Parton Propagation Studies at EIC:

measuring the saturation scale
quark energy loss
mechanisms of hadronization

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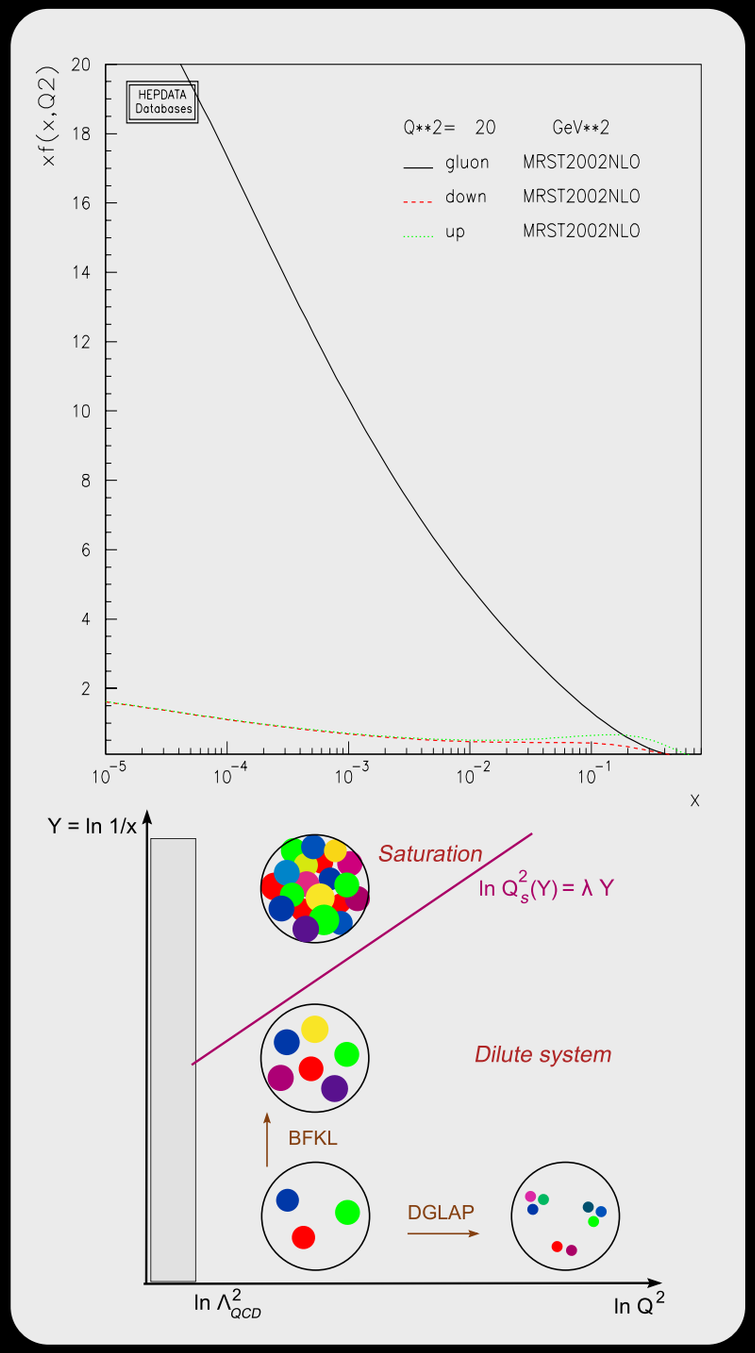
U. Santa María, Valparaíso, Chile

EIC meeting, Catholic U., July 2010

measuring the saturation scale

Saturation Scale

What is "saturation"?



- High energy limit of QCD a topic of study for decades
- Experimental evidence for increase of parton densities at low x, plus unitarity, implies saturation of parton densities, particularly for gluons (recombination, self-screening, etc.)
- Color Glass Condensate - high energy effective field theory describing universal properties of saturated gluons in hadronic systems
- The saturation scale is the gluon transverse momentum scale characterizing the degree to which saturation is occurring: saturation occurs *first* at low k_T

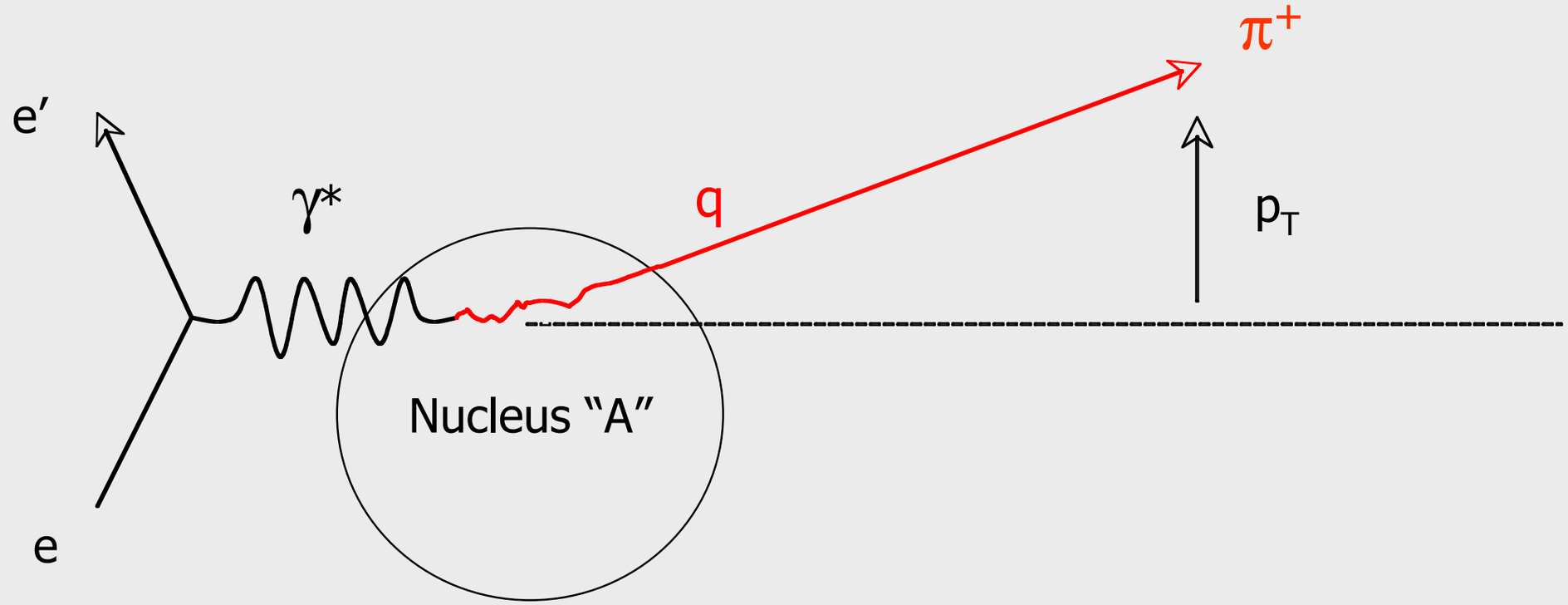
CGC Review: F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan, http://arxiv.org/abs/1002.0333

Saturation Scale

How to access saturation experimentally?

- Observable: p_T broadening in semi-inclusive DIS:

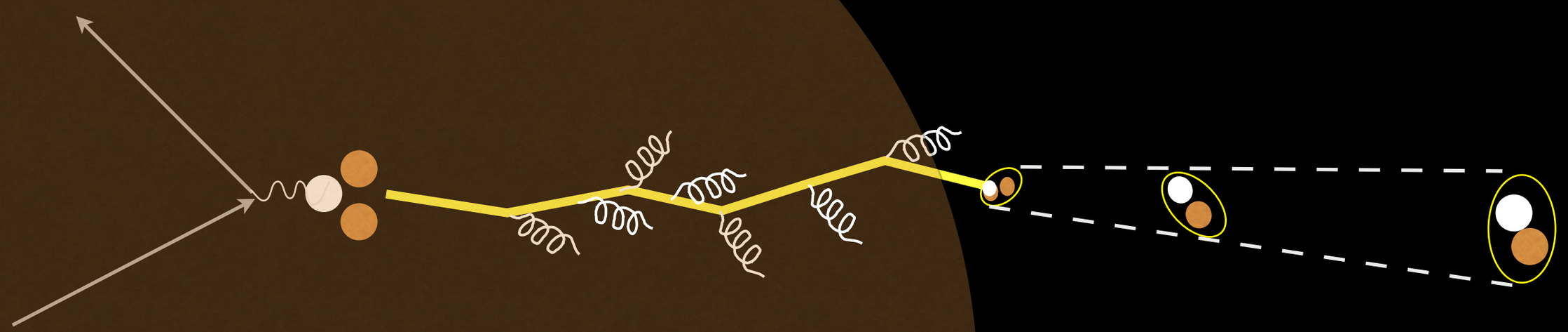
$$p_T\ broadening: \quad \Delta p_T^2 \equiv \left\langle p_T^2 \right\rangle_A^{DIS} - \left\langle p_T^2 \right\rangle_D^{DIS}$$



Saturation Scale

Why does it work?

