High energy color transparency - an effective tool to study strong interaction dynamics, structure of photon, GPDs

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Main tool for exclusive processes is color coherence (CC) property of QCD and resulting **Color transparency (CT)**

CT phenomenon plays a dual role:

- probe of the high energy dynamics of strong interaction
- probe of minimal small size components of the hadrons

at intermediate energies also a unique probe of the space time evolution of wave packages

Basic tool of CT: suppression of interaction of small size color singlet configurations = CC

QCD factorization theorems for hard exclusive processes
Brodsky et al 94, Collins et al 97,....

For a dipole of transverse size d:

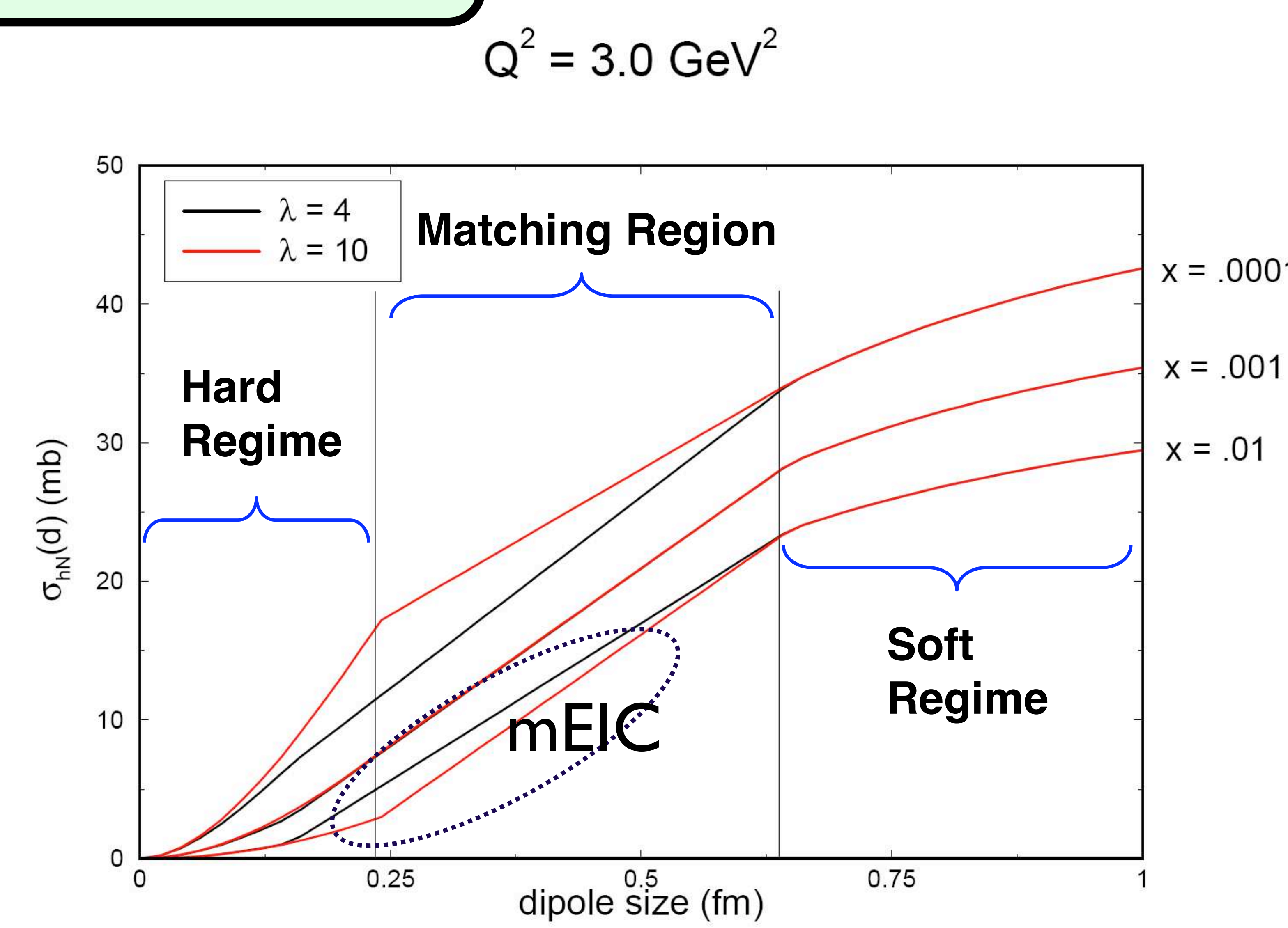
$\sigma = cd^2$ *in the lowest order in* α_s *(two gluon exchange F.Low 75)*

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

Important at E_{dipole} < 10 GeV

Here S is sea quark distribution for quarks making up the dipole.

(Baym et al 93, FS&Miller 93 & 2000)



Brief Summary of CT: squeeze and freeze

Squeezing: *(a) high energy CT*

- Select special final states: diffraction of pion into two high p_t jets: $d_{q\bar{q}} \sim 1/p_t$

- Select a small initial state: γ^*_L - $d_{q\bar{q}} \sim 1/Q$ in $\gamma^*_L + N \to M + B$

QCD factorization theorems are valid for these processes with the proof based on the CT property of QCD

(b) Intermediate energy CT

- Nucleon form factor
- γ^*_L (γ^*_T ?)+ $N \to M + B$
- Large angle (t/s = const) two body processes: $a + b \to c + d$ Brodsky & Mueller 82

talks on ρ,π,N CT at Jlab energies

↕ Problem: *strong correlation* between t (Q) and lab momentum of produced hadron

Freezing: ***Main challenge:*** |qqq> (|q$\bar{q}$>) is not an eigenstate of the QCD Hamiltonian. So even if we find an elementary process in which interaction is dominated by small size configurations - they are not frozen. They evolve with time - expand after interaction to average configurations and contract before interaction from average configurations (FFLS88)

$$|\Psi_{PLC}(t)\rangle = \sum_{i=1}^{\infty} a_i \exp(iE_i t)\,|\Psi_i t)\rangle = \exp(iE_1)\sum_{i=1}^{\infty} a_i \exp\left(\frac{i(m_i^2 - m_1^2)t}{2P}\right)|\Psi_i t)\rangle$$

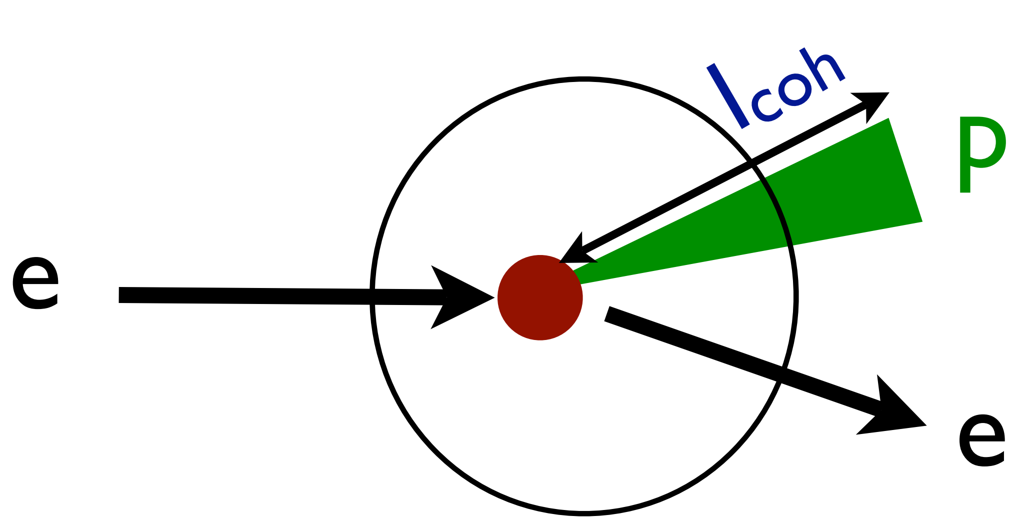
$$\sigma^{PLC}(z) = \left(\sigma_{hard} + \frac{z}{l_{coh}}\left[\sigma - \sigma_{hard}\right]\right)\theta(l_{coh} - z) + \sigma\theta(z - l_{coh})$$

← Quantum Diffusion model of expansion

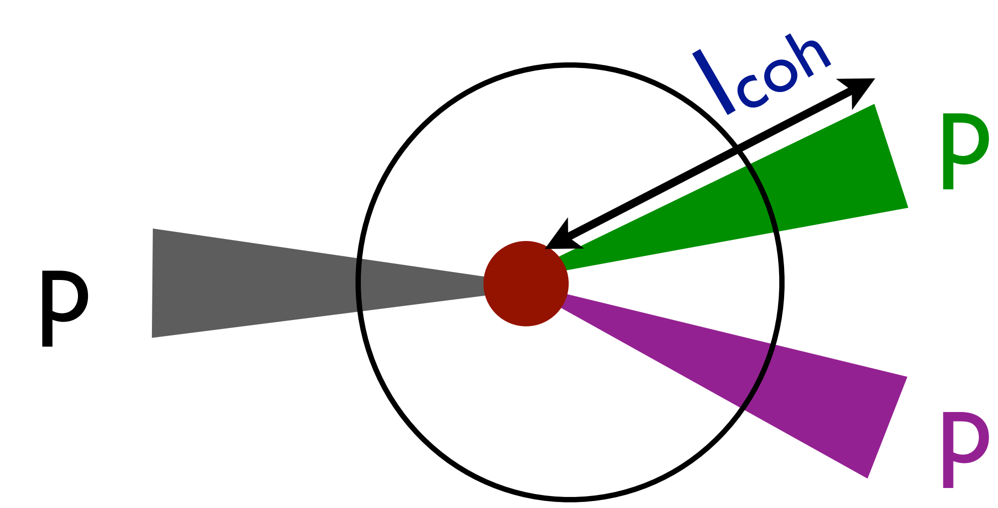
$l_{coh} \sim$ (0.4- 0.8) fm E_h[GeV]

actually incoherence length

The same expression with the same parameters describes production of leading hadrons in DIS - U.Mozel et al



eA→ ep (A-1) at large Q



pA→ pp (A-1) at large t and intermediate energies

MC's at RHIC assume much larger l_{coh}= 1fm E_h/m_h;
for pions l_{coh}= 7 fm E_h[GeV] -
a factor of 10 difference !!!

Note - one can use multihadron basis with build in CT (Miller and Jennings) or diffusion model - numerical results for σ^{PLC} are very similar.

Implication for mEIC.

In the range of momentum transfers to the target nucleon feasible for collider lumi - $-t < 2$ GeV^2 expansion is fast and so *color transparency effects for propagation of nucleons in the nucleus fragmentation region are very small*.

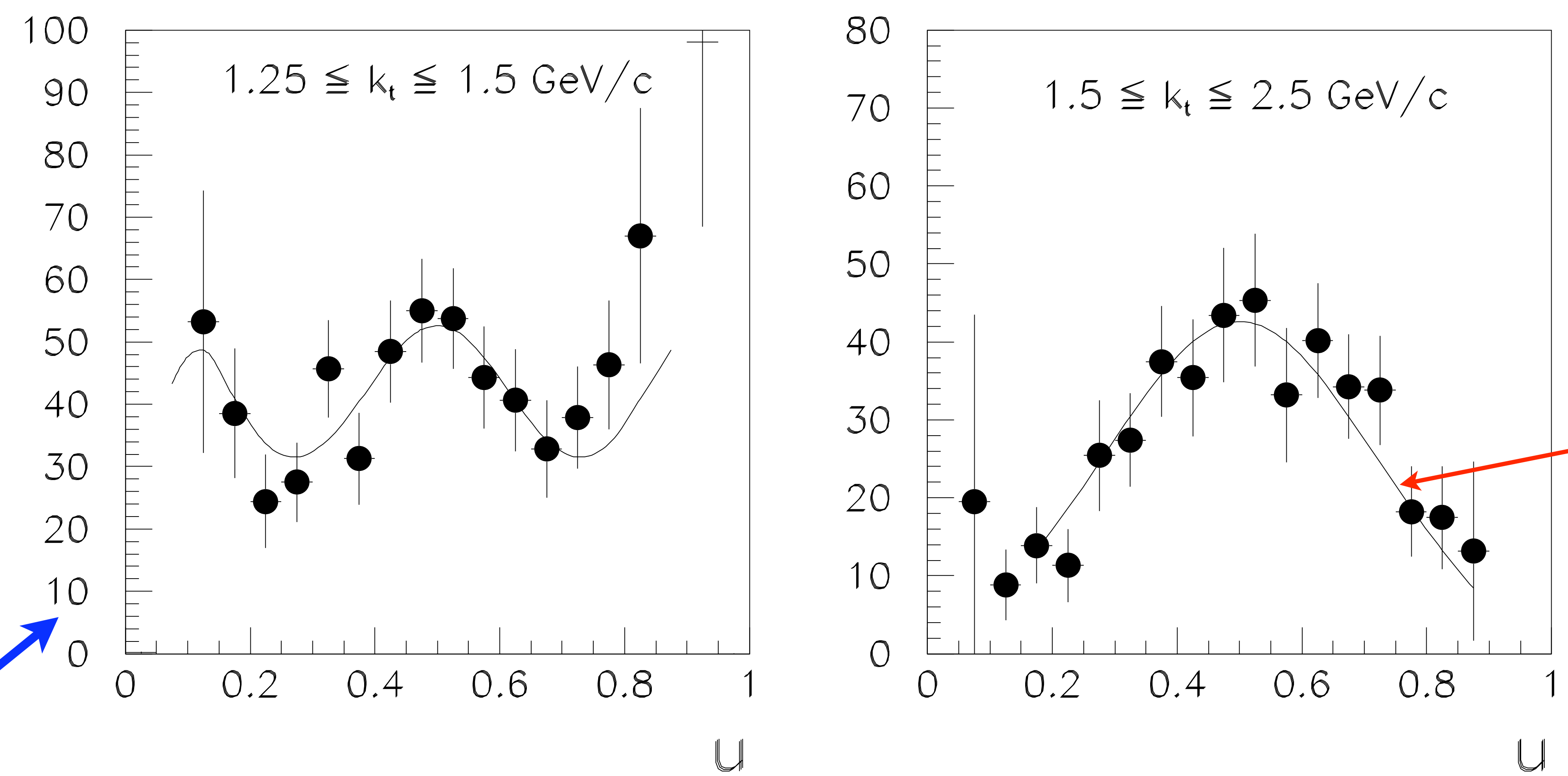
Possible exception - chiral transparency effects - will discuss briefly

In the current fragmentation region freezing is very effective ⇒ *color transparency effects for propagation of hadronic components of the photon are not suppressed by diffusion effects.*

High energy color transparency is well established

At high energies weakness of interaction of point-like configurations with nucleons - is routinely used for explanation of DIS phenomena at HERA.

