Toward probing GPDs in the hadron induced processes

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Outline

- Color transparency (CT) is the necessary condition for extracting from the hard exclusive process generalized parton distributions
- CT = squeezing + freezing, experimental confirmations
- Large enhancement of transparency in $\pi^- A \to e^+ e^- A^*$
- Large enhancement of transparency in $\pi^- A \to J/\psi\, A^*$
- Examples of promising hadronic final states ($2 \to 3$ branching processes with proton and nuclear targets):

  $\pi^- A \to \pi^+ \pi^- A^*$, $pA \to p\pi^- (A-1)^*$

  for p^h_t (final) > 1.5 GeV

Workshop on hadron tomography at J-PARC and KEKB, 1/6/17

Studies of the diffraction at HERA stimulated derivation of new QCD factorization theorems. In difference from derivation in the inclusive case which used closure, main ingredient is the color transparency(CT) property of QCD. *CT = smallness of the interaction of small color singlets with media.*

Hard Exclusive processes

$$\gamma^* + N \to \gamma + N(baryonic\, system)$$

D.Muller 94 et al, Radyushkin 96, Ji 96, Collins &Freund 98

$$\pi + T(A,N) \to jet_1 + jet_2 + T(A,N)$$

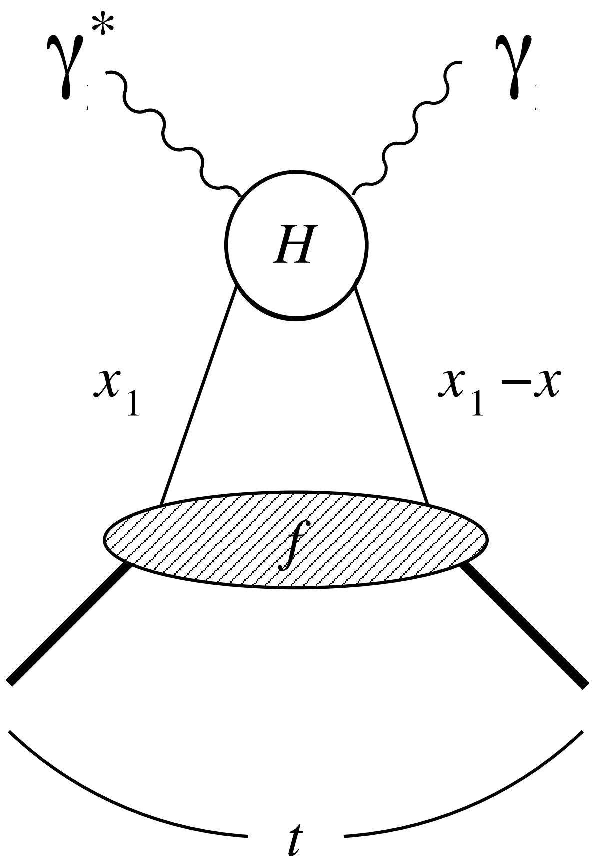
Frankfurt, Miller, MS 93 & 03

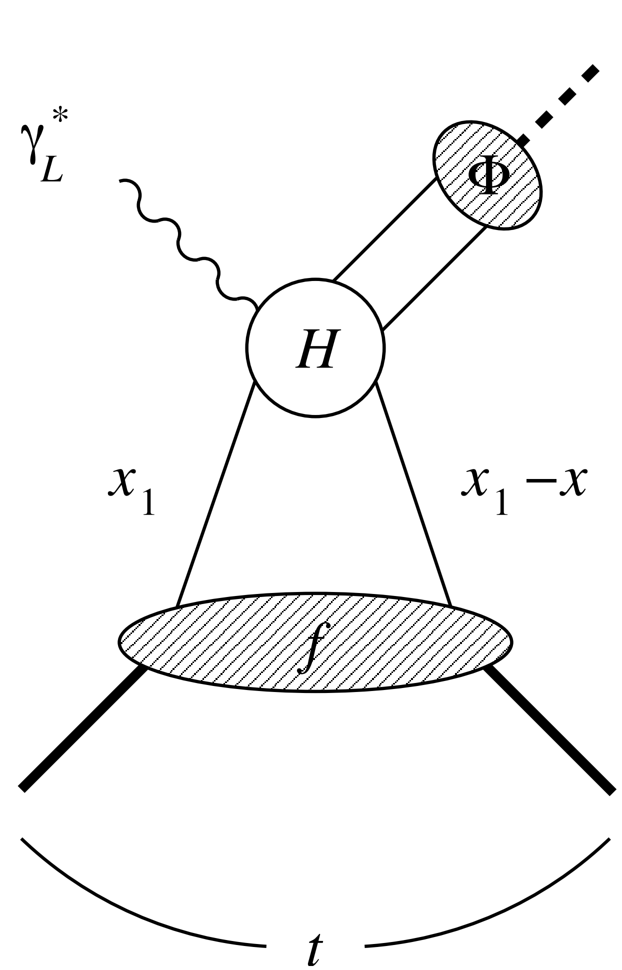
$$\gamma_L^* + N \to \text{"}meson\text{"}(mesons) + N(baryonic\, system)$$

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, color transparency, etc





t-dependence only from GPD's

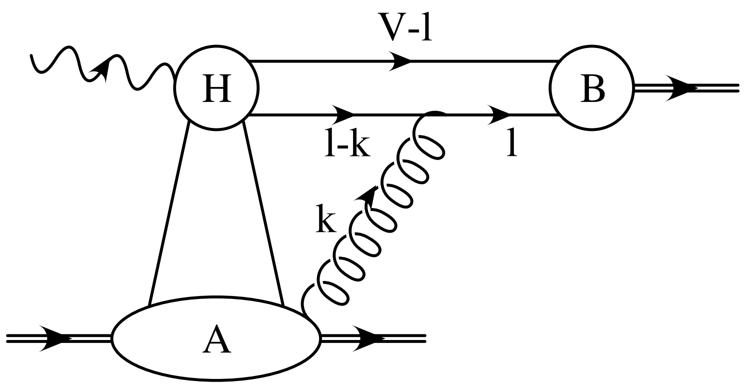
transverse spatial distribution of partons

$$f(x,\rho) \equiv \int d^2\vec{\Delta} e^{i\vec{\Delta}_\perp \rho} f(x,x,t), \; -t = \Delta^2$$

$$\rho_{c.m.} = \sum_i \rho_i x_i$$

ρ - transverse distance from the c.m. of proton

Diagrams like:



where an extra gluon is exchanged between the hard blocks are suppressed by a factor $\frac{1}{Q^2}$. —Very lengthy proof - CFS

Qualitatively - due to color screening/transparency - small transverse size of γ_L^* selects small size (point-like) configurations in meson.

Presence of color transparency in the process is necessary condition for using it for measurement of GPDs

For the process under discussion $\pi^- p \to l^+ l^- n$

no proof of the factorization theorem so far - hence CT test is especially important

Basic measurements of transparency

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

as a function of incident energy, $Q^2 = M^2(l^+ l^-)$

Expectation: $T_A = 1$ for large energies and Q^2

Brief Summary of CT: squeeze and freeze

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

two original selection methods

- Special final states: diffraction $\pi + A \to$ "two high p_t jets" + A: $d_{q\bar{q}} \sim 1/p_t$

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

(b) Intermediate energy CT

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

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)

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

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

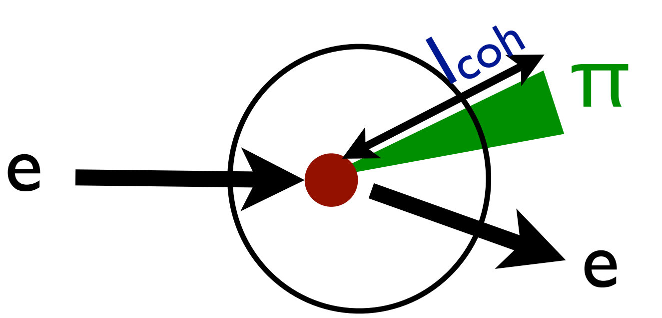
Quantum Diffusion model of expansion

$$l_{coh} = \frac{2P_h}{\underbrace{m_{h*}^2 - m_h^2}_{0.7 \div 1.1\ \mathrm{GeV}^2}}$$

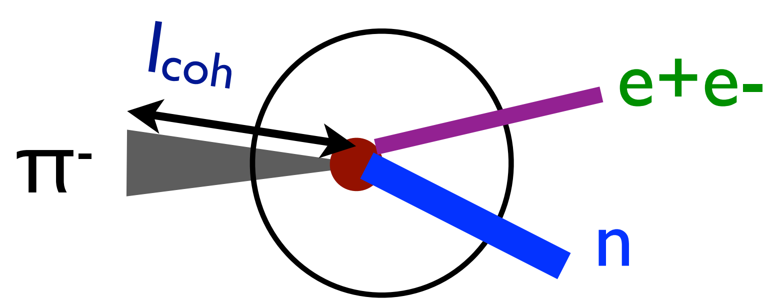
$l_{coh} \sim (0.4 - 0.6)$ fm E_h[GeV]

light hadrons

actually expansion length



eA→ eπ A* at large Q



π⁻ A→ e⁺e⁻ A* at large Q
and intermediate energies

$l_{coh}(p_\pi = 20$ GeV$)$
$= 12$ fm ~2 R_{Pb}

Experimental situation

Mesons

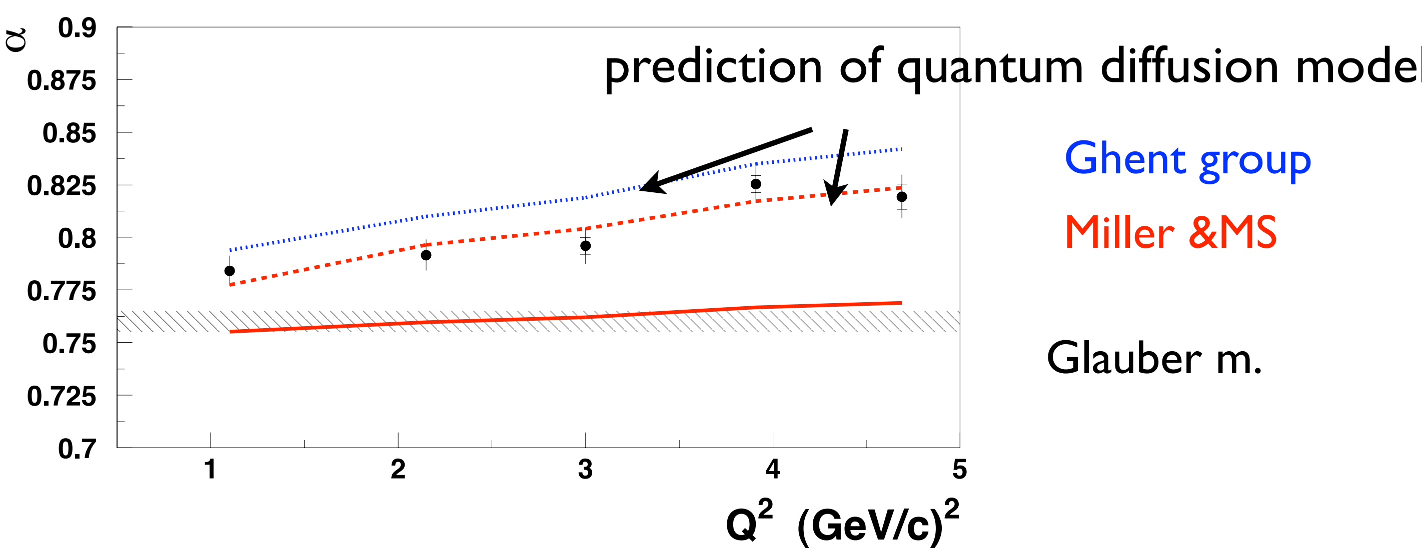
☀ $\gamma^* + A \to \pi A^*$ evidence for increase of transparency with Q (Dutta et al 07)

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

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

In exclusive coherent dijet production $p_t \sim 1$ GeV/c corresponding to $Q^2 \sim 4 p_t^2 \sim 4\text{GeV}^2$ seemed to be enough to squeeze the system (though not yet to reach asymptotic in z distribution)

$\sigma \propto A^{\alpha}$



data from Jlab experiment at 6 GeV, new data expected from 11 GeV run

☺ $\gamma^* + A \to \rho A^*$ Jlab data are also consistent with our predictions with the same values of l_{coh}.

