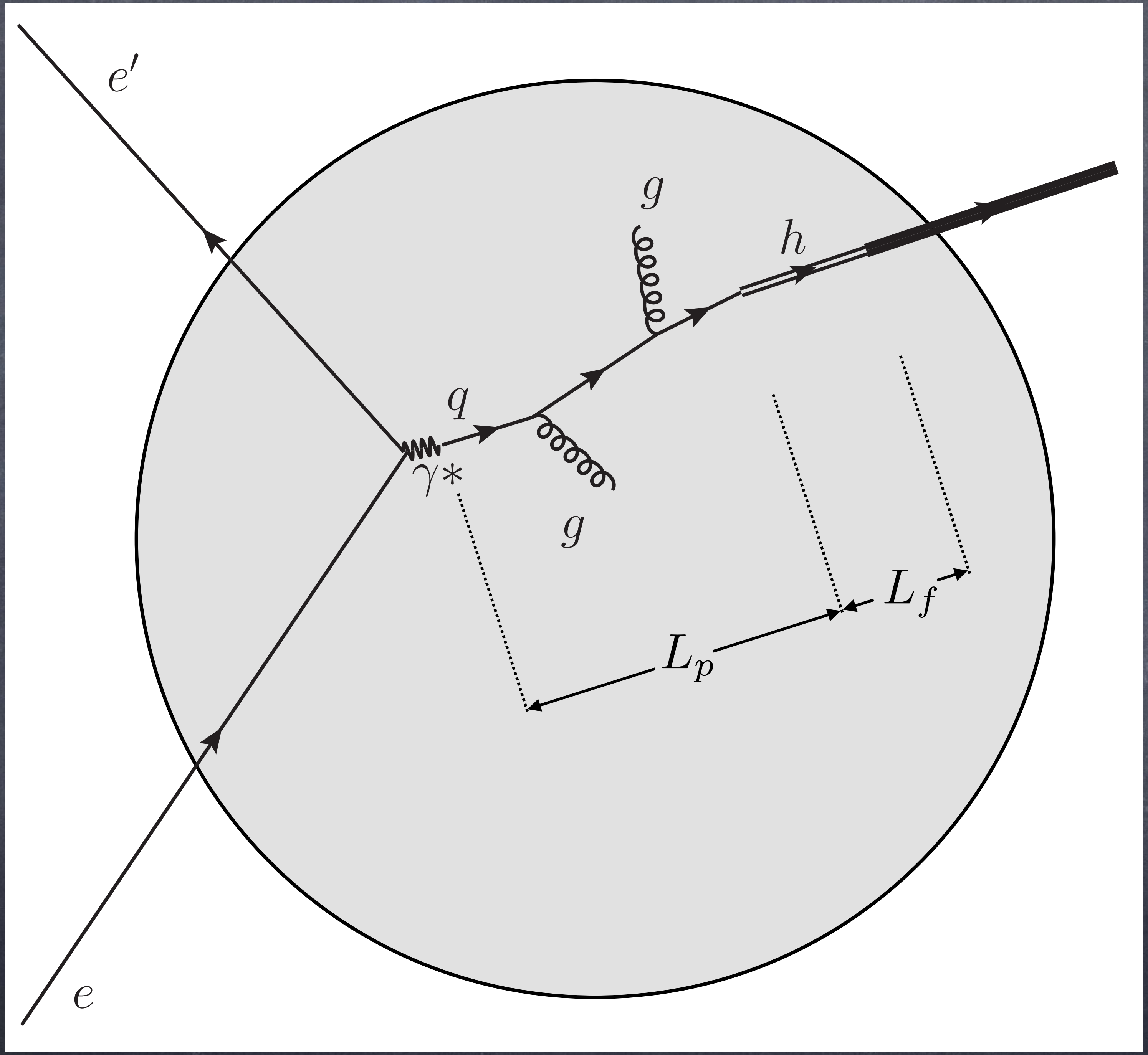
Color propagation in eA with CLAS, CLAS12 and EIC

Taisiya Mineeva

Universidad Técnica Federico Santa María

for the EG2 collaboration

Color propagation (x>0.1)



EG2 collaboration

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Engineer
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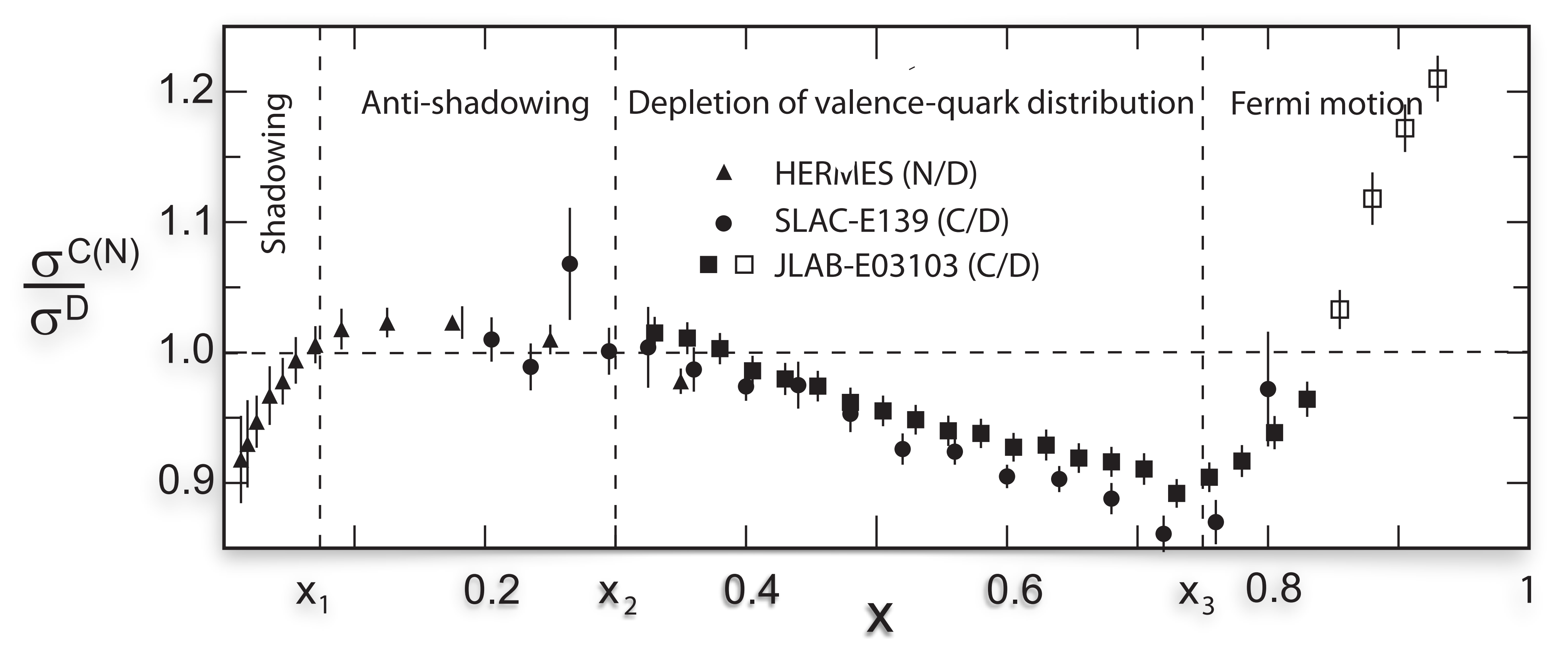
Quarks in nuclei: experimental data

✔ **EMC effect -** observation that structure functions are modified in nuclei
over ~1000 papers published in the past 35 years!
NO CONSENSUS AS OF ITS ORIGIN



“Present status of EMC effect” Klaus Rith arXiv:1402.5000v1 (2014)

Quarks in nuclei: experimental data

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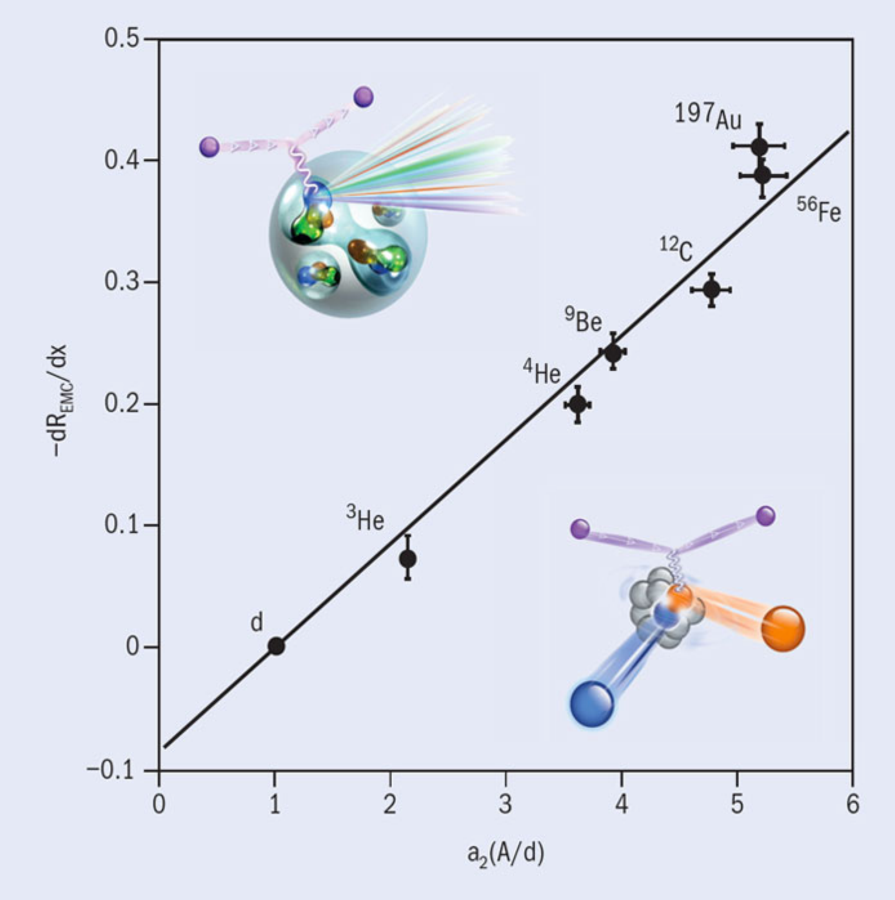
- ✔ Short Range Correlations - short distance structure of nuclei, correlated nucleons.

Correlation between EMC effect and SRC
high virtuality nucleons in nuclei?

talk by A.Schmidt



Higinbotham, Miller, Hen, and Rith. CERN Cour. 53N4, 35 (2013)

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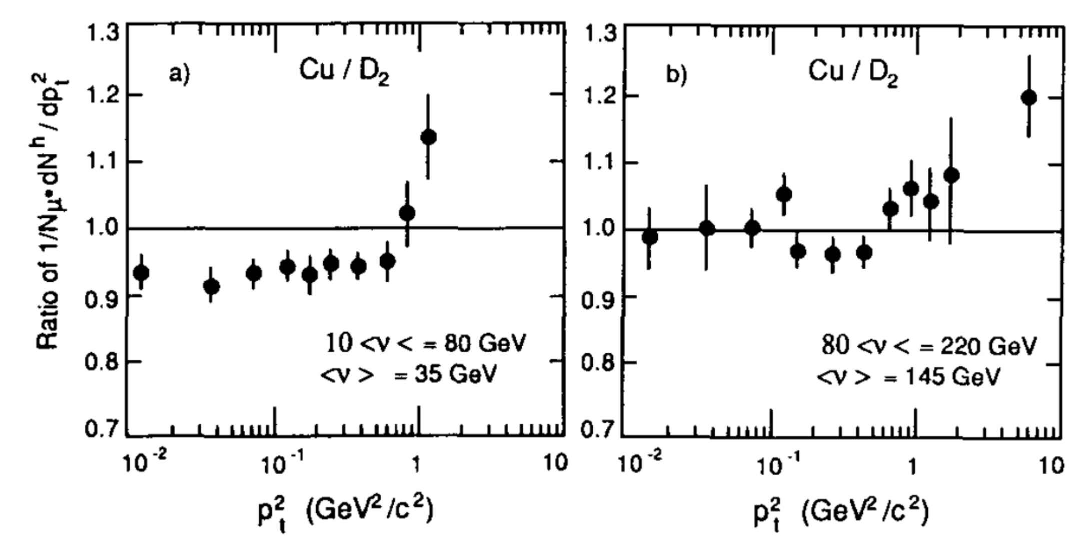
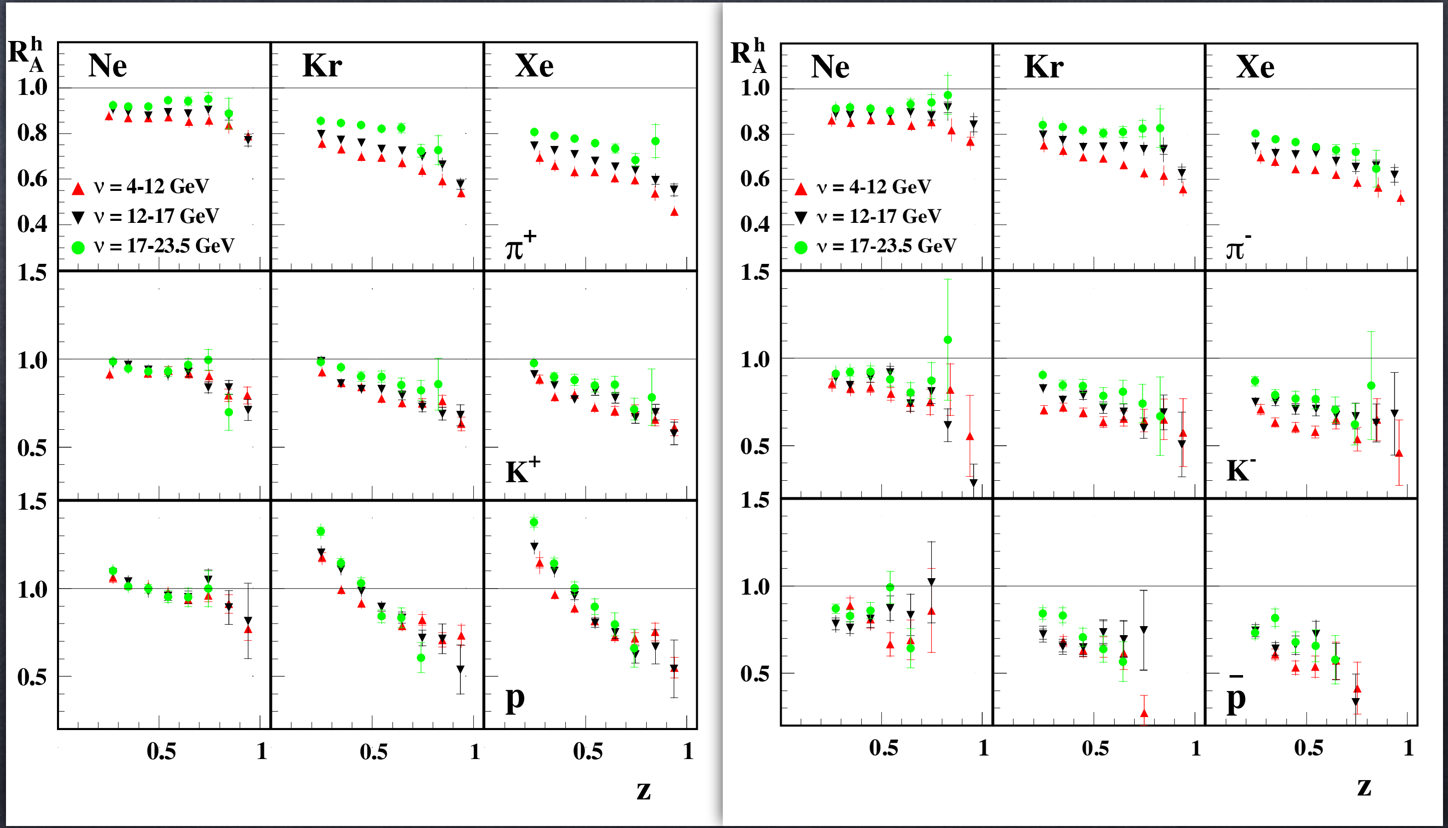
EMC data: μ beam on Cu and D



J. Ashman *et al*. Z.Phys., vol. C52 (1991)

HERMES data: e+ beam on Ne, Kr, Xe and D



HERMES collaboration, Eur. Phys. J. A (2011)

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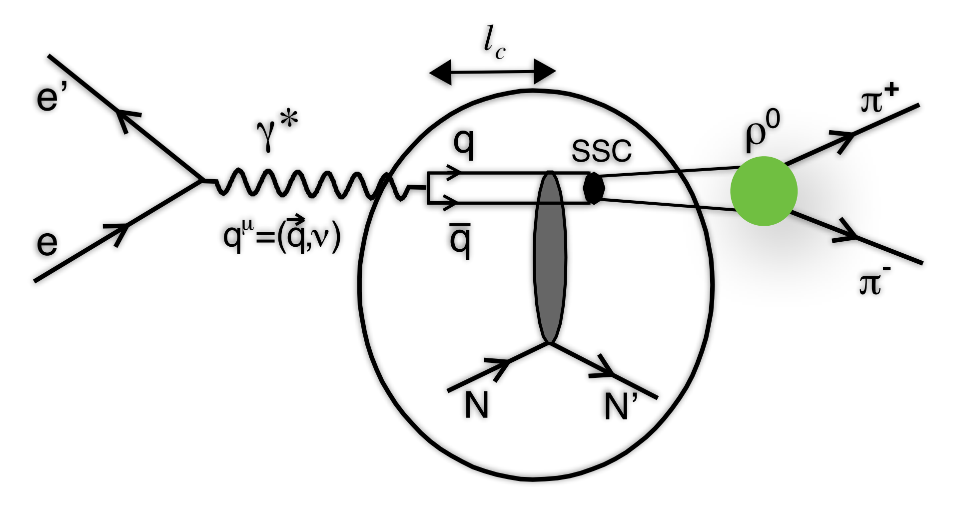
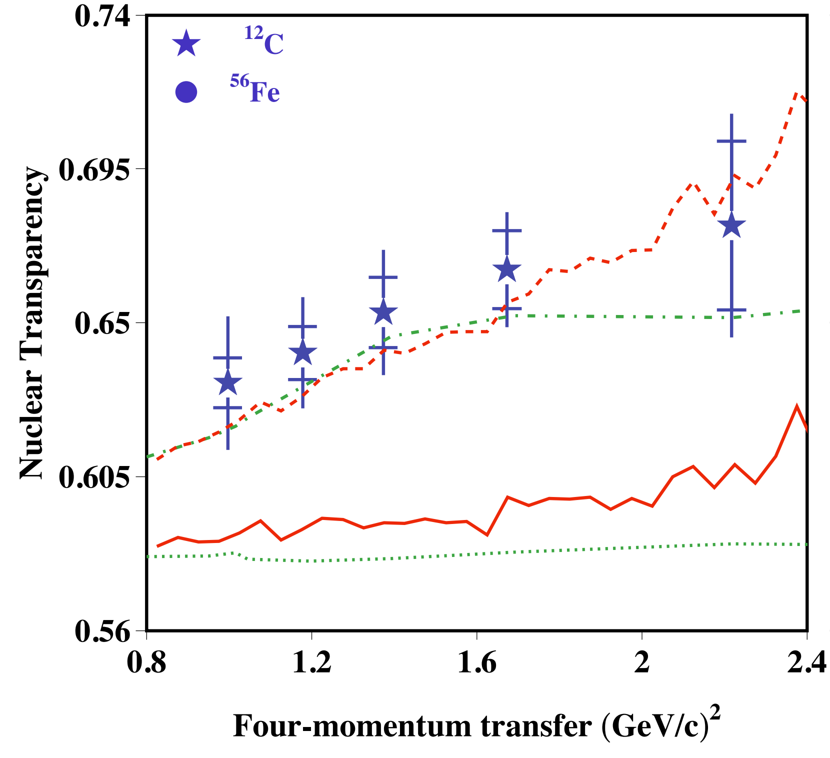


