Microscopic Studies of Parton Propagation and Hadron Formation

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The Science of an EIC - Golden Experiments

What is the Role of Gluons in Nuclei?

What Governs the Transition of Quarks and Gluons into Pions and Nucleons?

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5) Gluon momentum measurements in nuclei - signatures of (approach to) gluon saturation
6) Measurements of the probability for a nucleus to stay intact in a high-energy scattering process

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8) Map the physical mechanism of fragmentation of correlated quarks and gluons, and understand how we can calculate it quantitatively

From Tuesday's discussion session

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- Goal: study space-time properties of fragmentation
    - Characteristic times
    - Hadronization mechanisms
- Use nuclei as spatial filters with known properties:
    - size, density, interactions
- *Unique kinematic window* at low energies
- *Simpler physical picture* at high energies?

A ***golden experiment***: measure the *saturation scale* in nuclei

- vs. parton energy, to highest energies
- connects to saturation: RHIC, LHC HI, future EIC upgrades, 'gluons in nuclei'
- moderate requirements for luminosity and PID, more stringent requirements for angular resolution

See B. Kopeliovich talk on Thursday

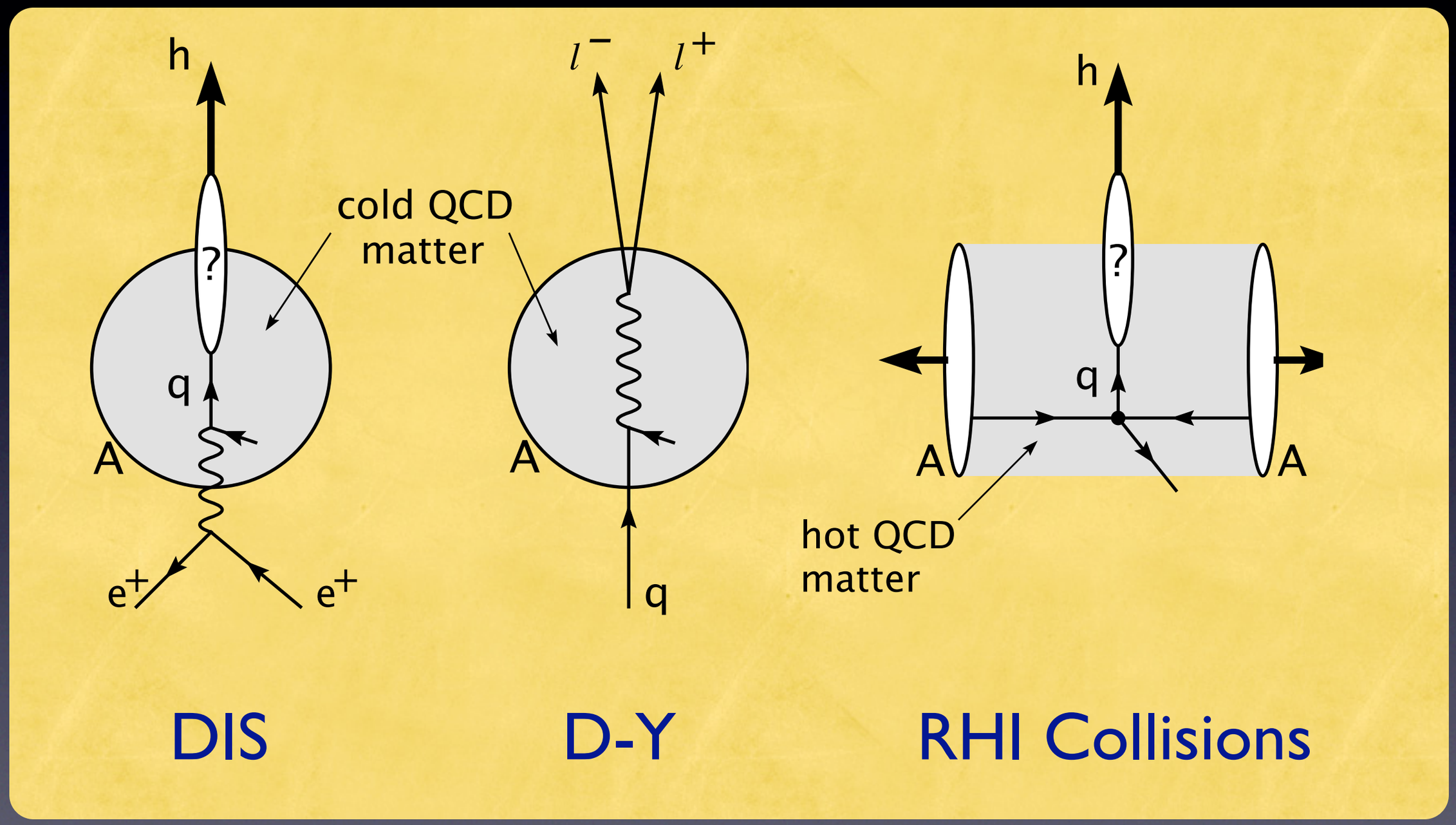
At ***LOW ENERGIES***:

- What is the *lifetime* of an energetic free quark?
- How long does it take to *form a hadron*, starting from an energetic light quark? How does it happen?

At ***HIGH ENERGIES***:

- Test the predicted universal breakdown of QCD factorization at large Feynman *x (B. Kopeliovich)*
- Expect perturbative energy loss to be purely proportional to path length squared
- Expect increase in jet broadening ("saturation scale") and quark energy loss

Comparison of Parton Propagation in Three Processes



recent review by Accardi et al, arXiv:0907.3534v1

Deep Inelastic Scattering - Vacuum

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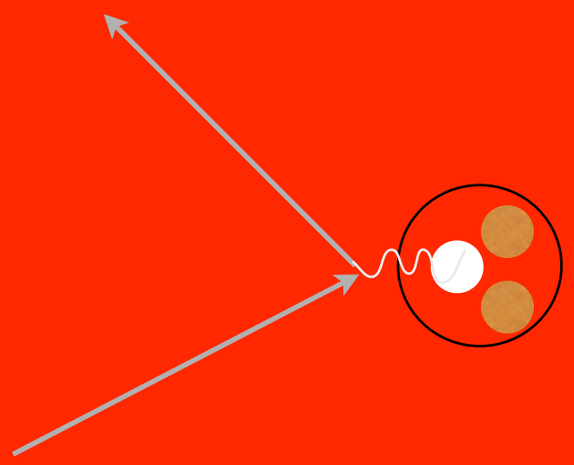

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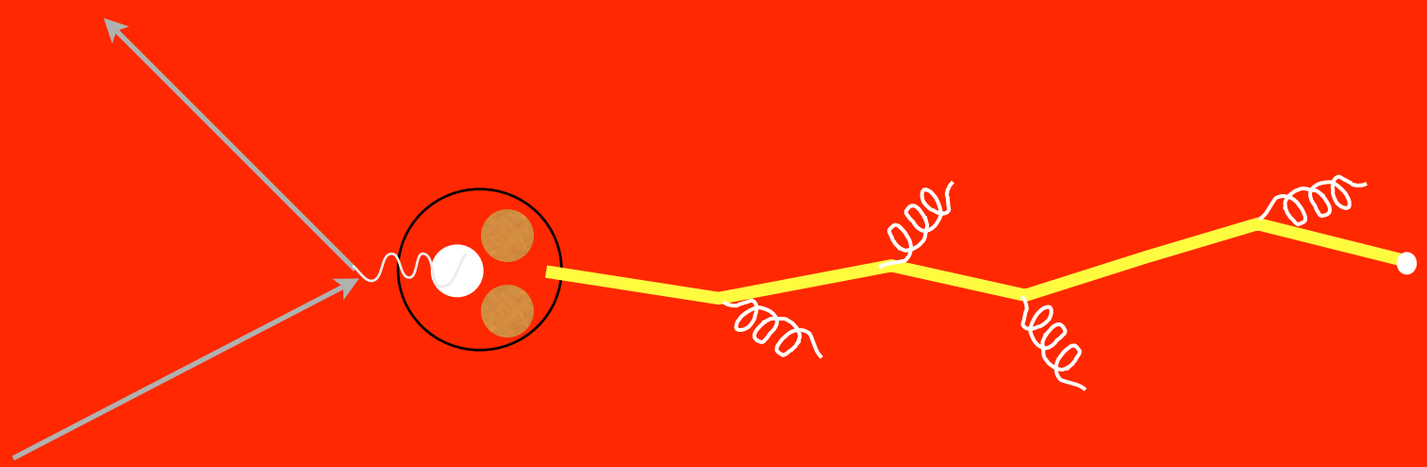

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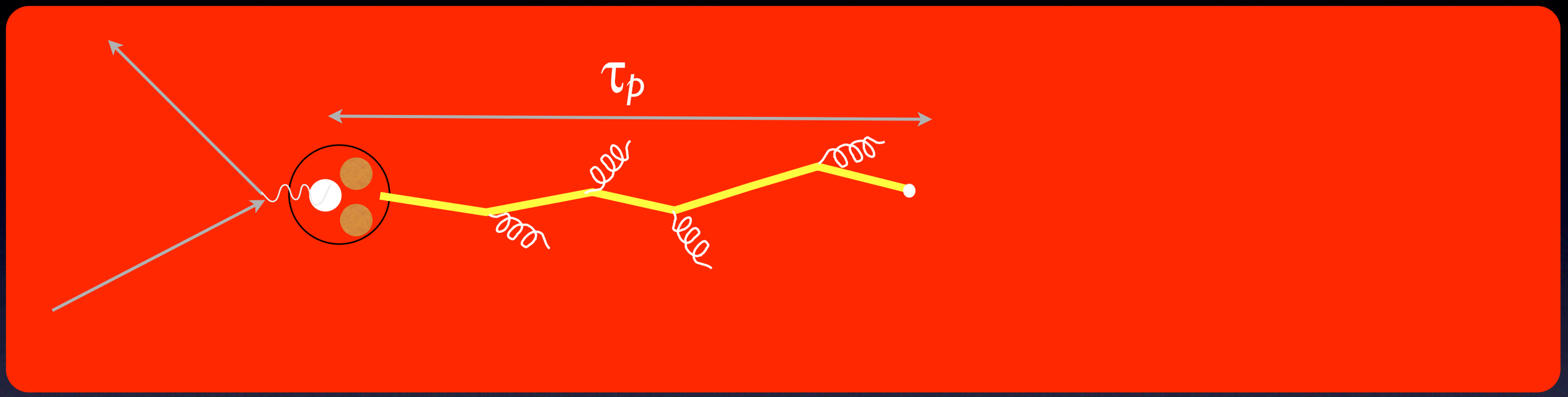

- *production time τ_p* - propagating quark

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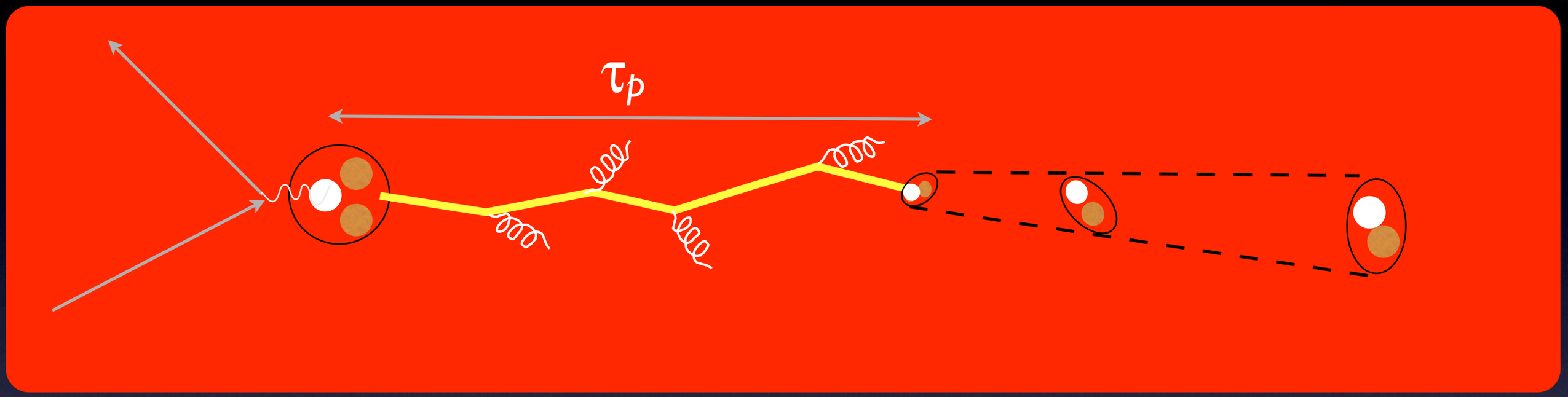

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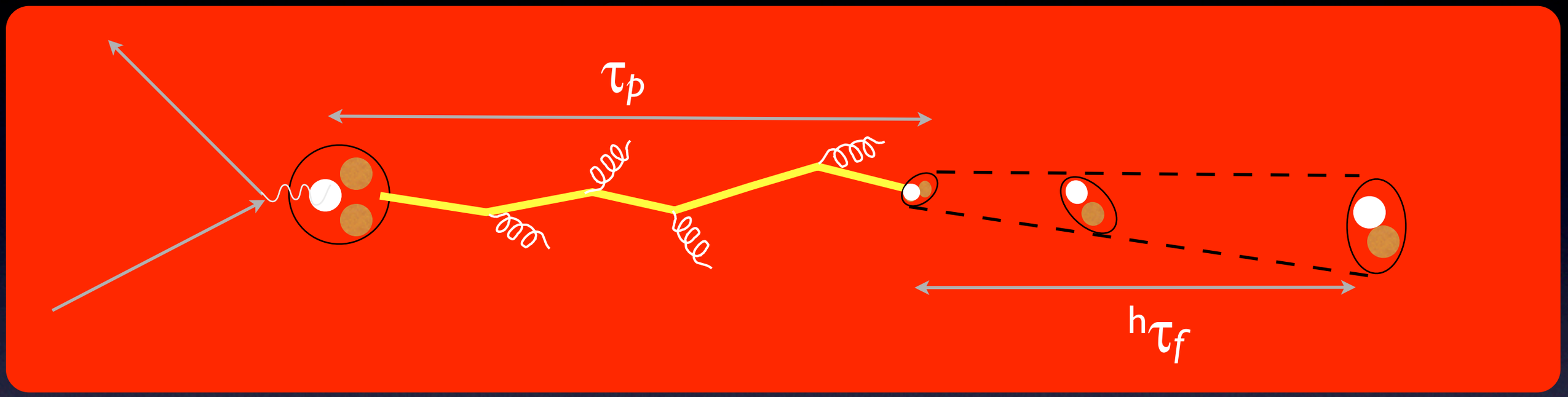
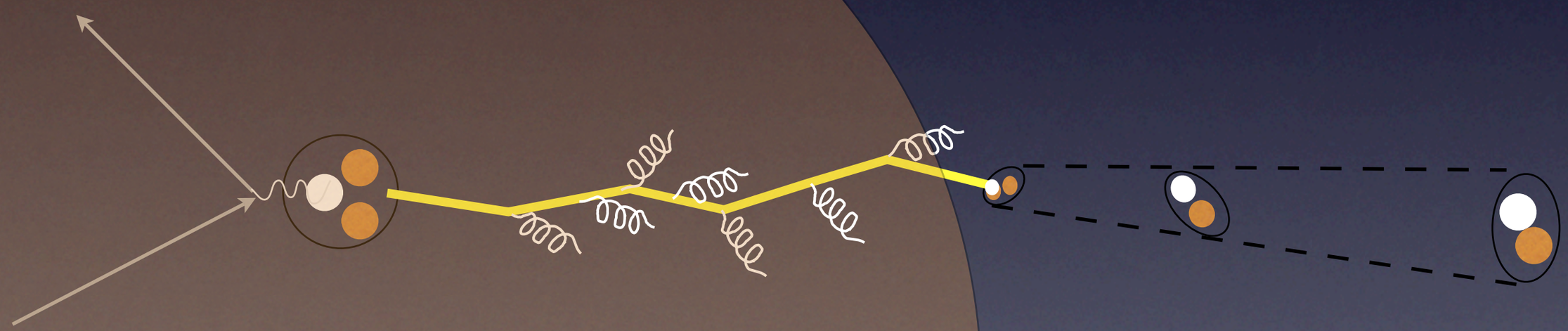


- *production time* τ_p - propagating quark
- *formation time* $^h\tau_f$ - dipole grows to hadron

Low-Energy DIS in Cold Nuclear Medium

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



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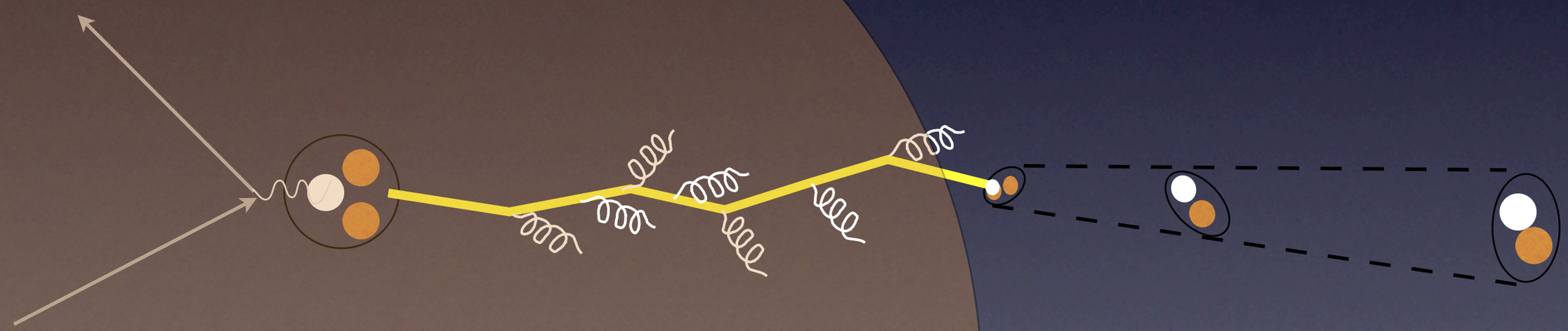
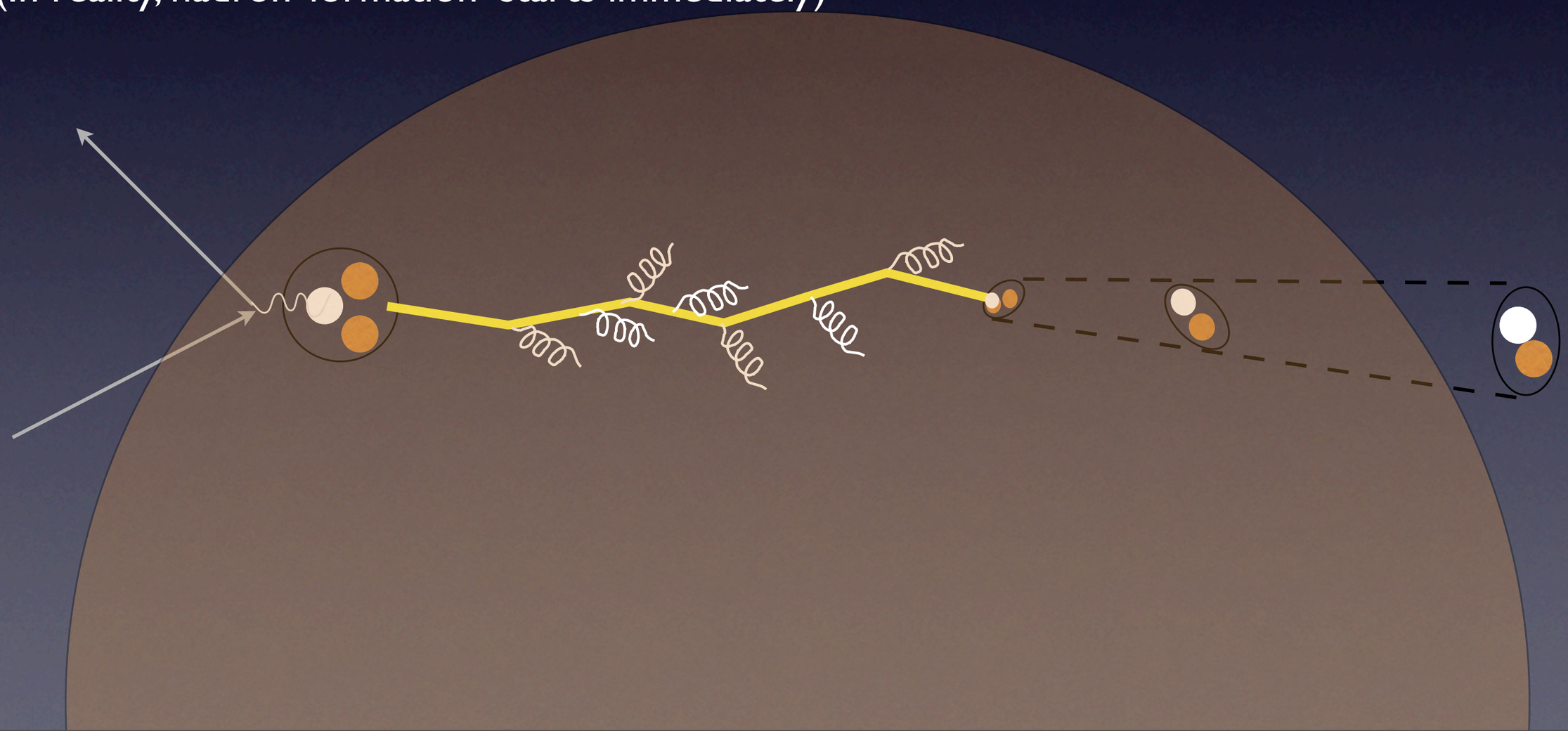


Hadron forms *outside* the medium; or....

