"Revealing short-range structure of nuclei with high energy probes: recent results and open questions

bridging different resolution scales

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Sacley, March 8, 2016

Main topics

Open questions of microscopic nuclear structure

Four resolution scales in resolving structure of nuclei

Why high energies are necessary to probe short-range structure of nuclei

Δ-isobars, 3N in nuclei - towards direct observations;
2N - directions for detailed studies (very briefly)

EMC effect: unambiguous evidence of non-nucleonic degrees of freedom in A; constrains on the mechanism, message from LHC pA collisions

Strategies for further studies: Jlab, muon beams, EIC...

① Nuclear observables at low energy scale: treat nucleus as a Landau-Migdal Fermi liquid with nucleons as quasiparticles (close connection to mean field approaches) - should work for processes with energy transfer $\lesssim E_F$ and momentum transfer $q \lesssim k_F$. Nucleon effective masses ~0.7 m_N, effective interactions - SRC are hidden in effective parameters. Similar logic in the chiral perturbation theory / effective field theory approaches - very careful treatment at large distances ~ $1/m_\pi$, exponential cutoff of high momentum tail of the NN potential

② Nuclear observables at intermediate energy scale: energy transfer < 1 GeV and momentum transfer q < 1 GeV. Transition from quasiparticles to bare nucleons - very difficult region - observation of the momentum dependence of quenching (suppression) factor Q for A(e,e'p) (Lapikas, MS, LF, Van Steenhoven, Zhalov 2000)

③ Hard nuclear reactions I: energy transfer > 1 GeV and momentum transfer q > 1 GeV. Resolve SRCs = direct observation of SRCs but not sensitive to quark-gluon structure of the bound states

④ 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

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.

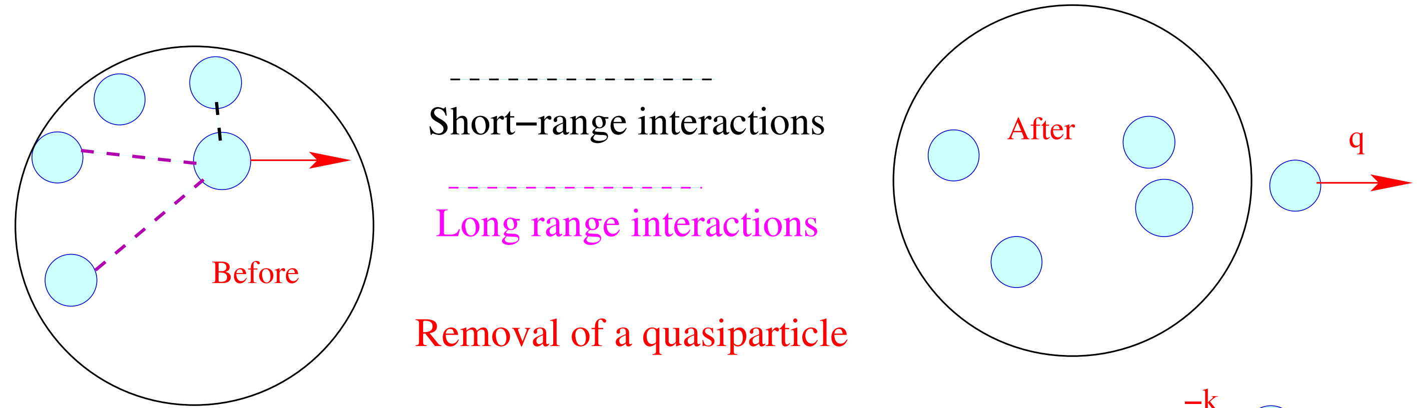
➟ Complexity of the problem

Precision determination of the nuclear structure at different resolution scales requires also understanding of the fine details of the interaction dynamics.

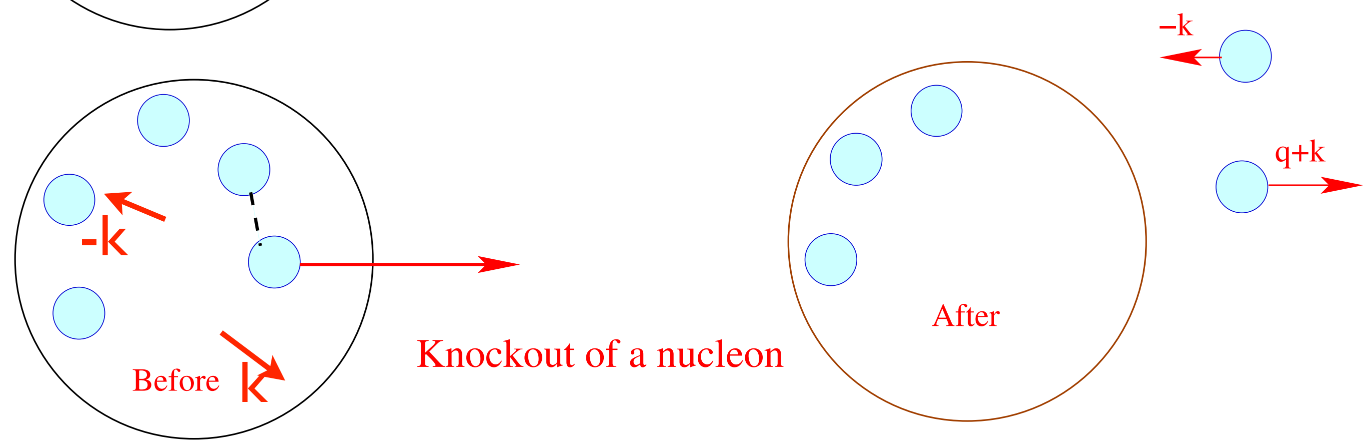
Examples: *At what Q squeezing sets in for the nucleon form factors ?*

Final state interactions in eA scattering: formation time, etc

Low Q^2 scale



High Q^2 scale I

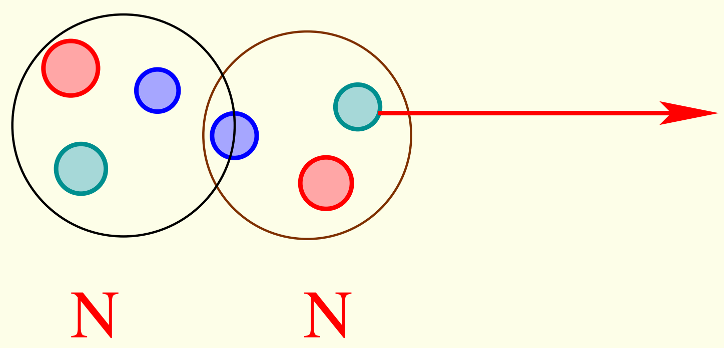


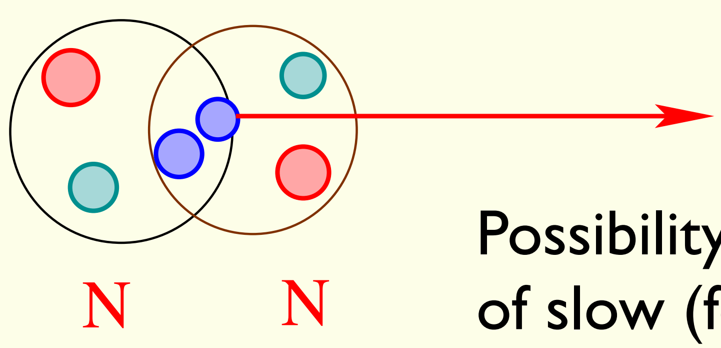
from short-range correlation
(SRC)

our informal definition: 2 N SRC = two nearby nucleons with momenta approximately back to back

SRC - understood generically as correlations in the two nucleon wave function at small r_1-r_2 for decades were considered an elusive property of nuclei

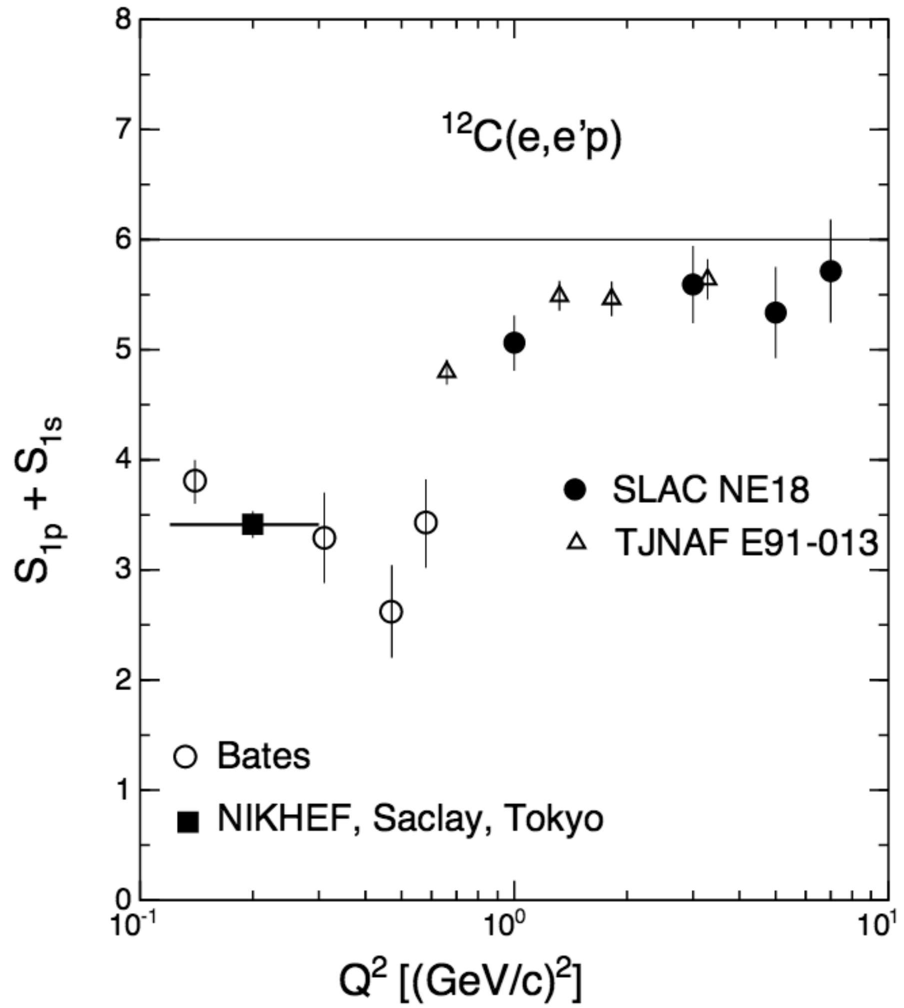
High Q^2 scale II Quark removal in the DIS kinematics





Possibility of decay of the residual system with production of slow (for example backward in the nucleus rest frame) baryons like N*, Δ-isobar if color is not localized in one nucleon.

Any new effects if one would remove a valence gluon (EIC)



Lapikas, van der Steenhoven, Frankfurt, MS Zhalov, Phys.Rev. C, 2000

Q^2 dependence of the spectroscopic factor

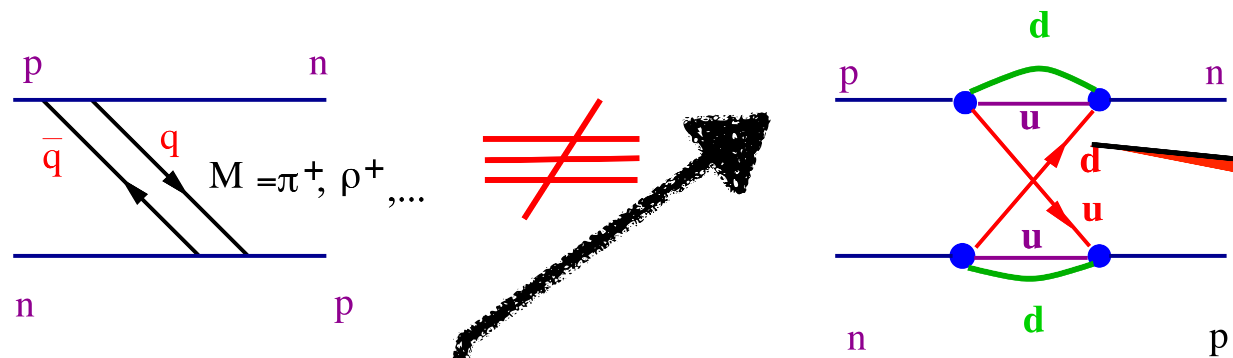
Rather rapid transition from regime of interaction with quasiparticles to regime of interaction with nucleons

$Q^2_{transition} \approx 0.8$ GeV^2

Still need to study transition in a single experiment.

Interaction picture also depends on resolution: low scale instantaneous effective resolution, high Q scale non-static interaction: interaction time >> 1/Q

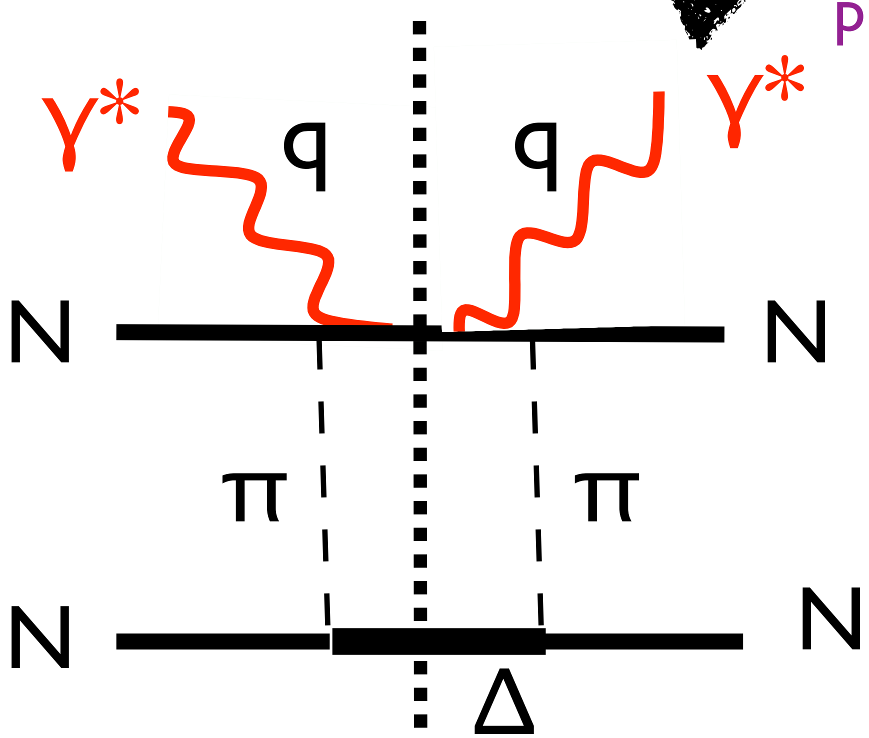
Meson exchange forces: pions in the intermediate states, Δ-isobars



Meson Exchange ***Quark interchange***

Intermediate state may not be = pn, but say ΔN.

may correspond to a tower of meson exchanges with coherent phases - high energy example is Reggeon;
pion exchange for low t special - due to small mass



Two gluon interchange? Much larger mass scale in t -channel - very short distances

Why studying SRC is important

- Best chance to observe new physics beyond many nucleon approximation - Δ's, quark - gluon degrees of freedom, etc

- Properties of drops of very dense nuclear matter ➜ Eq. of state for cores of neutron stars

Very different strength of pp and pn SRC, practical disappearance of the Fermi step for protons for ρ(neutron star) >ρ (nuclear matter)

- ~80% of kinetic energy of heavy nuclei is due to SRCs = powerhouse of nuclei

- Microscopic origin of intermediate and short-range nuclear forces

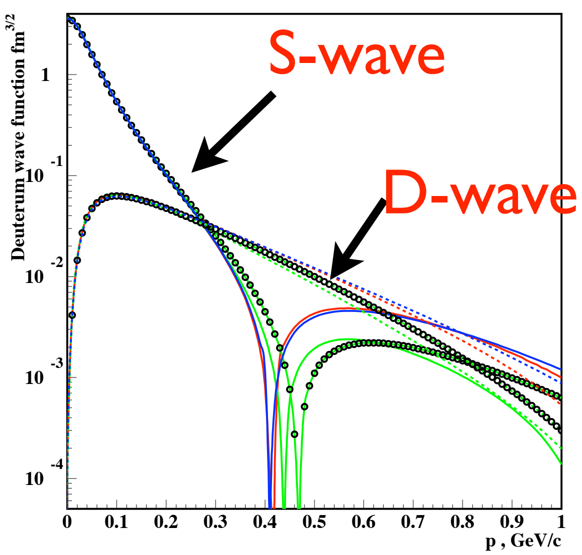
- Numerous applications

Modeling of νA quasielastic scattering

Neutron production in AA collisions at RHIC, LHC

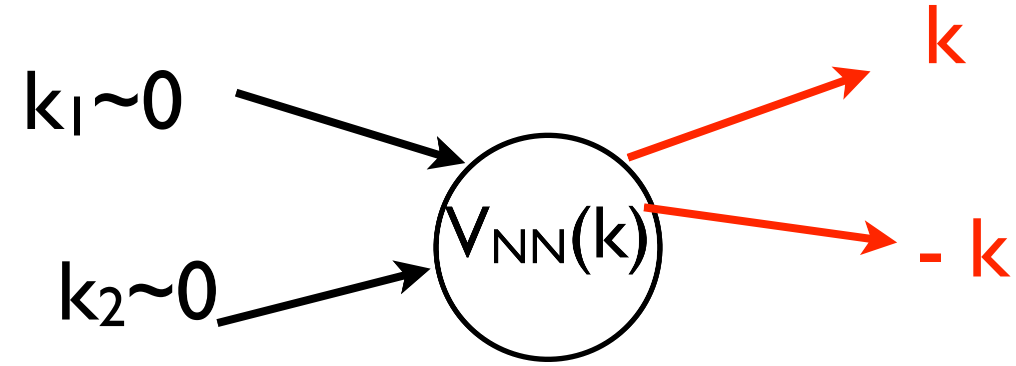
Properties of SRCs

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

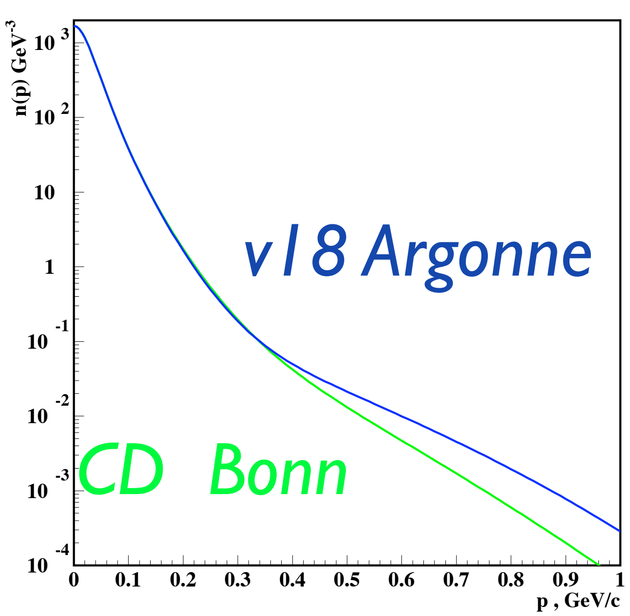
$$\psi_D^2(k)_{|k\to\infty} \propto \frac{V_{NN}^2(k)}{k^4}$$



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.