L. El Fassi et al. PLB 2012



Quarks in nuclei: experimental data

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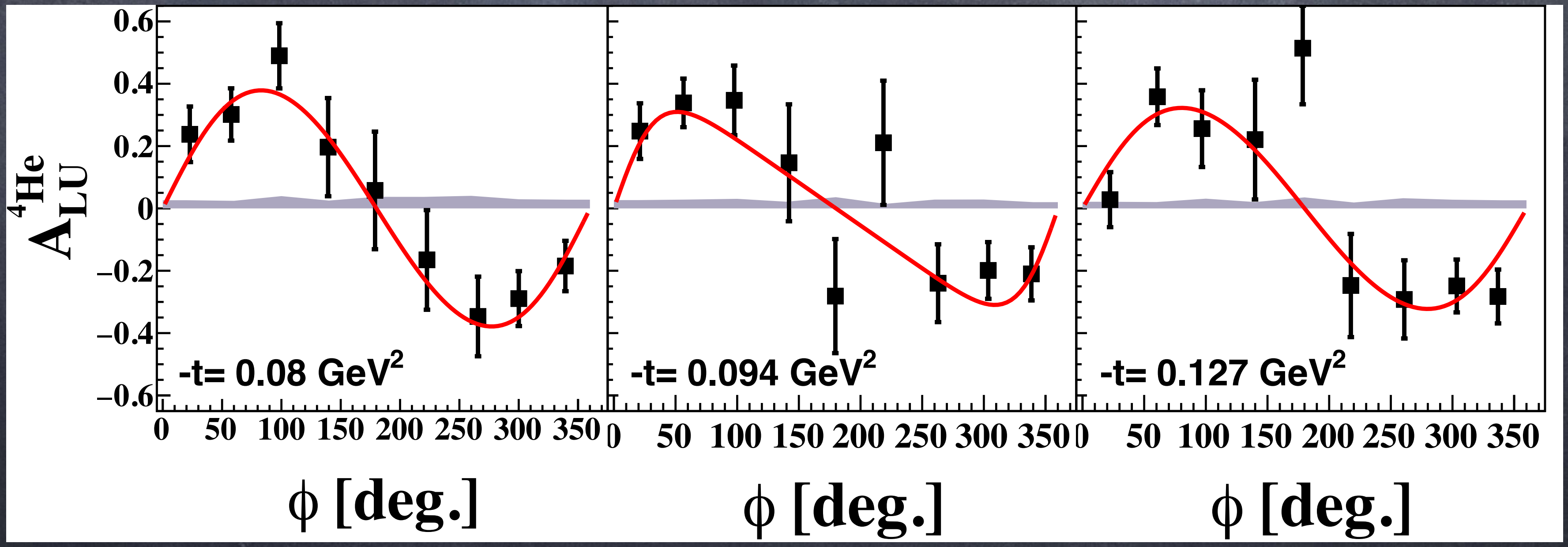
- ✓ Color transparency - decreased interaction in nuclei of small sized object
- ✓ Nuclear DVCS: 3D tomography of partonic structure of nuclei



M.Hattaway, N.Baltzell, R.Dupré *et al.*, "First exclusive measurement of DVCS off 4He" Phys. Rev. Lett. 2017

In the eA context I will discuss:

- Color propagation - fundamental process of QCD
- Experimental realization: CLAS (E-02-104) at 5 GeV
- Continuation at CLAS12 (E-12-06-117)
- Future measurements at the EIC

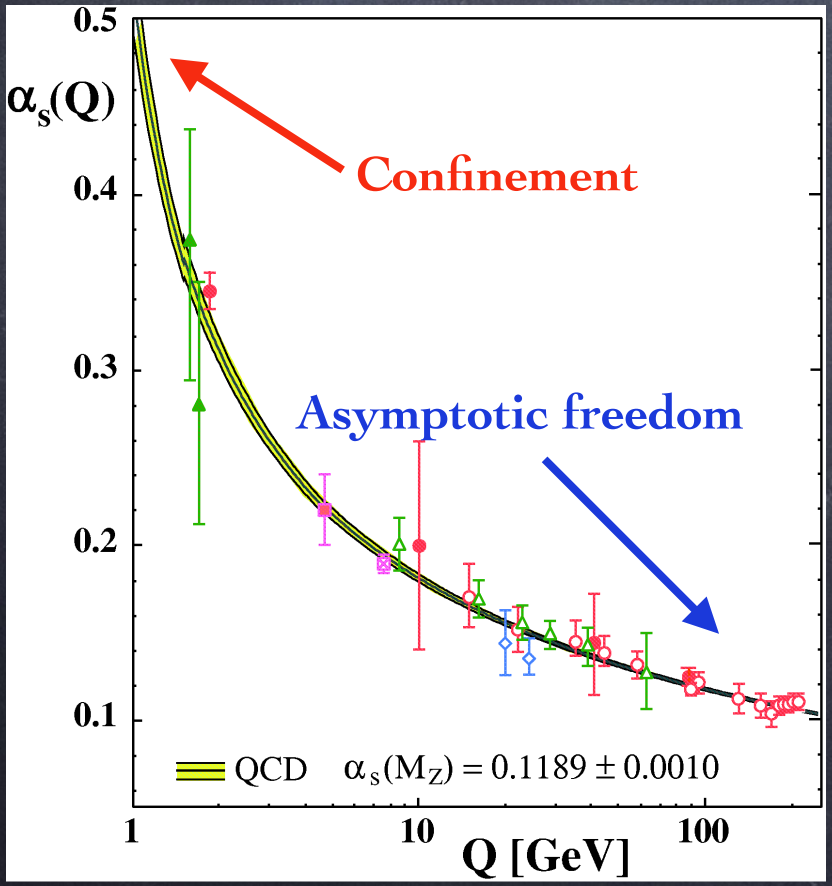
Color propagation - *why is it interesting?*

Color propagation is a fundamental QCD process

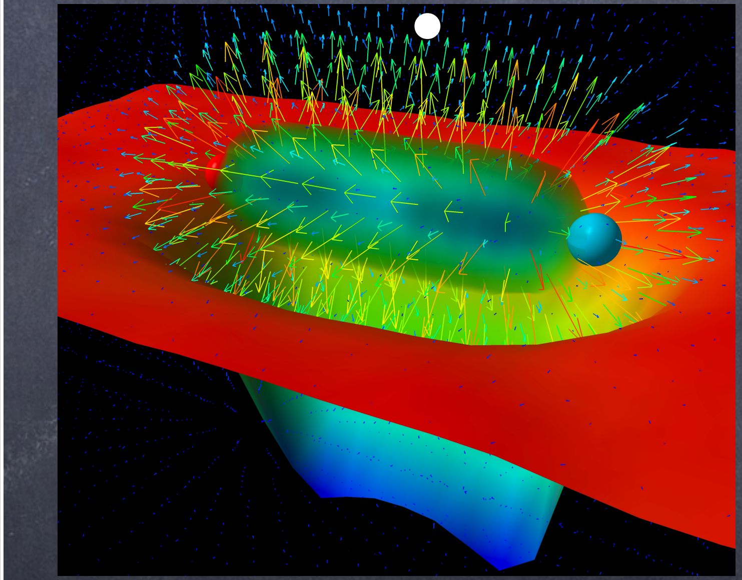
Hadronization describes the transition between colored d.o.f to composite colorless objects

*Propagation of color relies on key property of QCD as color gauge theory - **asymptotic freedom***

*Restoration of color neutrality from QCD vacuum is dynamical enforcement of **confinement***



from S.Bethke Prog.Part.Nucl.Phys.58 (2007)



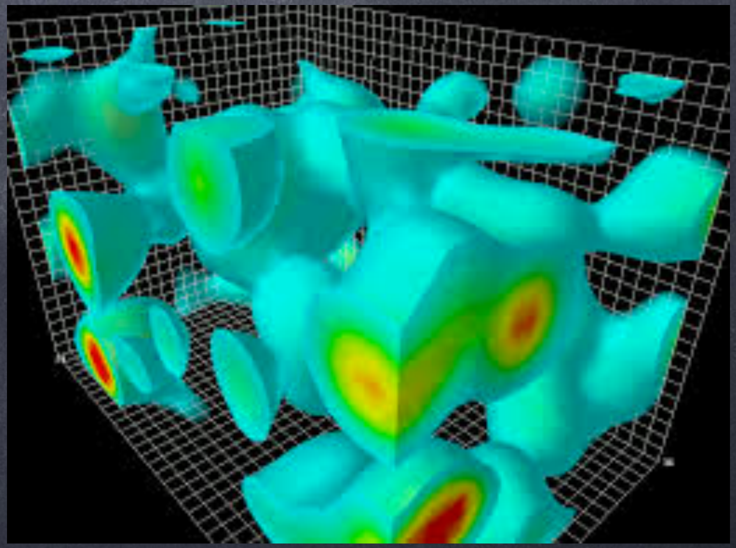
Long distances

color charge anti-screening

color flux tube between qq

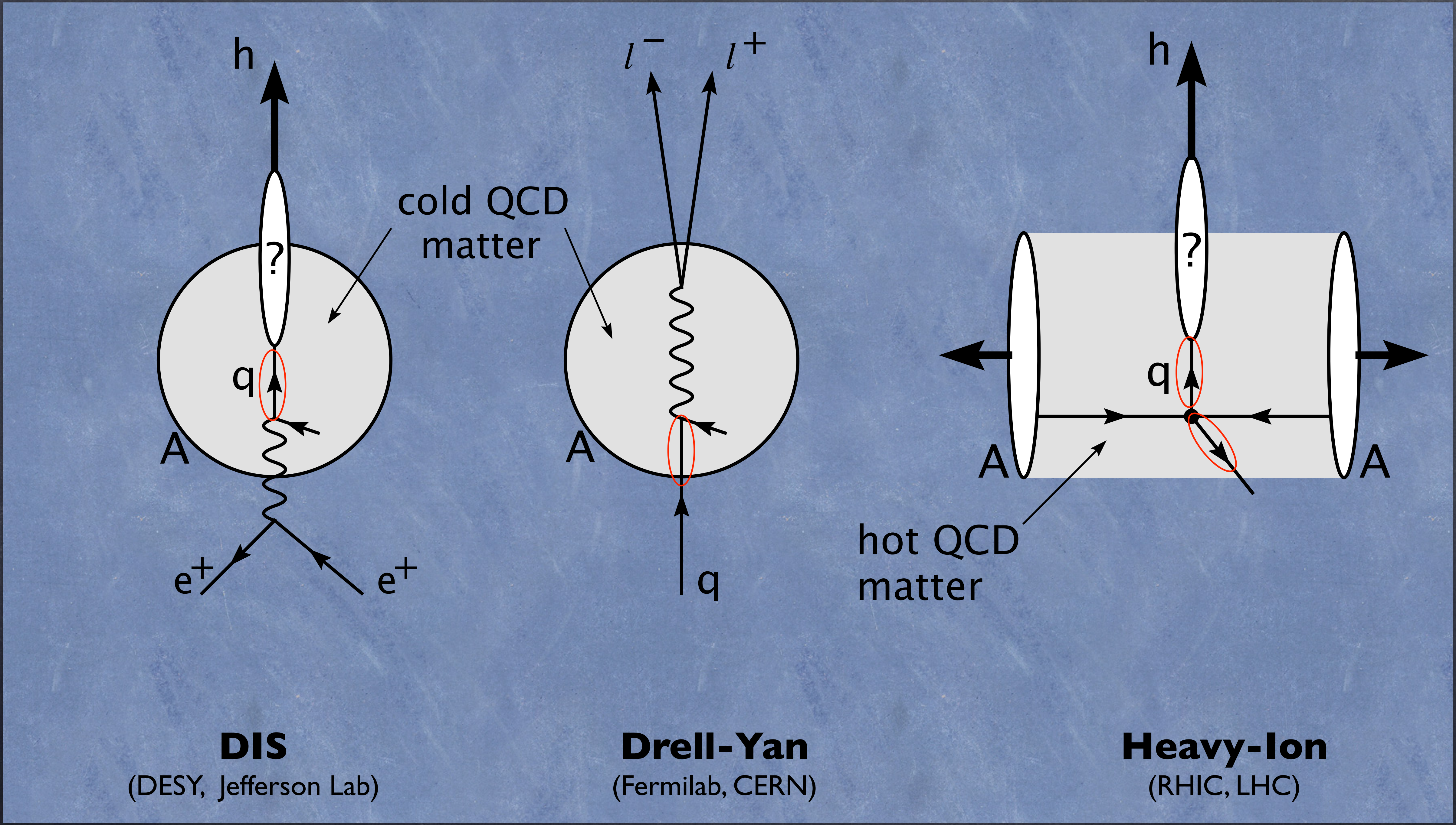
Short distances l<<1fm

q and g in QCD vacuum



Visualization of QCD from D.Leinweber

Color propagation in DIS, DY and HI



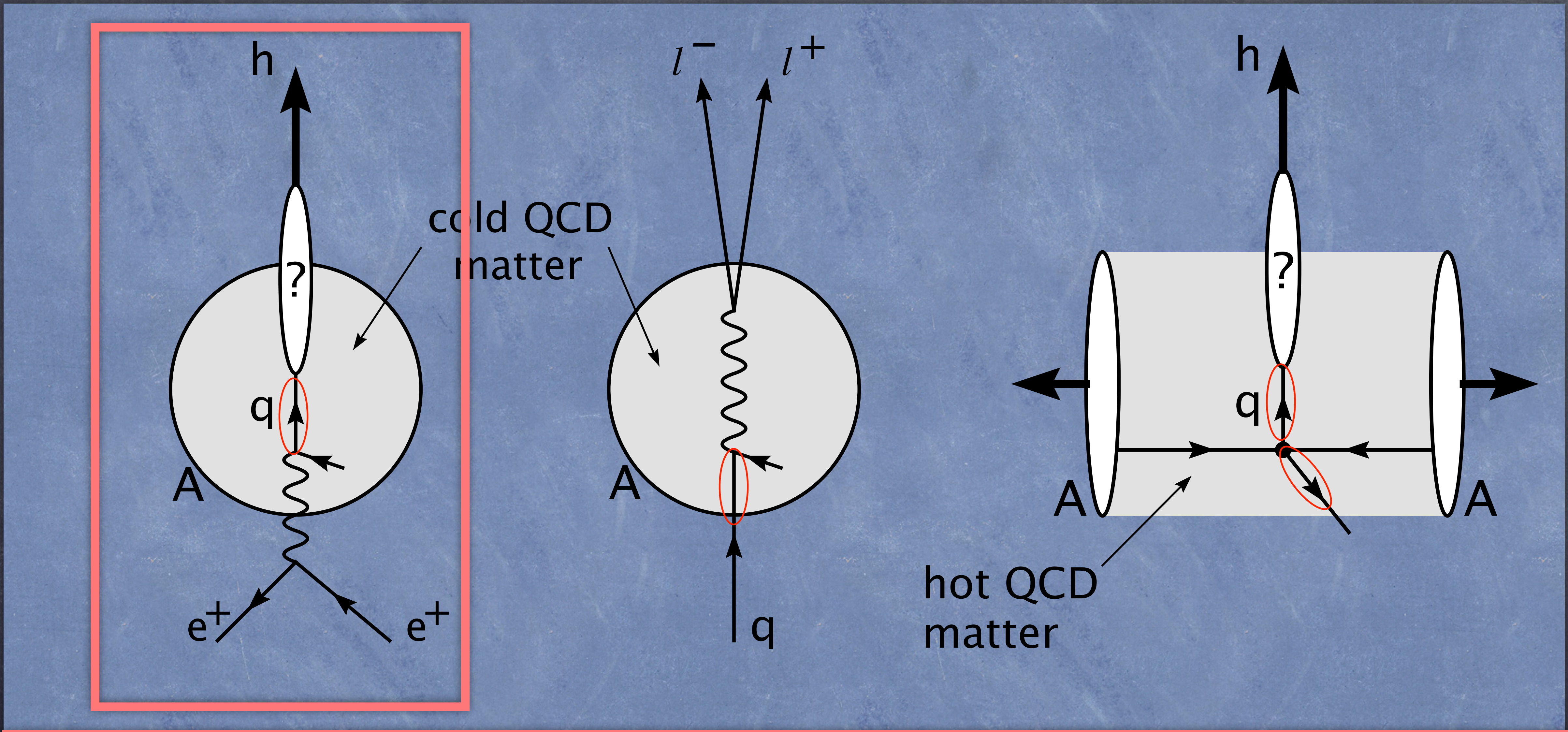
DIS
(DESY, Jefferson Lab)

Drell-Yan
(Fermilab, CERN)

Heavy-Ion
(RHIC, LHC)

Accardi, Arleo, Brooks, d'Enterria, Muccifora Riv.Nuovo Cim.032:439553,2010 [arXiv:0907.3534]

