Multiplicity ratio measurements at CLAS

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University of Connecticut

Jefferson Lab

Hadronic multiplicity ratio and FF

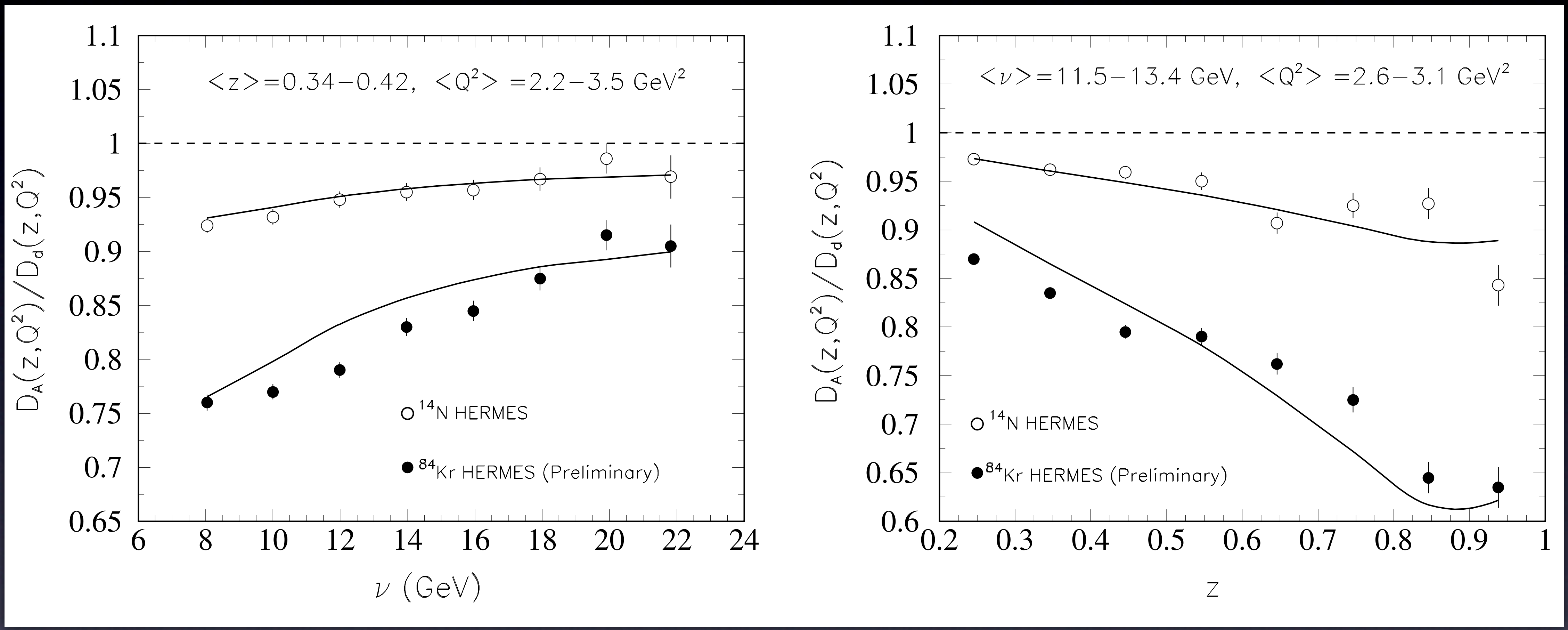
$$R_M^h(z,\nu) = \frac{\left\{\dfrac{N_h(z,\nu)}{N_e(\nu)}\right\}_A}{\left\{\dfrac{N_h(z,\nu)}{N_e(\nu)}\right\}_D} = \frac{\left\{\dfrac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}\right\}_A}{\left\{\dfrac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}\right\}_D}$$

experimental ratio of of hadrons
to electrons in DIS events for nucleus
A to deuterium (D)

QPM expression

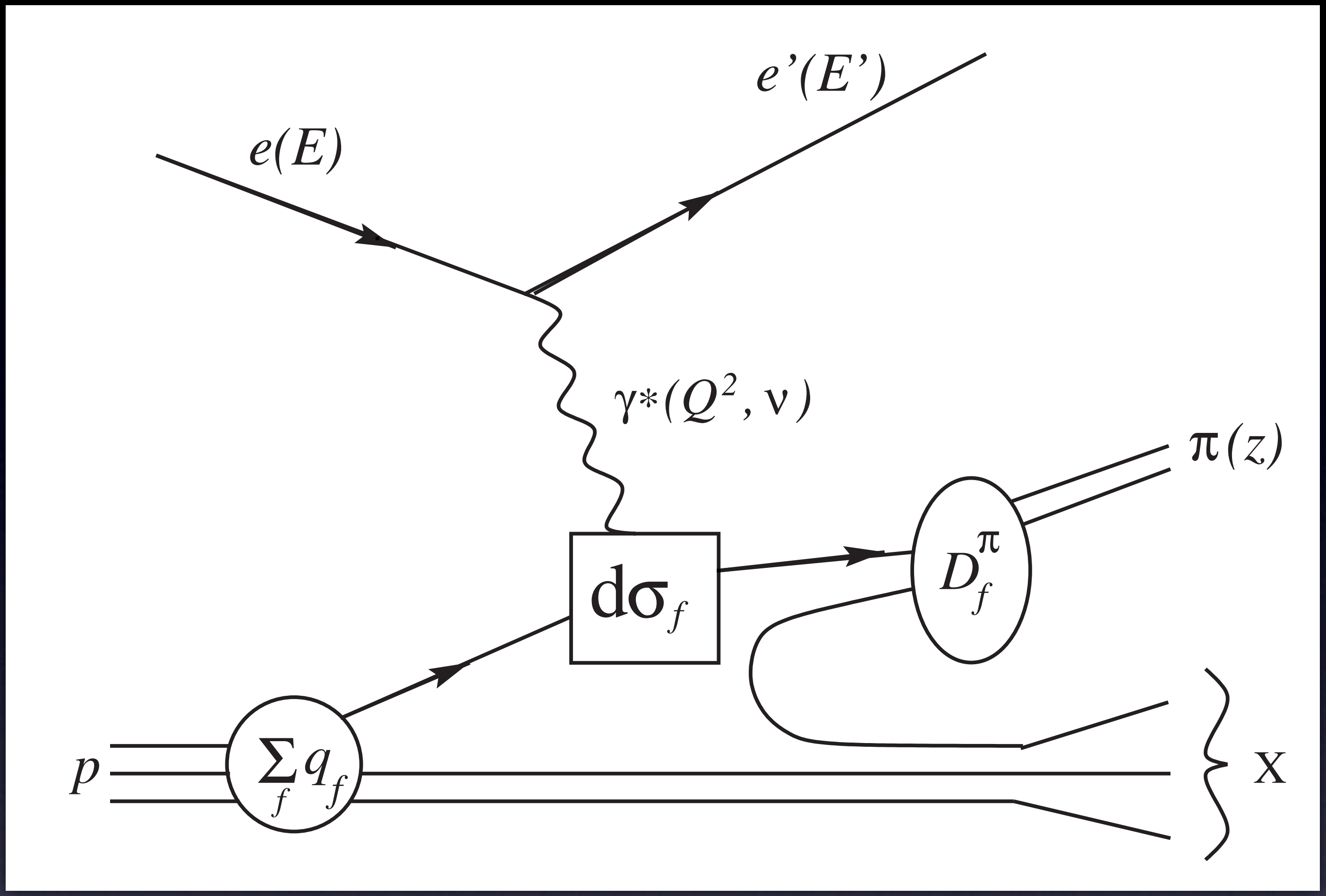
Hadronic multiplicity ratio and FF

Prediction of nuclear FF compared to HERMES data on $\pi^{\pm}$



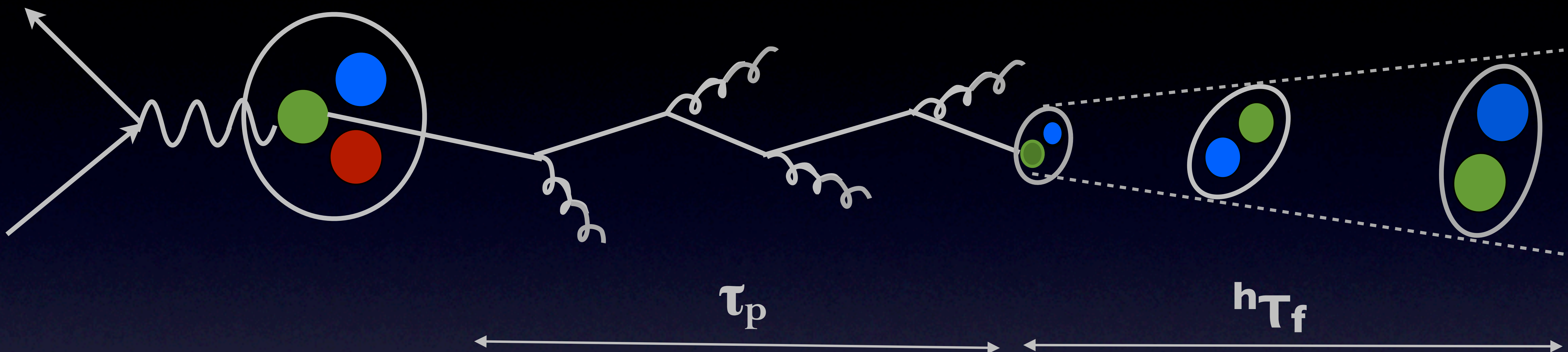
GuoXandWangXN2000*Phys.Rev.Lett.***85**3591 Wang E and Wang X N 2002 *Phys. Rev. Lett.* **89** 162301-1

SIDIS



$\mathbf{Q^2}$ = -$q2$ four-momentum transferred by the electron
ν = E-E‘ (lab) energy transferred by the electron;
z = Eh/ν fraction of initial quark energy carried by hadron;
$\mathbf{p_T}$ hadron momentum transverse to the initial γ^* direction

