Color propagation in eA from CLAS at Jefferson Lab

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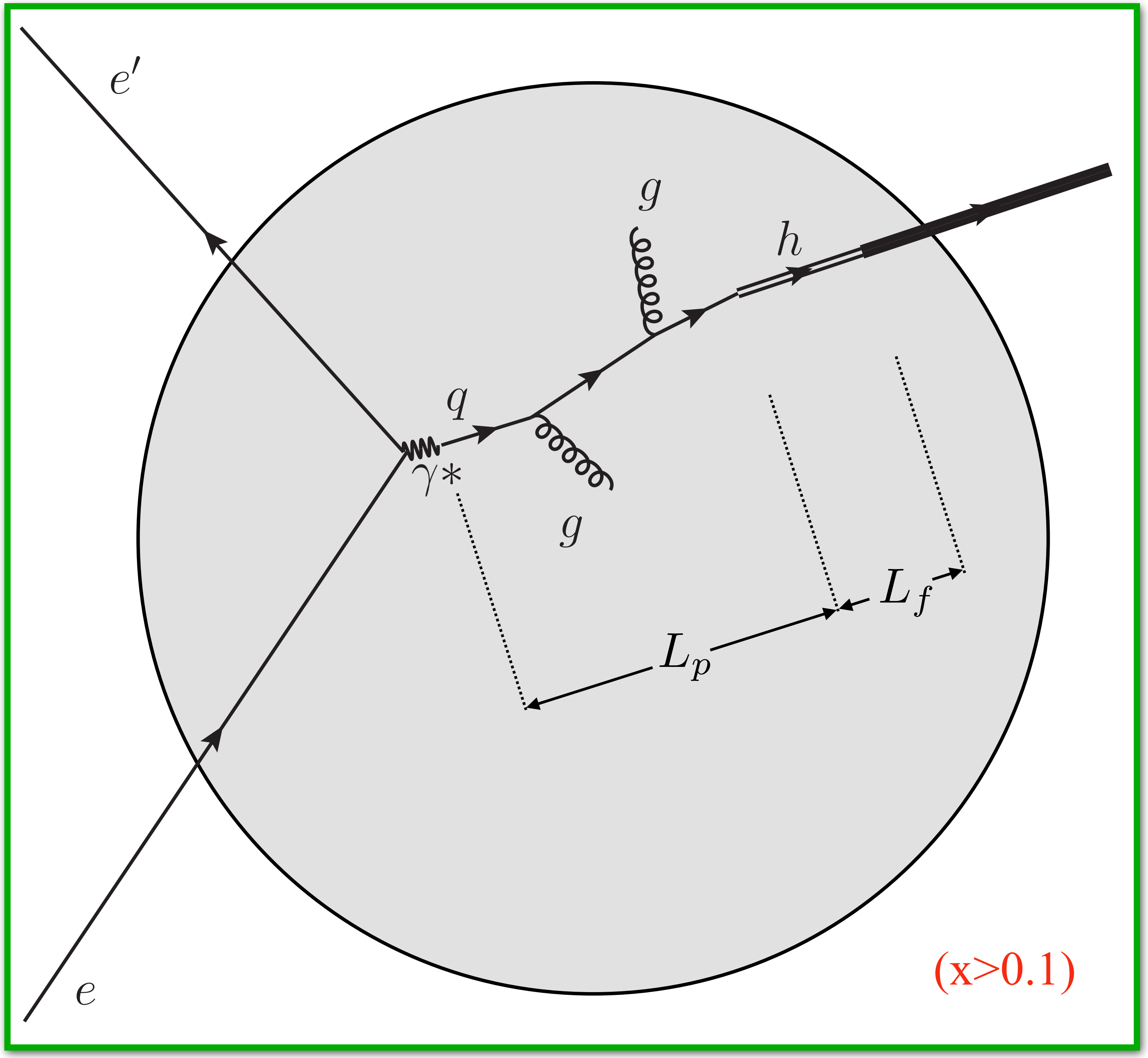
Color propagation

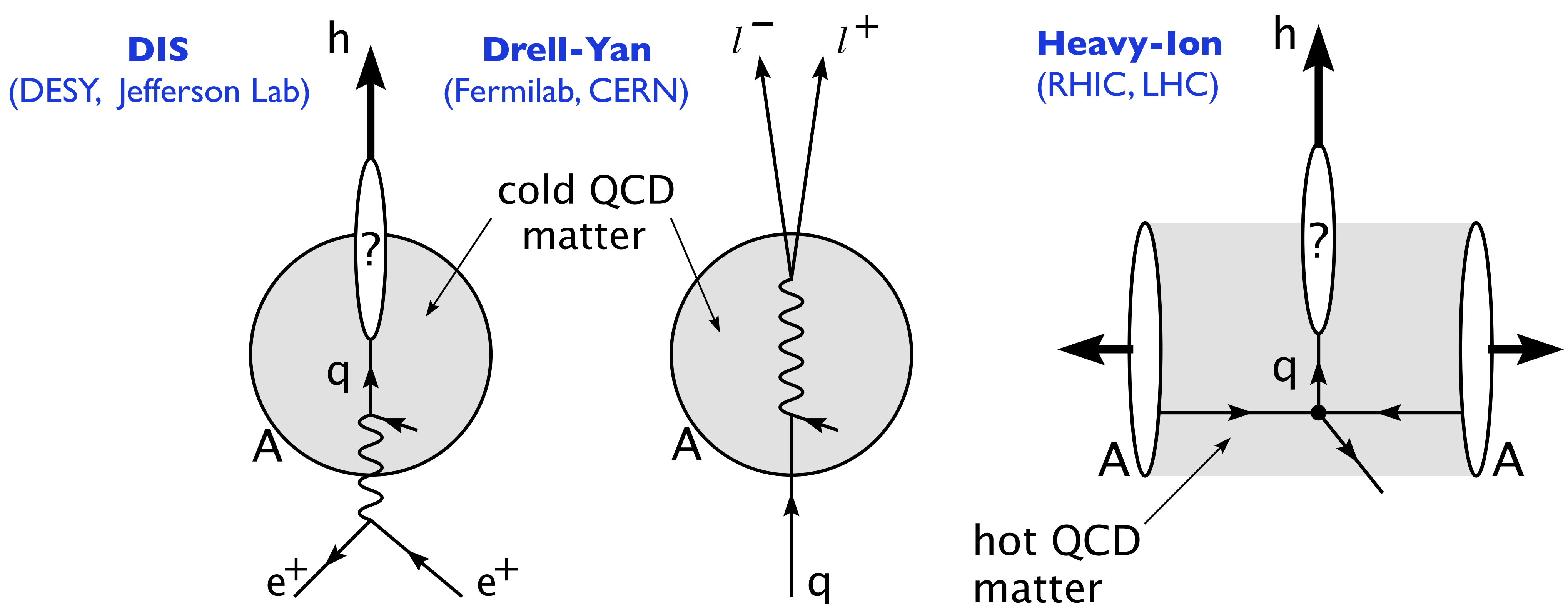


Quark propagation and hadron formation

Fundamental QCD process

- describes transition from colored d.o.f to colorless objects
- depends on flavor, mass and baryon number

