Hadronization via π electroproduction off nuclear targets

Taisiya Mineeva

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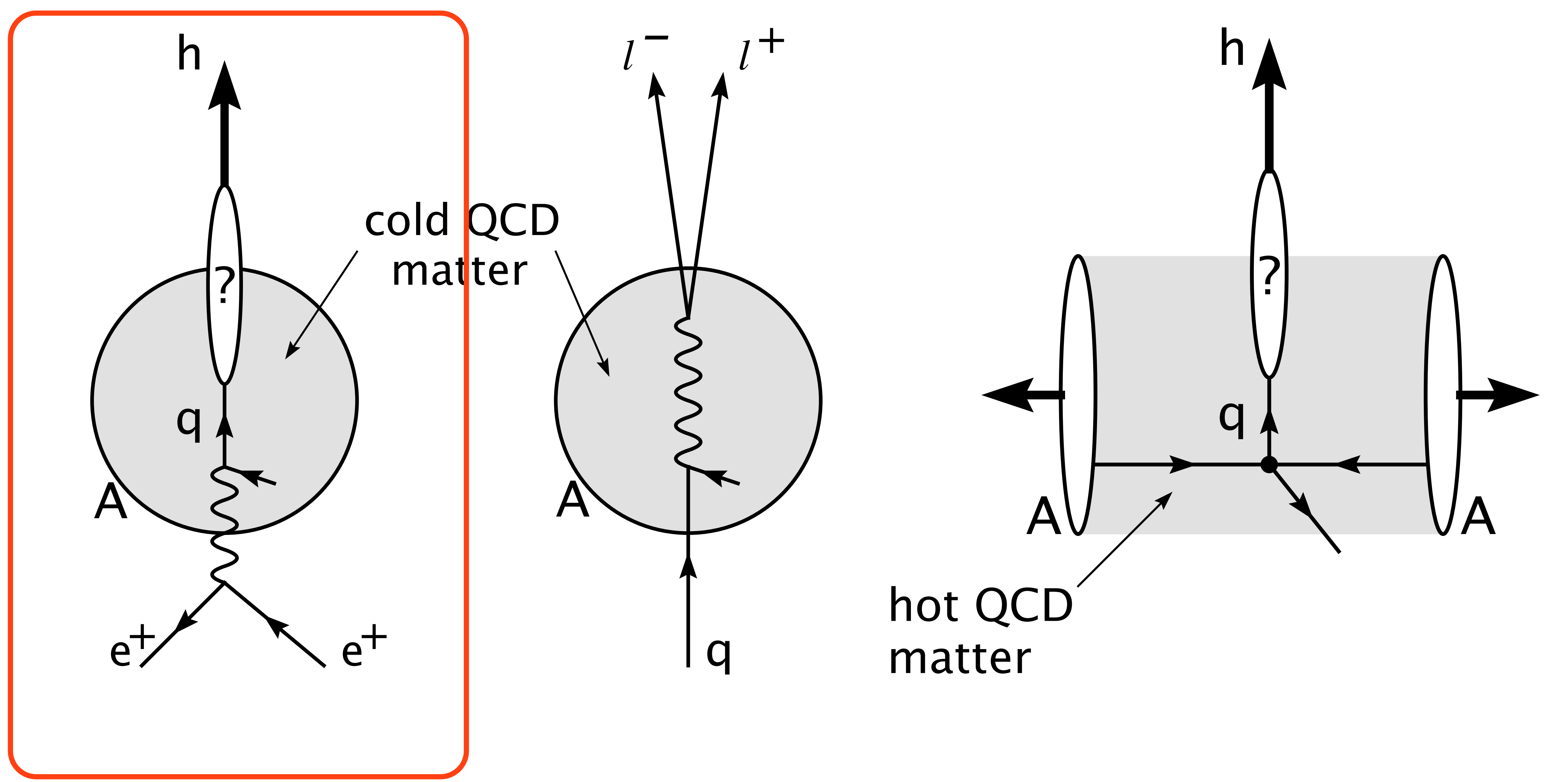
Why study hadronization?

- Mysterious: how all the color from initial state is neutralized into colorless hadrons dynamical enforcement of confinement

- Fundamental: comes from non-Abelian feature of QCD

Comparison of Parton Propagation in Three Processes



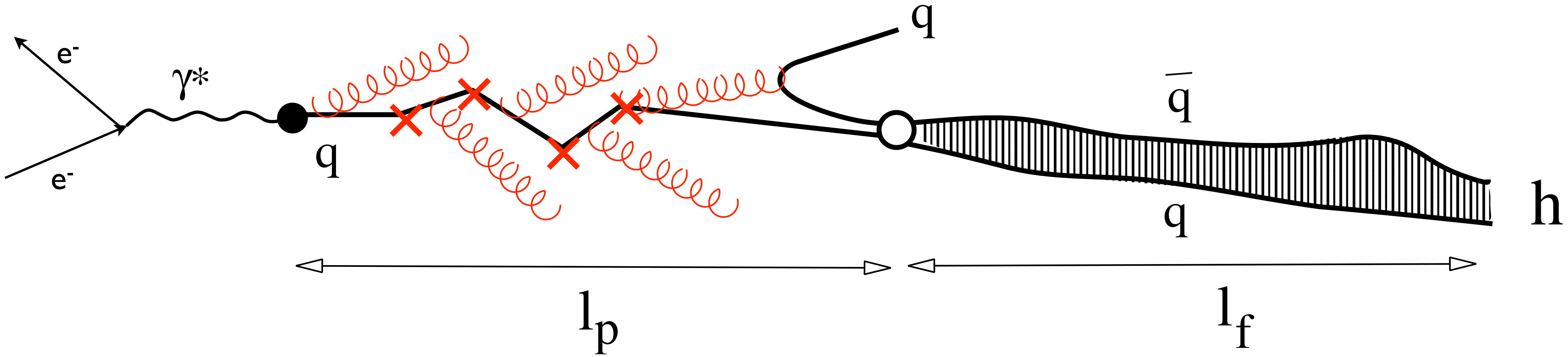
DIS
(DESY, Jefferson Lab)

Drell-Yan
(Fermilab, CERN)

Heavy-Ion
(RHIC, LHC)

Parton Propagation and Fragmentation in QCD Matter, A.Accardi, F.Arleo, W.K. Brooks , D. D'Enterria, V.Muccifora arXiv:0907.3534v1 [nucl-th]

Deep-Inelastic Scattering in Vacuum



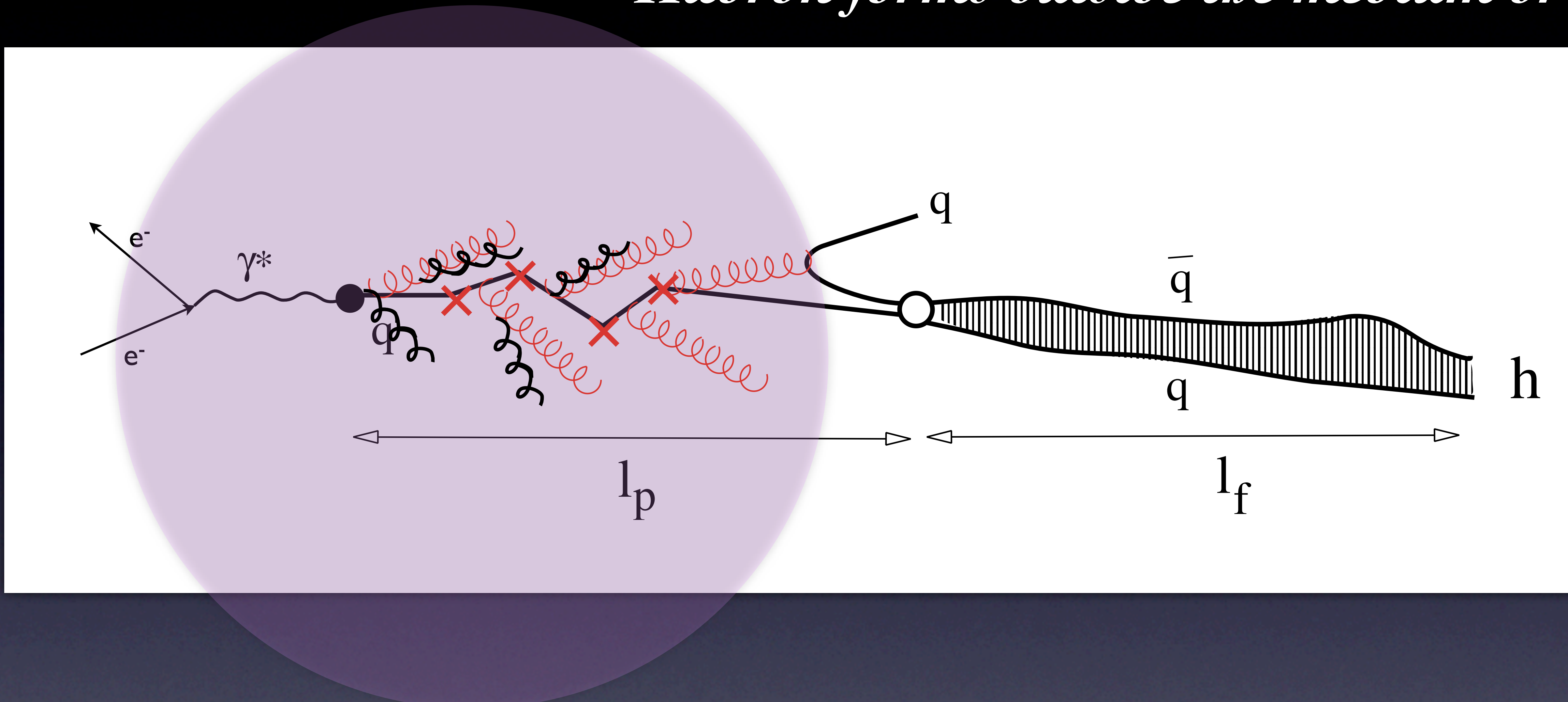
Time Evolution of Jets and perturbative color neutralization B.Z.Kopeliovich, J.Nemchik, I,Schmidt Nucl. Phys A 782 (2007)

Production time τ_p - propagating quark

Formation time τ_f - dipole grows to hadron

Deep-Inelastic Scattering in Medium

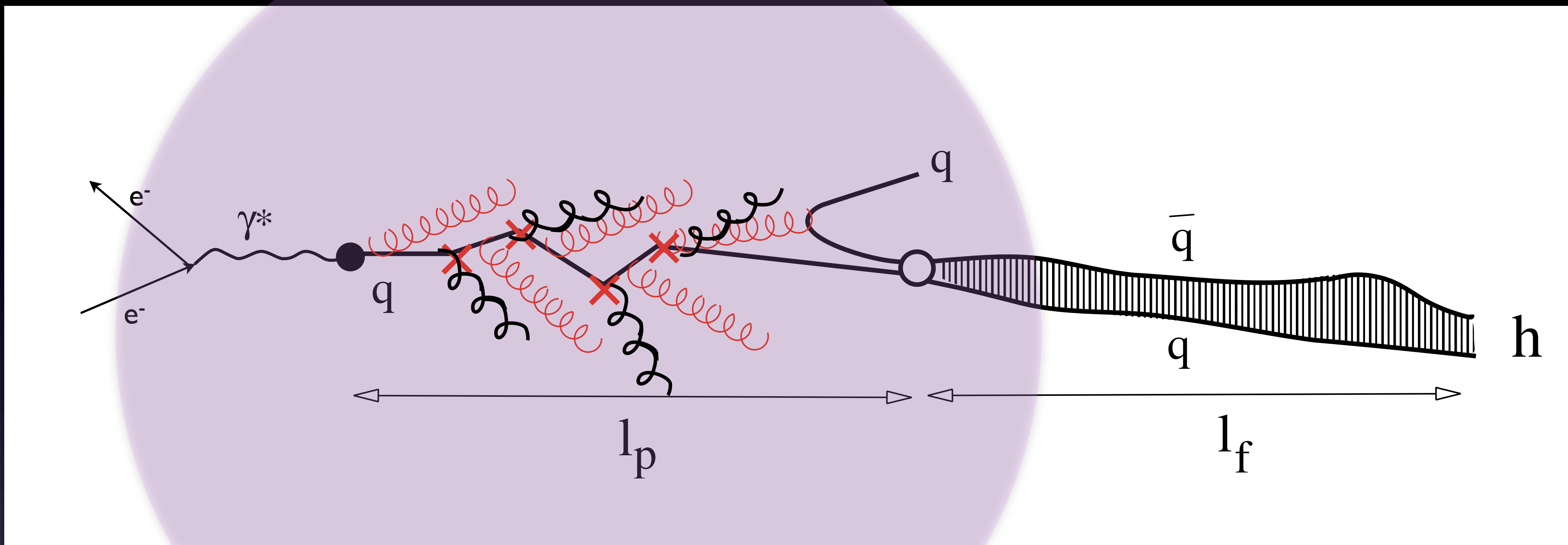
Hadron forms outside the medium or ....



