Revealing the nucleon and nucleus short-range structure in large t (semi) exclusive processes

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Physics program for the first stage of the NICA SPD experiment

Questions involved in studies of the short-range / high momentum nuclear structure and understanding global nucleon structure and dynamics of large momentum transfer processes are delicately intertwined. Energy range of NICA is similar to the one investigated before at fixed target facilities.

However motivation is different - going beyond single parton densities - parton - parton correlations, etc. Hence interest in large momentum transfer semi/exclusive processes with rather small cross sections, detection of many body final states requiring acceptance over wide range of angles and momenta and one can benefit from a collider kinematics and nearly 4π acceptance

Outline

study of the properties on cold dense nuclear matter - structure of the short-range correlations (SRC)

large angle two body processes

color transparency phenomena

branching processes and GPDs

which of the processes discussed in the talk can be measured at the first stage and which have to wait till the second stage requires further numerical studies

Study of short range/ high momentum/ high density (a core of neutron star level) nucleon correlations in nuclei

Experience of quantum field theory - interactions at different resolutions (momentum transfer) resolve different degrees of freedom - renormalization,.... No simple relation between relevant degrees of freedom at different scales.

$\boxed{\text{➟ Complexity of the problem}}$

Three important energy momentum transfer scales in structure (interactions with) nuclei with different role of low momentum nucleons ($k< k_F$ -naive estimate of the highest momenta in nuclei for non-interacting gas) *and high momentum nucleons due to local NN interactions (slow decrease with k distribution).*

Three important scales

① To resolve nucleons with $k < k_F$, one needs $Q^2 \geq 0.8\ GeV^2$.

related effect: Q^2 dependence of quenching

② Hard nuclear reactions I: energy transfer > 1 GeV and momentum transfer q > 1 GeV.

$$q_0 \geq 1GeV \gg |V_{NN}^{SR}|, \vec{q} \geq 1GeV/c \gg 2\ k_F$$

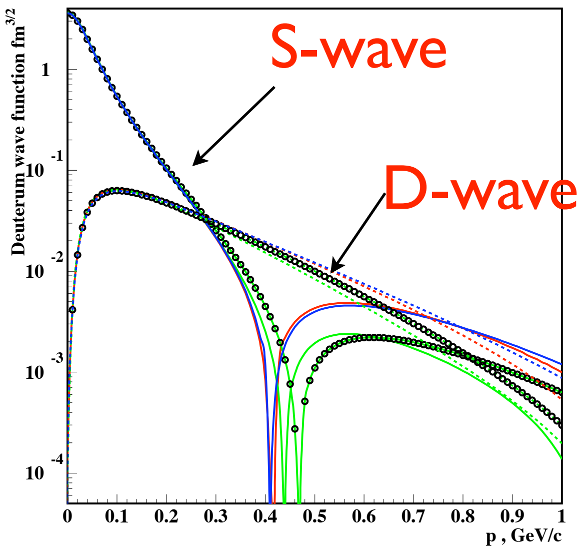
Sufficient to resolve short-range correlations (SRCs) = direct observation of SRCs but not sensitive to quark-gluon structure of the constituents

Principle of resolution scales was ignored in 70's leading to believe that SRC could not be unambiguously observed. Hence very limited data

③ Hard nuclear reactions II: energy transfer ≫ 1 GeV and momentum transfer q ≫ 1 GeV. May involve nucleons in special (for example small size configurations). Allow to resolve quark-gluon structure of SRC: difference between bound and free nucleon wave function, exotic configurations

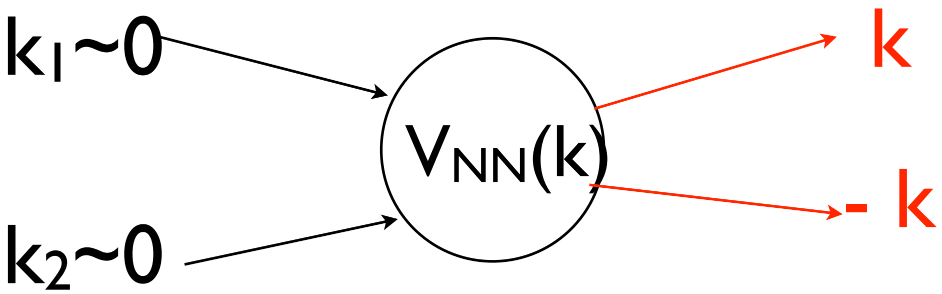
Properties of SRCs - a brief summary

Realistic NN interactions - NN potential slowly (power law) decreases at large momenta -- nuclear wf high momentum asymptotic determined by singularity of potential:



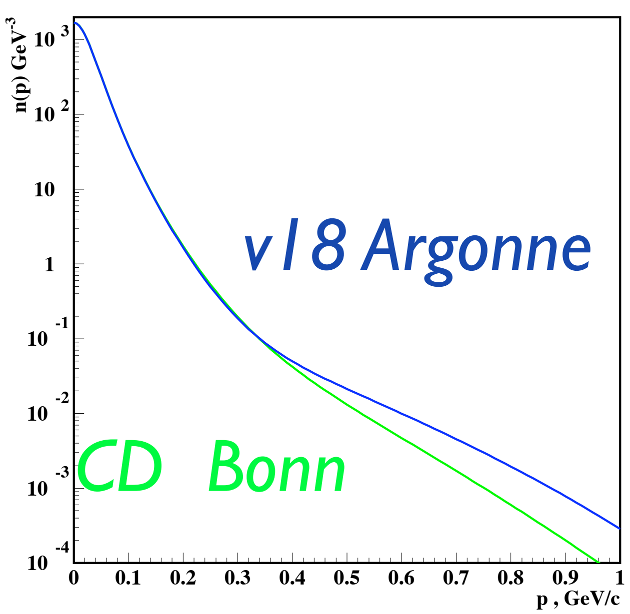
Deuteron wave function

$$\psi_D^2(k)_{|k\to\infty} \propto \frac{V_{NN}^2(k)}{k^4}$$



D-wave dominates in the Deuteron wf for 300 MeV/c < k < 700 MeV/c

D-wave is due to tensor forces which are much more important for pn than pp



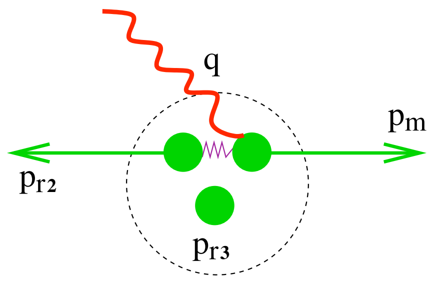
Tensor forces are pretty singular ➟ manifestations very similar to *shorter* range correlations - so we refer to both of them as SRC

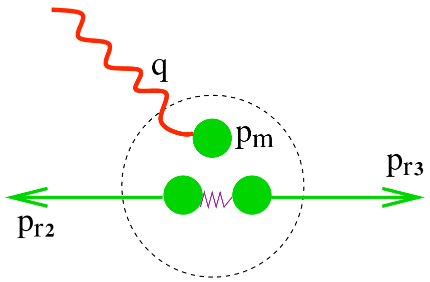
Large differences between in $n_D(p)=\psi^2_D(p)$ for $p>0.4$ GeV/c - absolute value and relative importance of S and D waves between currently popular models though they fit equally well pn phase shifts. Traditional nuclear physics probes are not adequate to discriminate between these models.

Operational definition of the SRC: nucleon belongs to SRC if its instantaneous removal from the nucleus leads to emission of one or two nucleons which balance its momentum: includes not only repulsive core but also tensor force interactions. Prediction of back - to - back correlation between momenta of spectator and hit nucleon.

For 2N SRC we can model decay function as decay of a NN pair moving in mean field (like for spectral function in the model of Ciofi, Simula and Frankfurt and MS91), Piasetzky et al 06

Spectator is released





Emission of fast nucleons "2" and "3" is ***strongly suppressed due to FSI***

resembles 2N momentum distribution

does not resemble 2N momentum distribution -

Studies of the spectral and decay function of ^{3}He reveal both two nucleon and three nucleon correlations

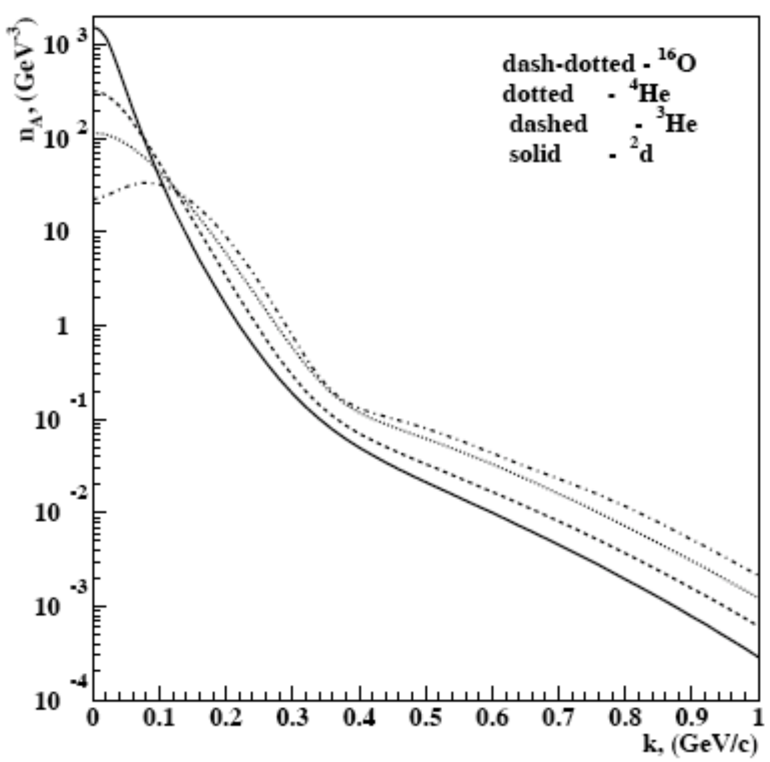
Sargsian et al 2004

Similarly for $n_A(k) = \int \prod_{i=1}^{i=A} d^3k_i \psi_A^2(k_i)\delta^3(k-k_1)$

$$n_A(k)_{|k\to\infty} \propto \frac{V_{NN}^2(k)}{k^4}$$

$$\Longrightarrow n_A(k) \approx a_2(A)\psi_D^2(k)_{|k\to\infty}$$

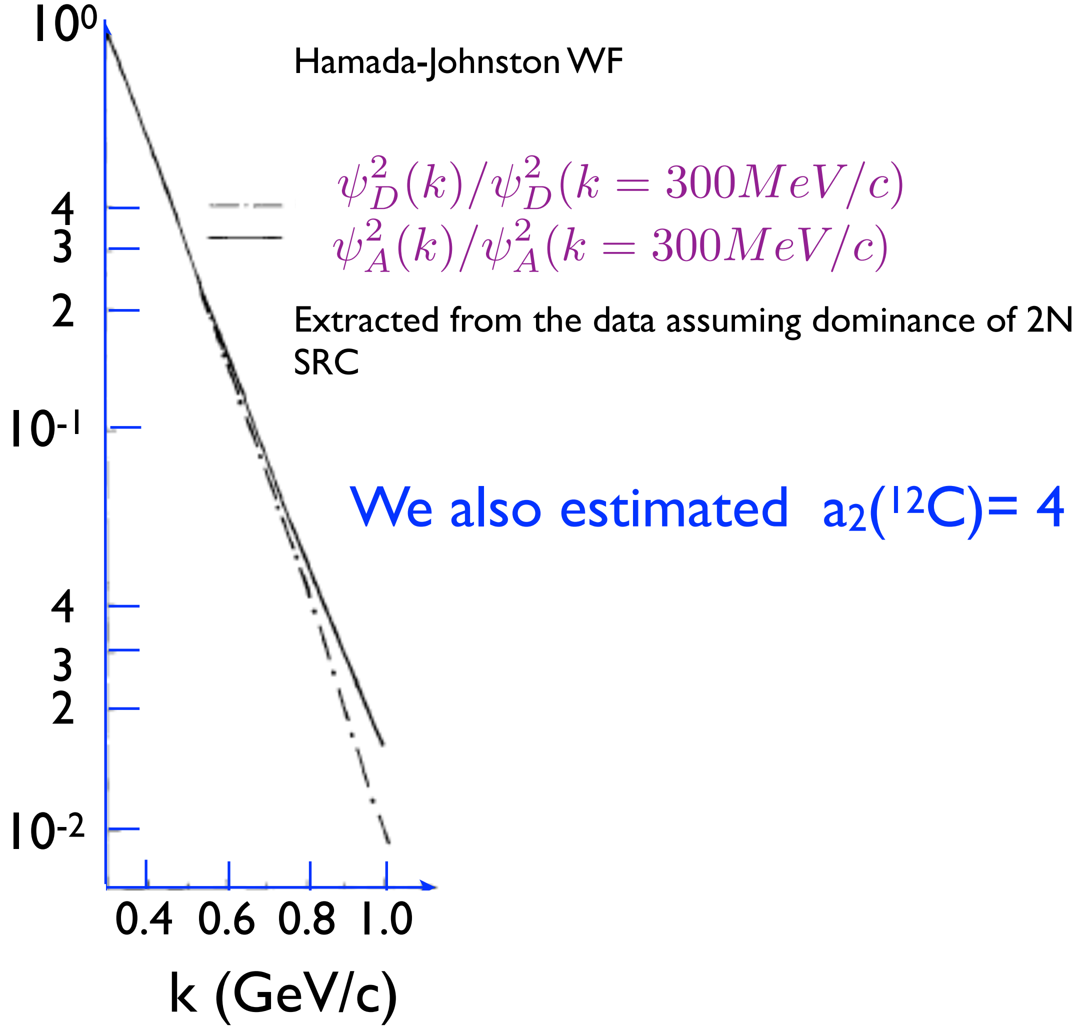
confirmed by numerical calculations starting ~ 1980



Pieper et al 92

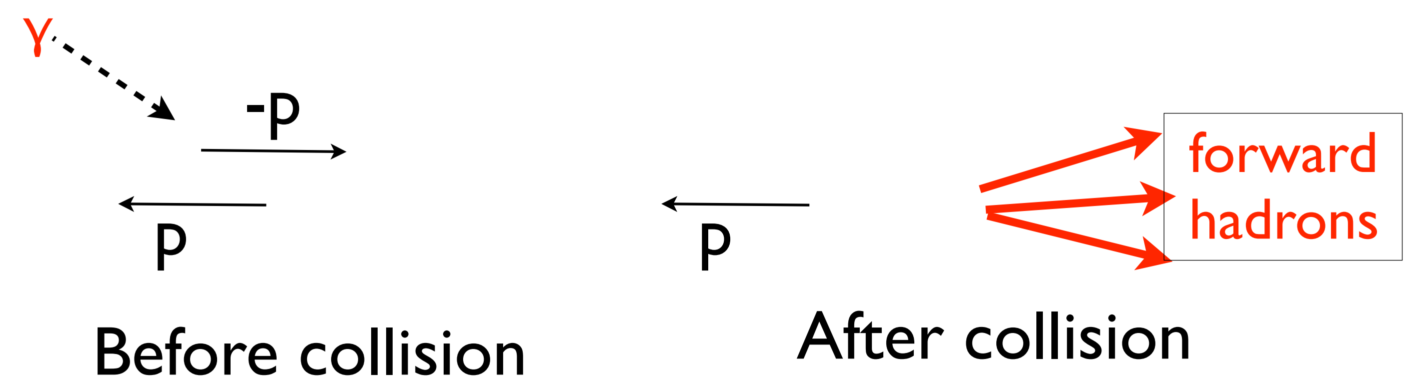
First application of the logic of decay function - spectator mechanism of production of fast backward nucleons - observed in high energy proton, pion , photon - nucleus interactions with a number of simple regularities. We suggested - spectator mechanism - breaking of 2N, 3N SRCs. We extracted (Phys.Lett 1977) two nucleon correlation function from analysis of K.Egiyan et al data on $\gamma(p)\ {}^{12}C \to$ backward $p+X$ processes [no backward nucleons are produced in the scattering off free protons!!!]

