Novel hard exclusive QCD phenomena with COMPASS:

new method to study GPDs, Color transparency, hard meson - meson scattering

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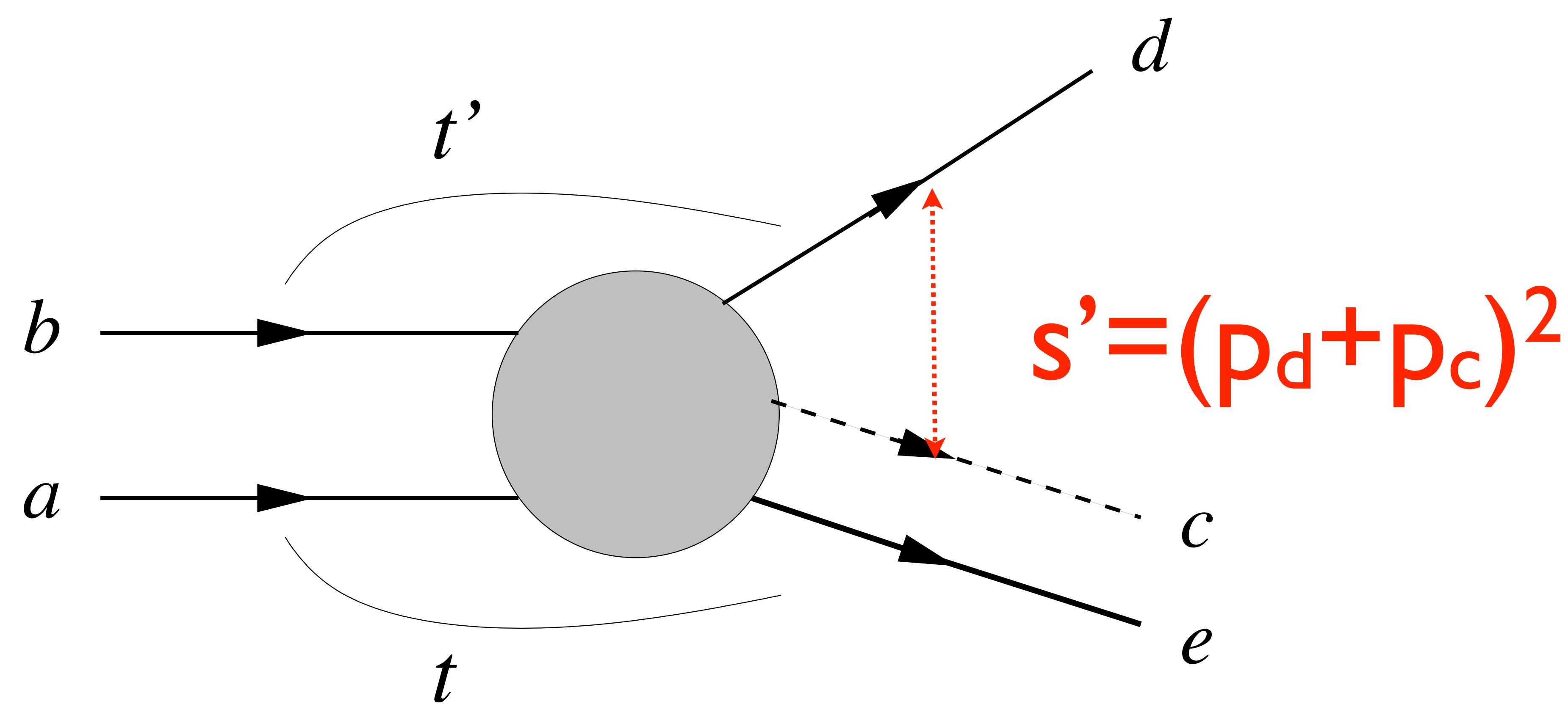
☀ New type of hard hadronic processes - *branching exclusive processes* of large c.m. angle scattering off a "a color singlet cluster" in a target/projectile (MS94)

to study both color transparency (CT) (suppression of absorption) in $2 \to 2$
& hadron generalized parton distributions (GPDs)



Limit:

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

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

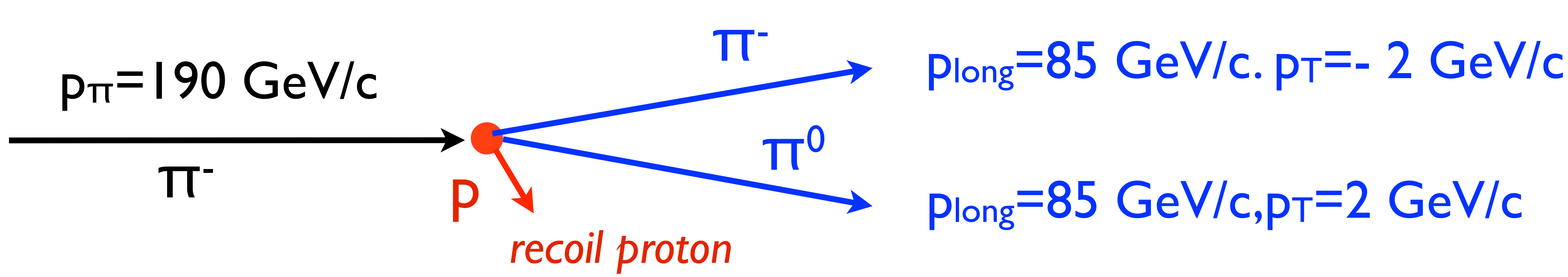
➡ $s'/s=y<<1$,

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

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

COMPASS can observe for example:

$\pi^- + p \to \pi^- + \pi^0 + p$



Major objectives

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

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

$2 \to 3$ hadronic processes with nuclear targets

many other interesting twists, 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)

$$R(p_t) = \sigma(\pi^- Pb \to \pi^- \pi^0 + A')/A\sigma(\pi^- Pb \to \pi^- \pi^0 + p)$$

- 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 & pave the way to studies of GPDs of other hadrons

Use beams at lower energies to measure pattern of freezing of space evolution of small size configurations

QCD factorization in hard exclusive processes and color transparency

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

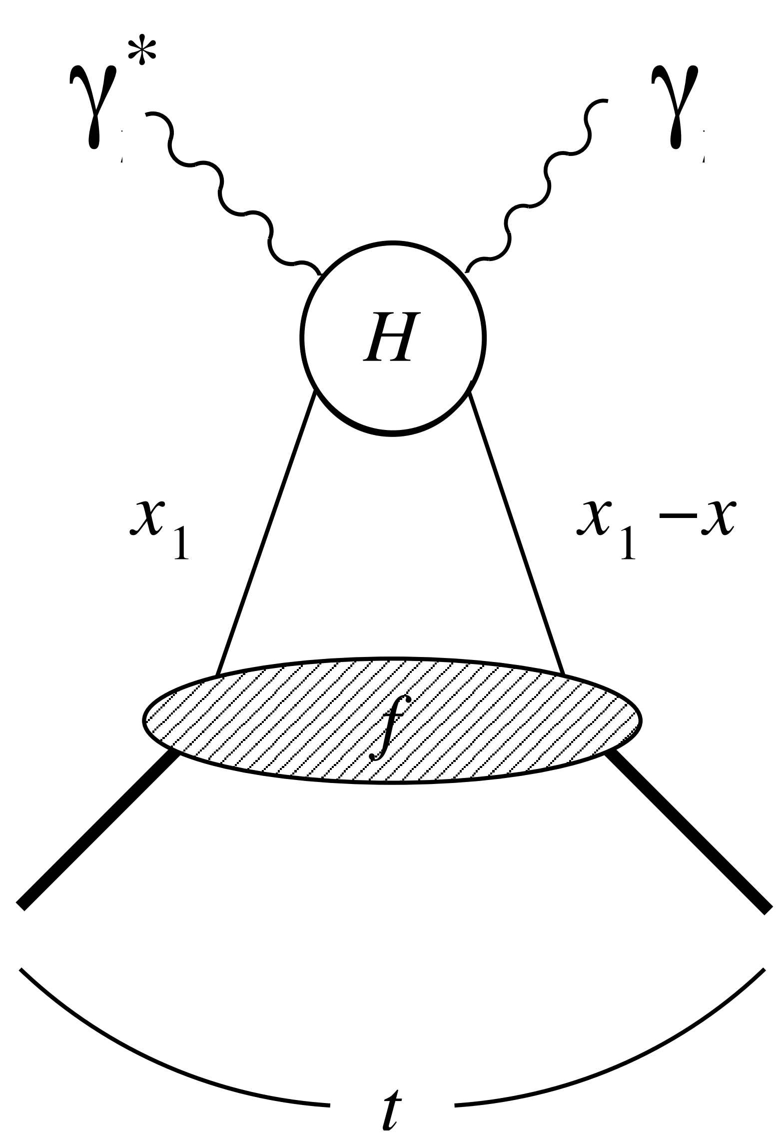
$\gamma^* + N \to \gamma + N(baryonic\, system)$ D.Muller 94 et al, Radyushkin 96, Ji 96, Collins &Freund 98

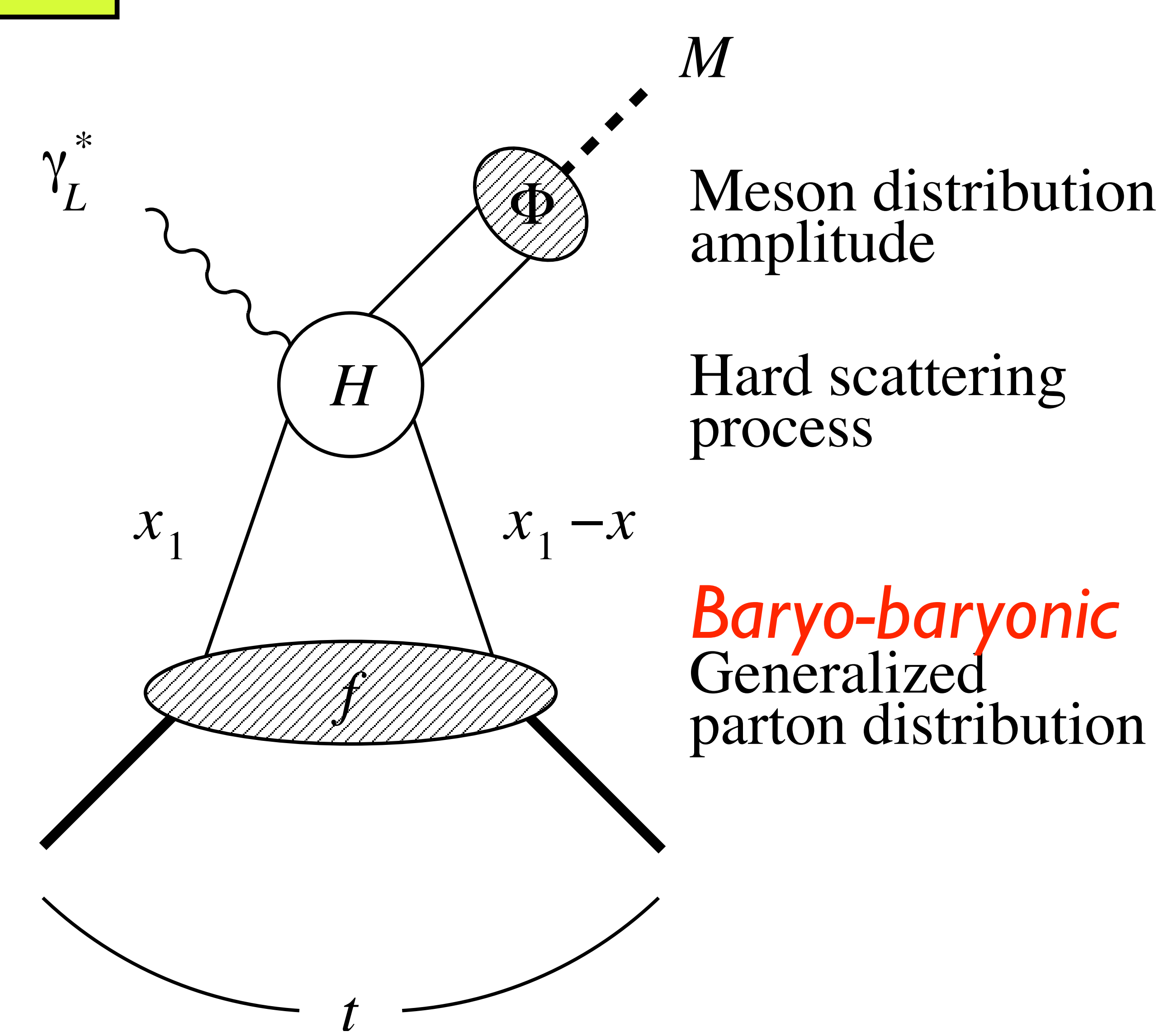
$\pi + T(A,N) \to jet_1 + jet_2 + T(A,N)$ Frankfurt, Miller, MS 93 & 03

