(Color) transparency studies with photon beams: - probing structure of photon, hadrons andynamics of two body reactions

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Hall D workshop, April 28

“Pre outline”

Theme of this and two following talks:

- ***QCD with nuclei***
- ***QCD in nuclei (Nuclear structure using hard probes)***

High energy large angle processes with nuclei - brief history:

Test large angle dynamics: Brodsky & Mueller - $\sigma \sim A$

Not so quick - quantum diffusion (Farrar, Frankfurt, MS)

But nearly perfect probe of short-range nuclear structure (Farrar, LF, MS)

Outline

- Theoretical summary of transparency phenomena
- Three regimes of transparency for $\gamma A \to M+B+(A-1)$:
  (a) onset of point-like photon regime, (b) geometric regime
  (c) onset of color transparency regime
- Precision studies with ^2H, ^4He

QCD with nuclei

Color transparency (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 *relevant for example for interpretation of Heavy Ion data*

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

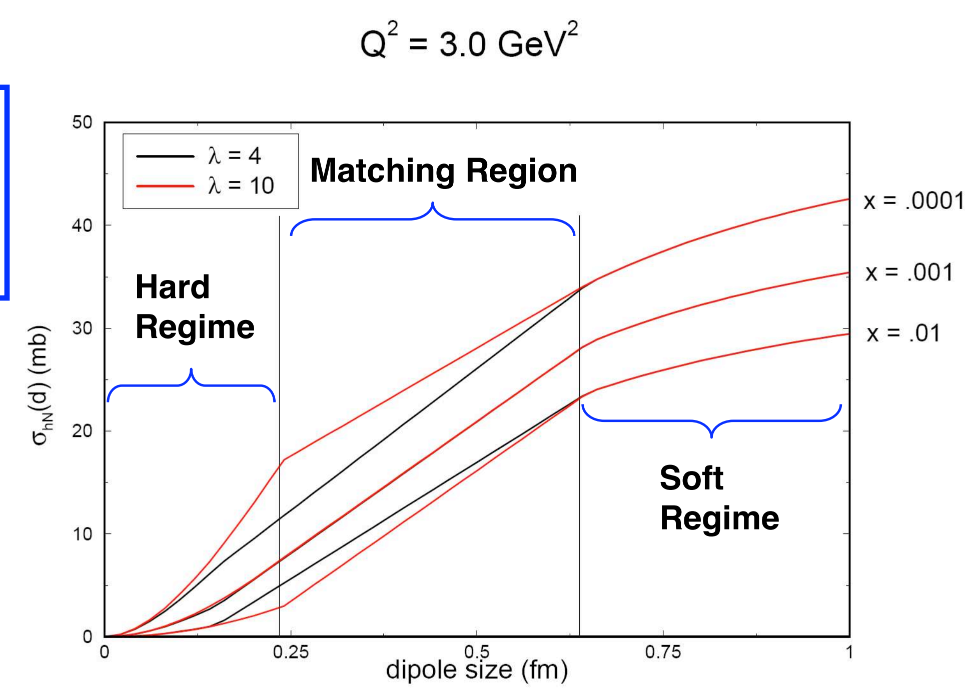
For a dipole of transverse size d:

$\sigma = cd^2$ *in the lowest order in* α_s *(two gluon exchange F.Low 75)*

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

$$\boxed{\left. +2/3 x_N S_N(x_N,Q^2_{eff})\right]}$$

Maybe important at Jlab energies



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

(Baym et al 93, FS&Miller 2000)

ABC of CT: squeeze and freeze

Squeezing: *(a) high energy CT*

- Select special final states: diffraction of pion into two high p_t jets: - $d_{qq} \sim 1/p_t$

- Select a small initial state: γ^*_L - $d_{qq} \sim 1/Q$ in $\gamma^*_L + N \to M + B$

QCD factorization is 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 ?)$+ N \to M + B$

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

Definition of transparency for incoherent processes

$$T(A) = \frac{\sigma(a+A)}{A\sigma(aN)}, \mathrm{where\ a{=}e,}\gamma, \mathrm{h}$$

Complete transparency: T=1 (impulse approximation)

Comment: at small x change of dynamics - CT disappears but generalized CT holds. Example:

$$R= \frac{\sigma(\gamma A \to J/\psi A)}{A^2\sigma(\gamma N \to J/\psi N)}_{|t=0} = \left[\frac{G_A(x, Q^2_{eff})}{AG_N(x, Q^2_{eff})}\right]^2$$

At LHC for $x=10^{-3}$, R=.36

agrees with predictions of Guzey, LF, MS

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 configurations - they are not frozen. They evolve with time - expand after interaction to average configurations and contract before interaction from average configurations (FFLS88)

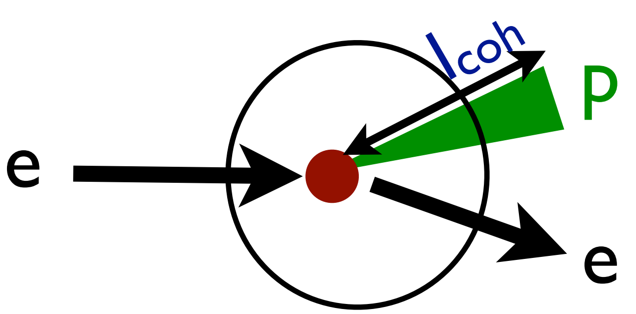
$$|\Psi_{PLC}(t)\rangle = \Sigma_{i=1}^{\infty} a_i \exp(iE_i t)\,|\Psi_i\rangle = \exp(iE_1 t)\Sigma_{i=1}^{\infty} a_i \exp\left(\frac{i(m_i^2 - m_1^2)t}{2P}\right)|\Psi_i\rangle ,$$

$$\sigma^{PLC}(Z) = (\sigma_{hard} + \frac{Z}{l_c}[\sigma - \sigma_{hard}])\theta(l_c - Z) + \sigma\theta(Z - l_c) .$$

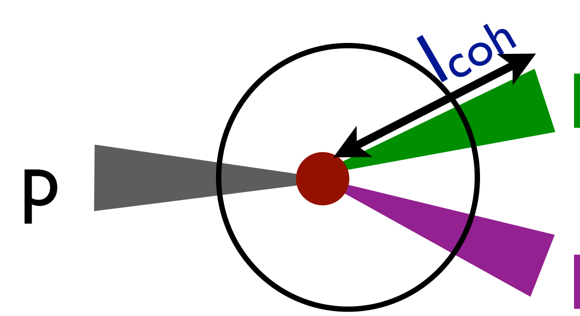
Quantum Diffusion model of expansion

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

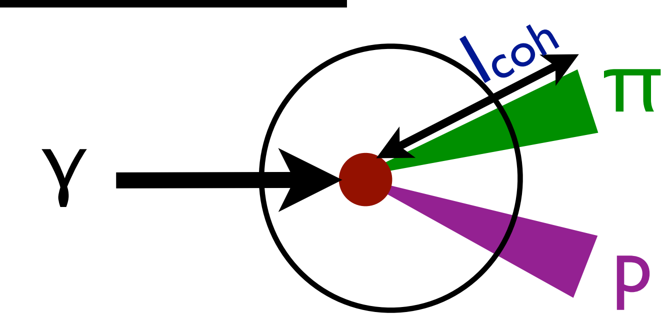
actually incoherence length



eA→ ep (A-1) at large Q



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



γA→ πp (A-1) at large t and intermediate energies

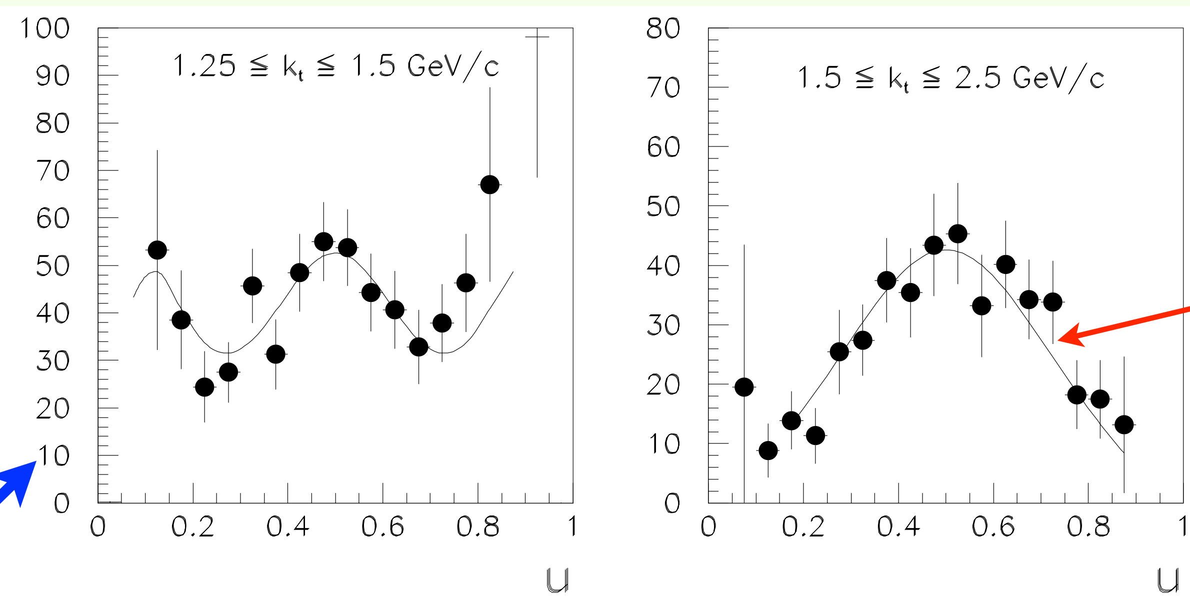
Note: Quantum diffusion model & multihadron basis with build in CT (Miller and Jennings) leads to similar numerical results for CT are very similar.

MC at RHIC assume much larger l_{coh}

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*



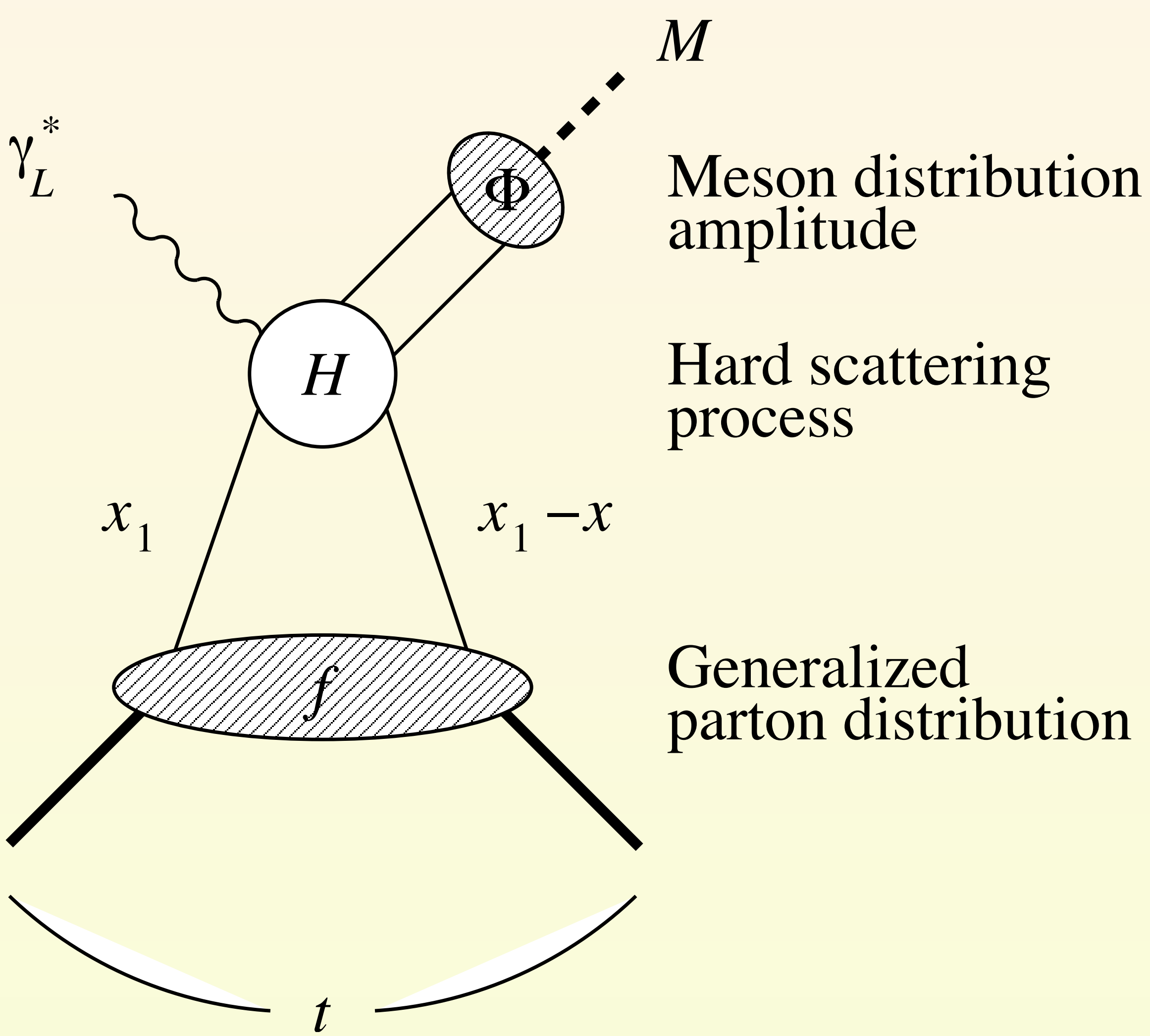
prediction

(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

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.



