Probing SRC and color transparency in hard exclusive processes at hadron facilities

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Outline

- **Introduction: Motivation and facilities**
- **Direction for study of SRC at hadron machines**
- **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***
- ***2→2 color transparency studies with J-PARC and PANDA***

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

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

Requirements to detector allow to study simultaneously SRC, color transparency dynamics and and generalized parton distributions (GPDs)

- *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:*

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

$$|meson\rangle = |q\bar{q}\rangle + |q\bar{q}g\rangle + ...$$

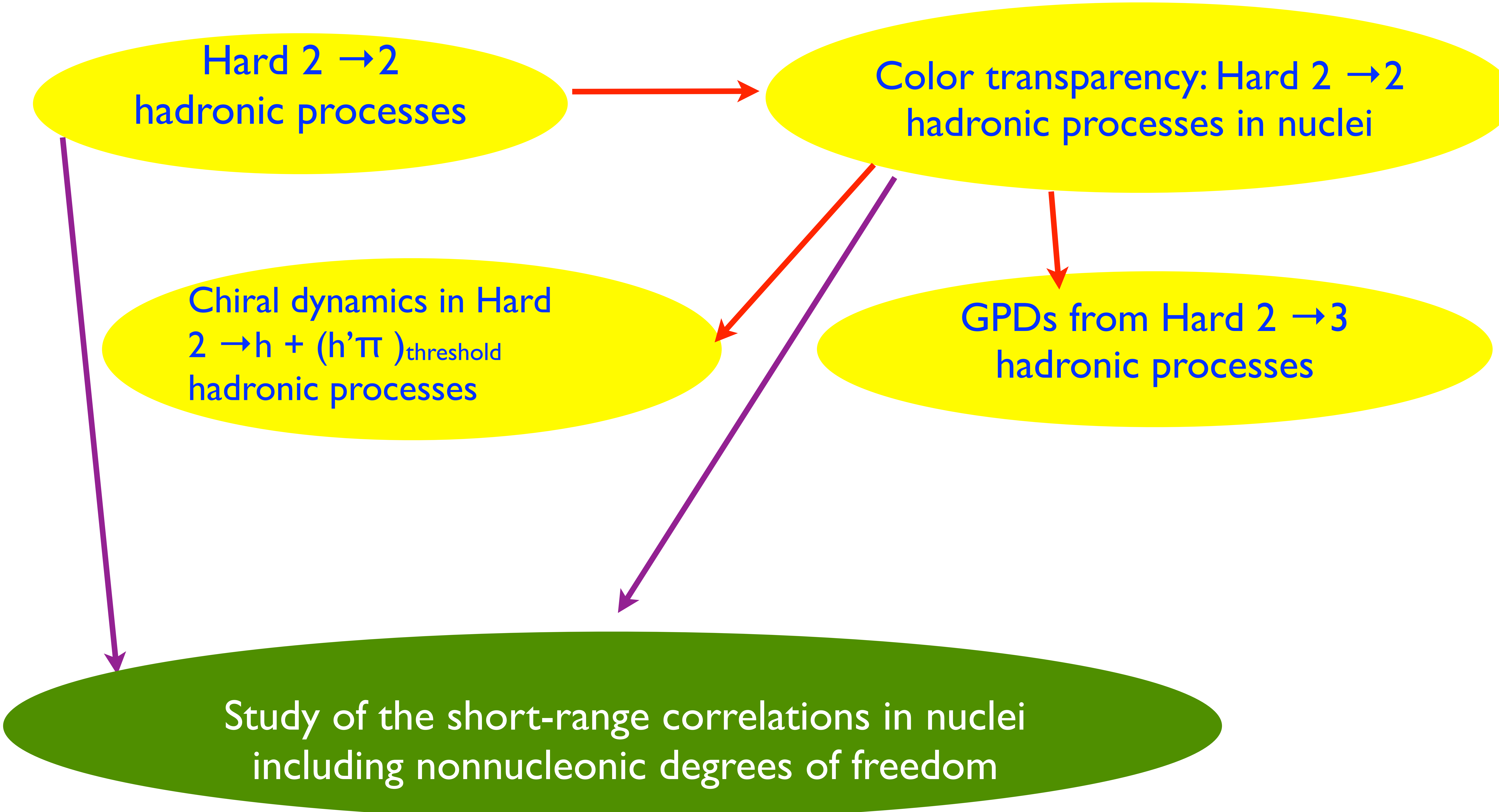
- Scan sizes involved in large t a+b → c+ d reaction, determine at what t point-like configurations dominate ➠ observe suppression of small configurations in bound nucleons

- 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 $2 \to 2$ large angle process allow to do analog of DIS - *select point - like configurations in hadrons*?



Facilities:

Jlab - 12 GeV upgrade (2015)

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

PANDA detector at FAIR (GSI) (2017?)

J-PARC 30 GeV proton and <15 GeV pion beams

FNAL booster up to 120 GeV ????

PANDA - brief information relevant for our discussion

antiproton beams ← P_{beam}= 1 - 15 GeV/c → *proton beams*

antiproton beams
- 6 months/year

High luminosity mode

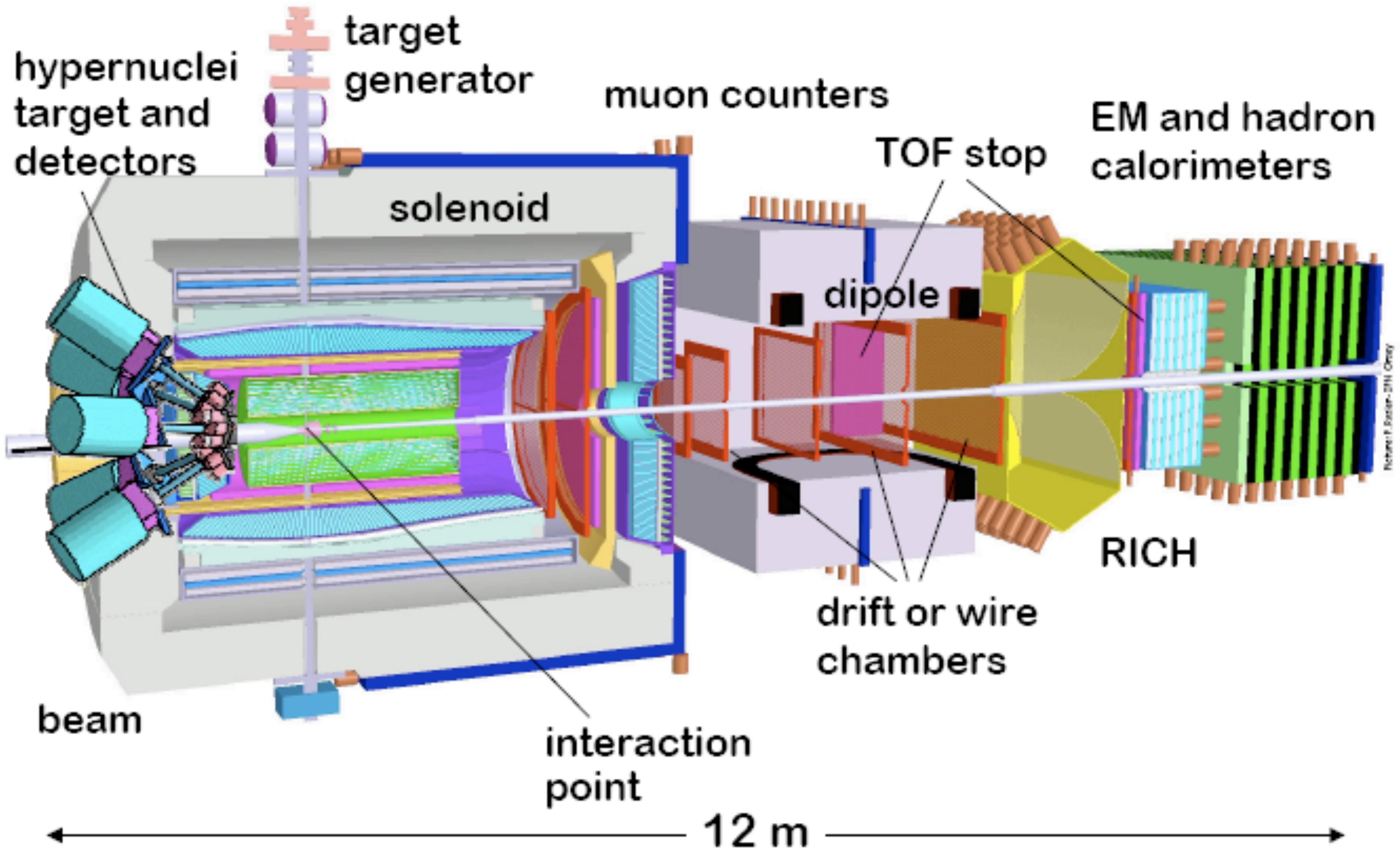
- Lumin. = 2 x 10^{32} cm^{-2} s^{-1}
- Production rate 2x10^{7}/sec
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)

proton beams
- 3 months/year possible not competing with antiproton runs

- Lumin. > 2 x10^{32} cm^{-2} s^{-1}
- Production rate few times 2x10^{7}/sec

Panda Detector

pellet target (hydrogen, deuteron, heavier nuclei,...)
- negligible absorption



Very good angular coverage, high momentum resolution, particle ID, neutral particle (pions, neutrons) detection,...

GPDs in PANDA

Generalized Parton Distributions

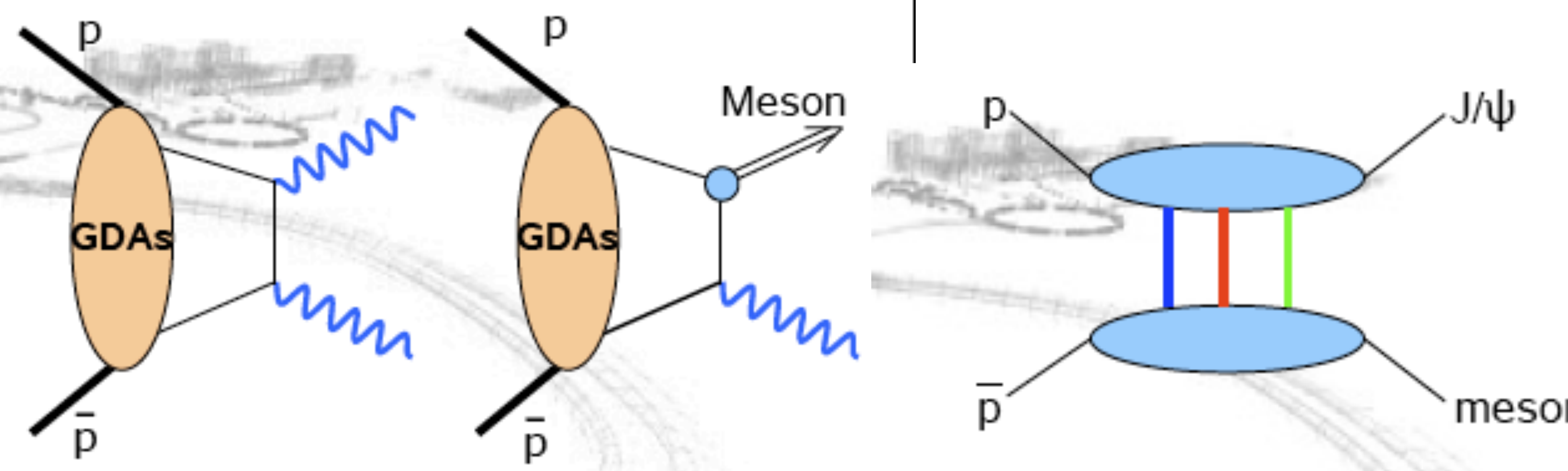
- Deeply virtual Compton scattering
- Hard exclusive meson production

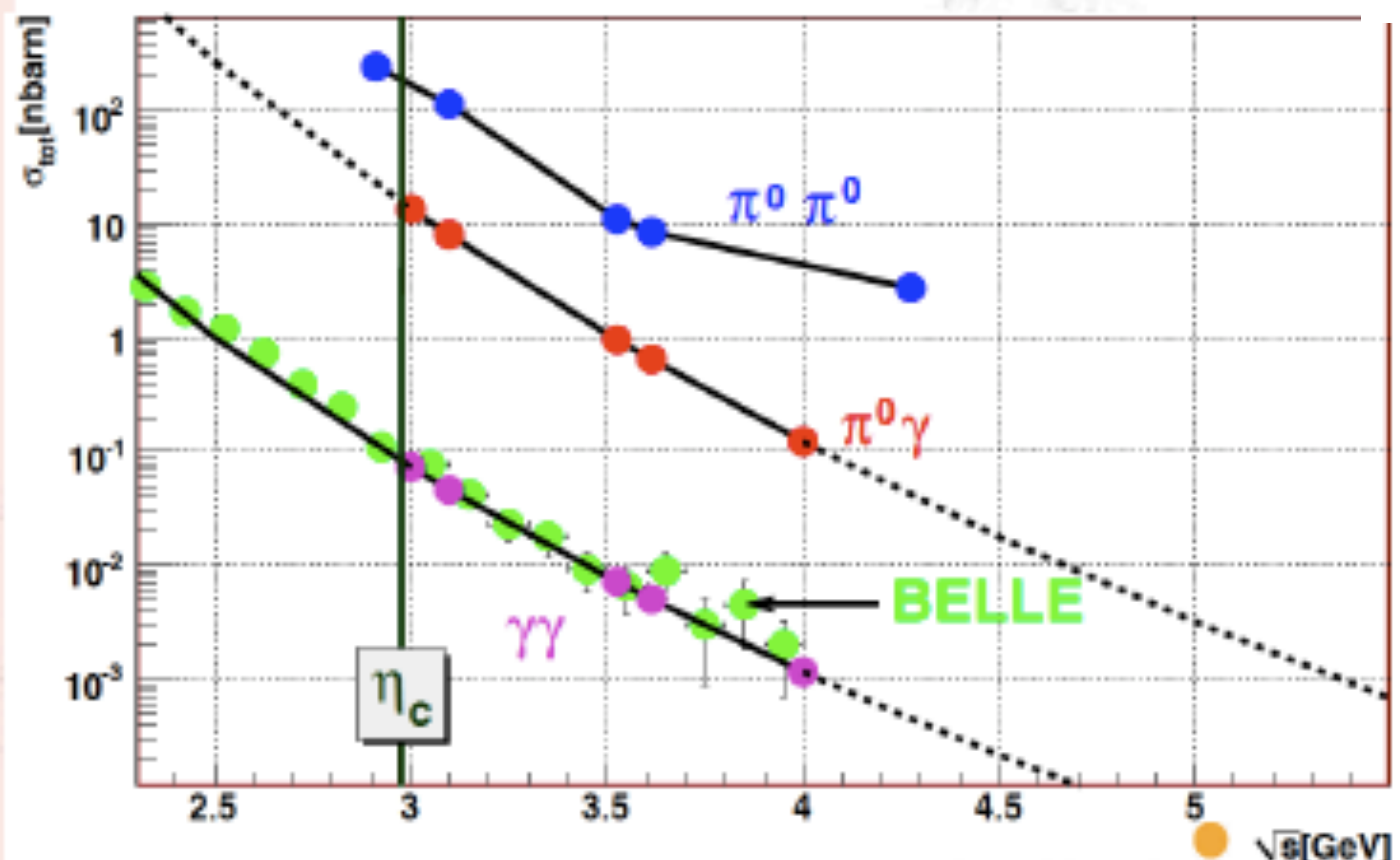
Crossed channels

- Wide angle Compton scattering
- Hard exclusive meson production

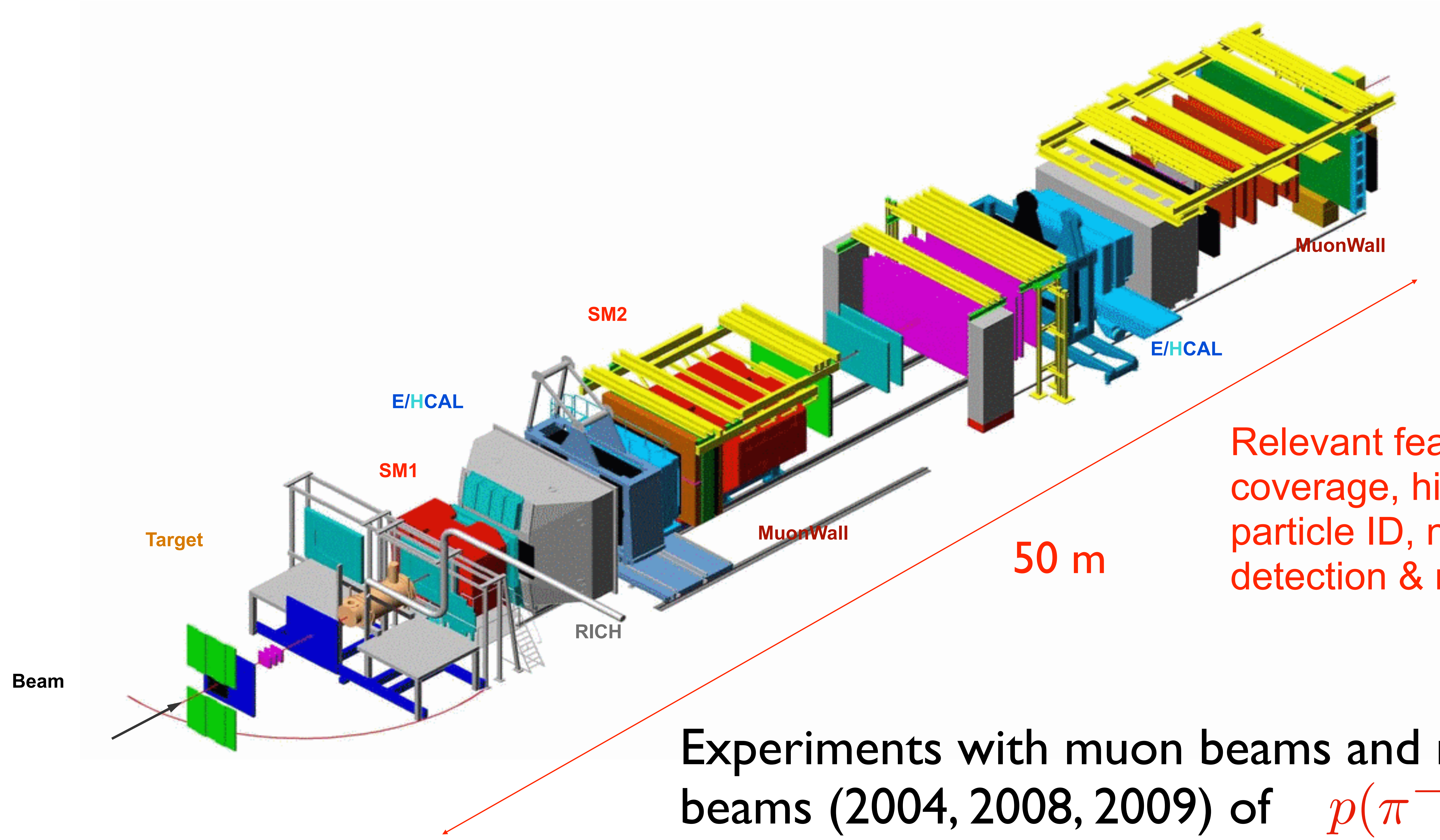
Simulation

- Signal: $p\bar{p} \to \gamma\gamma$
- Backgrounds: $p\bar{p} \to \gamma\pi^0$, $p\bar{p} \to \pi^0\pi^0$





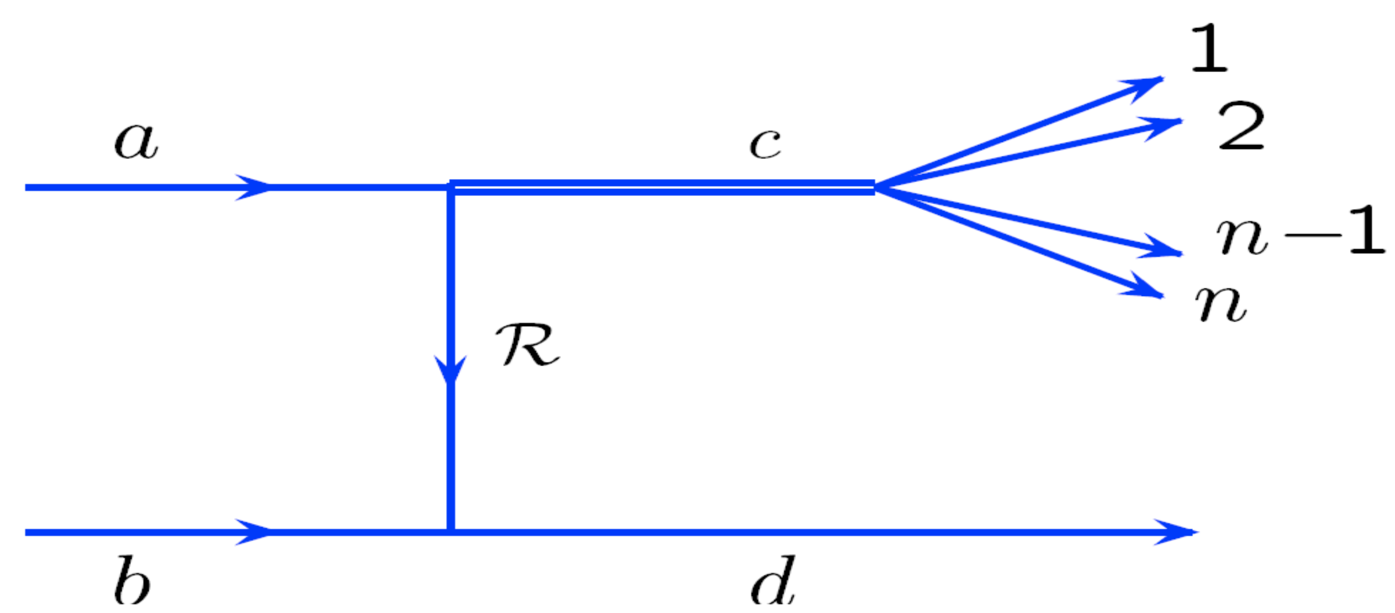
COMPASS Detector



Relevant features: Very good forward coverage, high momentum resolution, particle ID, neutral particle (pions) detection & recoil detector

Experiments with muon beams and more recently with pion beams (2004, 2008, 2009) of $p(\pi^-) = 190 GeV$