Low-Energy DIS in Cold Nuclear Medium

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

(In reality, hadron 'formation' starts immediately)



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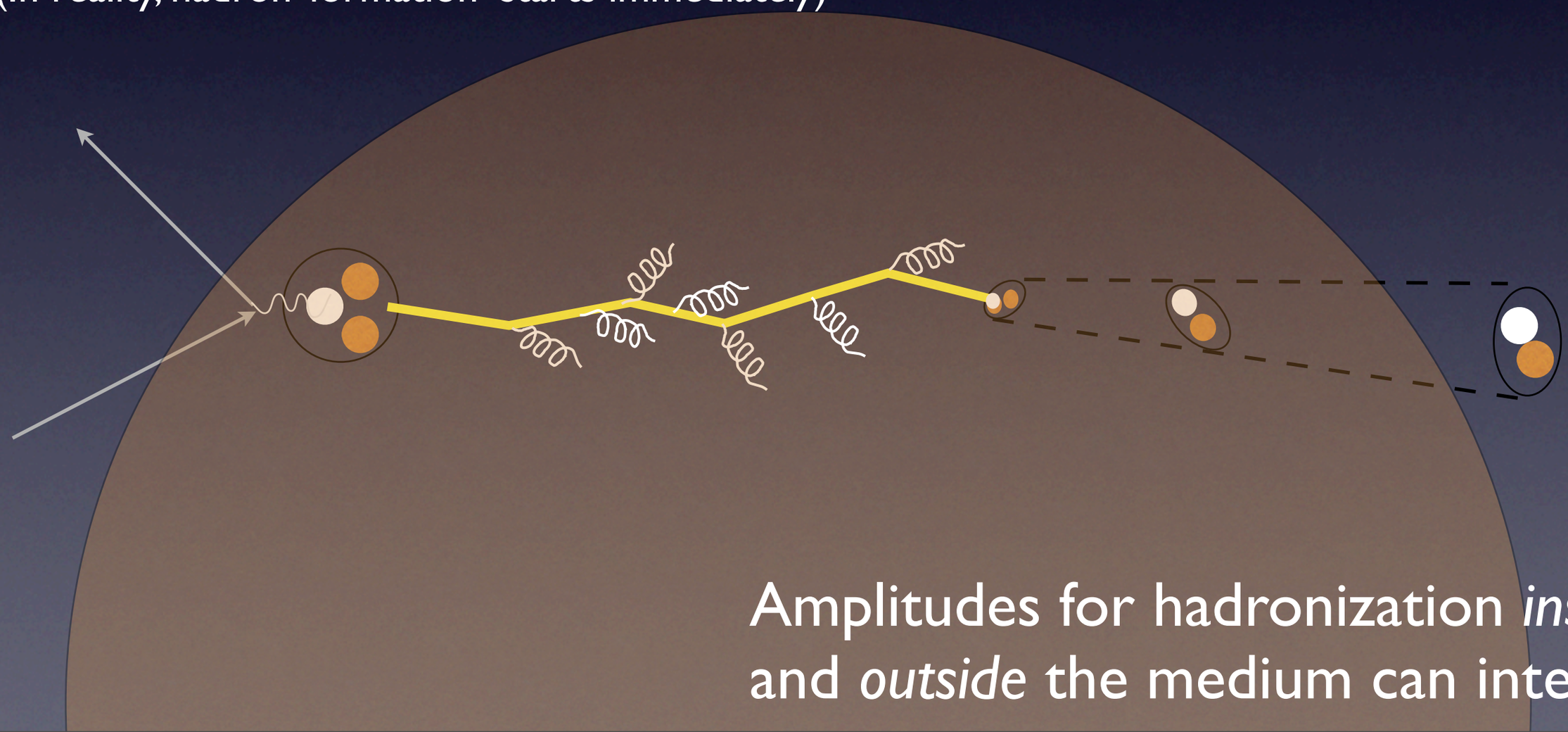
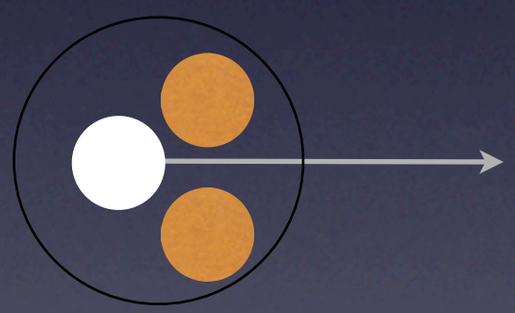


Amplitudes for hadronization *inside* and *outside* the medium can interfere

Drell-Yan in Cold Nuclear Medium

e.g., 800 GeV protons - no in-medium hadronization, but do have p_T broadening



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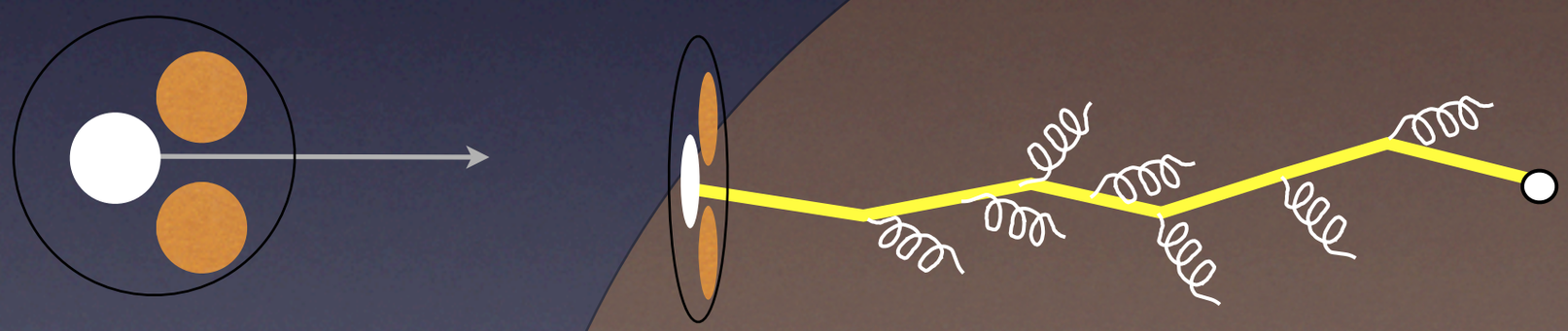

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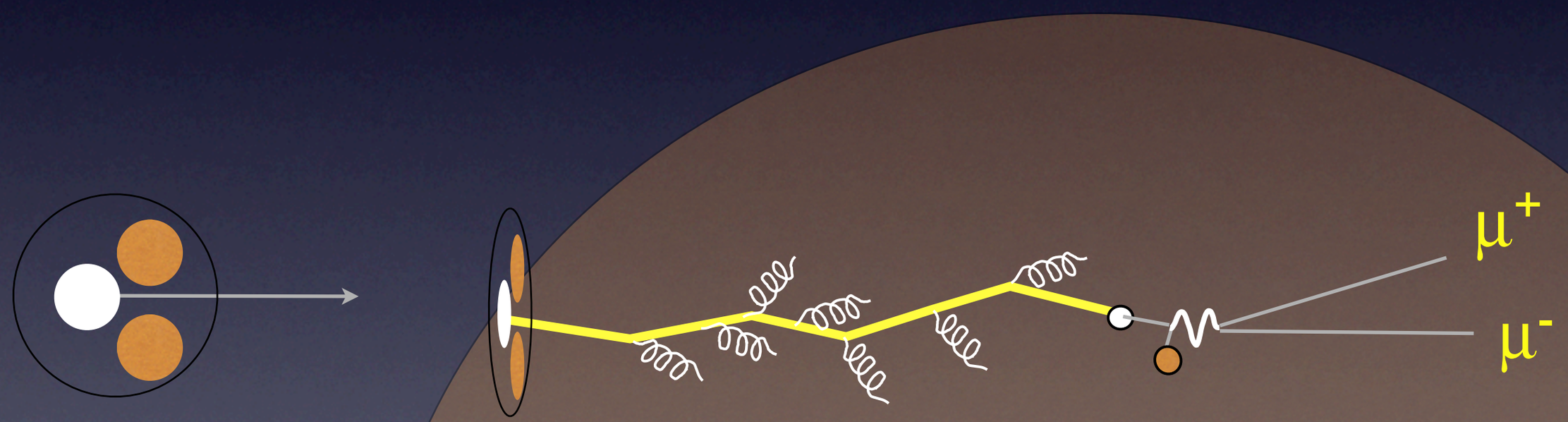
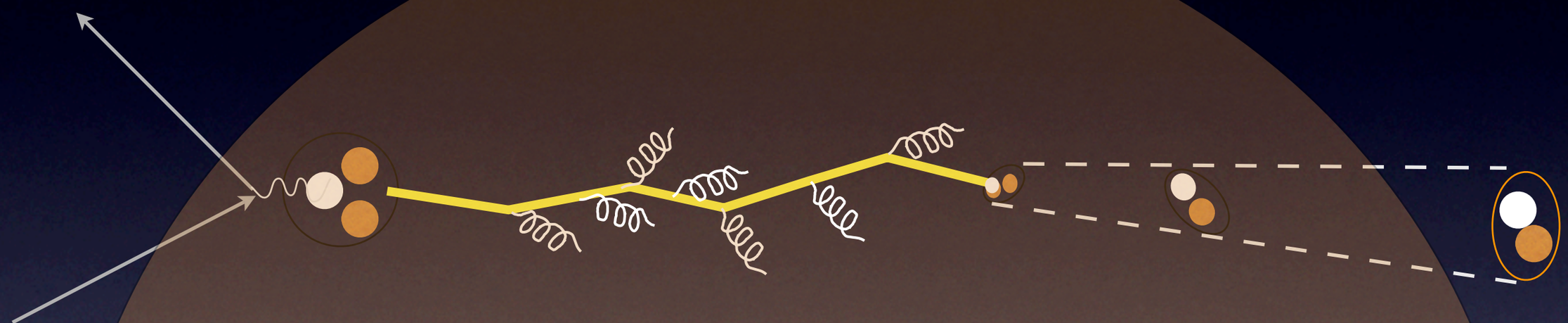


Summary of Method, Low-Energy DIS

Identify parton propagation phase by p_T broadening



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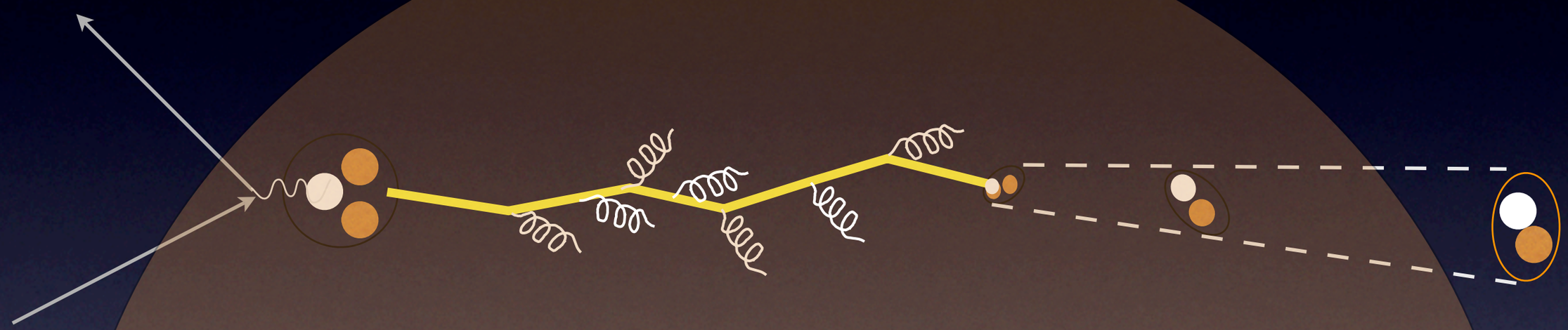

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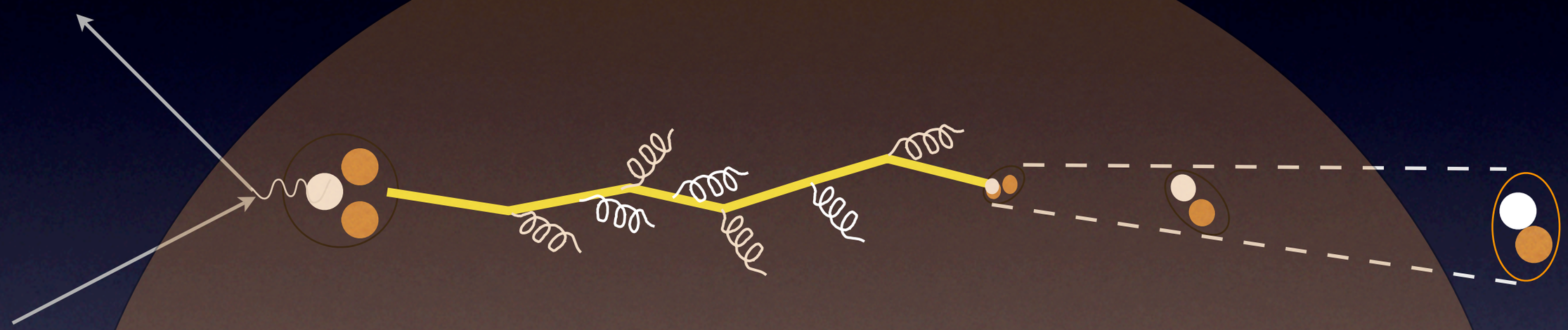
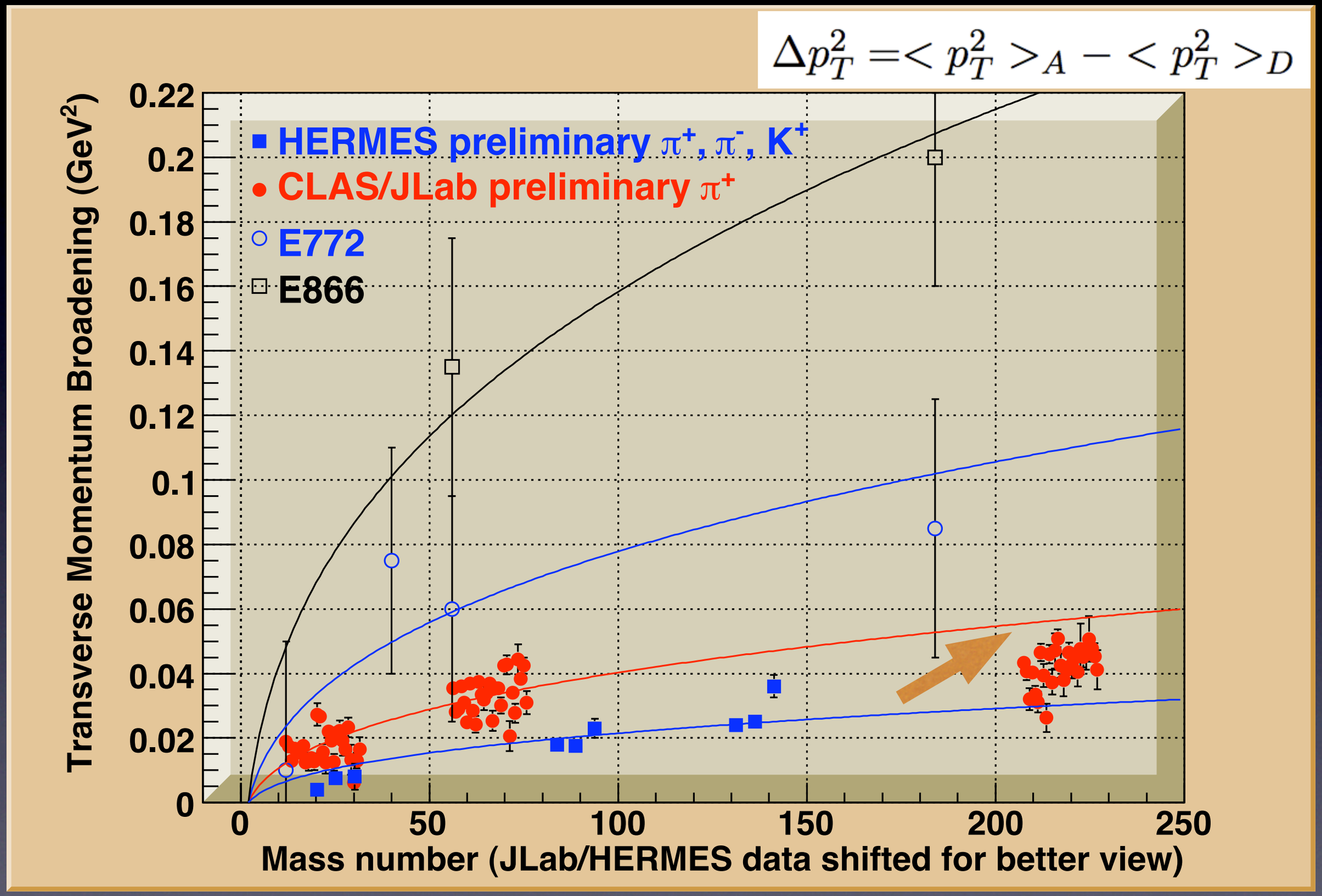


Identify hadron formation phase by hadron attenuation

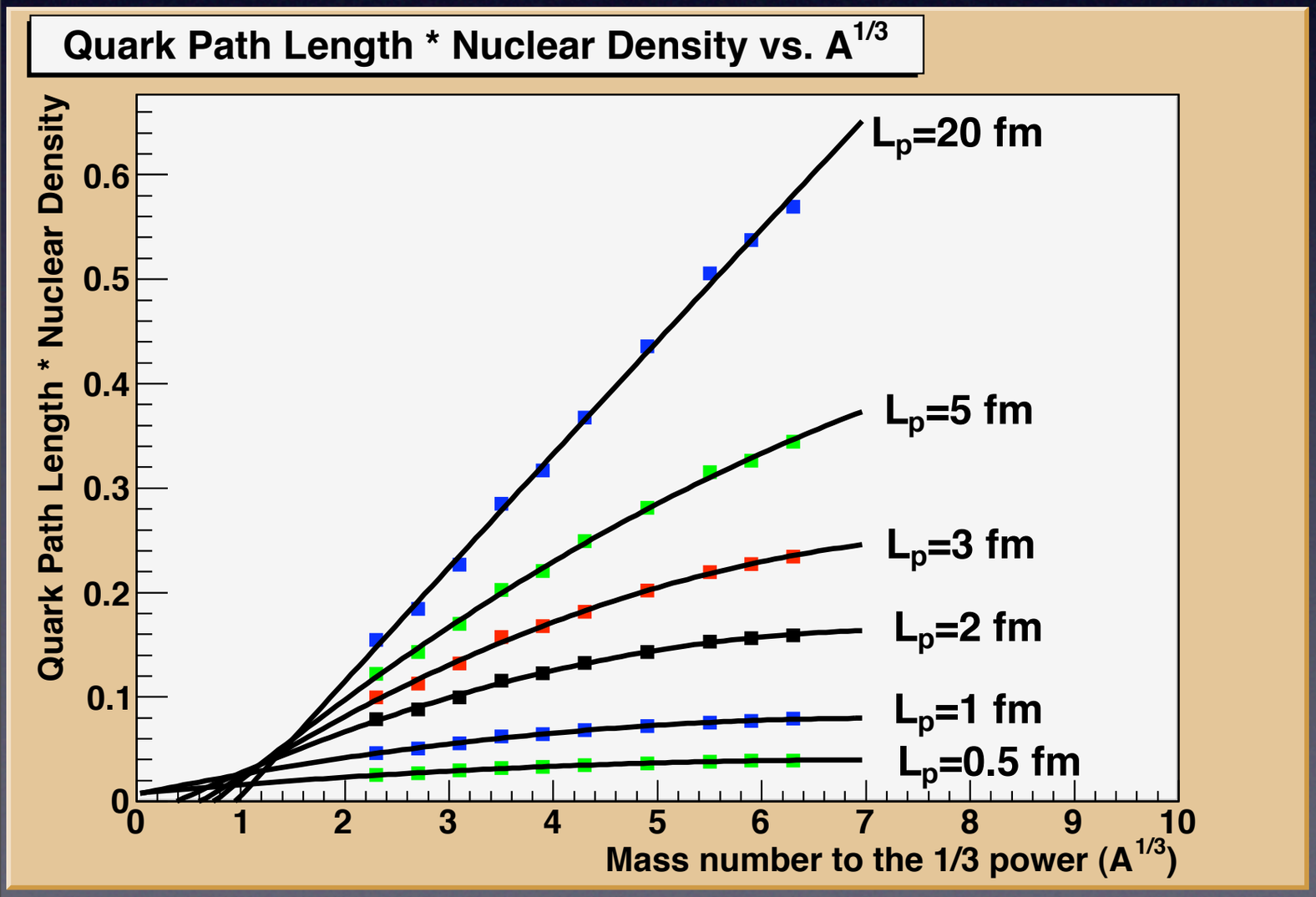
Extract characteristic times and reaction mechanisms using the variation of these observables with nuclear size

Comparison of p_T broadening data - Drell-Yan and DIS



See J. Qiu's talk on Tuesday

Production Time Extraction - Geometrical Effects



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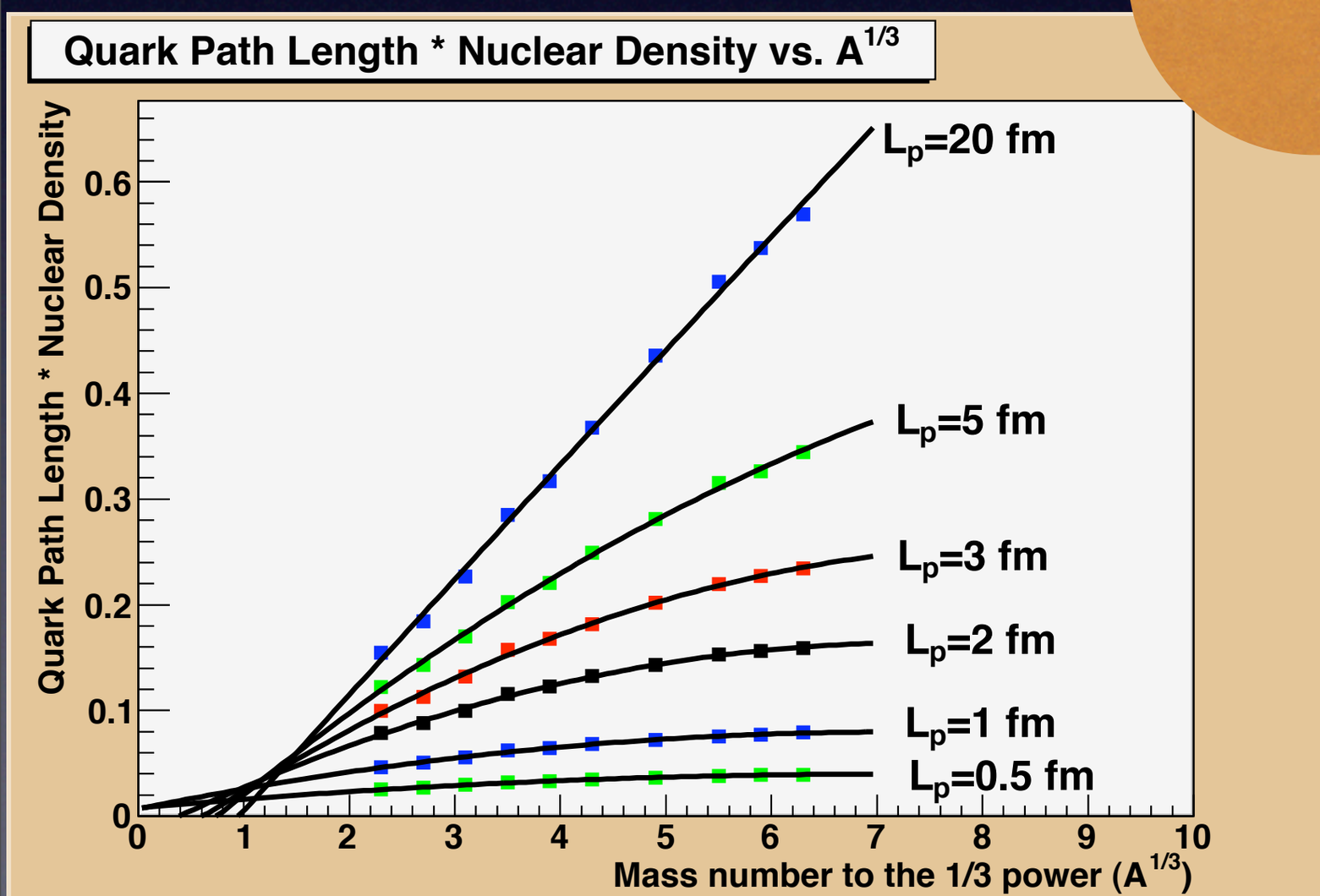

