AGATION

IN MATTER AND IN THE VACUUM

USING ATOMIC NUCLEI AS SPATIAL ANALYZERS

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Spatial and Momentum Tomography of Hadrons and Nuclei
INT Program INT-17-3 Week 3
September 2017

OUTLINE

WHY COLOR PROPAGATION IS INTERESTING

SPACE-TIME PROPERTIES OF SIDIS

THE BROOKS-LOPEZ GEOMETRICAL MODEL OF SIDIS ON NUCLEI

MEASUREMENTS: HERMES, JLAB, LHC

FUTURE PROSPECTS: JLAB, LHC, EIC

COLOR PROPAGATION: WHY IS IT INTERESTING?

RESTORATION OF COLOR NEUTRALITY IN HIGH ENERGY INTERACTIONS IS DYNAMICAL ENFORCEMENT OF **CONFINEMENT**

PRECISION PQCD RELIES ON THE CONCEPT OF **FACTORIZATION**

FUNDAMENTAL STRONG INTERACTION **THERMODYNAMICS**

NON-ADIABATIC COLOR DYNAMICS: QUANTUM COLOR **FLUCTUATIONS**

Terminology!

Production length and production time:

The time or distance required for a colored system to evolve into a color singlet system. Historical term; can be estimated in models. A “colored system” can be a quark, a gluon, a color dipole, etc.

Color lifetime, lifetime of highly virtual quark:

Means the same thing as “production time”

HIGHLIGHTS OF RESULTS I WILL SHOW

COLOR LIFETIME (COLD MATTER AND VACUUM)

CONSTRAINTS ON FUNCTIONAL FORM OF COLOR LIFETIME

TIME DILATION OF COLOR LIFETIME

CONFIRMATION OF LUND STRING CONSTANT

PREDICTION: COLOR LIFETIME AT EIC ENERGIES

QUARK ENERGY LOSS IN COLD MATTER

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 ("tomography")
  - energy loss in-medium: $\hat{e}$
  - transverse momentum broadening: $\hat{q}$

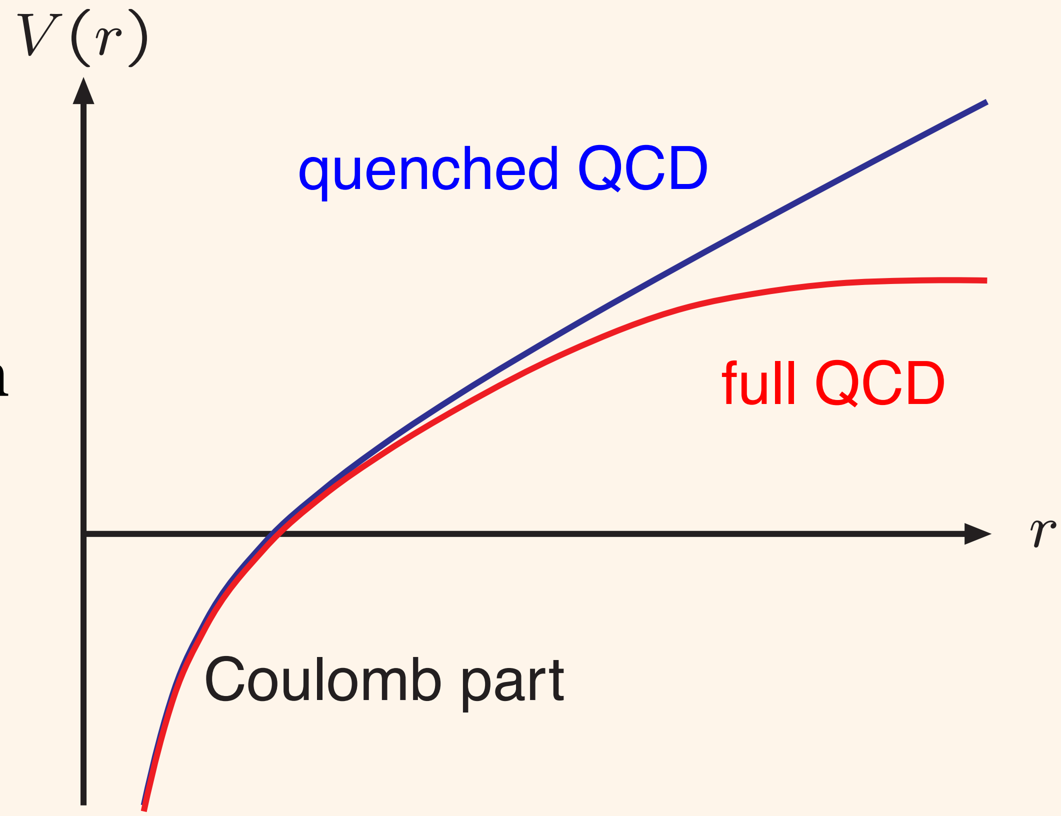
Method: struck quark from DIS probes nuclei of different sizes

Connection to Confinement

$V=0$ at ~0.4 fm

Connection to Confinement

V=0 at ~0.4 fm



Connection to Confinement

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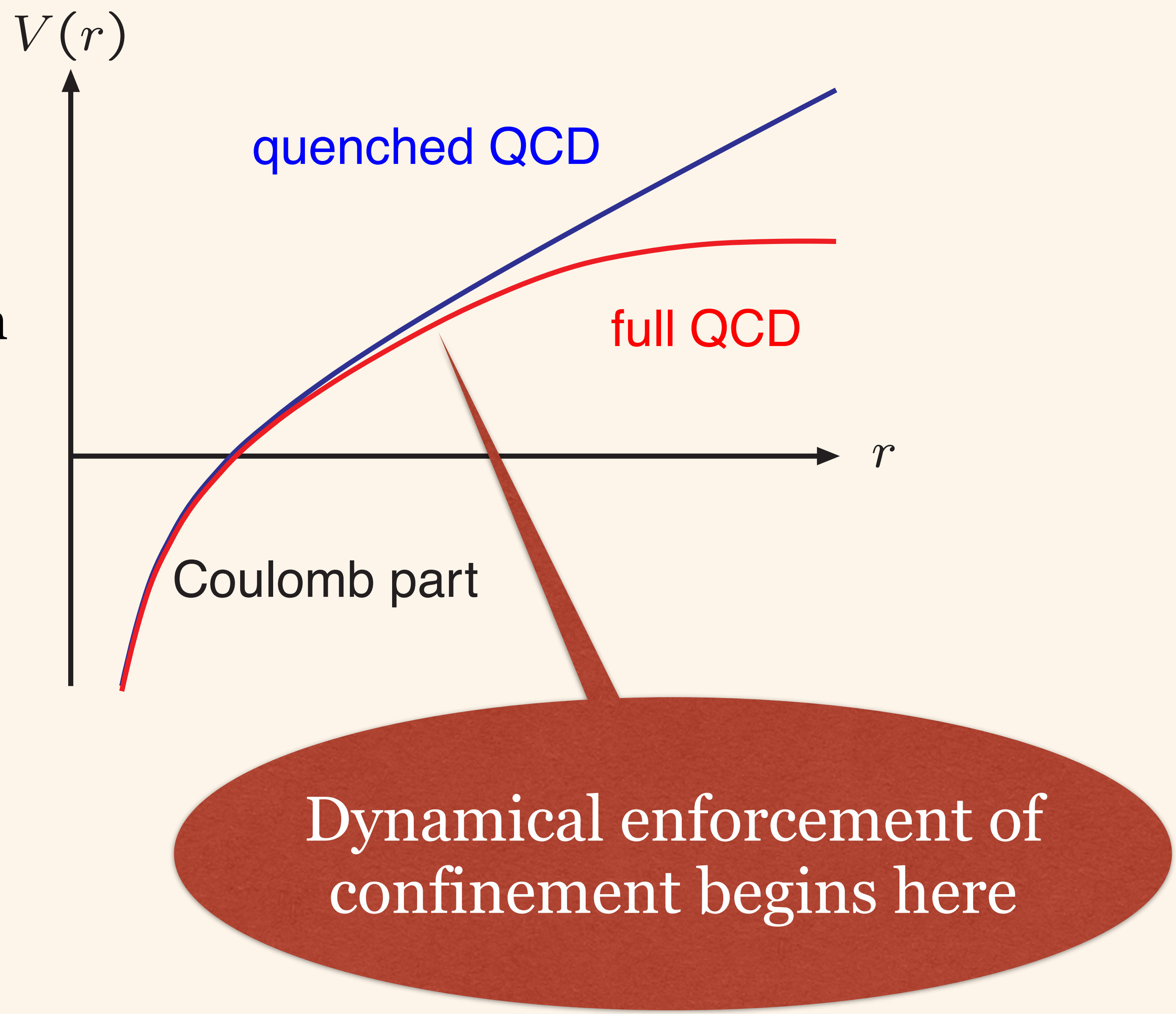
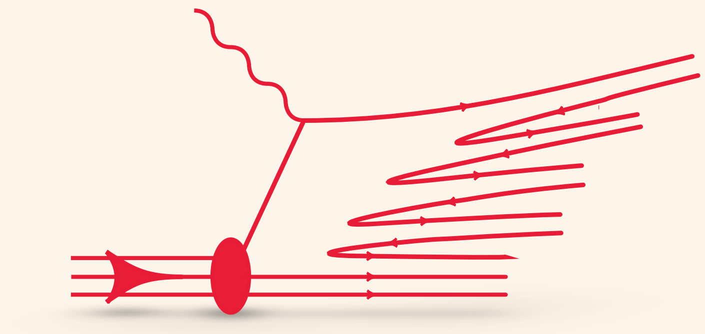
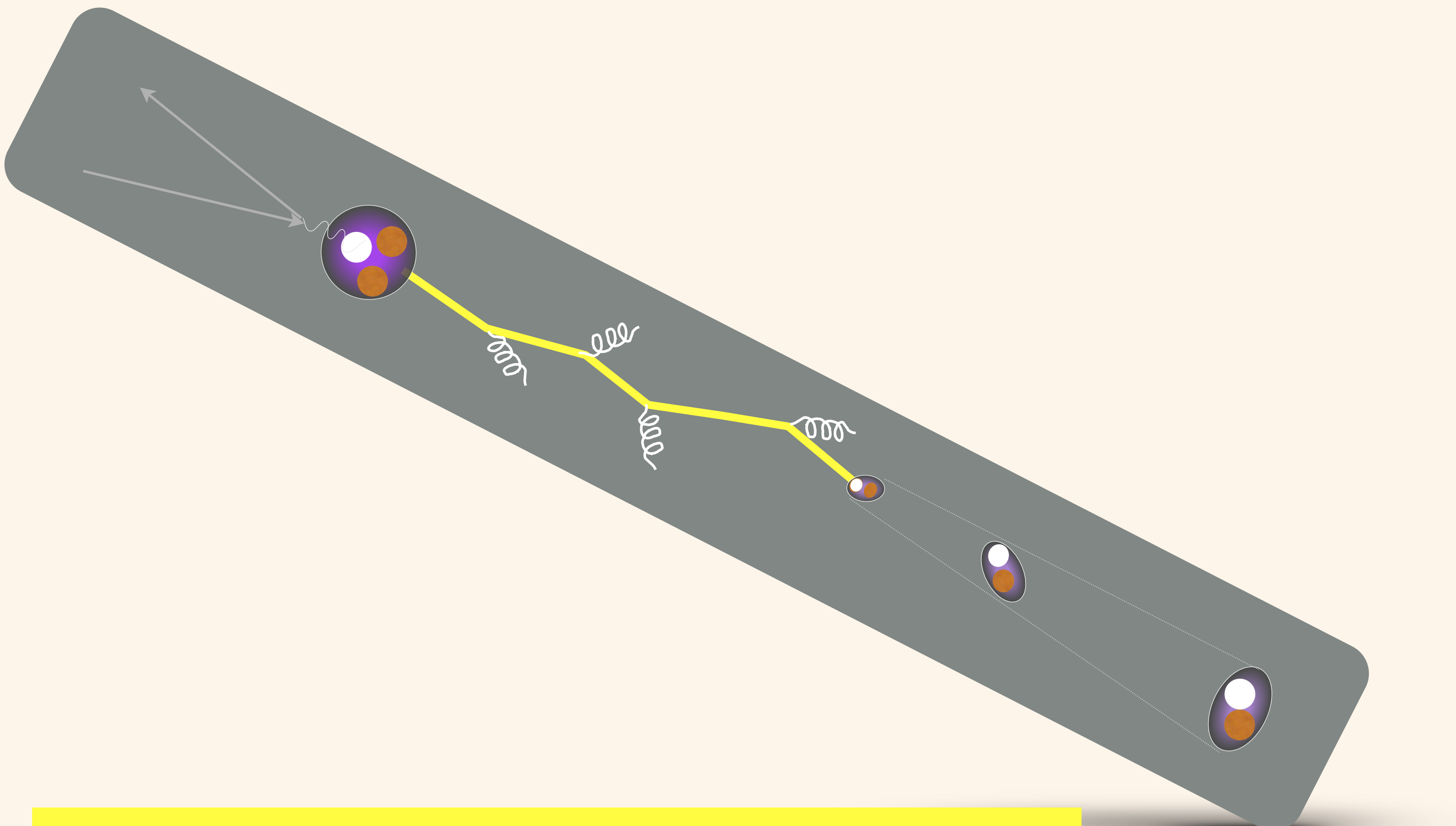


Beyond ~1 fm the potential is irrelevant but confinement is still enforced

FUNDAMENTAL QCD PROCESSES

(DIS, pQCD picture)



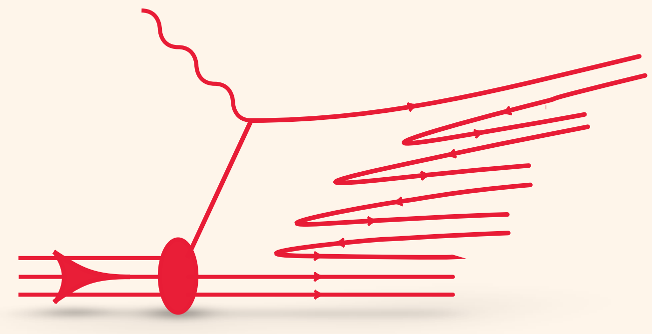


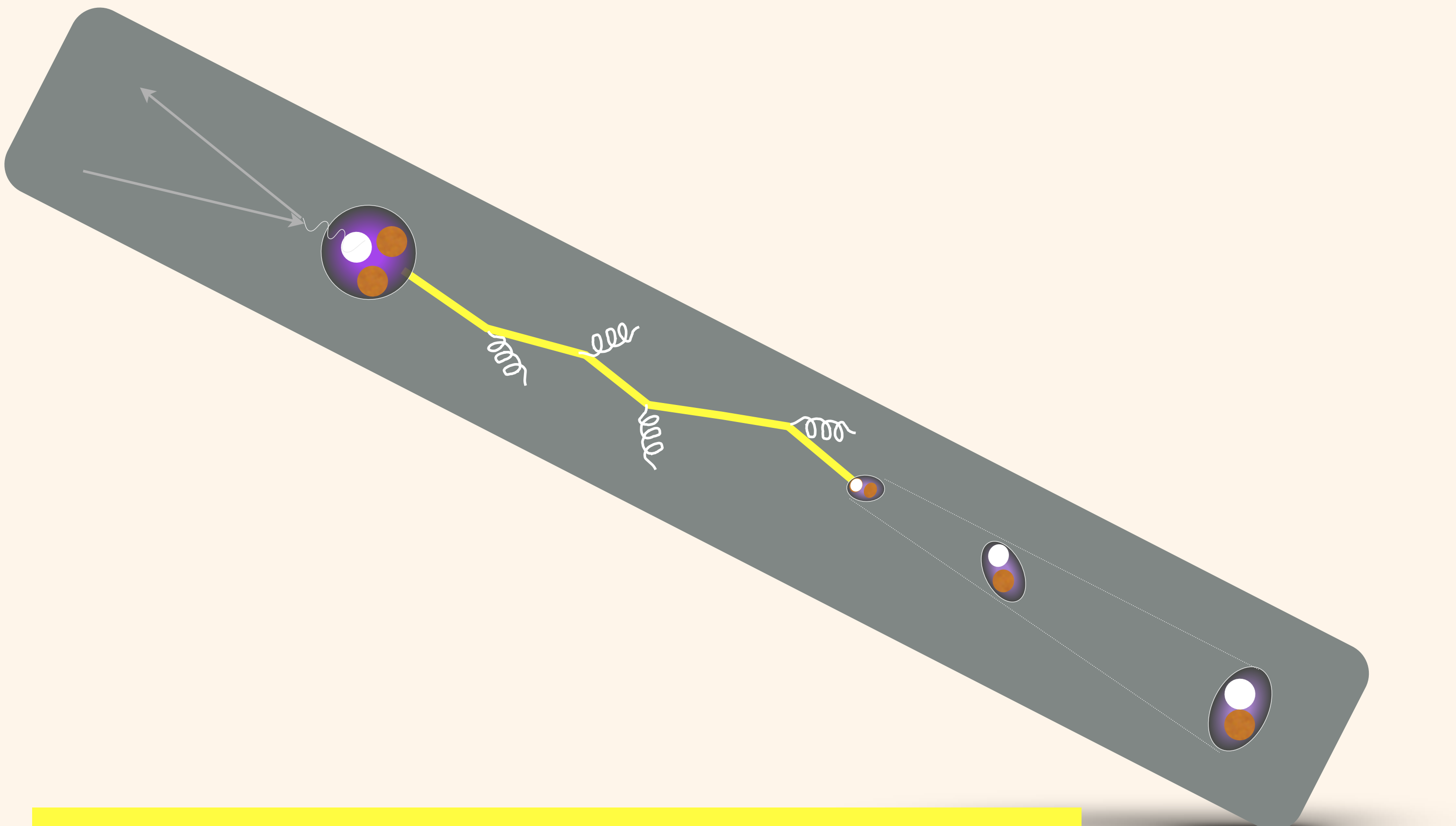
The production length is shown in yellow

FUNDAMENTAL QCD PROCESSES

(DIS, pQCD picture)

Partonic elastic scattering in medium





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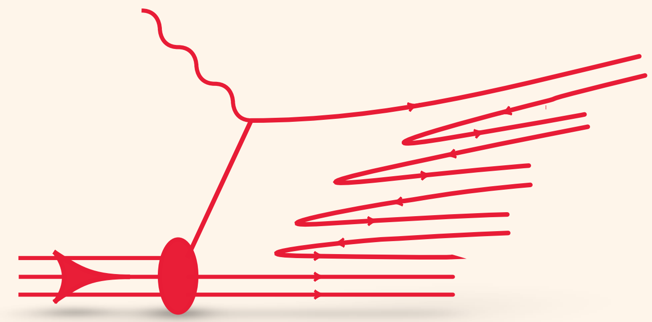
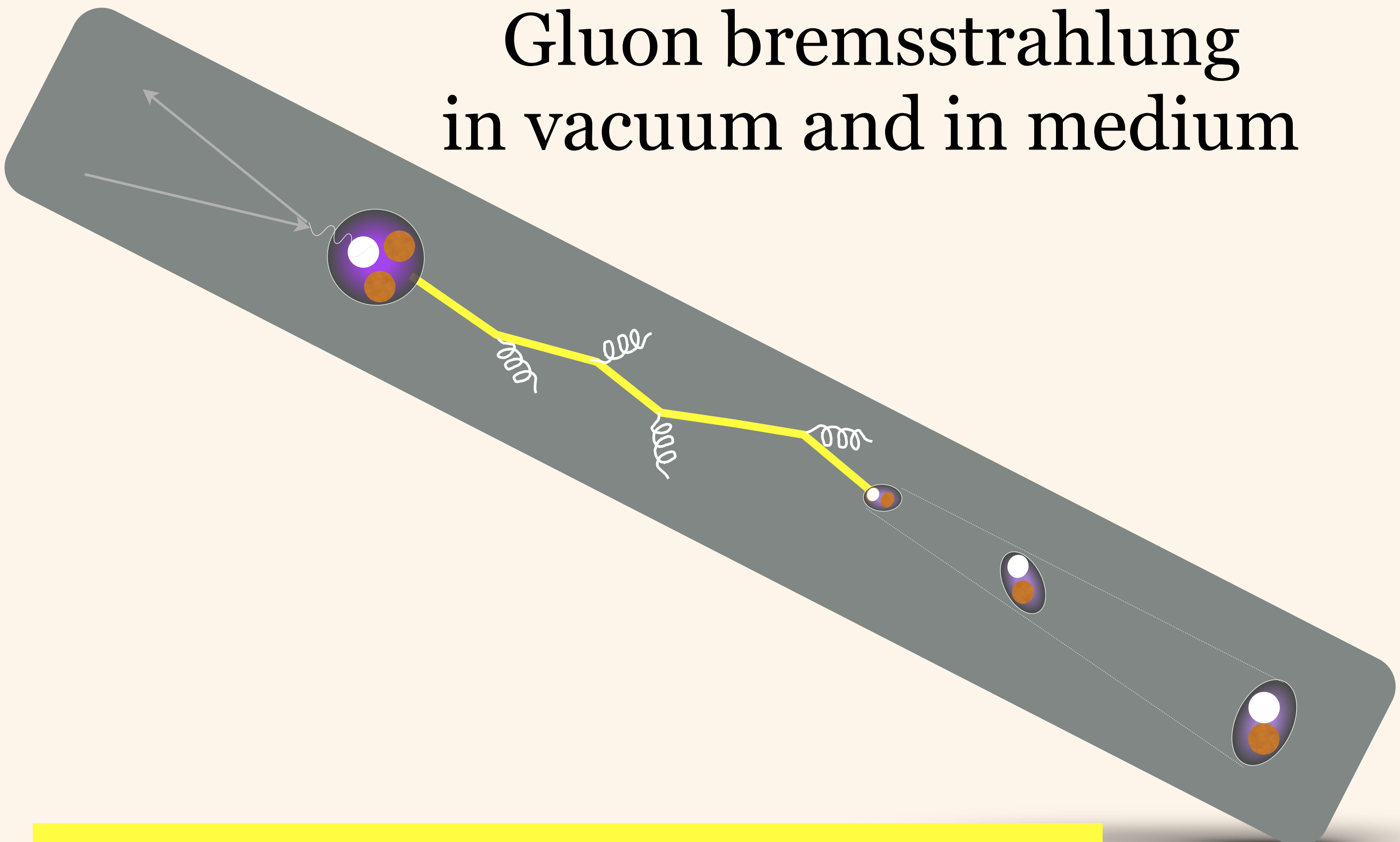


Gluon bremsstrahlung
in vacuum and in medium



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FUNDAMENTAL QCD PROCESSES

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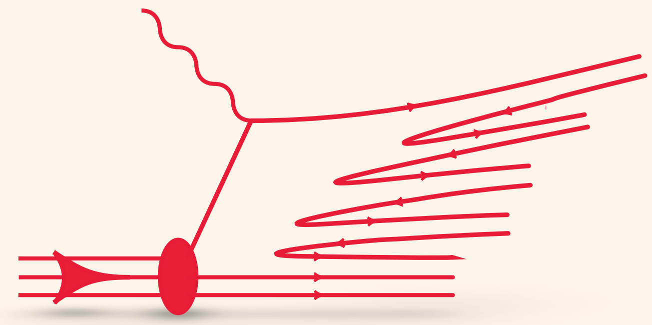

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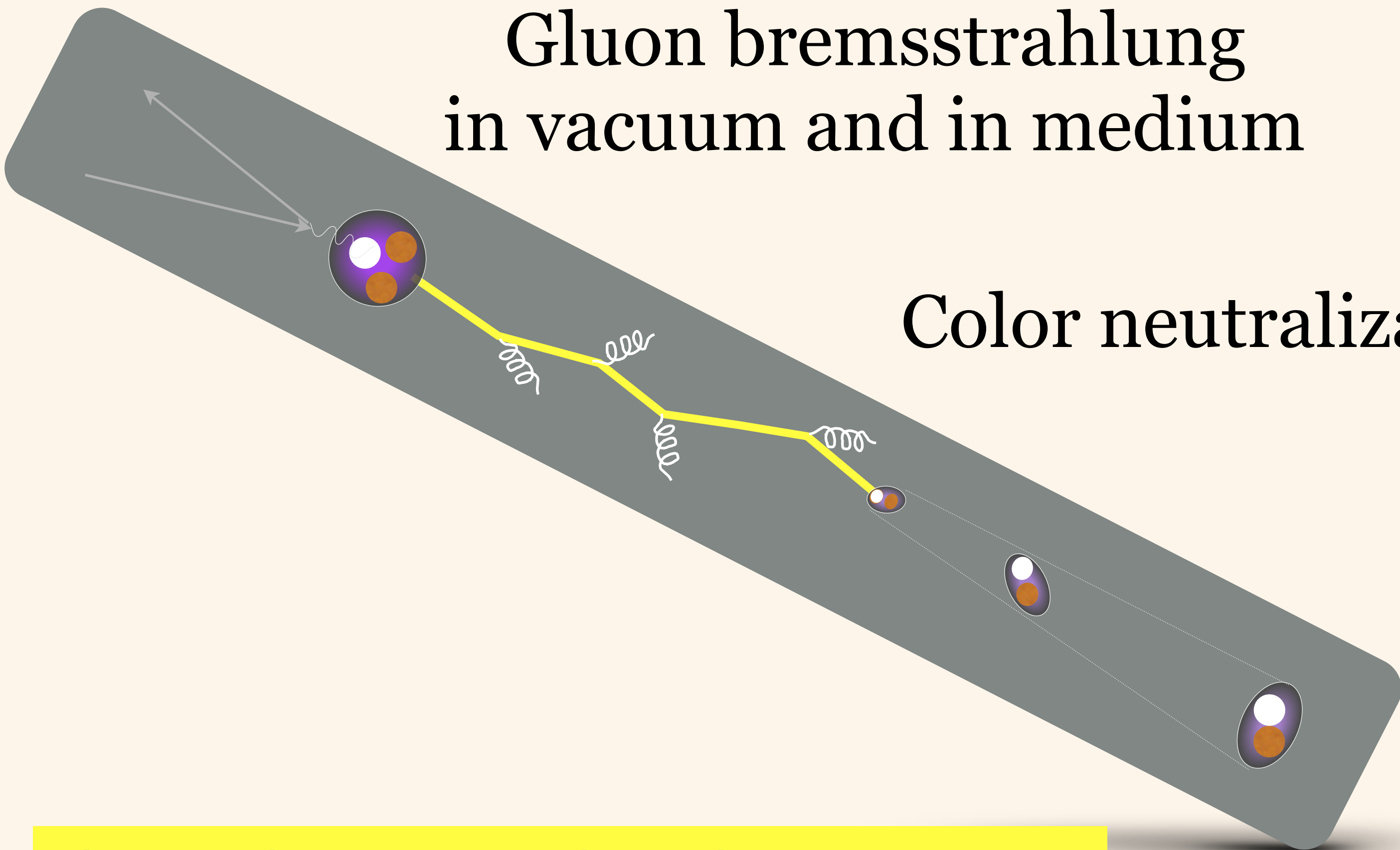

Color neutralization

The production length is shown in yellow

FUNDAMENTAL QCD PROCESSES

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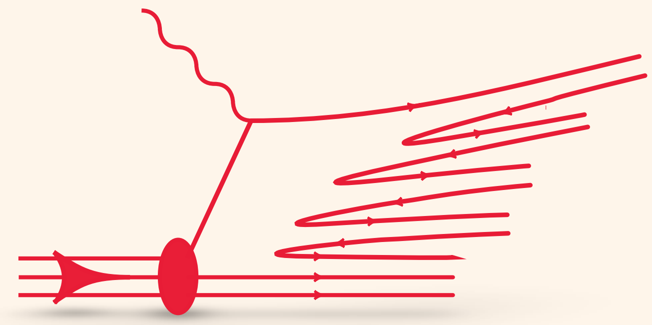
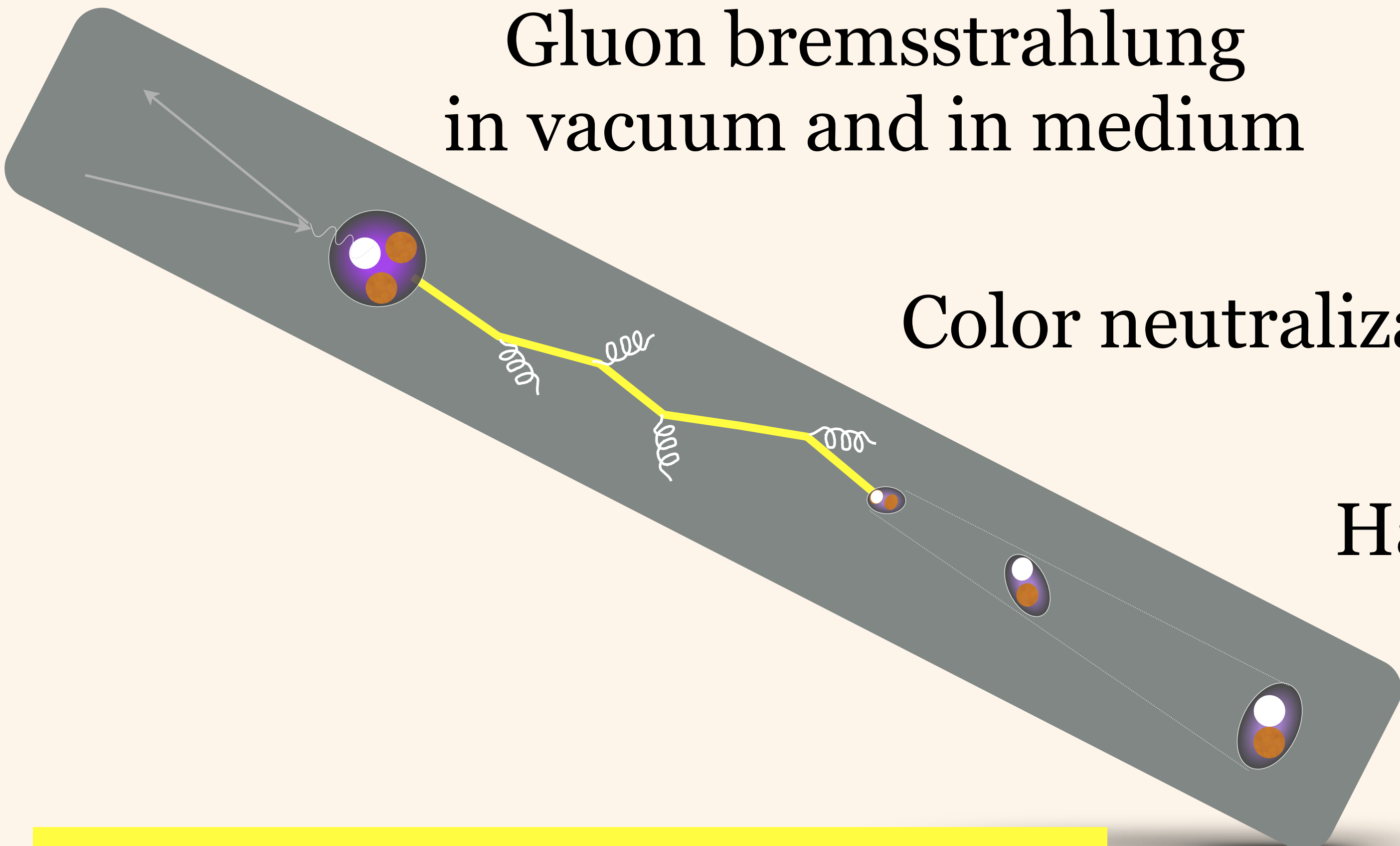