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

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.
- ☛ $l_{coh} = (0.4 \div 0.6\ \text{fm}\ )\ p_h\ [\text{GeV}] \ \rightarrow p_h = 6$ GeV corresponds $l_{coh} = 3$ fm $\sim 1/\sigma_{NN}\rho_0$

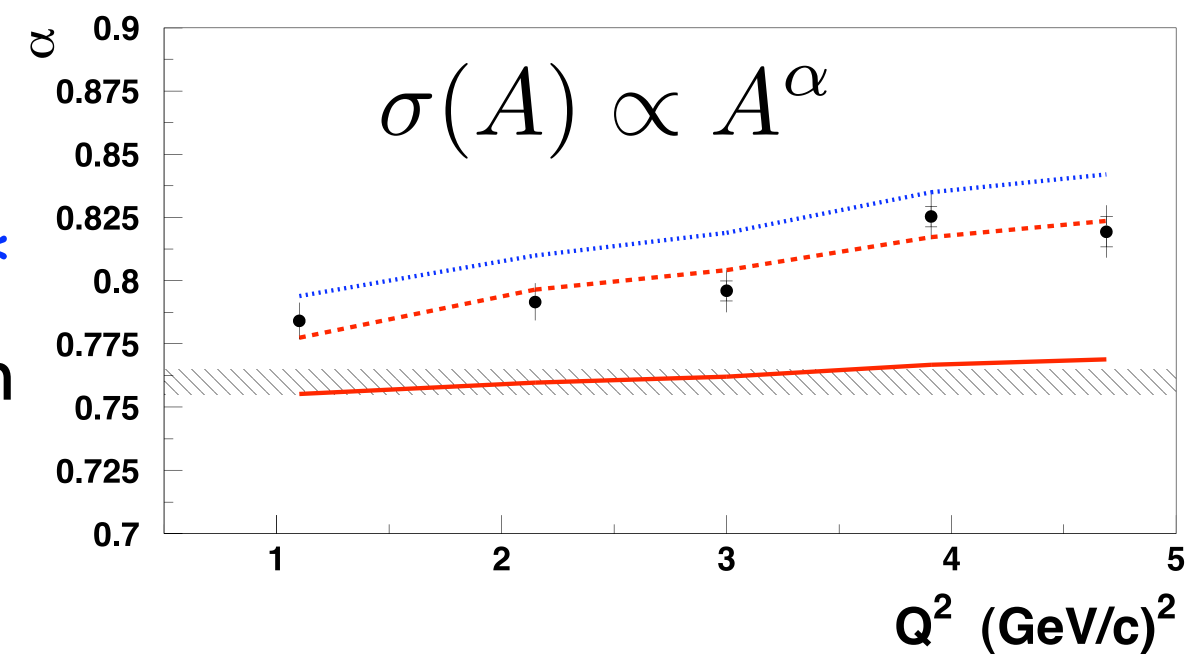
need high energies to see large CT effect even if squeezing is effective at lower energies

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.

- $\gamma^* + A \to \pi A^*$ evidence for increase of transparency with Q - (more details in Kawtar Hafidi talk)

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

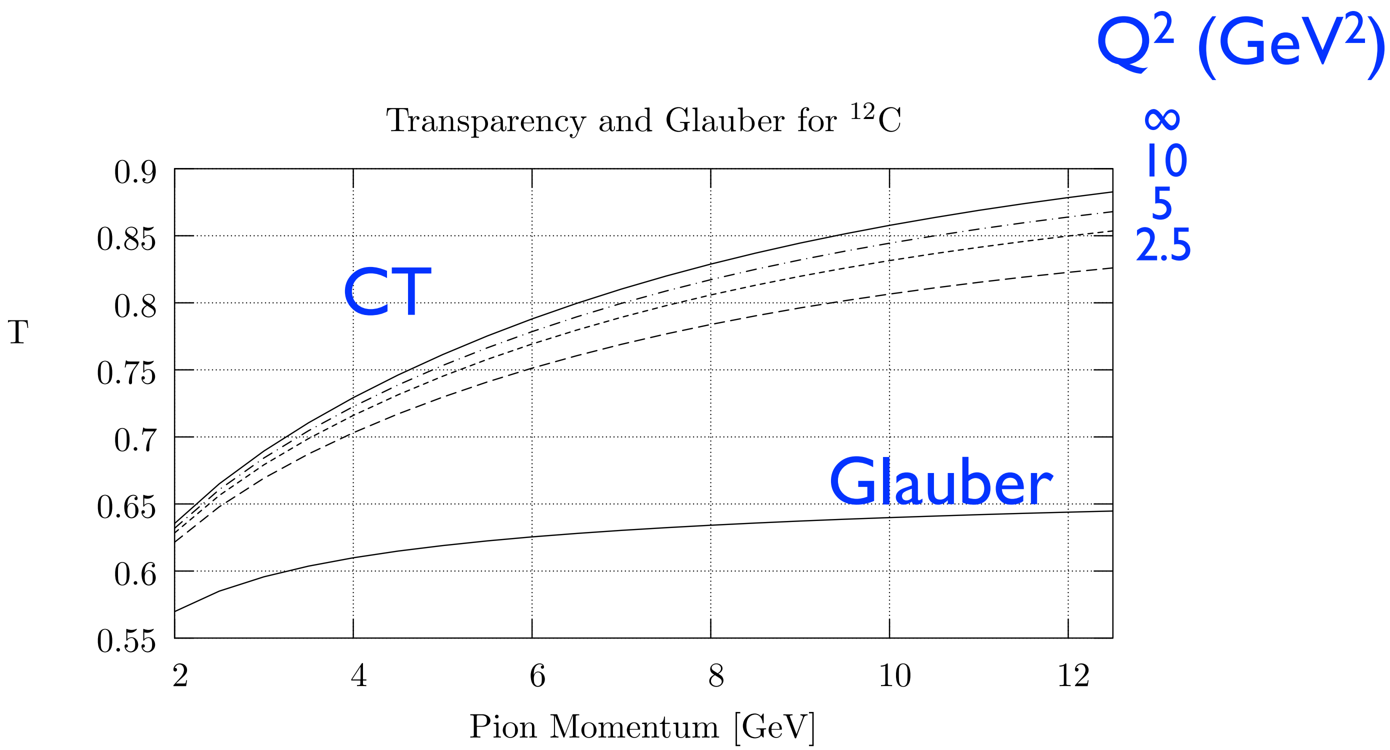


VM production

- CT is observed for $\gamma + A \to J/\psi + A$ at FNAL (Sokoloff et al)

- ρ -meson production at high energies - inconclusive - some evidence in incoherent scattering - E665, HERMES - missing energy is significant - hadrons can be produced - in principle a different type of process.

Critical test - experiments at 11 GeV a strong increase of the transparency with energy for fixed Q^2.



Diffusion model predictions (Larson, Miller, MS 06)

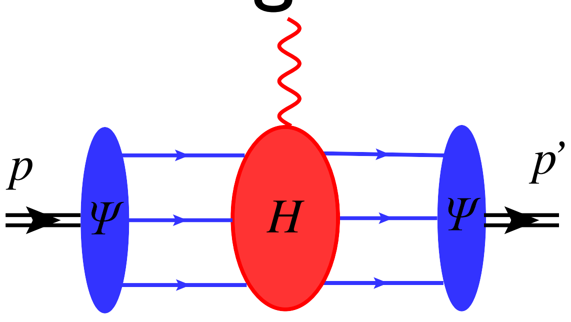
Gain in energy of a factor of two even for the same Q^2 should greatly improve freezing and hence amplify the effect

For large l_{coh} the CT effect is larger for heavy nuclei. Larger sensitivity to expansion than to degree of squeezing as soon as it is large enough.

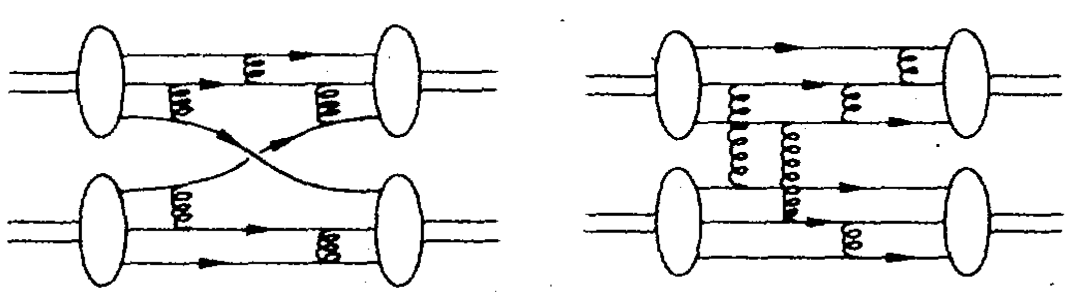
So far we do not understand the origin of **the most fundamental hadronic processes in pQCD -large angle two body reactions** (-t/s=const, s) π +p → π +p, p +p → p +p,... and even form factors

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



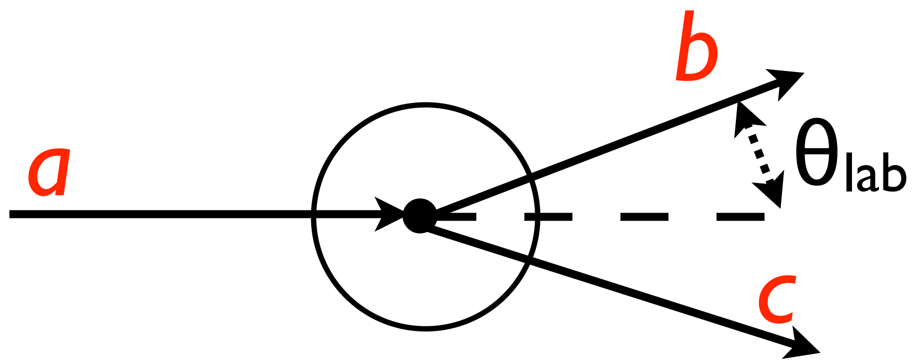
Typical pQCD diagrams for elastic pp scattering

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

Indicates dominance of minimal Fock components of small size:

