pEMC and Color Propagation: Novel Aspects and Opportunities for the Future

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“Polarized EMC effect”

- **Approved experiment E-12-14001 (S. Kuhn, WB)**
  - **55 days, B^+ rating**
- ”Scheduled” for ~2022^{++}
- Requires some polarized target development studies - ongoing collaboration: USM Valparaíso, UNH, UVA, ODU, JLAB
  - ^{7}Li is target, = polarized proton + medium
  - ^{7}LiD and ^{6}LiH two-cell target: control systematics

The goal: to measure $R_{pol} = g^z_{1A}/g_{1N}$

https://www.jlab.org/exp_prog/proposals/14/PR12-14-001.pdf

https://arxiv.org/pdf/1510.00737.pdf

Some History

- 4/2005 pEMC featured in DOE 12 GeV Science Review
- 1/2006 PAC 29 considered two 6 GeV LOIs, responded negatively
- 2010 Submitted 12 GeV LOI 10-005 to PAC 35, positive response
- 2014 Submitted full proposal to PAC 42, approved

Theoretical Descriptions

- Constraints from Bjorken Sum rule in an extension of Gribov theory were used to describe 0.03<x<0.2, Vadim Guzey and Mark Strikman
- Quark-Meson Coupling Model (QMC), Ian Cloet, Wolfgang Bentz, Tony Thomas
  - quarks inside nucleons in nucleus interact through exchange of mesons (MIT bag, NJL)
  - related to earlier work by Tsushima, Saito, Ueda, Thomas (2002) on Li nuclides
- Chiral Quark Soliton Model, Jason Smith, Jerry Miller
  - quarks in nucleons (soliton) exchange pairs of pions, vector mesons with nuclear medium

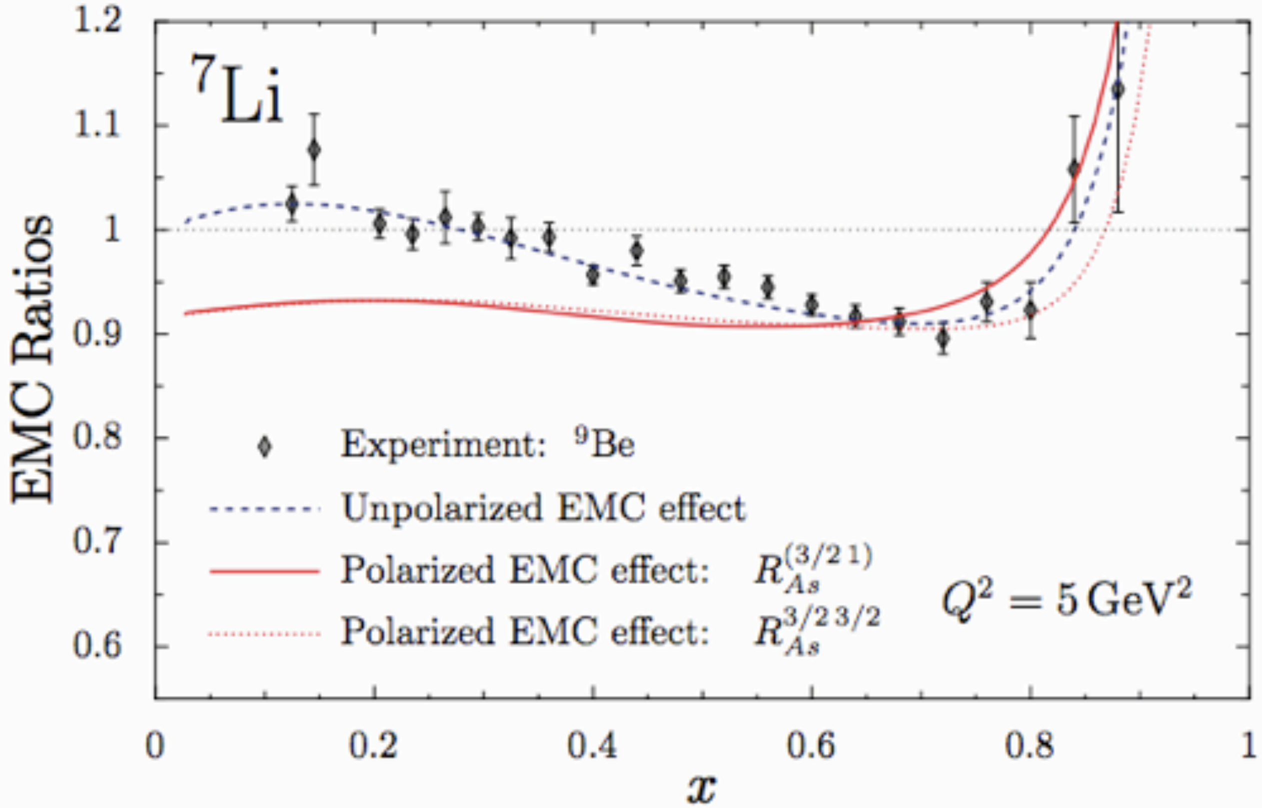

FIG. 6: The EMC and polarized EMC effect in ^{7}Li. The empirical data is from Ref. [31].

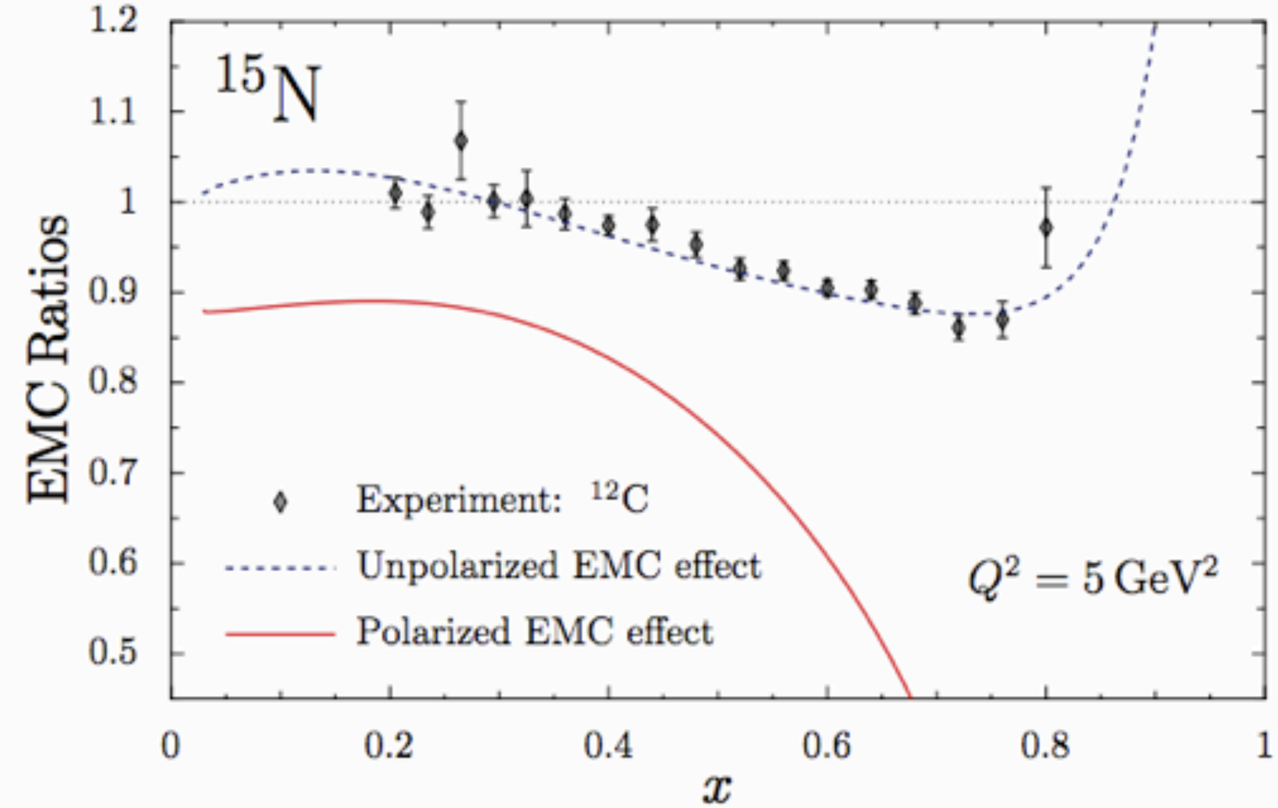

FIG. 8: The EMC and polarized EMC effect in ^{15}N. The empirical data is from Ref. [31].

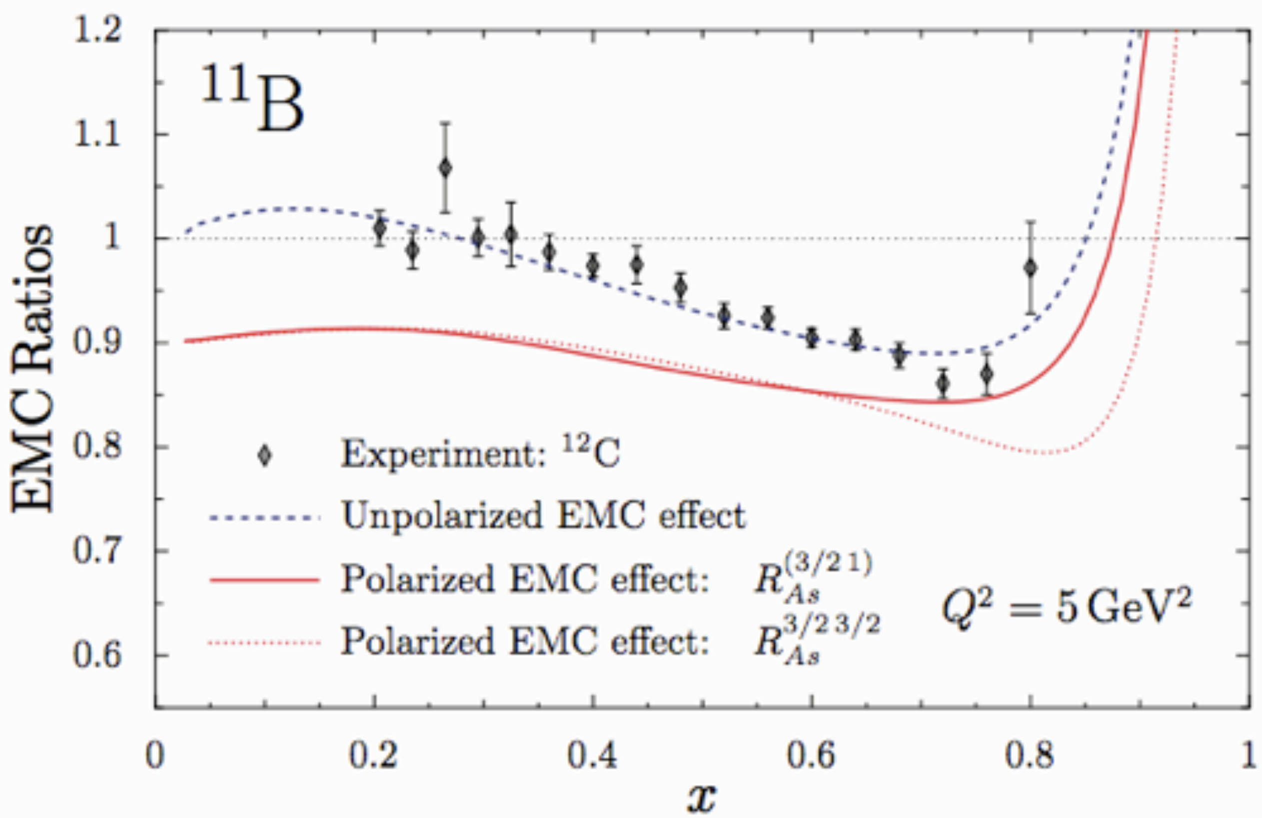

FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

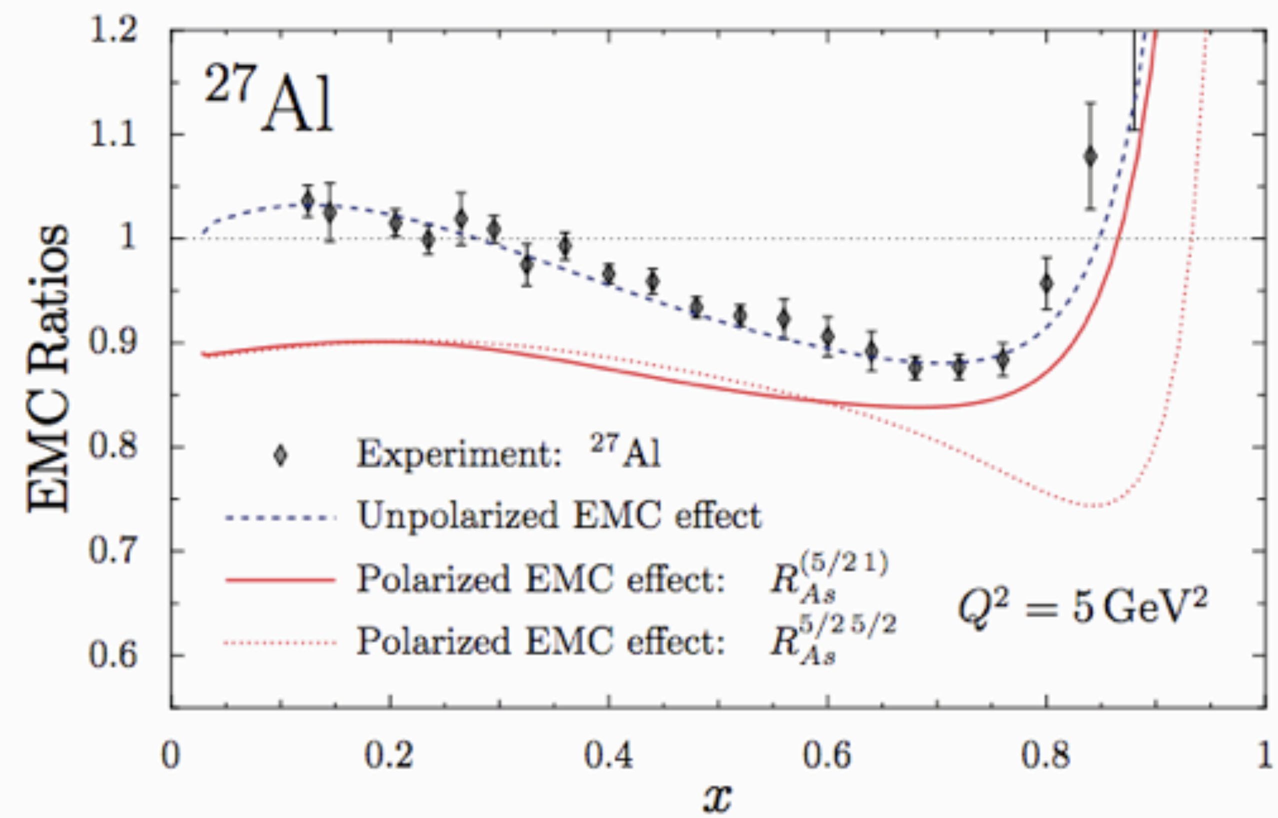

FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

I. C. Cloet, W. Bentz, A. W. Thomas, Phys.Lett. B642 (2006) 210-217

Valence only calculations consistent with Cloet, Bentz, Thomas calculations

Same model shows small effects due to sea quarks for the unpolarized case (consistent with data)

Miller, Smith

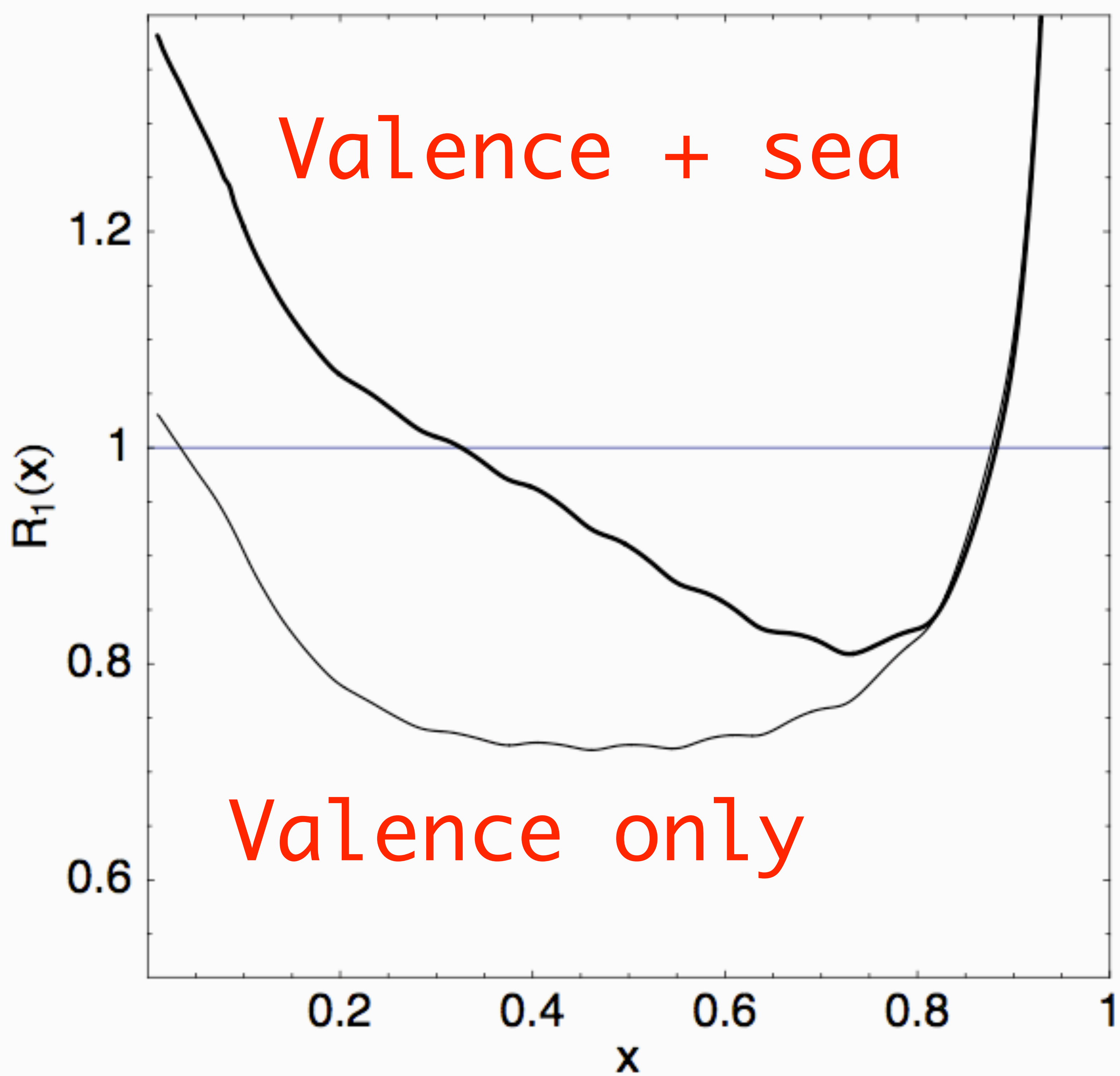

FIG. 1: The ratio Eq. (13) at scale $Q^2 = 10\ \mathrm{GeV}^2$ for nuclear matter. The heavy line is the full calculation for nuclear matter. The light line is the effect calulated using only medium modifications to the 'valence' energy level as decribed in the text.

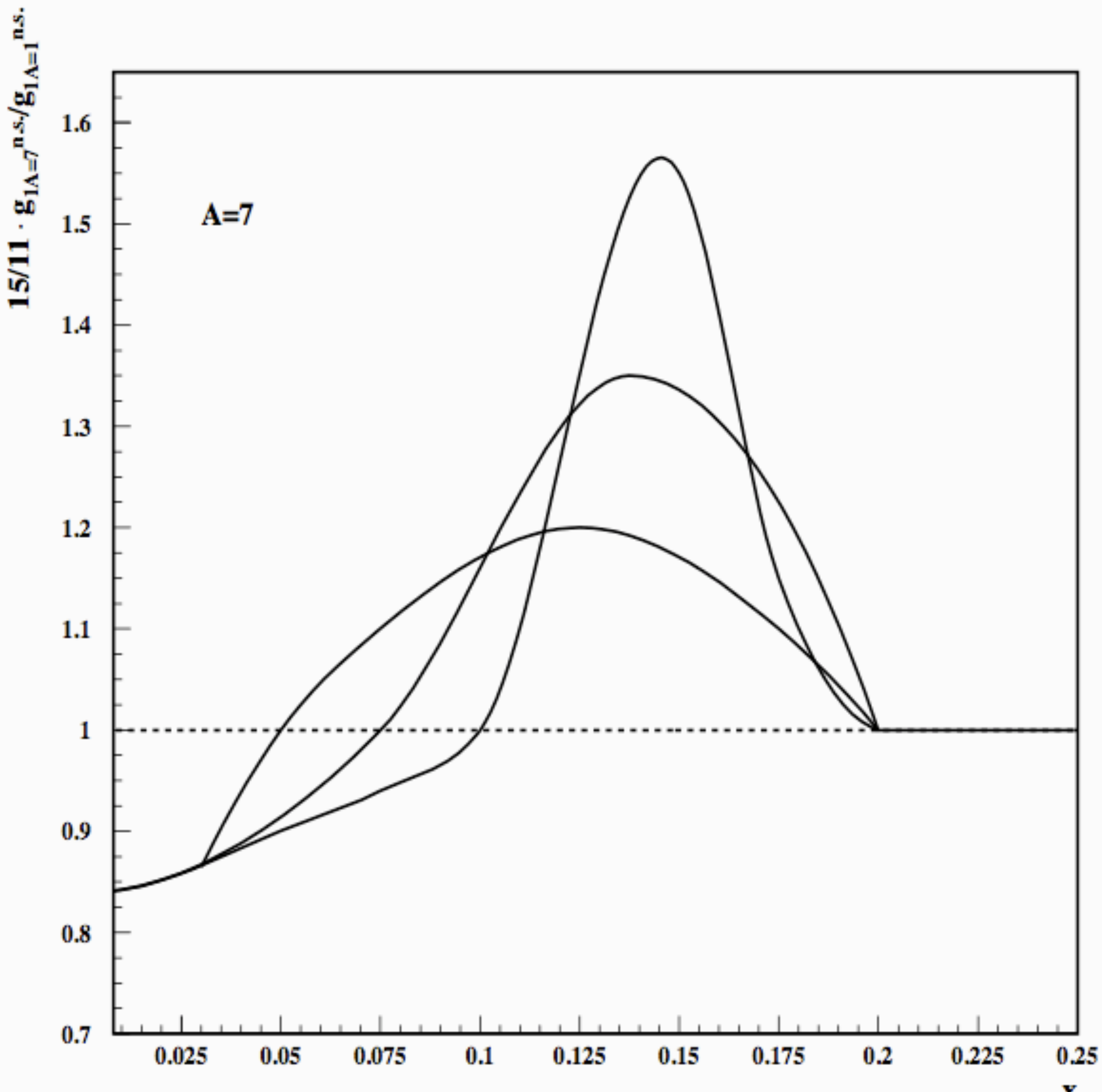

FIG. 1. $g_{1A=7}^{n.s.\,3/2}(x,Q^2)/g_{1A=1}(x,Q^2)$ as a function of x. The straight dashed line is the impulse approximation. The solid lines is a result of our calculation of shadowing and modeling of enhancement, which preserves R.

Constraints from Bjorken sum rule within an extension of Gribov theory

Ratio A=7/A=1 of non-singlet structure functions

Predict effects ranging from -15% to +50%

$$g_1^{3/2\,3/2}(x) \equiv \frac{1}{2}(q_\uparrow^{3/2\,3/2}(x) - q_\downarrow^{3/2\,3/2}(x))$$
$$g_1^{1/2\,1/2}(x) \equiv \frac{1}{2}(q_\uparrow^{3/2\,1/2}(x) - q_\downarrow^{3/2\,1/2}(x))$$

V. Guzey and M. Strikman, Phys.Rev. C61 (2000) 014002

How does it work?

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- In a polarized target, the nucleus is polarized overall

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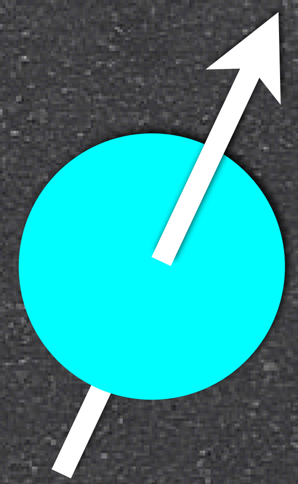

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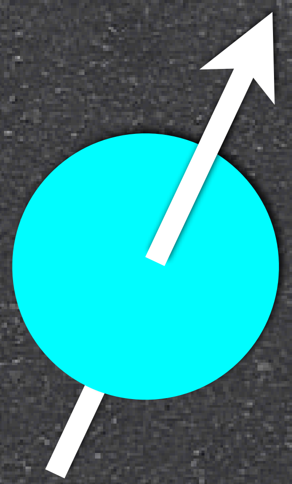

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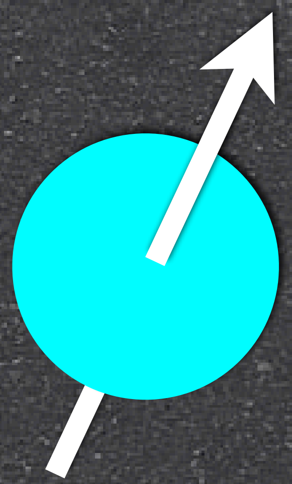

- Within the nucleus, the spins of specific nucleon states are aligned to varying degrees with the spin of the overall nucleus

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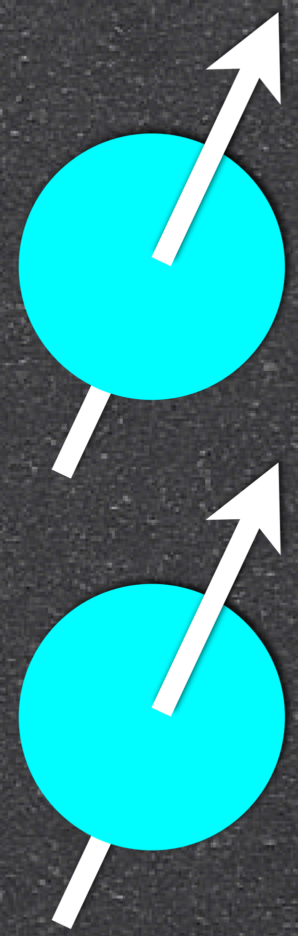

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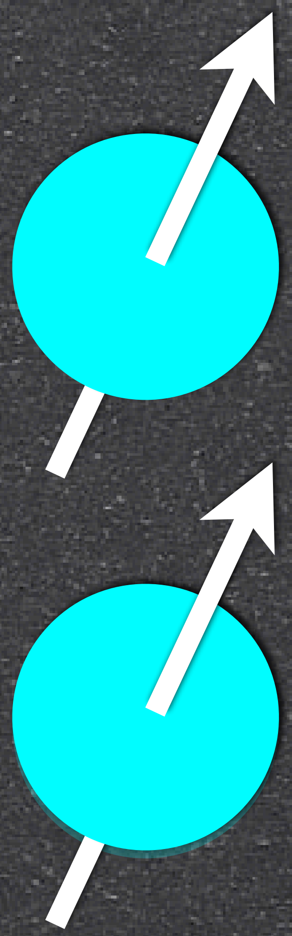

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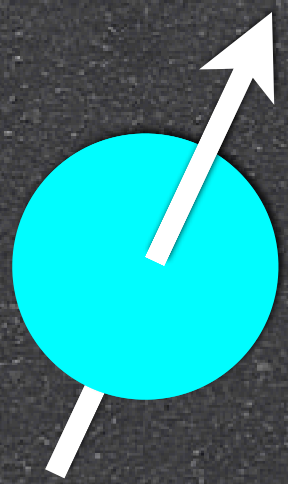

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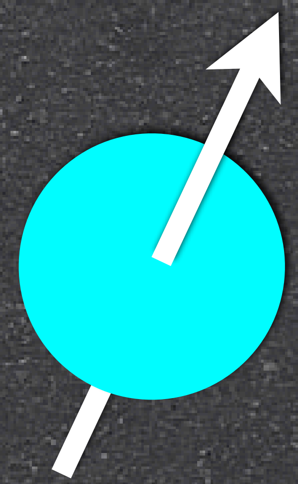

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    - thus, have polarized nucleons within the medium

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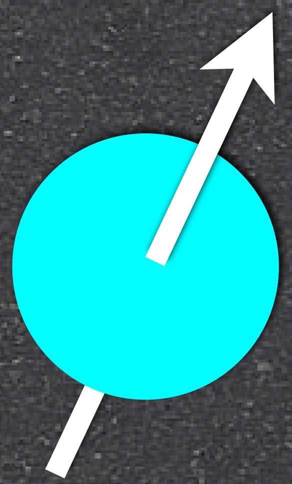

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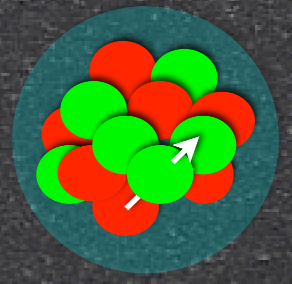


    - thus, have polarized nucleons within the medium

Probabilities for parallel spin of nucleon and nucleus

Nucleus	x	
D	0.927 ± 0.015	[7,9]
^{6}Li	0.866 ± 0.012	[8]
$^{7}Li_{p}$	~~0.596 ± 0.03~~ → 0.89*	[9–11]
$^{7}Li_{n}$	-0.02 ± 0.02	[9]

"Effective densities and polarizations of the targets for the GDH-experiments at MAMI and ELSA," Ch. Rohlof and H. Dutz, NIM A 526 (2004) 126

* Incorrect value often quoted in literature, per I. Cloet and V. Guzey. Correct number is ~0.89, even better for the experiment.

$g_1(A)$ – "Polarized EMC Effect" – Some Solid Target Possibilities

Nuclide	**Compound**	**Polarization (%)**
^{6}Li	^{6}LiD	45
^{7}Li	**^{7}LiD**	**90**
^{11}B	$C_2N_2BH_{13}$	75
^{13}C	$^{13}C_4H_9OH$	65
^{19}F	LiF	90

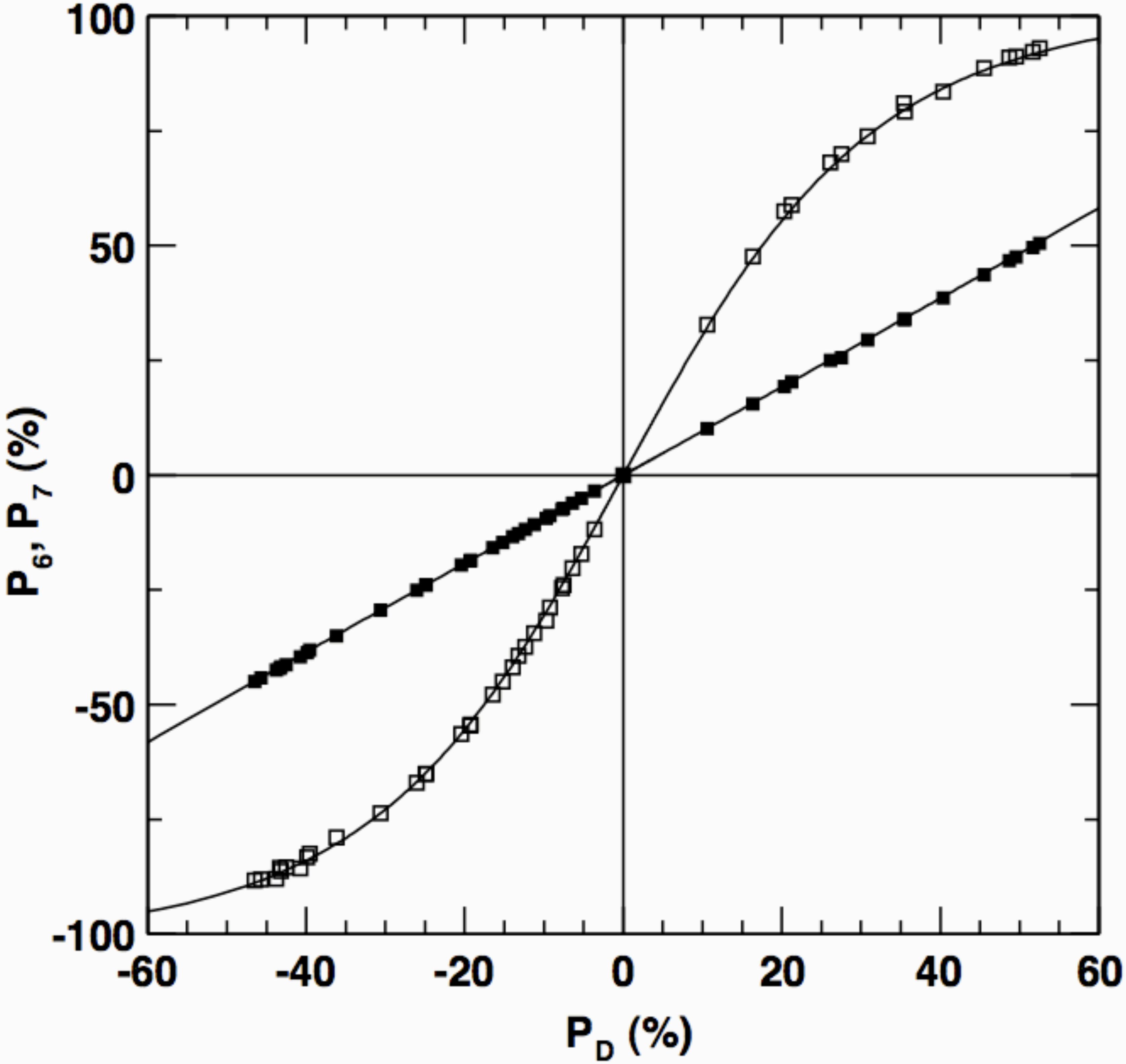


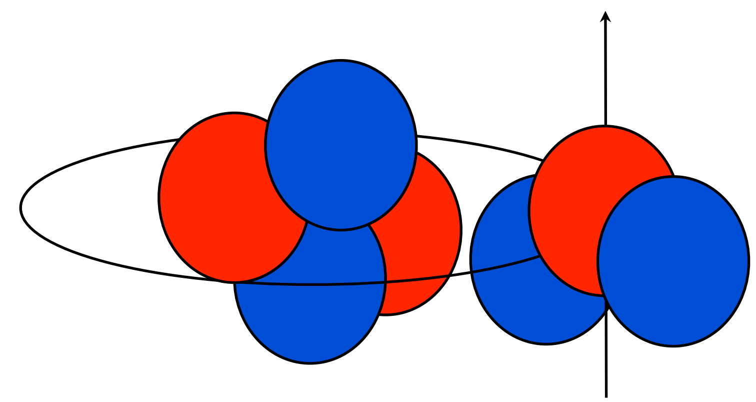
Fig. 6. The polarizations of the ^{6}Li and the ^{7}Li nuclei versus that of the deuteron. The closed (open) squares are the measured polarization of ^{6}Li (^{7}Li). The lines are the prediction by EST concept. The measurements are consistent with the EST concept.

First results of the large COMPASS 6LiD polarized target
J. Ball et al., NIM A498(2003)101

$g_1(A)$ – "Polarized EMC Effect" – ^7Li as Target

Shell model: 1 unpaired proton, 2 paired neutrons in $P_{3/2}$, closed $S_{1/2}$ shell.

Cluster model: triton + alpha



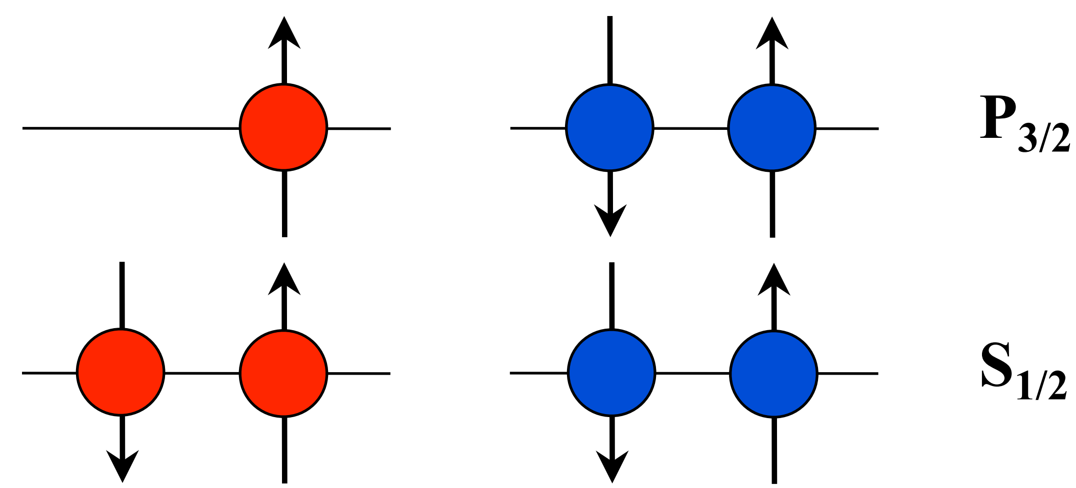
^7Li polarization: >90%

Nucleon polarization calculations:

Cluster model: 86%

GFMC: 89%

89% x 90% = 80%



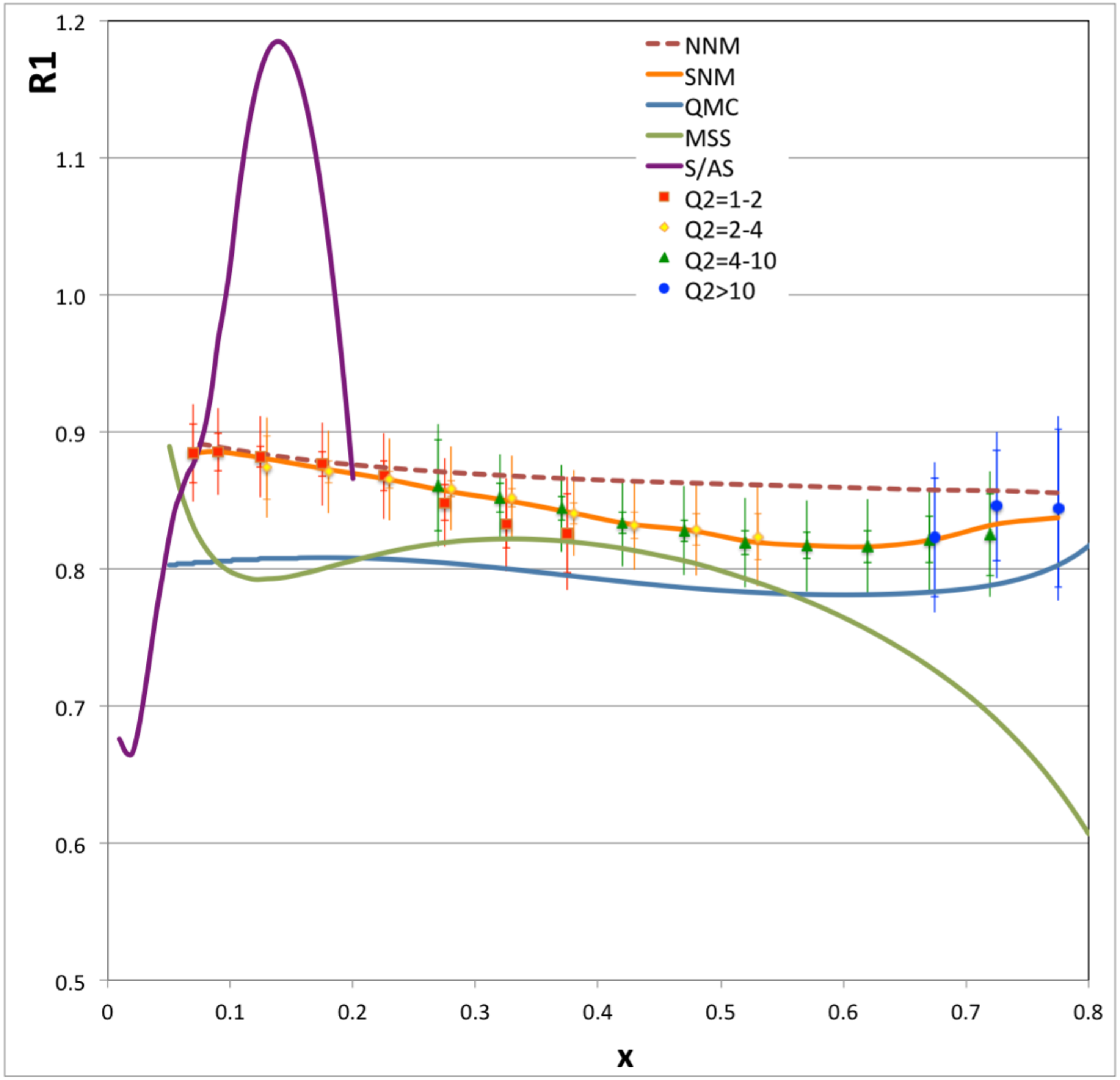
Proton embedded in ^7Li with over 80% polarization!

$$R_1 = \frac{[d\sigma^+ - d\sigma^-]_{^7\mathrm{Li}}}{[d\sigma^+ - d\sigma^-]_p} = \frac{g^z_{1\,^7\mathrm{Li}} + \frac{P_{zzz}}{P_z} g^{zzz}_{1\,^7\mathrm{Li}} + C_{^7\mathrm{Li}}(A_2)}{g^p_1 + C_p(A_2)}$$

$$g^z_{1A} = \frac{9}{10} g_{1A}^{3/2\ +3/2} + \frac{3}{10} g_{1A}^{3/2\ +1/2}$$

$$R_{pol} = g^z_{1A}/g_{1N}$$

Precision of expected results



NNM = Naive nuclear model (just counting percentage of polarization, and dilution factor, no Fermi motion); SNM = Standard Nuclear Model (nucleons-only); QMC = CBT (Cloet Bentz Thomas); MSS = H. Fanchiotti, C. Garca-Canal, T. Tarutina, and V. Vento, (2014), arXiv:1404.3047 [hep-ph]; S/AS=shadowing/antishadowing (Guzey-Strikman).

