Experimental Studies of Color Propagation

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Outline

- Introduction
- Direct measurement of quark energy loss
- Extracting characteristic times: semi-inclusive DIS
    - HERMES data - comparison of our model results to Lund string model
    - JLab data - strong evidence for time dilation, comparison to string model HERMES
    - Connections to QCD factorization, to much higher energies, and hadronization in vacuum
- Extrapolation to 12 GeV and EIC kinematics

Aims

Quark-Hadron Transition

Discover new fundamental features of hadronization

- Characteristic time distributions
- Mechanisms of color neutralization

Quark-Nucleus Interaction

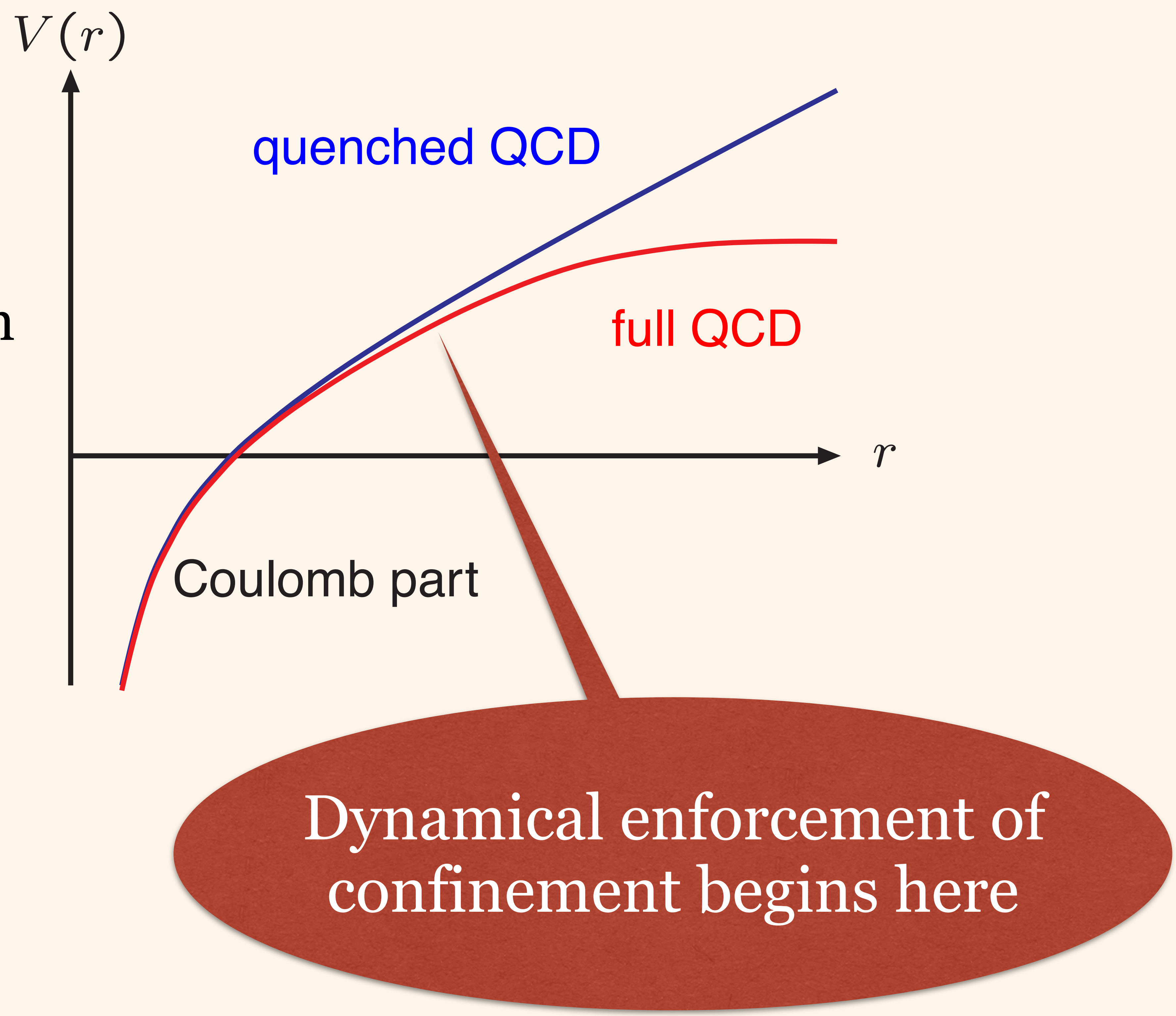
Understand how color interacts within nuclei

- Partonic interactions with medium
  - energy loss in-medium: $\hat{e}$
  - transverse momentum broadening: $\hat{q}$

Method: struck quark from DIS probes nuclei of different sizes

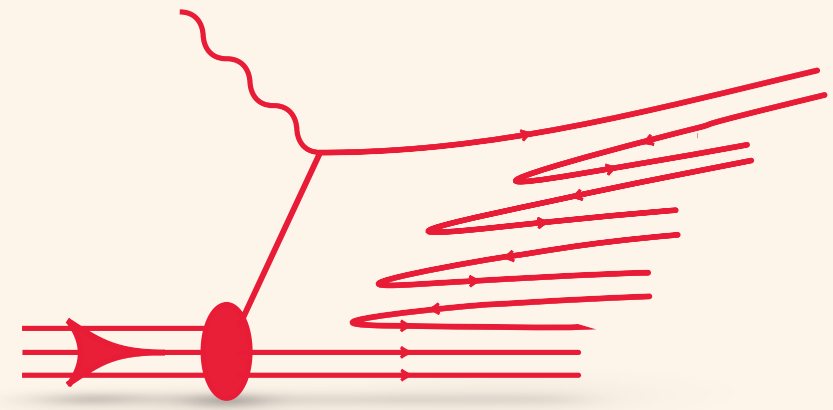
Connection to Confinement

V=0 at ~0.4 fm



Beyond ~1 fm the potential is irrelevant but confinement is still enforced

FUNDAMENTAL QCD PROCESSES
(DIS, pQCD picture)

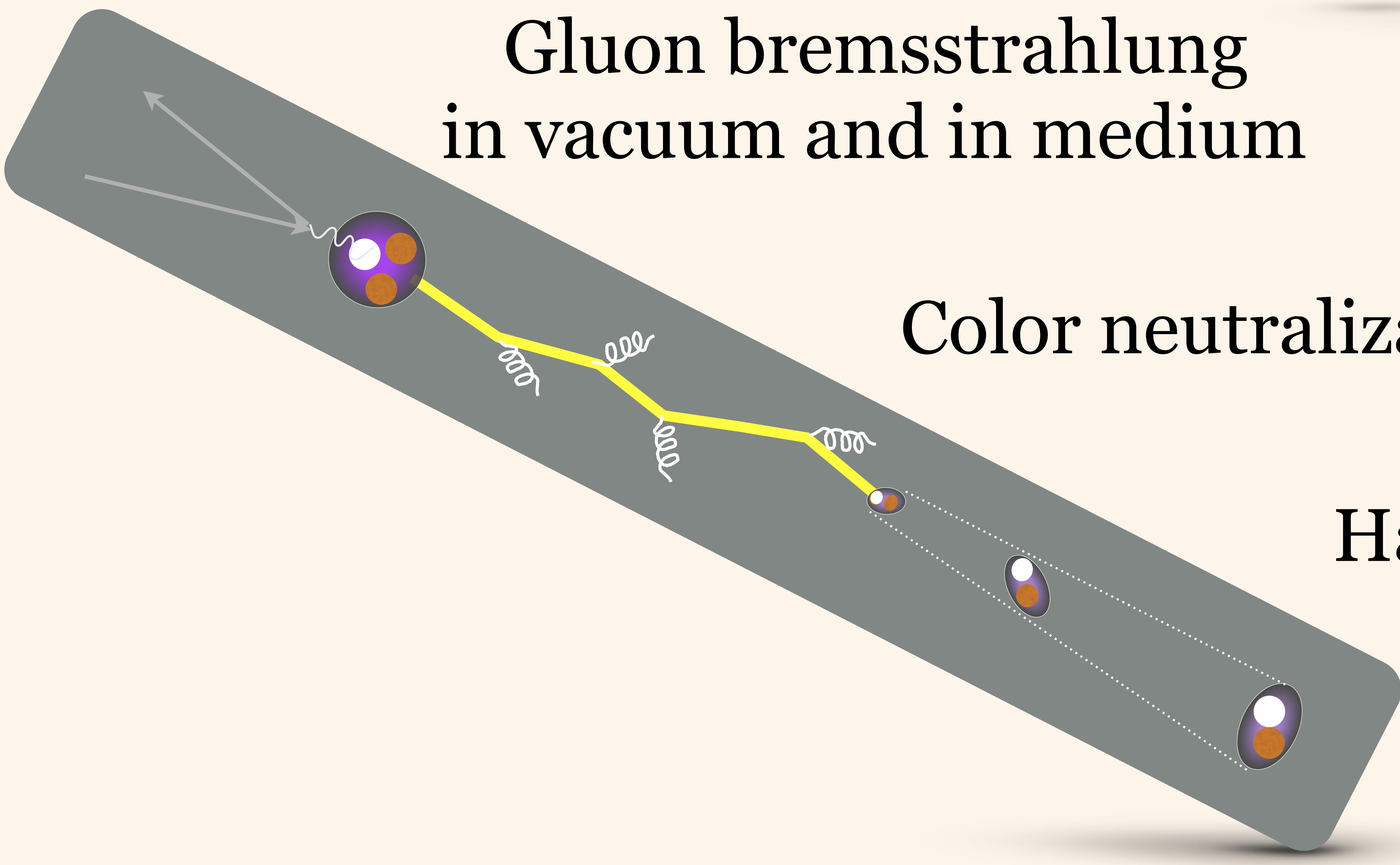


Partonic elastic scattering in medium

Gluon bremsstrahlung in vacuum and in medium

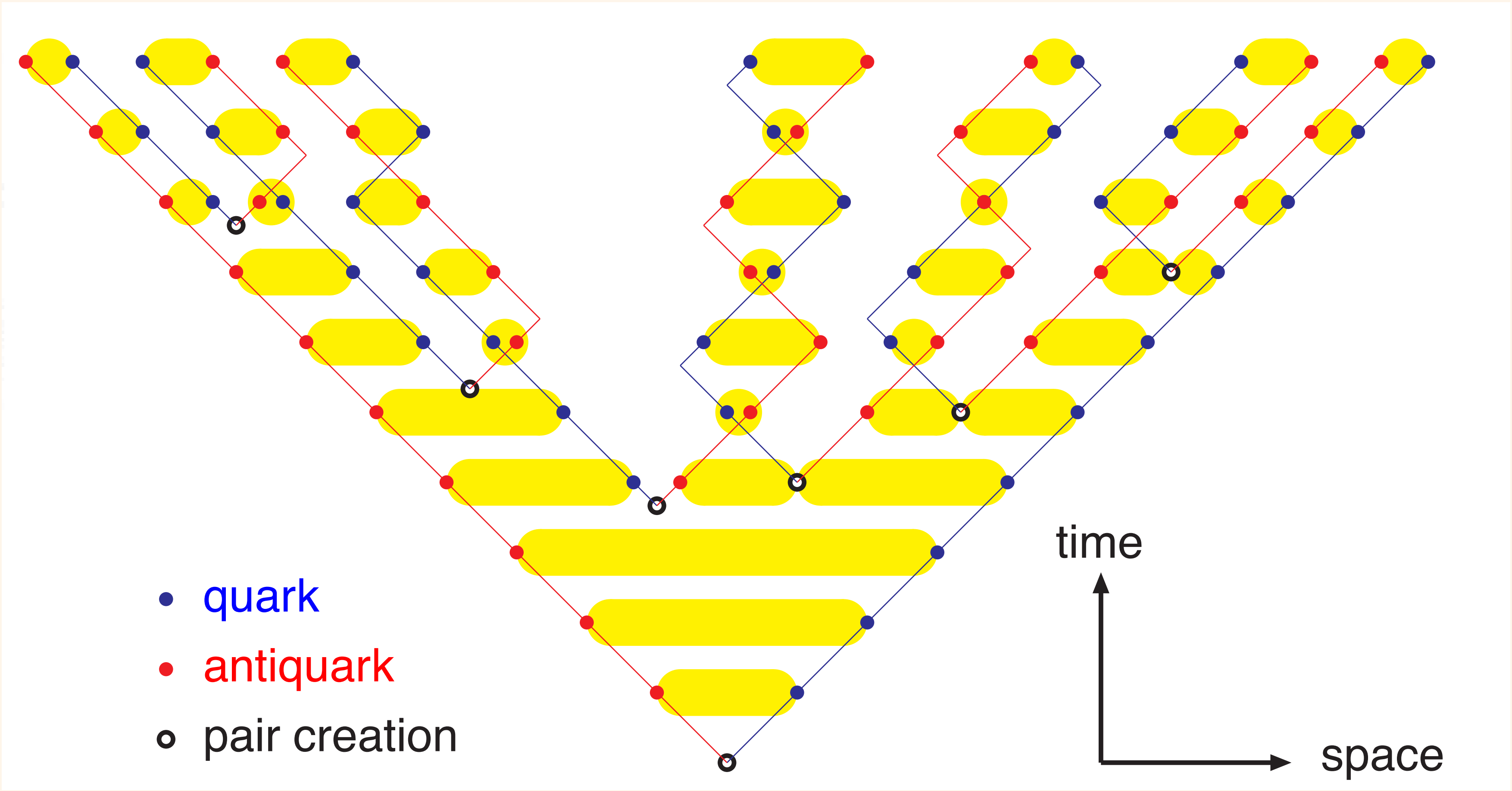
Color neutralization

Hadron formation



We implant this process in large nuclei and compare to deuterium

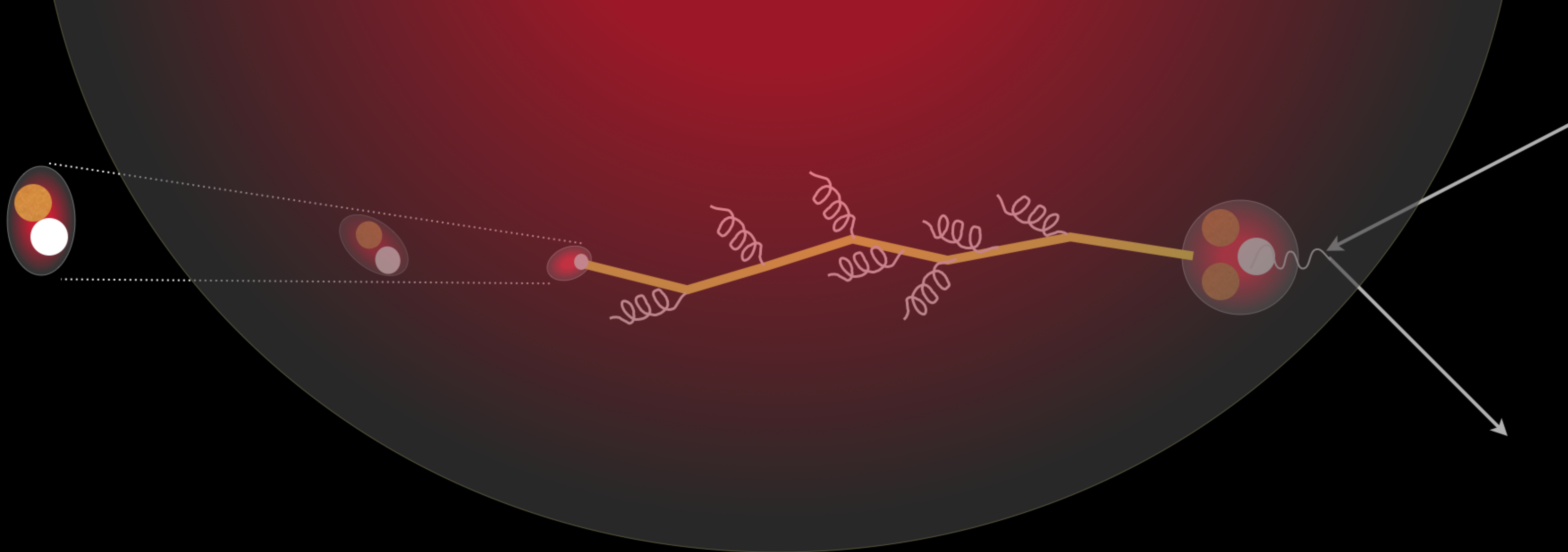
Lund String Model (~1983)



Remarkably successful model, foundational tool in HEP

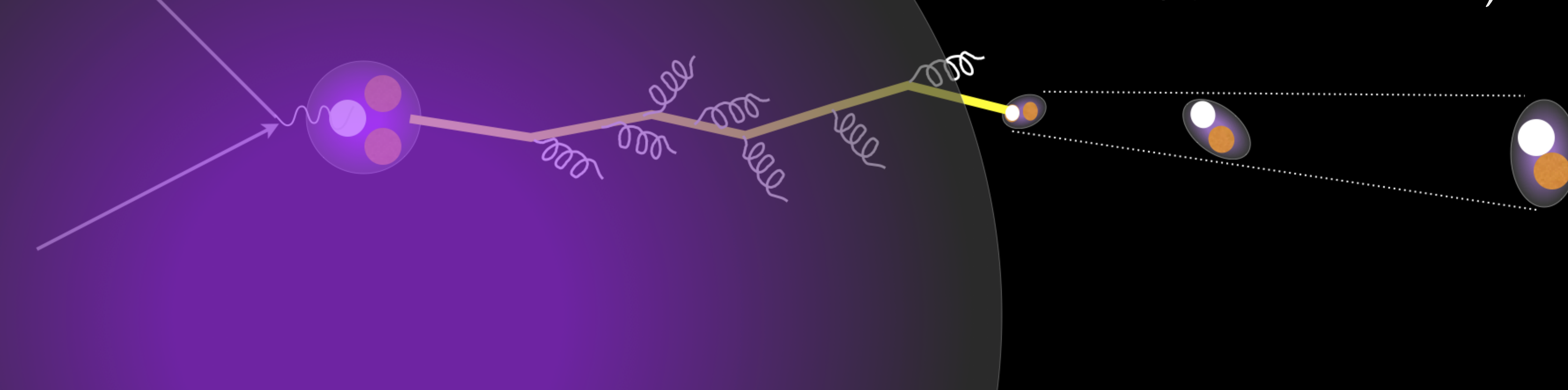
- Alternative physical picture to pQCD: emission of many gluons in vacuum, string as an average; quantitative
- Successful, but few connections to fundamental QCD
- We can *compare* some of our results to the Lund String Model, and other results to pQCD/Color Dipole Model

We use none of these in our analysis



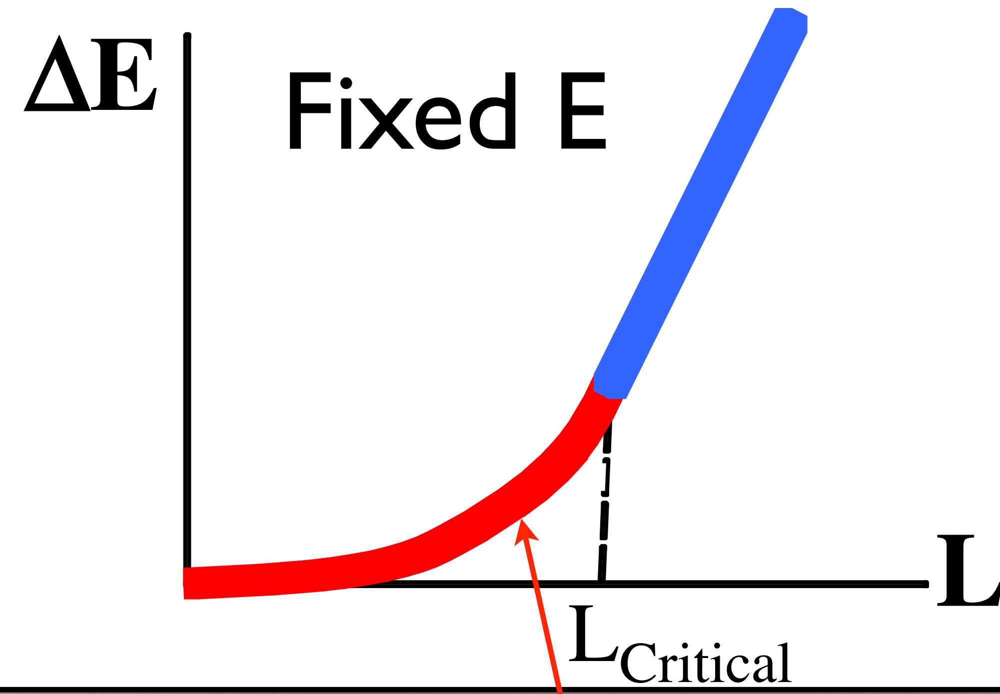
Direct measurement of quark energy loss

Collaboration: Miguel Arratia, Cristian Peña, Hayk Hakobyan, Sebastian Tapia, Oscar Aravena, WB



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

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

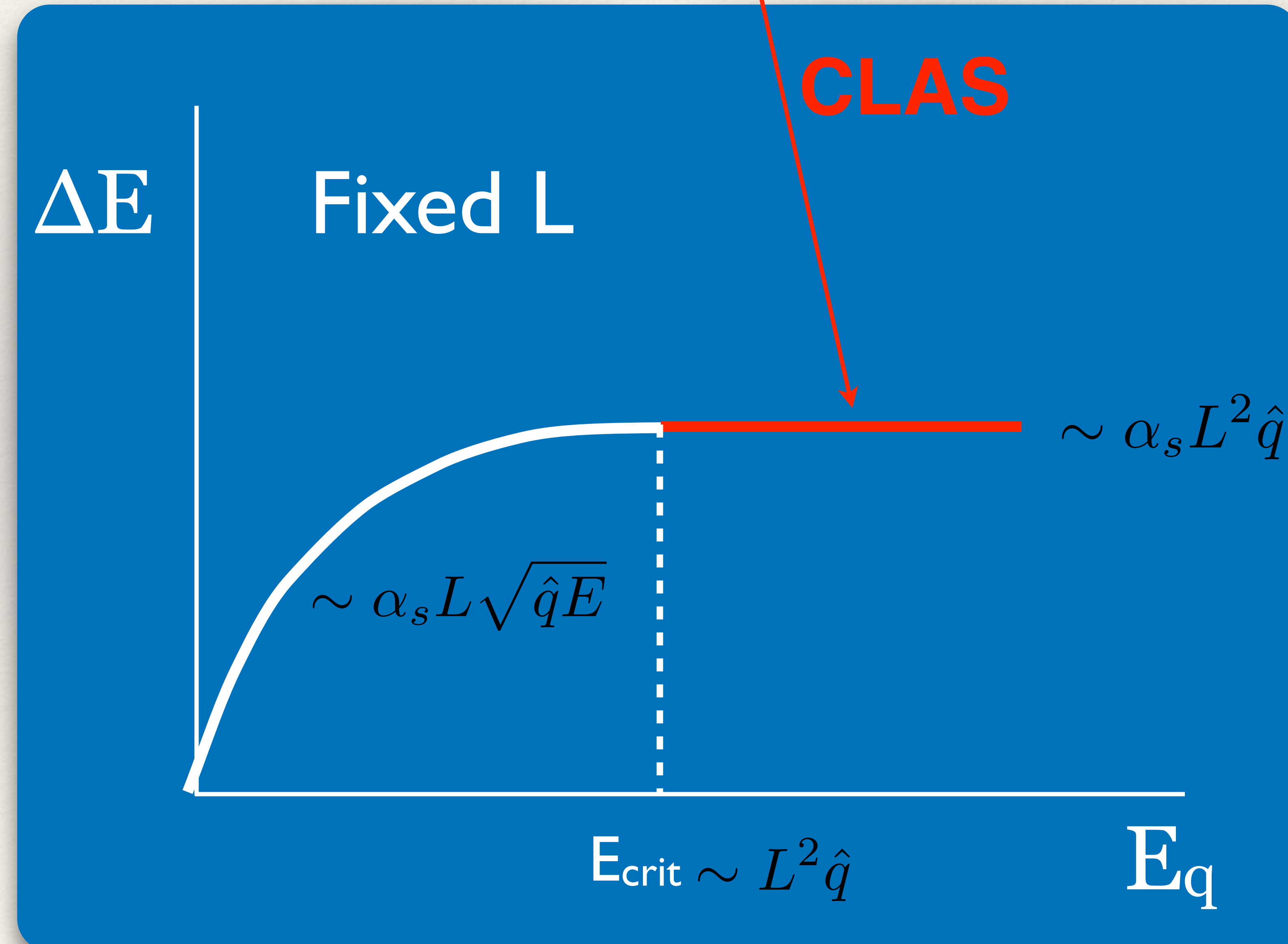


Partonic energy loss in pQCD (BDMPS-Z) exhibits a critical system length L_c and a critical energy E_c

$$L_c \propto \sqrt{\frac{E_q}{\hat{q}}}$$

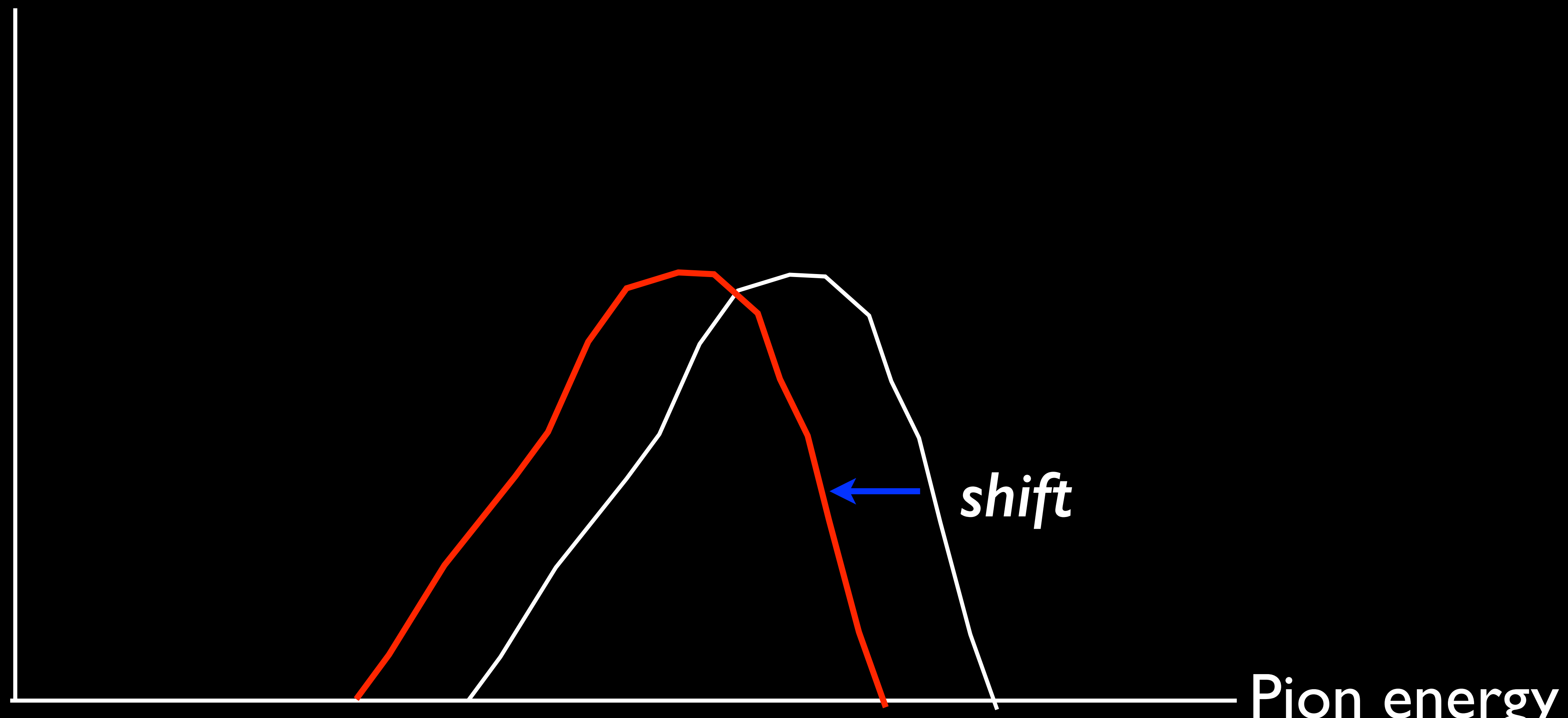
$$E_c \approx 0.4 \cdot \left(\frac{L}{1 \text{ fm}}\right)^2 \text{ GeV}$$

