Novel hard exclusive QCD phenomena with hadron beams:

new method to study generalized parton distributions, Color transparency, and hard meson - meson scattering

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Outline

- Introduction: Motivations and color transparency as a tool
- Brief summary of color coherence and color transparency
- Novel class of the processes hard 2→3 branching exclusive processes:
  - ☛ ***Effective way to test color transparency for hard 2→2 processes***
  - ☛ ***Measurement of GPDs of various hadrons in hadron induced processes***

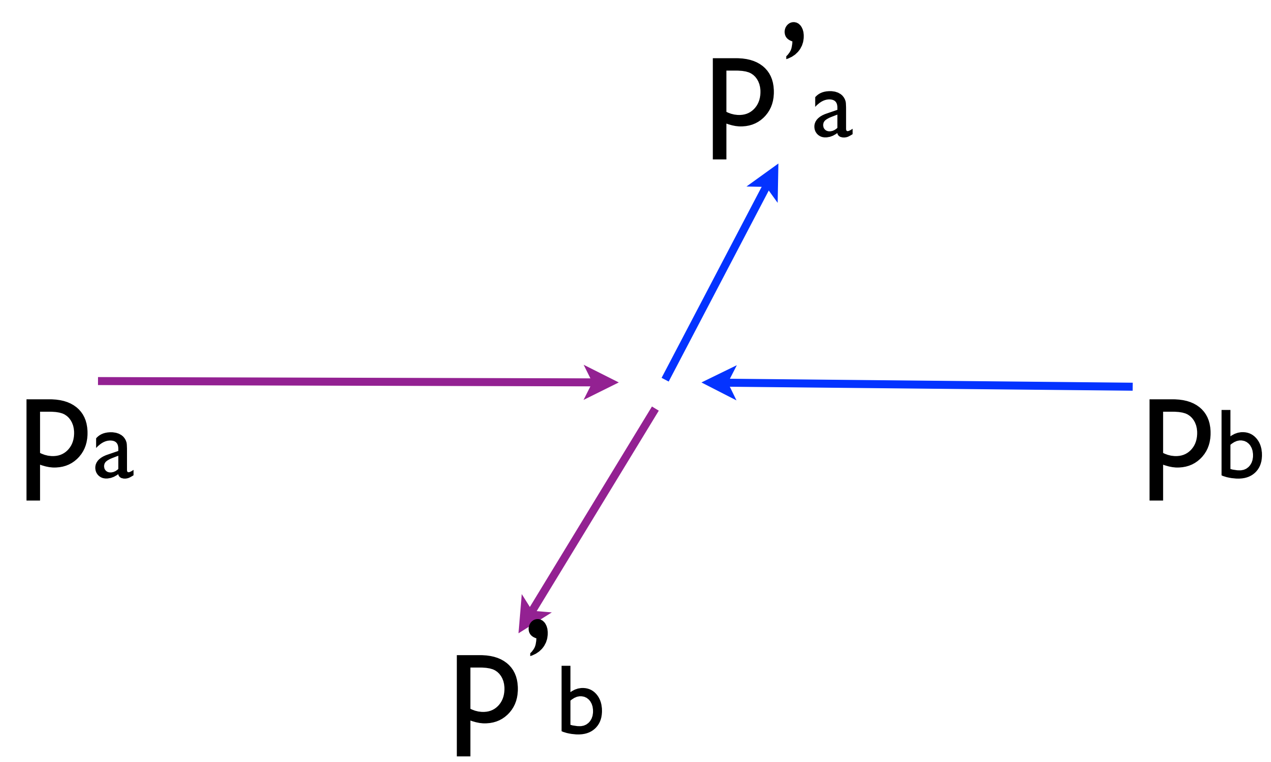
A big question: what is QCD dynamics of large angle (in c.m.) hadron - hadron scattering?

In inclusive processes like DIS, hadron production perturbative QCD works starting at $Q^2 \sim 2$ GeV^2.

What is corresponding parameter in large angle scattering?

Large t?

large c.m. scattering angle (t/s=const)??

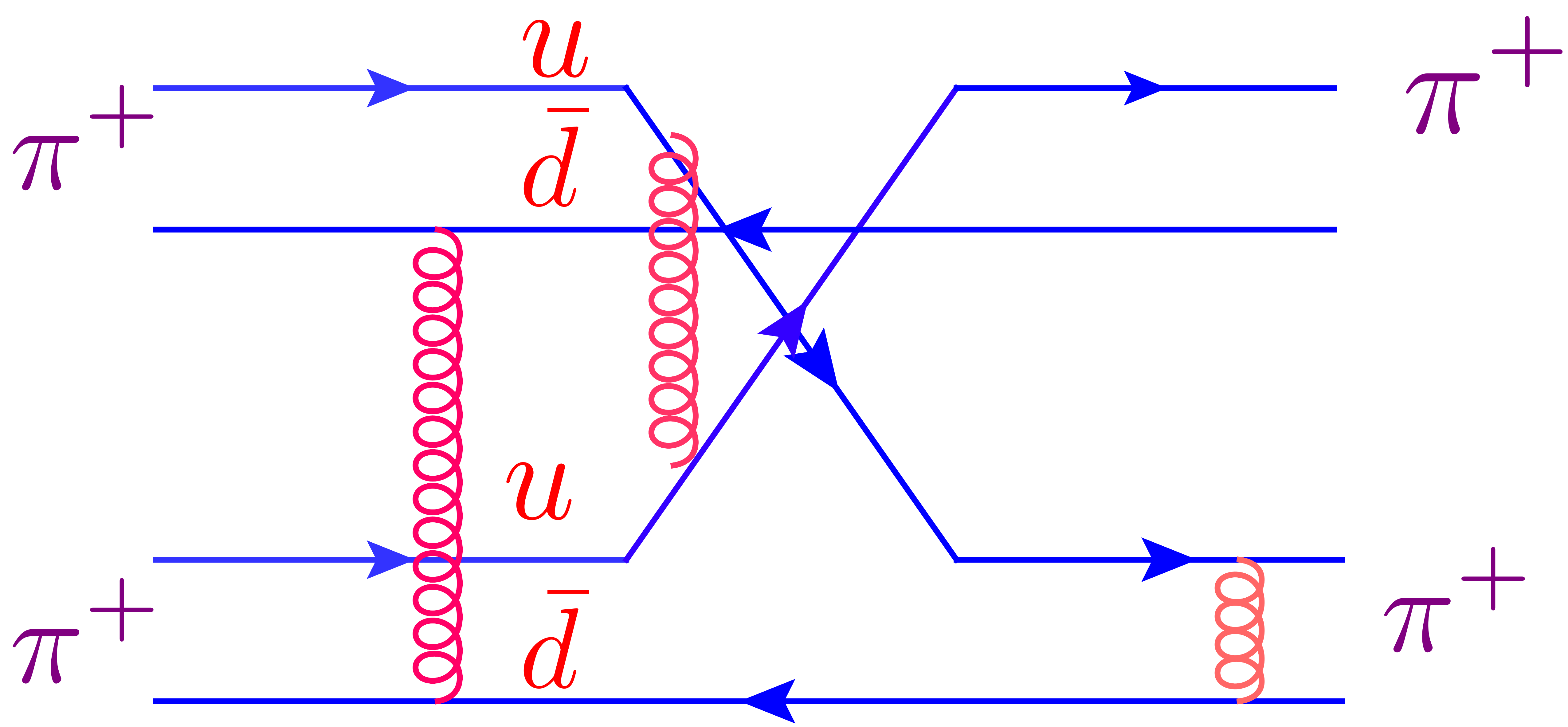


large angle scattering in c.m. frame

$$s = (p_a + p_b)^2$$
$$t = (p_a - p'_a)^2$$

pQCD diagrams for elastic large angle scattering -- minimal number of constituents + large momentum transfer between constituents

in the moment of interaction constituents of colliding hadrons are close together: $r_1 - r_2 \propto 1/\sqrt{-t}$



How to test? Use two important features of QCD

(a) In high energies hadron interacts in frozen configurations over large distances - coherence length $L_h = 2E_h/(M_n^2 - m_h^2) \gg R_A$

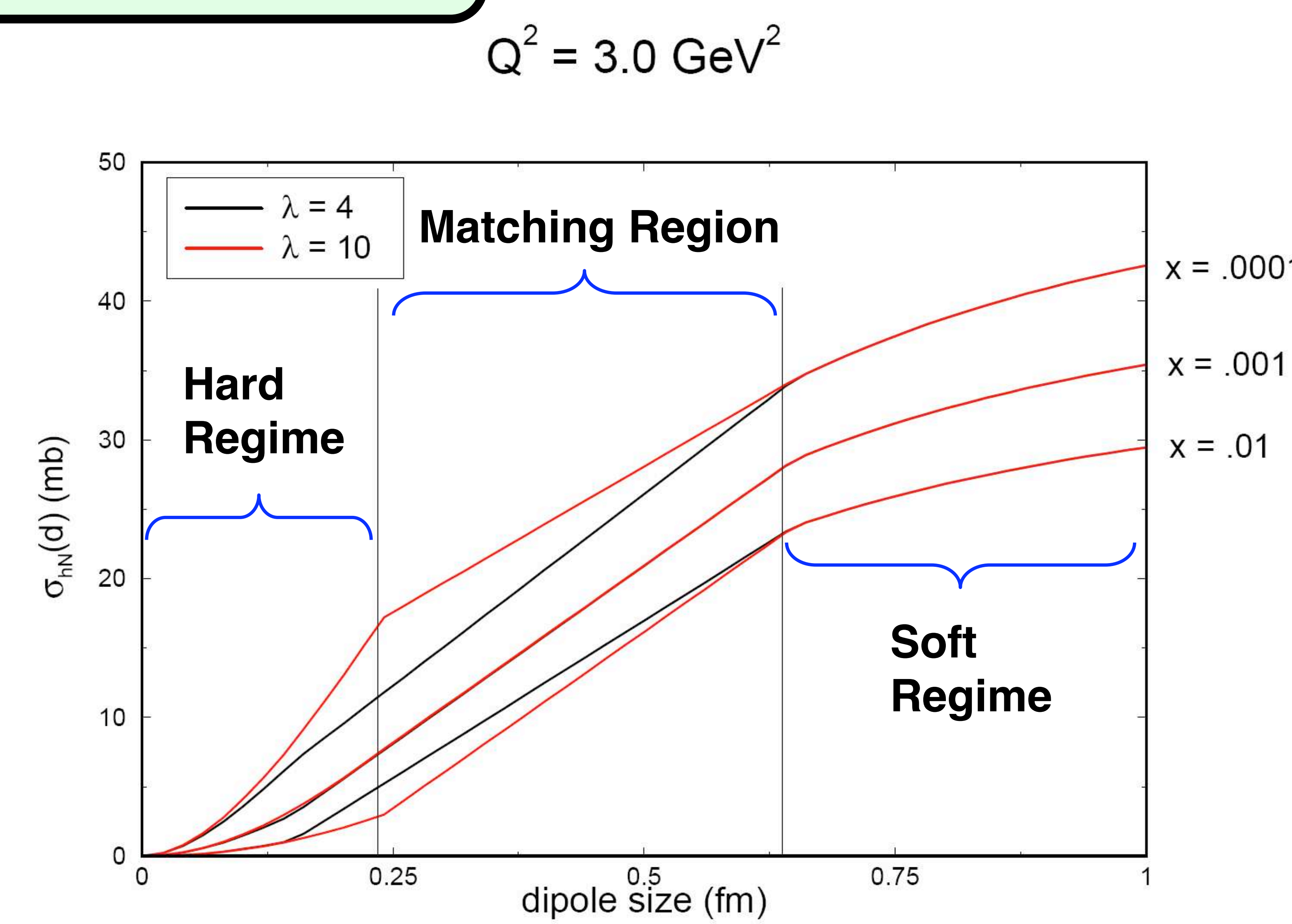
Projectile interacts in configurations with different interaction strength = color fluctuations) (relevant for AA collisions)

(b) Cross section of interaction of hadron in a small size configuration is small

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)

In the limit of very small sizes of projectile, interaction is small one expects

$$\sigma(h + A \to h + N + (A-1)) = A\sigma(h + N \to h + N)$$

referred to as color transparency (CT)

Observation of CT was suggested as a test of the origin of elastic large angle scattering by A.Mueller and S.Brodsky

Problem is that to reach the regime where $L_h > 2R_A$ where one expect to observe 100% CT one needs very large s where cross sections are very small + only proton beams are doable