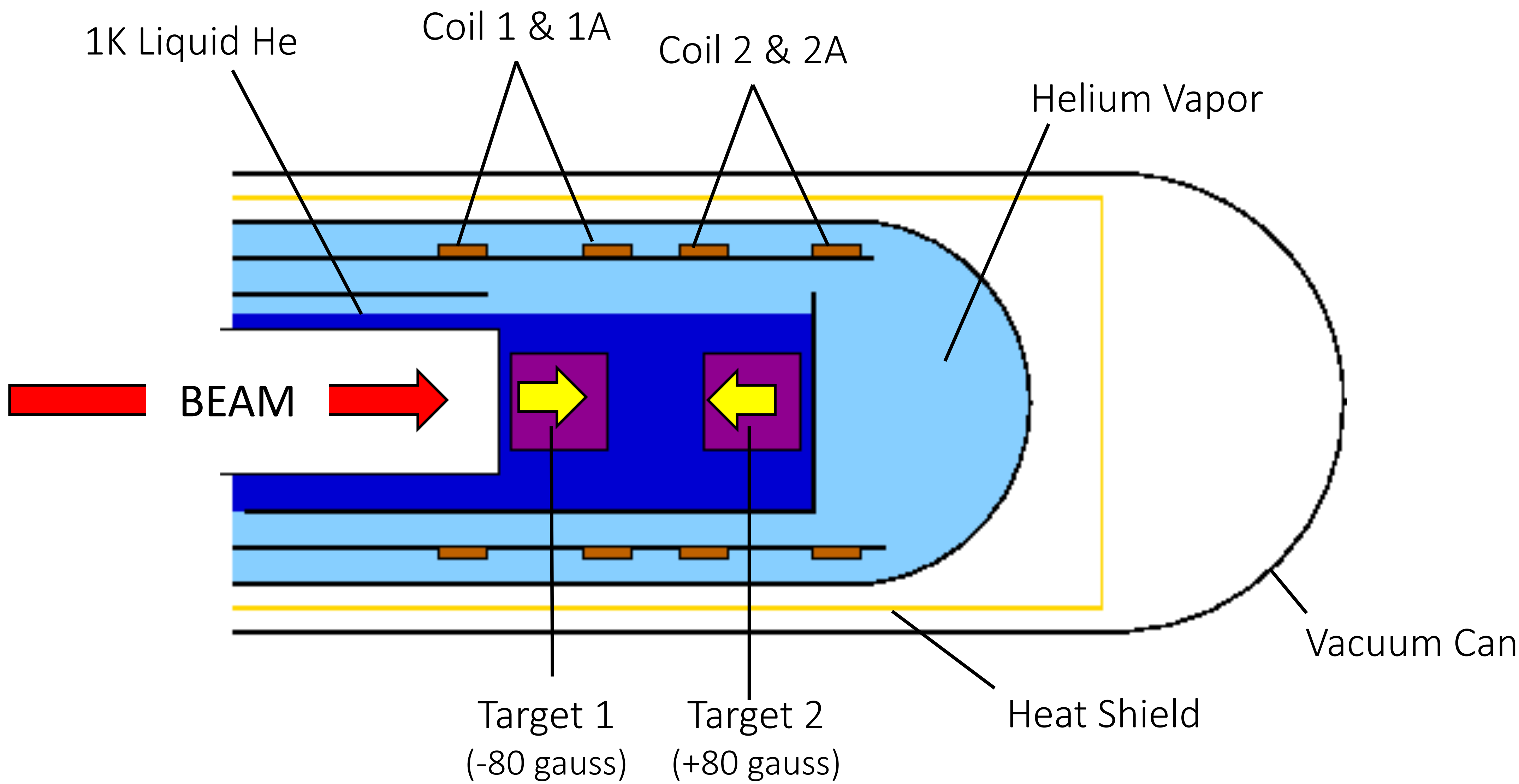
Systematic uncertainties

Source	Rel. unc. on R_1	Rel. unc. on R_2
Dilution	2%	–
Acceptance	–	2%
Polarized background	1% – 3%	1% – 3%
Model uncertainties	1%	1%
Radiative corrections	2%	2%
Total	3.2% – 4%	3.2% – 4%

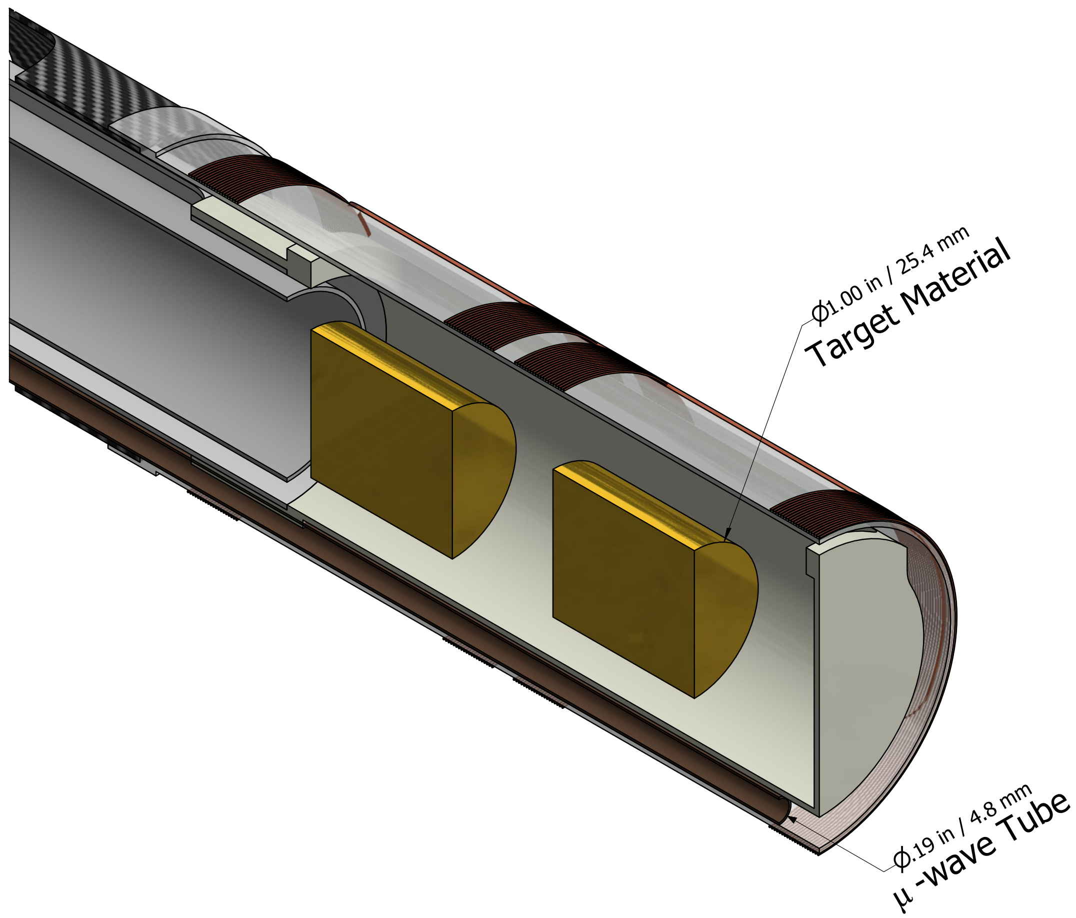
4% scale uncertainty not listed
Ranges indicate low x to high x

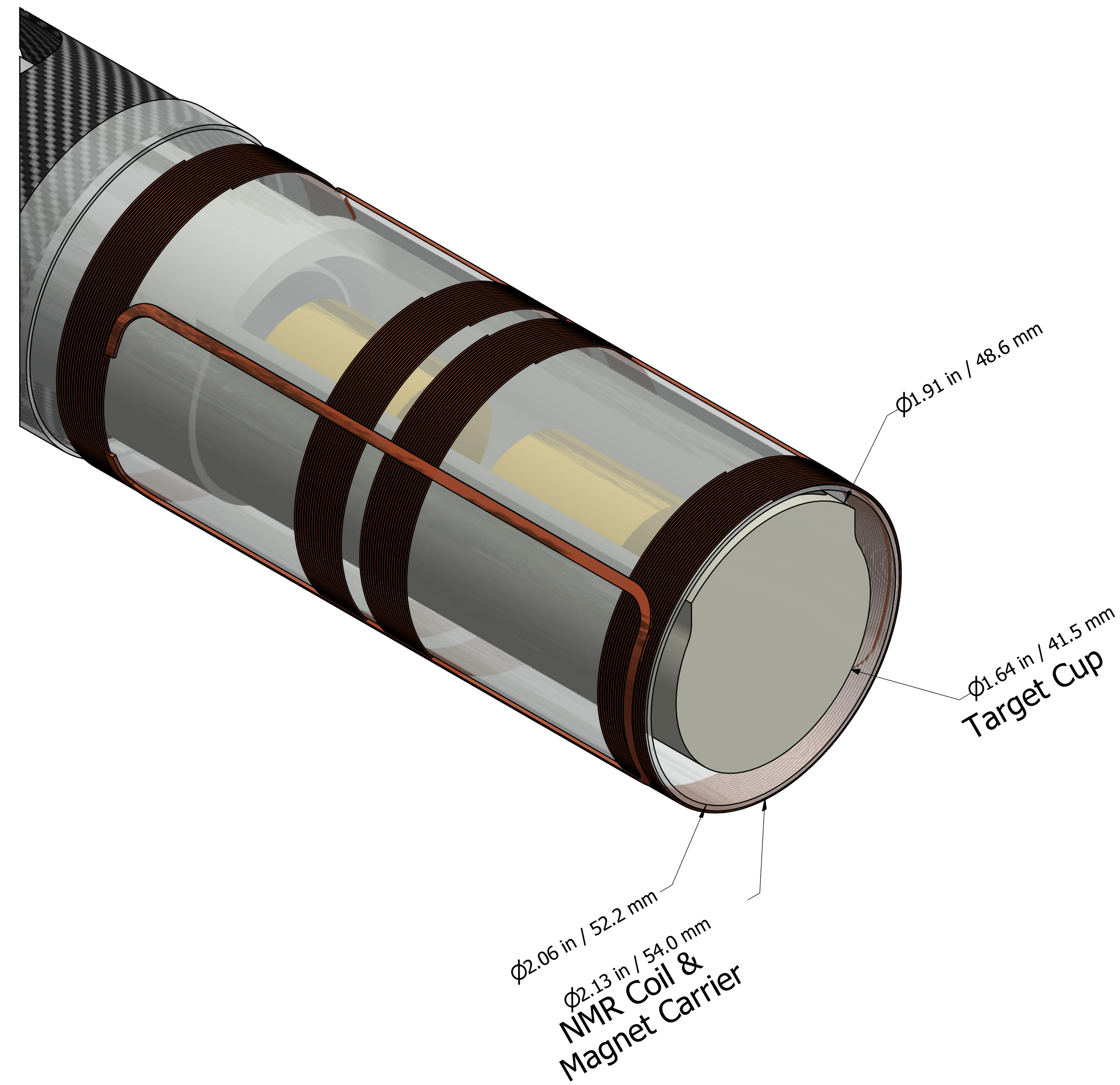
CLAS12 Polarized Target: two target cells

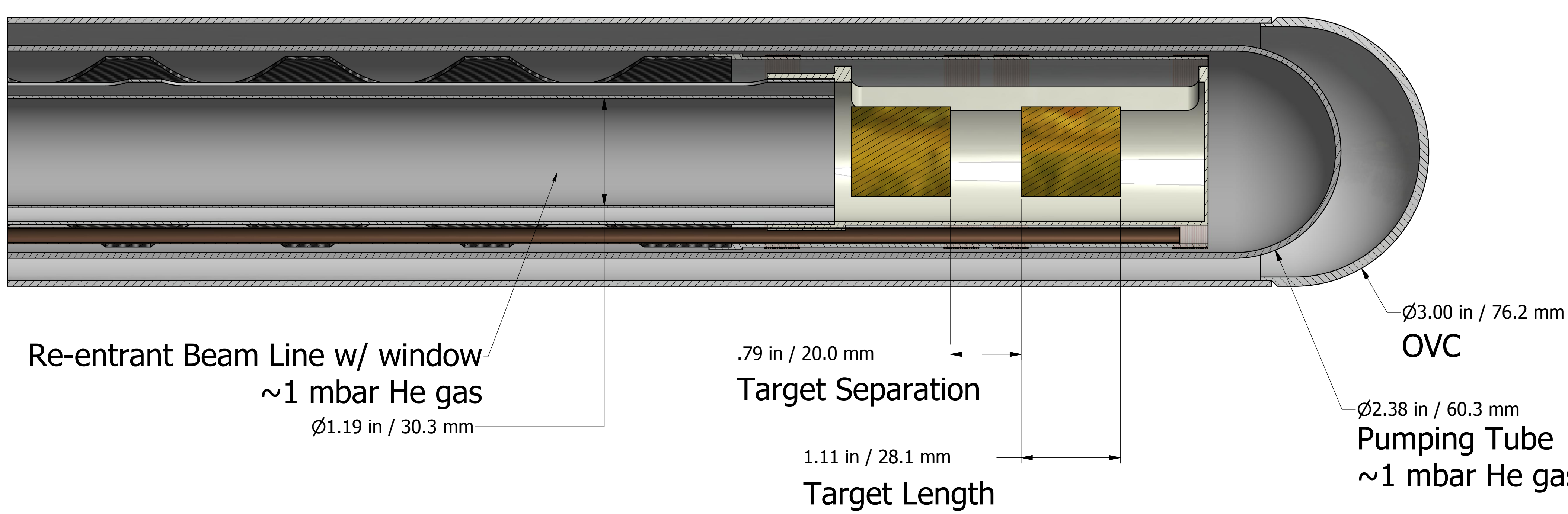
We can adjust the CLAS12 field with ± 80 gauss shim coils and simultaneously polarize two samples in opposite directions.



From Chris Keith



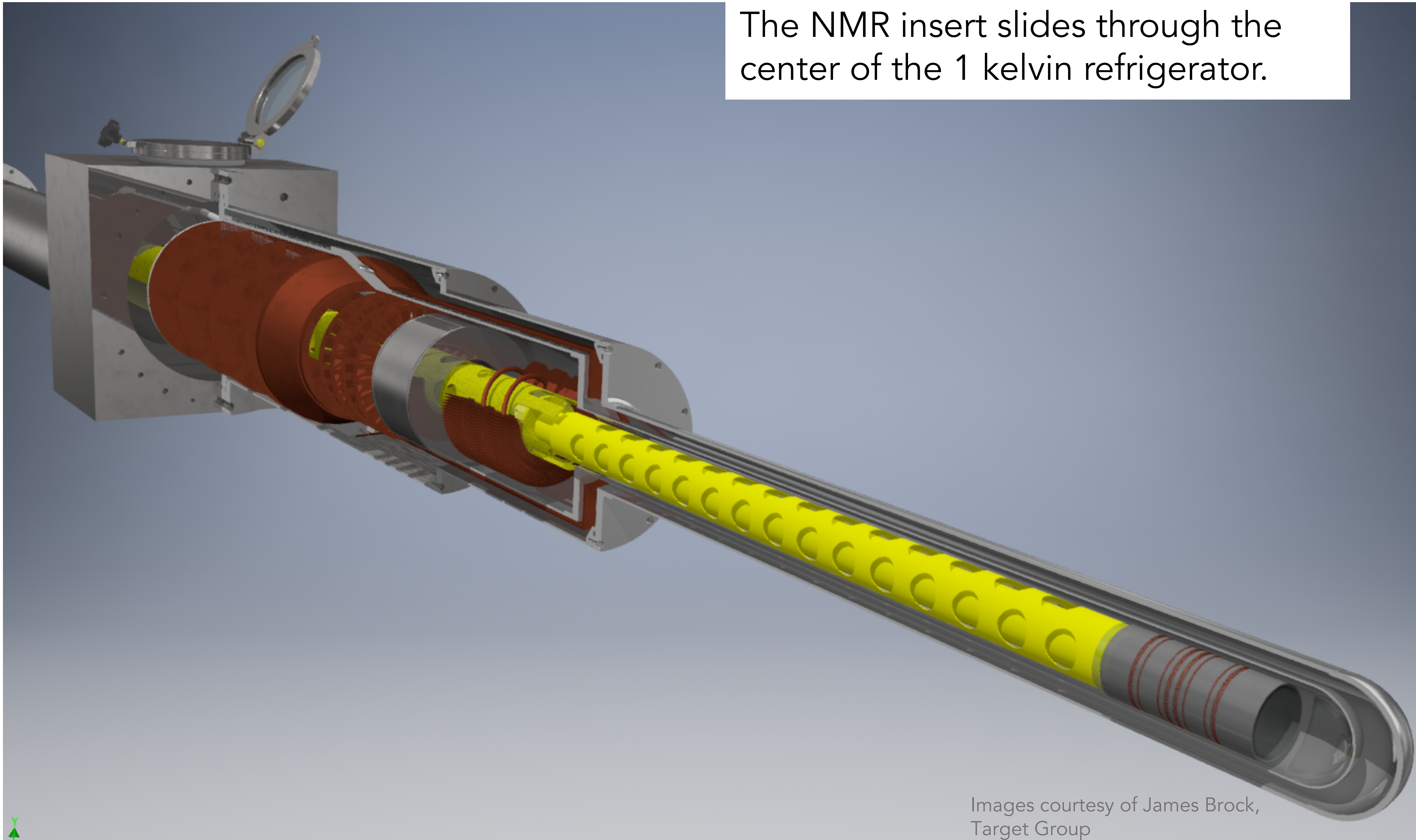




From Chris Keith

CLAS12 Polarized Target: 1 kelvin refrigerator

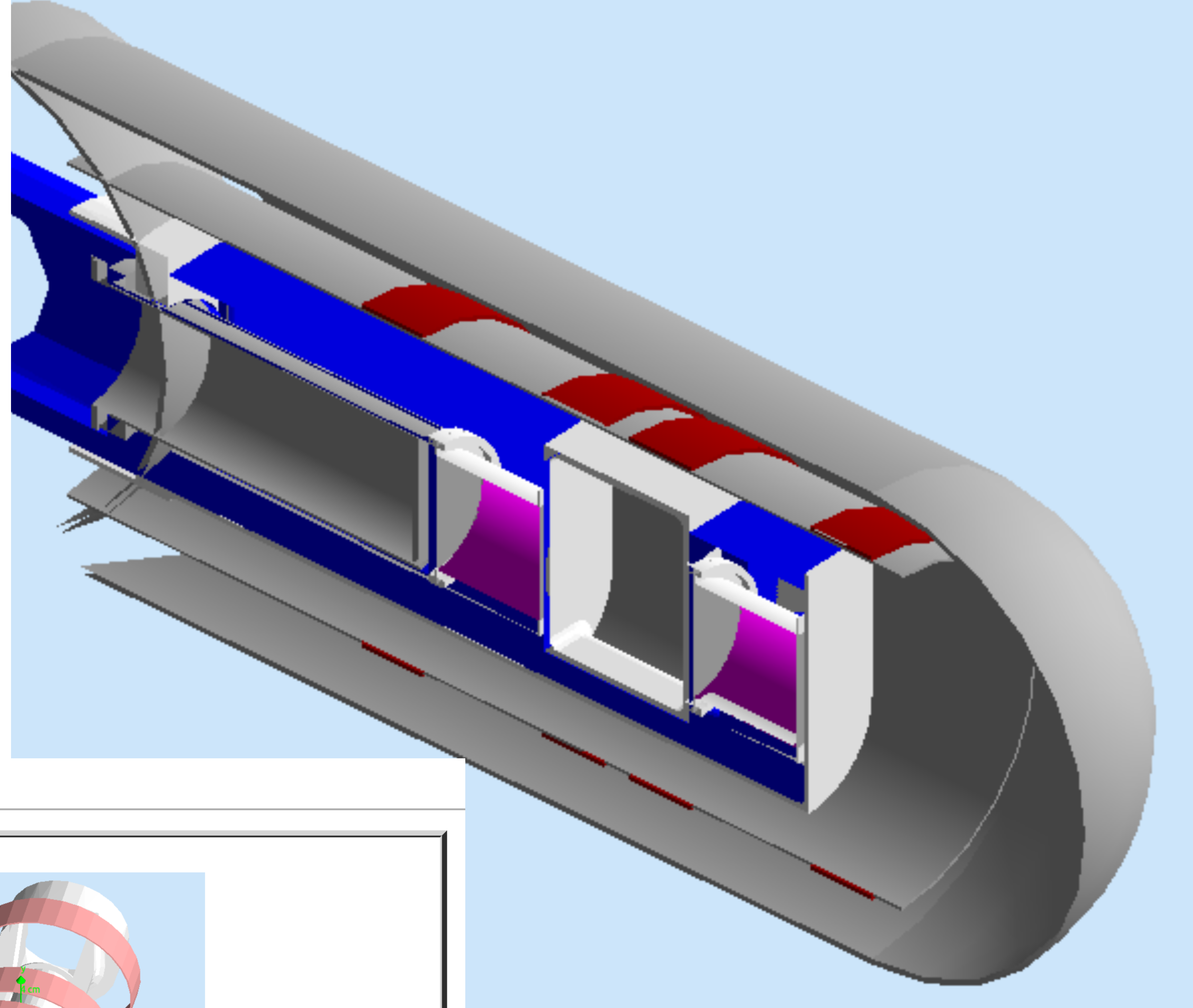
The NMR insert slides through the center of the 1 kelvin refrigerator.



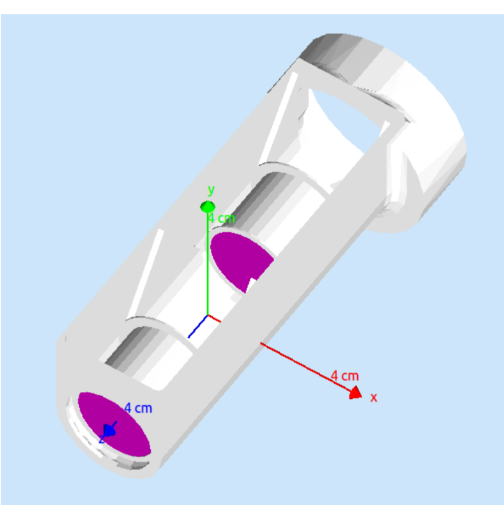
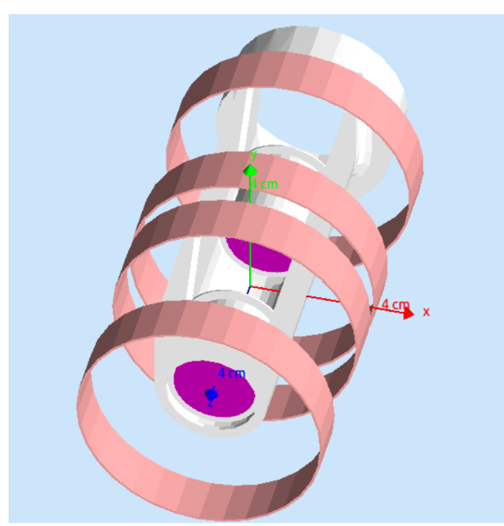
Images courtesy of James Brock, Target Group

From Chris Keith

Target in GEANT Simulation



GEMC PolTarg

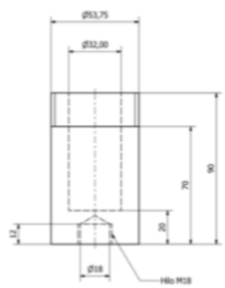
	
The Dual targets inside the Bath Insert	The Dual targets inside the Bath Insert with Shim Coils

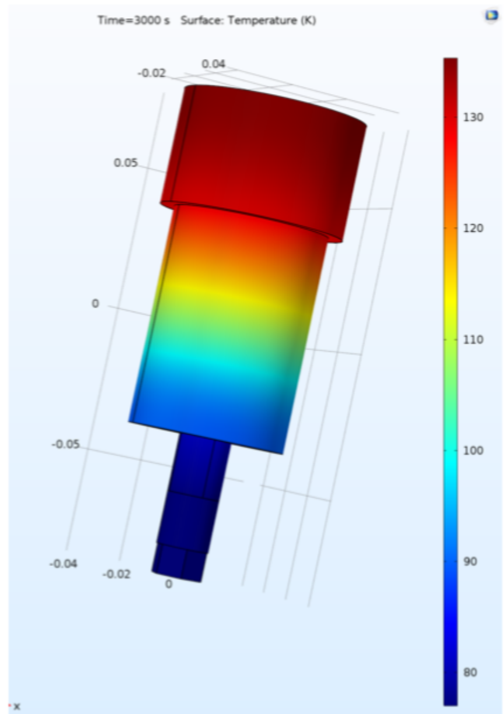
Revisión Avances COMSOL MULTIPHYSICS

Actividad 3 :

Se construyó un condensador de gases, actualmente en pruebas con CO2, Instalaciones para pruebas con NH3 están casi finalizadas.

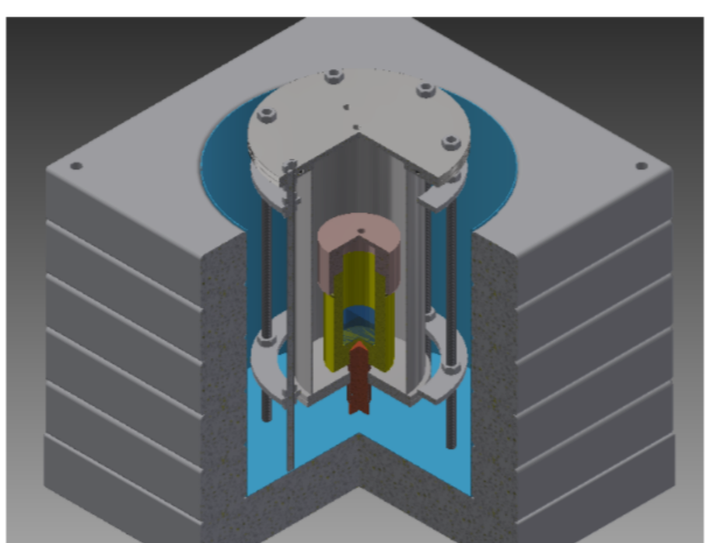
Pruebas con NH3 : 5 Junio en adelante.

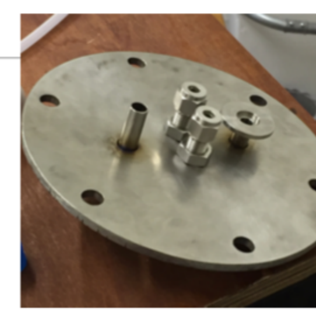




Revisión Avances

Actividad 3 :





Polarized target development at USM Valparaíso

Casting solid ammonia samples for highest density and optimal cooling

Hall B – Run Groups

HALL B

E12-06-109	Longitudinal Spin Structure of the Nucleon	Kuhn	A	80	185	Polarized target RICH (1 sector) Forward tagger	11	C S. Kuhn	NH_3 ND_3
E12-06-109A	DVCS on the neutron with polarized deuterium target	Niccolai		(60)					
E12-06- 119(b)	DVCS on longitudinally polarized proton target	Sabatie	A	120					
E12-07-107	Spin-Orbit Correl. with Longitudinally polarized target	Avakian	A-	103					
E12-09-007(b)	Study of partonic distributions using SIDIS K production	Hafidi	A-	80					
E12-09-009	Spin-Orbit correlations in K production w/ pol. targets	Avakian	B+	103					
E12-06-106	Color transparency in exclusive vector meson production	Hafidi	B+	60	60		11	D	
E12-06-117	Quark propagation and hadron formation	Brooks	A-	60	60		11	E	Nuclear
E12-06-113	Free Neutron structure at large x	Bueltman	A	42	42	Radial TPC	11	F	Gas D_2
E12-14-001	EMC effect in spin structure functions	Brooks	B+	55	55	Pol. LiH target	11	G	LiH
TOTAL CLAS12 run time (approved experiments)				**1466 (2118)**	**631**				

Proposal	Physics	Contact	Rating	Days	Group	Equipment	Energy	Group	Target
C12-11-111	SIDIS on transverse polarized target	Contalbrigo	A	110	110	Transverse target	11	H	HD
C12-12-009	Transversity w/ di-hadron on transvere target	Avakian	A	110					
C12-12-010	DVCS with transverse polarized target in CLAS12	Elouadrhriri	A	110					
All CLAS12 transverse target proposals				330	110				
E12-11-006	Heavy Photon Search at Jefferson Lab (HPS)	Jaros	A	180	180	Setup in alcove	2.2, 6.6	I	Nuclear
E12-11-106	High Precision Measurement of the Proton Charge Radius	Gasparian	A	15	15	Primex	1.1, 2.2	J	H2 gas
Beam time request from CLAS12 C1 experiments + non-CLAS12 experiments				**525**	**305**				
Beam time from approved CLAS12 experiments (from previous table)				**1466 (2118)**	**631**				
Beam time for Hall B experiments table 1 + table 2 (incl. 110 days of C1 approved exp.)				**1991 (2643)**	**936**				

Scheduling considerations

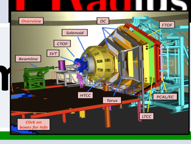
Hall B

Assuming all ERR reviews have been passed and beam time requested

- Experiment with hydrogen target to run first to understand detector responses, calibrations
- Provide all Run Groups with significant amount of data during first 5 years

  => schedule ~50% of total approved Run Group days
- Scientific ratings by the PAC
- Schedule ***High Impact*** experiments early (PAC41)
- Compatibility with energies used in other Halls
- Benefit to collaboration
- Operating luminosity
- Jeopardy process
- Final scheduling done in NPES committee

Possible RG Schedule (straw man)

Run Group	Days	2016	2017	2018	2019	2020	2021	2022	Remain
All Run Groups	**1036[#)]**	30	15	95	106	105	105	105	456
HPS	180*	**15**		35	10	10	10	10	90
PRad	15*	**15**							0
CLAS12 Comm 			3 30						0
RG-A + RG-K (proton)	239*		10	20/15 25		30	25		114*
RG-B (deuteron)	90*				45				45*
RG-F (BoNuS)	42*				21				21
RG-C (NH_3)	120				30	30			60
RG-C-b (ND_3)	65					35			30
RG-E (Hadr.)	60						35		25
RG-H (Transv. Target)	110*						35	25	50
RG-D (CT)	60							35	25
RG-G (LiD)	55							35	20

#) incl. RG-H

CEBAF Large Acceptance Spectrometer

JLab PAC 29 Report

Issues: The “spin dependent EMC effect “ is experimentally difficult to define. Since we cannot polarize all the nucleons in a given nucleus, the concept of mean field spin effect is ill defined compared to the unpolarized case. The spin structure function of a nucleus g1 is the product of the asymmetry A1 with the unpolarized structure function F1. The unpolarized structure function F1 has obviously a well defined “EMC” effect and A1 is an already small quantity which decreases with the atomic number A of the nucleus. Given the uncertainty in the nuclear spin structure effects and the small size of the asymmetry A1, it will be difficult to extract what the proponents call the “spin EMC effect”.

Recommendation: The PAC is skeptical that the interpretation of such a measurement would be meaningful.

PAC 42 report evaluation of the proposal

“If it can be measured with sufficient precision, this measurement provides a unique and valuable independent test of models of the EMC effect. However, while the proposed measurement is sensitive enough to see an effect for many of the models shown, the precision of the measurement is not sufficient to precisely map out a nuclear modification. In addition, it is not clear to what extent the results can be interpreted and used to help understand the EMC effect at this time.”

https://www.jlab.org/exp_prog/PACpage/PAC42/PAC42_FINAL_Report.pdf

pEMC - Conclusions

- A very interesting, **groundbreaking** measurement
- Technically challenging to achieve small uncertainties
- Theory predictions vary greatly - experimental results could be surprising
- Target instrumentation will clearly be ready on schedule
- Priority assigned by PAC is relatively low. Currently assigned to the very last CLAS12 running period, 2022++

Communicating and sharpening the physics case is crucial

Color Propagation Studies

- **Nuclear targets/collisions producing identified particles**
- Semi-inclusive DIS: HERMES, JLab (Hall B&C), EIC
- 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 Studies - COLD Matter

Old issues

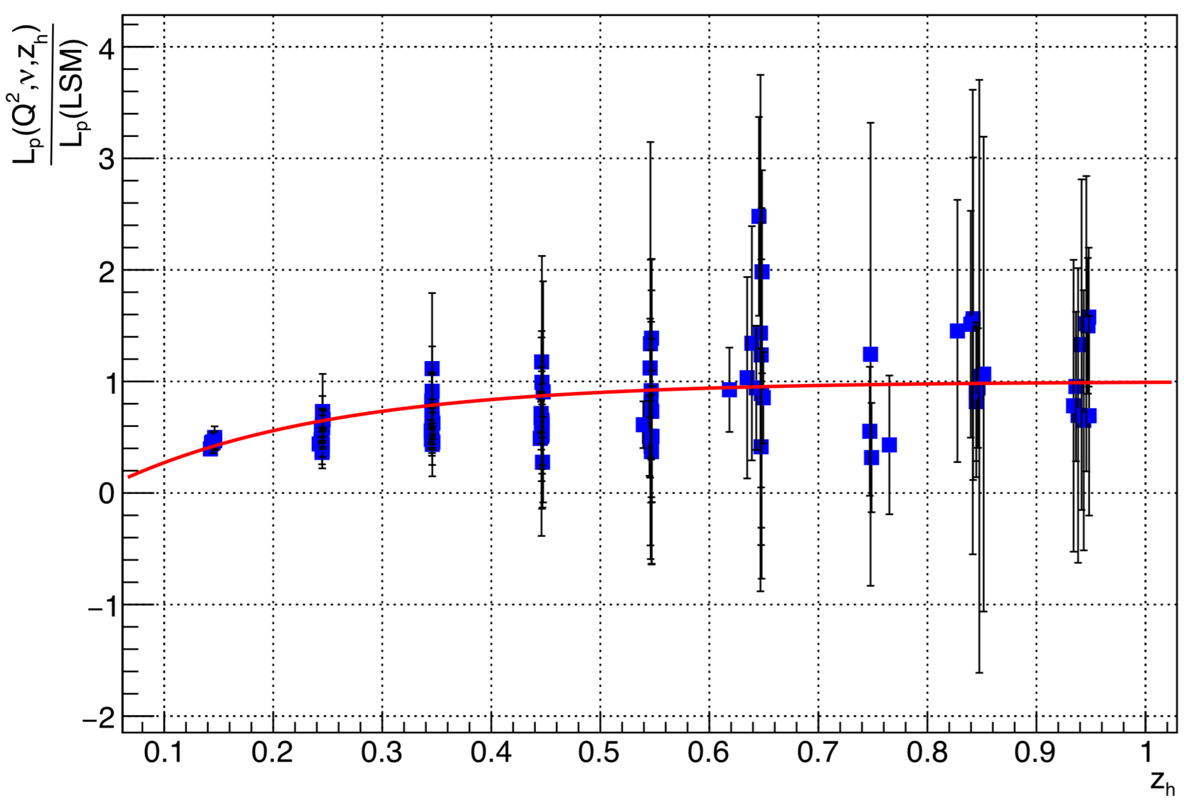
- **Pion/hadron attenuation primarily caused by hadronic interaction of forming hadron, or by energy loss? (Will be) resolved by CLAS12 data. (Hint: it's not energy loss.)**

Color Propagation Studies - COLD Matter

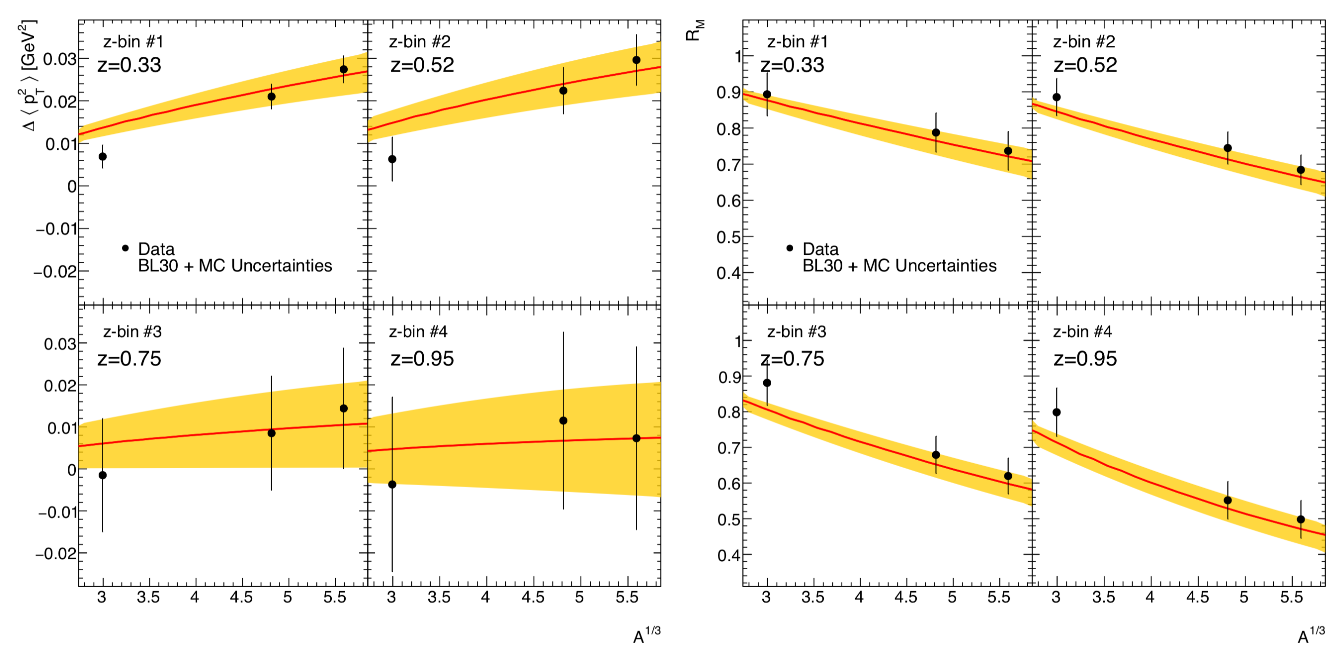
What we are learning from the HERMES data and new CLAS data:

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

CLAS Exploratory Analysis ≈ Lund String Model



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

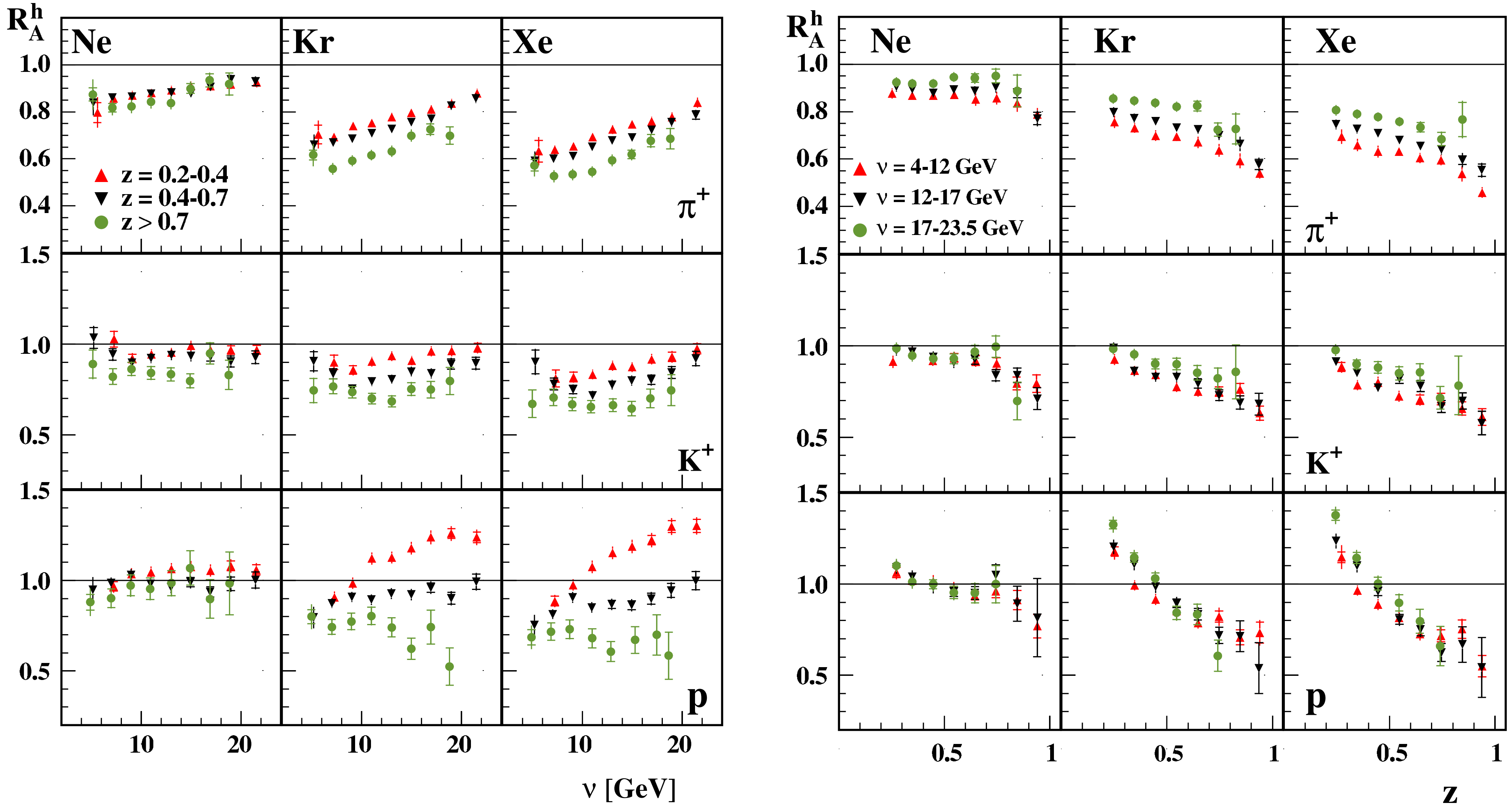


Result for model variant BL30, baseline model at fixed pre-hadron cross-section 30 mb.

Color Propagation Studies - COLD Matter

New and novel issues

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

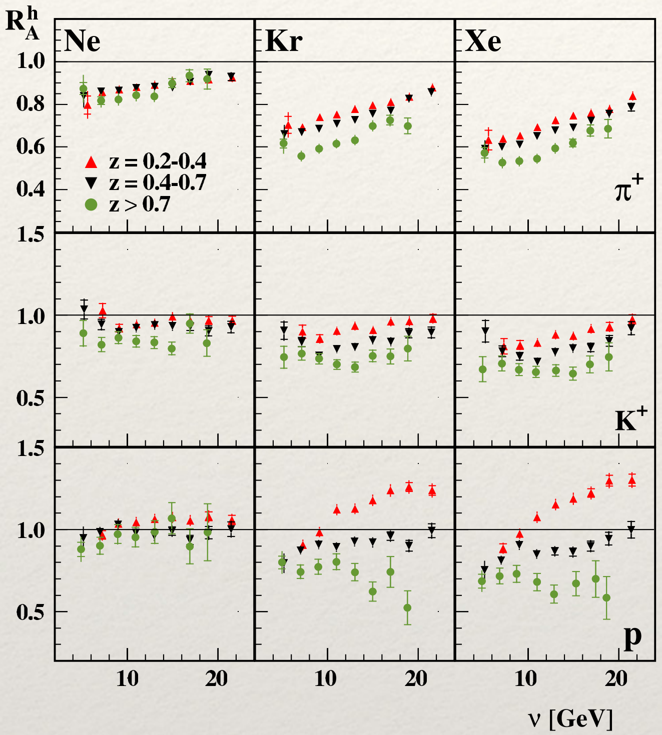


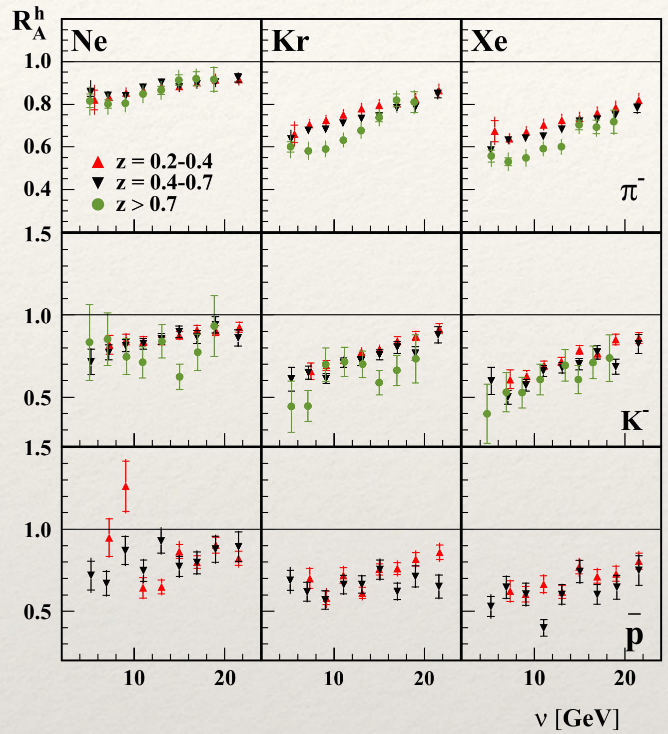
SRC+SSC?? Color recombination?? Exotic mechanisms??