Spectator production of the backward proton from 2N SRC



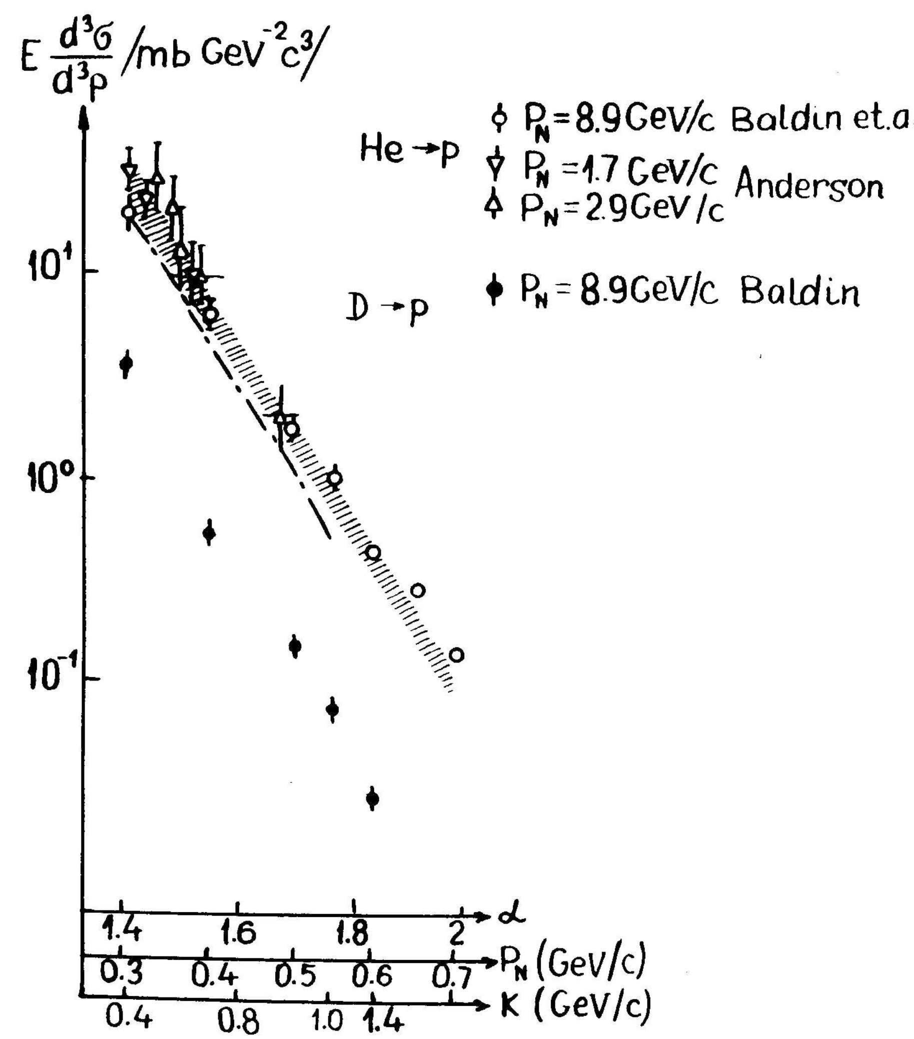
We also estimated $a_2(^{12}C) = 4 \div 5$

Momentum distributions normalized to its value at 300 MeV/c.



Backward direction is very good for looking for decay of SRCs

Next critical test - comparison of the data on pD → p +X and p^{4}He → p +X obtained in Dubna by Stavinskii group. Spectra of protons are similar for momenta of nucleons 300 MeV/c <k < 600 MeV/c

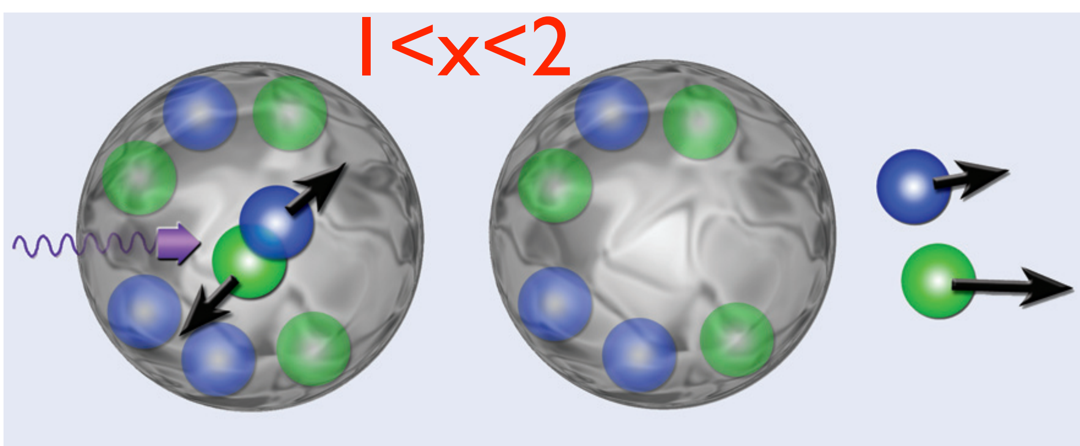


production of protons at 180°

Unfortunately no more data on pD, p^{4}He since 1980

A(e,e') at x>1 is the simplest reaction to check dominance of 2N, 3N SRC and to measure absolute probability of SRC

$x=AQ^2/2q_0m_A=1$ is **exact** kinematic limit **for all Q^2** for the scattering off a free nucleon; $x=2$ ($x=3$) is **exact** kinematic limit **for all Q^2** for the scattering off a A=2(A=3) system (up to <1% correction due to nuclear binding)



Before absorption of the photon

After absorption

two nucleons of SRC are fast

Only fsi close to mass shell when momentum of the struck nucleon is close to one for the scattering off a correlation. At very large Q - light-cone fraction of the struck nucleon should be close to x (similar to the parton model situation) - only for these nucleons fsi can contribute to the total cross section, though even this fsi is suppressed. Since the local structure of WFs is universal - these *local fsi should be also universal.*

Scaling of the ratios of (e,e') cross sections

Qualitative idea - to absorb a large Q at x>j at least j nucleons should come close together. For each configuration wave function is determined by *local* properties and hence universal. In the region where scattering of j nucleons is allowed, scattering off j+1 nucleons is a small correction.

$$\sigma_{eA}(x,Q^2)_{x>1} = \sum_{j=2} A \frac{a_j(A)}{j} \sigma_j(x,Q^2) \qquad \sigma_j(x>j,Q^2)=0$$

$$a_j(A) \propto \frac{1}{A}\int d^3r \rho_A^j(r) \qquad a_2 \sim A^{0.15}; \quad a_3 \sim A^{0.22}; \quad a_4 \sim A^{0.27}$$

for A> 12

$$\sigma_{A_1}(j-1<x<j,Q^2)/\sigma_{A_1}(j-1<x<j,Q^2) = (A_1/A_2)a_j(A_1)/a_j(A_2)$$

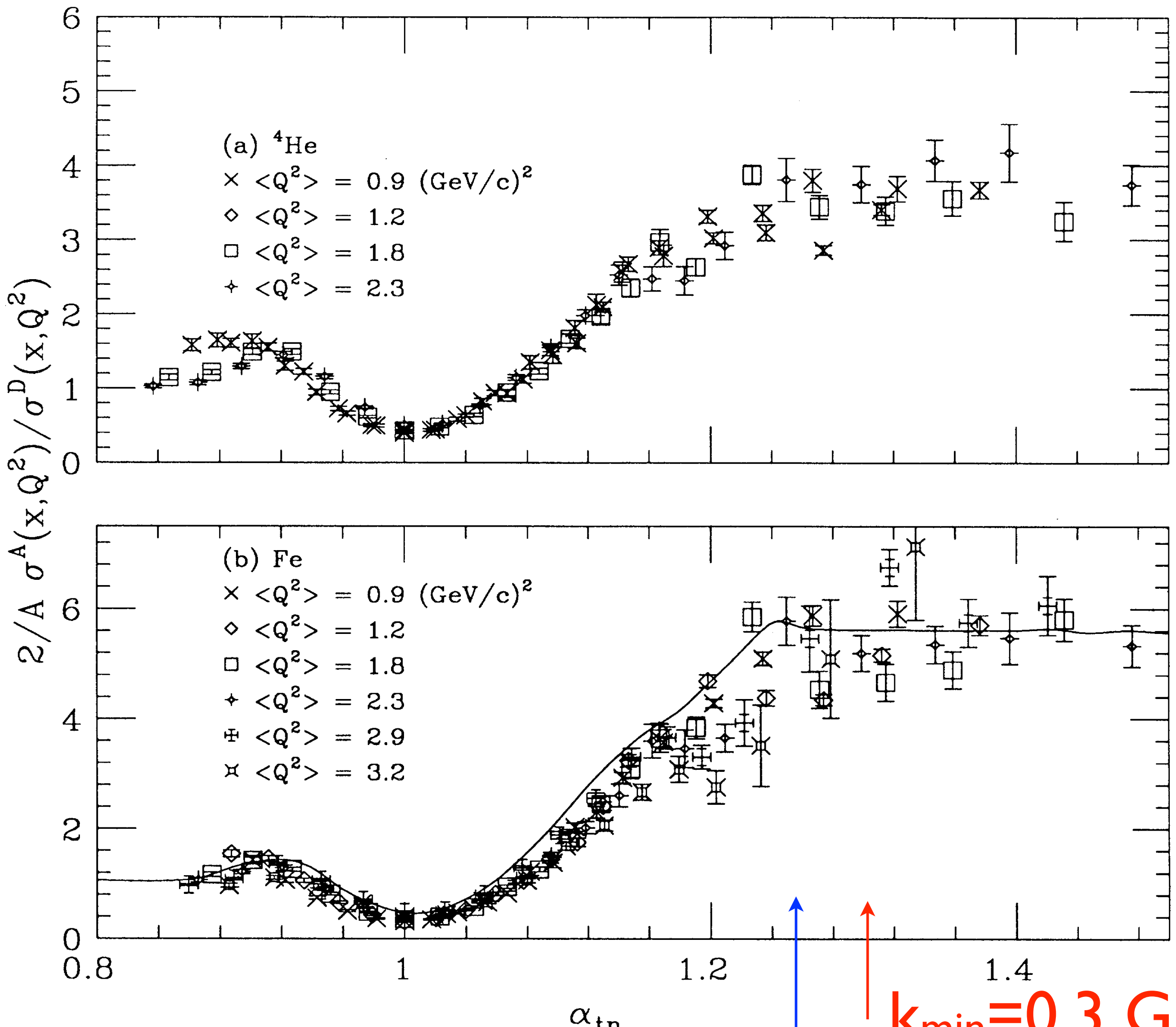
Scaling of the ratios FS80

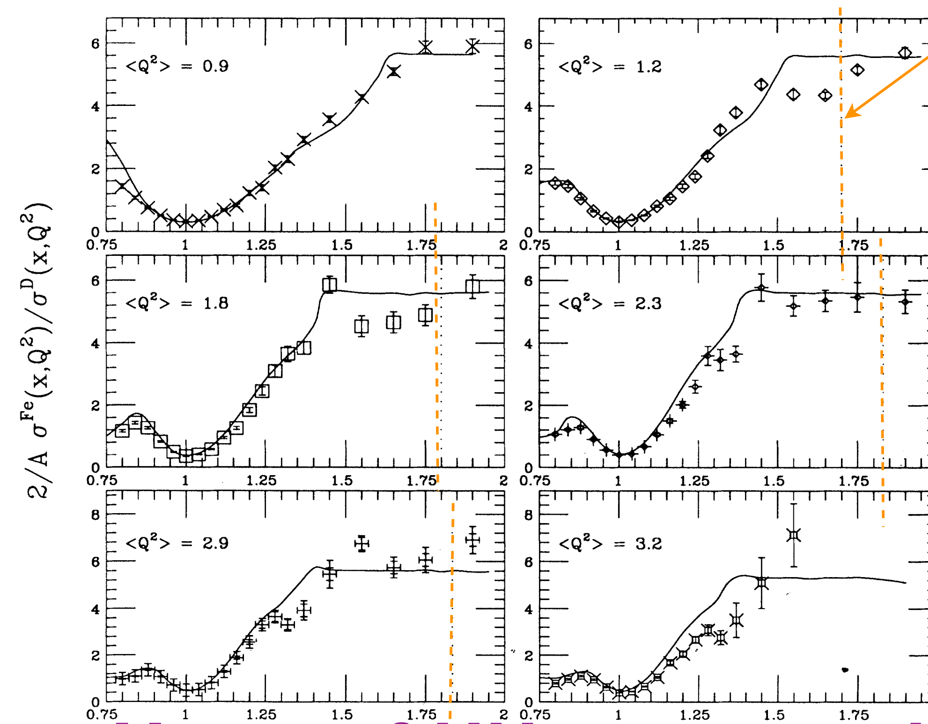
$$\Rightarrow \frac{\sigma_{A_1}(x,Q^2)}{\sigma_{A_2}(x,Q^2)} = \frac{\int \rho_{A_1}(\alpha_{tn},p_t)d^2p_t}{\int \rho_{A_2}(\alpha_{tn},p_t)d^2p_t} = \frac{a_2(A_1)}{a_2(A_2)}\Big|_{1.6>\alpha\geq 1.3}$$

ρ- Light-cone density

Note - local FSI interaction, up to a factor of 2 for σ(e,e'), cancels in the ratio of σ's

$W - M_D \leq 50\,MeV$





k_{min}=0.3 GeV

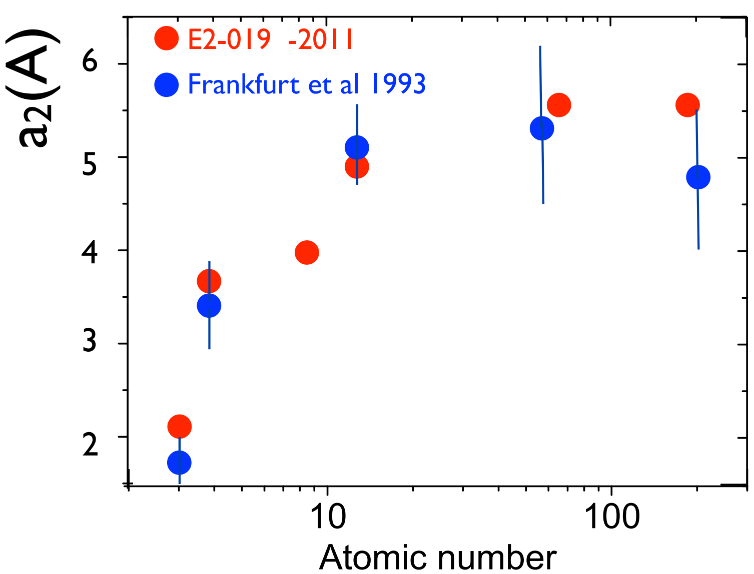
k_{min}=0.25 GeV

Frankfurt, Day, Sargsian, MS 93

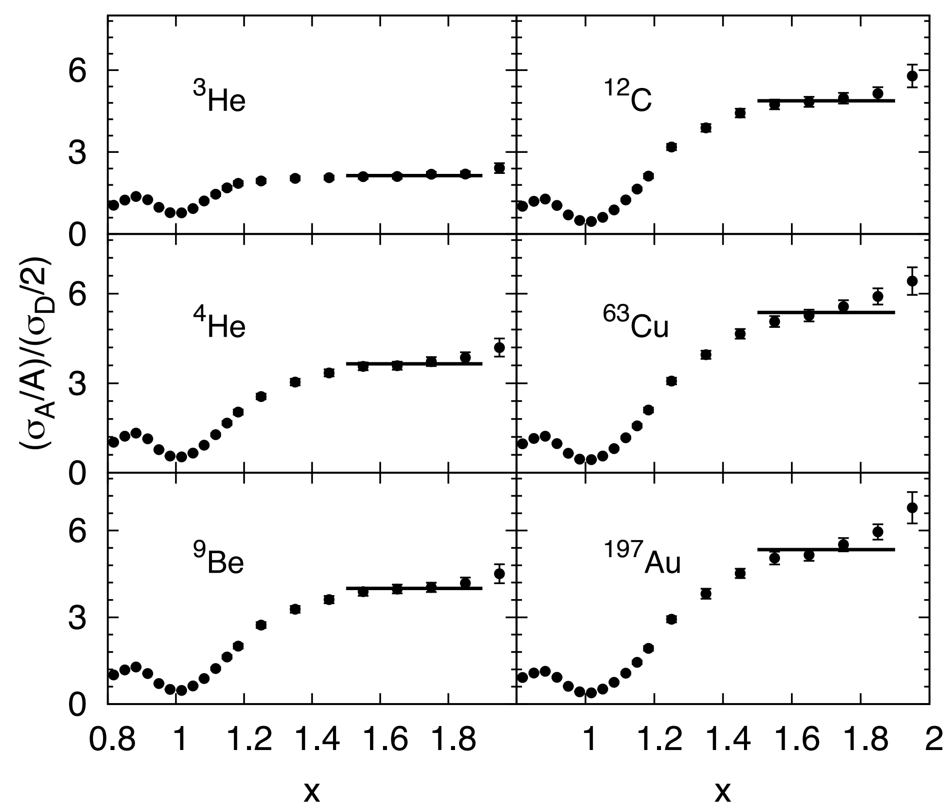
Masses of NN system produced in the process are small - strong suppression of isobar, 6q degrees of freedom.