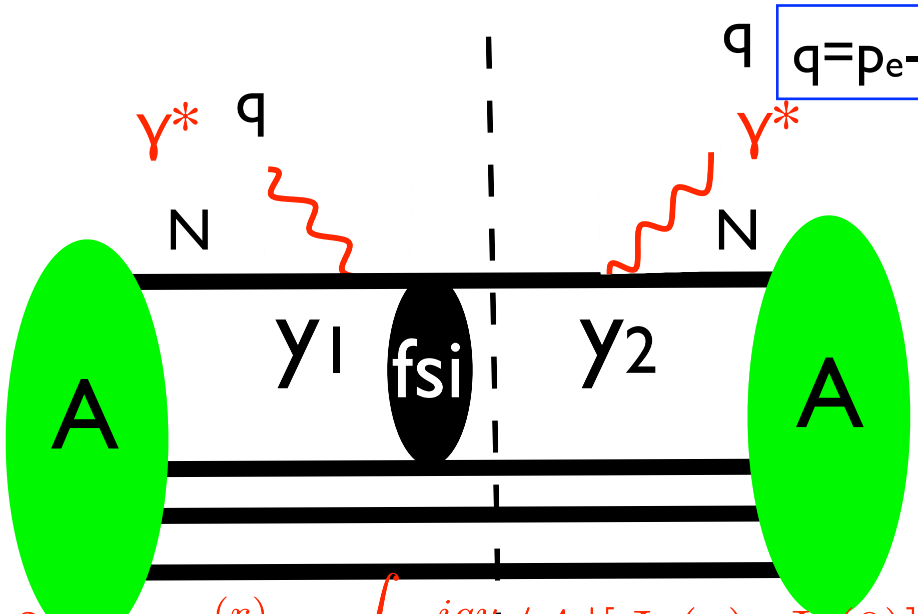
$$n_A(k)_{|k\to\infty} \propto \frac{V_{NN}^2(k)}{k^4}$$

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

Progress in the study of SRCs of the last several years is due to analysis of two classes of hard processes we suggested in the 80's: inclusive scattering in the kinematics forbidden for scattering off free nucleon & nucleus decay after removal of fast nucleus.

One group of processes which led to the progress in the studies of SRC at high momentum is A(e,e') at $x > 1$, $Q^2 > 1.5$ GeV^2

Closure approximation for A(e,e') at $x = AQ^2/2q_0m_A > 1$, $Q^2 > 1.5$ GeV^2 up to final state interaction (fsi) between constituents of the SRC



q=p_e-$p_{e'}$ is four momentum of virtual photon, $Q^2=-q^2$

$$2m_A q_3 \sigma^{(r)} = \int e^{iqy} \langle A \,|[J_\mu(y), J_\lambda(0)]|\, A\rangle \, \epsilon_\mu^{(r)} \epsilon_\lambda^{(r)} d^4y$$

In lab frame q= (q_0,q_z),

$q_- = q_0 - q_z << q_+ = q_0 + q_z$

DIS like kinematics for nucleons= partons

analog of Ioffe time in DIS $y_1^{(z)} - y_2^{(z)} <$ 1.2 fm

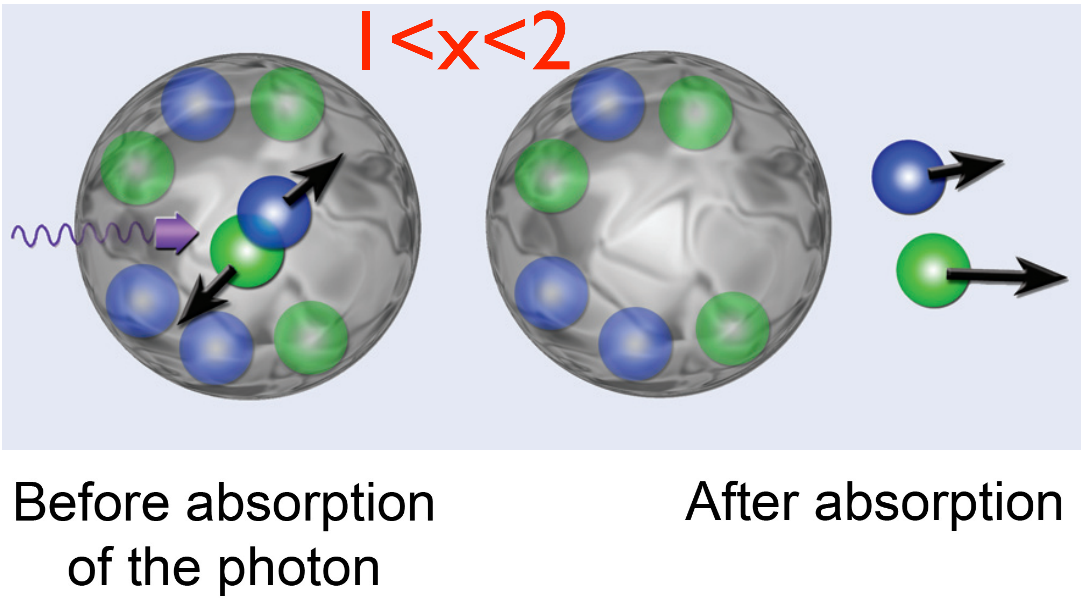
⇒

fsi **only** within SRC - may be large for some kinematics - but **universal**

Corrections could be calculated for large Q using generalized eikonal approximation. For interactions of knocked out nucleon with slow nucleons they are less than few % - LF & Misak Sargsian & MS (08)

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)



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.

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

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

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

Superscaling of the ratios FS88

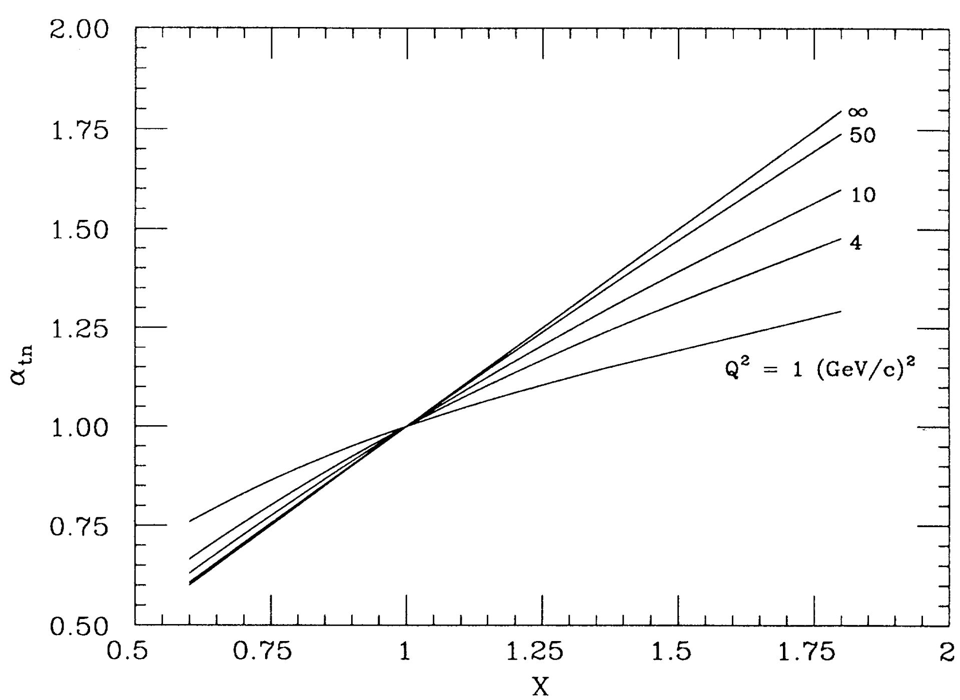
Compare the ratios for different Q^2 at x corresponding to the same momentum of nucleon in nuclei (including effect of excitation of the residual system - best done in the light-cone formalism)

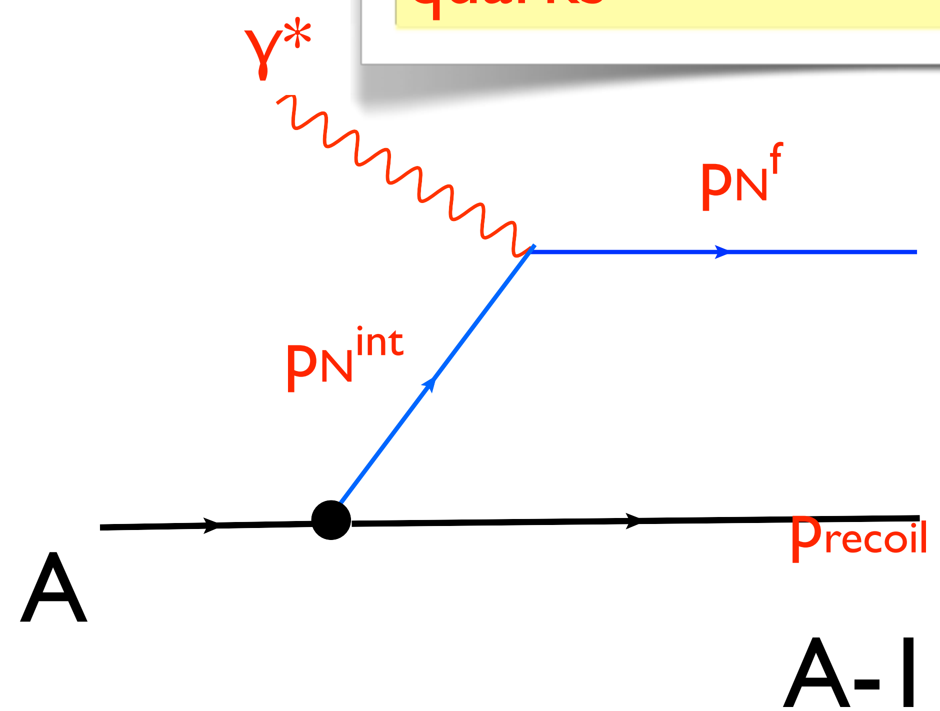
Main dependence is on "+" component (α) of p_N^{int}, allows to take "-" component in average point given by two nucleon SRC approximation

$$\alpha_{tn} = 2 - \frac{q_- + 2m_N}{2m_N}\left(1 + \frac{\sqrt{W^2 - 4m_N^2}}{W}\right)$$

$$where\ q_- = q_0 - q_3,\ W^2 = 4m_N^2 + 4q_0 m_N - Q^2$$

Remark for people with a QCD background: α_{tn} is rather close to Nachtmann variable for massive quarks



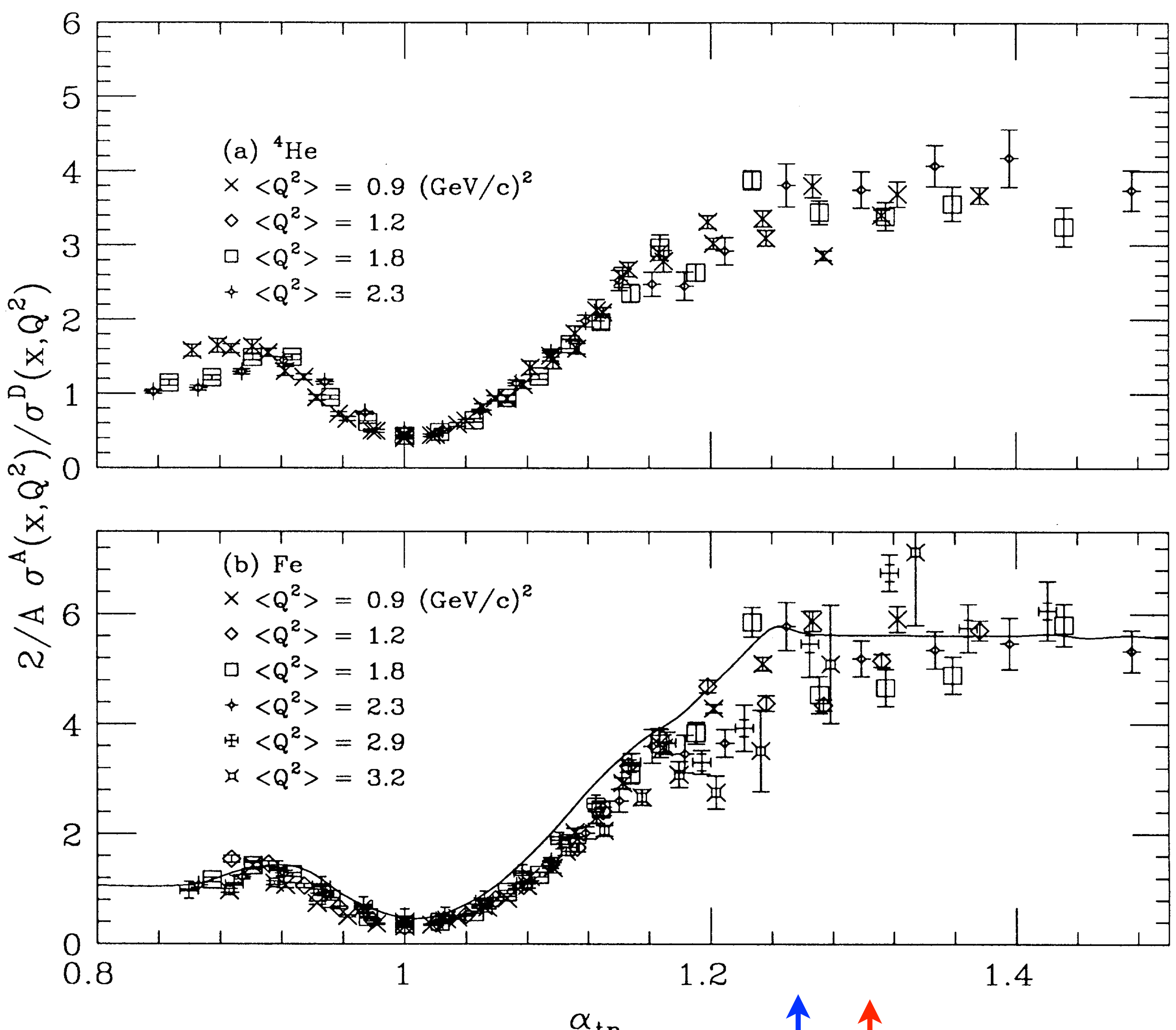


α_{tn} vs x for Q^2=1, 4, 10, 50, ∞. At $Q^2 \to \infty$, $\alpha_{tn} = x$

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

⇒ ρ- Light-cone density =

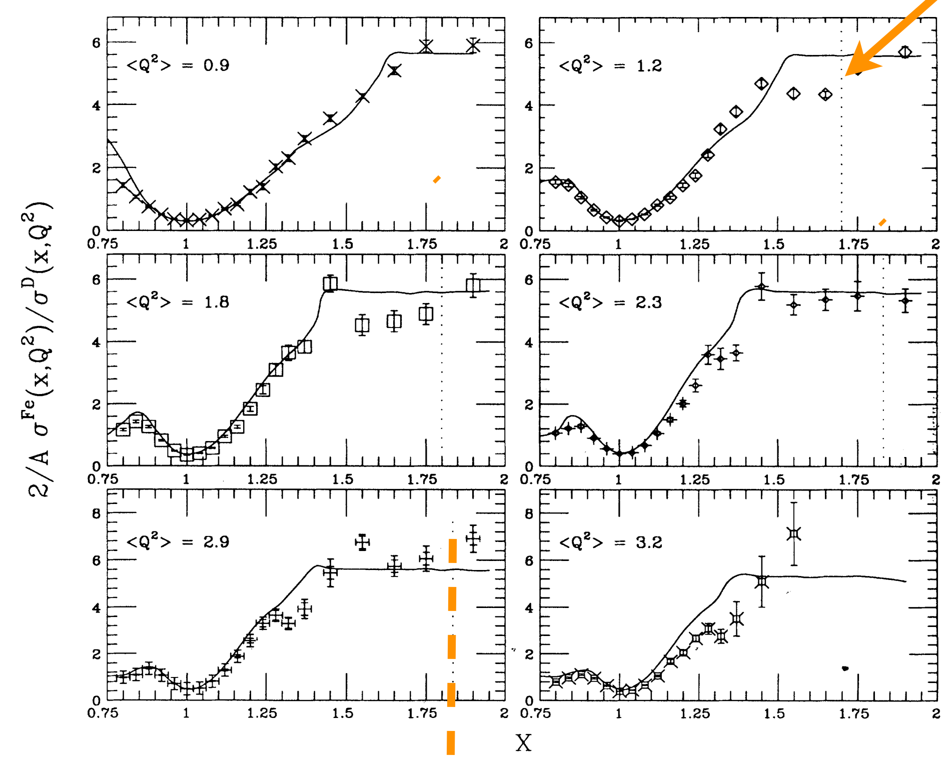
$$\frac{\sigma_{A_1}(x,Q^2)}{\sigma_{A_2}(x,Q^2)} = \frac{\int \rho_{A_1}(\alpha_{tn},p_t)d^2p_t}{\int \rho_{A_2}(\alpha_{tn},p_t)d^2p_t} \cdot \frac{a_2(A_1)}{a_2(A_2)}_{|1.6>\alpha\geq 1.3}$$



k_{min}=0.3 GeV

k_{min}=0.25 GeV

$W - M_D \leq 50\,MeV$

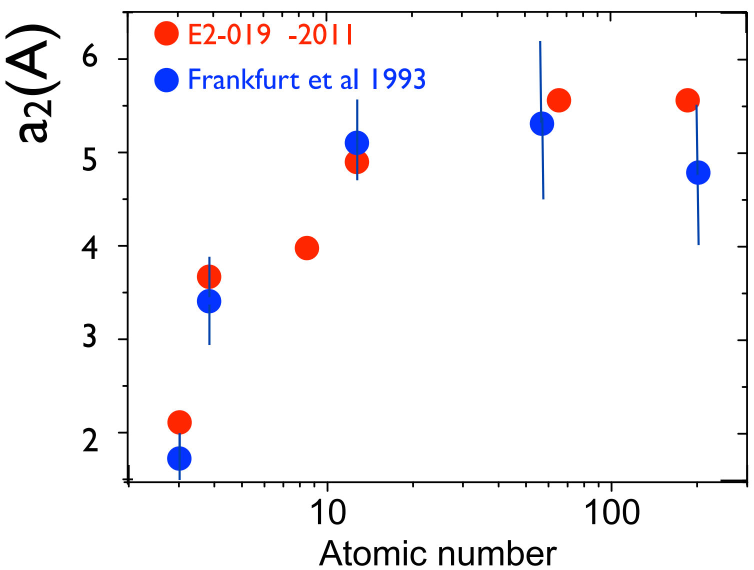


Masses of NN system produced in the process are small - strong suppression of isobar, 6q degrees of freedom.

