Pion Electroproduction at CLAS

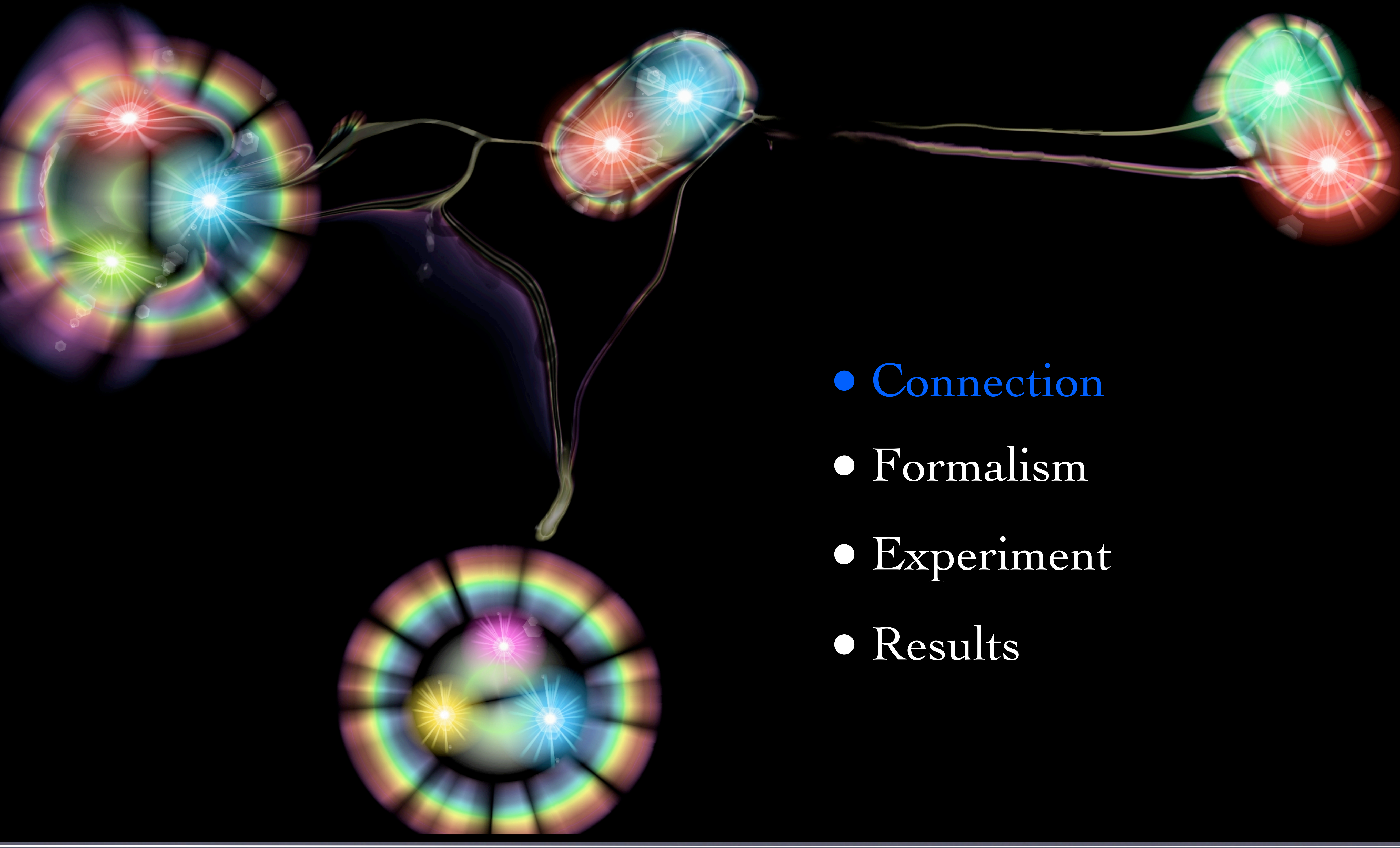
Taisiya Mineeva

Jefferson Lab

University of Connecticut

Synopsis

- Electroproduction measurements were performed off ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb nuclear targets in Jeffereson Lab Hall B using incoming electron energy of 5 GeV and CLAS detector
- The goal is to measure SIDIS yield of hadrons along with transverse momentum broadening in large nuclei compared to ^{2}H
- Such measurements will provide insights onto space-time development of hadronization in cold nuclear medium.



- Connection
- Formalism
- Experiment
- Results

Nuclear effects in neutrino scattering experiments

• Incoming ν_μ flux

uncertainties on the hadron yield produced off C(Be) targets as a function of P_z and P_T
knowledge on π/K ratio gives constraint on ν_μ background
-> MINOS: 9% for E_ν <6GeV on Δm^2

P.Adamson *et al.*, A study of muon neutrino disappearance using the Fermilab Main Injector Neutrino beam 6 arXiv 0711.0769

-> T2K: 7.43% (4.3%) on predicted number of events from SK (w/o oscillations)
model uncertainty on production rate of π is 50%, while for K is 15-100 %

K.Abe *et al.*, First muon-neutrino disappearance study with an off-Axis beam, arXiv:1201.1386

• Difference in $E_{visible}$ and E_ν

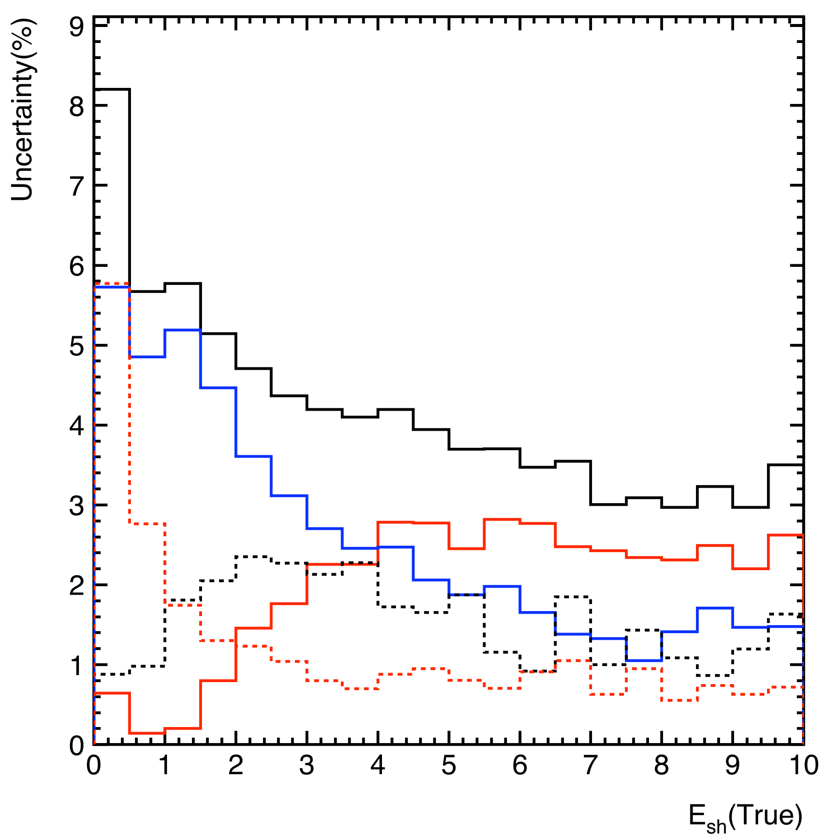
$E_\nu = E_\mu + E_{visible}(hadron) + E_{missing}$
FSI - one of the largest sources of background and inefficiency accounting for $E_{missing}$
-> MINOS: uncertainty of neutrino production of hadrons is 8.2%
-> T2K: uncertainty due to final-state interactions is 3.2% (5.9%) (w/o oscillations)

• NC π^0 production

background in $\nu_\mu \leftrightarrow \nu_e$: one of π^0 decay products can be misidentified as l from CC event (MiniBooNE, T2K (with dedicated Pi-Zero detector), Icarus, Noνa, etc)

Hadronic shower scale uncertainties

$$E_\nu = E_\mu + E_{visible}(\text{hadron}) + \mathbf{E_{missing}}$$

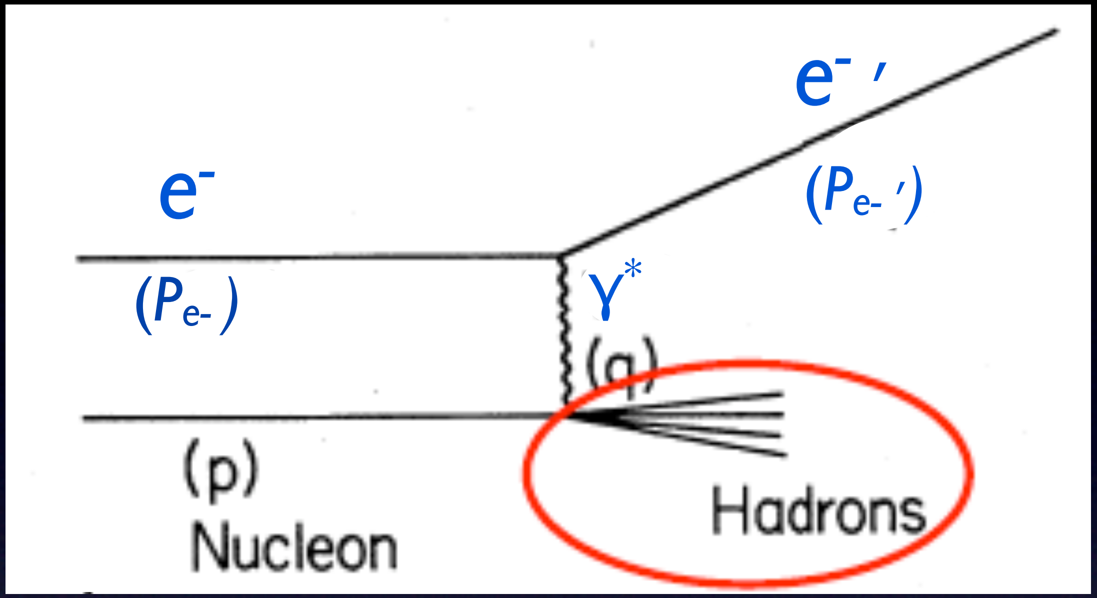


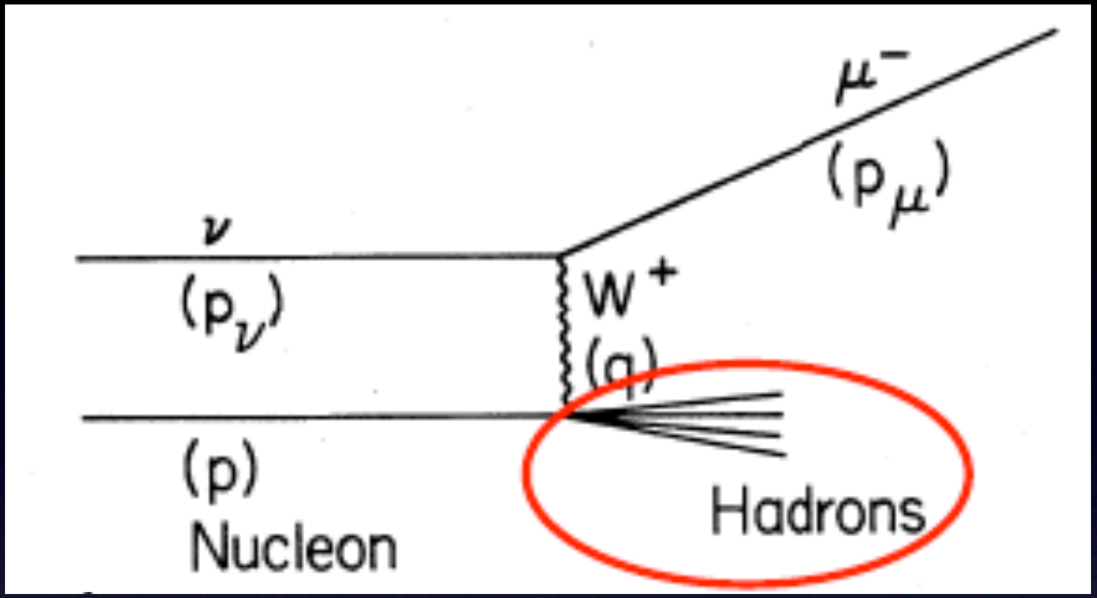
Total uncertainity on the shower energy scale from all the sources of MC parameters (solid black). Illustrated separately are contributions from hadronization model (red solid) uncertainities, formation time (dashed black), external data sources(dashed red), model assumptions (blues).