Partonic multiple scattering: medium-stimulated gluon emission, broadening of pT.

Deep-Inelastic Scattering in Medium

Hadron can form inside the medium



Then additionally have prehadron/hadron interaction

Observables

Transverse momentum broadening

defined with respect to the γ^* direction

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

The production time τ_p can be presumably accessed via broadening(A)

Hadronic multiplicity ratio

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

The formation time τ_f can be accessed via $R^h_A(Q^2, \nu, p_T, z_h)$

Observables

Transverse momentum broadening

defined with respect to the γ^* direction

Not in this talk

The production time τ_p can be presumably accessed via broadening(A)

Hadronic multiplicity ratio

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

The formation time τ_f can be accessed via $R^h{}_A(Q^2, \upsilon, p_T, z_h)$

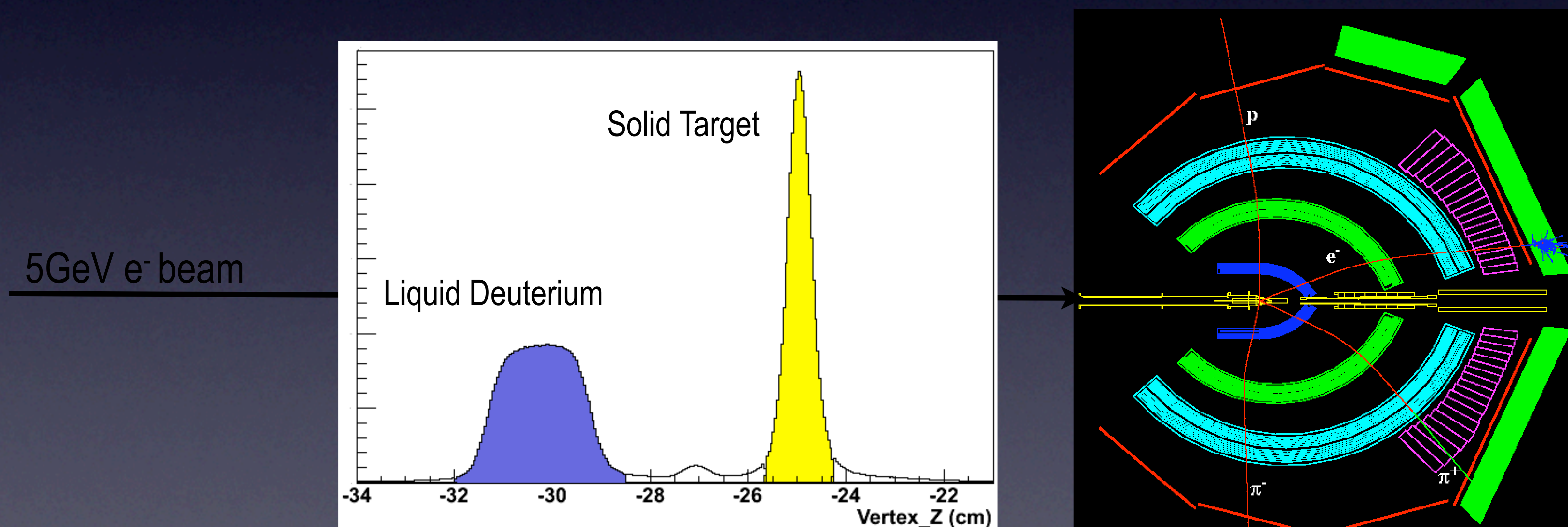
CLAS: experiment, analysis, results

Experiment

CLAS **EG2** (2004)

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

EG2 data on C, Fe, Pb (+D) was recooked (2009) using new tracking and EC clustering algorithms: recovered 44% more ‘clean’ electrons and 90% more π^0



Integrated Statistics (C, Fe, Pb +D): 130M DIS e-; 6.6 M π^+, 2.8 M π^- ,2.0 M π^0

π^0 Analysis

- Electron identification using all component of CLAS detector: DC, SC, CC, EC. DIS kinematics: $Q^2>1$ GeV^2 ;W>2 GeV; P>0.75 GeV
- Photon identification in EC , energy corrections
- π^0 is reconstructed via 2γ inv. mass, background treated using the shape from mixing two uncorrelated events and accounting for the differences in event topology
- Acceptance correction, purity cut off
- Radiative Corrections

Semi-inclusive radiative corrections off nuclear target

Available tools

- **HAPRAD**(2) *: SI RC for π^+ on proton + exclusive tail
  calculations for internal radiation are based
  on the convolution of leptonic and hadronic tensors

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

- **SEMIRC**: SI RC for three pion states off nuclear (polarized) targets
  model for cross section is based on experimental data
  calculations for external&internal radiation
  are based on Mo&Tsai approach + exclusive contribution

P.Bosted, note in preparation

- **RADGEN + MC** Event Generator: inclusive spectrum from RADGEN
  is input in the MC to produce SI RC
  all mesons on light nuclei

HERMES

* Original code written in FORTRAN, adaptation to C++ : https://github.com/usm-data-analysis/HAPRAD_cpp

Semi-inclusive radiative corrections off nuclear target

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HERMES

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Semi-inclusive RC from modified HAPRAD (1)

HAPRAD formalism (SI)

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

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

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

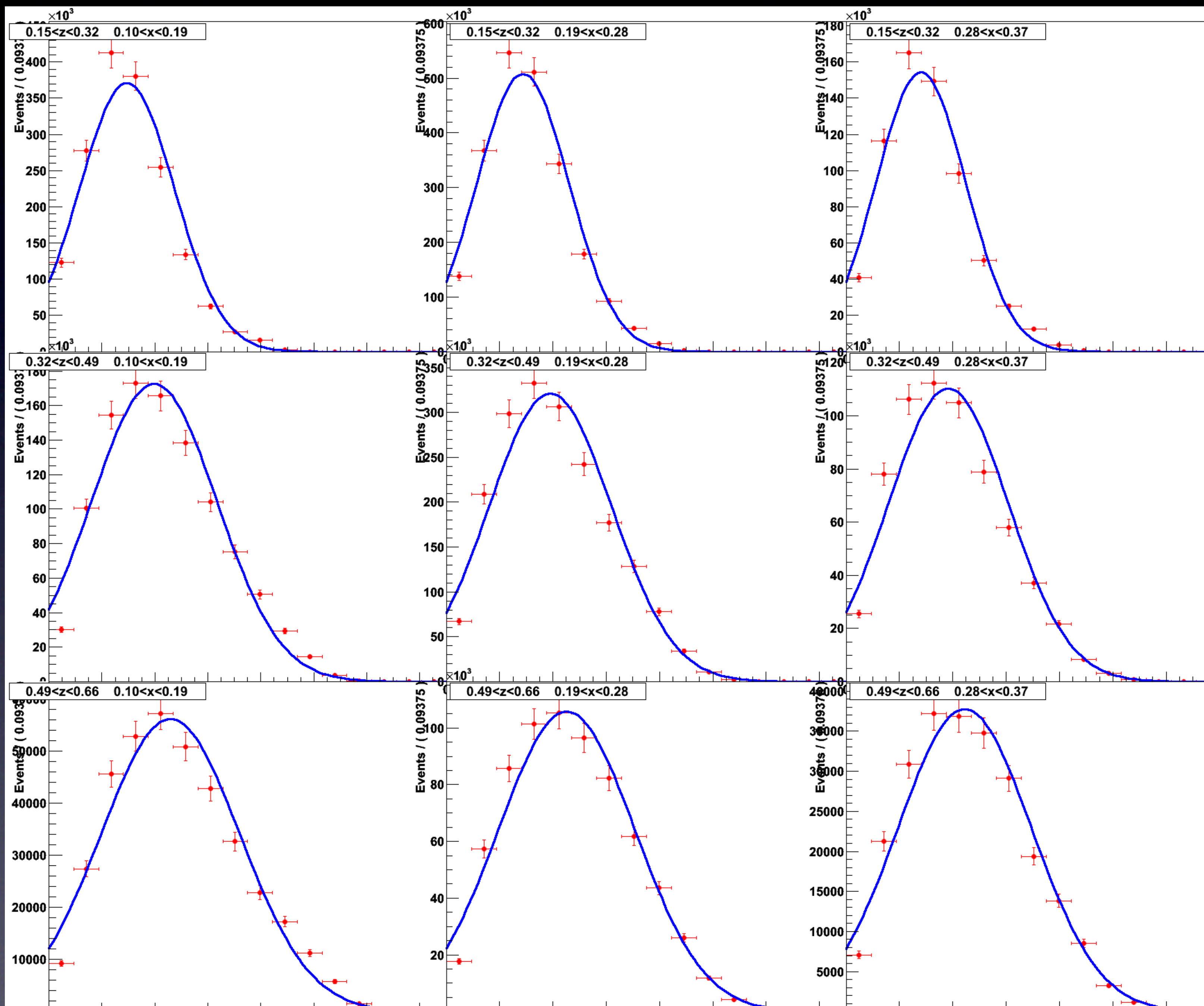
$$\mathcal{H}_3 = f(x, Q^2, z)|_{cos(\phi)} \sum_q e^2 f_q D_q \mathcal{G}$$

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

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

Method: substitute default structure functions (H_1, H_2, H_3, H_4) on proton by those on nuclei by performing fit to transverse momentum distribution G on a given dataset.

Semi-inclusive RC from modified HAPRAD (2)



p_T in the range (0, 1.5) GeV

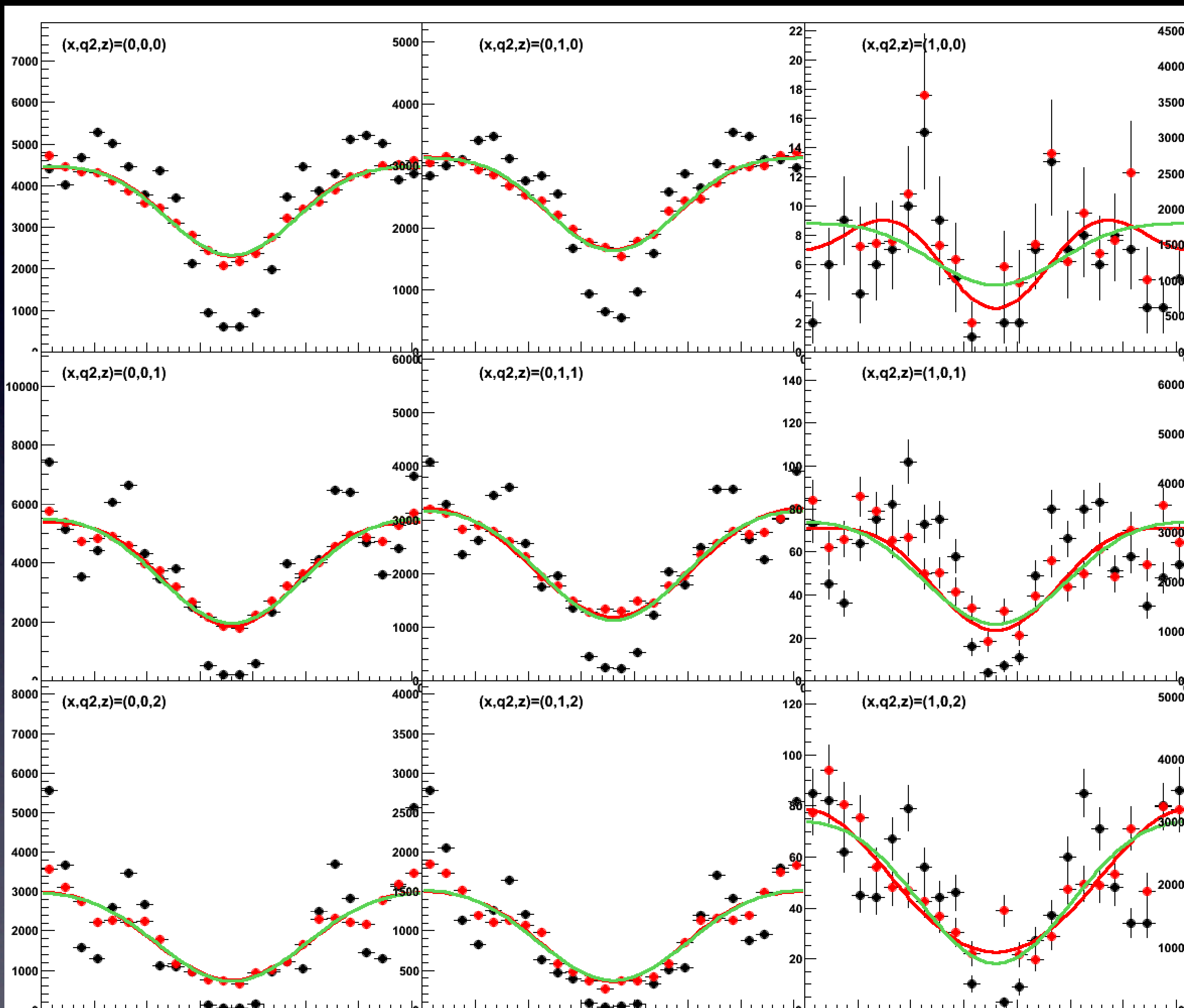
A slice of acceptance corrected p_T distribution (red points) for π^0 candidate in (x,z) bins on the example of iron target.