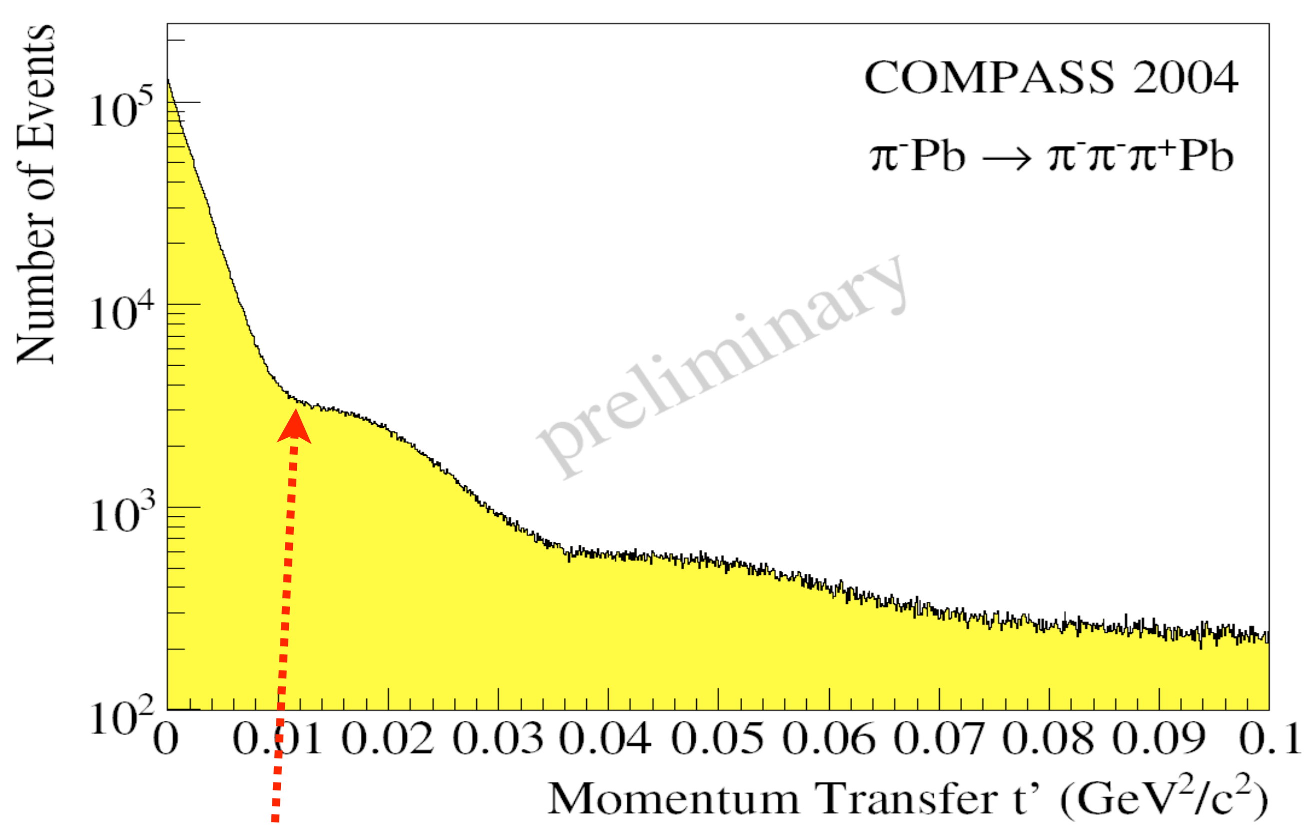
Example: $\pi^- + Pb \rightarrow \pi^-\pi^-\pi^+ + Pb$



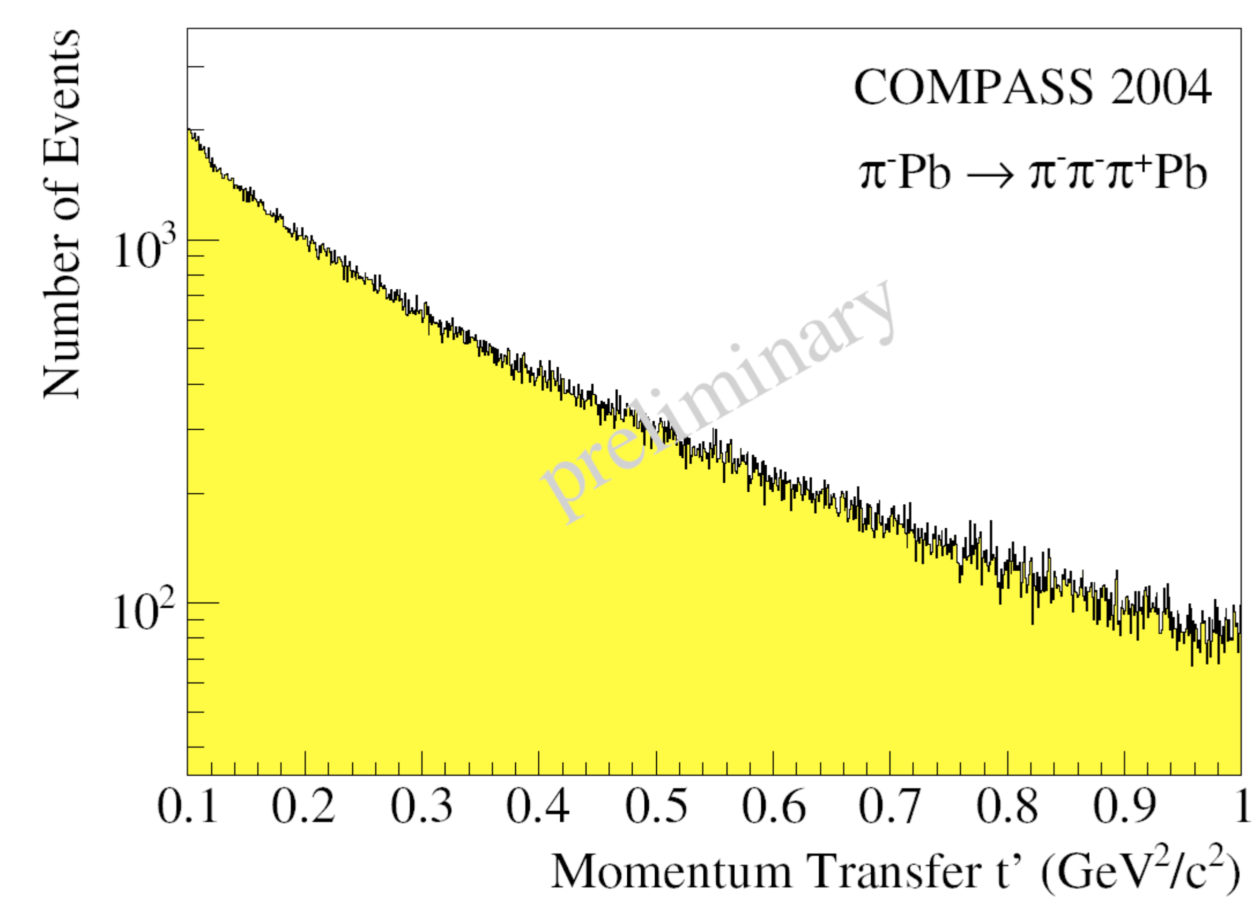
- 4π vertex in Pb target
- Exclusivity ⇨ target stays intact
- Momentum transfer

$$-t \equiv Q^2 = -(p_a - p_c)^2$$

Diffraction on Pb nuclei



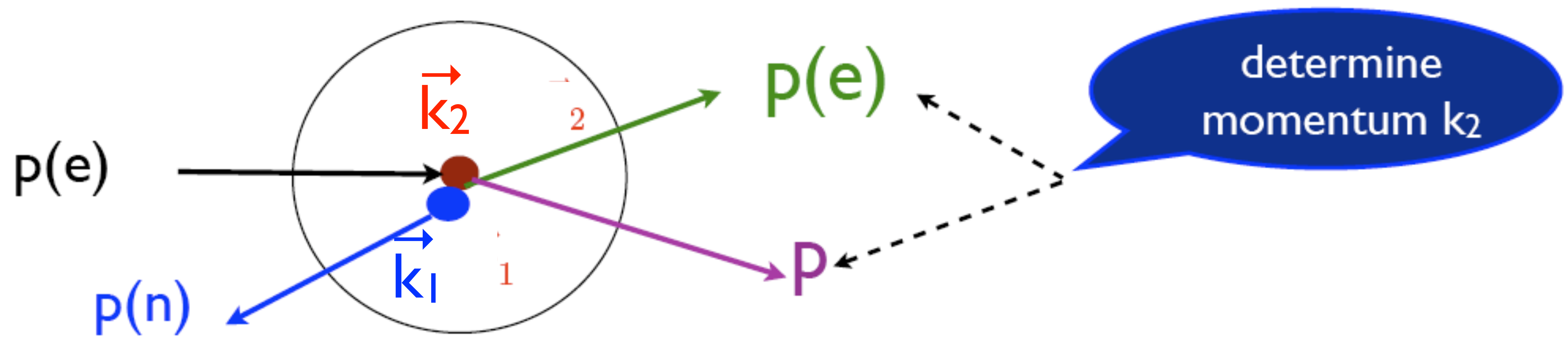
Incoherent Diffraction on nucleons



Traces of rescattering effects in t -dependence - indication of very good selection of exclusive channel

Effective way to observe SRC directly is to consider semi-exclusive processes
e(p) +A → e(p) + p + " nucleon from decay" +(A-2) since it measures
both momentum of struck nucleon and decay of the nucleus

(p,2p) is analog of the Rutherford proton discovery experiment



Two novel experiments reported results in the last 5 years

EVA BNL 5.9 GeV protons (p,2p)n $-t= 5\ GeV^2; t=(p_{in}-p_{fin})^2$

Based on our proposal of 88-89 based on the observation the $\propto s^{-10}$ dependence of elementary amplitude leads to a strong enhancement of scattering off fast forward nucleons.

⇒balancing nucleon should fly backward - is there an empty space in the detector???

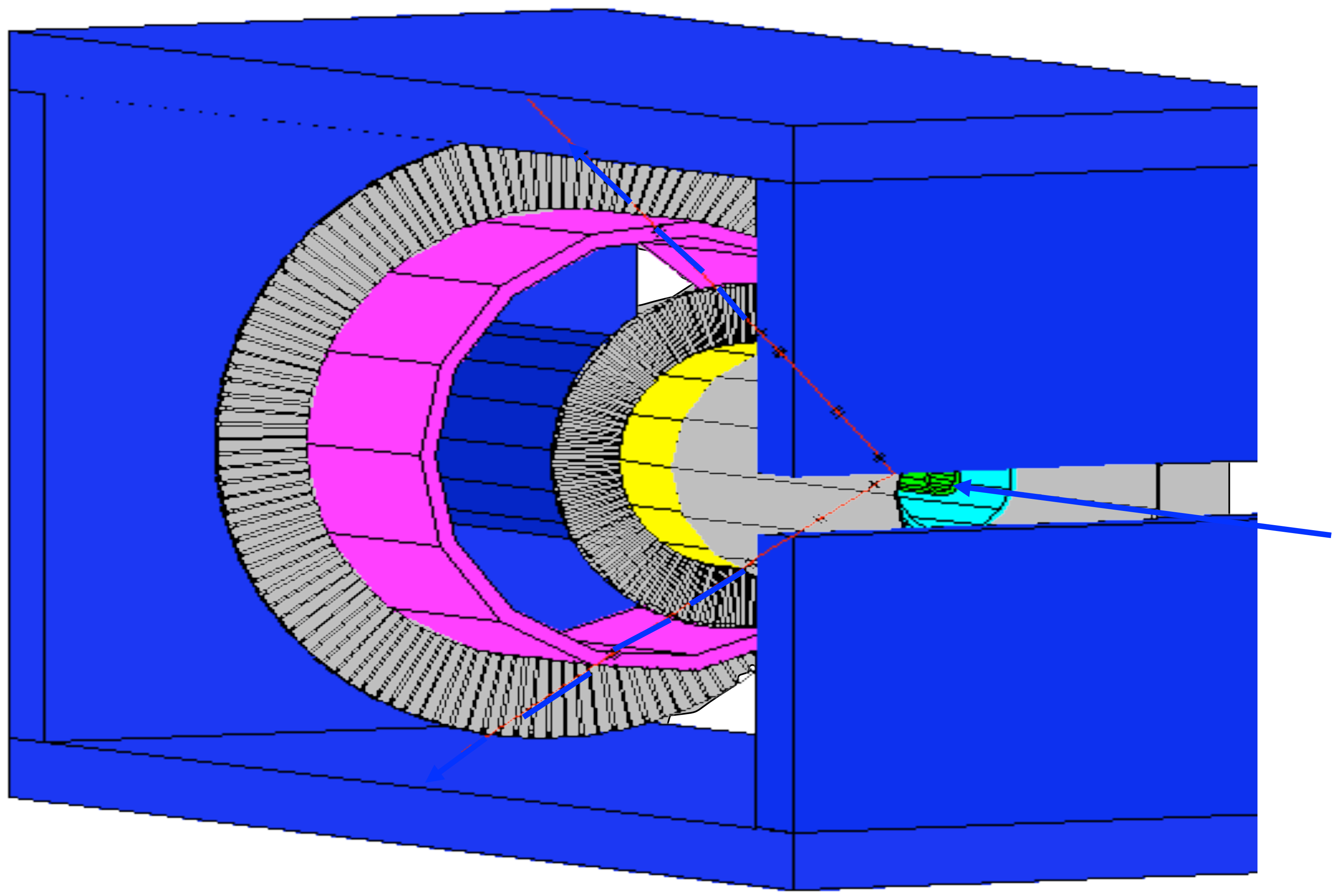
Follow up (e,e' pp), (e,e'pn) experiment at Jlab $Q^2= 2GeV^2$

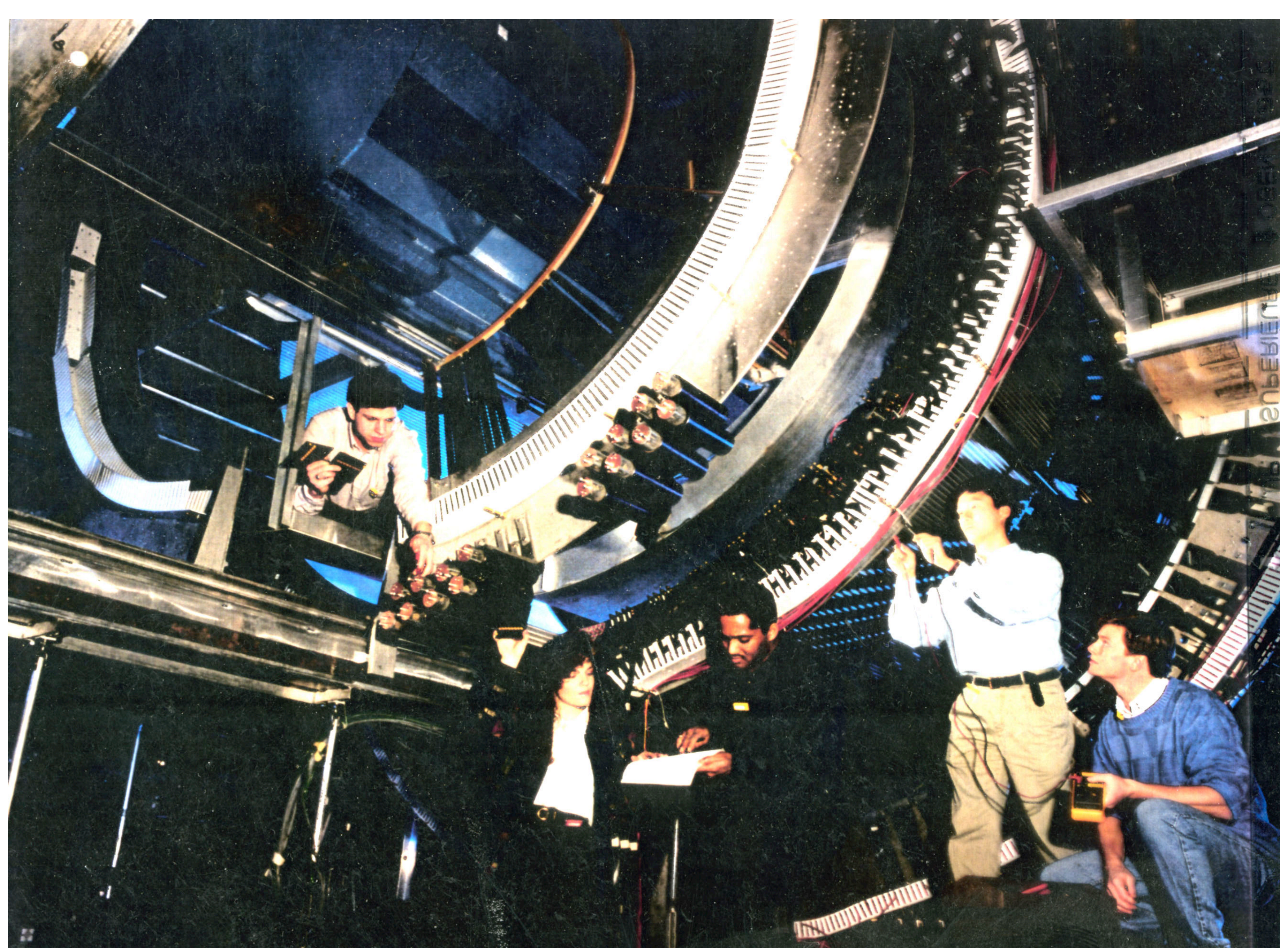
Future experiments need to check the important aspect of the production mechanism - factorization of the cross section into the product of the elementary cross section and decay function.

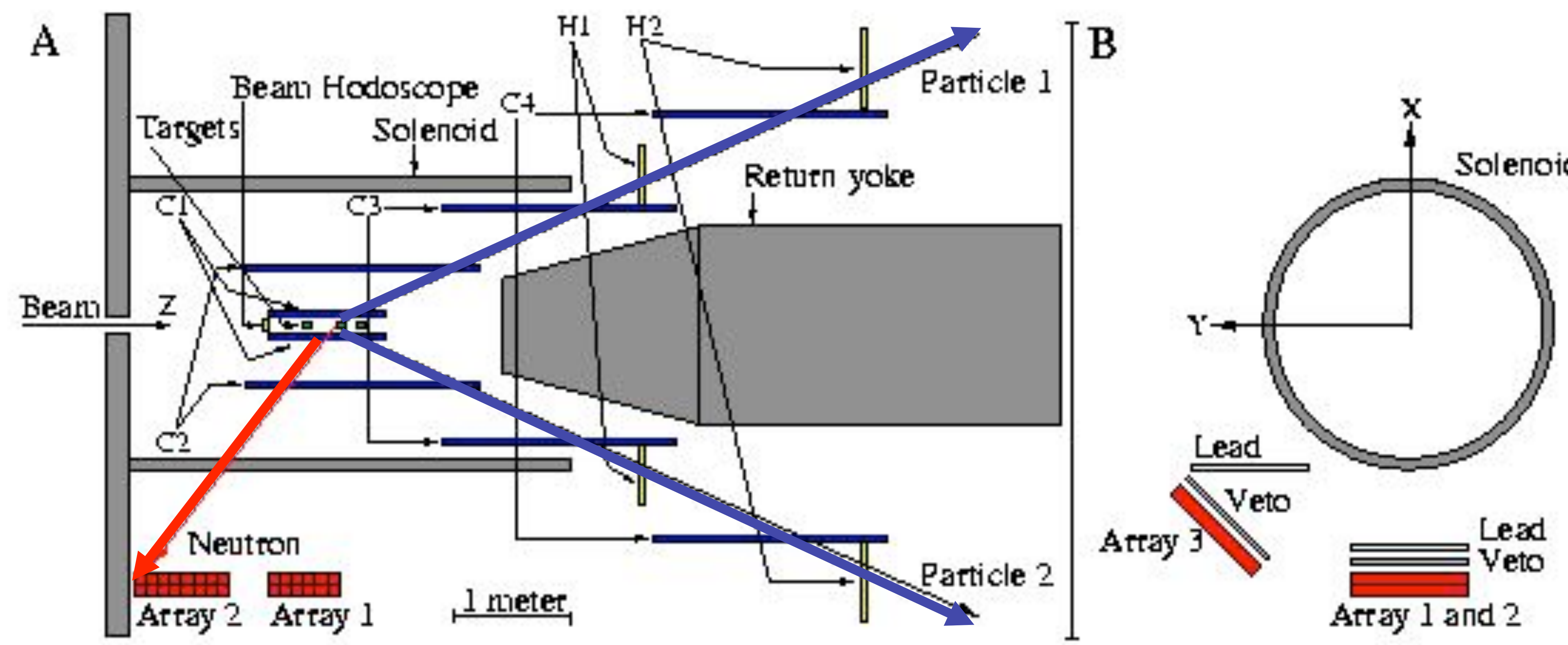
The EVA Apparatus AGS Experiment E850 BNL

E850 Eva

S.Heppelmann & A. Carroll







1989- Steve Heppelmann - “we discovered very convenient variables for our analysis”

