Revealing small-size configurations in high-t 2-2 processes using color transparency tools.

Mark Strikman, PSU

Jlab, March 25, 2011

Beginning of CT - discovery of ***narrow*** J/ψ - November 74 and observation of small cross section for its photoproduction which within VDM corresponded to

$$\sigma_{tot}^{VDM}(J/\psi N) \sim 1\, mb$$

Note this number is actually underestimates genuine J/ψ-N cross section due to production of J/ψ in small size configurations ~1/m_c FS85

$$\sigma_{tot}(J/\psi N) \sim 4\, mb$$

Future studies of A-dependence of J/ψ photoproduction at 12 GeV - will discuss tomorrow

⇒ Small objects interact weakly even at low energies where one did not check pQCD for such situation. Suppression of interaction is present in nonperturbative regime as well - small object cannot readily emit a meson (F&S 85)

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

new ones are feasible with COMPASS

(b) Intermediate energy CT

Nucleon form factor

γ^*_L (γ^*_T ?)$+ N \to M + B$

Large angle (t/s = const) two body processes: $a + b \to c + d$ Brodsky & Mueller 82

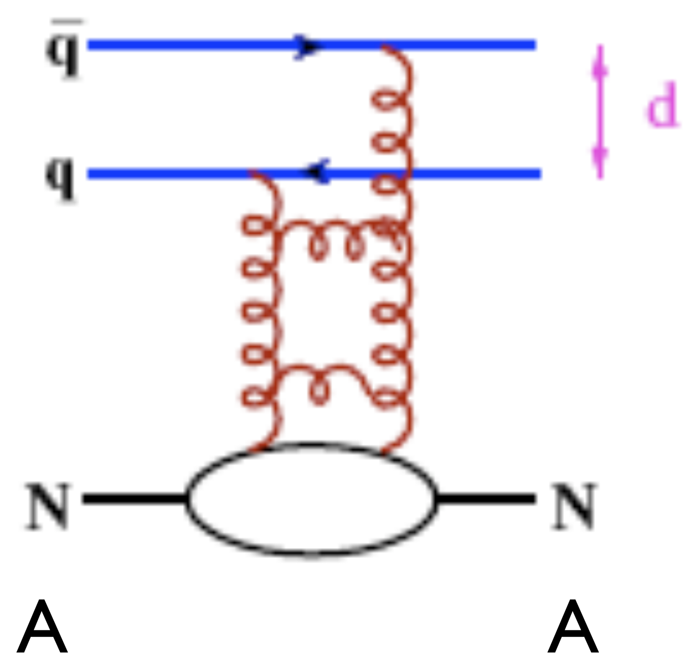
Problem: *strong correlation* between t (Q) and lab momentum of produced hadron

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

Color coherence is one of fundamental properties of high energy processes in QCD:

Up to very large energies including the ones probed at HERA the interaction of color neutral, spatially small quark dipole with a hadron(nuclear) target T is unambiguously calculable in QCD =QCD factorization theorems.

QCD factorization theorem for the interaction of small size color singlet wave package of quarks and gluons.



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

$$Q^2_{eff} = \lambda/d^2, \lambda = 4 \div 10$$

Baym, Blättel, Frankfurt, MS, 93; Frankfurt,Miller, MS 93

H1 and ZEUS observed processes of diffractive electroproduction of vector mesons.

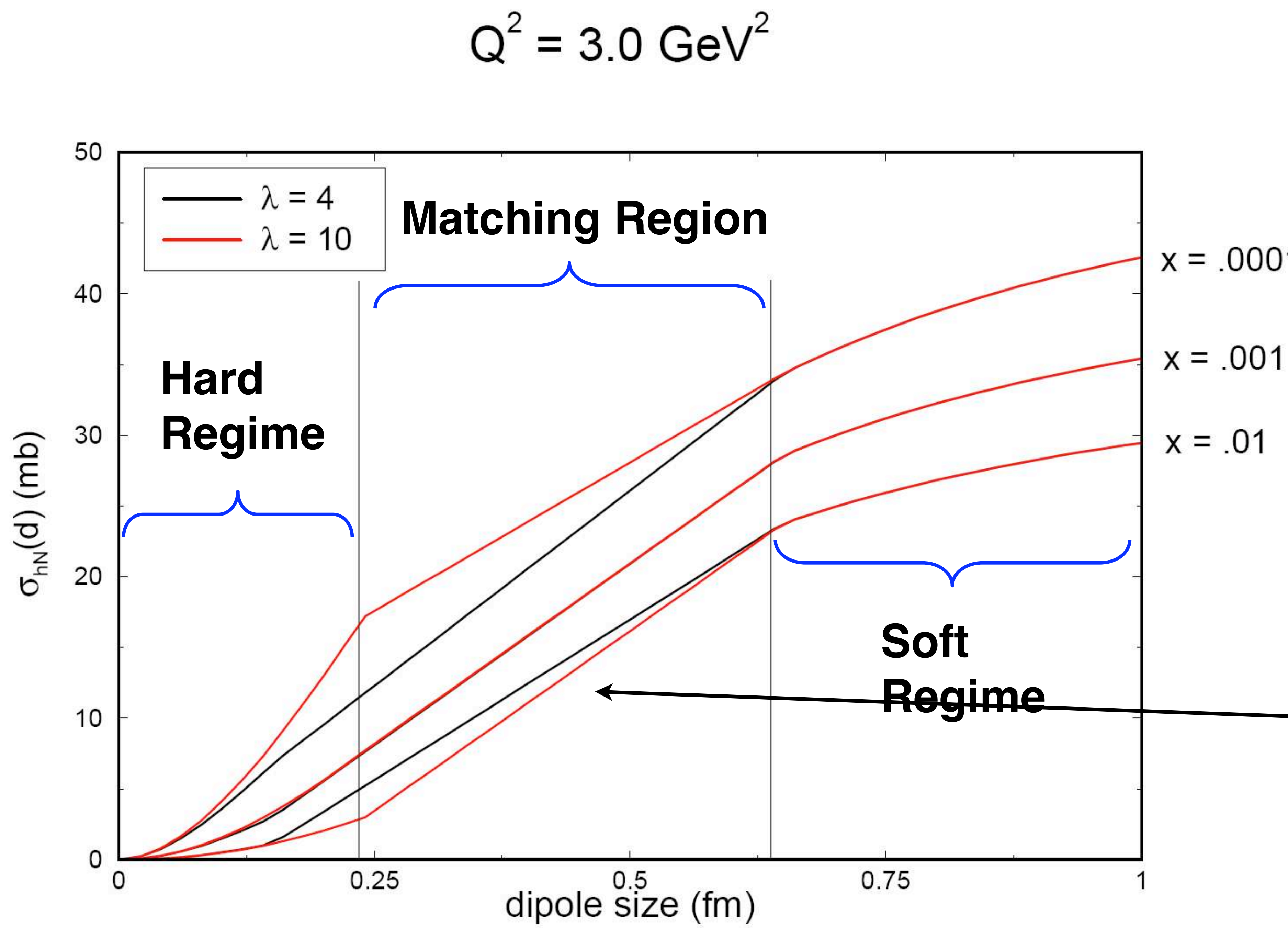
$$\gamma^* + p \to V + p$$

V=ω,ρ,φ,J/ψ

$$\gamma^* + p \to J/\psi + rap\ gap + X$$

Practically all regularities predicted by QCD factorization theorems and DGLAP approximation including *convergence of t and s- dependences,* were observed at HERA

HERA data confirm increase of the cross sections of small dipoles predicted by pQCD



Jlab12 energies correspond to x> 0.1 - sufficient to squeeze to d < 0.4 fm

The interaction cross-section, $\hat{\sigma}$ for CTEQ4L, $x = 0.01, 0.001, 0.0001$, $\lambda = 4, 10$. Based on pQCD expression for $\hat{\sigma}$ at small d_t, soft dynamics at large b, and smooth interpolation. Provides a good description of F_{2p} at HERA and J/ψ photoproduction. Provided a reasonable prediction for σ_L

Frankfurt, Guzey, McDermott, MS 2000-2001

First prediction and discovery of high energy CT phenomenon

$$\pi + N(A) \rightarrow \text{“}2\ high\ p_t\ jets\text{''} + N(A)$$

Mechanism: Pion approaches the target in a frozen small size $q\bar{q}$ configuration and scatters elastically via interaction with $G_{target}(x, Q^2)$.

- First attempt of the theoretical analysis of πN process - Randa 80 - power law dependence of p_t of the jet (wrong power)
- First attempt of the theoretical analysis of πA process - Brodsky et al 81 - exponential suppression of p_t spectra, weak A dependence ($A^{1/3}$)
- pQCD factorization theorem - Frankfurt, Miller, MS 93; elaborated arguments related to factorization 2003.Experiment confirmed a number of the predicted features of the reaction.: A-dependence (CT), p_t and $z=E_{jet}/E_\pi$ -dependence,.

- Presence of small size $q\bar{q}$ Fock components in light mesons is unambiguously 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 small dipole interaction with nucleons, nuclei (for $x \sim 10^{-2}$)

CT is easier to probe for mesons than for baryons as only two quarks have to come close

CT at intermediate energies requires *three conditions*: small configurations, small cross section and suppression of expansion

CT at high energies requires *two conditions*: small configurations, small cross section. However the small cross section condition is more difficult to satisfy (large gluon density at small x)

Warning - at low energies where gluons play relatively small role, small dipole cross section does not go to zero:

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

where S is sea quark distribution for quarks making up the dipole

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)

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

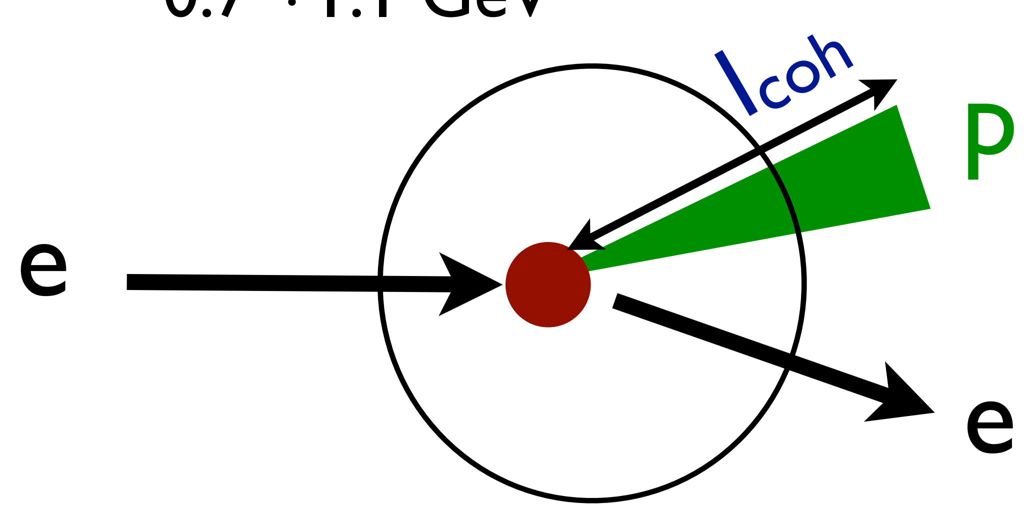
$$\sigma^{PLC}(z) = \left(\sigma_{hard} + \frac{z}{l_{coh}}\left[\sigma - \sigma_{hard}\right]\right)\theta(l_{coh} - z) + \sigma\theta(z - l_{coh})$$