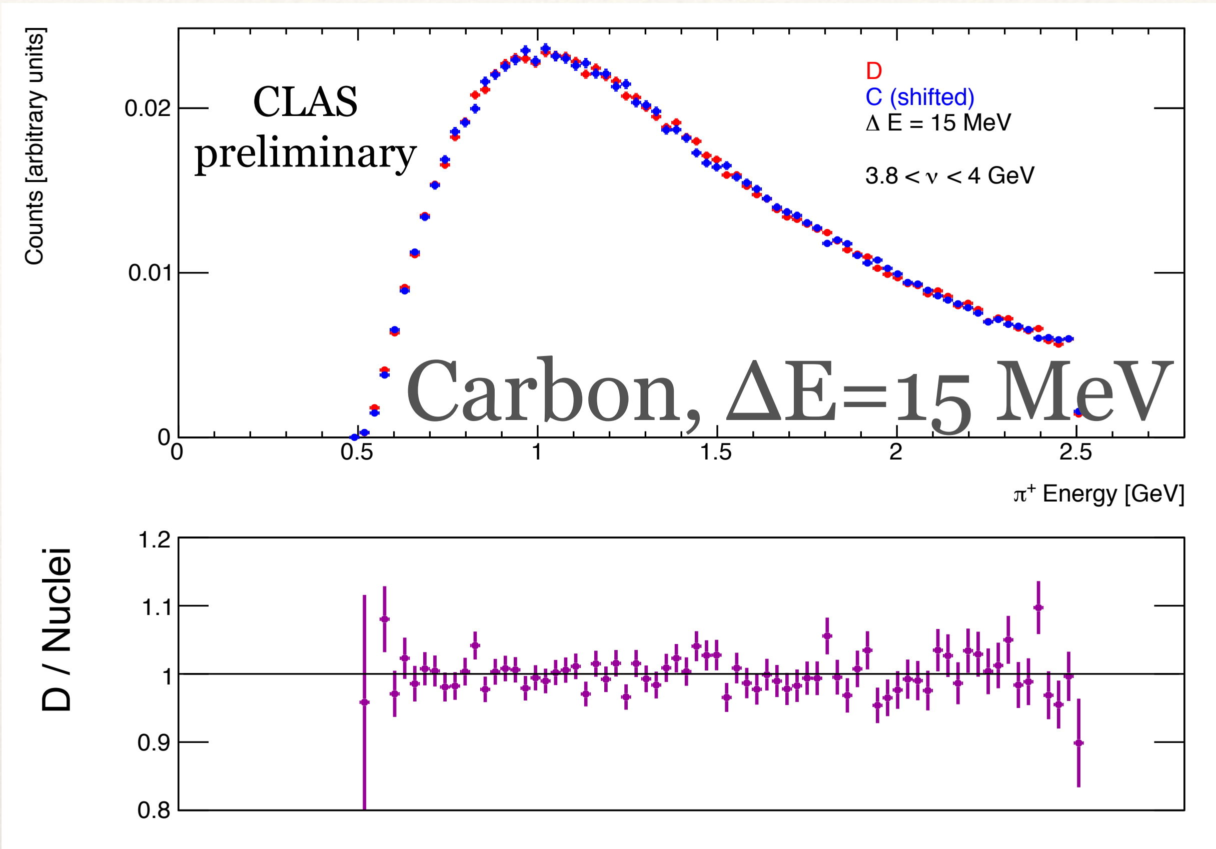
$$-\Delta E_q = \frac{\alpha_s}{4}\Delta k_T^2 \cdot L = \frac{\alpha_s}{4}\hat{q} \cdot L^2$$

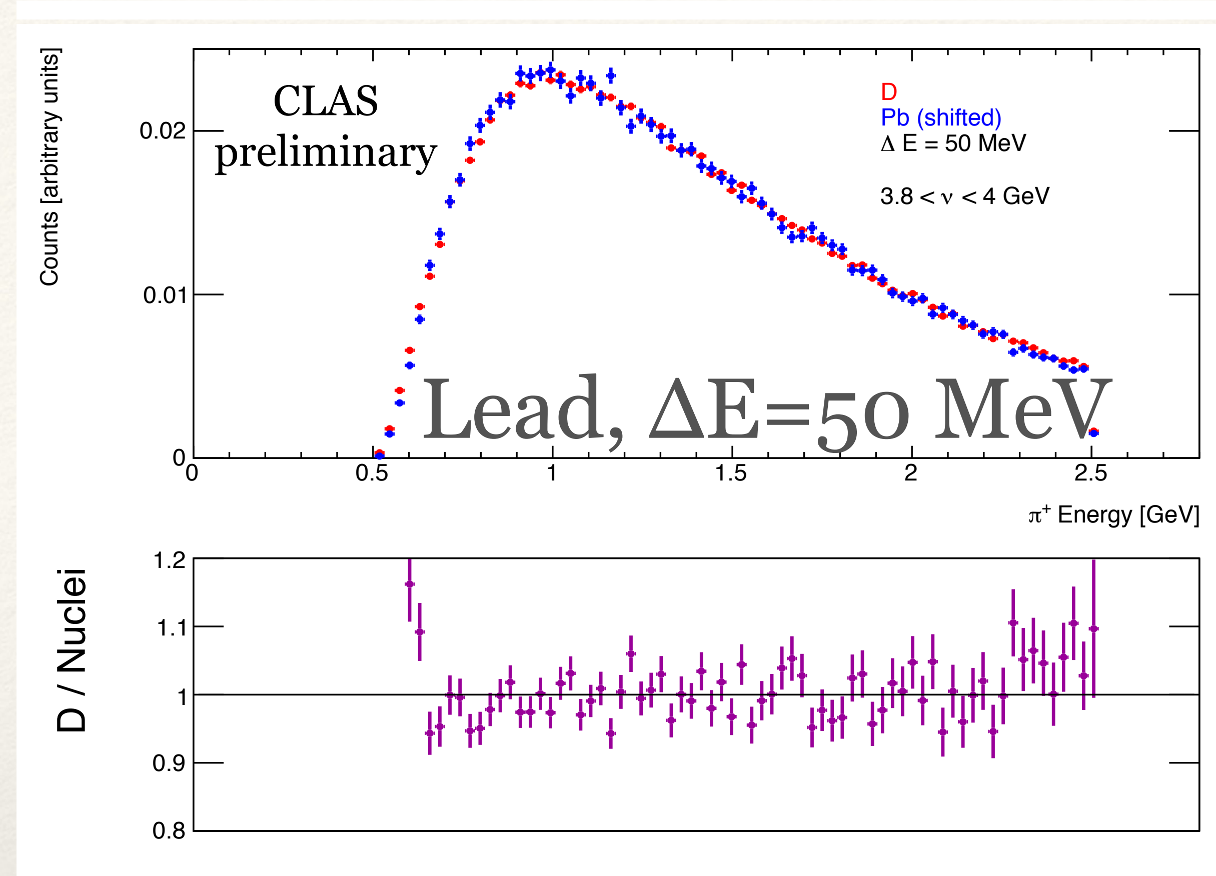


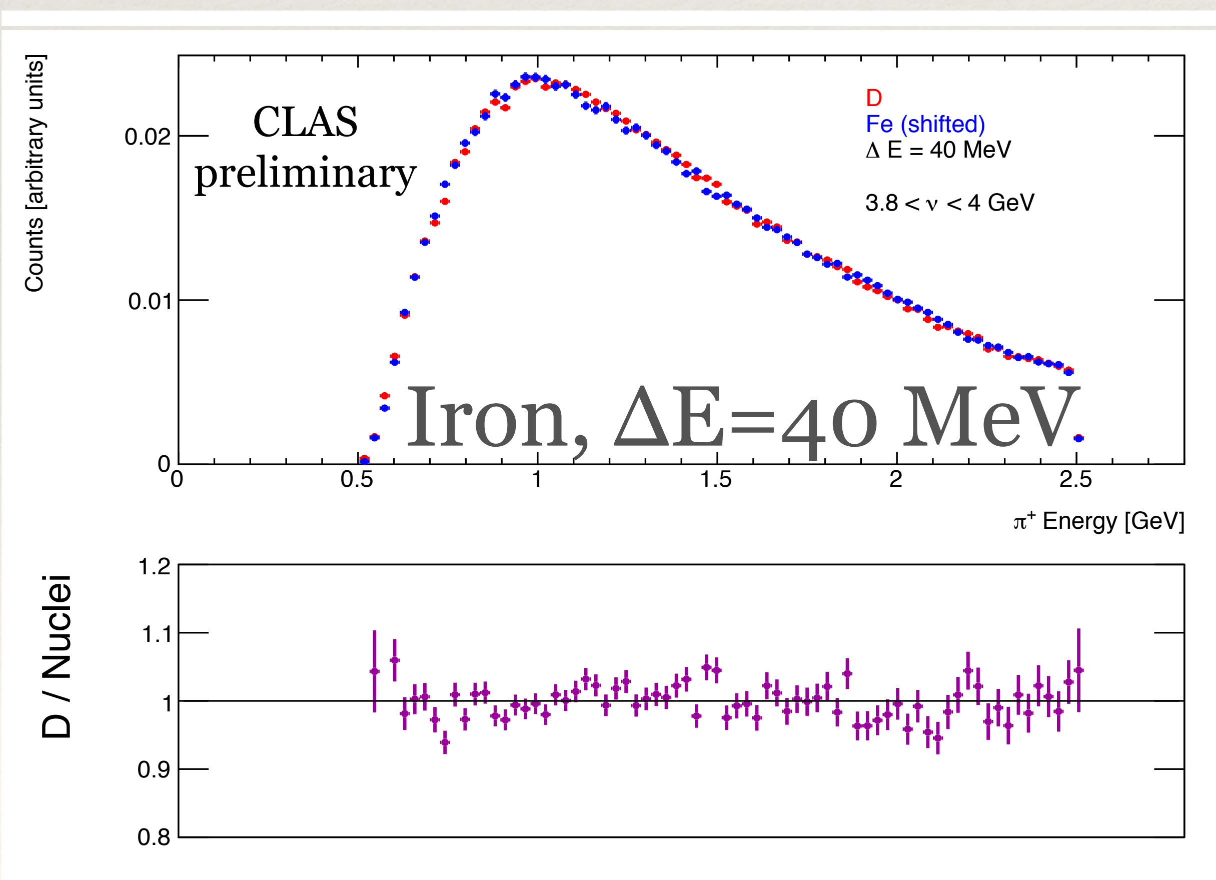
How to *directly* measure quark energy loss?

- Energy loss: *independent of energy* for thin medium
- "Thin enough" = quark energy should be greater than E_{crit}
- If energy loss is independent of energy, it will produce a ***shift*** of the energy spectrum, *without distortion of shape*.
- We can look for a ***shift*** of the Pb energy spectrum compared to that of the deuterium energy spectrum







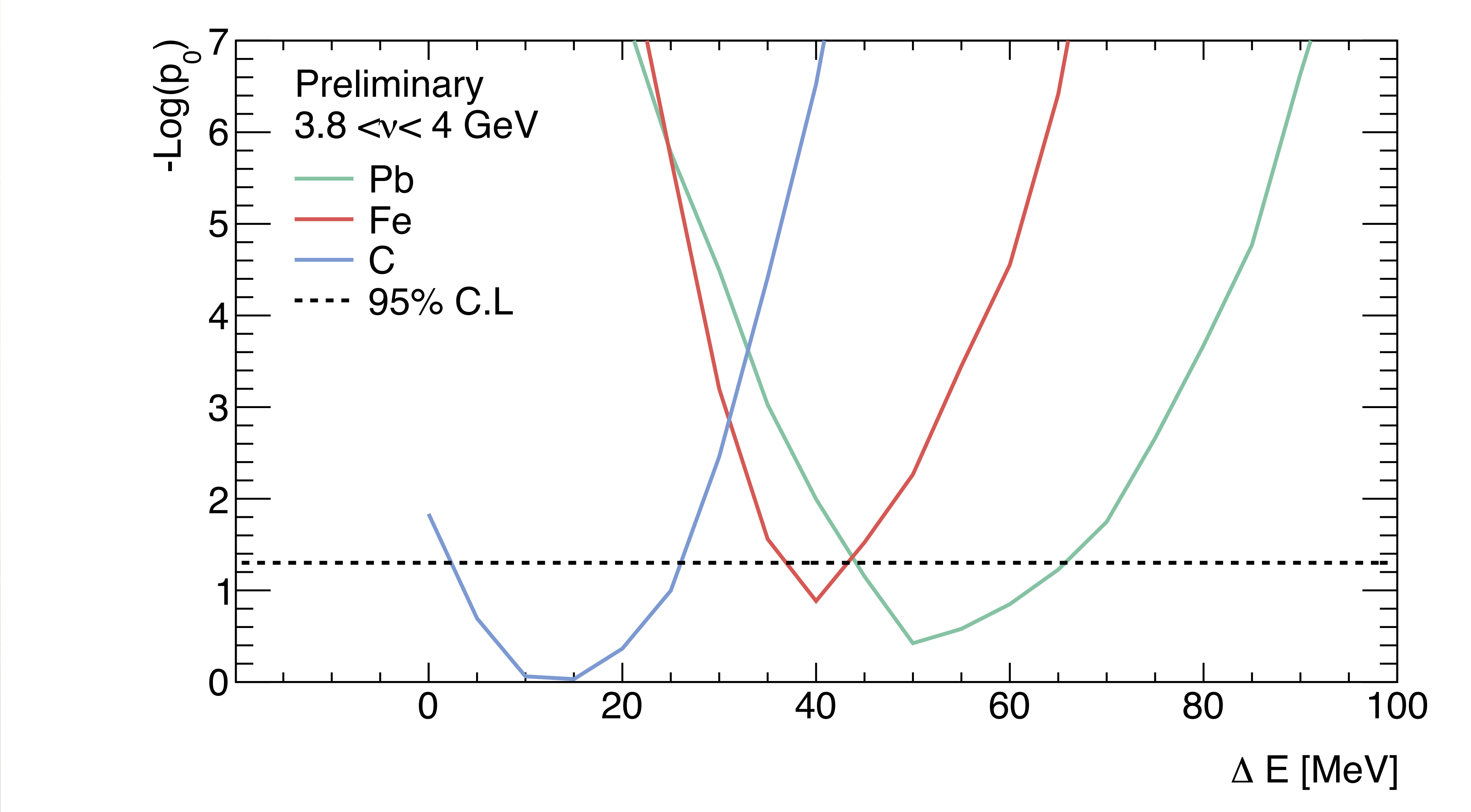


Energy spectrum of π^+ produced in C, Fe, Pb compared to that of deuterium, normalized to unity, with energy shifted by ΔE.

Acceptance corrected

Cut on X_F >0.1 is applied

Consistent with simple energy shift + unchanged fragmentation

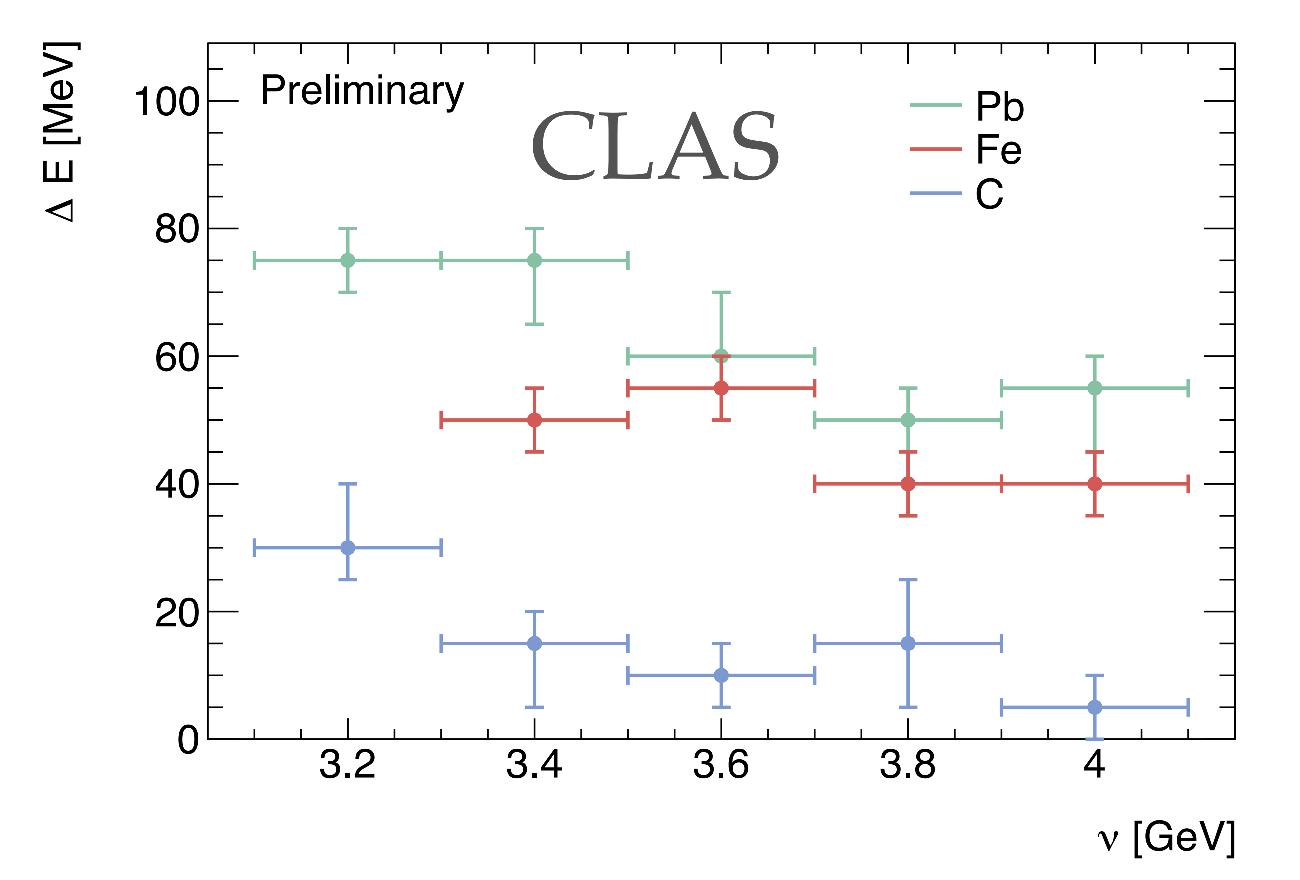


Log of p-values of Kolmogorov-Smirnov test as a function of energy shift ΔE: carbon, iron, lead.

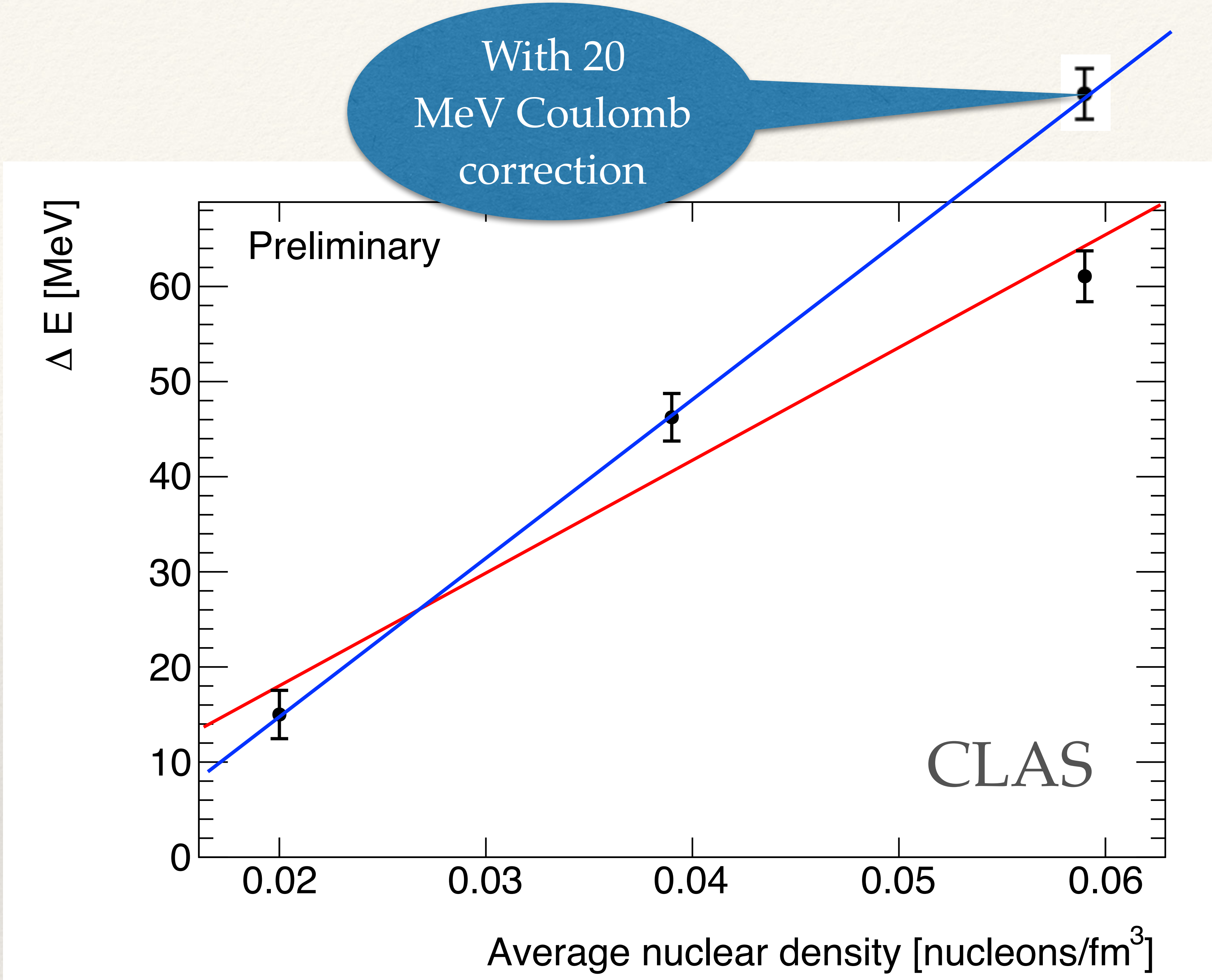
Dashed line corresponds to 95% confidence level

ν/GeV	Carbon	Iron	Lead
2.4–2.6	—	—	—
2.6–2.8	—	—	—
2.8–3.0	—	—	—
3.0–3.2	—	—	—
3.2–3.4	20–35	—	75
3.4–3.6	10–25	50	70–85
3.6–3.8	10–25	55	50–70
3.8–4.0	5–25	40	45–65
4.0–4.2	5–10	35-40	50–65

Range of possible energy shift in MeV obtained by Kolmogorov-Smirnov test in ν intervals

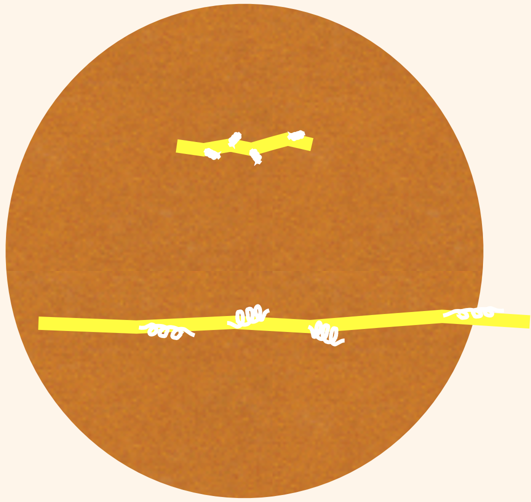


Approximately independent of quark energy, as expected from pQCD for $\nu > E_{crit}$



Approximately proportional to density, as expected.
(fixed pathlength)
Supports the premise that what we measure is ~energy loss!