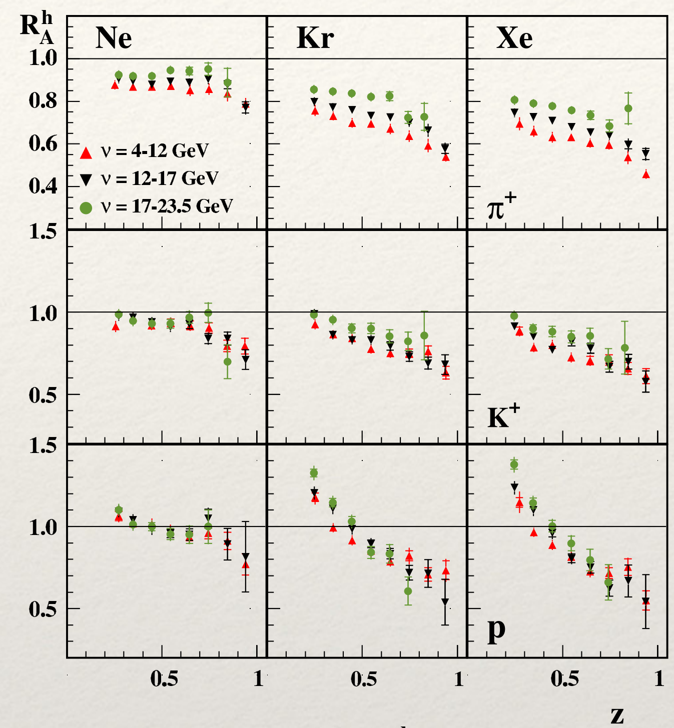
COMPARING DIFFERENT HADRONS

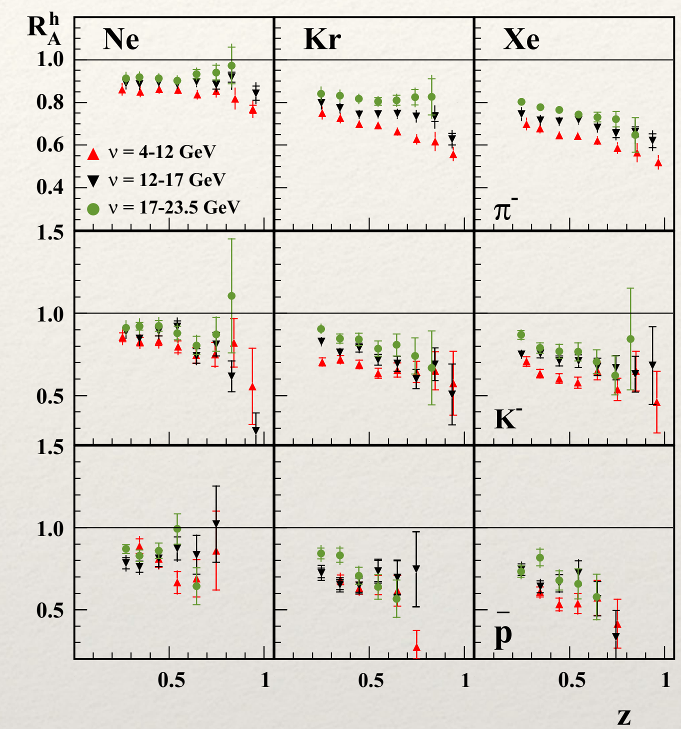
HERMES demonstrated that simple expectations about hadron flavor independence are naïve - Eur. Phys. J. A (2011) 47: 113.

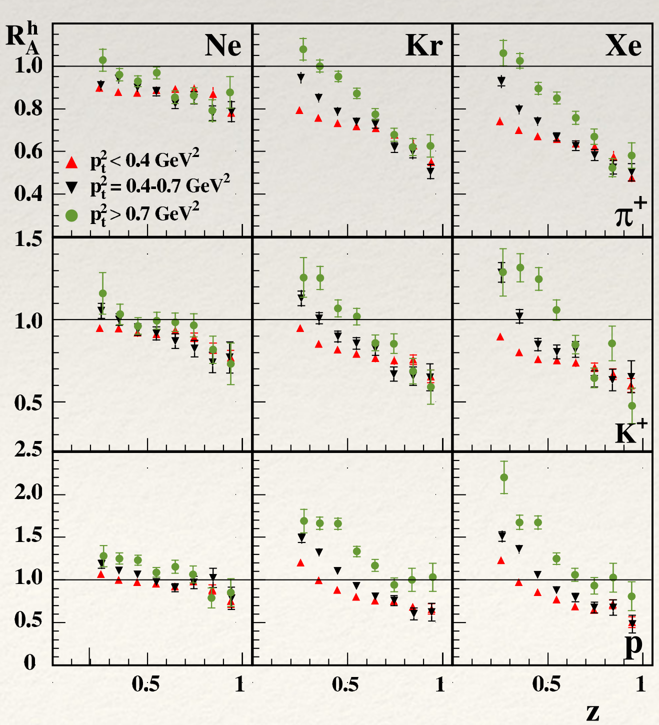
No model can describe all of these data

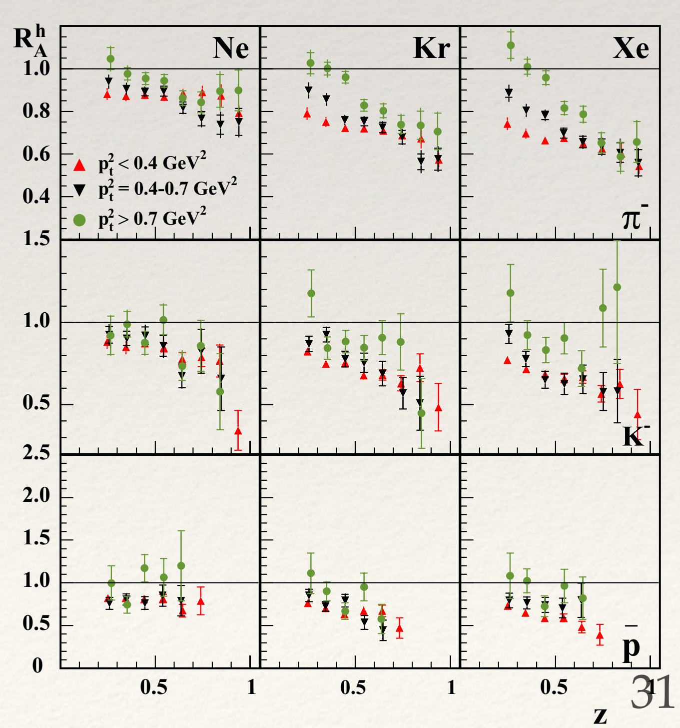


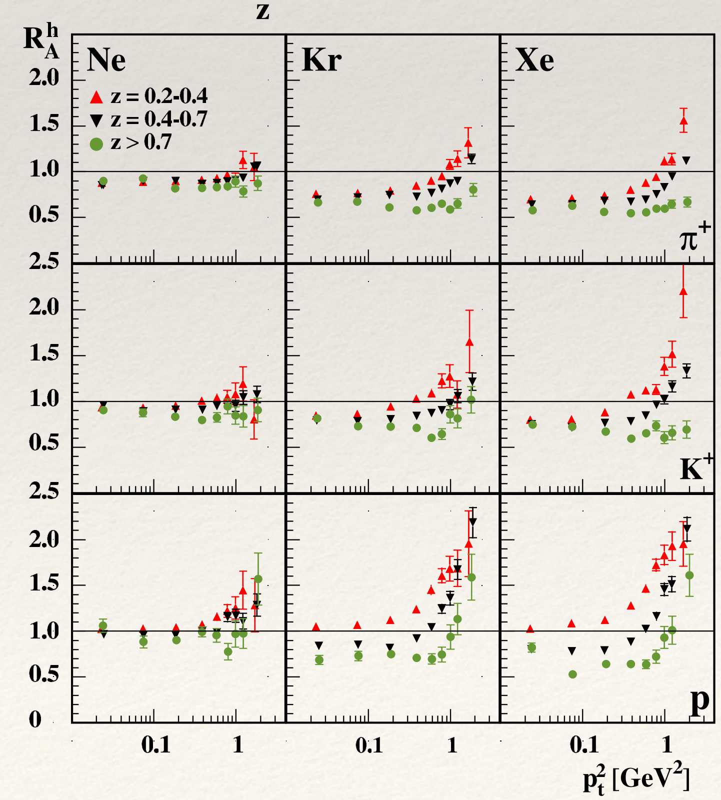












Assumed properties of the hard interaction

- For $x_{Bj} > 0.1$, no quark pair production $\gamma^* \to q\bar{q}$
- For large Q^2 & ν, interaction volume is very small, << 1% of proton

e.g. $Q^2 = \nu^2 - |\vec{q}|^2$. $Q^2 \sim 4\ GeV^2$, $\nu \sim 15\ GeV$, $\Rightarrow |\vec{q}|^2 > 200\ GeV^2$

$$\frac{0.2\ GeV\ fm}{\sqrt{200\ GeV^2}} \sim 0.01\ fm \quad \sim \text{transverse resolution}$$

$\Rightarrow$ virtual photon absorbed by ONE QUARK

What mechanism produces a large excess of high energy protons??

A small-sized configuration in SRC?

Otherwise, need a multistep HADRONIC process

but this is strongly suppressed for FORMING HADRONS!

Why is proton attenuation in neon so different from Kr/Xe?

Color Propagation Studies - COLD Matter

How to decipher the proton attenuation mechanism?

More multi-dimensional observables (e.g. pT broadening, two-particle correlations; others?)

More theory work.

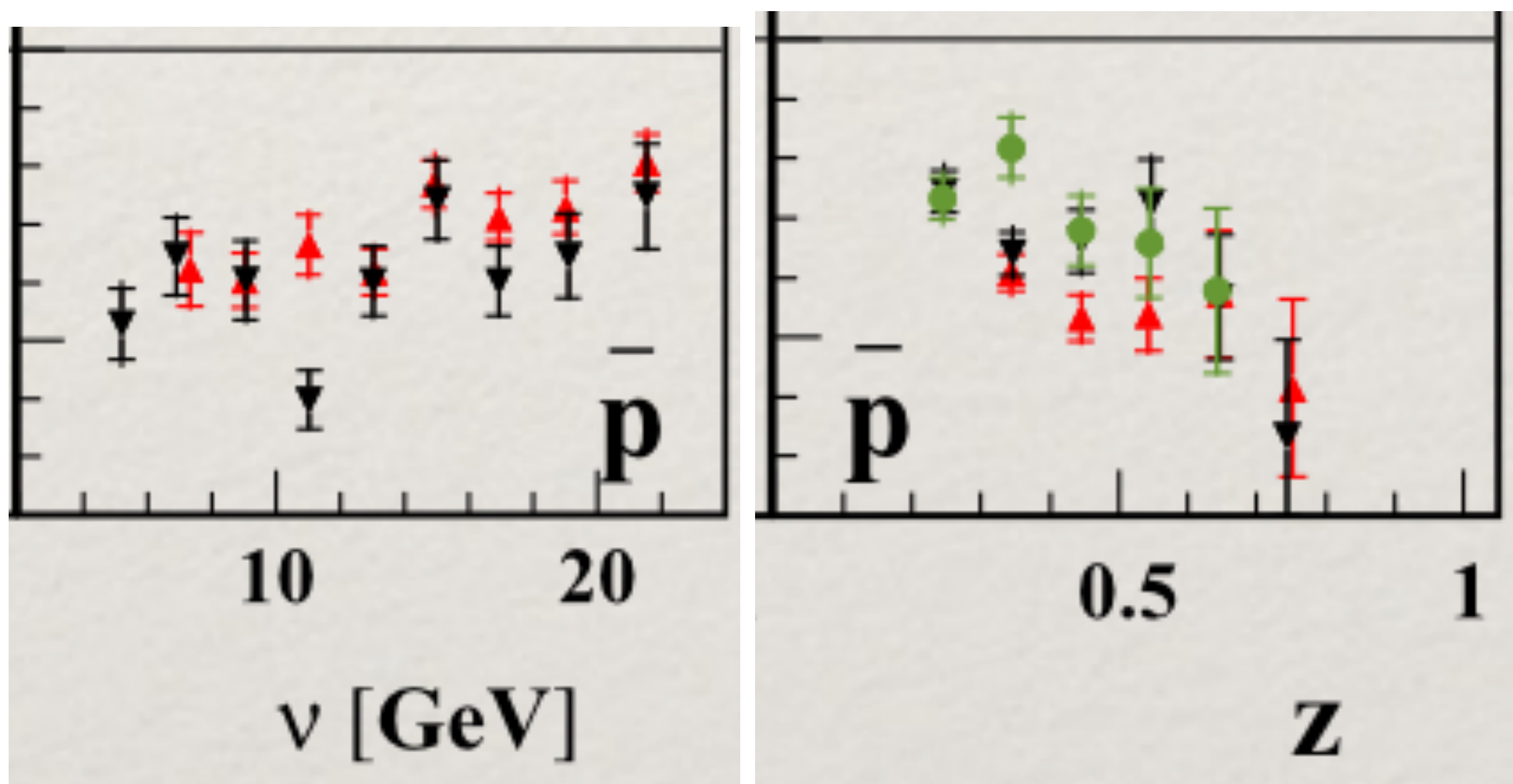
Two-dimensional analysis demonstrates that this is at least a 3-dimensional problem.

Color Propagation Studies - COLD Matter

New and novel issues

- **Attenuation of anti-protons - mechanism?**
  - **Seen by HERMES, (will be) studied at CLAS12 & EIC**

Same origins as K^- attenuation? (String rank? Cross section?)



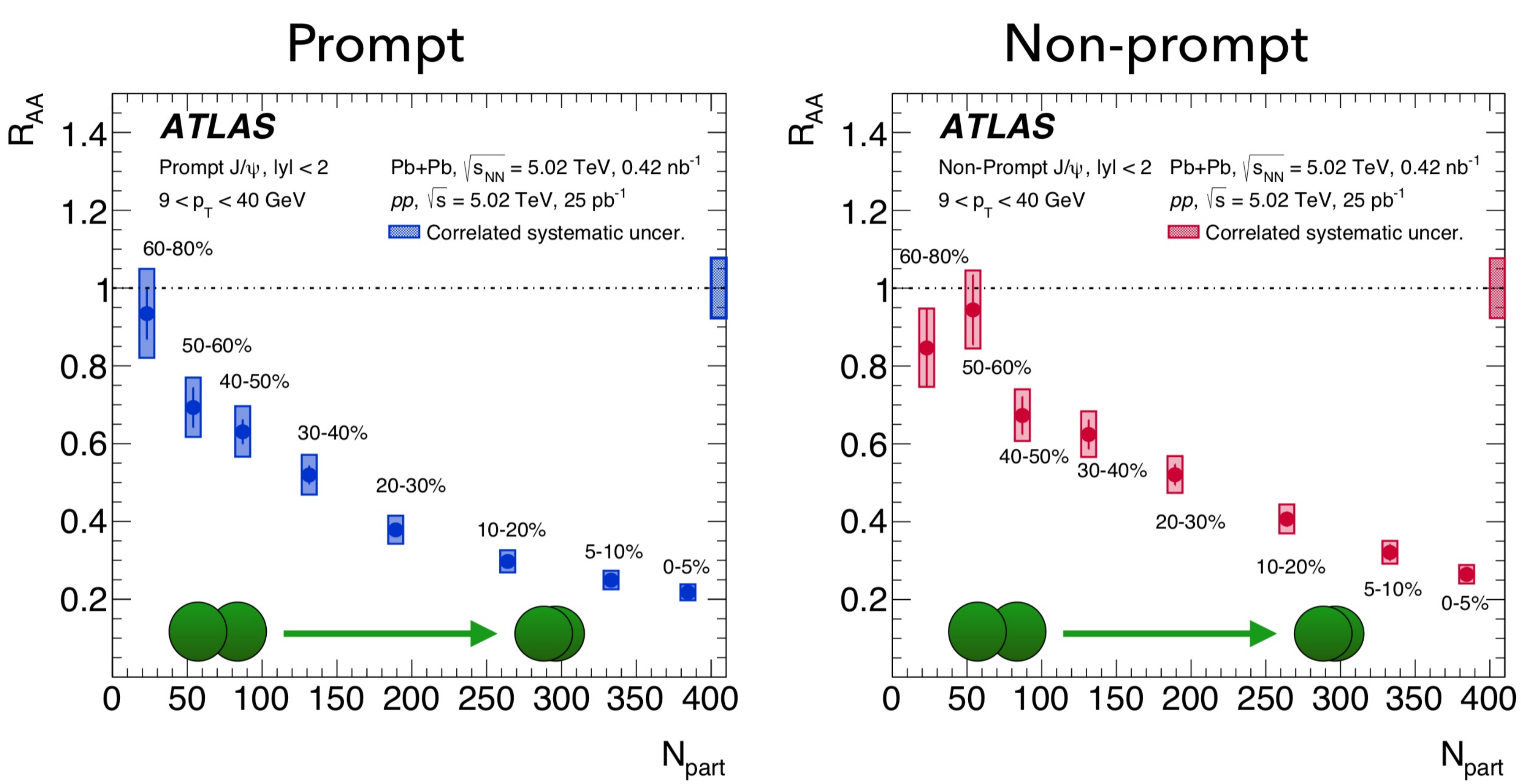
Color Propagation Studies - HOT Matter

New and novel issues

- **Attenuation of J/Ψ = attenuation of b quarks = 80% ??**

Accidental?

RESULTS - R_{AA} vs Number of Participants



- Increasing suppression w.r.t pp reference with increasing centrality
- Similar trend and magnitude for both component.

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
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

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

HERMES

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Actively underway with existing 5 GeV data

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

Actively underway with existing 5 GeV data (yellow circles)

HERMES (red circles)

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
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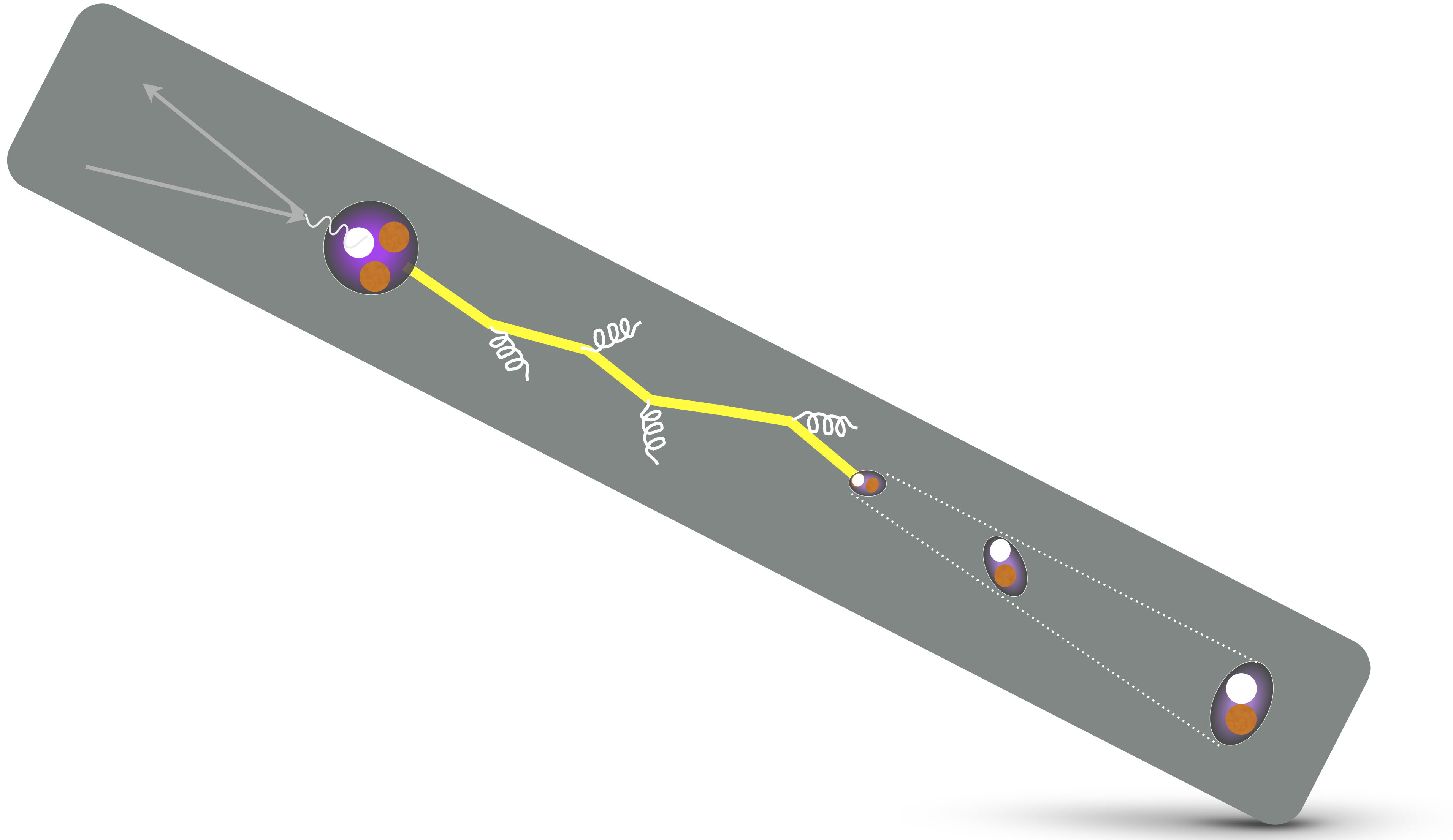
Ξ^0	87 mm	1.3	us
Ξ^-	49 mm	1.3	ds

EIC: heavy mesons and baryons; wide kinematic range!

Three possible distributions of production time



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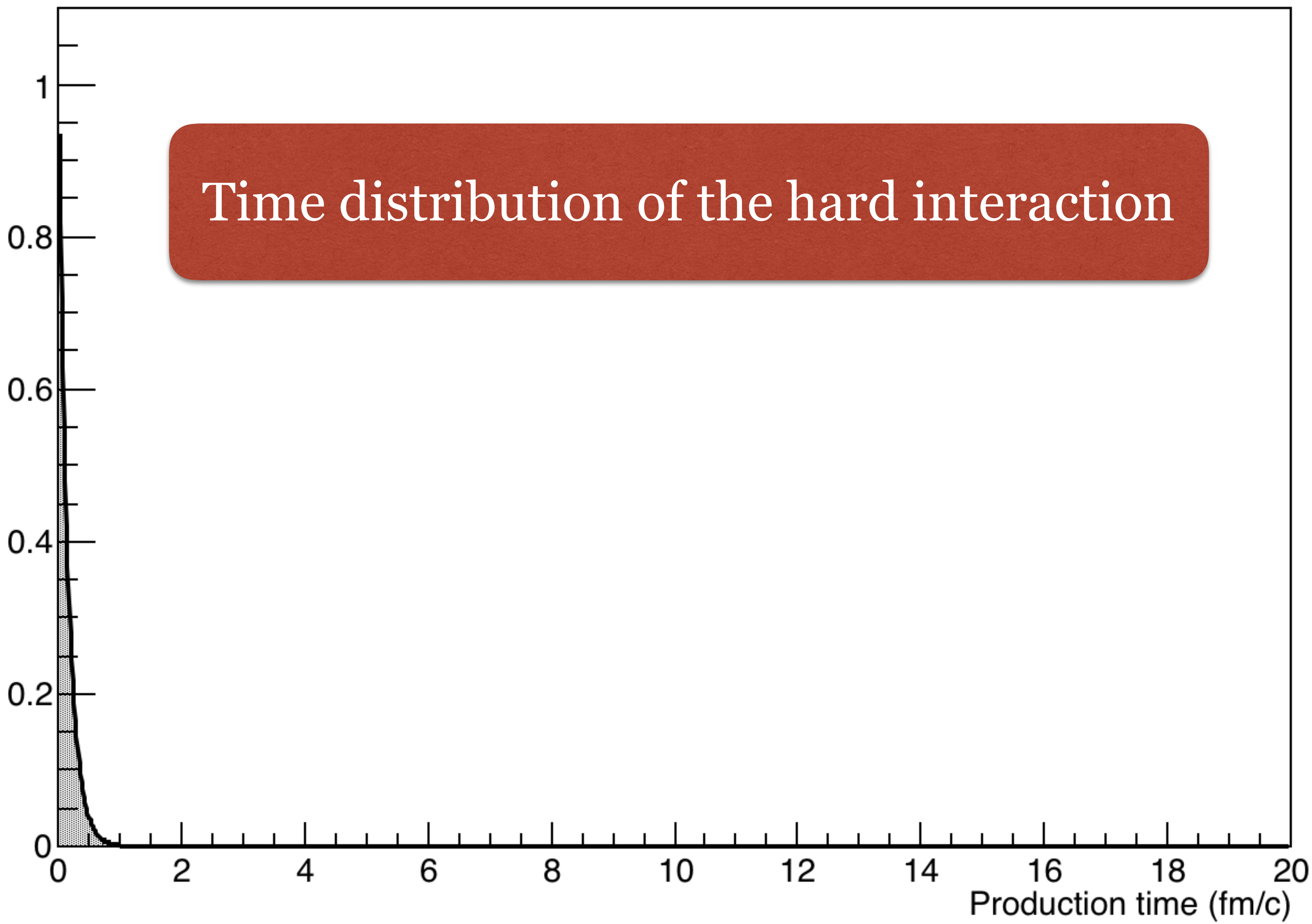

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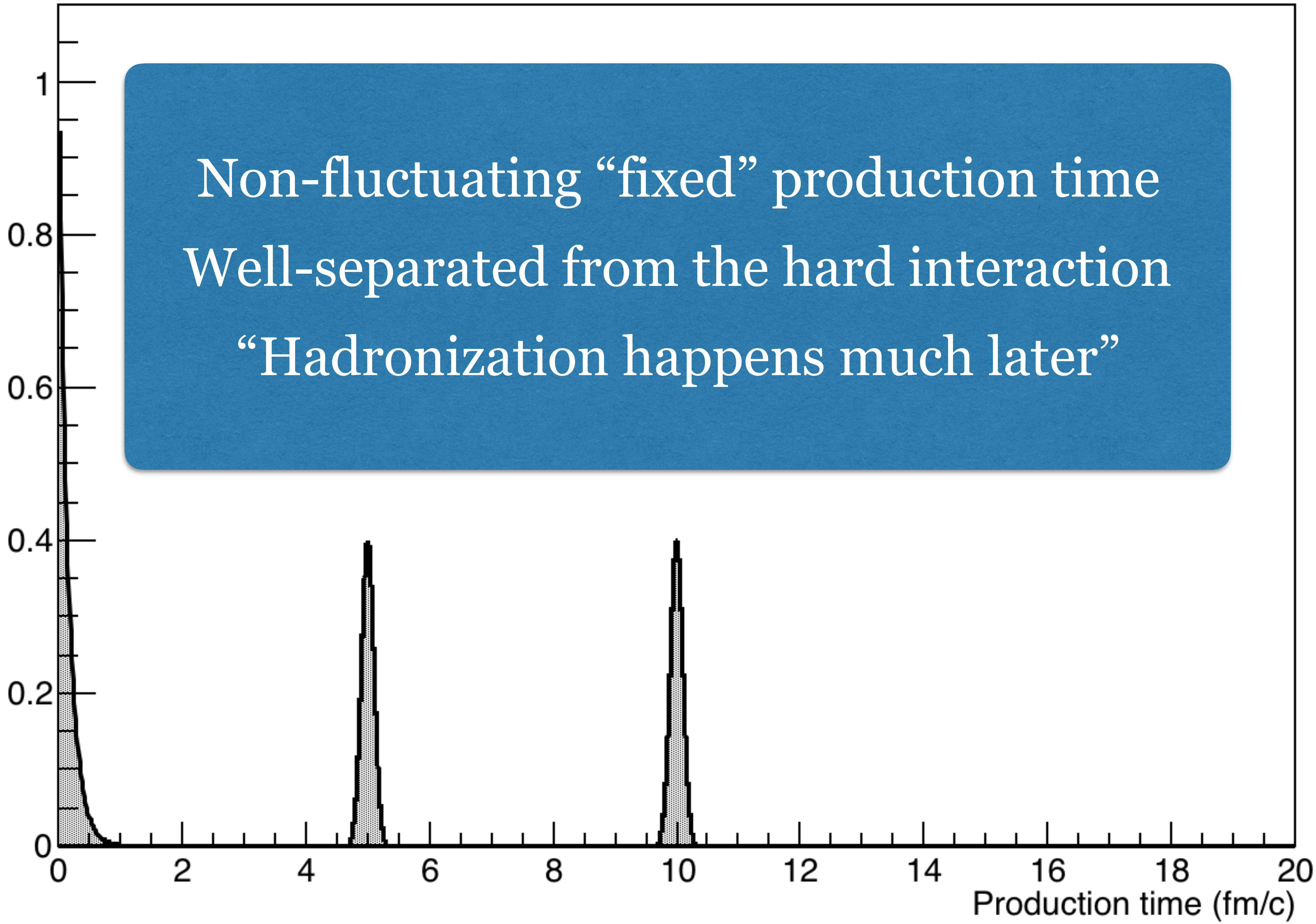
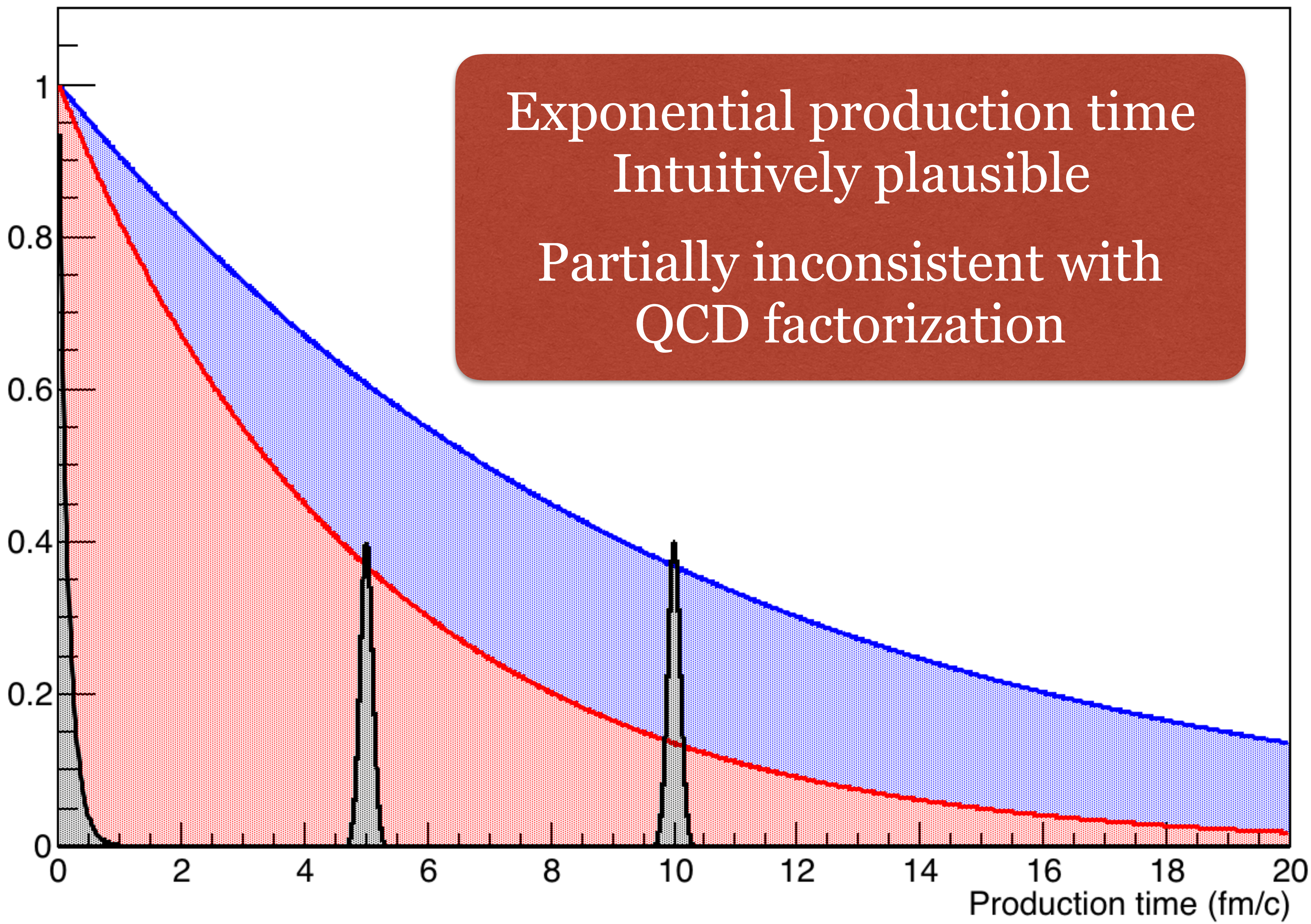


Non-fluctuating "fixed" production time
Well-separated from the hard interaction
"Hadronization happens much later"

Three possible distributions of production time



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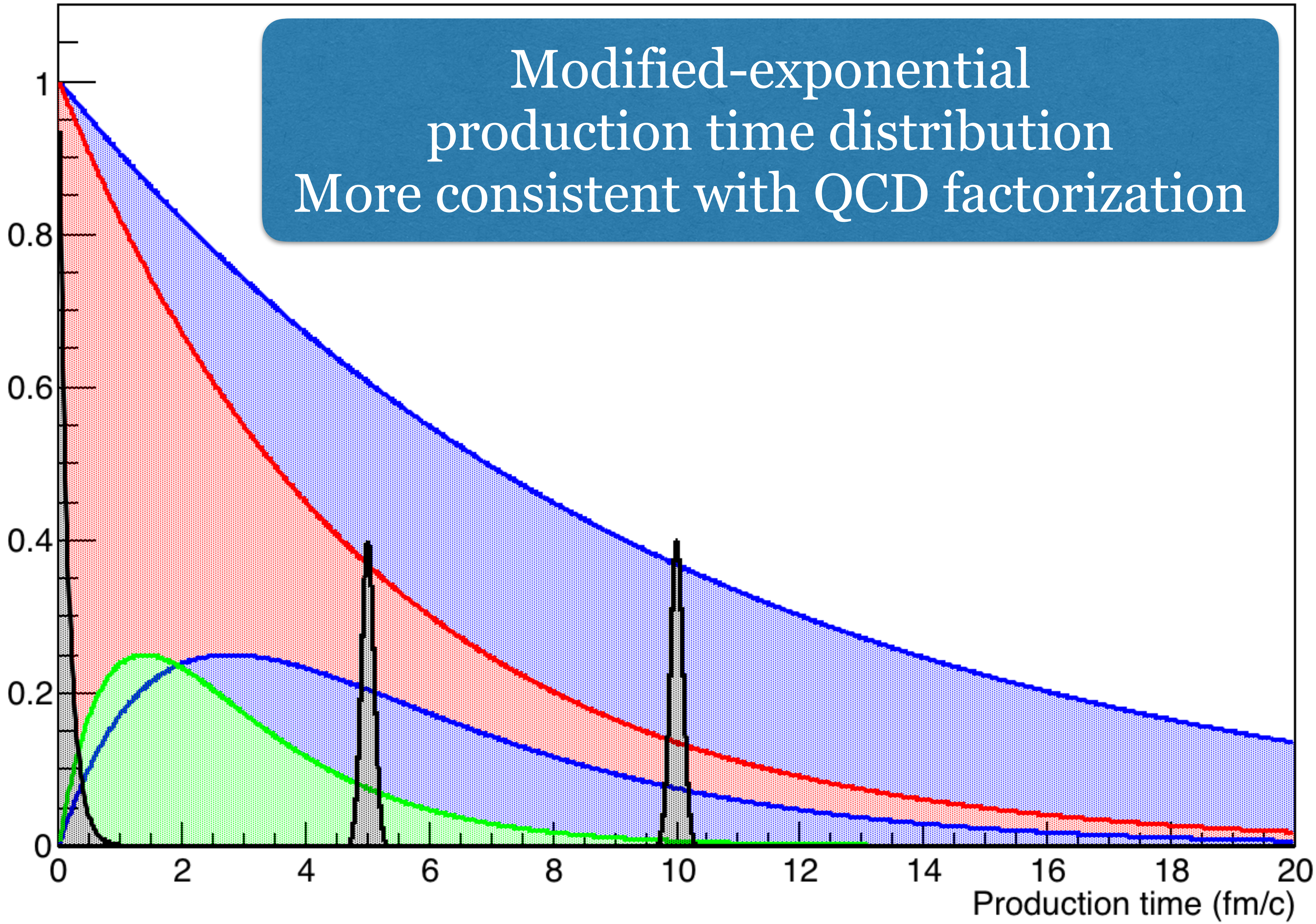
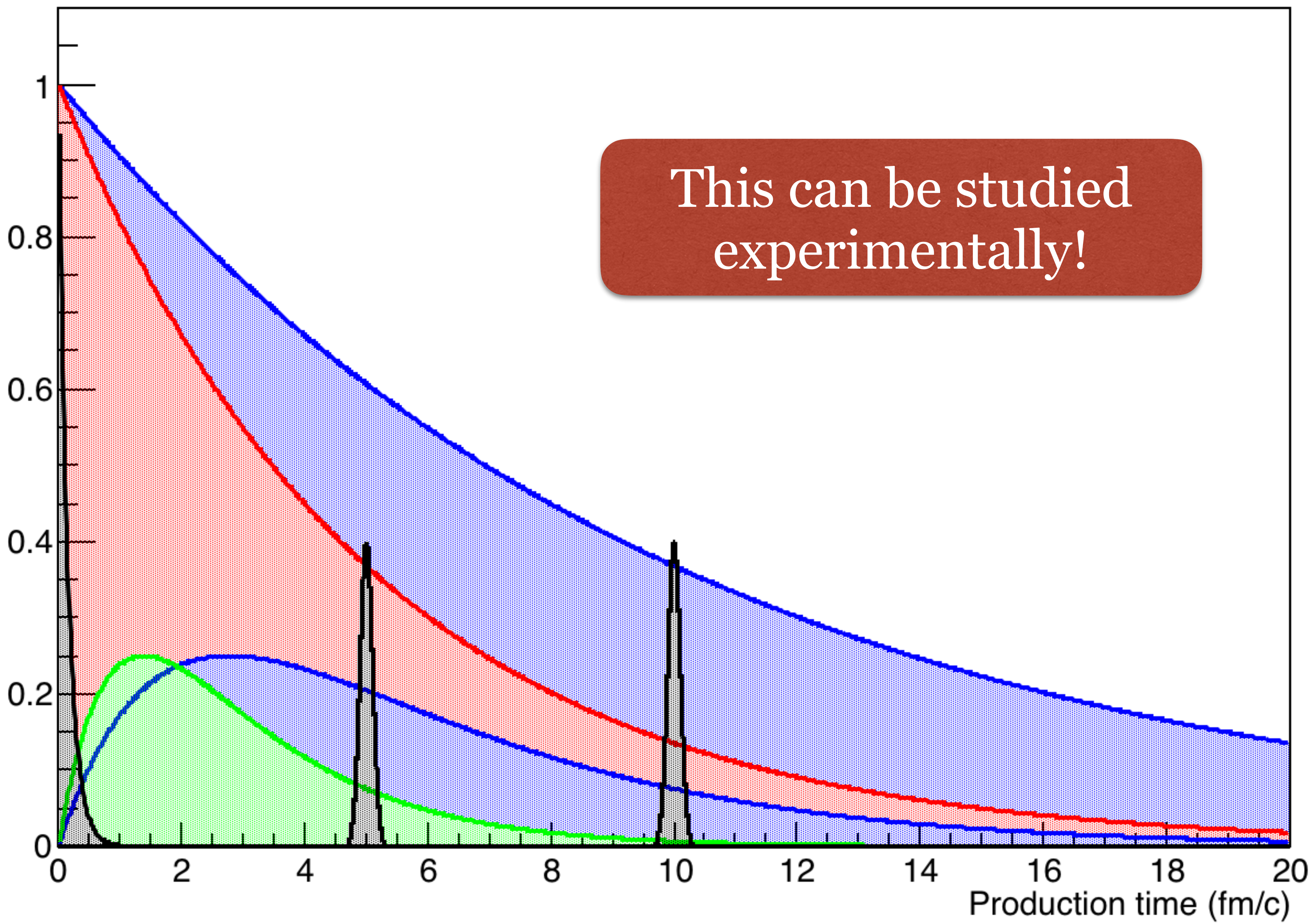


Three possible distributions of production time



Aims

Quark-Hadron Transition

Discover new fundamental features of hadronization

- Characteristic time distributions
- Mechanisms of color neutralization

Quark-Nucleus Interaction

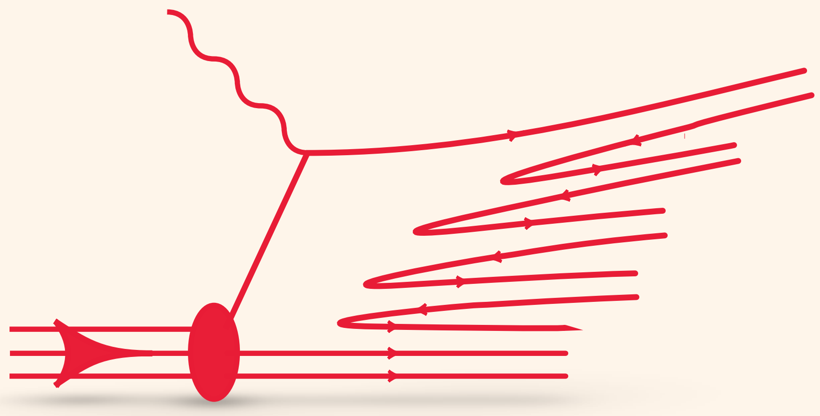
Understand how color interacts within nuclei

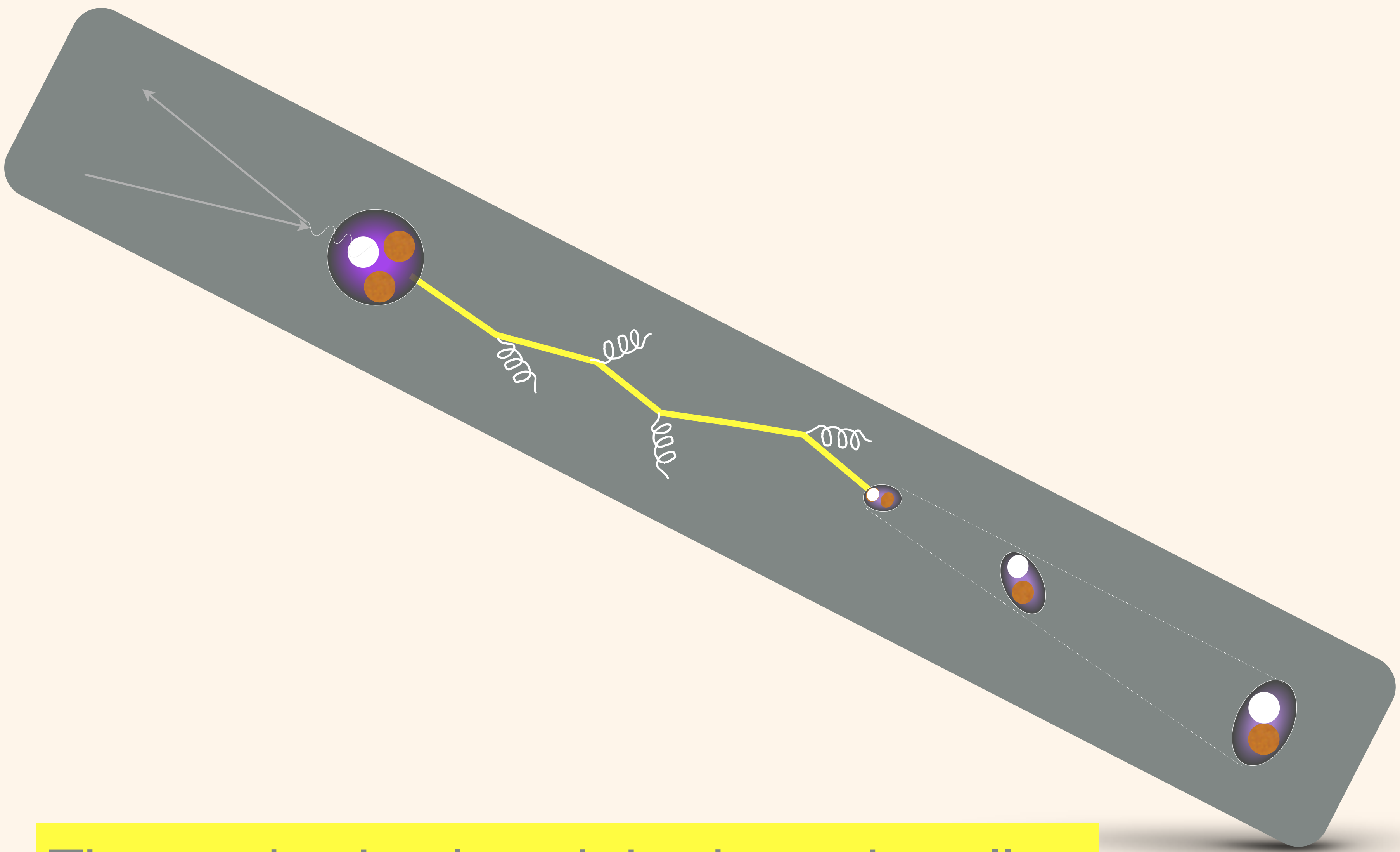
- Partonic interactions with medium ("tomography")
  - energy loss in-medium: $\hat{e}$
  - transverse momentum broadening: $\hat{q}$