Physical picture: DIS in vacuum



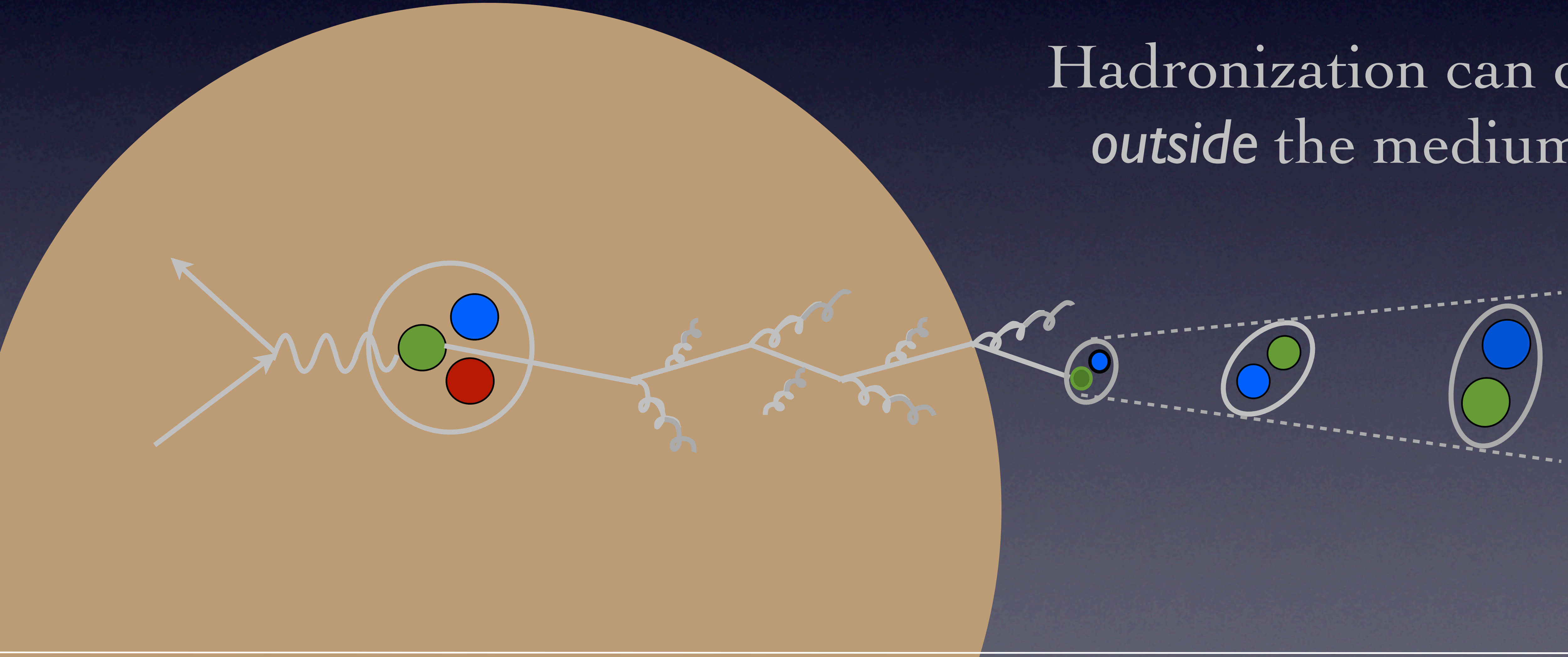
Production time τ_p - propagating quark

Formation time τ_f - dipole grows to hadron

Physical picture: DIS in medium

Partonic multiple scattering
medium-stimulated gluon emission

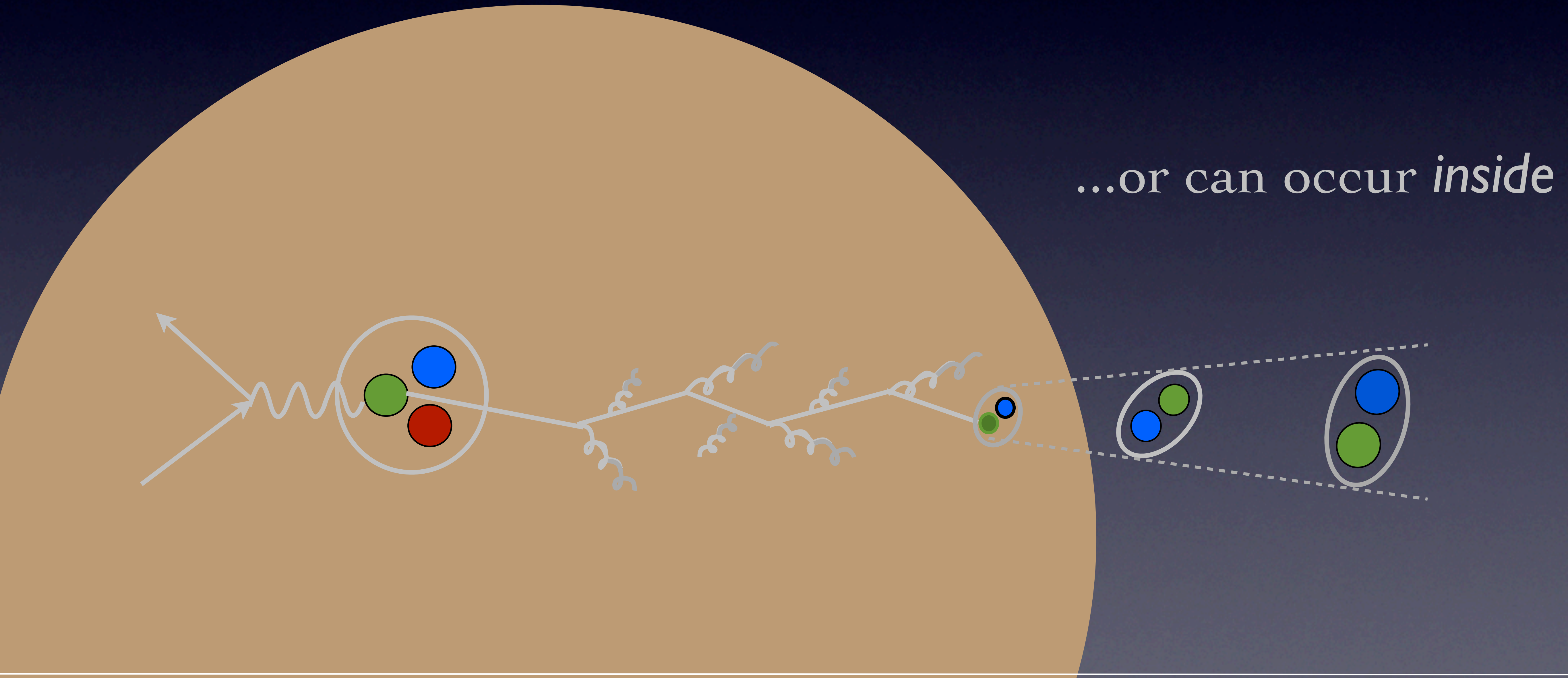
Hadronization can occur
outside the medium or...