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

Collins, Frankfurt, MS 97 - general case

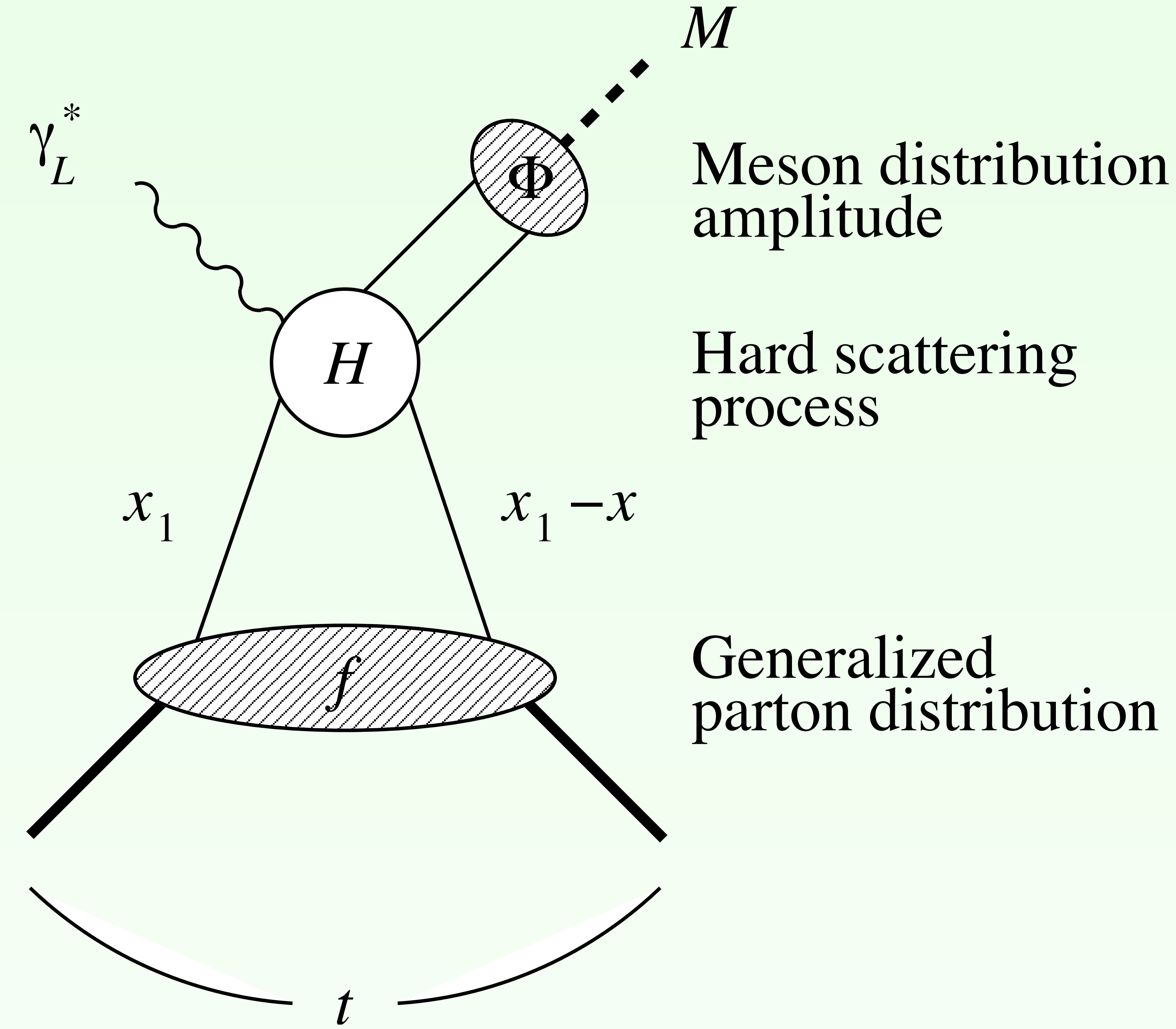
provide first effective tools for study of the 3D hadron structure





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

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 CT feature of QCD (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 corresponds to the interaction of the spatially small dipole.

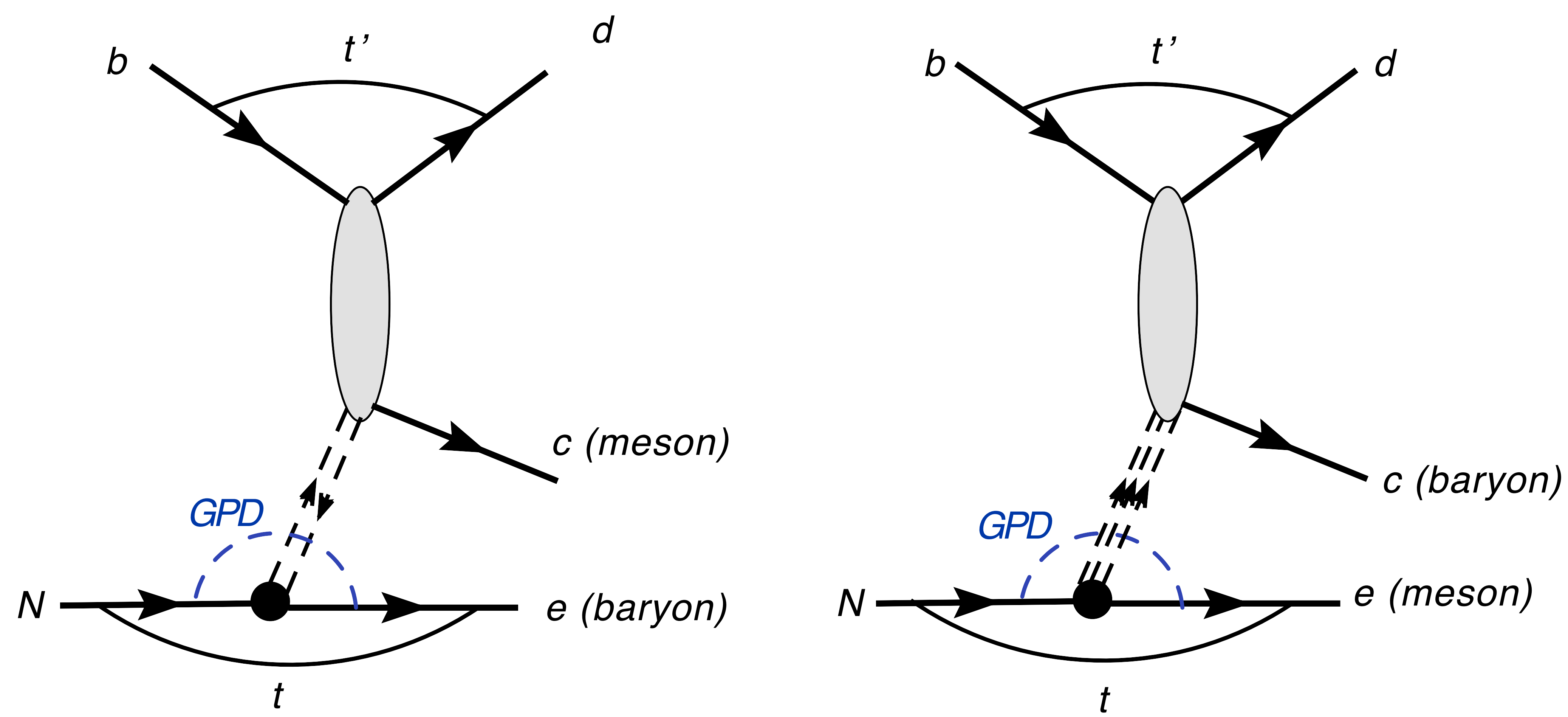
$\Longrightarrow$ **Need to trigger on small size configurations at high energies.**

First two ideas

$\diamond$ 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 $d \sim 1/p_t(jet)$

$\diamond$ $\diamond$ 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 γ^*_L, $d \propto 1/Q$.

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)

⇓

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

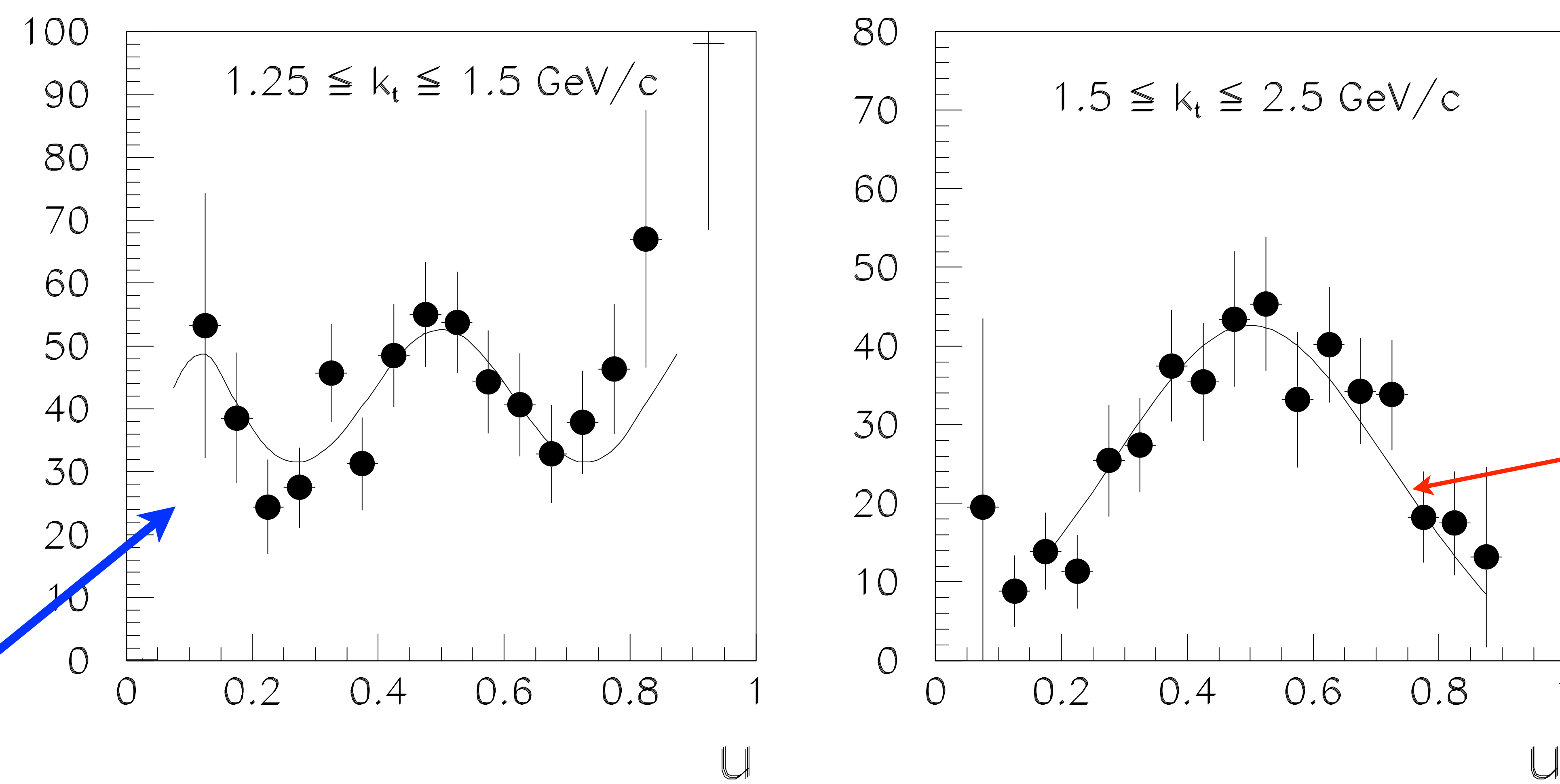
High energy color transparency is well established

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 π +A →"jet"+"jet" +A. (Ashery 2000):

Confirmed predictions of pQCD (Frankfurt ,Miller, MS93) for *A-dependence (much faster than in soft diffraction), 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 - COMPASS has data on tape!!!



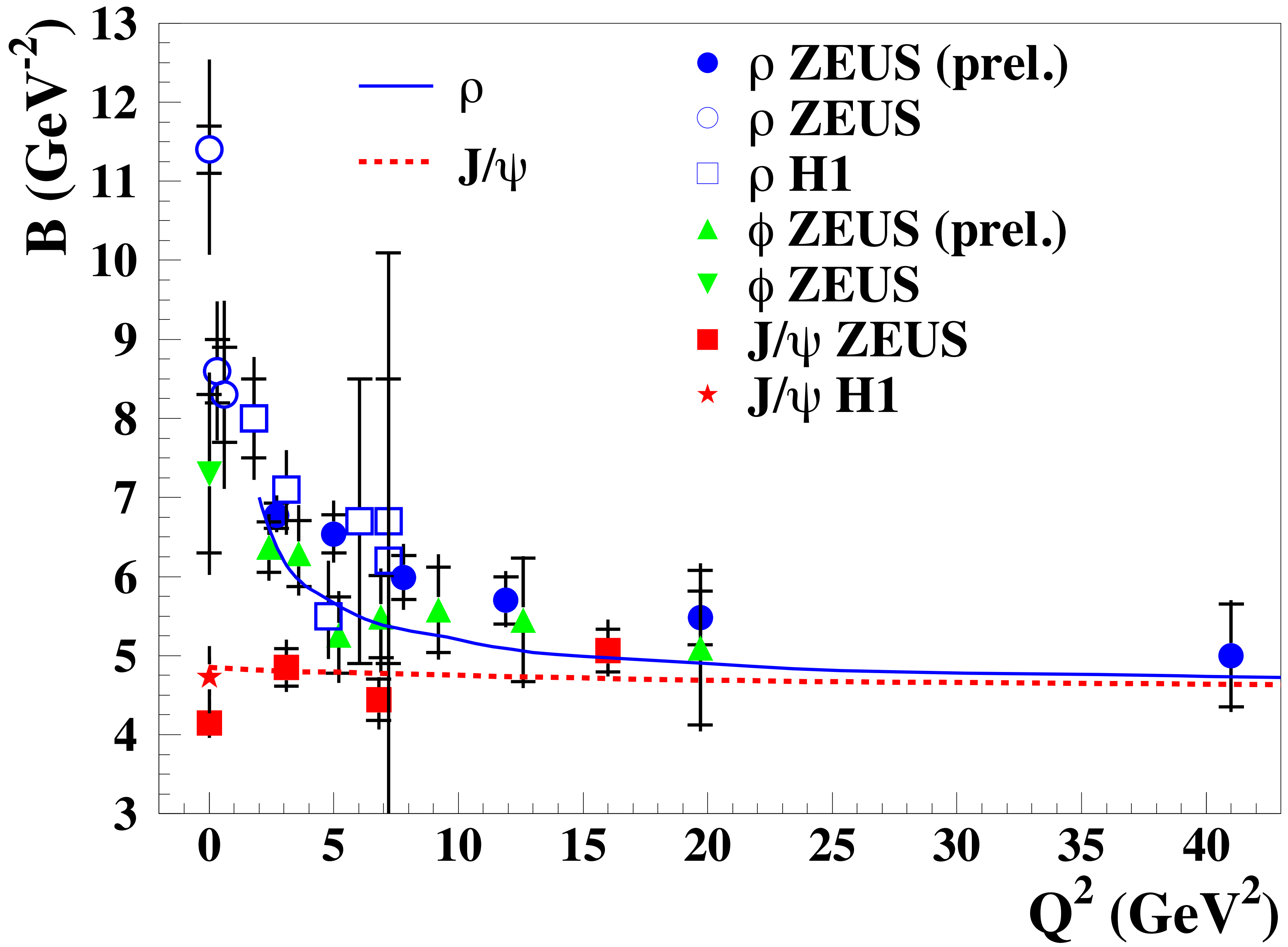
prediction

(π 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

Extensive data on VM production from HERA support dominance of the pQCD dynamics. Numerical calculations including finite transverse size effects explain key elements of high Q^2 data.