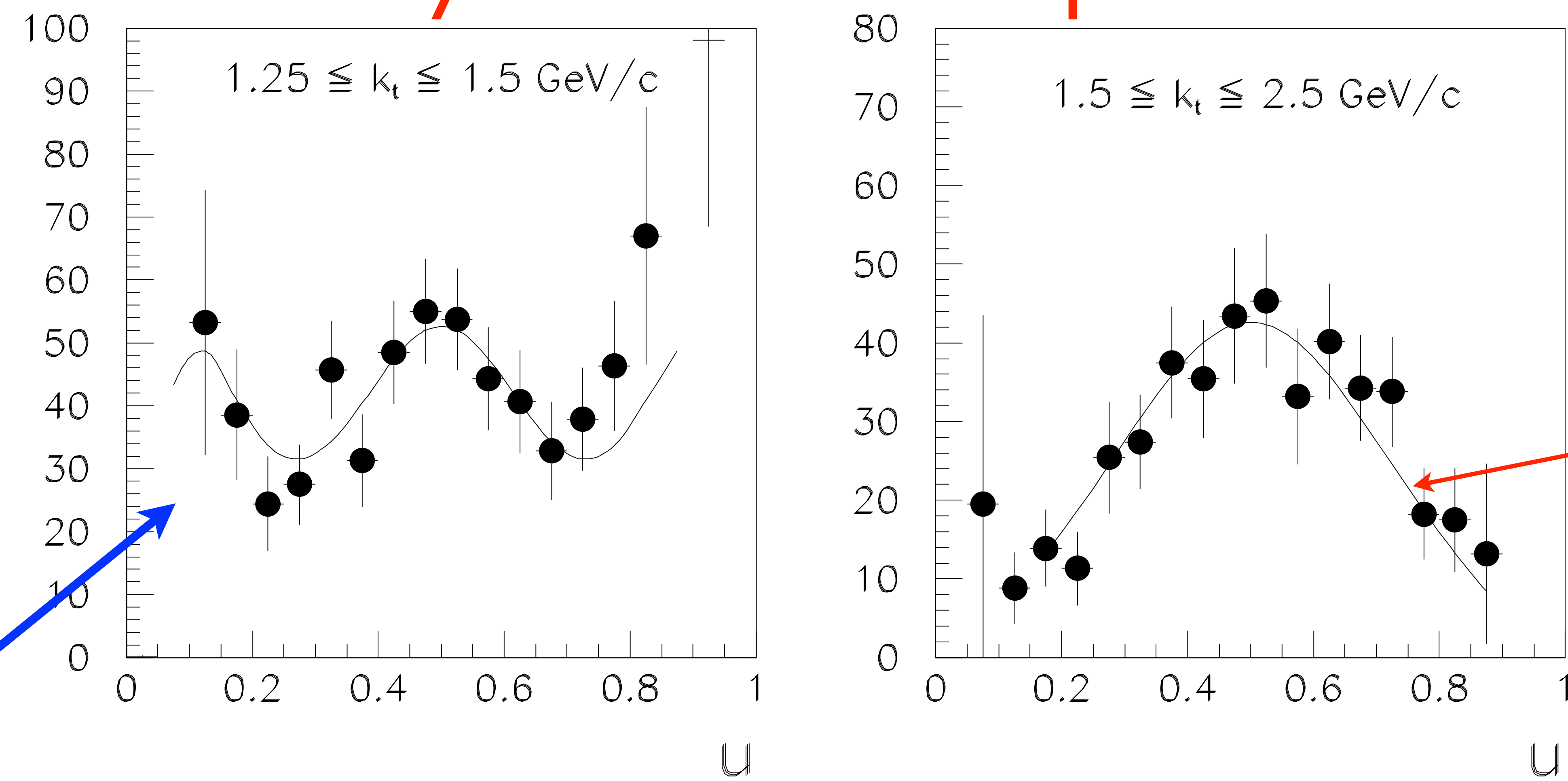
High energy color transparency is well established

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

First observation of high energy CT for $\pi + A \to$ "jet"+"jet" +A. (Ashery 2000):

Confirmed predictions of pQCD (Frankfurt ,Miller, MS93) for *A-dependence (much faster than in soft diffraction) & amplitude linear in A (100 % CT), distribution over energy fraction, u carried by one jet, dependence on p_t(jet), etc.*

MORE data is necessary in particular on the transition from soft to hard diffraction - NA61 & COMPASS may have data on tape!!!



prediction

$(\pi$ wave funct$)^2$

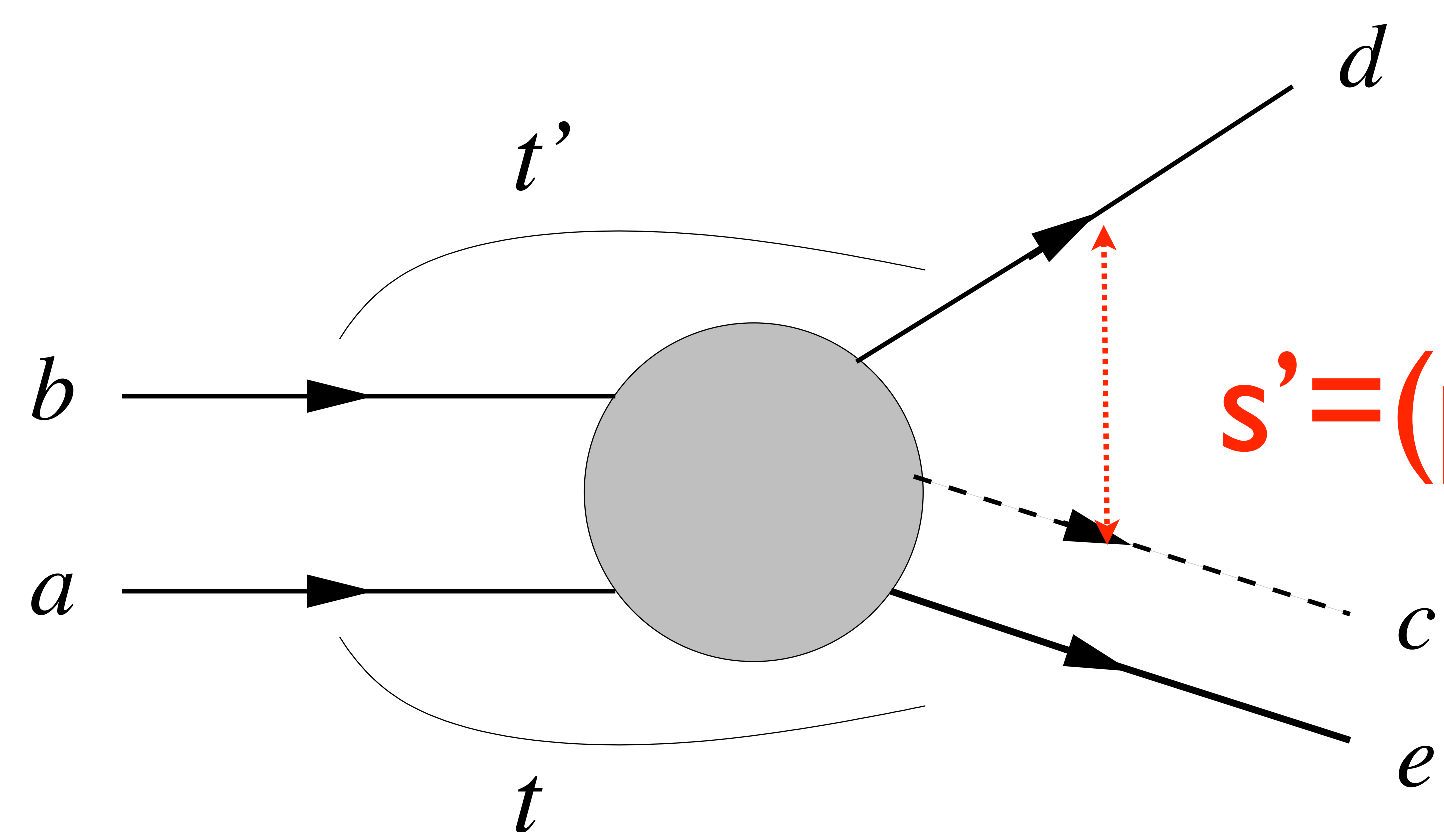
Squeezing occurs before the leading term $(1-u)^2u^2$ dominates!!!

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

Novel idea - to use high energy CT to study dynamics of intermediate energy large angle scattering using new type of hard hadronic processes

☀ - *branching exclusive processes* of large c.m. angle scattering off a "a color singlet cluster" in a target/projectile (MS94)

to study both CT (suppression of absorption) in 2 → 2 & hadron generalized parton distributions (GPDs) [will define GODs later)



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

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

Limit:

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

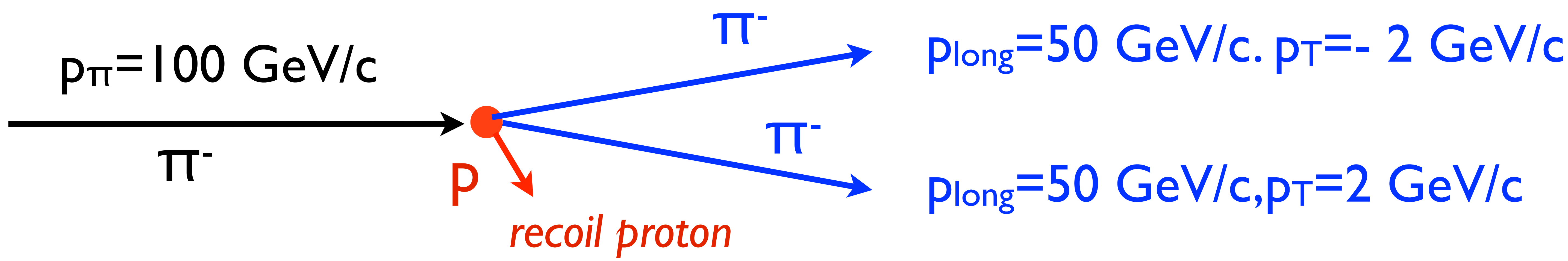
$-t = \mathrm{const} \sim 0$

➡ $s'/s = y \ll 1$,

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

Example of the discussed kinematics

one can
observe for example:



$\pi^- + p \rightarrow \pi^- + \pi^+ + n$

$\pi^- + n \rightarrow \pi^- \pi^- p$

reminder: CT seen in pion hard diffraction
already for $p_T \sim 1.5$ GeV/c

Major objectives

High energy color transparency: at what momentum transfer squeezing of hadron sizes takes place:

$2 \to 3$ hadronic processes with nuclear targets

Study of generalized parton distributions (GPD) in nucleons (and in the future in other hadrons) in non-vacuum channel with control of quantum numbers

Study of large angle (hard?) $2 \to 2$ hadronic processes for the simplest case of meson - meson scattering

many other interesting directions for study, for example

Chiral dynamics in Hard $a + b \to h + (h'\pi)_{threshold}$

2 →3 branching processes: first key steps of the study (using already existing COMPASS data)

- proton target - measure cross sections of large angle pion - pion (pion-kaon) scattering

- testing dynamics of 2 →2 scattering:
  at what $W_{\pi\pi}$, t scattering in small size configurations dominates - color transparency
  (unique feature of 2 →3 at large p_{inc} - no diffusion effects which reduce CT)

$$R(p_t) = \sigma(\pi^- Pb \to \pi^-\pi^- + A')/Z\sigma(\pi^- p \to \pi^-\pi^- + \Delta^{++})$$

A practical option use Fe and D targets and just require missing mass to be small enough (< 1.4 GeV)

- Use $R(p_t)$ to measure transverse sizes of the quark-gluon configuration in pions involved in the large angle scattering

If CT is observed

these data would allow to measure quark GPDs of nucleons in non-vacuum channel (defined a bit later) & pave the way to studies of GPDs of other hadrons

Use beams at energies between 20 and 200 GeV to measure pattern of freezing of space evolution of small size configurations

2 →3 branching processes is a natural generalization of the exclusive deep inelastic processes studied in the last 20 years for which QCD factorization theorems are proven using CT property of these reactions

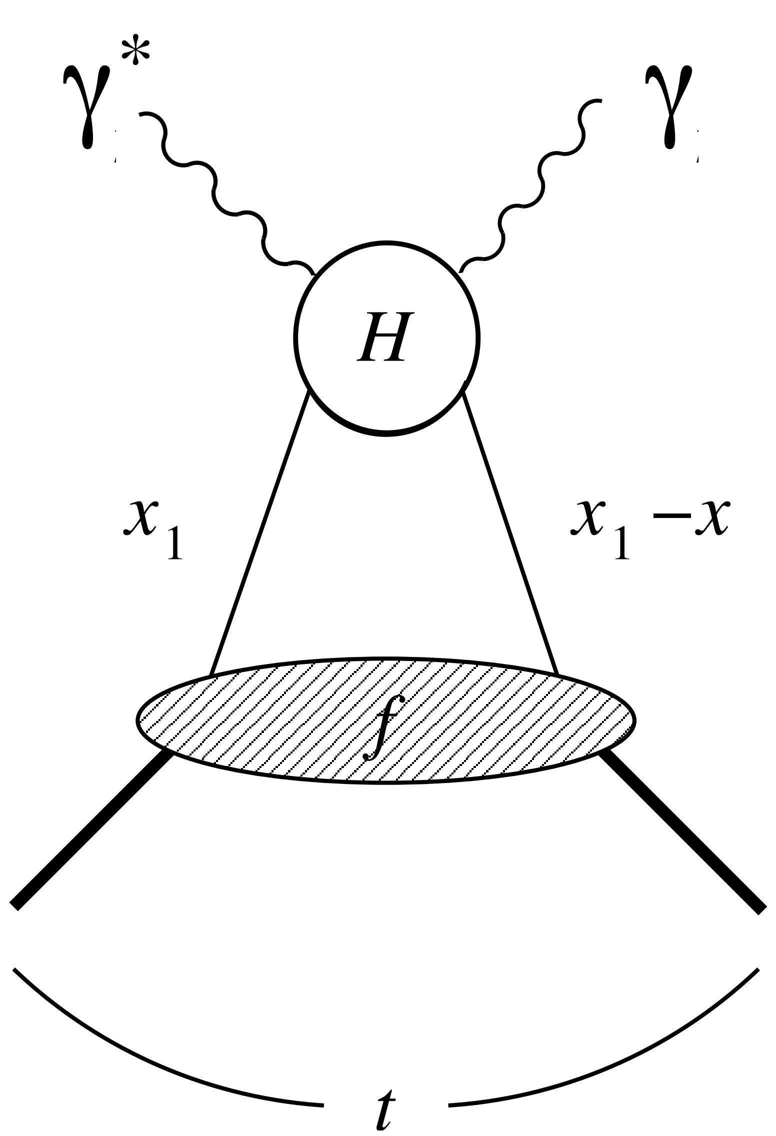
$$\gamma^* + N \to \gamma + N(baryonic\, system)$$ D.Muller 94 et al, Radyushkin 96, Ji 96, Collins &Freund 98

