Fragmentation in ep and eA collisions as a tool to study nucleon/nucleus structure and novel QCD phenomena

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Importance of fragmentation region in ep scattering

Focus of studies in DIS shifted from inclusive measurements to special exclusive and semiinclusive measurements sensitive to the QCD dynamics and structure of hadrons, nucleons.

important simplification - QCD factorization theorems for

e T → e +h +X where h is in the target fragmentation region and has fixed x_F, p_t
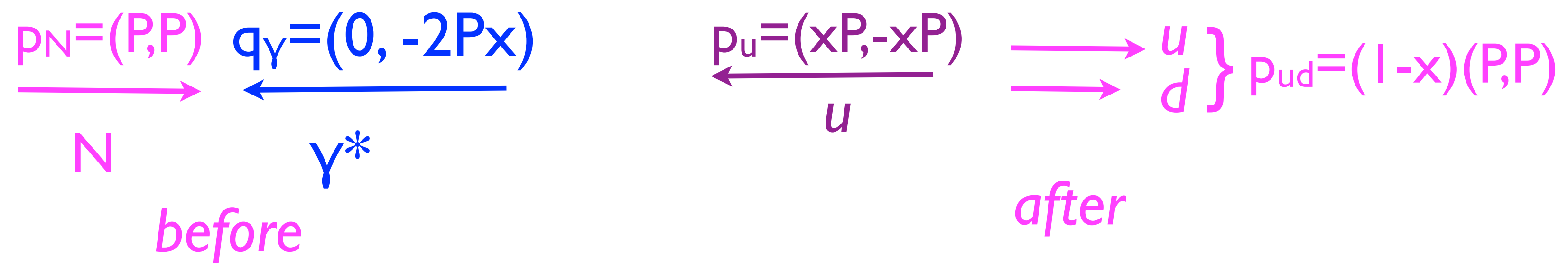
➠ Fracture (conditional) parton distribution functions:
how nucleon decays after a parton with given x was removed

factorization tested at HERA for $x_F > 0.9$ (diffraction)

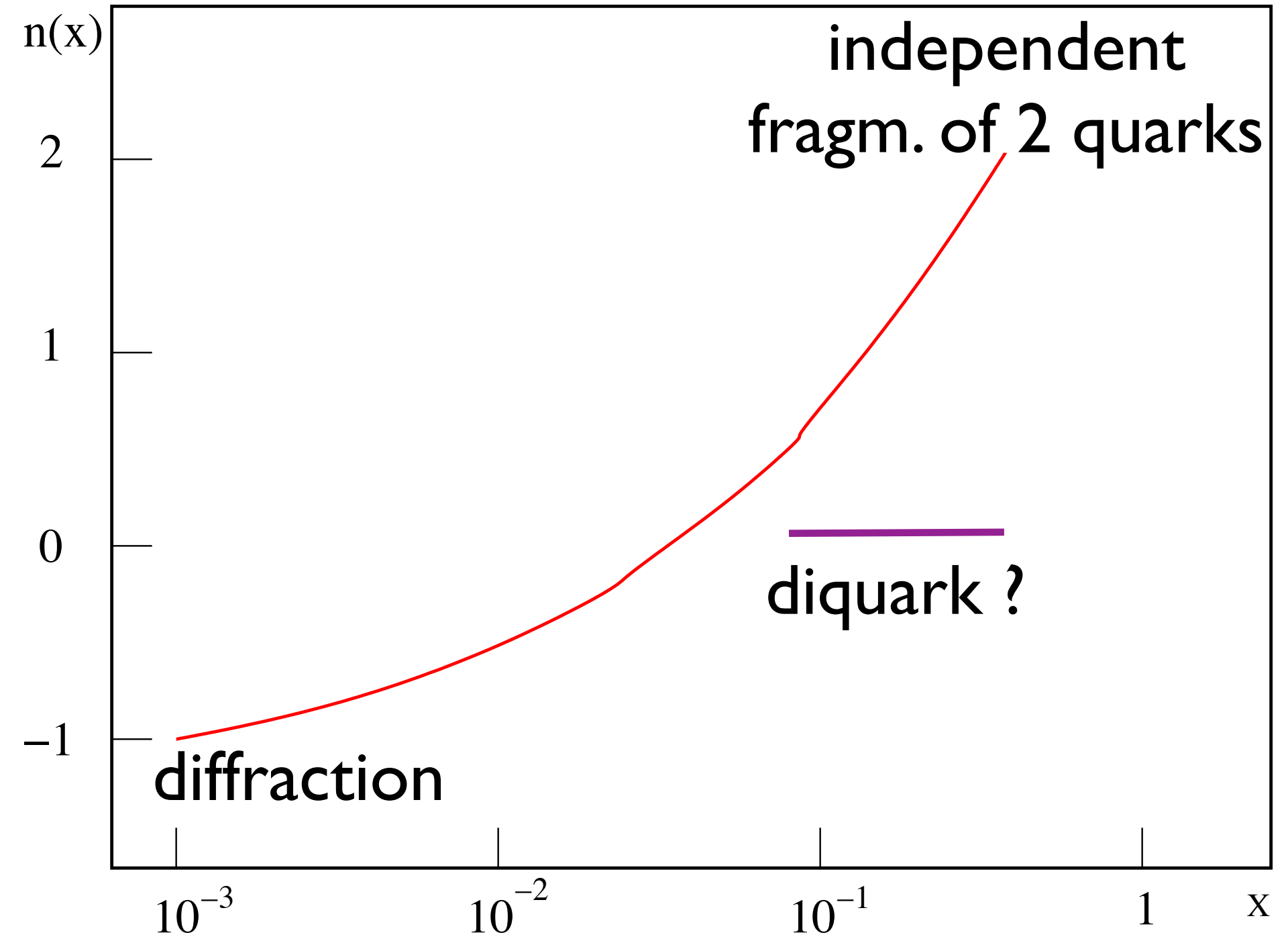➠ γ^*_L T → e +h +T'   generalized parton distributions, 3 D structure of nucleons

Nucleon fragmentation: $F_j(x, Q^2, z, p_t)$ - j - flavor. In collider frame $z = p_h/p_{proj}$ (1-x)

$0 < z < 1$

$p_N = (P, P)$ $q_\gamma = (0, -2Px)$ $p_u = (xP, -xP)$ $\longrightarrow$ $\left. \begin{matrix} u \\ d \end{matrix} \right\}$ $p_{ud} = (1-x)(P, P)$

$\overset{\longrightarrow}{N}$ $\overset{\longleftarrow}{\gamma^*}$ $\overset{\longleftarrow}{u}$

before   *after*

Qualitative difference from current fragmentation -
non-trivial dependence of F_j on x - can provide information about nucleon structure.

$$\frac{d\sigma(x, Q^2, z)}{dz} \propto (1-z)^{n(x)}$$

n(x)

2

1

0

−1

independent
fragm. of 2 quarks

diquark ?

diffraction

10^{-3} 10^{-2} 10^{-1} 1   x

Is n(x) the same for
g_{1P} and F_{2P}?

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Collider - unique opportunity to tag <u>flavor</u> of the removed
(anti) quark as well as its helicity (for polarized ep)

Sample of questions to address the question of where nucleon spin is

✔ What is the difference between the decay of diquark system with $\lambda=0$ and $\lambda=1$

  Large A_{LL} for forward pion production is observed at Jlab - Avagyan, ANL meeting

✔ What is correlation between transverse momenta of leading meson in current frag. region and leading baryon in the proton frag. region, how it depends on polarization?

✔ Spin alignment / polarization of the produced baryons/mesons

✔ Similar questions for transversely polarized proton (φ-dependence,...)
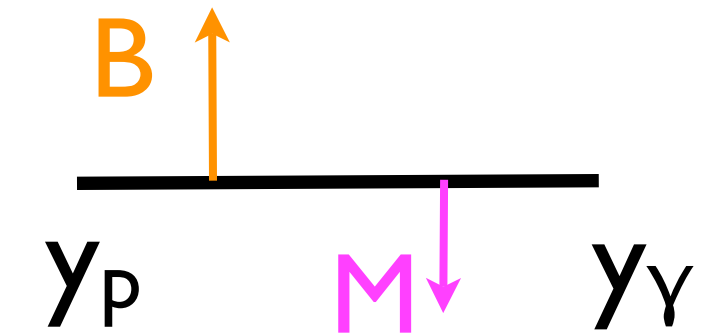
Prime aim - to study 3D structure of nucleon - GPDs measured as a function of t - need Fourier transform to determine b-shape

Slow convergence of the Fourier transform of $F_{2g}(t)$ for dipole fit. For b=0

$$\int_0^{-t_{max}} F_{2g}(t)dt = \frac{1}{1 - t_{max}/M_{2g}^2}$$

$$M_{2g}^2 \sim 1\text{GeV}^2$$

☞ *Need a design of the detector with proton detection up to large t with a good discrimination of inelastic channels which is >> elastic channel for -t≥0.8 GeV²*

☞ Inelastic channels for t=0 measure color fluctuations in nucleons

$$\omega_g \equiv \frac{\langle G^2 \rangle - \langle G \rangle^2}{\langle G \rangle^2} = \frac{d\sigma_{\gamma^*+p \to VM+X}}{dt} \Bigg/ \frac{d\sigma_{\gamma^*+p \to VM+p}}{dt}\Bigg|_{t=0}.$$

👉 *Non-vacuum channels* $\quad \gamma^* + p \to \pi^+ n, \pi\Delta, ..$

Issues - quark GPDs (large Q^2),

asymptotic non-vacuum high energy amplitudes for wide range of t, Q^2

Comment: rare processes - very difficult to model background - good coverage in fragmentation region appears very important especially for large t

👉 Rapidity gap processes at large t: hard vacuum exchange

At EIC critical to be able to fix small M_X to insure large Δy

$\alpha_{IP}(t)$

$\alpha_{IP}^{\text{eff}}(t)$ (pQCD)