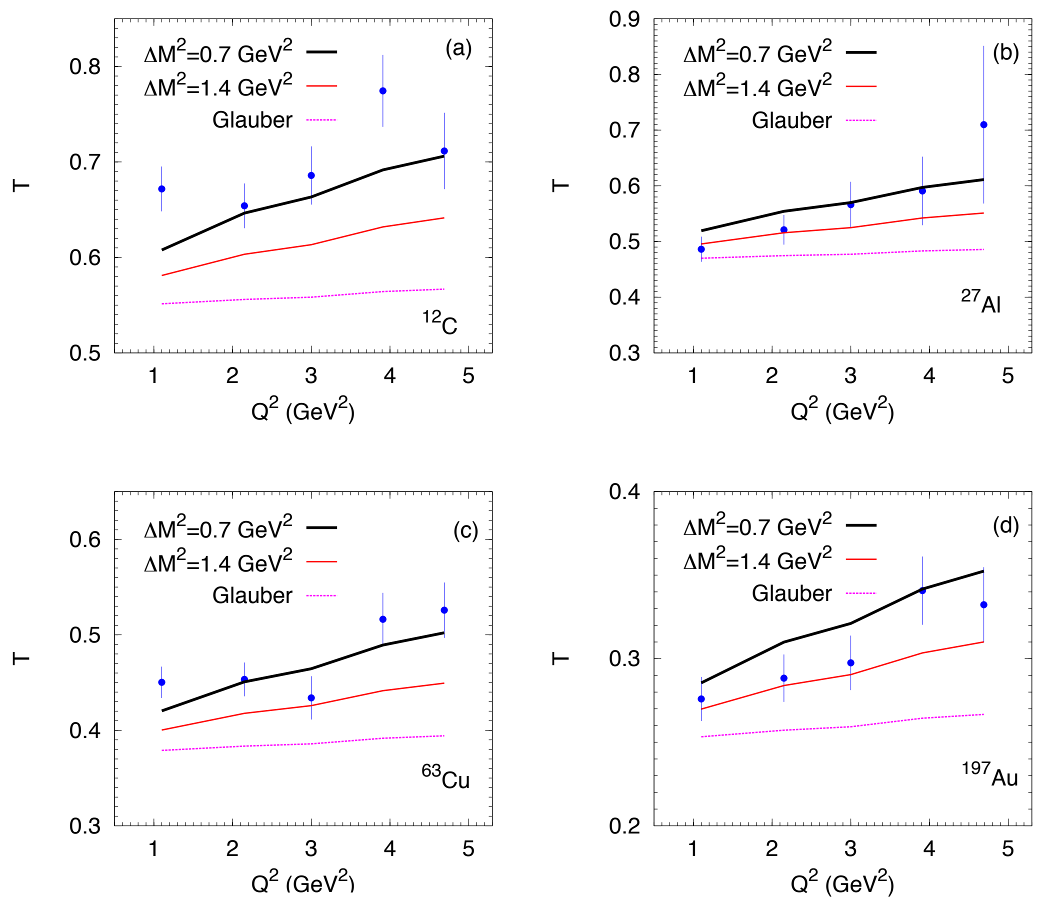
Approved further data taking at Jlab 12

$$\mathcal{P}_{\pi\,\mathrm{surv}}(\mathbf{b}, z, +\infty) = \exp\left(-\int_{z}^{+\infty} dz' \sigma^{\mathrm{PLC}}_{\pi N}(p_V, z' - z)\rho(\mathbf{b}, z')\right)$$

$$T = \int d^3 r \rho(b, z) P(b, z)$$

In exclusive coherent dijet production $p_t \sim 1$ GeV/c corresponding to $Q^2 \sim 4\, p_t^2 \sim 4 GeV^2$ seemed to be enough to squeeze the system (though not yet to reach asymptotic in z distribution)

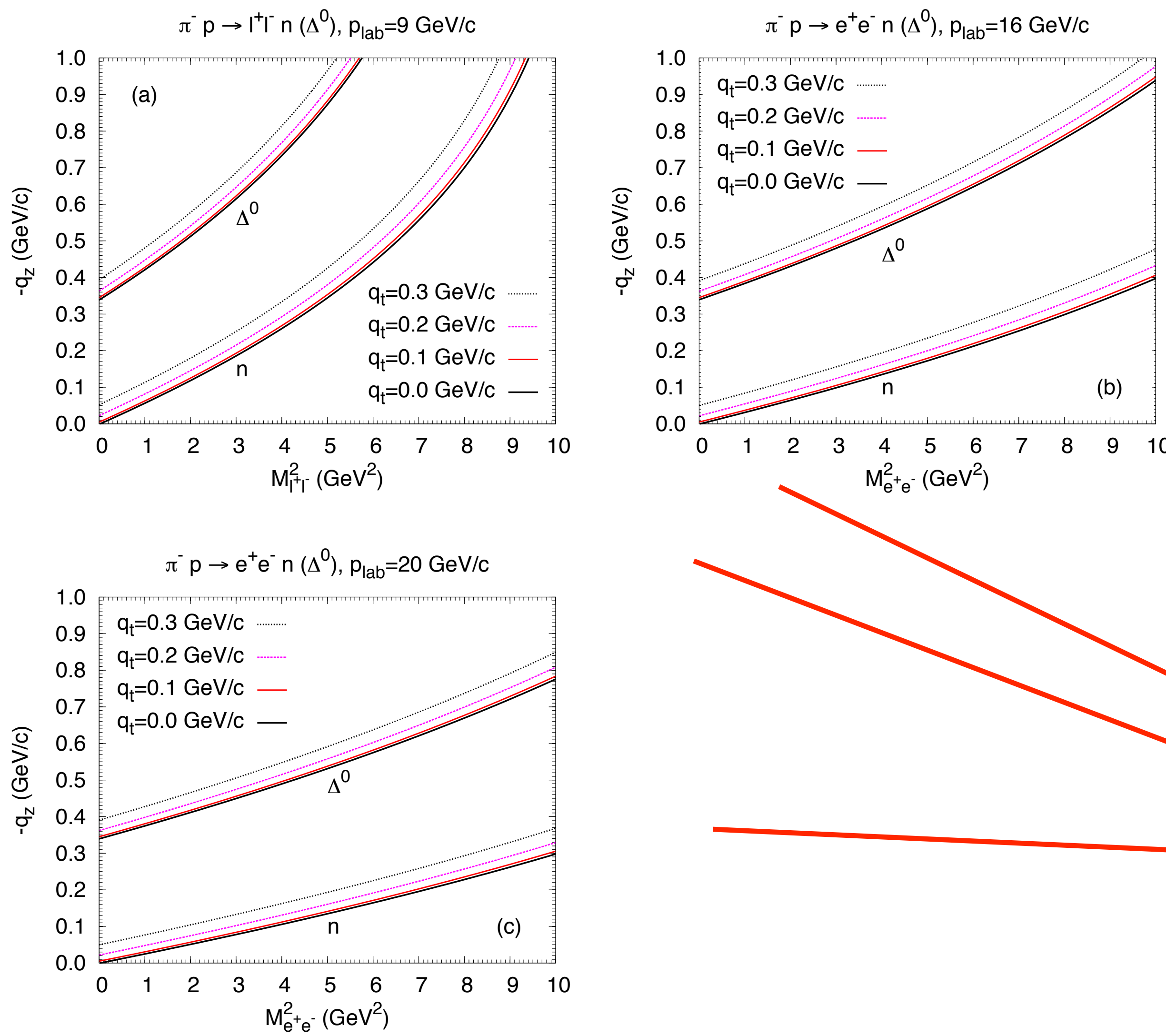
π^- A$\to$ e^+e^- (A-1)* at large Q (as well as J/ψ soft (ρ^0) final states) and intermediate energies was studied by A.Larionov, MS & M.Bleicher Phys.Rev. C 2016



Assume that in exclusive Drell Yan squeezing is the same as in pion exclusive electroproduction. Test again that quantum diffusion model describes the Jlab data well

Transparency vs Q^2 for the $(e, e'\pi^+)$ reaction on ^{12}C, ^{27}Al, ^{63}Cu, and ^{197}Au targets (panels (a), (b), (c), and (d), respectively) in the collinear kinematics. Dashed lines – Glauber model, thick (thin) solid lines – quantum diffusion model with $\Delta M^2 = 0.7(1.4)$ GeV^2. The values of pion momentum are chosen as $p_\pi = 2.793, 3.187, 3.418, 4.077$, and 4.412 GeV/c for $Q^2 = 1.10, 2.15, 3.00, 3.91$ and 4.69, respectively, according to the experimental conditions [13]. The experimental data are from Ref. [13].