Partonic elastic scattering in medium

Gluon bremsstrahlung in vacuum and in medium

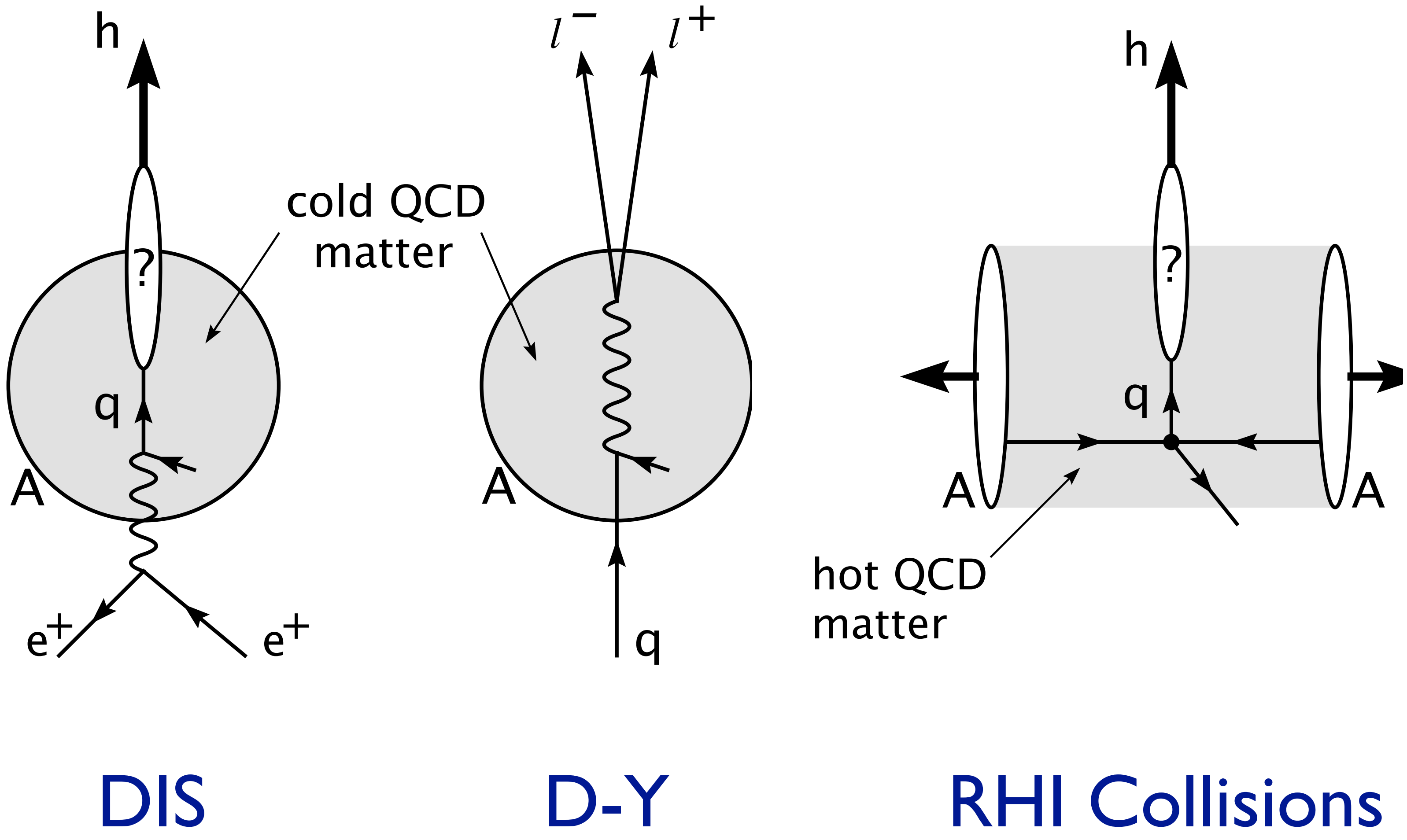
Color neutralization

Hadron formation



The production length is shown in yellow

Comparison of Color Propagation in Three Processes



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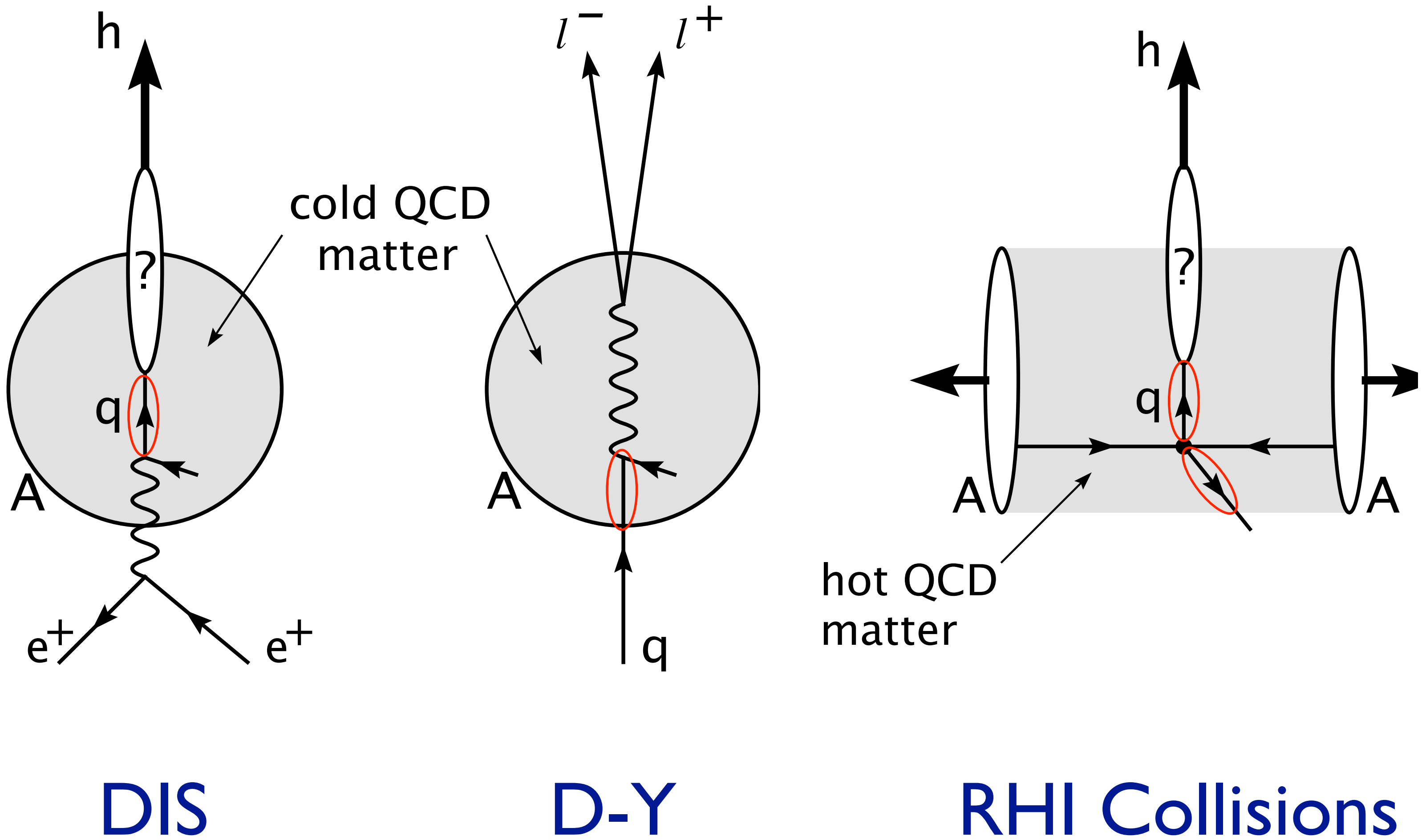
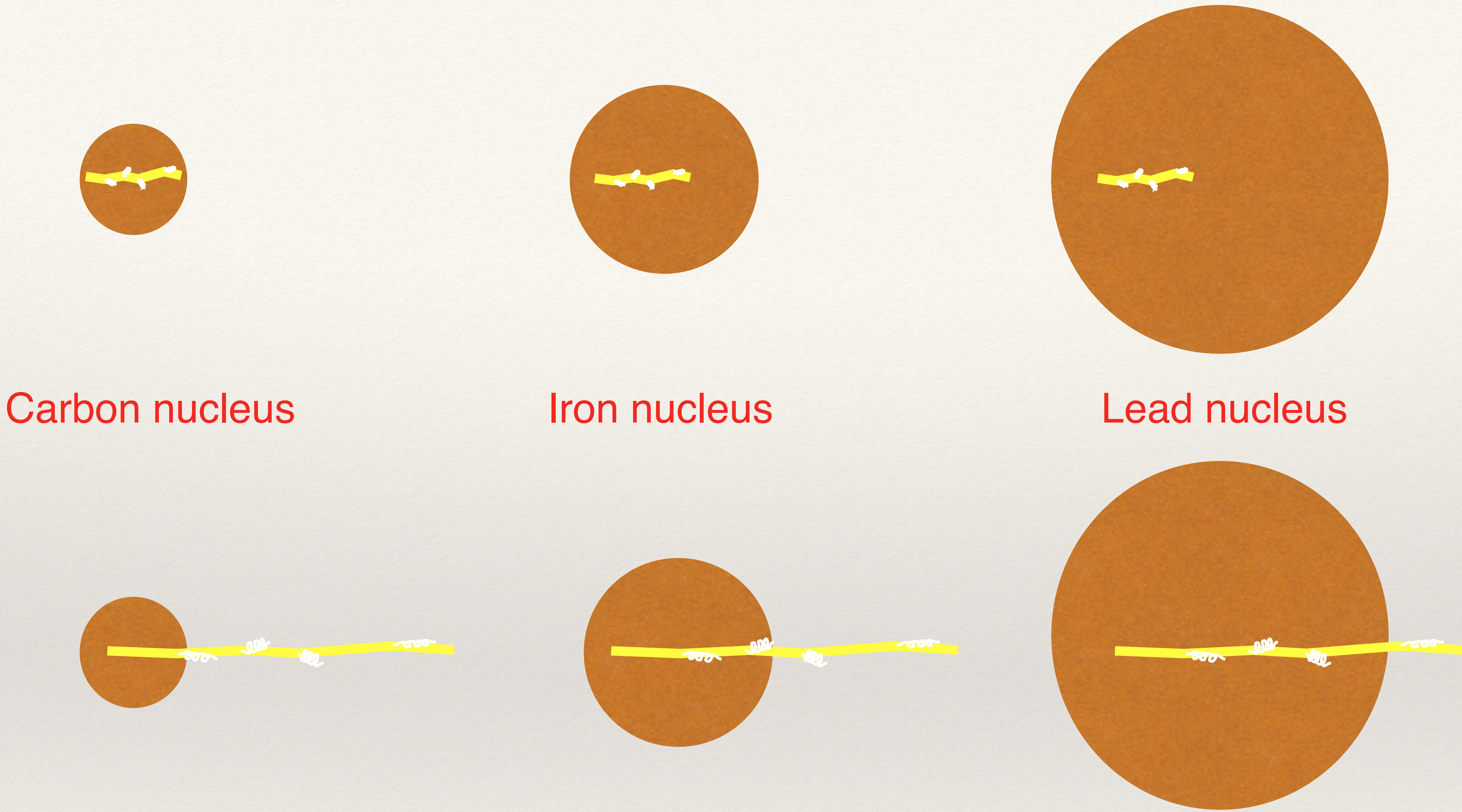
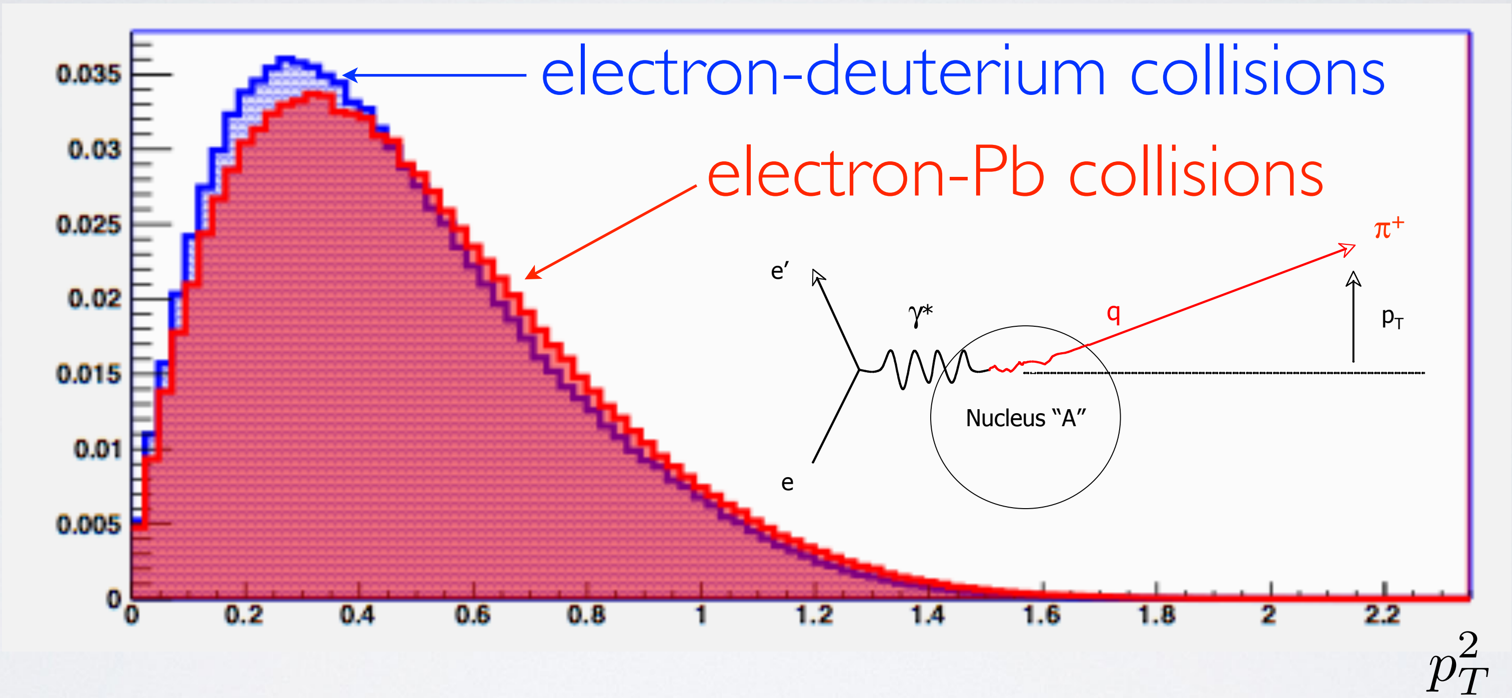




By comparing p_T broadening and hadron attenuation in nuclei of different sizes, one can measure the *length* of the color propagation process (fm scale)

Observable: p_T broadening

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



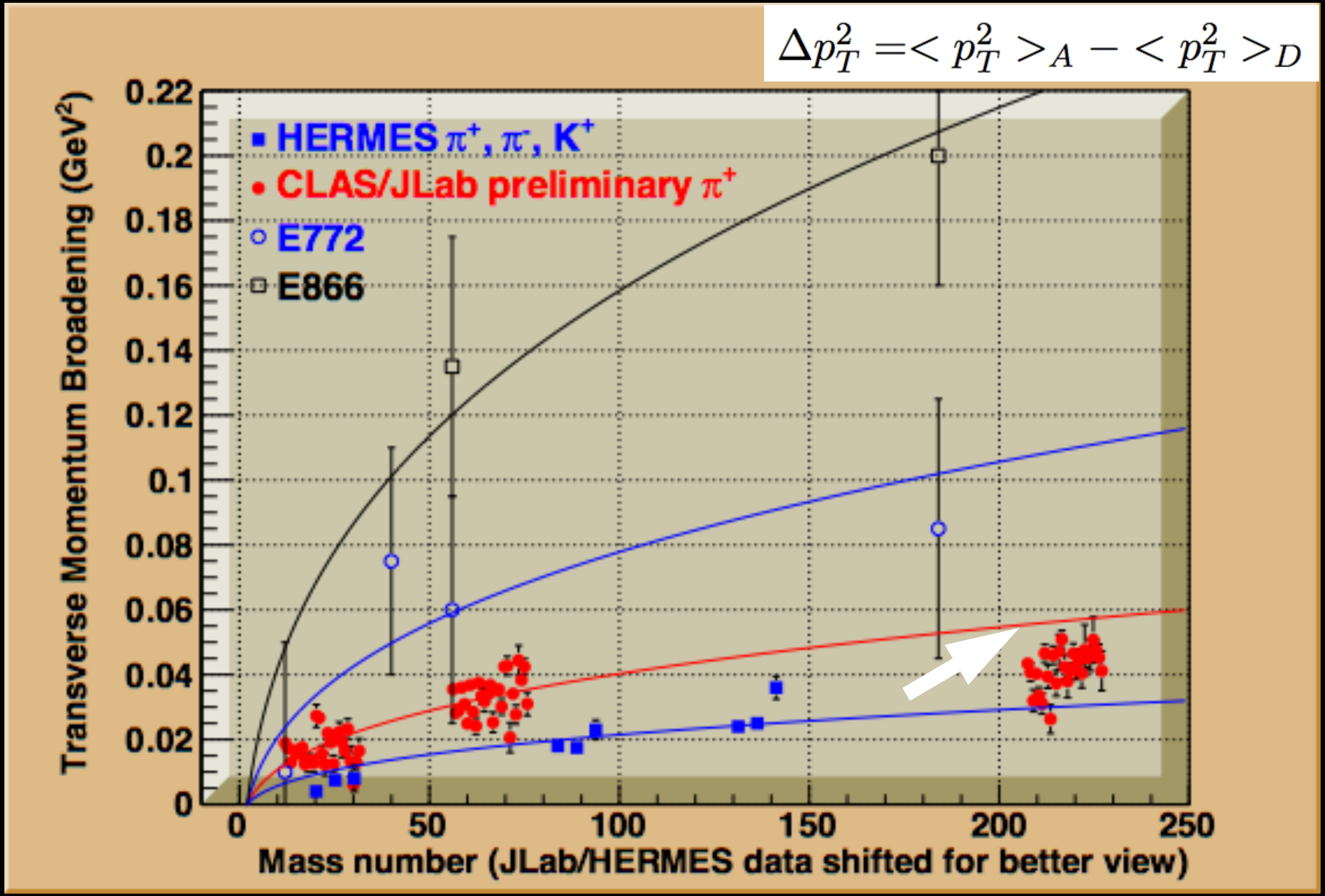
p_T broadening is a tool: sample the gluon field using a colored probe:

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

and radiative energy loss:

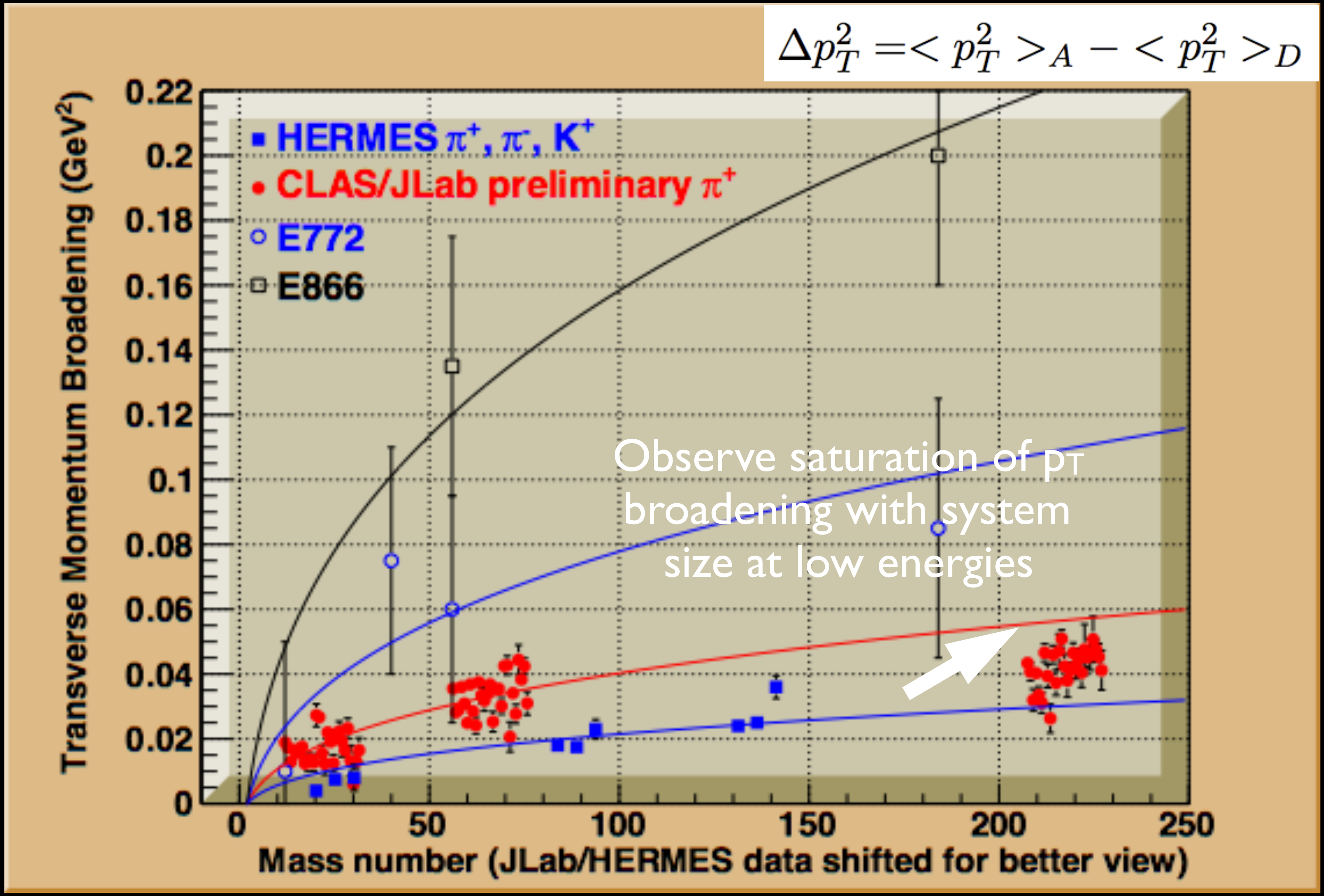
$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2$$

p_T broadening data - Drell-Yan and SIDIS



- 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?

p_T broadening data - Drell-Yan and SIDIS



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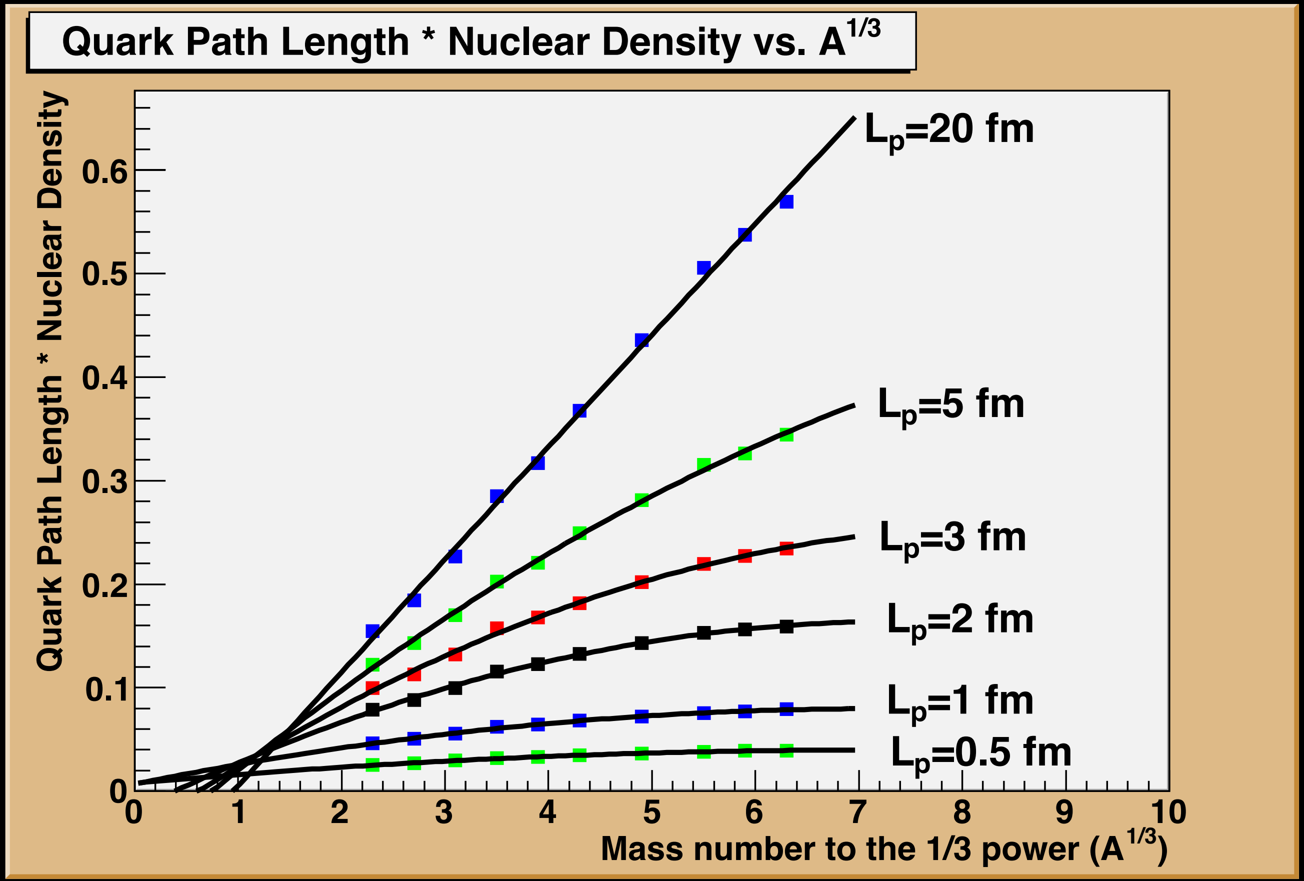
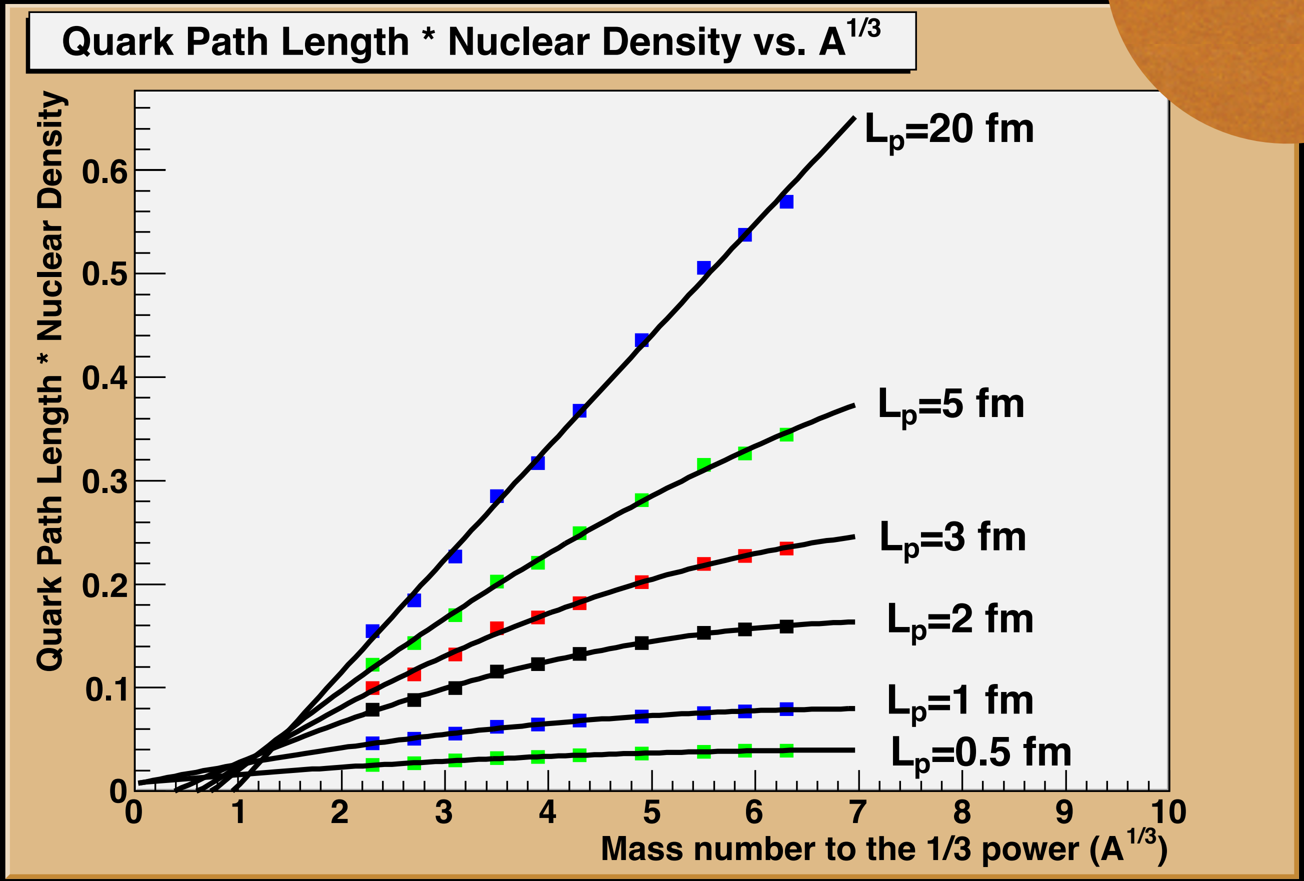
Production Time Extraction - Geometrical Effects