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

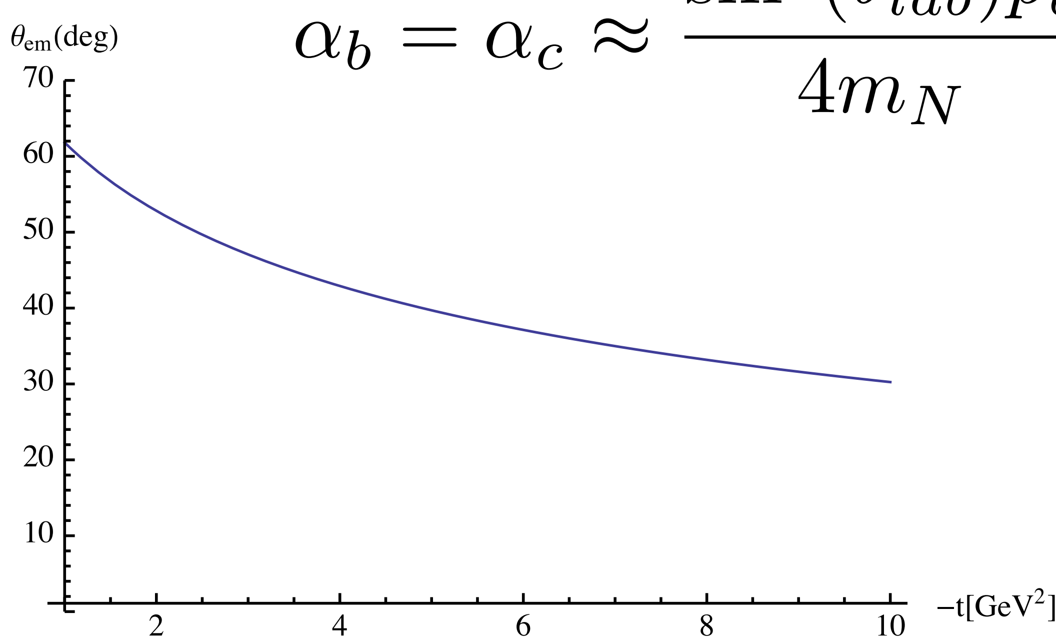
Kinematics for θ_{cm}=90°



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

Very good resolution in light-cone variable $\alpha_h=(E_h-p_{3h})/m_N$ for b, c

$$\alpha_b = \alpha_c \approx \frac{\sin^2(\theta_{lab})p_b}{4m_N}$$



Proton emission angle in the rest frame

Summary on exclusive two body reactions at large t

Spin =1 &3/2 are enhanced;
similar trend for pi - N scattering !!!

$$\frac{d\sigma(\gamma + p \rightarrow h + p)}{d\Omega_{c.m.}} = \frac{1}{s^7} f(\Omega_{c.m.})$$

7 → point γ

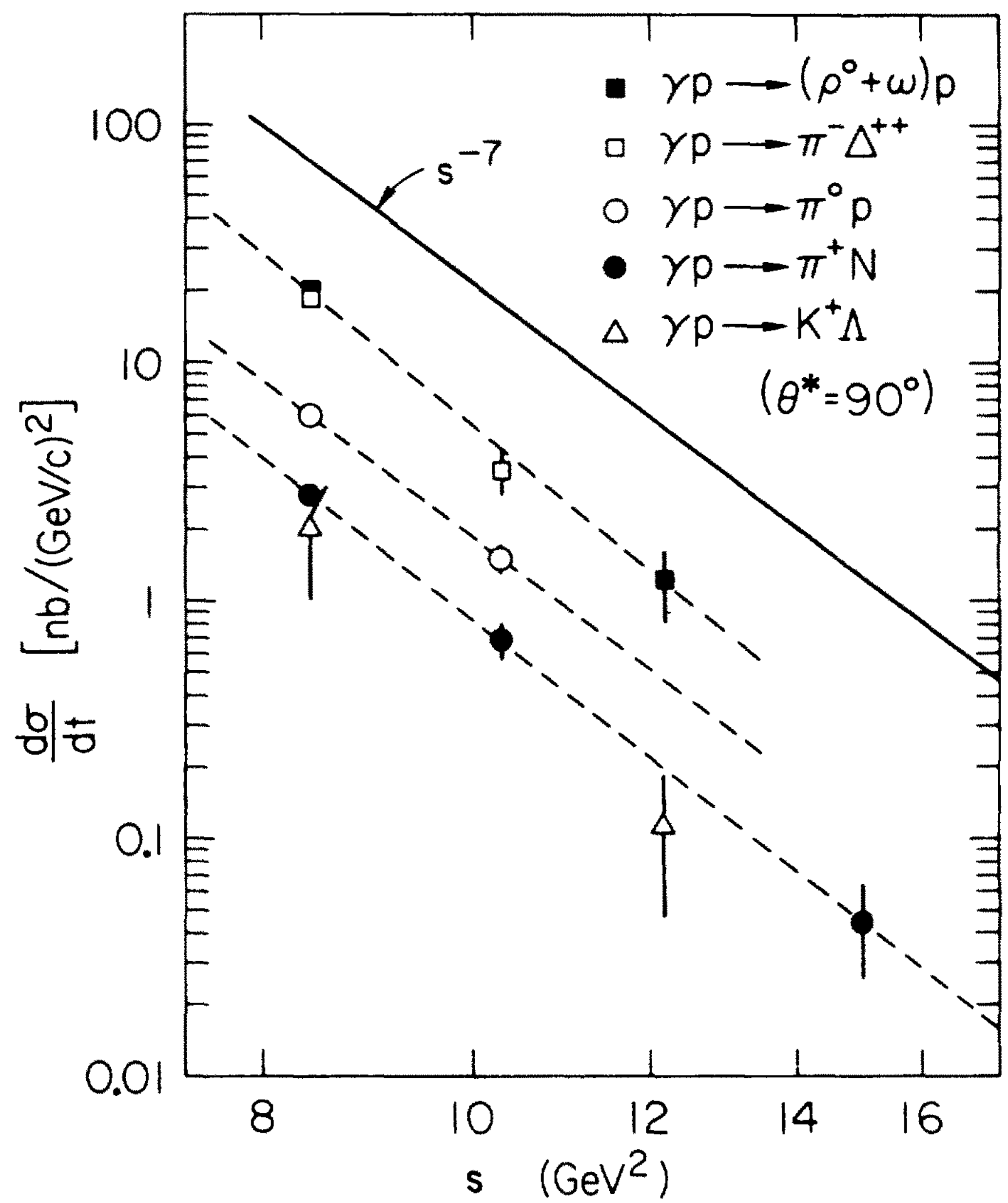
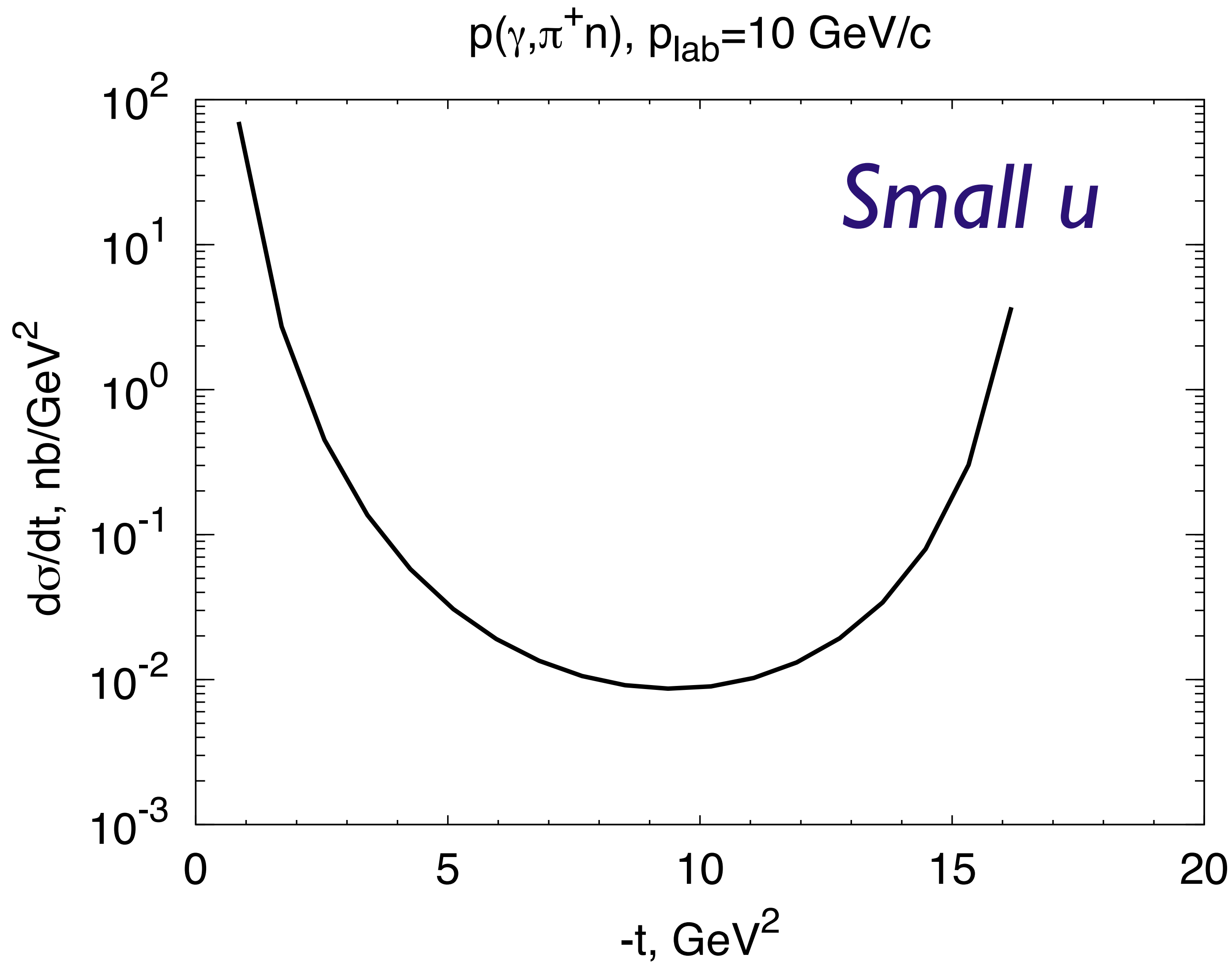


FIG. 19. 90° c.m. values of $d\sigma/dt$ versus s for some of the processes measured in this experiment. The function s^{-7} is shown as a solid line for reference, and the dashed lines represent the trend of the data.



The differential cross section of the γp → π+n scattering vs kinematic invariant −t at fixed beam momentum of 10 GeV/c.

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 $(\frac{d\sigma}{dt} \sim 1/s^{n-2})$
				n-2=8	
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		$8.3^{+0.6}_{-1.0}$
4	$K^- p \to pK^-$	18 ± 6	0.9 ± 0.9	n-2=8	≥ 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		≥ 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

Interesting regularity:

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

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

If quark exchanges dominates we expect if contribution of the wave function in the origin gives dominates

$$\frac{d\sigma^{K^+p\to K^+p}}{d\theta_{c.m.}}(\theta=90^o) / \frac{d\sigma^{\pi^+p\to \pi^+p}}{d\theta_{c.m.}}(\theta=90^o) \sim (f_K/f_\pi)^2 \sim 1.43$$

data ~1.69 ±.25

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

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

Similar pattern is observed at 9.9 GeV. There is an evidence of the change of the pattern at p=20 GeV but errors are too large. Overall it appears likely that these processes are dominated by short distances for -t> 5 GeV^2.
Measurements with photons + measurements with hadronic beams (J-PARC?) may clarify dynamics

Alternative approaches to pQCD minimal Fock state diagrams

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
- large angle Compton scattering

reminder: Jlab data contradict\ quark counting rules.

$$\frac{d\sigma(\gamma+p\to\gamma+p)}{d\Omega_{c.m.}} = \frac{1}{s^7} f(\Omega_{c.m.})$$ not $1/s^6$

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 $p\bar{p} \leftrightarrow \gamma\gamma$

Revealing mechanism of two body processes like $\gamma(\gamma^*) + N \to \gamma(\pi) + N$

and using them to understand hadronic structure of photon, compare interactions of different hadrons, CT

Three regimes to probe:

a) Discovering transition from regime of VDM photon to regime of unresolved photon acting as elementary particle (point-like)

$$t=-t_0 \sim 1 \div 2\ GeV^2$$

b) Exploring regime of geometric transparency for interaction of unresolved photon:

comparing strengths of interactions of various mesons (π, ρ, η, η', K^*,...), *baryons* (N,Δ)

c) Looking for onset of color transparency

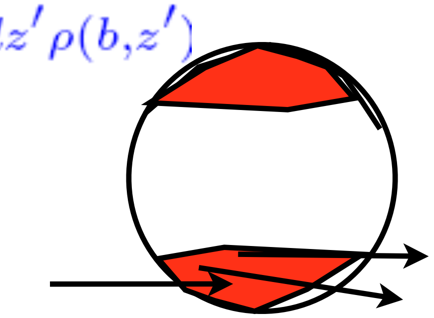
Revealing mechanism of two body processes like $\gamma(\gamma^*) + N \rightarrow \gamma(\pi) + N$

Question: at what t the processes become hard? At what t does transition occurs from hadronic to quark degrees of freedom?