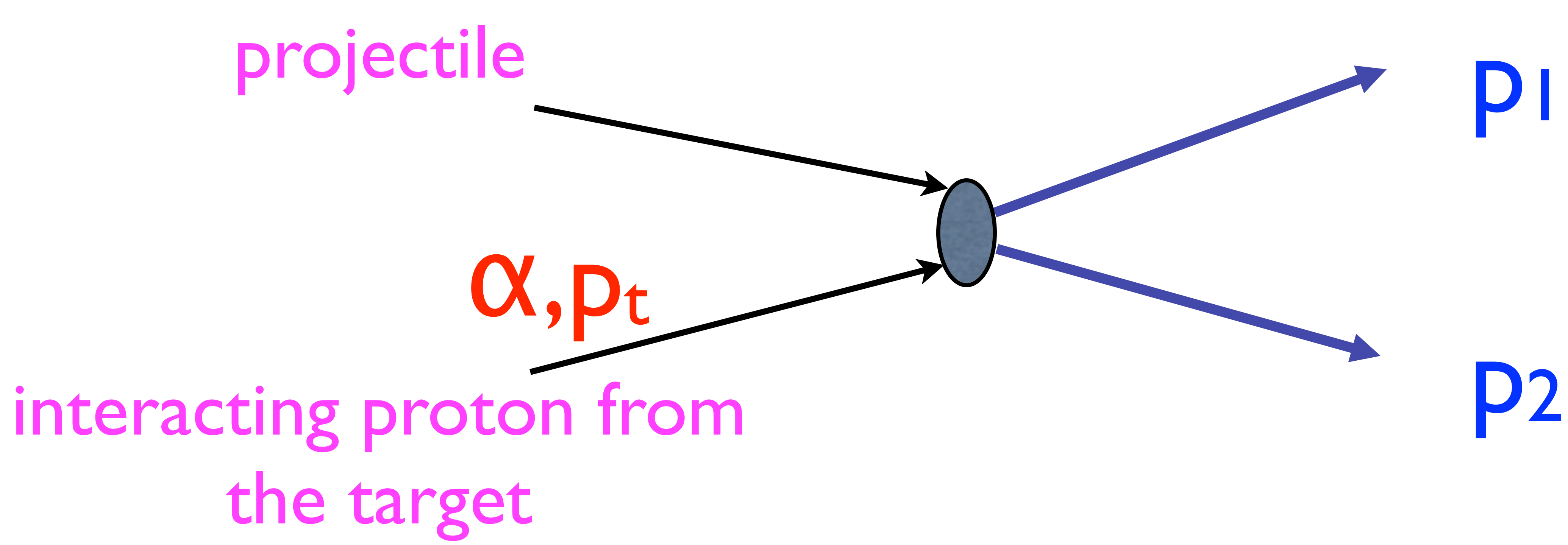
MS - Yes - you discovered light - cone

EVA - Very good resolution in $E - p_z = (m_N^2 + p_t^2)/(E + p_z)$

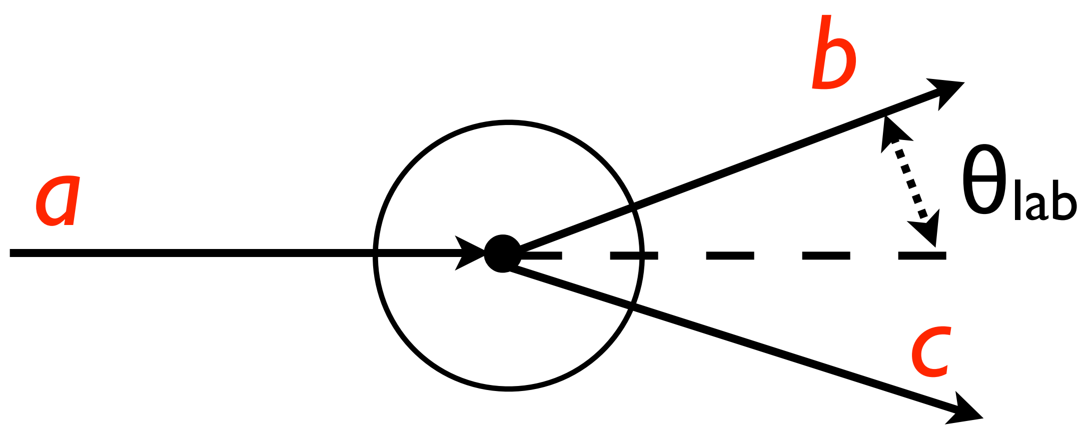
LC variables: $q_\pm = q_0 \pm q_z$

for any vector $a_\mu = (a_+, a_-, a_t)$

$$\alpha \equiv \frac{Ap_-^{int}}{P_-^A},\ p_t \equiv p_t^{int} = -p_t^{rec}$$



Kinematics for θ_{cm}~90°



θ_{lab} (for θ_{cm}=90°)$\approx m_N/\sqrt{s}$

Important kinematic high energy effect: it is easy to measure accurately the light cone fraction of the hit nucleon momentum α (α=1 for nucleon with small momentum) since one can very accurately measure $\alpha_{1,2}$ for two forward nucleons

$$\alpha_{1,2} = (E_p - p_3)/m_N = (m_N^2 + p_3^2 \cdot \sin^2(\theta))/(E_p + p_3)$$

➡ excellent resolution in $\alpha = \alpha_1 + \alpha_2 - \alpha_{inc.nucl.}$

Further improvements from veto on production of extra hadrons.

Can be done with PANDA for numerous channels of (anti)proton - "proton bound in nucleus" scattering.

J-PARC - detector for high energy beam line has to be designed and rates estimated. Should be high for a broad kinematic range analyzed. Study of SRC - probably should go in package with other experiments which I will discuss later.

Role of Fermi motion.

Detection of *b, c* provides accurate measurement of α_N, p_{tN} of the struck nucleon:

$$\alpha_N + \alpha_a = \alpha_b + \alpha_c \Longrightarrow \alpha_N \approx \alpha_b + \alpha_c$$

$$p_{t\,N} = p_{t\,a} + p_{t\,b},\ \alpha_N(\text{nucleon at rest}) = 1$$

$$\frac{d\sigma(hA \to hp(A-1))}{d\alpha_N} = \alpha_N^{-1}\rho_A^N(\alpha_N)\sigma^{hN}(\tilde{s} = s\alpha_N)$$

Light-cone density matrix

$$\sigma^{hN}(\tilde{s} = s\alpha_N) \propto \tilde{s}^{-n}, n = 6 \div 10$$

nonrelativistic limit

$$\rho_A^N(\alpha_N) = \int d^2k_t \rho(\alpha, k_t);$$

$$\alpha_N \approx 1 + k_3/m_N$$

$$\alpha_N^{-1}\rho_A^N(\alpha_N) \approx \int d^2k_t(1 + k_3/m_N)n_A(k)$$

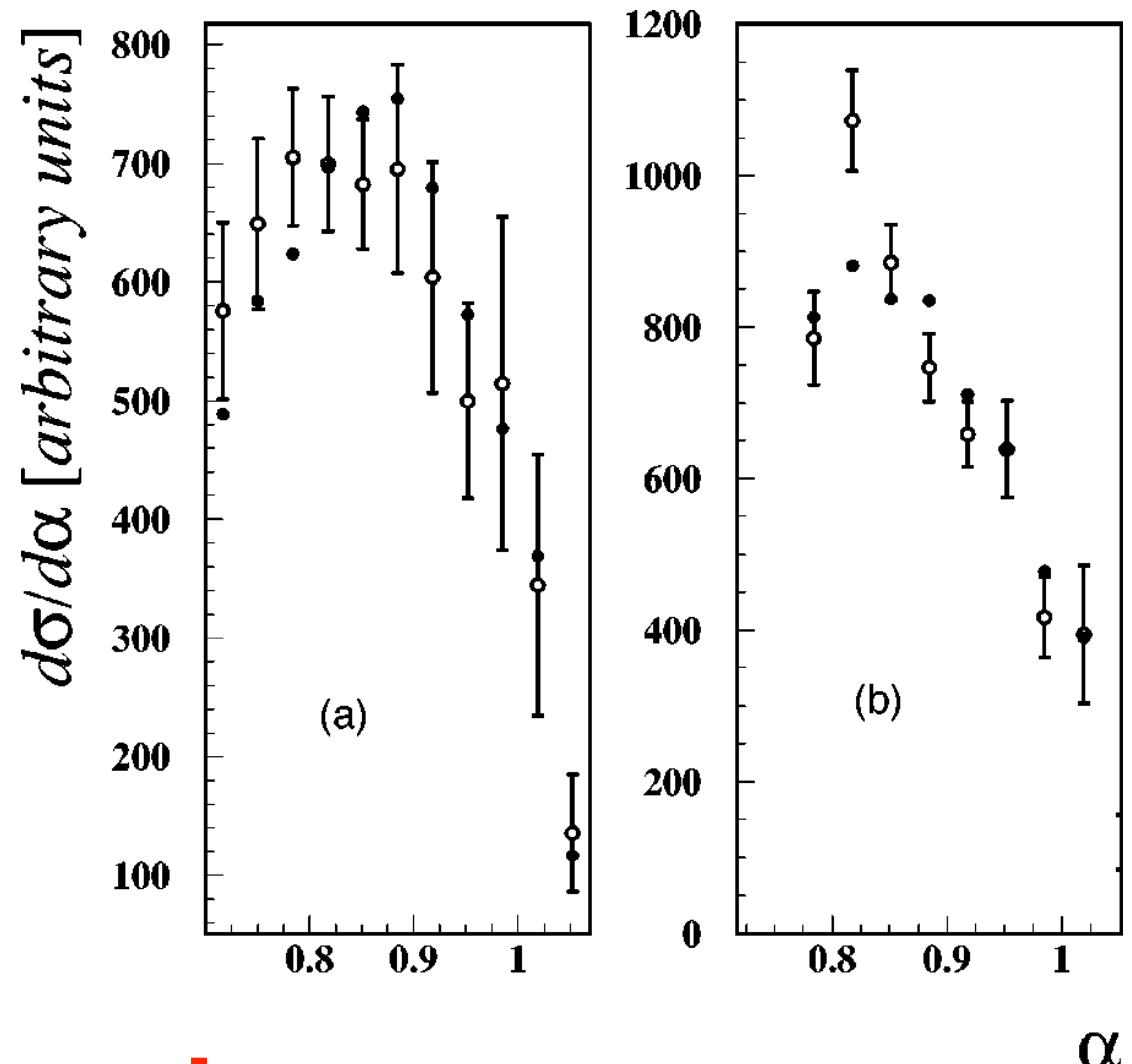
$$\Downarrow$$

Large enhancement of the contribution of scattering off nucleons with large momenta in forward (along the projectile) direction. Hence our prediction of large rate of backward neutron production

⇒ Strong shift of the α distribution to α<1

Farrar, Frankfurt, Liu, MS (FFLS) 89

This prediction agrees well with a detailed analysis of the EVA data by I.Yaron, E.Piasetzky, M.Sargsian and F&S 2002 within 2N SRC model including fsi effects, etc



A comparison between calculated α distributions (•) and the experimental data (O) at 5.9 GeV/c (a) and 7.5 GeV/c (b)

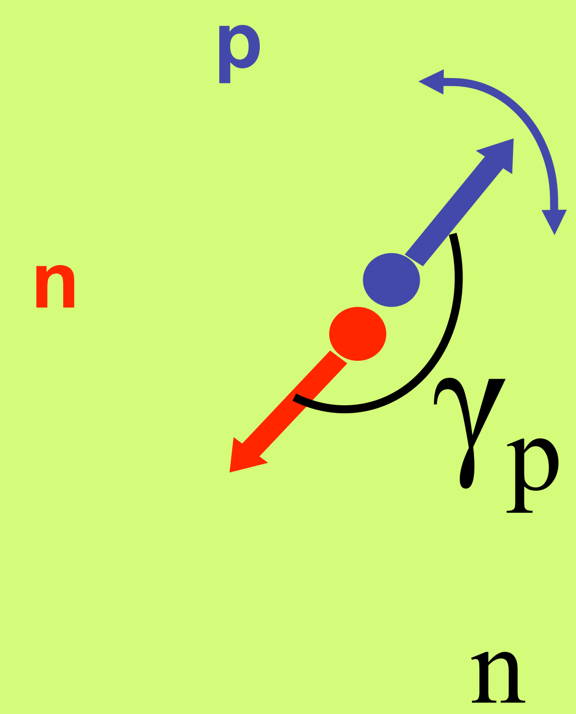
One can measure light-cone density matrix of nucleus at α < 1 in (p,pN)

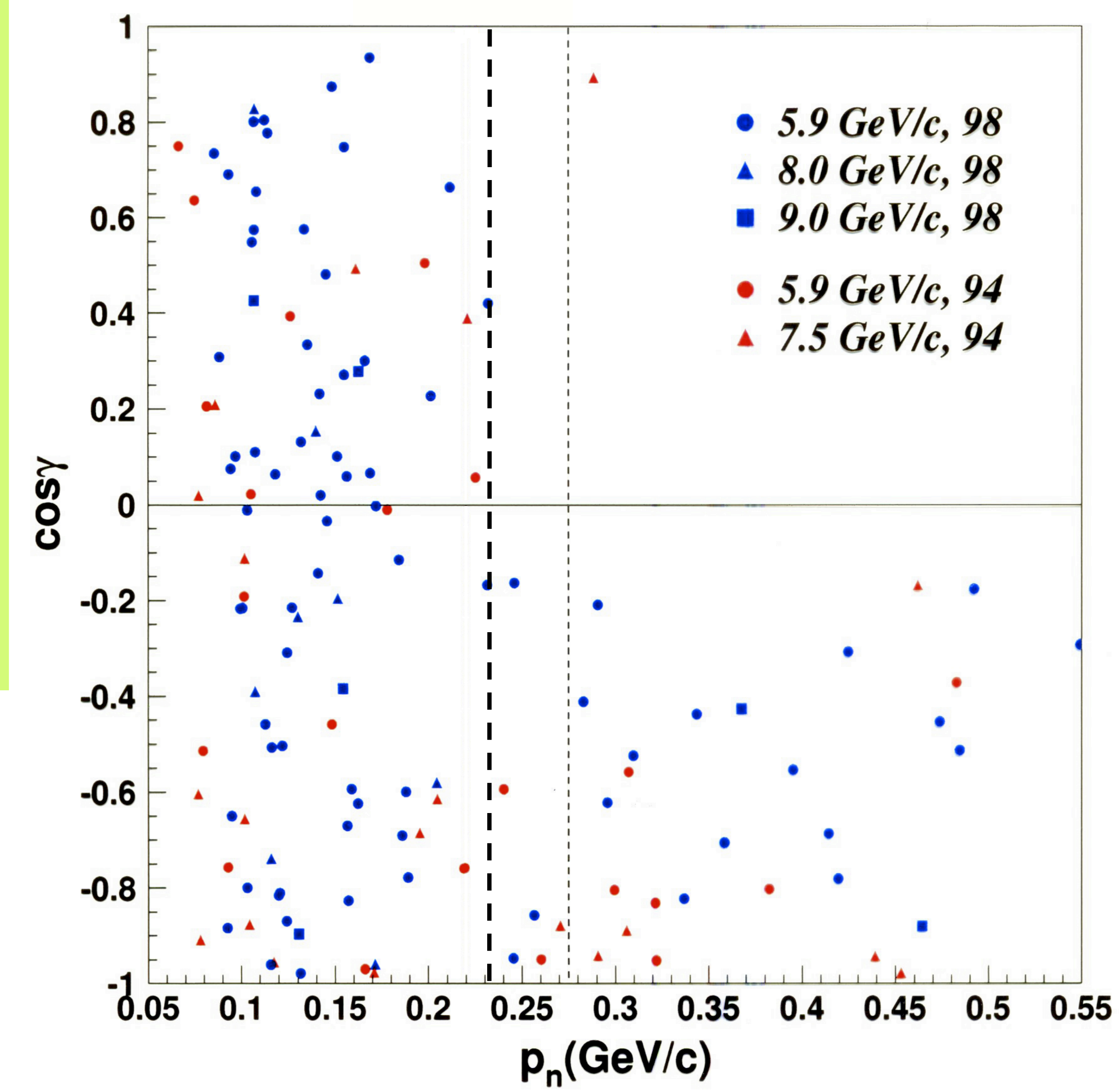
(p,2p) data do find high momentum component - is it mostly due to 2N SRC?

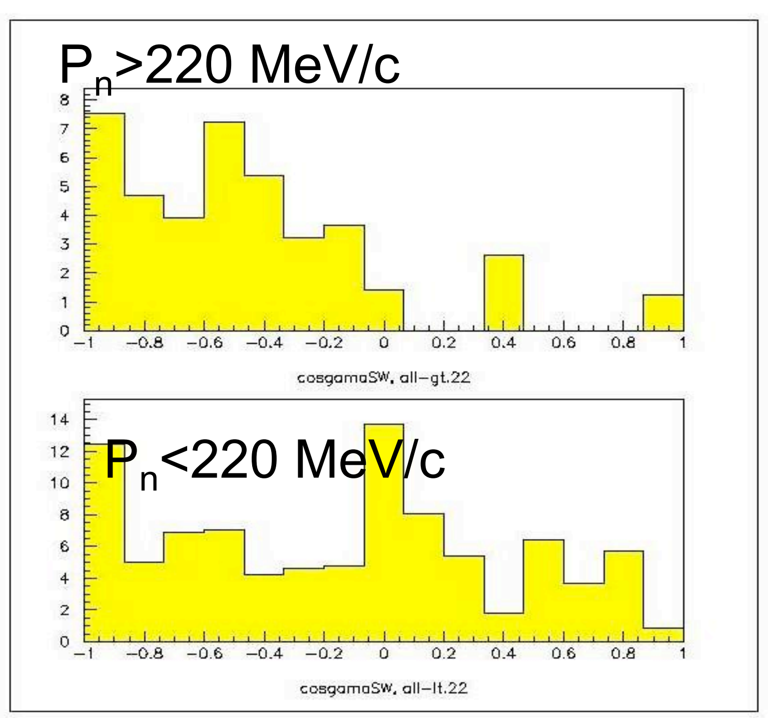
Confirmation of our prediction for correlated neutron emission

Directional correlation

(p,2pn)







The EVA/BNL collaboration

BNL experiments observed that it is possible to select A(p,2p) reaction via measurement of momentum and angle of one particle and angle of the second one. PANDA would have good momentum resolution for many channels and good herteticity

→ *It appears that PANDA can study processes where projectile scatters off bound neutrons like*

$$\bar{p}A \to \bar{p}n(A-1)$$

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

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

$$pA \to pn(A-1)$$

T could be different from pp → pp :

- ✷ *different quark exchanges*
- ✷ $\sigma(pp \to pp) > \sigma(pn \to pn)$
- ✷ *so far no indications of oscillations for fixed* θ_{cm}

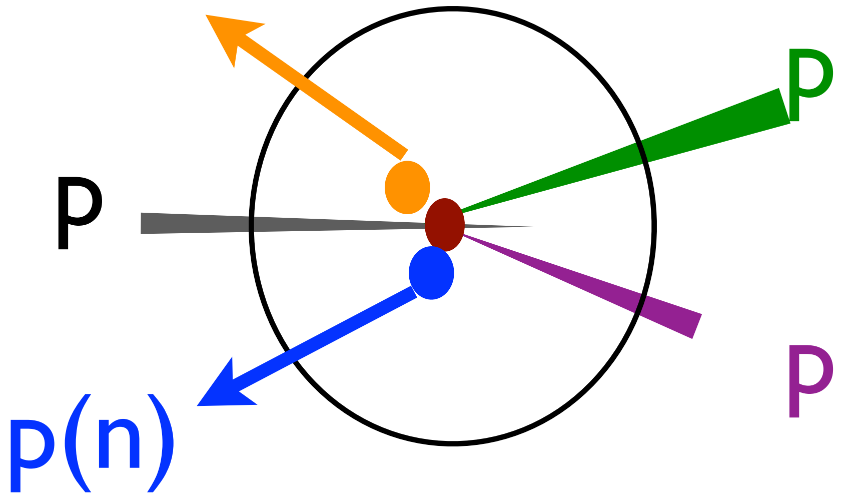
Advantages of PANDA as compared to BNL :

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

→ **Gain in statistics > 1000**

Further studies of SRC are necessary, preferably using both leptonic and hadronic projectiles. It is crucial to establish that different probes give the same results for SRC. For (anti) proton reactions set-up is the same as for CT measurements - can be done simultaneously.

Looking for effects of 3N correlations in A(p,p' p +2 backward nucleons). Reminder: for the neutron star dynamics mostly isotriplet nn, nnn,.. SRC are relevant.



PANDA has a good efficiency for detection of neutrons - can study both (p,2p) and (p,pn) channels

Looking for non-nucleonic degrees of freedom.

Look for channels forbidden for scattering off single nucleons but allowed for scattering off exotics: Δ's 6q... .

$$p + A \rightarrow \Delta^{++} + p + (A-1)$$

Important tool for the analysis: $\alpha_\Delta < 1$ cut as the α_Δ distribution is broader than α_N distribution.

In the kinematics where color transparency (CT) sets in look for effect of the suppression of point-like configurations in bound nucleons in reaction

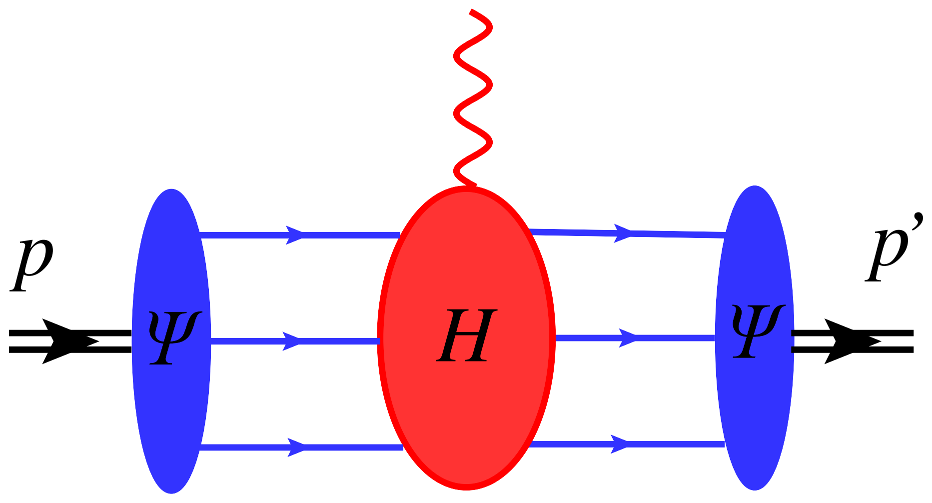
$$p + {}^2H(A) \rightarrow pp + \text{“backward neutron”} + (A-2)^*$$

In CT regime suppression of the effective nucleon momentum distribution by the factor $\delta(k^2)$ - the same as in the tagged EMC effect at large x

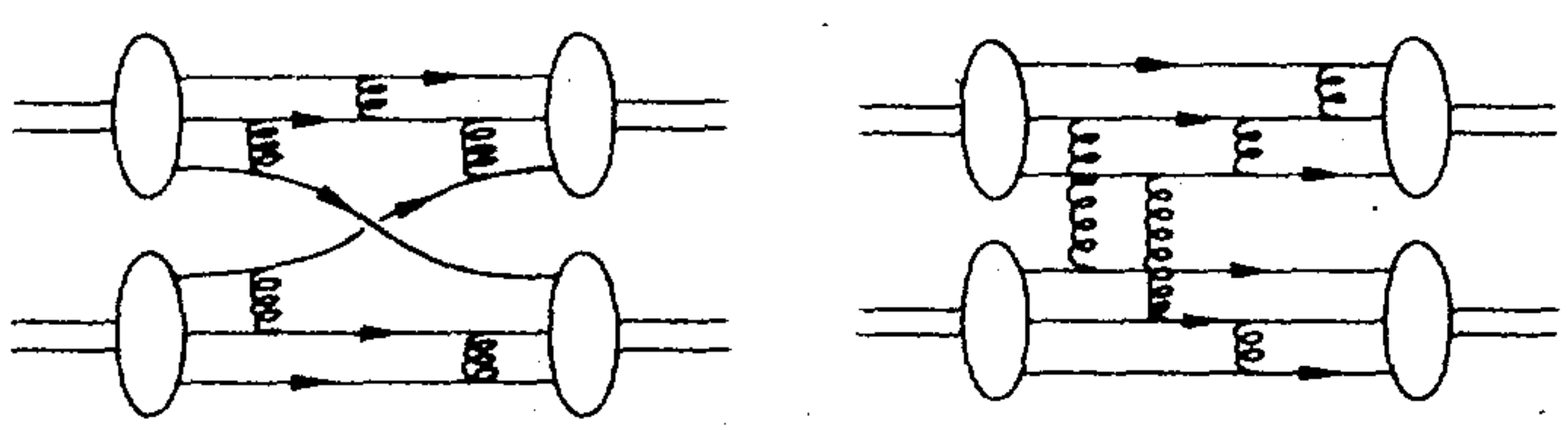
So far we do not understand the origin of **the most fundamental hadronic processes in pQCD -large angle two body reactions** (-t/s=const, s) π +p → π +p, p +p → p +p,... and even form factors

Early QCD approach (Brodsky - Farrar - Lepage)

Lowest order pQCD diagrams for form factors, two body processes involving **all constituents**



exchange of gluons between all three quarks



Typical pQCD diagrams for elastic pp scattering

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

Indicates dominance of minimal Fock components of small size:

$$r^2_{transverse} \propto 1/Q^2$$

Puzzle - power counting roughly works for many large angle processes- they do not look as soft physics - quark degrees of freedom are relevant.