Method: struck quark from DIS probes nuclei of different sizes

FUNDAMENTAL QCD PROCESSES

(DIS, pQCD picture)



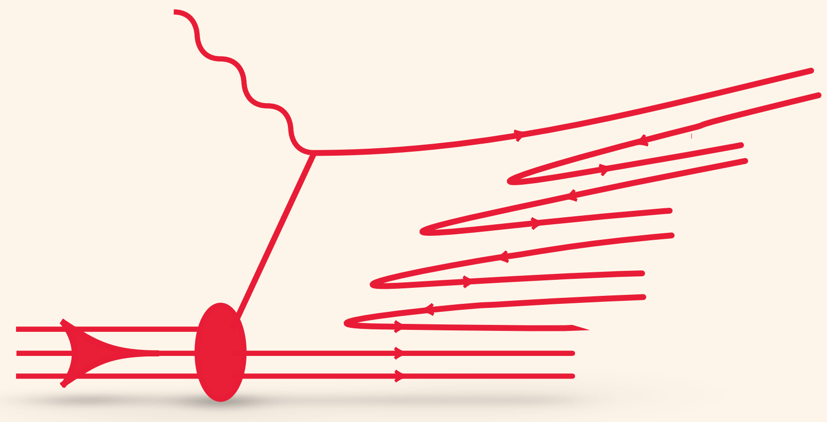


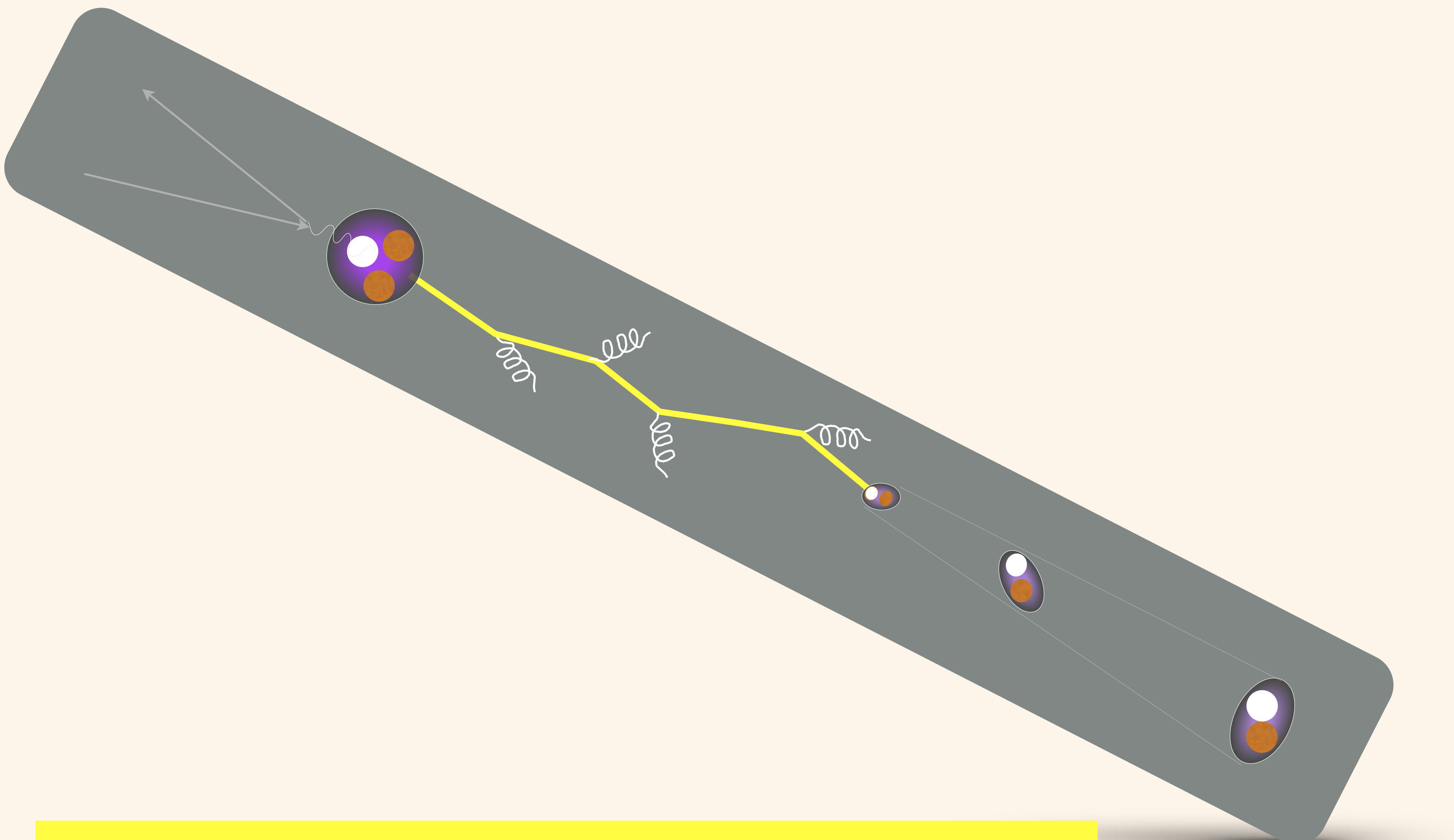
The production length is shown in yellow

FUNDAMENTAL QCD PROCESSES

(DIS, pQCD picture)

Partonic elastic scattering
in medium





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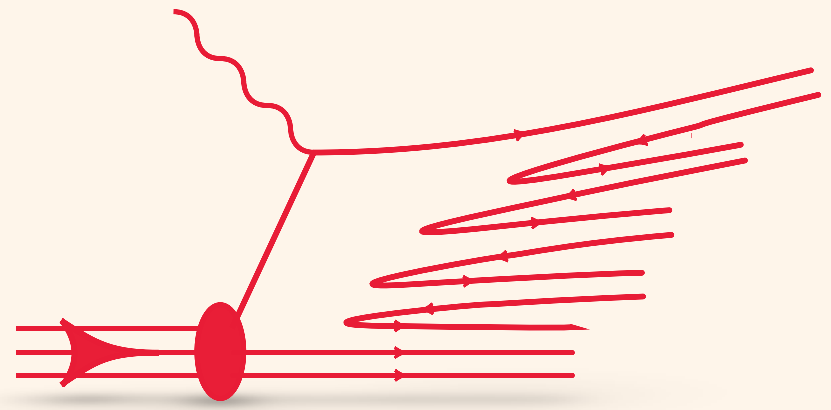
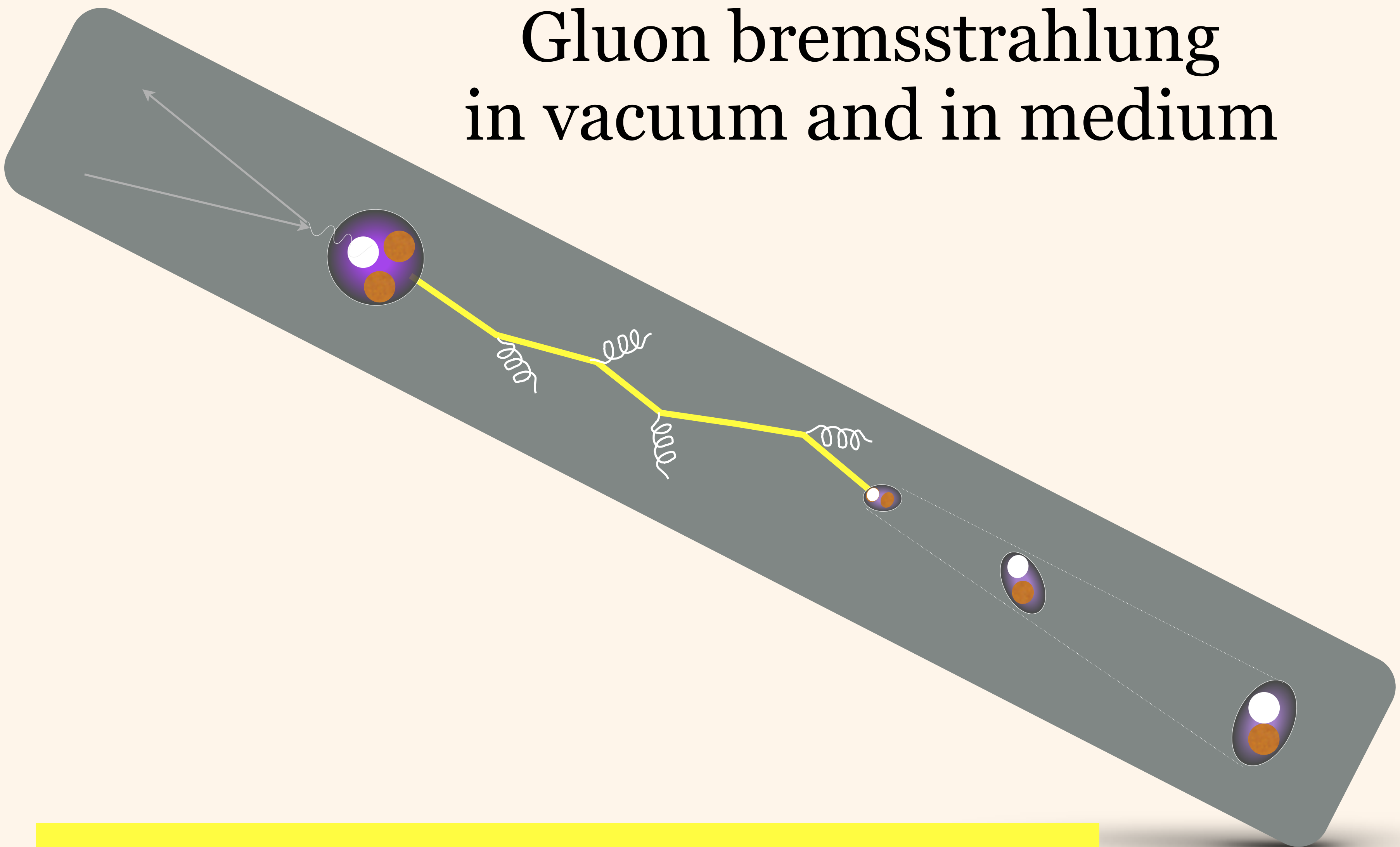


Partonic elastic scattering
in medium

Gluon bremsstrahlung
in vacuum and in medium



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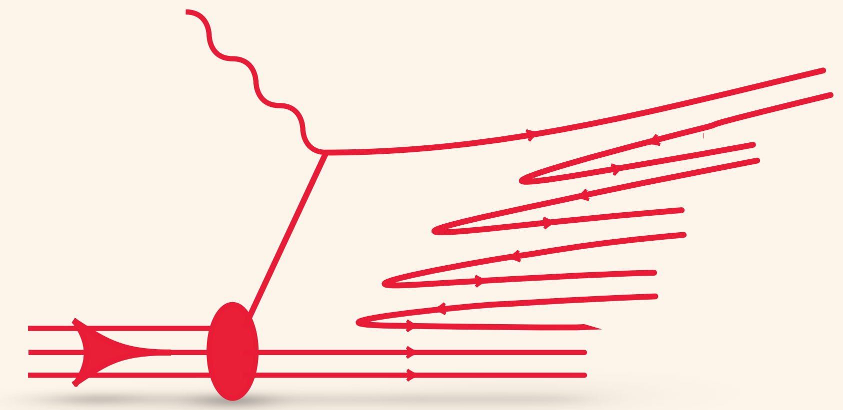
FUNDAMENTAL QCD PROCESSES

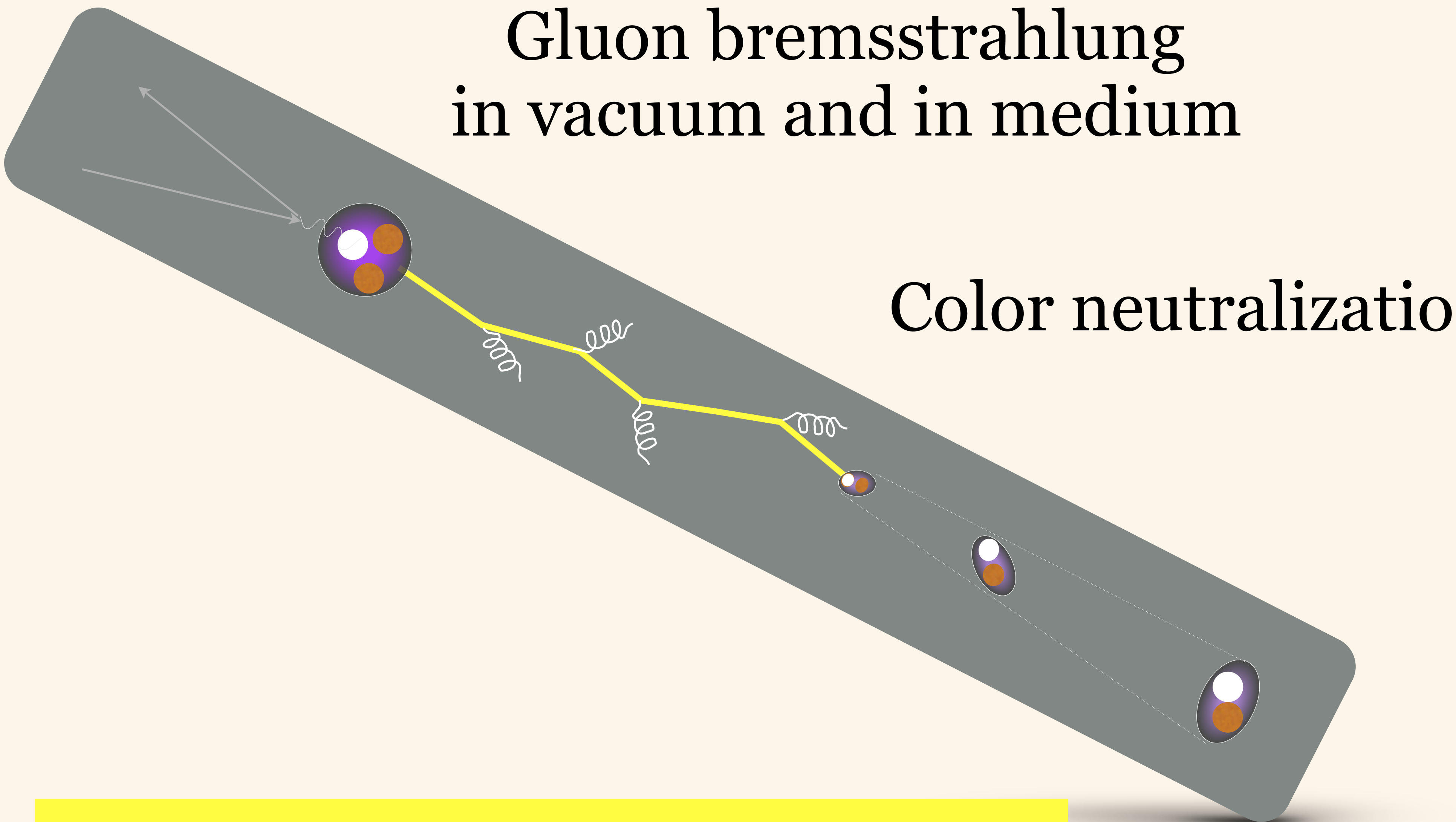
(DIS, pQCD picture)

Partonic elastic scattering
in medium



Gluon bremsstrahlung
in vacuum and in medium

Color neutralization



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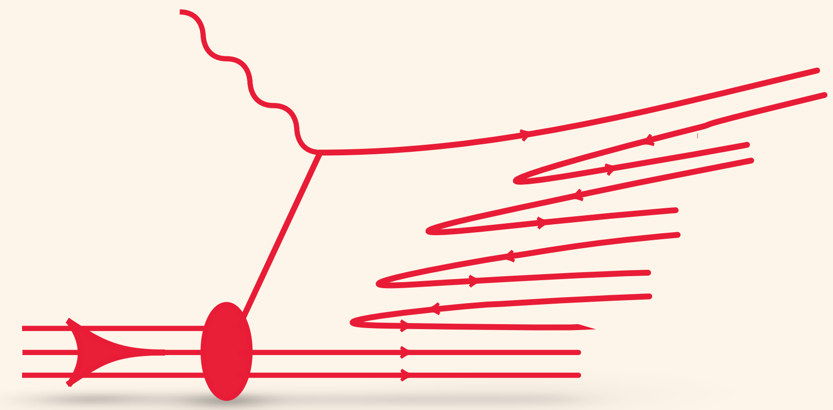
FUNDAMENTAL QCD PROCESSES

(DIS, pQCD picture)

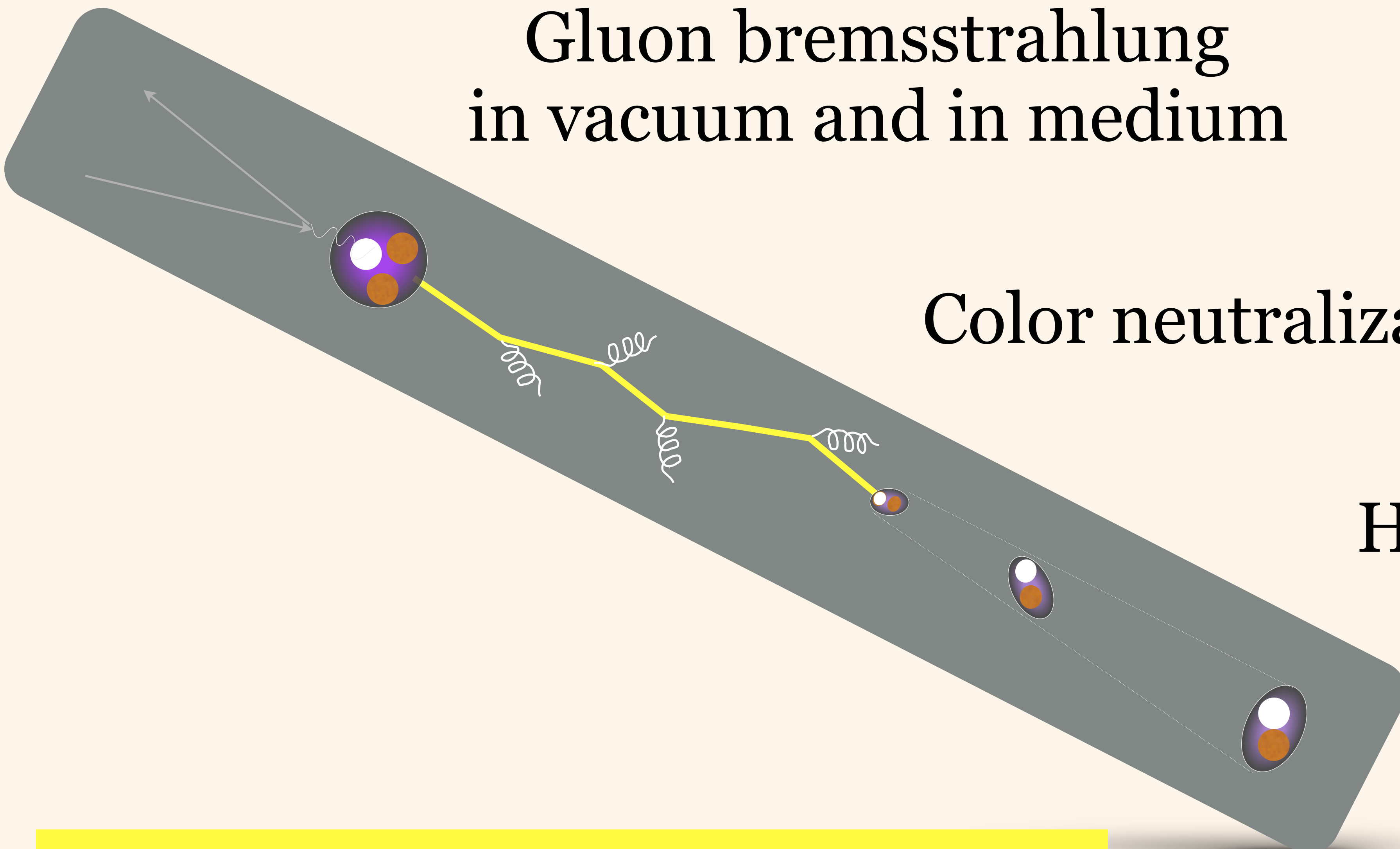
Partonic elastic scattering
in medium



Gluon bremsstrahlung
in vacuum and in medium

Color neutralization

Hadron formation



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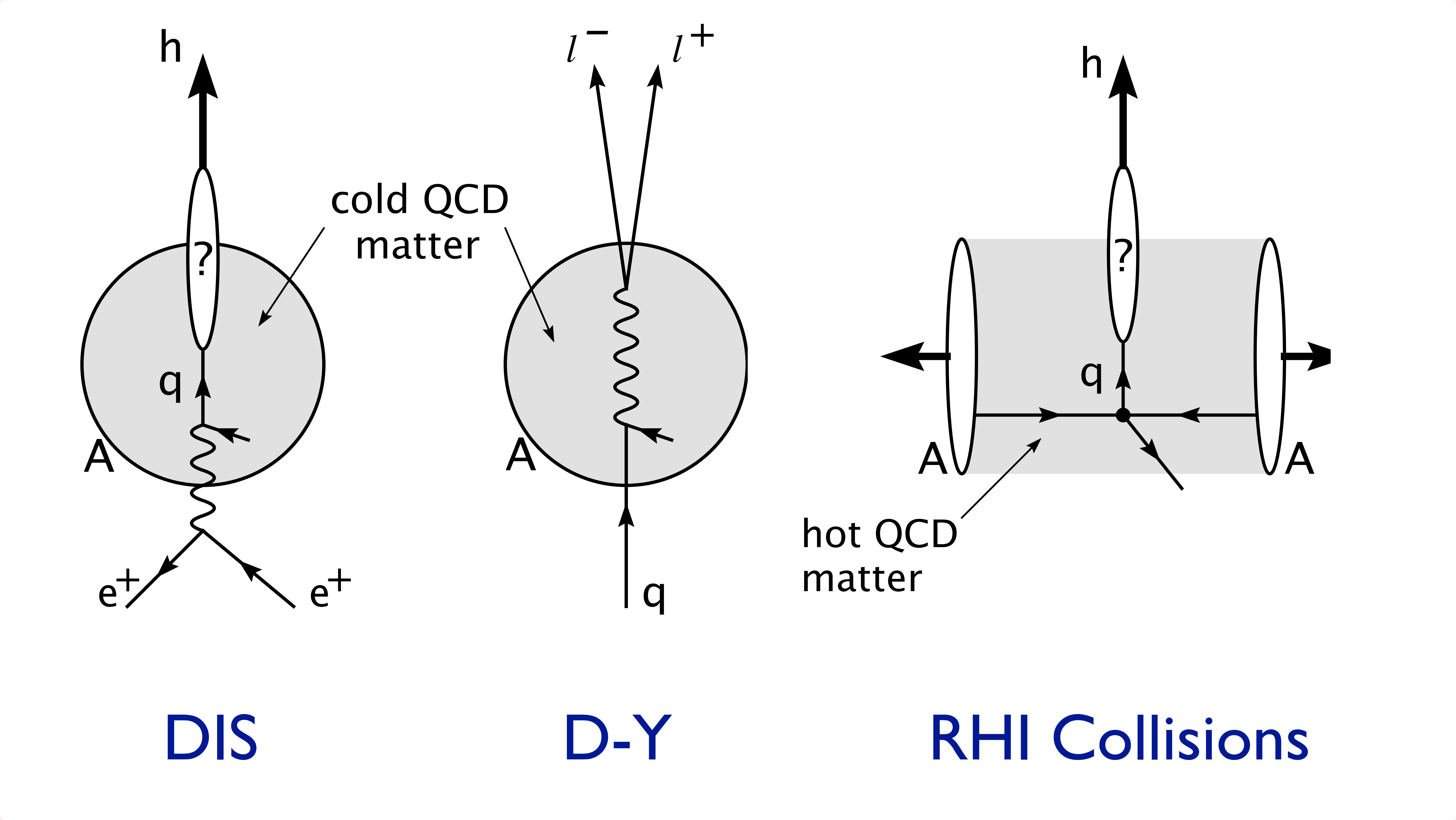
Comparison of Color Propagation in Three Processes



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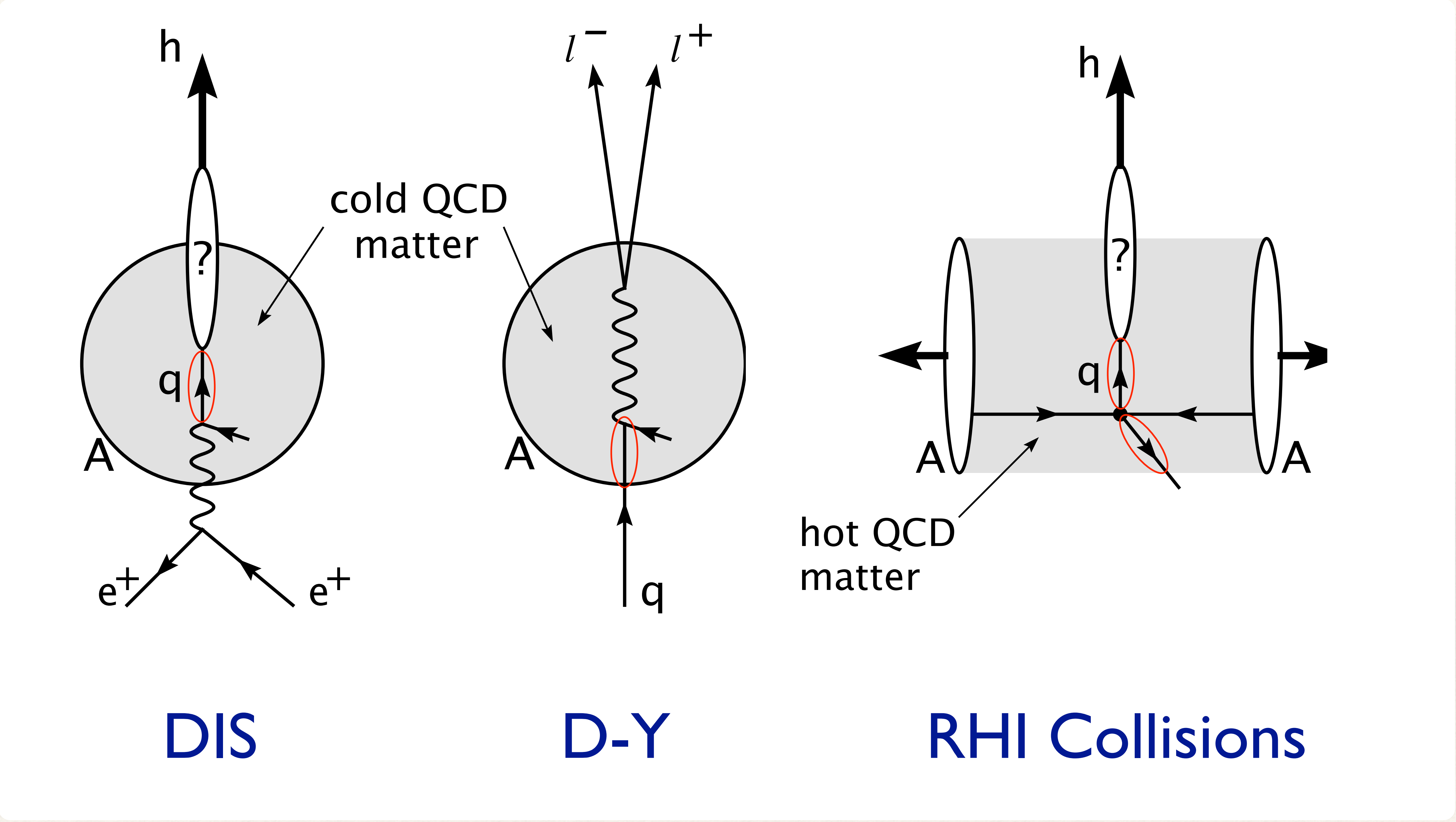
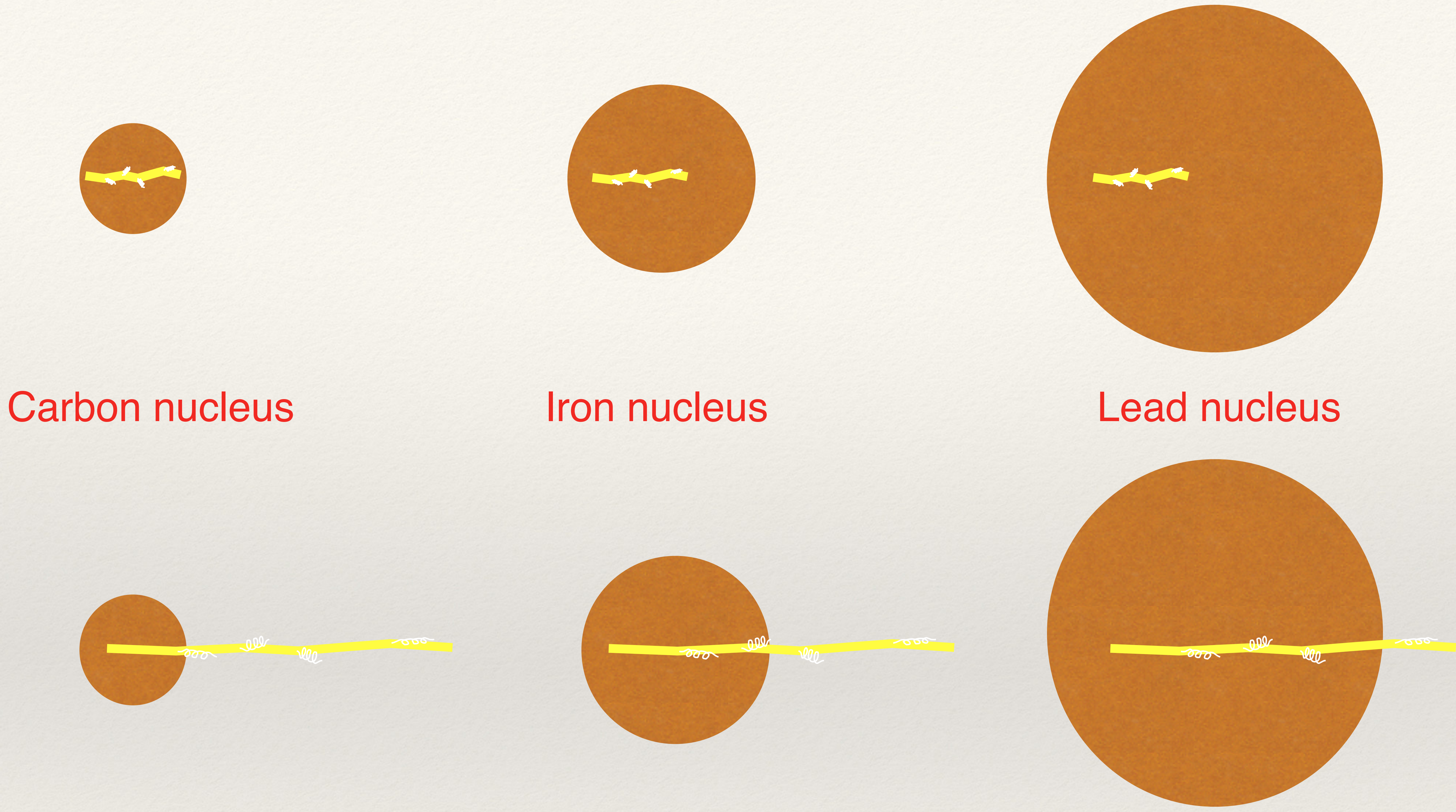
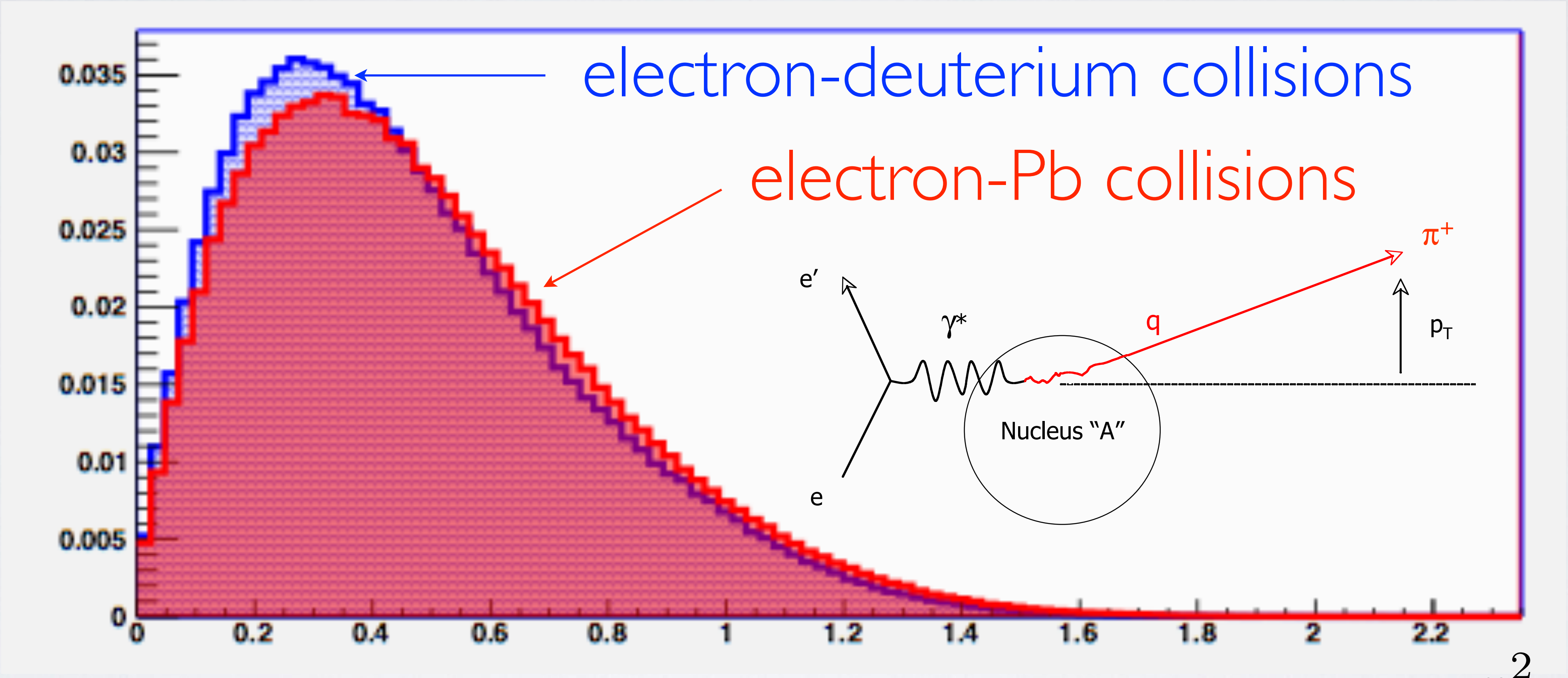




By comparing p_T broadening and hadron attenuation in nuclei of different sizes, one can measure the *length* of the color propagation process (fm scale)

Observable: p_T broadening

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



p_T^2

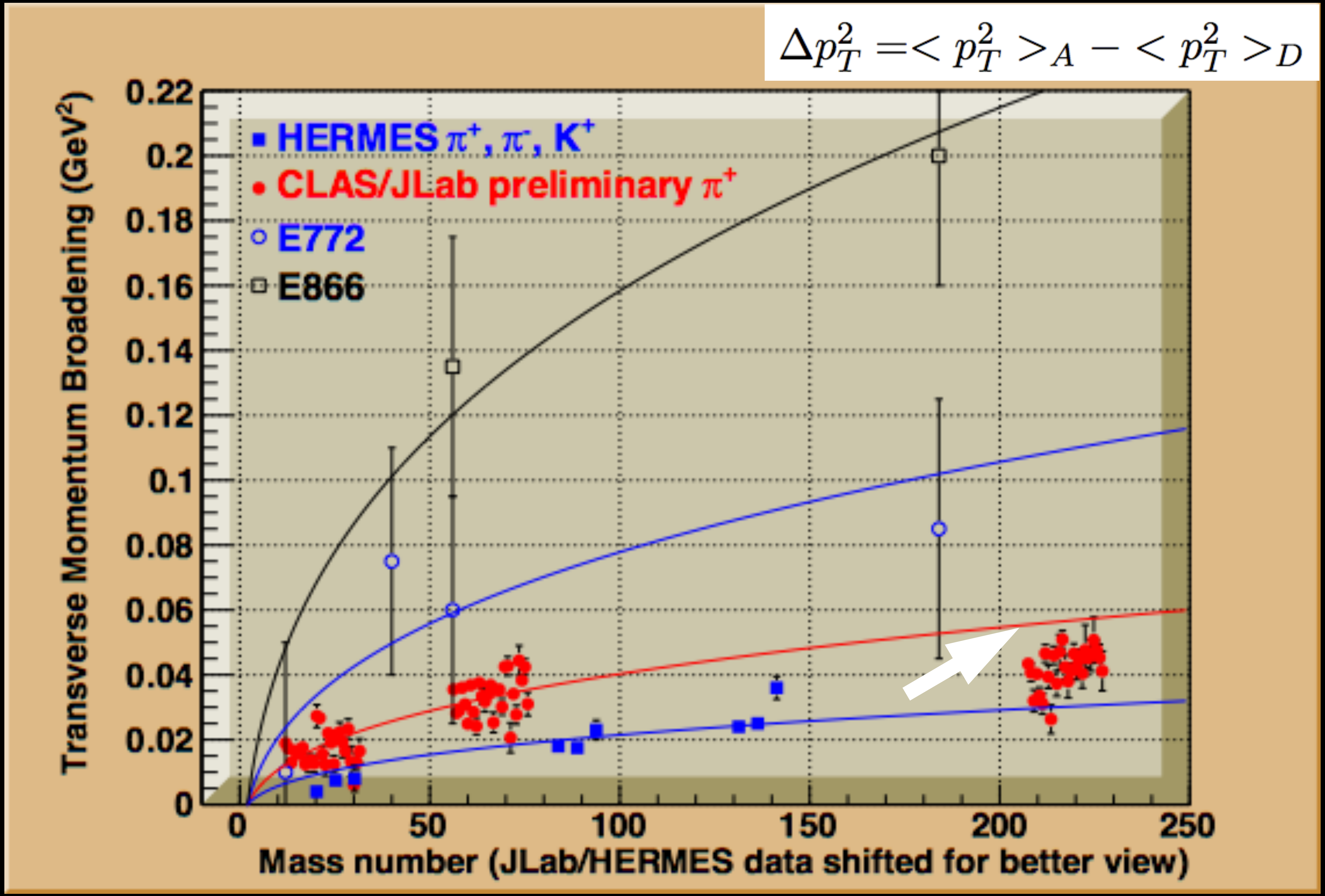
p_T broadening is a tool: sample the gluon field using a colored probe:

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

and radiative energy loss:

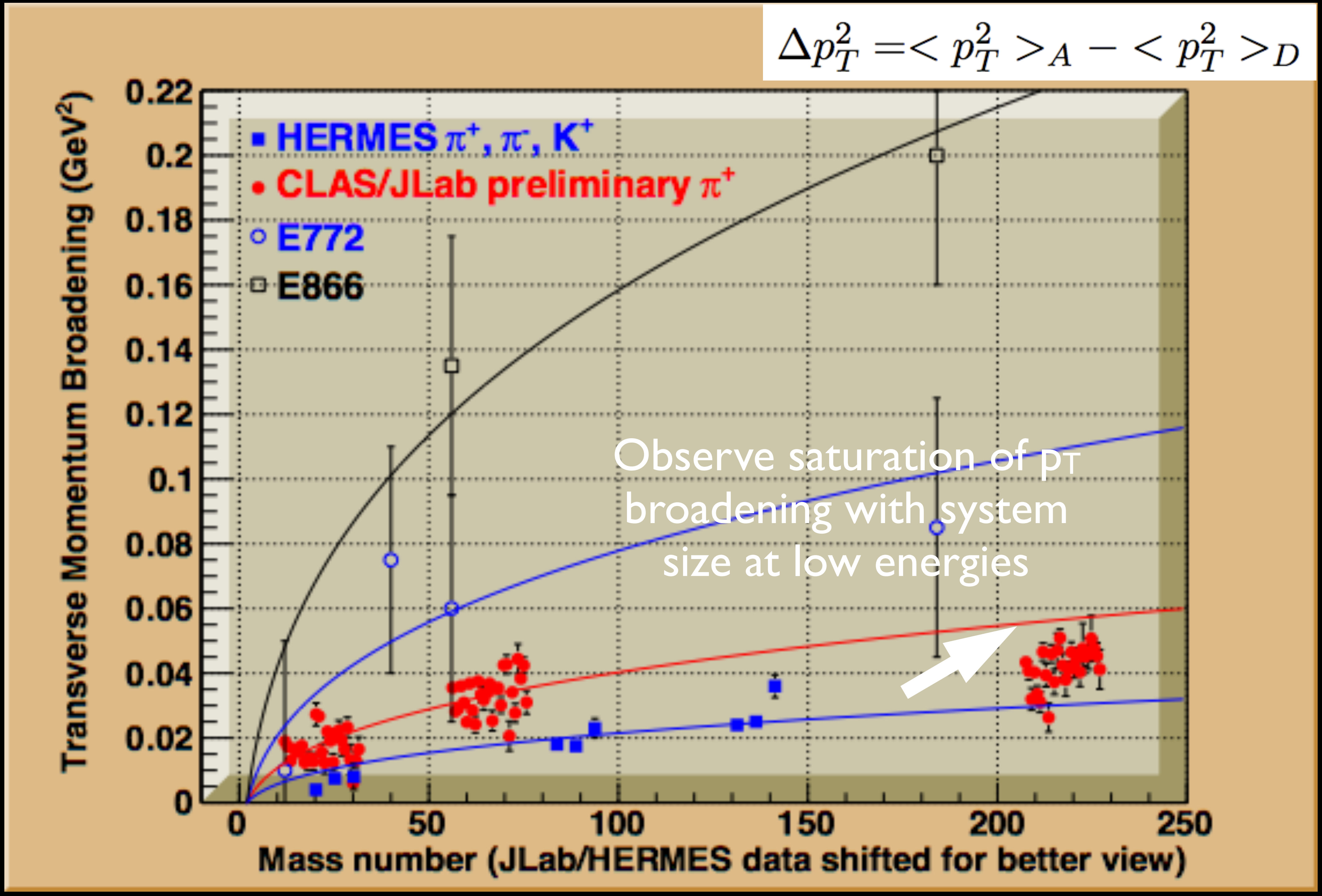
$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2$$

