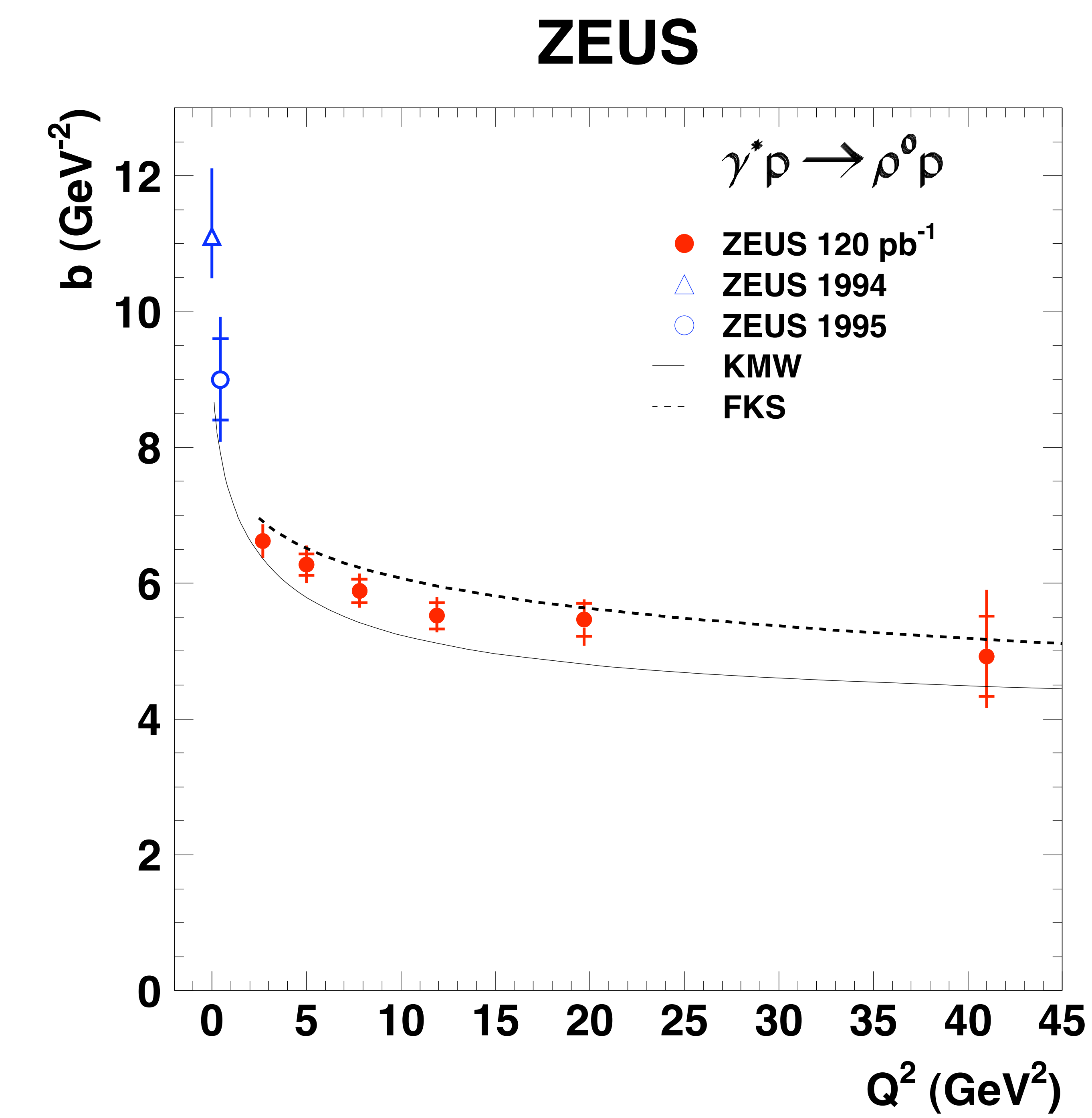
Predictions:

- A rather slow convergence of the t-slopes B of ρ and J/ψ at large Q
- Weak Q dependence of B(J/ψ)
- Onset of fast increase of σ(γ*→ρ) only at large Q

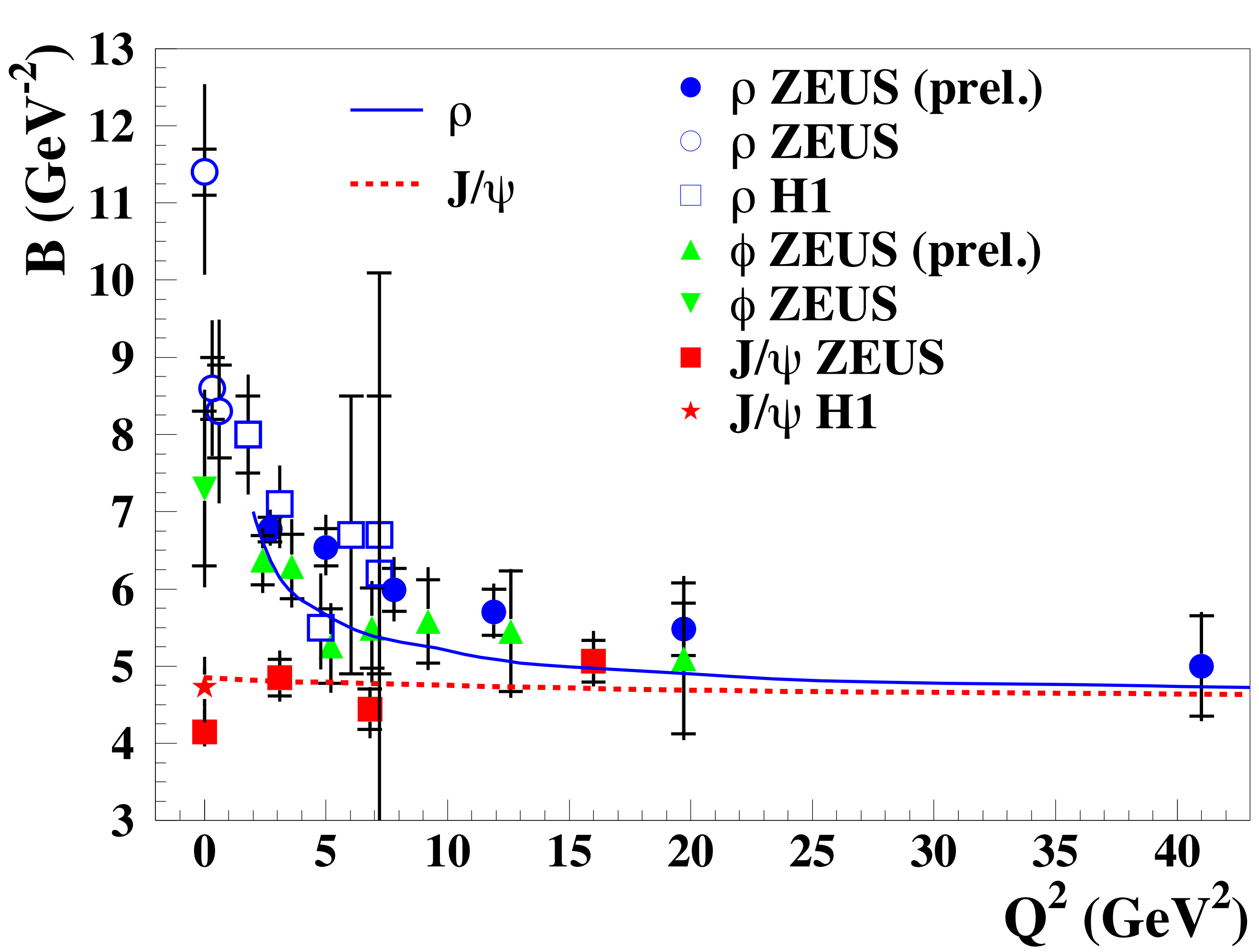
$$\frac{d\sigma}{dt} \propto \exp(Bt)$$



B

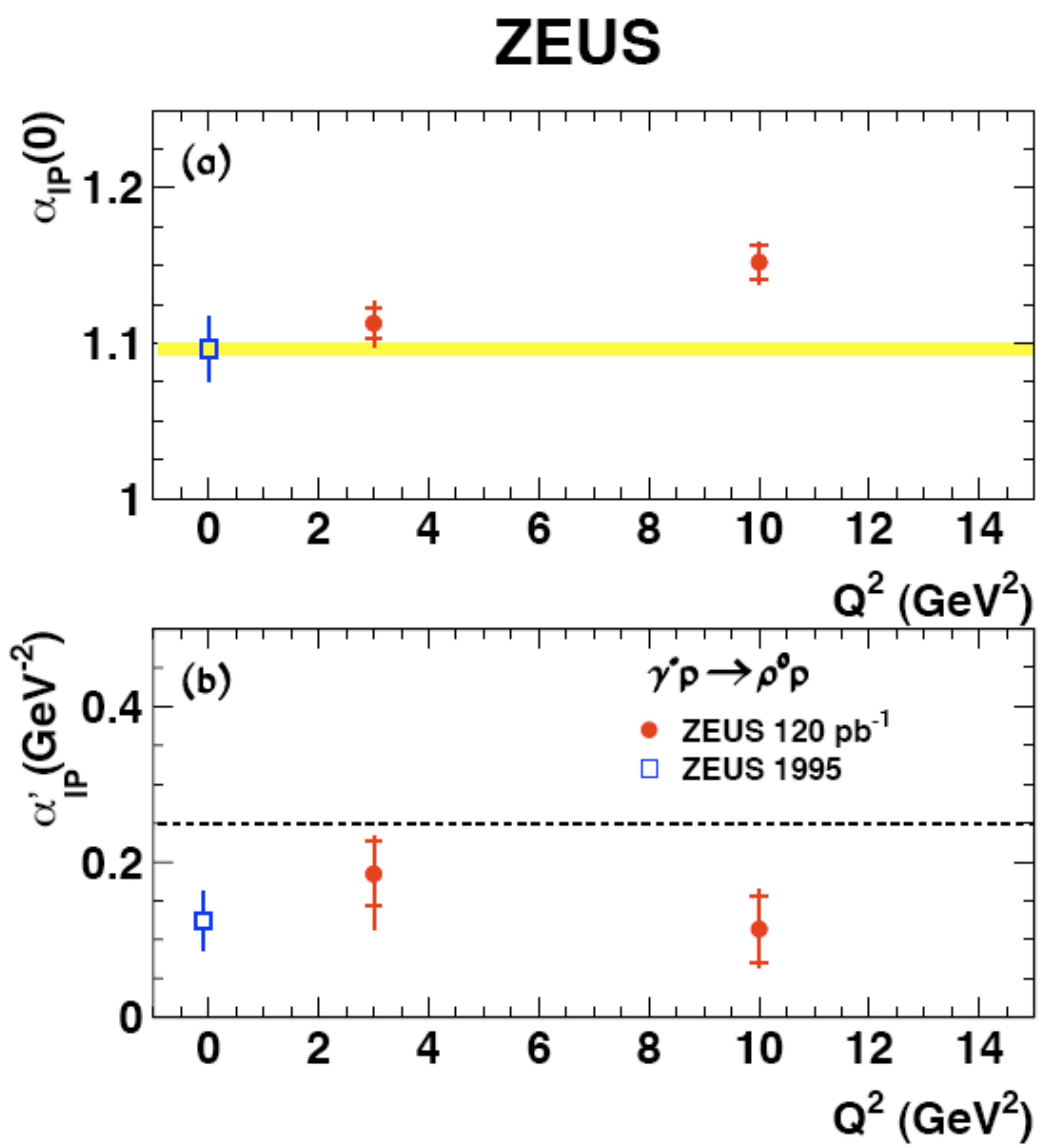


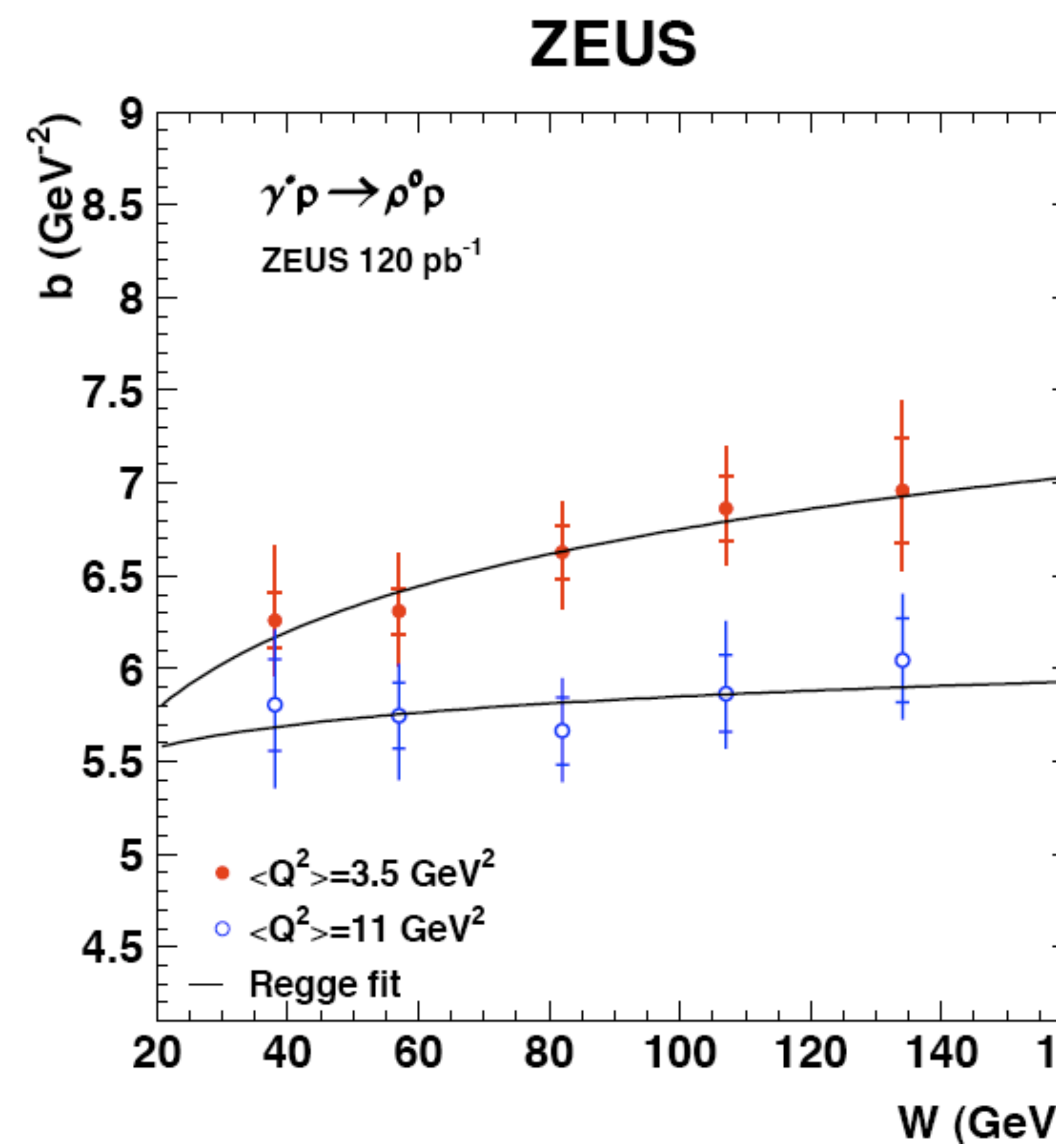
Drop of B is well reproduced by dipole approximation (in case of FKS actually a prediction of 12 years ago)



Convergence of t-slope, B of ρ-meson electroproduction to the slope of J/ψ photo(electro)production.

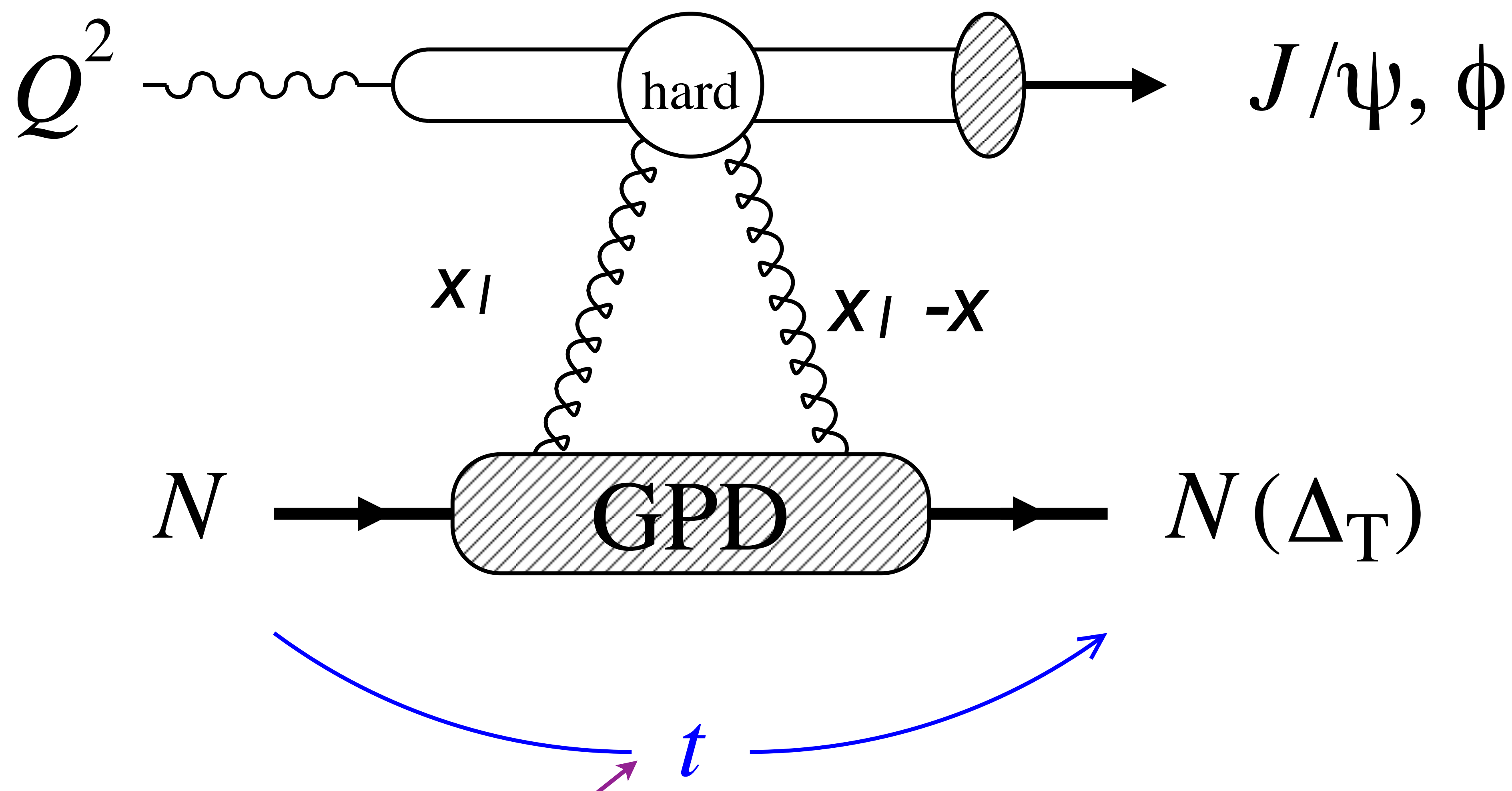
⇒ Transverse distribution of gluons can be extracted from $\gamma + p \rightarrow J/\psi + N$





$$B = B_0 + 2\alpha'_{I\!P} \ln(x_0/x)$$

Figure 23: *The parameters of the effective Pomeron trajectory in exclusive ρ^0 electroproduction, (a) $\alpha_{I\!P}(0)$ and (b) $\alpha'_{I\!P}$, as a function of Q^2. The inner error bars indicate the statistical uncertainty, the outer error bars represent the statistical and systematic uncertainty added in quadrature. The band in (a) and the dashed line in (b) are at the values of the parameters of the soft Pomeron [19, 20].*



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

In LT limit $x_l - x << x_l$

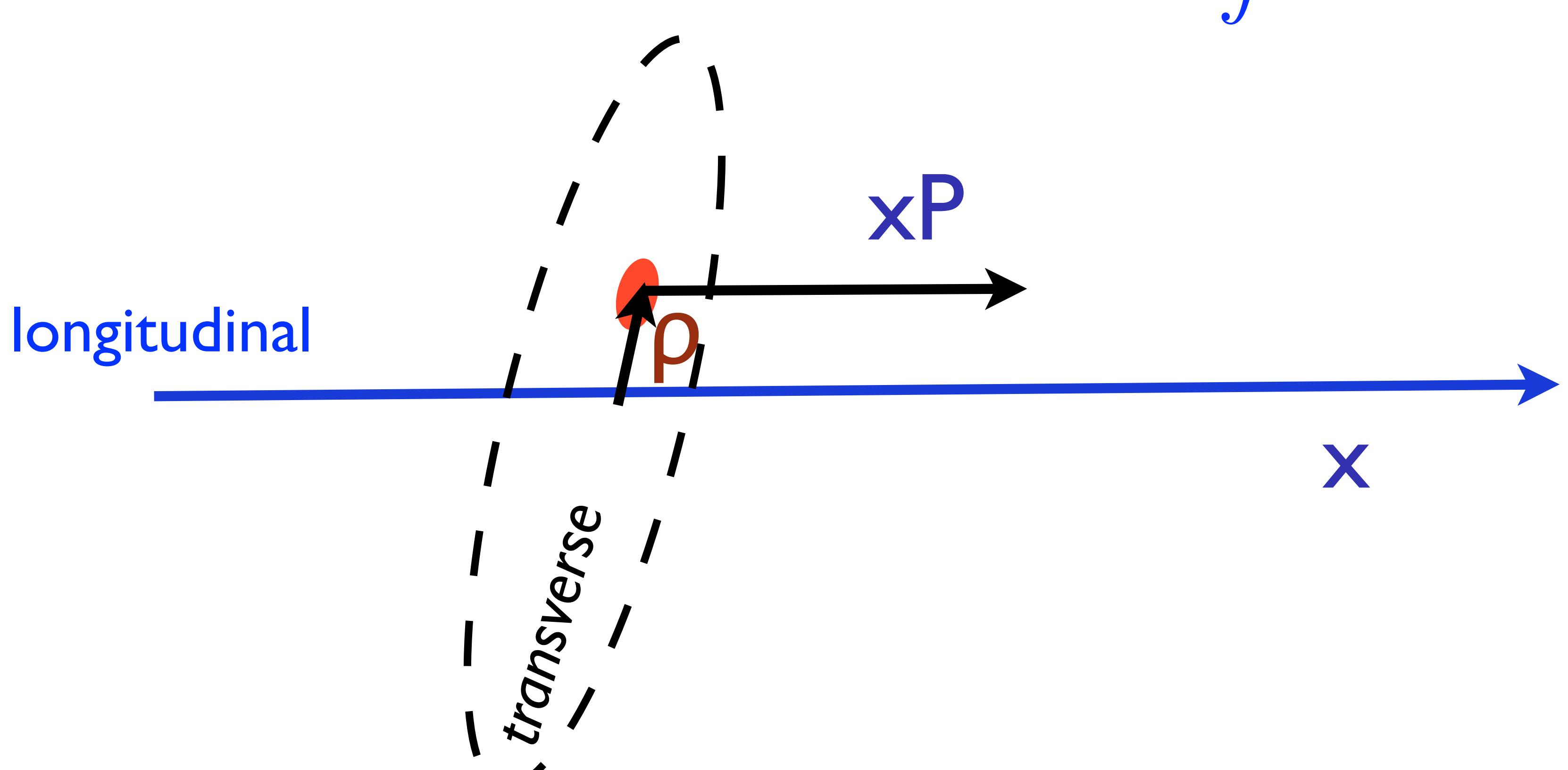
however due to DGLAP evolution skewed GPD kinematics for large Q probes diagonal GPD at Q_0 scale

Parton form factors of nucleon - universal (process independent)

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

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

transverse spatial distribution of gluons



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

total gluon density

Small size of J/ψ - t-dependence of J/ψ photo/electro production measures the two gluon f.f. of nucleon and hence transverse spread of gluons

Dipole fit to the two-gluon form factor with x-independent $M^2 \sim 1$ GeV^2 gives a reasonable description of the data F &S 02; gluon distribution is more compact than quark one for x ~ 0.02- 0.05 - can be quantitatively explained as effect of soft pions - Weiss & MS 04. Many implications for LHC and correlations of partons in nucleons

→ $M^2 \sim 1.1$ GeV^2 (correcting for finite size of J/psi)

