



**Color coherence with and in nuclei - theory,  
observations, directions for further studies**

**Mark Strikman, PSU**

“In-Medium Effects in Hadronic and Parton  
Systems” Obergurgl, February 2011

based on research we started in 1980 in collaboration with  
L.Frankfurt, and later also with G.Farrar, M.Zhalov, G.Baym,  
B.Blättel, G.Miller, M.Sargsian, L.Gerland, S.Kumano and  
several other people

# Outline



*Introduction - from 1D to 3D picture of hadrons*



*Color coherence and QCD factorization theorems*



*Discovery of high energy color transparency (CT) in  $\pi A \rightarrow 2 \text{ jets} + A$*



*2  $\rightarrow$  3 branching processes: new direction in probing GPDs and CT*



*CT potential of PANDA*



*EMC effect and color coherence - very briefly*



*Conclusions*

*Challenge of high energy QCD - to understand the wave functions of hadrons and hadron interactions in their complexity.*

In quantum mechanics - consider deuteron - in principle the task of measuring wave function (WF) is simple: *measure form factor - take Fourier transform - determine WF*

Landau and Peierls - measurement of the wave function is impossible since the use of the higher energy probe with a large momentum transfer leads to production of pions and localization at the distance scale below  $1/m_\pi$  is impossible - seemed correct before discovery of Bjorken scaling.

*First step in QCD - determination of the longitudinal momentum distribution - parton densities - QCD theorems for the inclusive cross sections - proofs based on closure.*

**Second step:** QCD factorization theorems for exclusive processes involving scattering or production of hadrons:

$\gamma^* + N \rightarrow \gamma + N(\text{baryonic system})$  D.Muller 94 et al, Radyushkin 96, Ji 96, Collins & Freund 98

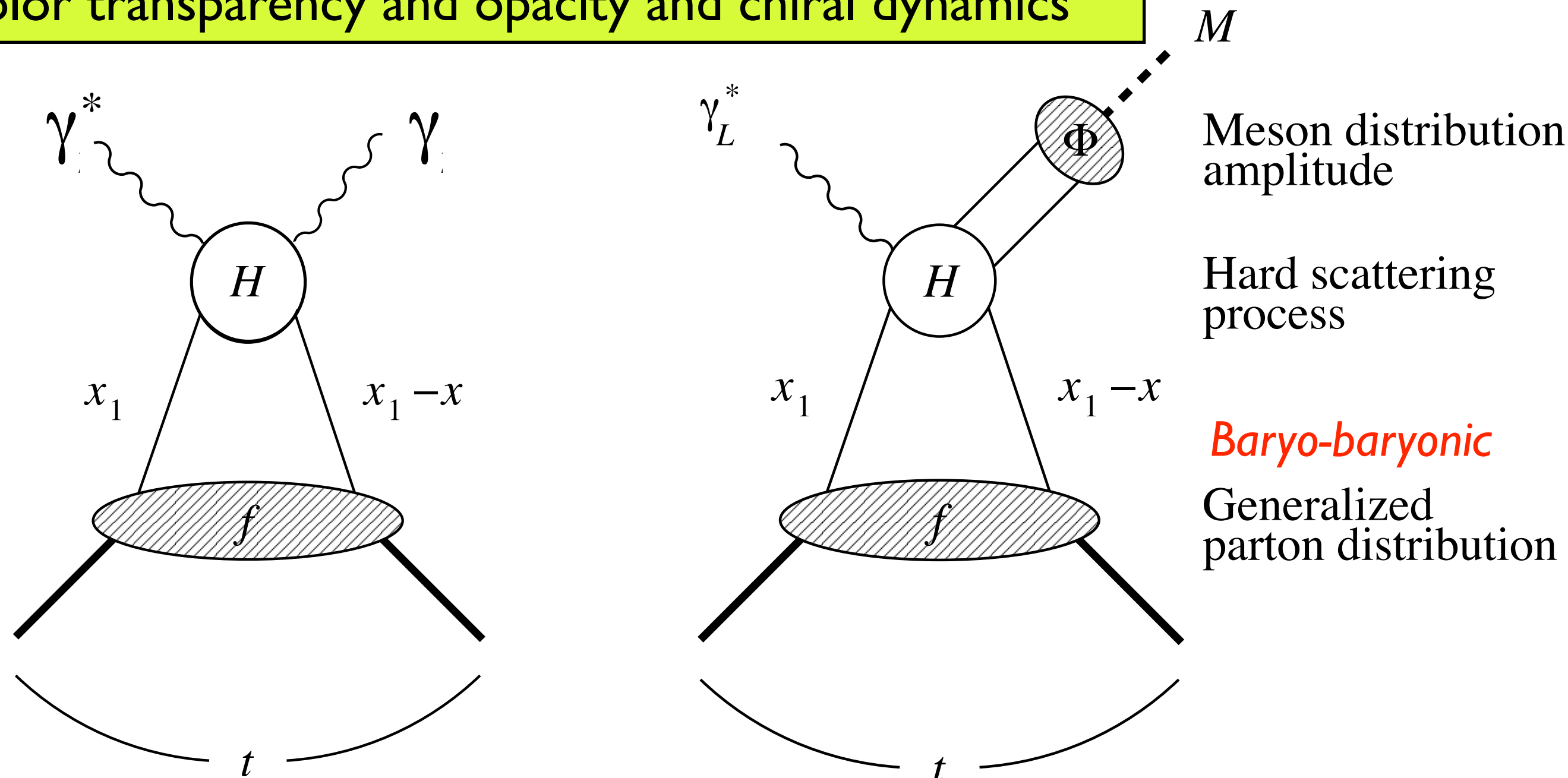
$\pi + T(A, N) \rightarrow jet_1 + jet_2 + T(A, N)$  Frankfurt, Miller, MS 93 & 03

$\gamma_L^* + N \rightarrow \text{"meson"} (\text{mesons}) + N(\text{baryonic system})$  Brodsky, Frankfurt, Gunion, Mueller, MS 94

- vector mesons, small x

Collins, Frankfurt, MS 97 - general case

provide new effective tools for study of the 3D hadron structure, high energy color coherence & color transparency and opacity and chiral dynamics



*t*-dependence only from GPD's

For large enough  $x$  ( $x > 0.1$ ?) the configuration in the nucleon which is likely to give the dominant contribution is when virtual photon hits a highly localized  $q\bar{q}$  pair. So the minimal Fock component in  $N$  which contributes is  $4q\bar{q}$ .

The key for the proofs is very different from the inclusive case: we have to prove that a specific hard process selects interaction in small size configurations and use **color coherence feature of QCD [small color singlets interact weakly]** (Frankfurt, Miller, MS 93 - dijets, Brodsky, Frankfurt, Gunion, Mueller, MS 94 - vector mesons, small x; general case Collins, Frankfurt, MS 97). The proves demonstrated squeezing of meson and that the interaction with a target is reduced to the interaction of the spatially small dipole.

⇒ Need to trigger on small size configurations at high energies.

## Two ideas:

- ◇ Select special final states: diffraction of pion into two high transverse momentum jets - an analog of the positronium inelastic diffraction. Qualitatively - from the uncertainty relation  $d \sim 1/p_t(\text{jet})$
- ◇ ◇ Select a small initial state - diffraction of longitudinally polarized virtual photon into mesons. Employs the decrease of the transverse separation between  $q$  and  $\bar{q}$  in the wave function of  $\gamma_L^*$ ,  $d \propto 1/Q$ .

# Generalized parton distributions

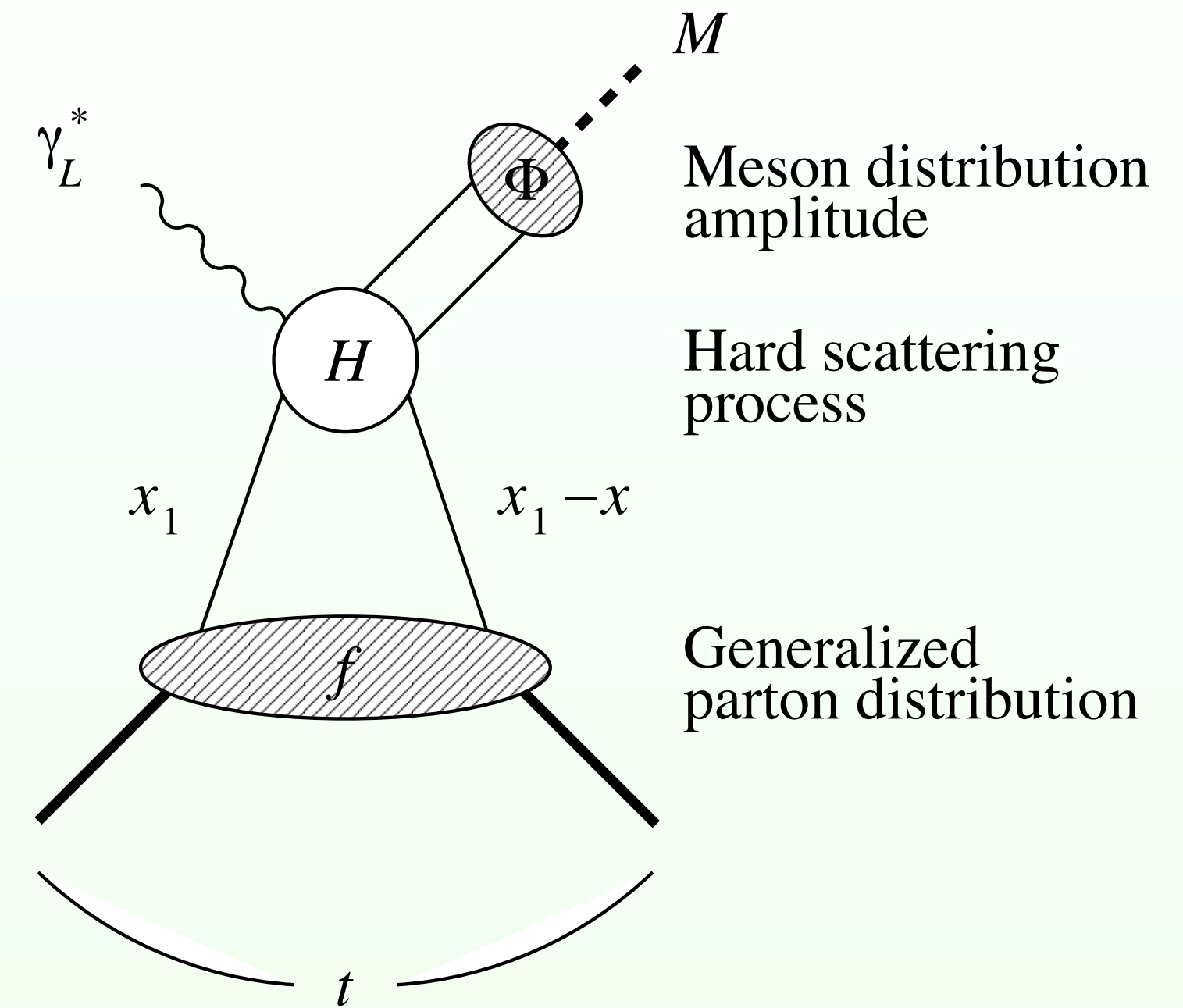
## Quark density

For a quark of flavor  $i$  -  $q_i$  (in case of charged mesons  $i$  stands for the flavor indices of the initial and final quarks)

$$f_{i/p}(x_1, x_1 - x, t, \mu) =$$

$$\int_{-\infty}^{\infty} \frac{dy^-}{4\pi} e^{-i(x_1-x)p^+ y^-} \langle p' | T \bar{\psi}(0, y^-, \mathbf{0}_T) \gamma^+ \mathcal{P} \psi(0) | p \rangle,$$

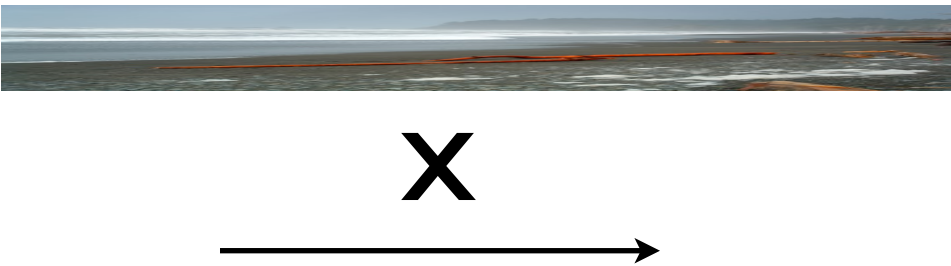
where  $\mathcal{P}$  is a path-ordered exponential of the gluon field along the light-like line joining the two operators for  $q_i$



Why interesting? Connects form factors and parton densities, allows to study transverse distribution of partons for fixed  $x$ . Critical for evaluation of proximity to black disk regime, building realistic MC of pp collisions.