Right momenta for onset of scaling of ratios !!!

✳ Universality of 2N SRC is confirmed by Jlab experiments



Probability of the high momentum component in nuclei per nucleon, normalized to the deuteron wave function



Per nucleon cross section ratio at Q^2=2.7 GeV^2 - E2-019-2011

Very good agreement between three (e,e') analyses for a_2 (A)

Our first result of 77 from backward proton production $a_2(C) \sim 4 \div 5$

Dominant mechanism of fast nucleon production appears to be established !!!

Impressive progress in the last 15 years

- *EVA BNL 5.9 GeV protons (p,2p)n*
- *(e,e' pp), (e,e'pn) Jlab* $Q^2 = 2 GeV^2$

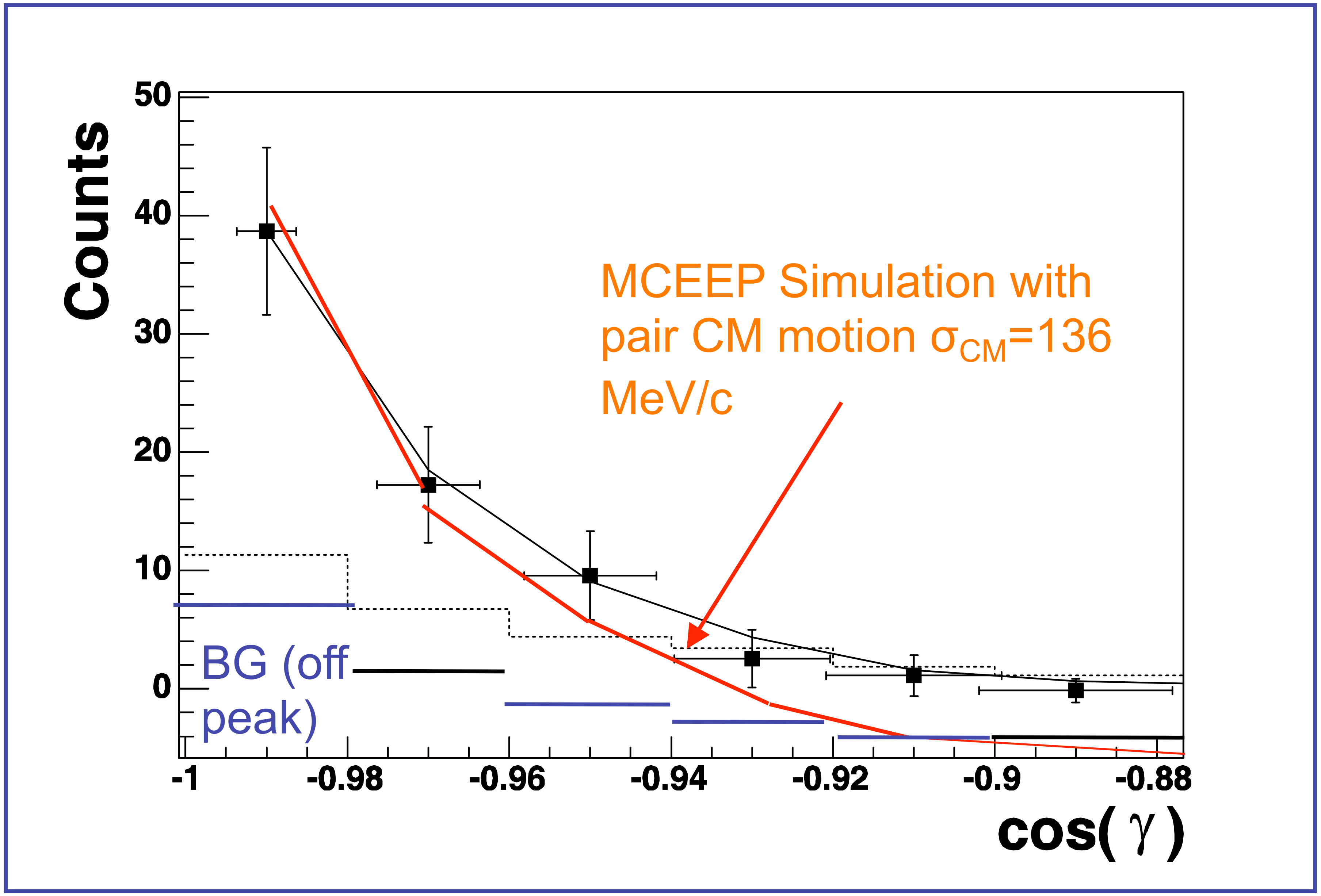
Different probes, different kinematics - the same pattern of very strong correlation - Universality= factorization is the answer to a question: "How to we know that (e,e'pN) is not due to meson exchange currents?"

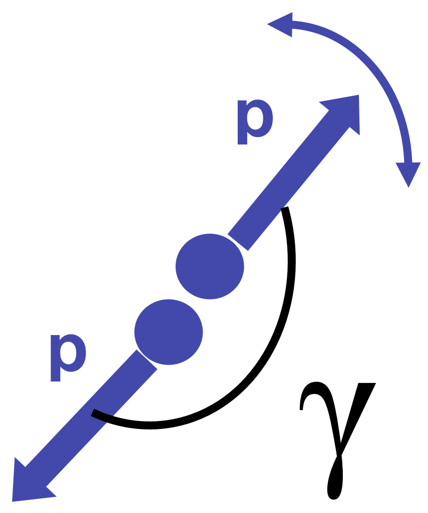
σ = nuclear (light cone) density (spectral / decay function) ⊗ elementary cross section

Further tests are necessary with different projectile, momentum transfer,…

Directional correlation

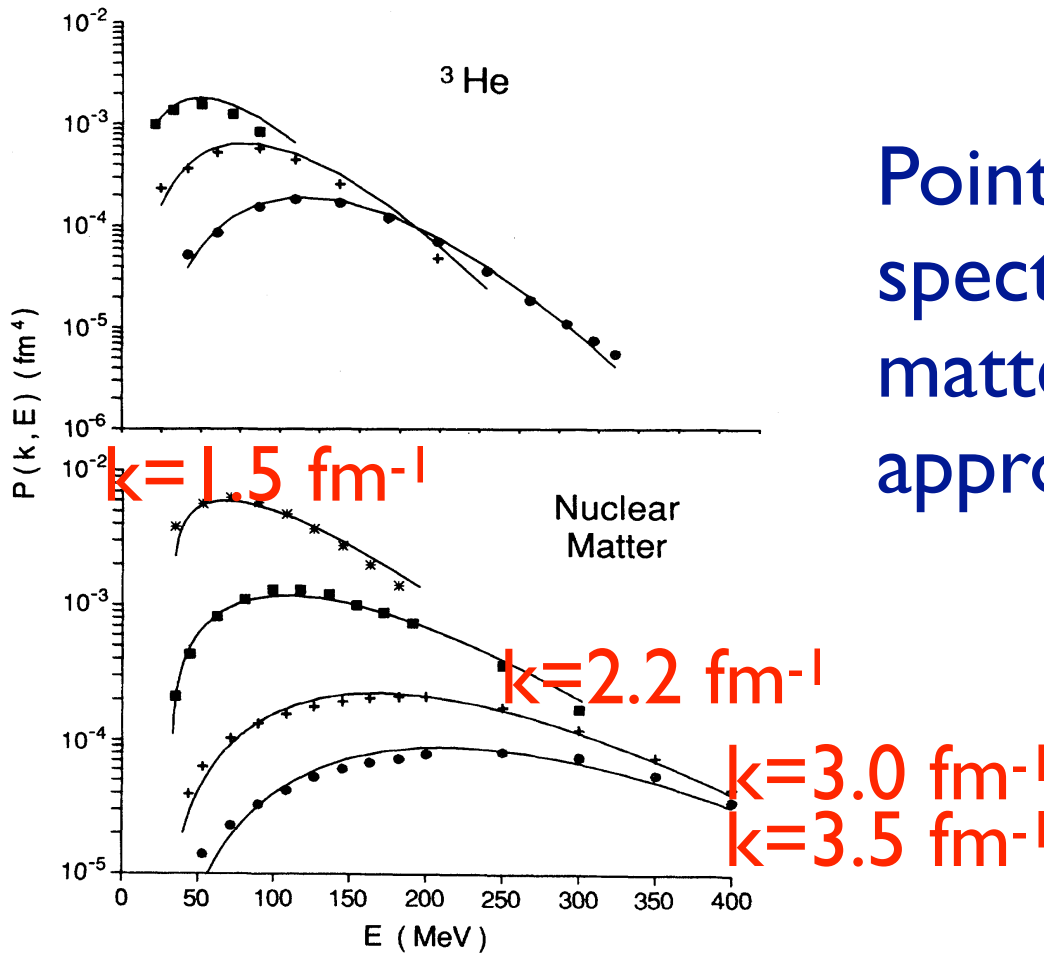
$^{12}C(e,e'pp)$



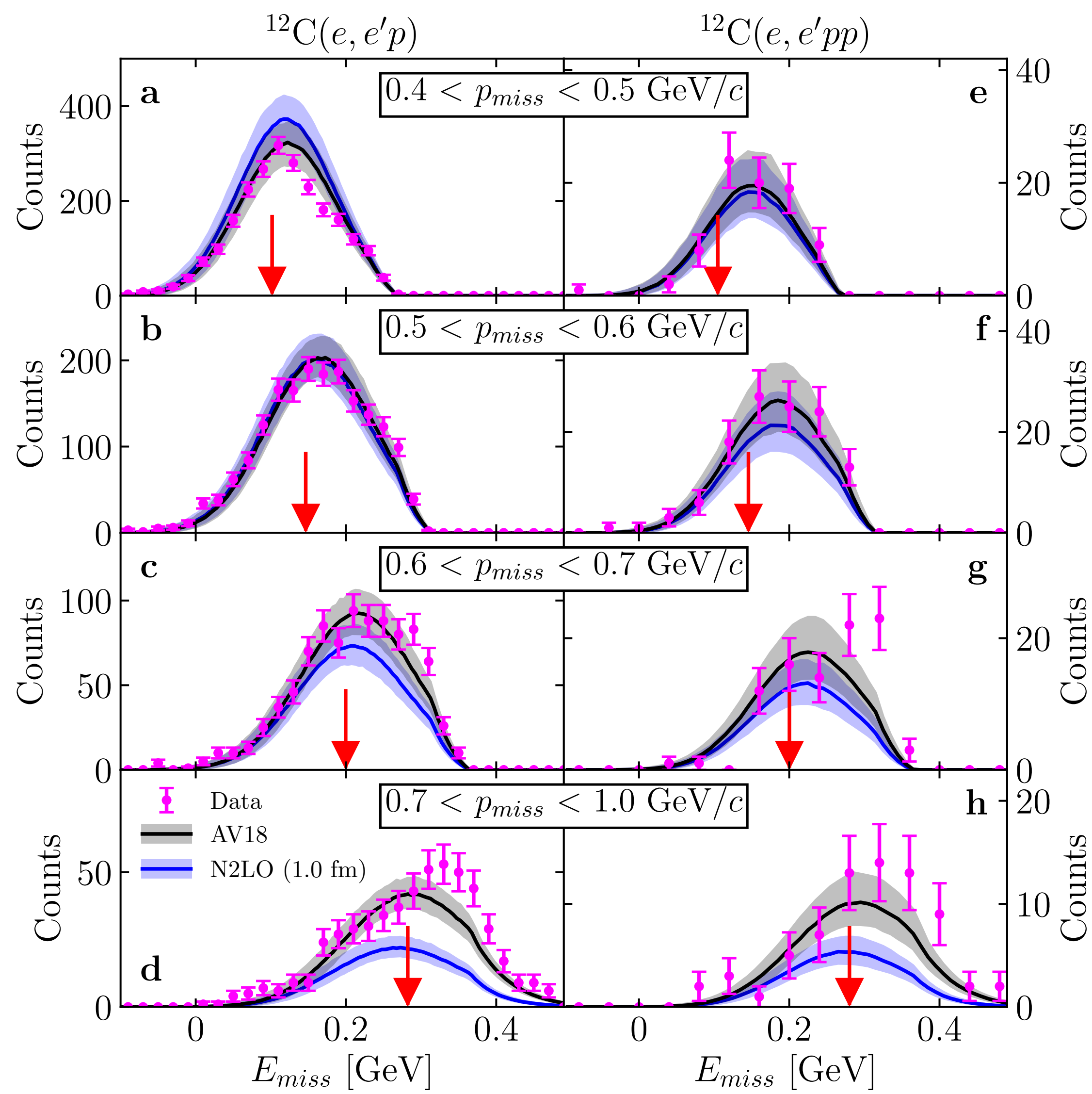


Numerical calculations in NR quantum mechanics confirm dominance of two nucleon correlations in the spectral functions of nuclei at k> 300 MeV/c - could be fitted by a motion of a pair in a mean field (Ciofi, Simula,Frankfurt, MS - 91). However numerical calculations ignored three nucleon correlations - 3p3h excitations.

Relativistic effects maybe important rather early as the recoil modeling does involve k^2/m_N^2 effects.



Points are numerical calculation of the spectral functions of ^{3}He and nuclear matter - curves two nucleon approximation from CSFS 91



MIT/Jlab 2019

Fig. 3 | Nuclear spectral function at high momentum. Measured ^{12}C(e,e'p) (a-d) and ^{12}C(e,e'pp) (e-h) event yields shown as a function of E_{miss} for different bins in (e,e'p) p_{miss}. The data are compared with theoretical calculations based on the GCF framework, using different models of the *NN* interaction. The arrows mark the expected energy for a stationary pair with relative momentum that equals the mean momentum of each missing-momentum bin (see Methods). The width of the bands and the data error bars show the model systematic uncertainties and data statistical uncertainties, respectively, each at the 1σ or 68% confidence level.

Due to the findings of the last few years at Jlab and BNL SRC are not anymore an elusive property of nuclei !!