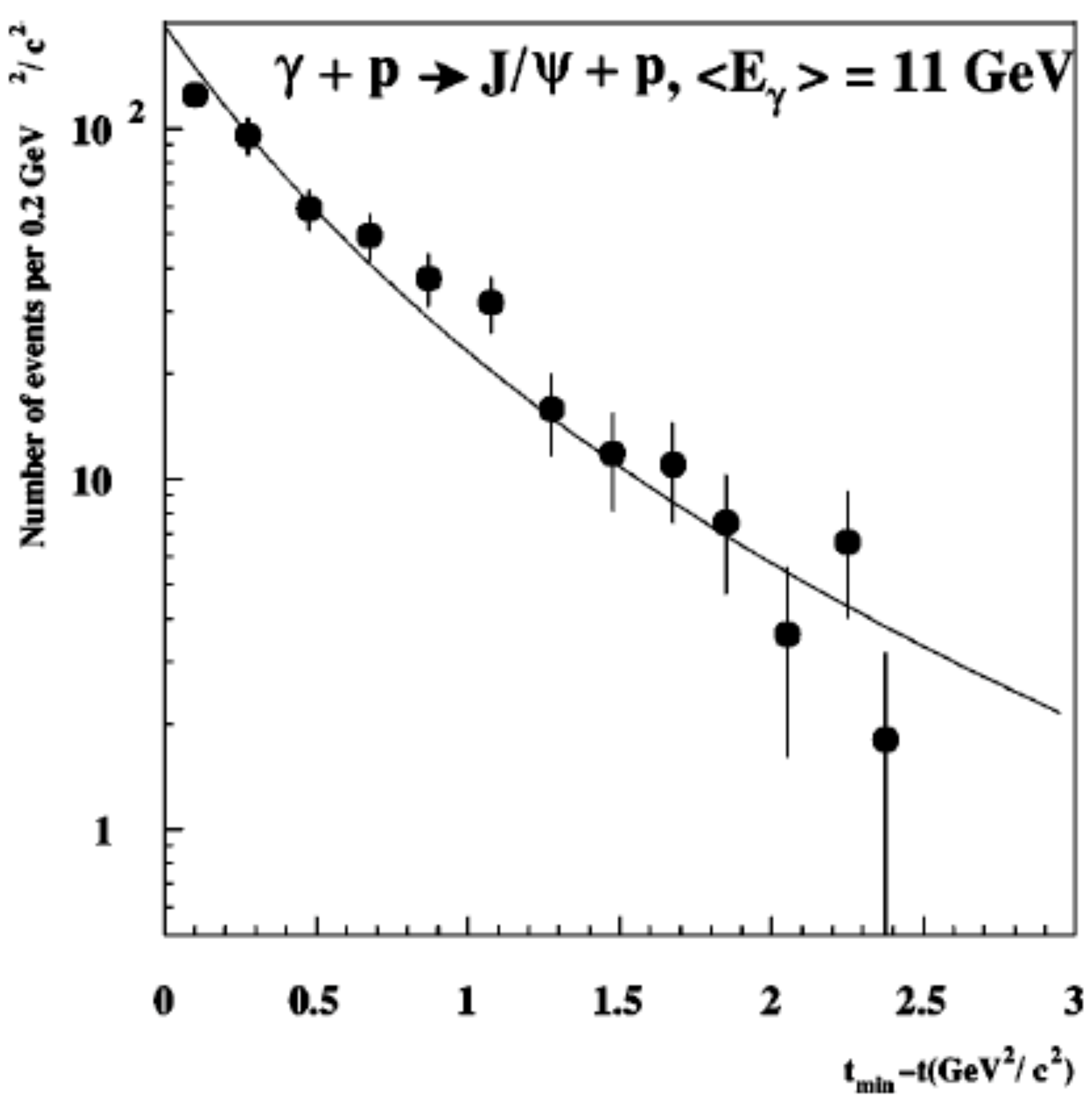


FIG. 3. Comparison of the dipole parametrization of Eq. (6) of the $d\sigma^{\gamma+p\to J/\psi+p}/dt$ with the data of [18] at $\langle E_\gamma\rangle = 11$ GeV.

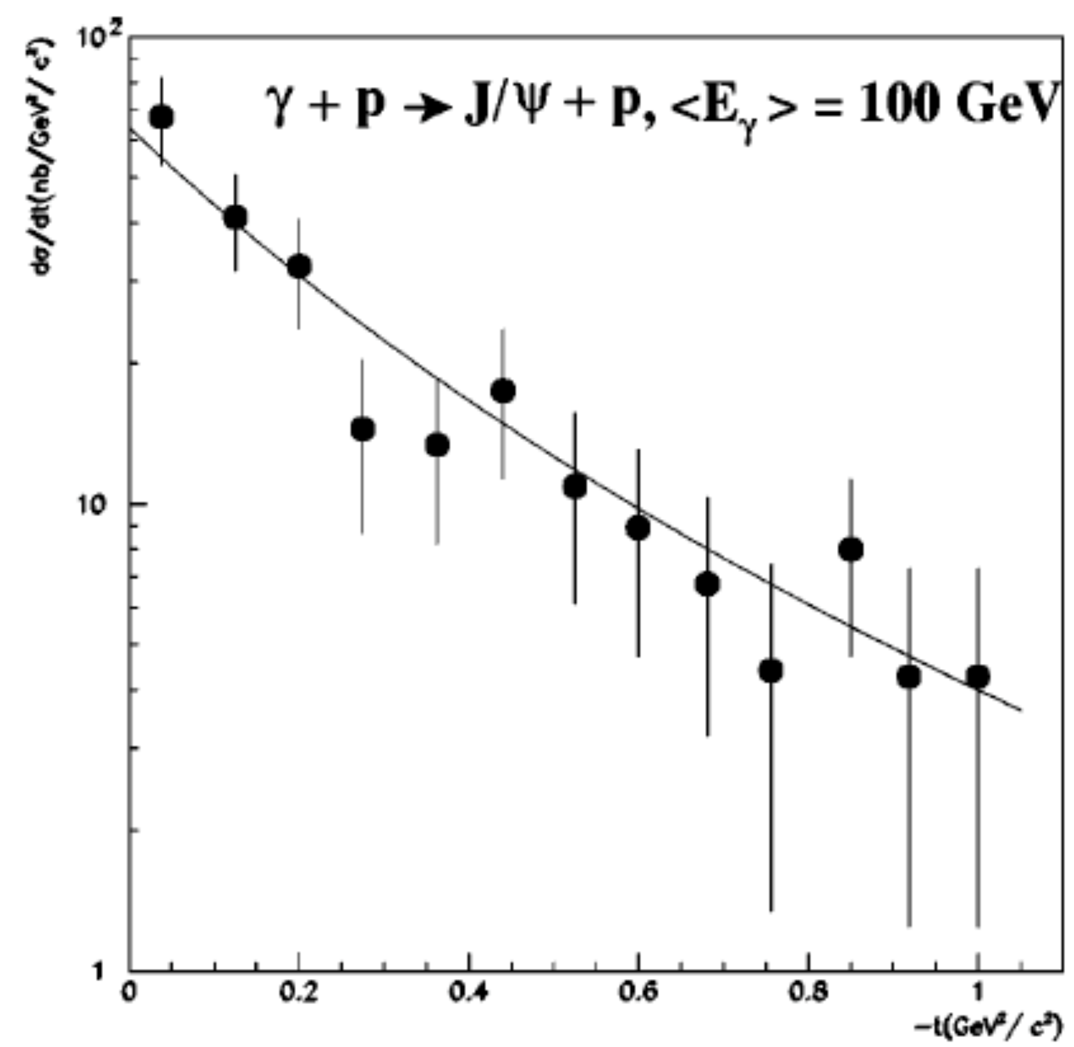


FIG. 1. Comparison of the dipole parametrization of Eq. (6) of the $d\sigma^{\gamma+p\to J/\psi+p}/dt$ with the data of [16] at $\langle E_\gamma\rangle = 100$ GeV.

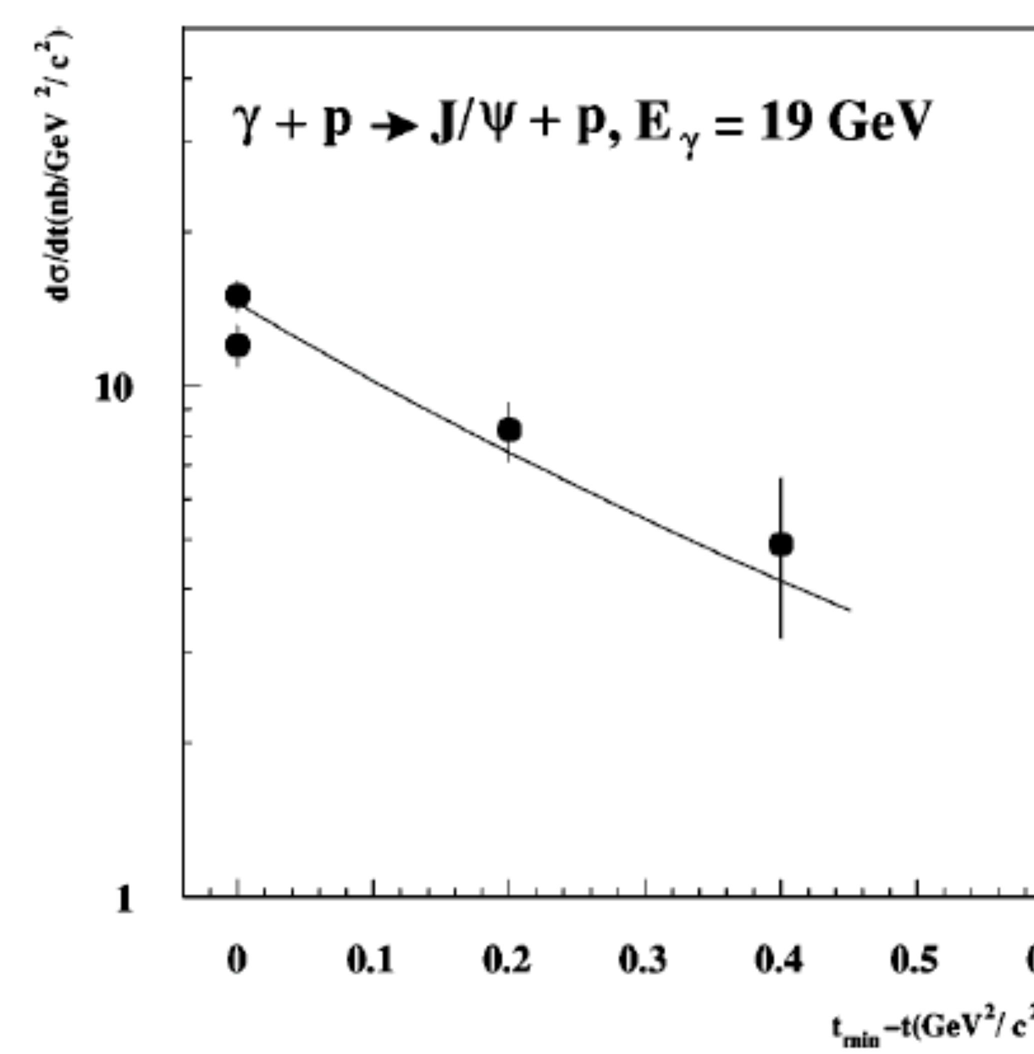
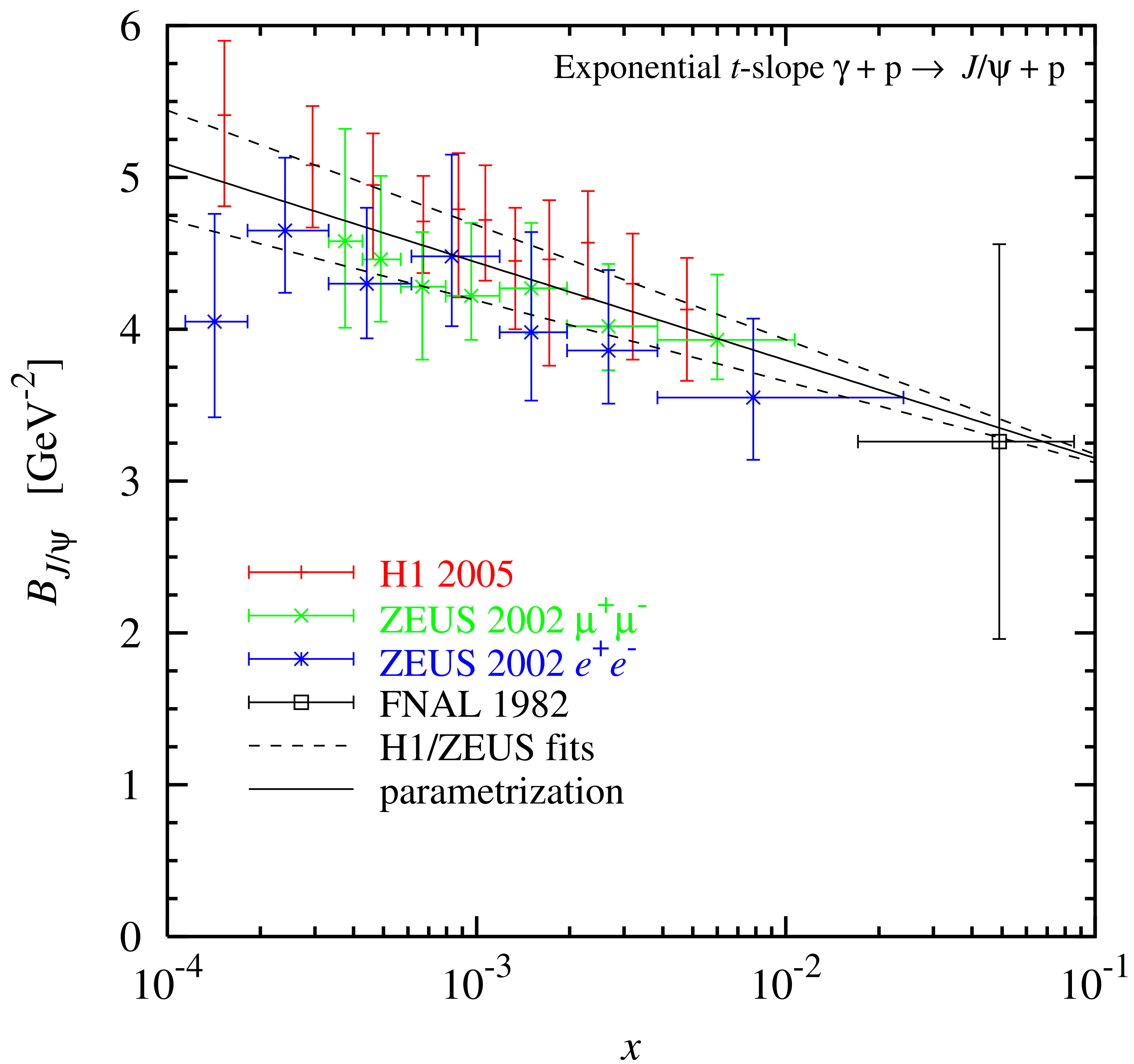
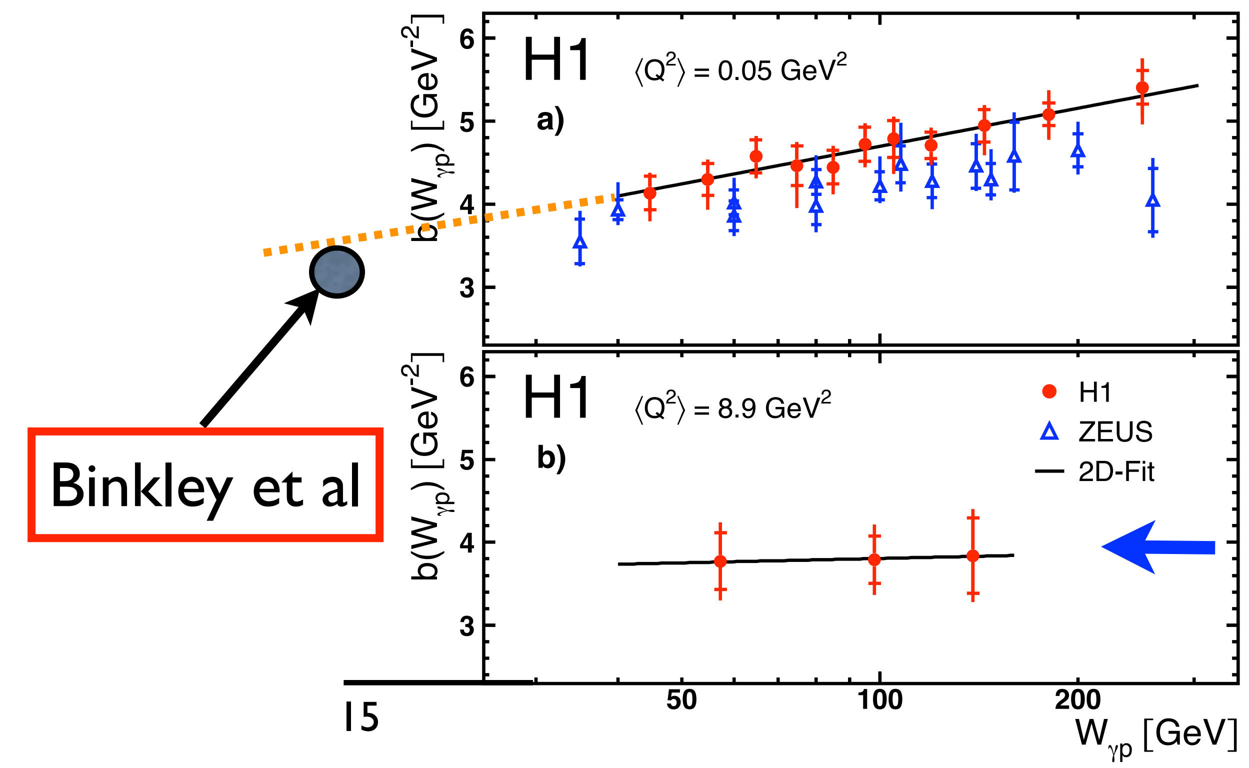


FIG. 2. Comparison of the dipole parametrization of Eq. (6) of the $d\sigma^{\gamma+p\to J/\psi+p}/dt$ with the data of [17] at $E_\gamma = 19$ GeV.

J/ψ elastic photo and electro production

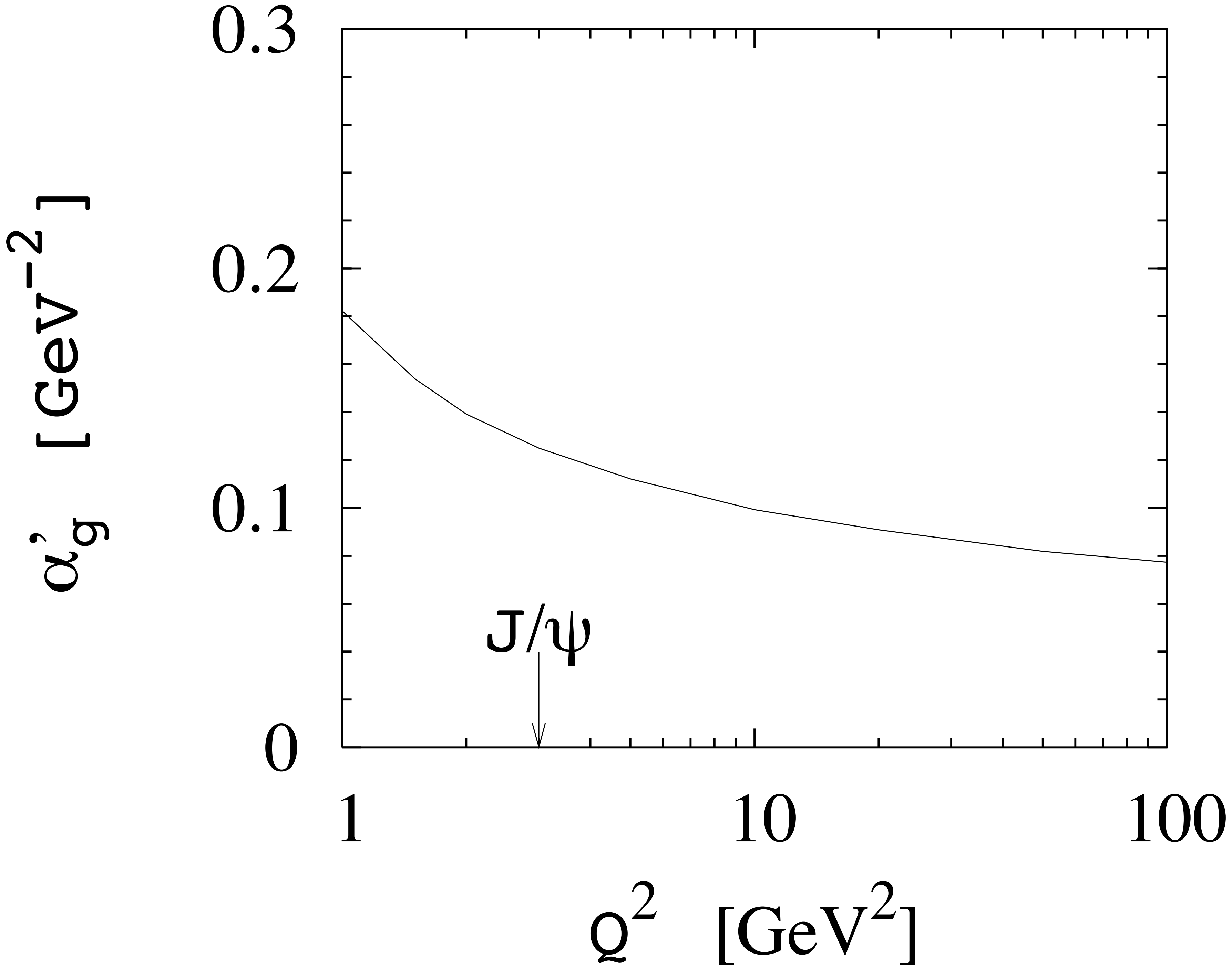


$$B = B(W_0) + 2\alpha' \ln(W^2/W_0^2)$$



At large Q^2 α' consistent with zero but there is a tension between different data sets!!!

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



pQCD (DGLAP approximation) - rather weak Q evolution of α' - Frankfurt, MS, Weiss 03

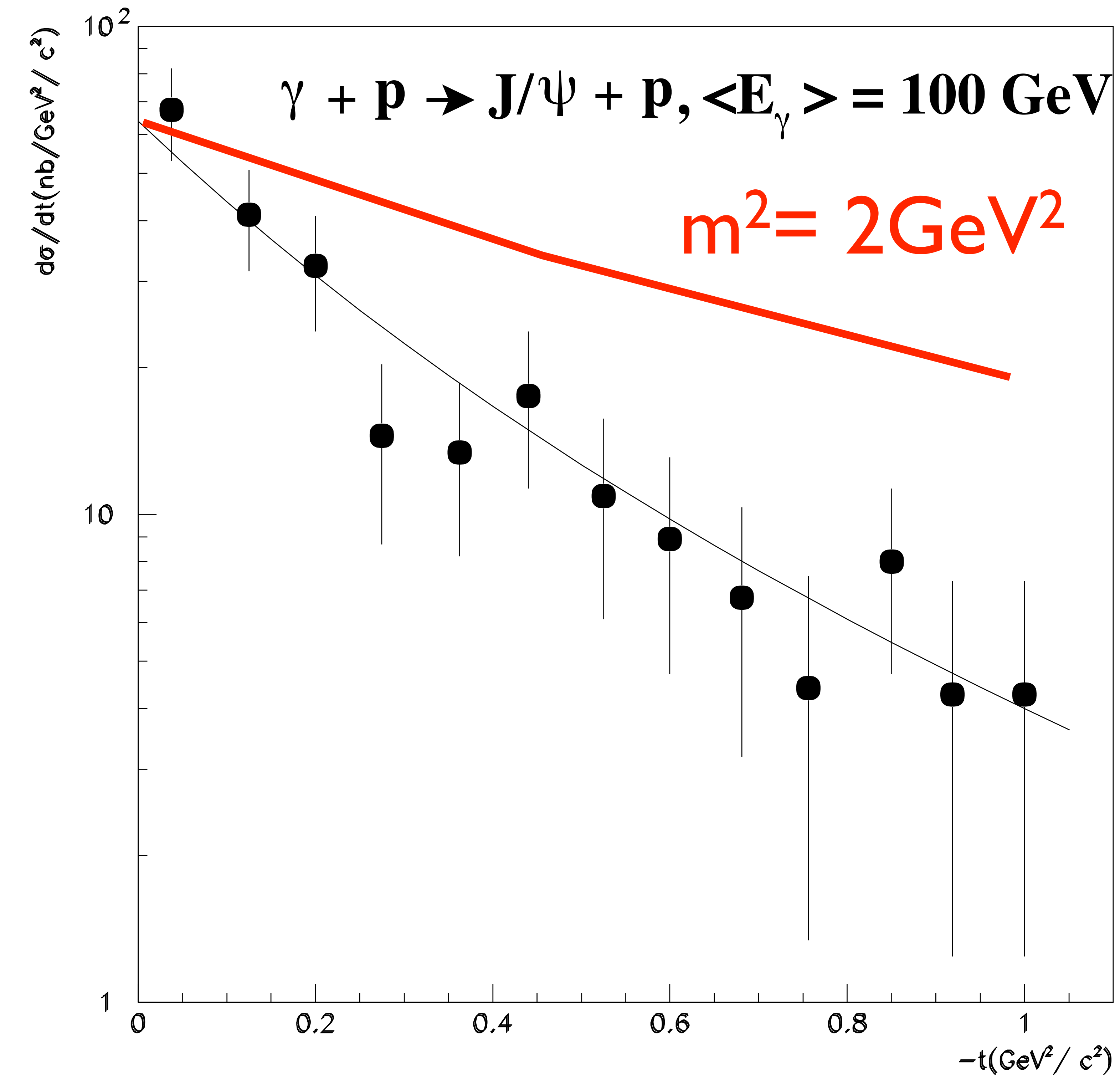
Change of transverse spread with x due to DGLAP evolution - leads to effective α´ which drops with Q but still remains finite even at very high Q.

