Experimental Overview

Jets, Energy Loss, Hadronization, Nuclear Structure:
Nuclear Physics with QCD color

EIC Users Group Meeting, CUA 2018

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Color Propagation Studies

- **Nuclear targets/collisions producing identified particles**
- Semi-inclusive DIS: HERMES, JLab (Hall B&C), EIC
- Drell-Yan: FNAL
- Heavy-ion collisions: RHIC and LHC
- Physics:
  - Parton energy loss in cold/hot medium, color lifetime
  - Hadron formation - mechanisms, time scales, color recombination, color screening, etc.

Color propagation at EIC

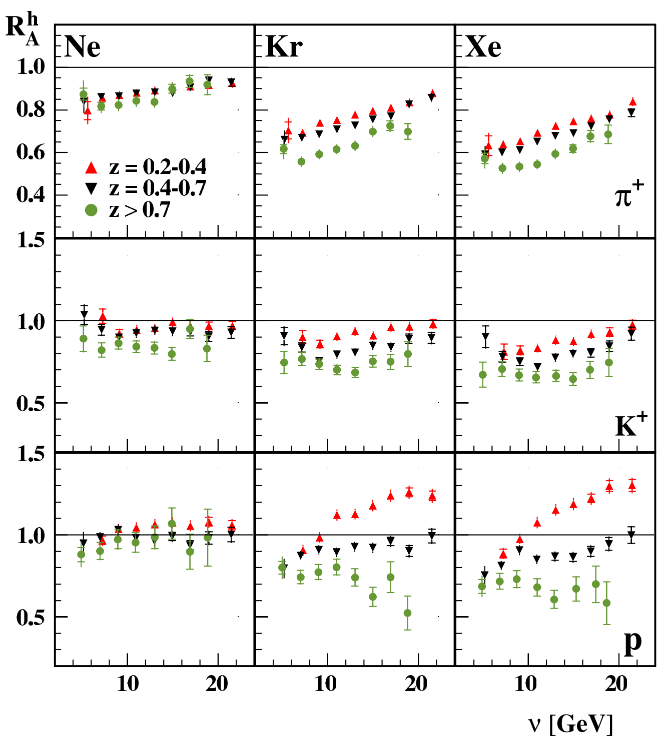
- Cold matter
- Identified hadrons
- CLAS < HERMES < EIC energy scale < LHC

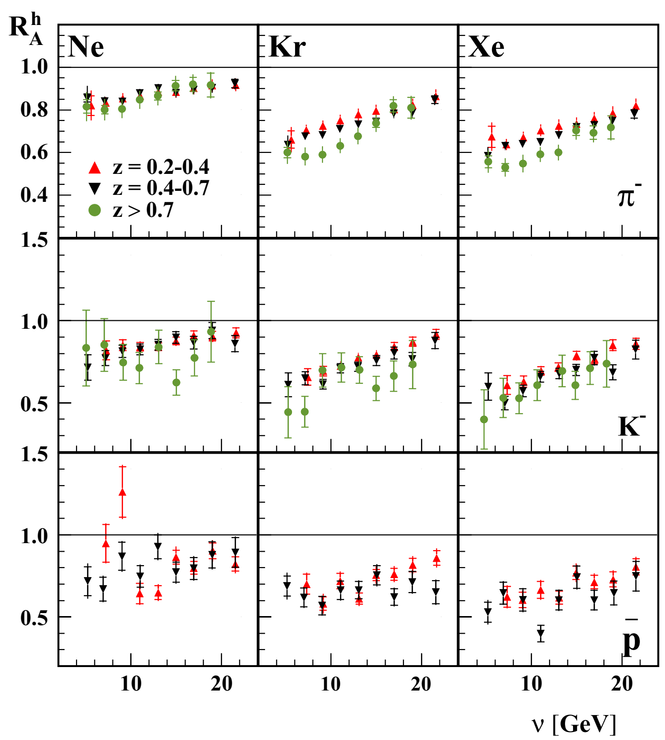
How well do we understand the data we already have?

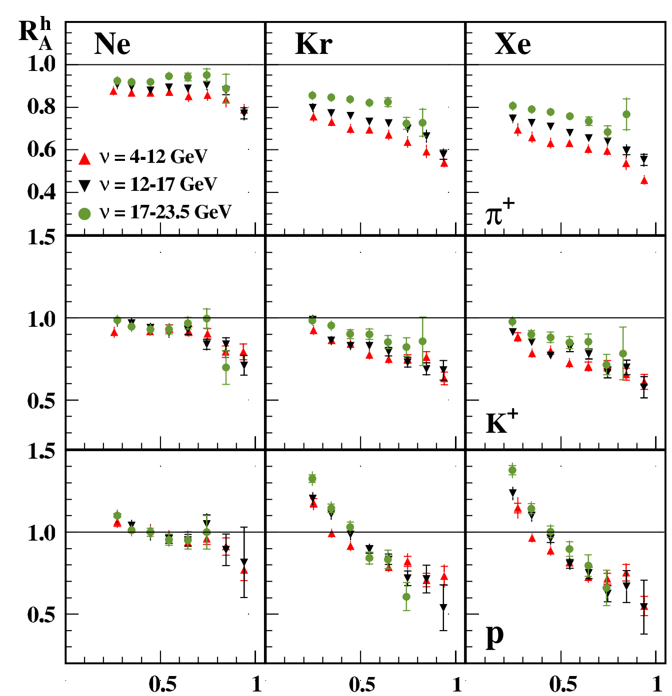
COMPARING DIFFERENT HADRONS

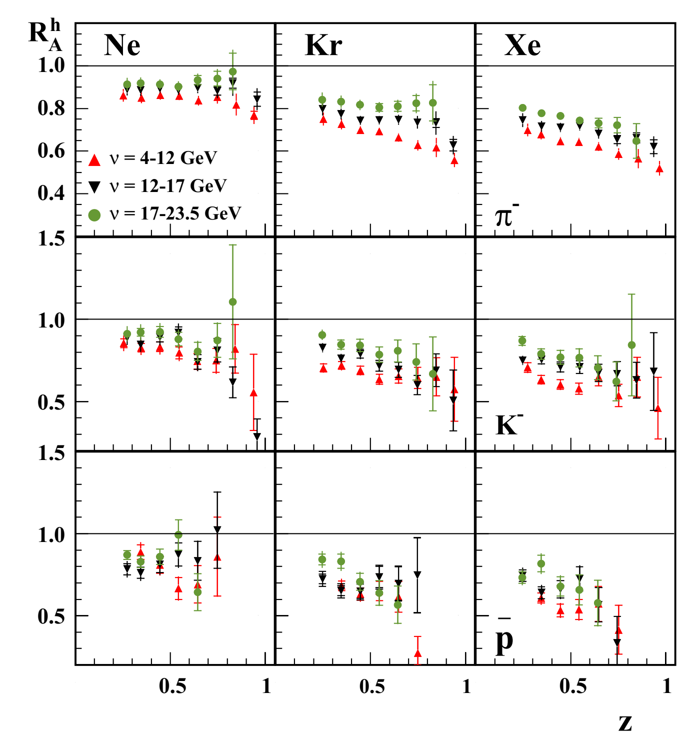
HERMES demonstrated that simple expectations about hadron flavor independence are naïve - Eur. Phys. J. A (2011) 47: 113.

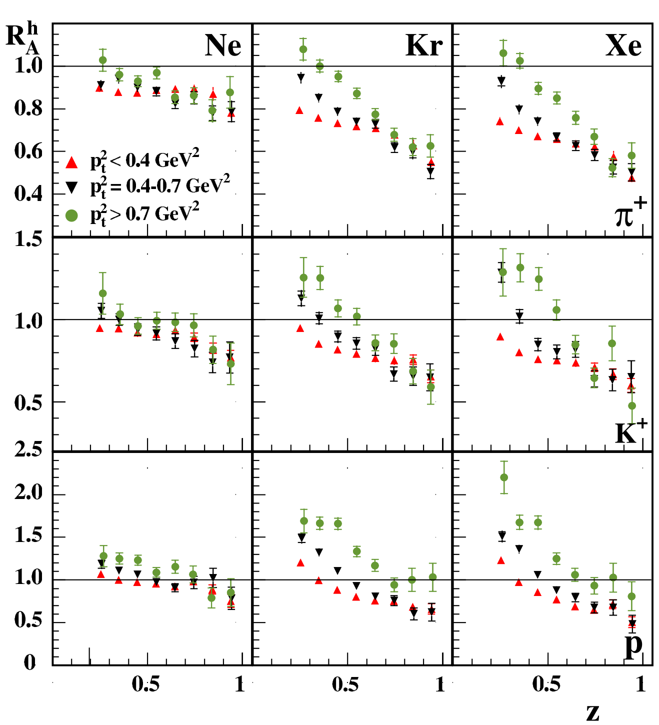
No model can describe all of these data

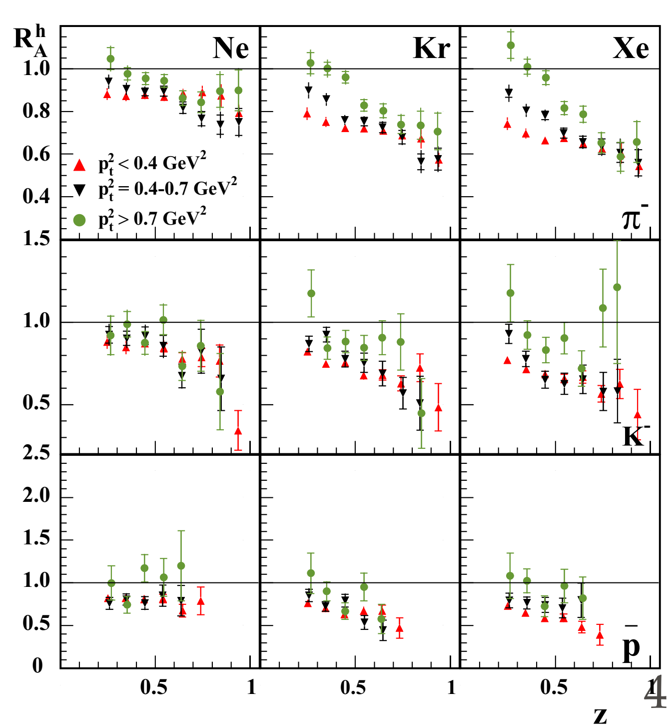


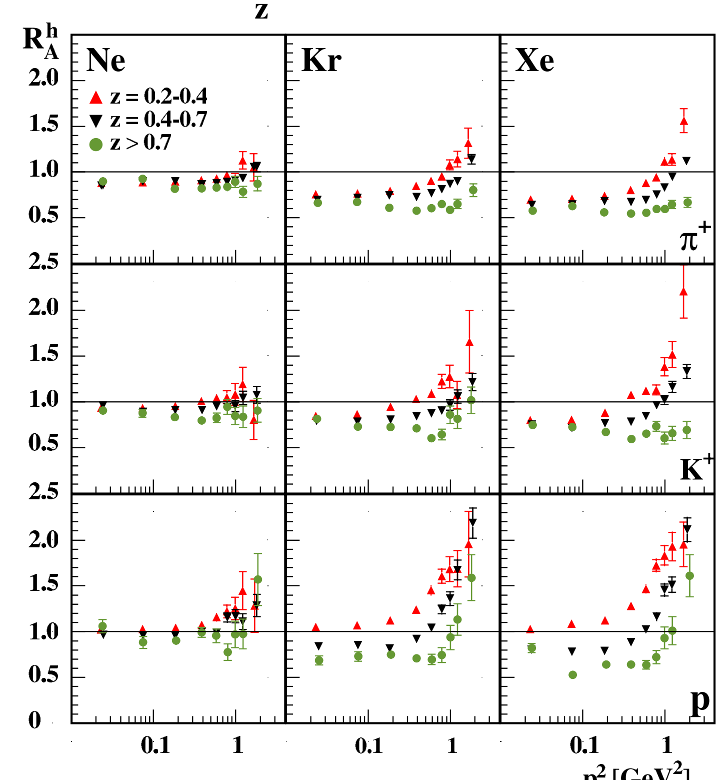


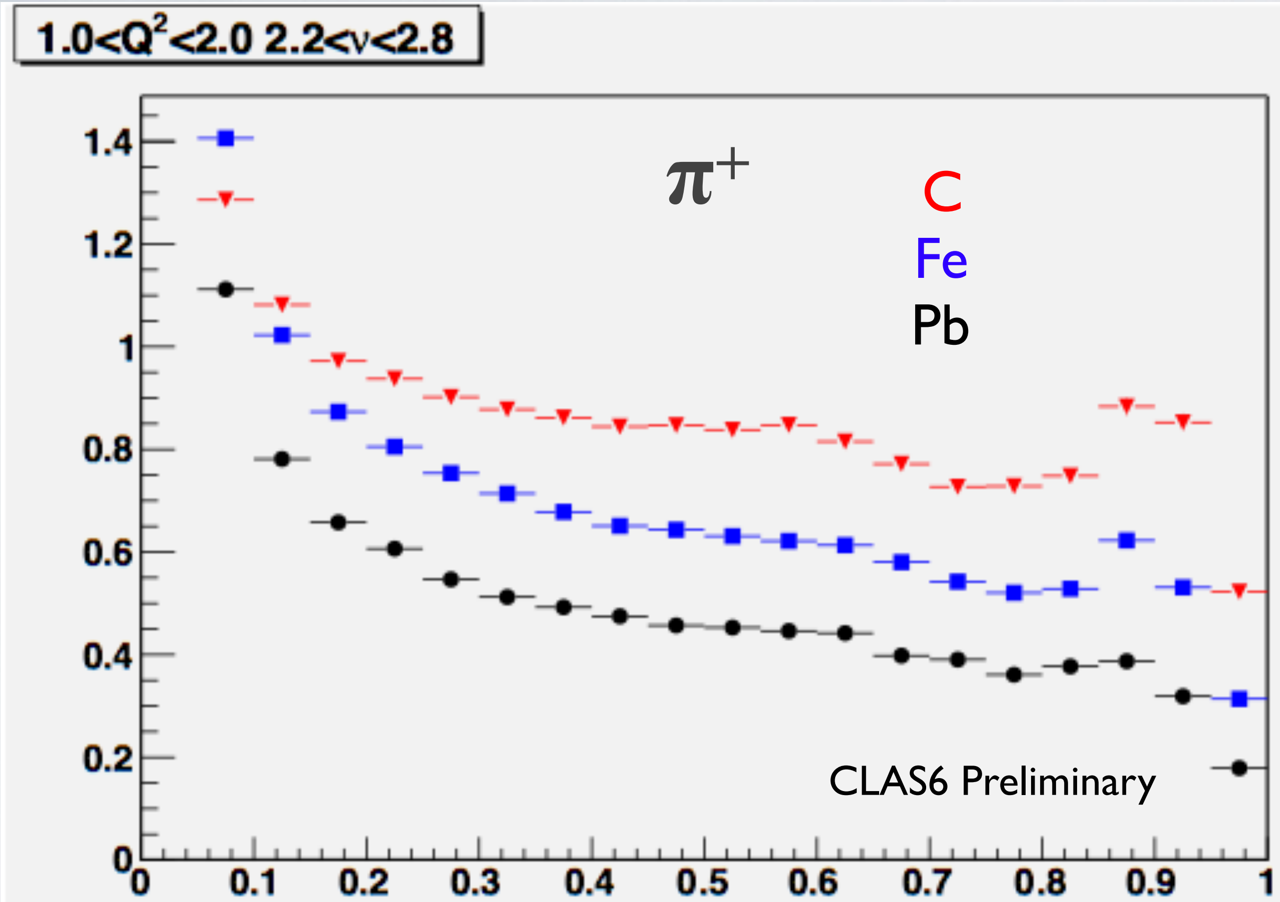


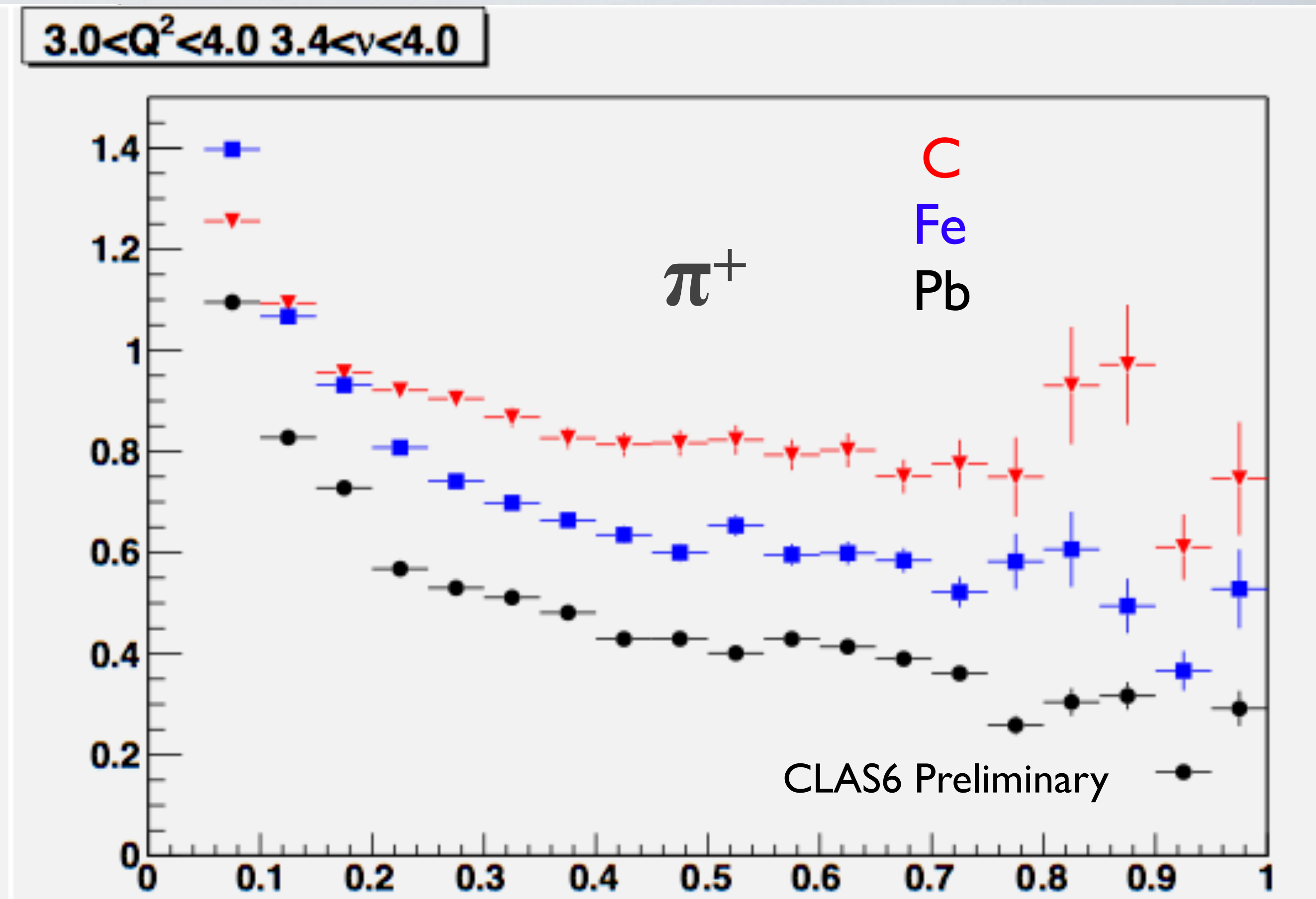




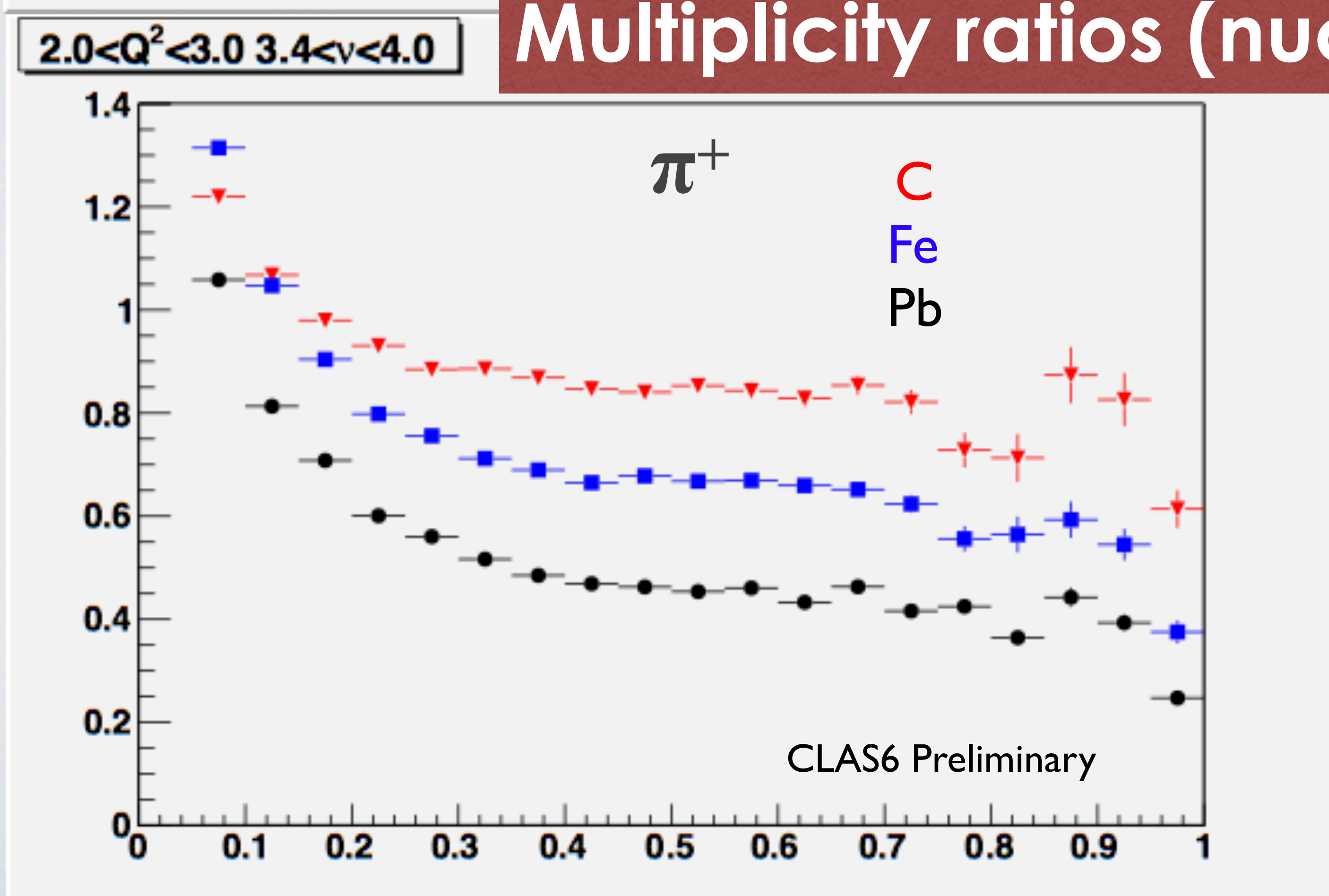








Multiplicity ratios (nucleus/deuterium)



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.

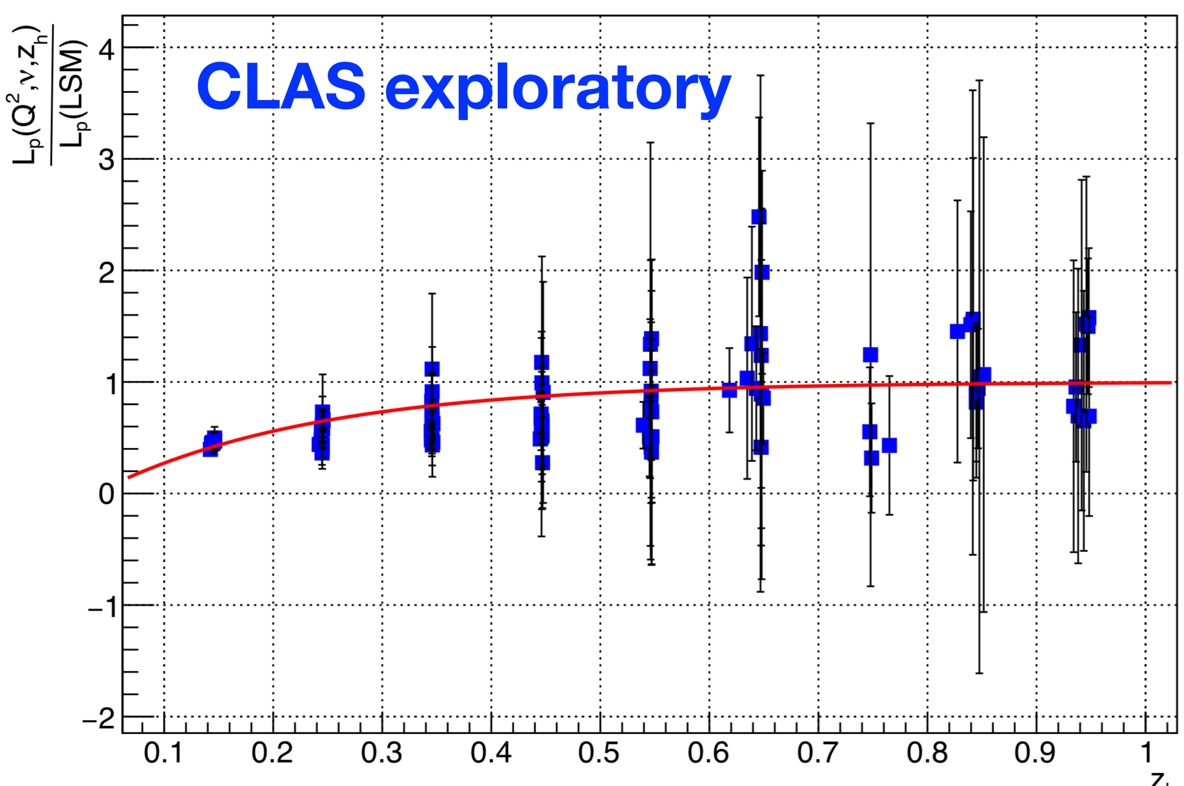
CLAS6: π^+ (K^0, π^0, π^-)

Color Propagation Studies - COLD Matter

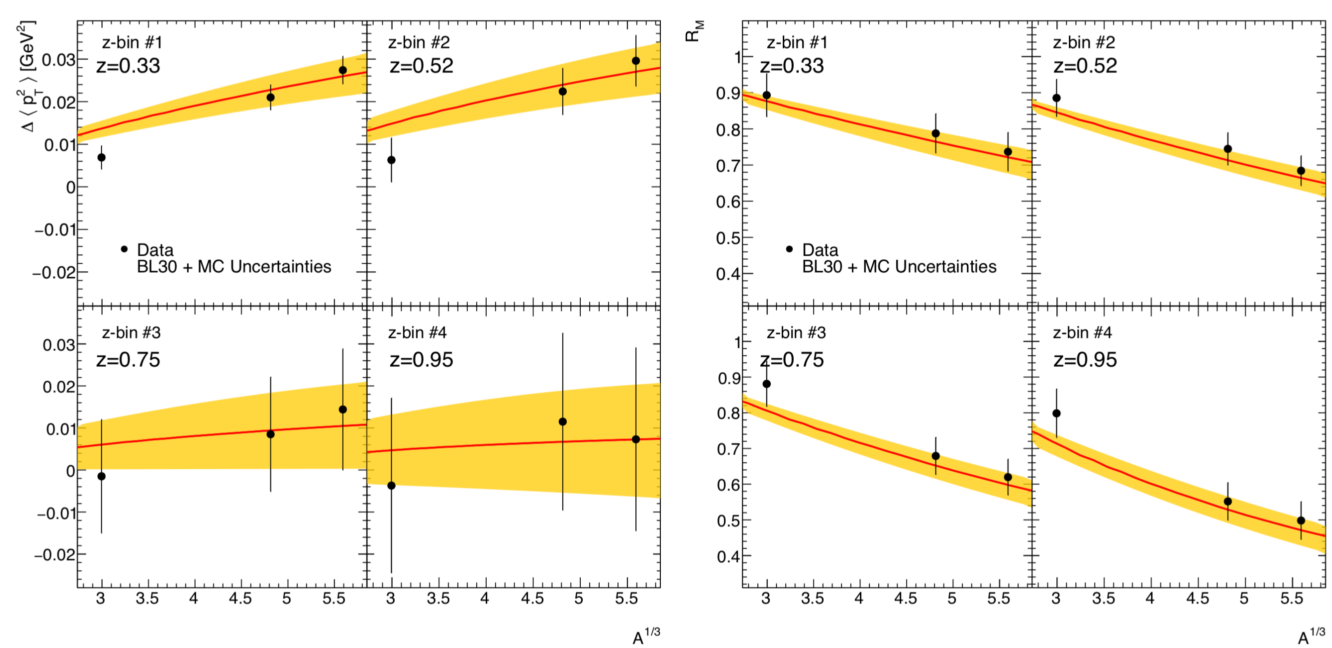
What we are learning from the HERMES data and new CLAS data:

- **Measurement of color lifetime**
- **Direct measurement of quark energy loss**
- **Color lifetime distribution - important impacts at high energies**

CLAS Exploratory Analysis ≈ Lund String Model



New analysis of HERMES data



Result for model variant BL30, baseline model at fixed pre-hadron cross-section 30 mb.

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
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Λ	79 mm	1.1	uds
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Actively underway with existing 5 GeV data

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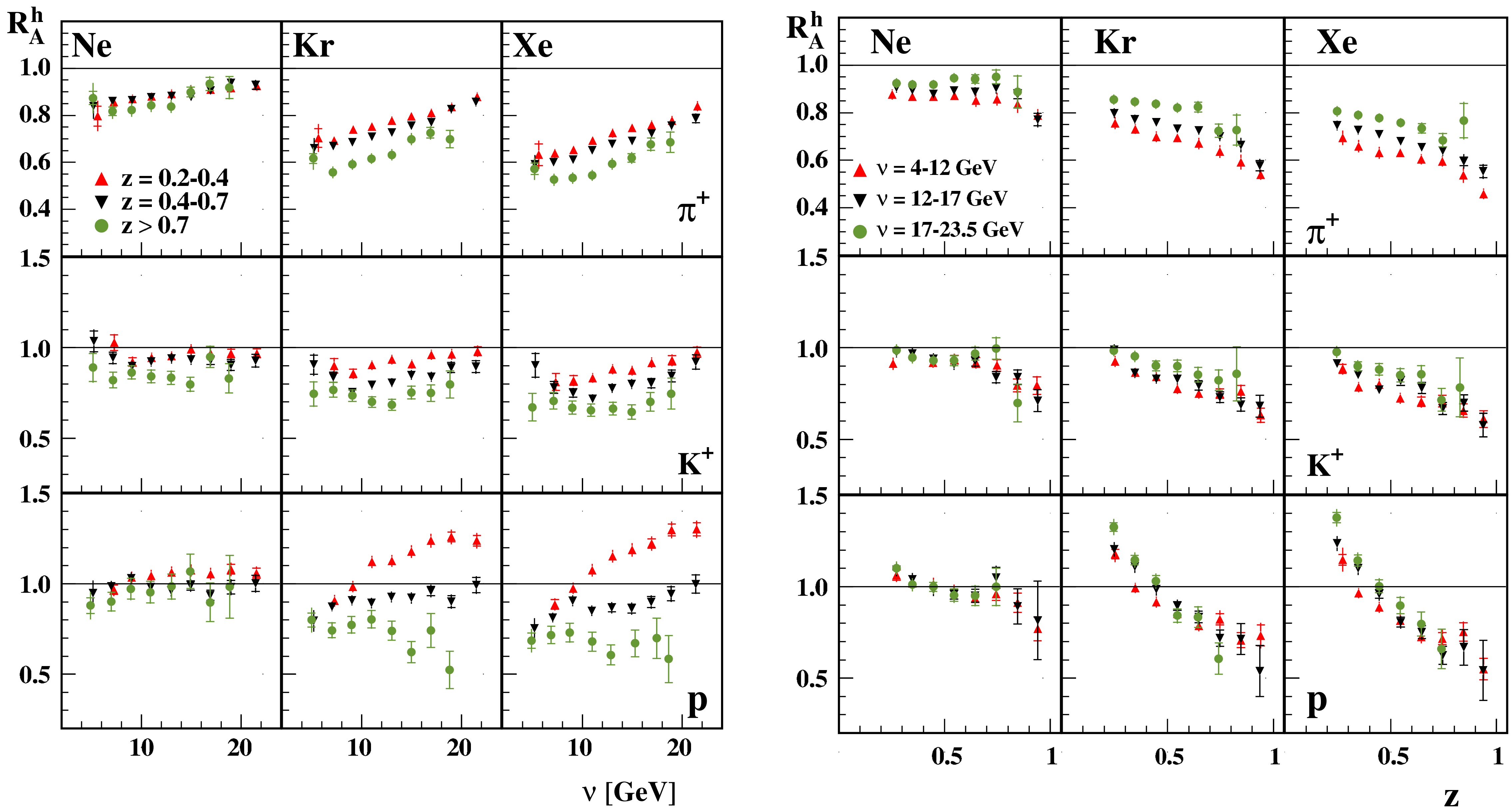
EIC: heavy mesons and baryons; wide kinematic range!