Direct Measurement of Quark Energy Loss in CLAS: Conclusions



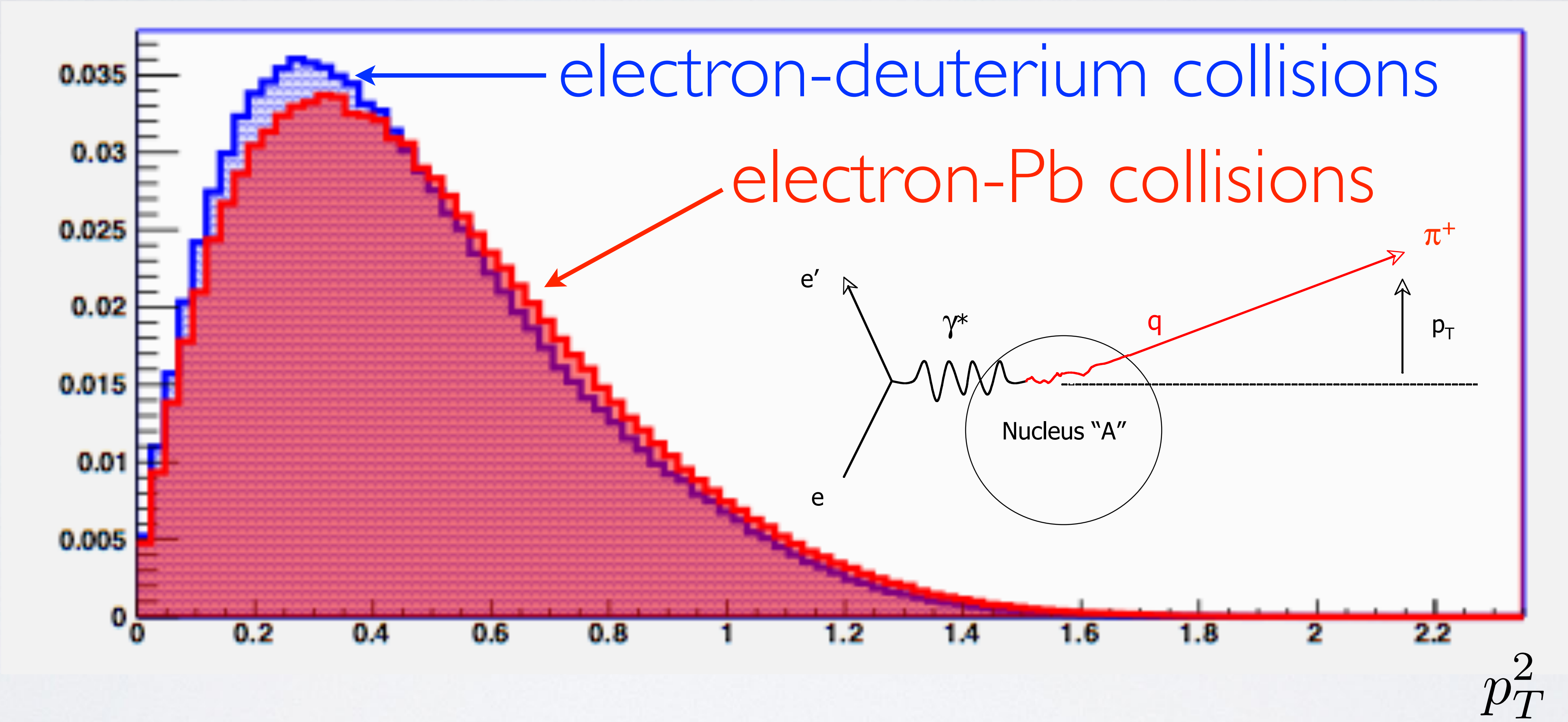
- It is small in magnitude. Why?
  - Best explanation: *short production time*
  - >500 MeV vs. 50 MeV in Pb
- It increases with nuclear size. Why?
  - Best explanation: *average nuclear density increases*.
  - Rate of change of virtuality nearly the same in all nuclei, therefore:
    - Path length is short, ~independent of nuclear size
    - Nuclear medium has little effect - simple to extrapolate to the vacuum case

More insights on these ideas in the next section!

Extracting characteristic times from HERMES and CLAS π^+ data

Observable: p_T broadening

$$\Delta p_T^2 \equiv \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$



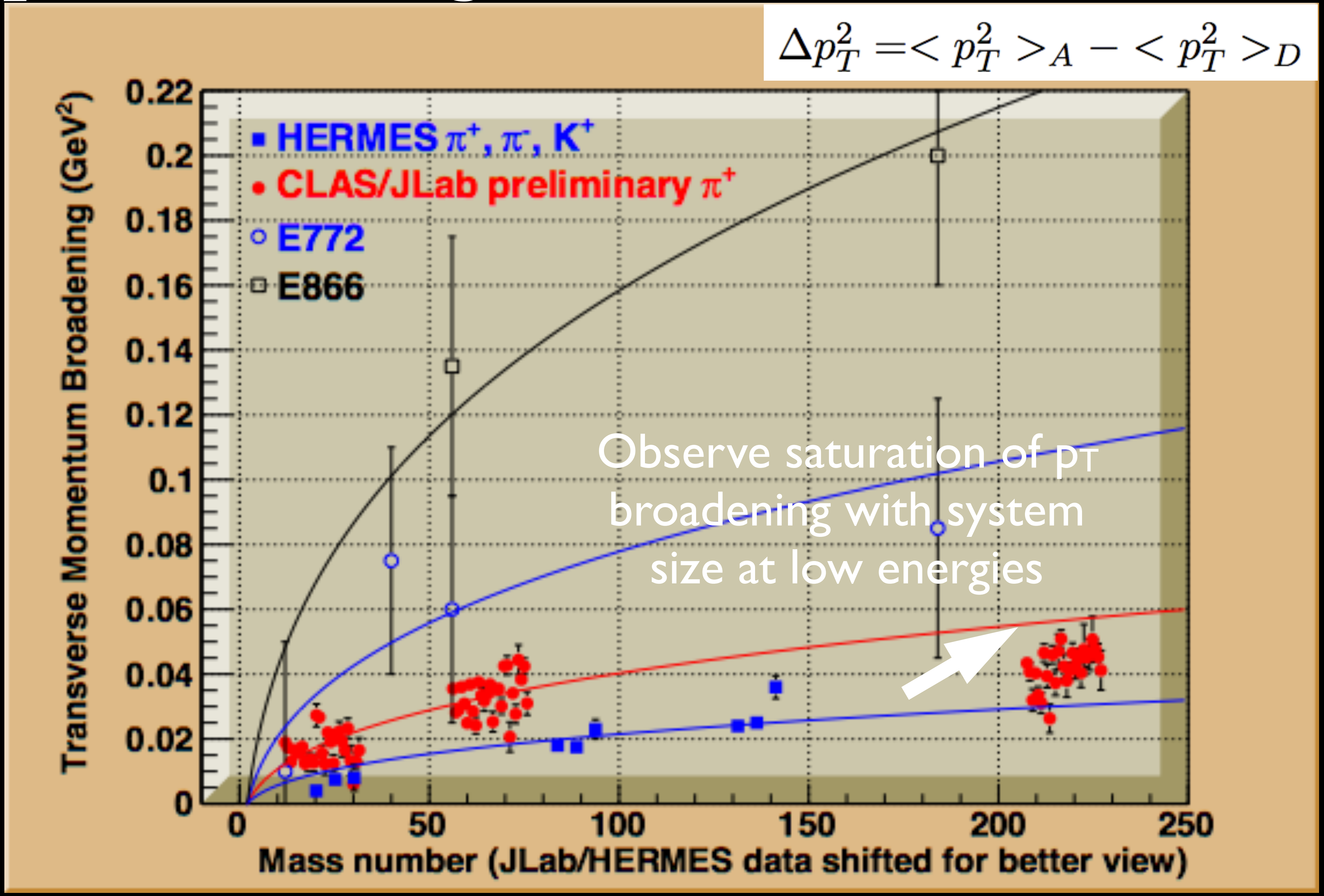
p_T broadening is a tool: sample the gluon field using a colored probe:

$$\Delta p_T^2 \propto G(x, Q^2)\rho L$$

and radiative energy loss:

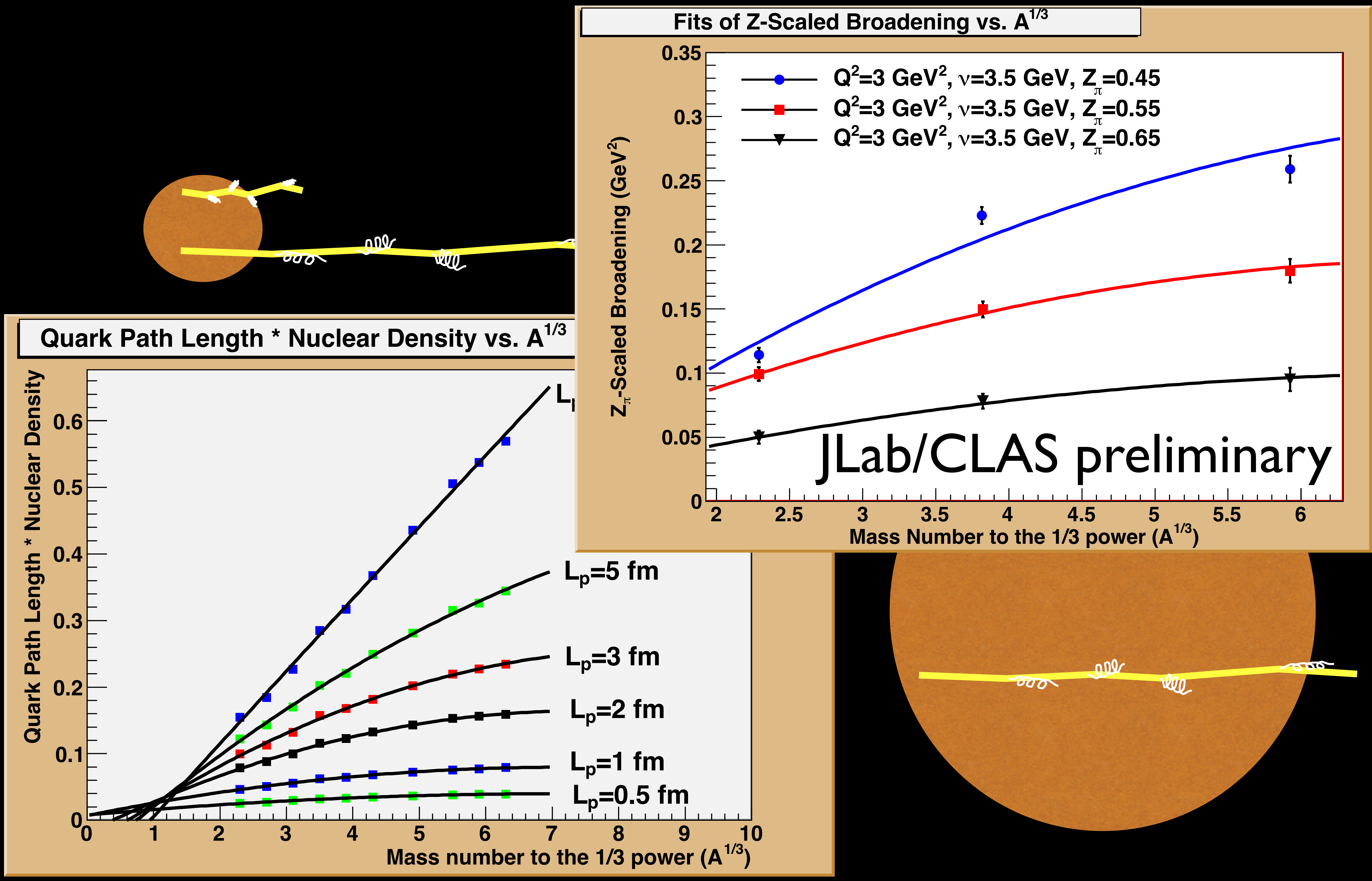
$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2$$

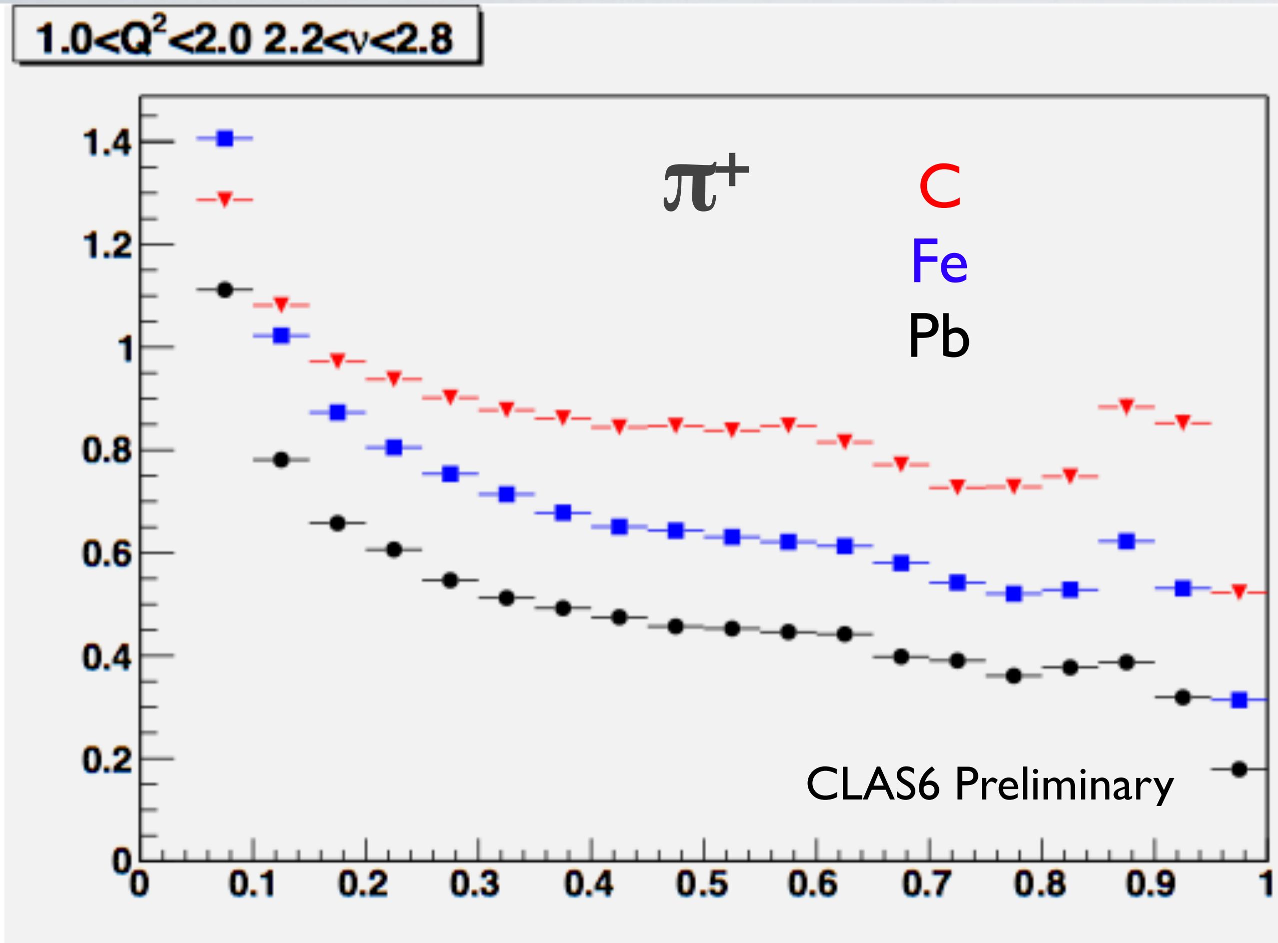
p_T broadening data - Drell-Yan and DIS

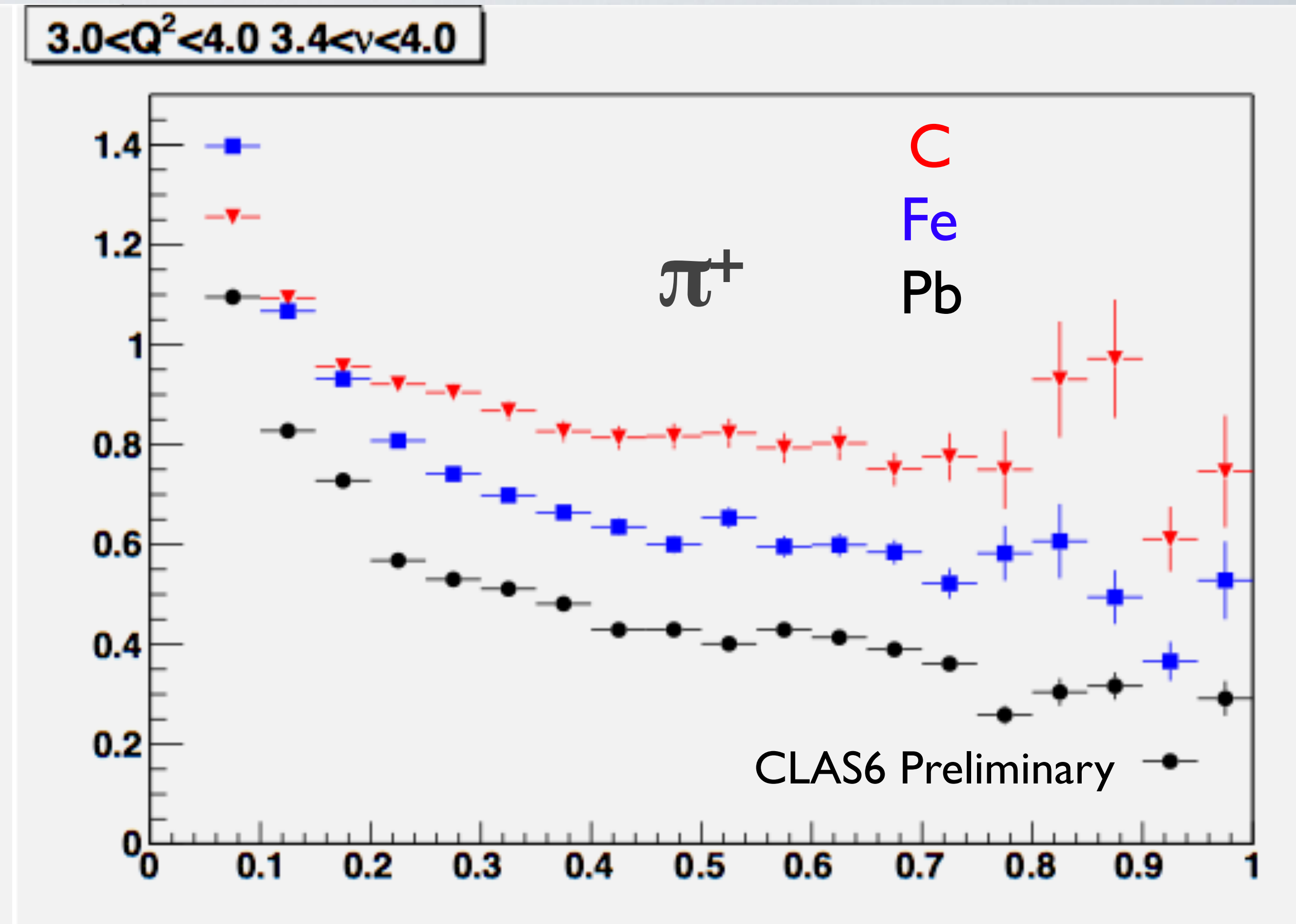


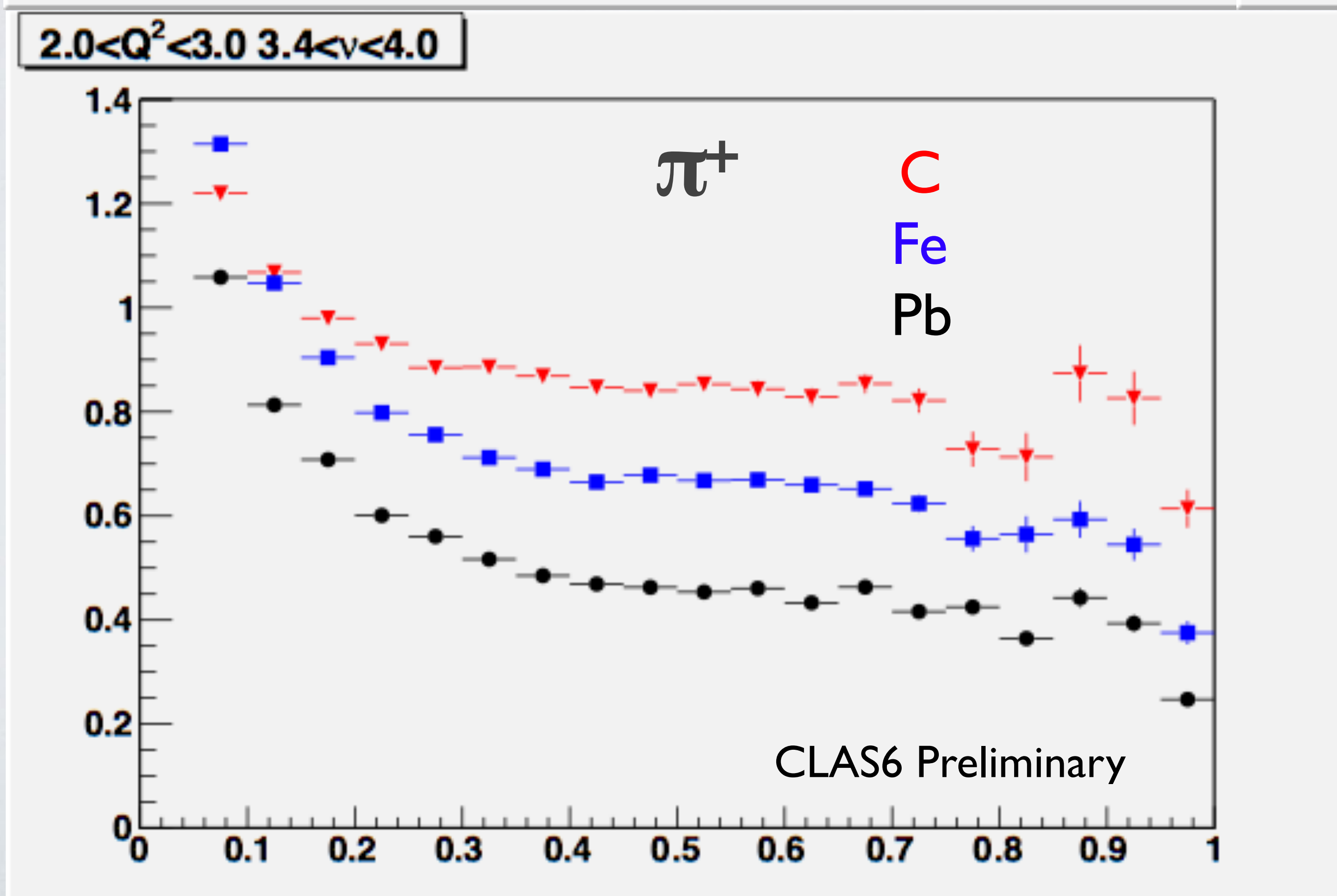
- New, precision data with identified hadrons!
- CLAS π^+: 81 four-dimensional bins in Q^2, ν, z_h, and A
- Intriguing *saturation*: production length or something else?

Production Time Extraction - Geometrical Effects









Data from CLAS6 and CLAS12 will provide the ultimate low-ν studies in up to 4-fold differential multiplicity ratios. EIC will have overlap and will provide the crucial high-ν studies.