Strong connection to neutrino physics and rest of nuclear HEP



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

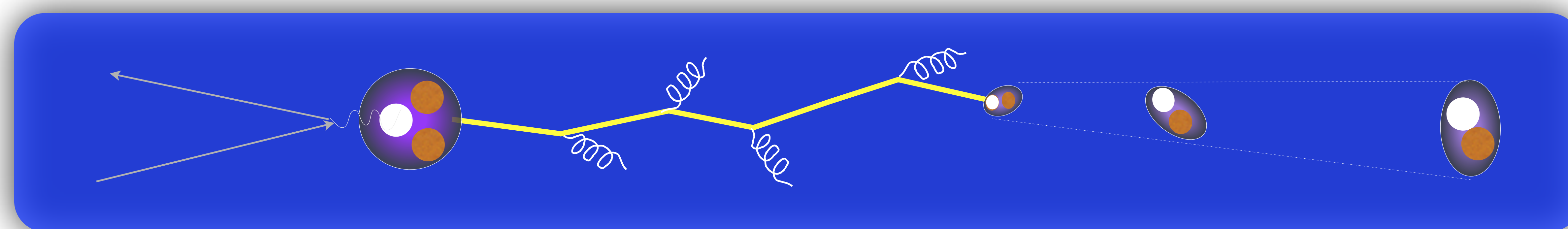
In-medium hadron formation in DIS

How long can an energetic quark remain ‘free’?
How do hadrons form from quarks?