Comparison with MC models

Interplay of hard and soft interactions in pp collisions, rate of multiple hard collisions is determined by the value of $<\rho^2_g>$ as compared to much larger radius of soft interactions. PYTHIA assumed before this year $<\rho^2_g> = <\rho^2_q>$ a factor ~ 2 -- 2.5 smaller than given by analysis of GPDs from J/ψ production and x-independent. Two exponentials - roughly equivalent to dipole with $m^2 = 2GeV^2$ (Andrzej Siodmok). No dependence on virtuality or x. Difference is probably even bigger for $<\rho^2_q>$. Evidence from analysis of DVCS that $<\rho^2 g>$ somewhat smaller than $<\rho^2 q>$

Why these assumptions were made?

To fit four jet cross section



Reminder (YuDok talk)

General expression for rate of DPI for collision of particles a and b in 2⊗2

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

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

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

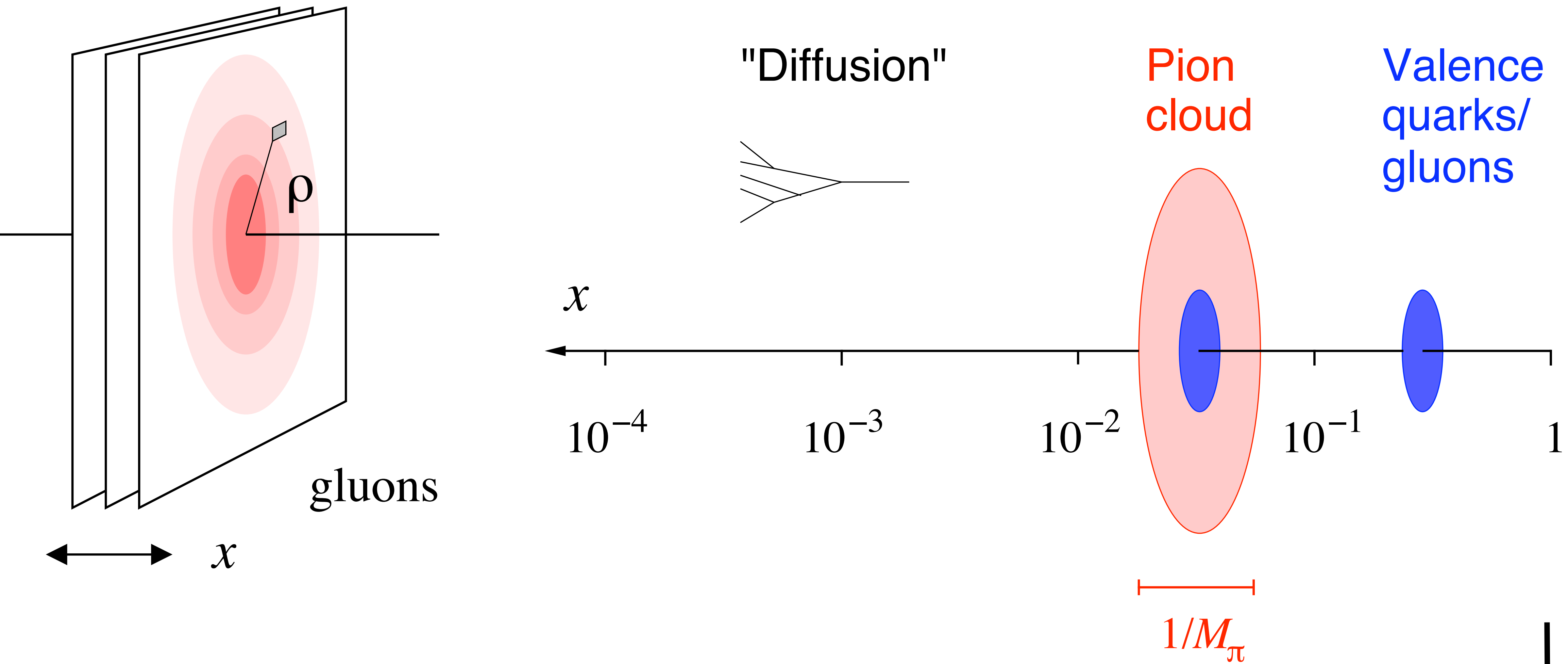
$$S = \frac{28\pi}{m_g^2} \sim 32 \text{ mb.}$$

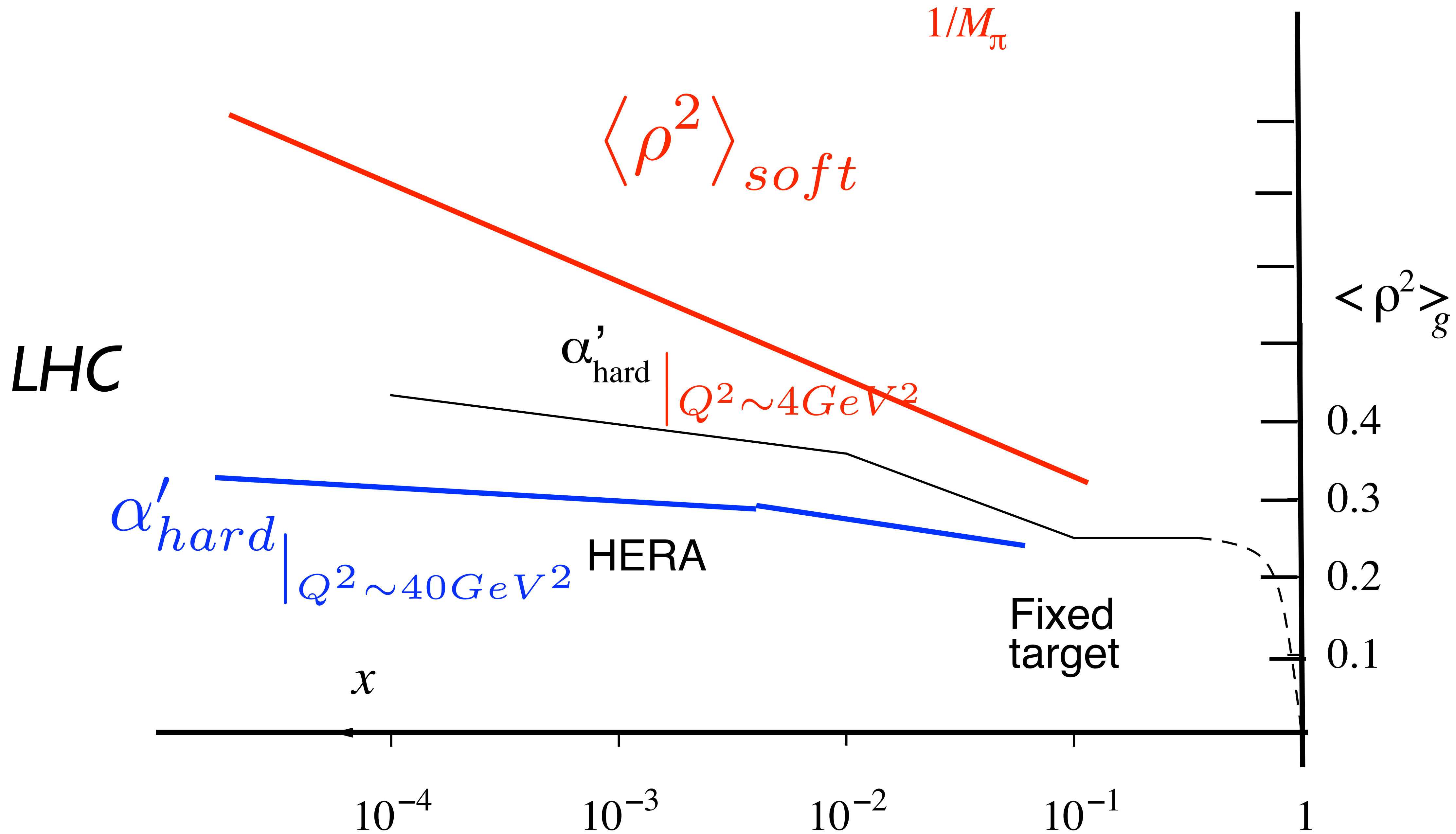
In FSW03 we obtained this result using coordinate space representation - potential problem uncertainties due to double Fourier transform - now we see it is pretty stable - since $F_{2g}^2(\Delta)$ is essentially measured directly.

So we are better off than naive S~ 54 mb - *still a factor of ~2 is missing:* *1⊗2 ?*

MC - two options - assume S=15 mb and choose m_g^2=2 GeV^2. or assume S=30 mb and ignore the data indicating smaller values of S.

- Gluonic transverse size - x dependence





Can be measured in ultraperipheral collisions at LHC

Gluon transverse size decreases with increase of x

Pion cloud contributes for $x<M_\pi/M_N$ [MS &C.Weiss 03]

Transverse size of large x partons is much smaller than the transverse range of soft strong interactions

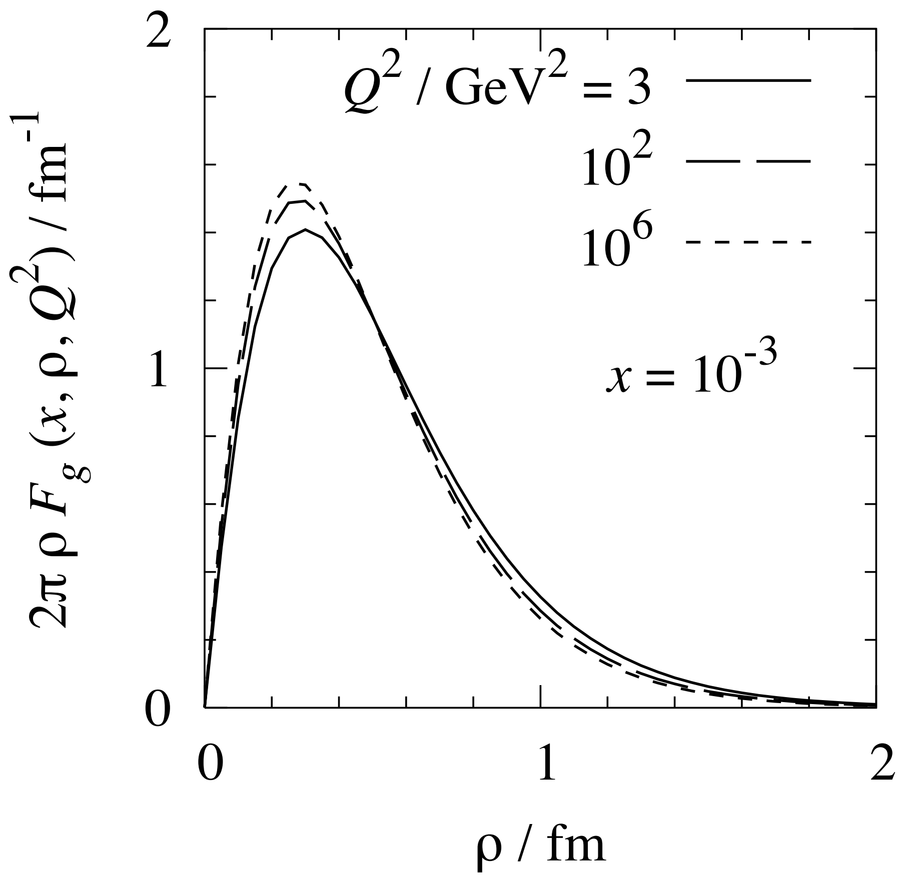
$$\langle\rho^2\rangle_g = \frac{\partial}{\partial t}\frac{G(x.t)}{G(x,0)}$$

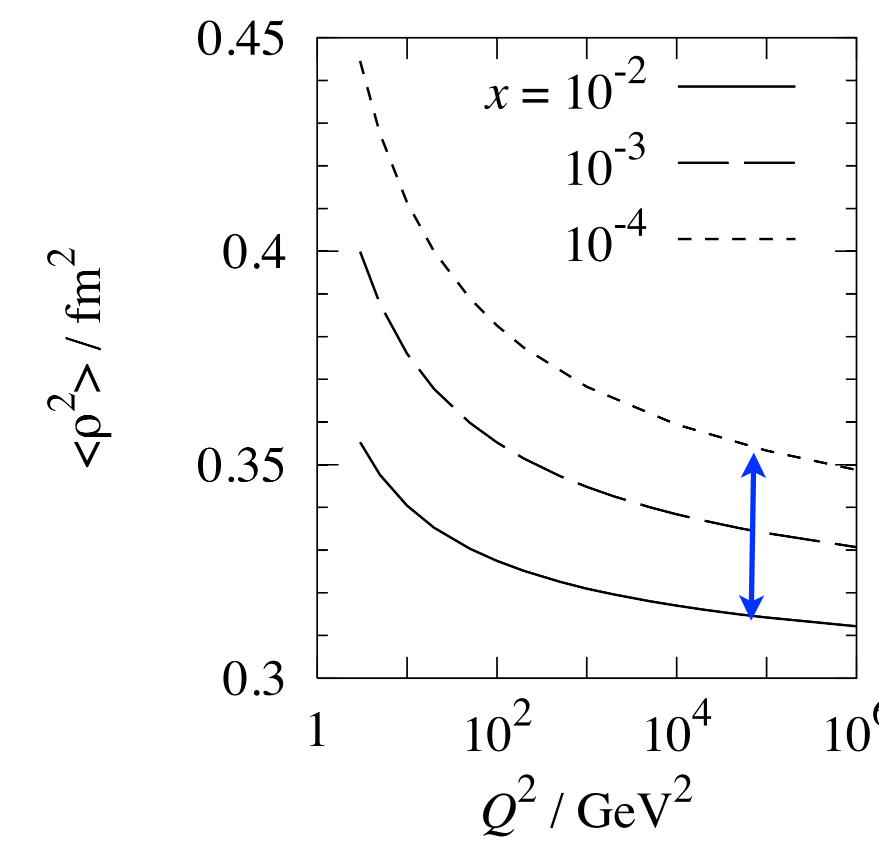
$$\langle\rho^2(x>10^{-2}\rangle \ll R^2_{soft}$$

$$\Downarrow$$

$\boxed{\text{Two scale picture}}$

Shrinkage of the transverse distribution with increase of Q is very modest.





$$\propto \alpha' \ln(x_1/x_2)$$

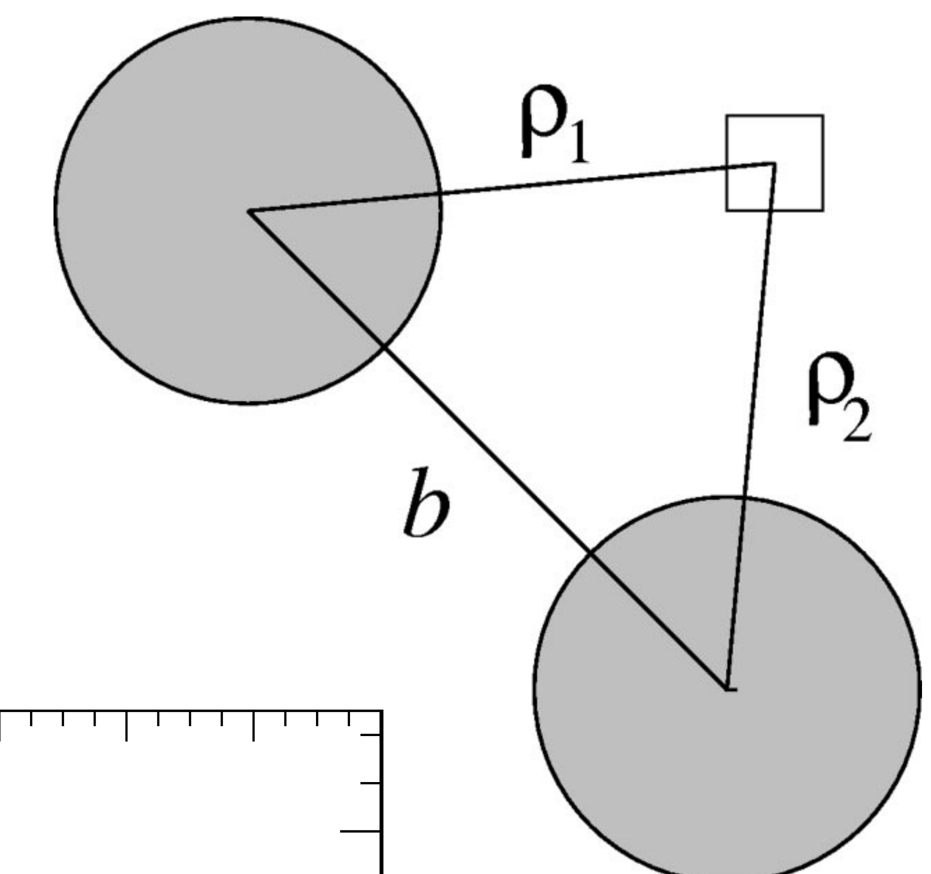
Change of $<\rho^2(Q^2)>$ with x due to DGLAP evolution - leads to effective α´ which drops with Q but still remains finite even at very high Q.

The change of the normalized ρ–profile of the gluon distribution, $F_g(x, \rho; Q^2)$, with Q^2, as due to DGLAP evolution, for $x = 10^{-3}$. The input gluon distribution is the GRV 98 parameterization at $Q_0^2 = 3\,GeV^2$, with a dipole–type b–profile.

Quantifying two scale picture - b distributions for dijet trigger and minimal bias

The distribution of interactions over b for events with *inclusive* dijet trigger (Higgs production,...) is given by

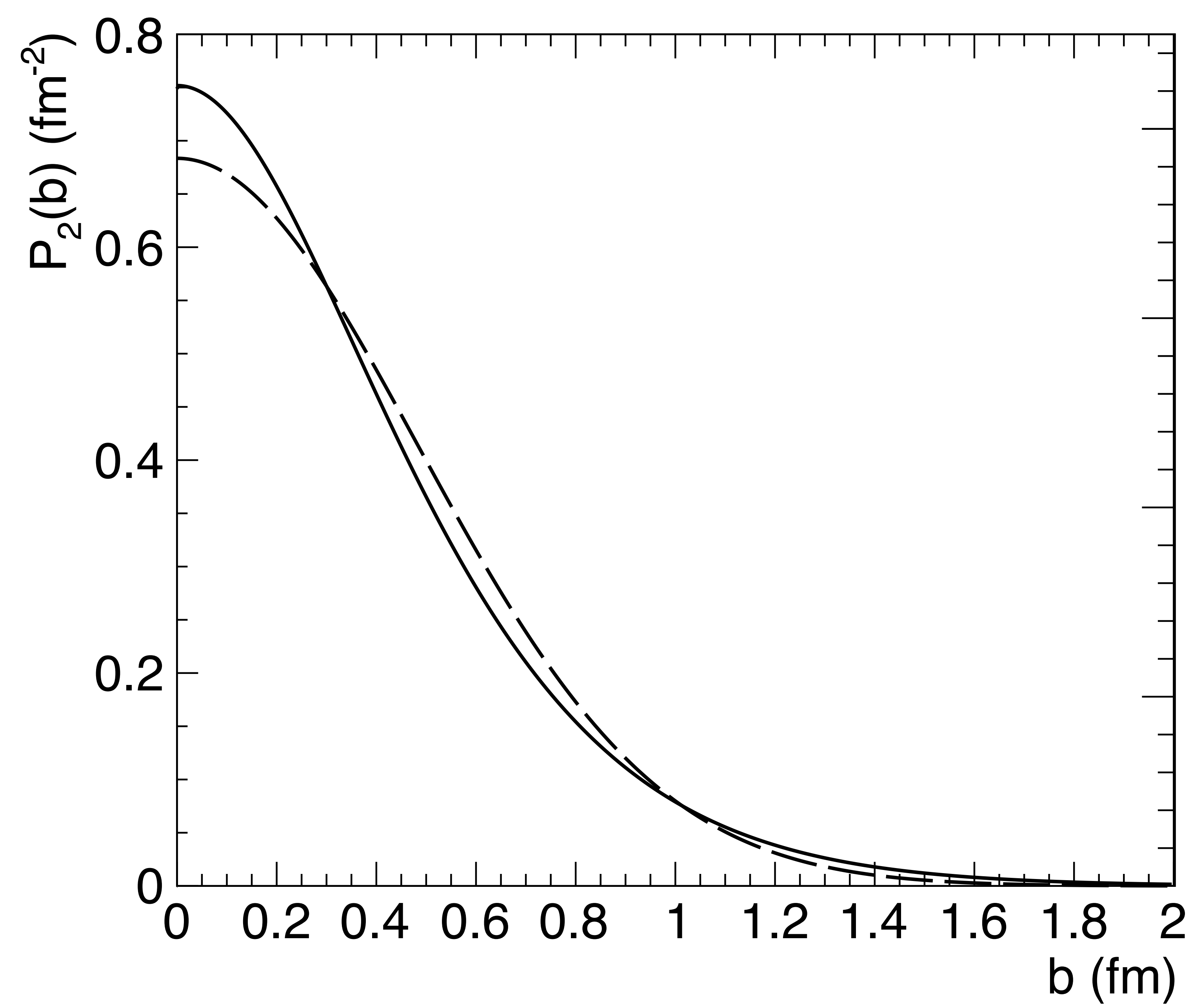
$$P_2(b) = \int d^2\rho_1 \int d^2\rho_2 \delta^{(2)}(\vec{b} - \vec{\rho}_1 + \vec{\rho}_2) F_g(x_1, \rho_1) F_g(x_2, \rho_2),$$



for $\quad F_g(x,t) = 1/(1 - t/m_g(x)^2)$

$$F_g(x,\rho) = \frac{m_g^2}{2\pi} \left(\frac{m_g \rho}{2}\right) K_1(m_g \rho)$$

$$P_2(b) = \frac{m_g^2}{12\pi} \left(\frac{m_g b}{2}\right)^3 K_3(m_g b)$$



Impact parameter amplitude in hp interaction

Study of the elastic scattering allows to determine how the strength of the interaction depends on the impact parameter, b:

$$\Gamma_h(s,b) = \frac{1}{2is}\frac{1}{(2\pi)^2}\int d^2\vec{q}e^{i\vec{q}\vec{b}}A_{hN}(s,t) \;\; ; \;\; ImA = s\sigma_{tot}\exp(Bt/2)$$

$$\sigma_{tot} = 2\int d^2b\mathrm{Re}\Gamma(s,b)$$

$$\sigma_{el} = \int d^2b|\Gamma(s,b)|^2$$

$$\sigma_{inel} = \int d^2b(1-(1-\mathrm{Re}\Gamma(s,b))^2 - [\mathrm{Im}\Gamma(s,b)]^2) \equiv \int d^2b\Gamma_{Inel}(b)$$

$$\Gamma_{Inel}(b) \approx 2Re\Gamma(b) - [Re\Gamma(b)]^2$$

$\Gamma(b) = 1 \equiv \sigma_{inel} = \sigma_{el}$ - black disk regime -BDR

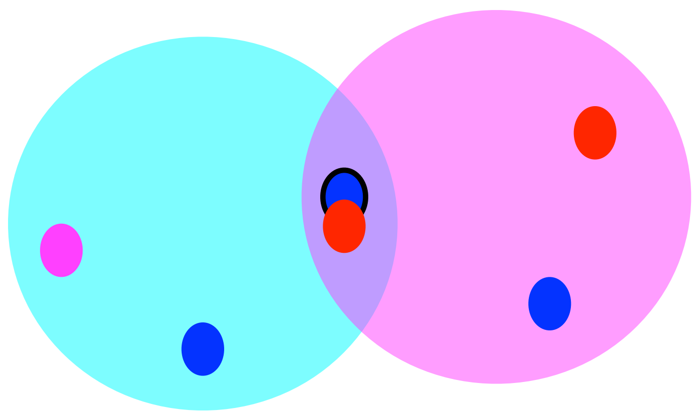
Compare with b-distribution for minimal bias (generic) inelastic pp scattering

$$P_{in}(s,b) \;=\; \frac{2Re\,\Gamma^{pp}(s,b) - |\Gamma^{pp}(s,b)|^2}{\sigma_{in}(s)}$$

where
$$\Gamma_h(s,b) = \frac{1}{2is}\frac{1}{(2\pi)^2}\int d^2\vec{q}\,e^{i\vec{q}\vec{b}}A_{hN}(s,t)$$