Color Propagation Studies - COLD Matter

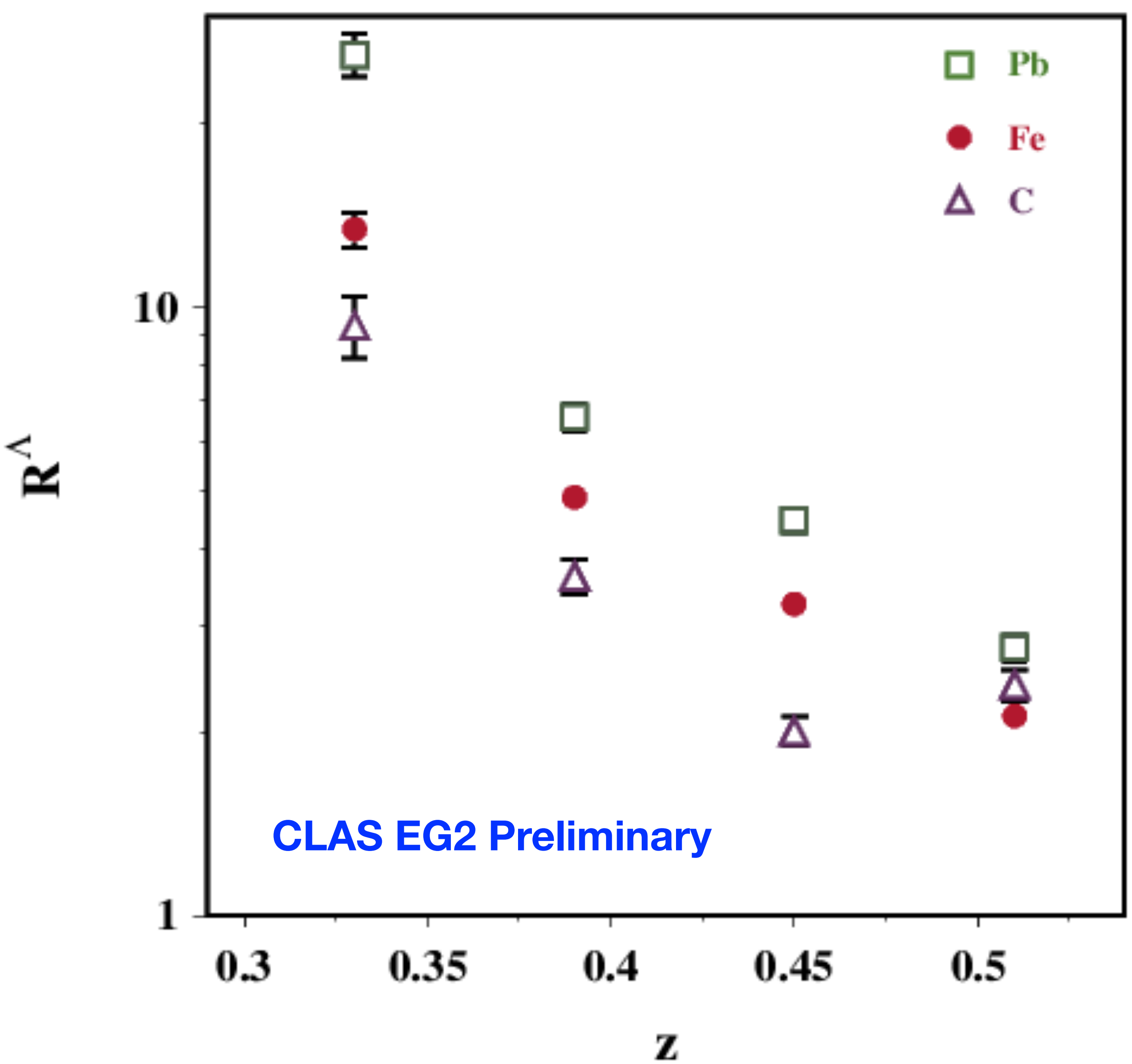
New and novel issues

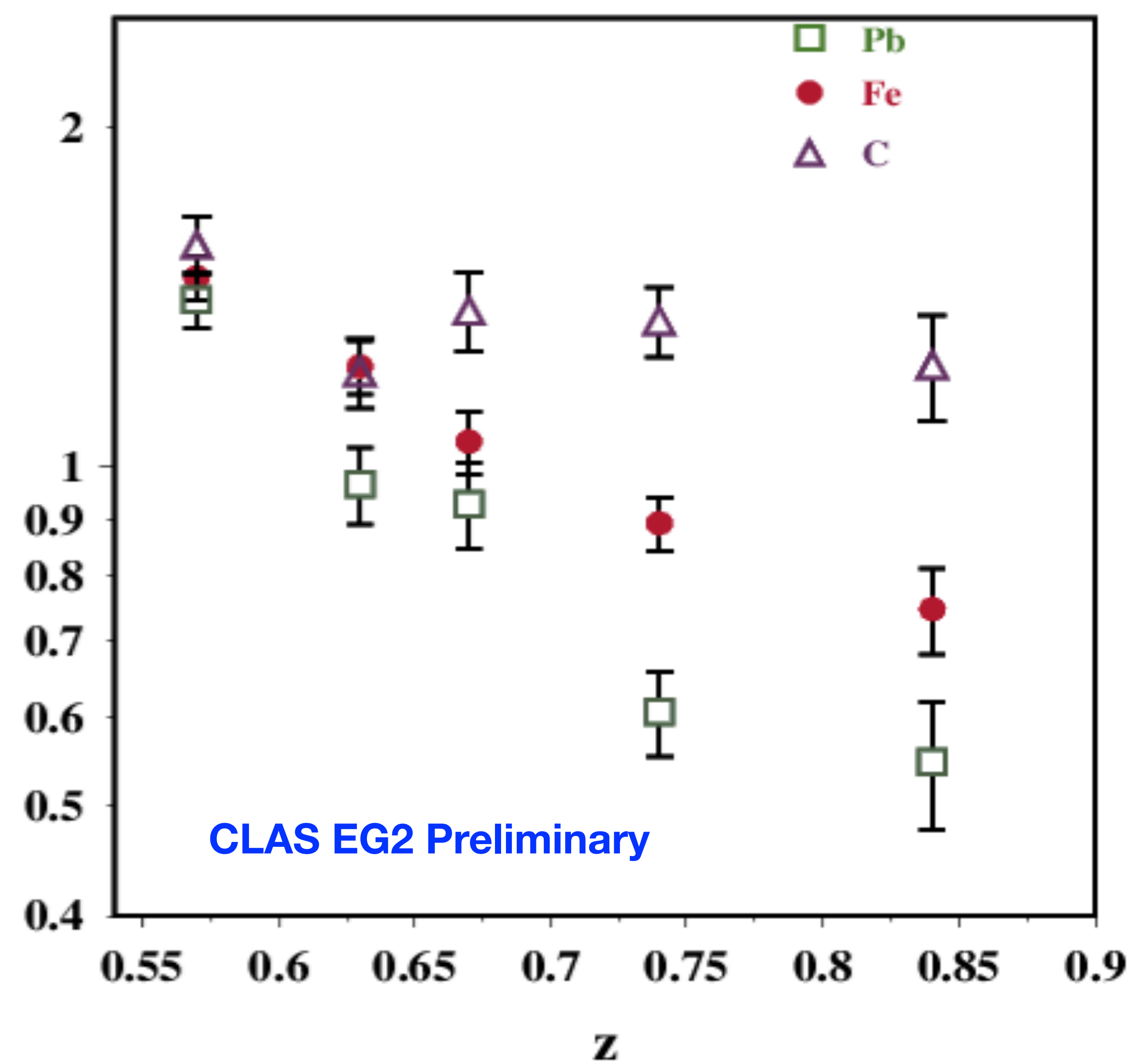
- **What causes the z-dependent (anti-) attenuation of protons?**
- **Seen by HERMES, (to be) confirmed by CLAS (CLAS12, EIC)**



SRC+SSC?? **Color recombination??** **Exotic mechanisms??**

New studies with the Lambda Baryon shown earlier by Lamiaa





Large enhancement of Lambda multiplicity ratio at low z.
Same pattern as HERMES protons! unique to baryons?
but not antiprotons….

New! Eta meson attenuation in nuclear siDIS

- **Eta meson: mass 548 MeV, $u\bar{u}+d\bar{d}-2s\bar{s}$, isospin 0. *O. Soto thesis.***
  - compare to: K^0 (CLAS), 498 MeV, $d\bar{s}+s\bar{d}$; $K^{\pm}$ (HERMES), 494 MeV $u\bar{s}$ or $s\bar{u}$, isospin 1/2
  - or compare to π^0, (CLAS and HERMES), 135 MeV, $u\bar{u}-d\bar{d}$, isospin 1

Is there a visible mass effect? a "string rank" effect? a flavor combination effect? forms faster, slower? interacts with the medium more or less?

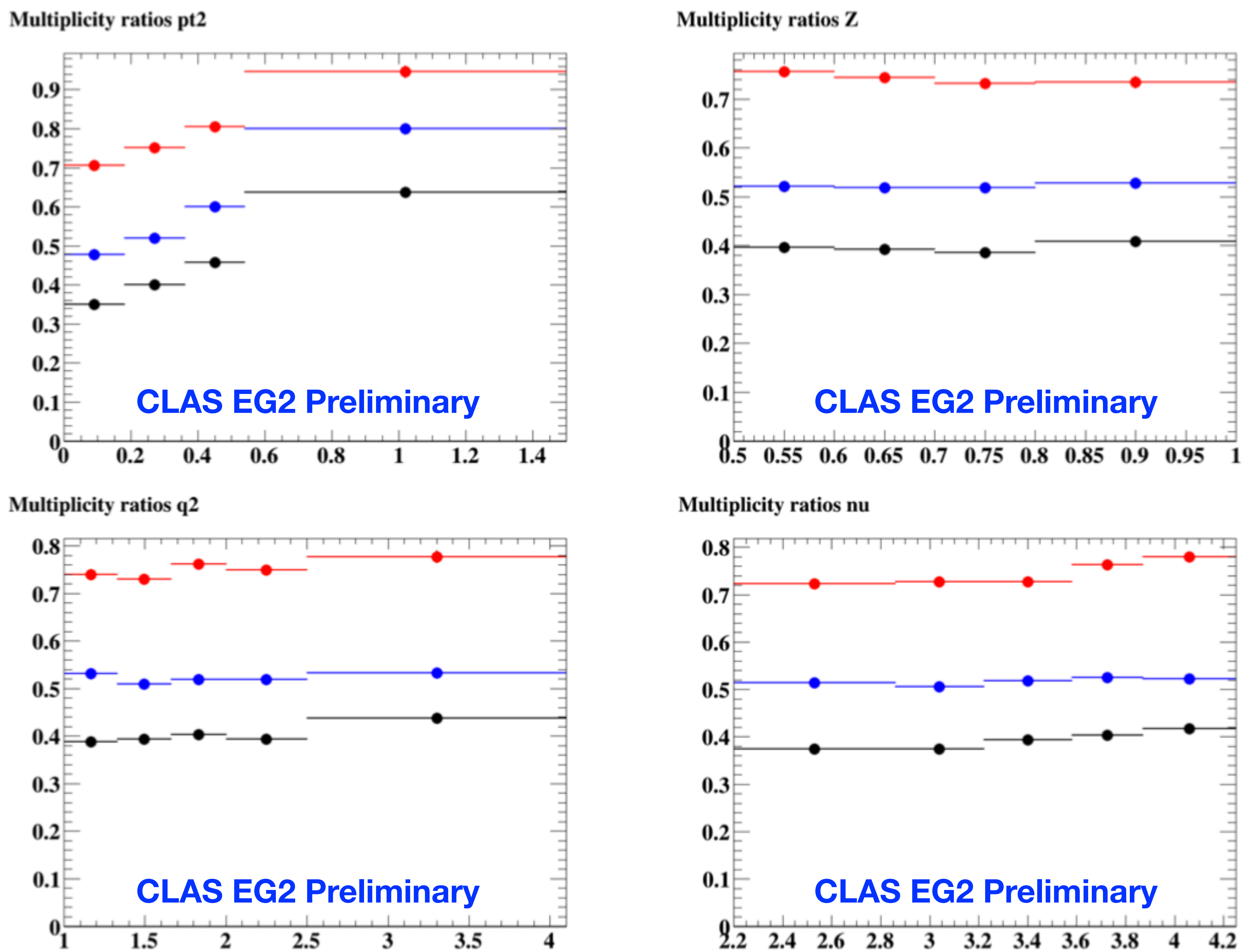
- New study in PhD thesis of Orlando Soto (Hayk Hakobyan, advisor) at UTFSM
- A *new hadron* for these kinds of studies, not observed by HERMES; and, the first such study in *two different decay channels*

Could the results depend on the decay channel?

Two photon channel multiplicity ratio

$$\eta \longrightarrow \gamma\gamma$$

Simplified acceptance and particle ID, to see the trends most clearly



Cronin-type behavior seen

Decrease with z is not really evident, unlike all other hadrons!

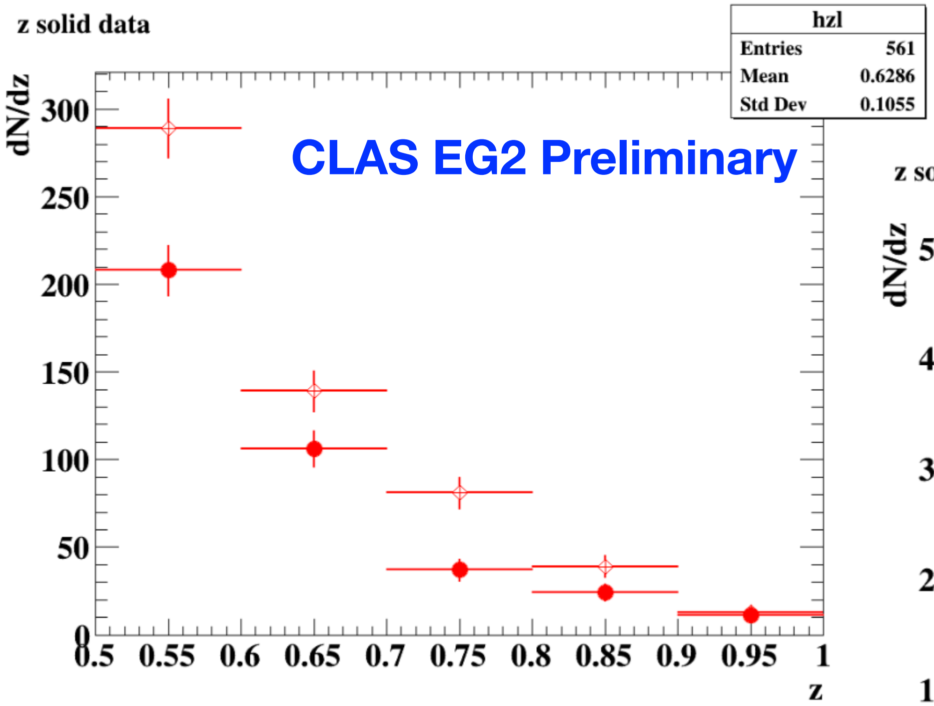
Increase with Q^2 and ν seems to be visible.

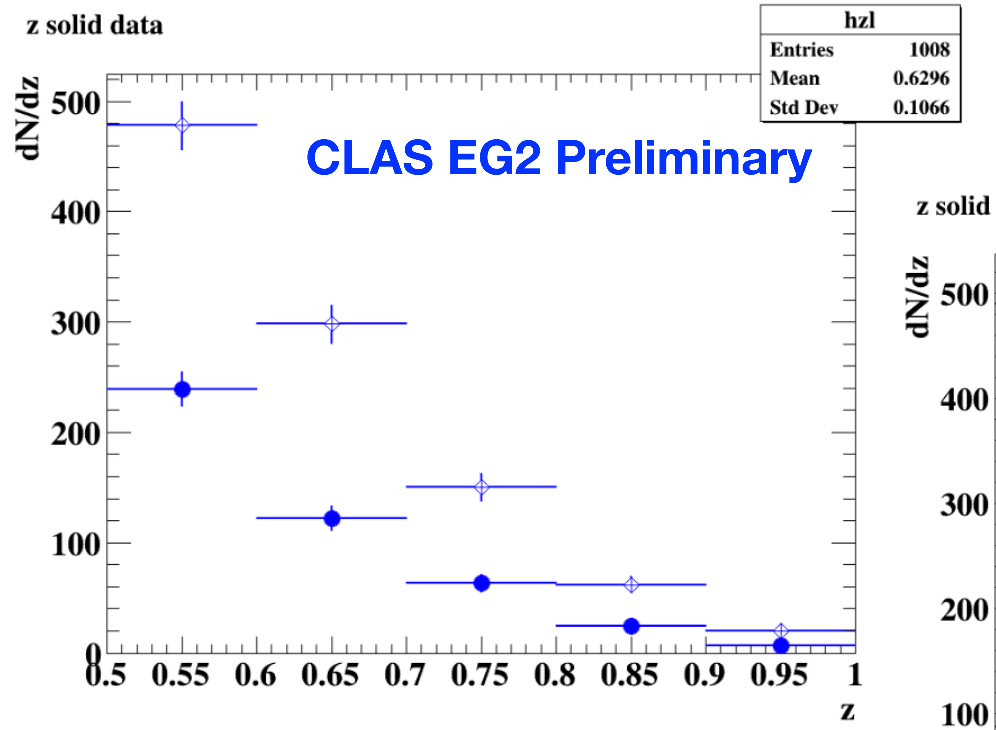
CLAS EG2 Preliminary

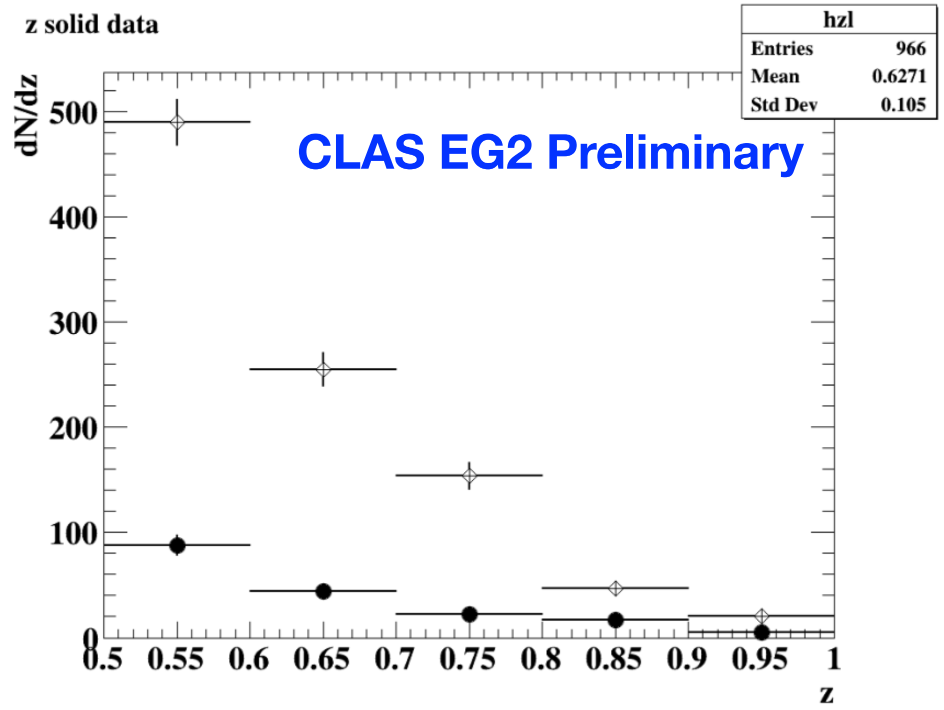
Three pion channel

$\eta \longrightarrow \pi^+\pi^-\pi^0$

Here, NOT corrected for acceptance nor target thickness, to show the statistical content of the data.





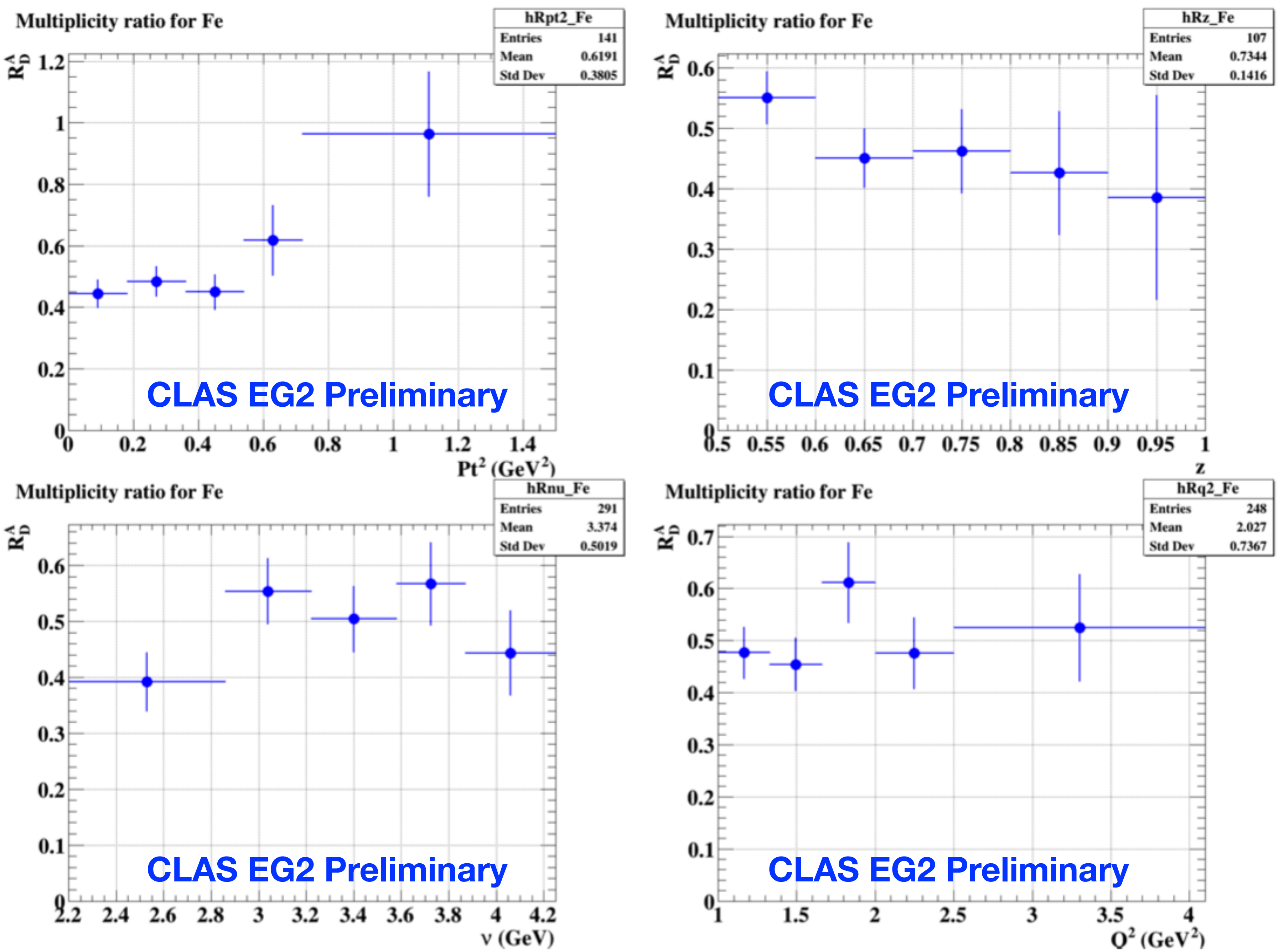


All targets (solid and deuterium) are approximately the same thickness except for Pb, which has half the thickness of the others.

The suppression is visible by eye.

CLAS EG2 Preliminary

Three pion channel
Iron target normalized to deuterium



For iron for four kinematic variables: p_T^2 , Q2, z, ν

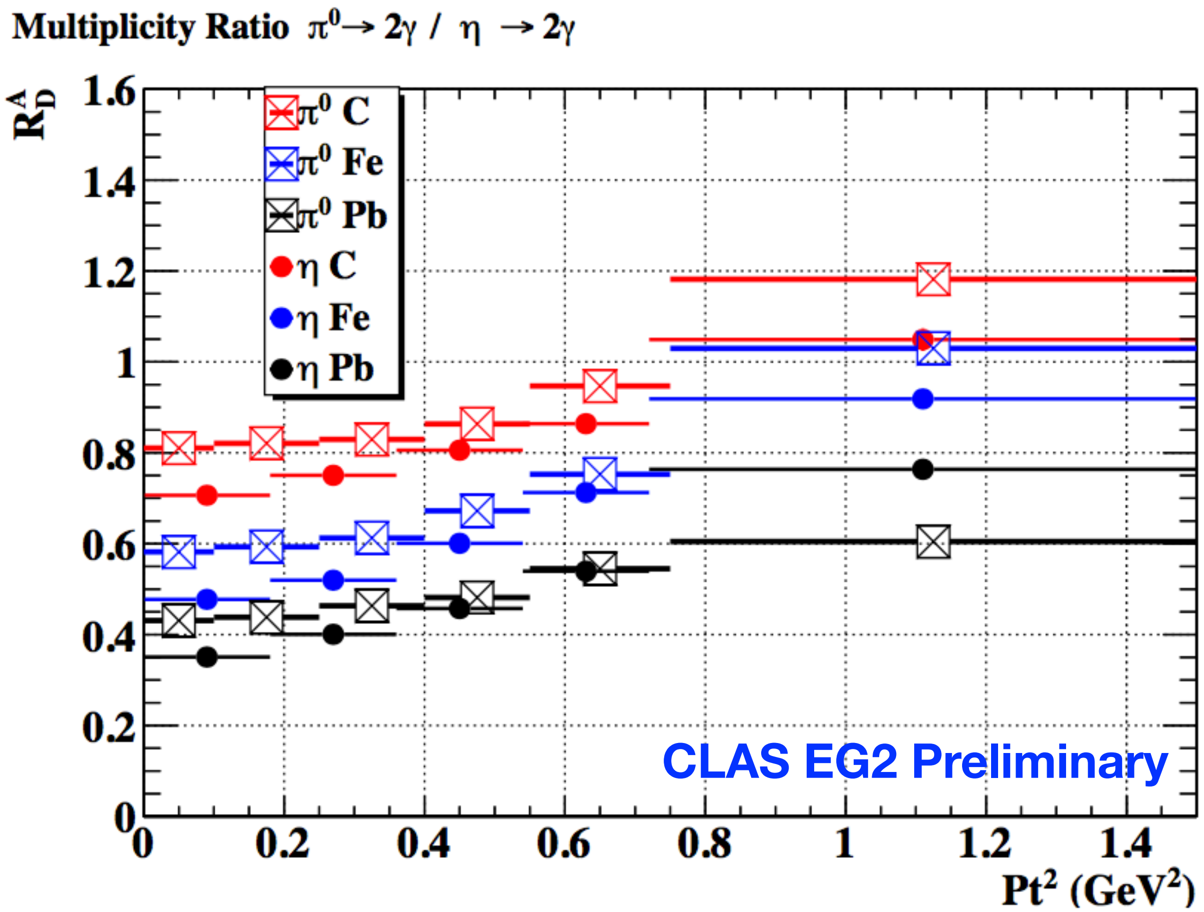
Cronin-type behavior seen

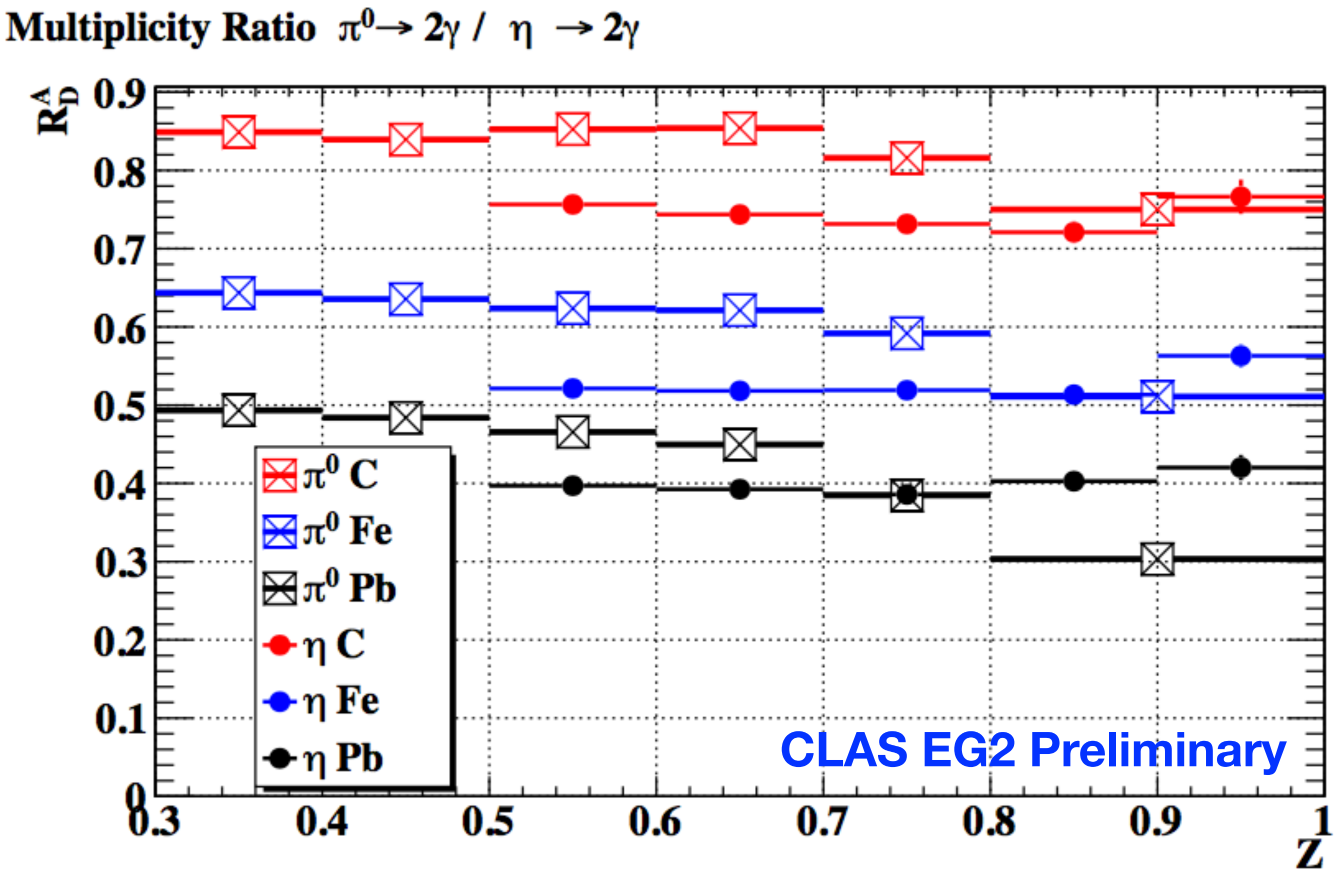
Decrease with z? not clear.

Increase with Q^2 and ν? not as clear in this channel

CLAS EG2 Preliminary

Comparison of eta ($\gamma\gamma$ channel) and neutral pion in the same analysis framework



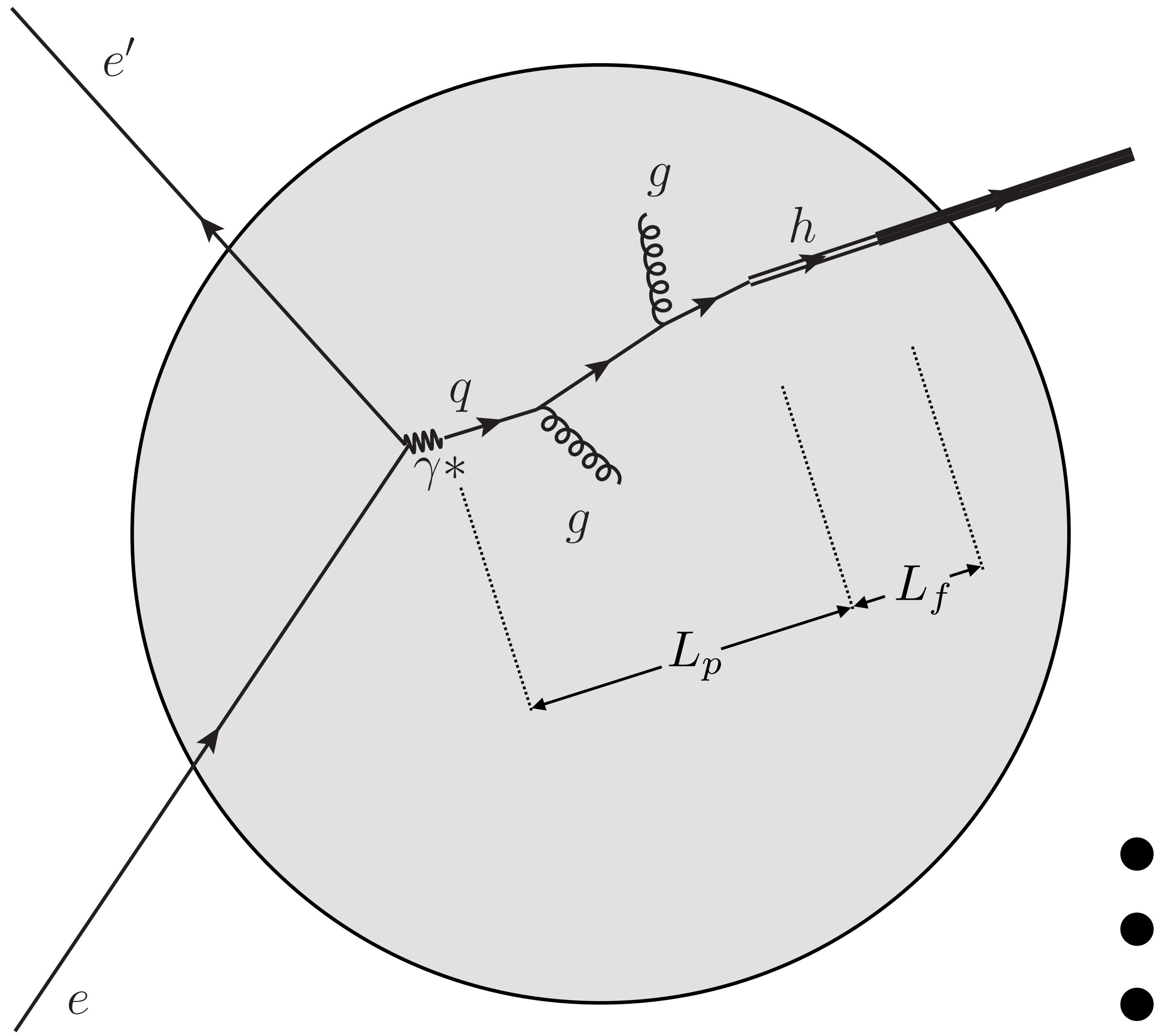


Broadly similar for the two mesons, however:

Eta meson seems to have (1) flatter z dependence and (2) more suppression on average.