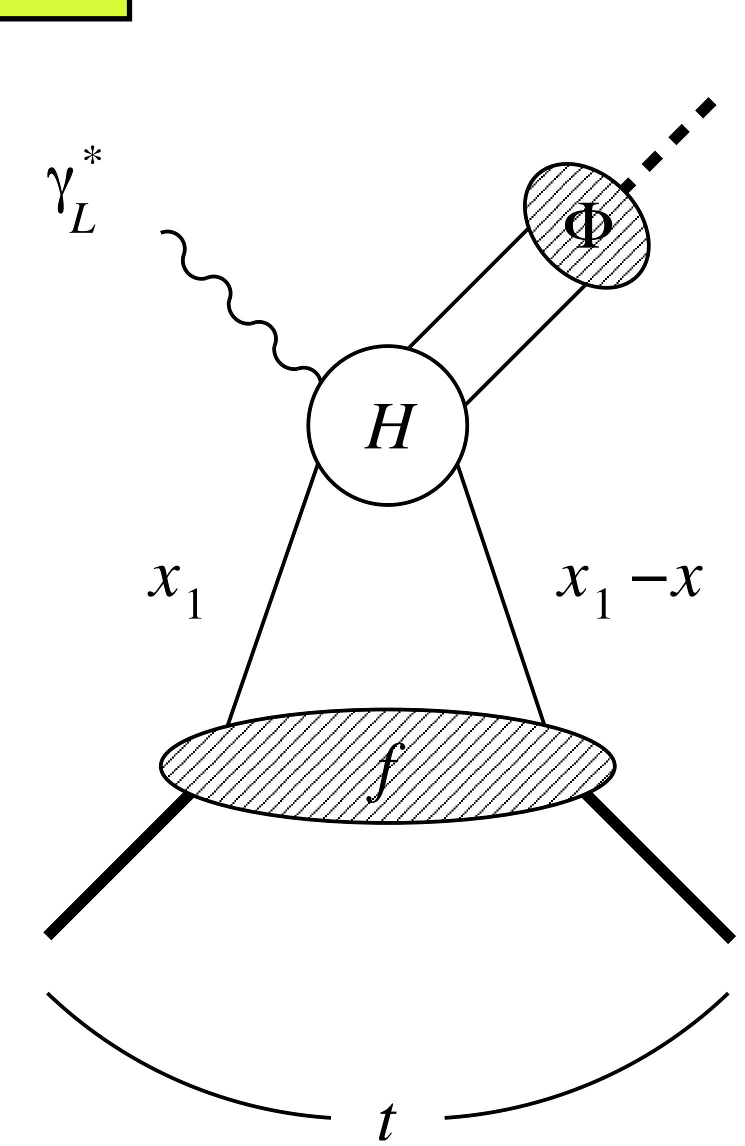
$$\pi + T(A,N) \to jet_1 + jet_2 + T(A,N)$$ Frankfurt, Miller, MS 93 & 03

$$\gamma_L^* + N \to "meson" (mesons) + N(baryonic\, system)$$ Brodsky,Frankfurt, Gunion,Mueller, MS 94 - vector mesons, small x

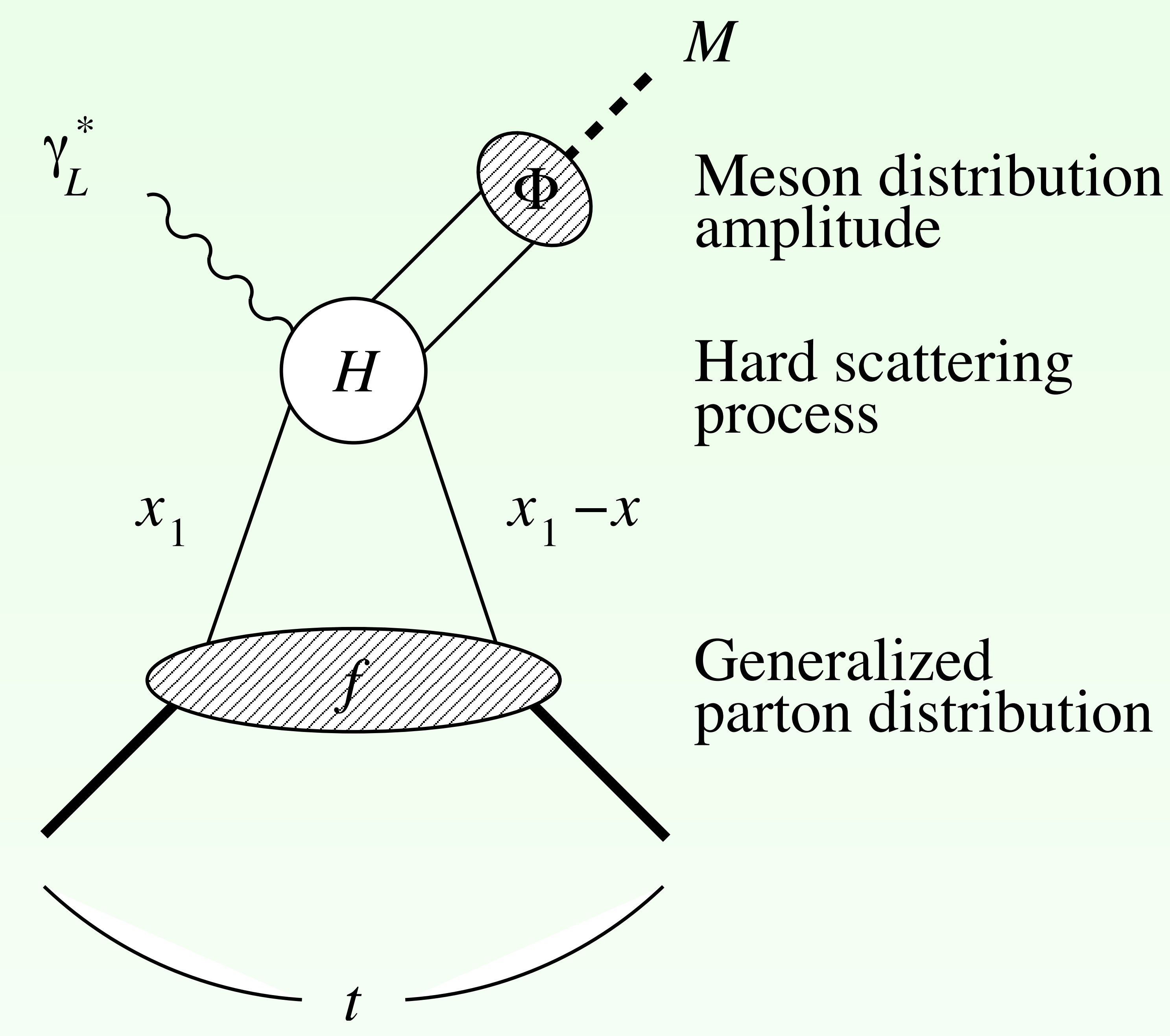
Collins, Frankfurt, MS 97 - general case

provide first effective tools for study of the 3D hadron structure





Generalized parton distributions
= form factor to remove quark with x_1 , p_t~Q
and put it back with $x' = x_1 - x$, $p_t' = p_t + q$ ($t \sim q^2$)
with the **same** transverse coordinate



Quark density

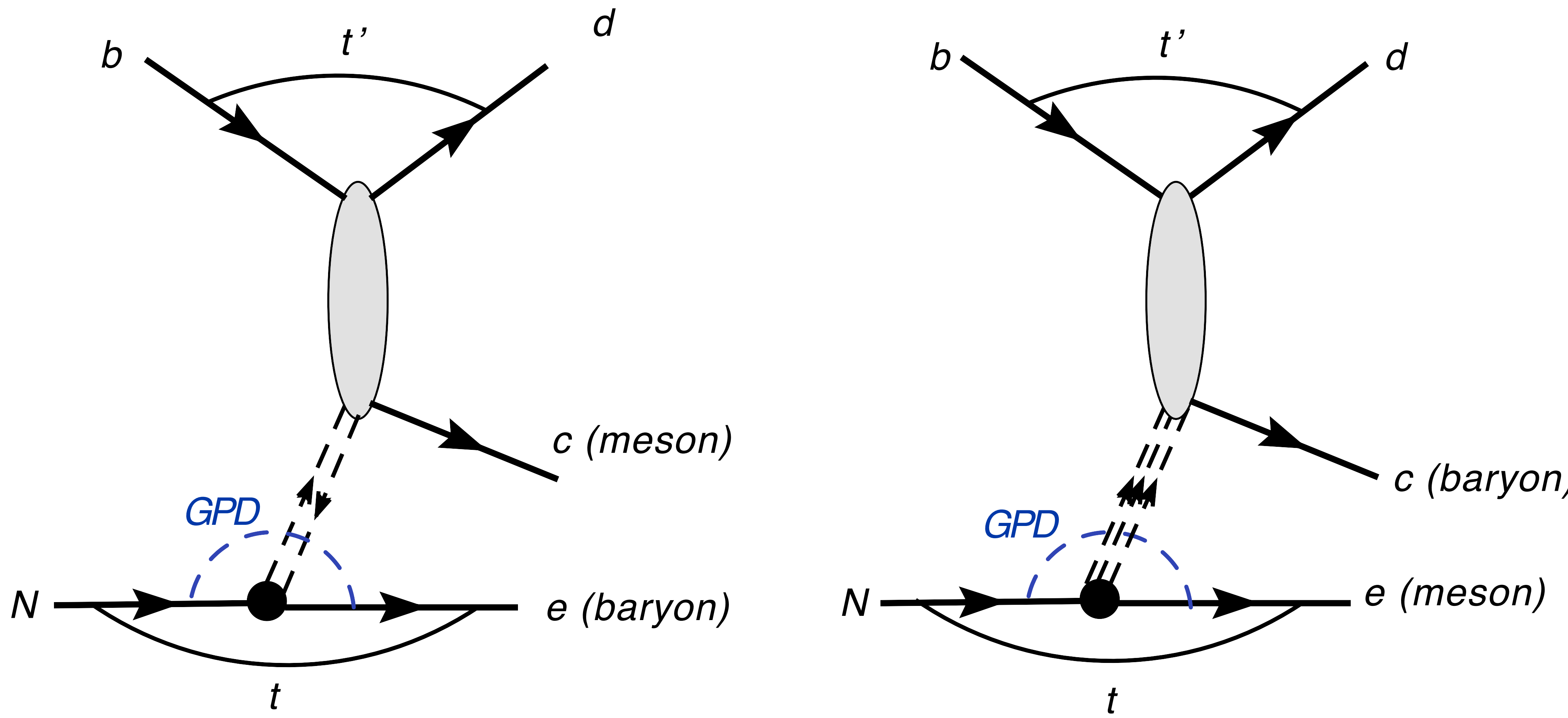
For a quark of flavor i - q_i (in case of charged mesons i stands for the flavor indices of the initial and final quarks)

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

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

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

New idea - if squeezing occurs in large angle 2 →2 process, factorization in 2 →3 processes



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)

⇓

2 →3 amplitude is convolution of several blocks:

$$\mathcal{M}_{\pi N \to \pi\pi N} = GPD(N \to N) \otimes \psi^{i}_{\pi} \otimes H \otimes \psi_{\pi_f} \otimes \psi_{\pi'_f}$$