- p_T broadening is a boost-invariant way of sampling the (transverse) gluon density distribution
- p_T broadening is proportional to the gluon density



Saturation Scale

pQCD view of p_T broadening

Zuo-tang Liang, Xin-Nian Wang, Jian Zhou, arXiv:0801.0434v2 [hep-ph], Phys. Rev. D77:125010, 2008

Transverse Momentum Dependent (TMD) quark distribution function in nucleus:

$$f_q^A(x,\vec{k}_\perp) = \int \frac{dy^-}{2\pi}\frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - i\vec{k}_\perp\cdot\vec{y}_\perp} \langle A \mid \bar{\psi}(0,\vec{0}_\perp)\frac{\gamma^+}{2}\mathcal{L}_{\rm TMD}(0,y)\psi(y^-,\vec{y}_\perp) \mid A\rangle$$

$$\mathcal{L}_{\rm TMD}(0,y) \equiv \mathcal{L}_{\parallel}^\dagger(-\infty,0;\vec{0}_\perp)\mathcal{L}_\perp^\dagger(-\infty;\vec{y}_\perp,\vec{0}_\perp)\mathcal{L}_\parallel(-\infty,y^-;\vec{y}_\perp)$$

complete gauge link

$$\mathcal{L}_\perp(-\infty;\vec{y}_\perp,\vec{0}_\perp) \equiv P\exp\left[-ig\int_{\vec{0}_\perp}^{\vec{y}_\perp} d\vec{\xi}_\perp\cdot\vec{A}_\perp(-\infty,\vec{\xi}_\perp)\right]$$

$$\mathcal{L}_\parallel(-\infty,y^-;\vec{y}_\perp) \equiv P\exp\left[-ig\int_{y^-}^{-\infty} d\xi^- A_+(\xi^-,\vec{y}_\perp)\right]$$

transverse and longitudinal gauge links

$$\hat{q}_A(\xi_N,y_\perp^2) = \frac{4\pi^2\alpha_s C_A}{N_c^2-1}\rho_N^A(\xi_N)[xf_g^N(x,y_\perp^2)]_{x=0}$$

gluon transport parameter

$$Q_{\rm sat}^2(y_\perp^2) = \int d\xi_N^- \hat{q}_A(\xi_N,y_\perp^2) = \frac{4\pi^2\alpha_s C_A}{N_c^2-1}\int d\xi_N^- \rho_N^A(\xi_N)xf_g^N(x,y_\perp^2)$$

saturation scale

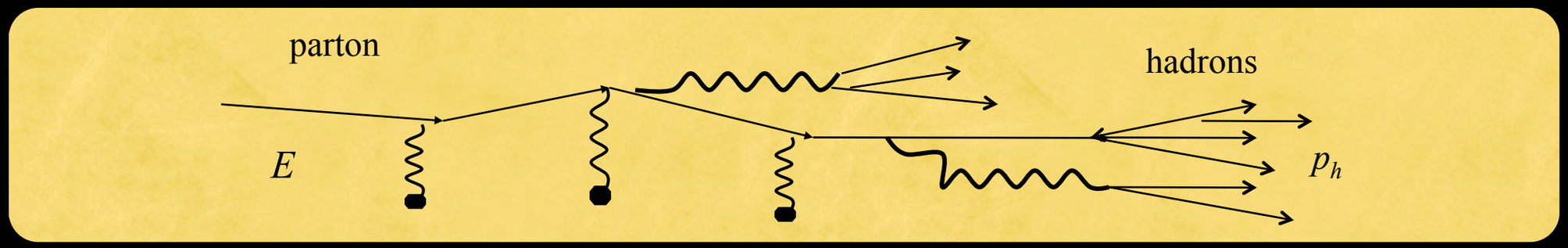
Various approximations, and last step invokes dipole model, see paper

Saturation Scale

pQCD view of p_T broadening

Zuo-tang Liang, Xin-Nian Wang, Jian Zhou, arXiv:0801.0434v2 [hep-ph], Phys. Rev. D77:125010, 2008

- Transverse scale dependence of the transport parameter, the dipole cross section and the saturation scale in this calculation come from contributions of higher-twist nucleon gluon matrix elements
- ➪ non-perturbative in nature
- At very short transverse distance scales, radiative corrections will become important at the leading twist and they will give rise to a transverse scale dependence of the transport parameter that is governed by the Dokshitzer- Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations



Saturation Scale

dipole model view of p_T broadening

B. Z. Kopeliovich, I. K. Potashnikova, Ivan Schmidt, arXiv:1001.4281v1 [hep-ph], Phys. Rev. C 81, 035204 (2010)

$$f^A_{\bar{q}q}(b) = 1 - e^{-\frac{1}{2}\sigma^N_{\bar{q}q}(r_T,E)\,T_A(b)}$$

elastic dipole-nucleus amplitude

$$T_A(b) = \int_{-\infty}^{\infty} dz\,\rho_A(b,z)$$

nuclear thickness function

$$\sigma^N_{\bar{q}q}(r_T,E) \approx C_q(E,r_T)\,r_T^2$$

dipole approximation; r_T is separation

$$C_q(E,r_T) = \frac{\pi^2}{3}\,\alpha_s(1/r_T^2)\,xG(x,1/r_T^2)$$

small r_T, $Q \sim 1/r_T$ and C is the gluon distribution and $1/x = 2m_N E\,r_T^2$

$$Q^2_{sat}(b,E) = 2C_q(E,r_T = 1/Q_{qA})T_A(b)$$

saturation momentum scale

$$\longrightarrow \quad f^A_{\bar{q}q}(b) = 1 - \exp\left[-\frac{r_T^2\,Q^2_{sat}(b,E)}{4}\right]$$

$$\Delta p_T^2 = 2T_A(b)\left.\frac{d\sigma^N_{\bar{q}q}(r_T)}{dr_T^2}\right|_{r_T=0} = 2T_A(b)C_q(E,r_T=0)$$

connection between p_T broadening and C_q

J. Dolejsi, J. Hufner and B. Z. Kopeliovich, Phys. Lett. B 312, 235 (1993)
M. B. Johnson, B. Z. Kopeliovich and A. V. Tarasov, Phys. Rev. C 63, 035203 (2001).

Saturation Scale

dipole model view of p_T broadening

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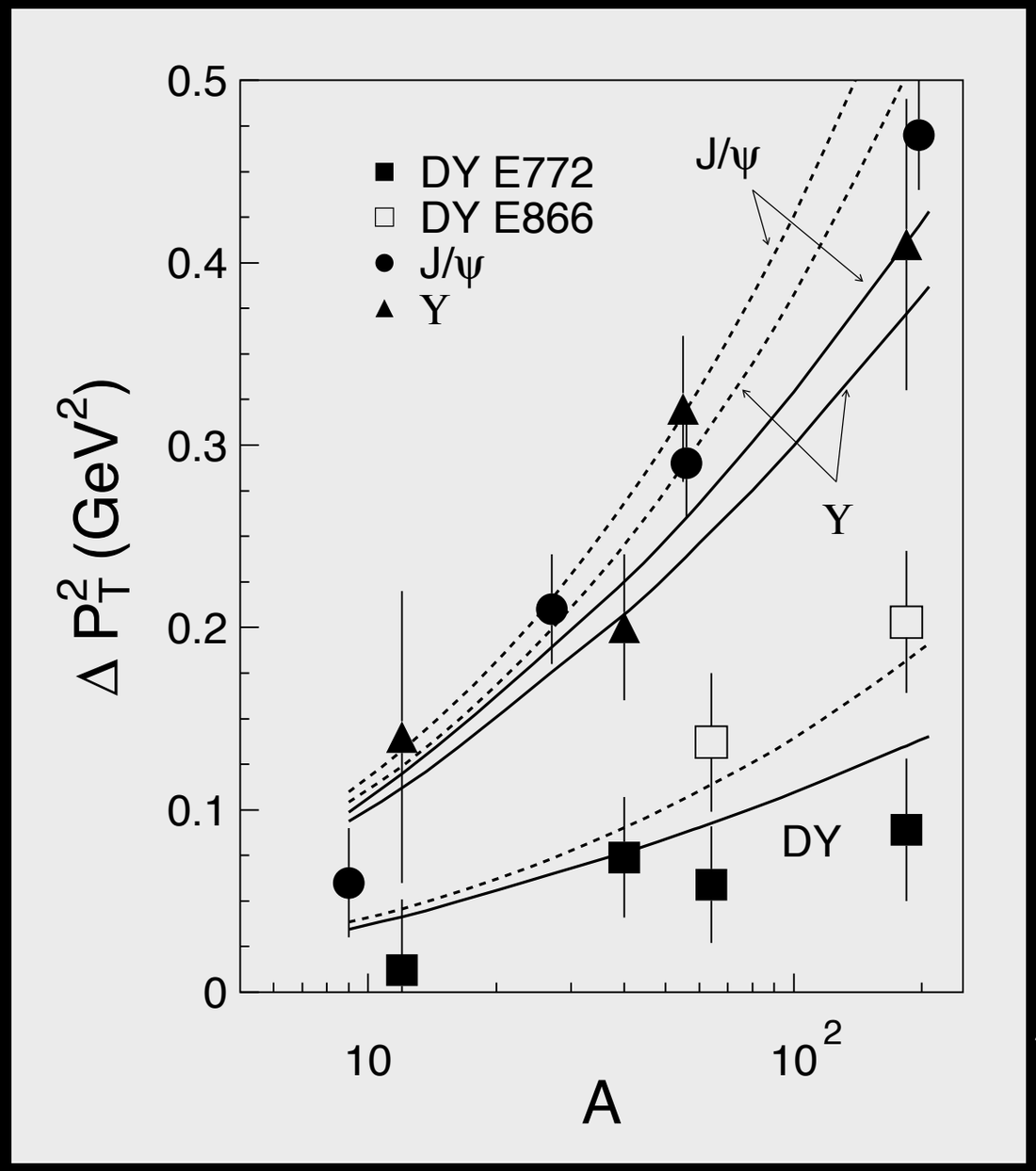


UV divergence:

$$C(E, r_T) \propto \ln(1/r_T) \text{ at } r_T \to 0$$

To repair divergence, choose:

$$r_T^2 \sim 1/\Delta p_T^2$$

Final result: saturation momentum in infinite momentum frame found to be equal to p_T broadening in target rest frame:

$$Q_{sat}^2(b, E) = \Delta p_T^2(b, E)$$

Agreement with high energy data is good

(solid lines include gluon shadowing correction)

Saturation Scale

experimental considerations

- Measure p_T broadening of identified hadrons
  - directly identified (RICH) or indirect (e.g., J/Ψ)
- Di-jet complication for $x<0.1$
- Need very good vertex resolution, good momentum resolution
- A broad program is possible given the above requirements

measuring quark energy loss

Quark Energy Loss

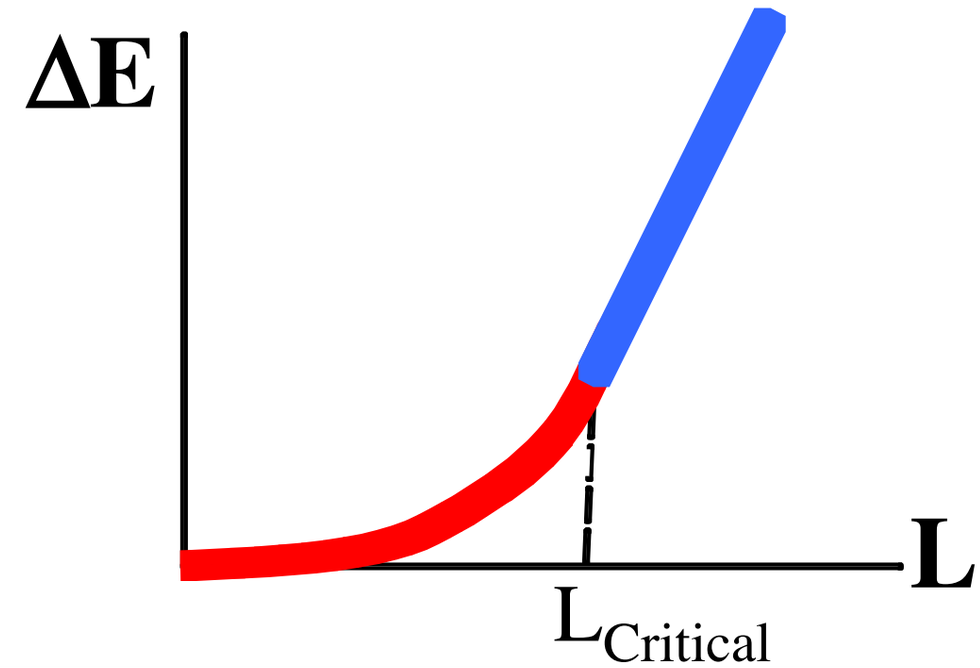
- Quark energy loss has been studied for more than two decades, ~few dozen papers
- loss from gluon radiation >> loss from elastic scattering for cold matter
- high importance in RHI data; jet quenching a primary evidence for QGP
- vacuum energy loss >> medium-induced for cold matter
- energy independence connected to factorization in QCD