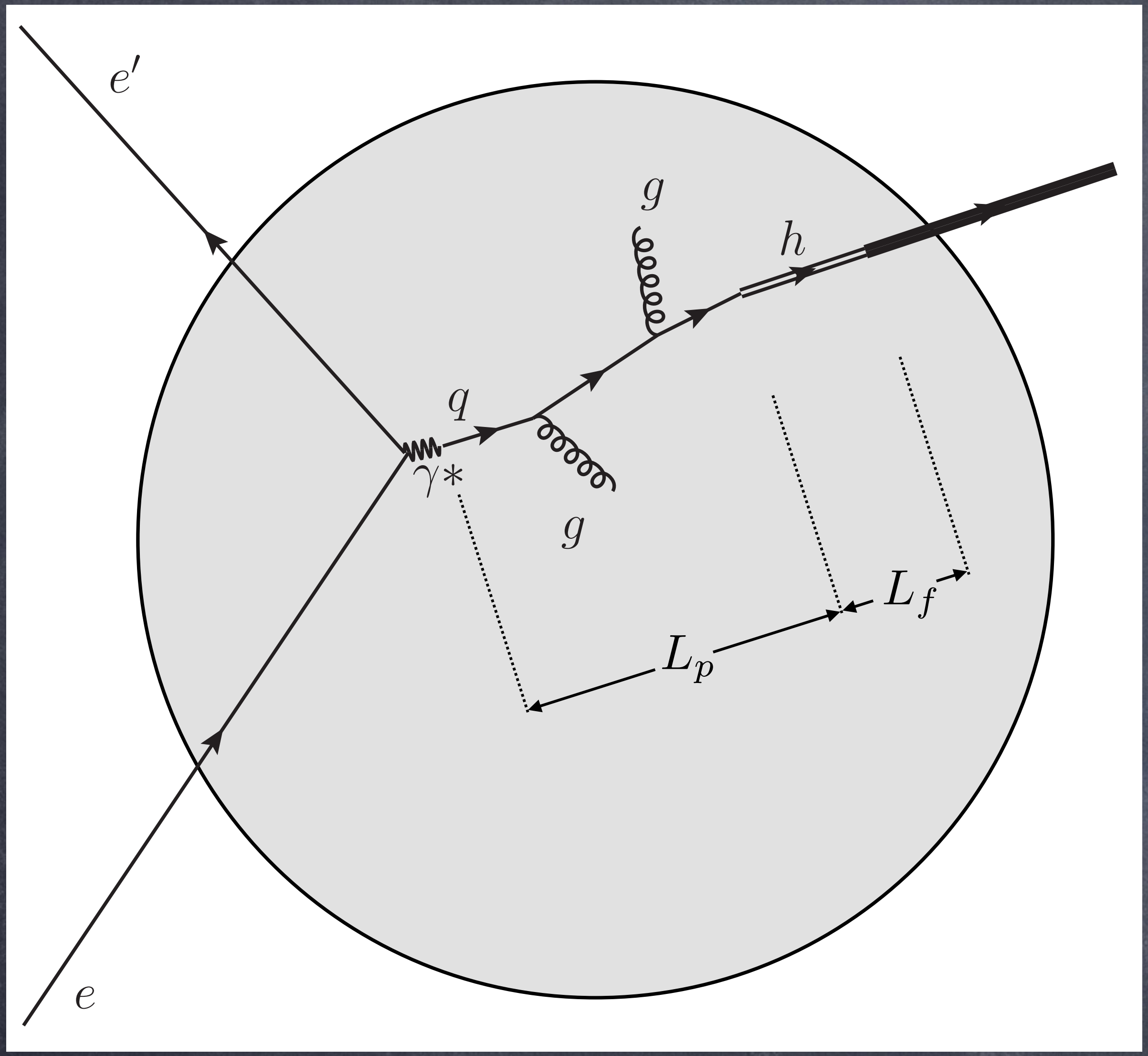
Color propagation in DIS, DY and HI



IN l+A NUCLEAR DIS WE LOOK DIRECTLY
AT QUARK STRUCTURE OF NUCLEI

Accardi, Arleo, Brooks, d'Enterria, Muccifora Riv.Nuovo Cim.032:439553,2010 [arXiv:0907.3534]

Space-time view of eA in DIS regime



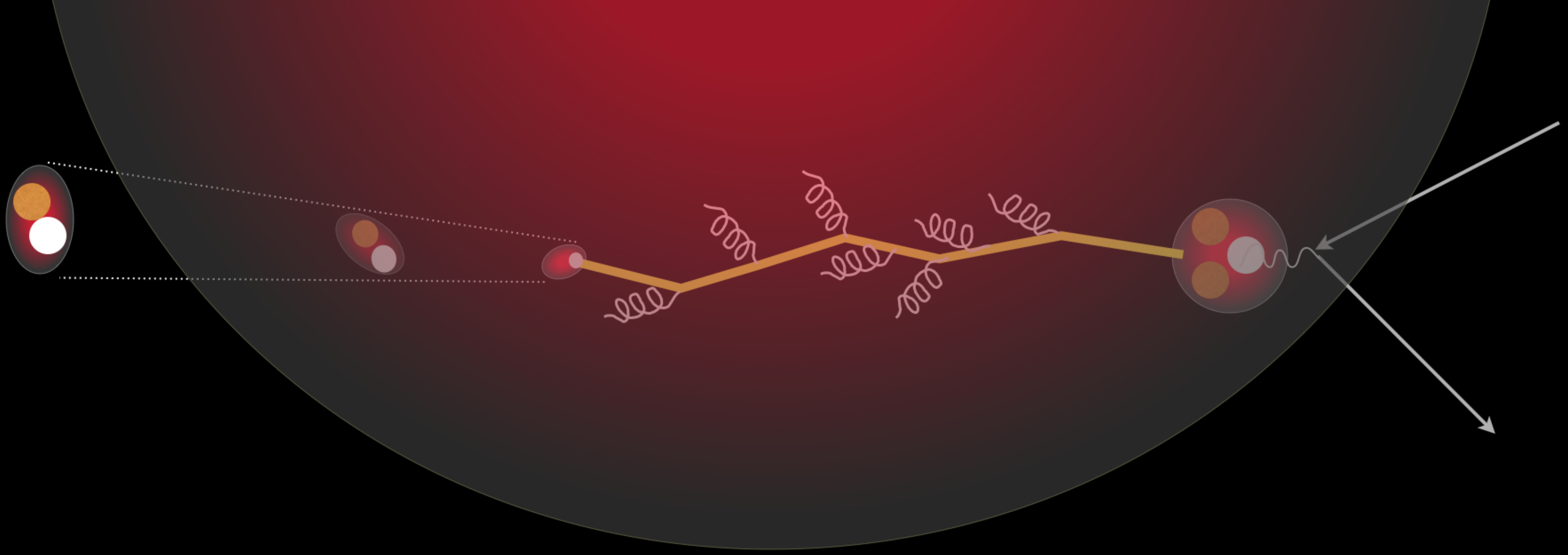
Fundamental QCD processes:

- Partonic elastic scattering
- Gluon bremsstrahlung, vacuum and medium
- Color neutralization
- Hadron formation
- Final State Interactions

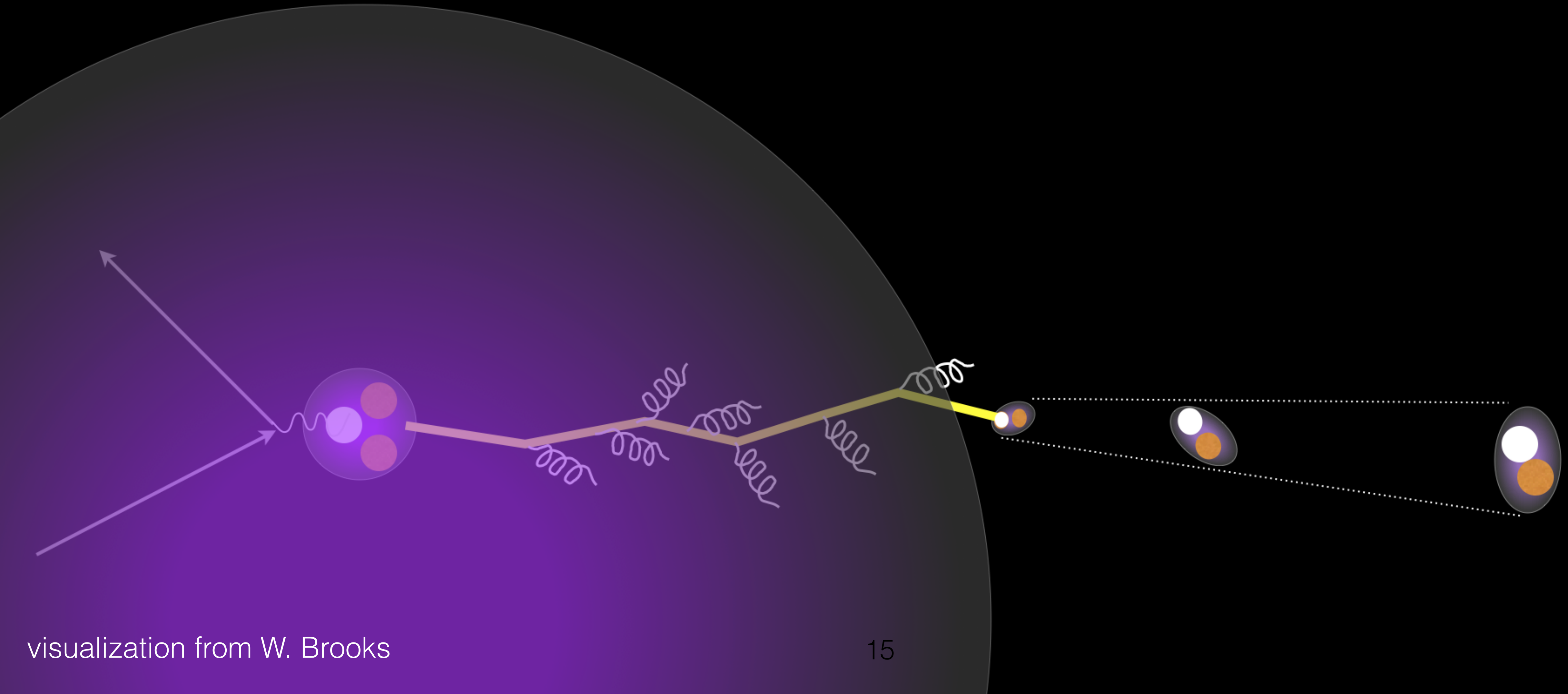
Production length L_p relates to 'color lifetime' of quark following hard collision; it is the length required for colored system to neutralize its color

Formation length L_f is a distance over which a color neutral object *pre-hadron* evolves into observed hadron

Methodology



e A : nuclei of increasing size act as space-time analyzer



visualization from W. Brooks

Observables & Measurements

Transverse Momentum Broadening

Connects to color lifetime **L_p** , quark k_T, transport coefficient **q**hat and quark energy losses

$$\Delta\langle p_{\mathrm{T}}^2\rangle = \langle p_{\mathrm{T}}^2\rangle_A - \langle p_{\mathrm{T}}^2\rangle_p$$

Hadronic Multiplicity Ratio

Connects to hadron formation phase **L_f**

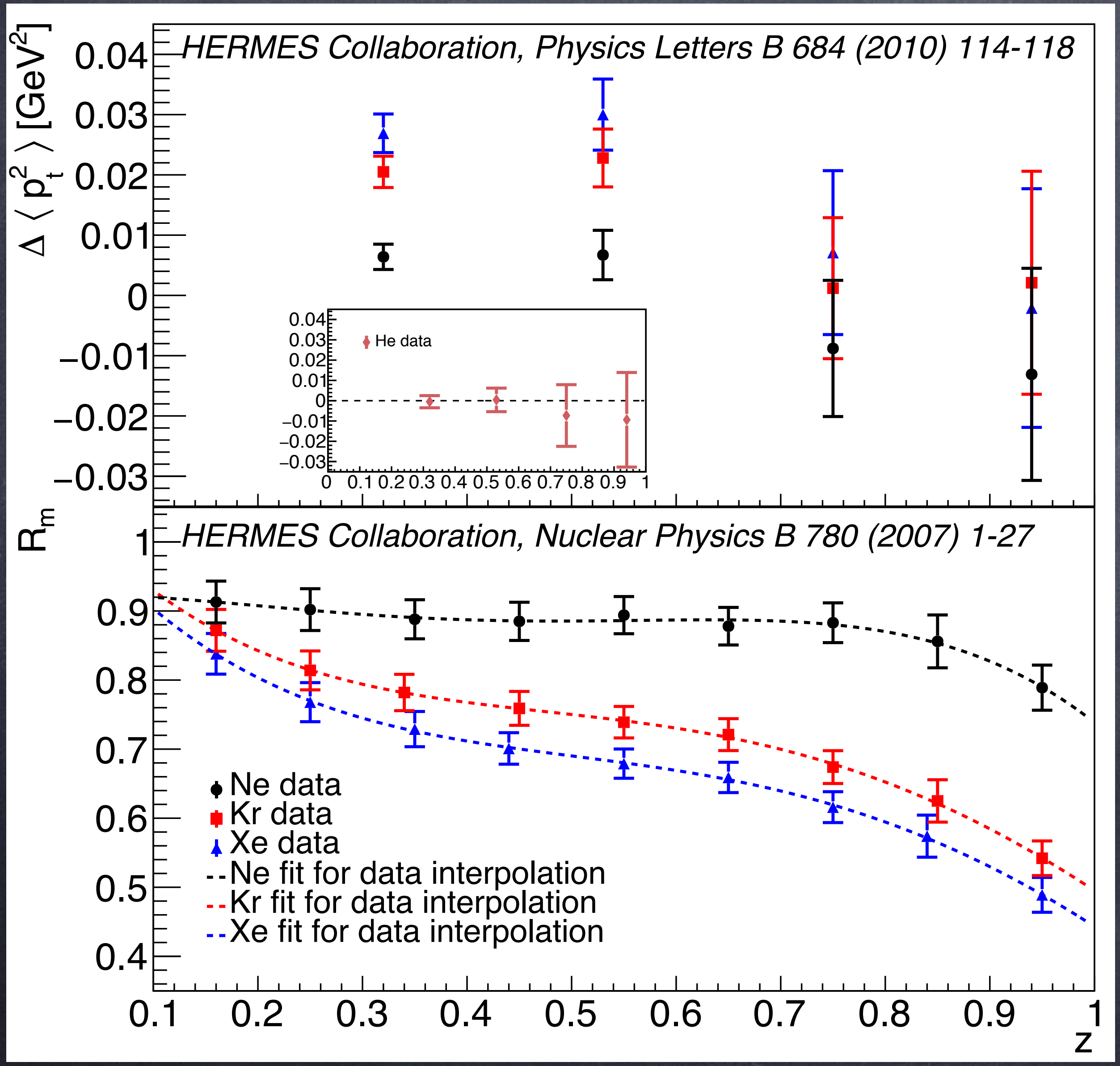
Particle yield N = σ *L* , where *L* is luminosity
For a double target system with same *L*,
Multiplicity Ratio is the ratio of cross sections

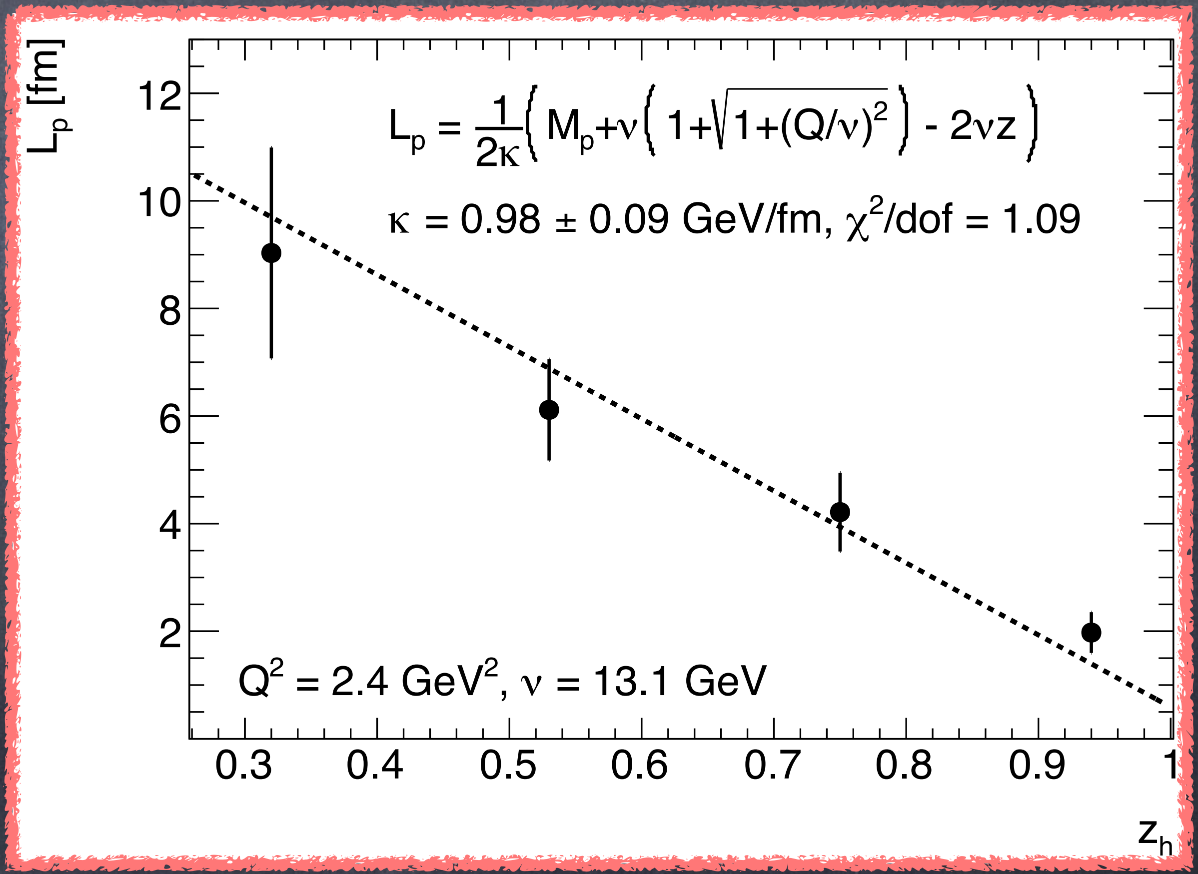
$$R_{\mathrm{A}}^h\left(\nu, Q^2, z, p_T\right) = \frac{\left.\frac{N_h(\nu,Q^2,z,p_T)}{N_e(\nu,Q^2)|_{\mathrm{DIS}}}\right|_{\mathrm{A}}}{\left.\frac{N_h(\nu,Q^2,z,p_T)}{N_e(\nu,Q^2)|_{\mathrm{DIS}}}\right|_{\mathrm{D}}}$$

In parton model, assuming factorization, Multiplicity Ratio is expressed in terms of the ratios of PDF and FF

Extraction of color lifetime: Brooks - Lopez model

First measurement of color lifetime **L_p** from based on simultaneous fits to HERMES data on ***pT broadening*** and ***hadron attenuation*** as a function of *z*