Physical picture: DIS in medium

Partonic multiple scattering
medium-stimulated gluon emission

Additional prehadron interaction

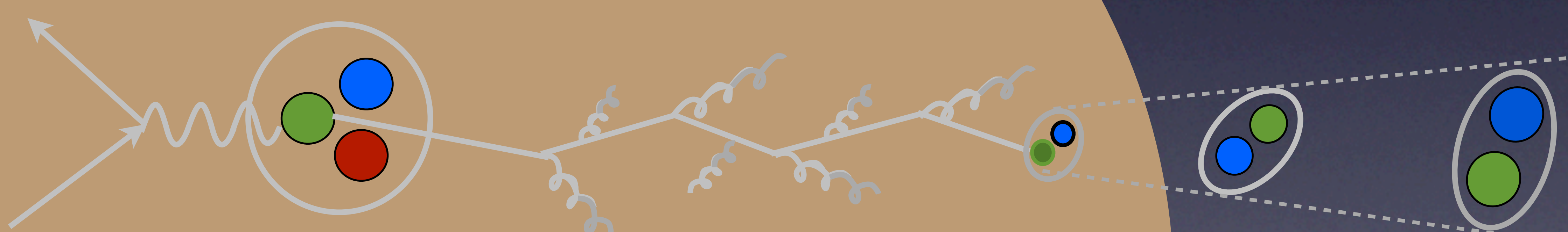


Physical picture: DIS in medium

Partonic multiple scattering
medium-stimulated gluon emission

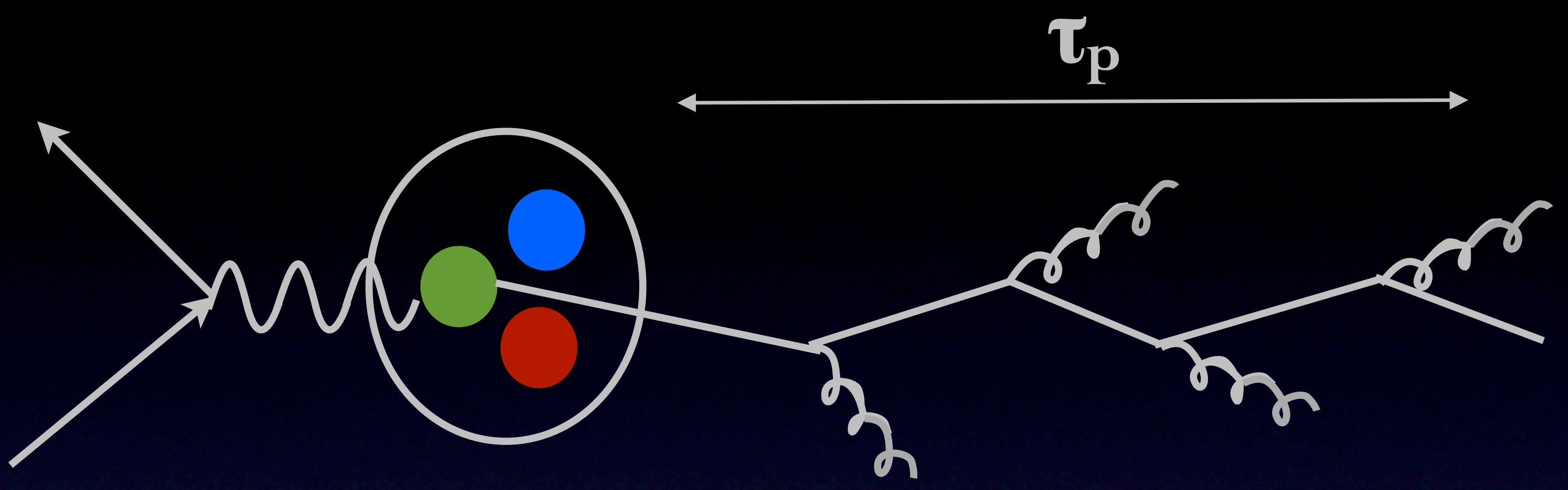
Additional prehadron interaction

...or can occur *inside*



Nuclear medium acts as spatial analyzer

Observables



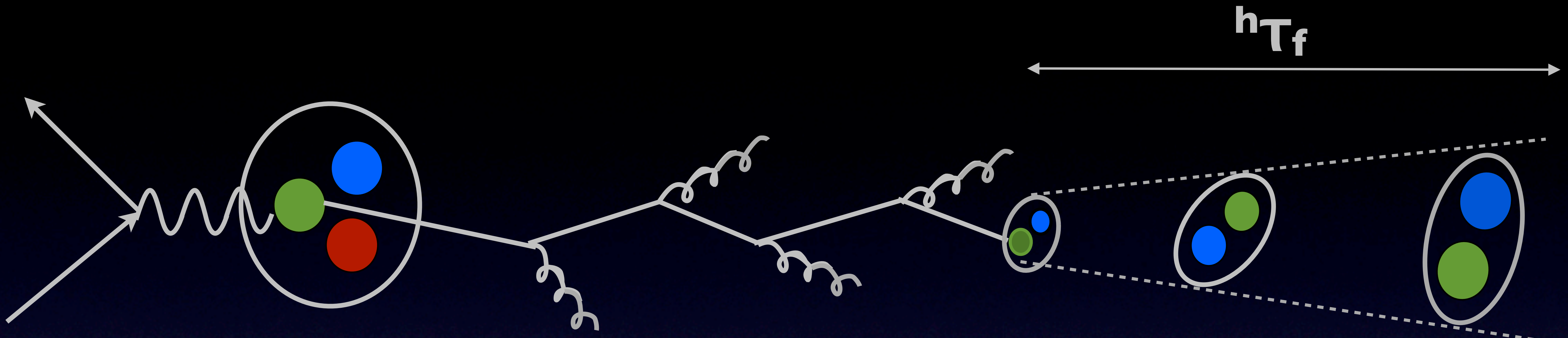
Transverse momentum broadening

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

Connects to partonic phase

- in-medium scattering
- quark energy loss
- access to production time τ_p

Observables



Hadronic multiplicity ratio

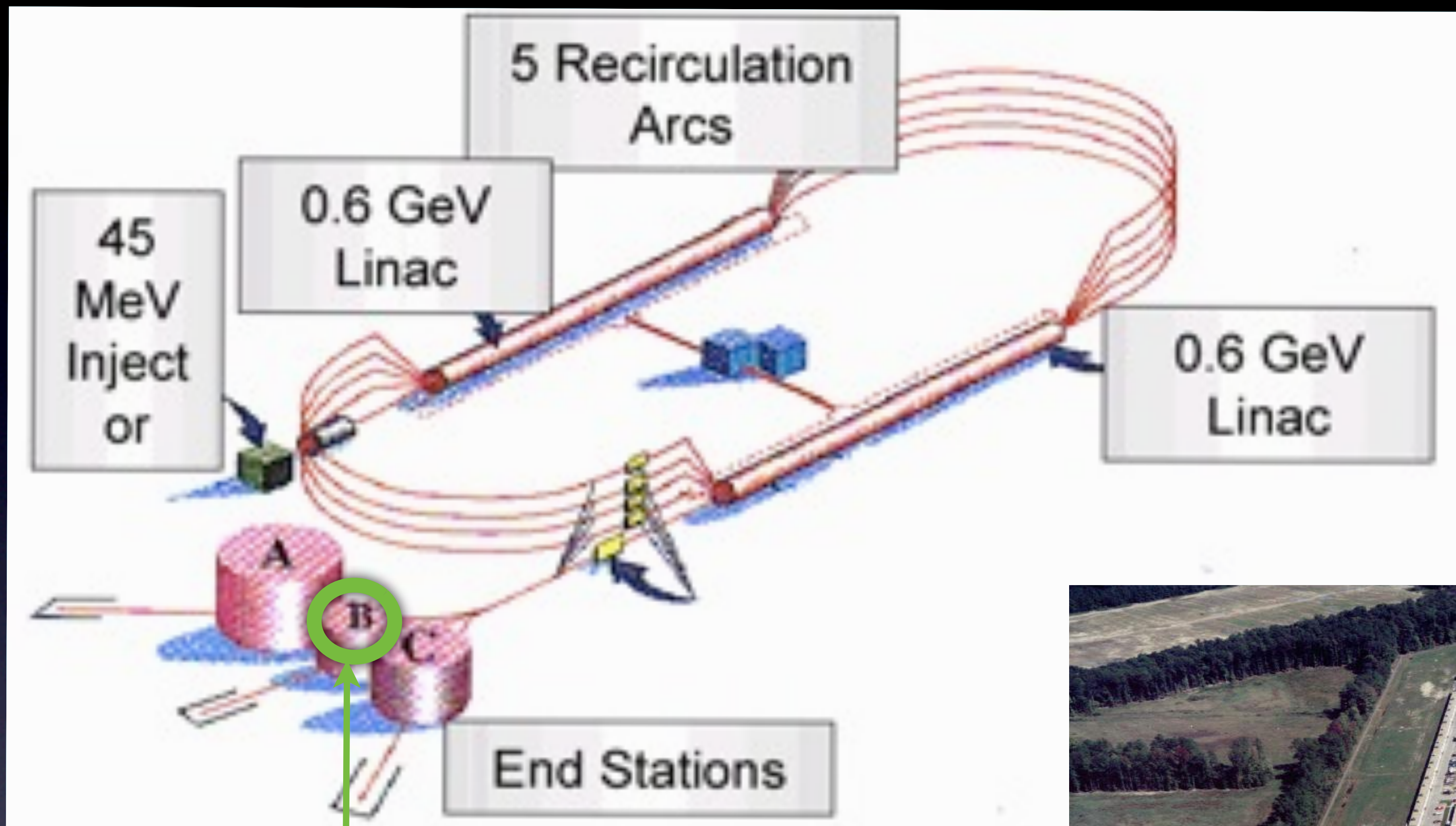
$$R_A^h\left(\nu, Q^2, z, p_T, \phi\right) = \frac{\left.\frac{N_h(\nu, Q^2, z, p_T, \phi)}{N_e(\nu, Q^2)|_{DIS}}\right|_A}{\left.\frac{N_h(\nu, Q^2, z, p_T, \phi)}{N_e(\nu, Q^2)|_{DIS}}\right|_D}$$

Connects to hadronic phase

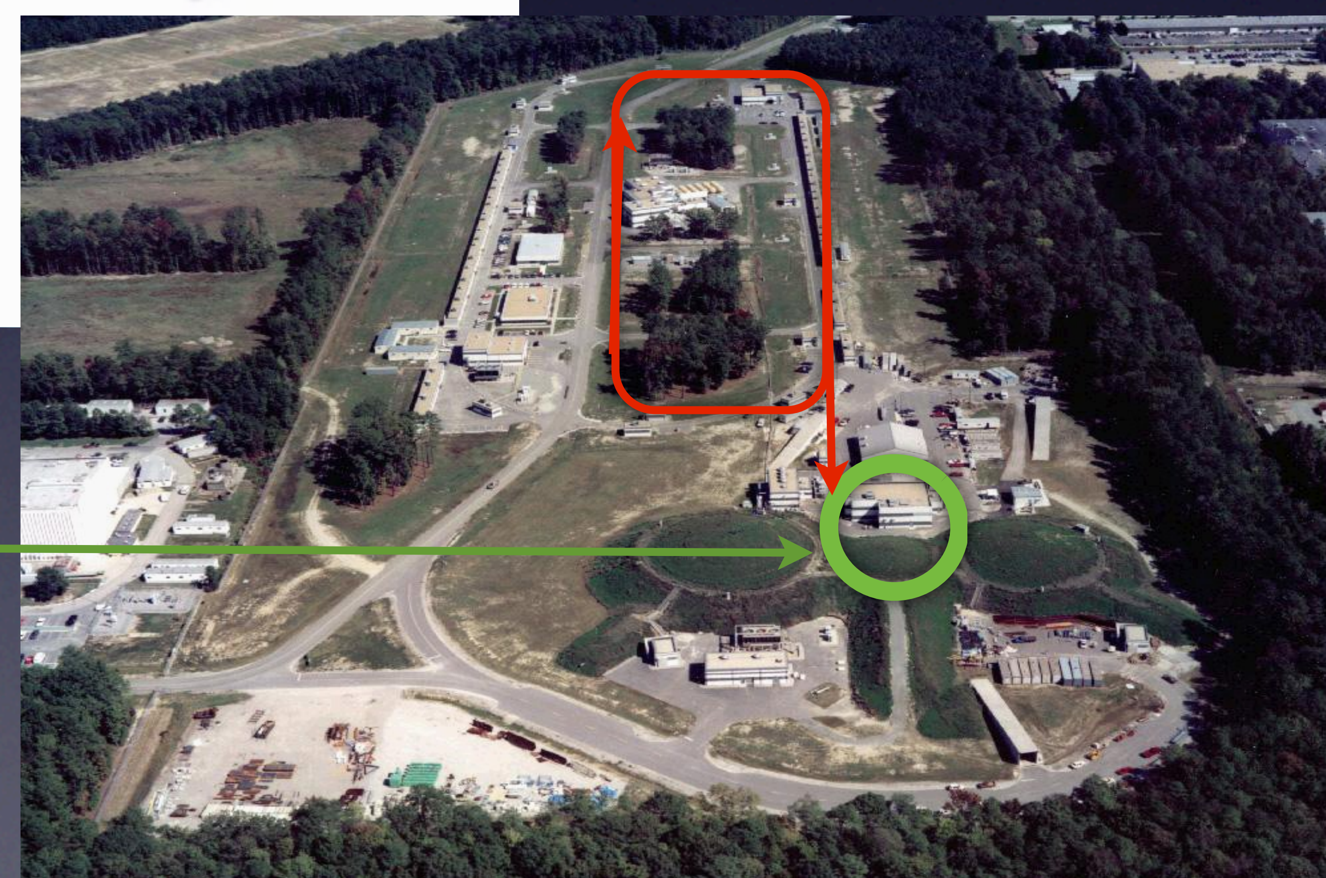
- hadron formation space-time mechanisms
- access to formation time τ_f via $R^h{}_A(Q^2, \nu, p_T, z_h)$

Experiment

CEBAF @ 6 GeV



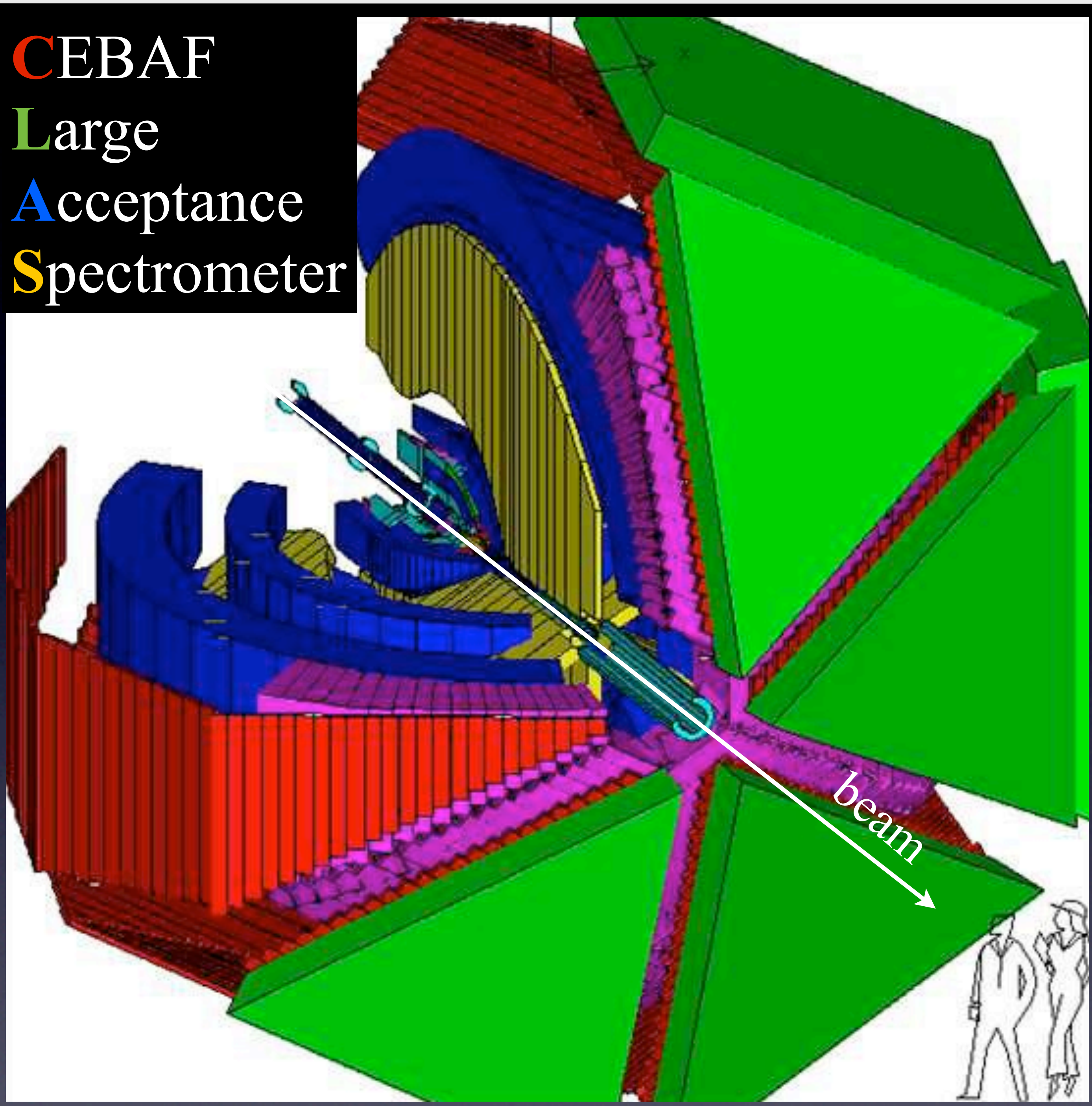
E_{max}	6 GeV
I_{max}	200 μA
Duty Factor	100%



Hall B CLAS

CLAS

- **Torus magnet**
  6 superconducting coils
  bend particles trajectory
- **Drift chambers** ($e^{\pm}$, $\pi^{\pm}$, p)
  filled with Ar/CO_2
  determination of charged particle momentum
- **Čerenkov counters**
  filled with C_4F_{10} gas
  π/e separation up to 2.5 GeV/c
- **Time-Of-Flight counters**
  plastic scintillators and PMTs
  determine particle velocity
- **Electromagnetic calorimeters**
  alternating Pb/scintillator layers
  determines energy of γ,n