Quark Energy Loss

Characteristics in pQCD

$L < L_{Critical}$ $$-\frac{dE}{dx} \propto L\hat{q}$$

$L > L_{Critical}$ $$-\frac{dE}{dx} \propto \sqrt{E\hat{q}}$$



- quadratic vs linear
- LPM (quadratic region)
- critical length, ~square root of E
  - JLab/CLAS data suggest: ν~3 GeV, $L_{Critical}$ = ~4-5 fm, < R_{Pb}

Quark Energy Loss

Experimental considerations

- Can perform direct measurement
  - expect ~2-3 GeV of loss in Pb
  - only feasible for lower energies, but ~model-independent
  - can study the critical length and transition region, unfold from production length (effective quark lifetime)
- Can in principle infer from indirect measurement
  - hadron attenuation vs. z ($=E_{hadron}/\nu$) for high ν
  - have to unfold dijets or measure with $x>0.1$
  - model dependent, but simpler than for lower energies (minimal hadronization in medium)

determining the mechanisms of hadronization

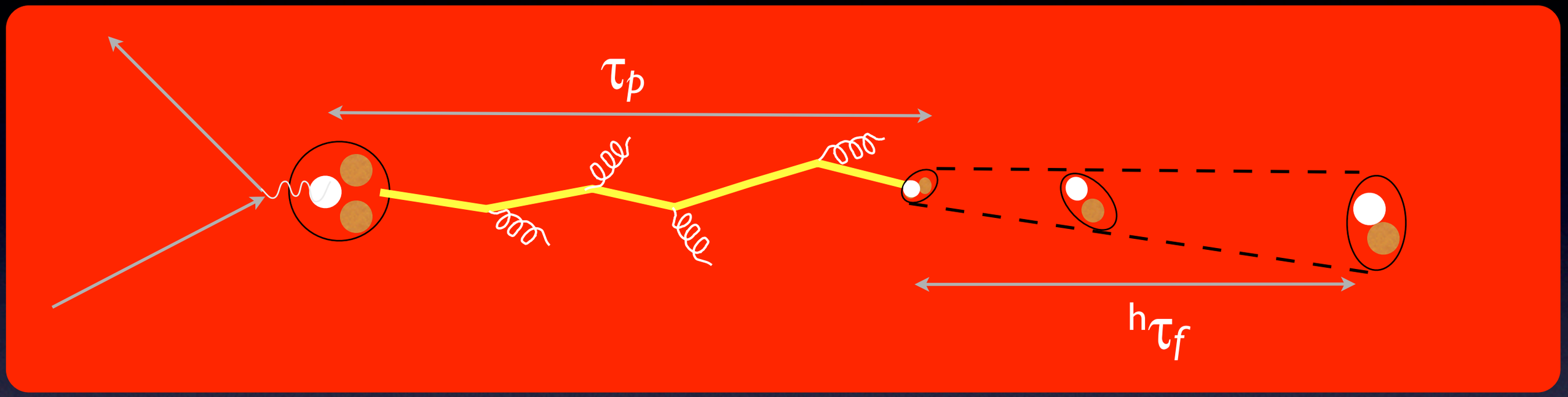
Mechanisms of Hadronization

- Hadronization (quark fragmentation into hadrons) is a ubiquitous process in QCD
  - Often said to be inaccessible experimentally
  - Phenomenology constrained primarily by particle multiplicities, kinematic distributions
- Little-explored connection to confinement:
  - how do the flux tubes arise in hadron formation? takes longer or shorter to form flux tube than 'fuzzy ball of gluons'?

Accardi, Arleo, Brooks, d'Enterria, Muccifora, Riv.Nuovo Cim.032:439-553,2010 [arXiv:0907.3534]
Majumder, van Leuween, arXiv:1002.2206

Mechanisms of Hadronization

Deep inelastic scattering - physical picture in ***vacuum***

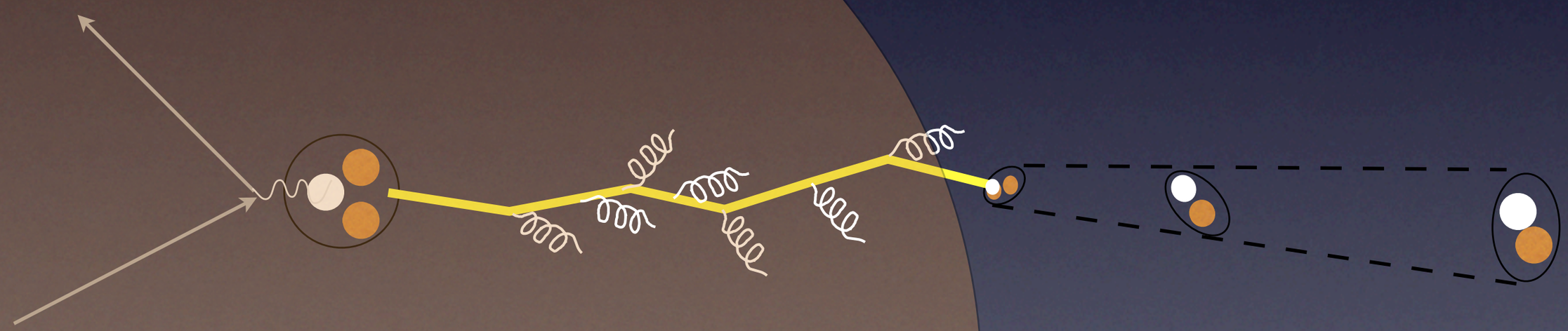


- *production time τ_p* - propagating quark
- *formation time $^h\tau_f$* - dipole grows to hadron

Mechanisms of Hadronization

Deep inelastic scattering - physical picture in ***cold medium***

Partonic multiple scattering:
medium-stimulated
gluon emission,
broadened p_T



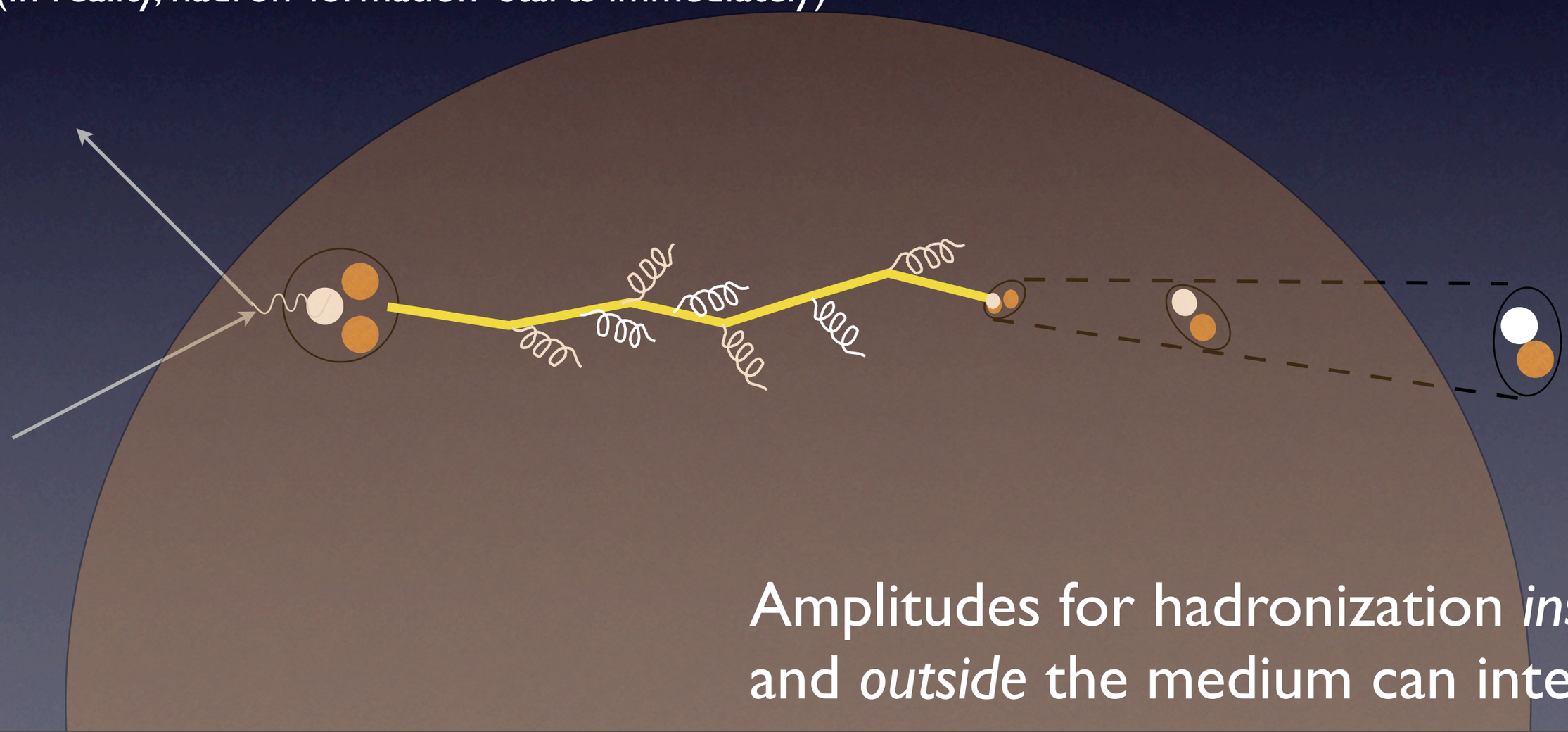
Hadron forms *outside* the medium; or....