$$\frac{B(Q^2) - B_{2g}}{B(Q^2 = 0) - B_{2g}} \sim \frac{R^2(dipole)}{R_\rho^2}$$

Convergence of the t-slopes, B ($\frac{d\sigma}{dt} = A\exp(Bt)$), of ρ-meson electroproduction to the slope of J/psi photo(electro)production - **direct proof of squeezing**

$$\frac{R^2(dipole)(Q^2 \geq 3GeV^2)}{R_\rho^2} \leq 1/2$$

- Presence of small size $q\bar{q}$ Fock componentss in light mesons is unambigously established
- At transverse separations $d \leq 0.3$ fm pQCD reasonably describes "small $q\bar{q}$ - dipole"- nucleon interaction for $10^{-4} < x < 10^{-2}$
- Color transparency is established for the interaction of small dipoles with nucleons and with nuclei (for $x \sim 10^{-2}$)

Main challenge for CT studies performed at intermediate energies is lack of freezing: |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 - expand after interaction to average configurations and contract before interaction from average configurations (Frankfurt,Farrar,Liu, MS88)

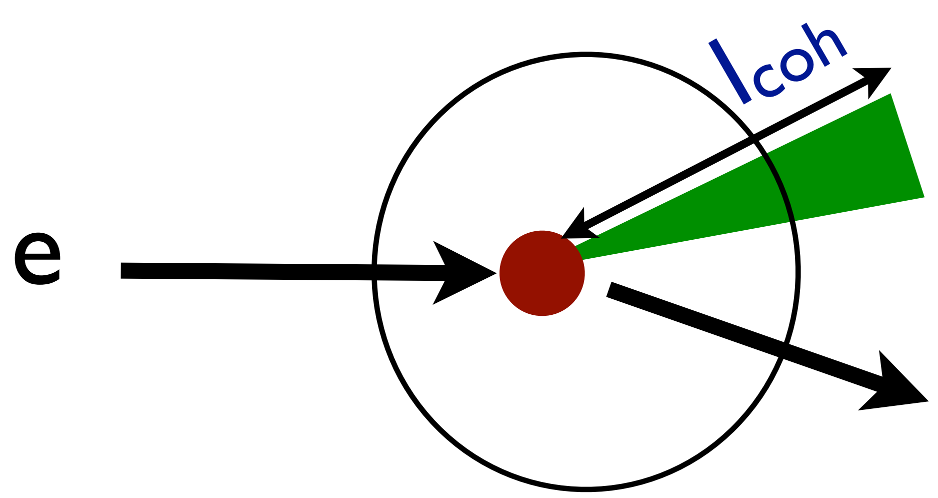
$$|\Psi_{PLC}(t)\rangle = \sum_{i=1}^{\infty} a_i \exp(iE_i t)\,|\Psi_i t\rangle\rangle = \exp(iE_1)\sum_{i=1}^{\infty} a_i \exp\left(\frac{i(m_i^2 - m_1^2)t}{2P}\right)|\Psi_i t\rangle\rangle$$

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

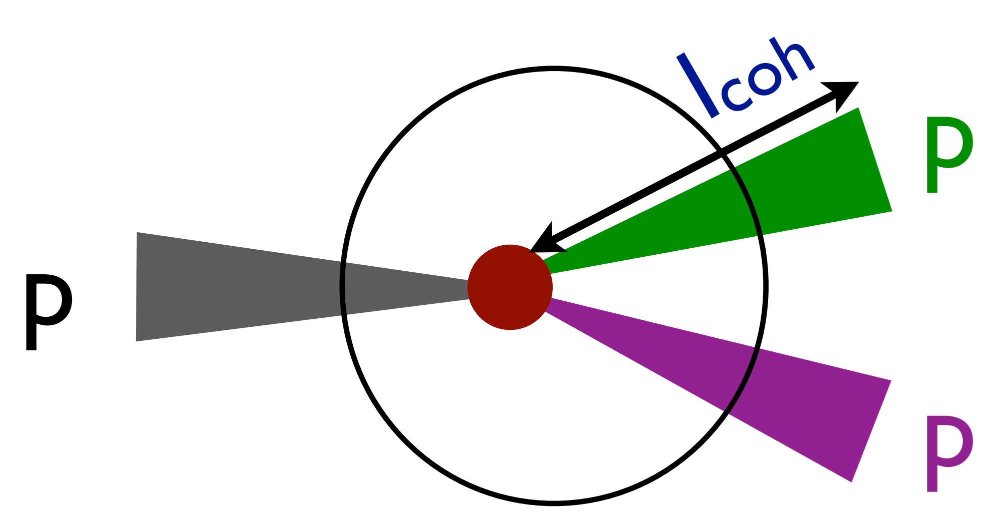
← Quantum Diffusion model of expansion

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

actually incoherence length



eA→ ep (A-1) at large Q

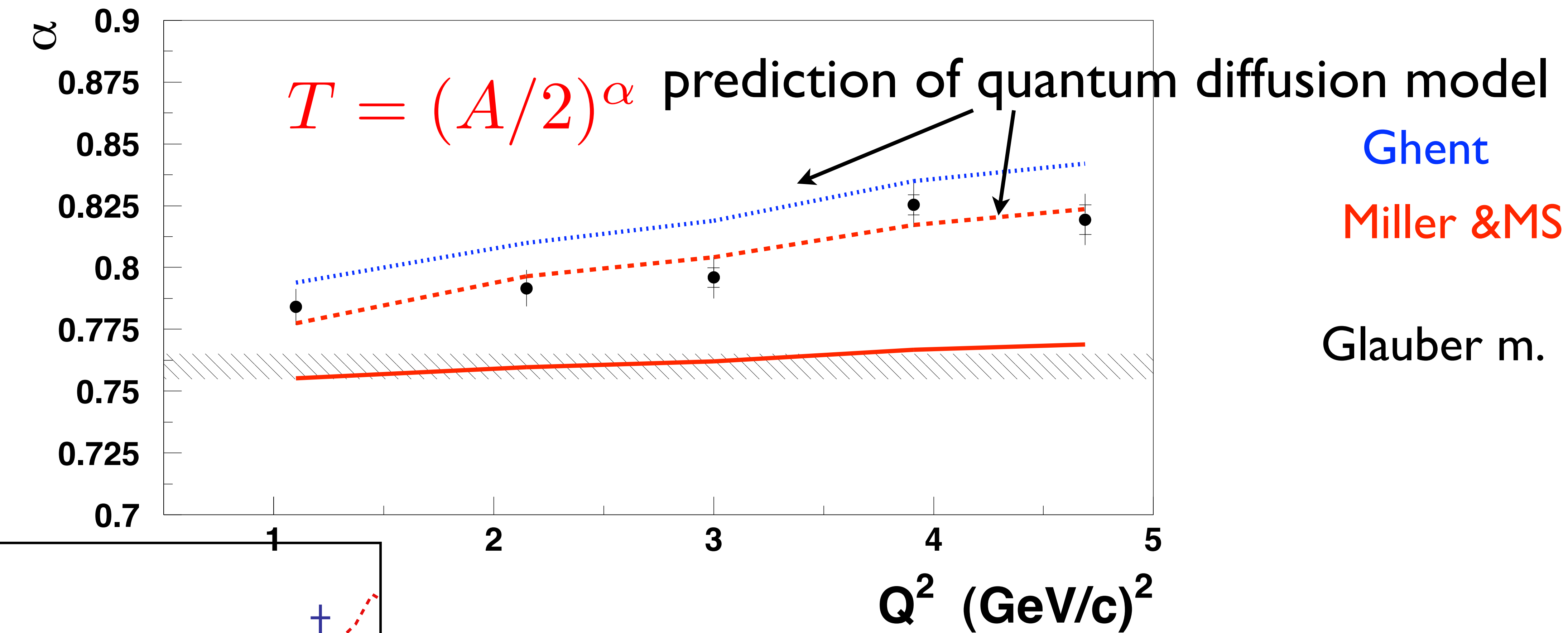


pA→ pp (A-1) at large t and intermediate energies

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

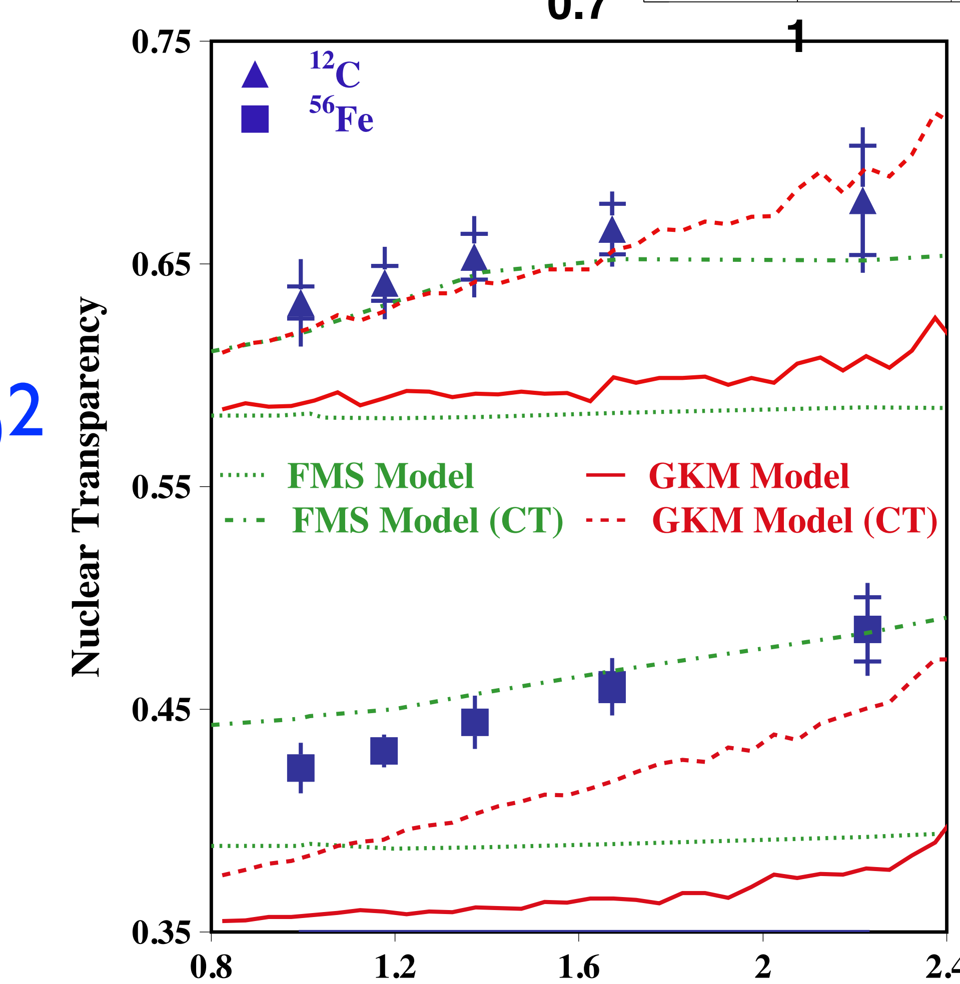
☀ $\gamma^* + A \to \pi A^*$ transparency increases with Q^2 (Dutta et al 07)



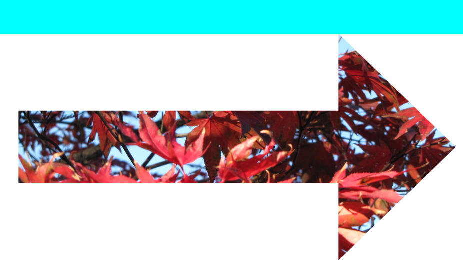
A- dependence checks not only squeezing but **small** l_{coh} as well

☺ $\gamma^* + A \to \rho A^*$ 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 COMPASS kinematics freezing is very effective:

$L_{coh}(p_\pi=100\text{ GeV}) = 60\text{ fm} >> 2R_{Pb} = 12\text{ fm}$

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 → ∞)

π +p → π +p, p +p → p +p,...