Partonic elastic scattering in medium

Gluon bremsstrahlung
Parton rescattering
Quark energy loss

Color neutralization
Hadron formation
Final state interaction



τ_C

Color lifetime τ_C

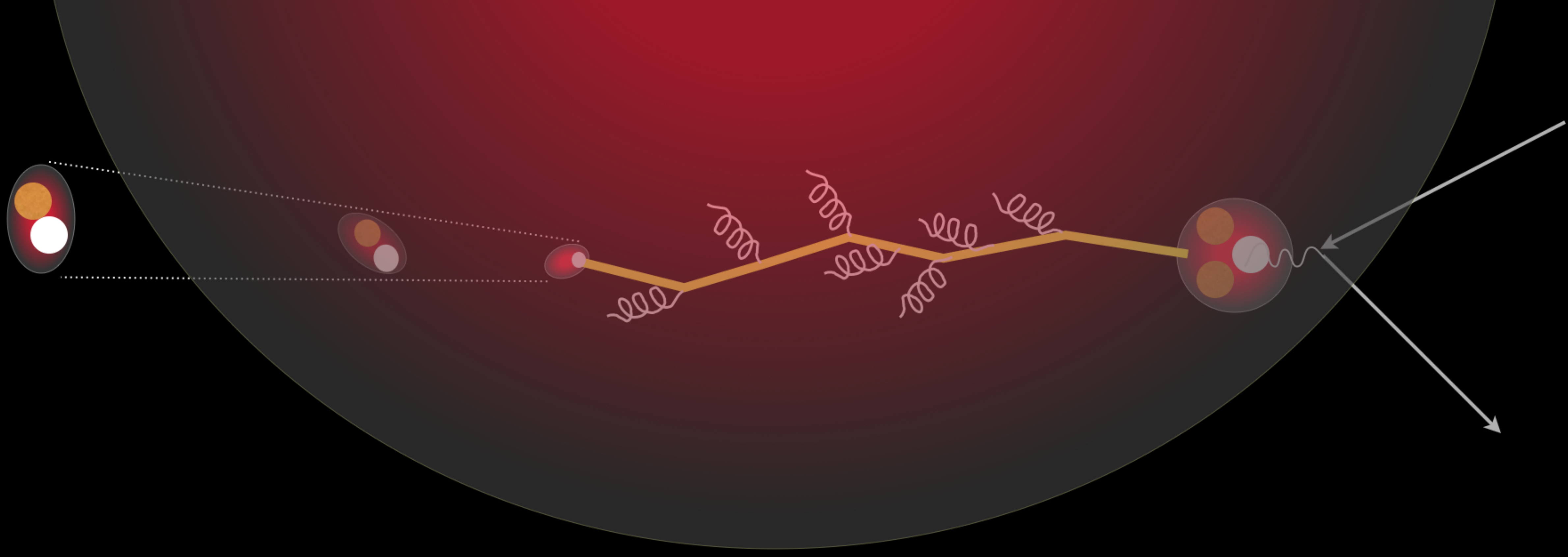
lifetime of highly virtual ‘free’ quark

τ_f

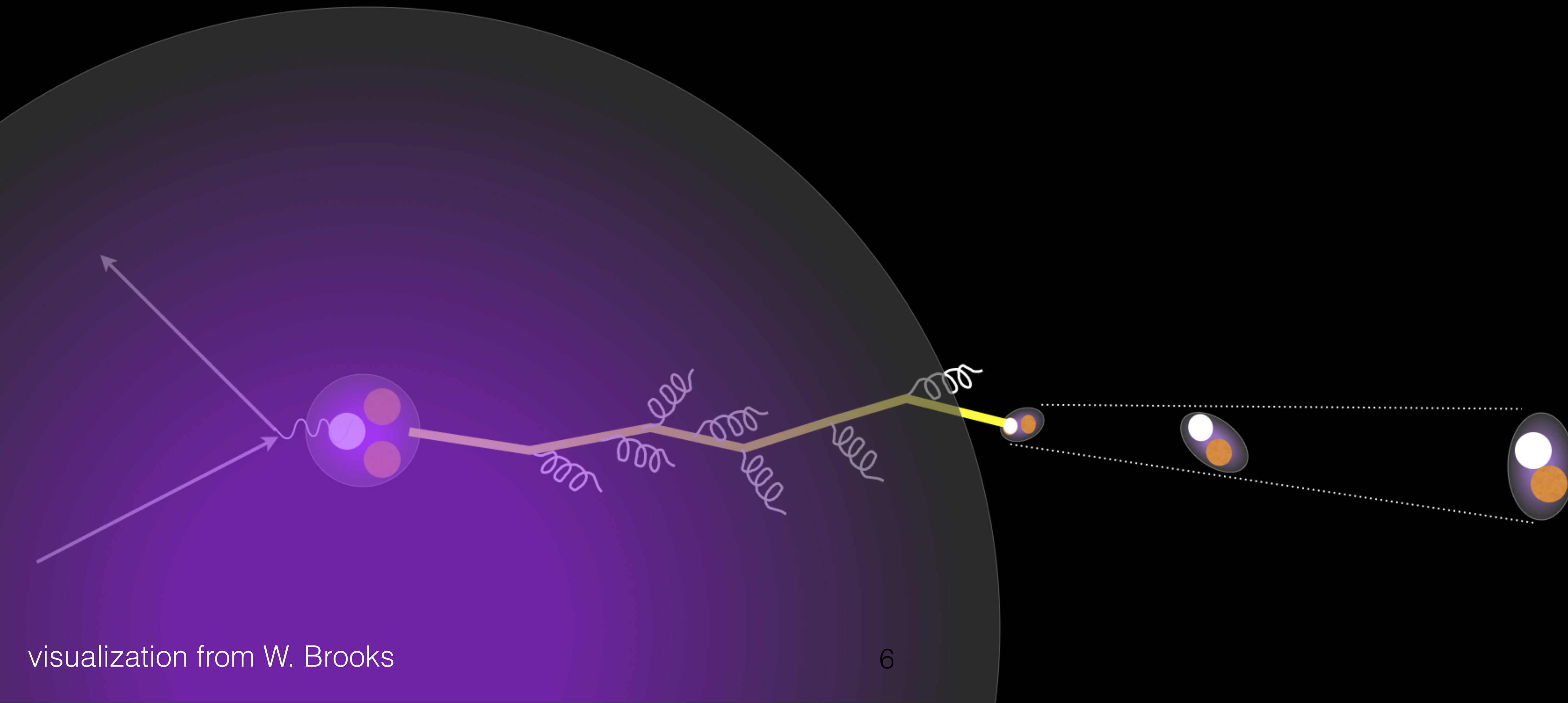
Formation time τ_f

time required for a colored system to evolve into a colorless

Methodology



Use nuclei of increasing size as space-time analyzer



visualization from W. Brooks

Observables

Transverse momentum broadening

Connects to color lifetime τ_p , quark k_T,
transport coefficient qhat and quark E 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
In-medium interaction of forming hadron

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

HERMES data

One dimensional

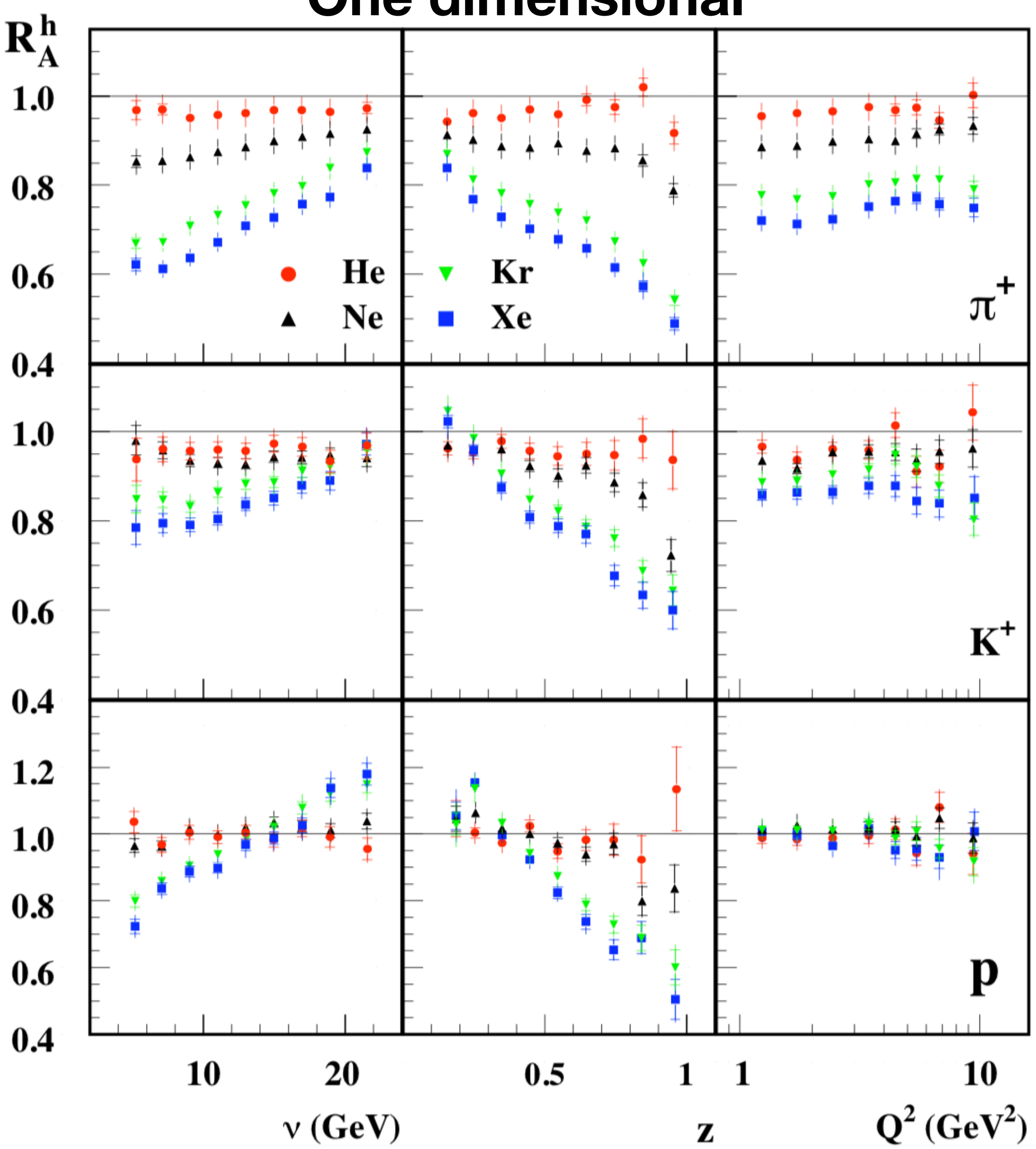


Fig. 2. Values of R_A^h for positively charged hadrons as a function of ν, z, and Q^2. The data as a function of ν are shown for $\nu > 4$ GeV and those as a function of z for $z > 0.1$. The inner error bars represent the statistical uncertainty, while the outer ones show the total uncertainty. https://arxiv.org/abs/0704.3270v1