Mechanisms of Hadronization

Deep inelastic scattering - physical picture in ***cold medium***

Hadron forms *inside* the medium; then also have prehadron/hadron interaction

(In reality, hadron 'formation' starts immediately)



Amplitudes for hadronization *inside* and *outside* the medium can interfere

Mechanisms of Hadronization

Examples of recent theory progress

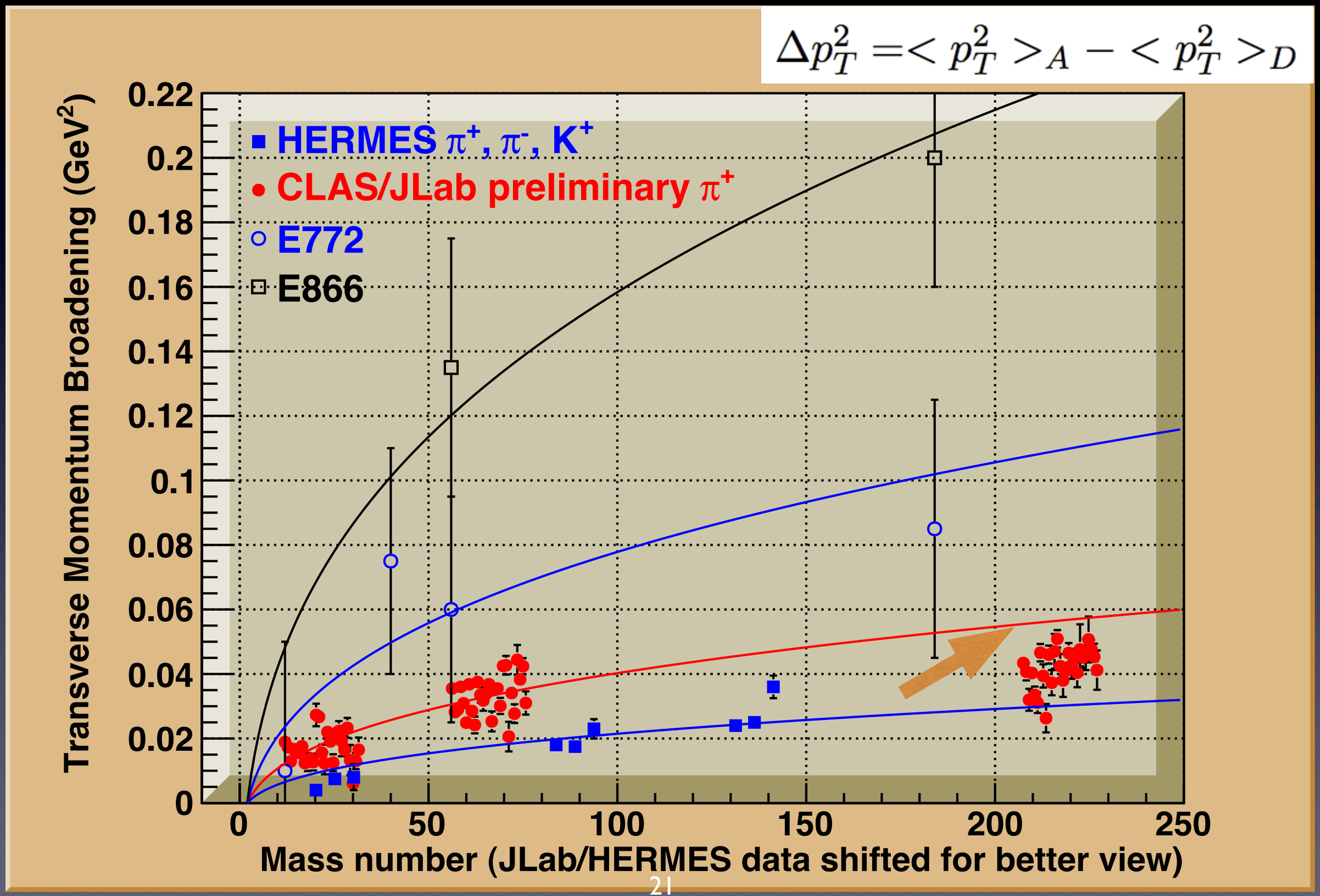
- First fully quantum-mechanical calculation of in-medium hadronization
- Perturbative fragmentation via the KPPS-Berger model (KPPS, Phys. Lett. **B**662:117-122, 2008, arXiv:0706.3059v1 [hep-ph]
- Path-integral formulation of quantum mechanics (LCGF)
    - phases and interferences; all relevant timescales
    - includes the probability of prehadron production both inside and outside the medium

Inner/outer interference generates hadron 'attenuation': in-medium interactions affect overlap of dipole to pion wave function

B.Z. **K**opeliovich, H.-J. **P**irner, I.K. **P**otashnikova, Ivan **S**chmidt, A.V. Tarasov, O.O. Voskresenskaya, Phys. Rev. C78:055204,2008 arXiv:0809.4613v2 [hep-ph]