Production Time Extraction - Geometrical Effects



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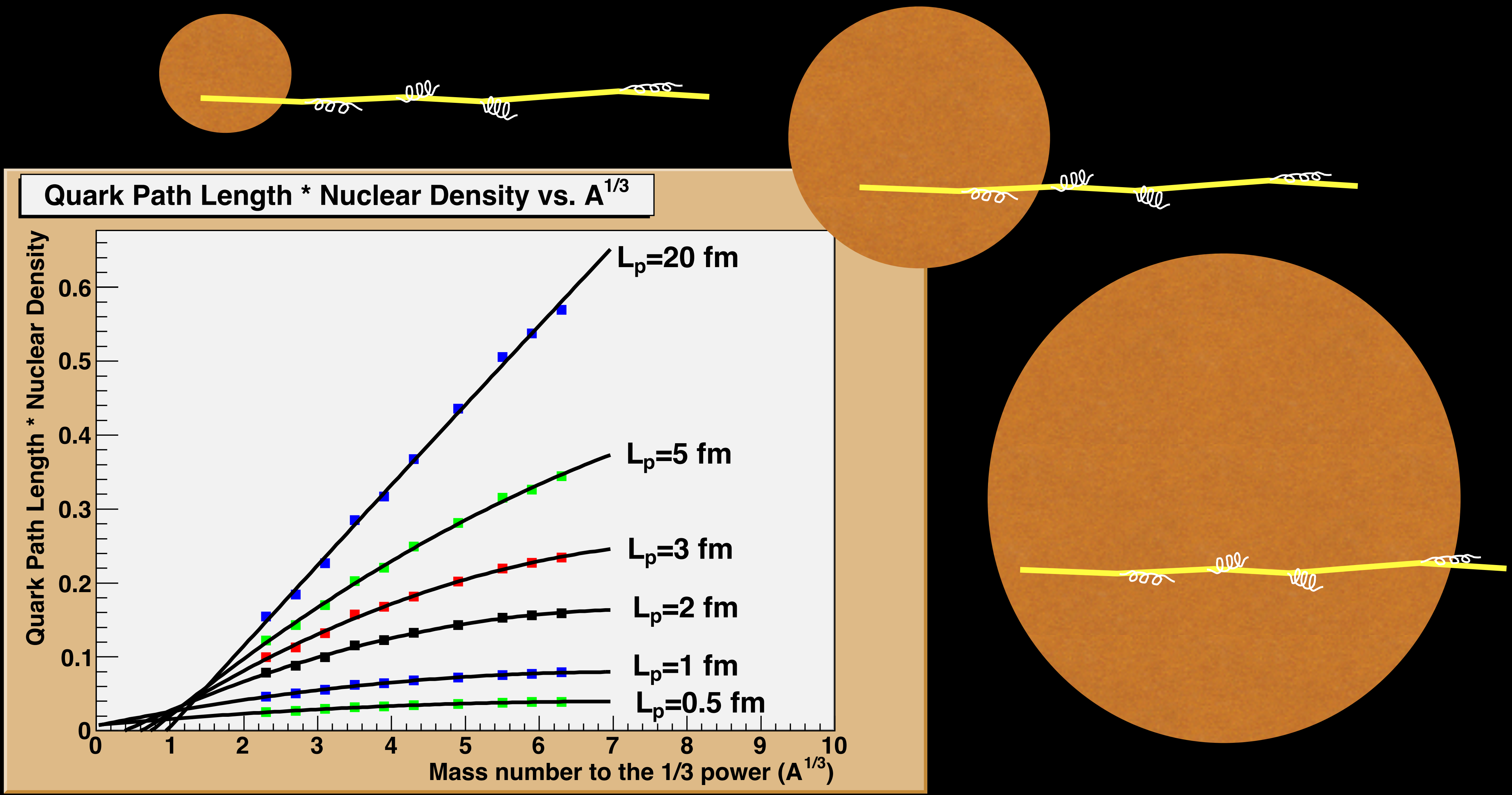

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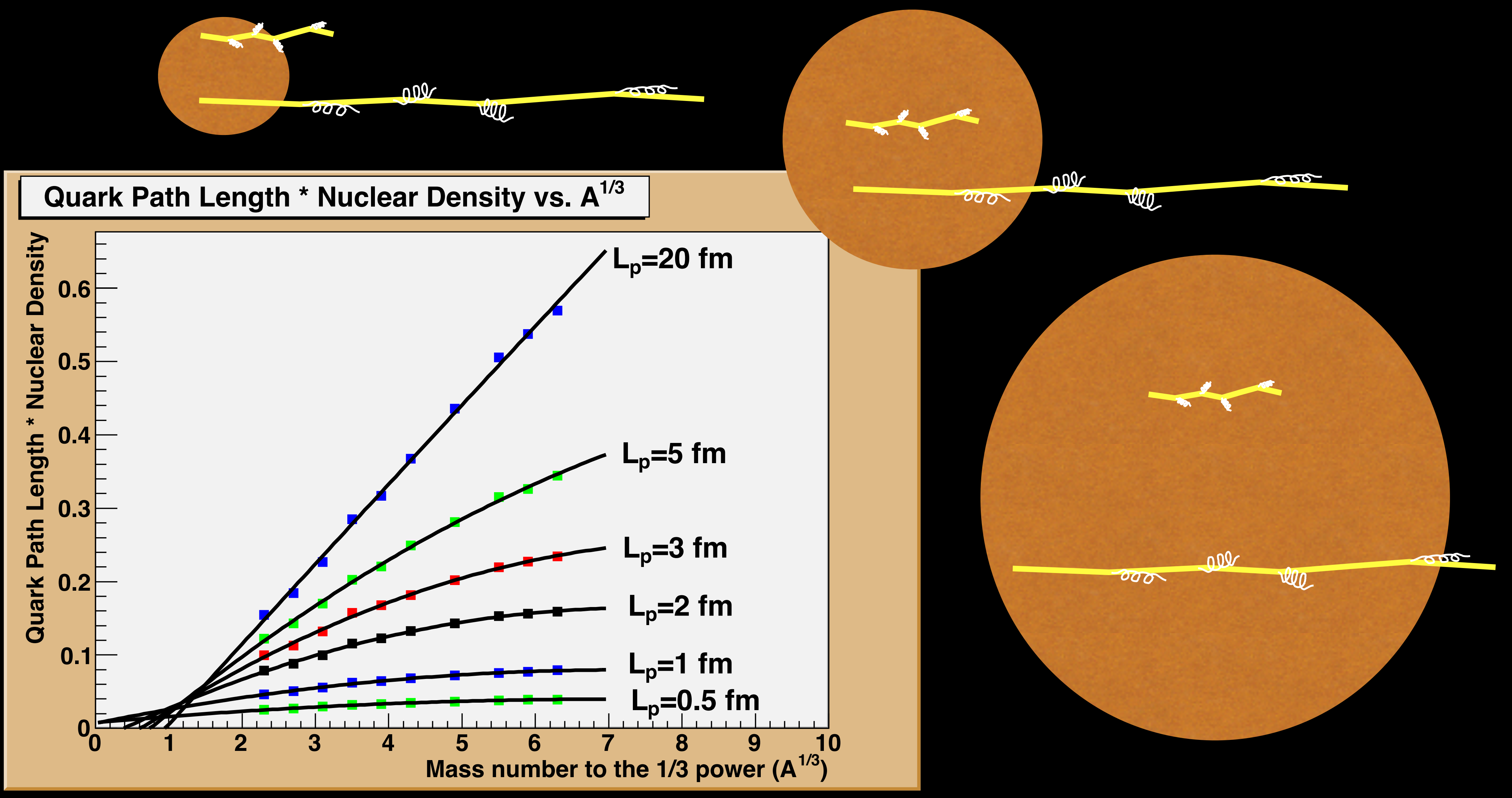

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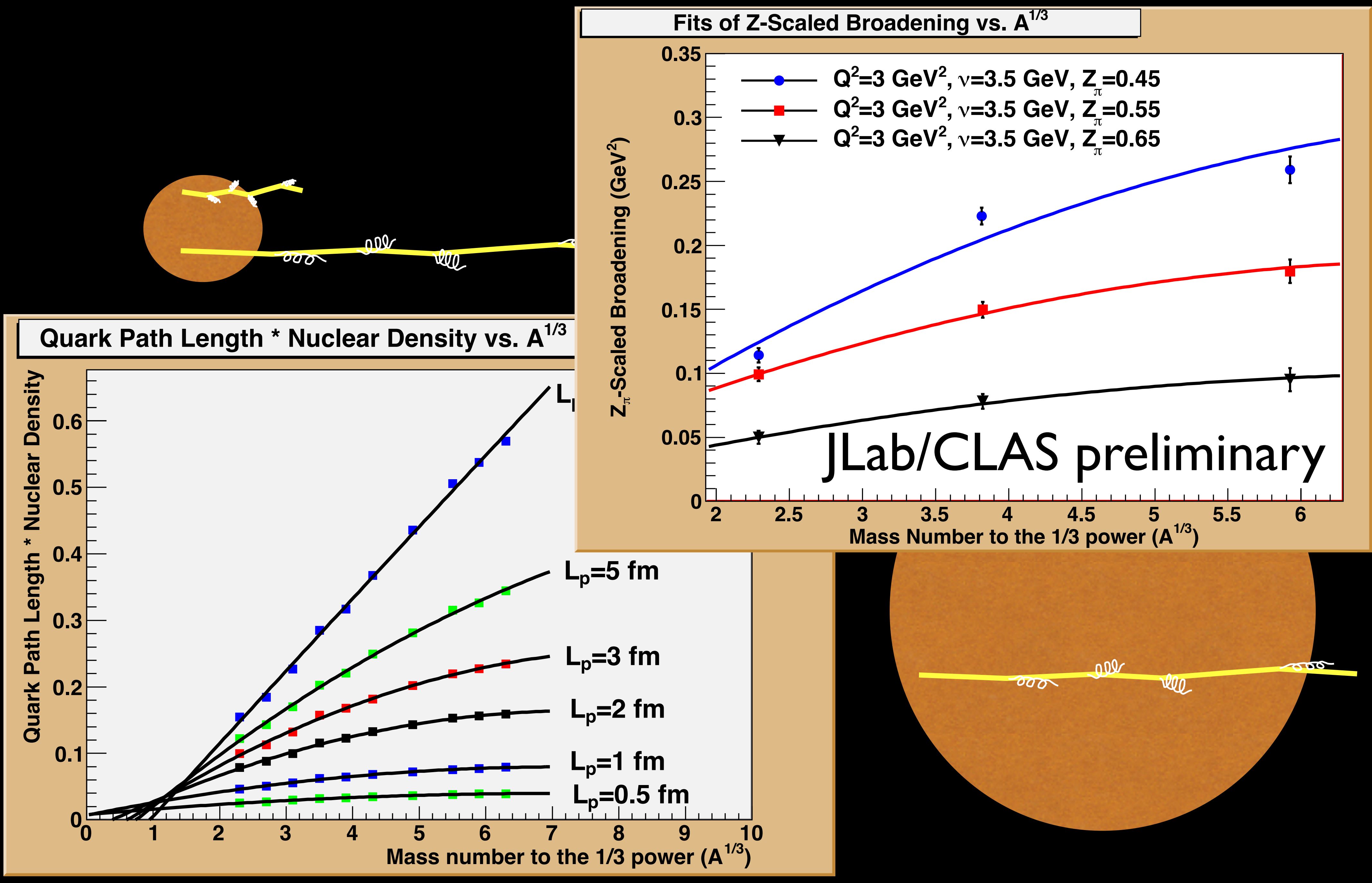
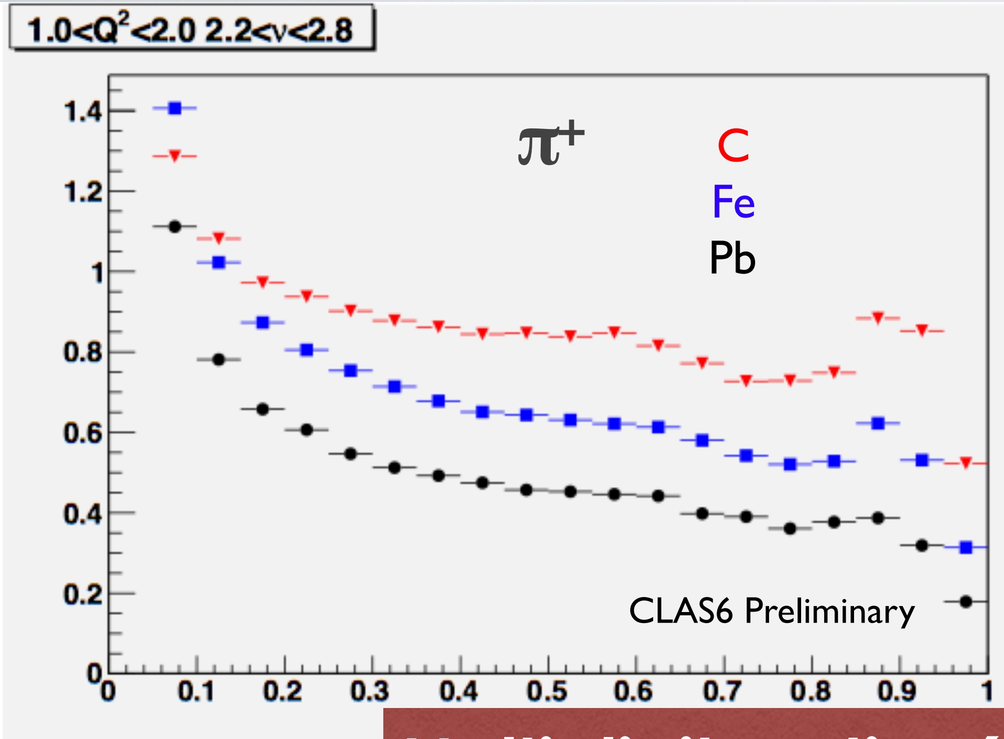
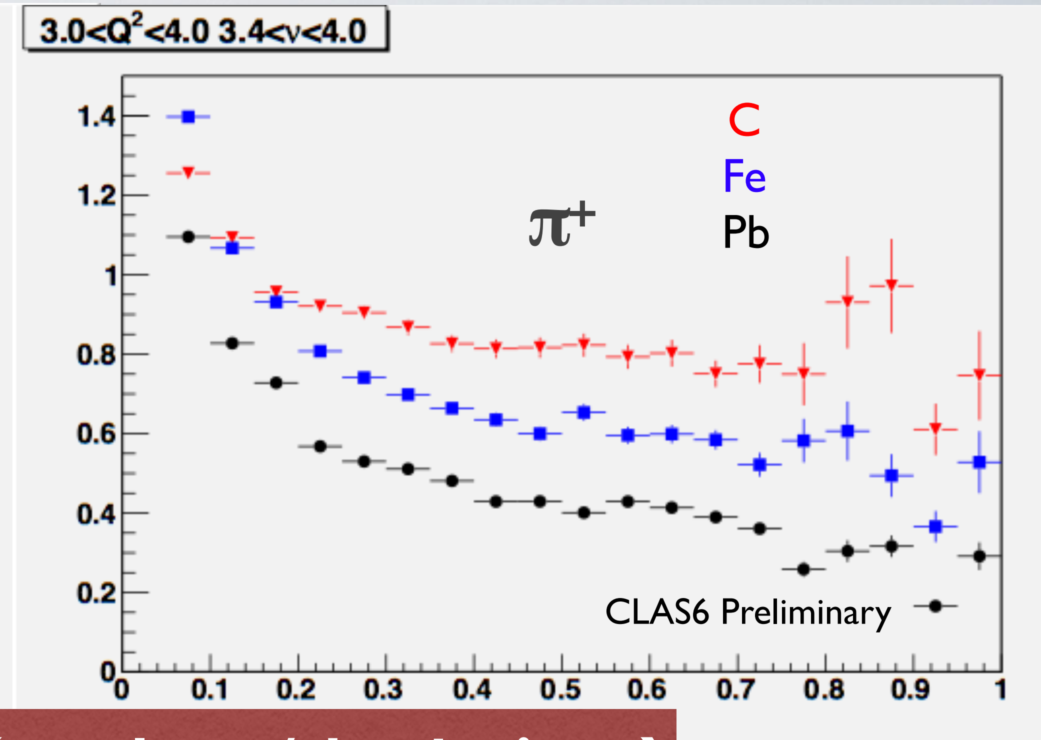
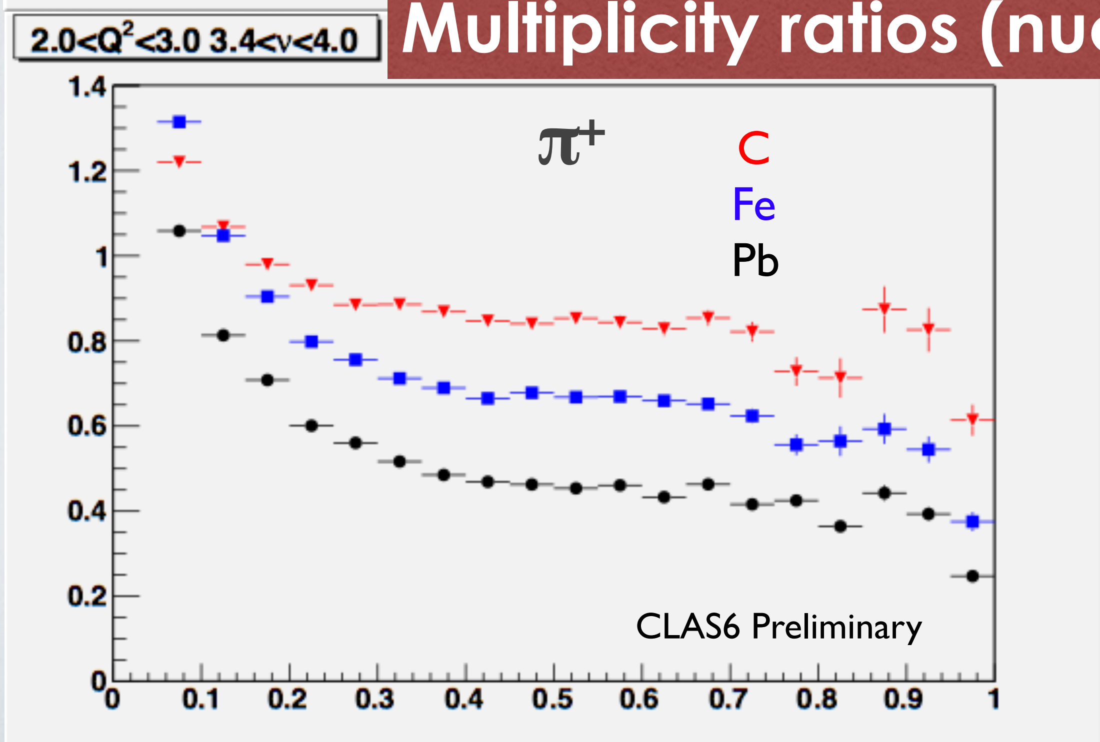






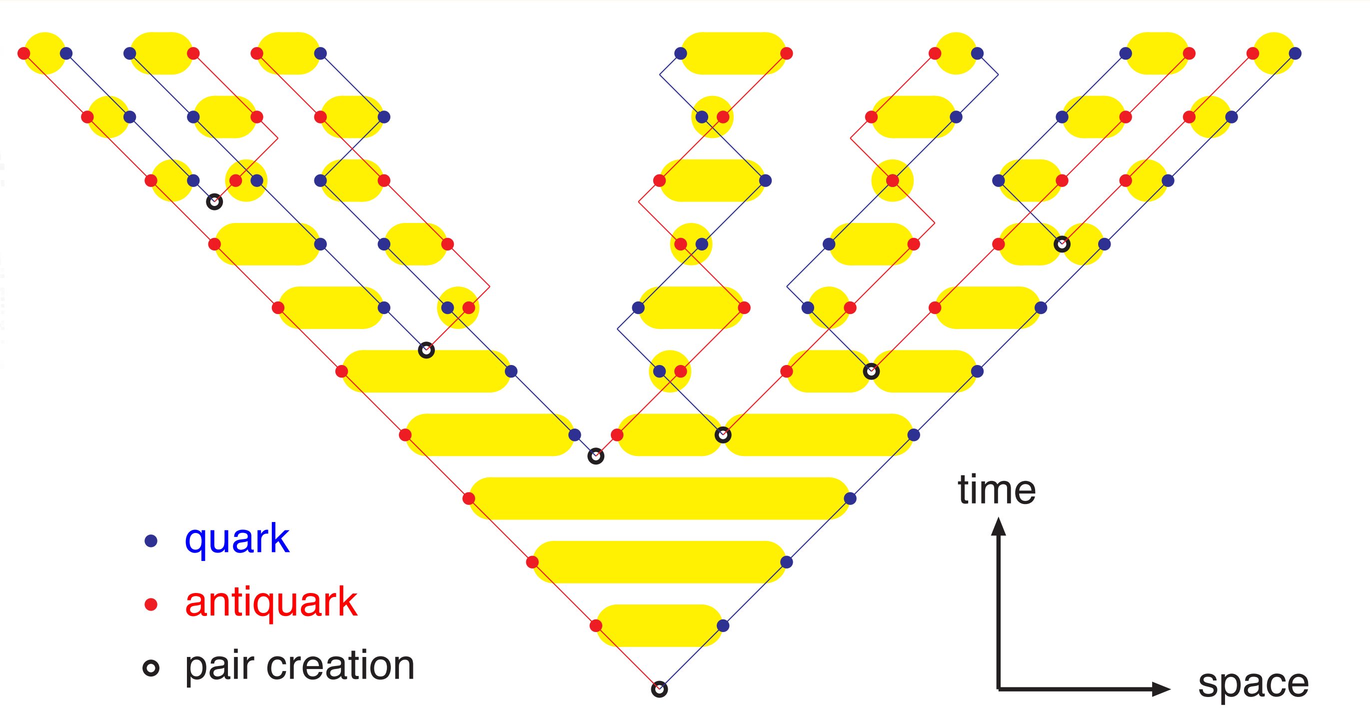
Multiplicity ratios (nucleus/deuterium)



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^-)

Lund String Model (~1983)



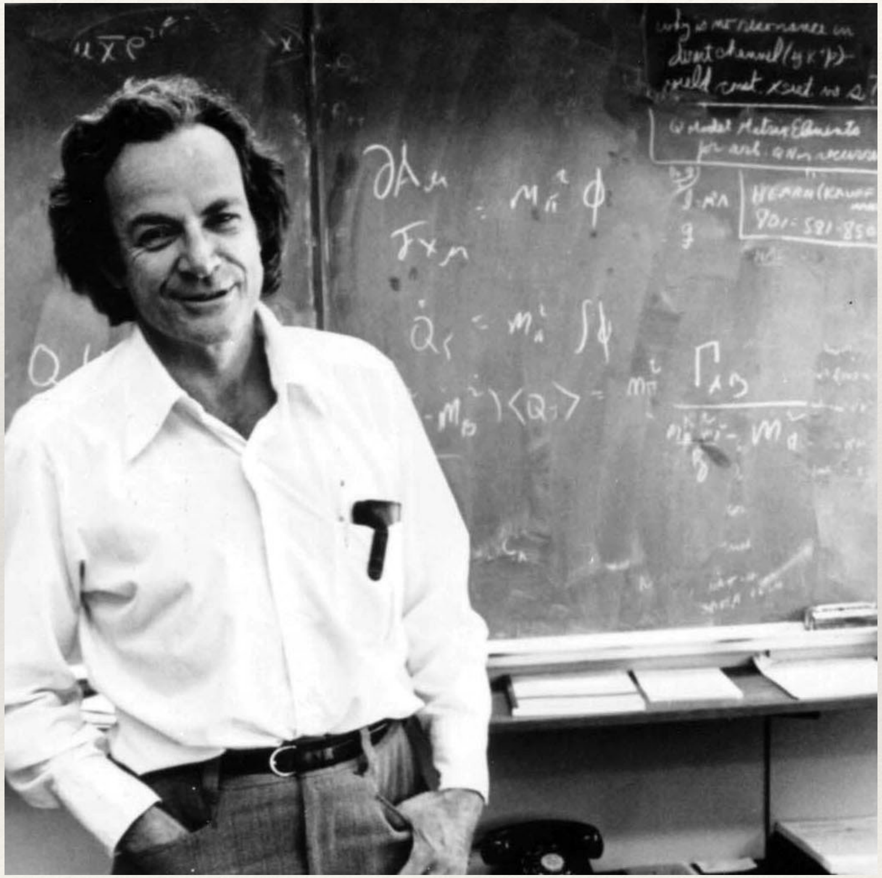
Remarkably successful model, foundational tool in HEP

- 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

Richard P. Feynman - Nobel Lecture

Nobel Lecture, December 11, 1965

The Development of the Space-Time View of Quantum Electrodynamics



https://www.nobelprize.org/nobel_prizes/physics/laureates/1965/feynman-lecture.html

A Future Nobel Prize to a theorist for Space-Time View of QCD?

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 is $\beta = p_{\gamma^*}/\nu$.

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

Space-time characteristics of the struck quark, cont'd

Comments on terminology and conceptual consequences in space-time physics

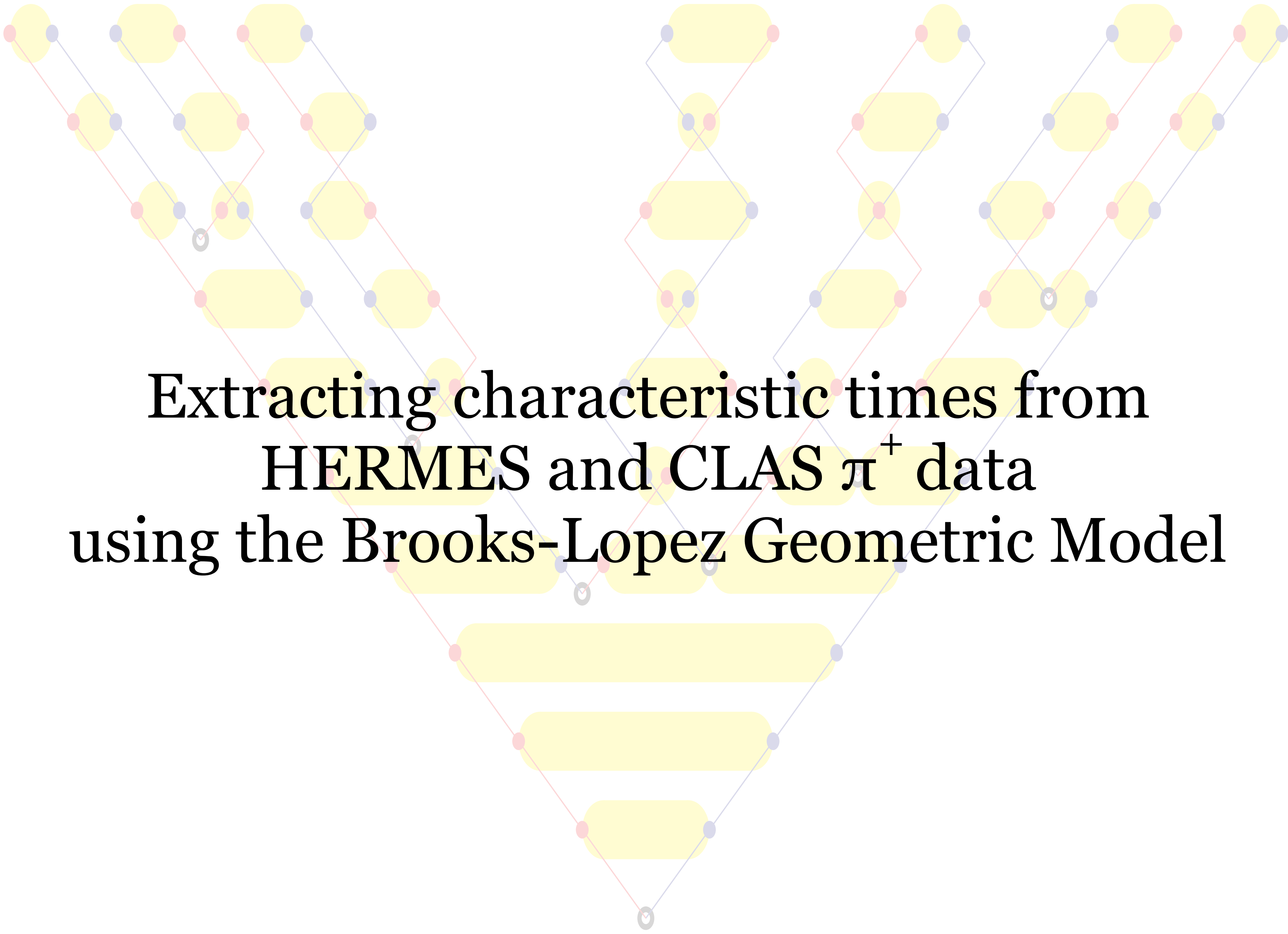
In momentum space, the LHC has typical energies that are **4000** times greater than at JLab. It appears totally different.