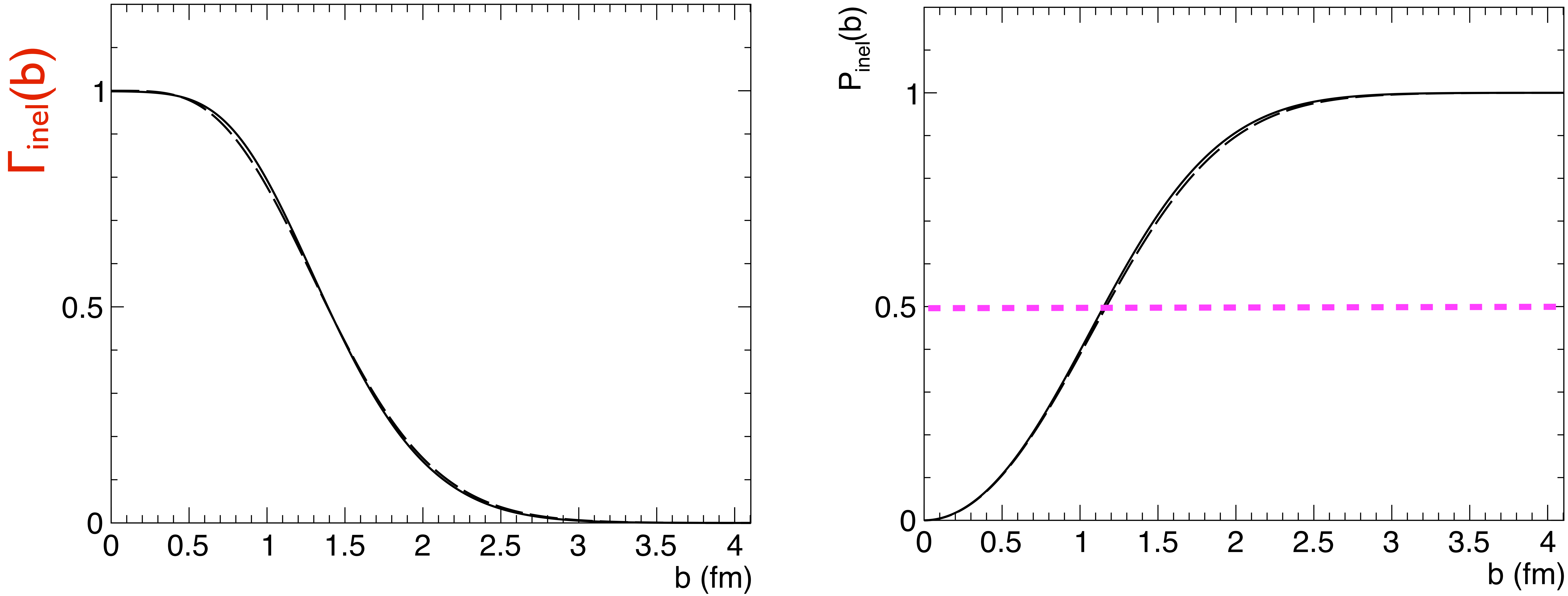
$$\Gamma(b) = 1 \;\equiv\; \sigma_{inel} = \sigma_{el}$$ - black disk regime (BDR).

Warning: b for dijet event and for minimal bias events are a priori two different quantities since ρ_i are distances from c.m.. However for small x_1,x_2 of colliding partons they are close - recoil effects are small



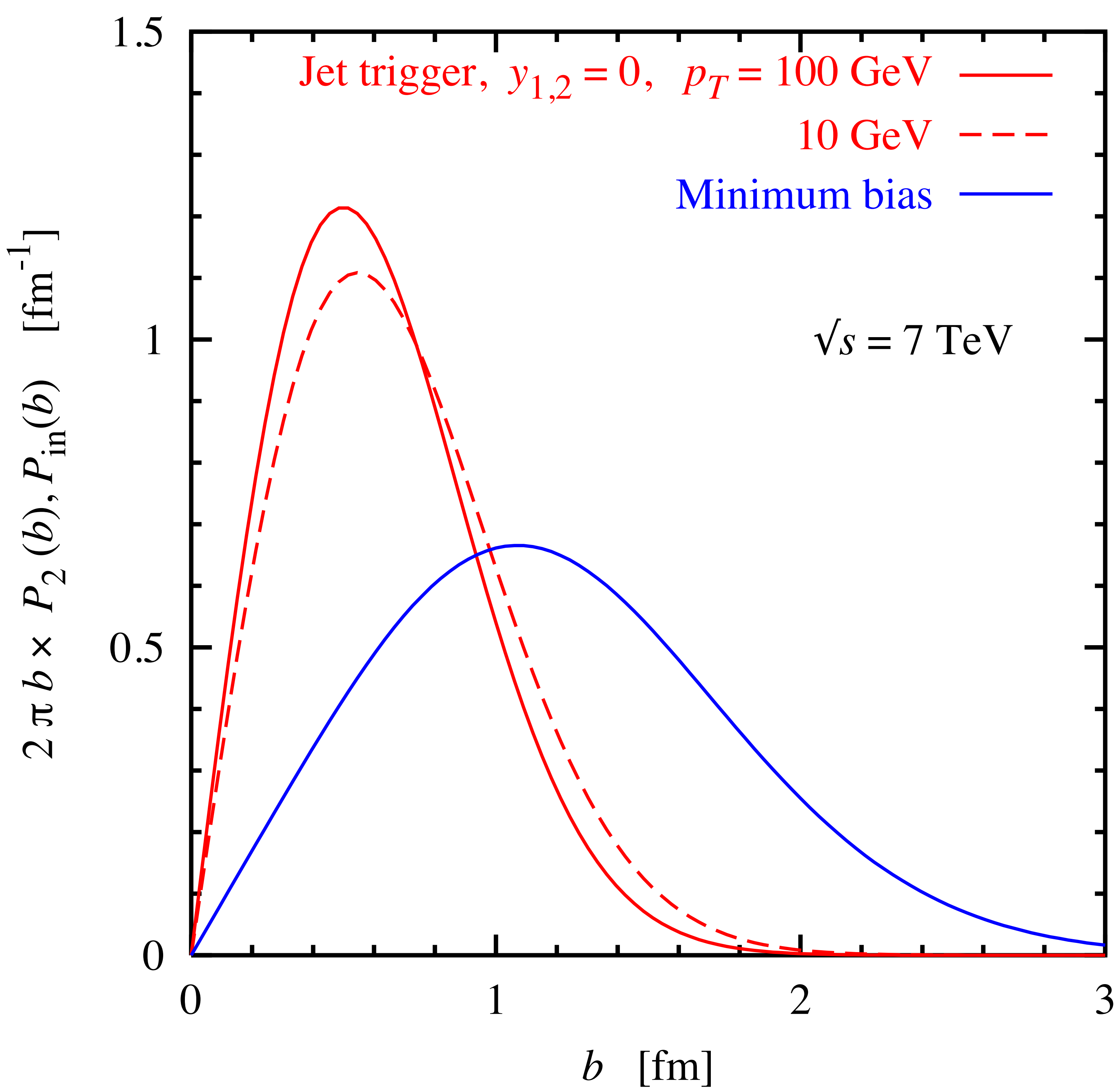
If x_1,x_2 ~ 1 this would be b~0 collision.

interaction at LHC is black for b< 0.8 fm but gray interactions give dominant contribution to the total inelastic cross section. Inelastic diffraction = 0 at BDR but at LHC it is 20 -- 30% of $\sigma_{inel.}$

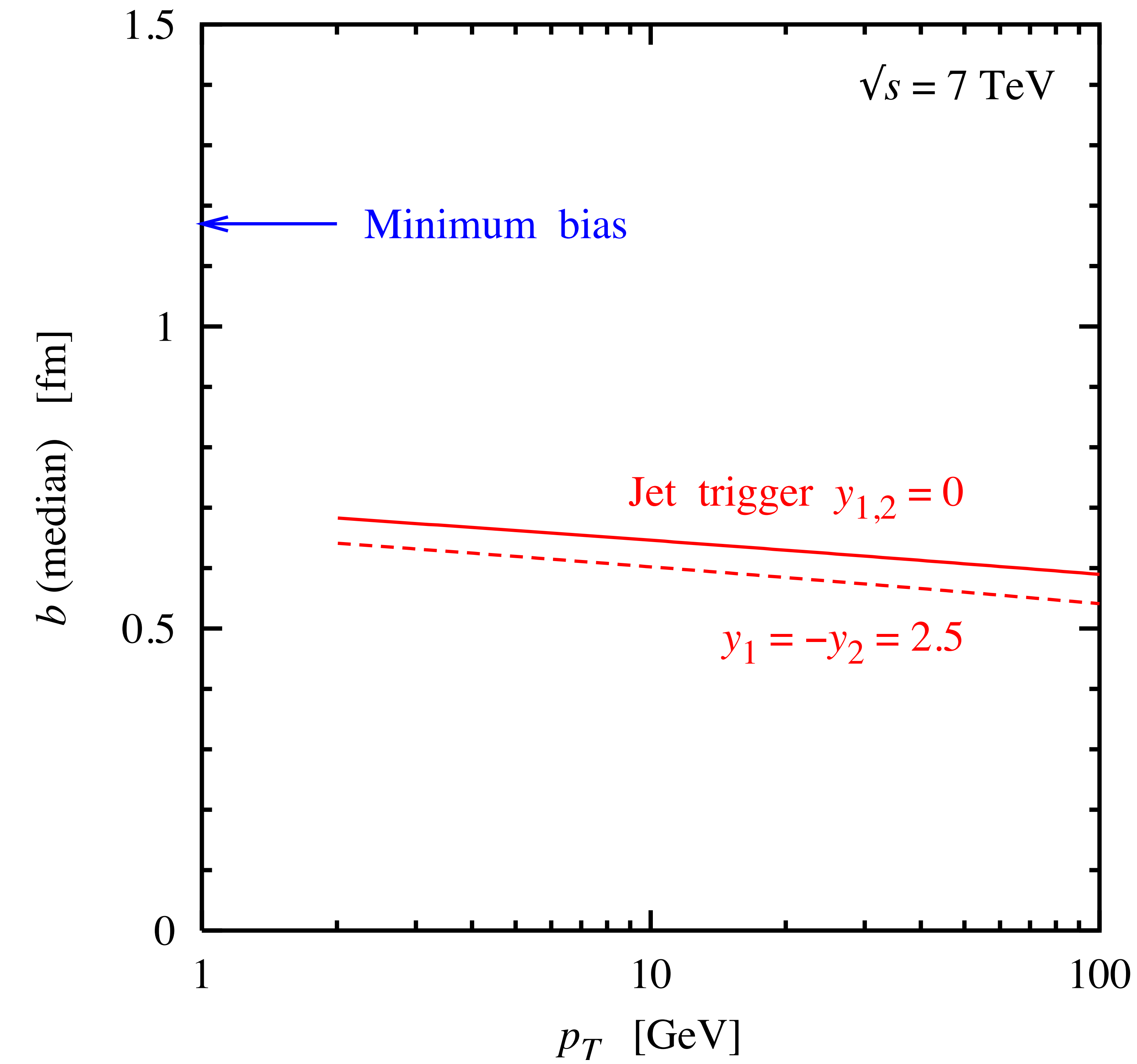


Overlap function $\Gamma_{inel}(b)$ and probability of inelastic collision with an impact parameter smaller than b using fit to the elastic differential cross section (solid line) and exponential parameterization of the elastic cross section

Two -scale picture of strong interaction at the LHC (LF, MS, Weiss 2003



Impact parameter distributions of inelastic pp collisions at $\sqrt{s}$ = 7TeV. Solid (dashed) line: Distribution of events with a dijet trigger at zero rapidity, $y_{1,2} = 0$, c, for p_T = 100 (10) GeV . Dotted line: Distribution of minimum–bias inelastic events (which includes diffraction).



Median impact parameter b(median) of events with a dijet trigger, as a function of the transverse momentum p_T , cf. left plot. Solid line: Dijet at zero rapidity $y_{1,2} = 0$. Dashed line: Dijet with rapidities $y_{1,2} = \pm 2.5$. The arrow indicates the median b for minimum–bias inelastic events.

Weak dependence of $P_2(b)$ on rapidity and p_T of the dijet

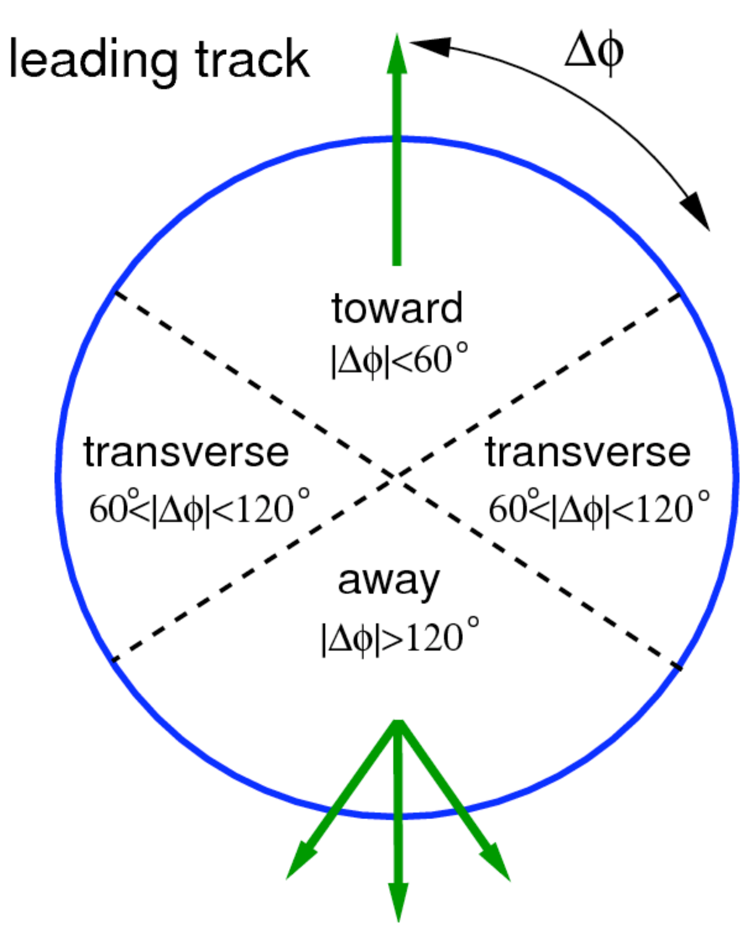
Much smaller impact parameters for hard dijet trigger

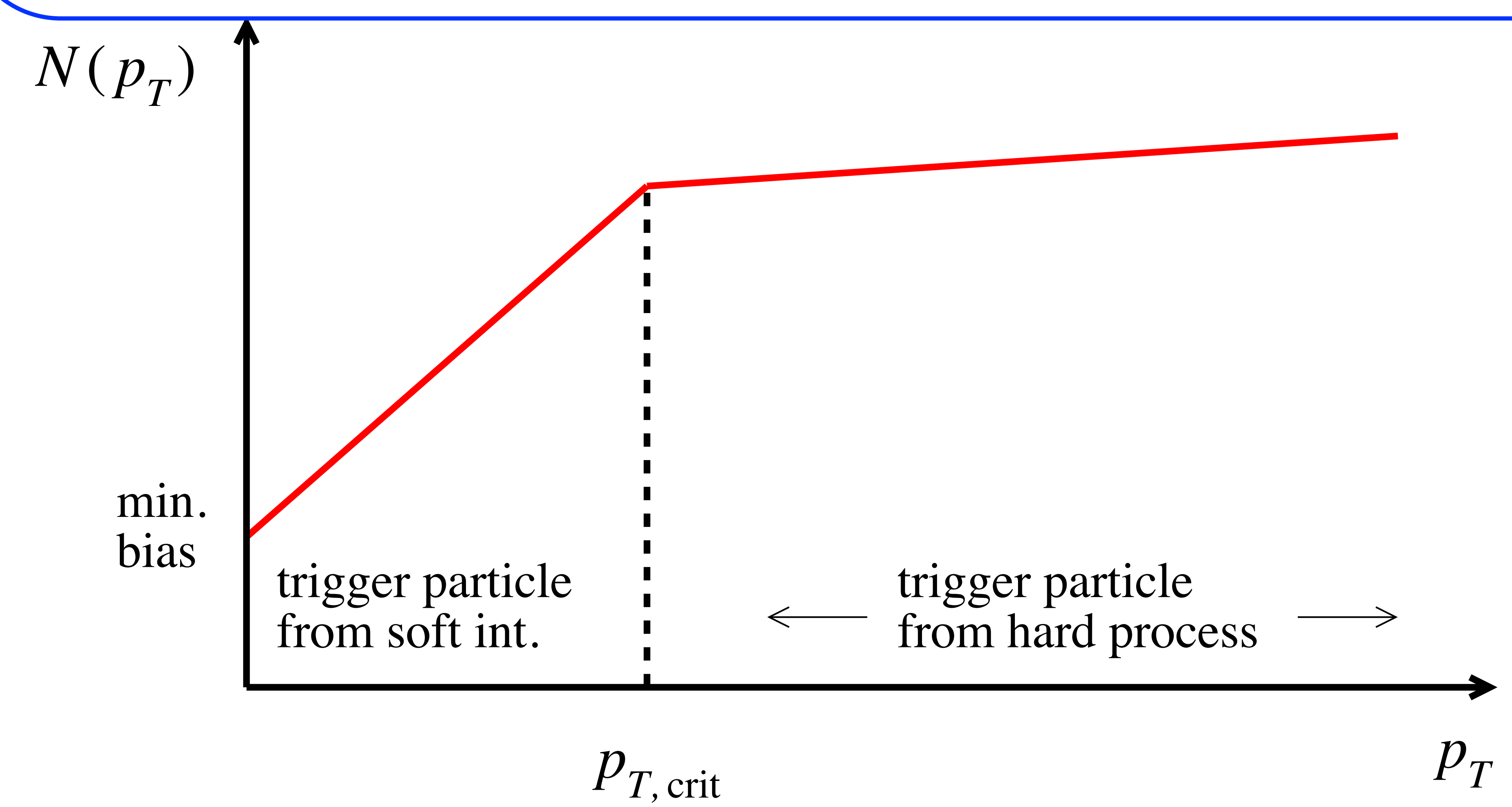
Impact parameters for hard dijet triggers with different rapidities, p_t's are practically the same

Universal underlying event for dijet triggers with much higher activity than for minimal bias events

large b softish

$$N(p_T) = \lambda_{\rm hard}(p_T) N_{\rm hard} + [1 - \lambda_{\rm hard}(p_T)] N_{\rm soft}$$

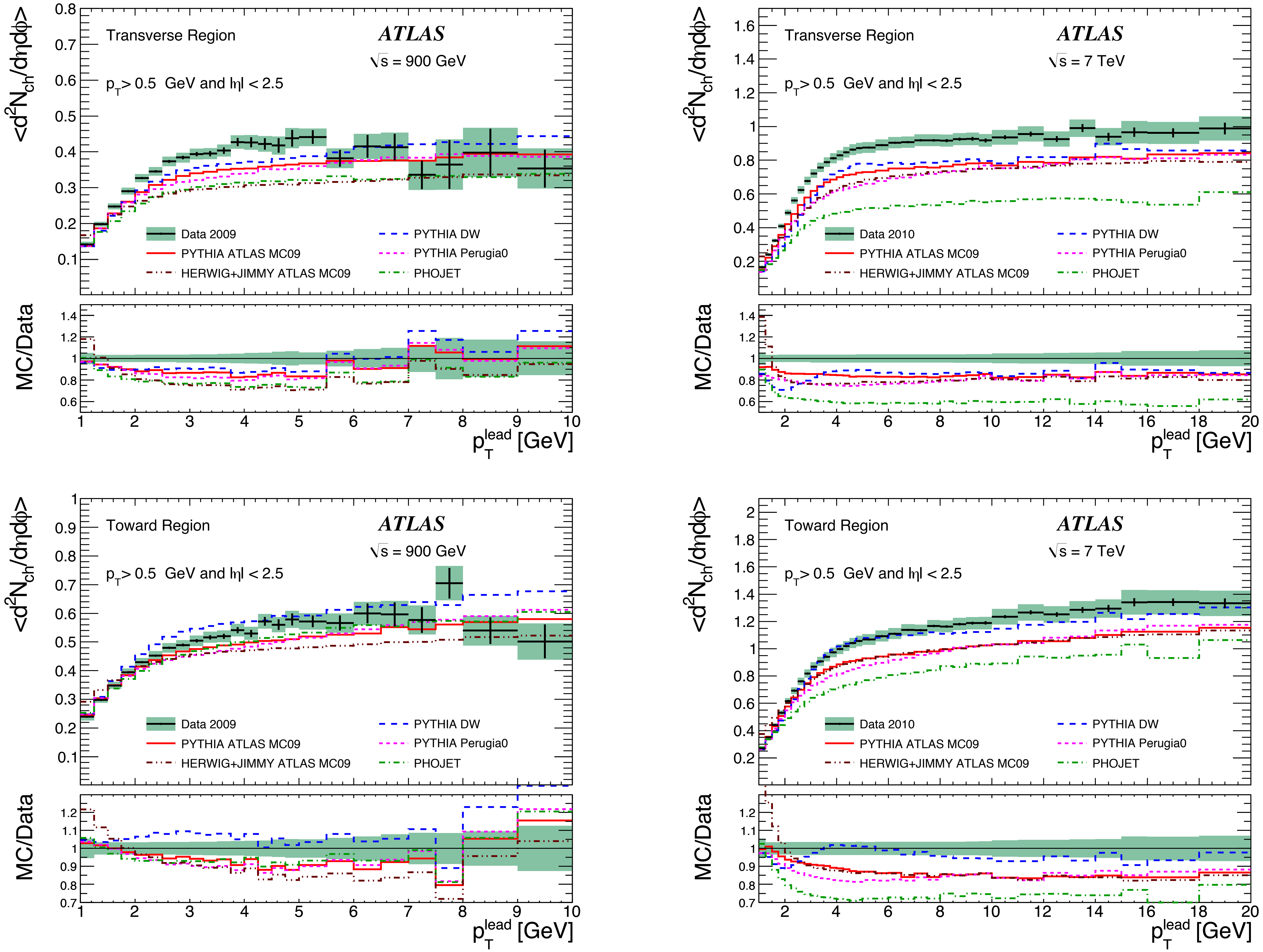


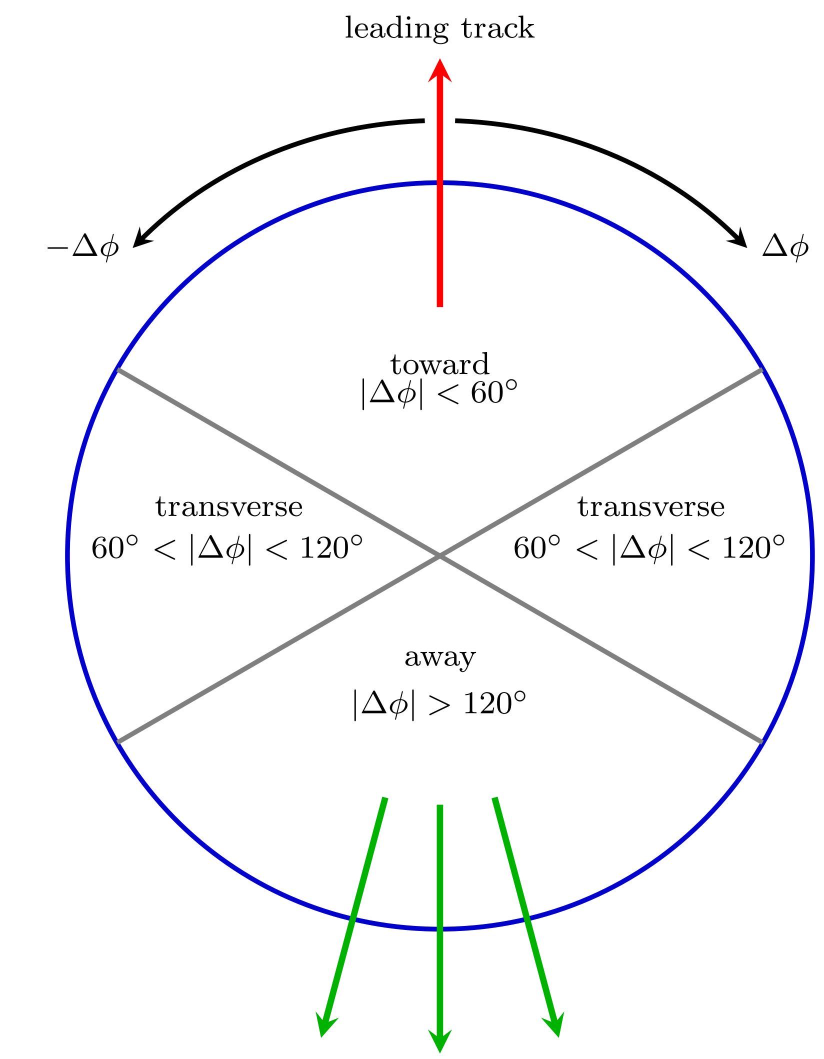


Warning: experimental procedure - selection of particle with maximal p_t is not exactly inclusive

Schematic illustration of the expected dependence of the transverse multiplicity, N (p_T), on the p_T of the trigger.

