High-t exclusive processes in hadron-hadron and photon-hadron scattering

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Exclusive meson production workshop, Jan. 23-25, 2015

Outline

- **Introduction: Motivation and facilities**
- **Brief summary of color coherence and color transparency**
- ***Novel class of the processes hard 2→3 branching exclusive processes:***
  - ***Measurement of GPDs of various hadrons in hadron induced processes***
  - ***More effective way to test color transparency for hard 2→2 processes***

Motivations for the hard exclusive hadron induced processes with nucleons and nuclei

- *Going beyond one dimensional image of nucleon - GPDs & correlations in the wave functions of baryons and mesons*

- *What is* ***the multiparton structure*** *of hadrons and how it is different for mesons and baryons:*

$$|baryon\rangle = |qqq\rangle + |qqq(q\bar{q})\rangle + |qqqg\rangle + ...$$
$$|meson\rangle = |q\bar{q}\rangle + |q\bar{q}g\rangle + ...$$

- Need probes with high resolution - in addition to virtual photon probe discussed in a number of talks. Natural candidate - large t / large angle hadron - hadron scattering.

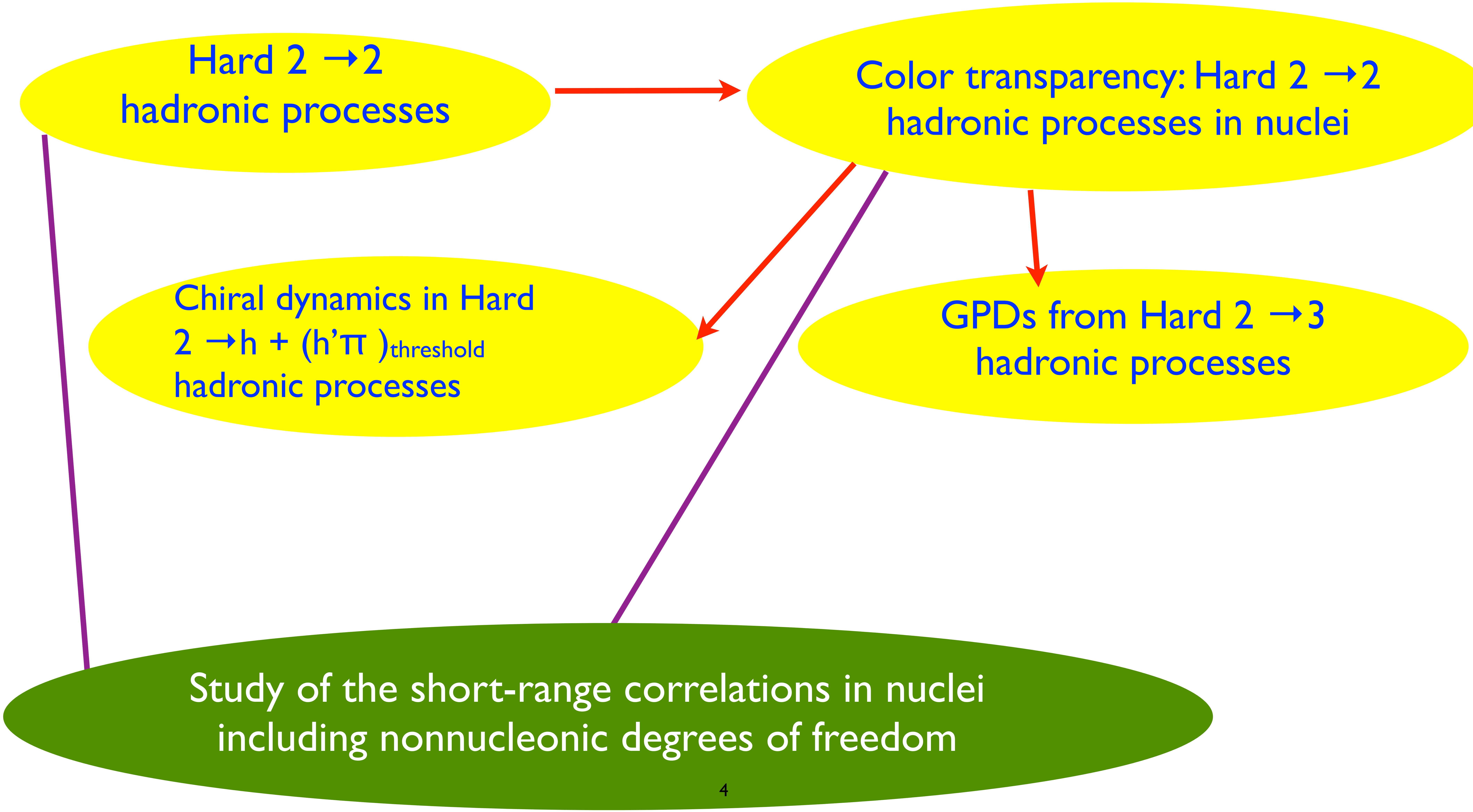
- Scan sizes involved in large t a+b → c+ d reaction, determine at what t point-like configurations dominate.

- Understand dynamics of 2 →2 reaction.

- *How fast do wave packets of quarks evolve into hadrons?*

- Use chiral degrees of freedom to probe dynamics

Starting at what t 2 →2 large angle process allow to do analog of DIS - *select point - like configurations in hadrons?*



Facilities:

Jlab - 12 GeV

COMPASS detector at CERN (collected data, will run for few years)

J-Park 2017 - protons 30 GeV pions < 15 GeV

PANDA detector at FAIR (GSI) (20XX?)

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

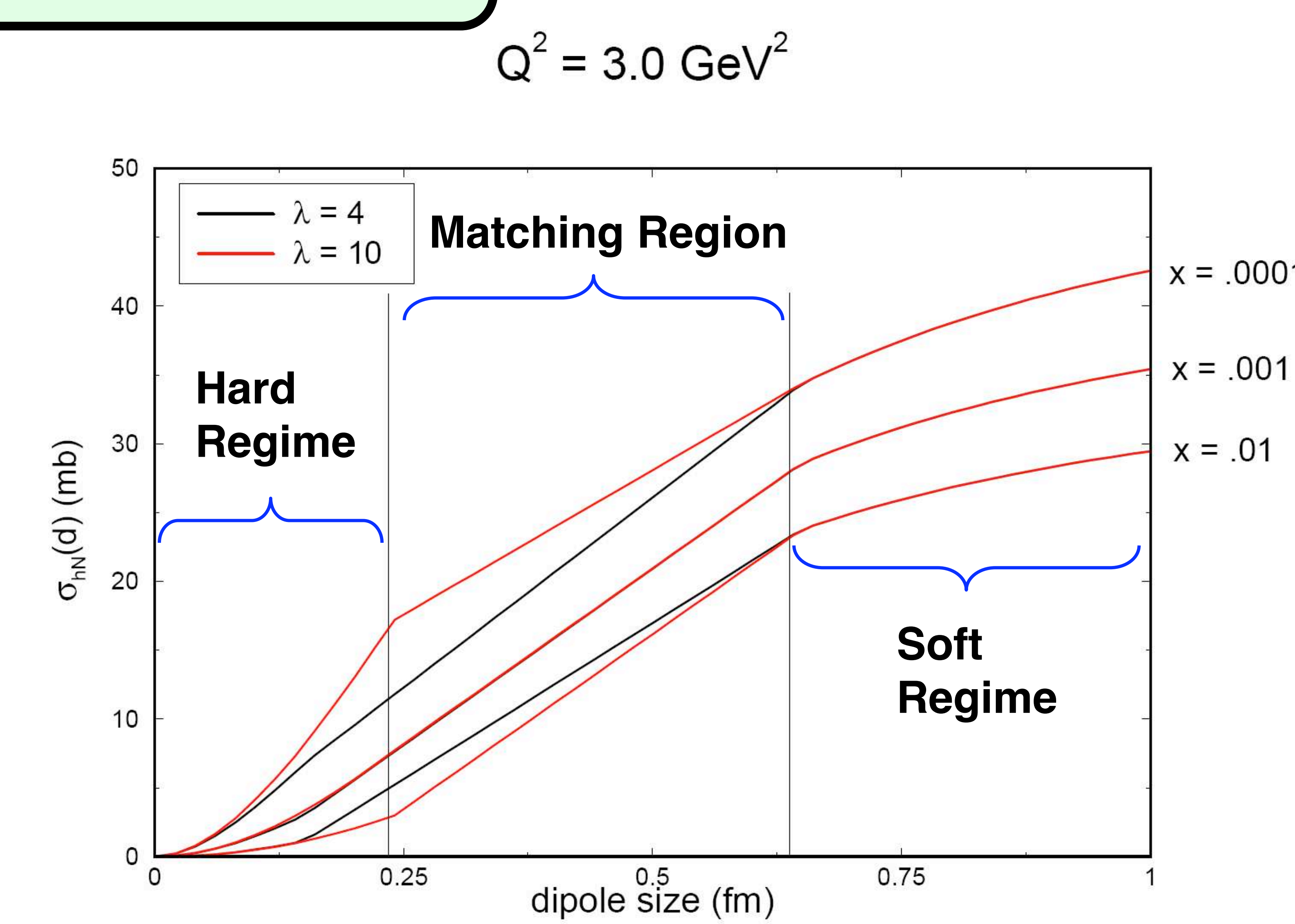
Basic tool of CT: suppression of interaction of small size color singlet configurations = CC

For a dipole of transverse size d:

$\sigma = cd^2$ *in the lowest order in* αs *(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→ M+ B
- Large angle (t/s = const) two body processes: a+ b →c+ d Brodsky & Mueller 82

↕ 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)

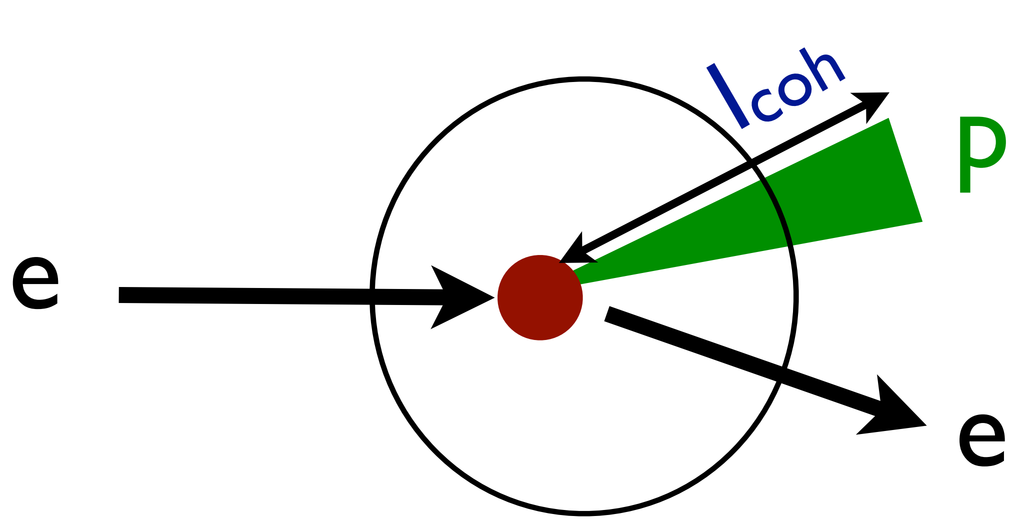
$$|\Psi_{PLC}(t)\rangle = \sum_{i=1}^{\infty} a_i \exp(iE_i t)\,|\Psi_i t)\rangle = \exp(iE_1)\sum_{i=1}^{\infty} a_i \exp\left(\frac{i(m_i^2 - m_1^2)t}{2P}\right)|\Psi_i t)\rangle$$

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

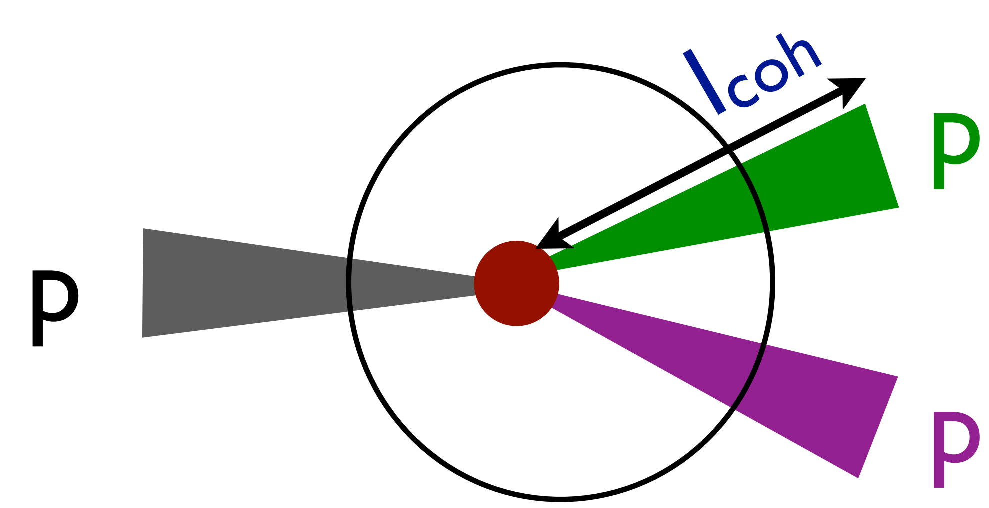
Quantum Diffusion model of expansion

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

actually incoherence length



eA→ ep (A-1) at large Q



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

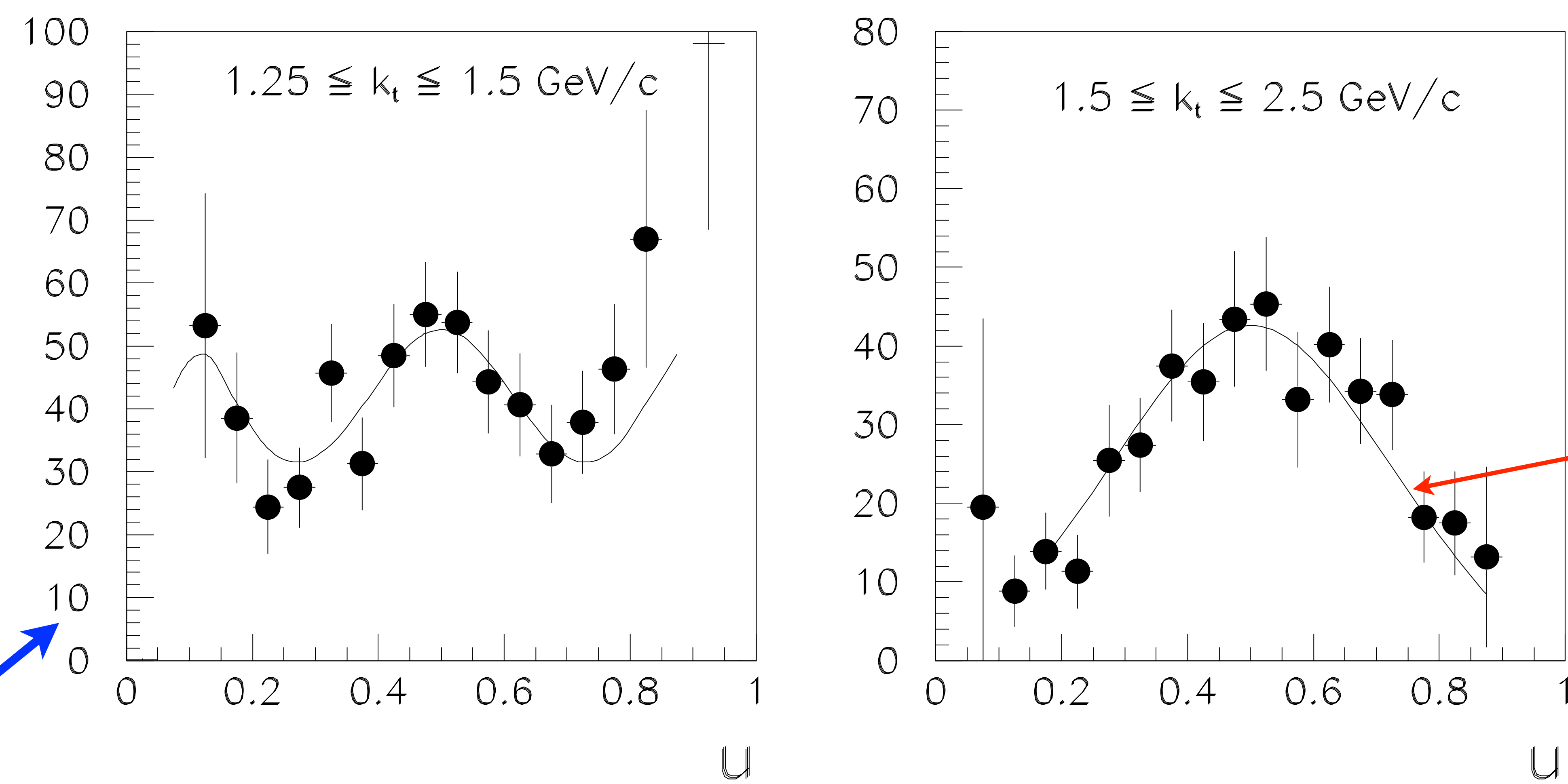
MC's at RHIC assume much larger l_{coh}= 1fm E_h/m_h;
for pions l_{coh}= 7 fm E_h[GeV] -
a factor of 10 difference !!!