Summary of the findings

- Practically all nucleons with momenta k≥300 MeV belong to two nucleon SRC correlations

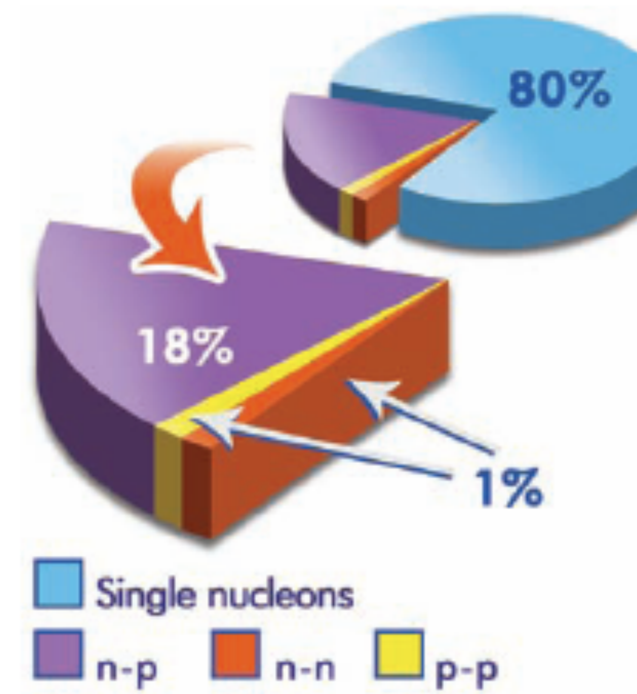
  BNL + Jlab +SLAC

- Probability for a given proton with momenta 600> k > 300 MeV/c to belong to pn correlation is ~ 18 times larger than for pp correlation

  BNL + Jlab

- Probability for a nucleon to have momentum > 300 MeV/c in medium nuclei is ~25%

  BNL + Jlab 04 +SLAC 93



The average fraction of nucleons in the various initial-state configurations of ^{12}C.

- In heavy nuclei protons have in average higher momenta than neutrons.

  Jlab 18 -19

  anti Fermi step result

New stage of the SRC studies

Open questions:

Accuracy of factorization ?

At what momentum transfer factorization sets in ?

Accuracy of universality (same spectral/ decay functions work for electron, photon, proton projectiles .

Three nucleon SRC (so far only in backward proton production and hints in (e,e') at x>2).

focus of pA studies on high precision p^2H, p^3He (hopefully 4He, C would be added at some point). Exclusive measurements over large range of momentum transfer :

$$p^2H \to ppn, p^3He \to pppn$$

Deuteron is a hydrogen atom of short range nuclear structure studies

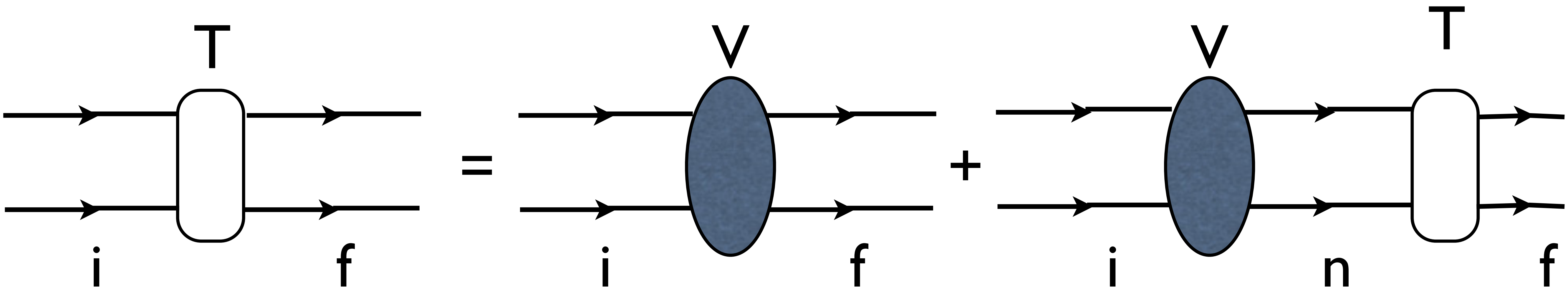
The process $pD \to ppn$ dual role:

(i) study of the deuteron wave function (at some point S and D wave separately

(ii) 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. Can choose kinematics with minimal and maximal fsi.

Deuteron: $\psi_D(\alpha, p_t)$

For two nucleon approximation we have in addition an angular condition that Lippman-Schwinger type equation for NN interaction



should lead to rotationally invariant scattering amplitudes (pretty lengthy proof) results in

$$\psi_D(\alpha, p_t) \rightarrow \psi_D(M_{NN}^2), M_{NN}^2 = 4\left(\frac{m^2 + p_t^2}{\alpha(2-\alpha)}\right)$$

Spin zero /unpolarized case

Relation between LC and NR wf.

$$\int \Psi^2_{NN}\left(\frac{m^2+k_t^2}{\alpha(2-\alpha)}\right)\frac{d\alpha d^2k_t}{\alpha(2-\alpha)}=1 \qquad \int \phi^2(k)d^3k=1$$

$$\Psi^2_{NN}\left(\frac{m^2+k_t^2}{\alpha(2-\alpha)}\right)=\frac{\phi^2(k)}{\sqrt{(m^2+k^2)}}$$

Similarly for the spin 1 case we have two invariant vertices as in NR theory:

$$\psi^D_\mu \epsilon^D_\mu=\bar{u}(p_1)\left(\gamma_\mu G_1(M^2_{NN})+(p_1-p_2)_\mu G_2(M^2_{NN})\right)u(-p_2)\epsilon^D_\mu$$

hence there is a simple connection to the S- and D- wave NR WF of D

For two body system in two nucleon approximation

the biggest difference between NR and virtual nucleon approximation LC is in the relation of the wave function and the scattering amplitude

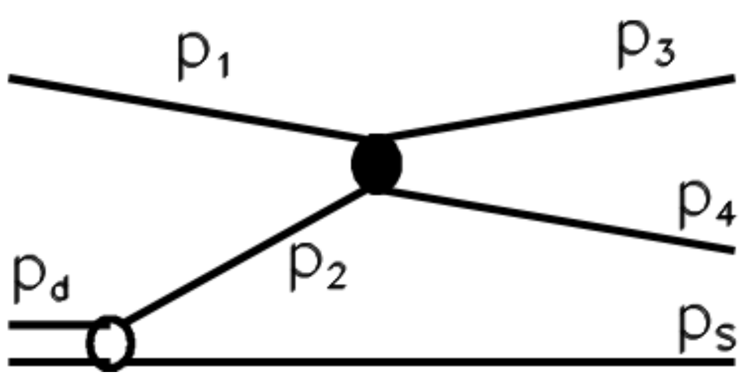
due to implicit presence of $N\bar{N}$ pairs in virtual nucleon approximation

$$\left(\frac{m^2+p_t^2}{\alpha(2-\alpha)}\right) = m^2+k^2 \rightarrow \alpha = 1+\frac{k_3}{\sqrt{m^2+k^2}}$$

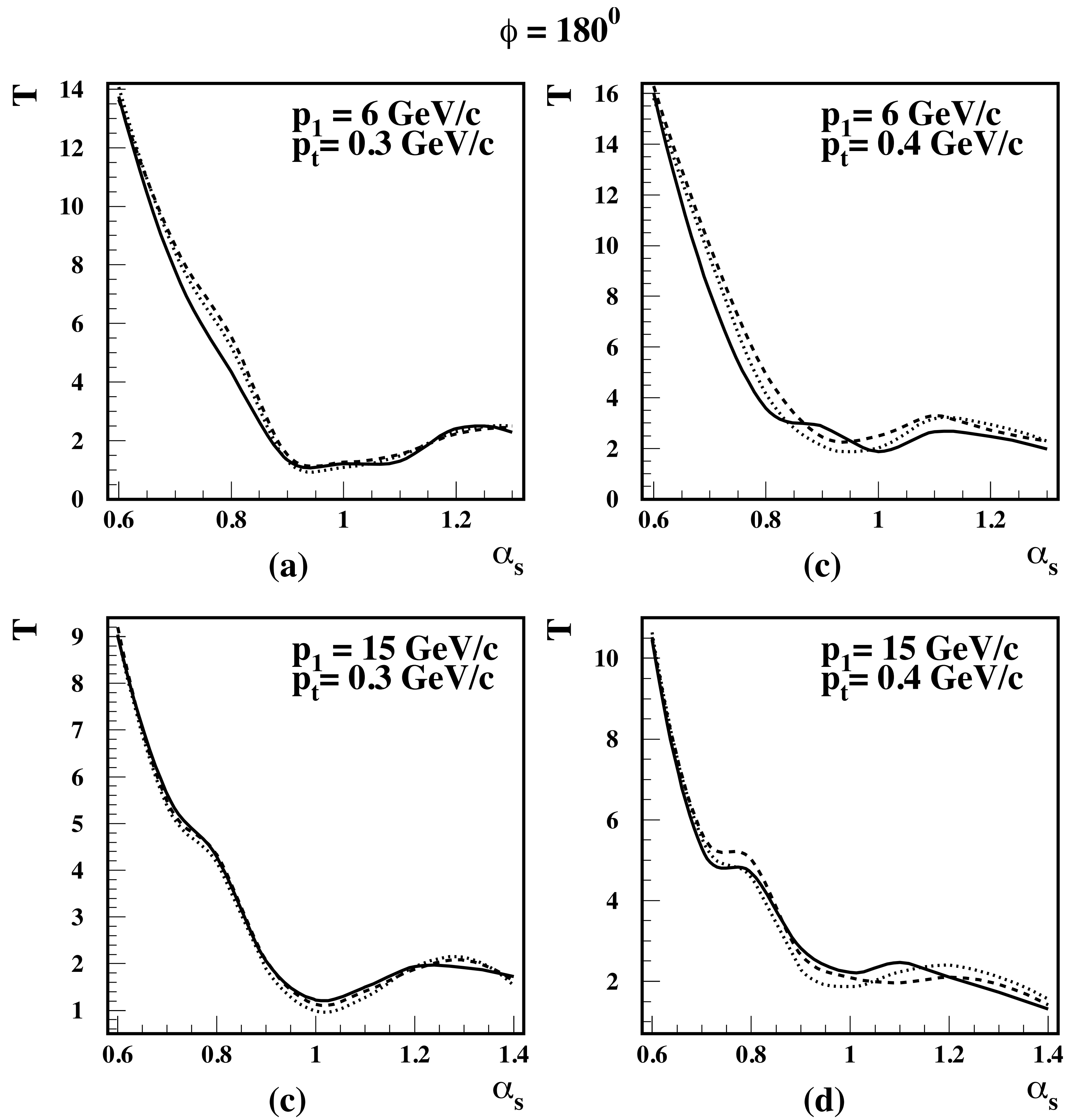
$$\alpha = \left(\sqrt{m^2+p_N^2}+p_{3,N}\right)/m_D$$

Nonlinear connection between momentum k in wave function and p_N - momentum of spectator in the deuteron rest frame

Optimal kinematics- spectator nucleon has large LC fraction $\alpha_s > 1$, momentum transfer $-t=(p_1-p_3)^2 > 1\ \mathrm{GeV}^2$

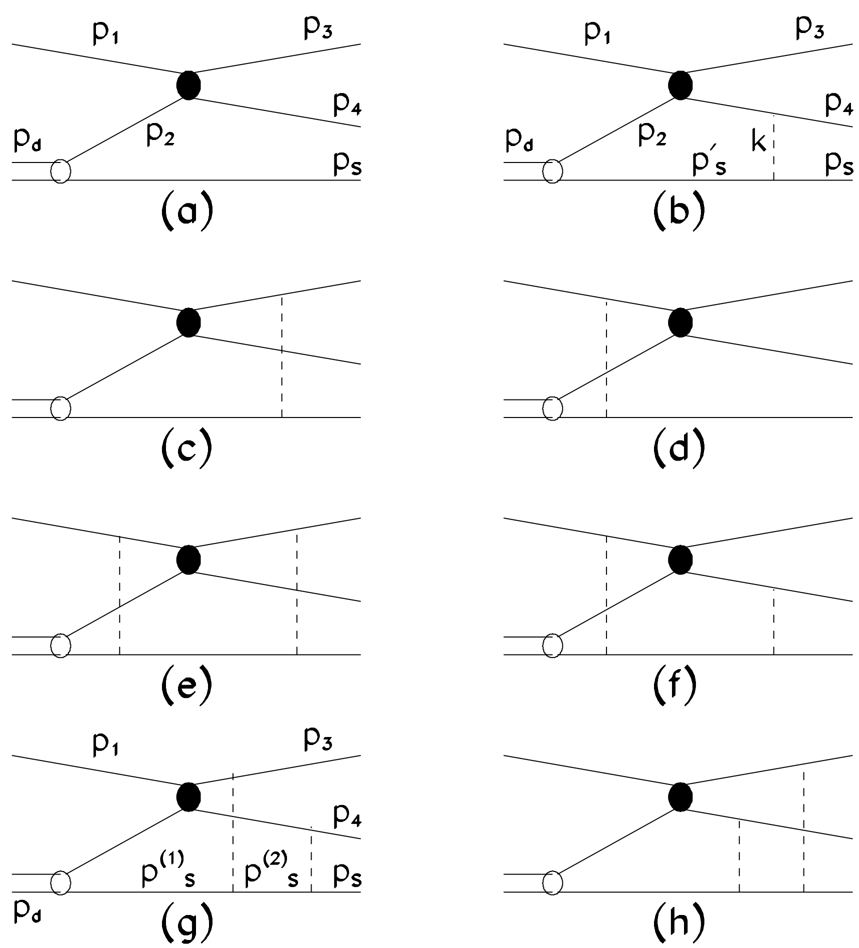


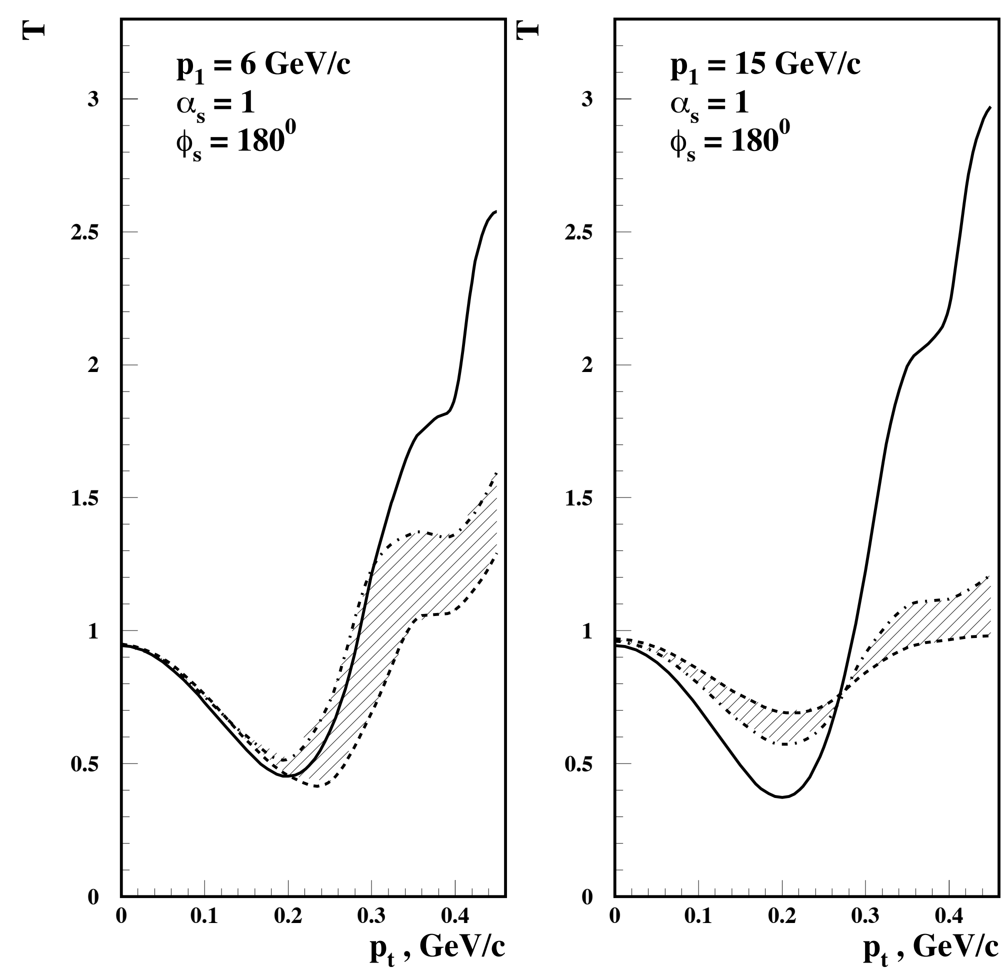
Rescattering corrections can be reliably calculated using generalized eikonal approximation



Ratio of the cross section calculated in the eikonal approximation at in the impulse approximation as a function of α_s for different p_t. Solid line is complete factorization of the hard amplitude. Study of SRC is optimal for small enough p_t.