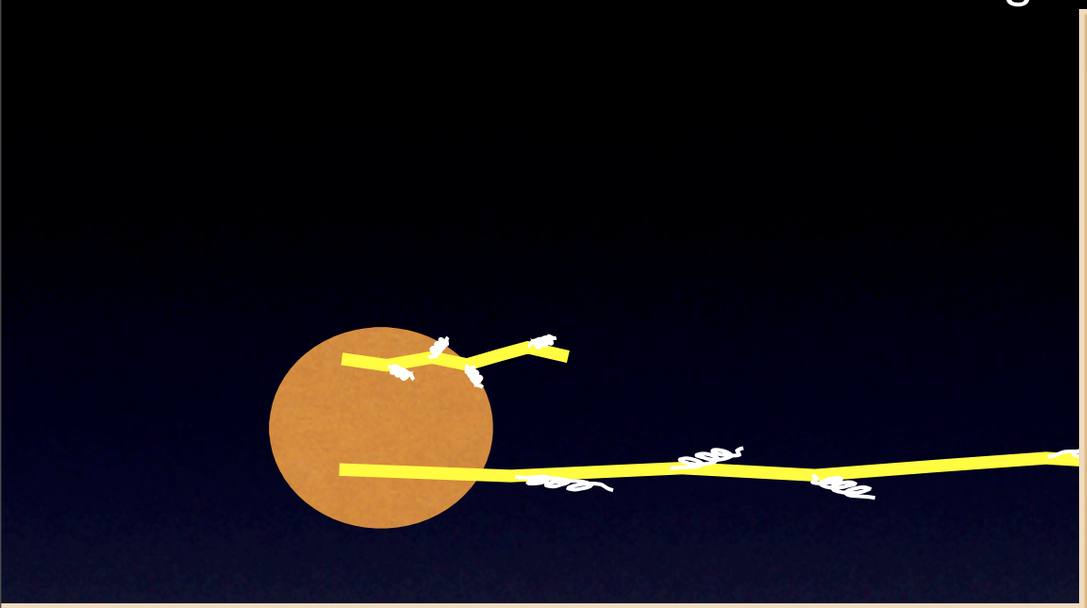
Mechanisms of Hadronization

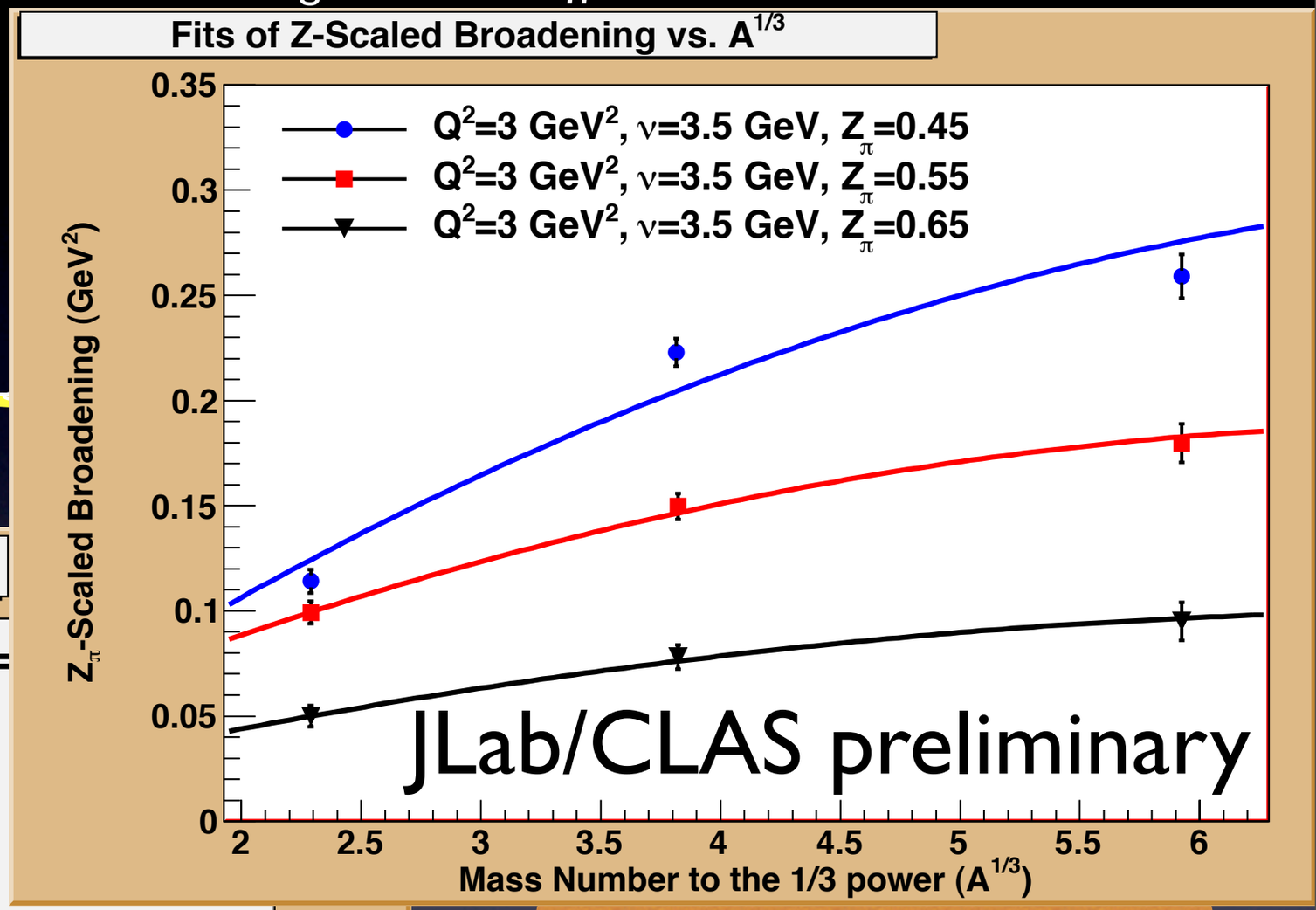
Production length extraction

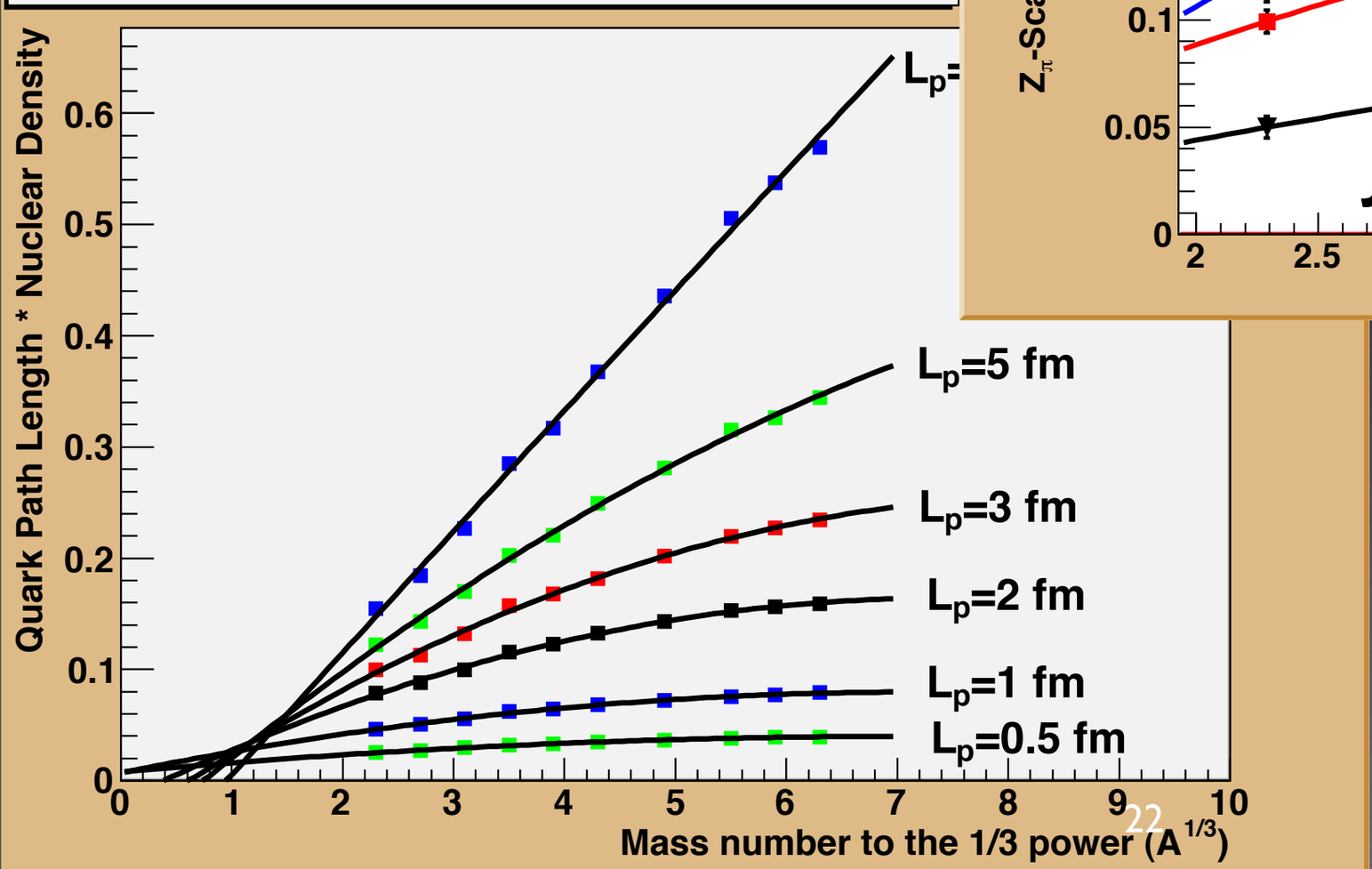


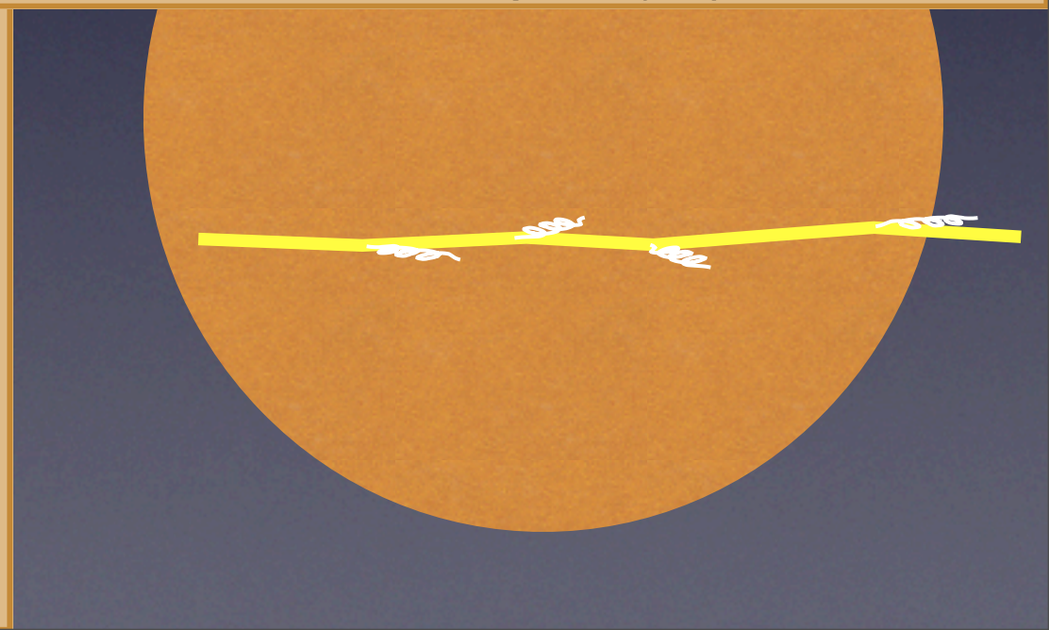
Mechanisms of Hadronization

Production length extraction via geometrical effects





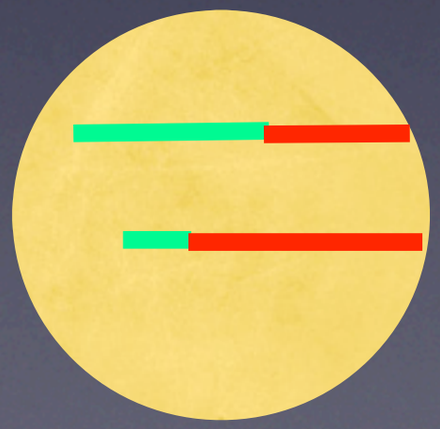




Mechanisms of Hadronization

Production length extraction via geometrical model

- Three-parameter ***geometric model***:
  - scale factor (proportional to transport coefficient)
  - production time (distributed exponentially)
  - effective absorption cross section
- ***Simultaneous fit*** *of pT broadening and multiplicity ratio in the same 3-fold kinematic bin in* Q^2, ν, *and z*
- Realistic nuclear densities

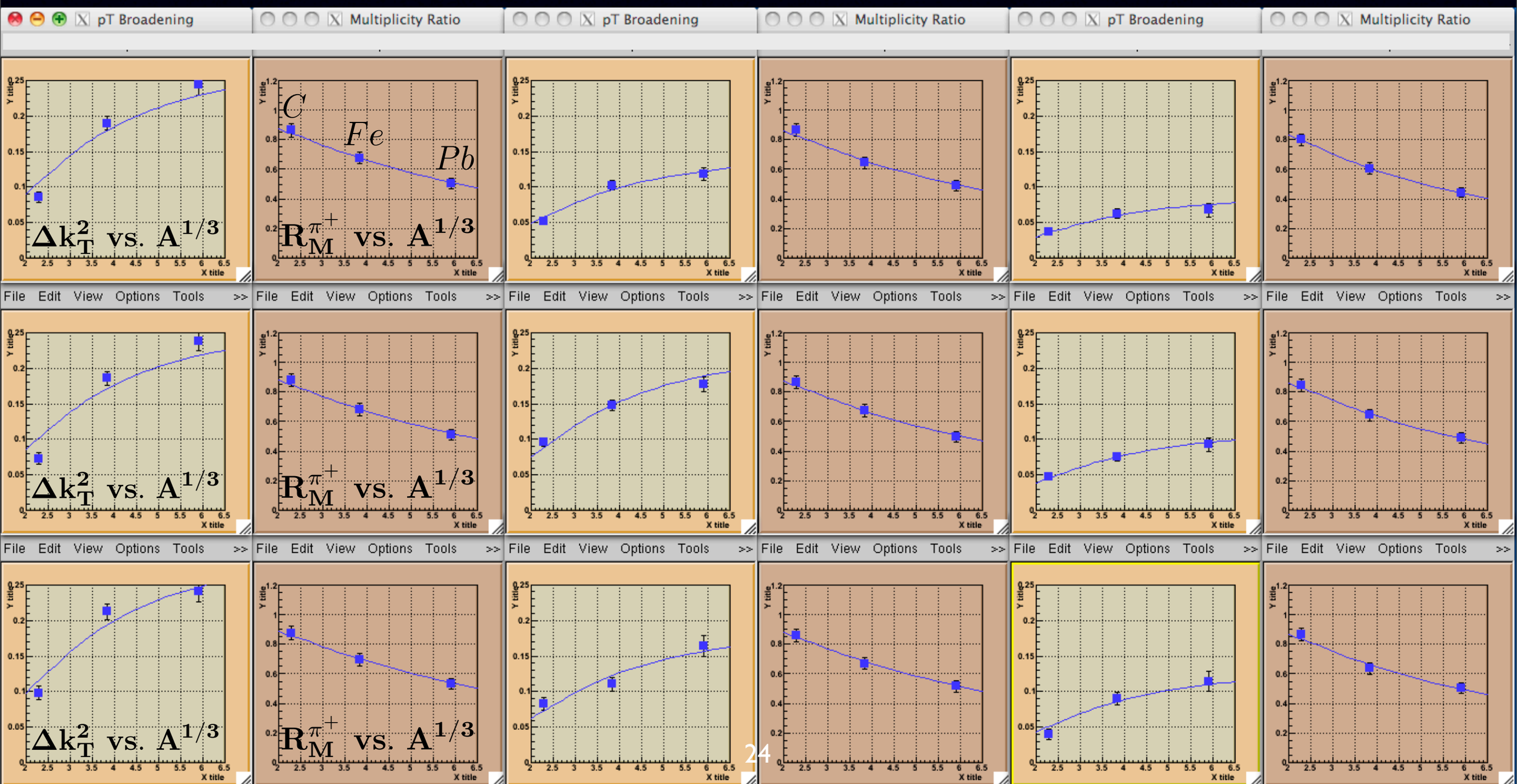


  - Path begins at point with probability proportional to density
  - Part of path is quark, part of path is (pre-)hadron