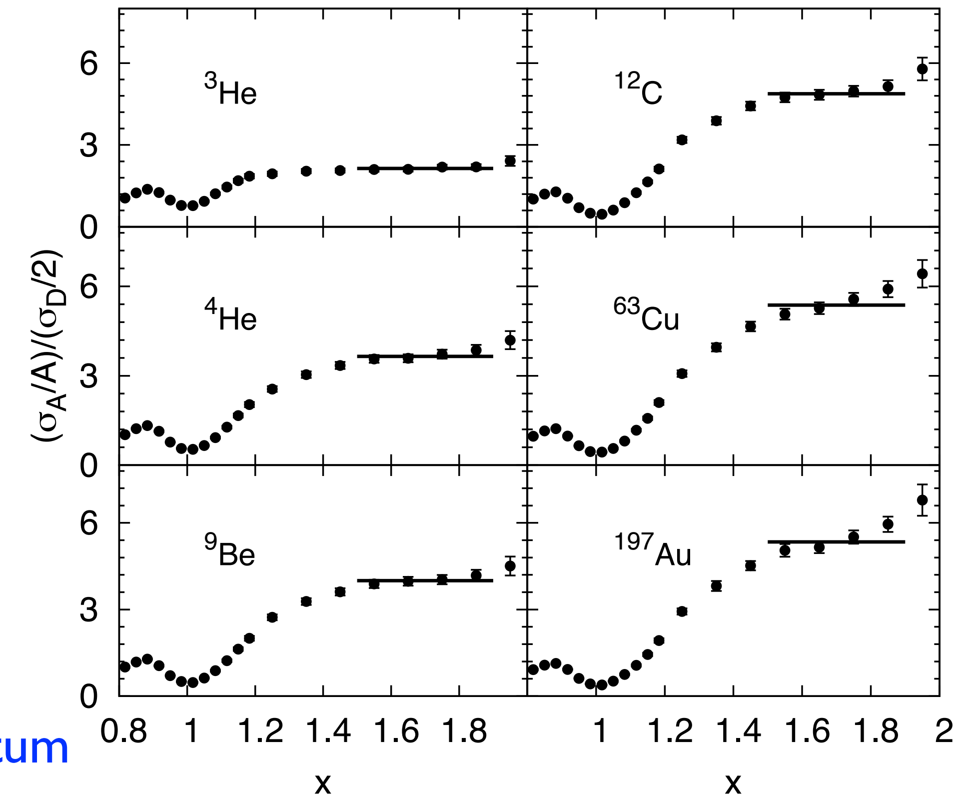
Frankfurt et al, 93

Right momenta for onset of scaling of ratios !!!

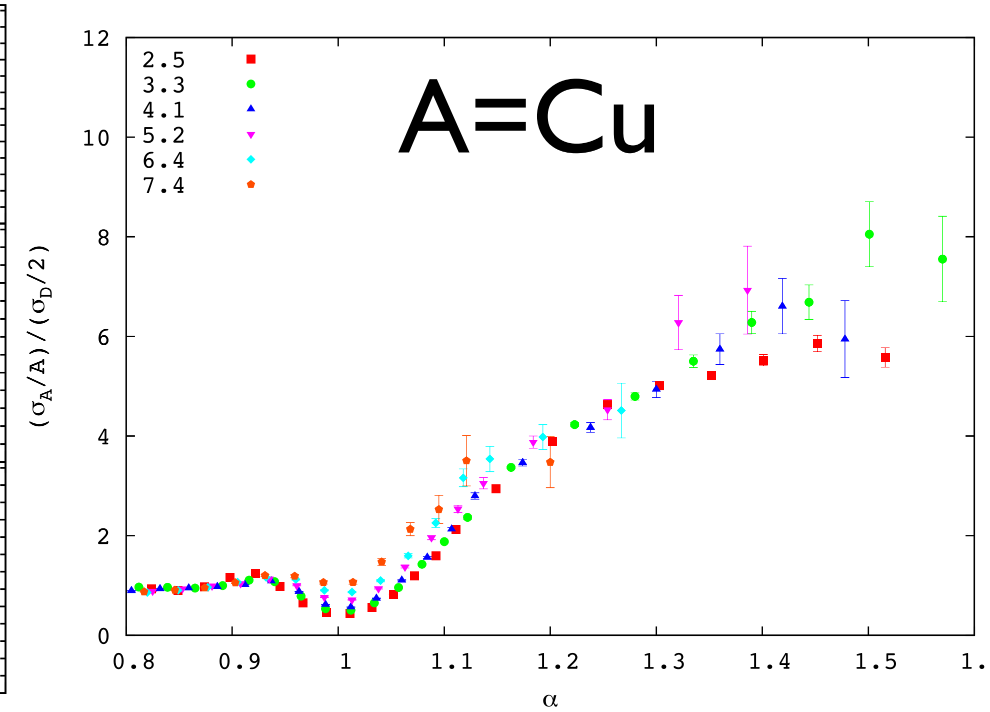
Universality of 2N SRC is confirmed by Jlab experiments



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



From N.Fomin thesis

E2-019-2011

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

Currently the ratios are the best way to determine absolute probability of SRC - main uncertainty ~20% - deuteron wave function

The second group of processes (both lepton and hadron induced) which led to the progress in the studies of SRC is investigation of the decay of SRC after one of its nucleons is removed via large energy- momentum transfer process.

Nuclear Decay Function

What happens if a nucleon with momentum k belonging to SRC is instantaneously removed from the nucleus (hard process)? Our guess is that associated nucleon from SRC with momentum ~ -k should be produced.

Formal definition of a new object - nuclear decay function (FS 77-88) - probability to emit a nucleon with momentum k_2 after removal of a fast nucleon with momentum k_1, leading to a state with excitation energy E_r (nonrelativistic formulation)

$$D_A(k_2, k_1, E_r) = |\langle\phi_{A-1}(k_2, ...)\,|\delta(H_{A-1} - E_r)a(k_1)|\,\psi_A\rangle|^2$$

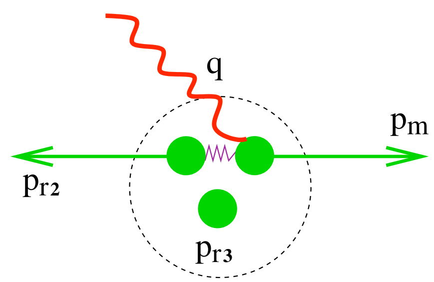
General principle (FS77): to release a nucleon of a SRC - necessary to remove nucleons from the same correlation - perform a work against potential $V_{12}(r)$

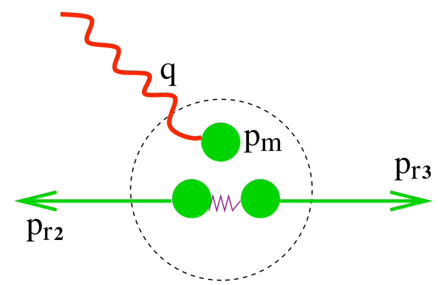
If we would consider the decay in the collider kinematics: nucleus with momentum Ap scatters off a proton at rest - removal of a nucleon with momentum αp leads to removal of a nucleon with momentum $(2-\alpha)$p

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.

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

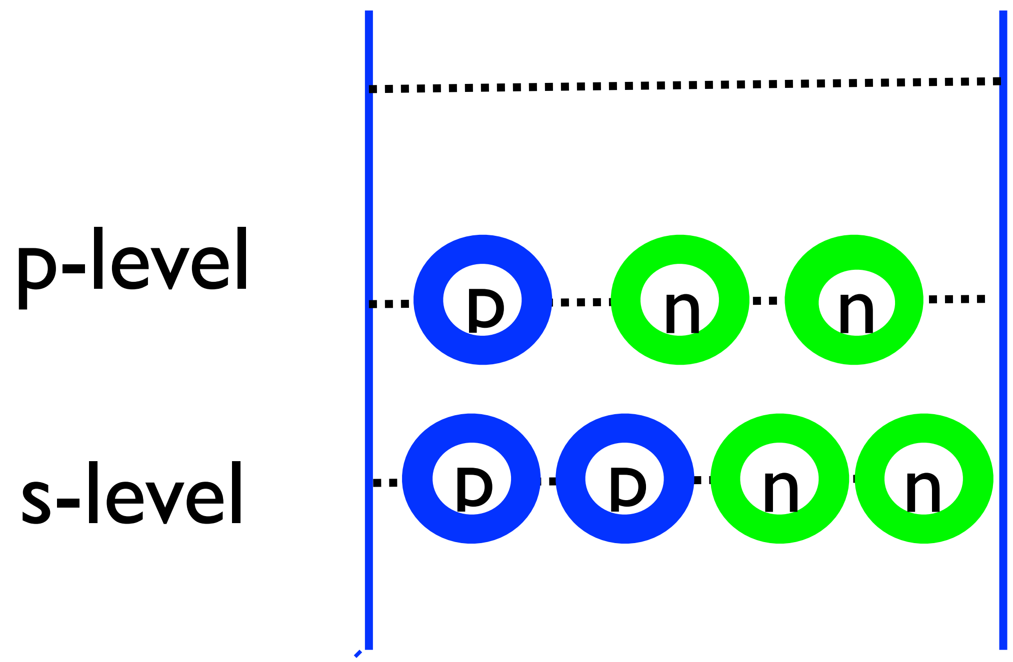
resembles 2N momentum distribution

does not resemble 2N momentum distribution -

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

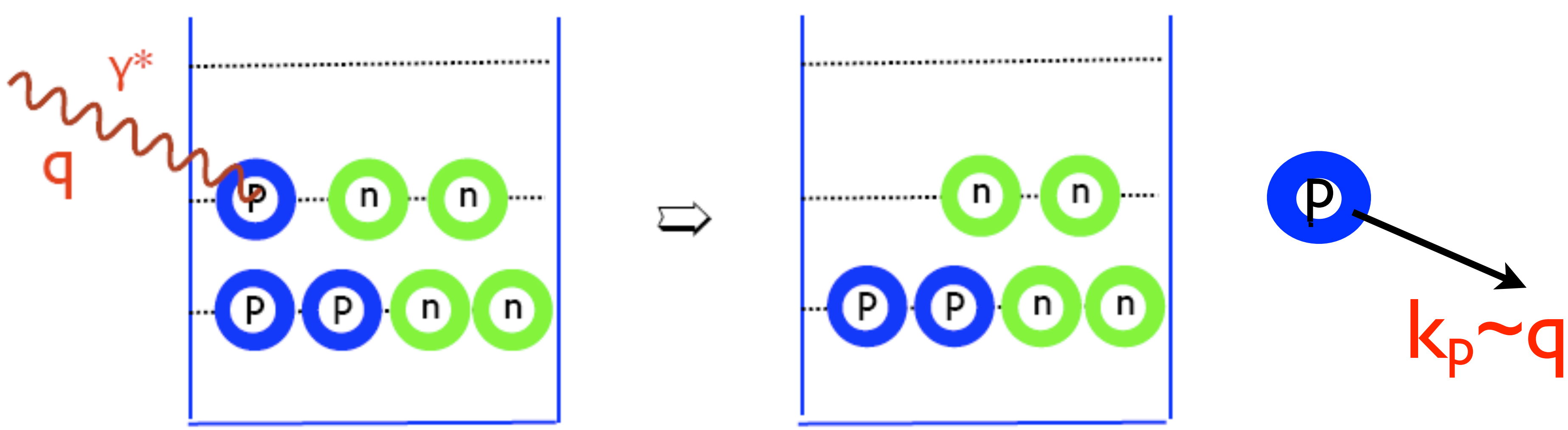
Sargsian et al 2004

The prediction of back - to - back correlation differs from the expectations based on the textbook picture of nuclei:



Nucleons occupy the lowest levels given by the shell model

What happens if a nucleon is removed from the nucleus?

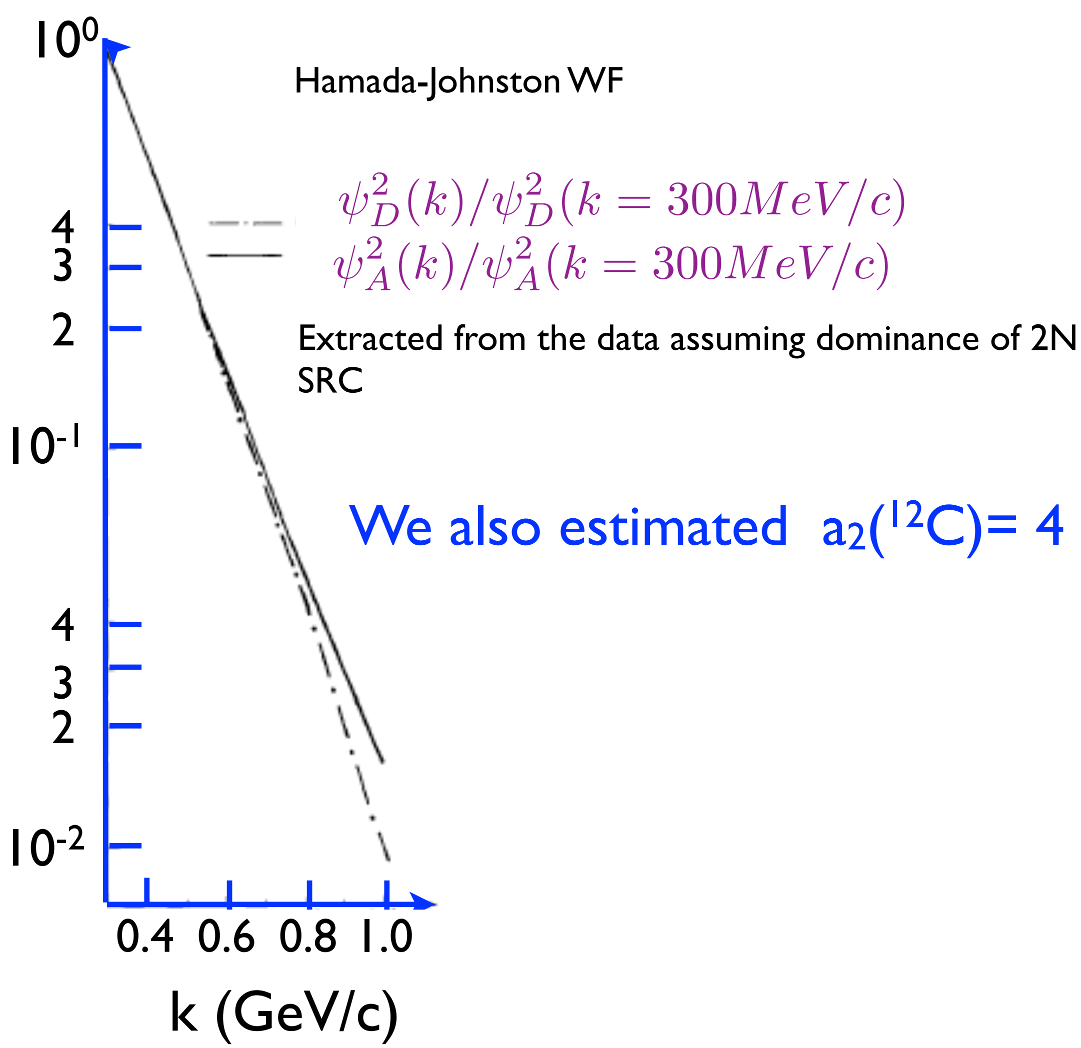


removal of a nucleon

Residual nucleus in ground or excited state of the shell model Hamiltonian - decay product practically do not remember direction of momentum of struck proton. RIKEN studies such decays including complicated ones where several nucleons were emitted.

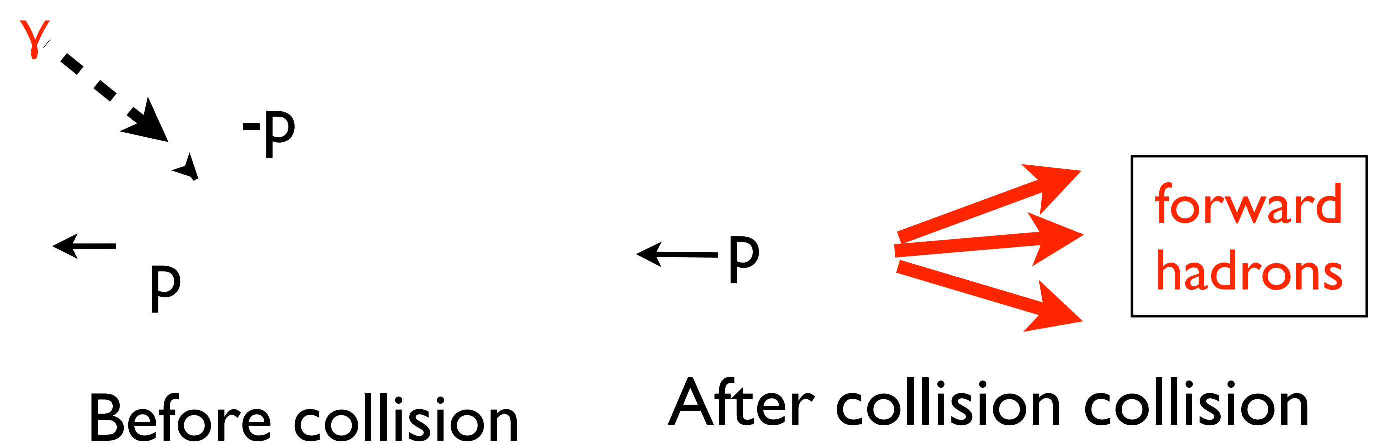
First application of the logic of decay function - spectator mechanism of production of fast backward nucleons - observed in high energy proton, pion , photon - nucleus interactions with a number of simple regularities. We suggested - spectator mechanism - breaking of 2N, 3N SRCs. We extracted (Phys.Lett 1977) two nucleon correlation function from analysis of $\gamma(p)\,{}^{12}C \to$ 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.



In the collider frame where nucleus has momentum Ap: SRC is two nucleons with momenta αp and $(2-\alpha)p$

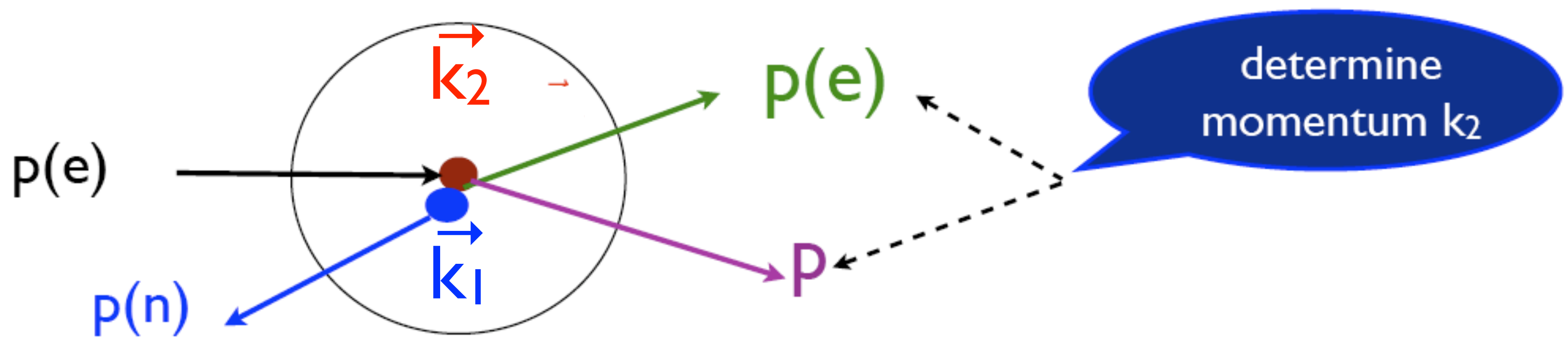
Backward direction is very good for looking for decay of SRCs

We were prompted by G. Farrar in 86 to discuss large angle pp scattering off the bound nucleon: p + A → pp (A-1)* - prime topic was color transparency. Next we realized that this process selects scattering off the fast forward moving protons since elastic pp cross section

$$\frac{d\sigma}{d\theta_{c.m.}} = \frac{1}{s^{10}} f(\theta_{c.m.})$$

Hence in a large fraction of the events there should be fast neutrons flying backward. We heard of plans of a new experiment - EVA. So without much expectation that somebody would notice we wrote that it would be nice to have a backward neutron detector added to EVA. Eli Piazetski did notice.