Testing rescattering dynamics (including color transparency effects - dashed curves)





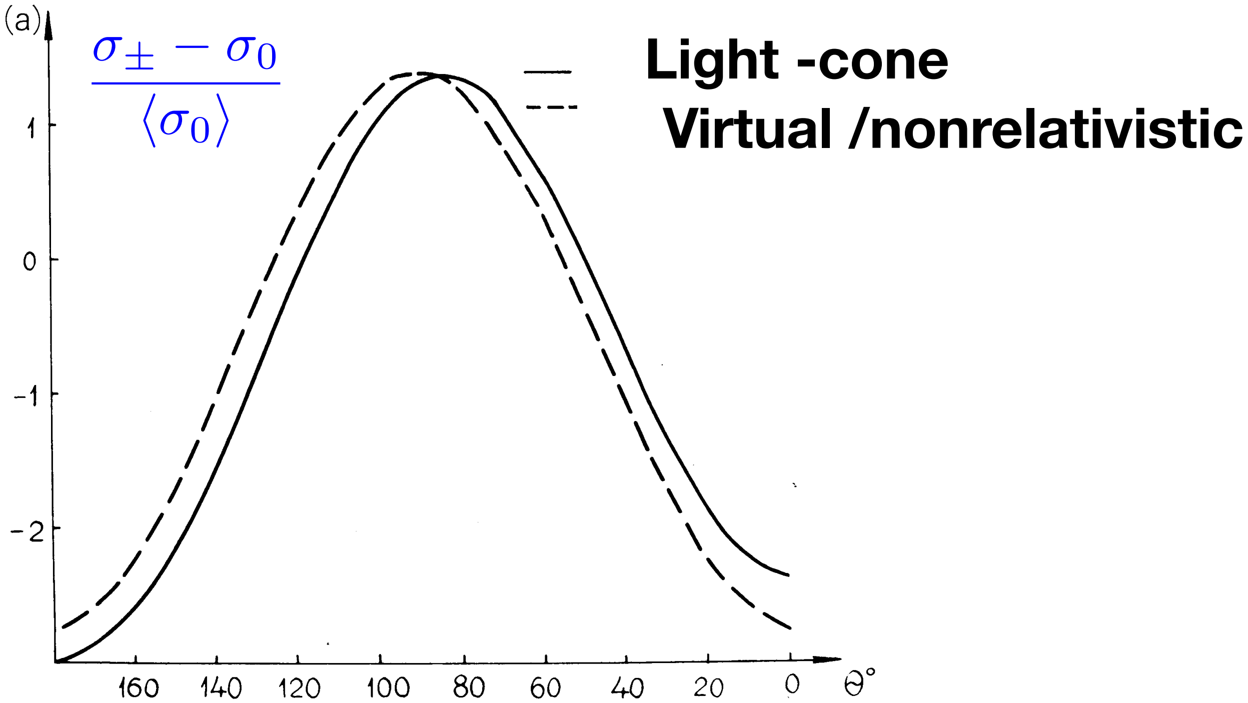
α_s =1 optimal for testing dynamics of multinucleon rescatterings

Deuteron polarization effects where calculated for eD scattering for tensor polarization. Analogous effects for deuteron polarized perpendicular to the beam direction

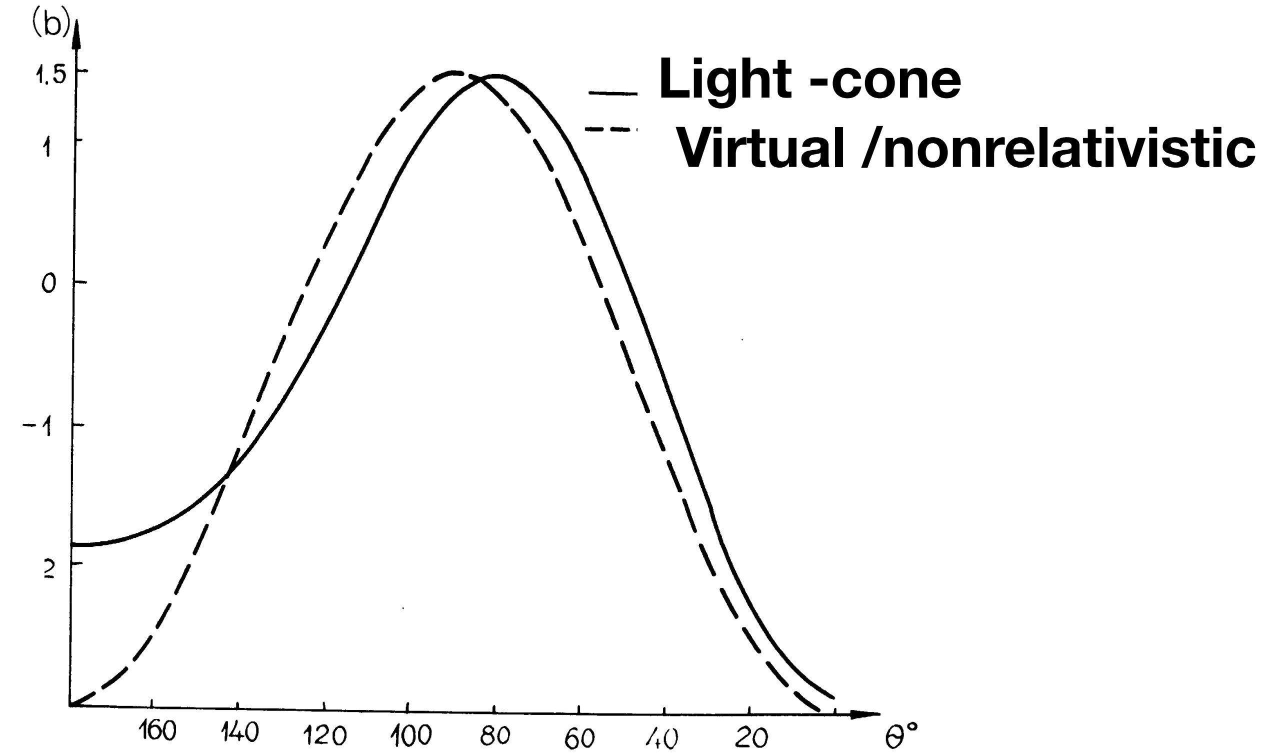
However tensor polarization is preferable - smaller rescattering effects

$e + \vec{D} \to N + X, p_N = .25GeV/c$

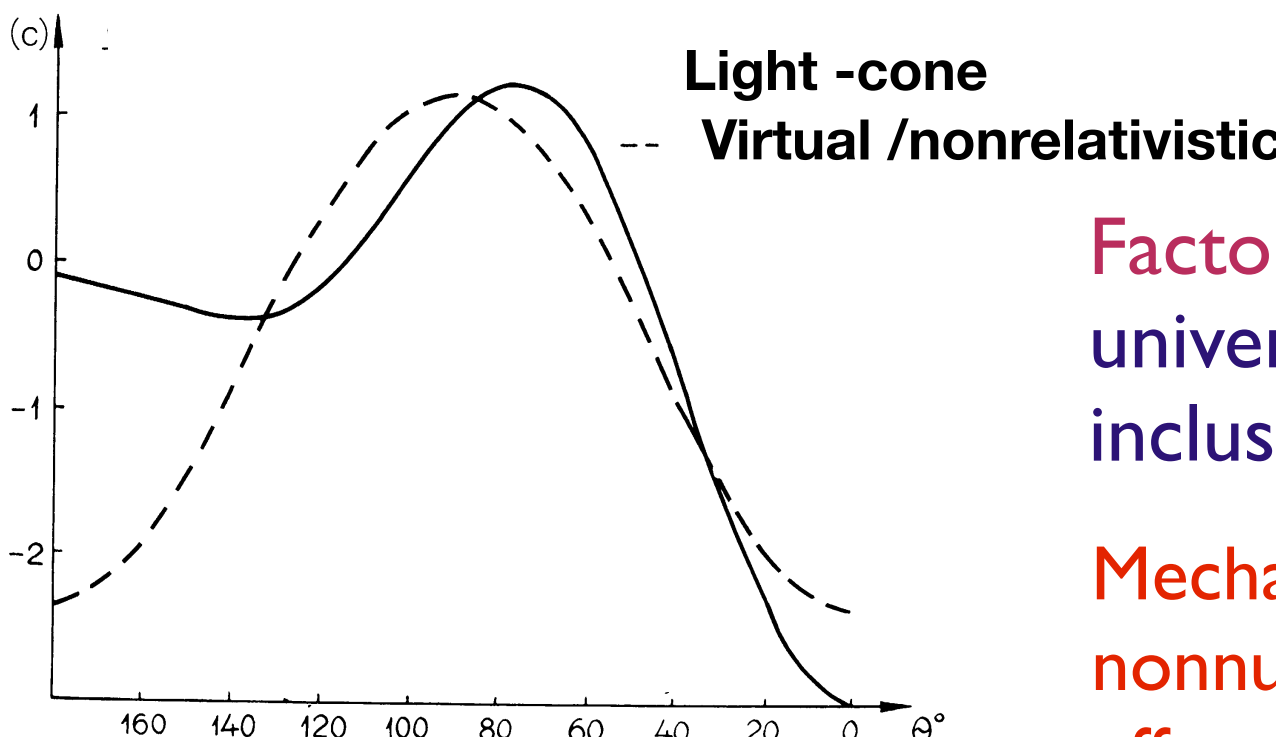
$\frac{\sigma_\pm - \sigma_0}{\langle \sigma_0 \rangle}$



$\frac{\sigma_\pm - \sigma_0}{\langle \sigma_0 \rangle}$ $e + \vec{D} \to N + X, p_N = .3GeV/c$

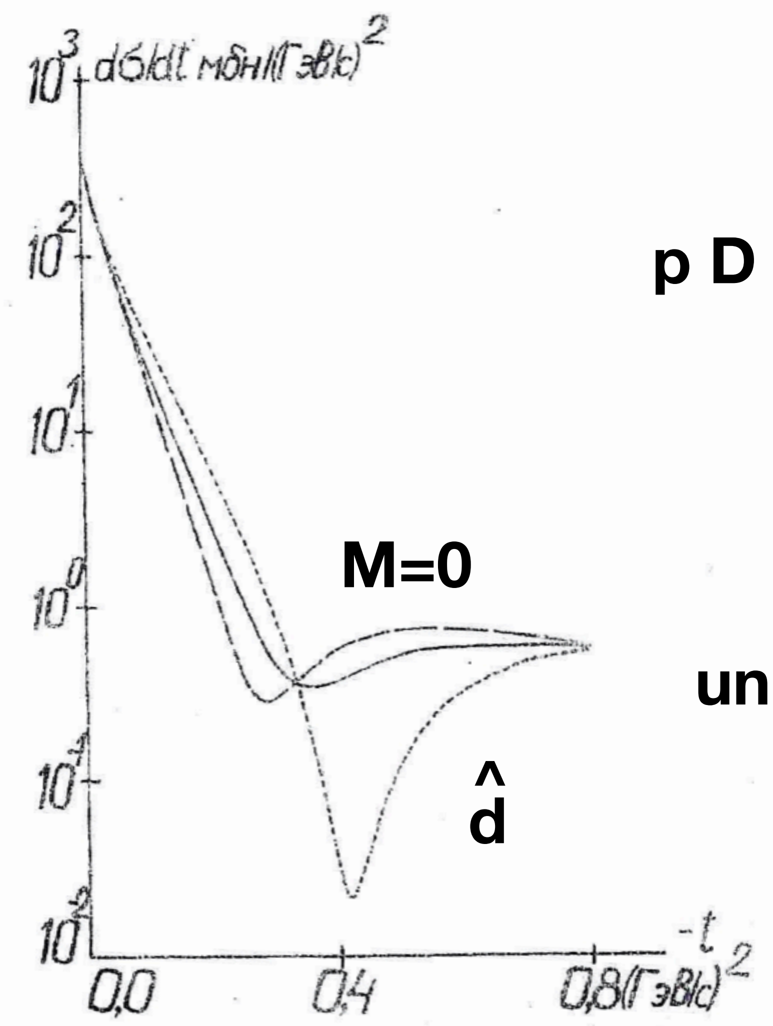


$\frac{\sigma_\pm - \sigma_0}{\langle \sigma_0 \rangle}$ $e + \vec{D} \to N + X, p_N = .35GeV/c$



Factorization test: T_{20} should be universal - the same for various hard inclusive and exclusive processes

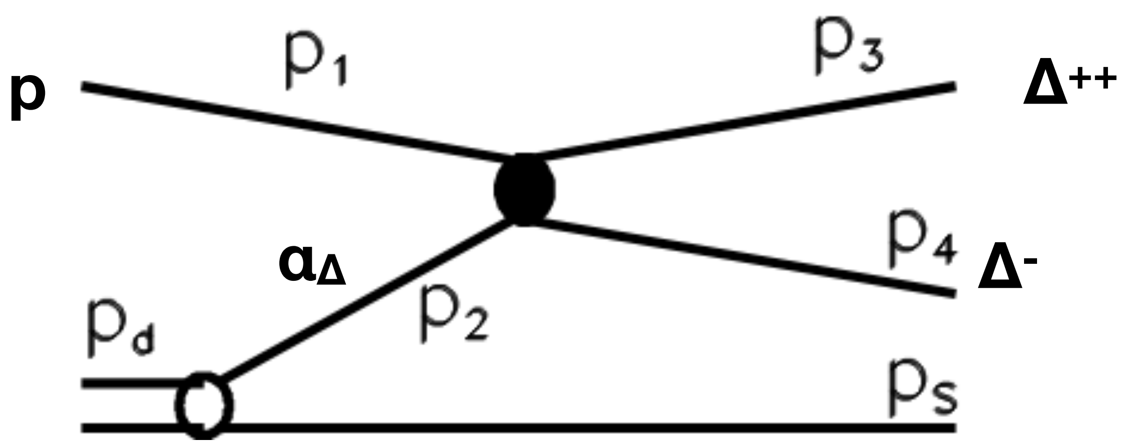
Mechanisms of violation of factorization: nonnucleonic degrees of freedom in D /EMC effect, fsi p D elastic scattering



V.Komarov 1976

Looking for Δ 's, 6q…. in D

pD—> $\Delta^{++}\Delta^{-}$ +p



α_Δ >1 - use of a broad distribution in α_Δ >1 (cf. Larionov and MS-2019)

$-t=(p_1-p_3)^2 > 2$ GeV^2 to reduce charge exchange effects.