(a) A rather fast change of A-dependence from $A^{1/3}$ to $A^{2/3}$

low transverse momentum transfer $|-t|$

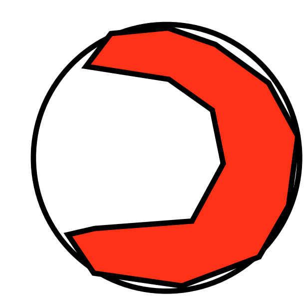
$$T_{\rm Low}(A) = \int d^2b \int_{-\infty}^{\infty} dz\, \rho(b,z) e^{-\sigma_{\rho N} \int_{-\infty}^{z} dz' \rho(b,z')} e^{-(\sigma_{\pi N}+\sigma_{NN}) \int_z^{\infty} dz' \rho(b,z')}$$



$$T_{\rm Low}(A) \propto A^{1/3}$$

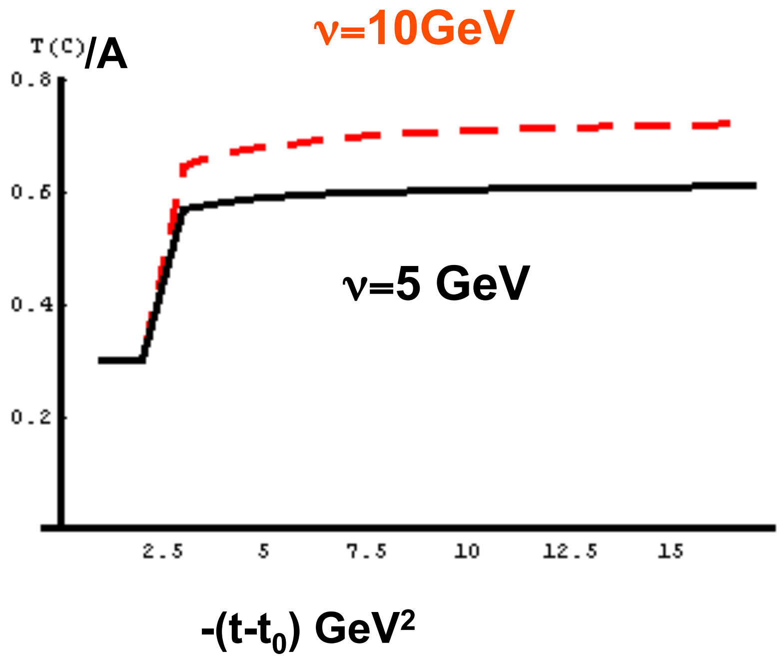
High transverse momentum transfer $|-t|$

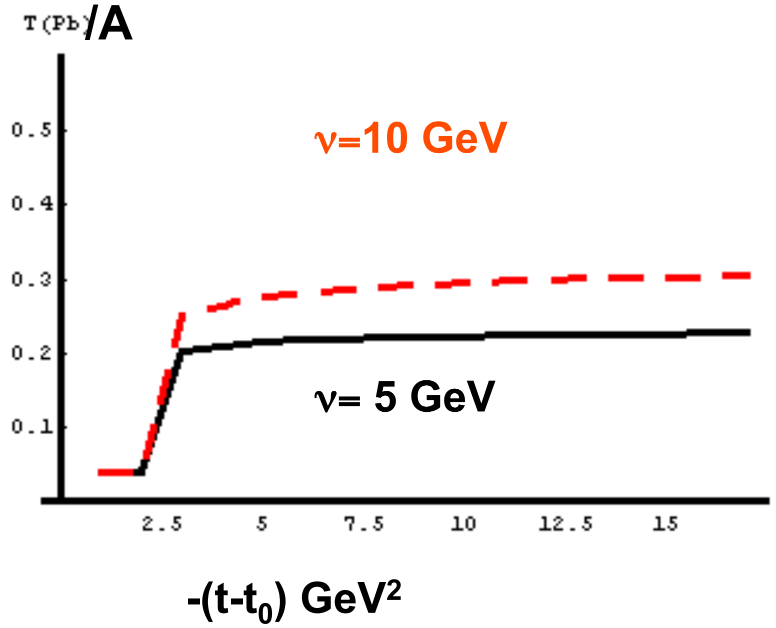
$$T_{\rm High}(A) = \int d^2b \int_{-\infty}^{\infty} dz\, \rho(b,z) 1 e^{-(\sigma_{\pi N}+\sigma_{NN}) \int_z^{\infty} dz' \rho(b,z')}$$



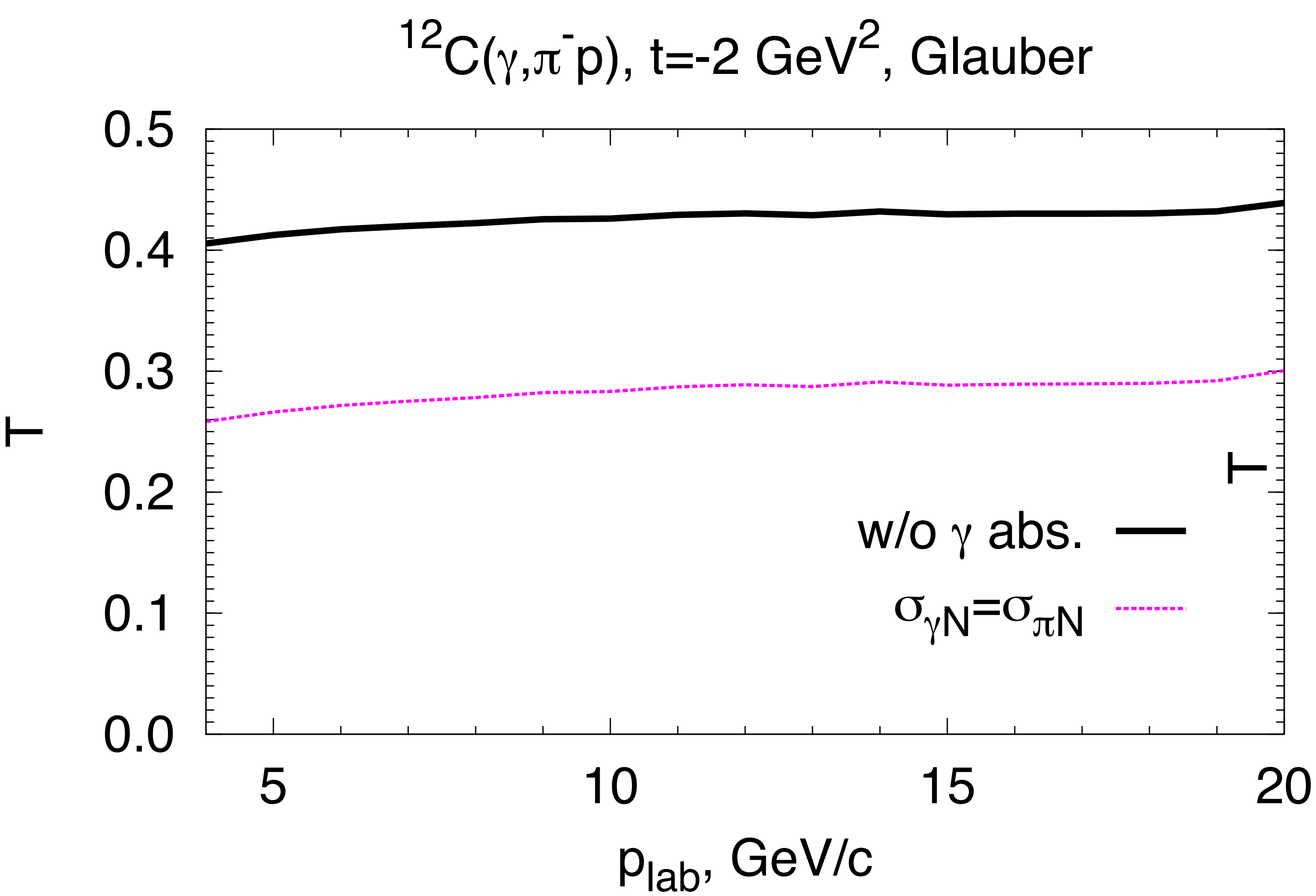
$$T_{\rm High}(A) \propto A^{2/3}$$

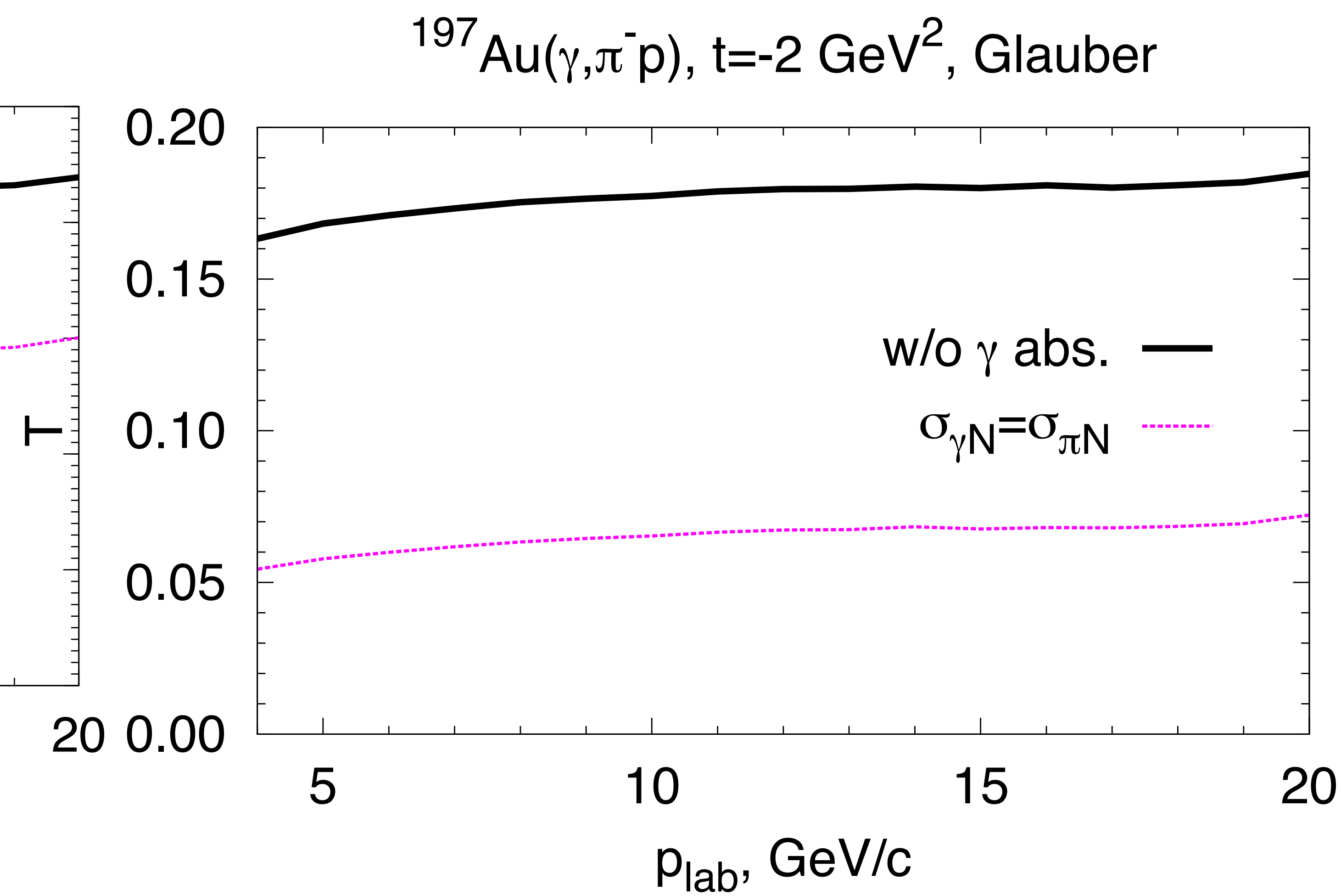
G.Miller and MS





Transition from "VDM" photon to point-like photon





A.Larionov & MS

AL&MS

Very large change of T near $t \sim t_0$

In the region of $-t \sim t0$ we can check squeezing of meson by detecting only meson but allowing only modest recoil masses to suppress soft pion production. In this case we expect approach to CT much earlier. If CT is observed it would be possible to measure nondiagonal nucleon GPDs at large t.