- **Hadronization model** determines set of particles produced from DIS event.
  modified KNO, JETSET, and linear extrapolation between (2.3<W<3 Gev/c)
- **Hadron formation timescale**
  time to form a hadron during which its interaction cross section in the nucleus is set to zero
- **Intranuclear rescaterring** model - how this set of hadrons is altered as by FSI as they exit the target nucleus.
  σ(h)modification on bound N, *etc*
  π absorption/rescattering
  low momenta secondary nucleon production

S.Dytman, H.Gallagher, M.Kordosky Hadronic shower scale uncertainities in the MINOS experiment, arXiv:0806.2119

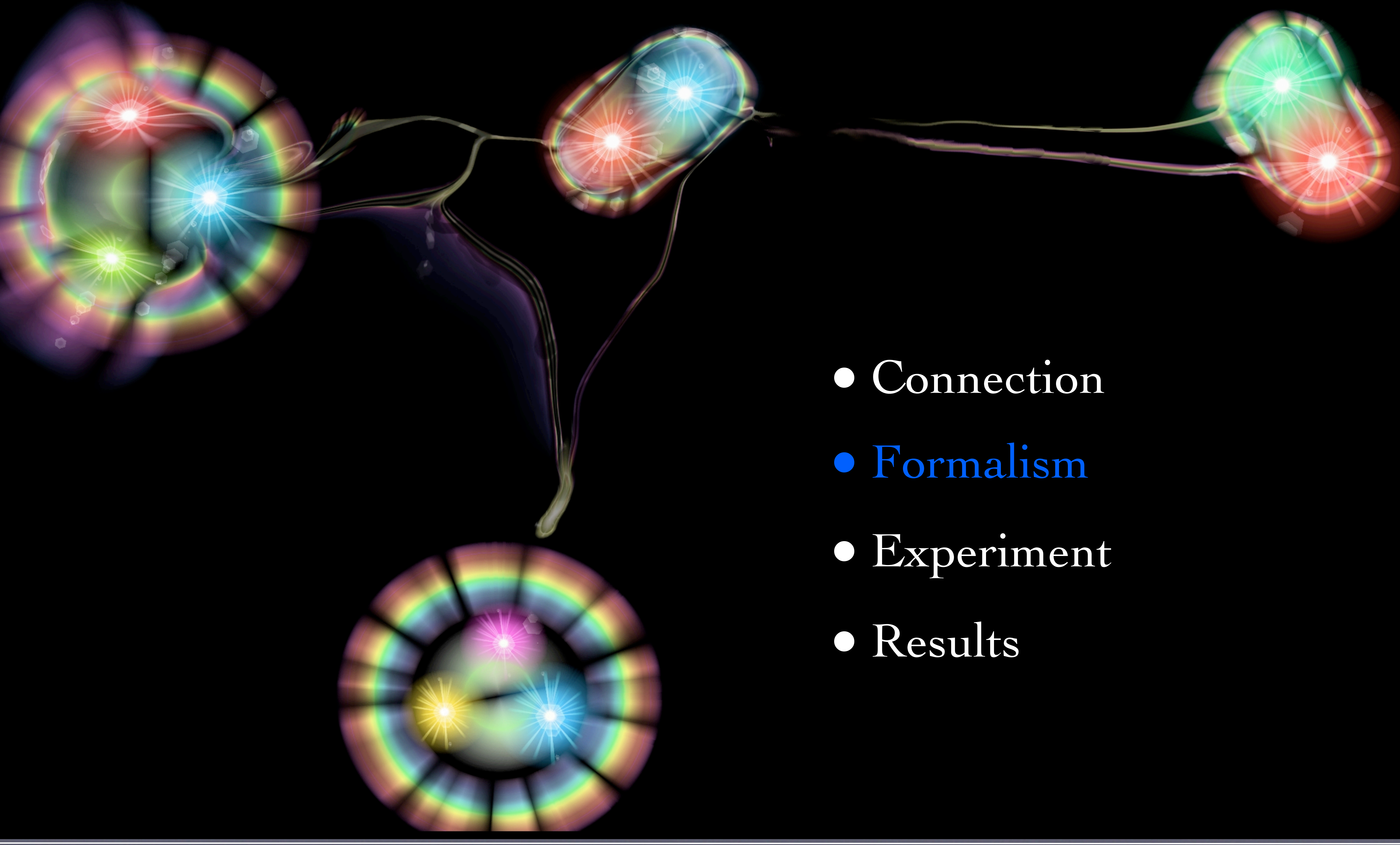
Connection to electron scattering





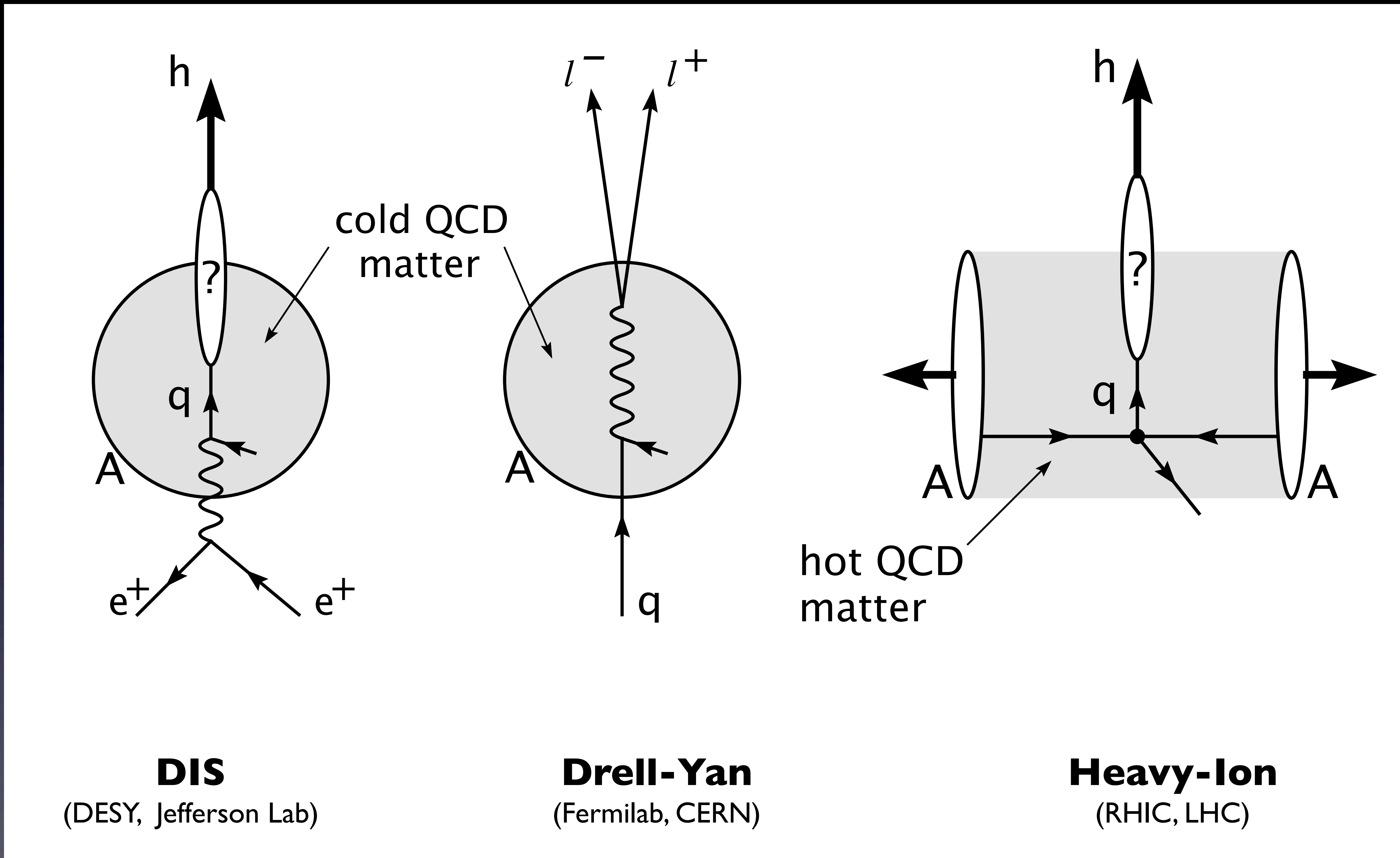
- fragments of the struck parton in ν and e^- scattering should suffer the same FSI: at large (W>2 GeV/c^2) invariant masses hadronic systems produced in ν systems are similar to those produced in charged lepton and hadron scattering

- neutrino experiment can greatly benefit by tuning their MC based on the improved understanding of parton dynamics and hadronization mechanism constrained by multidimensional data on electroproduction