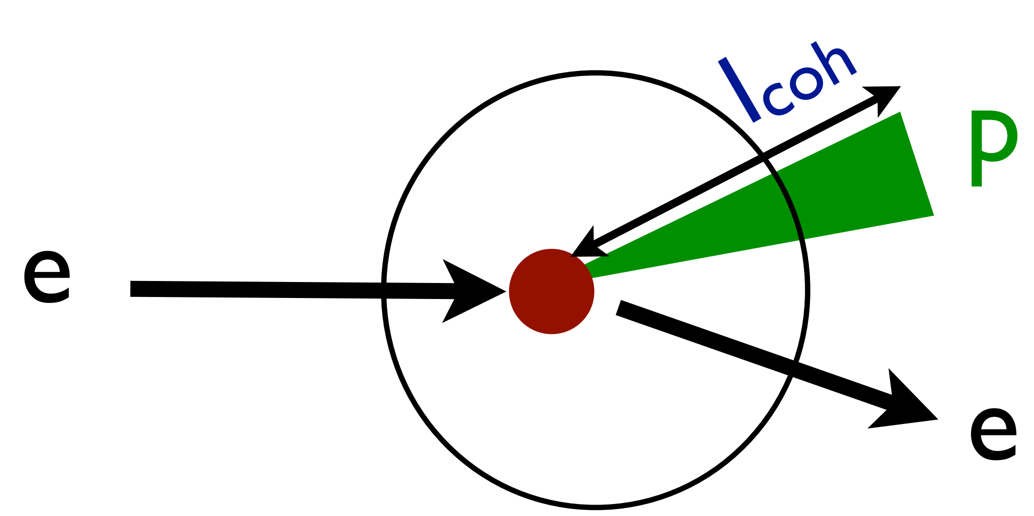
Main challenge for CT studies performed at intermediate energies is lack of freezing: |qqq> (|qq> is not an eigenstate of the QCD Hamiltonian. So even if we find an elementary process in which interaction is dominated by small size configurations - they are not frozen. They evolve - expand after interaction to average configurations and contract before interaction from average configurations (Frankfurt,Farrar,Liu, MS88)

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

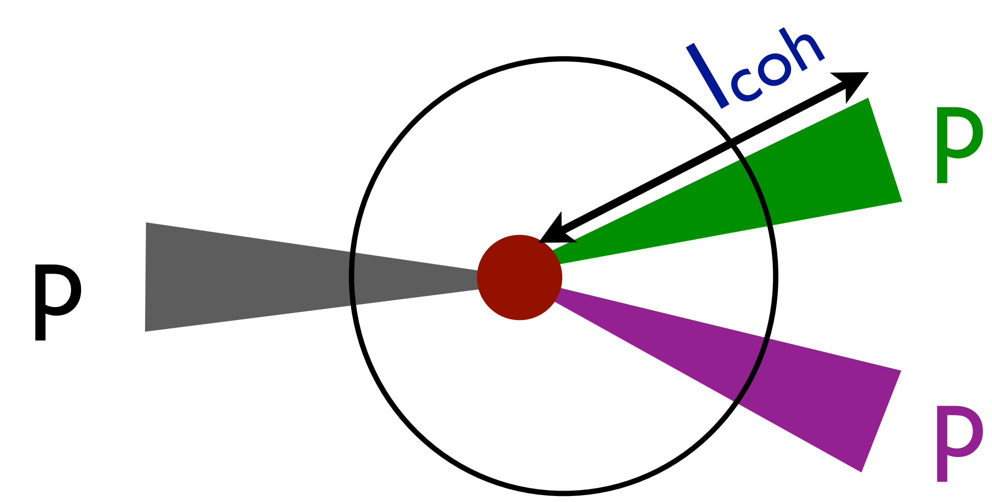
$$\sigma^{PLC}(z) = \left(\sigma_{hard} + \frac{z}{l_{coh}}\left[\sigma - \sigma_{hard}\right]\right)\theta(l_{coh} - z) + \sigma\theta(z - l_{coh})$$

← Quantum Diffusion model of expansion

$l_{coh} \sim (0.4\text{-}\ 0.8)$ fm E_h[GeV] *actually incoherence length*



eA→ ep (A-1) at large Q



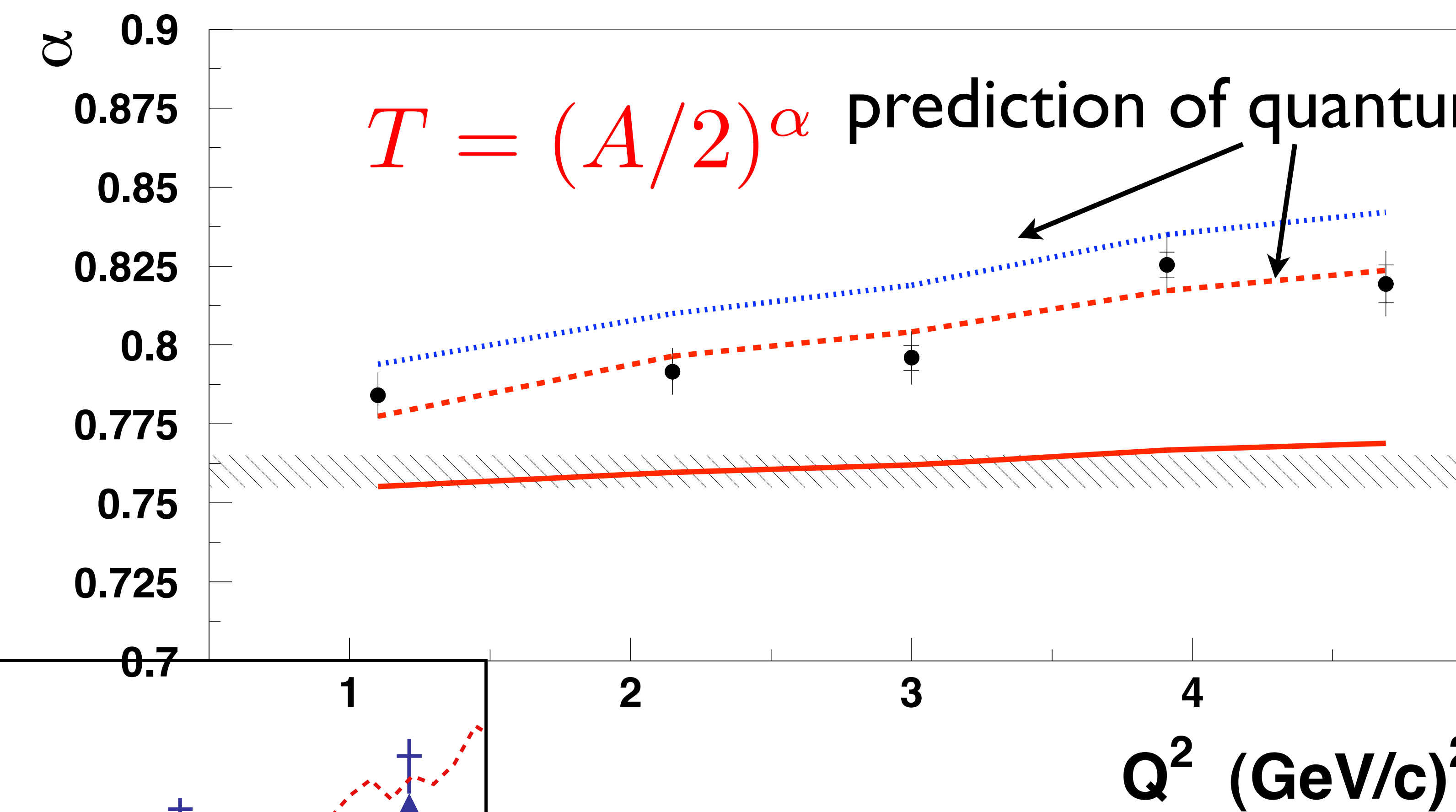
pA→ pp (A-1) at large t and intermediate energies

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 !!!

Experimental evidence for CT in electroproduction meson production

☀ $\gamma^* + A \to \pi A^*$ transparency increases with Q^2 (Dutta et al 07)

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



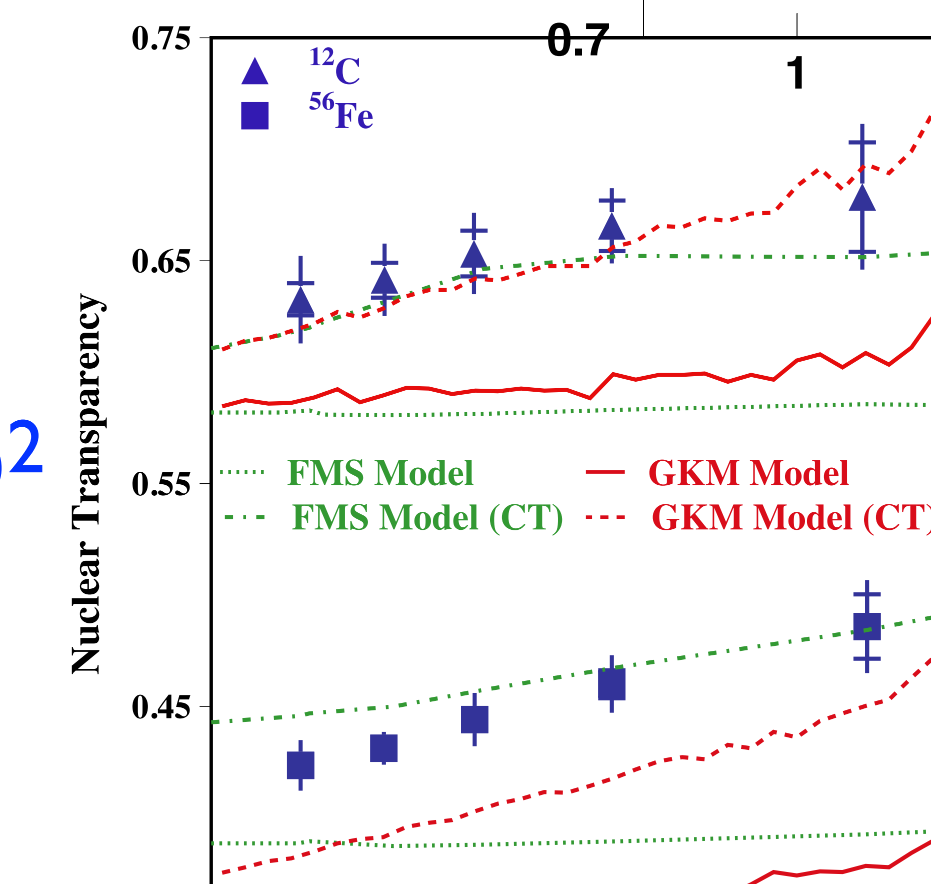
Ghent

Miller &MS

Glauber m.

☺ $\gamma^* + A \to \rho A^*$ also report increase of transparency with Q^2

El Fassi et al , 2012



The Jlab π,ρ data are consistent with CT predictions with coherence length $l_{coh} \sim 0.6 \text{fm}\, p_h$ [GeV] .Additional evidence for presence of small size components in mesons

➡ *For typical CERN kinematics freezing is very effective:*

$L_{coh}(p_\pi = 50\text{ GeV}) = 30\text{ fm} >> 2R_{Pb} = 12\text{ fm}$

$L_{coh}(p_\pi = 30\text{ GeV}) = 20\text{ fm} >> 2R_{Fe}$

Are large angle two body processes being point like probes?

So far we don't have a good understand the origin of one of **the most fundamental hadronic processes in pQCD -large angle two body reactions** (-t/s=const, s → ∞)