Underlying event distribution

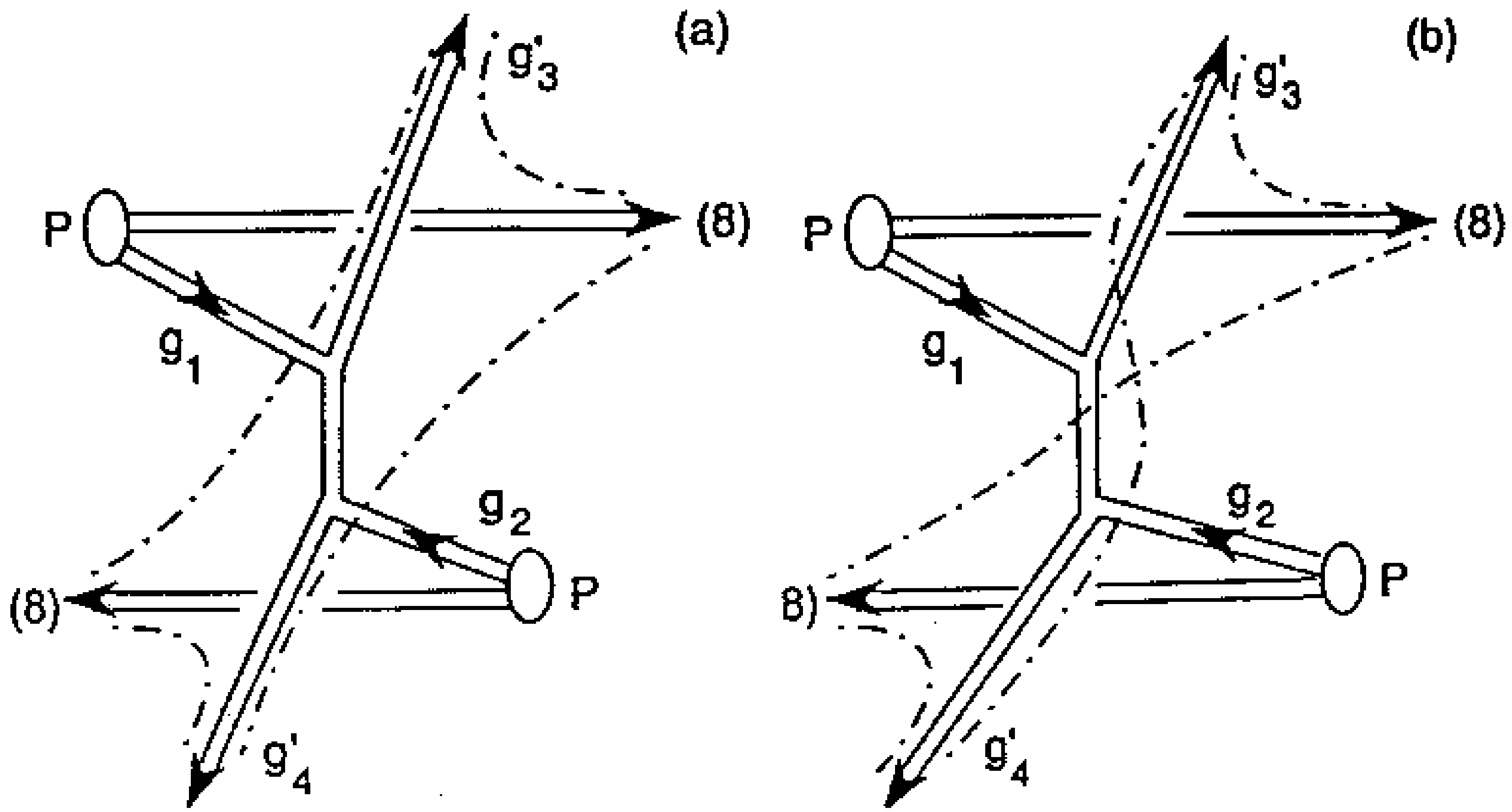




Warning - when determining enhancement factor for smaller $\sqrt{s}$ ~ 1 ÷2 TeV - underlying event one should subtract jet contribution in the away region more carefully - smaller angular range.

Contribution of color antennae to transverse multiplicity?

Should grow with p_T of the trigger?



Color antennae for hard scattering $g_1 + g_2 \rightarrow g_3 + g_4$ in the case when t-channel gluon exchange dominates ($\Theta_s \ll 1$). Leads to ridges.

Key observation: color antennae are functions of p_T not s_{NN}

LHC - plateau transverse multiplicity $N_{tr}(\sqrt{s} = 7\ \mathrm{TeV})/N_{tr}(\sqrt{s} = 0.9\ \mathrm{TeV})/ \approx 2$

Transverse multiplicity predominantly due to MPI's. At large p_T pQCD antennae contributions should be subtracted. Subtraction is more important for smaller $\sqrt{s} \sim 2$ TeV (for fixed p_t)

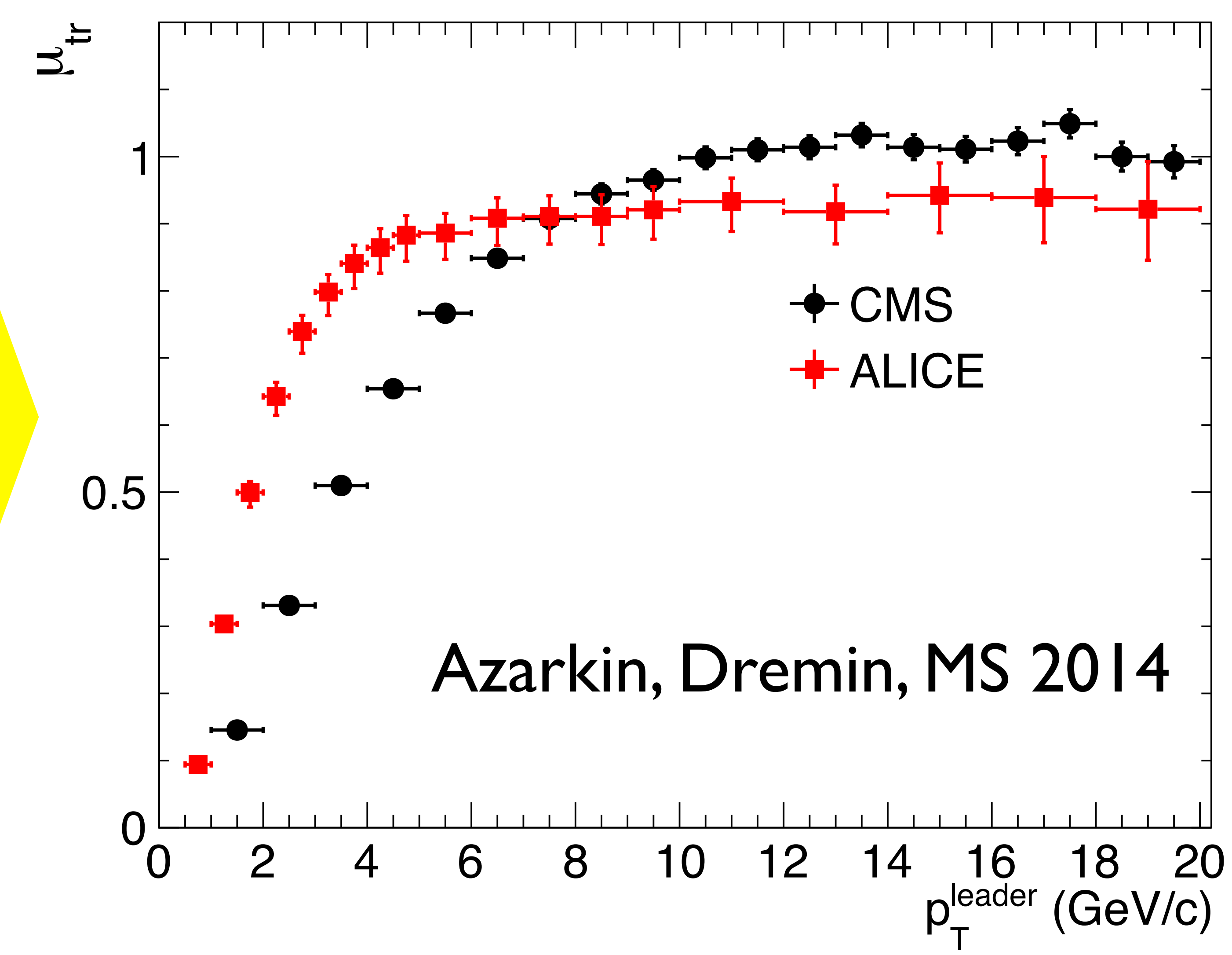
Conclusions from analysis of the ATLAS and CMS data

pQCD become the dominate charged particle production mechanism at relatively large and growing with s p_T:

$$p_{T,crit}(\sqrt{s} = .9 \text{ TeV}) \sim 4 \text{ GeV/c},$$
$$p_{T,crit}(\sqrt{s} = 1.8 \text{ TeV}) \sim 5 \text{ GeV/c},$$
$$p_{T,crit}(\sqrt{s} = 7.0 \text{ TeV}) \sim 6 - 8 \text{ GeV/c}$$

Flattening of dependence on p_T for $p_T > p_{T,crit}$

Charged-particle density in the transverse region as a function of pT of leading object (CMS - charged-particle jet, ALICE - charged particle). CMS analyses particles with p_T >0.5GeV/ and |η|<2.4, ALICE-p_T >0.5GeV/c and |η|<0.8.



Difference between onsets of flat regime is due to single particle carrying a fraction of jet momentum.

Geometrical considerations explain the observed pattern confirm difference of transverse scale for minimal bias and hard collisions and indicate that mechanisms different from two parton collisions are important for hadron production with p_T < 3 GeV/c

Energy dependence of transverse multiplicity for central collisions $\propto \sqrt{s}^{0.34}$ is much stronger than for peripheral collisions where it is practically energy independent.

Test of geometrical picture and observing its breakdown at very high soft multiplicities

More central collision, larger the rate of the hard collisions per collision. Larger hadron multiplicity smaller b. What are quantitative expectations.

Consider multiplicity - M (trigger)- of an inclusive hard process - dijet,... as a function of overall hadron multiplicity:

Build the ratio: $$R = \frac{M(trigger)}{M(minimal\, bias)}$$

If no fluctuations - maximal R due to effect of geometry - selection of b ~0

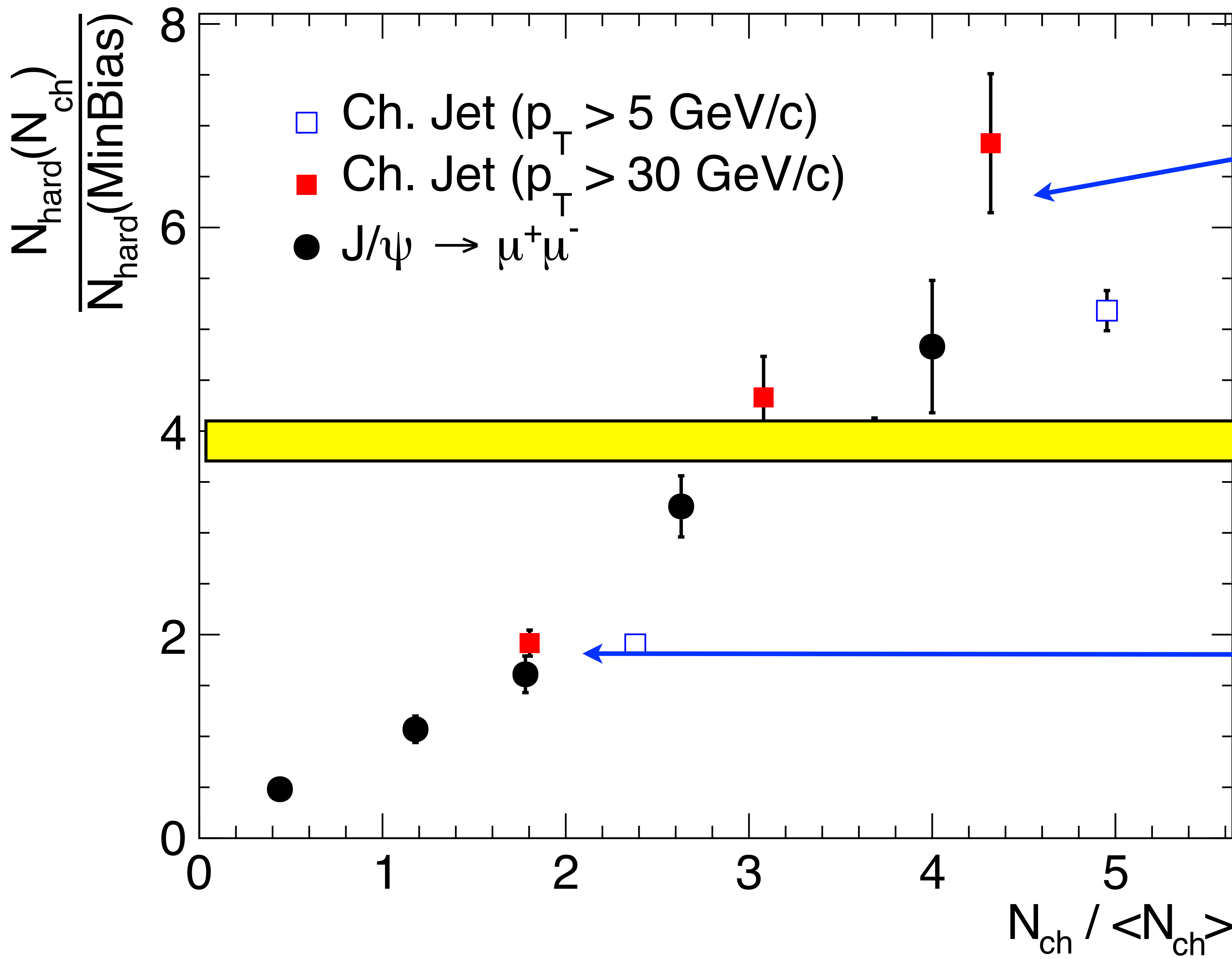
$$\boxed{R = P_2(0)\sigma_{in}(pp) = \frac{m_g^2}{12\pi}\sigma_{in}(pp) \quad \sim 4.5}$$

MS 11

σ(min.bias)= $\sigma_{in}(pp)$ or smaller - diffraction excluded

Using $$P_2(b) = \frac{m_g^2}{12\pi}\left(\frac{m_g b}{2}\right)^3 K_3(m_g b)$$

Analysis of CMS data (Azarkin, Dremin , MS, 14)

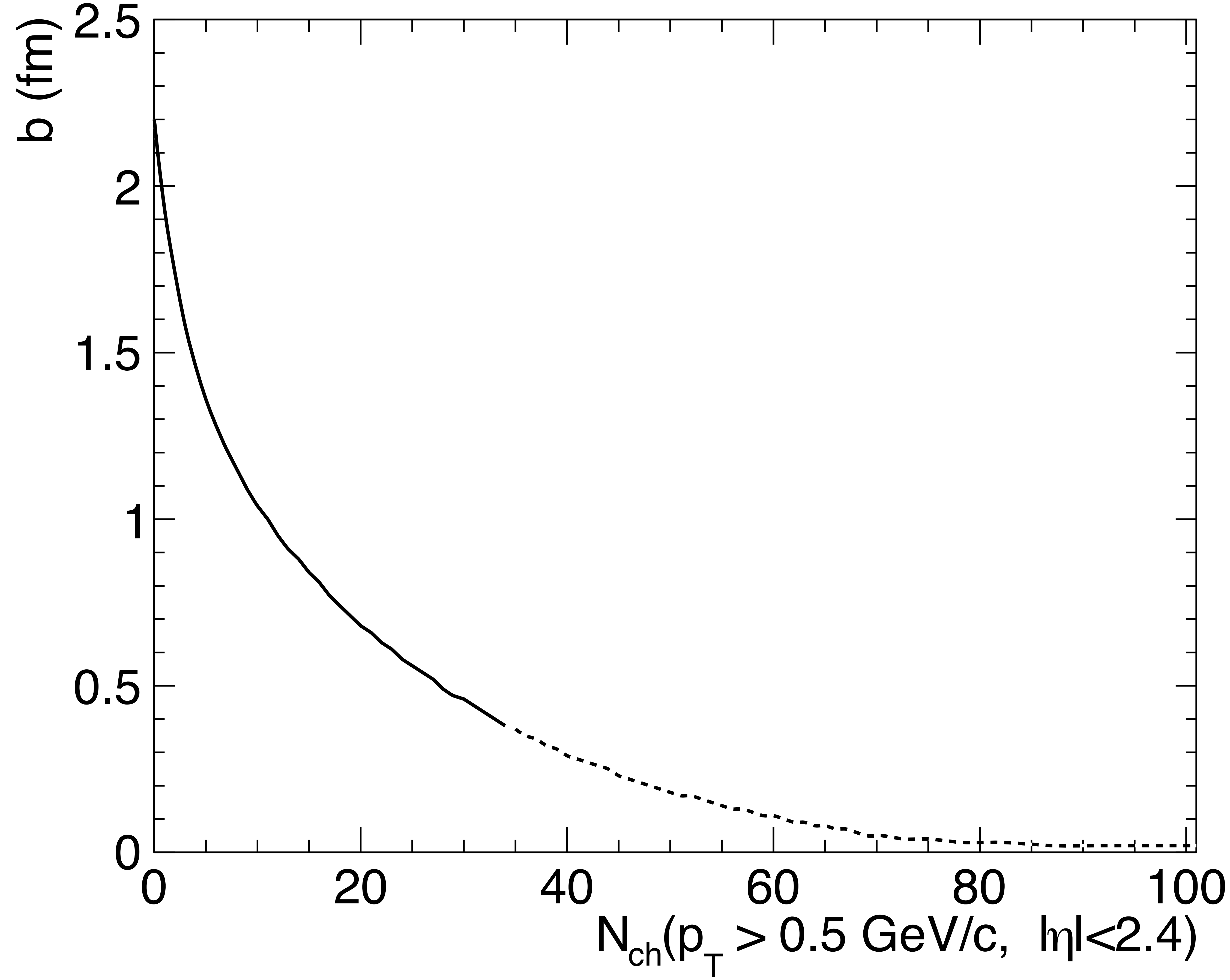


Superhigh multiplicities appear to require special rare configurations in nucleons

max value from geometry

reproduced by $P_2(b)$

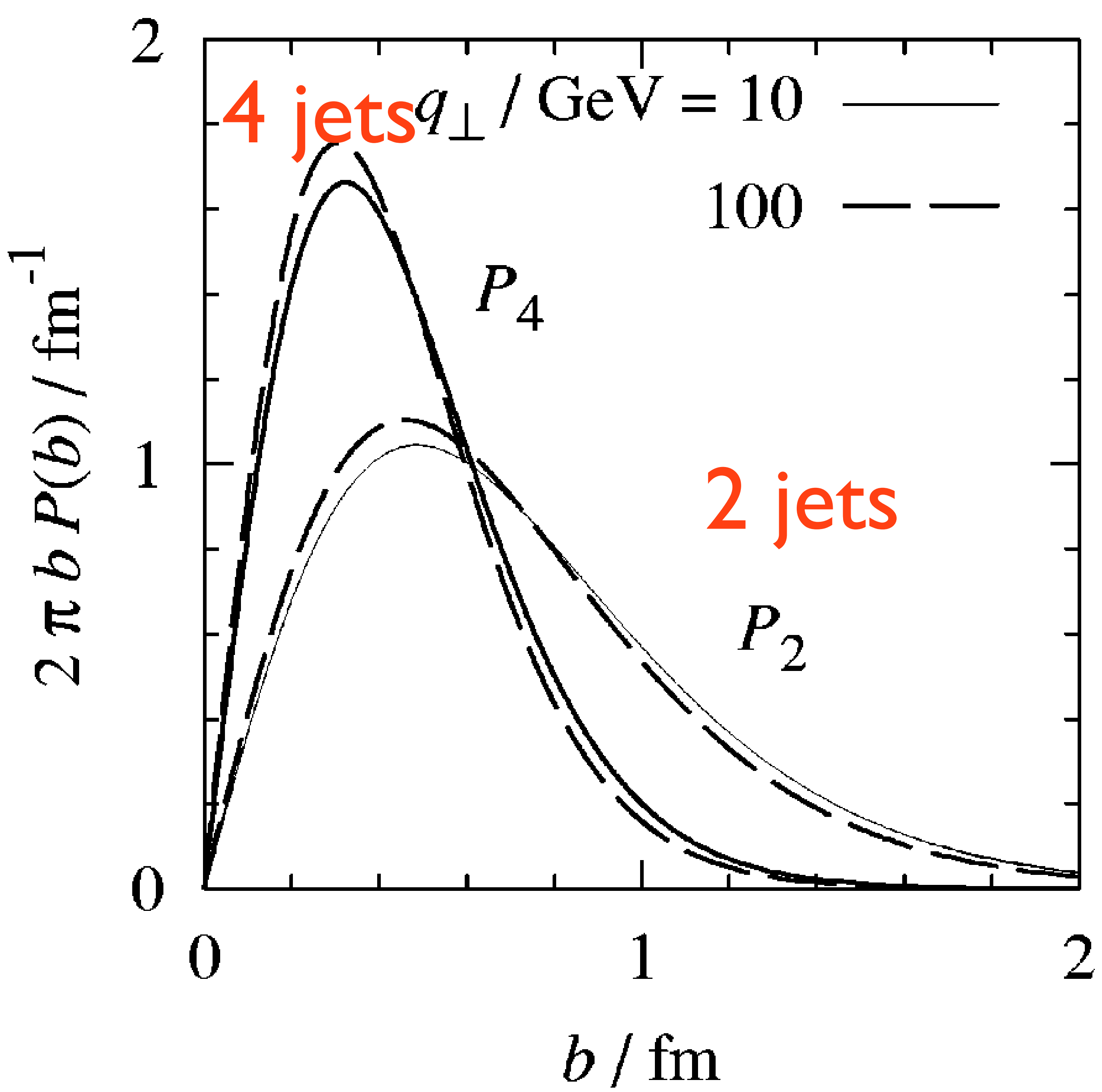
Universality of scaling of for hard processes scales with multiplicity: simple trigger - dijets(CMS) & direct J/ψ , D and B-mesons (Alice)



Correspondence between impact parameter and N_{ch}. N_{ch} is defined here as a number of charged particles with $|\eta| < 2.4$ and $p_T > 0.5$ GeV/c. Since events with $N_{ch} > 35$ are effectively central as shown below, the correspondence is not valid there.