TABLE V. The scaling between E755 and E838 has been measured for eight meson-baryon and 2 baryon-baryon interactions at $\theta_{\mathrm{c.m.}} = 90°$. 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 ±13% for E838 and ±9% for E755.

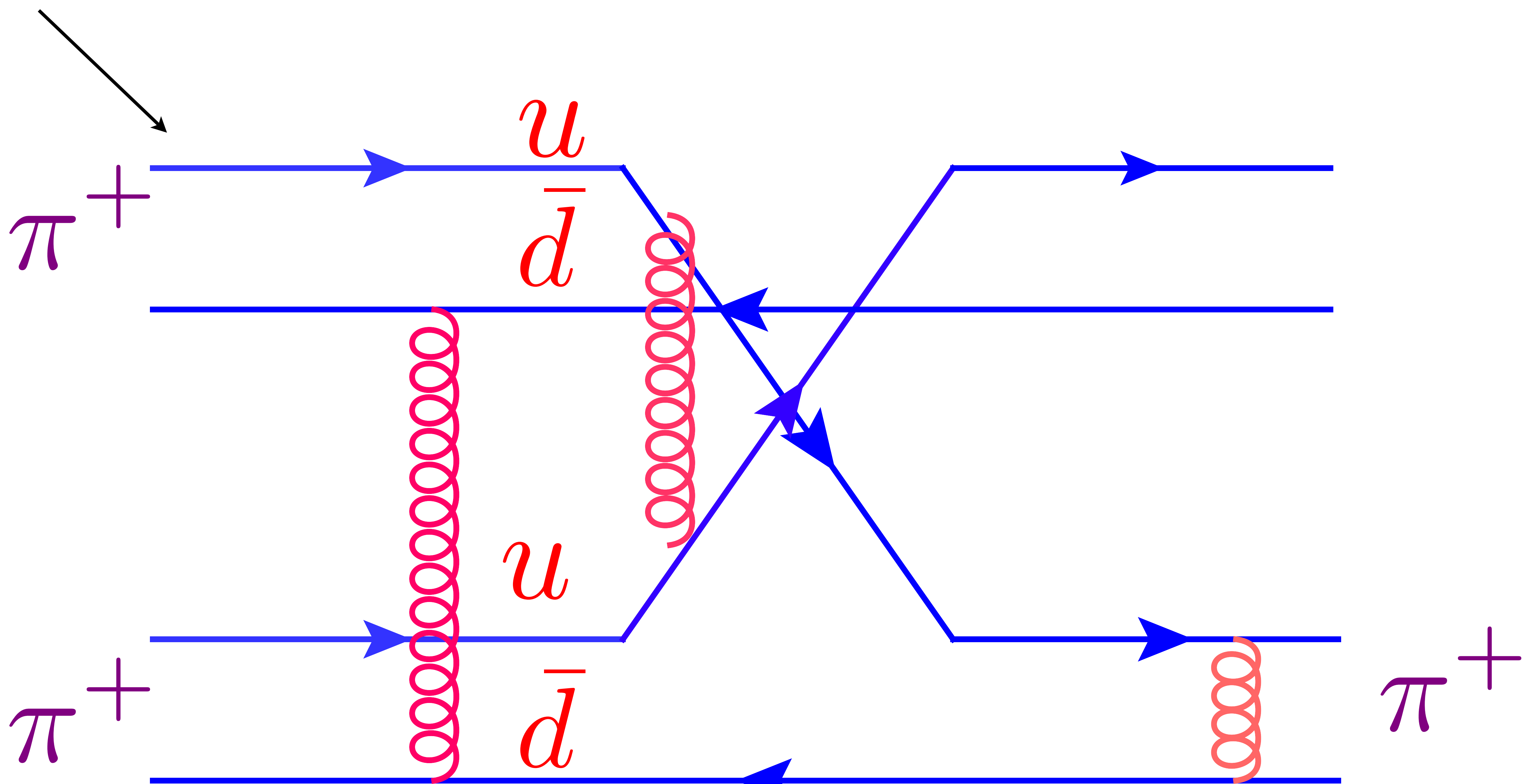
No.	Interaction	Cross section E838	Cross section E755		n-2 $(\frac{d\sigma}{dt} \sim 1/s^{n-2})$
1	$\pi^+ p \to p\pi^+$	132 ± 10	4.6 ± 0.3	n-2=8	6.7 ± 0.2
2	$\pi^- p \to p\pi^-$	73 ± 5	1.7 ± 0.2	n-2=8	7.5 ± 0.3
3	$K^+ p \to pK^+$	219 ± 30	3.4 ± 1.4	n-2=8	$8.3^{+0.6}_{-1.0}$
4	$K^- p \to pK^-$	18 ± 6	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

Reactions where quark exchanges are allowed have much larger cross sections

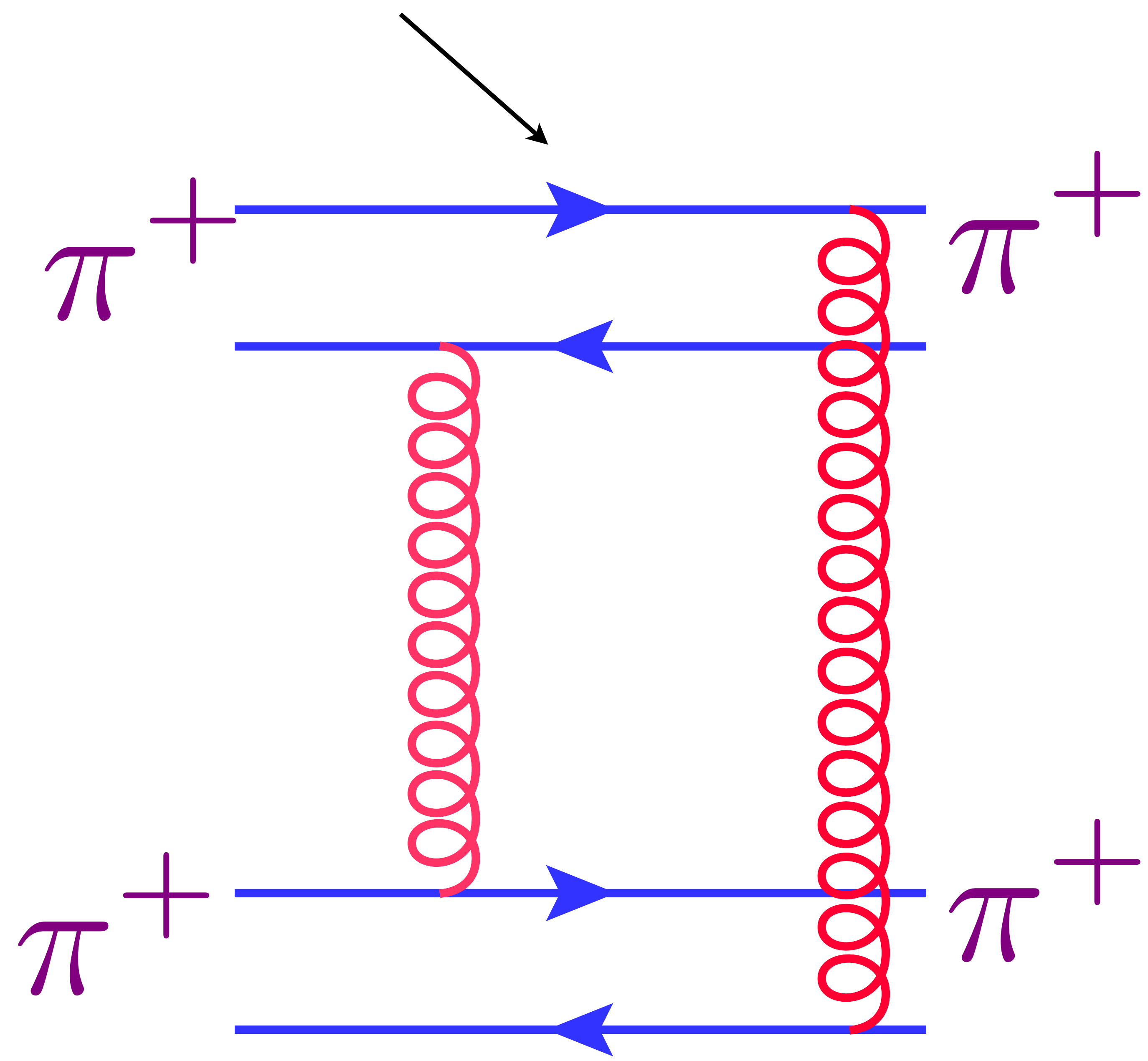
However absolute values of say form factors are too small, large angle Compton expectations contradict the data, etc

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* $\to 1/s^6$

??

New idea: Kivel, Vanderhaeghen PRD,2010

Intermediate scale $Q^2 \gg Q\Lambda \sim m_N^2$ hard-collinear scale is not large

applied to

space like --- nucleon form factor and large angle Compton scattering

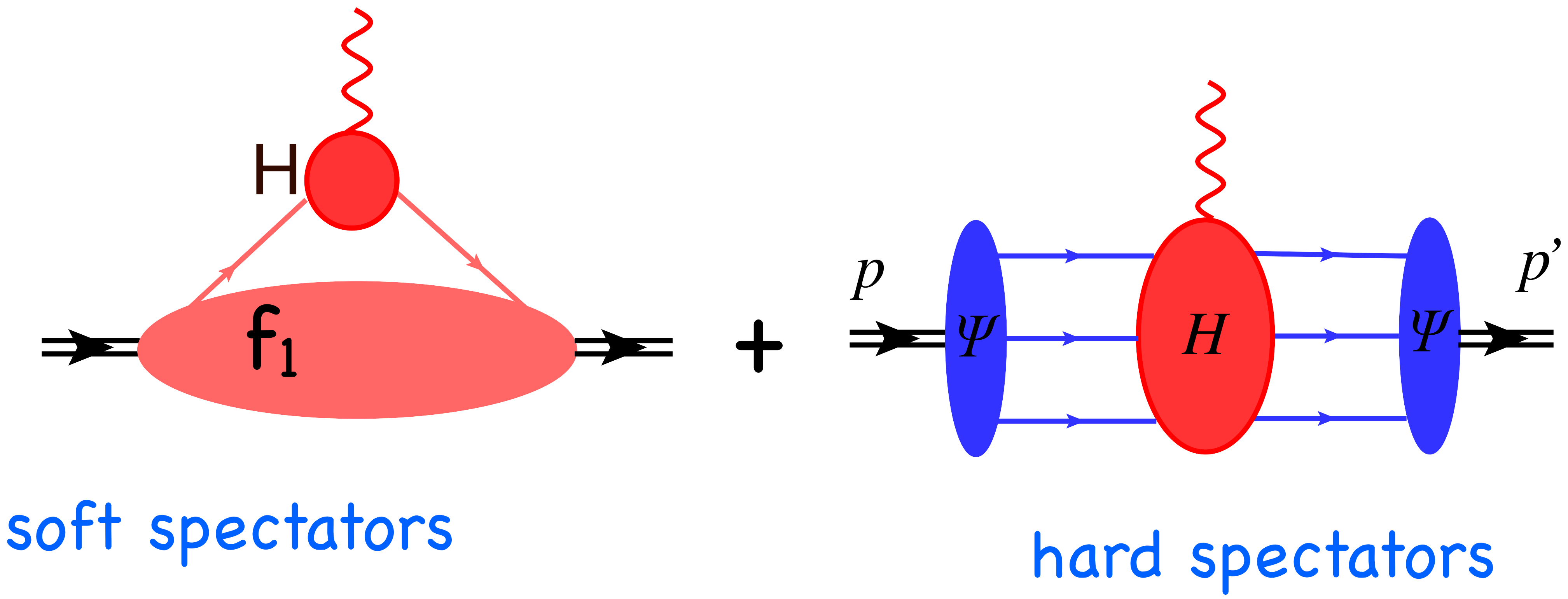
time like --- nucleon form factor $p\bar{p} \leftrightarrow e^+e^-$ and $p\bar{p} \leftrightarrow \gamma\gamma$

Soft spectator scattering at large Q^2 (space like (SL) scattering)

☛ moderate values of Q^2: $Q\Lambda \sim m_N^2$ hard-collinear scale is not large

$$Q^2 = 9 - 25\text{GeV}^2 \qquad \Lambda \simeq 0.3\text{GeV} \quad \Rightarrow \quad Q\Lambda \simeq 0.9 - 1.5\text{GeV}^2$$

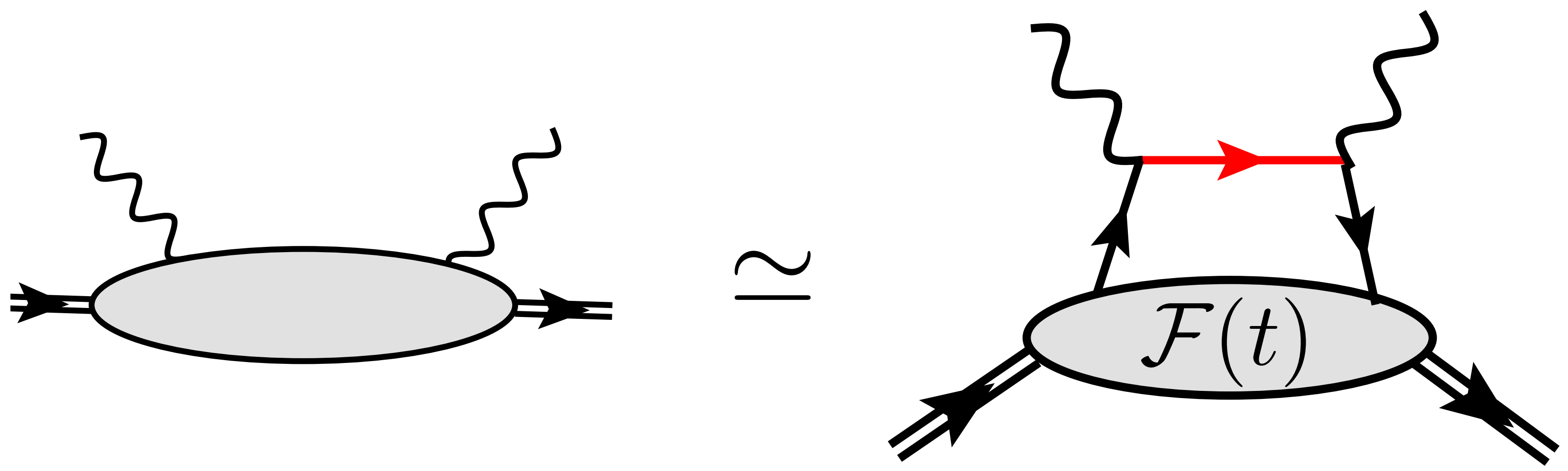
$F_1(Q) =$



dominates at moderate Q^2

Wide Angle Compton Scattering: SL and TL

$-t, -u, s \gg \Lambda^2$



$Q\Lambda \sim m_N^2$

Soft spectator scattering

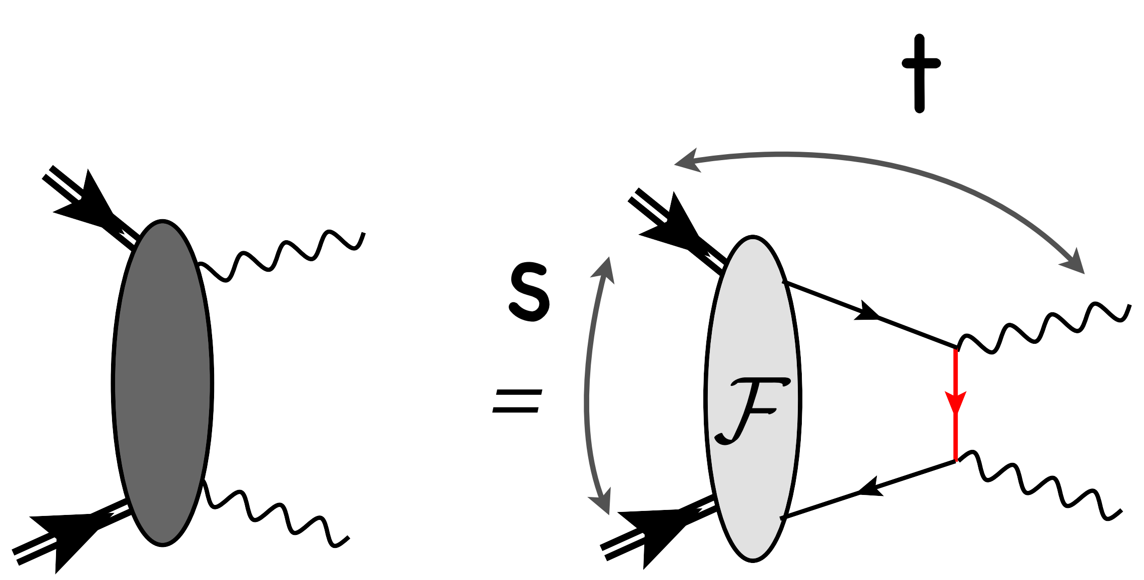
Kivel, Vanderhaeghen (to appear)

ratio $\quad \mathcal{F}(t) \simeq \frac{T_2(s,t)}{H_2(s,t)} \simeq \frac{T_4(s,t)}{H_4(s,t)} \simeq \frac{T_6(s,t)}{H_6(s,t)} \quad \frac{\text{dominant amplitude}}{\text{hard coeff. function}}$

s-independent!

TL version

wide angle annihilation $p\bar{p} \to \gamma\gamma$ or production $\gamma\gamma \to p\bar{p}$



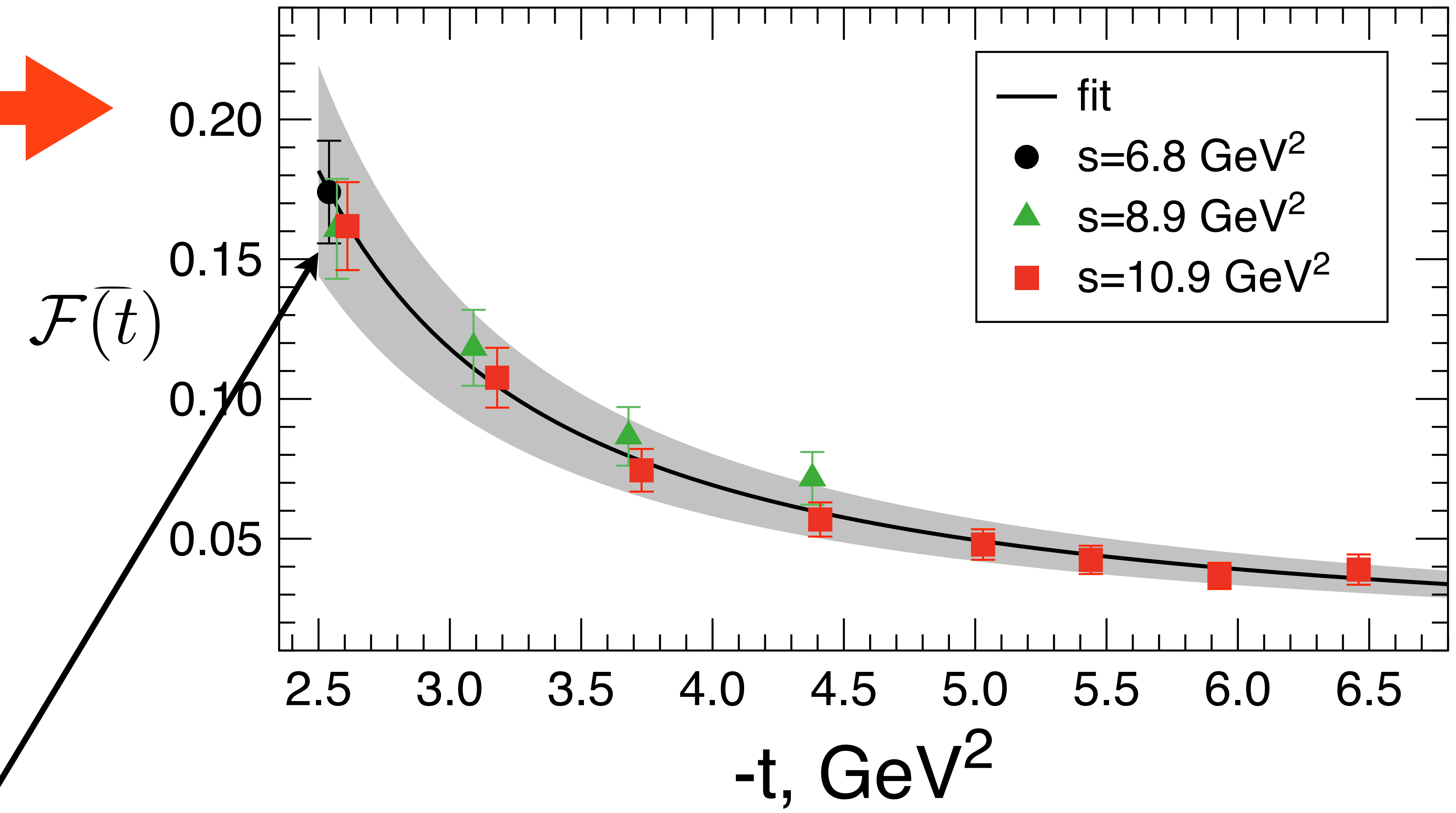
Kivel, Vanderhaeghen (in progress)

$$|\mathcal{F}(s)| \simeq \frac{T_2(s,\cos\theta)}{H_2(s,\cos\theta)} \simeq \frac{T_4(s,\cos\theta)}{H_4(s,\cos\theta)} \simeq \frac{T_6(s,\cos\theta)}{H_6(s,\cos\theta)}$$

$\cos\theta$ -independent!

