Semi-Inclusive eA Scattering and Final State Interactions

LHeC Workshop 2009
Divonne, France

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Outline

- Introduction
- Physical pictures
- Parton propagation: p_T broadening
- Hadron formation: multiplicity ratios
- Future prospects

Introduction

- Goal: study space-time properties of QCD
    - in vacuum, in medium
- Use nuclei as spatial filters with known properties:
    - size, density, interactions
- *Unique kinematic window* at low energies
- *Simpler physical picture* at high energies?

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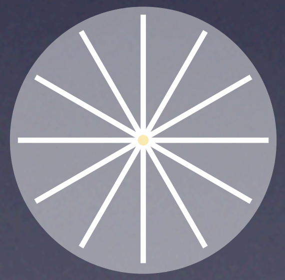

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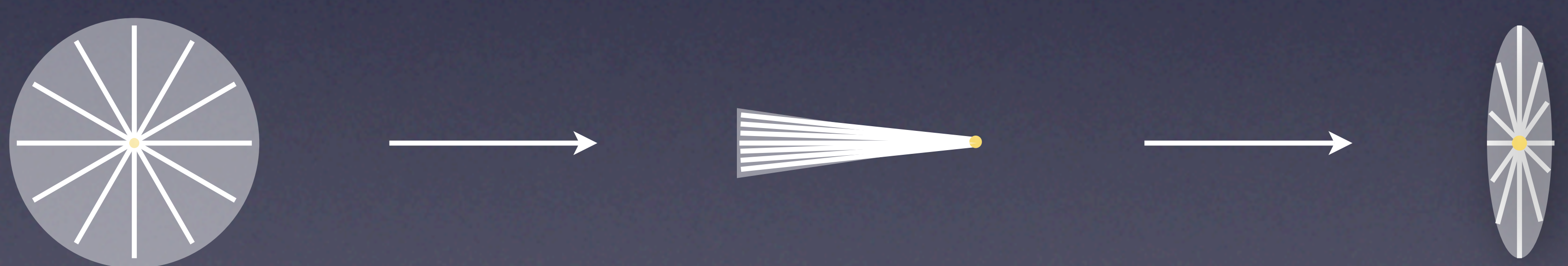

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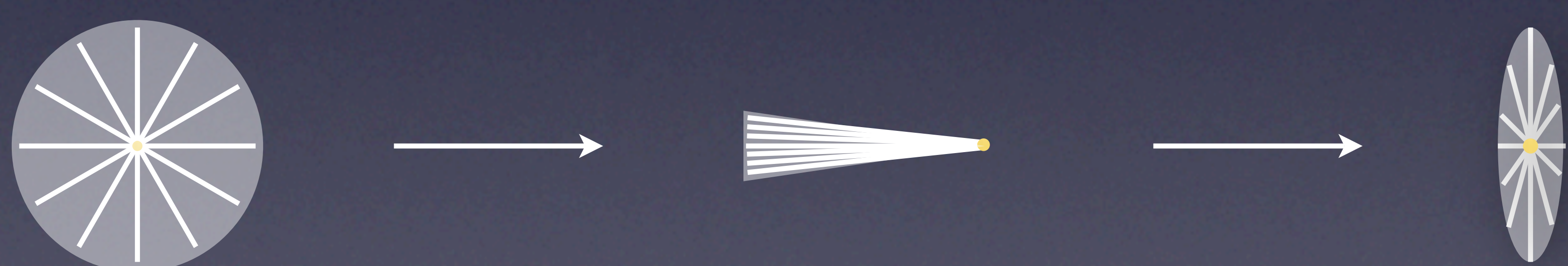


QCD equivalent:

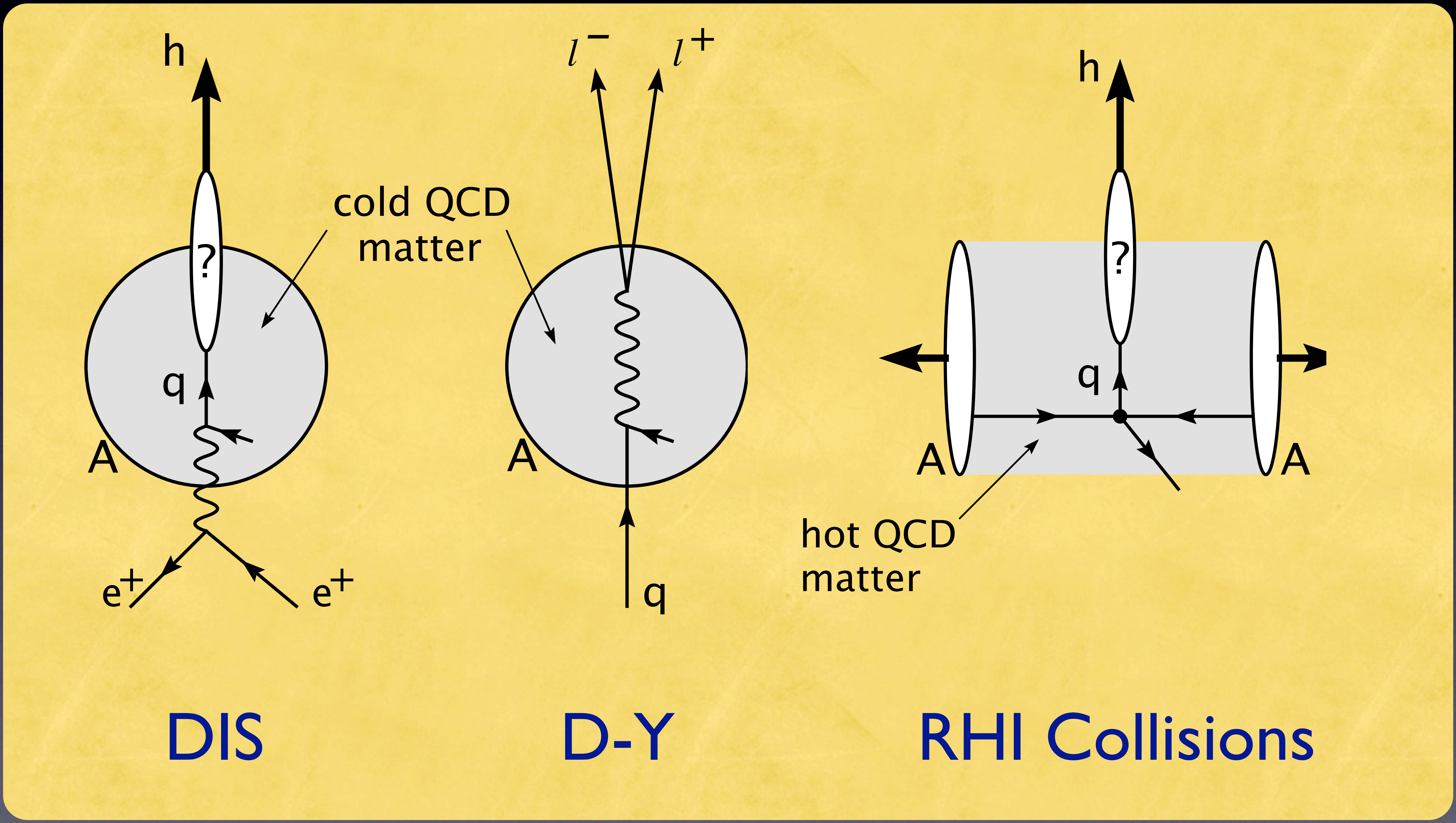
- $T_{restoration} \sim E_q{*}R^2 \sim$ ***2.3 fm/GeV * E_q***

At ***HIGH ENERGIES***:

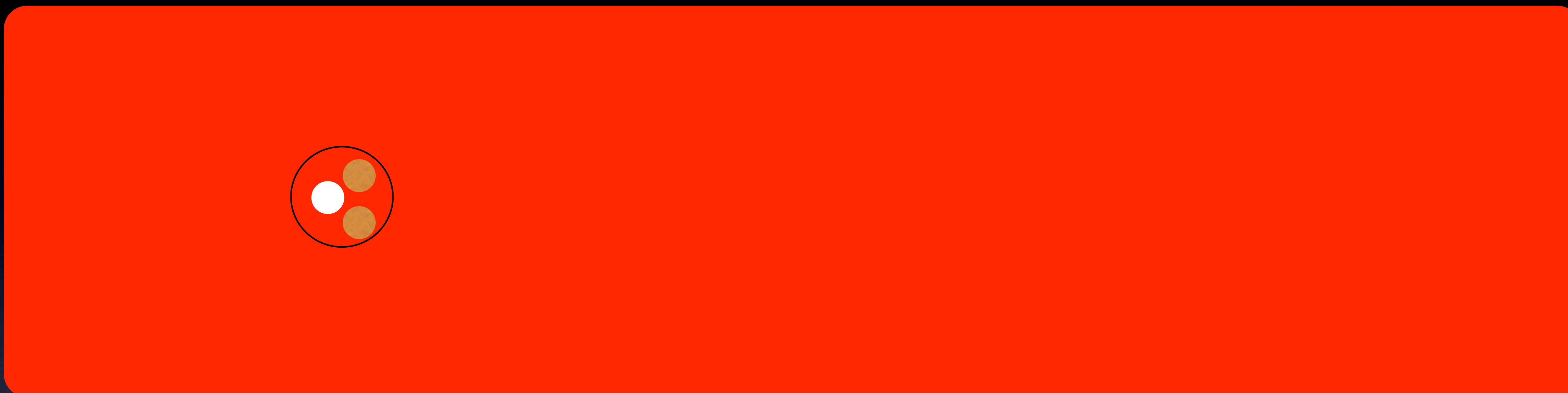
- Test the predicted universal breakdown of QCD factorization at large Feynman *x*
- Expect perturbative energy loss to be purely proportional to path length squared
- Expect increase in jet broadening and quark energy loss
- Quark pair production for x<0.1 complicates analysis
  V. Del Duca, S. J. Brodsky, P. Hoyer, Phys. Rev. D46, 931 (1992)

Physical Pictures

Comparison of Parton Propagation in Three Processes



Deep Inelastic Scattering - Vacuum



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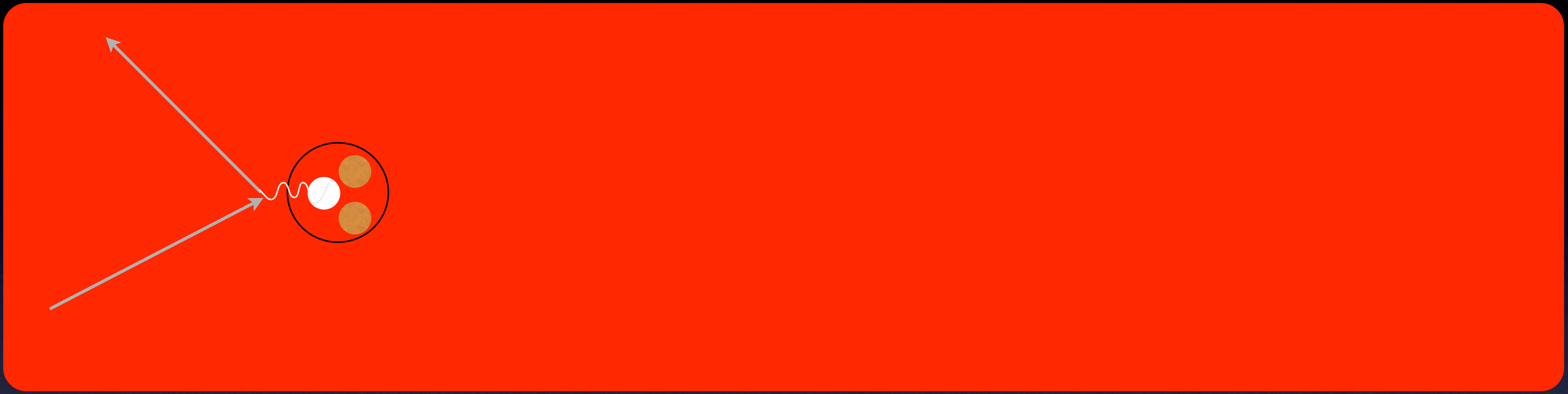

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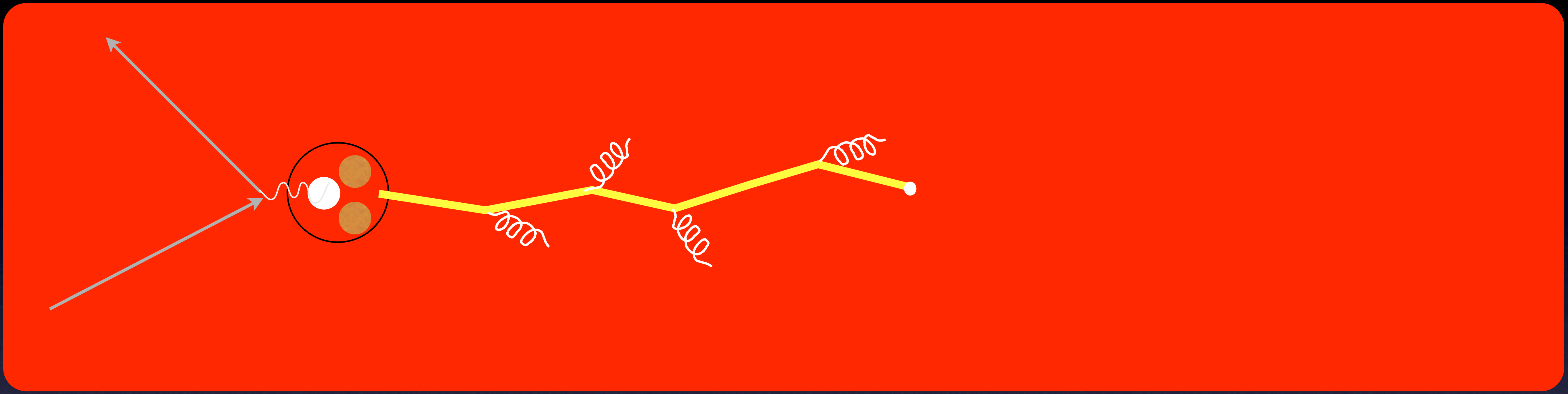

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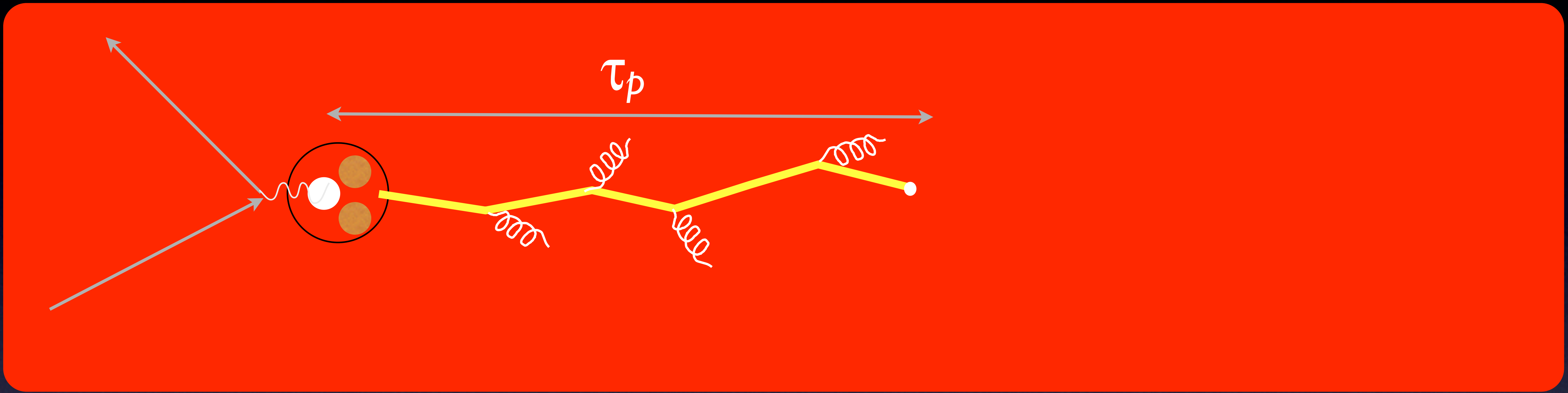

- <u>*production time* τ_p</u> - propagating quark

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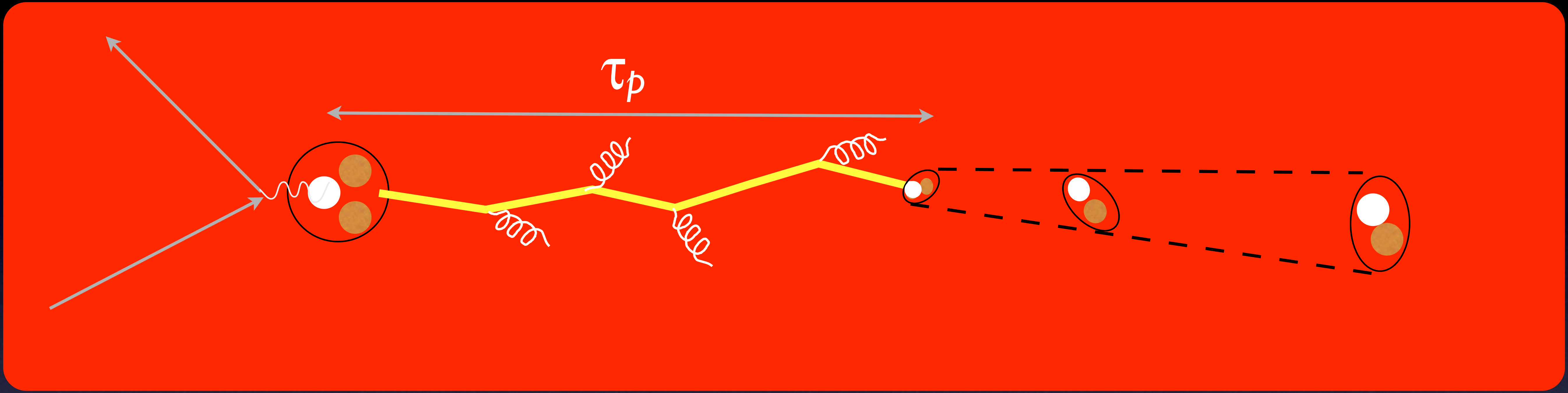

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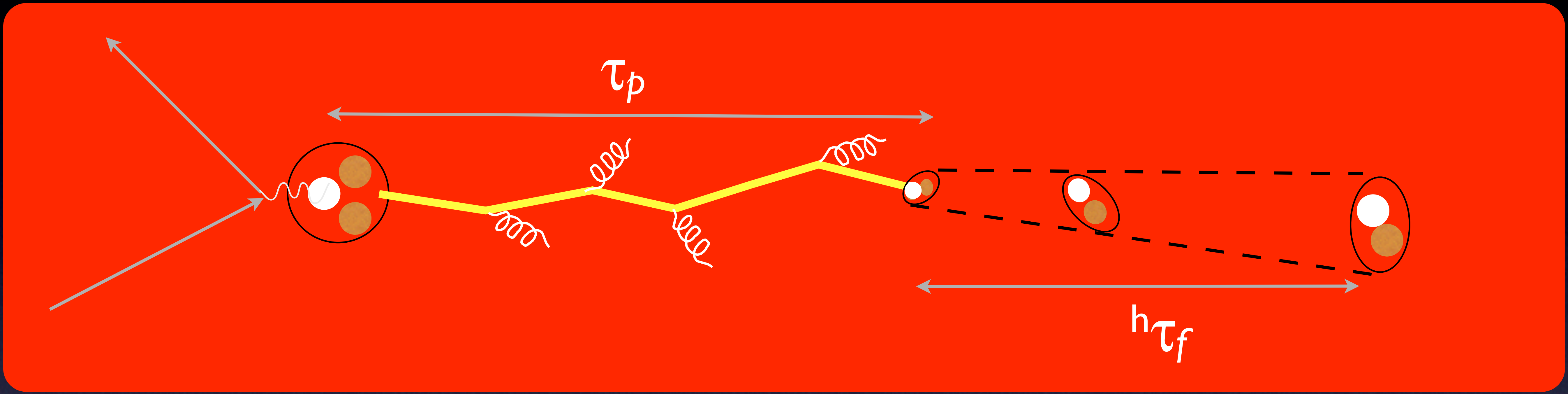
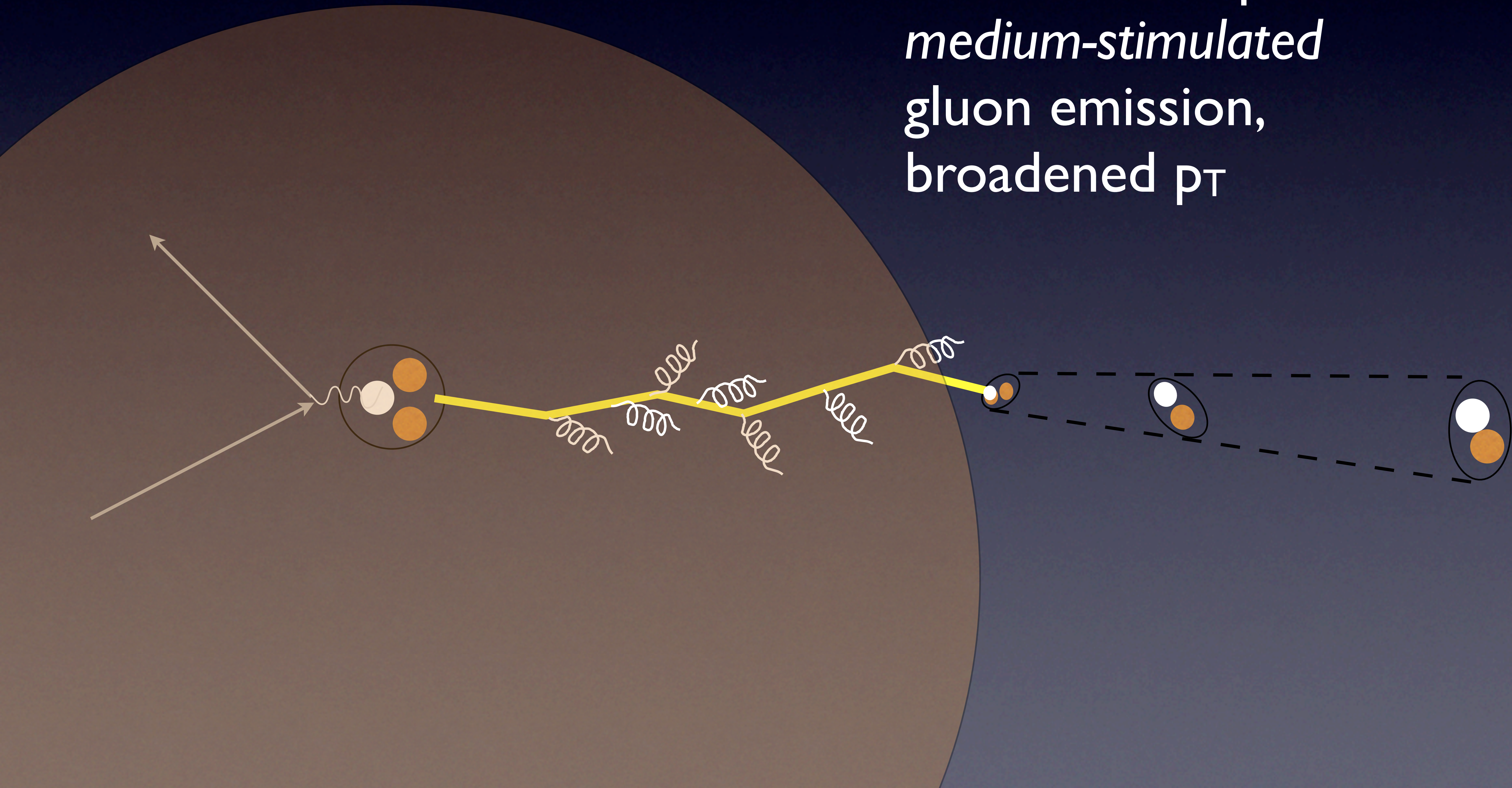


- *production time* τ_p - propagating quark
- *formation time* $^h\tau_f$ - dipole grows to hadron

Low-Energy DIS in Cold Nuclear Medium

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



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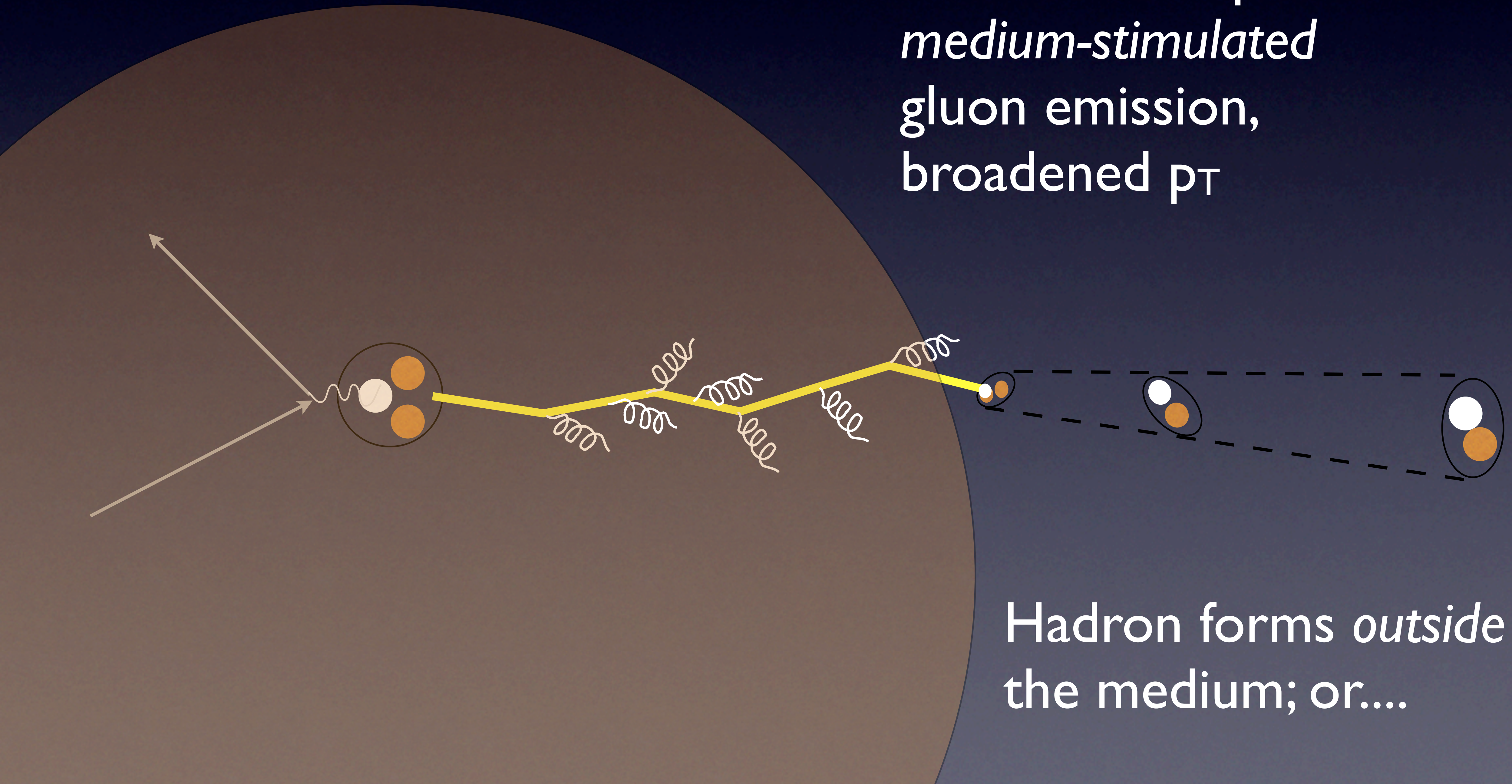
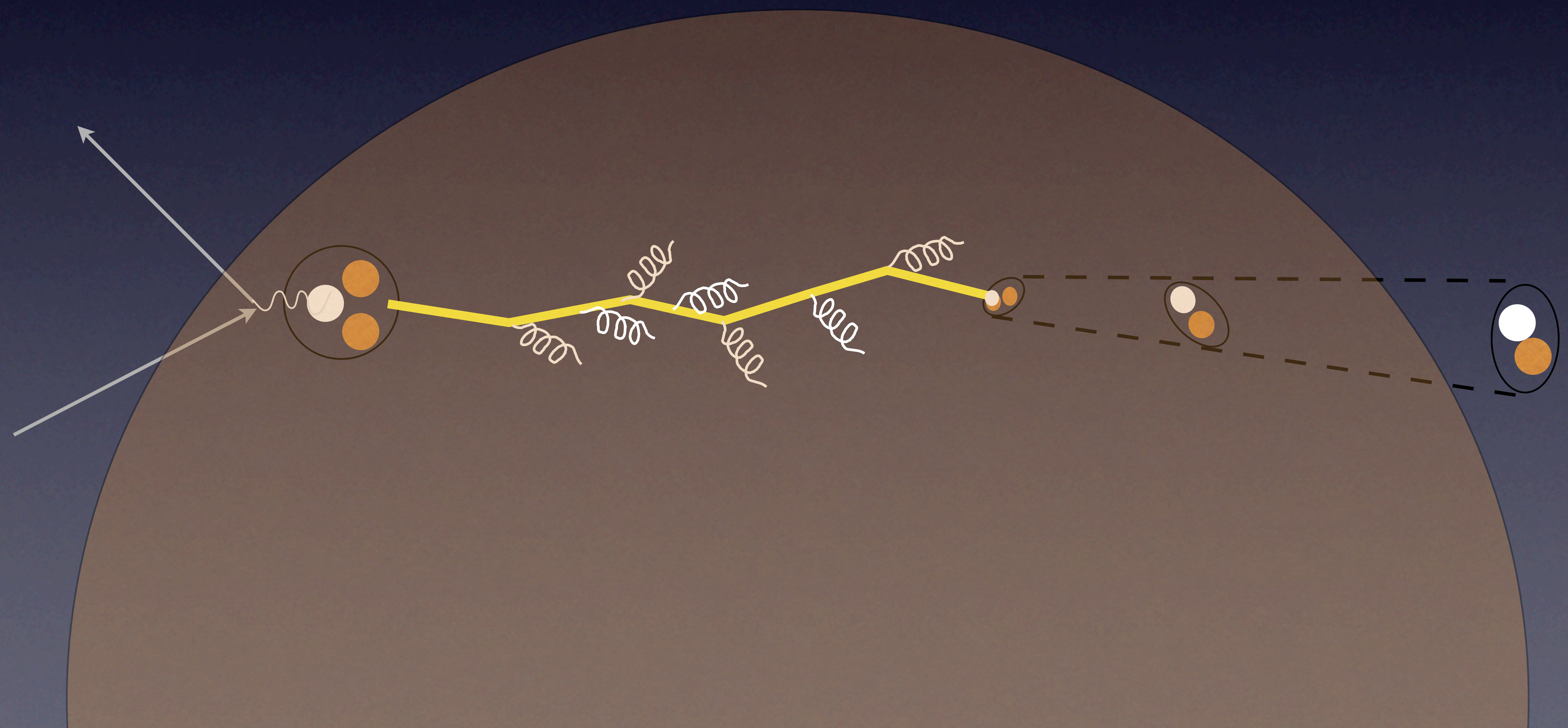


Hadron forms *outside*
the medium; or....