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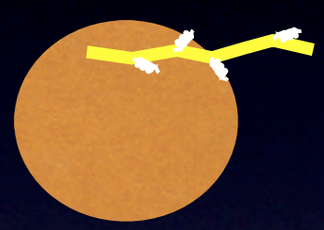

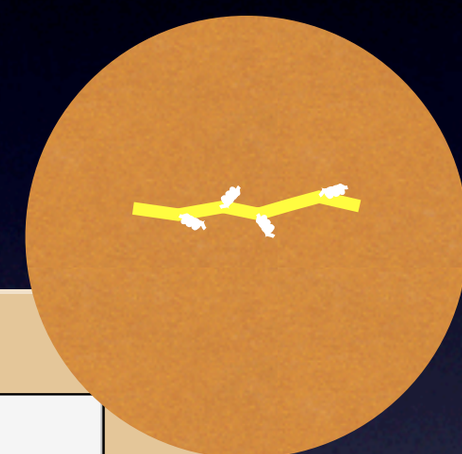

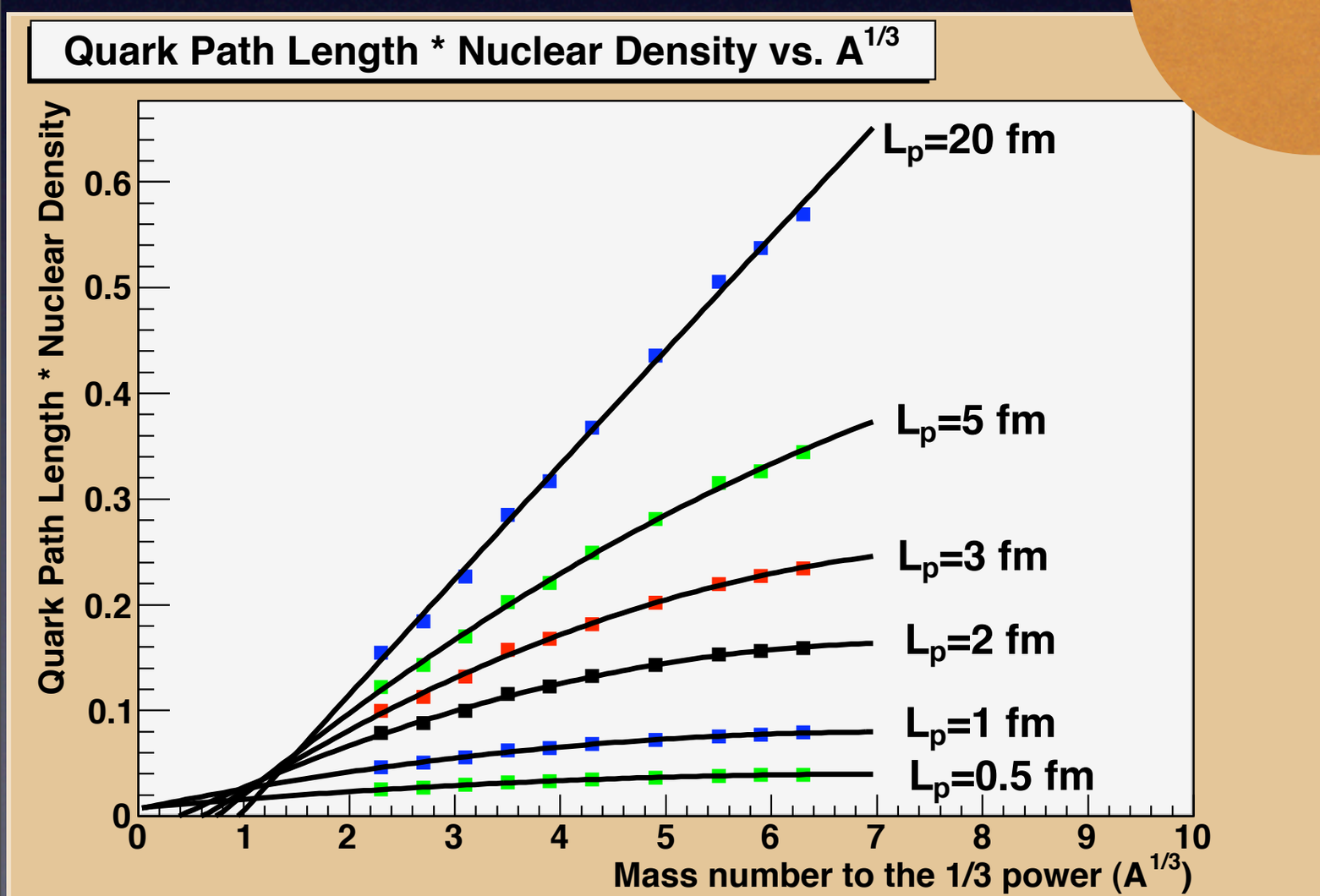

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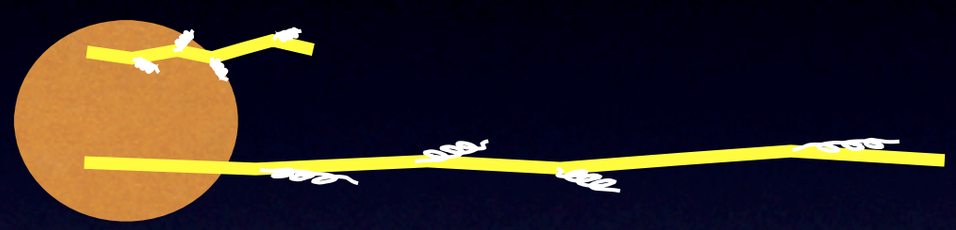

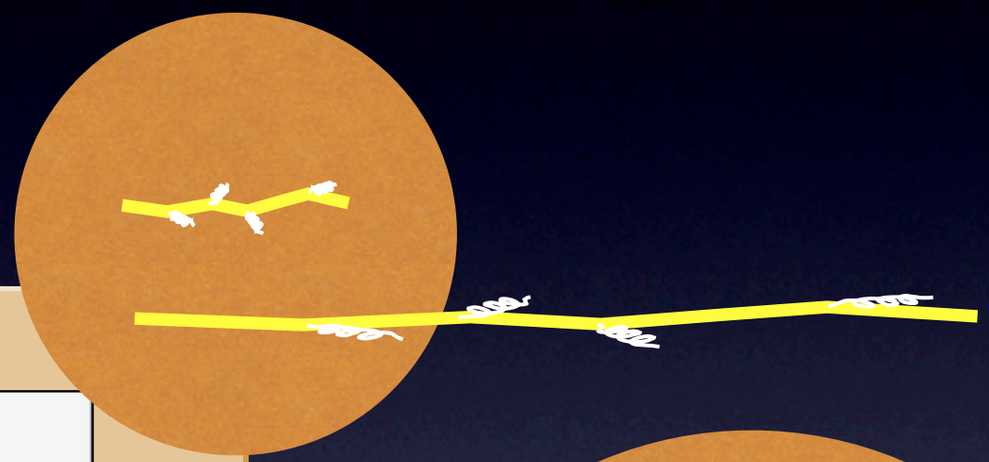

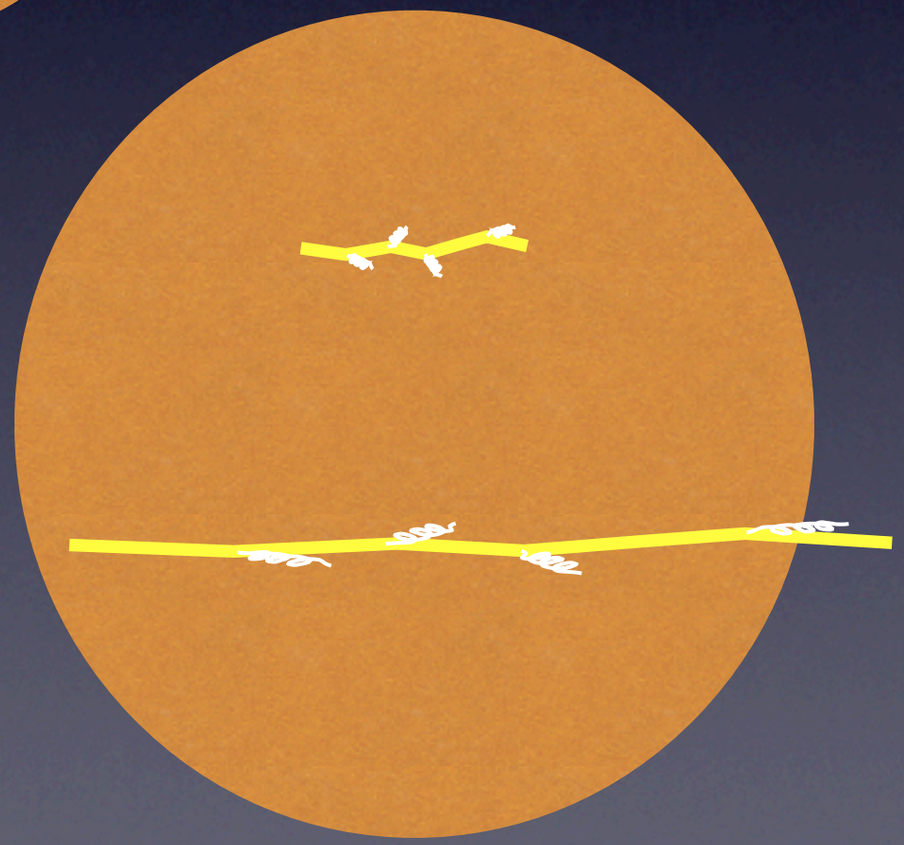

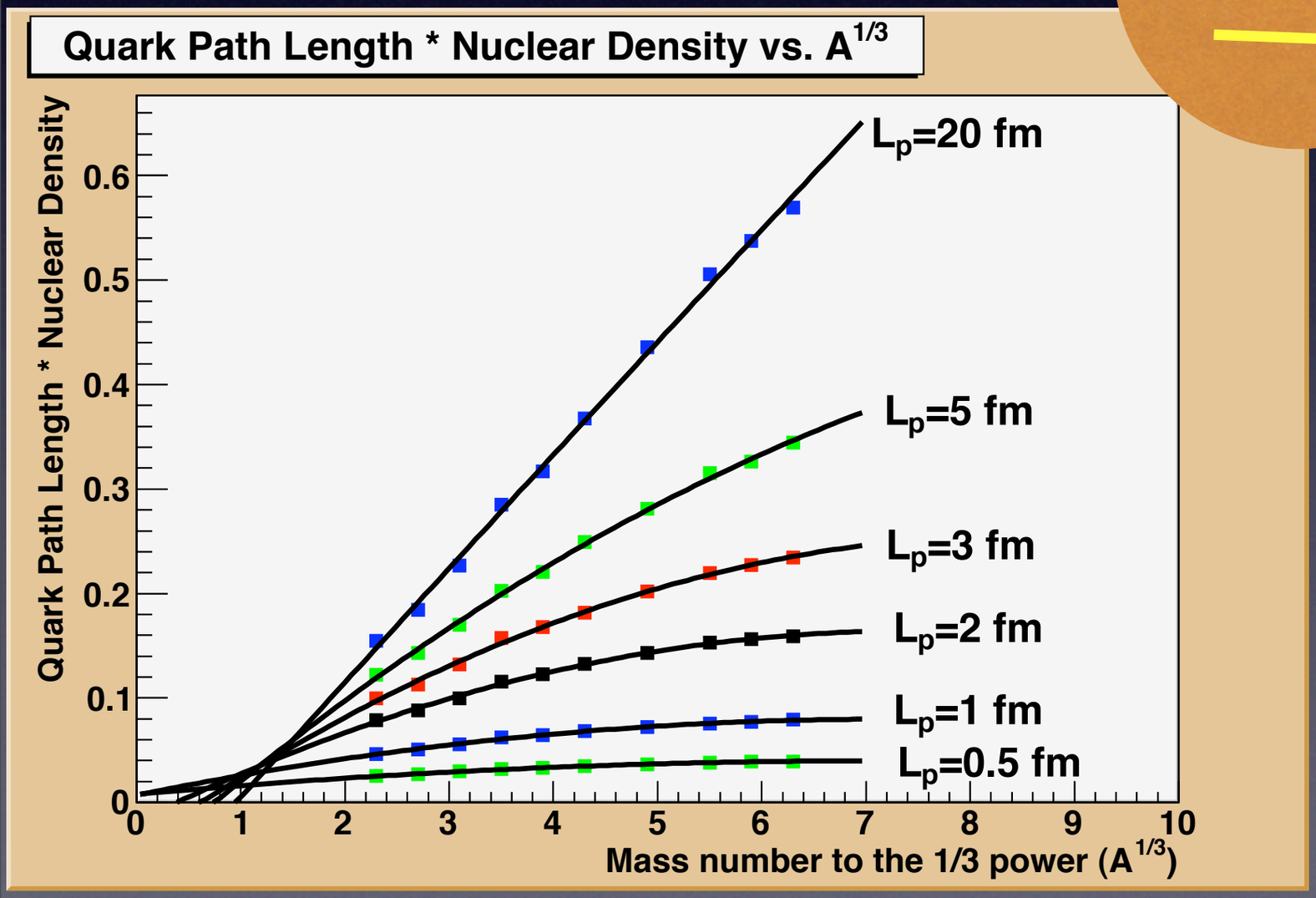

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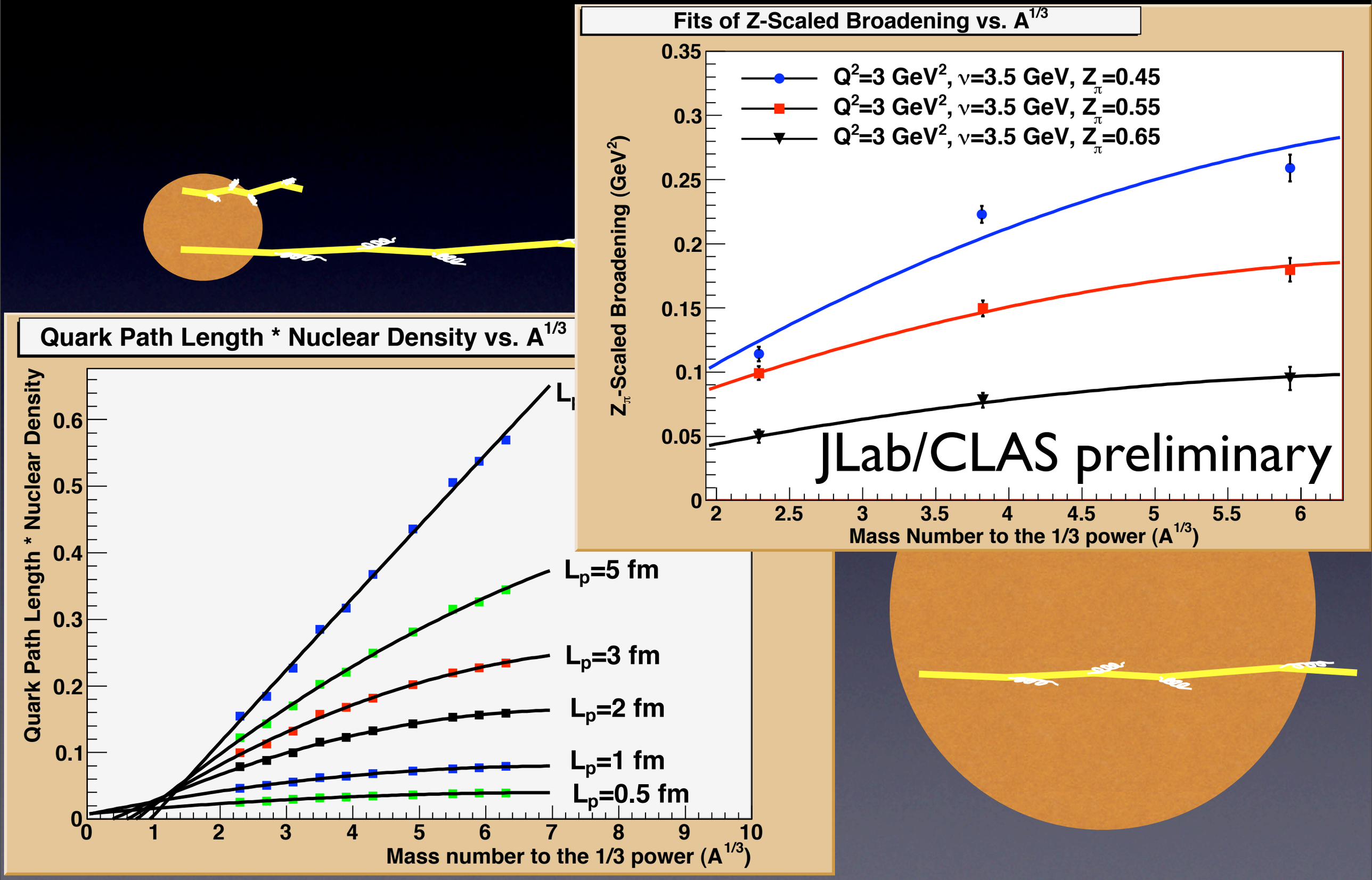

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- saturation for Pb at low z always undershoots
- model too primitive? or
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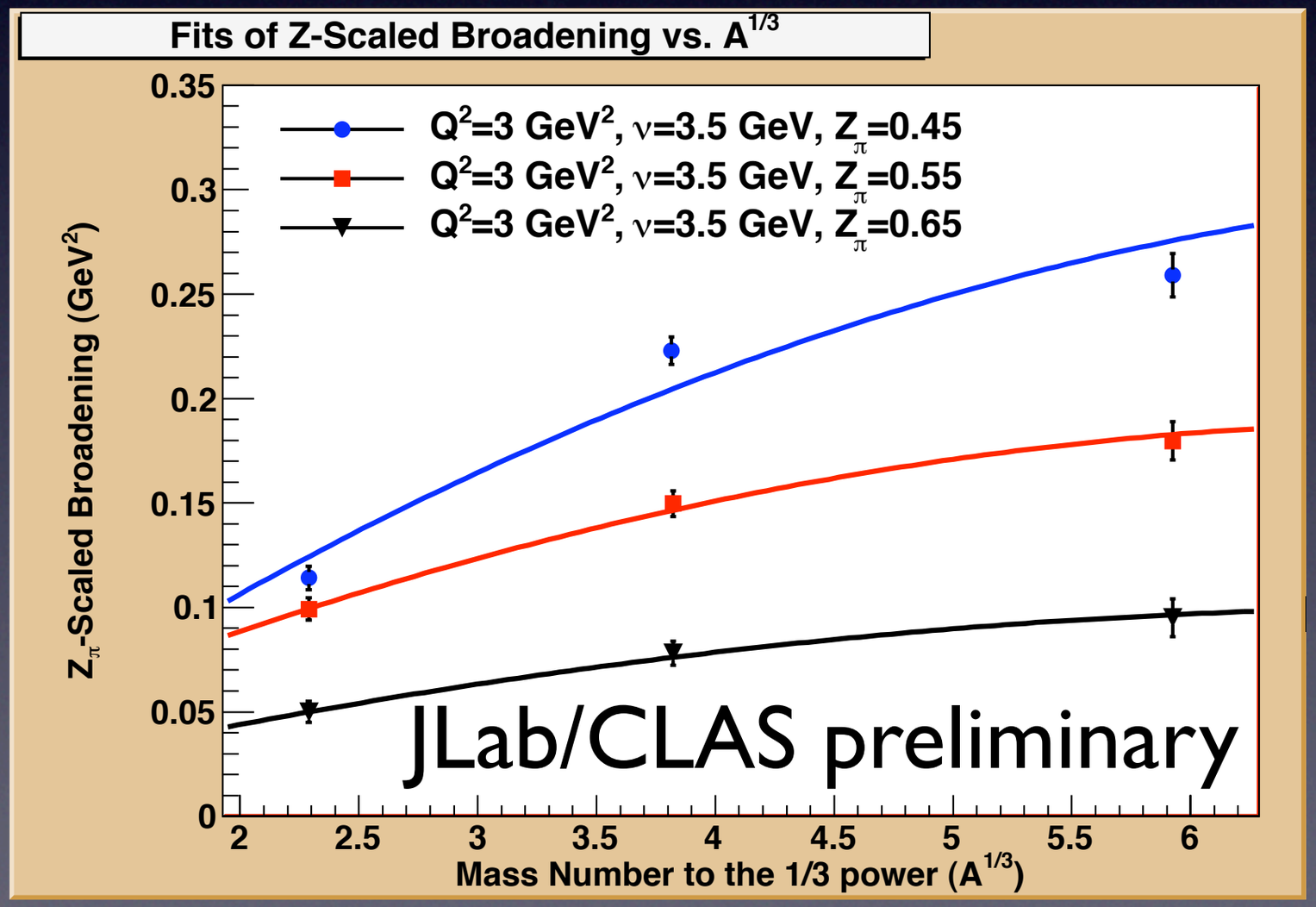
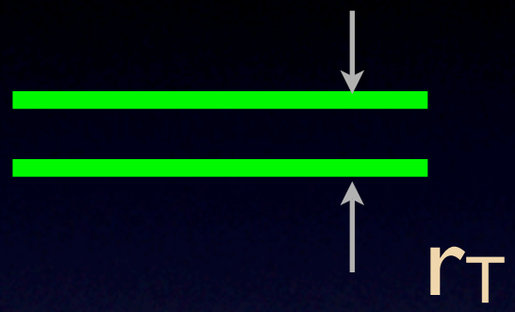