CLAS EG2 Preliminary

Space-time perspective of DIS on nuclei



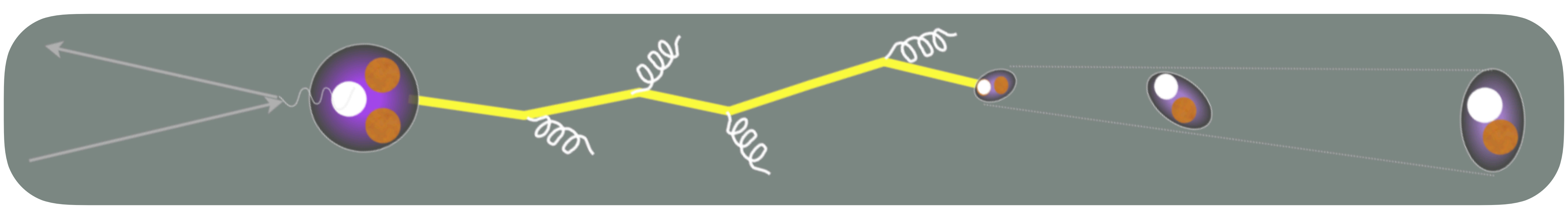
Production length (L_p): distance required for a colored system to evolve into a color singlet system.

"color lifetime"

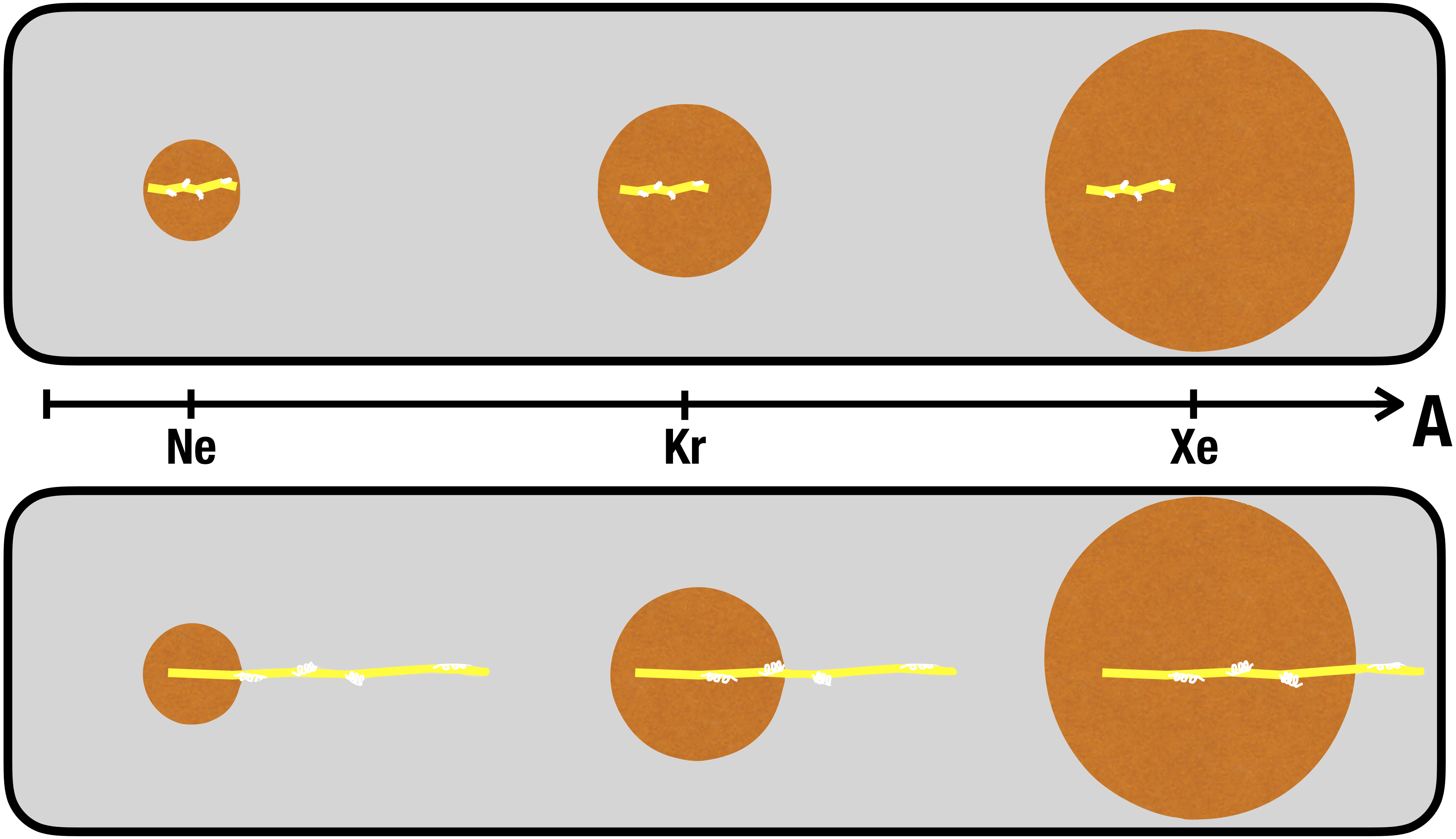
Formation length (L_f): distance required for a pre-hadron to get fully formed.

FUNDAMENTAL QCD PROCESSES:

- Partonic elastic scattering in medium
- Gluon bremsstrahlung in vacuum and in medium
- Color neutralization
- Hadron formation



Methodology



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

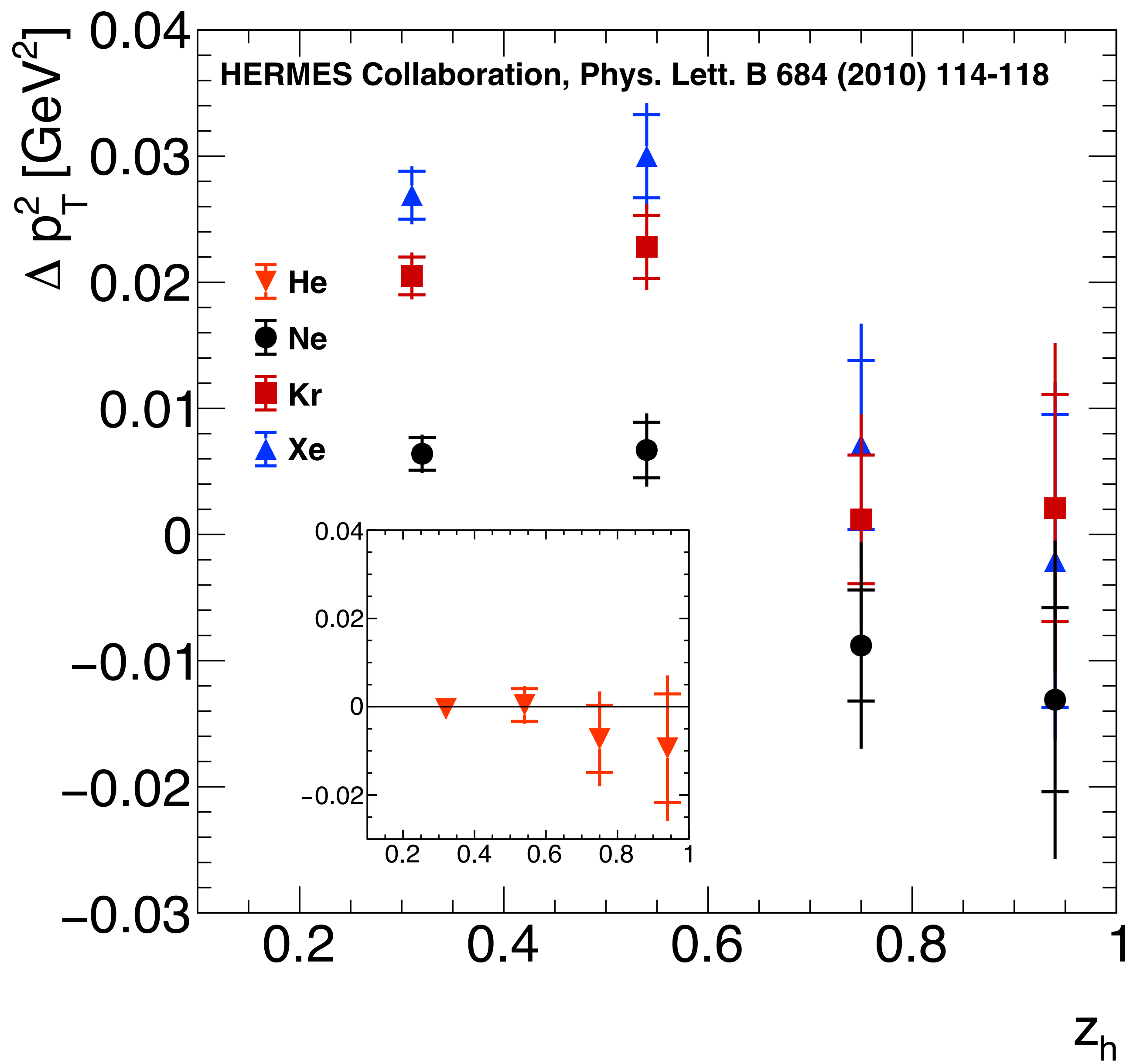
HERMES data – Observables

Transverse momentum broadening

$$\Delta\langle p_{\mathrm{T}}^2\rangle = \langle p_{\mathrm{T}}^2\rangle_A - \langle p_{\mathrm{T}}^2\rangle_p$$

Multiplicity ratio or hadron attenuation

$$R_{\mathrm{M}} = \frac{N_h(Q^2,\nu,z,p_{\mathrm{T}})/N_e(Q^2,\nu)|_A}{N_h(Q^2,\nu,z,p_{\mathrm{T}})/N_e(Q^2,\nu)|_p}$$



Simultaneous description of both observables

http://www-hermes.desy.de/notes/pub/publications.html

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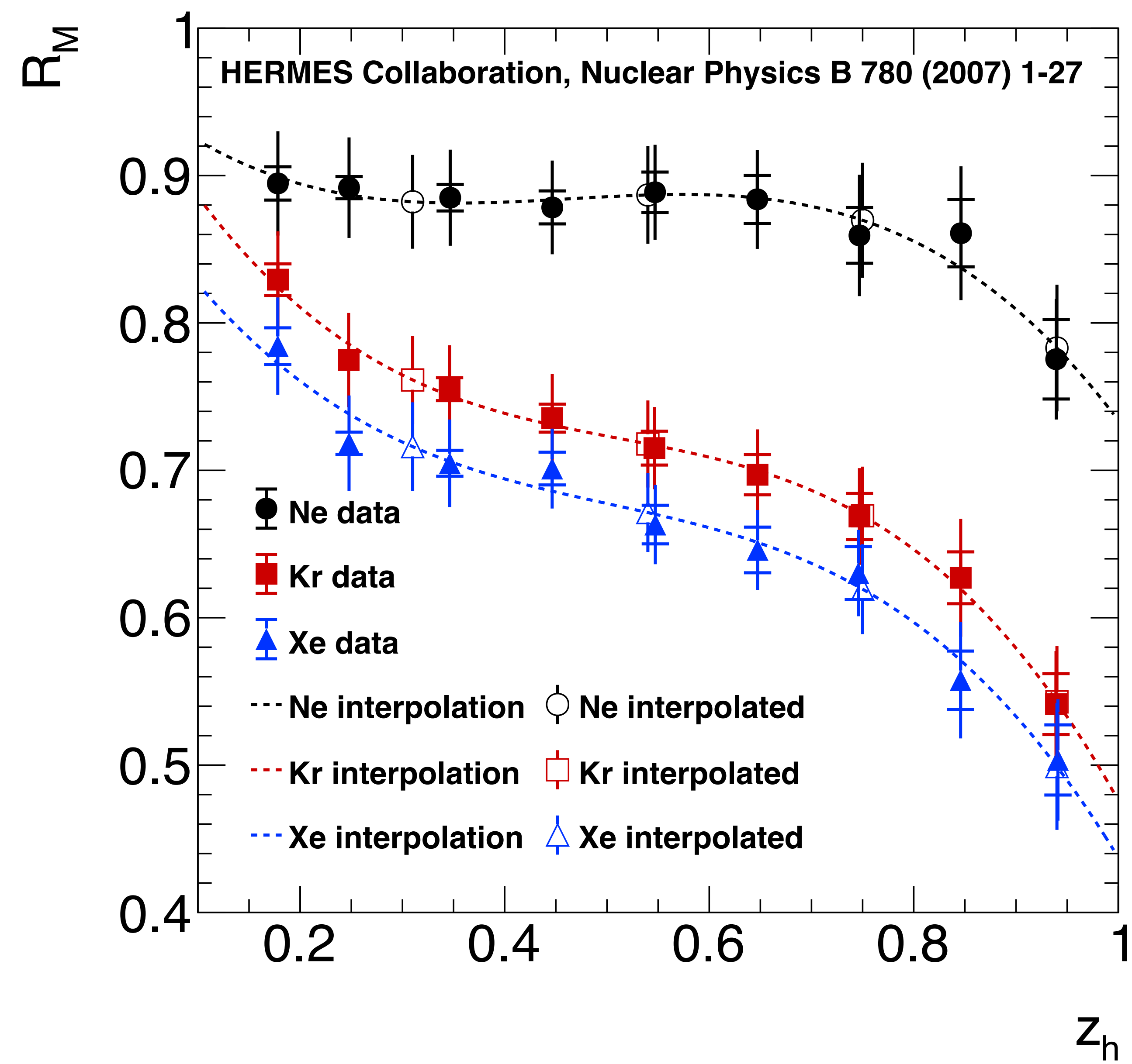

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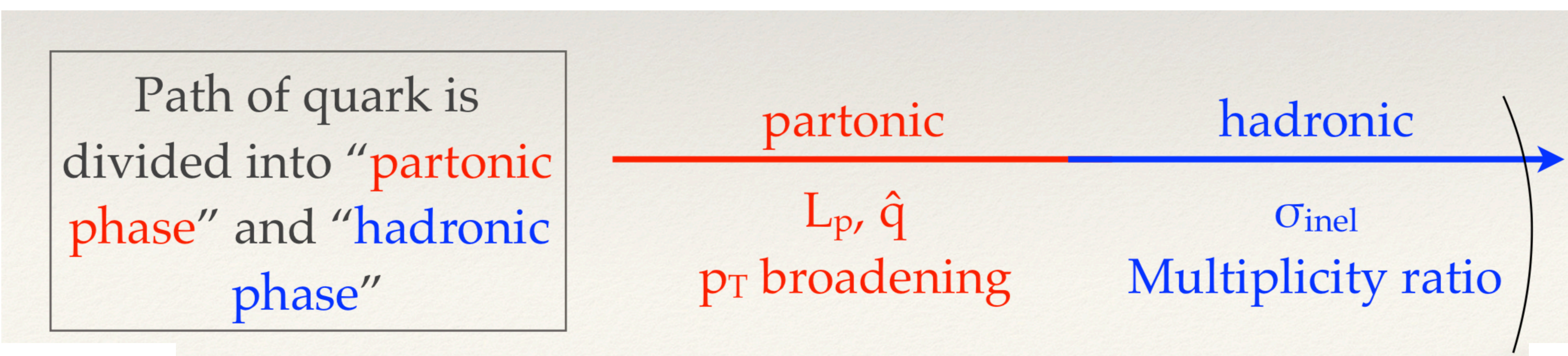
Geometric model

- Propagating quark causes p_T broadening of final hadron
- Propagating pre-hadron “disappears” when it undergoes an inelastic interaction with cross section σ.

$$\Delta\langle p_{\mathrm{T}}^2\rangle = \left\langle q_0 \int_{z_0}^{z_0+L_p} \rho(x_0, y_0, z)\mathrm{d}z \right\rangle_{\mathrm{MC}}$$

$$R_{\mathrm{M}} = \left\langle \exp\left(-\sigma_{\mathrm{hn}} \int_{z_0+L_p}^{r_A} \rho(x_0, y_0, z)\mathrm{d}z\right)\right\rangle_{\mathrm{MC}}$$

- Implemented as Monte Carlo calculation.
- Interaction point (x_0, y_0, z_0) thrown uniformly in sphere, weighted by $\rho(x_0, y_0, z_0)$.



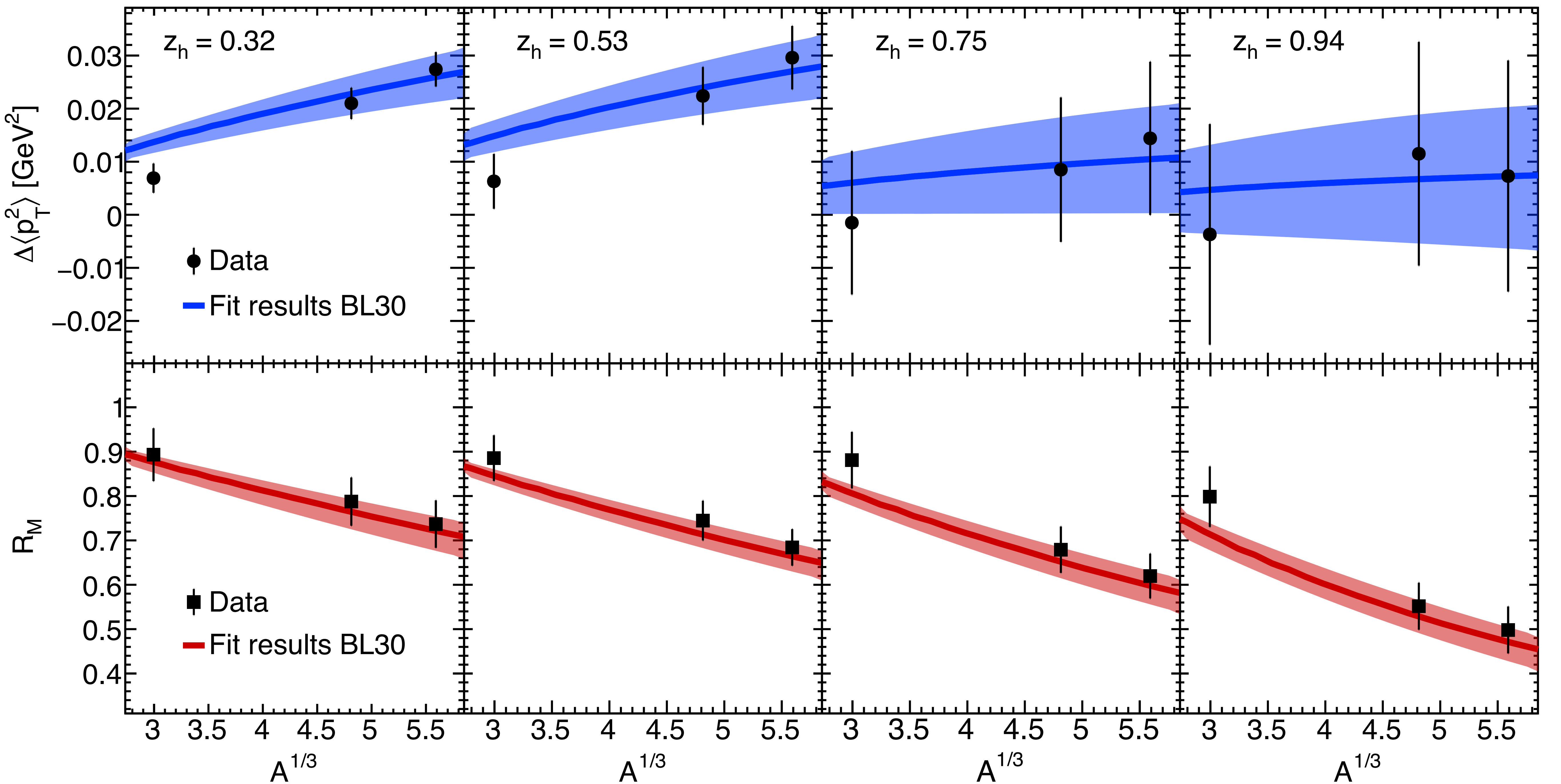
Geometric model

- Baseline model implemented with 3 parameters:
  - q_0: sets the scale of p_T broadening
  - Production length L_p: distance over which p_T broadening and energy loss occur. Assumed exponential form.
  - Cross section for pre-hadron to interact with nucleus.
- No dynamical information is assumed; it emerges from simultaneous fit of both observables:

$$\chi^2 = \left(\frac{\text{data} - \text{model}}{\text{uncertainties}}\right)^2_{p_T\text{-broadening}} + \left(\frac{\text{data} - \text{model}}{\text{uncertainties}}\right)^2_{\text{multiplicity}}$$

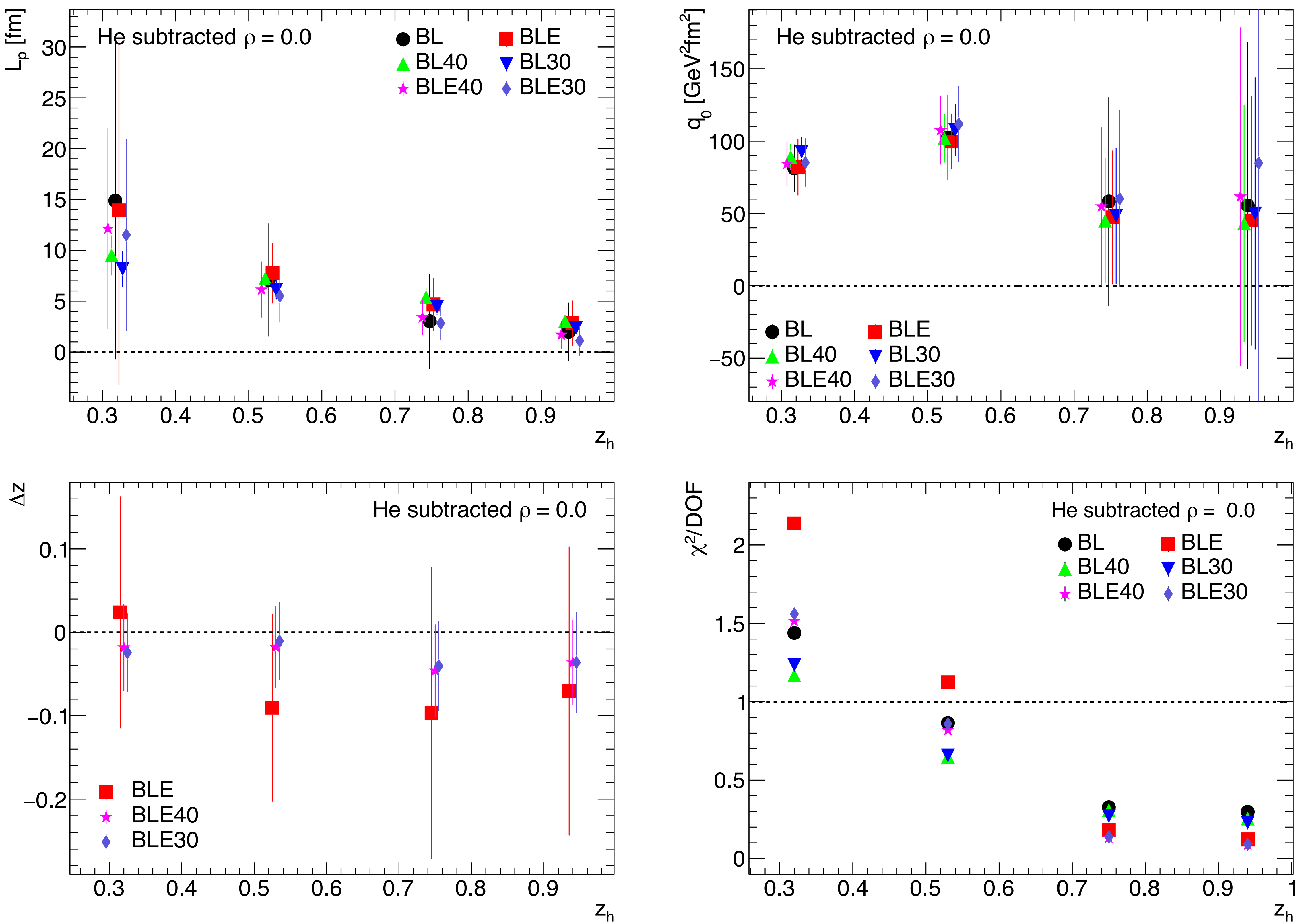
Variant	**Number of free parameters**	**Description**
BLE	4	Free parameters are: q_0, L_p, σ, and energy loss
BL30	2	Fixed cross-section @ 30 mb, no energy loss
BLE30	3	Fixed cross-section @ 30 mb

Results: model vs nucleus size ~ $A^{1/3}$



Result for model variant BL30, baseline model at fixed pre-hadron cross-section 30 mb.

Results: model parameters vs z_h

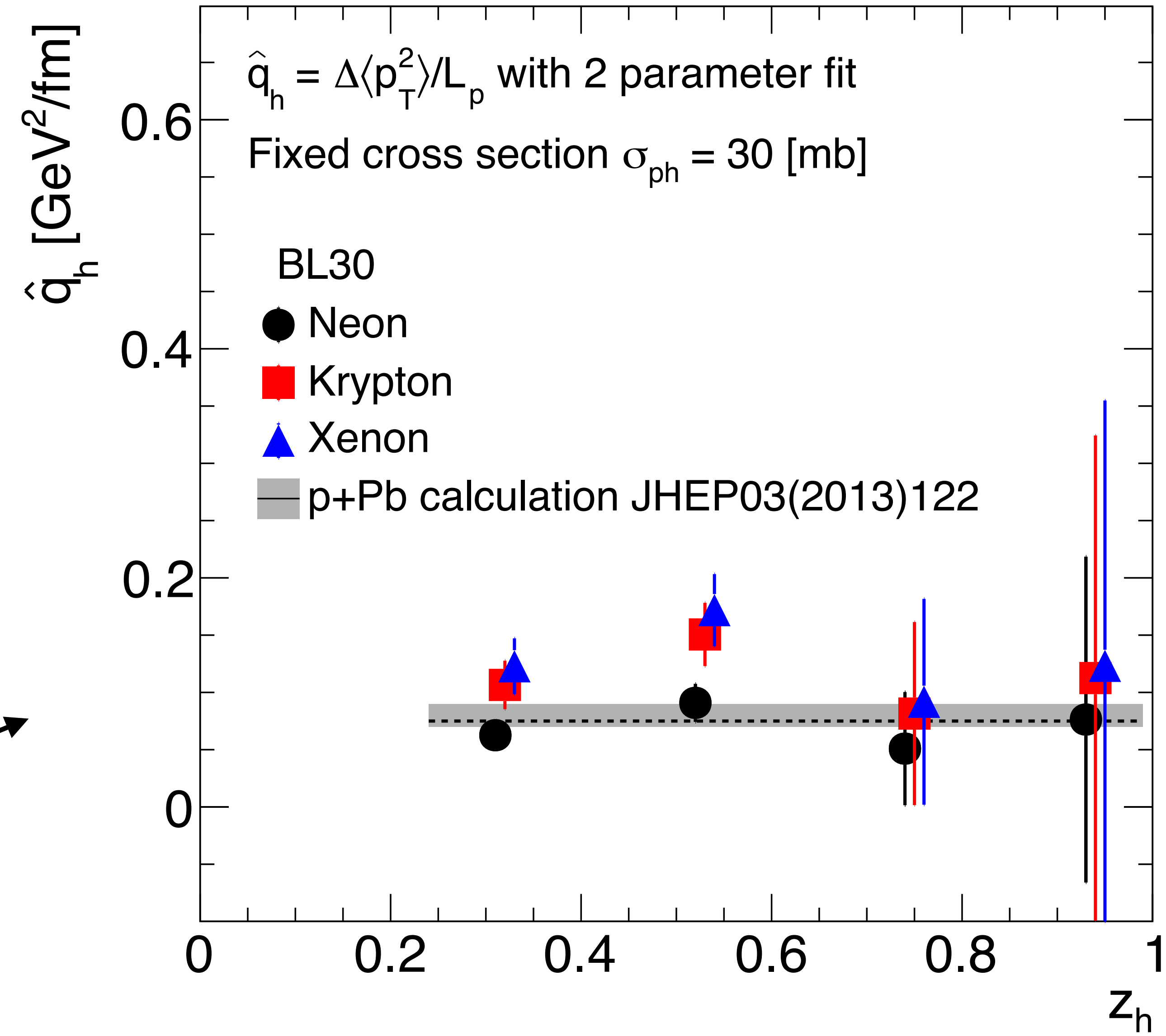


Transport coefficient

In a simple picture:

$$\hat{q} = \frac{\Delta\langle p_{\mathrm{T}}^2\rangle}{L_{\mathrm{p}}}$$

$$\hat{q} = q_0 \left\langle \frac{1}{l_{\mathrm{p}}} \int_{z_0}^{z_0+l_{\mathrm{p}}} \rho(x_0, y_0, z)\mathrm{d}z \right\rangle_{x_0,y_0,z_0,L_{\mathrm{p}}}$$



Compatible with calculations for p+A physics at the LHC:

$$\hat{q} = 0.075^{+0.015}_{-0.005}\ \mathrm{GeV}^2/\mathrm{fm}$$

https://arxiv.org/pdf/1212.0434.pdf
https://arxiv.org/pdf/1707.09973.pdf

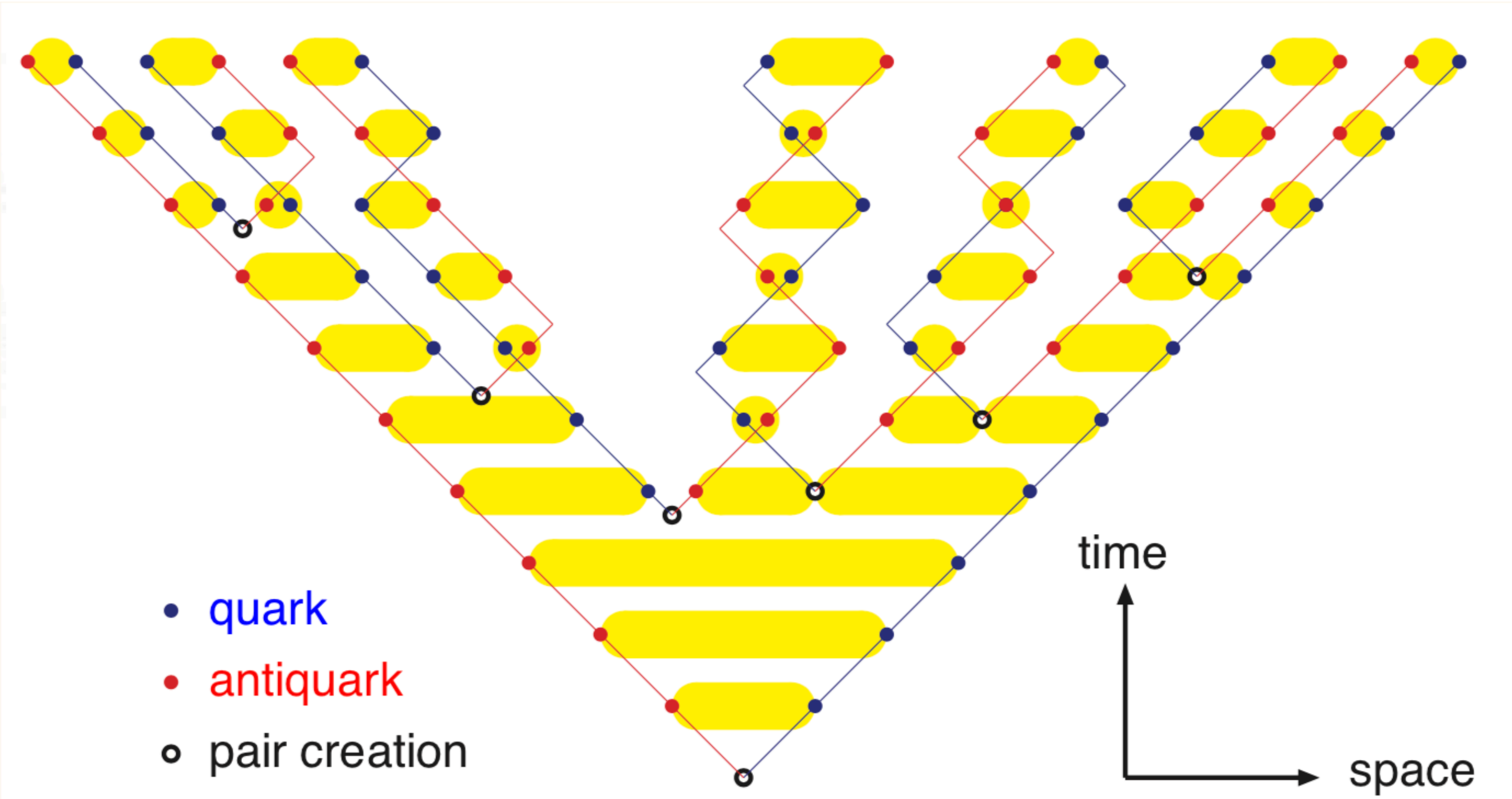
Average over z_h:

$$\hat{q}(\mathrm{Ne}) = 0.072 \pm 0.006\ \mathrm{GeV}^2/\mathrm{fm}$$

$$\hat{q}(\mathrm{Kr}) = 0.120 \pm 0.010\ \mathrm{GeV}^2/\mathrm{fm}$$

$$\hat{q}(\mathrm{Xe}) = 0.137 \pm 0.011\ \mathrm{GeV}^2/\mathrm{fm}$$

Lund String Model



Remarkably successful model, foundational tool in HEP

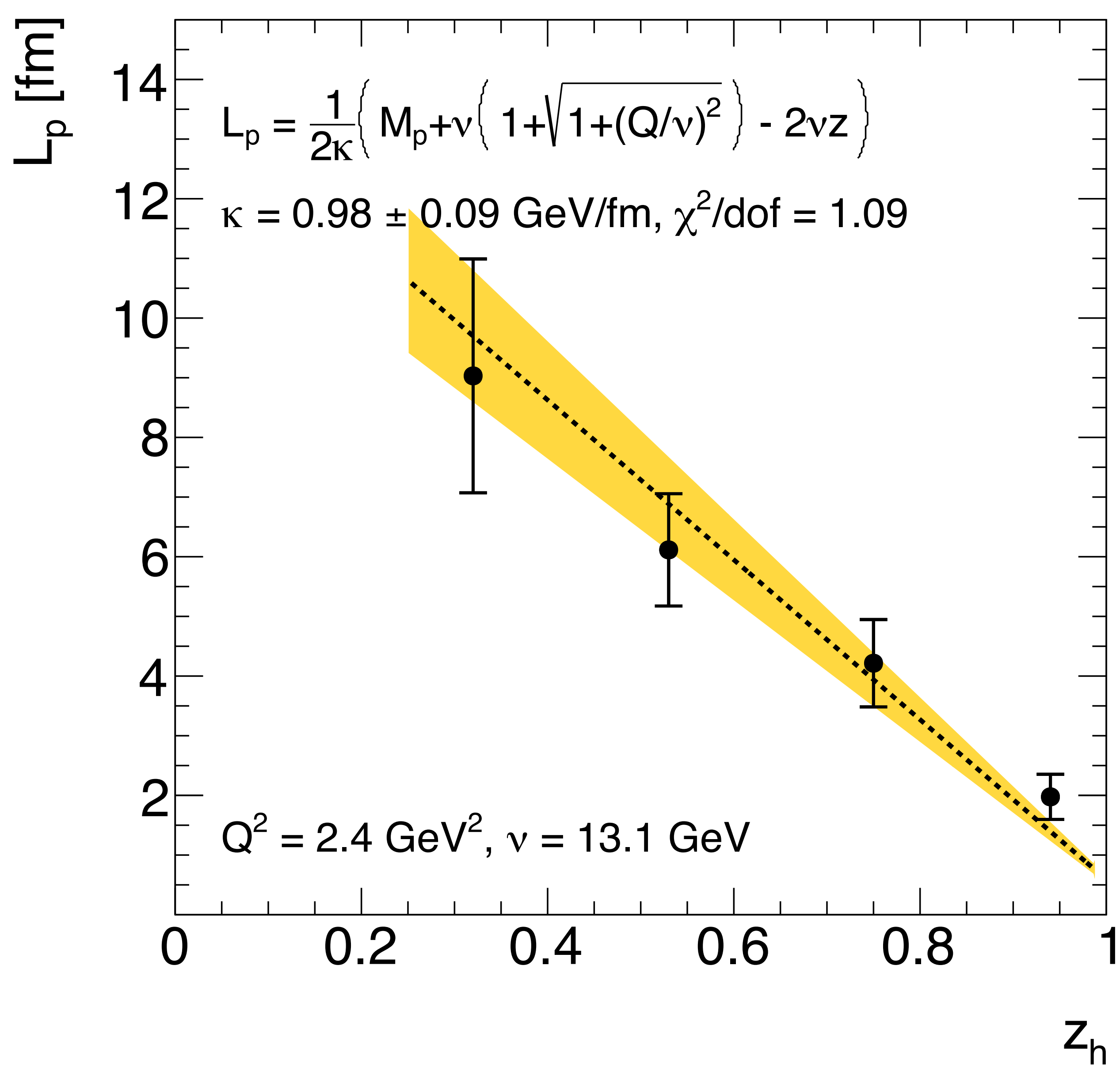
- Alternative physical picture to pQCD: emission of many gluons in vacuum, string as an average; quantitative
- Successful, but few connections to fundamental QCD
- We can *compare* some of our results to the Lund String Model, and other results to pQCD

