Hadronization in Semi-Inclusive DIS from CLAS at Jefferson Lab

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for the CLAS collaboration

Outline of my talk

- Hadronization - fundamental process of QCD
- Experimental realization: CLAS at 6 GeV
- Future at CLAS12 and EIC

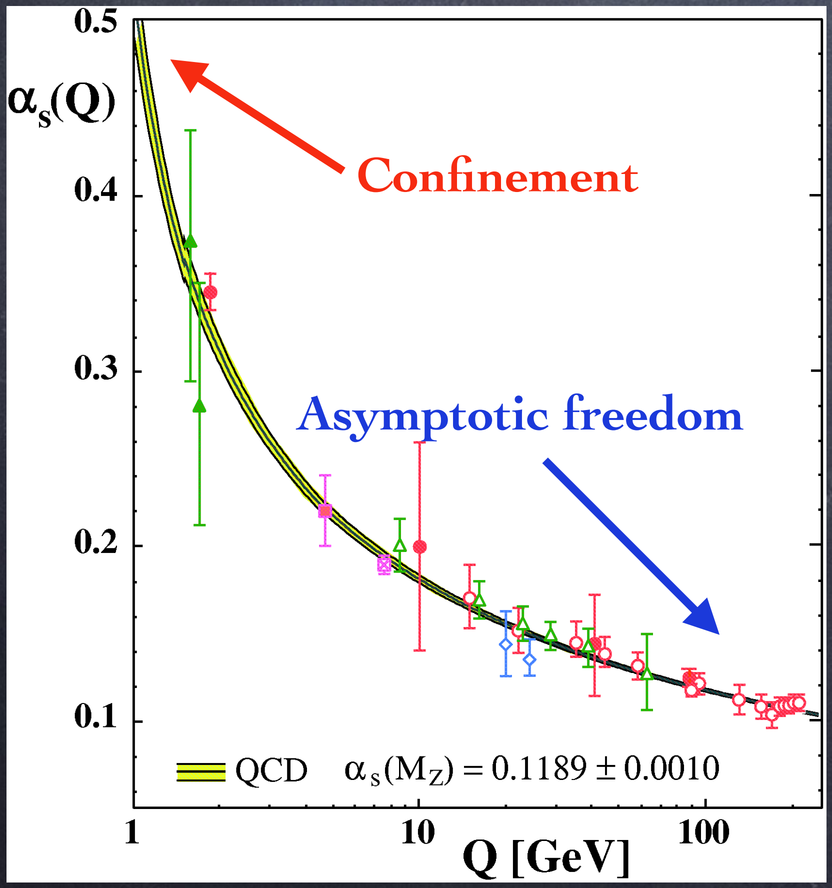
Hadronization - *why is it interesting?*

Hadronization is fundamental QCD process

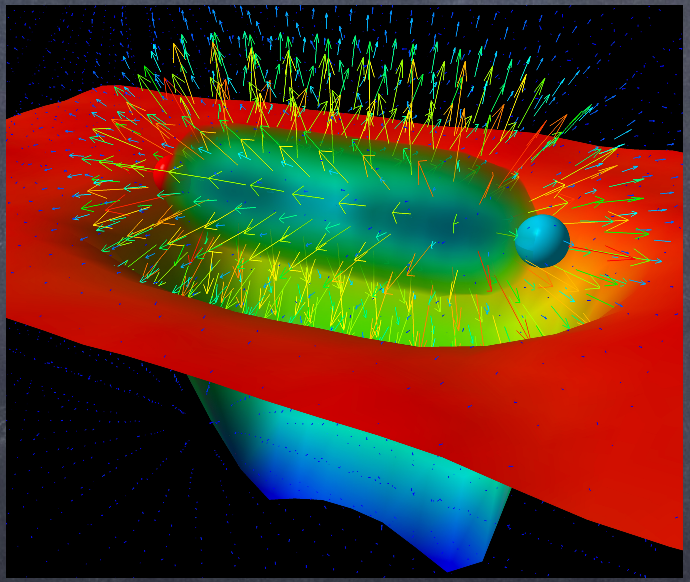
✔ *Hadronization describes the transition between colored d.o.f to composite colorless objects*

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)



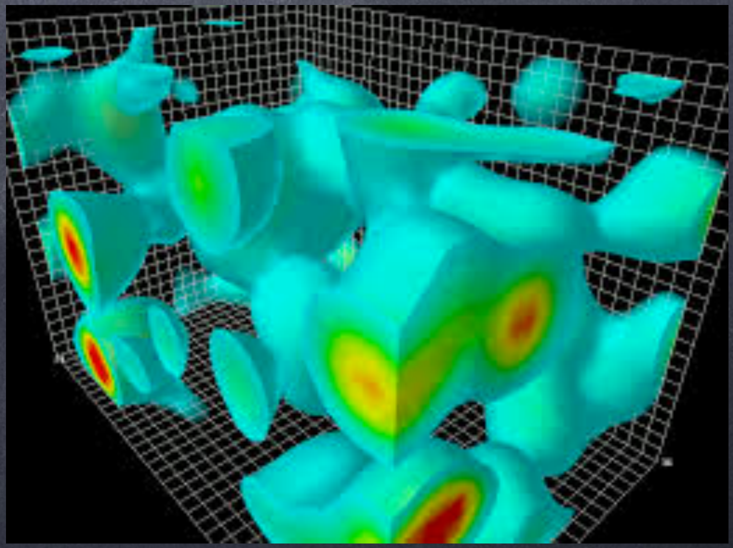
Long distances

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

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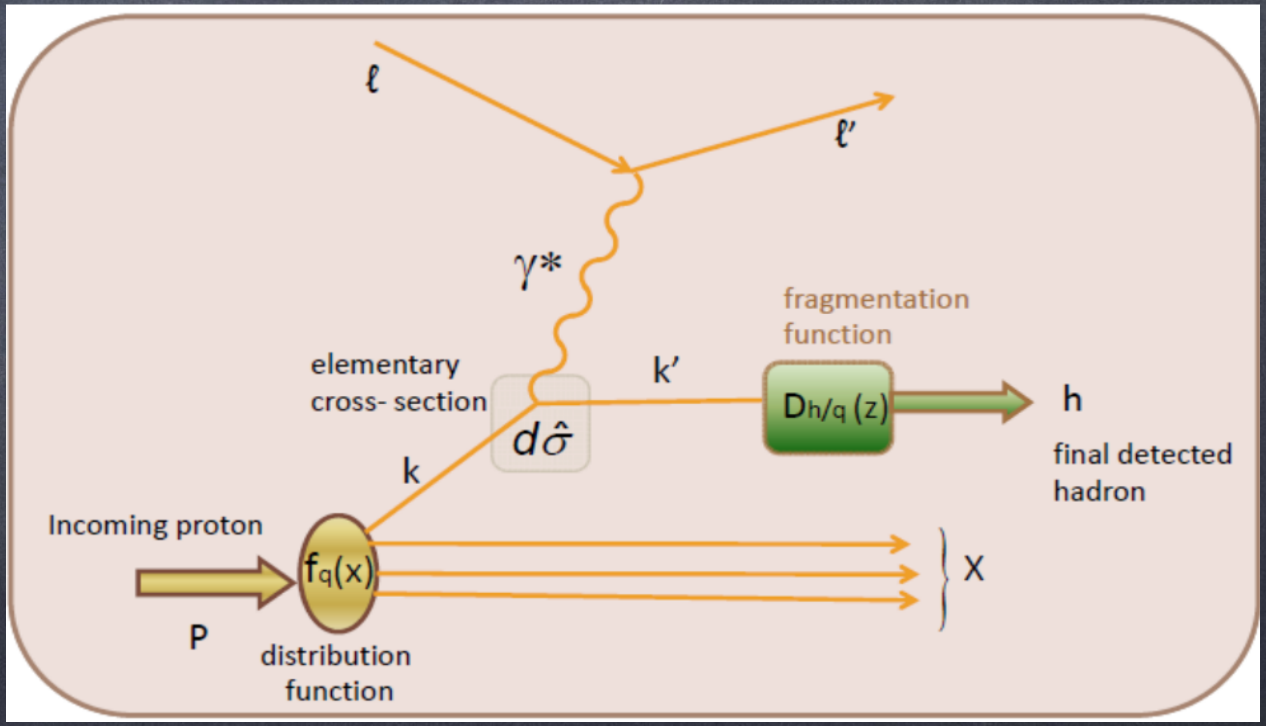
✔ *Hadronization spans over pQCD & non-pQCD regimes - space-time view of factorization*