J.Lopez, W.Brooks DIS2018

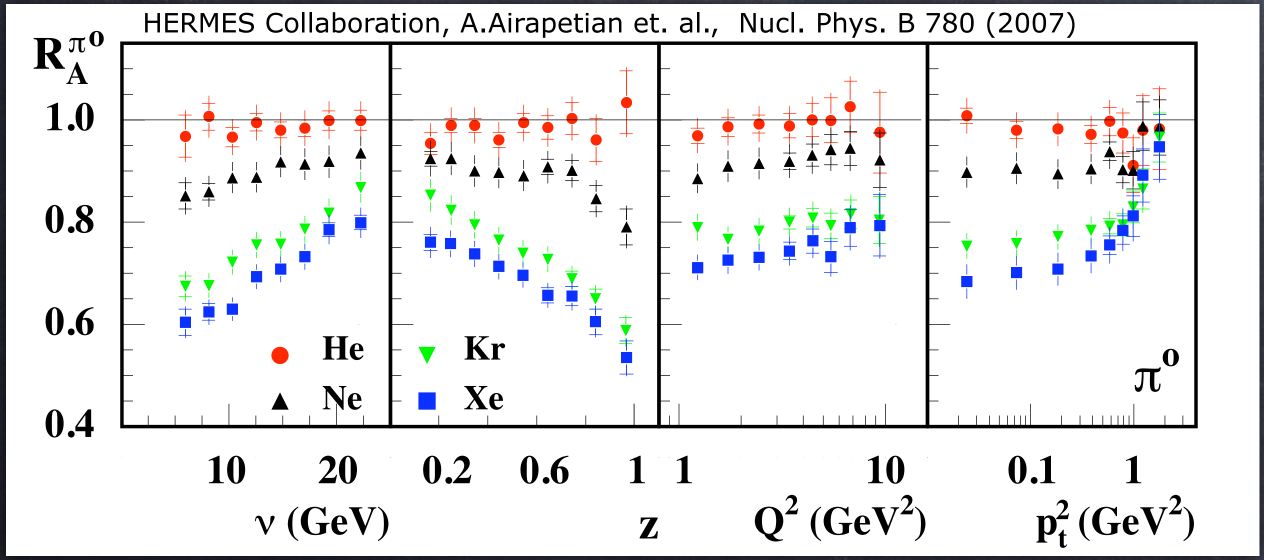
HERMES

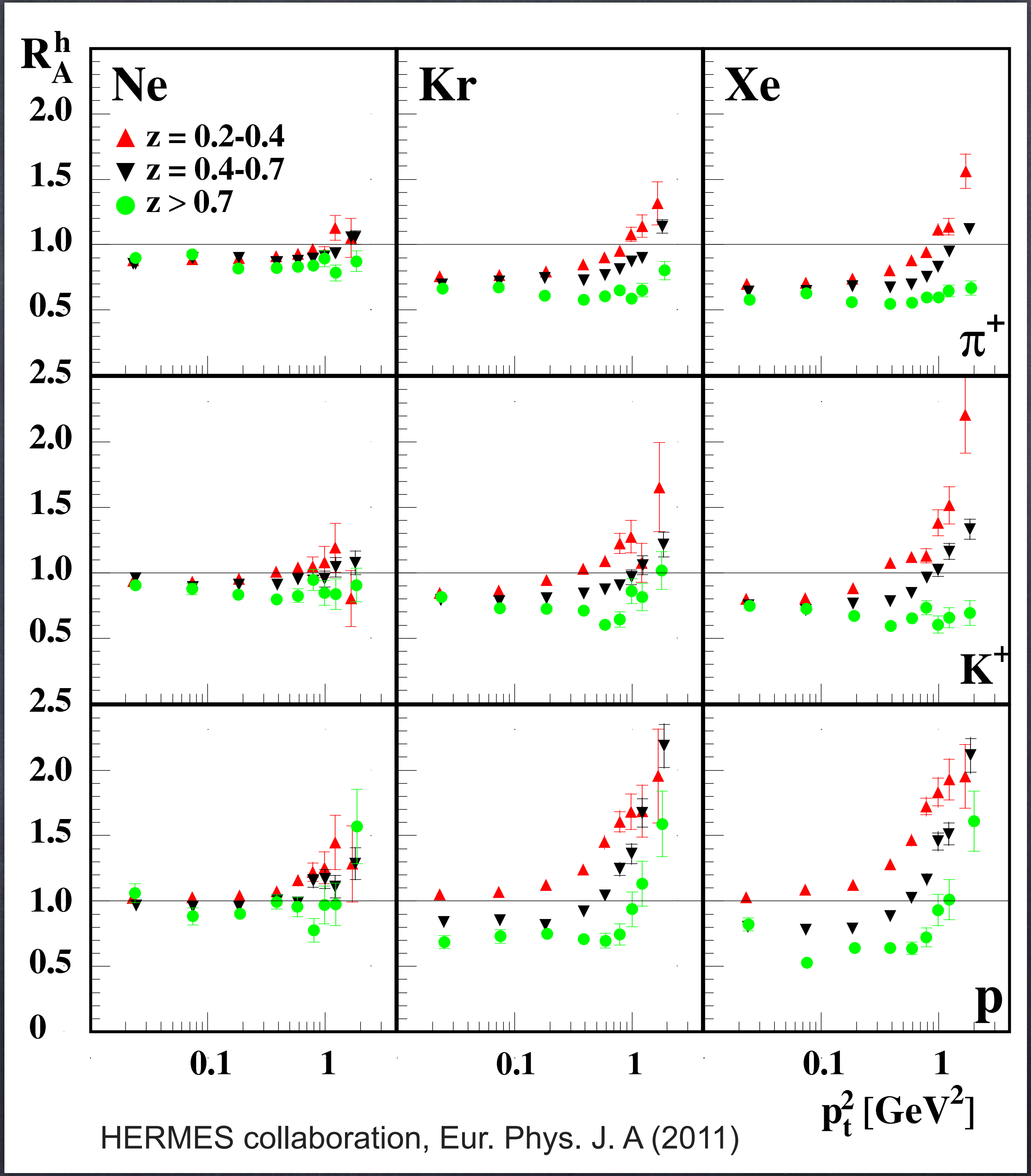
multiplicities $R(z, pT^2)$ integrated over ν, Q^2

Flavor separation: $\pi^{+/-}$*,* $K^{+/-}$ *and* $p/\bar{p}$

2D distributions for charged hadrons

1D extraction of multiplicities for π^0


HERMES Collaboration, A.Airapetian et. al., Nucl. Phys. B 780 (2007)


HERMES collaboration, Eur. Phys. J. A (2011)

HERMES

multiplicities R(z, *pT*²) integrated over ν, Q²

Flavor separation: $\pi^{+/-}$, $K^{+/-}$ and $p/\bar{p}$

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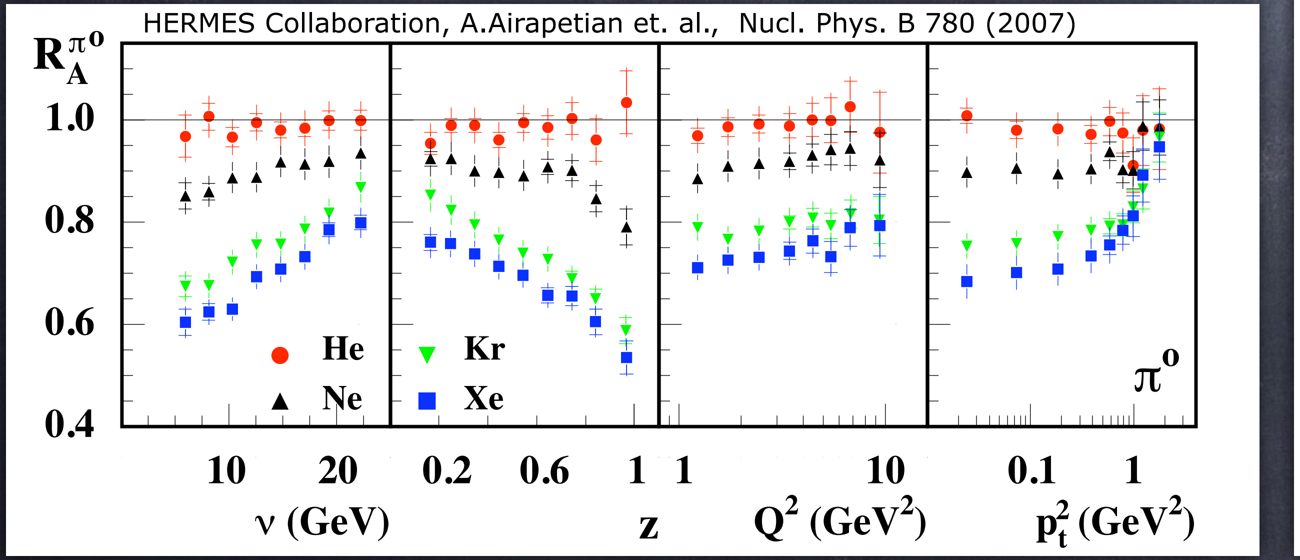
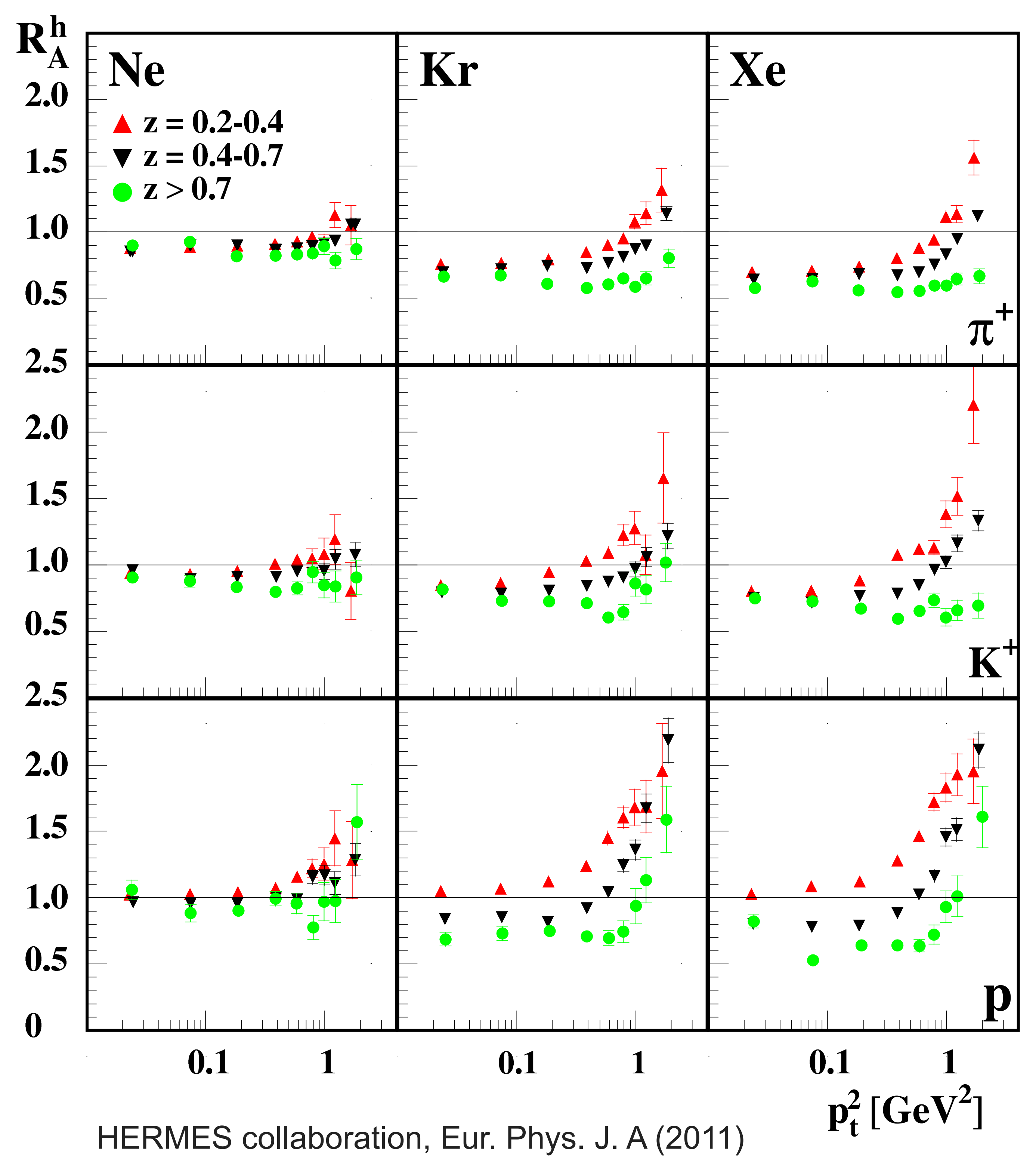

HERMES Collaboration, A.Airapetian et. al., Nucl. Phys. B 780 (2007)



HERMES collaboration, Eur. Phys. J. A (2011)

Need multidimensional data to distinguish between proposed mechanisms: pure quark energy loss vs pure absorption vs dipole approach!

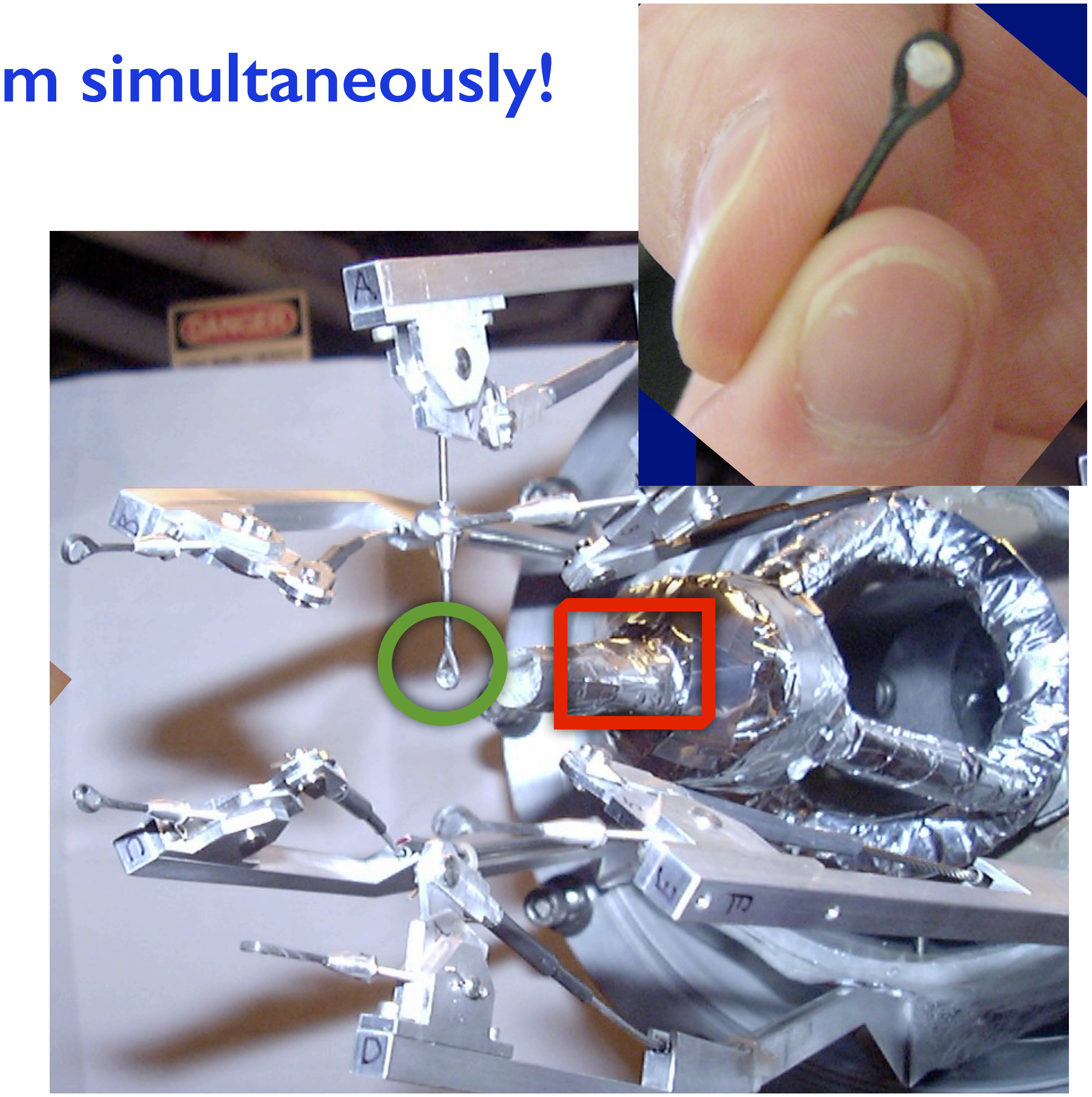
Experimental realization: CLAS at 5 GeV

EG2 experiment @ 5 GEV

Two targets in the beam simultaneously!

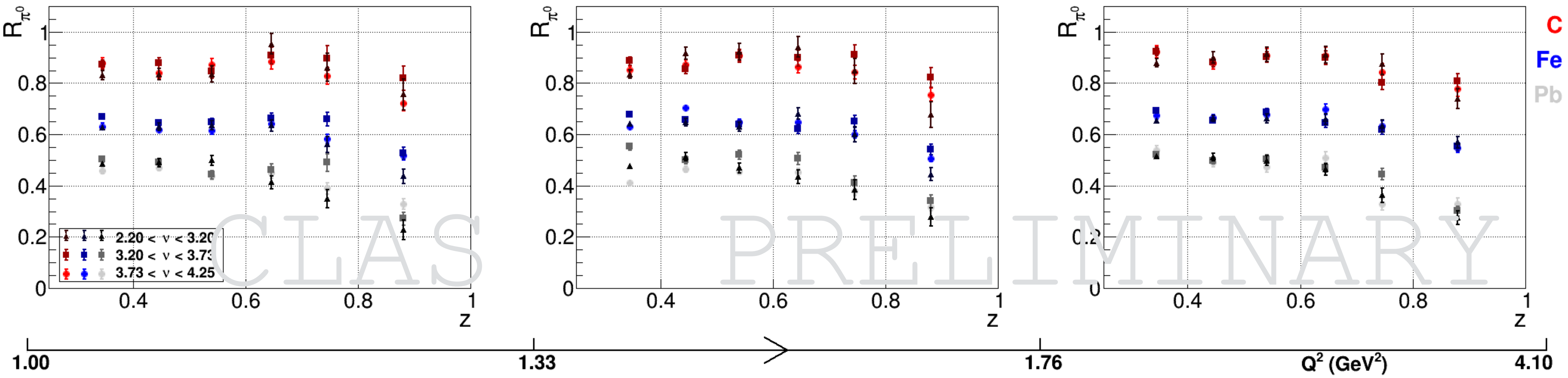
CLAS **EG2** experimental conditions:

- Electron beam 5.014 GeV
- Targets **^{2}H**, **^{12}C, ^{56}Fe, ^{207}Pb (Al, Sn)**
- ^{2}H separated from solid targets by 4cm
- Instant luminosity $2 \cdot 10^{34}\ 1/(s \cdot cm^{2})$



Multiplicity ratios: data from EG2

3D π^0 Multiplicities $R_{\pi 0}(Q^2, \nu, z)$ on ^{12}C, ^{56}Fe, ^{207}Pb to D



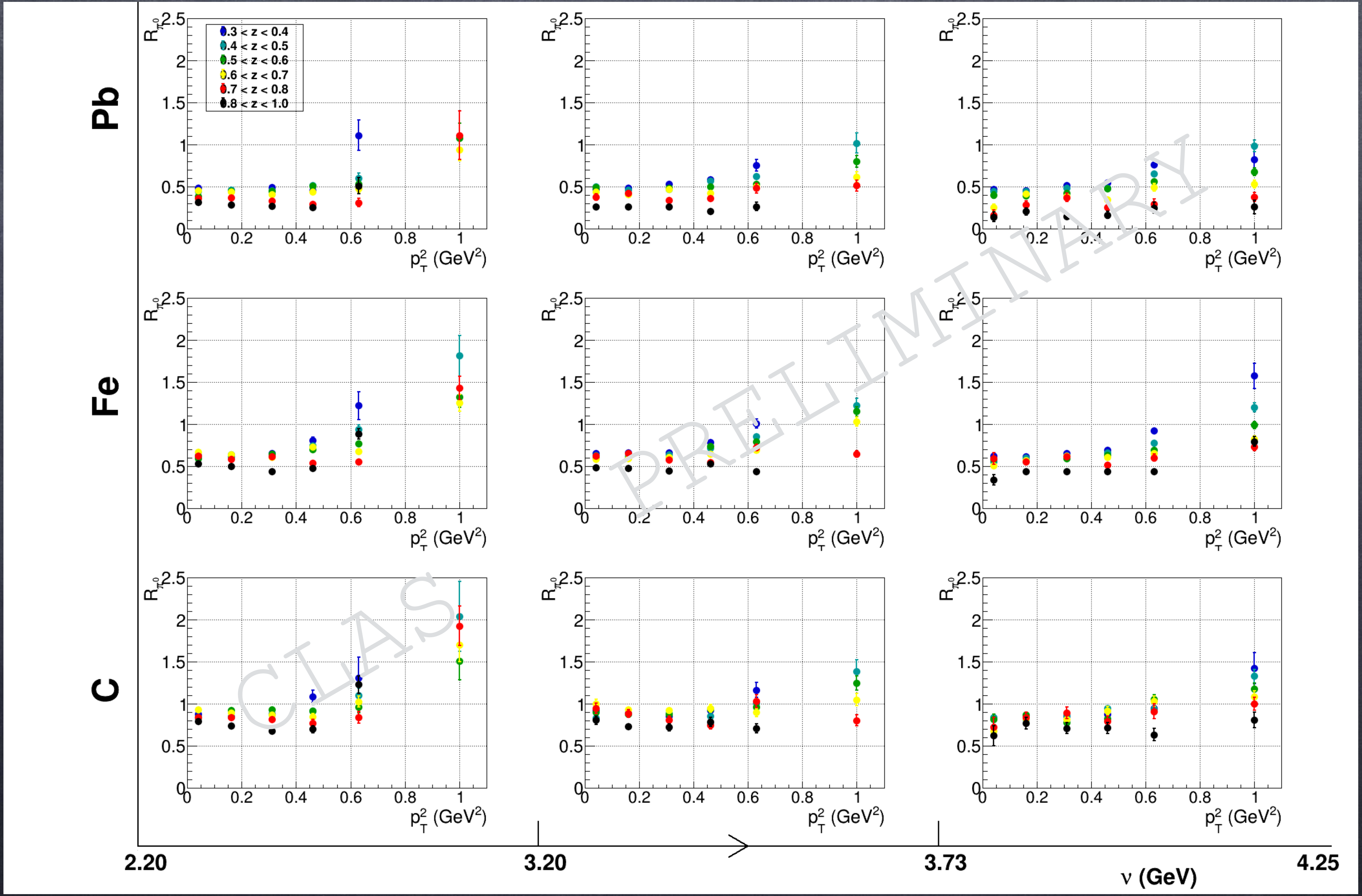
Results corrected for acceptance, RC and CC on e-. Average systematics does not exceed 6%.