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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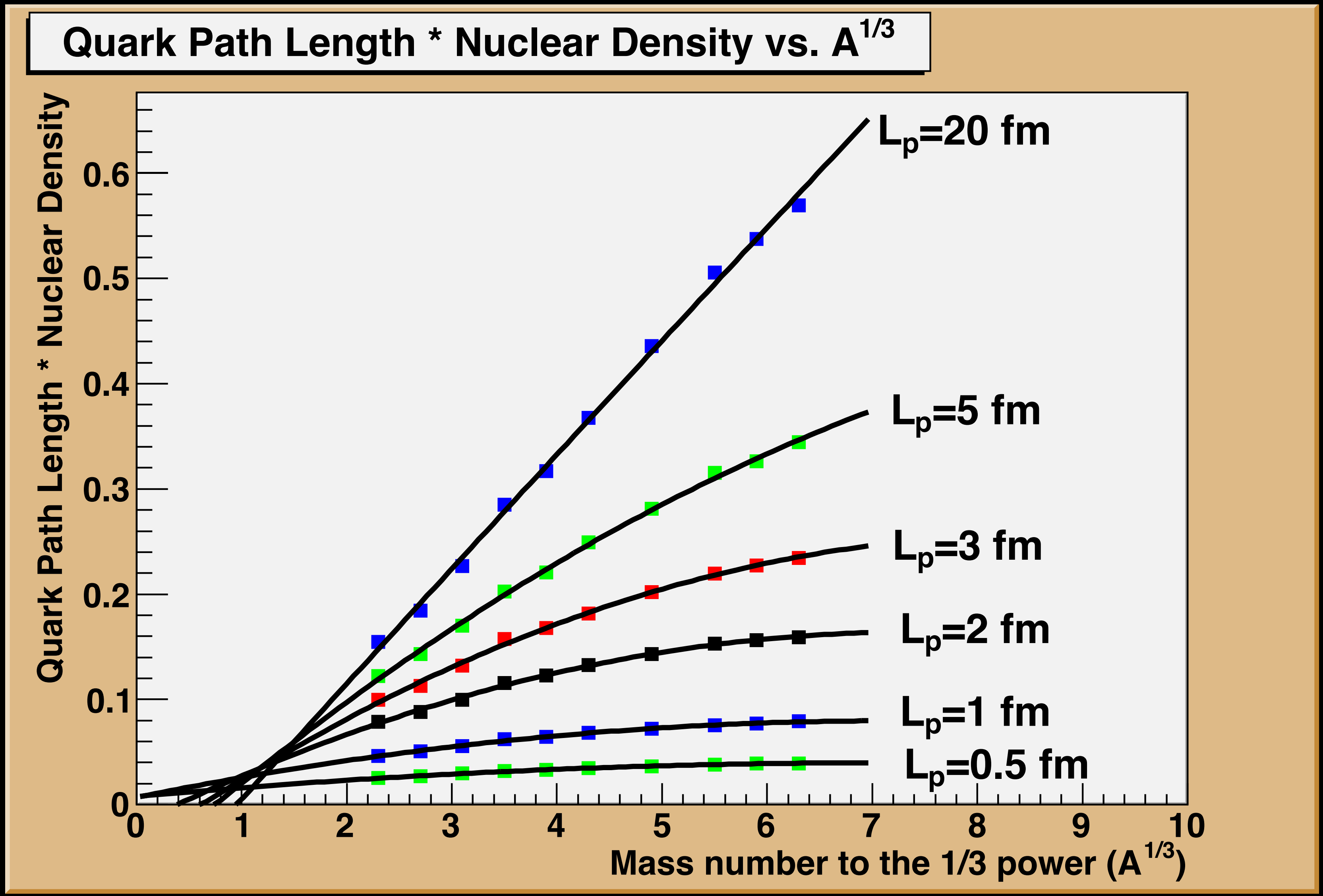
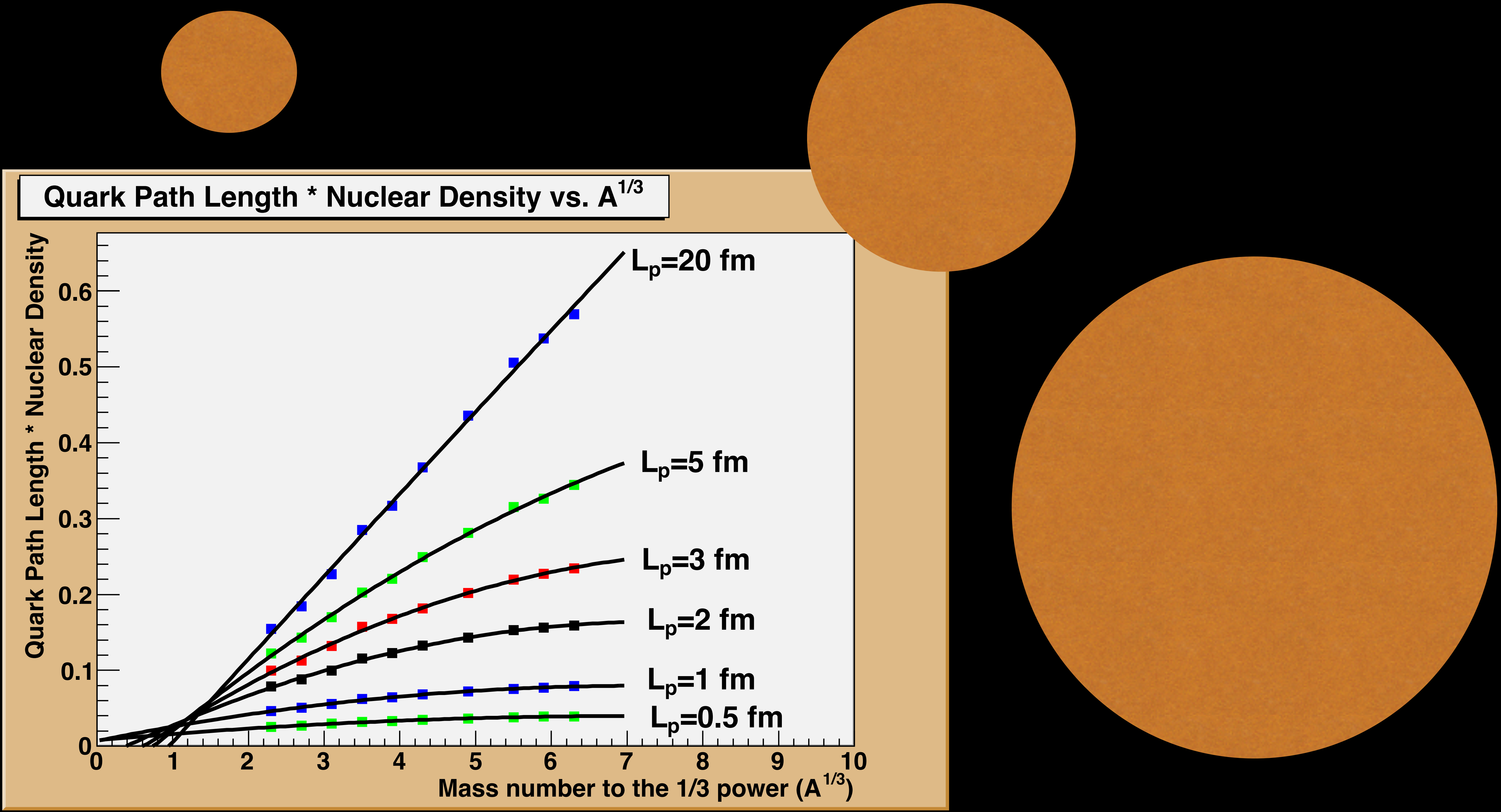
Production Time Extraction - Geometrical Effects



Production Time Extraction - Geometrical Effects



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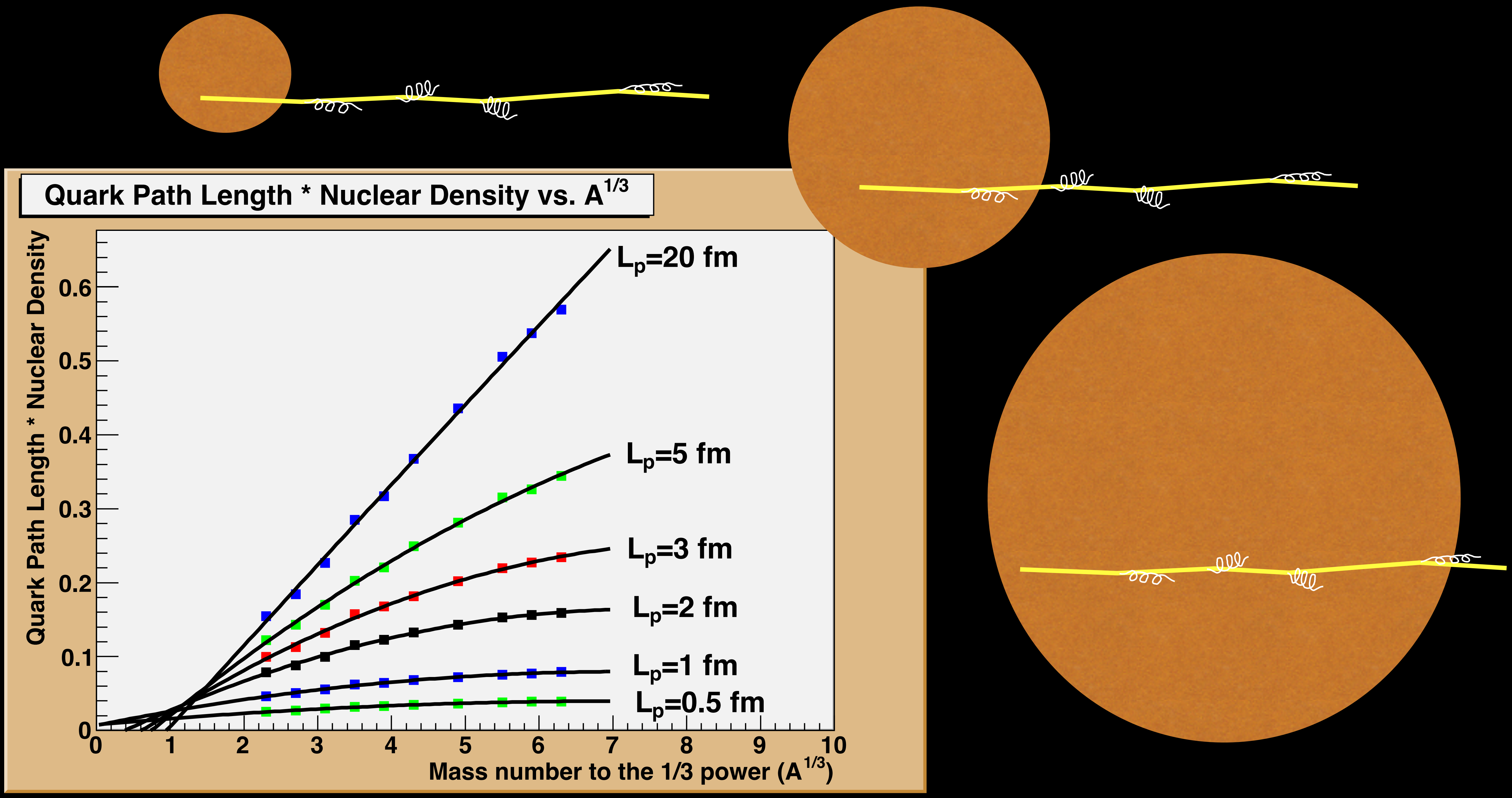

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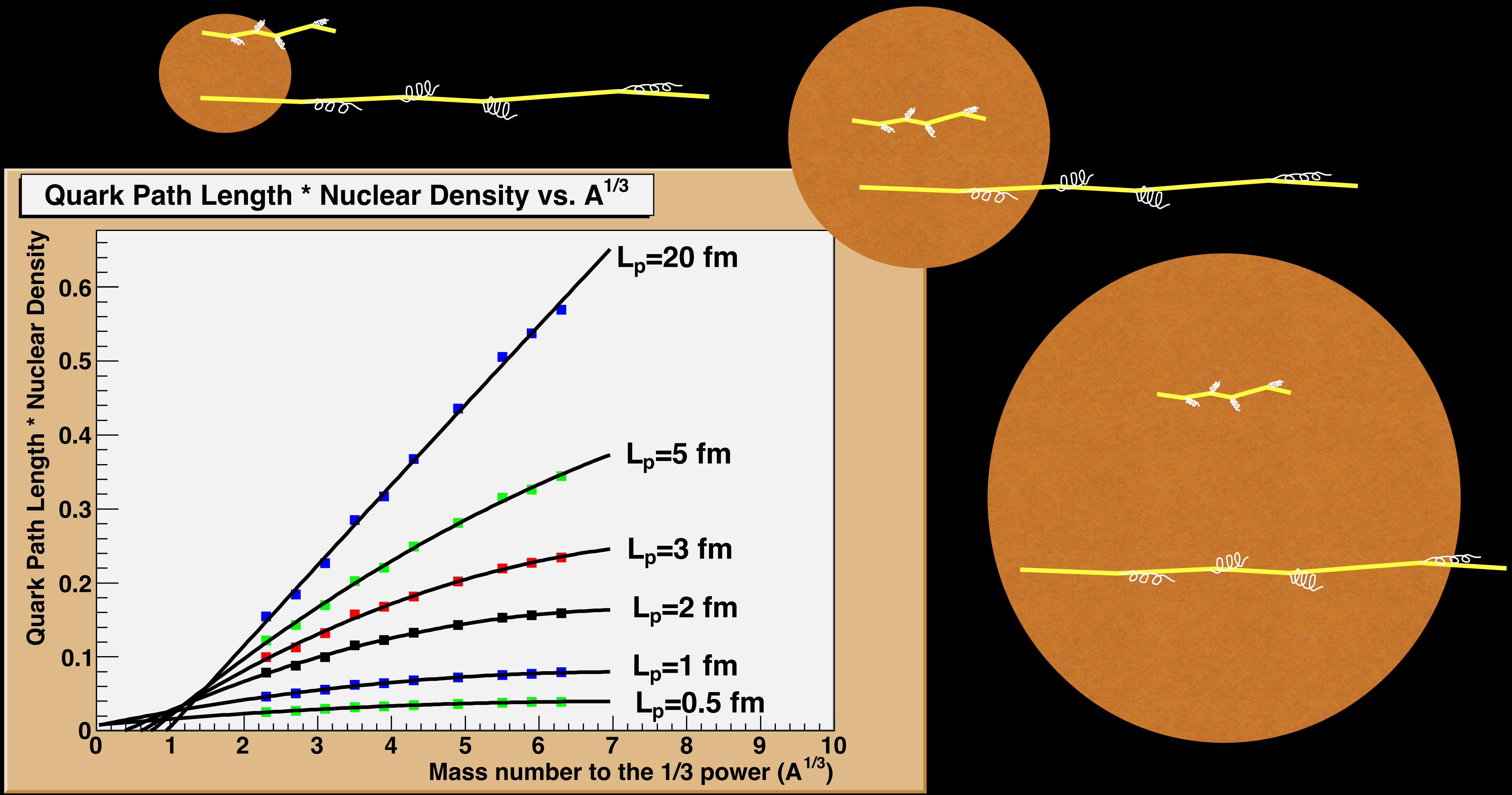

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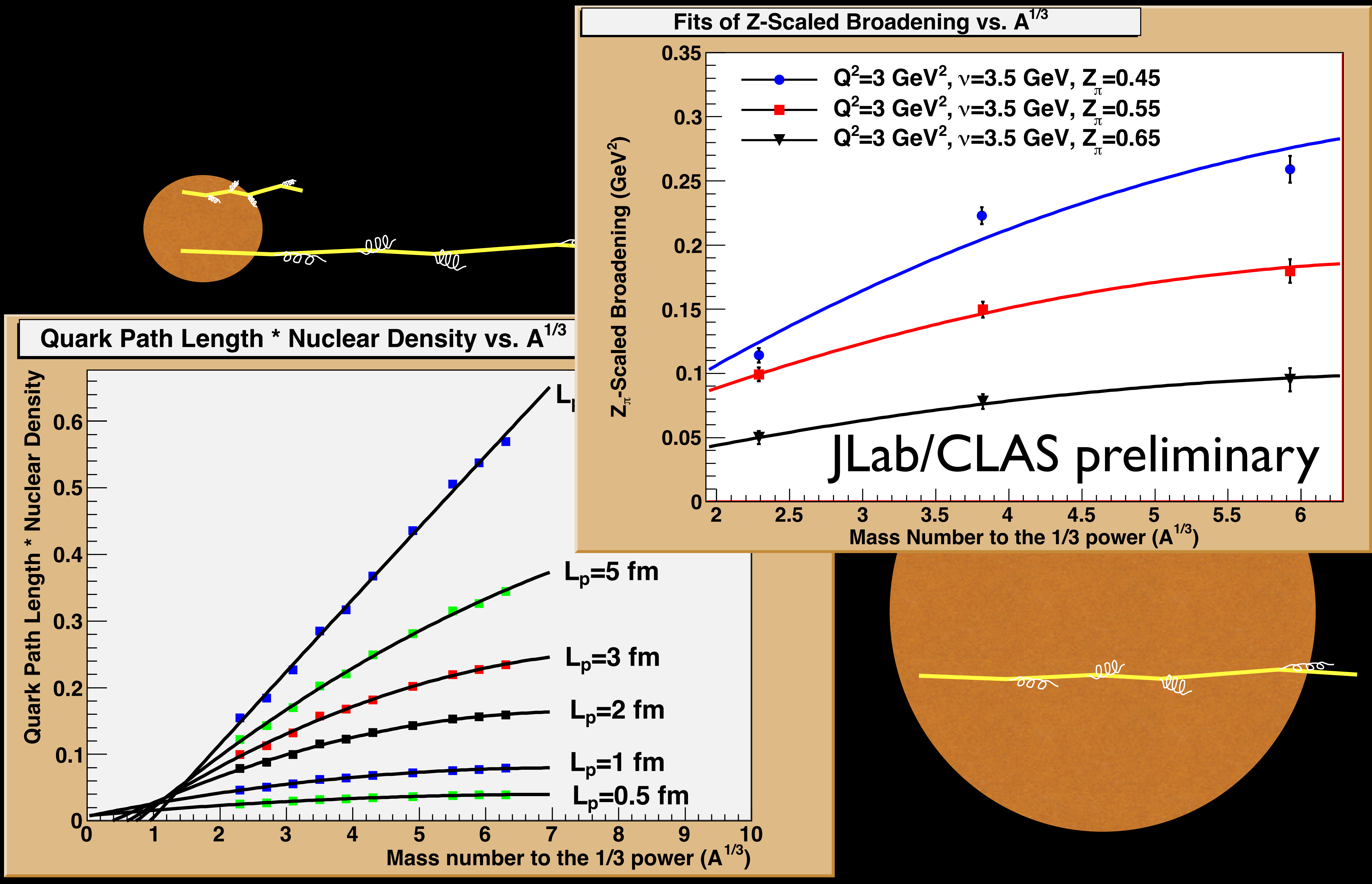
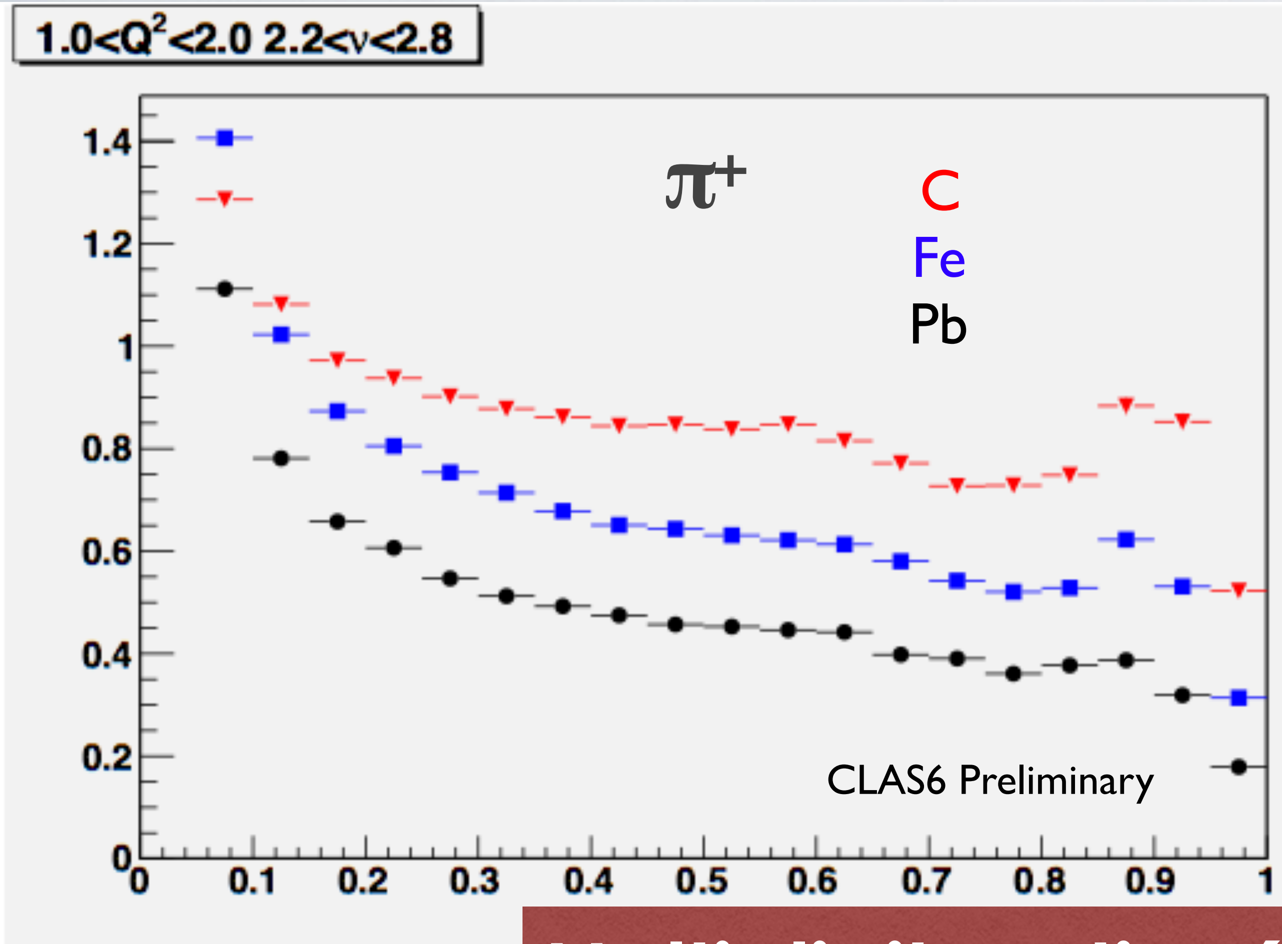
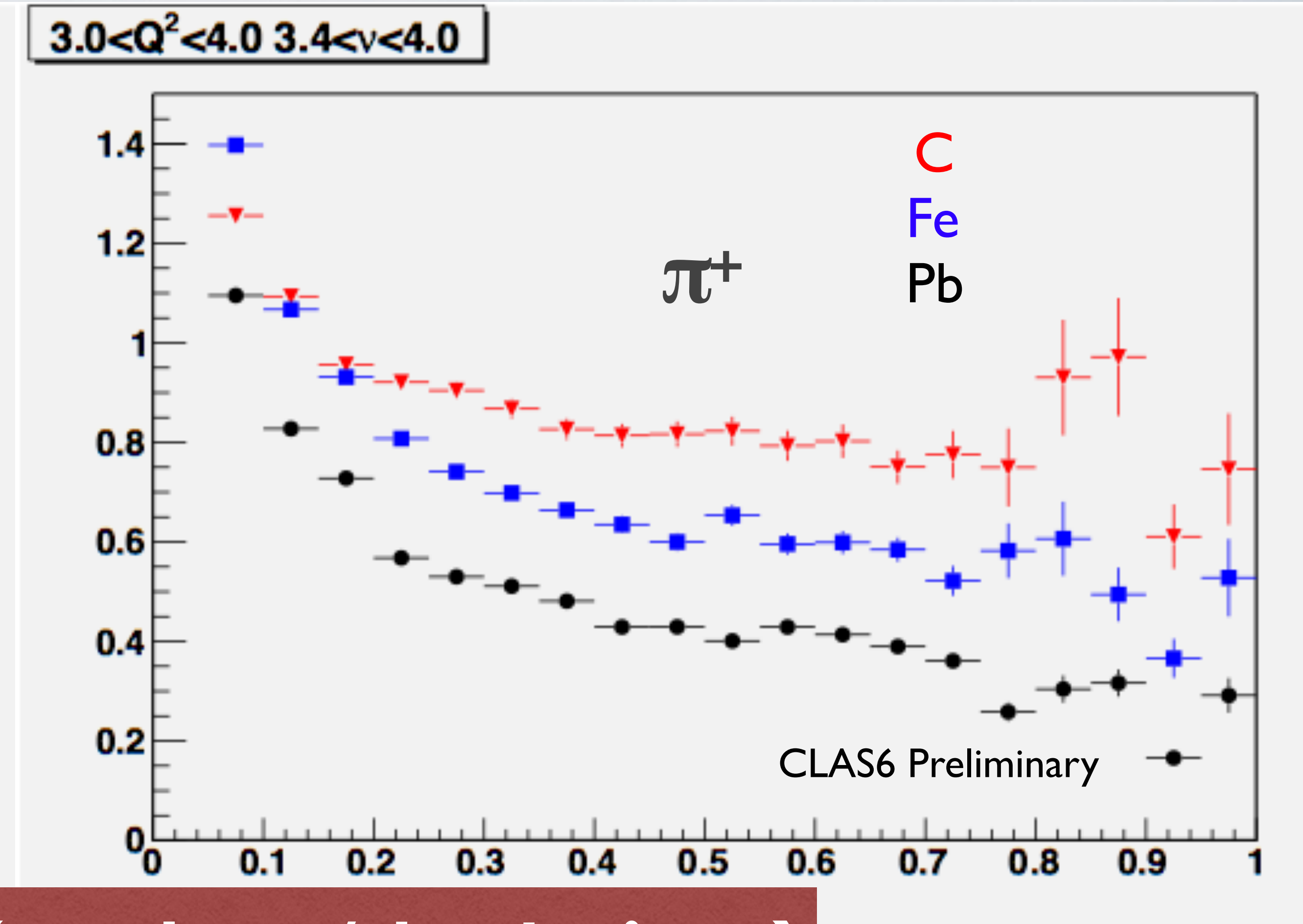
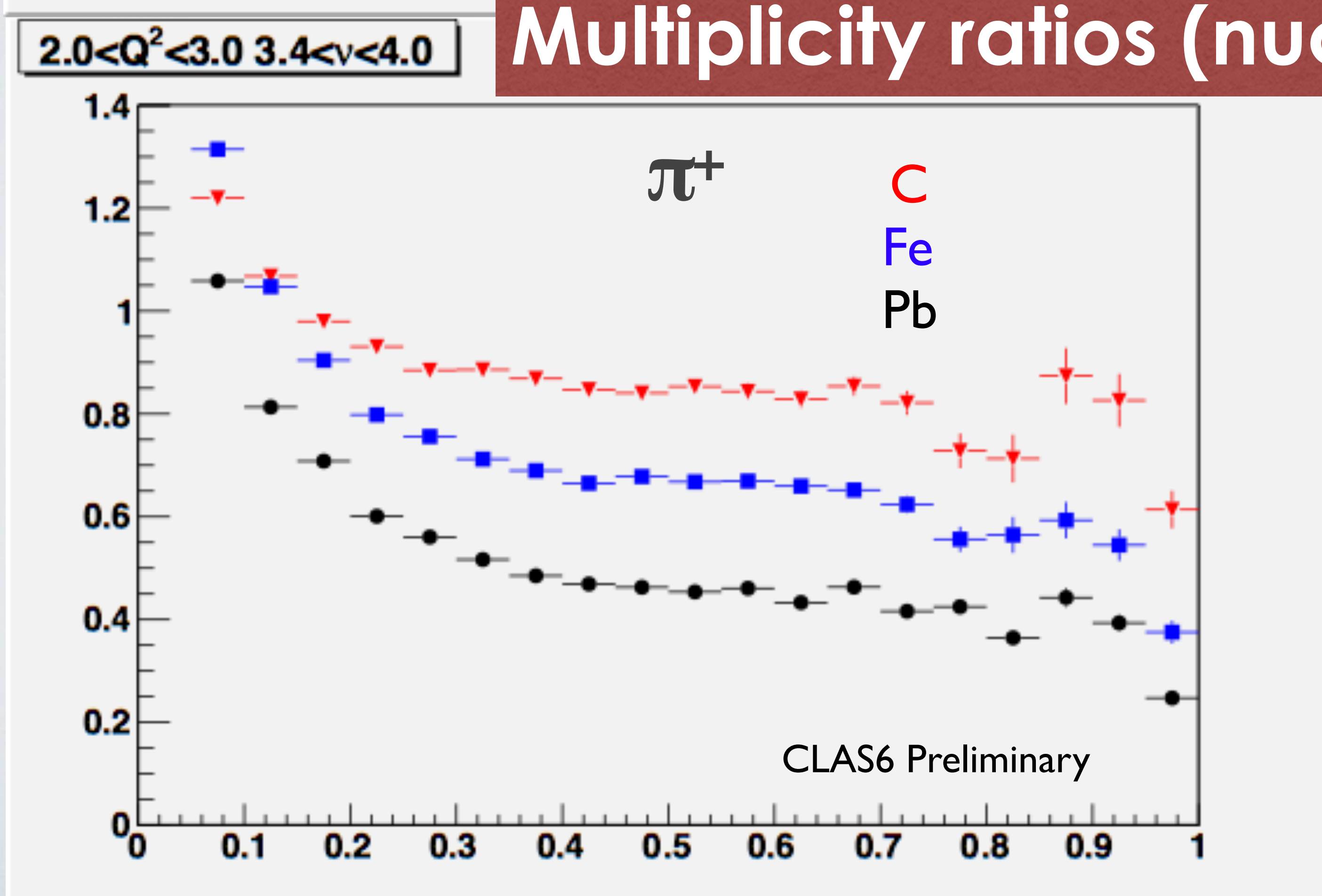






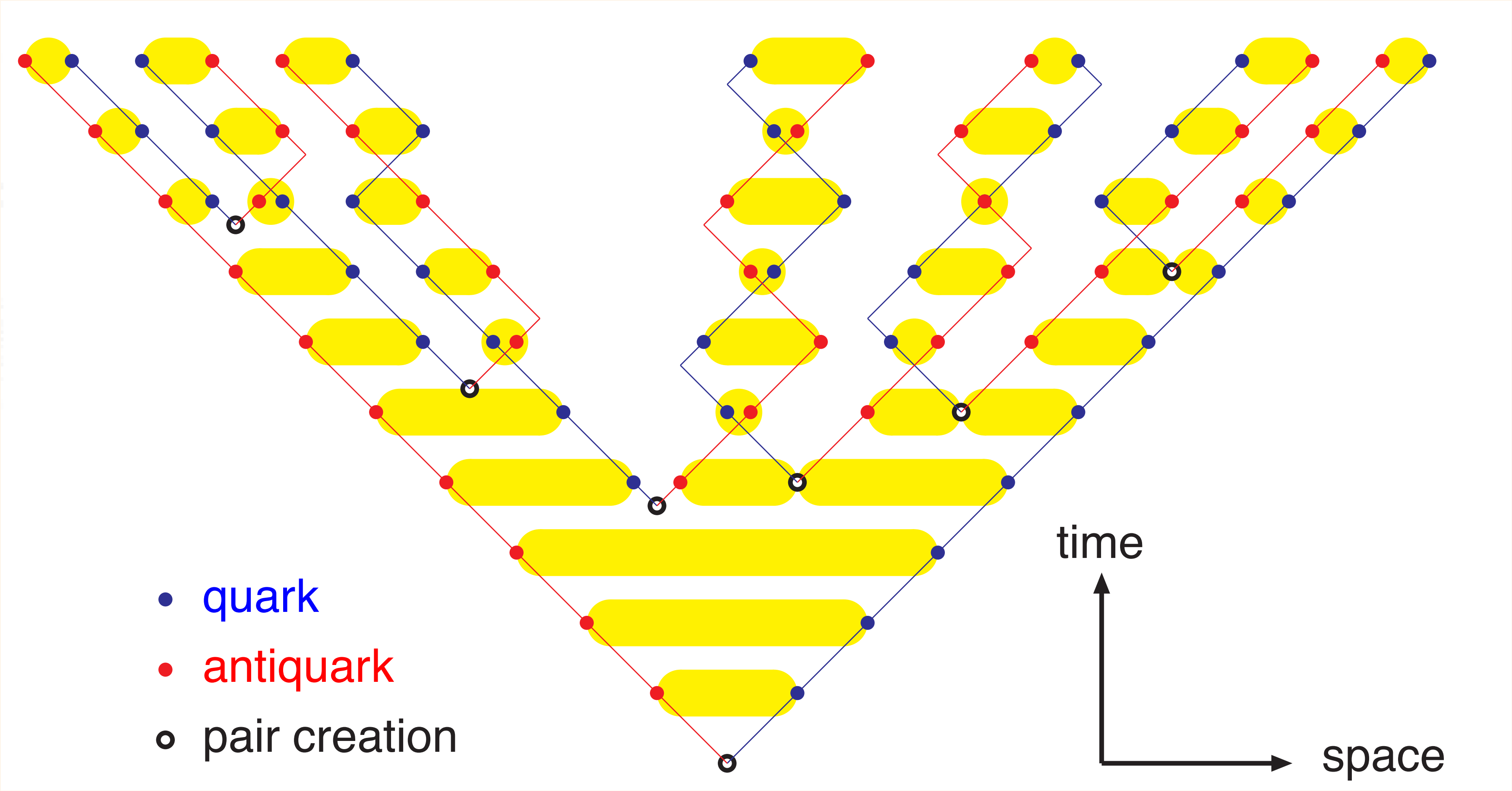
Multiplicity ratios (nucleus/deuterium)



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)



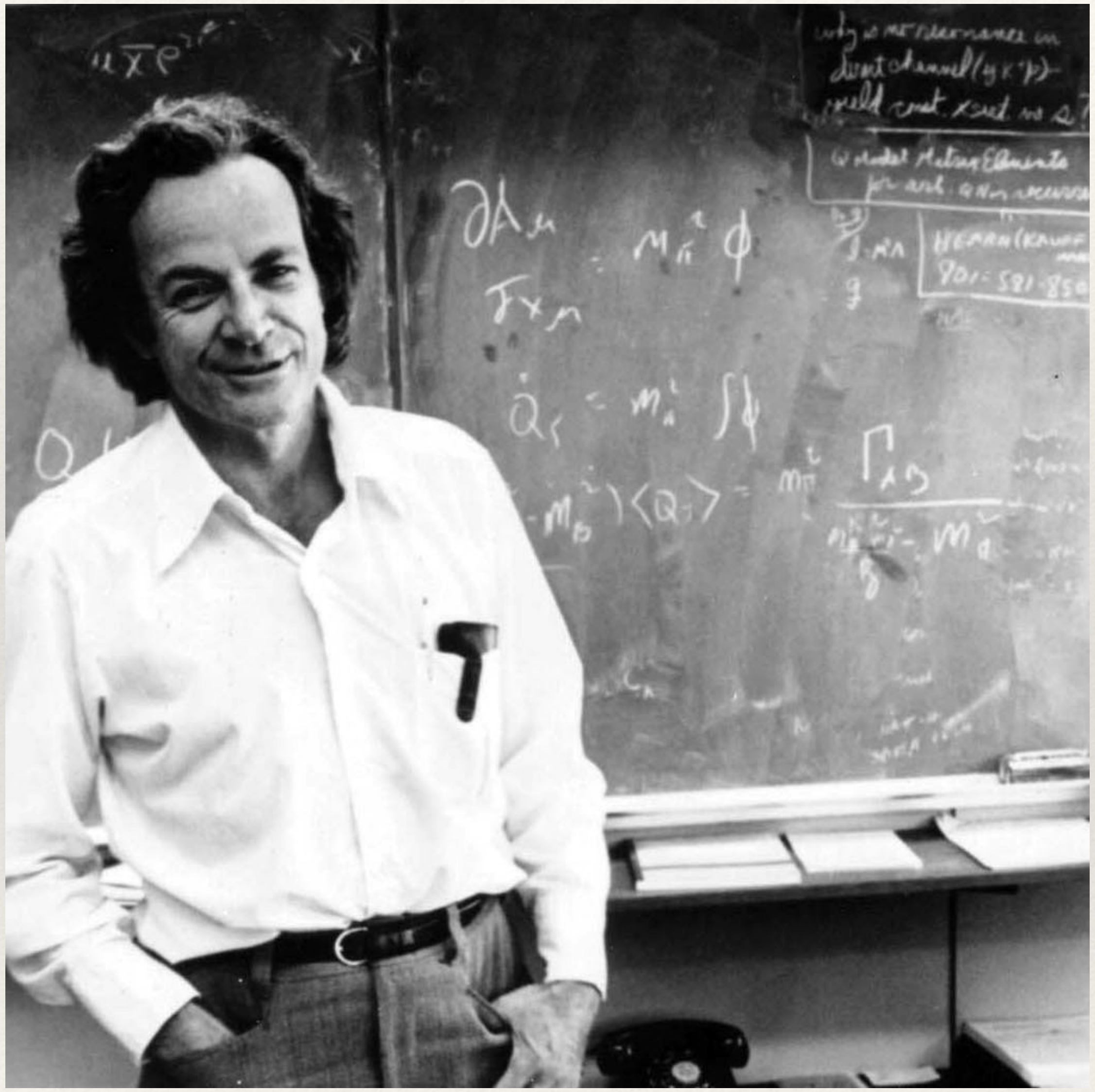
Remarkably successful model, foundational tool in HEP

- 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:

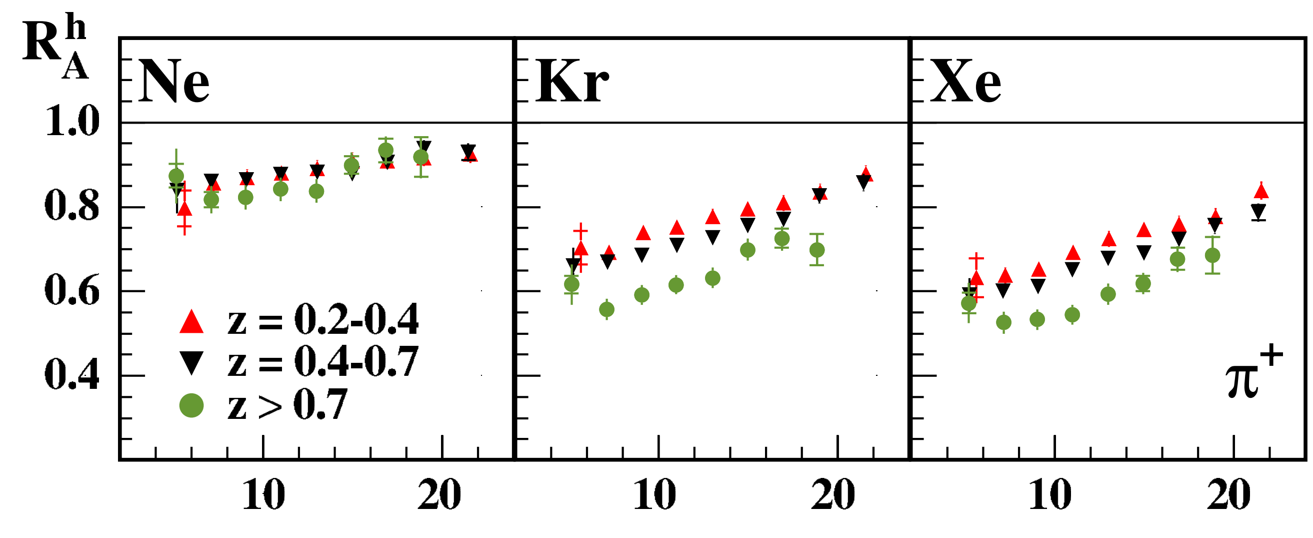
1. extrapolations to EIC kinematics,
2. test of time dilation in CLAS fits, and
3. direct comparison between JLab and HERMES fits

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

HERMES Study - Observables

Multiplicity ratio

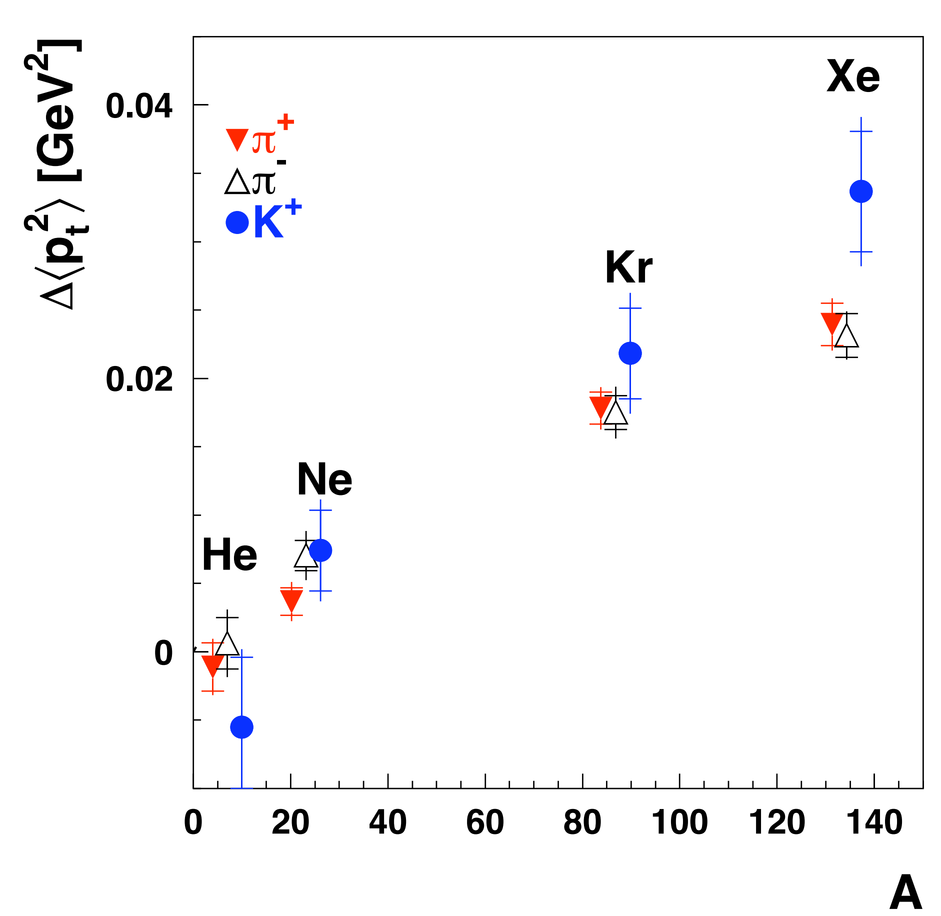
$$R^h_M(Q^2,\nu,z,p_T) \equiv \frac{\frac{1}{N_e(Q^2,\nu)}\cdot N_h(Q^2,\nu,z,p_T)|_A}{\frac{1}{N_e(Q^2,\nu)}\cdot N_h(Q^2,\nu,z,p_T)|_p}$$