First experimental observation of high energy CT for pion interaction (Ashery 2000): $\pi + A \to$"jet"+"jet" +A. Confirmed predictions of pQCD (Frankfurt ,Miller, MS93) for *A-dependence, distribution over energy fraction, u carried by one jet, dependence on p_t(jet), etc*



prediction

(π wave funct)^2

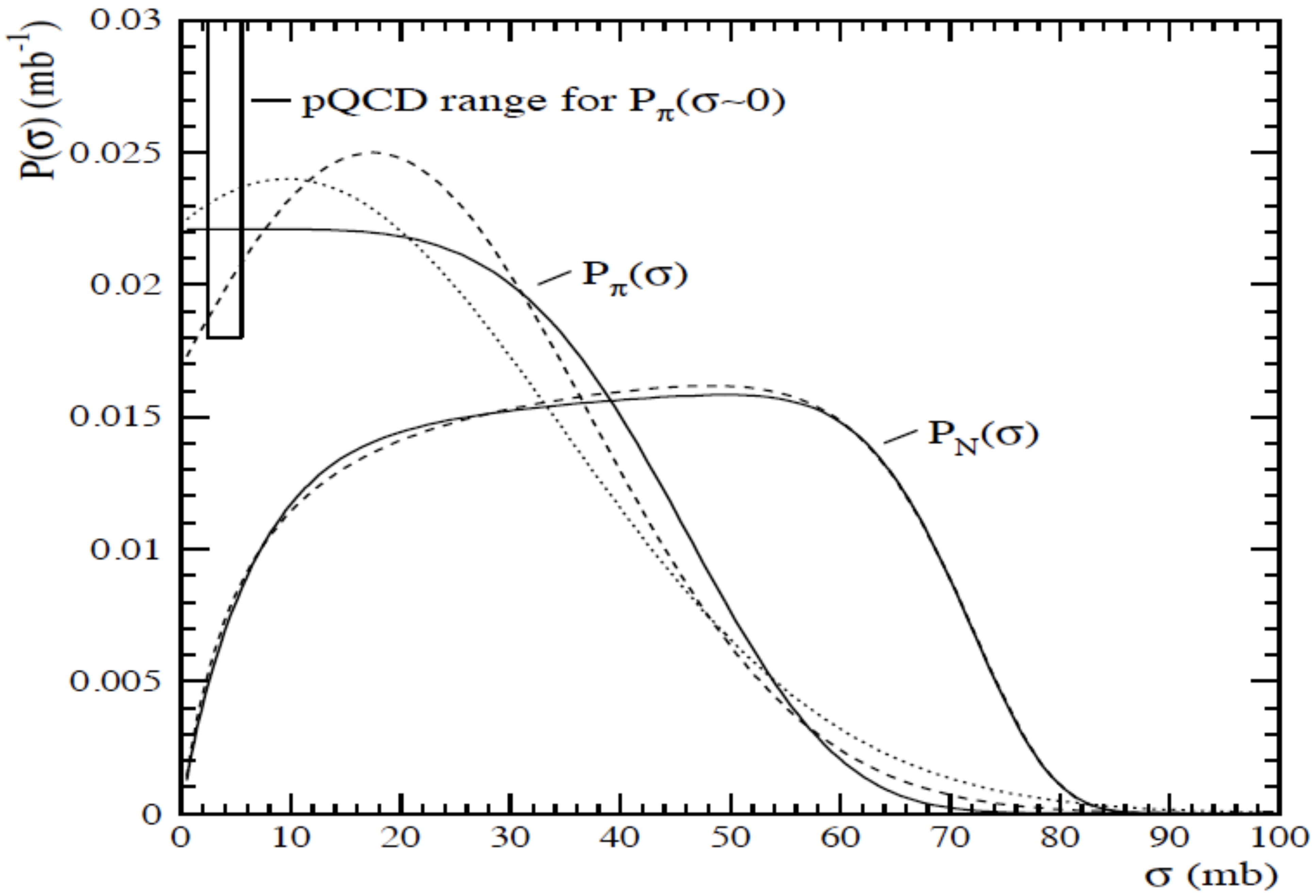
Squeezing occurs already before the leading term (1-z)z dominates!!!

$$Q^2(\pi\ f.f.) \sim 4k_t^2(jet)$$
$$\Downarrow$$
strong squeezing in π form factor for Q^2=6 GeV^2

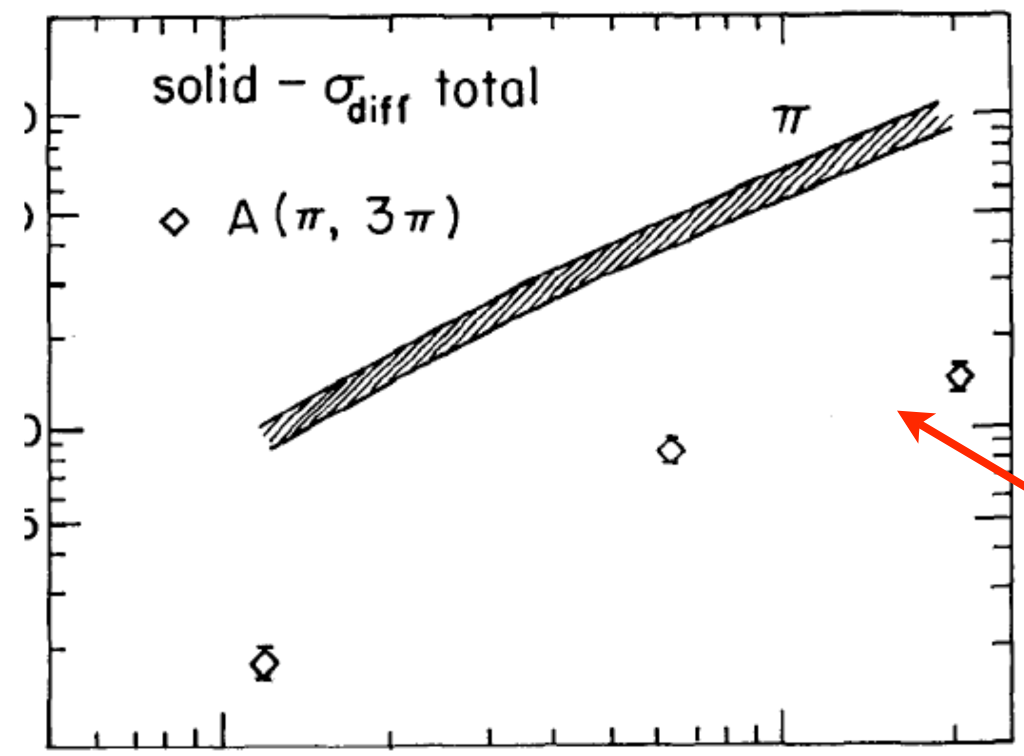
Presence of small configurations in pion

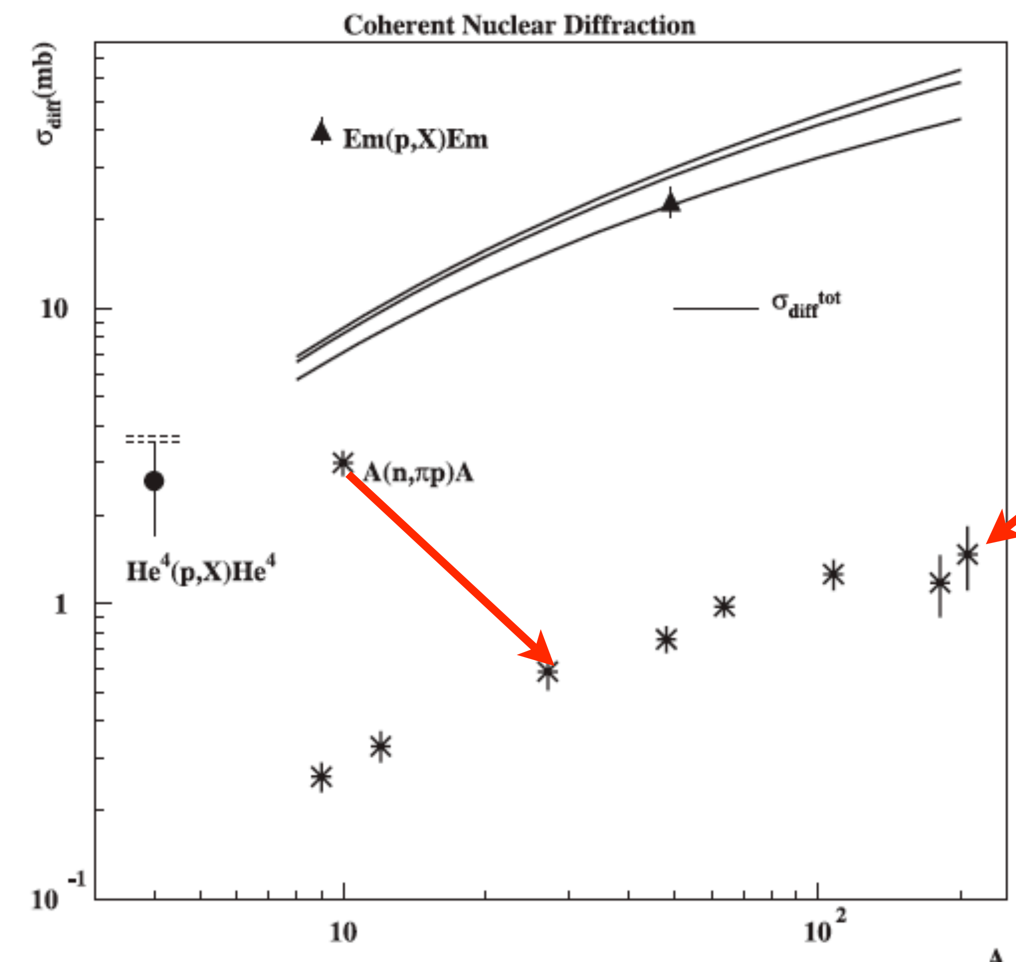
⇒ **presence of configurations with superstrong interaction (SSC's)**

⇒ *color fluctuations in hadrons*



Cross-section probability for pions $P_\pi(\sigma)$ and nucleons $P_N(\sigma)$ as extracted from experimental data. $P_\pi(\sigma=0)$ is compared with the perturbative QCD prediction (BBFS93).

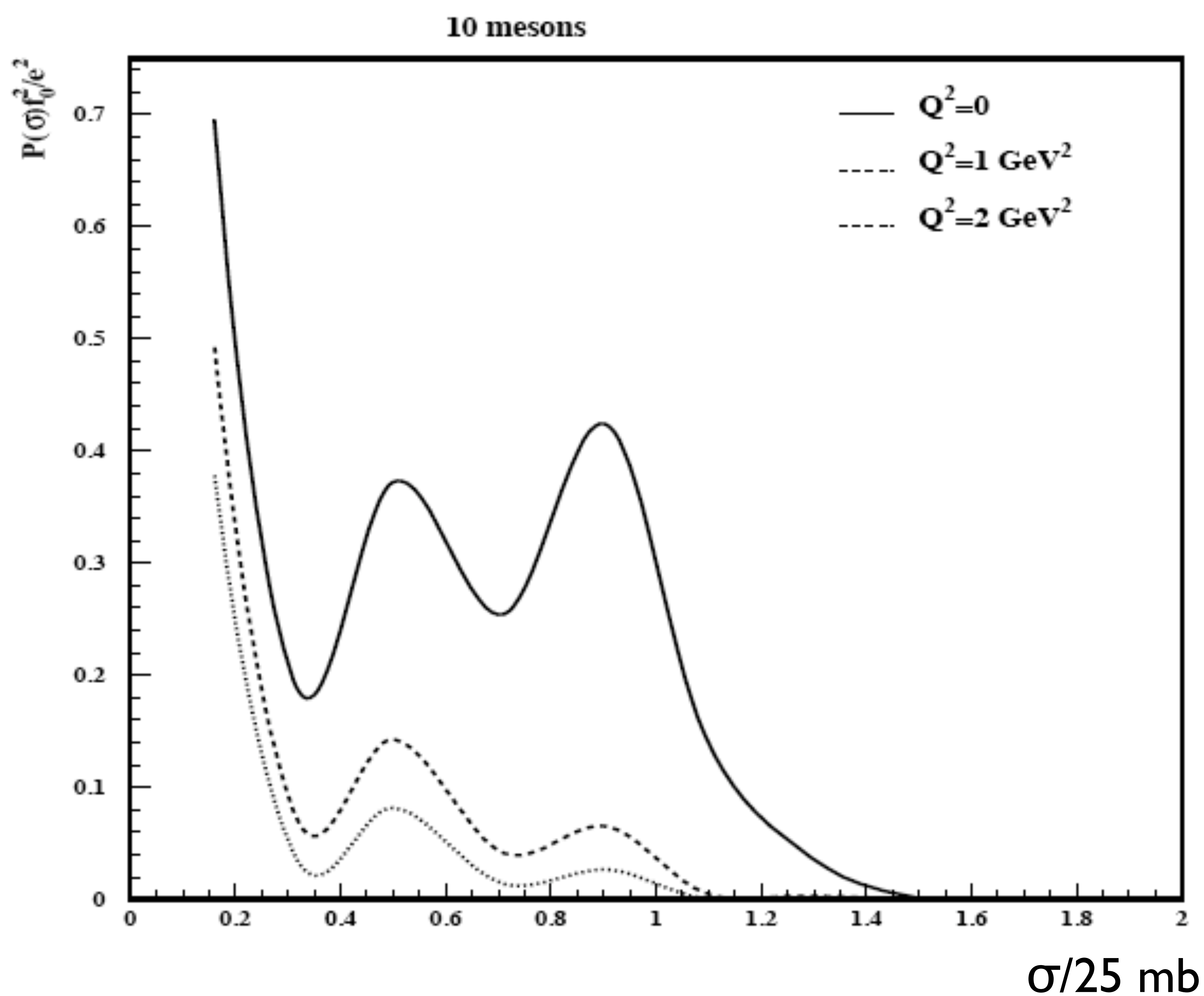




A- dependence for exclusive channel is reproduced

Color fluctuations explains cross section of coherent diffraction off nuclei (FMS93, ...)