CTEQ6L

CTEQ6M

$\alpha_{IP}^{\text{DGLAP}}(t)$

$-t(\text{GeV}^2)$
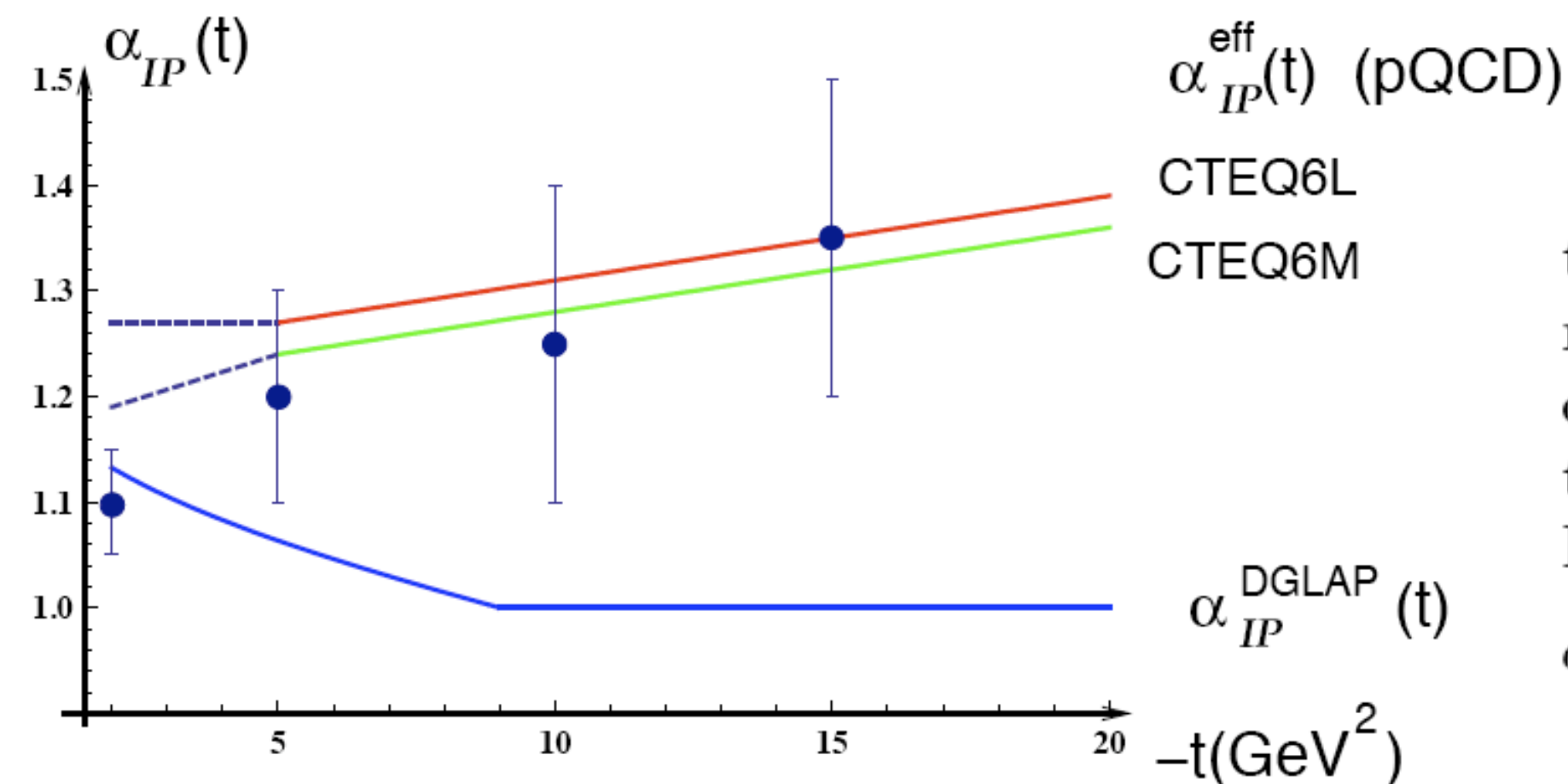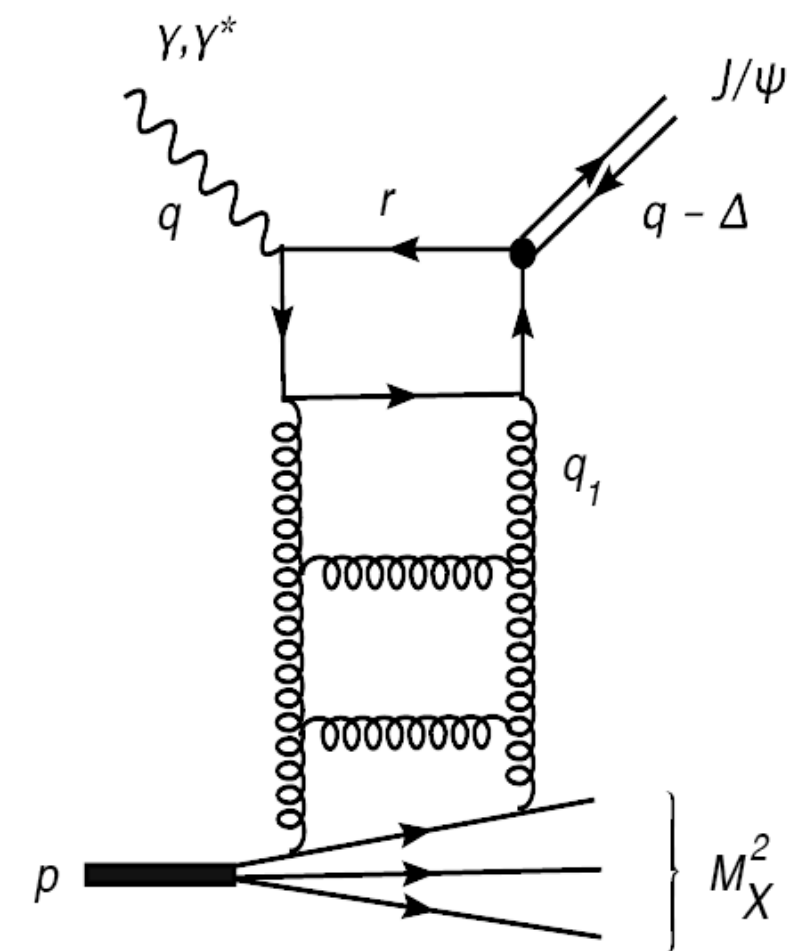
The comparison between the experimental data and theoretical prediction for the HID cross section at HERA for the "effective Pomeron" $\alpha_P^{\text{eff}}(t)$, i.e. $(1/2)$ logarithmic derivative of the cross section $d\sigma/dt$, obtained after integrating between the energy dependent cuts, as given in the text. The dashed curve means large theoretical uncertainties in the corresponding kinematic region. The values are given at for $W_{\gamma p} = 150$ GeV. In the same figure we depict also "true (DGLAP)" Pomeron", i.e. logarithmic derivative

$\alpha_P(t)^{\text{DGLAP}} = 0.5 \dfrac{d(d\sigma/)dtdx_J))}{dlog(x/x_J)}$ at this energy. $\Lambda_{\text{QCD}} = 300$ MeV.
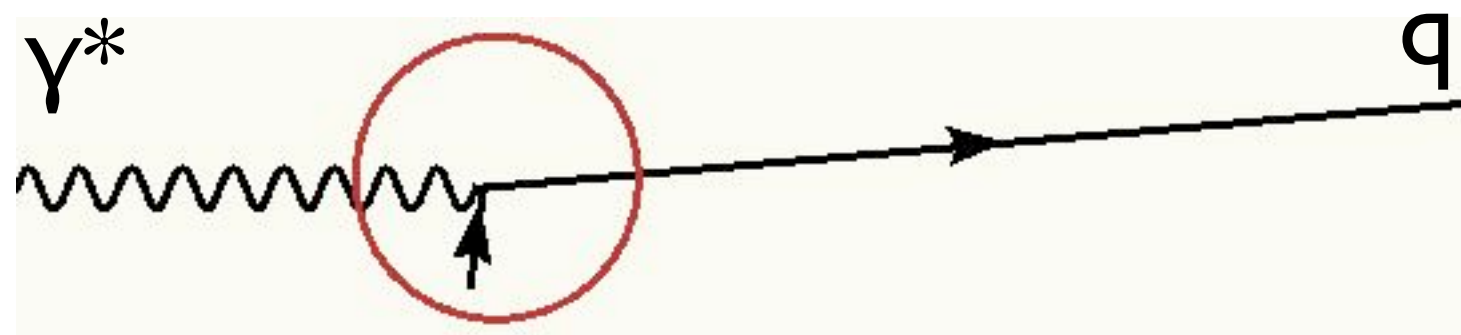
Open questions in eA fragmentation physics

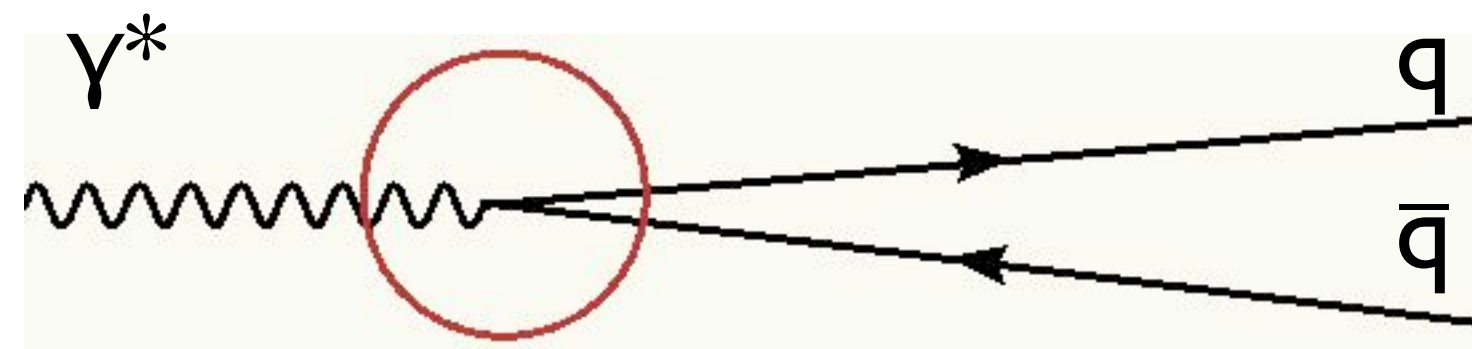*Are color tubes formed in propagation of quarks through nuclear media?*

How propagation of quark and dipole differ?
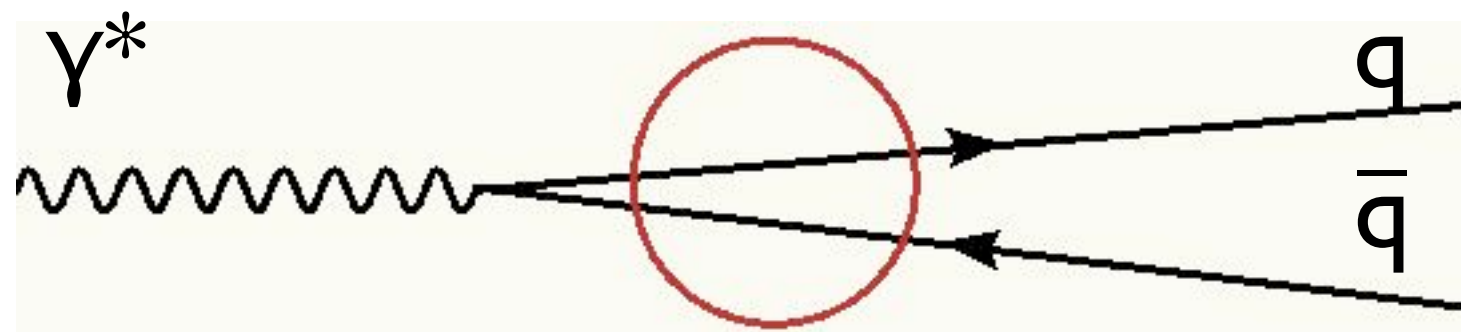
Rest frame picture of DIS

Knockout of a quark $x > 0.1$

propagation of quarks through nuclear media

Conversion of virtual photon into $q\bar{q}$ pair inside the nucleus: $1/2R_A m_N < x < 0.1$

comparison of propagation of quarks and dipoles through nuclear media

Conversion of virtual photon into $q\bar{q}$ pair before the nucleus: $l_{coh} = 1/2m_N x \gg 2R_A$

propagation of color singlet dipoles through nuclear media

How do we know where in nucleus virtual photon first interacts?