Production length L_p

From the Lund String Model, and for the struck quark (in a simple approximation):

$$2\kappa L_p = M_p + \nu(1 + \sqrt{1 + Q^2/\nu^2}) - 2\nu z$$

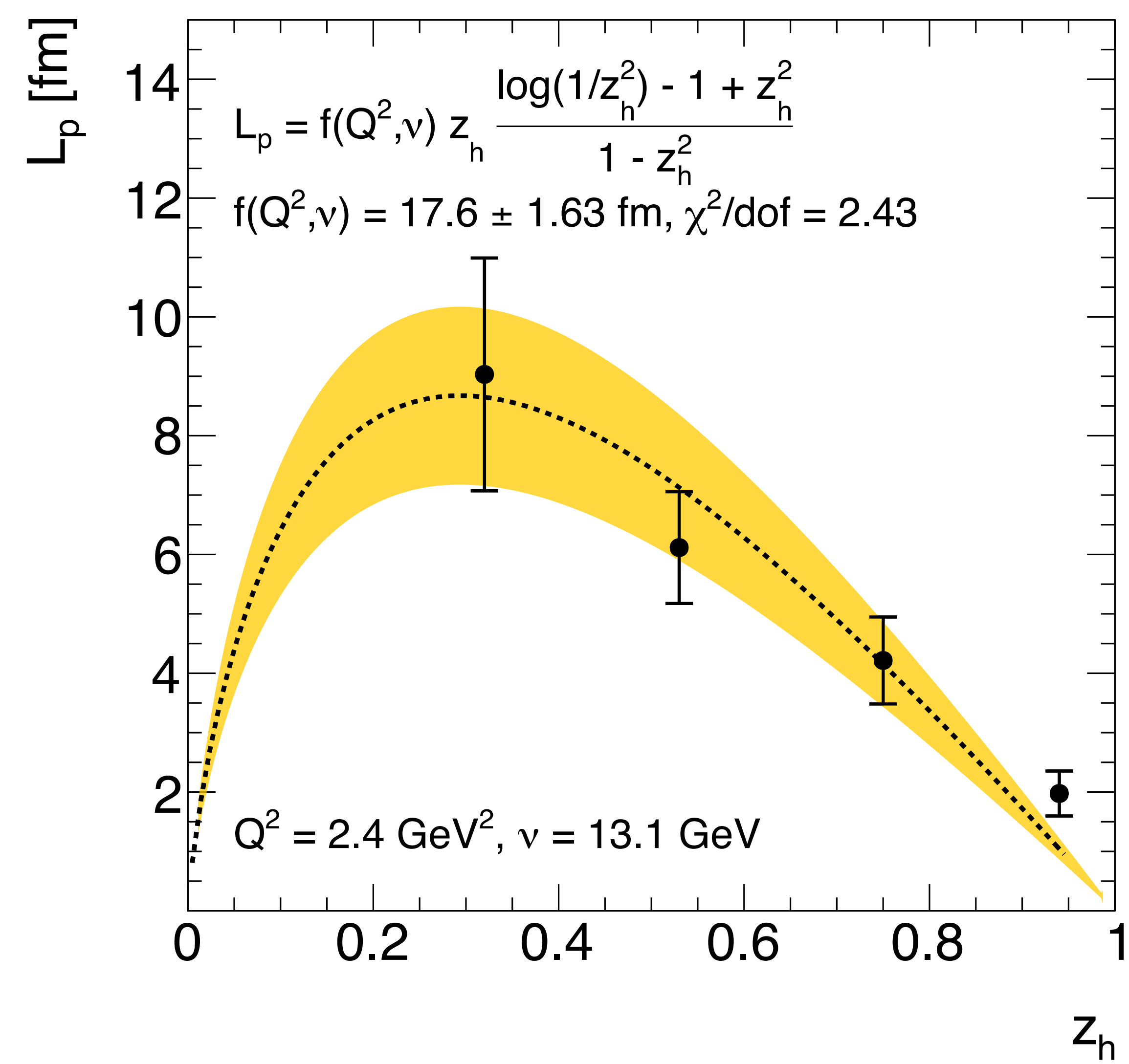
Predicted value κ ~ 1 GeV/fm



In a more general case:

$$L_{\rm p}(z_{\rm h}) \propto z_{\rm h} \frac{\log\left(1/z_{\rm h}^2\right) - 1 + z_{\rm h}^2}{1 - z_{\rm h}^2}$$

Bialas et al., Nucl. Phys. B 291 (1987) 793-812



Strong validation of the geometric BL model

Estimations for future experiments

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 $p_{\gamma^*} = |\vec{p}_{\gamma^*}| = \sqrt{(\nu^2 - Q^2)}$.

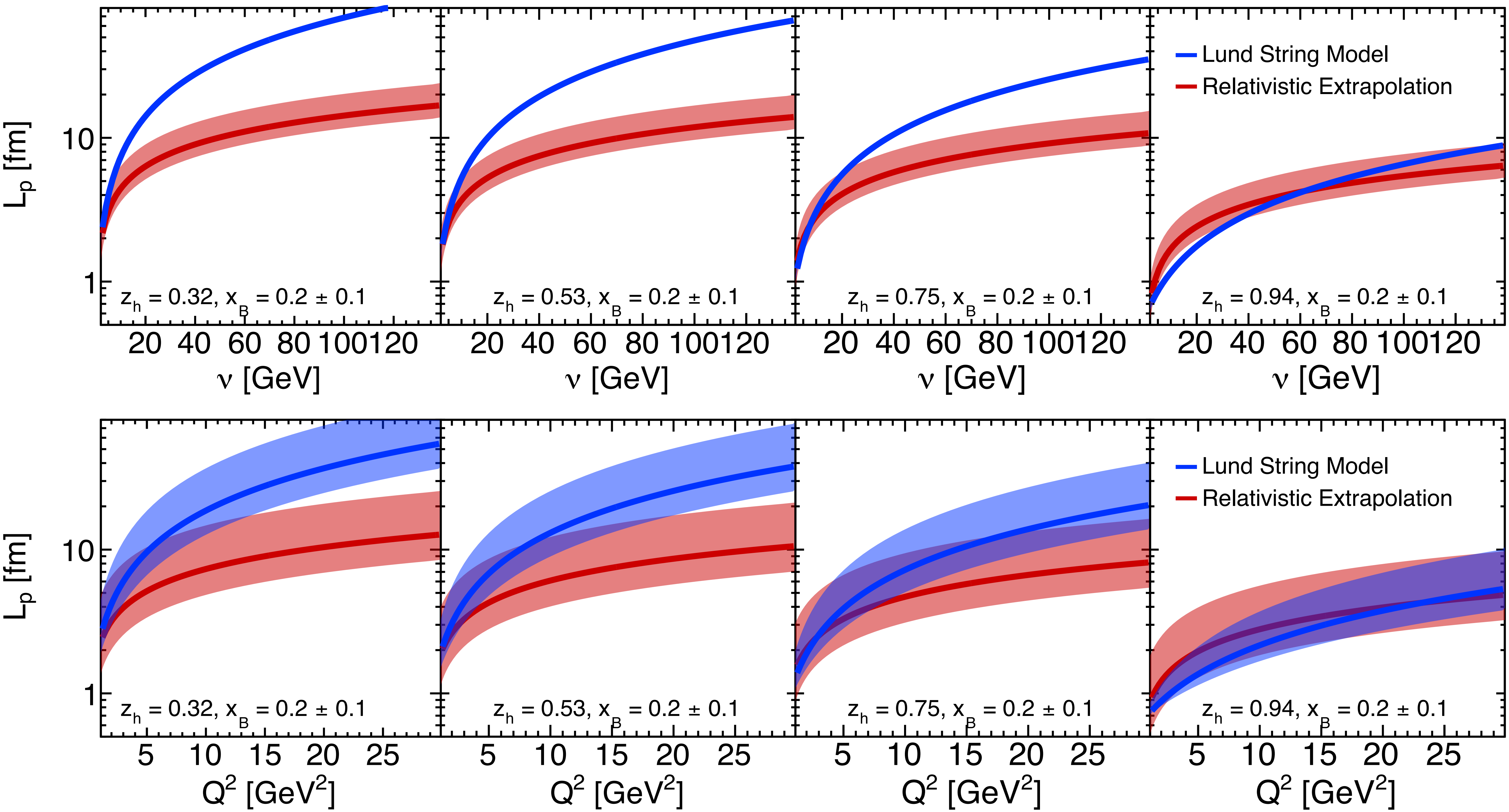
- Neglect any initial momentum/mass of quark
- Immediately after the interaction, quark mass $m_q = Q = \sqrt{(Q^2)}$.
- Gamma factor is therefore $\gamma = \nu/Q$, beta is $\beta = p_{\gamma^*}/\nu$.

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

Rigorous? γ, β allow:

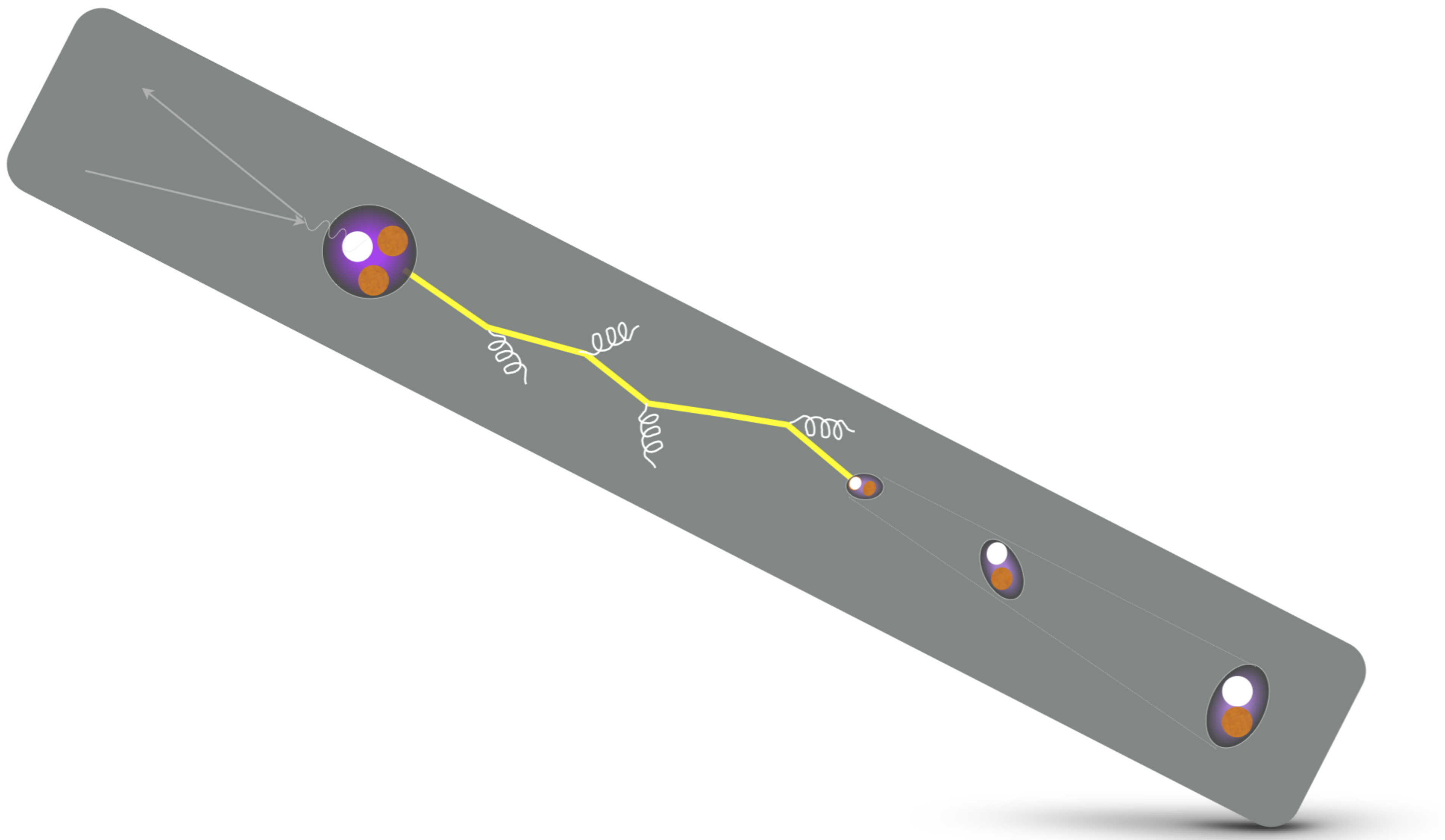
1. extrapolations to EIC kinematics,
2. test of time dilation in CLAS fits, and
3. direct comparison between JLab and HERMES fits

Estimations for future experiments



Space-time analysis and Lund string model provide close estimates for L_p for future experiments with assumptions of Q^2, ν.

Three possible distributions of production time



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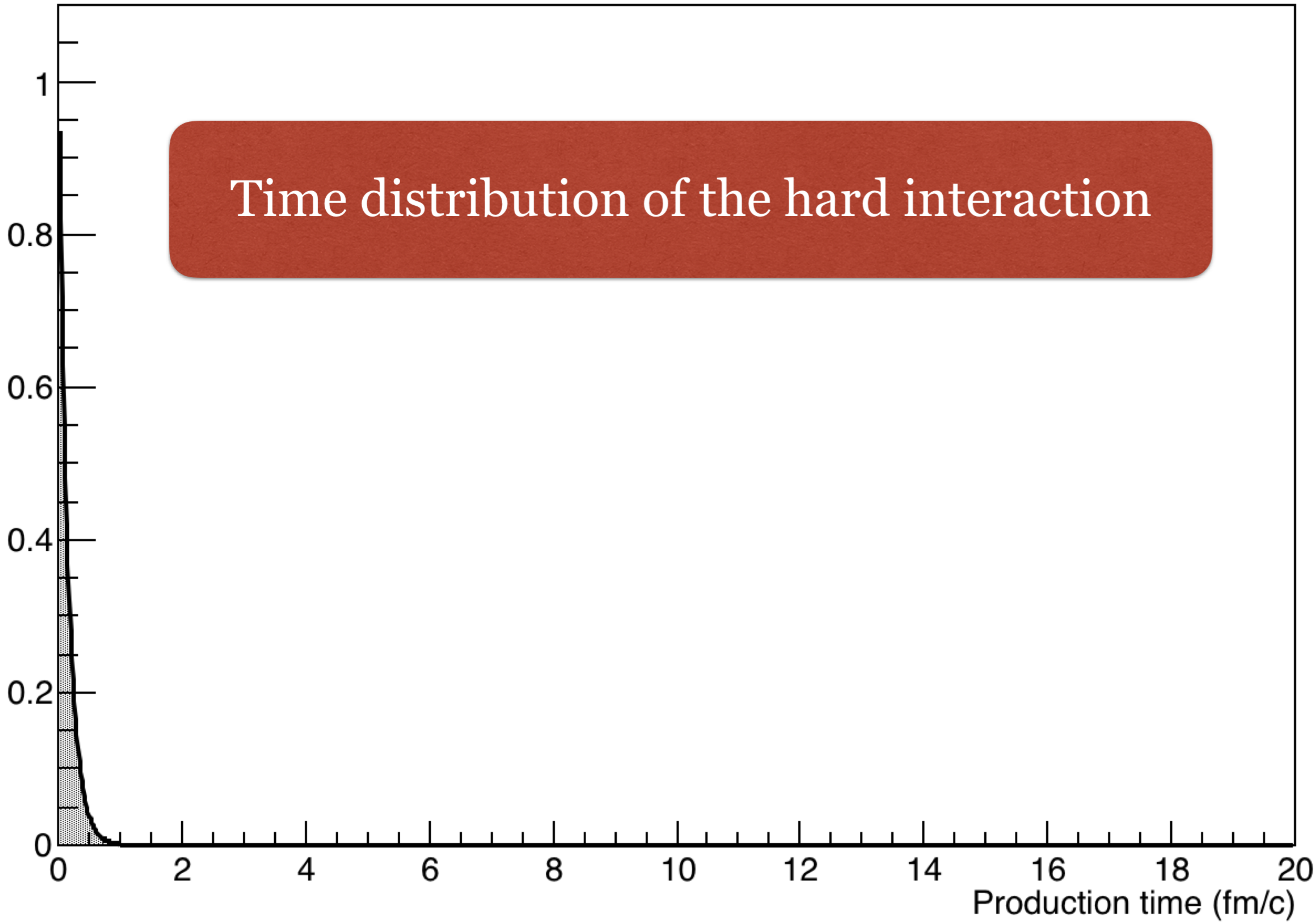
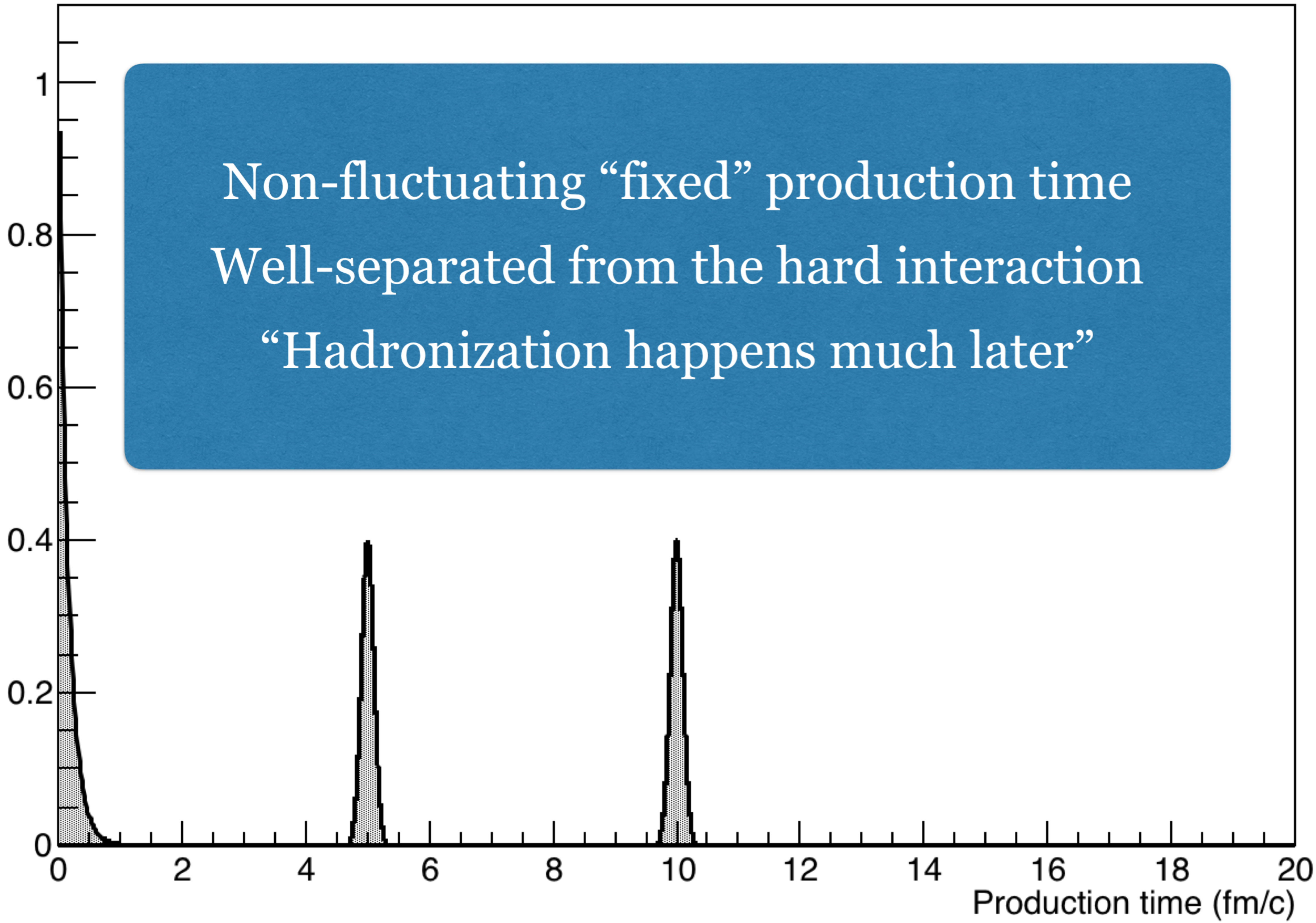
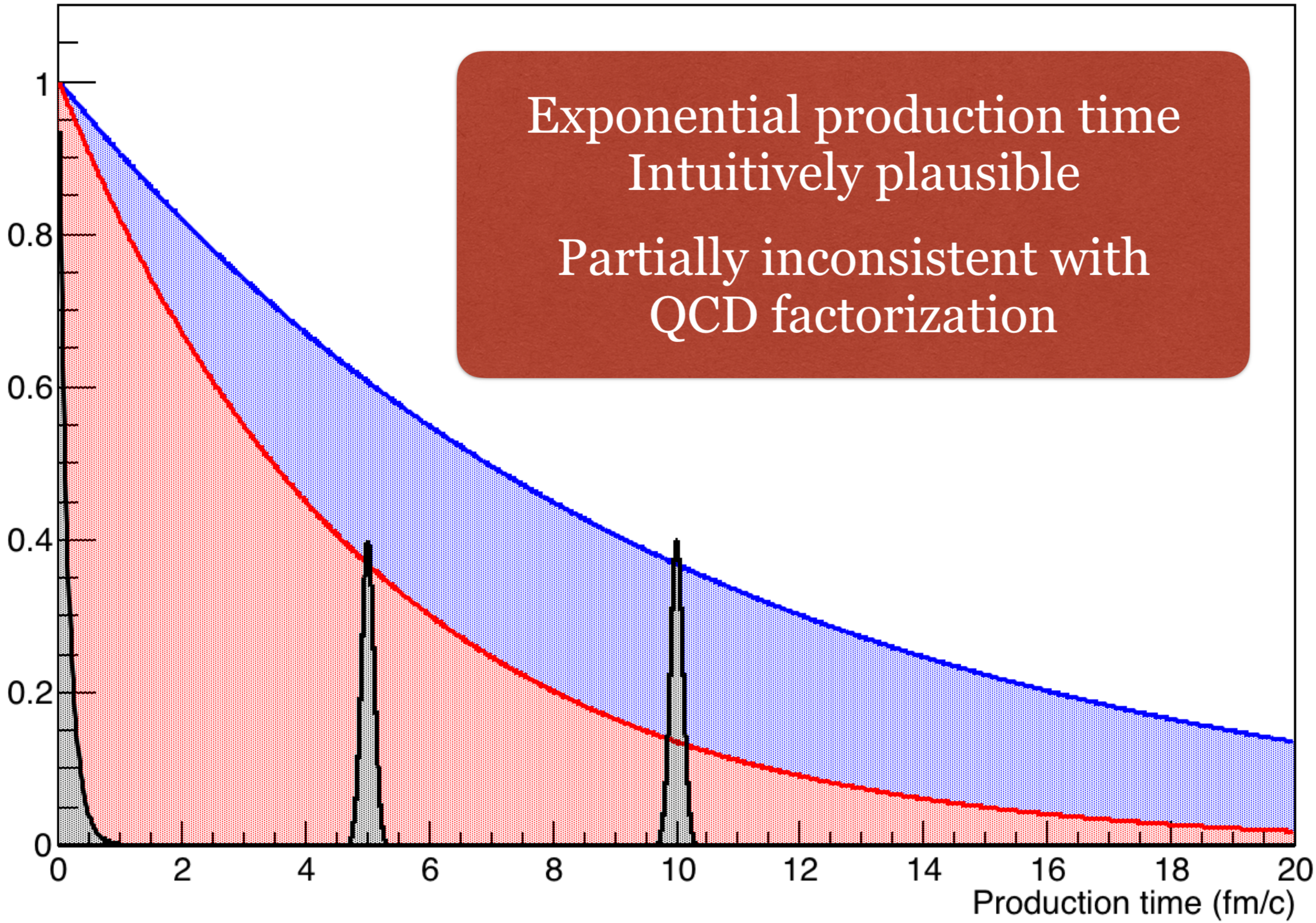


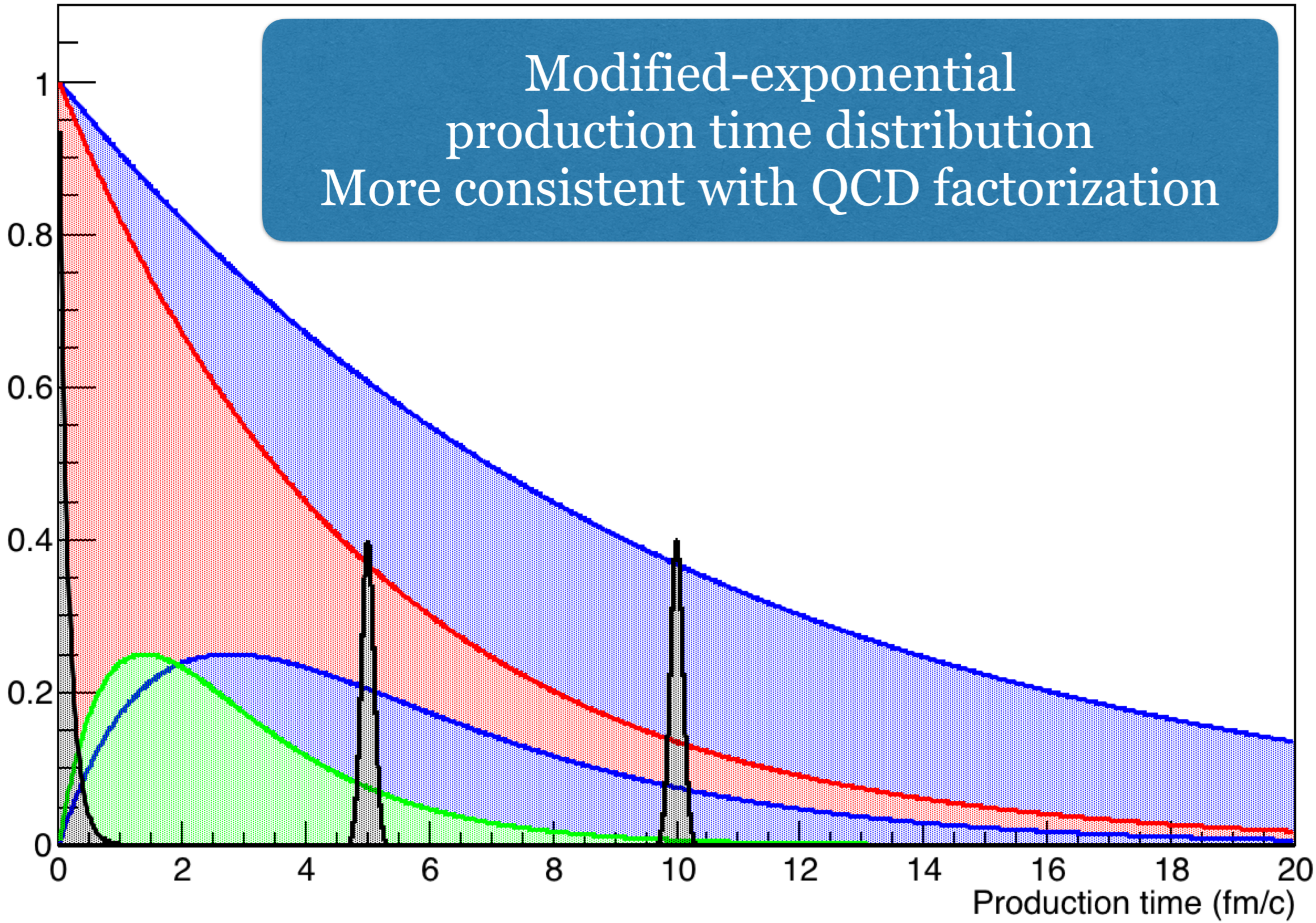
Three possible distributions of production time



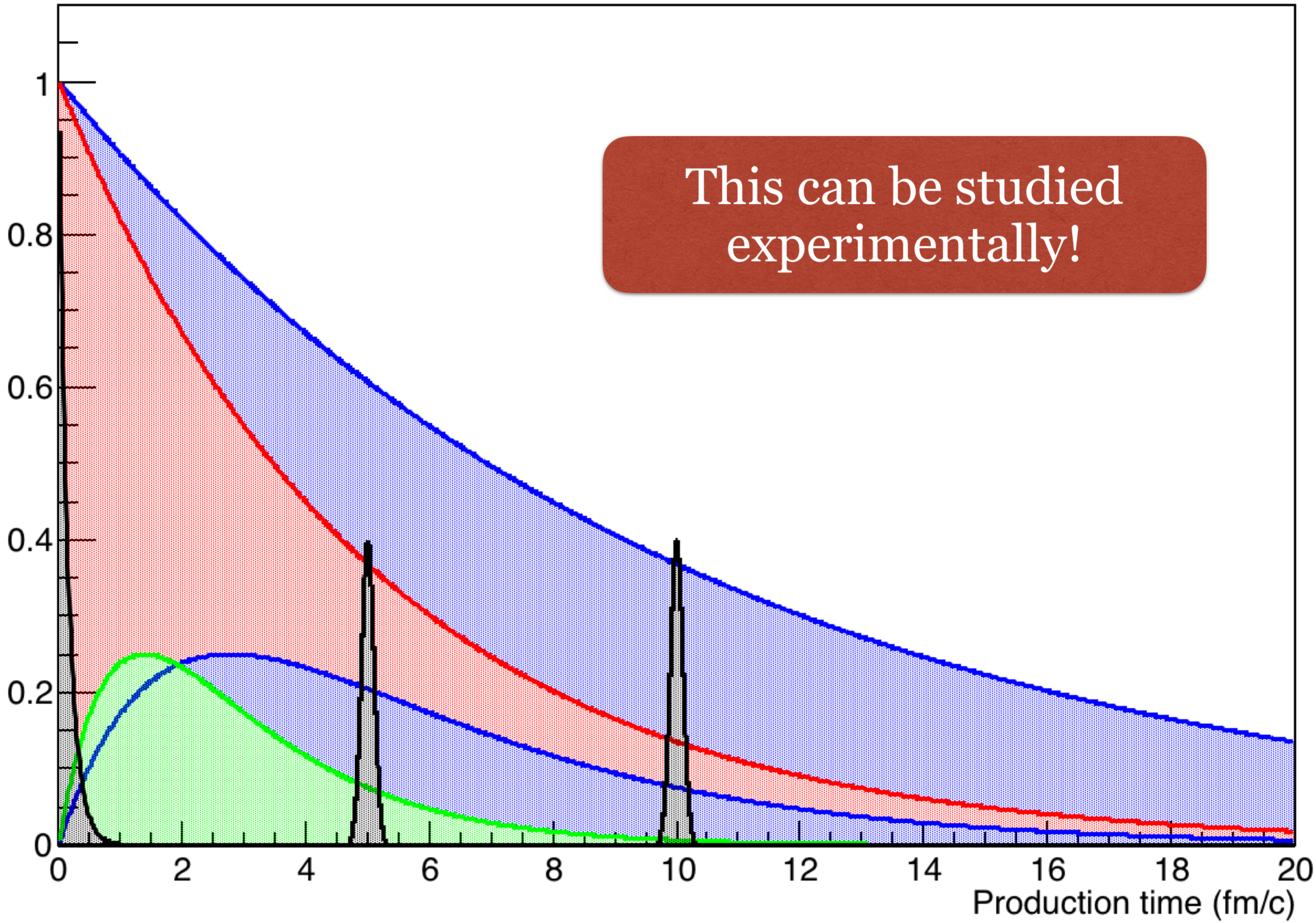
Three possible distributions of production time