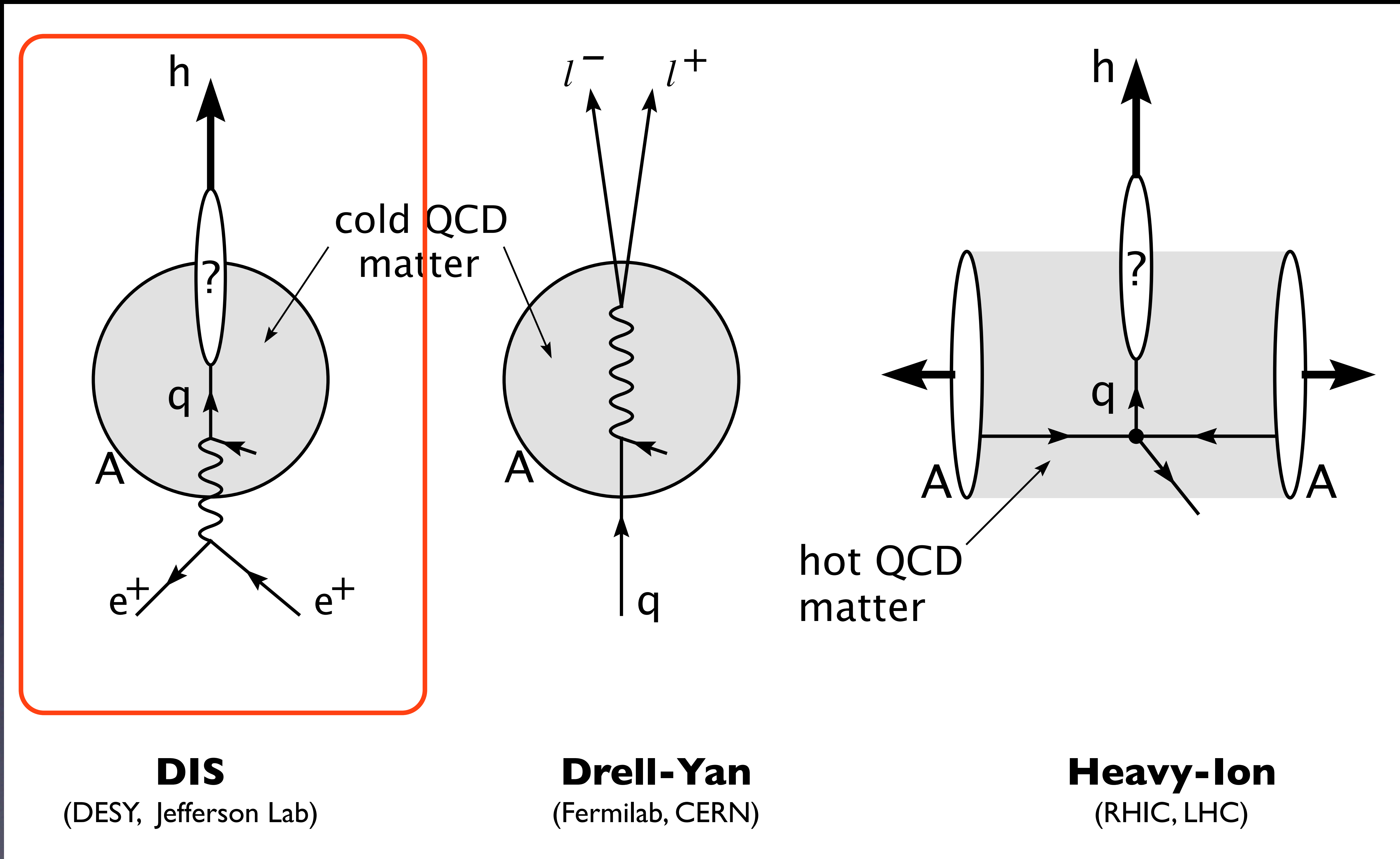
- Connection
- **Formalism**
- Experiment
- Results

Reactions



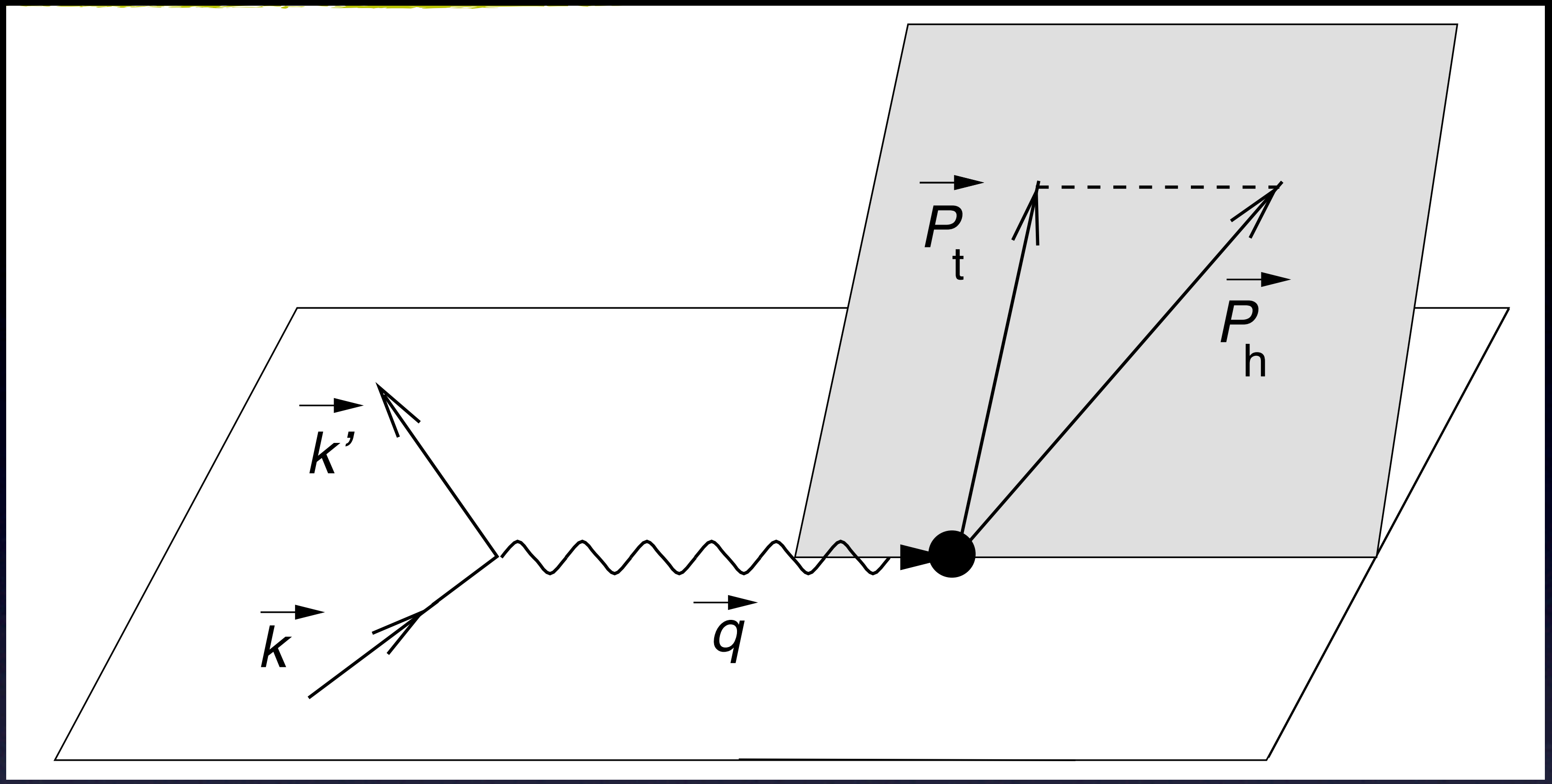
Parton Propagation and Fragmentation in QCD Matter, A.Accardi, F.Arleo, W.K. Brooks , D. D'Enterria, V.Muccifora arXiv:0907.3534v1 [nucl-th]

Reactions



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

SIDIS



$Q^2 = -q^2$ four-momentum transferred by the electron;

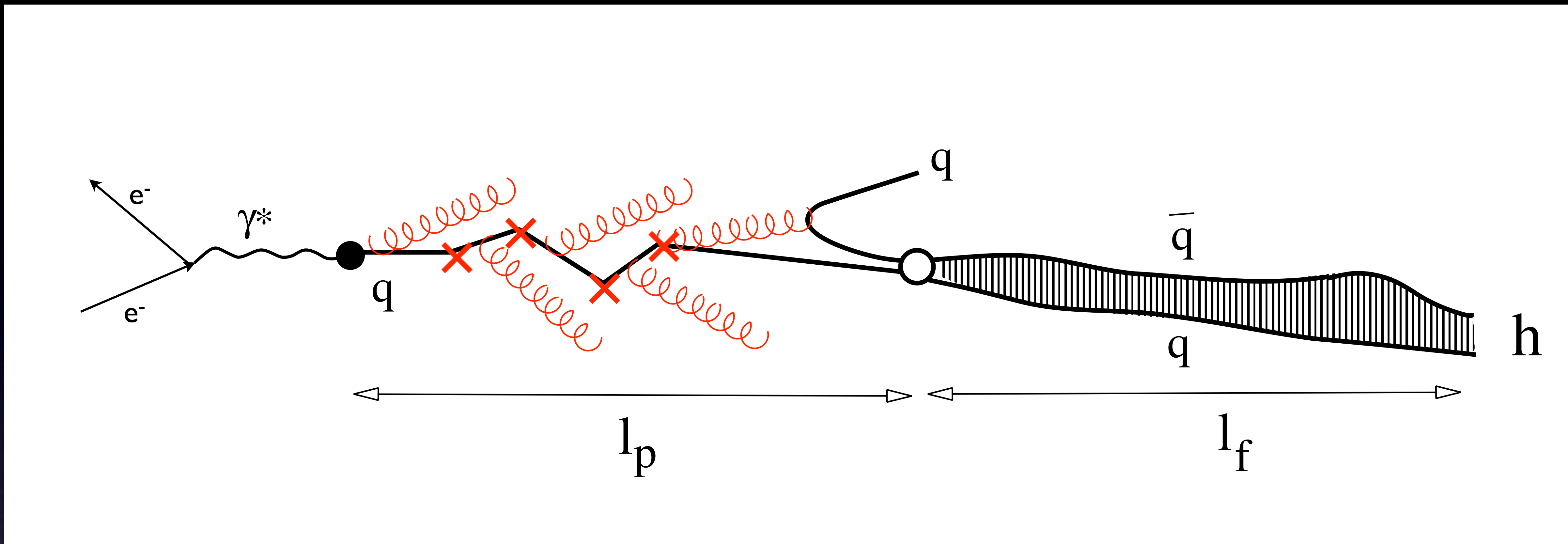
$\nu = E - E'$ energy transferred by the electron, = Initial energy of struck quark;

$z = E_h/\nu$ fraction of the struck quark's initial energy that is carried by hadron;

p_T hadron momentum transverse to virtual photon direction;

CLAS kinematics: $Q^2 > 1$ GeV^2 ; $W > 2$ GeV; $0.1 < x_B < 0.55$;