In *time* space the LHC has <20% faster times (e.g. of interacting parton) than at JLab. Almost the same.

We loosely use expressions like "frozen during the interaction" and "fast quarks". These ideas are only approximations, with limited validity. The interaction time, even for hard interactions, is finite, and not always small compared to the system size of 1 fm/c.

→ Space-time view of *factorization*

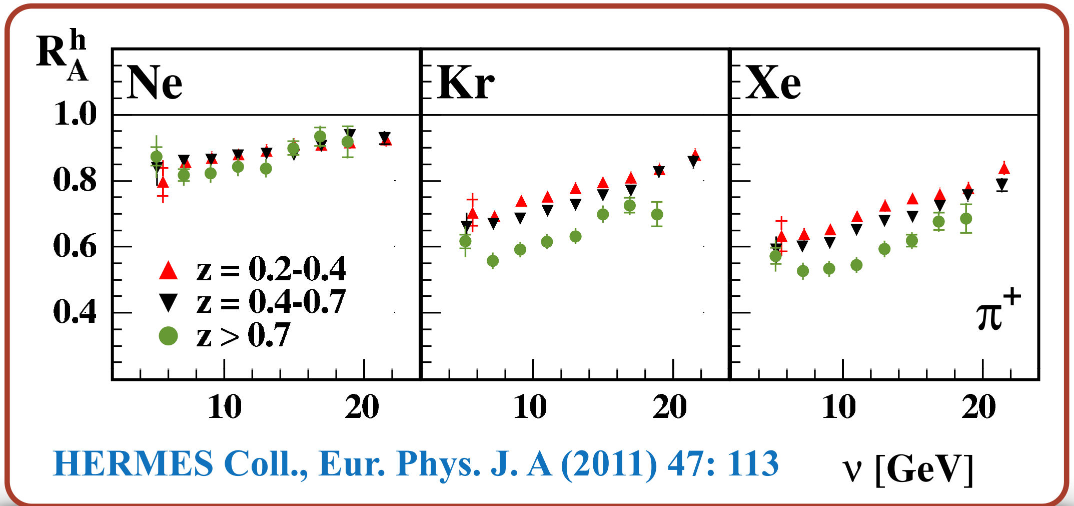
Extracting characteristic times from HERMES and CLAS π^+ data using the Brooks-Lopez Geometric Model



HERMES Study - Observables

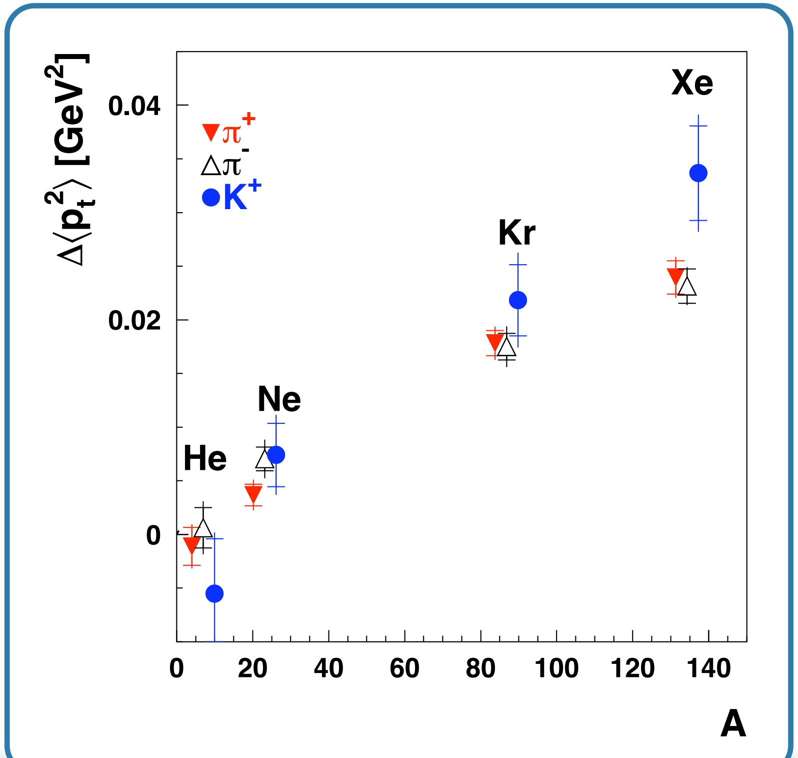
Multiplicity ratio

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



p_T 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

B-L Geometric model description I

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

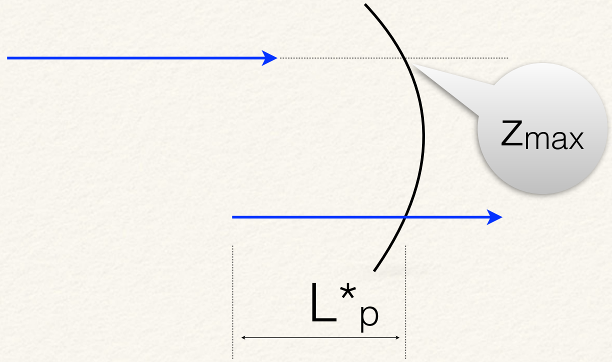
Path of quark is divided into "partonic phase" and "hadronic phase"

B-L Geometric model description II

Baseline Model ("BL") implemented with 3 **parameters**:

1. **q-hat** parameter (transport coefficient) that sets the scale of p_T broadening
2. Production length **$\langle L_p \rangle$**: distance over which p_T broadening and energy loss occur. Assumed exponential form.
3. **Cross section** for prehadron to interact with nucleus.

B-L 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

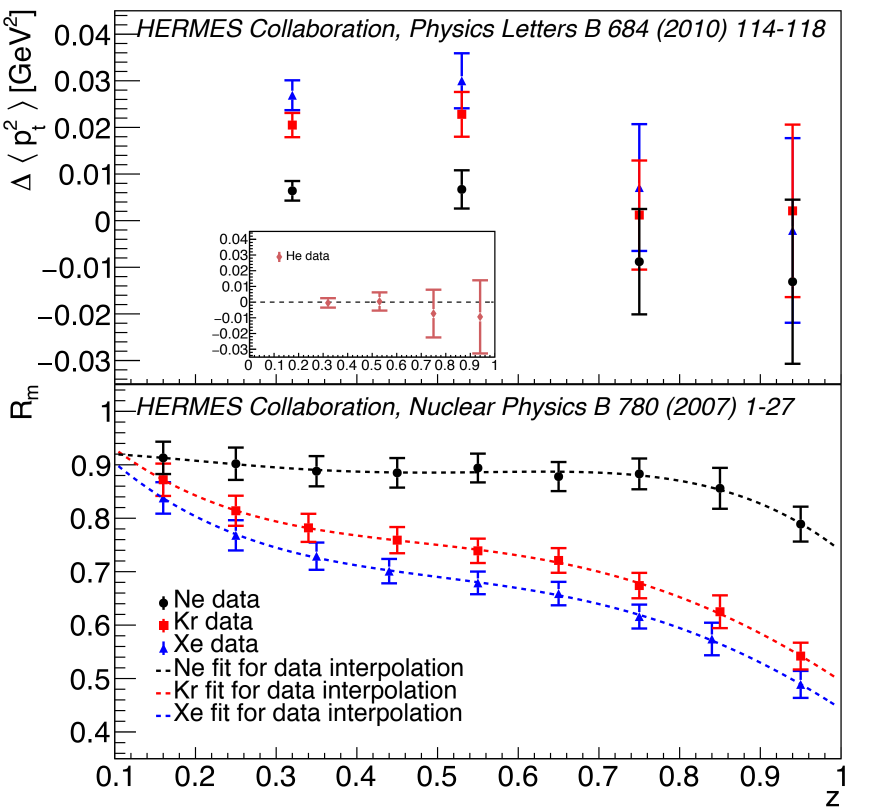
No dynamical information is assumed; it emerges from fit

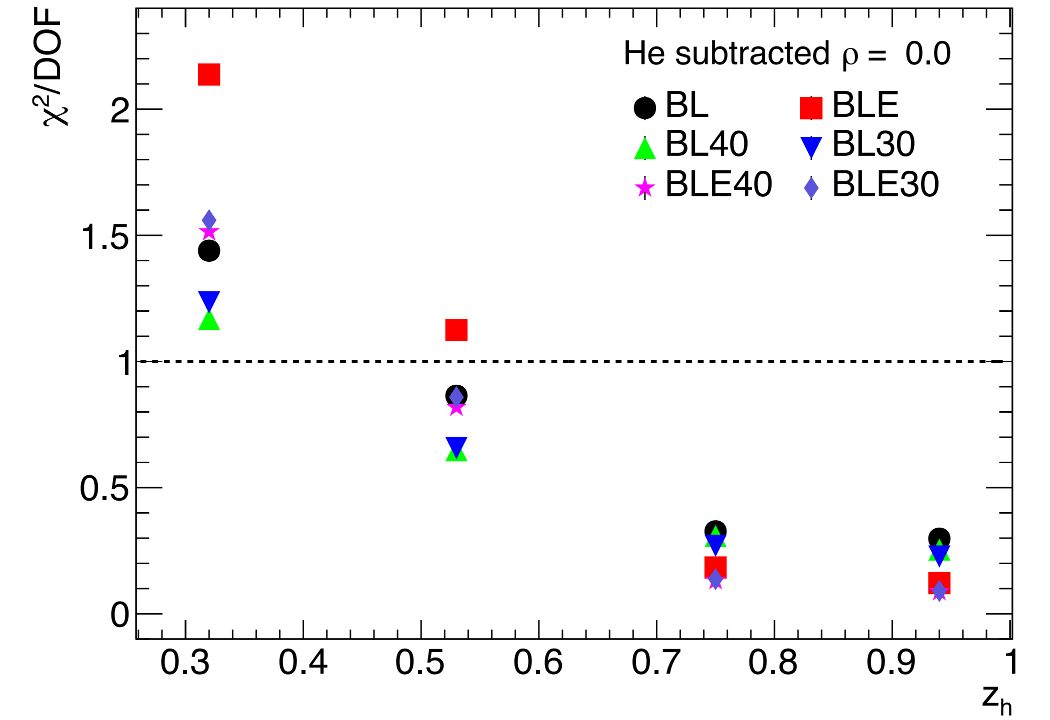
Systematic errors: 3% for multiplicity ratio, 4% for p_T broadening

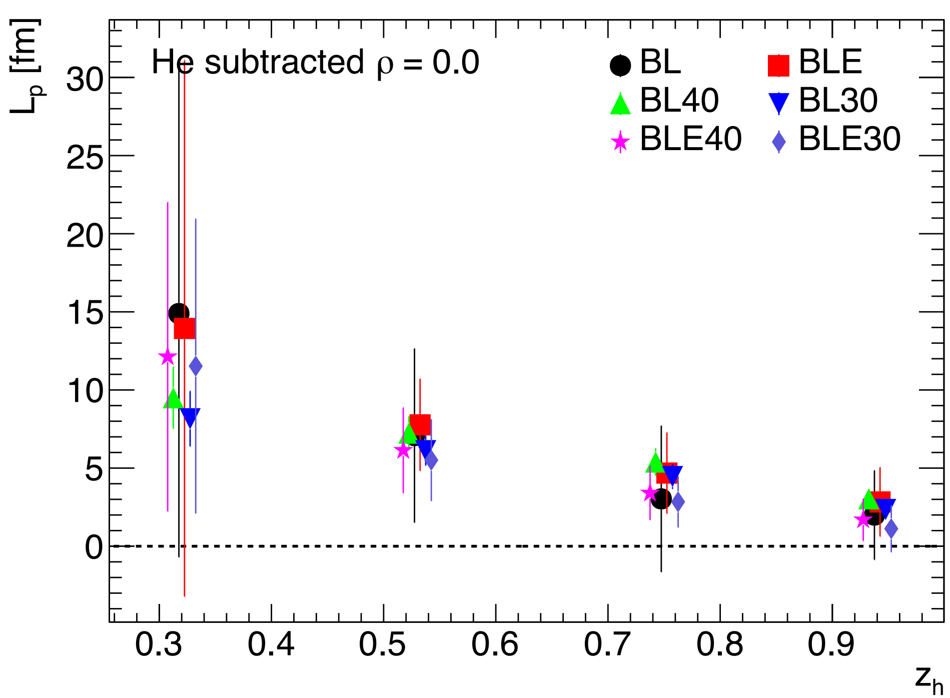
Comment on the B-L model

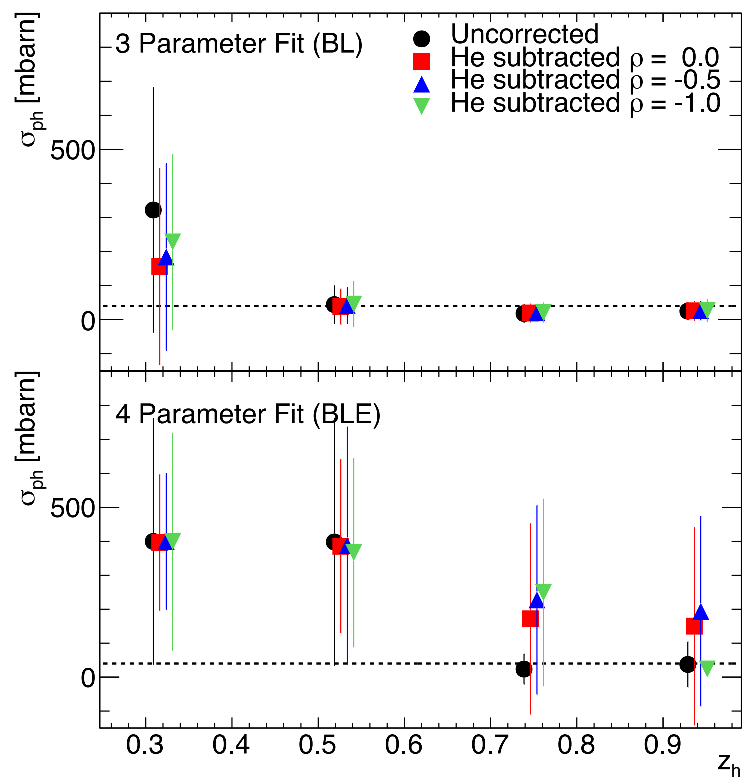
I believe that studies of this kind can be carried out at the same level of validity as the estimation of centrality in heavy ion collisions.

This model has the same foundation as the well-known “Glauber Model” used to estimate centrality in heavy ion collisions: the spatial mass distribution of protons and neutrons in the nucleus.


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

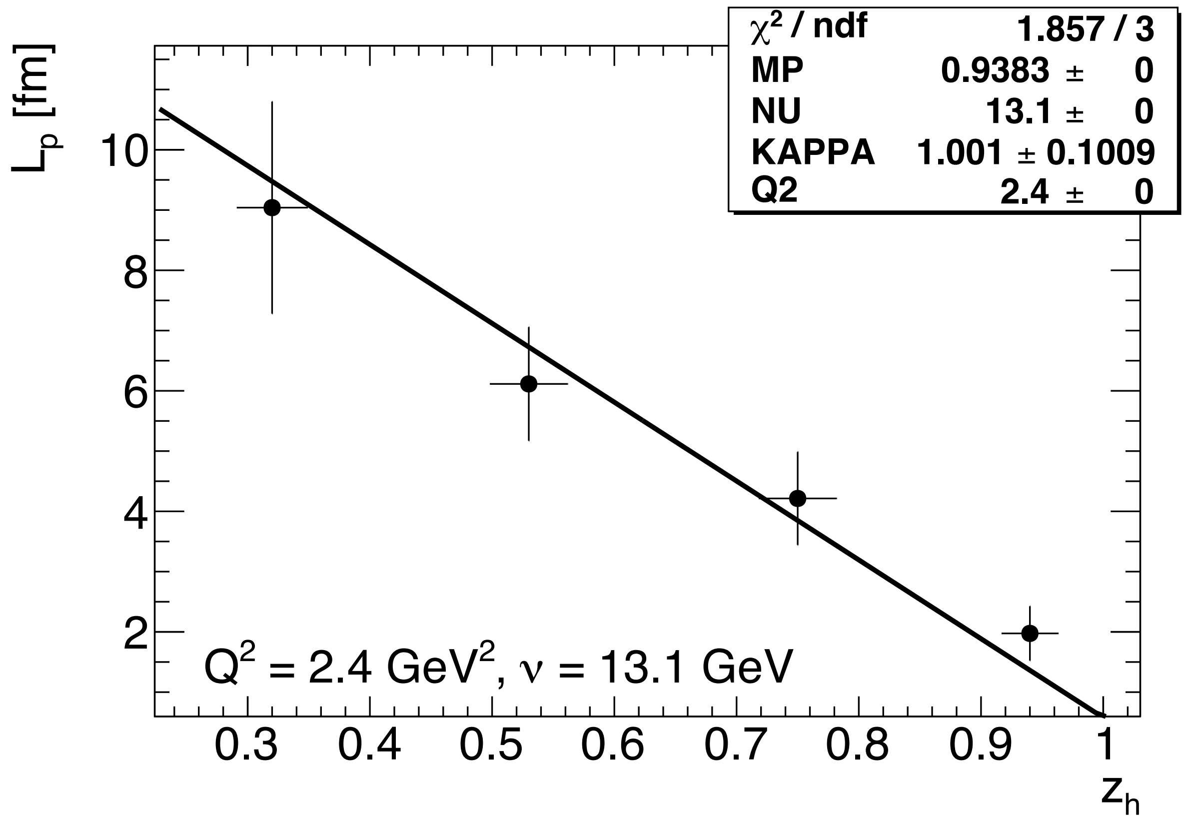

χ^2/DOF
He subtracted ρ = 0.0
BL
BLE
BL40
BL30
BLE40
BLE30
z_h


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


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

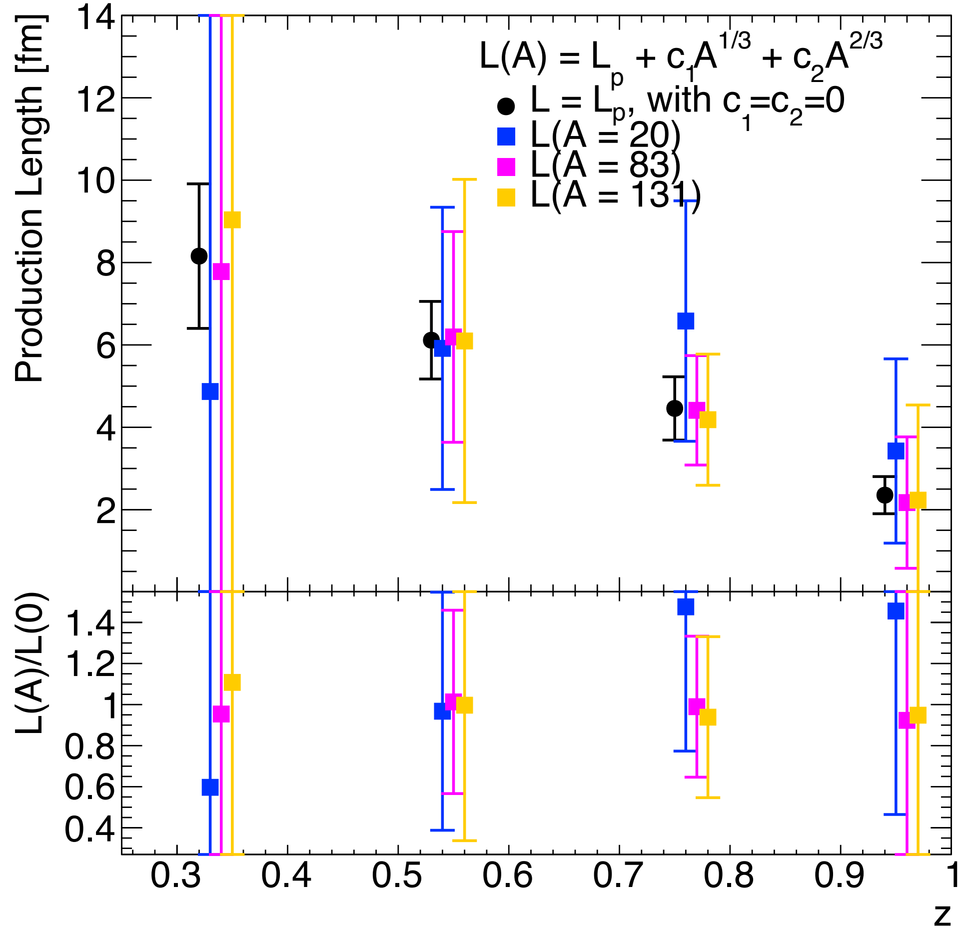
Light cone Lund String Model form for lab frame:

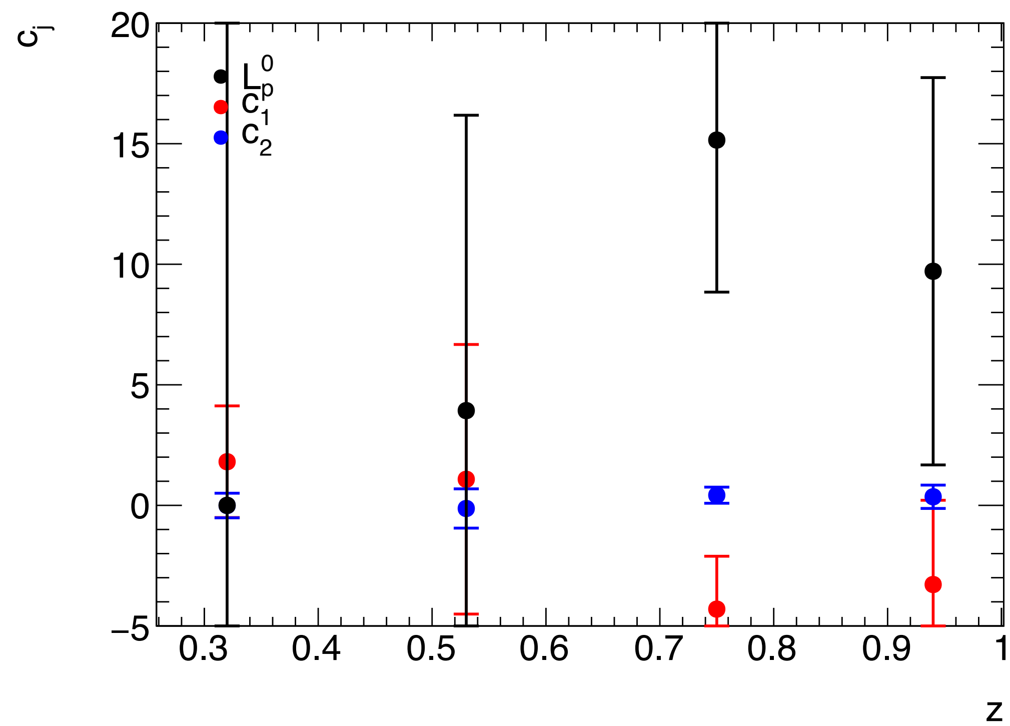
$$l_p = \frac{1}{2\mathcal{K}} \cdot \left(M_p + \nu + \sqrt{\nu^2 + Q^2} - 2 \cdot \nu \cdot z' \right)$$

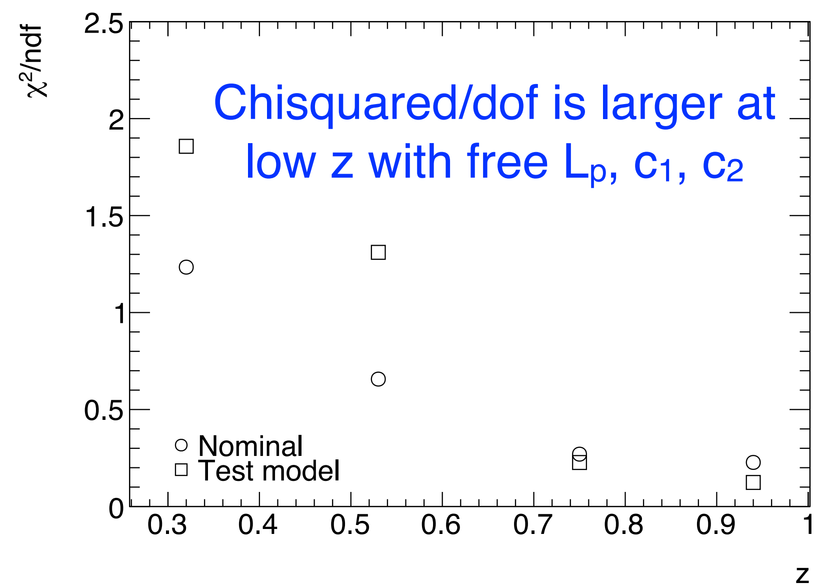
HERMES data analysis: exploring potential nuclear dependence of production time, and extrapolation to the vacuum

$$L_p(A) = L_{po} + c_1 A^{1/3} + c_2 A^{2/3}$$

The case with **free** L_{p0}, c_1 and c_2





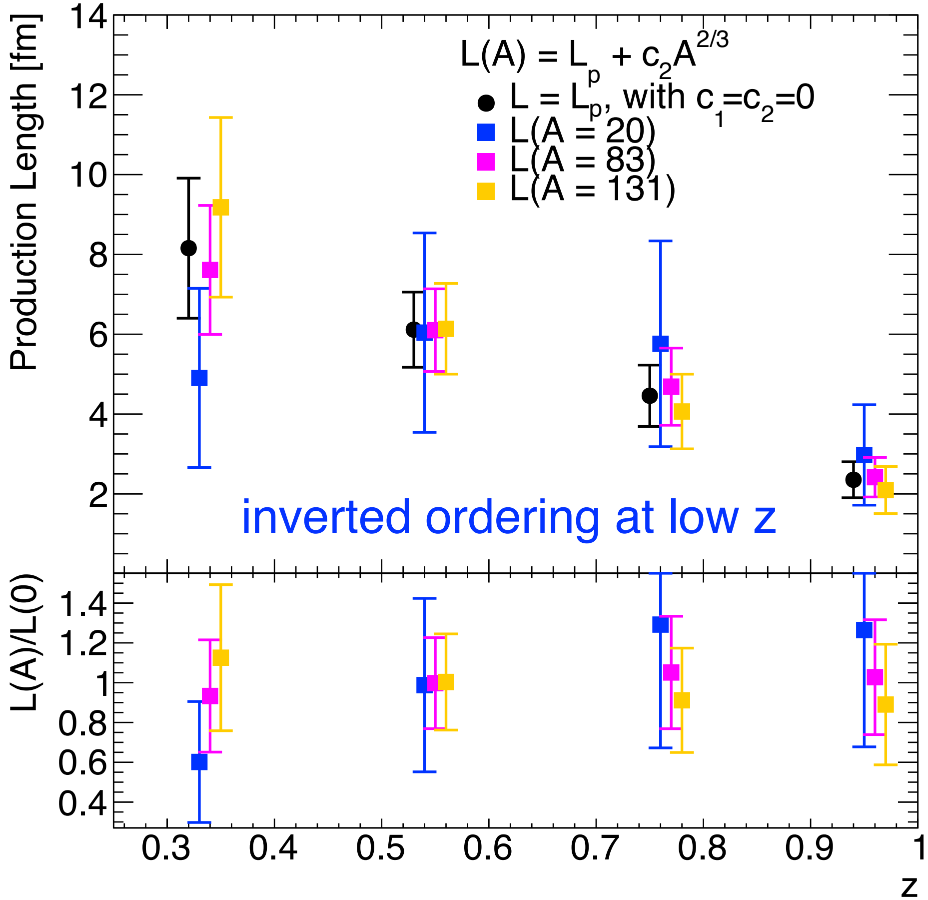


We see a strong fit correlation between L_p and c_1

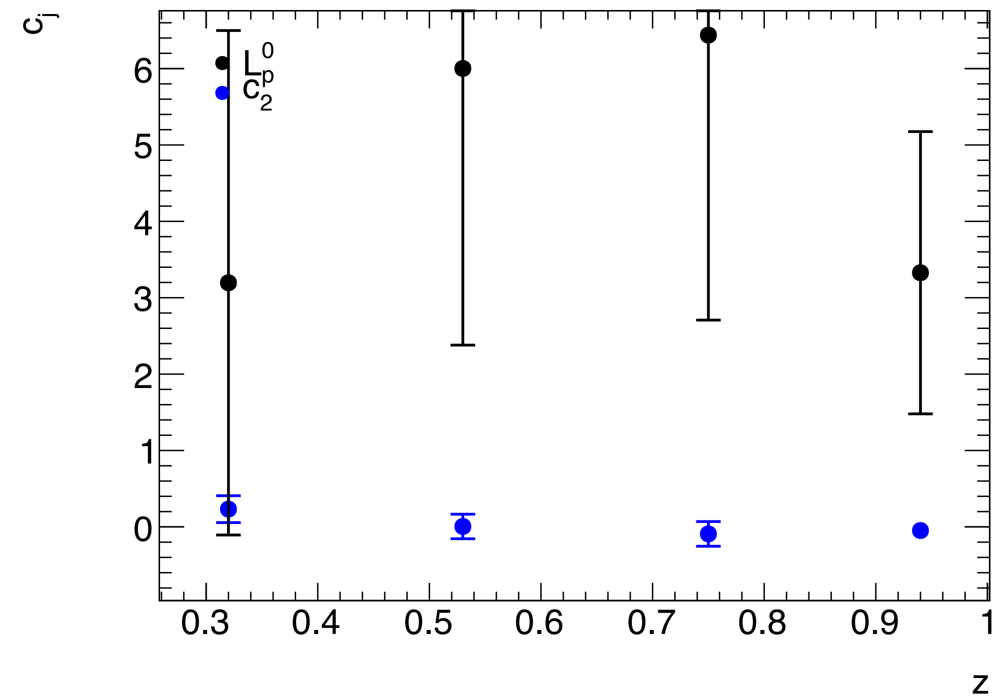
Therefore, in the next slide we fix c1=0

(BL30 model variant)

The case with **free L_{p0} and c_2**, and **fixed c_1=0**

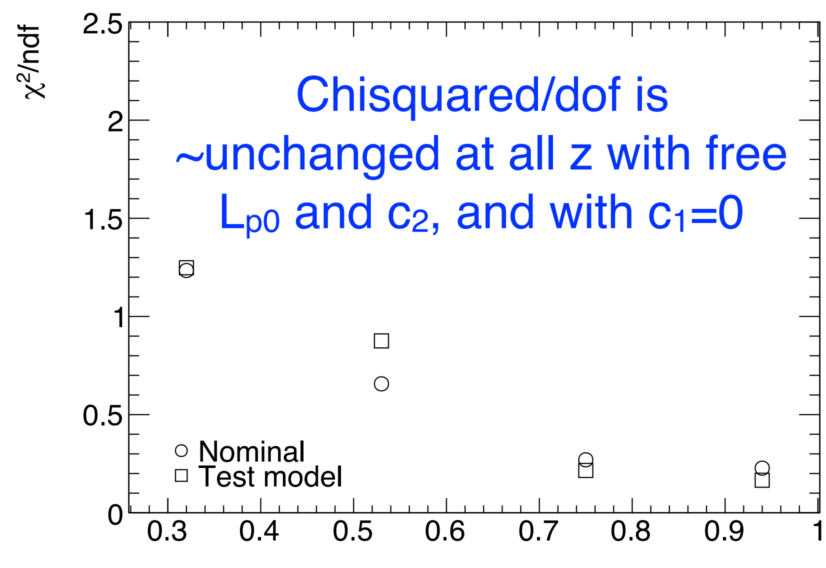


Extrapolation to vacuum: A=0



Suggests vacuum L_p is smaller for low z, ~unchanged at high z

Uncertainties are large in this study (HERMES data). A future JLab study may be better constrained.