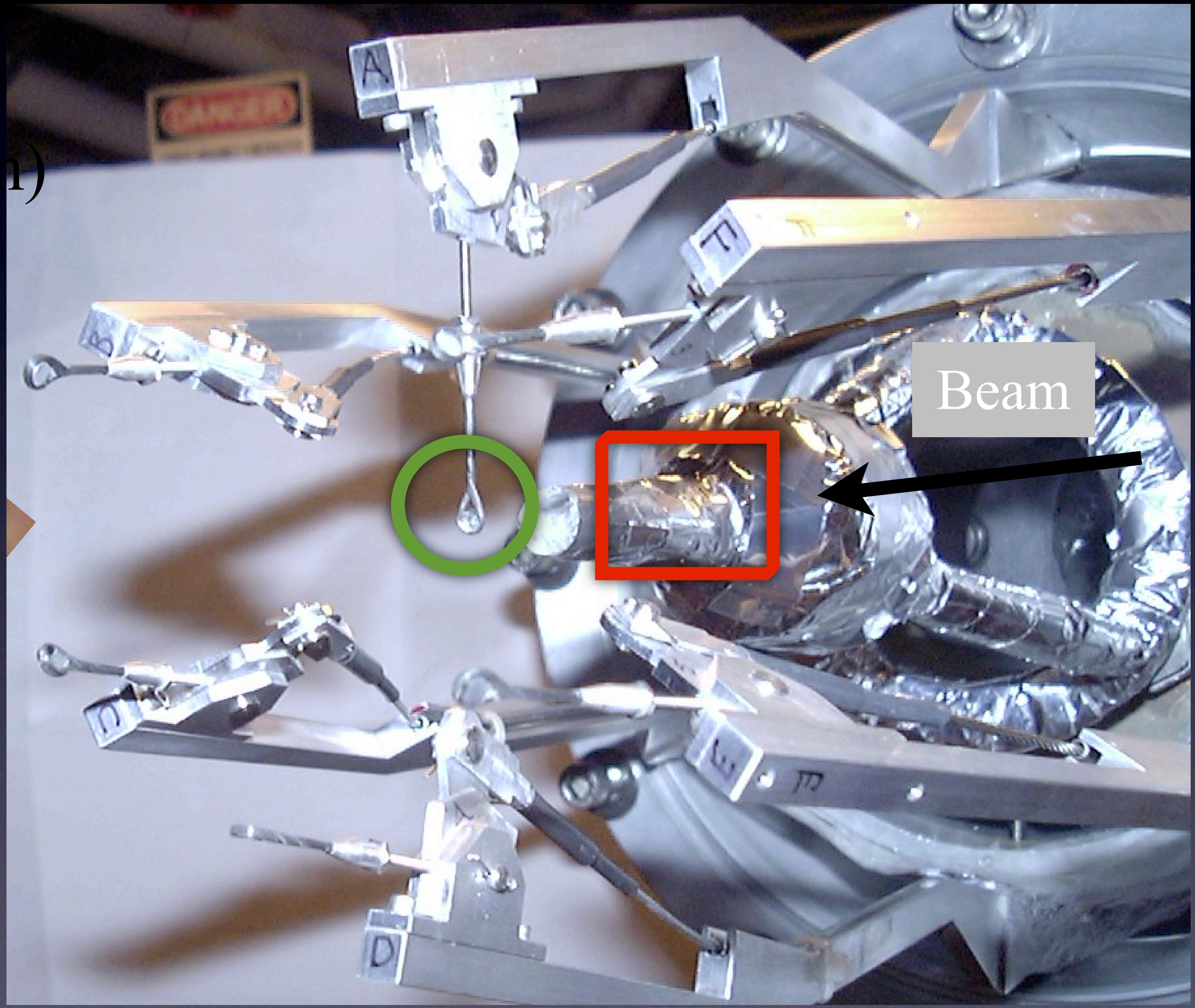


N. A. Mecking *et al.*, *The CEBAF large acceptance spectrometer (CLAS)*, Nucl. Inst. and Meth. A 503, 513 (2003).

Experiment EG2

Proposed by W.Brooks *et. al* in 'Quark Propagation Through Cold QCD Matter'

- Electron beam 5.014 GeV
- Running for 50 days (2004)
- Targets **^{2}H**, **^{12}C**, **^{56}Fe**, **^{208}Pb** (Al, Sn)
- Luminosity $2 \cdot 10^{34}$ $1/(s \cdot cm^2)$
- $N_{DIS}(e) \sim 1.3 \cdot 10^{8}$



H.Hakobyan, W.K.Brooks *et al.*, *A double-target system for precision measurements of nuclear medium effects*, Nucl. Inst. and Meth. A592, pages 218-223 (2008).

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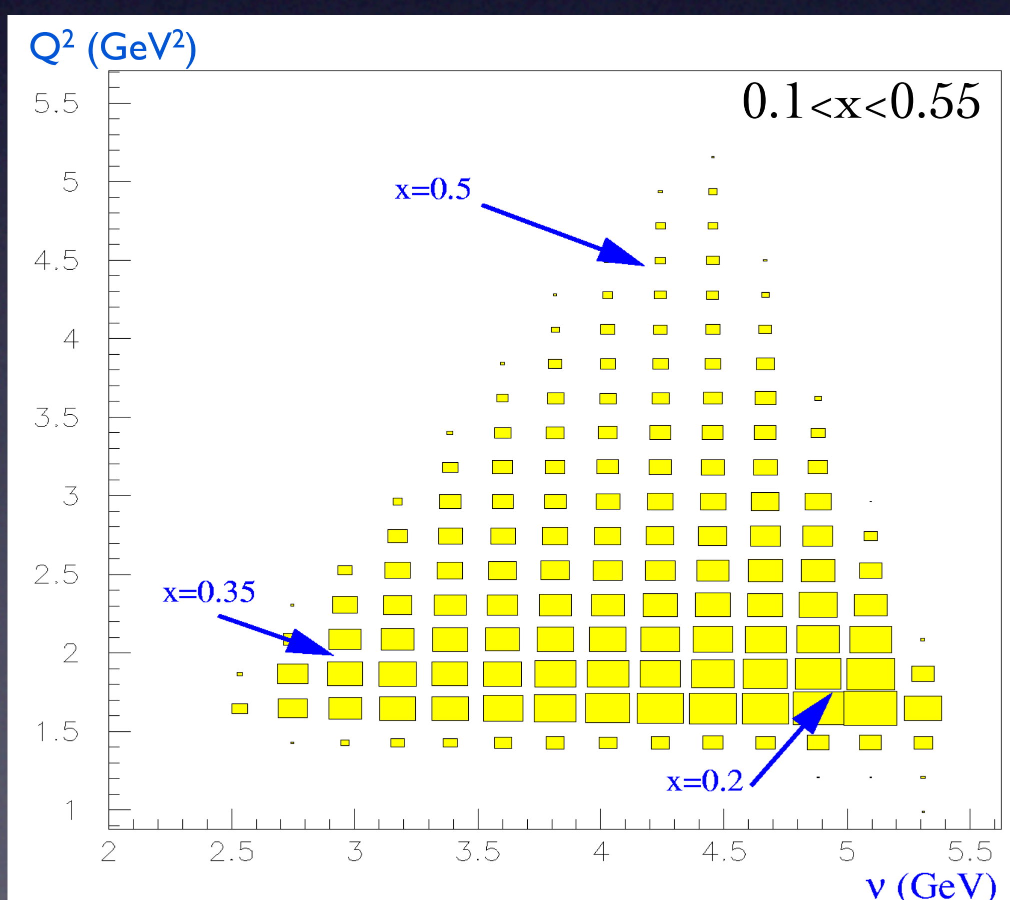

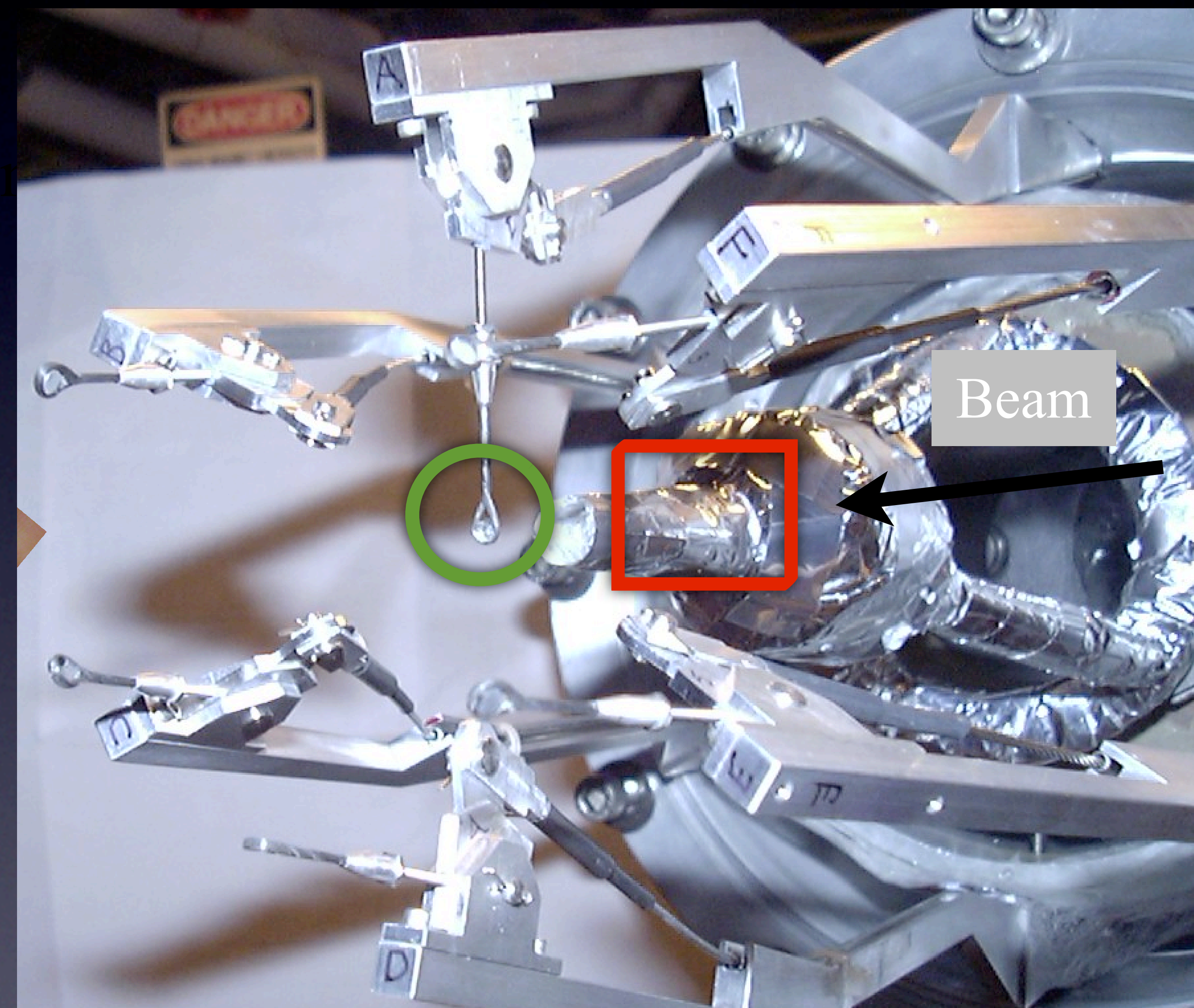

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Comparison of HERMES/DESY and CLAS/Jefferson Lab

- HERMES has higher beam energy (27 GeV and 12 GeV, vs. 5 GeV)
  - Much wider range in ν
  - Access to higher W and W'
- 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 - 0.8	0 - 0.9
HERMES	7 - 23	1.0 - 10	0.2 - 1.0	0 - 1.1

Accesible hadrons

Actively underway with existing 5 GeV data

Hayk Hakobyan, Taya Mineeva, Raphaël Dupré, Lamiaa El Fassi, Aji Daniel, Ken Hicks, Ioana and Gabriel Niculescu

meson	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$
π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$
f1	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$
K^0	27 mm	0.50	$d\bar{s}$
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$

baryon	cτ	mass	flavor content
p	stable	0.94	ud
$\bar{p}$	stable	0.94	$\overline{ud}$
Λ	79 mm	1.1	uds
$\Lambda(1520)$	13 fm	1.5	uds
Σ^+	24 mm	1.2	us
Σ^-	44 mm	1.2	ds
Σ^0	22 pm	1.2	uds
Ξ^0	87 mm	1.3	us
Ξ^-	49 mm	1.3	ds

Available statistics

π^+	6.60M
π^-	2.85M
π^0	2.05M
K_s^0	32K
η	300K

Radiative Corrections

Radiative corrections (RC)

- Correction due to photon radiation in the field of nucleon or nuclei. Calculation of lowest order QED effects contributing to Born cross section.

$$R_A^h(\nu, Q^2, z, p_T, \phi) = \frac{\frac{\boxed{N_h(\nu, Q^2, z, p_T, \phi)}}{\boxed{N_e(\nu, Q^2)|_{\text{DIS}}}}\Big|_A}{\frac{\boxed{N_h(\nu, Q^2, z, p_T, \phi)}}{\boxed{N_e(\nu, Q^2)|_{\text{DIS}}}}\Big|_D}$$

- **Inclusive** ($eA \rightarrow e'A$) radiative corrections were calculated based on Mo&Tsai approach for target thickness A and D. They were found to vary from 8% up to 27%; the ratio of radiative corrections on D to A varies within 3%.
- **Semi-inclusive** ($eA \rightarrow e'\pi^0 X$) corrections and **exclusive** ($ep \rightarrow e'\pi^0 p$) contribution were calculated based on HAPRAD code. They were found to vary from ~1% up to ~30%; the ratio of radiative corrections on A to D varies at maximum up to 18%.

Radiative corrections: semi-inclusive

- Caveat: original HAPRAD code is designed to calculate RC for **π^+ on p(n)**.
- Solution: modify original code to calculate RC for **π^0 on A**.