Two dimensional

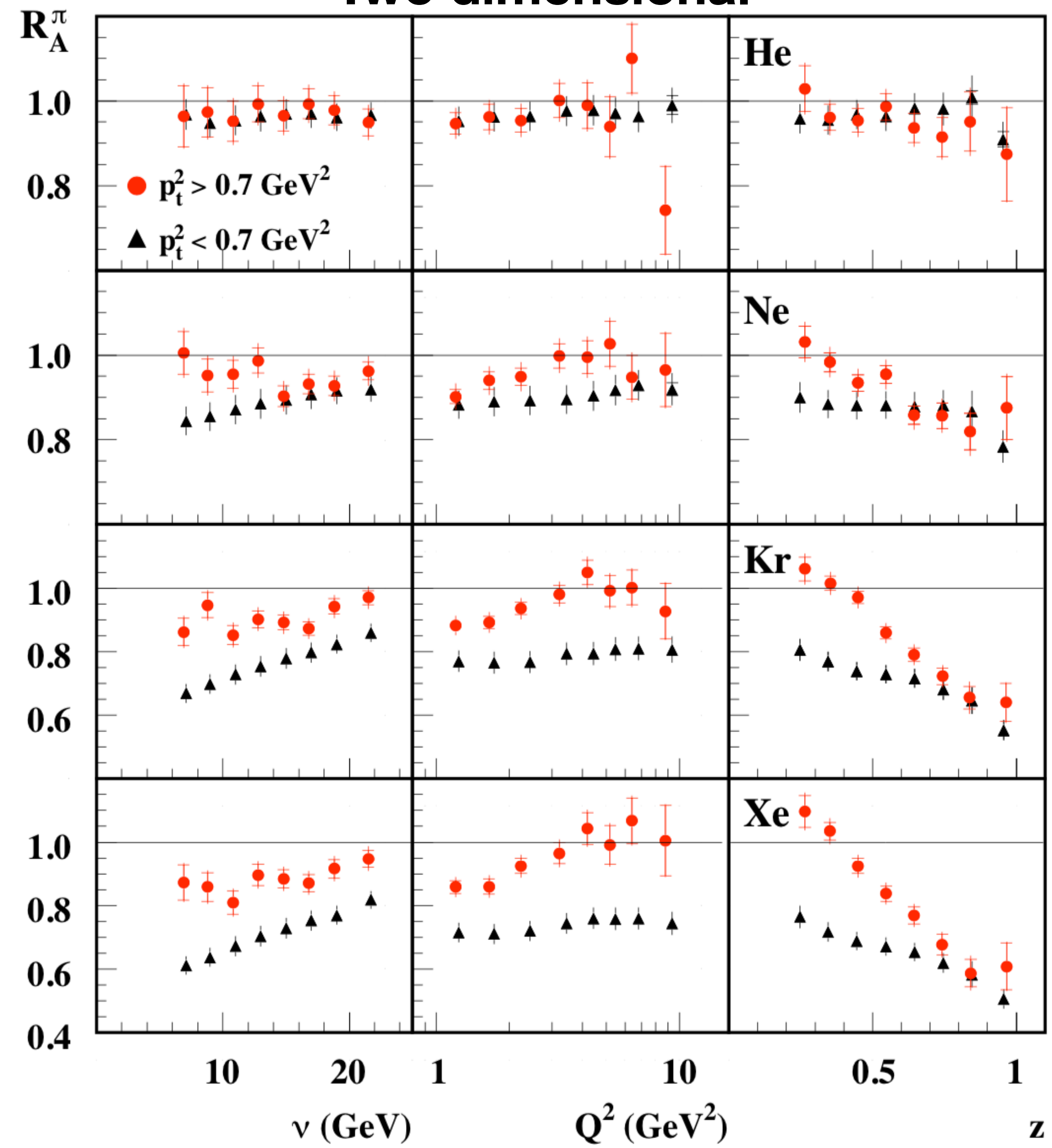
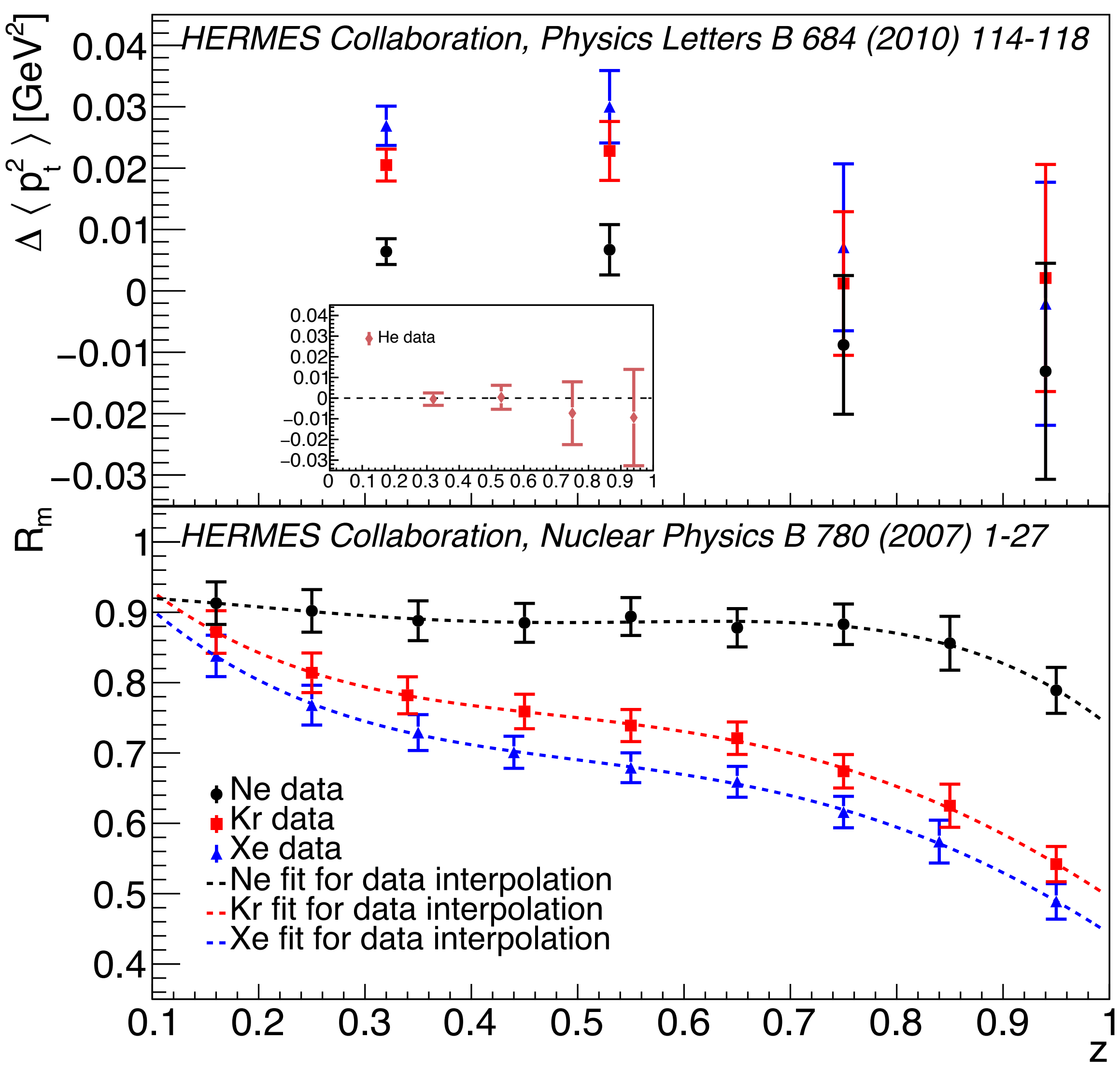
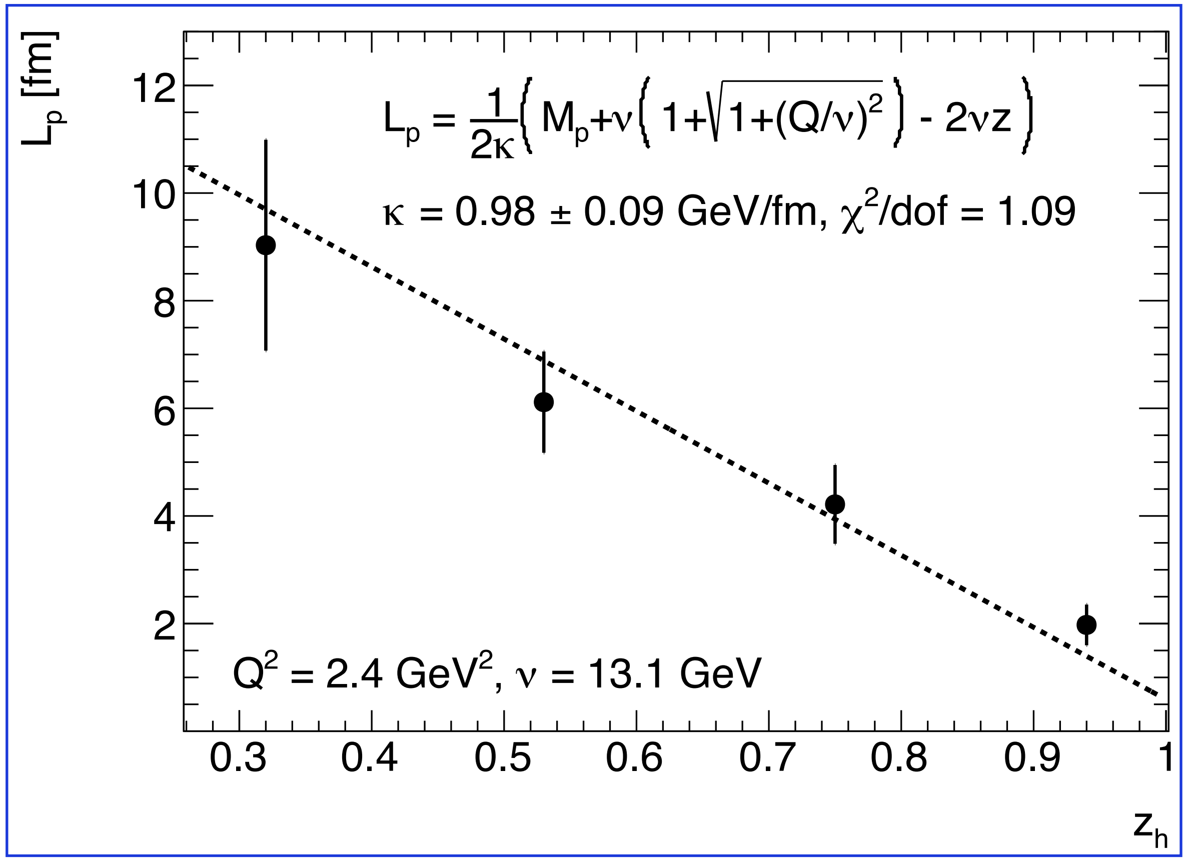