HERMES Coll., Eur. Phys. J. A (2011) 47: 113

p_T broadening

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

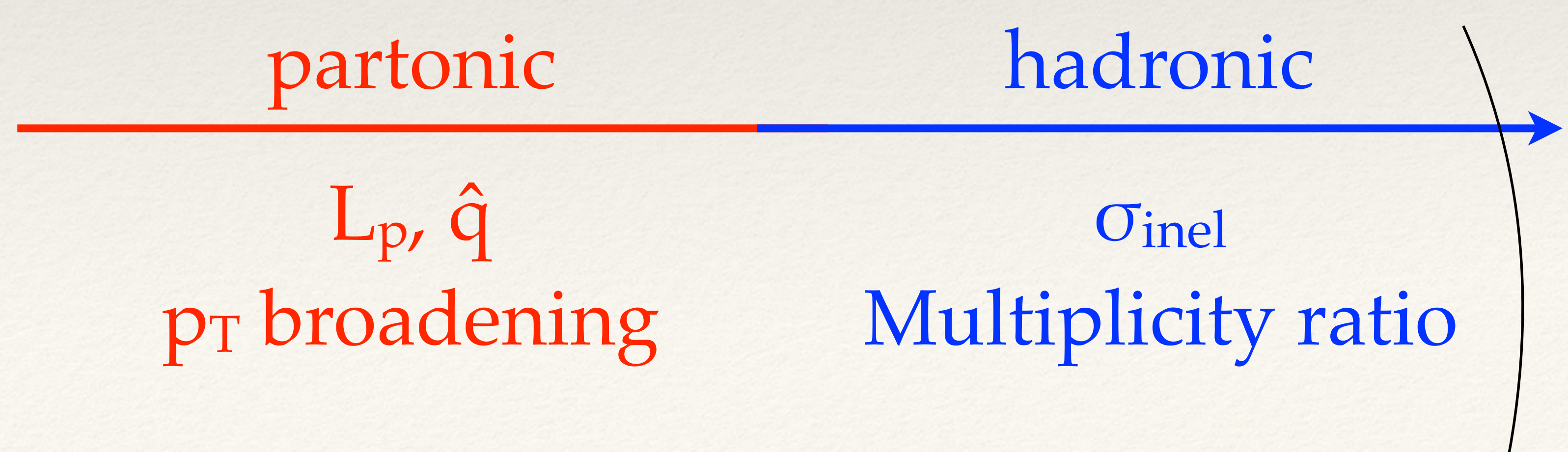


We fit both observables simultaneously

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"

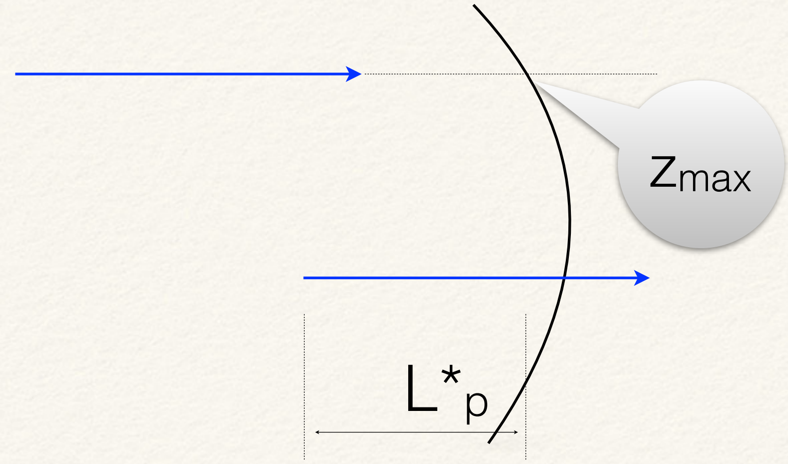


B-L Geometric model description II

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 <u>pre</u>hadron 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 ρ(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

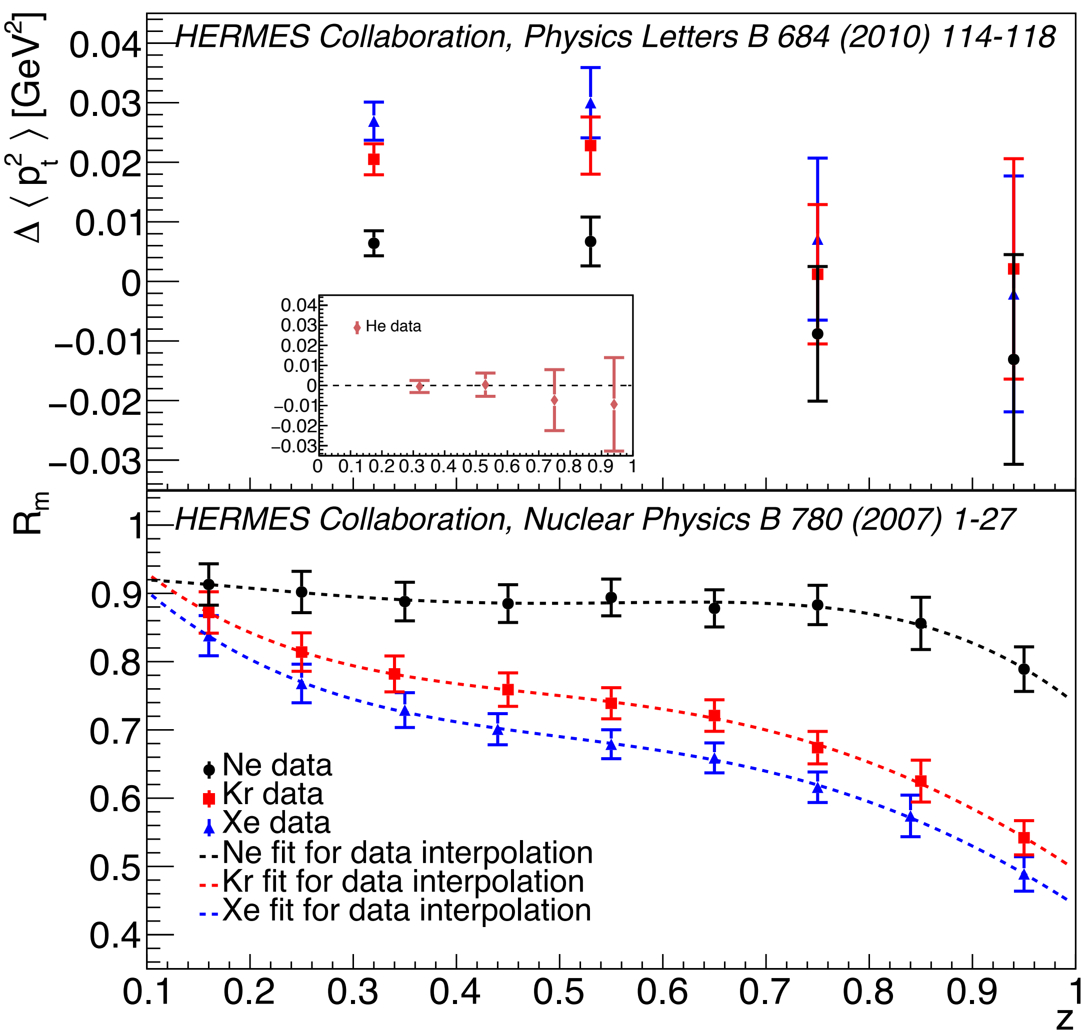
No dynamical information is assumed; it emerges from fit

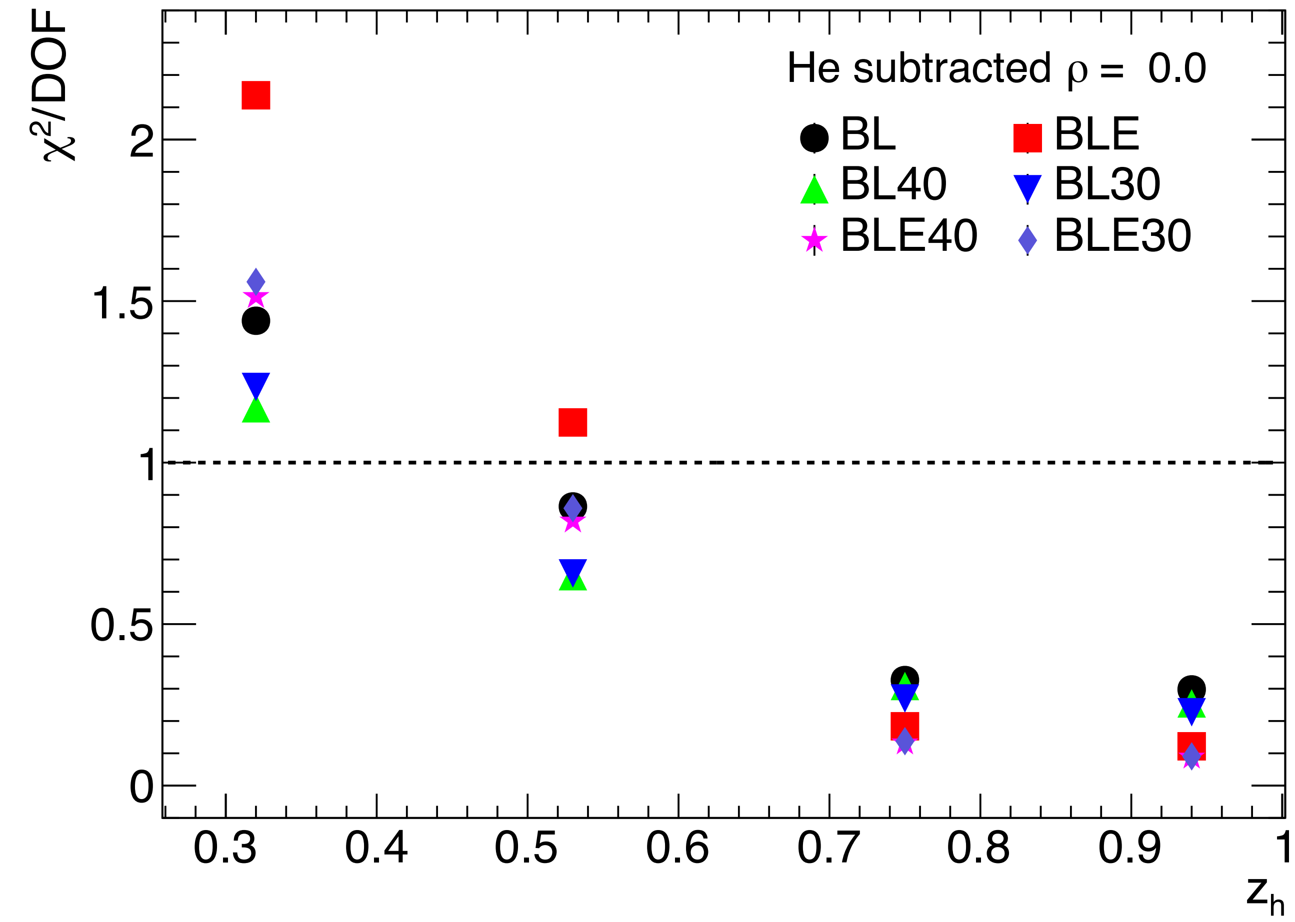
Systematic errors: 3% for multiplicity ratio, 4% for p_T broadening

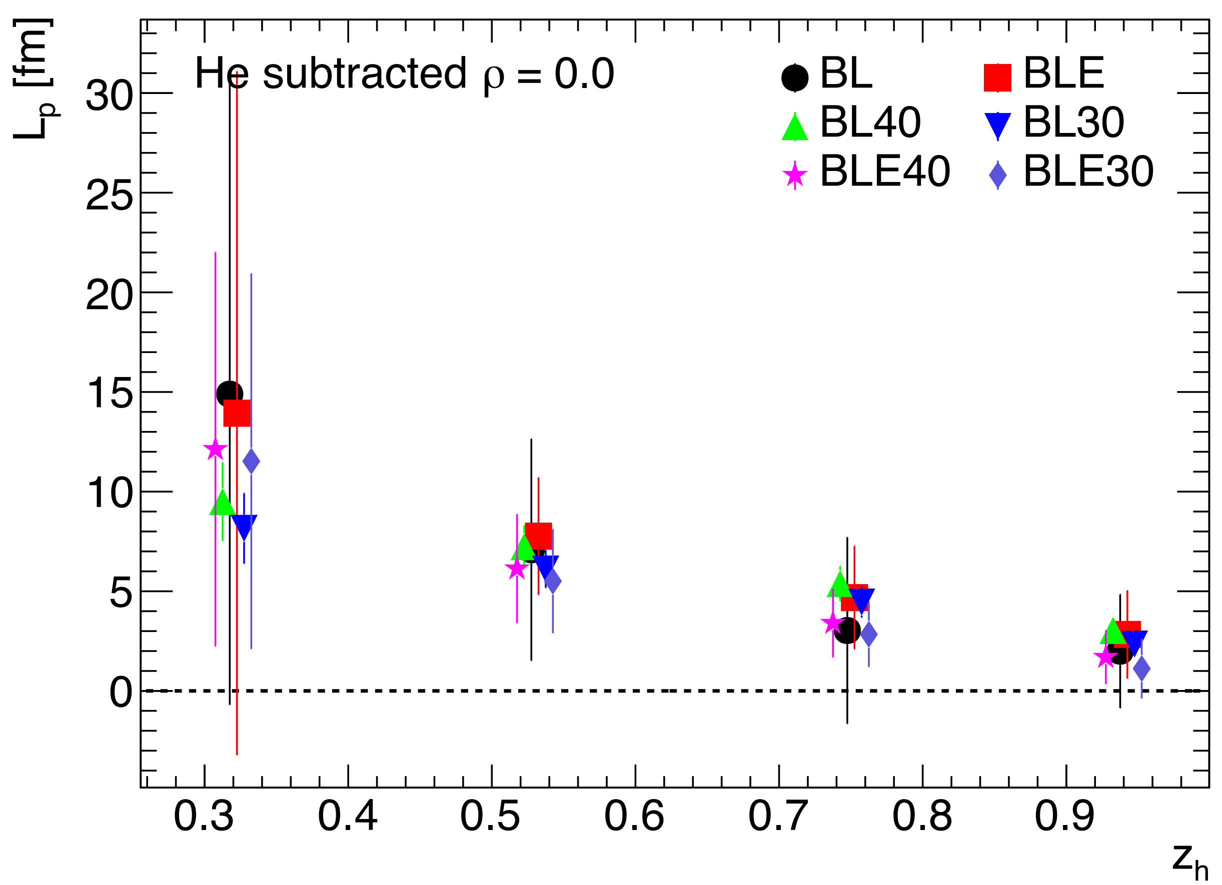
Comment on the B-L model

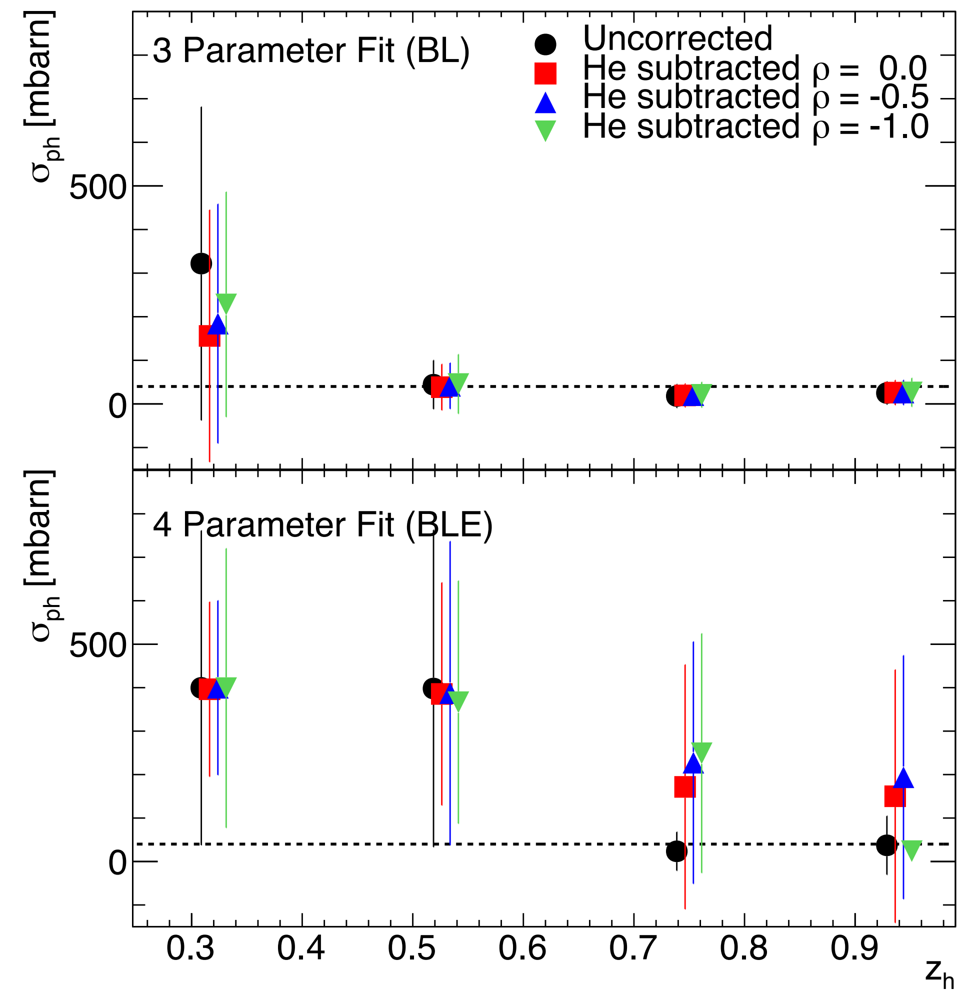
I believe that studies of this kind can be carried out at the same level of validity as the estimation of centrality in heavy ion collisions.

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
Δ ⟨p_t^2⟩ [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

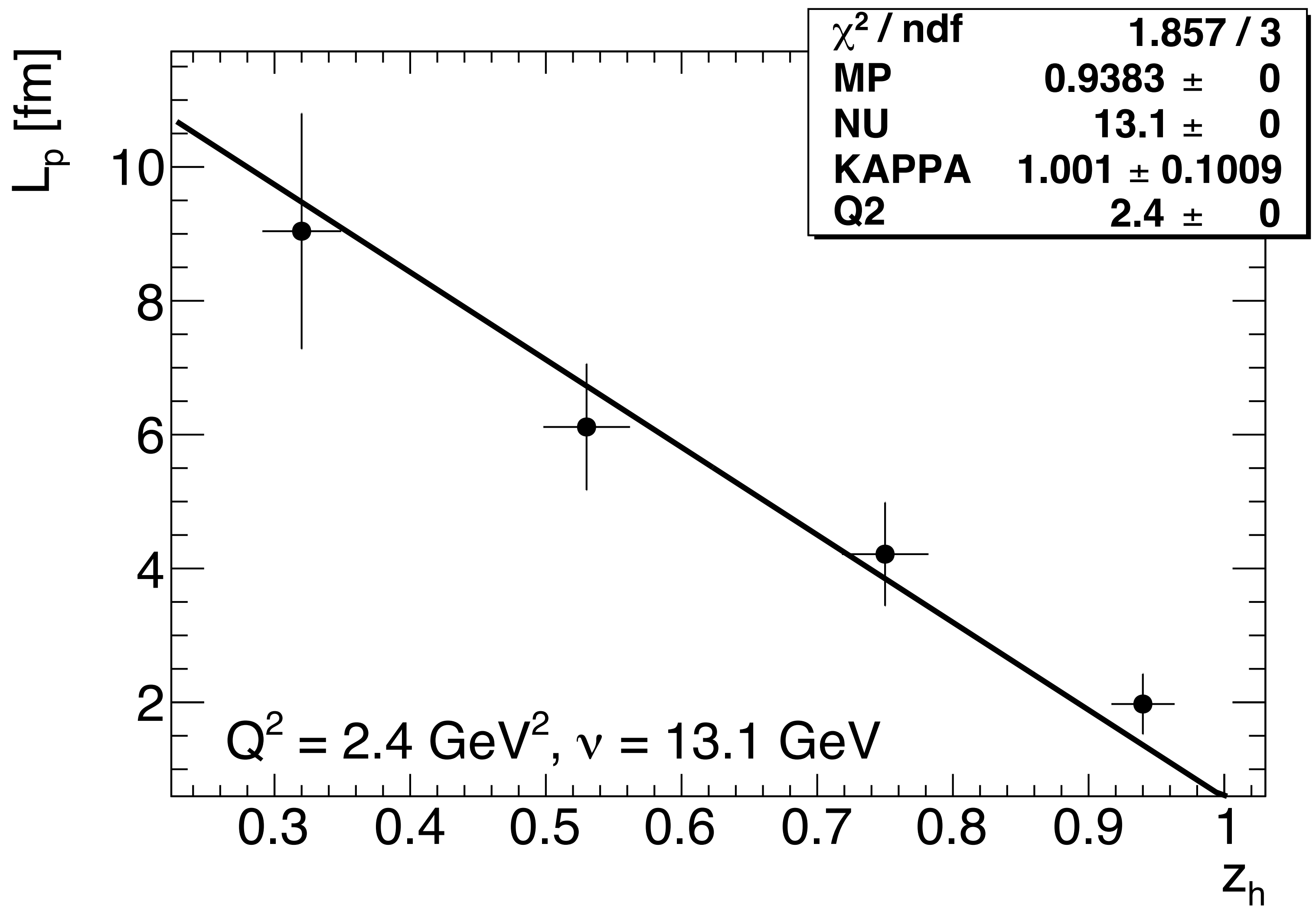

χ^2/DOF
He subtracted ρ = 0.0
BL
BLE
BL40
BL30
BLE40
BLE30
z_h


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!

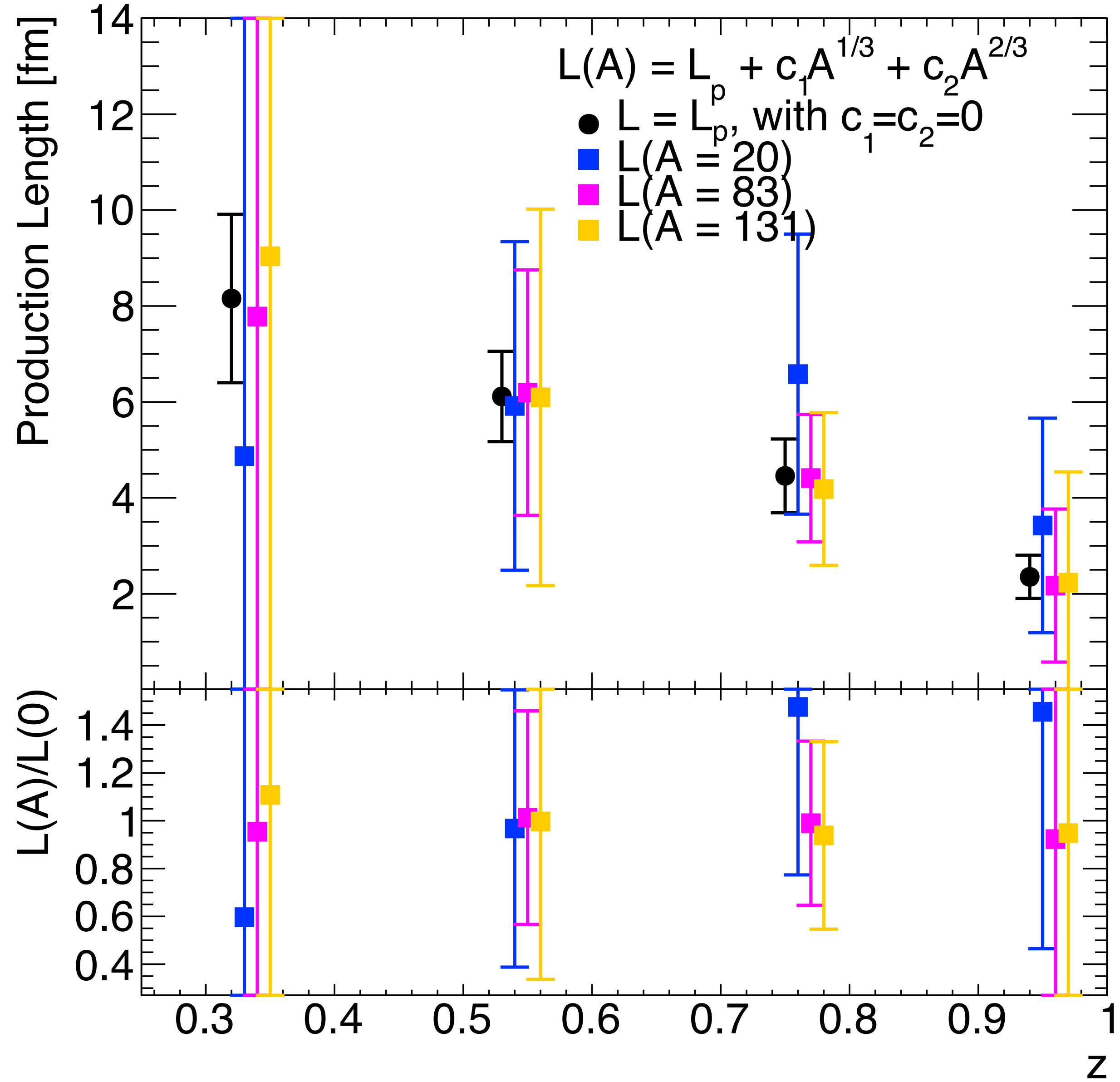
Light cone Lund String Model form for lab frame:

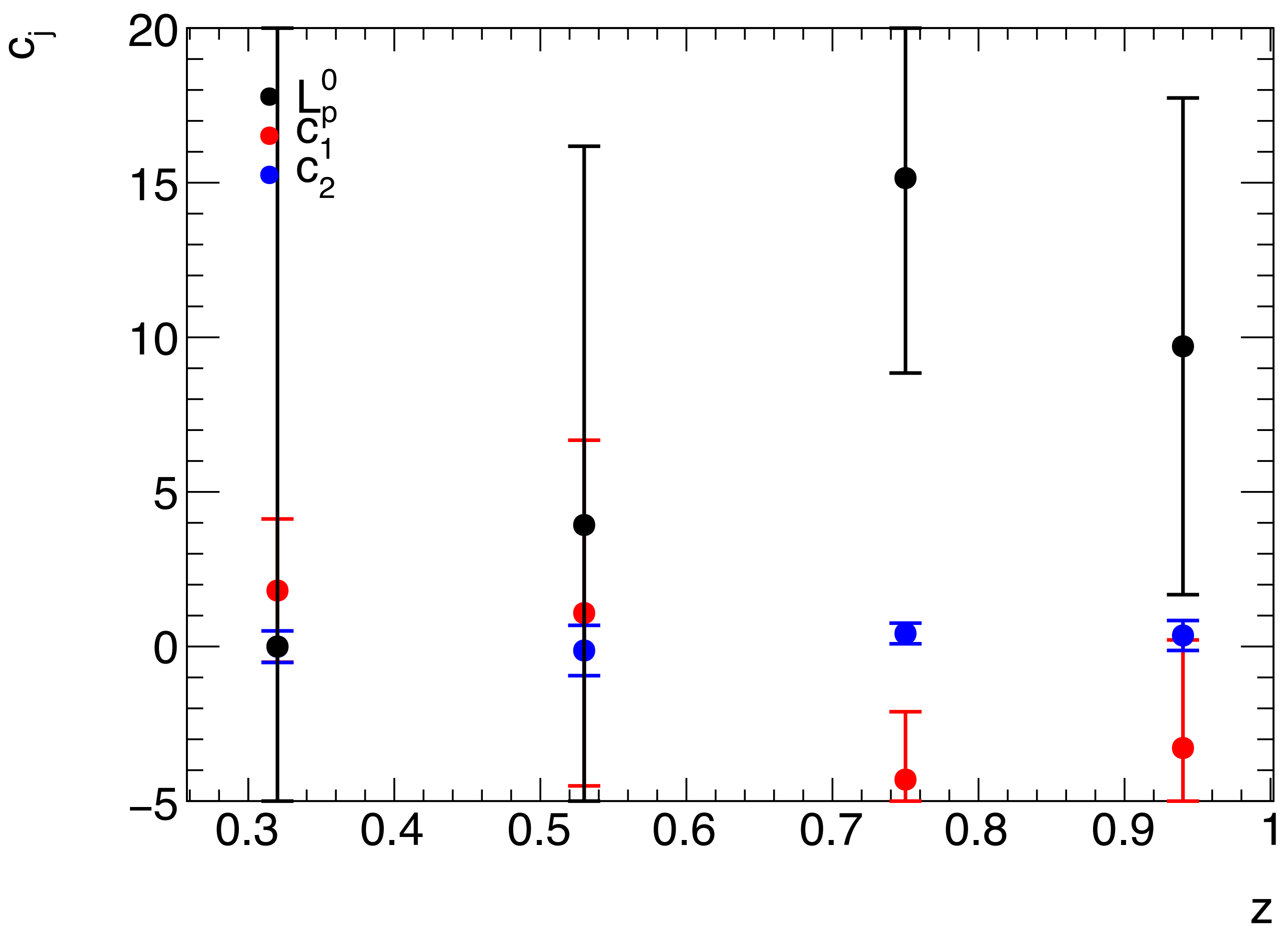
$$l_p = \frac{1}{2\mathcal{K}} \cdot \left(M_p + \nu + \sqrt{\nu^2 + Q^2} - 2 \cdot \nu \cdot z' \right)$$

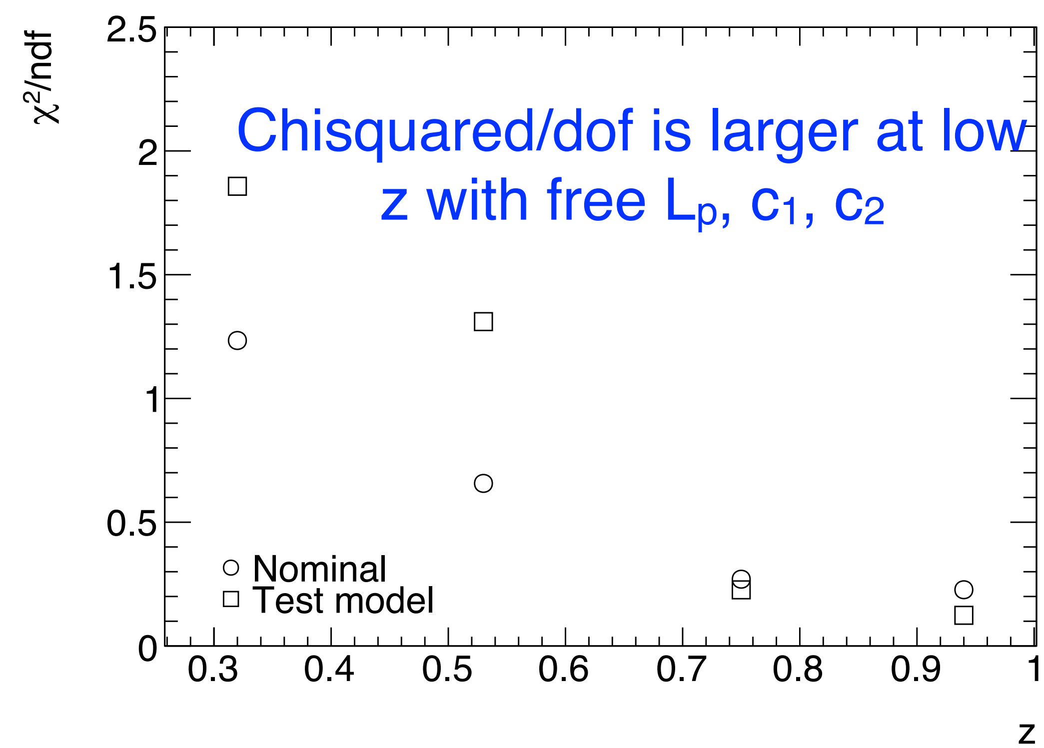
HERMES data analysis: exploring potential nuclear dependence of production time, and extrapolation to the vacuum

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

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





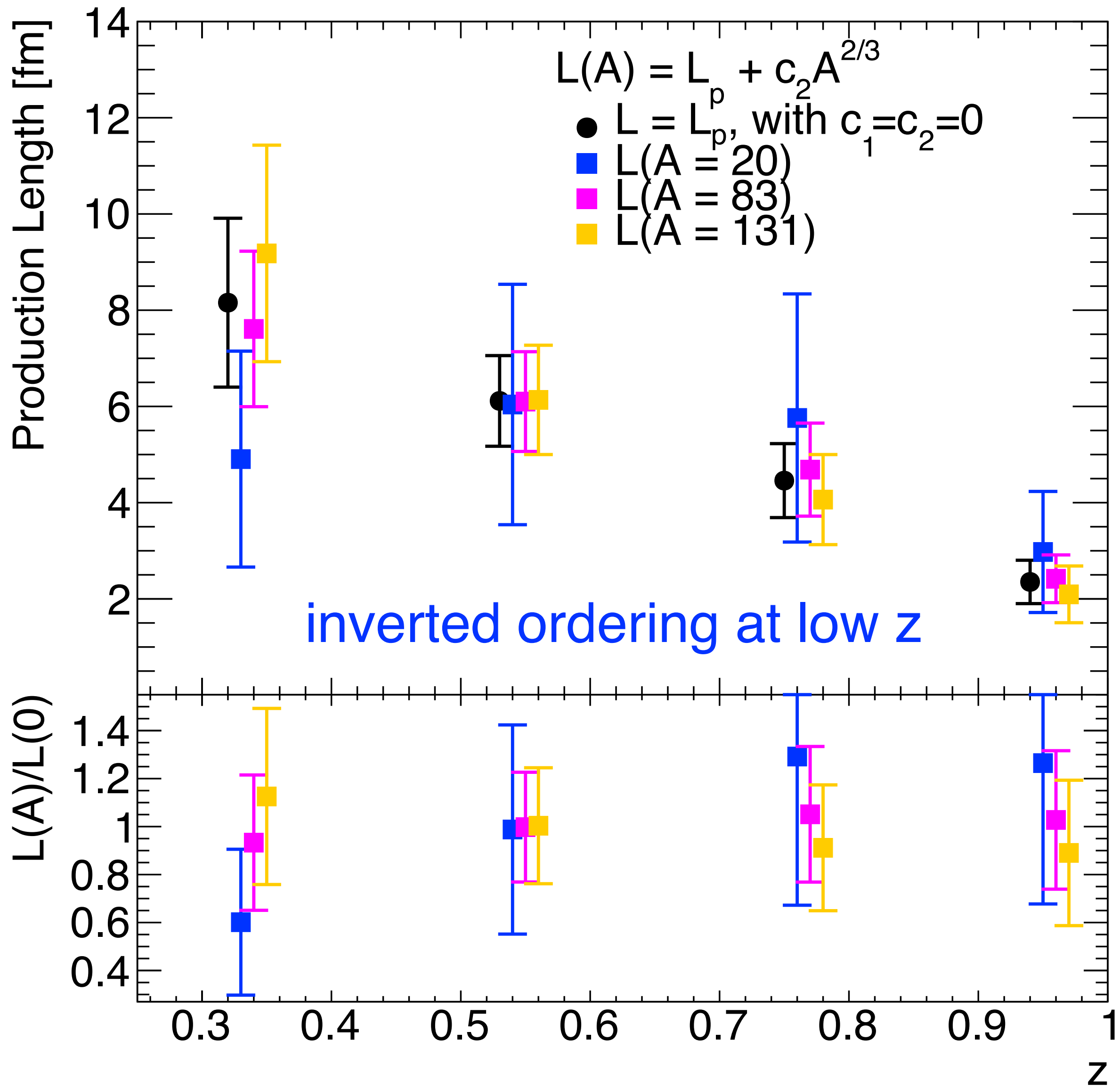


We see a strong fit correlation between L_p and c_1

Therefore, in the next slide we fix c1=0

(BL30 model variant)

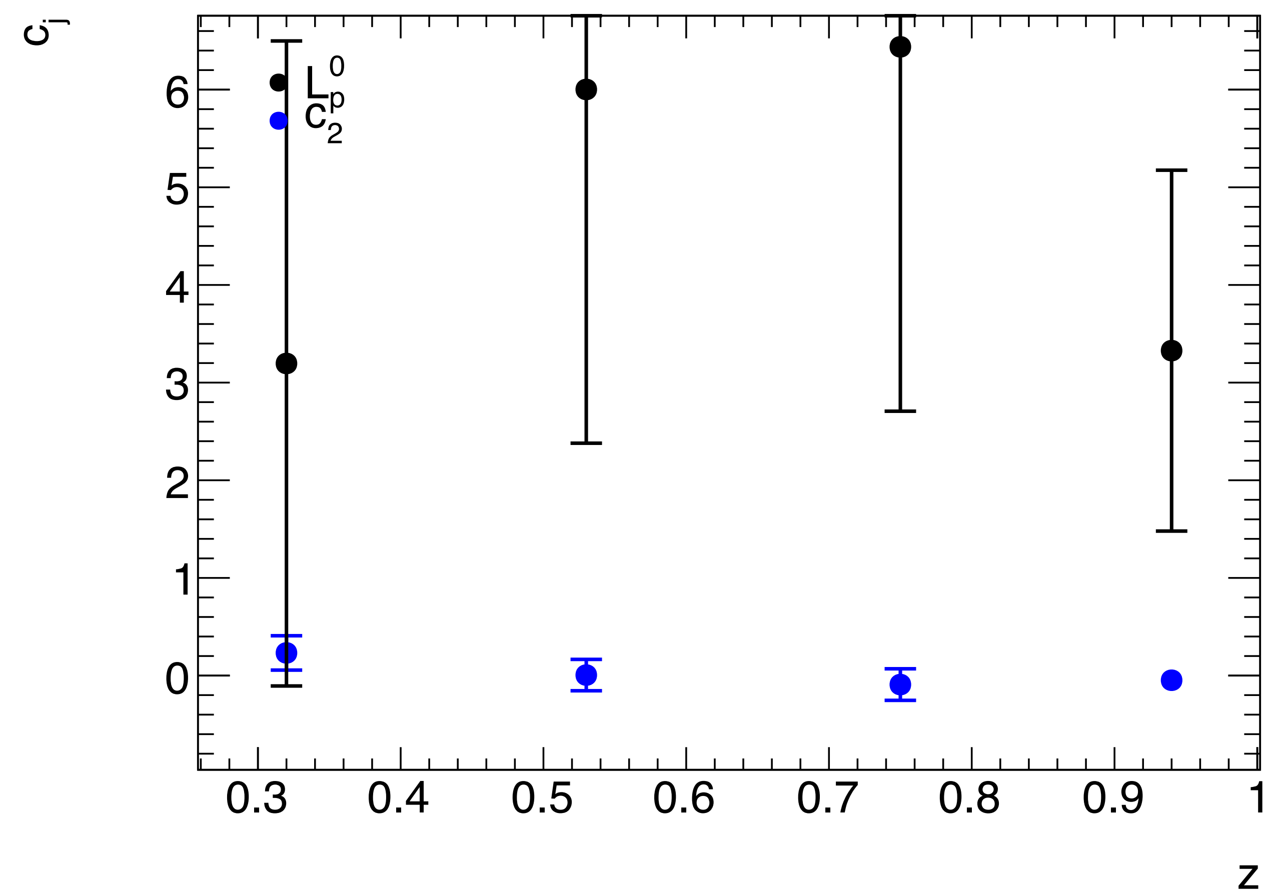
The case with **free L_{po} and c_2**, and **fixed c_1=0**

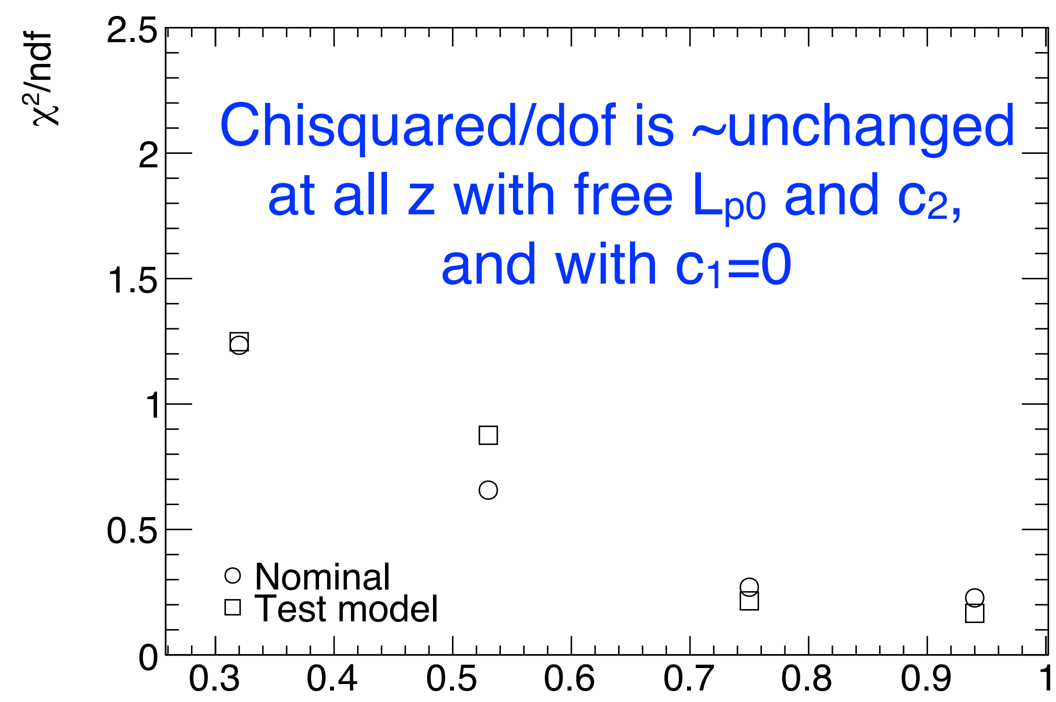


Extrapolation to vacuum: A=0

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.