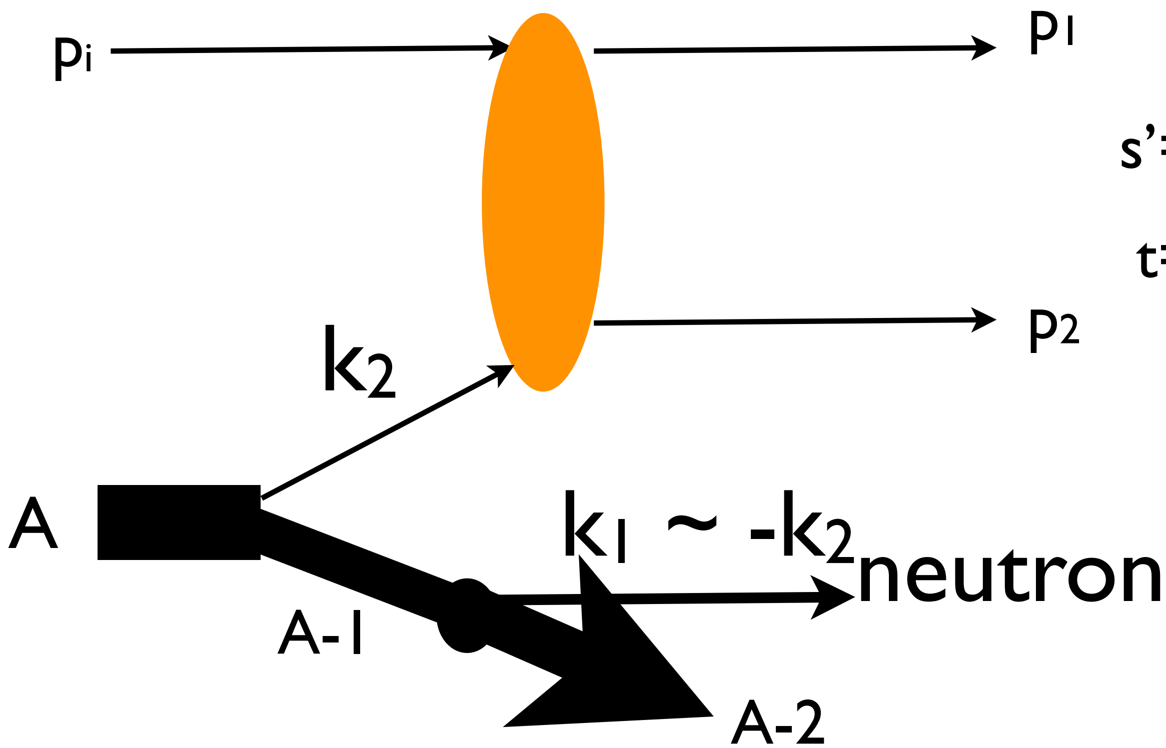
To observe SRC directly it is far better to consider semi-exclusive processes e(p) +A → e(p) + p + " nucleon from decay" +(A-2) since it measures both momentum of struck nucleon and decay of the nucleus



Several novel experiments reported results in the last 10 years starting with

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

- *(e,e' pp), (e,e'pn) Jlab* $Q^2 = 2GeV^2$



$s' = (p_1 + p_2)^2$ $k_2 = p_1 + p_2 - p_i$

$t = (p_1 - p_p)^2$

Collider frame

$s' = \alpha s_{NN}$, $\alpha < 1$

neutron momentum $(2-\alpha)p$

From measurement of p_1, p_2 $p_{neutron}$ choose small excitation energy of A-2 (< 100 MeV)

$\sigma = d\, \sigma^{pp \to pp}/dt(s',t)$ * (Decay function)

Test of Factorization: $\sigma / d\, \sigma^{pp \to pp}/dt(s',t)$ independent of s', t

Analysis of BNL E850 data

$pC \rightarrow ppn + (A-2)^*$

at energy and momentum transfer ≥ 3 GeV

Evidence for the Strong Dominance of Proton-Neutron Correlations in Nuclei

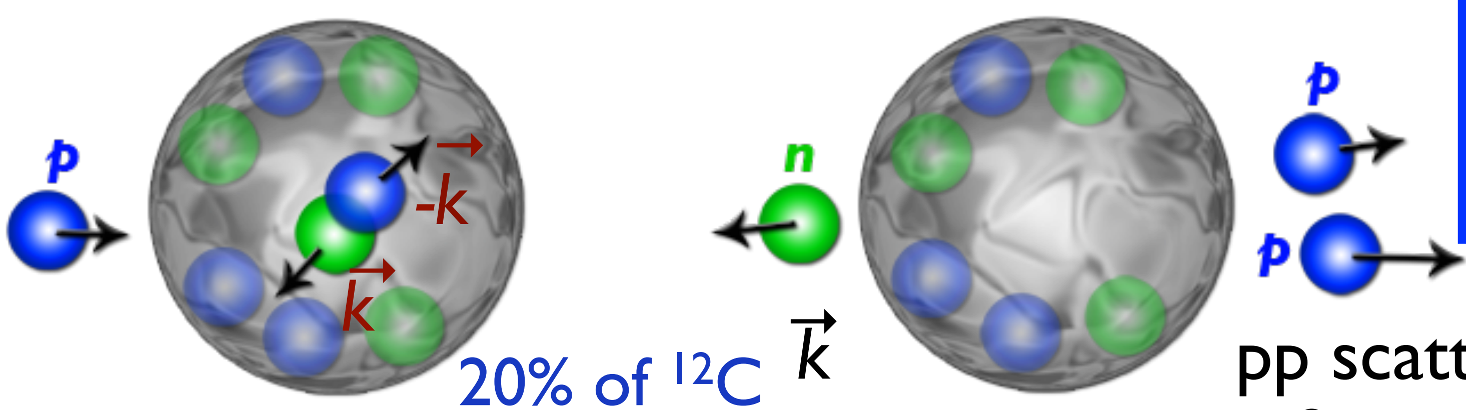
E. Piasetzky,[1] M. Sargsian,[2] L. Frankfurt,[1] M. Strikman,[3] and J. W. Watson[4]

PRL 06

spectator mechanism of backward nucleon production
FS77

Analysis using decay function modeled using 2N correlation model (including relativistic effects) - the same approximation as for spectral function in CSFS 91

Probability to emit neutron is amazingly high ~90% after we accounted for the motion of the pair (measured/calculated independently) and detector acceptance



20% of ^{12}C wave function

pp scatter at $\theta_{c.m.}=90°$

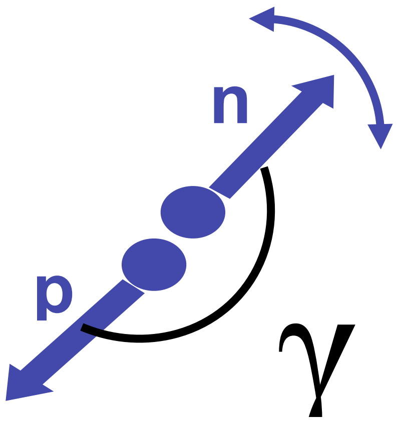
Before collision **After collision**

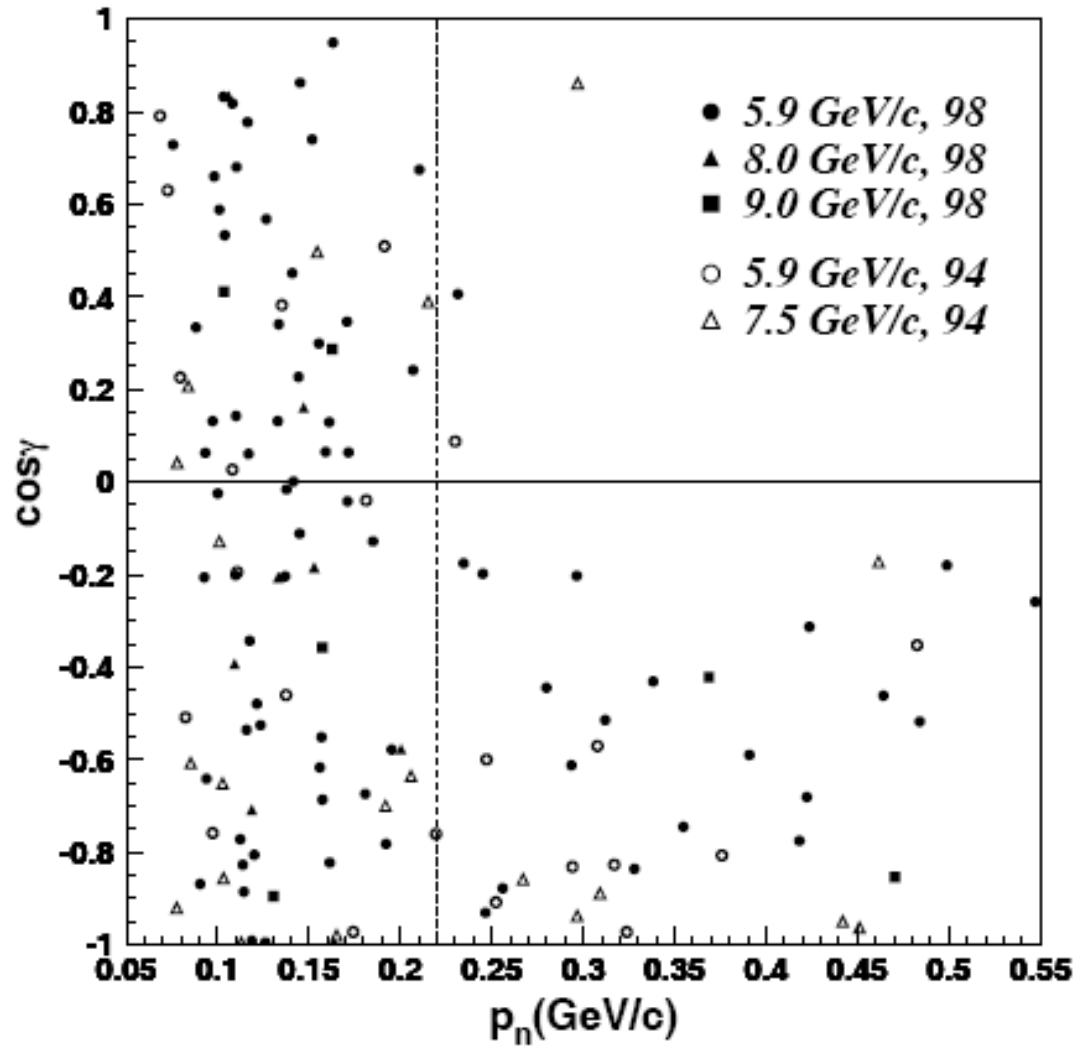
pn/pp > 16; I=0 dominance - qualitatively consistent with current calculations of nuclear wave functions

removal of a proton with momentum > 250 MeV/c

~90% probability of emission of neutron with similar but opposite momentum

k_F=220 MeV/c

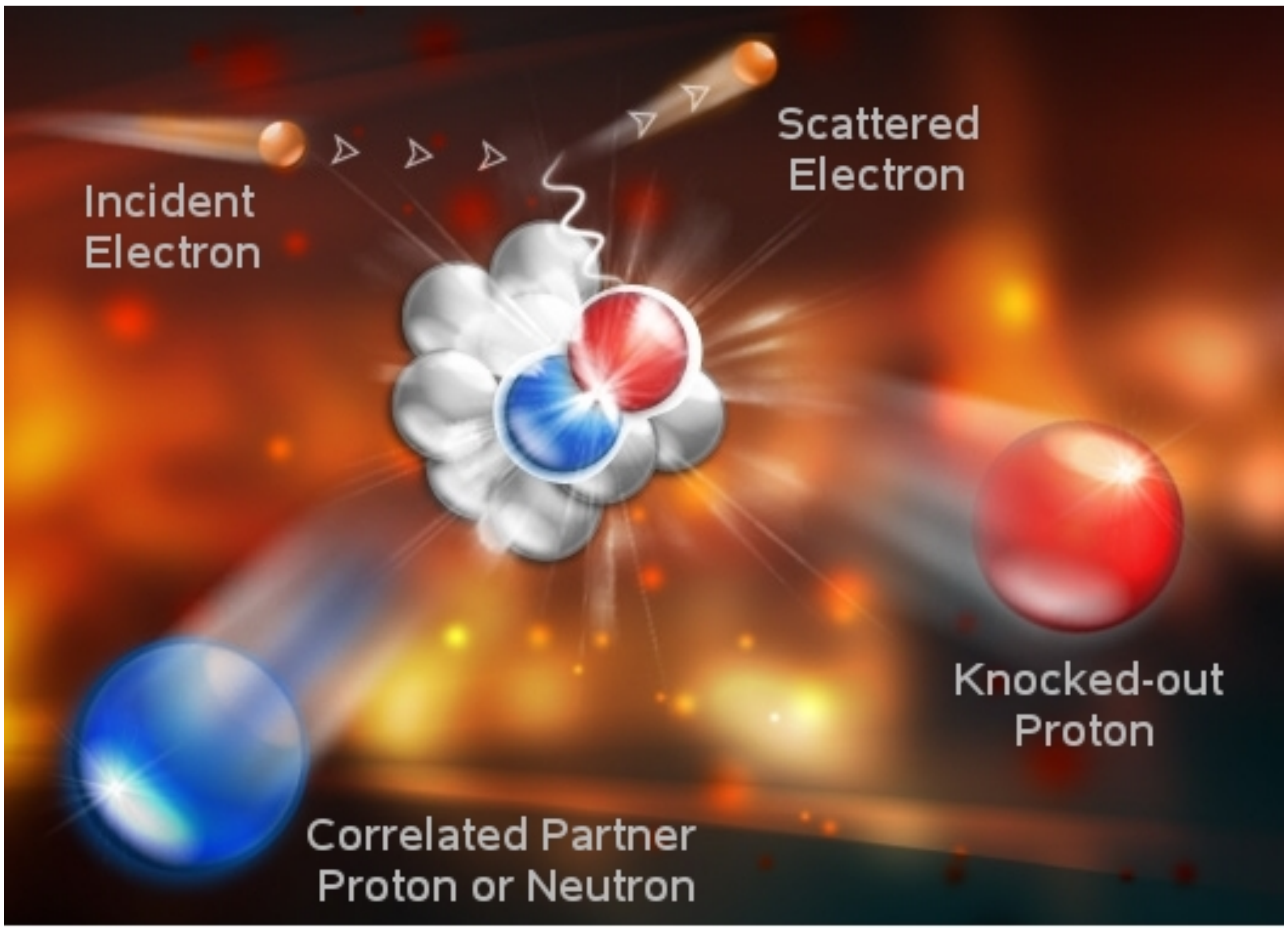




BNL Carbon data of 94-98. The correlation between p_n and its direction γ relative to p_i. The momenta on the labels are the beam momenta. The dotted vertical line corresponds to k_F=220 MeV/c.

SRC appear to dominate at momenta k> 250 MeV/c - very close to k_F. *A bit of surprise* - we expected dominance for k> 300 - 350 MeV/c. Naive inspection of the realistic model predictions for $n_A(k)$ clearly shows dominance only for k > 350 MeV/c. Important to check a.s.p. - Can be done at lower momentum transfer than at $k \gg k_F$

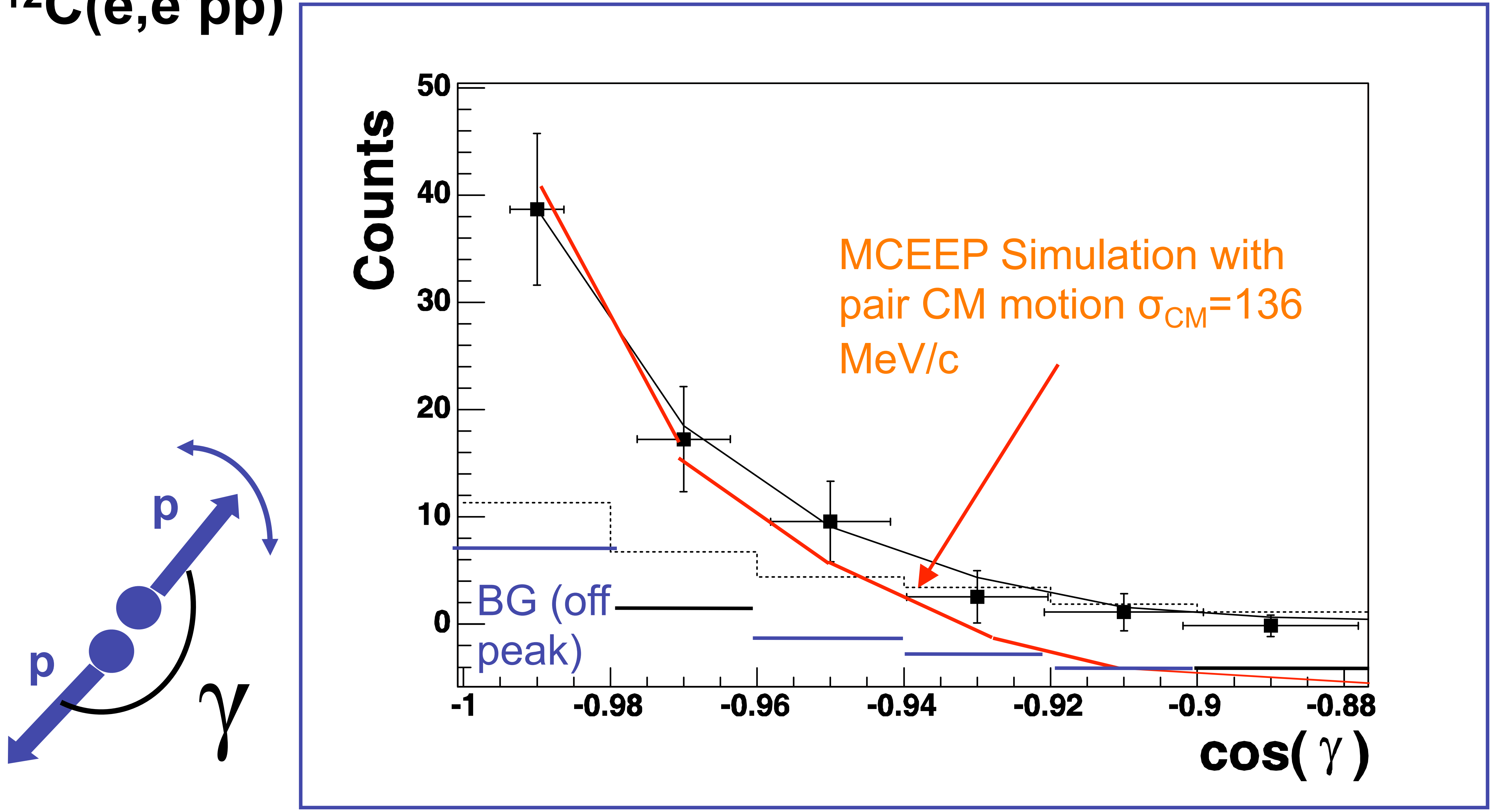
Jlab: from study of (e,e'pp), (e,e'pn)~10% probability of proton emission, strong enhancement of pn vs pp. The rate of pn coincidences is similar to the one inferred from the BNL data