Blue line illustrates Gaussian fit to p_T performed simultaneously in (x,z).

The parametrization of p_T with μ(x,z) and σ(x,z) enters in H_n via:

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

Semi-inclusive RC from modified HAPRAD (3)



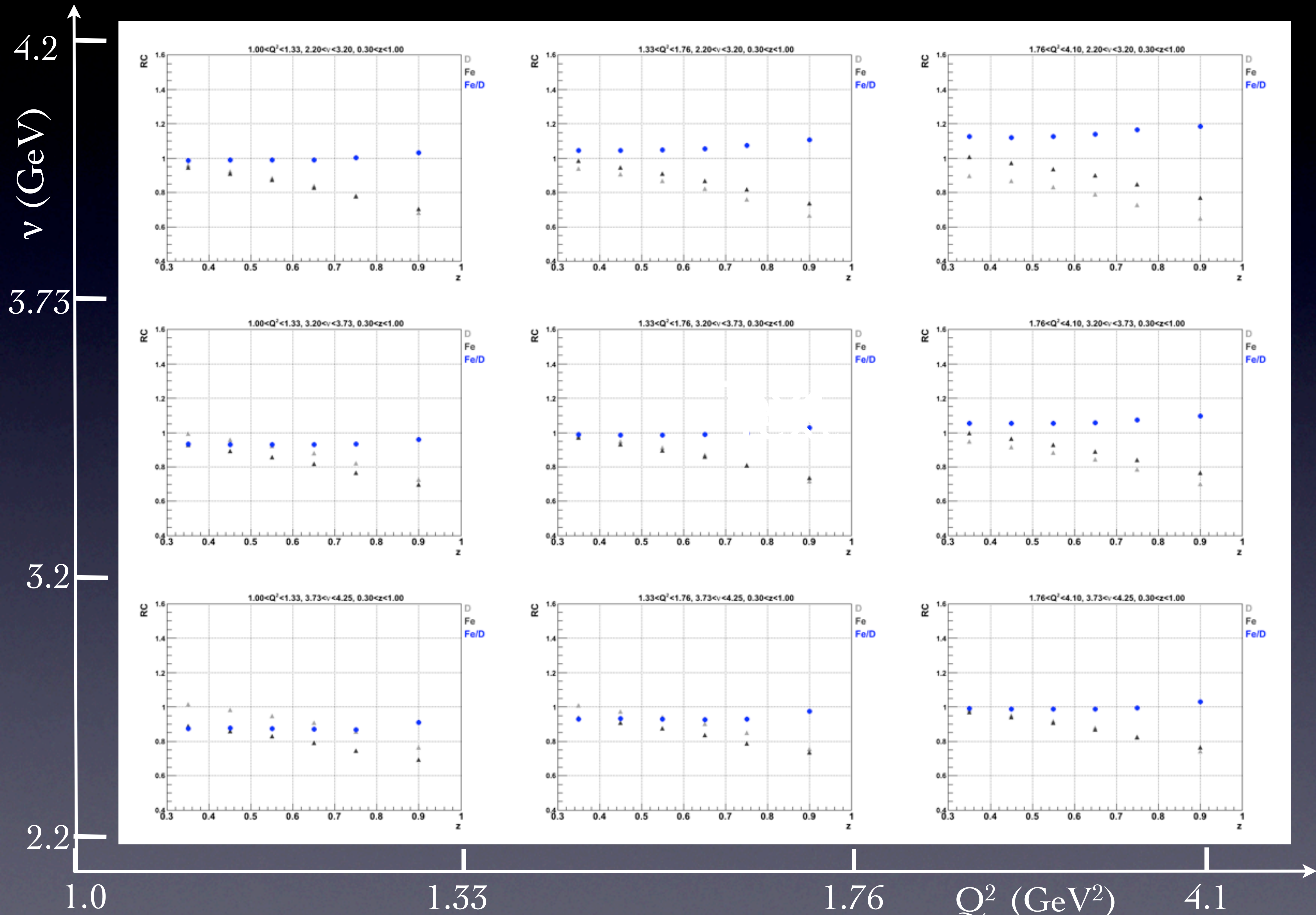
φ in the range (0, 180)°

A slice of acceptance corrected φ distributions in bins (x,Q^2,z) on the example of iron target: black points - w/o acceptance correction, red - corrected for acceptance.

Red and green curves correspond to the fit: $1+A\cos(\phi)+B\cos(2\phi)$. The coefficients in the red, used in H_3, H_4, depend only on z.

Semi-inclusive RC from modified HAPRAD (4)

RC factors for D, Fe and **Fe/D** ratio in set of (Q^2, ν, z)



Exclusive Tails from modified HAPRAD

Exclusive cross section

$$\sigma_{EXCL} = \frac{d\sigma}{dE' d\Omega d\Omega_h^*} = \Gamma \frac{d\sigma}{d\Omega_h^*}$$

$$\Gamma = \frac{\alpha}{2\pi^2} \frac{E'}{E} \frac{k_\gamma}{Q^2} \frac{1}{1-\epsilon}$$

The structure functions for exclusive cross section come from two sources:

1. W<2 GeV: MAID2007 parametrization (MAID2003 in default version for π^+)
2. W>2 GeV: Cornell interpolation * based on π^+ electroproduction in 1.2<W<3.0 (GeV)

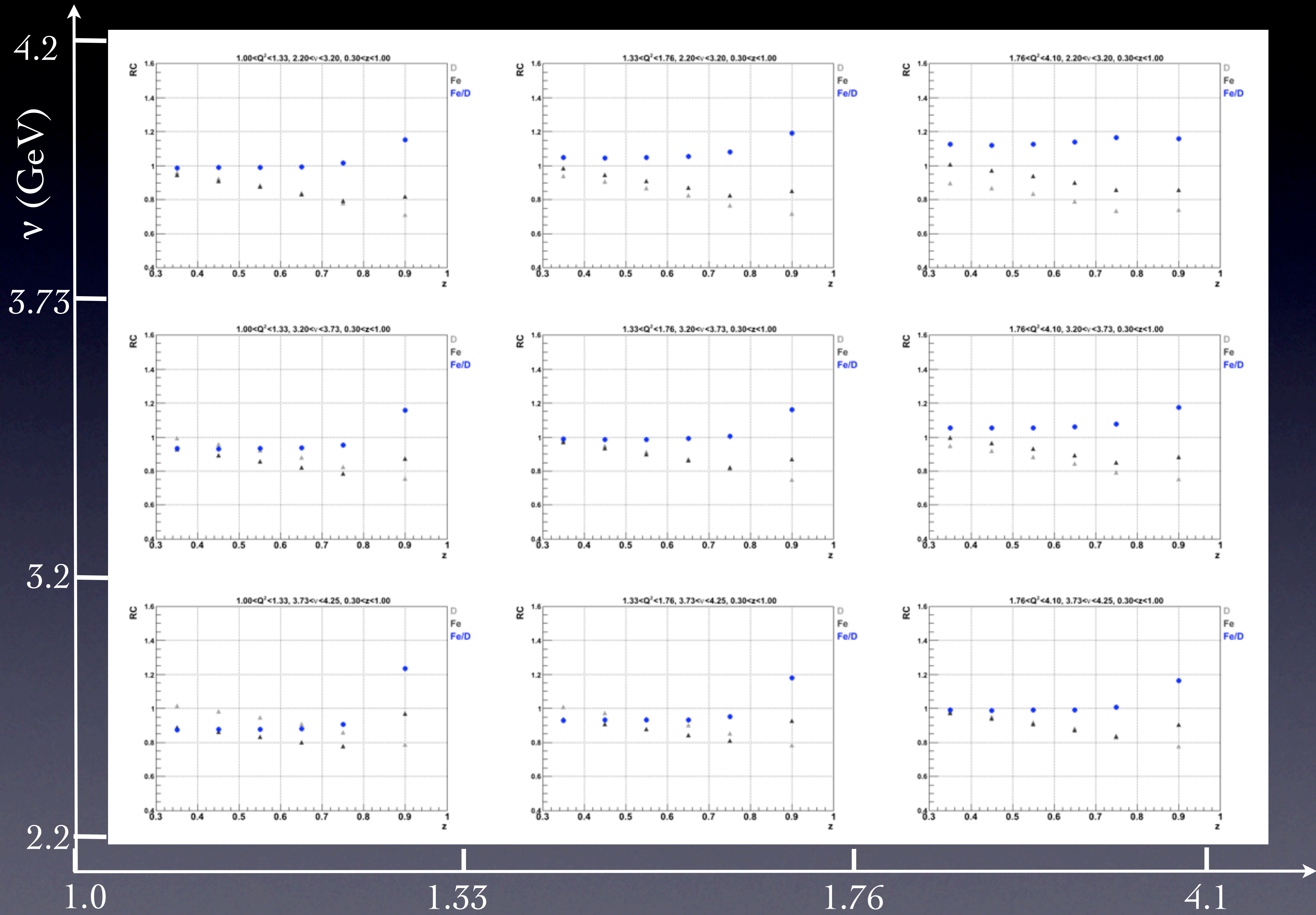
Alternative for π^0 case:
Employ structure functions from parametrization (V.Kubarovsky) based on phenomenological model (V.Kubarovsky) fitted to exclusive π^0 data at W>2 (GeV) **

* A. Browman et al., *Electroproduction of single pions with large transverse momenta* Phys. Rev. Lett. 35 (1975) 1313.