Kinematics: residual system is nearly at rest but difference of longitudinal momenta for proton and even lowest excitation is significant recoiling particle is nucleon

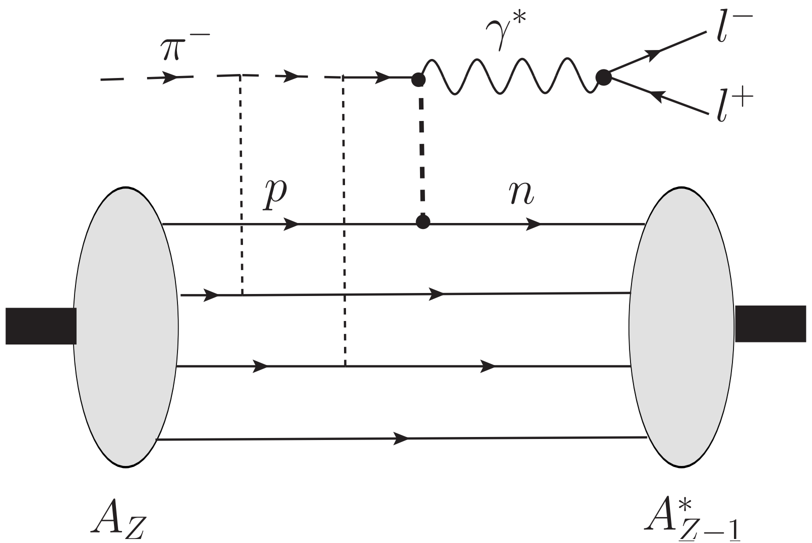


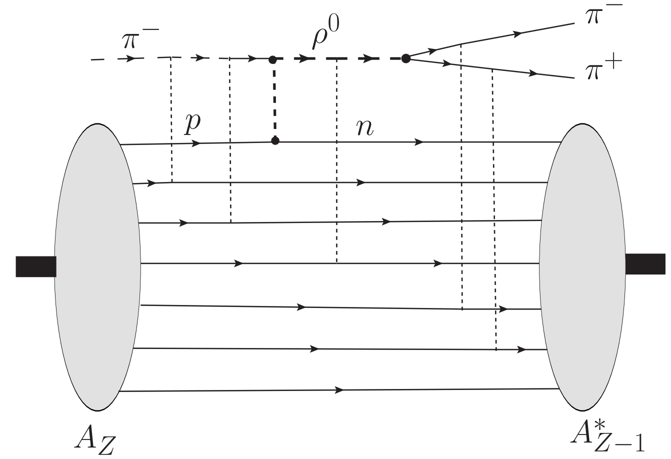
$$q_3(\Delta) - q_3(n) \approx 300MeV/c$$

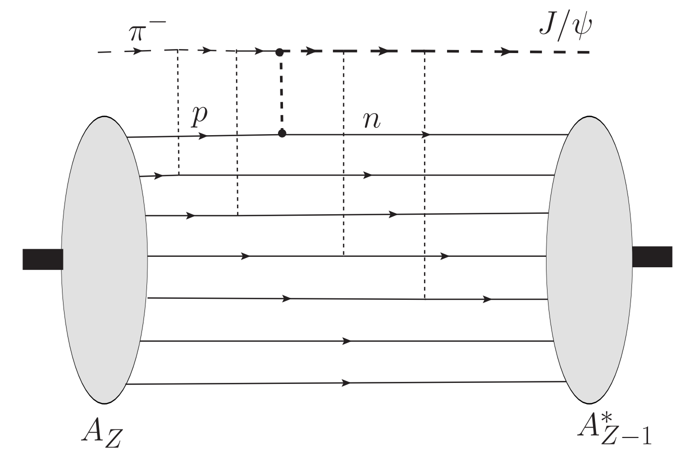
1- 2 % momentum resolution will be sufficient to separate nucleon channel

The longitudinal component of the momentum of outgoing neutron or Δ^0 in the reaction $\pi^- p \to l^+ l^- n(\Delta^0)$ on proton at rest as a function of the invariant mass of the l^+l^- pair for several values of the transverse momentum transfer and beam momentum as indicated.

Comment: pion and leptons carry very small light cone fraction in "-" direction. So resolution in this variable is very good even if momentum resolution is moderate







The Feynman graph describing the amplitude of the semiexclusive $A_Z(\pi^-, l^+l^-)A^*_{Z-1}$ and ρ^0, J/ψ processes. Thin short-dashed lines represent the pion (ρ^0)-nucleon soft elastic scattering amplitudes, while a thick short-dashed line represents the transition amplitude $\sigma\ \pi^- p \to \gamma^* n$. The gray ellipsoids correspond to the wave functions of the initial ground state nucleus A_Z and final excited nucleus A^*_{Z-1}.

$$\mathcal{P}_{\pi,\mathrm{surv}}(\mathbf{b},-\infty,z) = \exp\left(-\sigma_{\pi N}\int\limits_{-\infty}^{z} dz'\rho(\mathbf{b},z')\right)$$

$$T_{l^-l^+} = \frac{d^4\sigma_{\pi^- A\to l^- l^+}/d^4q}{Zd^4\sigma_{\pi^- p\to l^- l^+ n}/d^4q} = \frac{1}{Z}\int d^3r\mathcal{P}_{\pi,\mathrm{surv}}(\mathbf{b},-\infty,z)\rho_p(\mathbf{r})$$

$\Big\}$ *Glauber*

$$\sigma^{\mathrm{eff}}_{\pi N}(p_\pi,z) = \sigma_{\pi N}(p_\pi)\left(\left[\frac{z}{l_\pi} + \frac{<n^2k_t^2>}{M^2_{l^+l^-}}\left(1-\frac{z}{l_\pi}\right)\right]\Theta(l_\pi - z) + \Theta(z-l_\pi)\right)$$

$< k_t^2 >^{1/2} \simeq 0.35$ GeV/c **n=2**

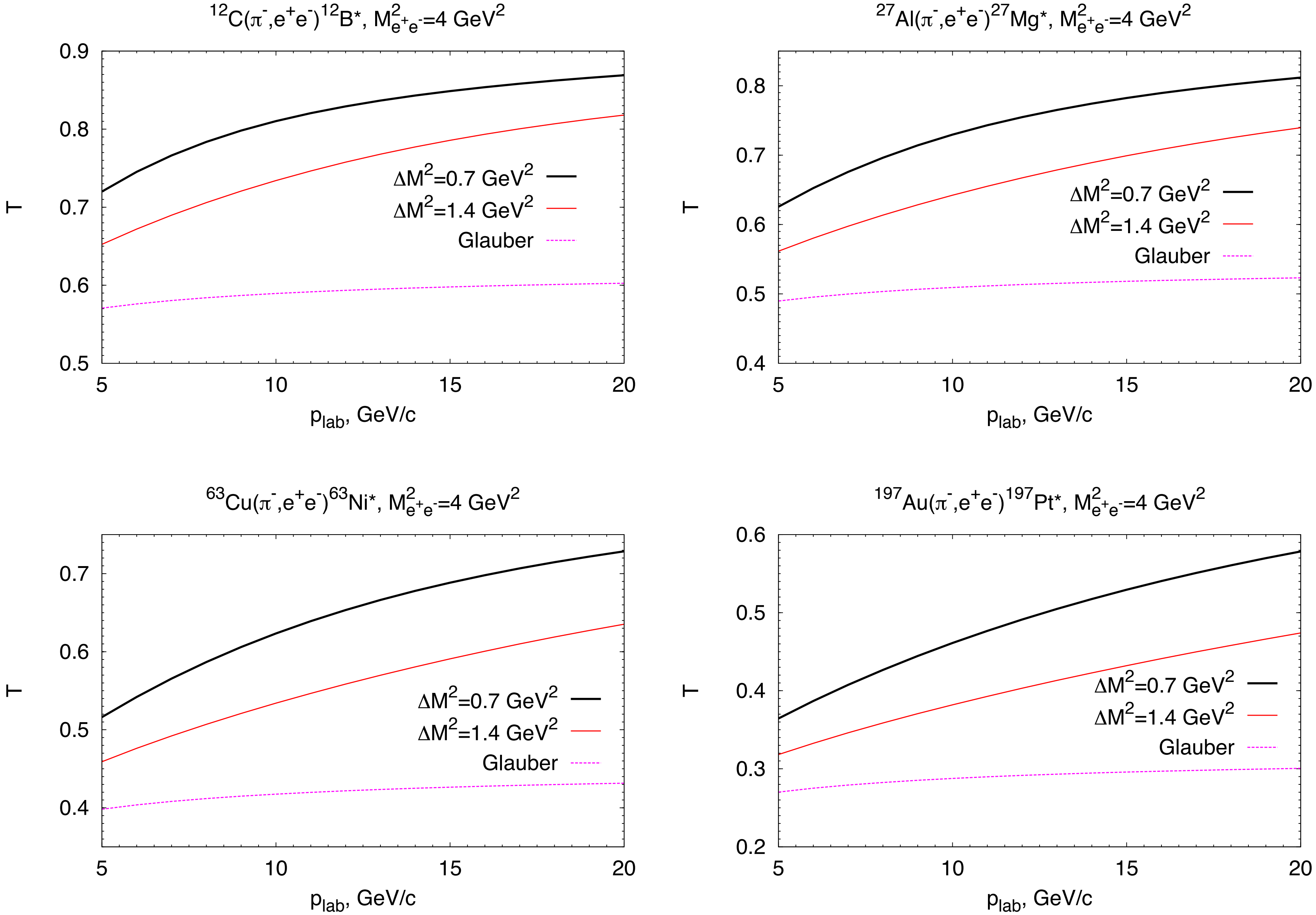
$$l_\pi = \frac{2p_{\mathrm{lab}}}{\Delta M^2}, \qquad \Delta M^2 = 0.7\ \mathrm{GeV}^2$$

$$\mathcal{P}^{\mathrm{CT}}_{\pi,\mathrm{surv}}(\mathbf{b},-\infty,z) = \exp\left(-\int\limits_{-\infty}^{z} dz'\sigma^{\mathrm{eff}}_{\pi N}(p_\pi,z-z')\rho(\mathbf{b},z')\right)$$

$\Big\}$ *Quantum diffusion model*

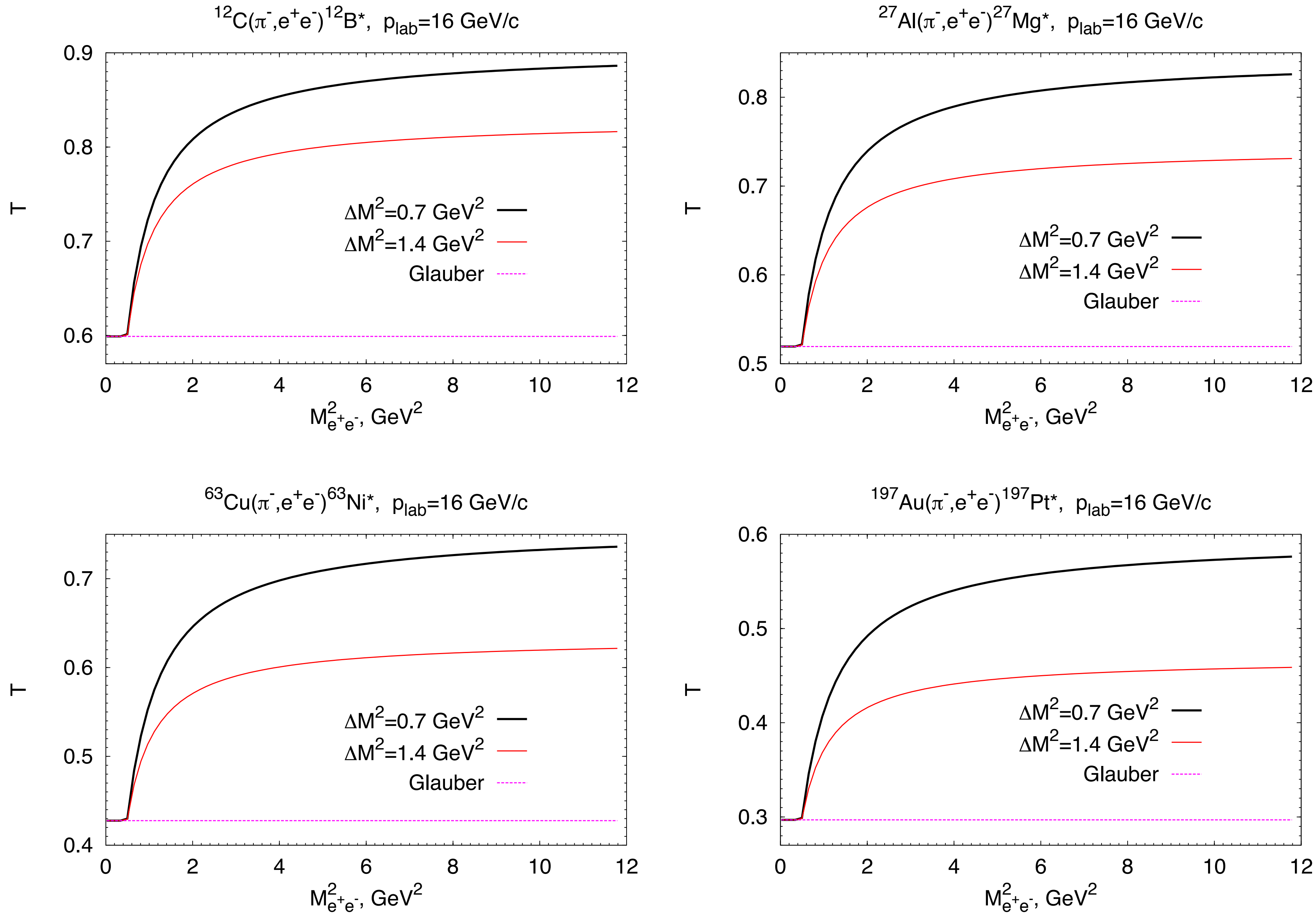
with assumption of the same squeezing at positive and negative Q^2