### 3 dimensional single parton distribution in nucleon



1D - parton distribution



$p$ - transverse coordinate

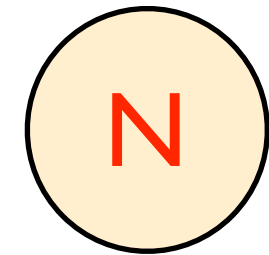


3D - generalized parton distribution

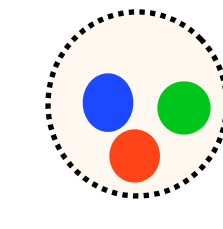
GPDs studies aim at obtaining single particle 3D parton densities of the nucleon (nucleus) [for large  $x$  there is also sensitivity to small quark-antiquark clusters in nucleons] and small quark-antiquark configurations in mesons. *However they correspond to averaging over different configuration in nucleons*



## Color fluctuations in hadrons

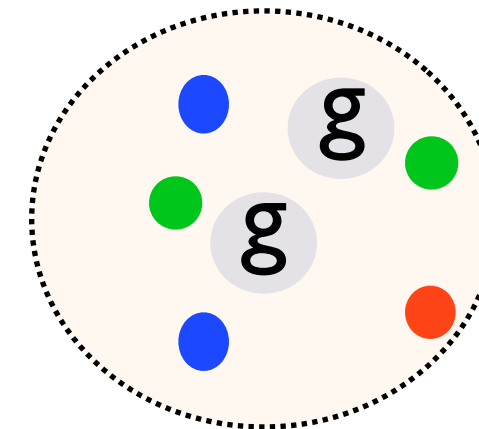
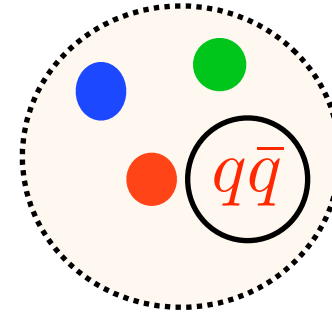


=



color

transparency



color opacity

Importance for AA Baym, B.Blättel, Heiselberg, Frankfurt, MS 91 wanted use abbreviations SSC and LHC

I will focus on color transparency (CT) phenomena which select “point-like” (small size) configurations (PLC) in the projectile which weakly interaction with media and hence probe pQCD dynamics and various GPDs

For nucleon point-like 3q configurations are responsible for nucleon decay in GUT. 3q ( $q\bar{q}$ ) configurations are responsible for baryon (meson) form factors at  $Q^2 \rightarrow \infty$ . For pion ( $\rho$ -meson),  $q\bar{q}$  wave function in the origin is expressed through decay constants  $f_\pi, f_\rho$ .

# New evidence for PLCs in pion from e.m. form factors - Miller, MS, Weiss (2010)

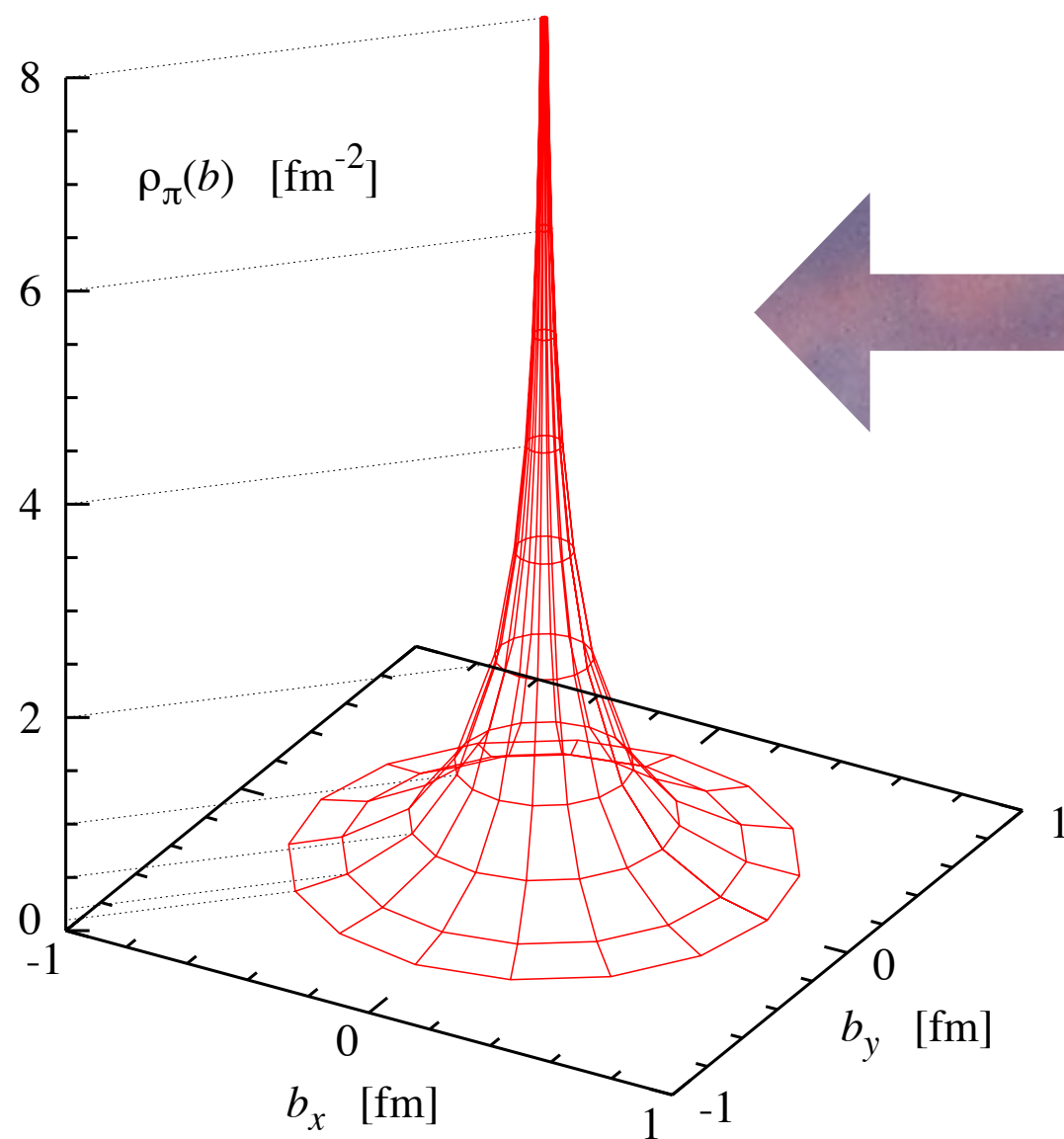
The transverse charge density in the pion is defined as the 2-dimensional Fourier transform of the spacelike pion form factor,

$$\rho_\pi(b) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(Qb) F_\pi(t = -Q^2)$$


$$\rho_\pi(b) = \int_{4m_\pi^2}^\infty \frac{dt}{2\pi} K_0(\sqrt{tb}) \frac{\text{Im} F_\pi(t + i0)}{\pi}$$



dispersion representation of transverse density



*Contribution of small transverse size quark-antiquark component in pion*

Three-dimensional rendering of the transverse charge density in the pion, as obtained from the dispersion integral  evaluated with the Gounaris-Sakurai form factor parametrization of Brush et al.

# Brief Summary of CT: squeeze and freeze

(a) high energy CT - only condition for CT is **Squeezing:**

two selection original methods mentioned before

\* Special final states: diffraction  $\pi \rightarrow$  two high  $p_t$  jets:  $d_{q\bar{q}} \sim 1/p_t$

\* Small initial state:  $\gamma^*_L$  -  $d_{q\bar{q}} \sim 1/Q$  in  $\gamma^*_L + N \rightarrow M + B$

will suggest new ones feasible with COMPASS

## (b) Intermediate energy CT

Nucleon form factor

$\gamma^*_L$  ( $\gamma^*_T$  ?) + N  $\rightarrow$  M + B

Large angle ( $t/s = \text{const}$ ) two body processes:  $a + b \rightarrow c + d$  Brodsky & Mueller 82

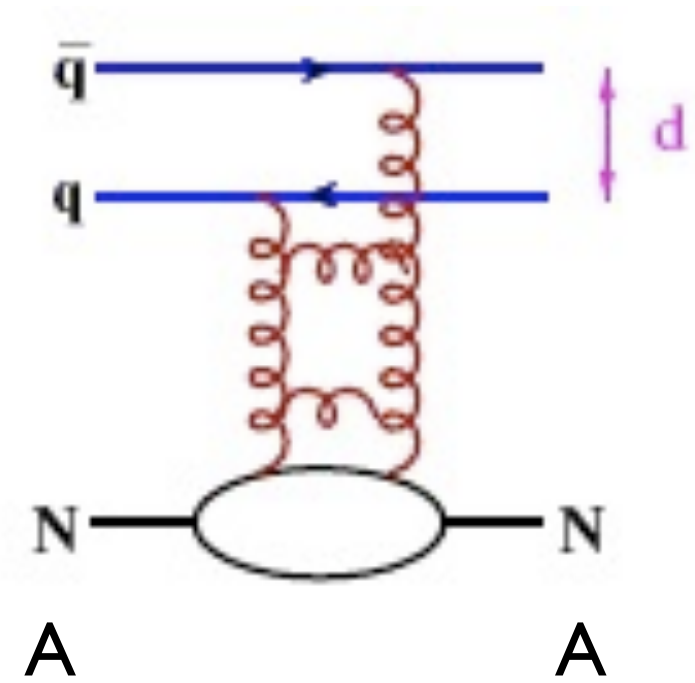
Freezing is a challenge - small size configurations tend to expand with away from the interaction point.

↑ Problem: strong correlation between  $t$  ( $Q$ ) and lab momentum of produced hadron  
↓

Color coherence is one of fundamental properties of high energy processes in QCD:

Up to very large energies including the ones probed at HERA the interaction of color neutral, spatially small quark dipole with a hadron(nuclear) target T is unambiguously calculable in QCD =QCD factorization theorems.

QCD factorization theorem for the interaction of small size color singlet wave package of quarks and gluons.