Results from combined fit

3 parameter geometric model

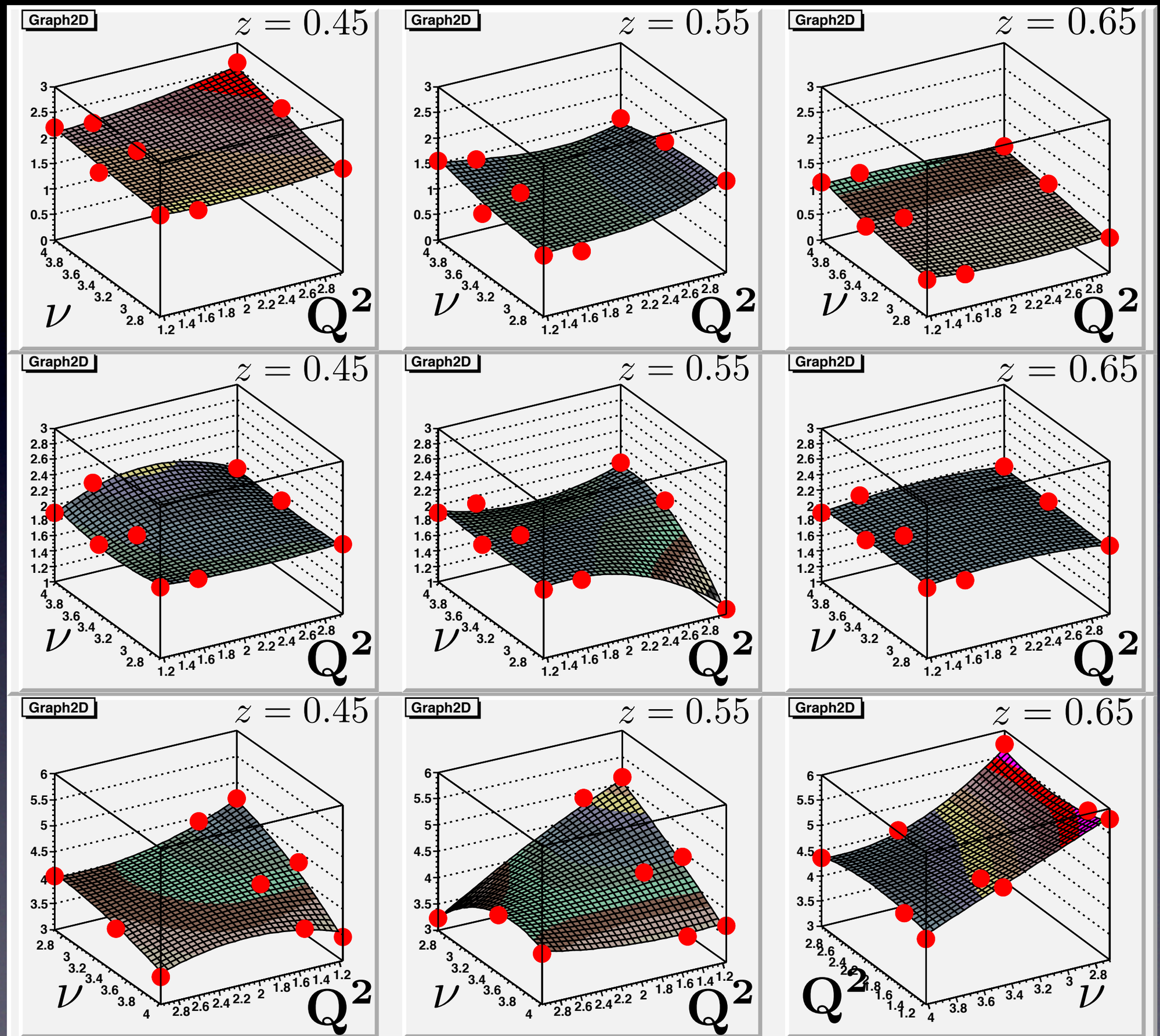
various bins in Q^2, ν, and z



Scale factor $\propto \hat{q}$

Production length l_p

Effective absorption cross section σ

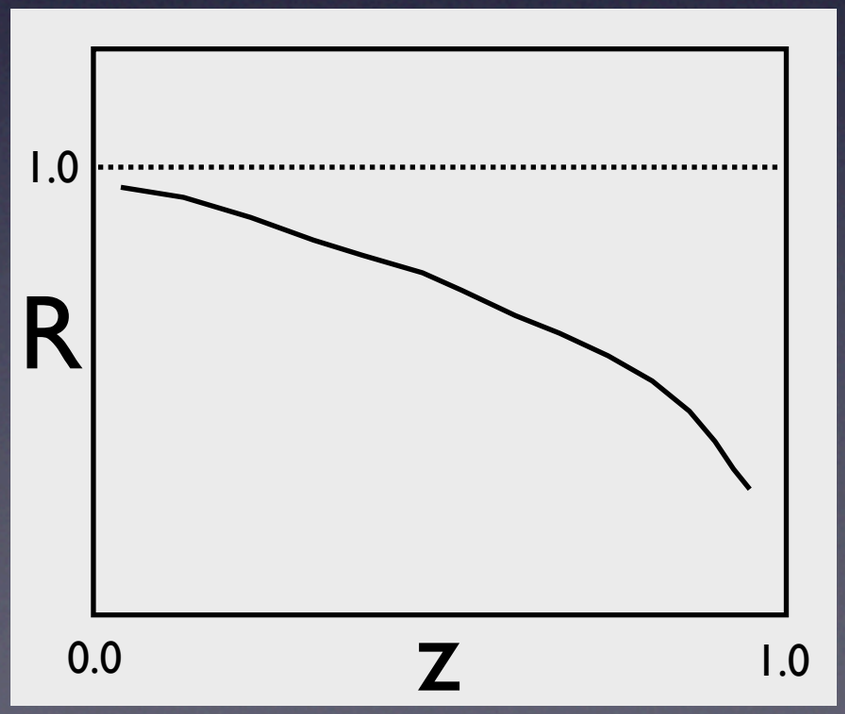


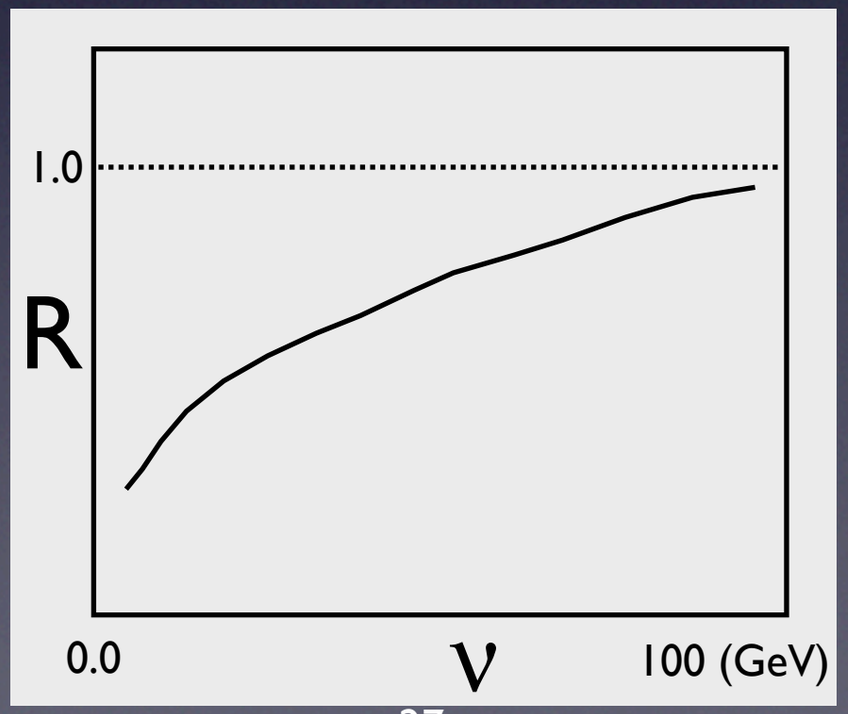
Conclusions from 3-parameter geometric model (exploratory study)

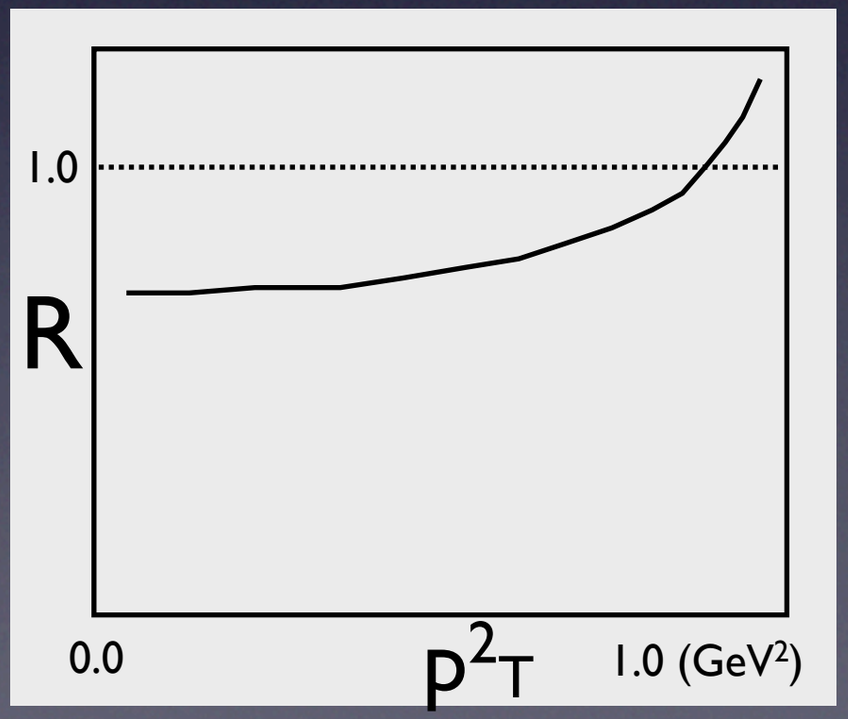
- Consistent with features of data
- Dependence of transport coefficient on z
  - Range: 0.05 - 0.15 GeV^2/fm
- Production length ~2 fm
- Effective cross section moderately larger than hadronic - energy loss mechanism visible (?)