Note: we consider the limit $x= M^2/s >0.1$ where lepton pair is produced practically in the interaction point

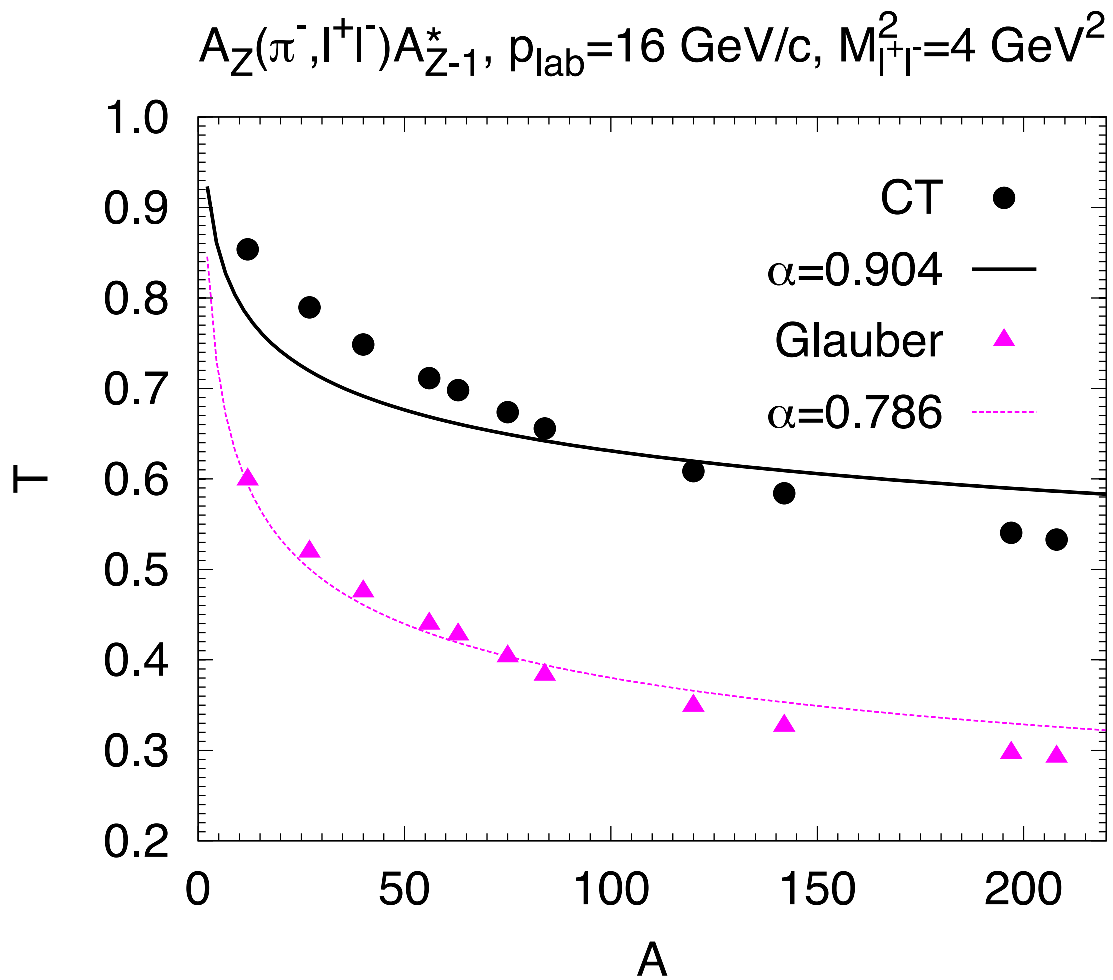


Transparency vs pion beam momentum for the (π^-,l^+l^-) reaction at fixed $M^2{}_{l+\,l-}$ = 4 GeV^2 on ^{12}C, ^{27}Al, ^{63}Cu, and ^{197}Au targets.

Large CT effect is predicted for all targets for $p\geq$ 10 GeV/c, with modest sensitivity to expansion parameter ΔM^2



Transparency vs invariant mass squared of the l^+l^- pair at p_{lab} = 16 GeV/c



Large difference between Glauber and CT predictions starting with C target

In this simplified discussion we neglected different dynamics for the interaction involving longitudinally and transversely polarized virtual photon.

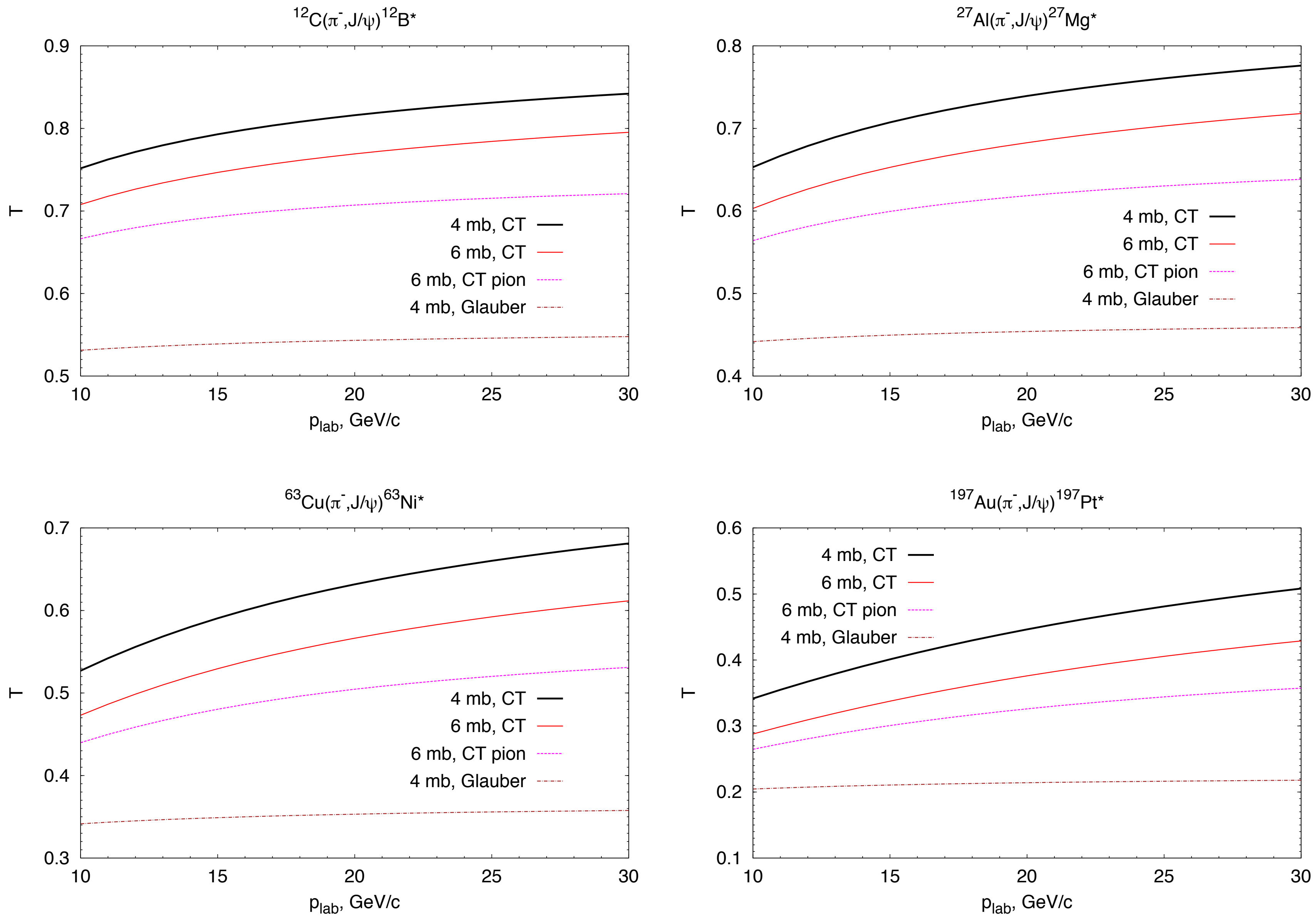
At large Q^2, $\sigma_L >> \sigma_T$ and squeezing for σ_L is due to the photon wave function while for σ_T contribution of large sizes is suppressed only by Sudakov form factor

Hence naively $T(\sigma_T) < T(\sigma_L)$

However at HERA no evidence for slower squeezing of ρ-mesons in exclusive production was found. Also in the Jlab data contribution of σ_T is large - still CT is observed.

Related very interesting reaction is exclusive production of J/ψ (χ - may have a larger cross section but more difficult to detect?)

Basic expectations: production in the small transverse area of radius ~ $r_{J/\psi}$; pion has to contract to produce onium; J/ψ interacts rather weakly with nucleons. CT is very likely and large.