Dimensional quark counting rules:

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

number of constituents in initial state

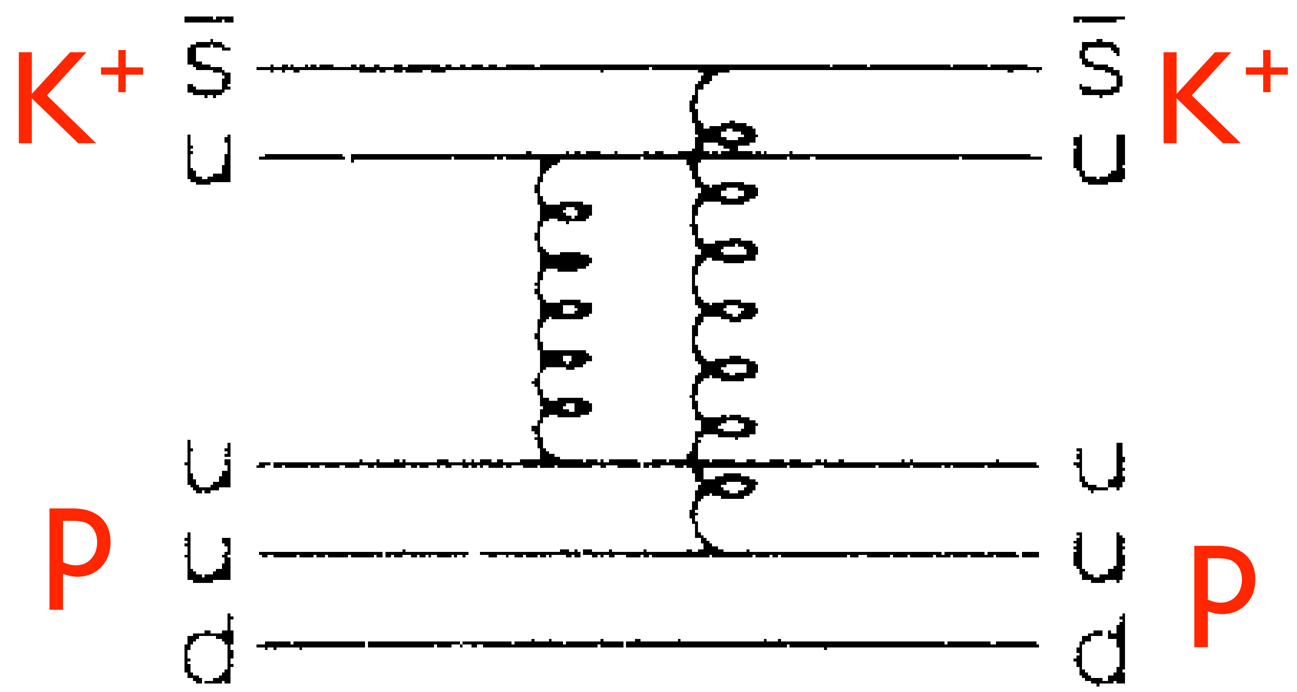
number of constituents in final state

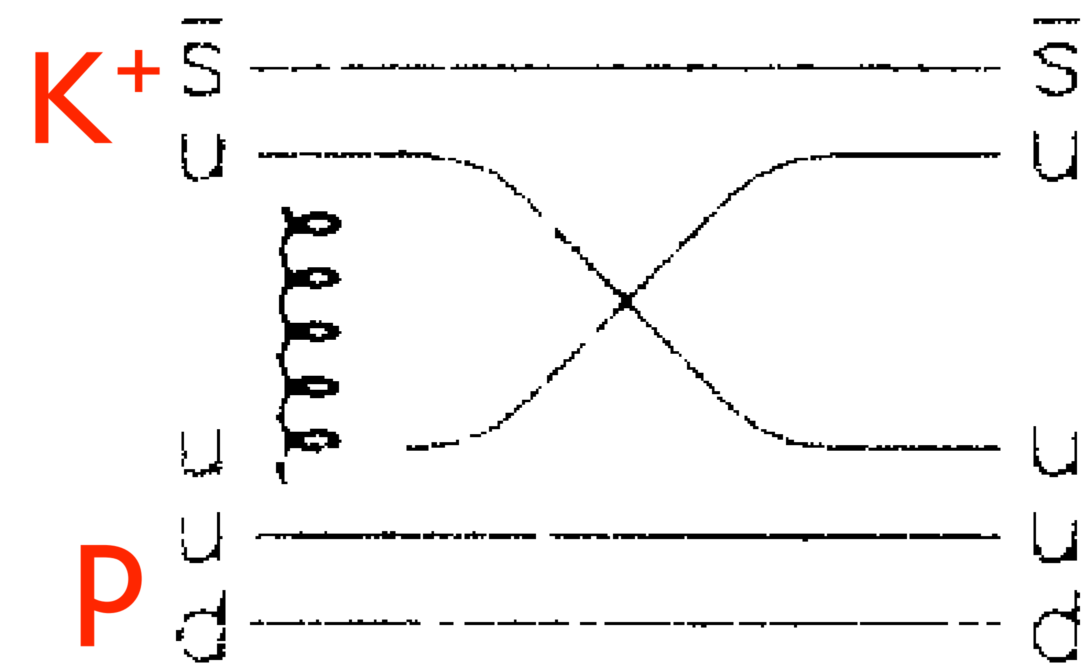
Quark counting expectations work pretty well:

TABLE V. The scaling between E755 and E838 has been measured for eight meson-baryon and 2 baryon-baryon interactions at $\theta_{\mathrm{c.m.}} = 90^\circ$. 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 $\Delta n_{\mathrm{syst}} = \pm 0.3$ from systematic errors of $\pm 13\%$ for E838 and $\pm 9\%$ for E755.

		Cross section			n-2
No.	Interaction	E838	E755		$(\frac{d\sigma}{dt} \sim 1/s^{n-2})$
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	$K^+ p \to p K^+$	219 ± 30	3.4 ± 1.4	n-2=8	$8.3^{+0.6}_{-1.0}$
4	$K^- p \to p K^-$	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

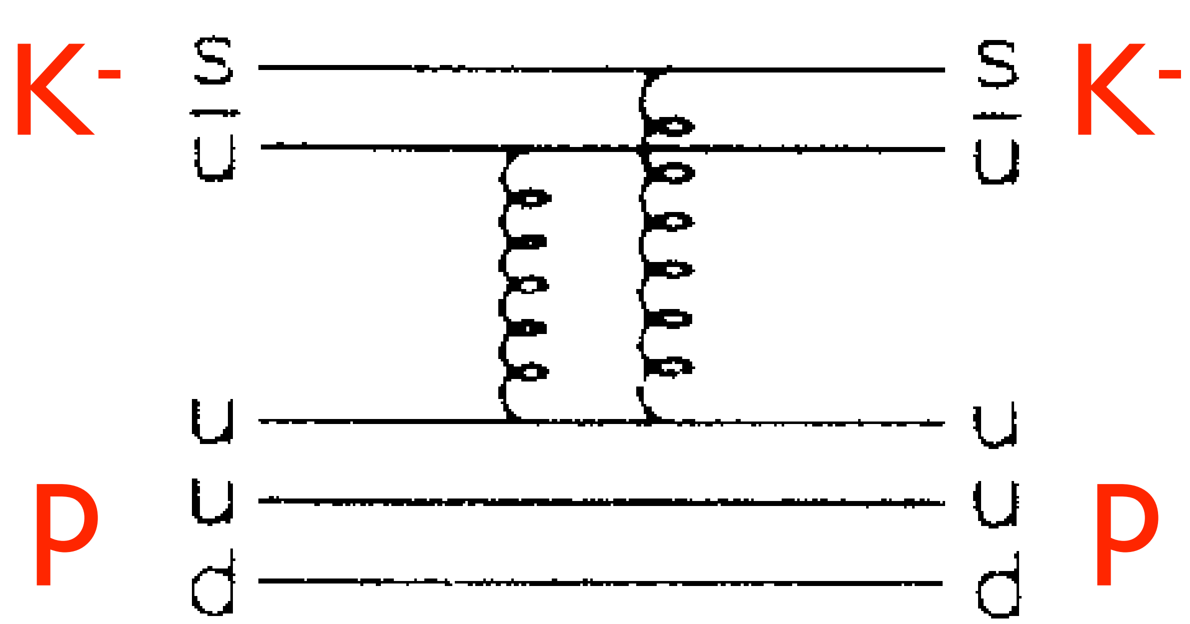
Another interesting observation - cross sections of reactions where quark exchanges is allowed have much larger cross section. For example -- pp elastic >> $\bar{p}p$ elastic