Color Dipole Formalism

- Total cross section, color dipole with nucleon:

$$\sigma_{\bar{q}q}(r_T, s) = C(r, s) r_T^2$$



- At small r_T, C is related to the *proton gluon density*:

$$C(r_T, s) = \frac{\pi^2}{3} G(x, Q^2)$$

- ***p_T broadening*** of the quark can be expressed in terms of $C(r_T,s)$:

$$\Delta \langle k_T^2 \rangle = 2C\rho_A L = \hat{q}L = \frac{2\pi^2}{3} G(x, Q^2)\rho_A L$$

M. B. Johnson, B. Z. Kopeliovich, and A. V. Tarasov, Phys. Rev. C **63**, 035203 (2001)

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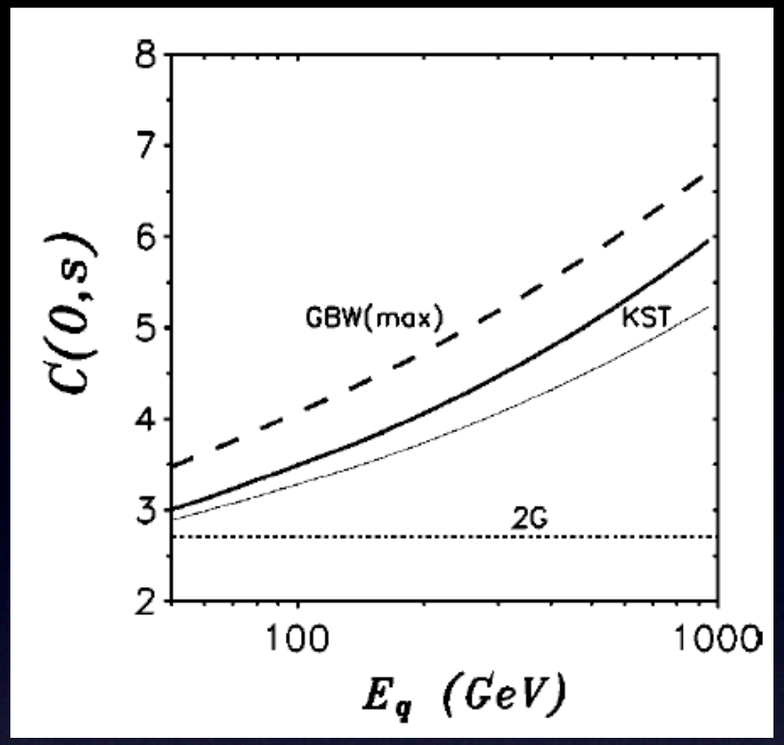

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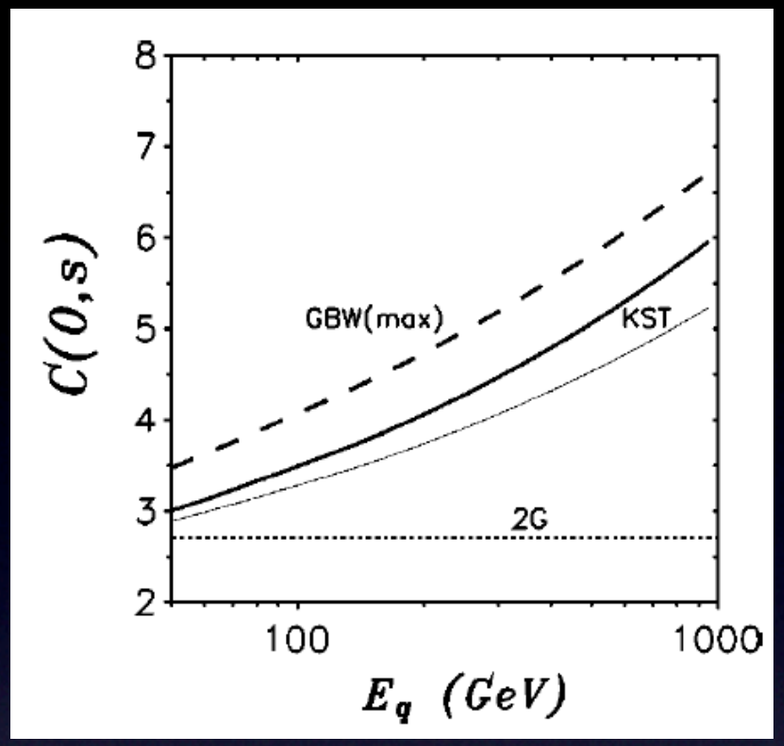
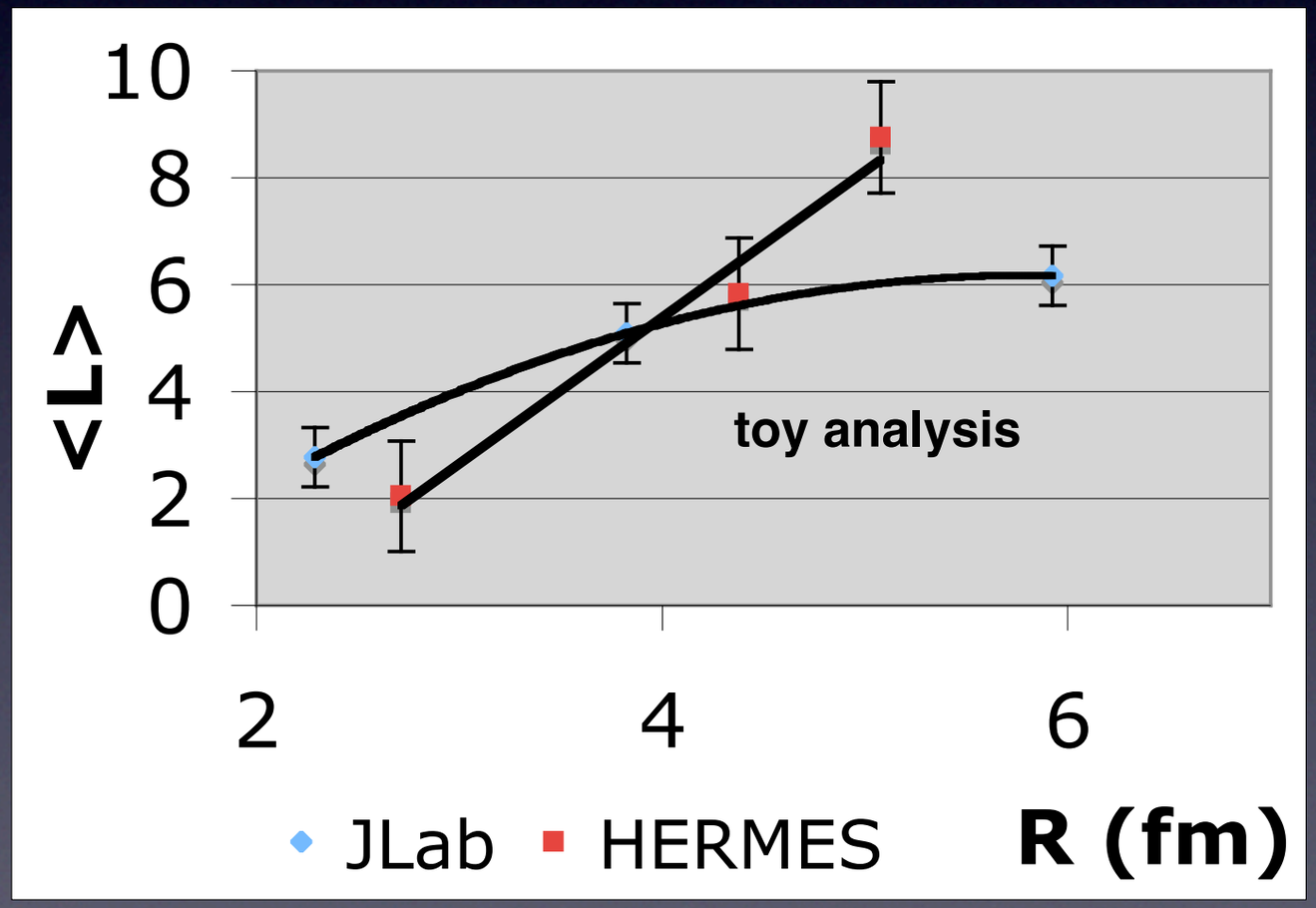


- Can assume C=2 and derive <L>:



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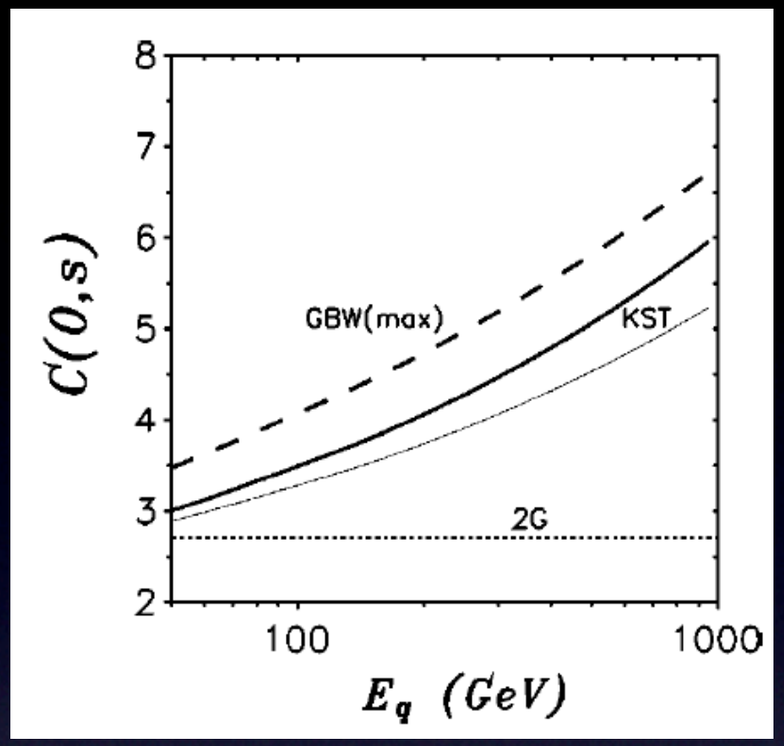

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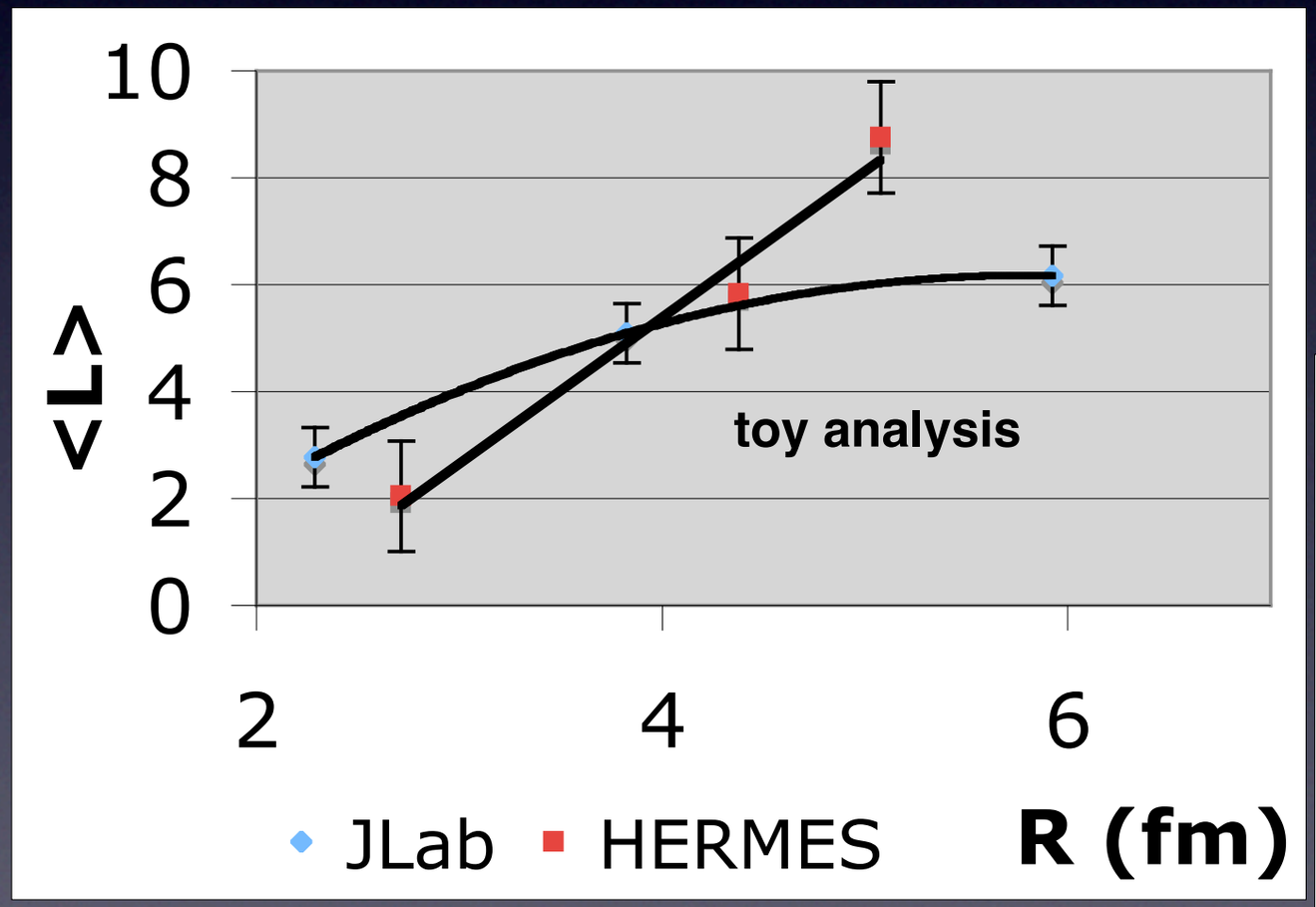
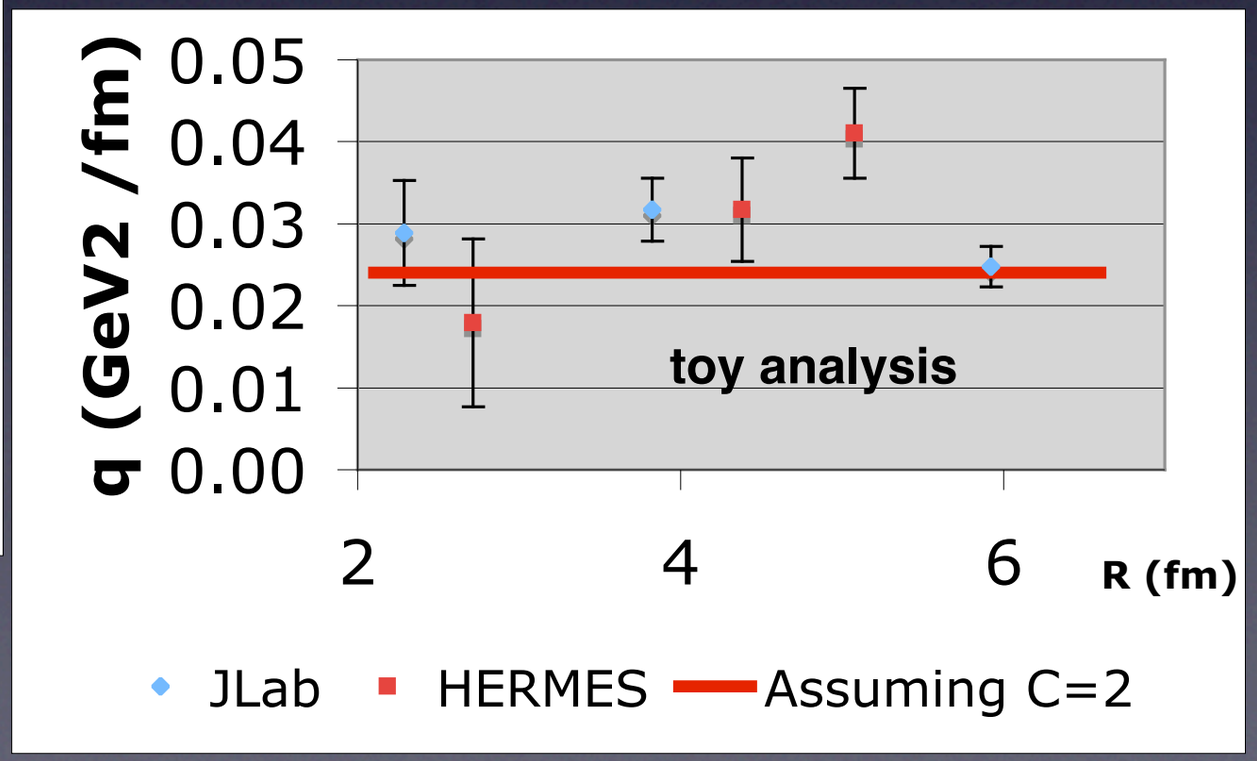


- Or assume <L> >> R, derive q:

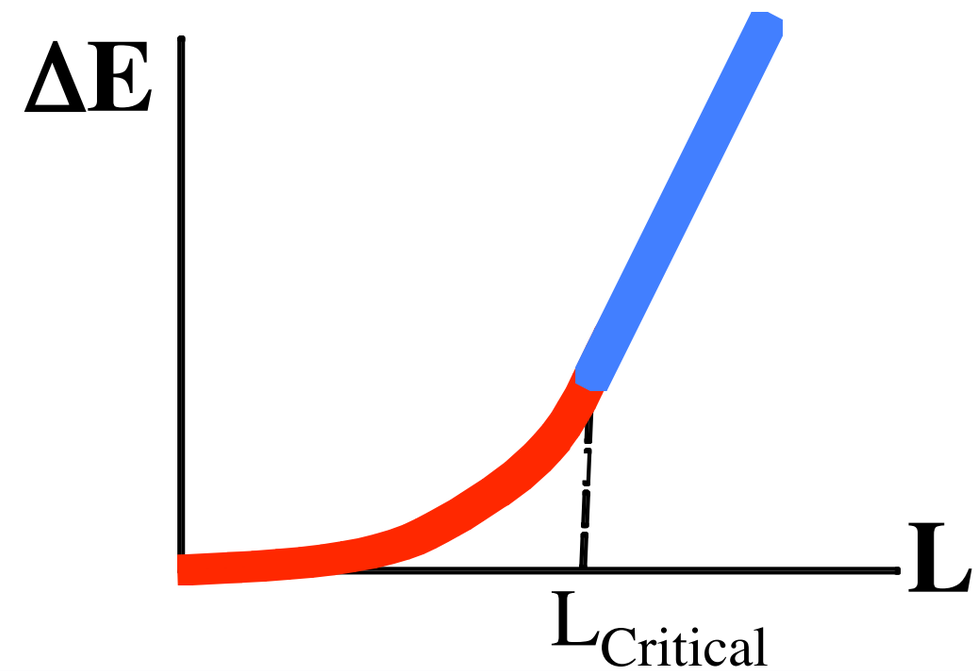


Energy Loss in pQCD

(BDMPS version)

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

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



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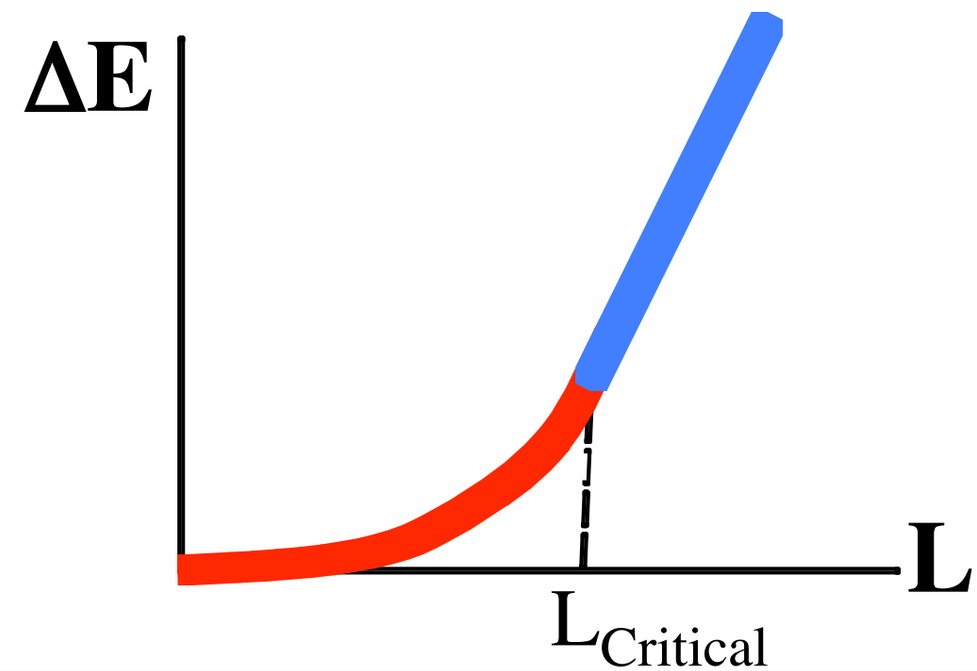
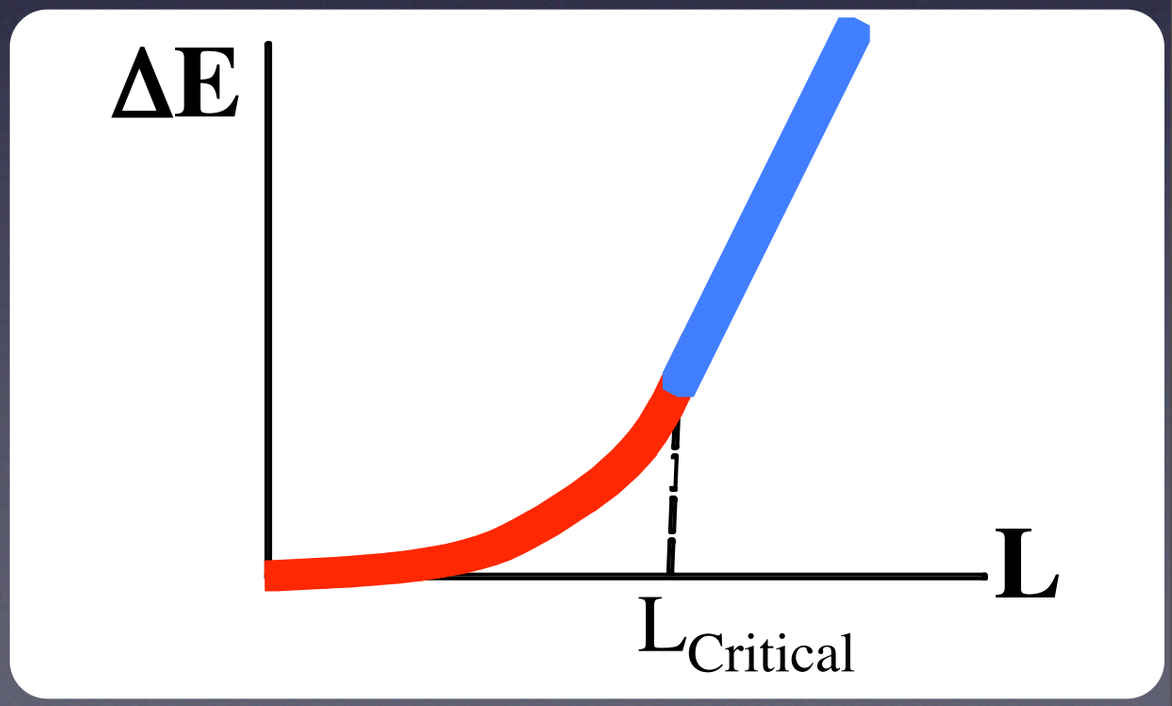


For ν~3 GeV and q~0.025 GeV2/fm,

$L_{Critical}$ = ~**4-5 fm**, < R_{Pb}

- broadening due primarily to multiple scattering, but 10-20% could be due to medium-stimulated emission
- exceeding $L_{Critical}$ in Pb would stop the broadening due to energy loss, creating flatter plateau
- if correct, can measure $L_{Critical}$ and/or dE/dx !!