It is desirable also to study a reference soft process: $\pi^- + A \to \rho^0 + A^*$

new element - ρ^0 decay at moderate energies

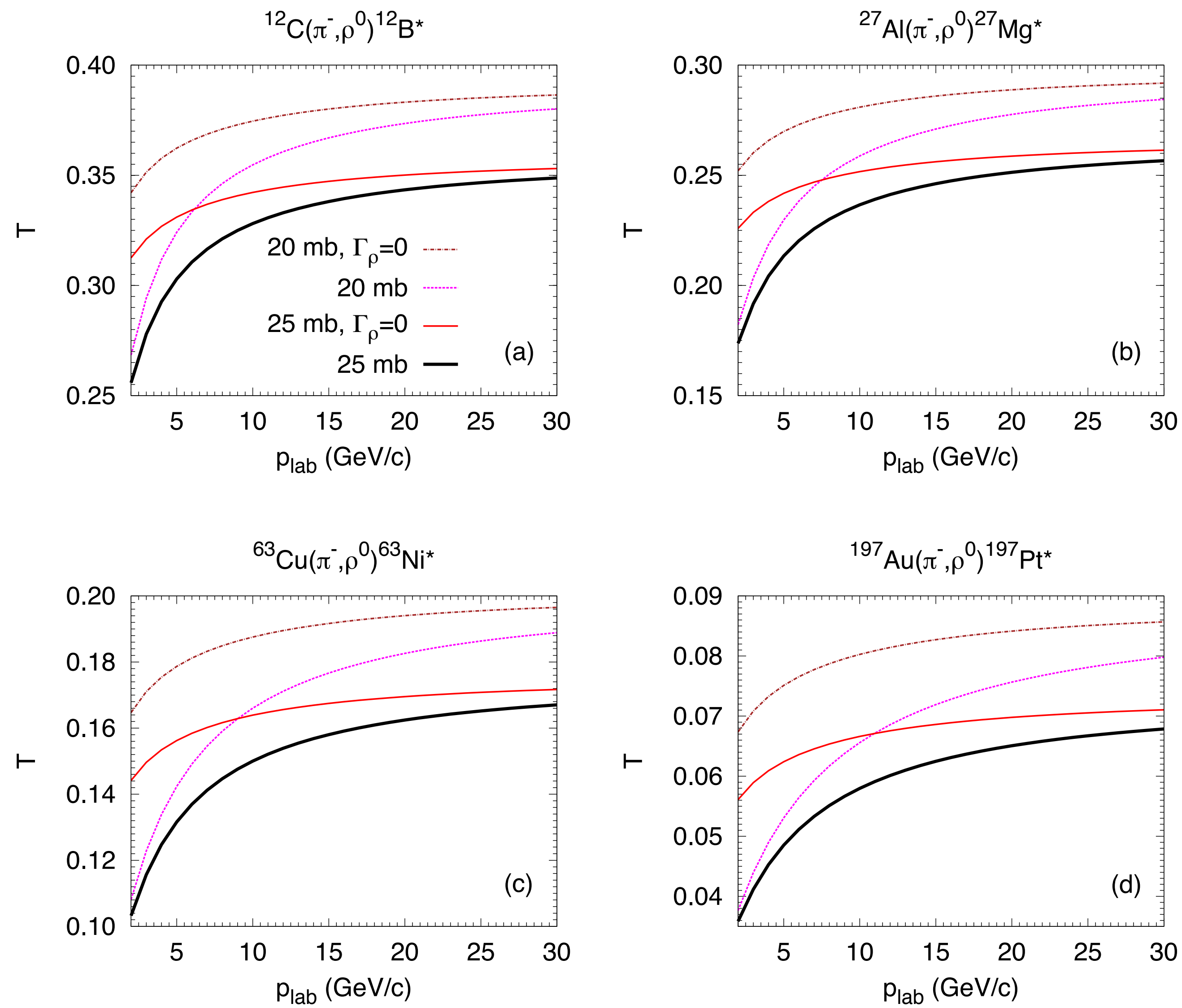
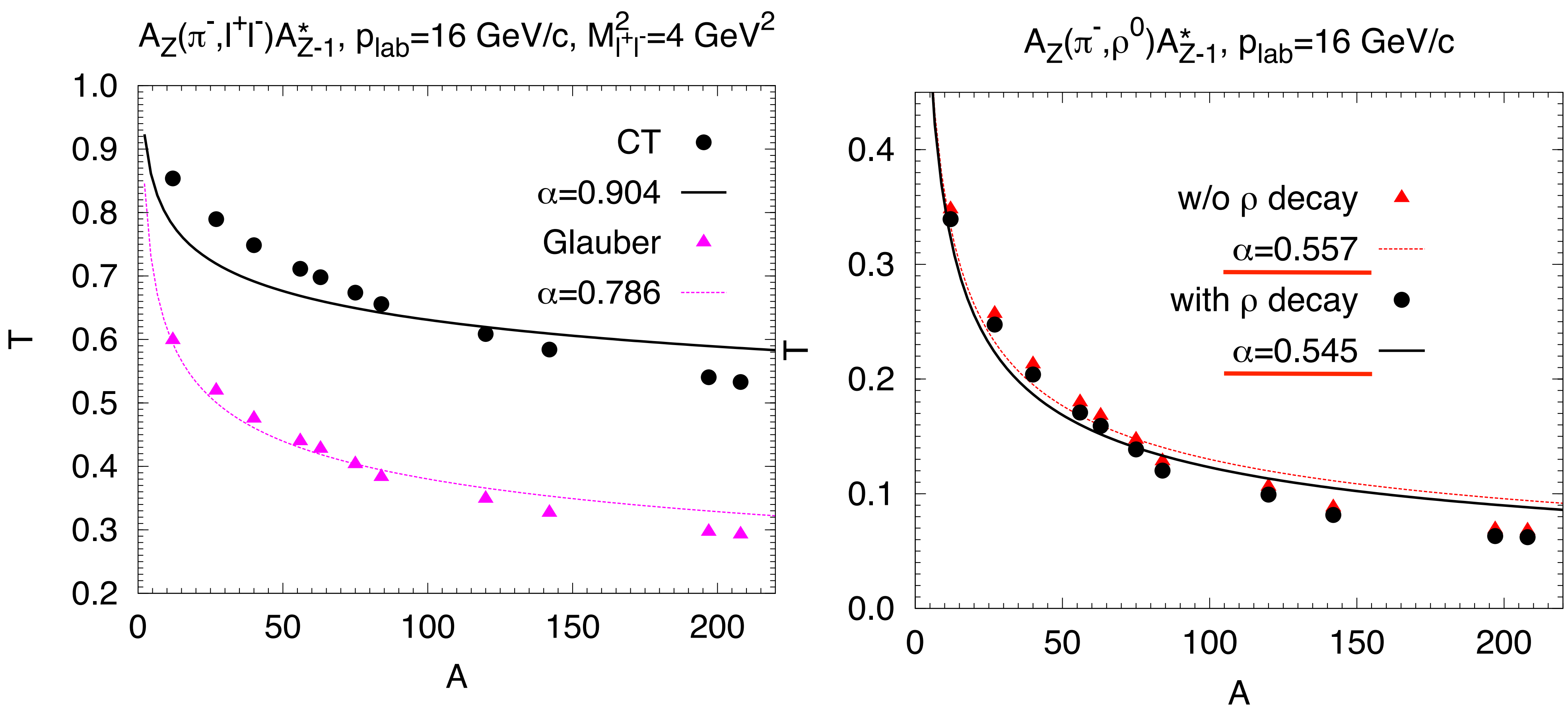


FIG. 9. (color online) Transparency vs beam momentum for the (π^-, ρ^0) reaction on ^{12}C, ^{27}Al, ^{63}Cu, and ^{197}Au targets (panels (a), (b), (c), and (d), respectively). The calculations are performed with and without ρ decay inside nucleus by setting the total ρN cross section equal to 25 and 20 mb as indicated.

At what M_{ll} transition from hard to soft regime?

Very large difference in the transparency



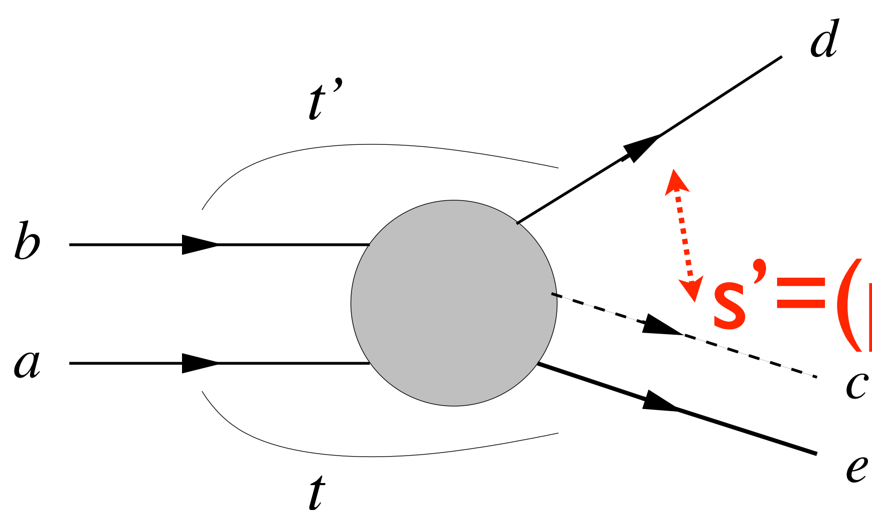
α_{ll}=0.9 vs α_{ρ}=0.55

Very briefly

Examples of promising hadronic final states: $\pi^- A \to \pi^+\pi^- A^*$, $pA \to p\pi^- (A-1)^*$

for p^h_t (final) > 1.0 GeV

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, $-t'/s' \sim 1/2$

$-t$=const ~ 0

⇒ $s'/s = y < 1$,

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

Since CT is expected to set in earlier for mesons than for baryons probably most promising reaction production of two pions back to back (the same kinematics as for leptons in exclusive DY.

$\pi^- A \to \pi^+ \pi^- A^*$

$$P_{\pi^-,in} = 16\ \mathrm{GeV}, P_{\pi^-,fin,t} = 1.0\ \mathrm{GeV}, P_{\pi^+,fin,t} = -1.0\ \mathrm{GeV}$$

$$P_{\pi^\pm,fin,long} = 7.8\ \mathrm{GeV}$$

In the regime of CT this reaction measures nondiagonal GPDS

$p A \to p \pi^- A^*$, $p A \to p \pi^+ A^*$, $p A \to pp\, (A-1)^*$

reach regime of CT probably at larger t / incident energies, so higher energy beams are necessary.

Conclusions

Study of the A-dependence of the exclusive DY (J/ψ) *(including polarization effects)* , and observation of CT are critical steps for testing theory of these reactions & learning how to probe GPDs in these processes.