CLAS6: π^+ (K^0, π^0, π^-)

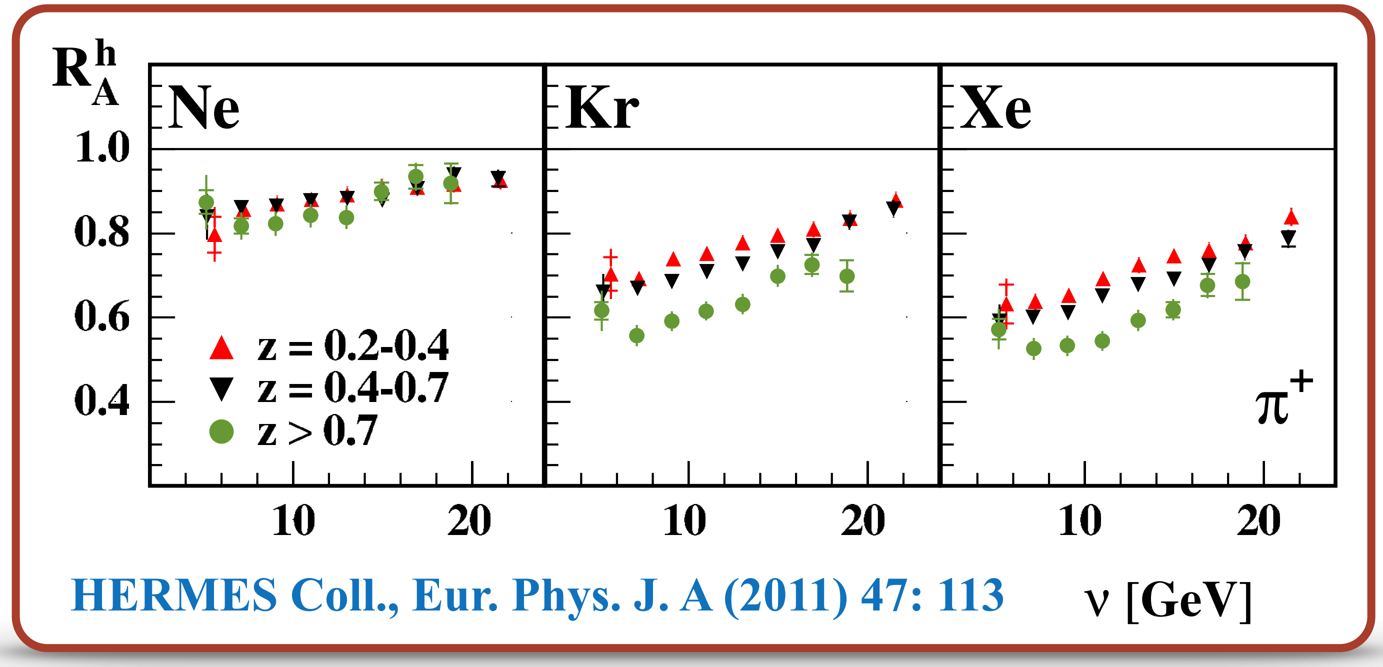
Geometrical Model approach

- Struck quark absorbs energy and momentum of γ^*
- Pathlength in medium: *either* parton *or* prehadron
- p_T broadening of final hadron: *only* from partonic multiple scattering, $\propto L_p$
- Inelastic prehadron interactions 'attenuate' produced hadrons, $\propto L_h$
- Partonic energy loss can also 'attenuate' produced hadrons (but we find this is a small effect)
- We extract the dynamical behavior, *separating geometry from dynamics*

Coupled fit of HERMES data

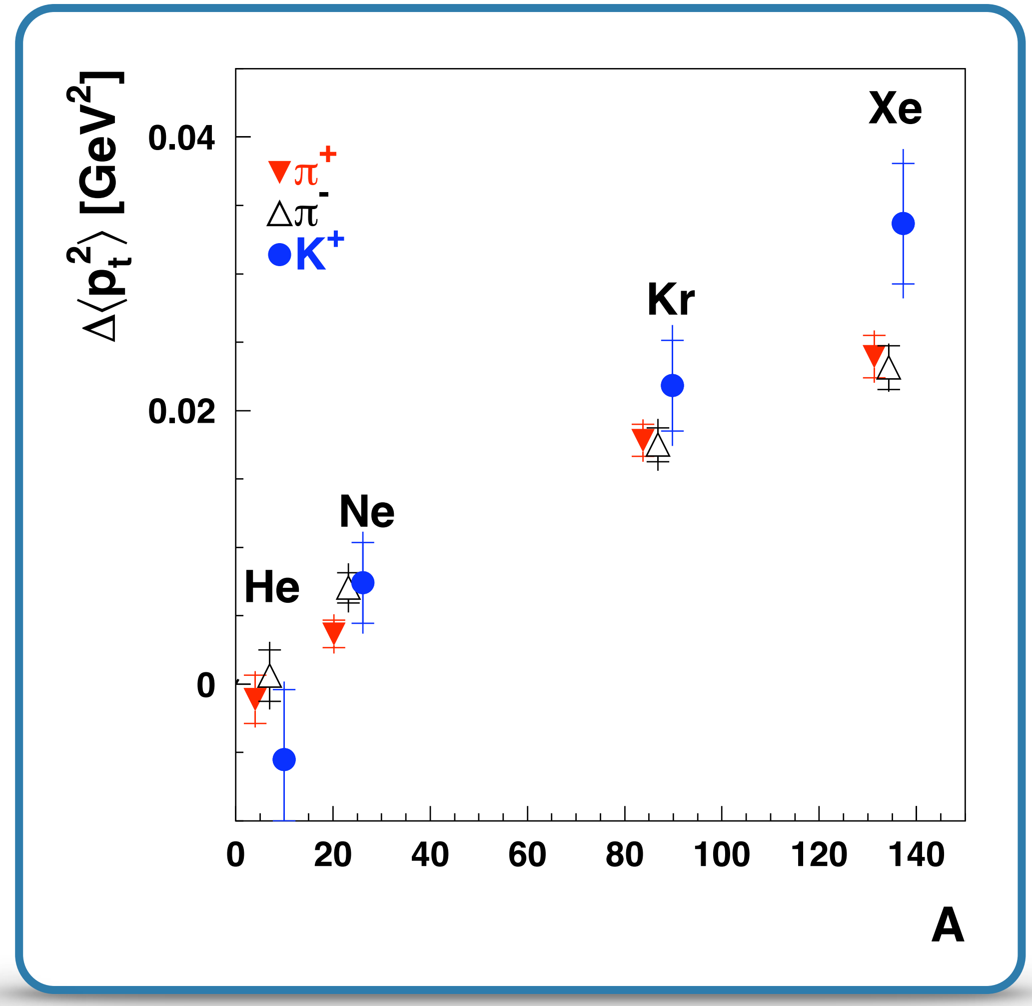
Multiplicity ratio

$$R^h_M(Q^2,\nu,z,p_T) \equiv \frac{\frac{1}{N_e(Q^2,\nu)}\cdot N_h(Q^2,\nu,z,p_T)|_A}{\frac{1}{N_e(Q^2,\nu)}\cdot N_h(Q^2,\nu,z,p_T)|_p}$$

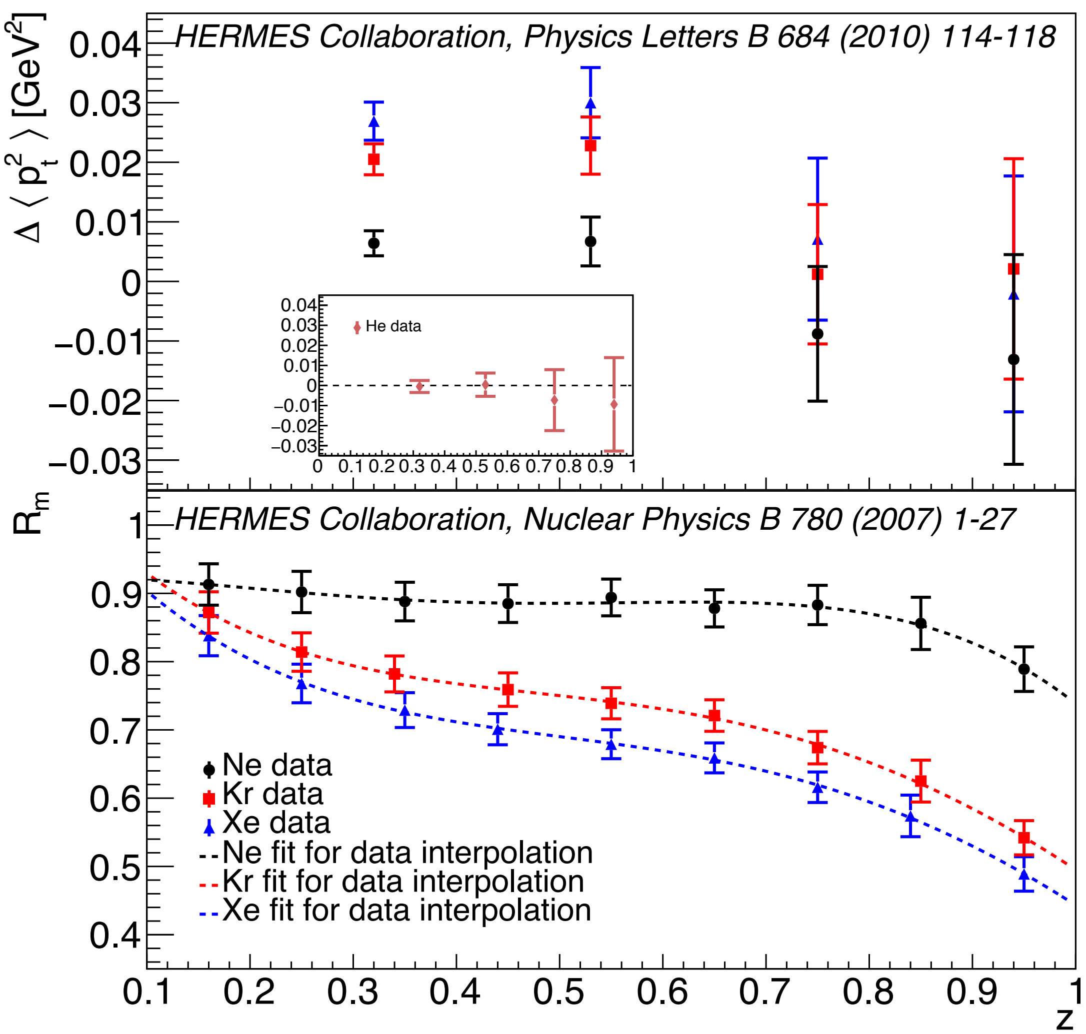


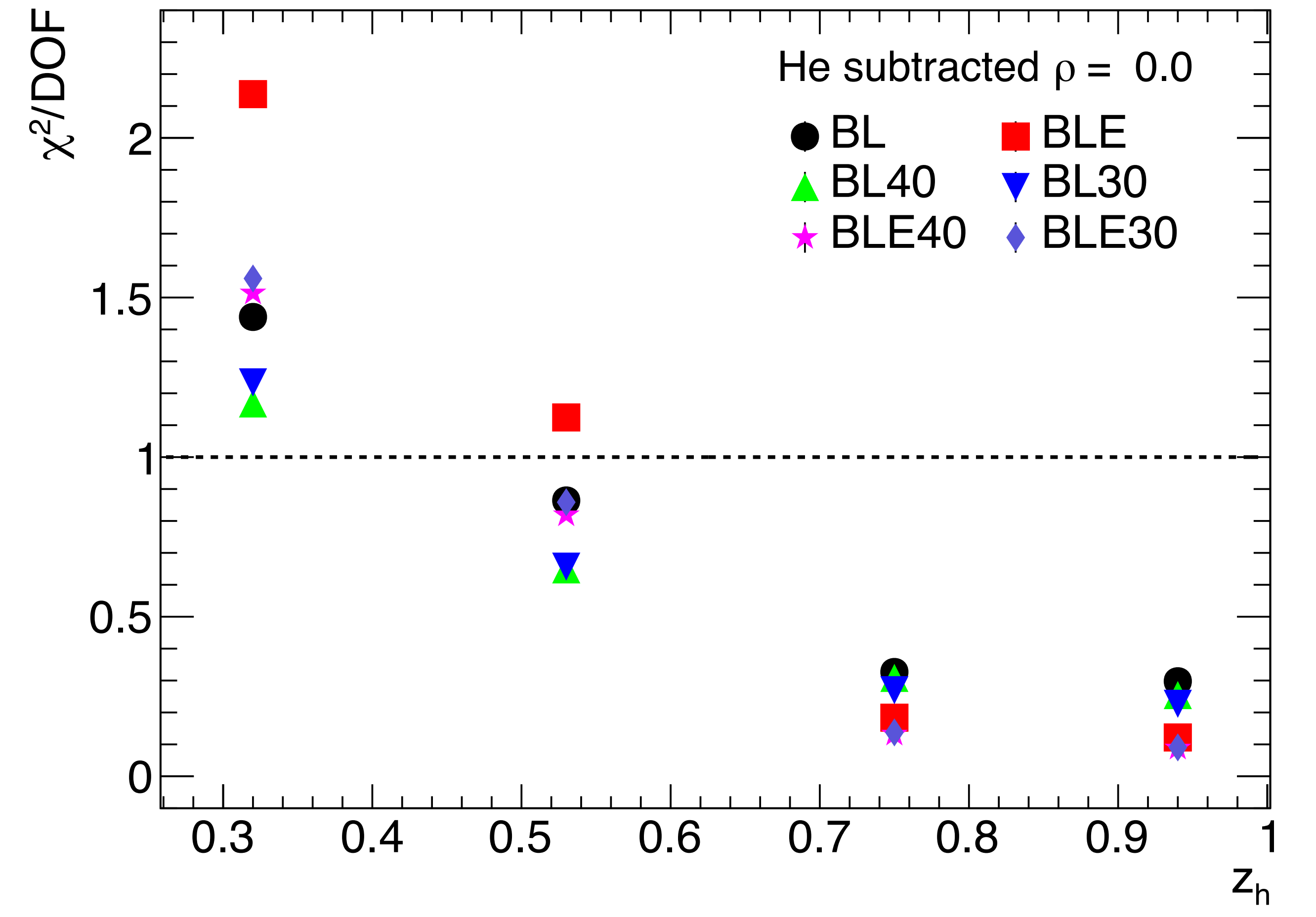
pT broadening

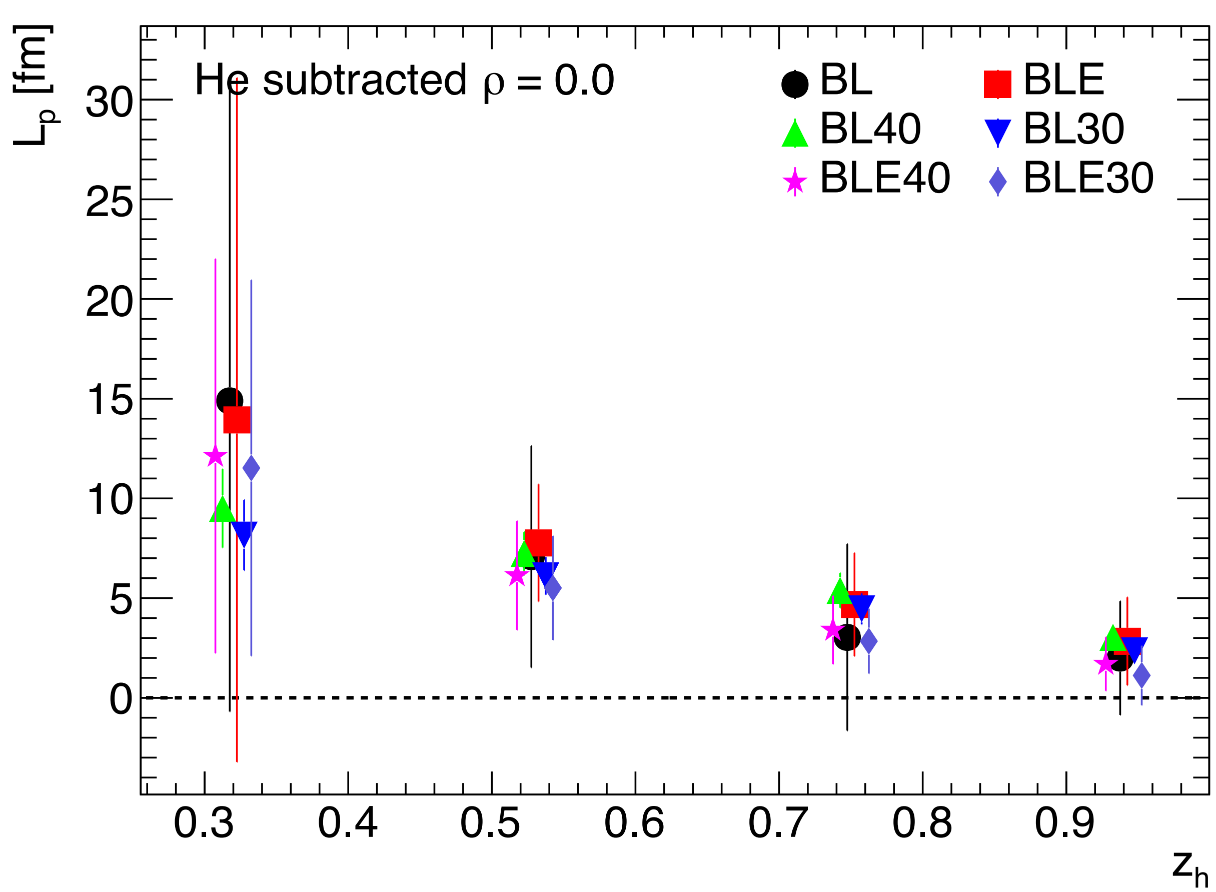
$$\Delta p_T^2(Q^2,\nu,z) \equiv \langle p_T^2(Q^2,\nu,z)\rangle|_A - \langle p_T^2(Q^2,\nu,z)\rangle|_p$$

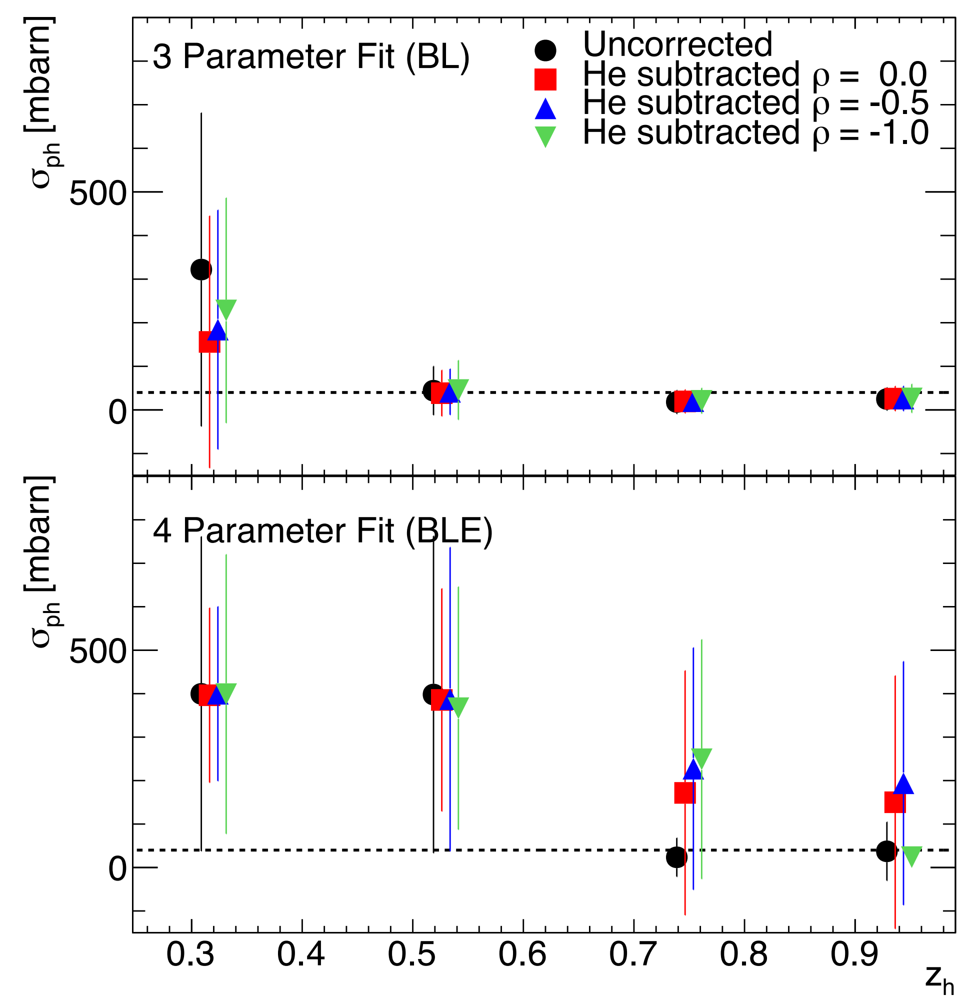


We fit both observables simultaneously


HERMES Collaboration, Physics Letters B 684 (2010) 114-118
$\Delta \langle p_t^2 \rangle$ [GeV^2]
He data
HERMES Collaboration, Nuclear Physics B 780 (2007) 1-27
R_m
Ne data
Kr data
Xe data
Ne fit for data interpolation
Kr fit for data interpolation
Xe fit for data interpolation
z

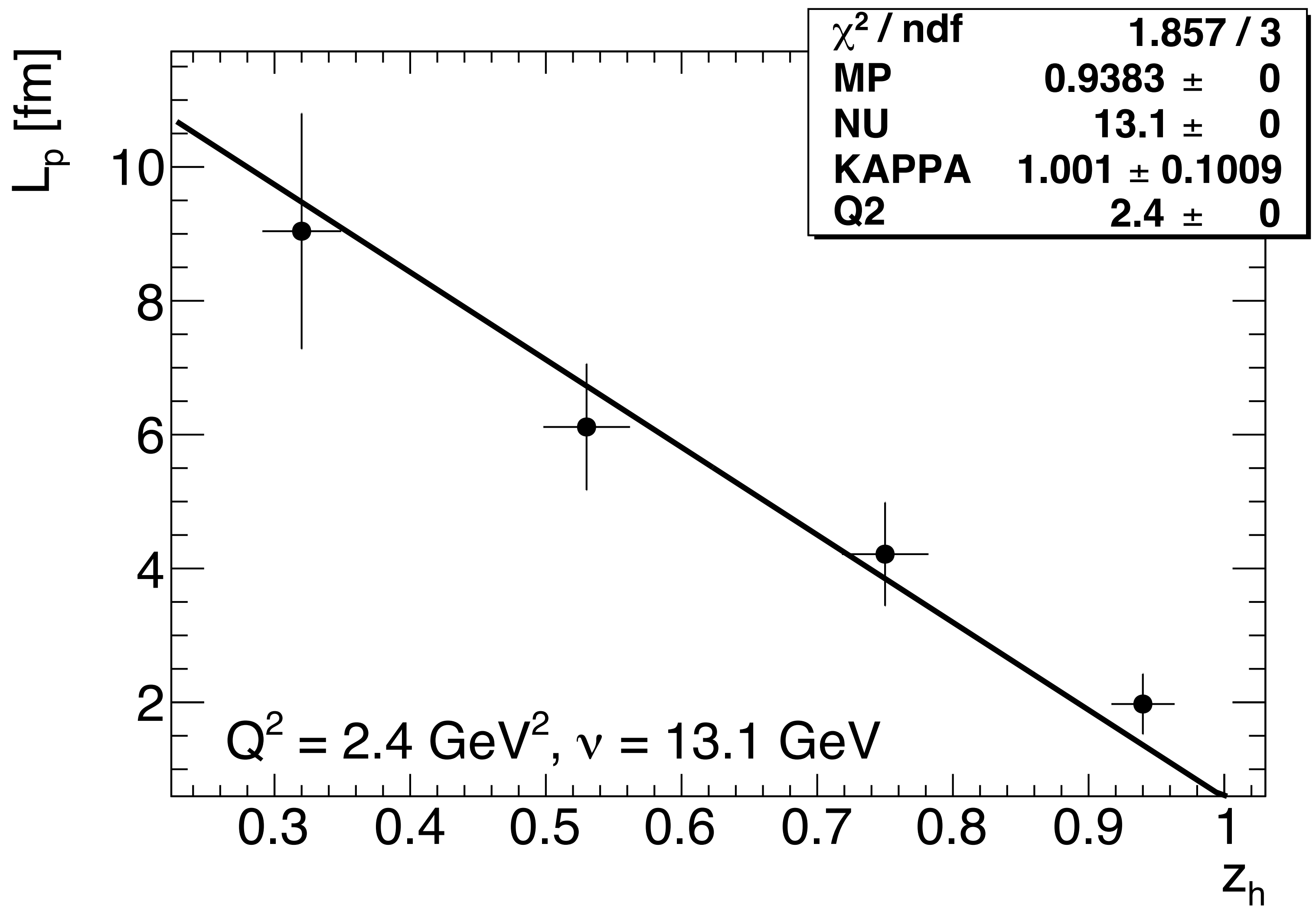

χ^2/DOF
He subtracted ρ = 0.0
BL
BLE
BL40
BL30
BLE40
BLE30
z_h


L_p [fm]
He subtracted ρ = 0.0
BL
BLE
BL40
BL30
BLE40
BLE30
z_h


3 Parameter Fit (BL)
Uncorrected
He subtracted ρ = 0.0
He subtracted ρ = -0.5
He subtracted ρ = -1.0
σ_{ph} [mbarn]
4 Parameter Fit (BLE)
σ_{ph} [mbarn]
z_h

Fit of HERMES L_p results to Lund Model form

A fit of our HERMES results to the Lund model form



This is a strong validation of our model

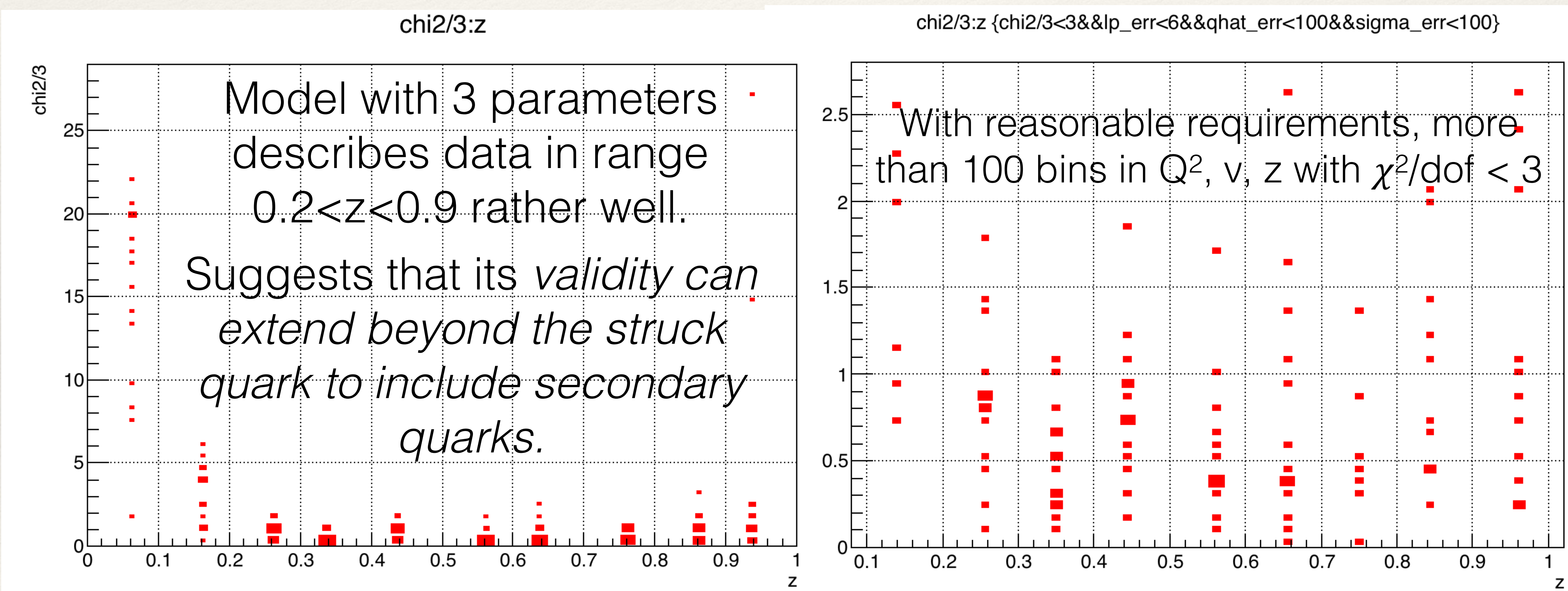
We recover the known value of the string constant completely independently!