For photons fluctuations are enhanced since $P_\gamma(\sigma) \propto 1/\sigma$ for small σ



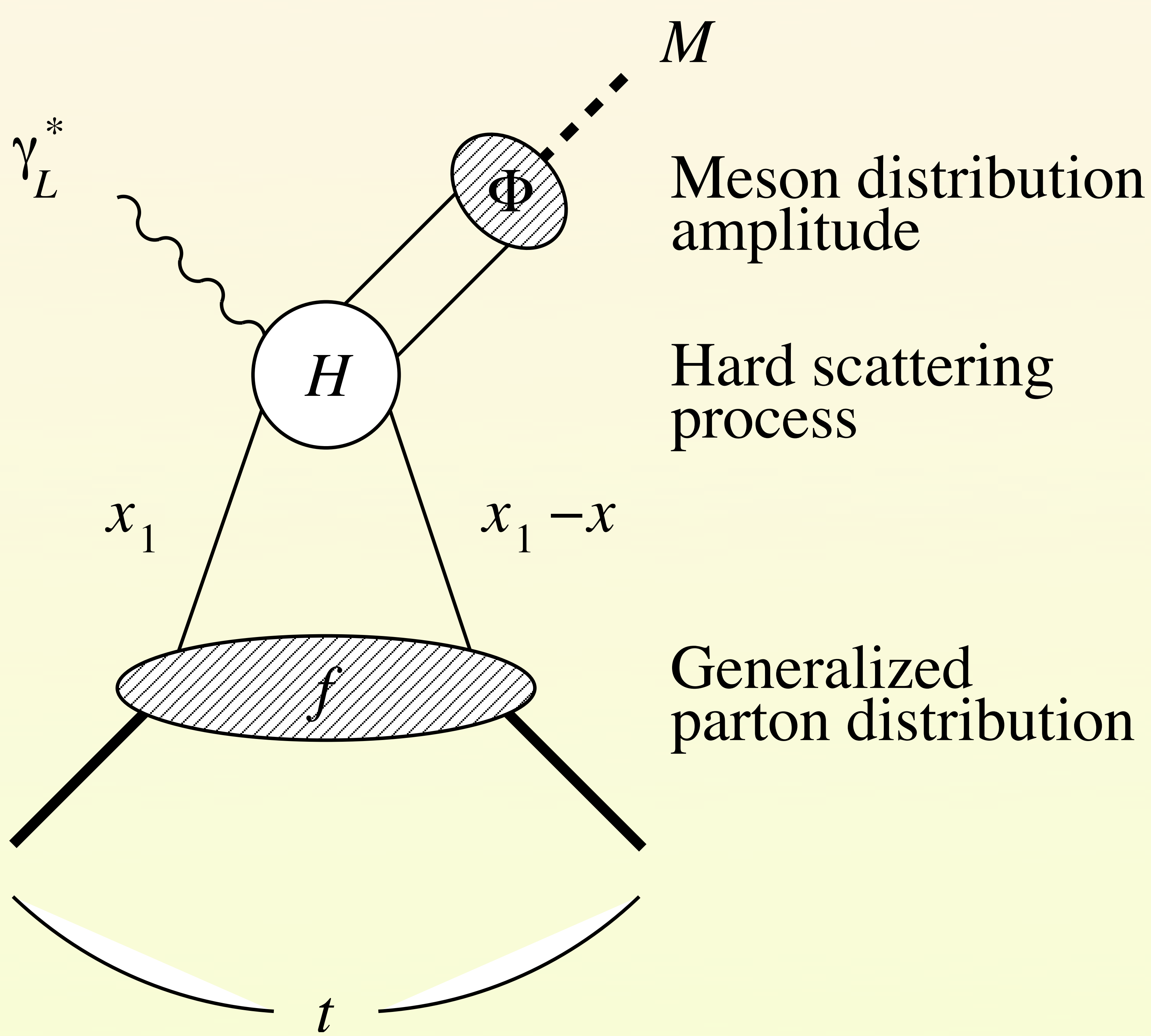
Coherent diffraction in $\gamma(\gamma^*)\, A \rightarrow M\, A$ mapping of the color fluctuations in photons, interplay between soft and hard contributions - looking CT configurations and SSC's. Example - are small mass $\pi^+\pi^-$ configurations interact with $\sigma \sim 2\sigma_{\pi N}$?

Delicate point: in γ^* case one measures sum of coherent and incoherent diffract

pQCD + vector meson contributions to $P_\gamma(\sigma)$

LF +Guzey +MS 98

High energy CT = QCD factorization theorem for DIS exclusive meson processes (Brodsky,Frankfurt, Gunion,Mueller, MS 94 - vector mesons,small x; general case Collins, Frankfurt, MS 97). The prove is based (as for dijet production) on the CT property of QCD not on closure like the factorization theorem for inclusive DIS.



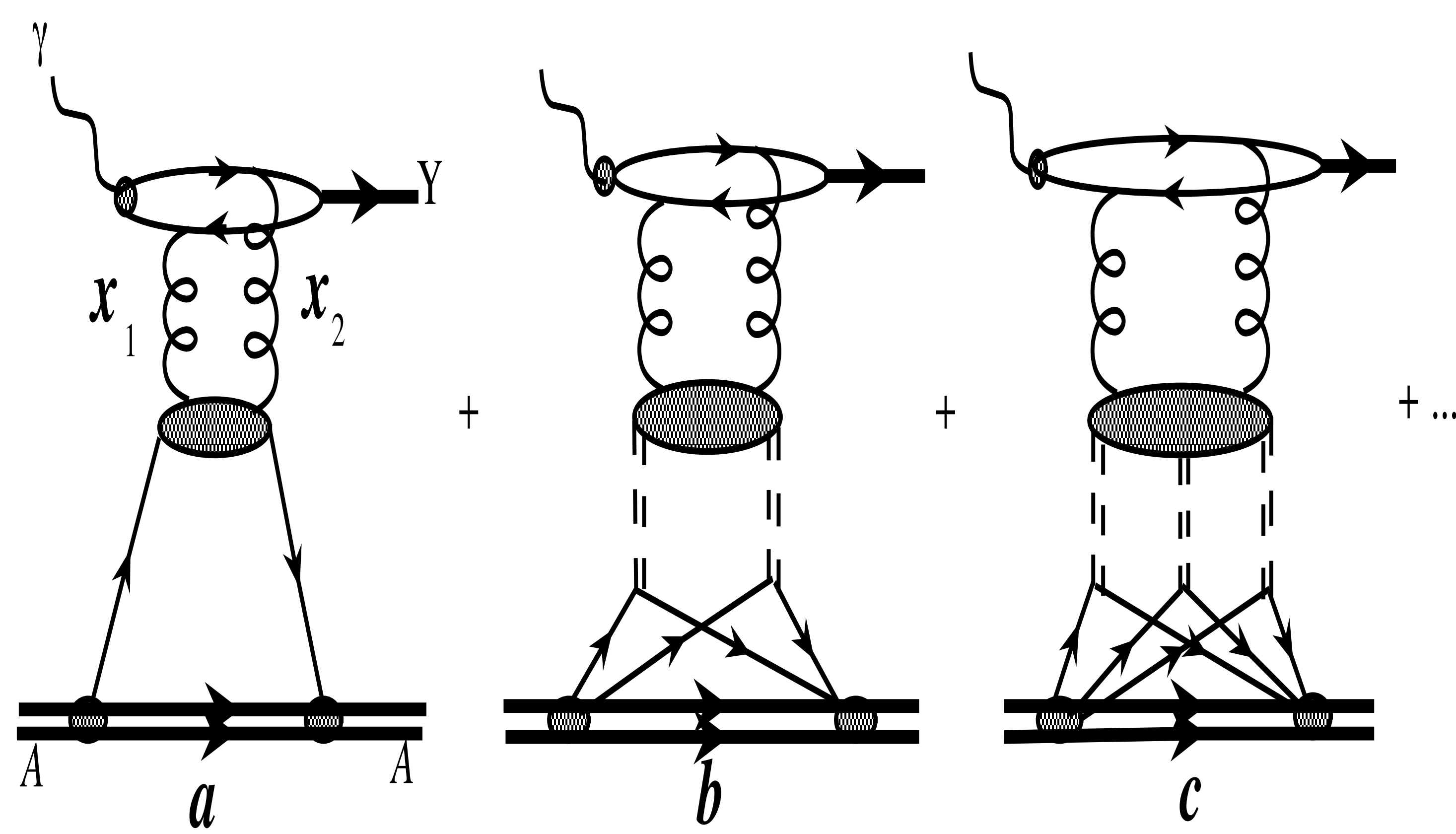
Coherent exclusive vector meson production in DIS (onium in photoproduction)

The leading twist prediction (neglecting small t dependence of shadowing)

$$\sigma_{\gamma A\to VA}(s) = \frac{d\sigma_{\gamma N\to VN}(s,t_{min})}{dt}\left[\frac{G_A(x_1,x_2,Q^2_{eff},t=0)}{AG_N(x_x,x_2,Q^2_{eff},t=0)}\right]^2 \int\limits_{-\infty}^{t_{min}} dt \left|\int d^2b dz e^{i\vec{q}_t\cdot\vec{b}} e^{iq_l z}\rho(\vec{b},z)\right|^2.$$

$$where\ x = x_1 - x_2 = m_V^2/W^2_{\gamma N} = (m_V^2+Q^2)W^2_{\gamma^* N}$$

Generalized/ QCD CT



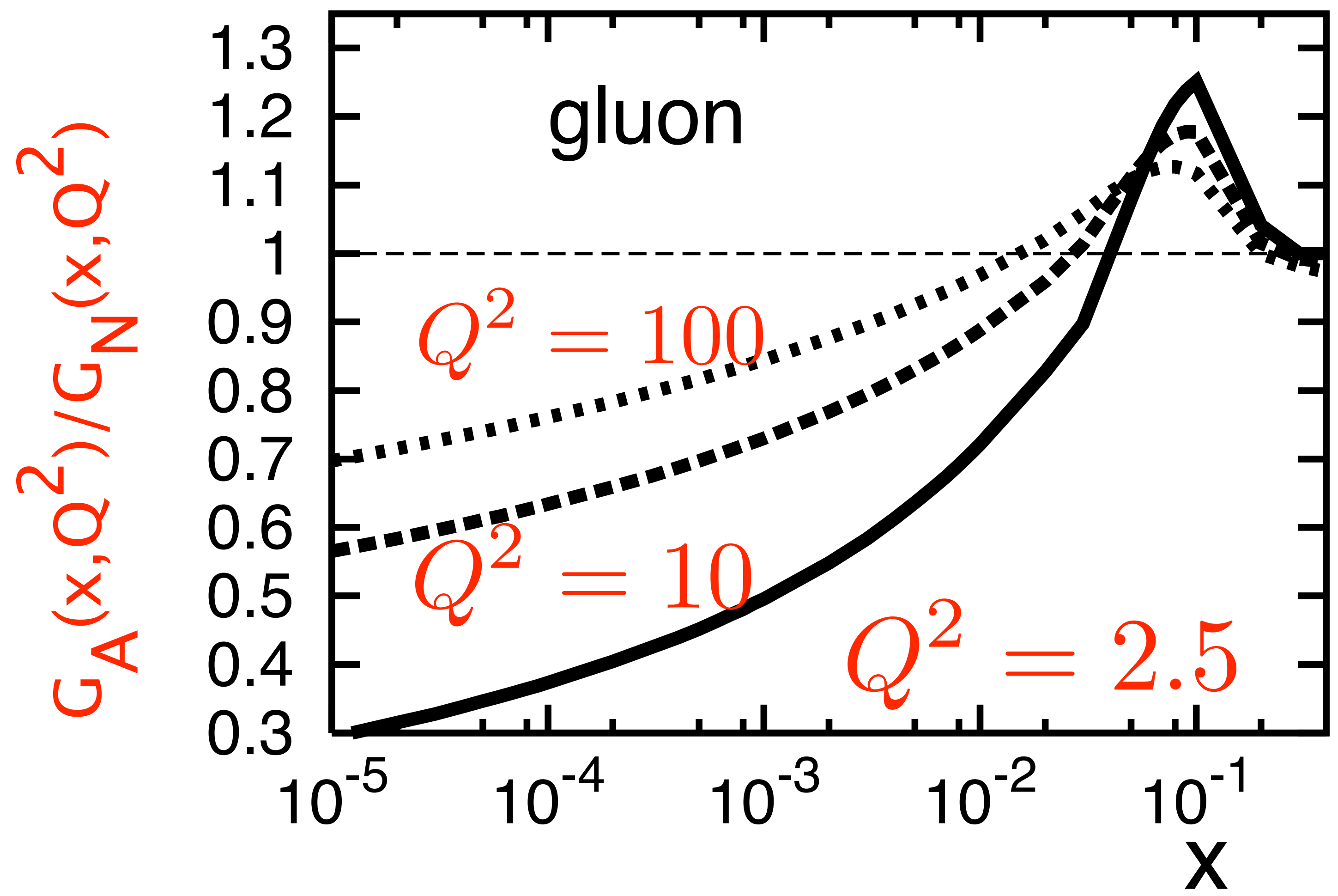
: High energy quarkonium photoproduction in the leading twist approximation.

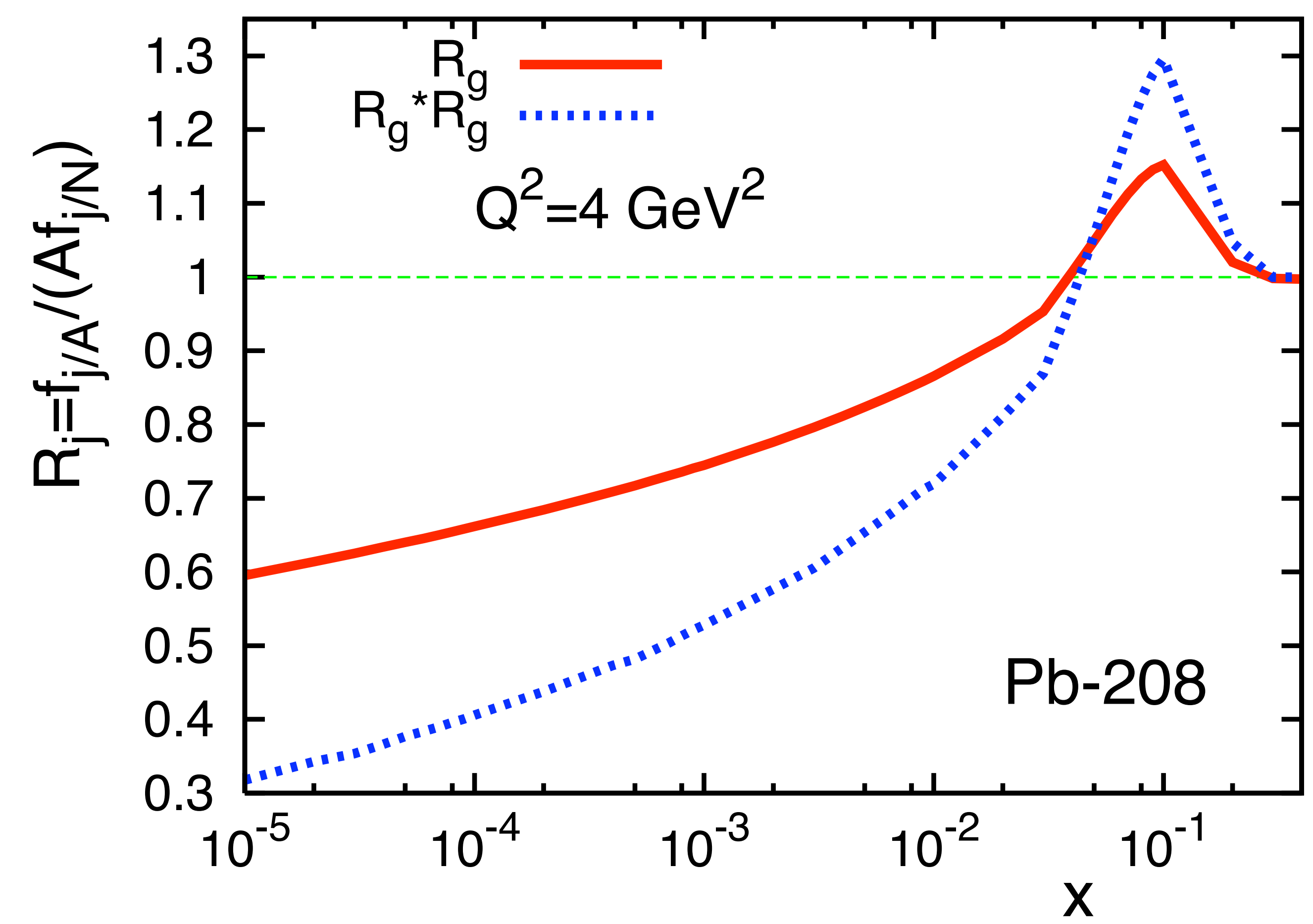
for small sizes - LT much larger screening than eikonal

$$\Downarrow$$

$$\frac{G_A(x_1,x_2,Q^2_{eff},t=0)}{G_N(x_1,x_2,Q^2_{eff},t=0)} \approx \frac{G_A((x_1+x_2)/2,Q^2_{eff},t=0)}{G_N((x_1+x_2)/2,Q^2_{eff},t=0)}$$

$$\frac{(x_1+x_2)_{J/\psi}}{2} \approx x;\ \ \frac{(x_1+x_2)_{\Upsilon}}{2} \approx x/2$$





factor > 2 shadowing effects for J/ψ for x< 10^{-2}
& for ϒ for x< 10^{-4}

In the kinematics of mEIC (x ≥ 0.01) mostly CT without significant shadowing - transition from the soft dynamics with Gribov-Glauber type screening to the CT regime without LT gluon shadowing.