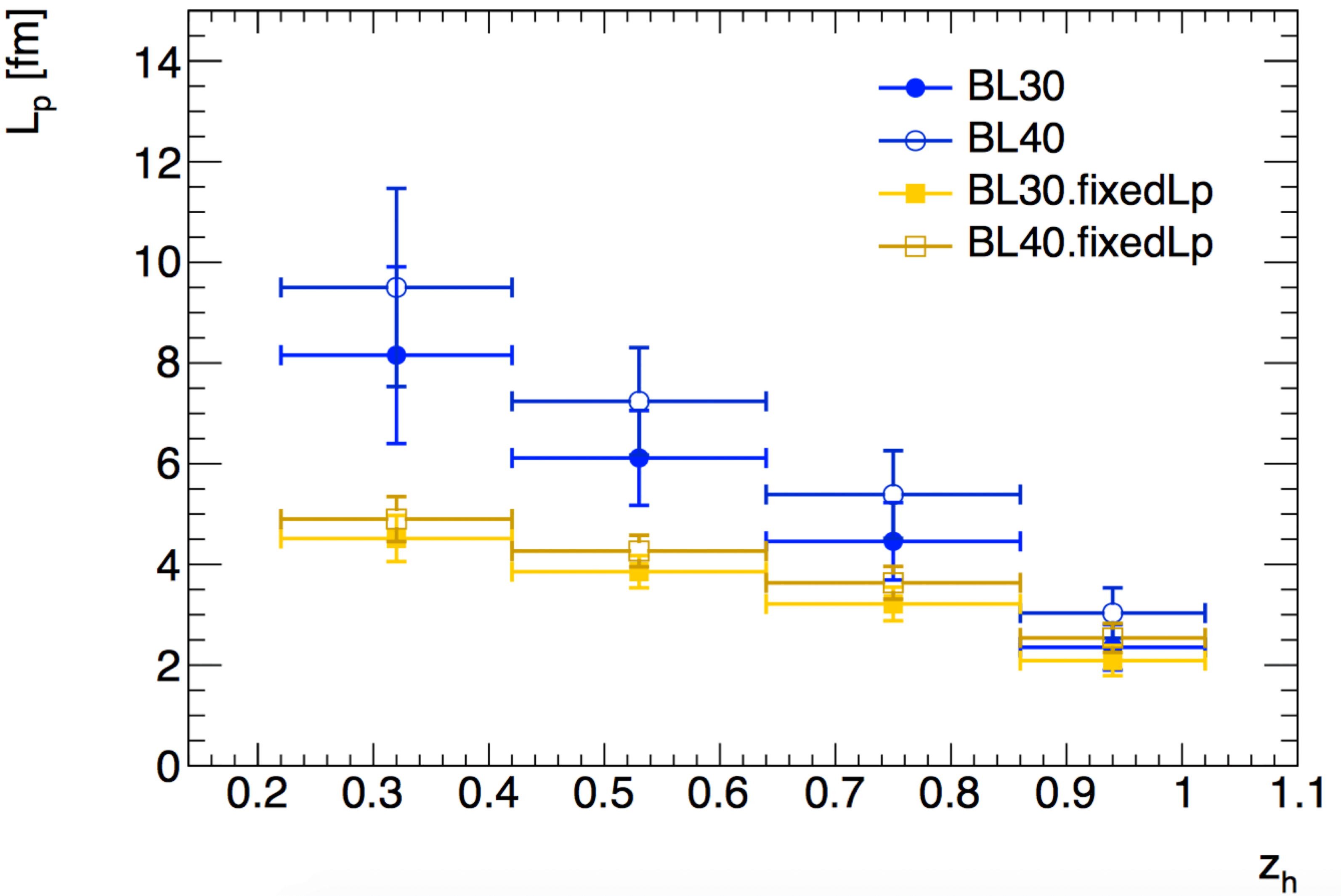


(BL30 model variant)

Conclusion: good evidence for the following functional form. The vacuum term L_{po} is determined, but with large uncertainties. There are hints that may help us to understand color propagation mechanisms at lower and higher z_h. The JLab data should allow a more precise study.

$$L_p(A) = L_{po} + c_2 A^{2/3}$$

HERMES data analysis: comparison of two possible functional forms of the production length distributions: *exponential* and *fixed(delta function)*

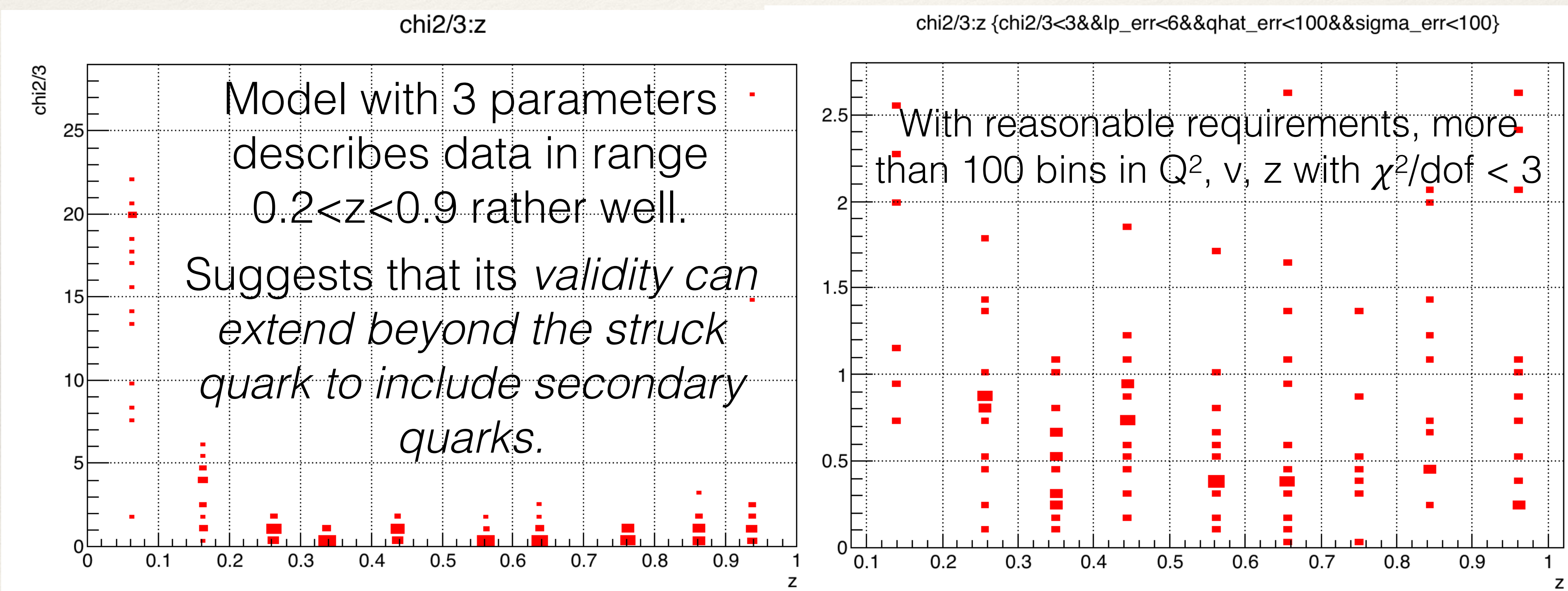


The fit has some sensitivity to the functional form of the production length.
More comments in upcoming slides.

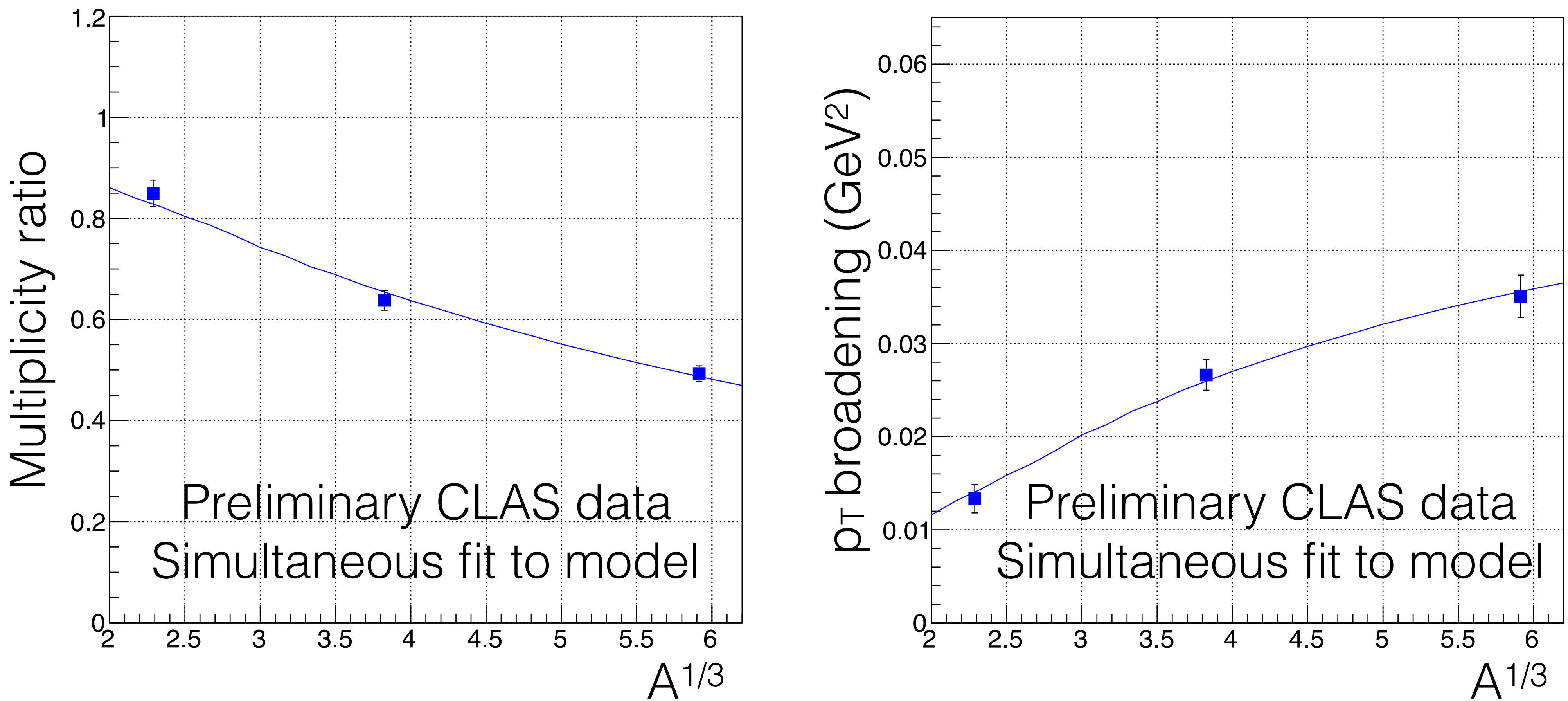
Color lifetime extraction: B-L model applied to CLAS 5 GeV data

Color lifetime extraction: B-L model applied to CLAS 5 GeV data

χ^2/dof vs. z



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



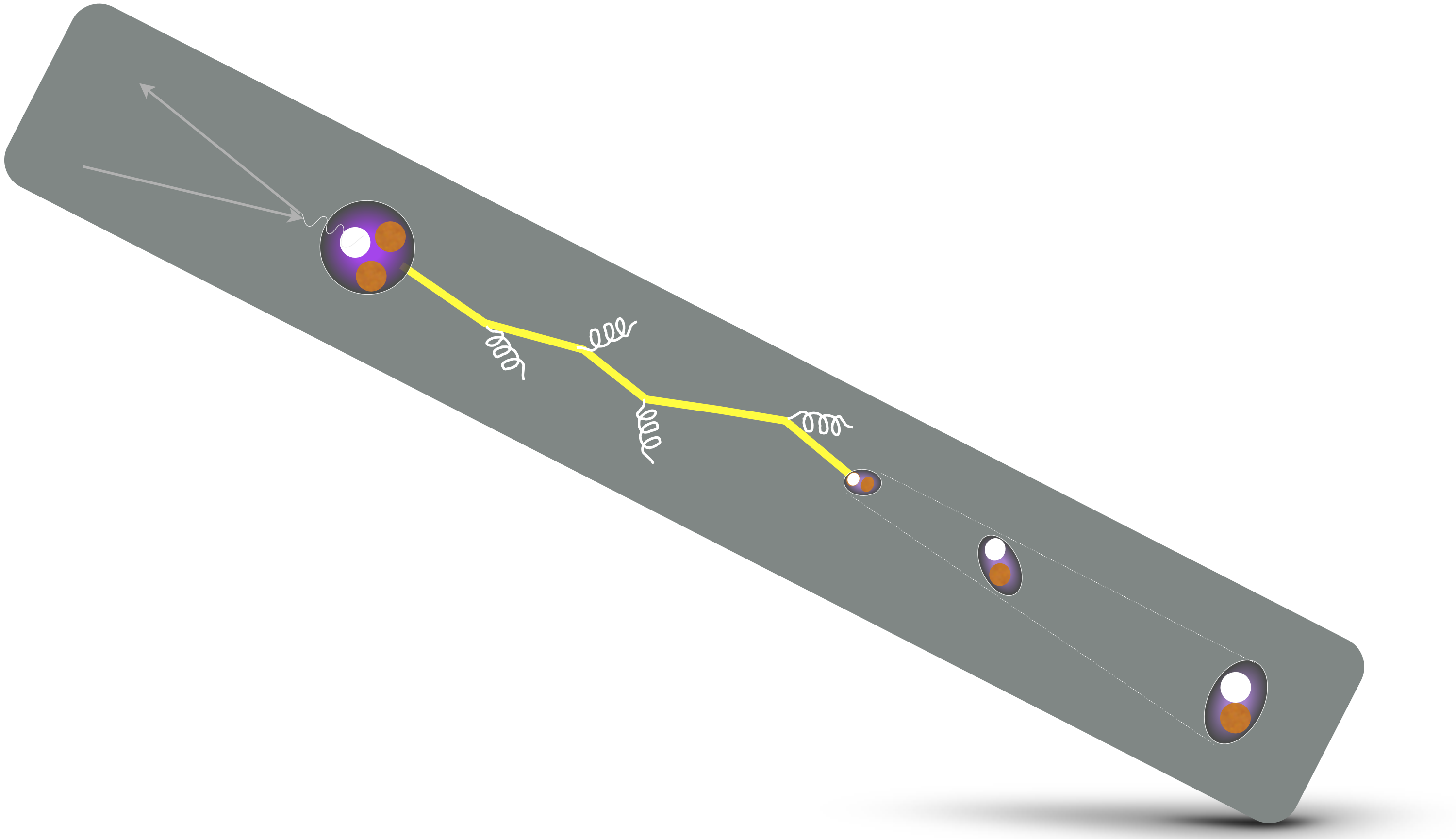
<x>=0.166, <Q^2>=1.17 GeV^2, (<ν>=3.76 GeV), <z>=0.445

L_p=1.8±0.4 fm

χ^2/dof = 0.5

Simultaneous fit *couples* p_T broadening to multiplicity ratio

Three possible distributions of production time



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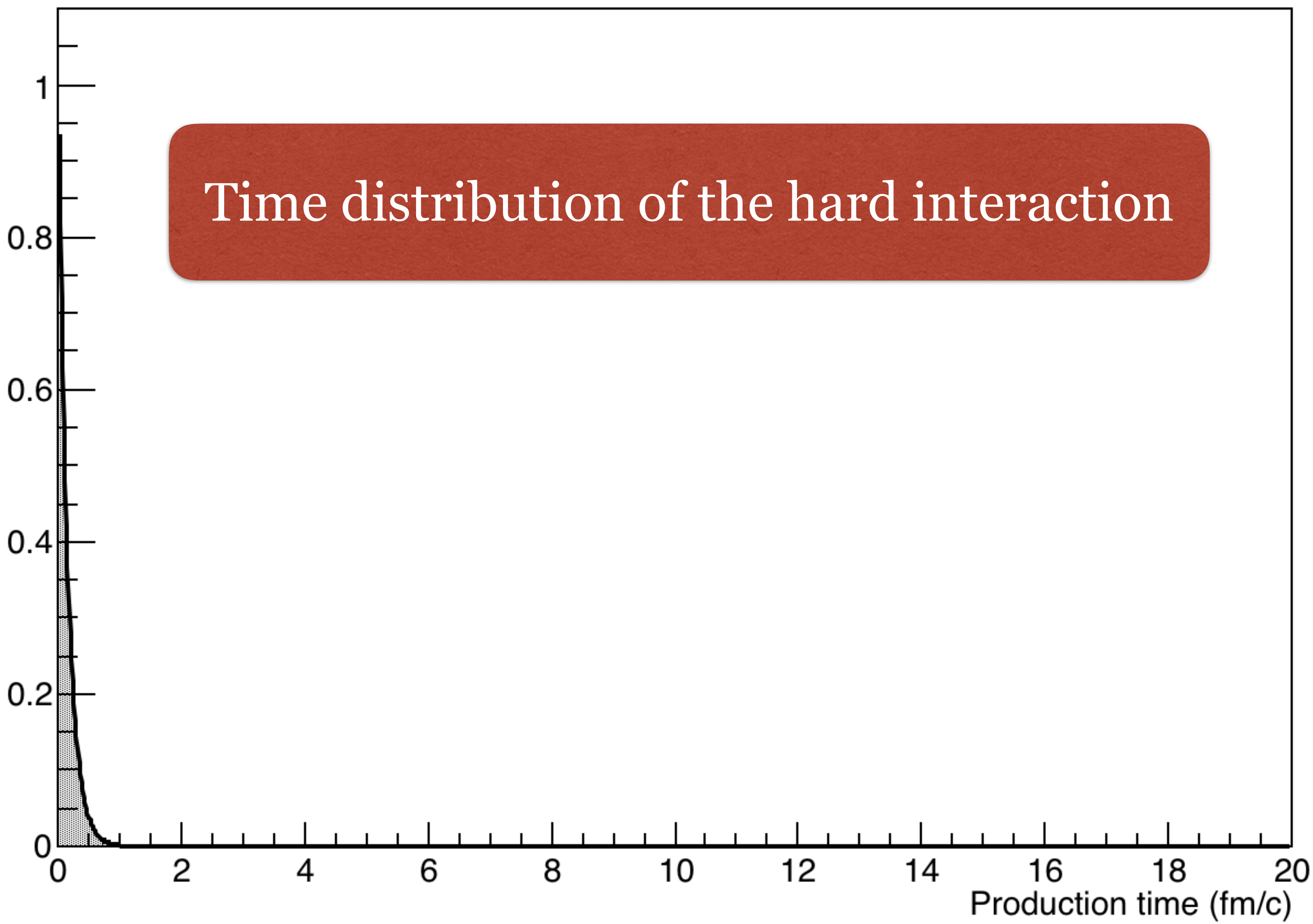

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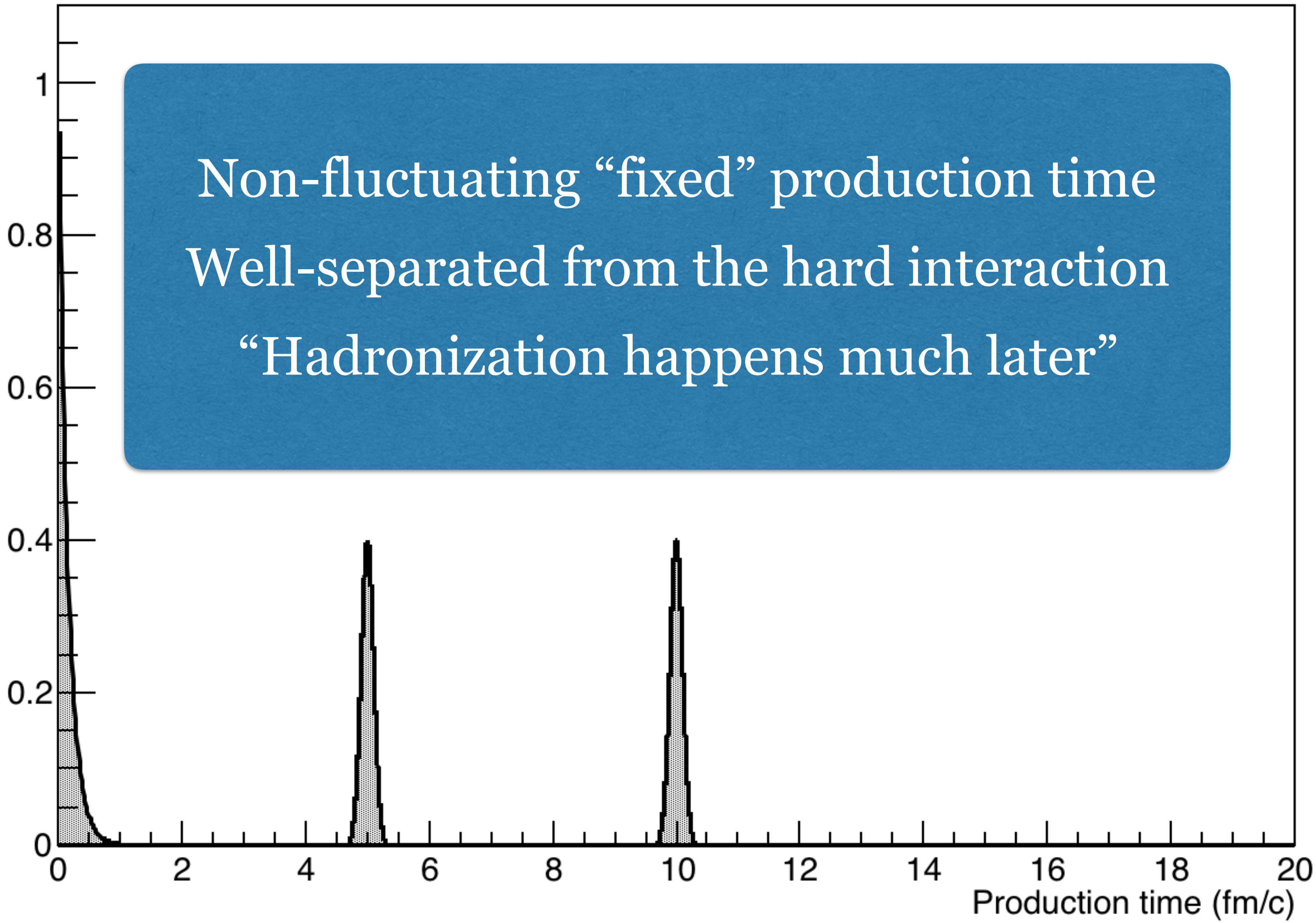

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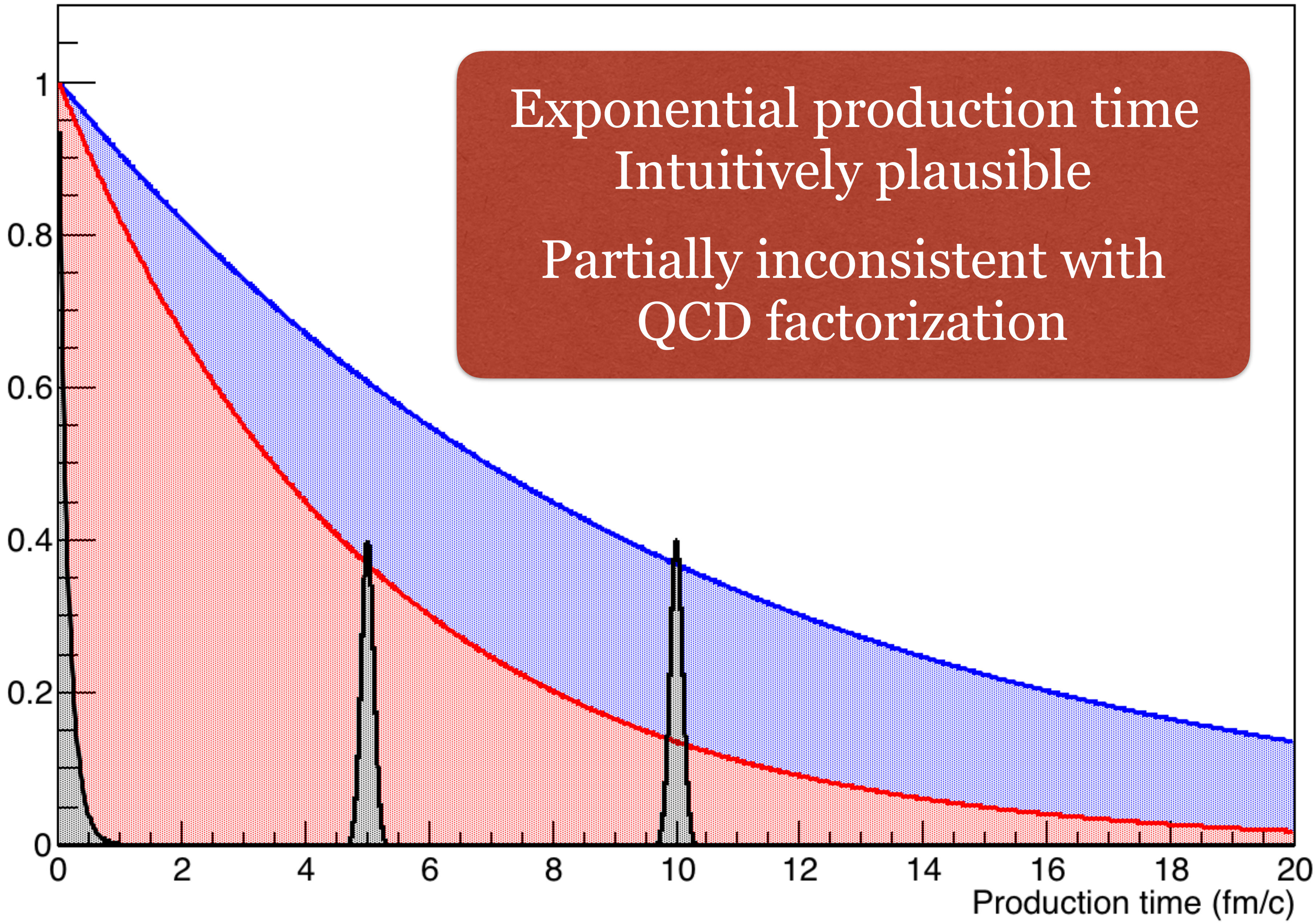