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

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*



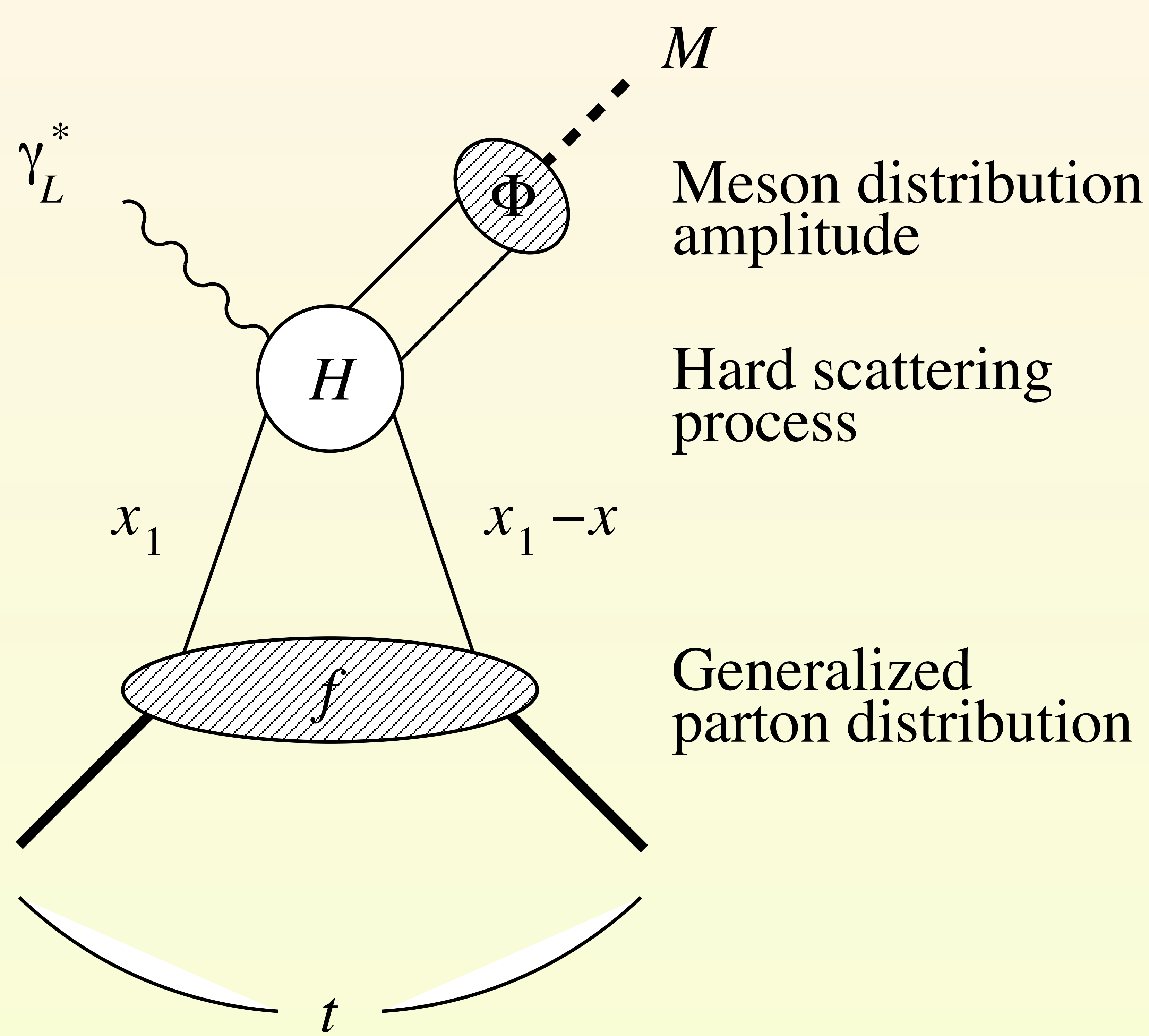
prediction

(π wave funct)^2

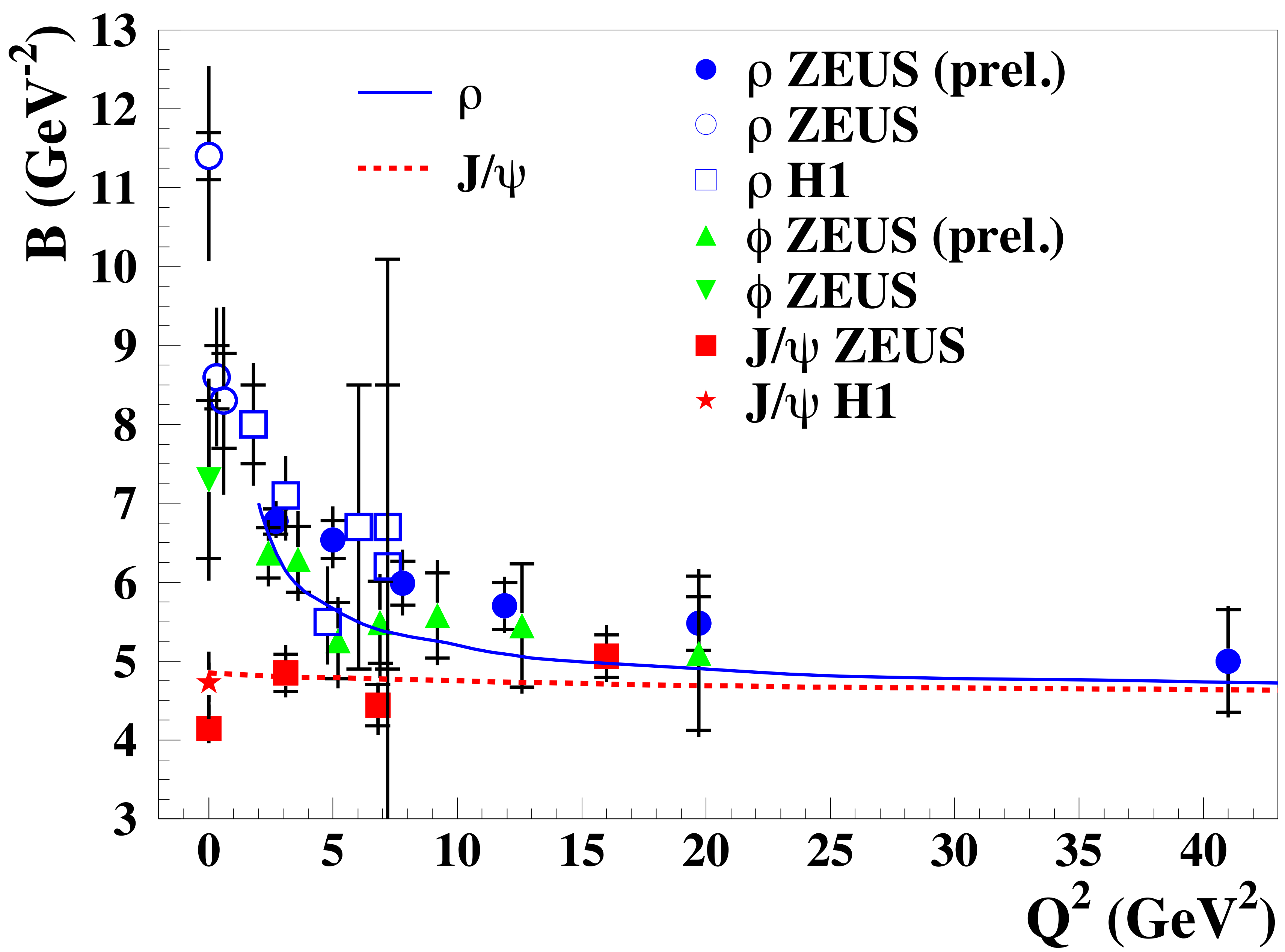
Squeezing occurs already before the leading term (1-z)z dominates!!!

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

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.



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 $d \le 0.3$ 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 $x \sim 10^{-2}$)

Intermediate energies

Main issues

☛ At what Q^2 / t particular processes select PLC - for example interplay of end point and LT contributions in the e.m. form factors, exclusive meson production.

☛ $l_{coh} = (0.4 \div 0.8 \text{ fm}) \, p_h$ [GeV] ➜ p_h=6 GeV corresponds $l_{coh} = 4$ fm $\sim 1/\sigma_{NN}\rho_0$

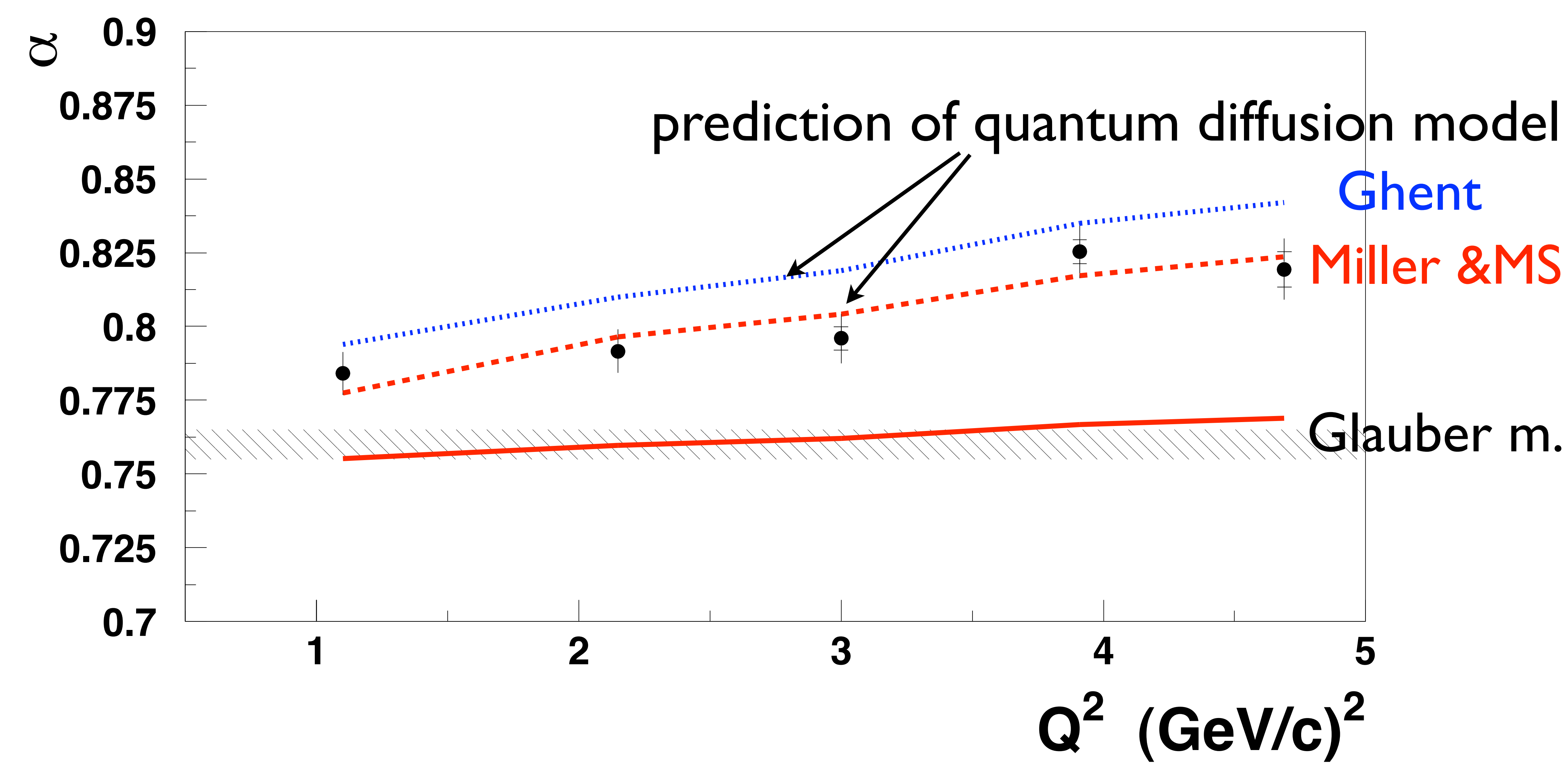
need high energies to see large CT effect even if squeezing is effective at E~ few GeV

Experimental situation

- Energy dependence of transparency in (p,2p) is observed for energies corresponding to $l_{coh} \geq$ 3 fm. Such dependence is impossible without freezing. But not clear whether effect is CT or something else? Needs independent study & new approaches.