Will improve our understanding of the dynamics of space-time evolution of wave packets

Probe in a new way J/ψ *(χ ?)* - nucleon interactions

At least one interesting hadronic process - exclusive production of $\pi^+\pi^-$ takes place in the exclusive DY kinematics

Supplementary slides on 2 to 3 processes

Two kinematics - different detector strategies

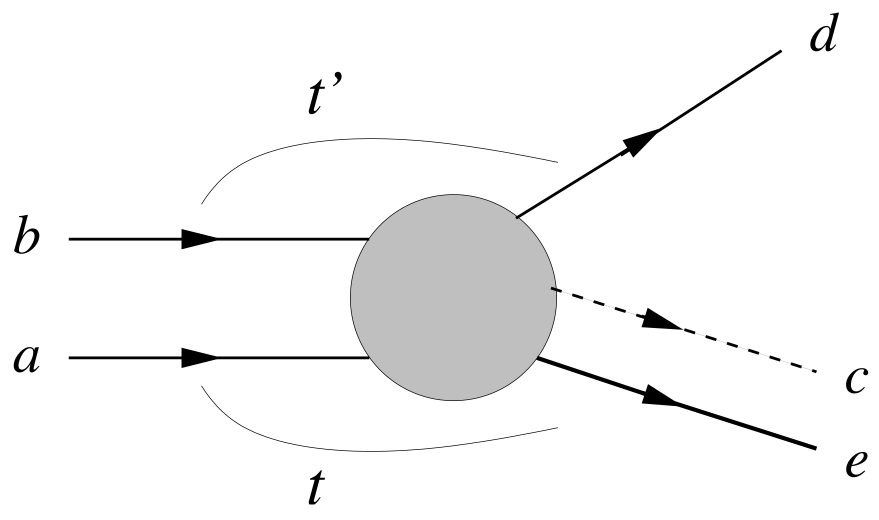
"a" at rest - "d" and "c" in forward spectrometer ($p_d + p_c \approx p_a$)

"e" in recoil detector

➠ can use both proton and neutron (^2H)/ transversely polarized target

"b" at rest - "d", "c" and "e" in forward spectrometer;

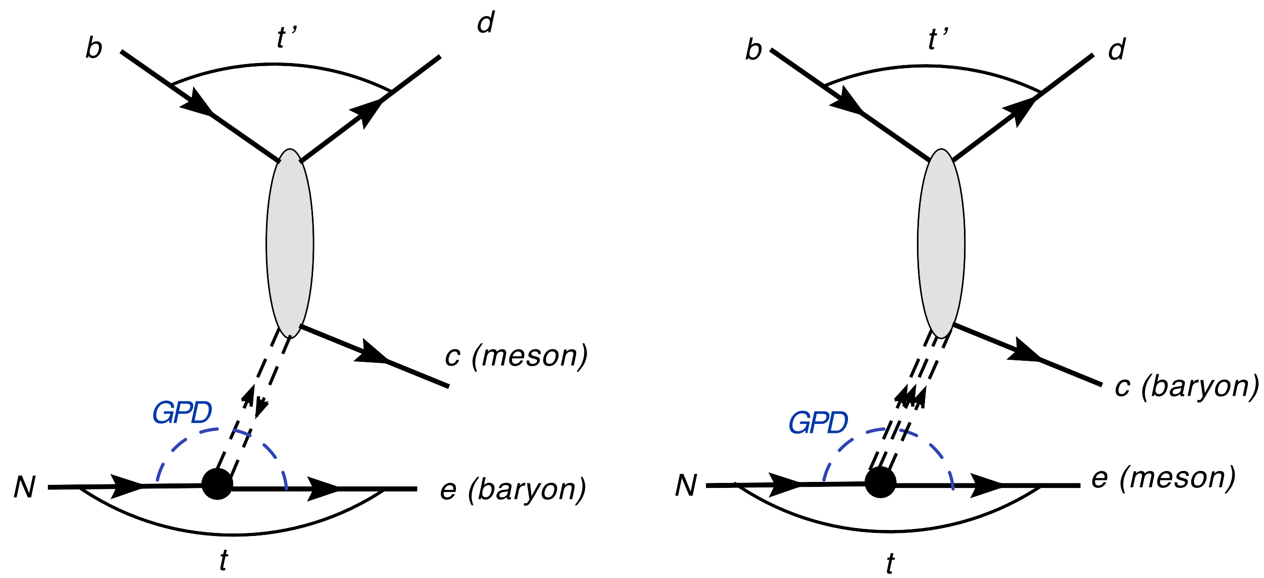
e has small transverse momentum while pt's of d, c are back to back



$2 \to 3$ branching processes:

- test onset of CT for $2 \to 2$ 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:



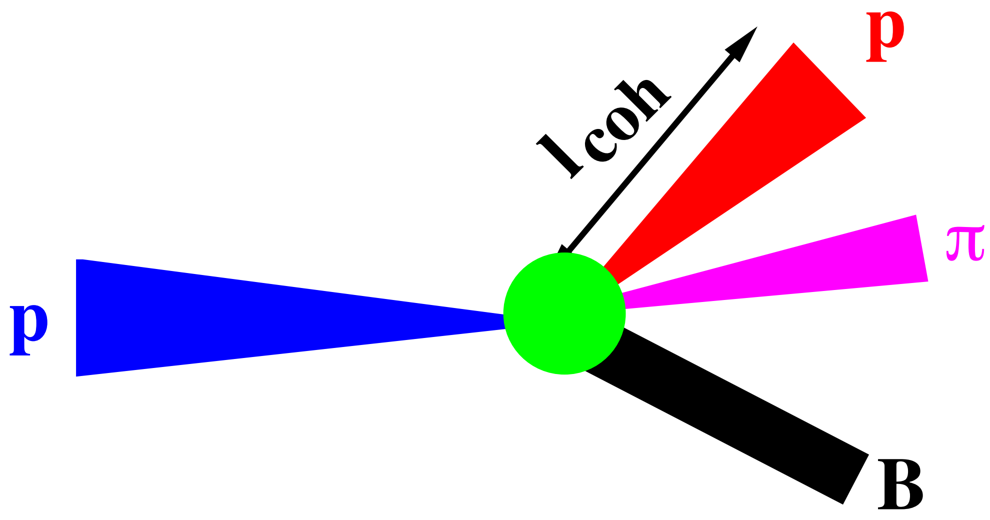
If the upper block is a hard (2 →2) process, "b","d","c" are in small size configurations as well as exchange system (qq, qqq). Can use CT argument as in the proof of QCD factorization of meson exclusive production in DIS (Collins, LF, MS 97)

$$\Downarrow$$

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

Minimal condition for factorization:

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



Time evolution of the 2 → 3 process

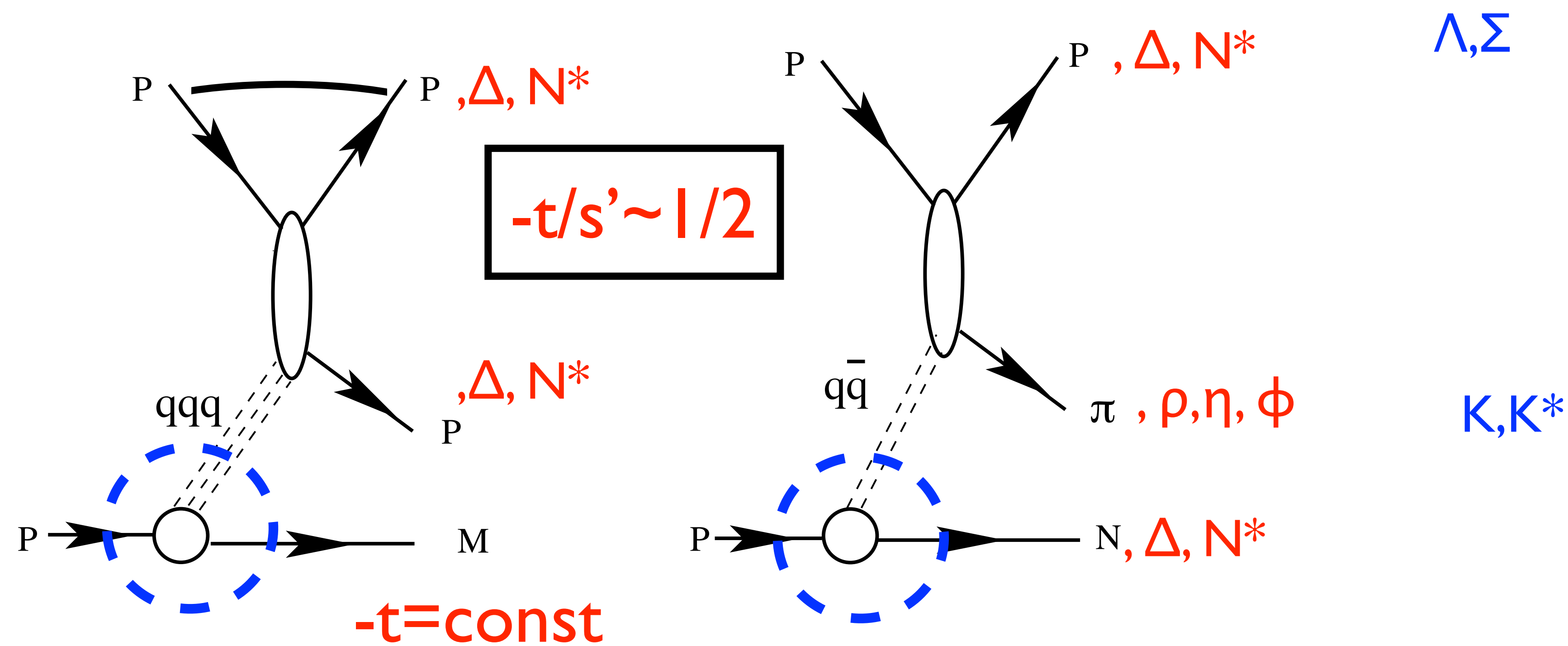
$$l_{coh} = (0.4 \div 0.6 \text{ fm}) \cdot p_h/(\mathrm{GeV}/c)$$

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

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

easier to reach than in CT reactions with nuclei

Examples



GPD (N→M)

GPD (N→B)

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

M=gluonium ??