Cross section of SI process is expressed in terms of four structure functions:

$$\sigma_{SIDIS} = \sigma_{SIDIS}(\mathcal{H}_1, \mathcal{H}_2, \mathcal{H}_3, \mathcal{H}_4)$$

$$\mathcal{H}_1 = \sum_q e^2 f_q D_q \mathcal{G}$$

$$\mathcal{H}_2 \approx \mathcal{H}_1$$

$$\mathcal{H}_3 = f(x, Q^2, z)|_{cos(\phi)} \sum_q e^2 f_q D_q \mathcal{G}$$

$$\mathcal{H}_4 = f(x, Q^2, z)|_{cos(2\phi)} \sum_q e^2 f_q D_q \mathcal{G}$$

$$\mathcal{G} = \frac{1}{2\pi\sigma} \cdot \exp - \frac{(p_T - \mu)^2}{2\sigma^2}$$

f_q is parton distribution function

D_q is parton fragmentation function

G is hadron transverse momentum distribution

I.Akushevich, A.Ilyichev, M.Osipenko, Lowest order QED radiative corrections to five-fold differential cross section of hadron leptoproduction, arXiv:0711.4789

Semi-inclusive RC: from proton to A

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G is hadron transverse momentum distribution

To transition from structure functions on proton to those on atomic nuclei A, we extract parametrizations ***G*** and ***ϕ*** from our data based on multidimensional fit to: $p_T(x,z)$ and $1+A(z)\cos(\phi) + B\cos(2\phi)$.

Semi-inclusive RC: from proton to A

- Caveat: original HAPRAD code is designed to calculate RC for **<u>π⁺ on p(n)</u>**.
- Solution: modify original code to calculate RC for **<u>π⁰ on A</u>**.

Cross section of SI process is expressed in terms of four structure functions:

$$\sigma_{SIDIS} = \sigma_{SIDIS}(\mathcal{H}_1, \mathcal{H}_2, \mathcal{H}_3, \mathcal{H}_4)$$

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***D*$_q$** is parton fragmentation function

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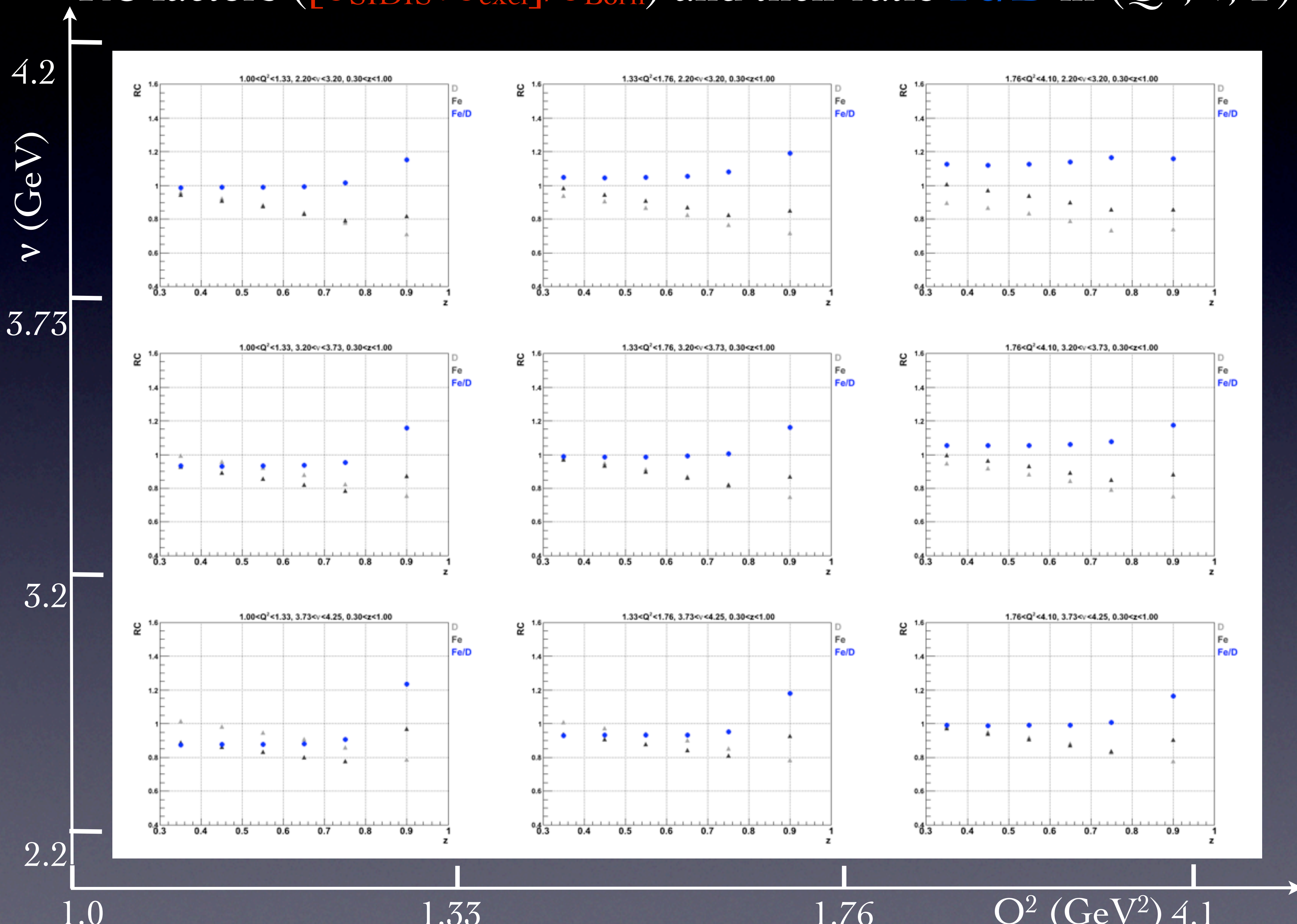
π^0 radiative corrections (RC)

RC factors ($[\sigma_{SIDIS+}\sigma_{excl}]/\sigma_{Born}$) and their ratio **Fe/D** in (Q^2 , ν, z)



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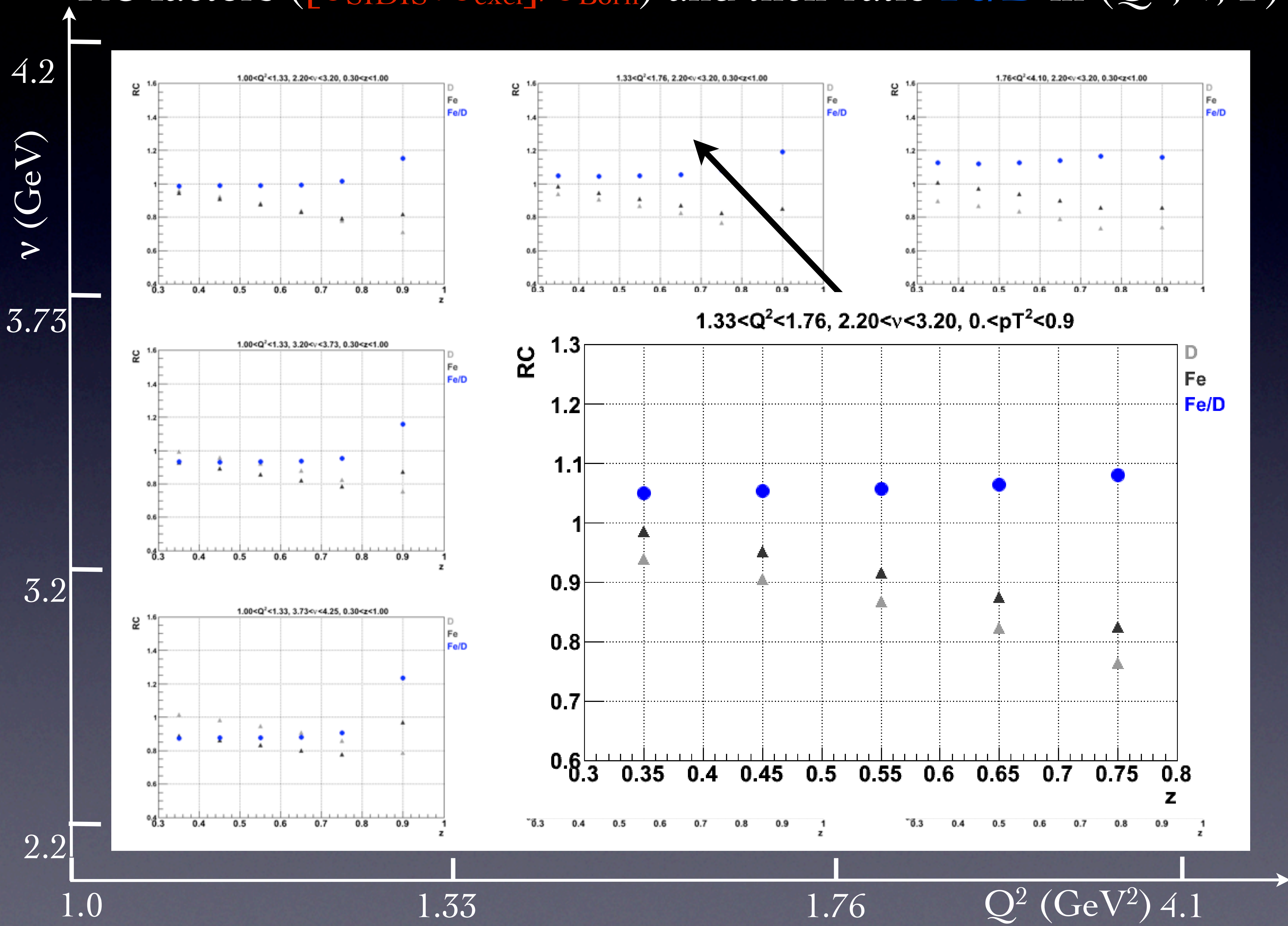
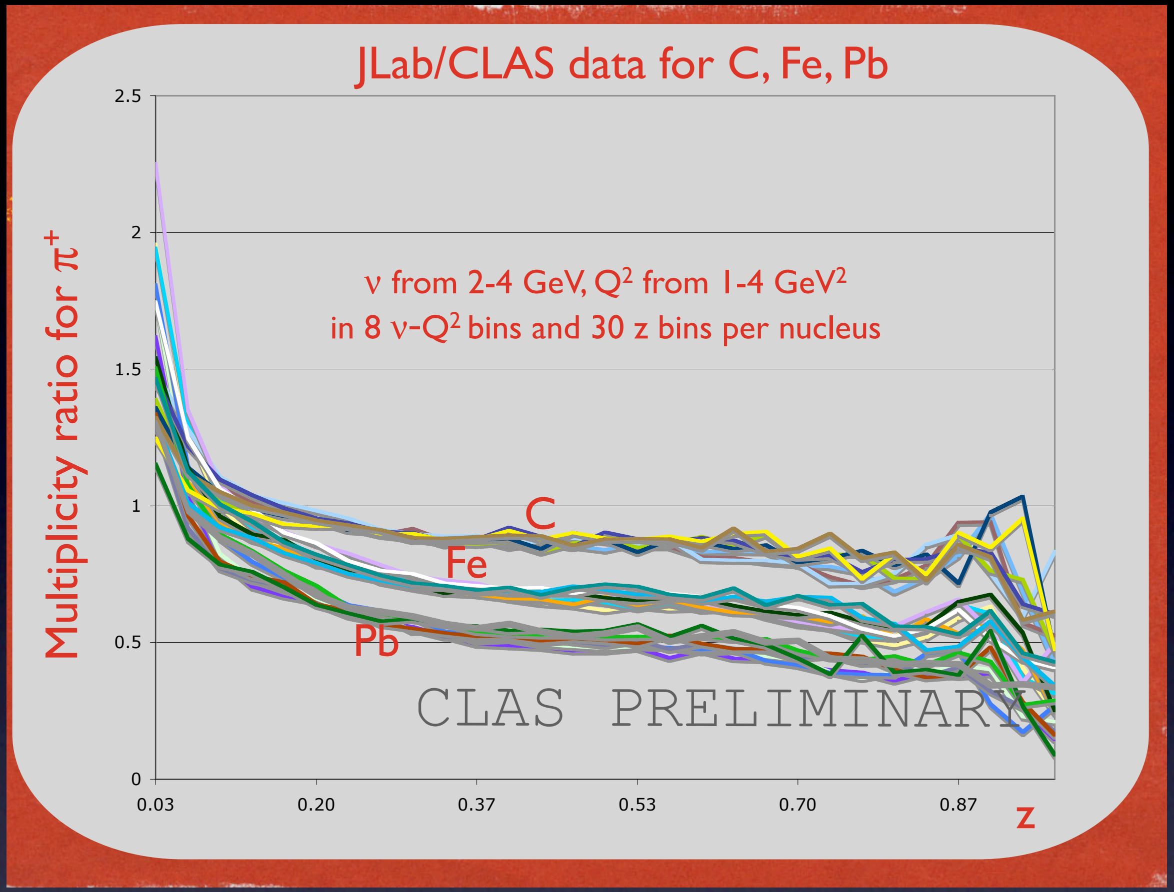