Quantum Diffusion model of expansion

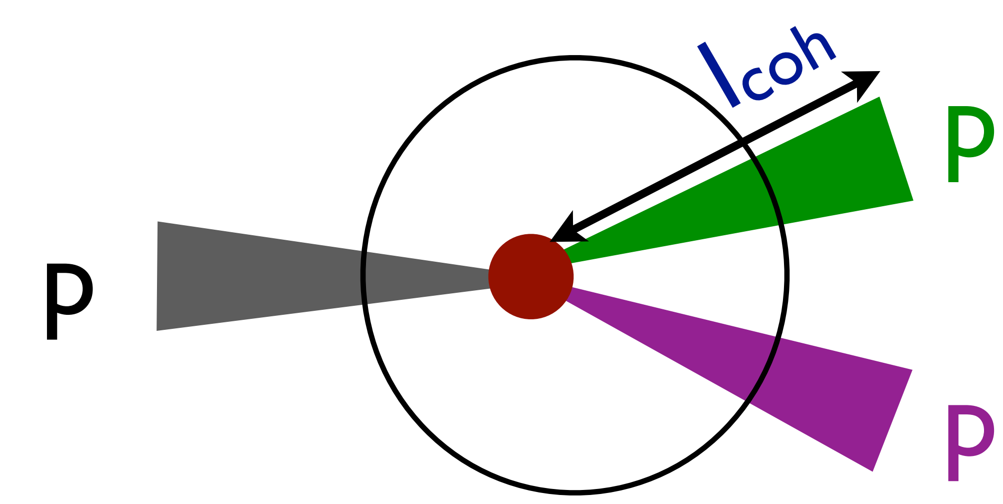
$$l_{coh} = \frac{2P_h}{\underbrace{m_{h*}^2 - m_h^2}_{0.7 \div 1.1\ \mathrm{GeV}^2}}$$

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

actually incoherence length



eA→ ep (A-1) at large Q



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

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

The same logic should be applicable to quark fragmentation in hard processes. Also quantum diffusion - mentioned first in Dokshitzer et al book "Basics of pQCD"

The same expression with the same parameters describes production of leading hadrons in DIS - U.Mosel et al.

Implications

Conspiracy - absorption in quark and quark- antiquark propagation maybe similar leading to similar CT effect (Mosel et al). May need finer observables - like exclusive π^0,η

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 !!!
Maybe a reason why one needs large parton - nucleon cross section in AA modeling

For charm $l_D = \frac{p_D}{m_D} 0.2 fm$ $\Rightarrow$ At RHIC l_D < 1 fm

Experimental situation

Mesons

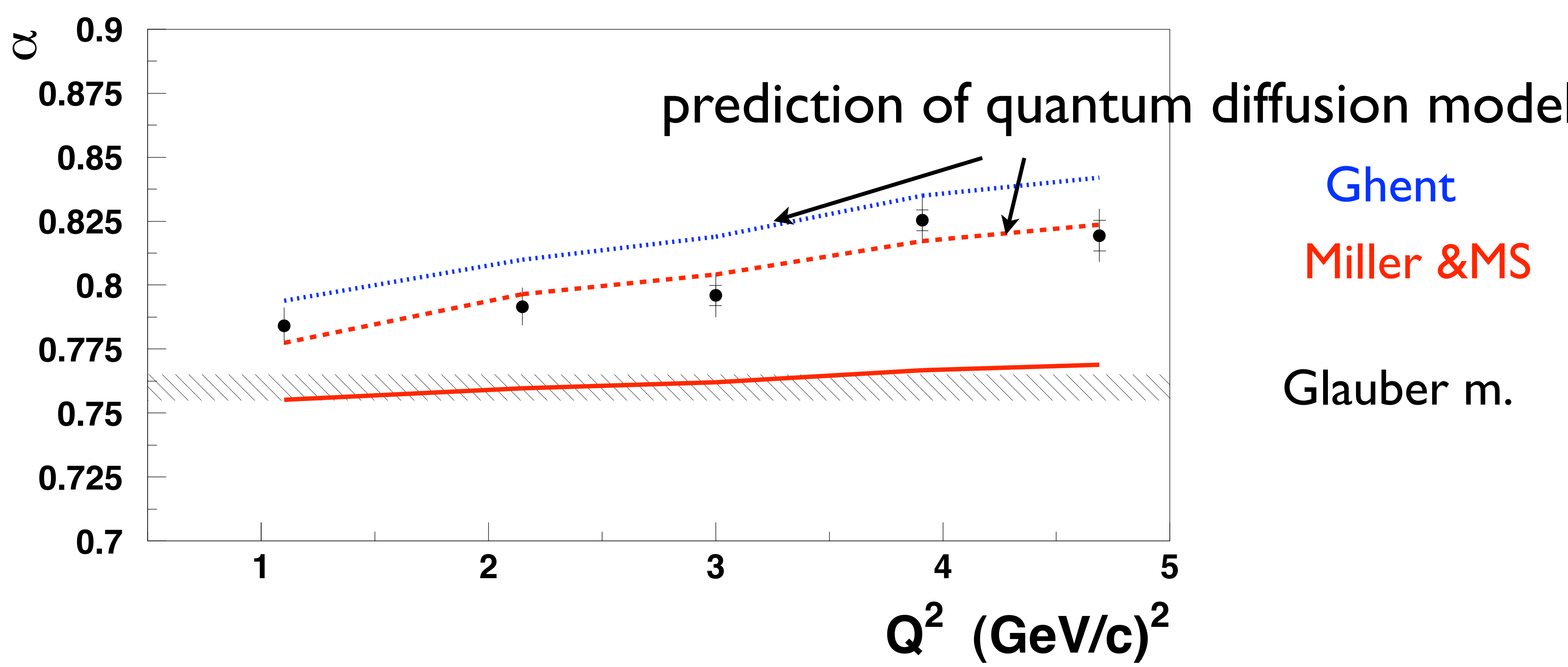
☀ $\gamma^* + A \rightarrow \pi A^*$ evidence for increase of transparency with Q (Dutta et al 07)

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

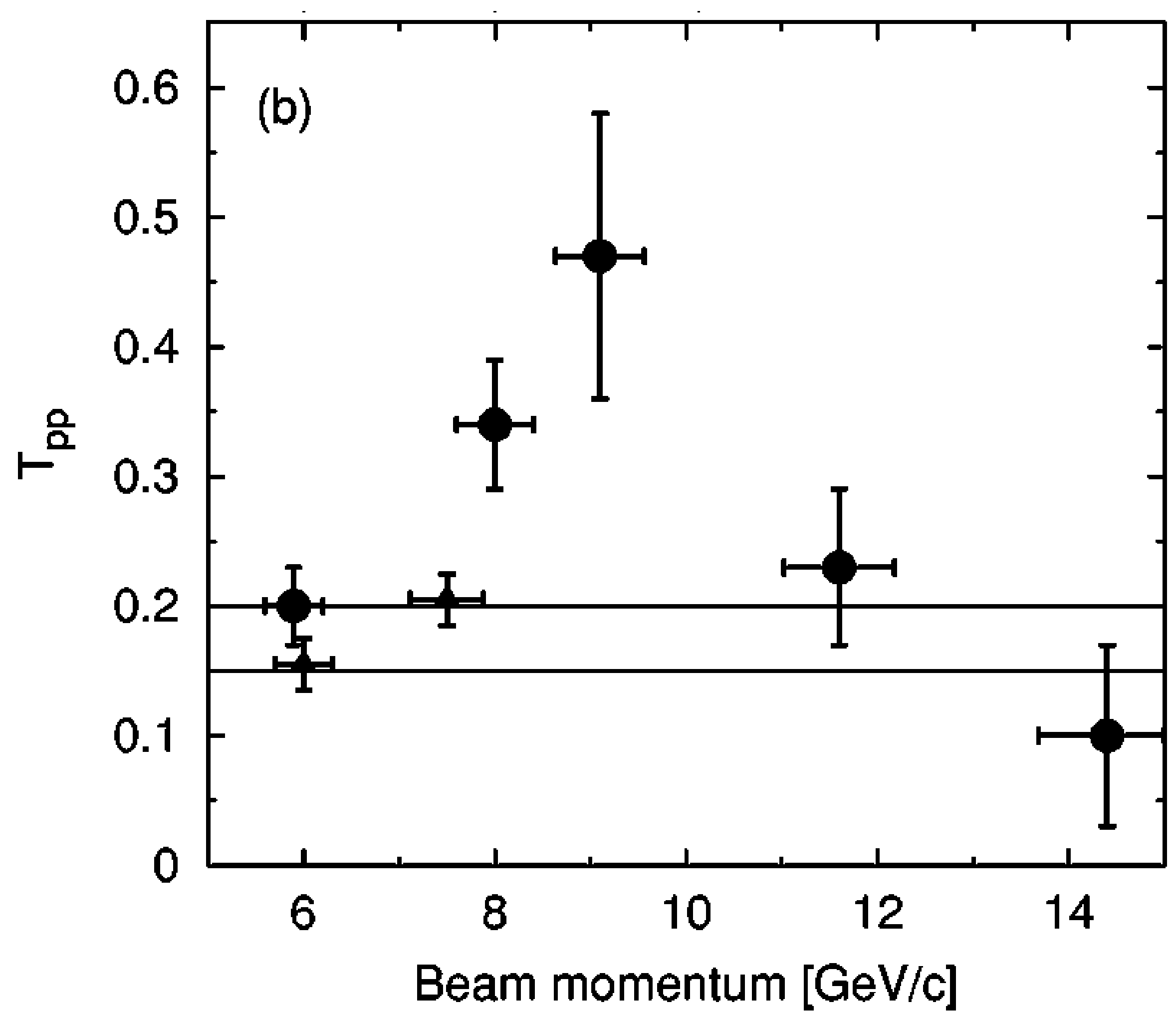
In dijet production $p_t \sim 1$ GeV/c corresponding to $Q^2 \sim 4 p_t^2 \sim 4 GeV^2$

seemed to be enough to squeeze the system (though not yet to reach asymptotic in z distribution)



☺ $\gamma^* + A \rightarrow \rho A^*$ data to be released shortly - so far seem to be reasonably consistent with our predictions. Some data from higher energies - but with a ratehr poor energy resolution.

Baryons



The nuclear transparency for carbon target as a function of beam energy - final EVA BNL data

- Eikonal approximation calculation with proper normalization of the wave function (Frankfurt, Zhalov, MS) agrees well the 5.9 GeV data.