** I.Bedlinsky et al., *Measurement of exclusive π^0 electroproduction structcture funscions and their relationship to transversity GPD* Phys.Rev.Lett, 109 (2012) 112001

Semi-inclusive RC + Exclusive contribution

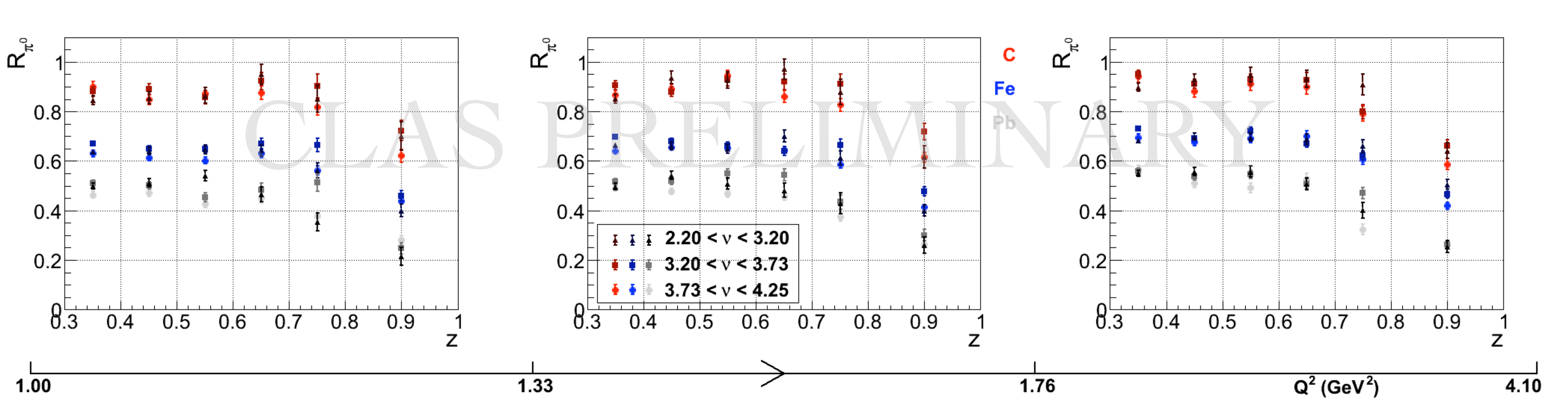
RC factors for D, Fe and **Fe/D** ratio in set of (Q^2, ν, z)



Pion Multiplicities

π^0 Multiplicities

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

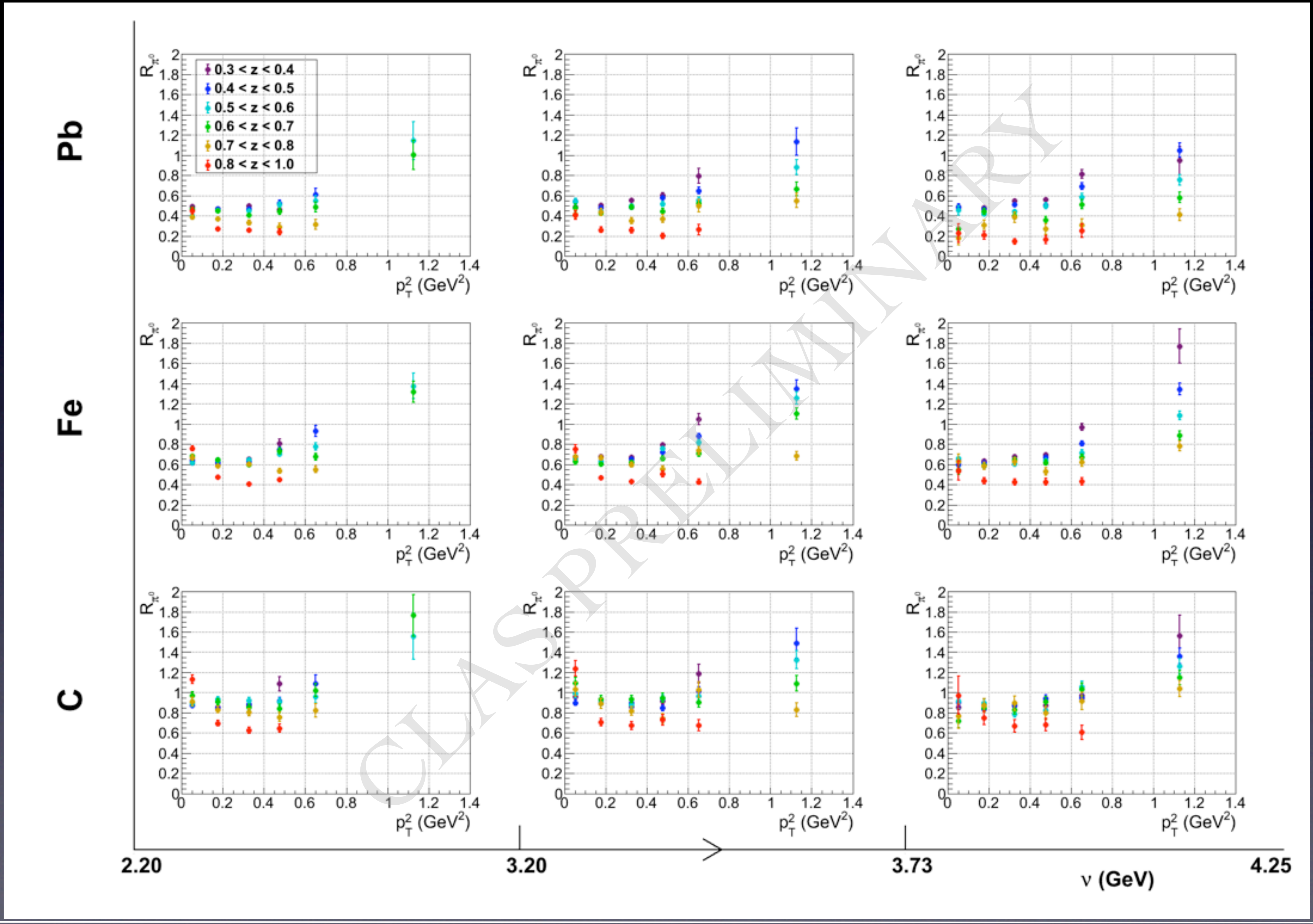


Results do not include systematic errors

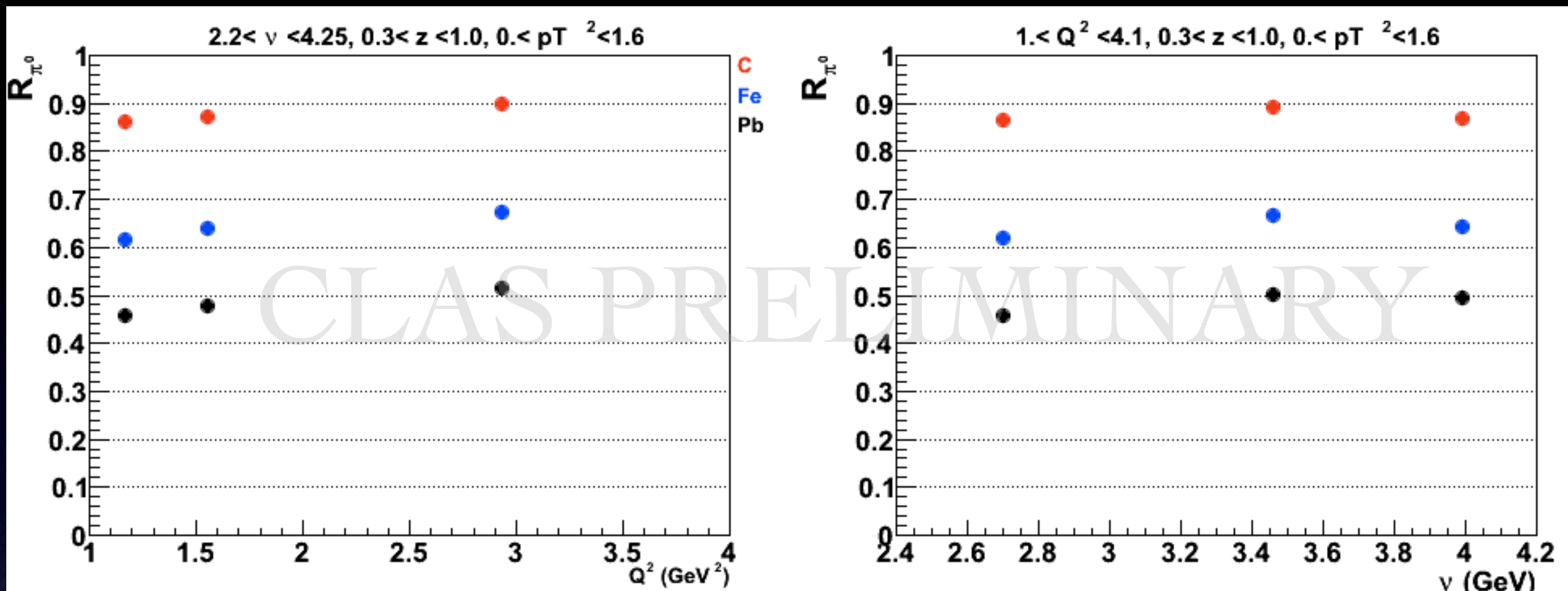
- Attenuation systematically increases for the larger nuclei
- Attenuation of high z hadrons
- Small dependence on Q^2 and ν

π^0 Multiplicities

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



π^0 Multiplicities: comparison

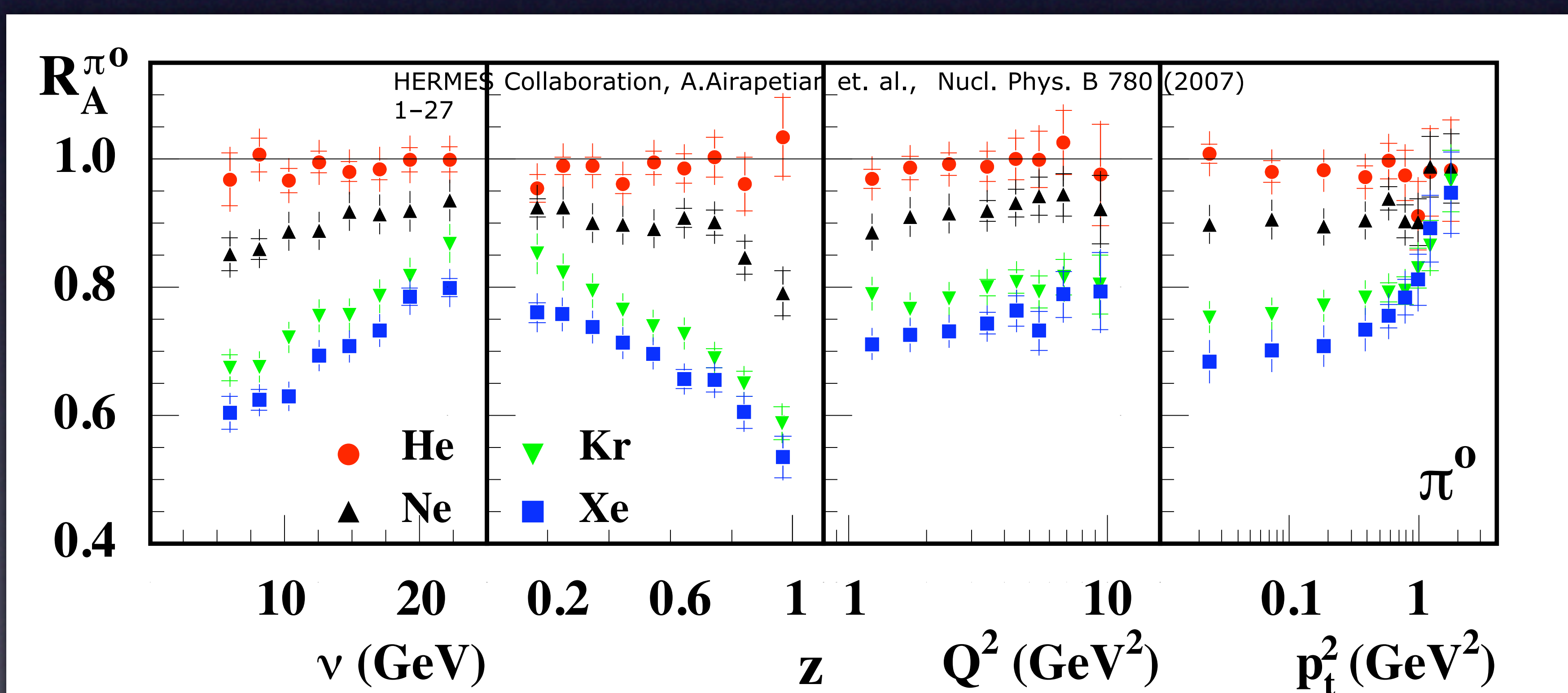


CLAS

$2.2 < \nu < 4.2$ (GeV)

$1. < Q^2 < 4.1$ (GeV^2)