- Attenuation depends on nuclear size
- Hadron attenuation at high z
- Quantitative behavior compatible with Hermes

Taisiya Mineeva
Analysis under review

Multiplicity ratios: data from EG2

3D π^0 Multiplicities $R_{\pi 0}(\nu, z, pT^2)$ on ^{12}C,^{56}Fe,^{207}Pb to D

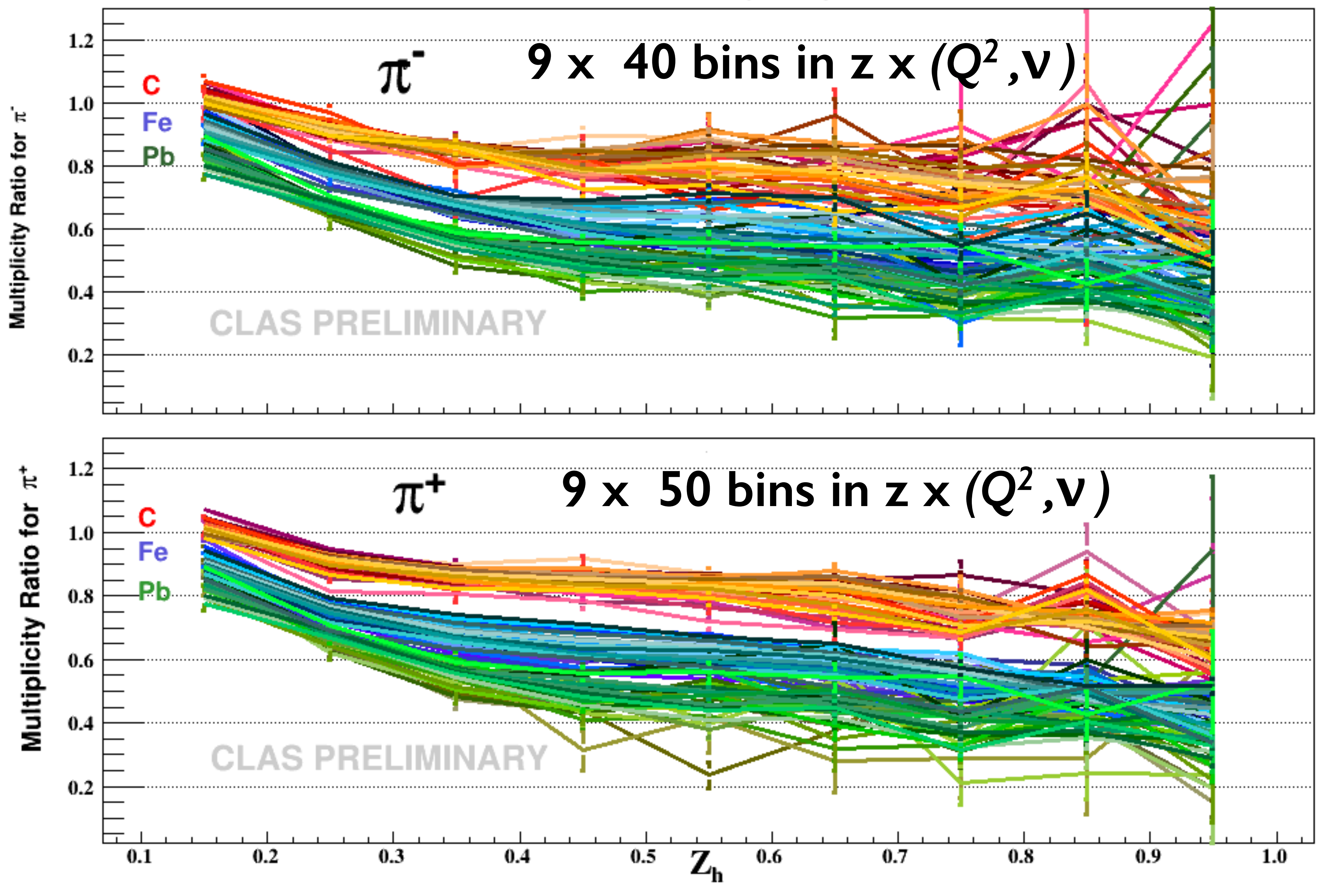


Results corrected for acceptance, RC and CC on e-. Average systematics does not exceed 7%.

Taisiya Mineeva
Analysis under review

Multiplicity ratios: data from EG2

3D π^+ and π^- Multiplicities R_π (Q^2, ν, z)



Results corrected for acceptance.

Hayk Hakobyan,
Sebastian Moran

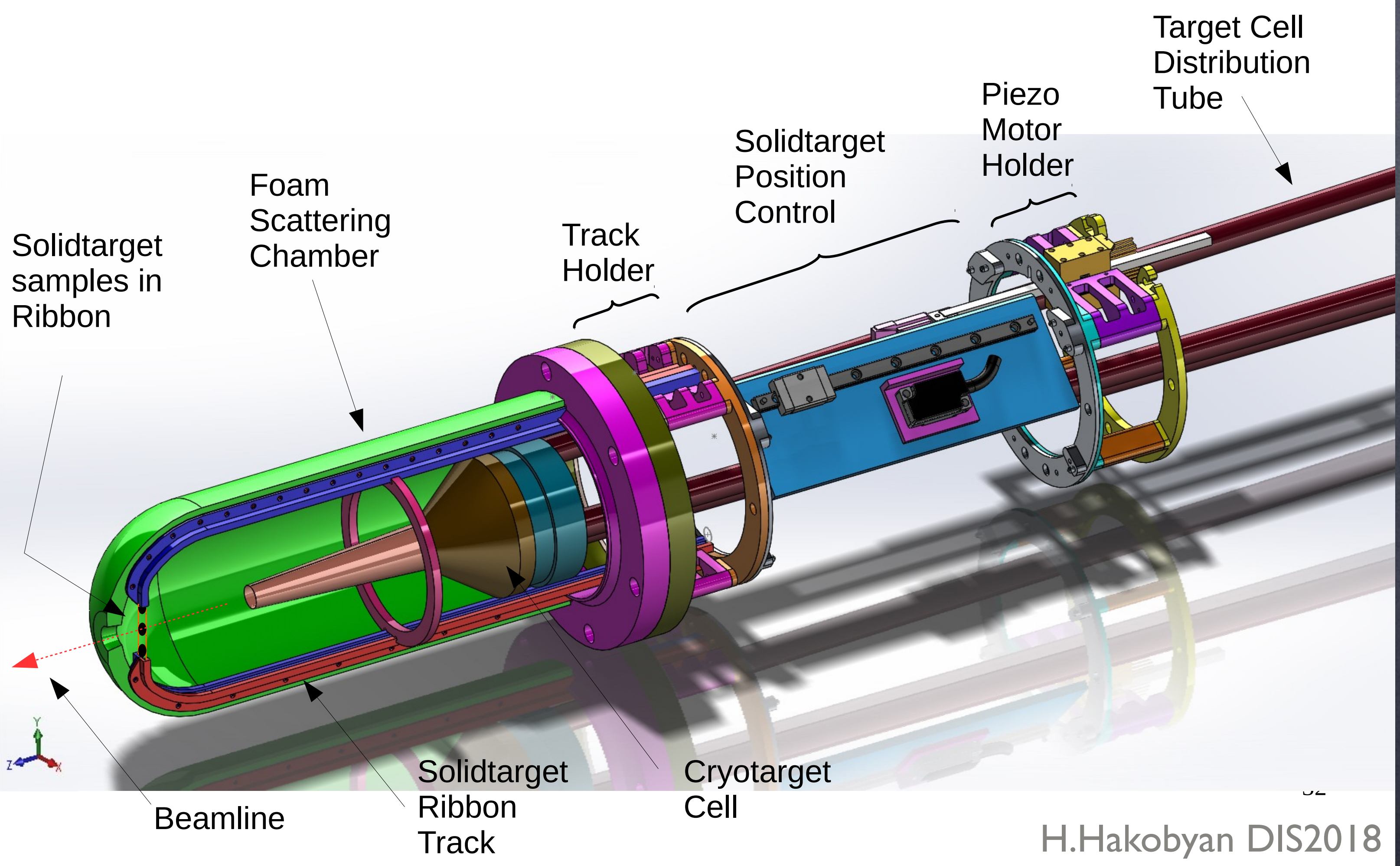
CLAS12
Approved experiment
E-12-06-117

Solid target assembly for CLAS12

New targets types will include: 4He, C, O, Ar, Pb and others. Unfortunately no Fe.

Extreme conditions @CLAS12

- High vacuum (6x10E-6 mbar)
- Magnetic field (5 Tesla)
- Cryotarget at 30 °K
- Radiation hardness
- Reduced space



H.Hakobyan DIS2018

DIS channels: *stable* hadrons, accessible with 11 GeV JLab future experiment PR12-06-117

🟩 currently accessible at CLAS 5 GeV data ○ measured by HERMES

meson	$c\tau$	mass, GeV	flavor content
π^0	25 nm	0.13	ud
π^+, π^-	7.8 m	0.14	ud
η	170 pm	0.55	uds
ω	23 fm	0.78	uds
η'	0.98 pm	0.96	uds
φ	44 fm	1	uds
f1	8 fm	1.3	uds
K^0	27 mm	0.5	ds
K^+, K^-	3.7 m	0.49	us

W. Brooks INT 2017

eA kinematics: past & near future

CLAS at 5 GeV $\sqrt{s}$ = 3.2 GeV

CLAS12 at 11 GeV $\sqrt{s}$ = 4.6 GeV *

HERMES at 27 GeV $\sqrt{s}$ = 7.2 GeV *

eA EIC projected kinematics

JLEIC $\sqrt{s}$ = 12-140 GeV

small x, large ν, large Q^2 reach

Note, available kinematical phase space at CLAS 12 vs HERMES is not that far apart due to y-cut

The Physics Program of an EIC

I) Map the spin and spatial structure of quarks and gluons in nucleons

Sea quark and gluon polarization
Transverse spatial distributions
Orbital motion of quarks/gluons
Parton correlations: beyond one-body densities

(show the nucleon structure picture of the day…)

Needs high luminosity and range of energies

II) Discover the collective effects of gluons in atomic nuclei

Color transparency: Small-size configurations
Nuclear gluons: EMC effect, shadowing
Strong color fields: Unitarity limit, saturation
Fluctuations: Diffraction

(without gluons there are no protons, no neutrons, no atomic nuclei)

III) Understand the emergence of hadronic matter from color charge

Materialization of color: **Fragmentation**, hadron breakup, color correlations
Parton propagation in matter: Radiation, energy loss

(how <u>does</u> $M = E/c^2$ work to create pions and nucleons?)

from Rolf Ent QNP2012

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from Rolf Ent QNP2012

Parton propagation studies in eA @ EIC

measurement of the saturation scale

access to quark energy loss

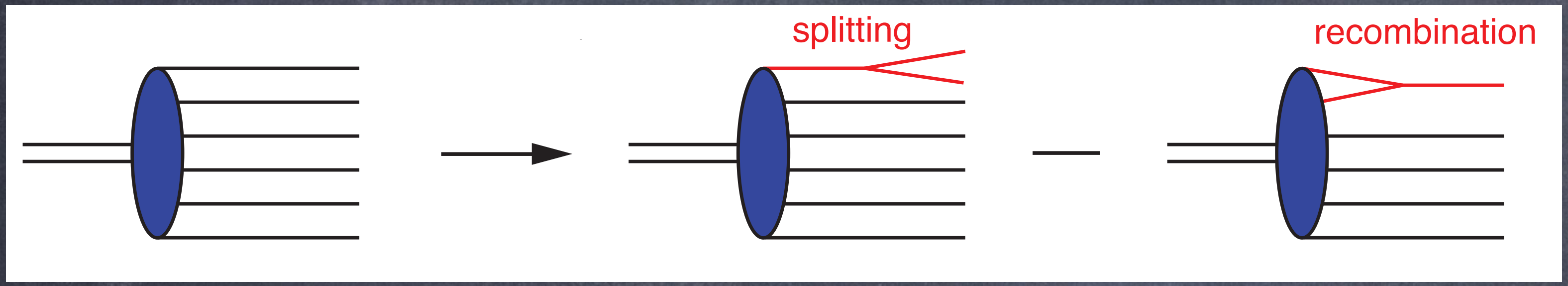
mechanisms of hadronization

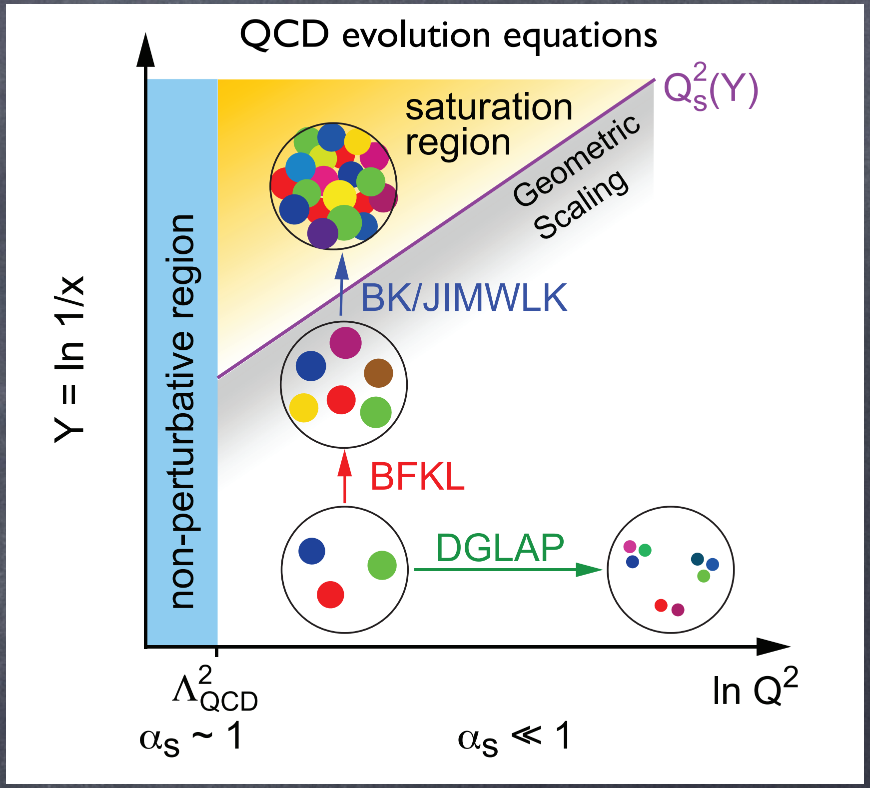
Saturation scale

Saturation scale

What is saturation?

- From HERA, RHIC and LHC data we know that the PDFs of sea quarks and gluons grow at low x
- No bound on number densities of q and g at low x; but, due to unitarity, non-linear recombination limits the density growth





Electron-Ion Collider: The next QCD frontier, A. Accardi et al, EPJ A (2016)

- *Saturation* of parton densities, particularly for gluons
- Color Glass Condensate - high energy effective theory describing universal properties of saturated gluons
- Gluon transverse momentum k_T characterizes degree to which saturation is occurring: $Q_s \sim k_T$

The CGC: F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan Ann.Rev.Nucl.Part.Sci.60:463-489,2010

Saturation scale

Unique window at the EIC

eA @ EIC can probe saturation scale at far lower energies than ep since saturation scale is enhanced by the nuclear diameter!

$$Q_s^2(x) \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

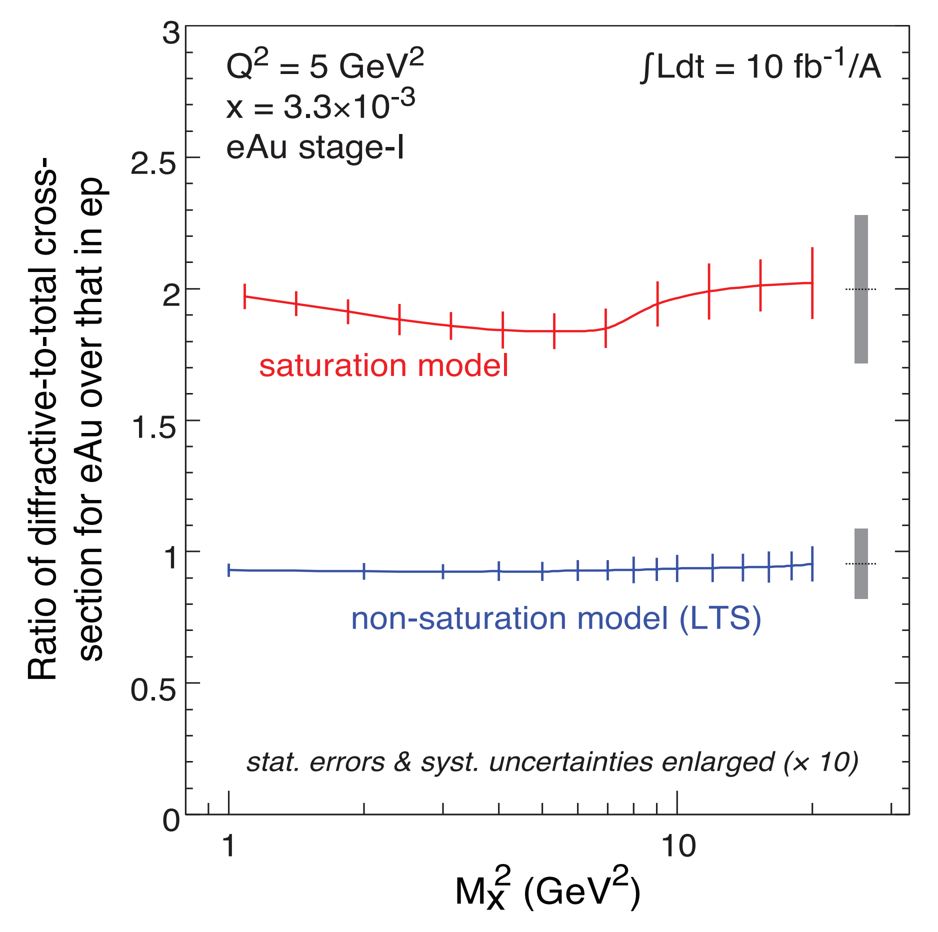
Saturation scale

How to access it experimentally?