- Significant effect for p= 9 GeV where l_{coh} ~ 4 fm.
  ⇒ 10 GeV is sufficient to suppress rather significantly expansion effects. Hence one can use energies above ~10 GeV to study other aspects of the dynamics

- Glauber level transparency for 11.5 -14.2 GeV a problem for all models as 24 $GeV^2 \leq s' \leq$ 30 GeV^2 since it is too broad for a resonance of for interference of quark exchange and Landshoff mechanisms

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

K.Garrow et al 02

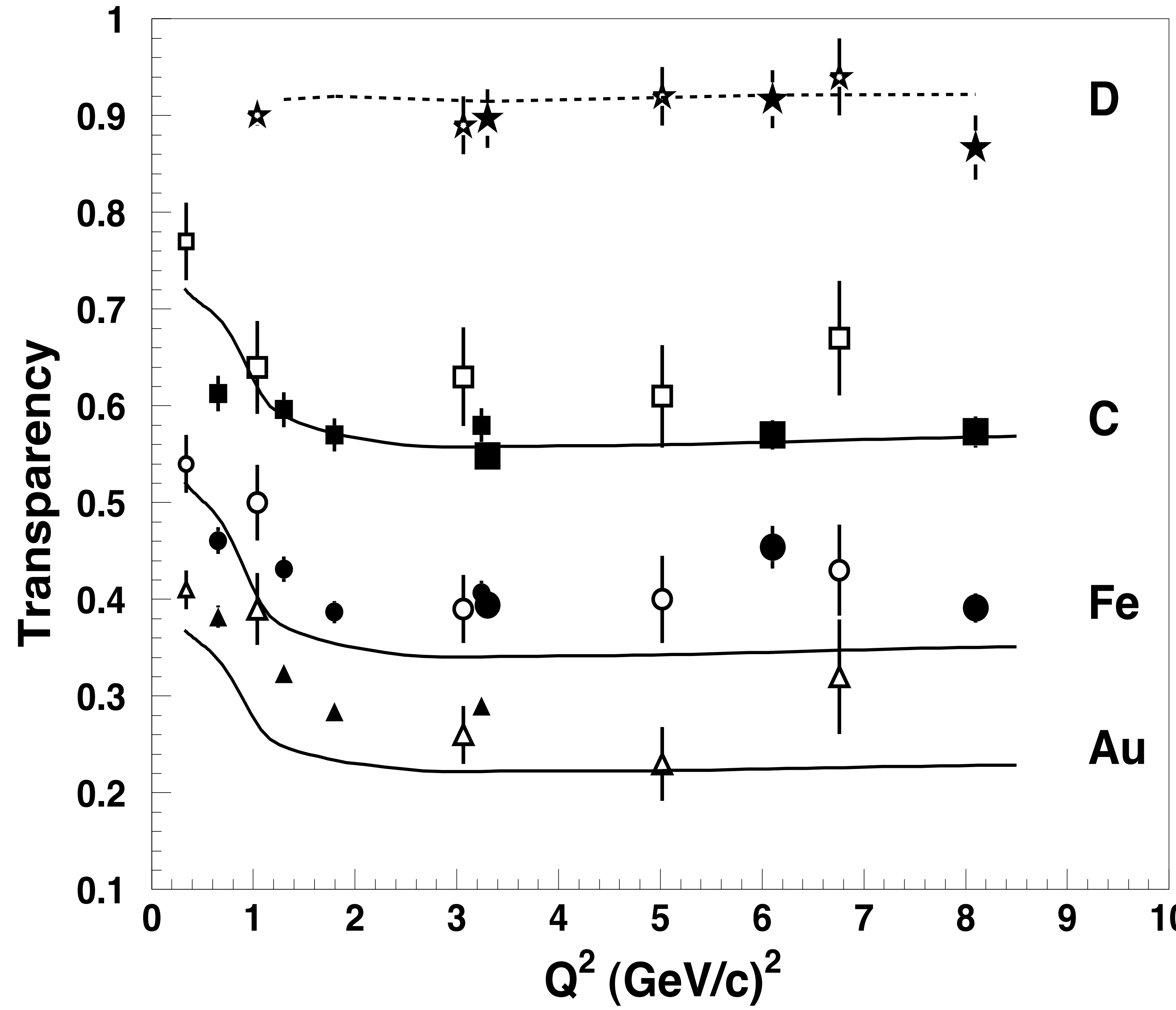
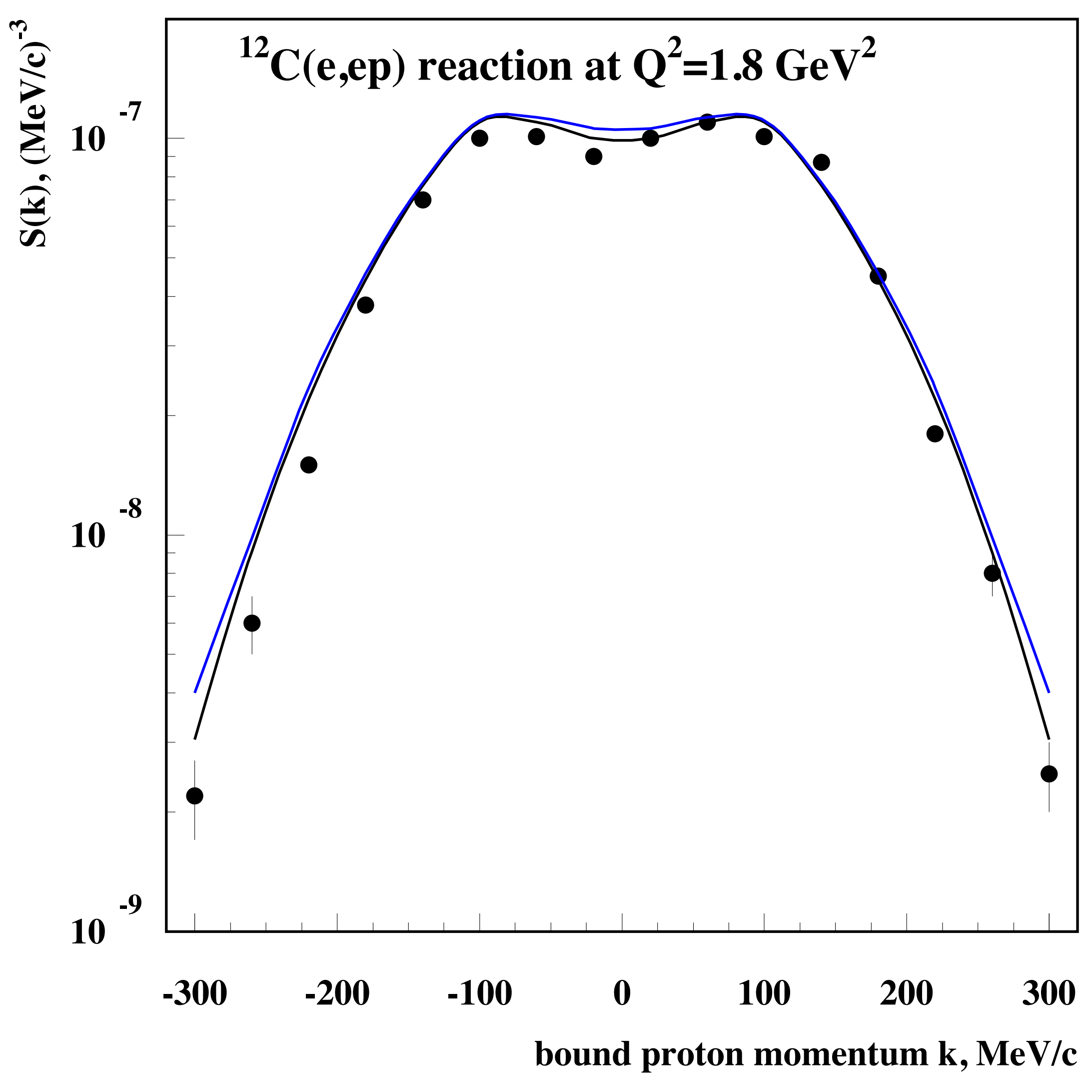


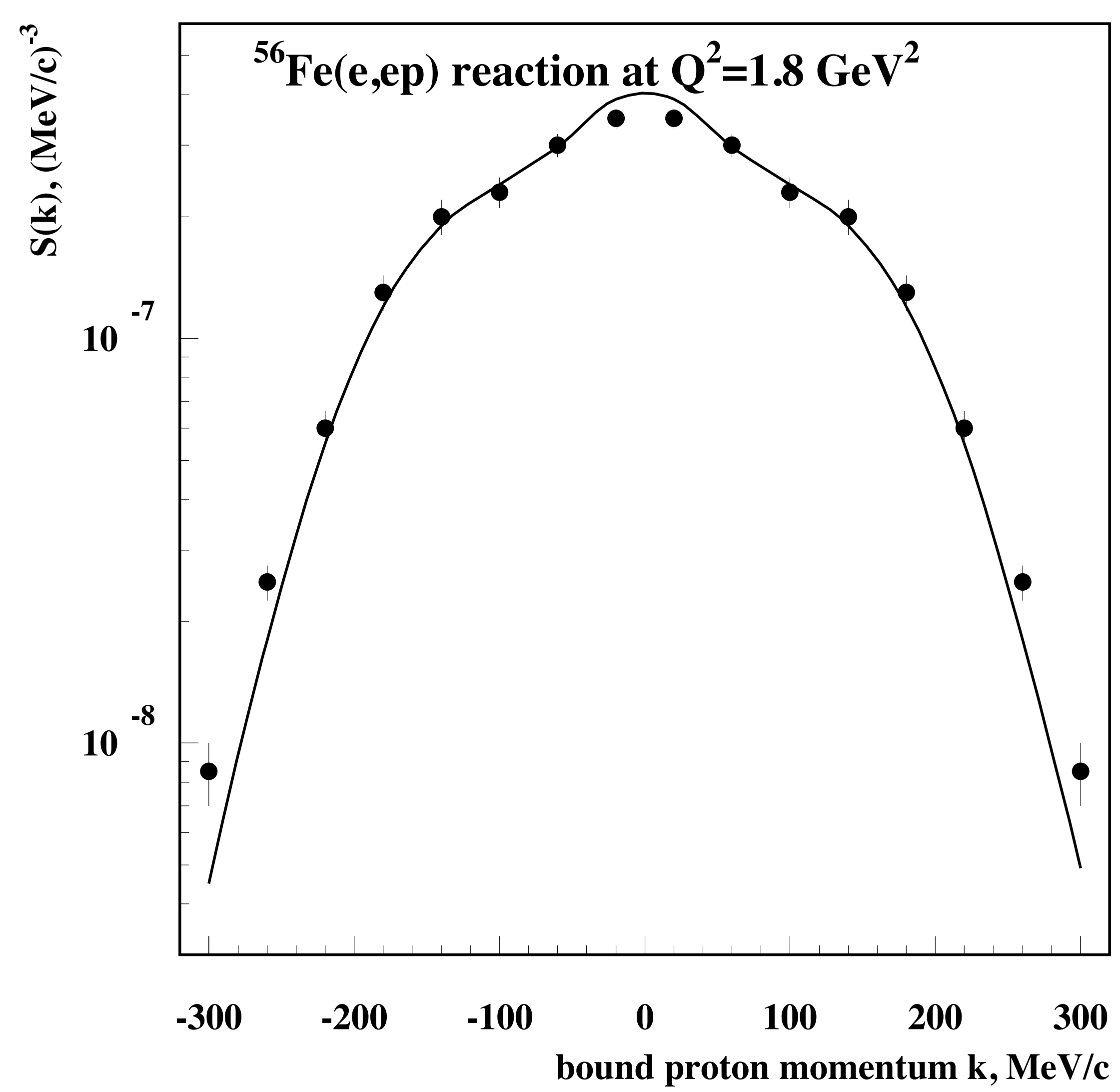
FIG. 3. Transparency for (e,e′p) quasielastic scattering from D (stars), C (squares), Fe (circles), and Au (triangles). Data from the present work are the large solid stars, squares, and circles, respectively. Previous JLab data (small solid squares, circles, and triangles) are from Ref. [16]. Previous SLAC data (large open symbols) are from Ref. [8,9]. Previous Bates data (small open symbols) at the lowest Q^2 on C, Ni, and Ta targets, respectively, are from Ref. [25]. The errors shown include statistical and systematic (± 2.3%) uncertainties, but do not include model-dependent systematic uncertainties on the simulations. The solid curves shown from $0.2 < Q^2 < 8.5$ (GeV/c)^2 are Glauber calculations from Ref. [26]. In the case of D, the dashed curve is a Glauber calculation from Ref. [27].