Model independent evidence in favor of $l_{coh} \sim 1/2m_N x$ - < nucleon radius for x > 0.3 and > $2R_A$ at x< 0.005 from the analysis of the representation of the forward Compton scattering amplitude expressed as a Fourier transform of the matrix element of the commutator of two electromagnetic (weak) current operators:

$$\text{Im } A^{\gamma^* N}_{\mu\lambda}(q^2 = -Q^2, 2qp) = \frac{1}{\pi} \int e^{iqy} \langle p | j_\mu(y) j_\lambda(0) | p \rangle \, d^4 y \, .$$

y_1 and y_2 are the points where γ^* is absorbed and emitted.

$y_1=y, y_2=0$

Small   X

Large   X
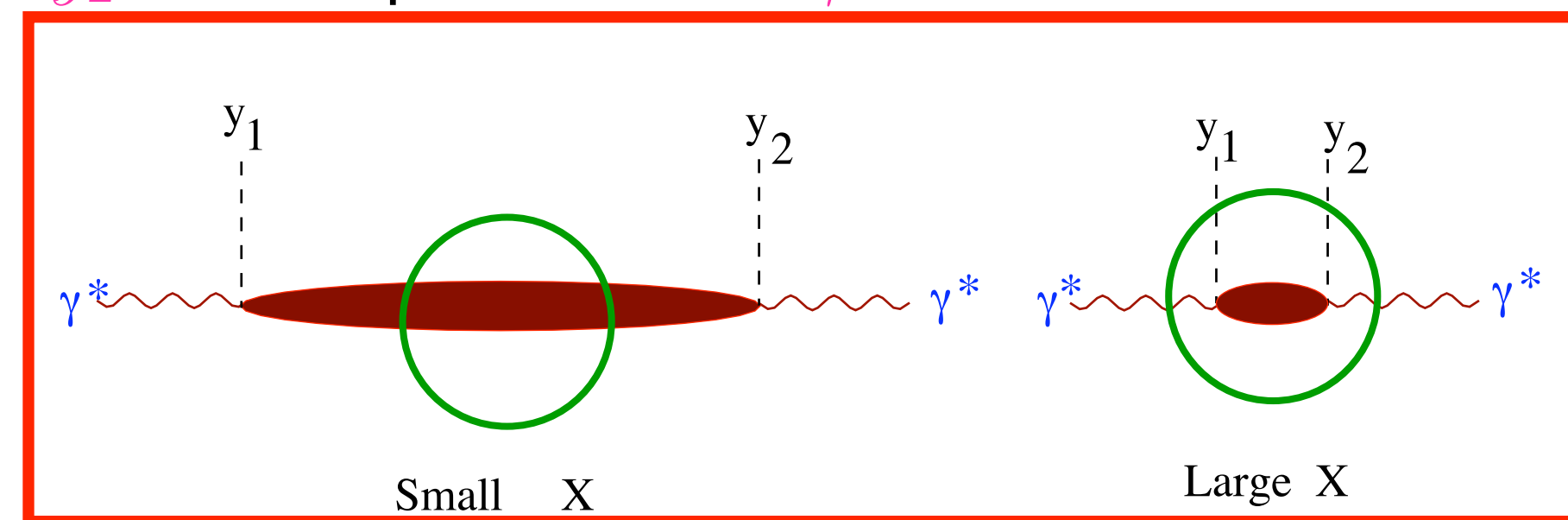
In the nucleus rest frame for z component of y - z

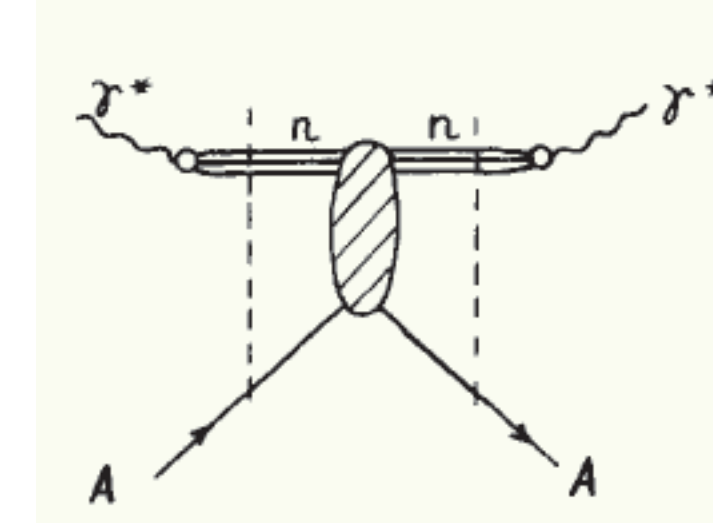$$z \sim \lambda_s(x)/2m_N x, \qquad z \sim \lambda_v(x)/2m_N x,$$

$$\lambda_s(x) \sim \lambda_v(x) \sim 1 \qquad \text{for } x \lesssim 0.5, \qquad \lambda_s(x), \qquad \lambda_v(x) \to 0, \quad x \to 1 \, .$$

Scaling violation for small x $\Rightarrow \lambda_s$ drops (<< 1) with increase of Q^2

Direct test of this feature of QCD is a paradoxical phenomenon of nuclear shadowing in $\gamma(\gamma^*) - A$ scattering: $\frac{\sigma_{\gamma A}}{A \sigma_{\gamma N}} < 1$ in spite of the small value of $\sigma_{\gamma N}$.

Qualitative explanation

Life time of virtual photon in a state of mass M_X is

$$\Delta t = 1/\Delta E, \Delta E = E_{M_X} - E_{\gamma^*} \implies \Delta E = \sqrt{M_X^2 + p_\gamma^2} - \sqrt{q^2 + p_\gamma^2} \approx \frac{M_X^2 + Q^2}{2p_\gamma}$$

$$\implies l_{coh} = c\Delta t = \frac{2p_\gamma}{M_X^2 + Q^2} \gg R_A \qquad \implies l_{coh} = \frac{1}{2m_N x}, \ for \ M_X^2 \sim Q^2$$

Over what distances one can effectively treat quark propagation in quark - gluon basic (time formation)?

Similar energy - time uncertainty arguments - lead to

$$l_{form} = \frac{2P}{\Delta m_h^2} \sim p_h(GeV) \cdot 0.5fm. \qquad \text{for light hadrons (π,ρ...)}$$

$$l_{form} \gg 2R_A, \quad for \ 40 \div 60 GeV$$

Consistent with the DIS data and in particular with

$$\frac{1}{\sigma_{eA}} \frac{d\sigma(e + A \to e + h + X)}{dz dx dQ^2} = \frac{1}{\sigma_{eN}} \frac{d\sigma(e + N \to e + h + X)}{dz dx dQ^2} \qquad \text{for ν > 70 GeV} \quad \sqrt{s_{eN}} \sim 15 \text{ GeV}$$

Only effect in the current fragmentation region observed at higher energies -
broadening of transverse momenta of leading hadrons $< p_t^2 >_A = < p_t^2 >_N + cA^{1/3}$

What EIC can add? Naively - not much if only leading hadrons are measured until the small x region ~ 10^{-3} is reached BDR scale is large enough - where "c" should start growing.

However if nuclear fragmentation region is added, situation changes dramatically.
Possible to study *dynamics of breaking of the color tubes in nuclear media*
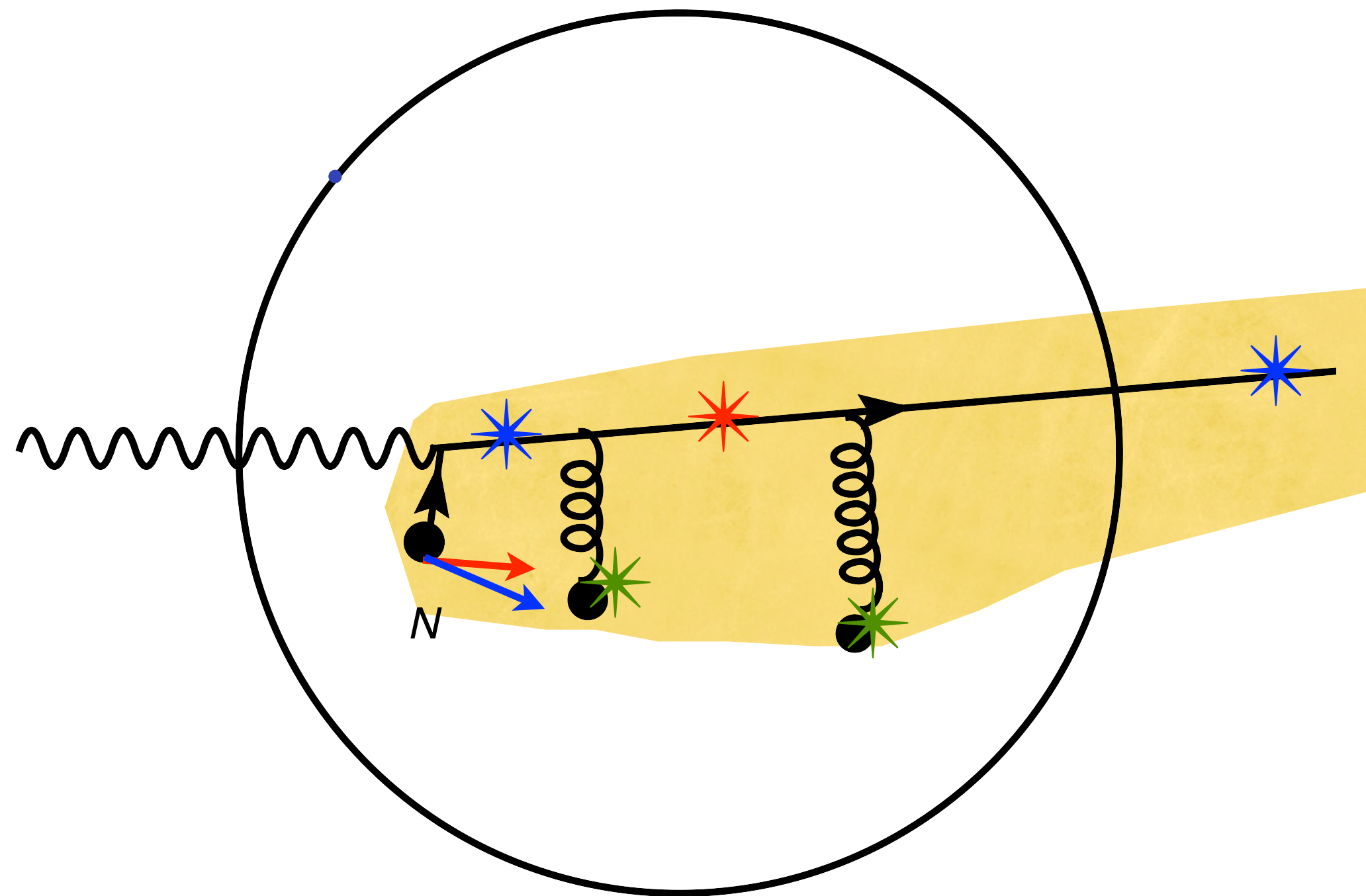
Flux tube extending distance ~ 7 fm inside the nucleus

Several nucleons are wounded, more energy is released in the nucleus ⟹ change in the spectrum of hadrons in the nucleus fragmentation region. Naive expectation - this effect as well formation of produced hadrons inside the nucleus should strongly modify the spectrum for p_h < few GeV - broad range of rapidities. High energies are crucial here as they allow to separate the fragmentation and central regions.