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

$$Q_{eff}^2 = \lambda/d^2, \lambda = 4 \div 10$$

Baym, Blättel, Frankfurt, MS, 93; Frankfurt, Miller, MS 93

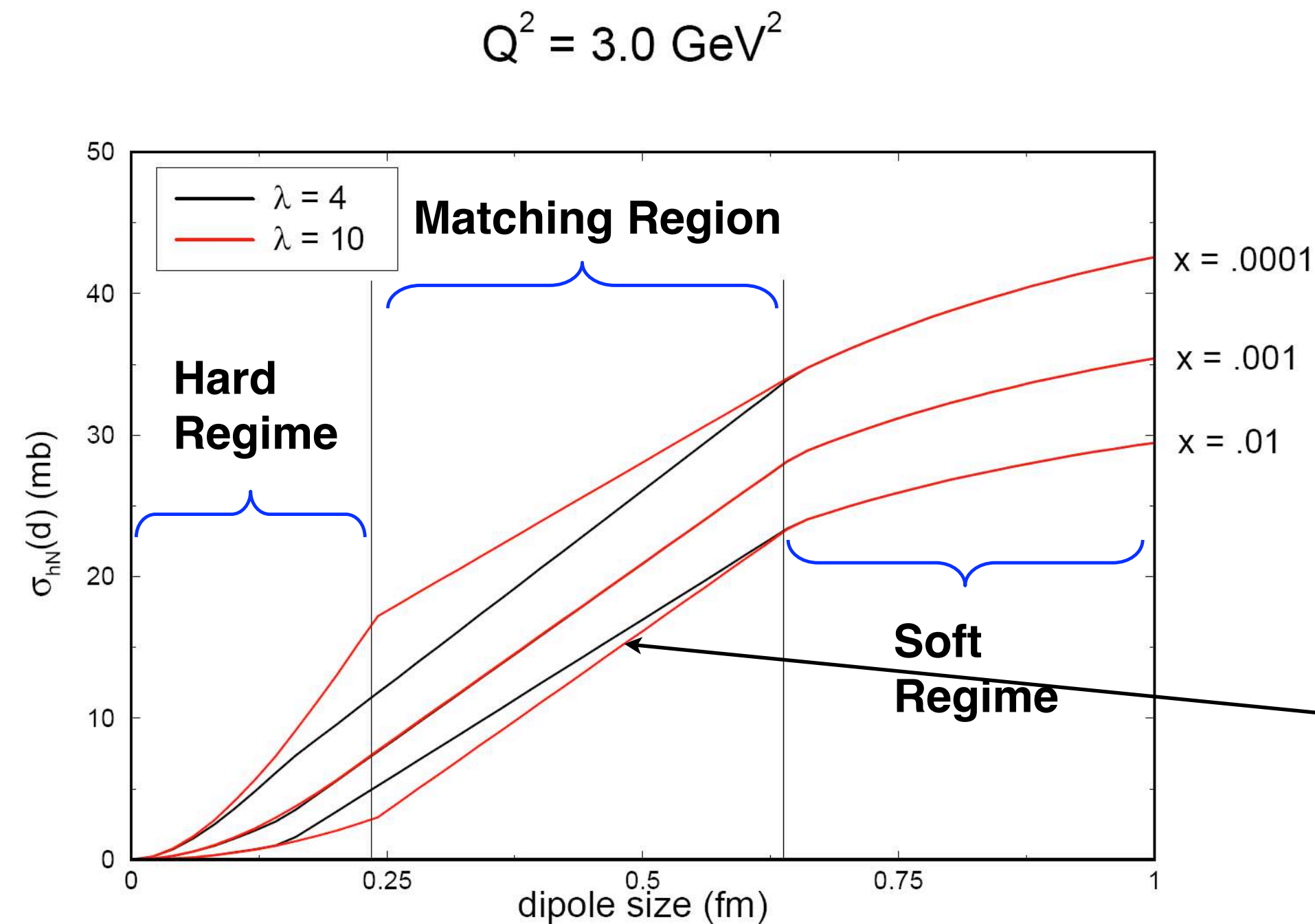
HI and ZEUS observed processes of diffractive electroproduction of vector mesons.

$$\gamma^* + p \rightarrow V + p \quad V = \omega, \rho, \varphi, J/\psi$$

$$\gamma^* + p \rightarrow J/\psi + rap\ gap + X$$

Practically all regularities predicted by QCD factorization theorems and DGLAP approximation including *convergence of  $t$  and  $s$ -dependences*, were observed at HERA

# HERA data confirm increase of the cross sections of small dipoles predicted by pQCD



COMPASS energies correspond to  $x > 0.01$  - sufficient to squeeze to  $d < 0.5 \text{ fm}$

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  $J/\psi$  photoproduction. Provided a reasonable prediction for  $\sigma_L$

Frankfurt, Guzey, McDermott, MS 2000-2001

## First prediction and discovery of high energy CT phenomenon

$$\pi + N(A) \rightarrow \text{"2 high } p_t \text{ jets"} + N(A)$$

Mechanism:

Pion approaches the target in a **frozen** small size  $q\bar{q}$  configuration and scatters **elastically** via interaction with  $G_{target}(x, Q^2)$ .

- ❖ First attempt of the theoretical analysis of  $\pi N$  process - Randa 80 - power law dependence of  $p_t$  of the jet (wrong power)
- ❖ First attempt of the theoretical analysis of  $\pi A$  process - Brodsky et al 81 - exponential suppression of  $p_t$  spectra, weak A dependence ( $A^{1/3}$ )
- ❖ pQCD factorization theorem - Frankfurt, Miller, MS 93; elaborated arguments related to factorization 2003

*The final answer is*

$$A(\pi + N \rightarrow 2 \text{ jets} + N)(z, p_t, t = 0) \propto \int d^2 d \psi_{\pi}^{q\bar{q}} \sigma_{q\bar{q}-N(A)}(d, s) \exp(ip_t d)$$
$$d = r_t^q - r_t^{\bar{q}},$$

$\psi_{\pi}^{q\bar{q}}(z, d) \propto z(1-z)_{d \rightarrow 0}$  is the quark-antiquark Fock component of the meson light cone wave function

Plane wave in the final state - faster onset of scaling than for VM production

Proportionality of the amplitude to the gluon nuclear density (actually GPD) which for small  $x$  is not linear in  $A$  - *change of meaning of CT for high energies*. Dependence on  $t$  is the same as for diffractive vector meson production at HERA.

# Predictions

⇒ A-dependence:  $A^{4/3} \left[ \frac{G_A(x, k_t^2)}{AG_N(x, k_t^2)} \right]^2$  where  $x = M_{dijet}^2/s$

⇒  $\frac{d\sigma(u)}{du} \propto \phi_\pi^2(z) \approx u^2(1-u)^2$  where  $u = E_{jet_1}/E_\pi$

⇒  $k_t$  dependence  $\frac{d\sigma}{d^2k_t} \propto \frac{1}{k_t^n}, n \approx 8$  for  $x \sim 0.02$

⇒ Absolute cross section is also predicted

## E-791 (FNAL) experiment (PRL 2001) at $E_{\text{inc}}^{\pi}=500$ GeV

First experimental observation of high energy CT for pion interaction (Ashery 2001):  $\pi + A \rightarrow$  "jet" + "jet" + A. Confirmed predictions of pQCD (LF, Miller, Strikman93) for  $A$ -dependence, distribution over energy fraction,  $u$  carried by one jet, dependence on  $p_t(\text{jet})$ , etc

♡ Coherent peak is well resolved

♡♡ Observed  $A$ -dependence  $A^{1.61 \pm 0.08}$   $[C \rightarrow Pt]$

FMS prediction  $A^{1.54}$   $[C \rightarrow Pt]$  for large  $k_t$  & extra small enhancement for intermediate  $k_t$ .

For soft diffraction the  $Pt/C$  ratio is  $\sim 7$  times smaller!!

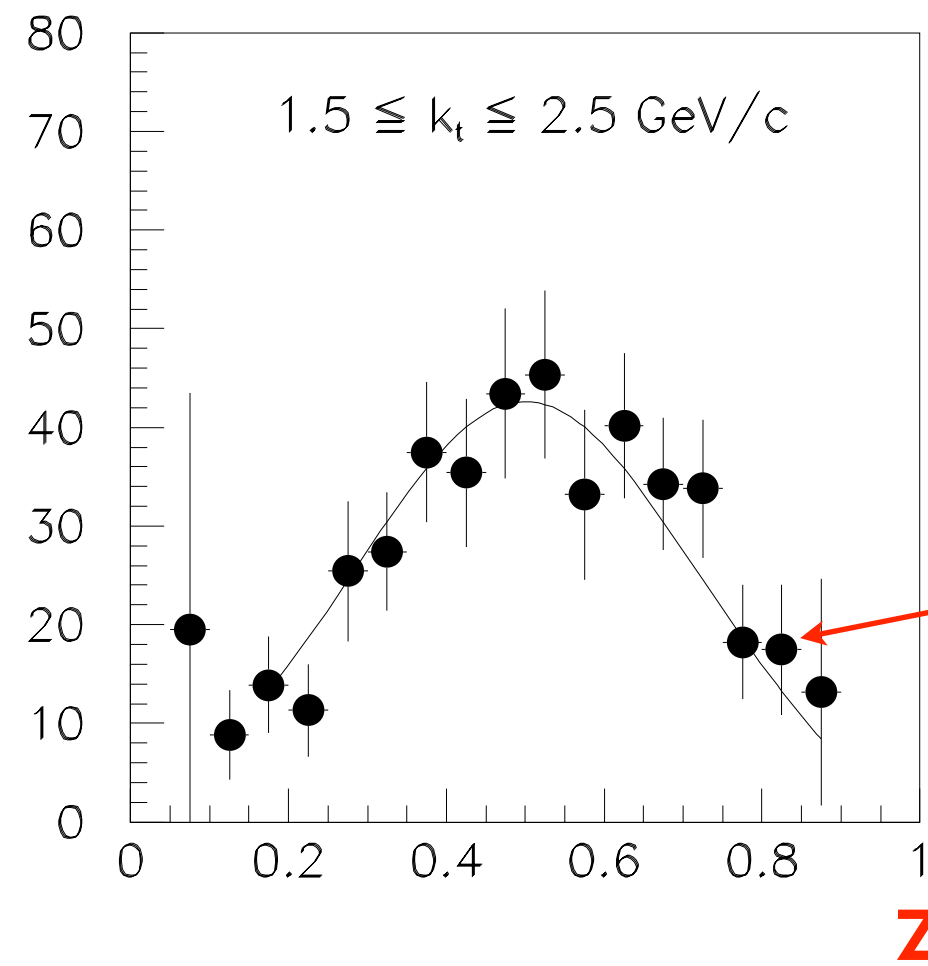
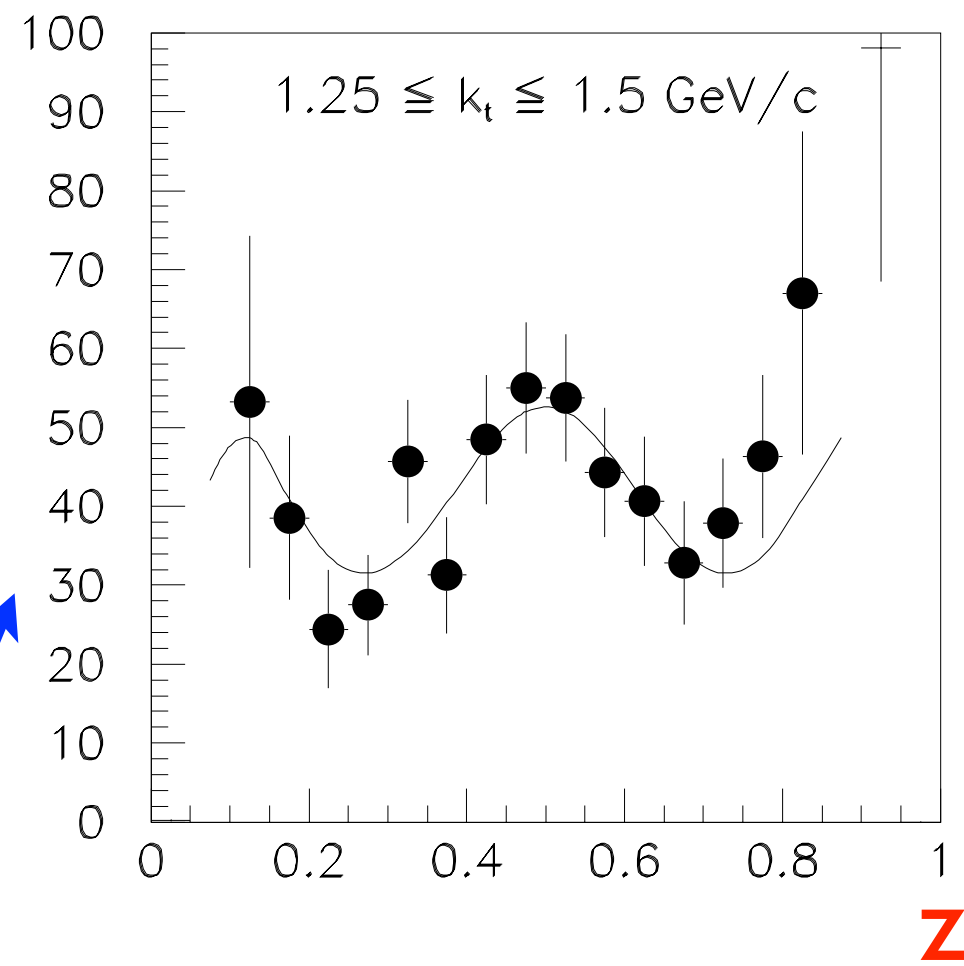
(An early prediction Bertsch, Brodsky, Goldhaber, Gunion 81