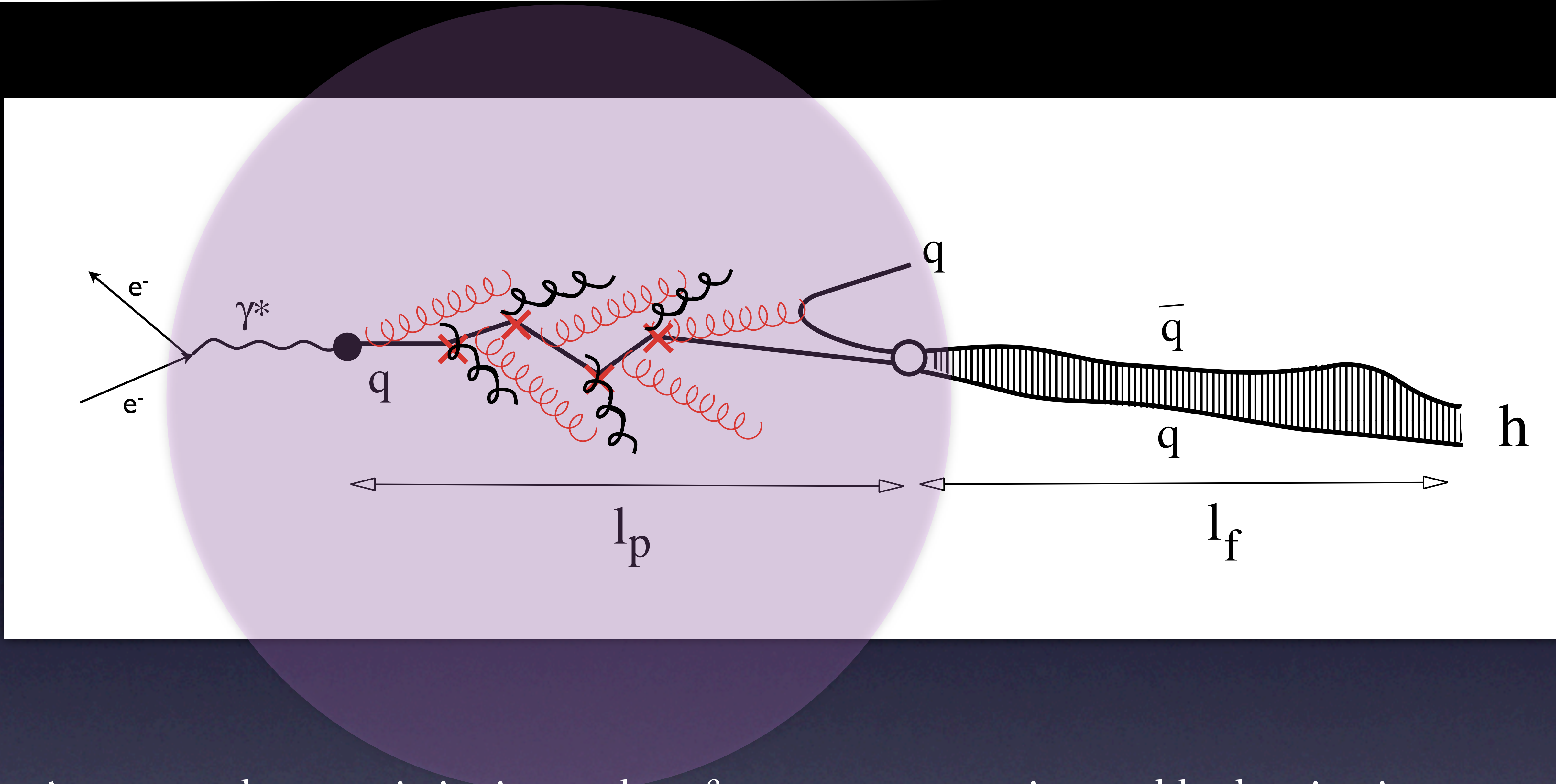
Hadronization in vacuum



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

- Access to characteristic timescales of parton propagation and hadronization:
  how long quark remains deconfined ? -> production time τ_p
  how long it takes to form full hadronic wave function? -> formation time τ_f

Hadronization in medium



- Access to characteristic timescales of parton propagation and hadronization:
  how long quark remains deconfined ? -> production time τ_p
  how long it takes to form full hadronic wave function? -> formation time τ_f

- Nuclear medium acts as spacial analyzer: the yields and kinematics of detected hadrons are modified by varying the nuclear size which accesses different time scales

Observables (1)

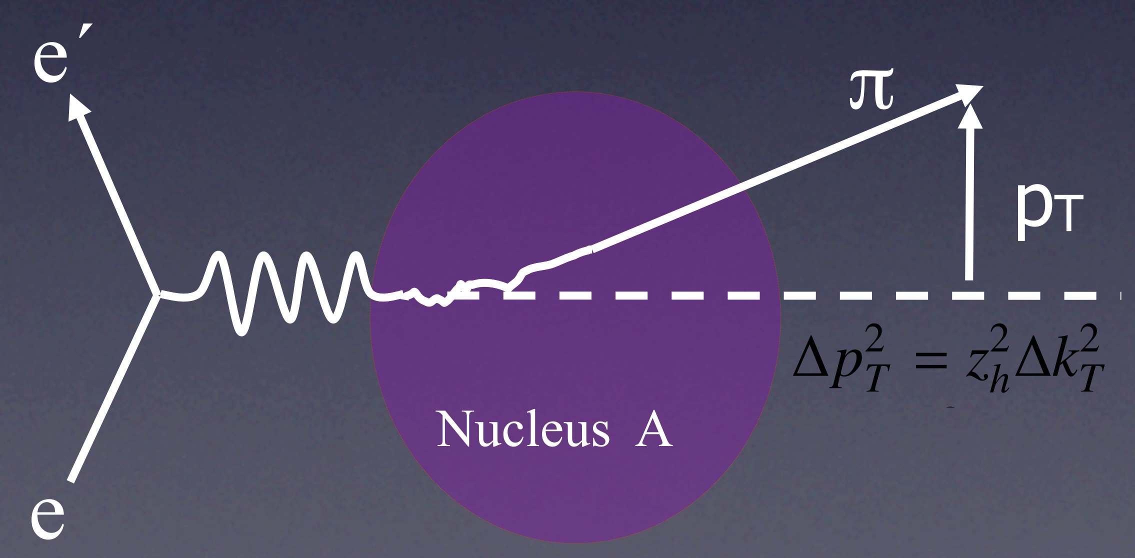
Transverse momentum broadening

defined with respect to the γ^* direction

$$\Delta p_T^2 = < p_T^2 >_A - < p_T^2 >_D$$

- propagation of a parton through the medium is accompanied by gluon bremsstrahlung (radiative energy losses) and multiple scattering (collisional energy losses) leading to accumulation of quark transverse momenta.

- *how long can a light quark remain deconfined ? how much energy it losses ?*
  The production time τ_p access this via shape and magnitude of A-dependence.



Observables

Hadronic multiplicity ratio

normalized change in production yields of hadrons in nuclei A to D

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

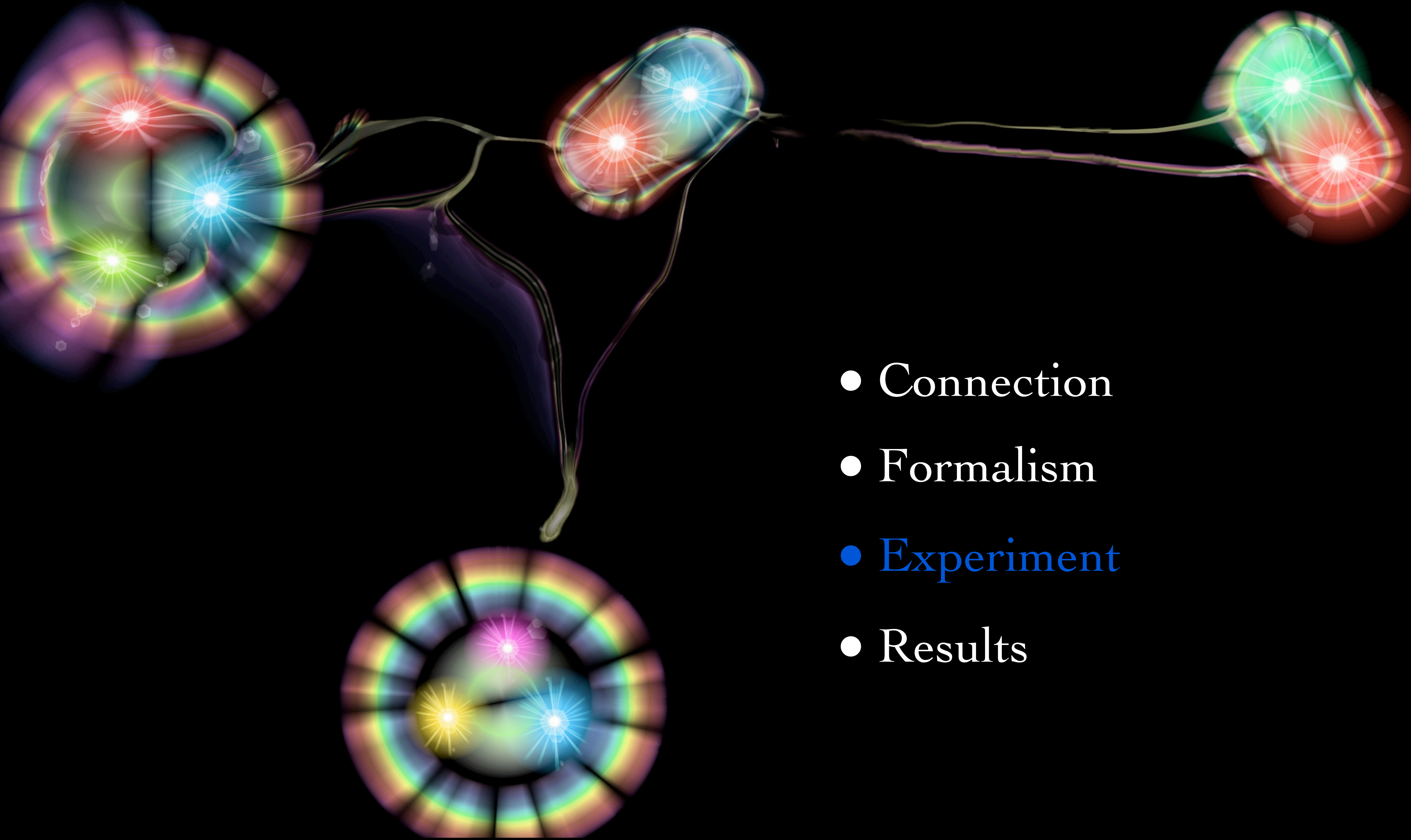
- colorless pre-hadron is created after quark color neutralization
- pre-hadron interaction is dominantly inelastic leading to attenuation
- *how long does it take to form the color field of the hadron ?*

  The formation time τ_f measures this via $R_h(Q^2, \upsilon, p_T, z_h)$

Glimpse at available models

Authors	References	Model Description	Multiplicity Results	$p_\perp^2$ Broadening Results
Accardi *et al.*	[Accardi 2003]	Q^2 rescaling of FF + hadron absorption	Few comparisons with HERMES & EMC	None
Arleo	[Arleo 2003b]	BDMPS based parton energy loss (quenching weight calculation)	Scarce comparison with HERMES	$\hat{q} = 0.75$ GeV/fm^2 too large for HERMES
Deng *et al.*	[Deng 2010] [Deng 2011]	Modified DGLAP evolution	Few comparisons with HERMES	$\hat{q} = 0.015$ GeV^2/fm coherent with HERMES
Falter *et al.* (GiBUU)	[Falter 2004] [Gallmeister 2005] [Gallmeister 2008]	Pure hadron/prehadron absorption	Extensive comparison with HERMES & EMC	None
Gyulassy and Plümer	[Gyulassy 1990]	Medium modified FF using string-flip model	Comparison with old data (EMC & SLAC)	None
Kopeliovich *et al.*	[Kopeliovich 2004] [Domdey 2009] [Ciofi degli Atti 2005]	Q^2 rescaling of FF, energy loss and prehadron absorption	Extensive comparison with HERMES & EMC	Extensive comparison with HERMES
Salgado and Wiedemann	[Salgado 2002] [Salgado 2003]	BDMPS based parton energy loss (quenching weight calculation)	Few comparisons with HERMES	Extensive comparison with HERMES
Wang and Wang	[Wang 2002]	Pure parton energy loss	Few comparisons with HERMES	None