$\pi + p \to \pi + p, p + p \to p + p, \ldots$

Dimensional quark counting rules:

$$\frac{d\sigma}{dt} = f(\theta_{c.m.}) s^{(-\sum n_{q_i} - \sum n_{q_f} + 2)}$$

number of constituents in initial state

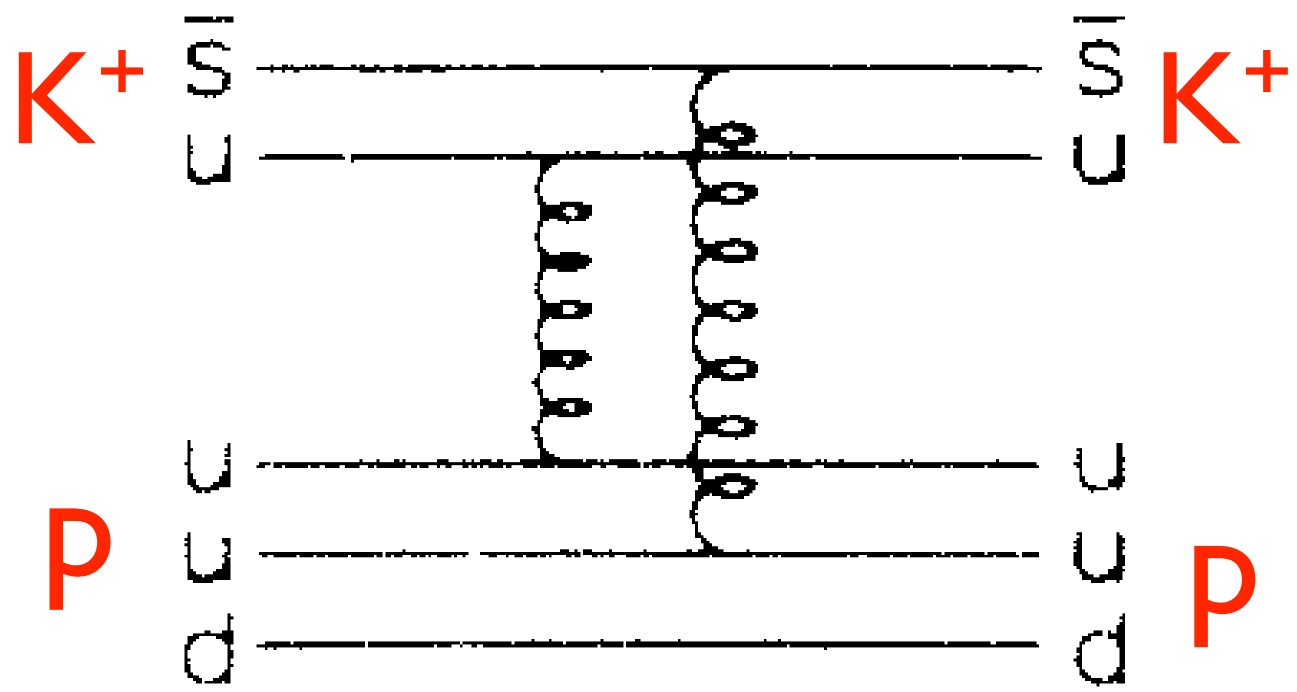
number of constituents in final state

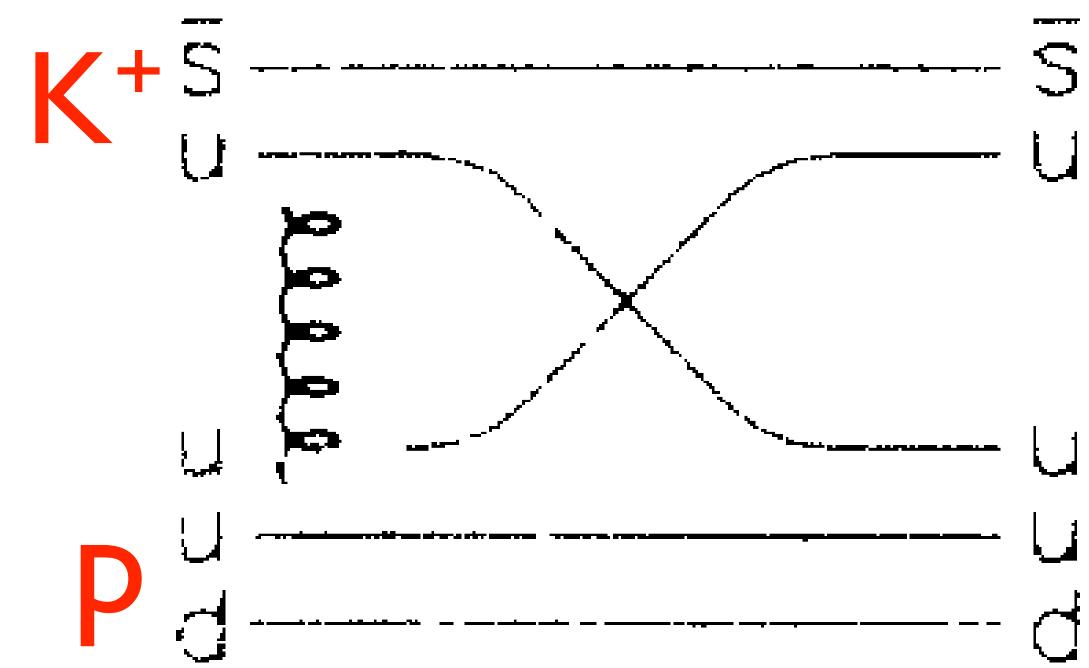
Quark counting expectations work pretty well:

TABLE V. The scaling between E755 and E838 has been measured for eight meson-baryon and 2 baryon-baryon interactions at $\theta_{c.m.} = 90^\circ$. The nominal beam momentum was 5.9 GeV/c and 9.9 GeV/c for E838 and E755, respectively. There is also an overall systematic error of $\Delta n_{syst} = \pm 0.3$ from systematic errors of $\pm 13\%$ for E838 and $\pm 9\%$ for E755.

No.	Interaction	Cross section E838	Cross section E755		n-2 ($\frac{d\sigma}{dt} \sim 1/s^{n-2}$)
1	$\pi^+ p \to p\pi^+$	132 ± 10	4.6 ± 0.3	n-2=8	6.7 ± 0.2
2	$\pi^- p \to p\pi^-$	73 ± 5	1.7 ± 0.2	n-2=8	7.5 ± 0.3
3	$K^+ p \to pK^+$	219 ± 30	3.4 ± 1.4	n-2=8	$8.3^{+0.6}_{-1.0}$
4	$K^- p \to pK^-$	18 ± 6	0.9 ± 0.9		≥ 3.9
5	$\pi^+ p \to p\rho^+$	214 ± 30	3.4 ± 0.7	n-2=8	8.3 ± 0.5
6	$\pi^- p \to p\rho^-$	99 ± 13	1.3 ± 0.6	n-2=8	8.7 ± 1.0
13	$\pi^+ p \to \pi^+ \Delta^+$	45 ± 10	2.0 ± 0.6	n-2=8	6.2 ± 0.8
15	$\pi^- p \to \pi^+ \Delta^-$	24 ± 5	≤ 0.12	n-2=8	≥ 10.1
17	$pp \to pp$	3300 ± 40	48 ± 5	n-2=10	9.1 ± 0.2
18	$\bar{p}p \to p\bar{p}$	75 ± 8	≤ 2.1	n-2=10	≥ 7.5

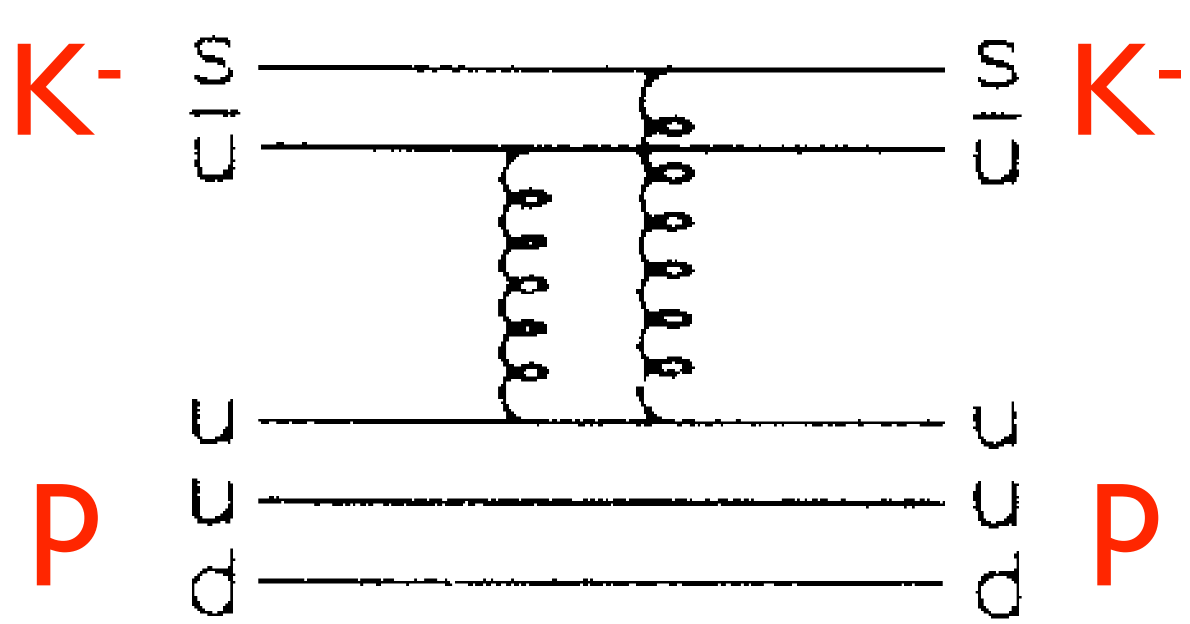
Another interesting observation - cross sections of reactions where quark exchanges is allowed have much larger cross section. For example -- pp elastic >> $\bar{p}p$ elastic