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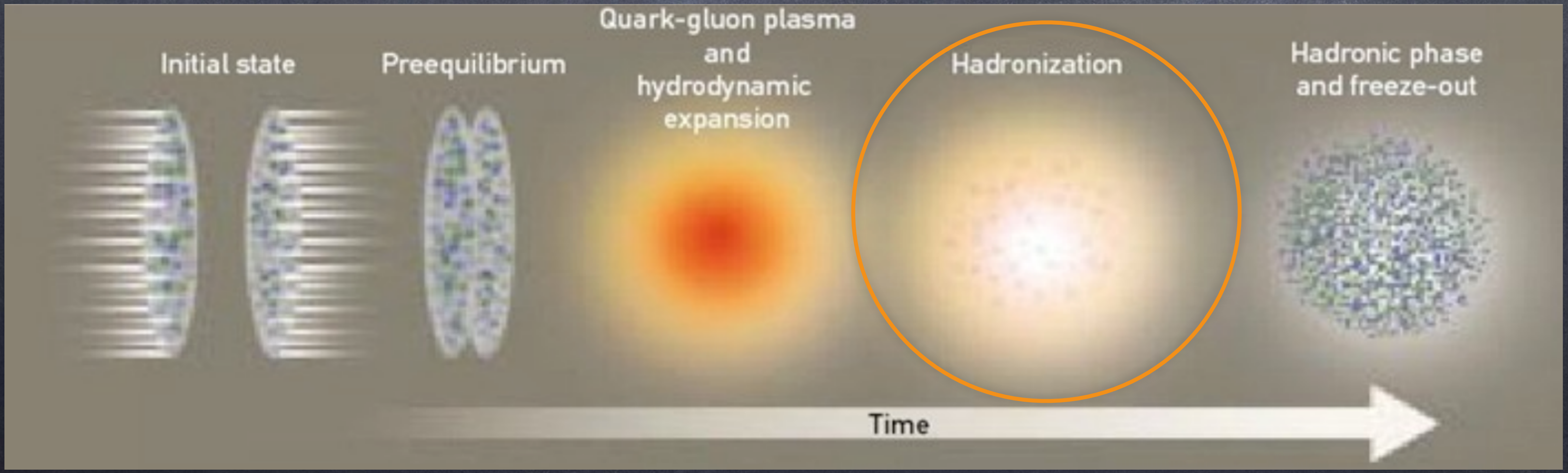
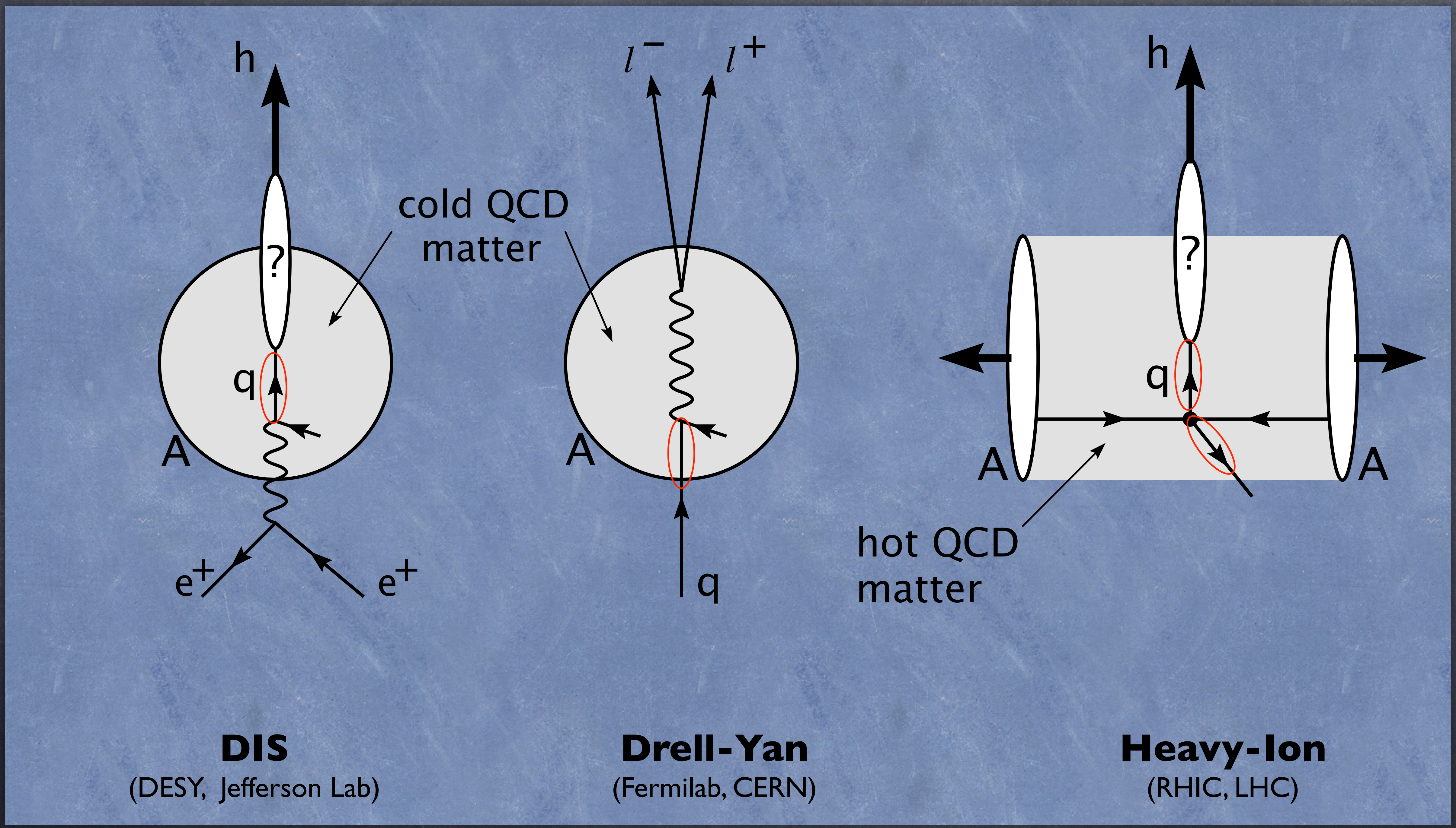
Benchmark in describing heavy ion collisions