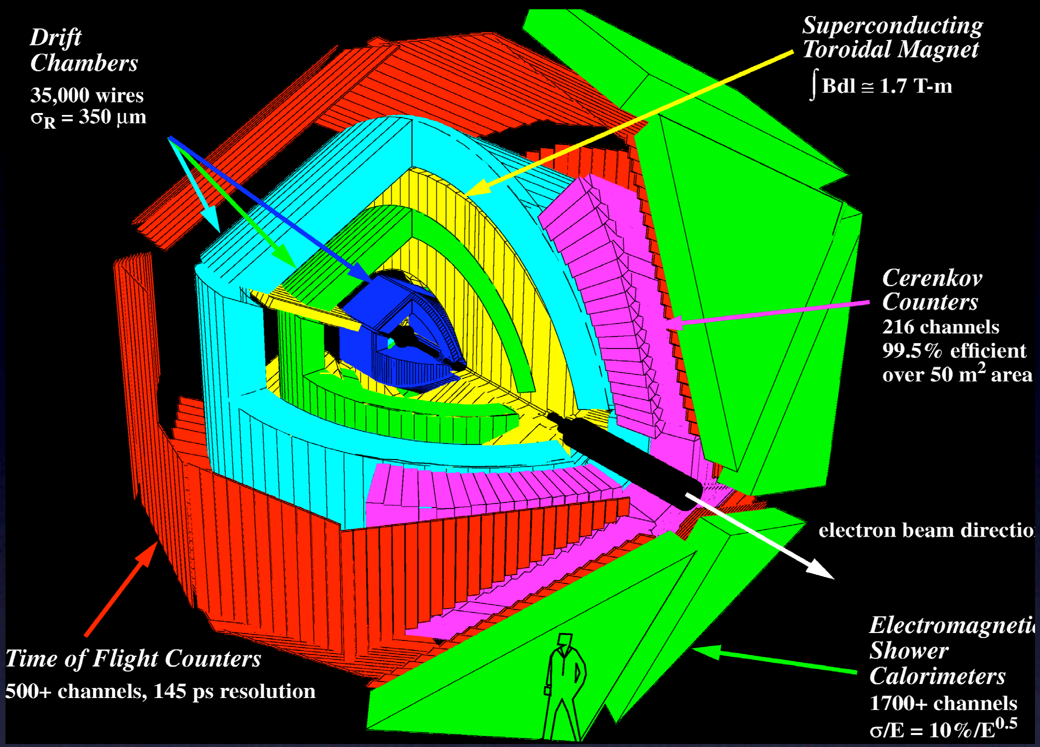
Based on HERMES data, models do not discriminate between two proposed mechanisms: partonic energy losses vs prehadron absorption. Need higher precision data.



- Connection
- Formalism
- Experiment
- Results

Experiment

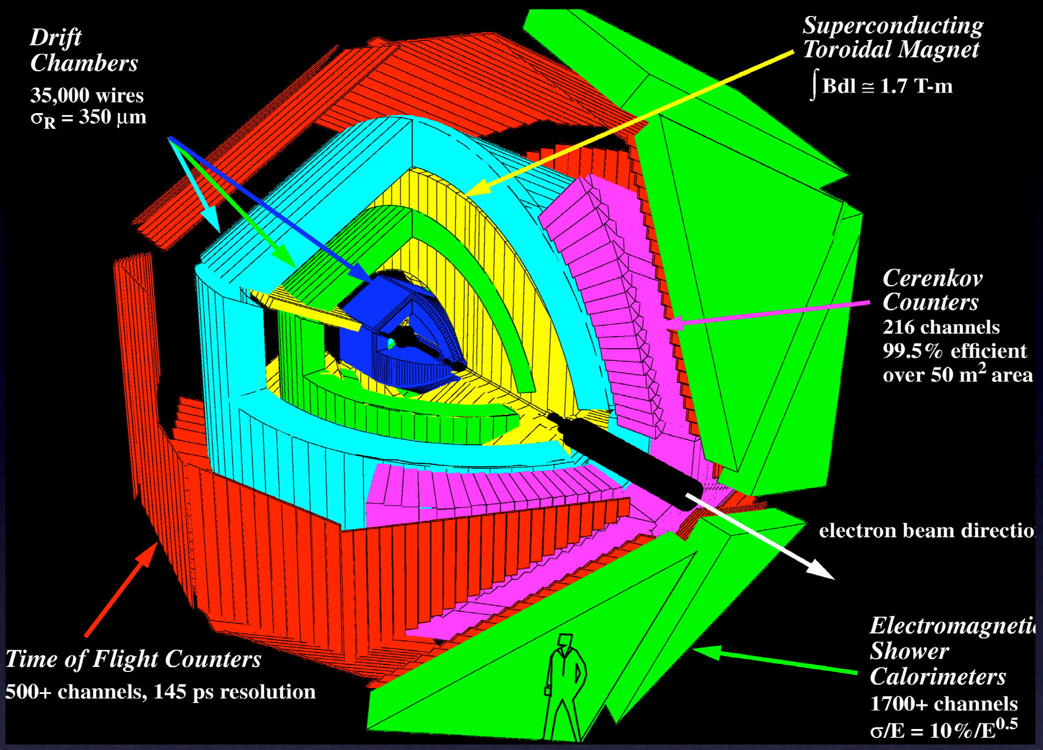
CEBAF Large Acceptance Spectrometer at Jefferson Lab



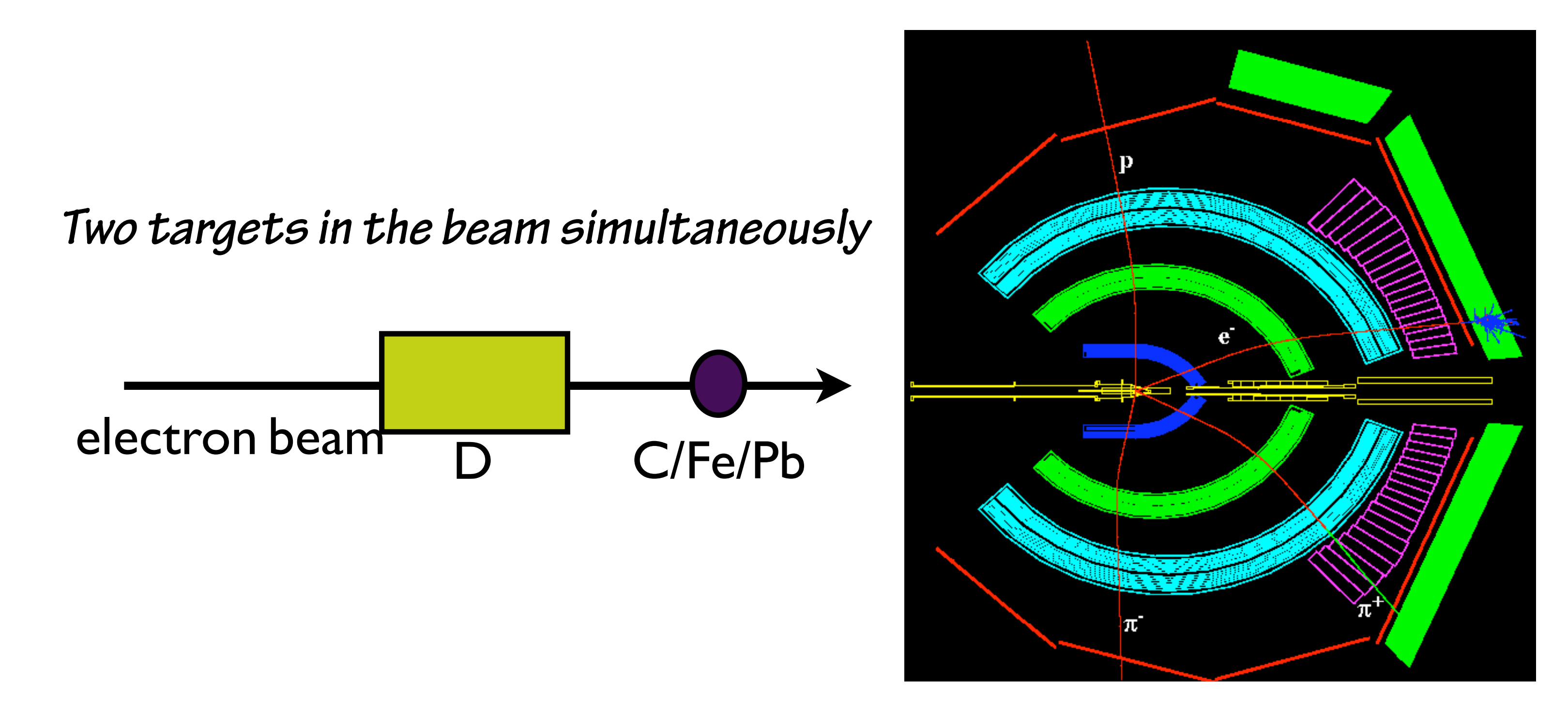
- Charged particles polar angles 8°-144°
  Momentum resolution 1% down to 0.2 GeV/c
- Neutral particles polar angles 8°-70°
  Momentum resolution 10%/√E down
- Identification of e^+/e^-, γ, p, n, $\pi^\pm$, $K^\pm$

Experiment

CEBAF Large Acceptance Spectrometer at Jefferson Lab



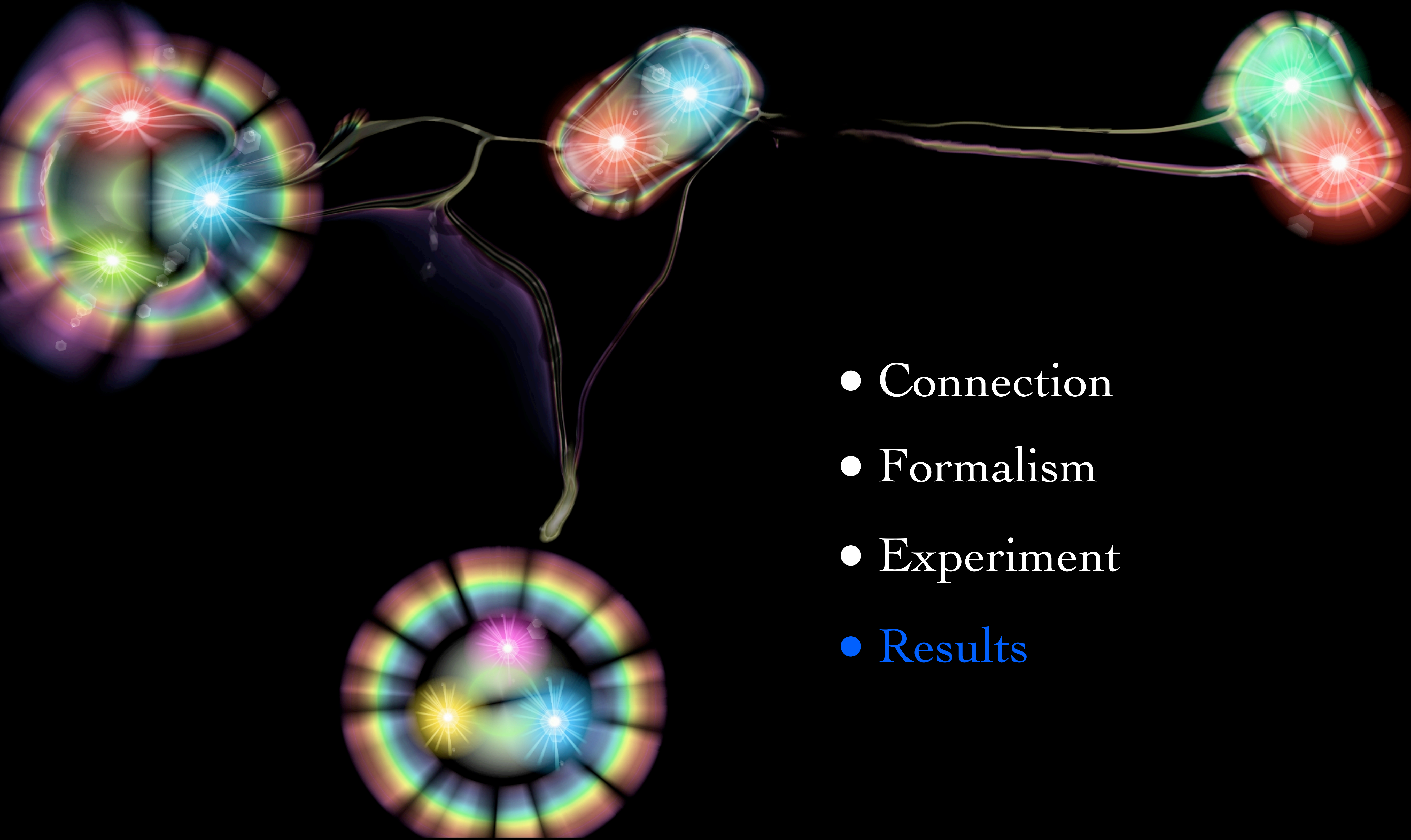
- Charged particles polar angles 8°-144°
  Momentum resolution 1% down to 0.2 GeV/c
- Neutral particles polar angles 8°-70°
  Momentum resolution 10%/√E down
- Identification of e^+/e^-, γ, p, n, $\pi^\pm$, $K^\pm$