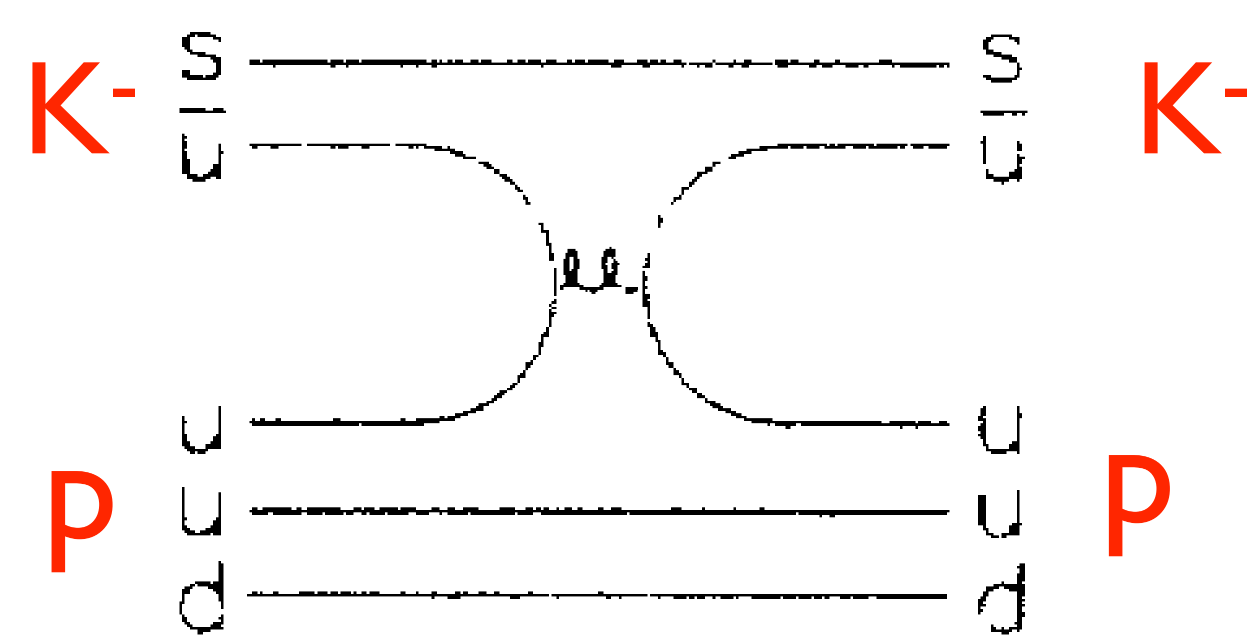




$K^+p \to K^+p$

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

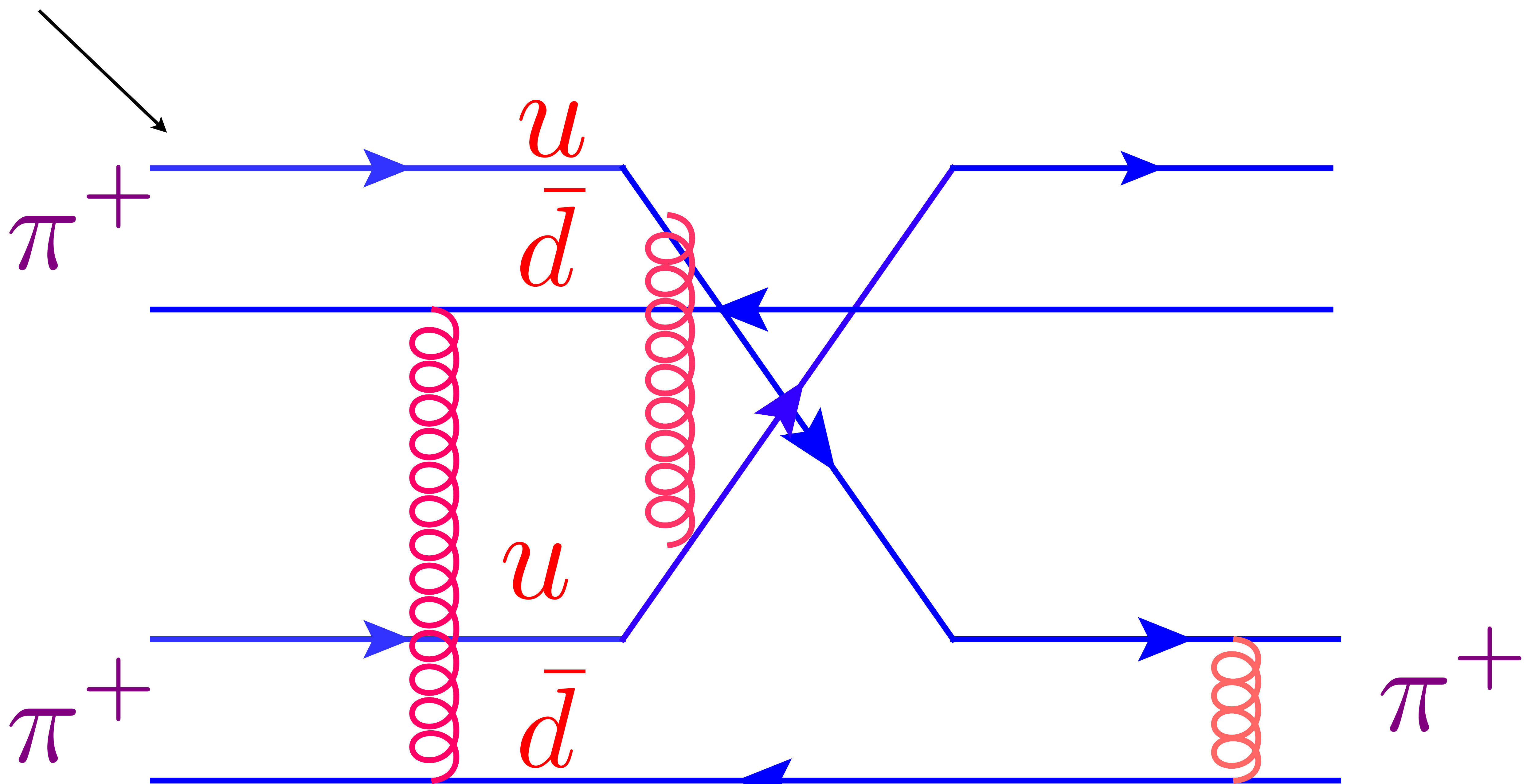




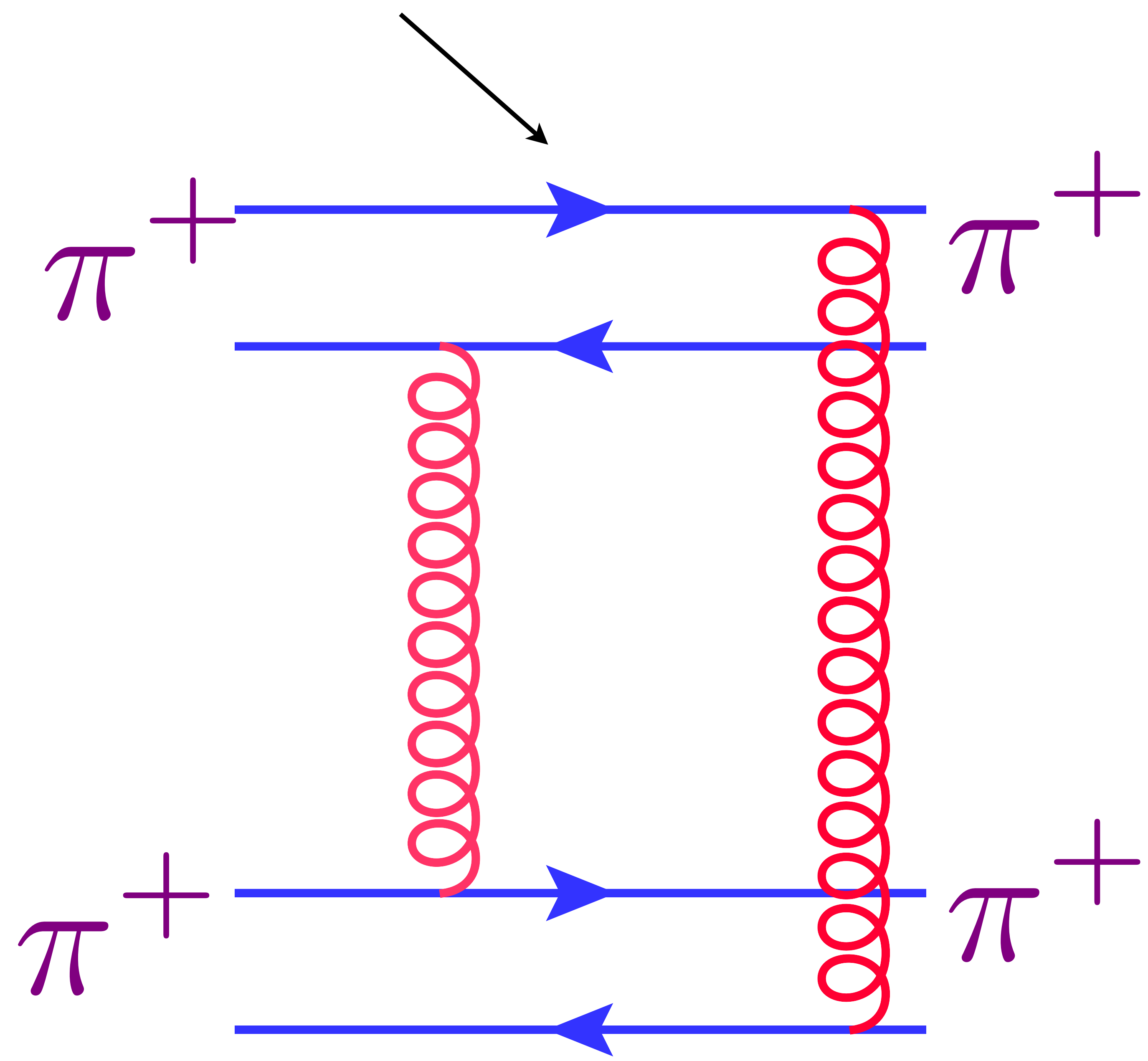
$K^-p \to K^-p$

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 → possible that 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 $\pi^- p \to \pi^-\pi\, N(\Delta)$

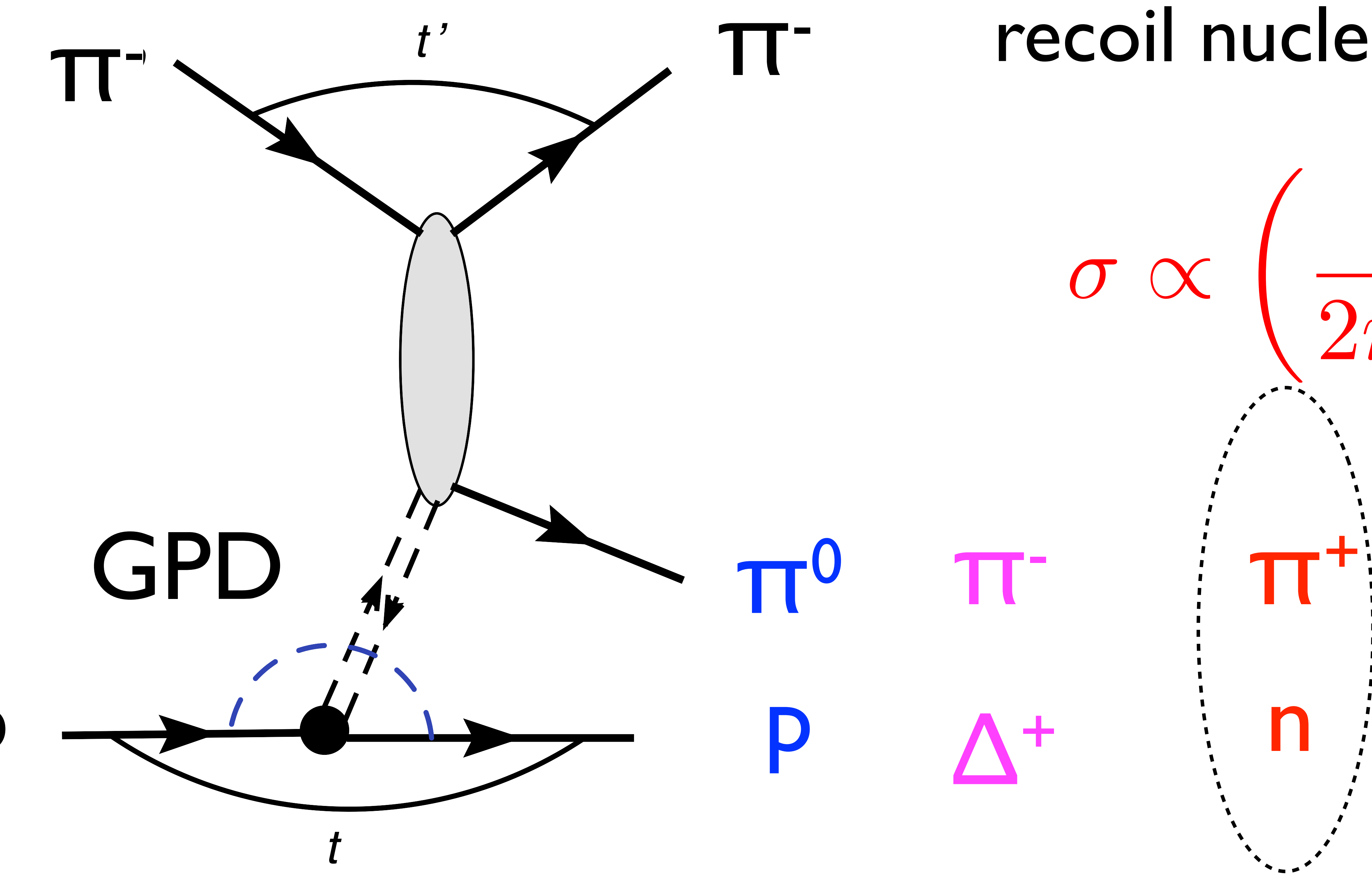
Kinematics

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

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

recoil nucleon kinematics very similar to diffractive case

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

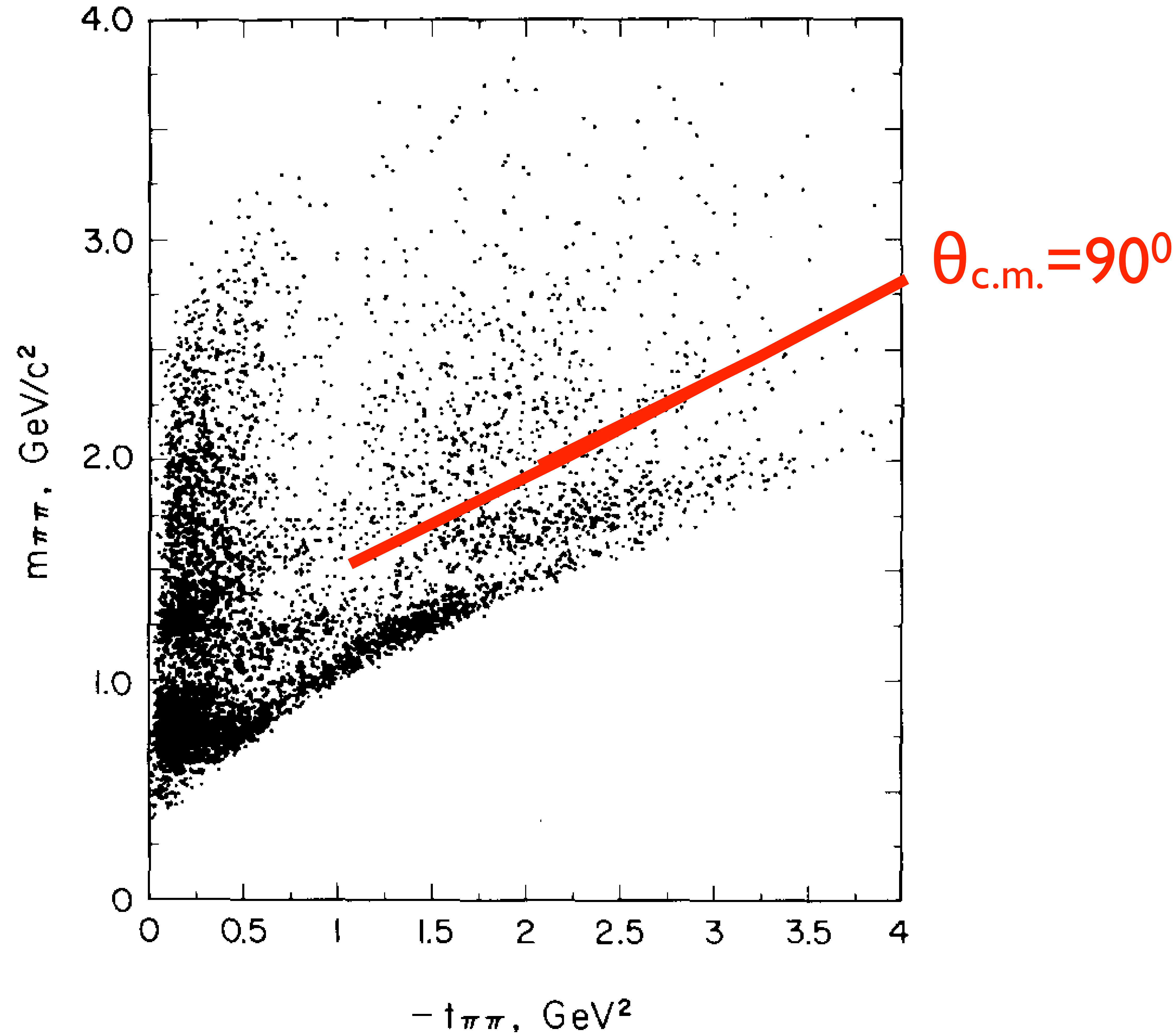


Bromberg et al 1981

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?