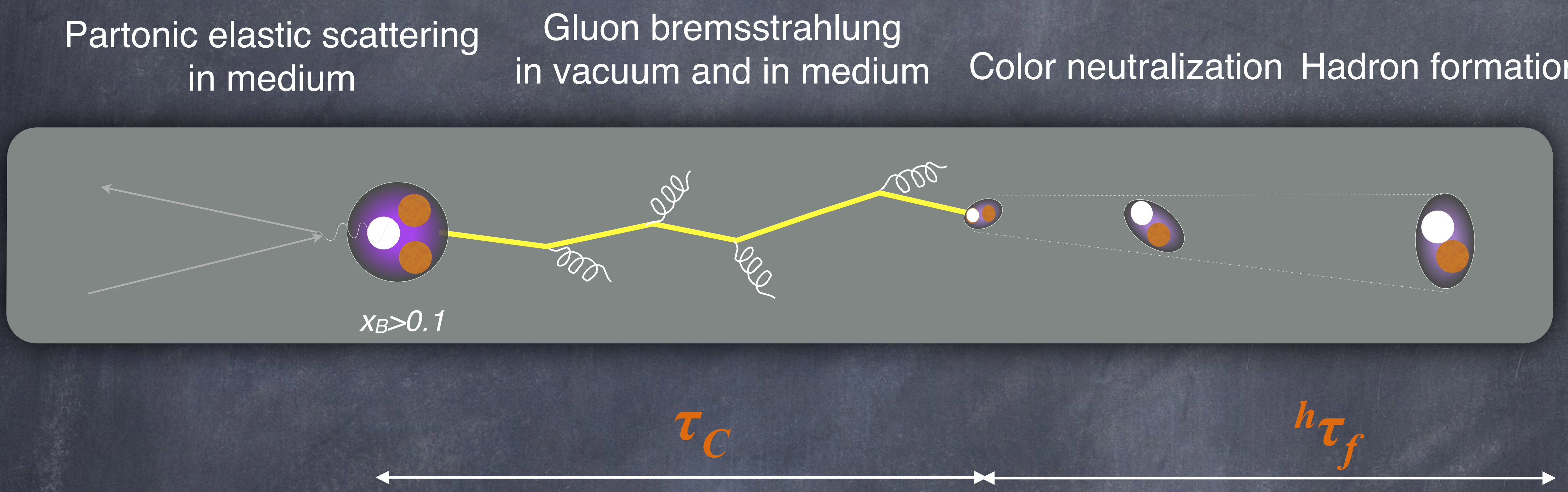


Color propagation in DIS, DY and HI



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

Fundamental QCD proceses in DIS



Color lifetime τ_C is the color lifetime or lifetime of highly virtual quark following hard processes

Formation time $^h\tau_f$ **is the time or distance required for a colored system to evolve into a color singlet system**

Quark - nucleus interactions: pQCD aspects

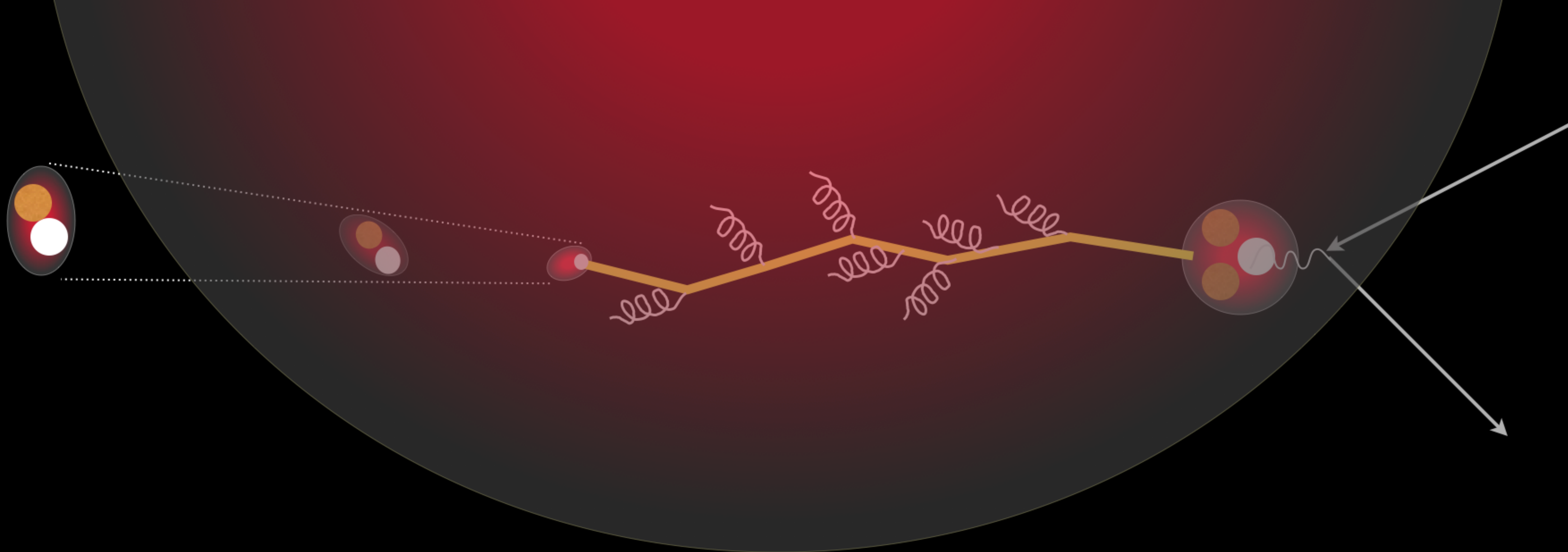
How does color interact with medium ?

- ✔ *Lifetime of propagating colored object - confinement*
- ✔ *Quark pQCD energy losses, transverse momentum broadening*

Quark - hadron evolution: non-pQCD aspects

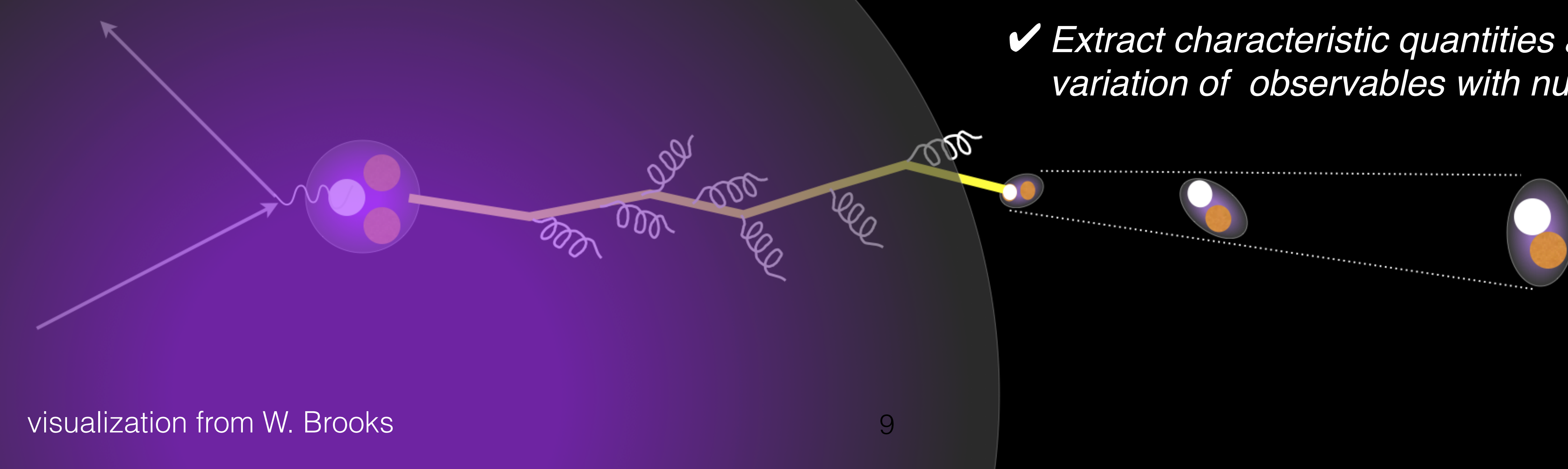
What are the mechanisms of color neutralization?