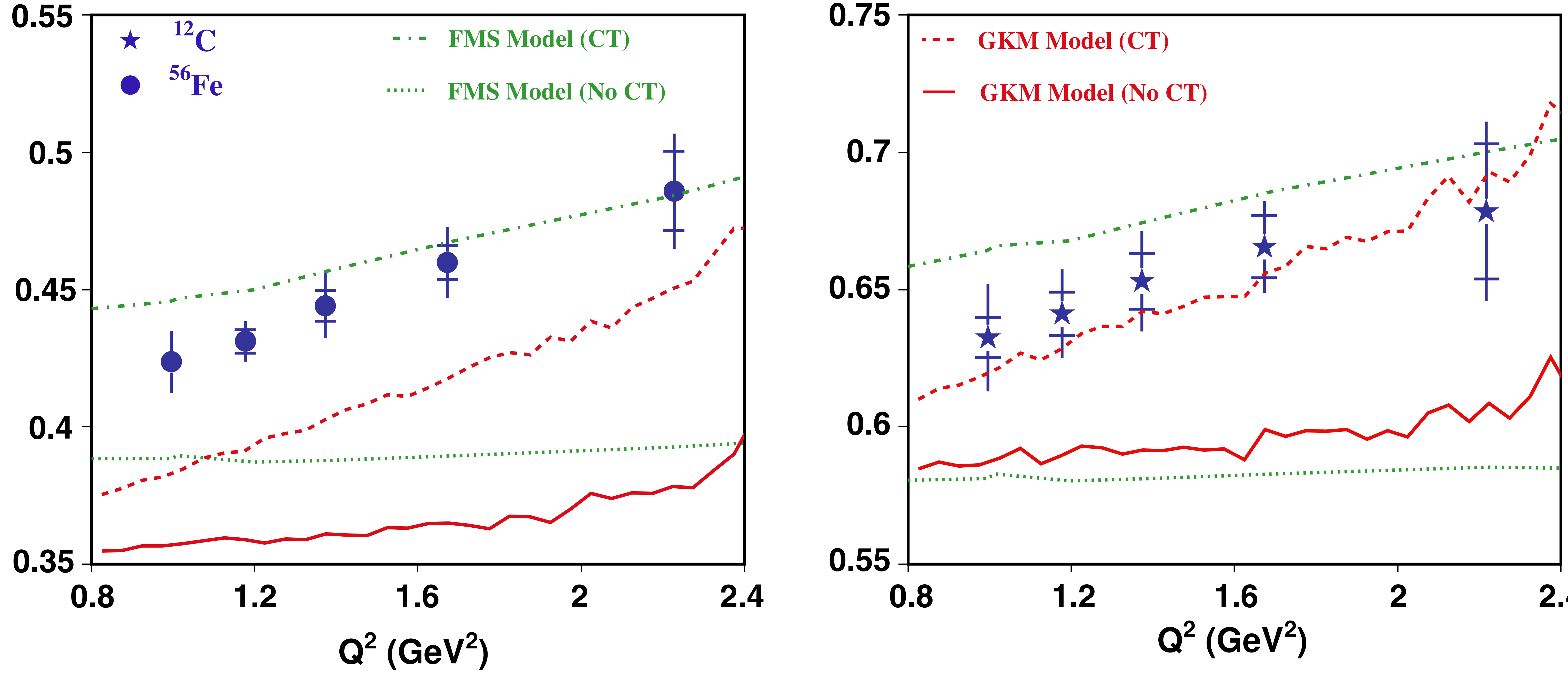
- $\gamma^* + A \to \pi A^*$ evidence for increase of transparency with Q (Dutta et al 07)

Note that elementary reaction for Jlab kinematics is dominated by ERBL term so $\gamma^* N$ interaction is local. γ^* does not transform to $q\bar{q}$ distance $1/m_N x$ before nucleon

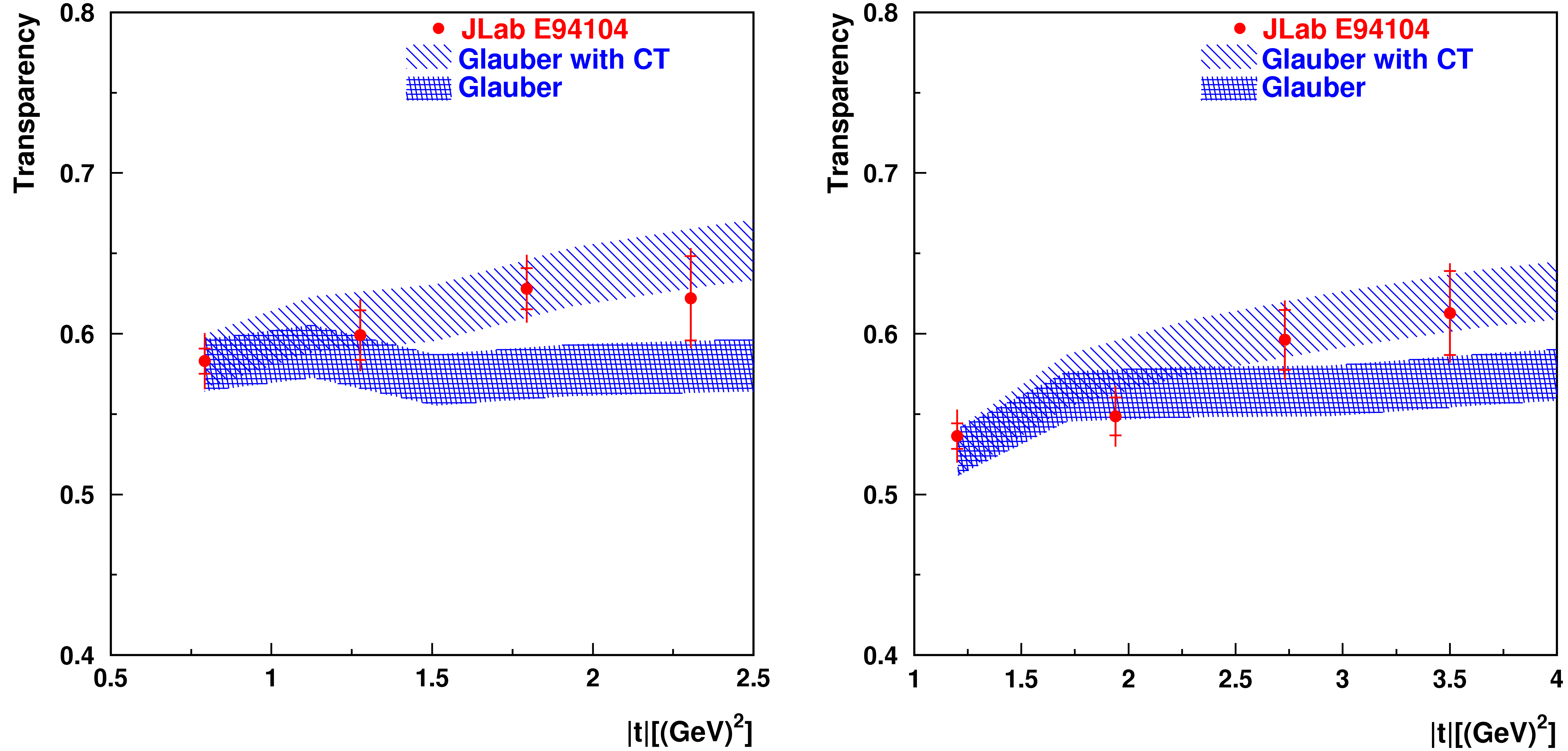


A- dependence checks not only squeezing but small l_{coh} as well

Also Jlab and HERMES ρ meson production data & FNAL J/ψ data indicate CT



Nuclear transparency as a function of Q^2. The inner error bars are statistic uncertainties and the outer ones are statistic and point-to-point (Q^2 dependent) systematic uncertainties added in quadrature . The curves are predictions of the FMS (red) and GKM (green) models with (dashed and dashed–dotted curves, respectively) and without (solid and dotted curves, respectively) CT. Both models include the pion absorption effect when the ρ0 meson decays inside the nucleus.

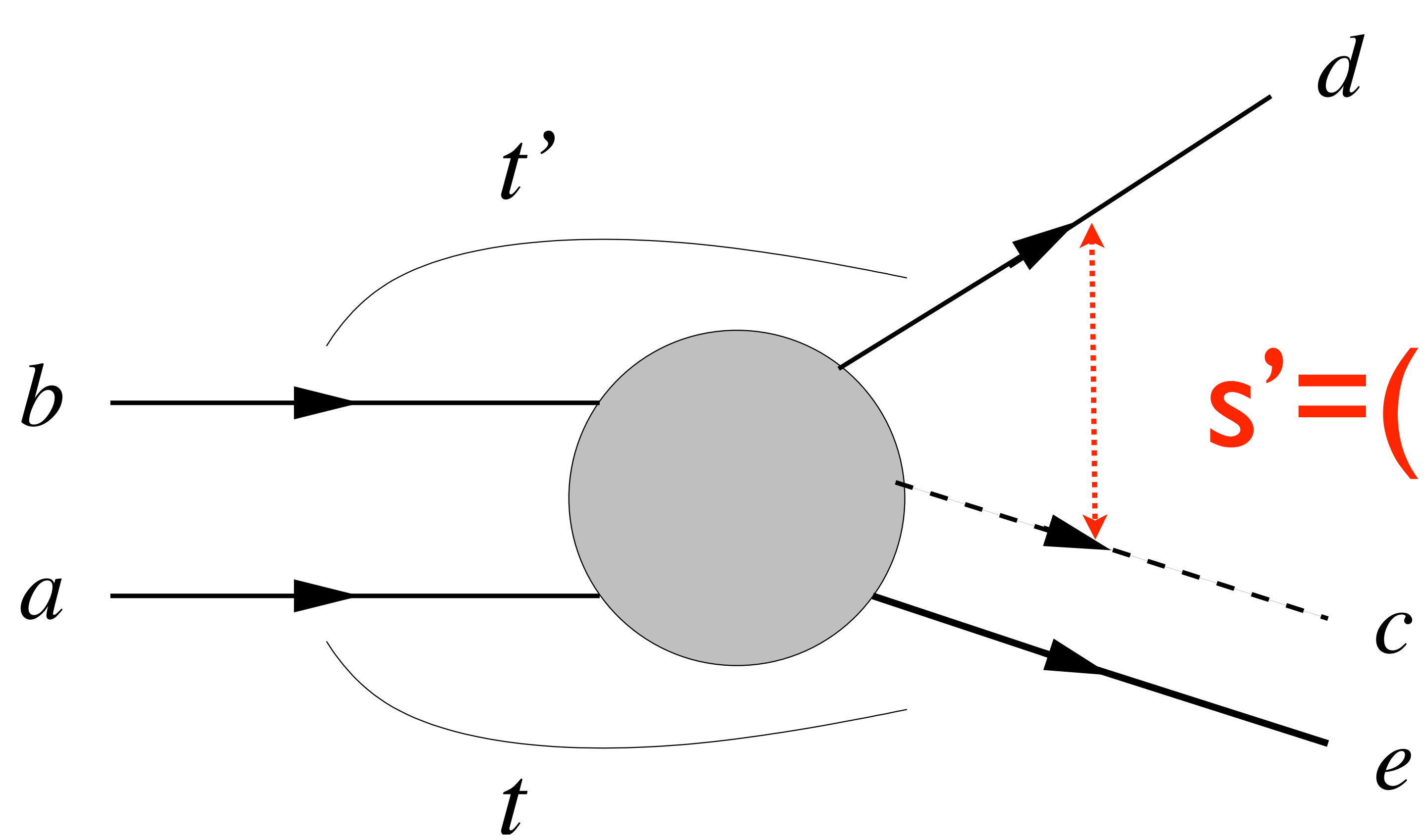


The nuclear transparency of 4 He(γ , pπ) at θ_π = 70° (left) and θ π = 90° (right), as a function of momentum transfer square |t | [Dutta et al]. The inner error bars shown are statistical uncertainties only, while the outer error bars are statistical and point-to-point systematic uncertainties (2.7%) added in quadrature. In addition there is a 4% normalization/ scale systematic uncertainty which leads to a total systematic uncertainty of 4.8%.

At x> 0.1 we can think of the exclusive DIS process as knock out of a quark-antiquark pair: measuring probability for nucleon to consist of nucleonic white cluster and small $\bar{q}q$ pair. Analogous effect - knocking out of three quarks: slow meson + forward baryon (MS+ Polyakov,.. 1999; B.~Pire, K.~Semenov-Tian-Shansky, L.~Szymanowski and S.~Wallon - extensive studies in pQCD): fluctuation compact 3q + white quark - antiquark cluster.

Idea is to consider new type of hard hadronic processes - *branching exclusive processes* of large c.m. angle scattering on a "cluster" in a target/projectile (MS94). Factorization into blocks like in DIS could set in much lower Q(t) than the limit where pQCD works for elementary process like nucleon form factor

to study both CT of 2 → 2 and hadron GPDs



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

Limit:

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

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

➡ $s'/s = y < 1$,

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

DIS exclusive process b=e, d=e', a=N, c=M(B), e=B(M) is the simplest example

Two papers focused on pp, πp: Kumano, MS, and Sudoh PRD 09; Kumano &MS Phys.Lett. 10

Two kinematics - different detector strategies

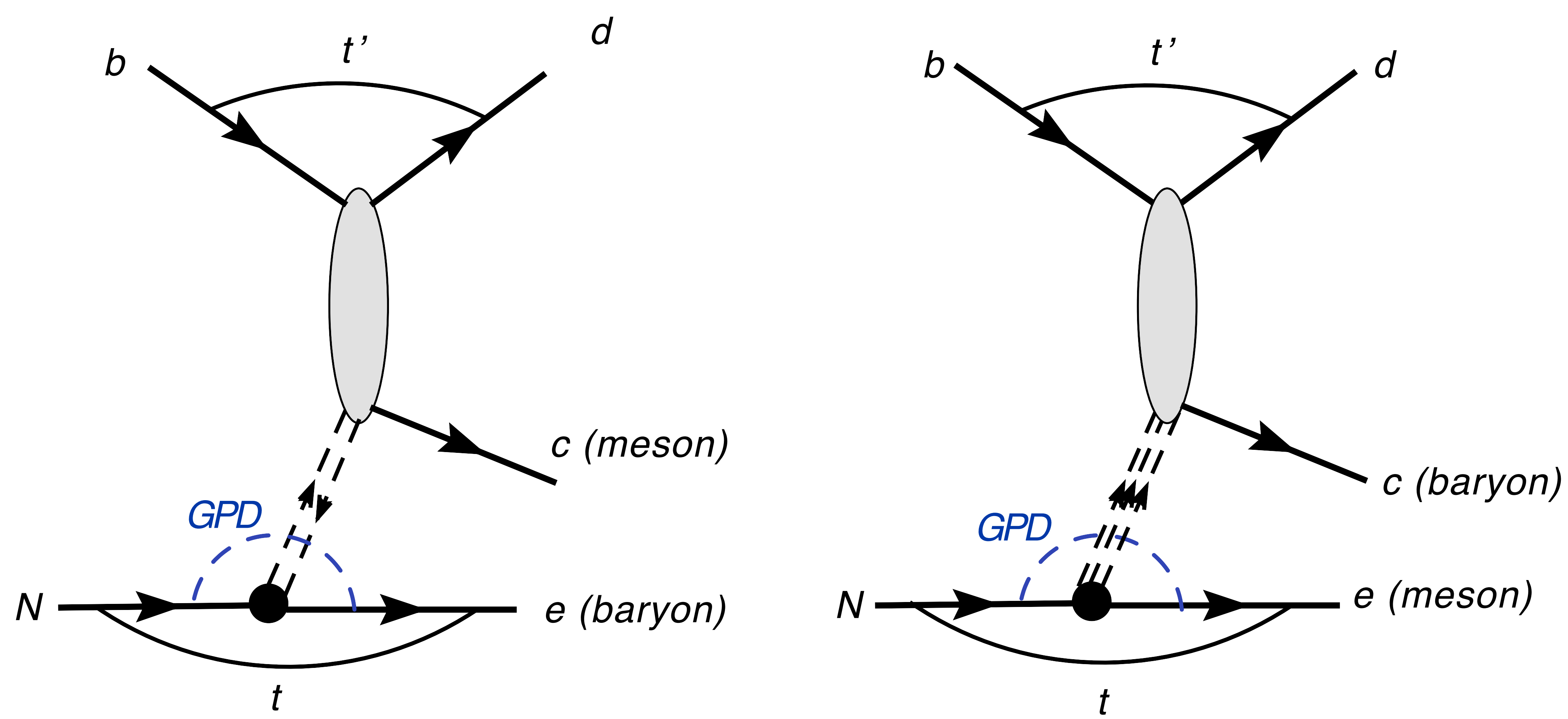
"a" at rest - "d" and "c" in forward spectrometer, "e" in recoil detector
➠ can use neutron (^2H)/ transversely polarized target

"b" at rest - "d", "c" and "e" in forward spectrometer ➠ can use neutron target

$2 \rightarrow 3$ branching processes:

- test onset of CT for $2 \rightarrow 2$ avoiding diffusion 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 and mesons& photons (!)
- measure pattern of freezing of space evolution of small size configurations

Factorization:



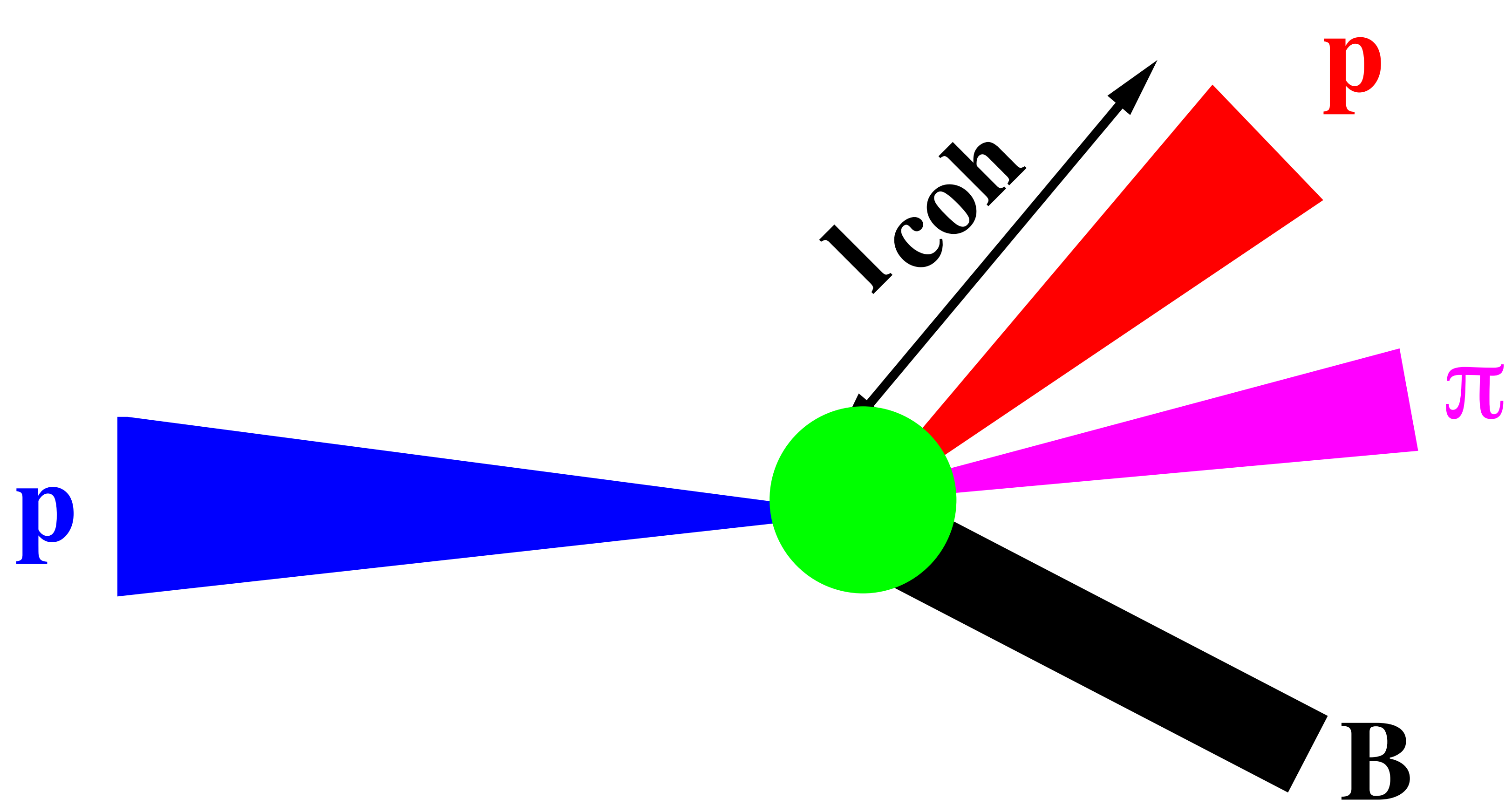
If the upper block is a hard (2 →2) process, "b", "d", "c" are in small size configurations as well as exchange system (qq, qqq). Can use CT argument as in the proof of QCD factorization of meson exclusive production in DIS (Collins, LF, MS 97)

$$\Downarrow$$

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

Minimal condition for factorization:

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



Time evolution of the 2 → 3 process

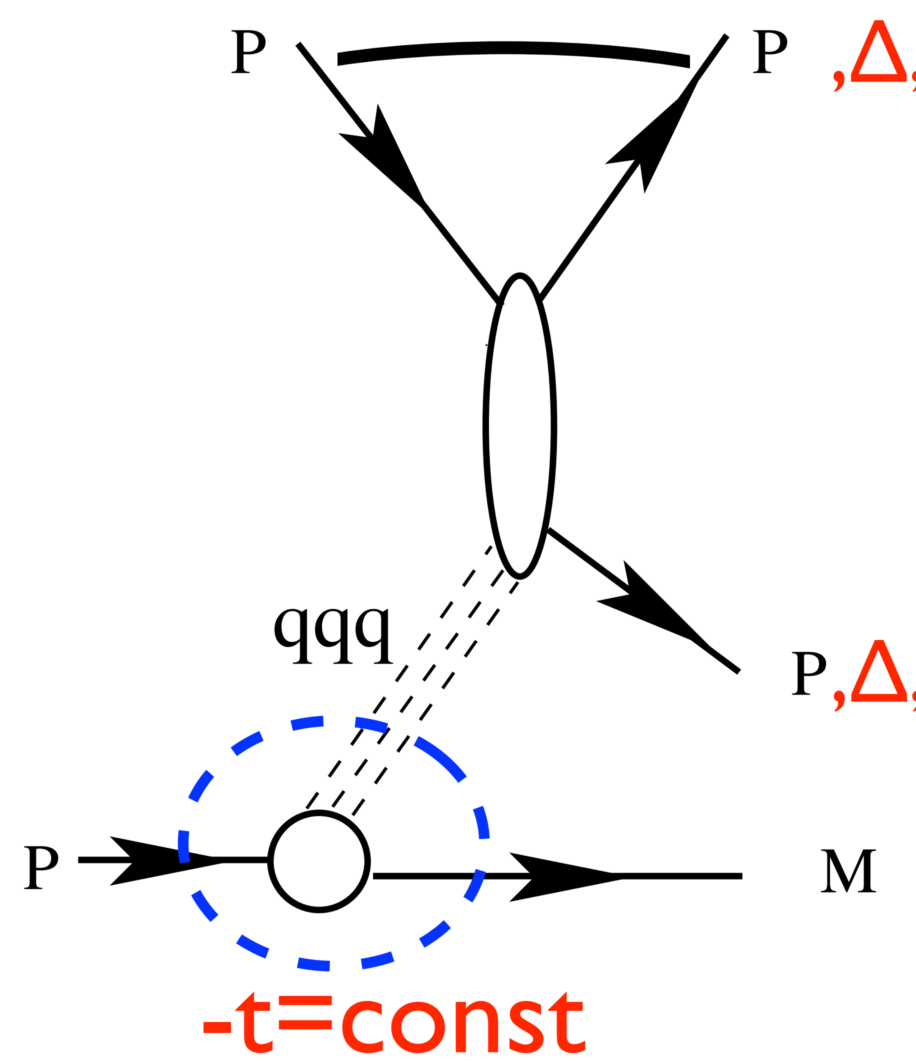
$$l_{coh} = (0.4 \div 0.6 \text{ fm}) \cdot p_h/(\text{GeV}/c)$$

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

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

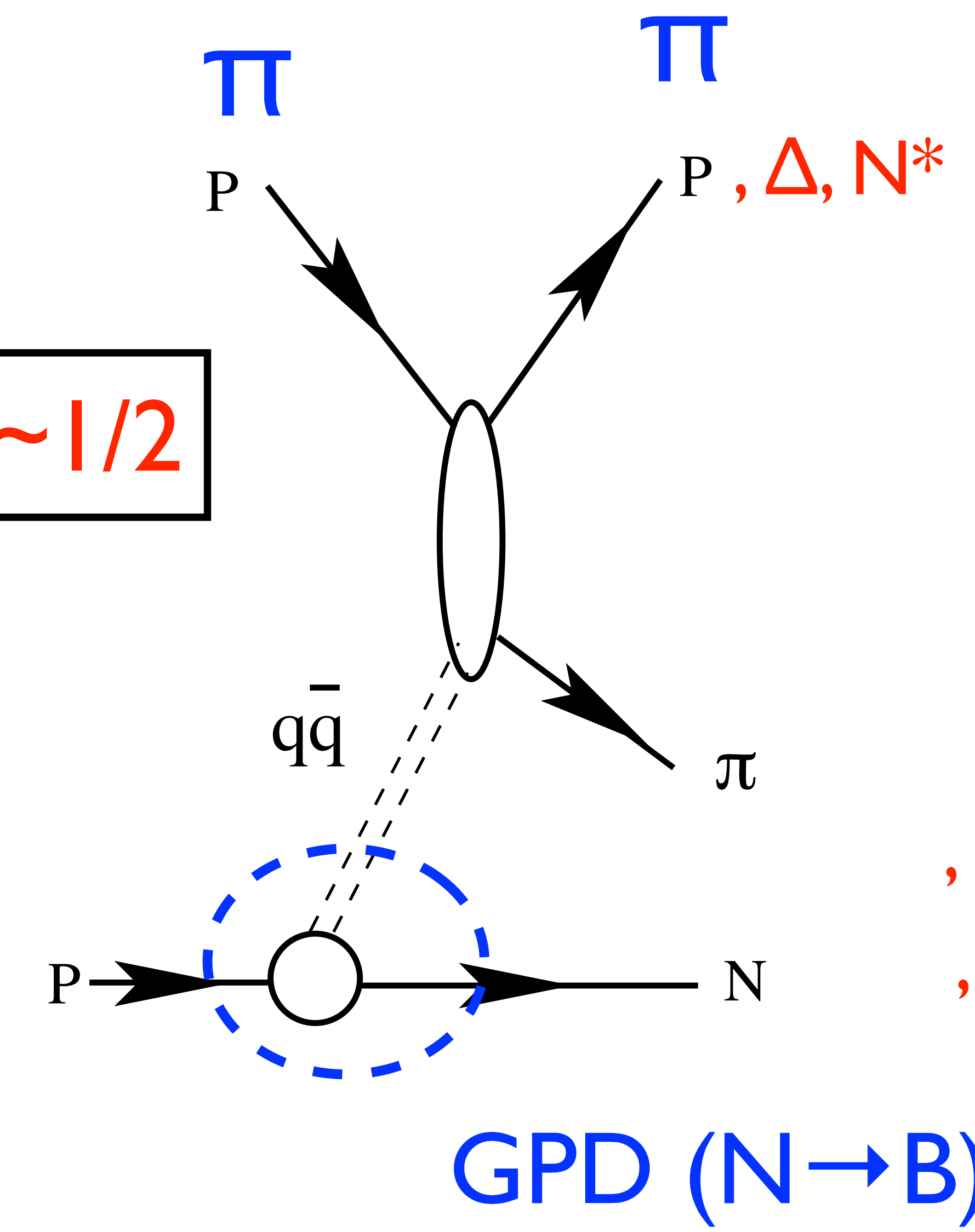
easier to reach than in CT reactions with nuclei

Examples



-t/s'~1/2

GPD
(N→M)



Λ,Σ

, ρ,η, ϕ K,K*

, Δ, N*

$$pp \to pN + M(\pi, \eta, \pi\pi)$$

$$pp \to p\Delta + M(\pi, \eta, \pi\pi)$$

$$pp \to p\Lambda + K^+$$

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

$$\pi^- p \to \pi^- \pi^- \Delta^{++},$$ COMPASS

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

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

J-PARC if beams of pions with energies 20 -40 GeV are doable

$$\pi^- p \to \pi^- p + (\pi^0\pi^0 - forward\ low\ p_t)$$

Study of Hidden/Intrinsic Strangeness & Charm in hadrons

$pp \rightarrow \Lambda_{sp}$ (any other strange baryon)+ $K^+(K^*)$ + p

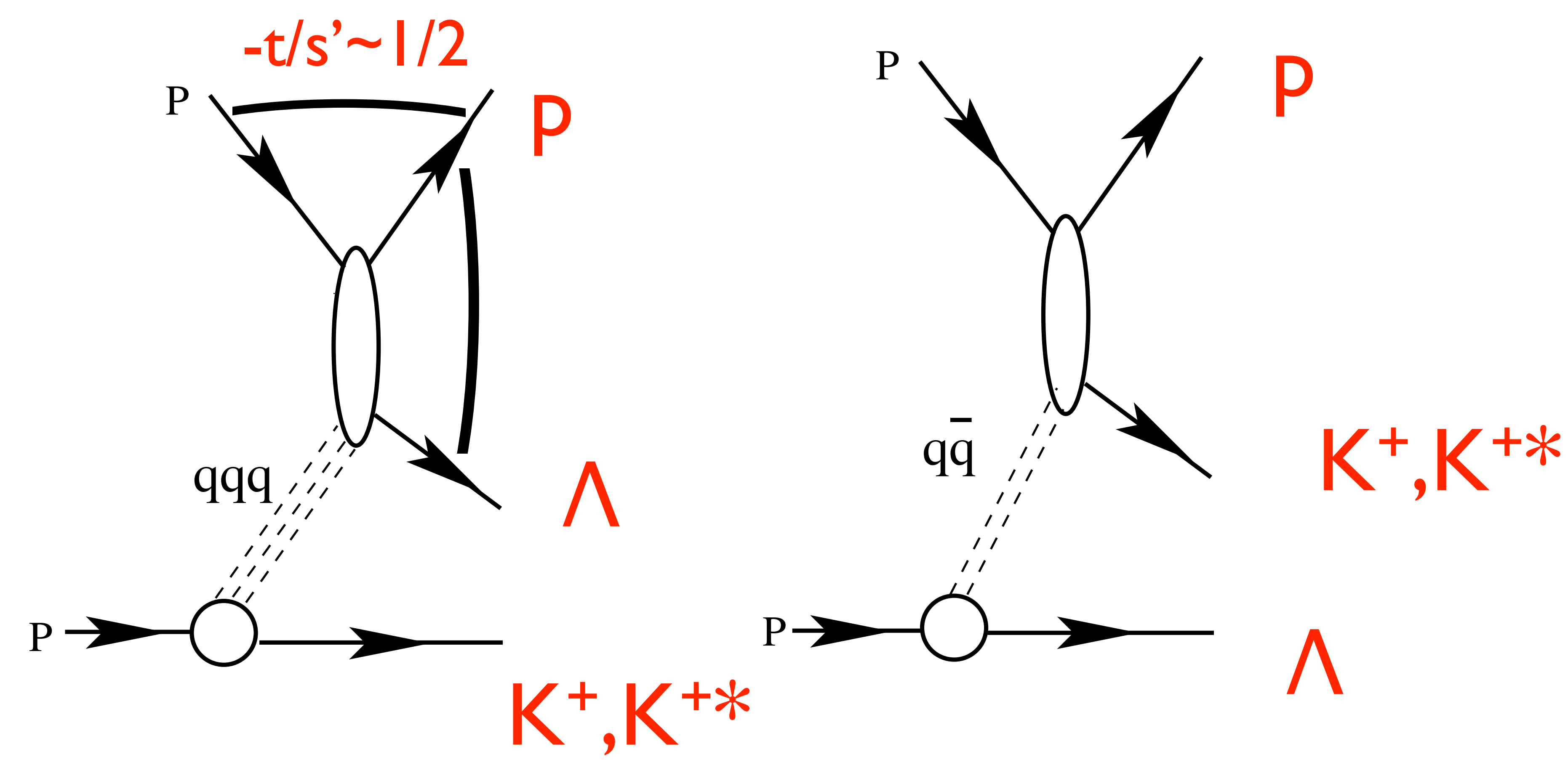
$pp \rightarrow K(K^*)_{sp} + \Lambda + p$