Sample of promising observables:

❑   soft neutron multiplicity - good measure of overall heating of the nucleus

❑   A-dependence of pion multiplicity as a function of y

❑   long range correlation between p_t of leading meson in current region and nucleus fragmentation observables

❑   gluon removal (charm production) vs quark (antiquark) removal

$R_A(y) = N_A/N_N$

y_A 0 $y_{cur.}$ y
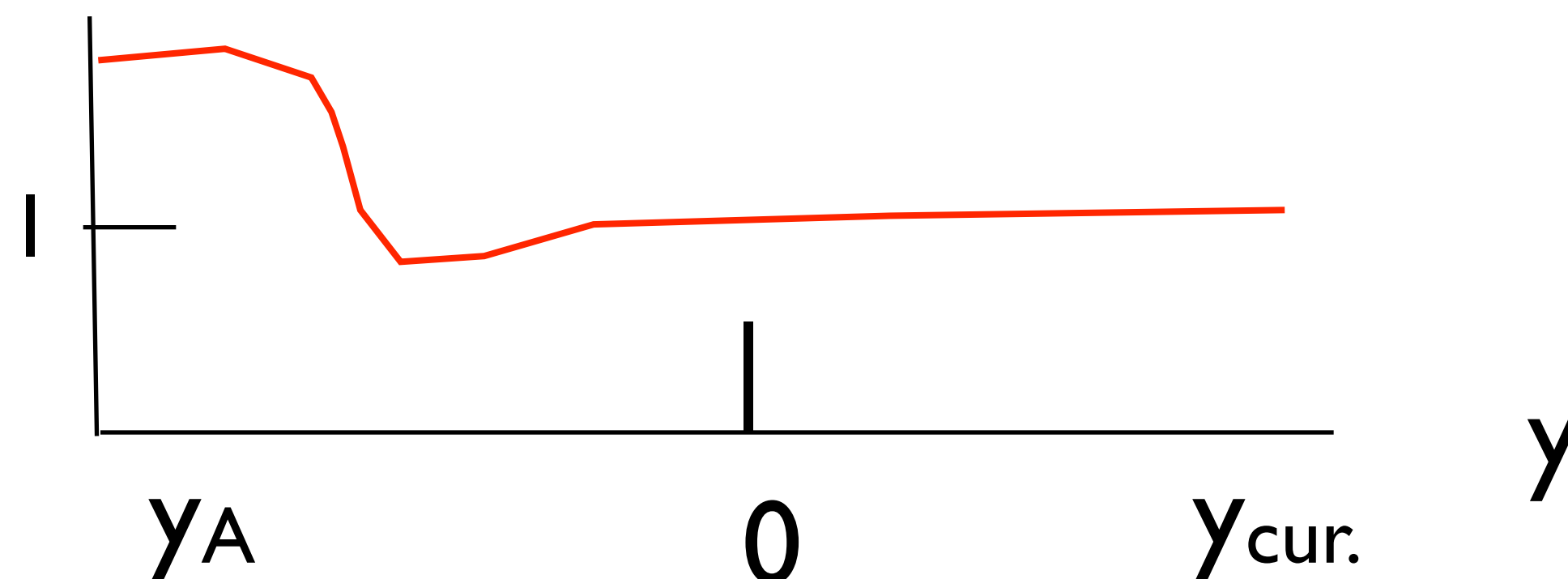
Current data - marginal - mostly neutrino bubble chamber data - show extra activity - but energy is not too large. The only high energy data are measurement of soft neutrons by from E665
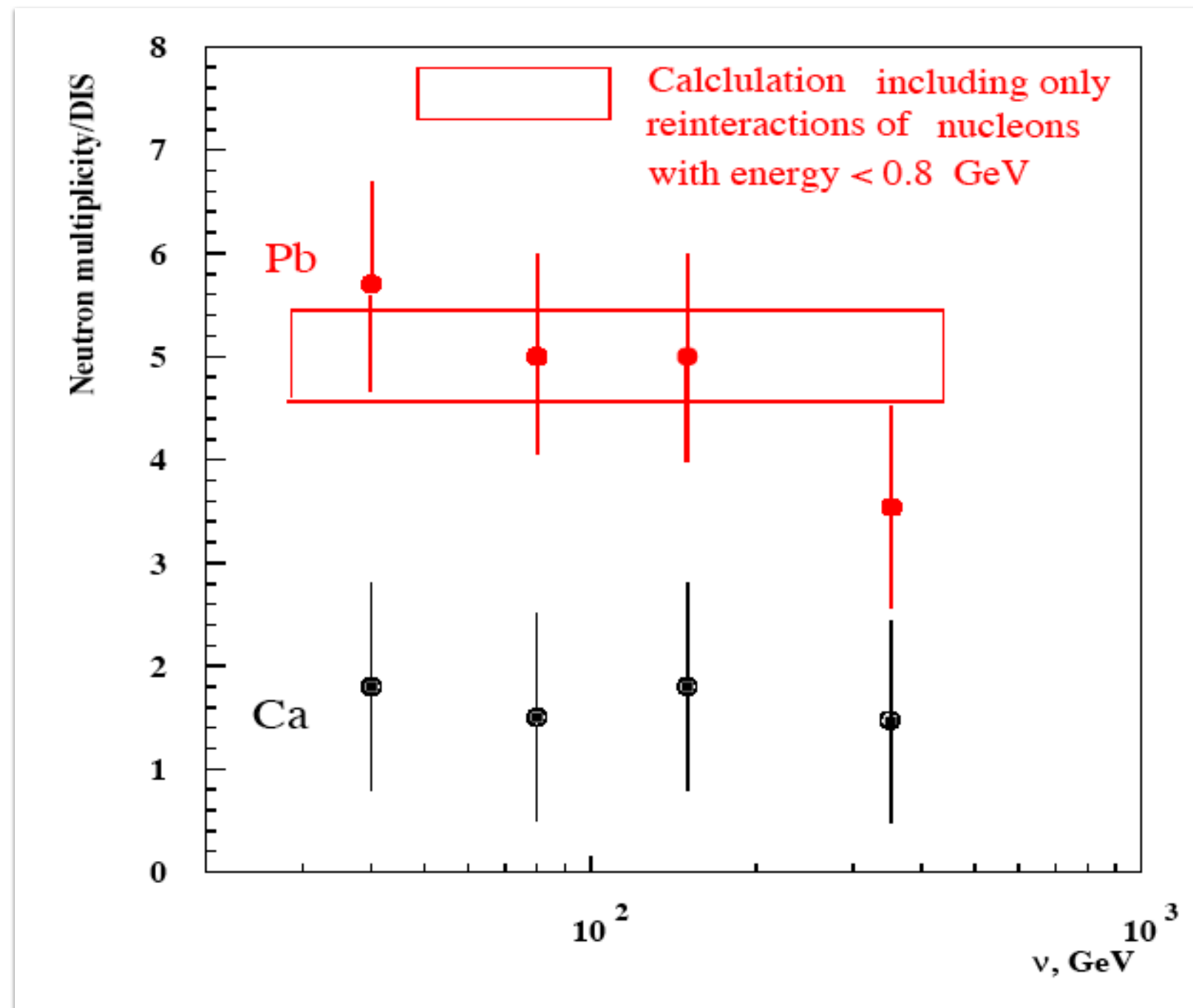
Puzzle !!!!

Calculations of Zhalov, Tverskoii and MS (96-98) indicate that in average five neutrons are produced per one interacting nucleon in lead. This explains the E-655 data (FNAL) on the spectrum & multiplicity of the neutron production at <x> ~0.05.

Where all other interactions have gone ?

Does the final state interaction drops with ν ?

Studies of color flux dynamics are possible only at √s ≥ 20 GeV, need a large energy range and good acceptance in the nucleus fragmentation region and are likely to bring many surprises
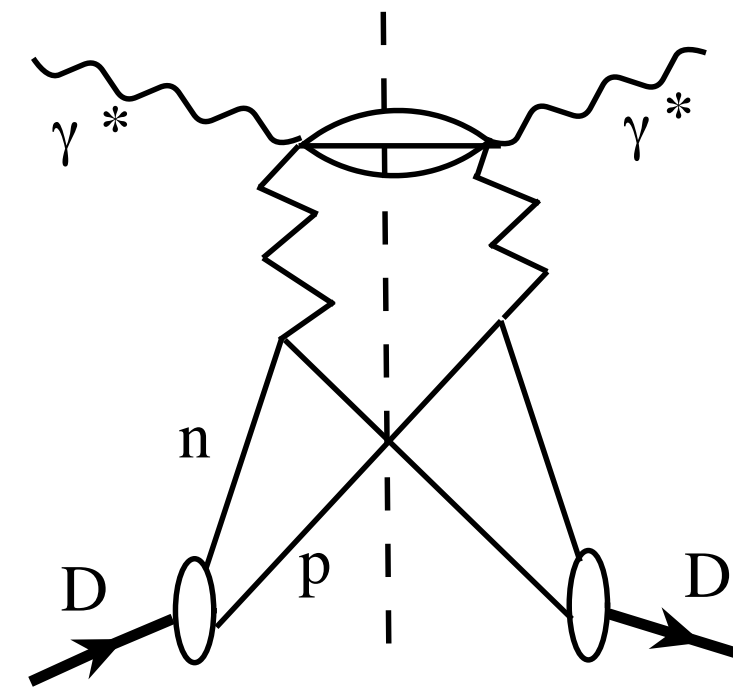
May help to device a Centrality trigger in eA