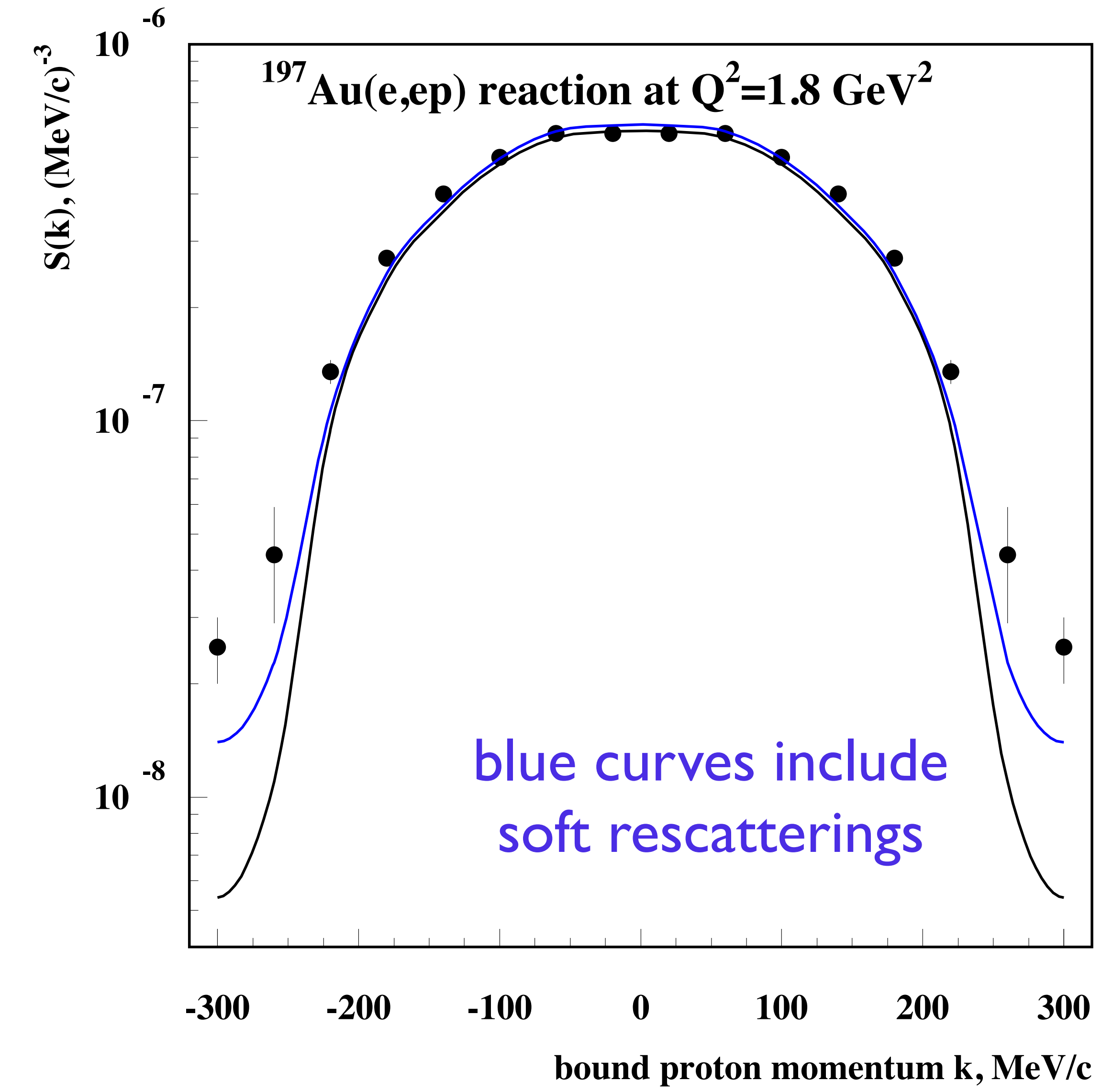
[26] H. Gao, V.R. Pandharipande, and S.C. Pieper (private communication); V.R. Pandharipande and S.C. Pieper, Phys. Rev. C **45**, 791 (1992).

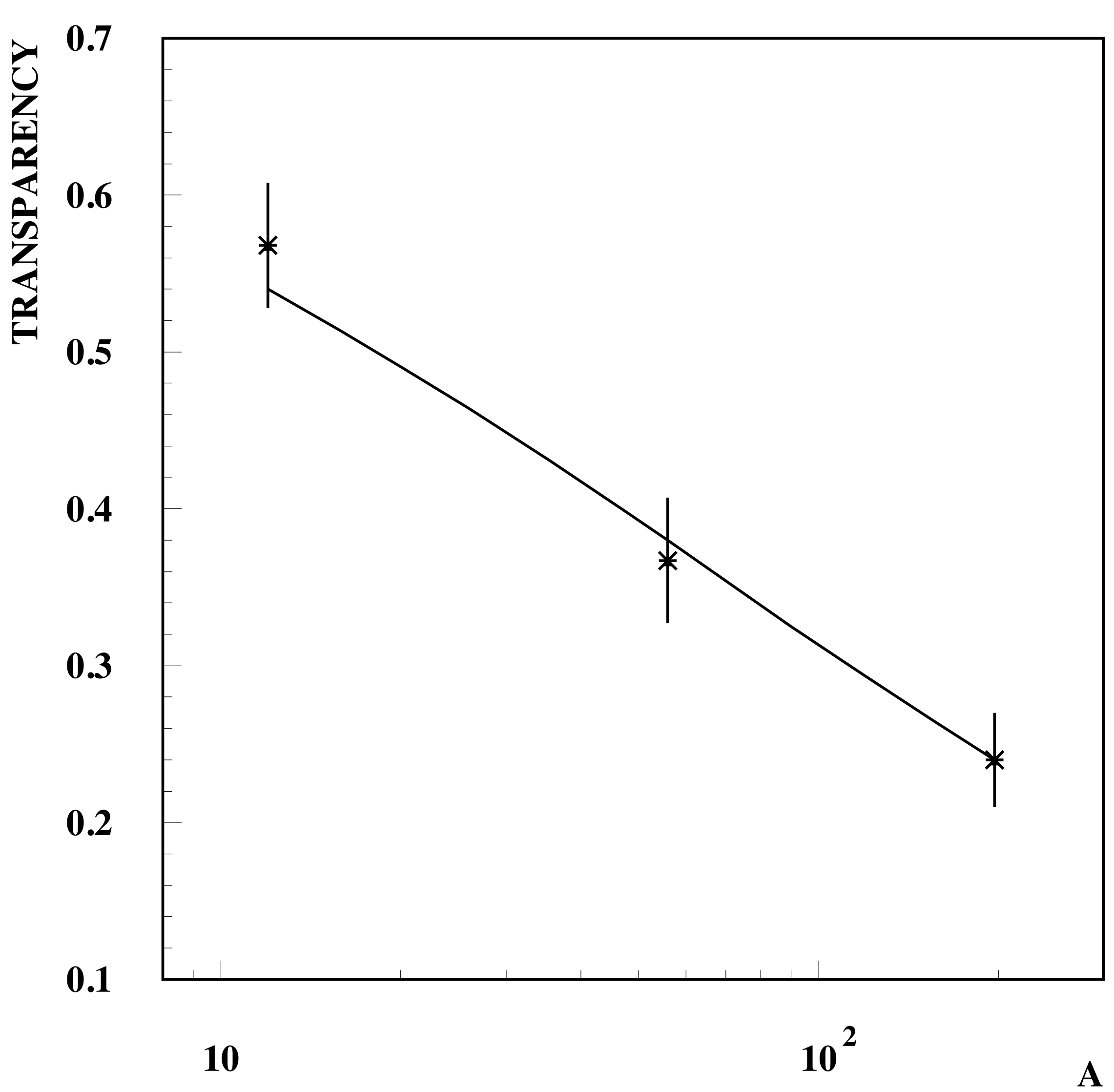
Discrepancy with Glauber calculation is typically 30% for heavy nuclei???

Glauber model (Frankfurt, Strikman, Zhalov) : very small suppression at large Q^2 : Q> 0.9









Comparison of transparency calculated using HFS spectral function with the data. No room for large quenching, though 10-15% effect does not contradict to the data.

Small quenching is consistent with a small strength at large excitation energies for the momentum range of the NE-18 experiment (R. Milner - private communication)

Jlab - 12 GeV

Overall proton expansion is a tough problem:

the lab momenta of produced nucleons are of the order -t/2m - cannot treat configurations as frozen up to very large t

$l_{coh\ proton}$= 0.4 fm p_N = 2 fm for $-t=Q^2$= 10 GeV^2. Large enough to lead to significantly large proton expansion effects

- Note that (e,e'p) up to $Q^2 \sim$ 10 -15 GeV^2 will be doable and will allow to determine whether nucleon f.f. are dominated by PLC or mean field configurations

Some squeezing must be present on the level of chiral fields - suppression of the pion field - moderate change of transparency but at much smaller Q

Large angle two body processes

So far we do not understand the origin of one of **the most fundamental hadronic processes in pQCD -large angle two body reactions** (-t/s=const, $s \to \infty$)

$\pi + p \to \pi + p$, $p + p \to p + p$,...