within acceptance of DY exp

$$pp \to p\pi^{\pm} + B$$

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

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

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

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

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

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

COMPASS

J-PARC

Study of Hidden/Intrinsic Strangeness & Charm in hadrons

cf J.C.Peng's talk at J-PARC workshop 2 years ago

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

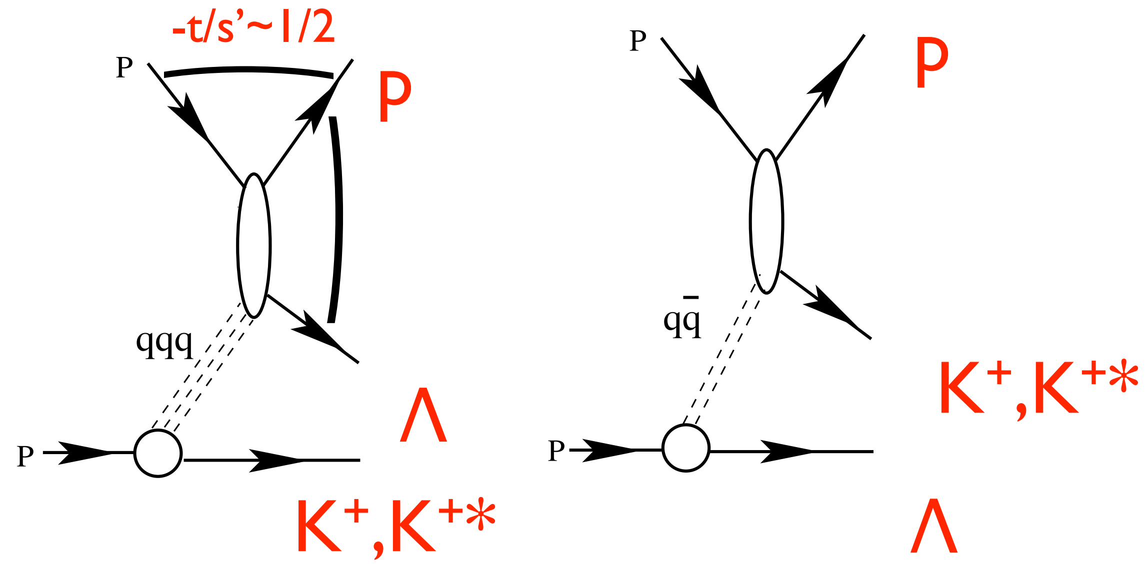
$pp \to K(K^*)_{sp} + \Lambda + p$

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

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

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

BNL experiment EVA has few candidate events

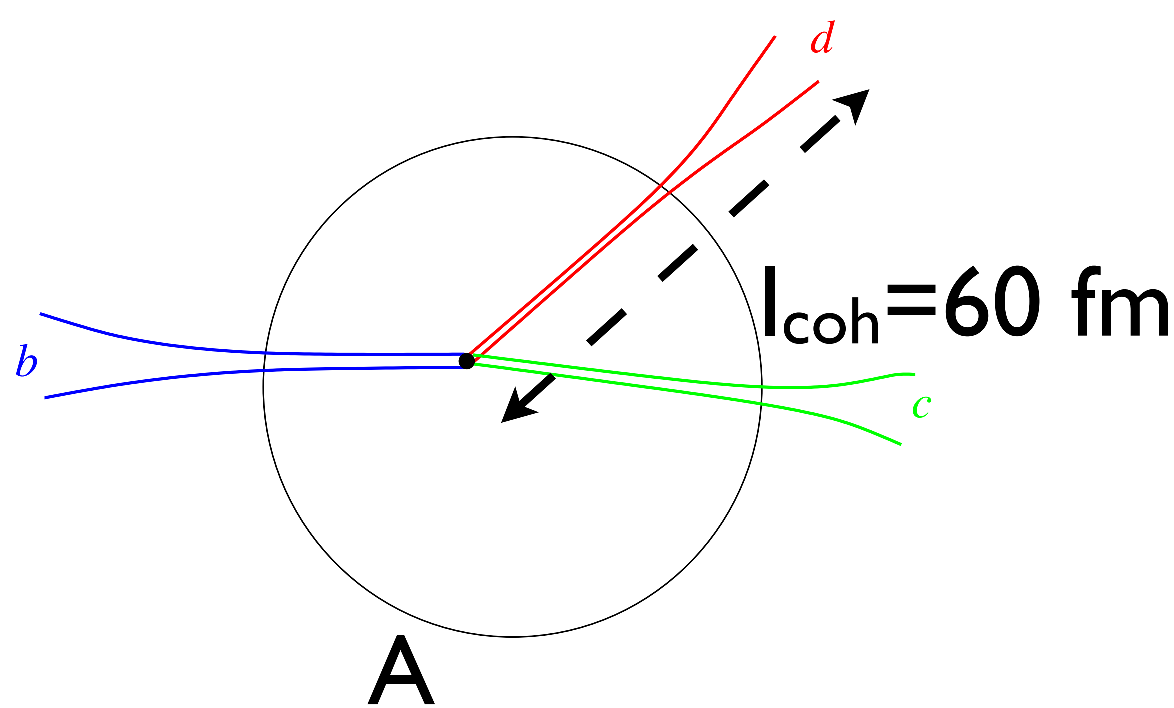


How to check that squeezing takes place so that one can use GPD logic?

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



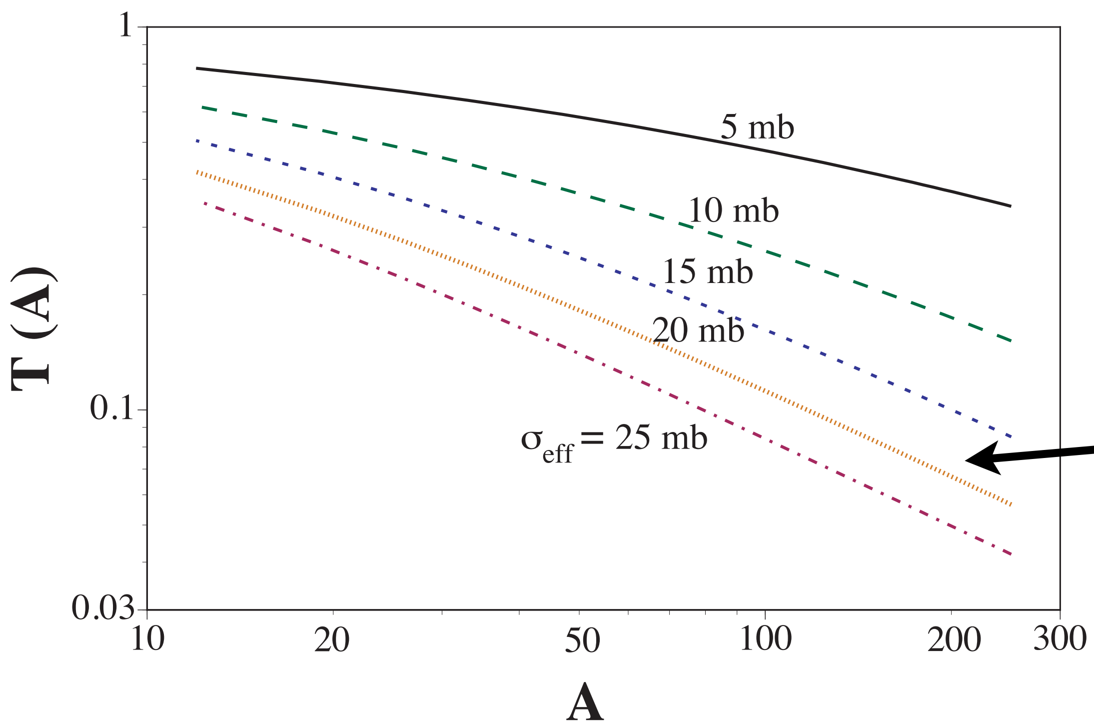
Branching ($2 \to 3$) processes with nuclei - freezing is 100% effective for $p_{inc} > 100$ GeV/c - study of one effect only - size of fast hadrons

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

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

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

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



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

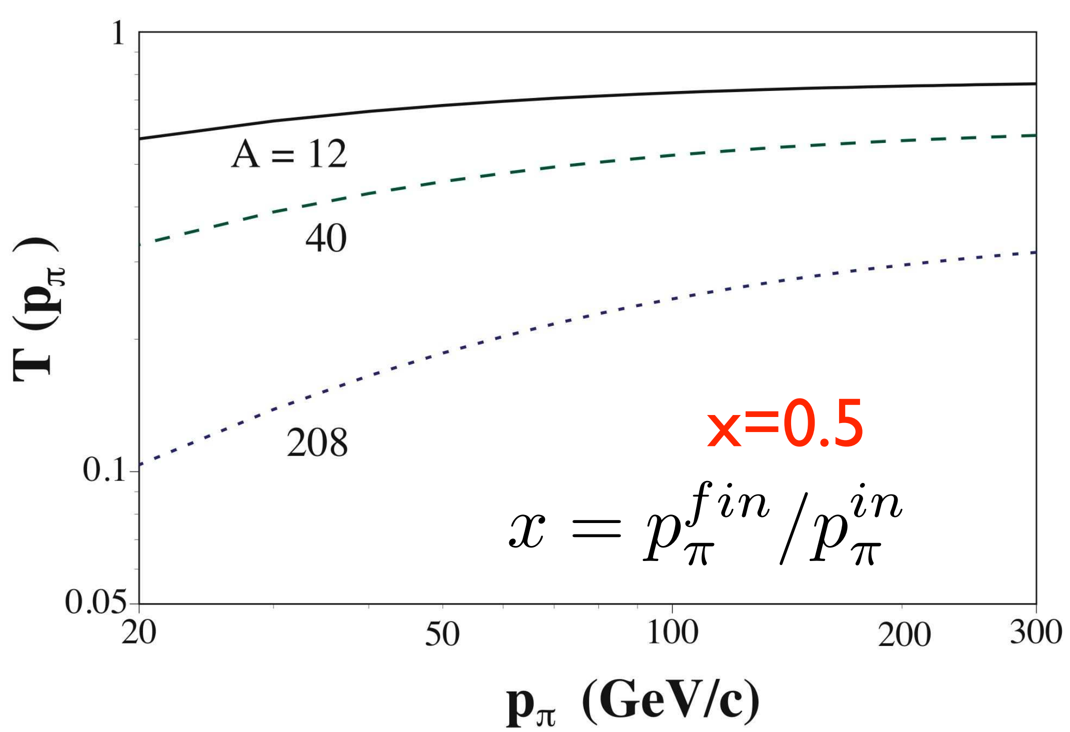
If squeezing is strong enough can measure quark- antiquark size using dipole - nucleon cross section to determine the size of the dipole.

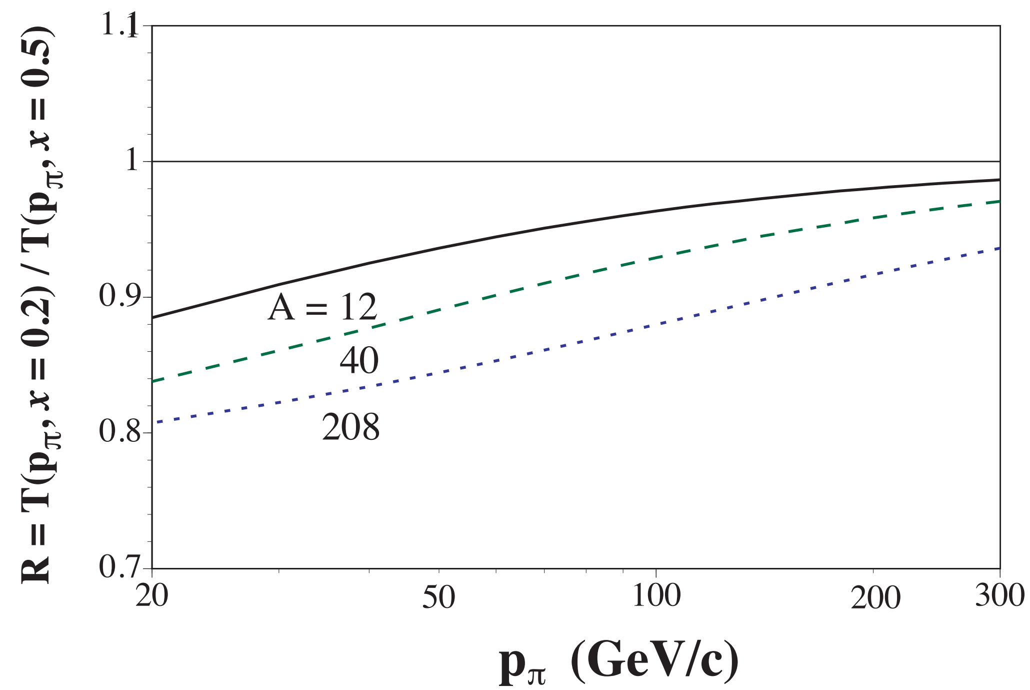
Defrosting point like configurations - energy dependence for fixed s',t'