$pp \rightarrow \varphi_{sp} + p + p$

$pp \rightarrow \bar{D}_{sp} + \Lambda_c + p$

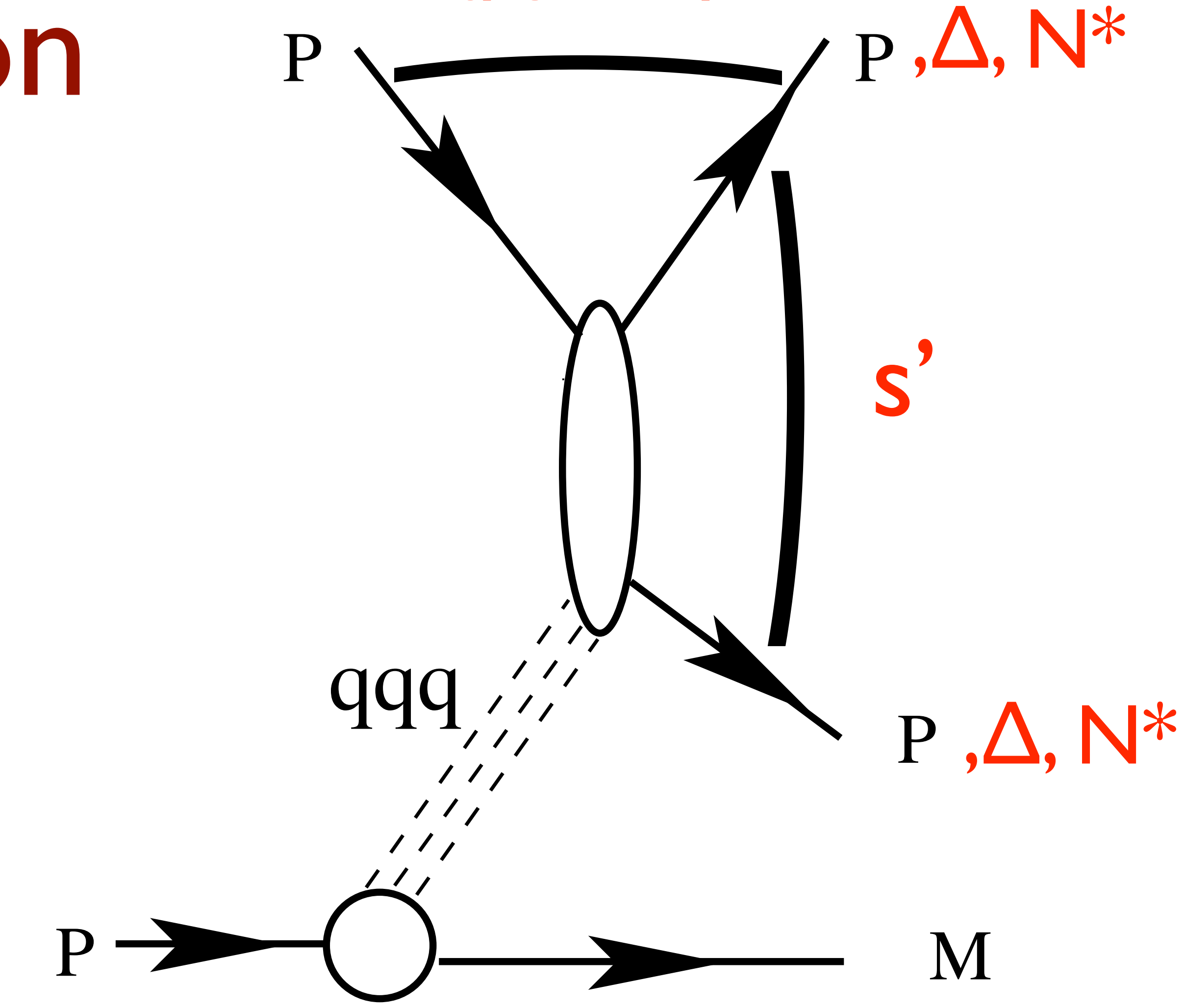
$\pi^+ p \rightarrow K^+_{sp} + \bar{K^0} + p$

BNL experiment: EVA has few candidate events



Study of the spin structure of the nucleon

use of polarized beams and/or targets



$\vec{p}\vec{p} \to \Lambda_{sp}$ (any other strange baryon)+ $K^+(K^*)$ + p

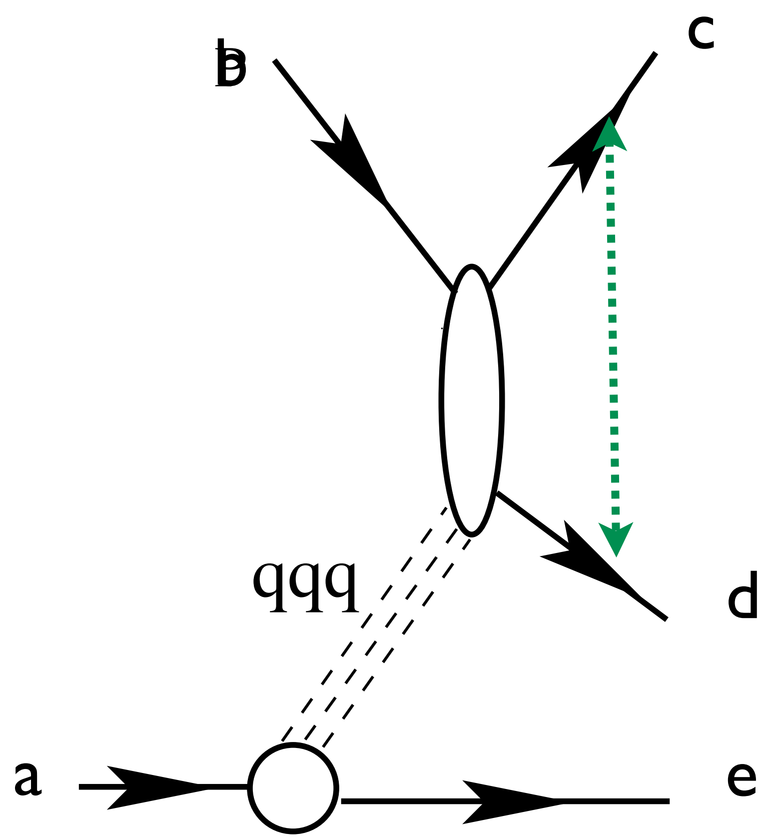
$\vec{p}\vec{p} \to K^+(K^*)_{sp} + \vec{\Lambda}$(any other strange baryon)+ p

$\vec{p}\vec{p} \to \Delta_{sp}$ (any other strange baryon)+ meson + p

study of the NΔ GPDs - more GPDs than for NN case - QCD chiral model - selection rules; single transverse spin asymmetries

Frankfurt, Pobilitsa, Polyakov, MS 98

Energy dependence of branching processes



$$s' = (p_c + p_d)^2 = (1 - \alpha_e) s_{ab}$$

$$\alpha_{spect} \equiv \alpha_e = p_-^e / p_-^a$$

$$\frac{d\sigma(a + b \to c + d + e)}{d\alpha_{sp} d^2 p_{t\ sp} / \alpha_{sp}} = \phi(\alpha_{sp}, p_{t\ sp}) R(\theta_{c.m.})\,(s_o/s')^n$$

$\sigma(2 \to 2)$

$$n = n_q(a) + n_q(cluster) + n_q(c) + n_q(d) - 2.$$

"e" flies along "a" - slow if "a" is the target - fast if "a" is the projectile

Scaling relations between hadron and electron projectiles

$$\frac{\frac{d\sigma(p+p\to p+p+\pi^0)}{d\alpha_{\pi^0} d^2 p_t/\alpha_{\pi^0}}}{\frac{d\sigma(e+N\to e+N+\pi^0)}{d\alpha_{\pi^0} d^2 p_t/\alpha_{\pi^0}}} \approx \frac{\sigma(p+p \to p+p)}{\sigma(eN \to eN)},$$

$$\frac{\frac{d\sigma^{pp\to p+\pi+B}}{d\alpha_B d^2 p_{tB} d\theta_{c.m.}(p\pi)}}{\frac{d\sigma^{p\pi\to p+\pi}}{d\theta_{c.m.}}(s_{p\pi})} = \frac{\frac{d\sigma^{\gamma_L^*+p\to\pi+B}(Q^2)}{d\alpha_B d^2 p_t}}{\sigma^{\gamma_L^*+\pi\to\pi}(Q^2)}$$

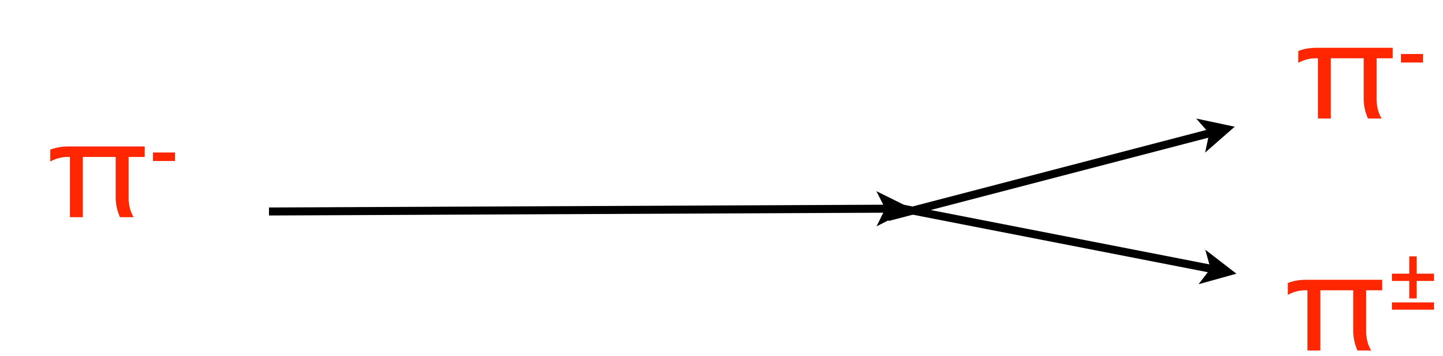
How to check that squeezing takes place and one can use GPD logic?

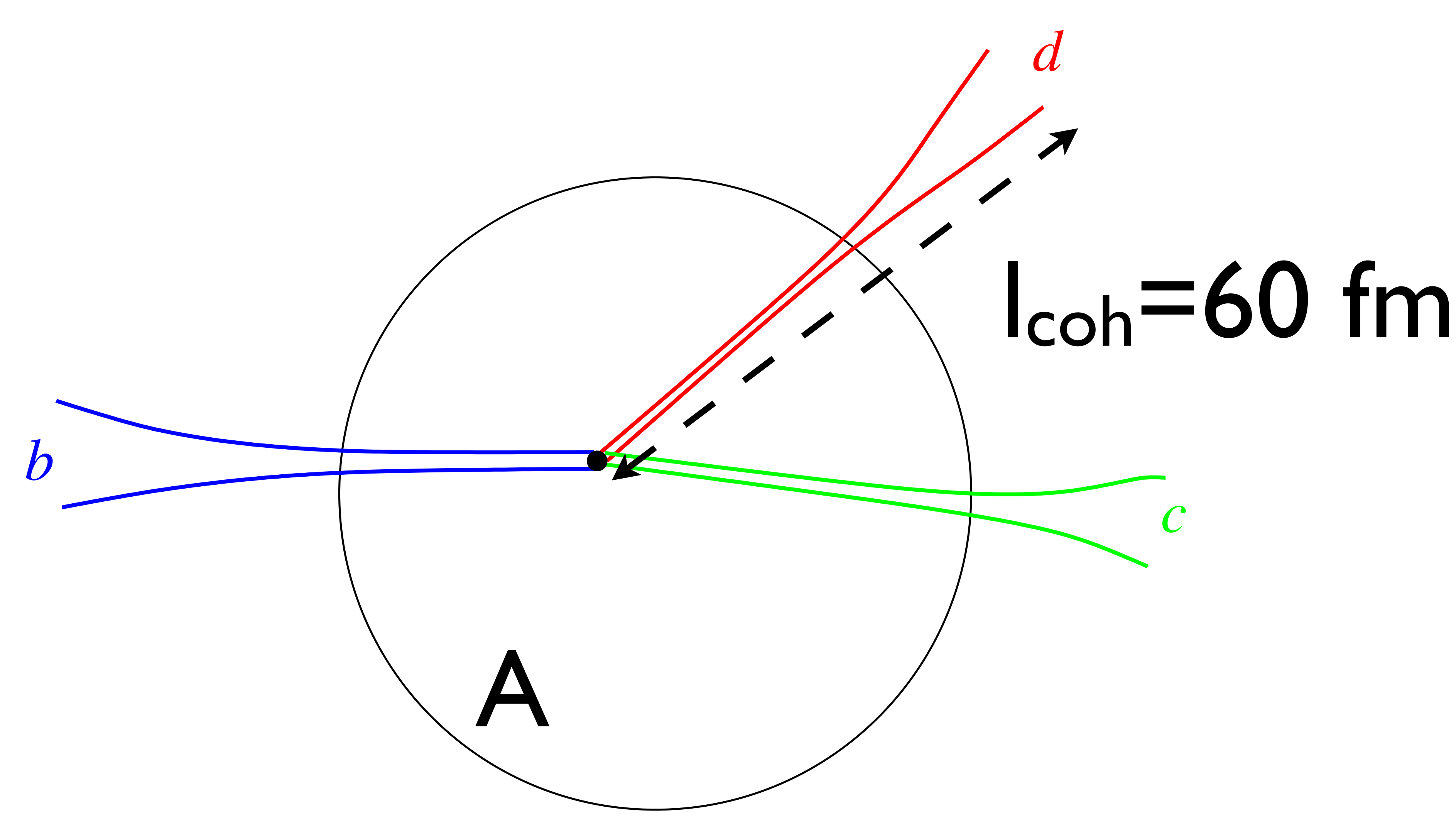
Use as example process $\pi^- A \to \pi^- \pi^\pm A^*$

- easier to squeeze
- COMPASS 190 GeV data on tape
- Early data from FNAL

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

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





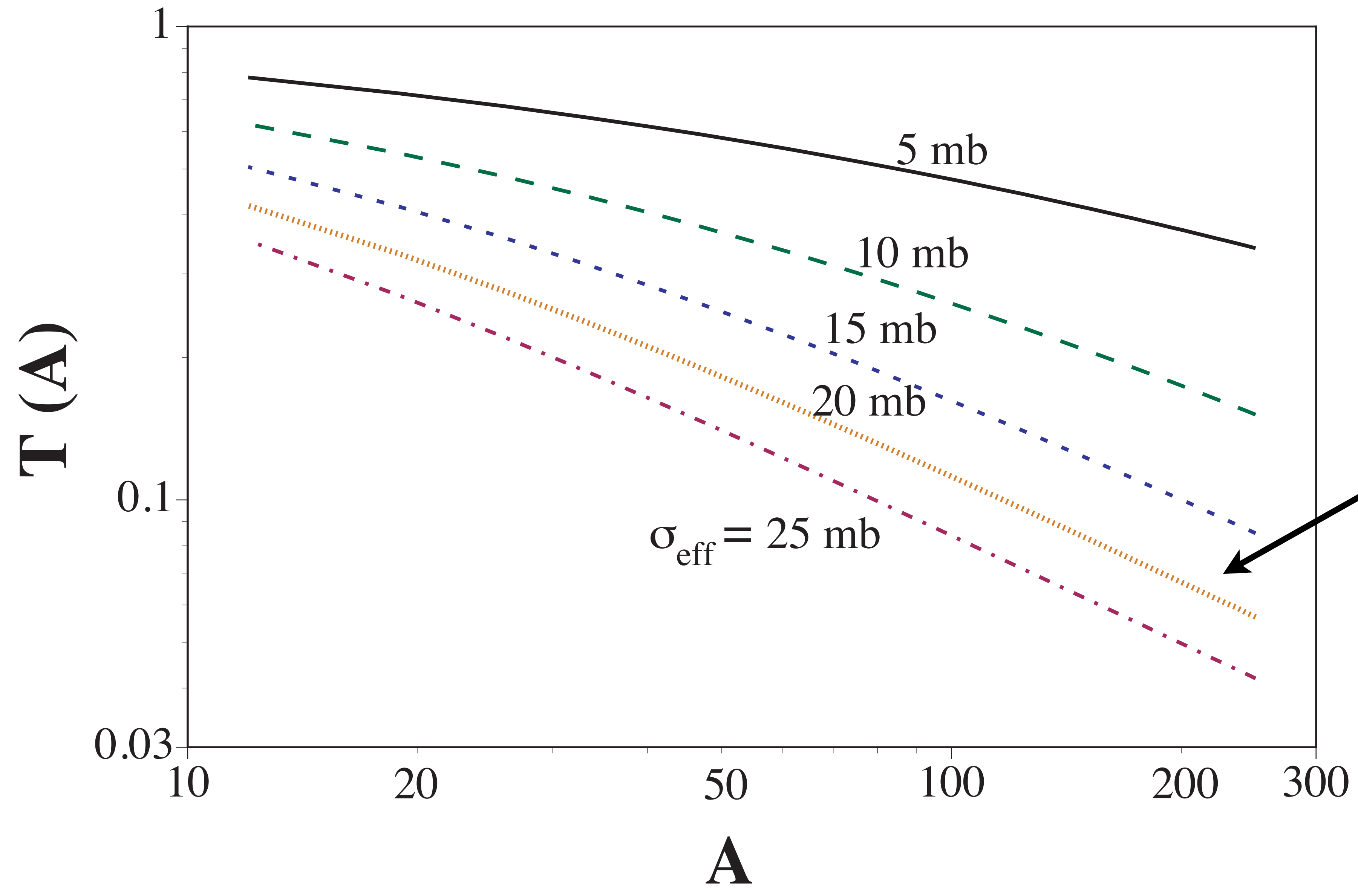
Branching (2→3) processes with nuclei - freezing is 100% effective for p_{inc} > 100 GeV/c - study of one effect only - size of fast hadrons