To use the proton - nucleus scattering to study SRC we need a better understanding of exclusive large momentum transfer pN scattering-

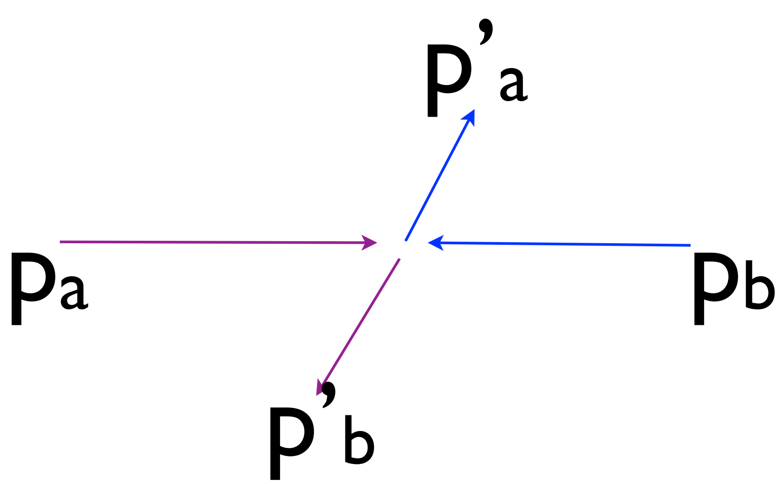
A challenging question: what is QCD dynamics of large angle (in c.m.) hadron - hadron scattering?

In inclusive processes like DIS, hadron production perturbative QCD works starting at $Q^2 \sim 2$ GeV^2.

What is corresponding parameter in large angle scattering?

Large t?

large c.m. scattering angle (t/s=const)??

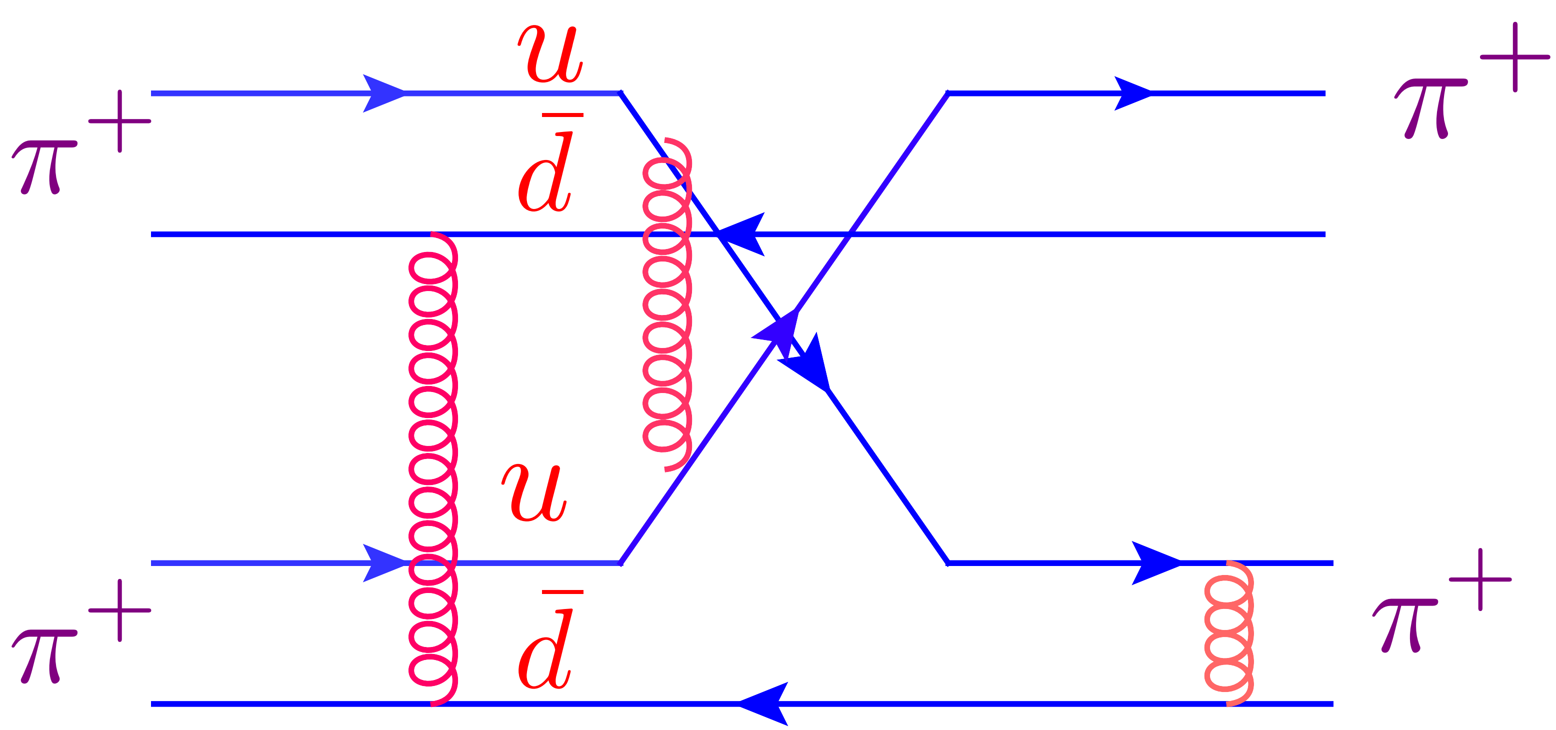


large angle scattering in c.m. frame

$$s = (p_a + p_b)^2$$
$$t = (p_a - p'_a)^2$$

pQCD diagrams for elastic large angle scattering -- minimal number of constituents + large momentum transfer between constituents

→ in the moment of interaction constituents of colliding hadrons are close together: $r_1 - r_2 \propto 1/\sqrt{-t}$



How to test? Use two important features of QCD

(a) In high energies hadron interacts in frozen configurations over large distances - coherence length

$$L_h = 2E_h/(M_n^2 - m_h^2) \gg R_A$$

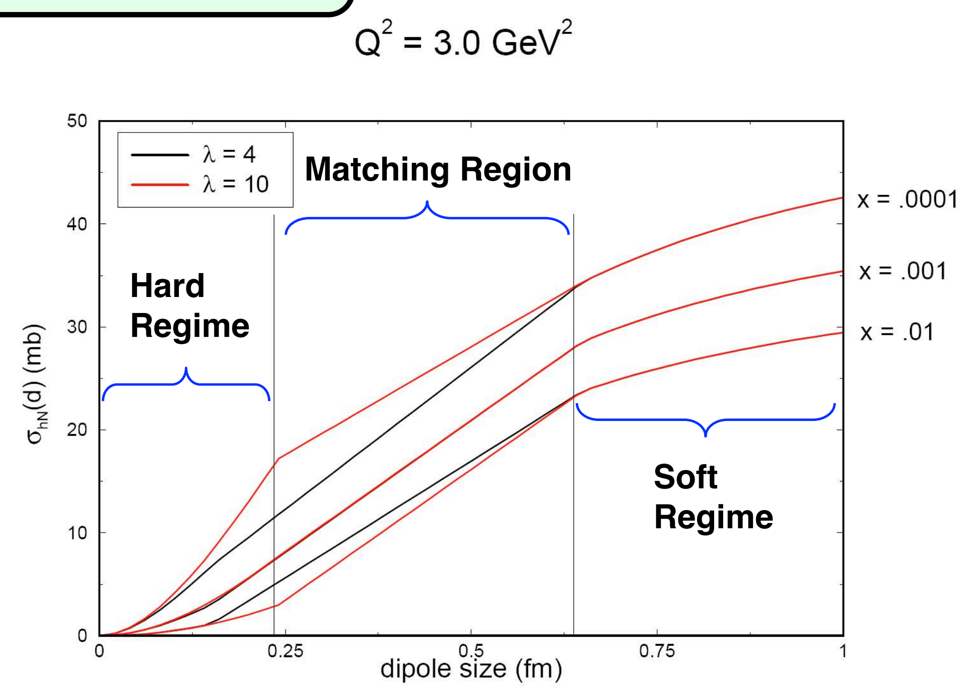
Projectile interacts in configurations with different interaction strength = color fluctuations) (relevant for AA collisions)

(b) Cross section of interaction of hadron in a small size configuration is small

For a dipole of transverse size d: $\sigma = cd^2$ *in the lowest order in* α_s *(two gluon exchange F.Low 75)*

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

Important at E_{dipole} < 10 GeV



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

(Baym et al 93, FS&Miller 93 & 2000)

In the limit of very small configurations in the projectile giving dominant interaction should be small leading to

$$\sigma(h + A \to h + N + (A-1)) = A\sigma(h + N \to h + N)$$

referred to as color transparency (CT)

Observation of CT was suggested as a test of the origin of elastic large angle scattering by A.Mueller and S.Brodsky

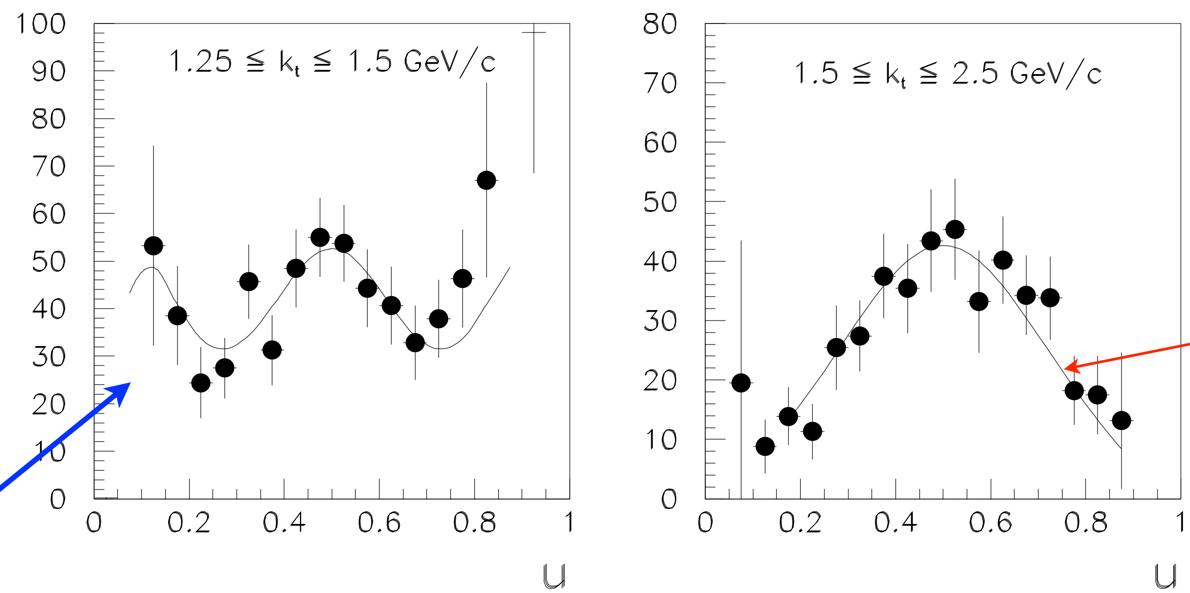
Problem is that to reach the regime where $L_h > 2R_A$ where one expect to observe 100% CT one needs very large s where cross sections are very small + only proton beams are doable

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 observation of high energy CT for π +A →"jet"+"jet" +A. (Ashery 2000):

Confirmed predictions of pQCD (Frankfurt ,Miller, MS93) for *A-dependence (much faster than in soft diffraction) & amplitude linear in A (100 % CT), distribution over energy fraction, u carried by one jet, dependence on p_t(jet)*, etc.



prediction

(π wave funct)^2

Squeezing occurs before the leading term $(1-u)^2u^2$ dominates!!!

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

Main challenge for CT studies performed at intermediate energies is lack of freezing: |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 - expand after interaction to average configurations and contract before interaction from average configurations (Frankfurt,Farrar,Liu, MS88)

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

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

Quantum Diffusion model of expansion

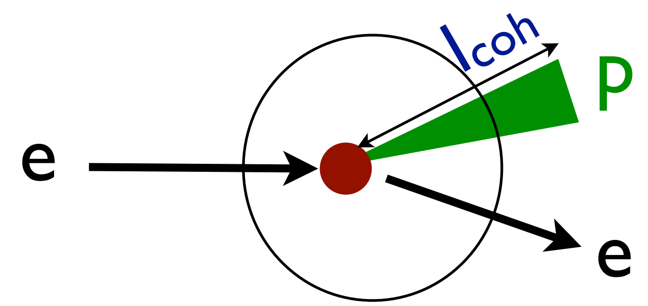
$l_{coh} \sim (0.4\text{-}\ 0.8)$ fm E_h[GeV]

actually incoherence length

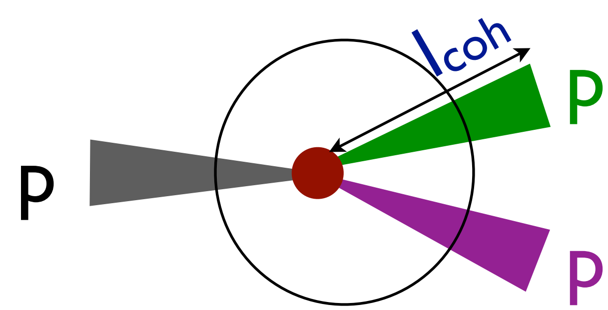
MC's at RHIC assume much larger

l_{coh}= 1fm E_h/m_h;

for pions l_{coh}= 7 fm E_h[GeV] - a factor of 10 difference !!!



eA→ ep (A-1) at large Q

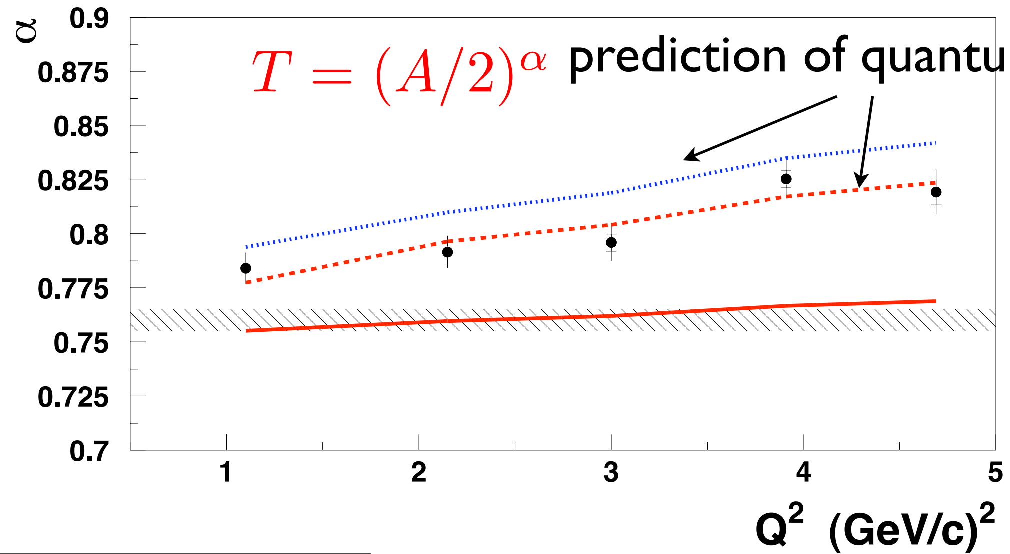


pA→ pp (A-1) at large t and intermediate energies

Experimental evidence for CT in electroproduction meson productio

$\gamma^* + A \rightarrow \pi A^*$ transparency increases with Q^2 (Dutta et al 07)

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



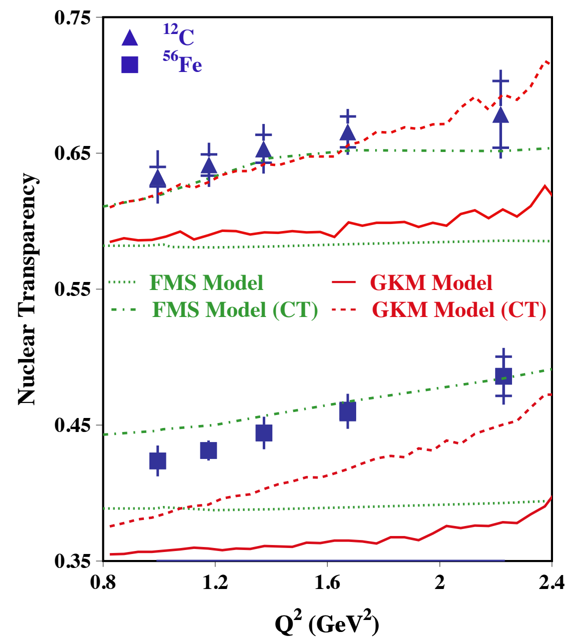
Ghent

Miller &MS

Glauber model.