$$\sigma(A) \propto A^{1/3}$$

*In soft diffraction color fluctuations are also important leading to*

$$\sigma_{\text{soft diffr}}(\pi + A \rightarrow X + A) \propto A^{.7}$$

*Miller Frankfurt & S, 93*



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

prediction  
 $(\pi \text{ wave funct})^2$

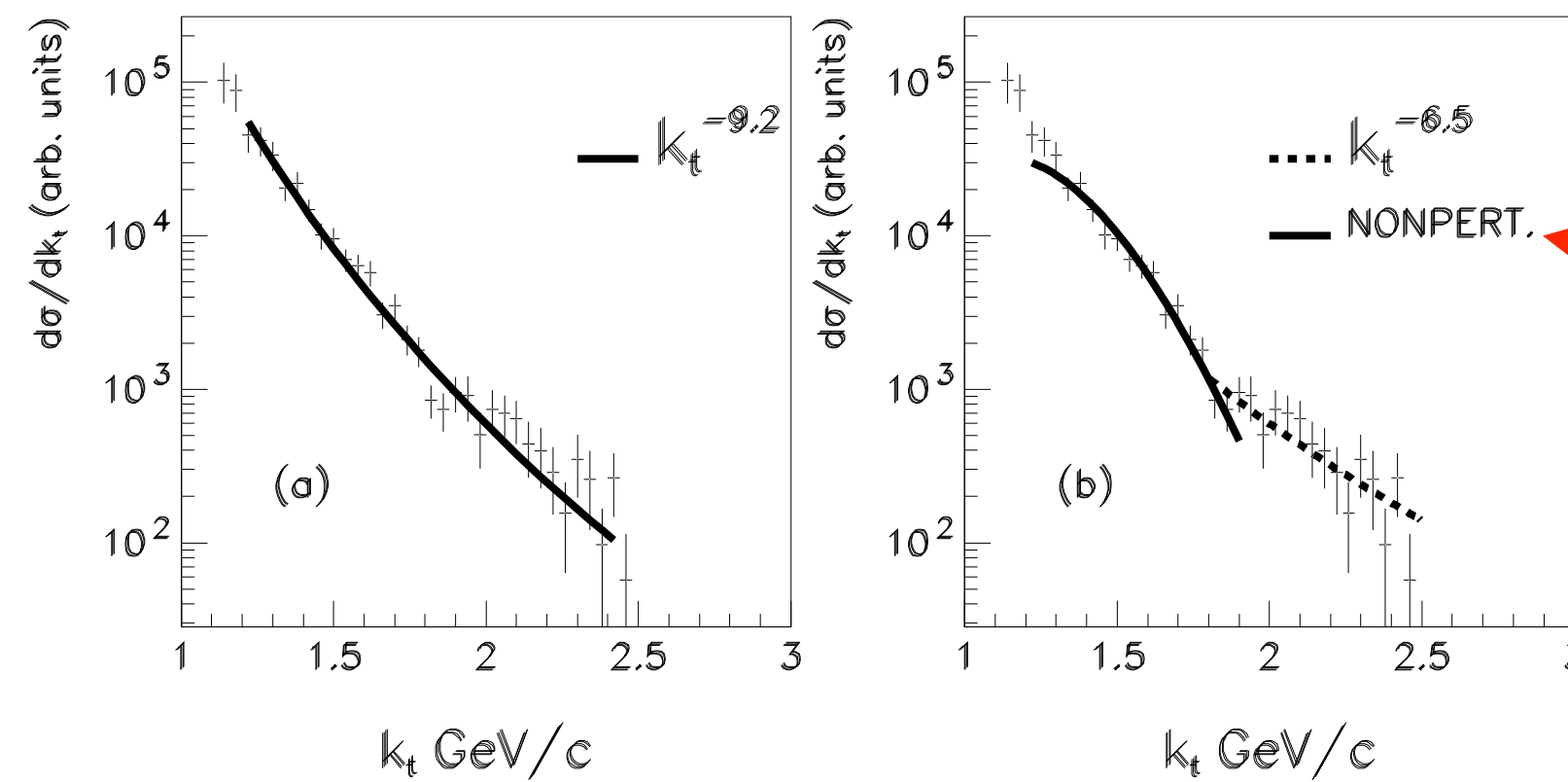
$$Q^2 (\pi \text{ f.f.}) \sim 4k_t^2 (\text{jet})$$



strong squeezing in  $\pi$  form factor for  $Q^2=6 \text{ GeV}^2$

Note that enhancement of  $z \rightarrow (0, 1)$  tail for moderate  $k_t$  may explain the observed by BaBar collaboration slow decrease with  $Q$  of the form factor for the process:  $\gamma^*(Q^2) + \gamma \rightarrow \pi^0$ .

♡♡♡♡  $k_t^{-n}$  dependence of  $d\sigma/dk_t^2 \propto 1/k_t^{7.5}$  for  $k_t \geq 1.7 \text{ GeV}/c$  close to the QCD prediction -  $n \sim 8.0$  for the kinematics of E971



or higher terms in Gegenbauer expansion???

CT has been observed also in the diffractive photoproduction of  $J/\psi$  at FNAL

CT for dijets  $\Rightarrow$  unique method to measure meson wave function and GPDs

- 👉 need detailed experimental studies as a function of  $k_t$ ,  $E_\pi$ ; incident energy, and kaon vs pion
- 👉 At what  $k_t$  CT transition to soft regime starts?
- 👉 Dijet production with quantum numbers different from that for projectile can be explored by COMPASS using hydrogen ( $^2\text{H}$ ) target and recoil detector. Measurements at a couple of energies would allow to measure decrease of  $\alpha'_R$  for GPDs with increase of  $k_t$  as expected in QCD.

**COMPASS has plenty of relevant data on tape !!!**

Important to have a toolkit of hadron induced processes which select small configurations and hence factorizable. Would allow to study *a variety of GPDs of different hadrons*

Natural candidate - large angle  $2 \rightarrow 2$  processes. One of the first applications of CT ideas was to use nuclei to test whether  $pp \rightarrow pp, \dots$  is dominated by point-like configurations (Brodsky & Mueller, 82).

*Tough Problem:*

*the lab momenta of produced nucleons are of the order  $-t/2m$  - cannot treat configurations as frozen up to very large  $t$*

**Freezing: Main challenge:**  $|qqq\rangle$  ( $|q\bar{q}\rangle$ ) 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)

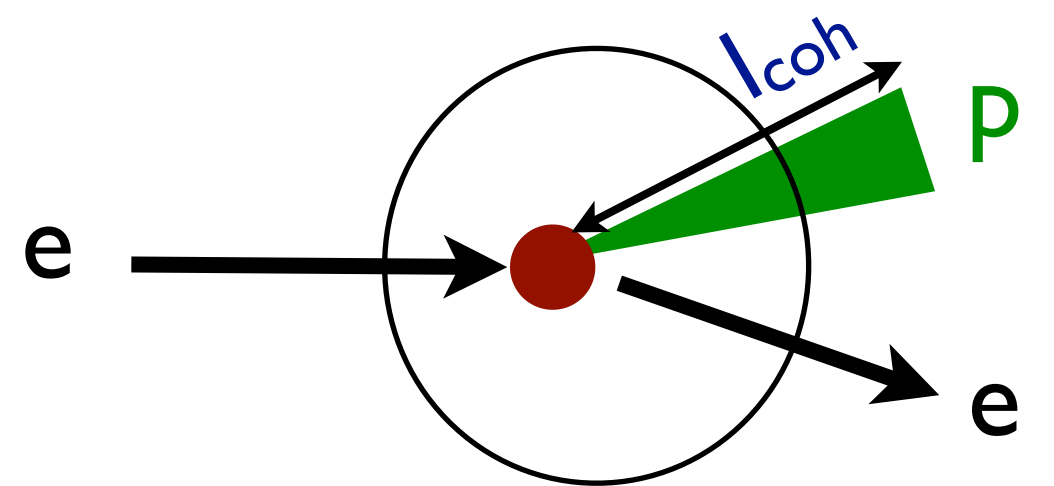
$$|\Psi_{PLC}(t)\rangle = \sum_{i=1}^{\infty} a_i \exp(iE_i t) |\Psi_i(t)\rangle = \exp(iE_1 t) \sum_{i=1}^{\infty} a_i \exp\left(\frac{i(m_i^2 - m_1^2)t}{2P}\right) |\Psi_i(t)\rangle$$

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

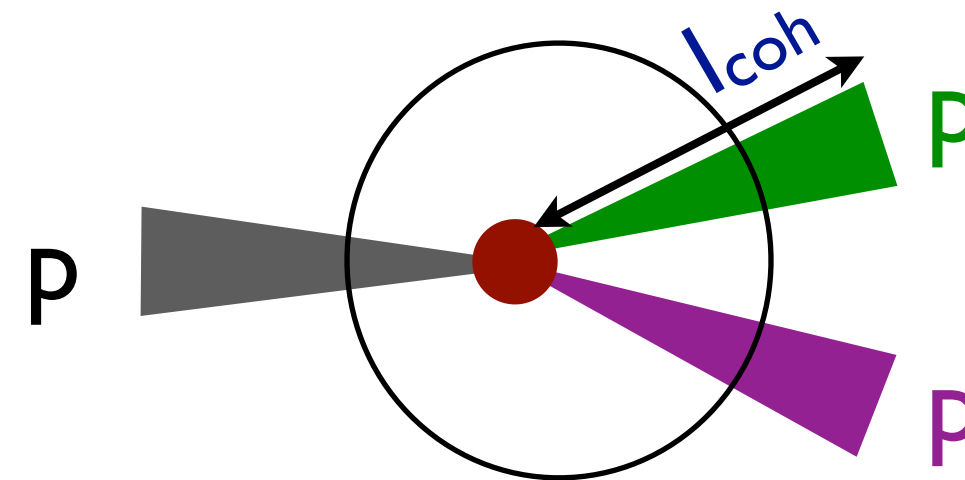
Quantum Diffusion model of expansion

$$l_{coh} = \frac{2P_h}{\underbrace{m_{h^*}^2 - m_h^2}_{0.7 \div 1.1 \text{ GeV}^2}} \xrightarrow{\text{light hadrons}} l_{coh} \sim (0.4 - 0.8) \text{ fm } E_h[\text{GeV}]$$

*actually incoherence length*



$eA \rightarrow ep$  (A-1) at large Q



$pA \rightarrow pp$  (A-1) at large t and intermediate energies

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

The same logic should be applicable to quark fragmentation in hard processes. Also quantum diffusion - mentioned first in Dokshitzer et al book "Basics of pQCD"

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

## Implications

*Conspiracy* - absorption in quark and quark- antiquark propagation maybe similar leading to similar CT effect (Mosel et al). May need finer observables - like exclusive  $\pi^0, \eta$

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

Maybe a reason why one needs large parton - nucleon cross section in AA modeling - talk of Che-Ming Ko

For charm  $l_D = \frac{p_D}{m_D} 0.2 \text{ fm} \Rightarrow \text{At RHIC } l_D < 1 \text{ fm}$