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

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

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 sectio

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

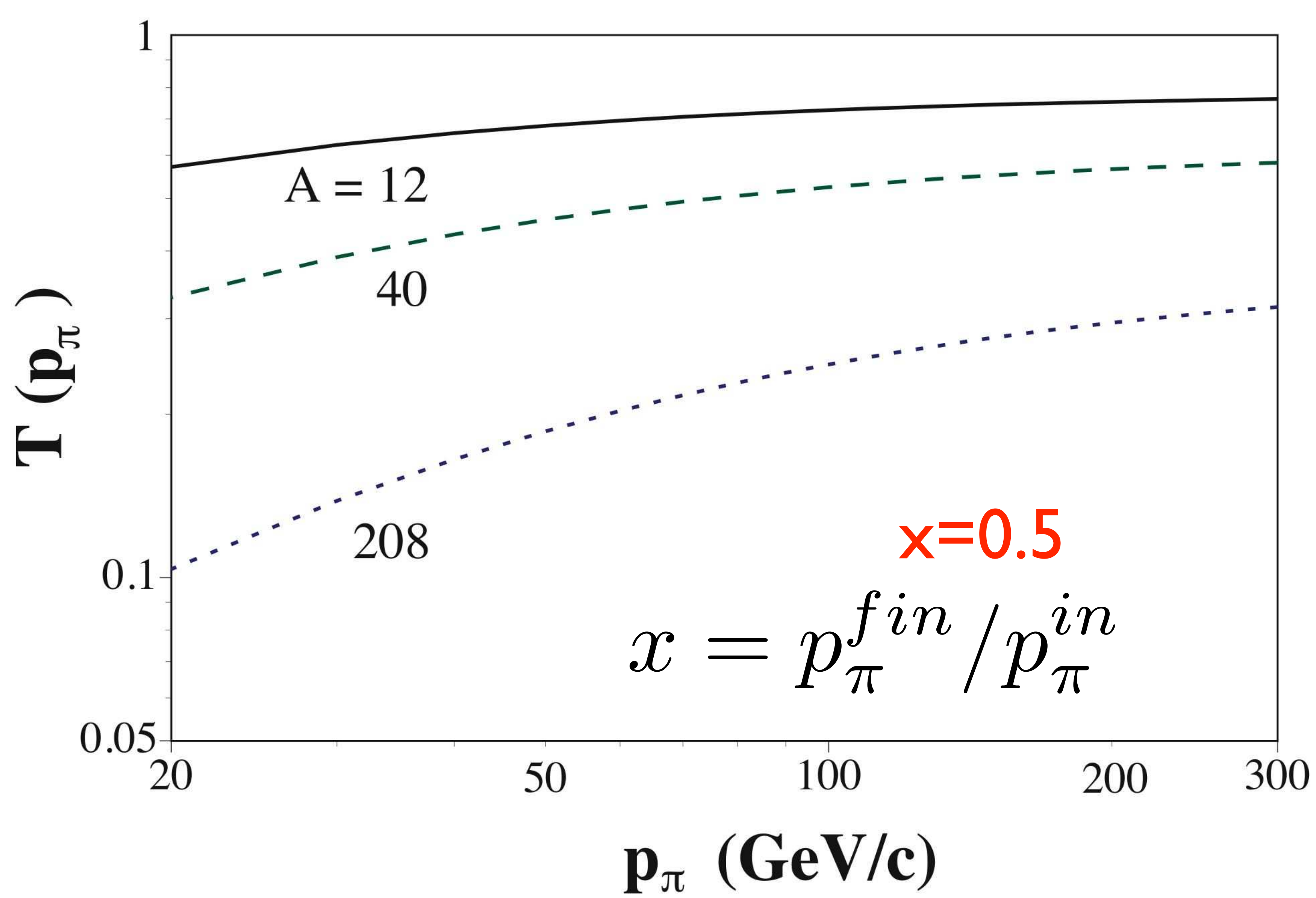
$$\sigma(d,x) = \frac{\pi^2}{3}\alpha_s(Q^2_{eff})d^2\left[xG_N(x,Q^2_{eff}) + \frac{2}{3}xS_N(x,Q^2_{eff})\right]$$

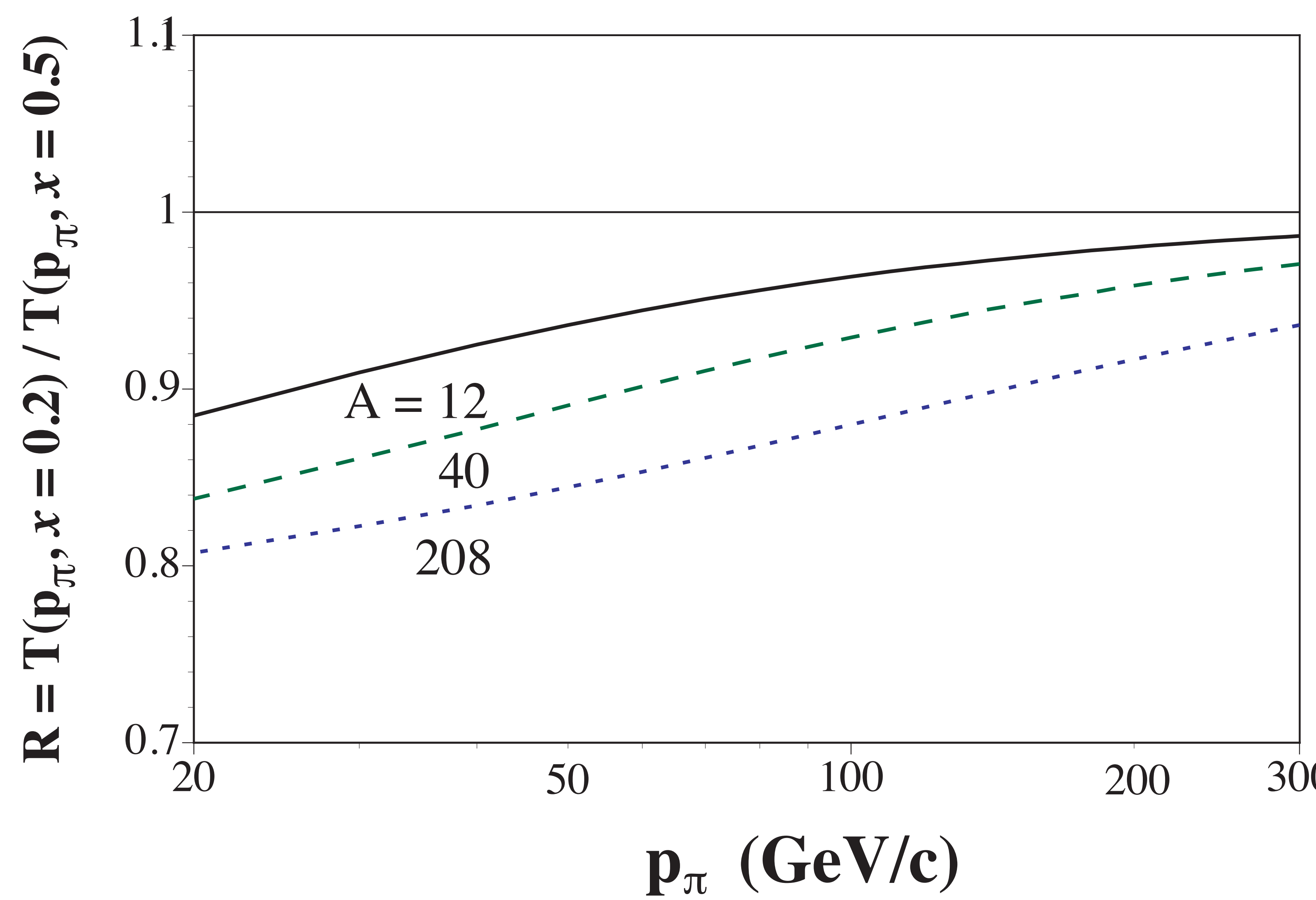
Defrosting point like configurations - energy dependence for fixed s',t'

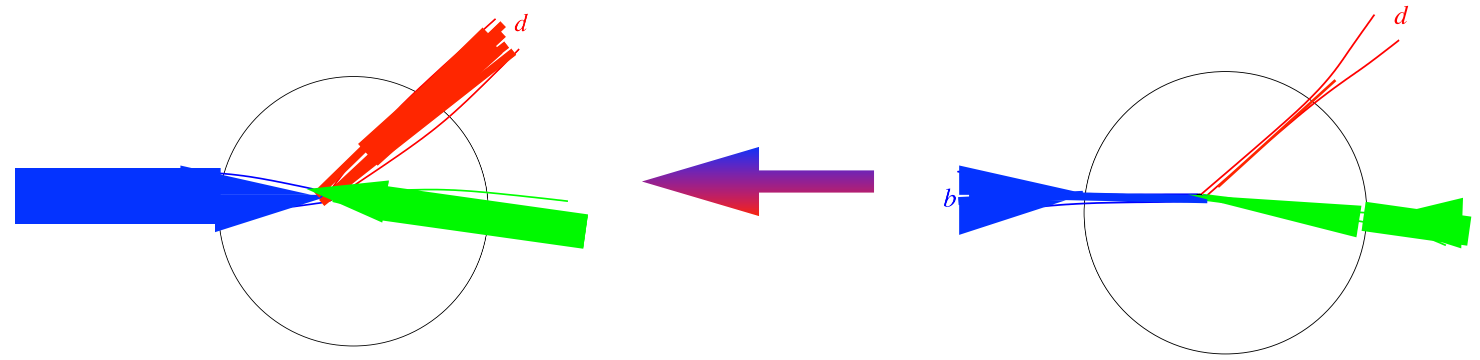
$$\sigma^{PLC}(z) = \left(\sigma_{hard} + \frac{z}{l_{coh}}[\sigma - \sigma_{hard}]\right)\theta(l_{coh} - z) + \sigma\theta(z - l_{coh})$$

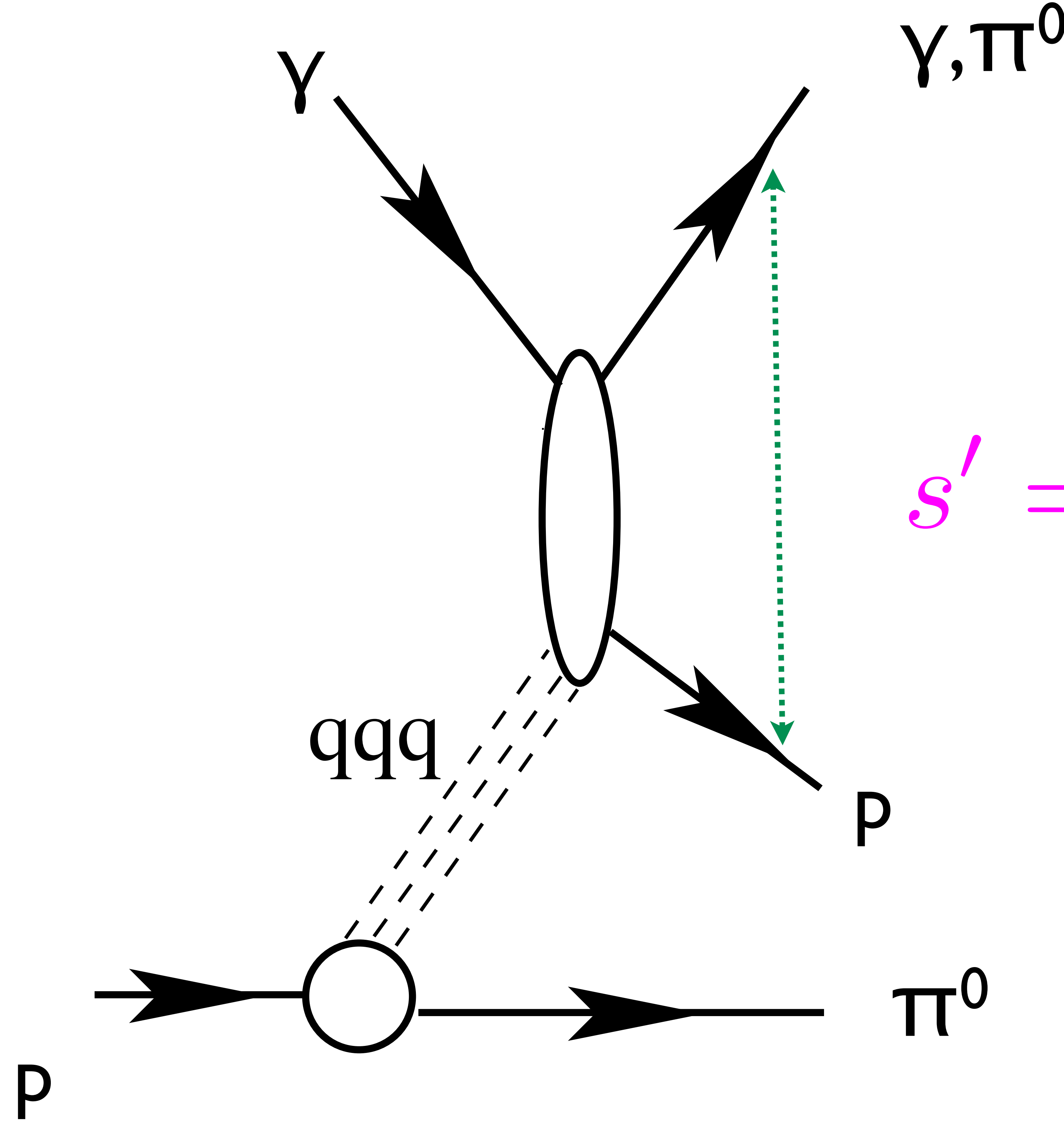
Quantum Diffusion model of expansion

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









$$s' = (1-\alpha_\pi)s$$

$$\alpha_\pi = (E_\pi - p_\pi^{(3)})/m_p$$

Slow pion corresponds to large s' and hence allows large t for a large range of c.m. angles for E_γ ~10 GeV

Small probability of πN is to some extent compensates by smaller s' since $\sigma_{\gamma N\to\pi N} \propto (s'/s)^{-7}$

A-dependence - large longitudinal momenta of p & π^0 → CT effects significant for fixed α_π and with increase of proton p_t .