- ✔ *Characteristic times of hadron system to evolve into color singlet*
- ✔ *Map the mechanism of fragmentation of correlated q and g*



Nuclei as space-time analyzer

- ✔ *Use nuclei of variable size as a 'ruler':*
  R_{Carbon} = 2.7 fm vs R_{Lead} = 7.1 fm
- ✔ *Medium well known, low final multiplicities*
- ✔ *Extract characteristic quantities as a variation of observables with nuclear size*

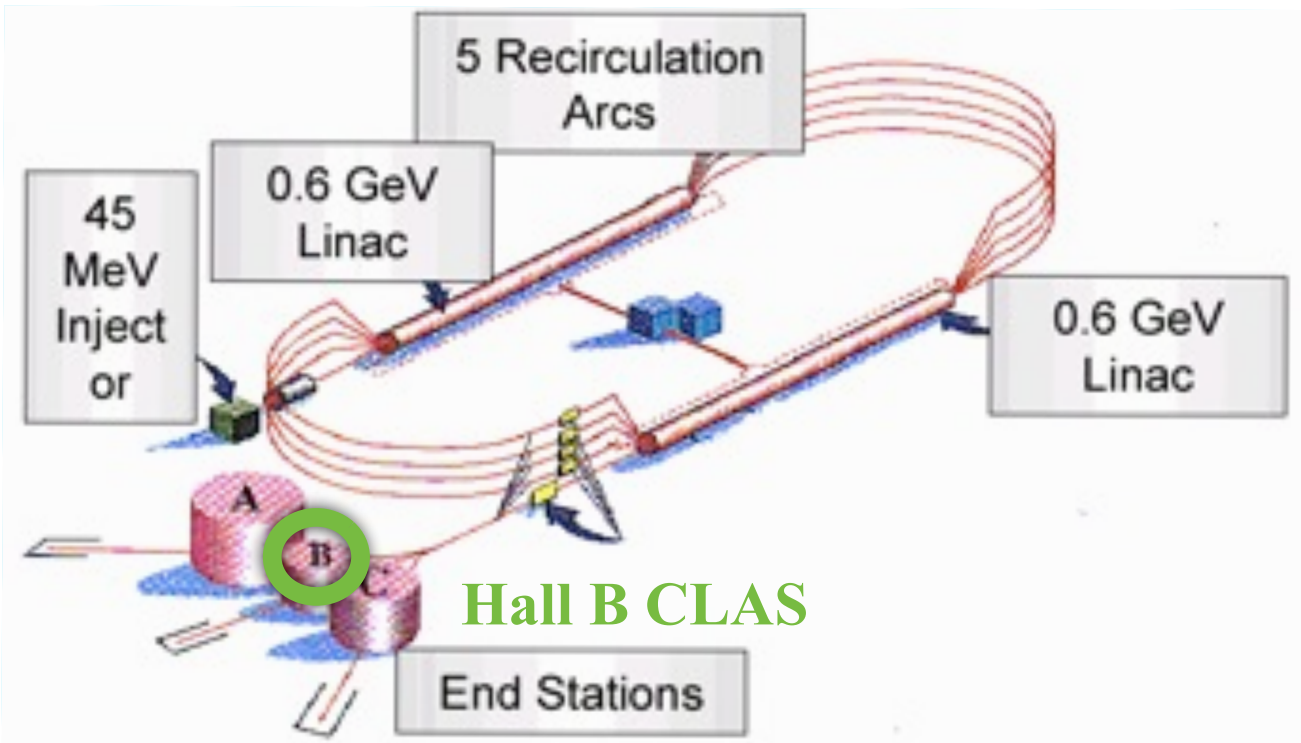


visualization from W. Brooks

Experimental realization:
CLAS at 6 GeV

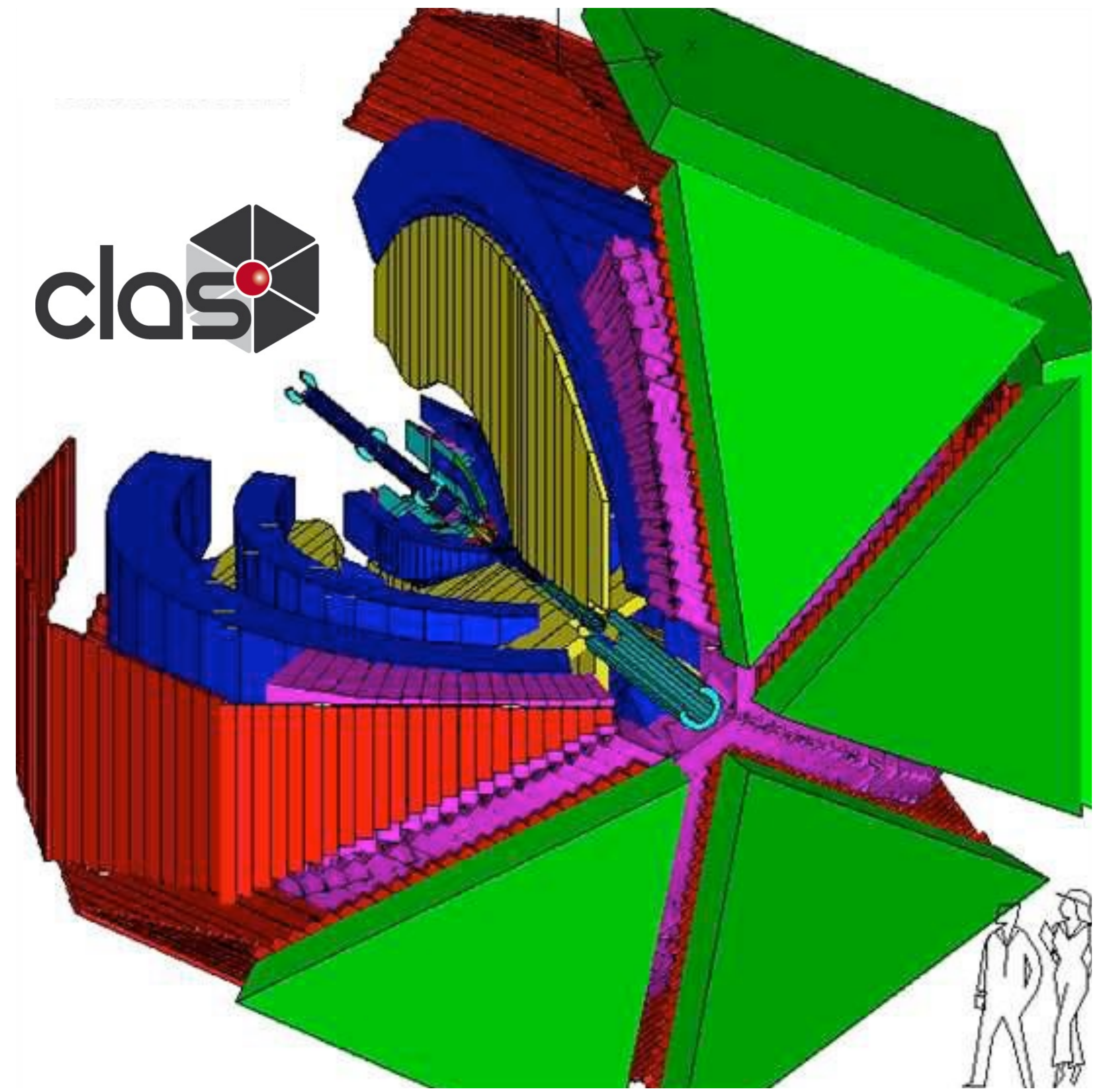
CEBAF and CLAS @ 6 GEV

Jefferson Lab



CEBAF **L**arge **A**cceptance **S**pectrometer

- Charged particle angles 8° - 144°
- Neutral particle angles 8° - 70°
- Momentum resolution ~0.5% (charged)
- Angular resolution ~0.5 mr (charged)
- Identification of p, π^+/π^-, K^+/K^-, e^-/e^+



N. A. Mecking *et al.*, *The CEBAF large acceptance spectrometer (CLAS)*, Nucl. Inst. and Meth. A 503, 513 (2003).

EG2 experiment @ 6 GEV

Jefferson Lab

clas

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 $2 \cdot 10^{34}$ $1/(s \cdot cm^{2})$

Spokes persons: W.Brooks, K.Hafidi,
L. El Fassi, H.Hakobyan, K.Joo et *al*.