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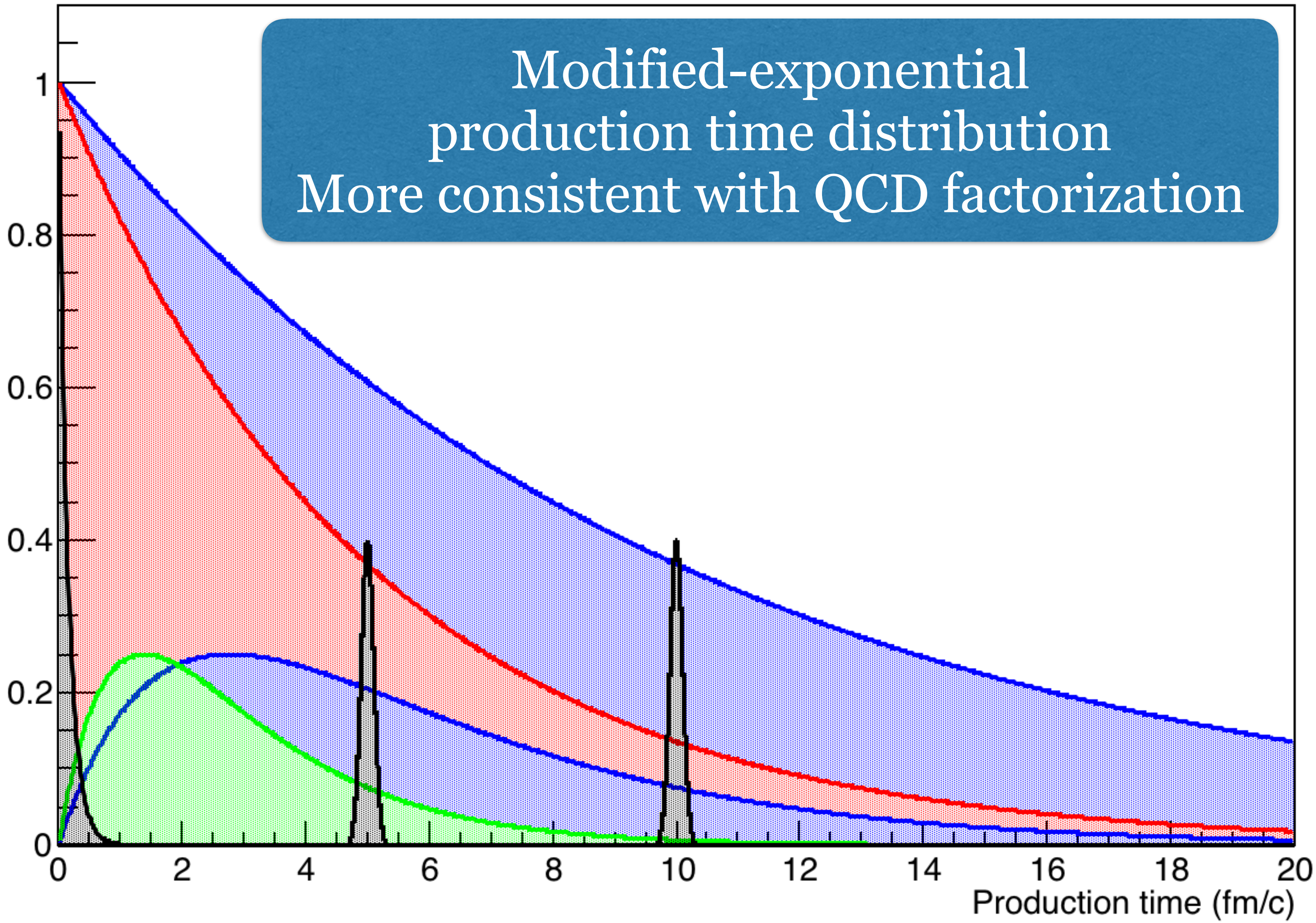
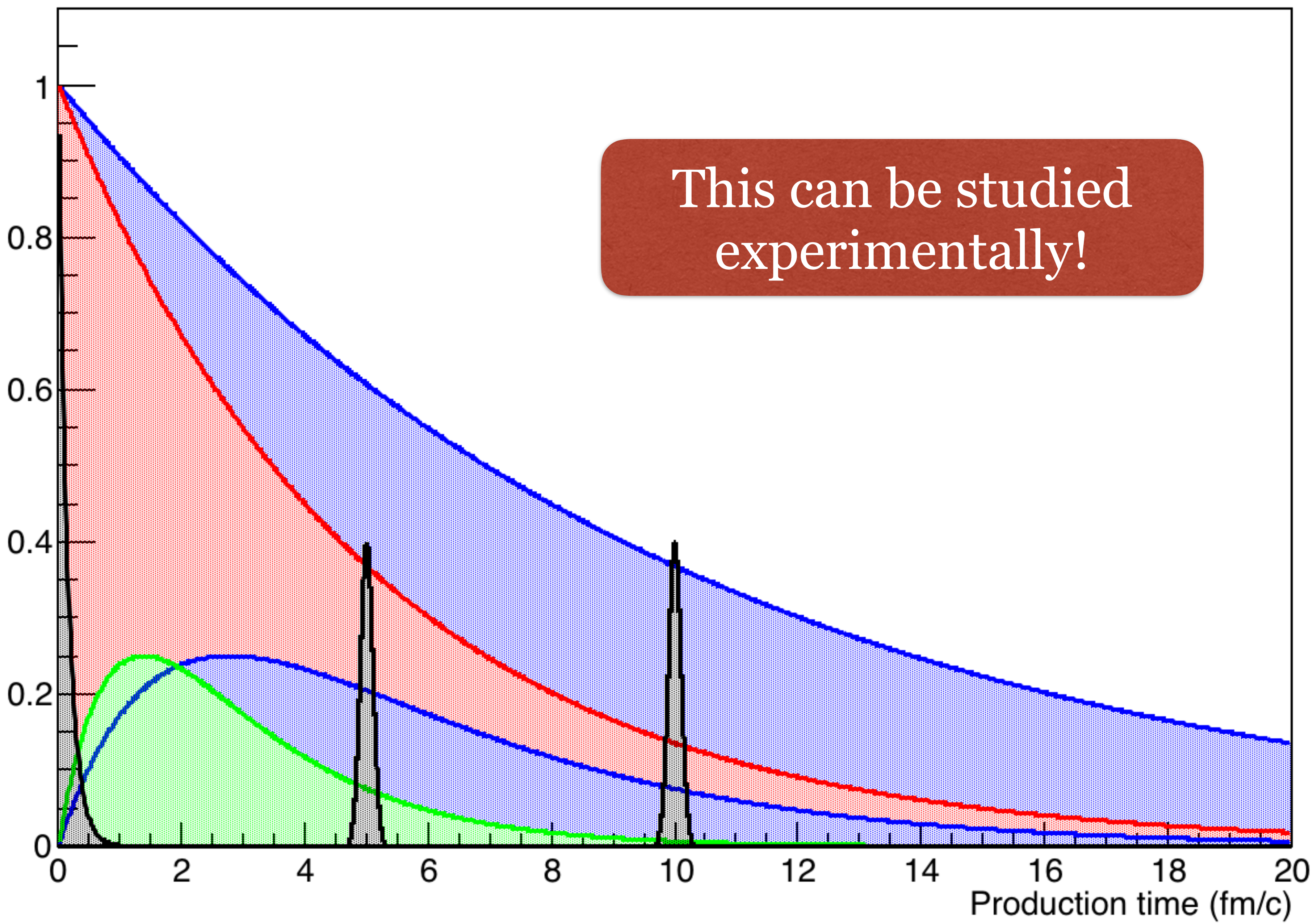
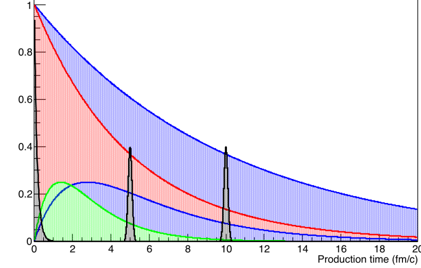


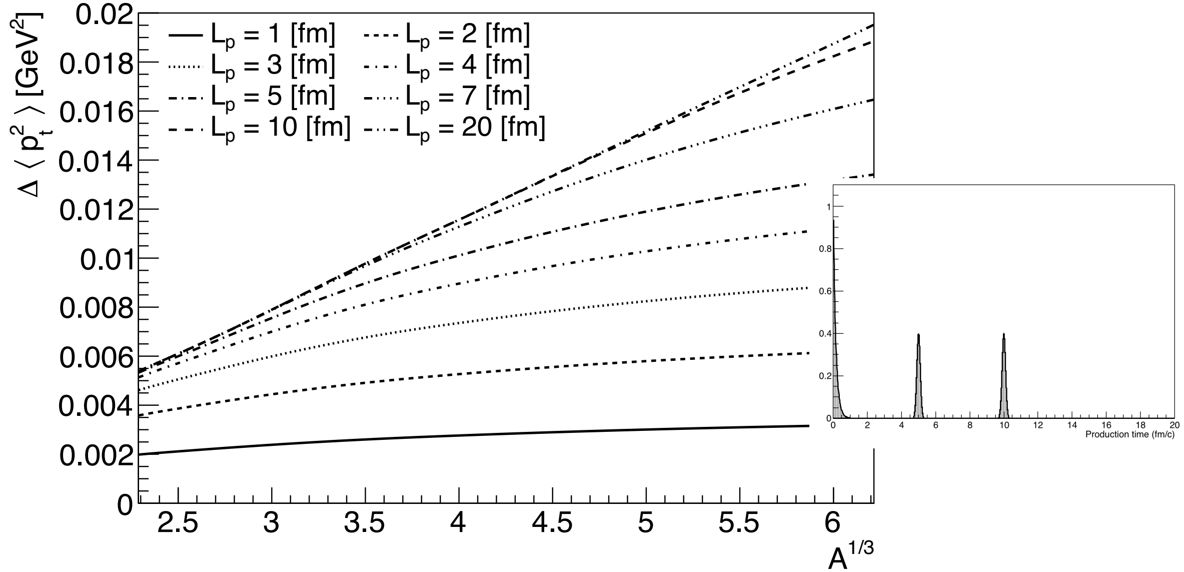
Three possible distributions of production time



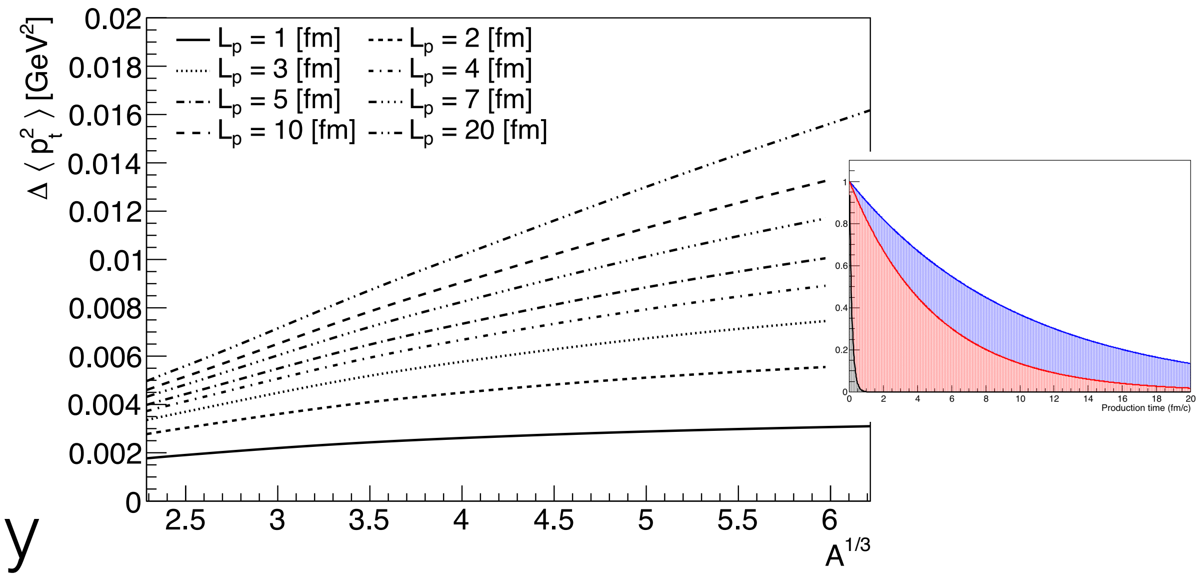
Effect of production length distribution on p_T broadening



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

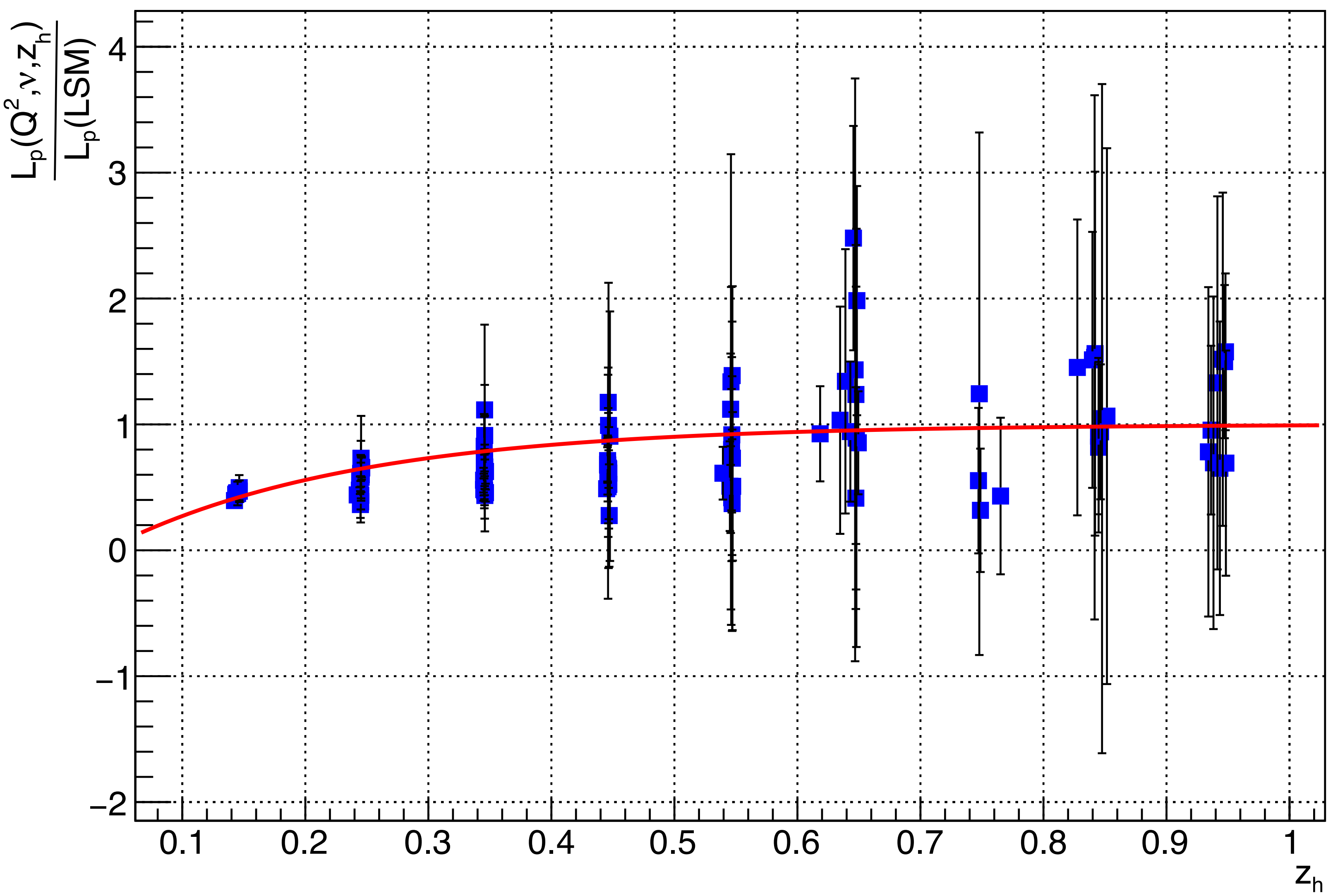
```
103 points, chisquared=69.2, chisq/dof = 0.685  MEDIUM event selection.
 FCN=69.2253 FROM MINOS     STATUS=SUCCESSFUL     10 CALLS          63 TOTAL
                     EDM=2.30163e-20    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                  STEP         FIRST
  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

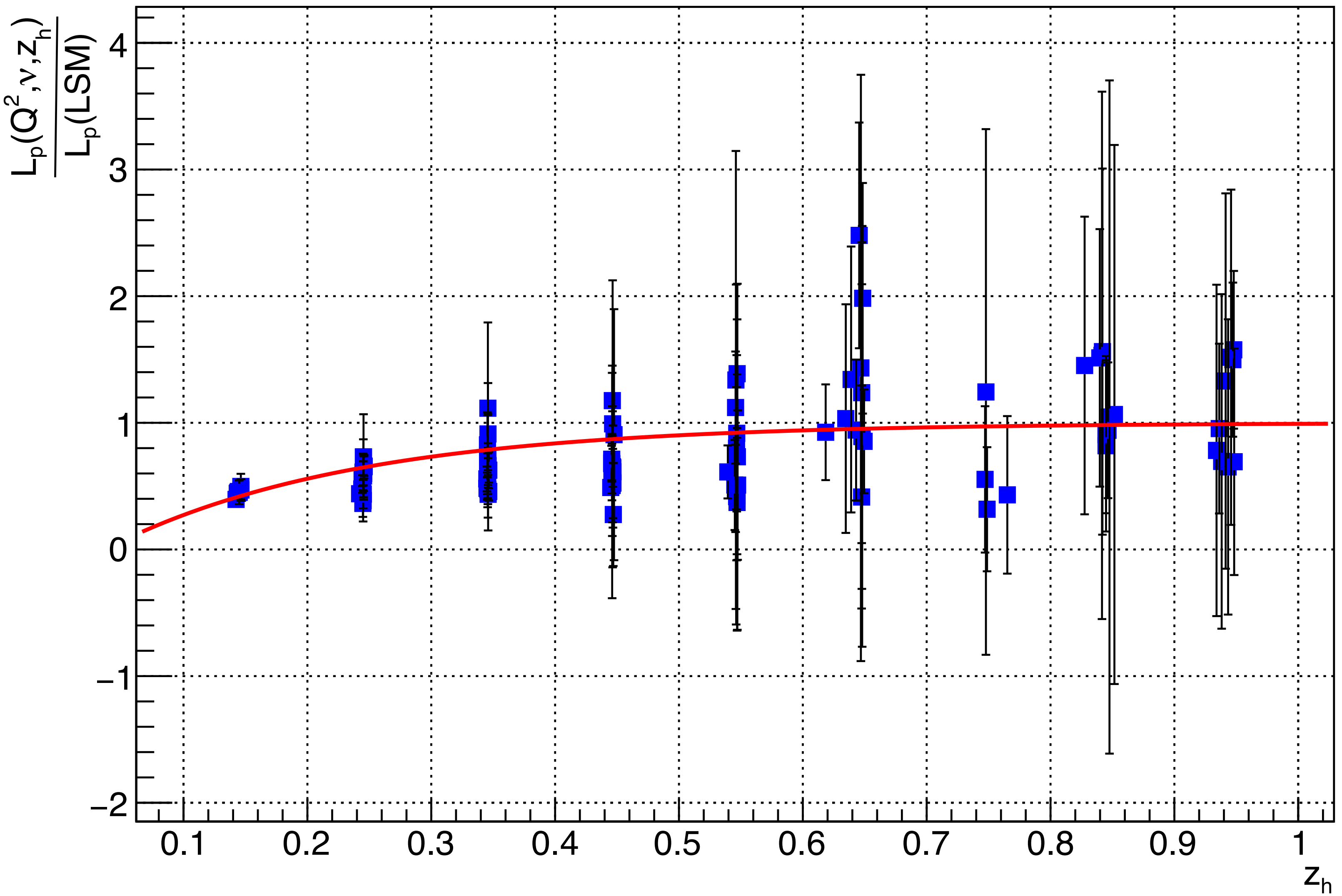
```
88 points, chisquared=289.5, chisq/dof = 3.36  MEDIUM event selection.
 FCN=289.533 FROM MINOS     STATUS=SUCCESSFUL      8 CALLS          63 TOTAL
                     EDM=3.95499e-19    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                  STEP         FIRST
  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

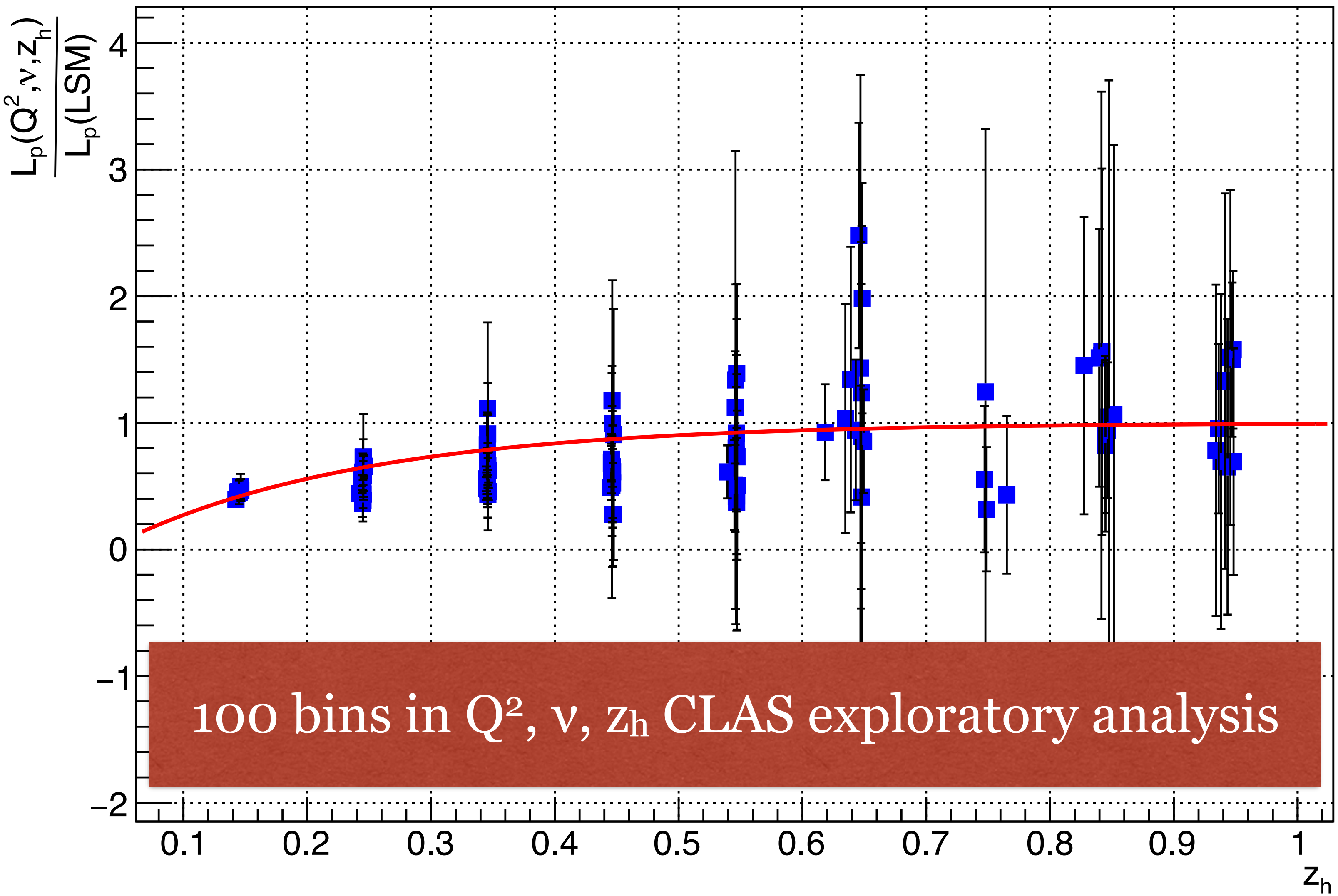


CLAS Exploratory Analysis ≈ Lund String Model



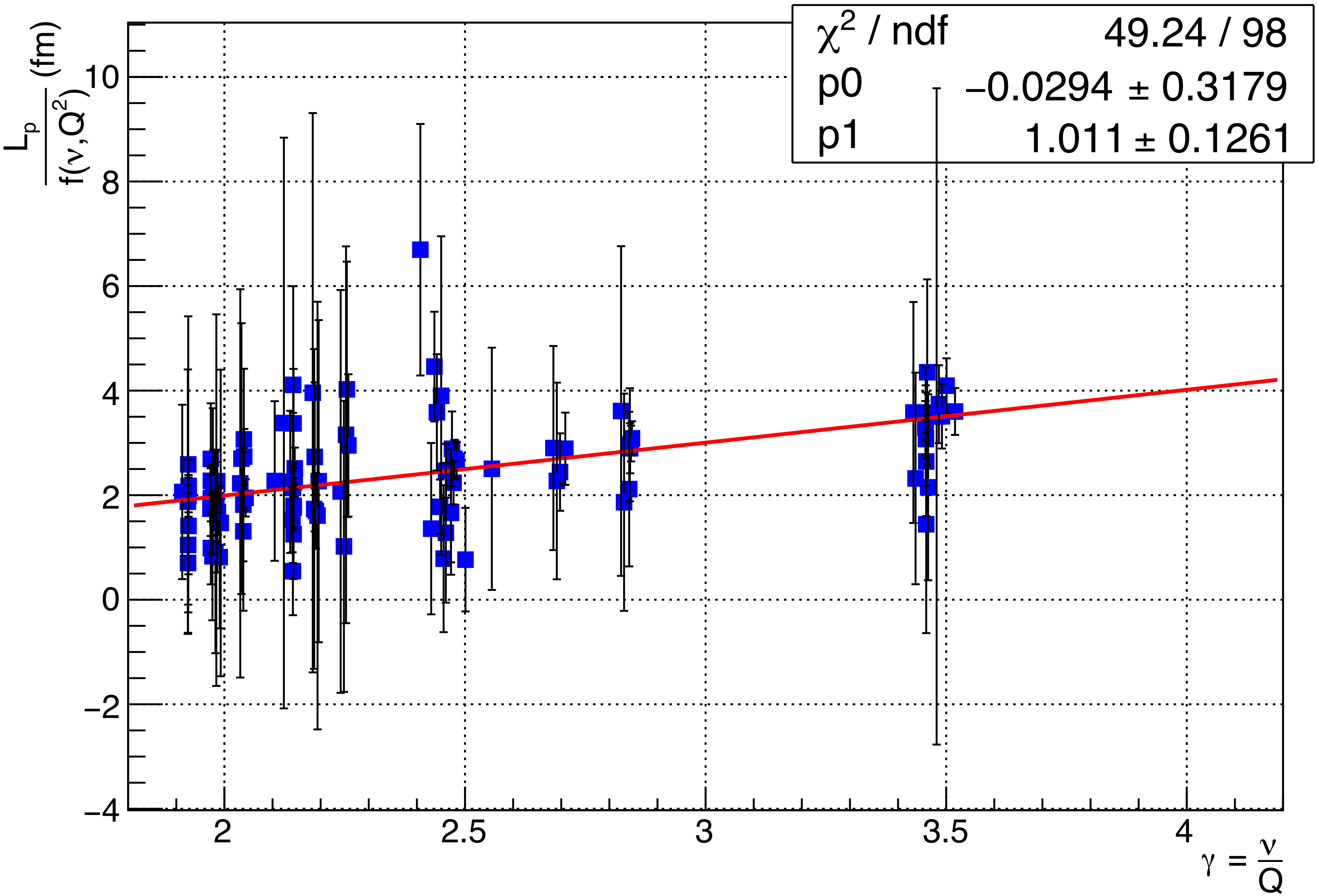
$L_p\ (Q^2, \nu, z_h)$ from CLAS analysis similar to values from the Lund String Model for $z_h>0.4$

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

Time dilation test of the results



Production time demonstrates time dilation

Average slope of L_p vs γ is 1 ± 0.1!

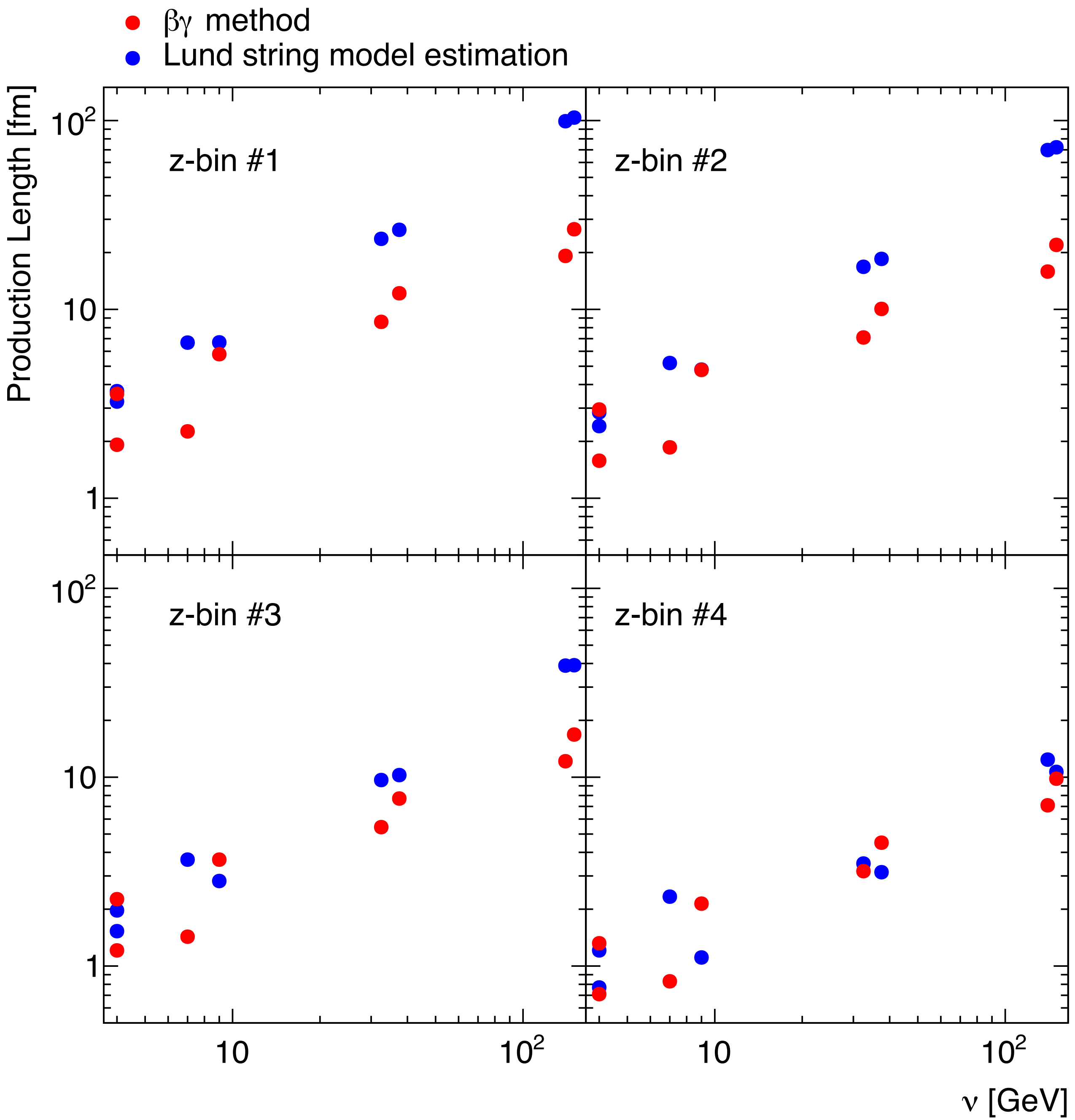
Extrapolation from HERMES to EIC and CLAS

Using the prescription $\gamma = \nu/Q$, $\beta = p_{\gamma^*}/\nu$, 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!