Transverse multiplicities with two dijet pair trigger

If no correlations between partons (too low rate of 4 jets)



$$\frac{\text{Median b for 4 jets}}{\text{Median b for 2 jets}} \approx 0.7$$

Parton Correlations likely to reduce the ratio of median b's from 0.7 to 0.8

$\langle b^2\rangle_{dijet} : \langle b^2\rangle_{3\to4} : \langle b^2\rangle_{4\to4} = 2 : 1.5 : 1$

If $3\to4 = 4\to4$, $\langle b^2\rangle_{dijet} / \langle b^2\rangle_{4\ jets} = 1.6$

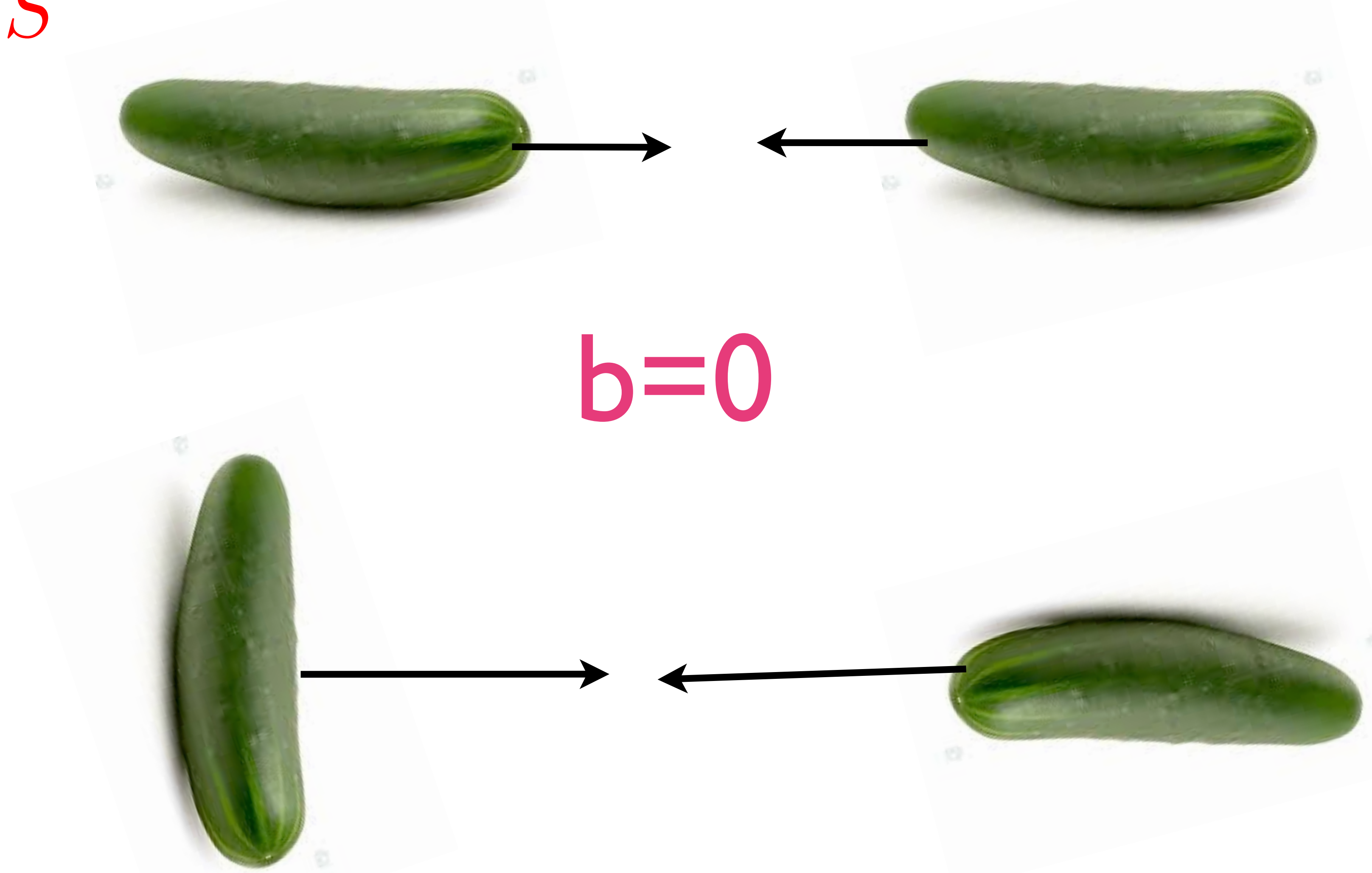
→ A significant (~ 40%) increase of the transverse multiplicities for 4 jets from MPI

What is mechanism of violation of the geometry limit?

Enhancement of hard processes due to fluctuations is expressed through fluctuations of GPDs (*more complicated because of the shape fluctuations*)

$$R_{fl} = P_2(0)\sigma_{in}(pp)\,\frac{g_N(x_1,Q^2|\sigma)g_{1N}(x_2,Q^2|\sigma)}{g_N(x_1,Q^2)g_{1N}(x_2,Q^2)}\,\frac{\langle S\rangle}{S}$$

S- transverse area of overlap.



Large fluctuations of S if nucleon (hard partons in the nucleon) has a pancake or a cucumber component

diquark model: $r_{string}/r_{tN} \sim 1/2 \div 1/3$ →
$\langle S\rangle/S_{head\text{-}on} \sim 4 \div 9$

Measurement of R as a function N_{ch} for different x's of colliding partons and observing R exceeding ~4 for large N_{ch} provides unambiguous evidence for gluon transverse fluctuations. More difficult to distinguish area fluctuation and gluon density fluctuations.

We found also evidence for gluon fluctuations in the analysis of HERA of the process $\gamma+p\to J/\psi + Y$ at $t=0$.

For highest studied multiplicities geometrical limit is exceeded by a factor of ~ 2 in the CMS data and probably in the ALICE data

Onset of nonlinear regime and suppression of minijets in pp collisions

Observation of MC models - need to suppress production of minijets

PYTHIA - suppression factor $R(p_T) = \left(\frac{p_T^2}{p_T^2 + p_0^2(s)}\right)^2$; $p_0(\sqrt{s} = 7TeV) \approx 3GeV/c$

$R(p_T = 4GeV/c) = 0.4$

HERWIG $\theta(p_T - p_0'(s))$ $p_0(s) \propto s^{0.12}$

Is the need for modification of dynamics for minijet range (p_0 ~10 GeV/c !! at GZK) been an artifact of MC or signal for serious problems?

Multijet Production and s-channel unitarity

Phys.Rev.D77:114009,2008 – T.Rogers, A. Stasto and M. Strikman

Phys.Rev. D 81, 016013,2010 – T.Rogers and M. Strikman

Minijet cross section: overlap function

- pp $\longrightarrow$ 2 jet + X cross section in impact parameter space.

$$\boxed{\sigma^{inc}_{2jet}(s,p_t^c) = \int d^2\mathbf{b}\, \underline{\mathcal{N}_2(b,s,p_t^c)}}$$

$$\underline{\mathcal{N}_2(b,s,p_t^c)} \equiv \sum_{k,l} C_{k,l} \int_{p_t^{c\,2}}^{\infty} d\,p_t^2 \frac{d\hat{\sigma}_{ij\to kl}}{dp_t^2} f_g(x_1,p_t^2) \otimes f_g(x_2,p_t^2) \underline{P_2(b,x_1,x_2,p_t)}$$

Overlap function

$$\underline{P_2(b,x_1,x_2,\mu)} = \int d^2\mathbf{r_1} \int d^2\mathbf{r_2}\, \mathcal{F}_g(x_1,r_1,\mu)\, \mathcal{F}_g(x_2,r_2,\mu) \delta^2(\mathbf{b}-\mathbf{r}_1-\mathbf{r}_2)$$

Reconstruct inelastic profile function

- Inclusive dijet cross section:
  - $$\mathcal{N}_2(b,s) = \sum_{n=1}^{\infty} n\,\tilde{\mathcal{N}}_{2n}(b,s)$$

where,

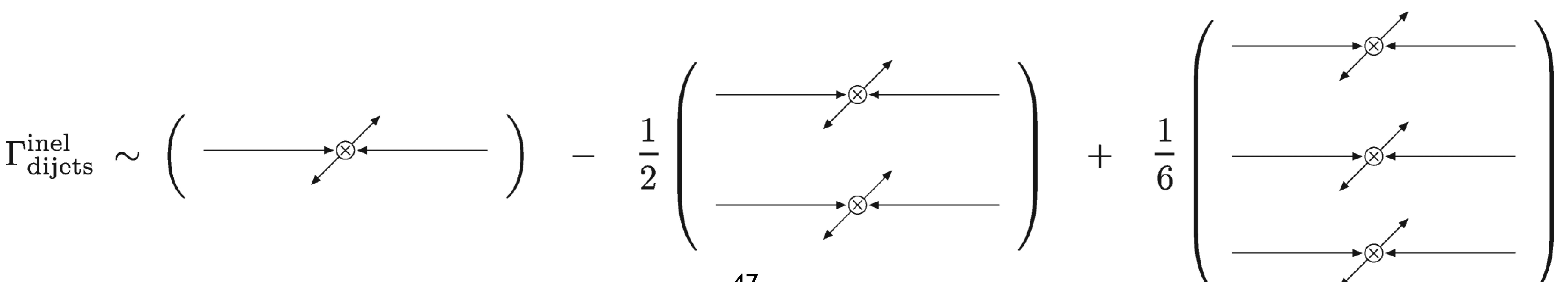
  - $$\int d^2\mathbf{b}\,\tilde{\mathcal{N}}_{2n}(b,s) = \sigma_{2k}^{ex}(s)$$

- In general:

$$\mathcal{N}_{2k}(b,s) = \sum_{n\geq k}^{\infty} \binom{n}{k} \tilde{\mathcal{N}}_{2n}(b,s)$$

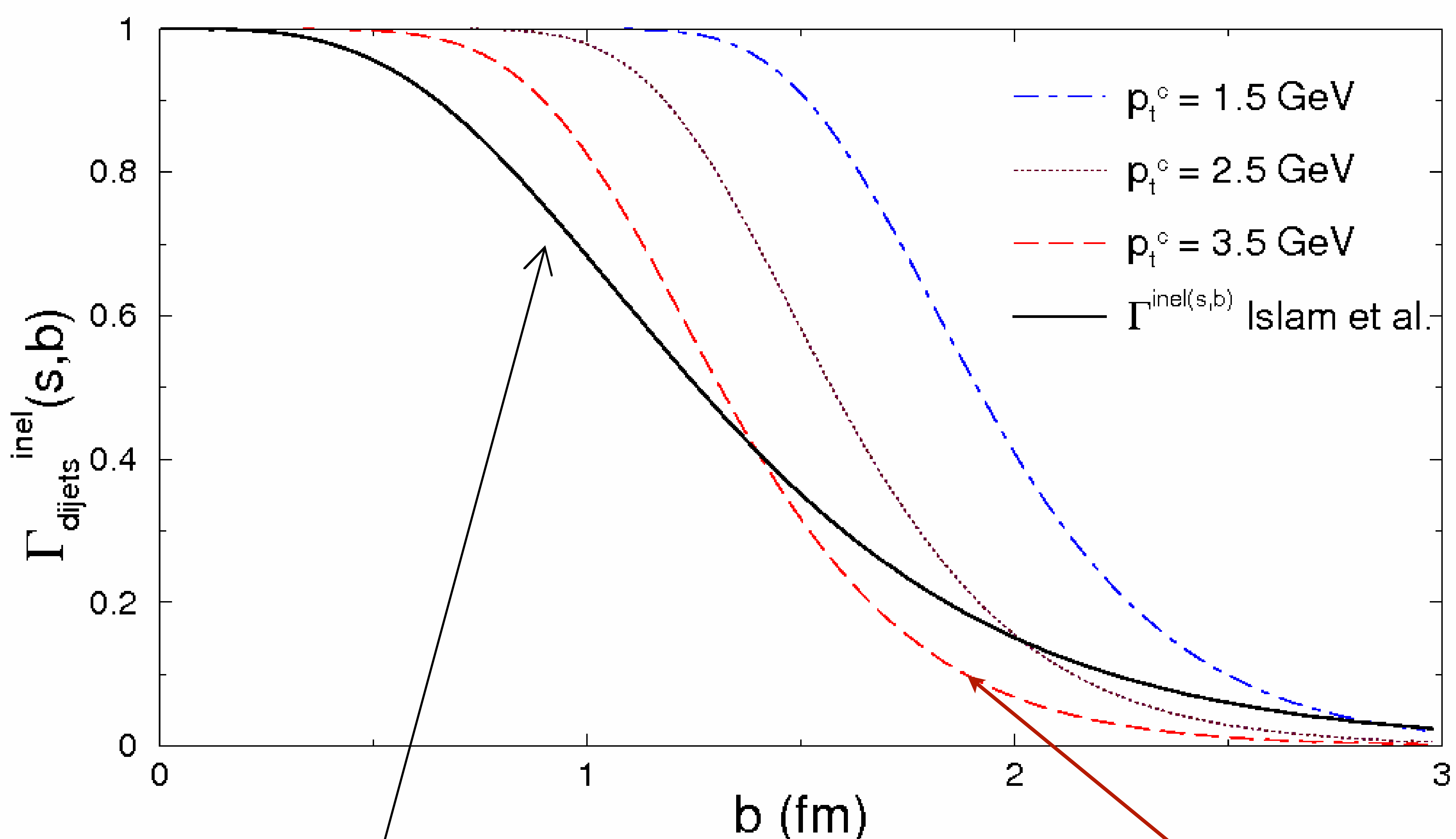
Invert:

$$\longrightarrow \quad \tilde{\mathcal{N}}_{2k}(b,s) = \sum_{n\geq k}^{\infty} \binom{n}{k} (-1)^{n-k} \mathcal{N}_{2n}(b,s)$$



Consistency requirement: $\Gamma^{inel}_{dijets}(s,b) \leq \Gamma^{inel}(x,b)$

Compare reconstructed profile with model extrapolation.



- Identical partons,
- CTEQ6M gluon PDF

$\sqrt{s} = 14$ TeV

extrapolated profile function from elastic cross section

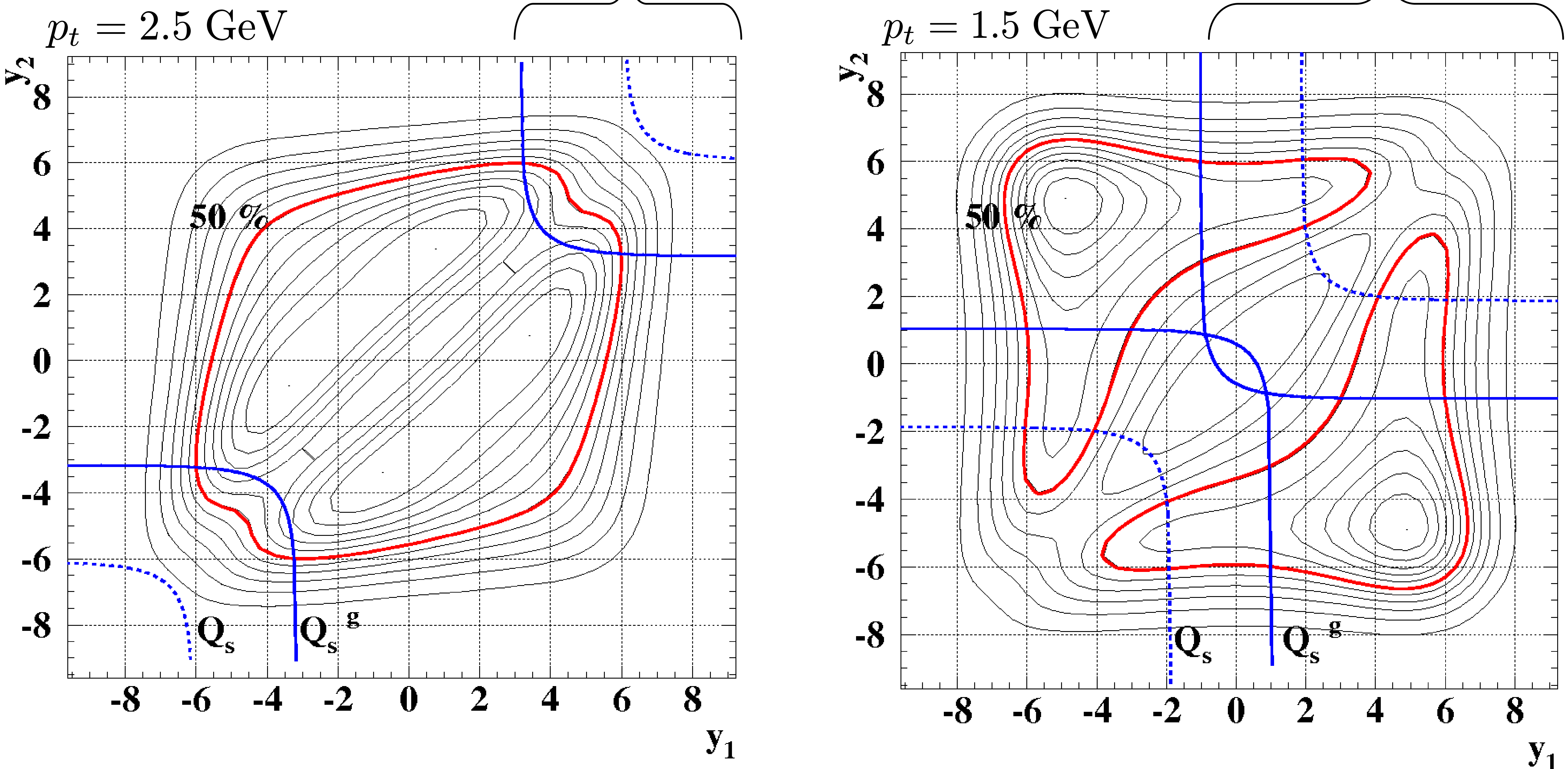
- **Mismatch in description at large impact parameters where naively we expect a small effect from correlations & where gluon densities for corresponding transverse distances from the center are rather small**

Also: At large b large contribution to Γ^{inel} is from diffraction where jet production is suppressed. LHC data correspond to as $\sigma_{diff} \approx 0.25\ \sigma_{inel}$

Problem is not due to break up LT approximation for nucleon pdfs - essential x are rather large and p_t cutoff is pretty high.

Region where gluon PDF is large enough to lead to saturation of small b partial waves in octet (triplet) dipole - nucleon scattering - small contribution

(solid line for octet dipoles)



$\sqrt{s} = 14$ TeV

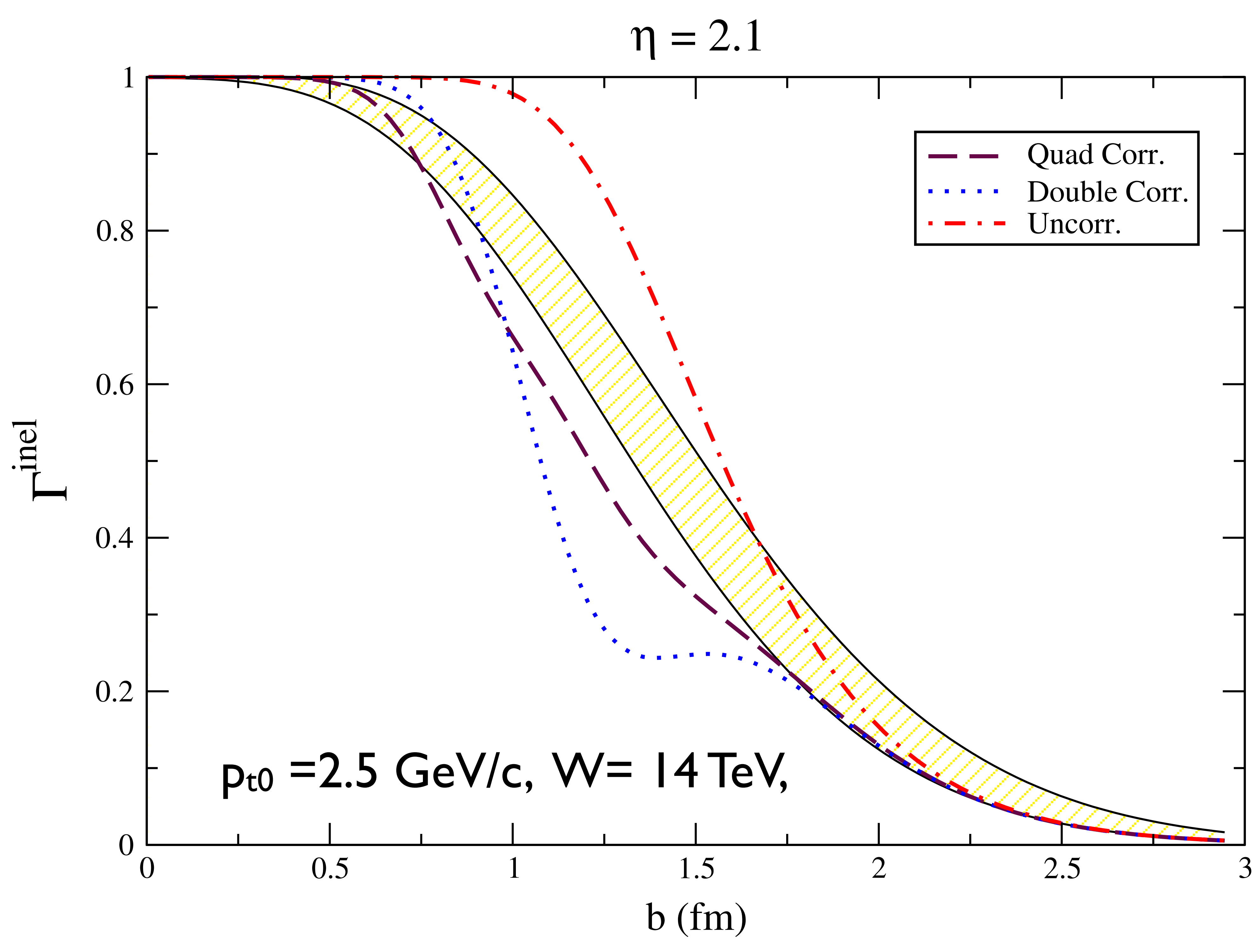
Could correlations change this conclusion?

Naively -- very little since GPDs at large ρ are small and so probability of double hard interaction is small. Explore an option of clumpy nucleon structure - example quarks with localized gluon field.

Denote $\eta = S_{uncorr}/S_{exp}$

Assume: (i) No correlations in x. (ii) *Strength of correlation does not decrease with* ρ_i

for example - color singlet clusters at nucleon periphery



Still problems at large b where one needs a room for diffraction

What could have been missed?