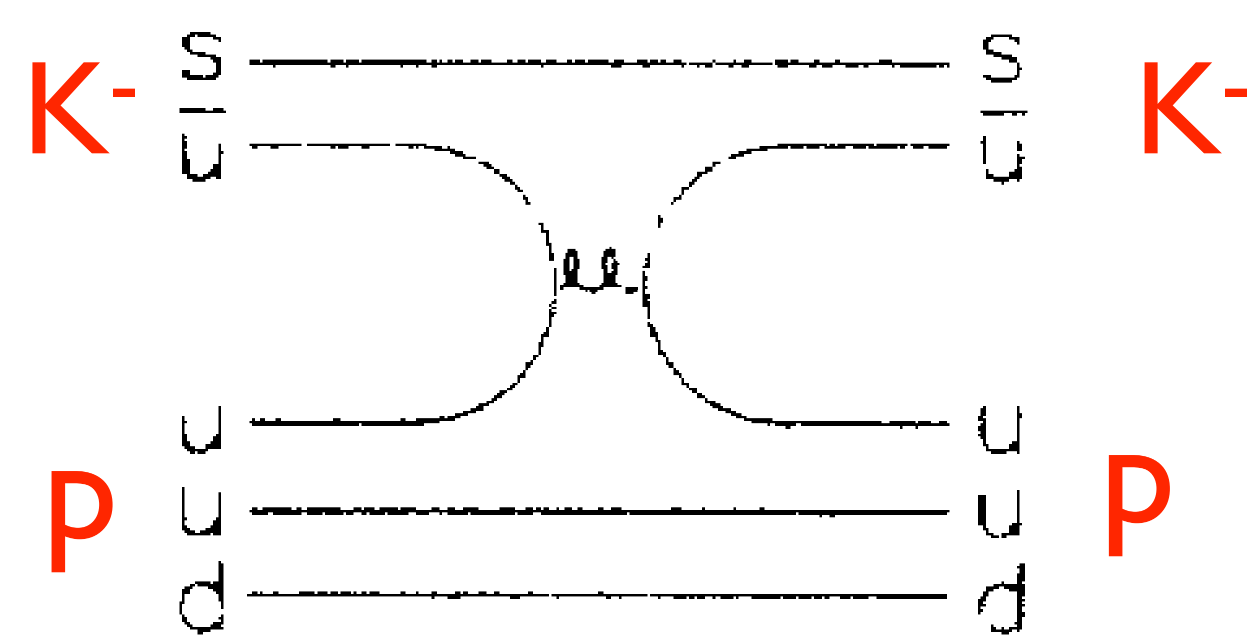




$K^+p \rightarrow K^+p$

$$\sigma(K^+p \rightarrow K^+p) \gg \sigma(K^-p \rightarrow K^-p)$$

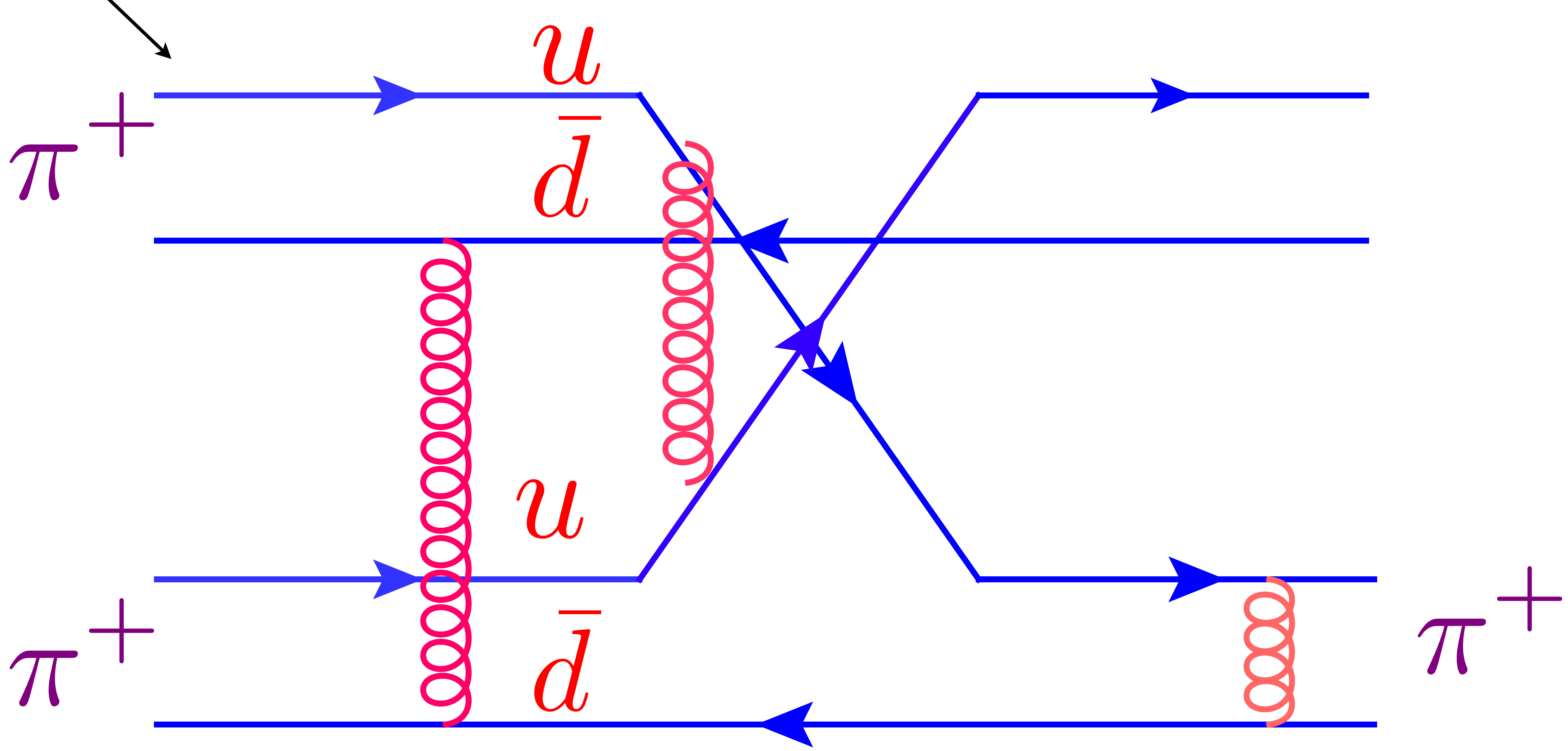




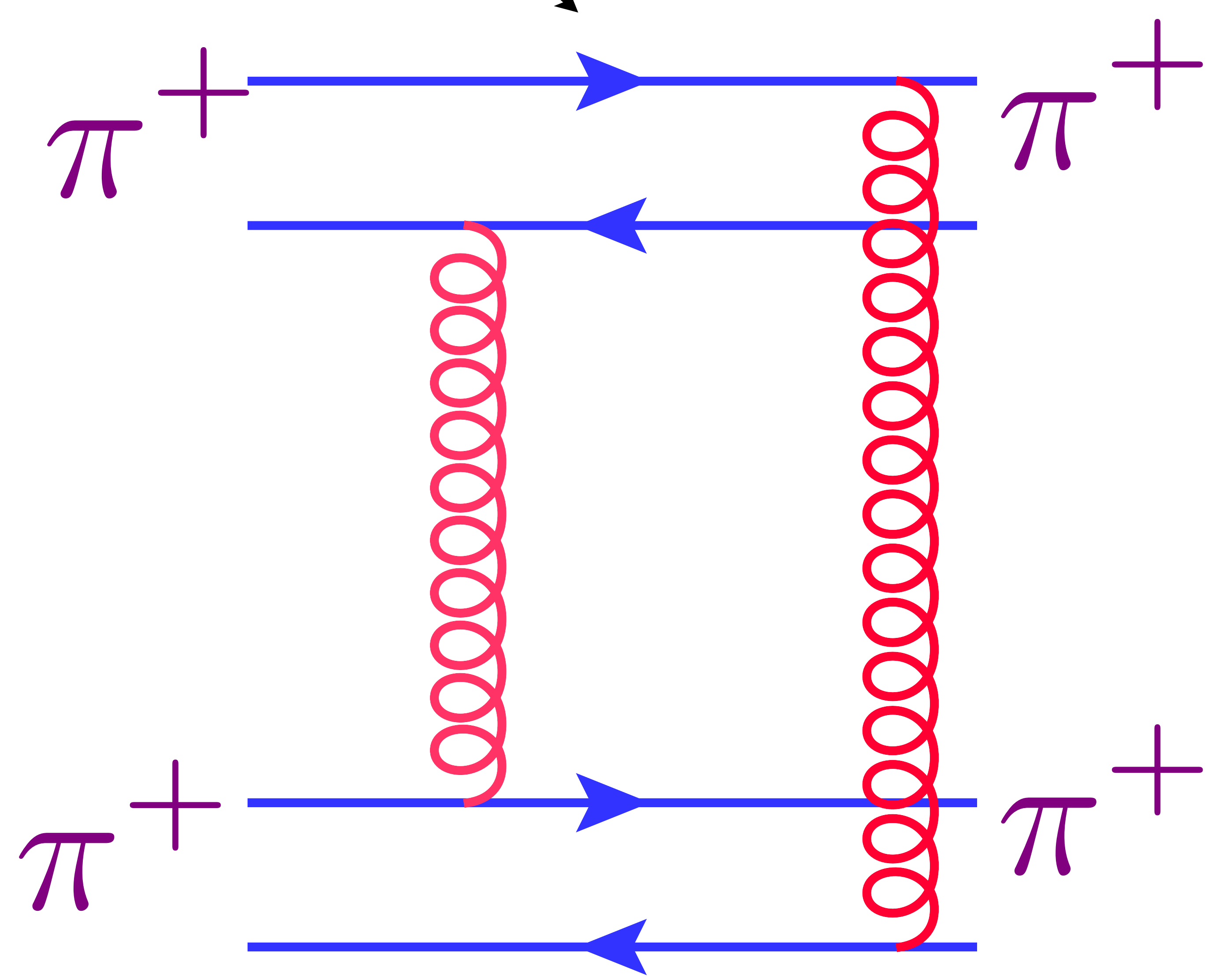
$K^-p \rightarrow K^-p$

Do these regularities indicates dominance of minimal Fock components of small size?

Theory (A.Mueller et al 80-81) - competition between diagrams corresponding to the scattering in small size configurations and pinch contribution (Landshoff diagrams)



$$\frac{1}{s^6}$$



$\frac{1}{s^5}$ + *Sudakov logarithm suppression of large size configurations* $\rightarrow 1/s^6$

??

- All mechanisms of large angle two body scattering predict squeezing of the colliding hadrons. However they lead to a different dependence of the squeezing rate on t.

- Landshoff mechanism cannot explain quark exchange dominance → it is possible that the rate of squeezing is stronger in processes where quark exchange is allowed

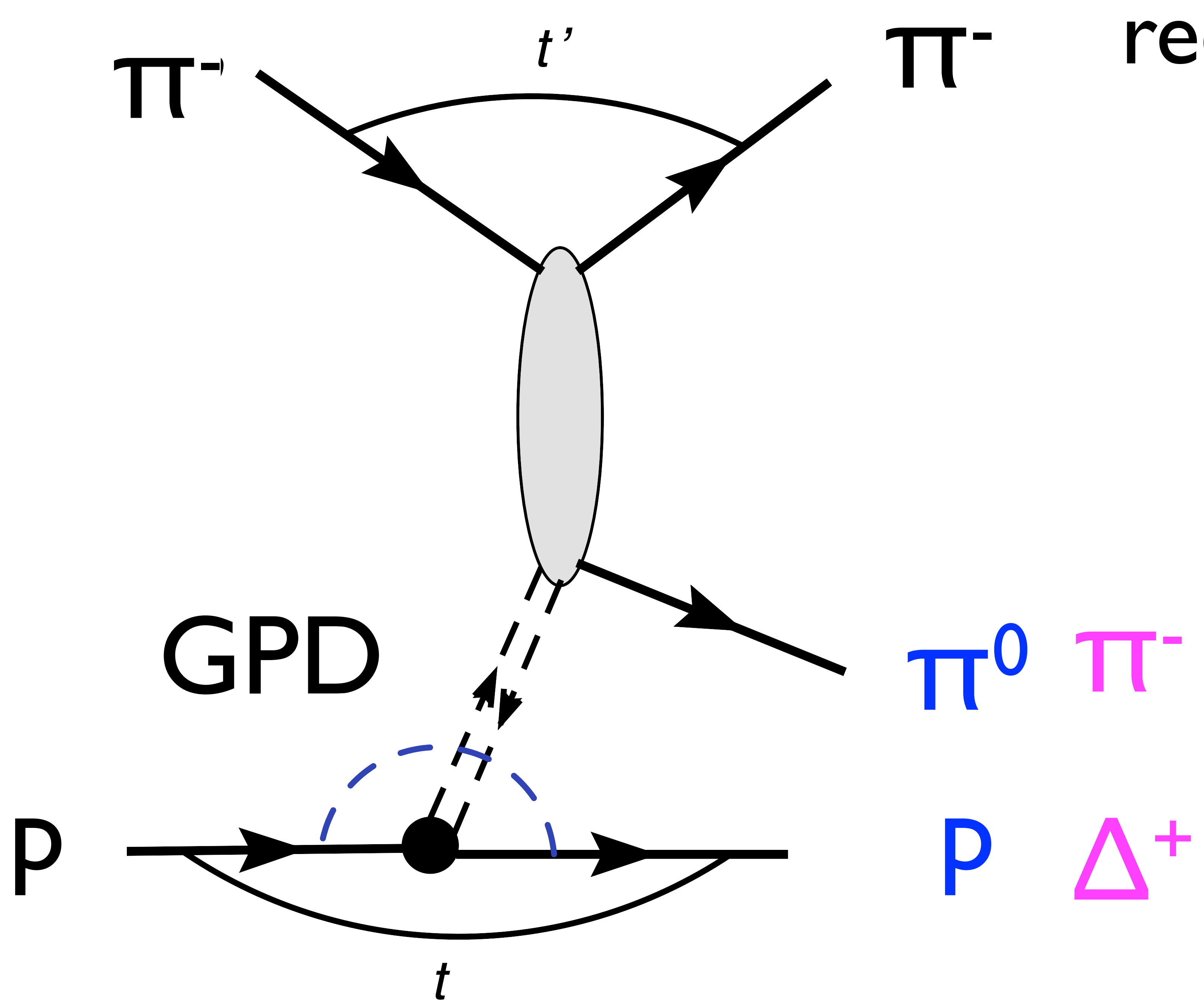
- Squeezed configurations are present with significant probability in mesons (evidence from observations of CT & and exclusive processes in DIS). Squeezing is likely to be more effective for mesons.

Expectations for the elementary reaction $\pi^- p \to \pi^- \pi \, N(\Delta)$

Kinematics

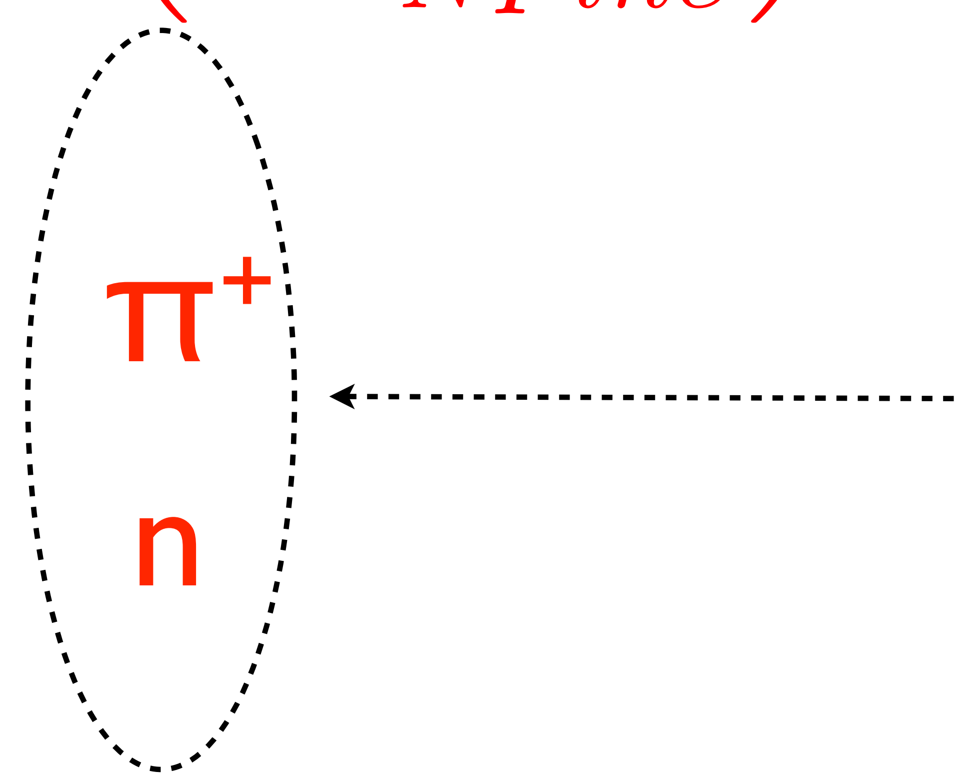
$$\frac{p(\pi_1)}{p_{inc}} = \alpha \sim 1/2, \frac{p(\pi_2)}{p_{inc}} = 1 - \alpha \qquad M^2_{\pi\pi} = \frac{p_t^2}{\alpha(1-\alpha)}$$

$$p_t(\pi_1) \approx -p_t(\pi_2) \geq 1GeV/c; -(p_t(\pi_1) + p_t(\pi_2)) \approx t \sim 0$$



recoil nucleon kinematics very similar to diffractive case

$$\sigma \propto \left(\frac{M^2_{\pi\pi}}{2m_N p_{inc}}\right)^2 \left(\frac{1}{M^2_{\pi\pi}}\right)^6$$