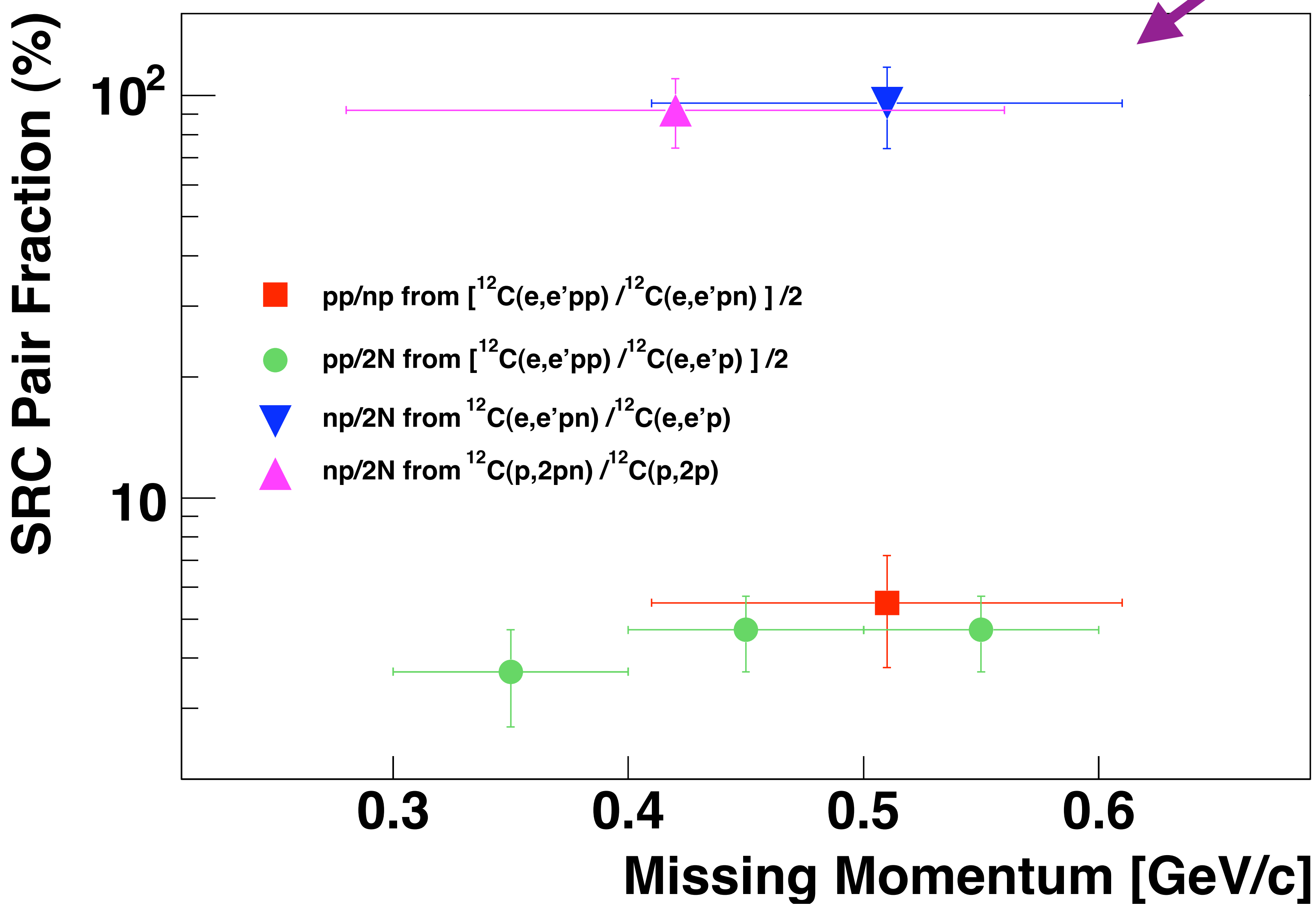
T-shirt of Jlab 09

Directional correlation

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



Note - BNL and Jlab studied very different kinematics for breakup of 2N SRC - similarity of the numbers is highly non-trivial



Our analysis of BNL Experiment measurement was $92^{+8}_{-18}\ \%$

accounting for charge exchange

$$\frac{np-SRC}{pp-SRC} = 18 \pm 5$$

In Carbon 12

The analysis of the absolute rates of EVA for (p,2p) - $a_2(C) \sim 5$

with a significant uncertainties in absolute scale

Yaron et al 02

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

Puzzle of fast backward nucleon production is solved!!!

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

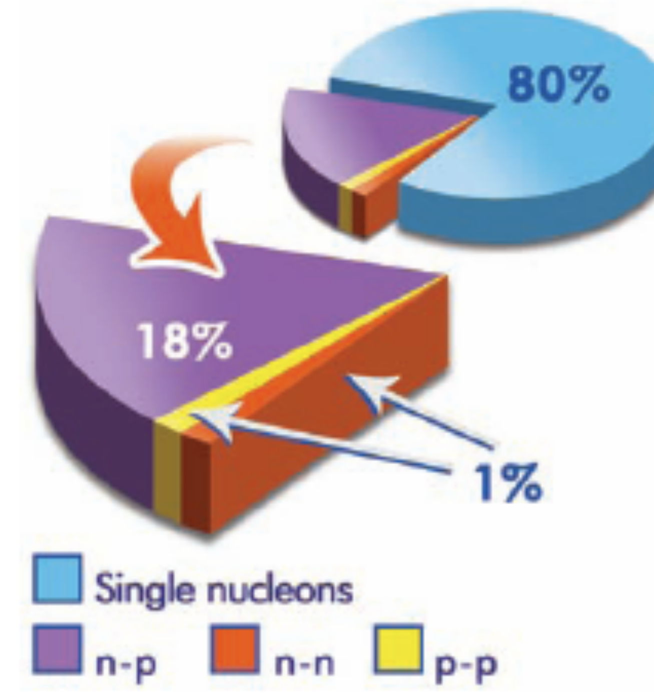
Summary of the findings

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

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



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

The findings confirm our predictions based on the study of the structure of SRC in nuclei (77-93), add new information about isotopic structure of SRC.

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

Open questions:

Precision measurements of 2N, tests of factorization

Direct observation of 3N SRC (electron scattering with production of two backward nucleons,...)

Discovery of non-nucleonic degrees of freedom in nuclei: Δ's ,..

,

Testing origin of the EMC effect (tagged structure functions)

Observation of superfast quarks

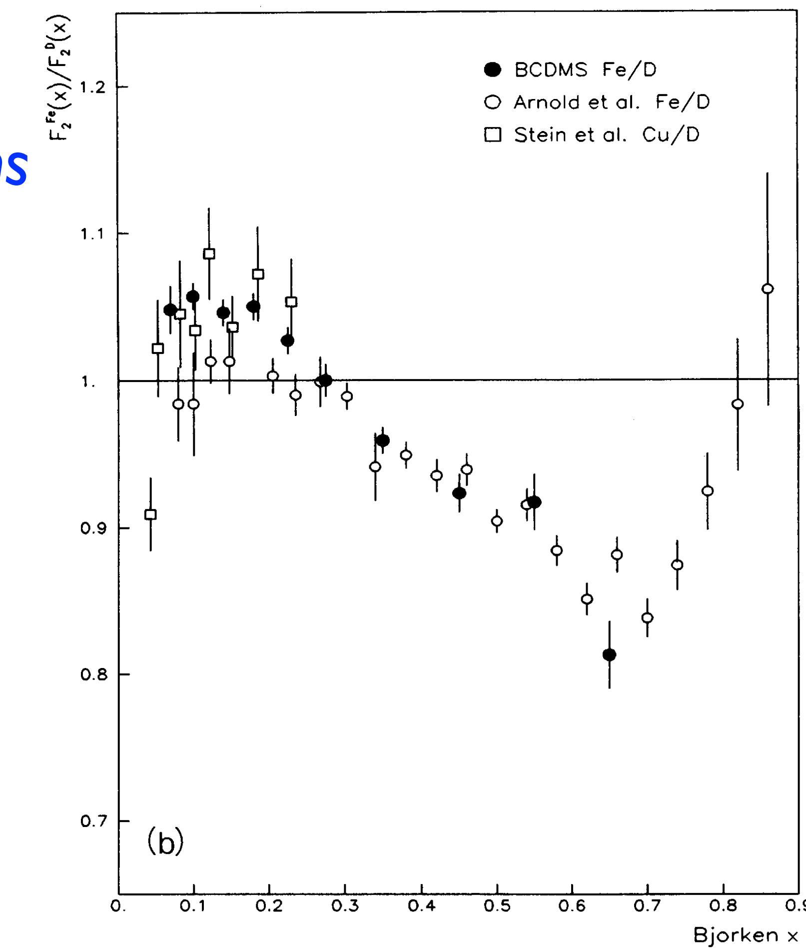
no time to discuss

Parton level nucleus resolution scale:
- summary of what we know and open questions

DIS (and other hard inclusive processes) = The highest resolution possible for probing the distribution of constituents in hadrons is deep inelastic scattering

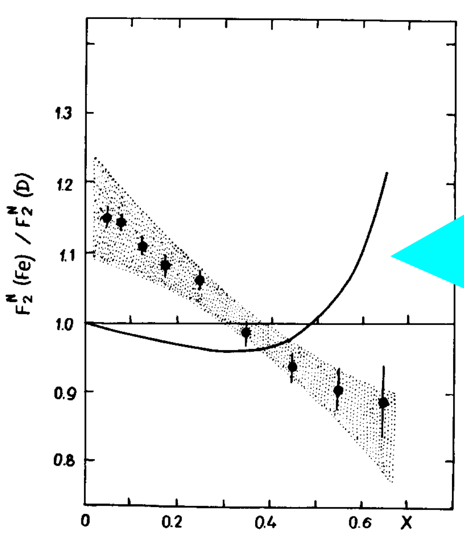
Reference point: nucleus is a collection of quasifree nucleons.

A hard probe incoherently interacts with individual nucleons



EMC ratio

$$R_A(x,Q^2) \equiv \frac{\sigma_A(x,Q^2)}{Z\sigma_p(x,Q^2)+N\sigma_n(x,Q^2)} = 1$$



Theoretical expectation under assumption that nucleus consists only of nucleons FS 81

One should not be surprised by presence of the effect but by its smallness for x<0.35 where bulk of quarks are. Since distances between nucleons are comparable to the radii of nucleons.

Large effects for atoms in this limit.

$$F_{2A}(x,Q^2) = \int \rho_A^N(\alpha,p_t) F_{2N}(x/\alpha) \frac{d\alpha}{\alpha} d^2p_t$$

Light cone nuclear nucleon density (light cone projection of the nuclear spectral function

≡probability to find a nucleon with longitudinal momentum $\alpha P_A/A$

Can account of Fermi motion describe the EMC effect?

YES : If one violates baryon charge conservation or momentum conservation or both

Many nucleon approximation:

$$\int \rho_A^N(\alpha,p_t) \frac{d\alpha}{\alpha} d^2p_t = A$$ baryon charge sum rule

$$\frac{1}{A}\int \alpha\rho_A^N(\alpha,p_t) \frac{d\alpha}{\alpha} d^2p_t = 1 - \lambda_A$$

fraction of nucleus momentum NOT carried by nucleons

=0 in many nucl. approx.

Since spread in α due to Fermi motion is modest ⇒ do Taylor series expansion in convolution formula in (1- α): α= 1+ (α-1)

Fermi motion - actually SRCs

$$R_A(x,Q^2) = 1 - \frac{\lambda_A x F'_N(x,Q^2)}{F_N(x,Q^2)} + \frac{xF'_{2N}(x,Q^2) + (x^2/2)F''_{2N}(x,Q^2)}{F_{2N}(x,Q^2)} \cdot \frac{2(T_A - T_{^2H})}{3m_N}$$

$$F_{2N} \propto (1-x)^n, n \approx 2(JLAB) \quad R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x} + \frac{xn\left[x(n+1)-2\right]}{(1-x)^2} \cdot \frac{(T_A - T_{^2H})}{3m_N}$$

$$n \approx 3(Leading\,twist)$$

R_A for x <2/(n+1) slightly below and rapidly growing for x > 2/(n+1)

$$n(Jlab) \approx 2$$

large higher twist contribution

➡ EMC effect is unambiguous evidence for presence of non nucleonic degrees of freedom in nuclei. The question is what they are?

Traditional nuclear physics:

EMC effect is trivial

λ_A ---fraction of momentum carried by pions is few %

$$R_A(x, Q^2) = 1 - \frac{\lambda_A n x}{1 - x}$$

Drell-Yan experiments:

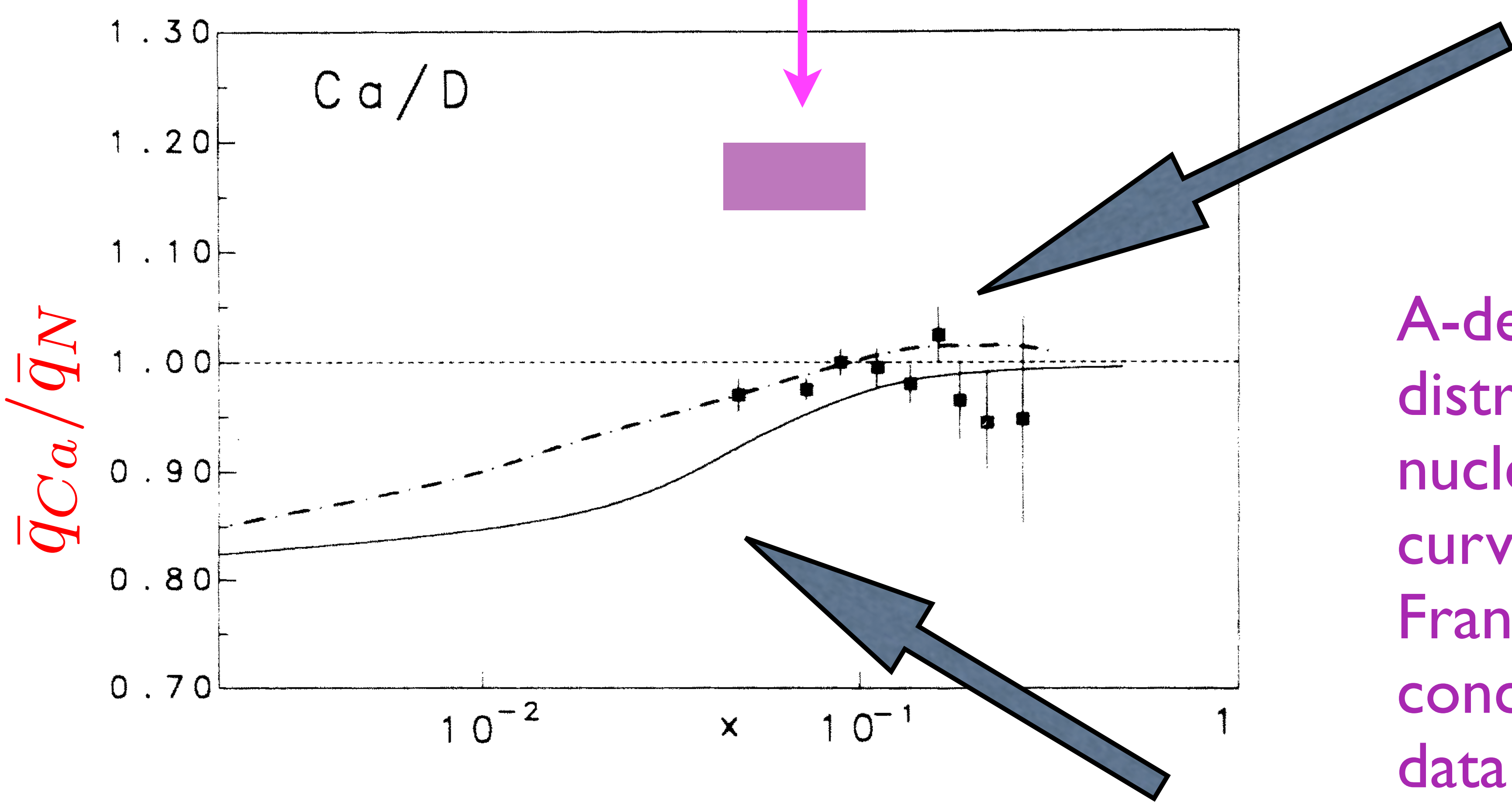
1989 $\bar{q}_{Ca}/\bar{q}_N \approx 0.97$

vs pion model Prediction

$\bar{q}_{Ca}(x)/\bar{q}_N = 1.1 \div 1.2_{|\,x=0.05\div0.1}$

$\bar{q}_{Ca}(x)/\bar{q}_N = 1.1 \div 1.2_{|\,x=0.05\div0.1}$

$Q^2 = 15$ GeV^2



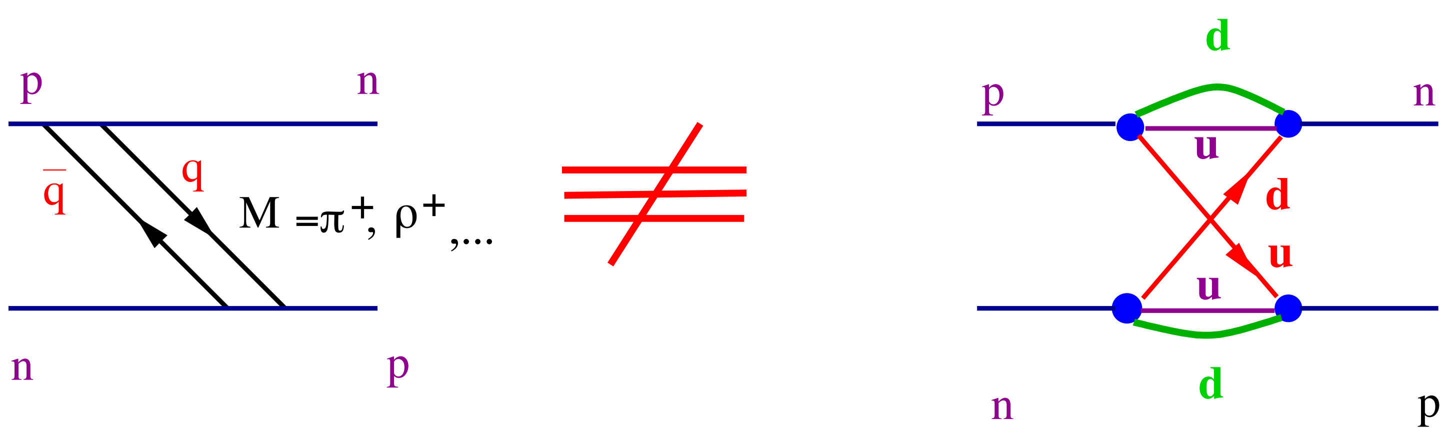
$Q^2 = 2$ GeV^2

A-dependence of antiquark distribution, data are from FNAL nuclear Drell-Yan experiment, curves - pQCD analysis of Frankfurt, Liuti, MS 90. Similar conclusions by Eskola et al 93-07 data analyses

DY + DIS → enhancement at x~ 0.1 is due to valence quarks

Pion model addresses a deep question - what is microscopic origin of intermediate and short-range nuclear forces - do nucleons exchange mesons or quarks/gluons? Duality?