# Experimental situation

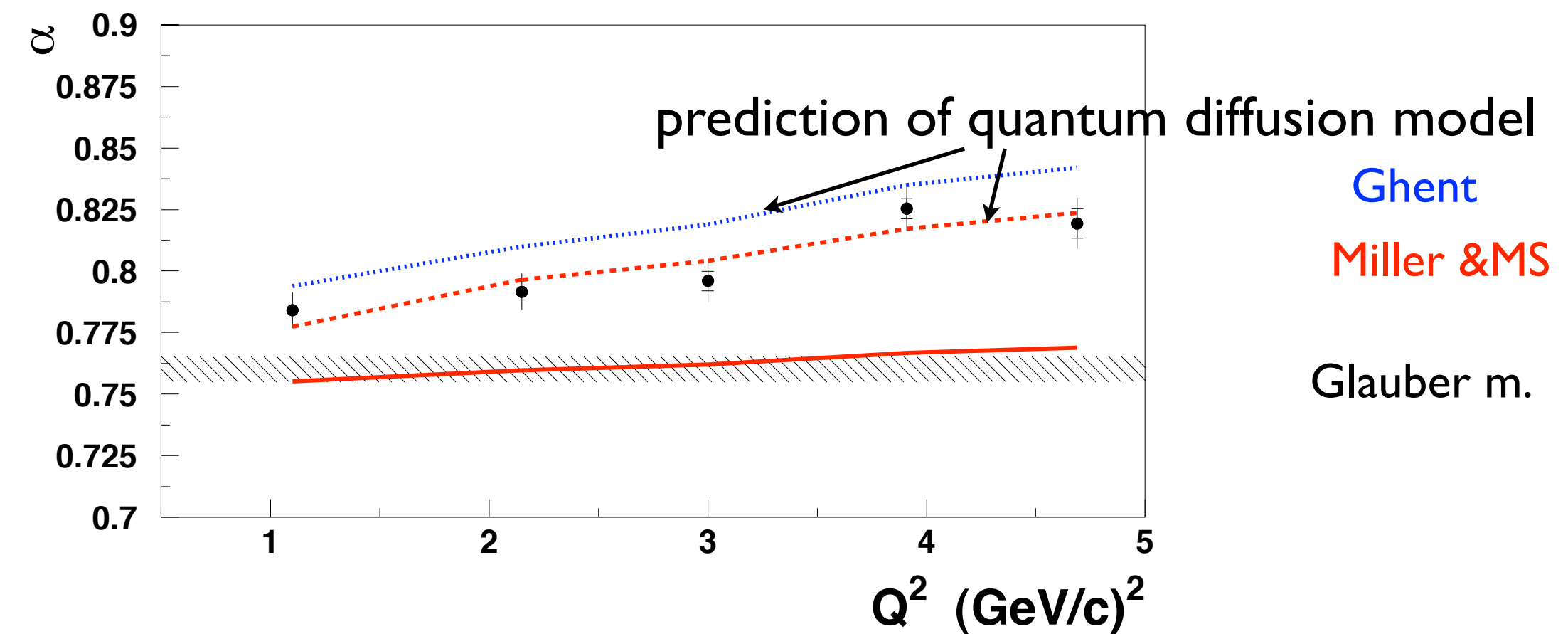
☀ Energy dependence of transparency in (p,2p) is observed for energies corresponding to  $l_{\text{coh}} \geq 2$  fm. Such dependence is impossible without freezing. But not clear whether effect is CT or something else? Needs independent study.

☀  $\gamma^* + A \rightarrow \pi A^*$  evidence for increase of transparency with Q (Dutta et al 07)

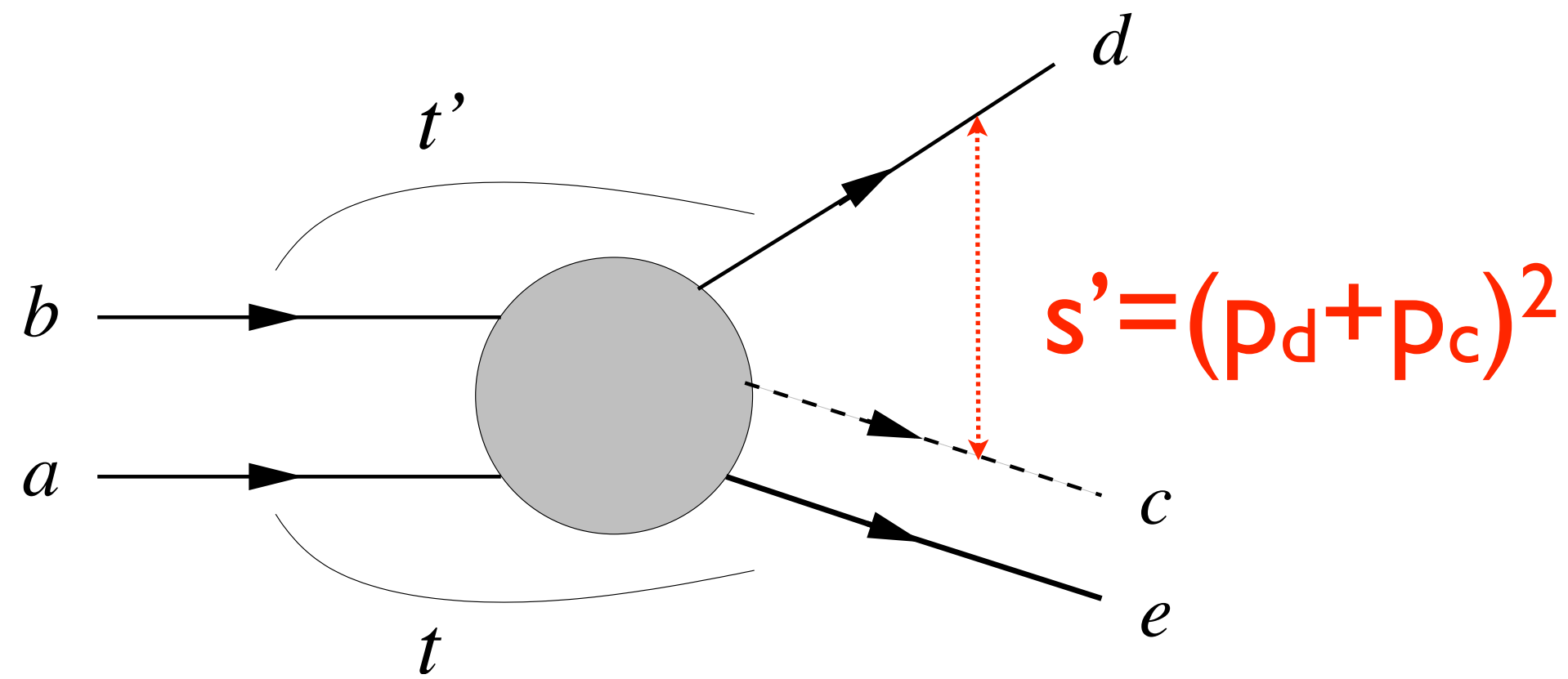
Note that elementary reaction for Jlab kinematics is dominated by ERBL term so  $\gamma^* N$  interaction is local.  $\gamma^*$  does not transform to  $q\bar{q}$  distance  $l/m_N X$  before nucleon

A- dependence checks not only squeezing but **small**  $l_{\text{coh}}$  as well

😊  $\gamma^* + A \rightarrow \rho A^*$  data to be released shortly  
- consistent with our predictions



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



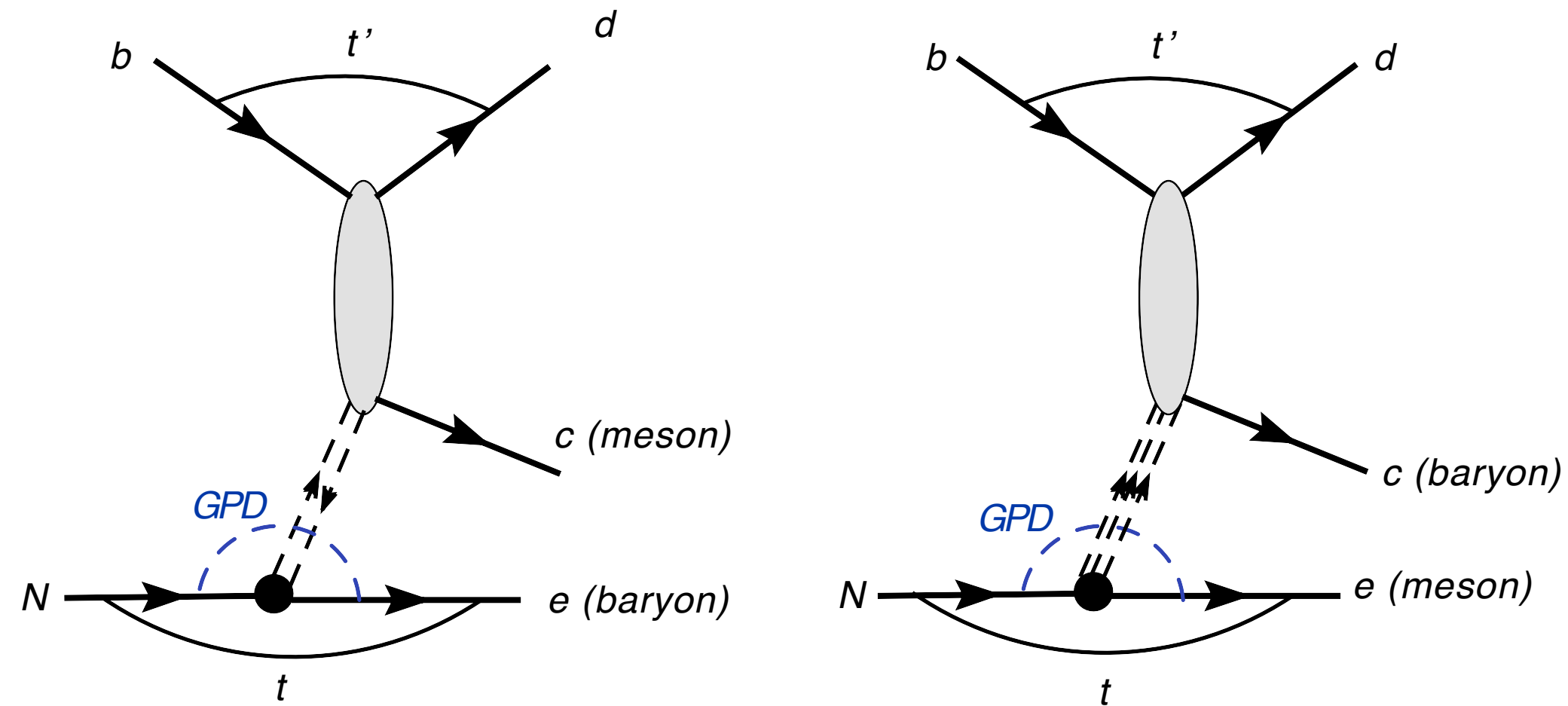
*Limit:*  
 - $t' > \text{few GeV}^2$ ,  $-t'/s' \sim 1/2$   
 - $t = \text{const} \sim 0$   
 $\Rightarrow s'/s \ll 1$

Two recent papers: [Kumano, MS, and Sudoh PRD 09](#); [Kumano & MS Phys.Lett. 10](#)

2 → 3 branching processes:

- ☀ test onset of CT for 2 → 2 avoiding freezing effects
- ☀ measure transverse sizes of b, d, c
- ☀ measure cross sections of large angle pion - pion (kaon) scattering
- ☀ probe 5q in nucleon and 4q in mesons
- ☀ measure GPDs of nucleons, mesons and photons(!)