➤ ***see Hayk Hakobyan talk on double-target systems @ CLAS and CLAS12***

Observables

Transverse momentum broadening

Connects to color propagation phase:

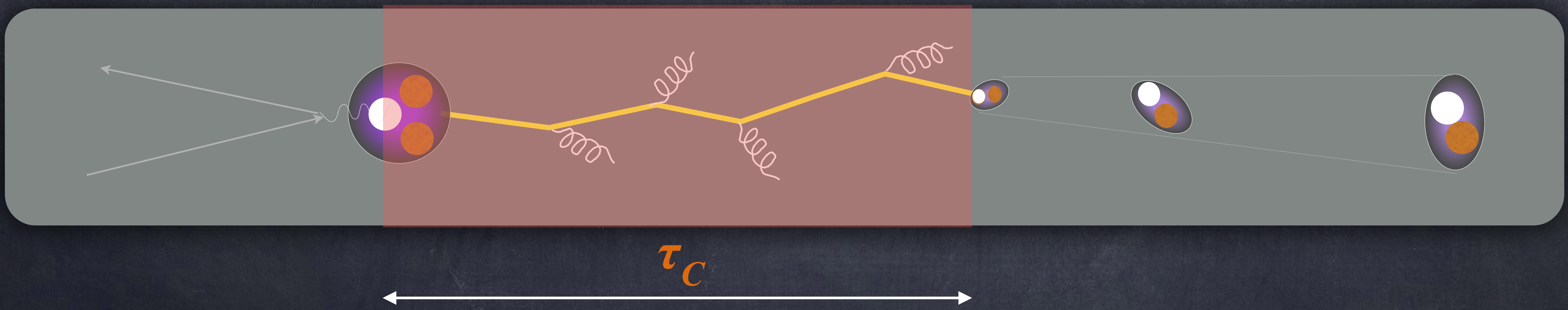
- color lifetime τ_C
- quark energy loss

Transverse momentum broadening

$$\Delta p_T^2 =< p_T^2 >_{\mathrm{A}} - < p_T^2 >_{\mathrm{D}}$$

where ***pT*** is transverse momentum w.r.t γ* direction

➤ ***see . Jorge Lopez talk on extraction of color lifetime from cold nuclei!***



Hadronic multiplicity ratio

The multiplicity rate M_n^h of hadrons *h* on nuclei *n* is defined as ratio of the differential SIDIS cross section over the differential DIS cross section.

$$M_n^h(x_B, Q^2, z_h, P_T) \equiv \frac{1}{\frac{d^2\sigma^{\mathrm{DIS}}(x_B, Q^2)}{dx_B\, dQ^2}} \frac{d^4\sigma(x_B, Q^2, z_h, P_T)}{dx_B\, dQ^2\, dz_h\, dP_T}$$

Experimentally, the particle yield N = σ *L* where *L* is luminosity

Measured hadronic multiplicity ratio R_A^h on nuclear target A normalized to D is then:

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

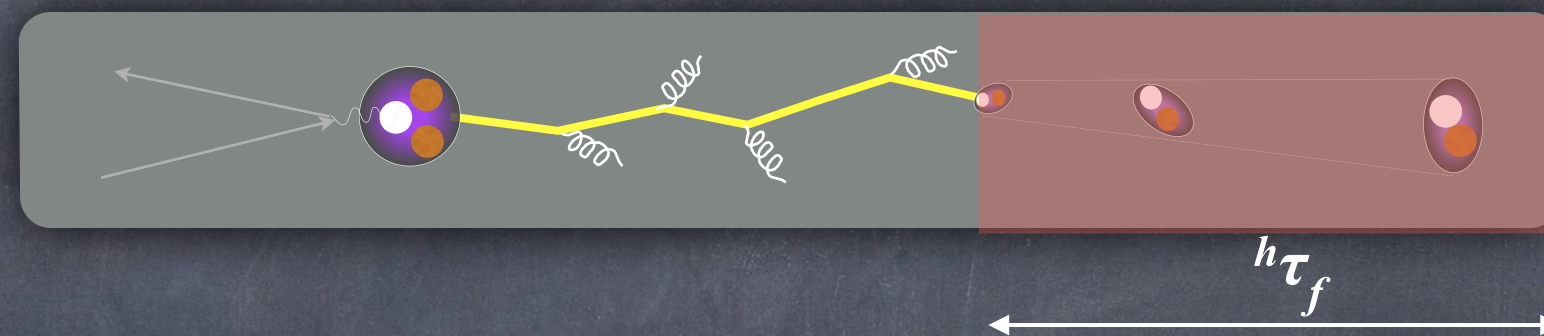
An expression of experimental R_A^h in parton model, assuming factorization, is expressed in terms of the ratio of PDF and FF

$$R_D^A = \frac{\left\{\frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}\right\}_A}{\left\{\frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}\right\}_D}$$

➤ Hadronic multiplicity ratio ◀

Connects to hadronic phase:

- hadron formation time ${}^{h}\tau_f$
- hadronization mechanisms



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Previous measurements

Comparison of CLAS/JLab and HERMES/DESY

- 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 .

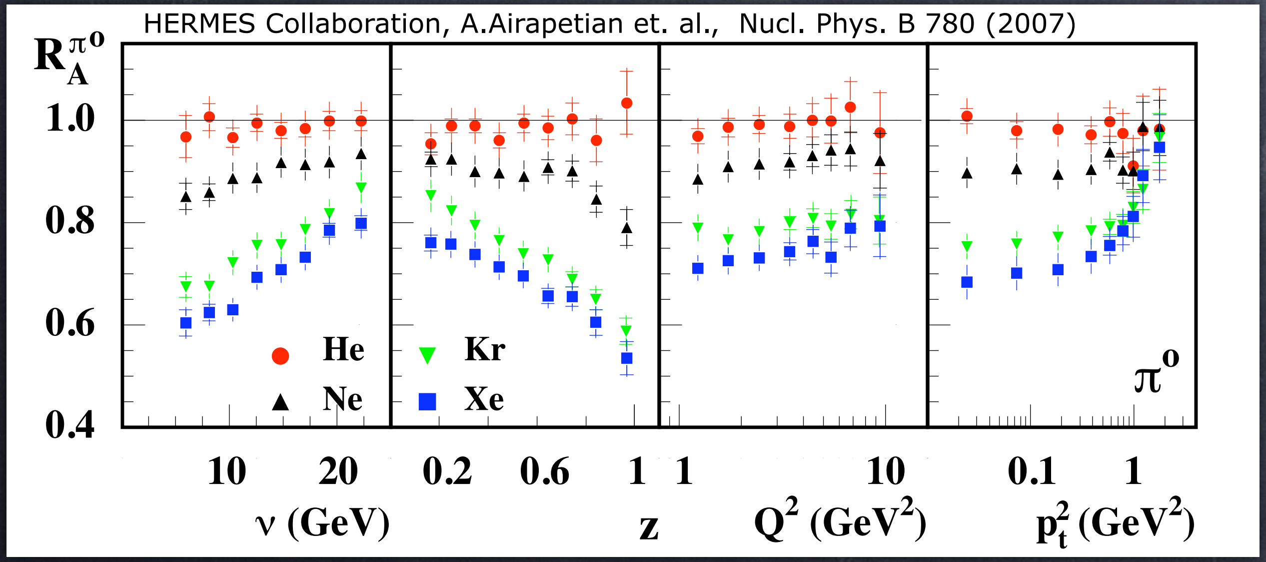
	ν (GeV)	Q^2 (GeV^2)	z	pT^2 (GeV^2)
CLAS	2.2 - 4.2	1.0 - 4.1	0,3 - 1,0	0 - 1.5
HERMES	7 - 23	1.0 - 10	0.2 - 1.0	0 - 1.1