Saturation scale

How to access it experimentally? (1)

Ratio of diffractive over total DIS events



Saturation scale

How to access it experimentally? (2)

Observable: transverse momentum broadening ΔpT

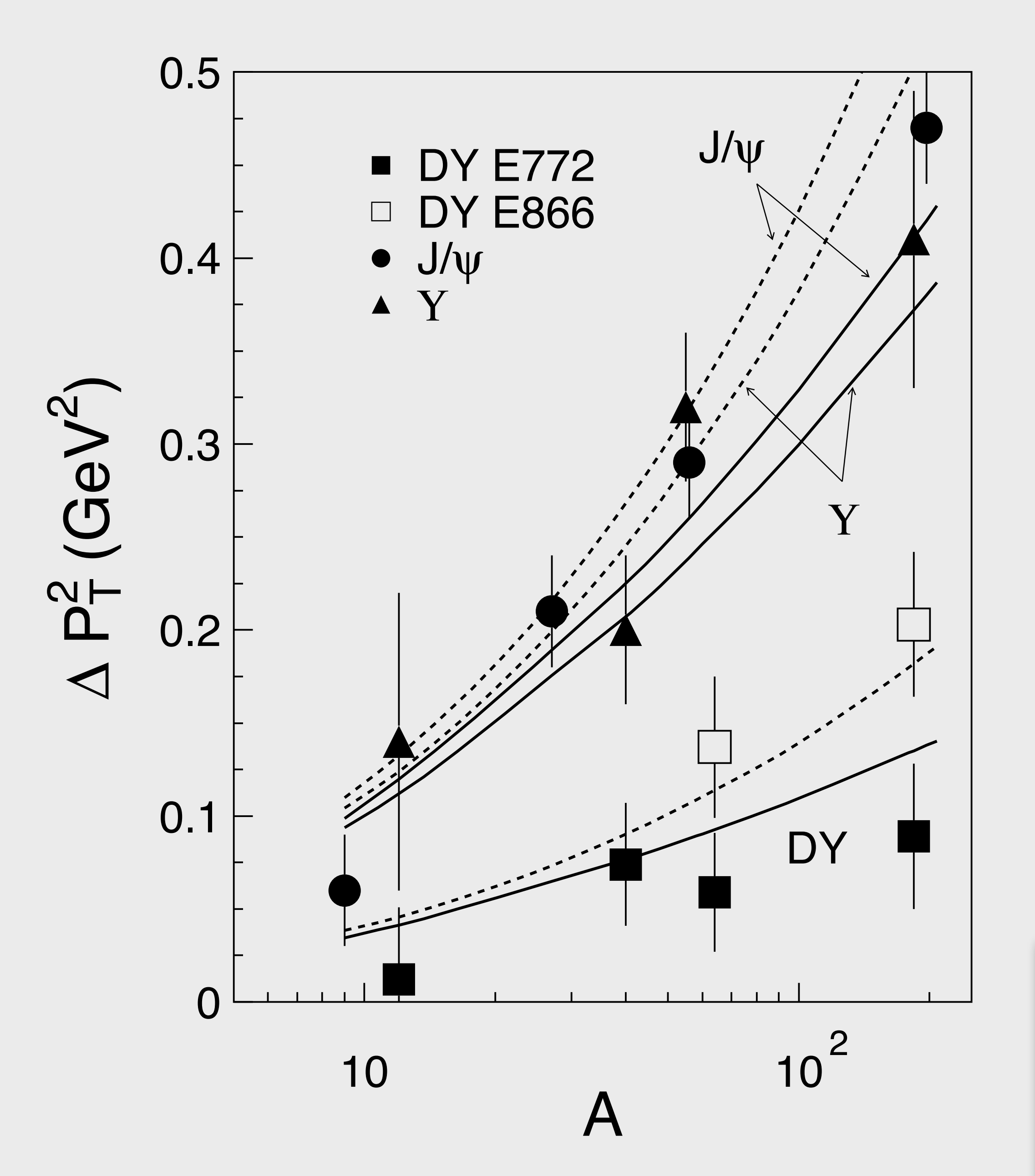
- pT broadening is a boost-invariant way of sampling the (transverse) gluon density distribution
- pT broadening is proportional to the gluon density

$$\Delta \mathrm{p}_{\mathrm{T}}^{2} \propto \mathrm{G}(\mathrm{x}, \mathrm{Q}^{2}) \rho \mathrm{L}$$

Saturation Scale

dipole model view of p_T broadening

B. Z. Kopeliovich, I. K. Potashnikova, Ivan Schmidt, arXiv:1001.4281v1 [hep-ph], Phys. Rev. C 81, 035204 (2010)



Final result: saturation momentum in infinite momentum frame found to be equal to p_T broadening in target rest frame:

$$Q^2_{sat}(b,E) = \Delta p^2_T(b,E)$$

from Will Brooks EIC meeting at CUA 2010

Saturation Scale

pQCD view of p_T broadening

Zuo-tang Liang, Xin-Nian Wang, Jian Zhou, arXiv:0801.0434v2 [hep-ph], Phys. Rev. D77:125010, 2008

Transverse Momentum Dependent (TMD) quark distribution function in nucleus:

$$f_q^A(x,\vec{k}_\perp) = \int \frac{dy^-}{2\pi}\frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - i\vec{k}_\perp\cdot\vec{y}_\perp}\langle A \mid \bar{\psi}(0,\vec{0}_\perp)\frac{\gamma^+}{2}\mathcal{L}_{\rm TMD}(0,y)\psi(y^-,\vec{y}_\perp) \mid A\rangle$$

$$\mathcal{L}_{\rm TMD}(0,y) \equiv \mathcal{L}_\parallel^\dagger(-\infty,0;\vec{0}_\perp)\mathcal{L}_\perp^\dagger(-\infty;\vec{y}_\perp,\vec{0}_\perp)\mathcal{L}_\parallel(-\infty,y^-;\vec{y}_\perp)$$

complete gauge link

$$\mathcal{L}_\perp(-\infty;\vec{y}_\perp,\vec{0}_\perp) \equiv P\exp\left[-ig\int_{\vec{0}_\perp}^{\vec{y}_\perp} d\vec{\xi}_\perp\cdot\vec{A}_\perp(-\infty,\vec{\xi}_\perp)\right]$$

$$\mathcal{L}_\parallel(-\infty,y^-;\vec{y}_\perp) \equiv P\exp\left[-ig\int_{y^-}^{-\infty} d\xi^- A_+(\xi^-,\vec{y}_\perp)\right]$$

transverse and longitudinal gauge links

$$\hat{q}_A(\xi_N,y_\perp^2) = \frac{4\pi^2\alpha_s C_A}{N_c^2-1}\rho_N^A(\xi_N)[xf_g^N(x,y_\perp^2)]_{x=0}$$

gluon transport parameter

$$Q_{\rm sat}^2(y_\perp^2) = \int d\xi_N^-\hat{q}_A(\xi_N,y_\perp^2) = \frac{4\pi^2\alpha_s C_A}{N_c^2-1}\int d\xi_N^-\rho_N^A(\xi_N)xf_g^N(x,y_\perp^2)$$

saturation scale

Various approximations, and last step invokes dipole model, see paper

from Will Brooks EIC meeting at CUA 2010

Quark energy loss

Energy loss in pQCD

General BDMPS version

- Vacuum energy losses are greater than medium-induced (cold matter)
- Energy losses due to gluon radiation are greater than collisional energy losses from parton elastic scattering (light particles)
- Energy loss is proportional to the gluon and parton density of the medium!!
- High importance in HI data; jet quenching is manifestation of quark energy loss

R. Baier, Y.L. Dokshitzer, A.H. Muller, D. Schiff, Nucl. Phys.B531 (1998)

R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff, Nucl. Phys. B484 (1997)

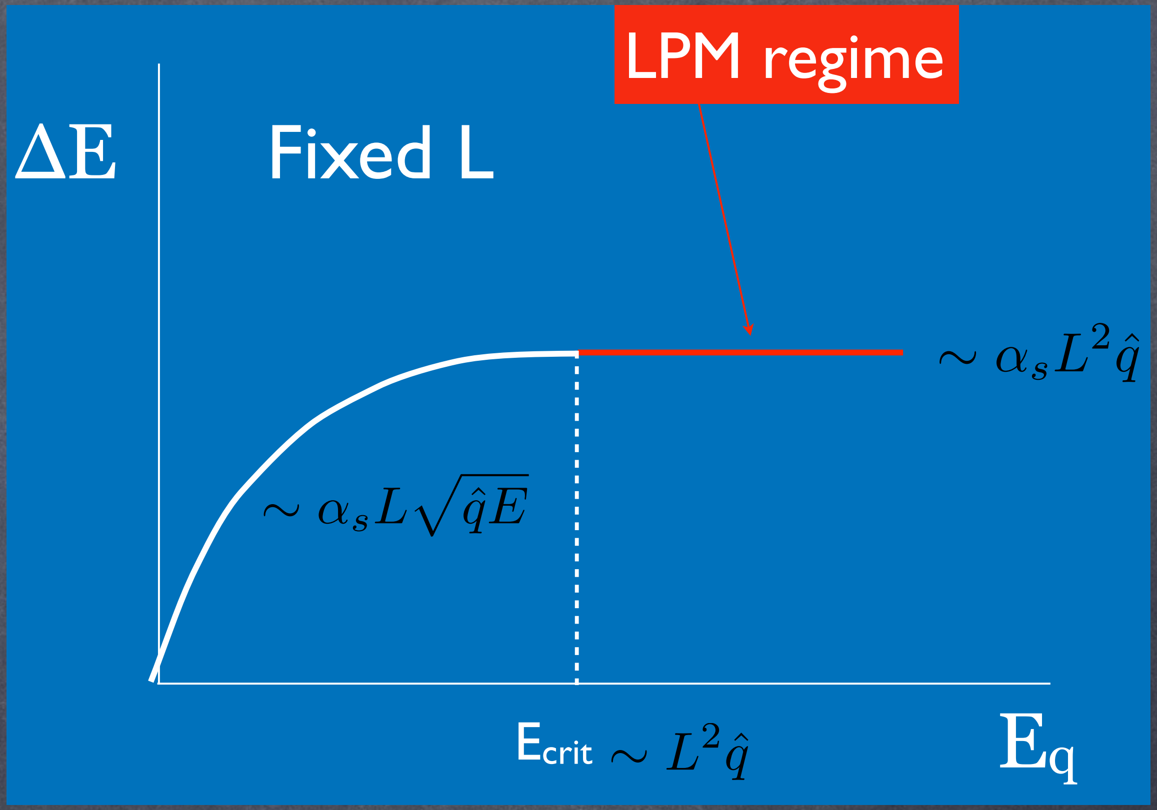
Energy loss in pQCD

(BDMPS version)

Partonic energy loss in pQCD depends on critical system length Lc and critical Ec

- Linear vs quadratic behavior in L
- LMP effect suppresses gluon bremsstrahlung

$$-\Delta E_q = \frac{\alpha_s}{4}\Delta k_T^2 \cdot L = \frac{\alpha_s}{4}\hat{q} \cdot L^2$$



HERMES data: qhat=0.075 GeV^2/fm
L_{Xe} = 4fm
Ecrit ~ 6GeV, and Ecrit << ν

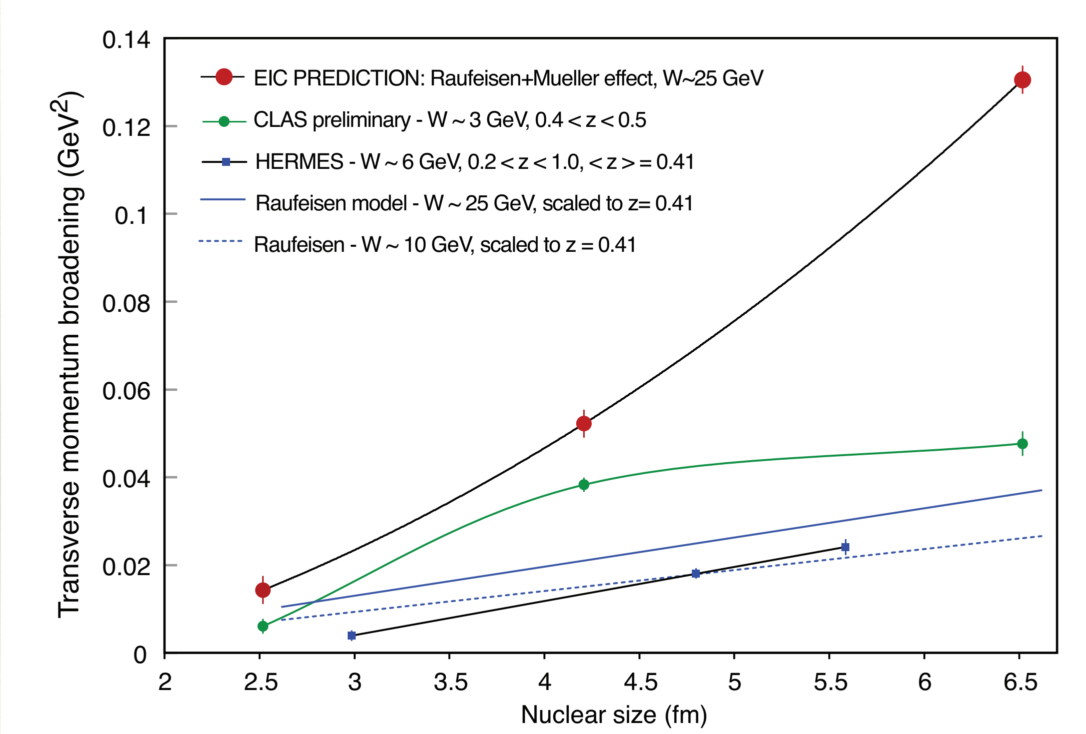
R. Baier, Y.L. Dokshitzer, A.H. Muller, D. Schiff, Nucl. Phys.B531 (1998)

R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff, Nucl. Phys. B484 (1997)

Quark energy loss at EIC

- Can be inferred *indirectly* via measurement of pT broadening and extracted from pQCD theory

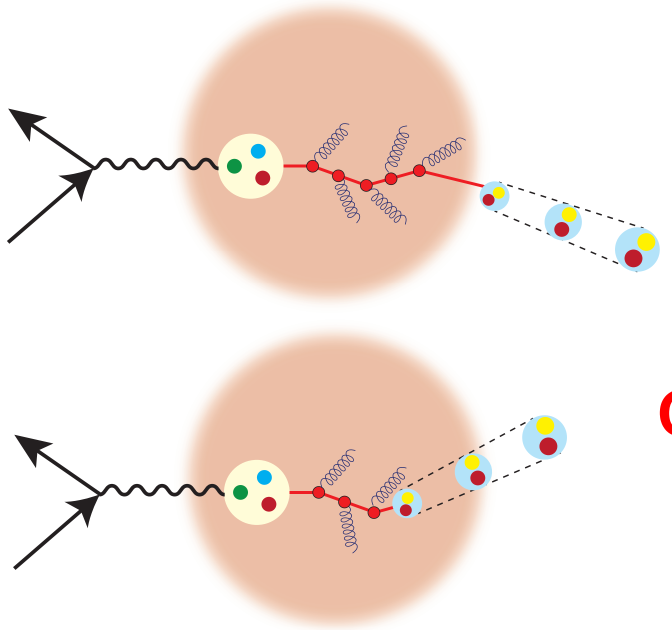
pQCD description of quark energy loss on p_T broadening