Small x (< 0.01) dynamics - interaction with the nucleus of color singlet dipoles of variable size - certain resemblance to hadron - nucleus scattering
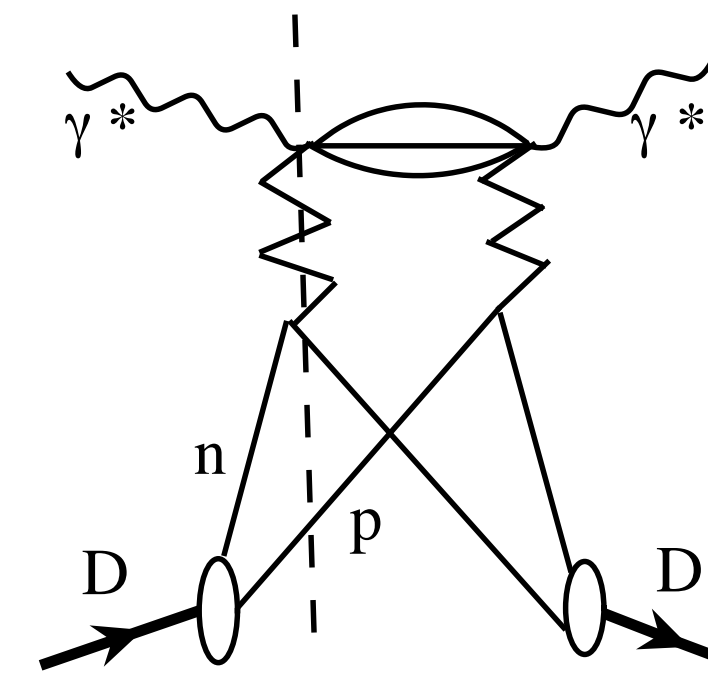
Abramovski, Gribov, Kancheli relation between different final states - further discussions in Guzey's talk)
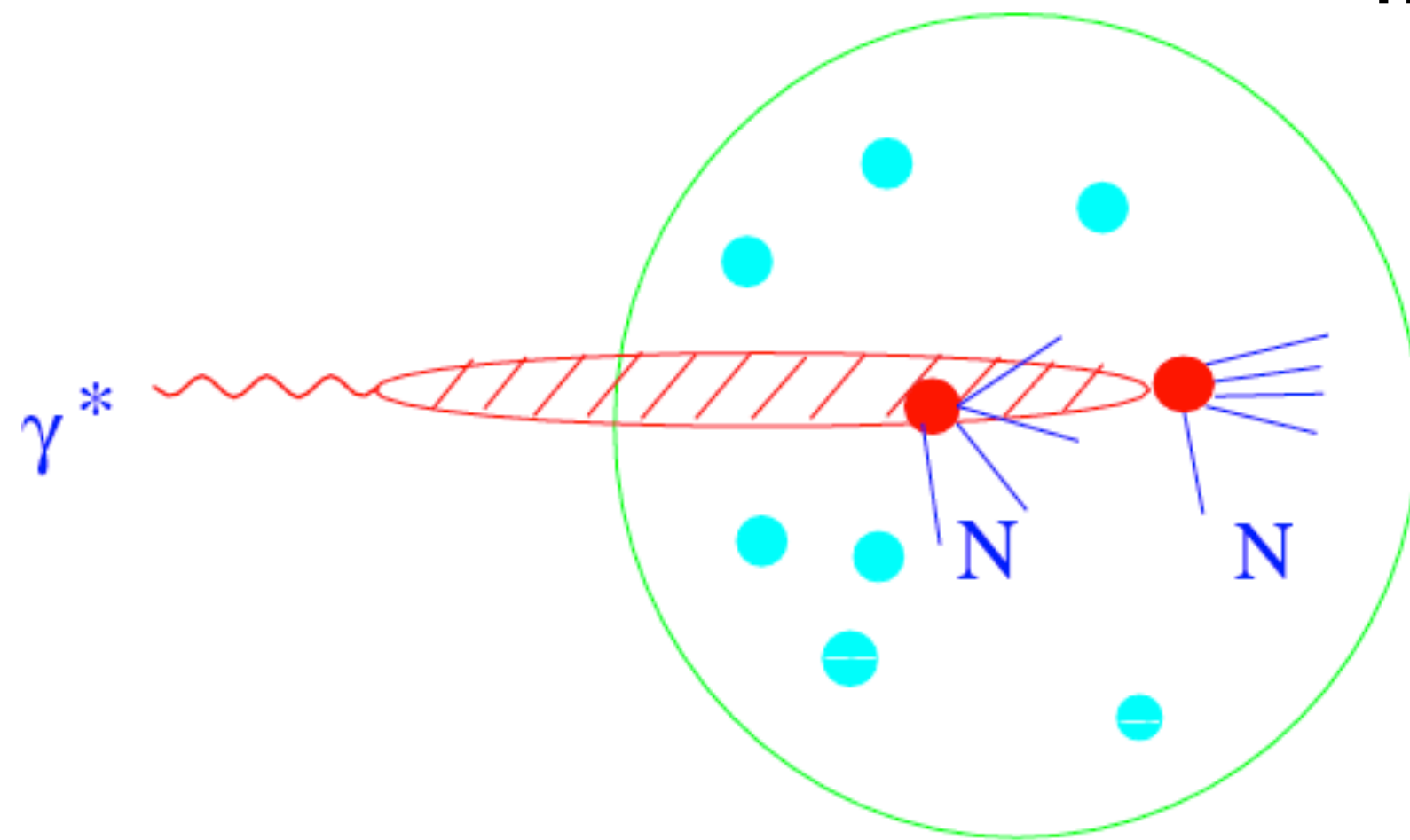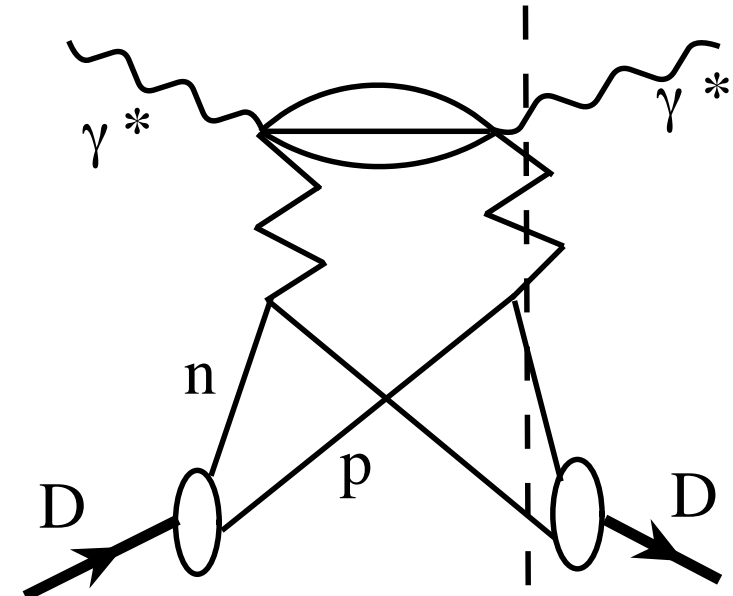

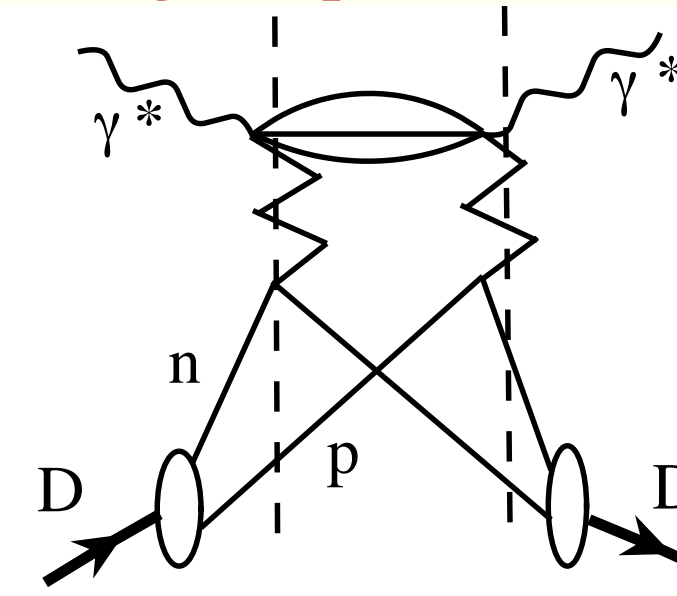$$\sigma_{tot} = \sigma_{impulse} - \sigma_2$$

$$\sigma_{dif} = \sigma_2$$

$$\sigma_{single\ "p"} = -2\sigma_2$$

$$\sigma_{single\ "n"} = -2\sigma_2 \qquad \sigma_{double} = 2\sigma_2$$

Small $x, l_{coh} \gg R_A$

Changes in the composition of final states are larger than for total cross section

Using AGK we re-derived original Gribov result for nuclear shadowing extending it to include the real part effects. This approach does not require separation of diffraction into leading twist and higher twist parts. It allows also to calculate nuclear pdf's and GPDs using QCD factorization - Guzey's talk