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

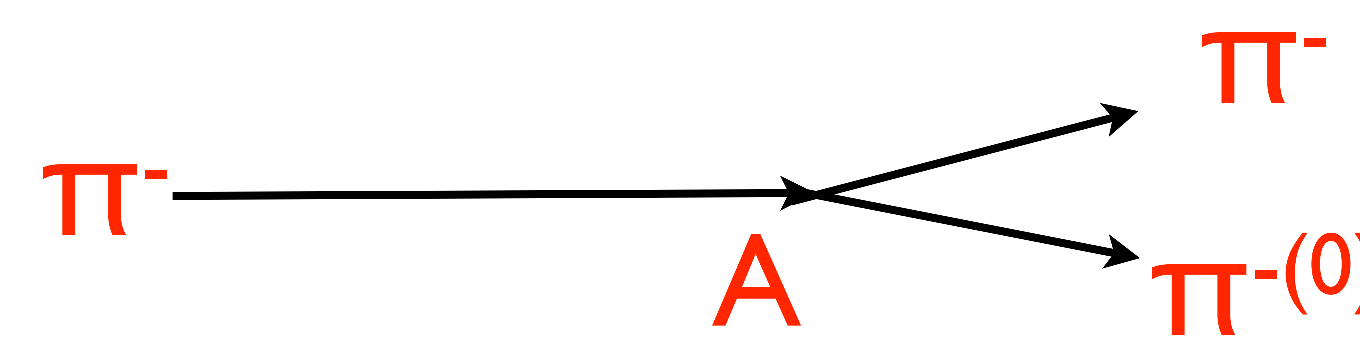
πρ production corresponds to different G-parity of quark - antiquark pair - different GPD . These nondiagonal GPDs are connected flavor diagonal GPDs via SU(2). K^+ - related through SU(3).

COMPASS is 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

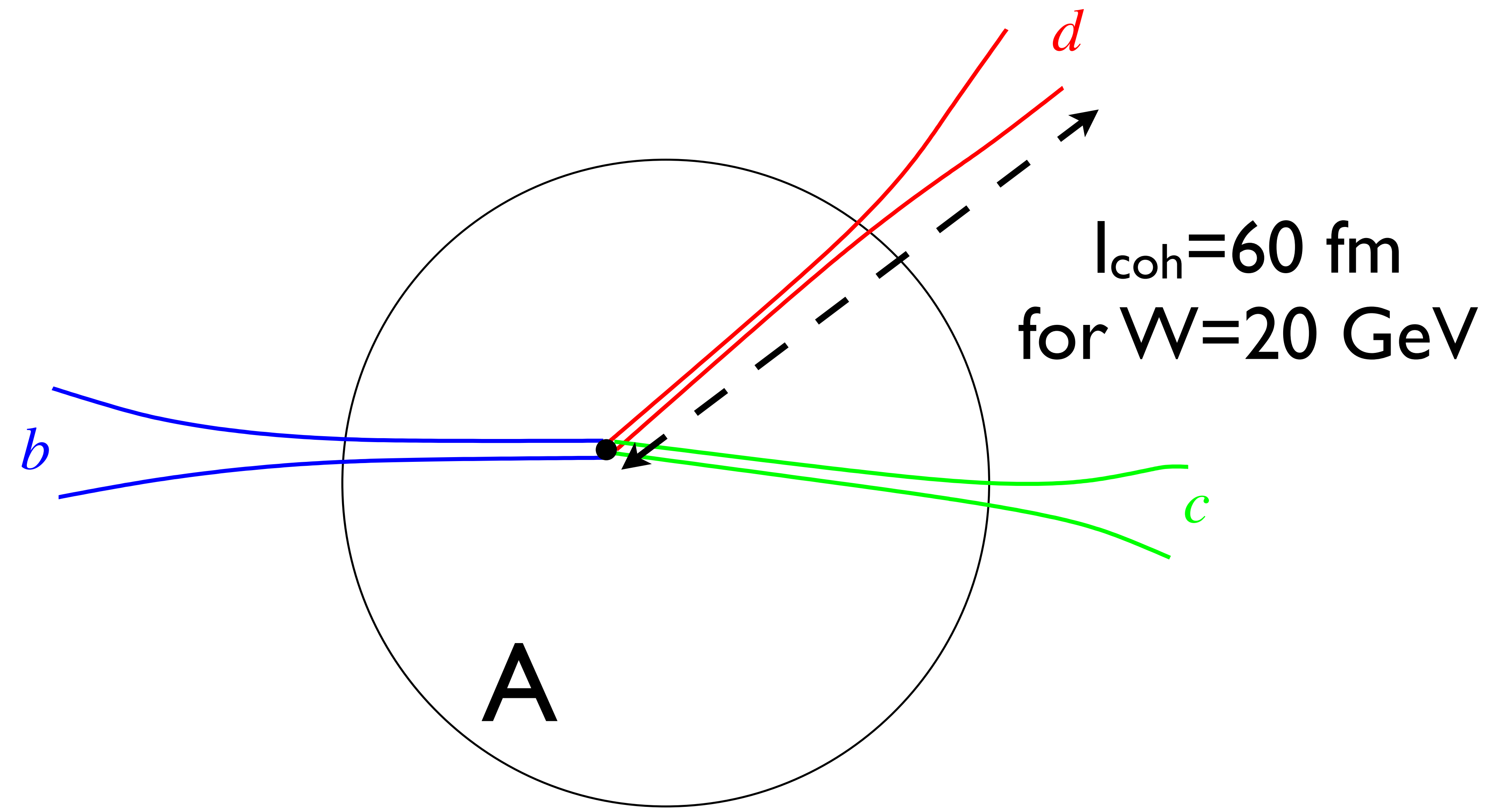
How to check that squeezing takes place and one can use GPD logic?

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



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

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

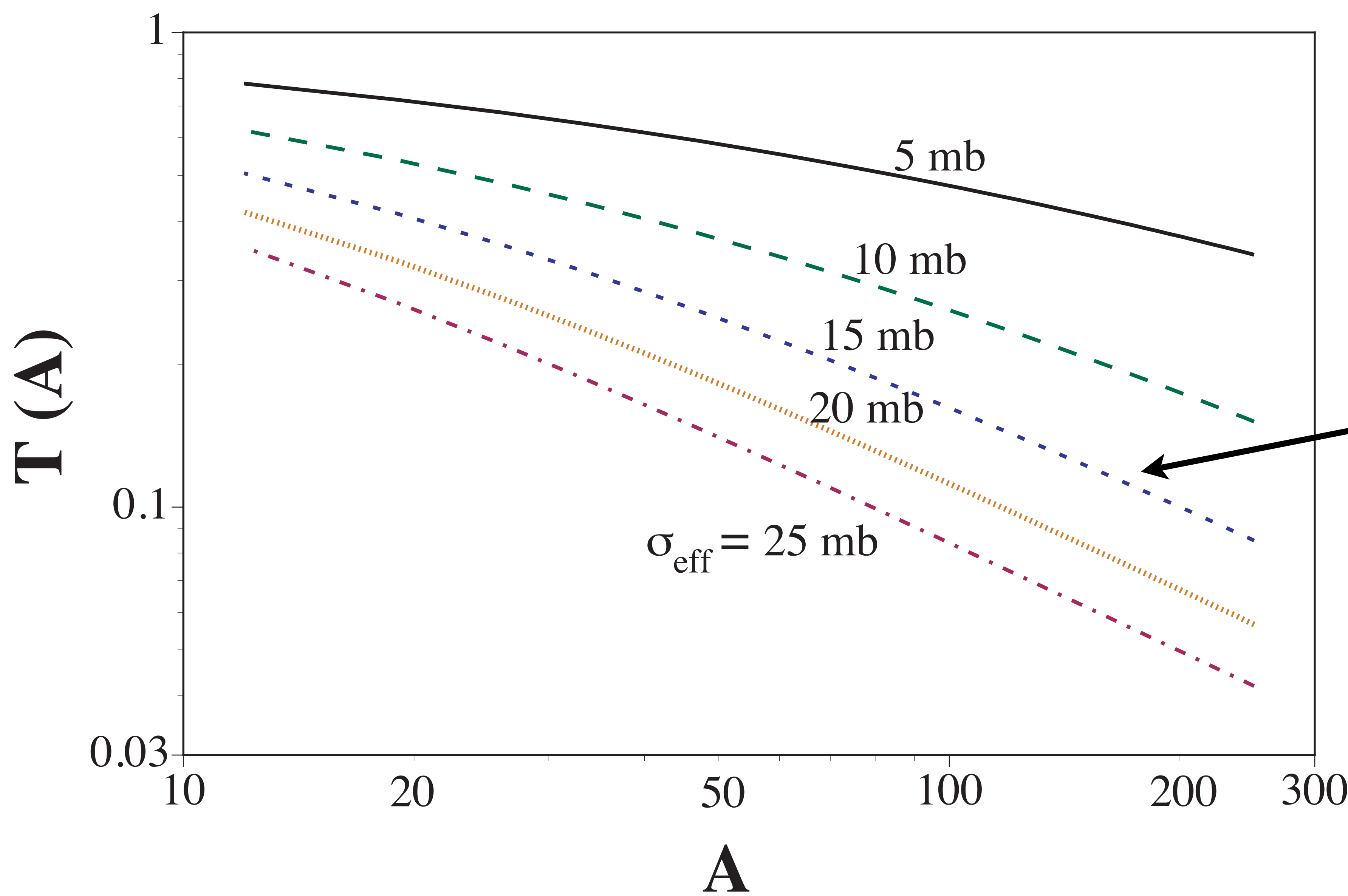
Qualitative advantage as compared to suggestion of Mueller and Brodsky to measure size using CT directly in 2→2 since for moderate t in difference from 2→3 it is impossible to suppress diffusion

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

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

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

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



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

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

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.

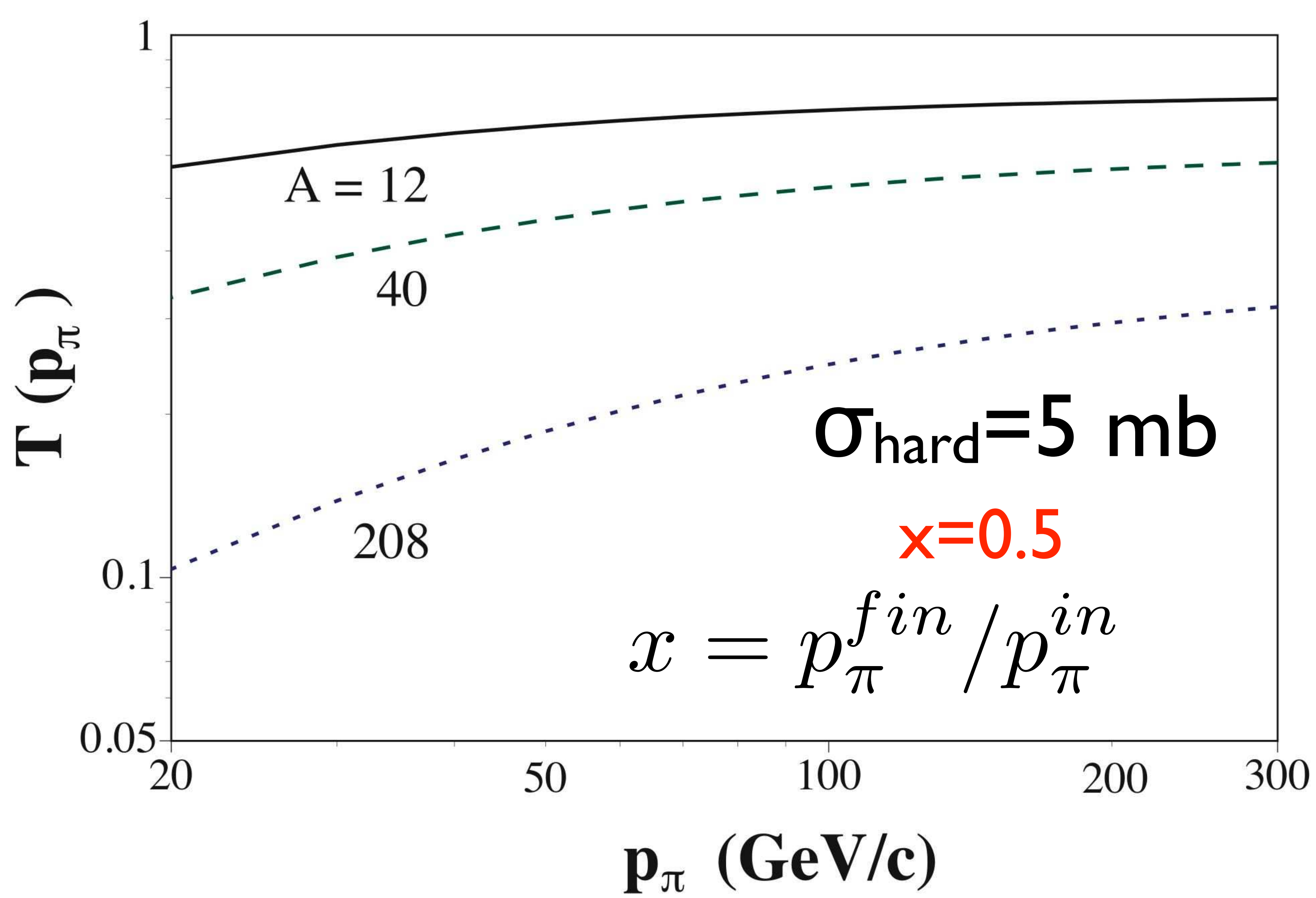
Another option: comparing proton and lead targets for other $\pi\pi$ channels*: study p_t dependence of T_A for the same cut on E_{mis}. Relies on factorization of GPD blob. Onset of CT = increase of T_A with p_t.*