CLAS EG2

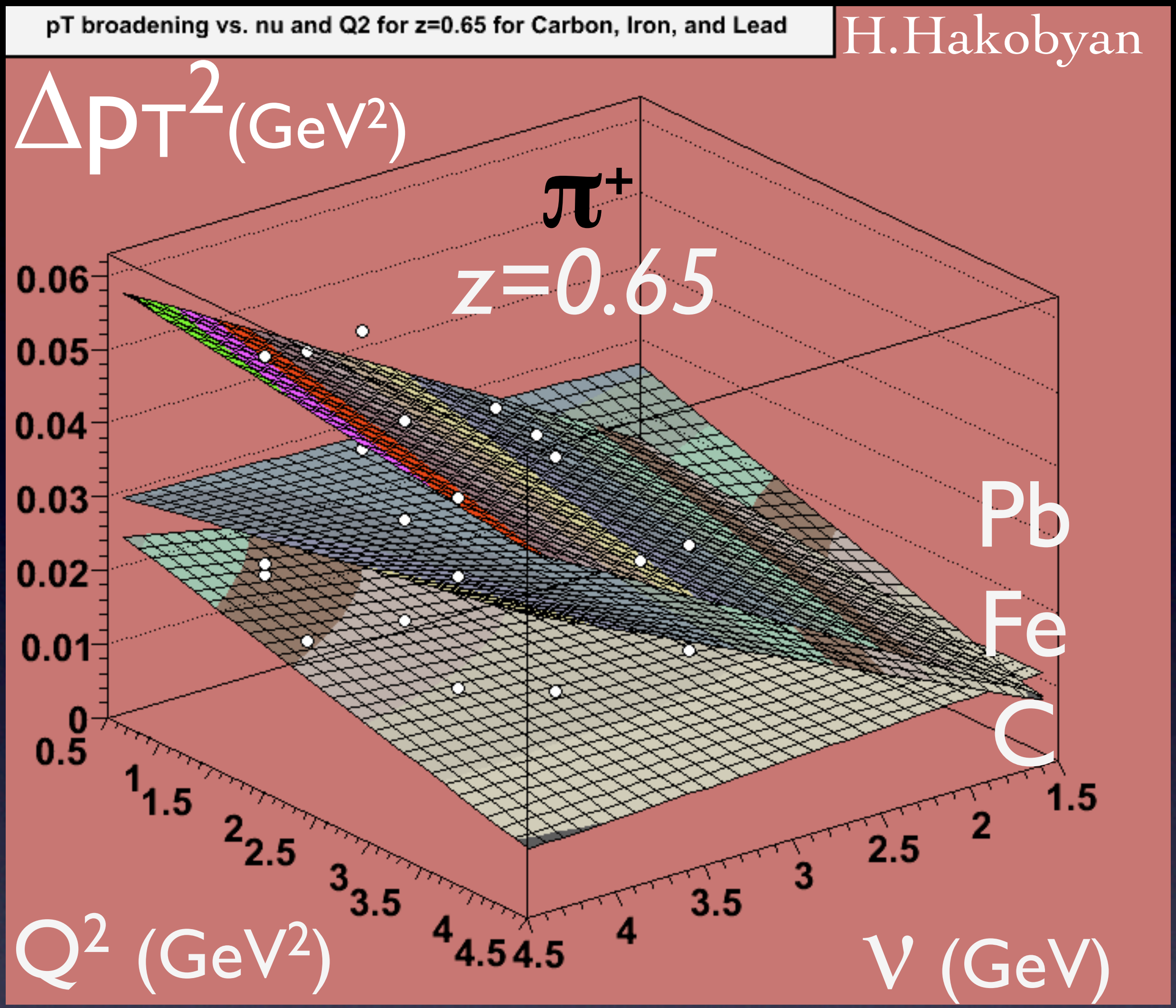
- Electron beam 5.014 GeV
- Targets ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb
- Luminosity $2 \cdot 10^{34}$ 1/(s · cm^2)

Statistics:
130M DIS electrons
6.6 M π^+, 2.8 M π^- ,2.0 M π^0



- Connection
- Formalism
- Experiment
- Results

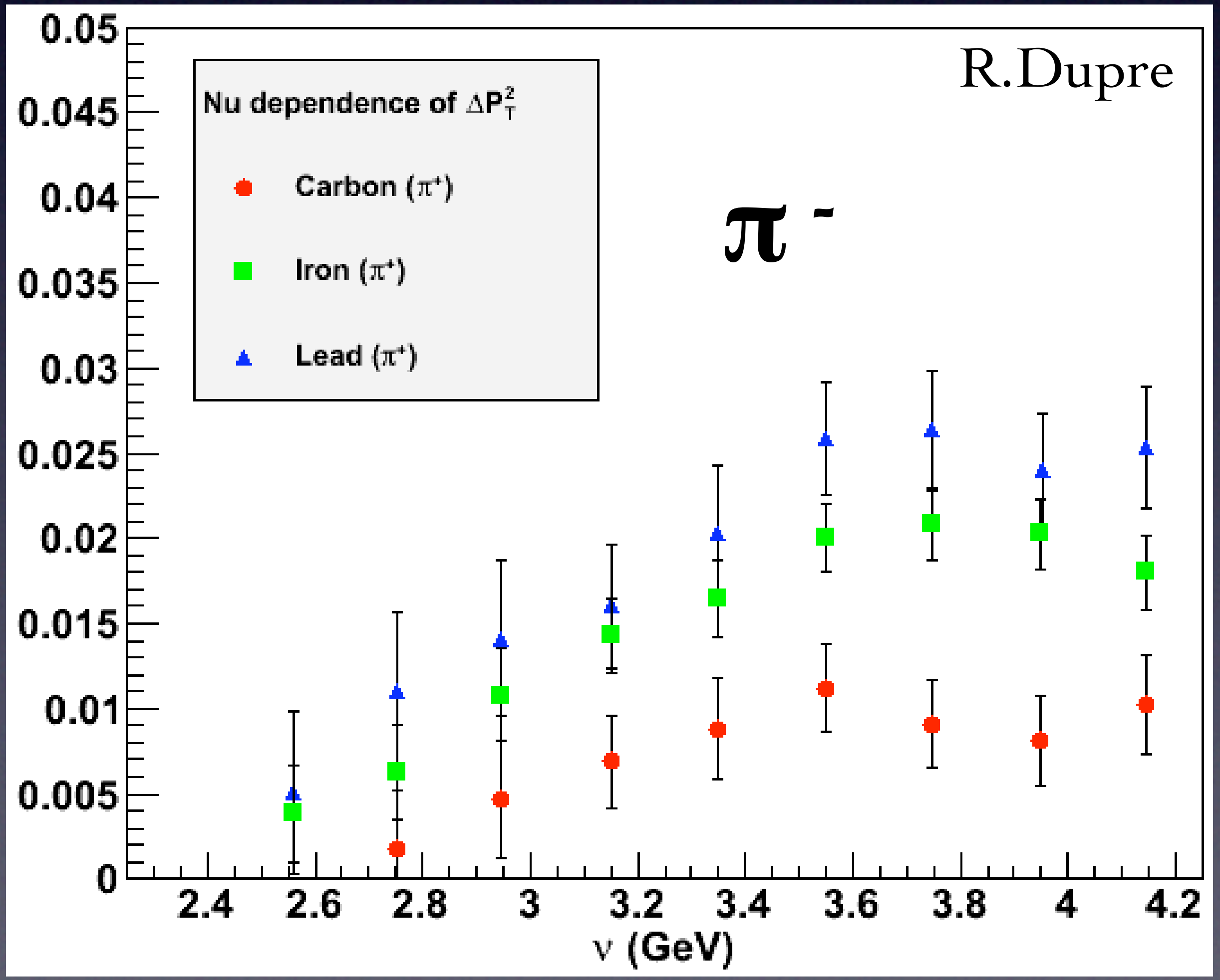
Transverse momentum broadening | $\pi^{\pm}$



π^+ :27 bins in ν, Q², z for each of 3 targets

Radiative corrections for ΔpT^2 (π^+) ~10%

Radiative corrections for ΔpT^2 (π^-) are within systematic uncertainties.