Summary: reactions are dominated by quark exchanges with

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

<u>*Indicates dominance of minimal Fock components of small size*</u>

Most extensive set of processes was studied by the BNL experiments at 5.9 and 9.9 GeV/c

E_h similar to Jlab 12

Quark counting expectations

$$\frac{d\sigma^{a+b\to c+d}}{dt} \propto \frac{1}{s^{q_a+q_b+q_c+q_d-2}}$$

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

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

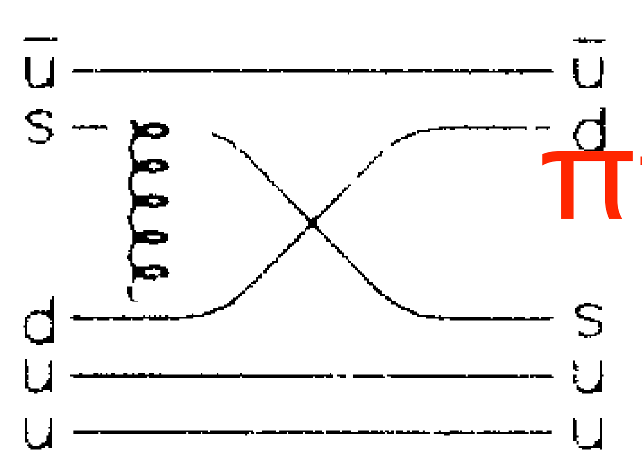
Is there an evidence for dominance of PLC in elementary reactions?

☺ Dimensional counting rules for energy dependence usually work (do not work for Compton scattering - Jlab)

☻ Reactions where quark exchange is allowed
>> those where it is forbidden

$K^- p \to \pi^- \Sigma^+$

K^-



π^-

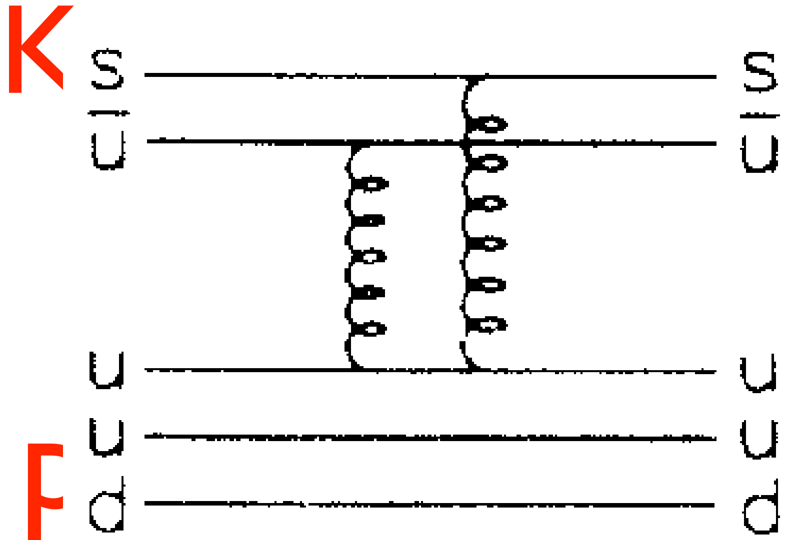
p

Σ^+

>>

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

K



p

K^-

p

If quark exchanges dominates and contribution of PLC in the mesons dominates we expect

$$\frac{d\sigma^{K^+p\to K^+p}}{d\theta_{c.m.}}(\theta = 90^o) > \frac{d\sigma^{\pi^+p\to\pi^+p}}{d\theta_{c.m.}}(\theta = 90^o) > \frac{d\sigma^{\pi^-p\to\pi^-p}}{d\theta_{c.m.}}(\theta = 90^o)$$

while at t=0 the cross sections are 1/2:1:1

f_π, f_K - pion and kaon decay constants - measure wave function in the origin

$$\frac{d\sigma^{K^+p\to K^+p}}{d\theta_{c.m.}}(\theta = 90^o) / \frac{d\sigma^{\pi^+p\to\pi^+p}}{d\theta_{c.m.}}(\theta = 90^o) \sim (f_K/f_\pi)^2 \sim 1.45$$

data ~1.69 (1 ±15%)

$$\frac{d\sigma^{\pi^+p\to\pi^+p}}{d\theta_{c.m.}}(\theta = 90^o) / \frac{d\sigma^{\pi^-p\to\pi^-p}}{d\theta_{c.m.}}(\theta = 90^o) \sim u(x)/d(x) \sim 2$$

data ~1.76 (elastic); 2.15 (for ρ-meson production) errors 10-15%

Similar pattern is observed at 9.9 GeV. There is an evidence of the change of the pattern at p=20 GeV/c but errors are too large. Overall it appears likely that these processes are dominated by short distances for -t> 5 GeV^2. t-channel for these processes.

Lessons from the study of 90° c.m. hadronic reactions

The largest cross sections are the ones where quark exchange is allowed

Interesting to compare processes where gluon exchange is allowed vs quark exchanges:

$$\gamma + p \rightarrow \rho^0 + p, \gamma + p \rightarrow \rho^0 + \Delta^+, \gamma + p \rightarrow \pi^+ + n, \ldots$$

Interesting to compare processes with different combinatorics of quark exchanges:

$\gamma + p \rightarrow \pi^0 + p$ *and* $\gamma + n \rightarrow \pi^0 + n$

Analogous situation - difference of np and pp elastic scattering for large angles

Is the ratio $\dfrac{d\sigma/dt(\gamma + p \rightarrow \rho^0 + p)}{d\sigma/dt(\gamma + p \rightarrow (\pi^+\pi^-) + p)}$ constant for non-resonance ππ

Different limits are interesting:

90° - equal freezing of both hadrons

moderate t - starting from transition of VDM photon to point-like photon

u-channel dominance limit - $\vartheta_{c.m.} \sim 180^{\circ}$: baryon forward - meson slow

How different are the A-dependences of reactions with different slow mesons: ρ,ω,φ,η

$$\alpha_M = (E_M - p_{3M})/m_N = 1$$

mesons with pretty small momenta for small p_t (u ~0)

Basic measurements

$$T_A = \frac{\sigma(\gamma(\gamma^*) + A \to M + N + (A-1)^*)}{\sigma(\gamma(\gamma^*) + N \to M + N)}$$

as a function of incident energy, t, Q^2

Probably easier to freeze meson. Hence probably best region is -t ~ 2 ÷ 4 GeV^2 depending on E_γ

Q^2 dependence? probably not much if -t >> Q^2

Interesting but experimentally difficult region -t ~ Q^2 ~ few GeV^2

Low t limit - only rim contributes T(A) $\propto A^{1/3}$

$$T_{Low}(A) = \int d^2b \int_{-\infty}^{\infty} dz \rho(b,z) \exp^{-\sigma_{MN} \int_{-\infty}^{z} dz' \rho(b,z')}$$

Transition to PL photon - only back surface contributes t limit - T(A) $\propto A^{2/3}$

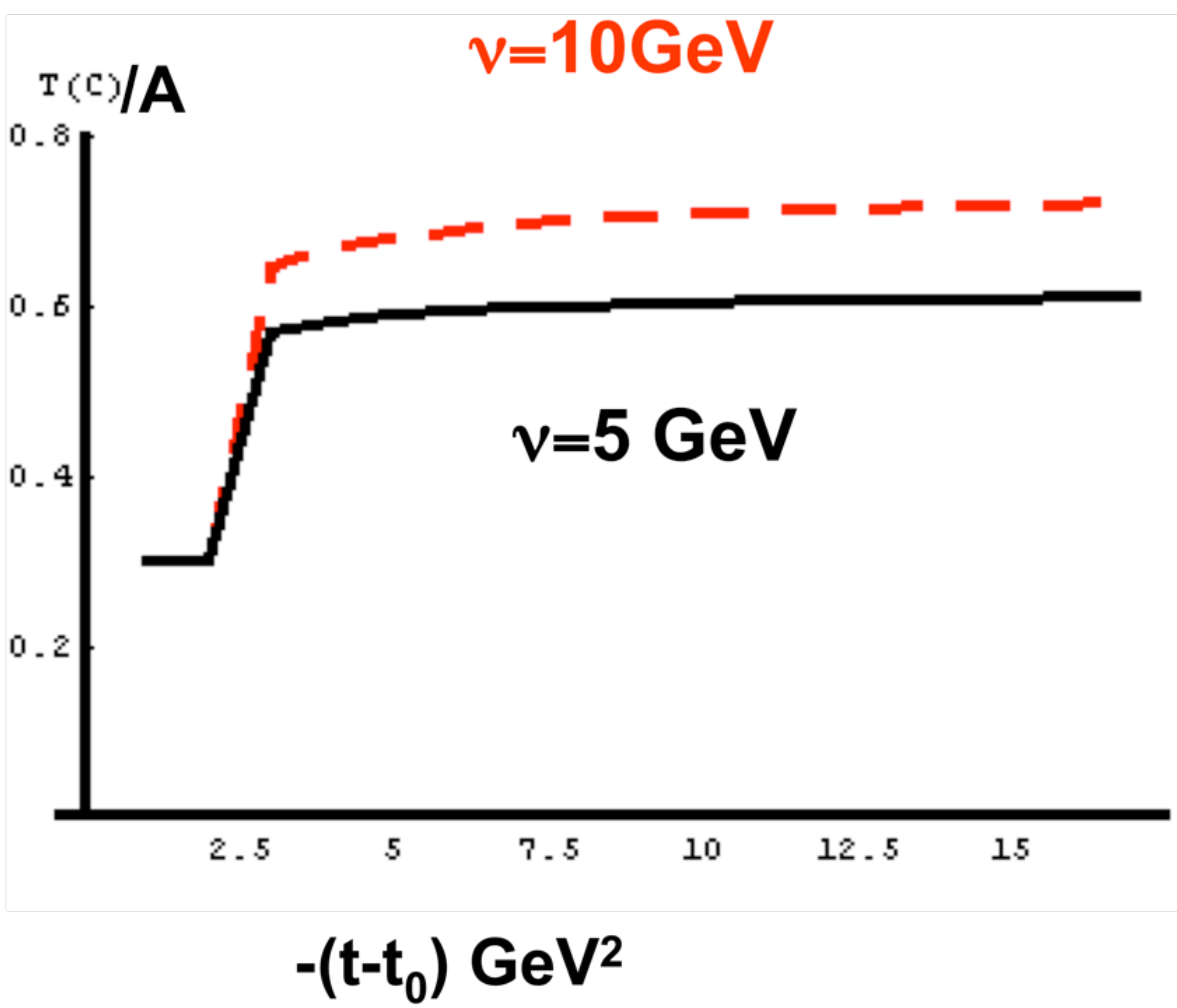
$$T_{High}(A) = \int d^2b \int_{-\infty}^{\infty} dz \rho(b,z) \exp^{-\sigma_{\rho N} \int_{\infty}^{z} dz' \rho(b,z')} \exp^{-(\sigma_{MN}+\sigma_{NN})\rho(b,z')}$$