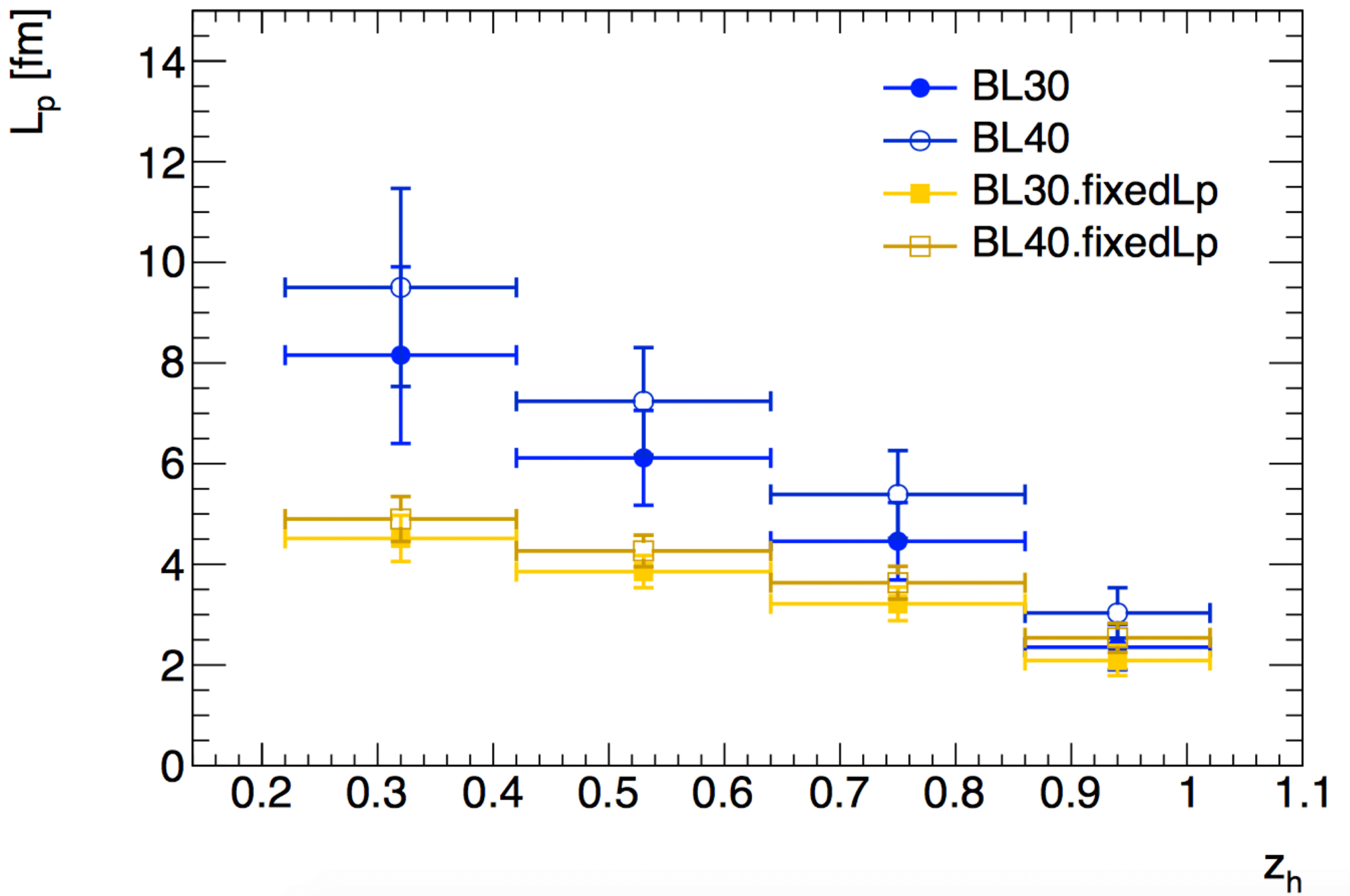


(BL30 model variant)

Conclusion: good evidence for the following functional form. The vacuum term L_{p0} 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.

$$L_p(A) = L_{p0} + c_2 A^{2/3}$$

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

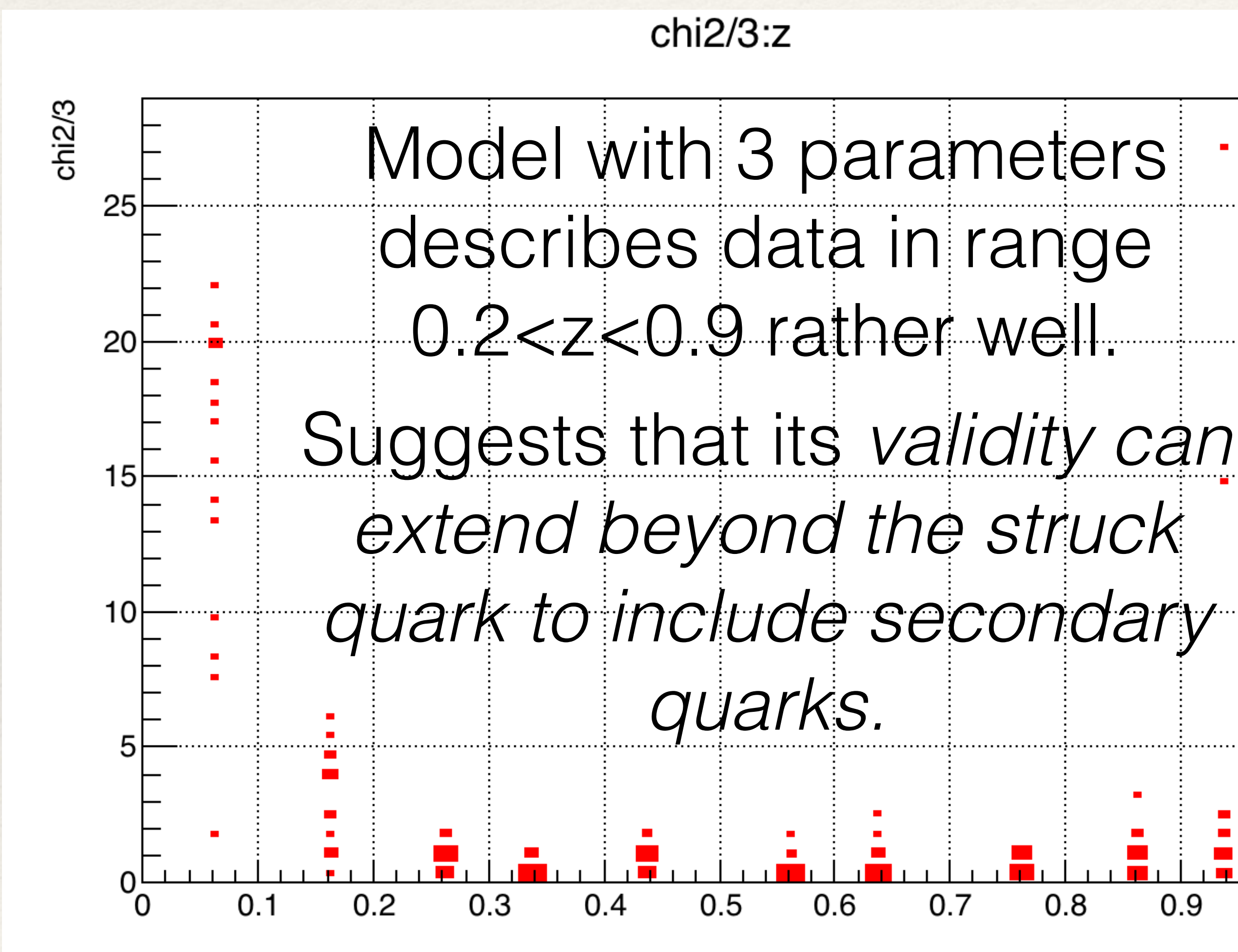


The fit has some sensitivity to the functional form of the production length.
More comments in upcoming slides.

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

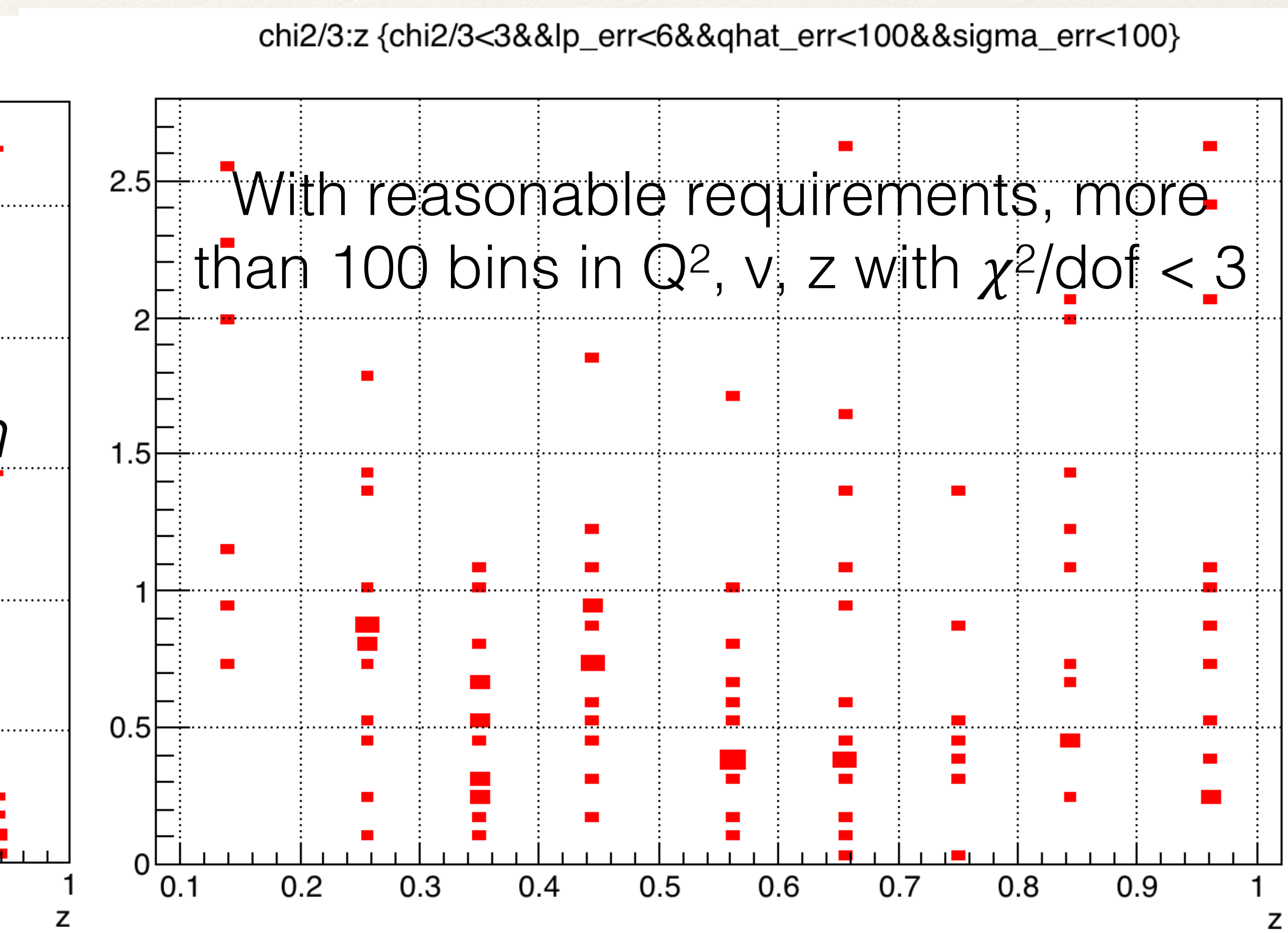
Color lifetime extraction: B-L model applied to CLAS 5 GeV data

χ^2/dof vs. z



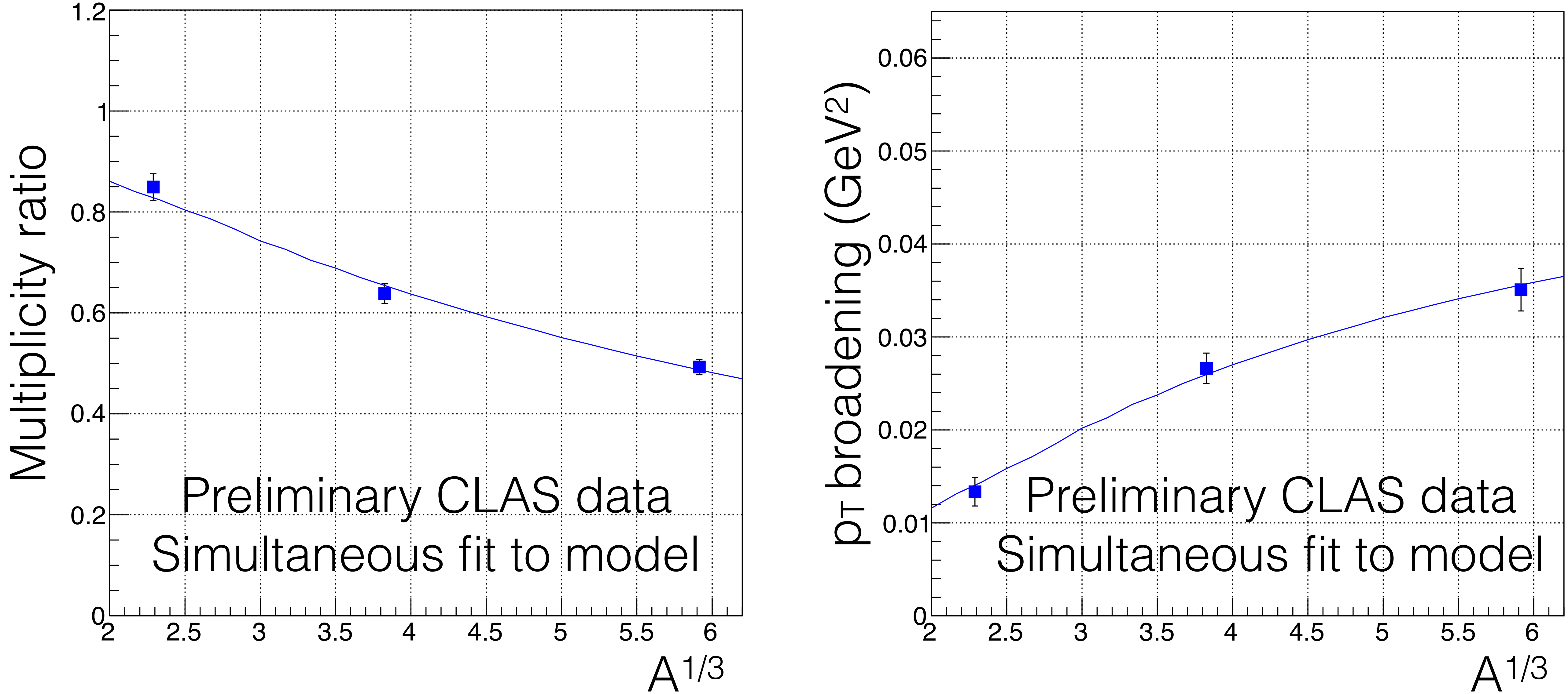
Model with 3 parameters describes data in range 0.2<z<0.9 rather well.

Suggests that its *validity can extend beyond the struck quark to include secondary quarks.*



With reasonable requirements, more than 100 bins in Q^2, ν, z with χ^2/dof < 3

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



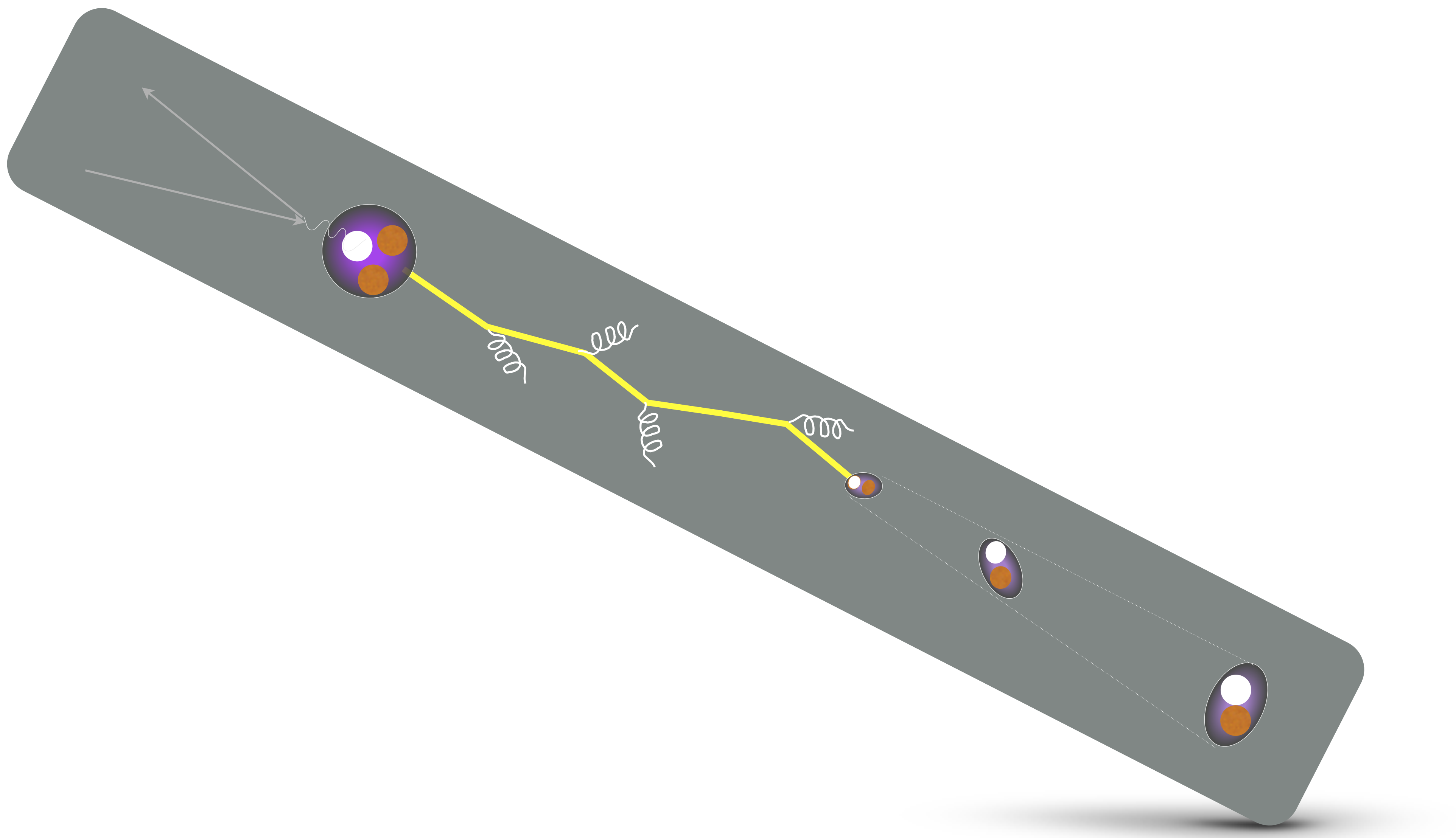
$\langle x \rangle = 0.166$, $\langle Q^2 \rangle = 1.17\ GeV^2$, ($\langle \nu \rangle = 3.76$ GeV), $\langle z \rangle = 0.445$

L_p=1.8±0.4 fm

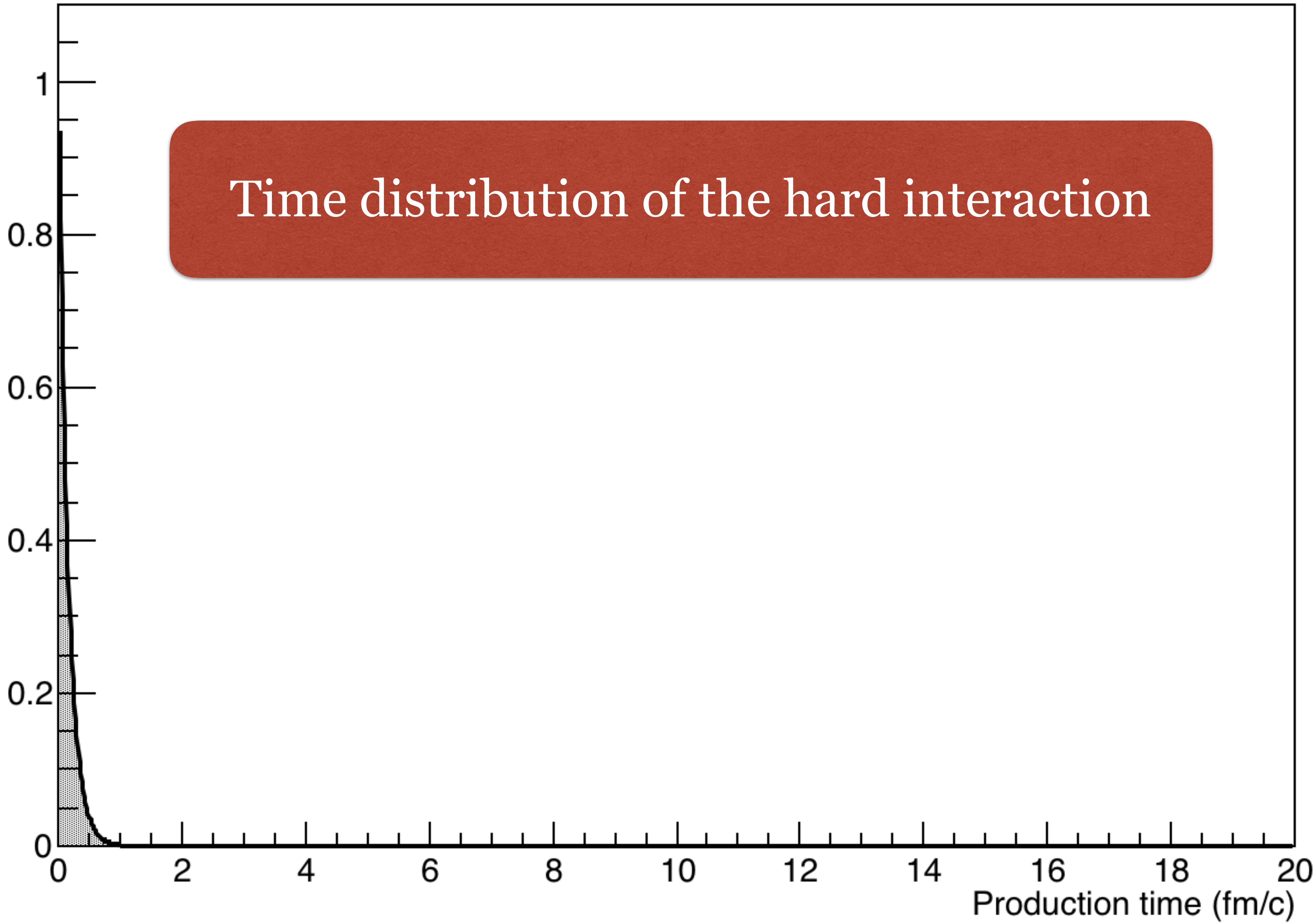
$\chi^2/dof = 0.5$

Simultaneous fit *couples* p_T broadening to multiplicity ratio

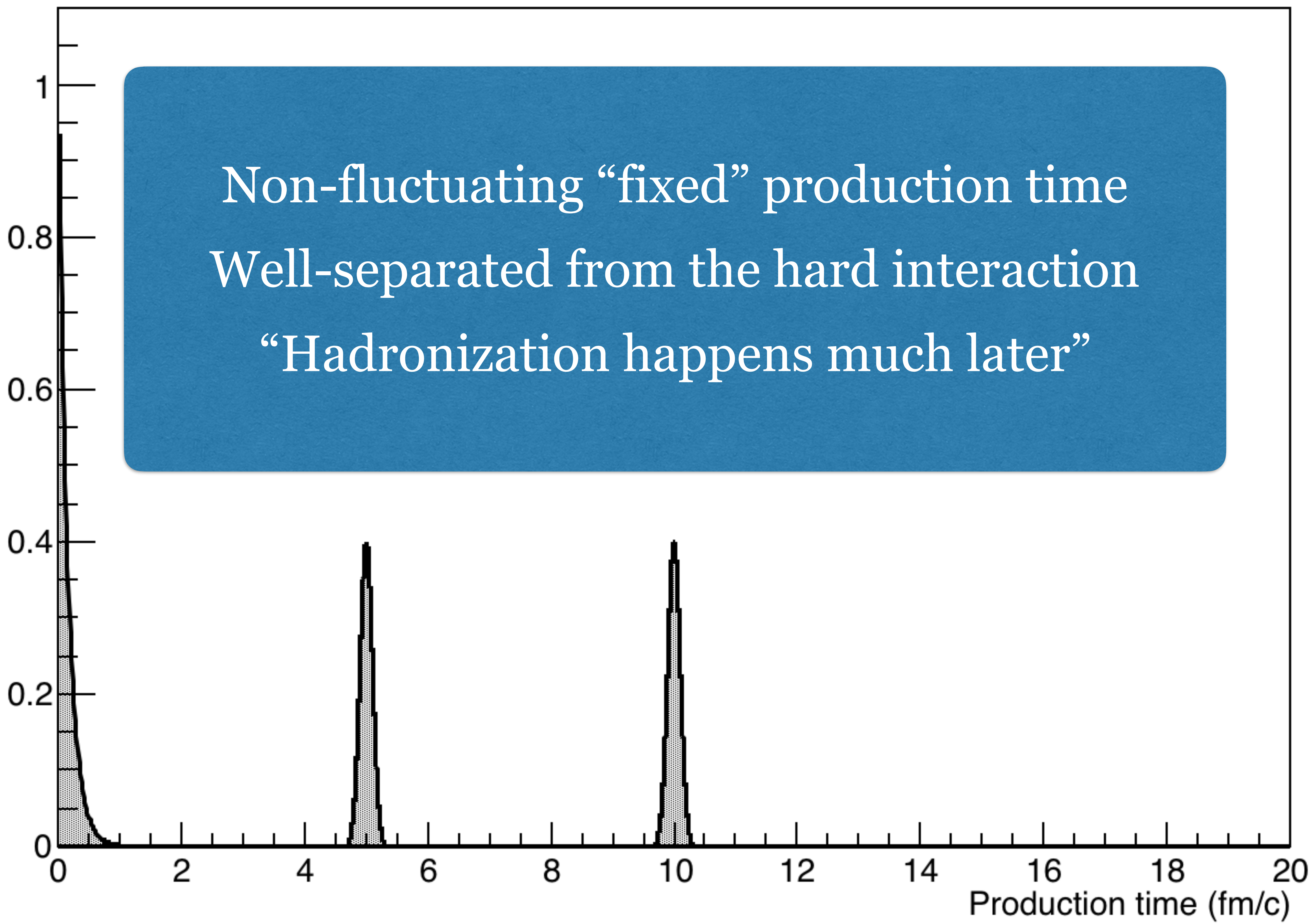
Three possible distributions of production time



Three possible distributions of production time



Three possible distributions of production time



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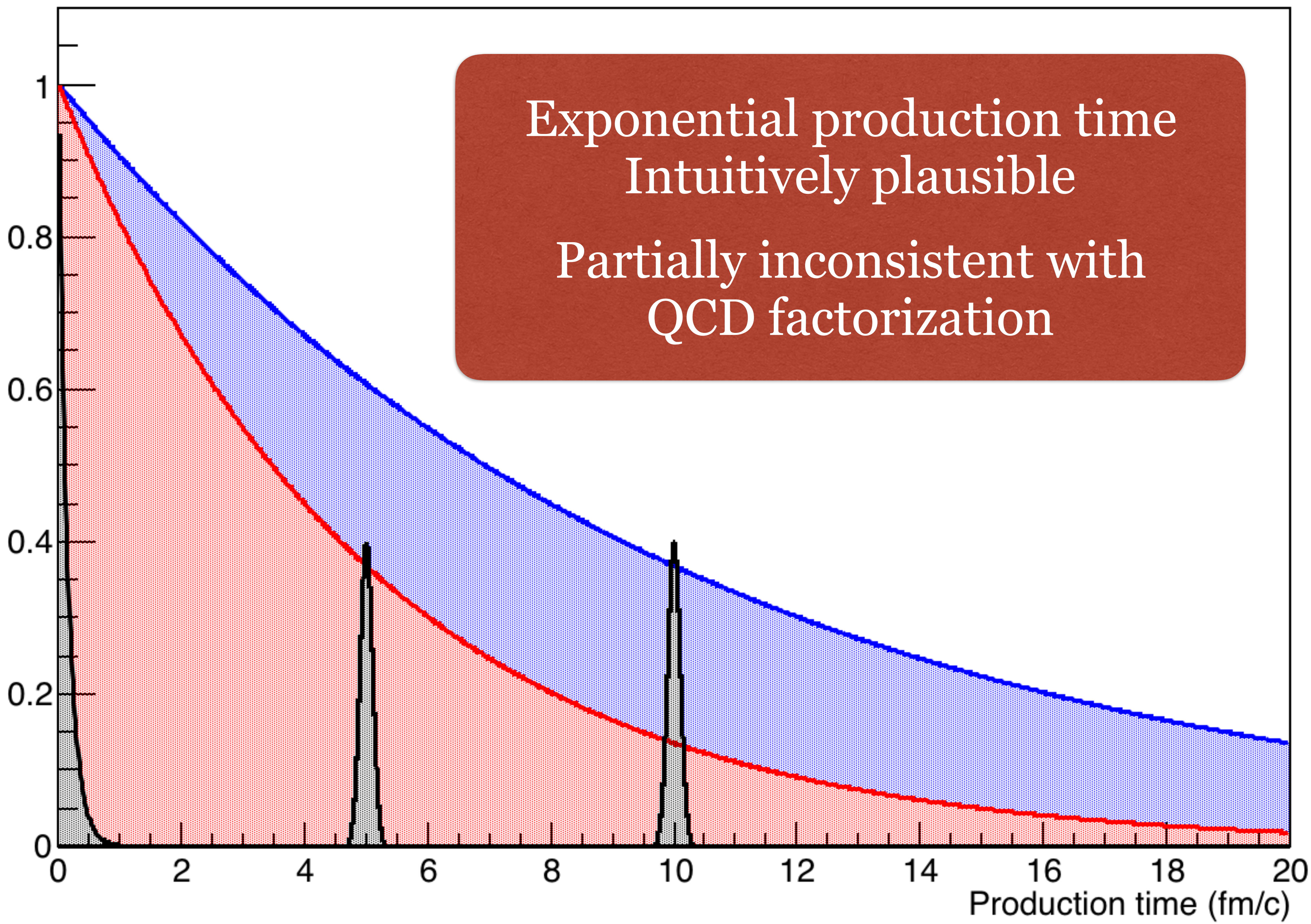
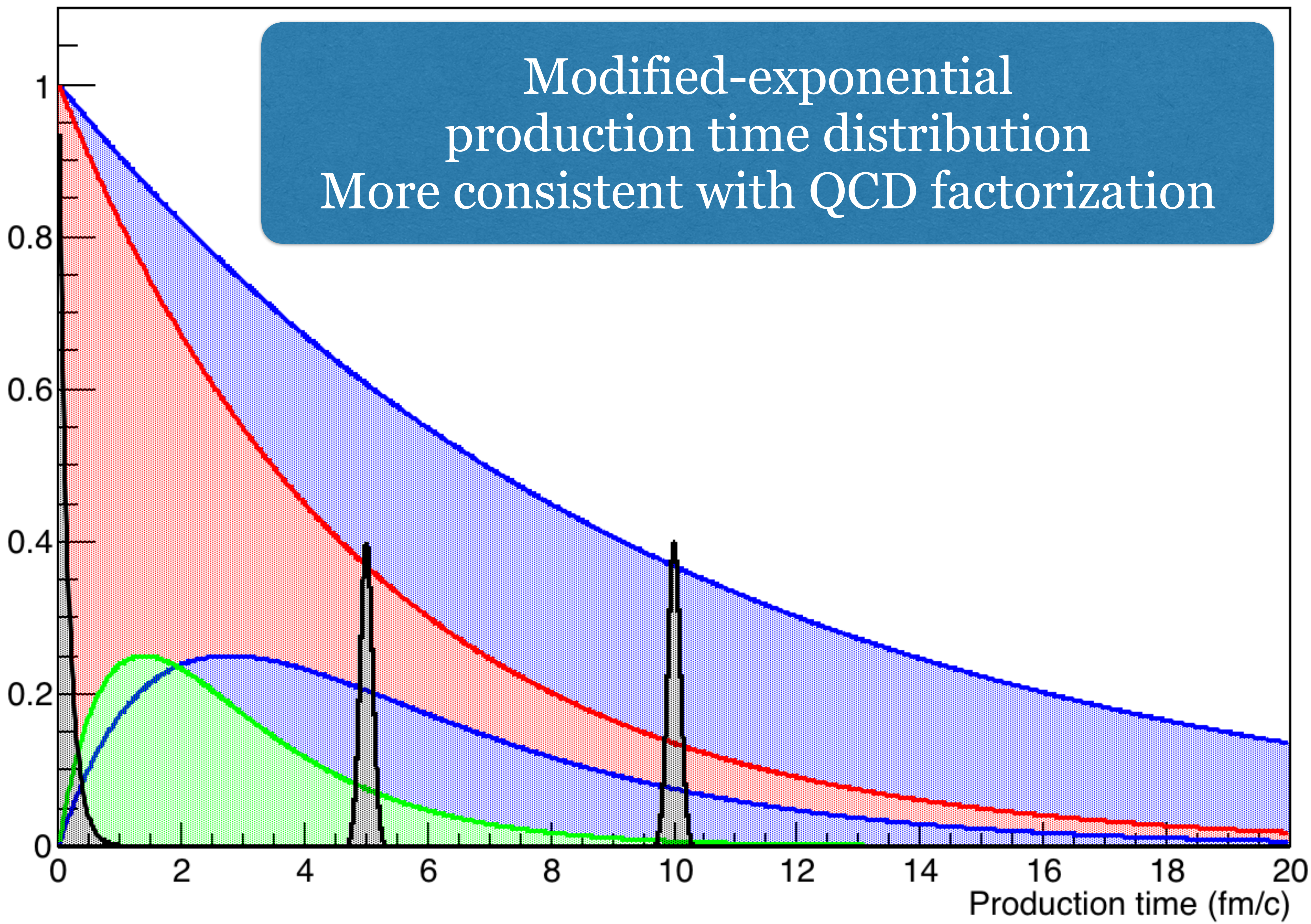
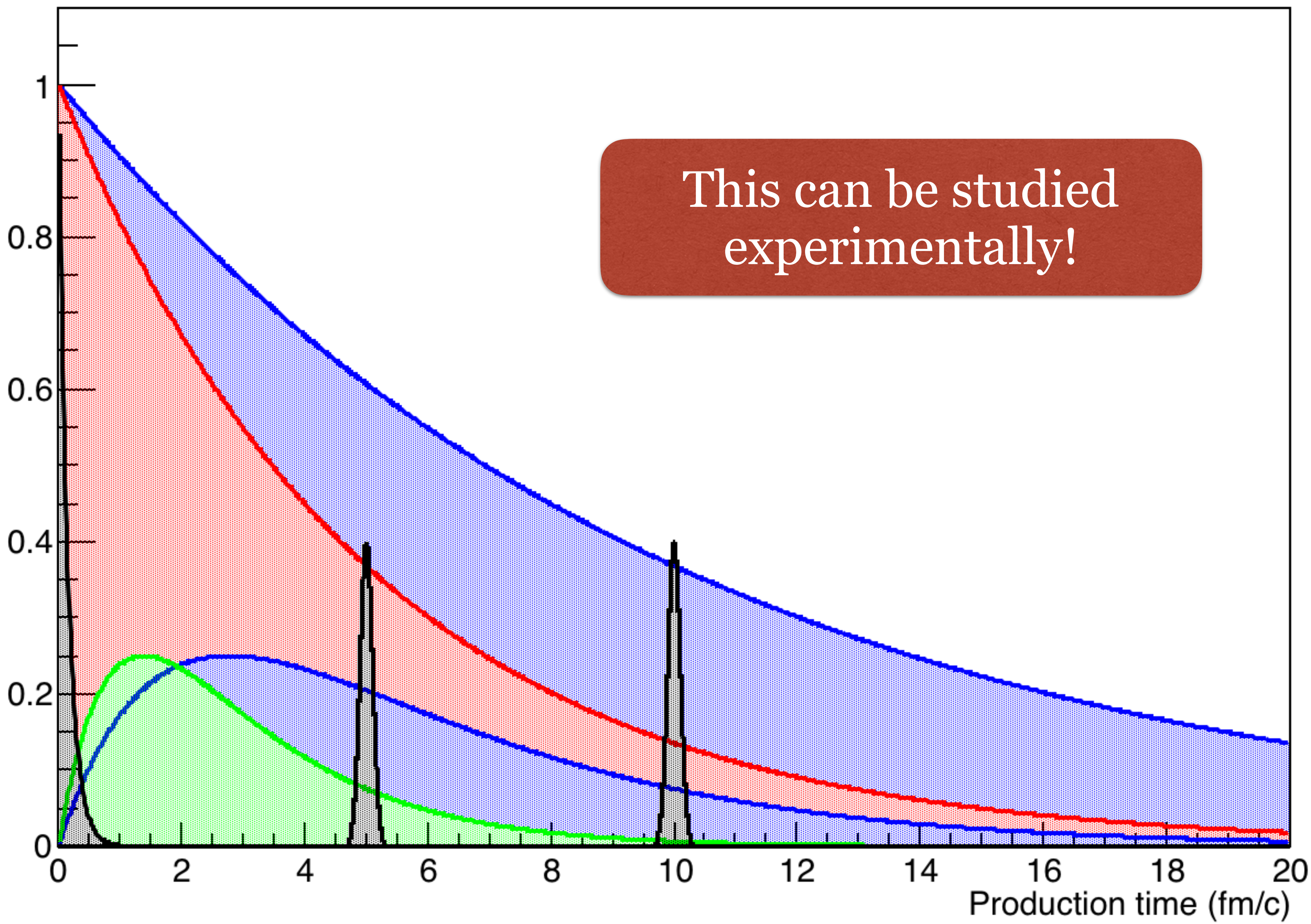


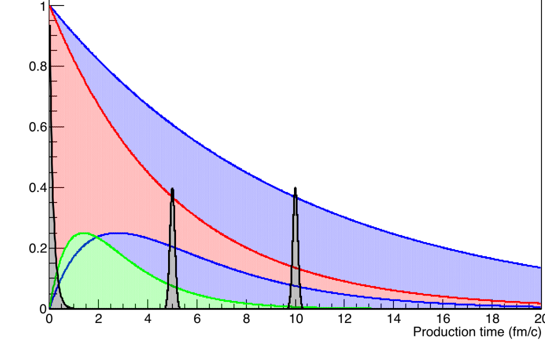
Three possible distributions of production time



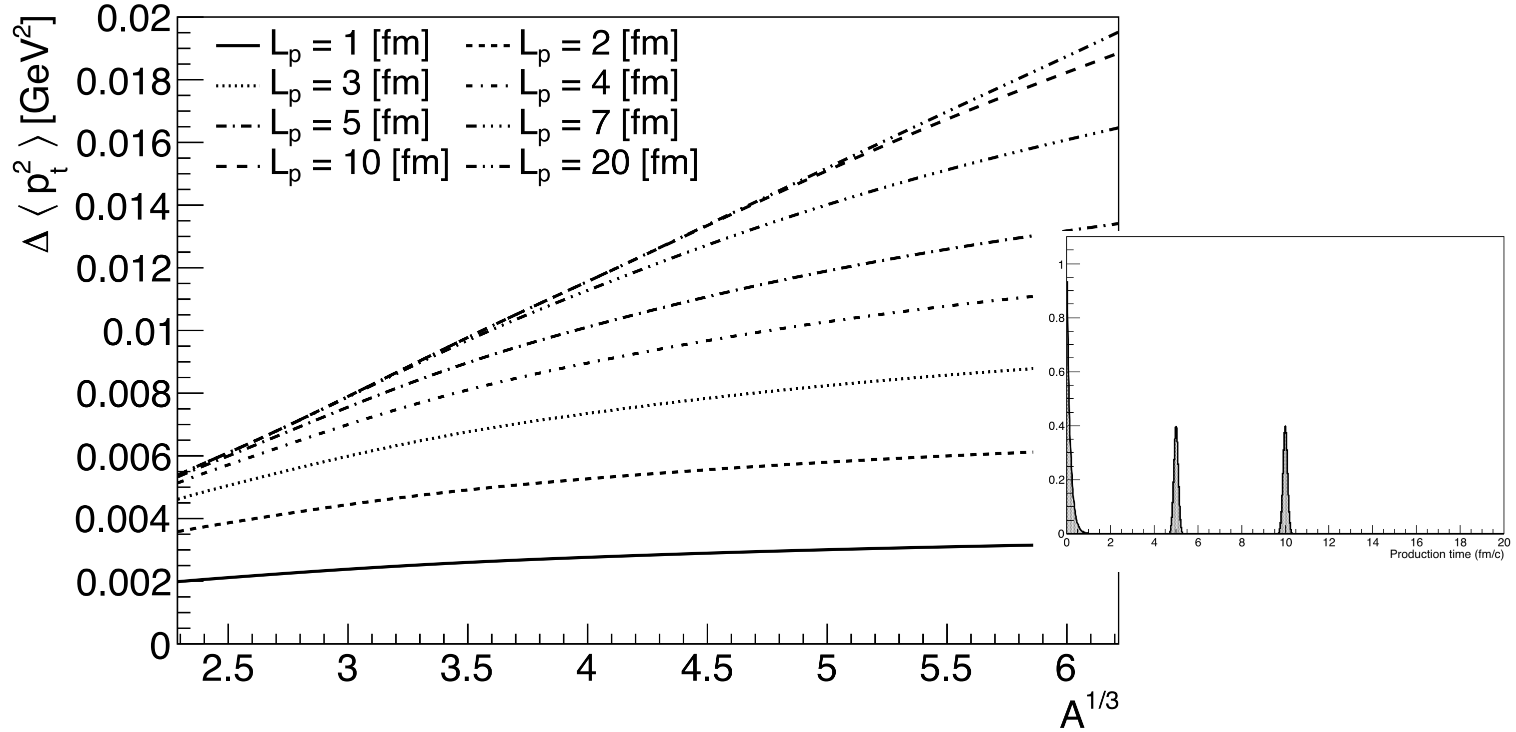
Three possible distributions of production time



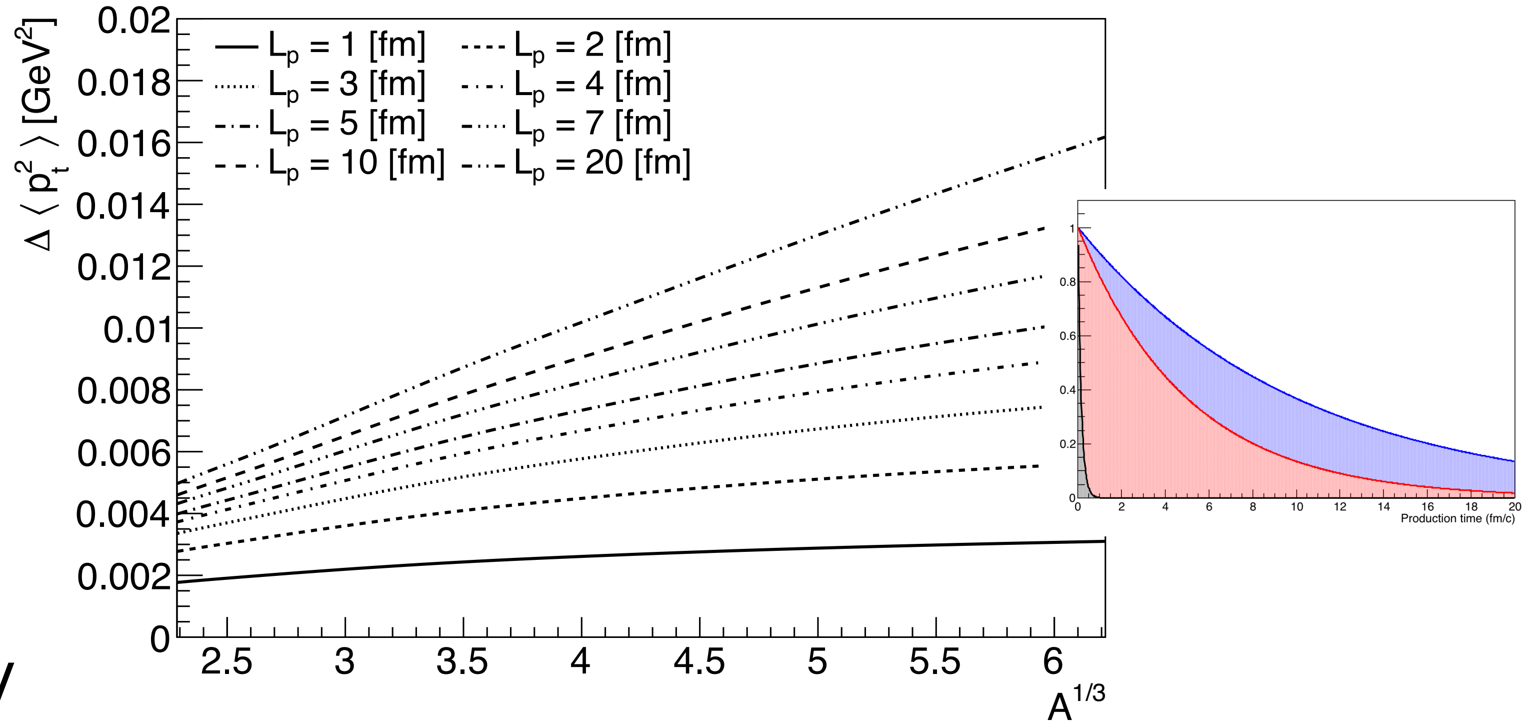
Effect of production length distribution on p_T broadening