Comment: What is doable and what is not in the studies of diffraction at eA collider with heavy nuclei

Four types of diffraction (small x: $1/2m_N x > 2R_A$)

☻ *Coherent diffraction - final nuclear state = A*

Dominates at small -t (below first minimum)

$\sigma \sim A^{4/3}$ (hard), $\sigma \sim A^{2/3}$ (soft),

☹ *Coherent excitation of nuclear levels - final nuclear state = A**

Dominates at small -t at and above the first minimum) $A^* \to A + \gamma(2\gamma)$...

Photon energy ~ few MeV in the nucleus rest frame; ~ 100 MeV in collider frame, average opening angle $1/\gamma_A \sim 10$ mrad for eRHIC. ~ 10% of the total coherent diffraction.

☻ *Incoherent diffraction - final nuclear state = A* with excitation energies above 8 MeV - decays with emission of neutrons - easy to detect*

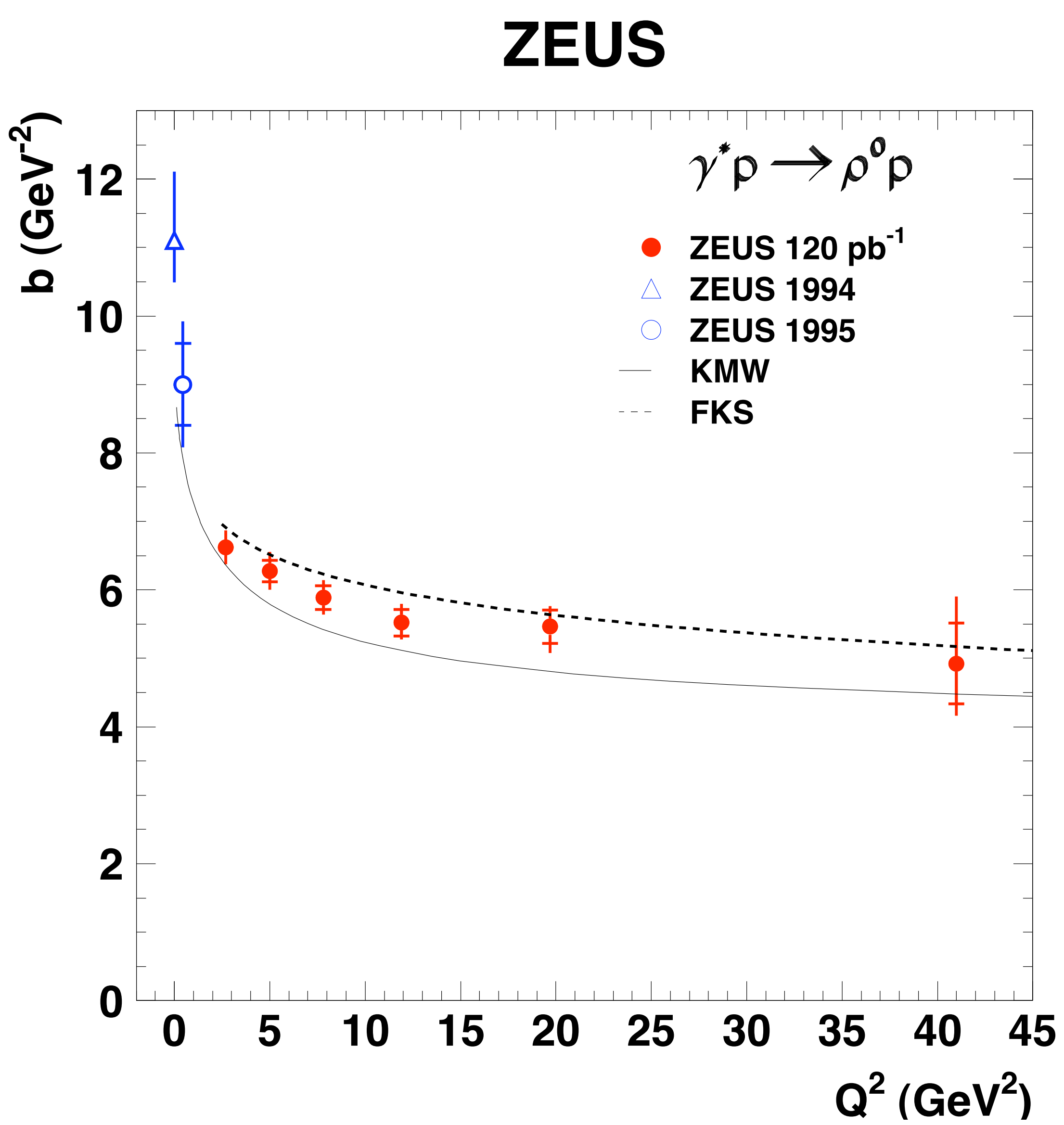
$\sigma \sim A$ (hard), $\sigma \sim A^{1/3}$ (soft) - the same change of power between "hard" and "soft" as for coherent case

$A^{1/3}$ larger effect than in $\gamma^* + A \to VM + A^*$ at x> 0.1

☞ *Inelastic incoherent diffraction - final nuclear state A* + hadrons - challenge to detect: 20% of incoherent diffraction for t~0; dominates for large t.*

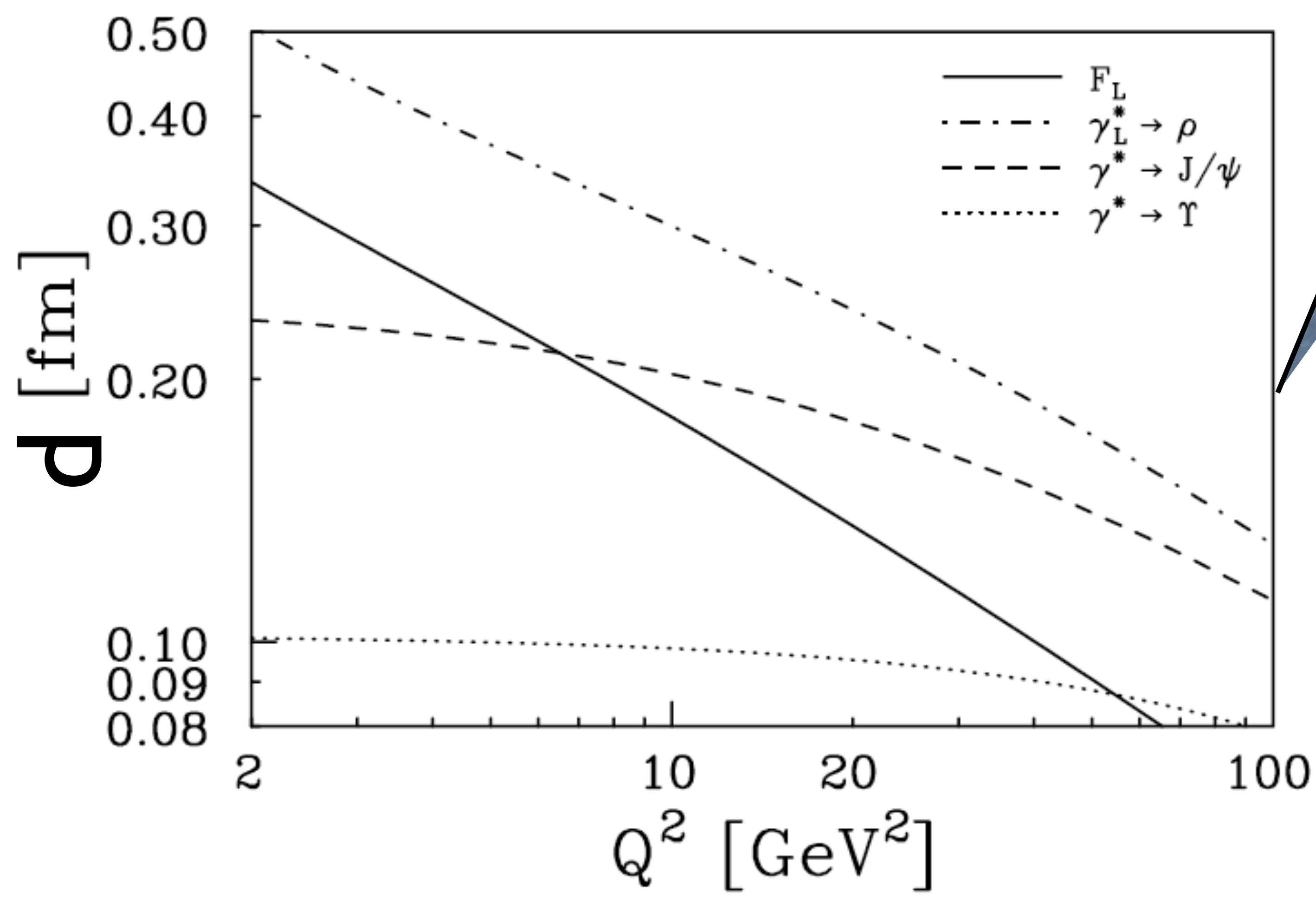
Example: light VM production in exclusive DIS

At what Q^2 squeezing becomes effective?



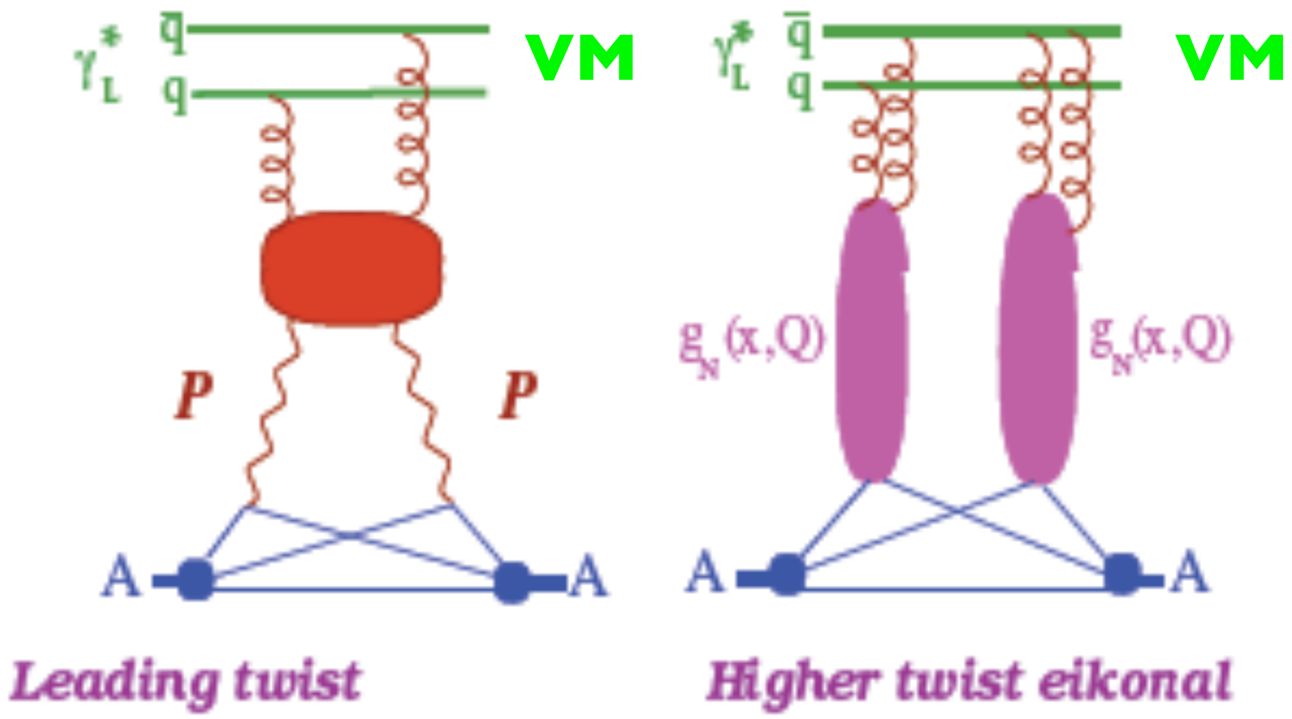
$$\frac{B(Q^2) - B_{2g}}{B(Q^2 = 0) - B_{2g}} \sim \frac{d^2(dipole)}{d_\rho^2}; \quad \frac{d^2(dipole)(Q^2 \geq 3\text{GeV}^2)}{d_\rho^2} \leq 1/2 \div 1/3$$