Exploring regime of geometric transparency for interaction of unresolved photon: comparing strength of interactions of mesons (π, ρ,η, η',K,...), baryons (N,Δ) with nucleons*

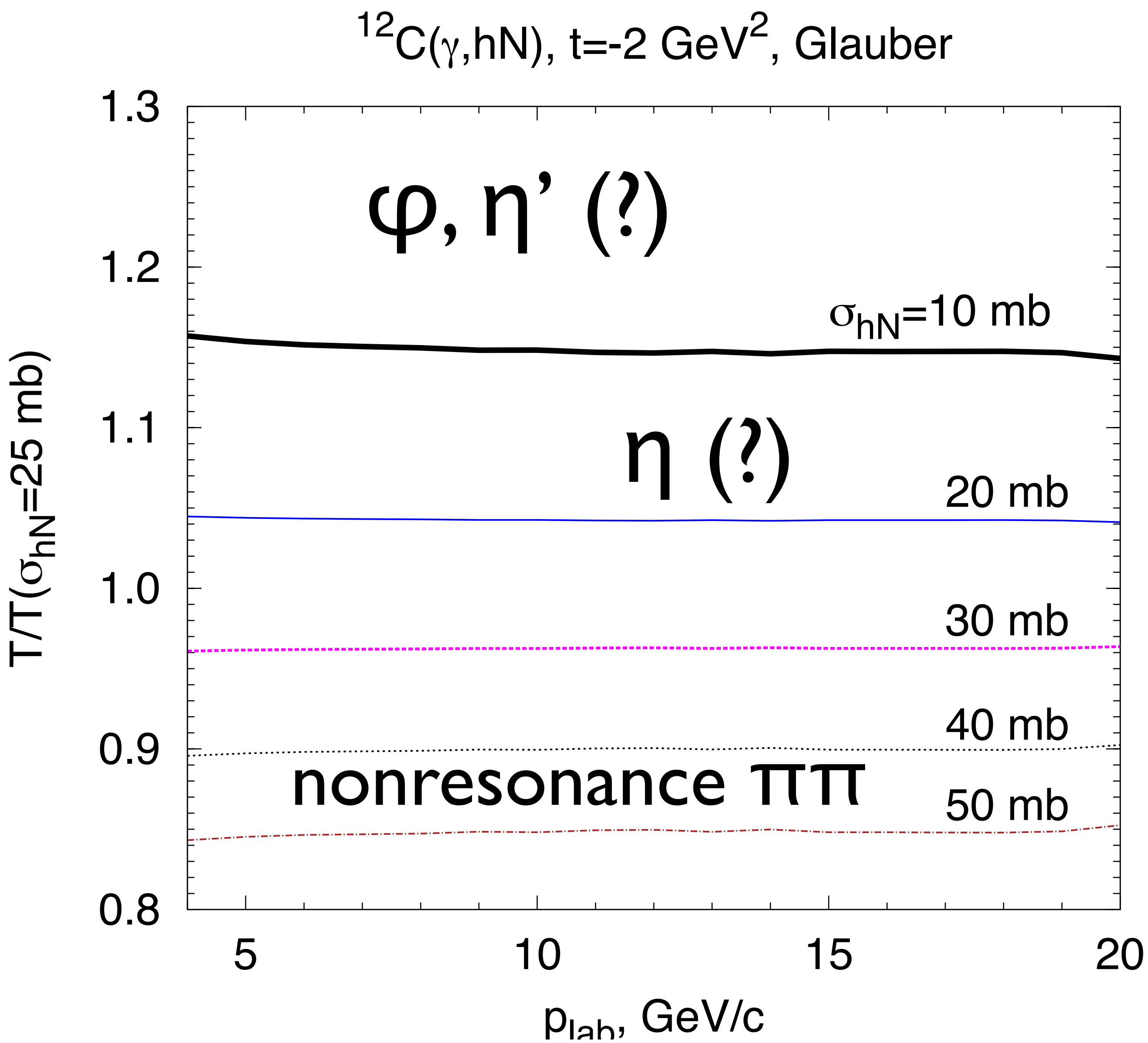
Starting point - Geometric model (semiclassical Glauber) works well in a large range of s,t.

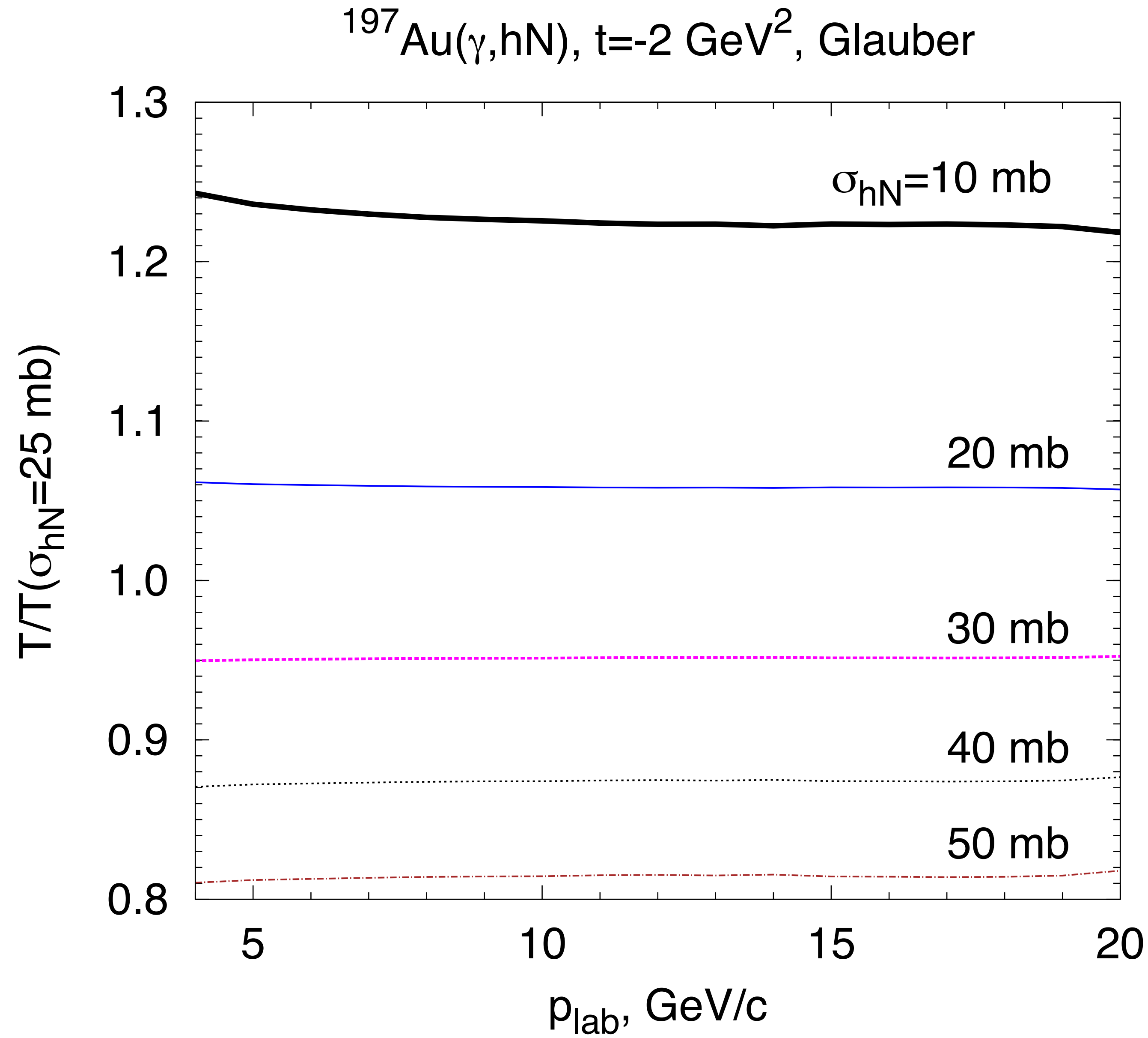
Double ratio

$$R(A) = \frac{\sigma(\gamma + A \to h_1 + N + (A-1)^*)}{\sigma(\gamma + A \to h_2 + N + (A-1)^*)} / \frac{\sigma(\gamma + N \to h_1 + N)}{\sigma(\gamma + N \to h_2 + N)}$$

is sensitive to $\sigma_{in}(h_1 N)/\sigma_{in}(h_2 N)$

R(meson/π)