At least one of two partons in the two parton interaction is typically has rapidity $|y|> 1$.
Effective W for propagation of such parton through the second nucleon is $W\sim 400$ GeV (W^2 invariant energy of parton - nucleon system)

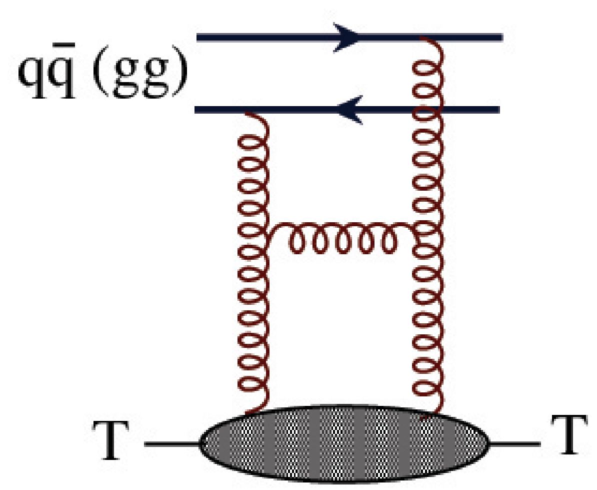
Nonlinear effects in propagation of partons through nucleons should be larger than at HERA

- A factor of 4 smaller x than minimal x at HERA
- Gluons instead of quarks
- Smaller b in events with dijet trigger - gluon propagates through stronger gluon field

$\Rightarrow$ What can be inferred from theoretical analysis of

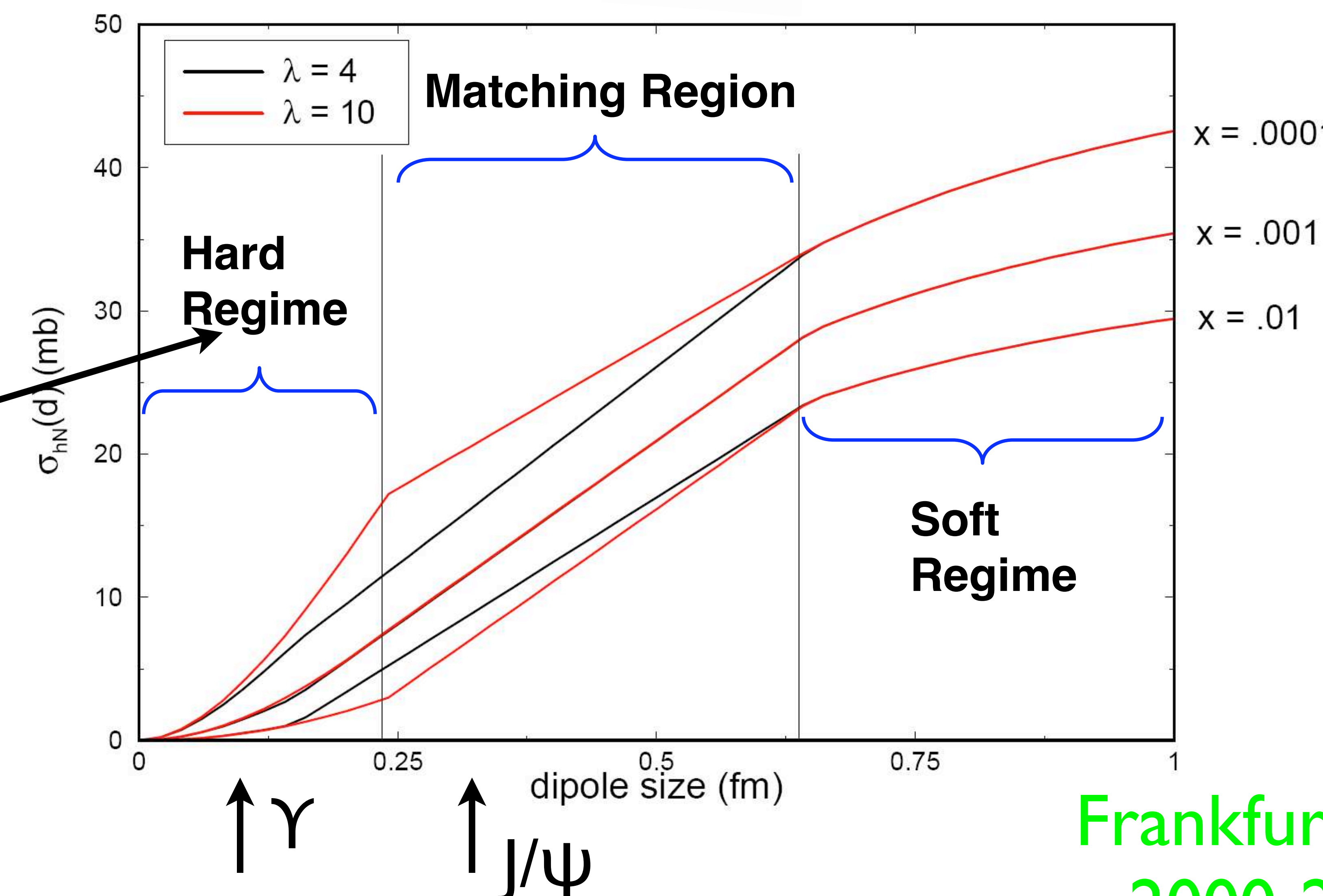
- HERA data ($W_{max} \sim 250$ GeV)
- forward pion production in d-Au collisions at RHIC ($W_{eff}\sim 150$ GeV)

To determine the strength of interaction at HERA energies one can use the dipole approximation.



$$\sigma_{inel} = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2) x G_T(x,\lambda/d^2)$$

F^2 Casimir operator of color SU(3)



studies of the "quark-antiquark dipole" (transverse size d) - nucleon cross section based pQCD and HERA data

Frankfurt et al 2000-2001

Leading log approximation. In NLO would need to include both $q\bar{q}$, and $q\bar{q}g$. Smaller NLO G(x,Q) compensates presence of two components.

S-channel unitarity (finite transverse size) - the growth should be tamed. Is it tamed when interaction reaches strength close to maximal possible - black disk regime of the complete absorption for small impact parameters? Did HERA reach this limit?

Impact parameter amplitude in "h"(dipole)p interaction

Study of the elastic scattering allows to determine how the strength of the interaction depends on the impact parameter, b:

$$\Gamma_h(s,b) = \frac{1}{2is}\frac{1}{(2\pi)^2}\int d^2\vec{q}e^{i\vec{q}\vec{b}}A_{hN}(s,t) \; ; \; ImA = s\sigma_{tot}\exp(Bt/2)$$

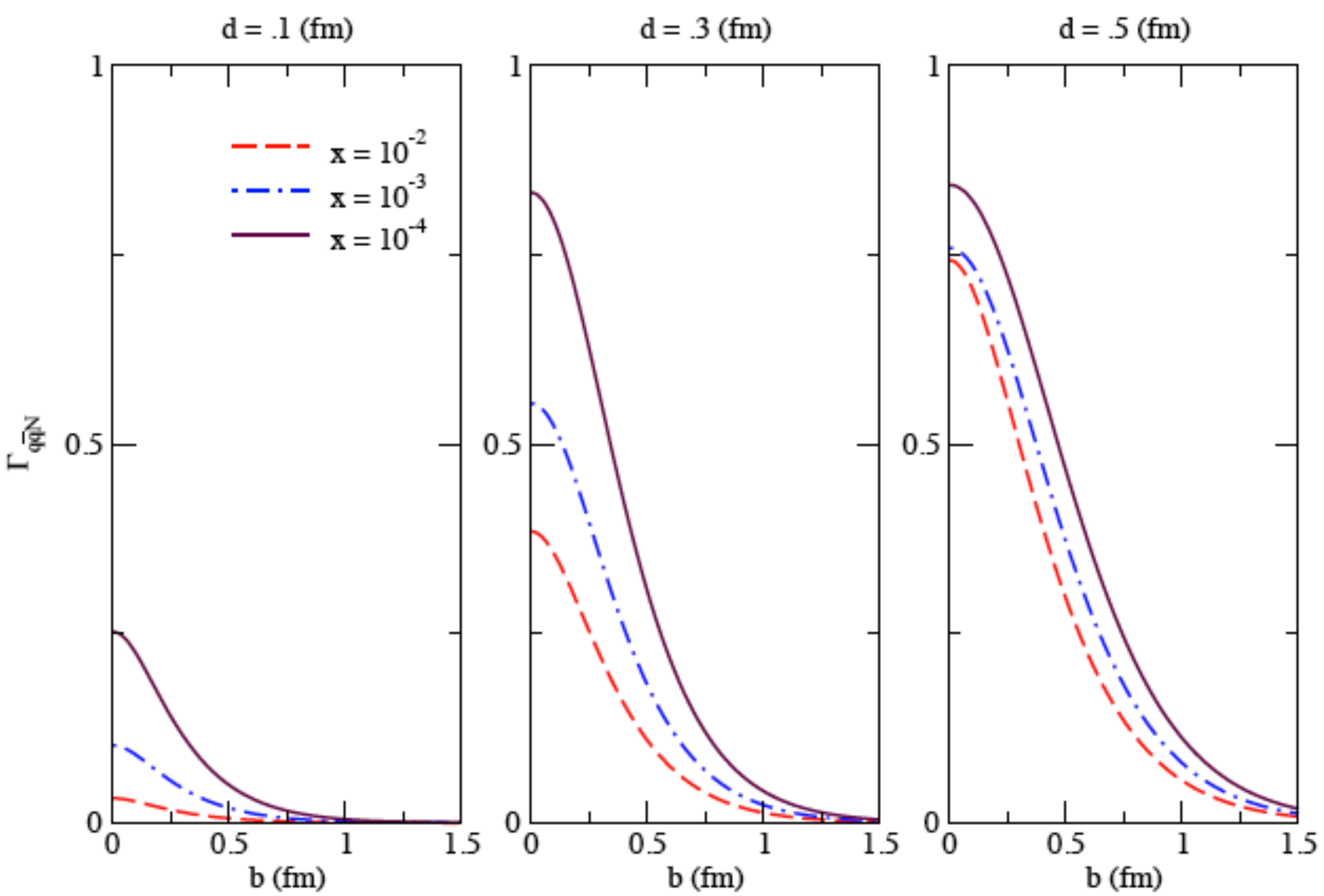
t-dependence from vector meson exclusive production in DIS + QCD factorization theorem from VM production

$$\sigma_{tot} = 2\int d^2b \mathrm{Re}\Gamma(s,b)$$

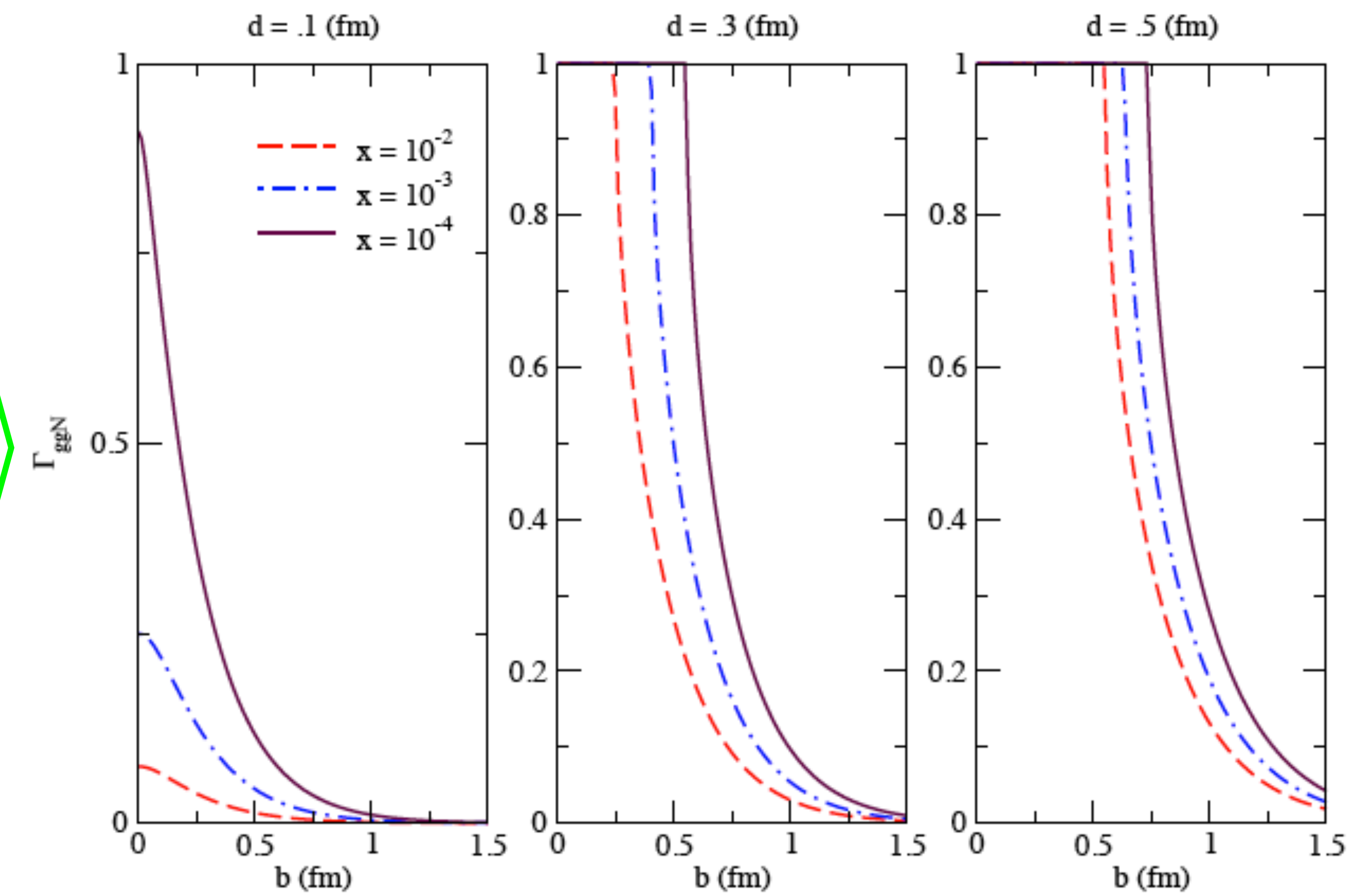
$$\sigma_{el} = \int d^2b|\Gamma(s,b)|^2$$

$$\sigma_{inel} = \int d^2b(1-(1-\mathrm{Re}\Gamma(s,b))^2 - [\mathrm{Im}\Gamma(s,b)]^2)$$

$$\Gamma(b) = 1 \equiv \sigma_{inel} = \sigma_{el}$$ - black disk regime -BDR



$$\Gamma_{gg}^{inel}(b) = \frac{9}{4}\Gamma_{q\bar{q}}^{inel}(b)$$



At HERA in quark channel range of b where interaction is close to BDR is small except for $Q^2 \sim 1$ GeV^2 where large size dipoles dominate

For gluons BDR range is much larger $Q^2 \sim 4$ GeV^2 for $x=10^{-4}$?

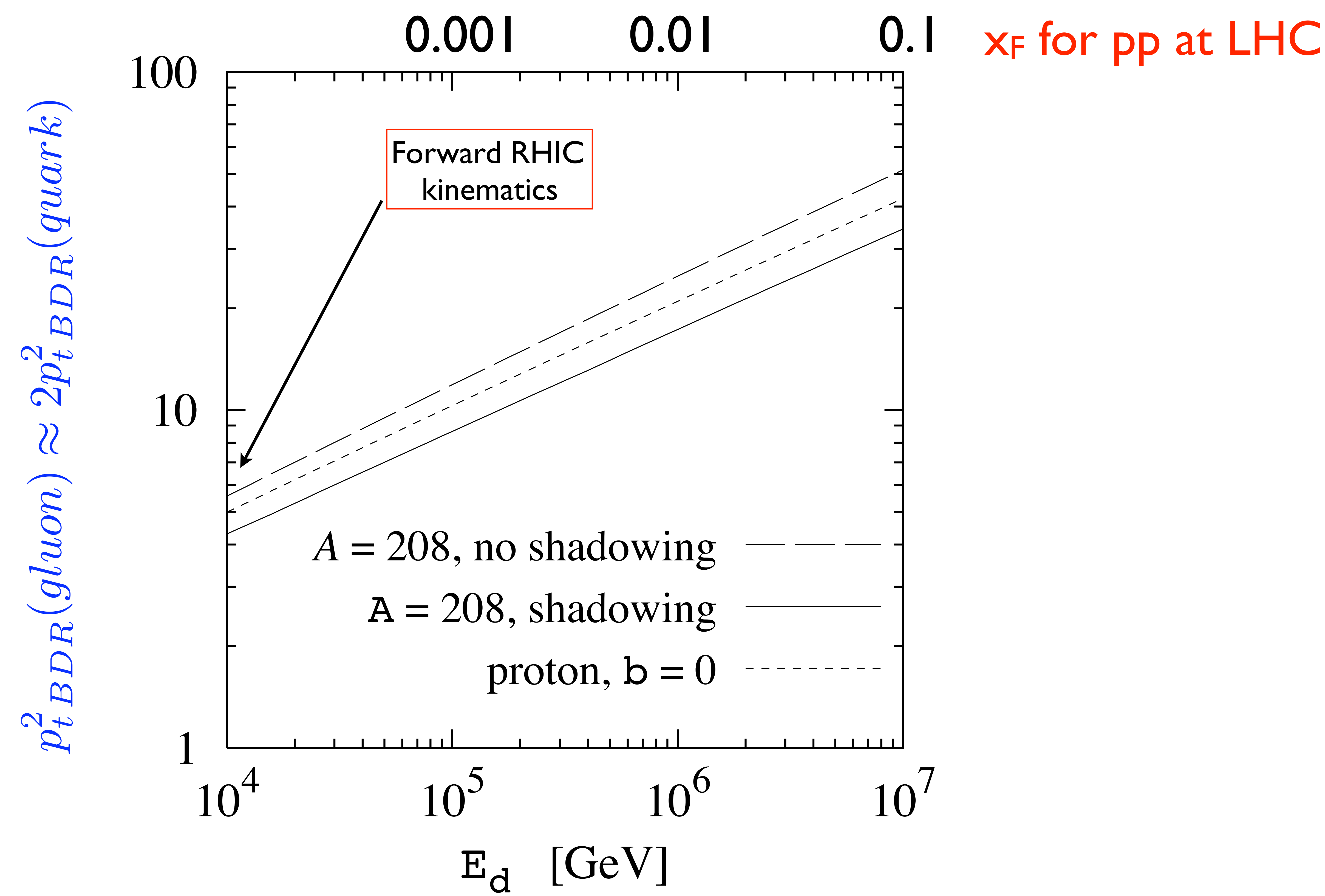
Large nonlinear effects at the LHC in wide range of rapidities down to y~0

in proton (A) - proton (A) collisions a parton with given x_R resolves partons in another nucleon with $x_2 = 4p_\perp^2/x_R s$

$$x_R = 0.01, p_\perp = 2GeV/c \ \Rightarrow \ x_2 \sim 8 \times 10^{-6}$$

Onset of BDR for interaction of a small dipole - break down of LT pQCD approximation - natural definition of boundary: $\Gamma_{dip}(b) = 1/2$ - corresponds the probability for dipole to pass through the target at given b without interaction:

$$|1-\Gamma_{dip}(b)|^2 < 1/4 \quad \Rightarrow \quad p_{t\,BDR} \sim \frac{\pi}{2d_{BDR}}$$



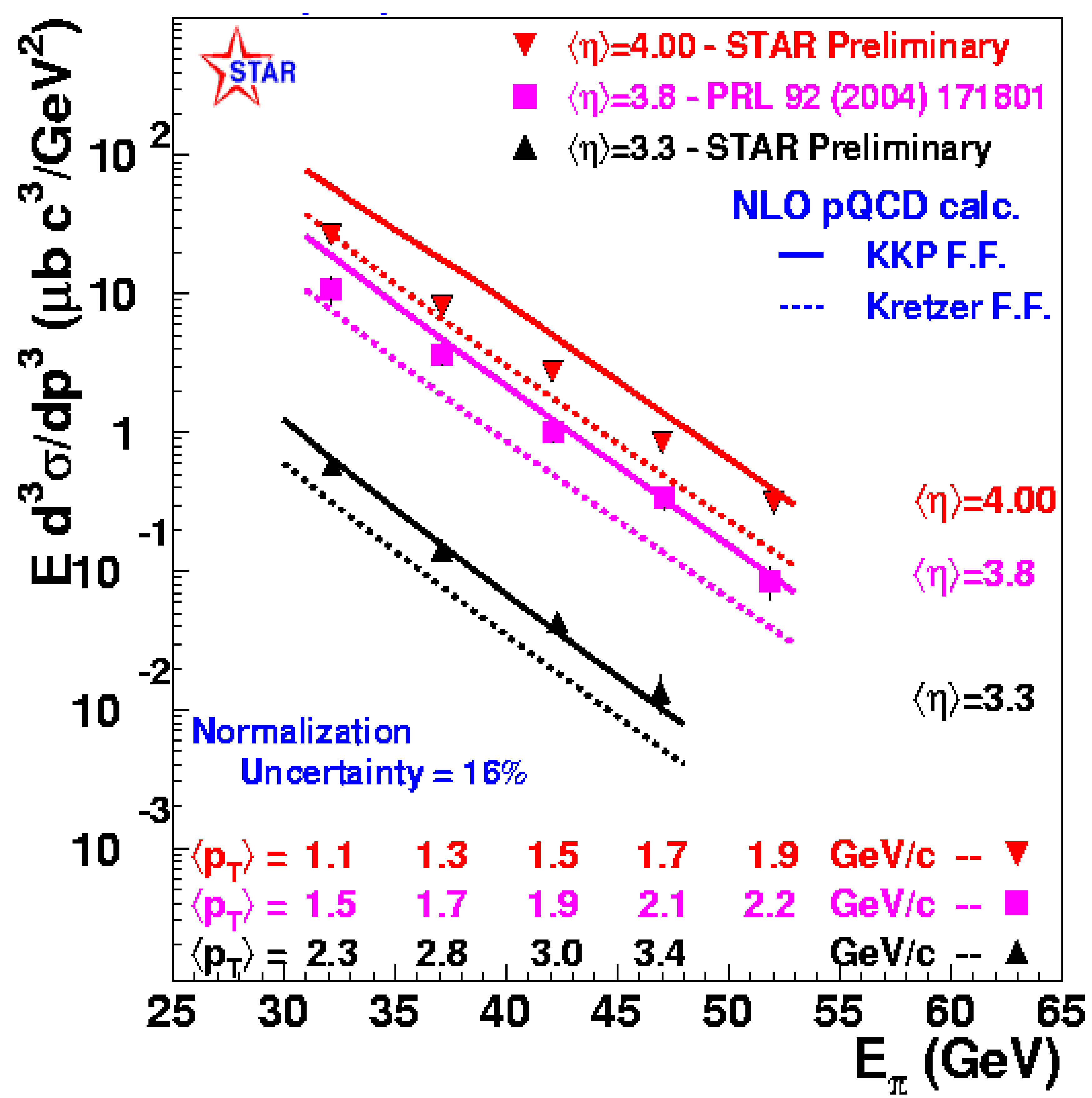
Warning - estimate assumes $x^{-\omega}$ regime for all x- may overestimate $p_{t\,BDR}$ for parton energies (in nucleus rest frame) $E_d > 10^5$ GeV - better to use double log approximation

☛ Breaking of pQCD mechanism in d -Au data (RHIC) in forward pion production

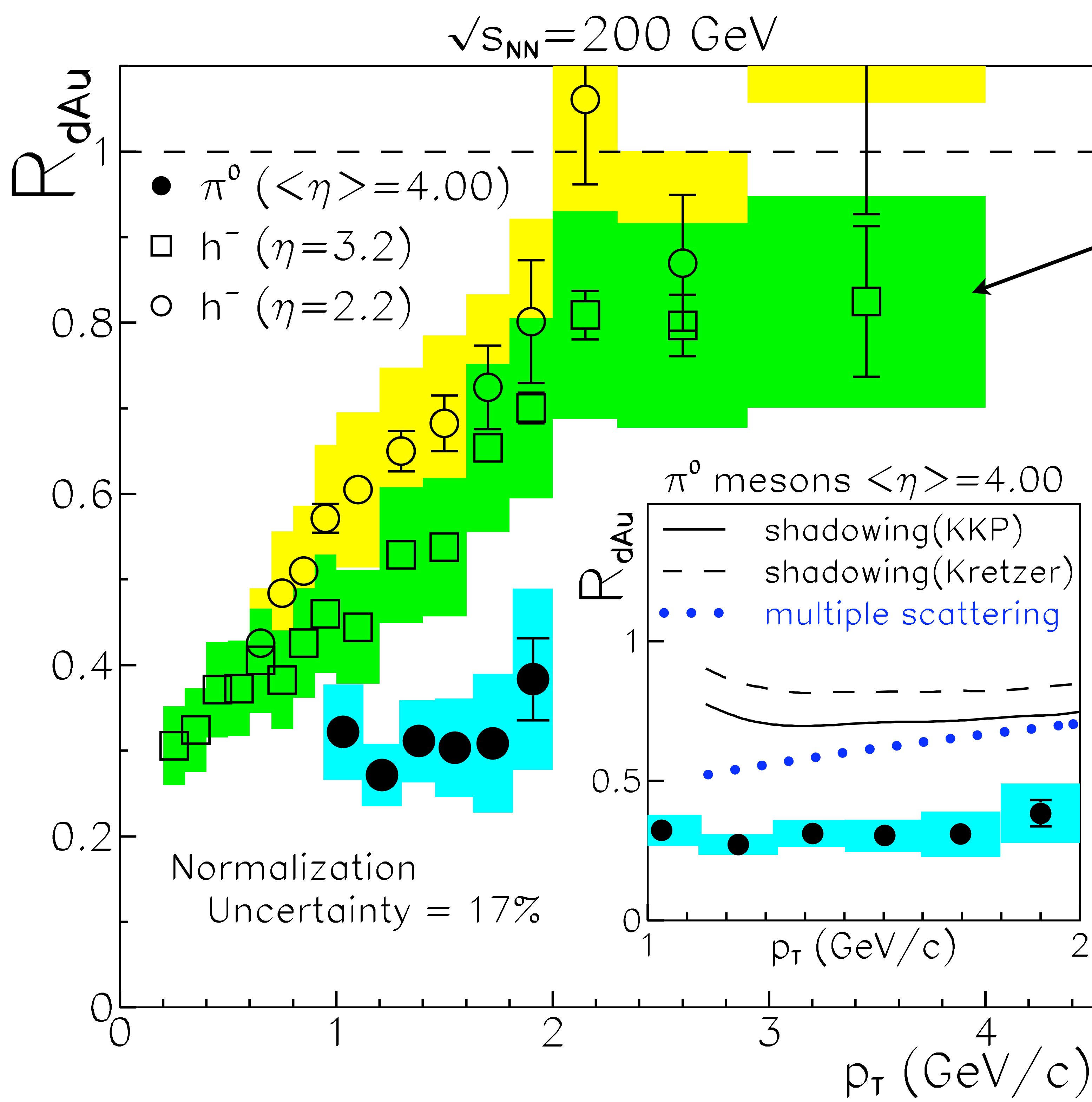
Brief summary of challenge / evidence

analyses of Guzey, Vogelsang and MS

✽ The pp data are consistent with NLO pQCD calculations of Vogelsang et al. for p_t >1.3 GeV/c. However they are sensitive to the gluon fragmentation which contributes !!! even at the highest pion energies.