Low-Energy DIS in Cold Nuclear Medium

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



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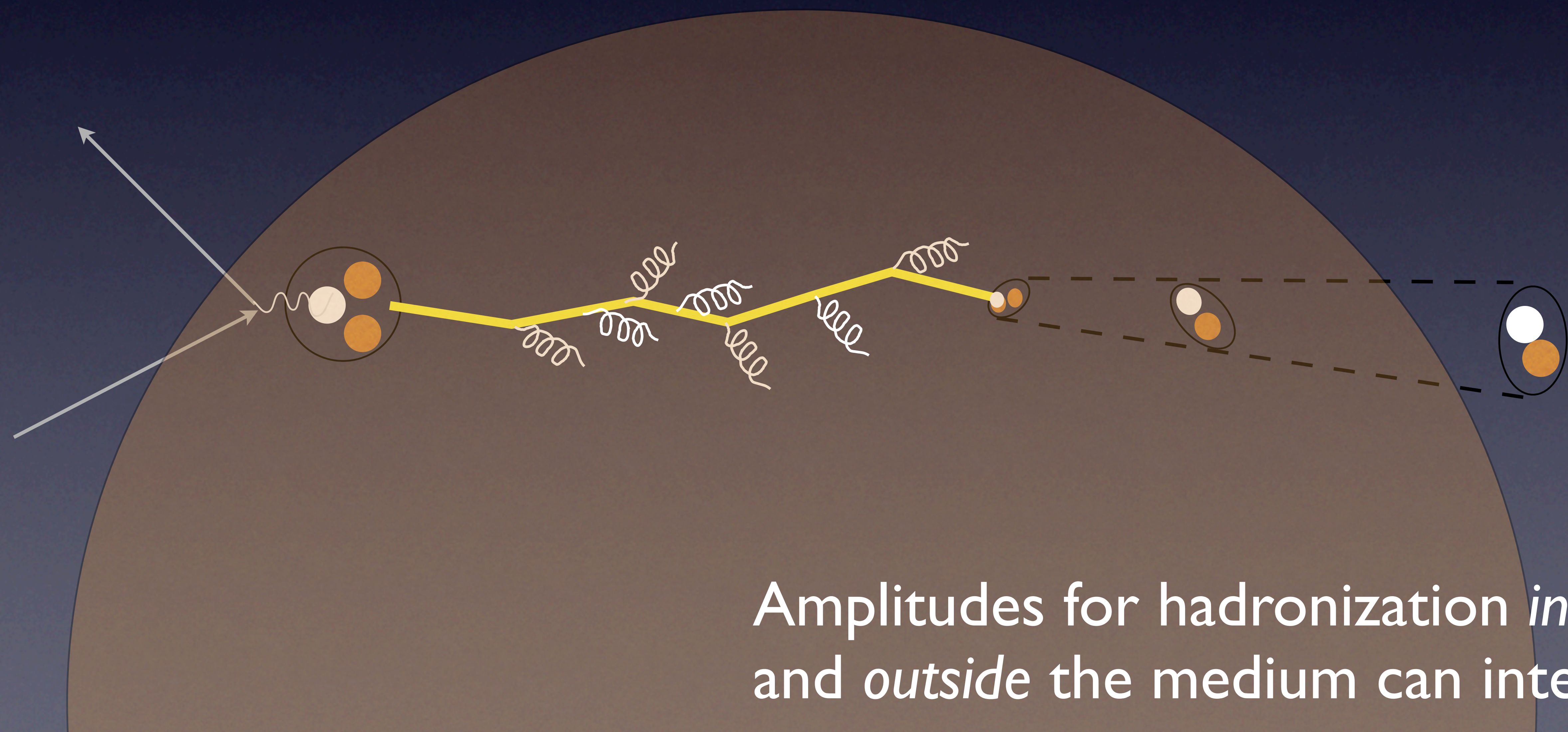

Amplitudes for hadronization *inside* and *outside* the medium can interfere

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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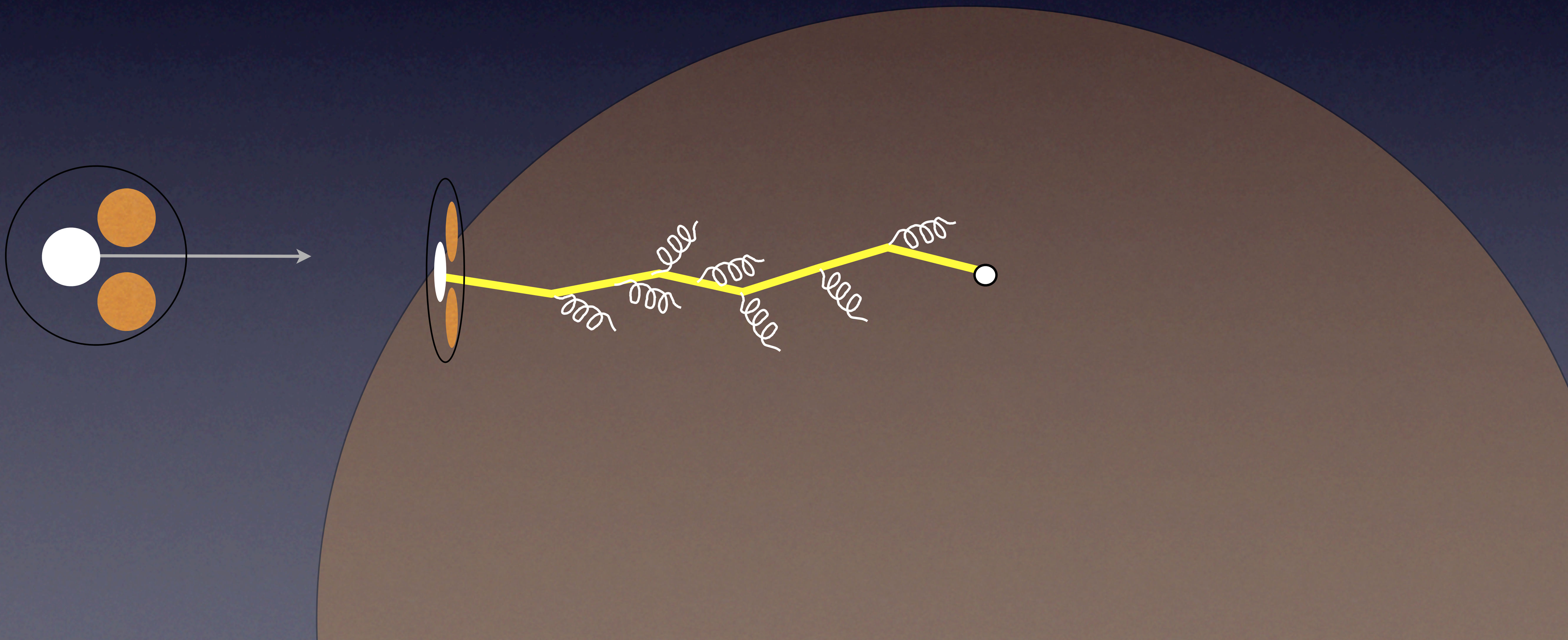

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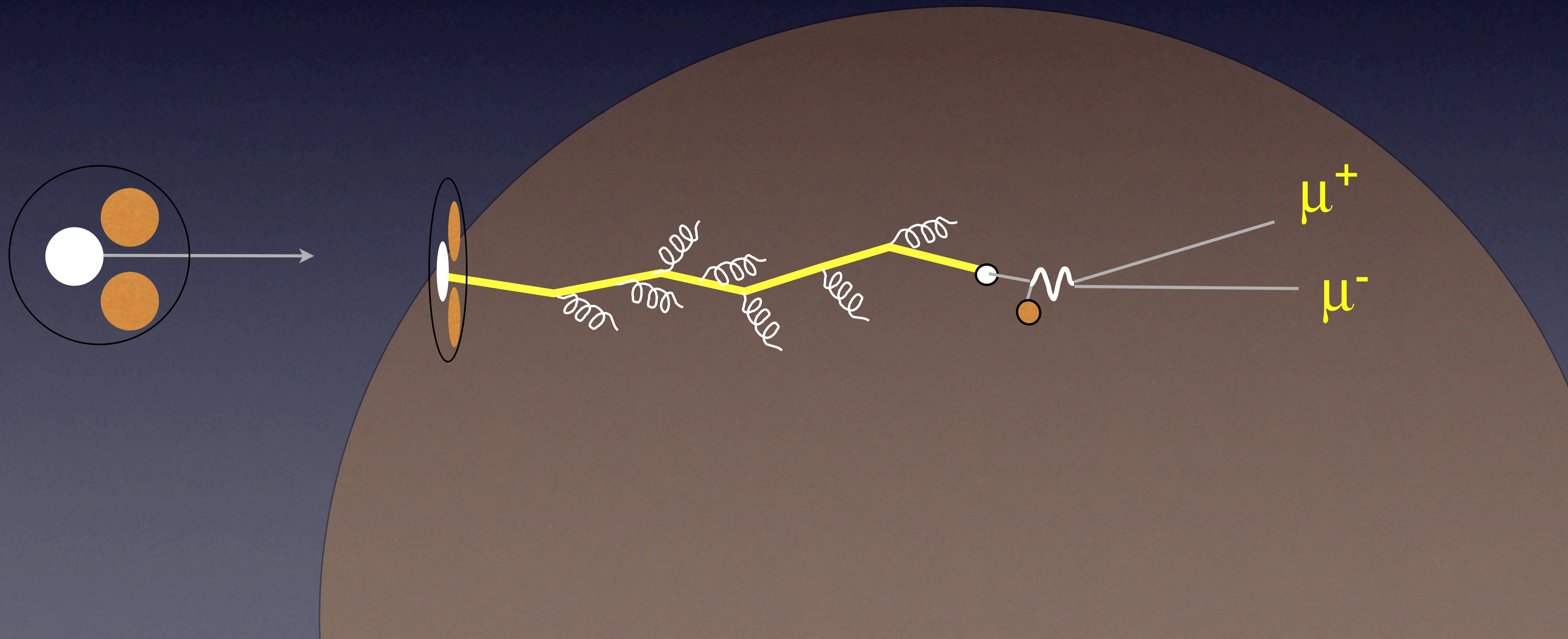
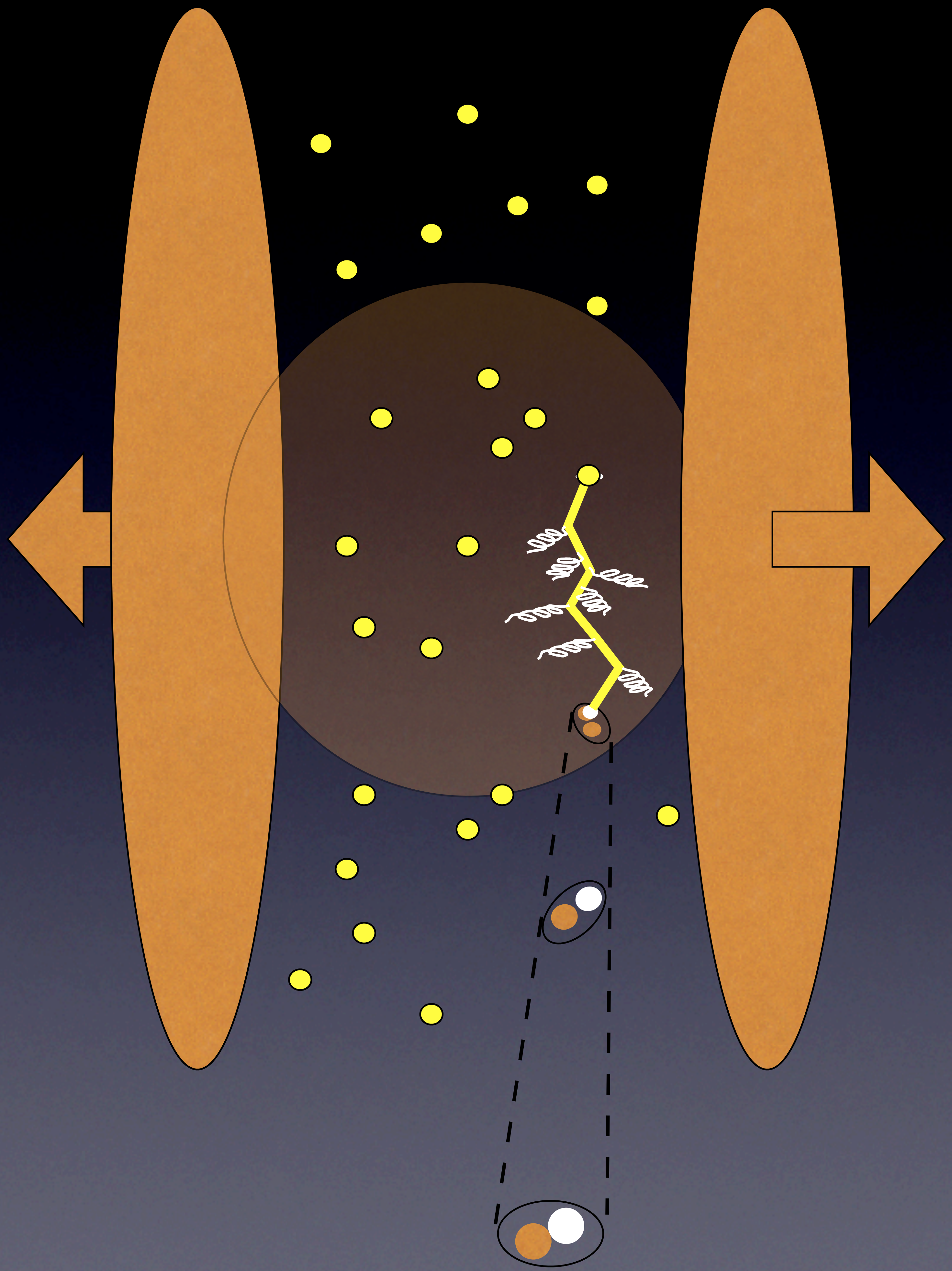
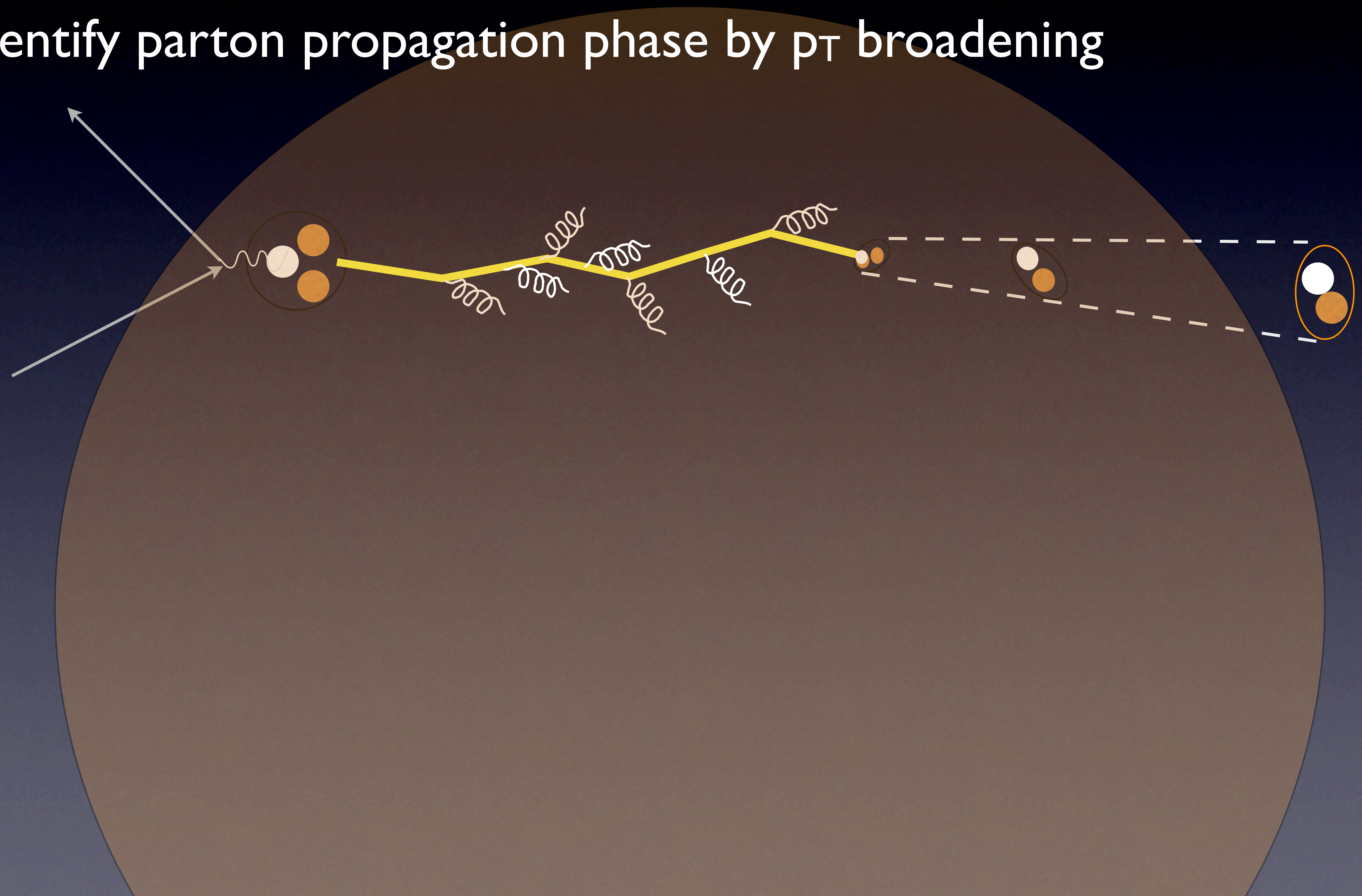




Relativistic Heavy Ion Collisions - parton propagation in a hot dense medium

Summary of Method, Low-Energy DIS

Identify parton propagation phase by p_T broadening



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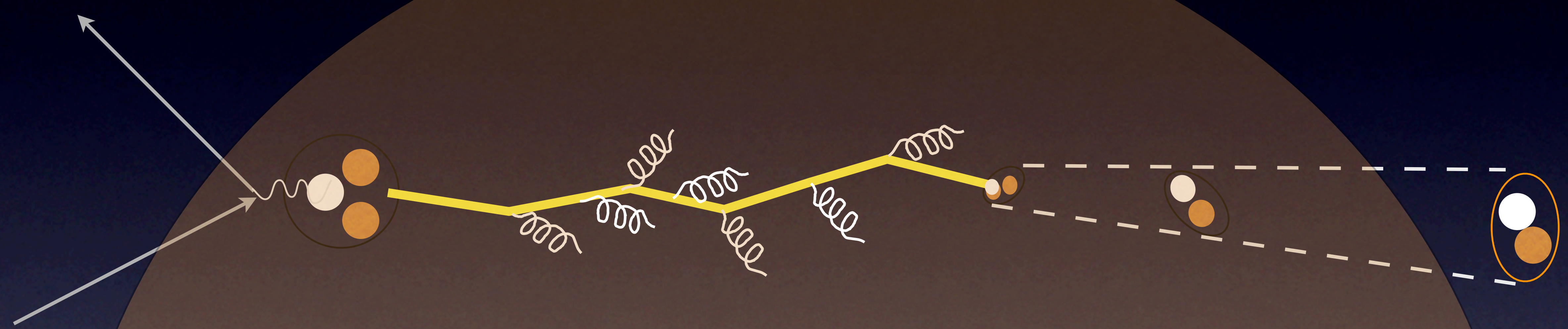

Identify hadron formation phase by hadron attenuation

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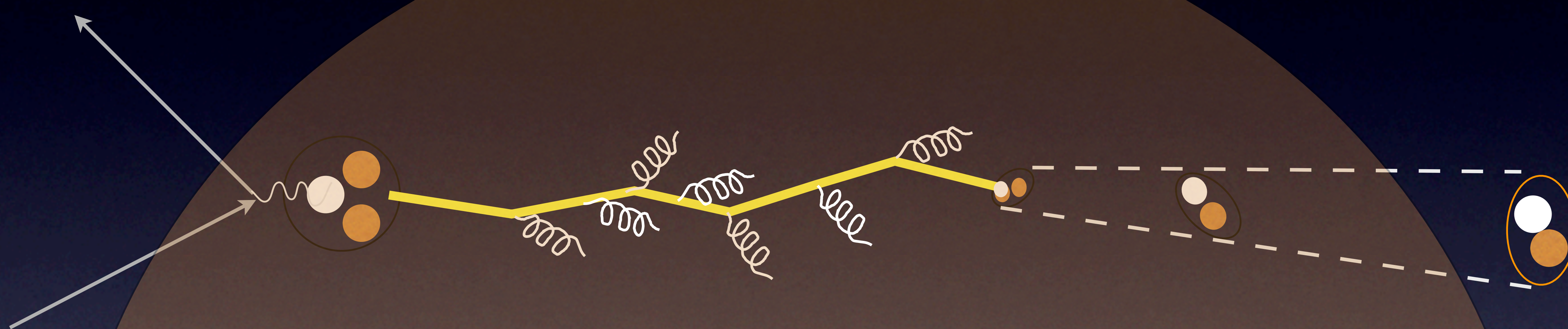


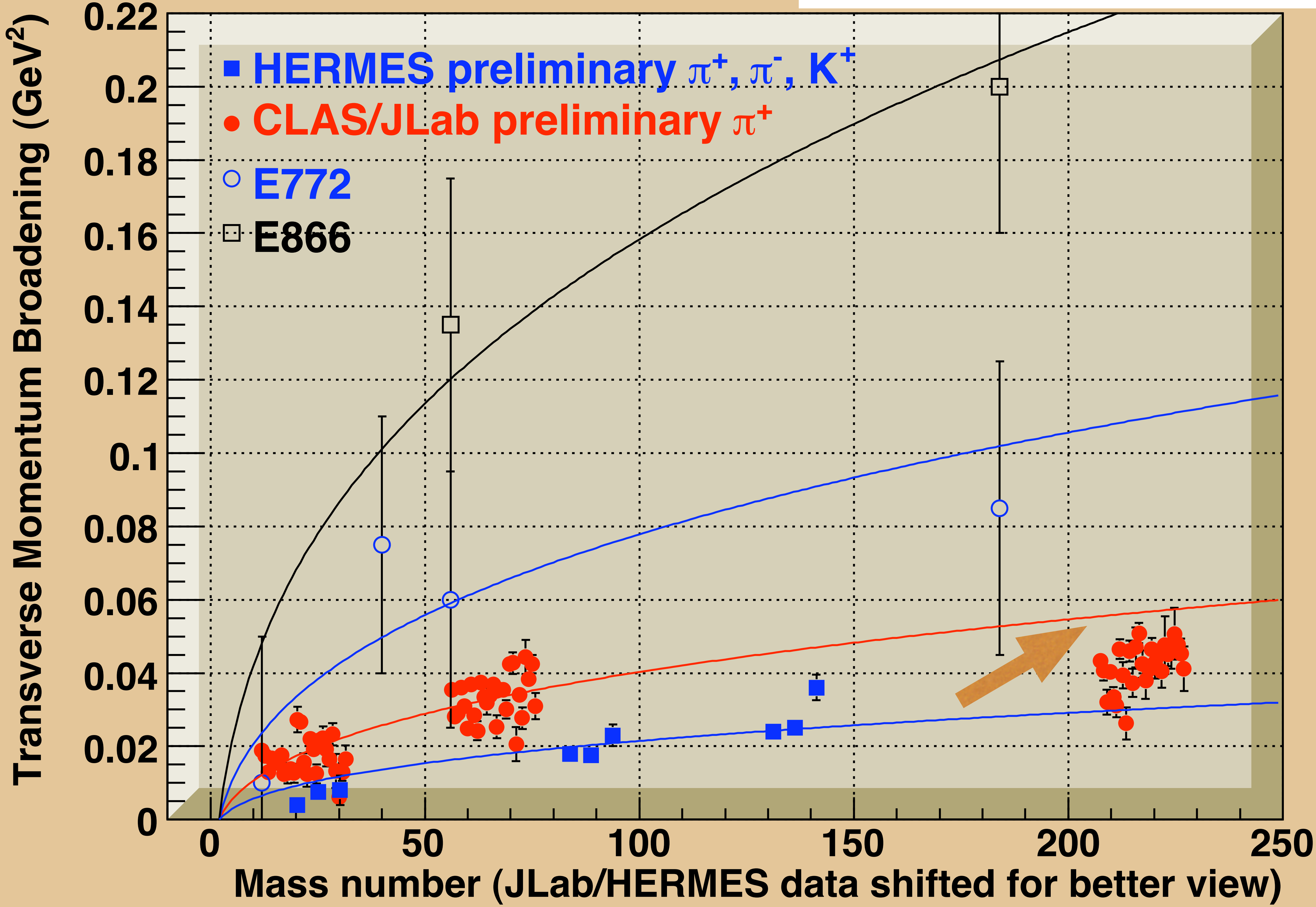
Identify hadron formation phase by hadron attenuation