Extrapolation of HERMES fits to EIC kinematics - two different methods



Fair agreement for several kinematic bins

Largest divergence at low z and high nu - target fragmentation region

Wide range of production lengths shows that an interesting program of measurements will be feasible at EIC

The Breakthrough Potential of EIC

The Breakthrough Potential of EIC

- Solving the heavy quark puzzle via heavy meson production (see following slides)

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- Precision time dilation tests over a wide range in ν

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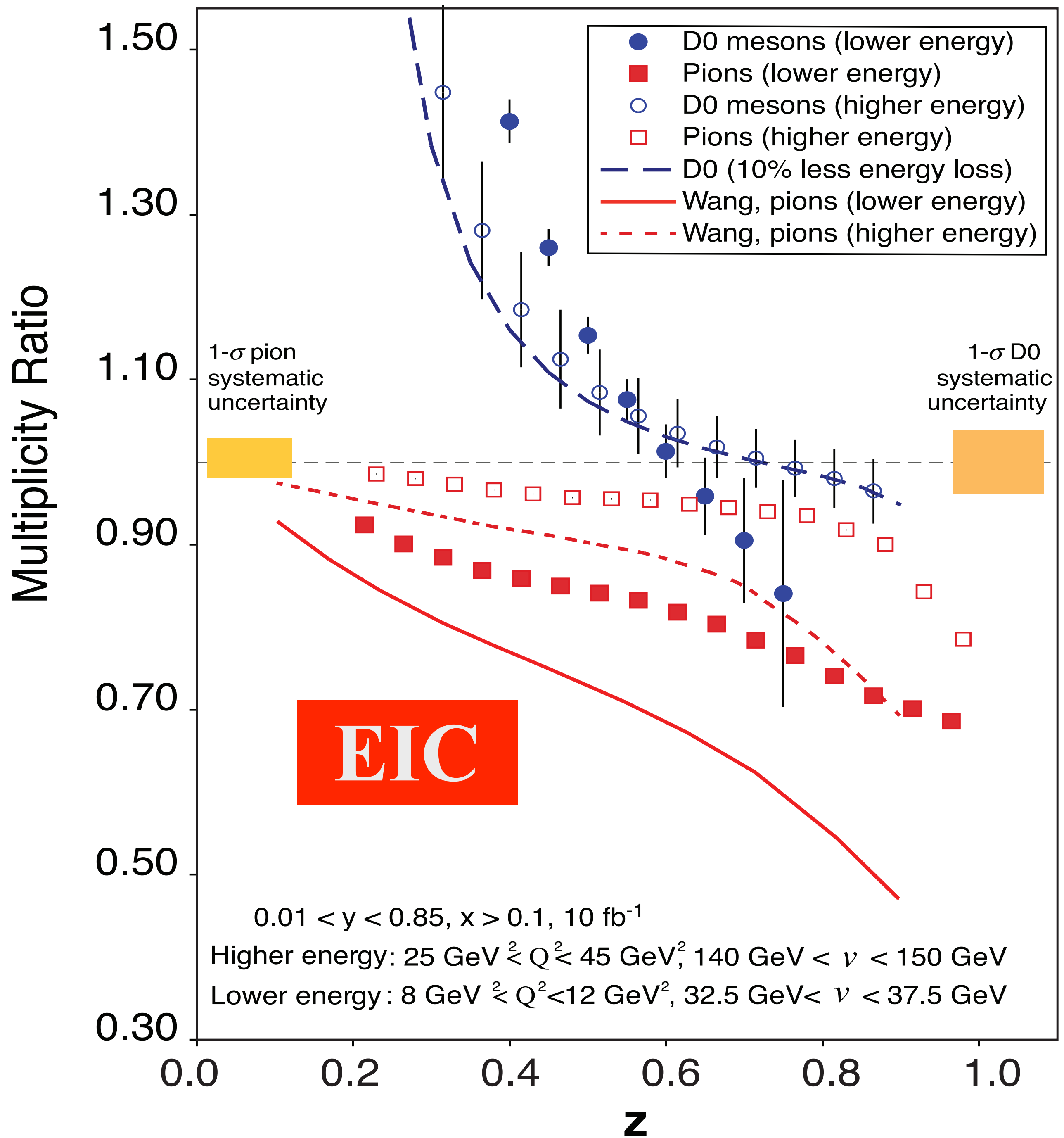
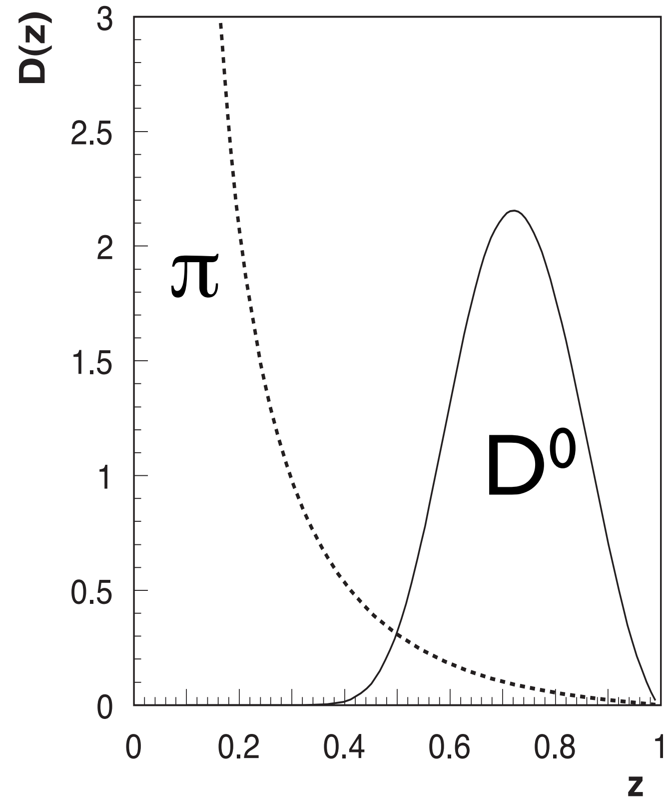
- pQCD enhanced non-linear broadening (see following)
- Flavor dependencies of formed hadrons
- L_p distribution determination





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

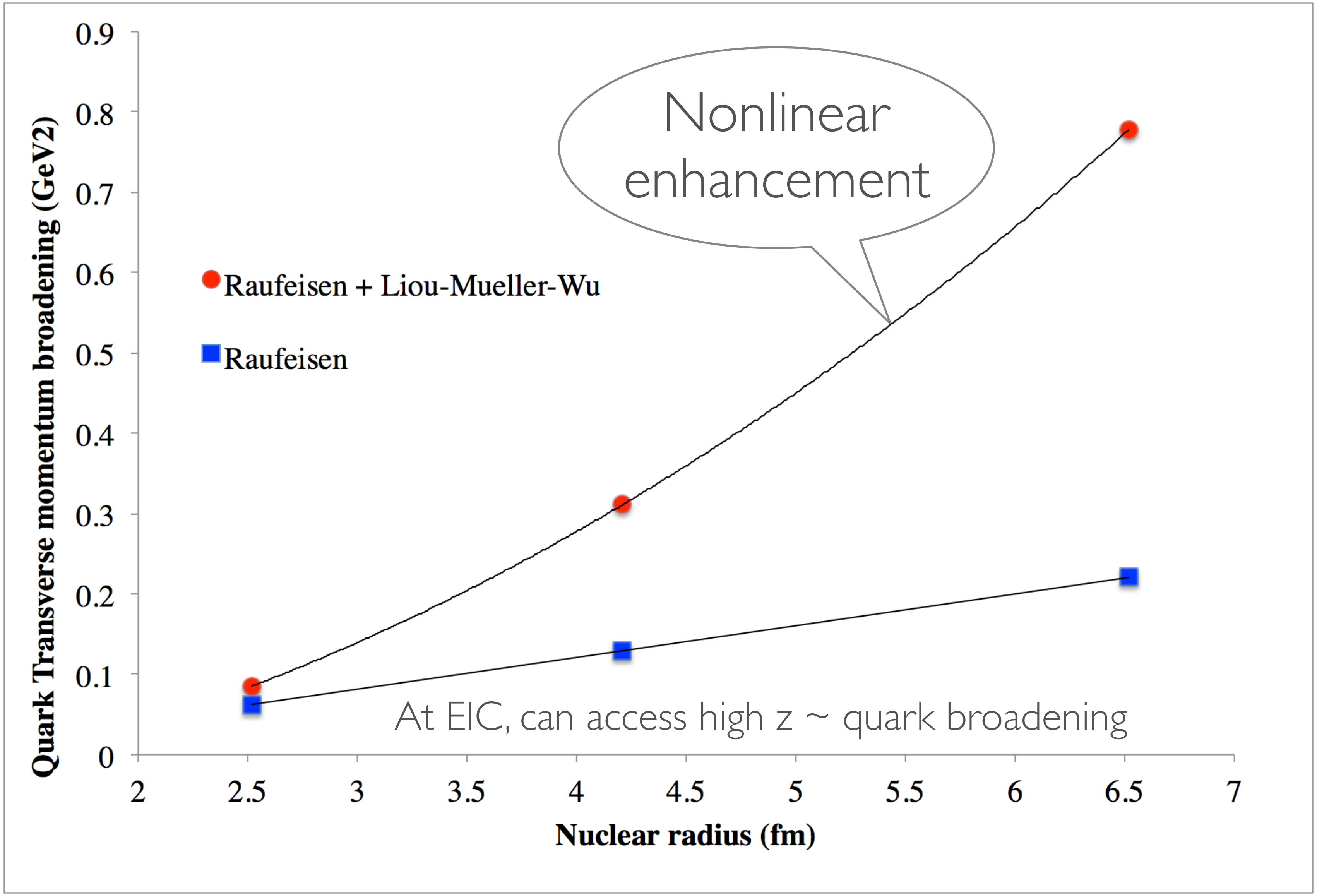
$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2 \;\propto\; \hat{q}\; L$$

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

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

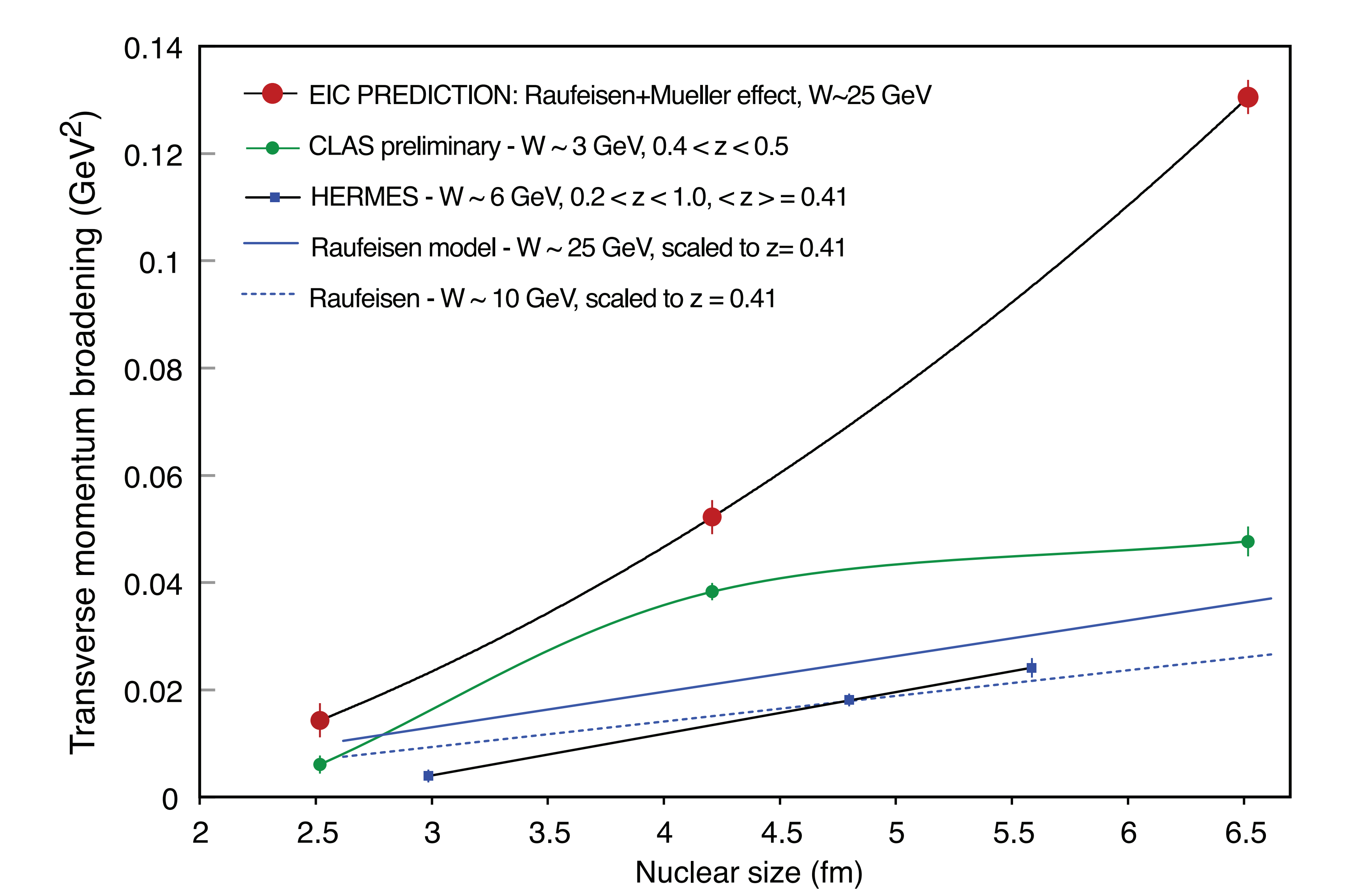
→ predicts a non-linear relationship between p_T broadening and L.
we can look for this at EIC!

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.

pQCD description of quark energy loss on p_T broadening



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

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
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Σ^+	24 mm	1.2	us
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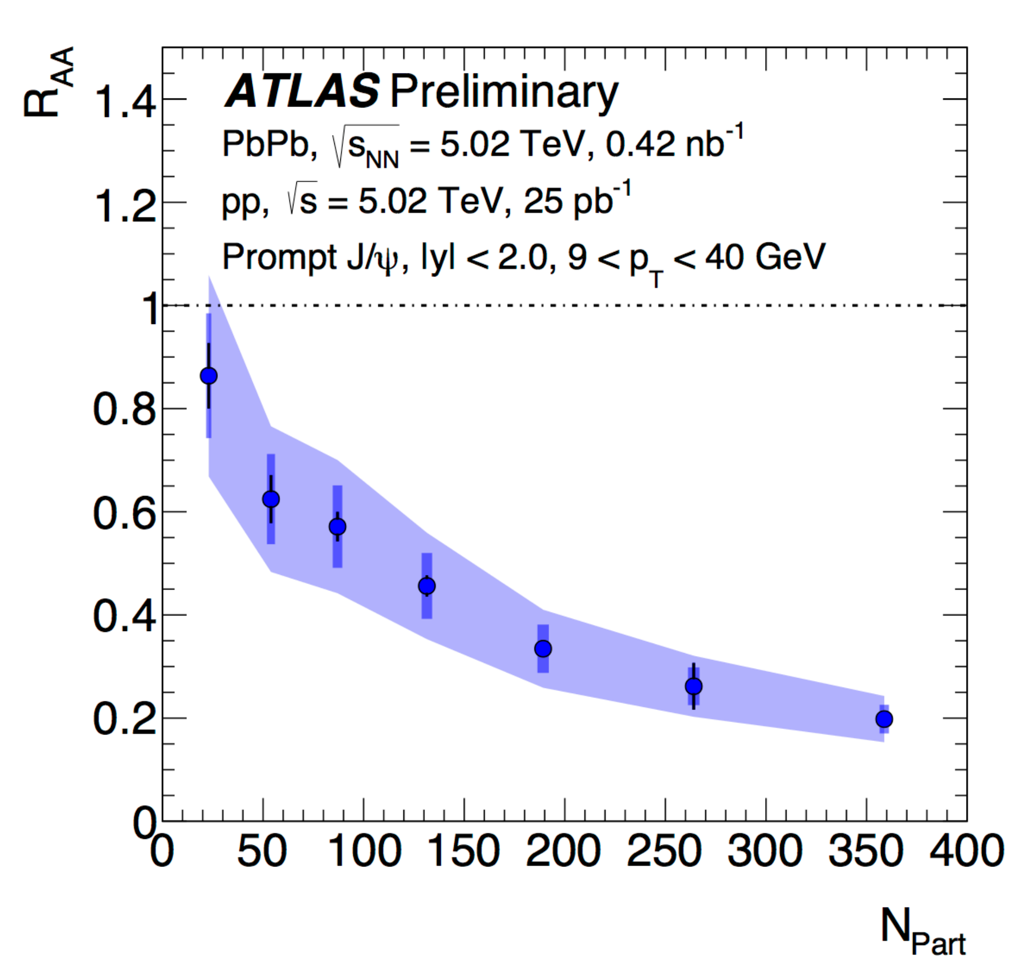
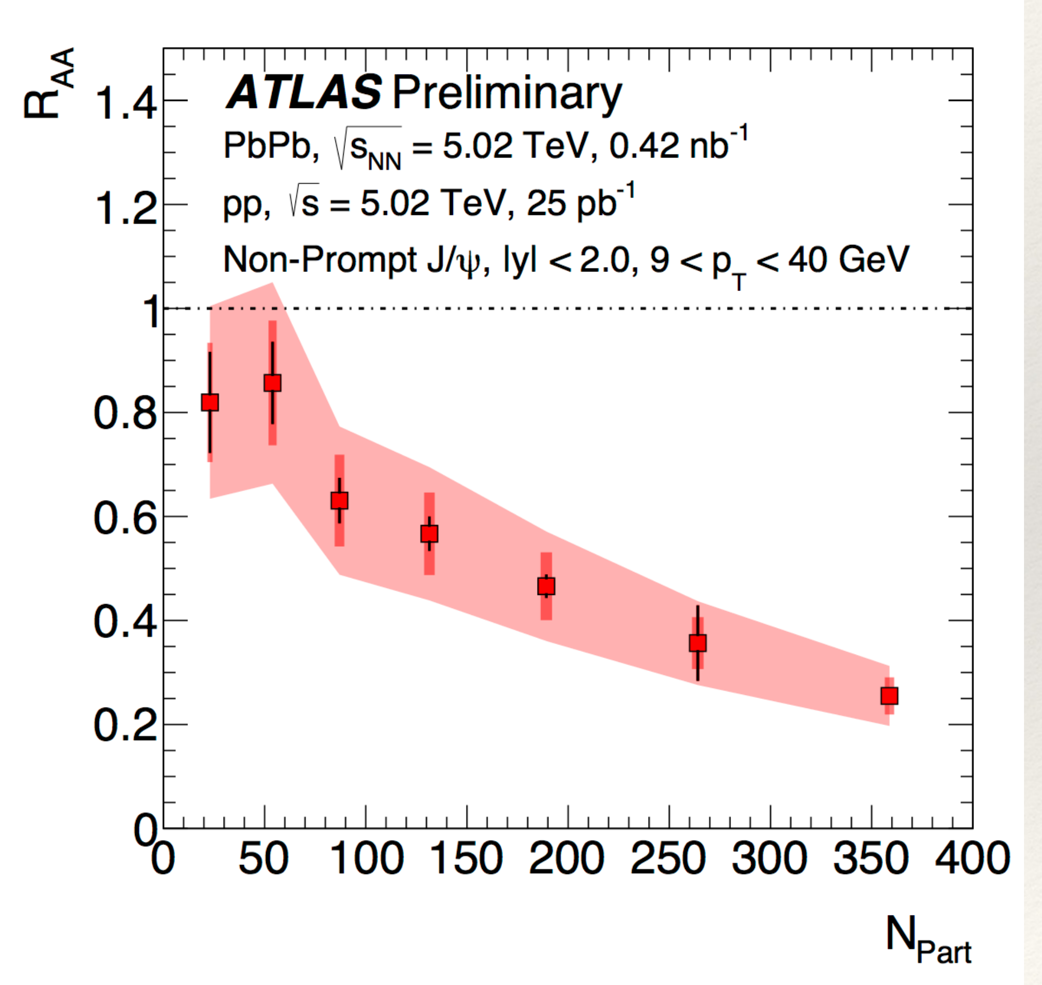
EIC: heavy mesons and baryons; wide kinematic range!

LHC Data: color propagation in the *hot* medium

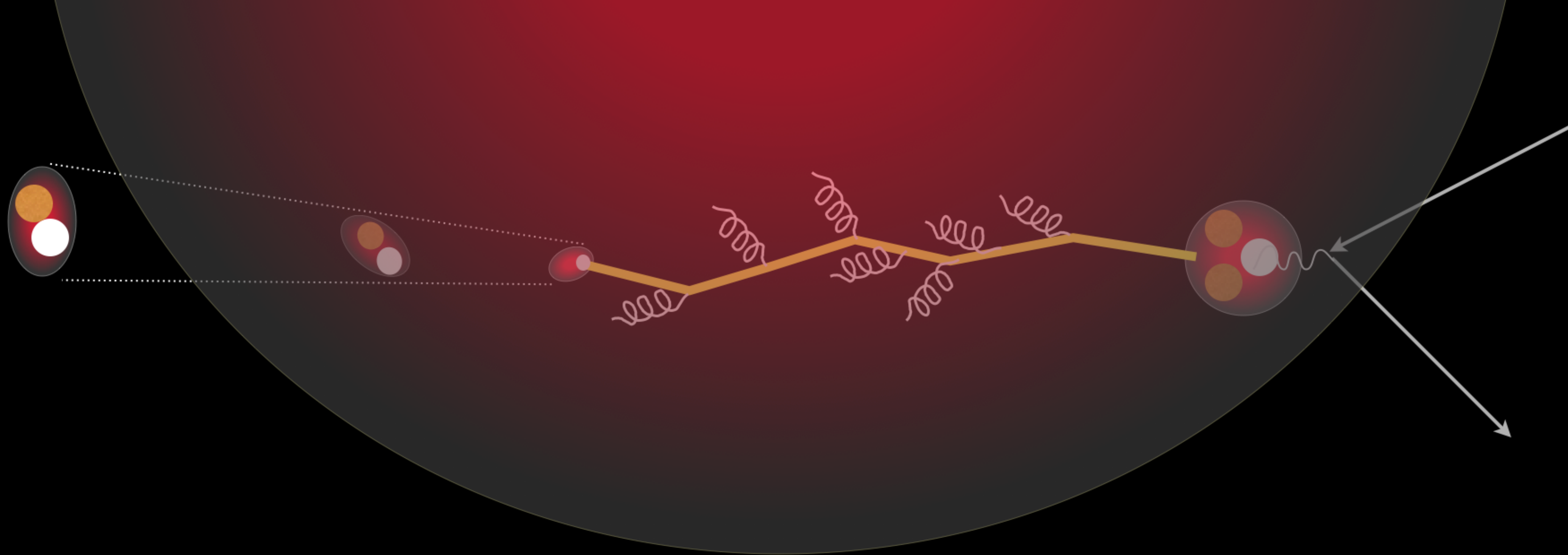
Study of $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ production with 2015 Pb+Pb data at $\sqrt{s_{NN}}$=5.02 TeV and pp data at sqrt(s)=5.02 TeV with the ATLAS detector

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-109/



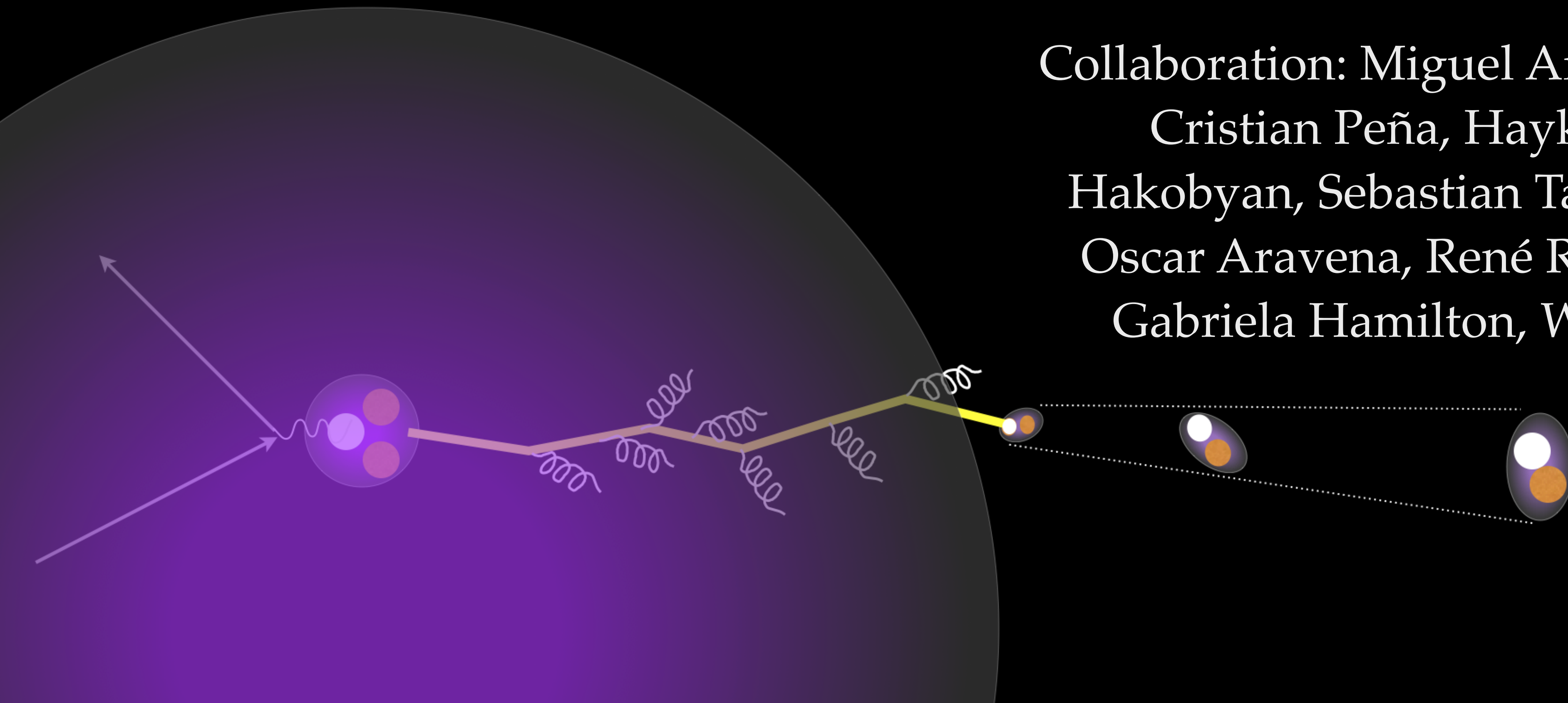


Heavy quarks and fragile mesons similarly suppressed with centrality!