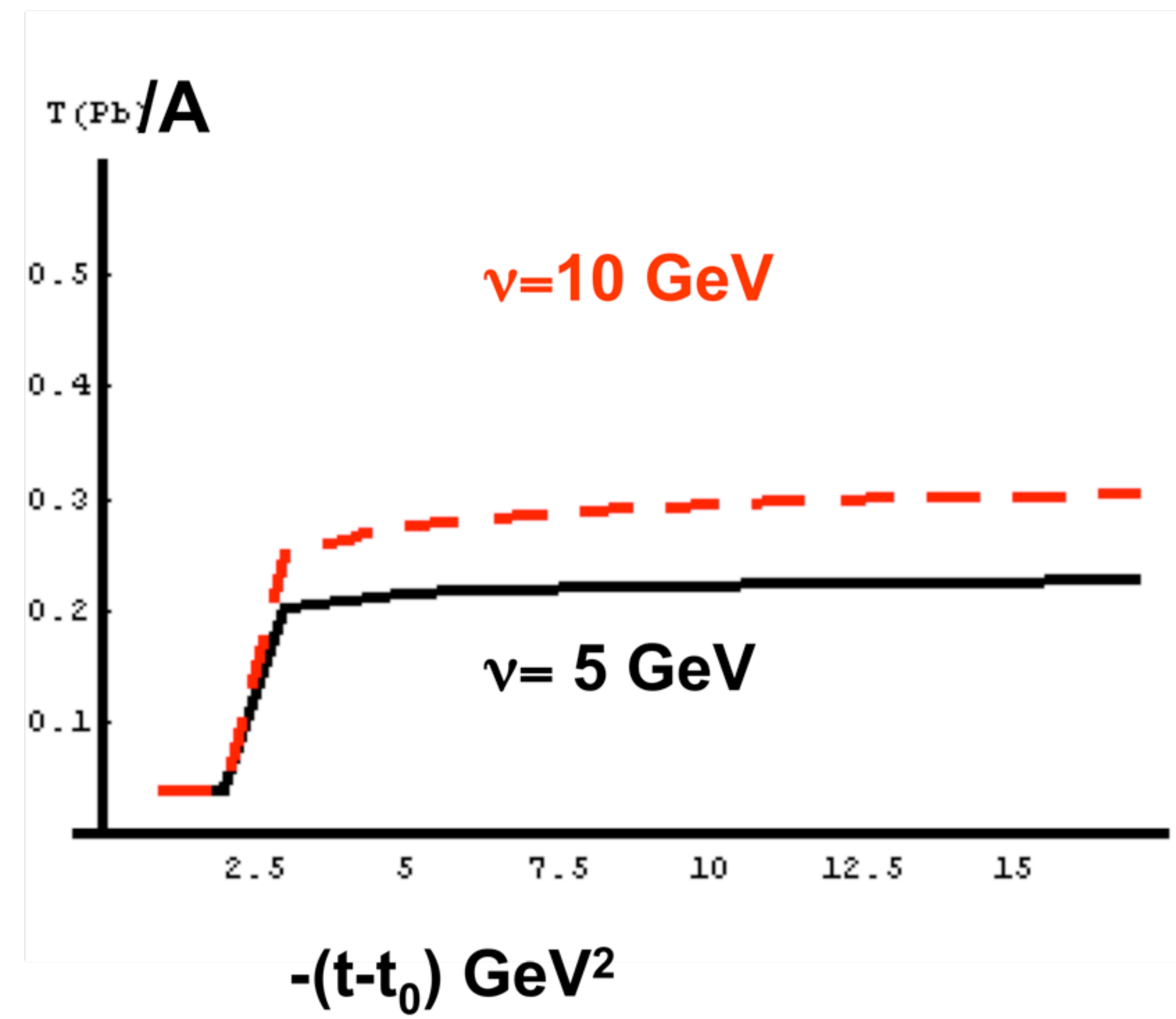
Transition to CT regime - asymptotically - T(A) $\propto$ A

In the interaction point $\sigma_{PLC} \propto 1/t$

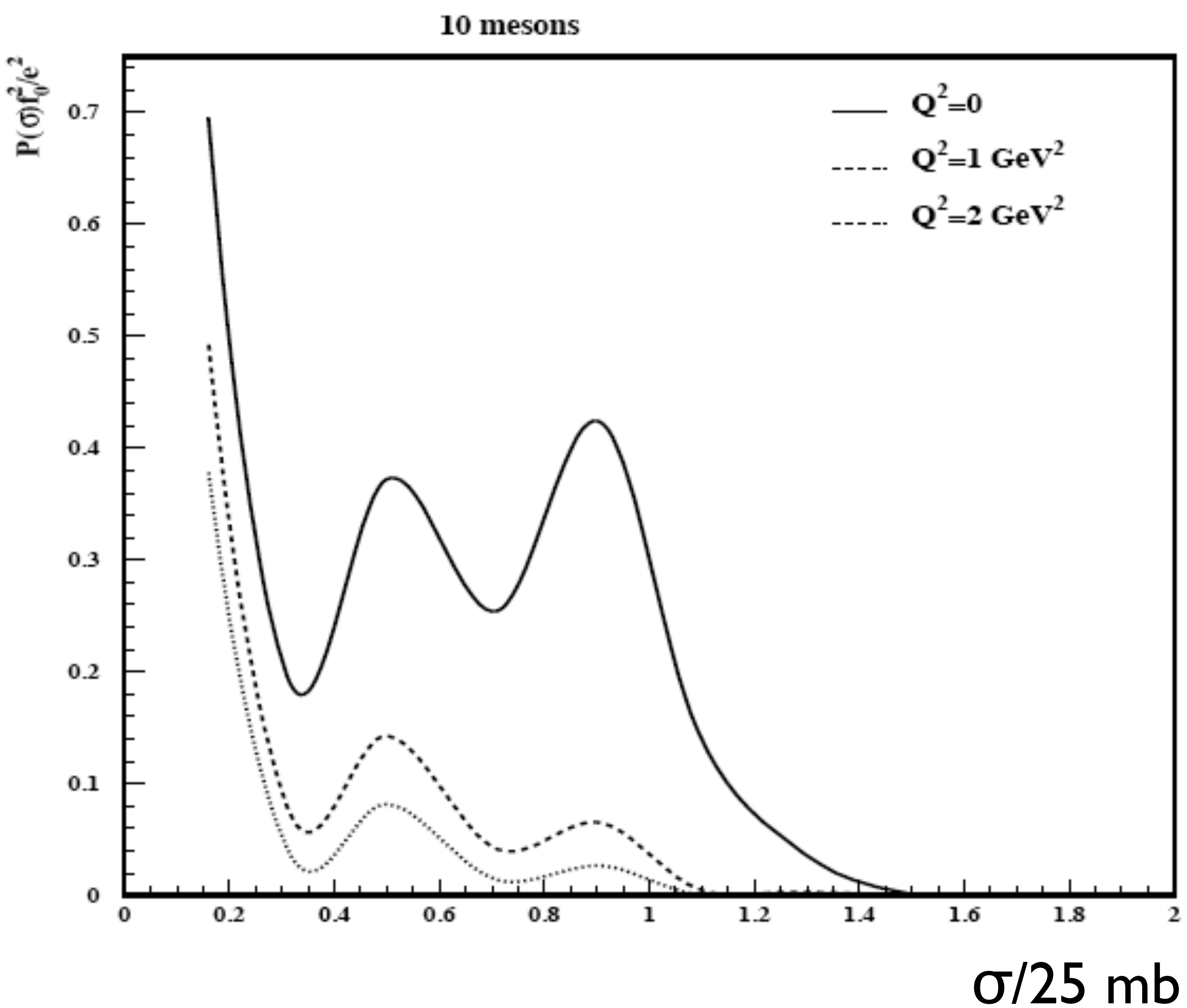
From G.Miller talk at the Hall D meeting 3 years ago.

γ N → π N Transparency vs. A, ν





Duality of vector meson and quark antiquark descriptions of the photon wave function.



Coherent diffraction in $\gamma(\gamma^*)\, A \to M\, A$ mapping of the color fluctuations in photons, interplay between soft and hard contributions - looking CT configurations and large size configuration. Example - are small mass $\pi^+\pi^-$ configurations interact with $\sigma \sim 2\sigma_{\pi N}$?

Delicate point: in γ^* case one measures the sum of diagonal and nondiagonal VM transitions with strong cancelations.

pQCD + vector meson contributions to $P_\gamma(\sigma)$

LF +Guzey +MS 98

Note that if the large t process is dominated by PLCs

$$\frac{d\sigma/dt(\gamma + p \to \rho^0 + p)}{d\sigma/dt(\gamma + p \to \rho' + p)} = \frac{R(\rho)}{R(\rho')}$$

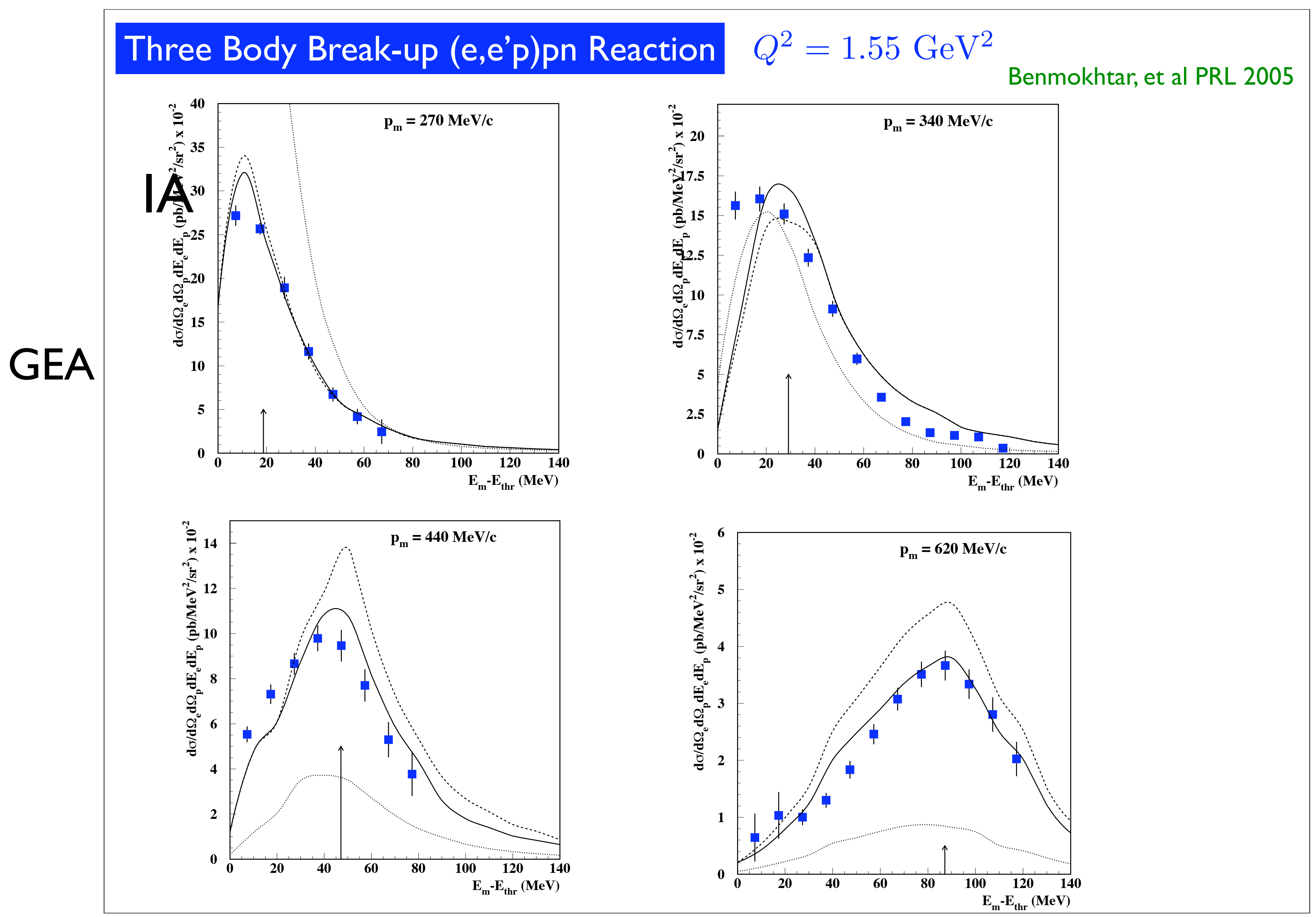
for -t >> M^2(VM)

$$R(M^2) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

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

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 $e^2H \to epn$ using just two high energy spectrometers. Issue - chose kinematics were contribution of Δ-isobar intermediate states is small.