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

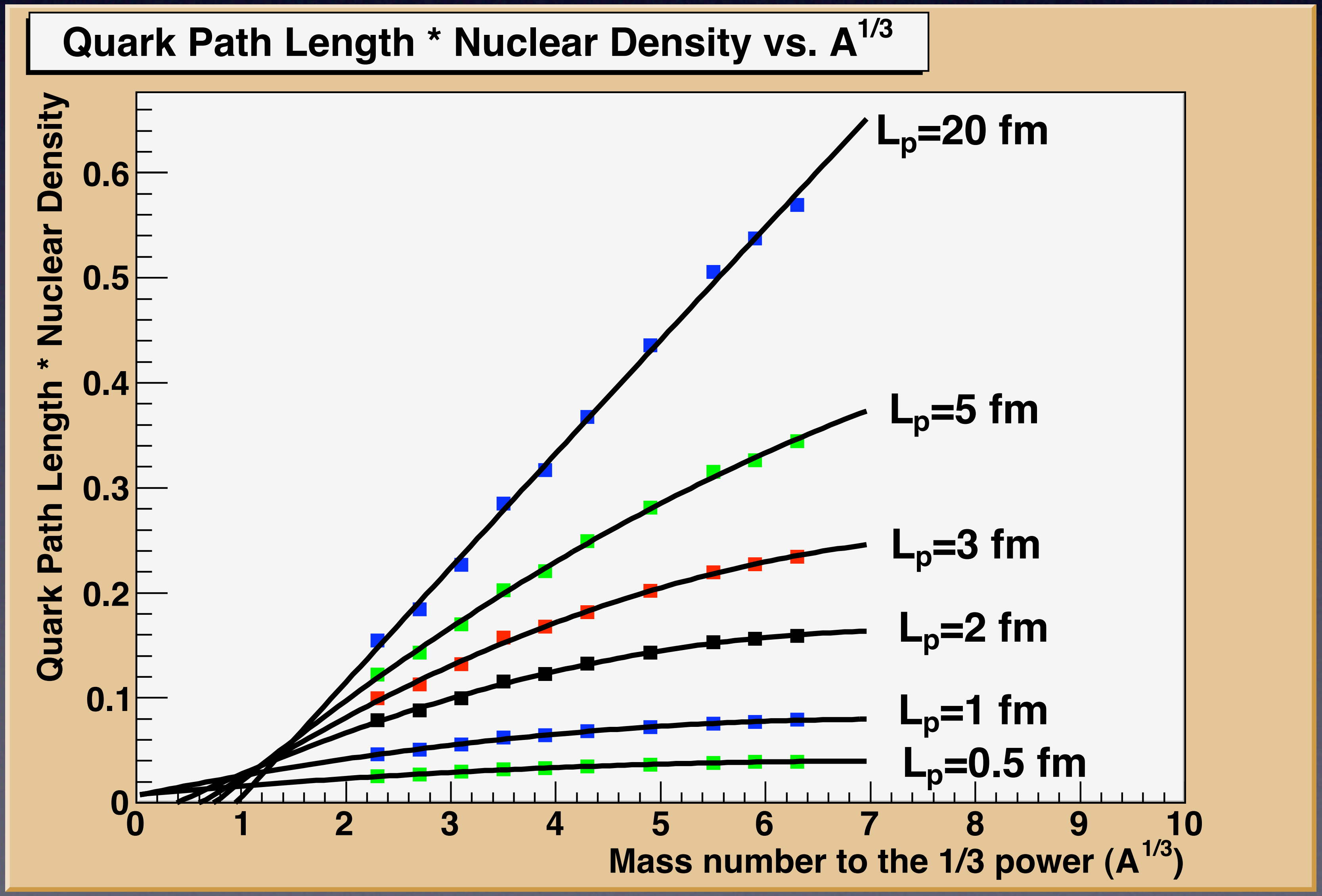
Parton Propagation: p_T Broadening

Comparison of p_T broadening data - Drell-Yan and DIS

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



Production Time Extraction - Geometrical Effects



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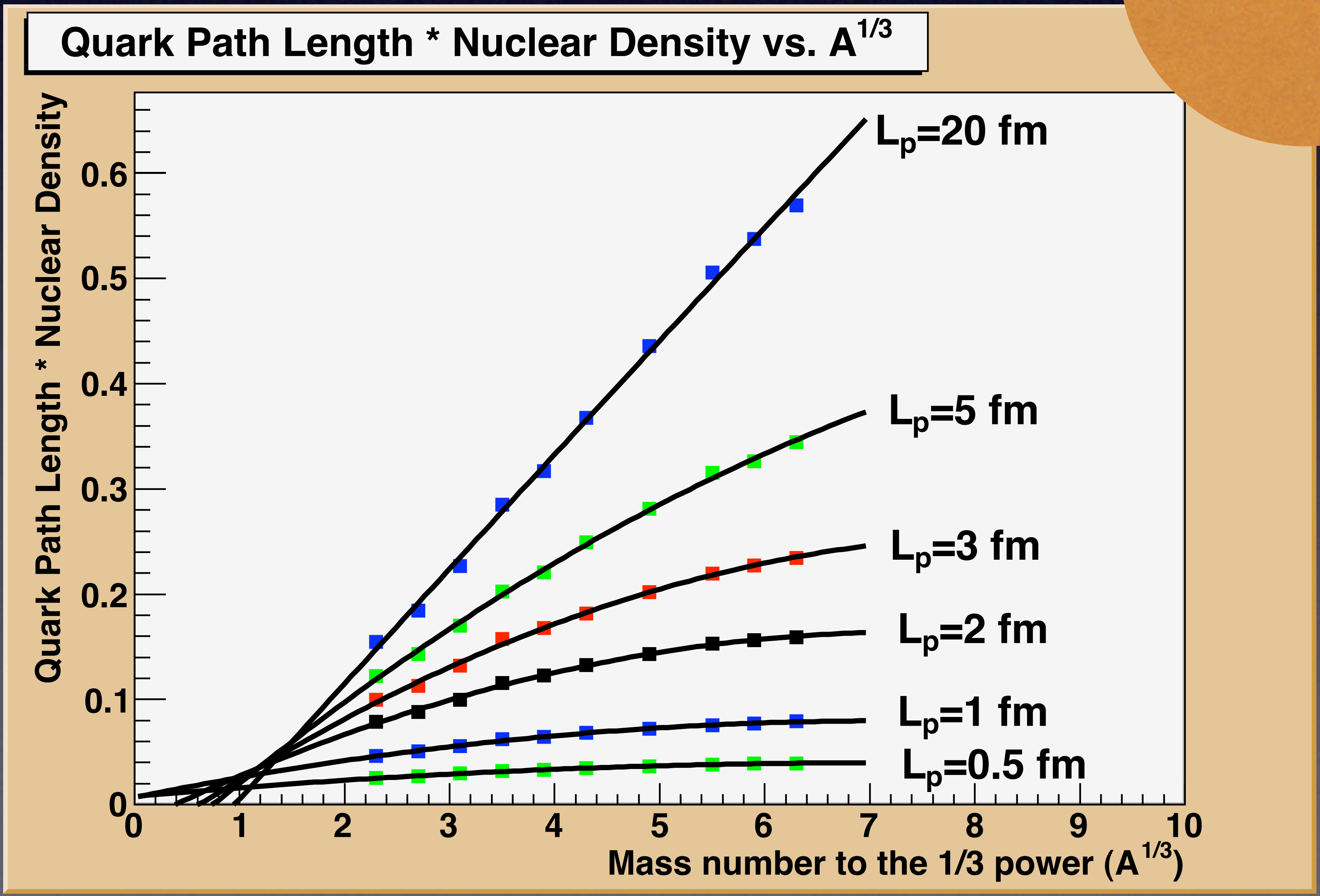

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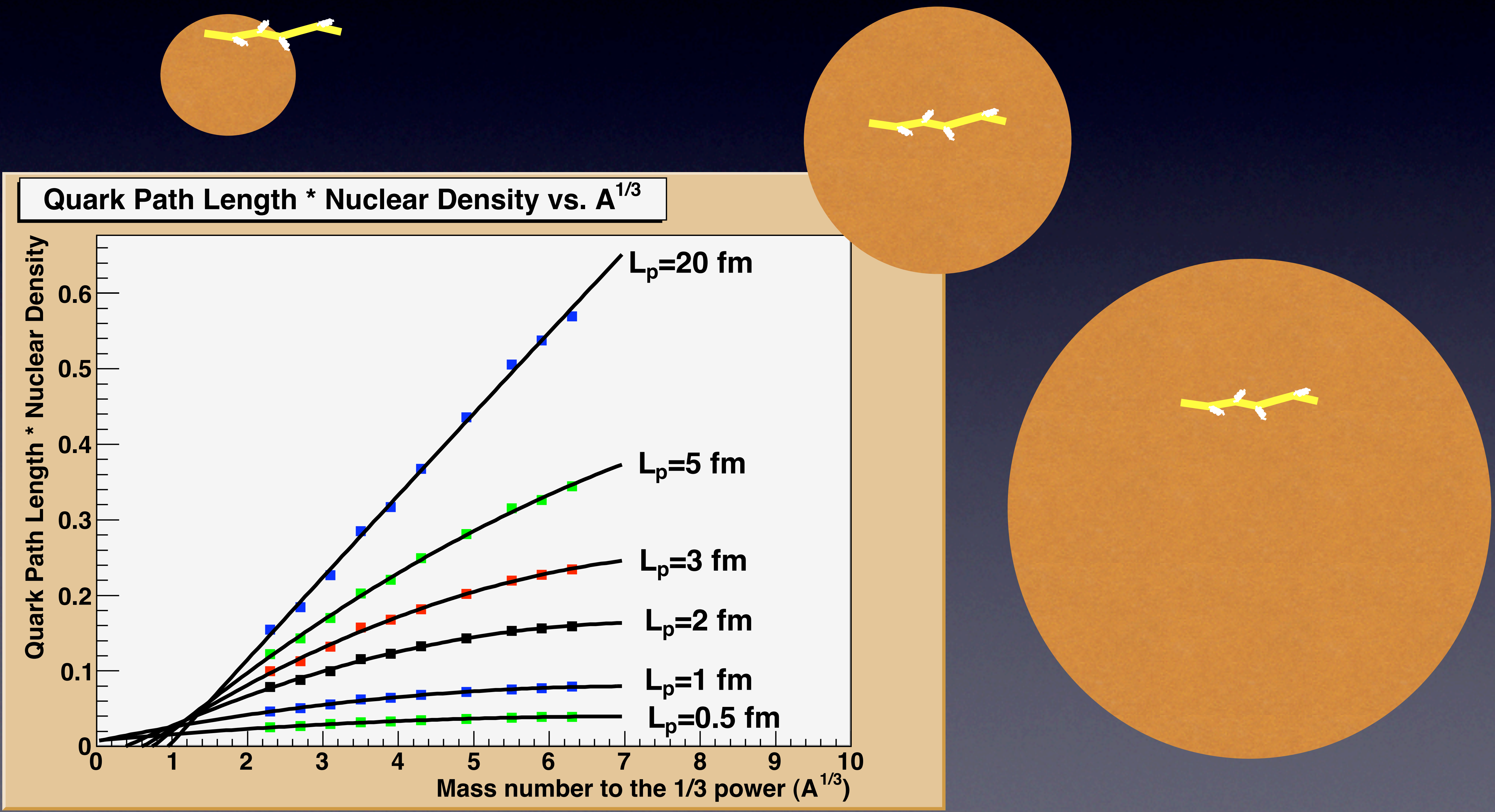

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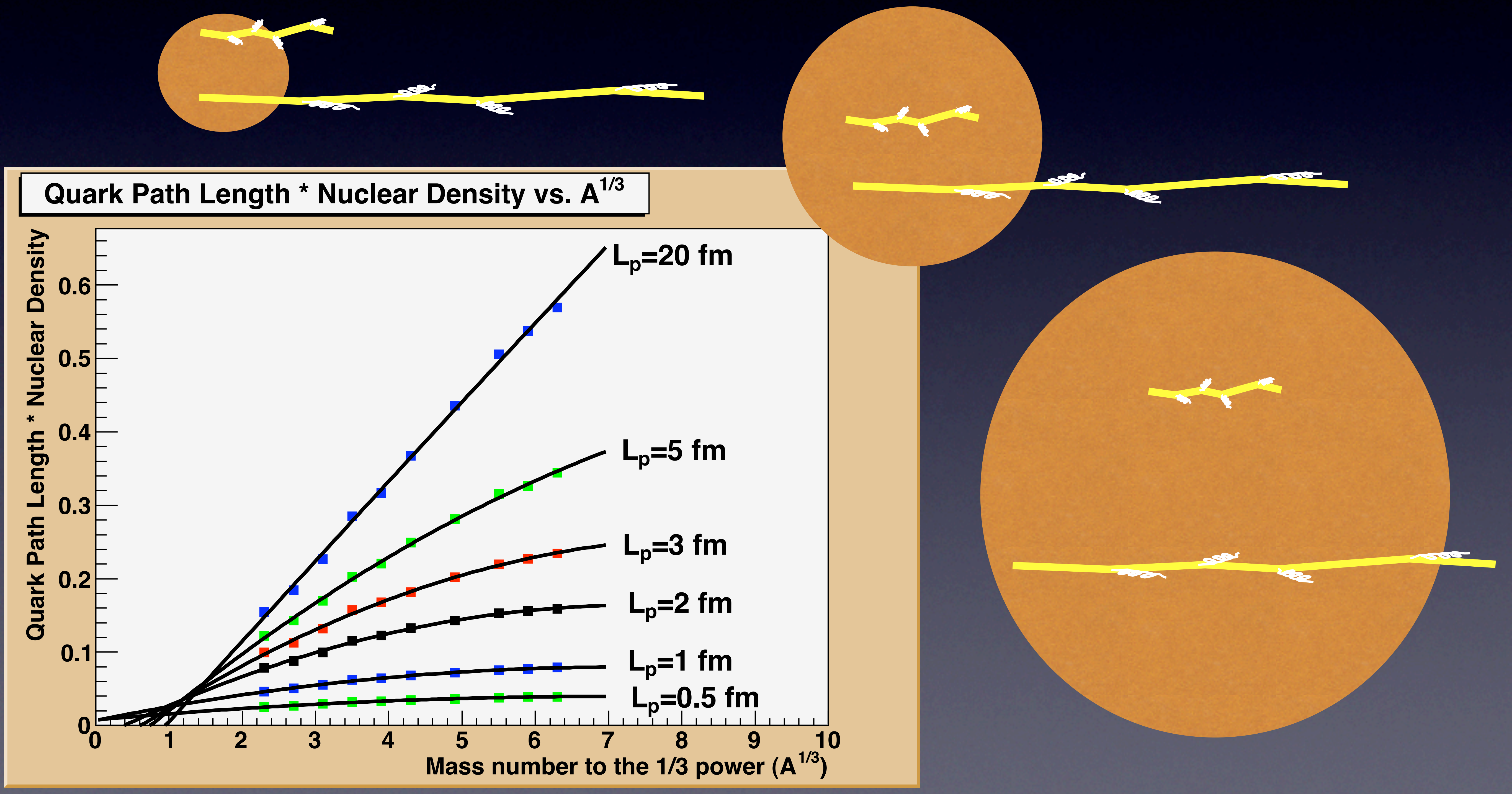

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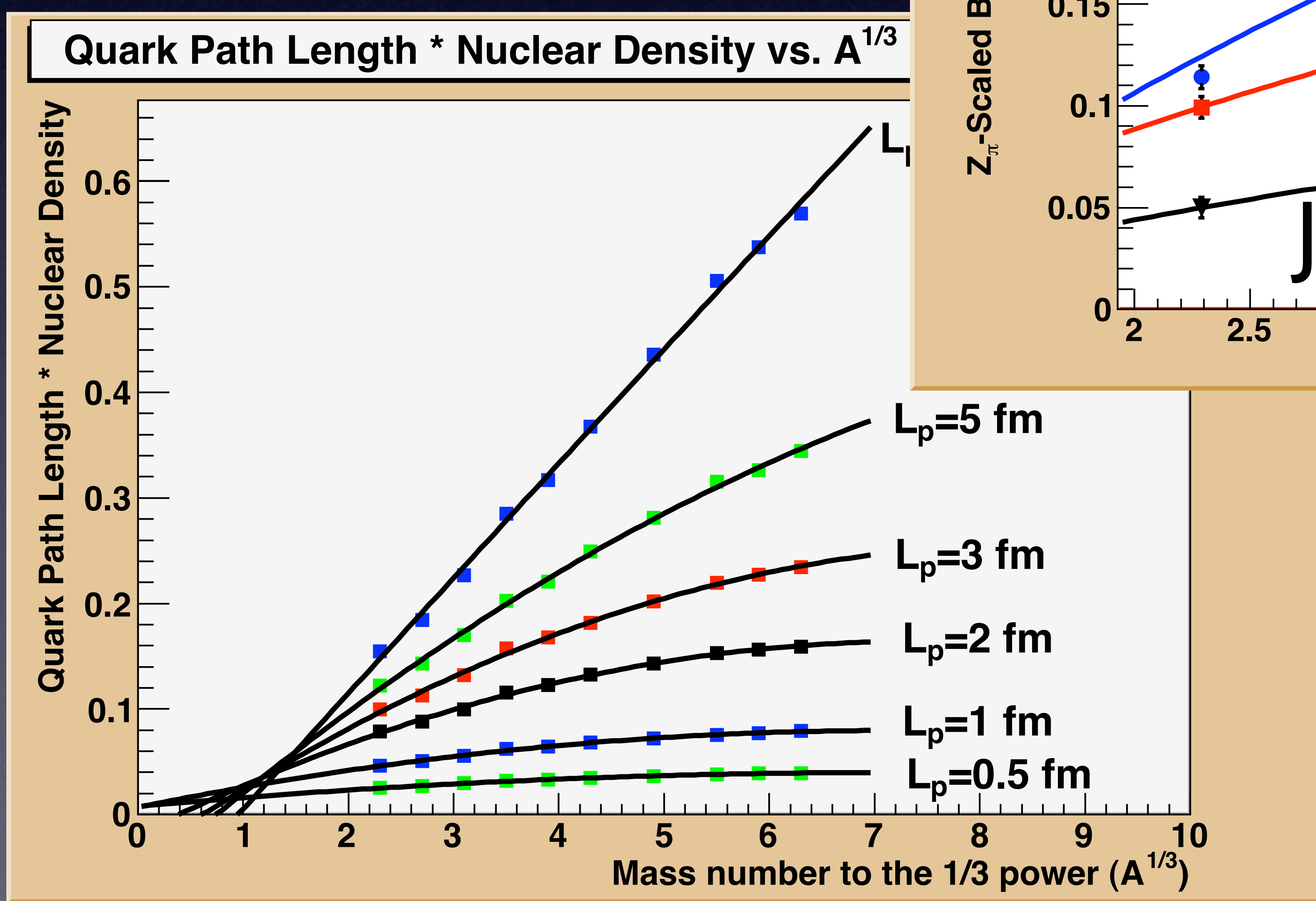
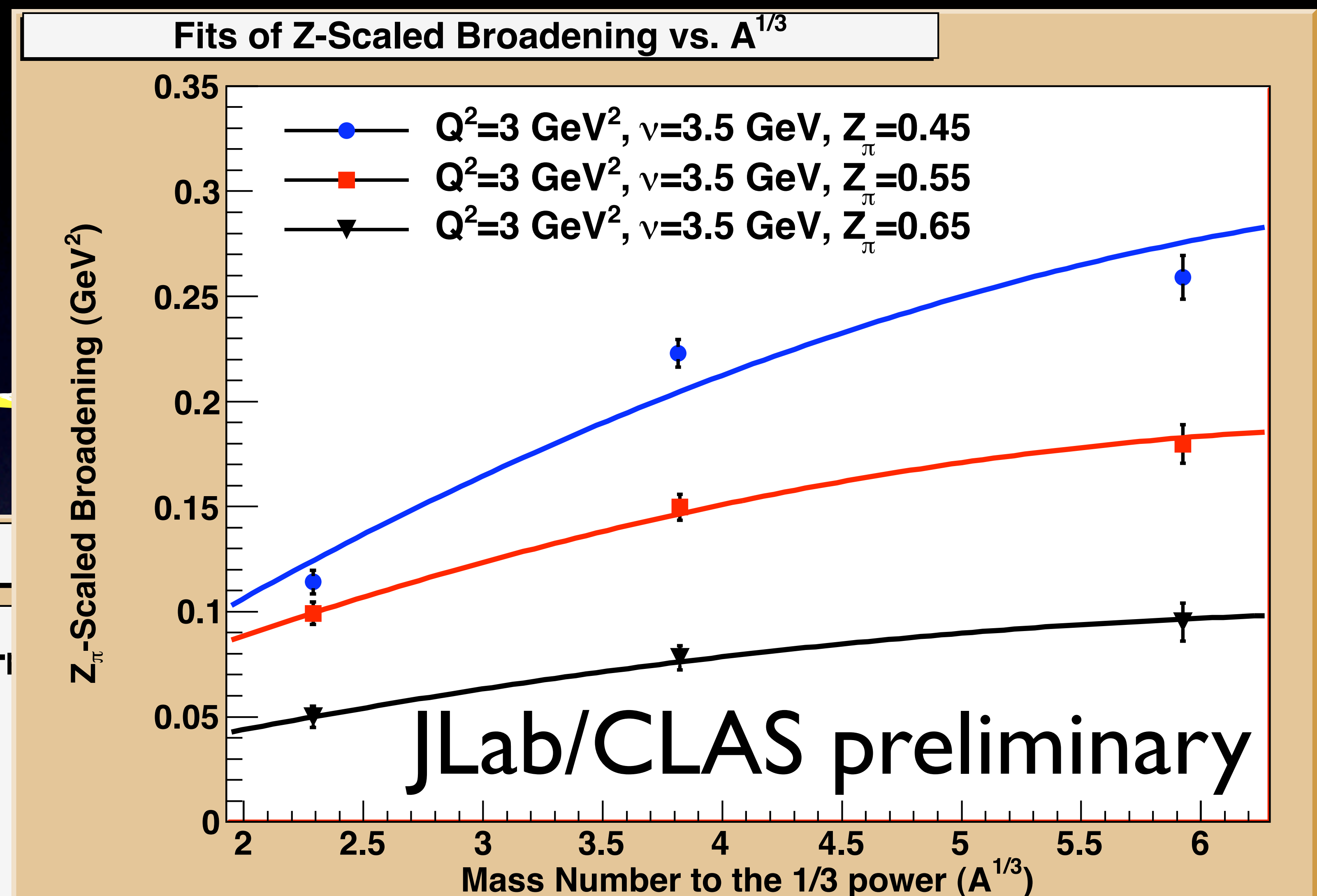




P_T Broadening - Theoretical Descriptions

- Color dipole formalism: Kopeliovich, Pirner
- pQCD: Majumder, Wang, BDMPS, Qiu, Guo,...
- Jet quenching in hot matter: HT, GLV, AMY, ASW, and alternatives. See:

A. Majumder, J. Phys. G34:S377-388, 2007

S. A. Bass et al., arXiv:0808.0908v3 [nucl-th]

B.Z.Kopeliovich, I.K.Potashnikova, I. Schmidt, J. Phys. G35:054001, 2008

Energy Loss in pQCD

- Partonic energy loss in QCD is well-studied: dozens of papers over past 15 years
- Dominant mechanism is gluon radiation; elastic scattering is minor for cold nuclei
- Coherence effects important: QCD analog of LPM effect

Energy Loss in pQCD

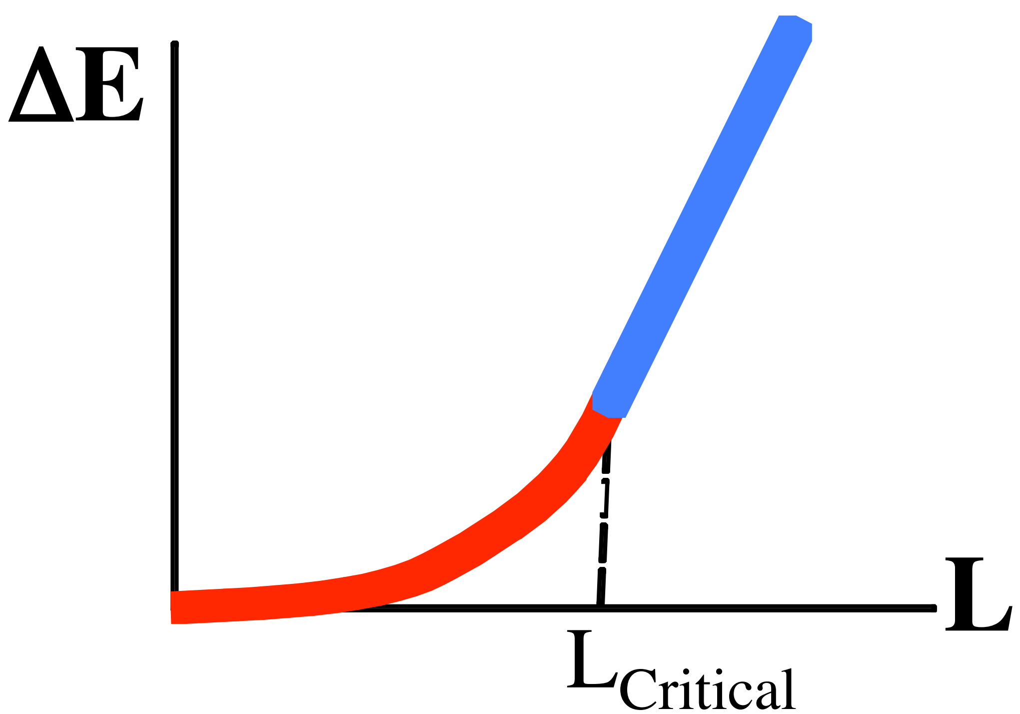
Coherence length $\ell_c \approx \dfrac{\omega}{\left\langle k_\perp^2 \right\rangle_{\ell_c}}$

Mean free path λ, medium length L:

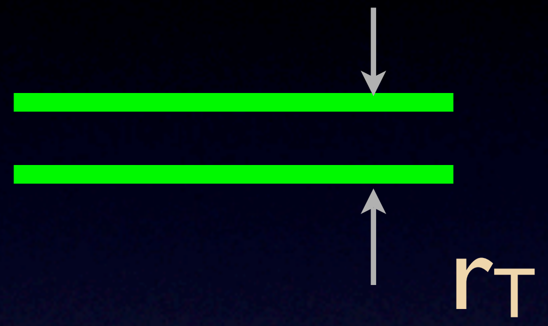
$\ell_c < \lambda$	incoherent gluon radiation
$\lambda < \ell_c < L$	coherent gluon radiation
$\ell_c > L$	single-scatter gluon radiation

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

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



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*:

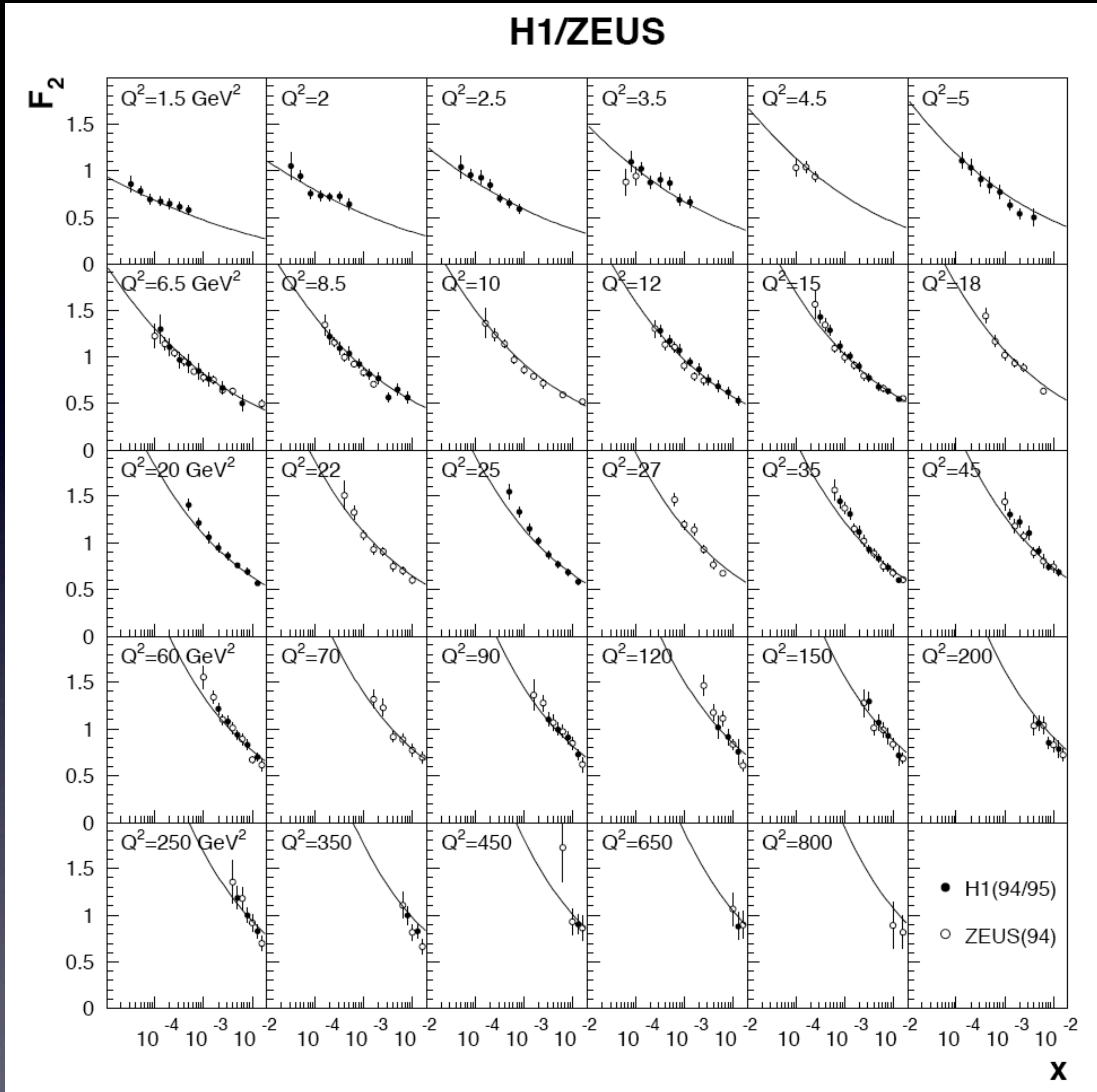
$$C(r_T, s) = \frac{\pi^2}{3} G(x, Q^2)$$

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

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

J. Dolejsi, J. Huefner, B.Z. Kopeliovich, Phys. Lett. B312 (1993) 235-239

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



K. Golec-Biernat, M. Wusthoff, Phys.Rev. D60 (1999) 114023

$$\Delta k_T^2 = \Delta p_T^2 / z^2 = 2C\rho_A L = \hat{q} L$$

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- Energy dependence of $C(r_T = 0, s)$ is expected to be small:

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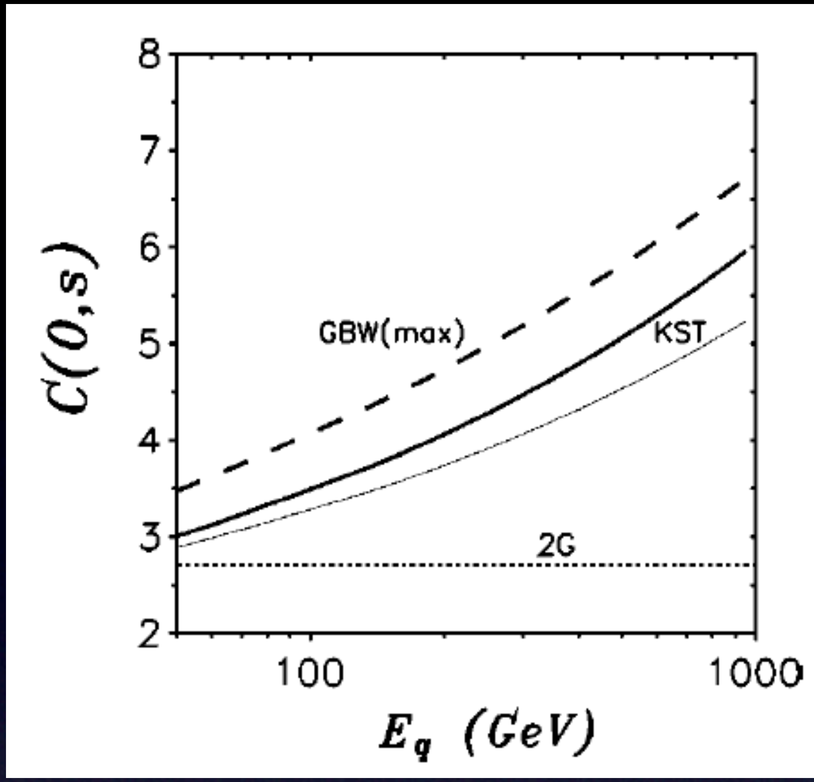

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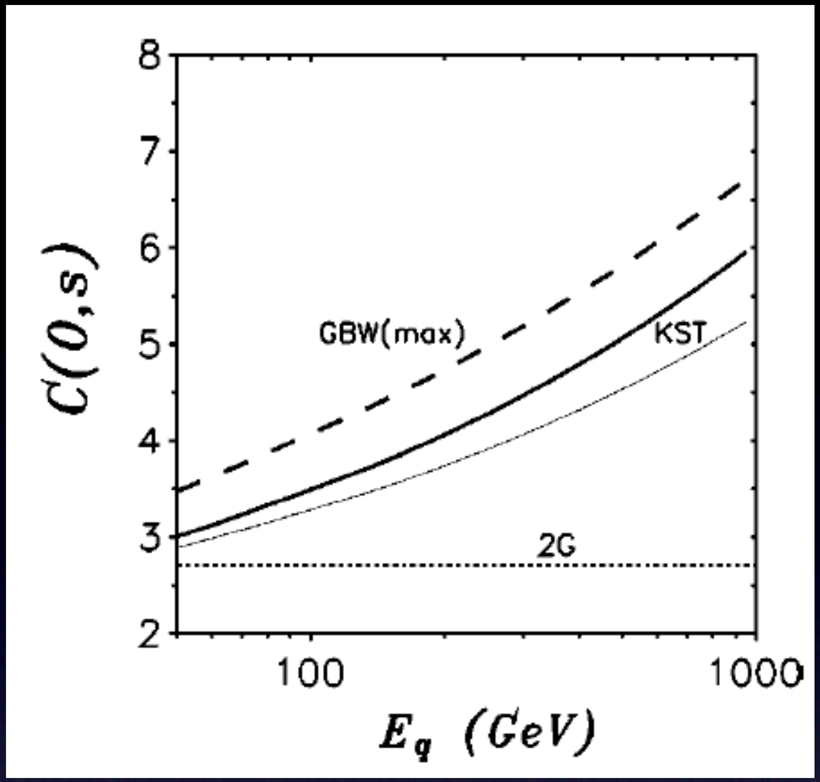
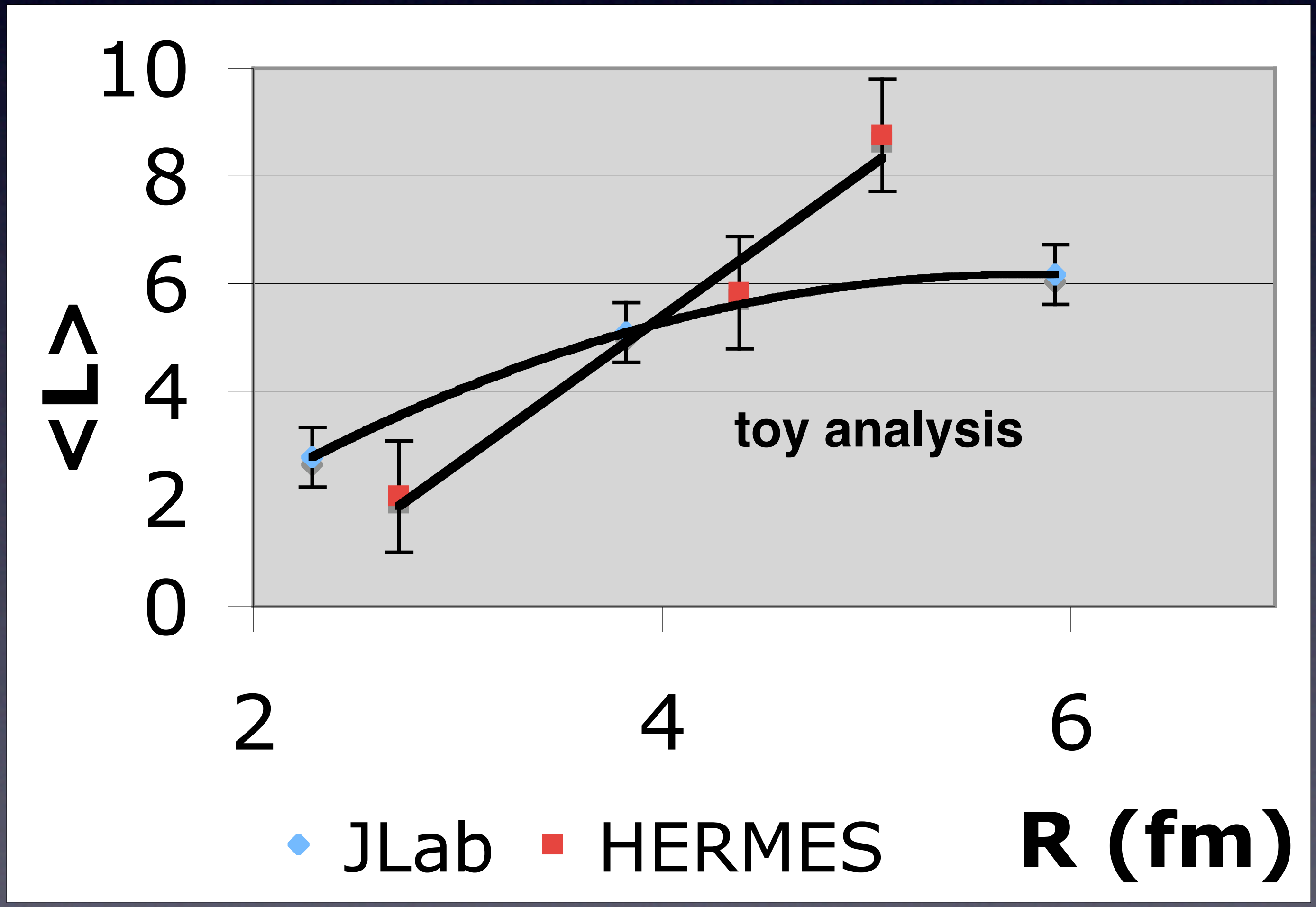


- Can assume C=2 and derive <L>:



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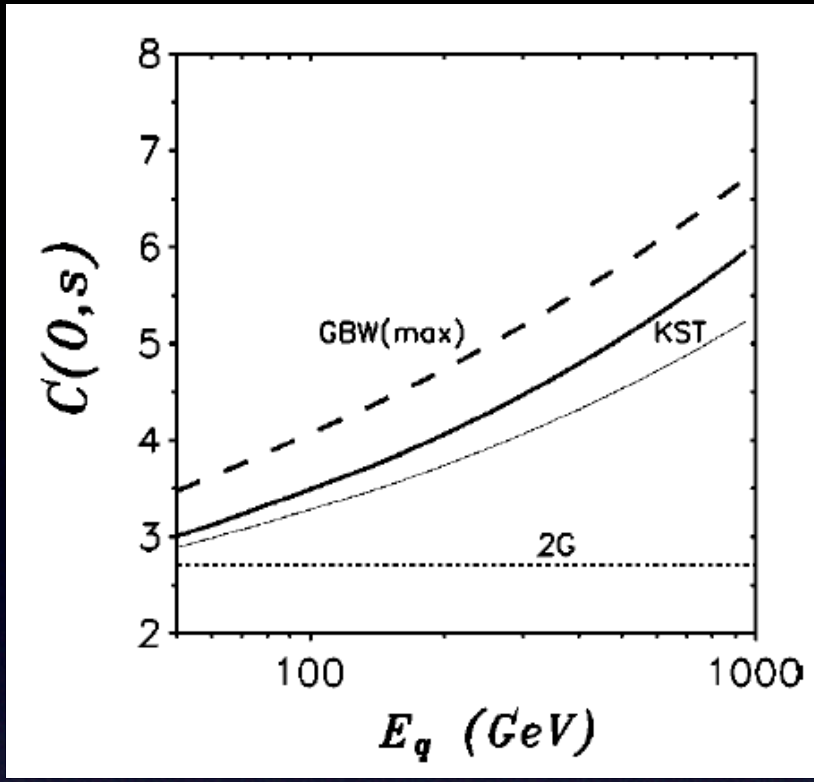

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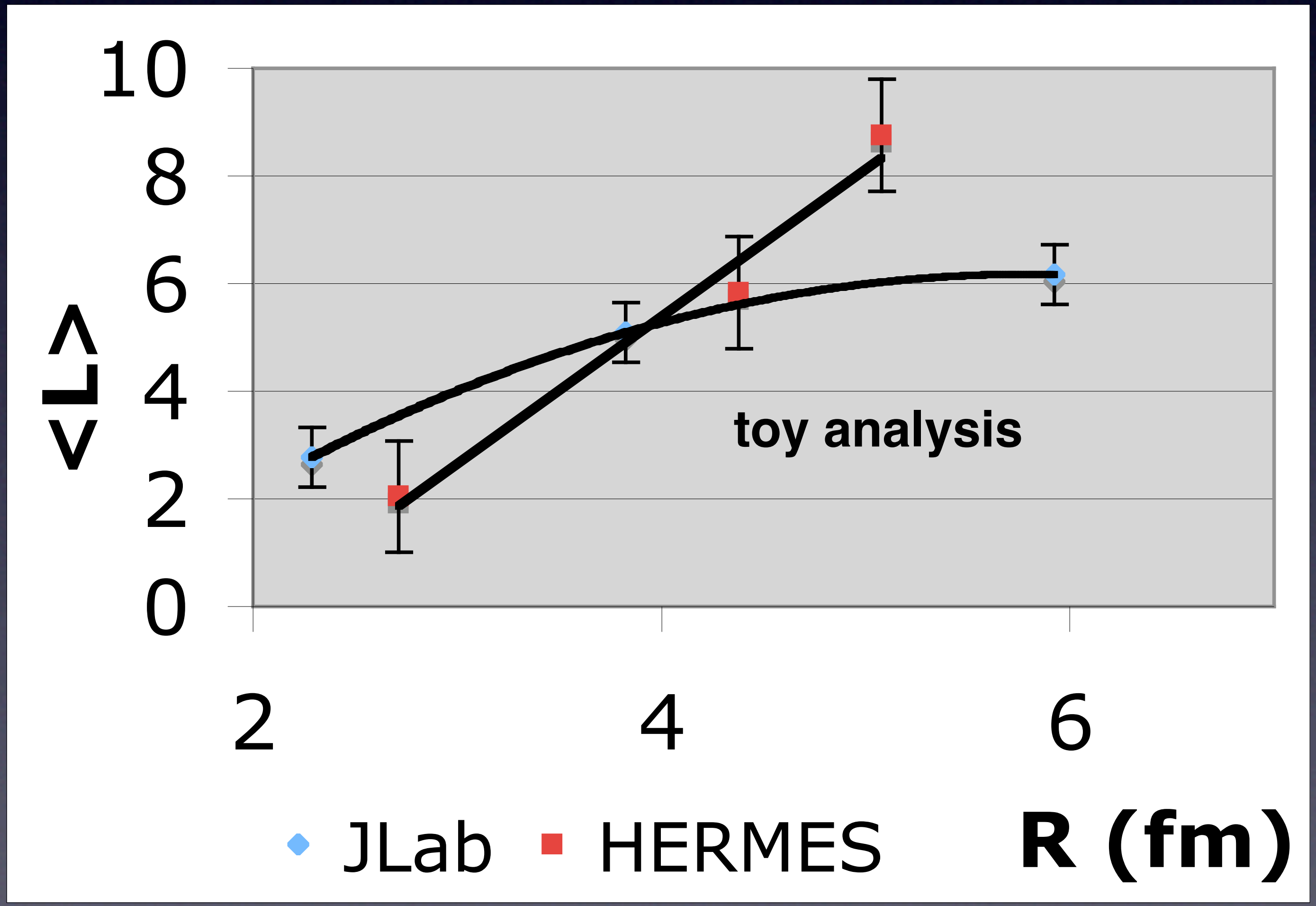
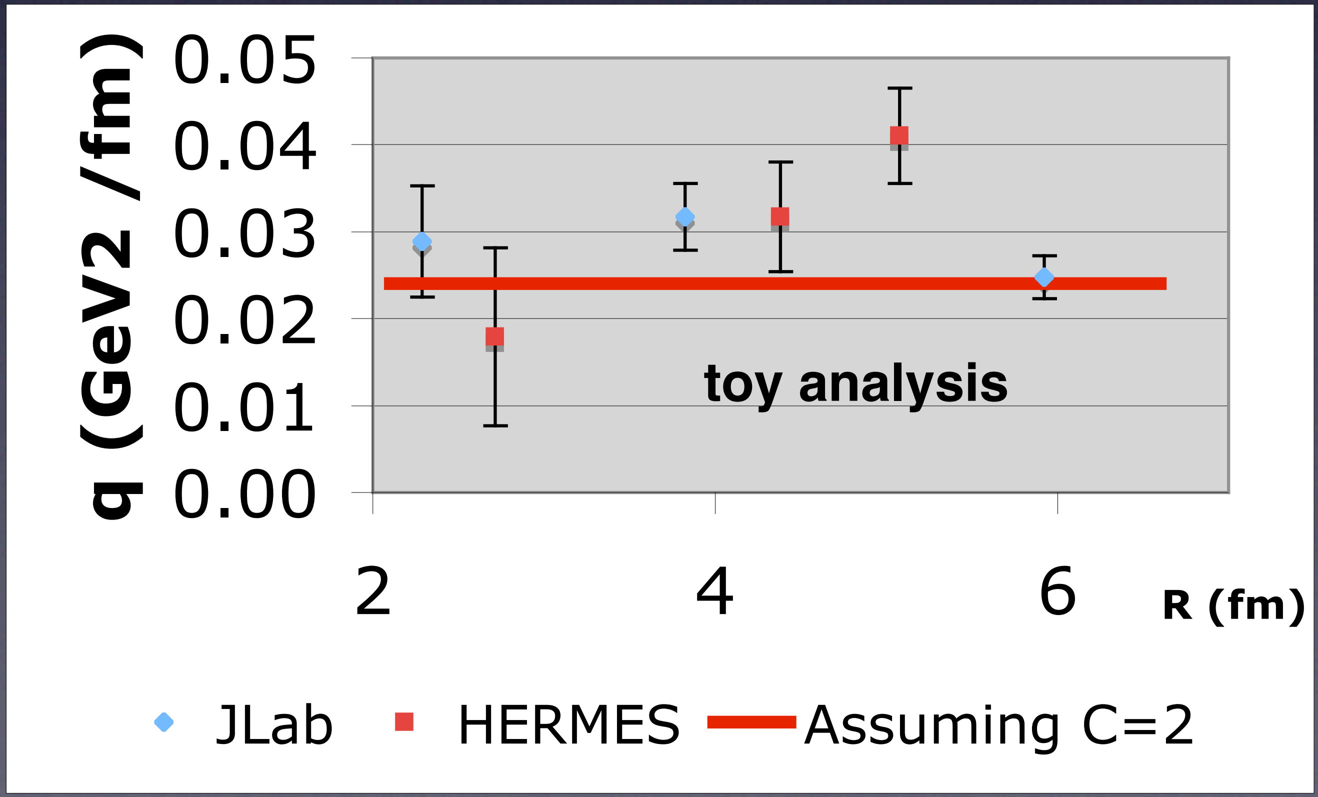
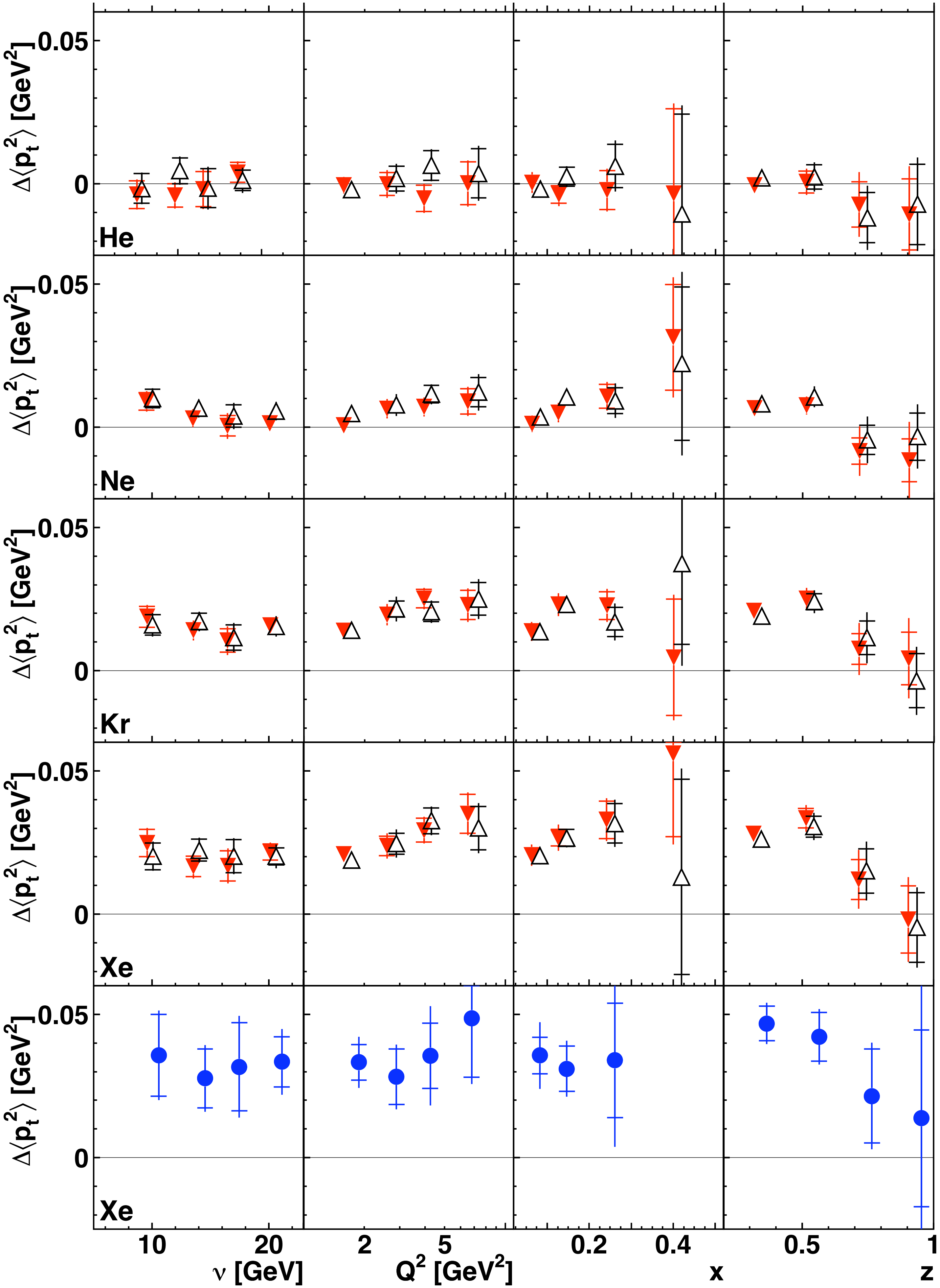
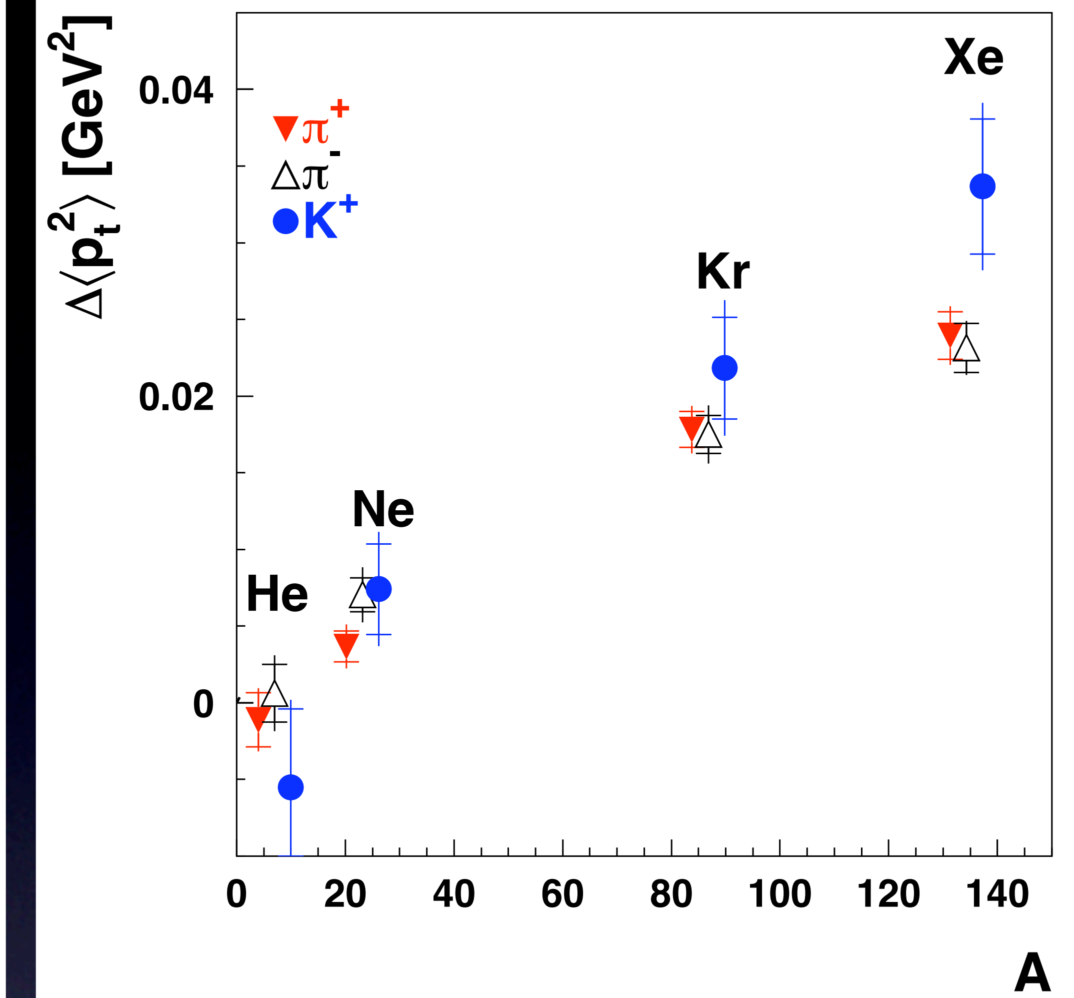


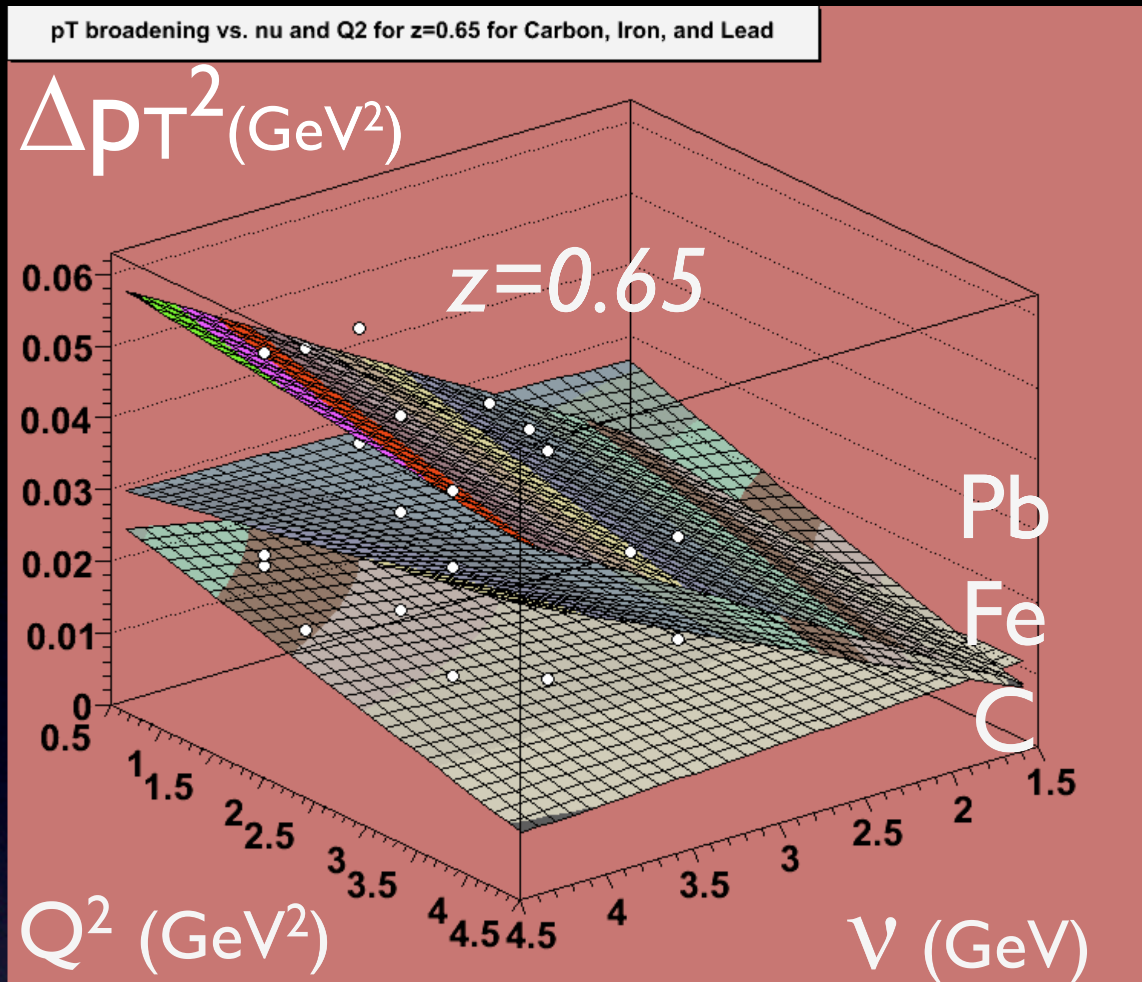
- Or assume <L> >> R, derive q:

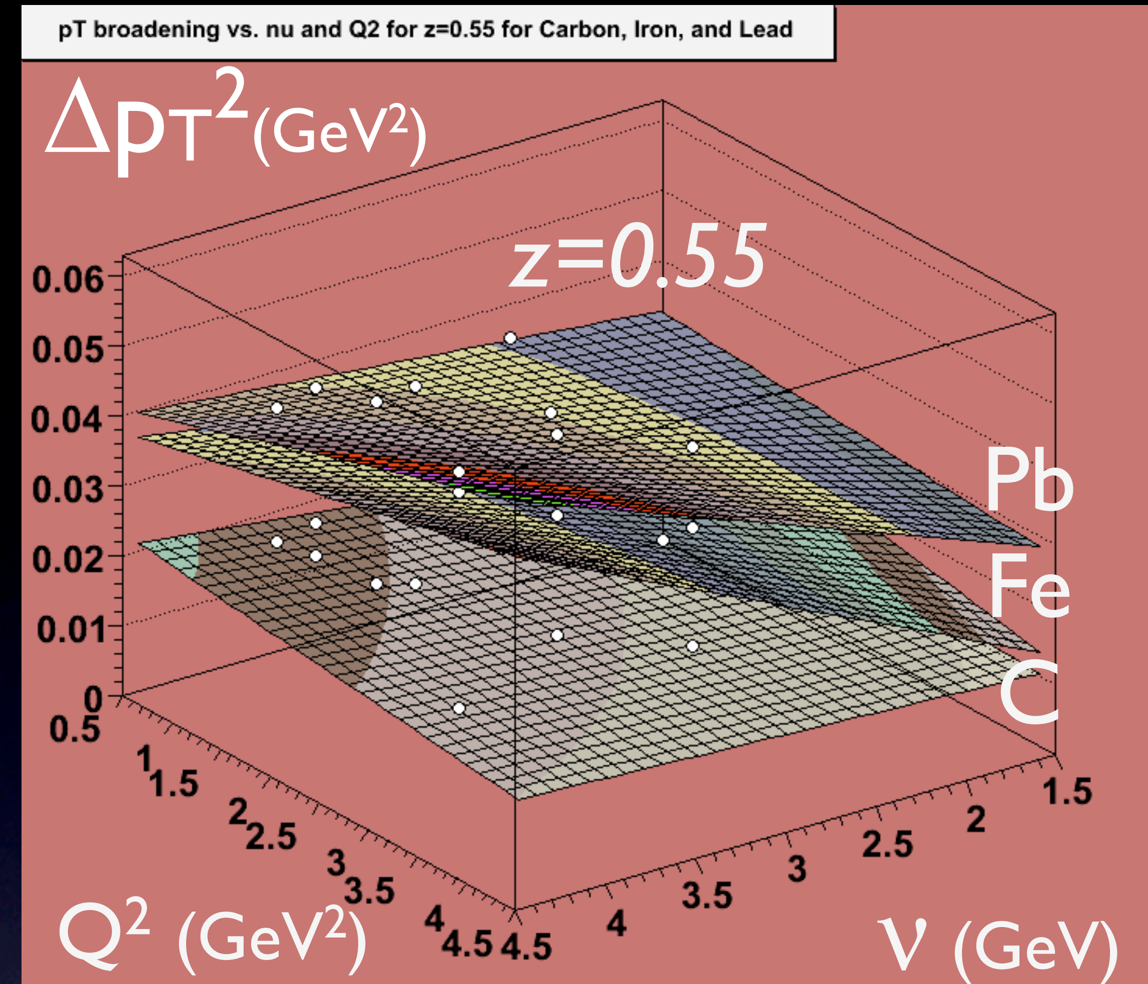






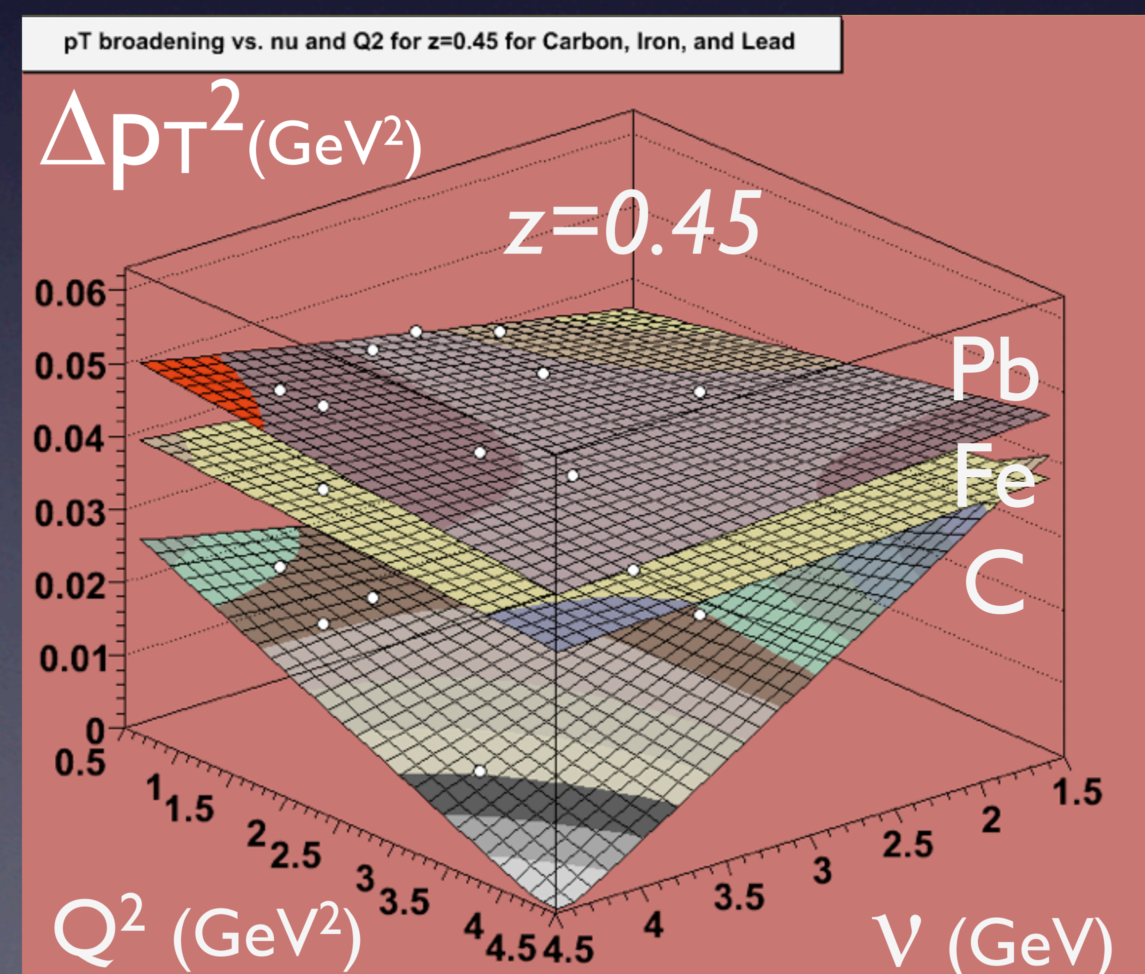
Hermes 1-D distributions for Δp^2_T vs. ν, z, Q^2, A





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! a major challenge for theory...

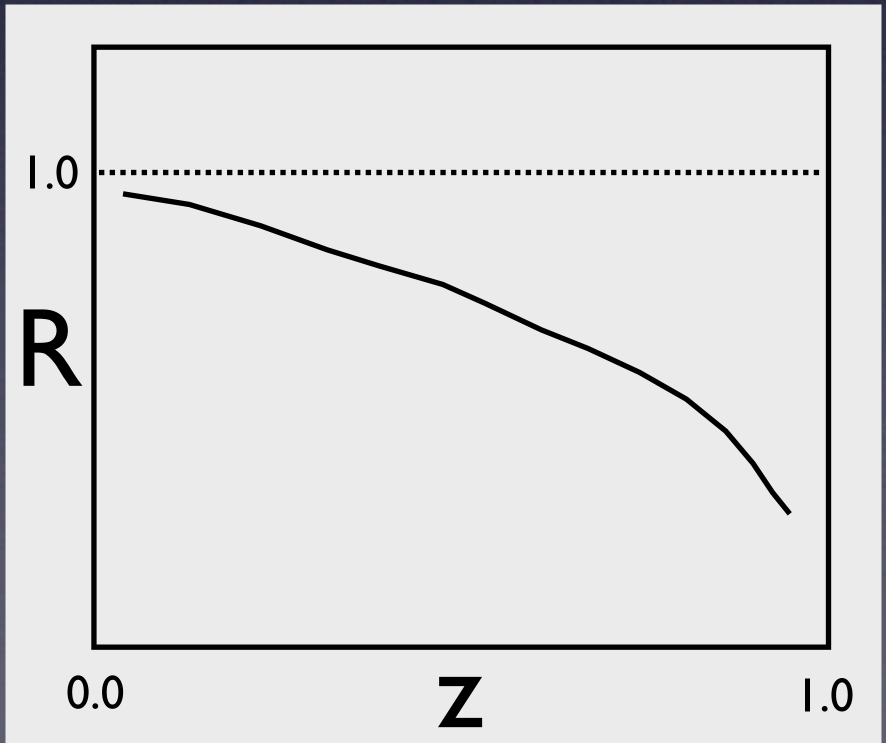
Implications for LHeC

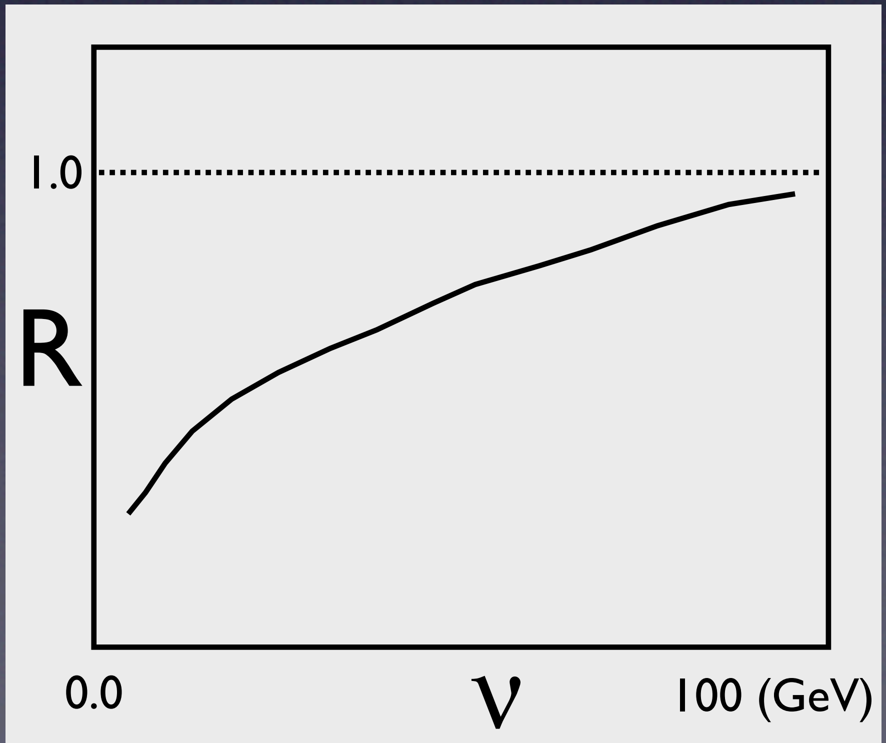
- Transverse momentum broadening will grow slowly as energy increases, to perhaps 0.6 GeV^2 at the partonic level for z=0.5
- Perturbative energy loss continues to be energy independent, proportional to L^2, and small: challenge to measure (target fragments?)
- Larger, clearly measurable effects (related to non-perturbative energy loss?): see next section

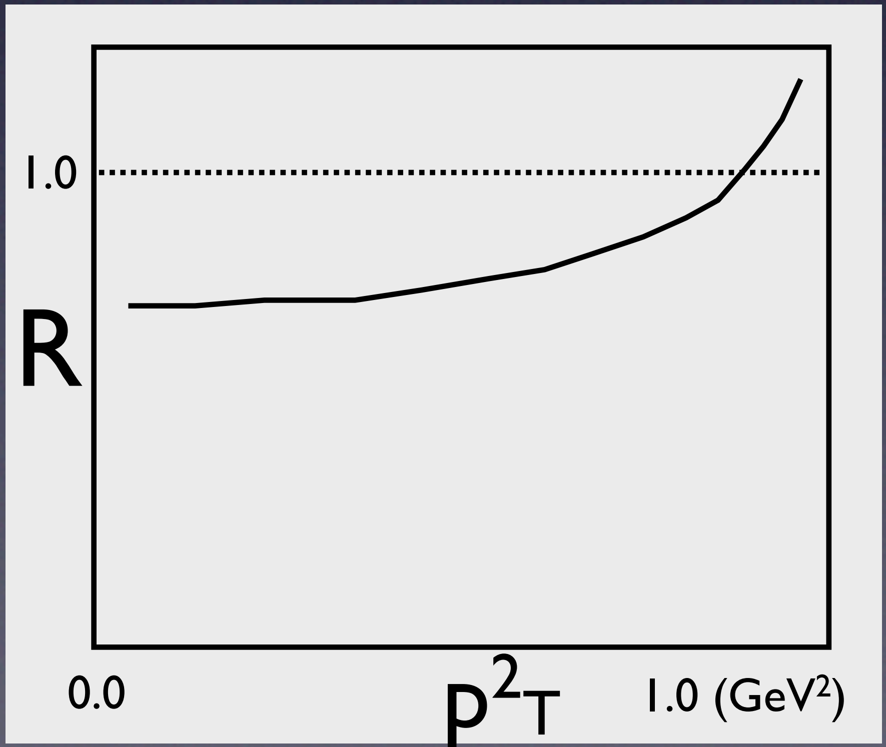
Hadron Formation: Multiplicity Ratios

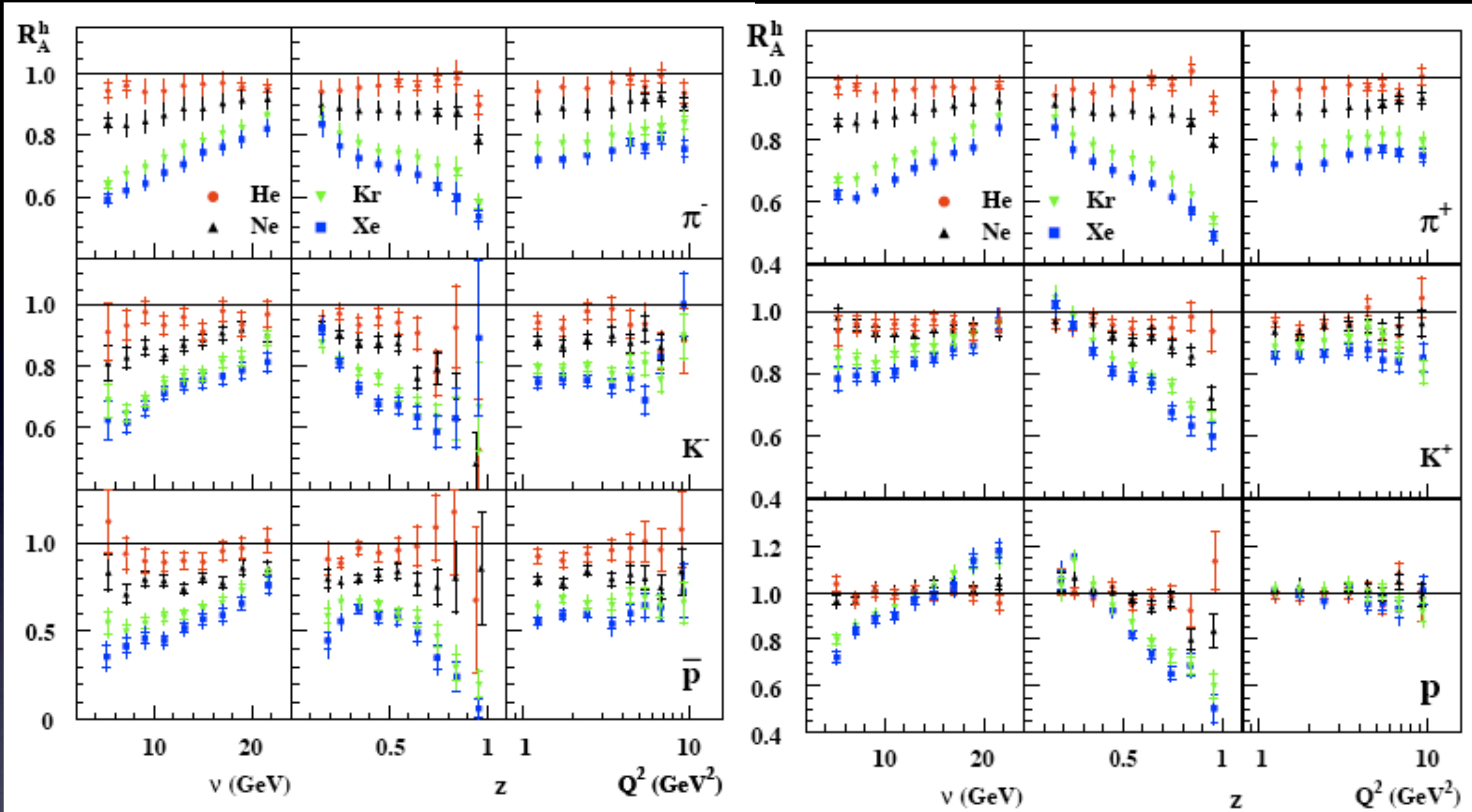
$$R_M^h(z,\nu,p_T^2,Q^2,\phi) = \frac{\left\{ \frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)} \right\}_A}{\left\{ \frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)} \right\}_D}$$

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)

Multiplicity Ratios Calculations - Two Mechanisms

Multiplicity Ratios Calculations - Two Mechanisms

Models based primarily on partonic energy loss

A. Majumder, arXiv:0901.4516v2 [nucl-th]
F. Arleo et al. (EPJ C 30, 213 (2003))
X. N. Wang et al. (PRL 89, 162301 (2002))

Models based primarily on (pre)-hadronic interaction

B. Z. Kopeliovich, J. Nemchik, et al. (e.g., NPA 740, 211 (2004))
T. Falter et al. (e.g., PLB 594 (2004) 61)
A. Accardi et al. (e.g., NPA 720, 131 (2003); NPA 761, 67 (2005))
N. Akopov et al. (Eur. Phys. J 44(2005) 219)
K. Gallmeister, U. Mosel (nucl-th/0701064; nucl-th/07122200)

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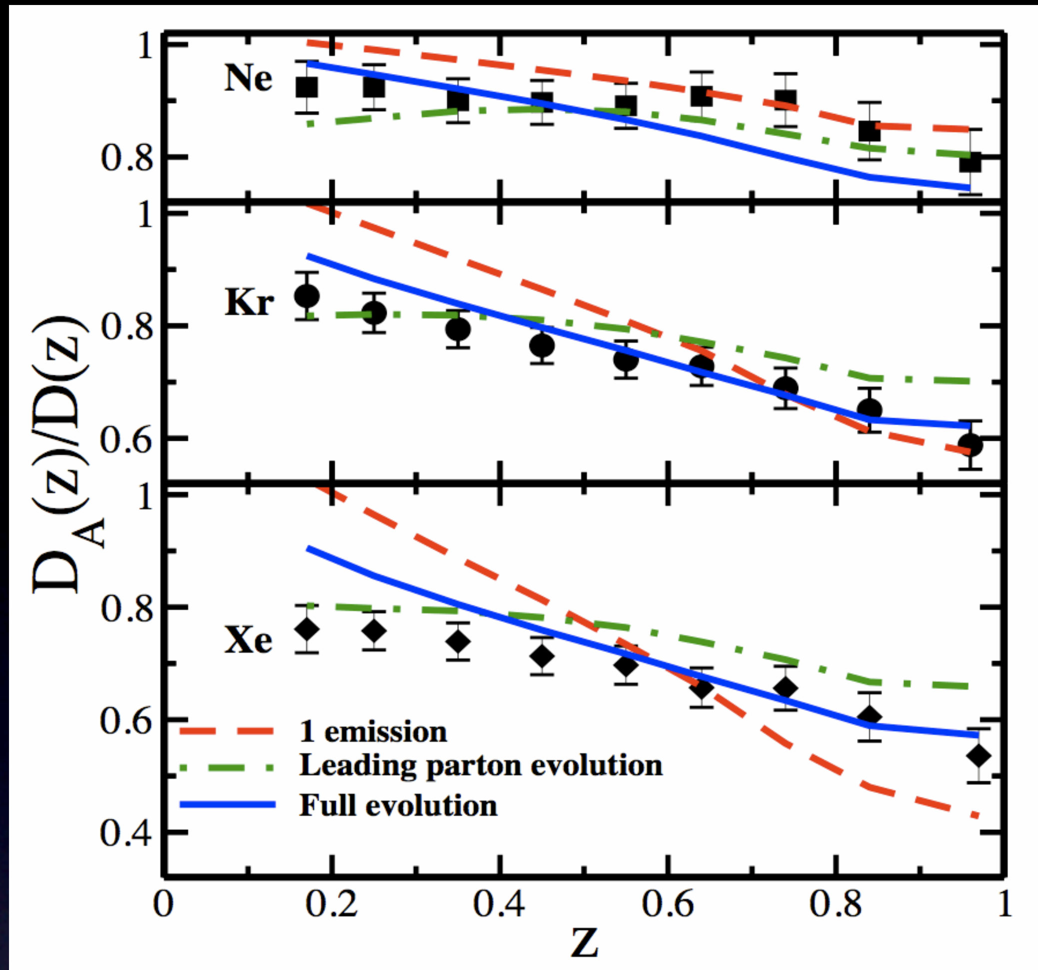
Models based primarily on partonic energy loss

A. Majumder, arXiv:0901.4516v2 [nucl-th]
F. Arleo et al. (EPJ C 30, 213 (2003))
X. N. Wang et al. (PRL 89, 162301 (2002))

Models based primarily on (pre)-hadronic interaction

B. Z. Kopeliovich, J. Nemchik, et al. (e.g., NPA 740, 211 (2004))
T. Falter et al. (e.g., PLB 594 (2004) 61)
A. Accardi et al. (e.g., NPA 720, 131 (2003); NPA 761, 67 (2005))
N. Akopov et al. (Eur. Phys. J 44(2005) 219)
K. Gallmeister, U. Mosel (nucl-th/0701064; nucl-th/07122200)

The HERMES 1-D data cannot yet unambiguously differentiate between the two basic mechanisms



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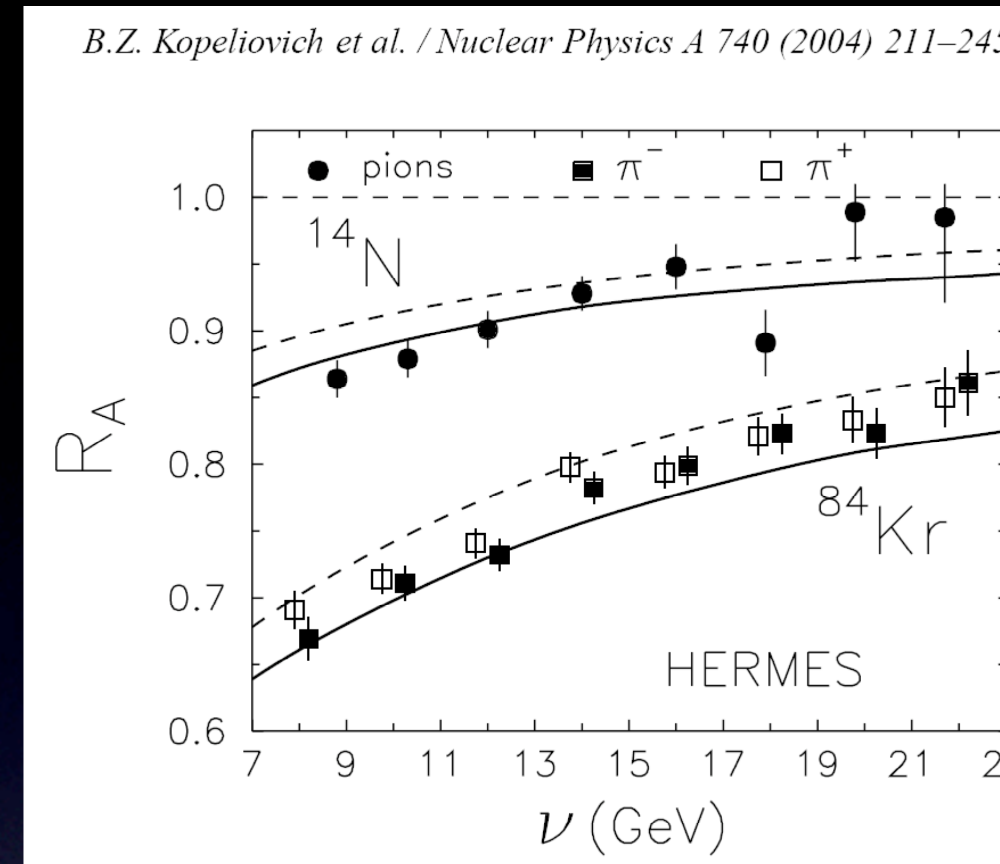
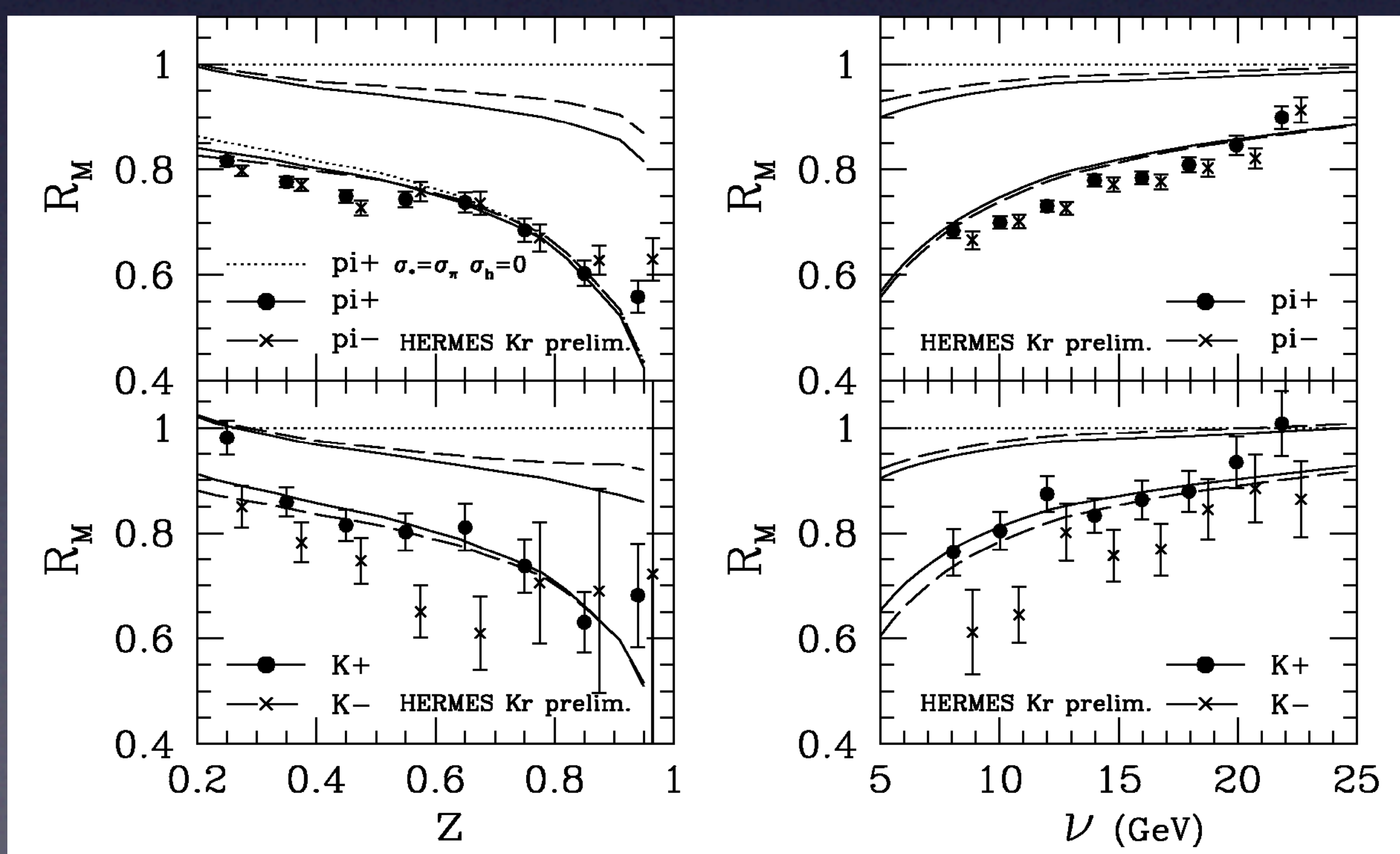
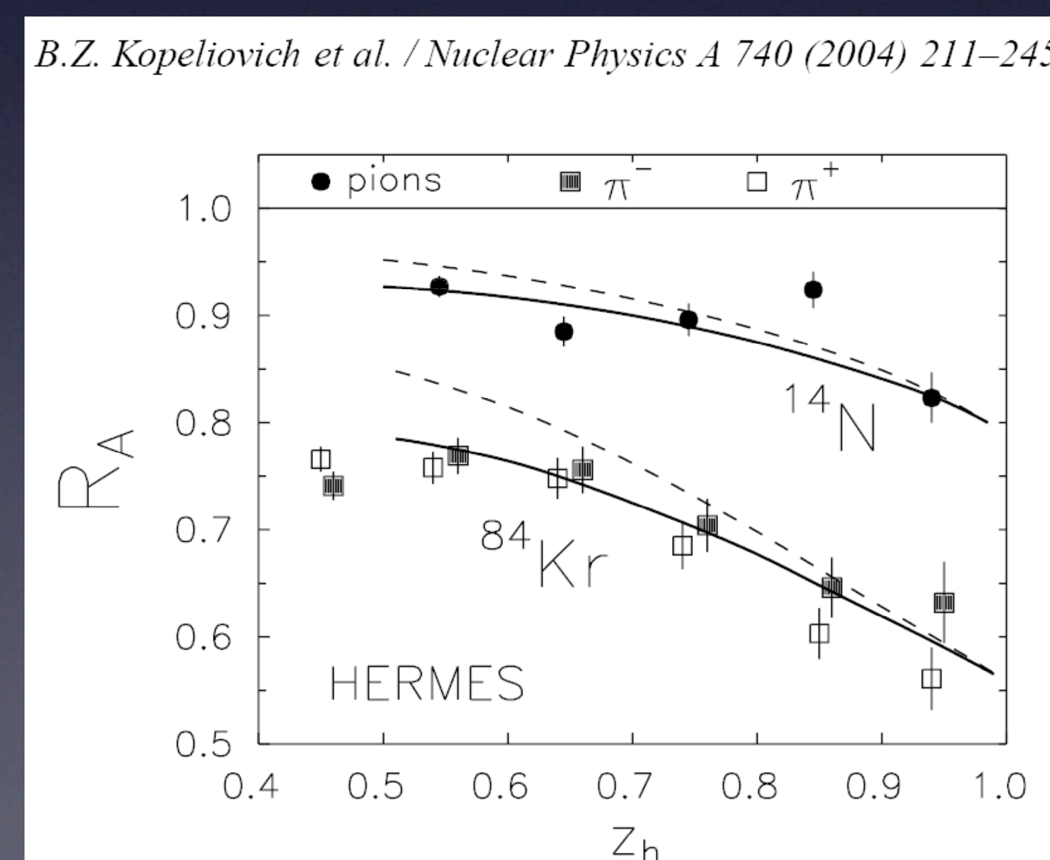
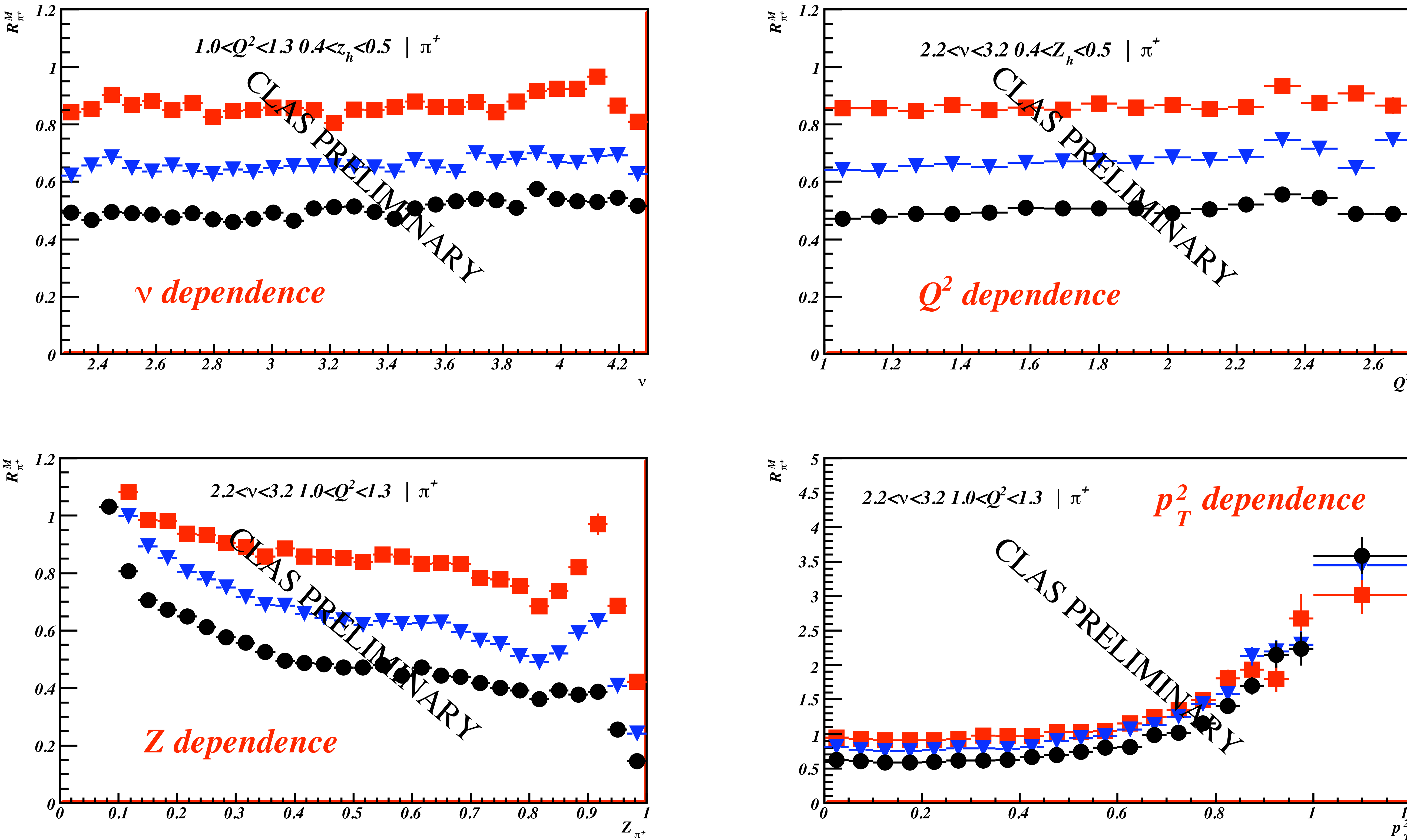