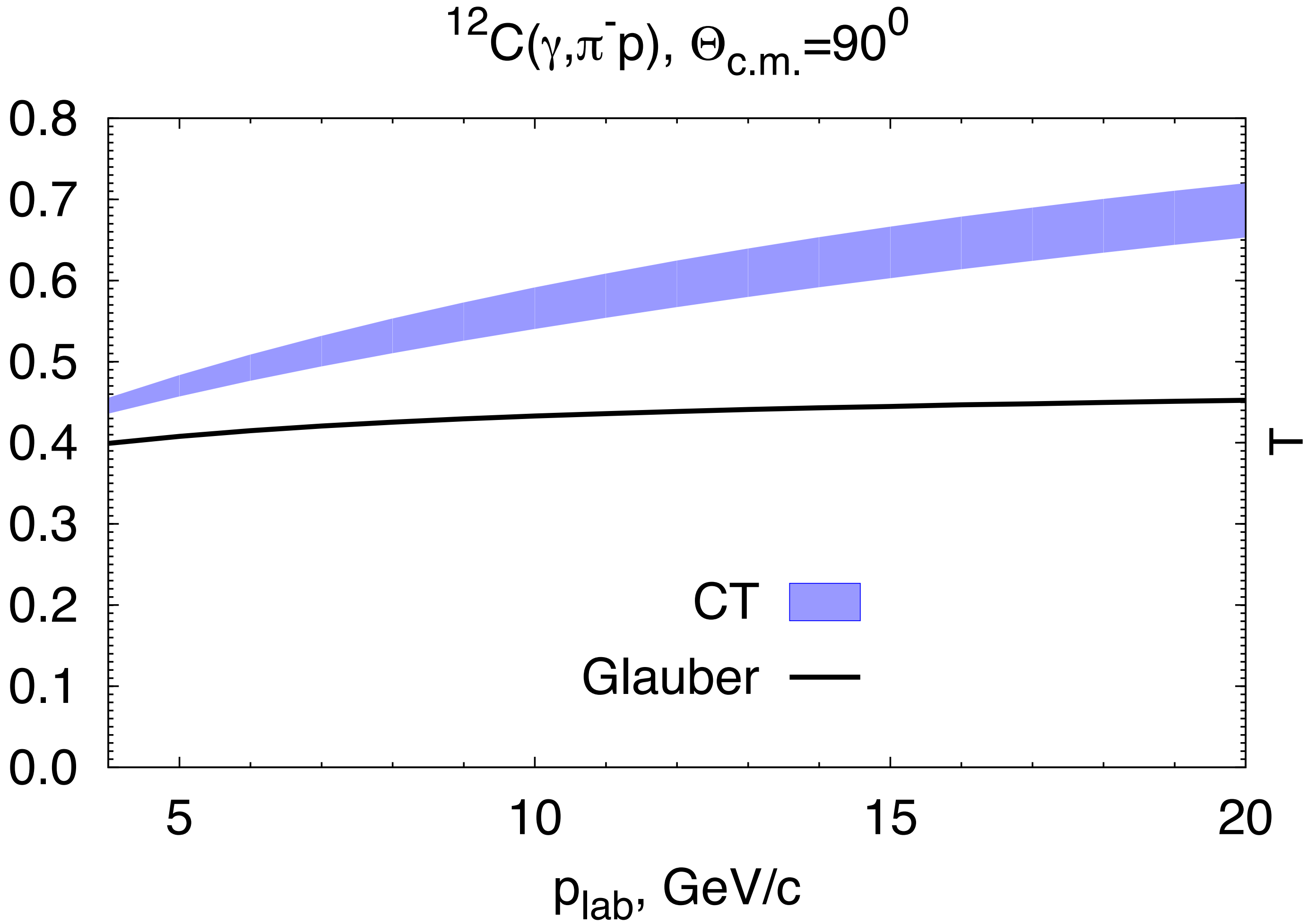


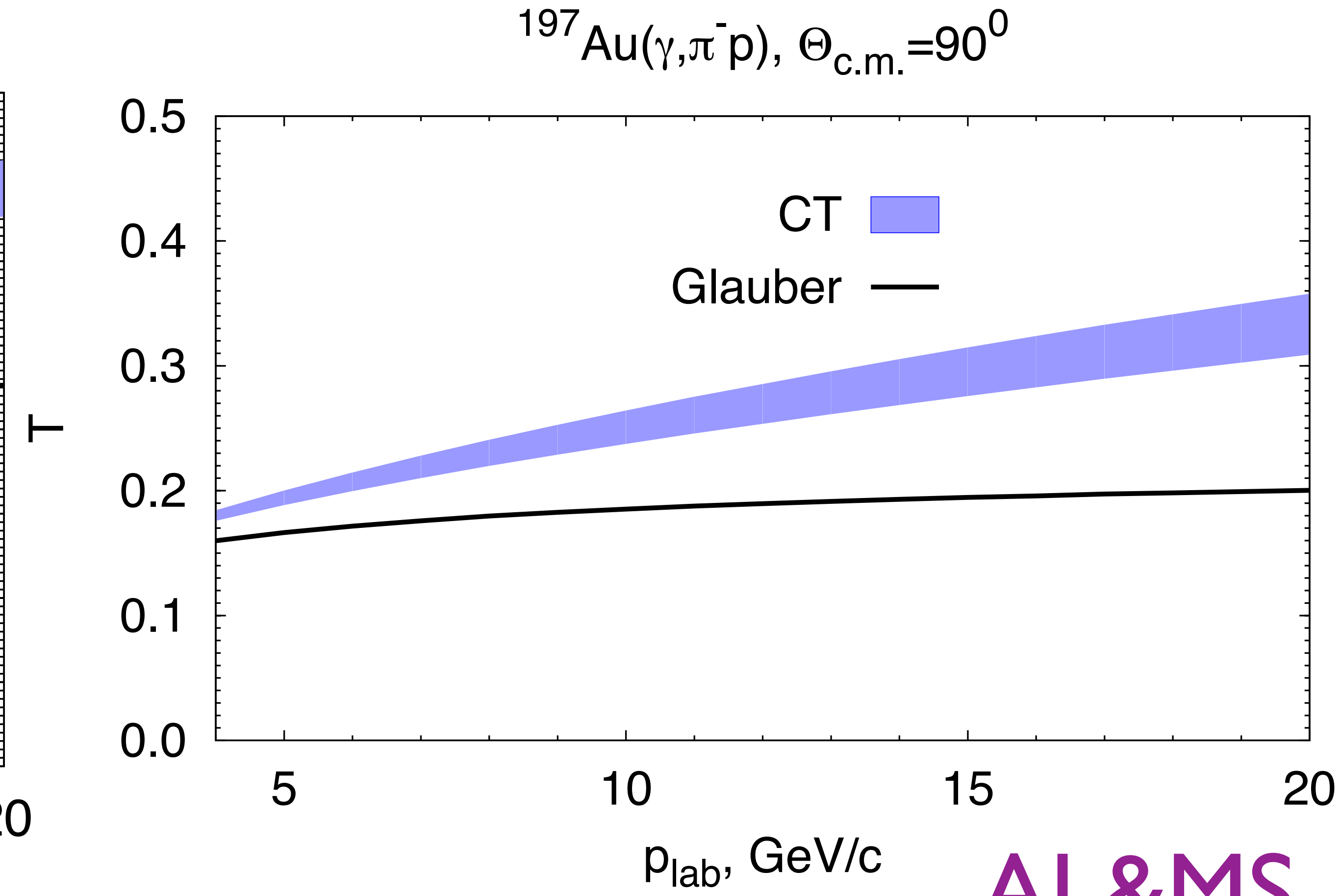


AL&MS

Side question - naively absorption of non-resonance system of say pion by nucleus is much larger than for a resonance - could it help resonances search program of Hall D

Testing squeezing of hadrons in large angle processes - color transparency. Jlab confirmed our estimates of the rate and pattern of space - time evolution of quark - antiquark wave packages. Under otimistic assumption that squeezing starts for -t ~ 1 GeV2 one finds a significant increase of transparency





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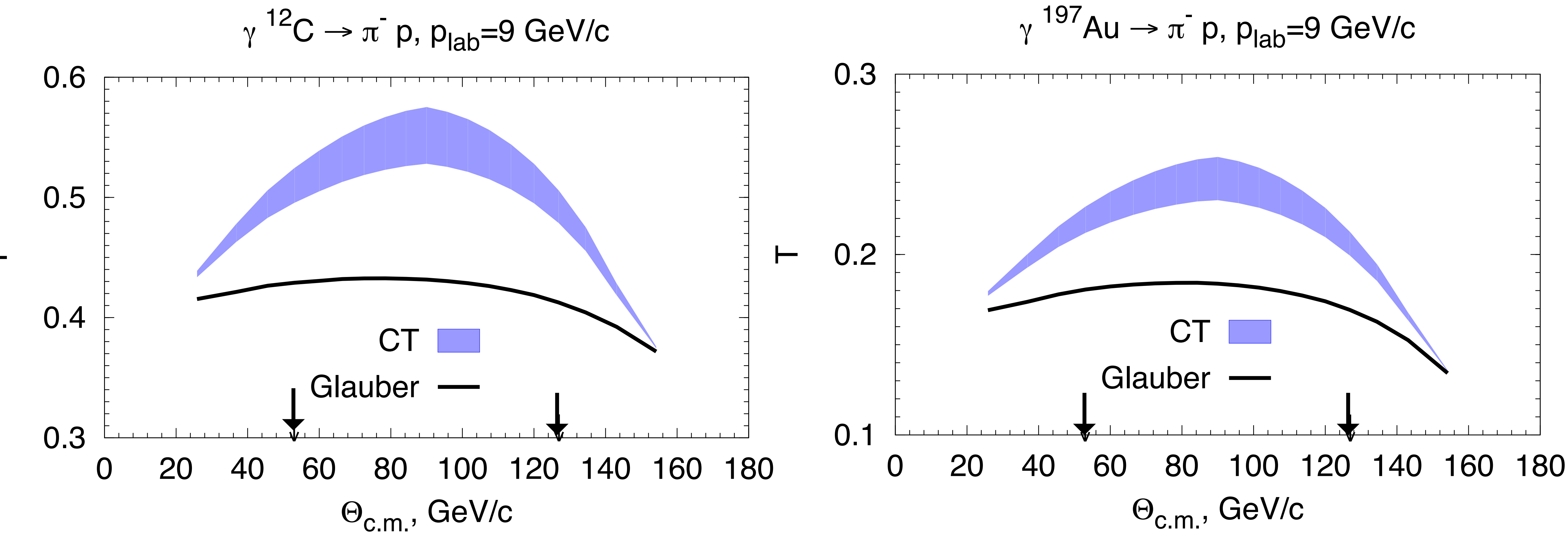
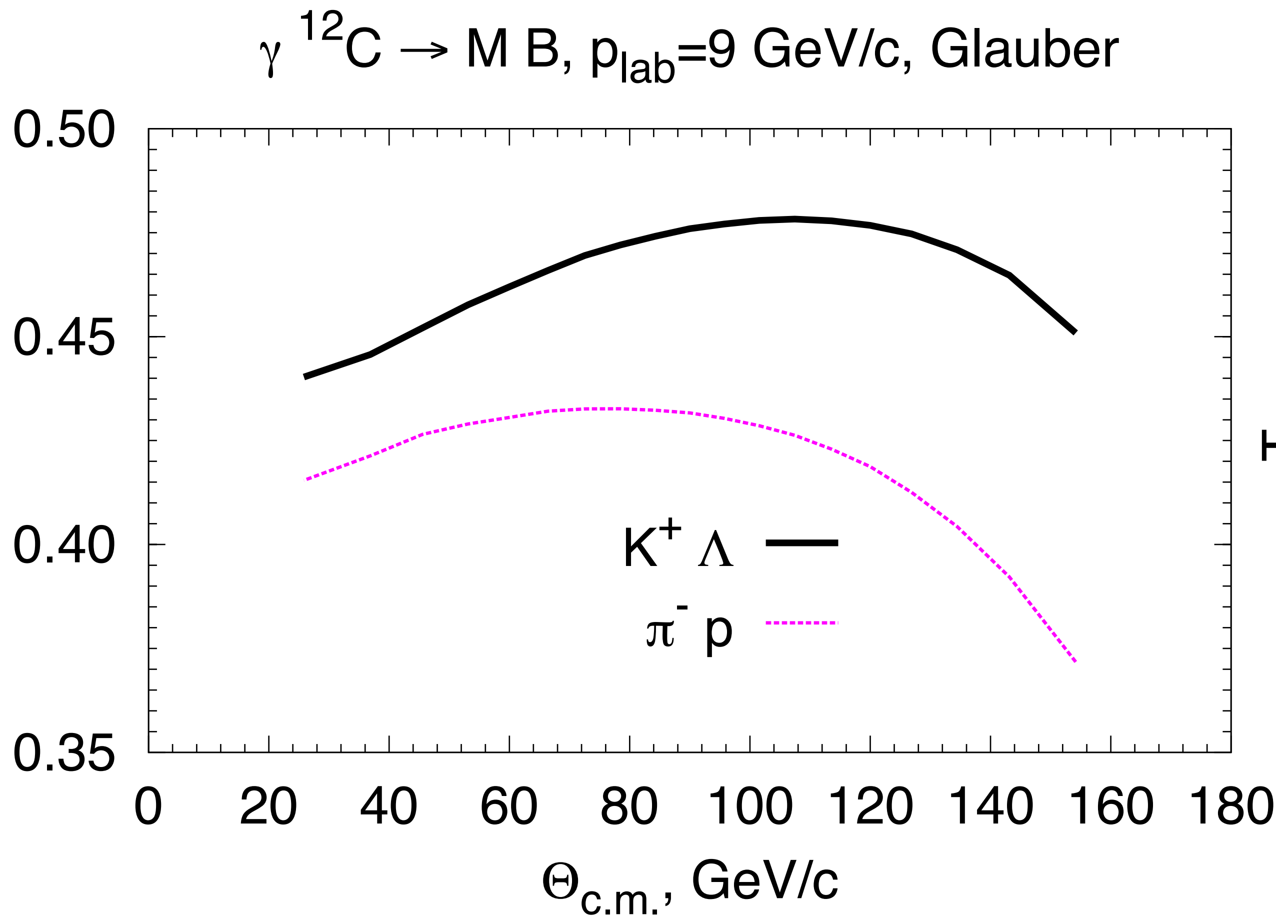
The bands are CT calculations with a fast squeezing, unresolved photon and $\Delta M^2 = 0.7\ (1.1)\ \mathrm{GeV}^2$

Spin dependent CT effects?