A better match to Drell Yan data



Meson Exchange ***Quark interchange***

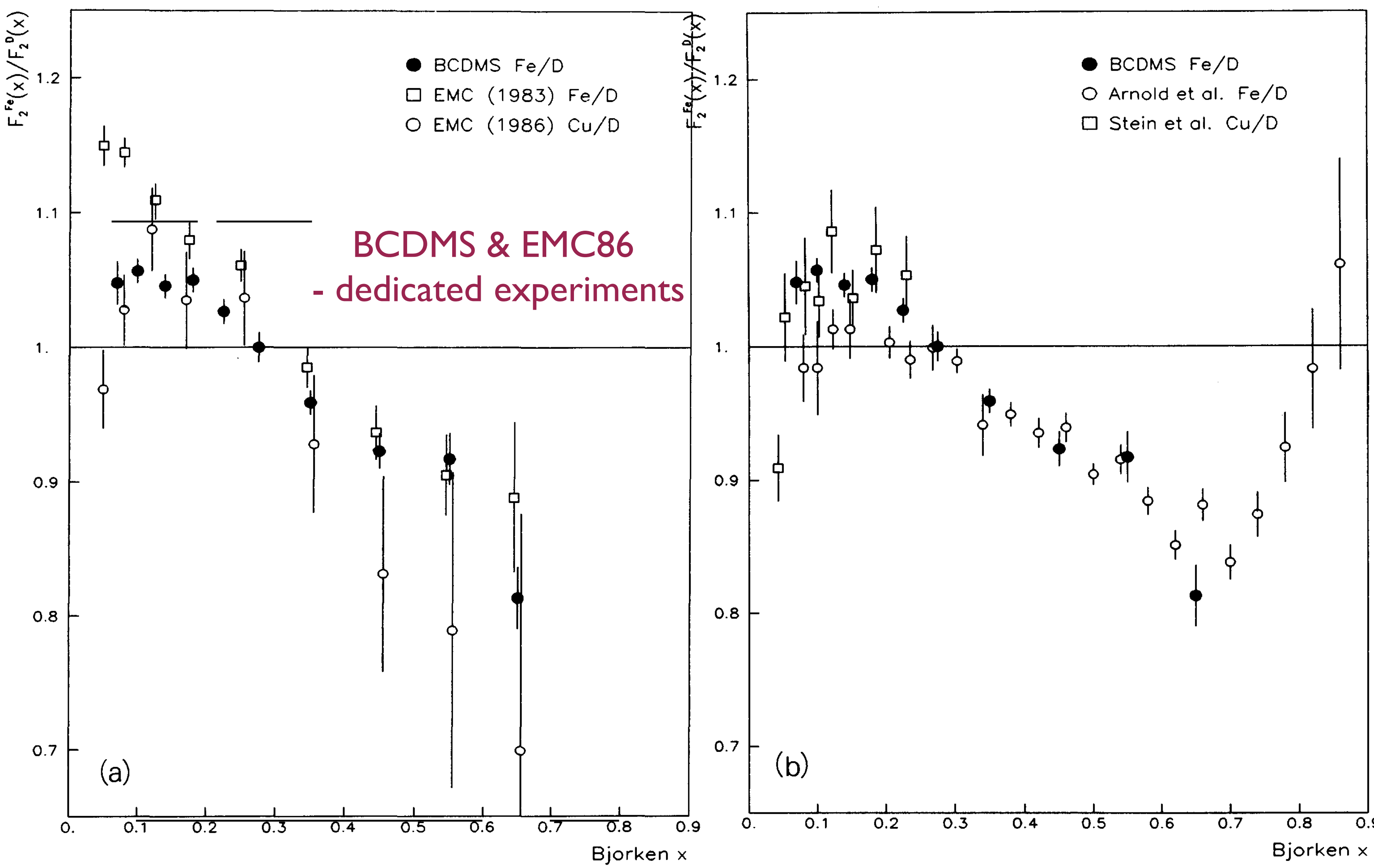
extra antiquarks in nuclei — no extra antiquarks

Comment - exchanges between nucleons correspond to change of LC fractions by ~0.1 - so enhancement at x ~0.1 may manifest what constituents are exchanged: data prefer enhancement of gluons and valence quarks

Before considering theoretical ideas - let us review what can be concluded about pdfs based on DIS and DY data + exact QCD sum rules.

Open question is the role of HT - experimentally - good scaling of the ratios at SLAC And Jlab - still x -dependence of HT and LT nucleon pdf is different.

$$R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x} + \frac{xn\,[x(n+1)-2]}{(1-x)^2} \cdot \frac{(T_A - T_{^2H})}{3m_N}$$



Differences of $R_A(x>0.5)$ reported by EMC, NMC and BCDMS are too large for making a firm conclusions about accuracy of Bj scaling for $R_A(x>0.4)$. Need additional data for large x and Q^2. Even bigger challenge - observing superfast (x > 1) quarks in DIS (currently a mess). pA LHC data may help.

Baryon charge sum rule

$$\int_0^A \frac{1}{A} V_A(x_A,Q^2)dx_A - \int_0^1 V_N(x,Q^2)dx = 0 \qquad (1)$$

From (1) + EMC effect ⇒ enhancement of $V_A(x\sim 0.1)$ at least partially

reflection of the EMC effect - some room for contribution compensating valence quark shadowing. FGS12 presented an argument now why shadowing for V_A is suppressed.

Comment: the best way to measure V_A/V_N is semi inclusive $\pi^+ - \pi^-$

$$\frac{D^{A/\pi^+}(x,x_F,Q^2) - D^{A/\pi^-}(x,x_F,Q^2)}{D^{N/\pi^+}(x,x_F,Q^2) - D^{N/\pi^-}(x,x_F,Q^2)} = \frac{F_{2N}(x,Q^2)}{F_{2A}(x,Q^2)} \frac{u_v^A(x,Q^2) - \frac{1}{4}d_v^A(x,Q^2)}{u_v^N(x,Q^2) - \frac{1}{4}d_v^N(x,Q^2)}$$

$$= \frac{F_{2N}(x,Q^2)}{F_{2A}(x,Q^2)} \frac{V_A(x,Q^2)}{V_N(x,Q^2)}\Bigg|_{N,A=\text{isosinglet}}$$

right hand side does not depend of x_F. Perhaps better to measure

$(\pi^+ - \pi^-)/(\pi^+ + \pi^-)$

LC momentum sum rule

$$\int_0^A \frac{1}{A}[G_A(x_A,Q^2)+V_A(x_A,Q^2)+S_A(x_A,Q^2)]x_A\,dx_A \qquad (2)$$

$$-\int_0^1 [G_N(x,Q^2)+V_N(x,Q^2)+S_N(x,Q^2)]x\,dx=0$$

Consider isoscalar target

$$\frac{F_2^{A(N)}(x,Q^2)}{x} = \frac{5}{18}[V_{A(N)}(x,Q^2)+S_{A(N)}(x,Q^2)] - \frac{s_{A(N)}(x,Q^2)+\bar{s}_{A(N)}(x,Q^2)}{6}$$

and use $\int_0^1 G_N(x,Q^2)x\,dx \approx 0.5$

define
$$\gamma_G^A = \frac{\int_0^A (1/A) G_A(x_A,Q^2) x_A\, dx_A}{\int_0^1 G_N(x,Q^2) x\, dx} - 1$$

$$\gamma_G^A \approx \frac{\int_0^1 F_2^N(x,Q^2)dx - \int_0^A (1/A) F_2^A(x_A,Q^2)dx_A}{\int_0^1 F_2^N(x,Q^2)dx} - \frac{6}{5}\,\frac{\int_0^A (1/A)\bar{s}_A(x_A,Q^2)x_A\,dx_A - \int_0^1 \bar{s}_N(x,Q^2)x\,dx}{\int_0^1 G_N(x,Q^2)x\,dx}$$

Use NMC data (the smallest relative normalization error)

$\gamma_G^A = (2.18 \pm 0.28 \pm 0.50)\%$,

$\gamma_G^A = (2.31 \pm 0.35 \pm 0.39)\%$,

for ^{40}Ca

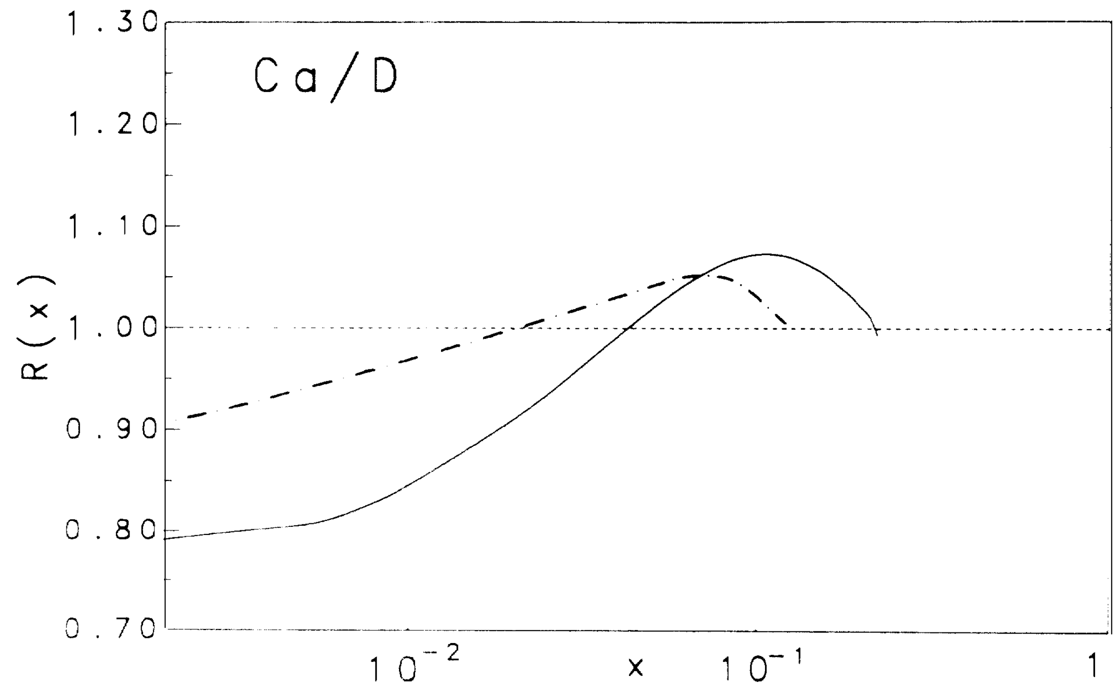
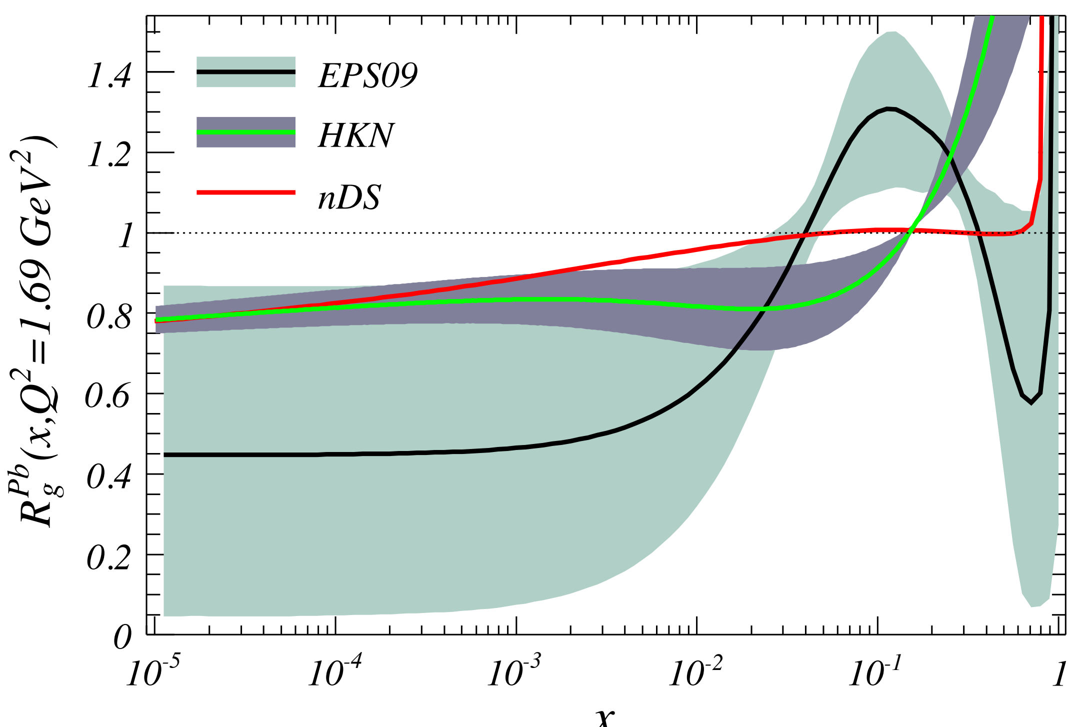


FIG. 1. Ratio $R \equiv R_G(x,Q^2) = (2/A)G_A(x,Q^2)/G_D(x,Q^2)$ plotted vs x, for different values of Q^2: solid line, $Q^2 = 2$ GeV^2; dot-dashed line, $Q^2 = 15$ GeV^2.

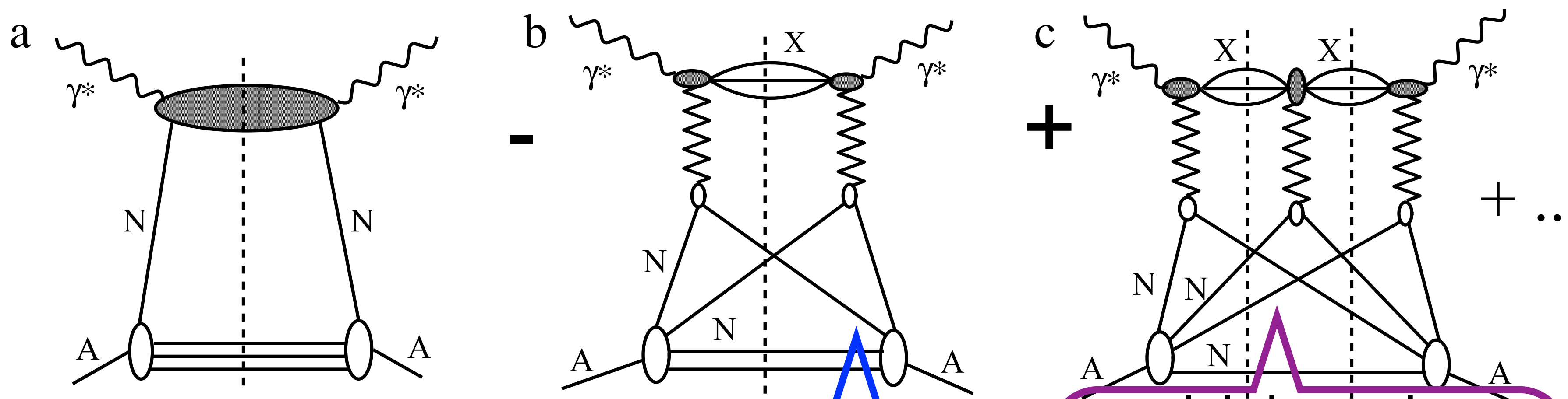


Frankfurt, Liuti, MS90

Before LHC, g_A/g_N was practically not constrained. Only exception are NMC data on scaling violation at x~0.1 (Sn/C) and J/ψ A-dependence (but systematic errors were too large)

Need theory to calculate small x pdfs

The Gribov theory of nuclear shadowing relates shadowing in γ^* A and diffraction in the elementary process: $\gamma^*+N \to X+N$.

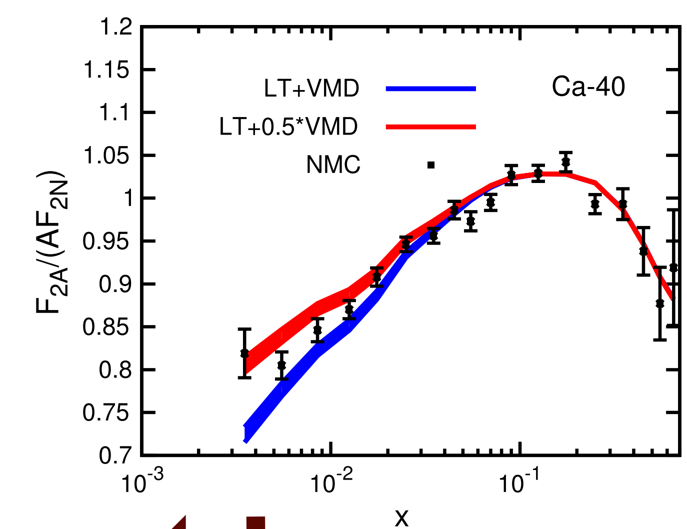


four fold rescattering a small correction for x> 10^{-3}

model independent

model dependent but universal (~ same for different A)

Before HERA one had to model ep diffraction to calculate shadowing for $\sigma_{\gamma^* A}$ (FS88-89, Kwiecinski89, Brodsky & Liu 90, Nikolaev & Zakharov 91). More recently several groups (Capella et al) used the HERA diffractive data as input to obtain a reasonable description of the NMC data (however this analysis made several simplifying assumptions). Also the diffractive data were used by several groups to describe shadowing in γ A scattering without free parameters.



$Q^2 \leq 2\, GeV^2$

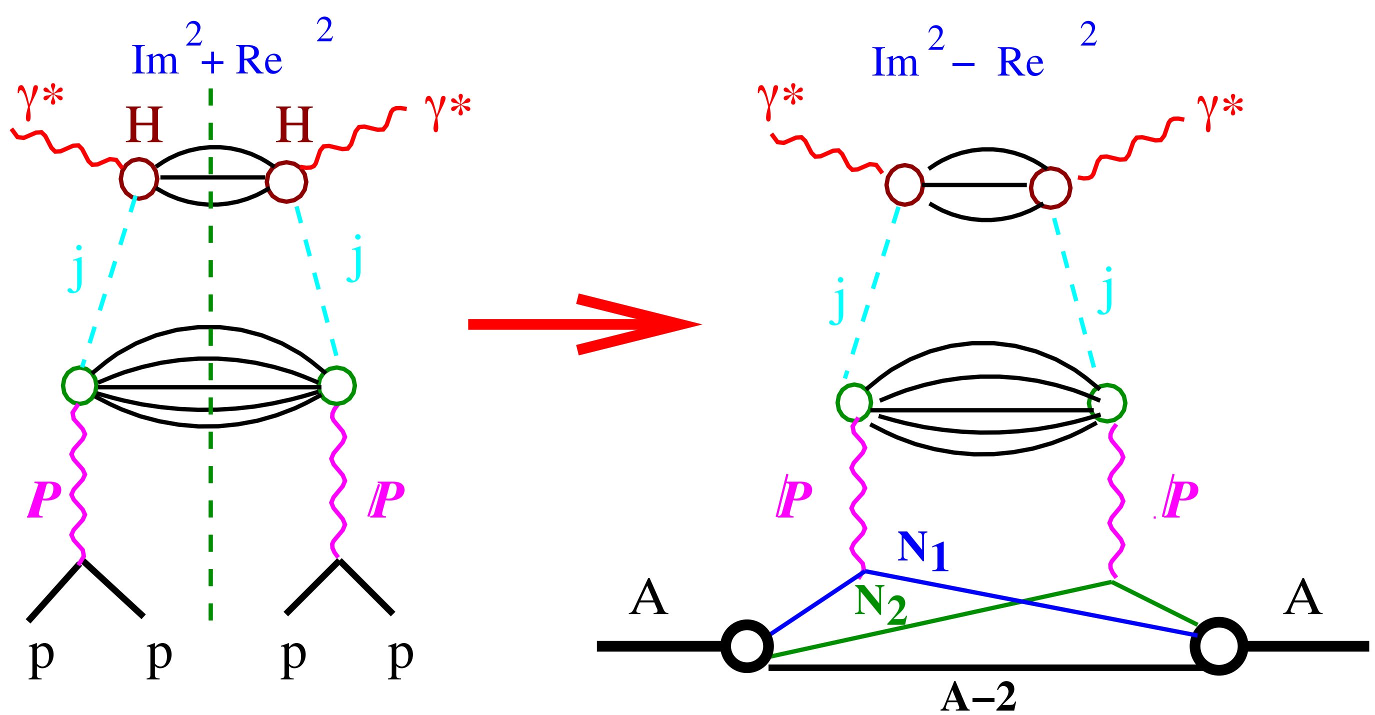
Does not allow to calculate gluon pdfs and even quark pdfs