Results

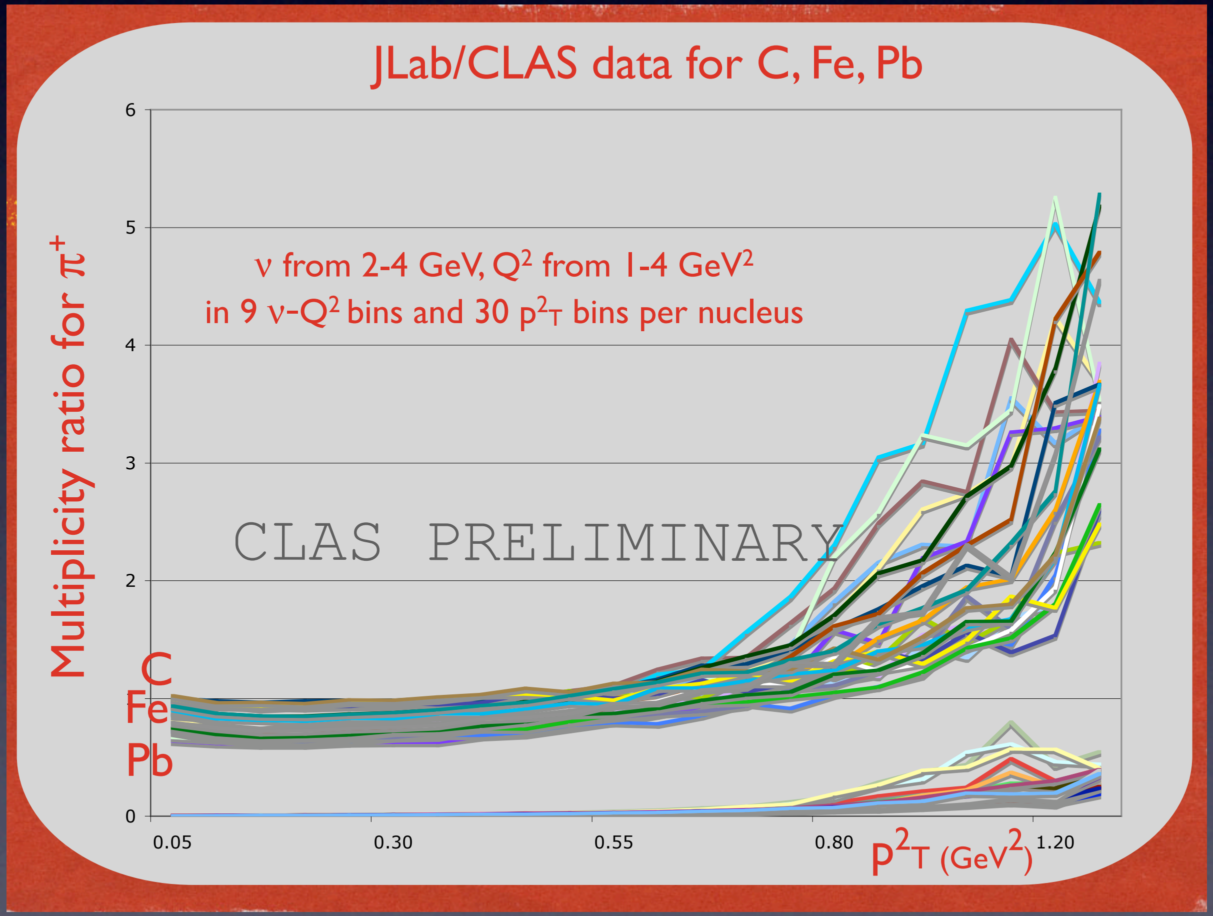
Hadronic multiplicity | π^+



Example of 3D multivariable slices of preliminary CLAS data on π^+

Results not corrected for radiative effects

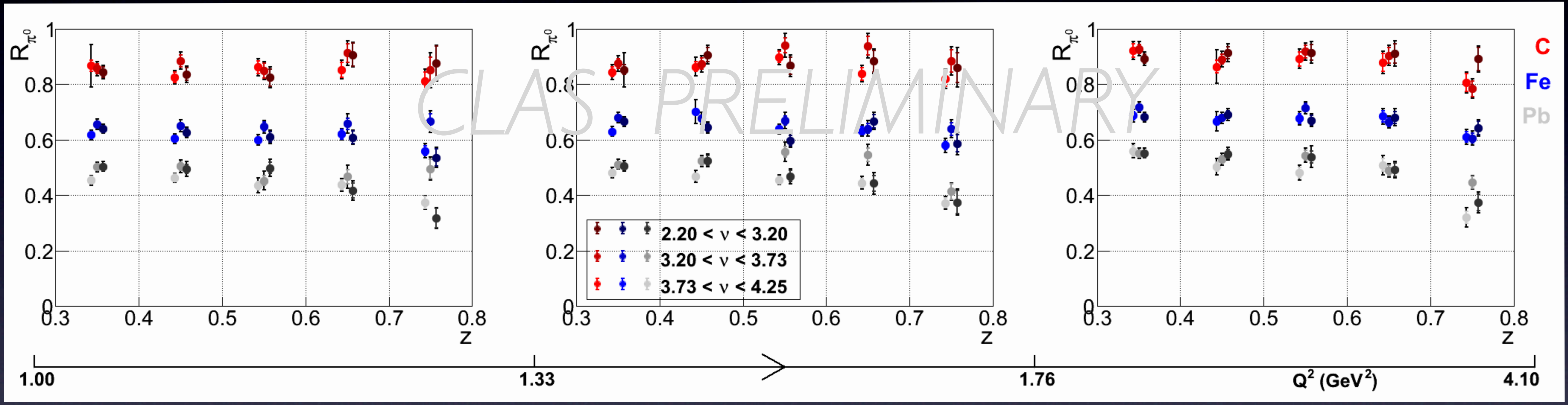
- Attenuation depends on nuclear size
- Increase of hadrons at low z, attenuation at high z
- Bears resemblance to Cronin effect at high p_T^2
- Quantitative behavior compatible with Hermes



Analysis by H.Hakobyan

Hadronic multiplicity | π^0

R_{π^0} in 3D set of (Q^2, ν, z) integrated over pT^2



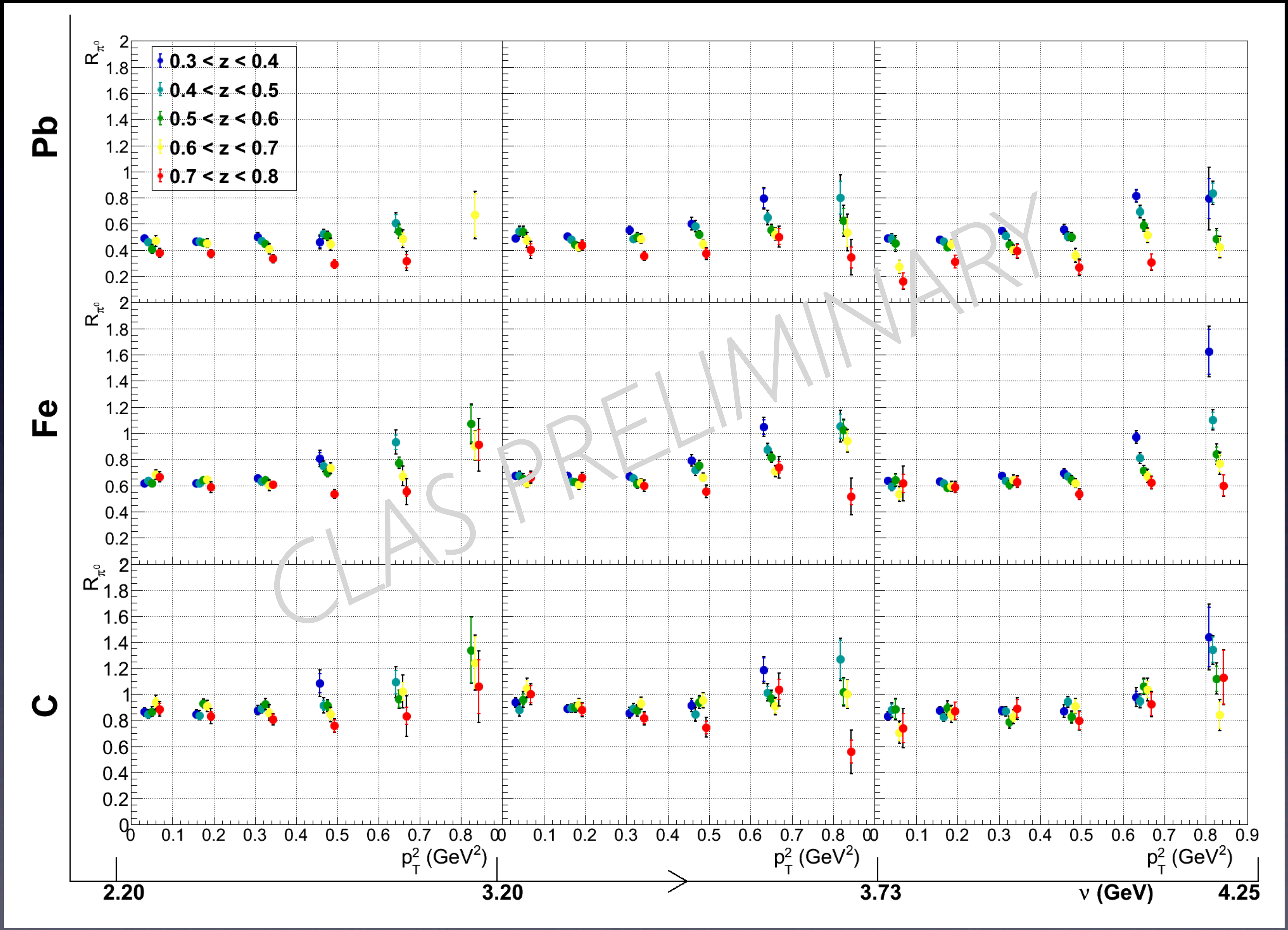
Results are corrected for radiative effects, include statistical (inner) and systematical (outer) errors.