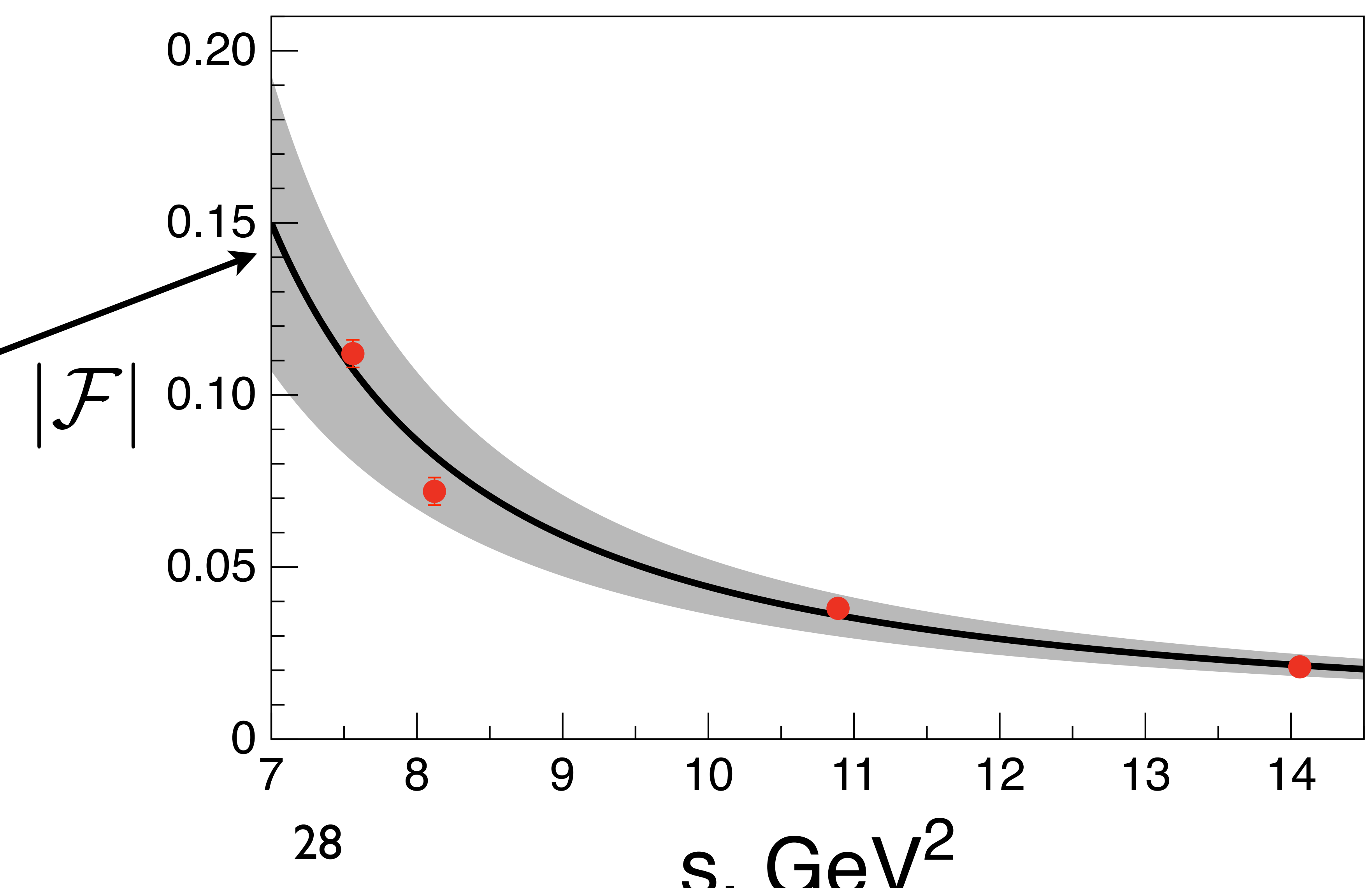
$$\frac{d\sigma}{dt} = \frac{d\sigma^{\gamma q \to \gamma q}(s,t)}{dt} |\mathcal{F}(t)|^2$$

used data: JLab, Hall A, 2007



$$\frac{d\sigma}{d\cos\theta} = \frac{d\sigma^{q\bar{q} \to \gamma\gamma}(s,\cos\theta)}{d\cos\theta} |\mathcal{F}(s)|^2$$

used data: BELLE, 2005 $\gamma\gamma \to p\bar{p}$



Soft spectator scattering dominance predicts that

$$\frac{|\mathcal{F}(s)|_{\rm TL}}{|\mathcal{F}(-t=s)|_{\rm SL}} > 1$$

enhancement in TL region as in FF case

Key question - what is the size of configuration in which proton and antiproton annihilate into e^+e^- or $\gamma\gamma$, dominate in nucleon form factor, or (anti)proton - proton transform to two hadrons?

My guess: in this mechanism $r^2_{transverse} \propto 1/Q\Lambda$

much smaller than soft scale but much larger than naive pQCD. Needs further theoretical studies.

Semihard mechanism is much more effective for 3 q states than for mesons

Earlier onset of CT for processes involving mesons

- 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.

- Precision studies of different 2→2 reactions are necessary

Example of discriminative power of comparing different reactions: $\frac{d\sigma(pp \to pp)}{d\theta_{c.m.}} / \frac{d\sigma(pn \to pn)}{d\theta_{c.m.}}$

very sensitive to the reaction mechanism C. Granados & M.Sargsian 2010

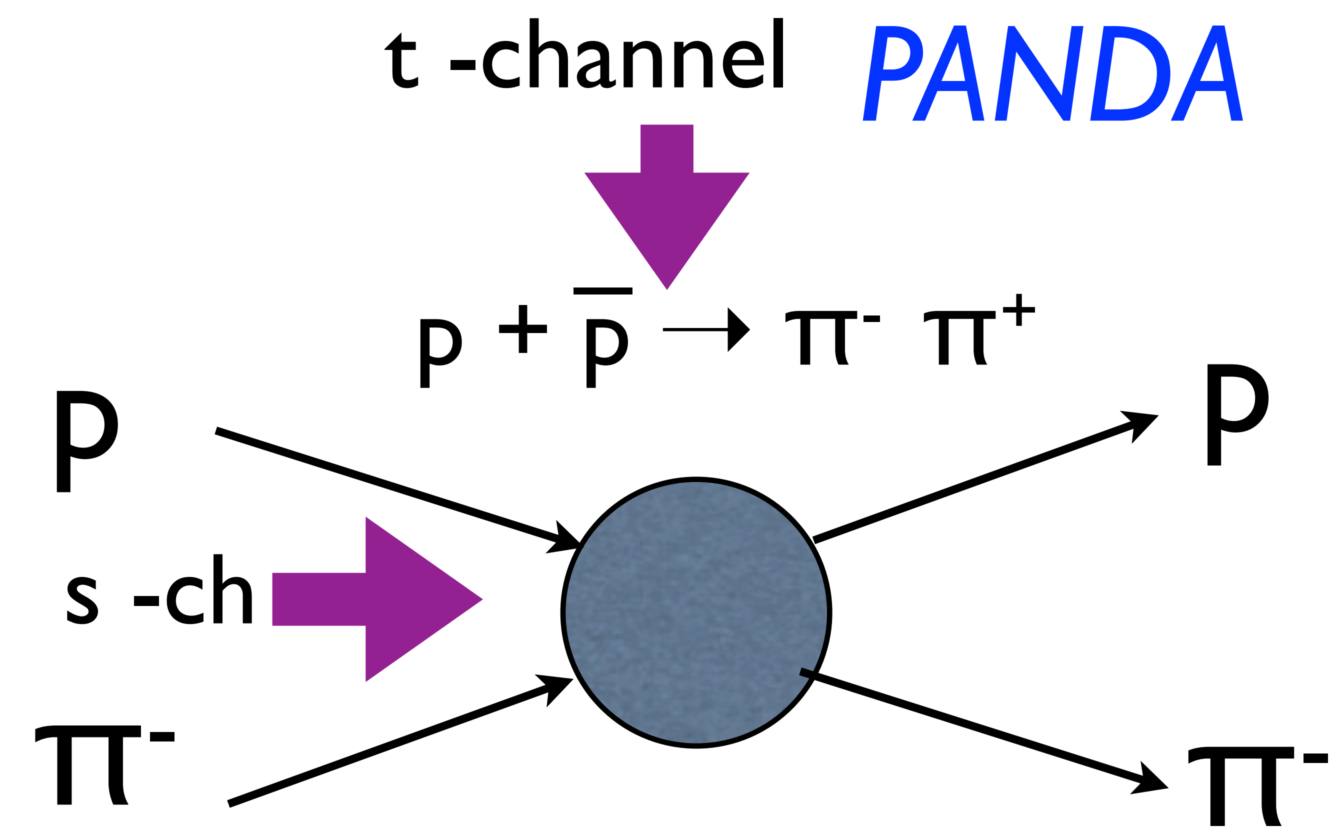
Fruitful to study s and t channel of the same amplitude:

J-PARC

$\pi^- (\pi^+) p \to \pi^- (\pi^+) p$

PANDA

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



Testing dynamics of 2 → 2 processes using scattering off nuclei

Color Transparency (CT) phenomena

CT phenomenon **for** 2 → 2 processes **(validity of impulse approximation of exclusive interaction of projectile with nucleus)**

$$T(A, E_{inc}) = \frac{\sigma(h + A \to h_1 + h_2)}{A\sigma(h + N \to h_1 + h_2)} \quad \underset{\textbf{CT}}{\Longrightarrow} \quad \textbf{1}$$

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 relevant for interpretation of heavy ion collisions

-

Freezing: ***Main challenge:*** |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 (point-like) configurations (PLCs)- they are not frozen. They evolve with time - expand after interaction to average configurations and contract before interaction from average configurations (FFLS88)

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

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

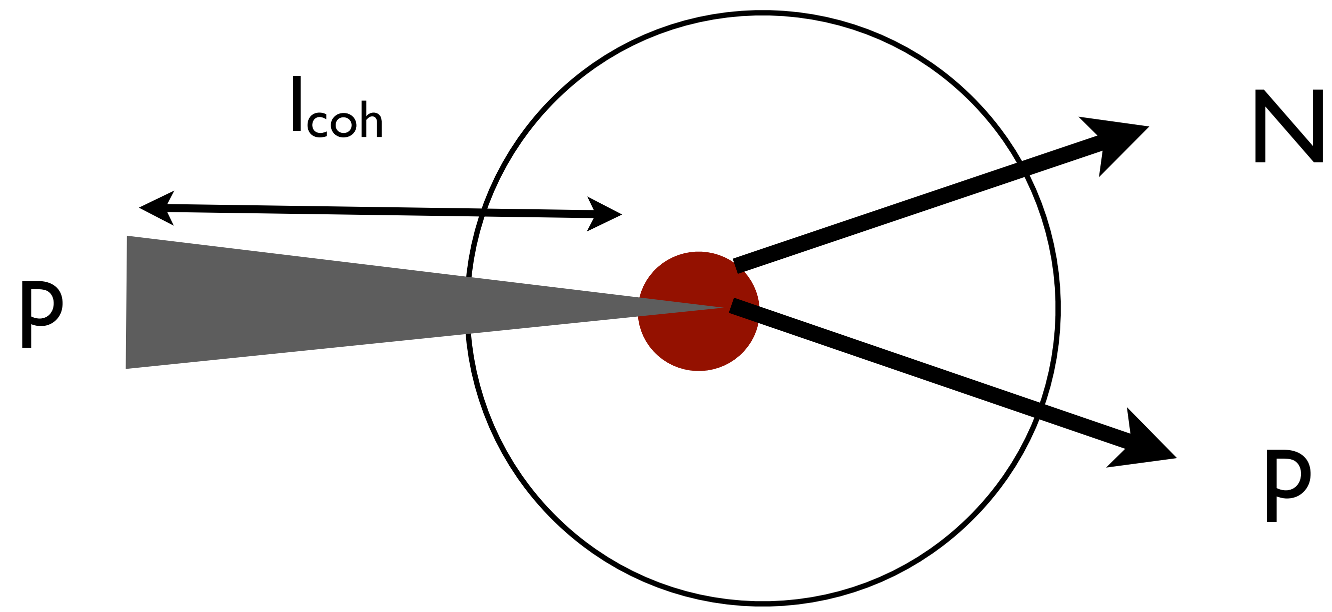
Quantum Diffusion model of expansion

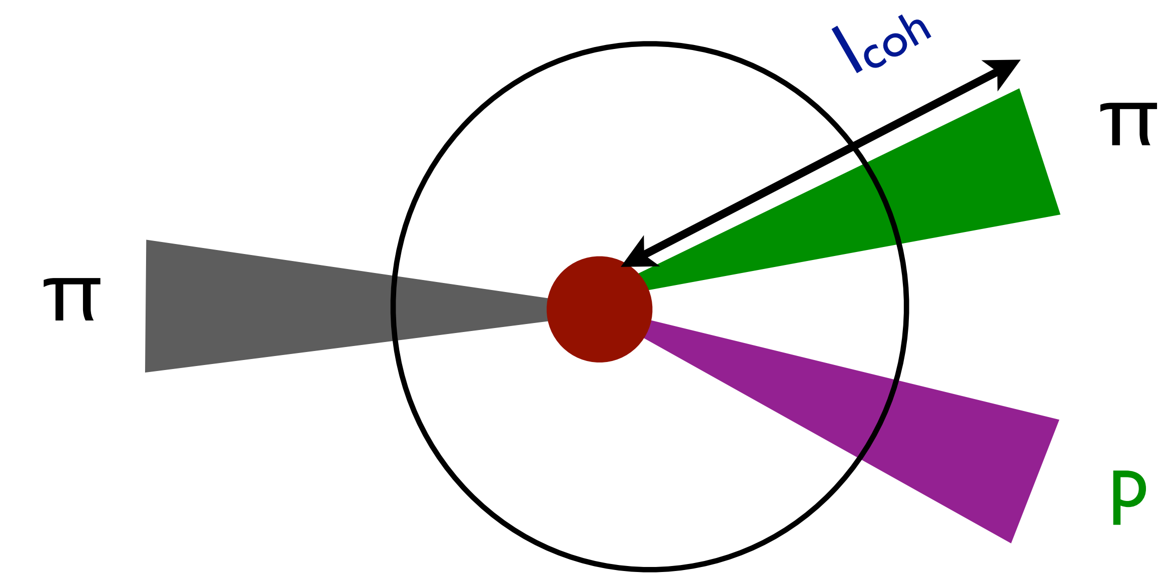
$l_{coh} \sim 2p_h/(m_2^2 - m_1^2) \sim (0.4\text{-}\ 0.6)$ fm E_h[GeV]

actually incoherence length

$\sigma^{PLC}(z) \propto z$ - diffusion in the transverse plane follows from the nonrelativistic structure of the energy denominators of the light-cone Hamiltonian FS88

Sketch of space-time evolution of hard exclusive processes





pA→ Np(A-1) at large s, $\theta_{c.m.}$ ~90

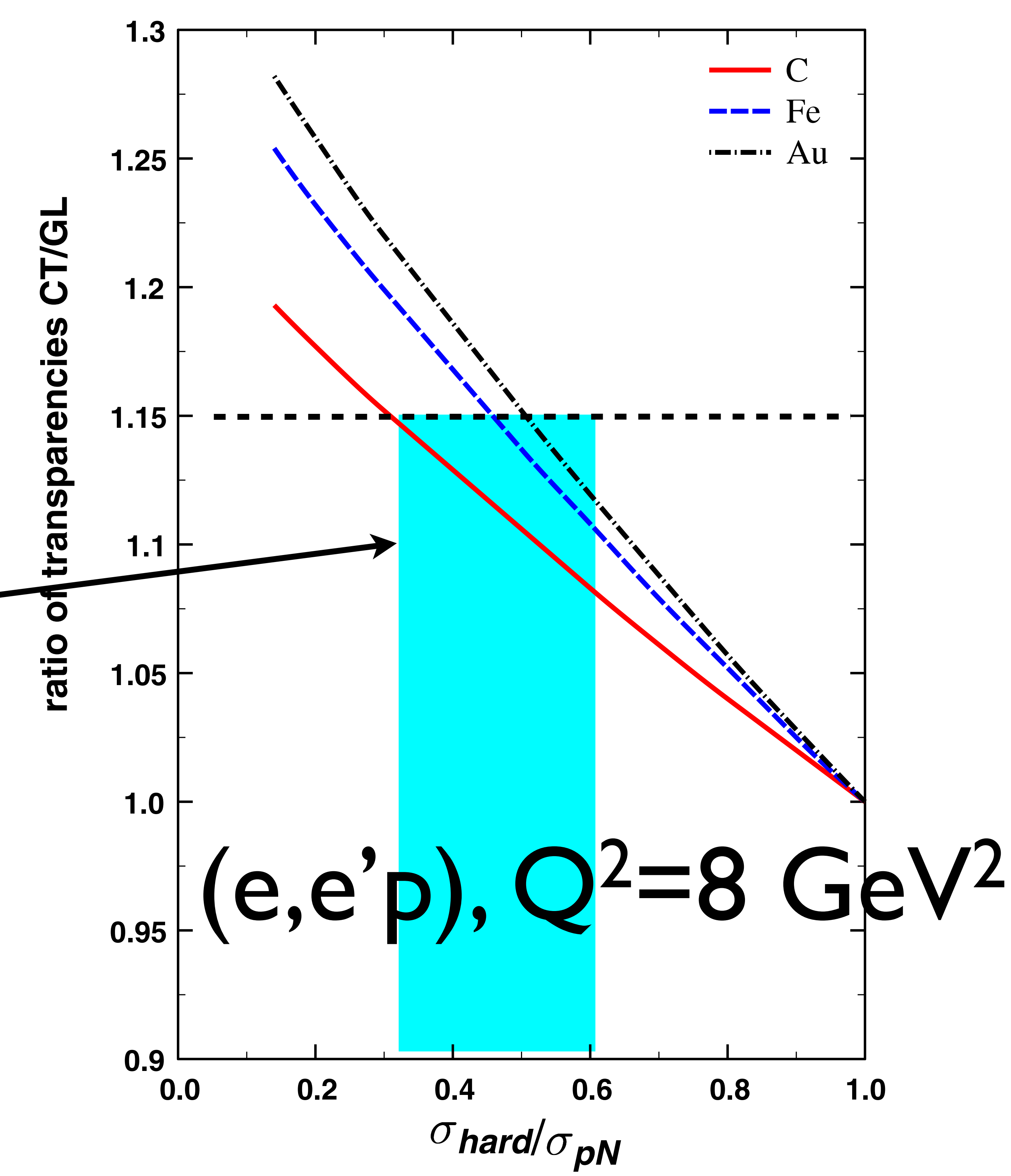
πA→ πp (A-1) at large s, $\theta_{c.m.}$ ~90

CT seen for π diffraction into two jets.

CT seen for π, ρ, J/ψ electro/photo production

CT have not been seen for A(e,e'p)

CT effect may have been seen for A(p,2p);



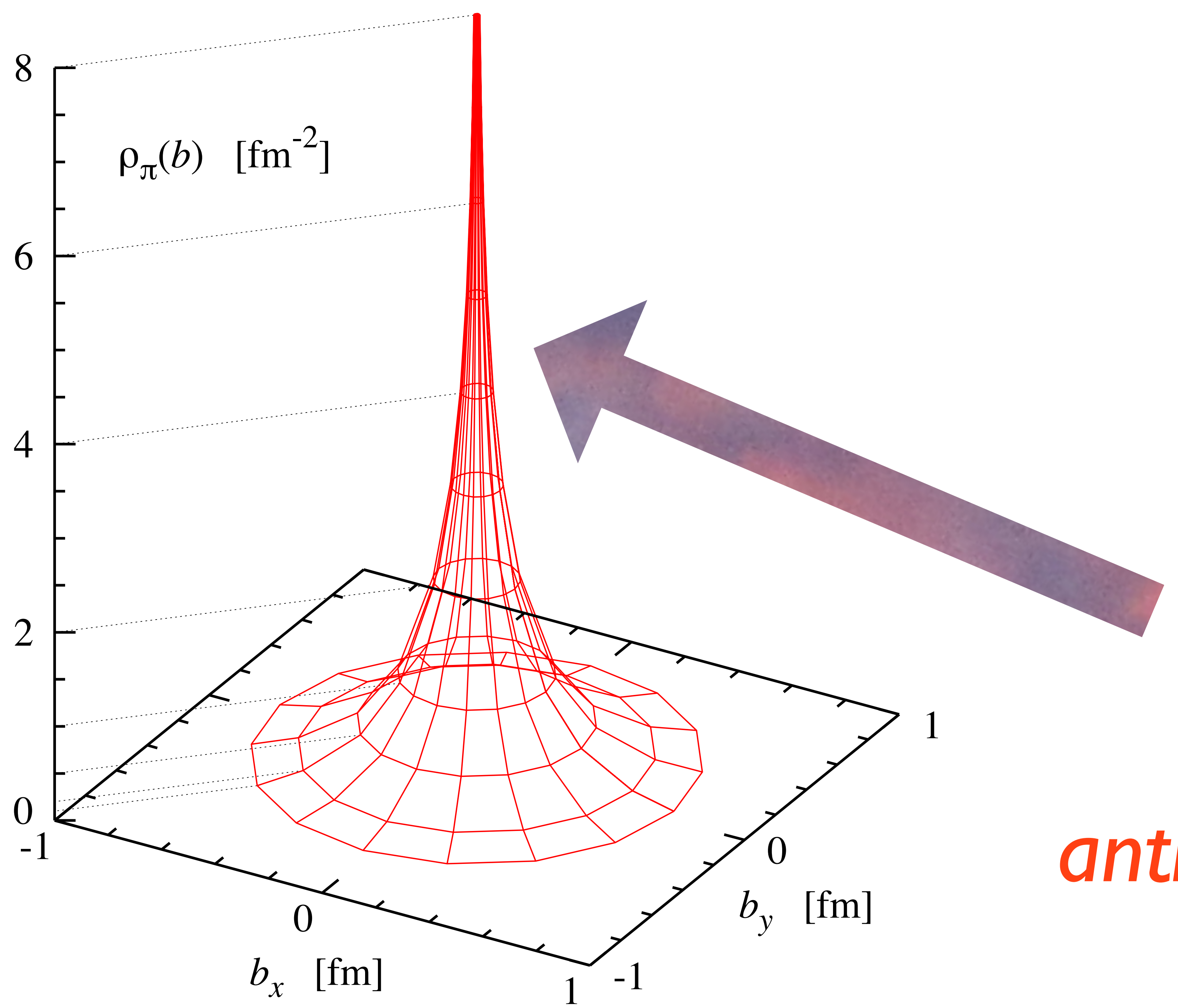
New evidence for PLCs in pion from e.m. form factors - Miller, MS, Weiss (2010)

Consistent with singular structure of the transverse charge density in the pion extracted from the data using dispersion technique

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

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

dispersion representation of transverse density



Contribution of small transverse size quark-antiquark component in pion

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

Critical to perform new studies of CT phenomenon in hadronic reactions at energies above 10 GeV where expansion effects are moderate to determine interplay between pQCD and nonpert. QCD for $2 \to 2$ reactions. WIll complement the program of CT in eA scattering at Jlab at 12 GeV.