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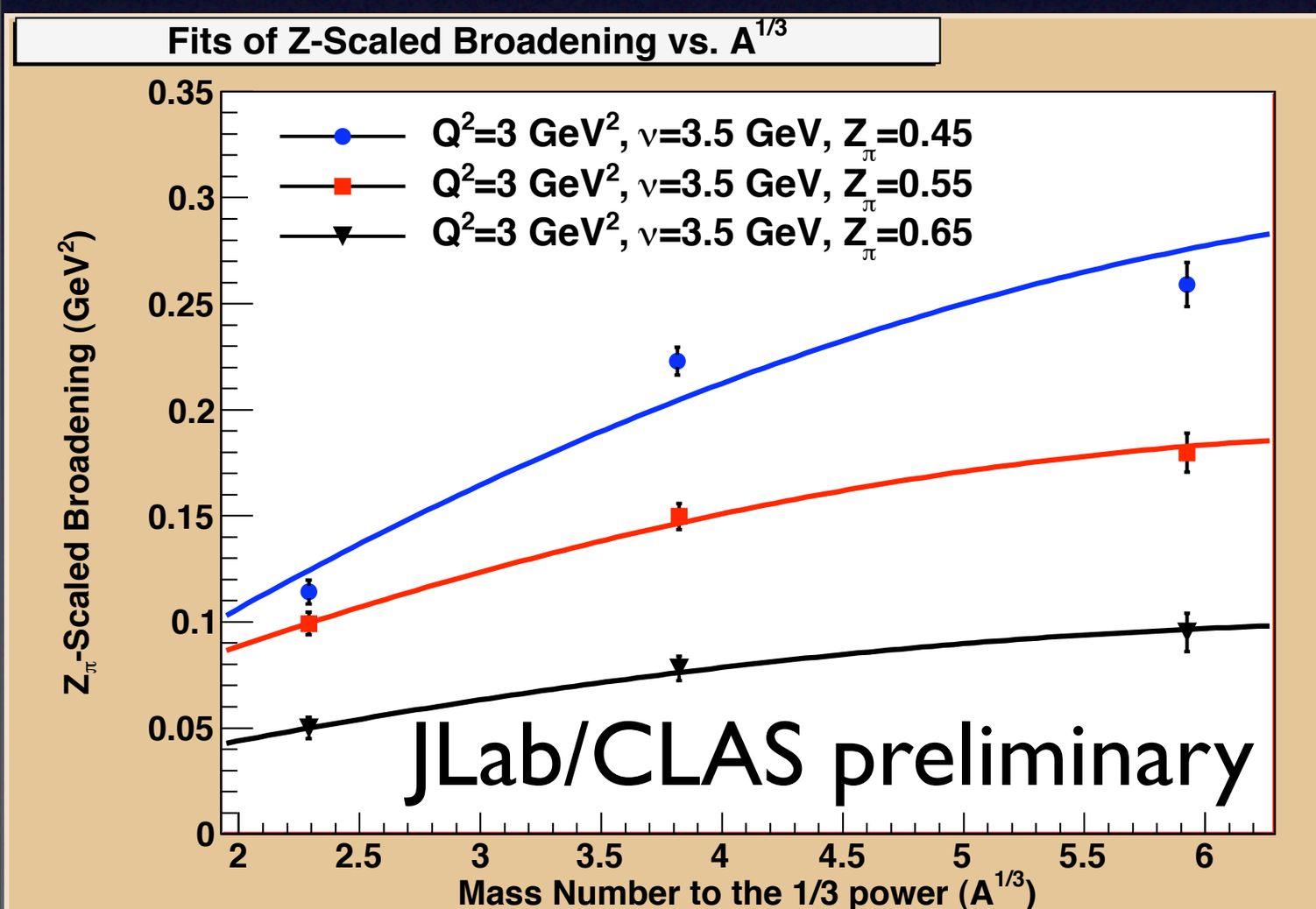

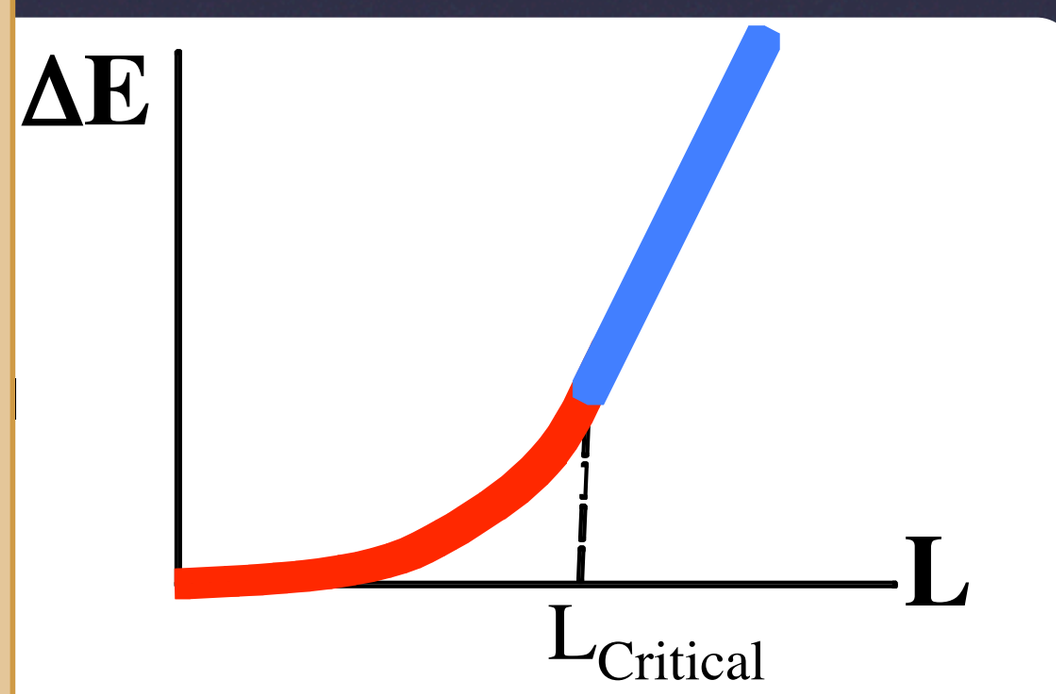

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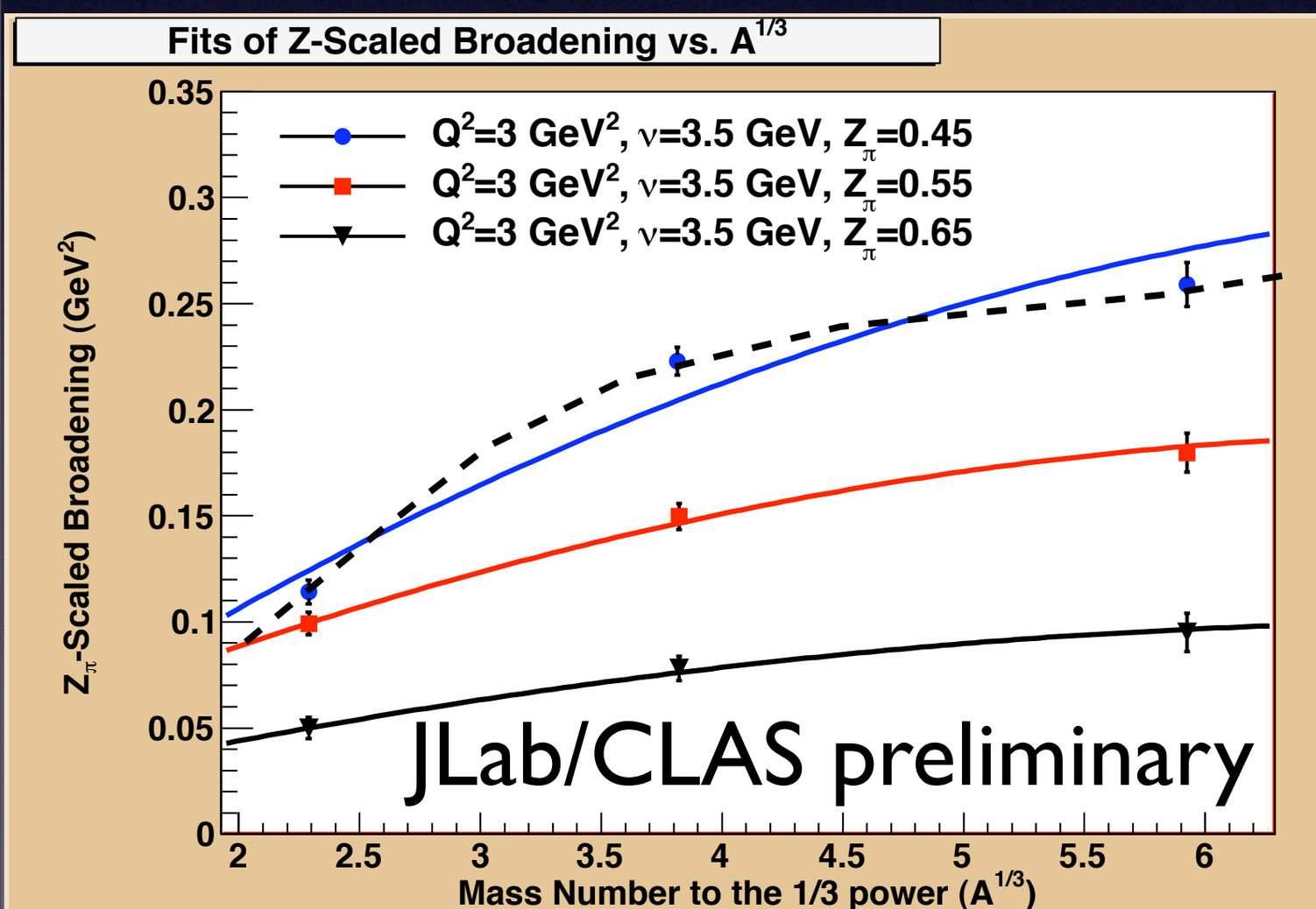
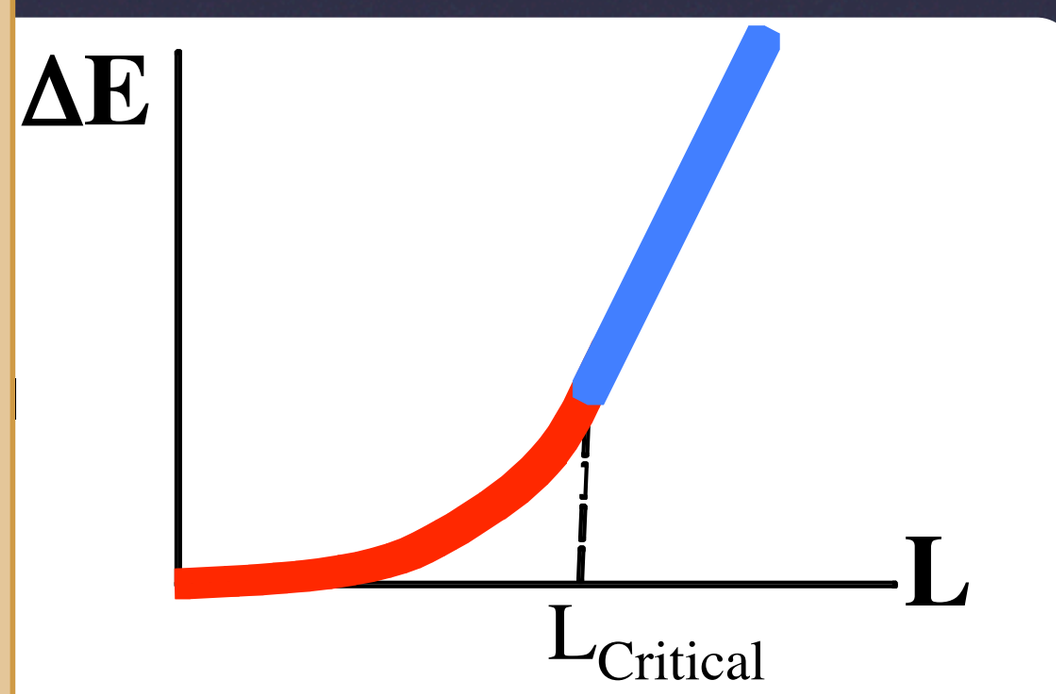
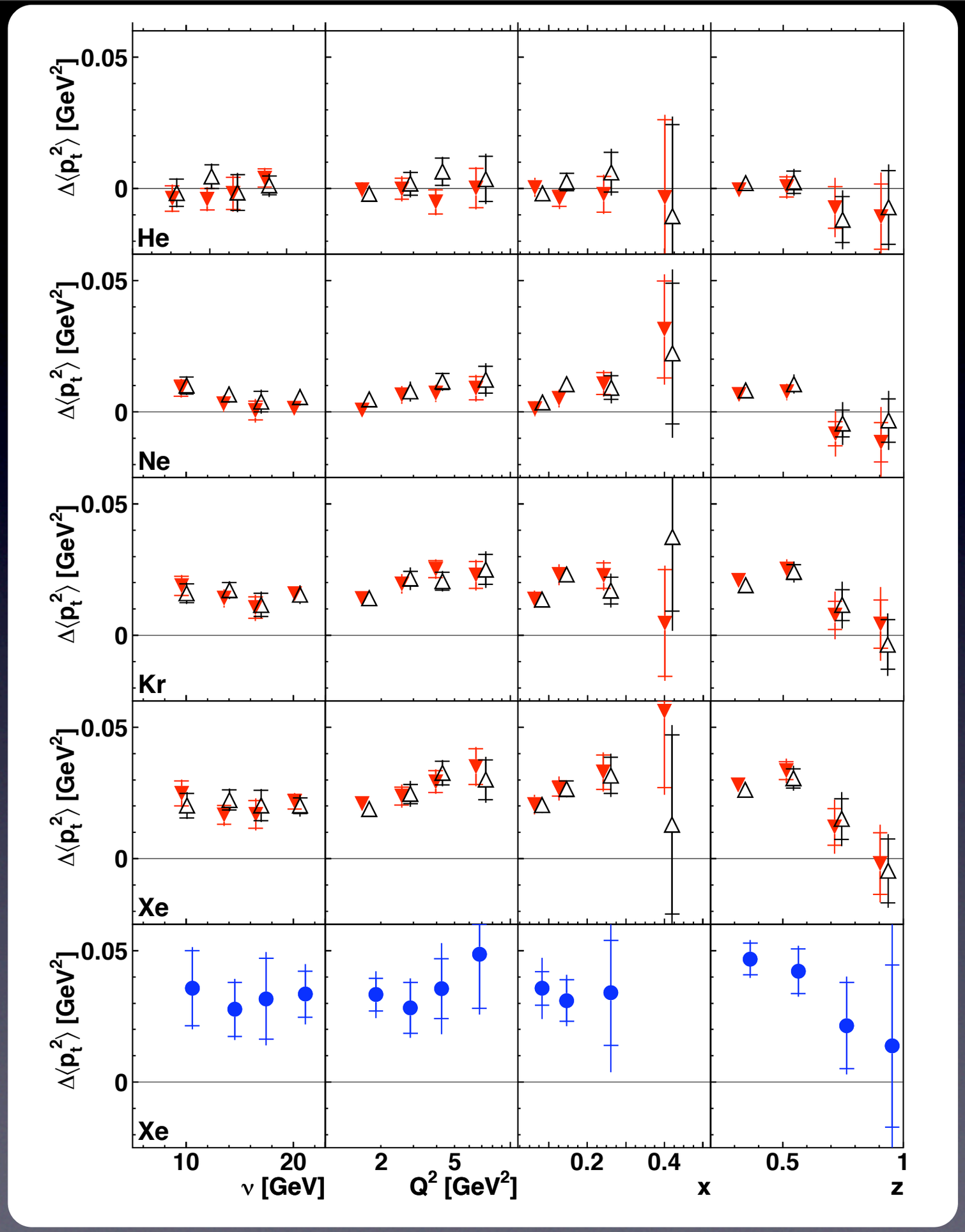
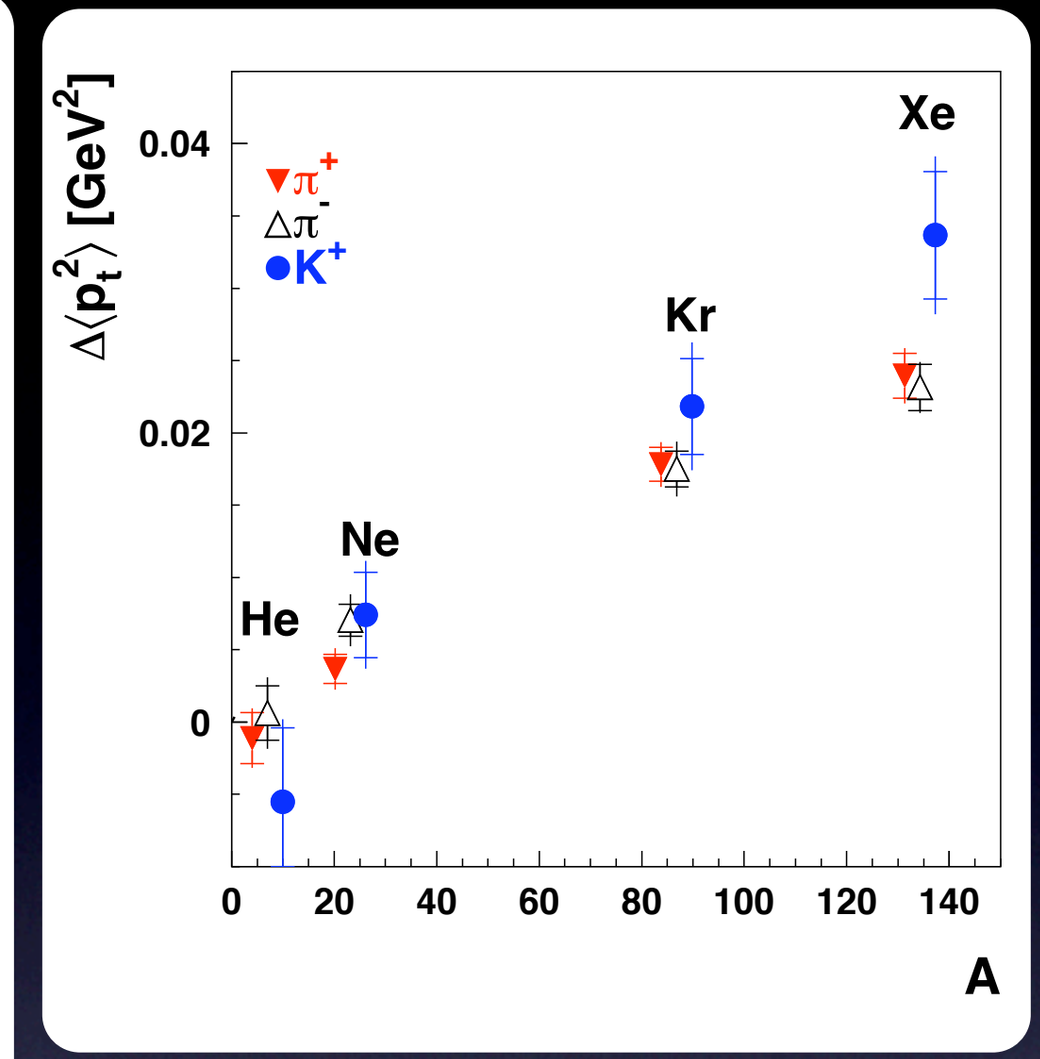
- if correct, can measure $L_{Critical}$ and/or dE/dx !!