- z range of the measurement: $0.3<z<0.8$
- Flat behavior of hadrons at medium low z, attenuation at high z
- Small dependence on Q^2 and ν

Analysis by T.Mineeva

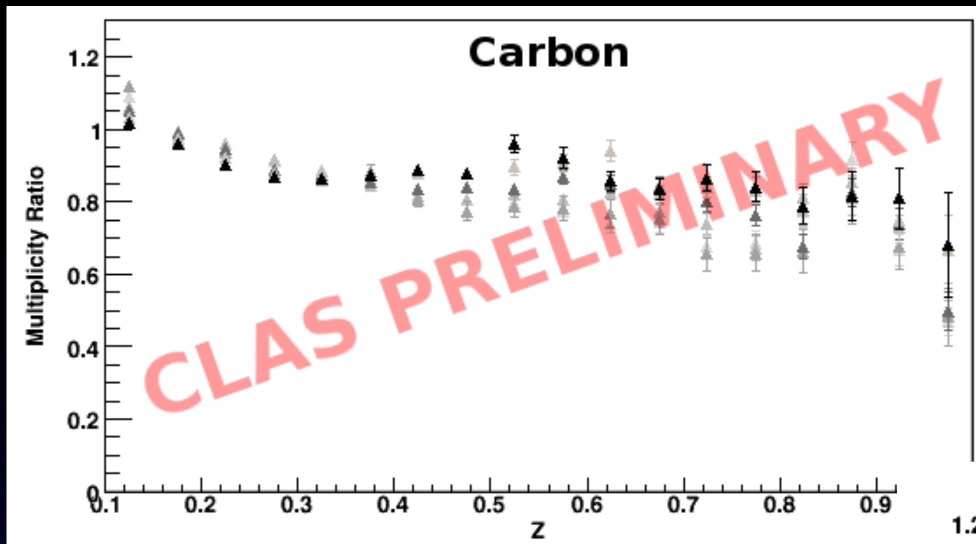
Hadronic multiplicity | π^0

R_{π^0} in 3D set of (ν, z, p_T^2) integrated over Q^2

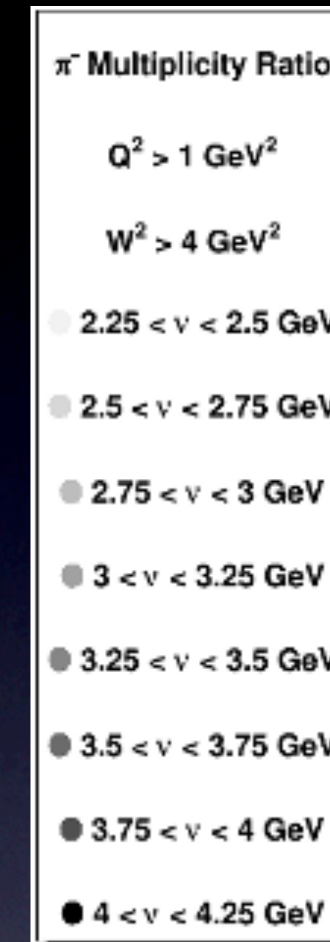


Results are corrected for radiative effects, include statistical (inner) and systematical (outer) errors. Analysis by T.Mineeva

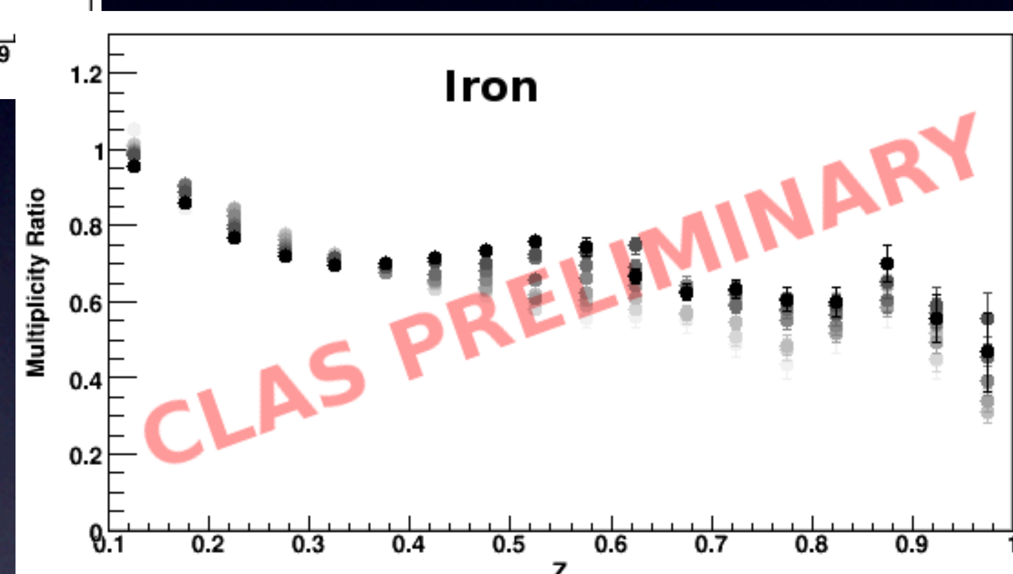
Hadronic multiplicity | π^-

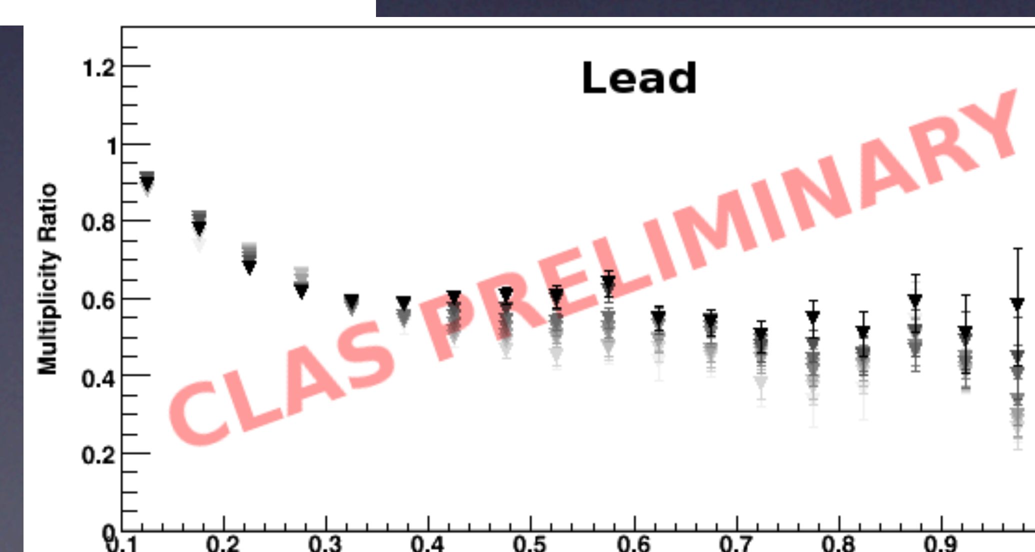


Example of 2D (z,ν) slices of preliminary CLAS data on π^+



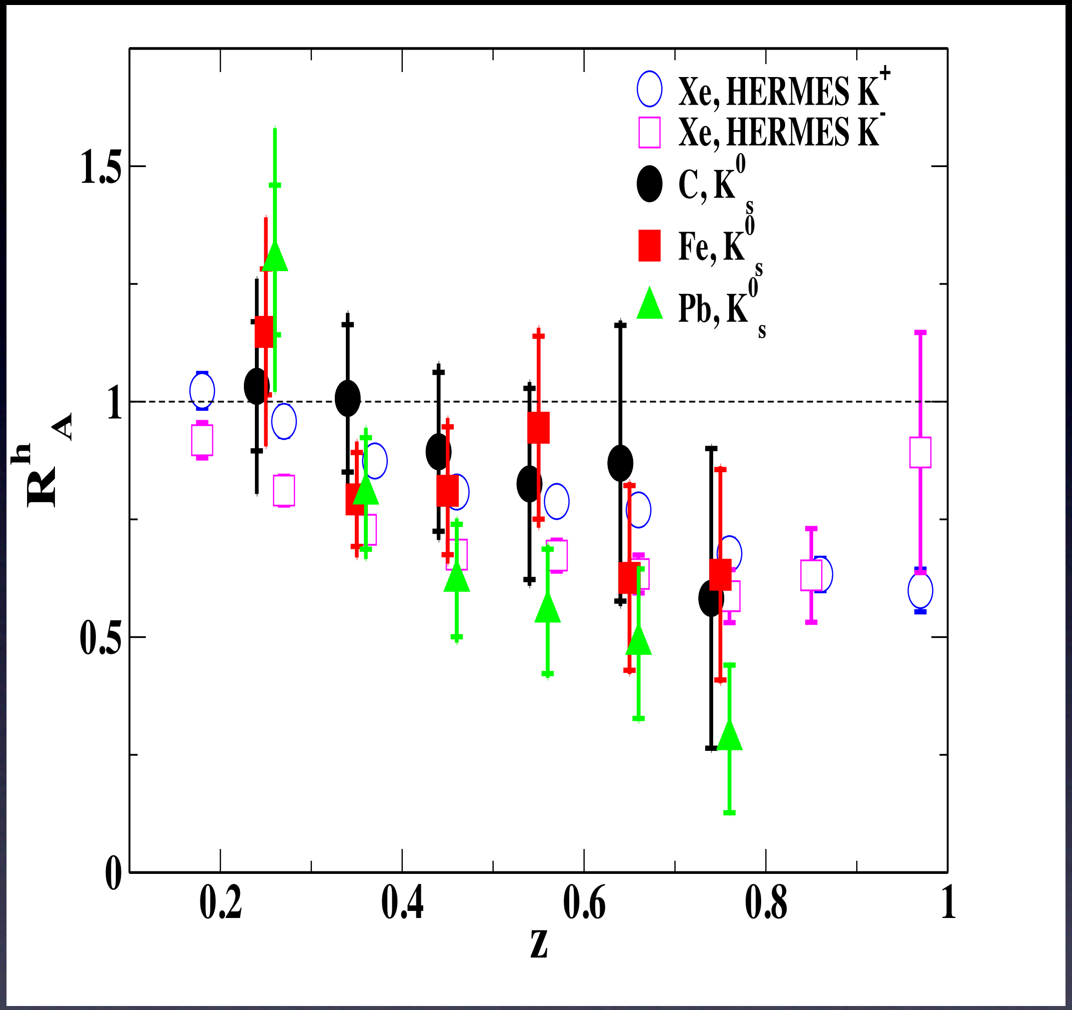
Results not corrected for acceptance, and radiative effects



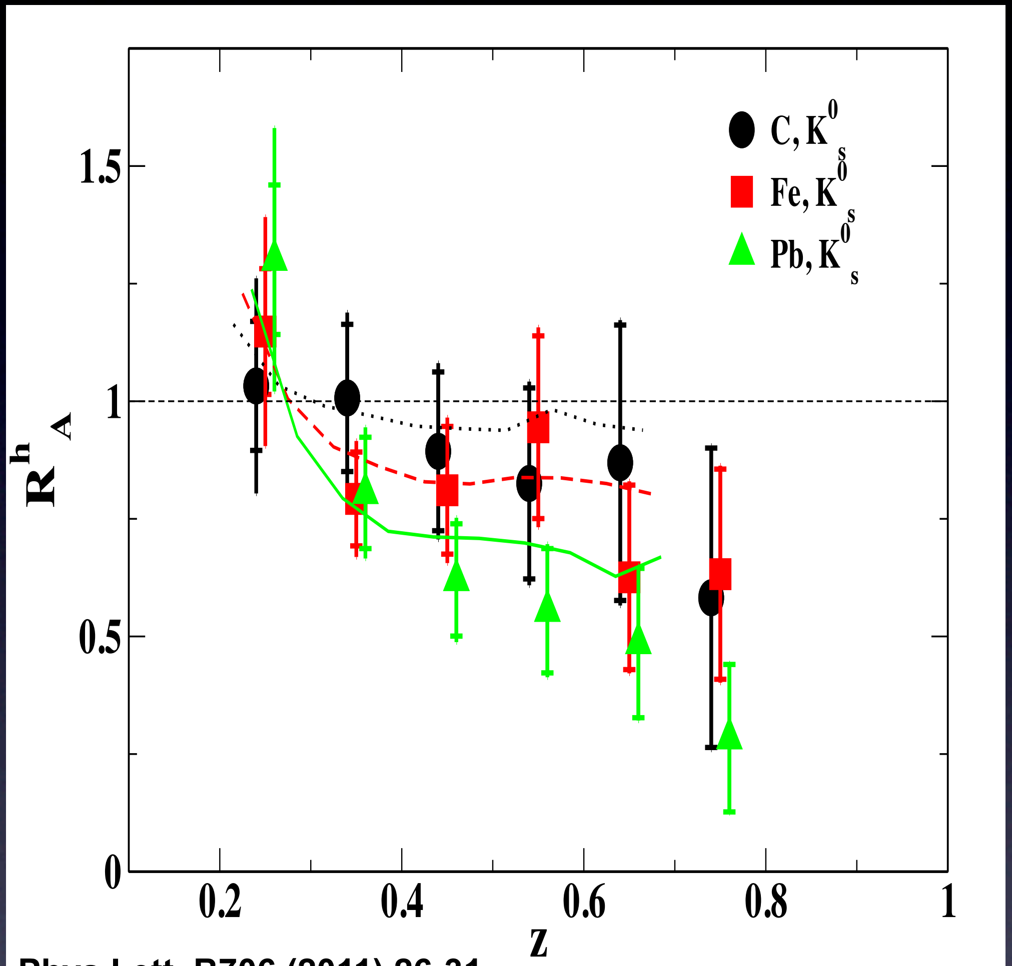


Analysis by R.Dupre

Hadronic multiplicity | K^0_S



Comparison with HERMES



Fits based on BUU transport model

(K. Gallmeister and U. Mosel, Nucl. Phys. A 801 (2008) 68.)