Mechanisms of hadronization

Emergence of Hadrons from quarks & gluons

- ❑ **Femtometer sized detector:**

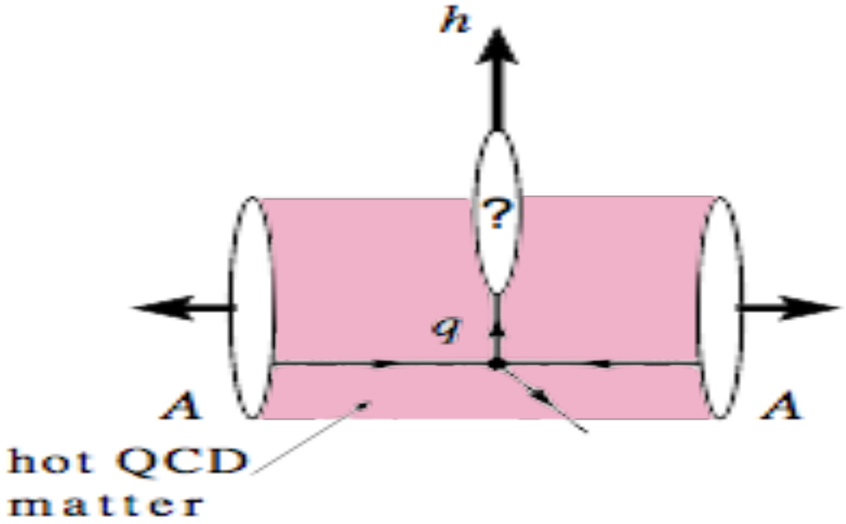


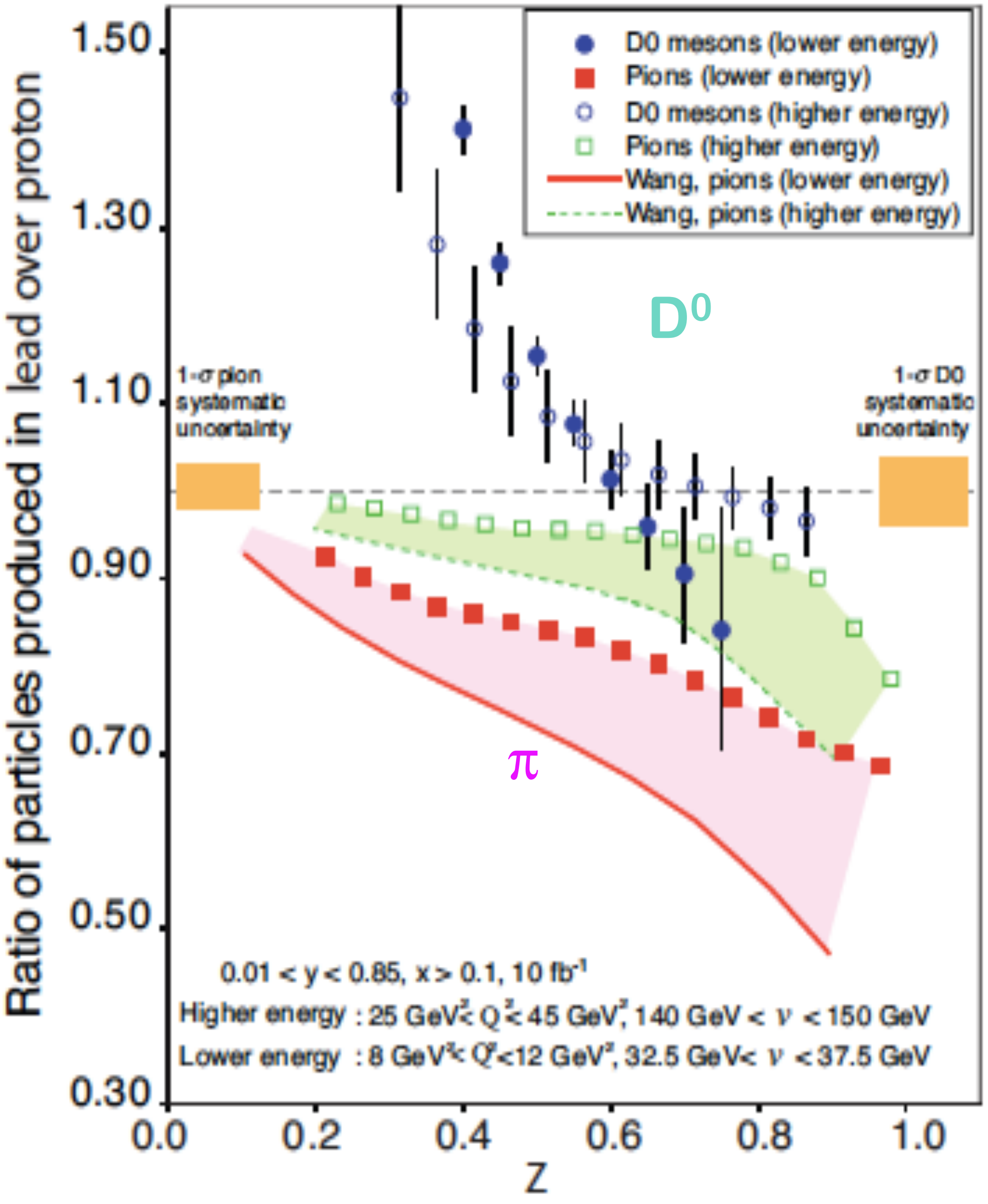
$$\nu = \frac{Q^2}{2mx}$$

Control of ν and medium length!

Mass dependence of hadronization

- ❑ **Apply to heavy-ion collisions:**





Need the collider energy of EIC and its control on parton kinematics

from Jianwei Qui DIS2018

Extrapolation of Lp from HERMES to EIC

Using the prescription $\gamma = \nu/Q$, $\beta = p_{\gamma^*}/\nu$, we can extrapolate:

Q2	nu	beta*gamma	lp, z=0.32	lp, z=0.53	lp, z=0.75	lp, z=0.94	Experiment	x
2.40	14.50	9.31	8.57				HERMES	0.09
2.40	13.10	8.40		6.39			HERMES	0.10
2.40	12.40	7.94			4.63		HERMES	0.10
2.30	10.80	7.05				2.40	HERMES	0.11
3.00	4.00	2.08	1.92	1.58	1.21	0.71	CLAS	0.40
7.00	7.00	2.45	2.26	1.86	1.43	0.83	CLAS12	0.53
1.00	4.00	3.87	3.57	2.95	2.26	1.32	CLAS	0.13
2.00	9.00	6.28	5.79	4.78	3.66	2.14	CLAS12	0.12
12.00	32.50	9.33	8.59	7.10	5.44	3.18	EIC	0.20
8.00	37.50	13.22	12.17	10.06	7.71	4.50	EIC	0.11
45.00	140.00	20.85	19.20	15.86	12.15	7.10	EIC	0.17
27.00	150.00	28.85	26.57	21.96	16.82	9.82	EIC	0.10

W. Brooks INT 2017

At the EIC we can study a wide range of production lengths!

Conclusion

Measurements that color propagation physics can access in EIC:

- **pT broadening observables**
  - saturation scale !!
  - pQCD energy loss
  - effective quark lifetime
  - transport coefficient
- **Multiplicity ratio observable**
  - hadronization mechanisms
  - hadron formation length

+ azimuthal φ-modulation of produced hadrons

Conclusion

Measurements that color propagation physics can access in EIC:

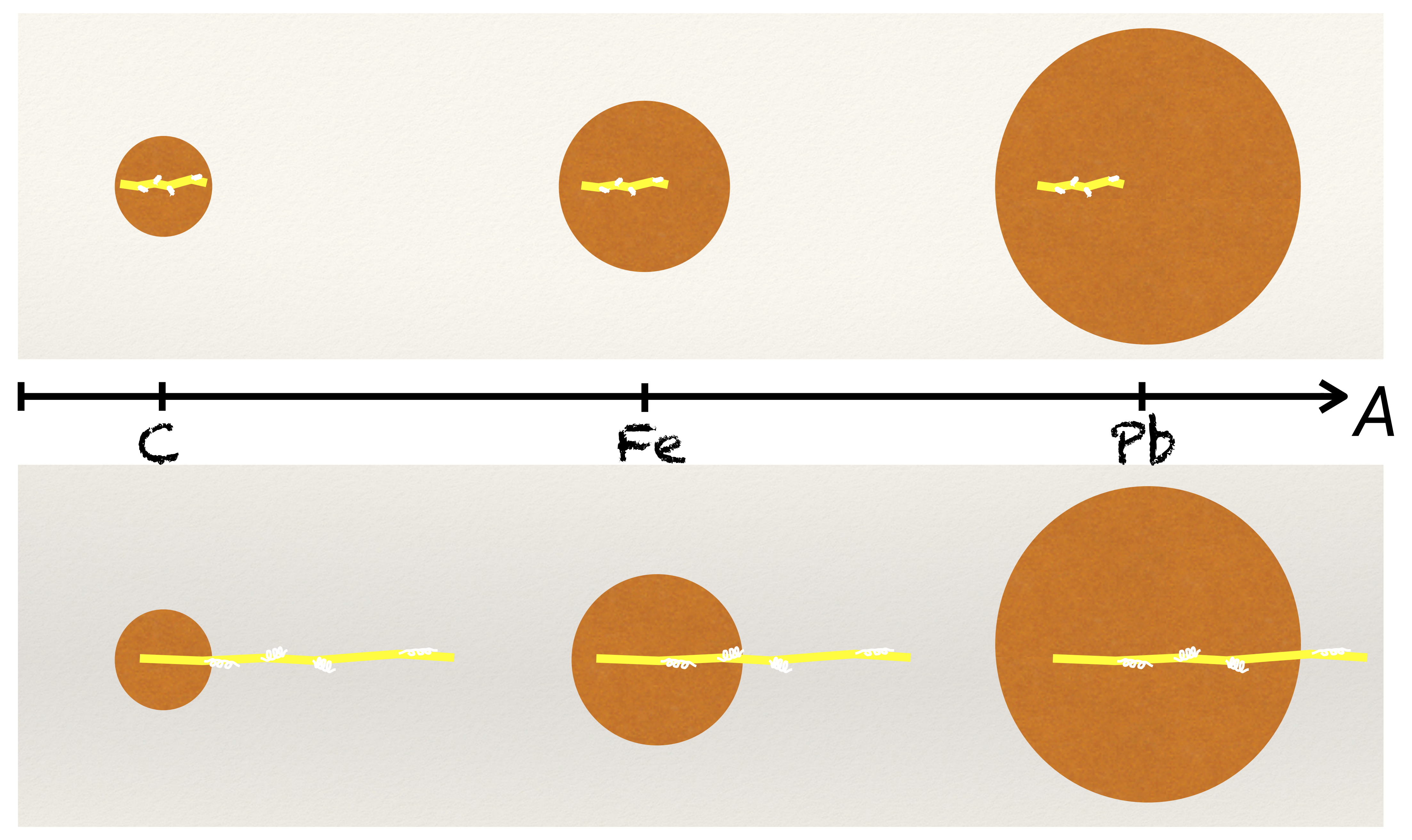
EIC can access all of this physics!

- **pT broadening observables**
  - saturation scale !!
  - pQCD energy loss
  - effective quark lifetime
  - transport coefficient
- **Multiplicity ratio observable**
  - hadronization mechanisms
  - hadron formation length

+ azimuthal φ-modulation of produced hadrons

Additional slides

Measurements of ***pT broadening*** and ***hadron attenuation*** ratios as a function of *nuclear size* ***A*** allow to calculate the length of color propagation and hadron formation processes at the femtometer scale



Back-of-the envelope τ_p

Energy conservation: if hadron carried away energy $E_h = z\nu$, string only has $\nu - E_h$

$$t_p = \frac{\nu}{\left.\frac{dE}{dx}\right|_{vacuum}}(1 - z_h)$$

If take, e.g., $z = E_h/\nu = 0.6$, $\nu = 5$ GeV, then

$\tau_p \sim 2$ fm/c

$$\left.\frac{dE}{dx}\right|_{vacuum} \approx \kappa \approx 1 \quad GeV / fm$$

Back-of-the envelope τ_f

Given hadron of size R_h, can build color field of hadron in its rest frame in time no less than $t_0 \sim R_h/c$. In lab frame this is boosted.

$$t_f \geq \frac{E}{m} R_h$$

If take, e.g., the pion mass, radius 0.66 fm, E = 4 GeV, then **$\tau_f \sim 20$ fm/c**

Comparison of CLAS and HERMES e+A

- Beam energy: 5.0 GeV at JLab vs 27.6 GeV at DESY

- Solid target in CLAS vs gas targets in HERMES

  Heaviest target ^{207}Pb in CLAS vs ^{131}Xe in HERMES

-Luminosity in CLAS is 100 times greater than HERMES

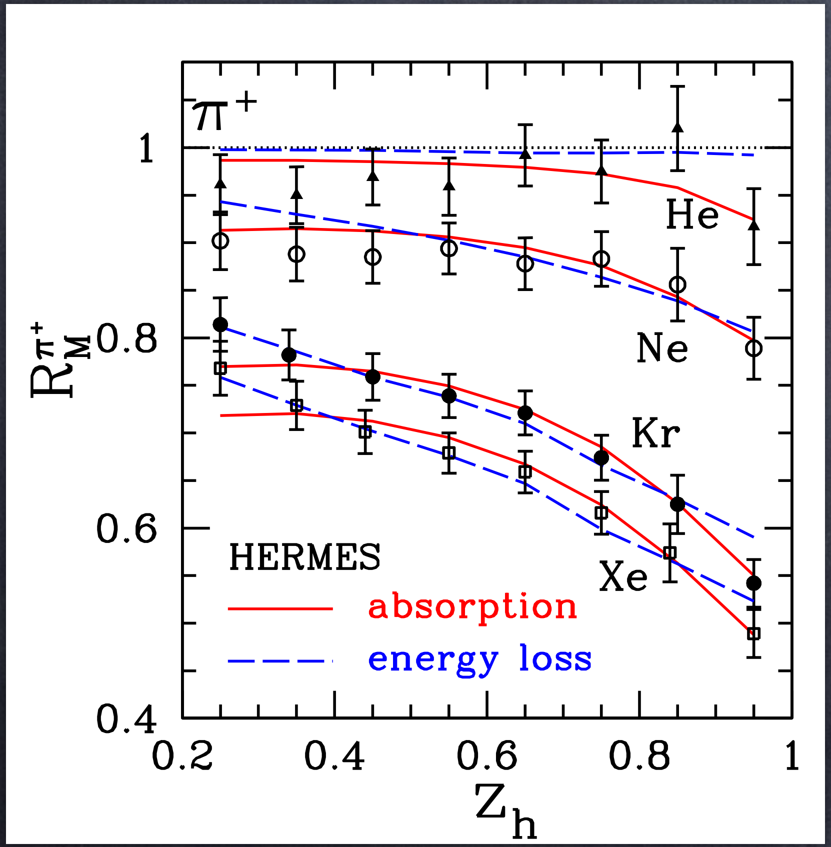
  Access to 3D binning in CLAS vs 1-2D binning in HERMES .

	ν (GeV)	Q^2 (GeV^2)	z	pT^2 (GeV^2)
CLAS	2.2 - 4.2	1.0 - 4.1	0,3 - 1,0	0 - 1.5
HERMES	7 - 23	1.0 - 10	0.2 - 1.0	0 - 1.1

Quark energy loss or Hadron absorption?

- Pure quark energy loss models: *a la* BDMPS (Arleo; Accardi)
  Higher twist FF (Wang; Majumder)

- Pure hadron absorption models: prehadron survival from transport model (Accardi)
  GiBUU transport Monte Carlo (Falter)



Accardi, Arleo, Brooks, d'Enterria, Muccifora
Riv.Nuovo Cim.032:439553,2010 [arXiv:0907.3534]

Both pure quark energy loss and pure hadron absorption models describe attenuation R^h as a fnc of z for HERMES

Modern Lund string model: abs. or en. loss (A.Accardi)

$$\frac{1}{N_A^{DIS}}\frac{dN_A^h(z)}{dz} = \frac{1}{\sigma_{\ell A}}\int_{\text{exp. cuts}} dx\,d\nu \sum_f e_f^2\, q_f(x,Q^2)\frac{d\sigma_{\ell f}}{dx\,d\nu} S^A_{f,h}(z,\nu) D_f^h(z,Q^2)\,.$$

Quark energy loss or Hadron absorption?

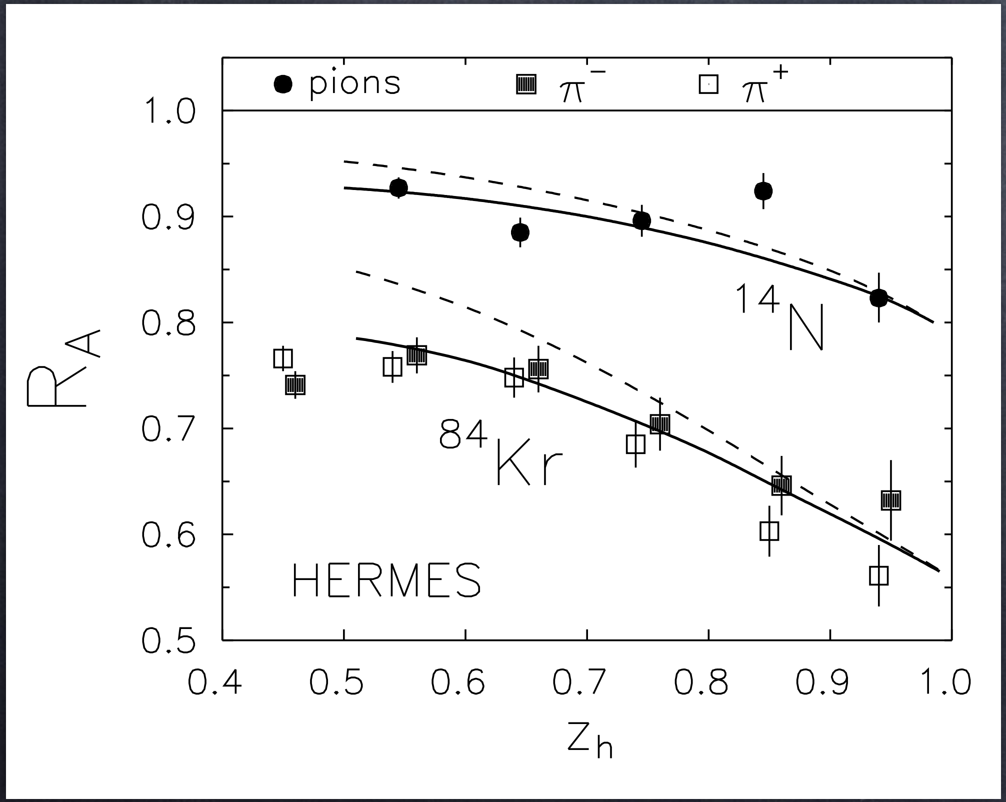
- Pure quark energy loss models: *a la* BDMPS (Arleo; Accardi)

  Higher twist FF (Wang; Majumder)

- Pure hadron absorption models: prehadron survival from transport model (Accardi)

  GiBuu transport Monte Carlo (Falter)

- Color dipole model (z>0.5): quark energy loss + prehadron absorption (B.Kopeliovich)



Kopeliovich et al., NPA 740(04)211

Dipole model which includes both quark energy loss and hadron absorption also ~ describes HERMES data

dashed line: absorption of color dipole qqbar

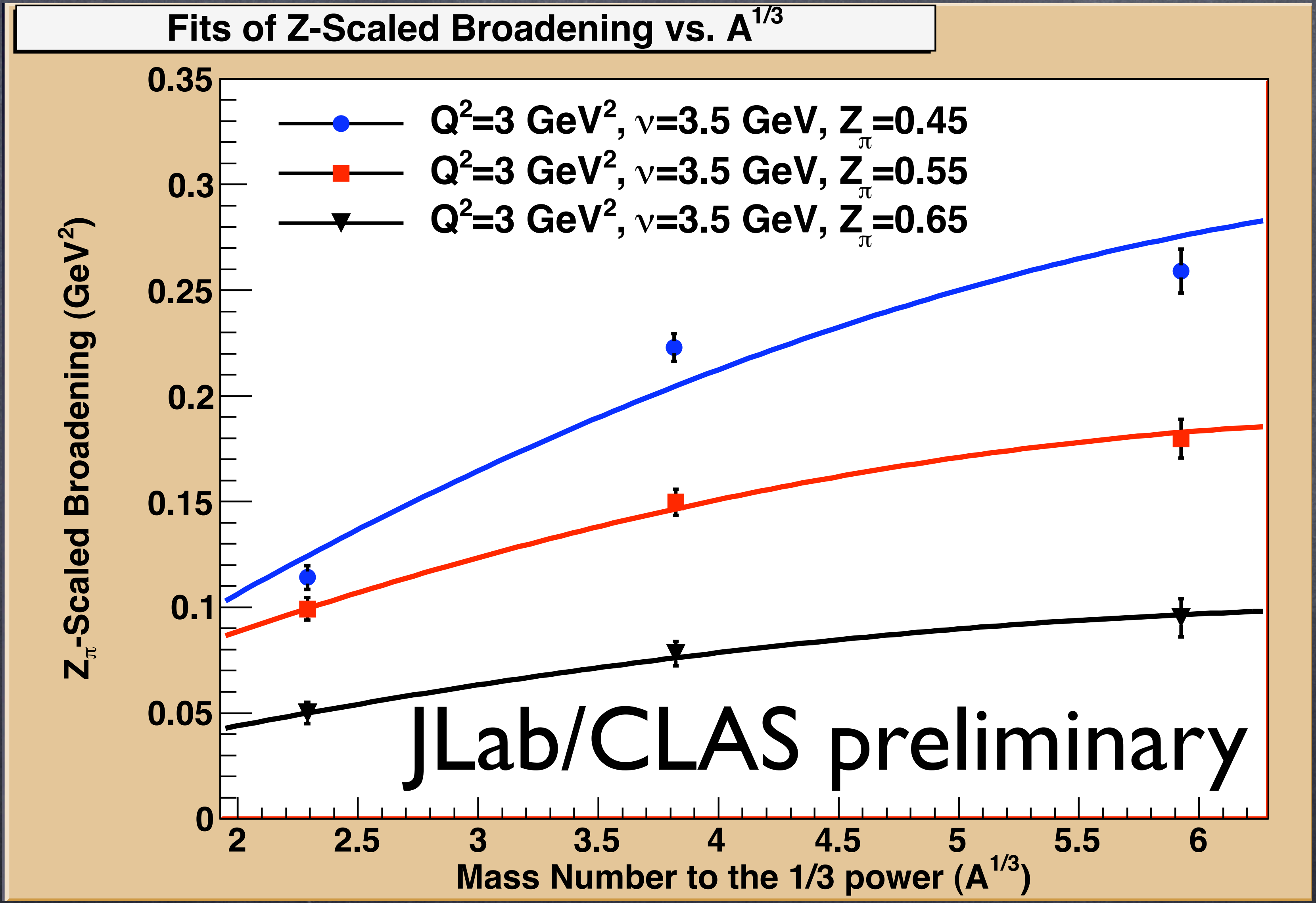
solid line: absorption and induced energy loss

Transverse momentum broadening π^+

Transverse momentum broadening of quarks Δk_T can be expressed in terms of gluon density C

$$\Delta k_T^2 = \Delta p_T^2 / z^2 = 2C\rho_A L = \hat{q}L$$

M. B. Johnson, B. Z. Kopeliovich, and A.V.Tarasov, Phys. Rev. C 63, 035203 (2001)



Space-time characteristics of struck quark

Assume: Single-photon exchange, no quark-pair production

Struck quark absorbs virtual photon energy ν and momentum $p_{\gamma^*} = |\vec{p}_{\gamma^*}| = \sqrt{(\nu^2 - Q^2)}$.