Three possible distributions of production time



Three possible distributions of production time

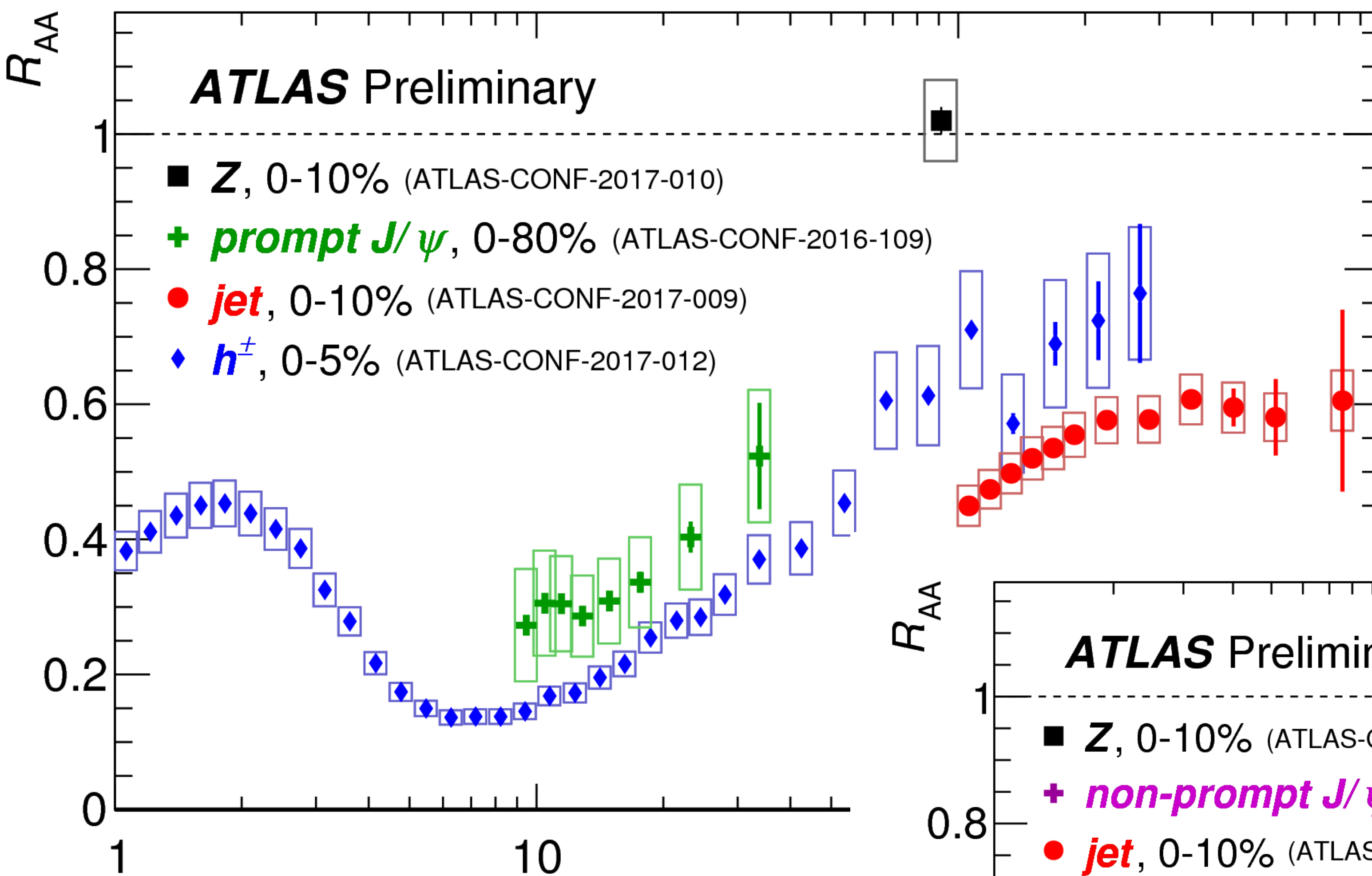


Summary

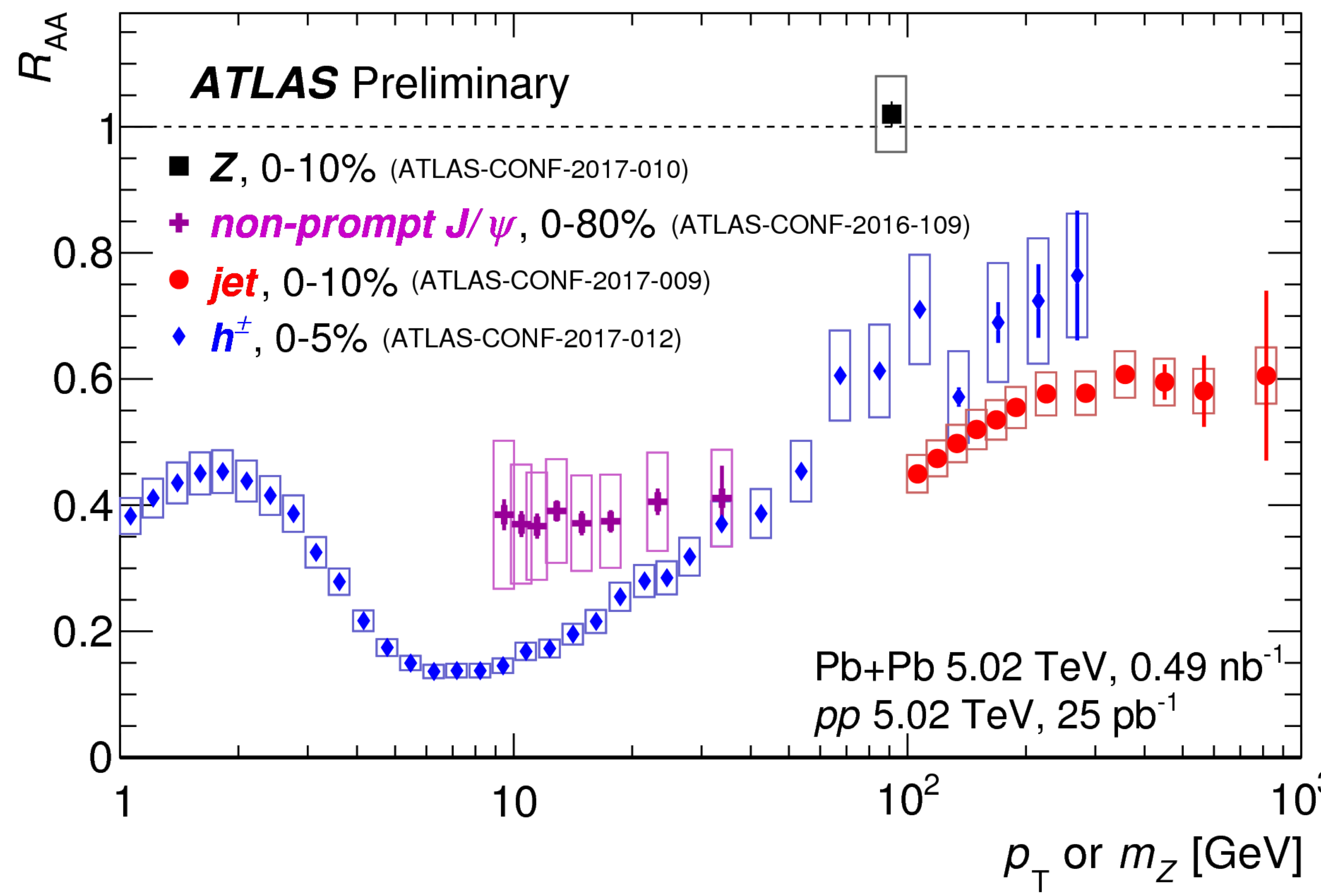
- We extract the characteristic production time of π^+ HERMES data using a geometric model.
- The model describes transverse momentum broadening and multiplicity ratios simultaneously.
- No dynamical information is assumed; it emerges from fit.
- Transport coefficient is compatible with some theoretical predictions.
- We recover the known value of the string constant completely independently, strong support of our model.
- Our approach estimates production length for future experiments using simple kinematical assumptions.

This is the first measurement of the color lifetime.

What do we see in hot and cold matter studies at the LHC at 5 TeV?



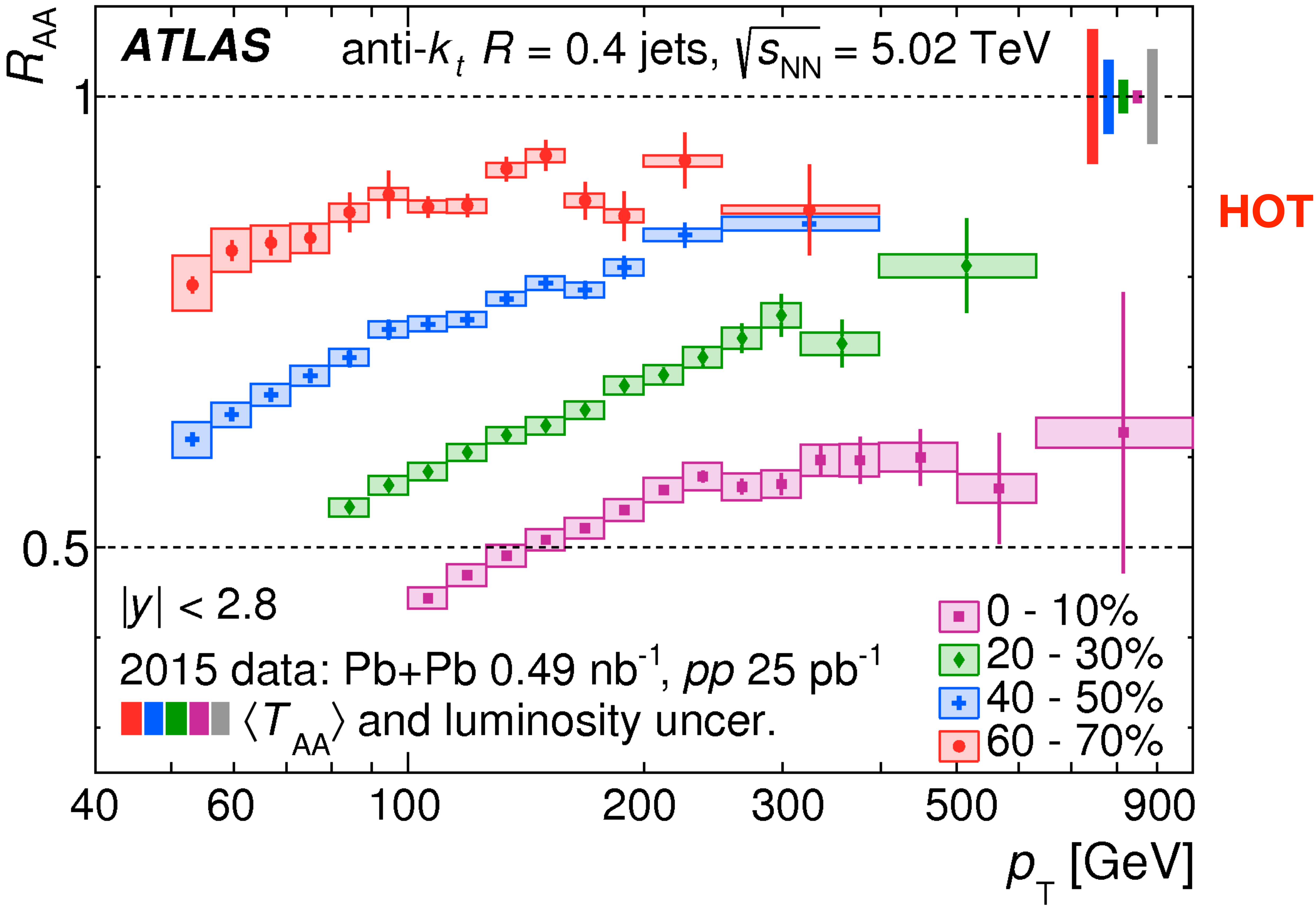
HOT



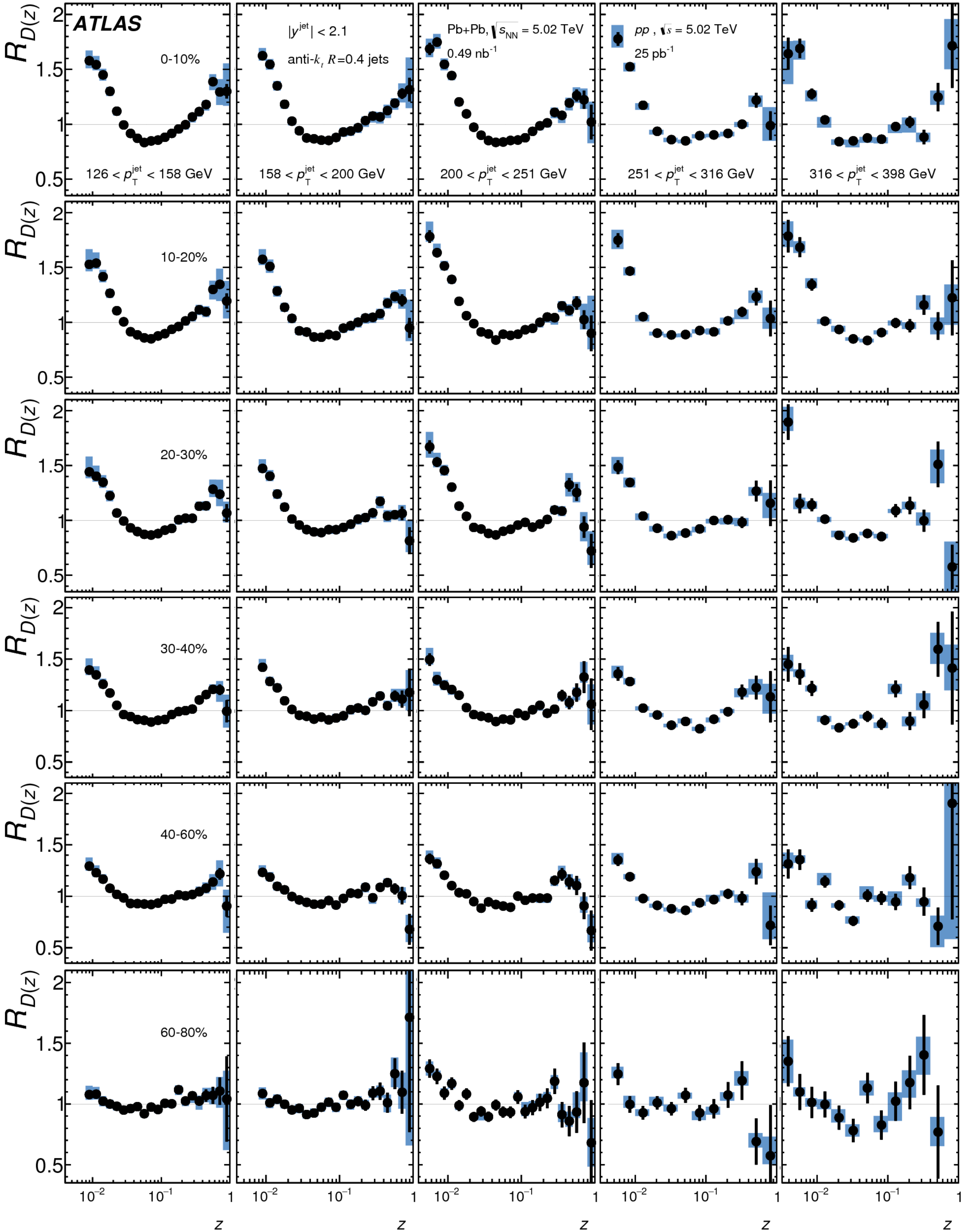
HOT

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HION/

Large amounts of jet suppression in Pb+Pb



https://arxiv.org/abs/1805.05635



Heavily modified jet fragmentation functions in Pb+Pb

HOT

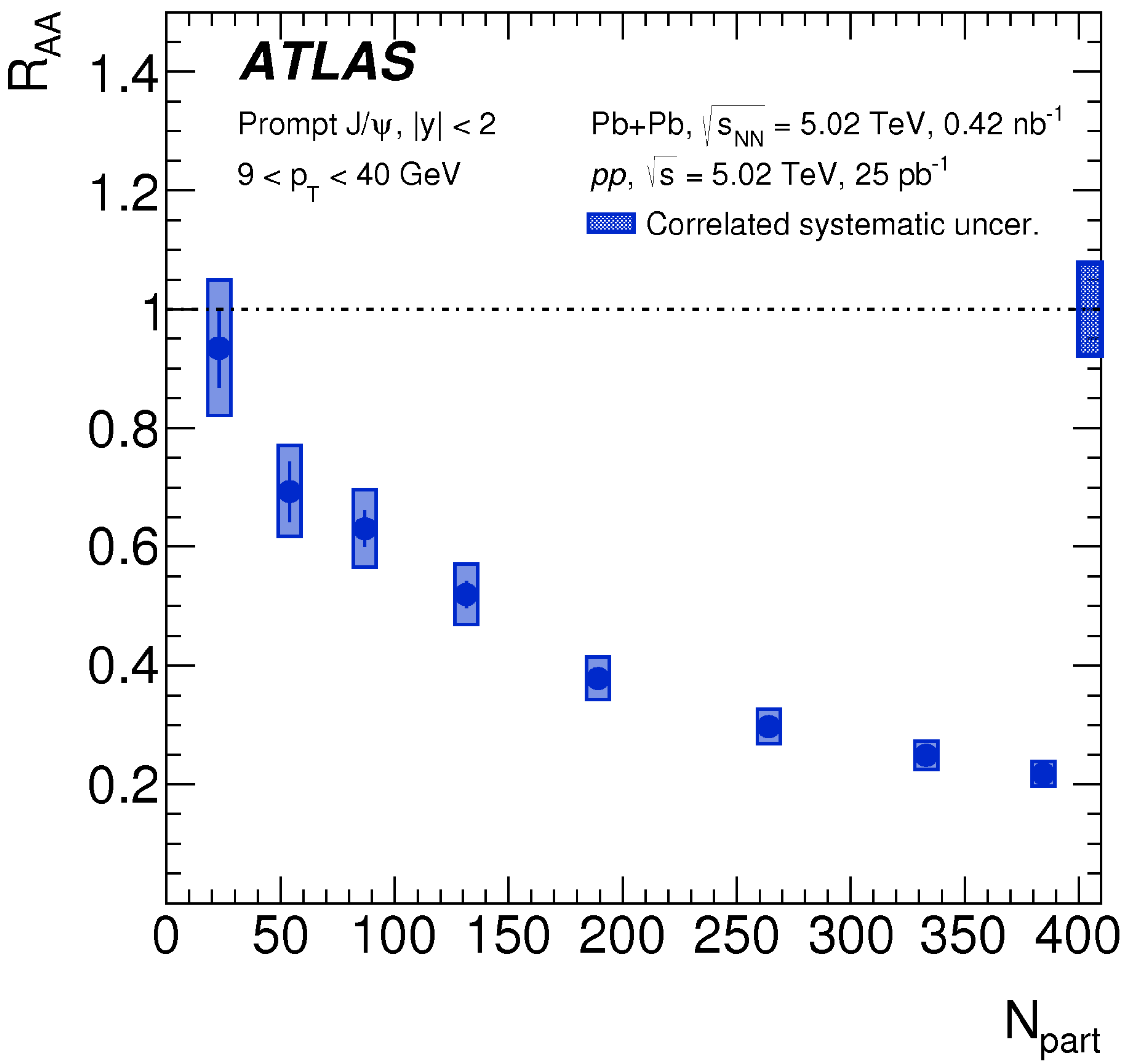
Effects > 50%!

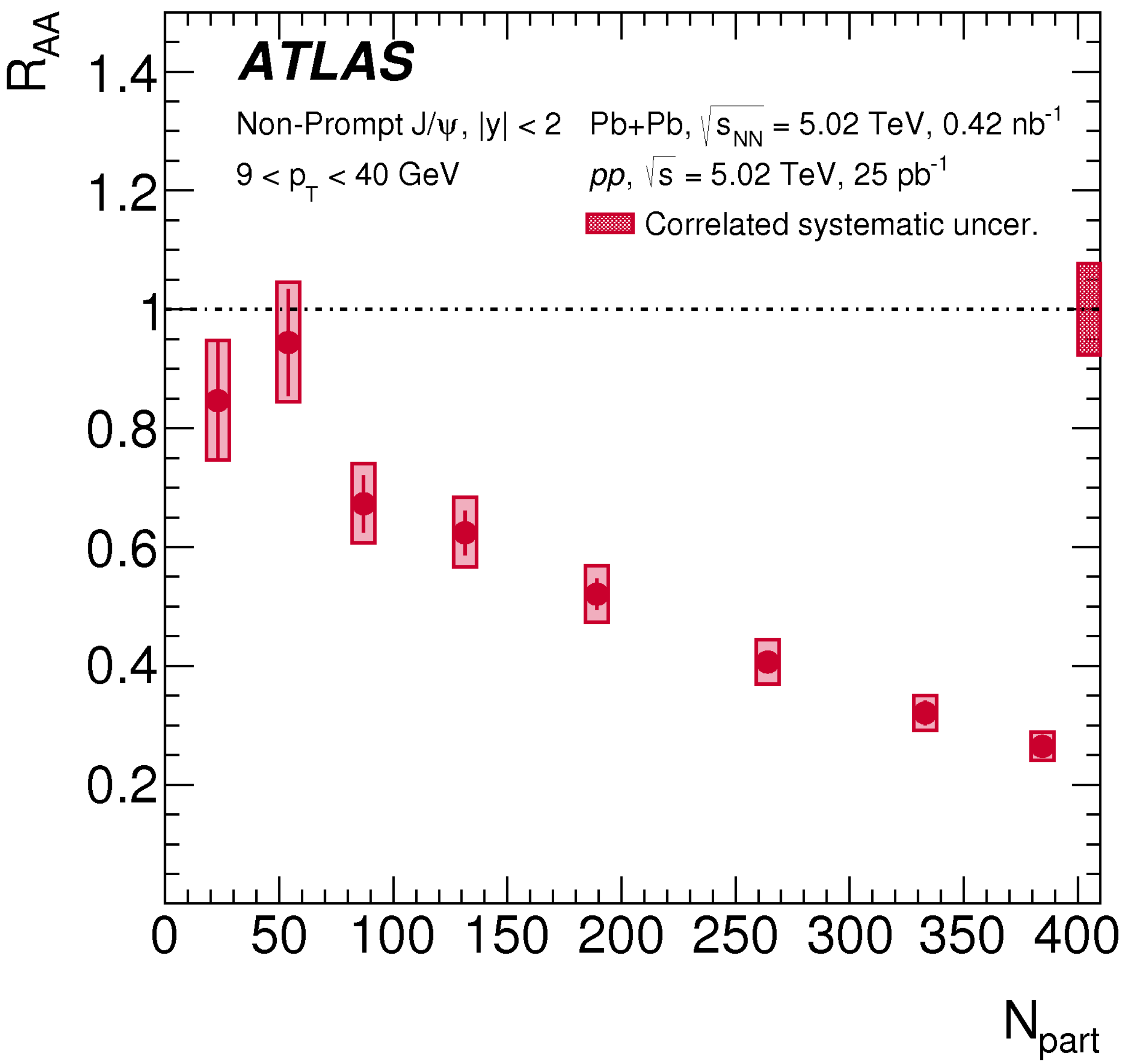
Enhancement at low and high z

https://arxiv.org/pdf/1805.05424.pdf

Prompt and non-prompt J/ψ suppression in Pb+Pb

HOT

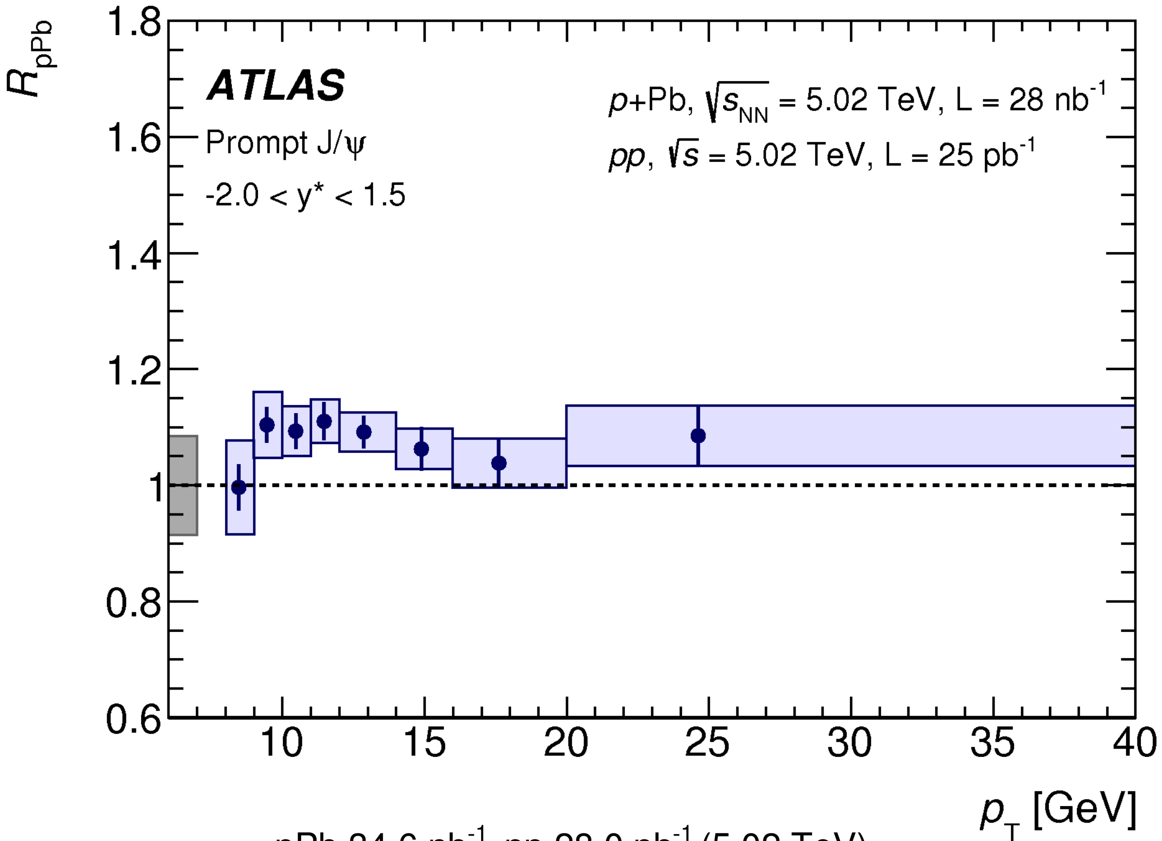




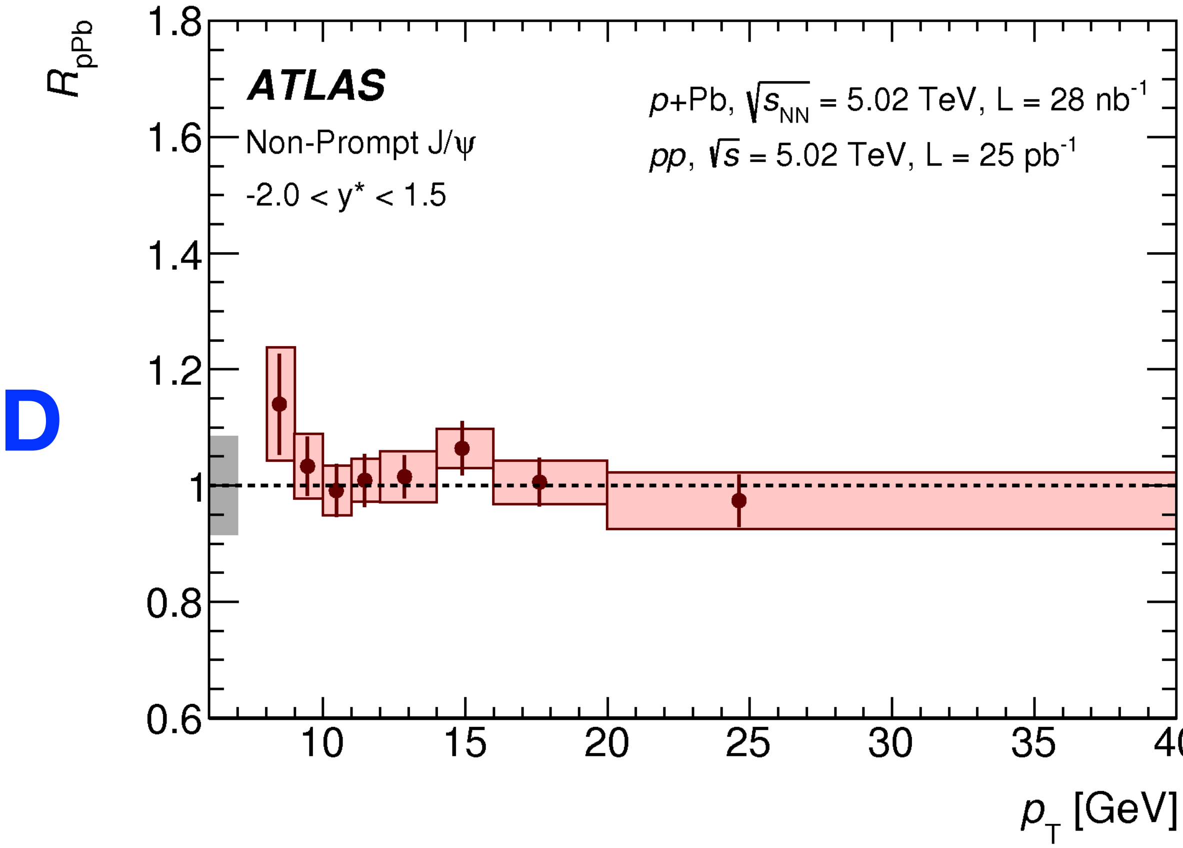
Suppression by a factor of 4-5!