Final states in DIS

$$\frac{\dfrac{dN^{eA \to h+X}}{dy}}{\dfrac{dN^{eN \to h+X}}{dy}}$$
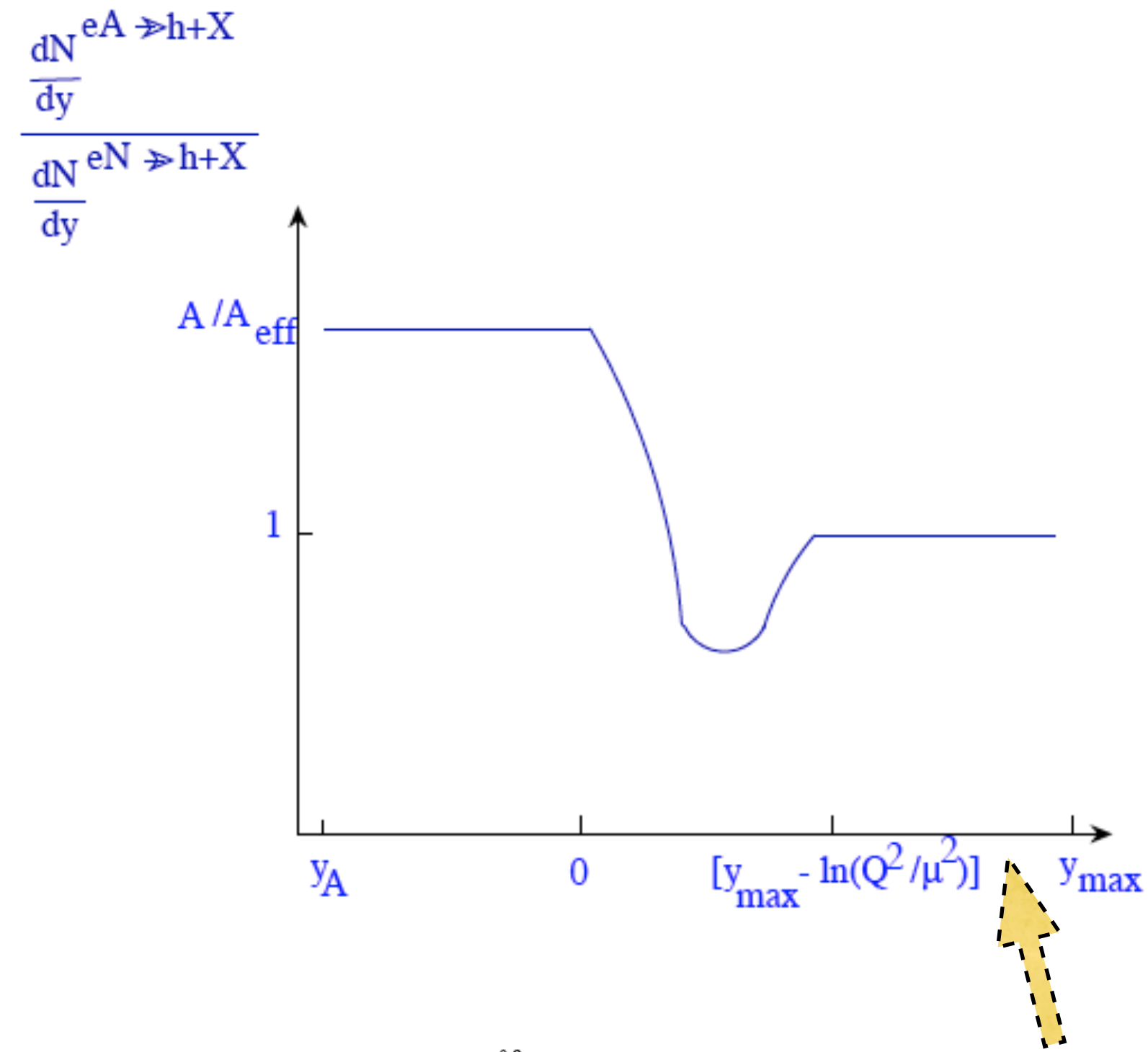
LT: A dip at the rapidities $y \sim y_{max} - \ln(\langle M_{dif}^2 \rangle / \mu^2)$ - a test of the rapidities of soft partons involved in the diffraction.
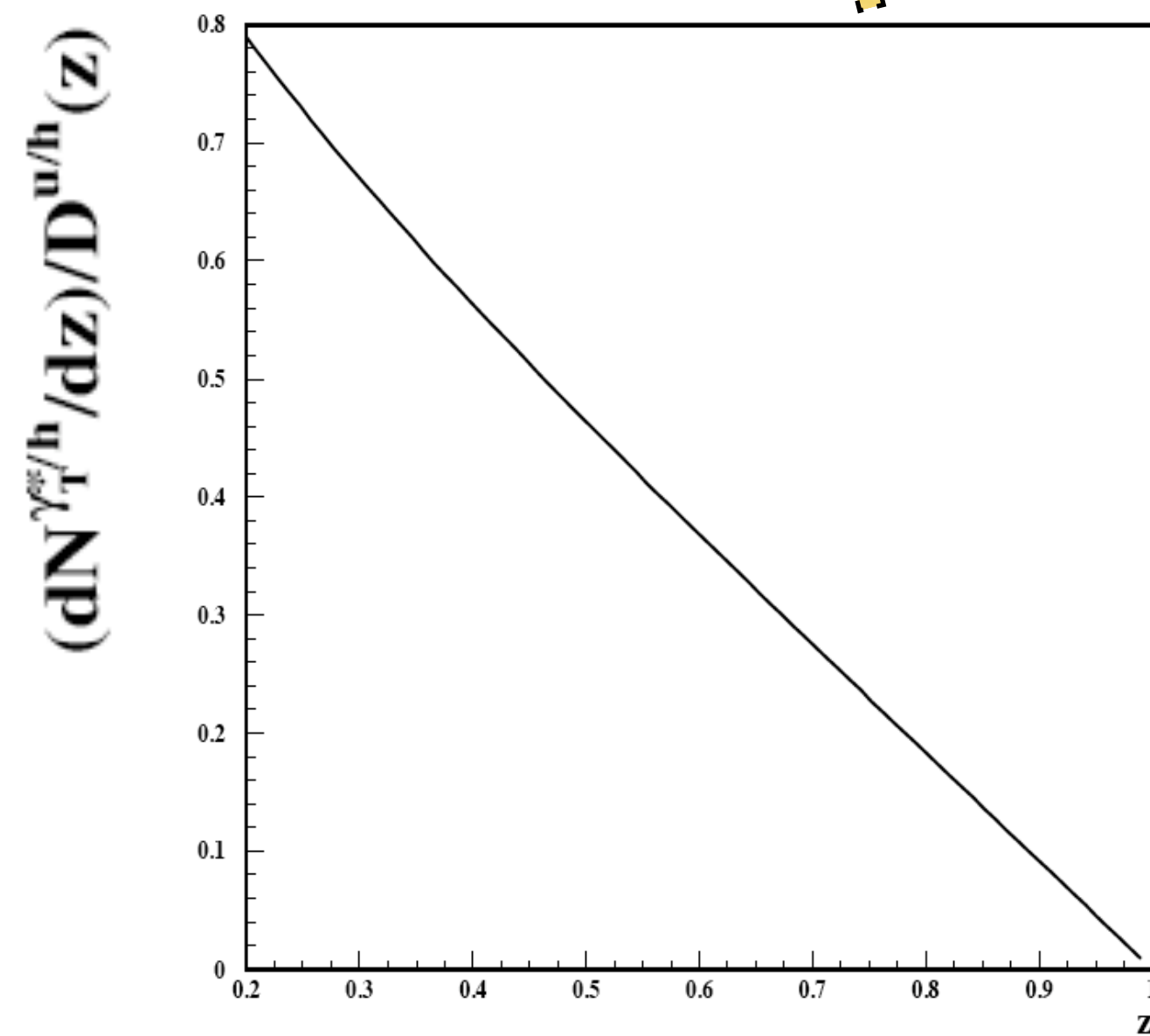
The total differential multiplicity normalized to the up quark fragmentation function as a function of z at $Q^2=2$ GeV^2 in the black regime

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Examples of studies involving hadrons in the fragmentation region:

◻ Correlations between neutron multiplicity and multiplicity at central rapidities - natural for soft physics and leading twist (LT) nuclear shadowing models. Note - detector should be able to detect multiplicities per unit rapidity (on the nucleus side) at least a factor 2 larger than in the proton case. Large fluctuations of multiplicity (much larger than in ep).

◻ Correlation of suppression of the leading spectrum at $y=y_{max} - \ln Q^2$ in the current fragmentation region and neutron multiplicity.

◻ Presence of leading hadron (along photon) with large transverse momentum (enhanced chance of rescattering) and larger neutron multiplicities

Tagged structure functions

One of the important components of the EIC project is the measurement of the nonsinglet structure function of the nucleon, $F_2^p - F_2^n$, down to rather small values of Bjorken x.

Key problem: $R = \dfrac{(F_2^p - F_2^n)}{(F_2^p + F_2^n)/2}$ is small at small x and comparable to the shadowing effect:

$R \equiv (F_2^p - F_2^n)/F_2^p \leq 4 \times 10^{-2}$ for $x \leq 10^{-2}$, while the shadowing effect modifies F_2^D by 1-2% and, hence, R by 2-4%.

Similar problem for measurement of g_{1n} for which one can use either ^{3}He or ^{2}H (challenge accurate control of nuclear effects)

Need to select events with soft (< 100 MeV/c in the nucleus rest frame) spectator nucleons: proton (^{2}H), two protons (^{3}He) to avoid effects of initial and final state interactions. Deuteron: On the level of double scattering effects delicate cancelations between shadowing and diffractive channels including fsi of pn.
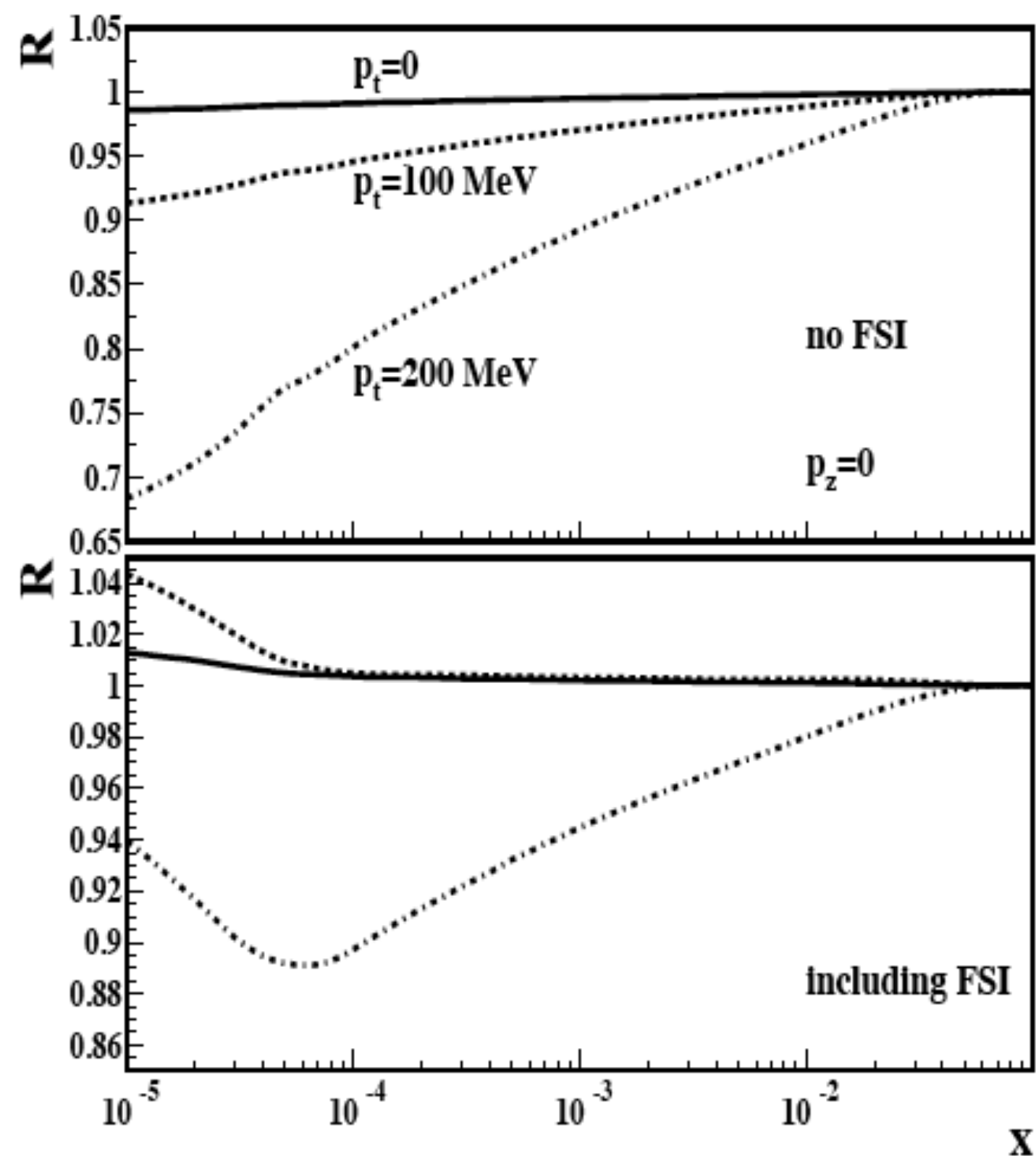
Guzey et al 03-05

Need further theoretical and experimental studies to determine magnitude of "cascade" type interactions

With realistic cuts tagging efficiency for ^{3}He case is probably at least a factor of 10 smaller than for ^{2}H

Guess: to do an accurate analysis one needs for small transverse momenta resolution of proton detector on the scale of 50 MeV/c, and $\delta p/p \sim$ 1% for $x_F \sim$ 0.5

Strategies for probing various types of Non-nucleonic degrees of freedom

◆ **_Bound Nucleon deformations_**

🔴 How EMC effect depends on the virtuality/off-energy-shellness of the nucleon?

Is dependence the same for u- and d- quarks?