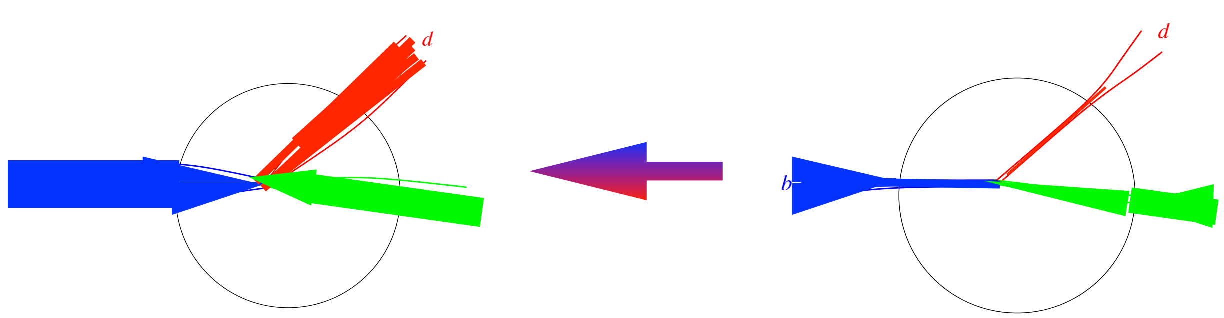
$$\sigma^{PLC}(z) = \left(\sigma_{hard} + \frac{z}{l_{coh}}\left[\sigma - \sigma_{hard}\right]\right)\theta(l_{coh} - z) + \sigma\theta(z - l_{coh})$$

Quantum Diffusion model of expansion

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



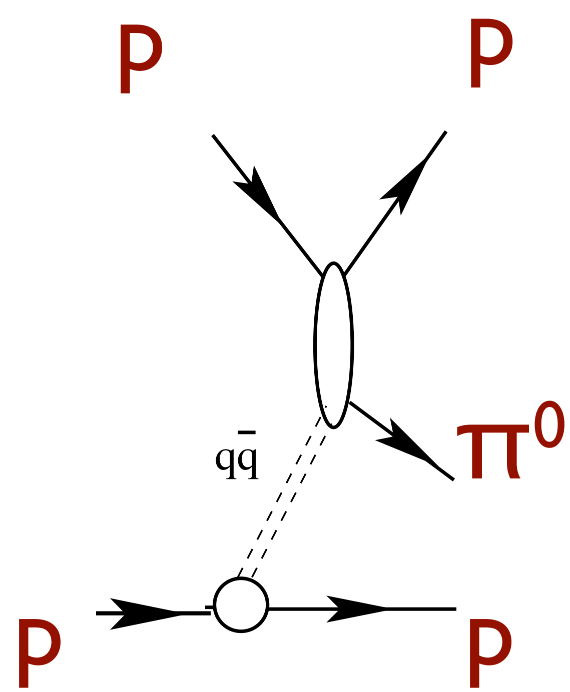


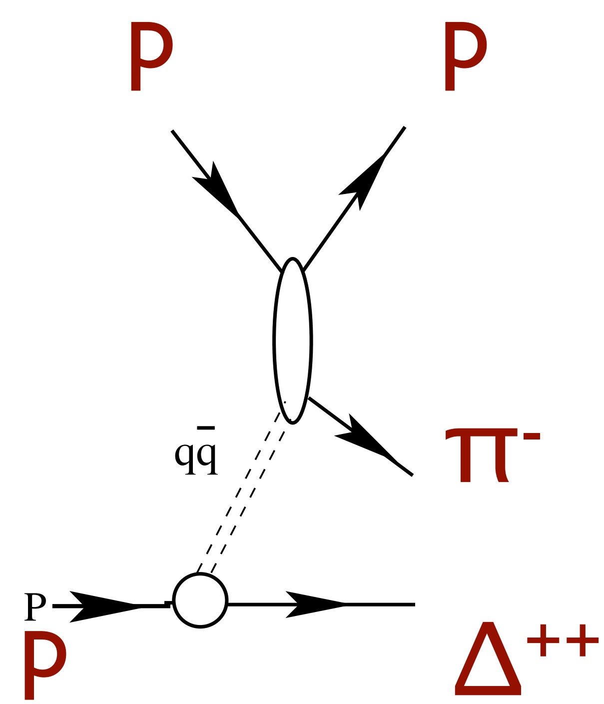


Change of p_{inc} for fixed p_t's and x's of produced two hadrons =Lorentz boost of hard block without changing its internal structure

A detailed theoretical study of the reactions $pp \to NN\pi$, $N\Delta\pi$ was recently completed. Factorization based on squeezing

Kumano, Strikman, and Sudoh 09





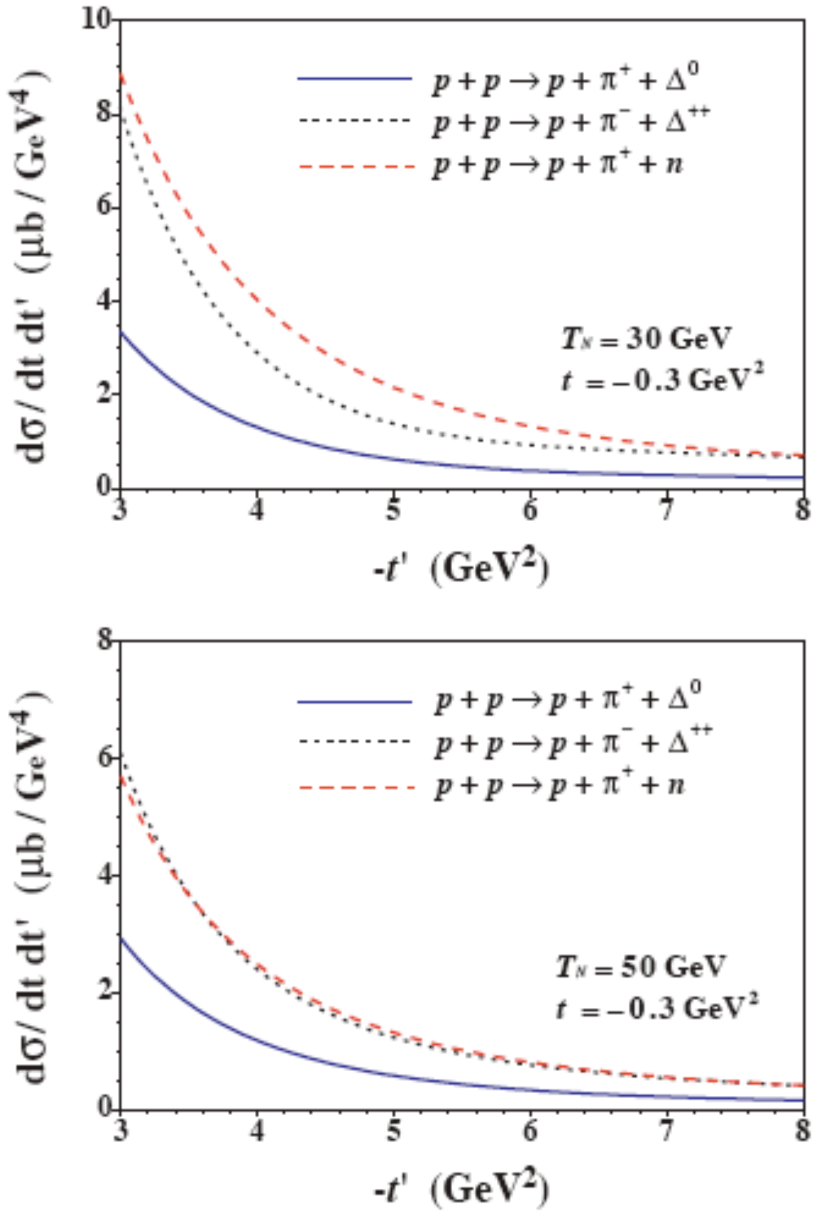


FIG. 11: Differential cross section as a function of t'. The incident proton-beam energy is 30 (50) GeV in the upper (lower) figure, and the momentum transfer is $t = -0.3$ GeV^2. The solid, dotted, and dashed curves indicate the cross sections for $p + p \to p + \pi^+ + \Delta^0$, $p + p \to p + \pi^-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

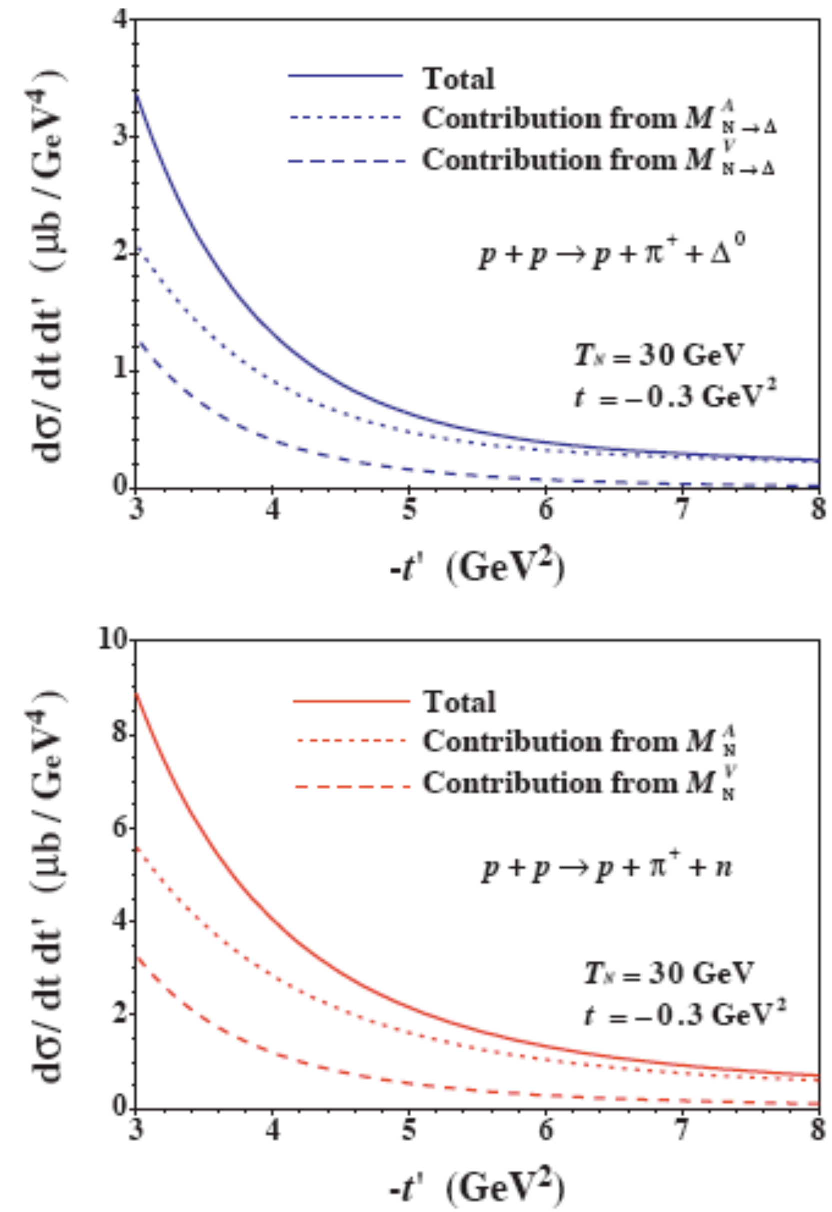


FIG. 12: Differential cross section as a function of t'. The incident proton-beam energy is 30 GeV, and the momentum transfer is $t = -0.3$ GeV^2. The upper (lower) figure indicates the cross section for the process $p + p \to p + \pi^+ + \Delta^0$ ($p + p \to p + \pi^+ + n$). The solid, dotted, and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