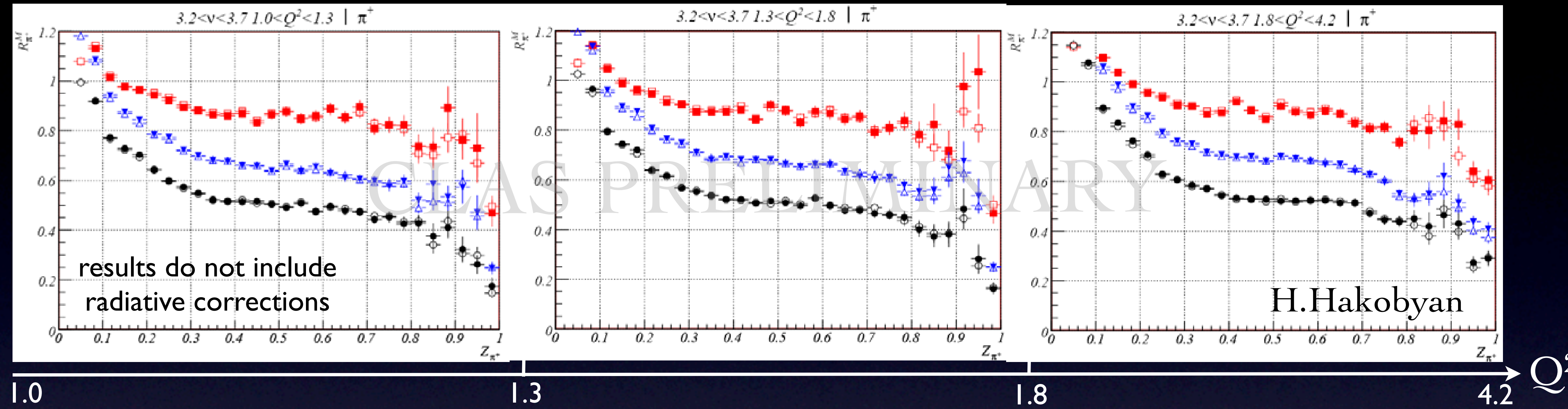
Assuming classical geometrical model:

$\Delta pT^2 \propto l_p$ and $l_p < R_{Pb}$ (6.5fm)

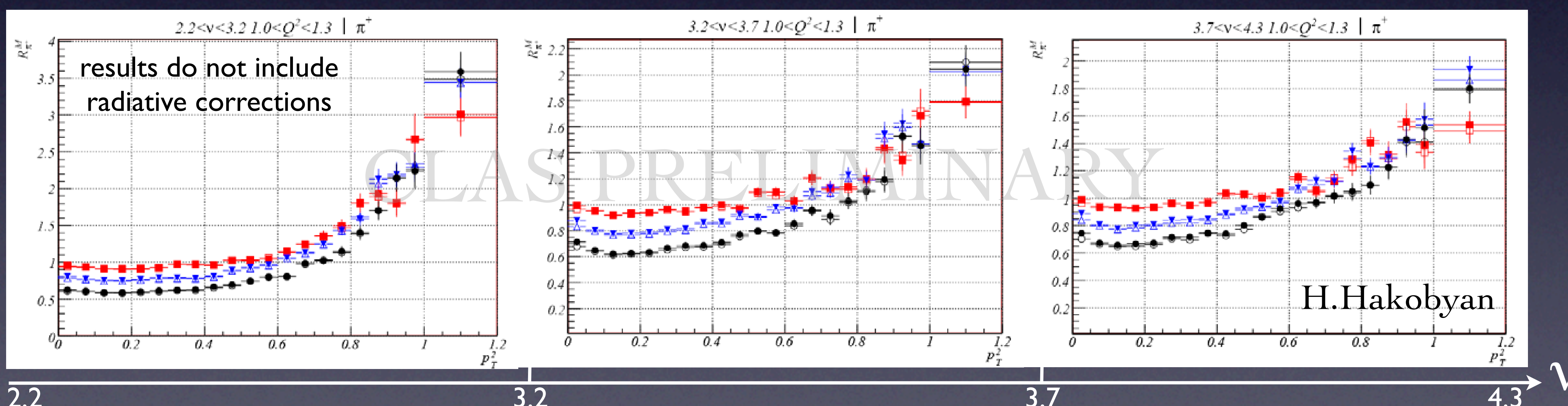
3(4) parameter fit to ΔpT^2 on π^+ gives range for τ_p to be 1.6-2.0 fm

Multiplicities | π⁺

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



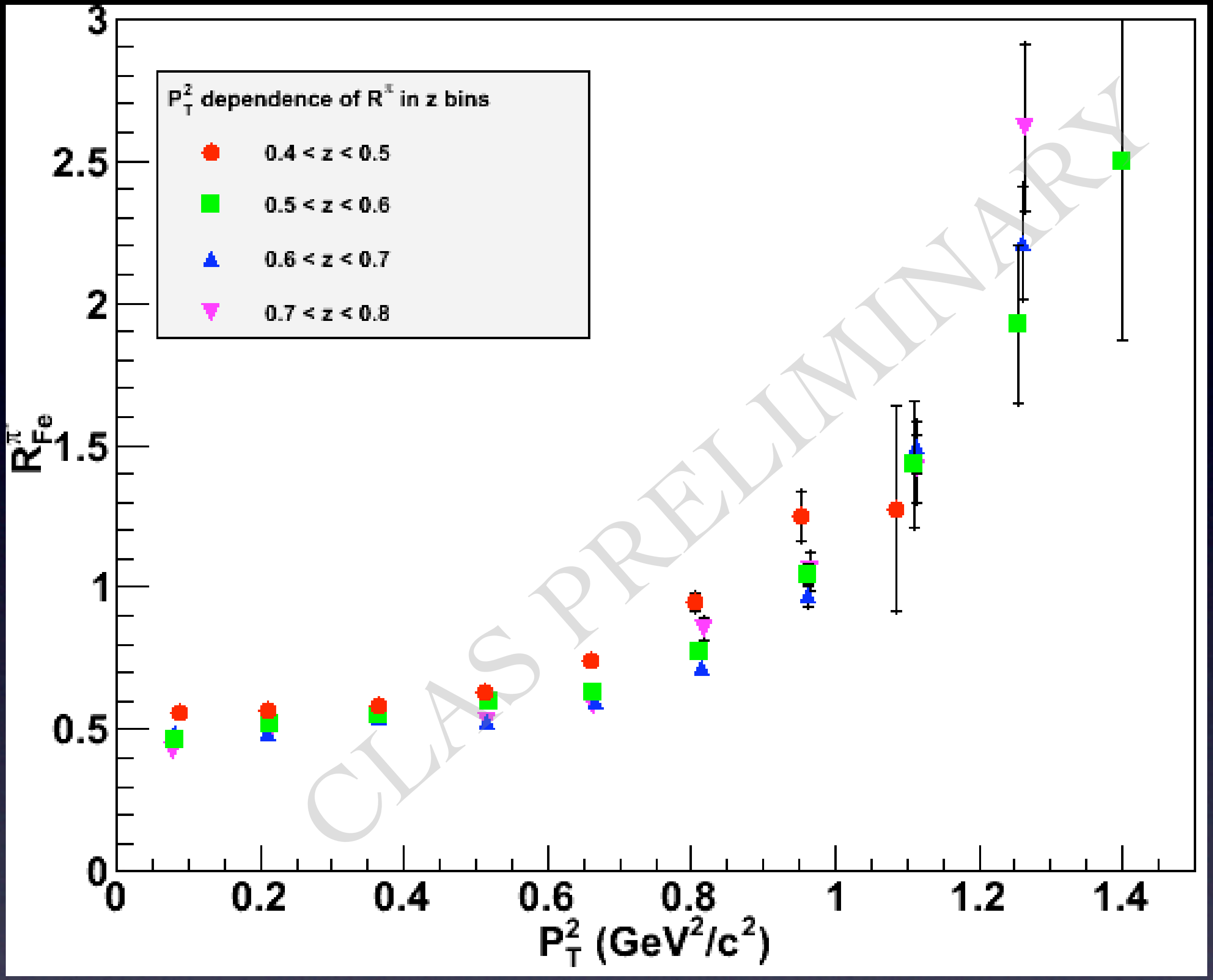
R_{π^+} slice in 3D set of bins (1.0<Q^2<1.3, ν, pT^2) for 0.4<z<0.7



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

Multiplicities | π^-

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

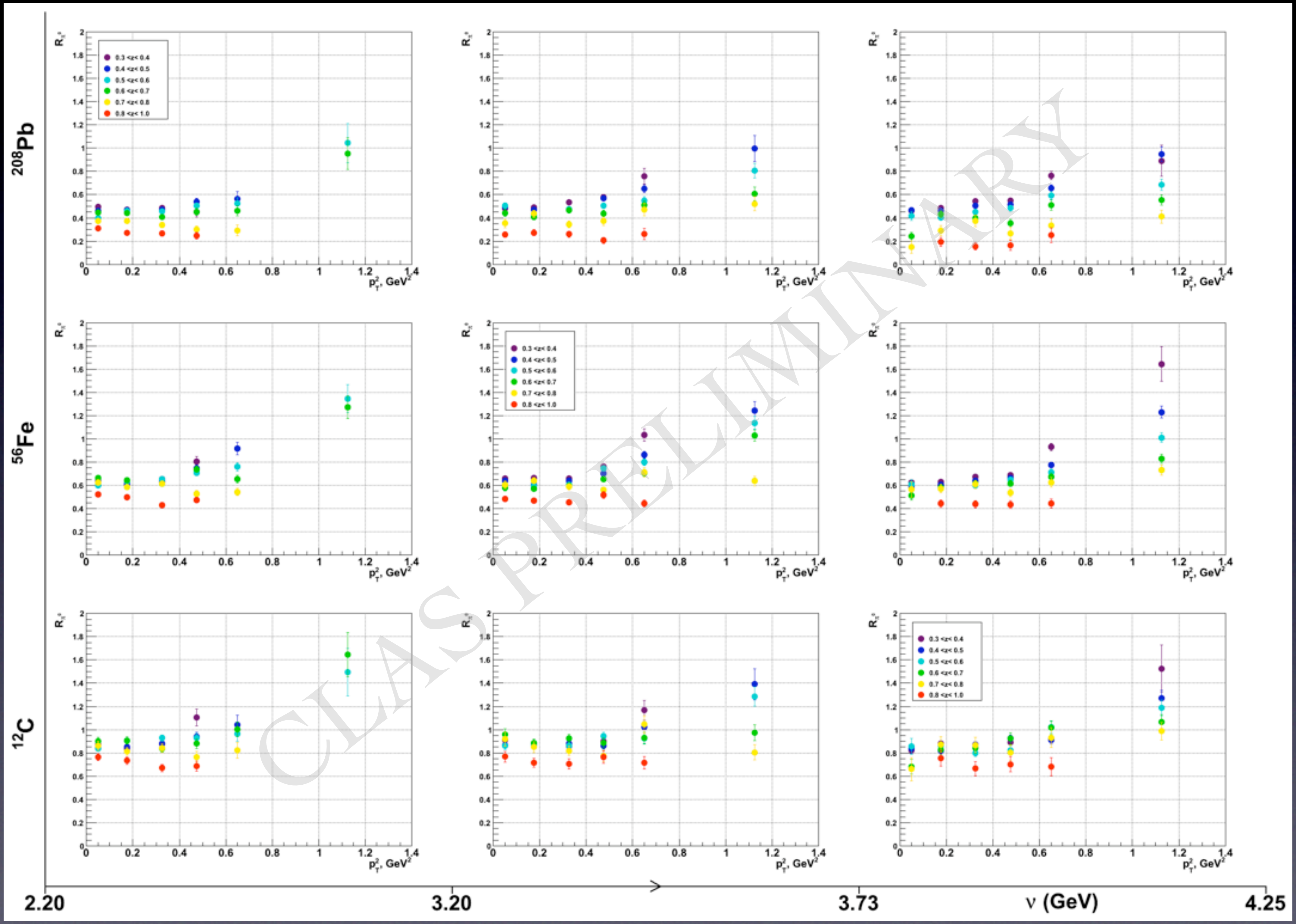


- Attenuation systematically increases for the larger nuclei
- Attenuation of high z hadrons, enhancement for high pT^2