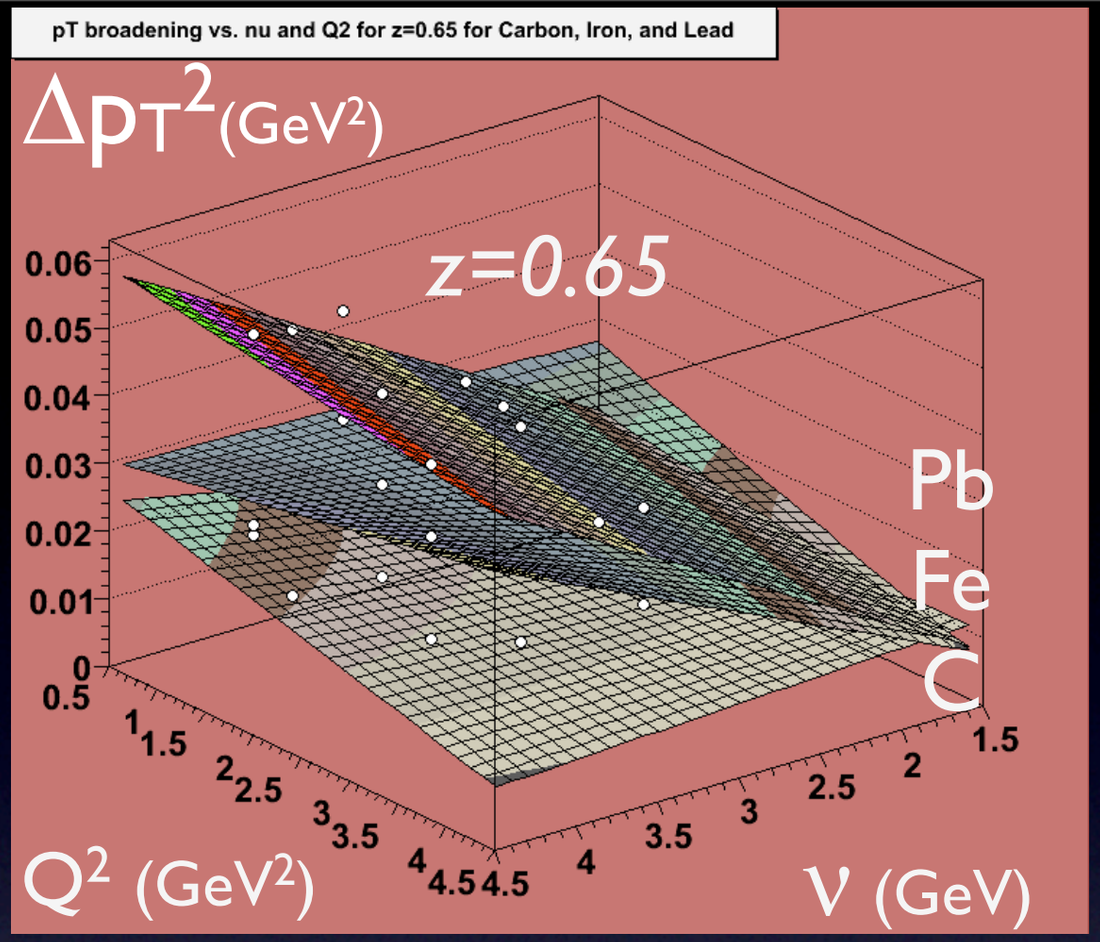


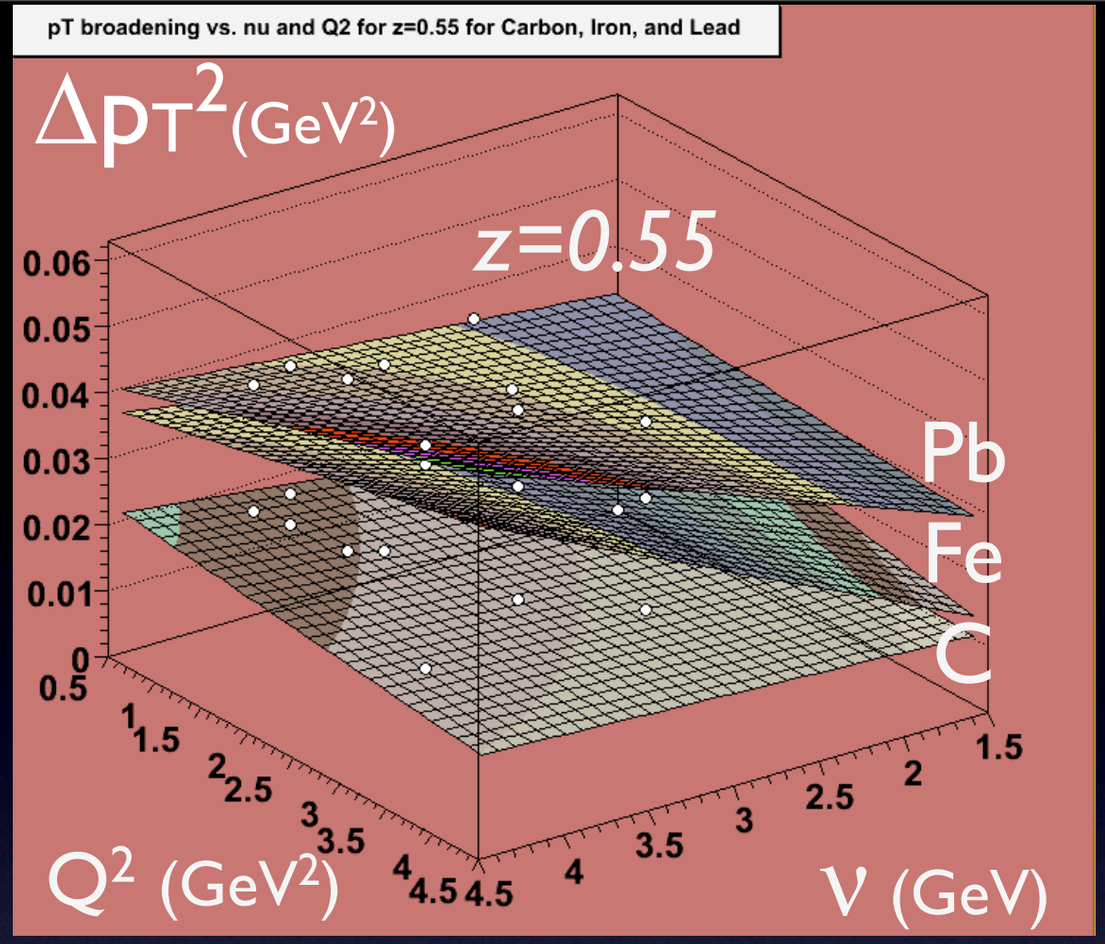




Hermes
1-D distributions for
Δp^2_T vs. ν, z, Q^2, A

no strong dependencies seen - good for EIC, luminosity less critical



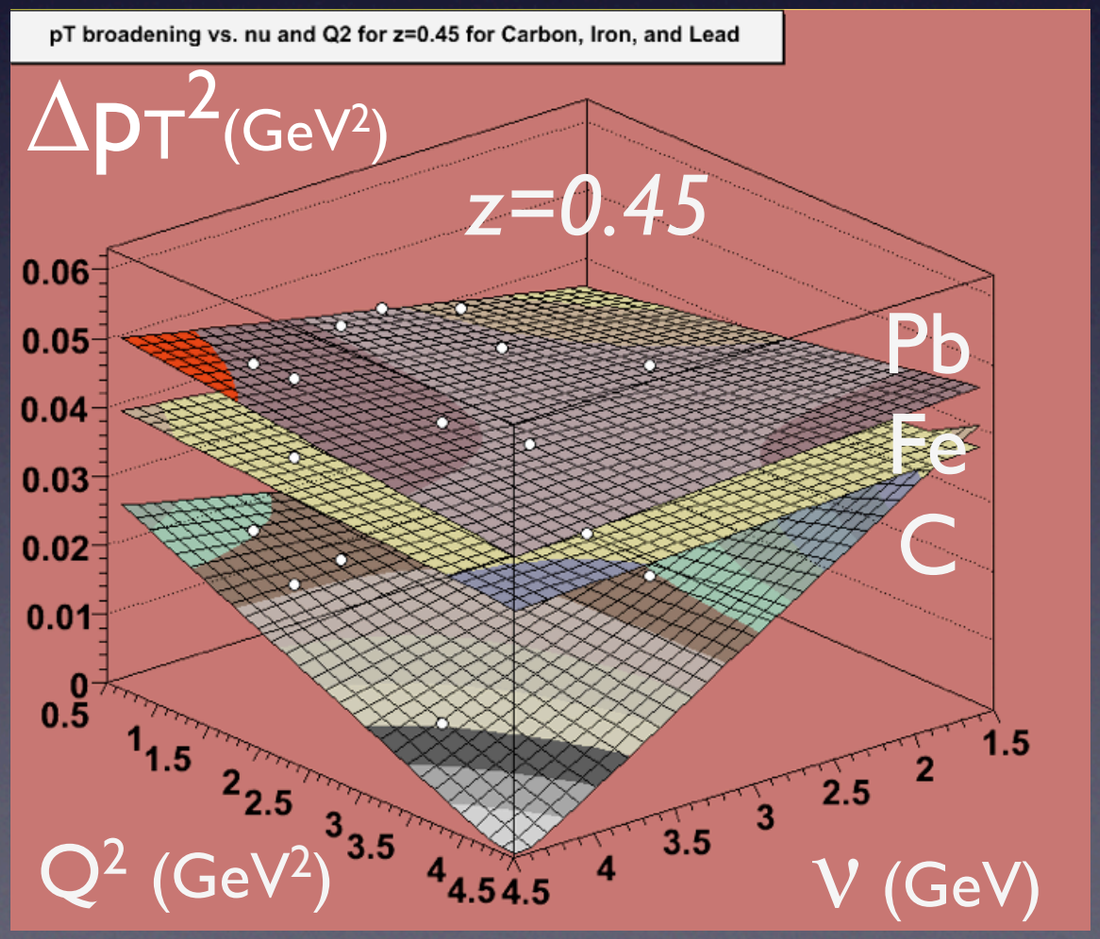


JLAB/CLAS 3-DIMENSIONAL VARIABLE DEPENDENCES

p_T Broadening

E.g., $$\tau \approx \frac{\nu z(1-z)}{Q^2}$$

27 bins in ν, Q^2, z each for 3 nuclei!



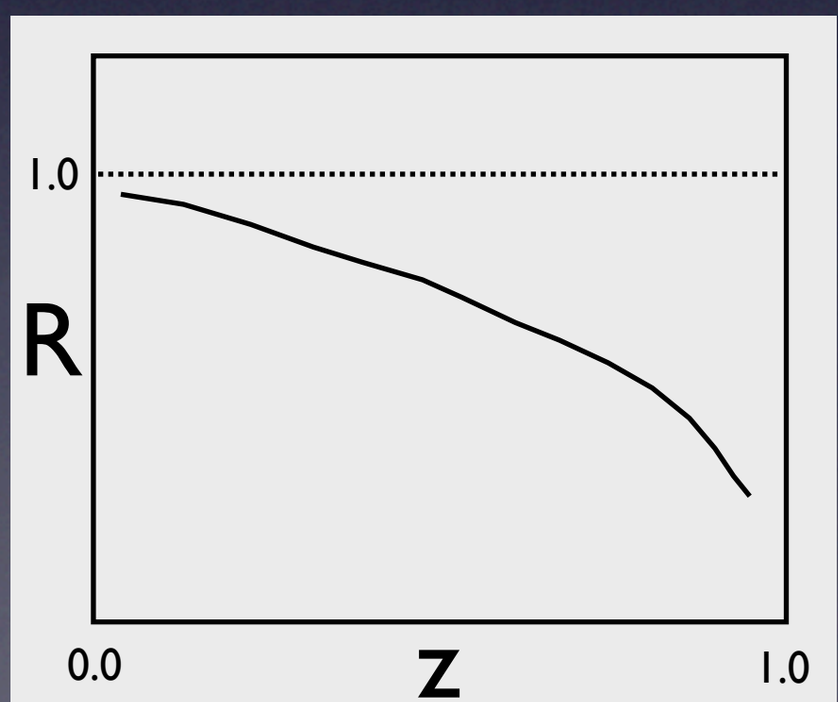
Measurements accessing this physics at EIC

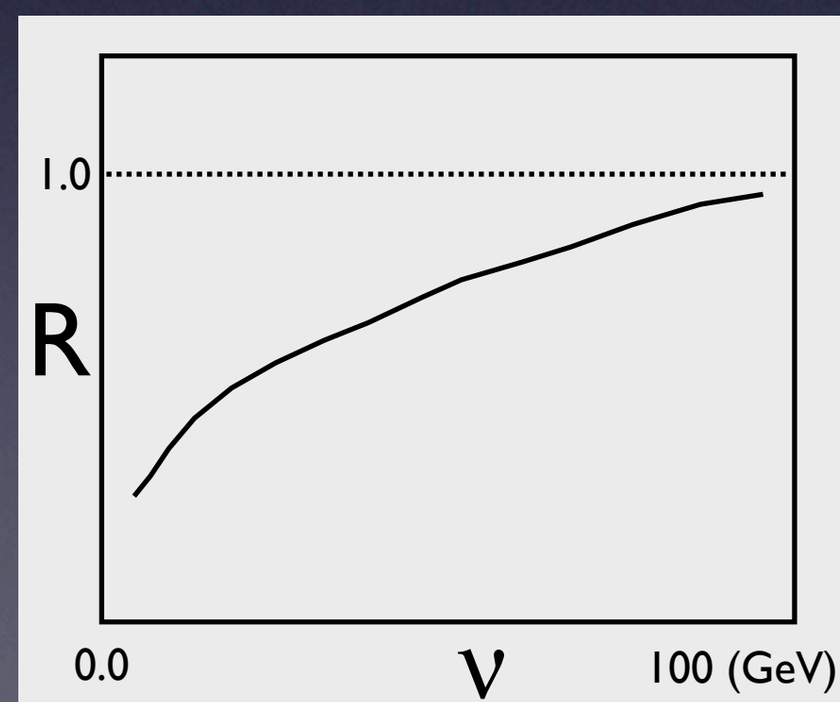
- **p_T broadening observable:**
  - saturation scale!!
  - effective quark lifetime/production time
  - transport coefficient
  - critical length? energy loss?
  - quark-gluon correlations (J. Qiu)
- **multiplicity ratio observable:**
  - hadron formation lengths
  - hadronization mechanisms

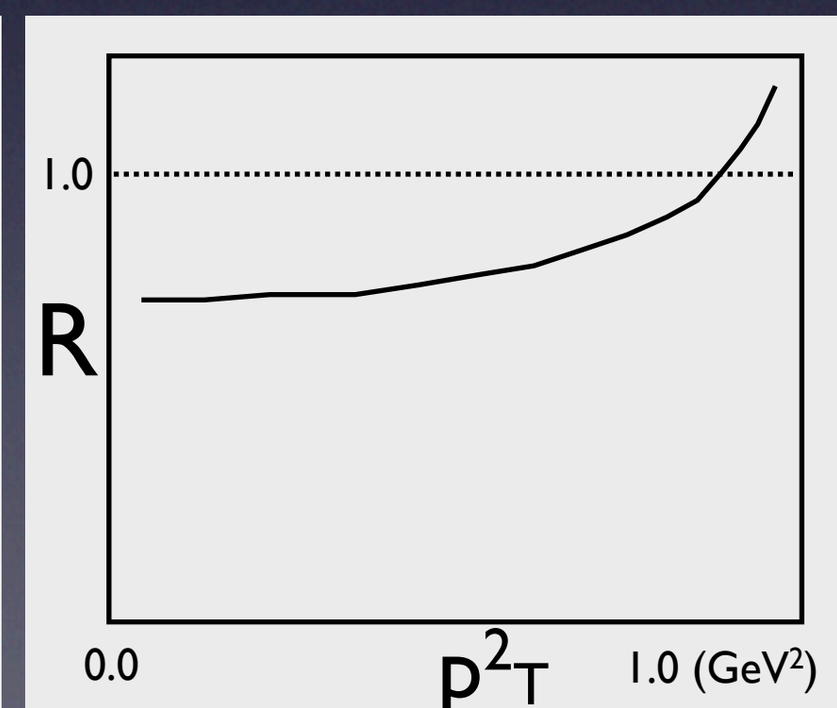
- **two-pion events:**
  - femptometer-scale measure of production region through Bose-Einstein/HBT correlations
  - multiplicity dependences
- **di-hadron multiplicity ratios:**
  - correlations within jet
  - hadronization mechanisms
- **associated photons**
  - gluon GPD? (Wang & Osborne; Majumder)
  - photon jet correlations
- **grey tracks** (C. Ciofi)

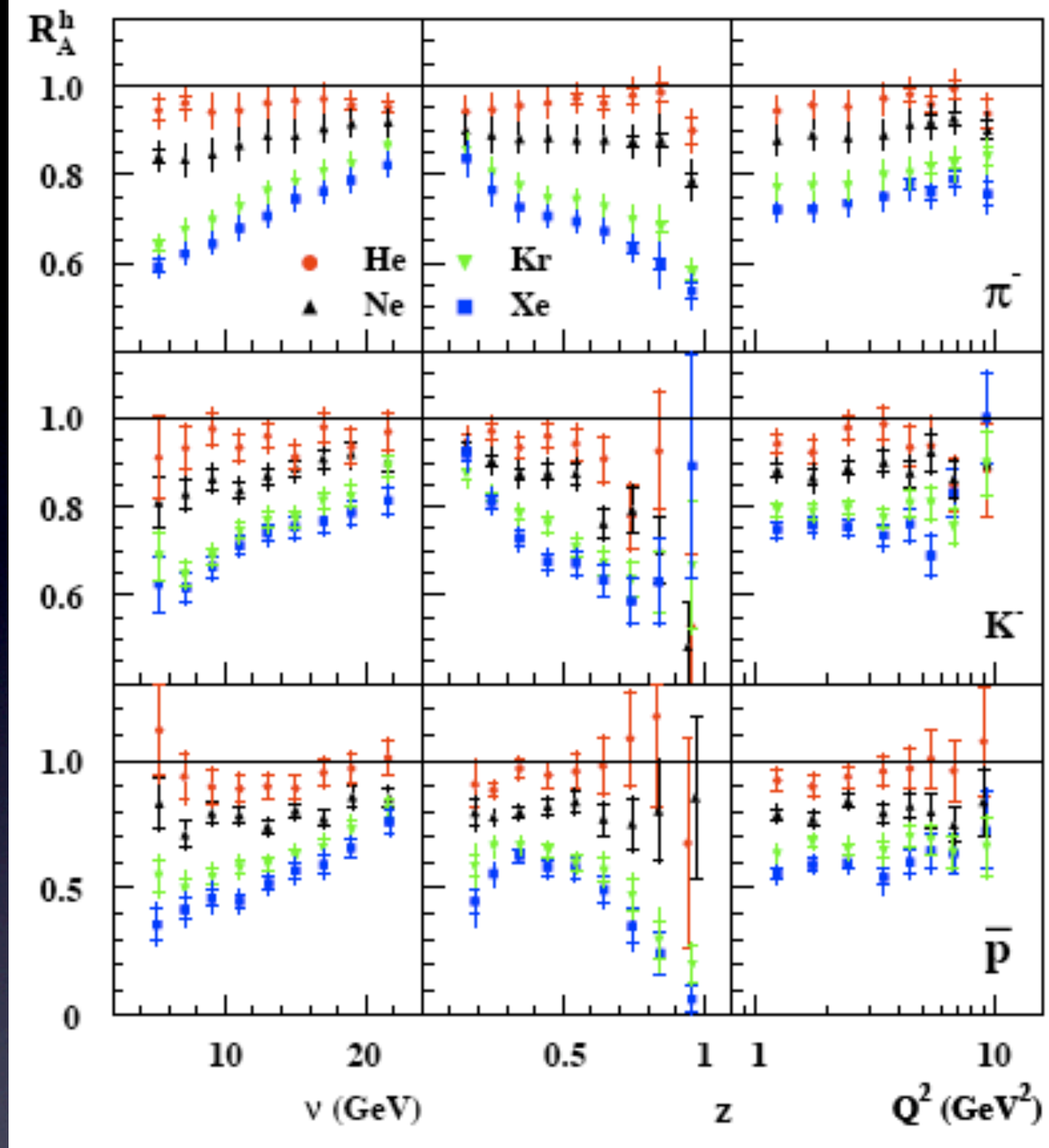
$$R_M^h(z,\nu,p_T^2,Q^2,\phi) = \frac{\left\{ \frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)} \right\}_A}{\left\{ \frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)} \right\}_D}$$