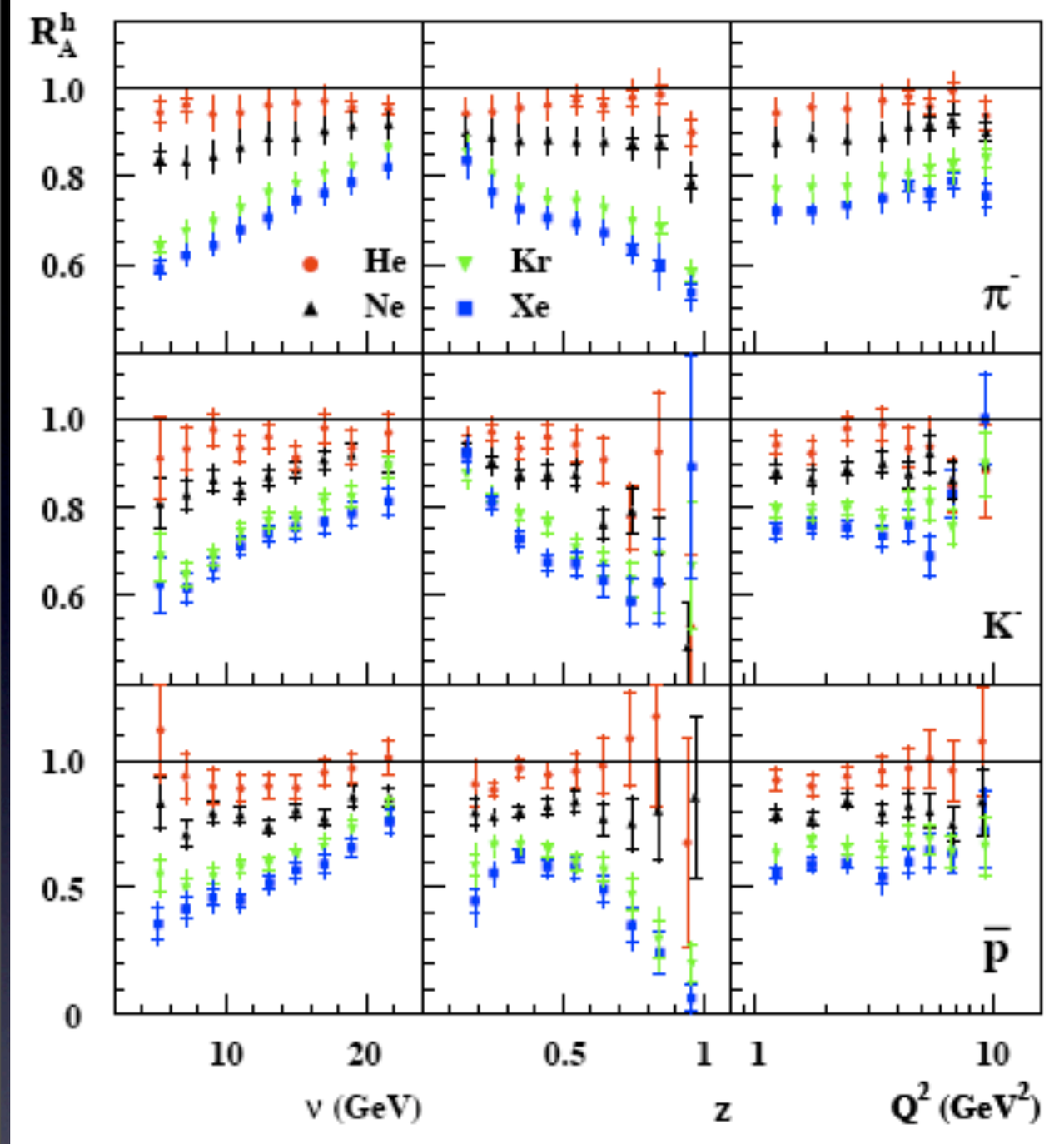
$$R_M^h(z,\nu,p_T^2,Q^2,\phi) = \frac{\left\{ \frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)} \right\}_A}{\left\{ \frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)} \right\}_D}$$

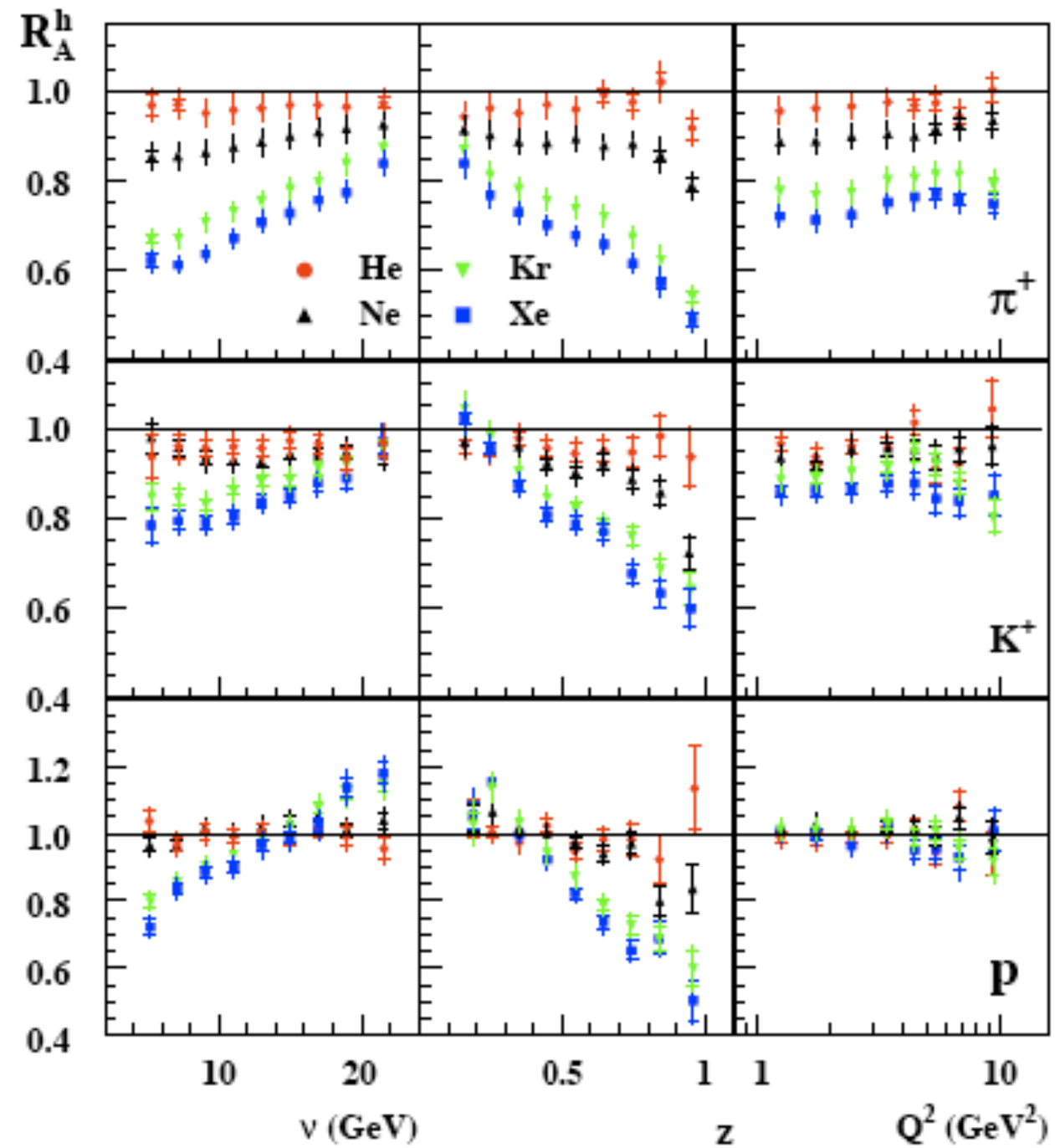
Hadronic multiplicity ratio











HERMES data for He, Ne, Kr, Xe: π^{+-}, K^{+-}, p, antiproton

pions act similarly, K^+ vs. K^-, proton vs. antiproton

(each 1-D plot is integrated over all other variables)