Theoretical expectations for shadowing in the LT limit

Combining Gribov theory of shadowing and pQCD factorization theorem for diffraction in DIS allows to calculate LT shadowing for all parton densities (FS98)

(instead of calculating F_{2A} only)

Theorem: In the low thickness limit the leading twist nuclear shadowing is unambiguously expressed through the nucleon diffractive parton densities $f_j^D(\frac{x}{x_{I\!P}}, Q^2, x_{I\!P}, t)$:



Hard diffraction

off parton "j"

Leading twist contribution

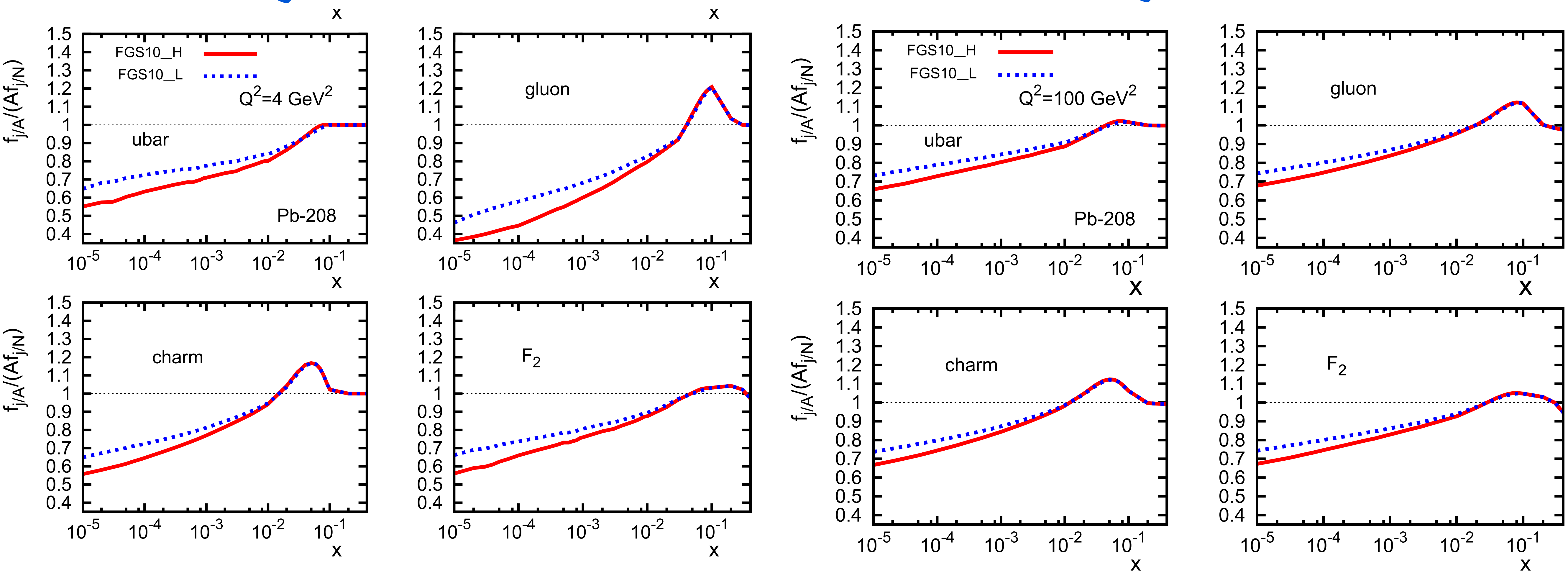
to the nuclear shadowing for

structure function $f_j(x,Q^2)$

Numerical studies impose antishadowing to satisfy the sum rules for baryon charge and momentum (LF + MS + Liuti 90) - sensitivity to model of fluctuations (interaction with N>2 nucleons) is rather weak. At the moment uncertainty from HERA measurements is comparable.

NLO pdfs - as diffractive pdfs are NLO

Q^2 = 4 GeV^2 Q^2 = 100 GeV^2

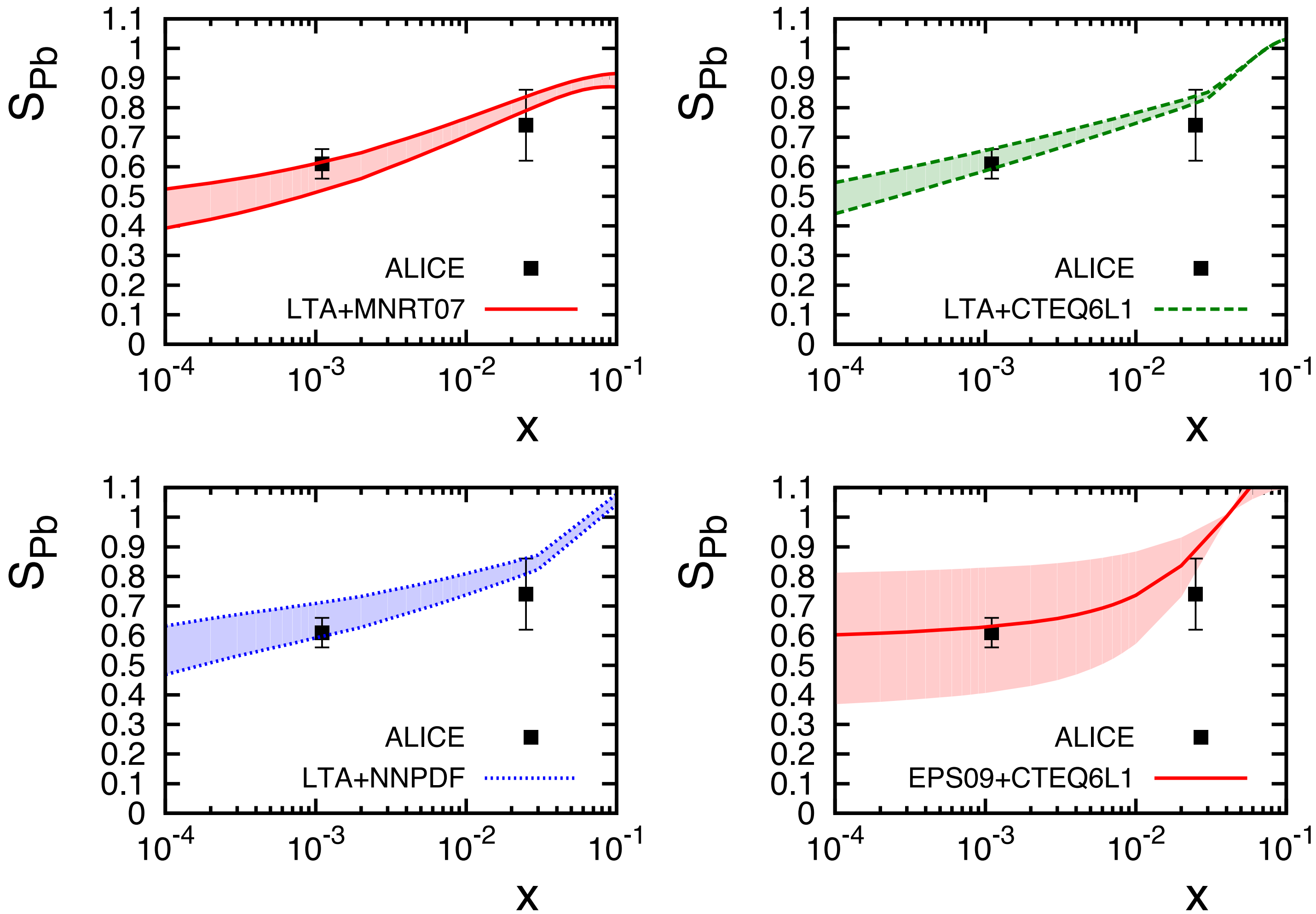


Predictions for nuclear shadowing at the input scale Q^2 = 4 GeV^2. and = 100 GeV^2. The ratios R_j ($\bar{u}$ and c quarks and gluons) and R_{F2} as functions of Bjorken x. Two sets of curves correspond to models FGS10_H and FGS10_L.

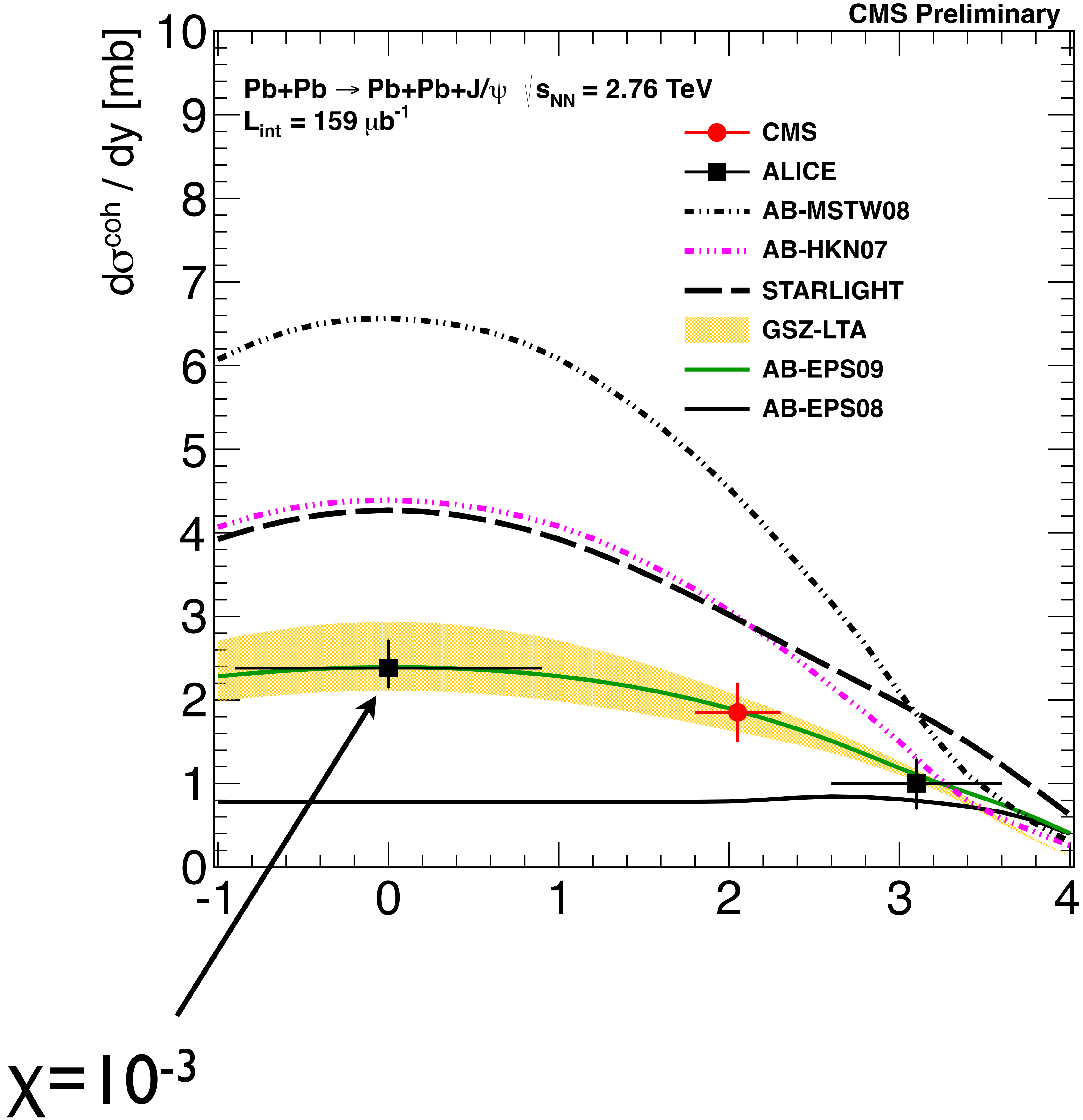
Sum rules require large gluon antishadowing

Gluon shadowing from J/ψ photoproduction

$$S_{Pb} = \left[\frac{\sigma(\gamma A \to J/\psi + A)}{\sigma_{imp.approx.}(\gamma A \to J/\psi + A)} \right]^{1/2} = \frac{g_A(x,Q^2)}{g_N(x,Q^2)}$$



Points - experimental values of S extracted by Guzey et al (arXiv: 1305.1724) from the ALICE data; Curves - analysis with determination of Q -scale by Guzey and Zhalov arXiv:1307.6689; JHEP 1402 (2014) 046.


CMS Preliminary
Pb+Pb → Pb+Pb+J/ψ √sNN = 2.76 TeV
Lint = 159 μb-1
CMS
ALICE
AB-MSTW08
AB-HKN07
STARLIGHT
GSZ-LTA
AB-EPS09
AB-EPS08
dσcoh / dy [mb]
χ=10-3

Dijets in p+Pb collisions and their quantitative constraints for nuclear PDFs

Hannu Paukkunen[a,b], Kari J. Eskola[a,b], Carlos Salgado[c]

Nuclear Physics A 00 (2014) 1–4

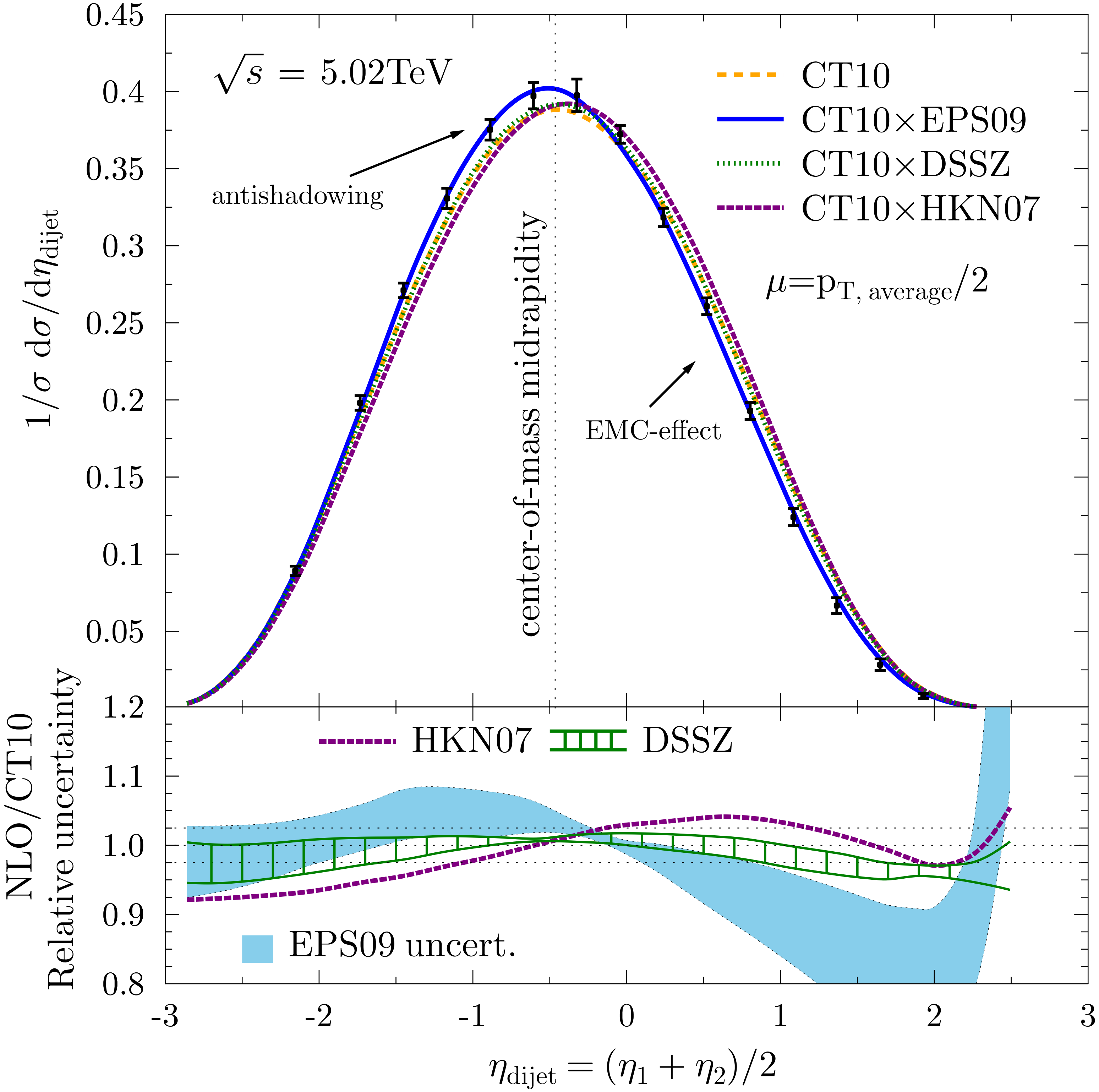


Figure 3. The preliminary CMS dijet data [11] compared to predictions with different PDFs. Figure adapted from [12].

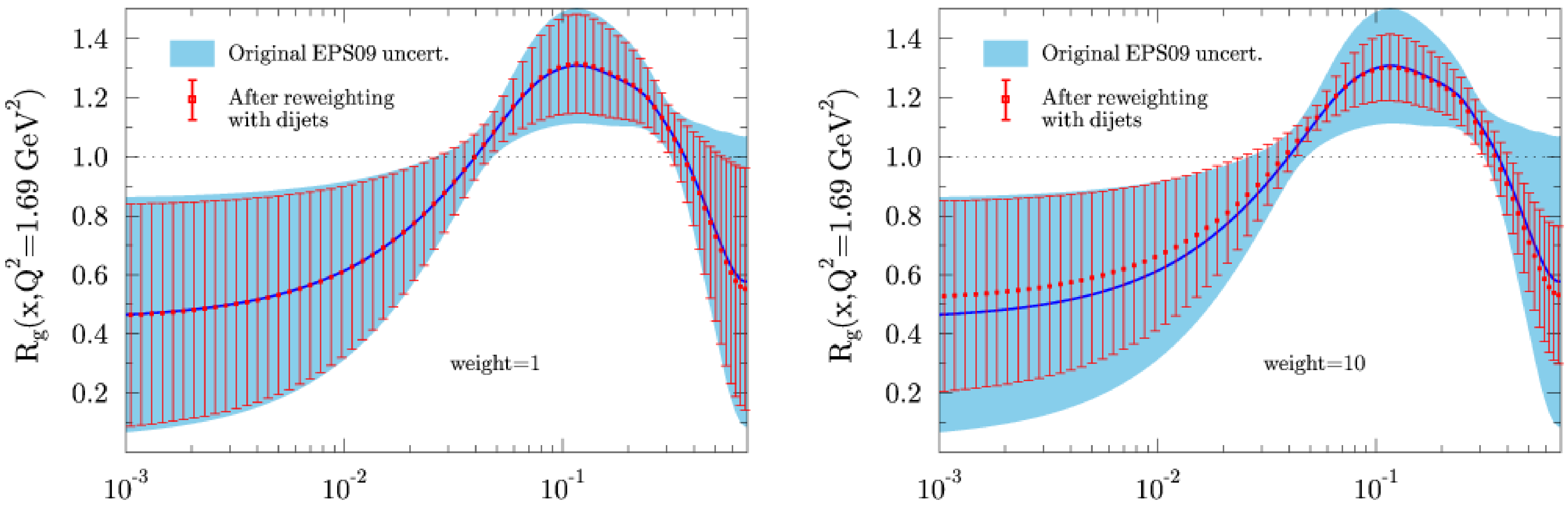


Figure 4. **Left-hand panel:** The EPS09 nuclear modification $R_G(x, Q^2 = 1.69\,\mathrm{GeV}^2)$ before and after the reweighting with CMS p+Pb dijet da
Right-hand panel: As the left-hand panel but giving the dijet data an extra weight of 10.