Fig. 8. Values of R_A^h for charged pions for two p_t^2 ranges. Error bars as in Fig. 2.

Extraction of color lifetime Brooks-Lopez model

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





J.Lopez, W.Brooks DIS2018

Quark energy loss of hadron absorption?

<u>Pure quark energy loss models:</u> *a la* BDMPS (Arleo; Accardi)

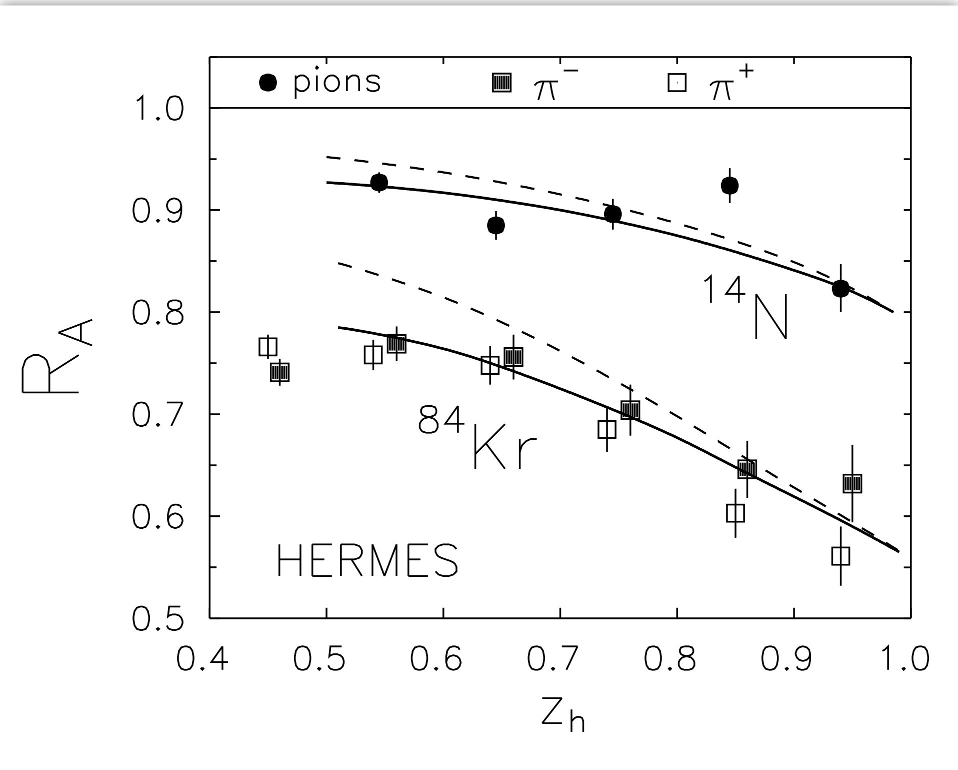
Higher twist FF (Wang; Majumder)

<u>Pure hadron absorption models:</u> GiBuu transport Monte Carlo

(Falter, Gallmeister)

<u>Color dipole model</u>: quark energy loss + prehadron absorption

(B.Kopeliovich)



Kopeliovich et al., NPA 740(04)211

Both mechanisms based on absorption of color dipole qqbar (dashed) and absorption and quark energy loss (solid) describe the data!