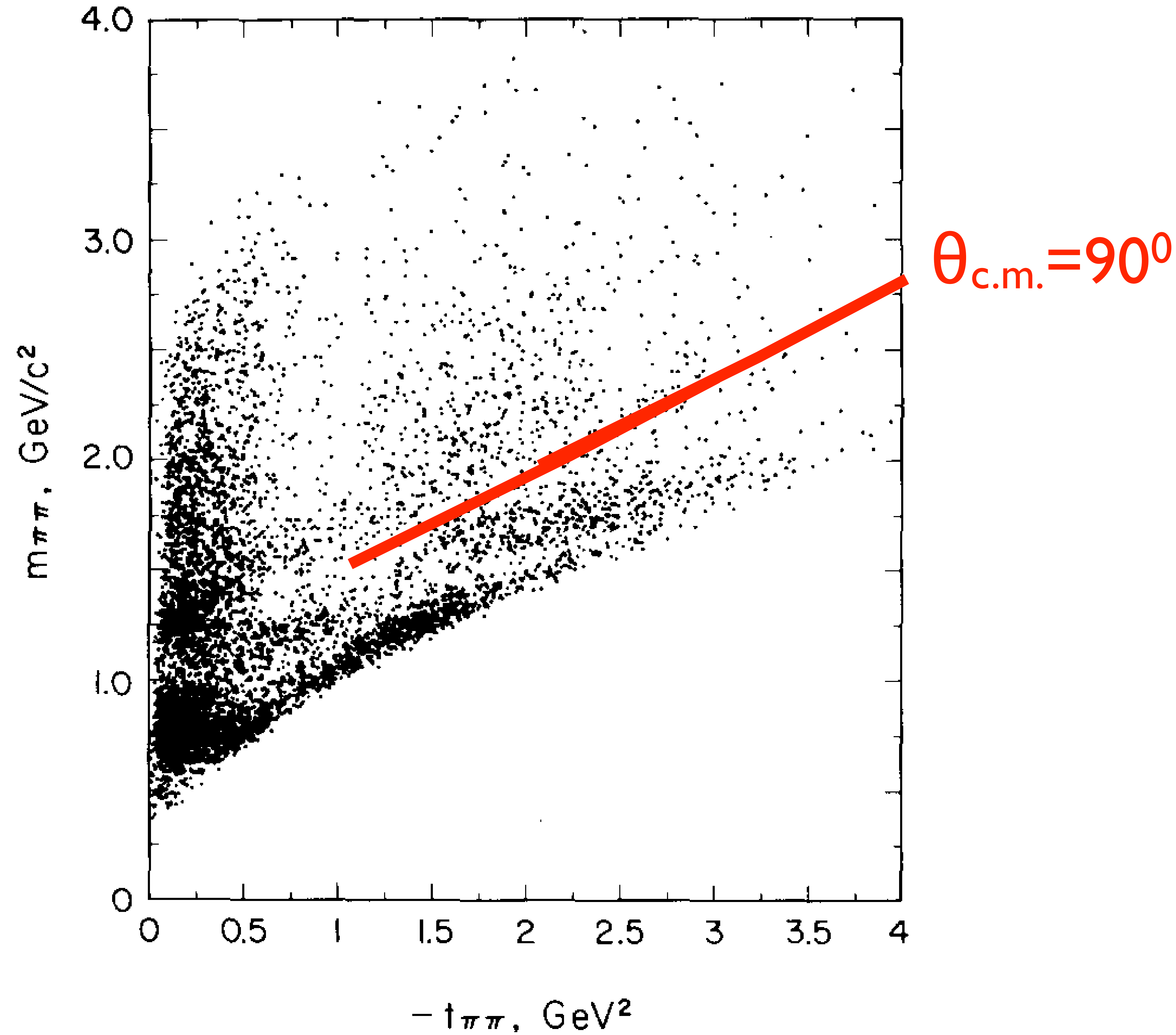
Bromberg et al 1981

p_{π^-}=100, 175 GeV/c

$M^2_{\pi\pi}$ up to 16 GeV^2, $\theta_{c.m.}=90^0$

Note - $\pi^-\pi^-$ -scattering - no s-channel resonances - early onset scaling?

C. Bromberg et al. / $\pi^- p \to \pi^+ \pi^- n$



100 GeV/c scatter plot of $-t_{\pi\pi}$ against $M_{\pi\pi}$ for $|t| < 0.10$ (GeV/c)^2.

Expectations for ππ elastic scattering blok based on dominance of quark exchange diagrams in the scattering amplitude

$$\sigma(\pi^-\pi^- \to \pi^-\pi^-) = \sigma(\pi^-\pi^0 \to \pi^-\pi^0)$$

$$\sigma(\pi^-\pi^- \to \pi^-\pi^-) \gg \sigma(\pi^-\pi^+ \to \pi^-\pi^+)$$

many other interesting channels: πρ, πη, $K^+\pi$, etc

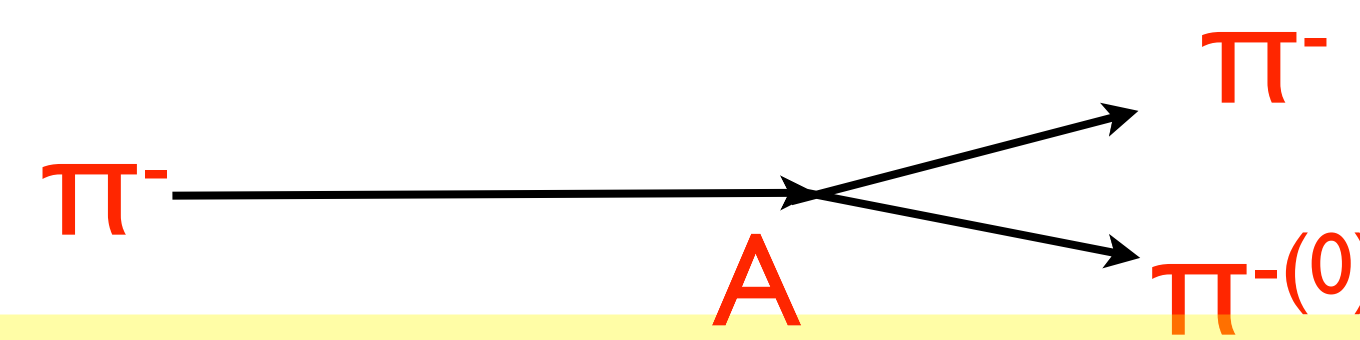
πρ production corresponds to different G-parity of quark - antiquark pair - different GPD . These nondiagonal GPDs are connected to flavor diagonal GPDs via SU(2). K^+ - related through SU(3).

CERN experiments are in position to produce the first data on high momentum transfer 2→3 processes. For small t pion exchange dominates - so interpretation is pretty simple independent of whether the process is hard

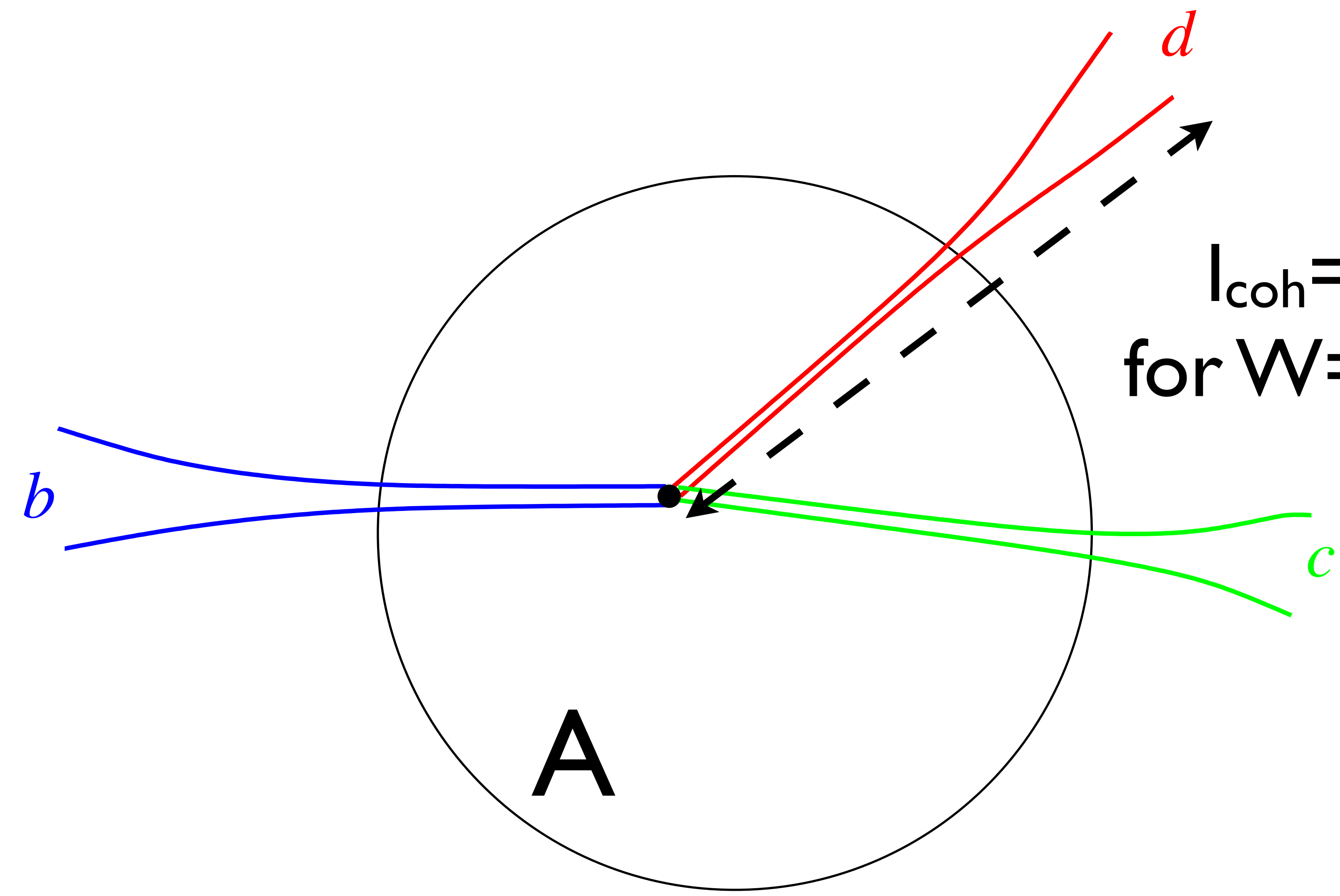
How to check that squeezing takes place and one can use GPD logic?

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

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



consider the rest frame of the nucleus



l_{coh}=60 fm
for W=20 GeV

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. Freezing remains strong for incident pion momenta down to 20 -- 30 GeV/c

If size is small, cross section is proportional to A - full CT

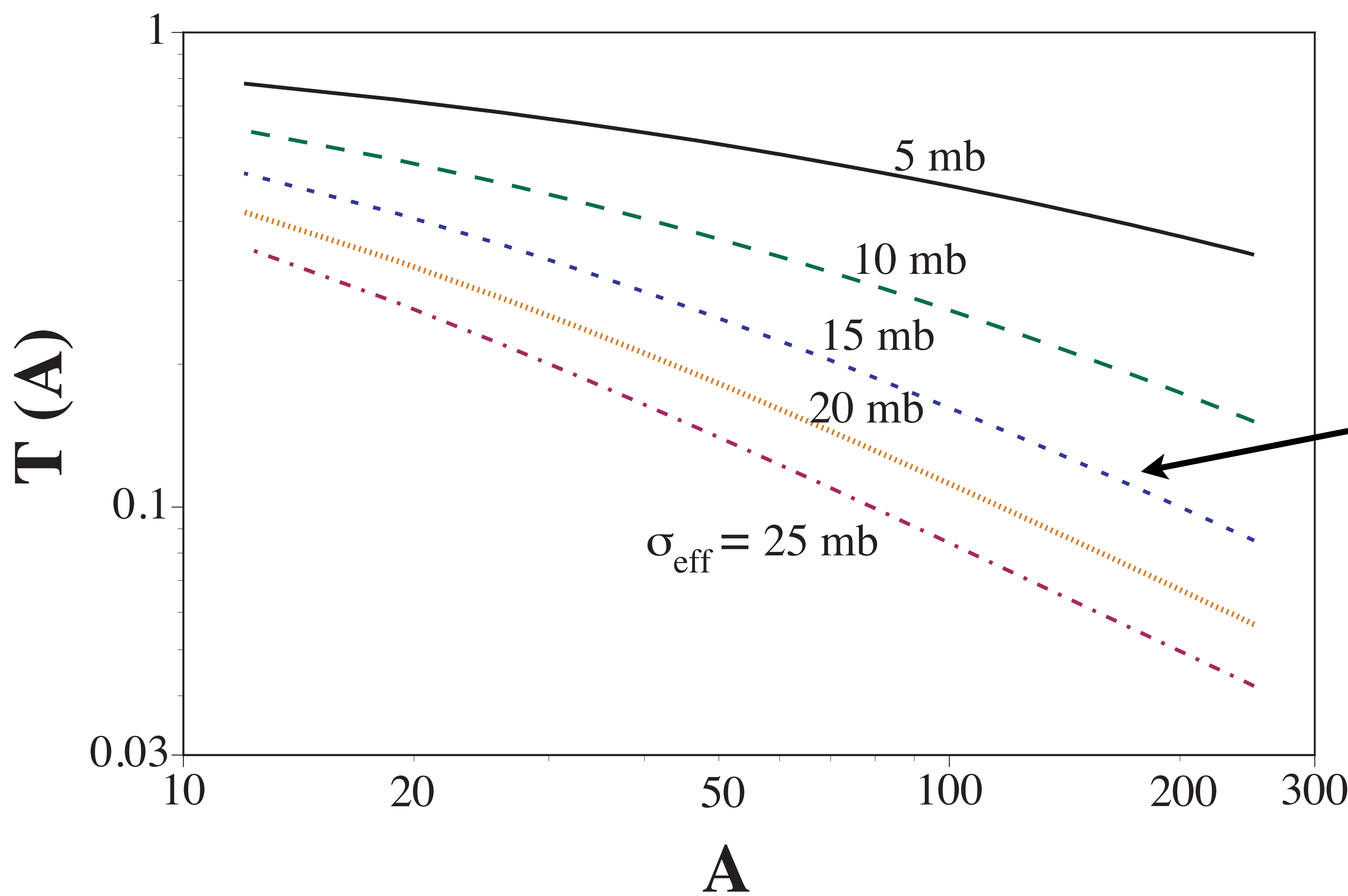
Qualitative advantage as compared to suggestion of Mueller and Brodsky to measure size using CT directly in 2→2 since for moderate t in difference from 2→3 it is impossible to suppress diffusion