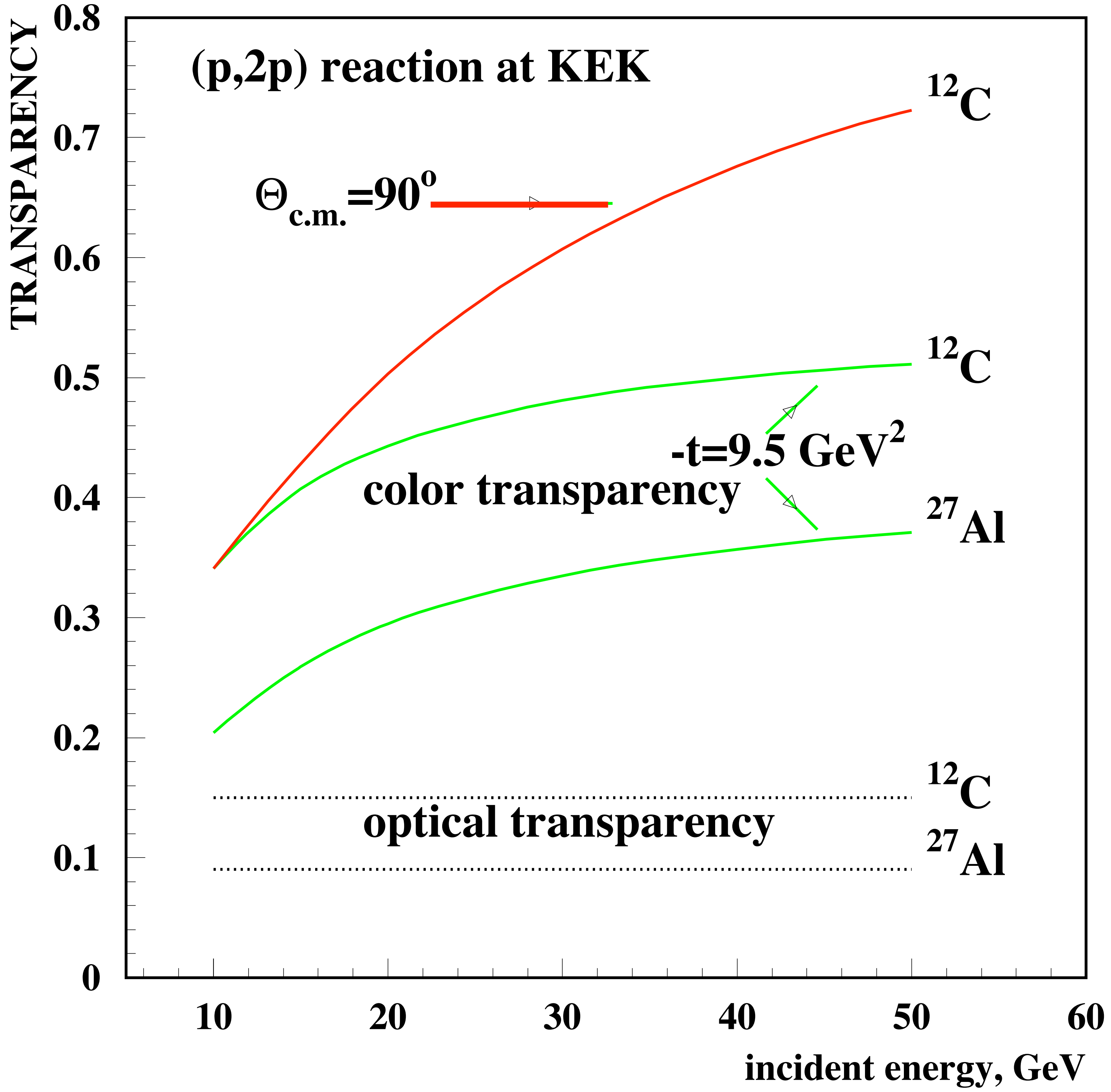
J-PARC & GSI(PANDA)

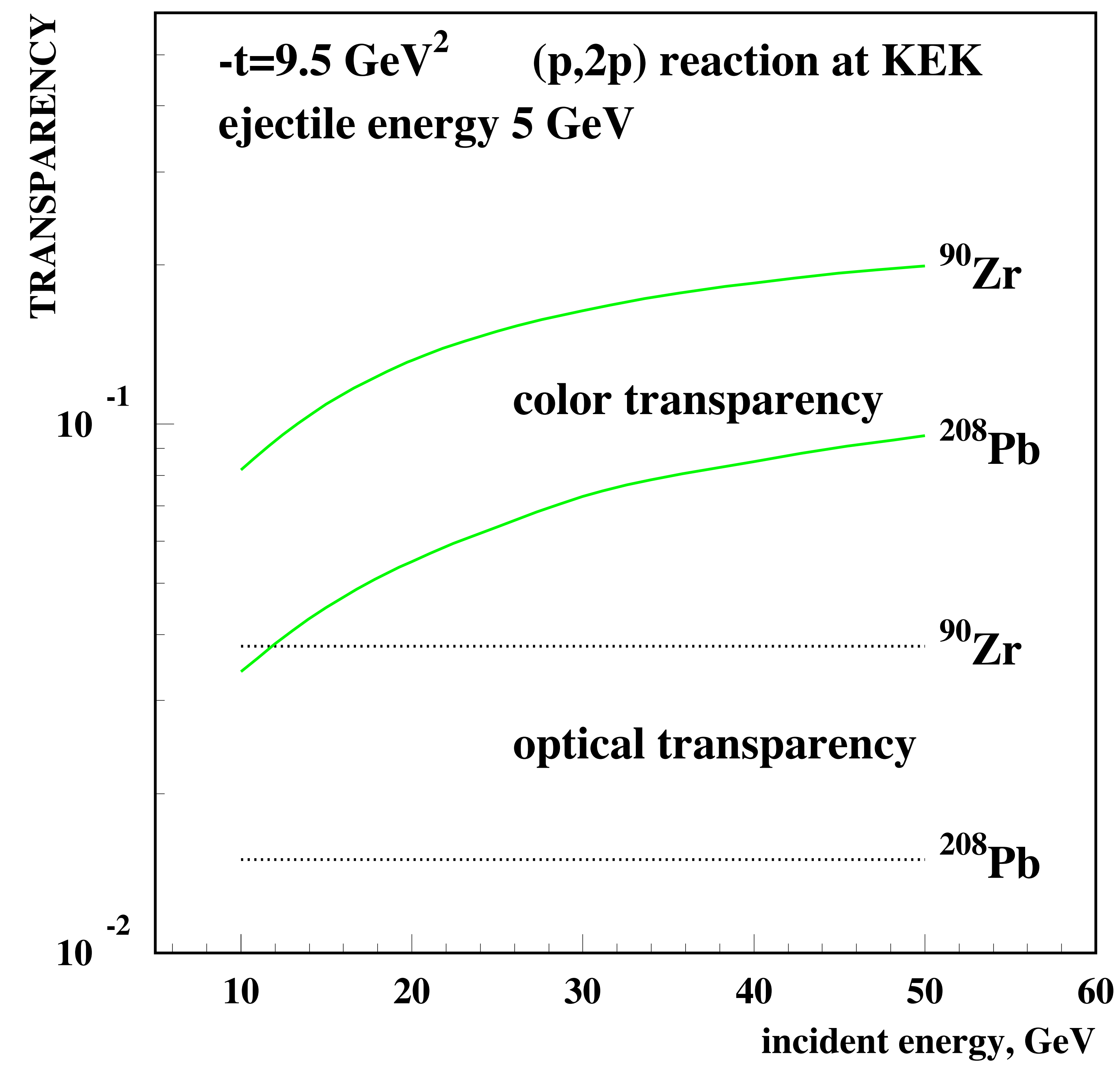
Advantages as compared to EVA - progress in electronics leading to a possibility to work at higher luminosity, wider range of hadron beams including antiprotons at GSI.

☛ (p,2p) at the range of 10-20 GeV for all angles including those close to $\theta_{c.m.} \sim 90^0$

☛ $(\pi, p\pi)$ for E_π= 6 --14 GeV. Benefit - knowledge of pion expansion rates from 6 GeV and future 12 GeV Jlab experiments

☛ E_p>20 GeV (p,2p) rates for $\theta_{c.m.} \sim 90^0$ are rather low (?). Different strategy - T (E_p) for large but fixed t. In this case l_{coh} for initial and the fastest of two final nucleons is very large. Only the slow nucleon has time to expand leading to transparency very similar to the one in A(e,e'p). (Zhalov &MS 89)



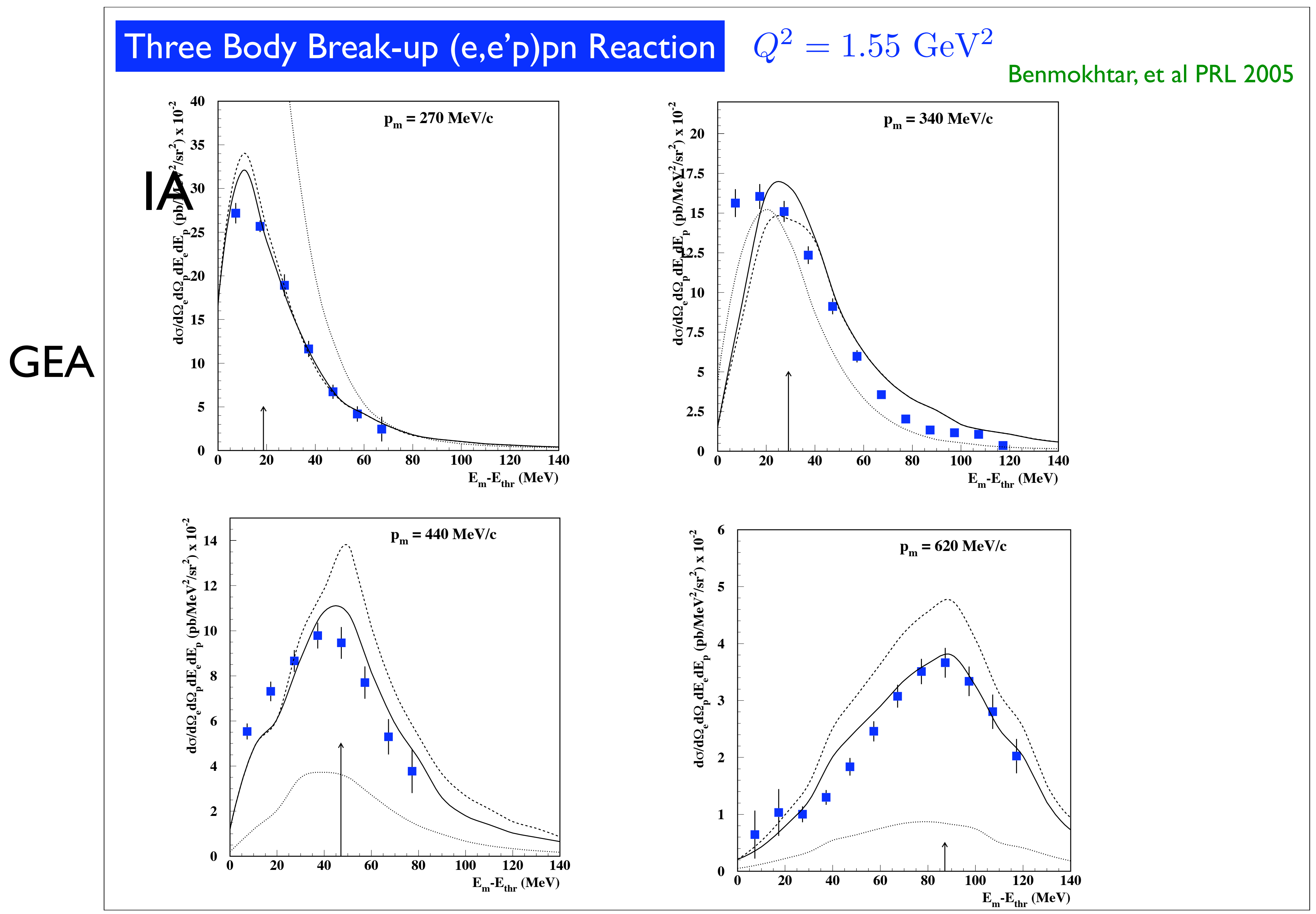


Energy dependence of the nuclear transparency calculated in the quantum diffusion model with l_{coh} = 0.4 fm p_N[GeV] ~ as compared to the expectations of the Glauber model.

Advanced methods to study evolution of wave packets - use processes where multiple rescatterings dominate in light nuclei (^{2}H,^{3}He)

Egiyan, Frankfurt, Miller, Sargsian, MS 94-95

Why: small distances - suppression of expansion, high power of σ_{eff}



Since distances in the rescatterings are < 2 fm, freezing condition is by far less demanding. Rather easy to select the proper channel like e^{2}H→ epn using just two high energy spectrometers. Issue - chose kinematics were contribution of Δ-isobar intermediate states is small.

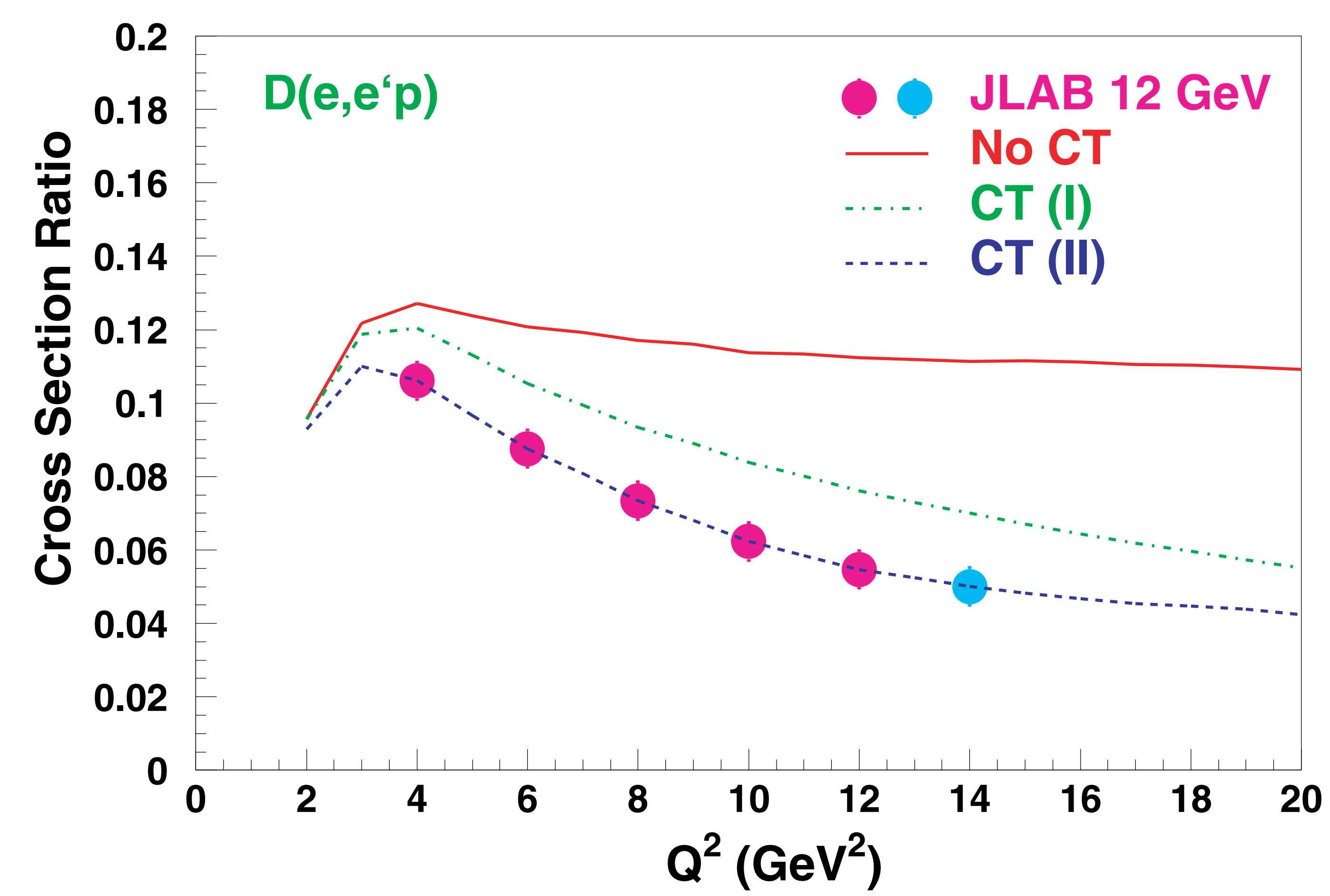
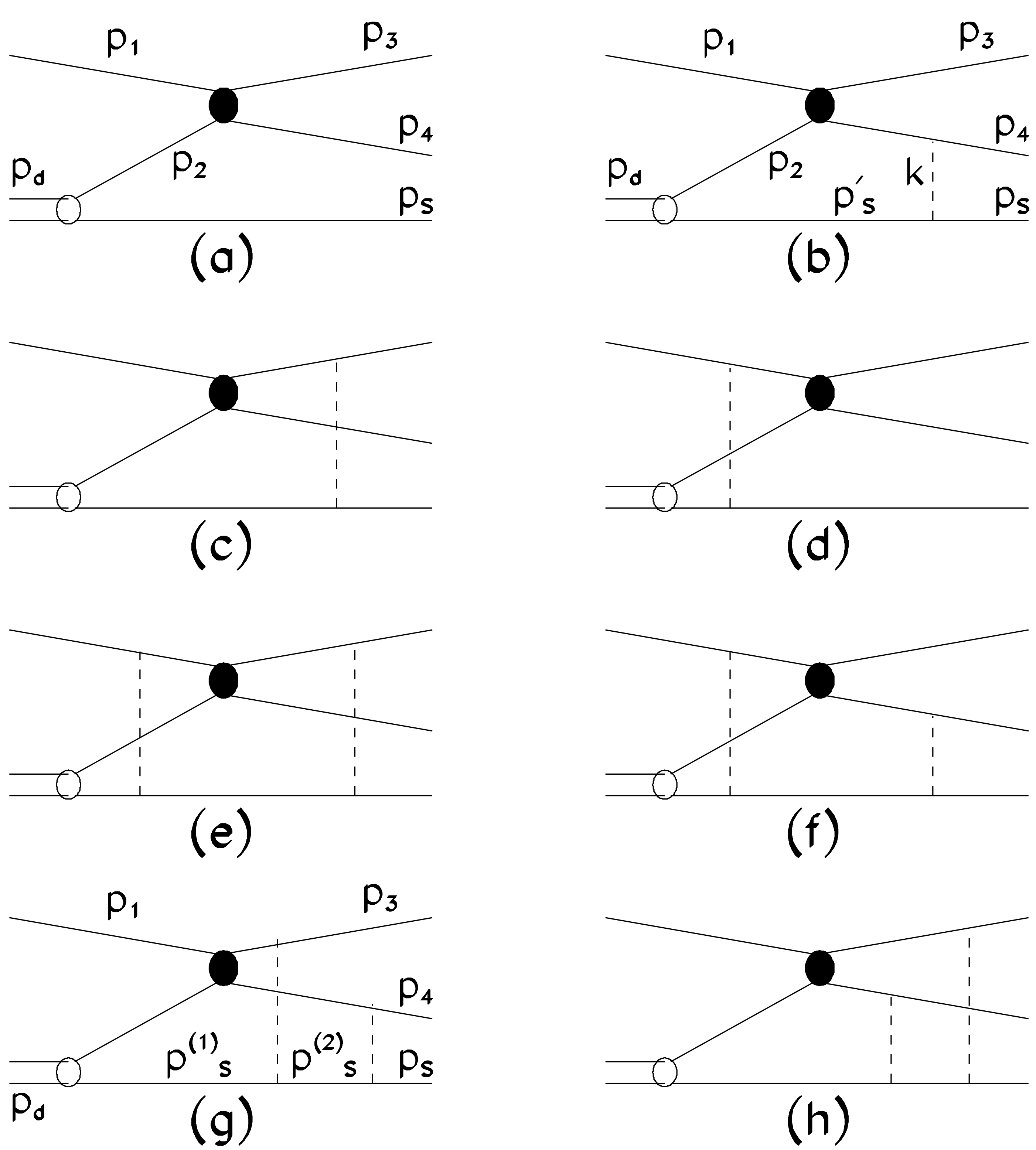