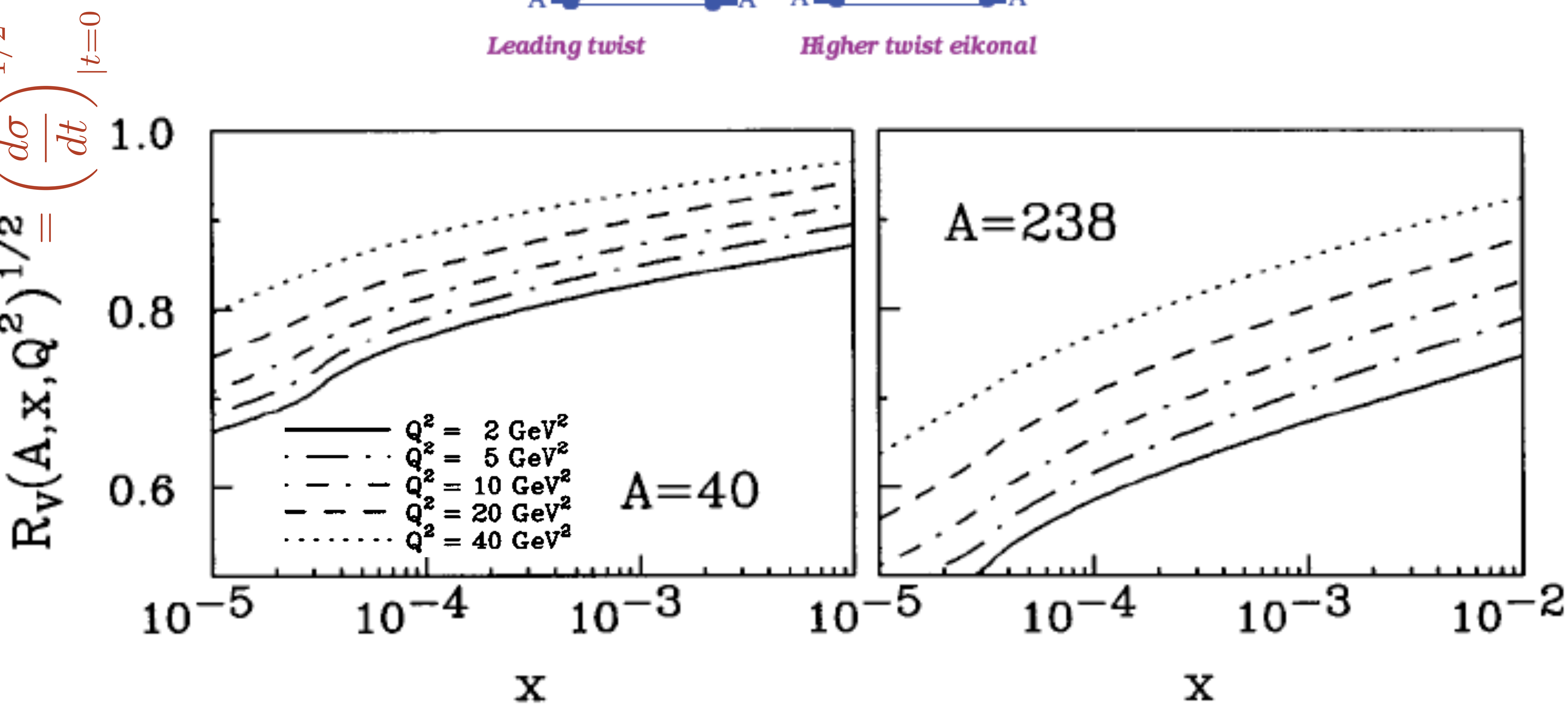
Convergence of B for ρ-meson electroproduction to the slope of J/ψ photo(electro)production - **direct proof of squeezing.**



Q^2 dependence of the dipole transverse size for VM production, FKS 95

Expect significant CT effects for meson production for $Q^2 \geq 3\text{GeV}^2$; HERMES - smaller squeezing for Q^2 3GeV^2? Energy dependence of squeezing due to increase of σ for small dipoles?





A-dependence of coherent ρ-meson production in dipole eikonal approximation - FKS95

General features of A-dependence of the coherent VM production : for fixed Q^2 - R_V decreases with decrease of x, for fixed x - R_V increases with Q^2

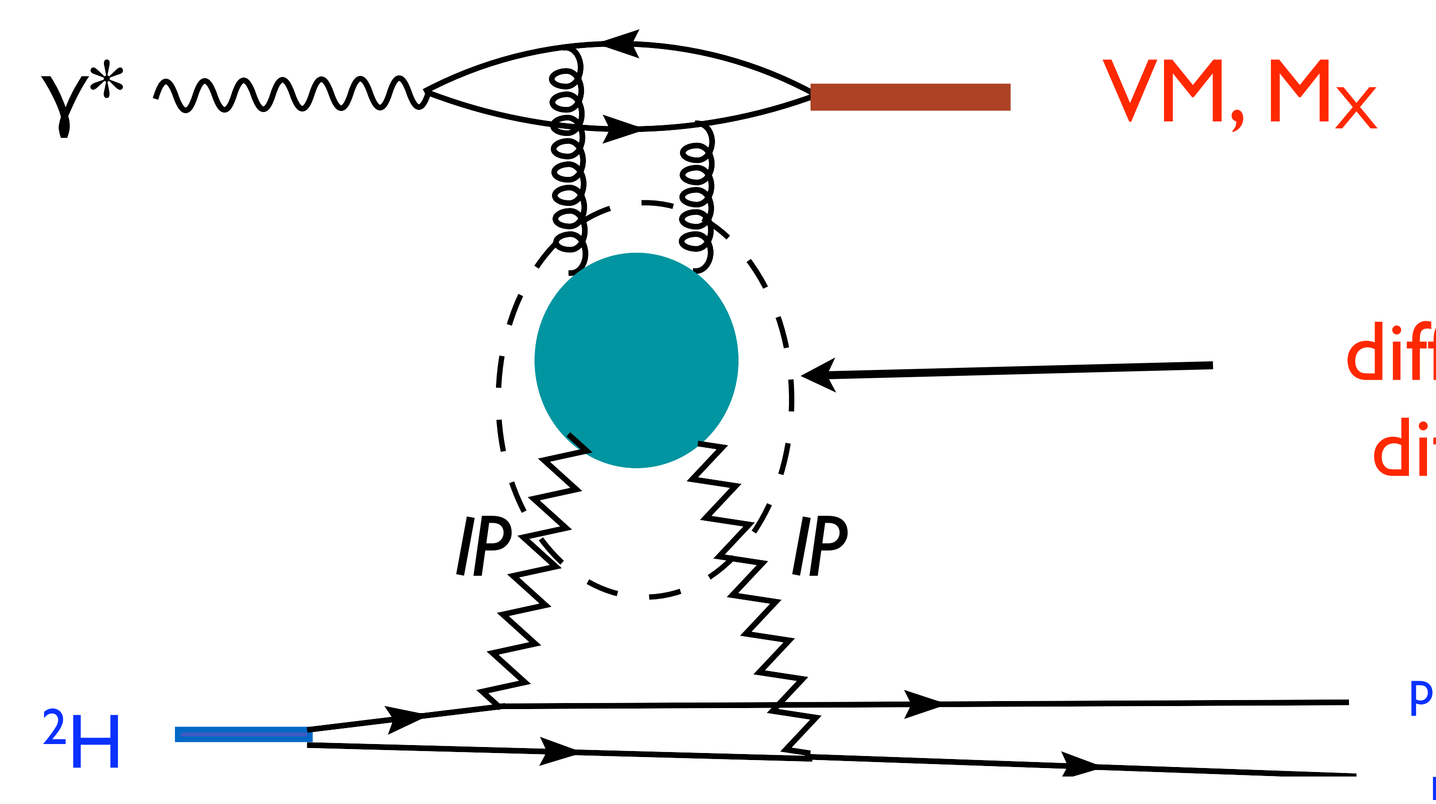
Precision studies of coherent dynamics with light nuclei: ^2H, ^3He, ^4He

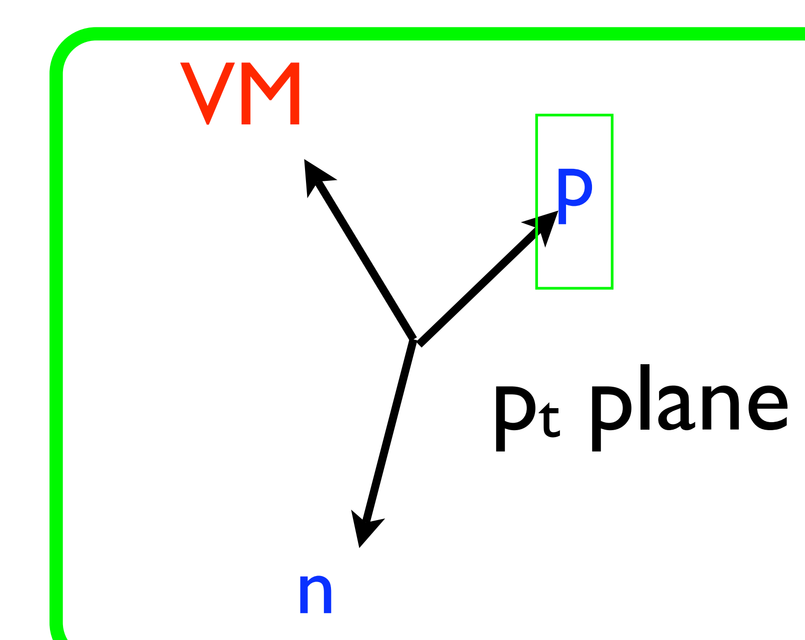
Advantages:

- ✔ *no excited bound states*
- ✔ *at mEIC: $l_{coh} > R_A$*
- ✔ *possible to perform details studies of the pattern of coherent interactions with two nucleons (triple coherent interactions are a small correction at mEIC anyway - Guzey talk*
- ✔ *runs with polarized ^2H or ^3He will be necessary for spin program*

Examples:

- Double scattering kinematics for scattering off ^2H (polarized ^2H will be an extra bonus)
  analog of $e^2H \rightarrow epn$ and $p^2H \rightarrow ppn$ rescattering
  four of the authors in the room)



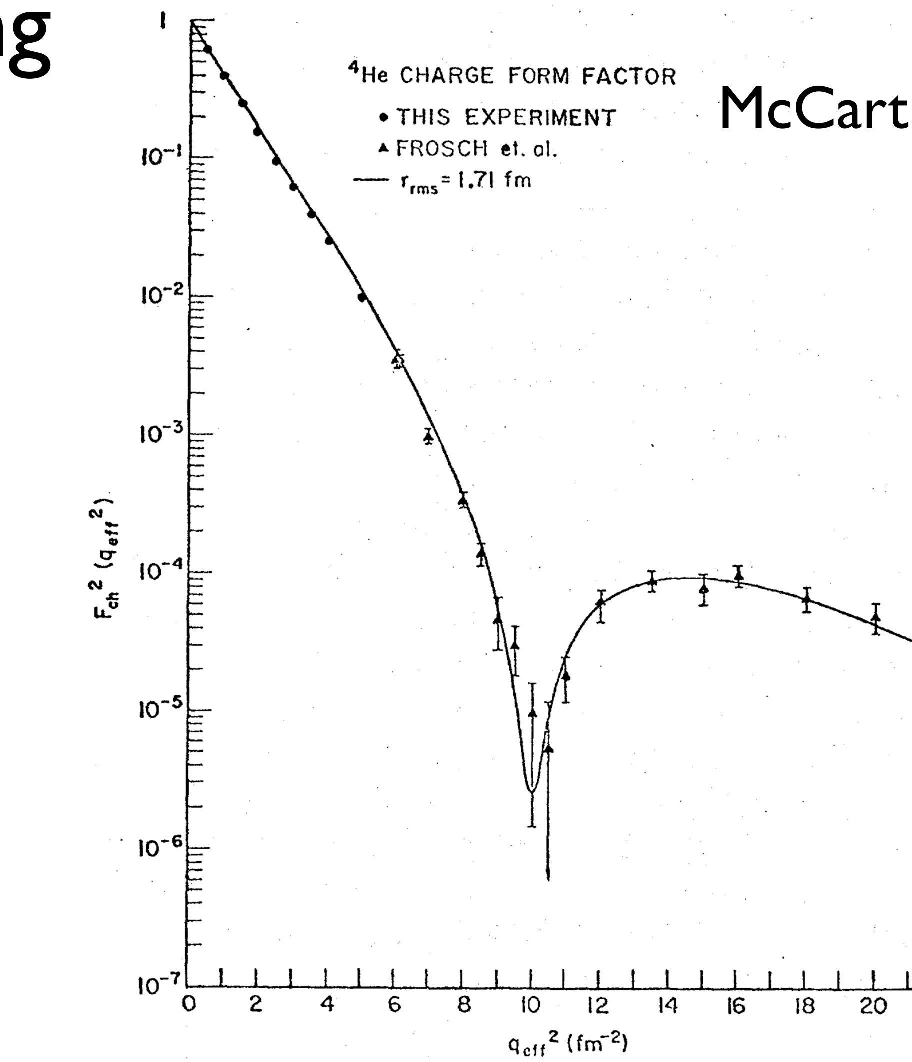


pp/ nn channel unique way to study IP - R interference

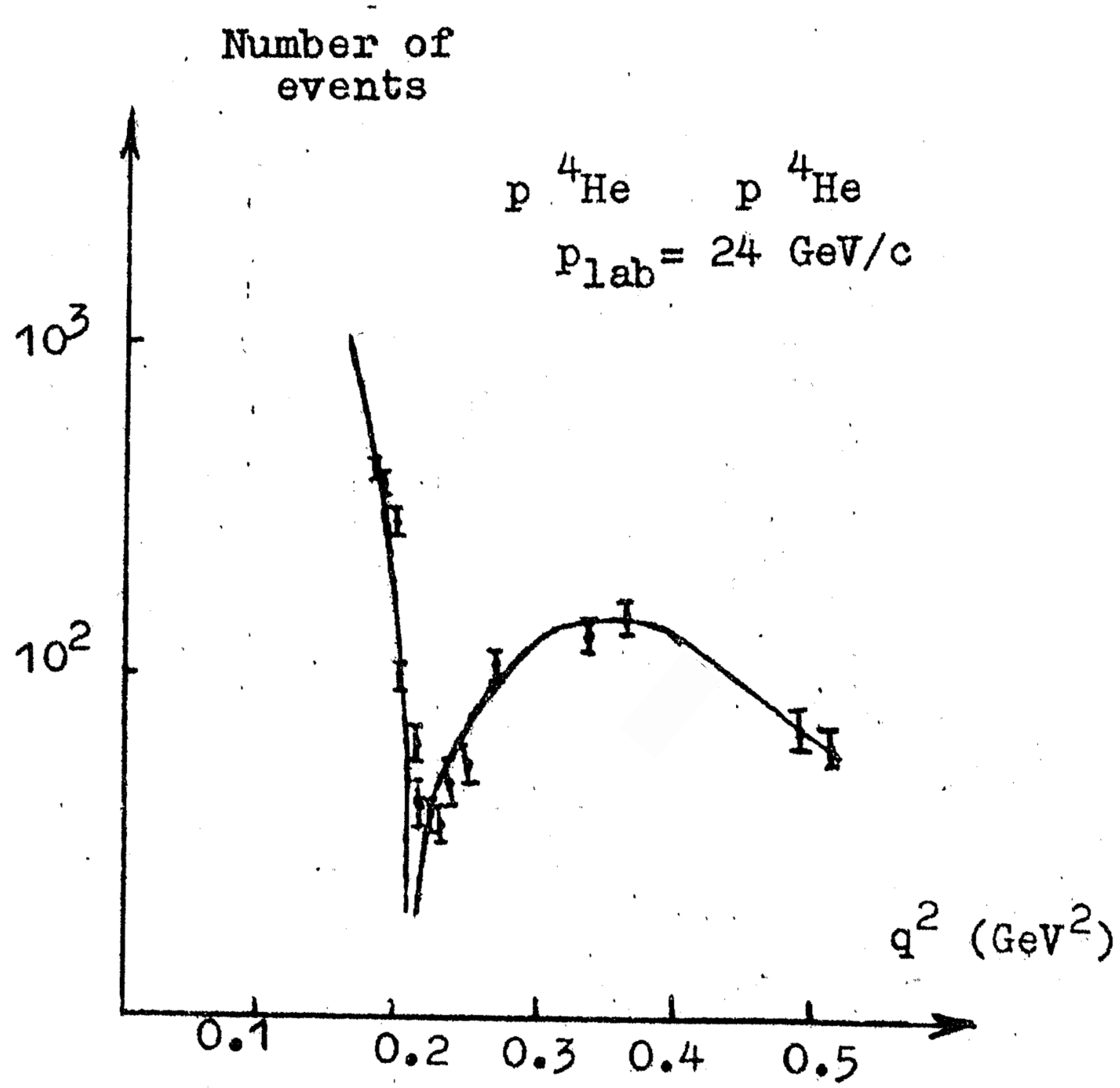
- Coherent scattering of ^{4}He. Simple nucleus with significant rescattering probability and negligible triple rescattering at to large -t.