Need higher precision data!

Experimental realization

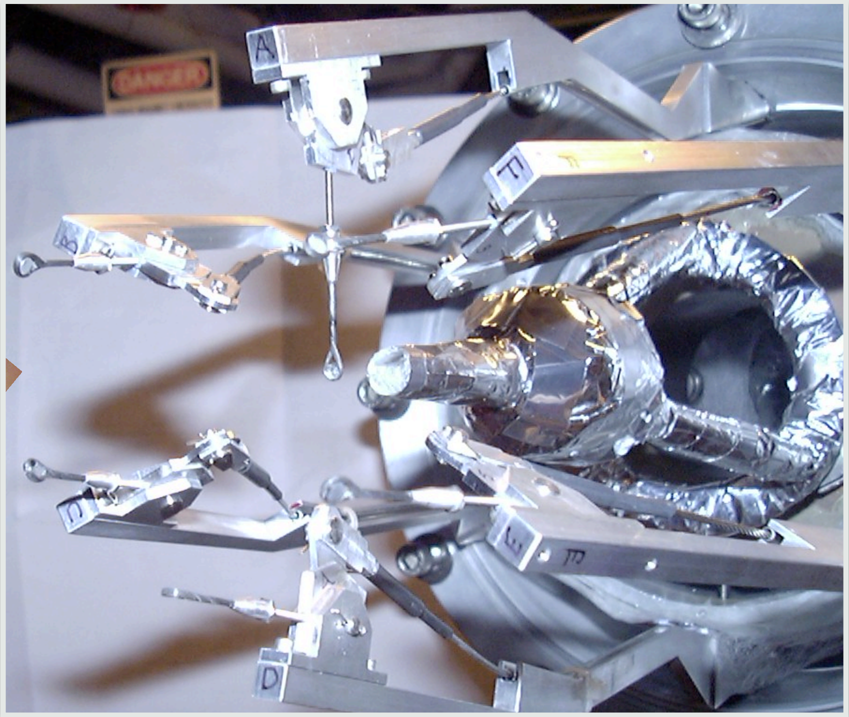
EG2 experiment @ 5 GEV

By using dual target approach, EG2 experiment makes a *precise* comparison of observables in a large nucleus A with respect to a small D

EG2 experiment running conditions

- Electron beam 5.014 GeV
- Targets ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb (Al, Sn)
- Luminosity $2 \cdot 10^{34}$ $1/(s \cdot cm^2)$

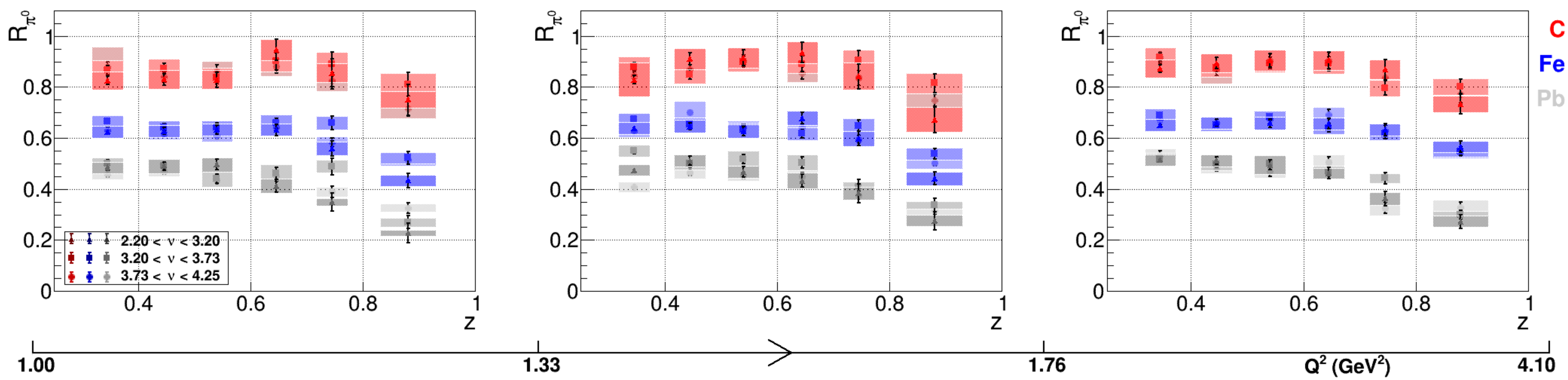
"A double-target system for precision measurements of nuclear medium effects," H. Hakobyan et al. NIM A 592 (2008) 218– 223



Results: 3D pion multiplicities

π^0 multiplicity ratios from EG2

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



CLAS preliminary

Attenuation depends on nuclear size

Hadron attenuation at high z (z>0.6)