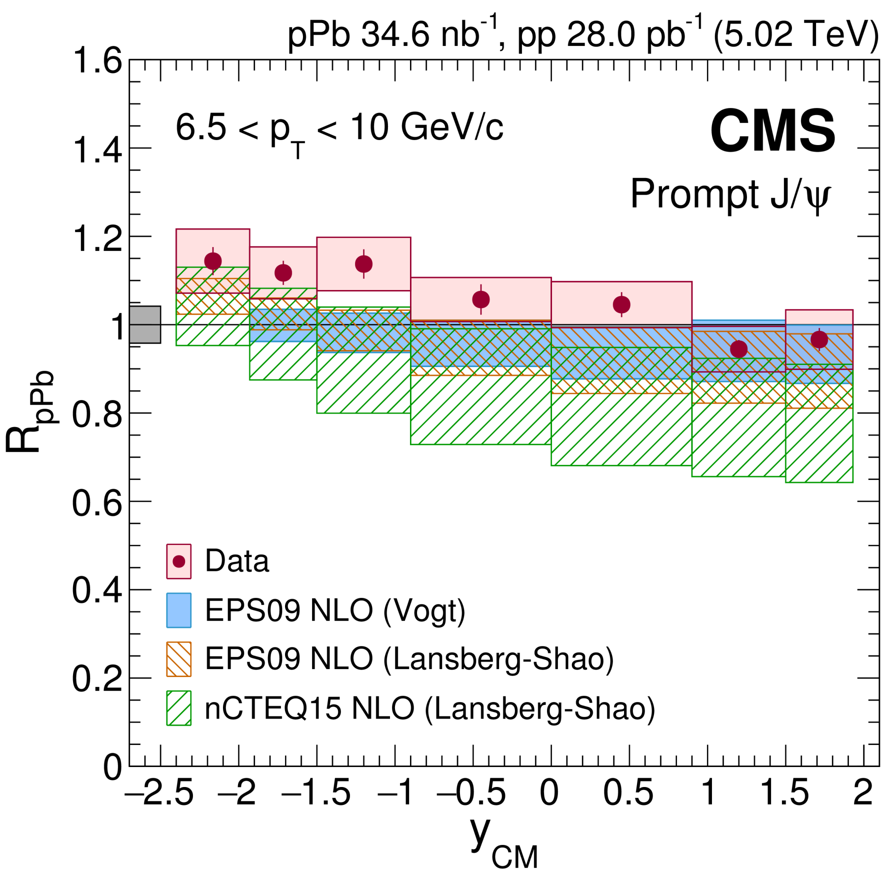
https://arxiv.org/abs/1805.04077

Prompt and non-prompt J/ψ and ϒ suppression in p+Pb

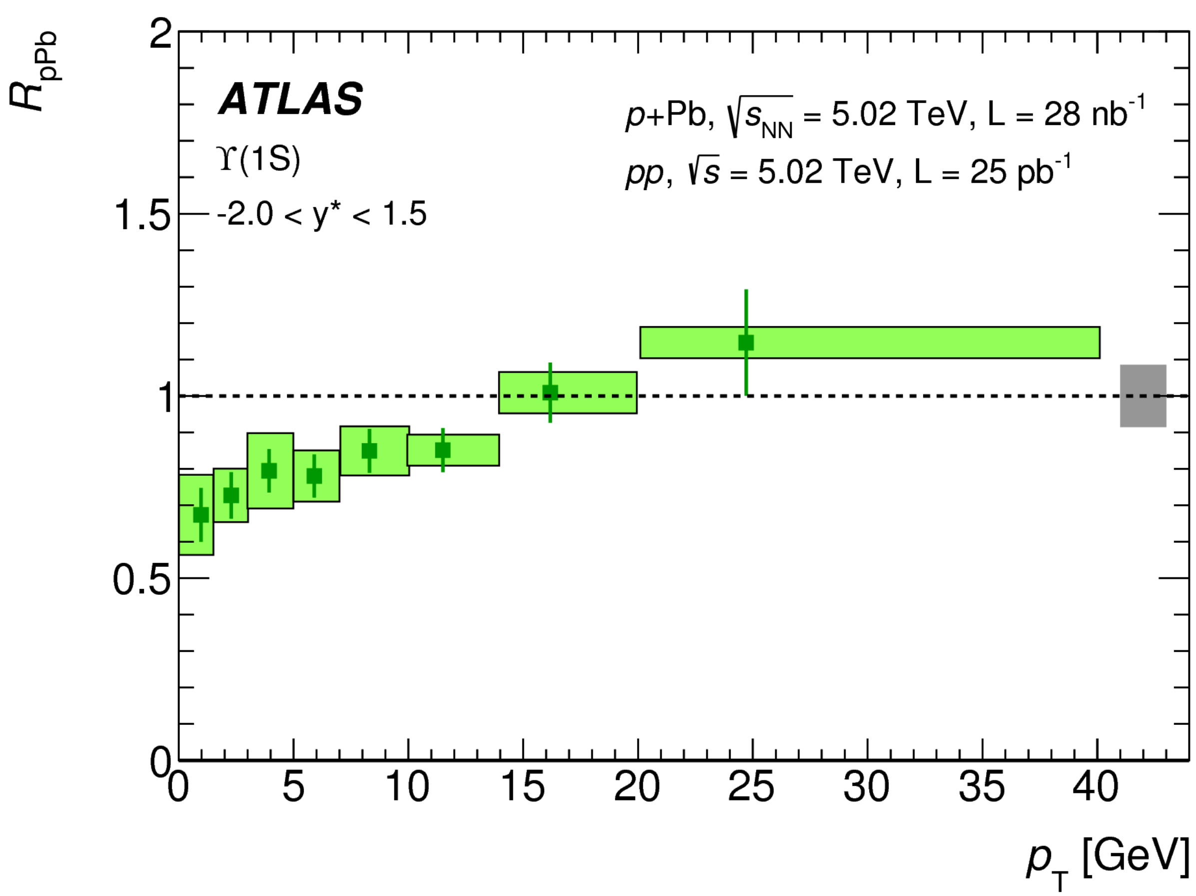


COLD





[Sirunyan, A.M., Tumasyan, A., Adam, W. et al. Eur. Phys. J. C (2017) 77: 269]



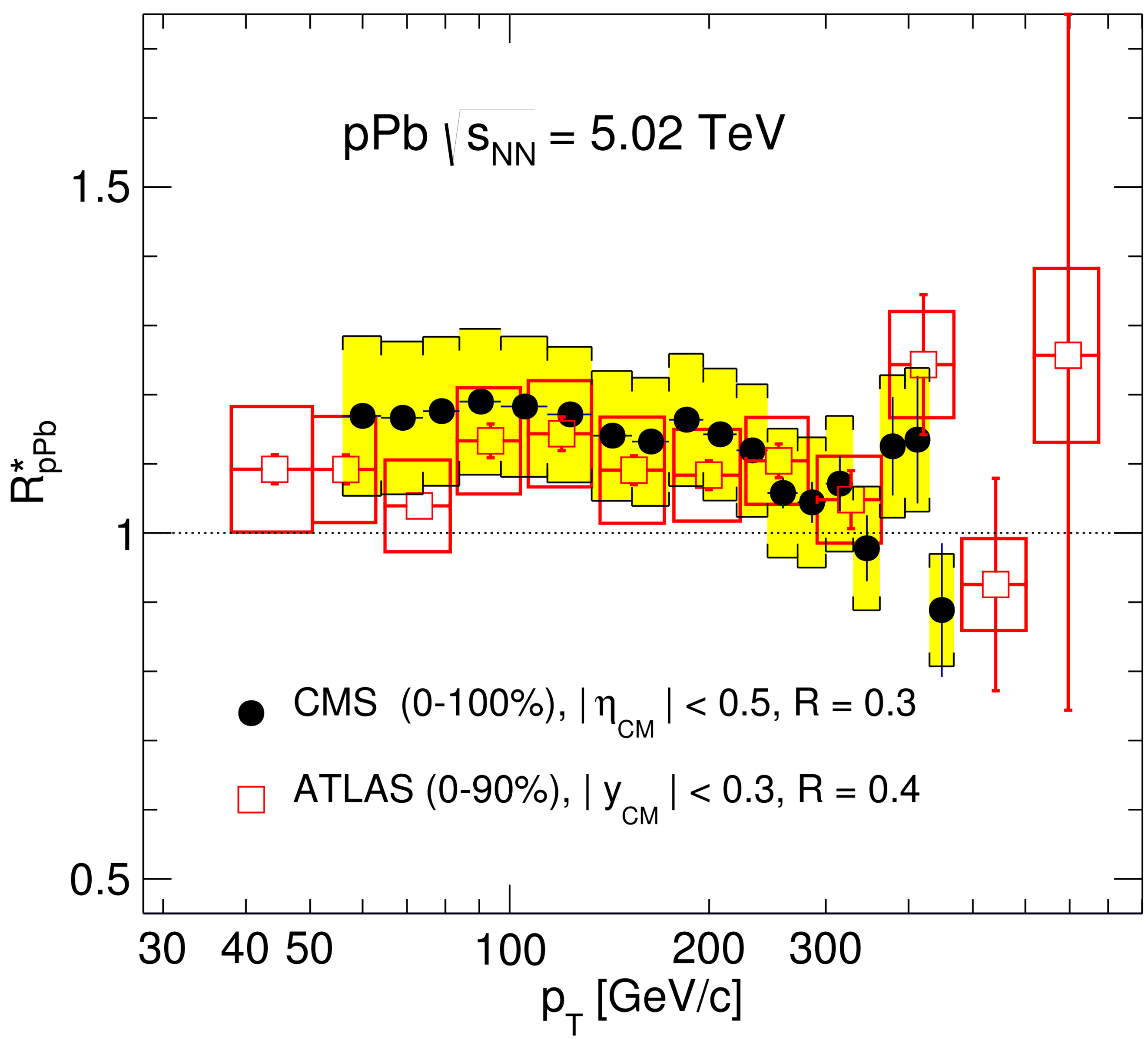
The effects are generally much more subtle in cold matter at TeV energies.

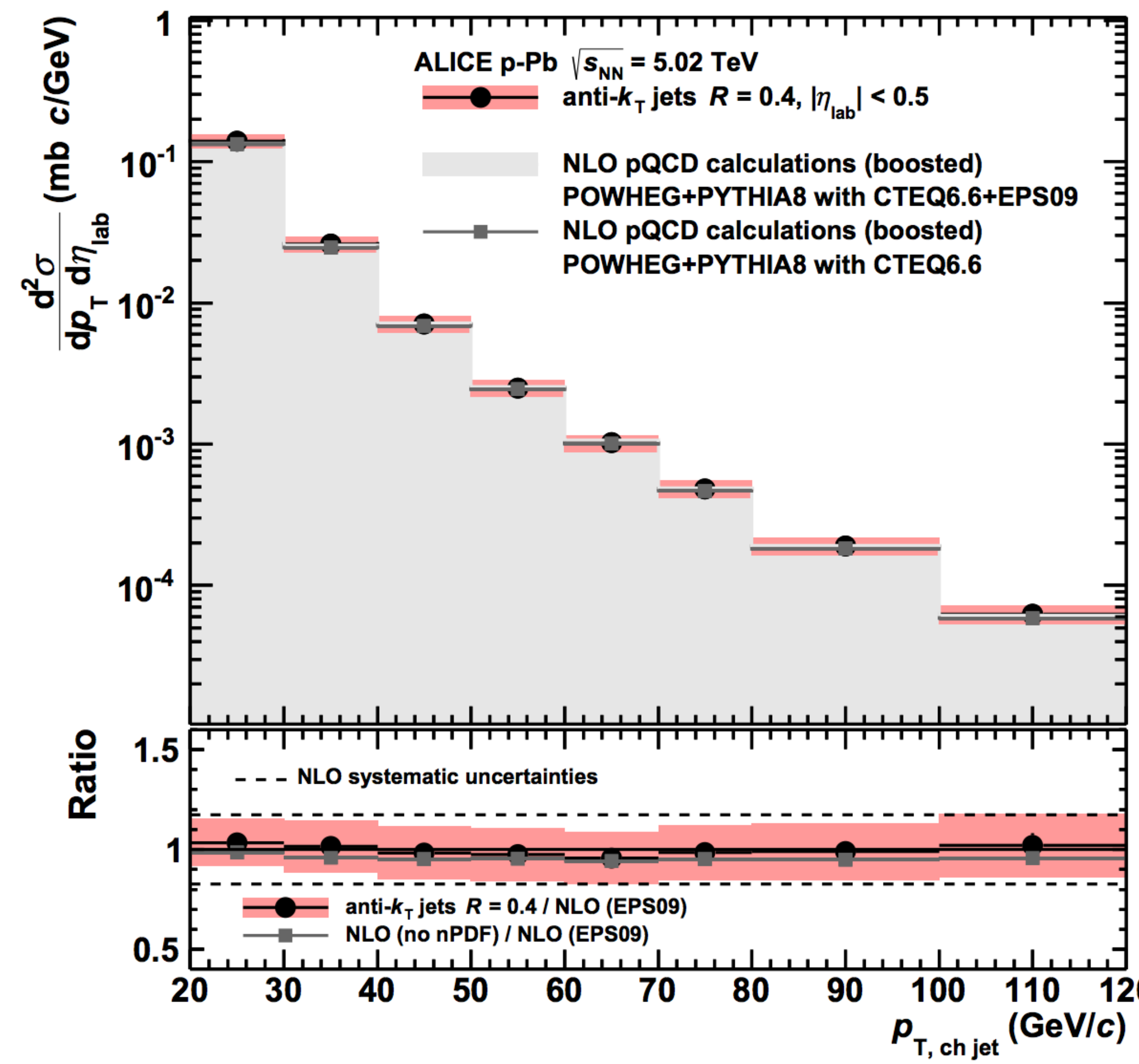
Without high precision, most cold matter effects are invisible.

[Eur. Phys. J. C 78 (2018) 171] / [https://arxiv.org/abs/1709.03089]

Inclusive Jet modifications in p+Pb

COLD





Eur. Phys. J. C 76 (2016) 372

PLB749 (2015) 68-81 / arXiv:1503.00681

Two-particle correlations at EIC

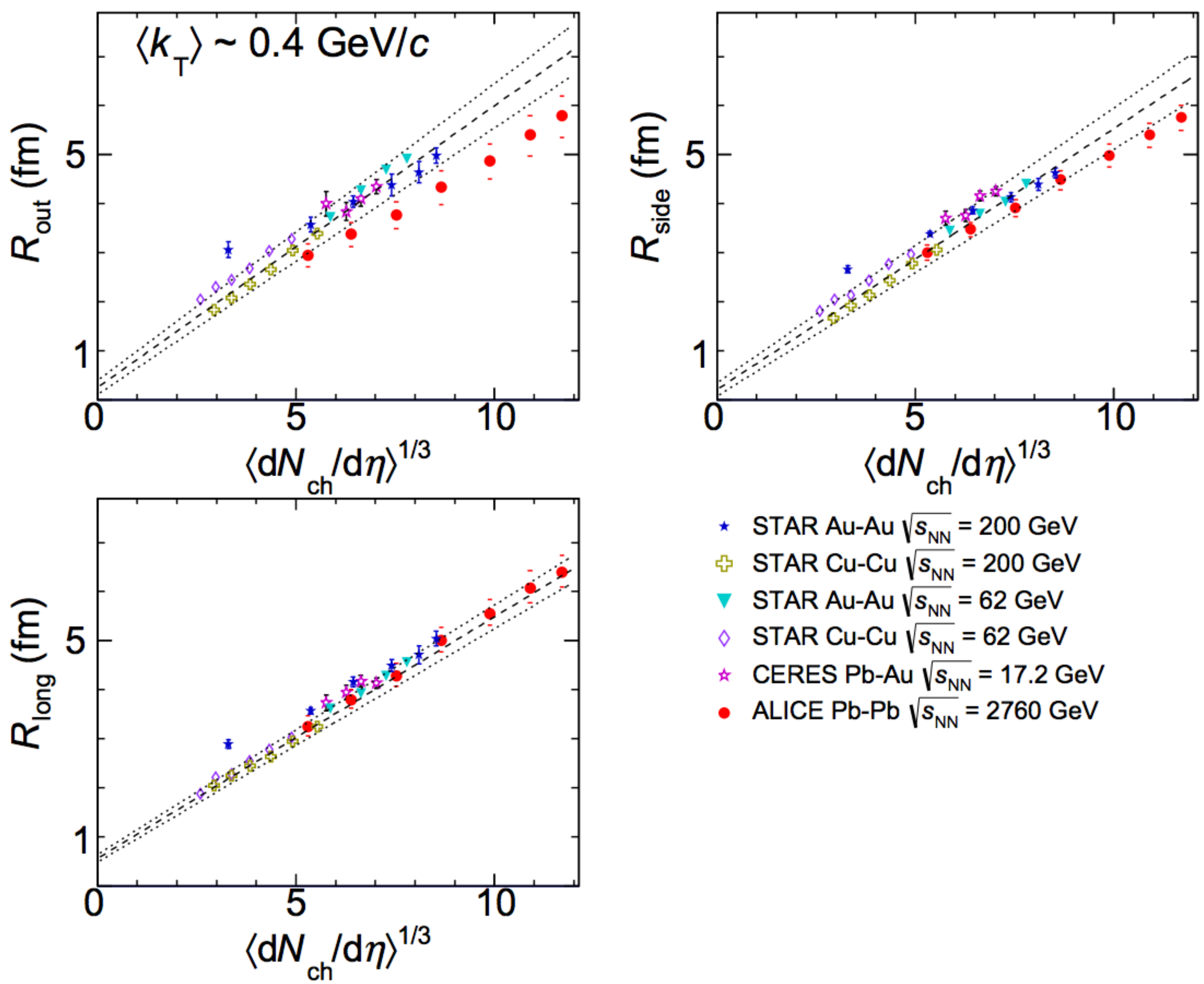
- Two-particle correlations studies have become highly developed for hadron beam experiments over the past two decades.

- The number of publications related to these topics has become quite large, and the scientific interest is high and increasing.

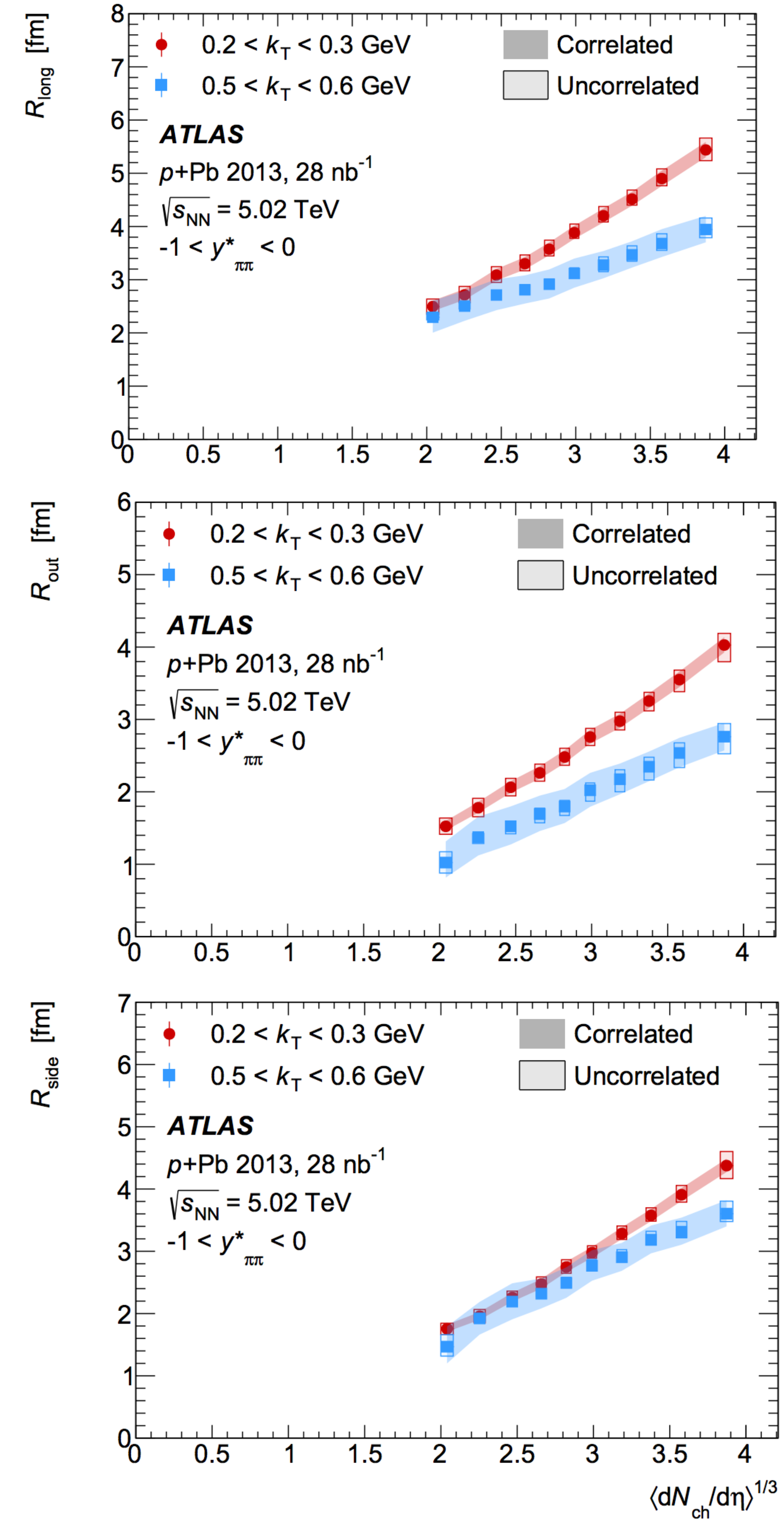
- Such studies may be feasible with 11 GeV (maybe even with 6 GeV) but with the higher hadron multiplicities of EIC, they should have higher statistical significance and a much larger signal sample, using semi-inclusive DIS with 2 or more hadrons in the final state.

- Both source size studies (HBT/Bose-Einstein "femtoscopy") with identified particles, and general correlations studies (e.g. cumulant analysis) will be very interesting to compare with the hadron beam results. (There was at least one HBT/Bose-Einstein study at HERA.)

- At RHIC and at the LHC, such studies produced a series of interesting surprises, such as non-zero v2 in p+Pb and in p+p, the "ridge" observation in small systems as well as large, and experimental access to event-by-event fluctuations. Why not explore these kinds of analyses at the EIC?



Phys. Rev. C 93 (2016) 024905 / https://arxiv.org/abs/1507.06842



Phys. Rev. C 96, 064908 (2017) / https://arxiv.org/abs/1704.01621

Probing Quantum Mechanical Properties of Jets

Jets in the extended nuclear medium may reveal new distinct quantum properties

Ideal to study at EIC: ~no ISI

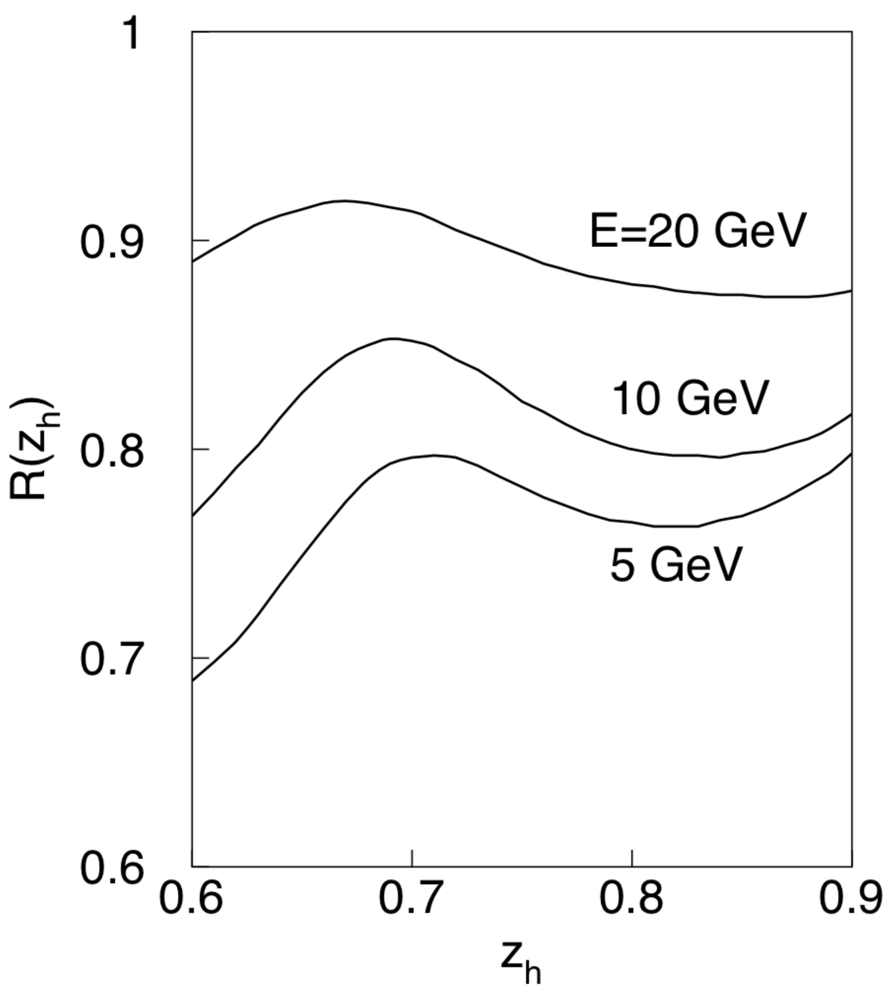


FIG. 6: Ratio $R(z_h)$ defined in (76) for lead at different photon energies $E = 5,\ 10,\ 15\,\mathrm{GeV}$.

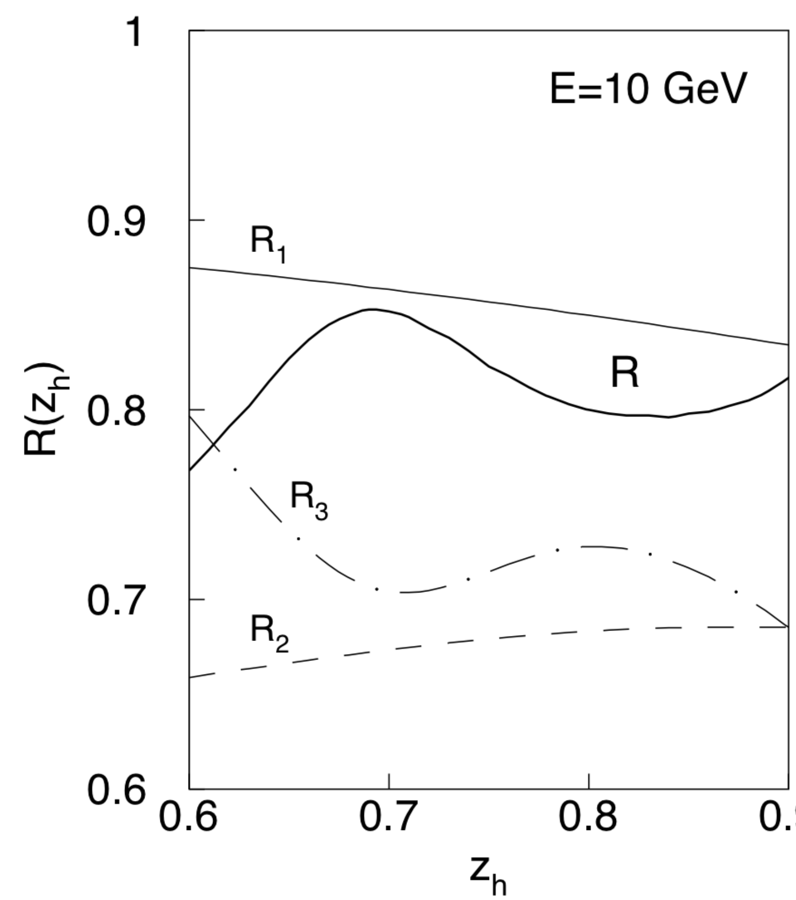


FIG. 4: Lead-to-proton target ratios for the cross sections corresponding to pre-hadron production outside (R_1) or inside (R_2) the nucleus in both amplitudes. The ratio for inside-outside interference is shown by the curve indicated by R_3. The ratio of the full cross sections $\sigma_1 + \sigma_2 + \sigma_3$, Eq. (76), is depicted by the solid curve indicated by R. Notice that the interference term σ_3 is negative.

This paper estimates interference between "inside" and "outside" hadronization on Pb. A structure is seen that is solely due to the interference.

https://arxiv.org/pdf/0809.4613.pdf

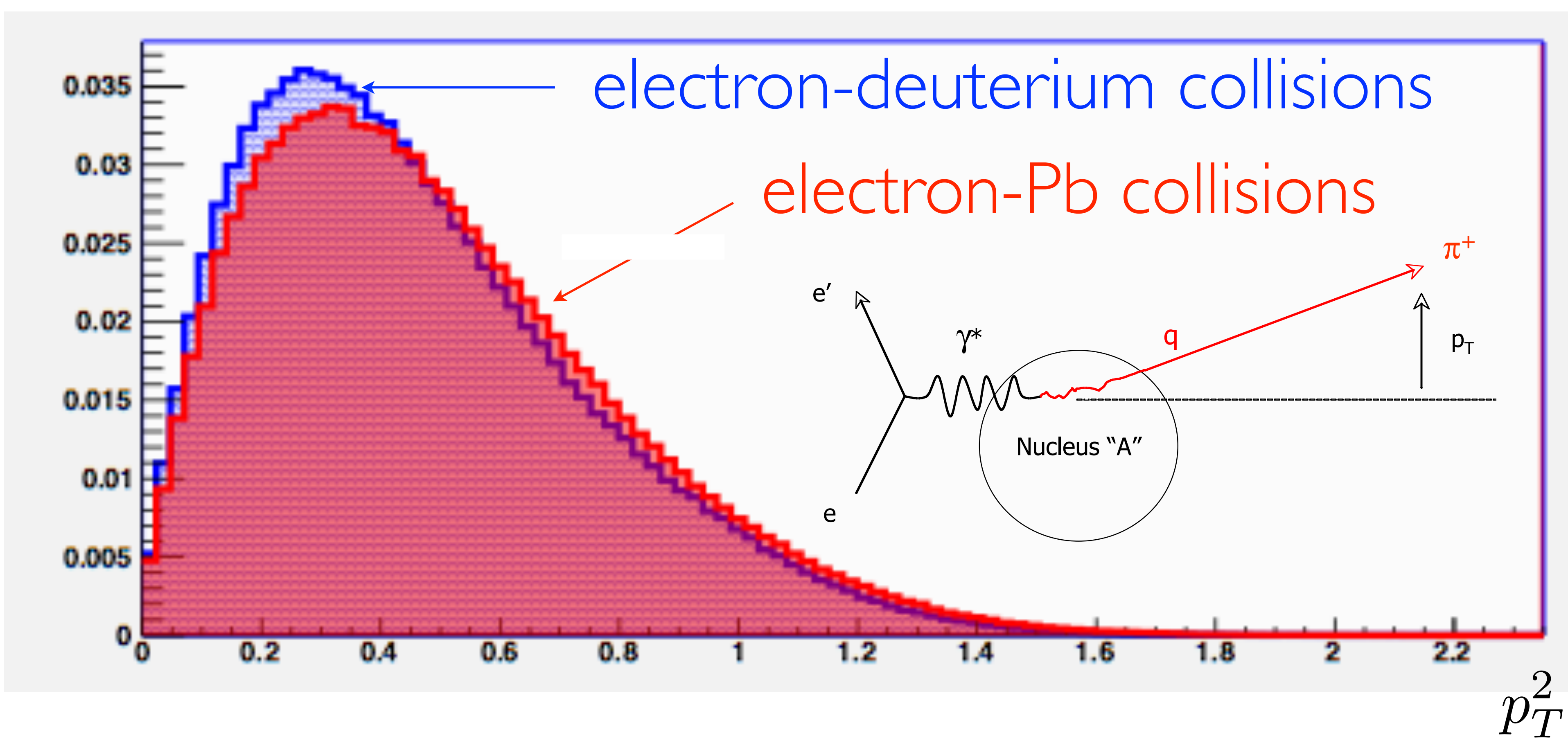
Quark Physics and the Nuclear Force

Transverse momentum broadening in cold matter is small - ~0.05 GeV²

Thus, the propagating quark scatters off *nucleons*

How can a quark interact with a nucleon? Conjecture:
tiny color fluctuations away from the color singlet state of the bound nucleon.
E.g., a transitory color dipole moment

If it's true: testable with p_T broadening, and another way of thinking about the origin of the nuclear force.



Conclusions

The study of QCD color in nuclei has many rich features and points of contact with experiment

One good way to prepare for the EIC is to understand the related data we already have

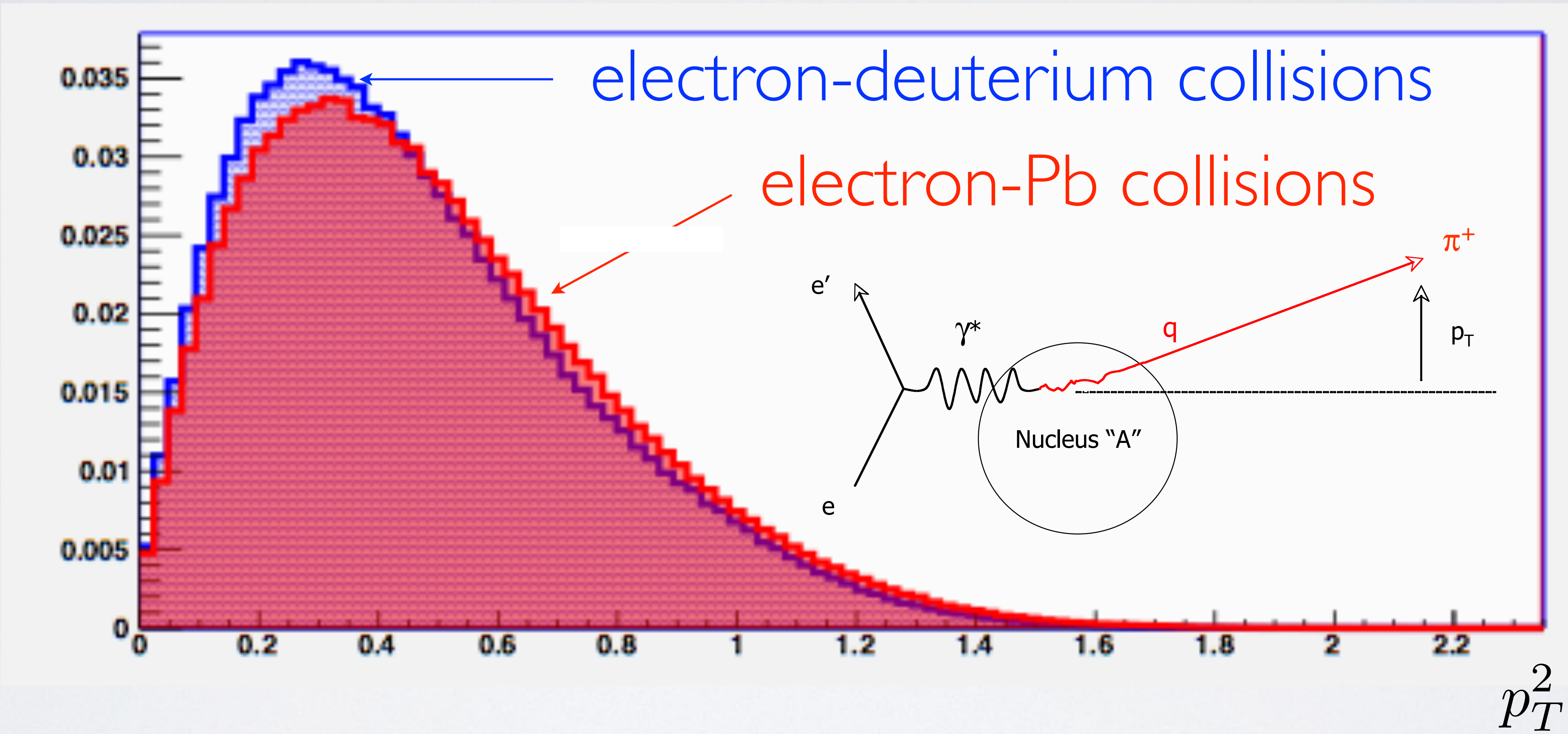
The color lifetime concept is a new, promising avenue into understanding color in nuclei

Quantum mechanical features of jets, a color-based view of the nuclear force, 2-particle correlations, other correlation studies, and much more.