Light cone Lund String Model form for lab frame:

$$l_p = \frac{1}{2\mathcal{K}} \cdot \left(M_p + \nu + \sqrt{\nu^2 + Q^2} - 2 \cdot \nu \cdot z' \right)$$

Virtual quark lifetime extraction: 3-parameter geometric model applied to CLAS 5 GeV data

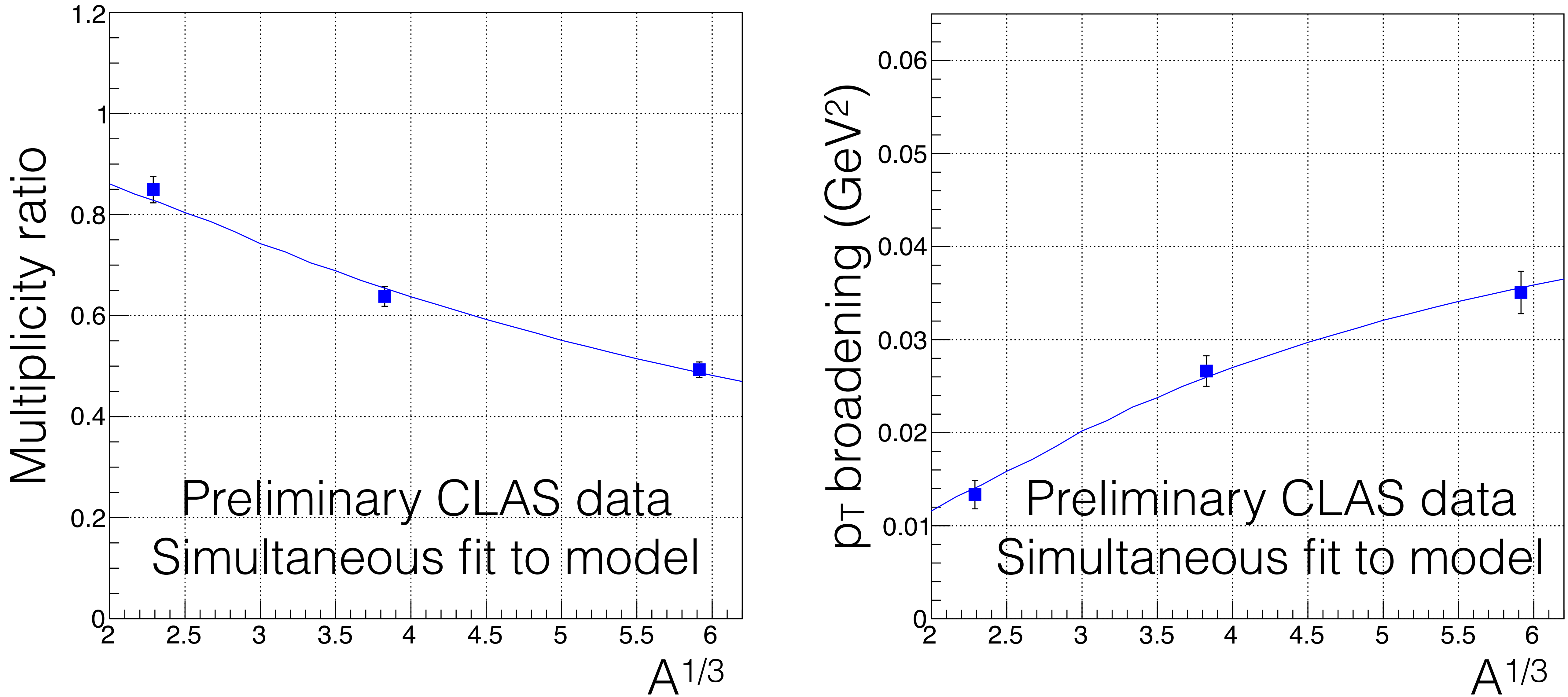
χ^2/dof vs. z



Good values of chi-squared/degrees of freedom for > 100 bins

Exploratory study

Example of fit (one of 150 bins in x, Q^2, and z)



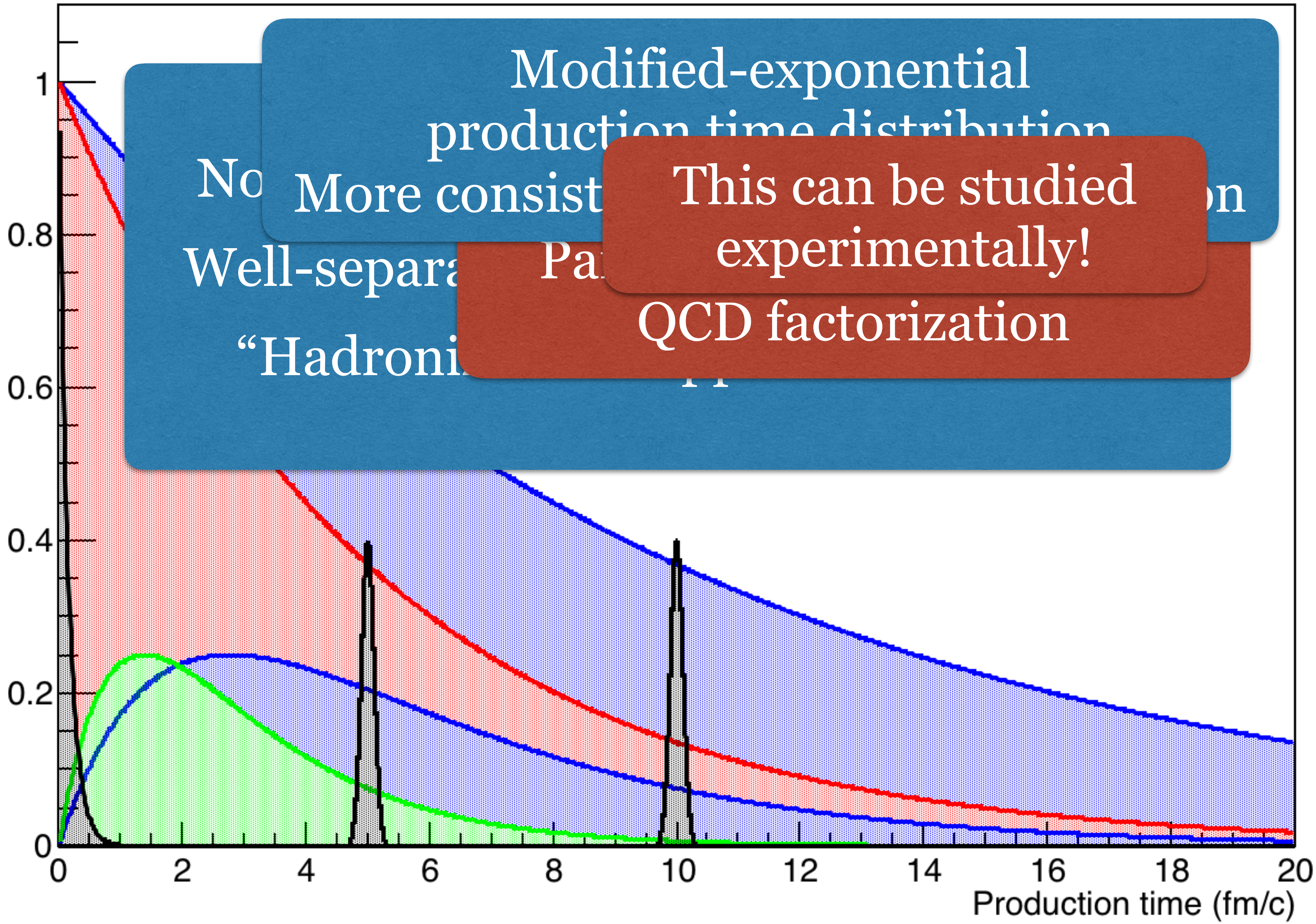
$\langle x \rangle = 0.166$, $\langle Q^2 \rangle = 1.17$ GeV^2, ($\langle \nu \rangle = 3.76$ GeV), $\langle z \rangle = 0.445$

$L_p = 1.8 \pm 0.4$ fm

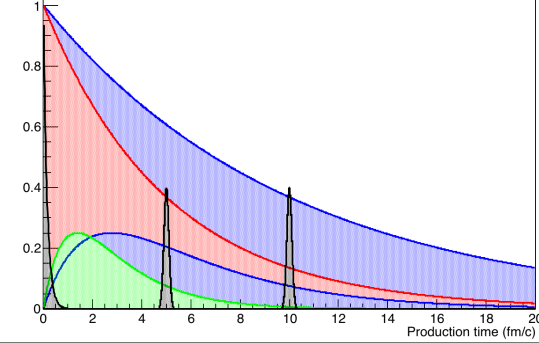
$\chi^2/\mathrm{dof} = 0.5$

Simultaneous fit *couples* p_T broadening to multiplicity ratio

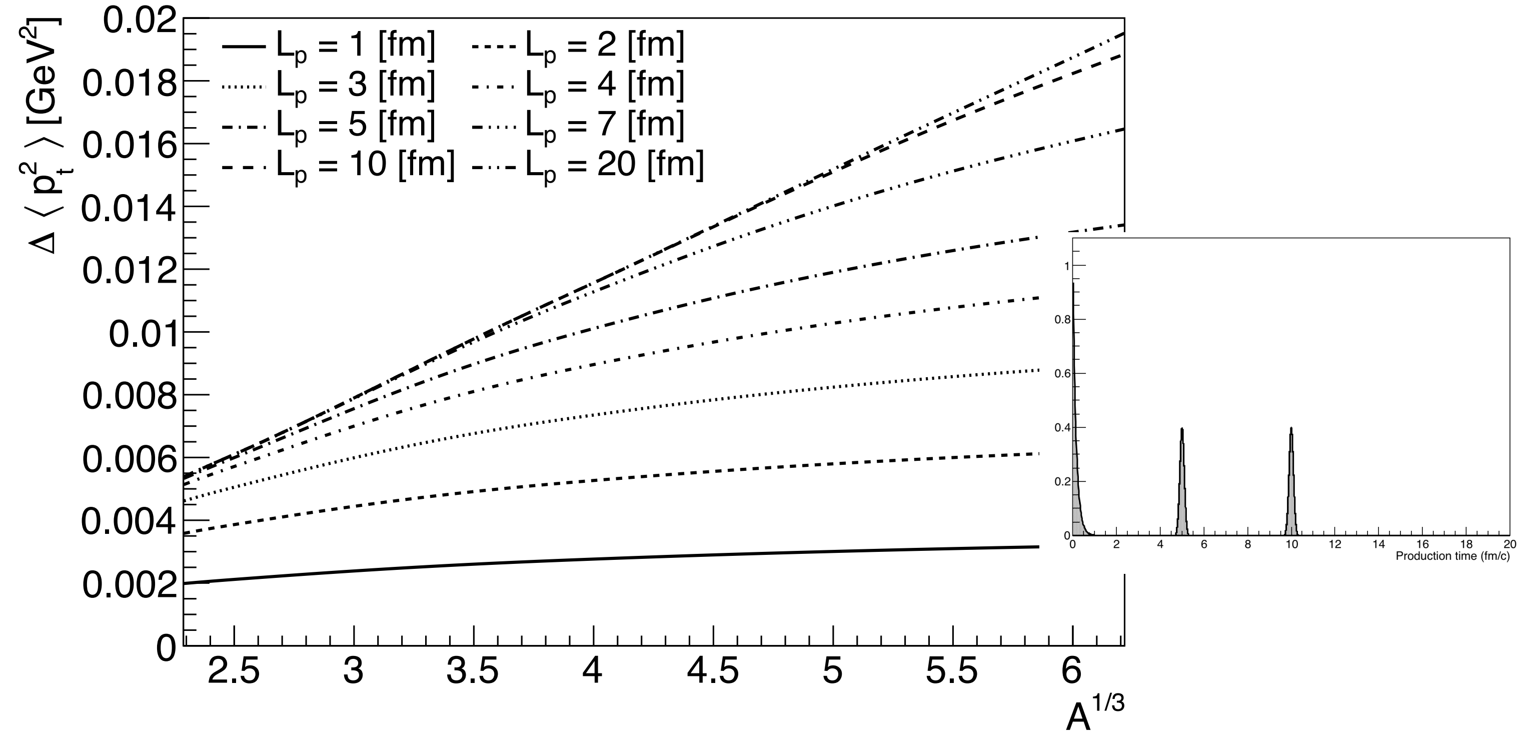
Three possible distributions of production time



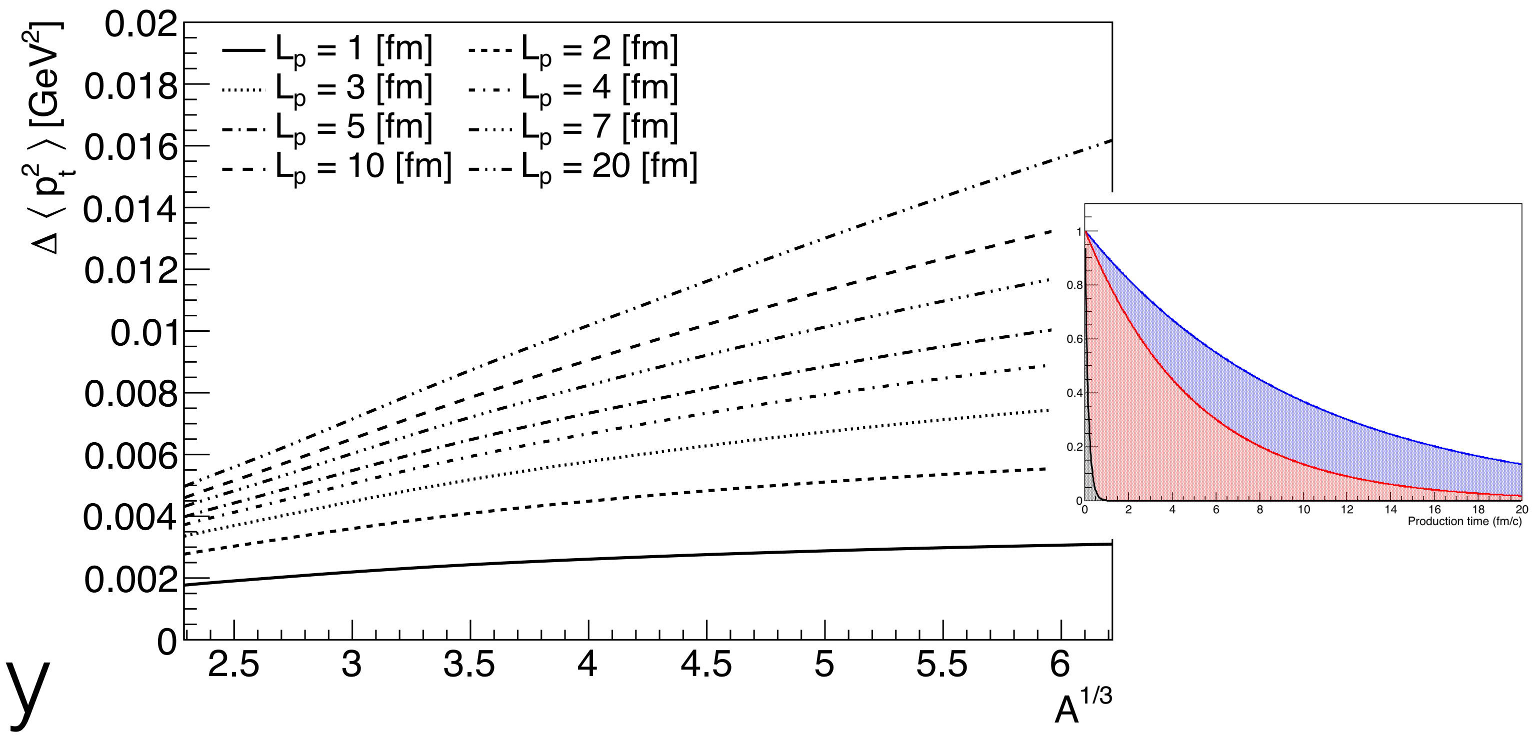
Effect of production length distribution on p_T broadening



Fixed production time



Exponential production time distribution



QCD factorization

Relevance at high energy

Relevance to EIC!

Tests of **exponential distribution** hypothesis for quark lifetime

CLAS Exploratory Study with 5 GeV Data

Exponential distribution of quark lifetime

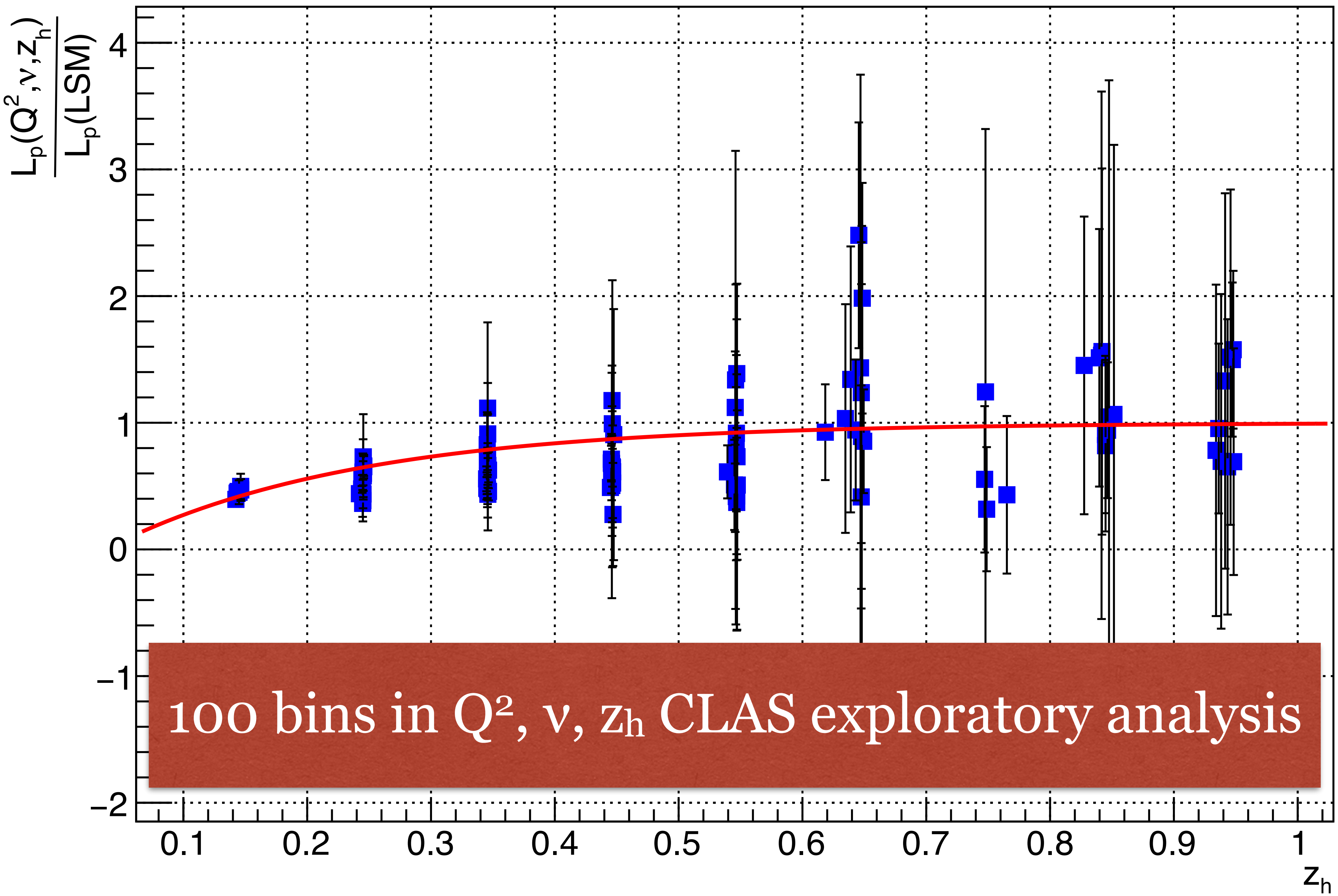
```
103 points, chisquared=69.2, chisq/dof = 0.685  MEDIUM event selection.
 FCN=69.2253 FROM MINOS     STATUS=SUCCESSFUL     10 CALLS          63 TOTAL
                     EDM=2.30163e-20    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                   STEP         FIRST
  NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
   1  p0           1.07864e+00   4.83476e-01  -0.00000e+00   6.52690e-07
   2  p1           9.33423e-01   2.45714e-01   2.45714e-01   7.34350e-11
```

Single value of quark lifetime

```
88 points, chisquared=289.5, chisq/dof = 3.36  MEDIUM event selection.
 FCN=289.533 FROM MINOS     STATUS=SUCCESSFUL      8 CALLS          63 TOTAL
                     EDM=3.95499e-19    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                   STEP         FIRST
  NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
   1  p0           1.95920e+00   2.75776e-01  -0.00000e+00   8.75252e-07
   2  p1           3.95062e-01   1.37012e-01   1.37012e-01  -3.09899e-10
```

The data clearly prefer an exponential distribution

CLAS Exploratory Analysis ≈ Lund String Model



L_p (Q^2, ν, z_h) from CLAS analysis similar to values from the Lund String Model for z_h>0.4

Space-time characteristics of the struck quark

Assume: Single-photon exchange, no quark-pair production

"JLab" example: $Q^2 = 3$ GeV^2, $\nu = 3$ GeV. ($x_{Bj} \sim 0.5$)

Struck quark absorbs virtual photon energy ν and momentum $p_{\gamma^*} = |\vec{p}_{\gamma^*}| = \sqrt{(\nu^2 - Q^2)}$.

- Neglect any initial momentum/mass of quark
- Immediately after the interaction, quark mass $m_q = Q = \sqrt{(Q^2)}$.
- Gamma factor is therefore $\gamma = \nu/Q$, $\beta = p_{\gamma^*}/\nu$.

JLab example: $\gamma = 1.73$, $\beta = 0.82$

Rigorous? γ, β allow:

1. extrapolations to EIC kinematics,
2. test of time dilation in CLAS fits, and
3. direct comparison between JLab and HERMES fits

Time dilation test of the CLAS exploratory fit

If what we are measuring is the lifetime of the virtual struck quark as we assert, it must be subject to time dilation

We can test this by plotting production time vs. relativistic γ

However, there are also dynamical processes affecting production time too ("predicted by Niedermayer in 1980's")

Try: fit L_p/γ in 100 bins to determine other dependencies.

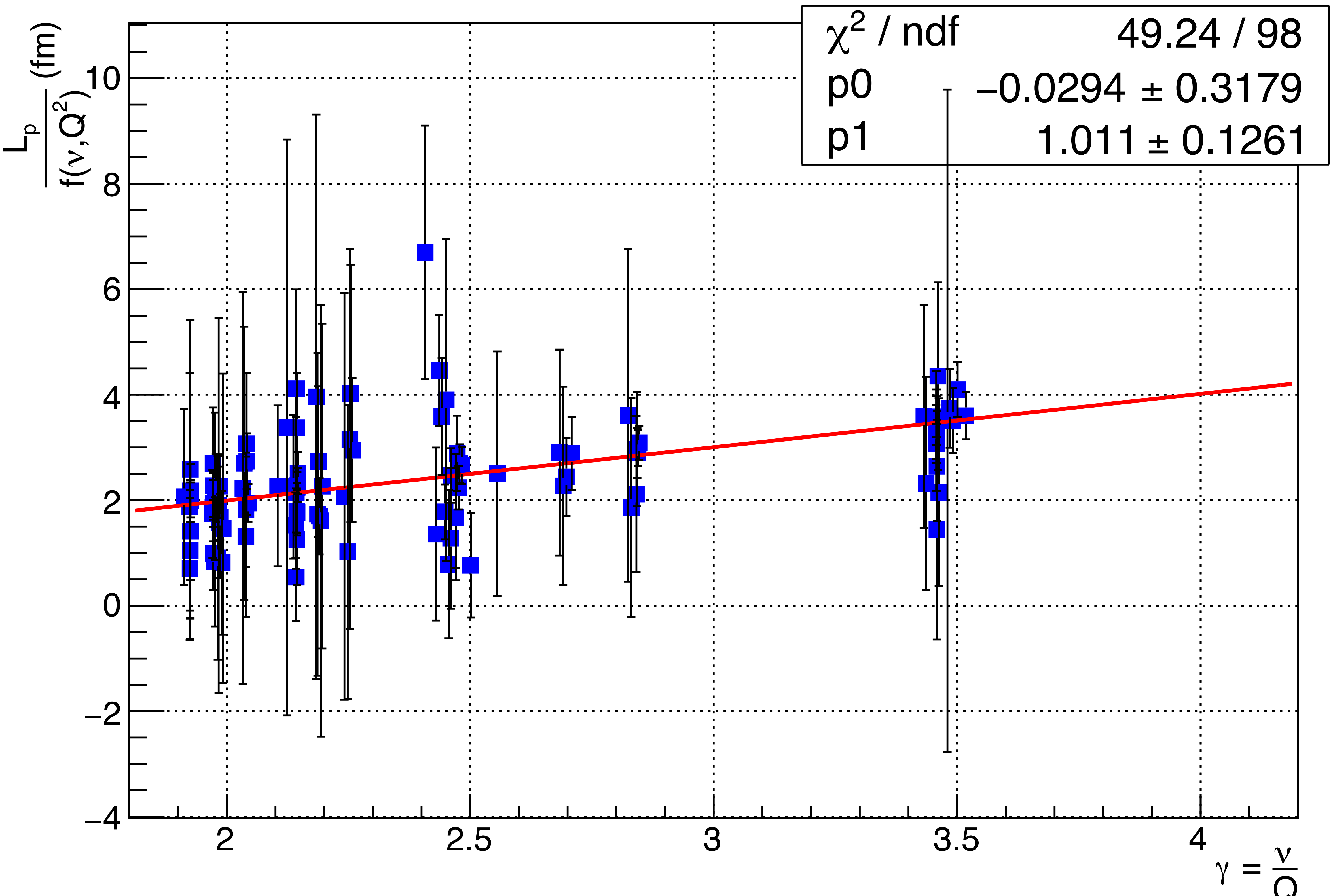
Find:

$$L_p/\gamma = 0.88 + 0.18{*}Q^2 - 0.16{*}\nu \equiv f(\nu,Q^2)$$

(Parameter uncertainties 10-20%, chisquared/dof ~0.5)

Next, fit $L_p/f(\nu,Q^2)$ to see if dependence on γ is consistent with time dilation. Results:

Time dilation test of the CLAS exploratory fit



Production time demonstrates time dilation
Average slope of L_p vs γ is 1 ± 0.1!