# Factorization:

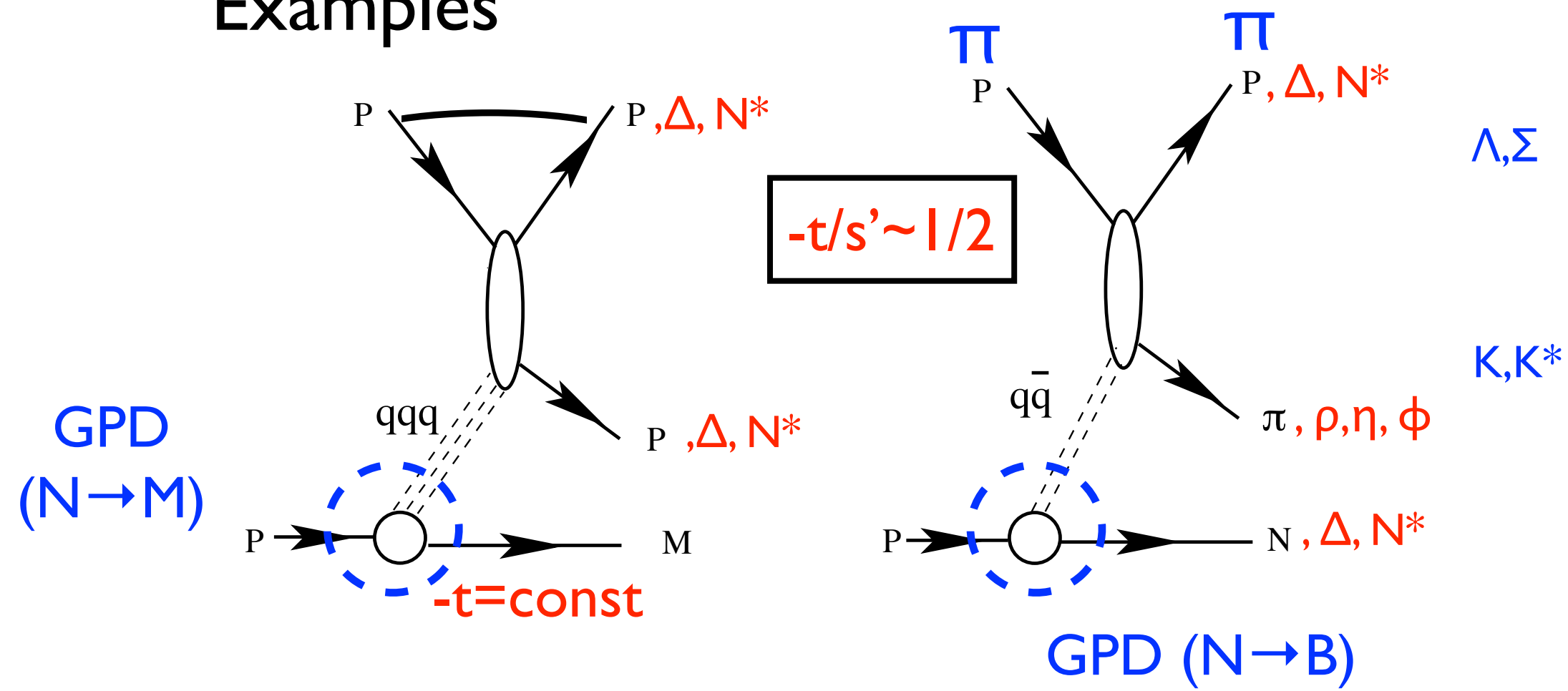


If the upper block is a hard ( $2 \rightarrow 2$ ) process, “b”, “d”, “c” are in small size configurations as well as exchange system ( $q\bar{q}$ ,  $qqq$ ). Can use CT argument as in the proof of QCD factorization of meson exclusive production in DIS (Collins, LF, MS 97)

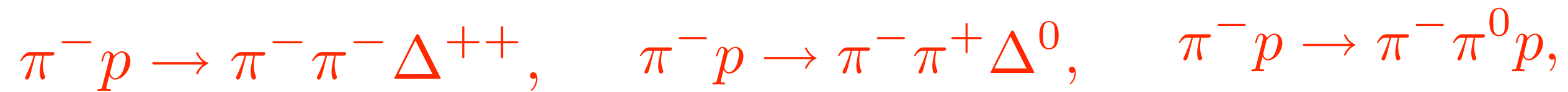


$$\mathcal{M}_{NN \rightarrow N\pi B} = GPD(N \rightarrow B) \otimes \psi_b^i \otimes H \otimes \psi_d \otimes \psi_c$$

# Examples



COMPASS with recoil detector



Advantage - CT for pions is observed, easier to squeeze pions. Measurements at small  $t$  - close to pion pole can normalize GPDs and determine elastic  $\pi^- \pi^-$ ,  $\pi^- \pi^+$ ,  $\pi^- \pi^0$  cross sections

**Data on tape !!!**

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

Use as example process  $\pi^- A \rightarrow \pi^- \pi^\pm A^*$



easier to squeeze



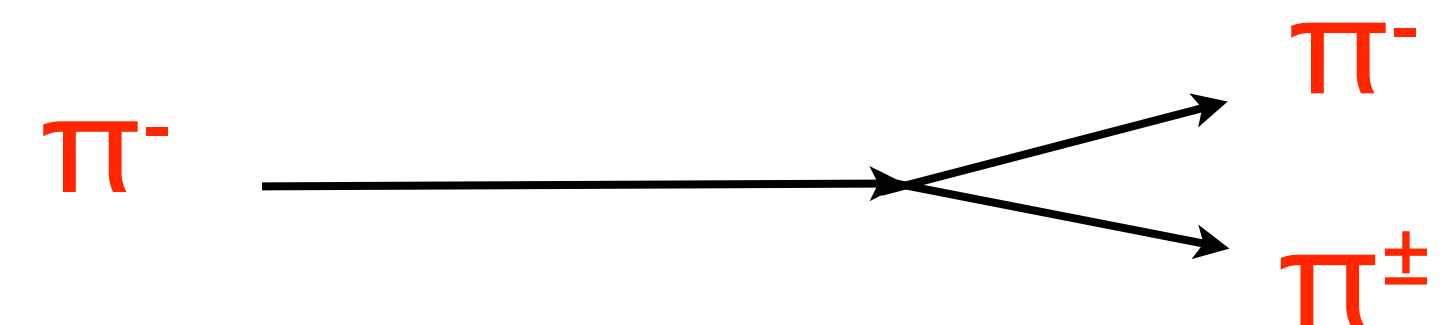
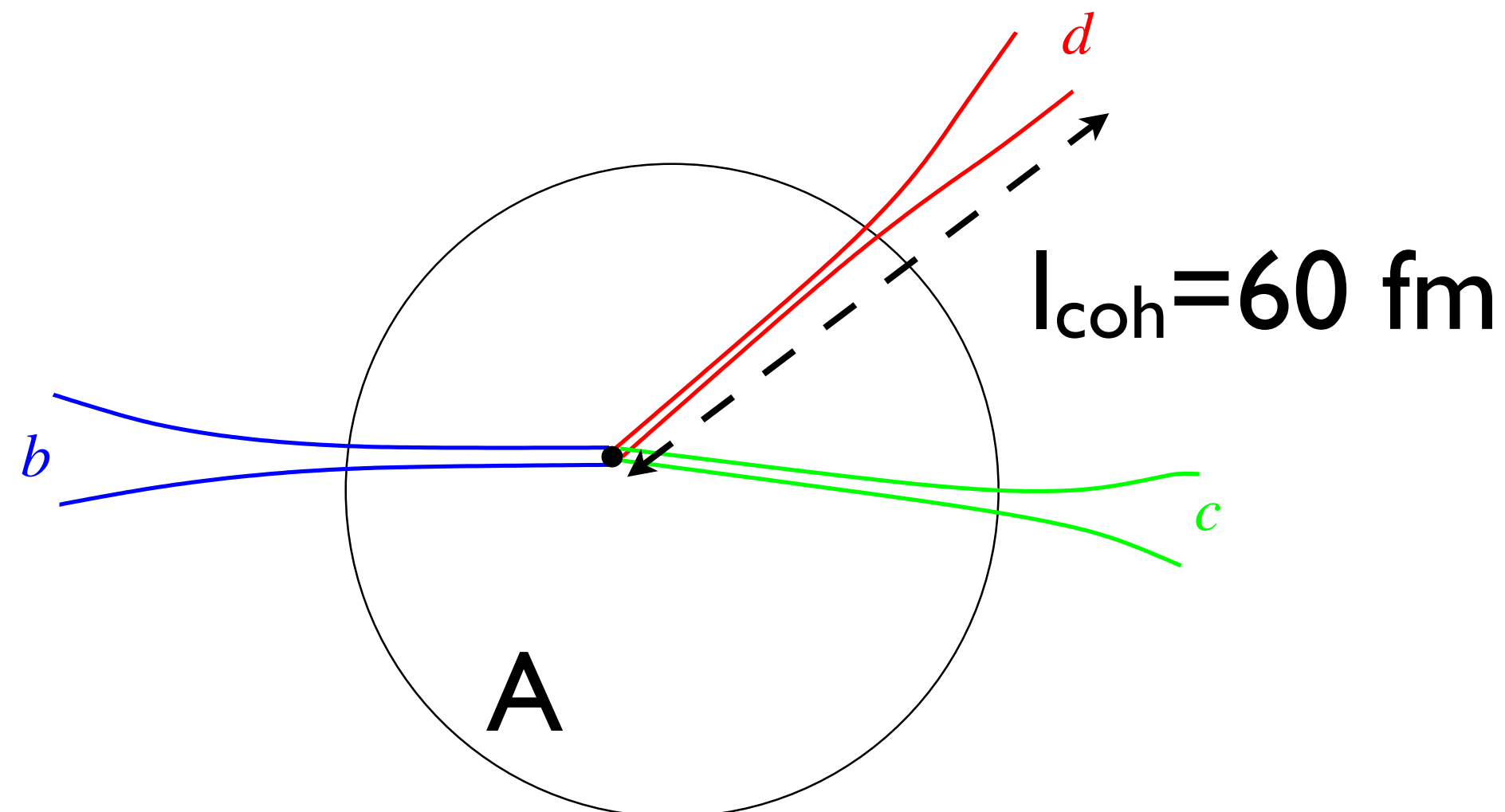
COMPASS 190 GeV data on tape



Early  $\pi^- p \rightarrow \pi^- \pi^\pm p$  data from FNAL

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

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



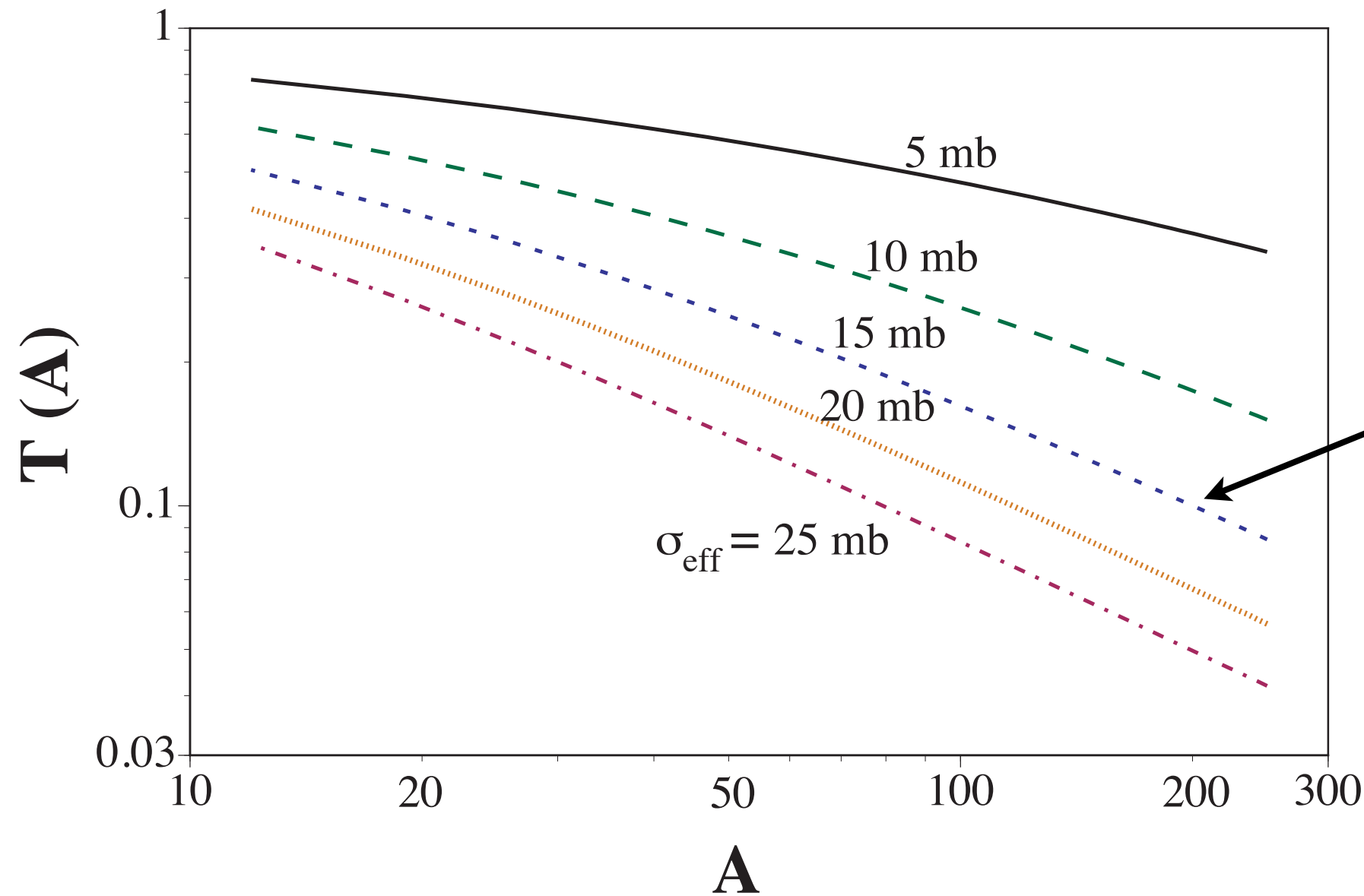
Branching ( $2 \rightarrow 3$ ) processes with nuclei - freezing is 100% effective for  $p_{inc} > 100 \text{ GeV}/c$  - study of one effect only - CT due to squeezing of the **size of fast hadrons**