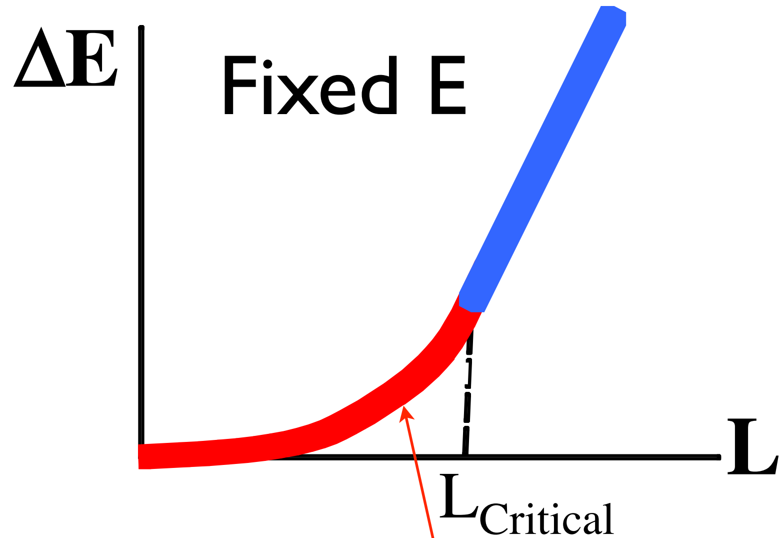
Direct measurement of quark energy loss

Collaboration: Miguel Arratia, Cristian Peña, Hayk Hakobyan, Sebastian Tapia, Oscar Aravena, René Rios, Gabriela Hamilton, WB



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

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

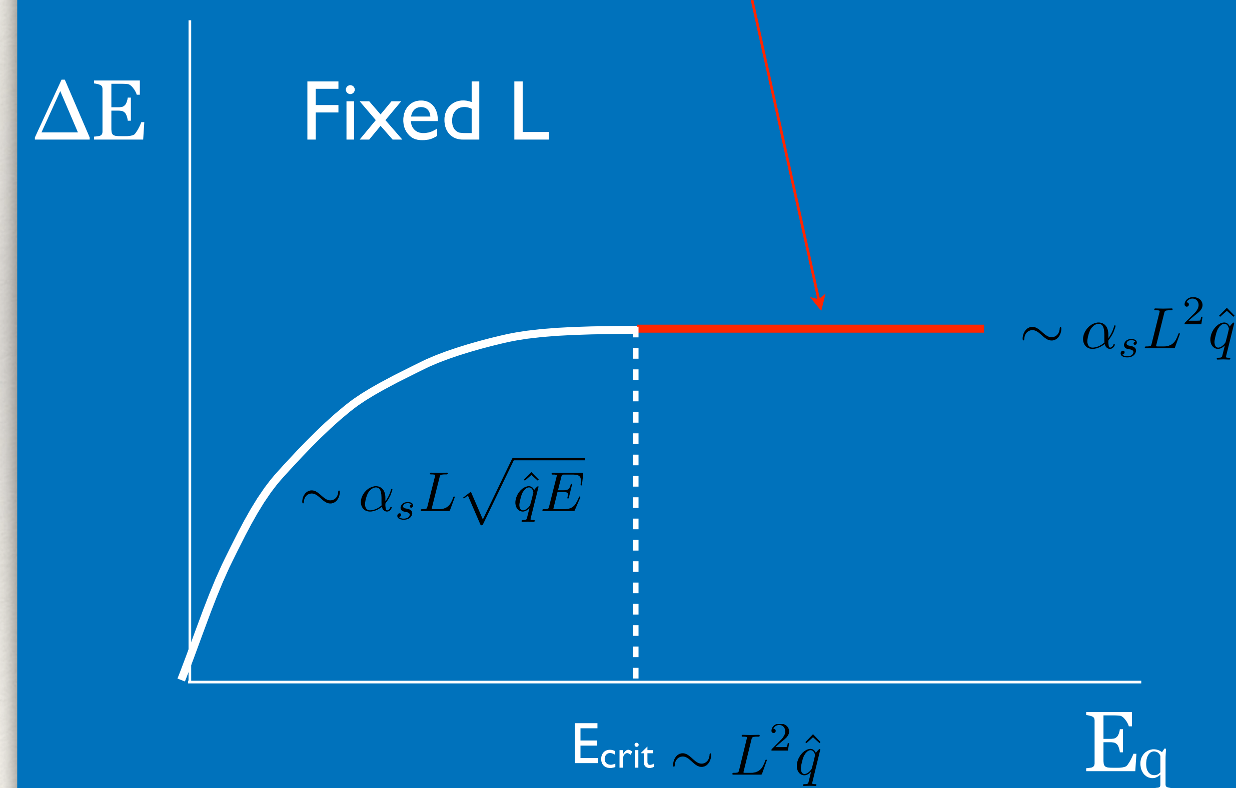


Partonic energy loss in pQCD (BDMPS-Z) exhibits a critical system length L_c and a critical energy E_c

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

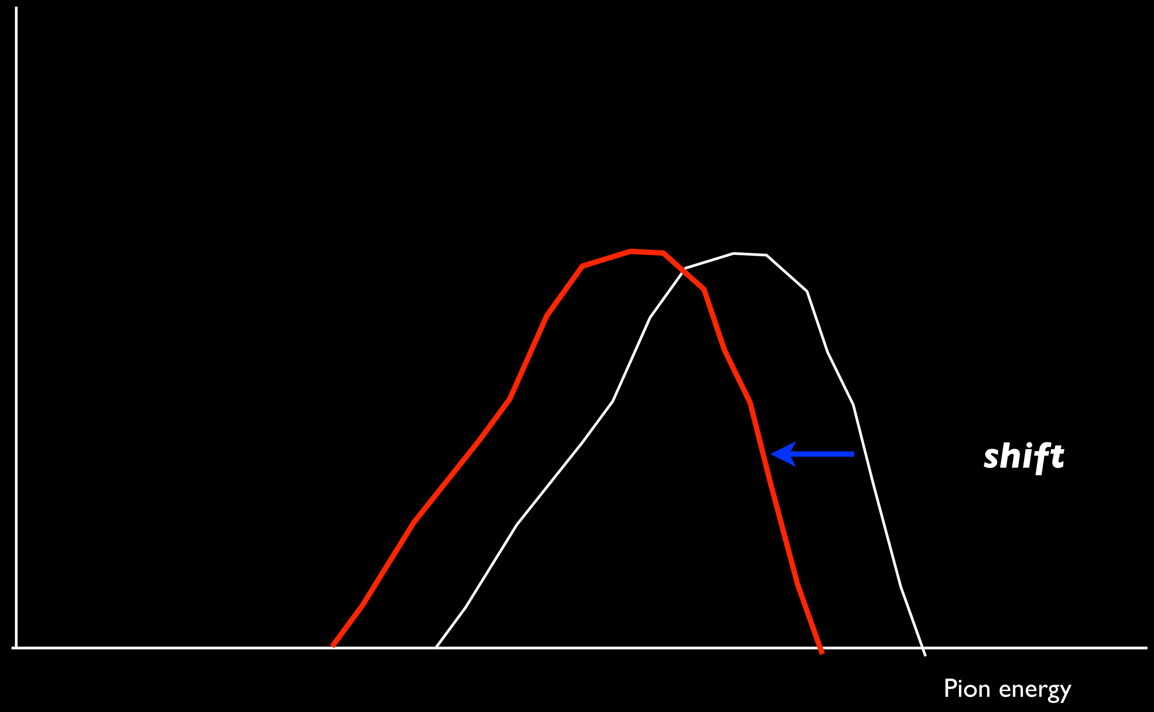
$$E_c \approx 0.4 \cdot \left(\frac{L}{1\ \mathrm{fm}}\right)^2\ \mathrm{GeV}$$

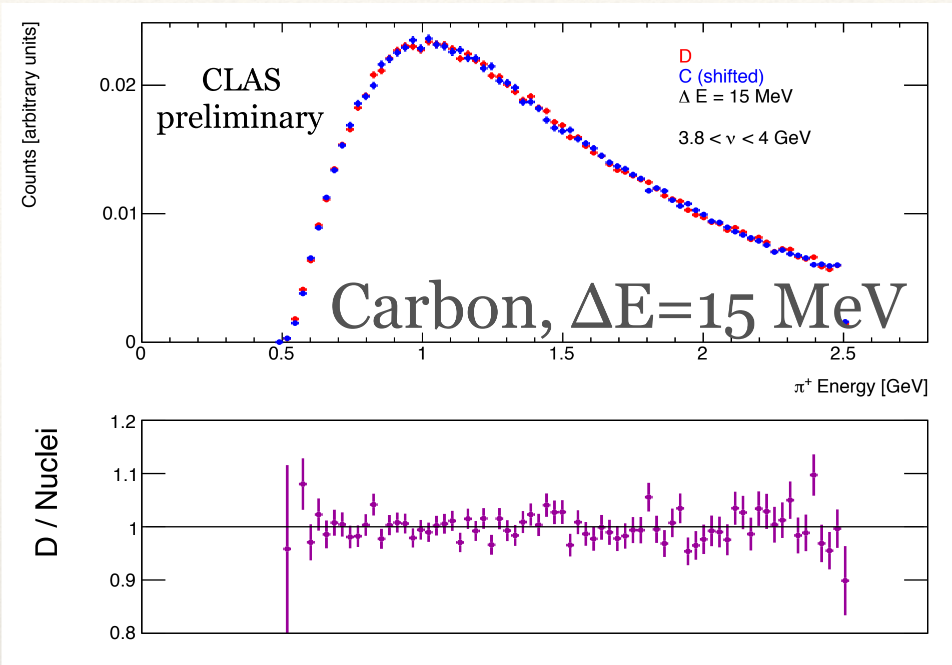
$$-\Delta E_q = \frac{\alpha_s}{4}\Delta k_T^2 \cdot L = \frac{\alpha_s}{4}\hat{q} \cdot L^2$$

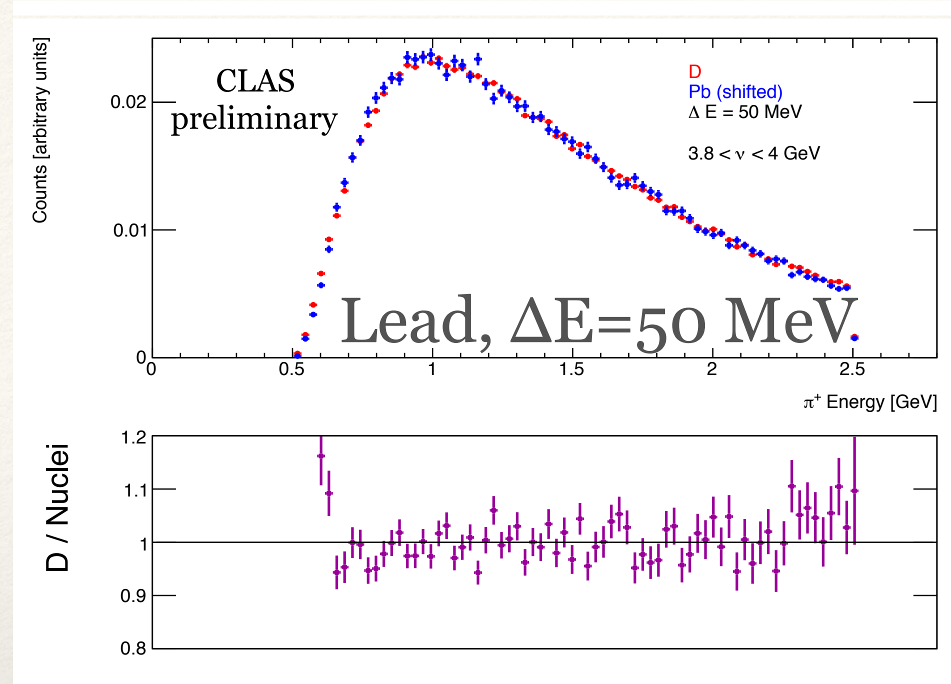


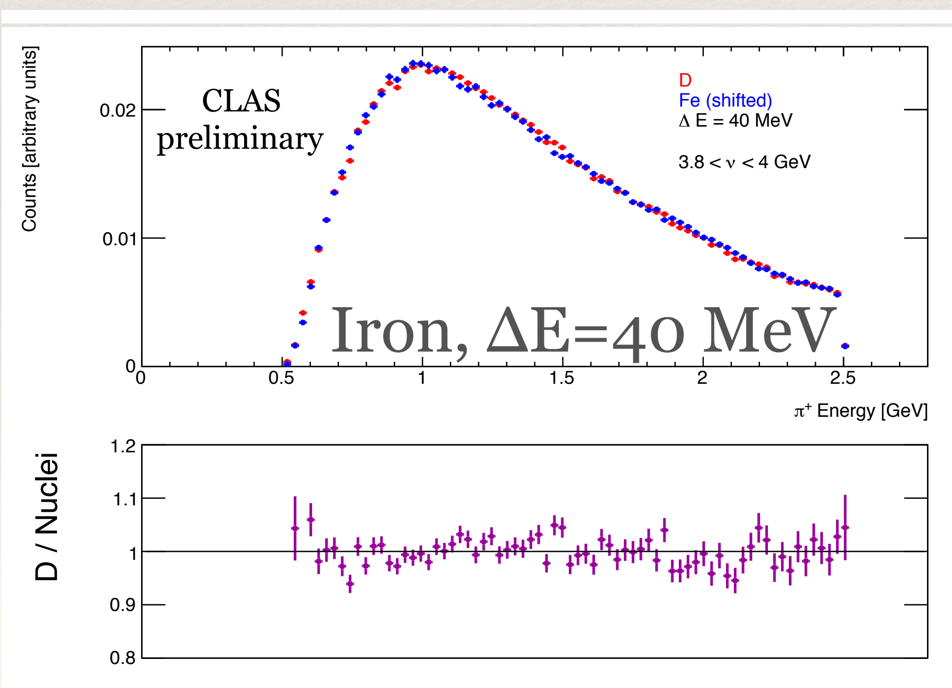
How to *directly* measure quark energy loss?

- Energy loss: *independent of energy* for thin medium
- "Thin enough" depends on quark energy
- If energy loss is independent of energy, it will produce a ***shift*** of the energy spectrum, for higher energies.
- We can look for a ***shift*** of the Pb energy spectrum compared to that of the deuterium energy spectrum







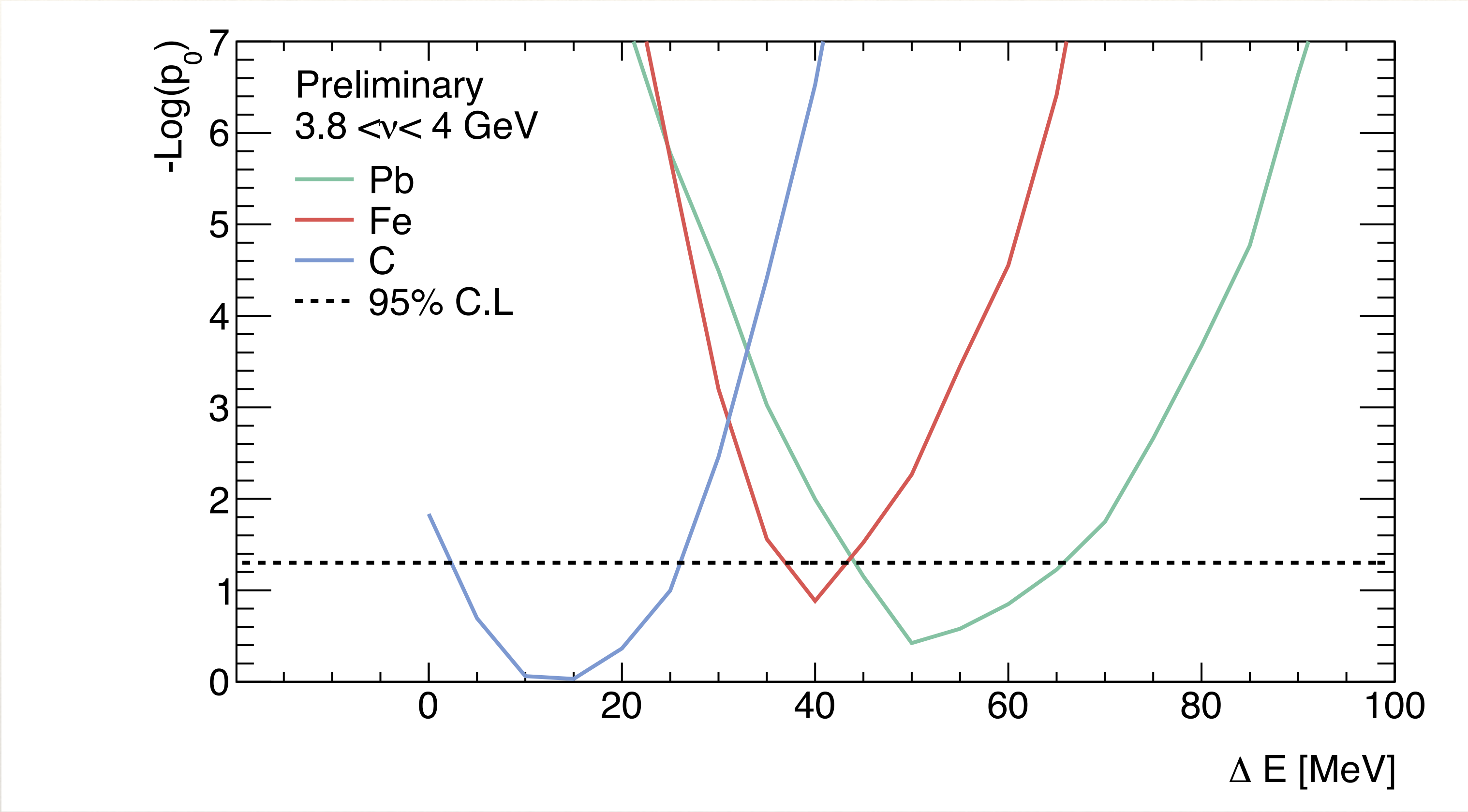


Energy spectrum of π^+ produced in C, Fe, Pb compared to that of deuterium, normalized to unity, with energy shifted by ΔE.

Acceptance corrected

Cut on X_F >0.1 is applied

Consistent with simple energy shift + unchanged fragmentation

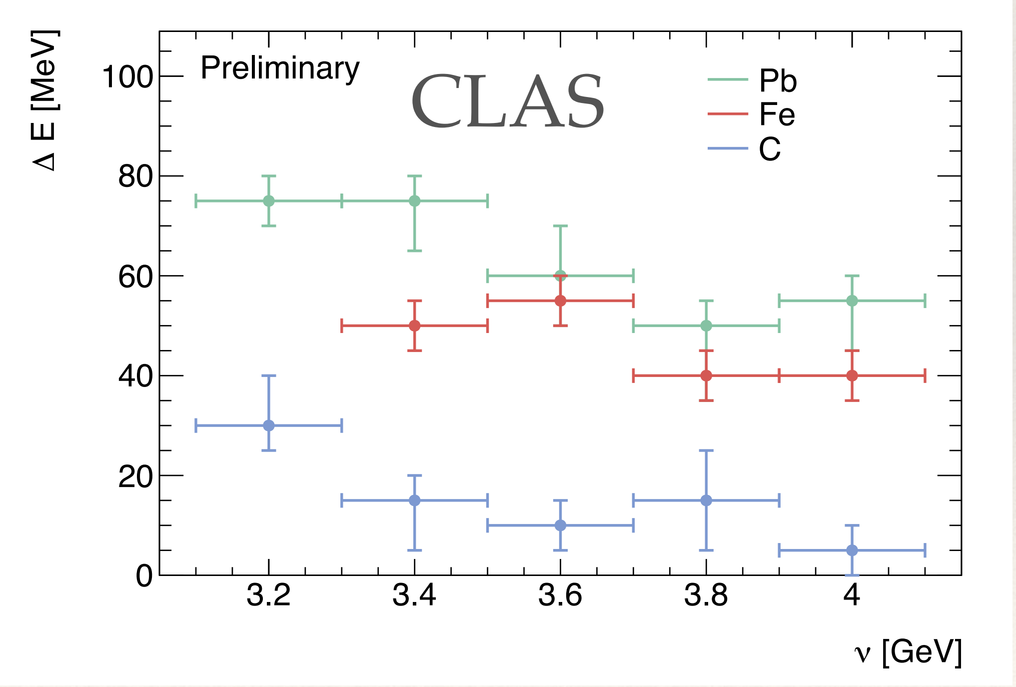


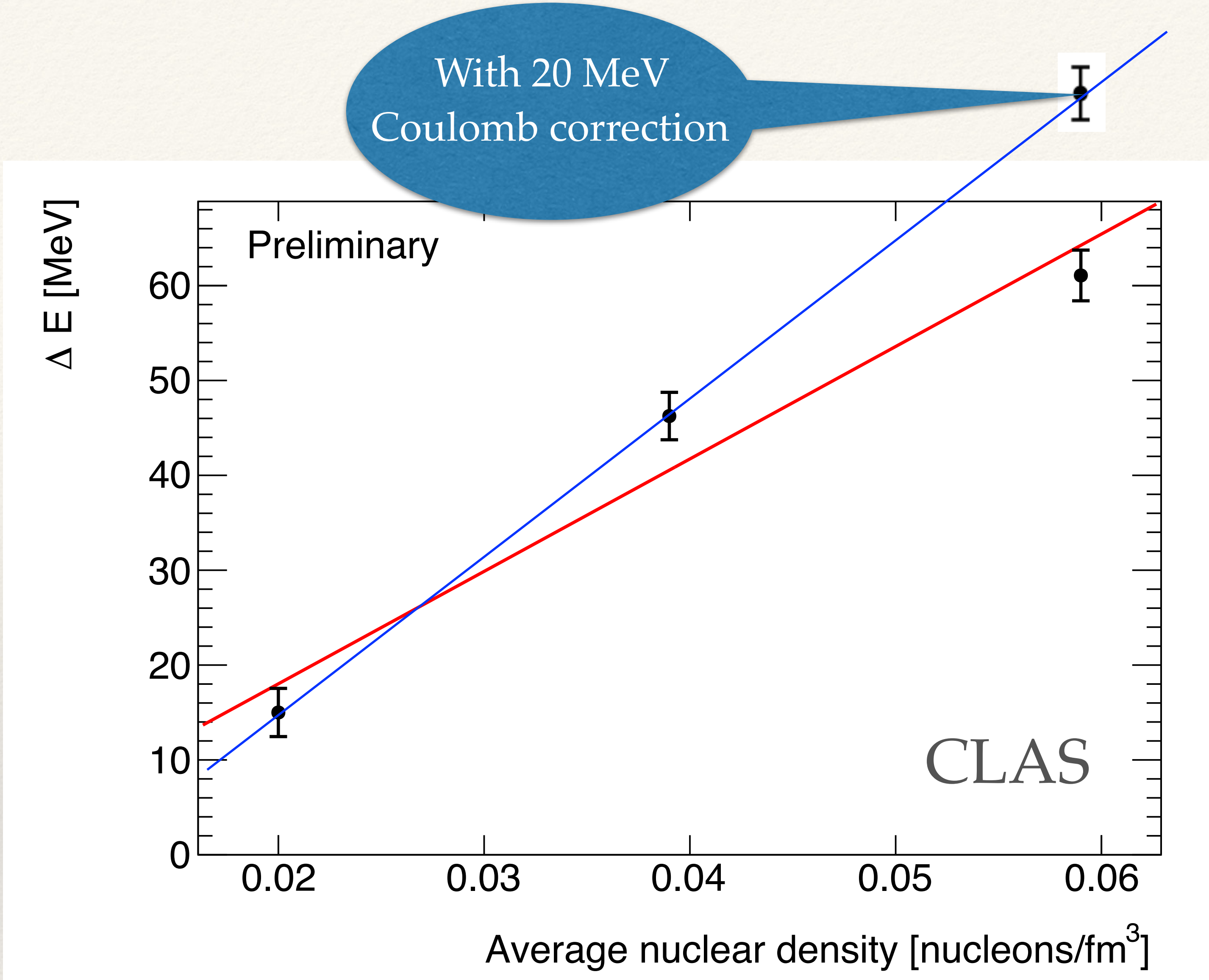
Log of p-values of Kolmogorov-Smirnov test as a function of energy shift ΔE: carbon, iron, lead.

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

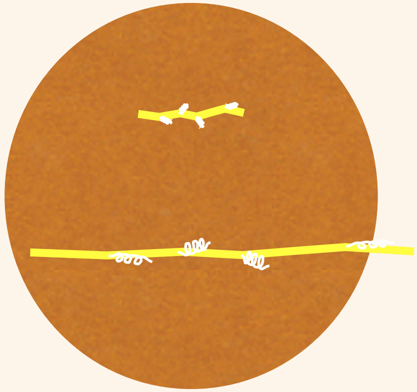
Range of possible energy shift in MeV obtained by Kolmogorov-Smirnov test in ν intervals





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

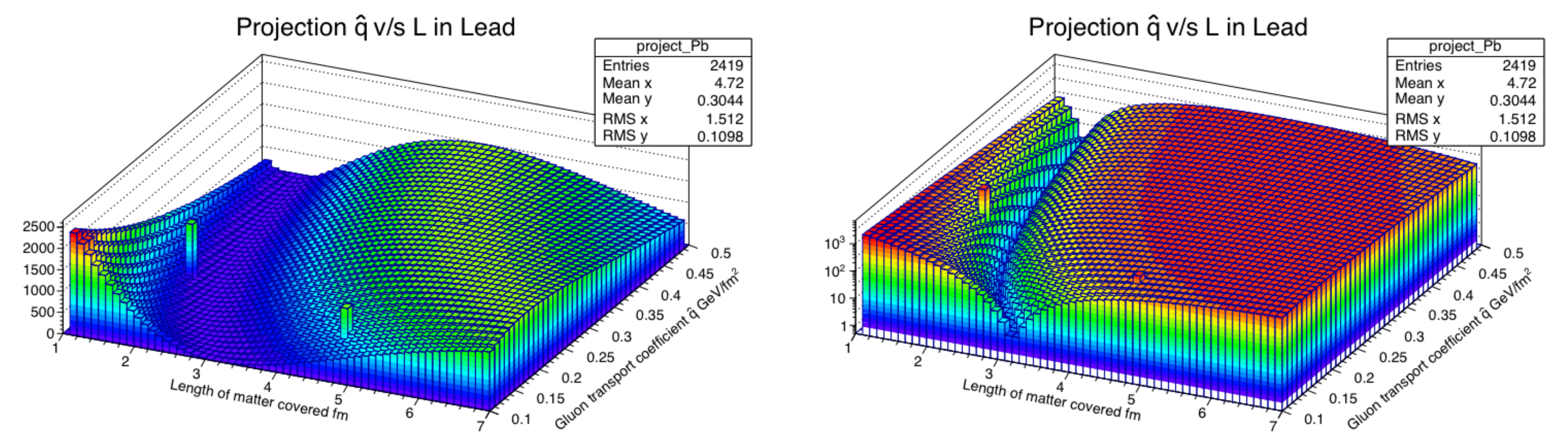
Direct Measurement of Quark Energy Loss in CLAS: Conclusions



- 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

Direct Measurement of Quark Energy Loss in CLAS: Extraction using a Dynamical Model

Oscar Aravena, Hayk Hakobyan, S. Peigne, WB



(a) 2D analysis in Lead (b) 2D analysis in Lead Log Z representation

	L (fm)	$\hat{q}$ (GeV/fm²)	χ^2/dof	ω_c GeV/fm^2
Carbon	4.2	0.14	0.462963	1.23
Iron	3.5	0.14	2.31124	0.86
Lead	2.9	0.13	3.44176	0.55

O. Aravena, MSc Thesis (H. Hakobyan, advisor), UTFSM Valparaíso, 2017

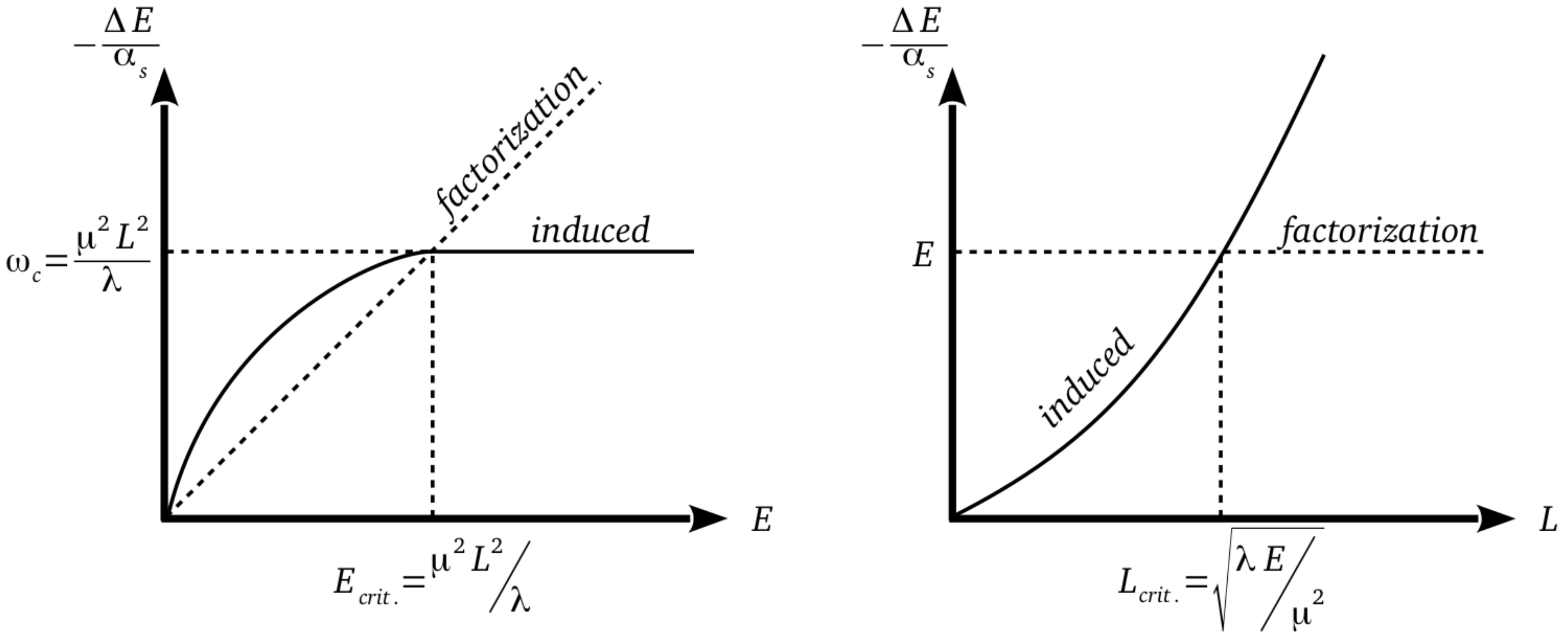


Figure 3.4: Schematic representation of total induced energy loss as a function of the parton energy E (left) and total induced energy loss as a function of the medium size L (right).

λ = mean free path for multiple scattering

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- Much more in future: 12 GeV and EIC:
  - Heavy quark puzzle; time dilation; pQCD enhanced broadening; flavor dependences; L_p distribution