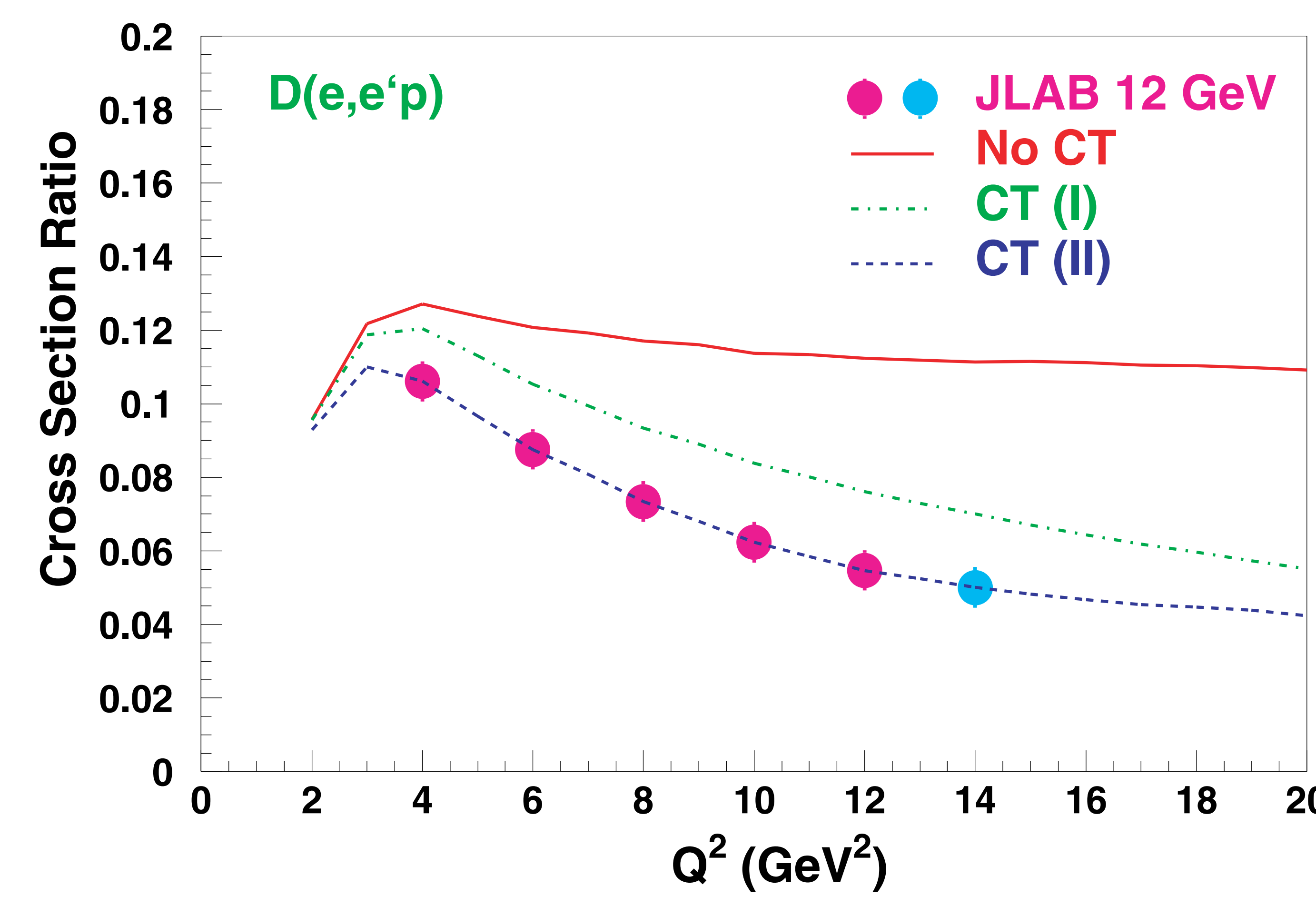
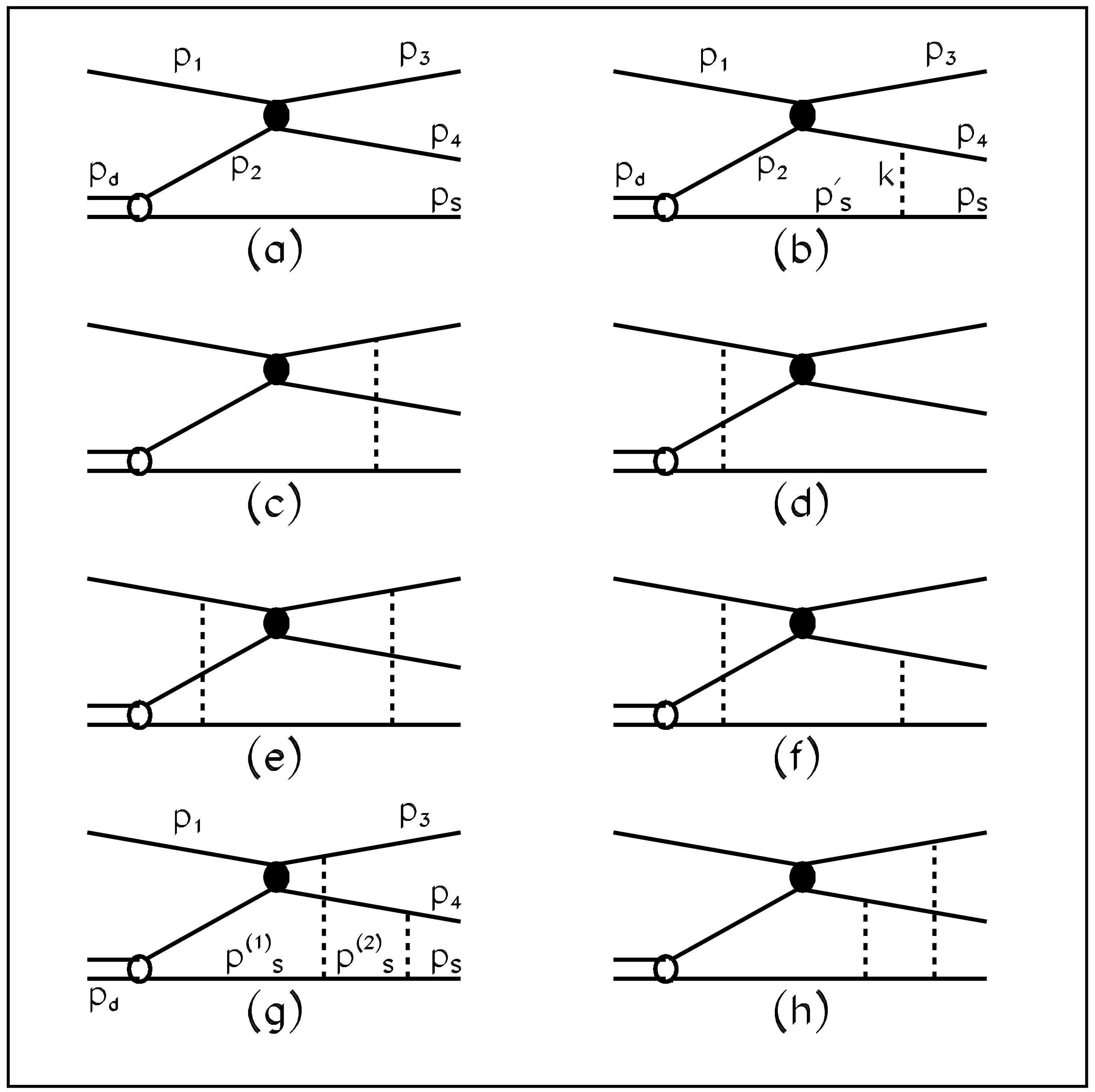
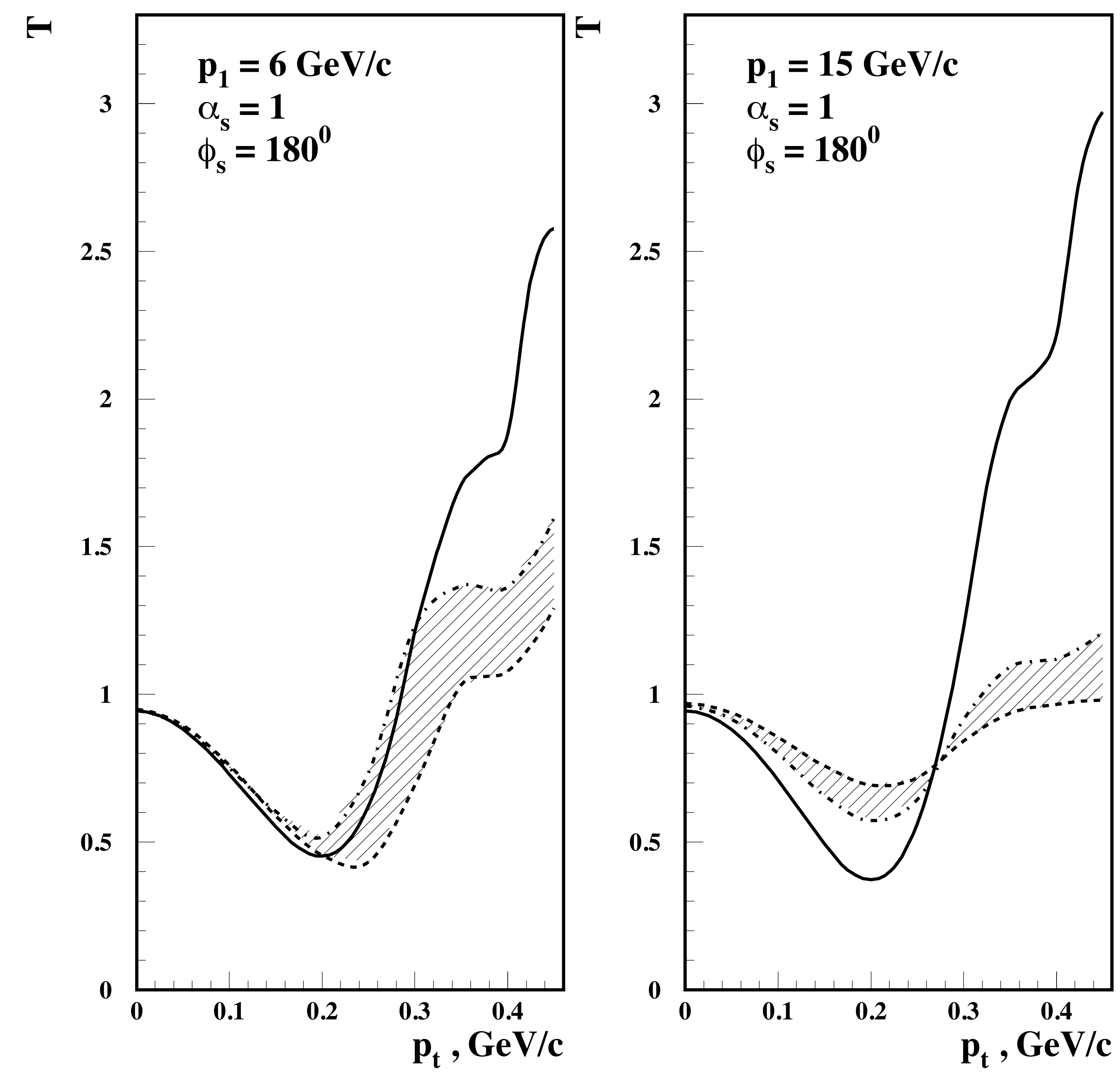