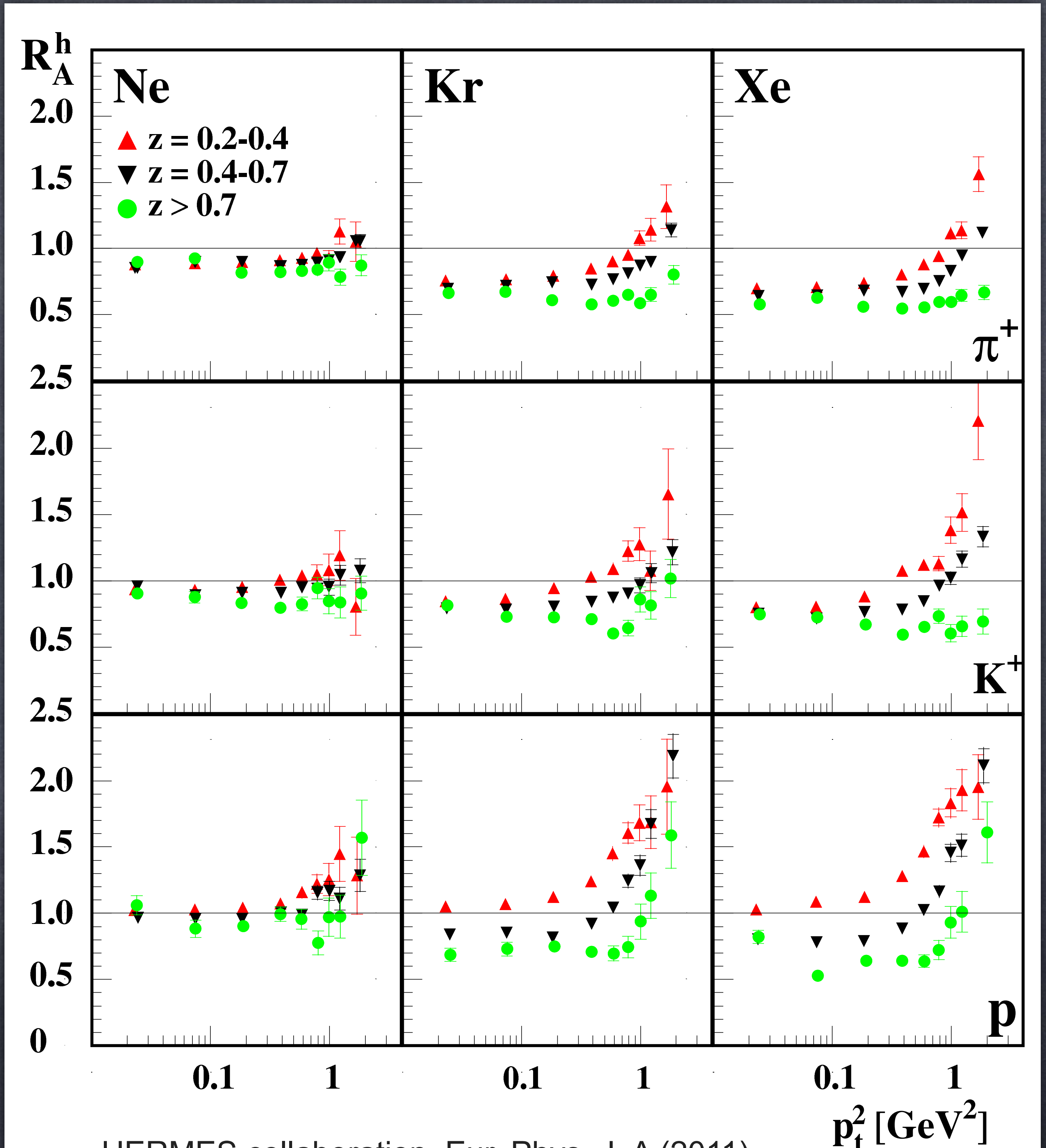
HERMES
multiplicities R(z, pT^2) integrated over ν, Q^2

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

2D distributions for charged hadrons

1D extraction of multiplicities for π^0





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

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)

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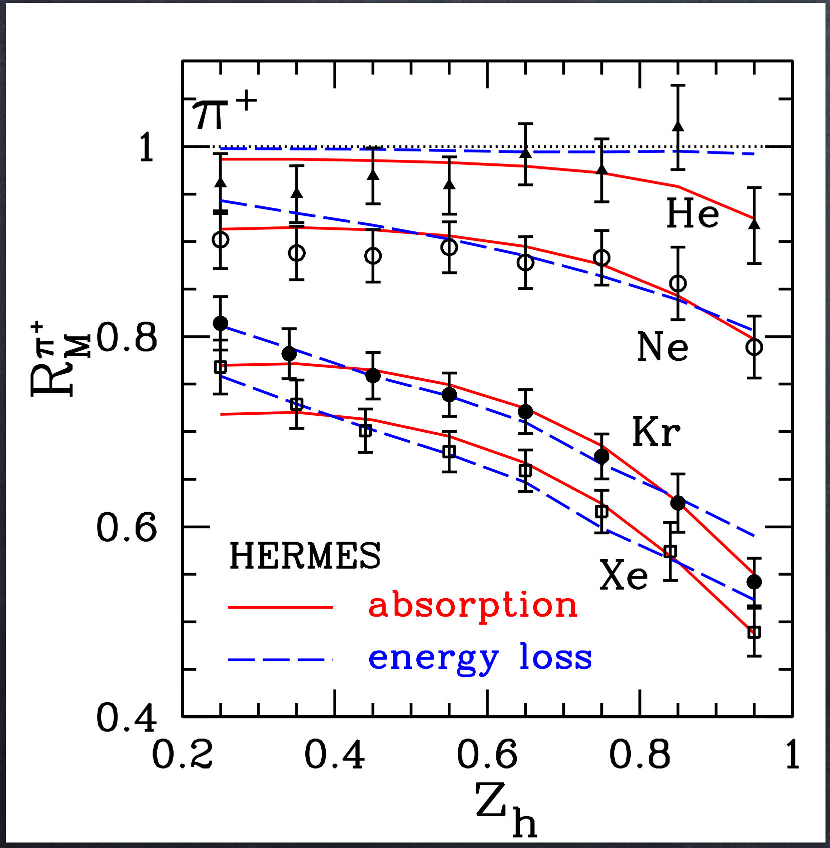

Accardi, Arleo, Brooks, d'Enterria, Muccifora
Riv.Nuovo Cim.032:439553,2010 [arXiv:0907.3534]

Both pure quark energy loss and pure hadron absorption describe attenuation R^h on z of HERMES

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

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

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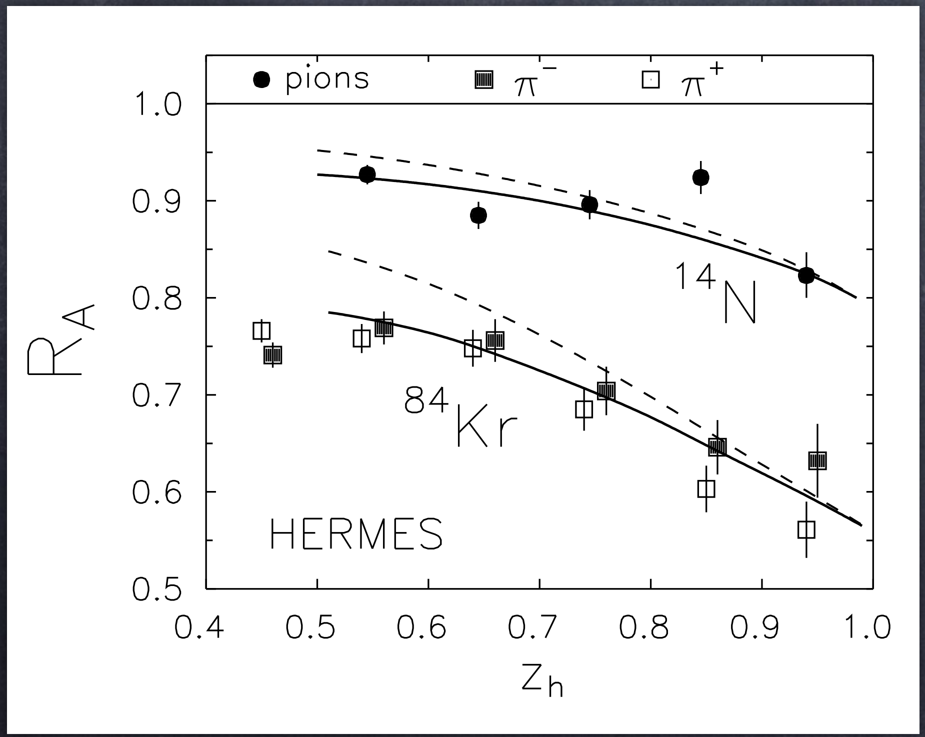
- <u>Color dipole model</u>: quark energy loss + prehadron absorption (B.Kopeliovich)