$W^2 > 4$



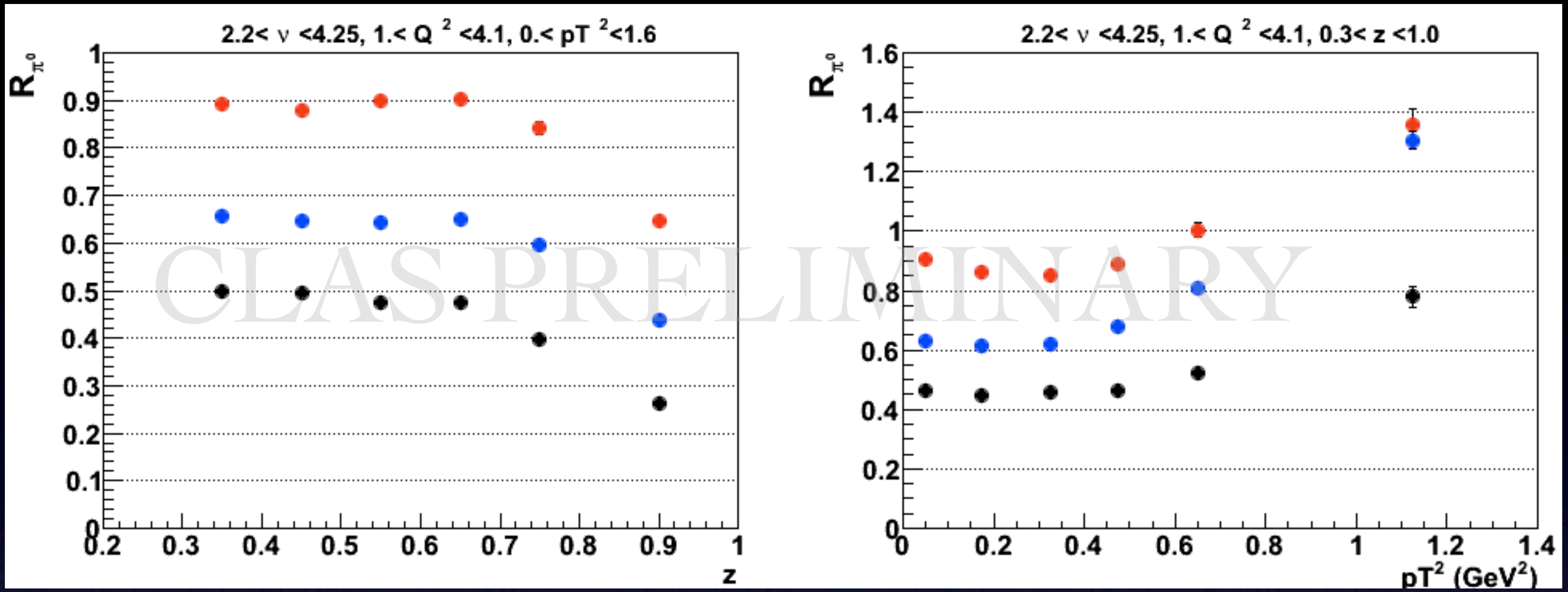
HERMES

$7 < \nu < 23$ (GeV)

$1 < Q^2 < 10$ (GeV^2)

$W^2 > 10$

π^0 Multiplicities: comparison



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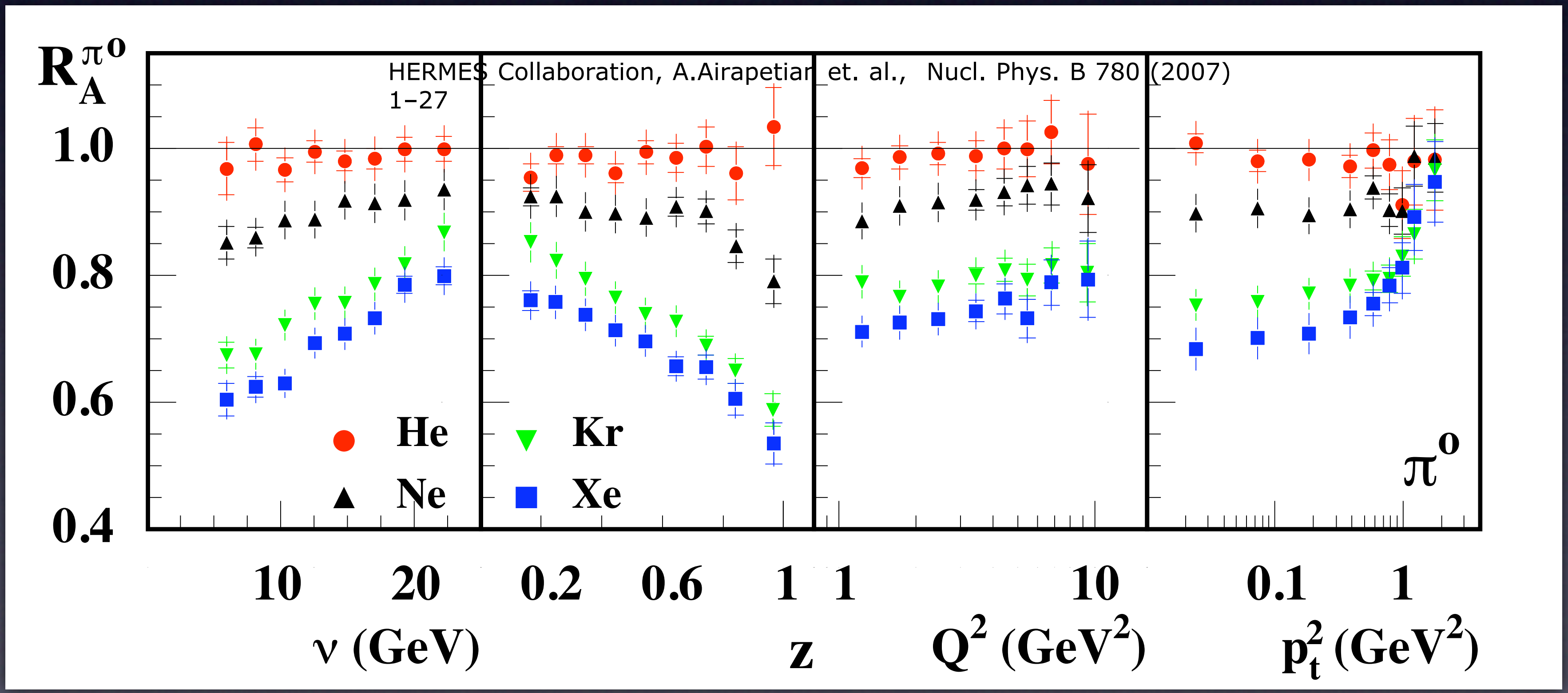


HERMES

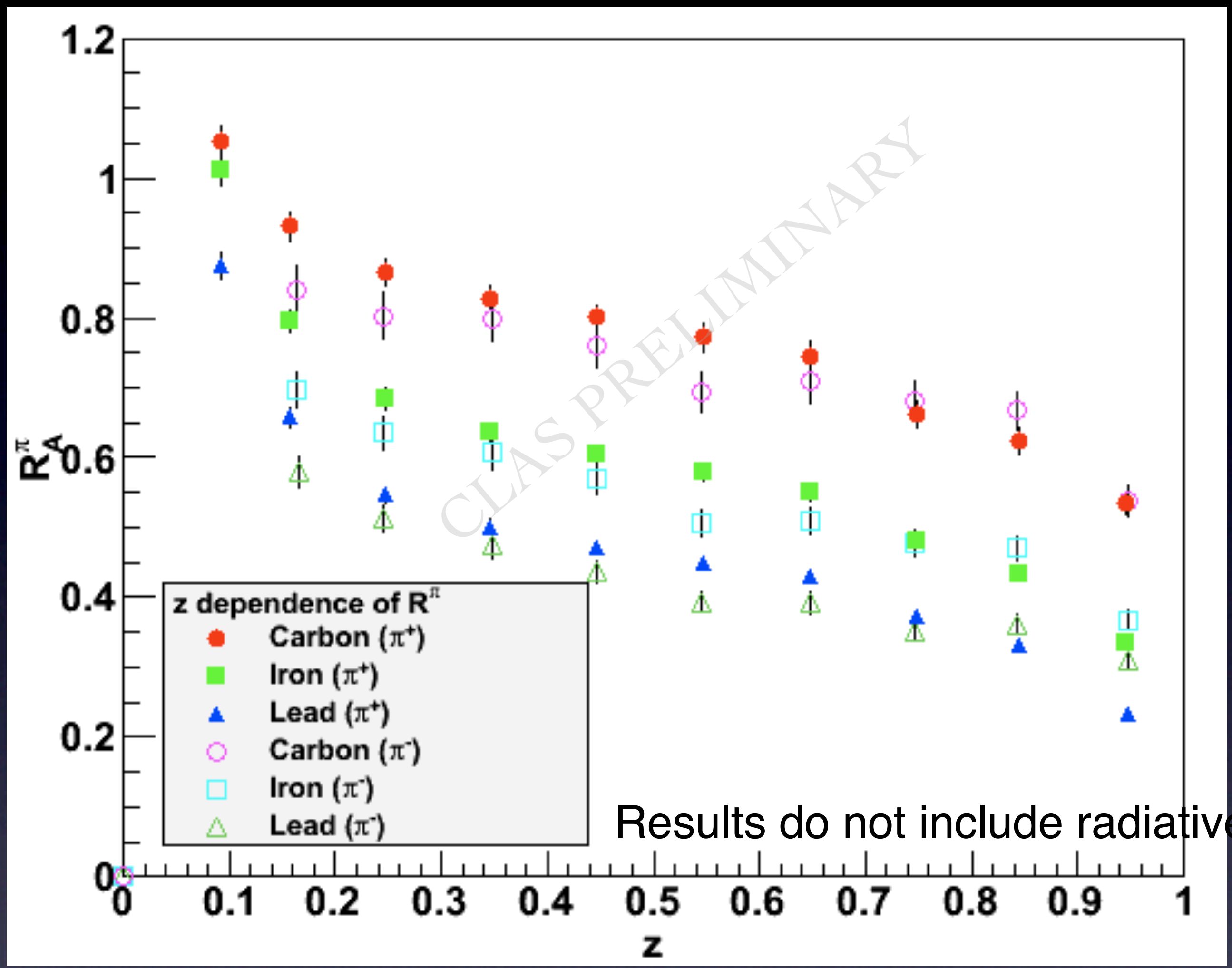
$7 < \nu < 23$ (GeV)

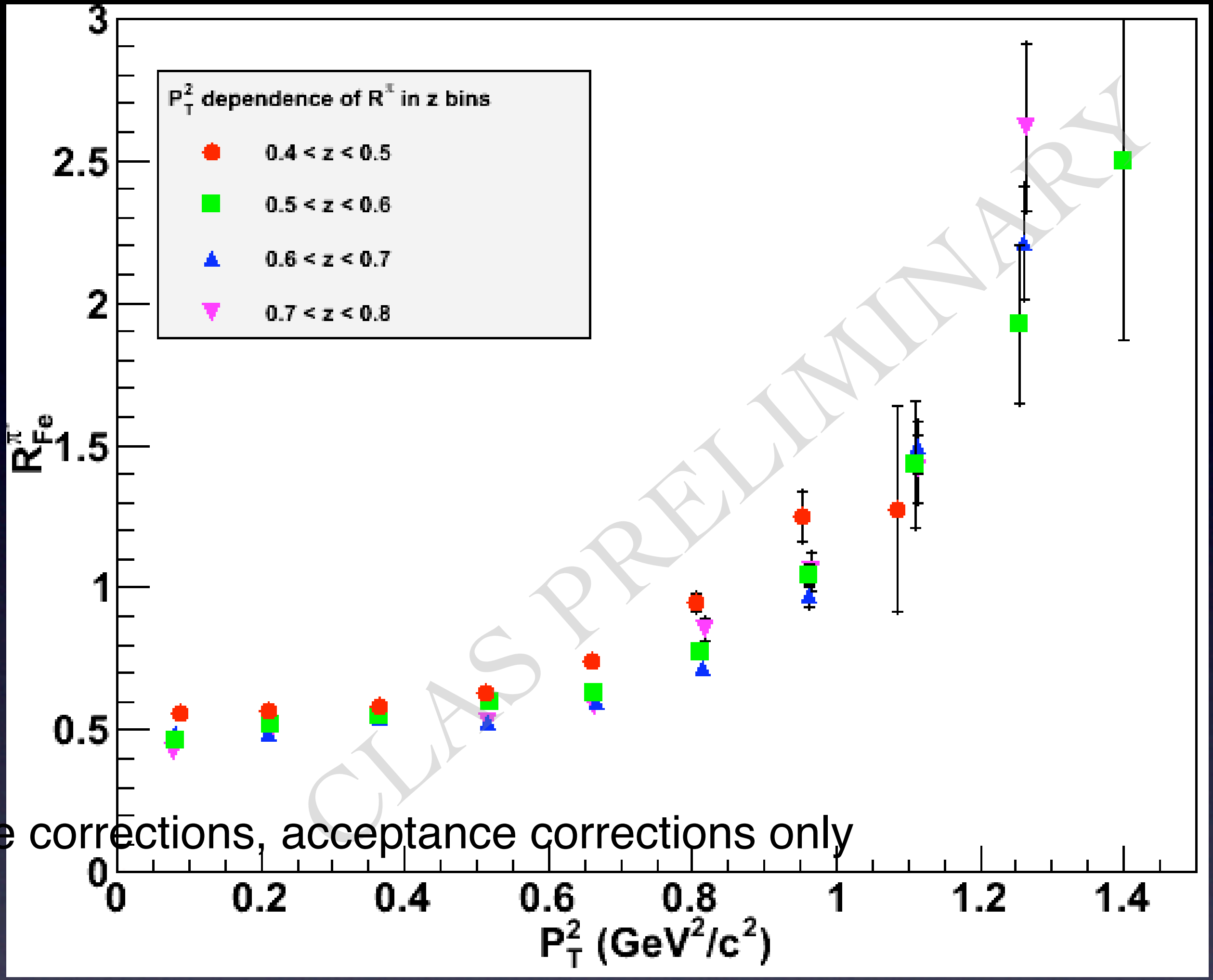
$1 < Q^2 < 10$ (GeV^2)