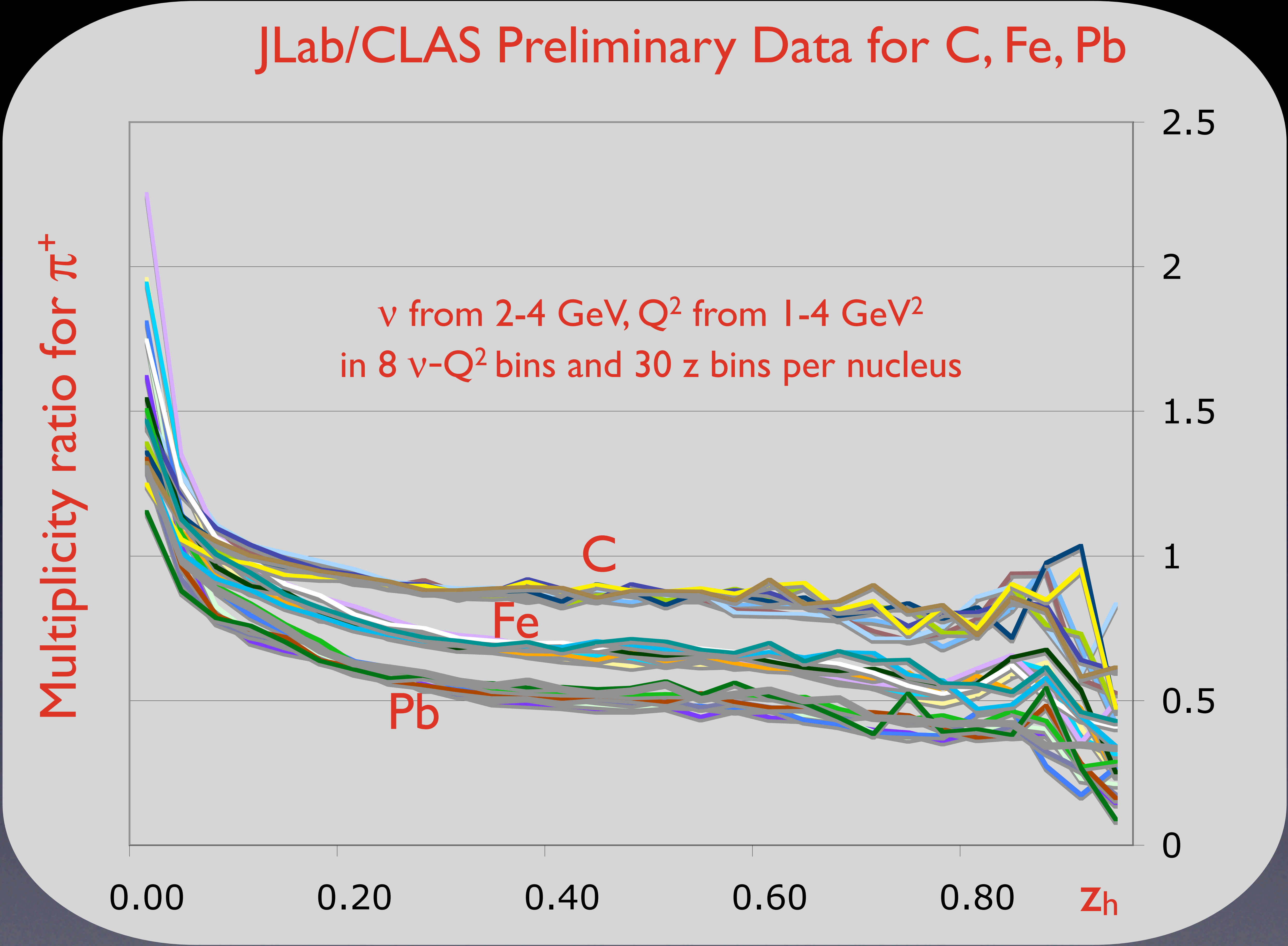




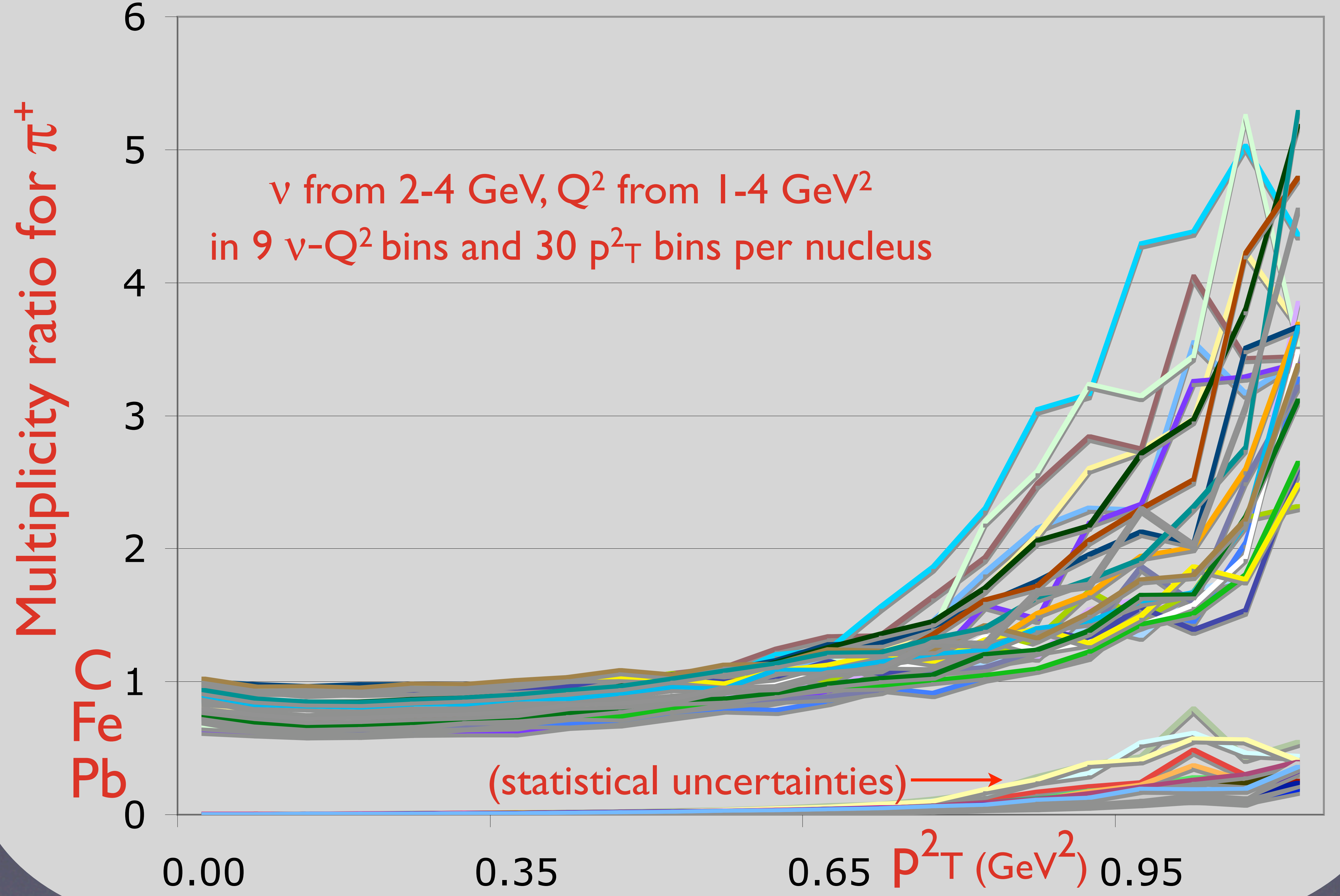
JLab/CLAS 3-D preliminary data

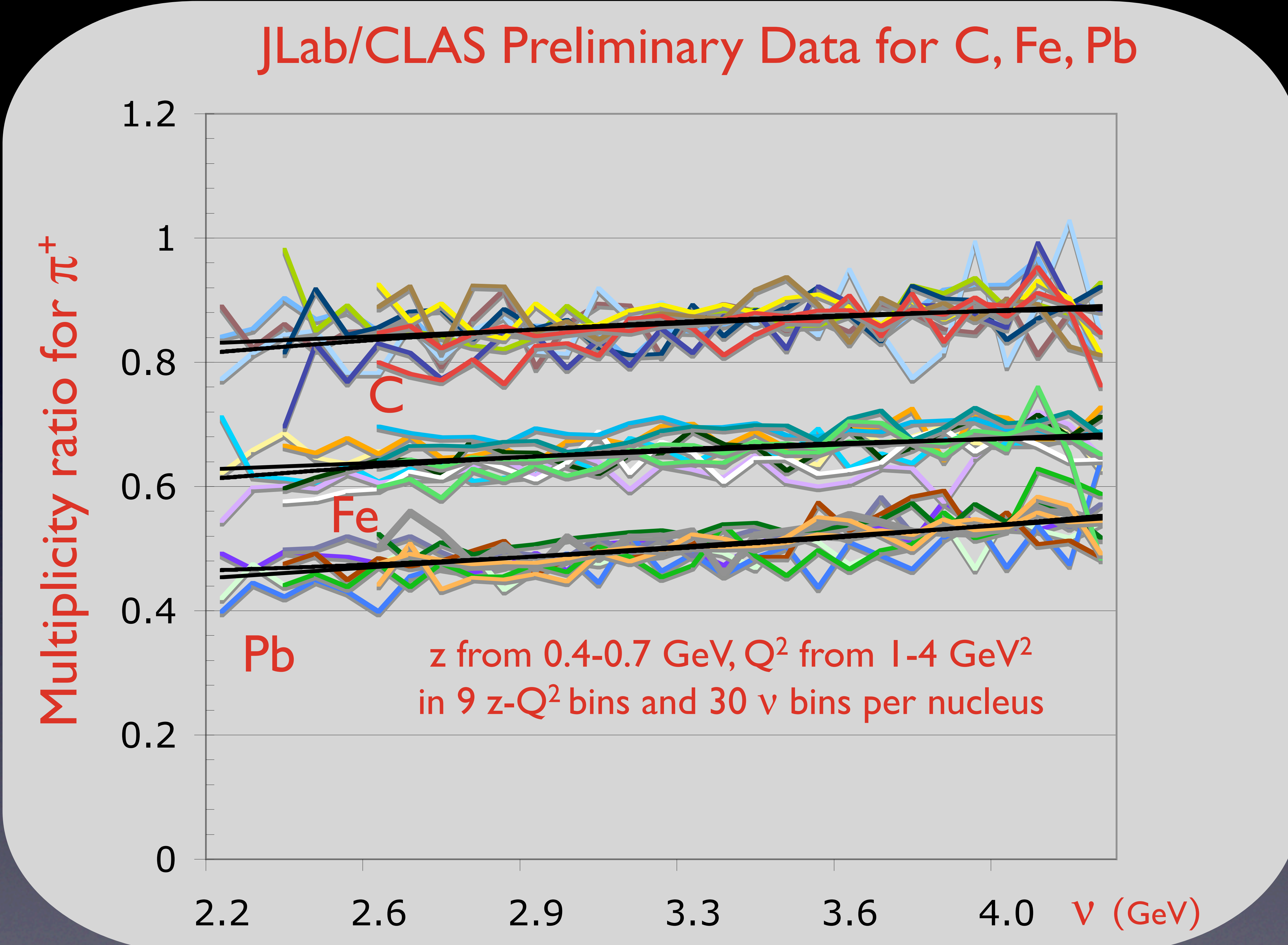


Four out of ~50 similar plots! K^0, π^-, π^0, Λ underway

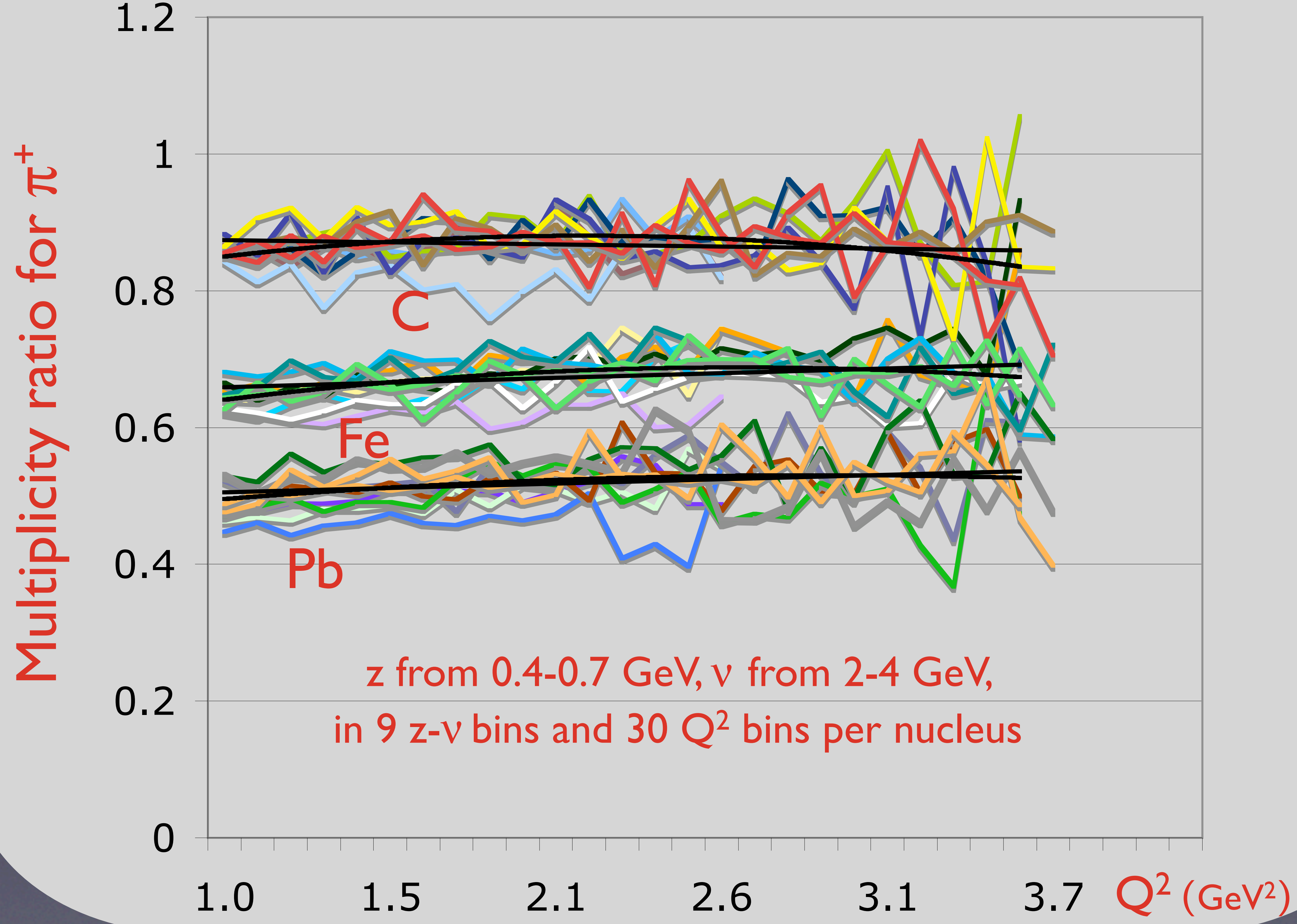

JLab/CLAS Preliminary Data for C, Fe, Pb
ν from 2-4 GeV, Q² from 1-4 GeV²
in 8 ν-Q² bins and 30 z bins per nucleus
Multiplicity ratio for π⁺
C
Fe
Pb
2.5
2
1.5
1
0.5
0
0.00
0.20
0.40
0.60
0.80
zh

JLab/CLAS Preliminary Data for C, Fe, Pb




JLab/CLAS Preliminary Data for C, Fe, Pb
Multiplicity ratio for π+
1.2
1
0.8
0.6
0.4
0.2
0
C
Fe
Pb
z from 0.4-0.7 GeV, Q2 from 1-4 GeV2
in 9 z-Q2 bins and 30 ν bins per nucleus
2.2
2.6
2.9
3.3
3.6
4.0
ν (GeV)

JLab/CLAS Preliminary Data for C, Fe, Pb

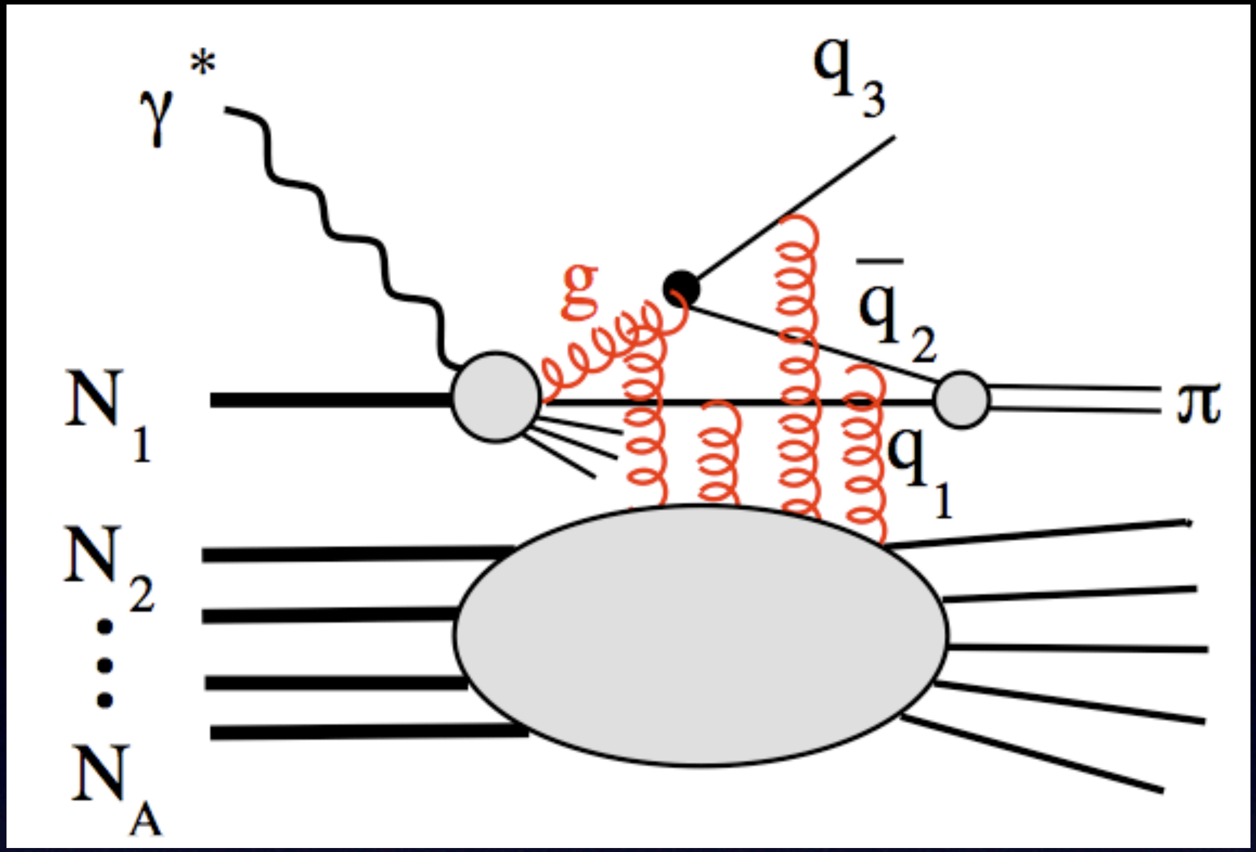


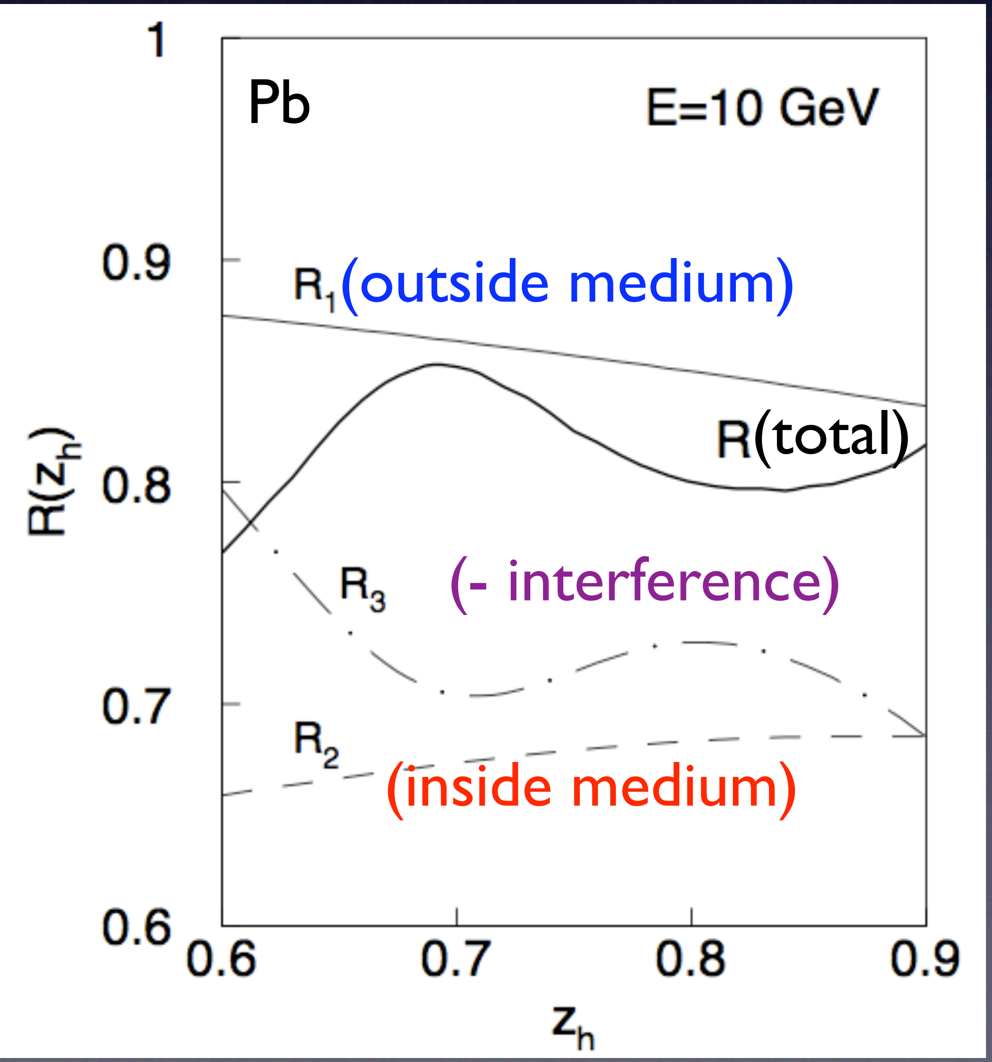
Latest Results: Hadron Attenuation from Quantum Interference