Figure 15. The ratio of the cross section at 400 MeV/c missing momentum to the cross section at 200 MeV/c as a function of Q^2. The solid line corresponds to the GEA prediction. The dashed and dash-dotted lines represent the quantum diffusion model of CT with $\Delta M^2 = 0.7$ and 1.1 GeV^2, respectively. 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

We studied in detail how to use the process pD→ppn to study wave package evolution over distances ~ 1 ÷ 1.5 fm interference between impulse approximation, single and double rescatterings. Complicated pattern of constructive and destructive interference along the cones with θ~70° associated with initial and final hadrons. Easy to extend to photon projectiles.



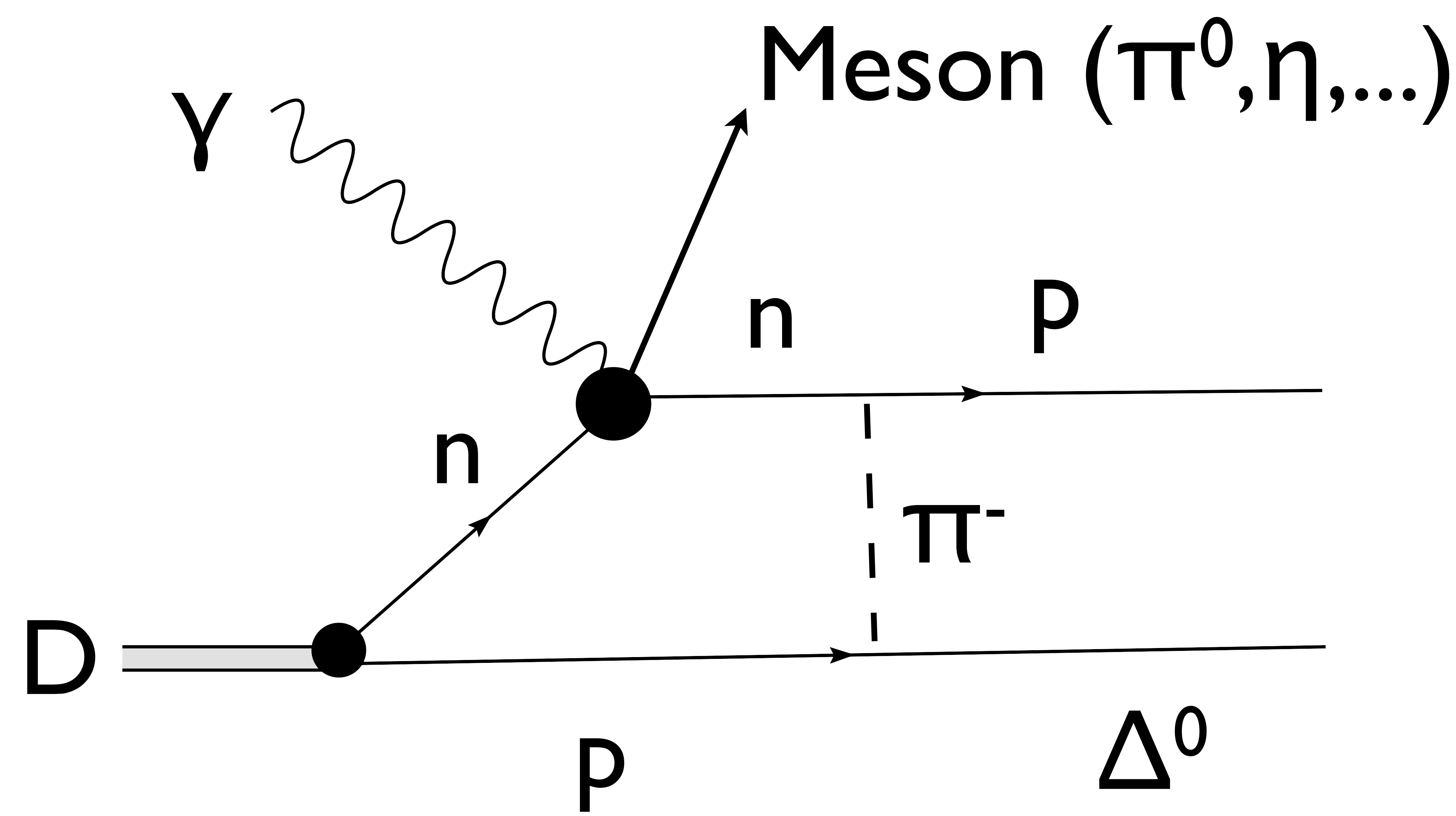


The p_t dependence of T at $\alpha_s = 1$. The solid line is for the elastic eikonal approximation which neglects color transparency effects. The shaded area corresponds to T calculated within the quantum diffusion model of CT. Dashed and dash-dotted curves correspond to QDM calculations with different rate of expansion.

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:

In large t 2 → 2 processes charge exchange interactions with spectators should be suppressed (similar to LF& H.Lee, Miller, Sargsian, MS- 97).



or

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

Example II: Chiral dynamics in production of pions near threshold

Large Q reaction γ^* N → Nπ 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

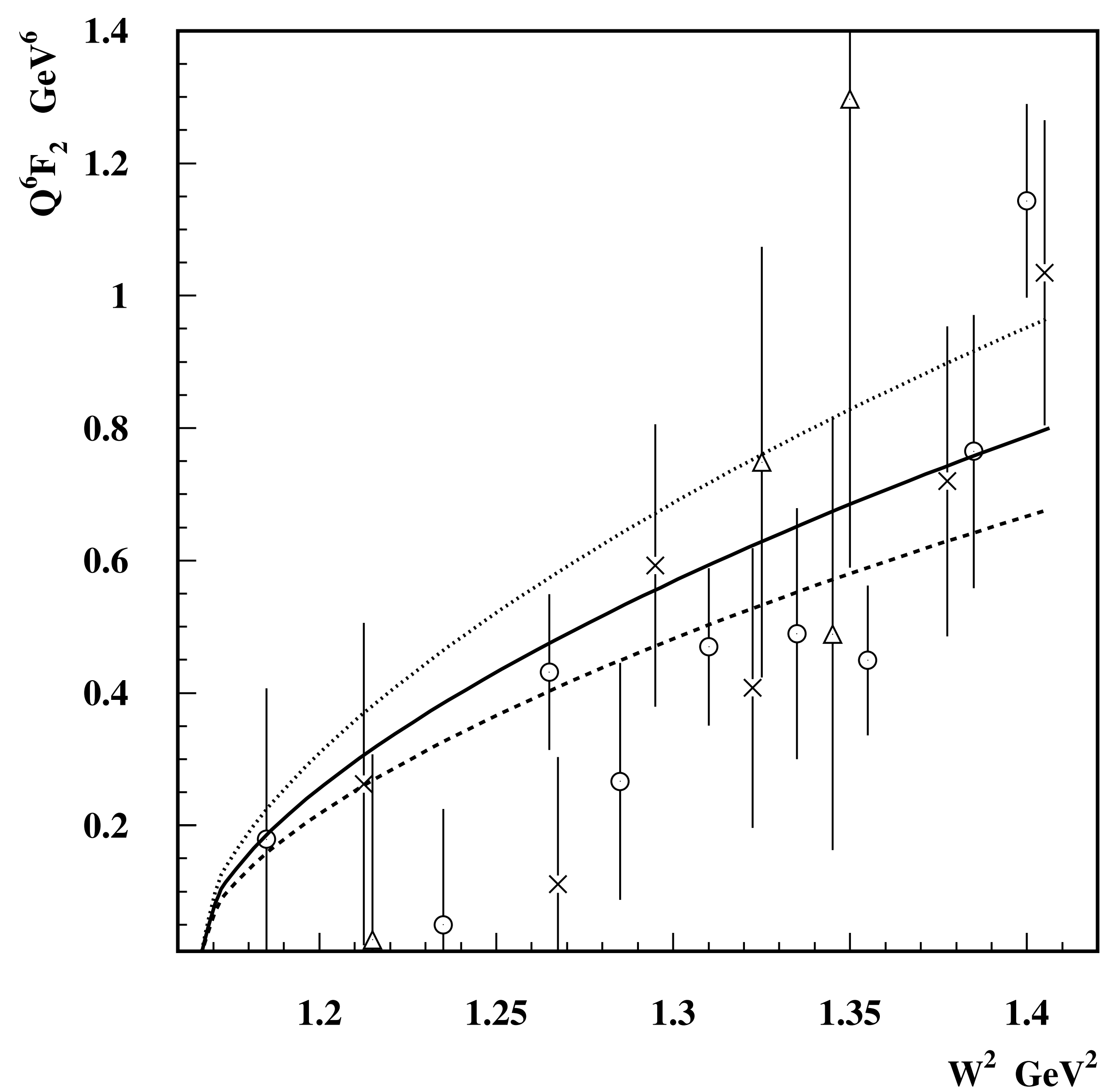


FIG. 2. Values of $F_2^p(W, Q^2)$ scaled by Q^6 as a function of W^2. The data of the E136 experiment are at average Q^2 values of 9.4, 11.8 (×), 15.5, 19.2 (○), 23, 26, and 31 (△) GeV^2. The theoretical predictions of the hSPT (18) at Q^2 = 10, 20, 30 GeV^2 are given by dotted, solid, and dashed lines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

Physical picture: γ^* hits 3q configuration which later emits a pion. Time scale is likely to correspond to $l_{coh} > l_{coh}$(form factor) as only pion cloud is removed from the nucleon.

Large t reaction $\gamma A \rightarrow (N\pi) + \text{Meson} + (A-1)$ 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 $-t \sim 5\text{-}7\ GeV^2$ 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 $eA \rightarrow e\,(N\pi)(A-1)$

Instead of conclusions

Are the rates high enough?

Is acceptance high enough?

Is missing energy resolution good enough?

If answer is yes - CT tools can help determine the dynamics of 2 - 2 processes. Complementary studies at FAIR, interesting possibilities with COMPASS.