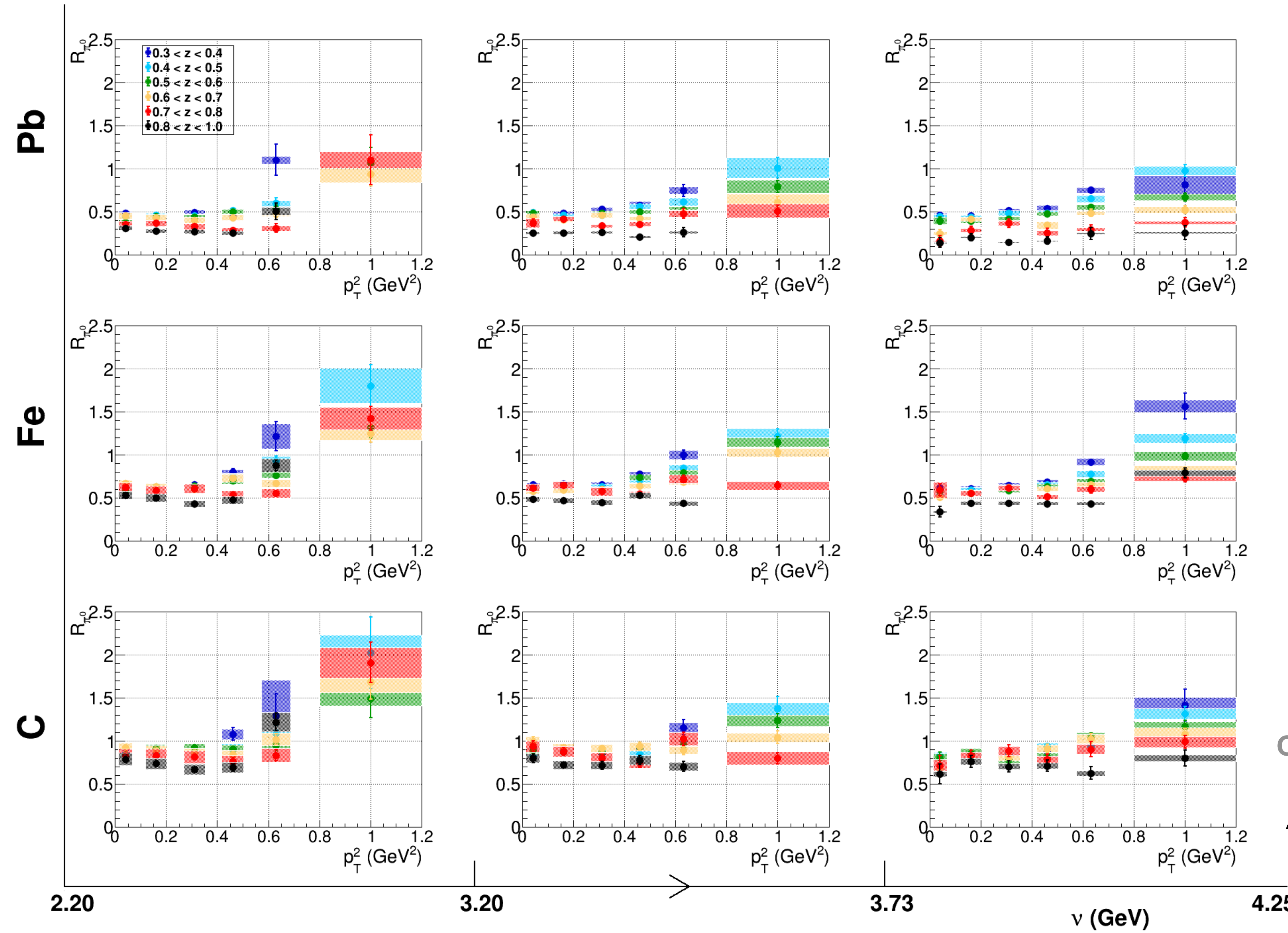
Quantitatively is compatible with Hermes