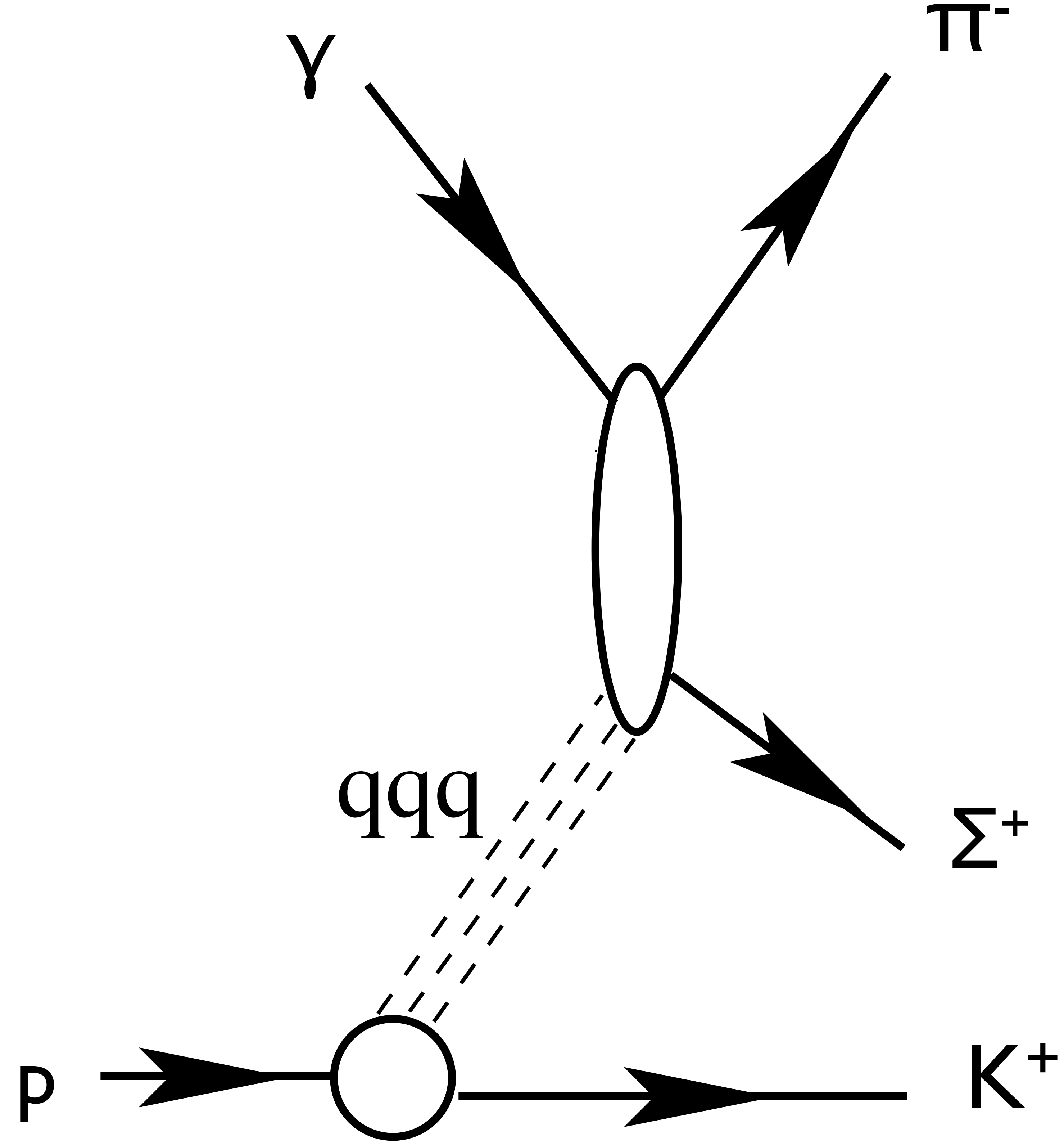
Very interesting channel: $\gamma + p \to \pi^0 + p + (\pi^0\pi^0), M_{\pi^0\pi^0} < 600\, MeV$

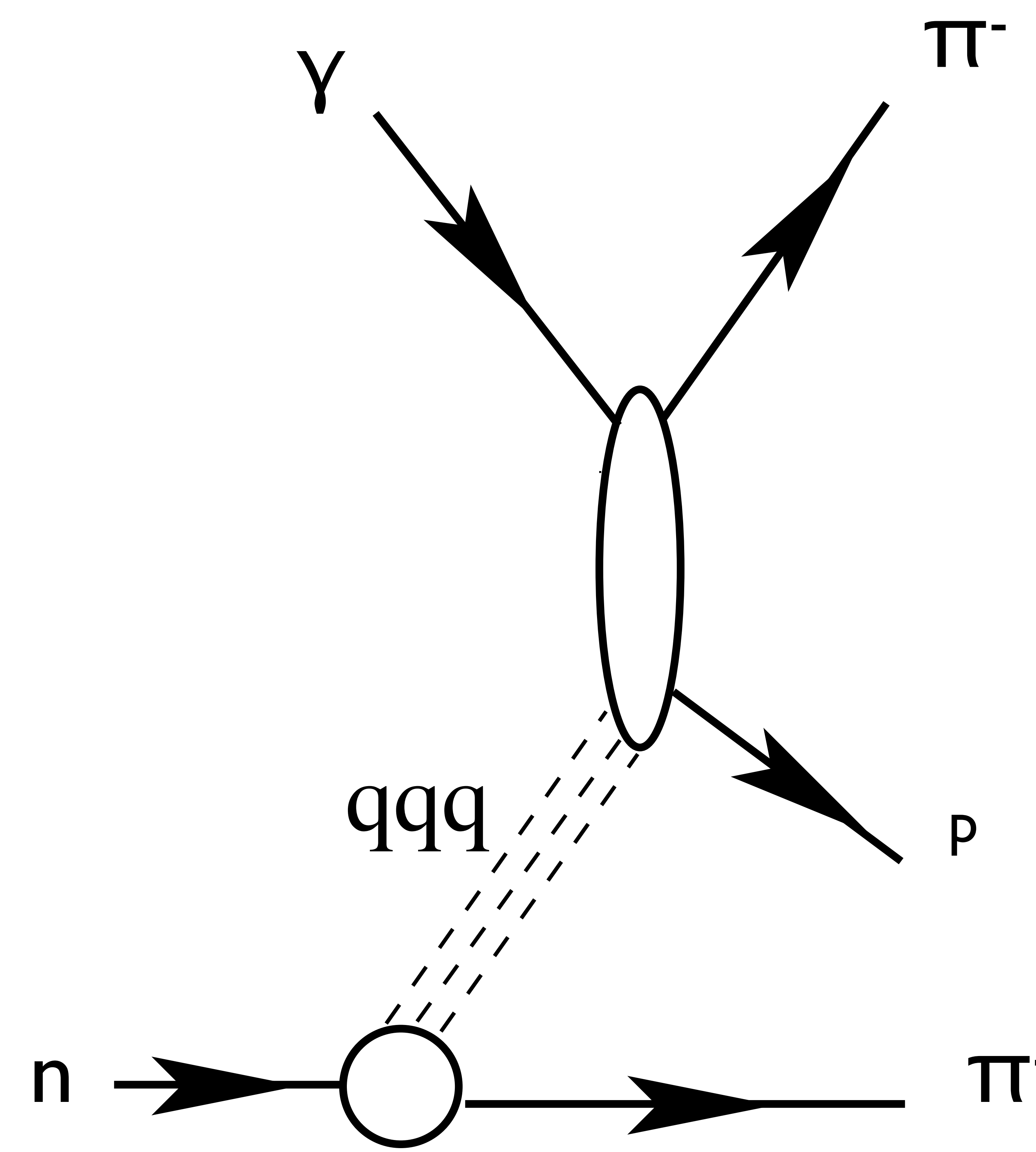
$\gamma + n \to \pi^- + p + (\pi^0\pi^0), M_{\pi^0\pi^0} < 600\, MeV$

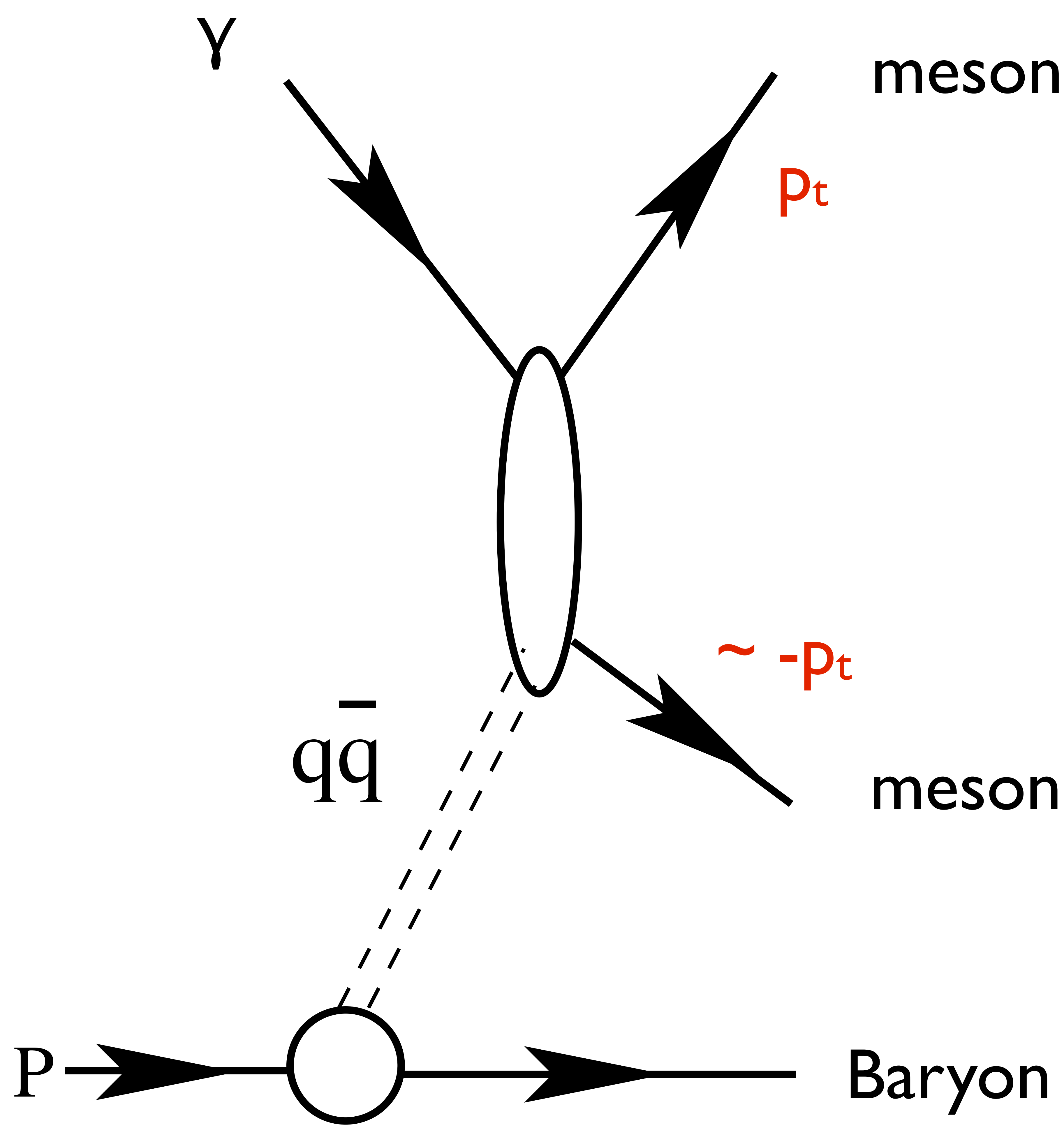
σ's?

Remark: α_γ=0 simplifies using photon beam without tagging

Other interesting channels







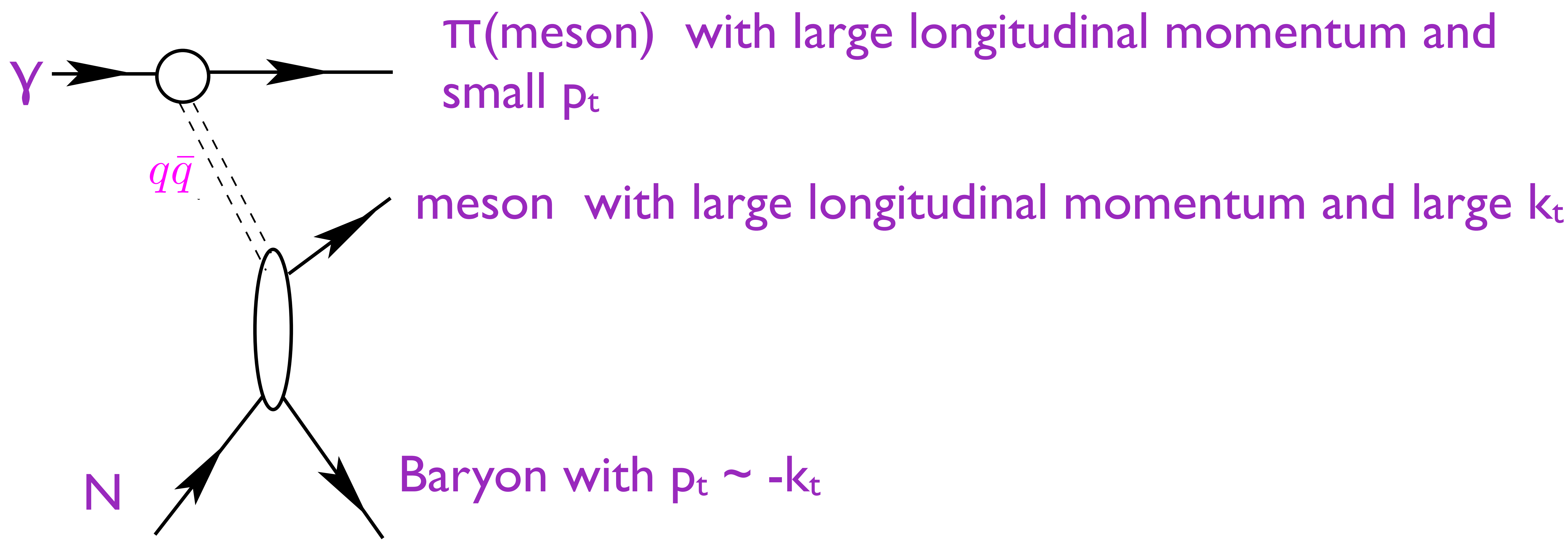
$\alpha_B < 0.5$

$$s' \approx (1 - \alpha_B)s \sim 4p_t^2$$

For $E_\gamma \sim 10$ GeV , $\alpha_B \sim 0.4$,
maximal $p_t \sim 1.5$ GeV/c for $\pi\pi$ channel