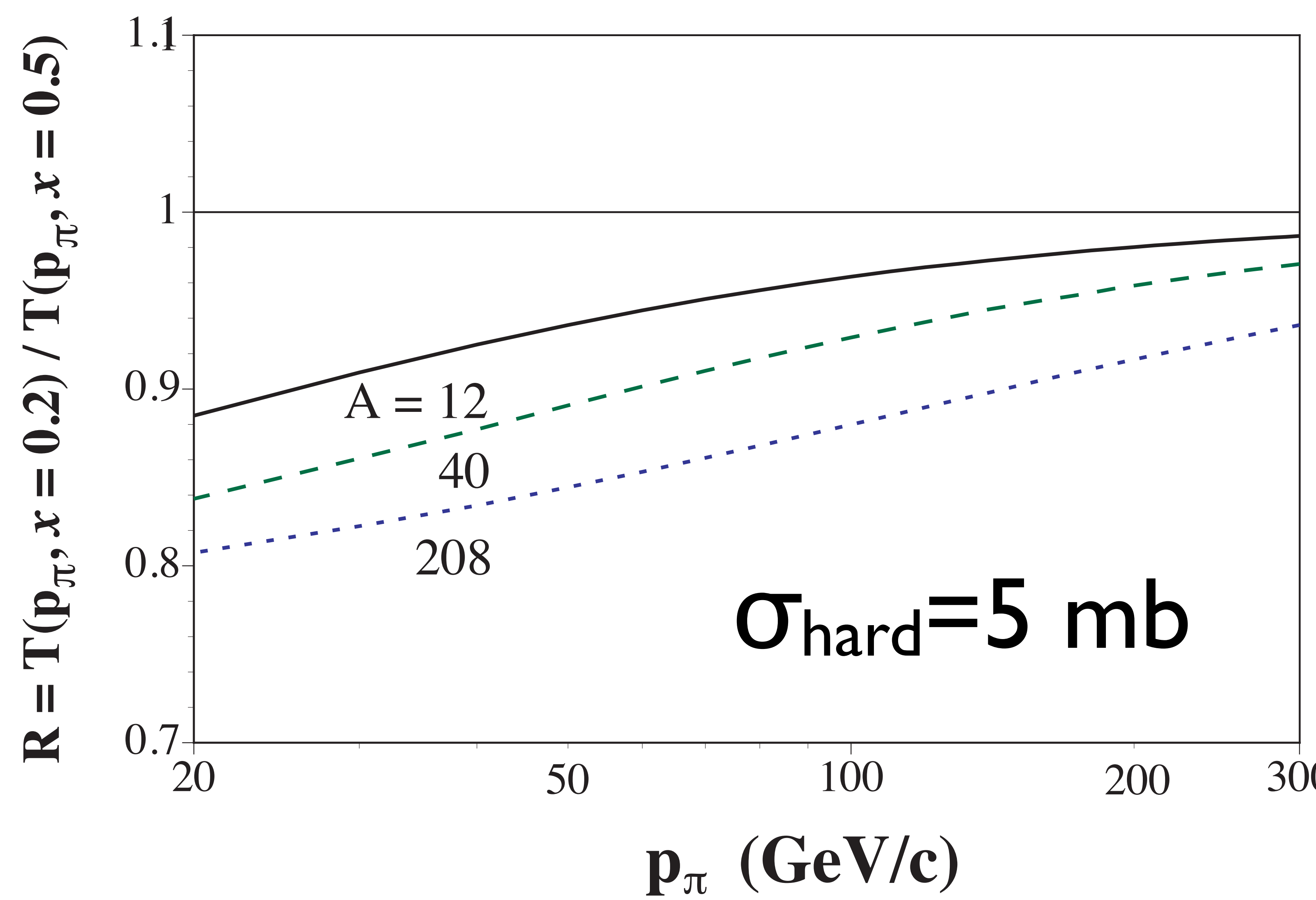
Defrosting point like configurations - energy dependence for fixed s',t'

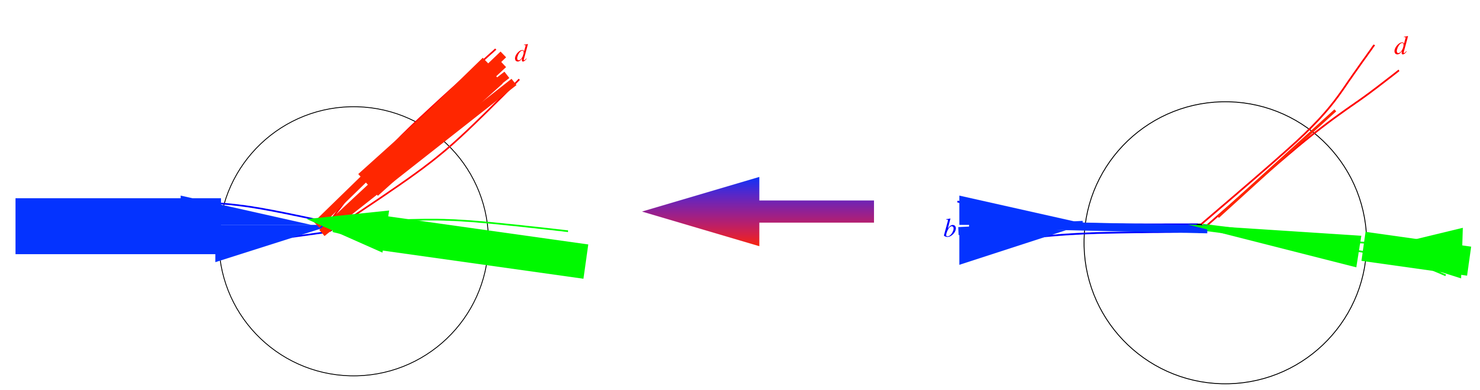
$$\sigma^{PLC}(z) = \left(\sigma_{hard} + \frac{z}{l_{coh}}[\sigma - \sigma_{hard}]\right)\theta(l_{coh} - z) + \sigma\theta(z - l_{coh})$$

Quantum Diffusion model of expansion

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







Conclusions

At the very least, analysis of the collected COMPASS data would allow

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

Resolve long standing puzzle of sizes involved in large angle scattering

If CT is observed, COMPASS will be able

to measure several nucleon quark GPDs.

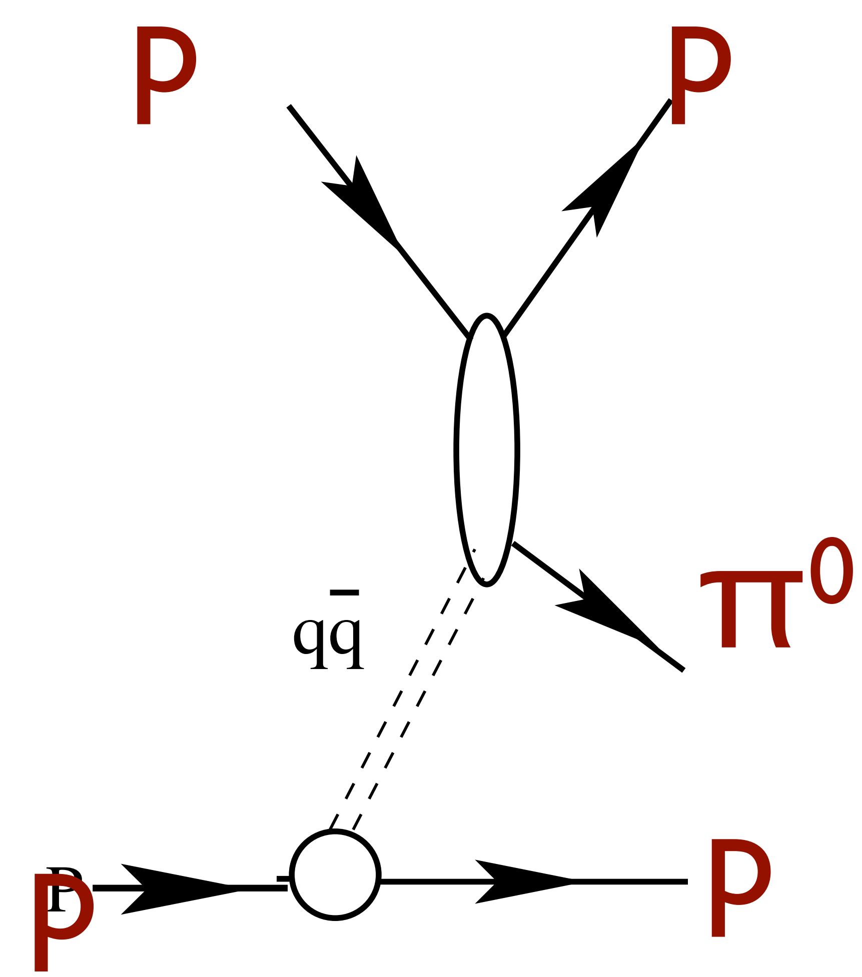
to measure quark GPDs of other hadrons and photon (tagged photons in DIS?)

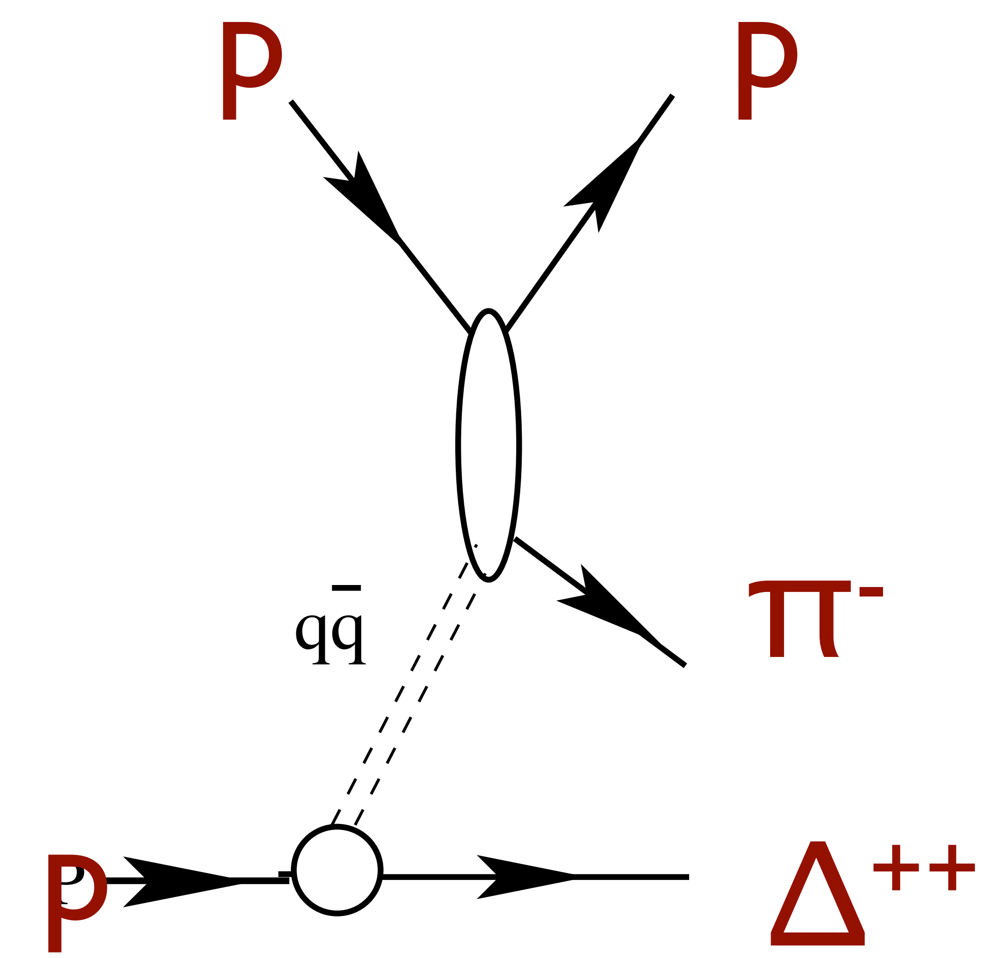
to use beams of lower energies to map space time evolution of small wave packets at distances $1 < z < 6$ fm.