Tagging of proton and neutron in
$e+^2H \to e+ N +X$; $e+^3He \to e+ pN +X$

tagged structure functions

Suppression of small size configurations mechanism - gives a reasonable magnitude of the effect at x ~ 0.6. Predict an effect increasing quadratically with spectator momentum

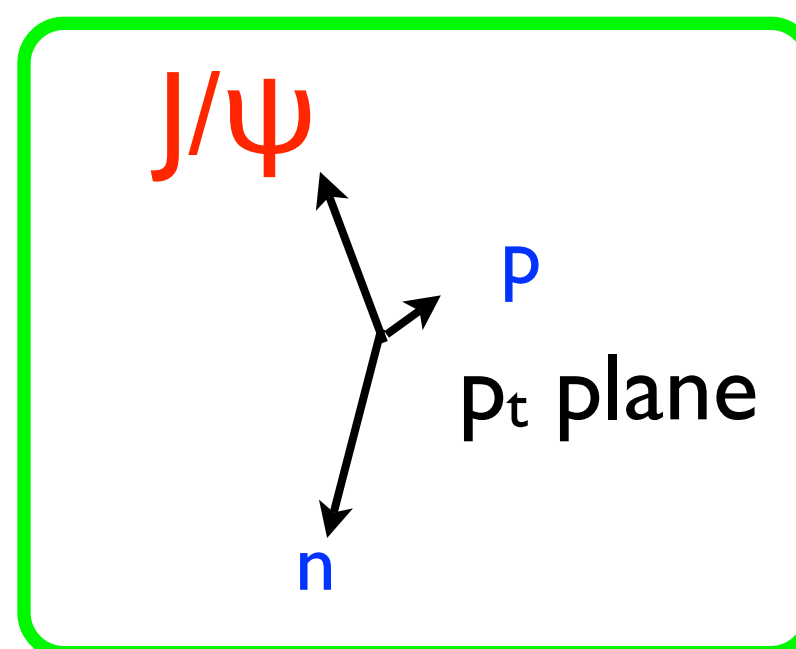✌ Different interaction in S and D wave→ different deformation?   Tensor polarized ^2H

✌ Different interaction for I=0 and I=1 → different deformation for pn and pp channels for ^3He ?

Is the transverse size of bound nucleon quark/ gluon distribution in bound nucleons modified?

$$\gamma +^2 H \rightarrow J/\psi + p + n$$ at -t > 0. 3 GeV^2 in the spectator kinematics

$$\gamma +^4 He \rightarrow J/\psi + p +^3 H$$

If t distribution is broader - swelling of gluon field in bound nucleons - compare with Jlab data for G_{Ep}/G_{Mp} bound (swelling ? of quark field). Is swelling different for S and D-wave (polarized deuteron)

♦ Hadronic degrees of freedom - Δ's,... $e +^2 H \rightarrow e + \Delta^{++} + X$

$$e +^2 H \rightarrow e + \Delta^{++} + leading \, \pi^{\pm} + X$$

ΣΣ *EIC will provide qualitatively new insight into quark-gluon structure of nuclei and nuclear matter.*

Main tool for exclusive processes is color coherence (CC) property of QCD and resulting **Color transparency (CT) - observed in pion diffraction to two jets, pion production at Jlab,...**

Four types of diffraction   (small x: $1/2m_N x > 2R_A$)

☺ *Coherent diffraction - final nuclear state $= A$*   Dominates at small -t (below first minimum)

$\sigma \sim A^{4/3}$ (hard), $\sigma \sim A^{2/3}$ (soft),

☹ *Coherent excitation of nuclear levels - final nuclear state $= A^*$*

Dominates at small -t at and above the first minimum) $A^* \rightarrow A + \gamma(2\gamma)...$

Photon energy ~ few MeV in the nucleus rest frame; ~ 100 MeV in collider frame, average opening angle $1/\gamma_A \sim 10$ mrad for eRHIC. ~ 10% of the total coherent diffraction.

☺ *Incoherent diffraction - final nuclear state $= A^*$ with excitation energies above 8 MeV - decays with emission of neutrons - easy to detect*

$\sigma \sim A$ (hard), $\sigma \sim A^{1/3}$ (soft) - the same change of power between "hard" and "soft" as for coherent case

$A^{1/3}$ larger effect than in $\gamma^* + A \rightarrow VM + A^*$ at x> 0.1

☞ *Inelastic incoherent diffraction - final nuclear state A^* + hadrons - challenge to detect: 20% of incoherent diffraction for t~0; dominates for large t.*

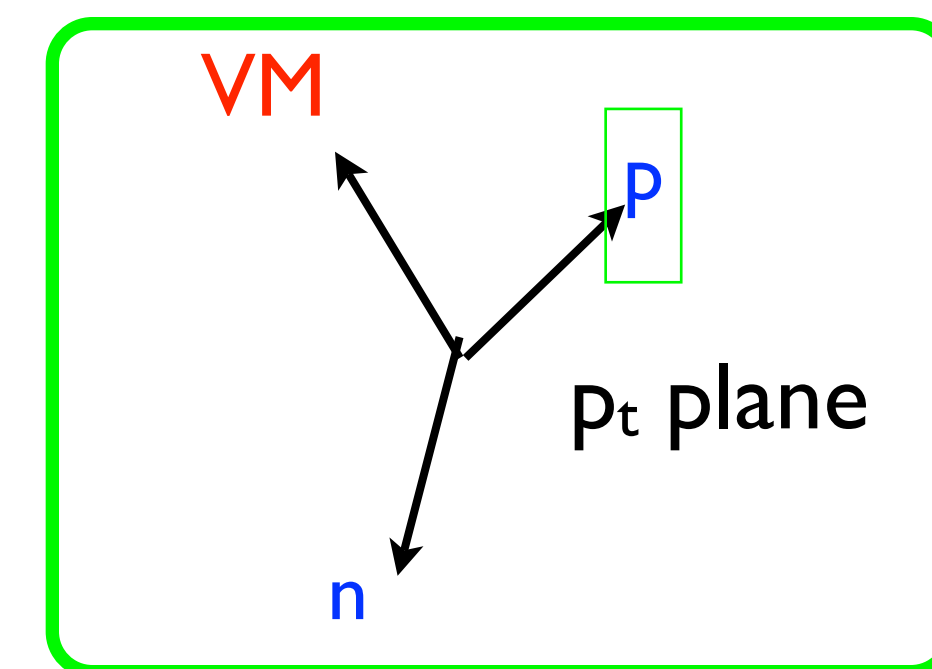☀ Precision studies of coherent dynamics with light nuclei: ^{2}H, ^{3}He, ^{4}He

Advantages:

✔ *no excited bound states*

✔ *at mEIC: $l_{coh} > R_A$*

✔ *possible to perform details studies of the pattern of coherent interactions with two nucleons (triple coherent interactions are a small correction at x>0.005*

✔ *runs with polarized ^{2}H or ^{3}He will be necessary for spin program*

Examples:

● Double scattering kinematics for scattering off ^{2}H
(polarized ^{2}H will be an extra bonus)

γ* — VM, M$_X$

diffractive GPD for VM,
difractive PDF for M$_X$

IP   IP

^{2}H

P

n

VM

P

n

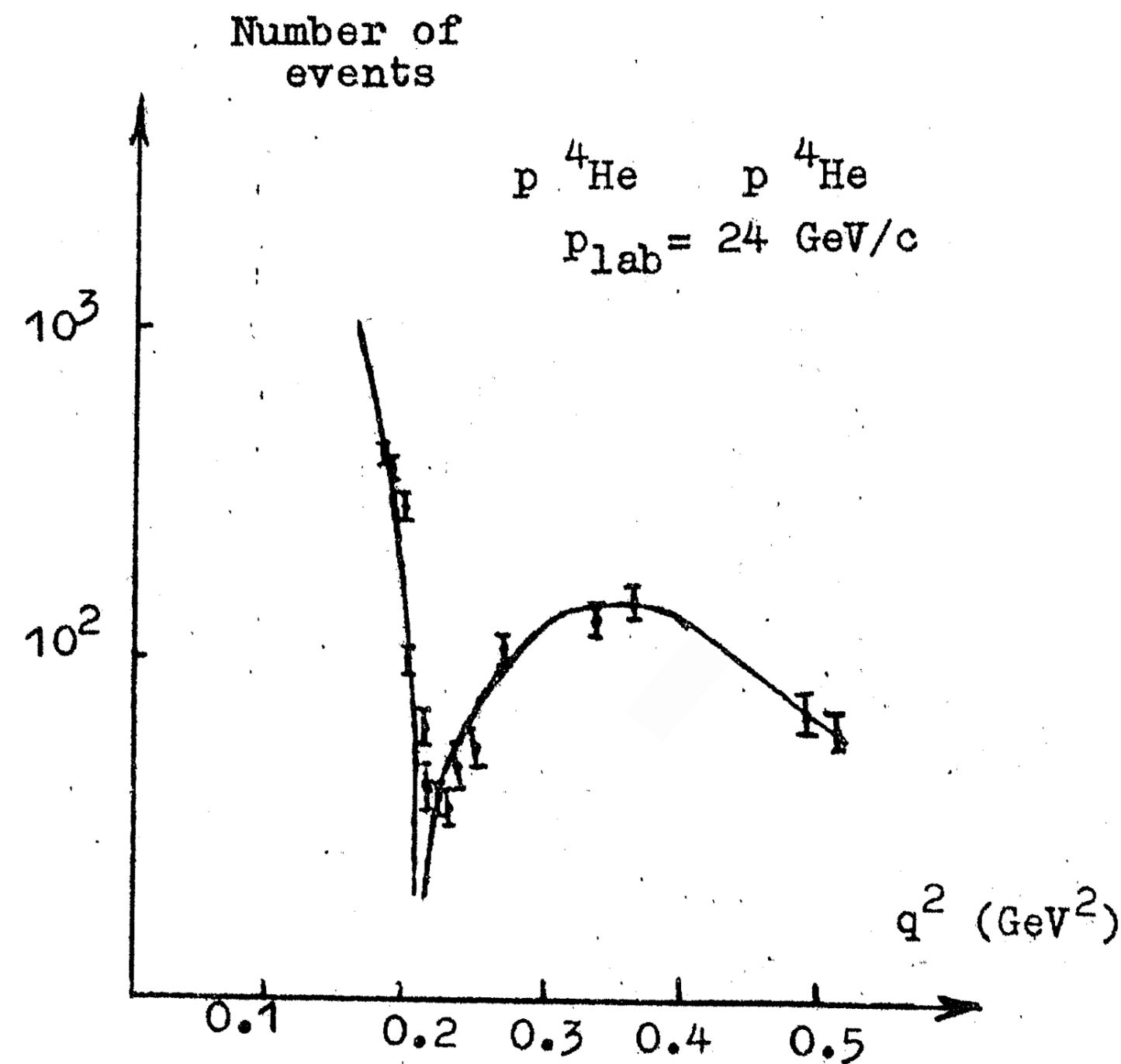p$_t$ plane
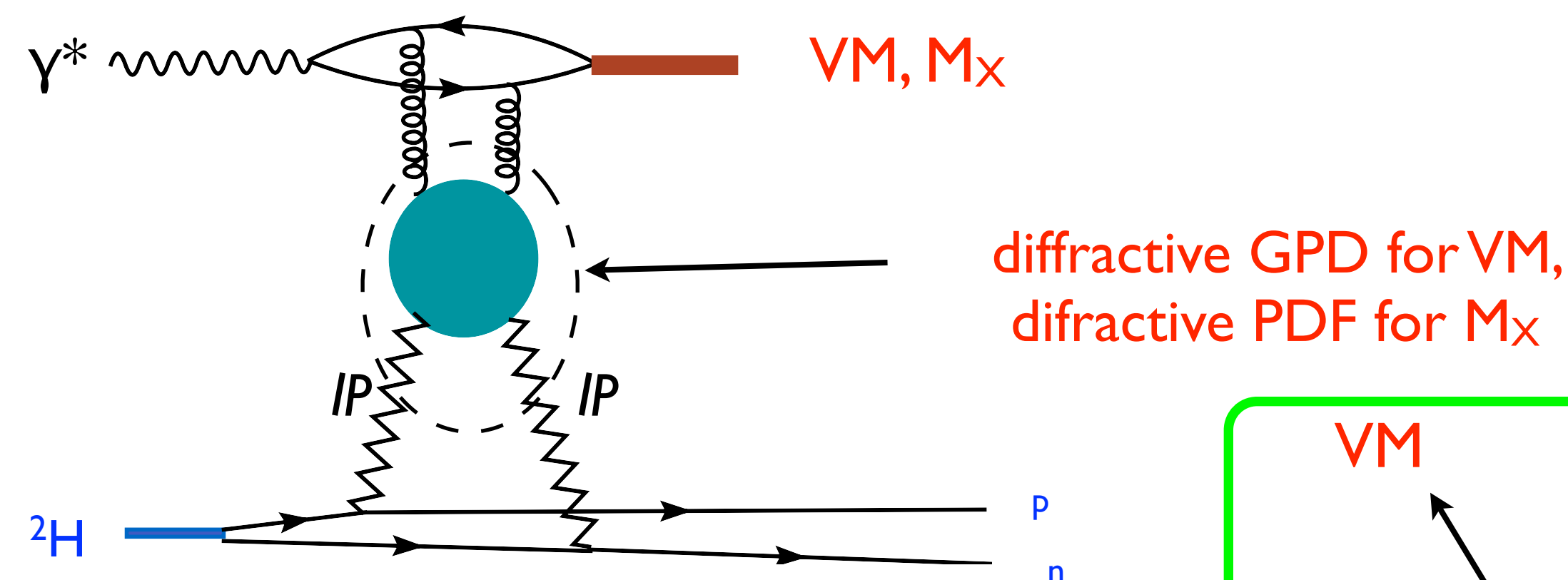
pp/ nn channel unique way to study IP - R interference