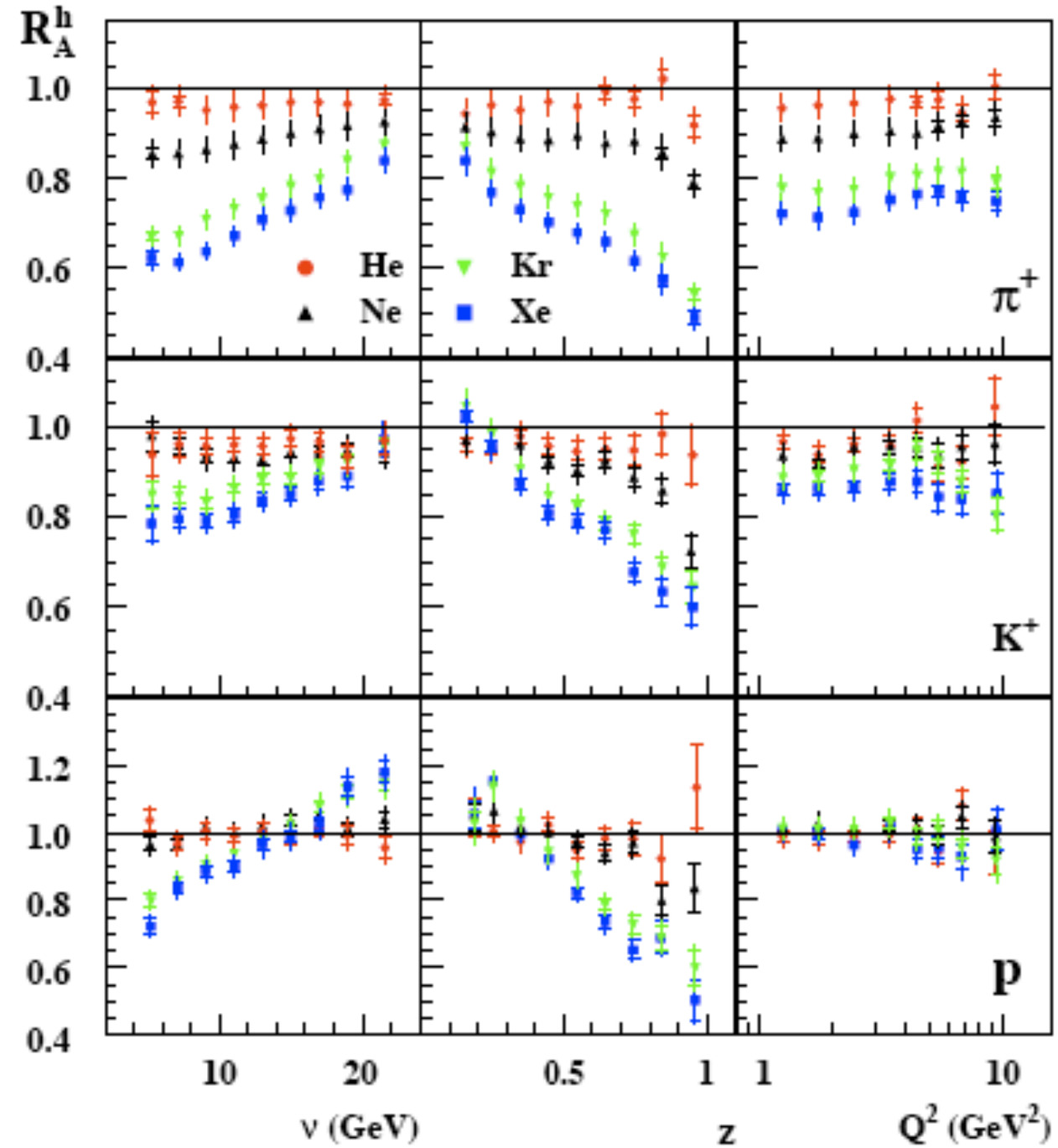
Hadronic multiplicity ratio











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

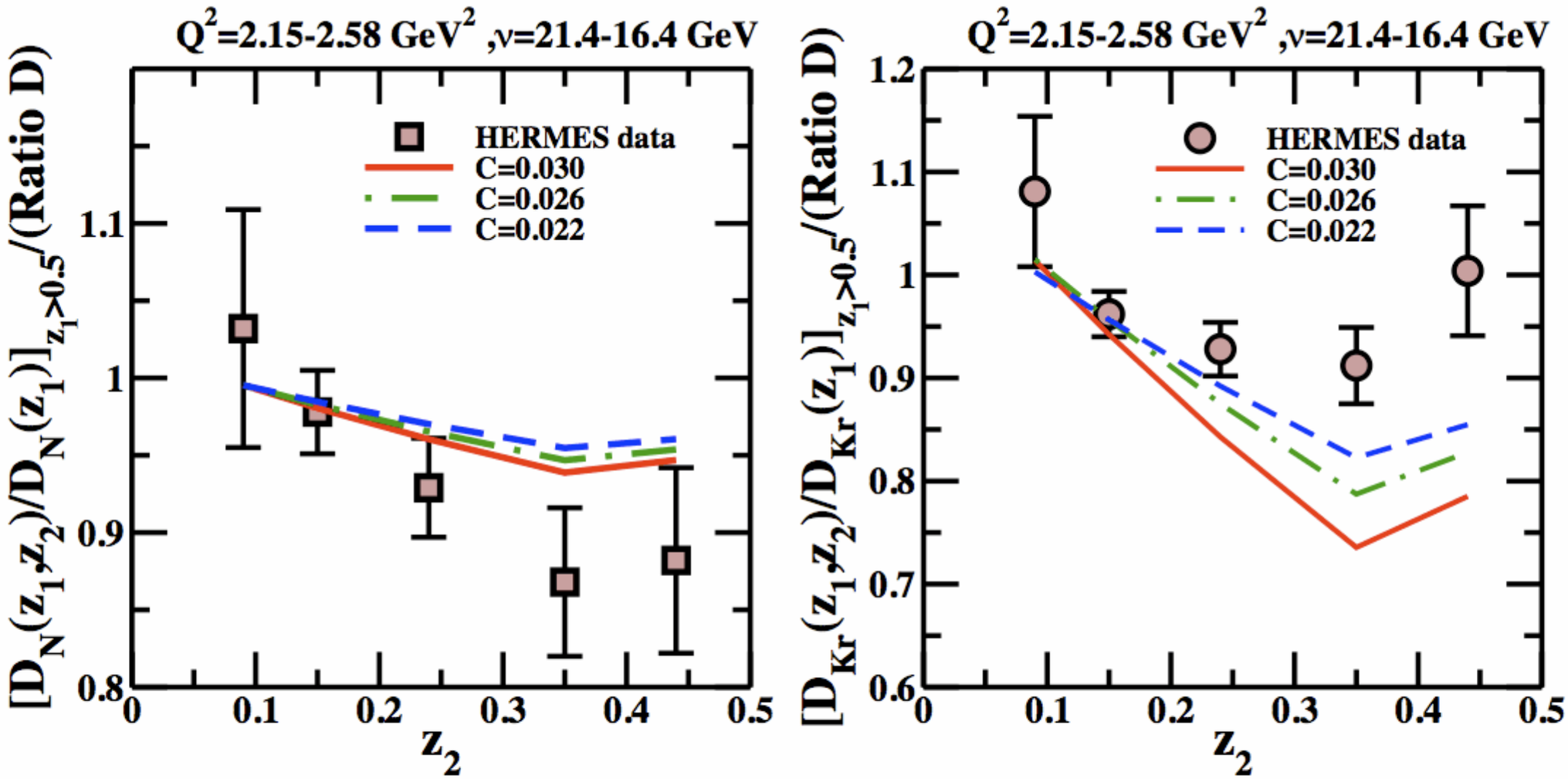
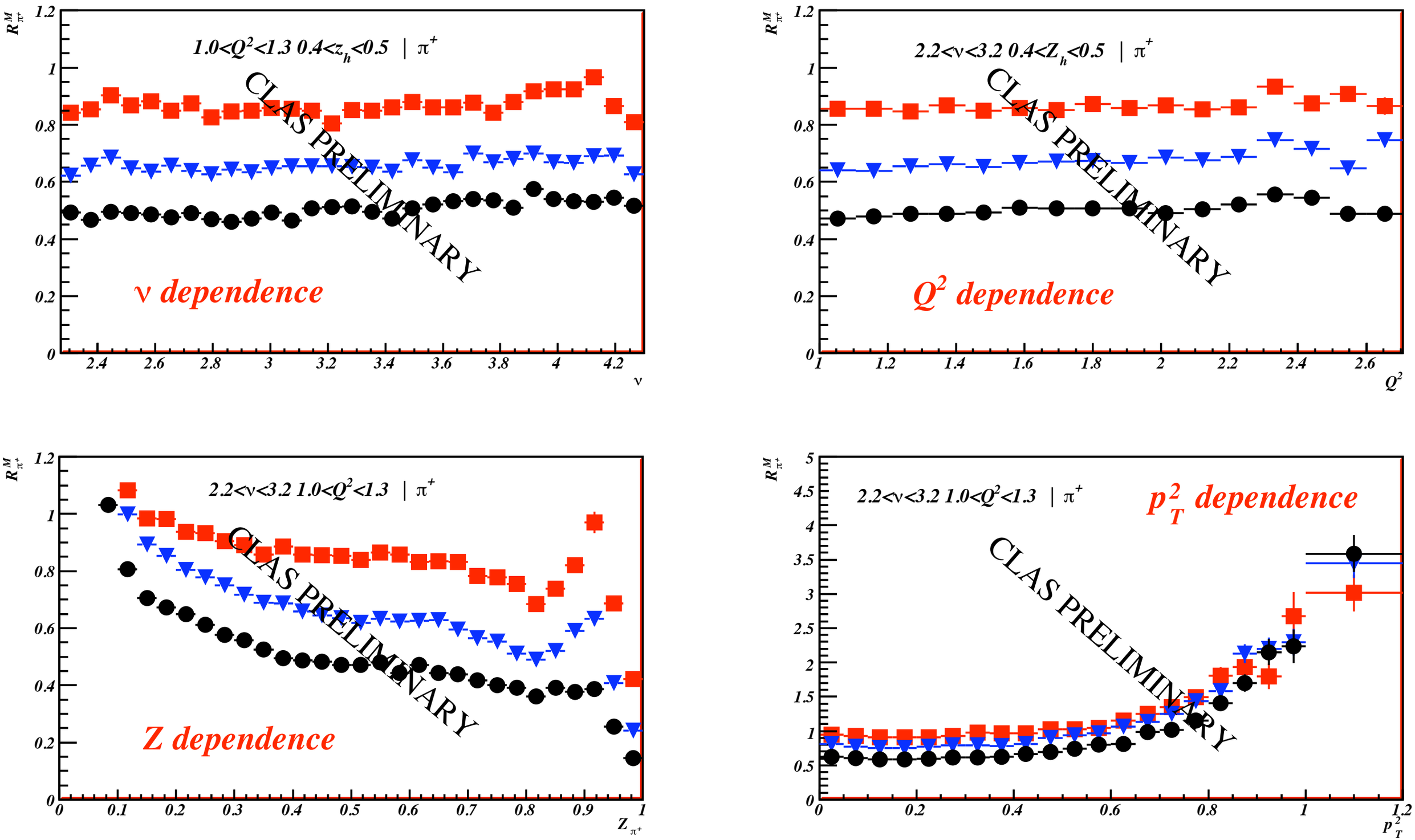


FIG. 9: Results of the medium modification of the quark fragmentation function in cold nuclear medium in a N and Kr nucleus versus the momentum fraction of the associated hadron. The momentum fraction of the trigger, is held above 0.5 and integrated over all allowed values. A hard-sphere distribution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

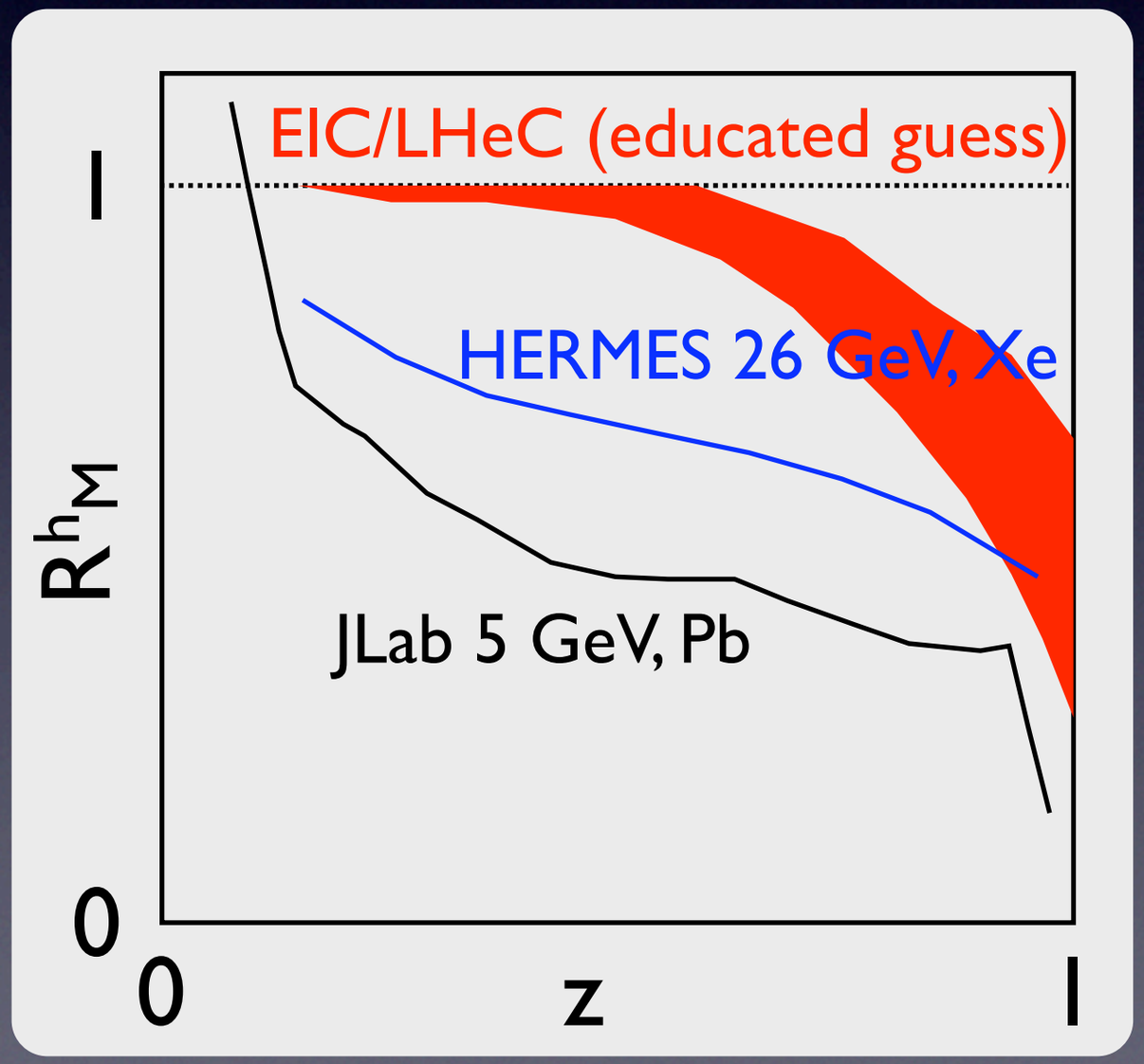


Four out of ~50 similar plots! K^0, π^-, π^0, η, Λ underway

CLAS12 Hadrons

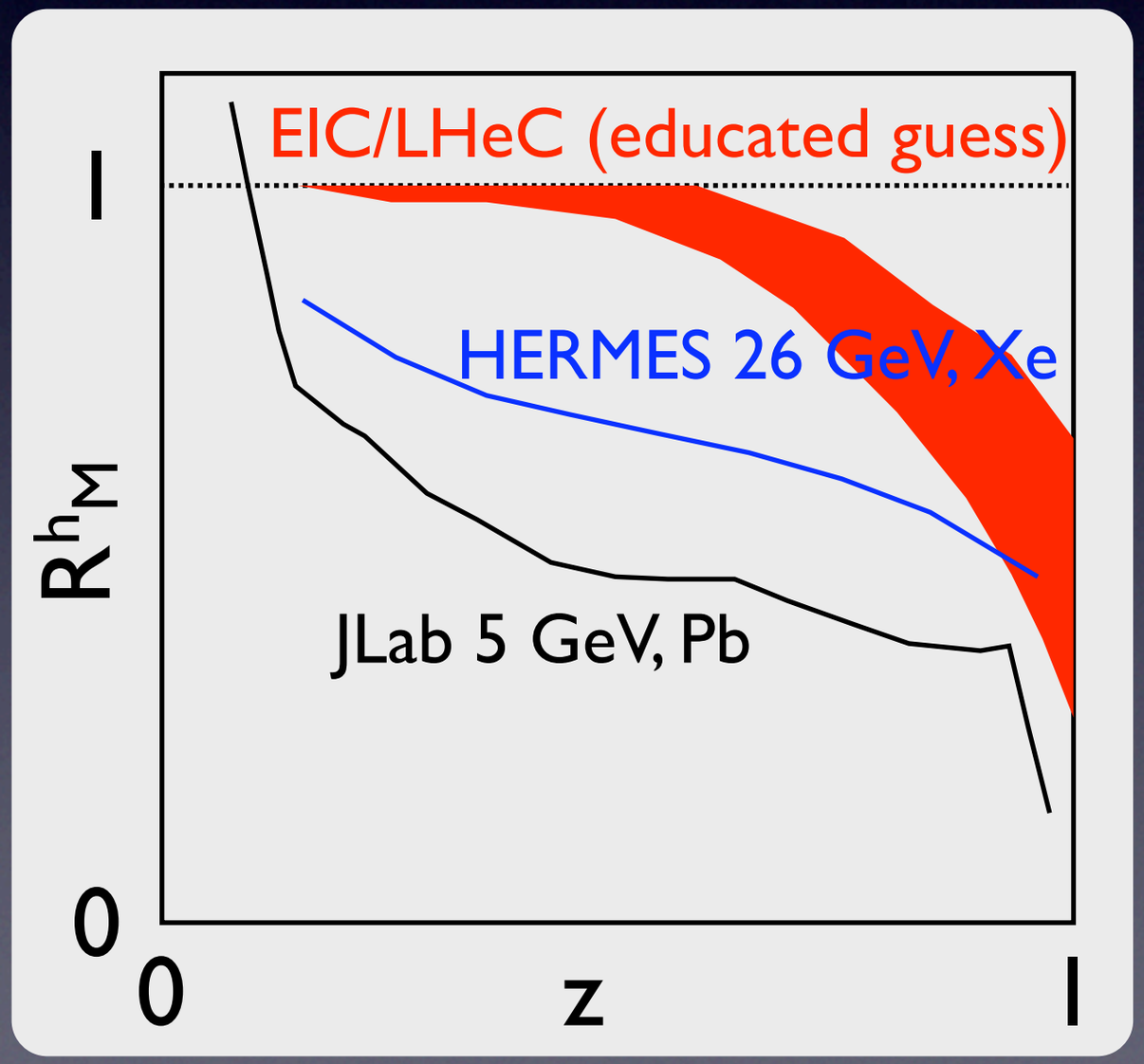
hadron	$c\tau$	mass (GeV)	flavor content	detection channel	Production rate per 1k DIS events
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	$\gamma\gamma$	1100
π^+	7.8 m	0.14	$u\bar{d}$	direct	1000
π^-	7.8 m	0.14	$d\bar{u}$	direct	1000
η	0.17 nm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	$\gamma\gamma$	120
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\pi^0$	170
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\eta$	27
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	K^+K^-	0.8
$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	$\pi\pi\pi\pi$	-
K^+	3.7 m	0.49	$u\bar{s}$	direct	75
K^-	3.7 m	0.49	$\bar{u}s$	direct	25
K^0	27 mm	0.50	$d\bar{s}$	$\pi^+\pi^-$	42
p	stable	0.94	ud	direct	530
$\bar{p}$	stable	0.94	$\bar{u}\bar{d}$	direct	3
Λ	79 mm	1.1	uds	$p\pi^-$	72
$\Lambda(1520)$	13 fm	1.5	uds	$p\pi^-$	-
Σ^+	24 mm	1.2	us	$p\pi^0$	6
Σ^0	22 pm	1.2	uds	$\Lambda\gamma$	11
Ξ^0	87 mm	1.3	us	$\Lambda\pi^0$	0.6
Ξ^-	49 mm	1.3	ds	$\Lambda\pi^-$	0.9

AT EIC/LHEC


EIC/LHeC (educated guess)
HERMES 26 GeV, Xe
JLab 5 GeV, Pb
R^h_M
1
0
0
z
1

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.



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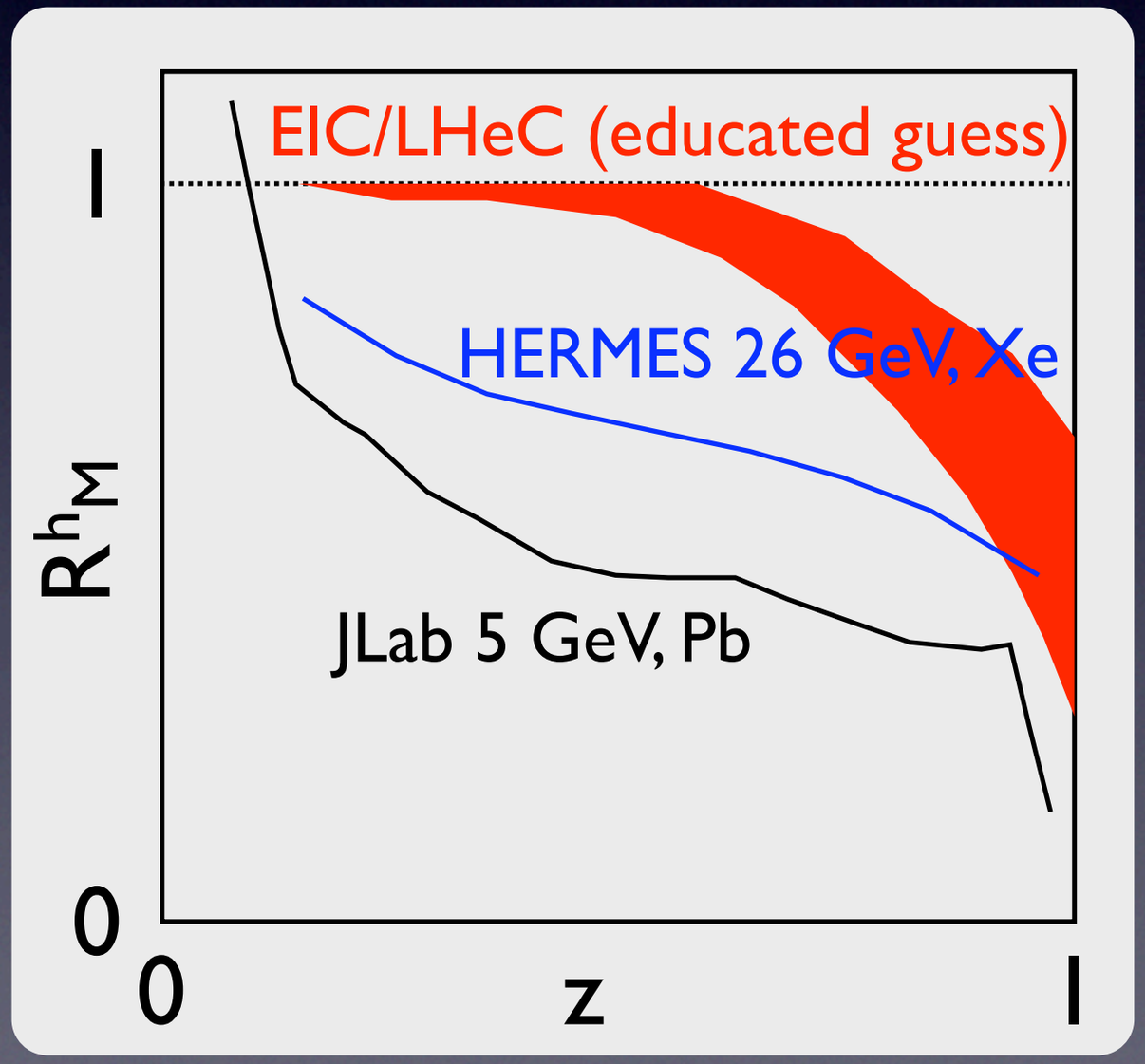

- Authors explain a variety of data within same picture - suppression of particle production in dA, pA at large x_F