- 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

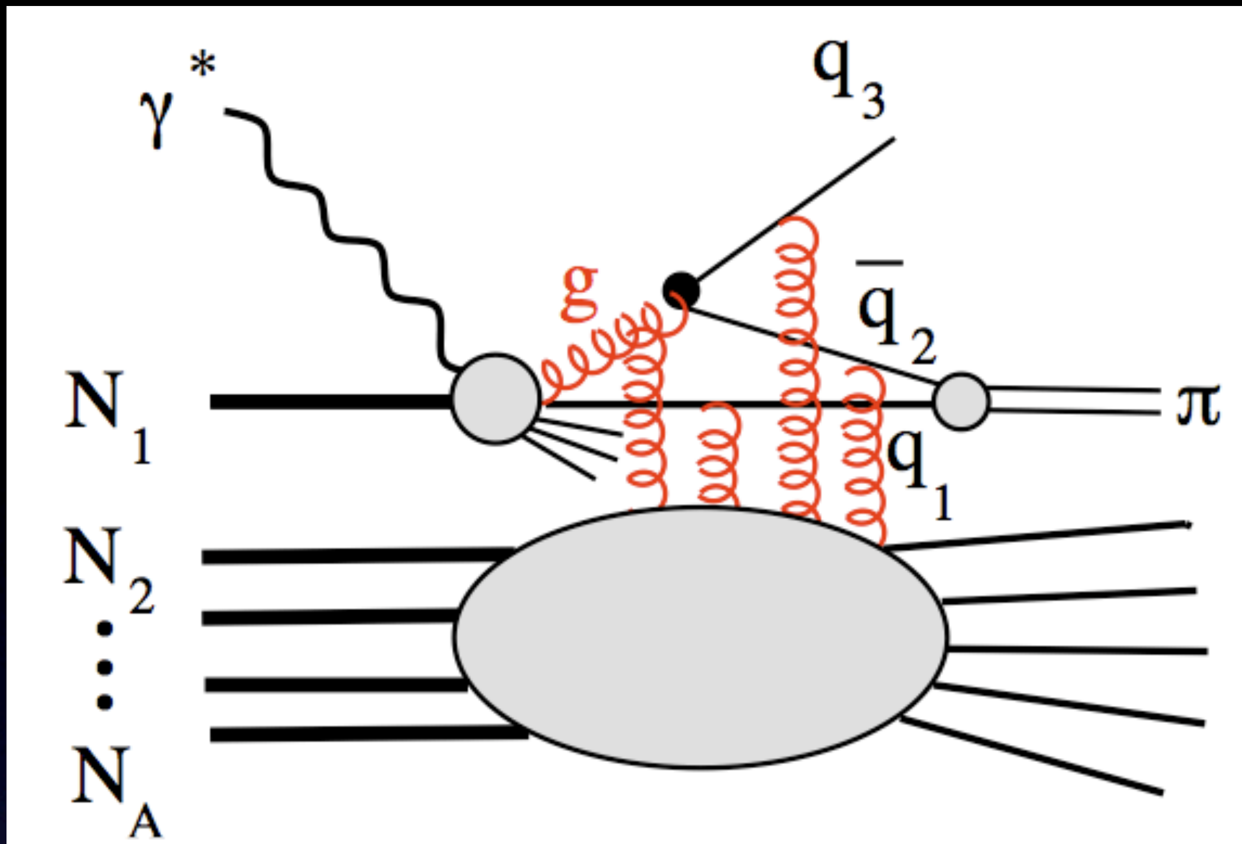
Inner/outer interference generates hadron 'attenuation': in-medium interactions affect overlap of dipole to pion wave function

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]

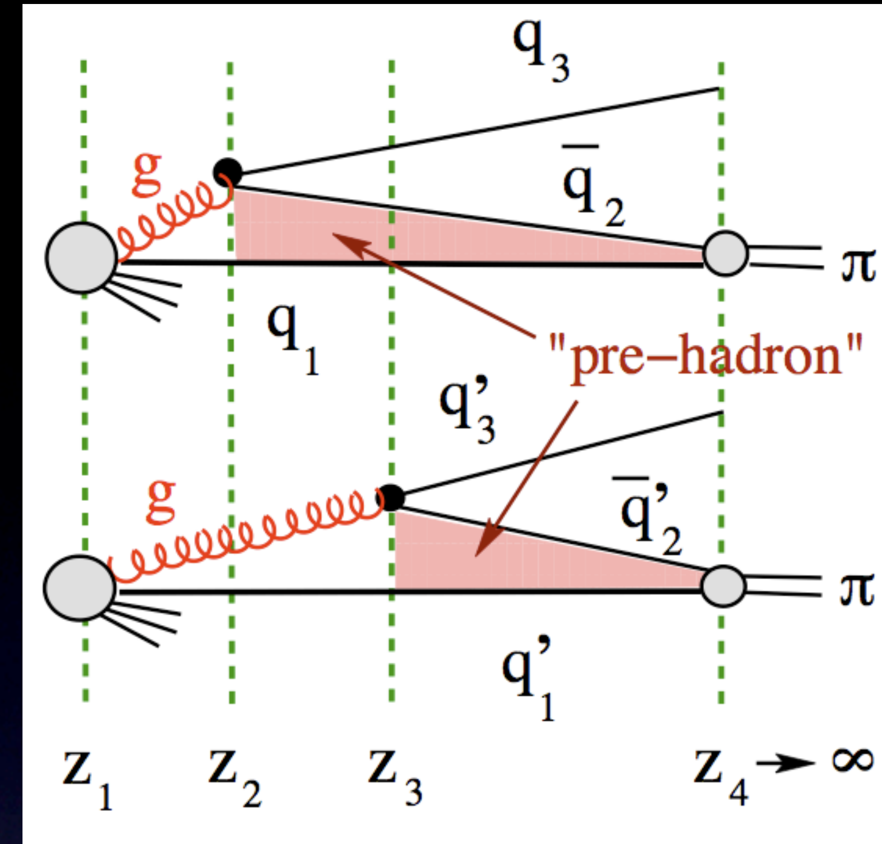

γ*
q3
g
q̄2
N1
π
q1
N2
NA


Pb
E=10 GeV
R1(outside medium)
R(total)
R3
(- interference)
R2
(inside medium)
R(zh)
zh
1
0.9
0.8
0.7
0.6
0.6
0.7
0.8
0.9

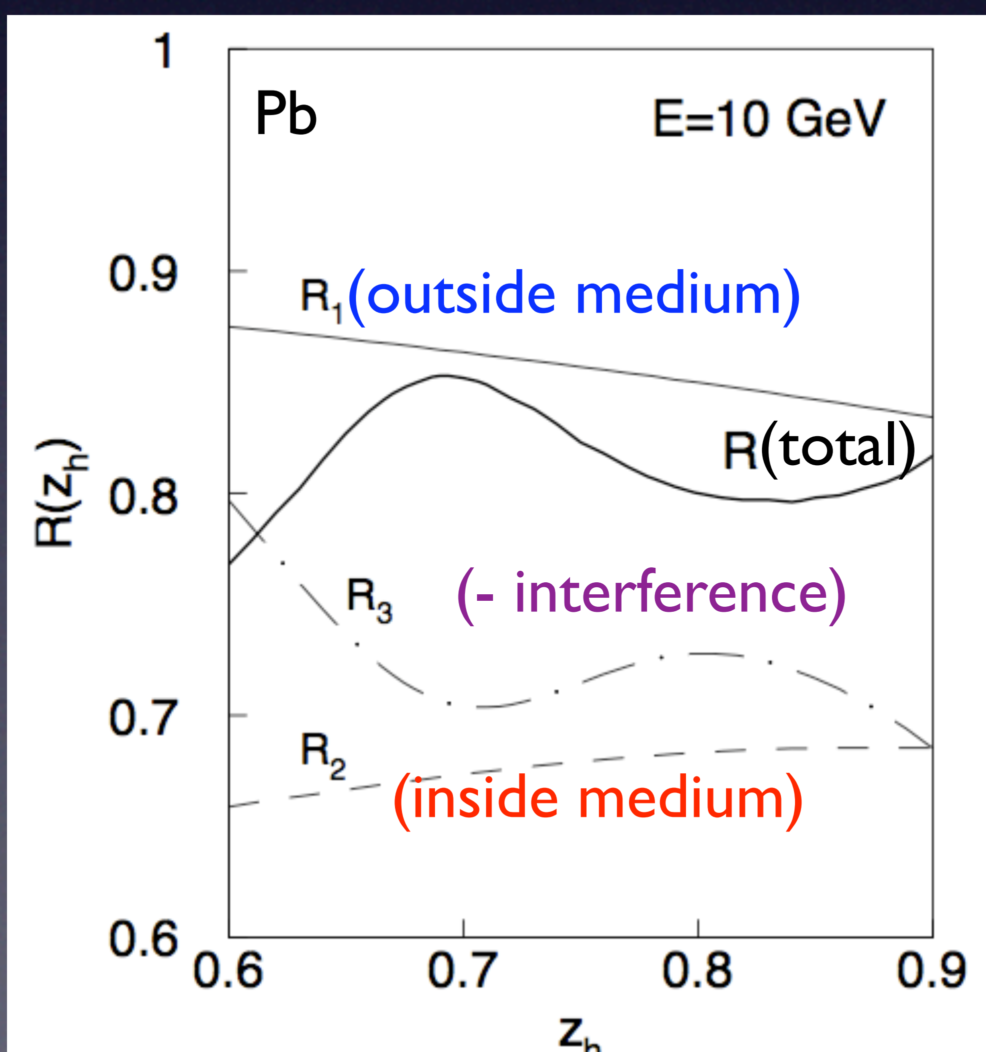
Pb



γ*
q3
g
q̄2
N1
π
q1
N2
NA

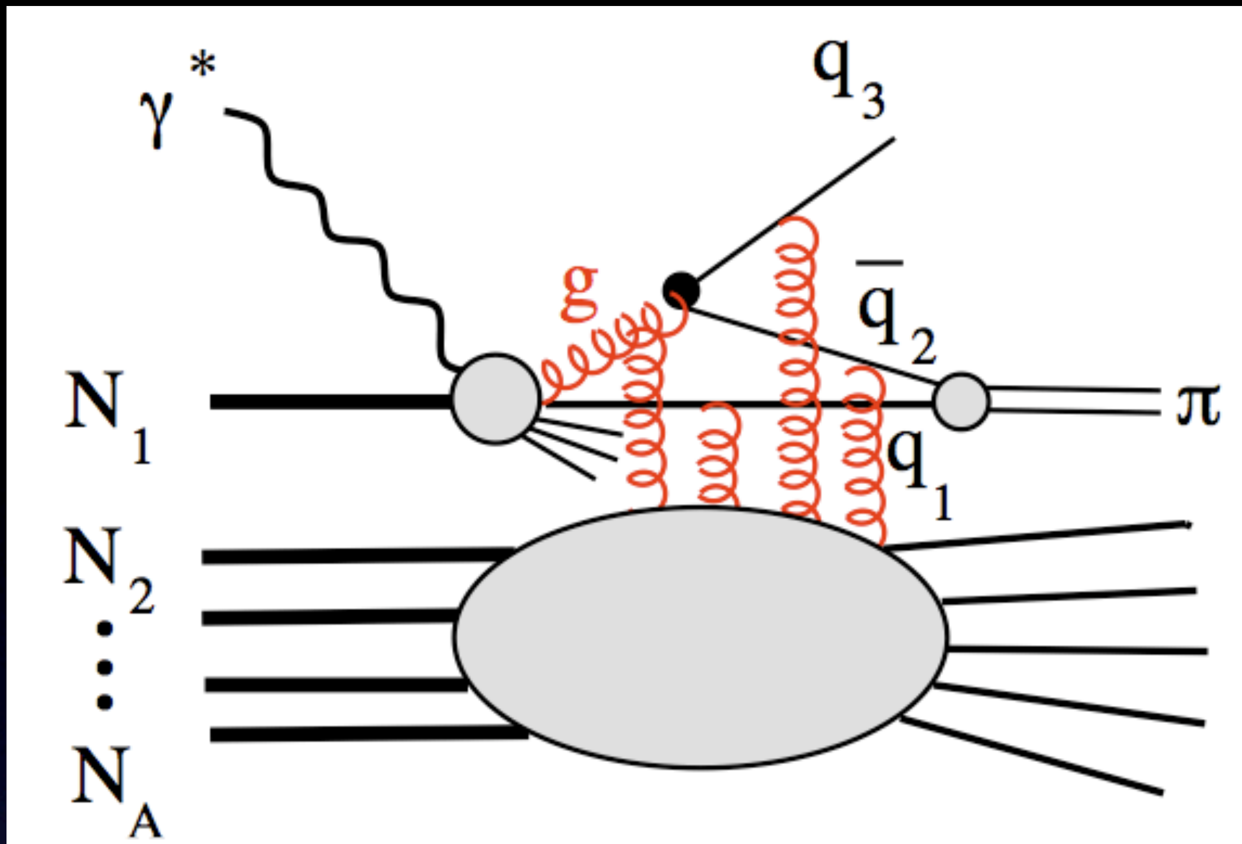


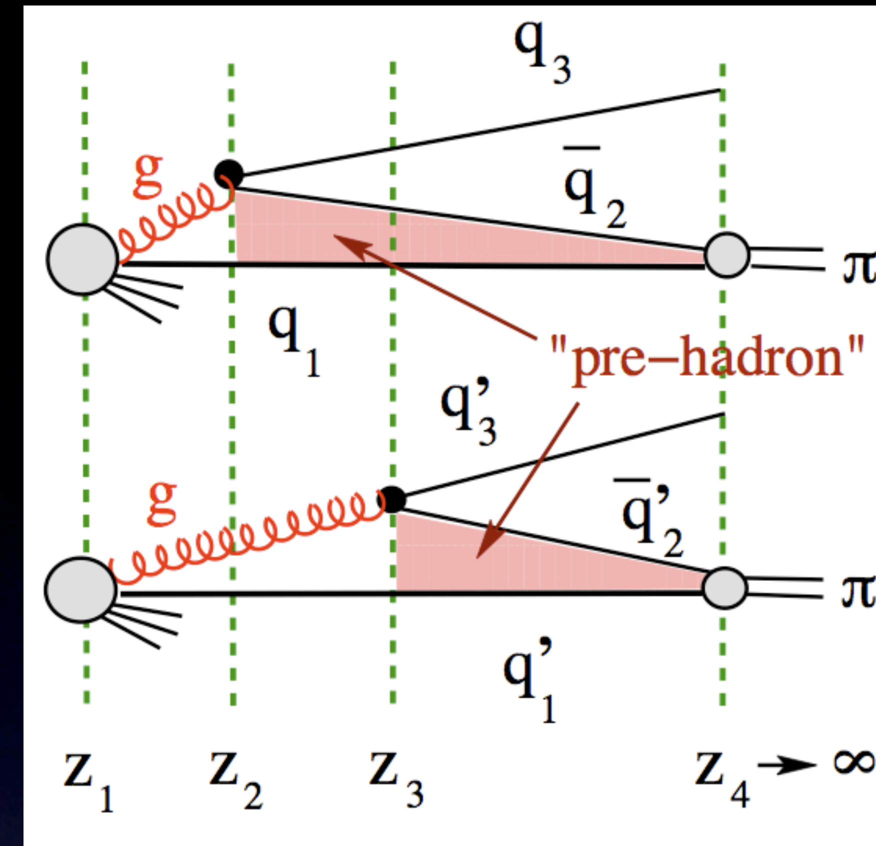
q3
g
q̄2
π
q1
"pre–hadron"
q'3
g
q̄'2
π
q'1
z1
z2
z3
z4 → ∞

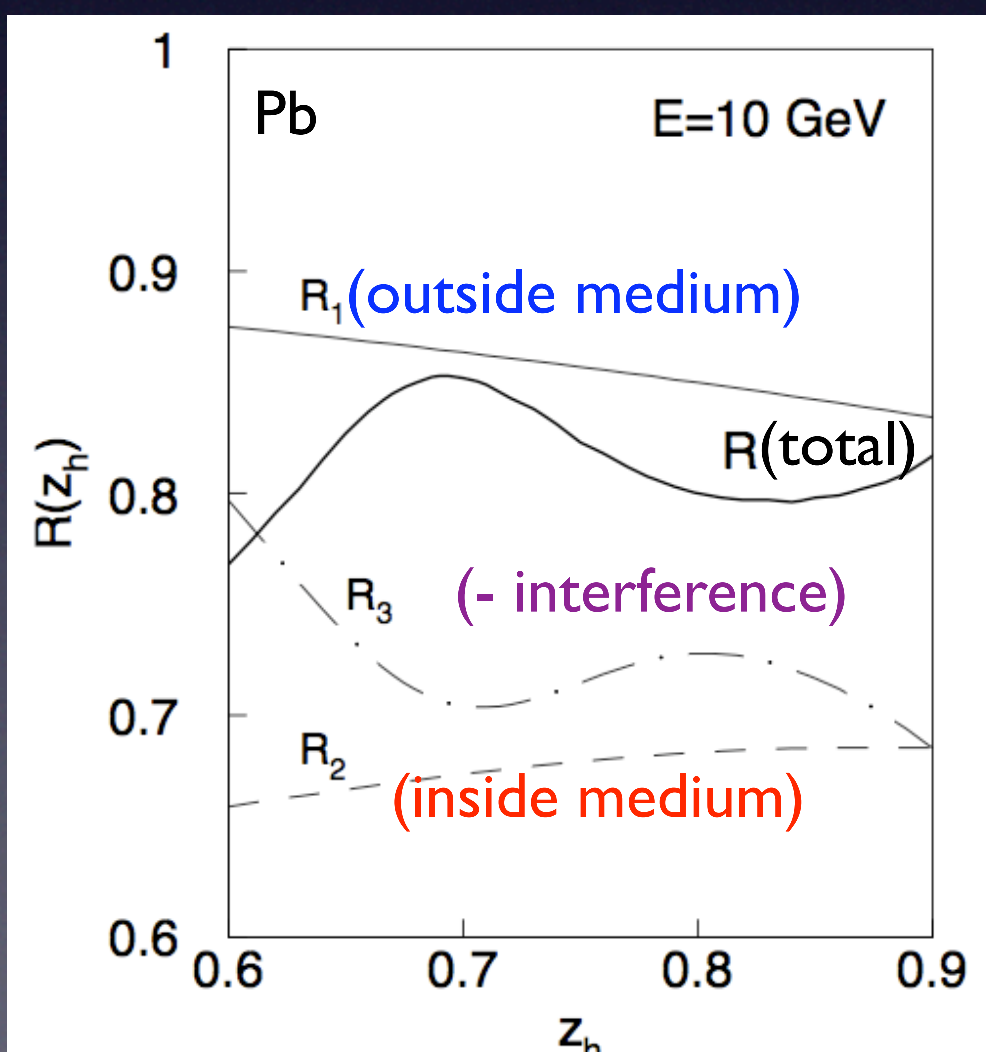


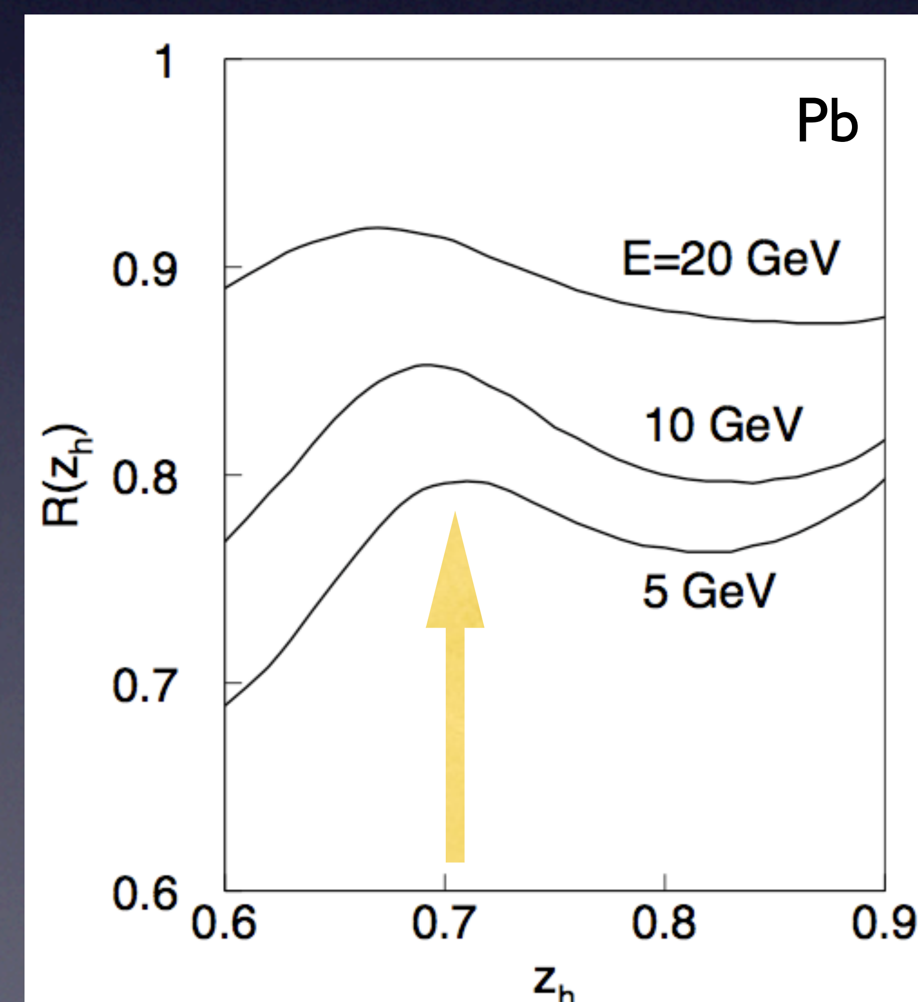
Pb
E=10 GeV
R1(outside medium)
R(total)
R3
(- interference)
R2
(inside medium)
R(zh)
zh
1
0.9
0.8
0.7
0.6
0.6
0.7
0.8
0.9

Pb


γ*
q3
g
q̄2
N1
π
q1
N2
NA

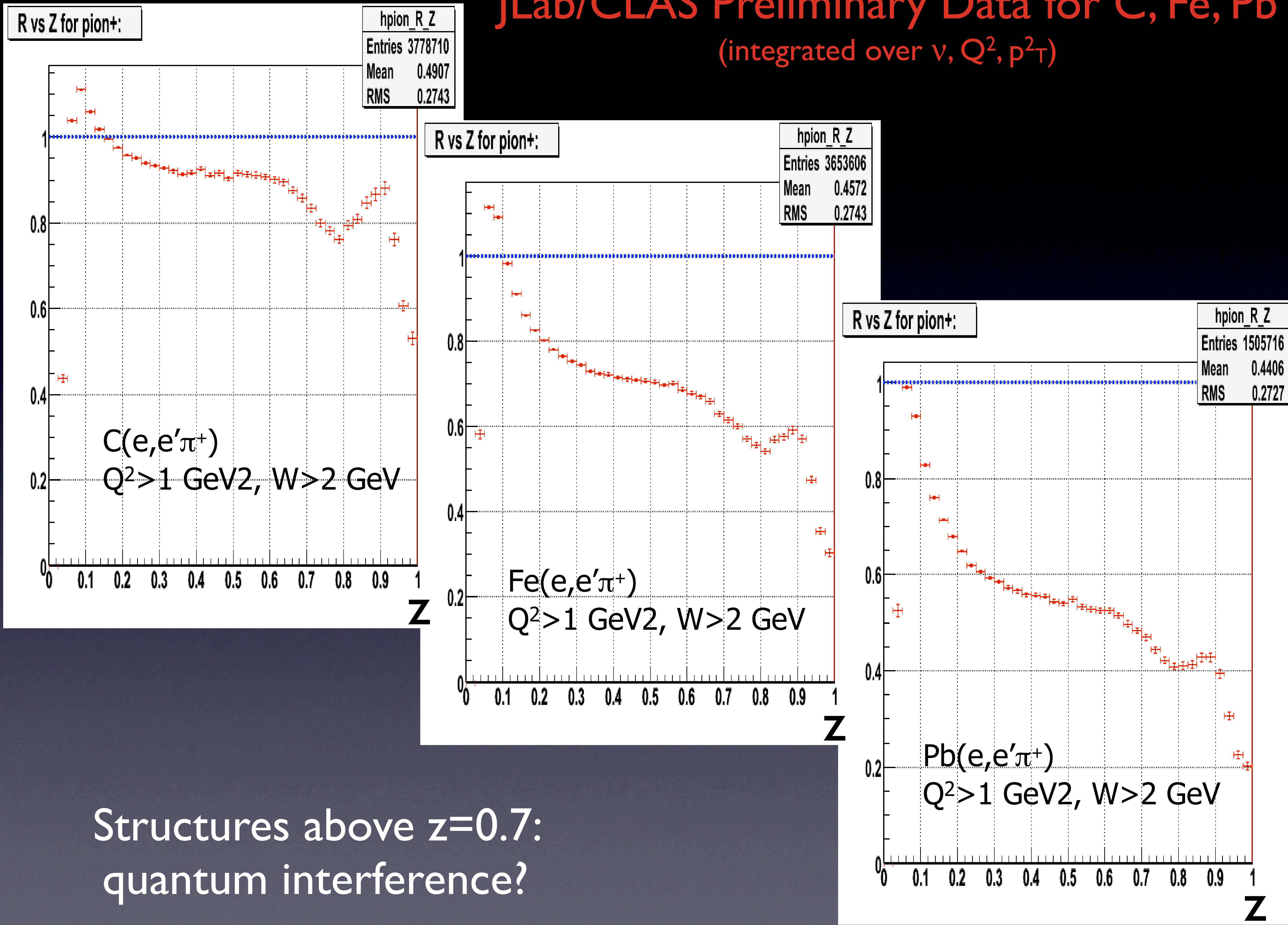

q3
g
q̄2
π
q1
"pre−hadron"
q'3
g
q̄'2
π
q'1
z1
z2
z3
z4 → ∞


Pb
E=10 GeV
R1(outside medium)
R(total)
R3
(- interference)
R2
(inside medium)
R(zh)
zh
1
0.9
0.8
0.7
0.6
0.6
0.7
0.8
0.9


Pb
E=20 GeV
10 GeV
5 GeV
R(zh)
zh
1
0.9
0.8
0.7
0.6
0.6
0.7
0.8
0.9

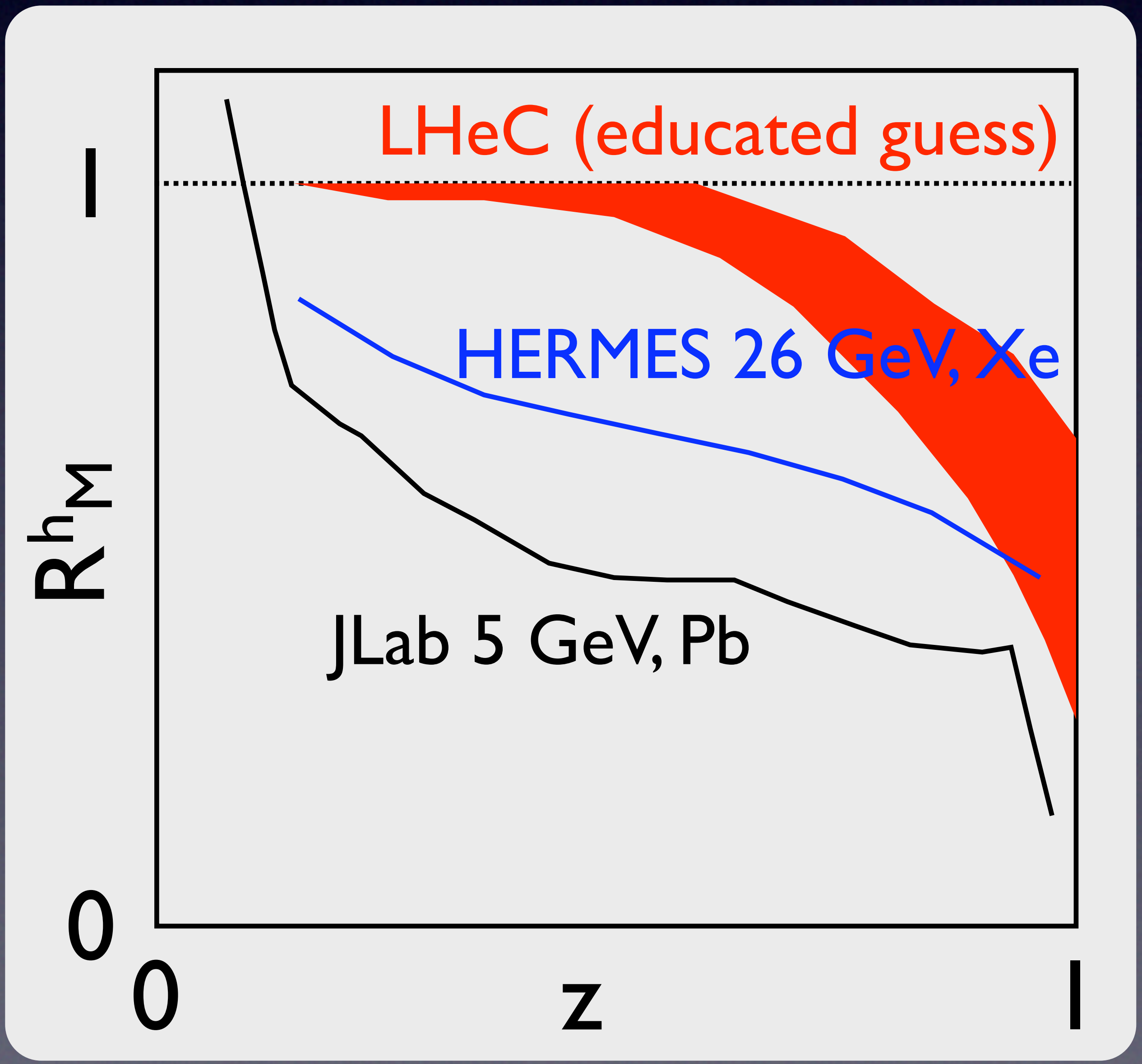
JLab/CLAS Preliminary Data for C, Fe, Pb

(integrated over ν, Q^2, p^2_T)



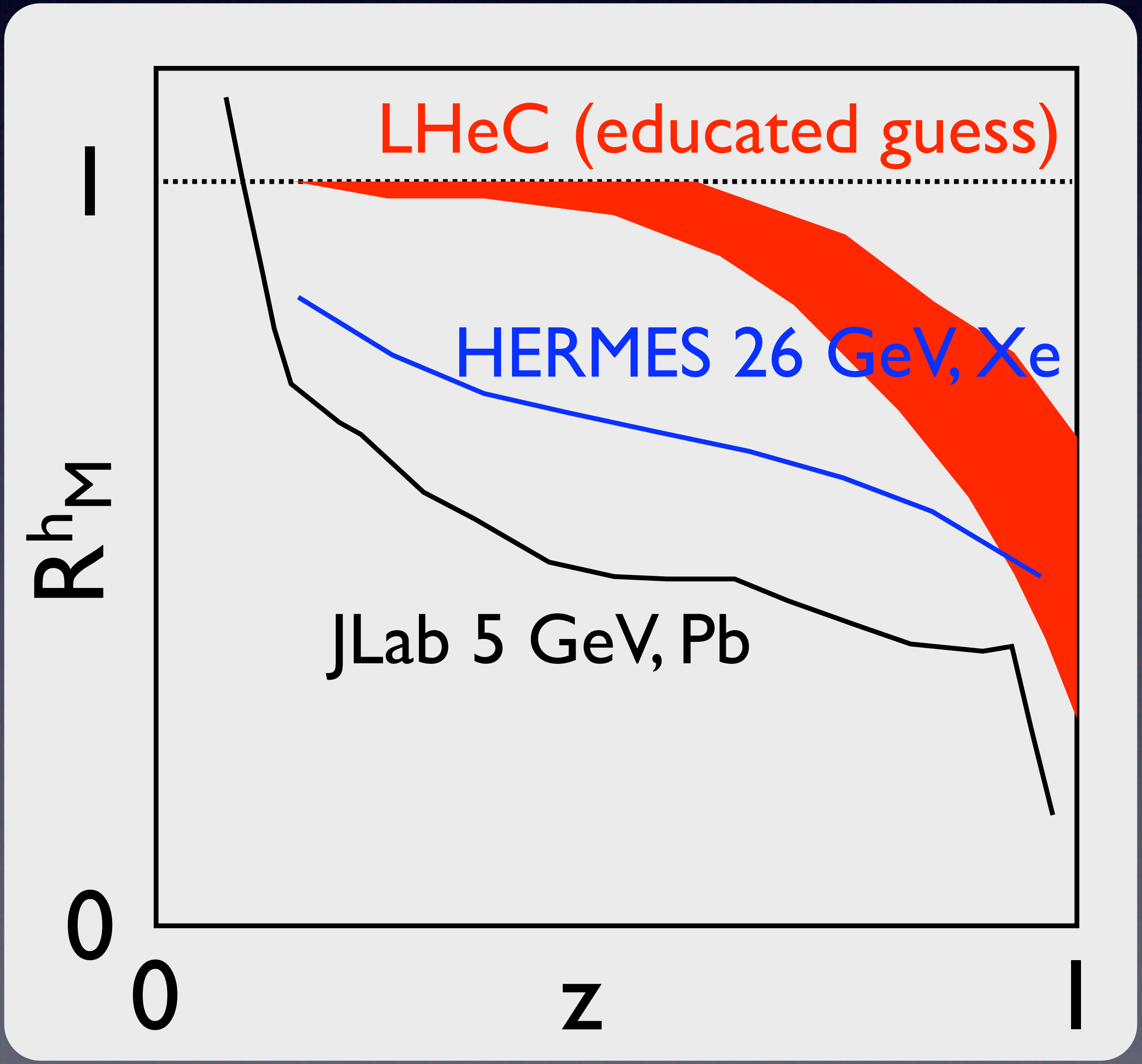
Structures above z=0.7:
quantum interference?