T.Mineeva
Analysis under review

Statistical uncertainties given by error bars; systematical - by color bars

π^0 multiplicity ratios from EG2

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



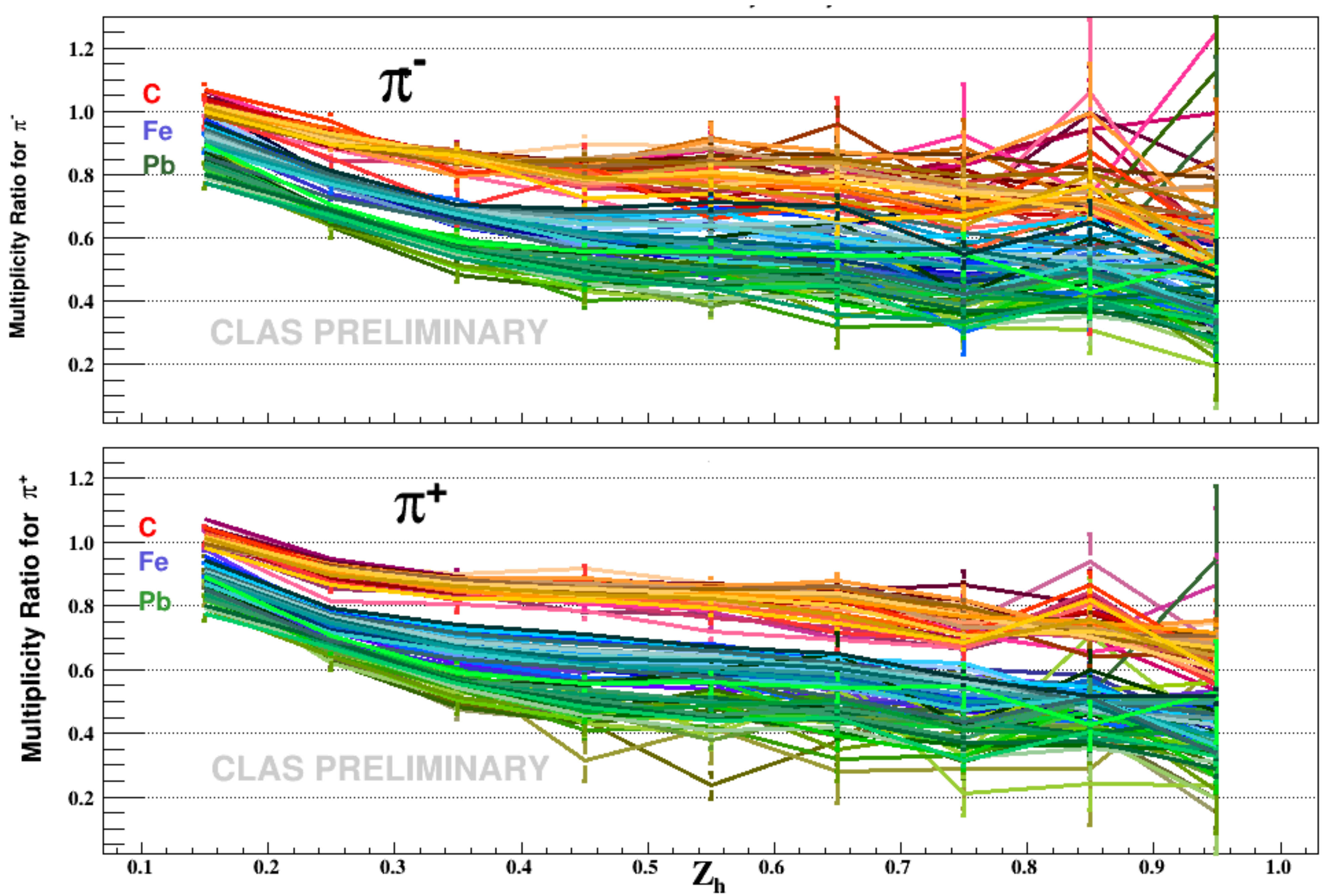
CLAS preliminary

T.Mineeva

Analysis under review

Charged π multiplicity ratios from EG2

3D π^+ and π^- Multiplicities $R_\pi(Q^2, \nu, z)$



H.Hakobyan, S.Moran
under review

Also on the way multiplicities of

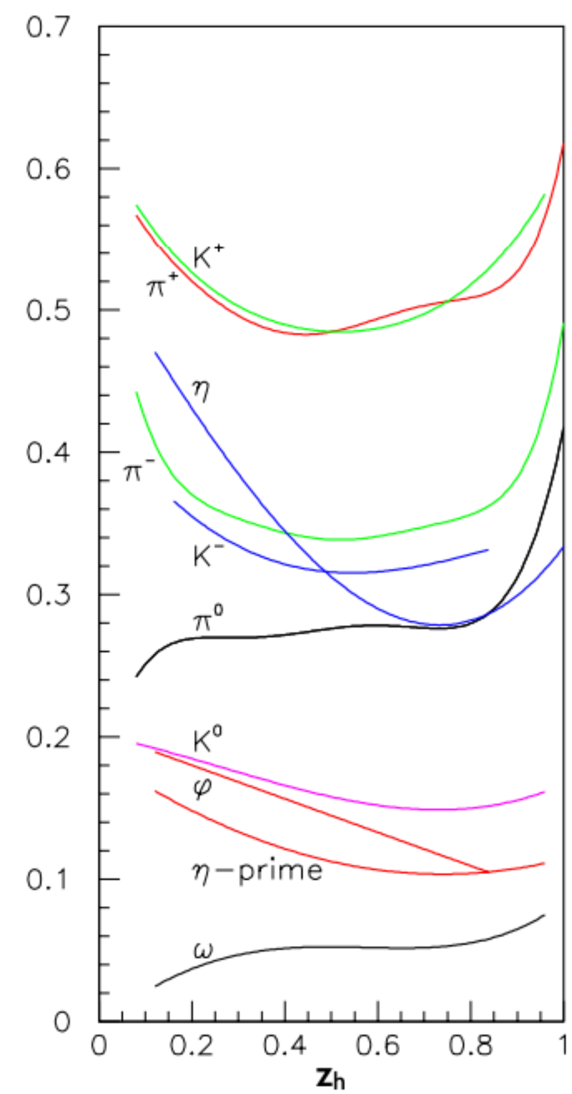
Λ, η and Omega

Future @ CLAS 12 at 11 GeV

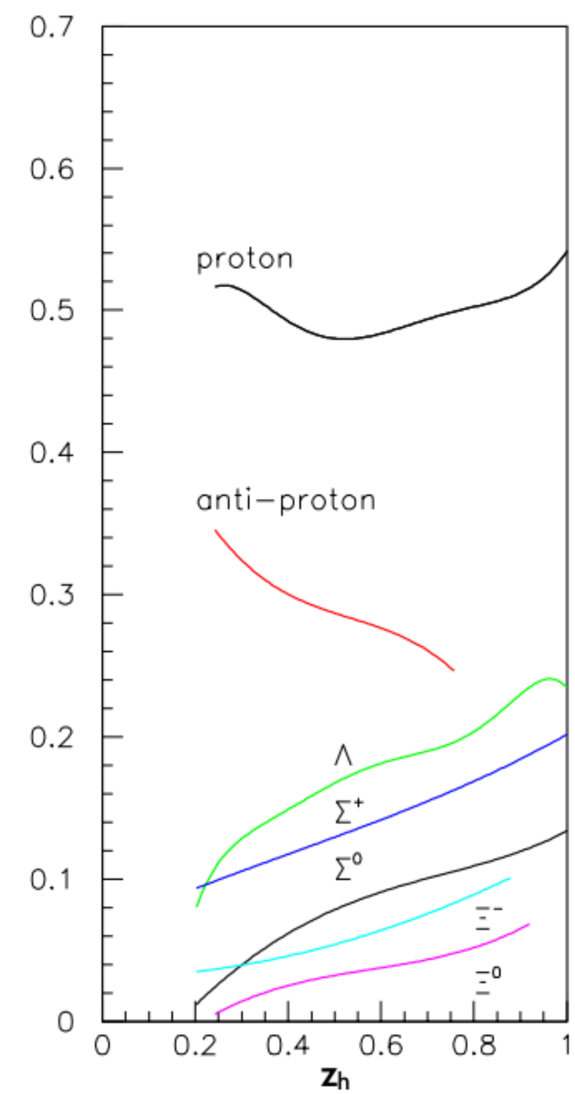
Planned targets: D, C, Al, Cu, Sn, Pb (no Fe due to strong magnetic fields)

Dependence of the observables on: mass, flavor and baryon number

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	5.7% (sys)
π^+, π	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$	3.2% (sys)
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	6.2% (sys)
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	6.7% (sys)
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	8.5% (sys)
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	5.0% (stat)*
f1	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	-
K^0	27 mm	0.50	$d\bar{s}$	4.7% (sys)
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$	4.4% (sys)
p	stable	0.94	ud	3.2% (sys)
$\bar{p}$	stable	0.94	$\overline{ud}$	5.9% (stat)**
Λ	79 mm	1.1	uds	4.1% (sys)
$\Lambda(1520)$	13 fm	1.5	uds	8.8% (sys)
Σ^+	24 mm	1.2	us	6.6% (sys)
Σ^-	44 mm	1.2	ds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	us	16% (stat)*
Ξ^-	49 mm	1.3	ds	7.8% (stat)*



CLAS12 Acceptance for Mesons



CLAS12 Acceptance for Baryons

Summary

- The microscopic information on space-time dynamics of hadronization can be accessed via DIS using nuclear medium of increasing size as an analyzer
- Transverse momentum broadening and hadronic multiplicity ratio observables provide insight on the lifetime of 'free' quark and formation of hadrons
- Past results provided first insights on hadronization mechanisms
  Need multidimensional data to constrain existing models
- CLAS at 6 GeV high luminosity data on ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb
  Extraction of three-dimensional pion multiplicities
  Analysis under review
- Future program with CLAS12 (E12-06-117) will provide higher statistics and enable extraction of 4D multiplicities for a large spectrum of hadrons.

Additional slide

HERMES @DESY and CLAS @Jefferson Lab

- HERMES has higher beam energy (27 GeV and 12 GeV, vs. 5 GeV)
- HERMES can identify a wider range of particle species
- CLAS has higher luminosity (10^{34}/cm2/s, ~factor 100)
  – Can do 3 and 4-fold differential binning (vs. 1-D or 2-D for HERMES)
  – Access to higher Q2 (good statistics for 4 GeV2) and higher pT2
- CLAS can use solid targets – Access to heaviest nuclei (^{207}Pb vs. ^{131}Xe)

	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