Multiplicities | π^0

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

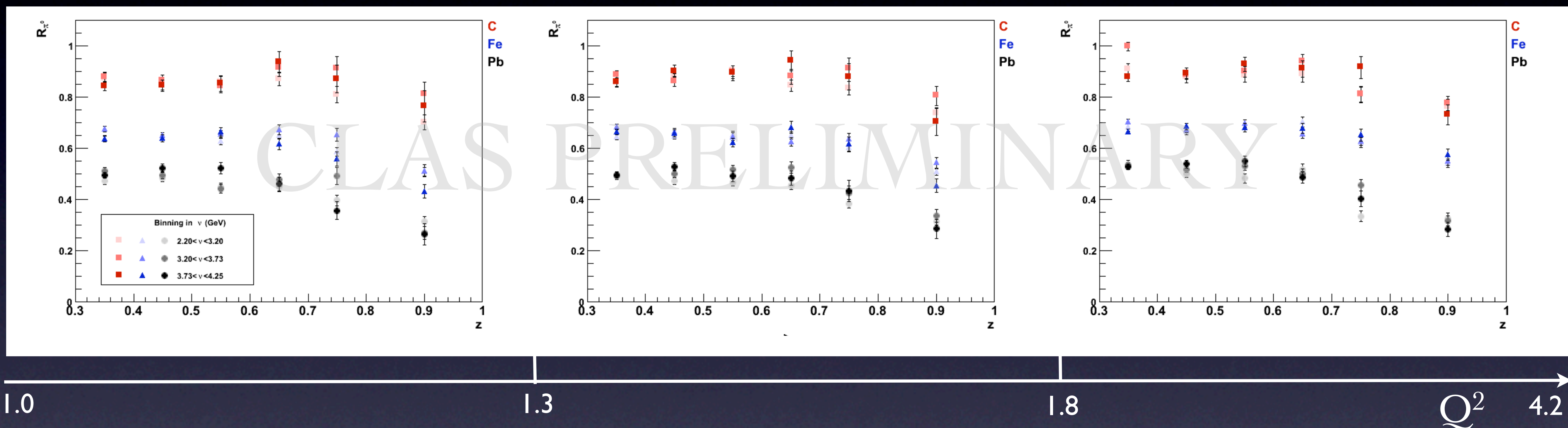
T.Mineeva



Multiplicities | π^0

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

T.Mineeva



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

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

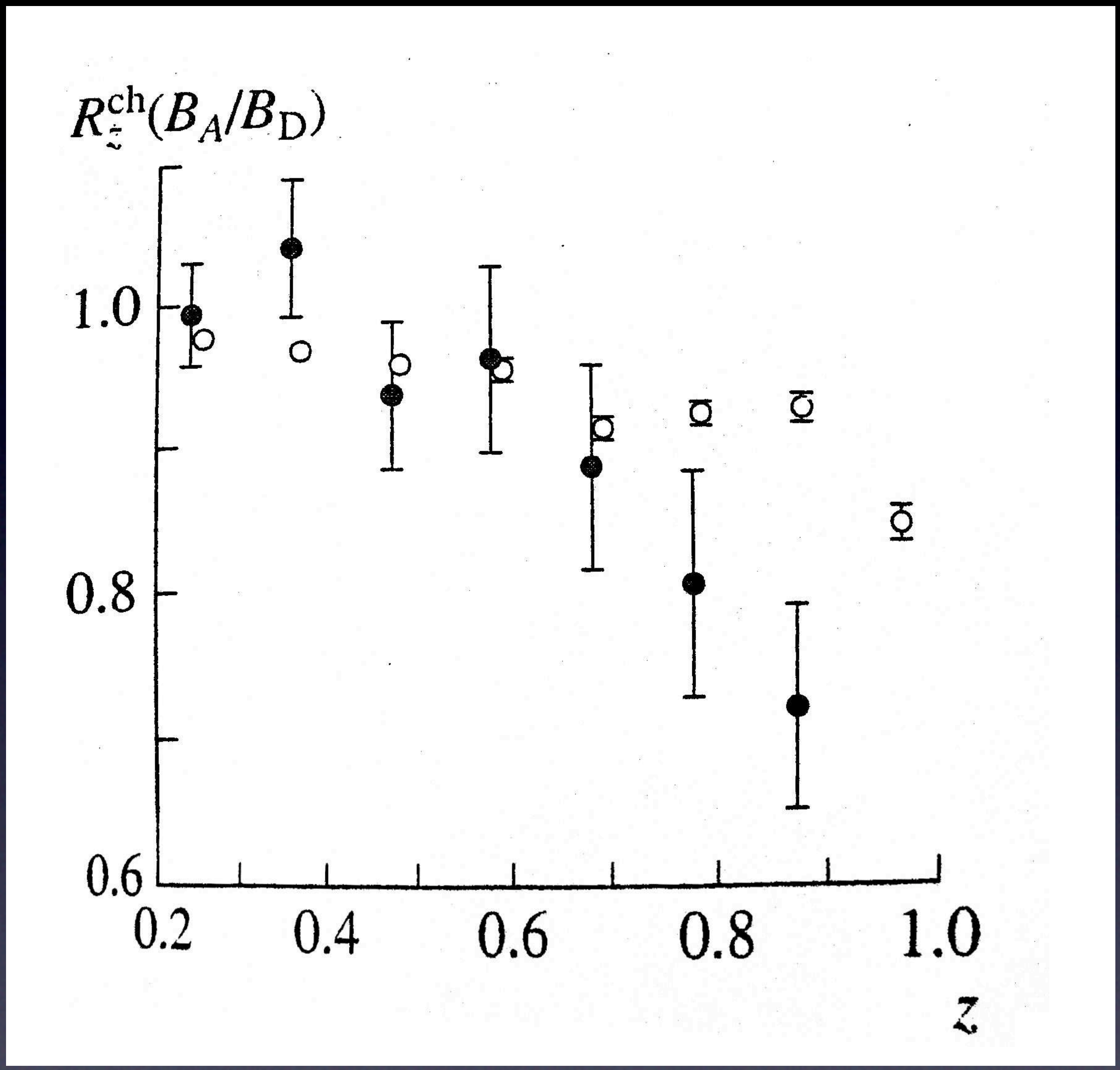
- In order to decrease systematic uncertainties from, for example, incoming ν_μ flux, difference in $E_{visible}$ and E_ν, and NC π^0 production neutrino experiment can greatly benefit from improved knowledge on hadroproduction by tuning their MC

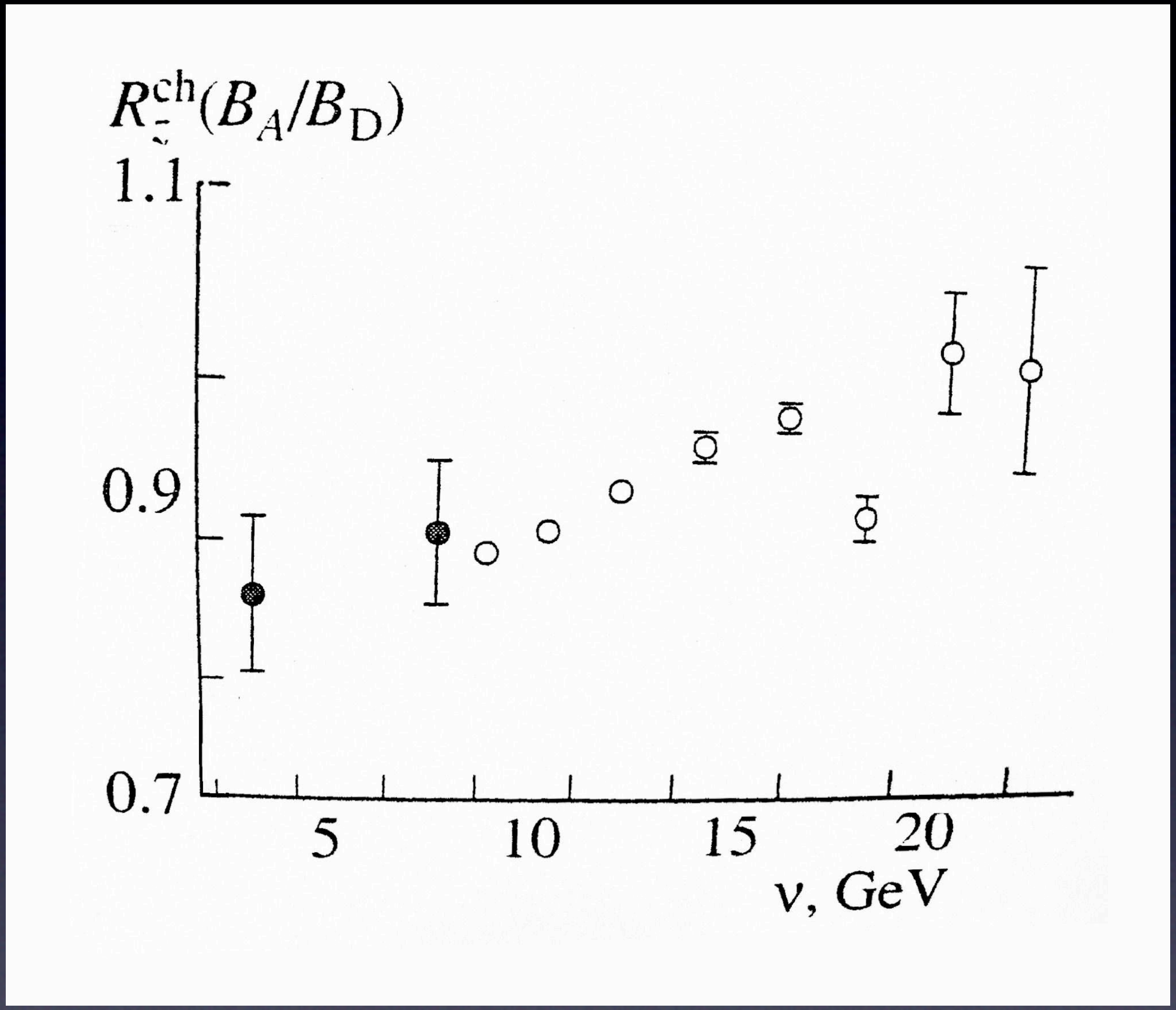
- CLAS data set on electroproduction off nuclei is consistent with previous measurements (HERMES) meanwhile providing an access to multidimensional extraction of characteristic time scales of hadronization and quark energy losses

- Program of hadronization studies will continue with CEBAF upgrade @ 11 GeV.

Backup

Comparison ν and e⁺ scattering off nuclei





Ratio of hadrons produced in DIS from ν scattering (open circles) on A=28 normalized to D at 2<ν<15 GeV (SKAT) compared with e^+ scattered off A=14 in 7<ν<24GeV (HERMES).

Neutrino data show the same trend as observed with electron beam.

Access to formation time τ_f

Model dependences on formation time extraction

Model Approach	Formula
single time-scale model	$\tau = \tau_q \frac{E_{quark}}{m_{quark}} \sim \upsilon$
time dilation of intrinsic size	$\tau = \tau_0 \frac{E_{hadron}}{m_{hadron}} = \tau_0 \frac{z\upsilon}{m_{hadron}}$
two-timescale parameteriza-tion based on the Lund model	$\tau = (1 - \ln(z)) \frac{z\nu}{\kappa c}$
QCD-based model	$\tau \approx \frac{1}{c} \frac{r_{hadron}}{k_{hadron}} E_h \sim z\nu$
gluon-bremsstrahlung model	$\tau = c_{hadron}(1 - z)\nu$

BACK-OF-ENVELOPE - τ_p

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

Energy conservation, time dialation

String model

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

If take, e.g., **z** = E_{hadron}/ν = 0.6, ν = 5 GeV, then ***$t_p \sim 2$ fm/c***

BACK-OF-ENVELOPE - ${}^{h}\tau_f$

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 $\tau_f \sim 20\ fm/c$.