Di-hadron fragmentation function

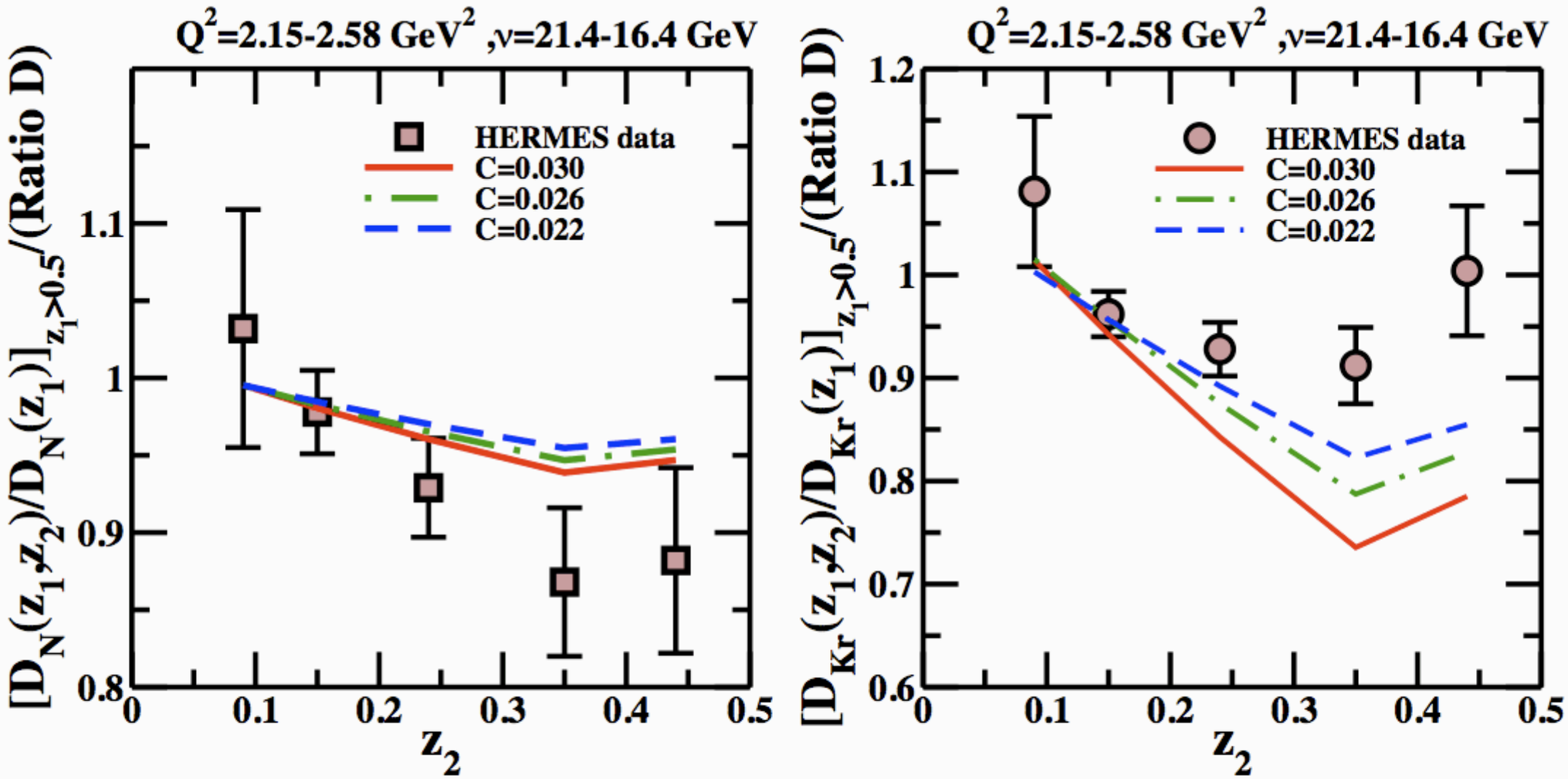
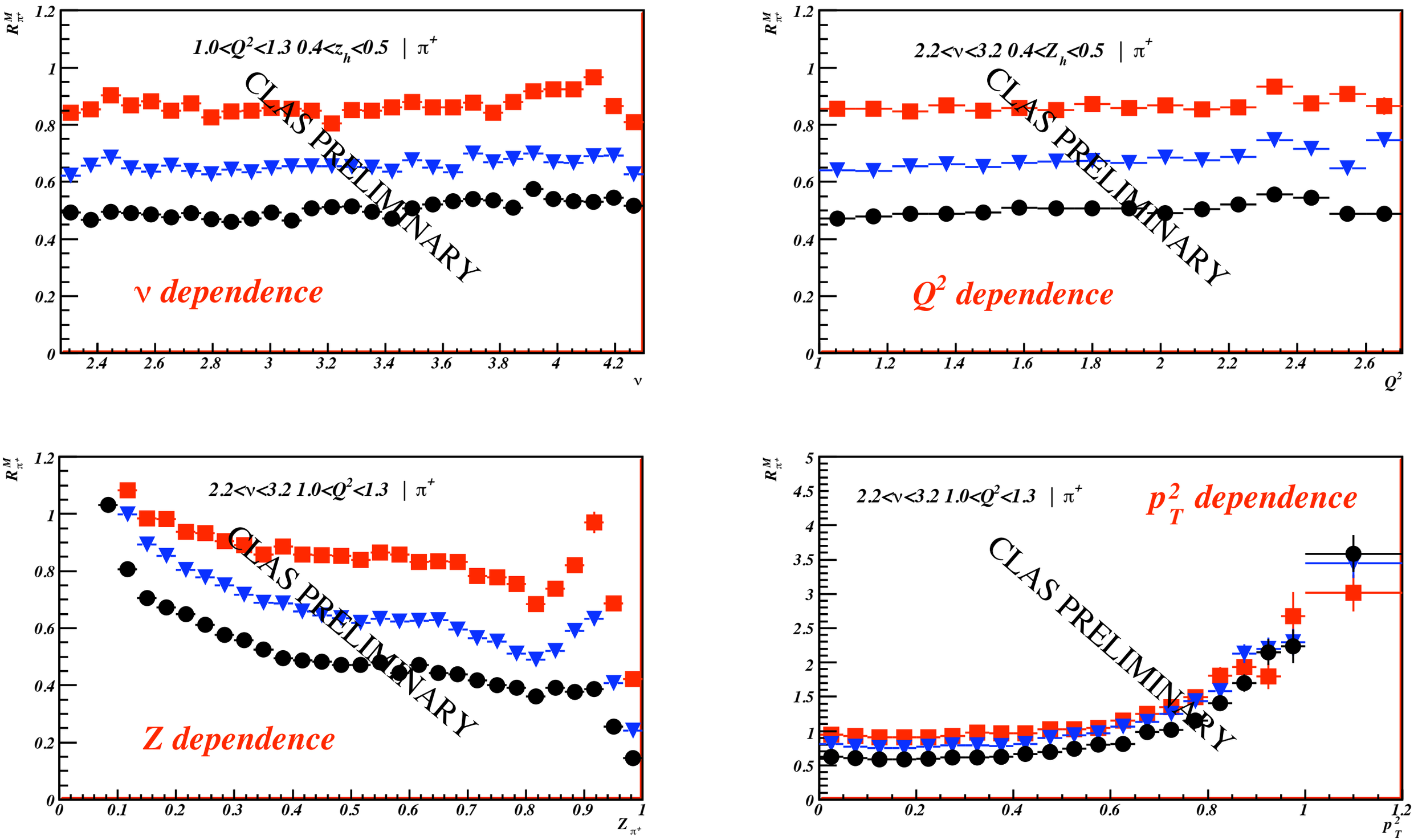


FIG. 9: Results of the medium modification of the quark fragmentation function in cold nuclear medium in a N and Kr nucleus versus the momentum fraction of the associated hadron. The momentum fraction of the trigger, is held above 0.5 and integrated over all allowed values. A hard-sphere distribution of nucleons in a nucleus is used. See text for details.

A. Majumder, X-N Wang, arXiv:0806.2653v2 [nucl-th]

JLab/CLAS 3-D preliminary data

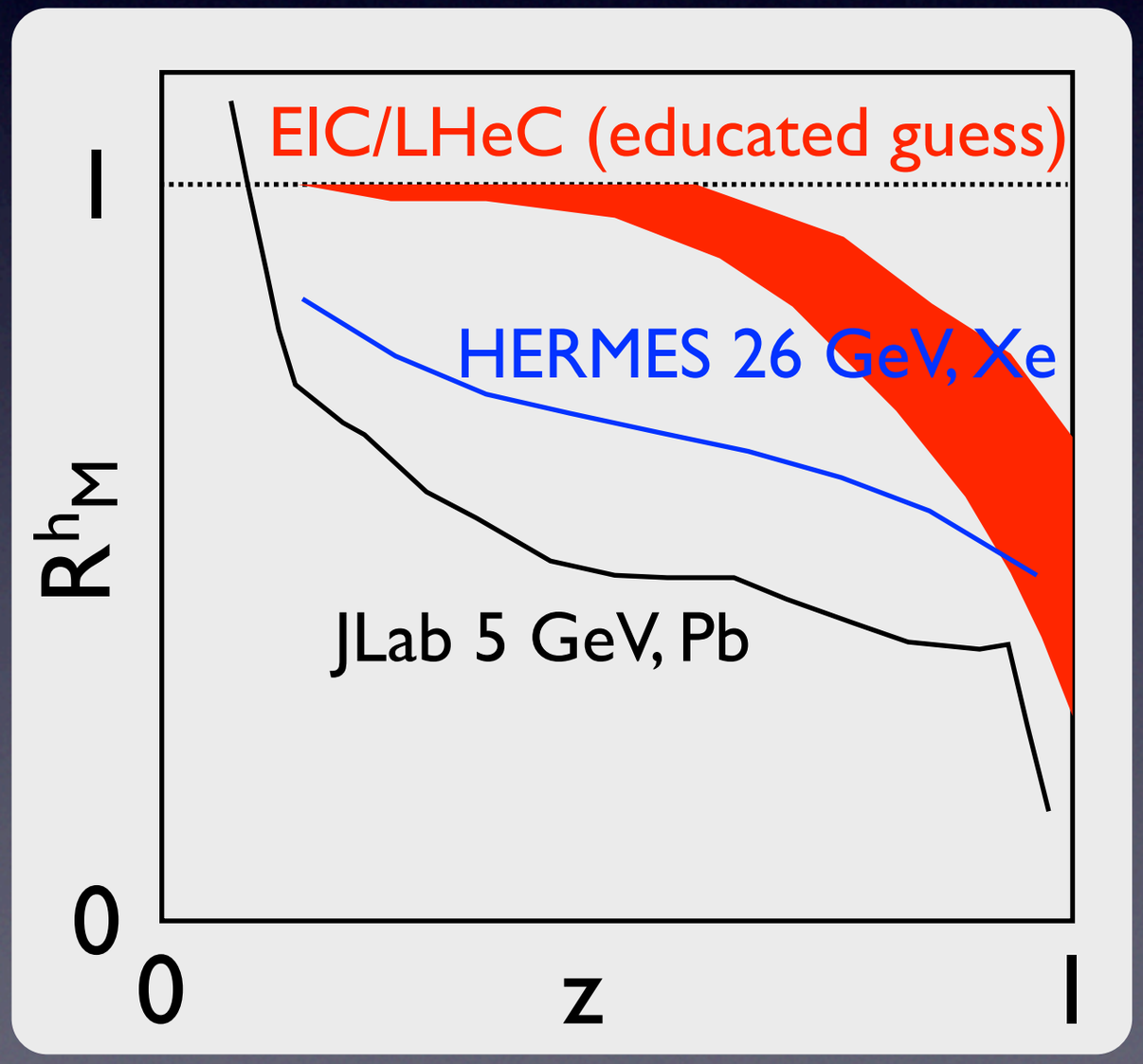


Four out of ~50 plots!

K^0, π^-, π^0, η, Λ underway

AT EIC/LHEC

- Prediction of factorization breakdown at large x_F:
  B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, M.B. Johnson, and Ivan Schmidt, Phys. Rev. C72:054606, 2005.



- Authors explain a variety of data within same picture - suppression of particle production in dA, pA at large x_F
- Prediction of a suppression from nuclear targets that persists at high z, at arbitrarily high energies
- Violates conventional wisdom that at high ν, 'nuclear effects disappear'

Mechanisms of Hadronization

What we can study at EIC

- At EIC, will have access to:
  - energy dependence
  - high z
  - heaviest nuclei
  - baryon hadronization
  - heavy quark hadronization mechanisms
- Need particle ID, good luminosity

Conclusions

- Three excellent experimental opportunities for the EIC in parton propagation physics:
  - measuring the saturation scale in nuclei
  - measuring quark energy loss
  - determining the mechanisms of hadronization
- Clear experimental opportunities, high theoretical interest
- Exciting, fundamental physics with strong connections to high-energy QCD worldwide