$W^2 > 10$

π^- Multiplicities

R_{π^-} in 2D set in (z, pT^2) R.Dupre

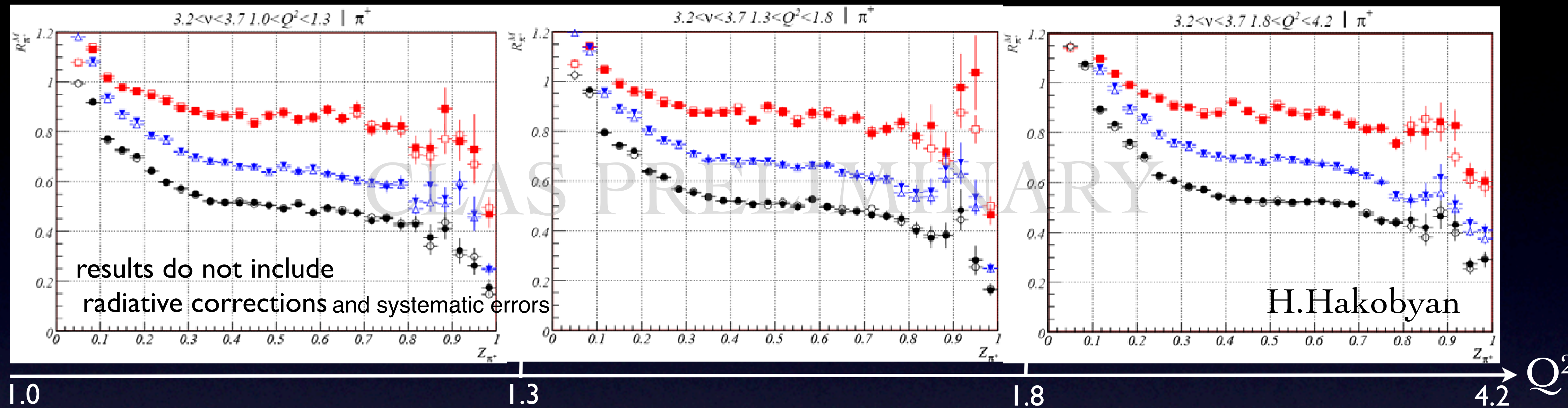




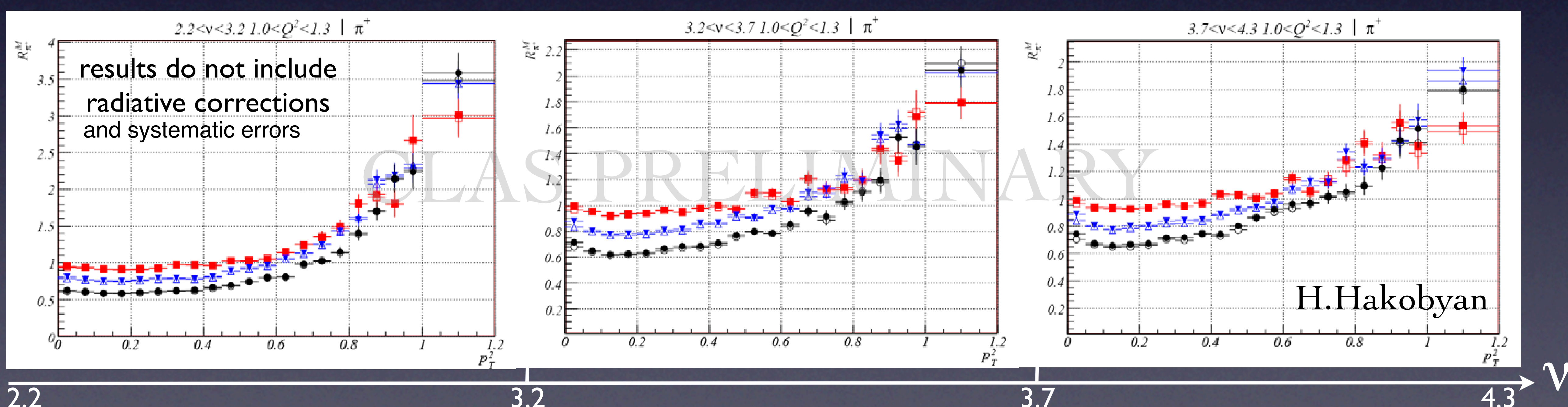
- Attenuation systematically increases for the larger nuclei
- Attenuation of high z hadrons, enhancement for high pT^2

π^+ Multiplicities

R_{π^+} slice in 3D set of bins (Q^2, $3.2<\nu<3.7$, z) integrated over pT^2



R_{π^+} slice in 3D set of bins ($1.0<Q^2<1.3$, ν, pT^2) for $0.4<z<0.7$



- Attenuation systematically increases for the larger nuclei
- Attenuation of high z hadrons, enhancement for high pT^2

Future Program

- Extraction of timescales and quark energy loses based on the finalized data analysis
- Measurement from existing EG2 set of π^0 vs η suppression (not previously accessed in cold matter), extraction of transverse momentum broadening for both mesons.
- The program to pursue hadronization studies at **CLAS12 (E12-**06-117) with 11 GeV electron beam has been approved for 120 beam days. It will provide by far the best experimental access to medium-simulated quark energy loss, and enable extraction of 4D multiplicities for wide range of hadrons.
- **EIC** will offer high energy eA collisions with E_{e^-} =11 GeV/c and unpolarized heavy nuclei E_A = 12-40 GeV/c per nucleon for A>200 (Au, Pb).
  Long parton life time, direct access to pQCD E_{loss} .

Summary

- Hadronization in DIS, also Drel-Yan and heavy ion collision
- Production time related to transverse momentum broadening
- Formation time related to hadronic multiplicity ratio

- CLAS eg2 three pion state analysis, on ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb
- Multidimensional multiplicity analysis: 3D for π^{0}/π^{+}, 2D for π^{-}
- RC for π off nuclear target + exclusive contribution

- Hadronization studies reach precision era
- Future program with CLAS12 (E12-06-117)

BACKUP SLIDES

Accessible hadrons in CLAS

W.Brooks

The tools: *stable* hadrons, accessible with 11 GeV experiment PR12-06-117 W.K. Brooks, J.G. Gilfoyle, K. Hafidi, M. Holtrop + 7 others not in this room

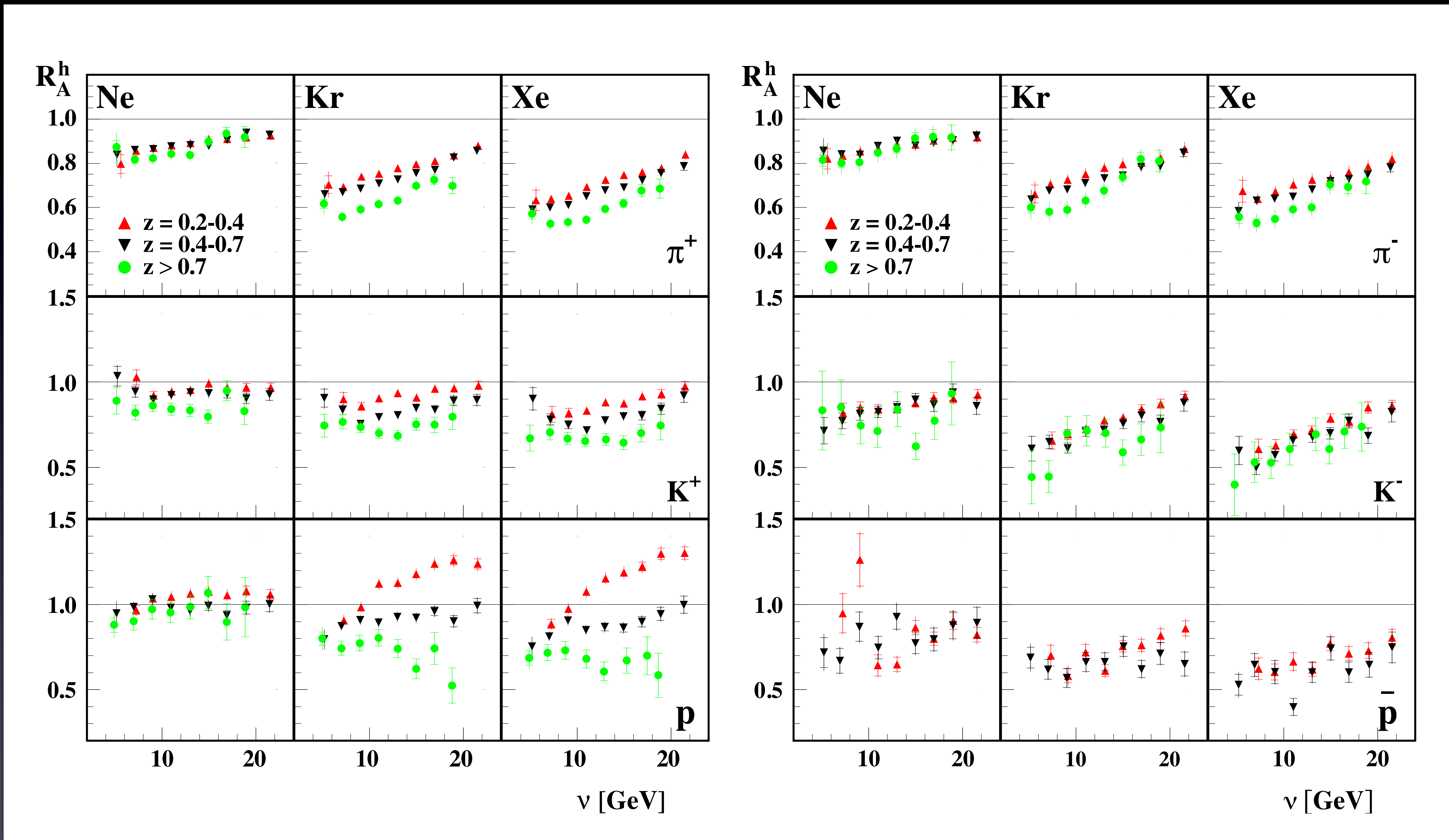
Actively underway with existing 5 GeV data