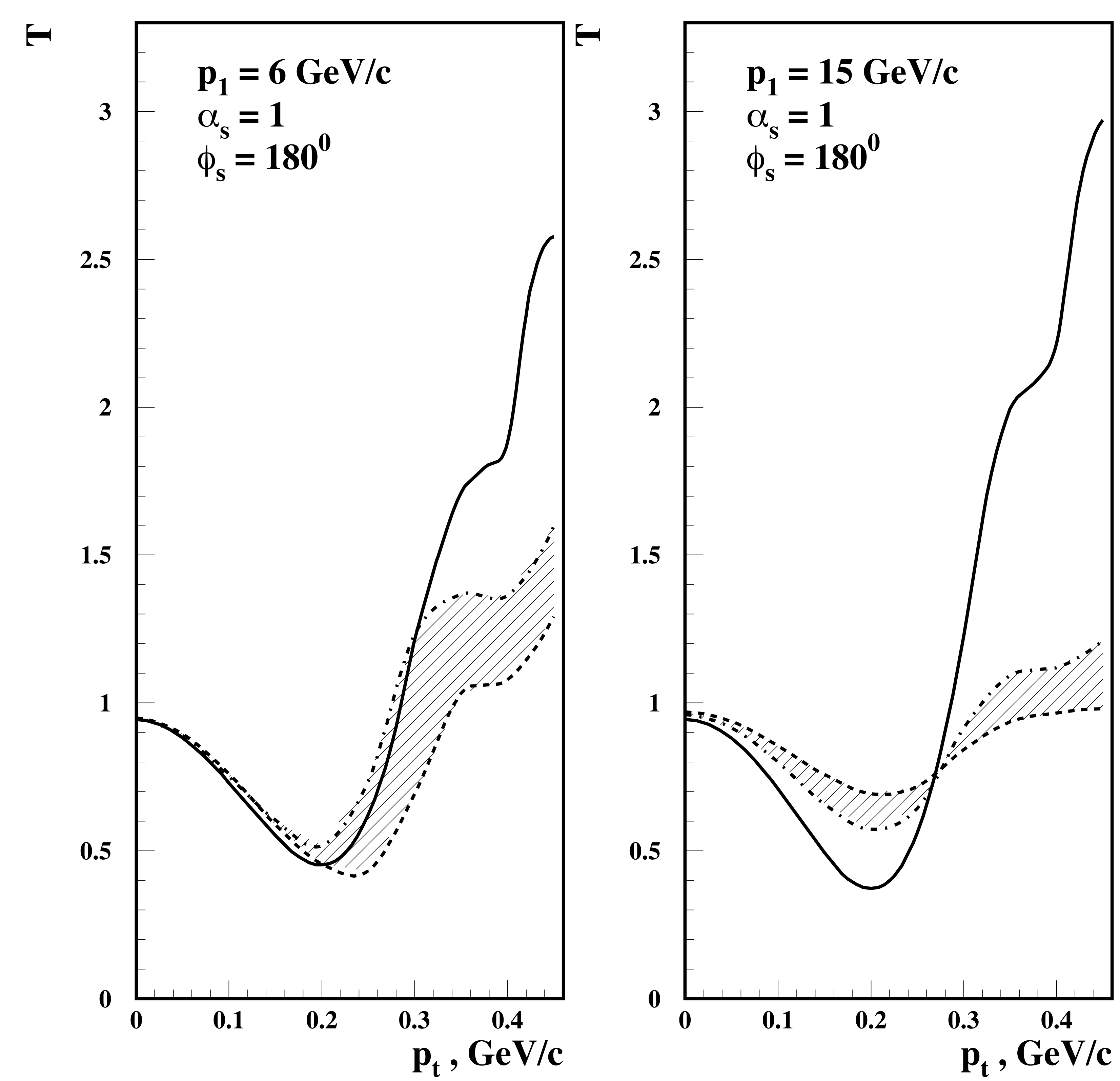
Figure 15. The ratio of the cross section at 400 MeV/c missing momentum to the cross section at 200 MeV/c as a function of Q^2. The solid line corresponds to the GEA prediction. The dashed and dash-dotted lines represent the quantum diffusion model of CT with $\Delta M^2 = 0.7$ and 1.1 GeV^2, respectively. The drop with Q^2 in the colour transparency models comes from a reduction in the rescattering of the struck nucleon, which is the dominant source of events with $p_m > k_F$.

Calculation by Sargsian in Generalized Eikonal Approximation (GEA). Very similar results from Schiavilla et al and Perugia group

Use of the process pD→ppn to study wave package evolution over distances < 2 fm interference between impulse approximation, single and double rescatterings. Complicated pattern along the cones associated with initial and final hadrons.

Use of polarized proton- polarized deuteron scattering to check the origin of the Krisch effect - *is rescattering larger or smaller than in average for two nucleons with parallel spins?*





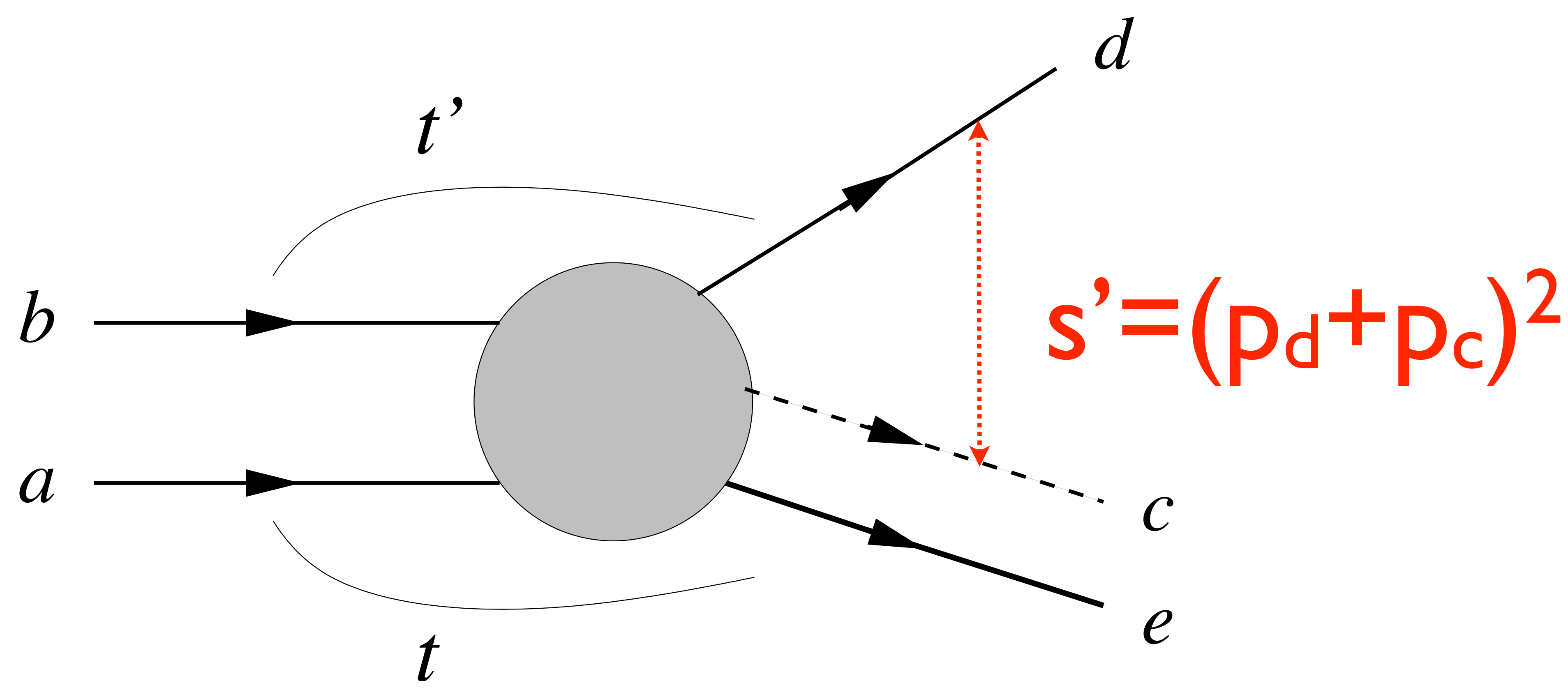
Another way to check the origin of the Krisch effect is to use polarized ^{6}Li or ^{7}Li target and study $T_{\uparrow\uparrow}$ and $T_{\downarrow\downarrow}$.

Advantage of polarized deuteron - practically no spin dilution factor. Spin dilution is large for lithium. Also a transparency effect is smaller.

Disadvantage: absolute cross section in the CT kinematics is small. Need to separate the signal from scattering off unpolarized nucleons in the target. Can be done by either detecting the recoil neutron or with a good spectrometer resolution.

$^6\vec{\mathrm{Li}}\vec{\mathrm{D}}$ target probably optimal

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



Limit:

-t' > few GeV^2, -t'/ s' ~1/2

-t=const ~ 0

➡ s'/s<<1

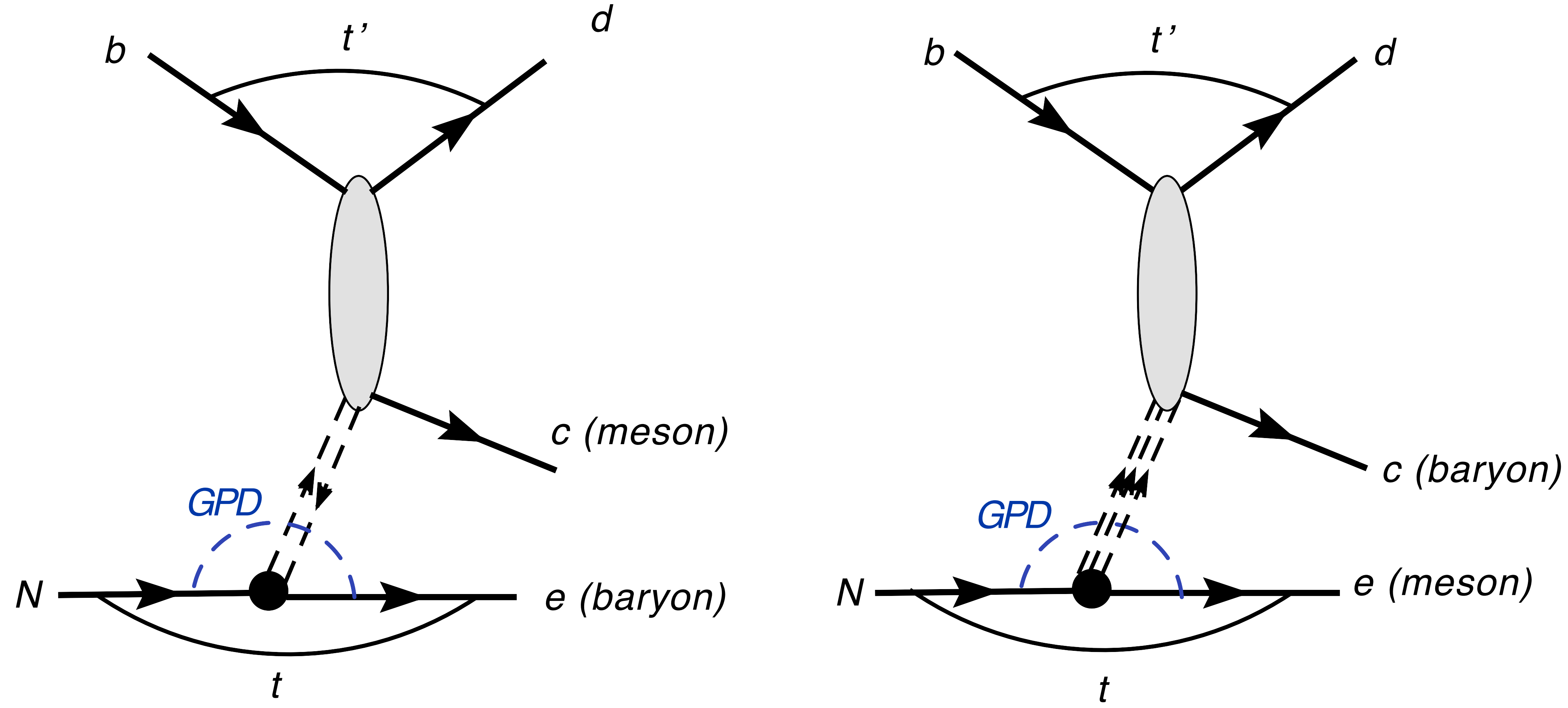
First dedicated studies: Kumano, MS, and Sudoh PRD 09; Kumano &MS Phys.Lett. 10

rates calculation A-dependence

2 →3 branching processes:

- test onset of CT for 2 →2 avoiding freezing effects
- measure transverse sizes of b, d,c
- measure cross sections of large angle pion - pion (kaon) scattering
- probe 5q in nucleon and 3q+\bar q in mesons
- measure generalized parton distributions GPDs of nucleons, mesons and photons(!)

Factorization:

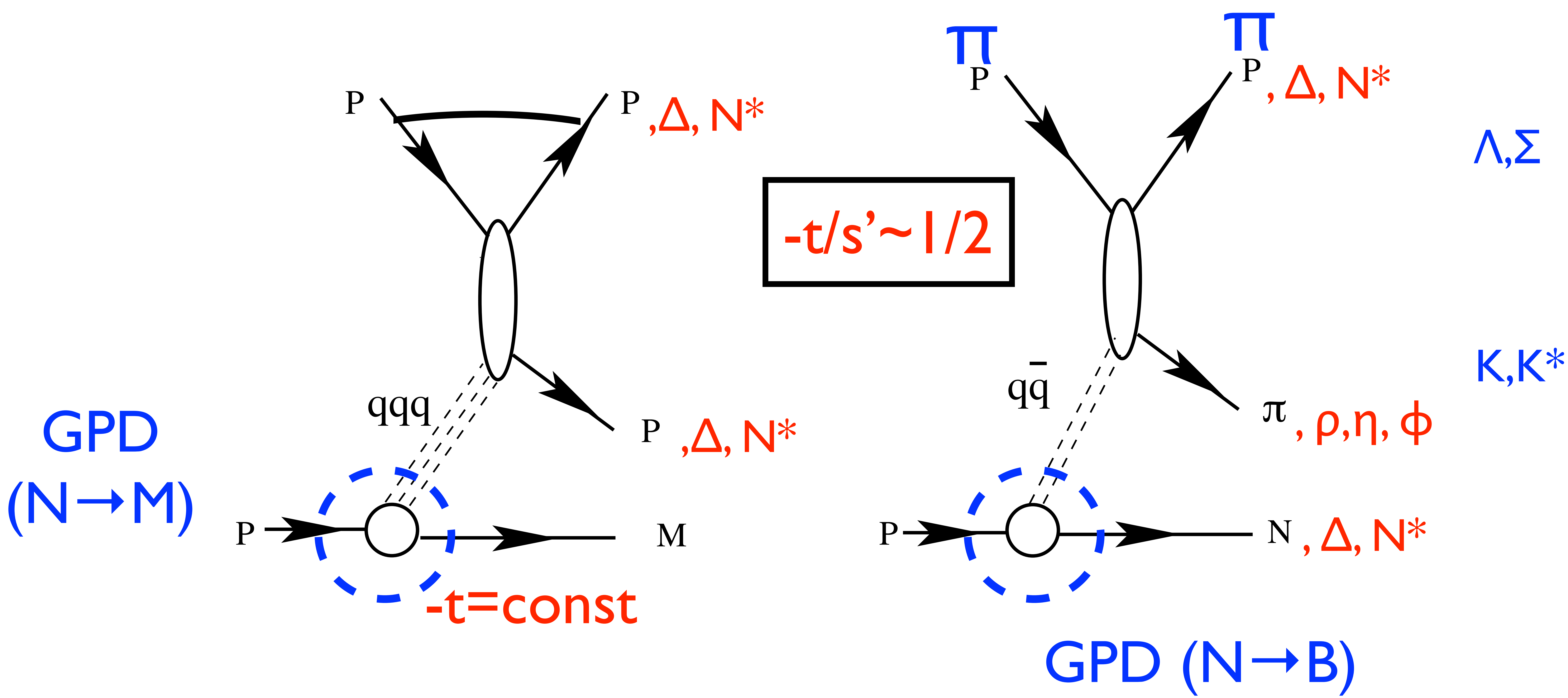


If the upper block is a hard (2 →2) process, "b","d","c" are in small size configurations as well as exchange system ($q\bar{q}$, qqq). Can use CT argument as in the proof of QCD factorization of meson exclusive production in DIS (Collins, LF, MS 97)

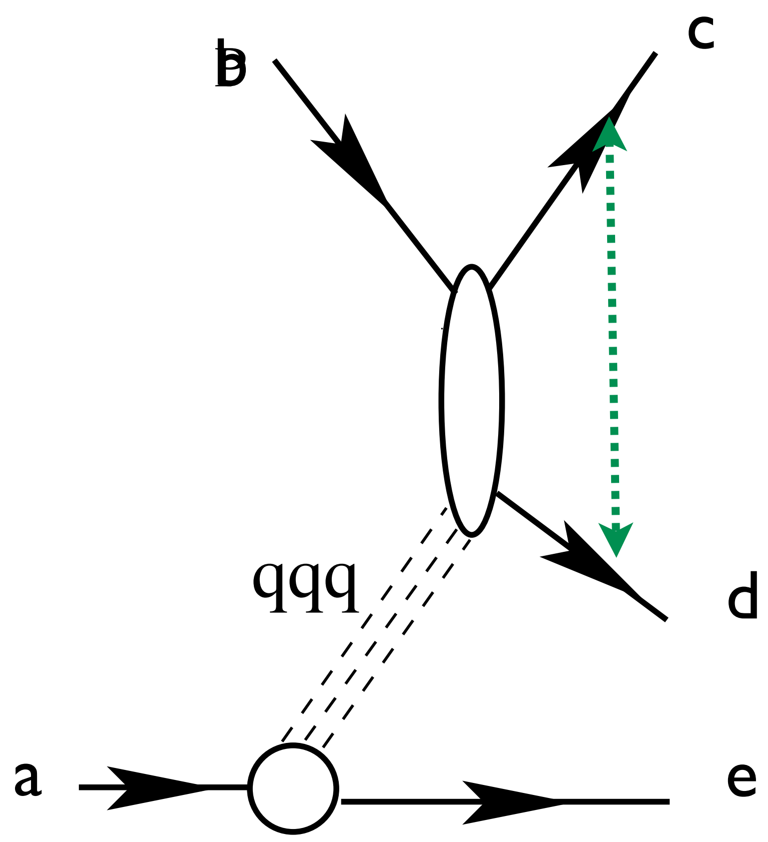
$$\Downarrow$$

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

Many interesting channels, for example



Energy dependence of branching processes



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

$$\alpha_{spect} \equiv \alpha_e = p^e_- / p^a_-$$

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

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

e flies along A - slow
if A is the target - fast
if A is the projectile

Scaling relations between hadron and electron projectiles

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

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

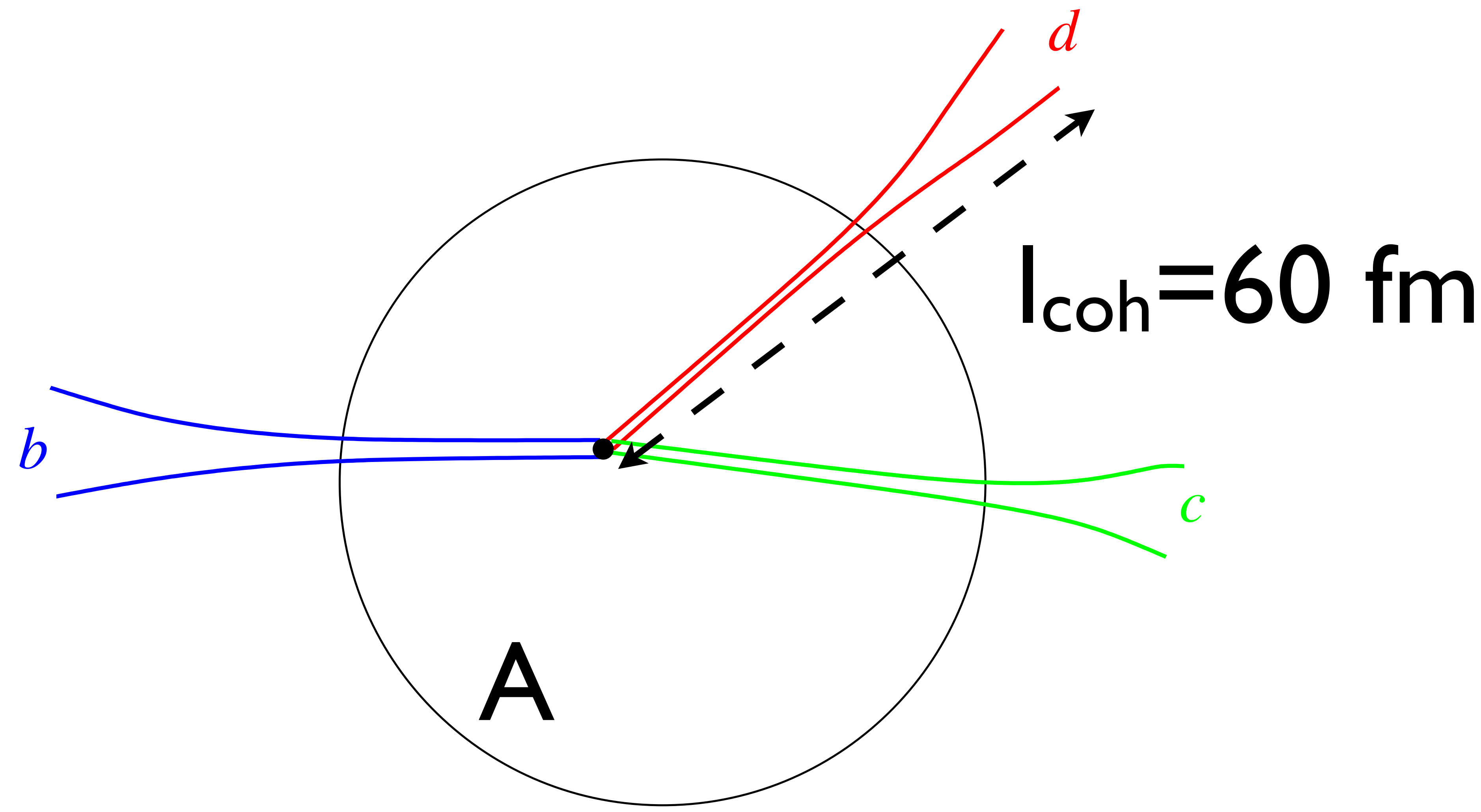
How to check that squeezing takes place and one can use GPD logic?