The dA data are << than NLO pQCD calculations of Guzey, MS, Vogelsang with LT nuclear shadowing since essential x_A are > 0.01.



Significant nuclear suppression = $R_{dAu}/1.5$

BRAHMS and STAR are consistent when an isospin correction which reduces h^- ration measured by BRAHMS by a factor ~ 1.5 (Guzey, MS, Vogelsang 04) is introduced.

FIG. 3: Nuclear modification factor (R_{dAu}) for minimum-bias d+Au collisions versus transverse momentum (p_T). The solid circles are for π^0 mesons. The open circles and boxes are for negative hadrons (h^-) at smaller η [10]. The error bars are statistical, while the shaded boxes are point-to-point systematic errors. (Inset) R_{dAu} for π^0 mesons at $\langle\eta\rangle = 4.00$

Forward - central correlation data

pp - pQCD OK

dAu - only peripheral collisions contribute and pQCD subprocess dominates.

Strong suppression of 2 → 2 ($qg \to \pi^0 + X, x_g \sim 0.02$) for NA collisions at central impact parameters: suppression is at least a factor of 4

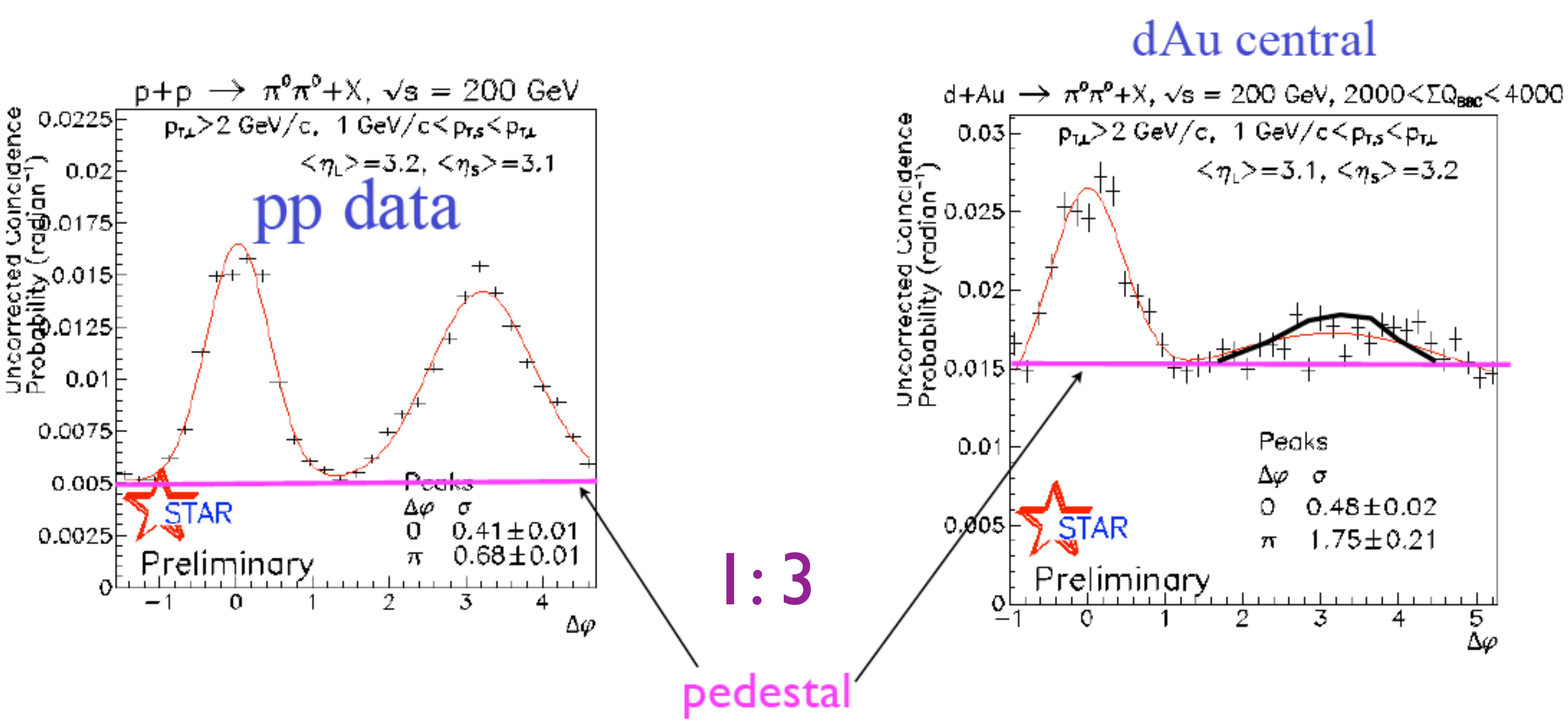
Resembles what we need for LHC ?

Need few % effective energy losses to explain the magnitude of the suppression - due to strong dependence of cross section on x_F

✿ Forward π^0- forward π^0 correlation data

Can be explained by taking into account (i) fractional energy losses, (ii) LT nuclear shadowing, (iii) multiparton mechanism of production of two leading pions

- ✶ $\Delta\phi$ independent pedestal in dA is 2.5 ÷ 4 times larger in pp
- ✶ Suppression of $\Delta\phi$ =180° peak by a factor ~ four

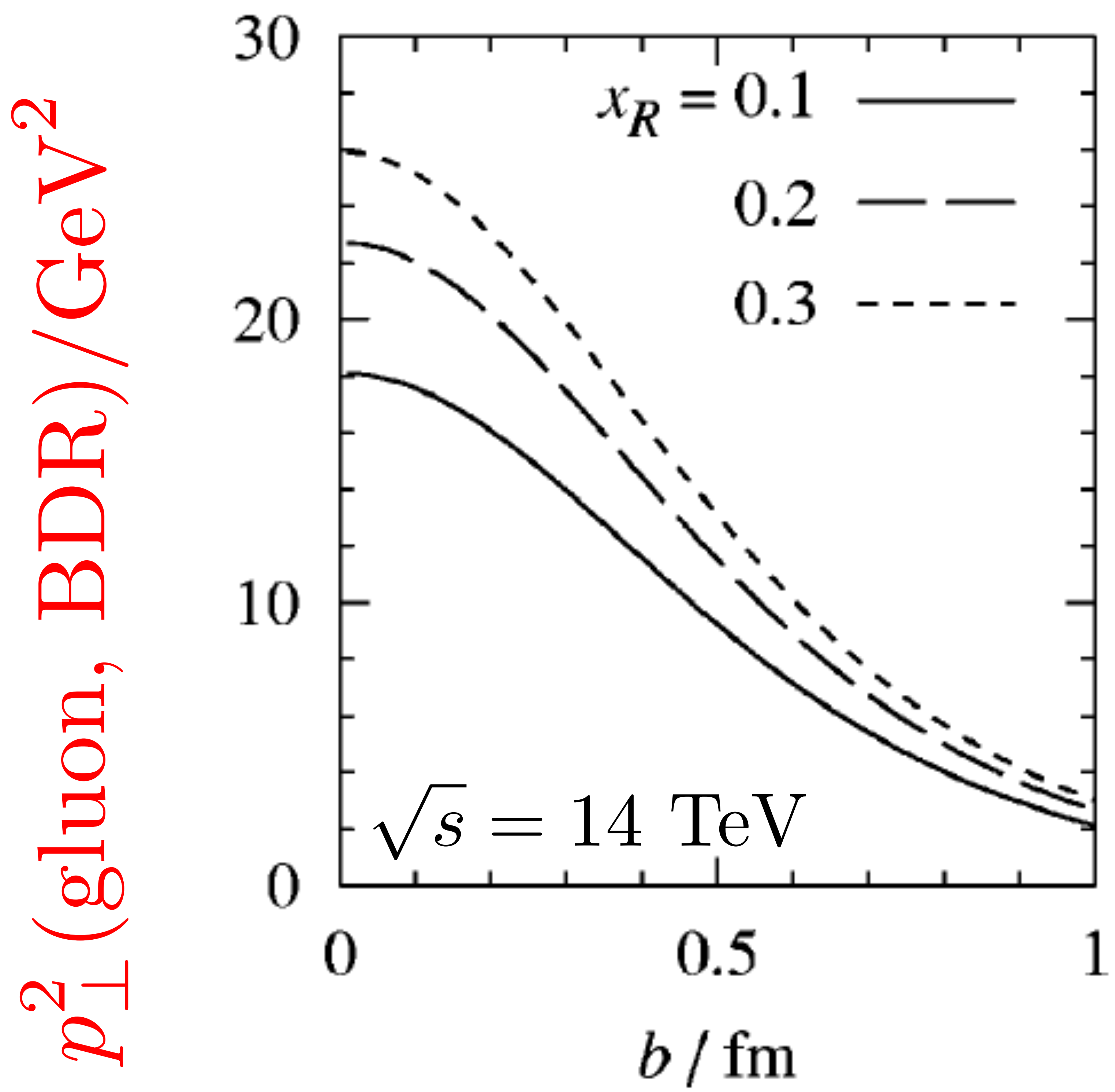


Black curve is the pp data peak above pedestal for φ ~π scaled down by a factor of 4

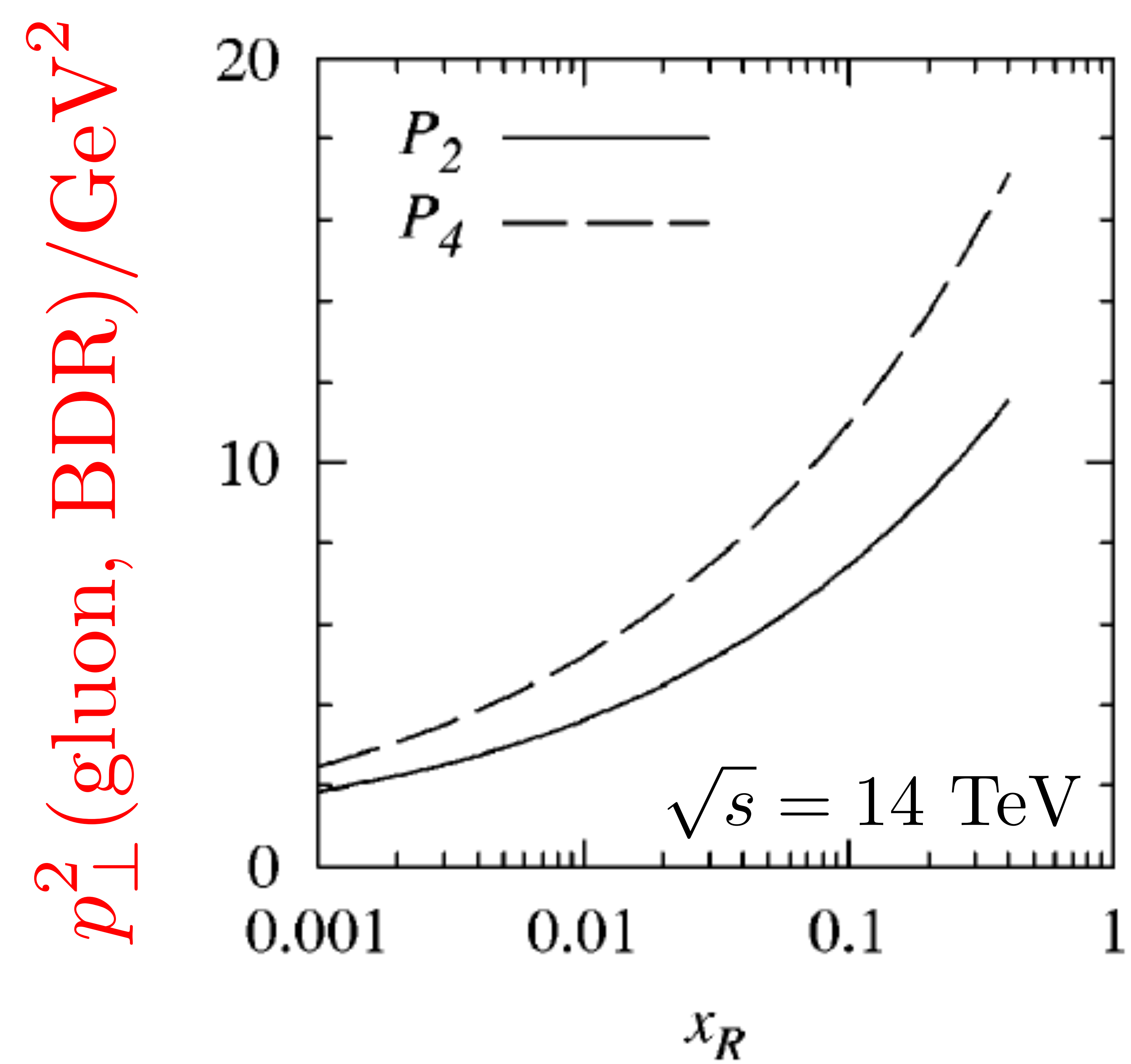
Overall suppression of f-f (dAu/pp) is about a factor of 10; hardly could be much larger - since the probability of fluctuations in the nucleus wave function leads to a probability of punch through of 5 - 10% (Alvioli + MS).

Conclusion - BDR for gluons is present in the kinematics relevant for the presence of effective cutoff of minijet production via interactions with the "spectator" partons. Implementation is not clear so far. Deficiency of the current procedure is that (x-independent) suppression factor allows a parton with large x_F to propagate through the the center of the nucleon without interaction. Contradicts the BDR pattern.

leading particles



events with centrality trigger - dijets (P_2); four jets via double parton interactions (P_4)



Large flow of energy to central rapidities

Pushing to large x for larger mass limits on SUSY, etc

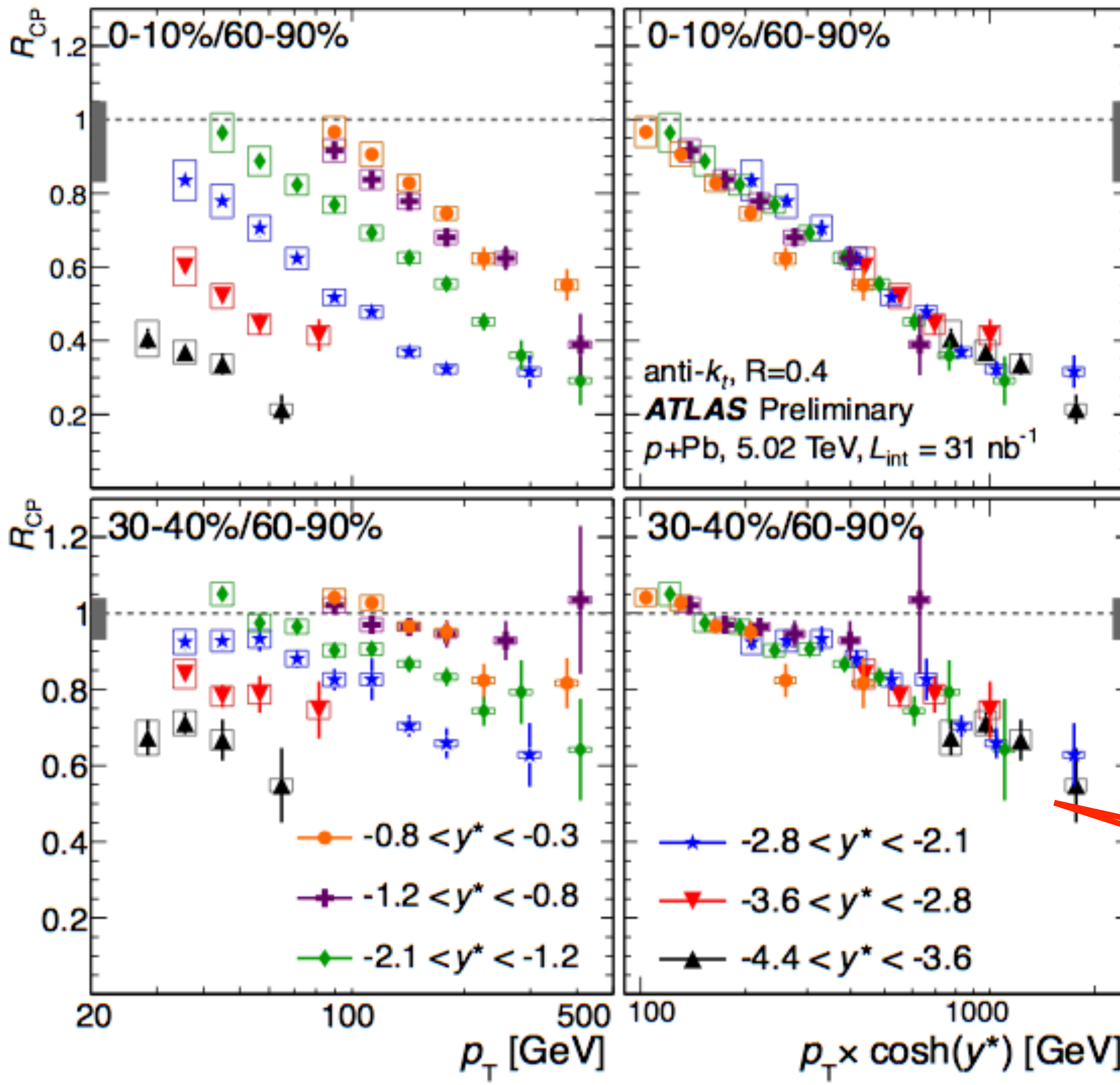
Selection of large x selects special configurations in colliding nucleons with smaller soft / minijet rates. Theoretical expectation - large x selects larger longitudinal and hence larger transverse momenta, and fewer gluons.

Jet production in pA collisions - possible evidence for x -dependent color fluctuations

Summary of some of the relevant experimental observations of CMS & ATLAS

- Inclusive jet production is consistent with pQCD expectations (CMS)

❖ x_p scaling (ATLAS) - enhancement/suppression effect scales with

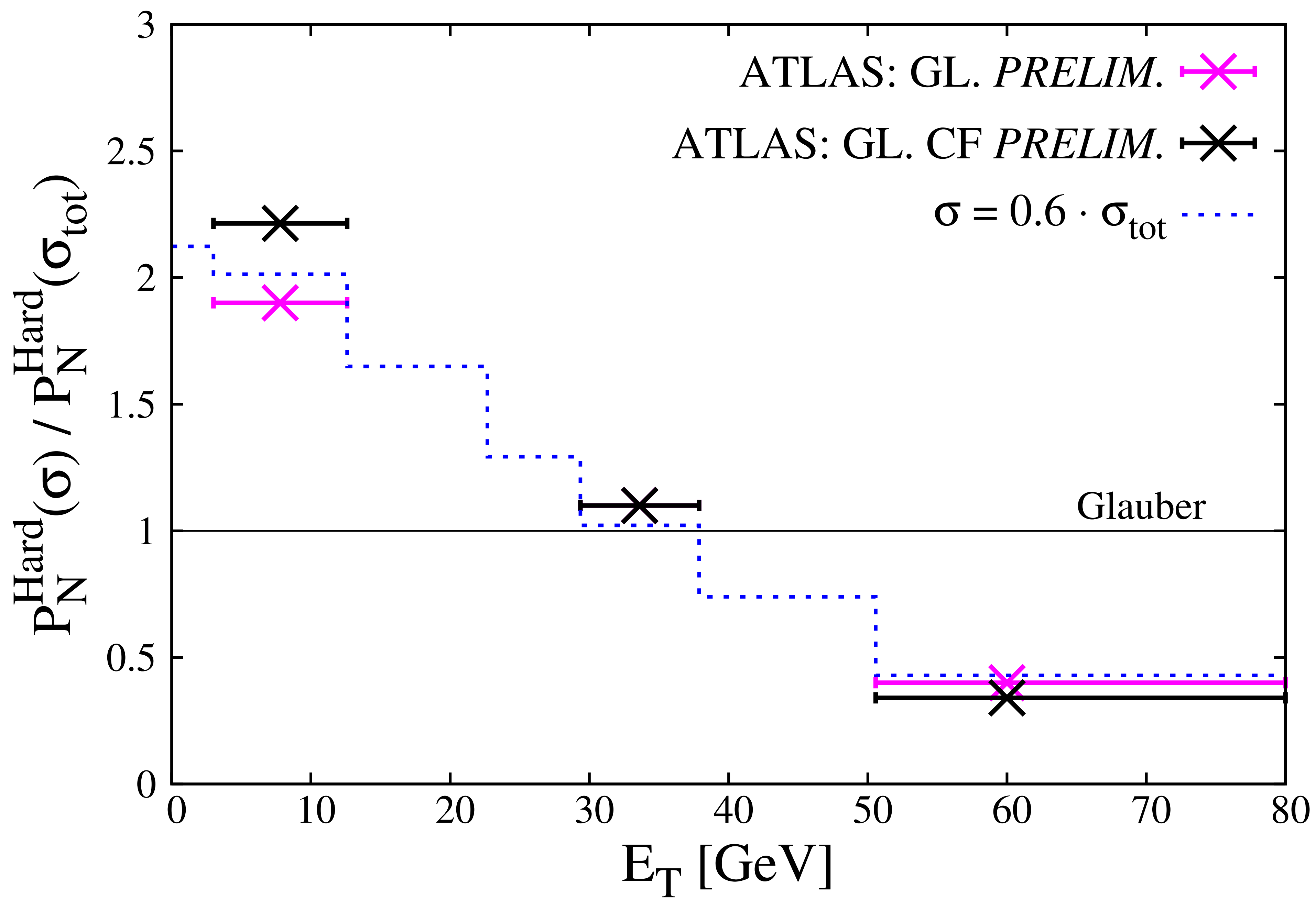


enhancement - problem for energy momentum conservation interpretation

$x_p = p_T \times \cosh(y^*) / E_{p\,(c.m,)}$

$x_p = 0.6$

$\sigma(x=0.6) \sim \sigma_{tot}/2$ gives a reasonable description of the data



→✕ corrects ATLAS data for difference of N_{coll} in Glauber and Color Fluctuation models

We can estimate $\sigma(x=0.6)/\sigma_{tot}$[fixed target]=1/4

from probability conservation relation:

$$\int_0^{\sigma(s_1)} P(\sigma, s_1) d\sigma = \int_0^{\sigma(s_2)} P(\sigma, s_2) d\sigma$$

➠ $x \geq 0.5$ configurations have small transverse size ($\sim 1/2\ r_N$)

➠ Implication for the LHC - different underling event structure than at smaller x

Supplementary slides

How strong are fluctuations of the gluon field strength?

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

Consider $\gamma_L^* + p \to V + X$ for Q^2 > few GeV^2

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

Expand initial proton state in a set of partonic states characterized by the number of partons and their transverse positions, summarily labeled as $|n\rangle$

$$|p\rangle = \sum_n a_n |n\rangle$$

Each configuration n has a definite gluon density $G(x, Q^2| n)$ given by the expectation value of the twist--2 gluon operator in the state $|n\rangle$

$$G(x, Q^2) \ = \ \sum_n |a_n|^2 G(x, Q^2|n) \ \equiv \ \langle G \rangle$$

$$\Rightarrow \quad \boxed{\omega_g \equiv \frac{\langle G^2\rangle - \langle G\rangle^2}{\langle G\rangle^2} = \frac{d\sigma_{\gamma^*+p\to VM+X}}{dt} \Bigg/ \frac{d\sigma_{\gamma^*+p\to VM+p}}{dt}\Bigg|_{t=0}}$$

Data from HERA -- $\omega_g = 0.15 \div 0.2$ for $x=10^{-3}$, $Q^2 \sim 4$ GeV^2

ω_g is a bit smaller than the corresponding quantity for pion - nucleon scattering.