$$T_A = \frac{\frac{d\sigma(\pi^- A \rightarrow \pi^- \pi^+ A^*)}{d\Omega}}{\sum \frac{d\sigma(\pi^- p \rightarrow \pi^- \pi^+ n)}{d\Omega}}$$

$$T_A(\vec{p}_b, \vec{p}_c, \vec{p}_d) = \frac{1}{A} \int d^3 r \rho_A(\vec{r}) P_b(\vec{p}_b, \vec{r}) P_c(\vec{p}_c, \vec{r}) P_d(\vec{p}_d, \vec{r})$$

where  $\vec{p}_b, \vec{p}_c, \vec{p}_d$  are three momenta of the incoming and outgoing particles b, c, d;  
 $\rho_A$  is the nuclear density normalized to 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 30%

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

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

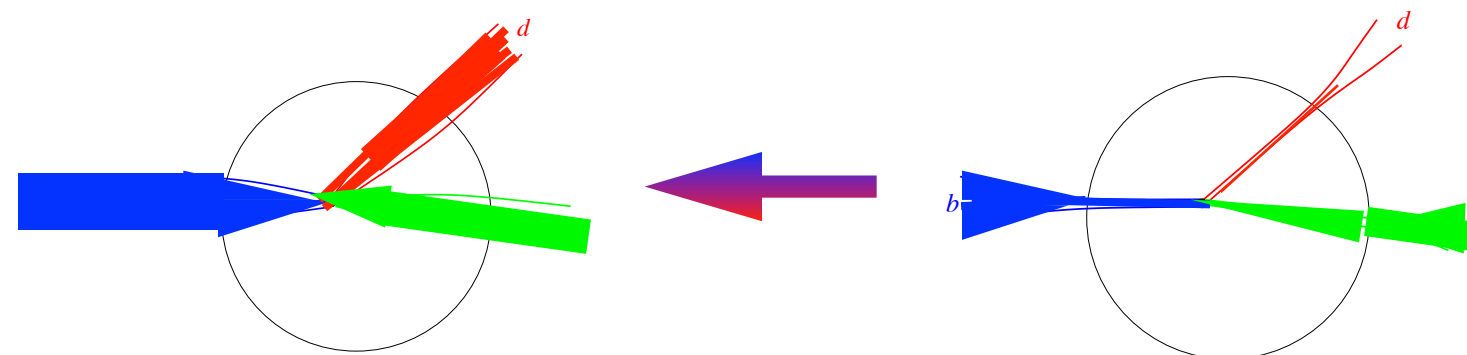
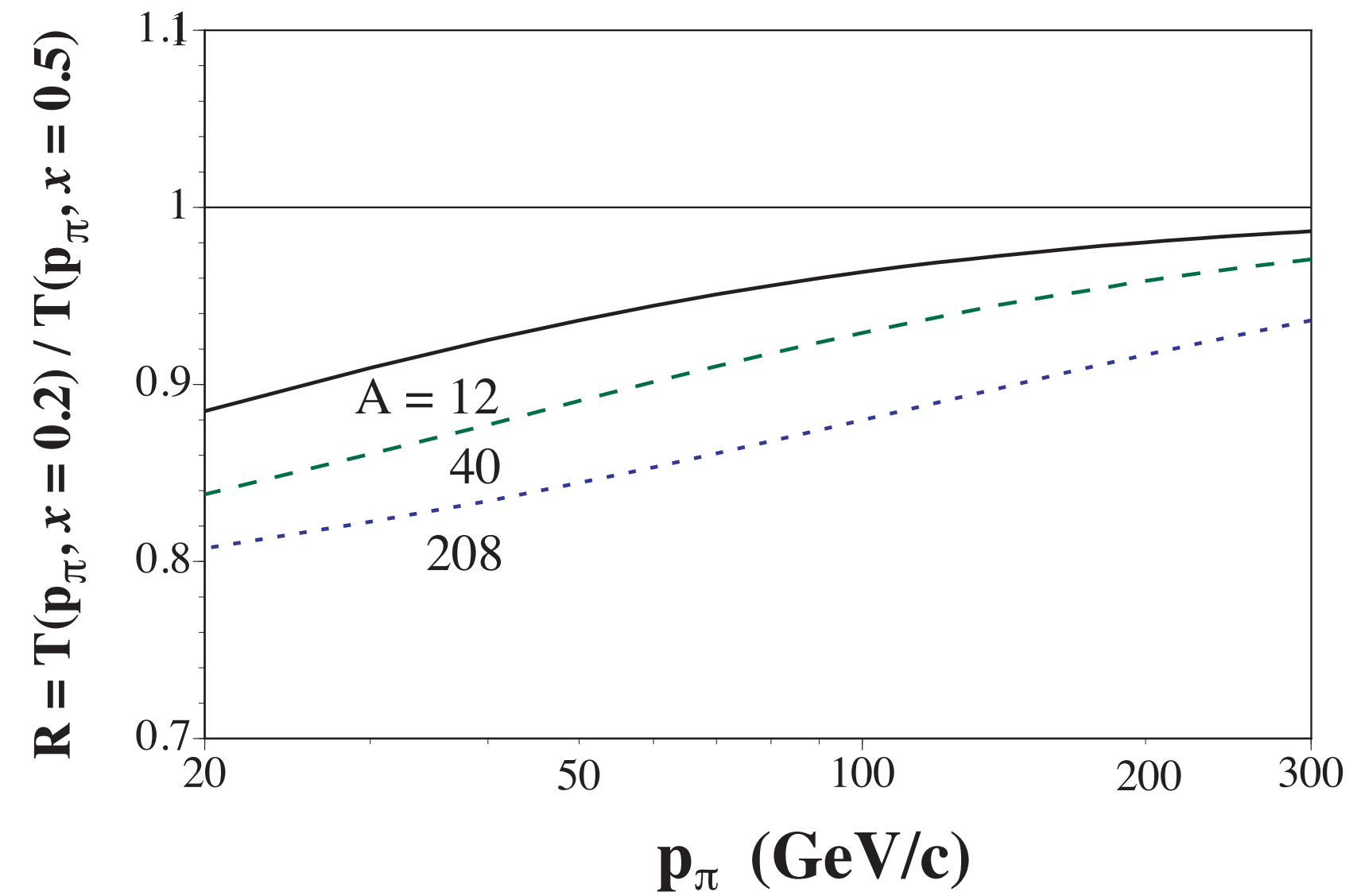
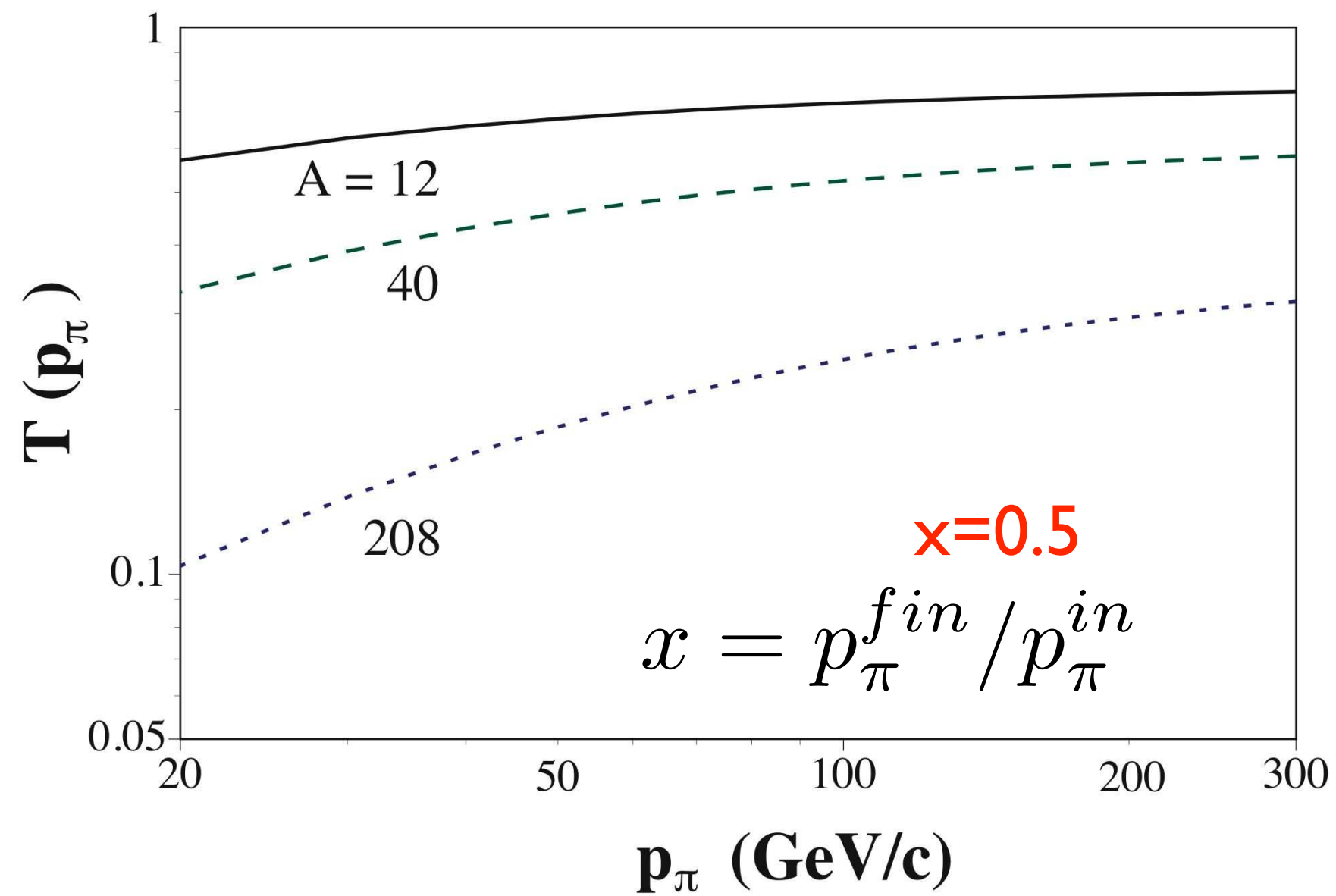
# Defrosting point like configurations - energy dependence for fixed s',t'