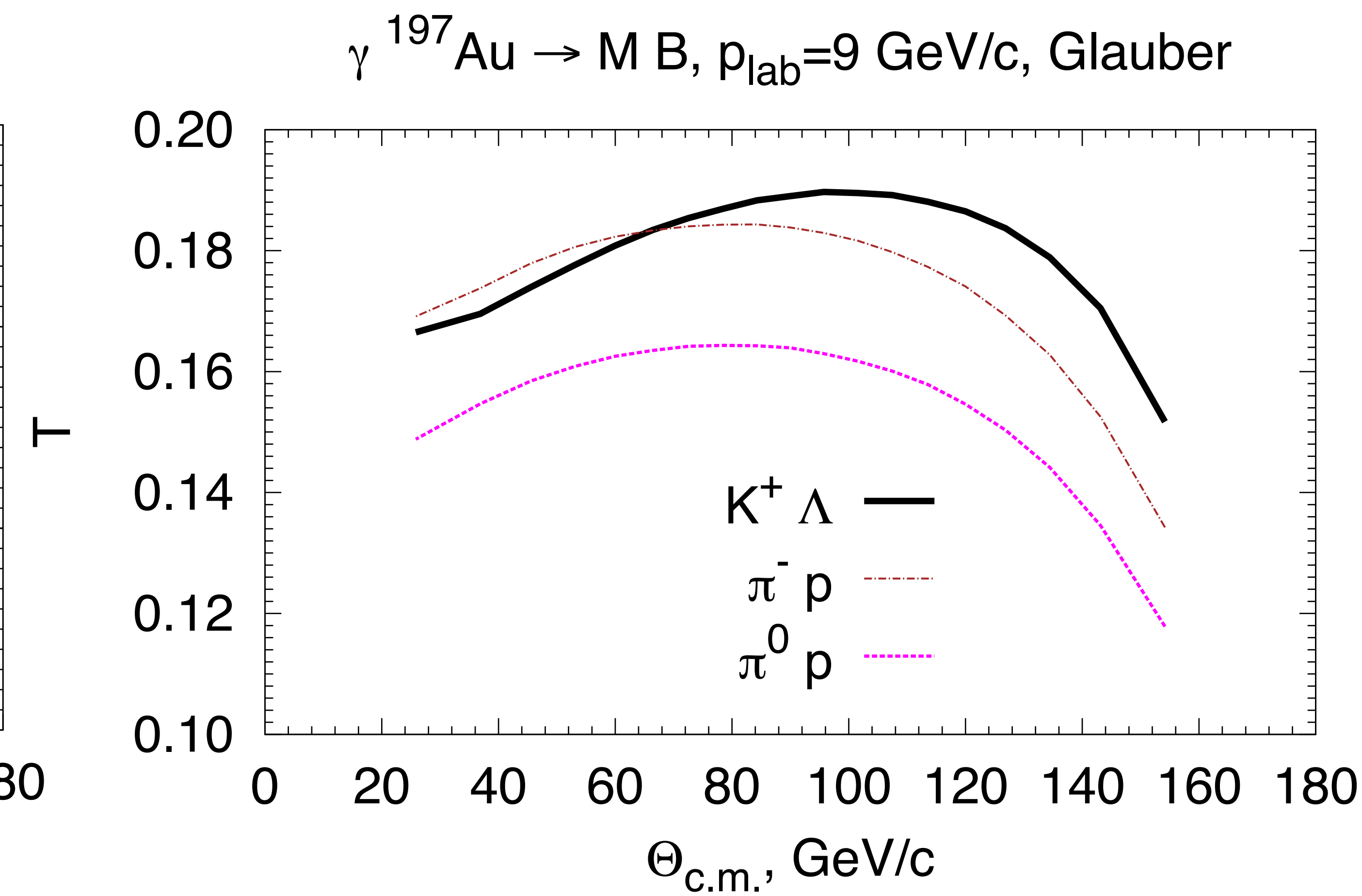


AL&MS

The transparency for the $^{12}C(\gamma,\pi^- p)$ $^{197}Au(\gamma,\pi^- p)$ semiexclusive processes at p_{lab} = 9 GeV/c vs $-t$ assuming that squeezing is determined by min{-t,-u} (↓ -t,& -u > 3 GeV^2 ↓)



$\gamma\ ^{12}C \to$ M B, p_{lab}=9 GeV/c, Glauber
0.50
0.45
0.40
0.35
0
20
40
60
80
100
120
140
160
180
$\Theta_{c.m.}$, GeV/c
$K^+\ \Lambda$
π^- p



$\gamma\ ^{197}Au \to$ M B, p_{lab}=9 GeV/c, Glauber
T
0.20
0.18
0.16
0.14
0.12
0.10
0
20
40
60
80
100
120
140
160
180
$\Theta_{c.m.}$, GeV/c
$K^+\ \Lambda$
π^- p
π^0 p

AL&MS

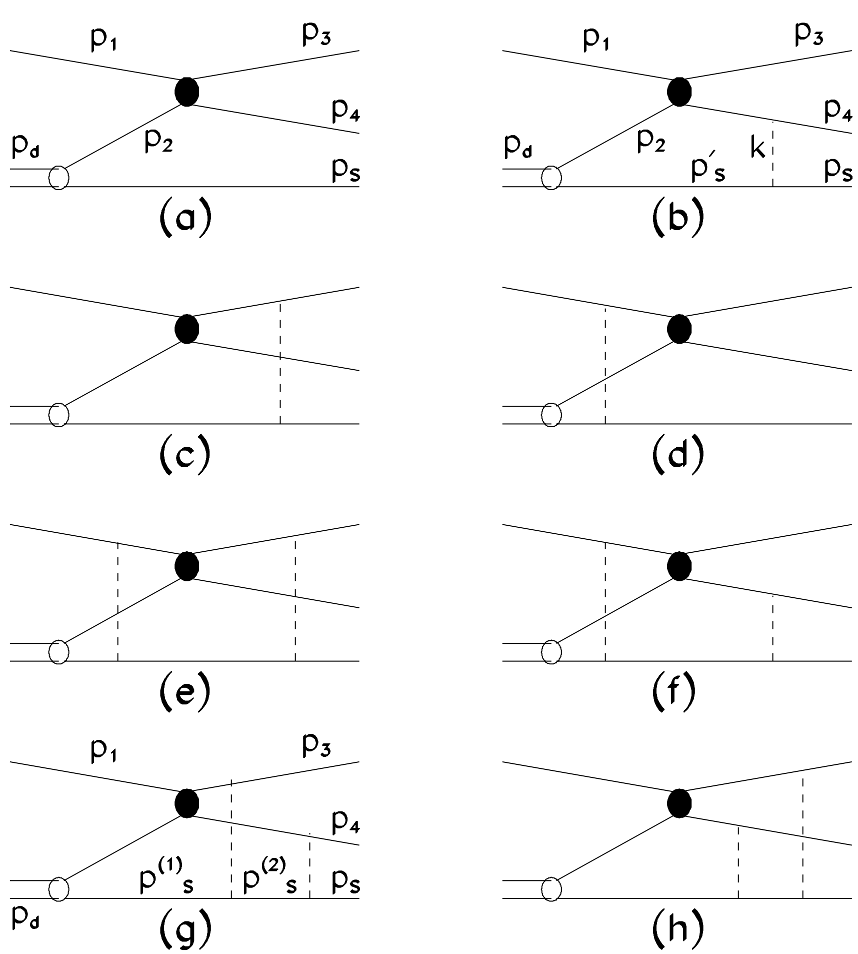
Summary: Two body large angle reactions with nuclei would allow to reveal interplay of hard and soft components of photon, compare properties of different mesons, discriminate between different reaction mechanism.

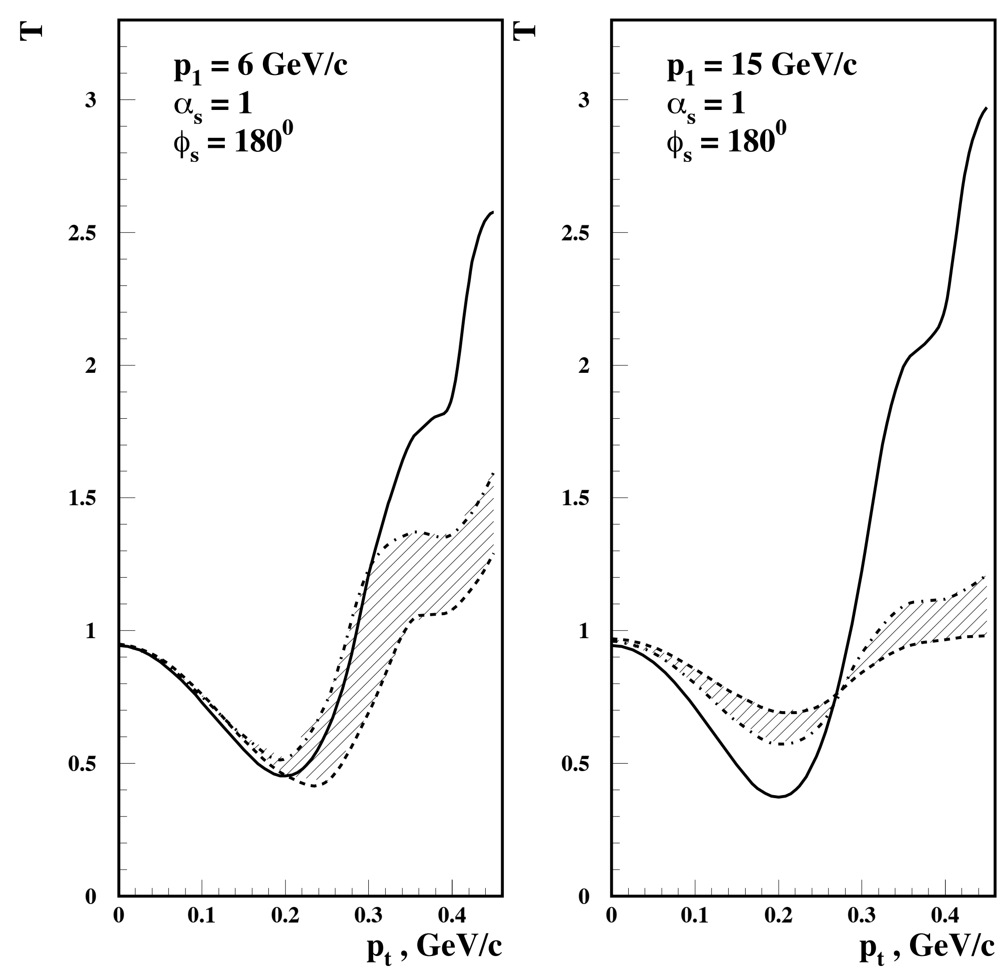
The same experiment will allow to study short-range structure of nuclei (next two talks)

Reactions with the lightest nuclei - precision tools

Use of the process $\gamma D \to \pi^- pp$ 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. Analog of the process we considered (Frankfurt , Piasetzky, Sargsian, MS)