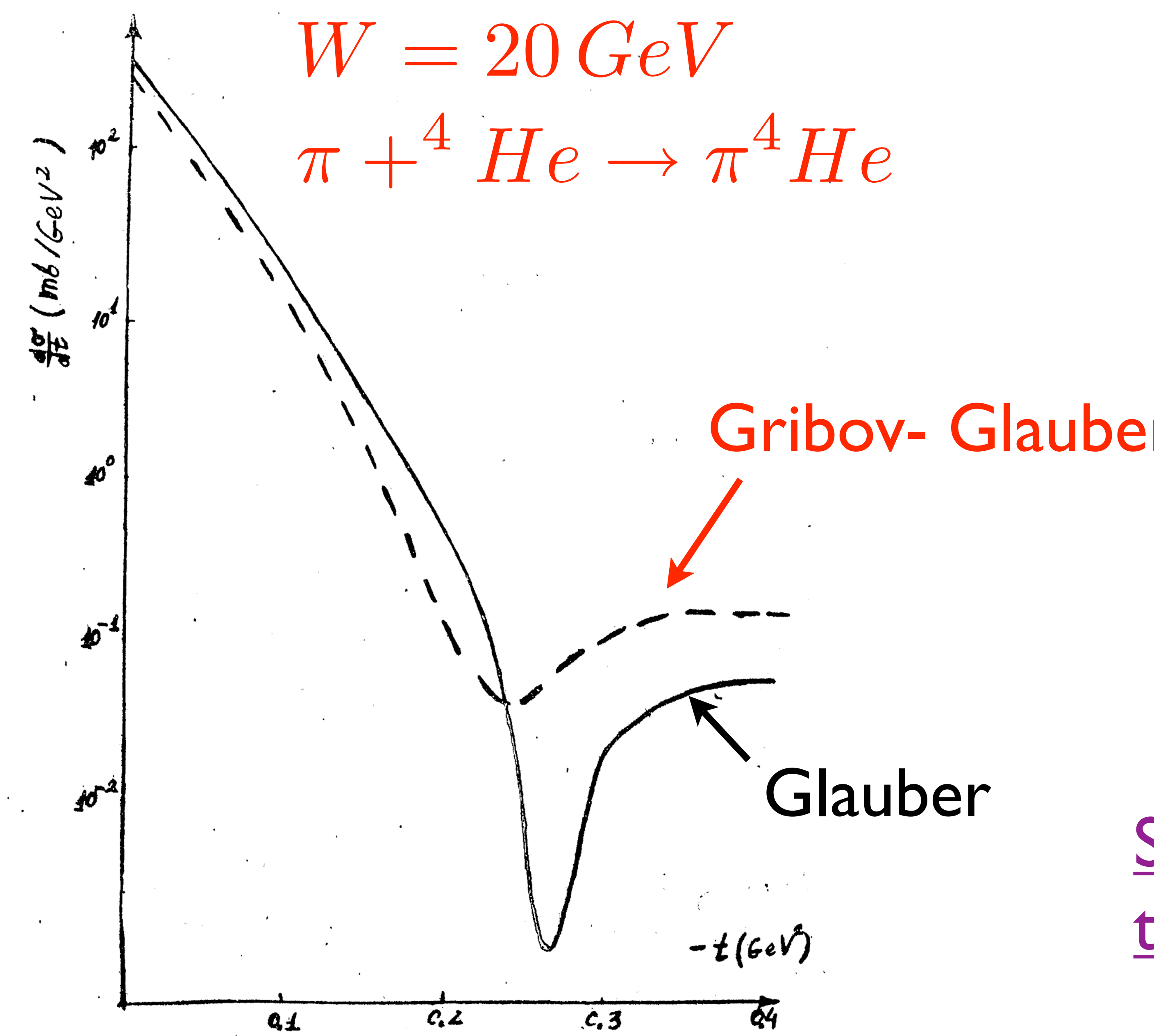
e.m. form factor goes through 0 at $-t \sim 0.4$ GeV^2

$\Rightarrow$ *strong sensitivity to double scattering starting at -t ~0.1 GeV^2*



McCarthy et al





Levin & MS 75

Strong sensitivity of the shape to the strength of double scattering

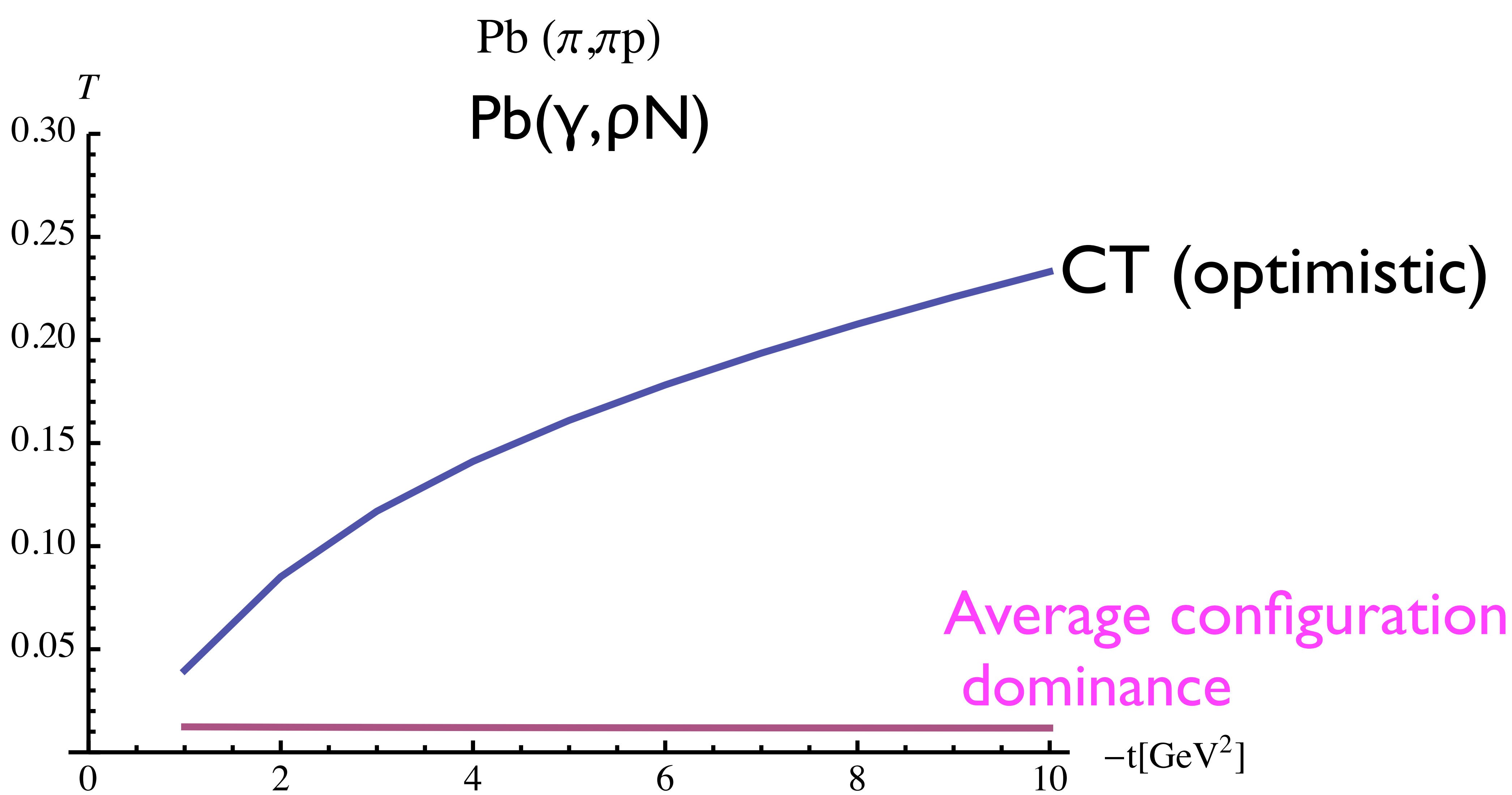
Other directions of study

☀ At what t squeezing occurs in elastic scattering like $\gamma + p \rightarrow \rho + p$?

If t is large enough we study pQCD interaction at large t.
Expectation - amplitude in this limit is ~ s ($\alpha_{eff}^{IP}(t)=1$) Blok, LF, MS 10

Consider $\gamma + A \rightarrow \rho + p + (A-1)^*$ $(p_t(\rho) + p_t(N) \leq k_F)$

Transparency ratio: $T = \sigma(\gamma + A \rightarrow \rho + p + (A-1)^*) / Z\sigma(\gamma + p \rightarrow \rho + p) >>$ Glauber value



It is likely that
$T(Pb(\gamma,\rho N)) > T(Pb(\pi,\pi N))$

Early squeezing - graduate shift of $<\sigma>$ for dominant configurations

Negligible effect from proton squeezing - fast expansion

G.Miller, MS

☀ Is recoil proton in somewhat squeezed state?

Consider $\gamma + A \rightarrow \rho + (N\pi) + (A-1)^*$ $(p_t(\rho) + p_t(N\pi) \leq k_F)$

$M_{N\pi}$ close enough to threshold

Transparency ratio: $T_{N\pi} = \sigma(\gamma + A \rightarrow \rho + N\pi + (A-1)^*) / Z\sigma(\gamma + p \rightarrow N\pi + p)$

$T_N > T_{N\pi}$????

Best to study with light nuclei where expansion is moderate.

☀ At what Q squeezing starts in the exclusive pion production at high energies?

Extend the Jlab experiment to larger energies where quark- antiquark pair is frozen.

If rates are high enough - extend to $x < 0.03$ where shadowing for valence quarks could be present. Note: for incoherent exclusive processes - soft →hard is a smaller effect at x> 0.1 due to small coherence length:

$$\sigma(x > 0.1) \propto A^{2/3} \to A; \quad \sigma(x < 0.01) \propto A^{1/3} \to A$$

☀ QCD dynamics near threshold: $\gamma^* + p \to \underbrace{\pi^+ \pi^0}_{\text{near threshold}} + n$

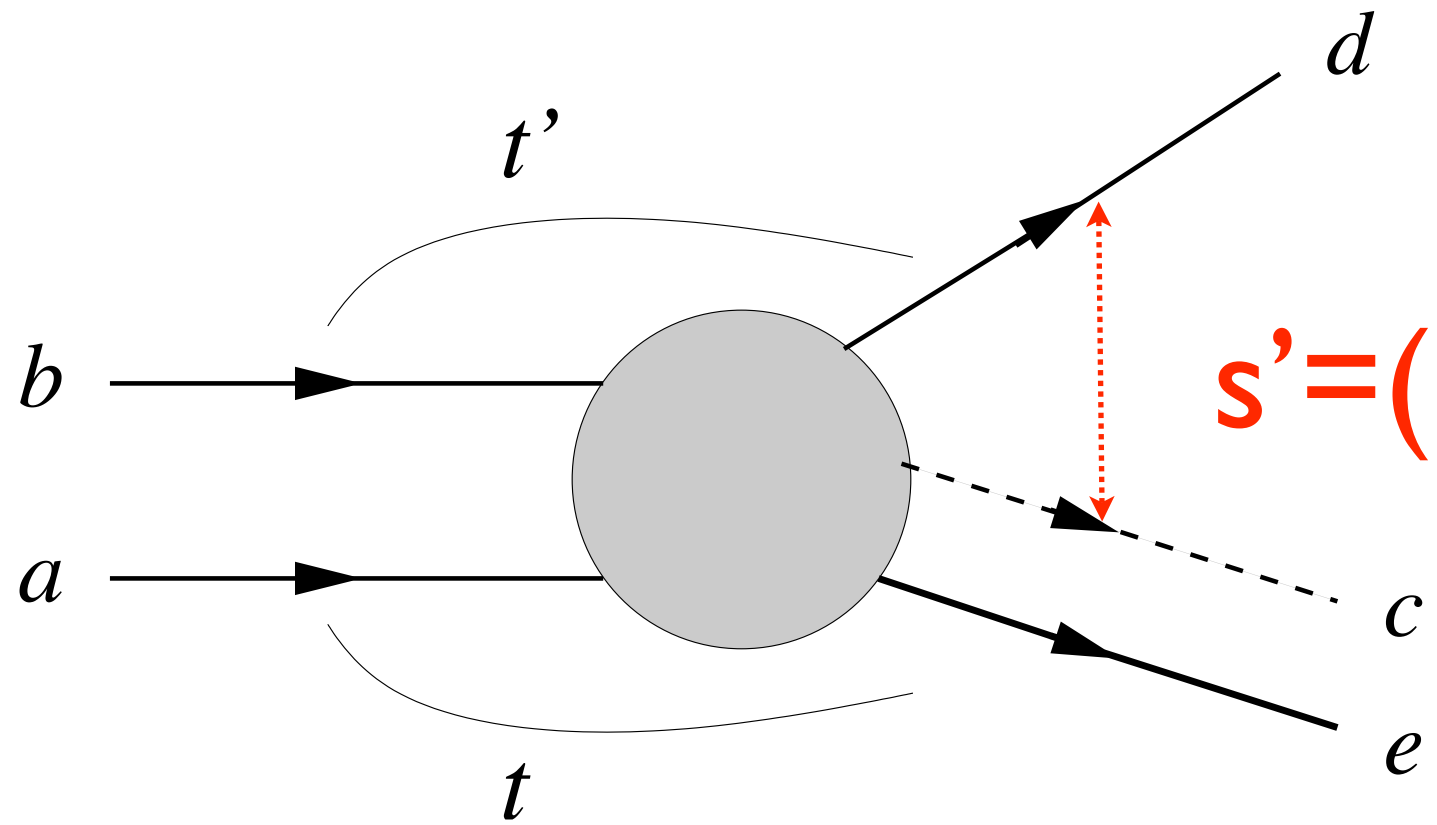
☞ $T(\gamma^* + A \to \pi^+ \pi^0 + A^*) \approx T(\gamma^* + A \to \rho^+ + A^*)$

if both processes via quark-antiquark pair with the nucleus

☞ $T(2\pi) < T(\pi)$ if early formation

☀ New type of hard hadronic processes - *branching exclusive processes* of large c.m. angle scattering on a "cluster" in a target/projectile (MS94)

to study both CT of $2 \to 2$ and hadron GPDs



$s' = (p_d + p_c)^2$

Limit:

$-t' >$ few GeV^2, $-t'/s' \sim 1/2$

$-t = const \sim 0$

➡ $s'/s = y < 1$,

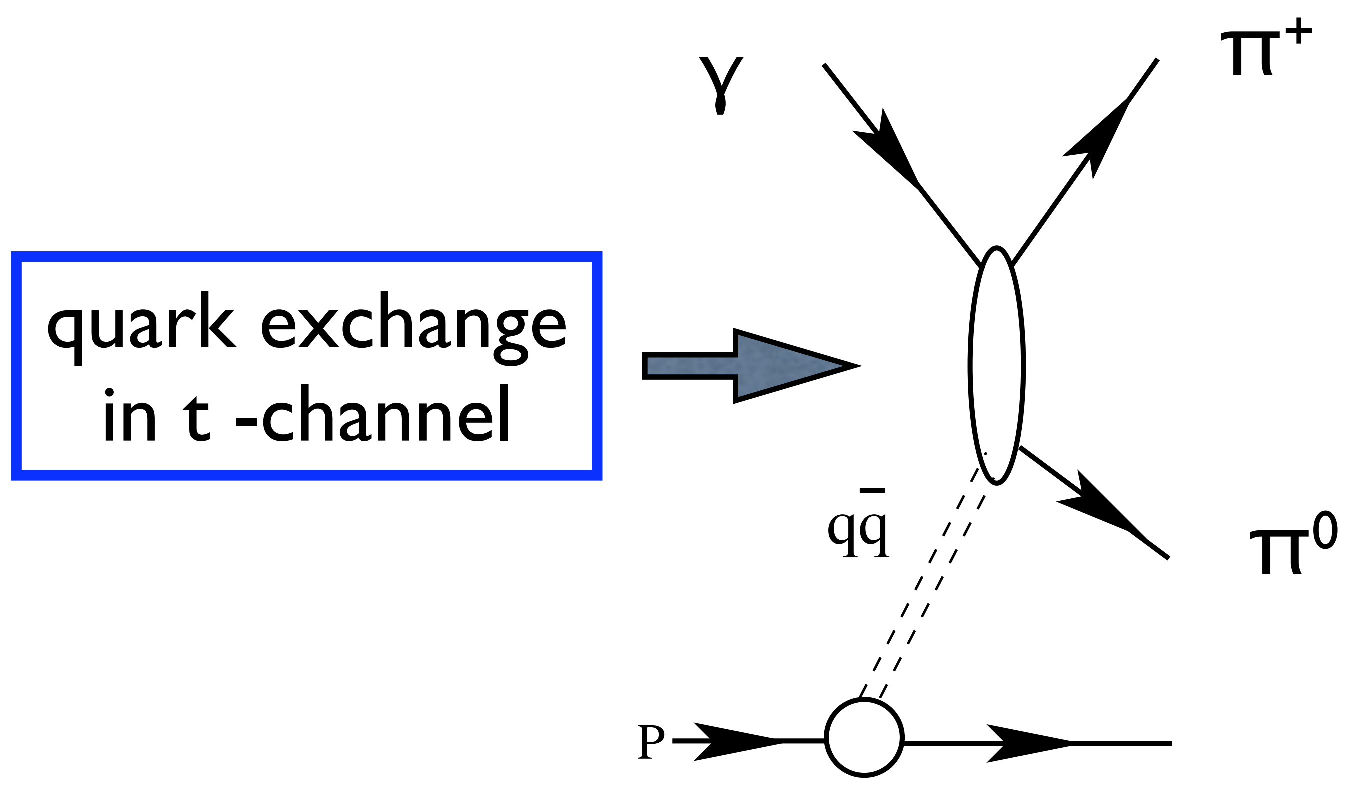
$t_{min} = [m_a^2 - m_b^2/(1-y)]y$

Two recent papers: Kumano, MS, and Sudoh PRD 09;
Kumano &MS arXiv:0909.1299, Phys.Lett. 2010

For e p collider possible processes

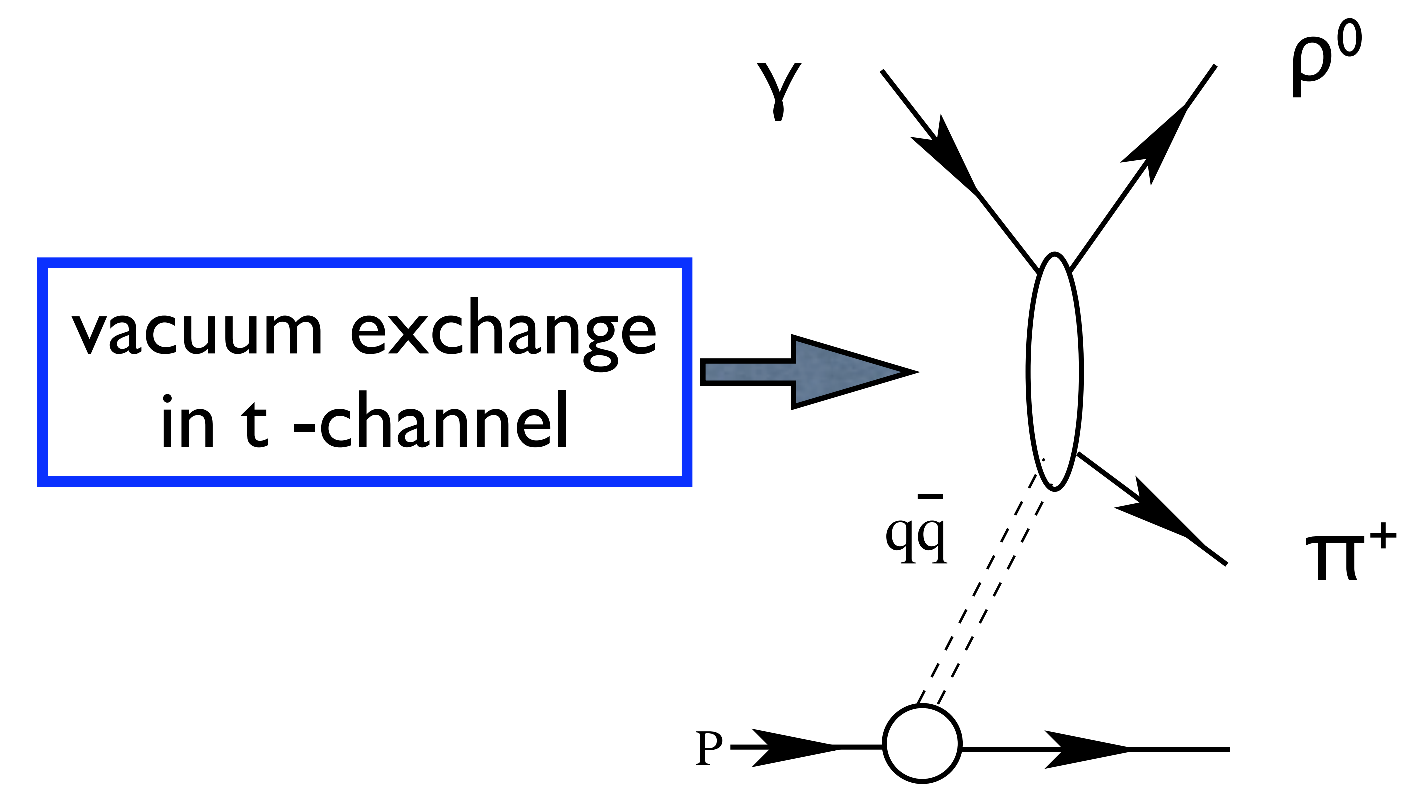
$\gamma\ (\gamma^*) + p \rightarrow \underbrace{\pi^+\pi^0}\ n$

current fragmentation



$\gamma\ (\gamma^*) + p \rightarrow \rho^0\ \underbrace{\pi^+ n}$

nucleon fragmentation



For e A collider examples of possible processes

$\gamma^* + A \rightarrow \underbrace{\pi^+\pi^0}\ A^*$

current fragmentation

$\gamma^* + A \rightarrow \rho^0\ \underbrace{\pi^+ A^*}$

nuclear fragmentation

rapidity interval between π^+ and A
regulates formation time and hence CT!!!

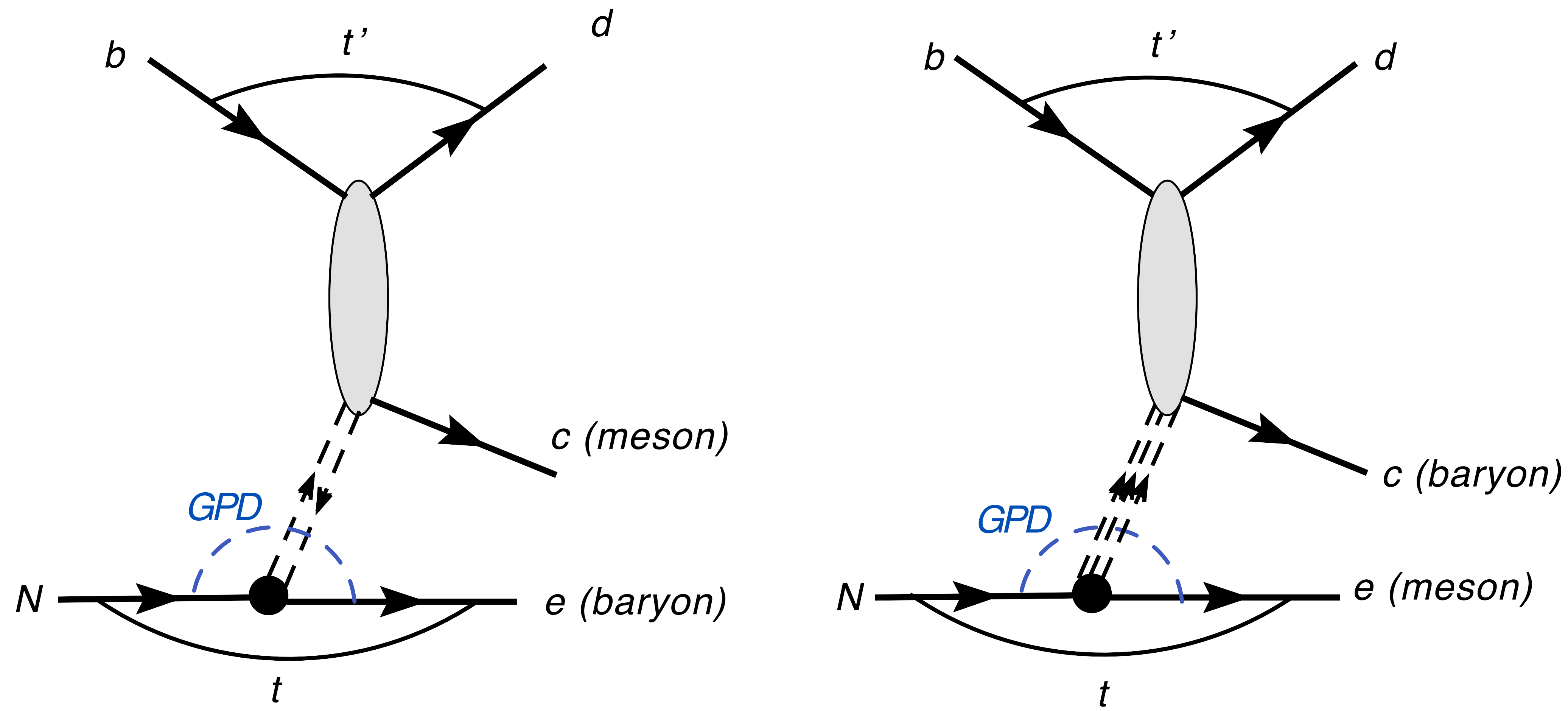
$2 \to 3$ branching processes:

- test onset of CT for $2 \to 2$ avoiding diffusion effects

For example at what s',t process $\gamma\pi \to \pi\pi$ is due to scattering in small configurations, when point -like component of photon starts to dominate.