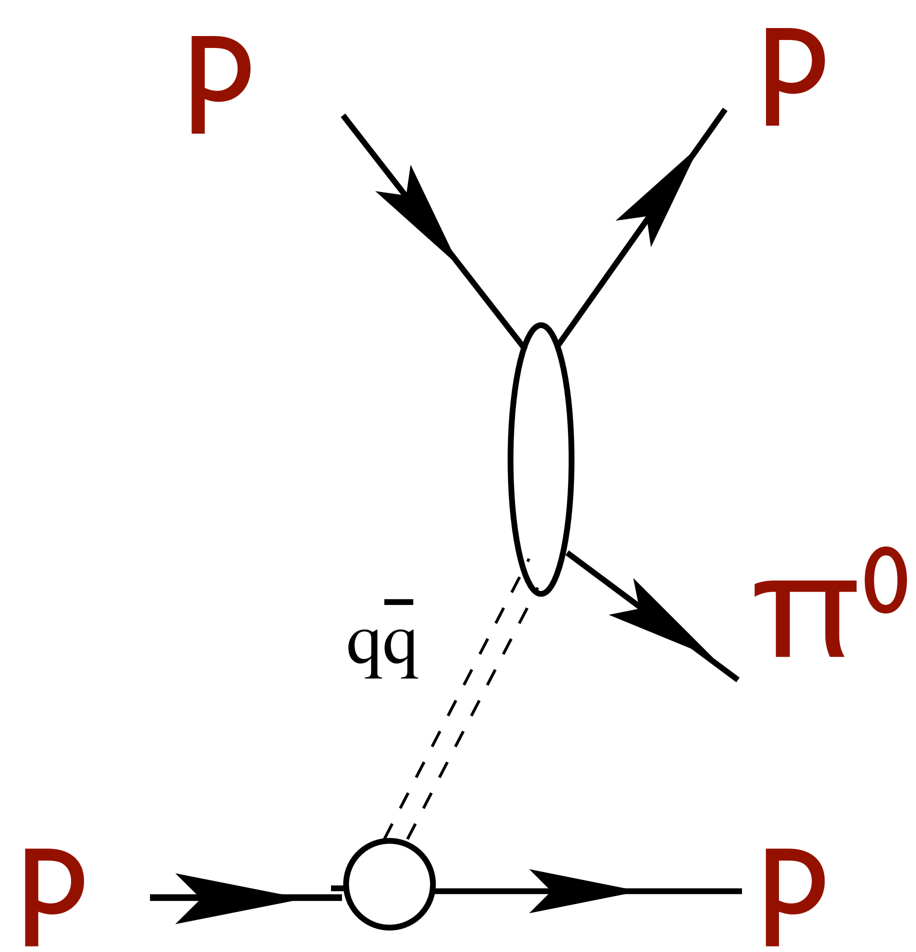
Reminder: CT for $\pi \to$ dijet observed for such p_t

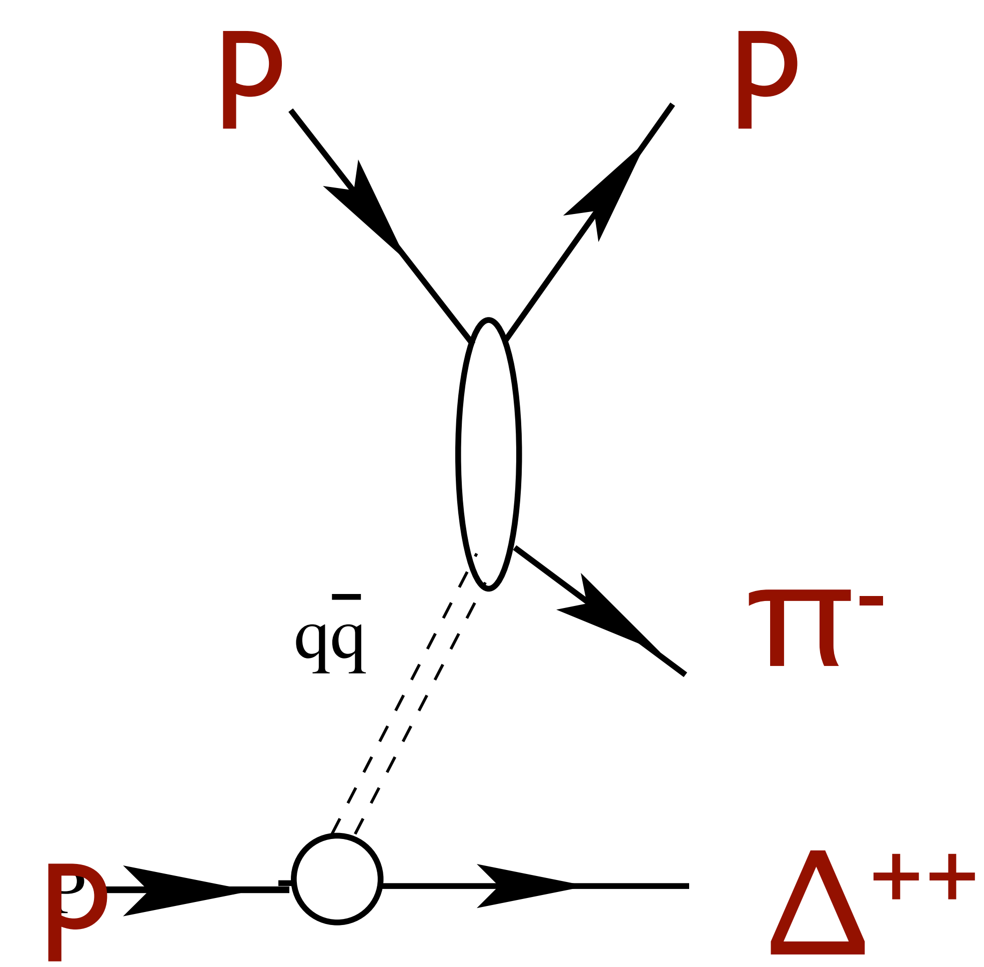
Four quark component in real photon



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!!!

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

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

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

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

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

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

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

$$= I_N \, \overline{\psi}_N(p_e) \big[H(x,\xi,t) \not{n} + E(x,\xi,t) \frac{i\sigma^{\alpha\beta} n_\alpha \Delta_\beta}{2m_N} \big] \psi_N(p_a)$$

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

$$\mathcal{M}_N^A = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle N, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \gamma_5 \psi(\lambda n/2) \right| N, p_a \right\rangle$$

$$= I_N \, \overline{\psi}_N(p_e) \big[\widetilde{H}(x,\xi,t) \not{n} \gamma_5 + \widetilde{E}(x,\xi,t) \frac{n \cdot \Delta \gamma_5}{2m_N} \big] \psi_N(p_a)$$

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

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

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

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

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

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

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

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

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

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

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

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

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

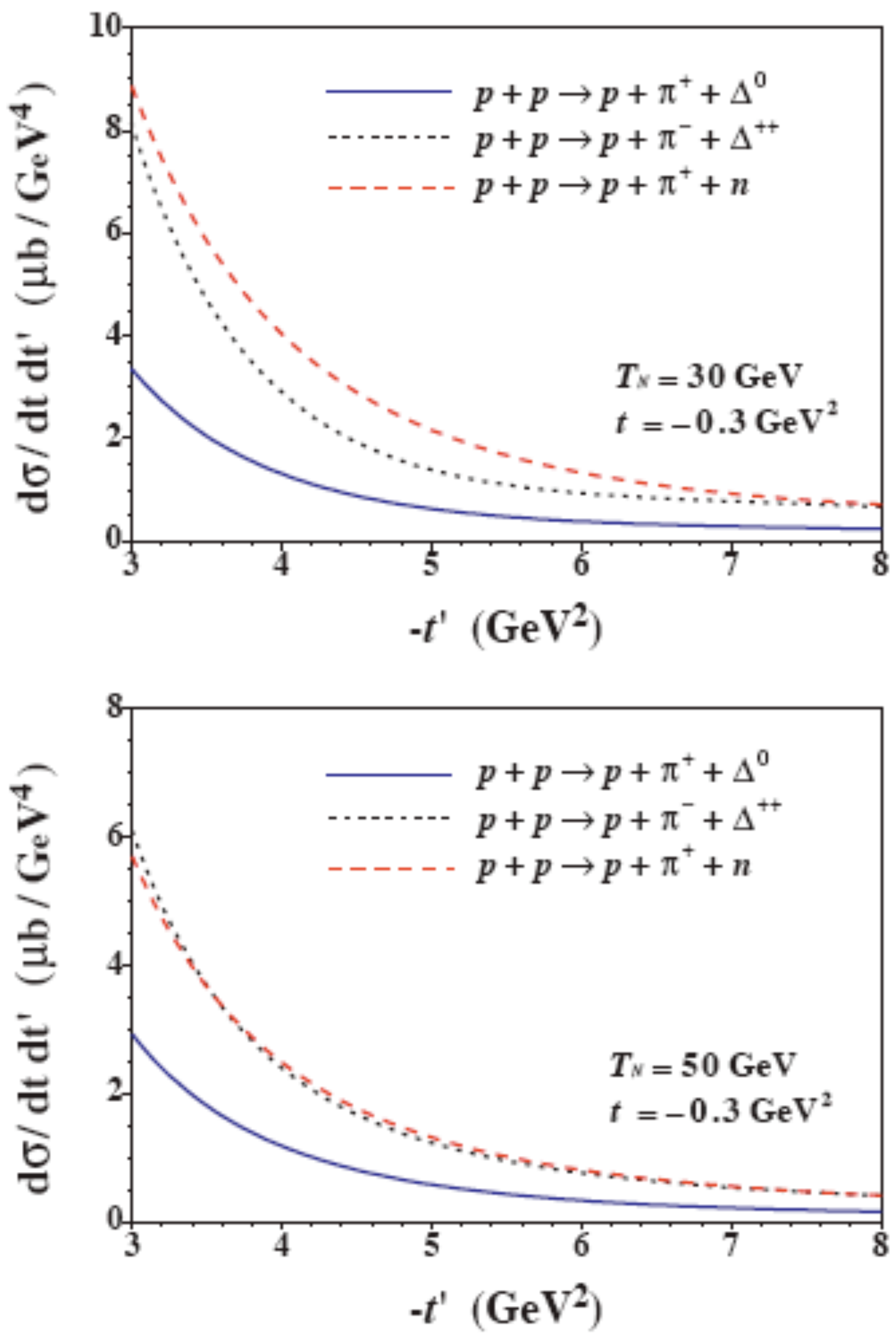


FIG. 11: Differential cross section as a function of t'. The incident proton-beam energy is 30 (50) GeV in the upper (lower) figure, and the momentum transfer is $t = -0.3$ GeV^2. The solid, dotted, and dashed curves indicate the cross sections for $p+p \to p+\pi^+ + \Delta^0$, $p+p \to p+\pi^- + \Delta^{++}$,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

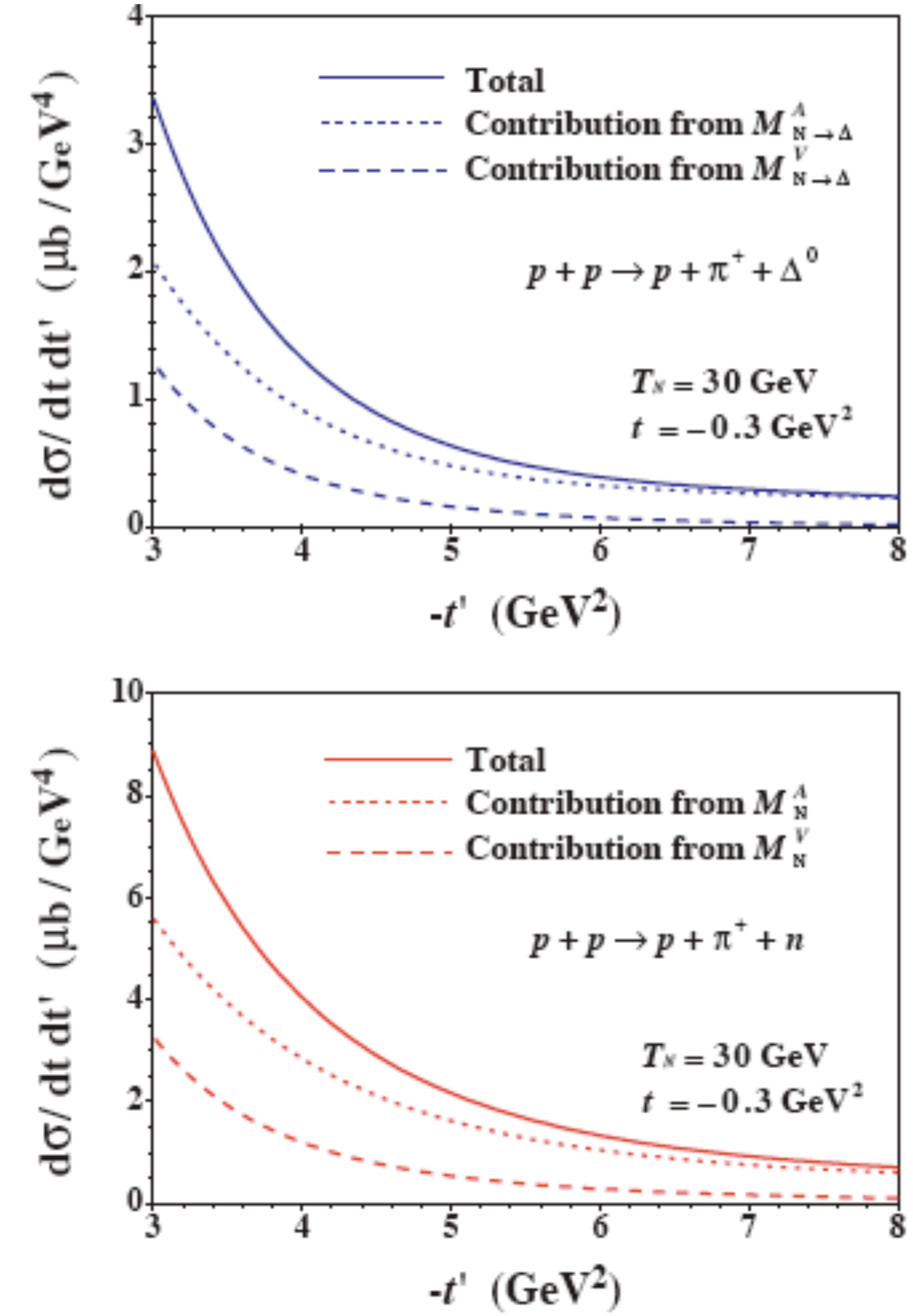


FIG. 12: Differential cross section as a function of t'. The incident proton-beam energy is 30 GeV, and the momentum transfer is $t = -0.3$ GeV^2. The upper (lower) figure indicates the cross section for the process $p+p \to p+\pi^+ + \Delta^0$ ($p+p \to p+\pi^+ + n$). The solid, dotted, and dashed curves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

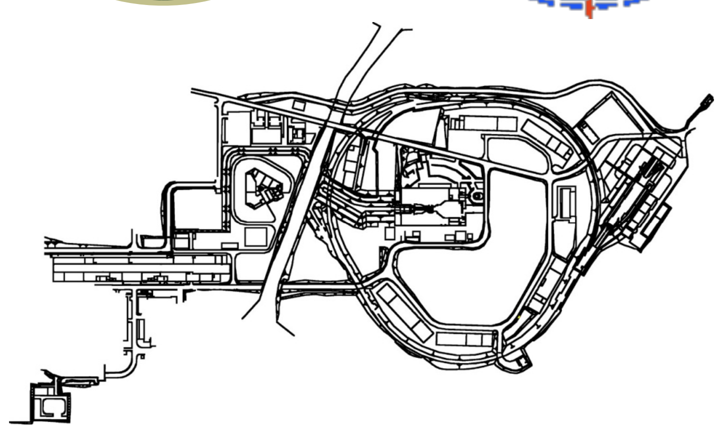
Same cross section for antiproton projectiles!

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)

Conclusions

Evidence for onset of CT in exclusive meson electroproduction - good news for Generalized Parton Distributions studies at Jlab. Similarly observation of CT in reactions with pions (COMPASS), antiprotons, protons would allow studies of Generalized Parton Distributions of various hadrons in hadronic interactions



programs with pions (kaons?)/antiprotons/protons allow to obtain novel information about dynamics of QCD interactions at the interface between hard and soft QCD, explore the quark-gluon structure of various mesons, role of quark mass in QCD dynamics. Variety of CT probes of dynamics.

Complementary studies of exclusive and CT phenomena using hadron beams and electron beams would greatly enhance quality of the results. Important to get COMPASS results soon to be able to plan for experiments with (anti)protons, as well as experiments with intermediate energy pion beams