Extrapolation from HERMES to EIC and CLAS

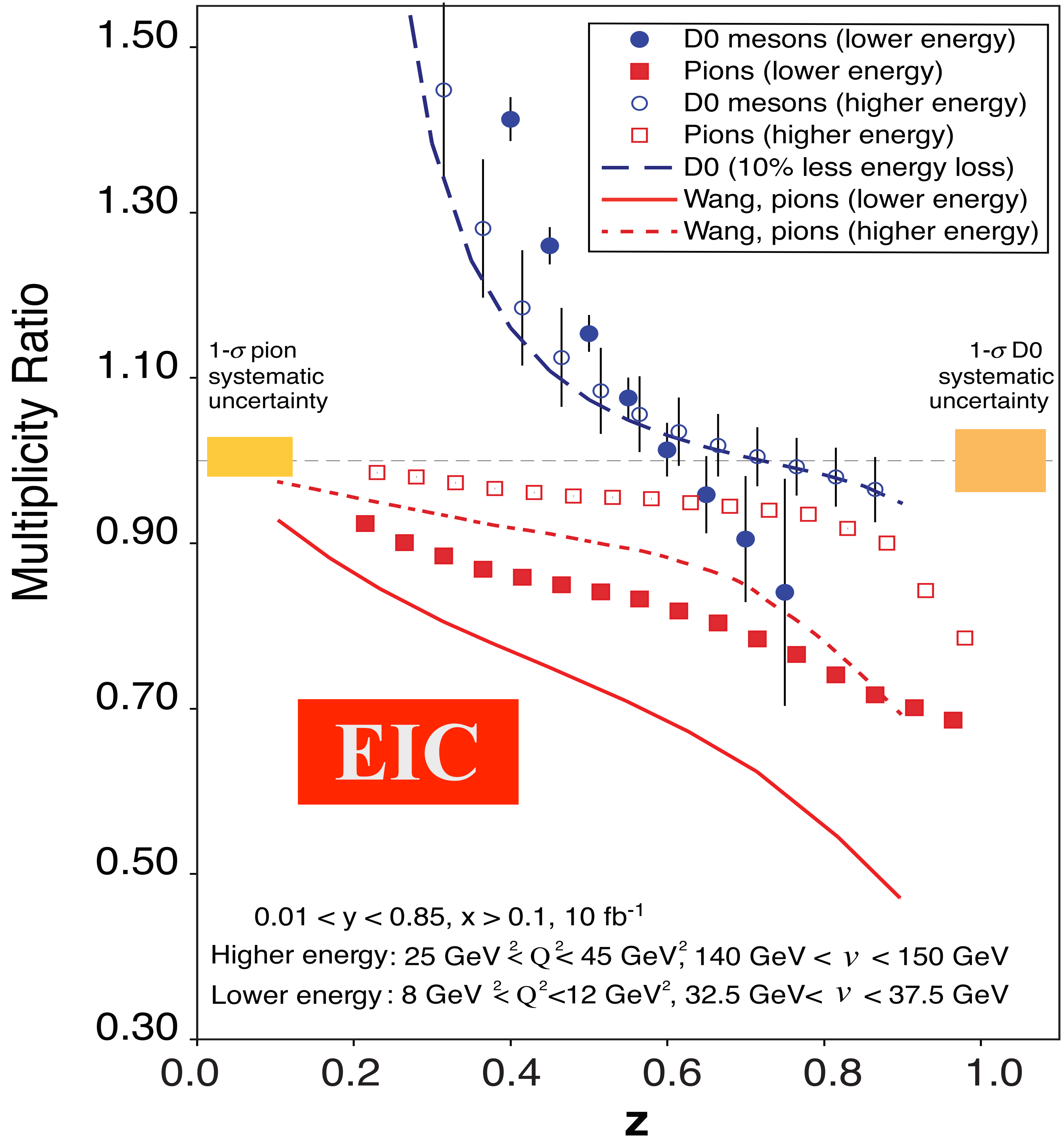
Using the prescription $\gamma=\nu/Q$ and $\beta = p_{\gamma^*}/\nu$, we can extrapolate:

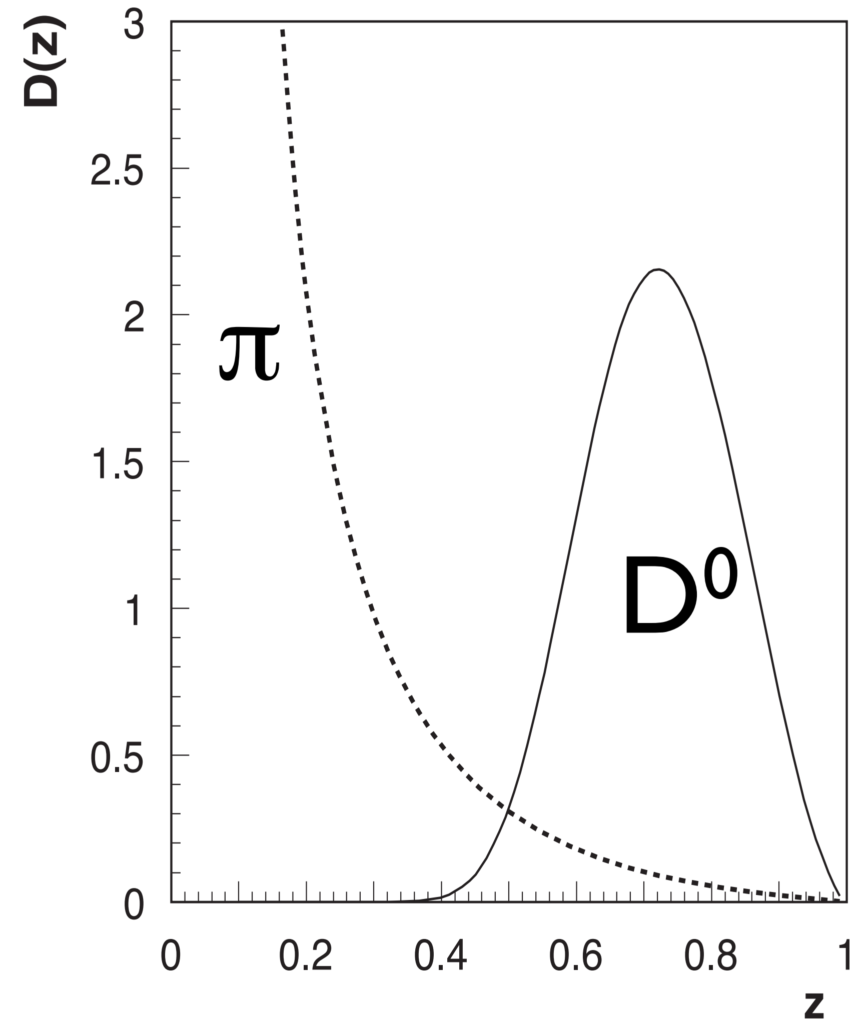
Q2	nu	beta*gamma	lp, z=0.32	lp, z=0.53	lp, z=0.75	lp, z=0.94	Experiment	x
2.40	14.50	9.31	8.57				HERMES	0.09
2.40	13.10	8.40		6.39			HERMES	0.10
2.40	12.40	7.94			4.63		HERMES	0.10
2.30	10.80	7.05				2.40	HERMES	0.11
3.00	4.00	2.08	1.92	1.58	1.21	0.71	CLAS	0.40
7.00	7.00	2.45	2.26	1.86	1.43	0.83	CLAS12	0.53
1.00	4.00	3.87	3.57	2.95	2.26	1.32	CLAS	0.13
2.00	9.00	6.28	5.79	4.78	3.66	2.14	CLAS12	0.12
12.00	32.50	9.33	8.59	7.10	5.44	3.18	EIC	0.20
8.00	37.50	13.22	12.17	10.06	7.71	4.50	EIC	0.11
45.00	140.00	20.85	19.20	15.86	12.15	7.10	EIC	0.17
27.00	150.00	28.85	26.57	21.96	16.82	9.82	EIC	0.10

At EIC we can study a wide range of production lengths!

The Breakthrough Potential of EIC

- Solving the heavy quark puzzle via heavy meson production (see following slides)
- Precision time dilation tests over a wide range in γ
- pQCD enhanced non-linear broadening (see following)
- Flavor dependencies of formed hadrons
- L_p distribution determination





EIC Year 1

Definitive comparisons of light quark and heavy quark energy loss

Access to very strong, unique light quark energy loss signature via D^0 heavy meson. Compare to s and c quark energy loss in D_s^+

NEW THEORY DEVELOPMENT

- T. Liou, A.H. Mueller, B. Wu: Nuclear Physics A 916 (2013) 102–125, arXiv:1304.7677

  - *Old*: multiple scattering → gluon emission, = energy loss

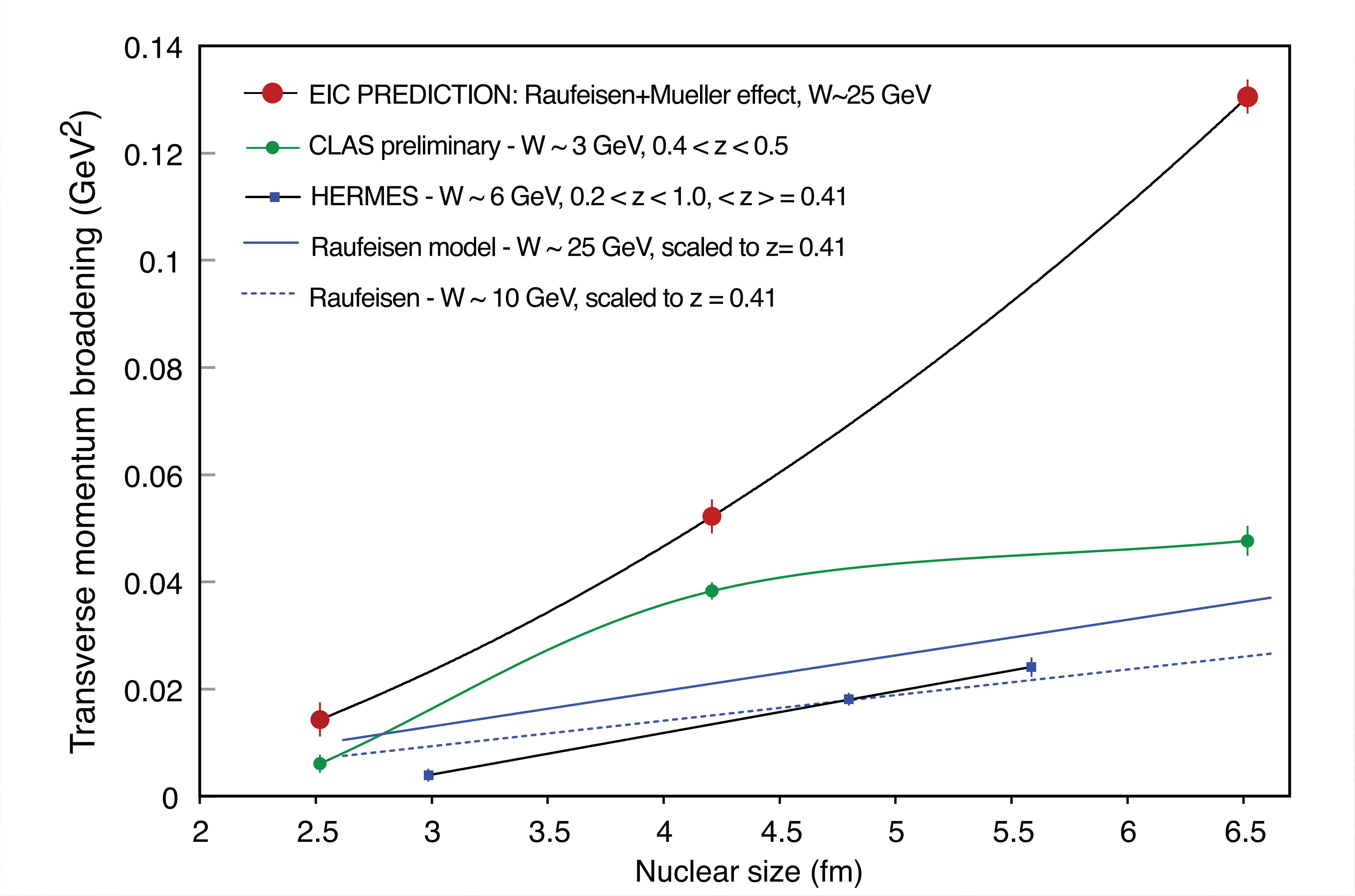
$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2 \ \propto \ \hat{q}\ L$$

  - *New*: this energy loss creates *more* p_T broadening

$$\Delta p_T^2 = \frac{\alpha_s N_c}{8\pi}\ \hat{q}\ L \boxed{\, ln^2 \frac{L^2}{l_0^2}} + ...$$

→ predicts a non-linear relationship between p_T broadening and L.
we can look for this at EIC!

pQCD description of quark energy loss on p_T broadening



DIS channels: *stable* hadrons, accessible with 11 GeV JLab future experiment PR12-06-117

Actively underway with existing 5 GeV data

HERMES

EIC: heavy mesons and baryons; wide kinematic range!

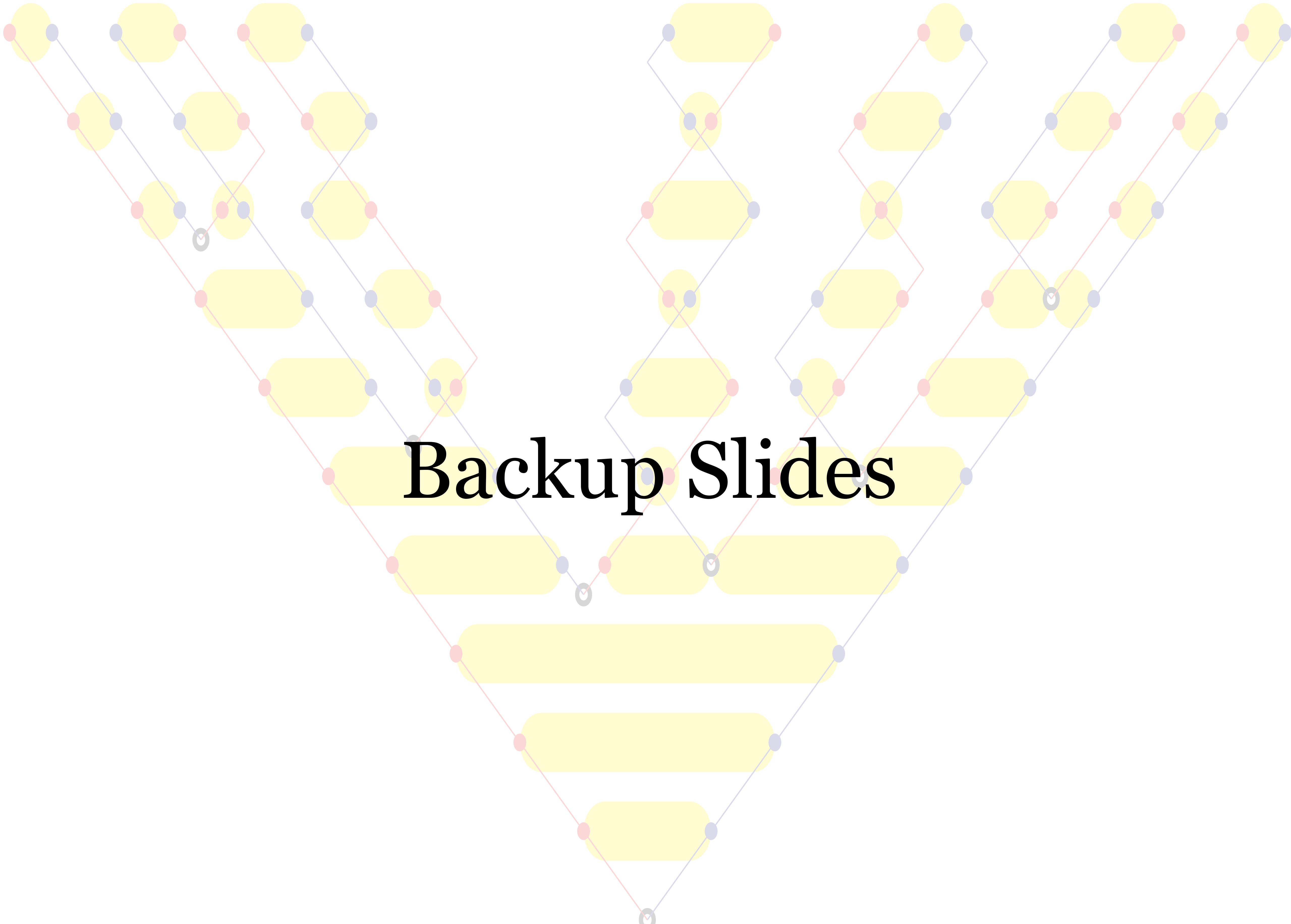
meson	cτ	mass	flavor content
π^0	25 nm	0.13	ud
π^+, π^-	7.8 m	0.14	ud
η	170 pm	0.55	uds
ω	23 fm	0.78	uds
η'	0.98 pm	0.96	uds
φ	44 fm	1	uds
f1	8 fm	1.3	uds
K^0	27 mm	0.5	ds
K^+, K^-	3.7 m	0.49	us

baryon	cτ	mass	flavor content
p	stable	0.94	ud
$\bar{p}$	stable	0.94	ud
Λ	79 mm	1.1	uds
Λ(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

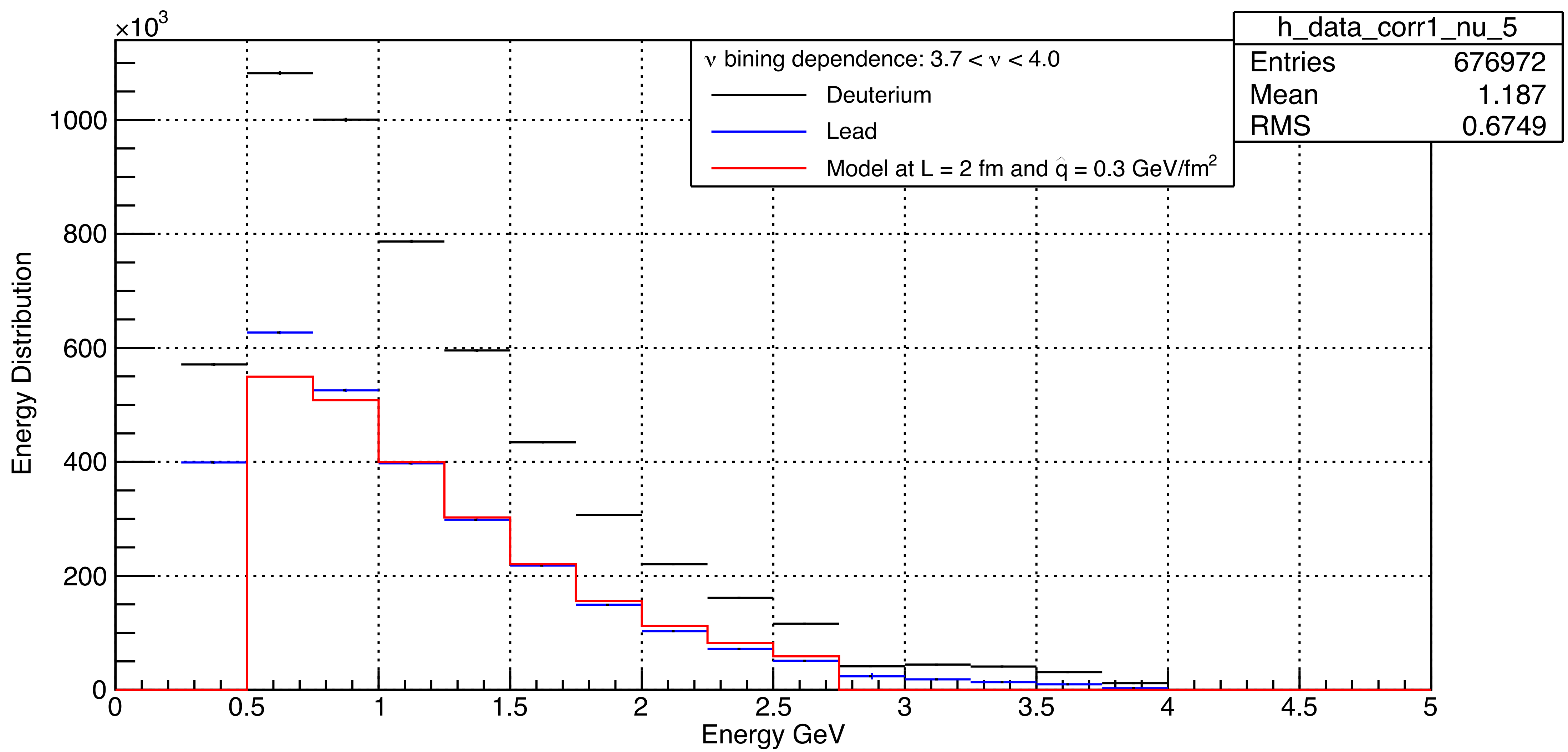
Conclusions

- Completely new categories of physics analyses. A broad and deep program of studies for the future!
- First direct measurement of quark energy loss
- Extracting characteristic times: semi-inclusive DIS
  - ➡ HERMES data - we measure the production time, and independently obtain the Lund string constant of *1 GeV/fm*
  - ➡ CLAS - (exploratory) observation of time dilation, sensitivity to production length distribution form, comparison to HERMES results through Lorentz boost
  - ➡ Clear connections to confinement, QCD factorization, Electron Ion Collider, higher energies
- Much much more in future: 12 GeV and EIC:
  - ➡ Heavy quark puzzle; time dilation; pQCD enhanced broadening; flavor dependences; L_p distribution studies

Backup Slides



Comparison to Arleo model

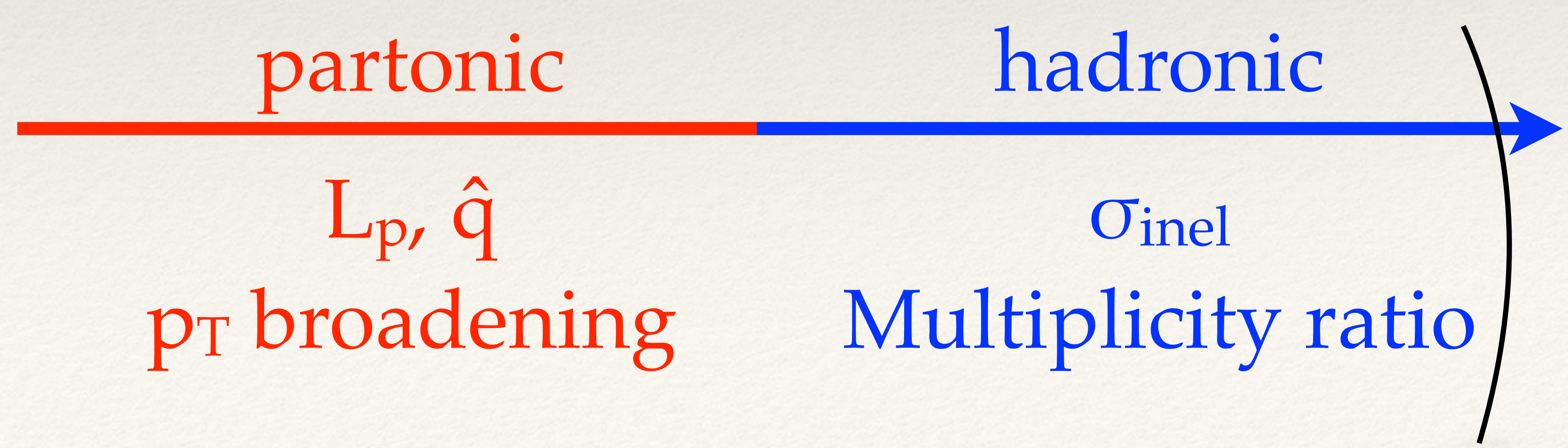


Black: Deuterium, Blue: Lead data
Red: Energy loss model evolution of deuterium to lead, production length 2 fm

Geometric model description I

- Propagating quark causes p_T broadening of hadron
- Propagating (pre-)hadron "disappears" when it undergoes an inelastic interaction with cross section σ
- Implemented as a Monte Carlo calculation in x, y, z, L_p
- Simultaneous fit of p_T broadening and multiplicity ratio
- Realistic nuclear density, integrated along path w/ GSL

Path of quark is divided into "partonic phase" and "hadronic phase"



Geometric model description II

Model implemented with 3, 4 or 5 **parameters**:

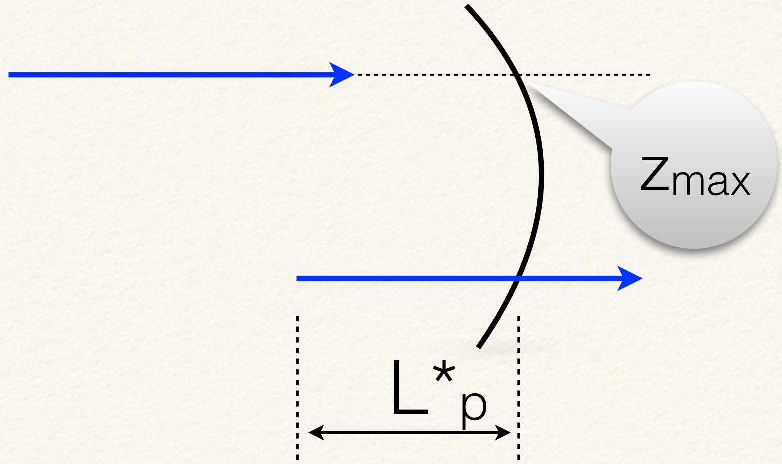
1. **q-hat** parameter (transport coefficient) that sets the scale of p_T broadening

2. Production length $\mathbf{L_p}$: distance over which p_T broadening and energy loss occur. Assumed exponential form.

3. **Cross section** for prehadron to interact with nucleus.