These kinds of studies are site-independent and could provide a good “first measurement” for the new EIC lab

Observable: p_T broadening

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



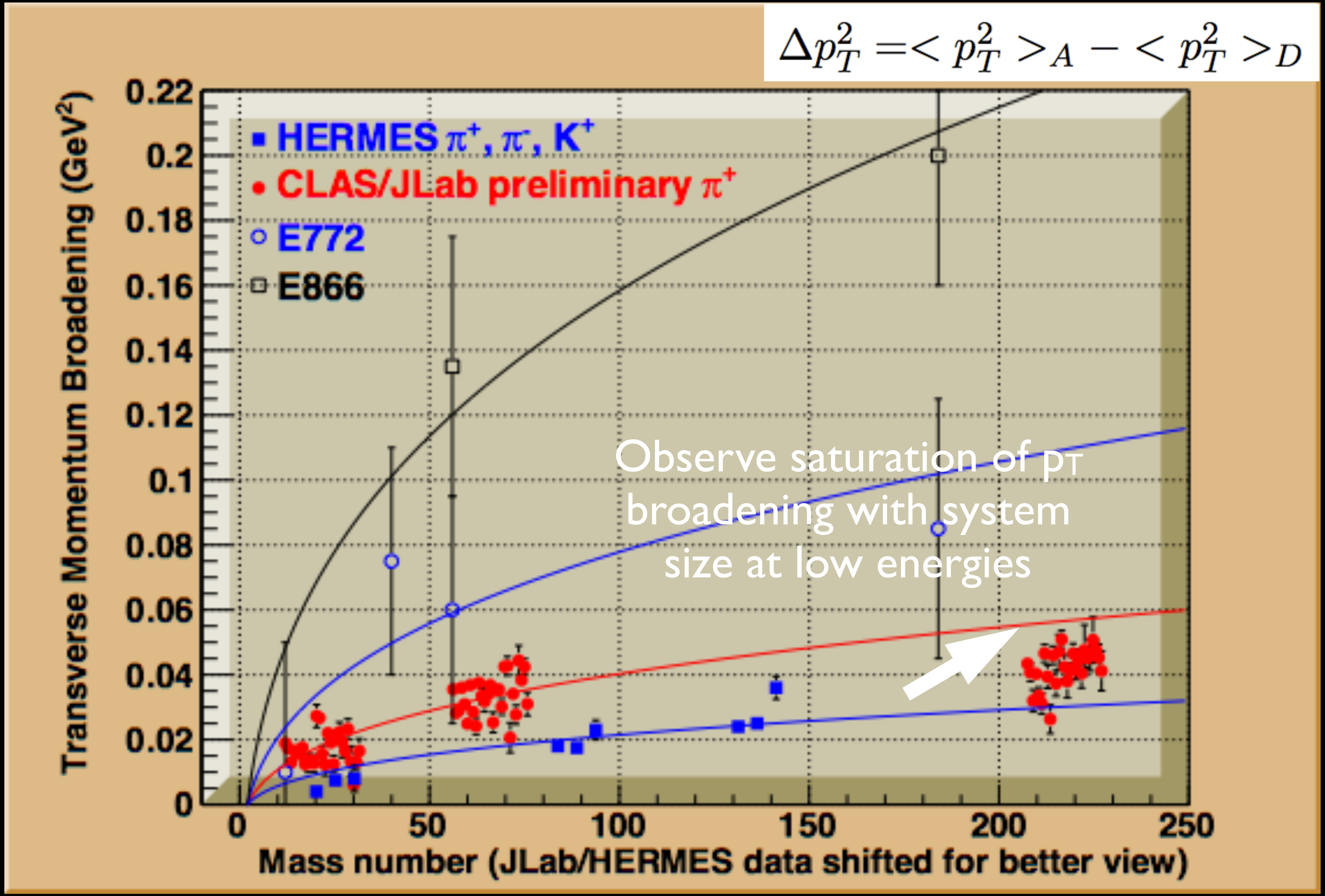
p_T broadening is a tool: sample the gluon field using a colored probe:

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

and radiative energy loss:

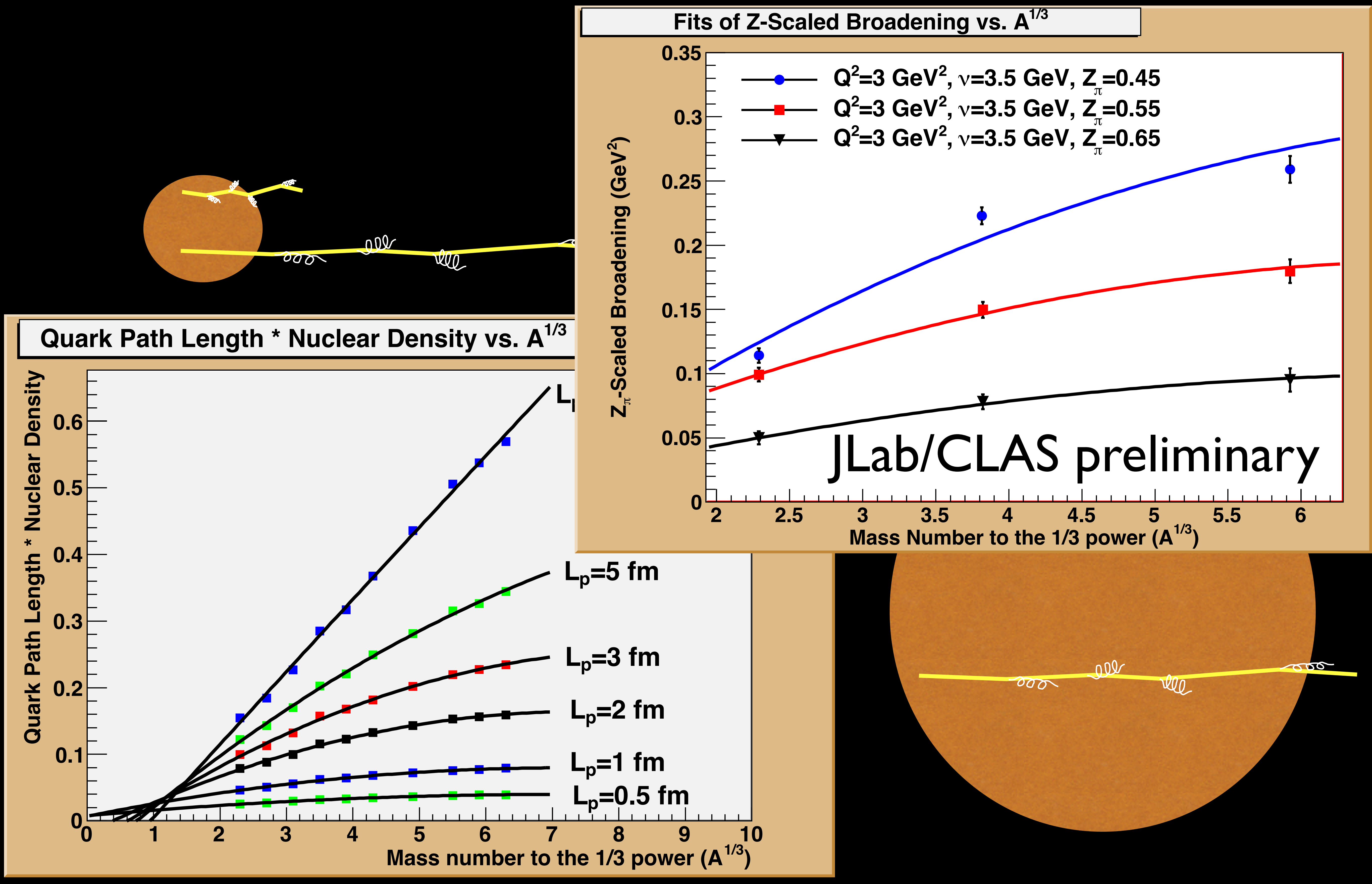
$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4}\Delta p_T^2$$

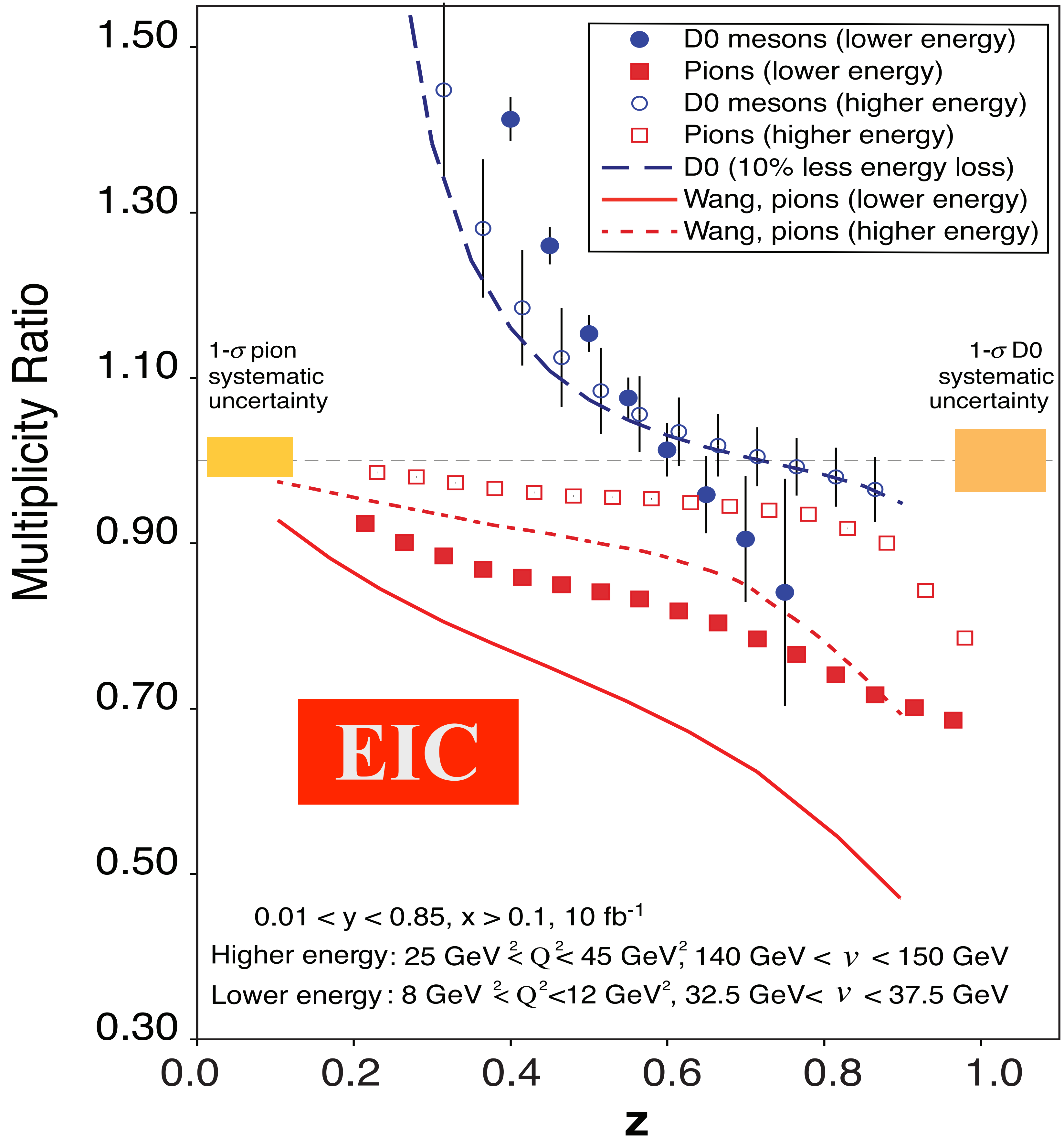
p_T broadening data - Drell-Yan and SIDIS

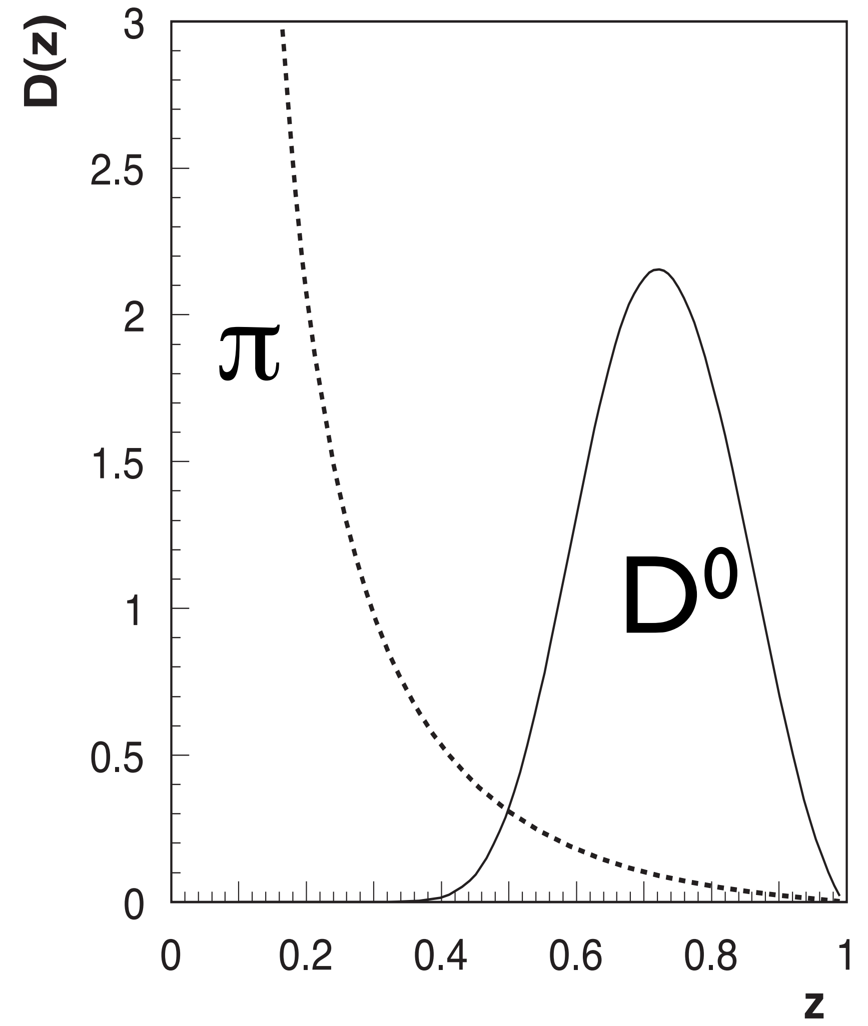


- New, precision data with identified hadrons!
- CLAS π^+: 81 four-dimensional bins in Q^2, ν, z_h, and A
- Intriguing *saturation*: production length or something else?

Production Time Extraction - Geometrical Effects







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***

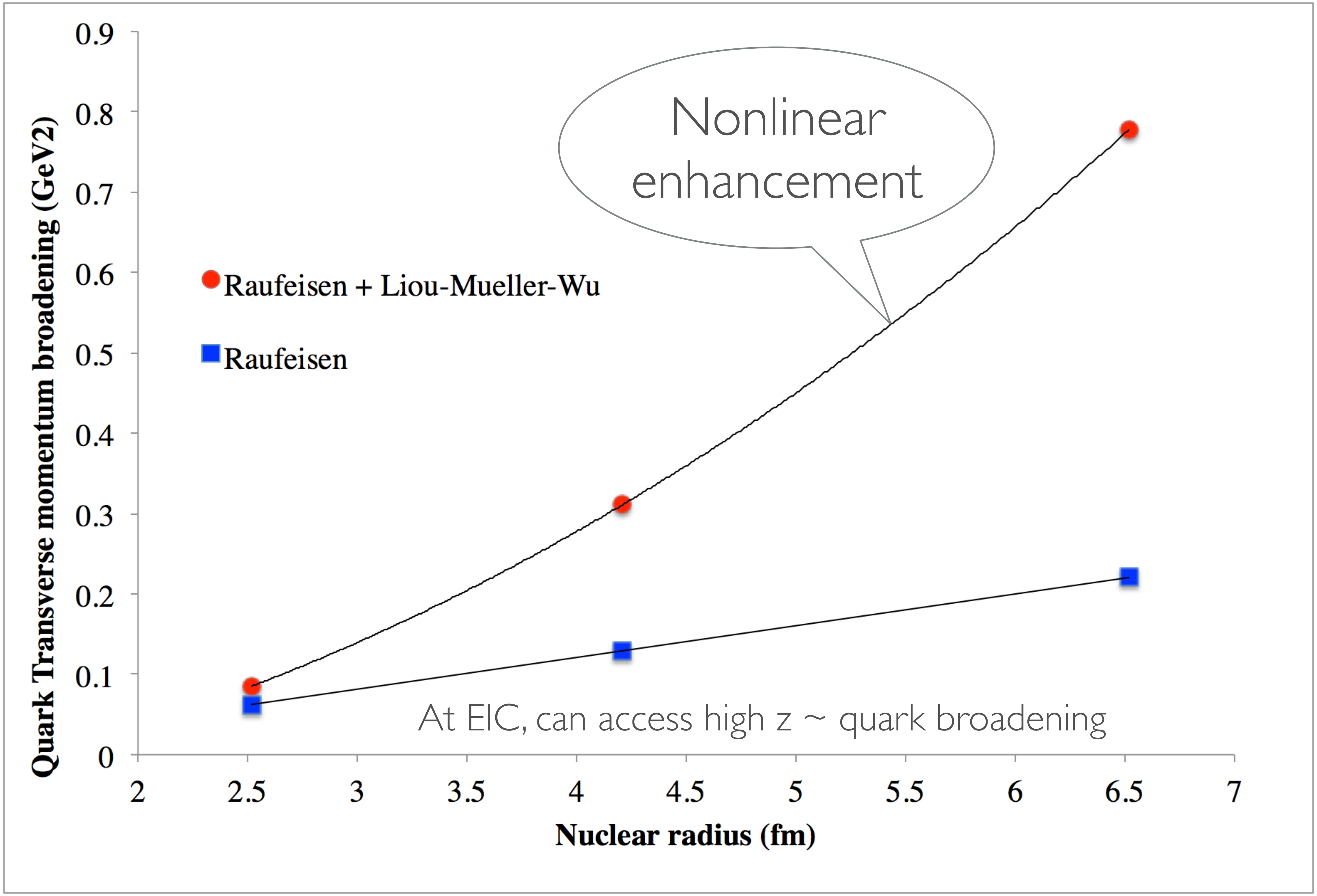
$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2 \;\; \propto \;\; \hat{q} \; L$$

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

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

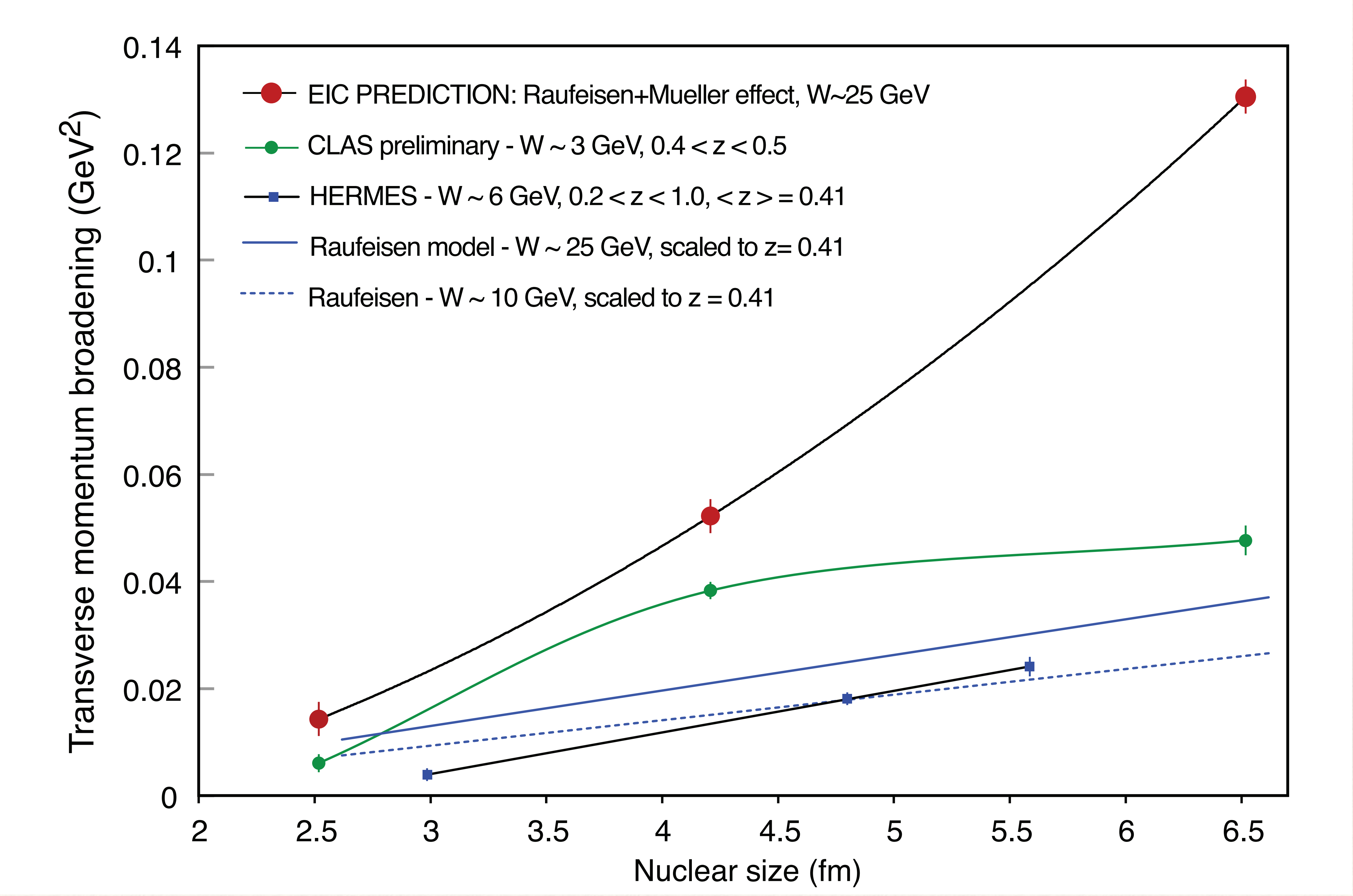
→ predicts a non-linear relationship between p_T broadening and L.
we can look for this at EIC!

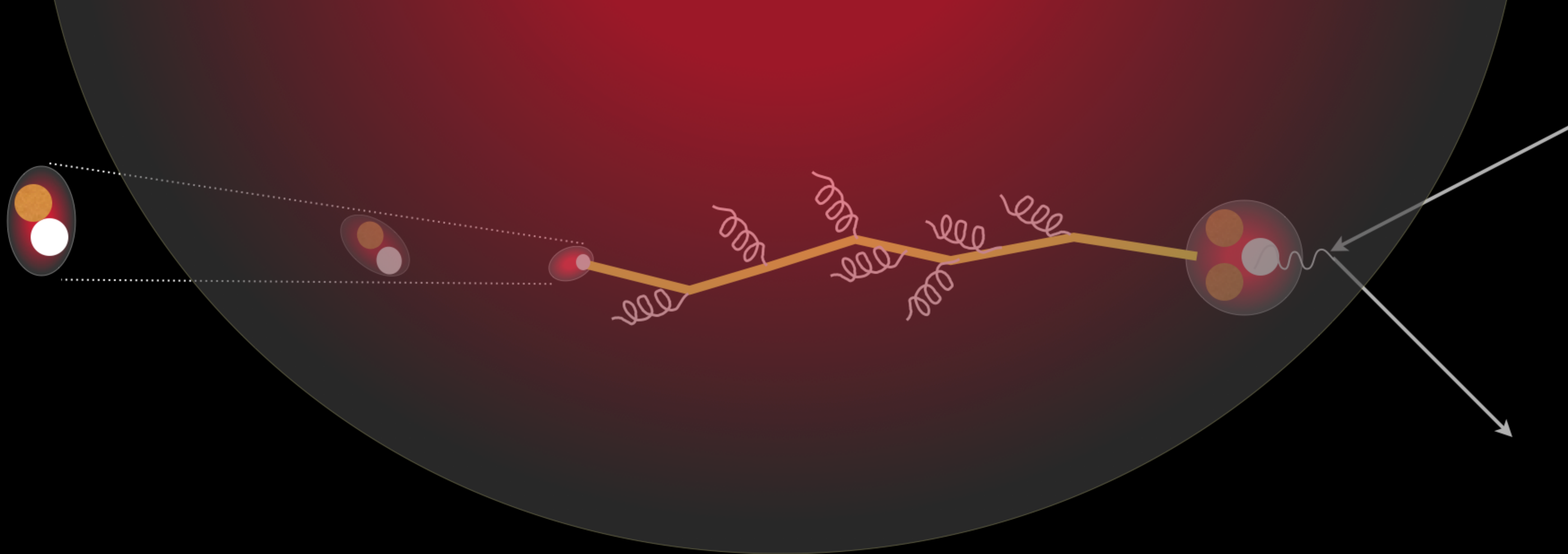
QUARK K_T BROADENING



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.

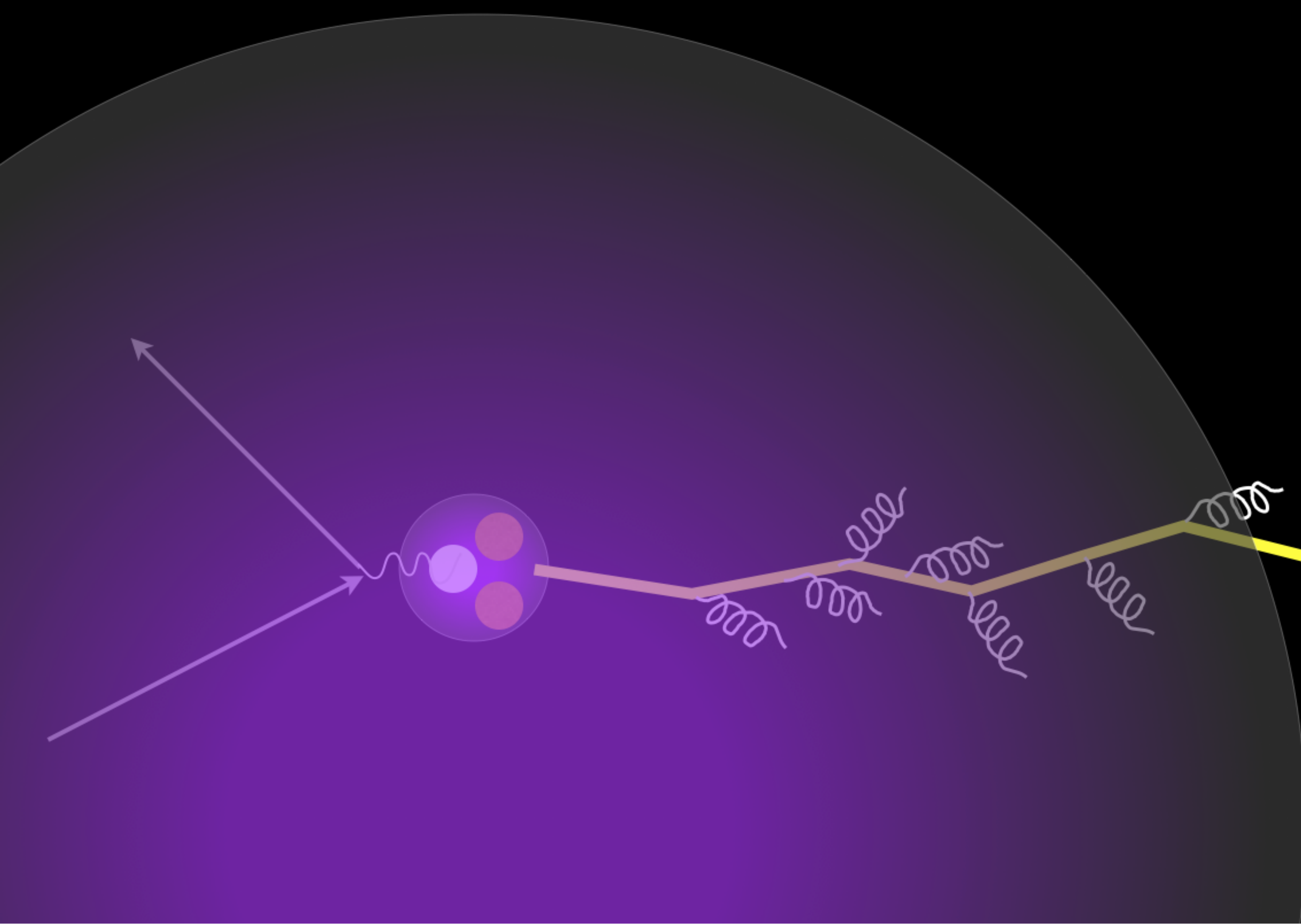
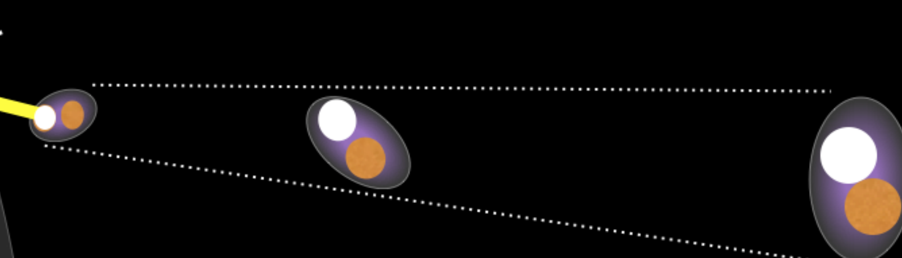
pQCD description of quark energy loss on p_T broadening





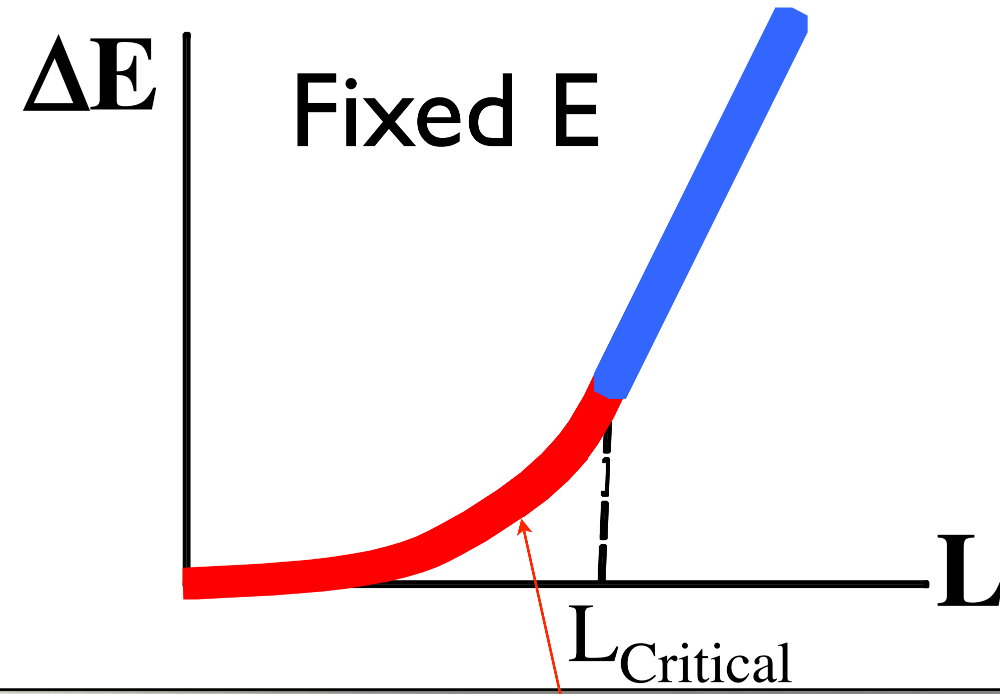
Direct measurement of quark energy loss

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

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

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

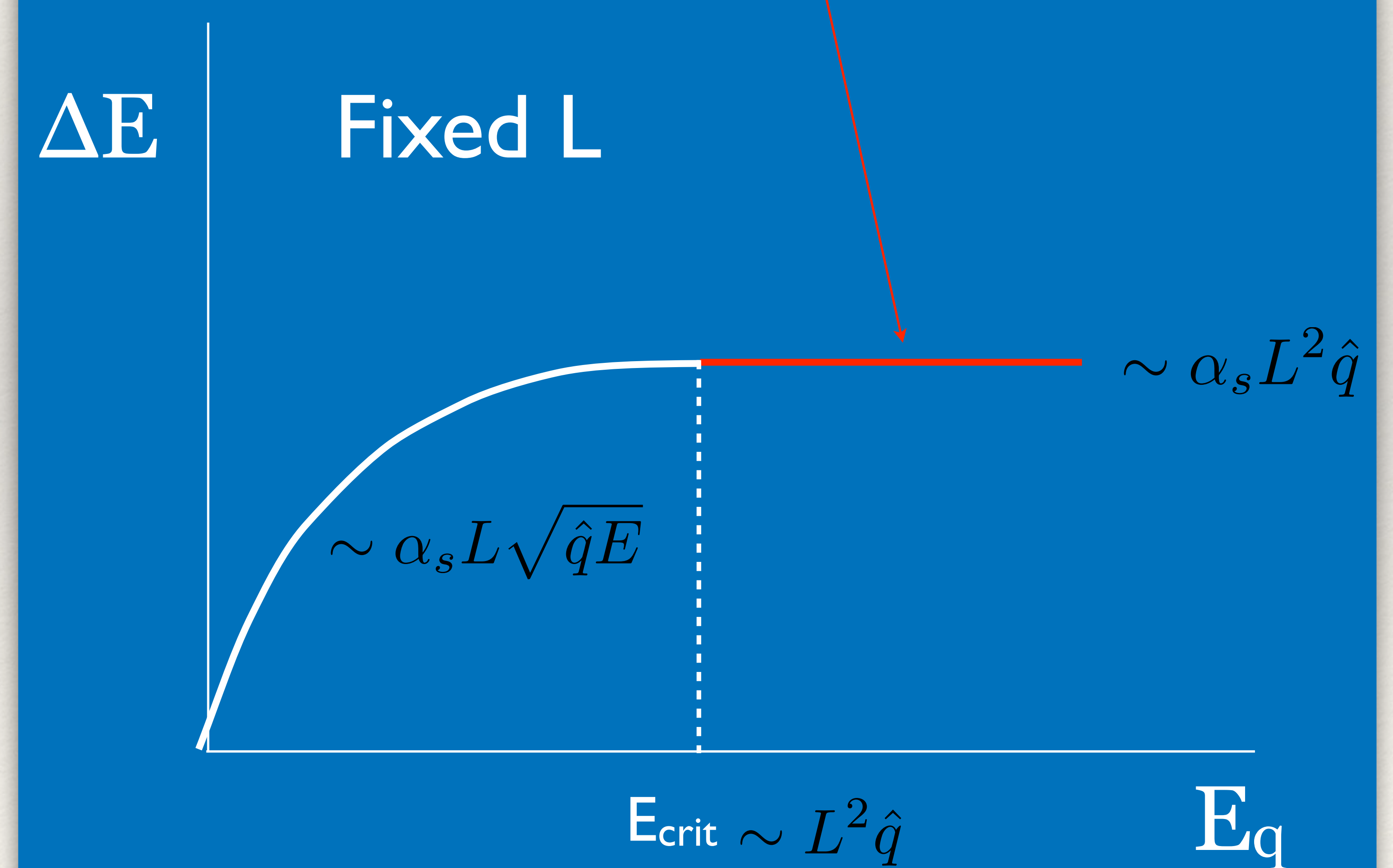


Partonic energy loss in pQCD (BDMPS-Z) exhibits a critical system length L_c and a critical energy E_c