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

Existing 2D Data on Multiplicities: HERMES

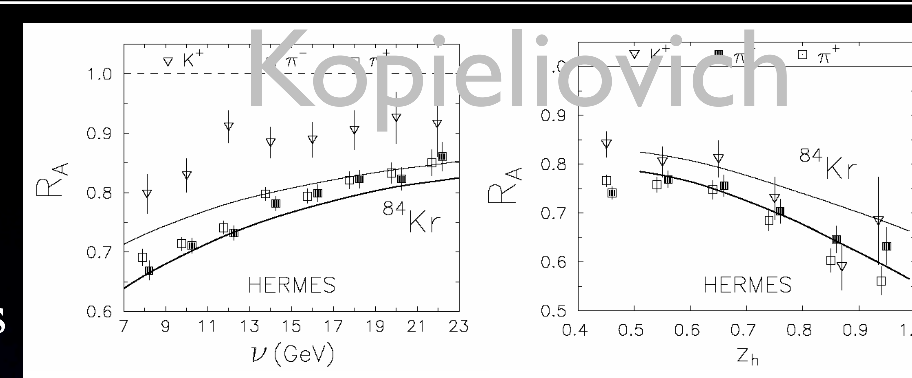


HERMES Collaboration, A.Airapetian et. al., Eur.Phys.J.A47:113,2011

Models

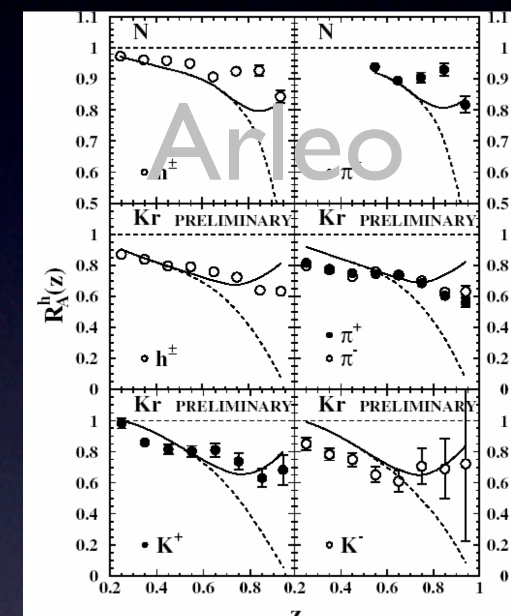
Phenomenological

A. Bialas and T. Chmaj, PhL 133B (1983) 241
A. Bialas and M. Gyulassy, NPh B291 (1987) 793
one or two time scales plus corresponding cross sections



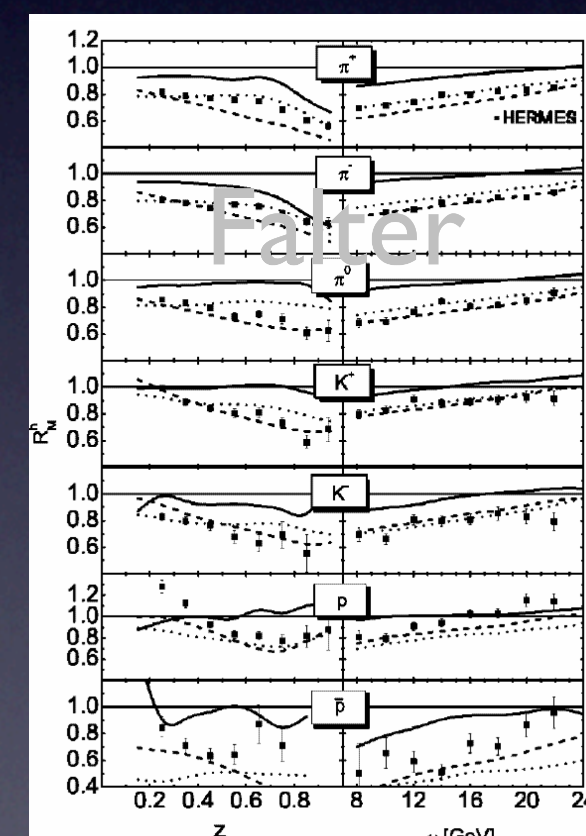
Energy loss type

X. Guo and X.N. Wang, PRL 85 (2000) 3591
E. Wang and X.N. Wang, PRL 89 (2002)162301
F. Arleo EPJ C30 (2003) 213
gluon radiation and quark-quark interaction
effective (increased) z in fragmentation function



Energy loss and absorption

A. Accardi, V. Muccifora, H.J. Pirner, NPh A720 (2003)131
B.Z. Kopeliovich, J. Nemchik, E. Predazzi, A. Hayashigaki, NPh A740 (204) 211
nuclear absorption cross sections after 'formation' time



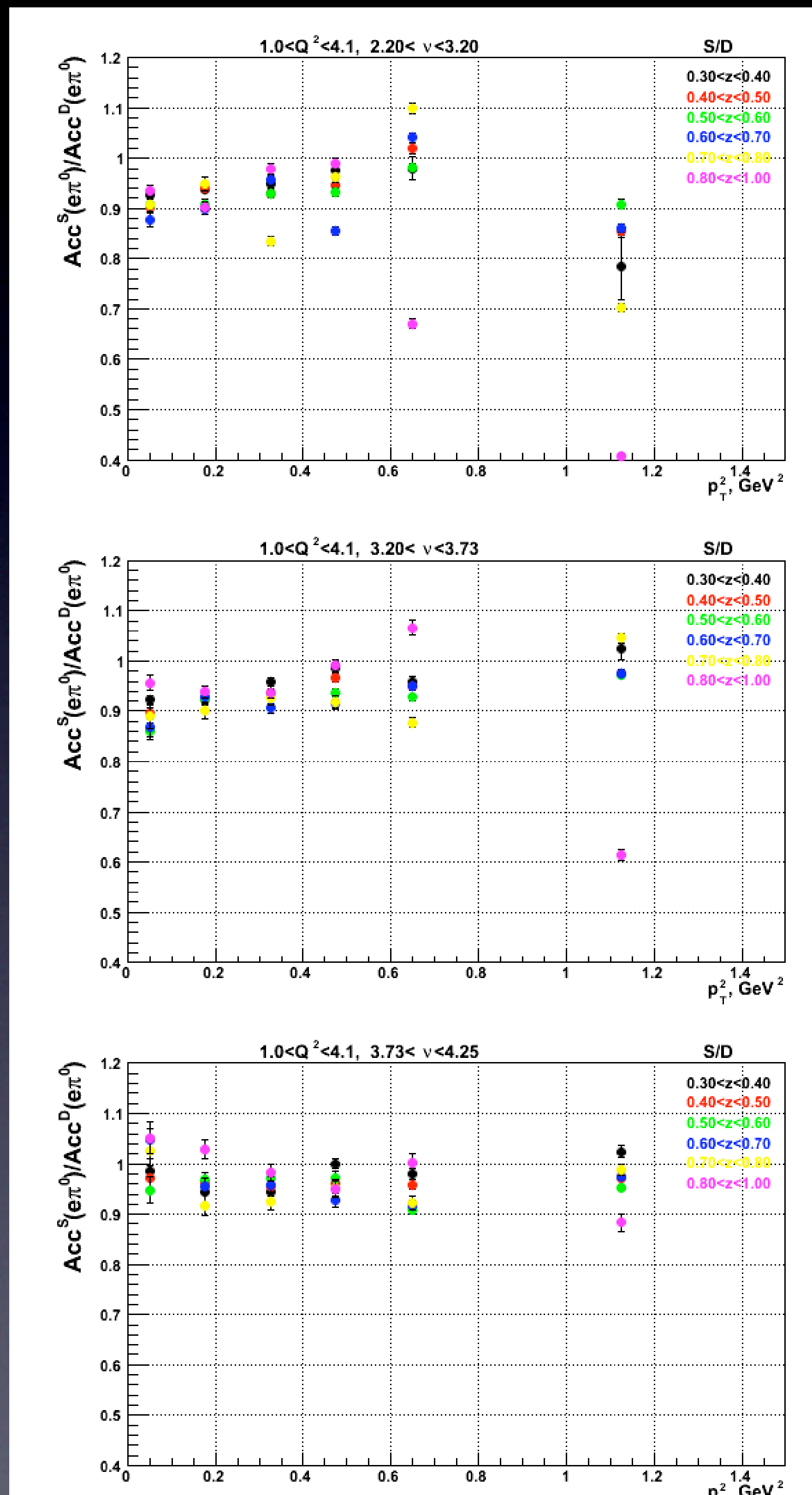
'Full FSI'

T. Falter, W. Cassing, K. Gallmeister, U.Mosel, PR C70 (2004) 054609
coupled-channel treatment of FSI by means of BUU transport model

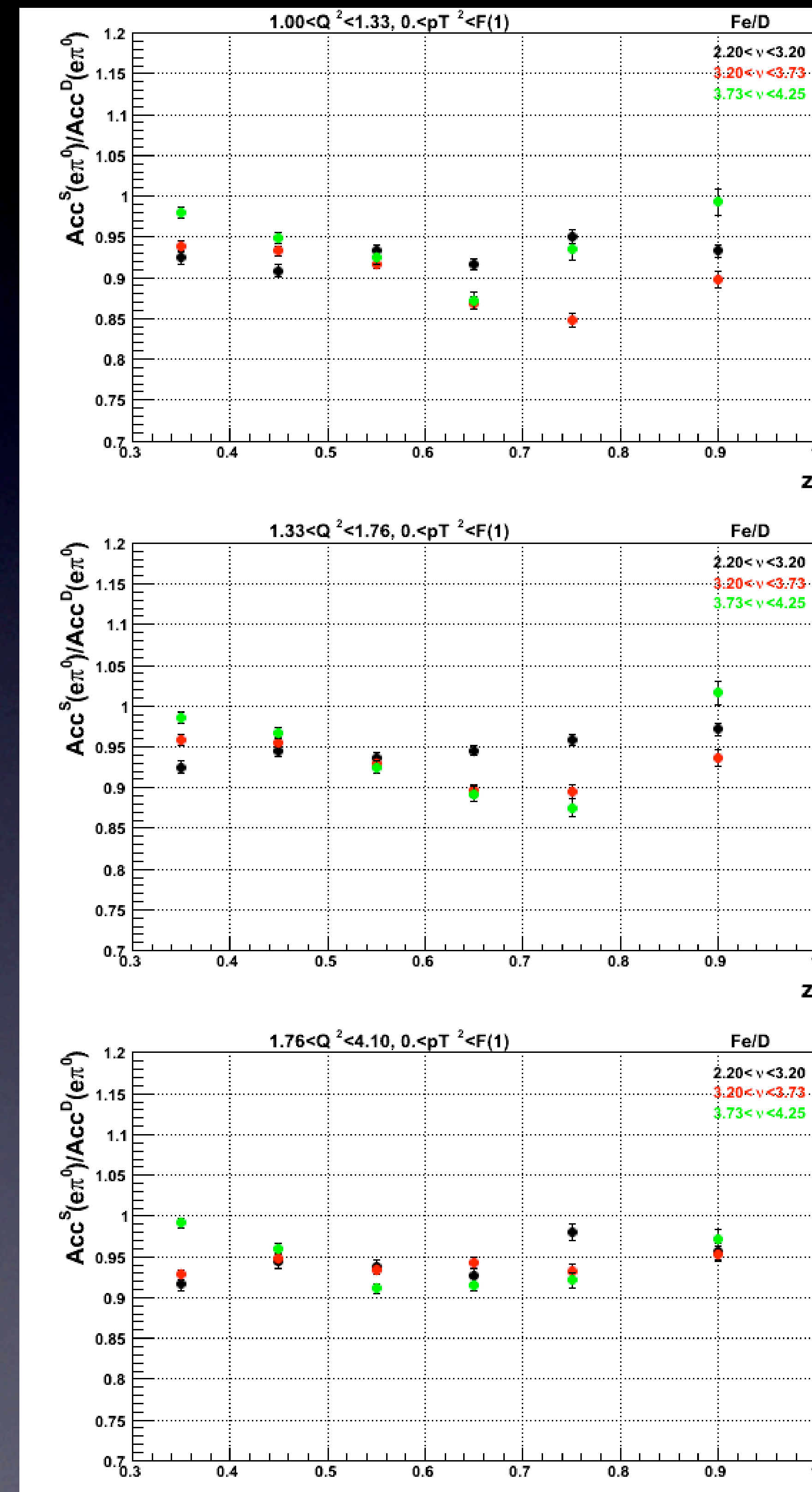
"None of the existing models are able to describe all aspects of hadronization", Gunar Schnell, HERMES

Analysis: Acceptance Ratio ($e\pi^0$)