- Neglect any initial momentum/mass of quark
- Immediately after the interaction, quark mass $m_q = Q = \sqrt{(Q^2)}$.
- Gamma factor is therefore $\gamma = \nu/Q$, beta is $\beta = p_{\gamma^*}/\nu$.

"JLab" example: $Q^2 = 3$ GeV^2, $\nu = 3$ GeV. ($x_{Bj} \sim 0.5$) yields $\gamma = 1.73$, $\beta = 0.82$

$$\boxed{L_p \sim \gamma \beta t_p}$$

Extrapolation to EIC kinematics!

Test of time dilation in CLAS/CLAS12!

Energy loss in pQCD

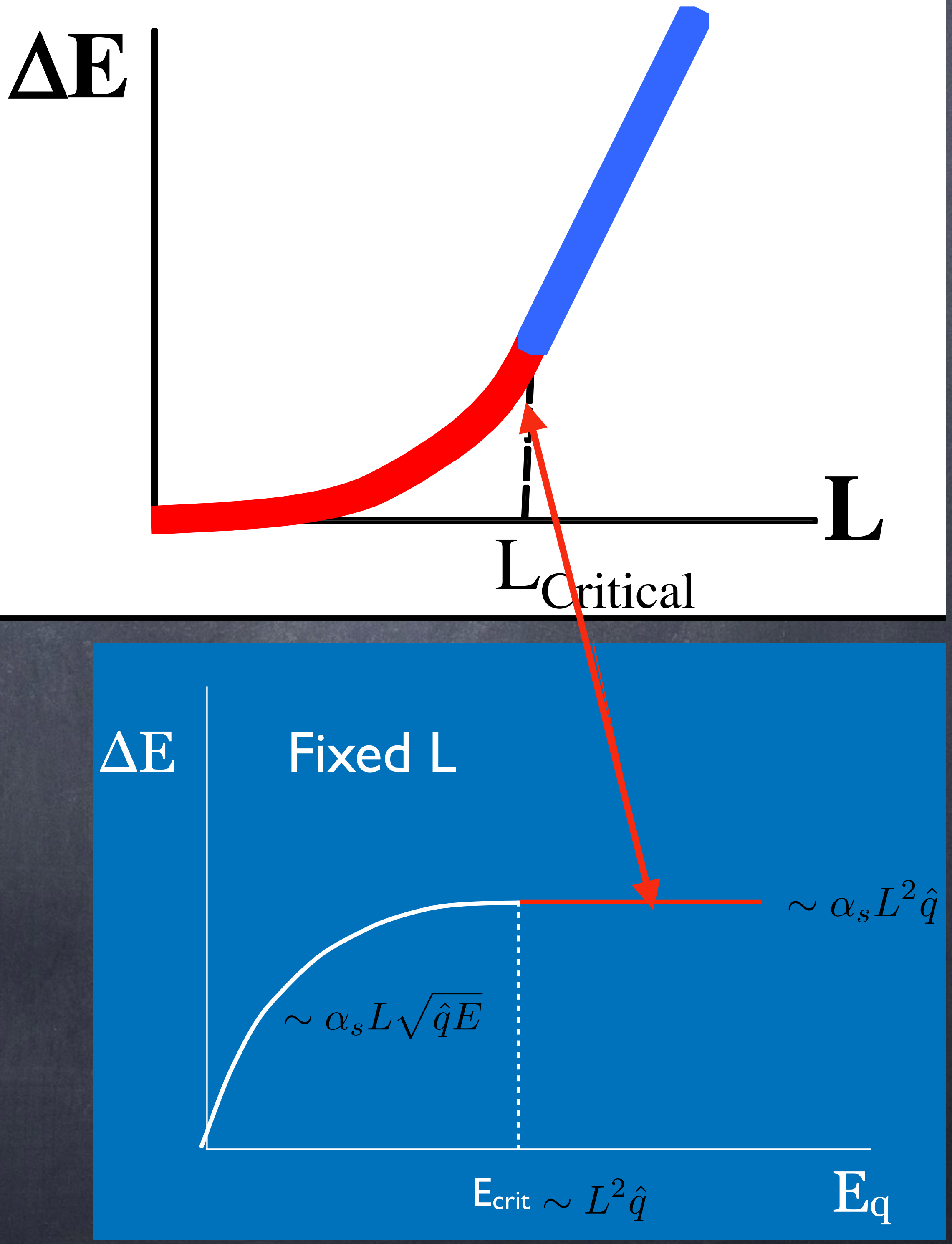
(BDMP version)

$L < L_{Critical}$

$$-\frac{dE}{dx} \propto L\hat{q}$$

$L > L_{Critical}$

$$-\frac{dE}{dx} \propto \sqrt{E\hat{q}}$$



Partonic energy loss in pQCD depends on critical system length Lc and critical Ec

For E > Ec, energy loss depends on path L:

$$-\Delta E_q = \frac{\alpha_s}{4}\Delta k_T^2 \cdot L = \frac{\alpha_s}{4}\hat{q} \cdot L^2$$

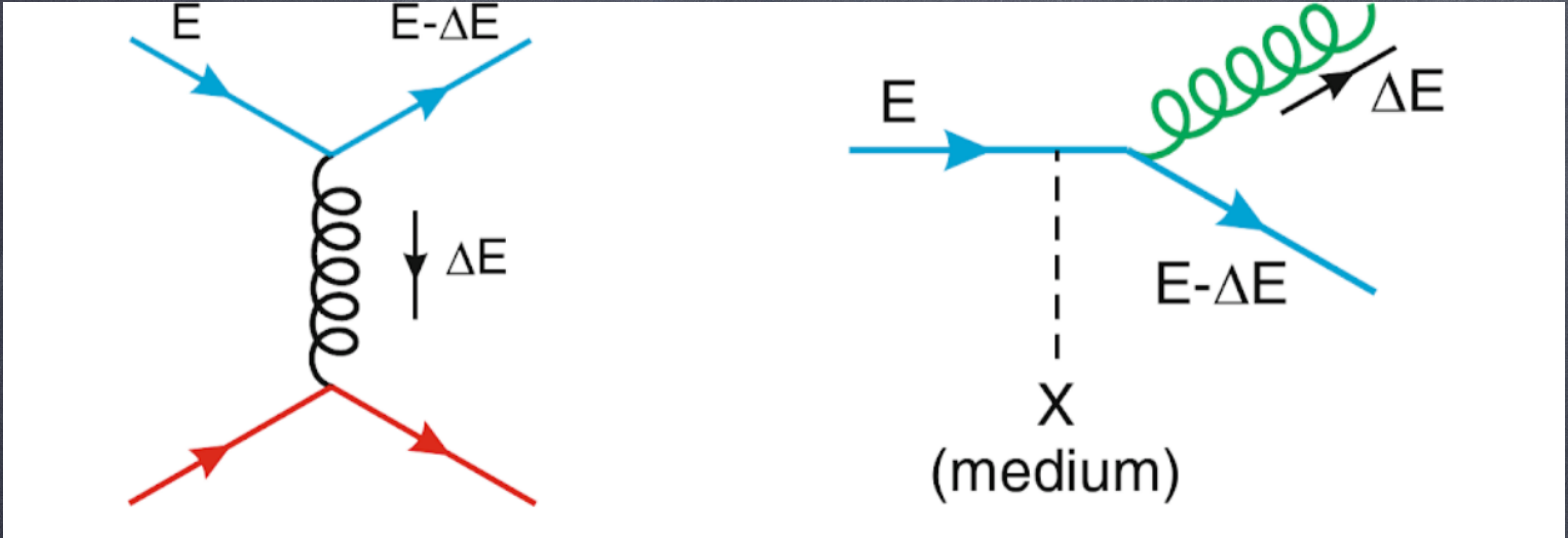
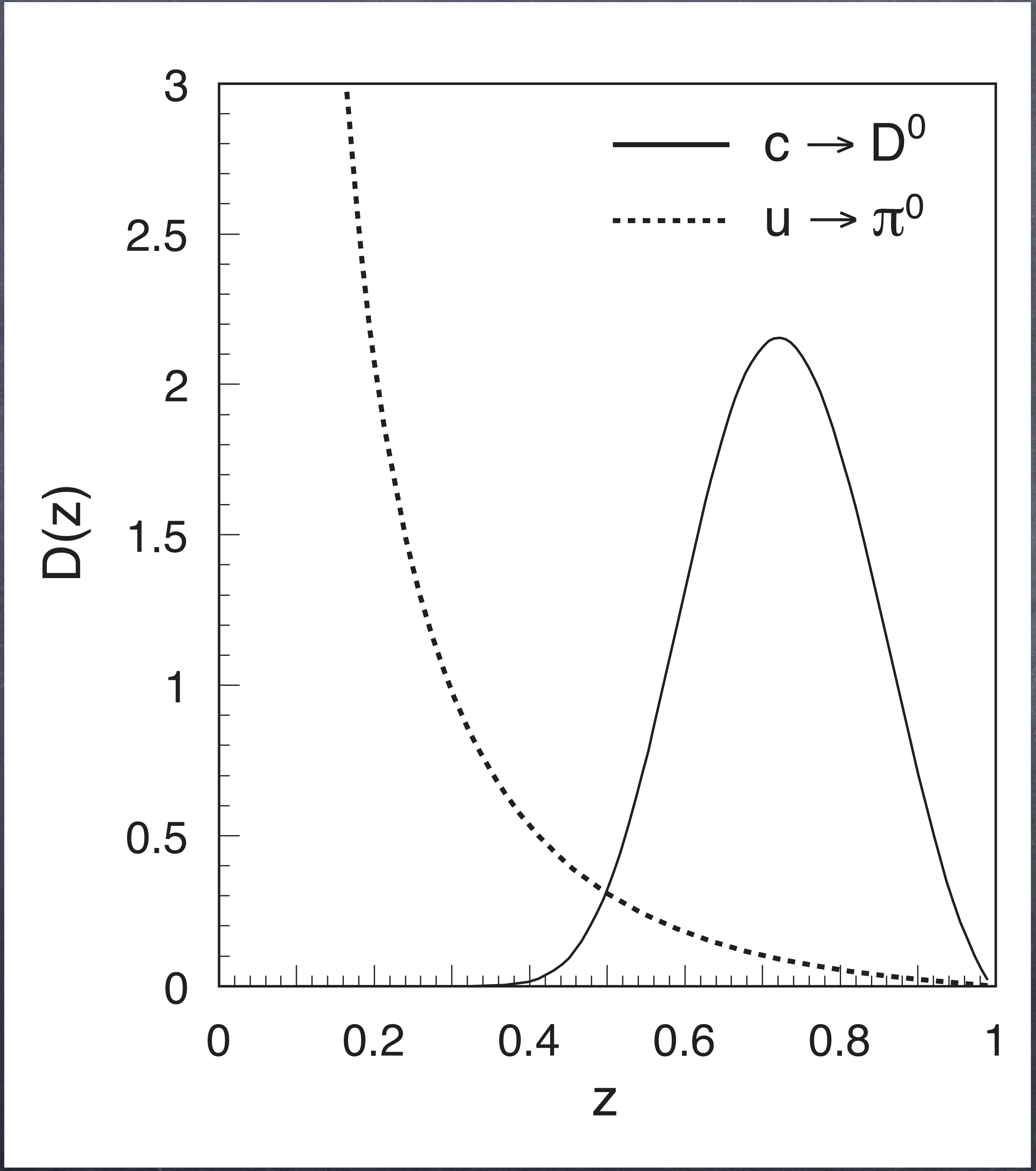


Fig. 2.3 Diagrams for collisional (*left*) and radiative (*right*) energy losses of a quark of energy *E* traversing a quark-gluon medium

A.Festani “Measurement of the D0 meson production in PbPb and pPb”

FF for light and heavy mesons



Complication: Quark Pair Production

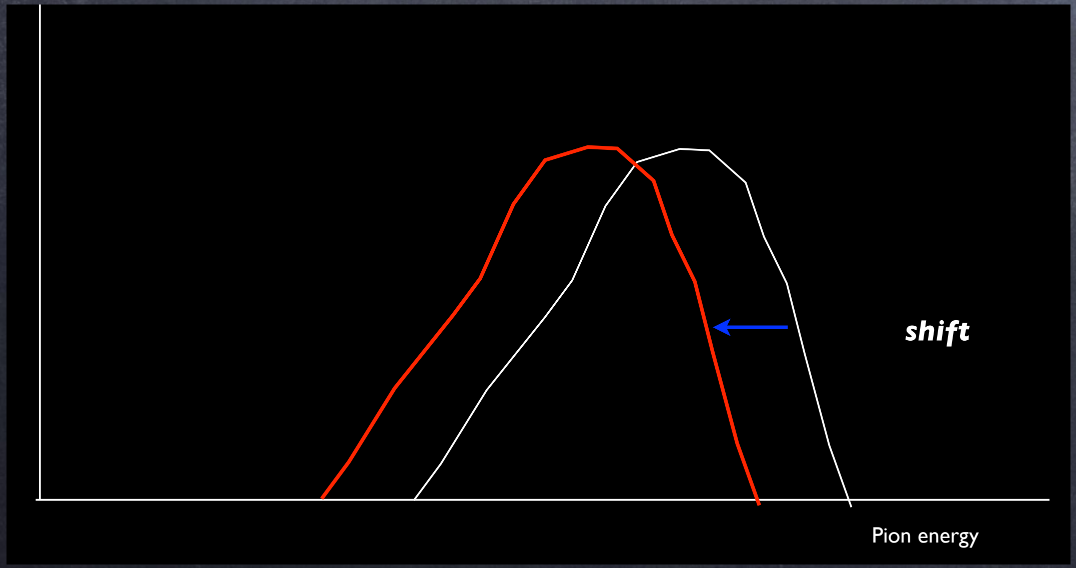
Two types of problems:

- Have $q\bar{q}$ pair instead of single propagating quark of known energy ν
    - Measure *both* jets, or else have an error in calculation of z
- Pair can fluctuate into existence before entering the nucleus, or within the nucleus
    - "Ioffe time" ~ $1/(x_{Bj} M_p)$ (up to 100+ fm for EIC)
    - → Path length in nucleus varies

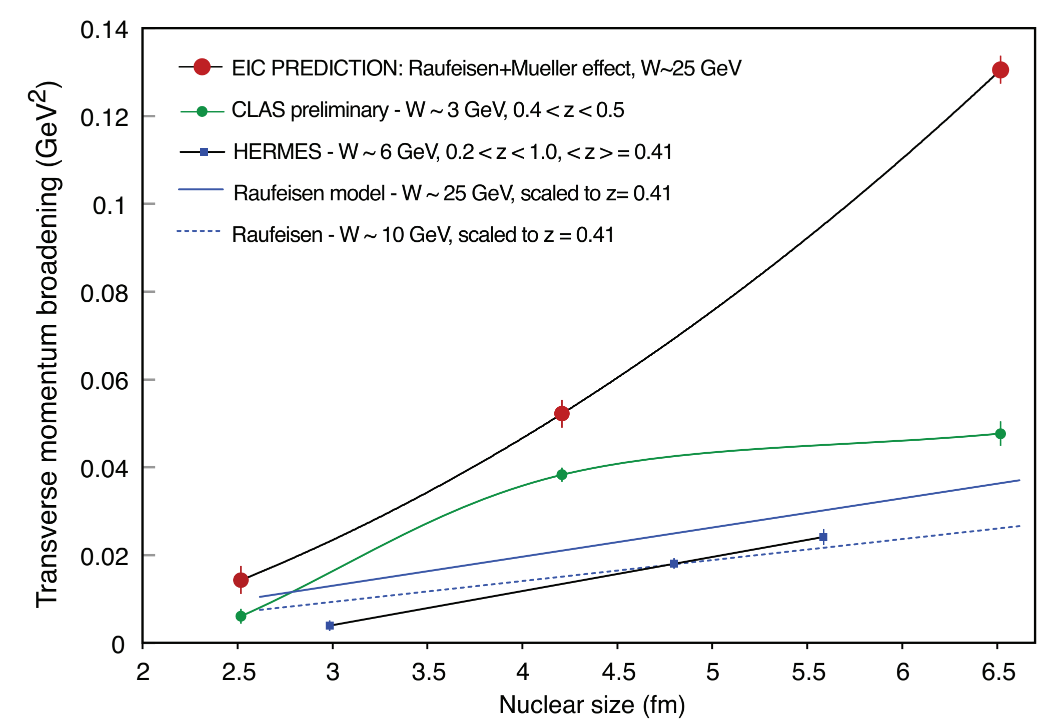
Quark energy loss

- Can be inferred *indirectly* via measurement of pT broadening and extracted from pQCD theory

- Can be measured *directly* via observed particle energy shift



pQCD description of quark energy loss on p_T broadening



for direct energy losses: sensitivity mostly at low energies!