Kopeliovich et al., NPA 740(04)211

describes formation of leading hadrons (z>0.5)

dashed line: absorption of color dipole qqbar

solid line: absorption and induced energy loss

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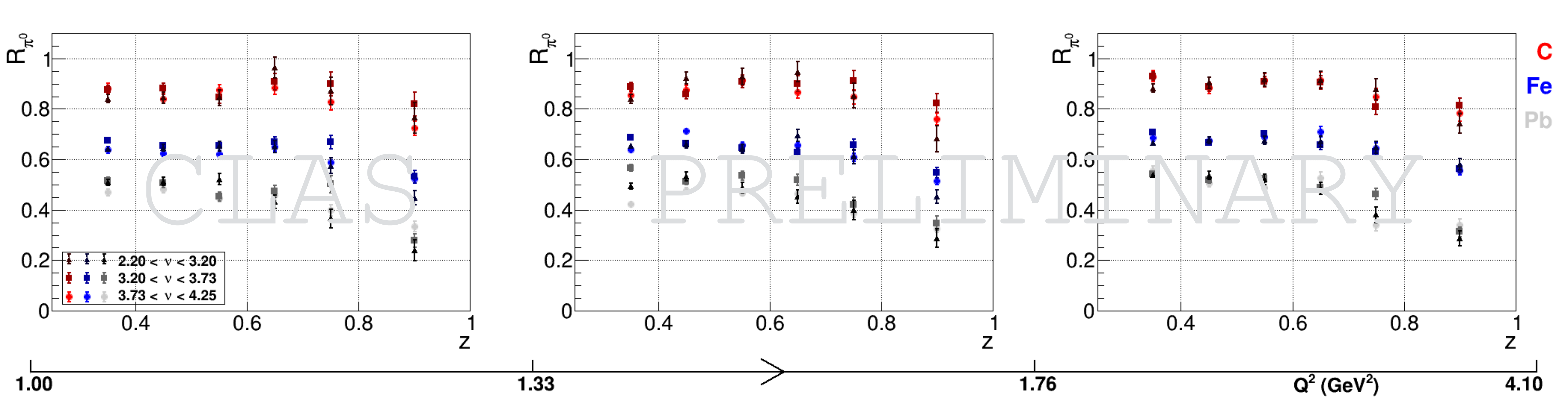
Multidimensional data are crucial in order to distinguish proposed mechanisms and constrain (many) available theoretical models !!

Results

Multiplicity ratios: data from EG2

3D π^0 Multiplicities on ^{12}C, ^{56}Fe, ^{207}Pb to D

$R_{\pi 0}$ in (Q^2, ν, z) integrated over p_T^2



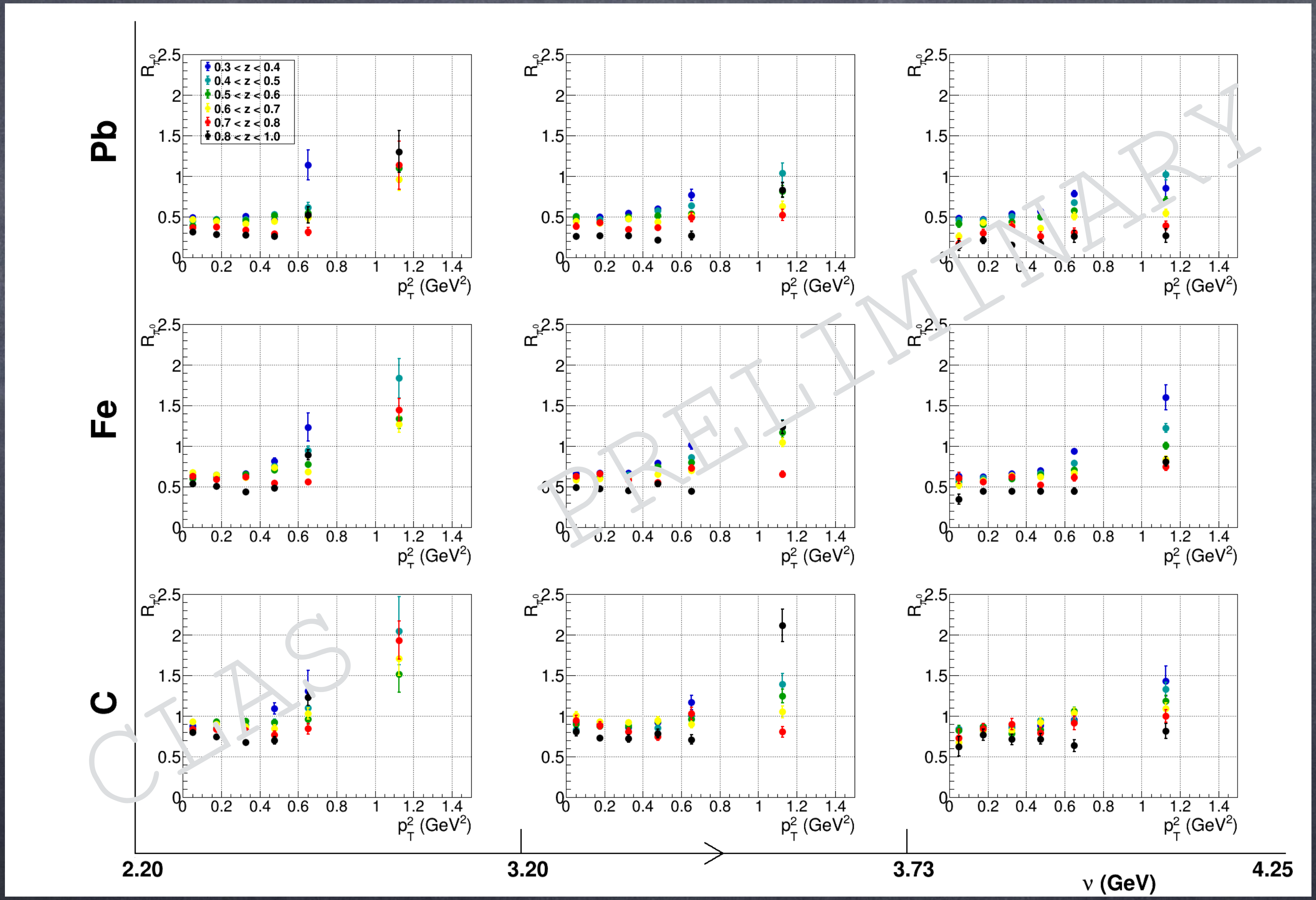
- Attenuation depends on nuclear size
- Hadron attenuation at high z
- Quantitative behavior compatible with Hermes