LHC data are sensitive to antishadowing, EMC effect for gluons is build into parametrization - not constrained by the data

Back to models of the EMC effect at x >0.3

First explanations/models of the EMC effect (no qualitatively new models in 30 years)

- Pionic model: extra pions - $\lambda_\pi \sim 4\%$ -actually for fitting Jlab and SLAC data ~ 6% for A> 40

  + enhancement from scattering off pion field with $\alpha_\pi \sim 0.15$

  $$R_A(x,Q^2) = 1 - \frac{\lambda_A n x}{1-x}$$ killed by DY data

- 6 quark configurations in nuclei with $P_{6q} \sim$ 20-30%

- *Nucleon swelling - radius of the nucleus is 20--15% larger in nuclei. Color is significantly delocalized in nuclei*

  Larger size →fewer fast quarks - possible mechanism: gluon radiation starting at lower Q^2

  $$(1/A)F_{2A}(x,Q^2) = F_{2D}(x, Q^2\xi_A(Q^2))/2$$

- Mini delocalization (color screening model) - small swelling - enhancement of deformation at large x due to suppression of small size configurations in bound nucleons + valence quark antishadowing with effect roughly $\propto k_{nucl}^2$

Traditional nuclear physics strikes back:

EMC effect is just effect of nuclear binding : account for the nucleus excitation in the final state: $e + A \to e' + X + (A-1)^*$

First try: baryon charge violation because of the use of non relativistic normalization

Second try: fix baryon charge ➔ violate momentum sum rule

Third try (not always done) fix momentum sum rule by adding mesons

⇓

version of pion model

Do we know that properties of nucleons in nuclei the same as for free nucleons?

Cannot use info from low momentum transfer processes - quasiparticles, complicated interactions of probe with nucleons: Nucleon effective masses ~0.7 m_N, strong quenching for A(e,e'p) processes: suppression factor Q~0.6 practically disappears at Q^2=1 GeV^2 .

Analysis of (e,e') SLAC data at x=1 -- tests Q^2 dependence of the nucleon form factor for nucleon momenta k_N < 150 MeV/c and Q^2 > 1 GeV^2 :

☛ $$r_N^{bound}/r_N^{free} < 1.036$$

Similar conclusions from combined analysis of (e,e'p) and (e,e') JLab data

Analysis of elastic pA scattering $|r_N^{\rm bound}/r_N^{\rm free} - 1| \lesssim 0.04$

Problem for the nucleon swelling models of the EMC effect which need 20% swelling

Theoretical analysis of the (p,ppn), (e,e'pN) data I discussed before.

✳ Structure of 2N correlations - probability ~ 20% for A>12

90% pn + 10% pp < 10% exotics ⇒ probability of exotics < 2%

- *EVA BNL 5.9 GeV protons (p,2p)n* $-t = 5\ GeV^2;\ t=(p_{in}-p_{fin})^2$
- *(e,e' pp), (e,e'pn) Jlab* $Q^2 = 2GeV^2$

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

One cannot introduce large exotic component in nuclei - 20 % 6q, Δ's

Very few models of the EMC effect survive when constraints due to the observations of the SRC are included as well as lack of enhancement of antiquarks and Q^2 dependence of the quasielastic (e,e') at x=1

- essentially one scenario survives - strong deformation of rare configurations in bound nucleons increasing with nucleon momentum and with most of the effect due to the SRCs .

<u>A-dependence of R_A</u> $1 - R_A(x, Q^2) = f(A) \cdot g(x, Q^2)$ for x <0.7

$$f(A) \propto < k^2 >, average\, excitation\, energy, \, a_2$$

$$f(A) \propto < \rho(r_1)\rho(r_2)\theta(r_0 - |r_1 - r_2|), \; r_0 \sim 1.2\, fm$$

At x > 0.7 gradual transition to regime $R_A(x, Q^2) \propto a_2(A)$

need very large Q

Dynamical model - color screening model of the EMC effect

(FS 83-85)

Combination of two ideas:

(a) Quark configurations in a nucleon of a size << average size (PLC) should interact weaker than in average. Application of the variational principle indicates that probability of such configurations in nucleons is suppressed.

(b) Quarks in nucleon with $x>0.5$ --0.6 belong to small size configurations with strongly suppressed pion field - while pion field is critical for SRC especially D-wave.

test was possible in pA LHC run in March 2013

In color screening model modification of **average** properties is < 2- 3 %.

Introducing in the wave function of the nucleus explicit dependence of the internal variables we find for weakly interacting configurations in the first order perturbation theory using closer we find

$$\tilde{\psi}_A(i) \approx \left(1 + \sum_{j \neq i} \frac{V_{ij}}{\Delta E}\right) \psi_A(i)$$

where $\Delta E \sim m_{N^*} - m_N \sim 600 - 800\, MeV$ average excitation energy in the energy denominator. Using equations of motion for ψ_A the momentum dependence for the probability to find a bound nucleon, $\delta_A(p)$ with momentum p in a PLC was determined for the case of two nucleon correlations and mean field approximation. In the lowest order $\delta_A(p) = 1 - 4(p^2/2m + \epsilon_A)/\Delta E_A$

After including higher order terms we obtained for SRCs and for deuteron:

$$\delta_D(\mathbf{p}) = \left(1 + \frac{2\frac{\mathbf{p}^2}{2m} + \epsilon_D}{\Delta E_D}\right)^{-2}$$

Accordingly $$\frac{F_{2A}(x,Q^2)}{F_{2N}(x,Q^2)} - 1 \propto \langle \delta(p) \rangle - 1 = -4 \left\langle \frac{\frac{\mathbf{p}^2}{2m} + \epsilon_A}{\Delta E_A} \right\rangle$$

which to the first approximation is proportional the average excitation energy and hence roughly to $a_2(A)$, which proportional to $<\rho^2(r)>$ for A>12 (FS85).
Accuracy is probably not better than 20%.But roughly it works - see Jlab studies

We extended calculations to the case of scattering off A=3 for a final state with a certain energy and momentum for the recoiling system FS & Ciofi Kaptari 06.
Introduce formally virtuality of the interacting nucleon as

$$p_{int}^2 - m^2 = (m_A - p_{spect})^2 - m^2.$$

Find the expression which is valid both for A=2 and for A=3(both NN and deuteron recoil channels):

$$\delta(p, E_{exc}) = \left(1 - \frac{p_{int}^2 - m^2}{2\Delta E}\right)^{-2}$$

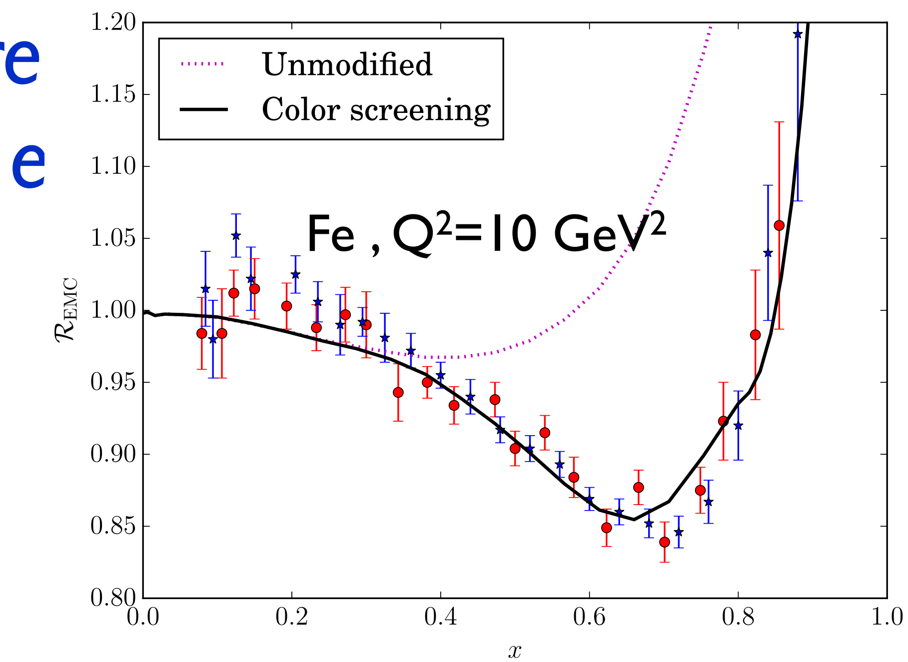
Dependence of suppression we find for small virtualities: $1-c(p^2_{int}-m^2)$

seems to be very general for the modification of the nucleon properties. Indeed, consider analytic continuation of the scattering amplitude to $p^2_{int}-m^2=0$. For this point modification should vanish. Our quantum mechanical treatment of 85 automatically took this into account.

Our dynamical model for dependence of bound nucleon pdf on virtuality - explains why effect is large for large x and practically absent for x~ 0.2 (average configurations V(conf) ~ <V>)

This generalization of initial formula allows a more accurate study of the A-dependence of the EMC e

Simple parametrization of suppression: no suppression x≤ 0.45, by factor $\delta_A(k)$ for x ≥0.65, and linear interpolation in between

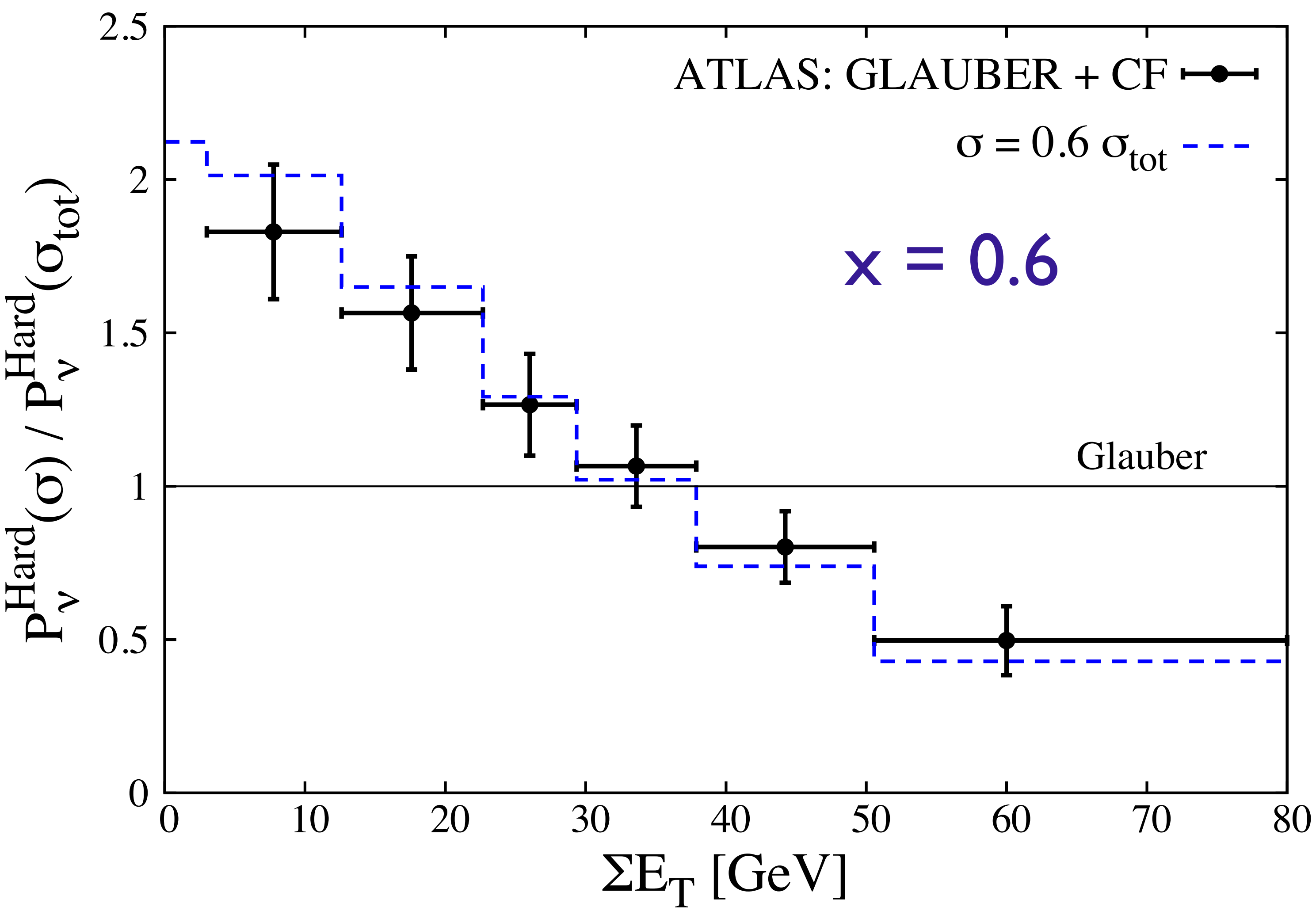


Freese, Sargsian, MS 14

Critical test we suggested in 1983:

pA scattering with trigger on large x hard process. If large x corresponds to small sizes hadron production will be suppressed. In other words - trigger for large activity - suppression of events with large x.

ATLAS and CMS report the effect of such kind. Our analysis (M.Alvioli, B.Cole. LF, . D.Perepelitsa, MS) suggests that for x~ 0.6 the transverse size of probed configurations is a factor of 0.6 smaller than average. Similar pattern in dAu is observed at RHIC.



Relative probability of hard processes corresponding to a small σ selection as a function of ΣE_T . ATLAS data are for x = 0.6 with black crosses taking into account the difference between number of wounded nucleons calculated in the Glauber and CF approaches

Conclusions for parton structure of nuclei part of the talk

Well grounded expectations for enhancement of gluons in nuclei at $x \sim 0.1$ and of shadowing at $x < 10^{-2}$

Precision measurements of the EMC effect at $x > 0.4$ - challenging but important.

Note that for LHC we need pdf'd of Pb
LHC may reach $x \sim 1$. Need DIS for such x.

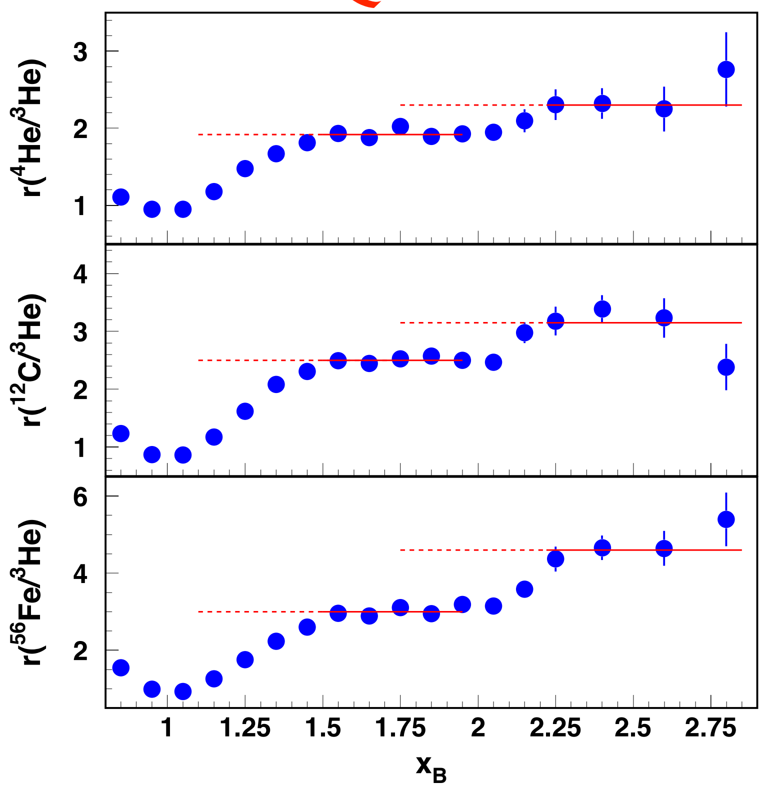
COMPASS kinematics - *large x for quarks*

$x \sim 0.1$ for quarks - best with pions

$x \sim 0.1$ for gluons via charm
A-dependence

Hall B (Kim Egiyan)

$Q^2 > 1.5\ GeV^2$



Ratio of the cross sections of (e,e')scattering off a $^{56}Fe(^{12}C, ^{4}He)$ and ^{3}He per nucleon

The evidence for presence of 3N SRC - not definitive - data are not consistent & Q2 are too low for 3N scaling. One probes here interaction at internucleon distances <1.2 fm corresponding to local matter densities $\geq 5\rho_0$ which is comparable to those in the cores of neutron stars!!!

Note - fsi in the studied Q range and x> 2 is probably very large but it is still local - within SRC.

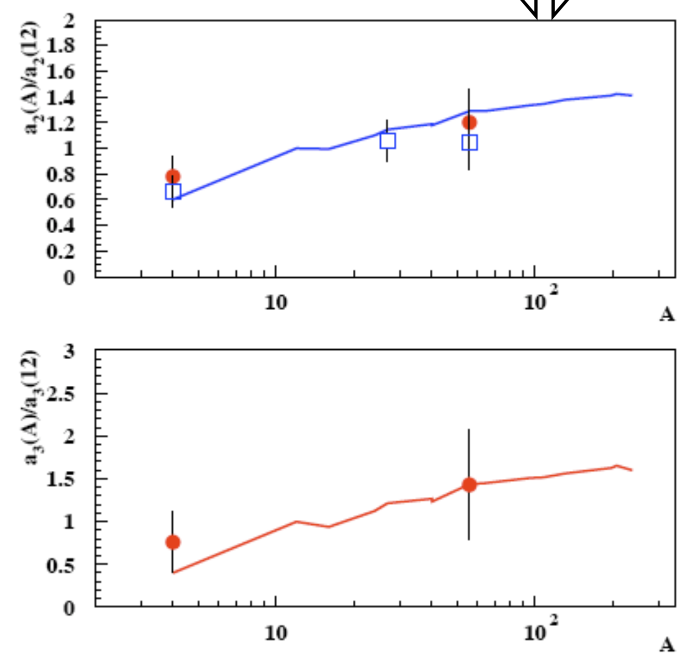
Currently the ratios are the best way to determine absolute probability of SRC - main uncertainty ~20% - deuteron wave function

confirm our 1980 prediction of scaling and A -dependence for the ratios due to SRC

Fe/C ratios for x~1.75, x~2.5 agree within experimental errors with our prediction - density based estimate:

$$a_2 \propto \int \rho_A^2(r) d^3r, r_2 = (A_1/A_2)^{0.15}$$

$$a_3 \propto \int \rho_A^3(r) d^3r, r_3 = (A_1/A_2)^{0.22}$$



Expectations for gluon EMC ratio for x >0.2

$$xG_N(x, Q^2 \sim 5\, GeV^2) \propto (1-x)^n,\ n \approx 5$$

If no EMC effect for gluons the crossover point from small suppression to enhancement is

$$x_{cross} = \frac{2}{n+1} = 0.33$$

In the color screening model squeezing of size of configuration with valence gluon likely already for x >0.2 - so suppression may show up effect. Does not contradict the LHC pA centrality data, but more detailed analysis is necessary.

In the rescaling model -- suppression already at x=0.1. Antishadowing?

Overall - my impression is that G_A/G_N suppression is likely at large x, but whether it starts already at x ~ 0.2 is an open question. If suppression starts only at x=0.3 it maybe masked by the Fermi motion and one would need nucleon tagging to look for this effect.