(ν, z, pT^2) = 108 bins

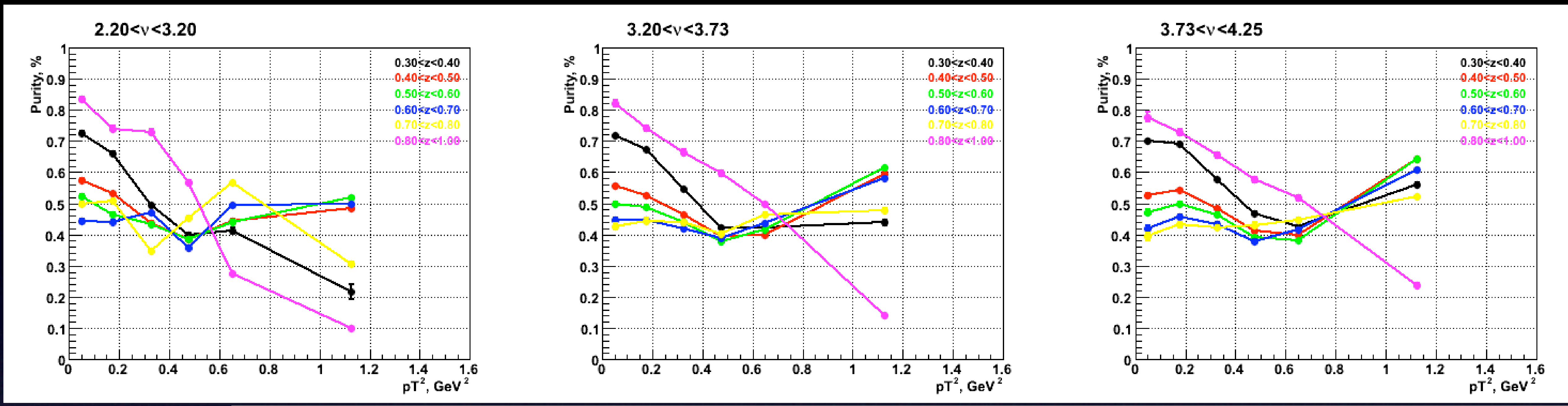


(Q^2, ν, z) = 54 bins

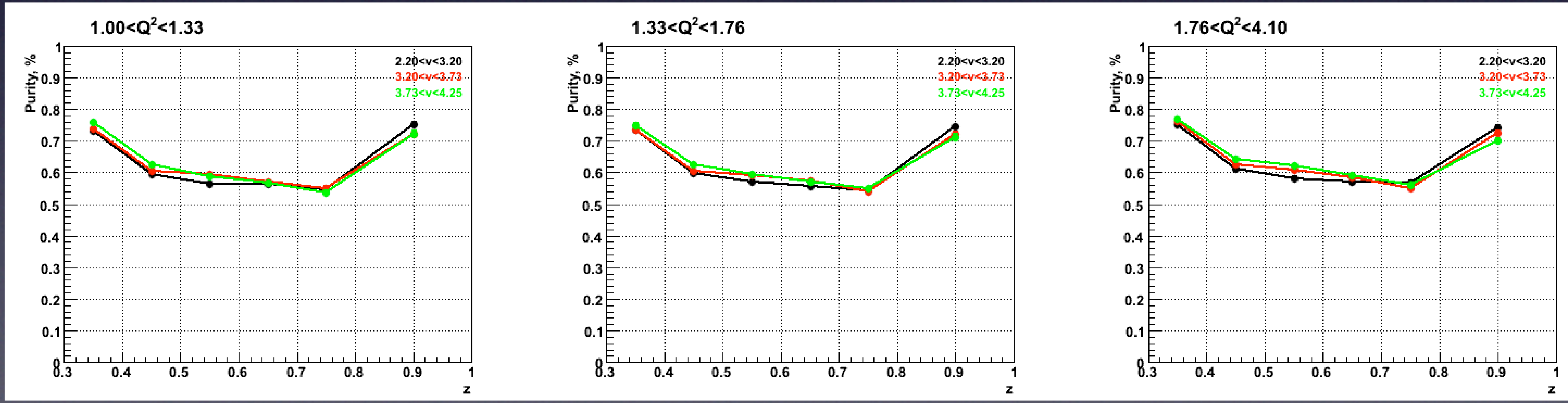


Purity

(ν, z, pT²)

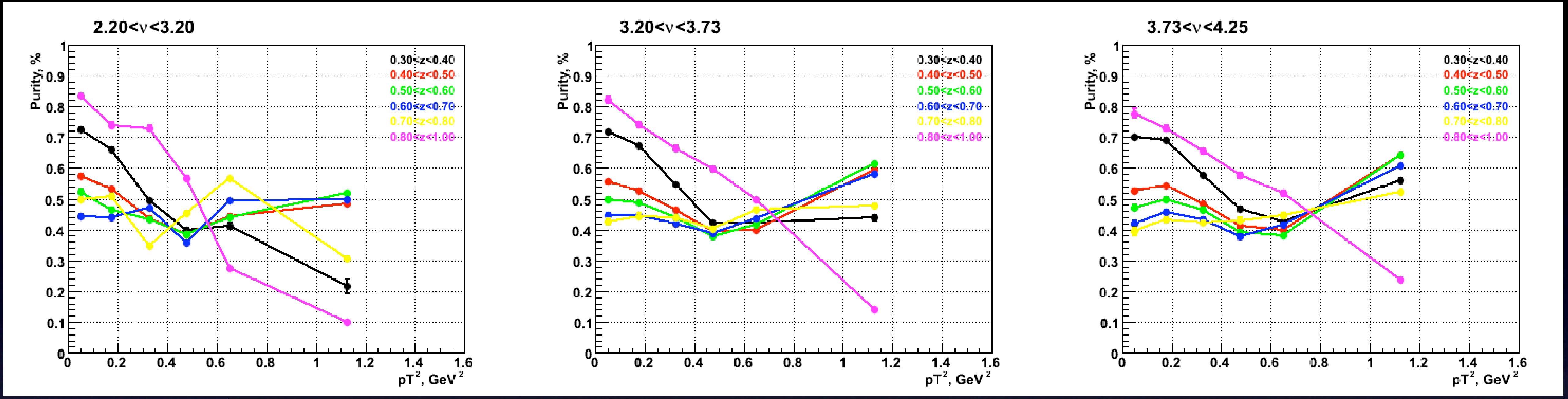


(Q²,ν, z)

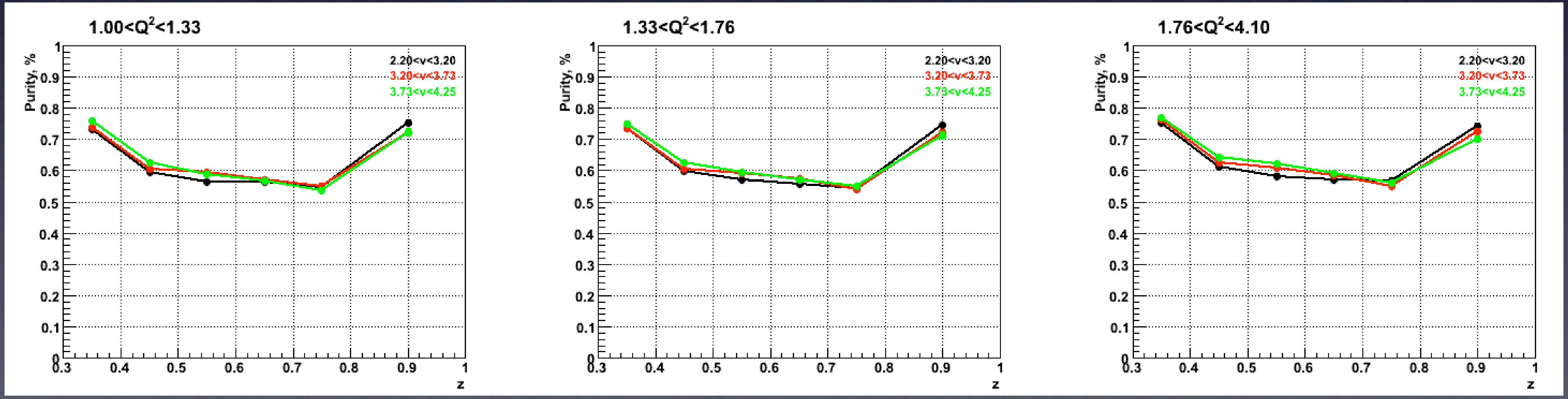


Purity

(ν, z, pT^2)



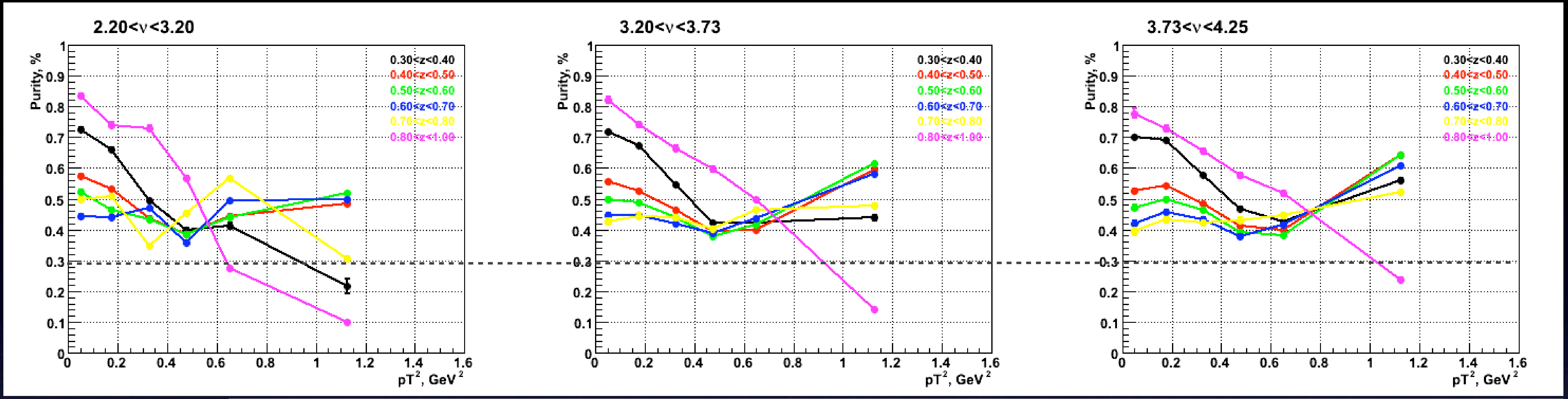
(Q^2, ν, z)



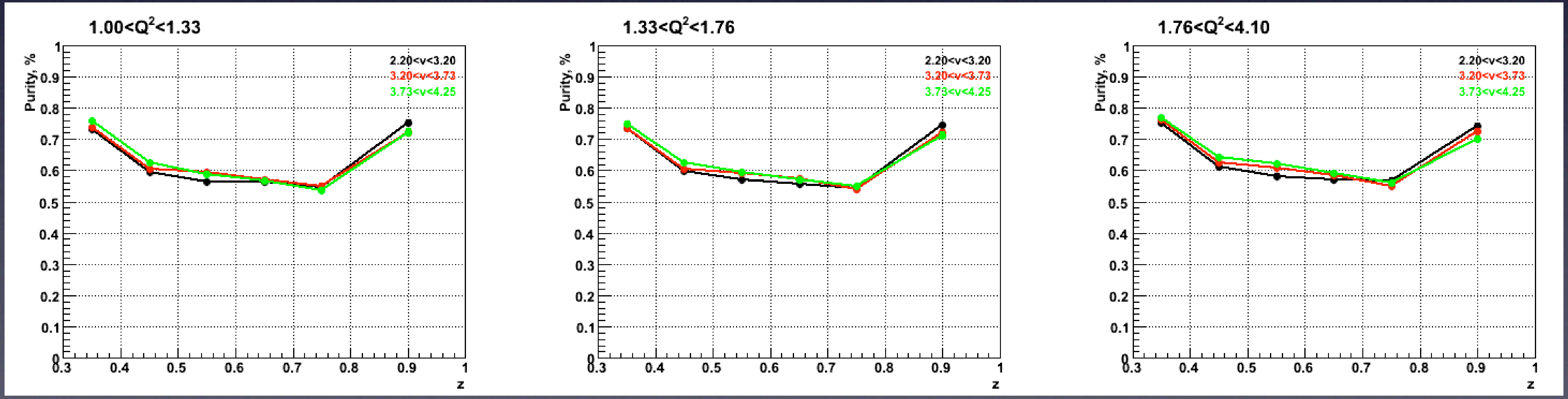
Ansatz: flat cross section with perfect efficiency in 1D bin with minimum resolution 1σ would have Purity = 68%.
In n-dimensions this yields $(0.68)^n$, n=3 dimensions we apply a cut off at Purity>30%

Purity

(ν, z, pT²)



(Q^2, ν, z)



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Hadronic broadening or partonic broadening?

p_T broadening for Pb does not show any strong trend with pion energy, while hadronic **elastic** scattering cross section changes by an order of magnitude