Taisiya Mineeva
Analysis under review

Multiplicity ratios: data from EG2

3D π^0 Multiplicities on ^{12}C, ^{56}Fe, ^{207}Pb to D

$R_{\pi 0}$ in (ν, z, pT^2) integrated over Q^2



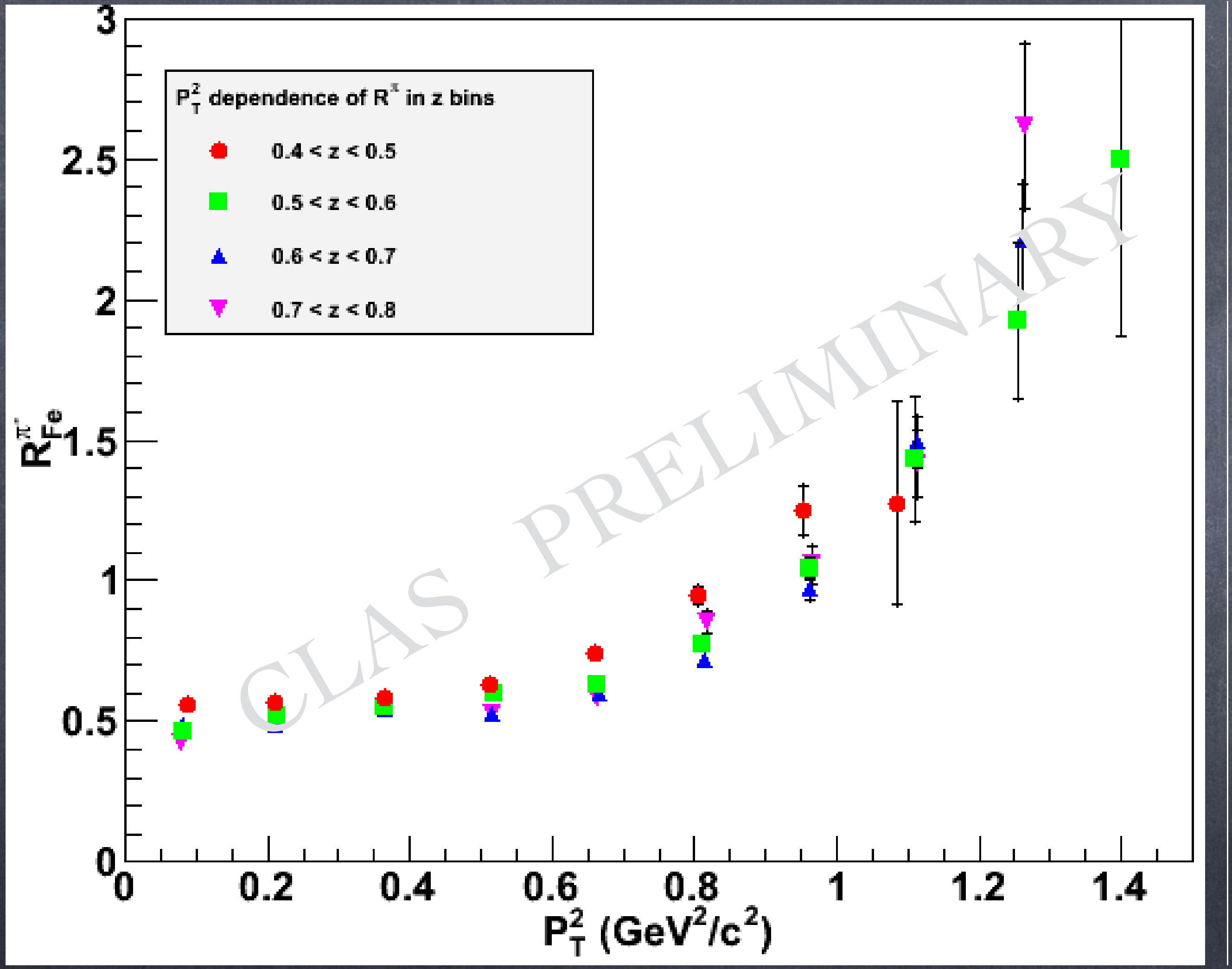
- Bears resemblance to Cronin effect at high pT2
- Quantitative behavior compatible with Hermes

Taisiya Mineeva
Analysis under review

Multiplicity ratios: data from EG2

2D π^- Multiplicities on ^{12}C, ^{56}Fe, ^{207}Pb to D

R_{π^-} in (z, p_T^2) integrated over ν, Q^2



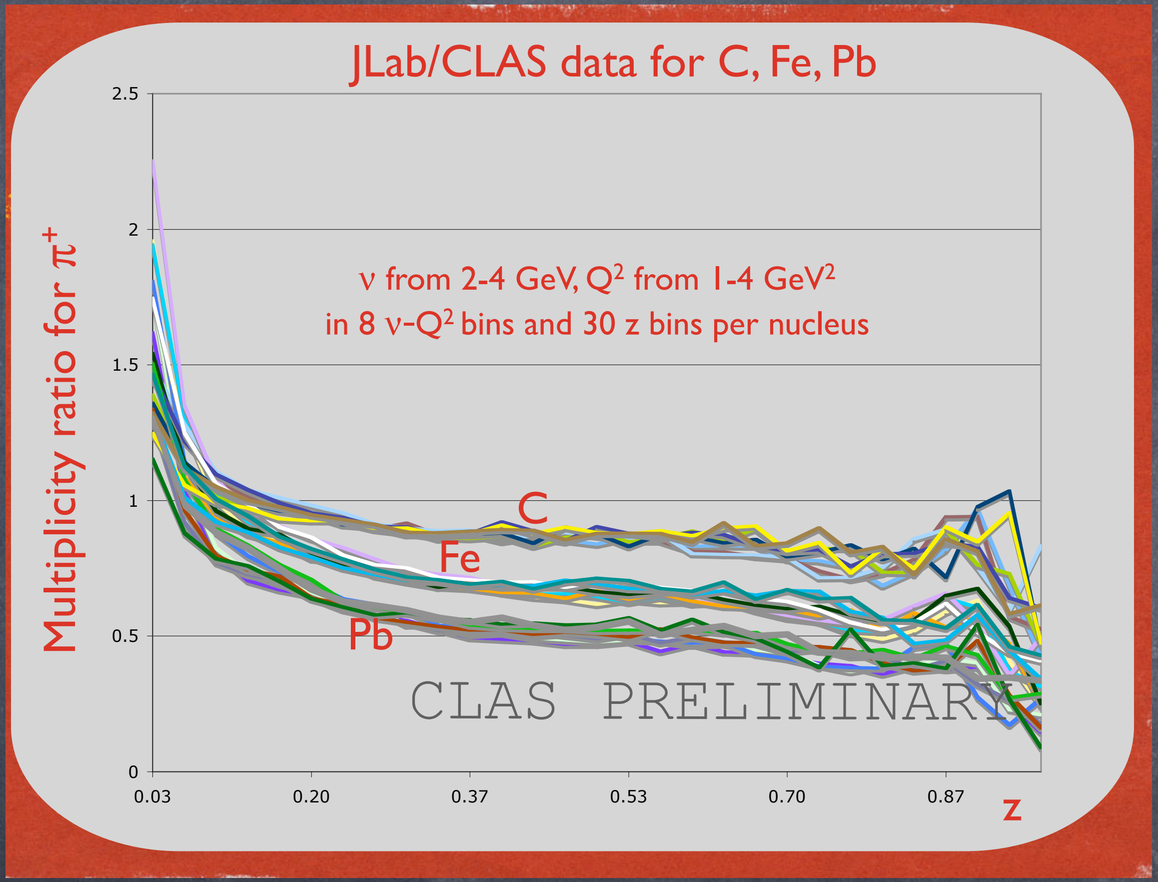
Raphael Dupré

Analysis under review

Multiplicity ratios: data from EG2

3D π^+ Multiplicities on ^{12}C, ^{56}Fe, ^{207}Pb to D

$R_{\pi+}$ in (Q^2, ν, z) integrated over p_T^2



Hayk Hakobyan

- Attenuation depends on nuclear size
- Increase of hadrons at low z, attenuation at high z
- Quantitative behavior compatible with Hermes

Future

CLAS12 Science Program

- Quark confinement and the role of the glue in hadron spectroscopy

- Unraveling confinement forces in the proton. Studying the multi-dimensional structure of the nucleon – from form factors and PDFs to GPDs and TMDs

- ***The strong interaction in nuclei – evolution of quark hadronization, nuclear transparency of hadrons***

- Search for science beyond the Standard Model – precision and intensity frontiers

from Latifa Elouadrhiri

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	cτ	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

Future Electron Ion Collider EIC Program:

Large leverage in ν and Q^2 → wide range of color lifetime lengths
→ access to pQCD quark energy loss

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

for details see Jorge Lopez talk

W. Brooks INT 2017

Summary

✔ Hadronization is a fundamental process of QCD

- Link between perturbative and non-perturbative domains
- A way to probe nuclear media, either cold or hot

✔ Past results gave the global picture of hadronization in medium

- CLAS high luminosity data on ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb
- Extraction of multidimensional multiplicities and momentum broadening
- Analysis under review

✔ Multi-dimensional analysis is crucial to constrain existing models

- CLAS12 experiment (E-12-06-117) will provide high statistics data and access to 4D multiplicities in meson and baryon channels

✔ Future Electron Ion Collider (EIC)