Supplementary slides

A detailed theoretical study of the reactions pp→NNπ, NΔπ was recently completed. Factorization based on squeezing

Kumano, Strikman, and Sudoh 09





Strategy of the first numerical analysis:

- account for contributions of GPDs corresponding to
  $q\bar{q}$ pairs with S=1 and 0

- Approximate the ERBL configurations by the pion and ρ-meson poles

- Use experimental information about

  $\pi^- p \to \pi^- p$, $\pi^- p \to \rho^- p$

  $\pi^+ p \to \pi^+ p$, $\pi^+ p \to \rho^+ p$

much better data are necessary for beams of energies of the order 10 GeV - J-PARC!!!

$$d\sigma = \frac{S}{4\sqrt{(p_a \cdot p_b)^2 - m_N^4}} \overline{\sum}_{\lambda_a, \lambda_b} \sum_{\lambda_d, \lambda_e} \left|\mathcal{M}_{NNN\pi B}\right|^2$$

$$\times \frac{1}{2E_c} \frac{d^3 p_c}{(2\pi)^3} \frac{1}{2E_d} \frac{d^3 p_d}{(2\pi)^3} \frac{1}{2E_e} \frac{d^3 p_e}{(2\pi)^3} (2\pi)^4 \delta^4(p_a + p_b - p_c - p_d - p_e)$$

$$\frac{d\sigma}{d\alpha d^2 p_{BT} d\theta_{cm}} = f(\alpha, p_{BT}) \phi(s', \theta_{cm})$$

$$\alpha \equiv \alpha_{spec} = (1 - \xi)/(1 + \xi)$$

$$s' = (1 - \alpha) s$$

$$\phi(s', \theta_{cm}) \approx (s')^n \gamma(\theta_{cm})$$

$$\mathcal{M}_N^V = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle N, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \psi(\lambda n/2) \right| N, p_a \right\rangle$$
$$= I_N \, \overline{\psi}_N(p_e) \big[H(x,\xi,t) \not{n} + E(x,\xi,t) \frac{i\sigma^{\alpha\beta} n_\alpha \Delta_\beta}{2m_N} \big] \psi_N(p_a)$$

$$I_N =< 1/2 || \widetilde{T} || 1/2 > \left\langle \tfrac{1}{2} M_N : 1m \middle| \tfrac{1}{2} M_N' \right\rangle / \sqrt{2}$$

$$\mathcal{M}_N^A = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle N, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \gamma_5 \psi(\lambda n/2) \right| N, p_a \right\rangle$$
$$= I_N \, \overline{\psi}_N(p_e) \big[\widetilde{H}(x,\xi,t) \not{n} \gamma_5 + \widetilde{E}(x,\xi,t) \frac{n \cdot \Delta \gamma_5}{2m_N} \big] \psi_N(p_a)$$

N →Δ transitions

$$\mathcal{M}^V_{N\to\Delta} = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle \Delta, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \psi(\lambda n/2) \right| N, p_a \right\rangle$$
$$= I_{\Delta N} \overline{\psi}^\mu_\Delta(p_e) \big[H_M(x,\xi,t) \mathcal{K}^M_{\mu\nu} n^\nu + H_E(x,\xi,t) \mathcal{K}^E_{\mu\nu} n^\nu$$
$$+ H_C(x,\xi,t) \mathcal{K}^C_{\mu\nu} n^\nu \big] \psi_N(p_a),$$

$$\mathcal{K}^M_{\mu\nu} = -i \frac{3(m_\Delta + m_N)}{2m_N[(m_\Delta + m_N)^2 - t]} \varepsilon_{\mu\nu\lambda\sigma} P^\lambda \Delta^\sigma,$$
$$\mathcal{K}^E_{\mu\nu} = -\mathcal{K}^M_{\mu\nu} - \frac{6(m_\Delta + m_N)}{m_N Z(t)} \varepsilon_{\mu\sigma\lambda\rho} P^\lambda \Delta^\rho \varepsilon^\sigma_{\nu\kappa\delta} P^\kappa \Delta^\delta \gamma^5,$$
$$\mathcal{K}^C_{\mu\nu} = -i \frac{3(m_\Delta + m_N)}{m_N Z(t)} \Delta_\mu (t P_\nu - \Delta \cdot P \Delta_\nu) \gamma^5,$$

where m_Δ is the Δ mass, and $Z(t)$ is defined by

$$Z(t) = [(m_\Delta + m_N)^2 - t][(m_\Delta - m_N)^2 - t].$$

$$\mathcal{M}^{A}_{N\to\Delta} = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle \Delta, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \gamma^5 \psi(\lambda n/2) \right| N, p_a \rangle$$

$$= I_{\Delta N}\, \overline{\psi}^{\mu}_{\Delta}(p_e) \Big[\widetilde{H}_1(x,\xi,t) n_\mu + \widetilde{H}_2(x,\xi,t) \frac{\Delta_\mu (n\cdot\Delta)}{m_N^2}$$

$$+ \widetilde{H}_3(x,\xi,t) \frac{n_\mu \not{\Delta} - \Delta_\mu \not{n}}{m_N}$$

$$+ \widetilde{H}_4(x,\xi,t) \frac{P\cdot\Delta n_\mu - 2\Delta_\mu}{m_N^2} \Big] \psi_N(p_a)$$

$$\phi_\pi(z) = \sqrt{3} f_\pi z(1-z),$$
$$\phi_\rho(z) = \sqrt{6} f_\rho z(1-z).$$

$$\frac{d\sigma_{NN \to N\pi B}}{dt\, dt'} = \int_{y_{min}}^{y_{max}} dy \; \frac{s}{16\,(2\pi)^2\, m_N\, p_N}$$

$$\times \sqrt{\frac{(ys - t - m_N^2)^2 - 4m_N^2 t}{(s - 2m_N^2)^2 - 4m_N^4}} \; \frac{d\sigma_{MN\pi N}(s'{=}ys, t')}{dt'}$$

$$\times \sum_{\lambda_a, \lambda_e} \frac{1}{[\phi_M(z)]^2} \left|\mathcal{M}_{N \to B}\right|^2$$

$$y \equiv \frac{s'}{s} = \frac{t + m_N^2 + 2(m_N E_N - E_B E_N + p_B p_N \cos\theta_e)}{s}$$

$$y_{min} = \frac{Q_0^2 + 2m_N^2 - t'}{s}, \quad -t' \geq Q_0^2$$

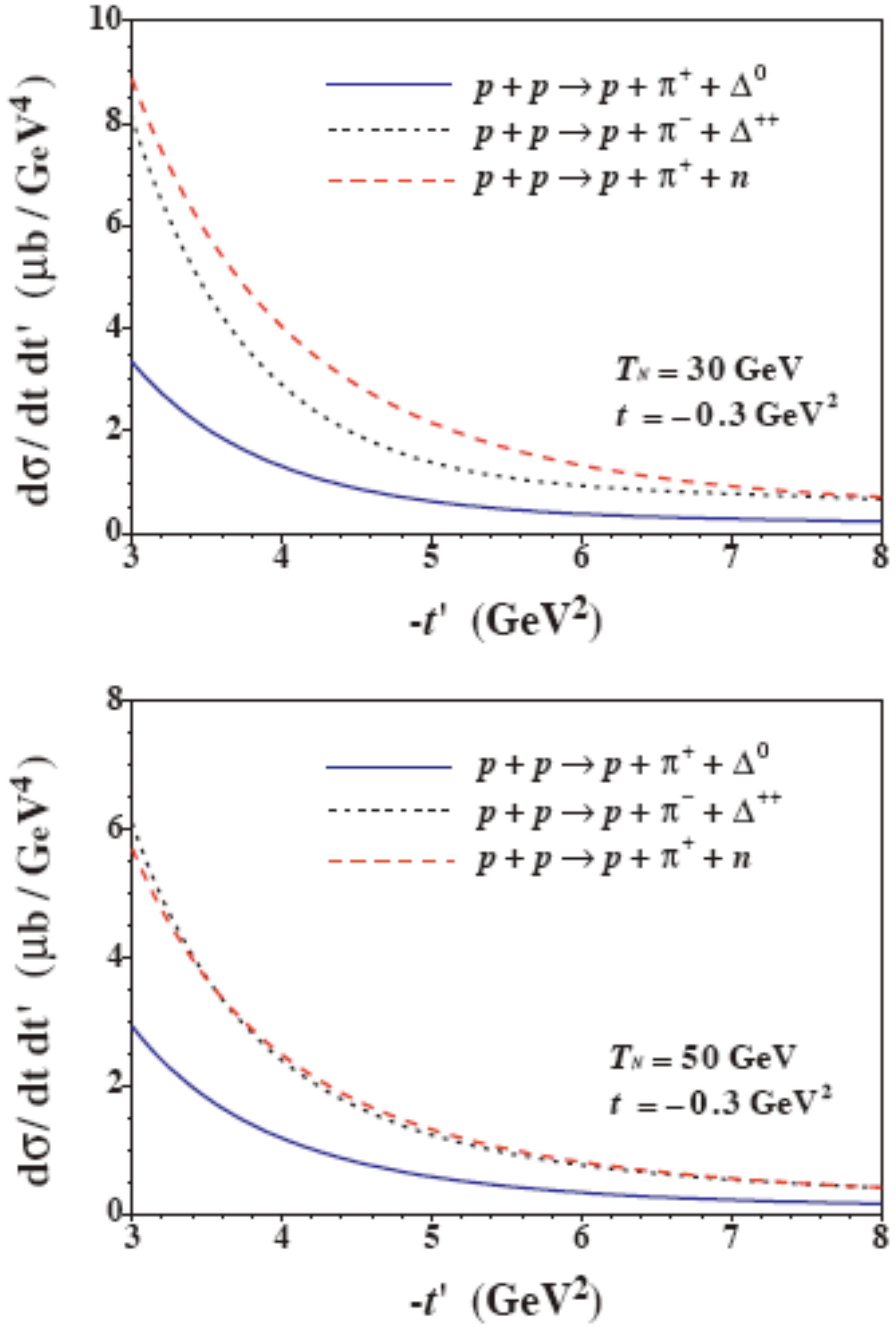


FIG. 11: Differential cross section as a function of t'. The incident proton-beam energy is 30 (50) GeV in the upper (lower) figure, and the momentum transfer is $t = -0.3$ GeV^2. The solid, dotted, and dashed curves indicate the cross sections for $p + p \to p + \pi^+ + \Delta^0$, $p + p \to p + \pi^- + \Delta^{++}$, and $p + p \to p + \pi^+ + n$, respectively.

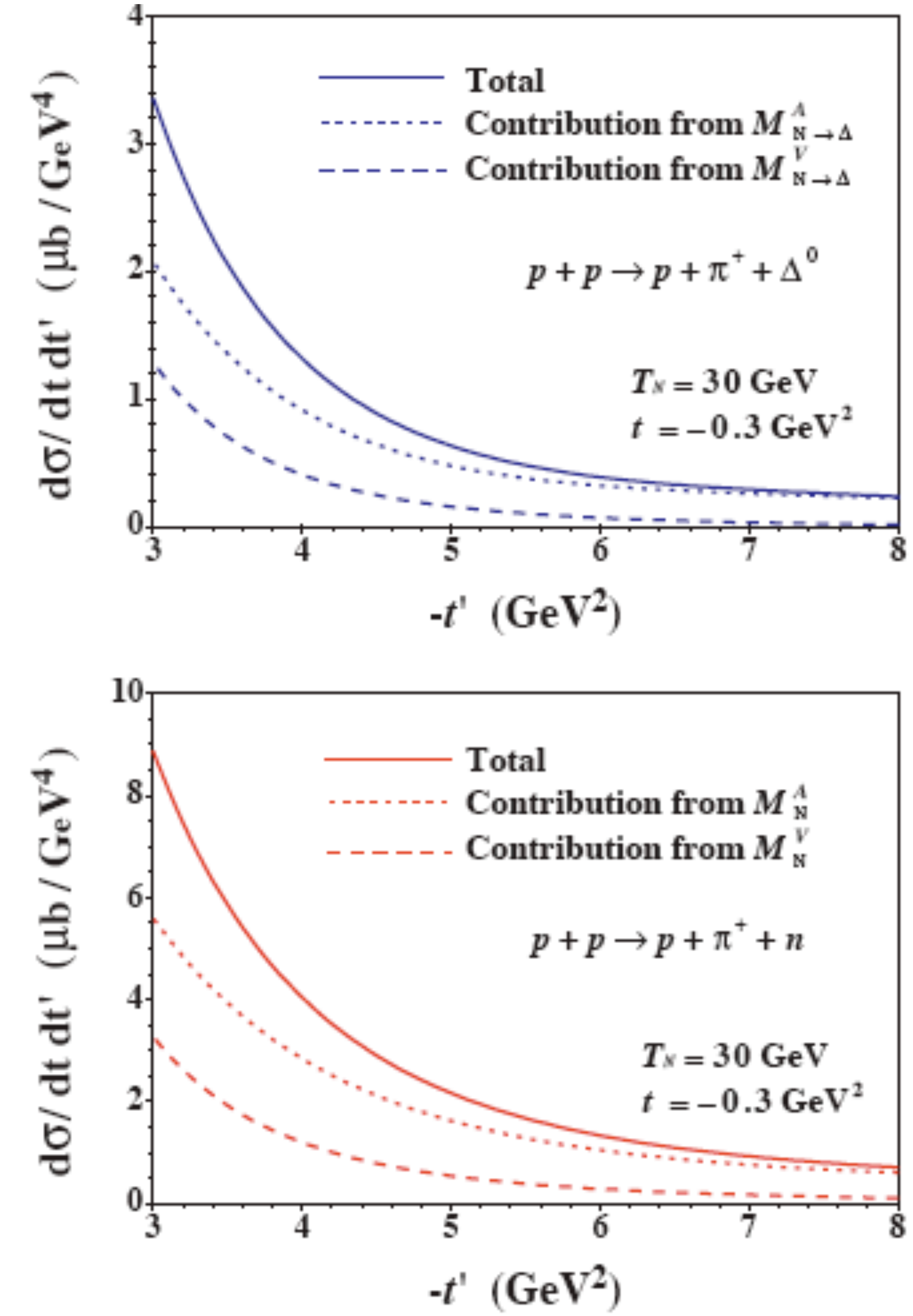


FIG. 12: Differential cross section as a function of t'. The incident proton-beam energy is 30 GeV, and the momentum transfer is $t = -0.3$ GeV^2. The upper (lower) figure indicates the cross section for the process $p+p \to p+\pi^+ + \Delta^0$ ($p+p \to p + \pi^+ + n$). The solid, dotted, and dashed curves indicate the cross sections for the total, axial-vector (π) contribution, vector (ρ) contribution, respectively.

Same cross section for antiproton projectiles!

Large enough cross sections to be measured with modern detectors

Strong dependence of σ on proton transverse polarization (similar to DIS case of pion production Frankfurt, Pobilitsa, Polyakov, MS)

Comment - the discussed reactions are optimal for studies GPDs corresponding to non-vacuum quantum numbers in t -channel at small x.

Interesting question is α'_R

Is it the same as for soft processes ~ 1 GeV^{-2} ?

My guesses: $\alpha'_R(pert) << \alpha'_R(nonperturb)$

$\alpha_R(pert)$ (- t > 1 GeV^2) ~ -0.2

Presence of many channels allows to perform many cross checks