$\gamma^* + A \rightarrow \rho A^*$ also report increase of transparency with Q^2

El Fassi et al , 2012



The Jlab π,ρ data are consistent with CT predictions with coherence length $l_{coh} \sim 0.6fm\ p_h\ [GeV]$. Additional evidence for presence of small size components in mesons

Are large angle two body processes being point like probes?

So far we don't have a good understand the origin of one of **the most fundamental hadronic processes in pQCD -large angle two body reactions** (-t/s=const, s $\to \infty$) π +p $\to$ π +p, p +p $\to$ p +p,...

Dimensional quark counting rules:

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

number of constituents in initial state

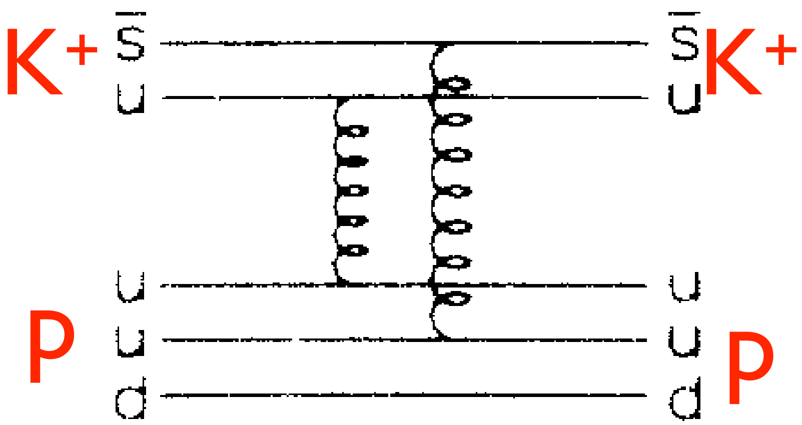
number of constituents in final state

Quark counting expectations work pretty well:

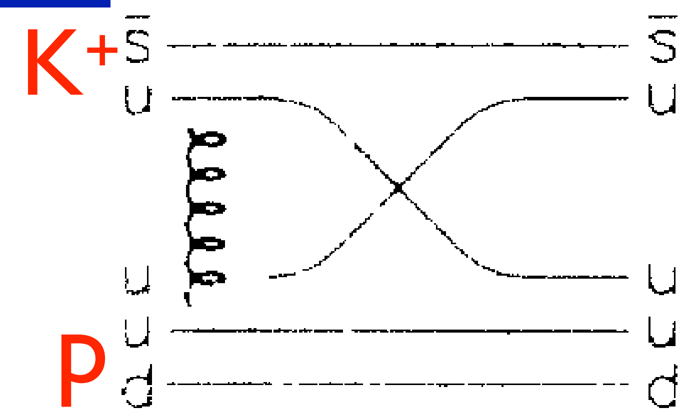
TABLE V. The scaling between E755 and E838 has been measured for eight meson-baryon and 2 baryon-baryon interactions at $\theta_{\mathrm{c.m.}} = 90^\circ$. The nominal beam momentum was 5.9 GeV/c and 9.9 GeV/c for E838 and E755, respectively. There is also an overall systematic error of $\Delta n_{\mathrm{syst}}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

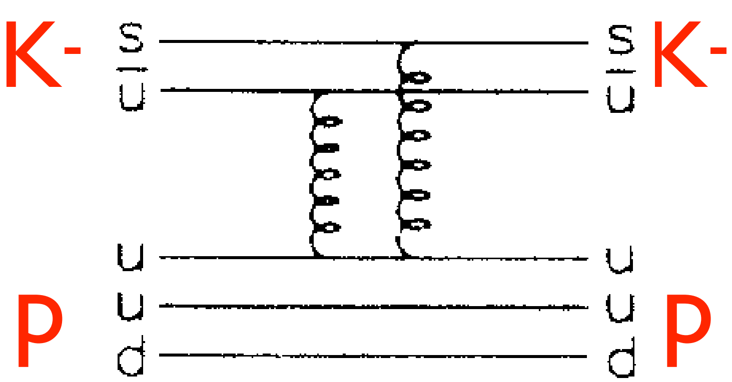
No.	Interaction	Cross section E838	Cross section E755		n-2 ($\frac{d\sigma}{dt} \sim 1/s^{n-2}$)
1	$\pi^+ p \to p\pi^+$	132 ± 10	4.6 ± 0.3	n-2=8	6.7 ± 0.2
2	$\pi^- p \to p\pi^-$	73 ± 5	1.7 ± 0.2	n-2=8	7.5 ± 0.3
3	$K^+ p \to pK^+$	219 ± 30	3.4 ± 1.4	n-2=8	$8.3^{+0.6}_{-1.0}$
4	$K^- p \to pK^-$	18 ± 6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

Another interesting observation - cross sections of reactions where quark exchanges is allowed have much larger cross section. For example -- pp elastic >> p$\bar{p}$ -elastic

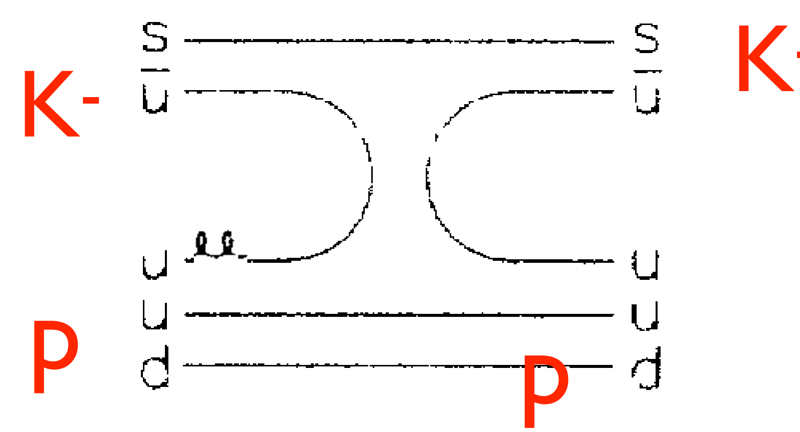


$\boxed{K^{+}p \rightarrow K^{+}p}$





$\boxed{K^{-}p \rightarrow K^{-}p}$



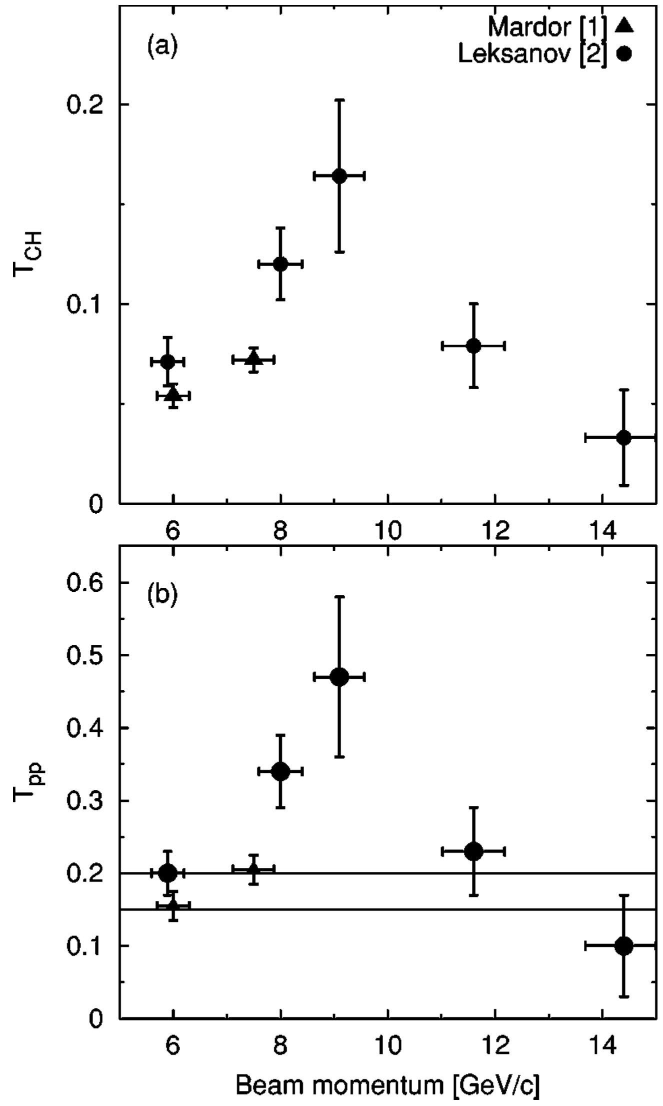
$$\sigma(K^+p \to K^+p) \gg \sigma(K^-p \to K^-p)$$

At NICA one can study: pp →pp, NΔ, ΔΔ, pn →pn, NΔ, ΔΔ

Experimental studies seem to indicate that in the case of ep scattering (eA—>ep A-1)

that CT effect is small up to Q2 where for meson s CT is already observed

Long story of the studies of p+A → pp (A-1) at BNL by EVA exp.



PUZZLE

Nuclear transparency T_{CH} as a function of beam momentum (experiment used CH target)

Nuclear transparency T_{pp} as a function of beam momentum (defined so $T_{pp}=1$ - corresponds to the impulse approximation). Errors shown are statistical which dominate for these measurements

Repeating measurements would be highly desirable.
Also explore T in pd—> ppn which I discussed earlier

- 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 → it is possible that the rate of squeezing is stronger in processes where quark exchange is allowed

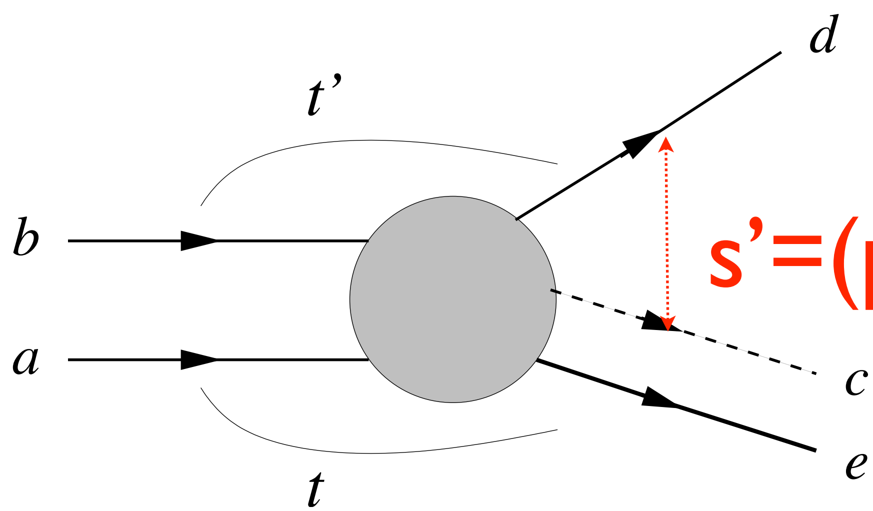
- Squeezed configurations are present with significant probability in mesons (evidence from observations of CT & and exclusive processes in DIS). Squeezing is likely to be more effective for mesons.

Branching exclusive processes

Another strategy - to use high energy CT to study dynamics of intermediate energy large angle scattering using new type of hard hadronic processes

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

to study both CT (suppression of absorption) in 2 → 2 & hadron generalized parton distributions (GPDs)



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

Limit:

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

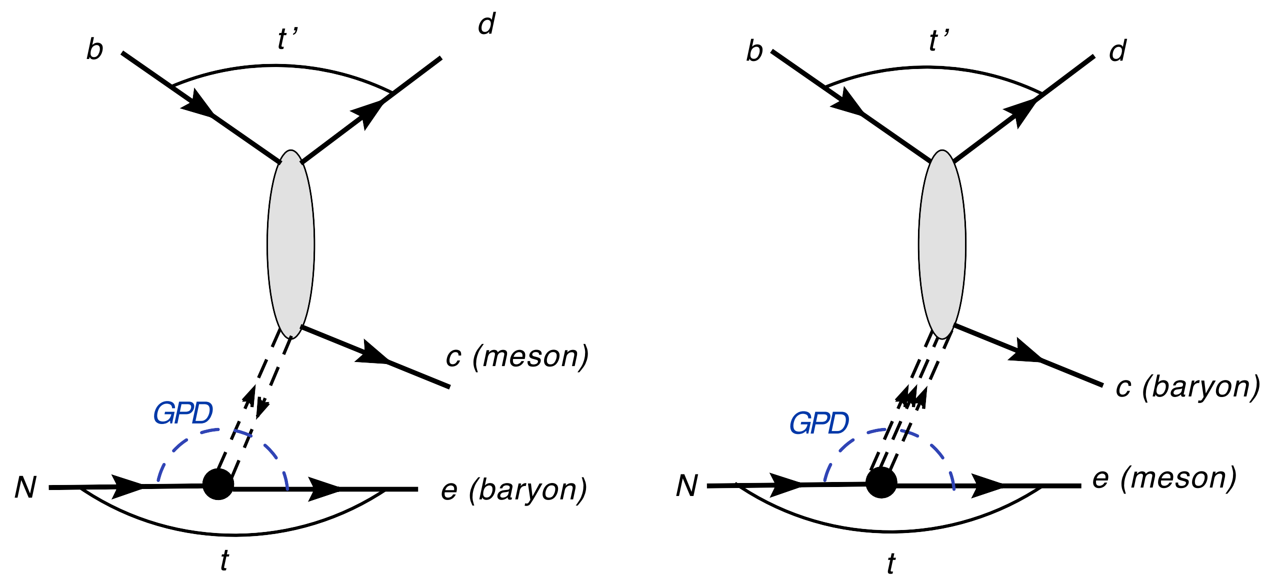
$-t = const \sim 0$

➡ $s'/s = y << 1$,

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

Two papers: Kumano, MS, and Sudoh PRD 09;
Kumano &MS Phys.Lett. 2010

*I*f squeezing occurs in large angle $2 \rightarrow 2$ process, factorization in $2 \rightarrow 3$ processes

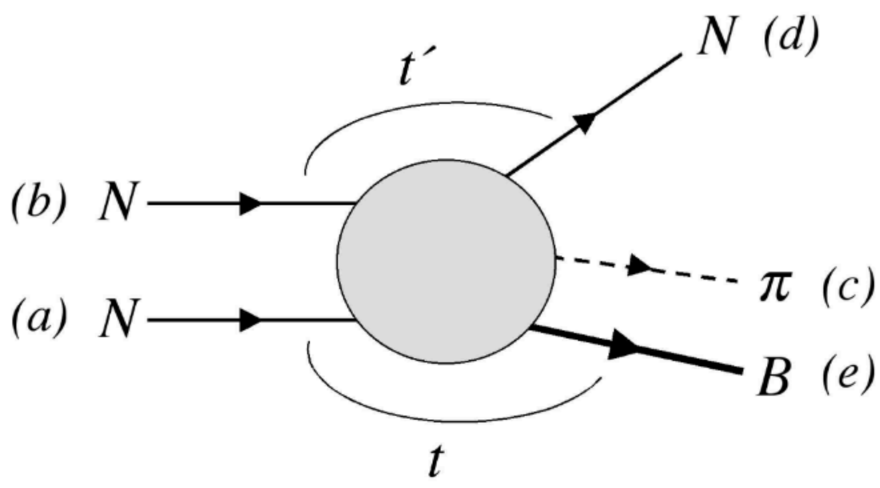


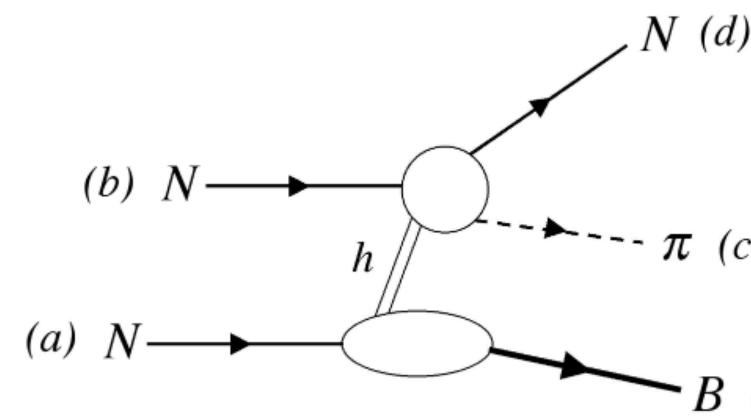
If the upper block is a hard ($2 \rightarrow 2$) process, "b","d","c" are in small size configurations as well as exchange system (qq, qqq). Can use CT argument as in the proof of QCD factorization of meson exclusive production in DIS (Collins, LF, MS 97)

$$\Downarrow$$

$2 \rightarrow 3$ amplitude is convolution of several blocks:

$$\mathcal{M}_{\pi N \to \pi\pi N} = GPD(N \to N) \otimes \psi^i_\pi \otimes H \otimes \psi_{\pi_f} \otimes \psi_{\pi'_f}$$





Factorization of $N + N \quad N + \pi + B$ process into $N \quad h + B$ and $h + N \quad \pi N$ amplitudes.