$$T_A = \frac{\frac{d\sigma(\pi^- A \to \pi_1 \pi_2 A^*)}{d\Omega}}{Z \frac{d\sigma(\pi^- p \to \pi_1 \pi_2 N(\Delta))}{d\Omega} + N \frac{d\sigma(\pi^- n \to \pi_1 \pi_2 N(\Delta))}{d\Omega}}$$

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

$\vec{p}_b, \vec{p}_c, \vec{p}_d$ three momenta of the incoming and outgoing particles

$$\int \rho_A(\vec{r}) d^3 r = A \qquad P_j(\vec{p}_j, \vec{r}) = \exp\left(-\int_{\text{path}} dz\, \sigma_{\text{eff}}(\vec{p}_j, z) \rho_A(z)\right)$$



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

If squeezing is large enough one can measure quark-antiquark size using "small dipole" - nucleon cross section known from pQCD

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

Model independent way to extract T_A from proton and lead data: use $\pi^- A \to \pi^- \pi^0 A^*$, since

$$\sigma(\pi^- p \to \pi^- \pi^0\, p\ (N^*)) = \sigma(\pi^- n \to \pi^- \pi^0\, n\ (N^*))$$

and make the same missing energy cut (reasonably small) for proton and lead data.

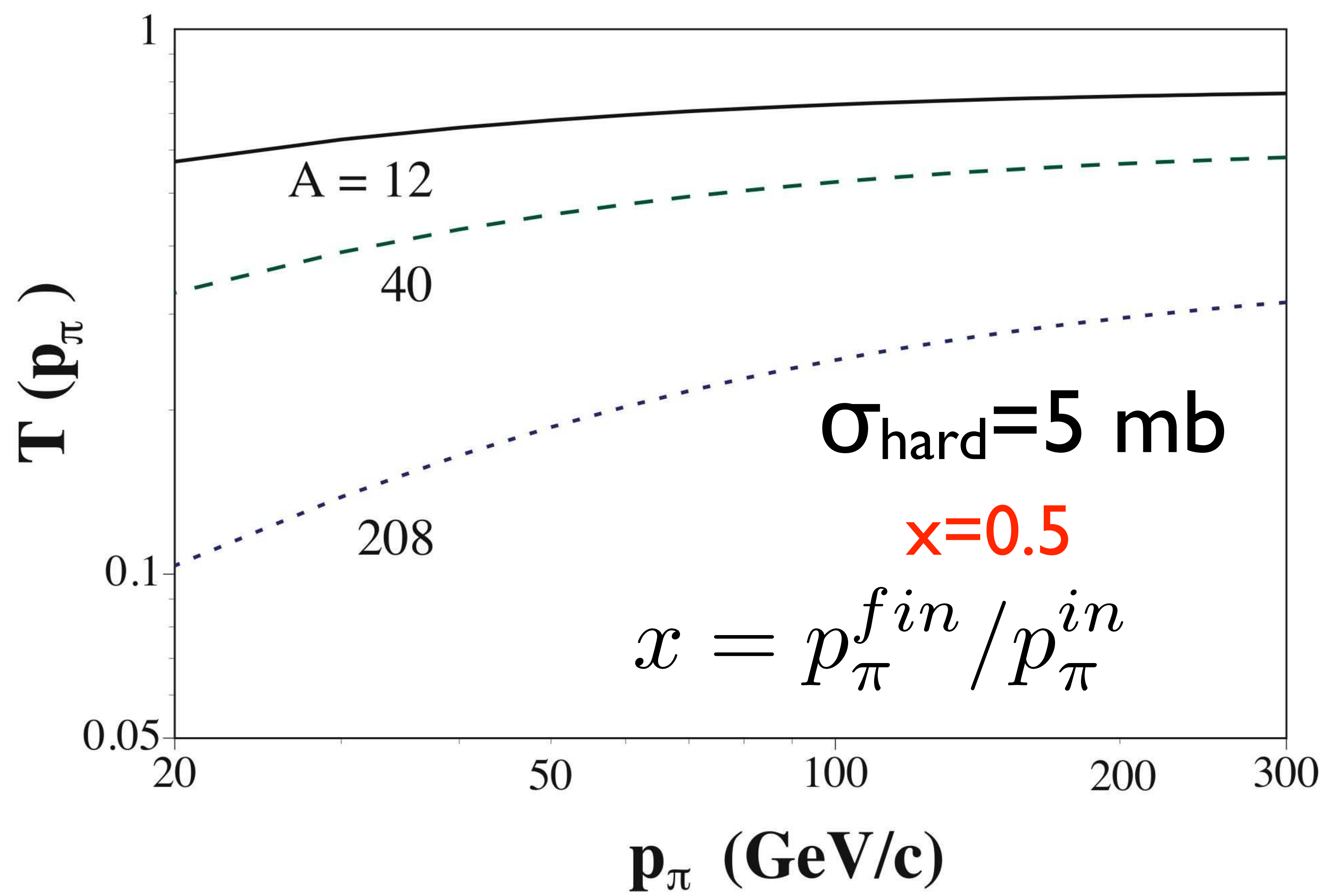
Another option: comparing proton (deuteron) and nuclear targets for other $\pi\pi$ channels: *study p_t dependence of T_A for the same cut on E_{mis}. Relies on factorization of GPD blob. Onset of CT = increase of T_A with p_t.*

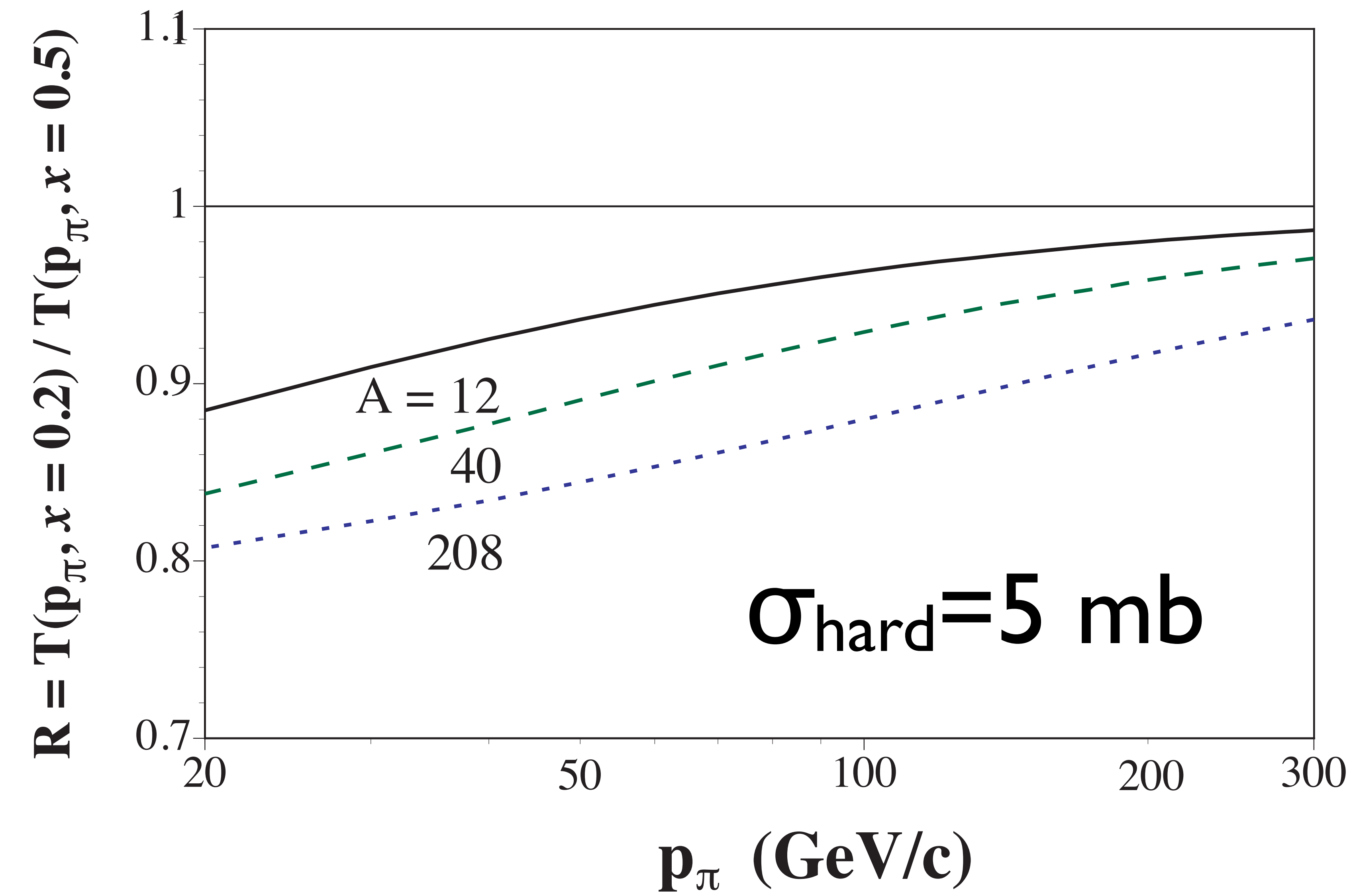
$$\sigma^{PLC}(z) = \left(\sigma_{hard} + \frac{z}{l_{coh}}\left[\sigma - \sigma_{hard}\right]\right)\theta(l_{coh} - z) + \sigma\theta(z - l_{coh})$$

Quantum Diffusion model of expansion

Use $l_{coh} \sim 0.6$ fm E_h[GeV] which describes well CT for pion and rho electroproduction

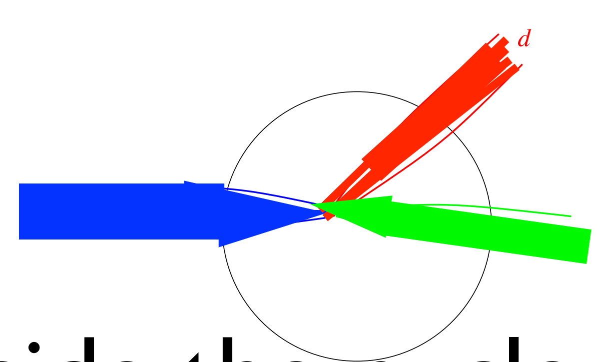
"Defrosting" point like configurations - energy dependence for fixed s',t'



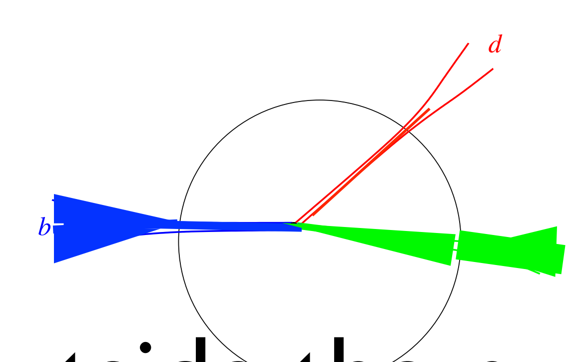


expansion and contraction of wave package

decrease of p_π



inside the nucleus



outside the nucleus

Conclusions

At the very least, analysis of the discussed processes would allow

to measure for the first time cross sections of large angle pion - pion scattering

Resolve long standing puzzle of sizes of configurations involved in large angle scattering

If CT is observed, it would be possible

to measure several nucleon quark GPDs.

to measure quark GPDs of other hadrons and photon (tagged photons in DIS?)

to use beams of lower energies to map space time evolution of small wave packets at distances $1 < z < 6$ fm.