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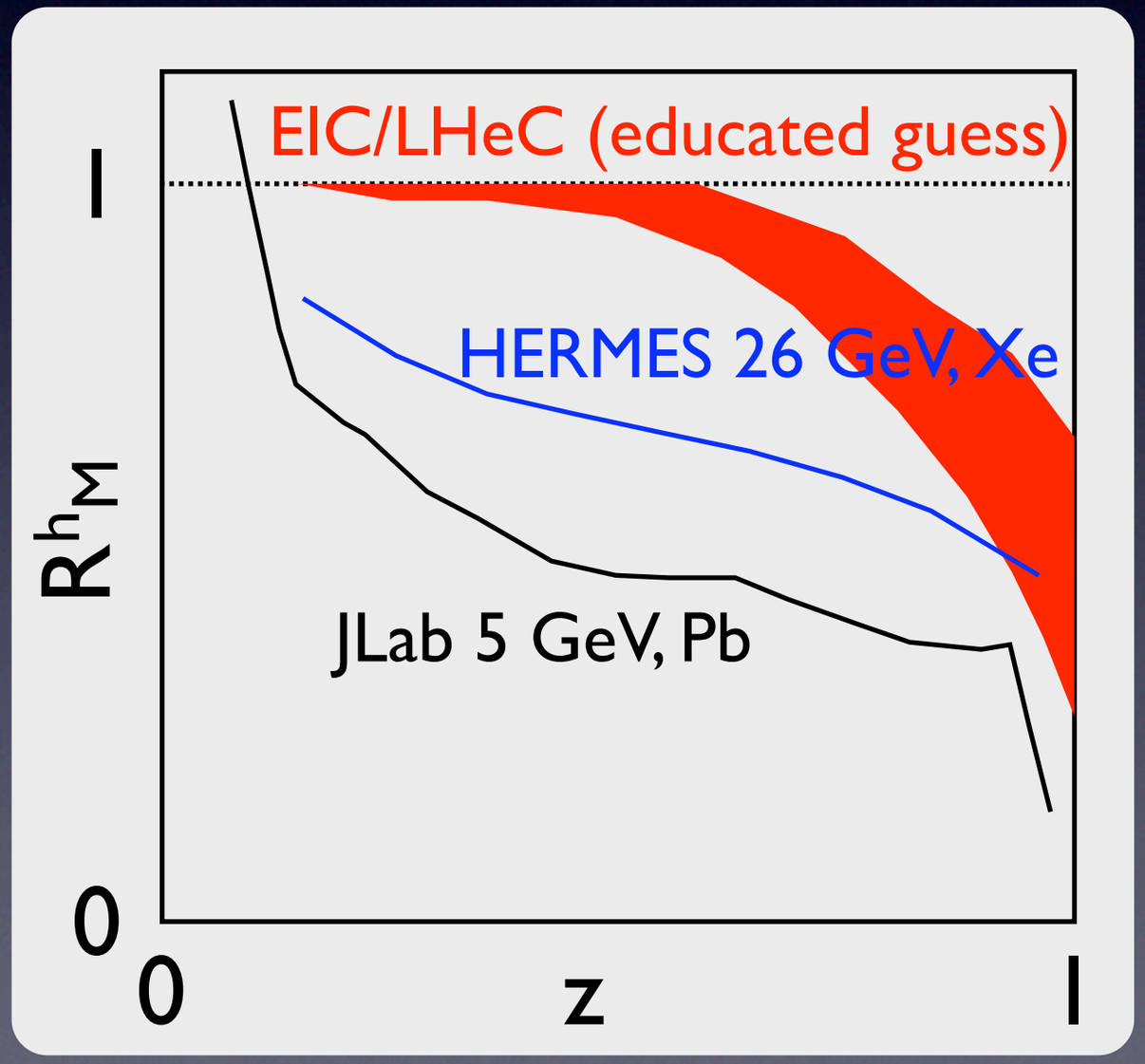
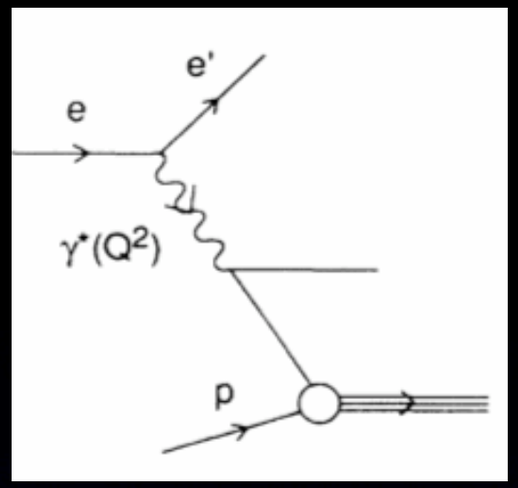


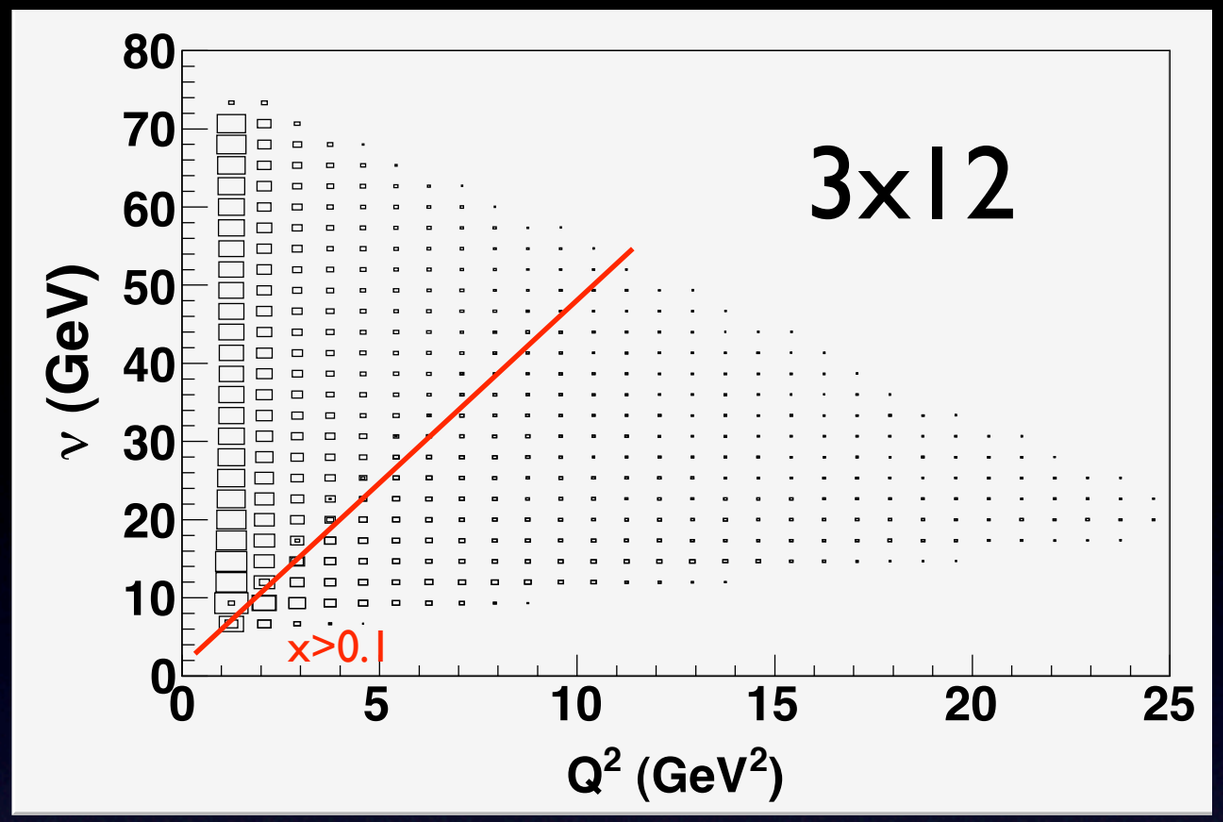
- Authors explain a variety of data within same picture - suppression of particle production in dA, pA at large x_F
- Explained alternatively as Sudakov suppression near kinematic limit, higher Fock state resolution from nucleus, or as an effective nonperturbative energy loss that rises linearly with energy

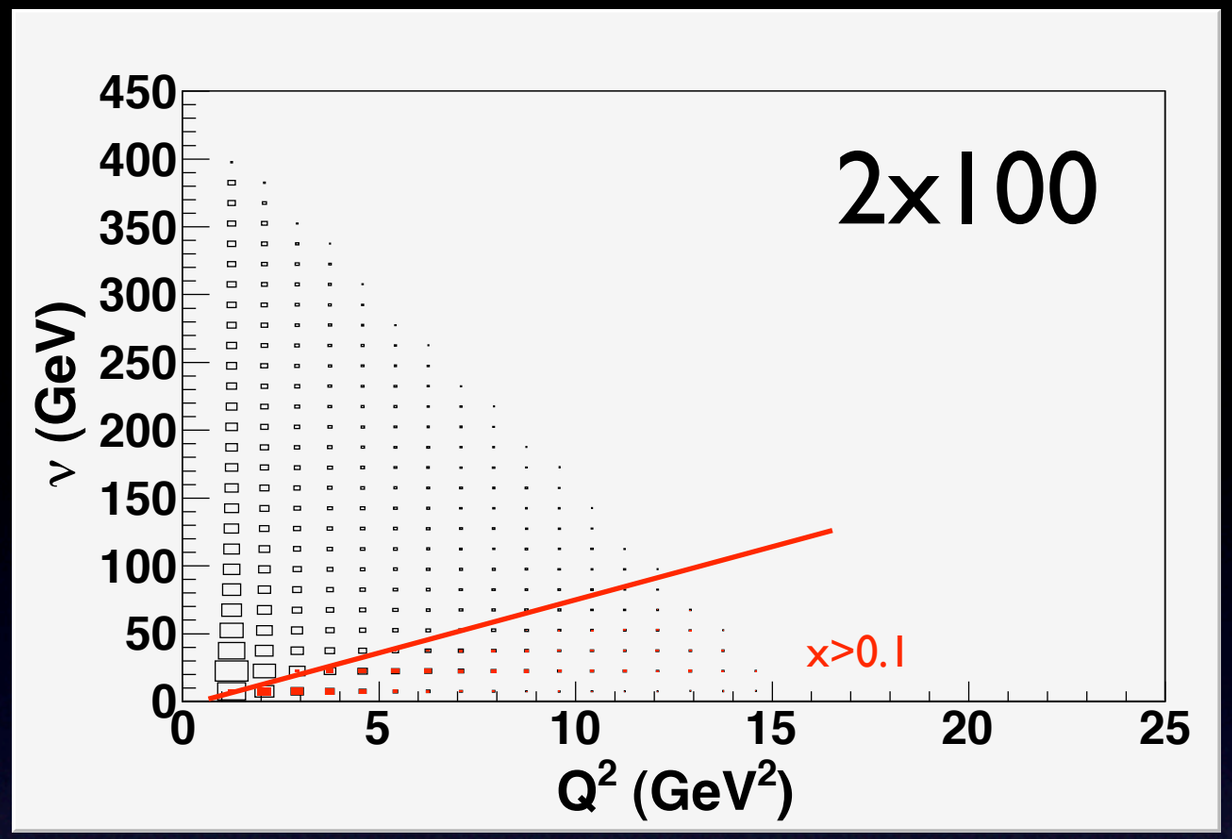
Complication: Quark Pair Production

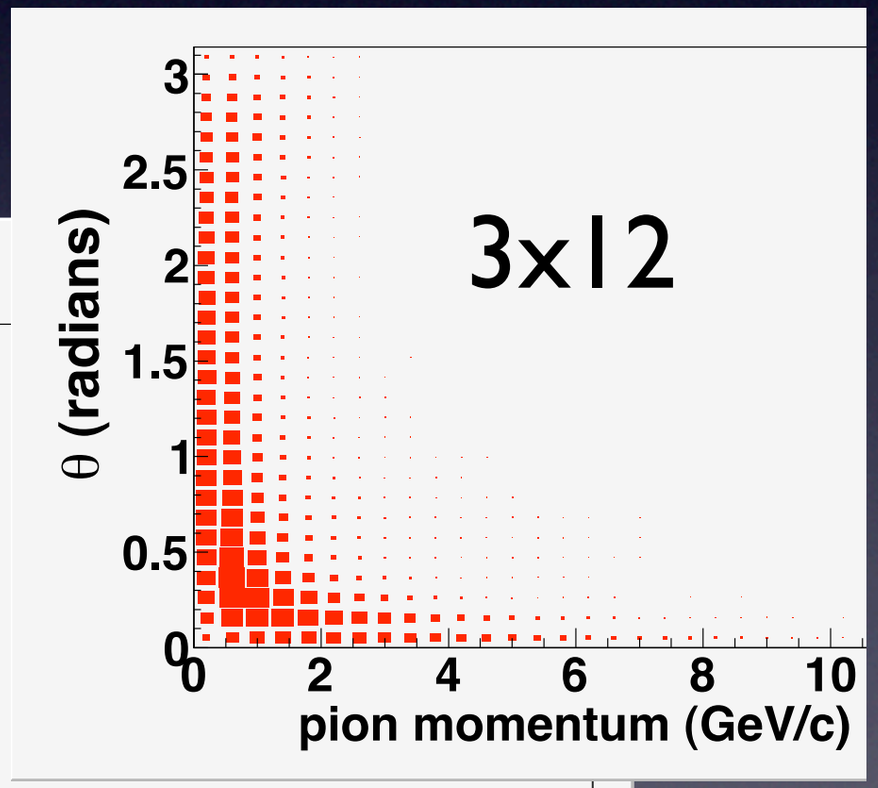


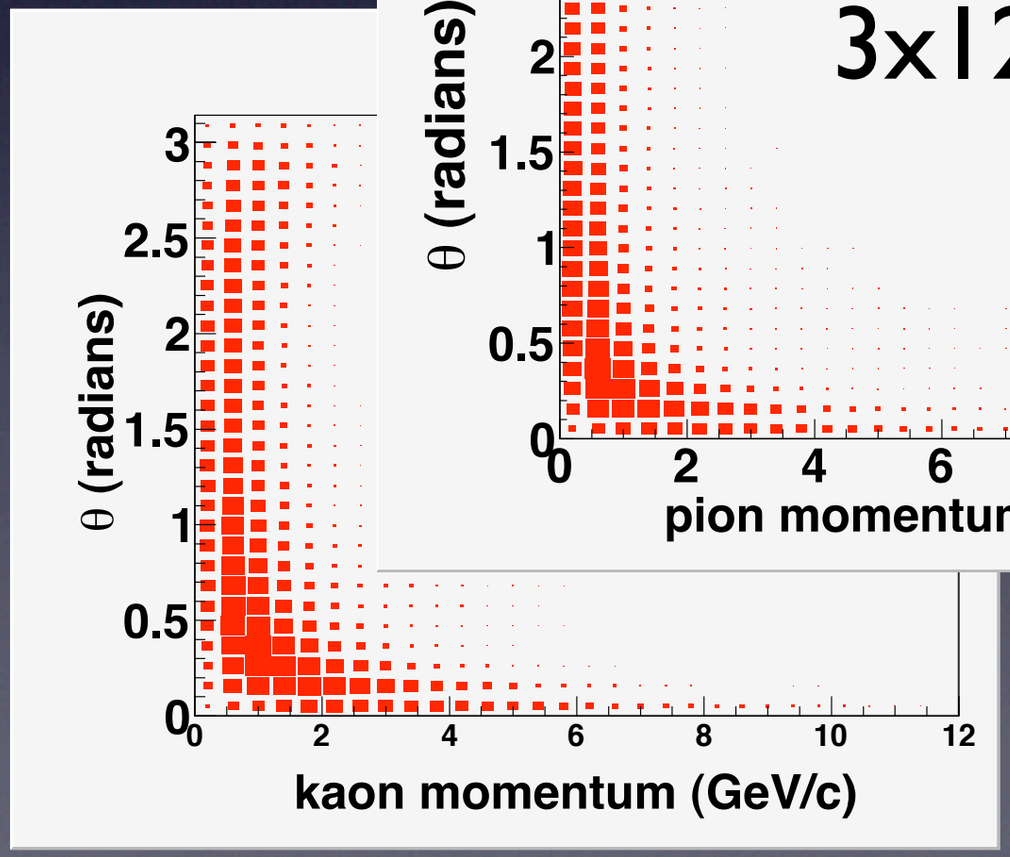
- Most natural analysis of data is in target rest frame:
  - Known wave functions, exchange currents, etc.
  - Properties not known in infinite momentum frame
- Process starts at x~0.1, dominates for low x, issue for EIC

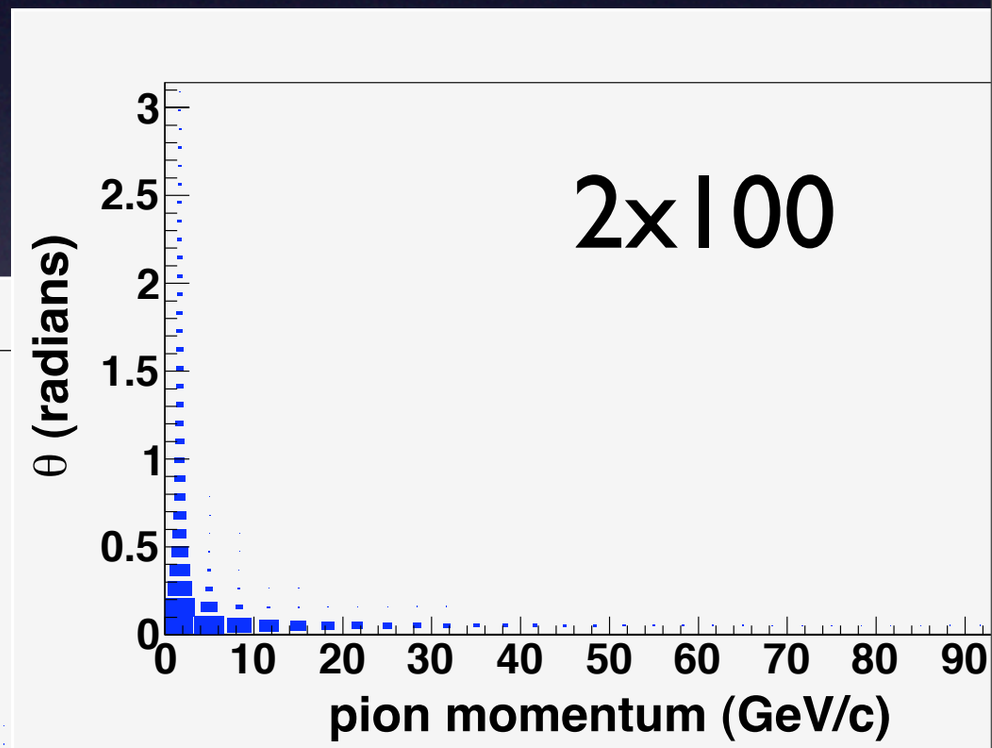
V. Del Duca, S. J. Brodsky, P. Hoyer, Phys. Rev. D46, 931 (1992)


3x12
x>0.1
ν (GeV)
Q² (GeV²)


2x100
x>0.1
ν (GeV)
Q² (GeV²)


3x12
θ (radians)
pion momentum (GeV/c)


θ (radians)
kaon momentum (GeV/c)


2x100
θ (radians)
pion momentum (GeV/c)

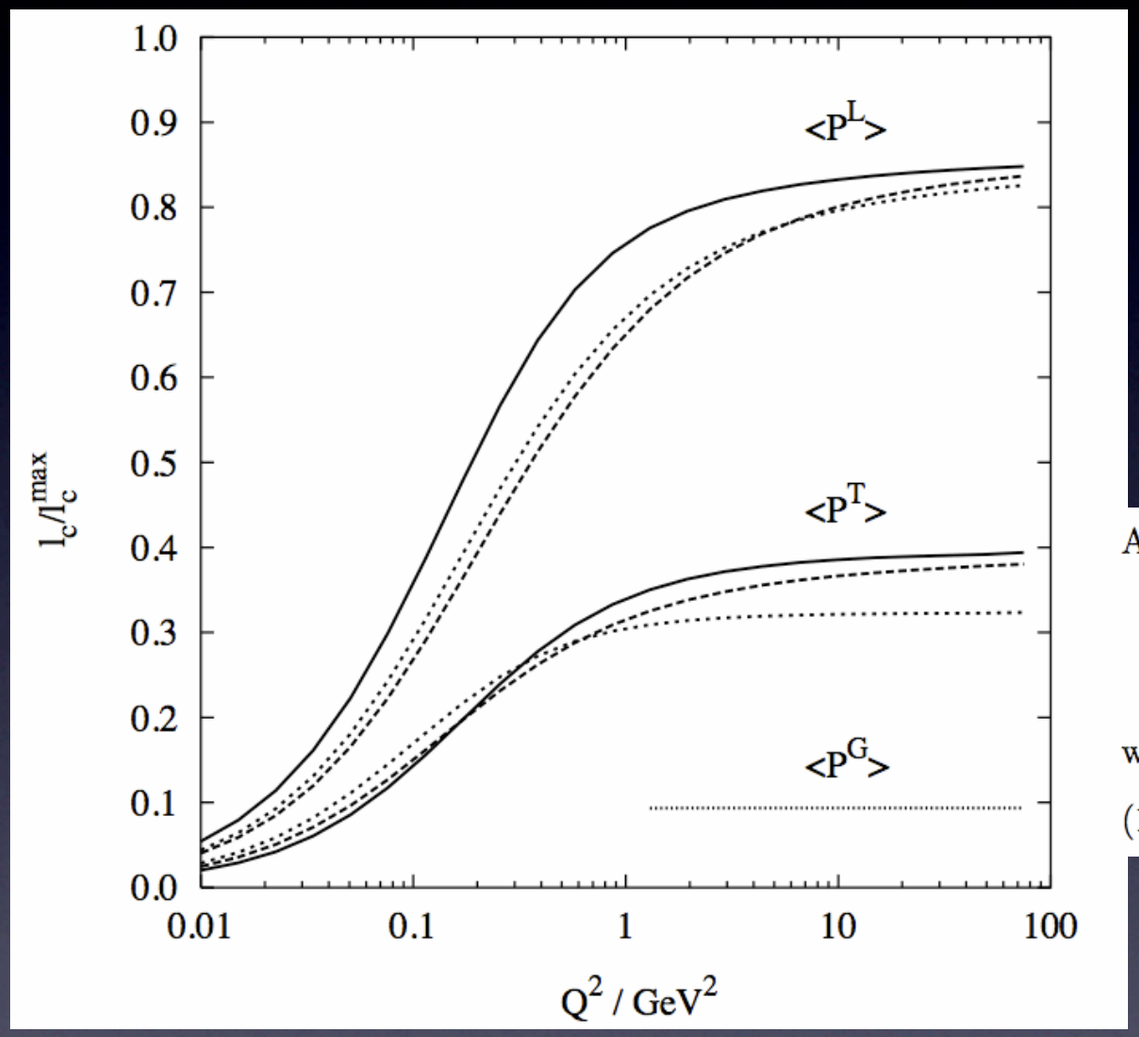
θ (radians)
kaon momentum (GeV/c)

Complication: Quark Pair Production

Two types of problems:

- Have $q\bar{q}$ pair instead of single propagating quark of known energy ν
  - Measure *both* jets, or else have an error in calculation of z
- Pair can fluctuate into existence before entering the nucleus, or within the nucleus
  - "Ioffe time" ~ $1/(x_{Bj} M_p)$ (up to 100+ fm for EIC)
  - → Path length in nucleus varies

Complication: Quark Pair Production



- Detailed calculation of coherence time exists, can make correction

A photon of virtuality Q^2 and energy ν can develop a hadronic fluctuation for a lifetime,

$$l_c = \frac{2\,\nu}{Q^2 + M^2} = \frac{P}{x_{Bj}\, m_N} = P\, l_c^{max} \ , \qquad (1)$$

where Bjorken $x_{Bj} = Q^2/2m_N\nu$, M is the effective mass of the fluctuation, factor $P = (1+M^2/Q^2)^{-1}$, and $l_c^{max} = 1/m_N x_{Bj}$. The usual approximation is to assume that $M^2 \approx Q^2$

B. Z. Kopeliovich, J. Raufeisen and A.V. Tarasov,
"Nuclear shadowing and coherence length for longitudinal and transverse photons,"
Phys. Rev. C **62**, 035204 (2000) [arXiv:hep-ph/0003136].

Conclusions

- **EIC can access all of this physics!**
  - saturation scale
  - transport coefficient
  - energy loss
  - hadron formation lengths
  - hadronization mechanisms/jet correlations
  - Bose-Einstein correlations/HBT
  - gluon GPD