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

Quantum Diffusion model of expansion

Use  $l_{coh} \sim 0.6 \text{ fm } E_h[\text{GeV}]$

which describes well CT for pion electroproduction





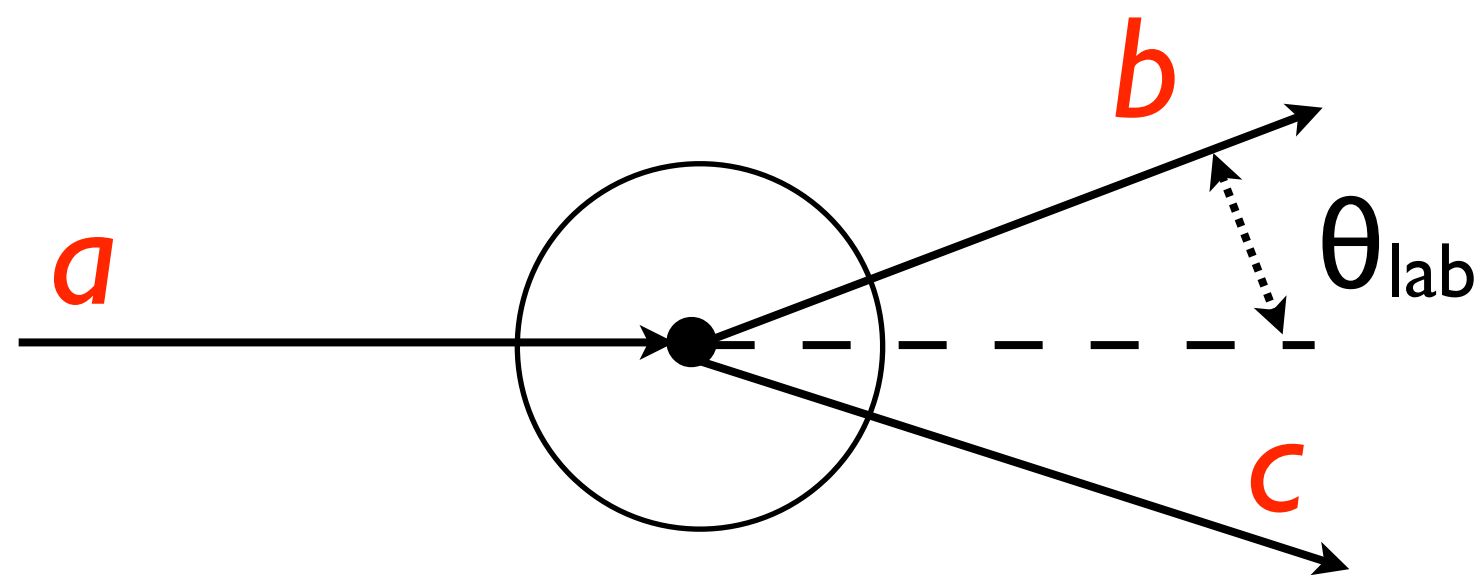
# CT with PANDA

Looking for Color Transparency (CT) in high energy  $A(p,2p)(A-1)$ ,  $A(\pi,\pi p)(A-1)$  reactions was suggested by A.Mueller and S.Brodsky in 82 to as a way to understand the origin of **large angle two body reactions** check :

$$\sigma(pA \rightarrow pp(A-1)) = Z\sigma(pp \rightarrow pp)$$

At intermediate energies ( $E_p \sim 1$  GeV)  $A(p,2p)(A-1)$  was used for decades for studies of the nuclear structure - the Glauber model based approximation works within 10%.

## Kinematics for $\theta_{cm}=90^\circ$



$$\theta_{lab} \text{ (for } \theta_{cm}=90^\circ) \approx m_N / \sqrt{s}$$

Very good resolution in light-cone variable  $\alpha_h = (E_h - p_{3h}) / m_N$  for b, c

$$\alpha_b = \alpha_c \approx \frac{\sin^2(\theta_{lab}) p_b}{4m_N}$$

BNL experiments observed that it is possible to select A(p,2p) reaction via measurement of momentum and angle of one particle and angle of the second one

→ *PANDA probably can study processes where projectile scatters off bound protons and off neutrons like*



T similar to  $\bar{p}p$  - no quark exchange

$$\sigma(\bar{p}p \rightarrow \bar{p}p) = \sigma(\bar{p}n \rightarrow \bar{p}n)$$



\* T could be different from  $pp \rightarrow pp$  :

\* *different quark exchanges*

$$\sigma(pp \rightarrow pp) > \sigma(pn \rightarrow pn)$$

\* *so far no indications of oscillations for fixed  $\theta_{cm}$*

*Advantages of PANDA as compared to BNL :*

- \* Much higher lumi - a factor > 10 for antiprotons and > 50 for protons
- \* Much better acceptance
- \* Running time - months vs days



**Gain in statistics > 1000**



One should look for CT effects in reactions



in all possible channels at  $E_{\text{inc}} > 4 \text{ GeV}$  when  $l_{\text{coh}} > 2 \text{ fm}$

Note that probabilities of PLC in different mesons:  $\pi, \rho, K$  are significantly different so onset of larger transparency regime may differ. Looking for a pair of mesons (away from a resonance - say  $m_{\pi\pi} \sim 400 \text{ MeV}$  instead of “meson<sub>1</sub>” is likely to enhance effect of CT as the system will propagate as a  $q\bar{q}$  before producing extra  $q\bar{q}$  pair.

If large  $-t$  and not large angle in c.m. is the parameter determining squeezing, doing scans at fixed large  $-t$  and changing  $s$  is a promising strategy (these cross sections are much larger than cross sections at  $\theta_{\text{cm}} = 90^\circ$ )

CT studies with the deuteron target (rescattering kinematics) - probes expansion at  $z \sim 2 \text{ fm}$

## *Discussed processes will allow*

✱ to discover that pattern of interplay of hard and soft physics in one of the most fundamental hadronic processes of large angle scattering

✱ compare wave function of different mesons and baryons

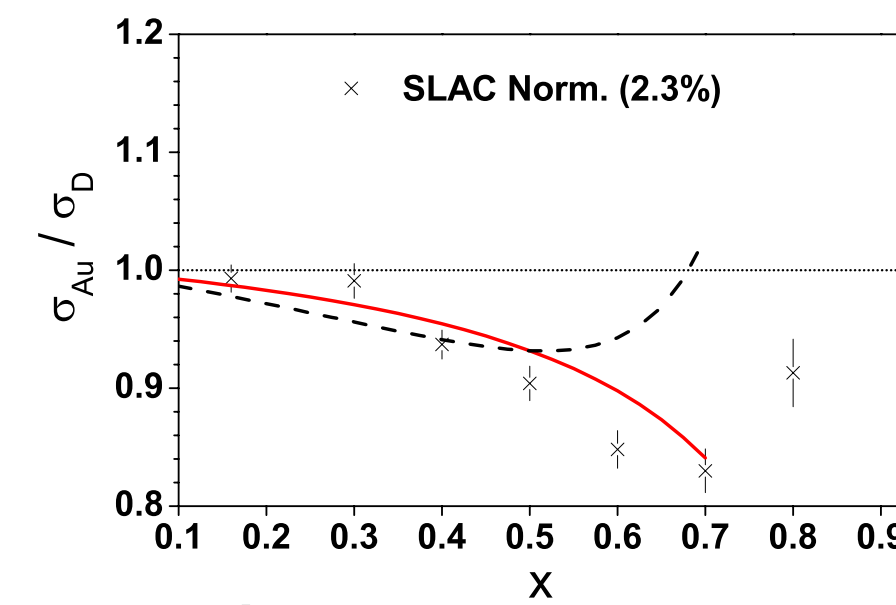
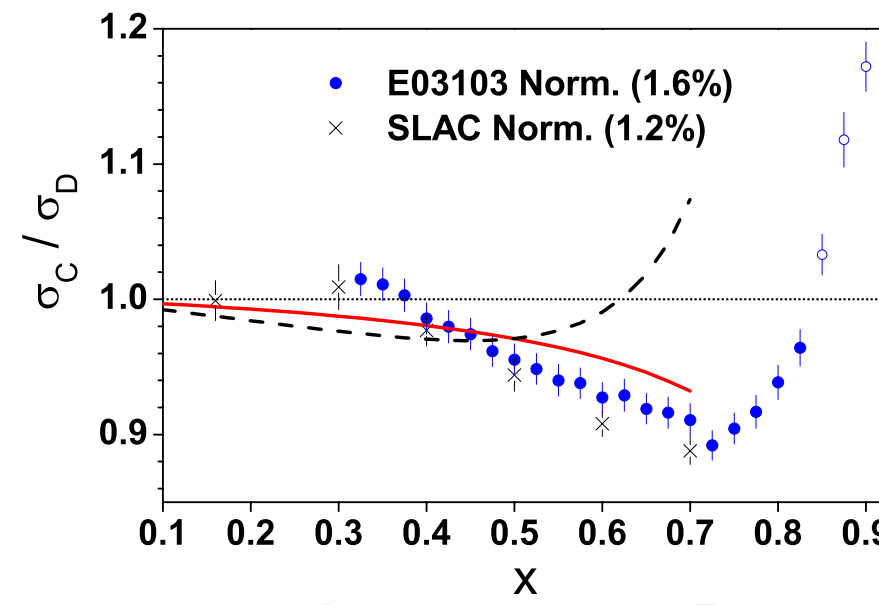
✱ map the space-time evolution of small wave packets at distances

$$| < z < 6 \text{ fm}$$

✱ test the role of chiral degrees of freedom in hard interactions

Analysis of high energy data: nucleons are weakly modified even when coming close - short - range correlations. Only evidence from large momentum transfer processes is the EMC effect.

Recent development (Frankfurt & MS10) - practically no hadronic EMC effect at  $x < 0.55$  - practically all effect is due to need to use correct Bj  $x$  and presence of Coulomb field in nuclei which carries finite fraction of the nucleus light cone momentum. Large  $x$  effect is proportional to  $\langle k^2 \rangle$  mostly short-range correlations.



red curves = Bj  $x$  + Coulomb

dashed curves = Bj  $x$  + Coulomb + Fermi motion

Need mechanism which kicks in only at large  $x$  corresponding to rare configurations in nucleons which are likely to be small size.

## Color coherence mechanism of the nucleon polarization Frankfurt & MS 85

nucleon in PLC have a weaker attraction to other nucleon



PLC's are suppressed in bound nucleons

$$\tilde{\psi}_A(i) \approx \left( 1 + \sum_{j \neq i} \frac{V_{ij}}{\Delta E} \right) \psi_A(i)$$

$$\Delta E \sim m_{N^*} - m_N \sim 600 - 800 \text{ MeV}$$

average excitation energy in the energy denominator.

PLC's suppression in deuteron/two nucleon short-range correlation

$$\delta_D(p) = \left( 1 + \frac{2 \frac{p^2}{2m} - \varepsilon_D}{\Delta E_D} \right)^{-2}$$

*Qualitative consideration* - consider dependence of deformation for the process  $e + A \rightarrow e + (A-1)^* + X$  [ $X=p$ , inclusive] on virtuality of the interacting nucleon  $p_{int}^2 \equiv (p_A - p_{(A-1)^*})^2$ . Analytically continue to  $p_{int}^2 = m_N^2$  expect no EMC effect. Natural to have deviations from the free nucleon case to be proportional in the lowest order to

$$(p_A - p_{(A-1)^*})^2 - m_N^2 \approx 2m \left( \frac{A}{A-1} \frac{p^2}{2m_N} + M_{A-1} + m_N - M_A \right)$$

Ciofi, Frankfurt, Kaptari, MS 07 performed detailed analysis including effects of nuclear excitations. Find the expression which is valid for all  $A$

$$\delta(p, E_{exc}) = \left( 1 - \frac{p_{int}^2 - m^2}{2m_N \Delta E} \right)^{-2}$$

Correct  $A$ -dependence and magnitude of the EMC effect. Need for correlation studies

# Conclusions



*Evidence for onset of CT in the diffractive pion production of double jets at FNAL, in  $J/\psi$  diffractive meson production at FNAL, in exclusive meson electroproduction demonstrates fruitfulness of the concept of spatially small dipole. Observation of CT in reactions with pions (COMPASS), antiprotons/protons (PANDA,..) would allow studies of Generalized Parton Distributions of various hadrons in hadronic interactions*



*Having few handles in the diffractive production of few hadrons by protons and pions will allow to investigate transitions between regimes of superstrong strong interaction and squeezing of hadrons and CT regime, dynamics of QCD interactions at the interface between hard and soft QCD, explore the quark-gluon structure of various mesons and baryons.*



*Hadron degrees of freedom are responsible for the EMC effect only for  $x > 0.55$  making color screening interpretation a natural candidate.*