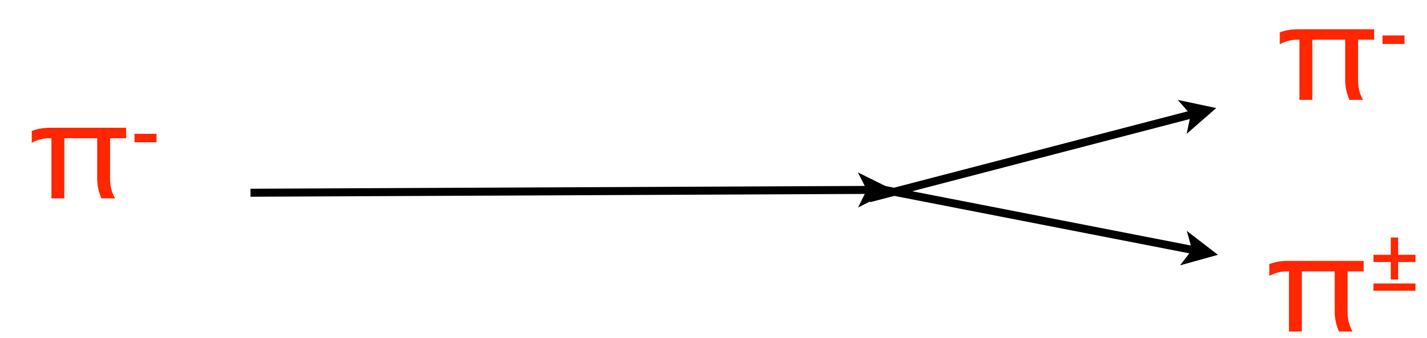
Use as example process $\pi^- A \to \pi^- \pi^\pm A^*$

J-PARC - also $pA \to \pi^+ p + A^*$

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





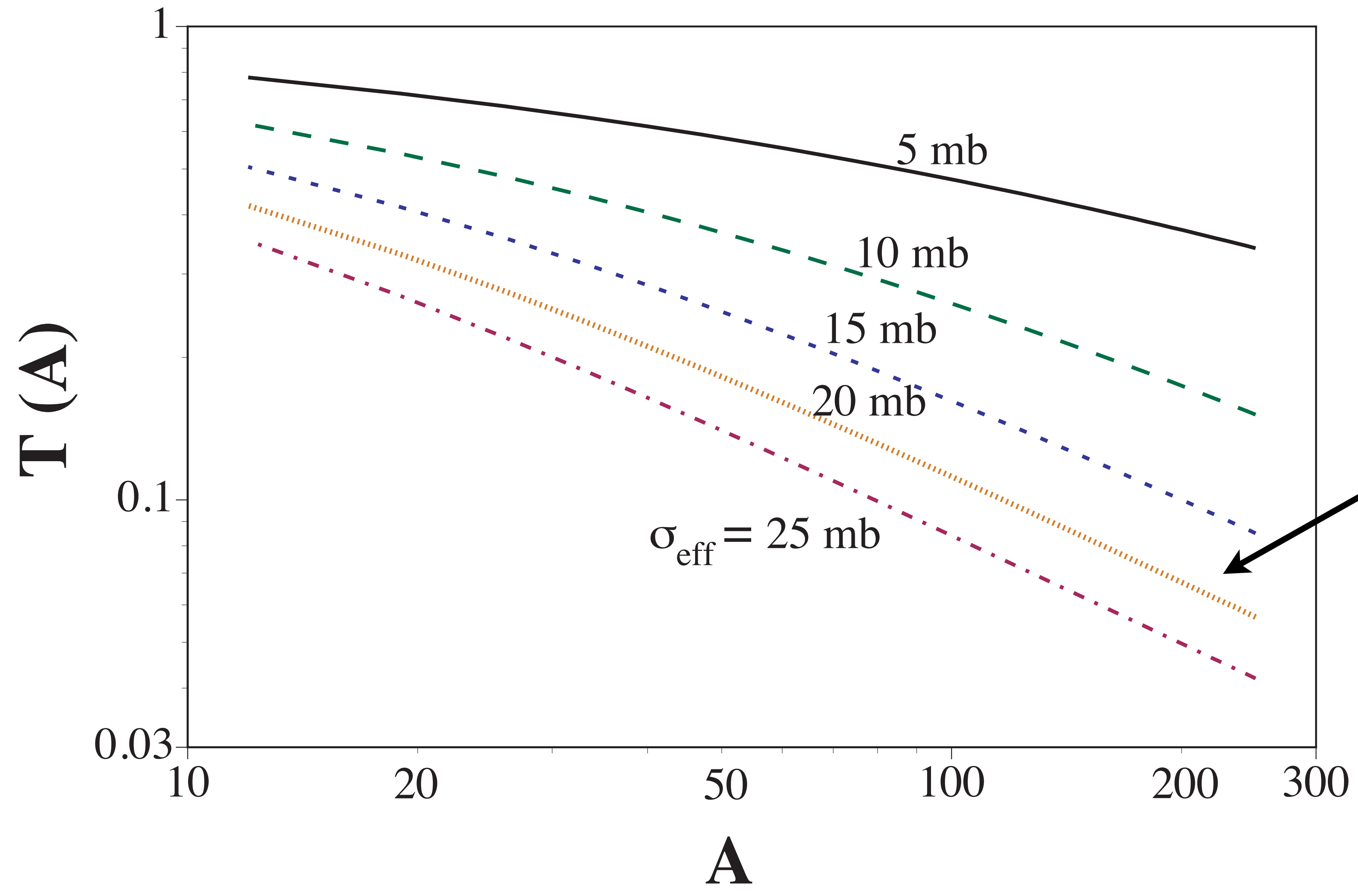
Branching (2→3) processes with nuclei - freezing is 100% effective for p_{inc} > 100 GeV/c - study of one effect only - size of fast hadrons

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

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

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 $\int \rho_A(\vec{r}) d^3r = A$

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



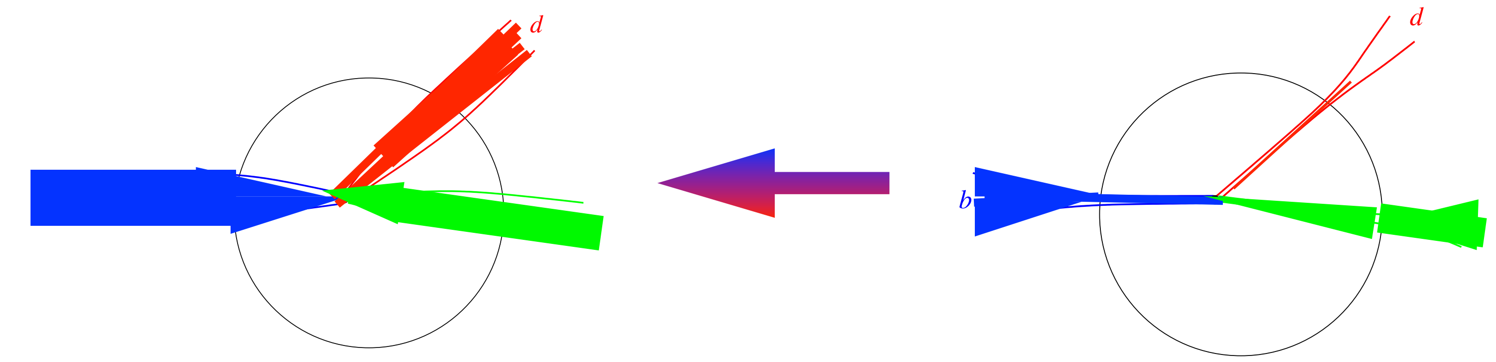
Large effect even if the pion radius is changed just by 20%

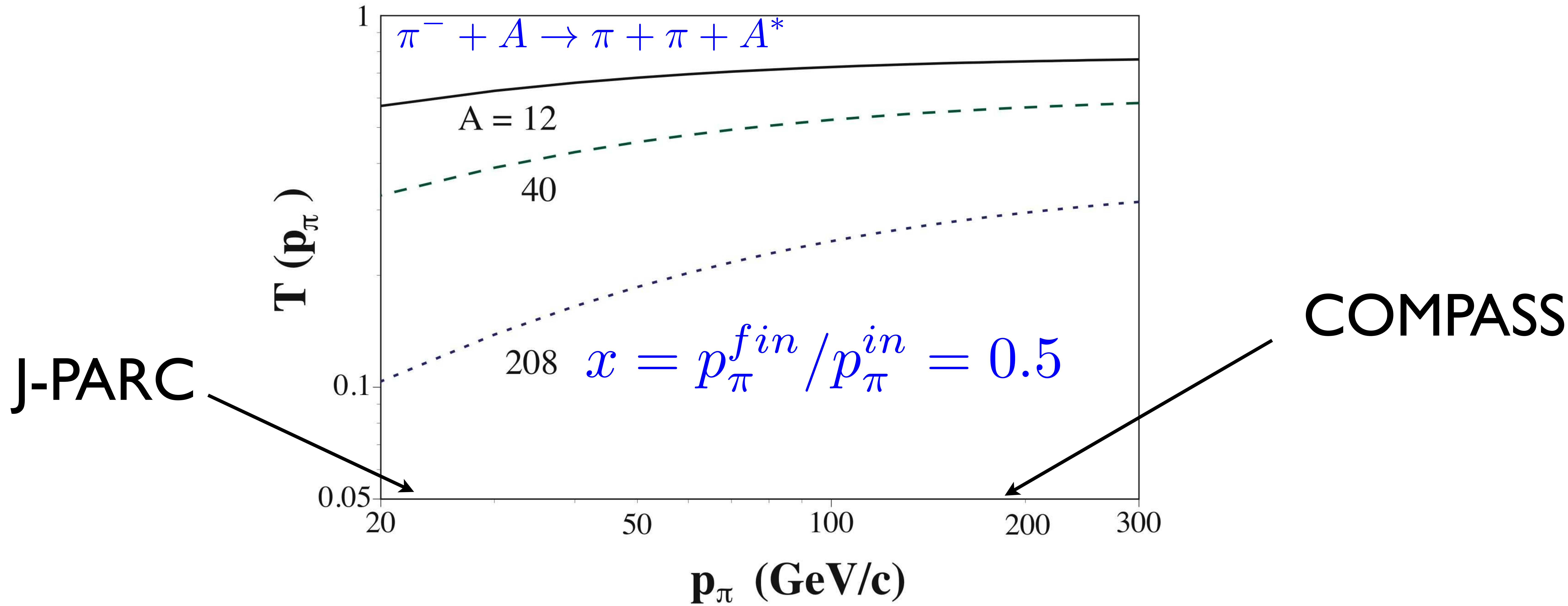
If there are two scales in pion (Gribov) - steps in $T(k_t^\pi)$ as a function of k_t^π

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

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

Use Quantum Diffusion model of expansion with $l_{coh} \sim 0.6$ fm E_h[GeV] which describes well CT for pion electroproduction and σ_{hard}= 5 mb:



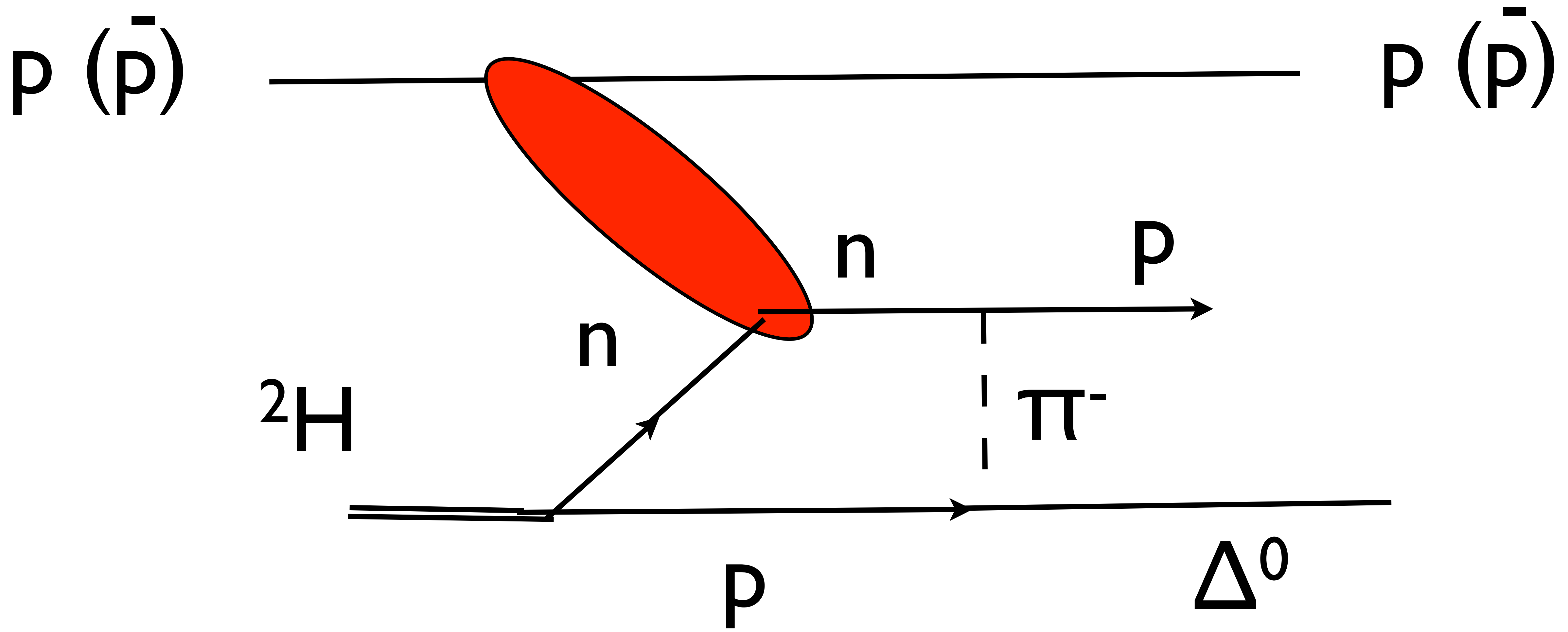


If squeezing is large enough can measure quark- antiquark size using pQCD dipole - nucleon X-section

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

As baryons are more complex systems than mesons it is natural before looking for color transparency search for effects of what we named "Chiral transparency" - pion cloud contribution which should become negligible in hard exclusive processes (for the nucleon form factor it is the case for $Q^2 > 1$ GeV^2 Weise et al)

Example 1: at large Q charge exchange processes should be suppressed (LF, H.Lee, Miller, MS- 97).



Chiral dynamics in production of pions near threshold in $2 \to h_1 + (h_2\pi)$

Large Q reaction $\gamma^* N \to N\pi$ for $M_{N\pi} - M_N - M_\pi < M_\pi$

Cross section is related to nucleon f.f. using chiral rotation and explains the SLAC data

Pobylitsa, Polyakov, MS 2001

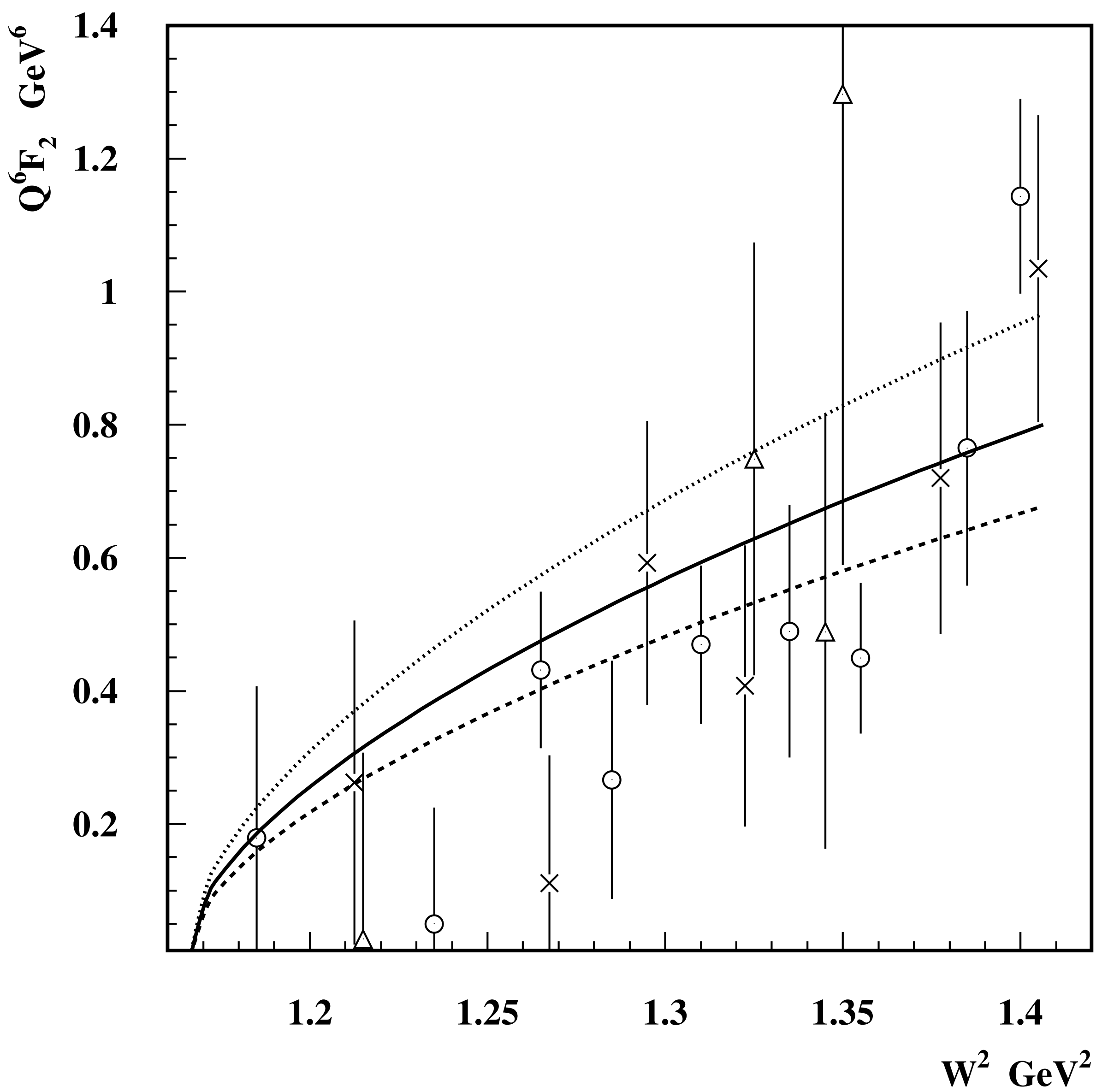


FIG. 2. Values of $F_2^p(W,Q^2)$ scaled by Q^6 as a function of W^2. The data of the E136 experiment are at average Q^2 values of 9.4, 11.8 (×), 15.5, 19.2 (○), 23, 26, and 31 (△) GeV^2. The theoretical predictions of the hSPT (18) at $Q^2 =$ 10, 20, 30 GeV^2 are given by dotted, solid, and dashed lines respectively.

Physical picture: γ^* hits 3q configuration which later emits a pion. Emission from initial state kinematically suppressed, from the vertex by power of Q^2. $\sigma(\pi N)/\sigma(N) \sim 0.1$, a factor of 4 larger than at low Q^2.

Similar for large t reaction $pA \to (N\pi) + p + (A-1)$ for $M(N\pi) - M_N - M_\pi < M_\pi$

Physical picture: projectile hits 3q configuration which later emits a pion (or itself emits a pion after scattering). Time scale is likely to correspond to $l_{coh} > l_{coh}$(nucleon) as only pion cloud is removed from nucleon

➠ At $-t \sim 5\text{-}7\ \mathrm{GeV}^2$ the system which propagates through nucleus interacts with $\sigma \sim 40$ mb not $\sigma = \sigma_{NN} + \sigma_{\pi N} \sim 70 - 80$ mb

$\Rightarrow$ Large chiral transparency effect

Complementary studies at Jlab at large Q^2 in $eA \to e\,(N\pi)(A-1)$ and in large angle hadron induced processes as well as in e^+e^- annihilation into $\bar{N}N\pi$.

Discussed processes will allow

- to discover the pattern of interplay of large and small transverse distance effects (soft and hard physics) in wide range of the processes including elastic scattering, large angle two body processes
- measure a variety of GPDs including GPDs of mesons, baryons and photon
- compare wave function of different mesons
- map the space-time evolution of small wave packets at distances $1 < z < 6$ fm
- test the role of chiral degrees of freedom in hard interactions

Conclusions

Studies of hard nuclear reactions sensitive to color & chiral transparency at several facilities: J-PARC, Jlab 12, FAIR (PANDA), CERN (COMPASS) would nicely complement and strengthen individual studies

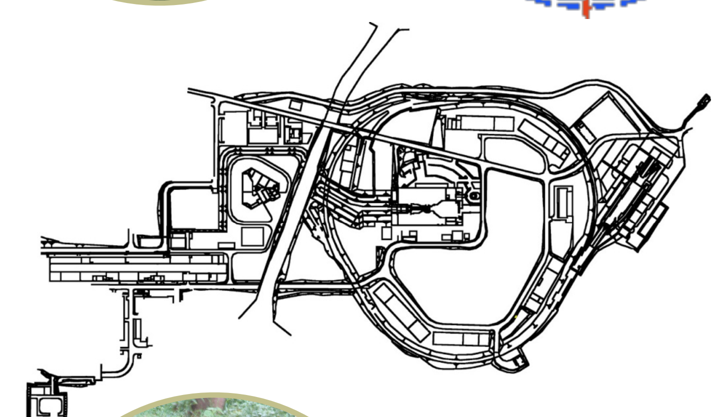
Observation of CT would provide new tools for study of nucleon GPDs and for the first time study meson GPDs

Several of these reactions will allow also to measure short-range correlations in new dynamic range more sensitive to non-nucleonic degrees of freedom than the current measurements.

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 will produce 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.



program with (anti)protons at PANDA will increase existing statistics by a factor > 10^3 solve the puzzling CT results of previous experiments, explore parton structure of a variety of baryons, will be complementary to that with antiprotons; J-PARC complementary measurements

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