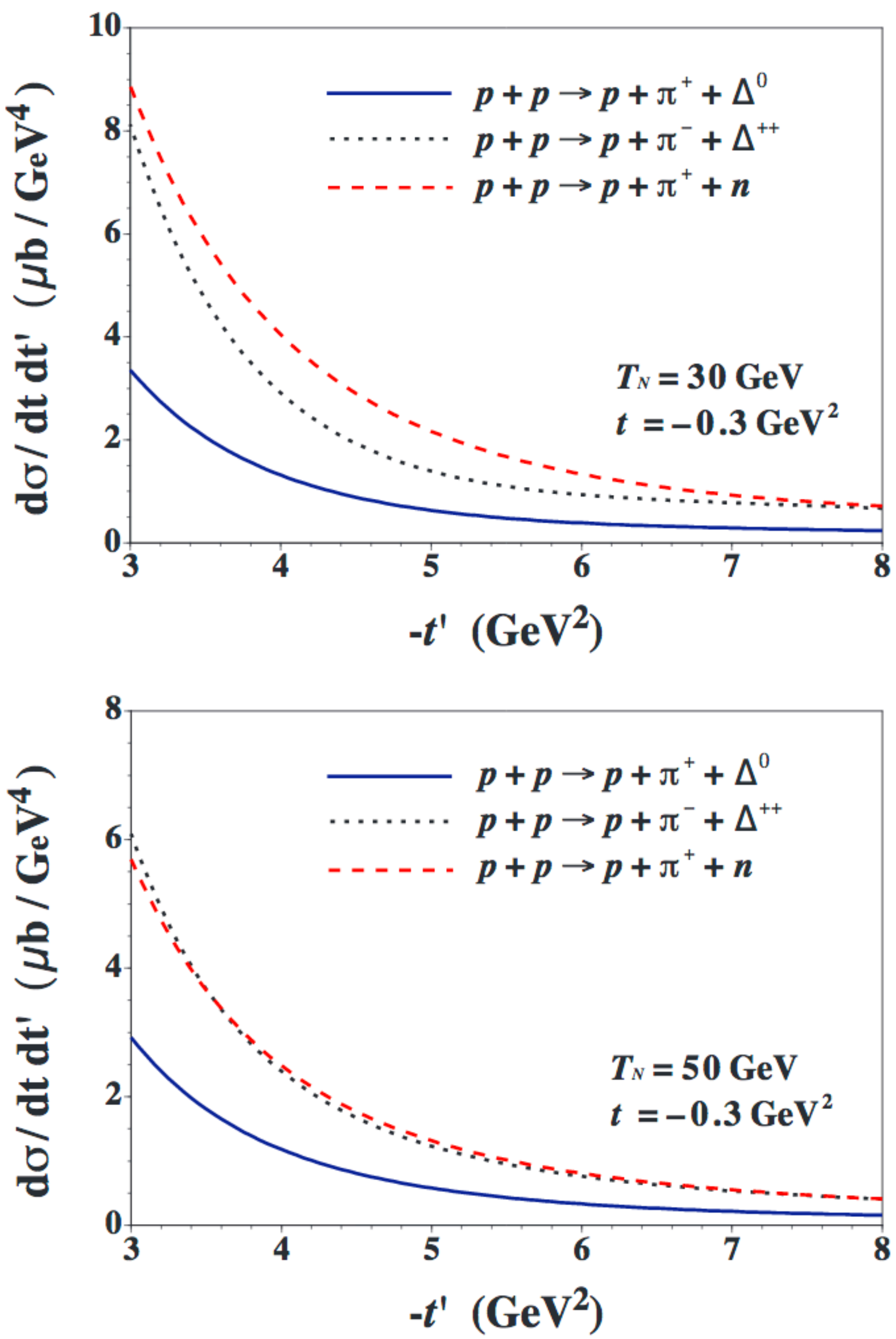


FIG. 11: Differential cross section as a function of t'. The incident proton-beam energy is 30 (50) GeV in the upper (lower) figure, and the momentum transfer is $t = -0.3$ GeV^2. The solid, dotted, and dashed curves indicate the cross sections for $p + p \to p + \pi^+ + \Delta^0$, $p + p \to p + \pi^-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

Study of Hidden/Intrinsic Strangeness & Charm in hadrons

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

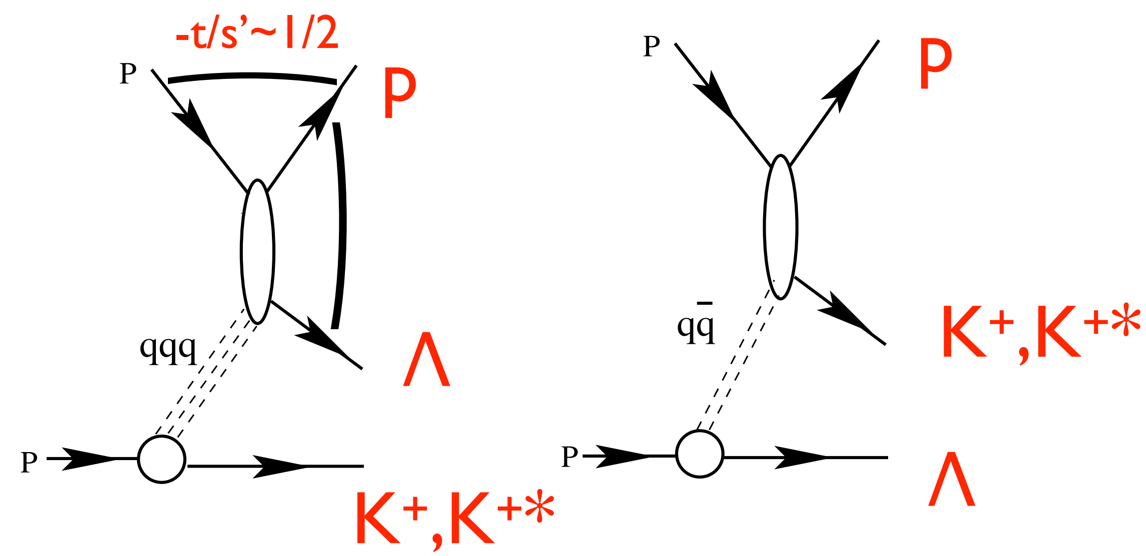
$pp \rightarrow K(K^*)_{sp} + \Lambda + p$

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

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

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

BNL experiment: EVA has few candidate eve



Many other interesting channels

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

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

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

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

COMPASS data on tape
for p ,A targets

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

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

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

Anybody from Dubna COMPASS group is around?

Conclusions

A diverse physics can be studied in (semi) exclusive processes which are within NICA range due to 4pi acceptance and possibility to take data at fixed s as a function of $\theta_{c.m.}$ and for fixed $\theta_{c.m.}$ as a function of s.

Exploring validity of factorization at a wide range of t, s

Complementary data will be forthcoming from FAIR/ PANDA (color transparency studies (Larionov & MS), factorization in SRC sensitive processes.

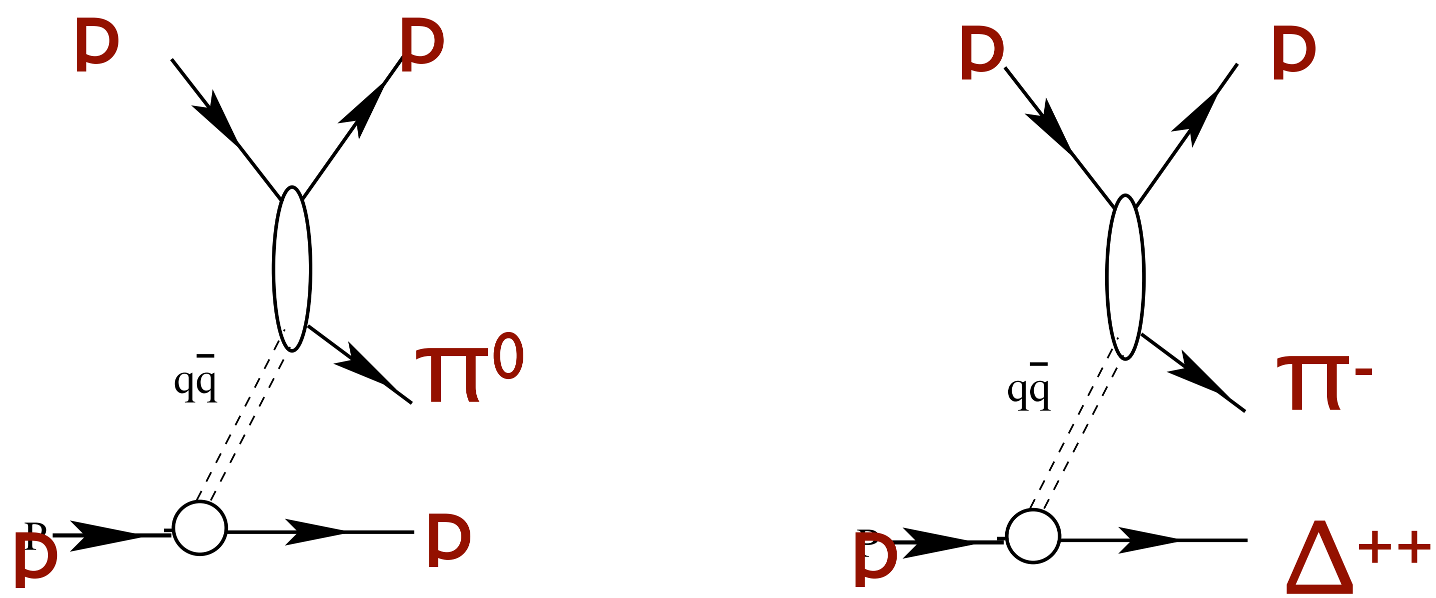
In long run polarization in pp, pd - will allow to address many issues left unresolved from old studies like Krish effect.

further studies are necessary how large are t doable at early stage and which would require a full luminosity

Supplementary slides

A detailed theoretical study of the reactions pp→NNπ, NΔπ was recently completed. Factorization based on squeezing

Kumano, Strikman, and Sudoh 09



Strategy of the first numerical analysis:

- account for contributions of GPDs corresponding to $q\bar{q}$ pairs with S=1 and 0
- Approximate the ERBL configurations by the pion and ρ-meson poles
- Use experimental information about
  $\pi^- p \to \pi^- p$, $\pi^- p \to \rho^- p$
  $\pi^+ p \to \pi^+ p$, $\pi^+ p \to \rho^+ p$

much better data are necessary for beams of energies of the order 10 GeV - J-PARC!!!

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

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

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

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

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

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

$$\mathcal{M}_N^V = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle N, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \psi(\lambda n/2) \right| N, p_a \right\rangle$$
$$= I_N \, \overline{\psi}_N(p_e) \big[H(x,\xi,t) \not{n} + E(x,\xi,t) \frac{i\sigma^{\alpha\beta} n_\alpha \Delta_\beta}{2m_N} \big] \psi_N(p_a)$$

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

$$\mathcal{M}_N^A = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle N, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \gamma_5 \psi(\lambda n/2) \right| N, p_a \right\rangle$$
$$= I_N \, \overline{\psi}_N(p_e) \big[\widetilde{H}(x,\xi,t) \not{n} \gamma_5 + \widetilde{E}(x,\xi,t) \frac{n \cdot \Delta \gamma_5}{2m_N} \big] \psi_N(p_a)$$

N →Δ transitions

$$\mathcal{M}^V_{N\to\Delta} = \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle \Delta, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \psi(\lambda n/2) \right| N, p_a \right\rangle$$
$$= I_{\Delta N} \overline{\psi}^\mu_\Delta(p_e) \big[H_M(x,\xi,t) \mathcal{K}^M_{\mu\nu} n^\nu + H_E(x,\xi,t) \mathcal{K}^E_{\mu\nu} n^\nu$$
$$+ H_C(x,\xi,t) \mathcal{K}^C_{\mu\nu} n^\nu \big] \psi_N(p_a),$$

$$\mathcal{K}^M_{\mu\nu} = -i \frac{3(m_\Delta + m_N)}{2m_N[(m_\Delta + m_N)^2 - t]} \varepsilon_{\mu\nu\lambda\sigma} P^\lambda \Delta^\sigma,$$
$$\mathcal{K}^E_{\mu\nu} = -\mathcal{K}^M_{\mu\nu} - \frac{6(m_\Delta + m_N)}{m_N Z(t)} \varepsilon_{\mu\sigma\lambda\rho} P^\lambda \Delta^\rho \varepsilon^\sigma_{\nu\kappa\delta} P^\kappa \Delta^\delta \gamma^5,$$
$$\mathcal{K}^C_{\mu\nu} = -i \frac{3(m_\Delta + m_N)}{m_N Z(t)} \Delta_\mu (t P_\nu - \Delta \cdot P \Delta_\nu) \gamma^5,$$

where m_Δ is the Δ mass, and $Z(t)$ is defined by

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

$$
\begin{aligned}
\mathcal{M}^{A}_{N\to\Delta} &= \int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle \Delta, p_e \left| \overline{\psi}(-\lambda n/2) \not{n} \gamma^5 \psi(\lambda n/2) \right| N, p_a \right\rangle \\
&= I_{\Delta N}\, \overline{\psi}^{\mu}_{\Delta}(p_e) \Big[\widetilde{H}_1(x,\xi,t) n_\mu + \widetilde{H}_2(x,\xi,t) \frac{\Delta_\mu (n\cdot\Delta)}{m_N^2} \\
&\quad + \widetilde{H}_3(x,\xi,t) \frac{n_\mu \not{\Delta} - \Delta_\mu \not{n}}{m_N} \\
&\quad + \widetilde{H}_4(x,\xi,t) \frac{P\cdot\Delta n_\mu - 2\Delta_\mu}{m_N^2} \Big] \psi_N(p_a)
\end{aligned}
$$

$$
\begin{aligned}
\phi_\pi(z) &= \sqrt{3} f_\pi z(1-z), \\
\phi_\rho(z) &= \sqrt{6} f_\rho z(1-z).
\end{aligned}
$$

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

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

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

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

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