Analysis by A.Daniel

Summary

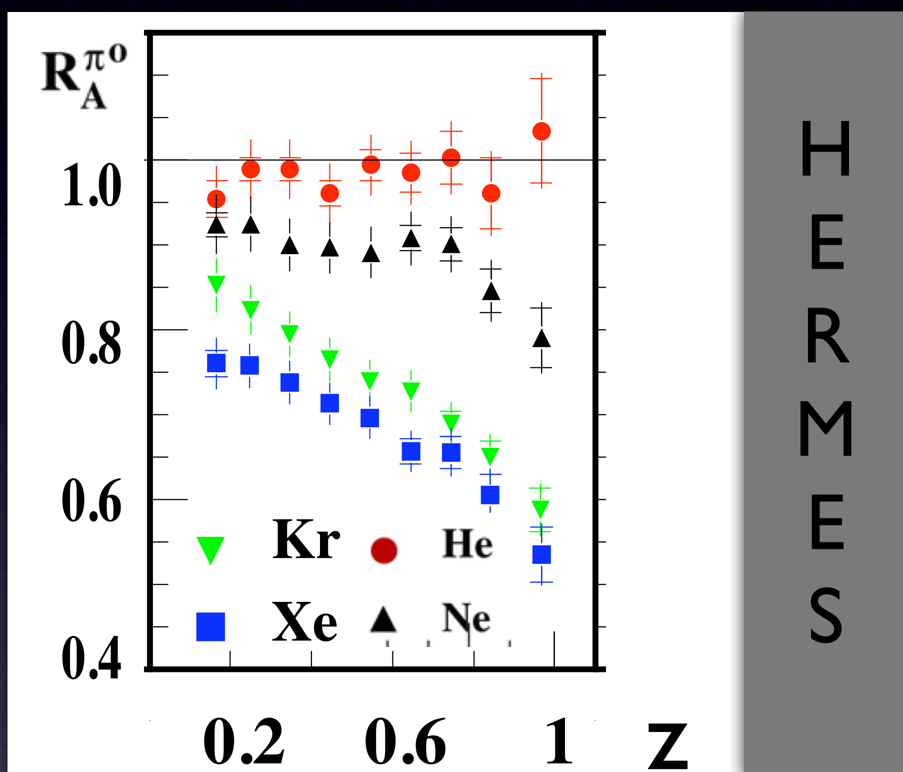
- Analysis of CLAS EG2 data on ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb
- Extraction of 3D π+ multiplicities: $R_{\pi^+}(Q^2, \nu, z)$ and $R_{\pi^+}(Q^2, \nu, pT^2)$.
- Extraction of 3D π^0 multiplicities: $R_{\pi^0}(Q^2, \nu, z)$ and $R_{\pi^0}(\nu, z, pT^2)$.
- Extraction of 2D π^- multiplicities: $R_{\pi^-}(\nu, z)$
- Extraction of 1D K^0_s multiplicities: $R_{K0s}(z)$
- Good consistency with existing 1D HERMES results

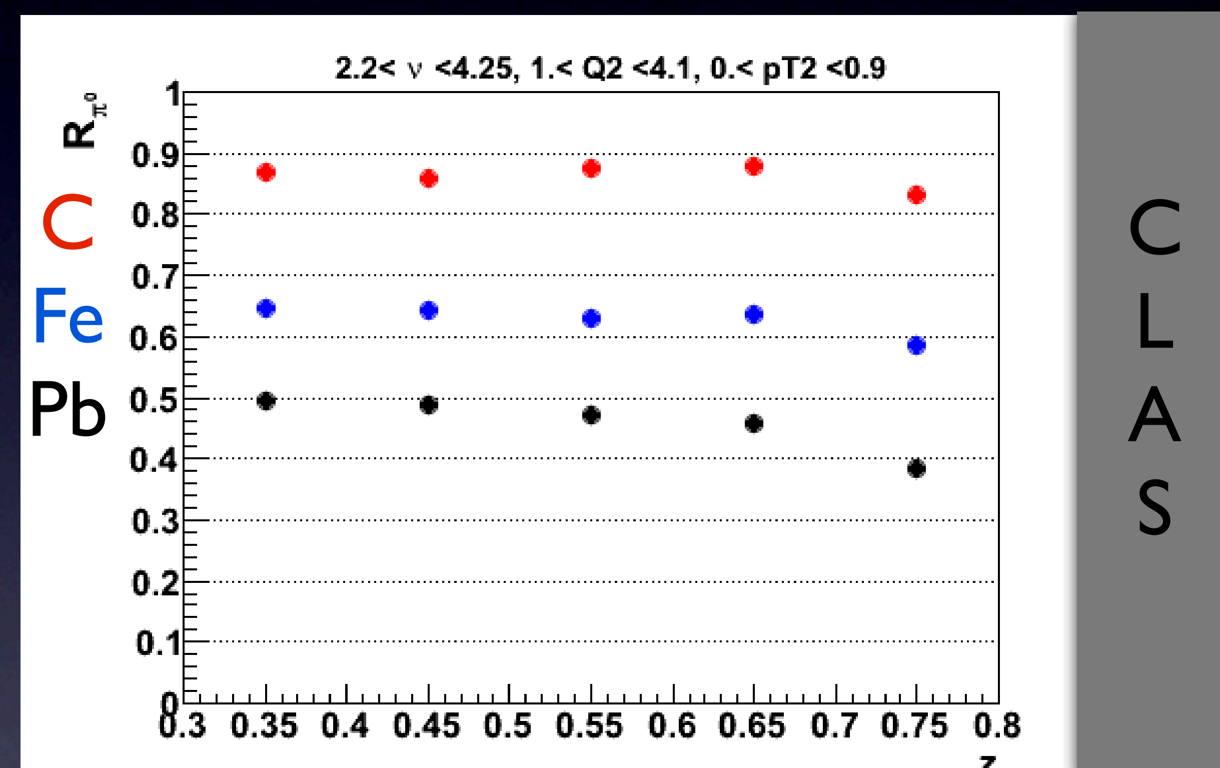
- Future program with CLAS12 (E12-06-117) will provide by far the best experimental access to medium-stimulated parton energy loss and enable extraction of 4D multiplicities for a large spectrum of hadrons.

BACKUP (ADD)

π^0 Multiplicities: z-dependence

	ν (GeV)	Q^2 (GeV^2)	z	pT^2 (GeV^2)
CLAS	2.2 - 4.2	1.0 - 4.1	0,3 - 0.8	0 - 0.9
HERMES	7 - 23	1.0 - 10	0.2 - 1.0	0 - 1.1





- HERMES: large dependence on z for heavy nuclei, vanishing for light.
- CLAS: moderate dependence on z for all nuclei
- HERMES data is integrated over large υ and Q^2, while CLAS data reveals differential behavior of z in both Q^2 and υ.

π^0 Multiplicities: p_T^2-dependence

	ν (GeV)	Q^2 (GeV^2)	z	pT^2 (GeV^2)
CLAS	2.2 - 4.2	1.0 - 4.1	0,3 - 0.8	0 - 0.9
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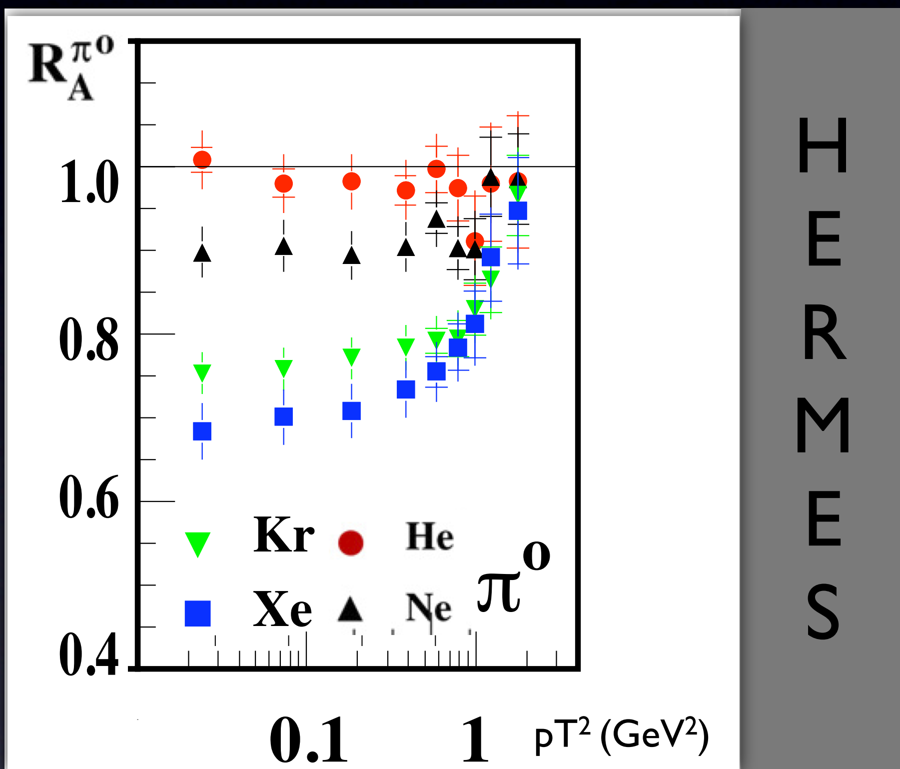

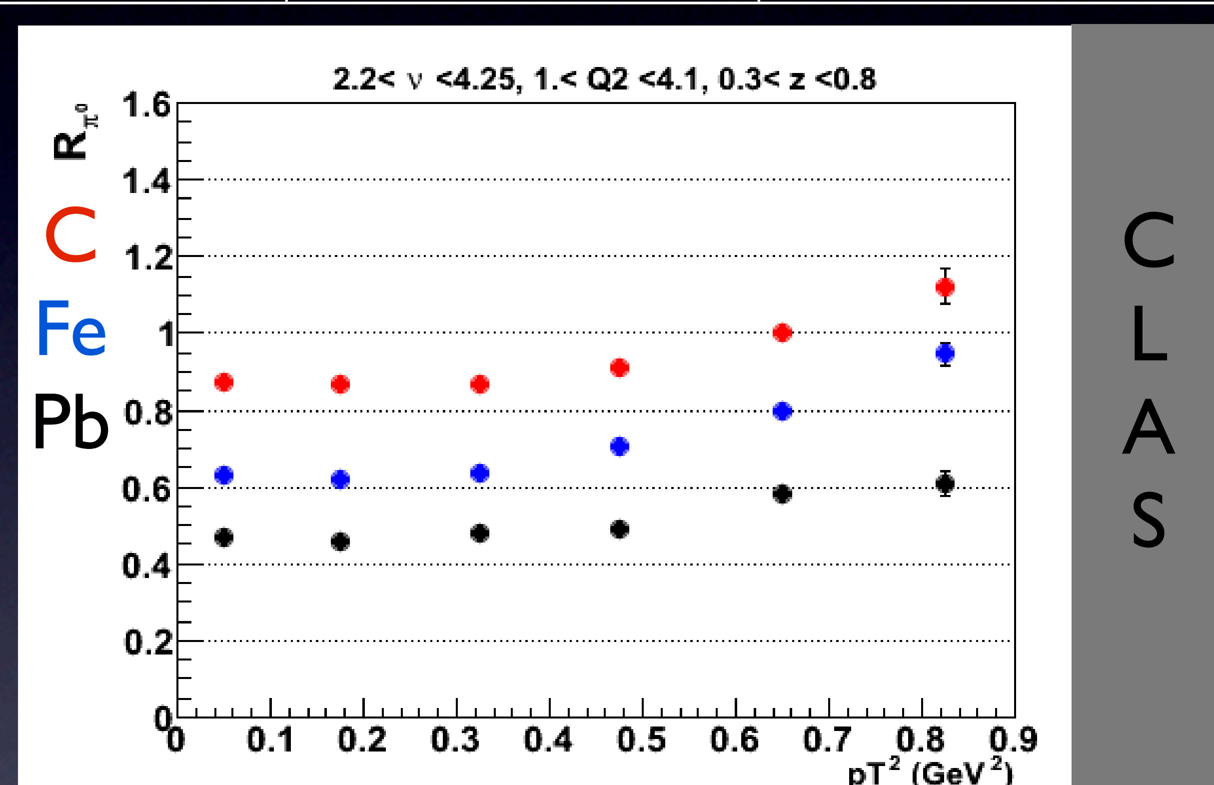

- HERMES: large enhancement for heavy nuclei, constant behavior for light.
- CLAS: moderate enhancement for all nuclei
- Dependence of (pT^2, z) differentiate partonic vs hadronic mechanism