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- Coherent scattering of ^{4}He. Simple nucleus with significant rescattering probability and negligible triple rescattering at to large -t.
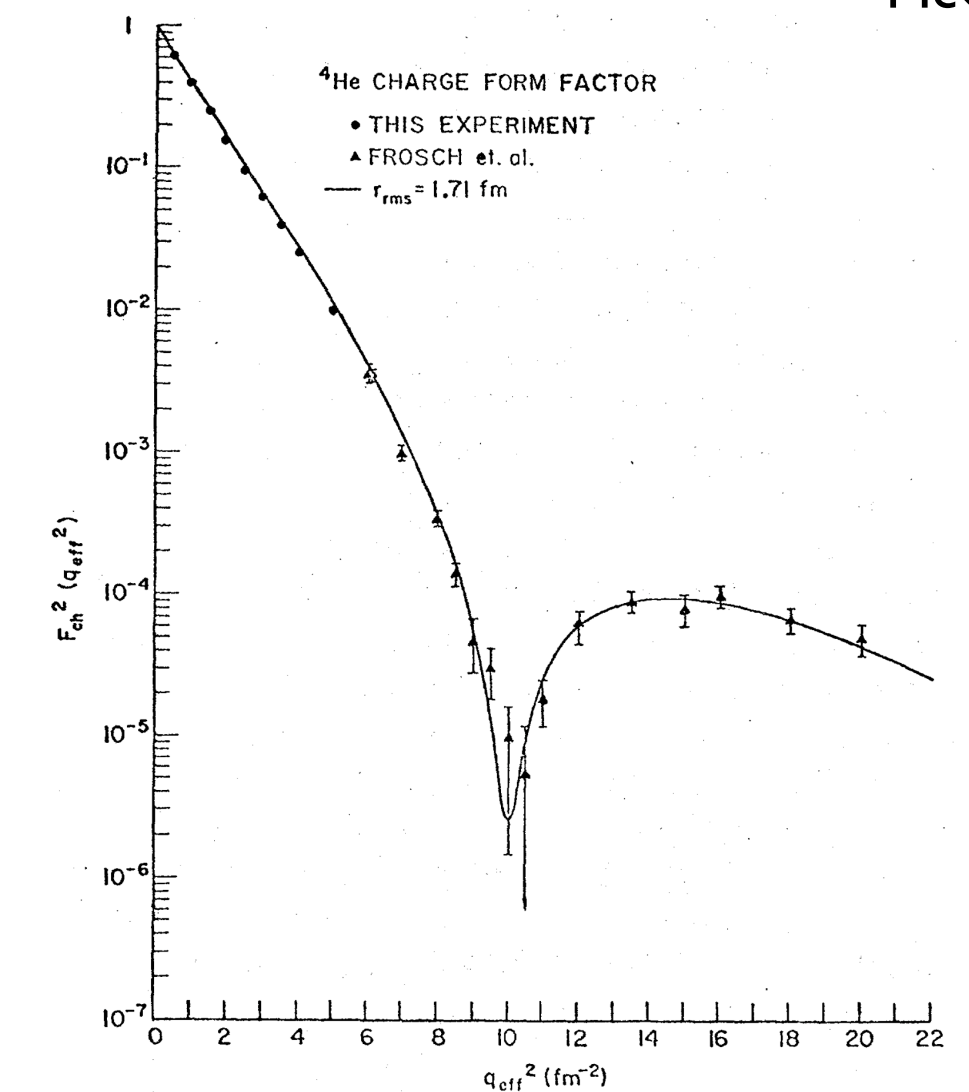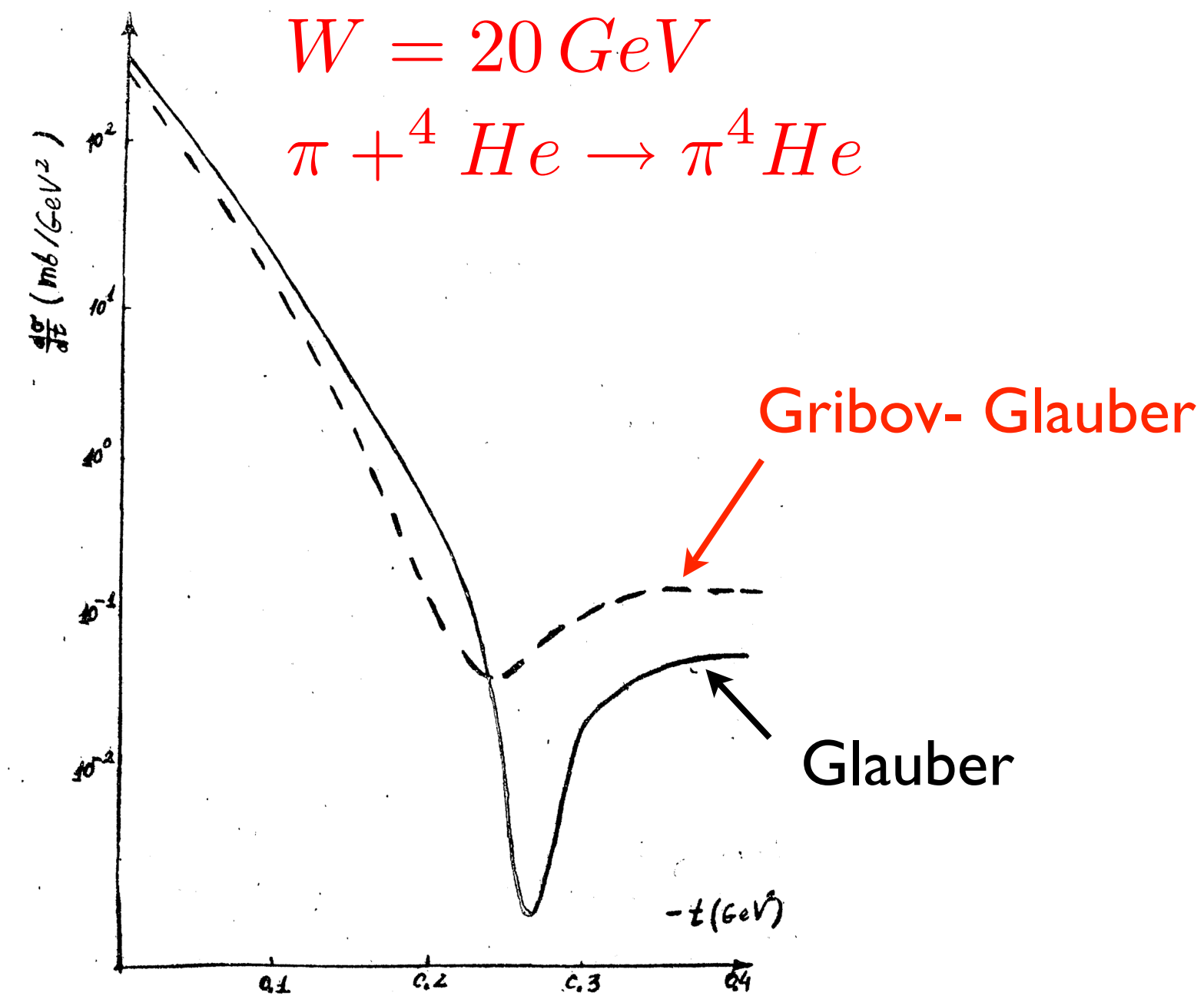
McCarthy et al

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*

^{4}He CHARGE FORM FACTOR
- THIS EXPERIMENT
▲ FROSCH et. al.
— r_{rms} = 1.71 fm

$W = 20\,GeV$
$\pi +^4He \to \pi^4He$

Gribov- Glauber

Glauber

Number of events

p ^{4}He   p ^{4}He
P_{lab} = 24 GeV/c

q^2 (GeV^2)

Strong sensitivity of the shape to the strength of double scattering

Levin & MS 75

☛Exclusive diffraction - photon & vector meson production.

x≥ 0.02 Parton densities practically A-independent. Leading twist expectation for the amplitudes:

$$M(\gamma^*+A\to\gamma(V)+ A)=AF_A(t)\ M(\gamma^*+A\to\gamma(V)+ A)$$

Observed for the J/ψ photoproduction at FNAL.

At what Q^2 LT works for vector mesons? Leading twist dominates in the elementary reaction for $Q^2 \geq 10 - 15\ GeV^2$ only. However, squeezing may work already for $Q^2 \geq 5\ GeV^2$ (FKS95) leading to the color transparency phenomenon for much larger range of Q and hence to a possibility to measure the ratios of nucleon GPDs for a broad range of reactions.

Alternative probe: incoherent exclusive processes for |t|≥0.1 GeV²:

$$d\sigma(\gamma^*+A\to\gamma(V,\pi,K..)+ A')/dt=$$
$$=Z\ d\sigma(\gamma^*+p\to\gamma(V,\pi,K..)+ N)/dt+ (A-Z)\ d\sigma(\gamma^*+n\to\gamma(V,\pi,K..)+ N)/dt$$

Need effective veto for production of mesons in the nucleus fragmentation region

Conclusions

☺ HERA left plenty of open questions related to the dynamics of exclusive VM production and characteristics of GPDs - especially the gluon GPD which dominates at small x, also left a gap at x>0.01 - precision measurements require hermetic detector in fragmentation region.

☺ Fragmentation in the polarized ep scattering is a new frontier for studies of nucleon 3D correlated structure

☺ Nuclear fragmentation region has highest sensitivity to the color tube dynamics

☺ EIC would allow to establish quark-gluon structure of nuclei at x> 0.01 - link to neutron stars

☺ Color transparency/opacity phenomena, first determinations of nuclear GPDs, establishing the Q^2 range for studies of GPDs of nucleon in hard exclusive processes.