4. **Shift in z** caused by quark energy loss in medium
5. Average **distance between scatterings** or “mean free path” l_0 (alternative form of pT broadening, proportional to $L_p * \log^2(L_p/l_0)$)

Geometric model description III



$$\langle \Delta p_T^2 \rangle = \langle\ \hat{q}_0 \int_{z=z_0}^{z=z_0+L_p^*} \rho(x_0, y_0, z)\ dz\ \rangle_{x_0,y_0,z_0,L_p}$$

L_p is distributed as exponential

x_0,y_0,z_0 thrown uniformly in sphere, weighted by $\rho(x,y,z)$

$L^*_p = L_p$ except where truncated by integration sphere

$$\langle R_M \rangle = \langle\ exp(-\sigma \int_{z=z_0+L_p}^{z=z_{max}} \rho(x,y,z)\ dx\ dy\ dz\ )\ \rangle_{x_0,y_0,z_0,L_p}$$

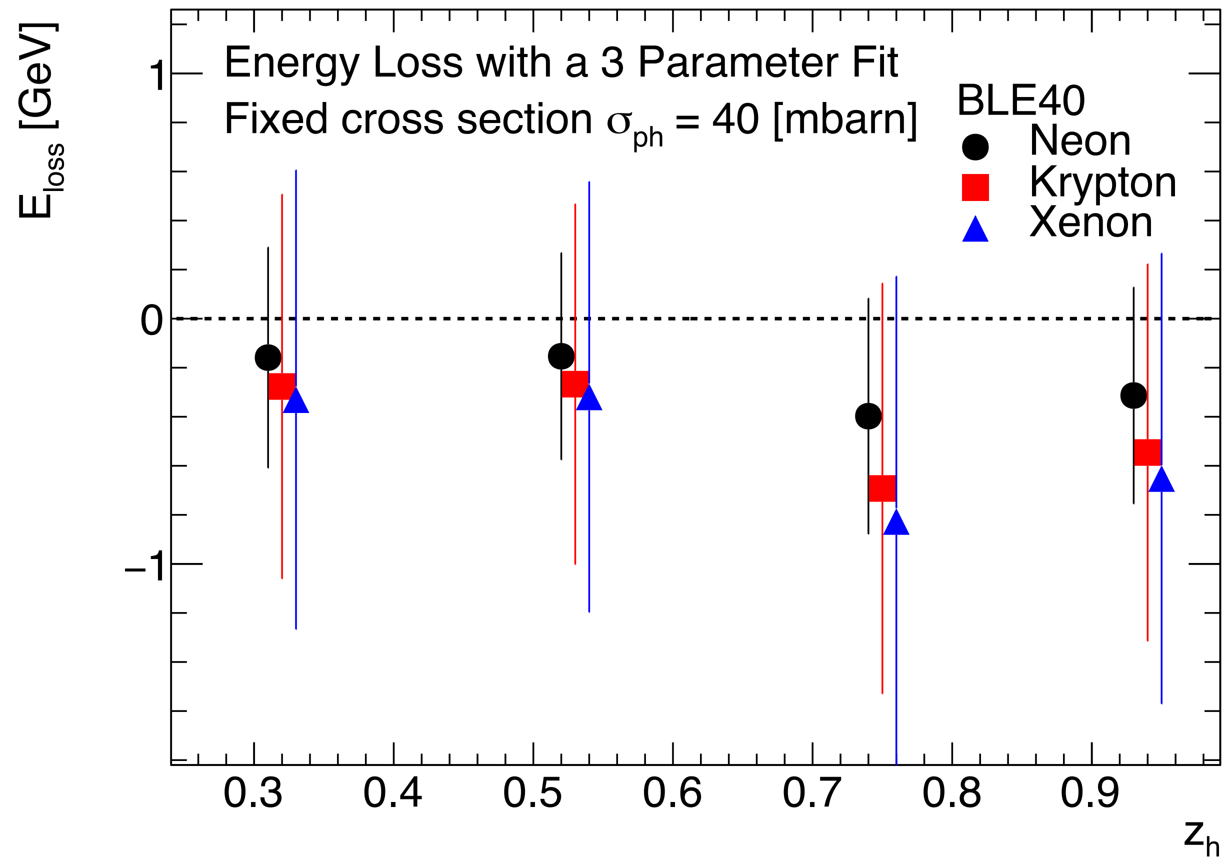
The above are computed sequentially (same x_0,y_0,z_0,L_p)

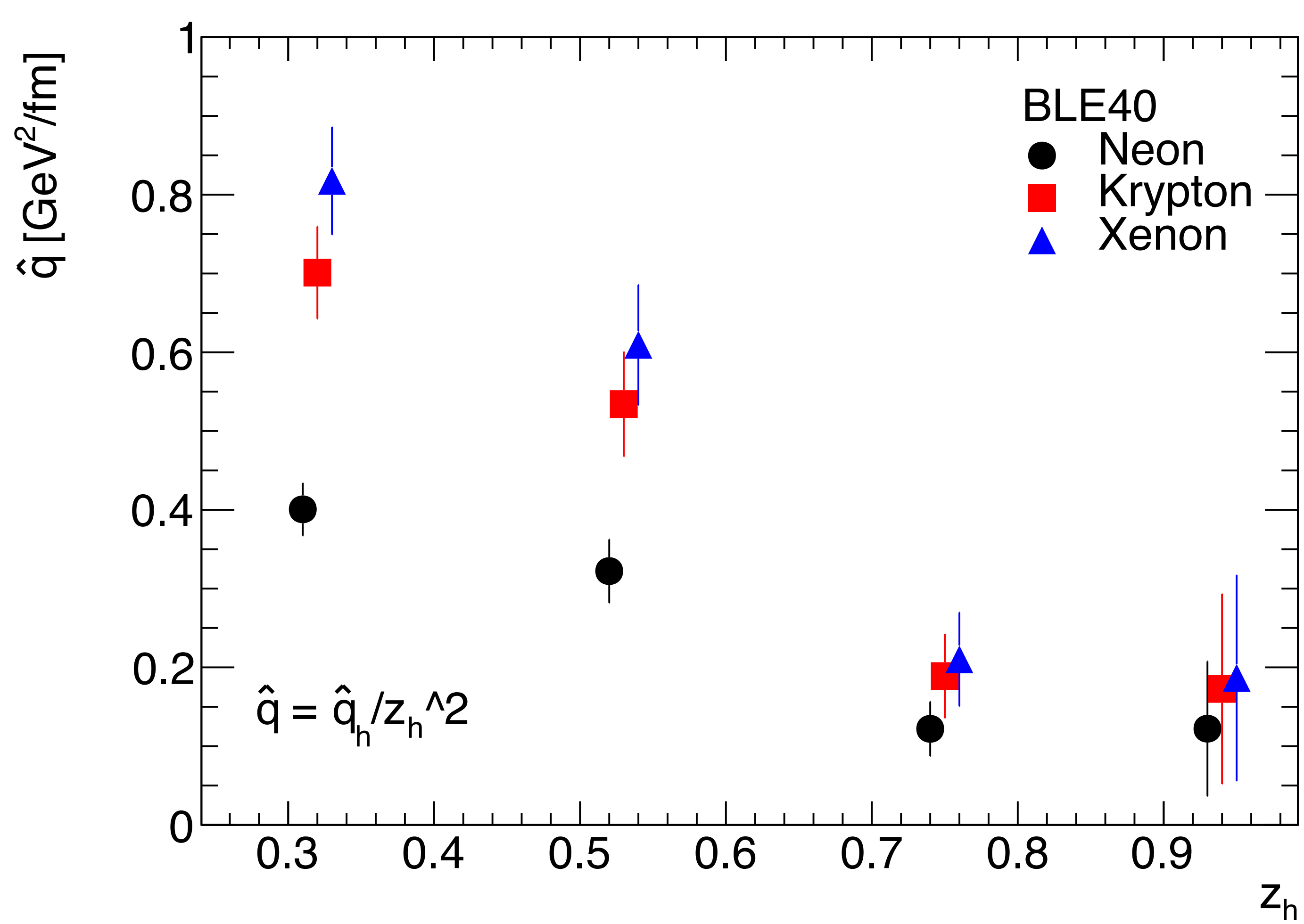
Data in (x,Q^2,z) bin: fitted to model, 3 parameters: $\hat{q}_0$,$<L_p>$,σ

No dynamical information is assumed; it emerges from fit

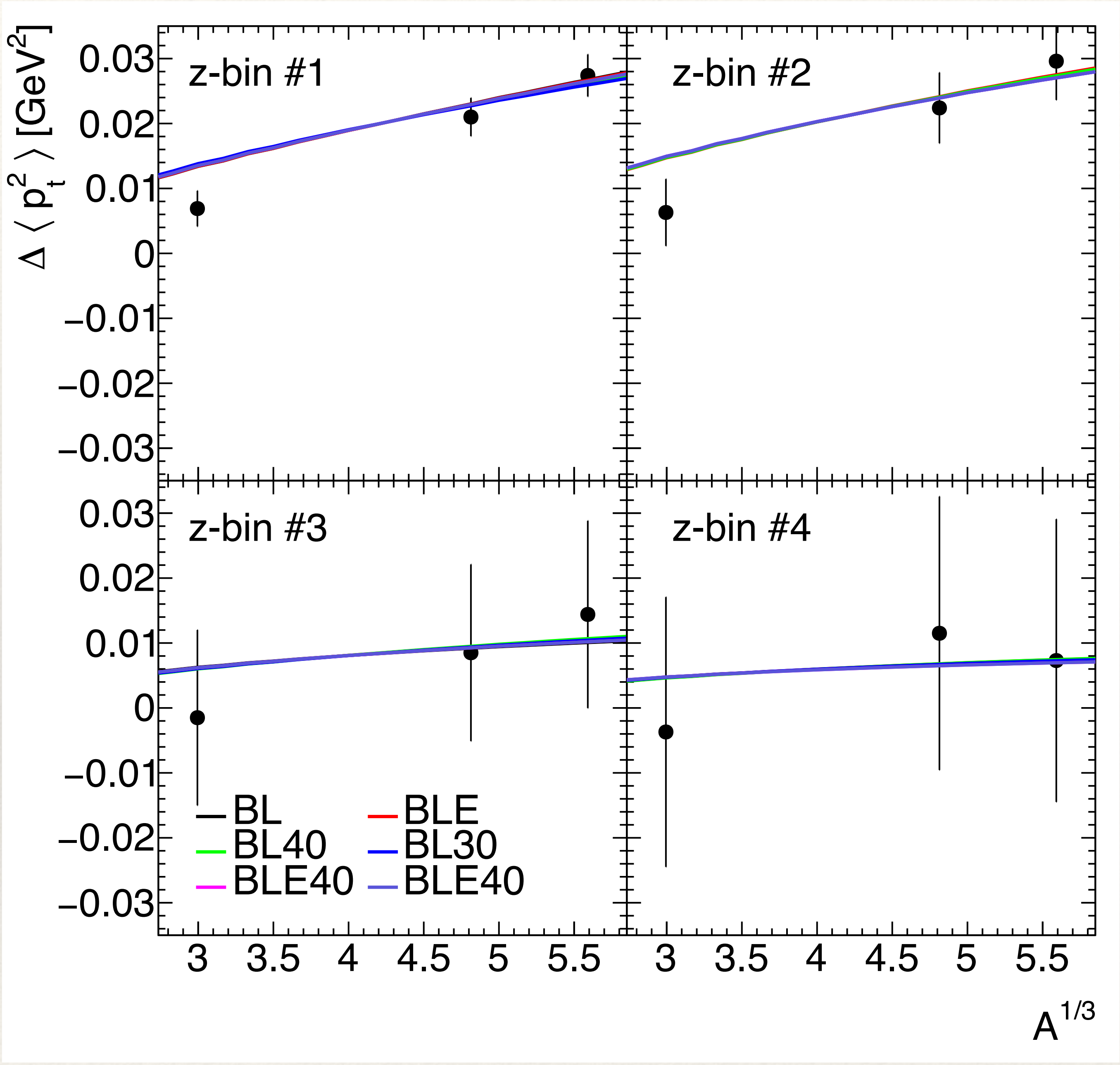
Systematic errors: 3% for multiplicity ratio, 4% for p_T broadening

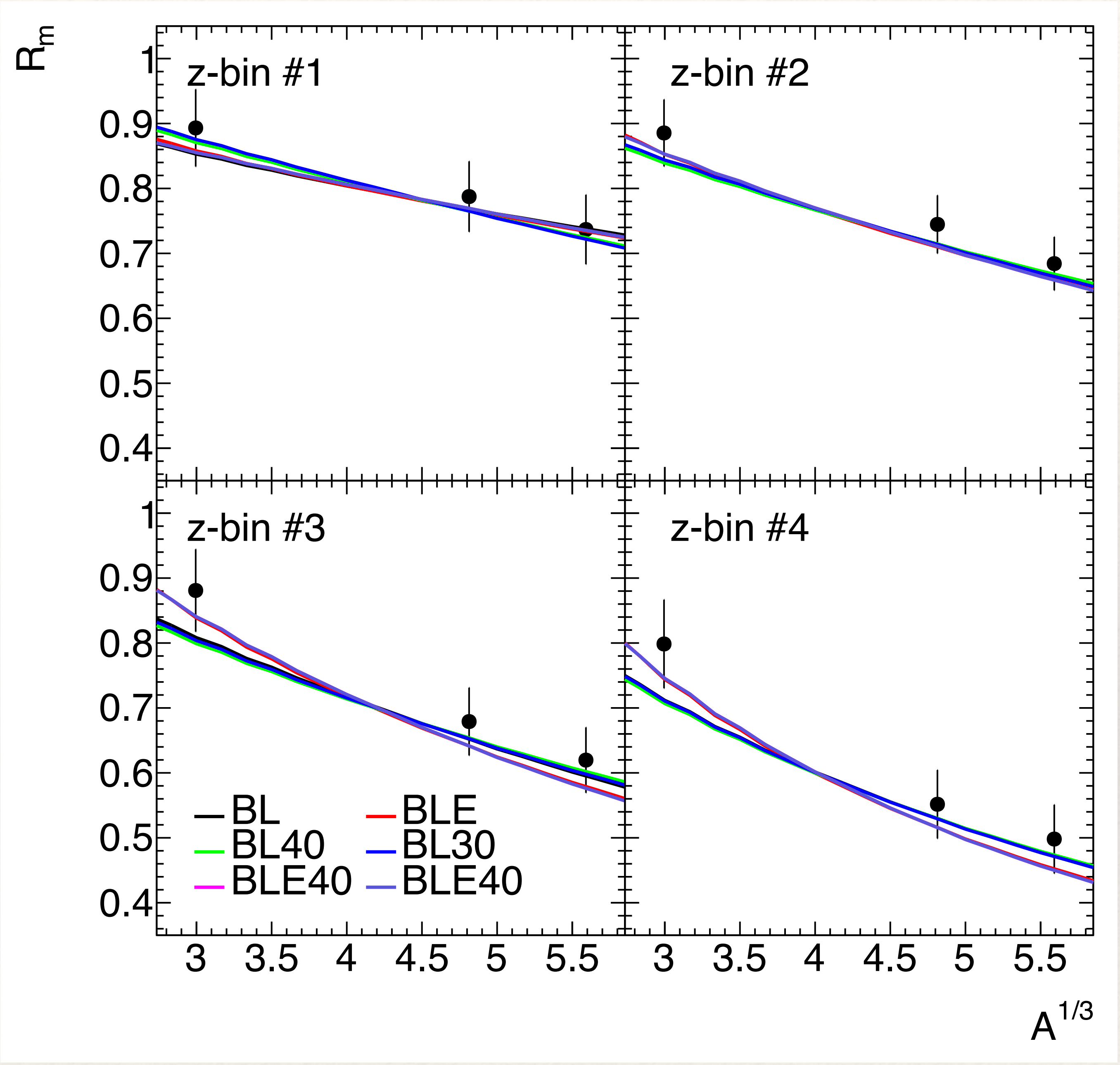
Energy loss and q̂ from our HERMES analysis





Fits of data from our HERMES analysis

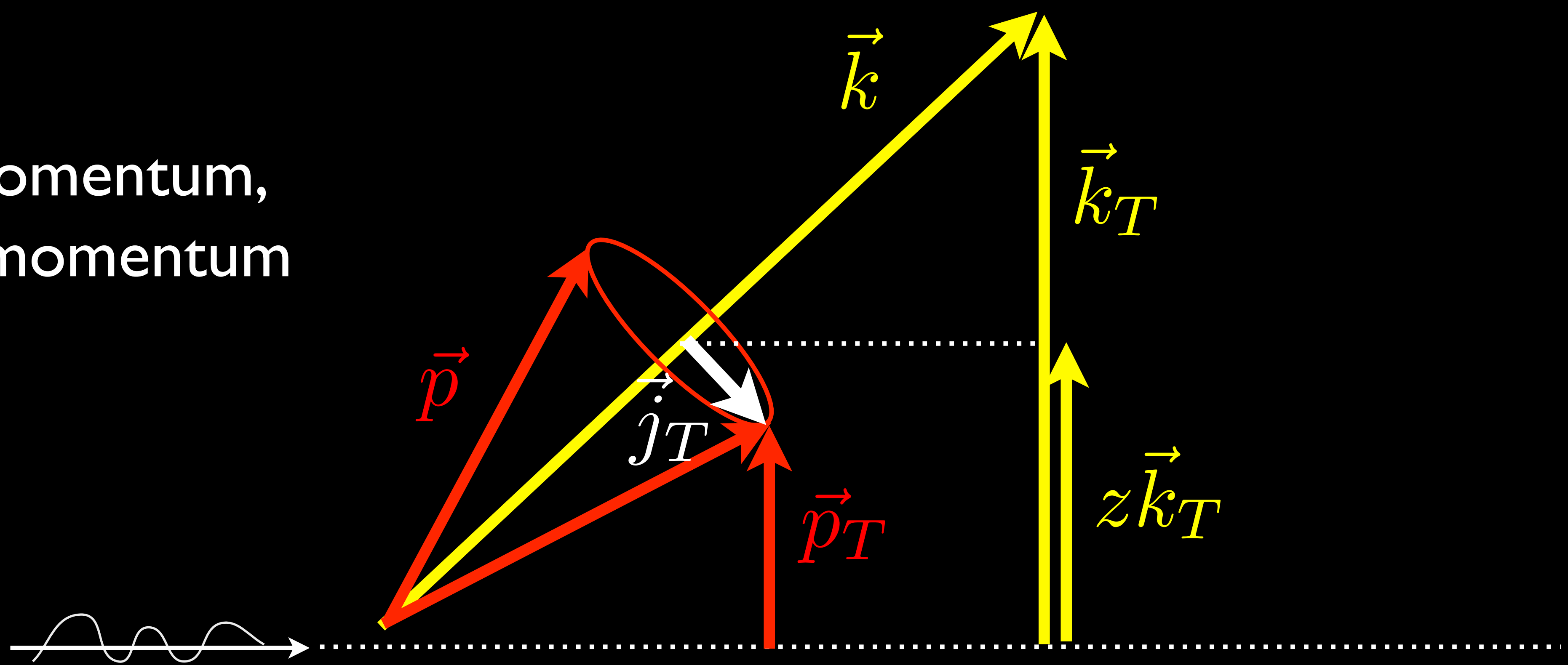




Quark k_T broadening vs. *hadron* p_T broadening

The k_T broadening experienced by a quark is "*diluted*" in the fragmention process

k is the ***quark*** momentum,
p is the ***hadron*** momentum



$$\vec{p}_T = z\vec{k}_T + \vec{j}_T$$

$$\langle p_T^2 \rangle = \langle z^2 k_T^2 \rangle + \langle j_T^2 \rangle$$

$$\Delta\langle p_T^2 \rangle = \Delta\langle z^2 k_T^2 \rangle + \Delta\langle j_T^2 \rangle$$

~0

$$\Delta\langle p_T^2 \rangle \approx z^2 \Delta\langle k_T^2 \rangle$$

Verified for pions to 5-10% accuracy for vacuum case, z=0.4-0.7, by Monte Carlo studies

Basic questions at low energies:

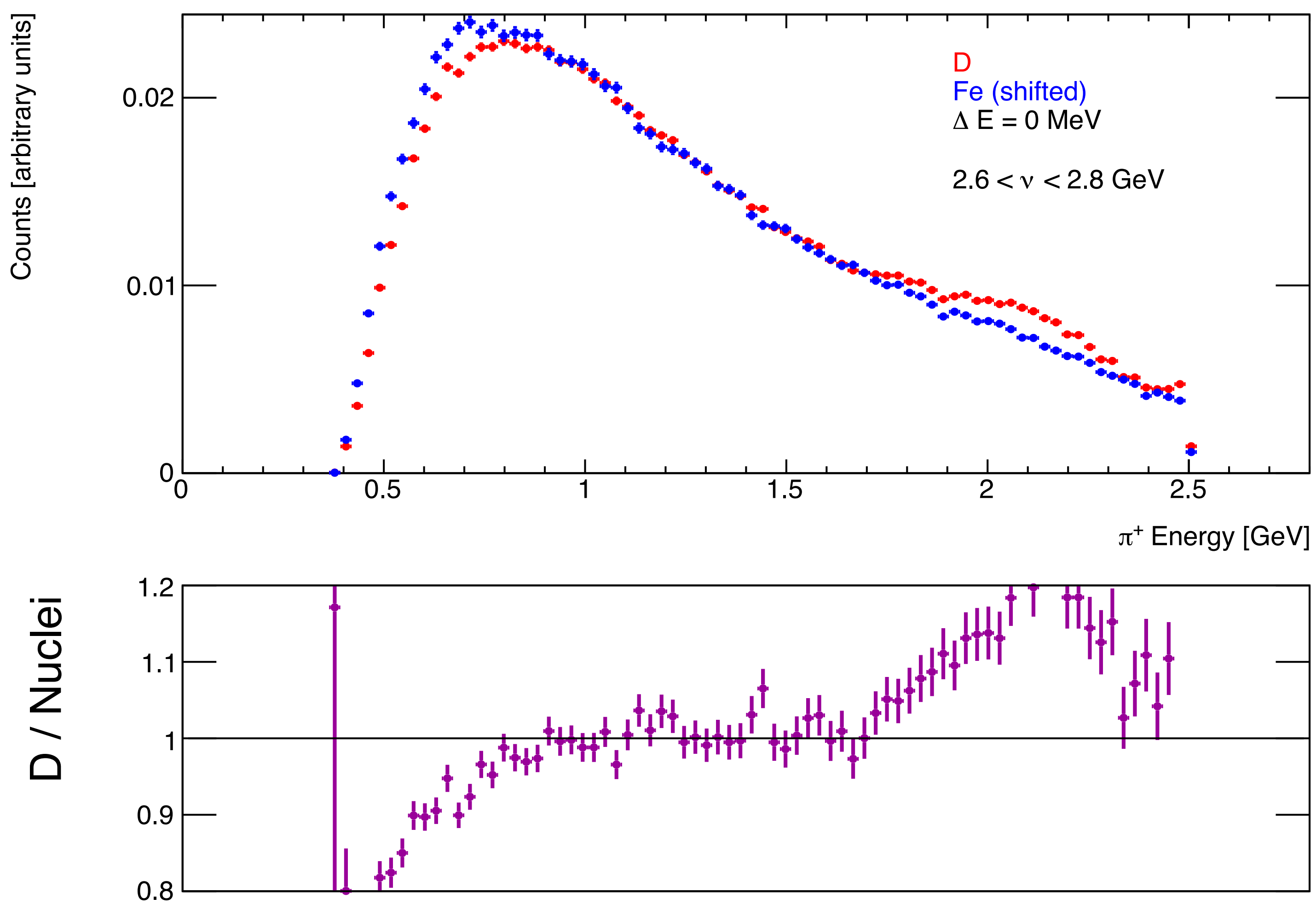
Partonic processes dominate, or hadronic? in which kinematic regime? classical or quantum?

Can identify dominant hadronization mechanisms, uniquely? what are the roles of flavor and mass?

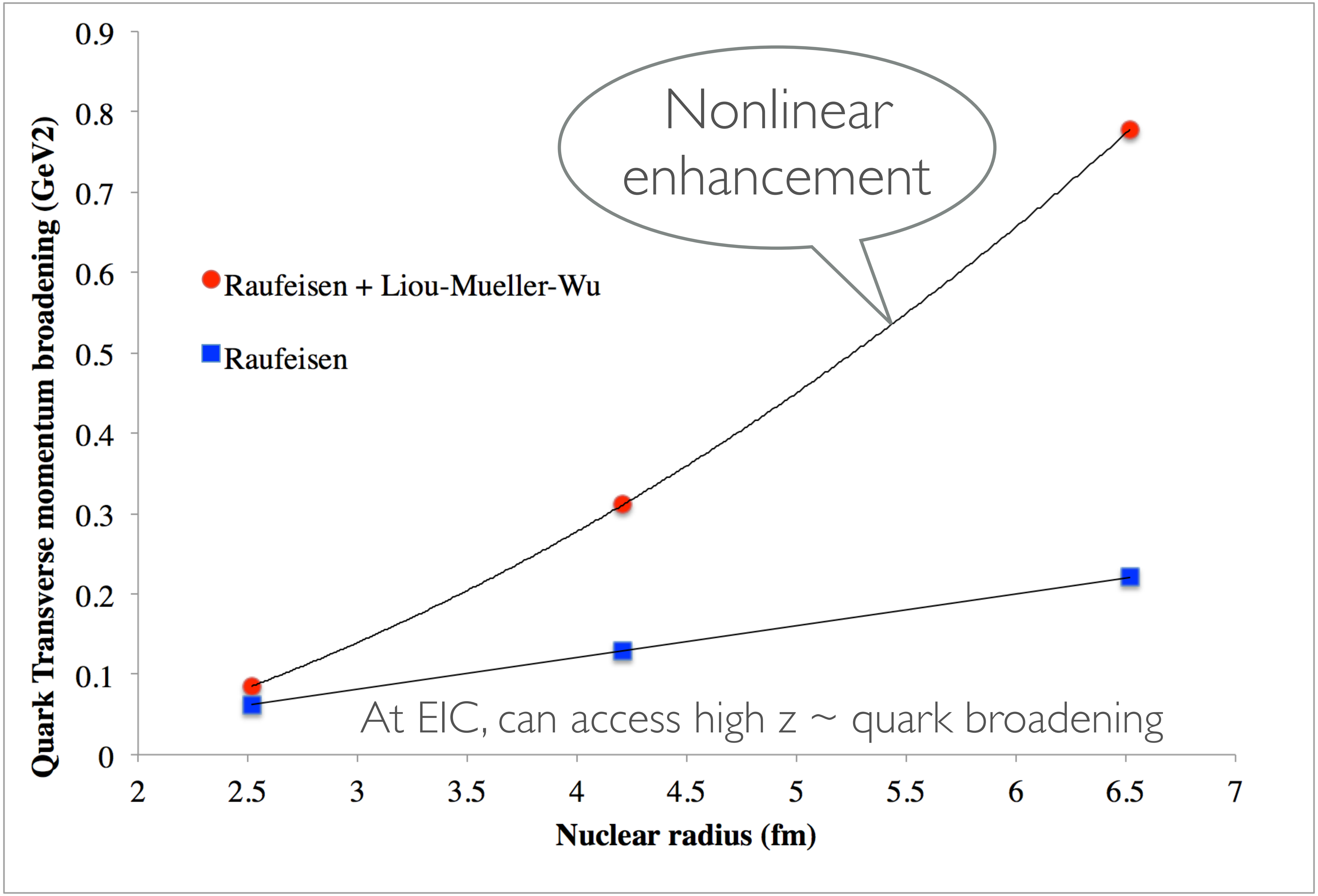
What can we infer about fundamental QCD processes by observing the interaction with the nucleus?