- measure transverse sizes of b, d,c
- measure cross sections of large angle (γ)pion - pion (kaon) scattering
- probe 5q in nucleon and 4q in mesons
- measure GPDs of nucleons, photons, and mesons(!)
- measure pattern of freezing of space evolution of small size configurations

Factorization:



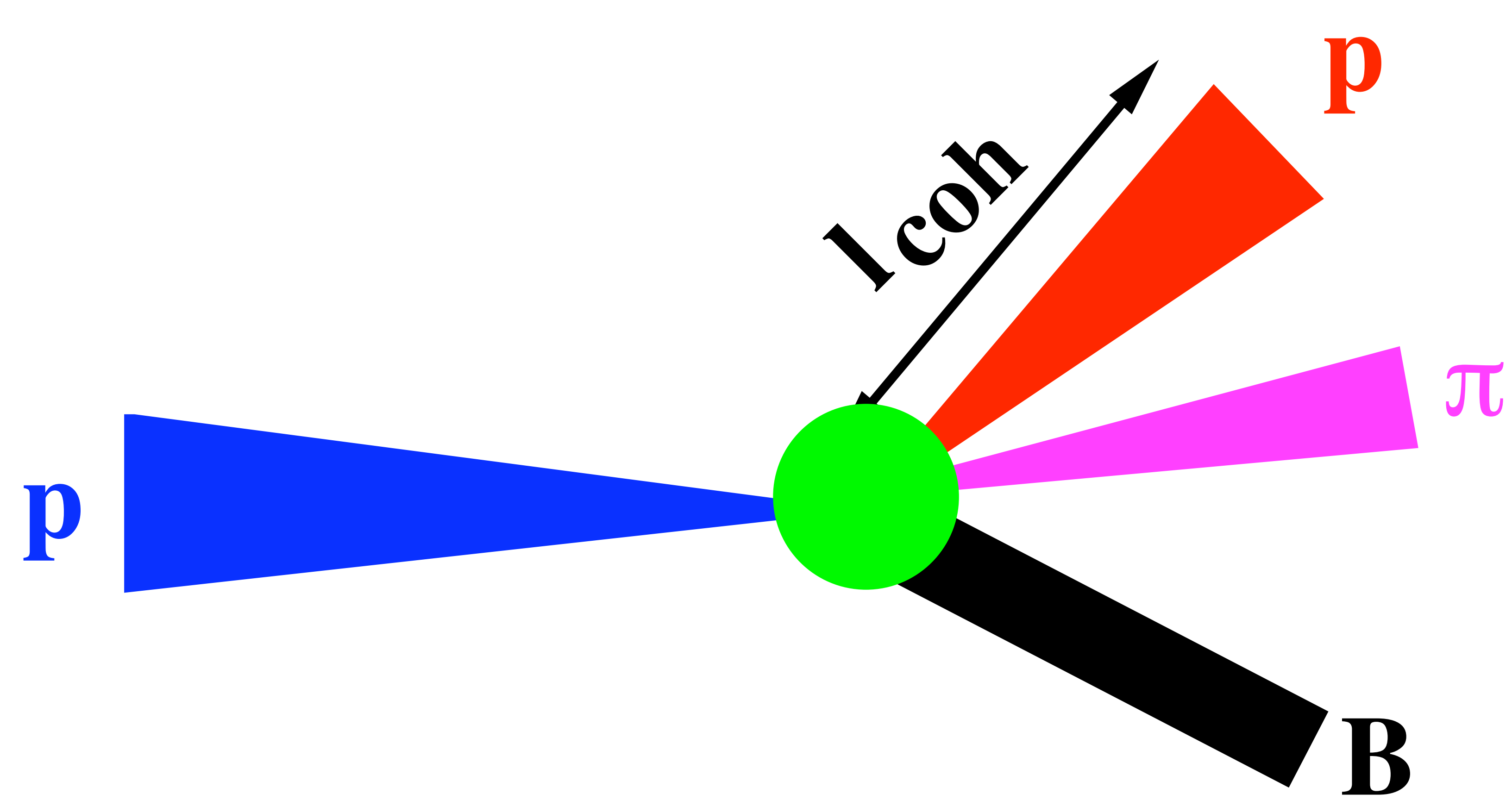
If the upper block is a hard (2 →2) process, "b","d","c" are in small size configurations as well as exchange system (qq, qqq). Can use CT argument as in the proof of QCD factorization of meson exclusive production in DIS (Collins, LF, MS 97)

$$\Downarrow$$

$$\mathcal{M}_{NN\to N\pi B} = GPD(N \to B) \otimes \psi_b^i \otimes H \otimes \psi_d \otimes \psi_c$$

Minimal condition for factorization:

$$l_{coh} > r_N \sim 0.8 \text{ fm}$$



Time evolution of the 2 → 3 process

$$l_{coh} = (0.4 \div 0.6 \text{ fm}) \cdot p_h/(\text{GeV}/c)$$

$$p_c \geq 3 \div 4 \text{ GeV}/c, \quad p_d \geq 3 \div 4 \text{ GeV}/c$$

$$p_b \geq 6 \div 8 \, \text{GeV}/\text{c}$$

trivially satisfied for EIC kinematics

How to check that squeezing takes place and one can use GPD logic?

Use as example process $\gamma A \to \pi^- \pi^- A^*$

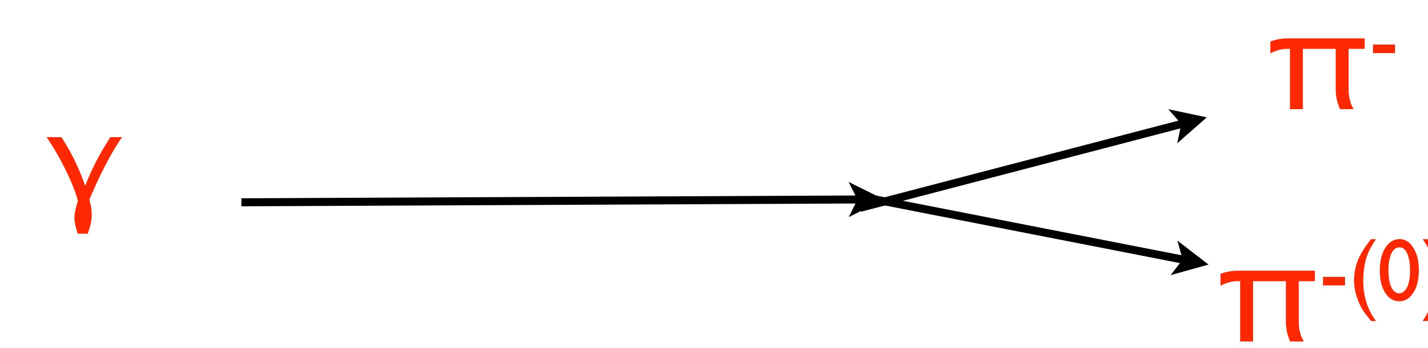
consider the rest frame of the nucleus

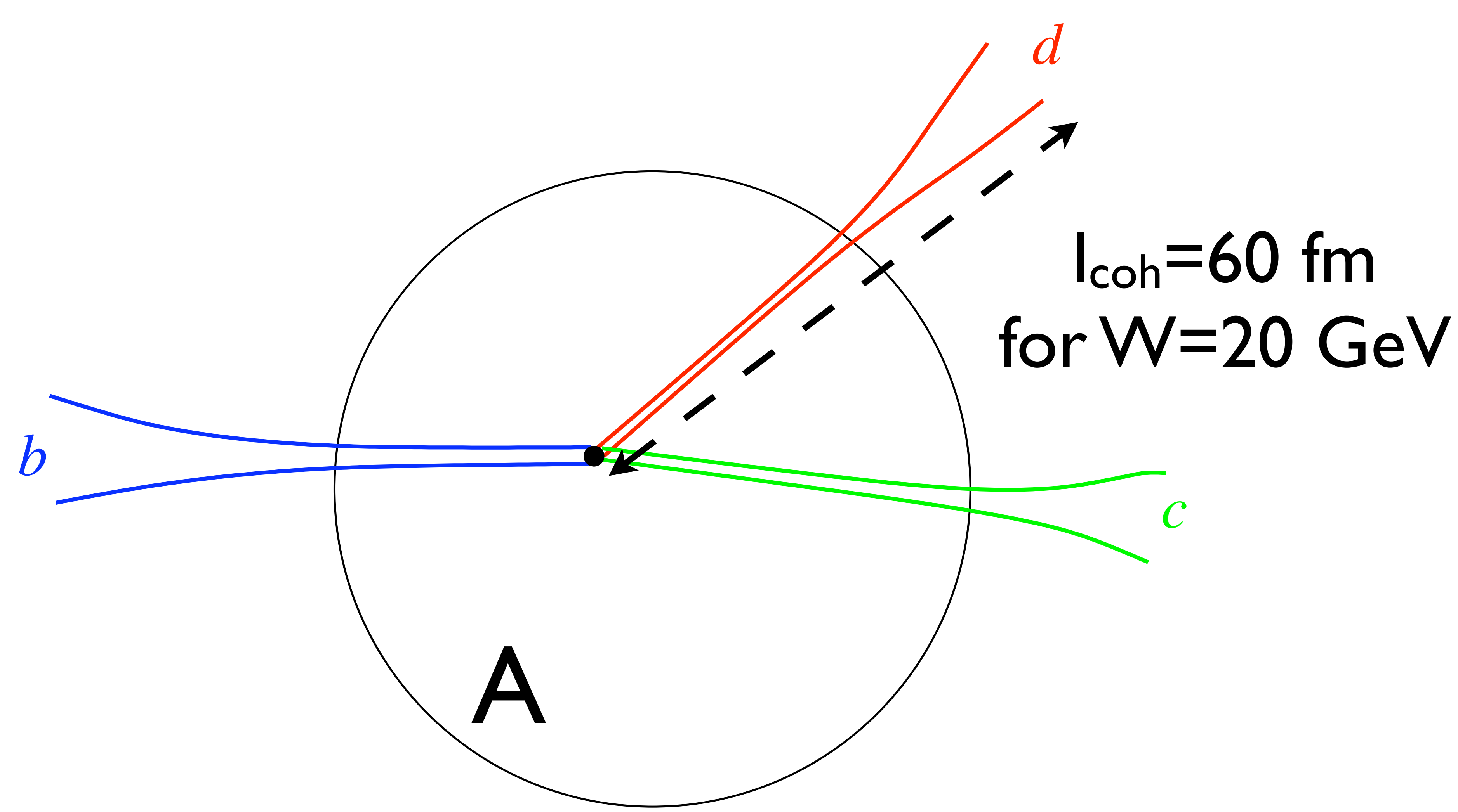
Obvious analog for pion beams $\pi^- \to \pi^- \pi^-$

- COMPASS 190 GeV data on tape
- Early data from FNAL

$p_f(\pi) = p_\gamma/2$, vary $p_{ft}(\pi) = 1 - 2$ GeV/c;

$p_{ft}(\pi^-) + p_{ft}(\pi^{-(0)}) \sim 0$



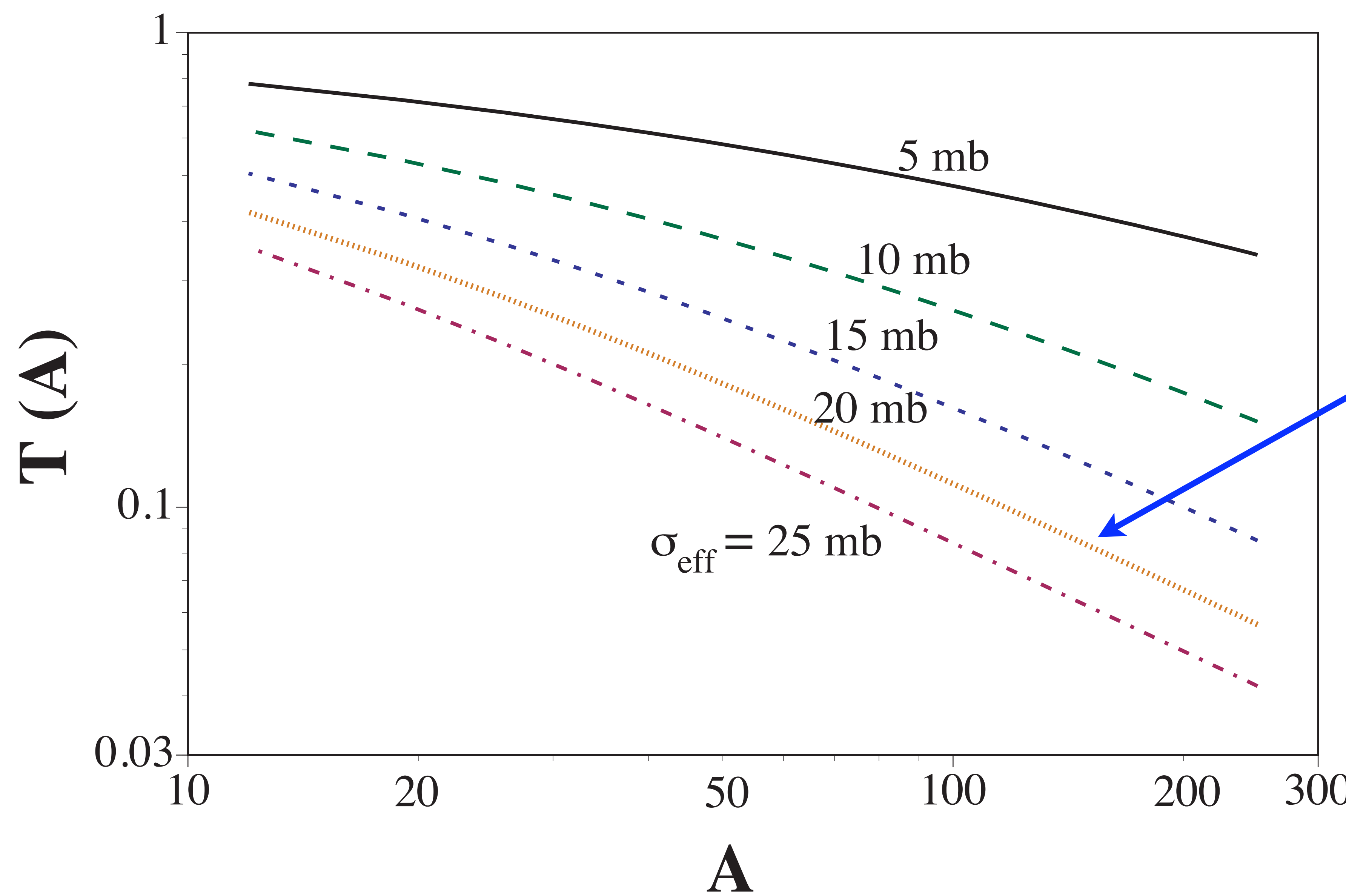


Branching (2→3) processes with nuclei - freezing is 100% effective for $p_{inc} > 100$ GeV/c - study of one effect only - size of fast hadrons

$$T_A = \frac{\frac{d\sigma(\gamma A \to \pi^- \pi^{-(0)} A^*)}{d\Omega}}{Z\frac{d\sigma(\gamma p \to \pi^- \pi^{-(0)} n)}{d\Omega}} \qquad T_A(\vec{p}_b, \vec{p}_c, \vec{p}_d) = \frac{1}{A}\int d^3r \rho_A(\vec{r}) P_b(\vec{p}_b, \vec{r}) P_c(\vec{p}_c, \vec{r}) P_d(\vec{p}_d, \vec{r})$$

where $\vec{p}_b, \vec{p}_c, \vec{p}_d$ are three momenta of the incoming and outgoing particles b, c, d; ρ_A is the nuclear density normalized to $\int \rho_A(\vec{r}) d^3r = A$

$$P_j(\vec{p}_j, \vec{r}) = \exp\left(-\int_{\text{path}} dz\, \sigma_{\text{eff}}(\vec{p}_j, z)\rho_A(z)\right)$$



Large effect even if the pion radius is changed just by 20%

If there are two scales in pion (Gribov) - steps in $T(k_t^\pi)$ as a function of k_t^π

If squeezing is large enough can measure quark- antiquark size using dipole - nucleon cross section which I discussed before

$$\sigma(d,x) = \frac{\pi^2}{3}\alpha_s(Q^2_{eff})d^2\left[xG_N(x,Q^2_{eff}) + \frac{2}{3}xS_N(x,Q^2_{eff})\right]$$

Discussed processes will allow

- to discover the pattern of interplay of large and small transverse distance effects (soft and hard physics) in wide range of the processes including elastic scattering, large angle two body processes
- measure a variety of GPDs including GPDs of photon
- compare wave function of different mesons
- map the space-time evolution of small wave packets at distances $1 < z < 6$ fm
- test the role of chiral degrees of freedom in hard interactions