AT LHEC



AT 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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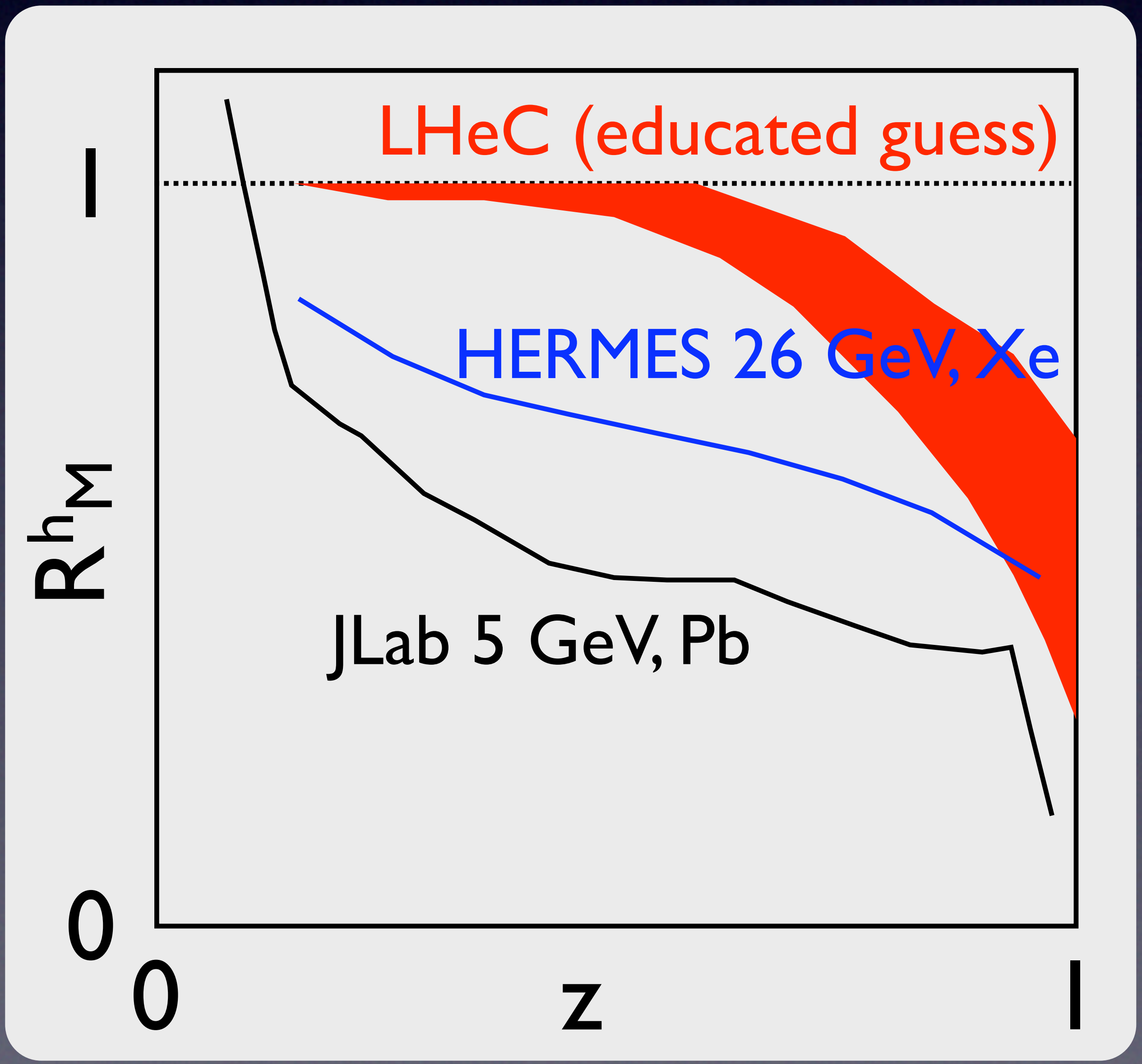

- Authors explain a variety of data within same picture - suppression of particle production in dA, pA at large x_F

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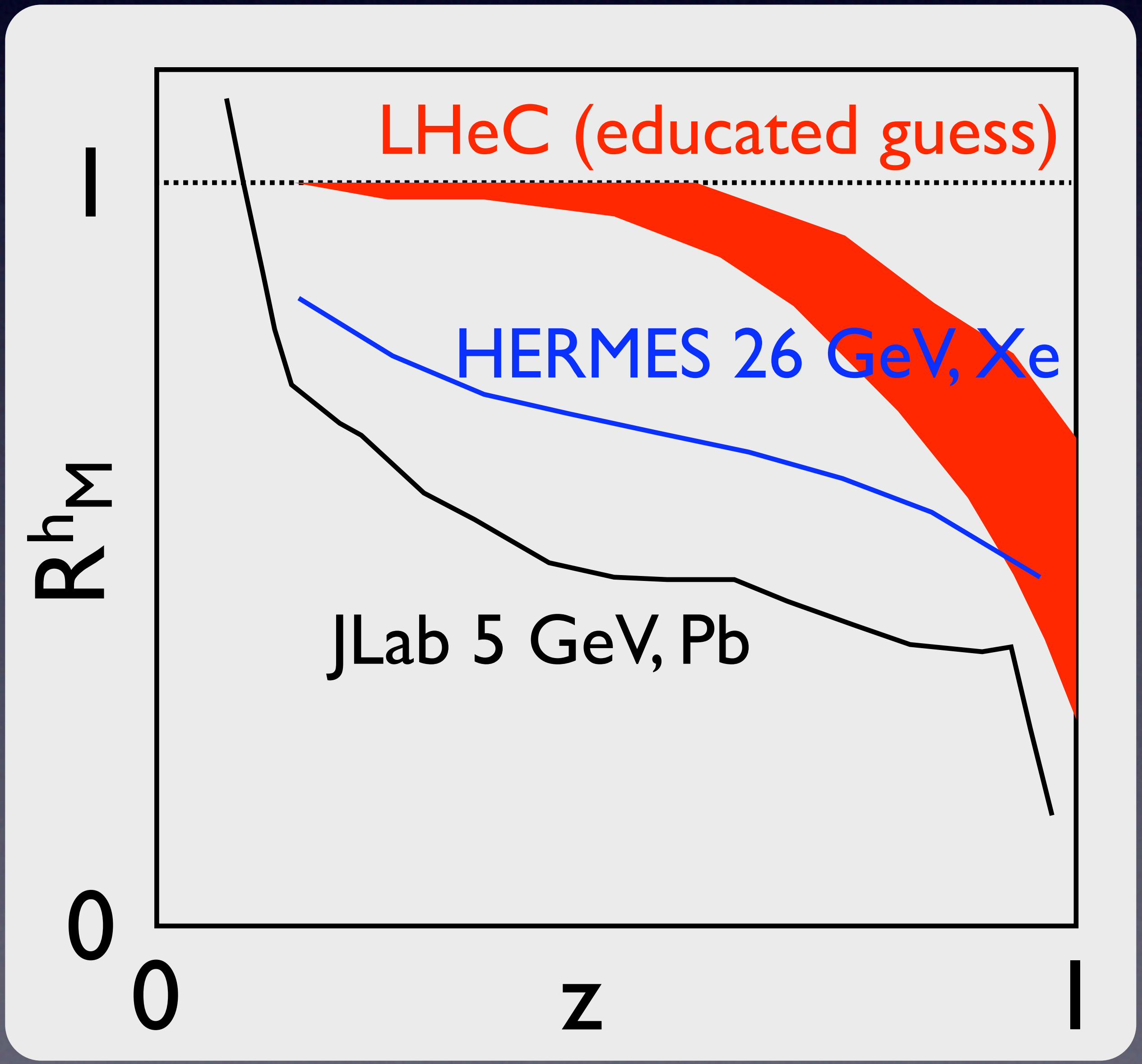

- Authors explain a variety of data within same picture - suppression of particle production in dA, pA at large x_F

- 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

FUTURE PROSPECTS

- FNAL: E906 Drell-Yan at 120 GeV
- LHC RHI data
- RHIC upgrades
- JLab@12 GeV - CLAS12 and Hall D
- EIC
- LHeC

CONCLUSIONS

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- A new wave of precision data!

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- Extraction of space-time behavior in fundamental QCD processes: gluon bremsstrahlung and hadron formation
    - production times
    - formation times
    - transport coefficients
    - possibly even the critical length L_c??

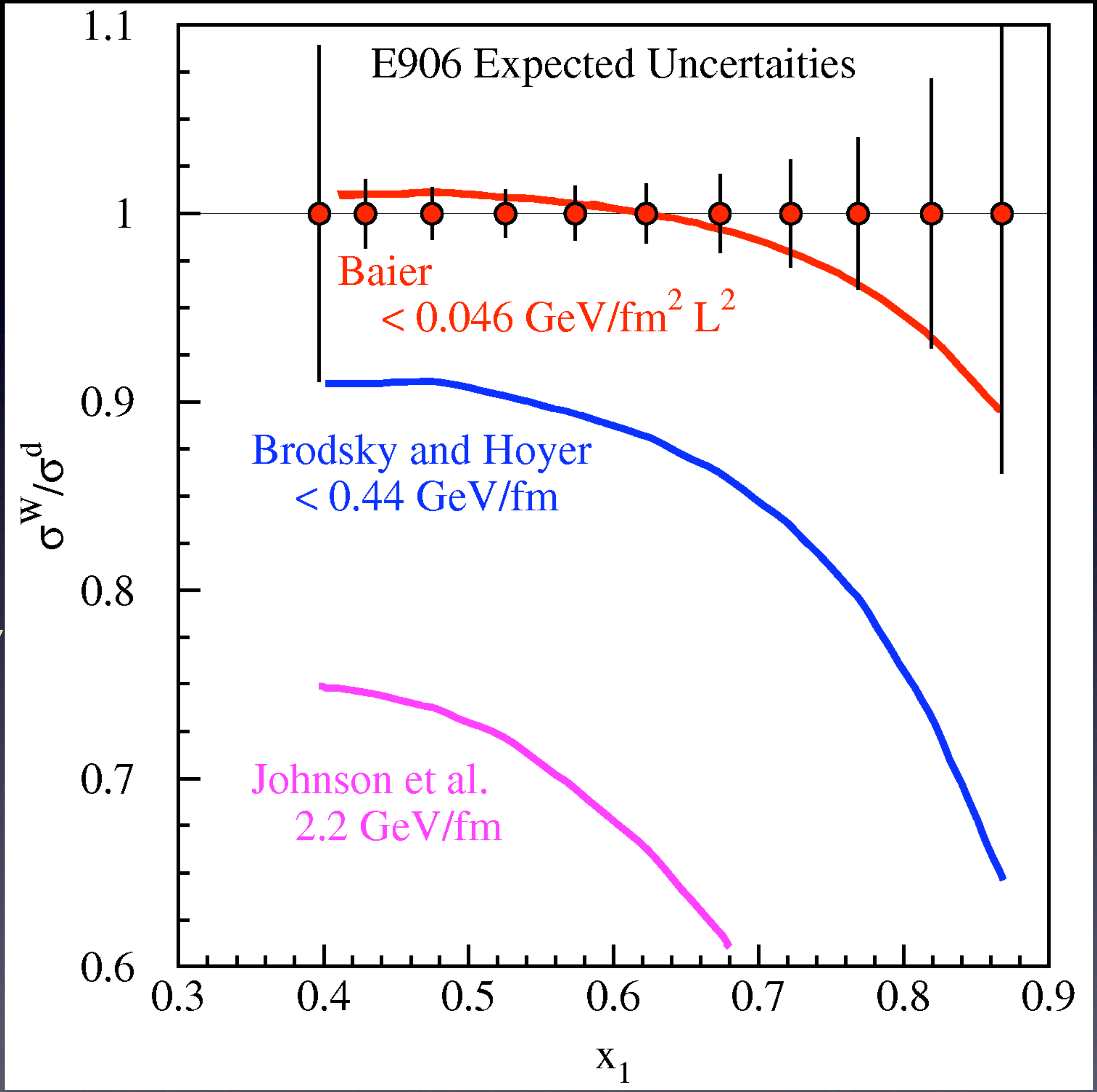
CONCLUSIONS

- A new wave of precision data!
- Extraction of space-time behavior in fundamental QCD processes: gluon bremsstrahlung and hadron formation
    - production times
    - formation times
    - transport coefficients
    - possibly even the critical length L_c??
- LHeC will test prediction of factorization breakdown at large x_F, may provide insight on p_T broadening/energy loss

Future Prospects

FNAL E906

- Drell-Yan at 120 GeV
- Remove analysis ambiguity between shadowing and energy loss



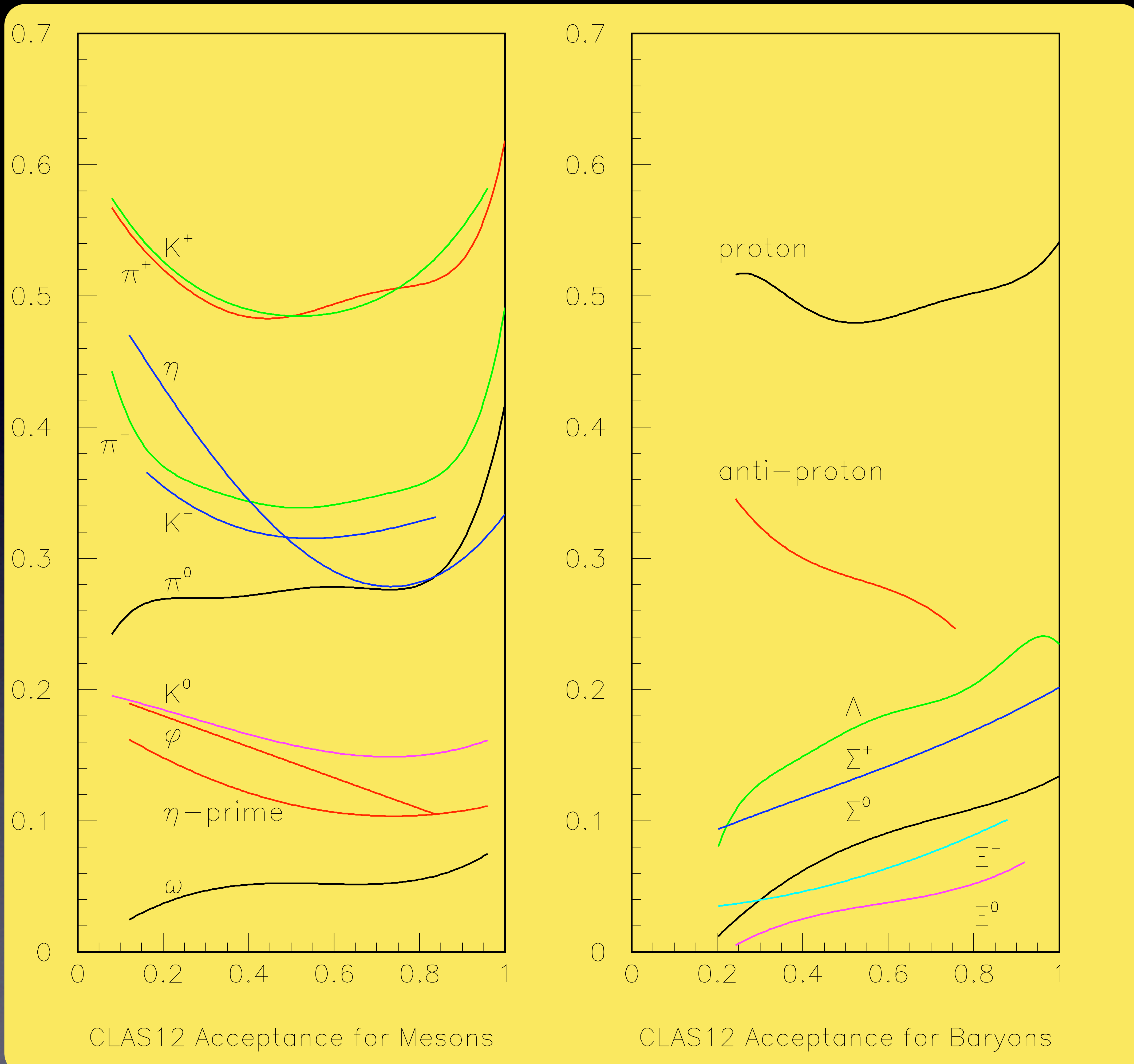
Paul Reimer, EINN 2005

Examples of Experimental Data and Theoretical Predictions

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

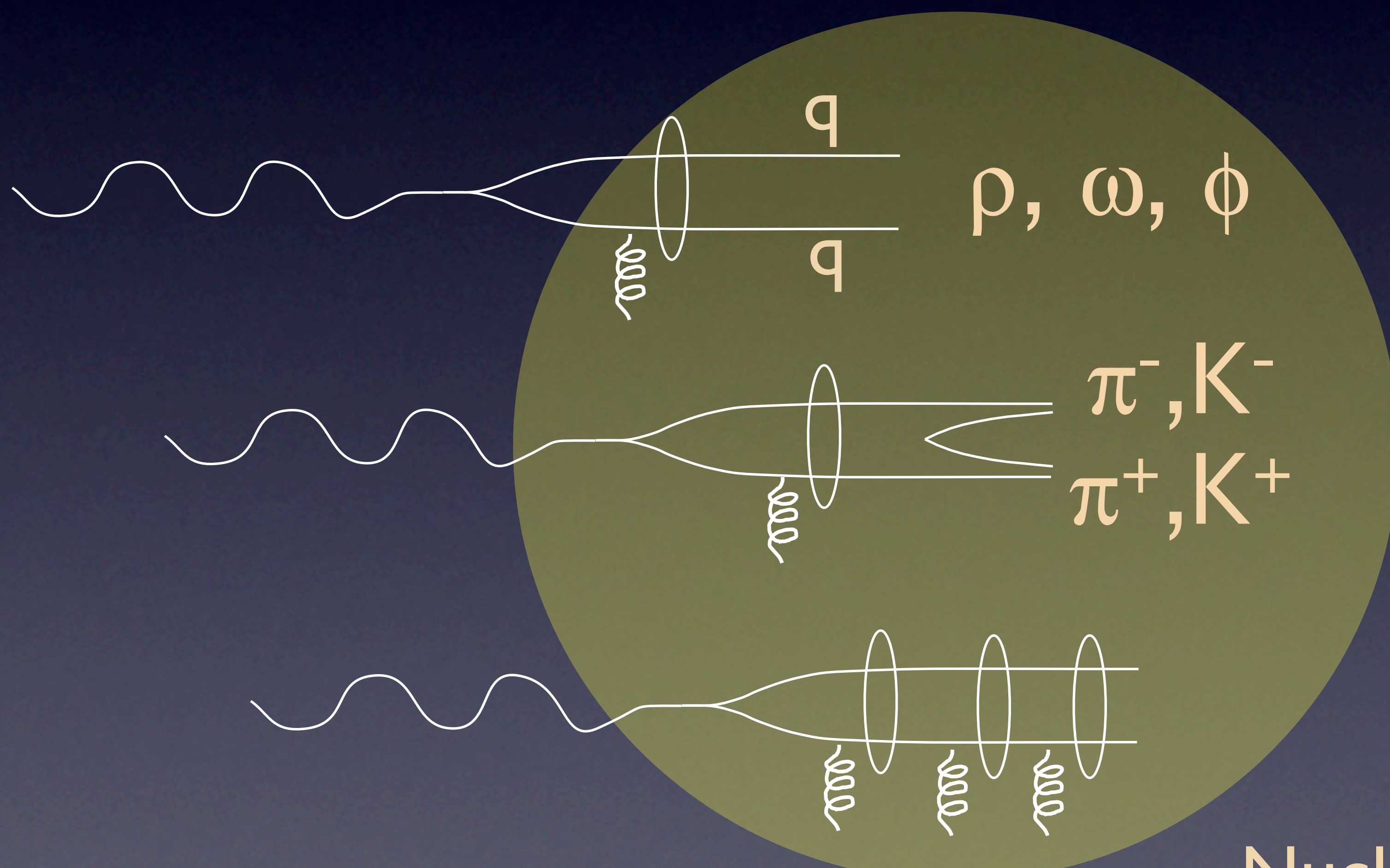
CLAS12 Geometric Acceptances for Mesons and Baryons



Hall D p_T Broadening Measurements

(Jefferson Lab at 12 GeV)

Processes in-medium:



Color-neutral
2-gluon exchange

In-medium **broadening of (transverse) dipole momentum**
(ρ, ω, ϕ, π, K)

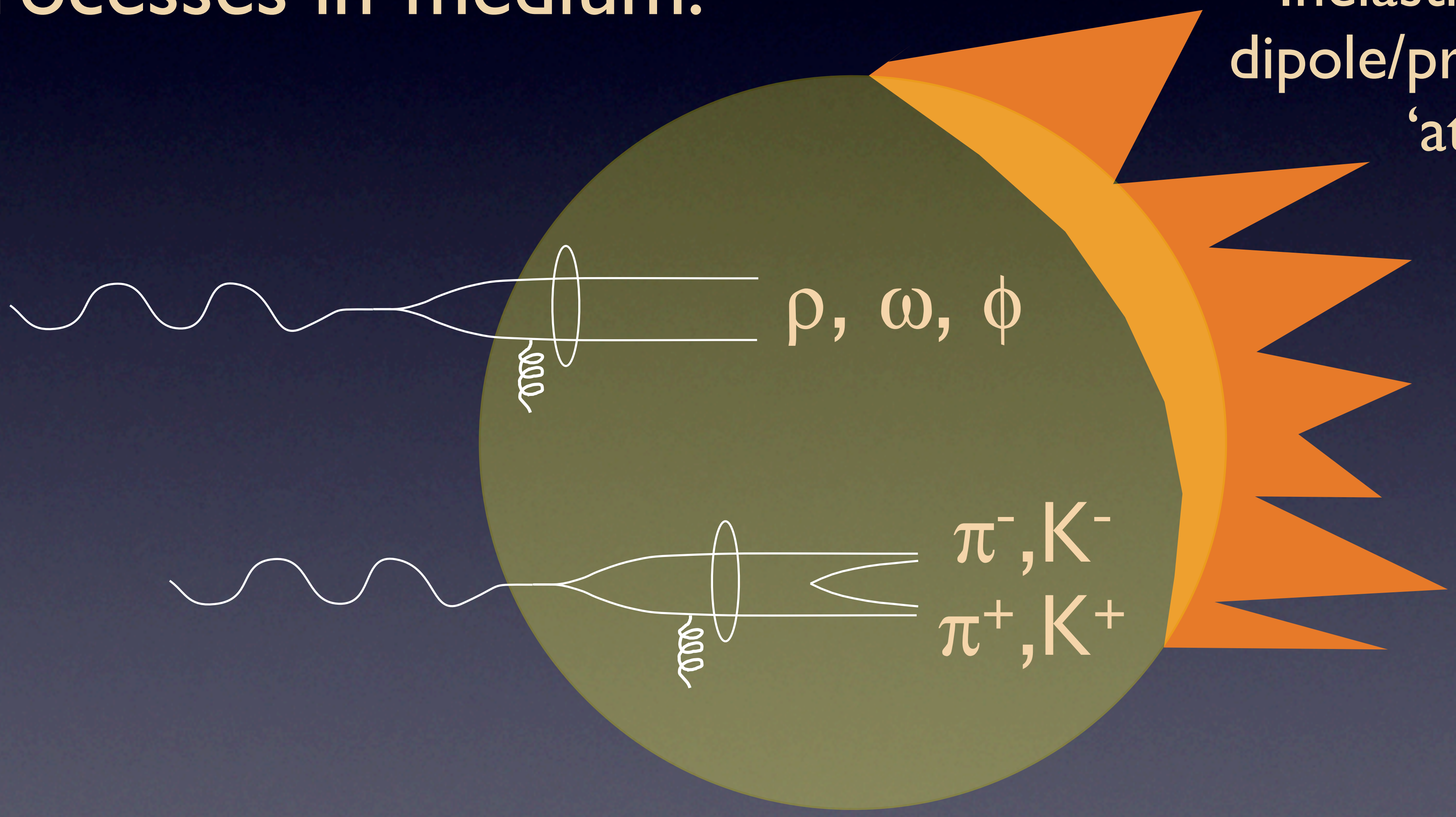
Nucleus not excited: coherent

Nucleus excited/breaks up: incoherent

Hall D Absorption Measurements

Processes in-medium:

Inelastic interaction of dipole/prehadron/meson - ‘attenuation’



Nucleus excited/breaks up: incoherent

COMPARISON: HERMES AND 6 GEV CLAS

- HERMES
  - More hadrons: all pions, protons, antiprotons, K^+, K^-
  - More ν (8-20 GeV vs. 2-4 GeV) and W_{max} (7 vs. 3)
- JLab
  - More luminosity (x100): 3D vs. 1D distributions
  - Heaviest targets (not limited to gas targets)