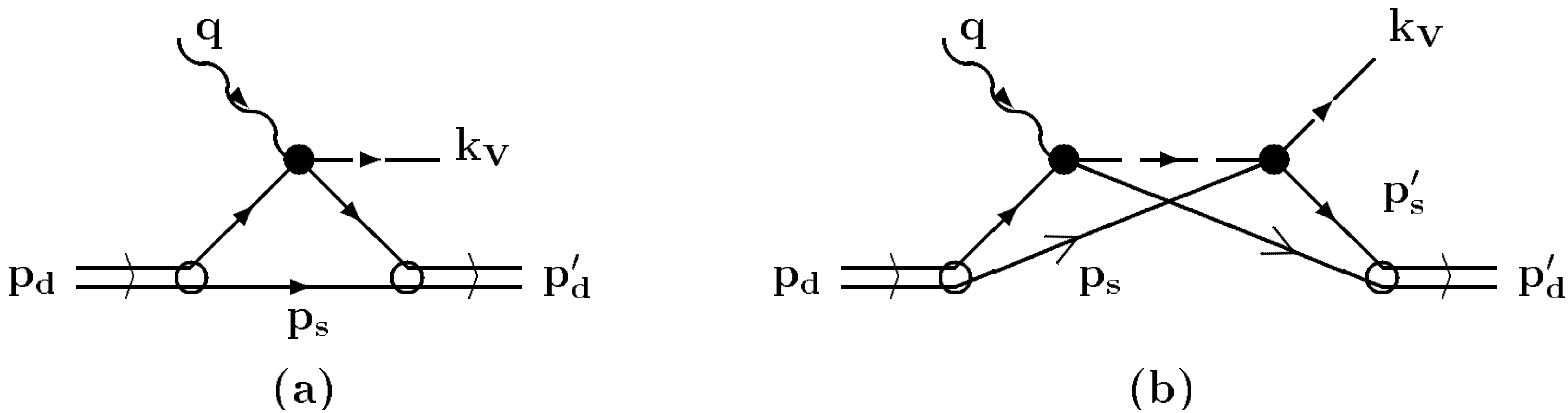
$pD \to ppn$

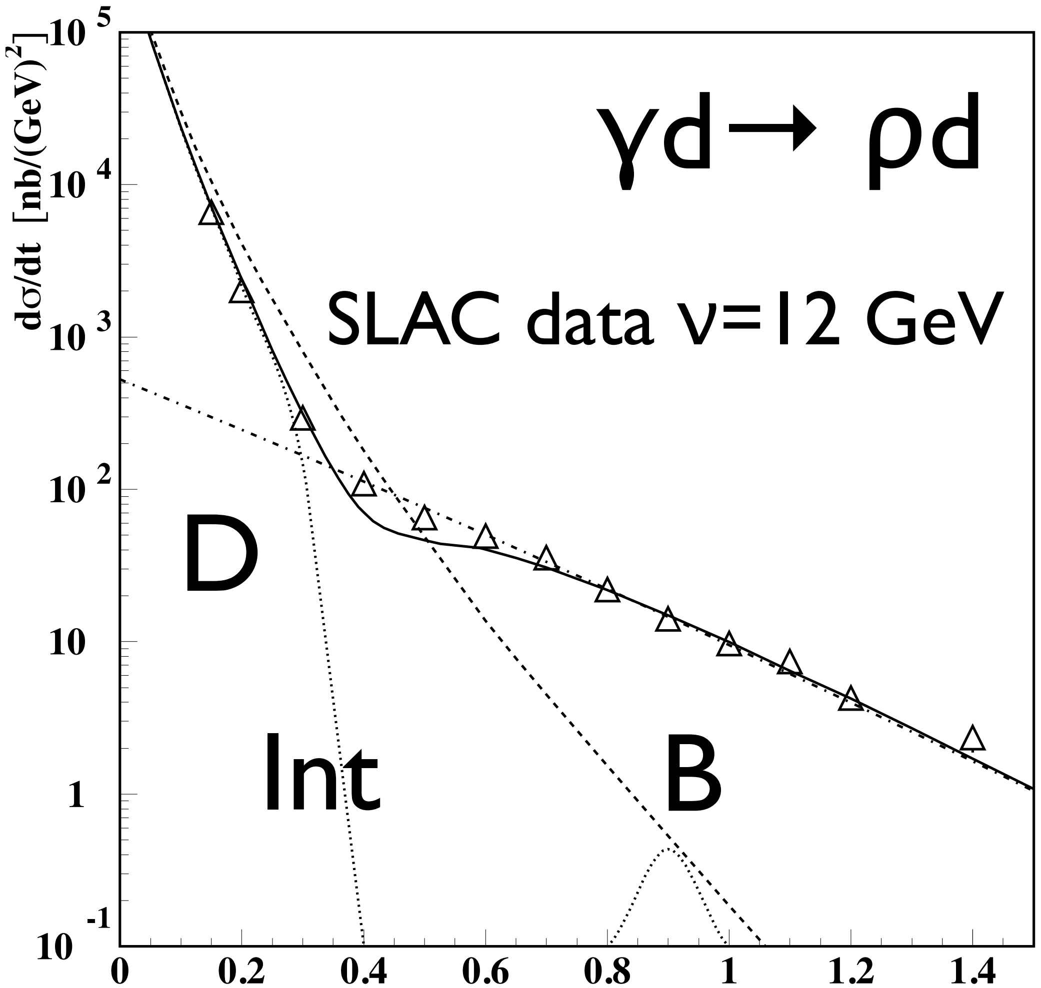


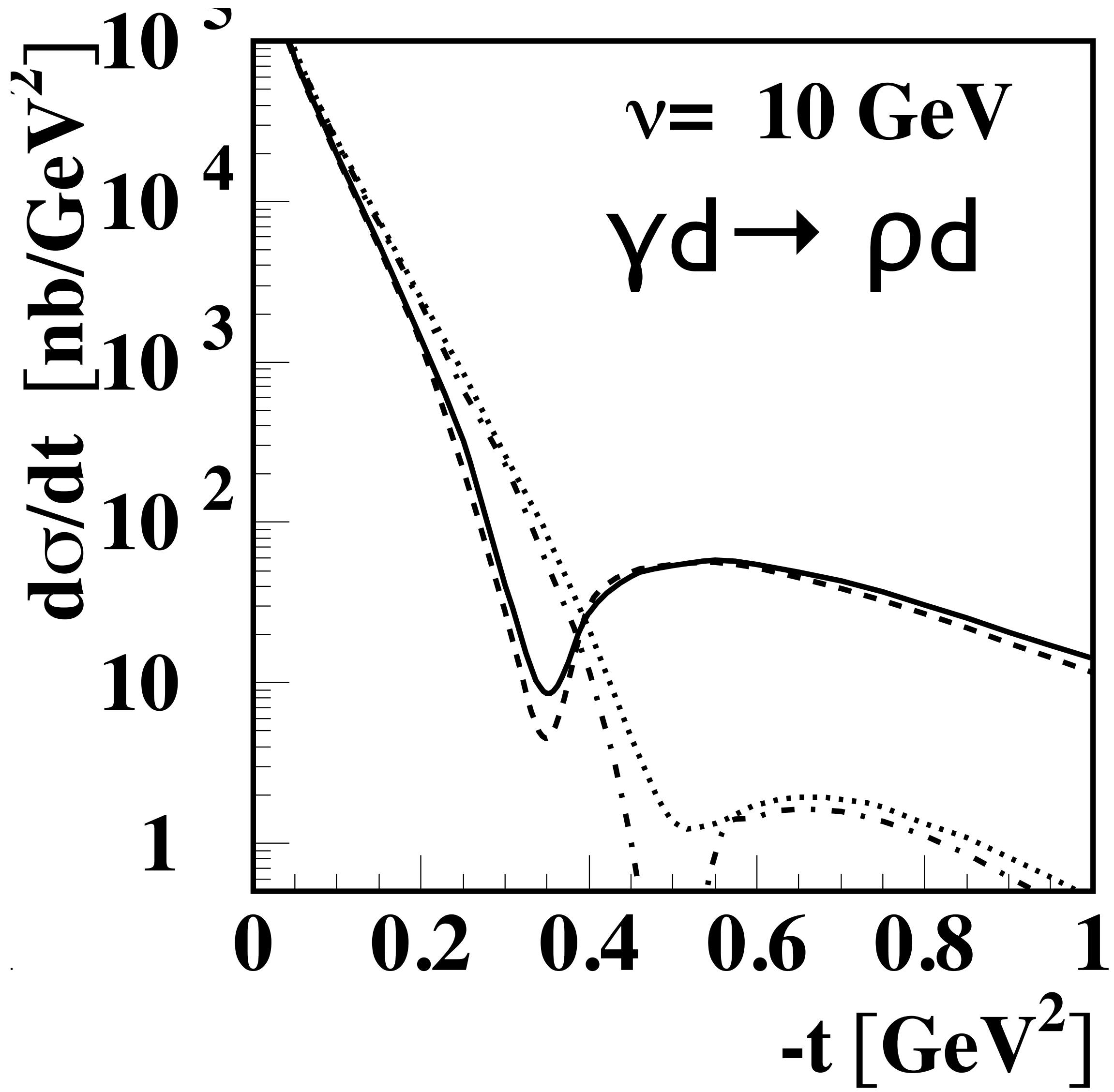


polarized D even better)

Coherent processes







D= double, B- Born

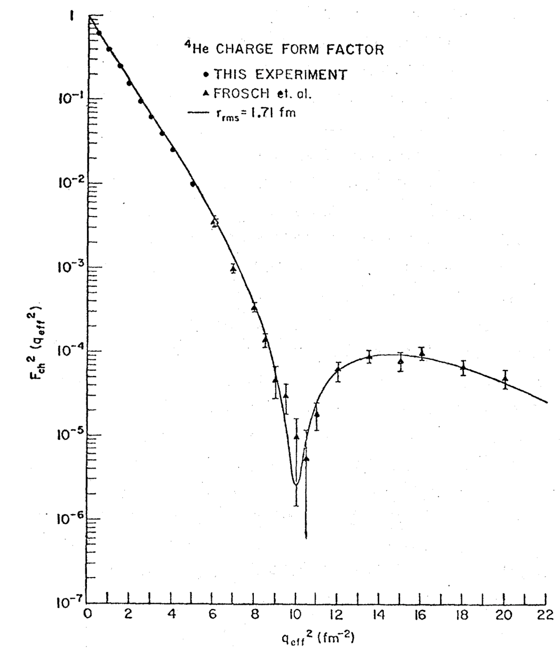
deuteron with polarization along photon momentum with m=0

easier to explore coherent interactions with two nucleons

Piller, Sargsian, LF, MS

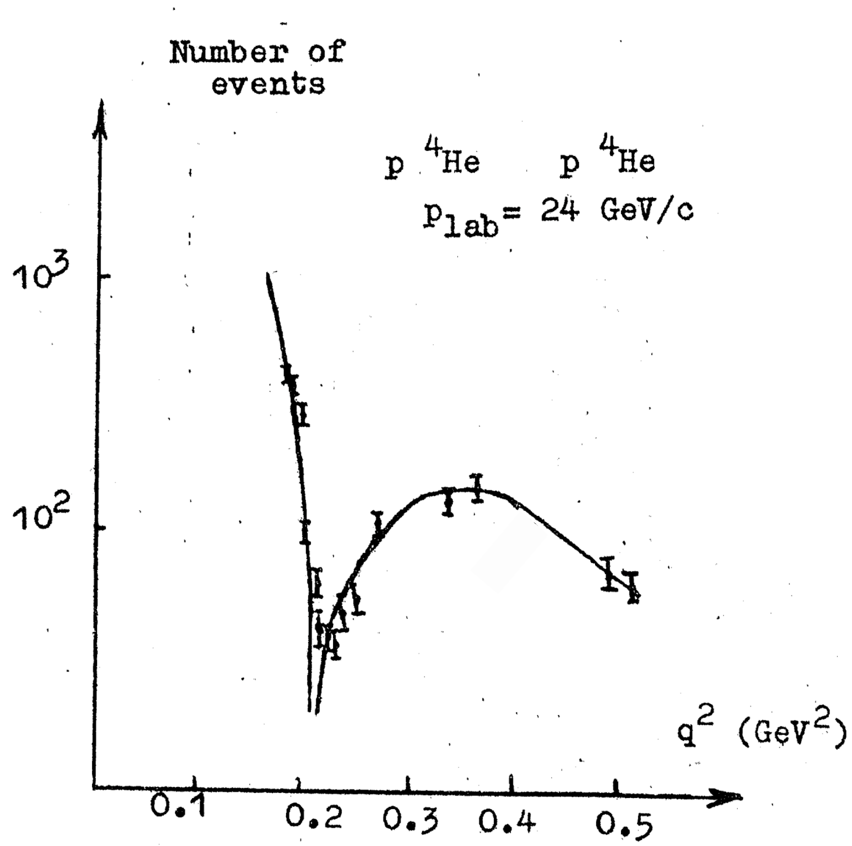
- Coherent scattering of ^{4}He. Simple nucleus with significant rescattering probability and negligible triple rescattering at not too large -t.

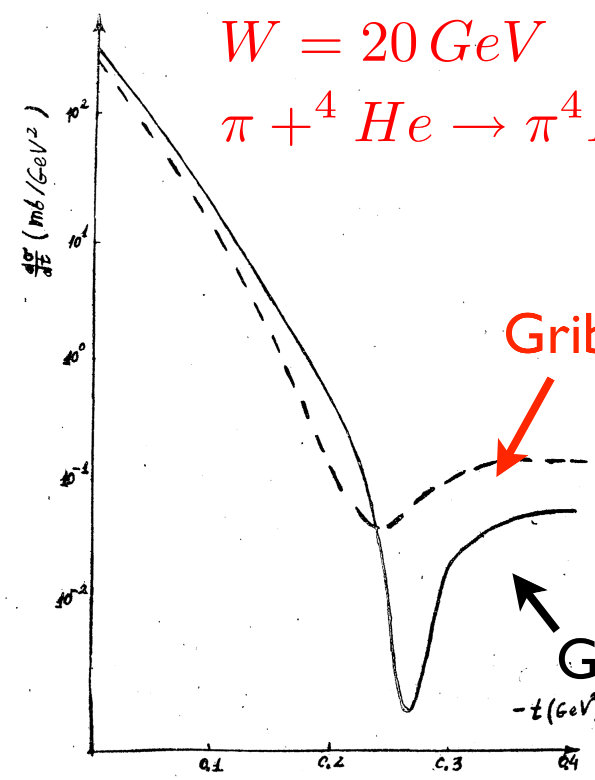
McCarthy et al



e.m. form factor goes through 0 at -t ~ 0.4 GeV^2

⇒ *strong sensitivity to double scattering starting at -t ~0.1 GeV^2*





$W = 20\,GeV$

$\pi + {}^4He \rightarrow \pi\, {}^4He$

Gribov- Glauber

Glauber

Strong sensitivity of the shape to the strength of double scattering

Levin & MS 75

Conclusions

Studies of two body large angle photoproduction of nuclei would

explore transition between point-like and soft photon regimes

compare global properties of various mesons and hadrons

study onset of color transparency regime

provide new effective probe of the short range nuclear structure

next two talks

Further precision studies with 2H (polarized?) & ^{4}He