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

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

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



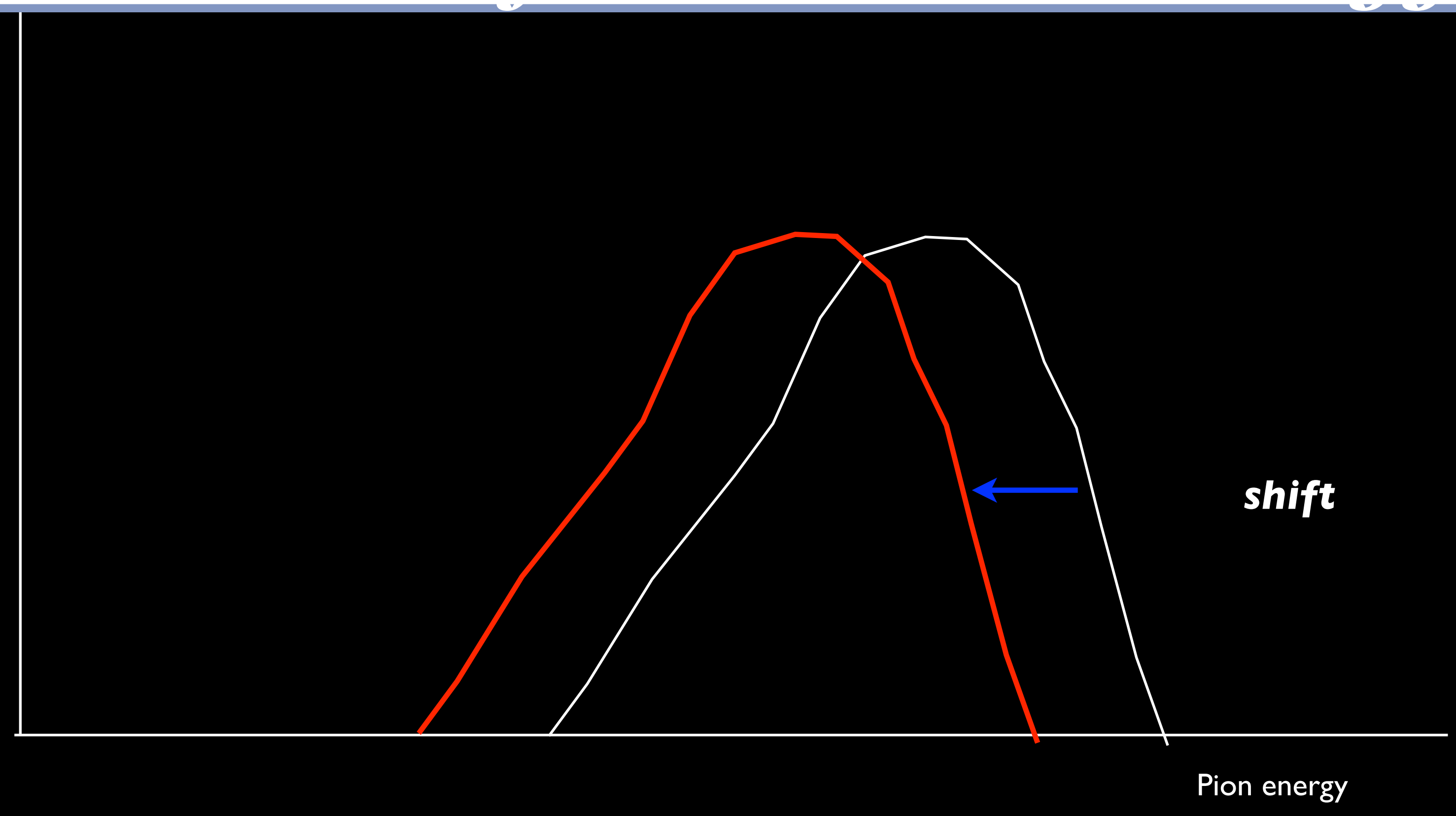
How to *directly* measure quark energy loss?

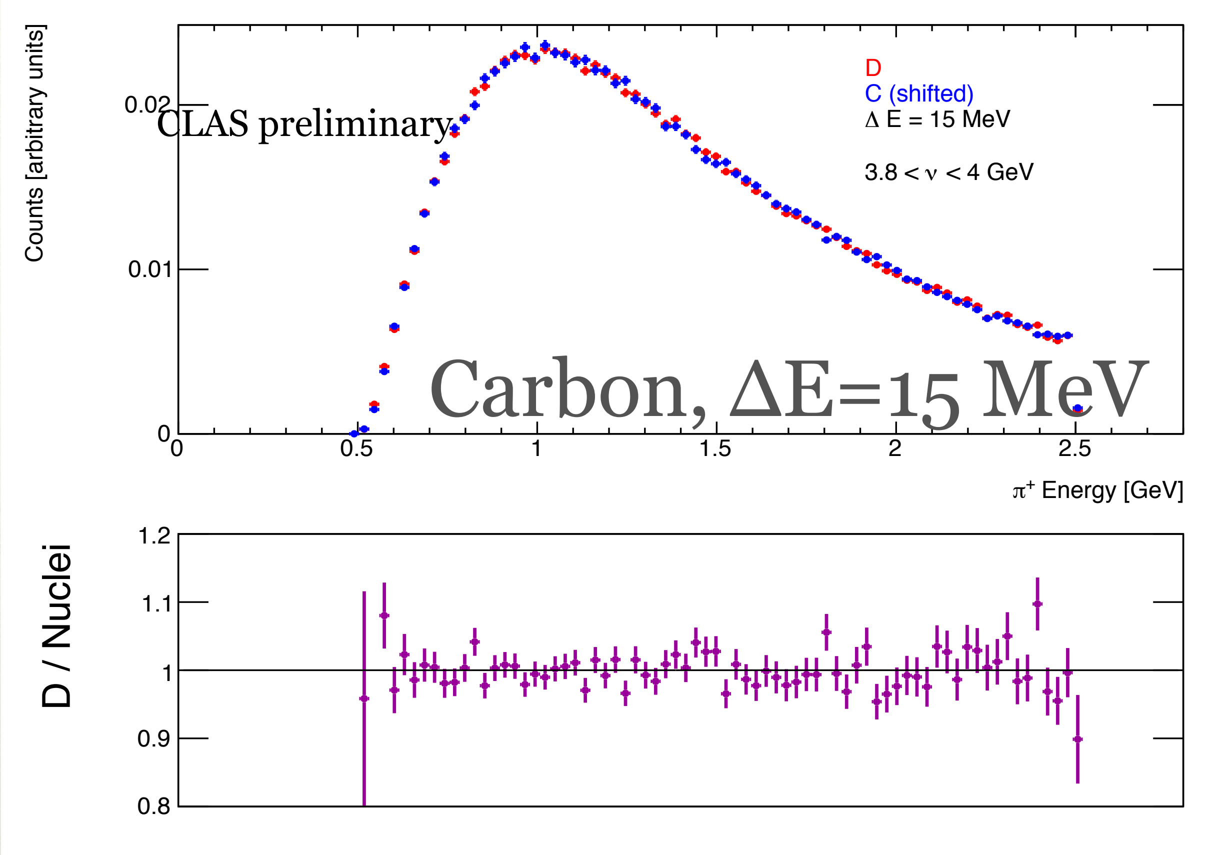
Energy loss: independent of energy for thin medium

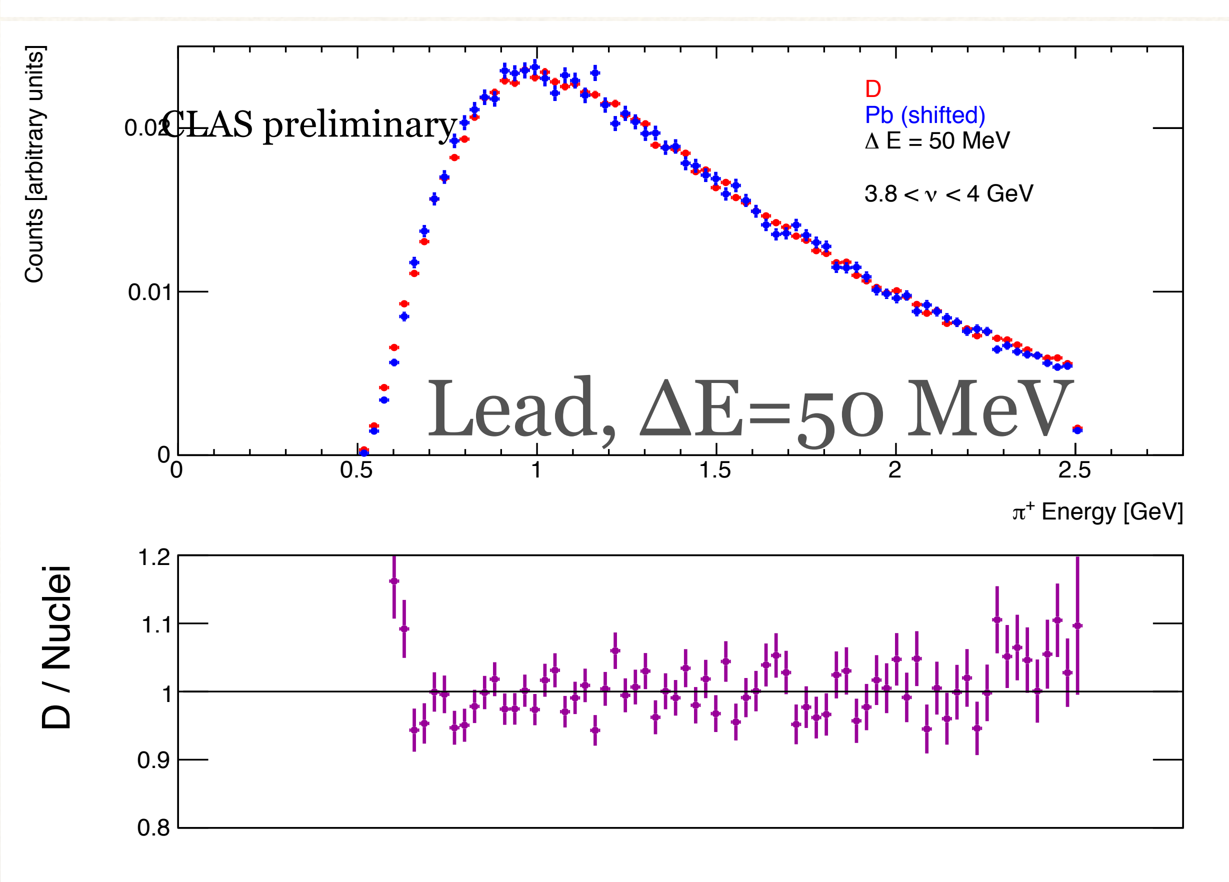
"Thin enough" depends on quark energy

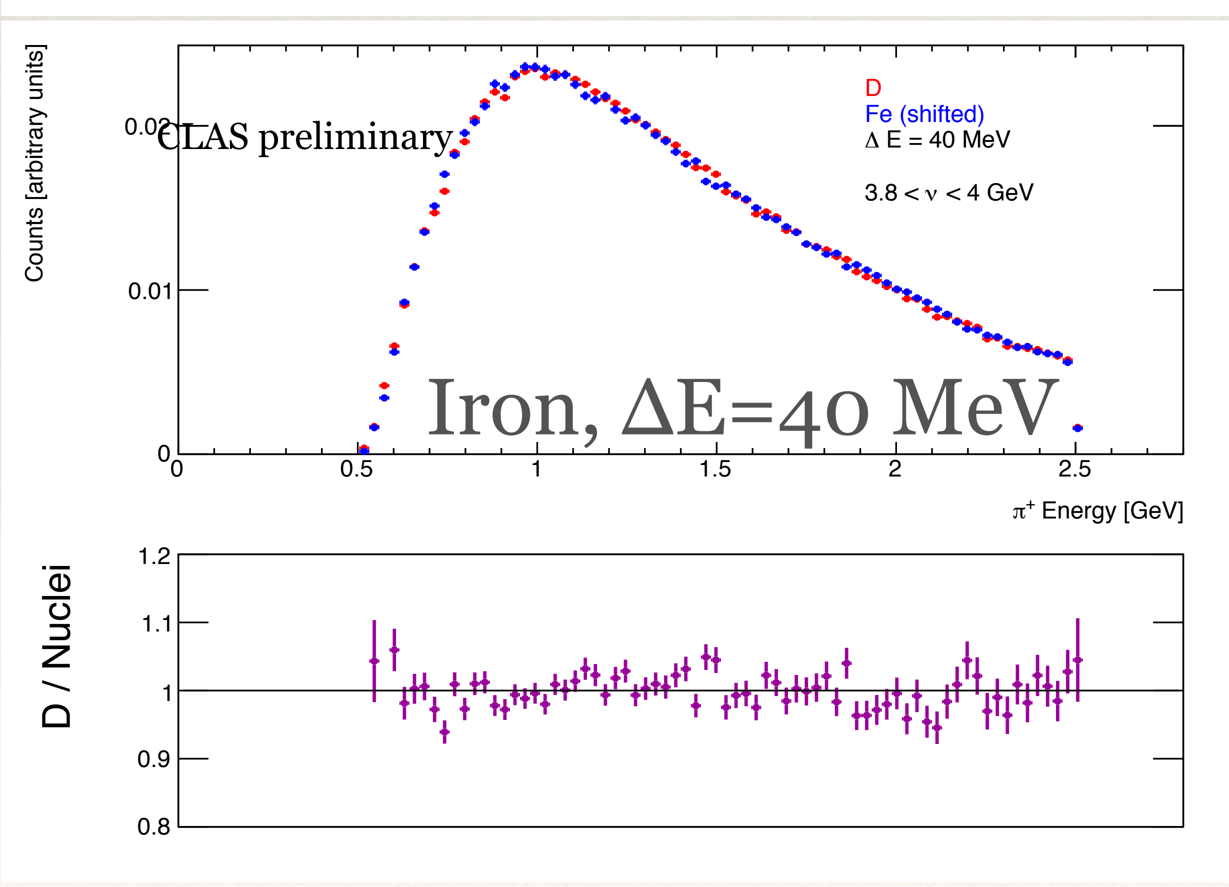
If energy loss is independent of energy, it will produce a shift of the energy spectrum, for higher energies.

We can look for a shift of the Pb energy spectrum compared to that of the deuterium energy spectrum







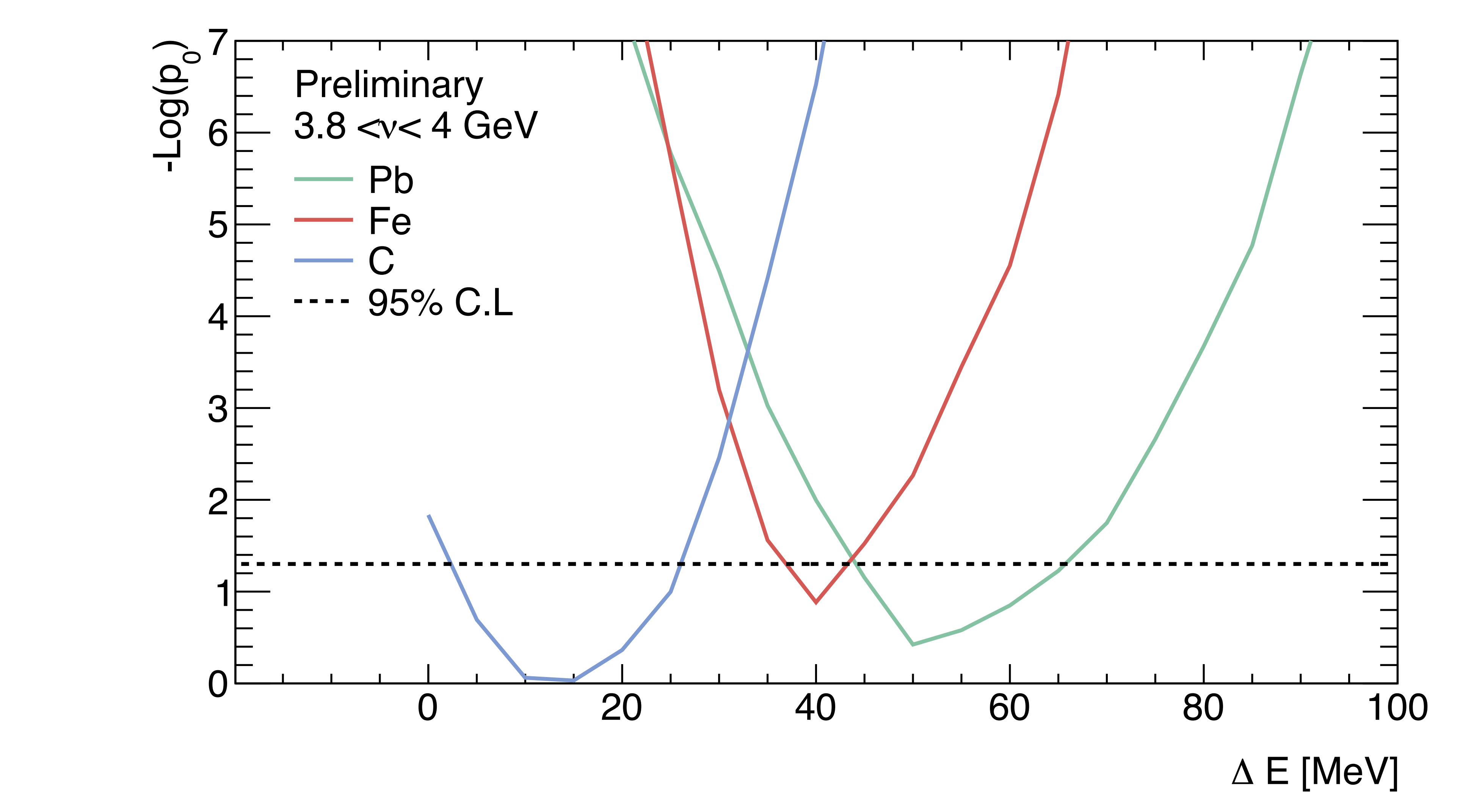


Energy spectrum of π^+ produced in C, Fe, Pb compared to that of deuterium, normalized to unity, with energy shifted by ΔE.

Acceptance corrected

Cut on X_F >0.1 is applied

Consistent with simple energy shift + unchanged fragmentation

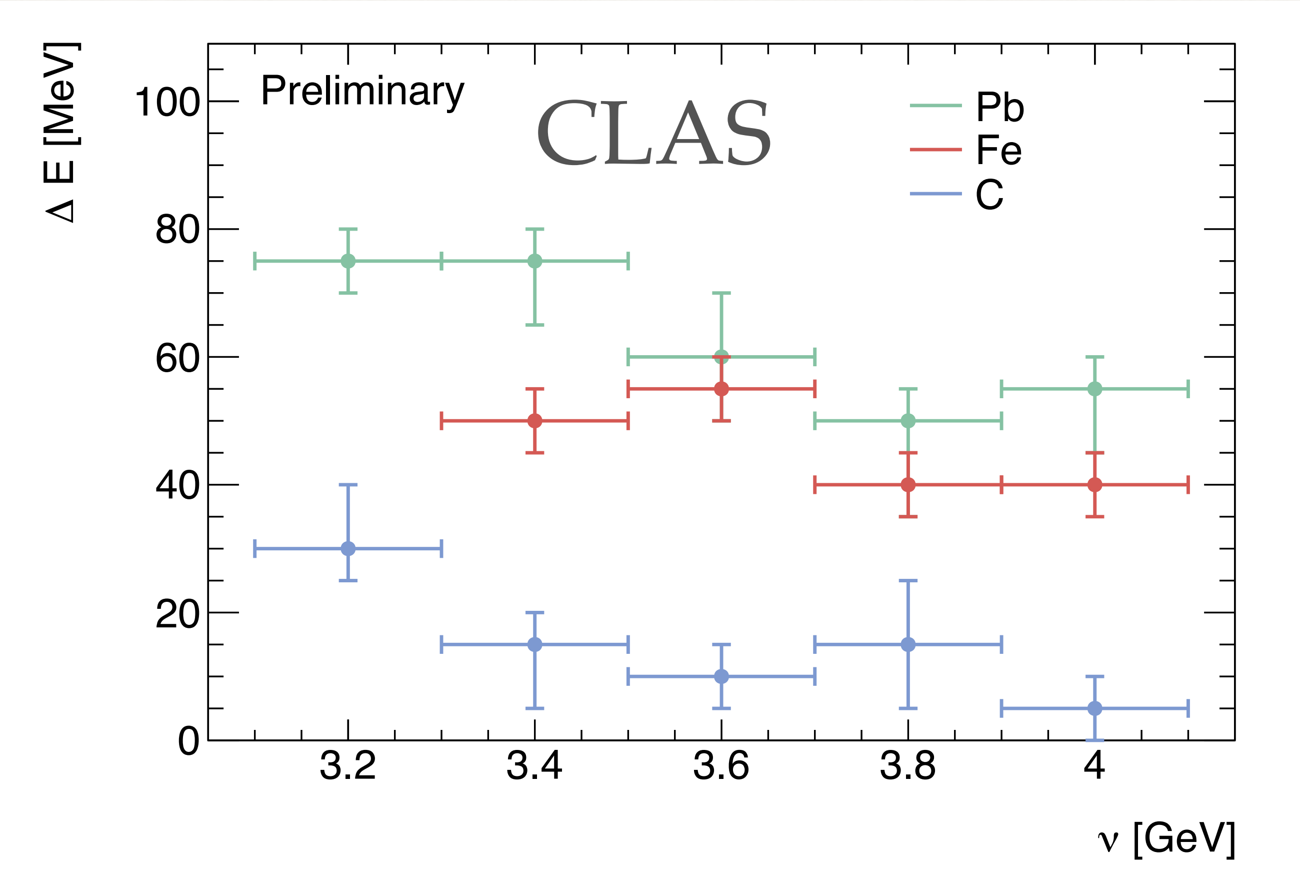


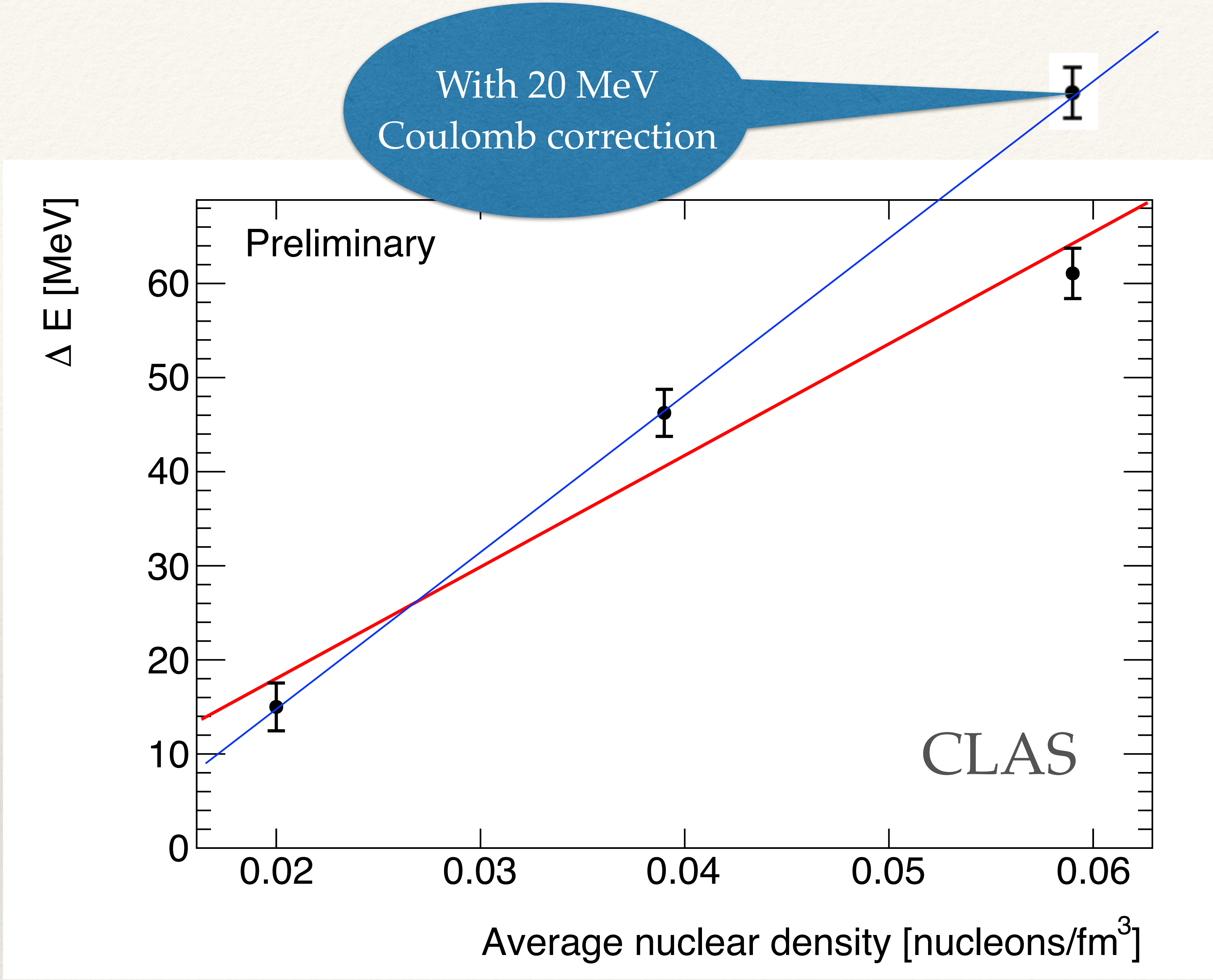
Log of p-values of Kolmogorov-Smirnov test as a function of energy shift ΔE: carbon, iron, lead.

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

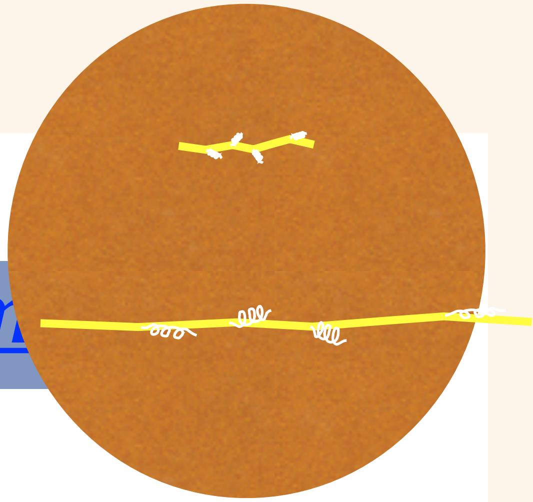
Range of possible energy shift in MeV obtained by Kolmogorov-Smirnov test in ν intervals





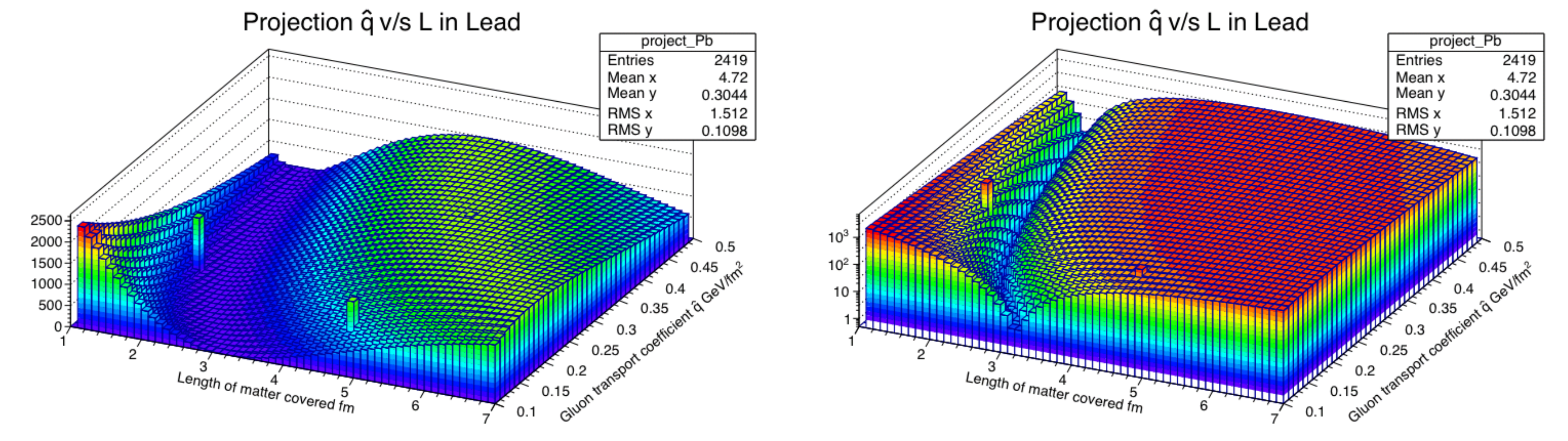
Approximately proportional to density, as expected.
(fixed pathlength)
Supports the premise that what we measure is ~energy loss!

Direct Measurement of Quark Energy Loss in CLAS: Conclusions



- ***It is small in magnitude. Why?***
  - ***Best explanation: short production tim***
  - ***>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)	$\chi^2_{/dof}$	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

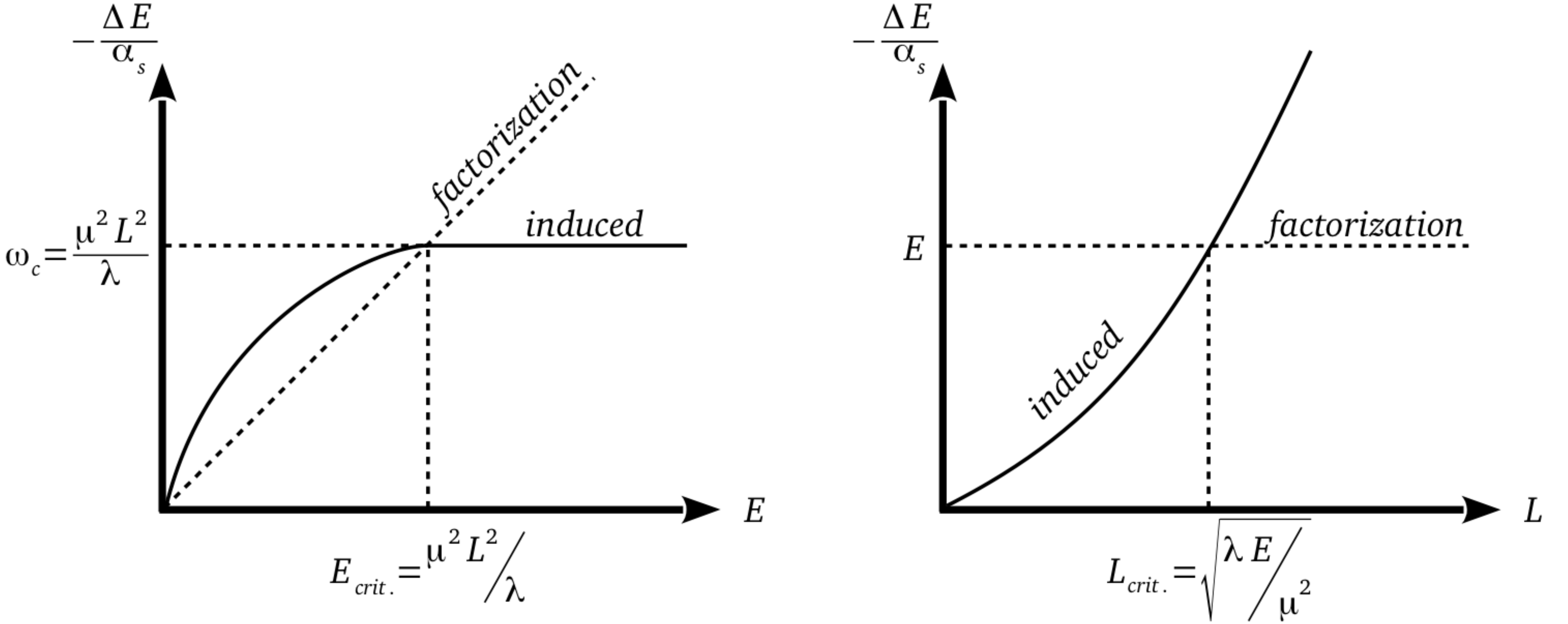


Figure 3.4: Schematic representation of total induced energy loss as a function of the parton energy E (left) and total induced energy loss as a function of the medium size L (right).

λ = mean free path for multiple scattering

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