If p_T broadening uniquely signals the partonic stage, can use this as one tool to answer these questions

What happens if ν is too low

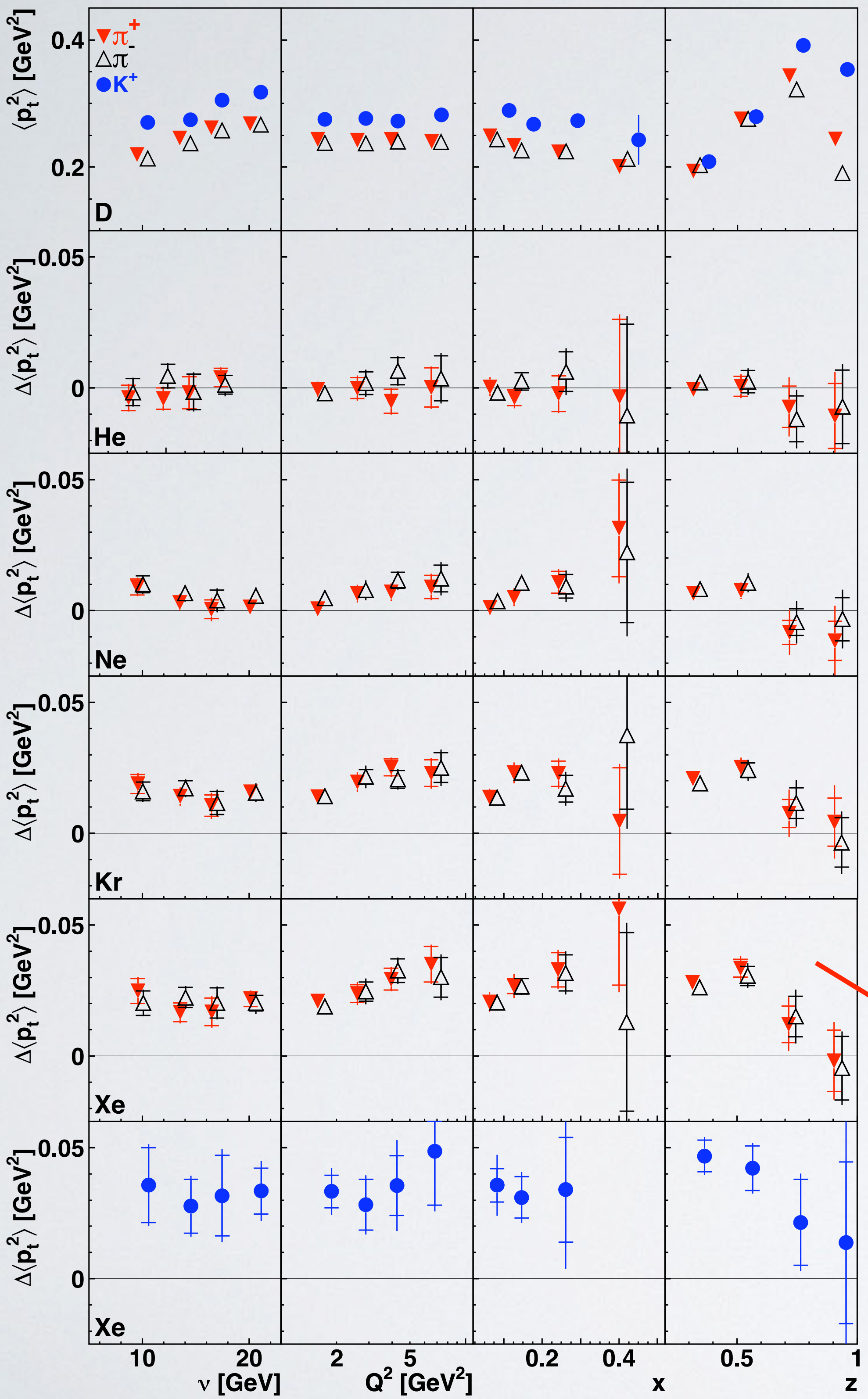


QUARK K_T BROADENING

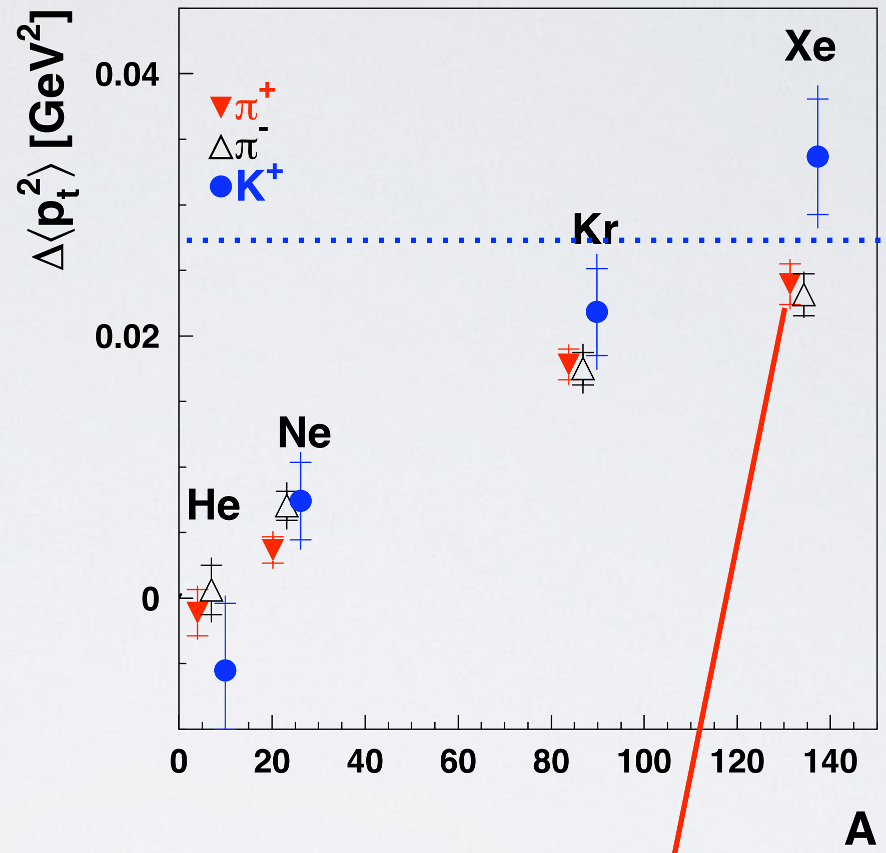


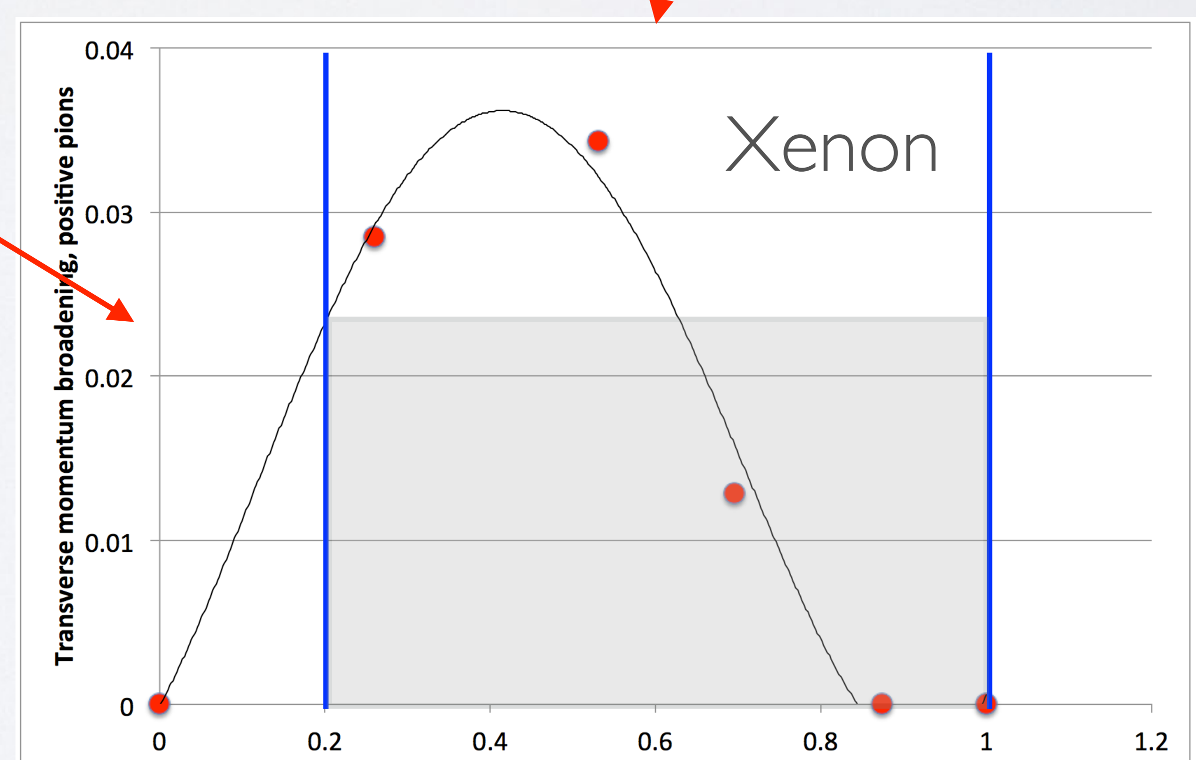
Jörg Raufeisen (Physics Letters B 557 (2003) 184–191) =
Dolejsi, Hüfner, Kopeliovich, Johnson, Tarasov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Zakharov, Guo^2, Luo, Qiu, Sterman, Majumder, Wang^2, Zhang, Kang, Zing, Song, Gao, Liang, Bodwin, Brodsky, Lepage, Michael, Wilk….color dipole, BDMPS-Z, higher-twist, etc.

P_T BROADENING FROM HERMES



I-D distributions, integrated over all other variables

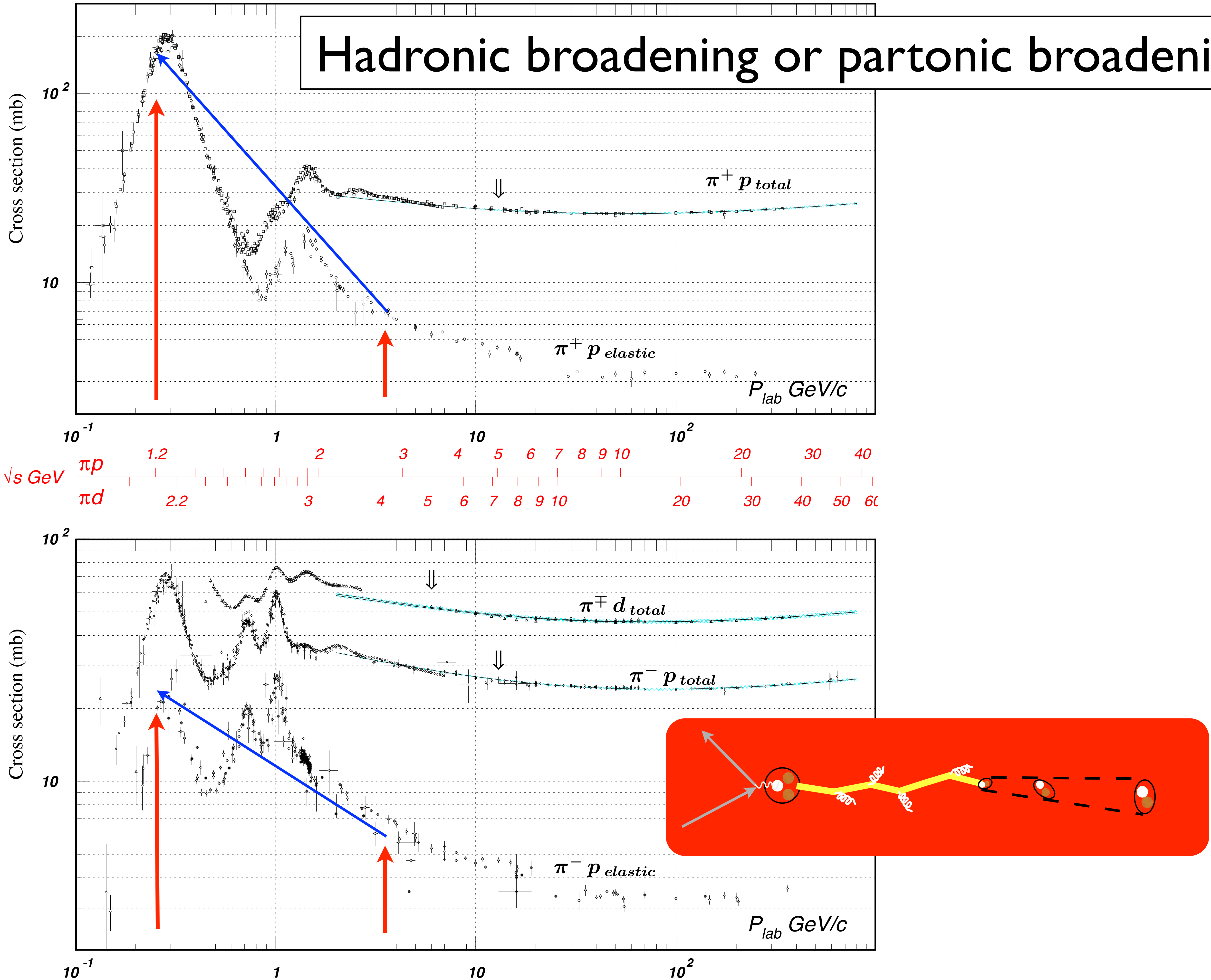


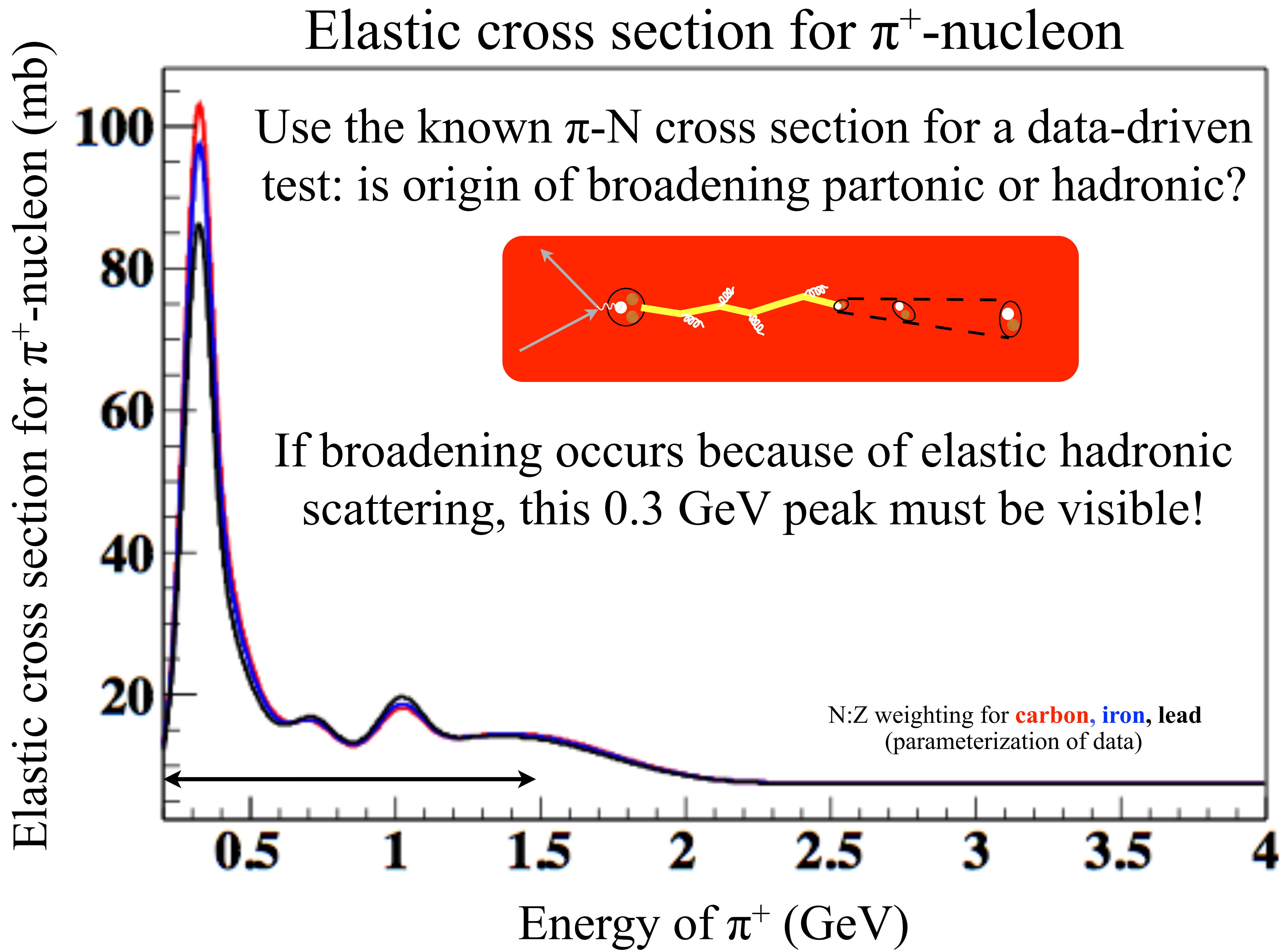


Q: Why is CLAS broadening larger than HERMES broadening?

A: Averaging over z results in reduced broadening. CLAS results are binned in **ν, Q², and z**. (Fermi motion seems to be small, suppressed by a factor of $\{z \cdot x_{Bj}\}^2$)

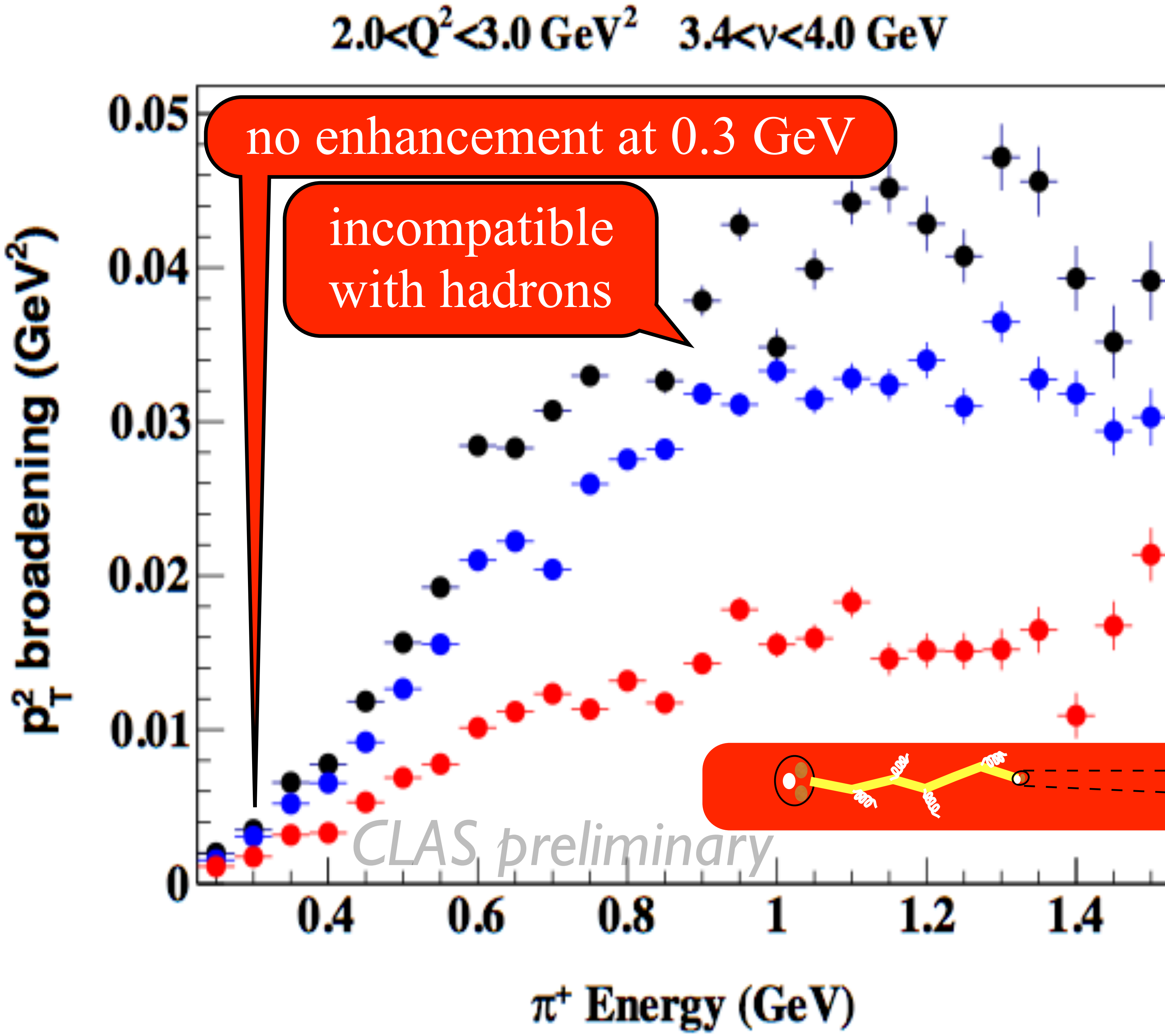
Hadronic broadening or partonic broadening?

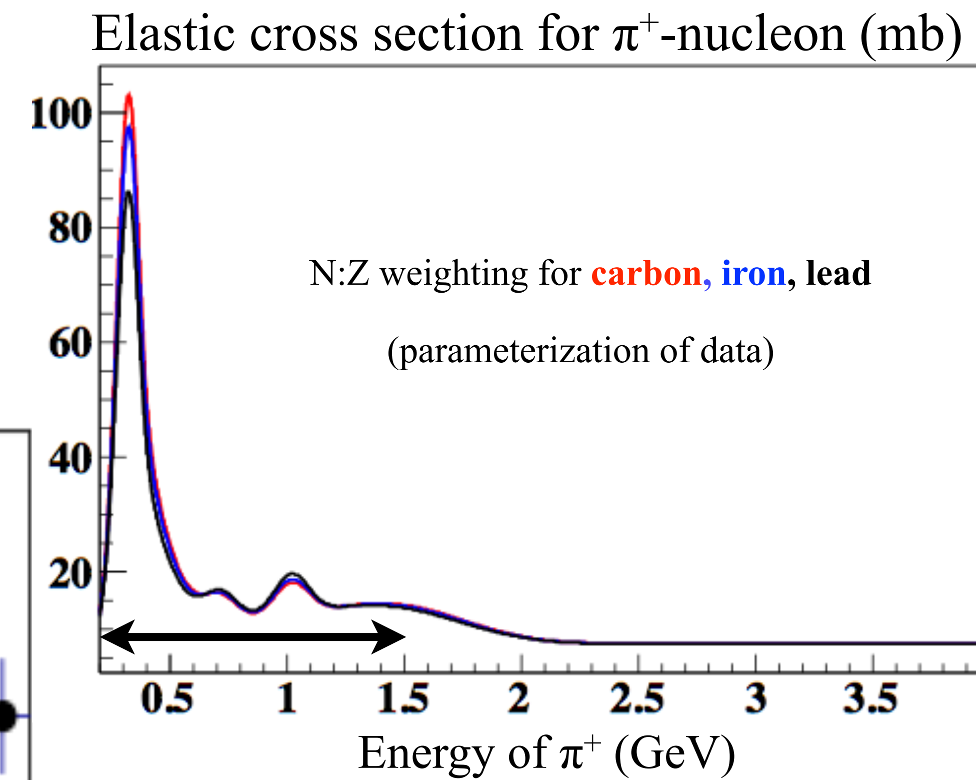




Elastic cross section for π+-nucleon
Use the known π-N cross section for a data-driven test: is origin of broadening partonic or hadronic?
If broadening occurs because of elastic hadronic scattering, this 0.3 GeV peak must be visible!
N:Z weighting for carbon, iron, lead
(parameterization of data)
Elastic cross section for π+-nucleon (mb)
100
80
60
40
20
0.5
1
1.5
2
2.5
3
3.5
4
Energy of π+ (GeV)

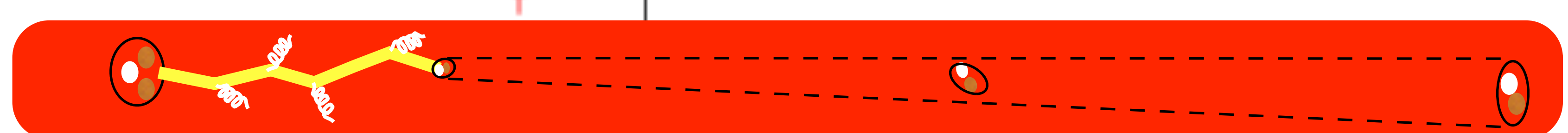
p_T^2 Broadening vs. Hadron Energy





No visible evidence of hadronic elastic scattering? Suggests:

1) formation length is very long



2) broadening is purely partonic