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

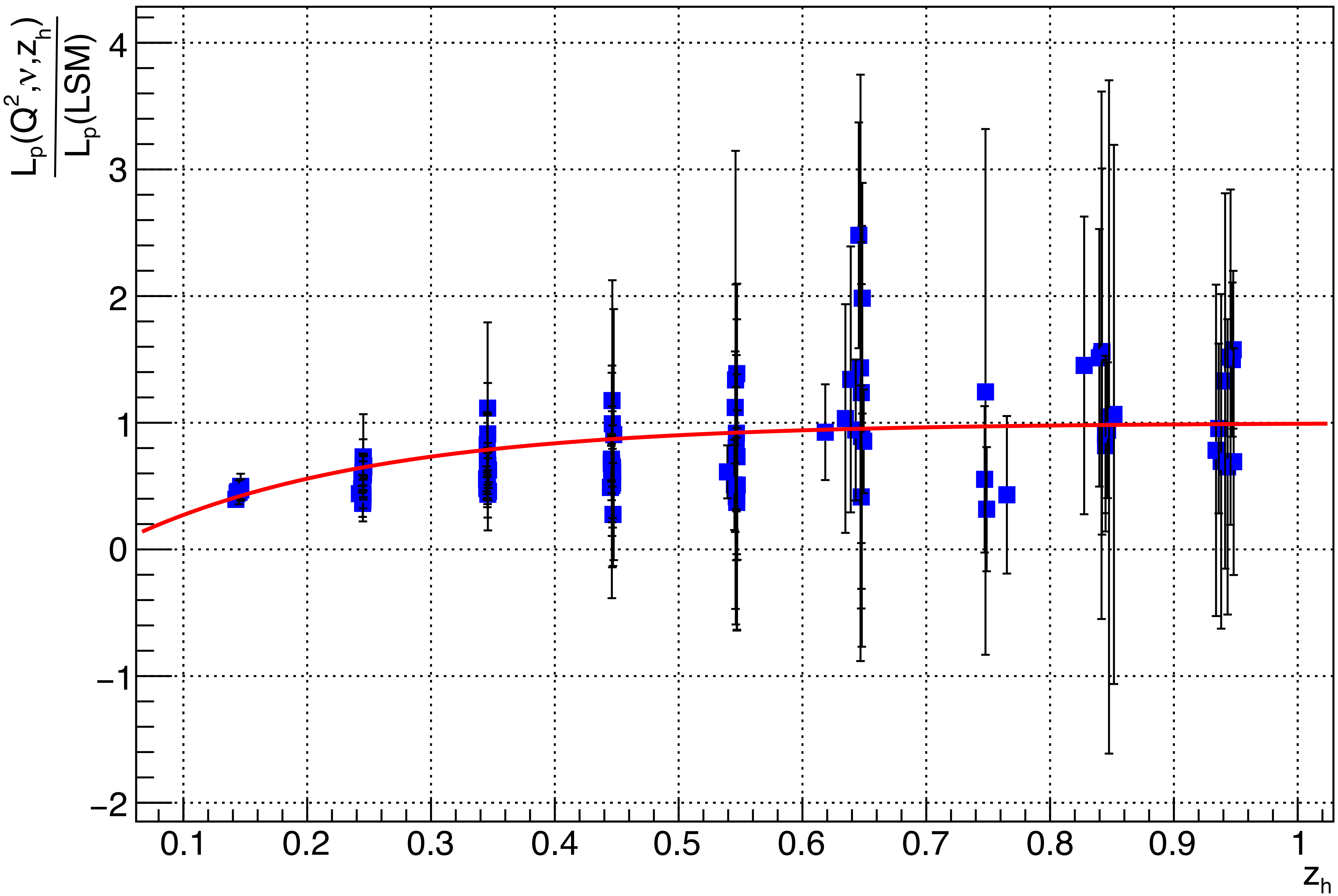
```
103 points, chisquared=69.2, chisq/dof = 0.685  MEDIUM event selection.
 FCN=69.2253 FROM MINOS     STATUS=SUCCESSFUL     10 CALLS           63 TOTAL
                     EDM=2.30163e-20    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                  STEP         FIRST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

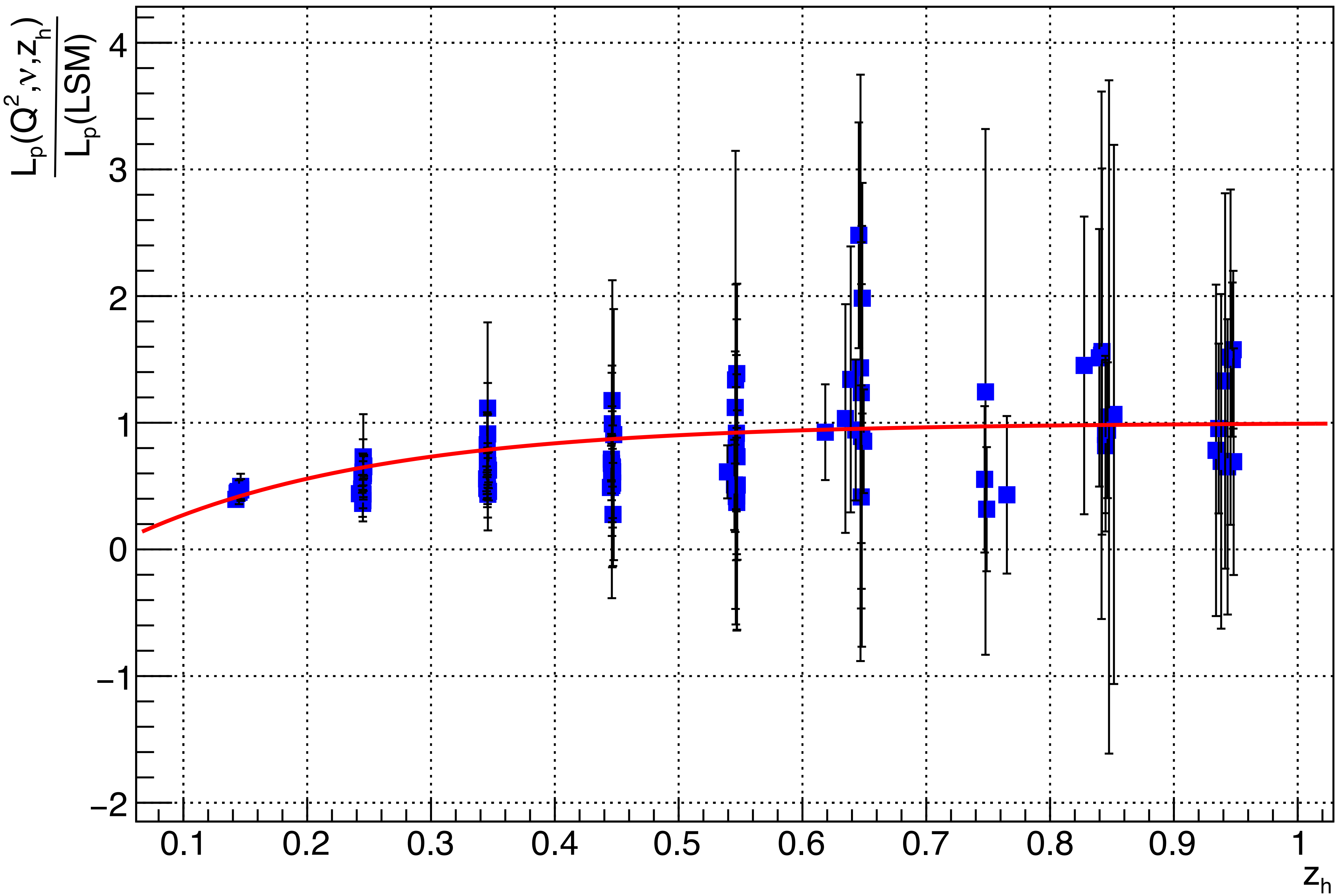
```
88 points, chisquared=289.5, chisq/dof = 3.36  MEDIUM event selection.
 FCN=289.533 FROM MINOS     STATUS=SUCCESSFUL      8 CALLS           63 TOTAL
                     EDM=3.95499e-19    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                  STEP         FIRST
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

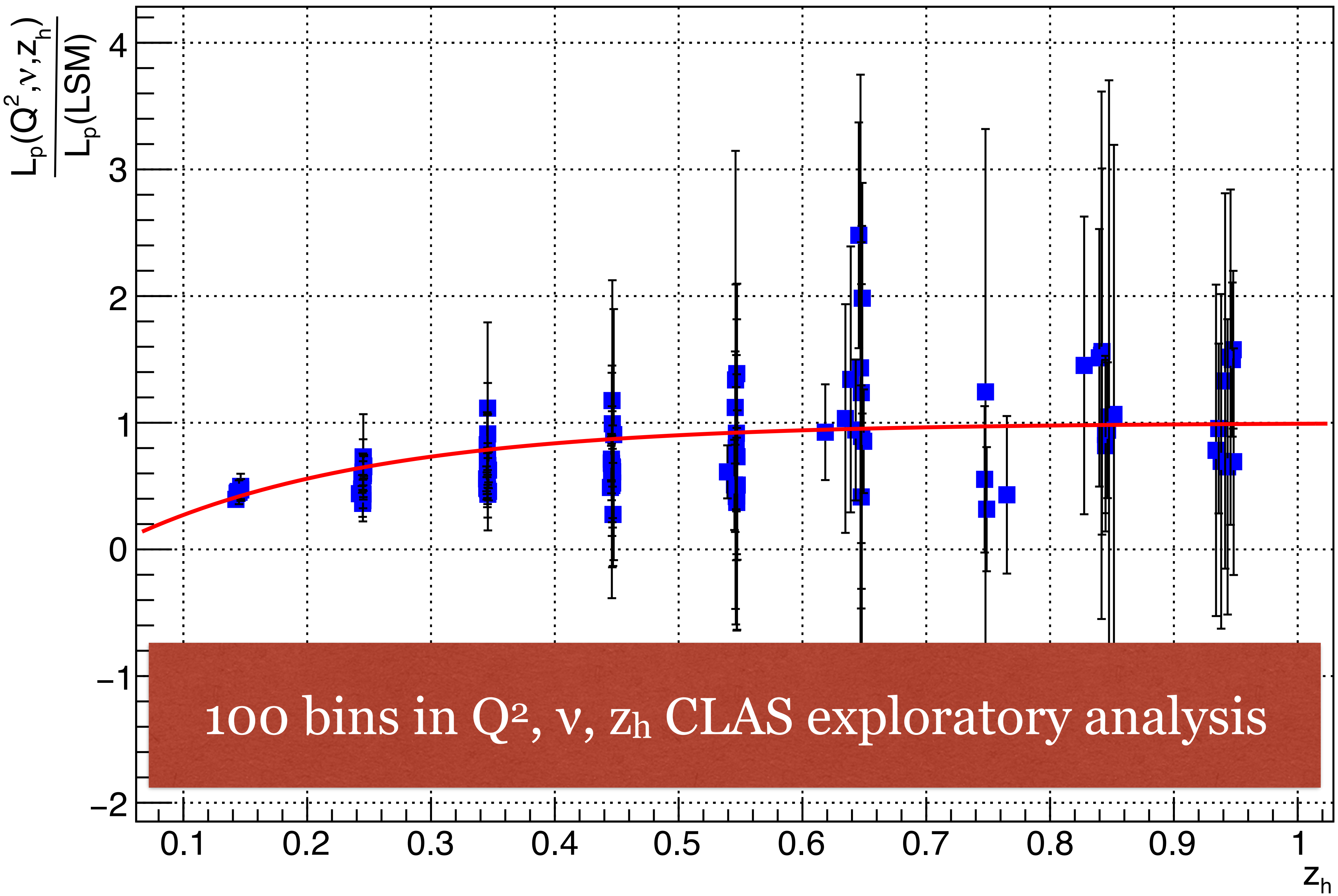


CLAS Exploratory Analysis ≈ Lund String Model



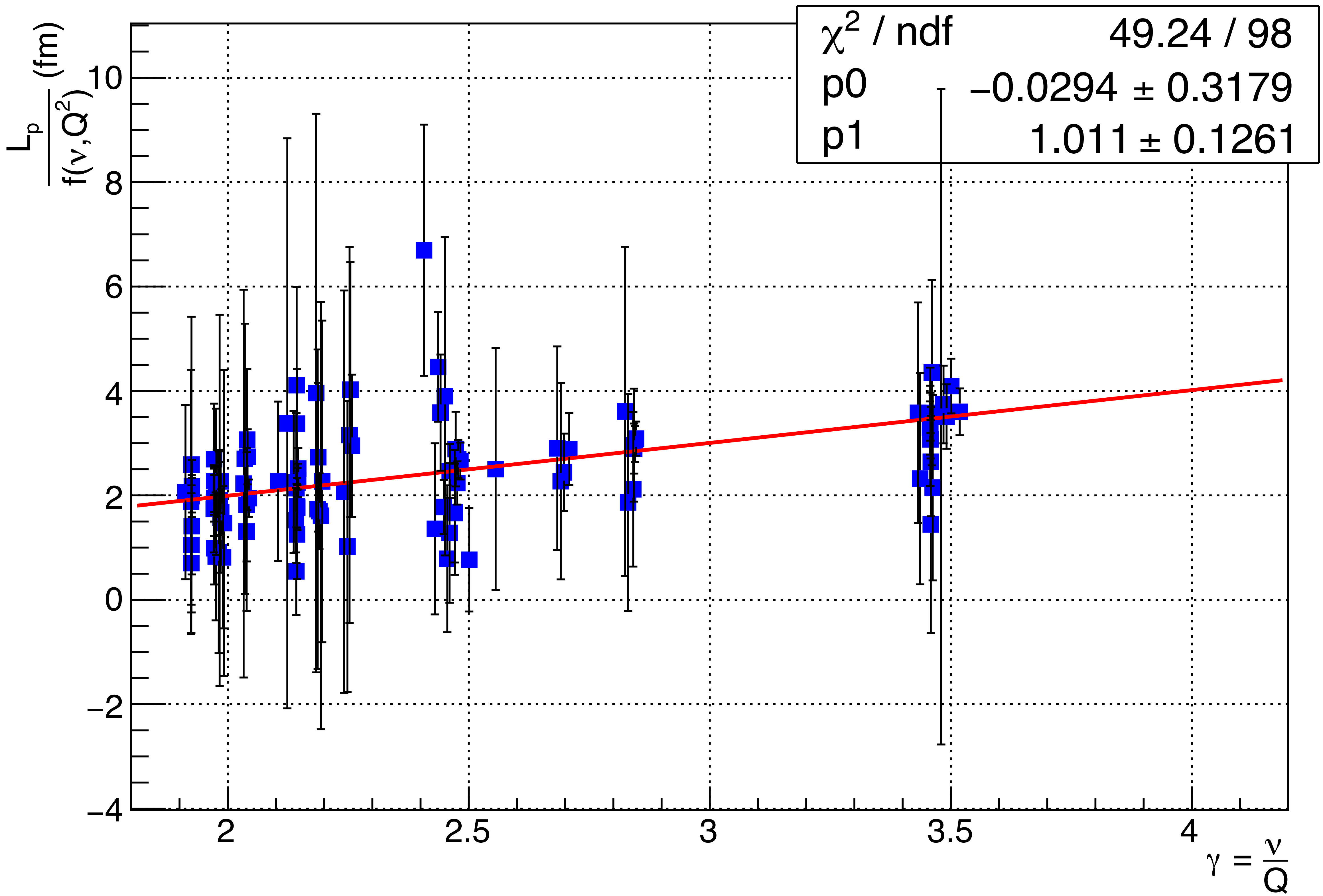
$L_p\ (Q^2, \nu, z_h)$ from CLAS analysis similar to values from the Lund String Model for $z_h>0.4$

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!

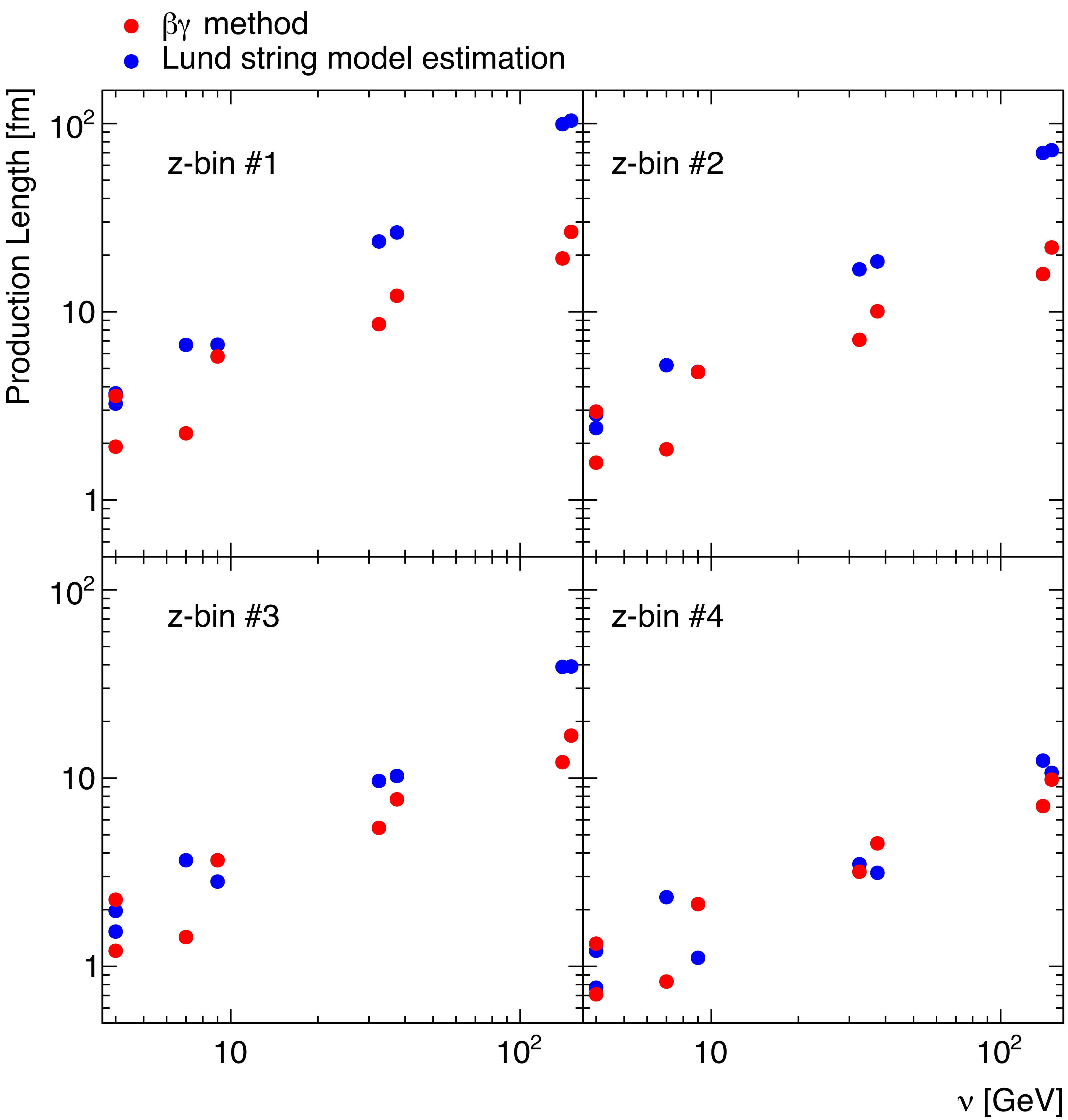
Extrapolation from HERMES to EIC and CLAS

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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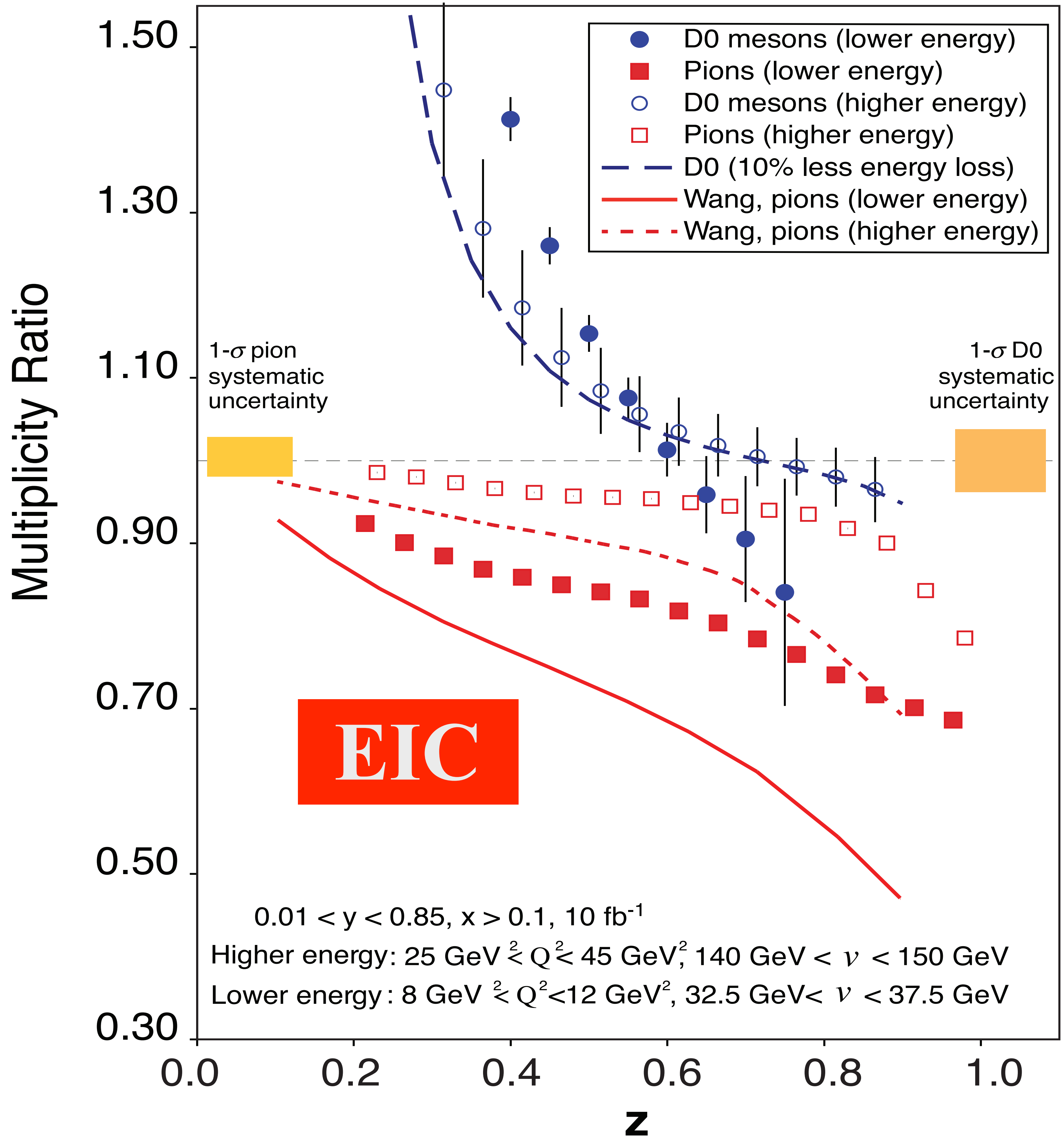
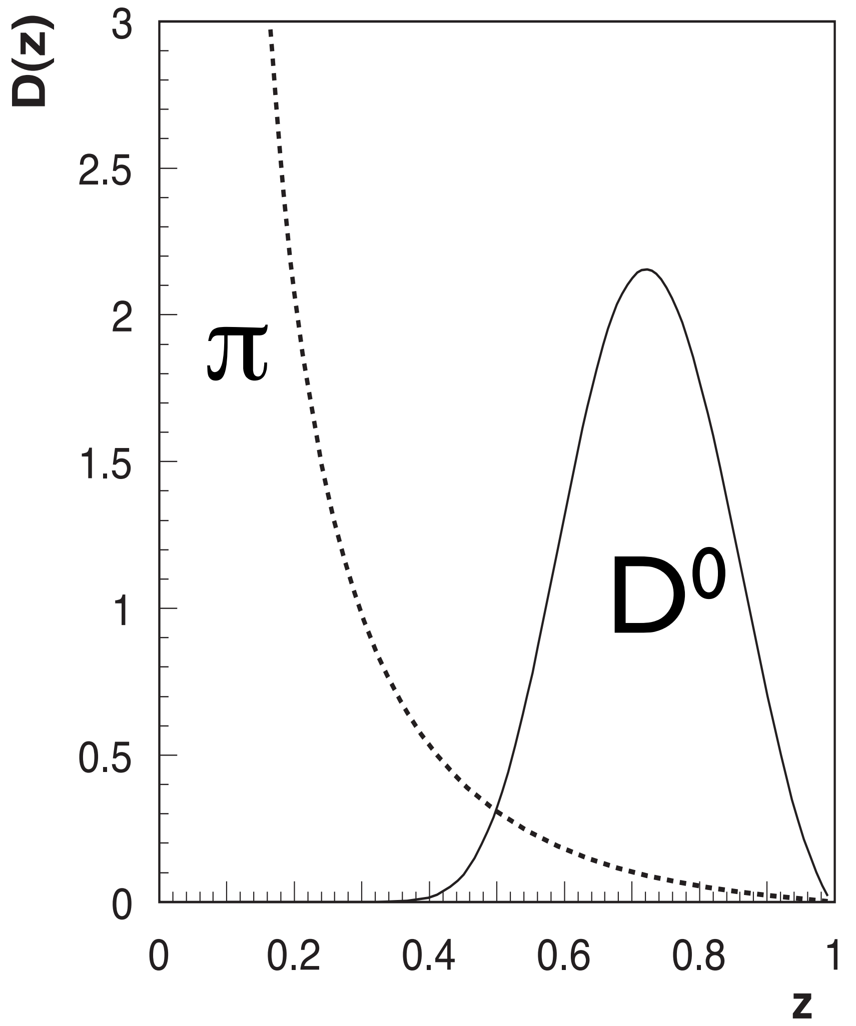
- Flavor dependencies of formed hadrons

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 ν
- 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

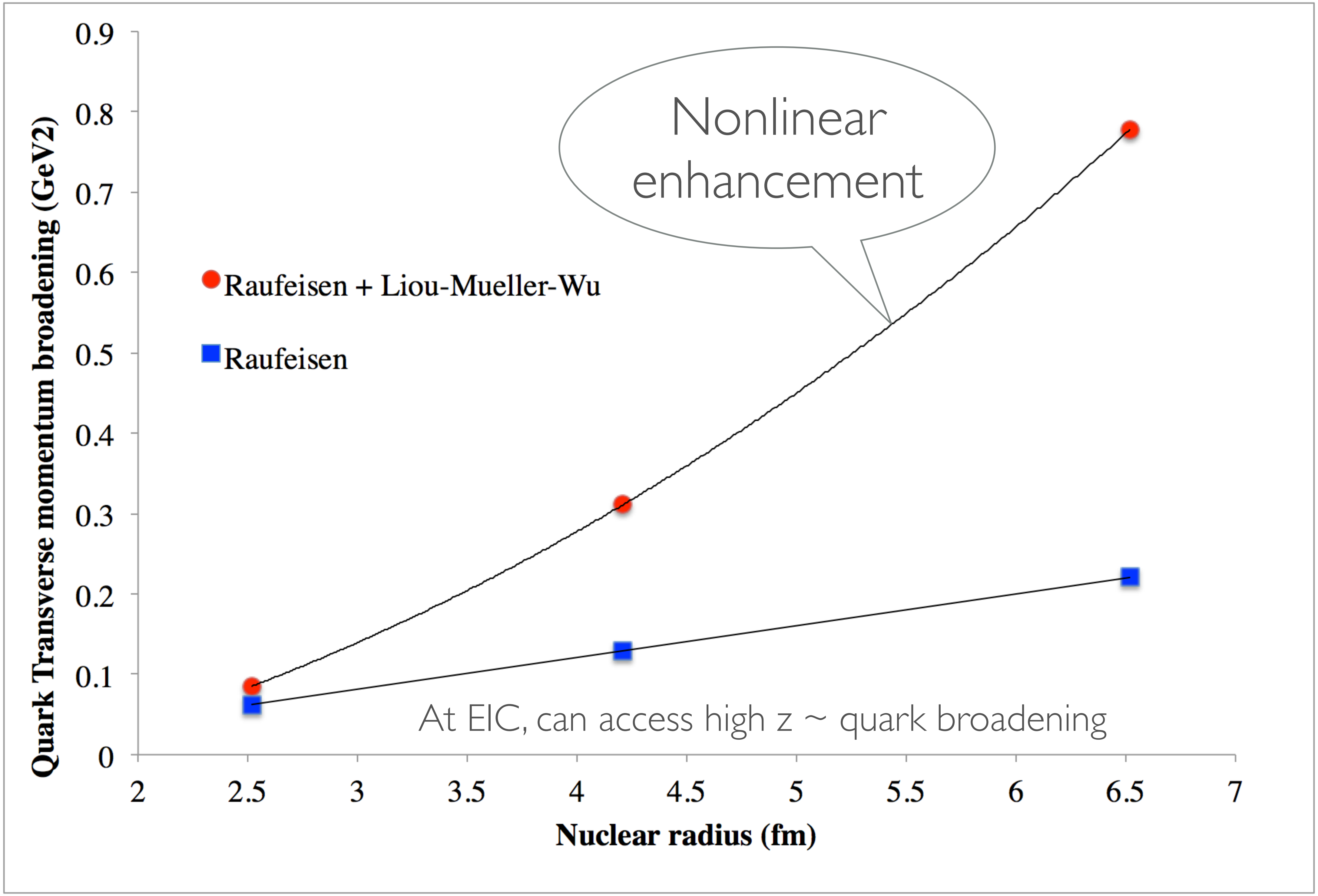
$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2 \; \propto \; \hat{q} \; L$$

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

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

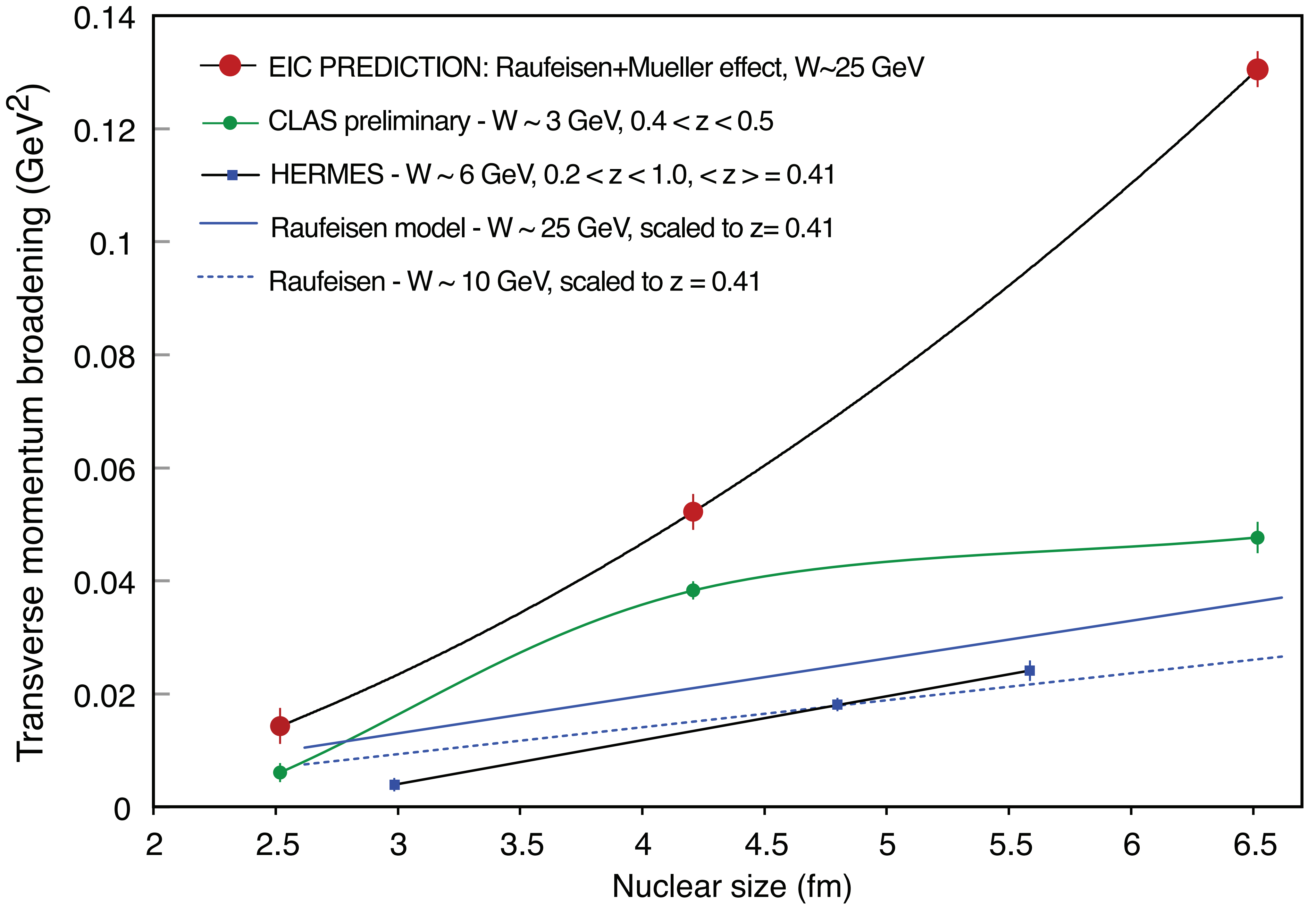
➞ predicts a non-linear relationship between p_T broadening and L.
we can look for this at EIC!

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	$c\tau$	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	$c\tau$	mass	flavor content
p	stable	0.94	ud
$\bar{p}$	stable	0.94	ud
Λ	79 mm	1.1	uds
$\Lambda(1520)$	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
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HERMES

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Actively underway with existing 5 GeV data

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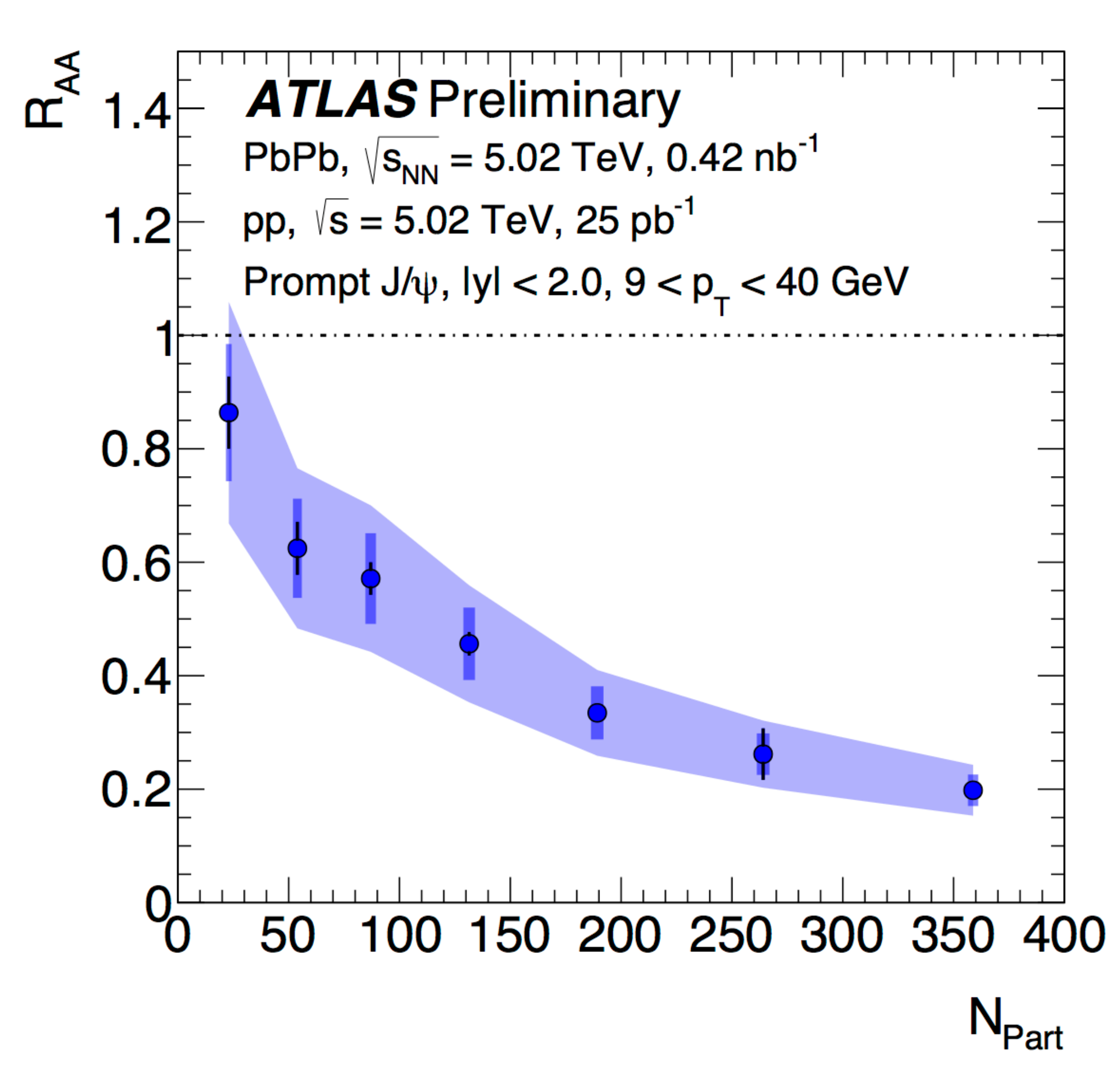
Ξ^-	49 mm	1.3	ds

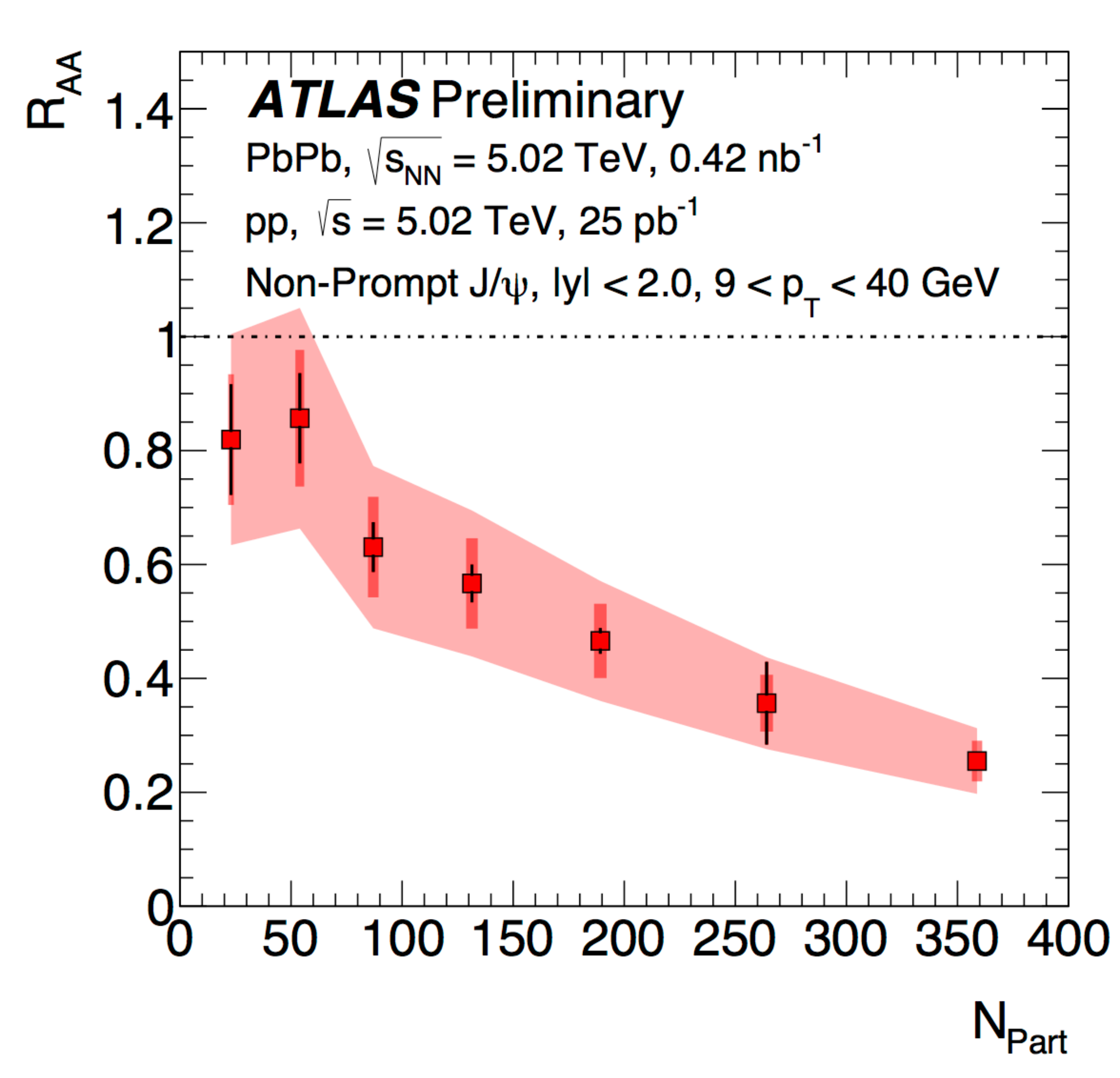
EIC: heavy mesons and baryons; wide kinematic range!

LHC Data: color propagation in the *hot* medium

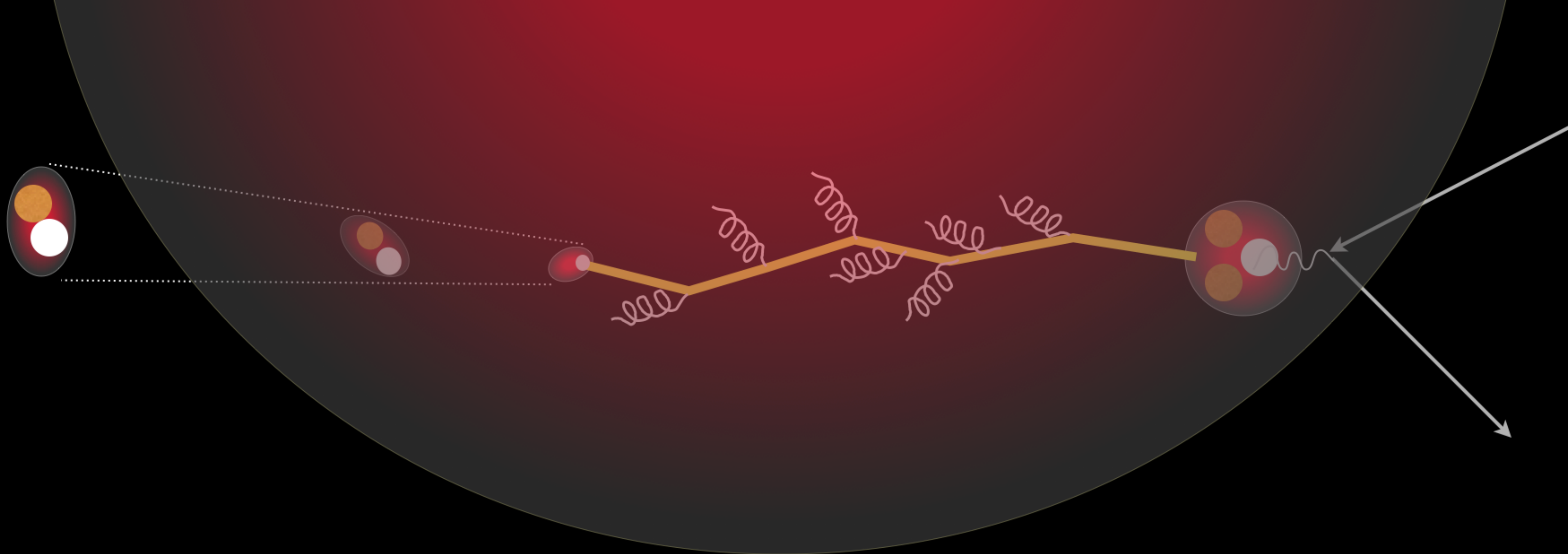
Study of J/ψ→μ⁺μ⁻ and ψ(2S)→μ⁺μ⁻ production with 2015 Pb+Pb data at $\sqrt{s_{NN}}$=5.02 TeV and pp data at sqrt(s)=5.02 TeV with the ATLAS detector

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



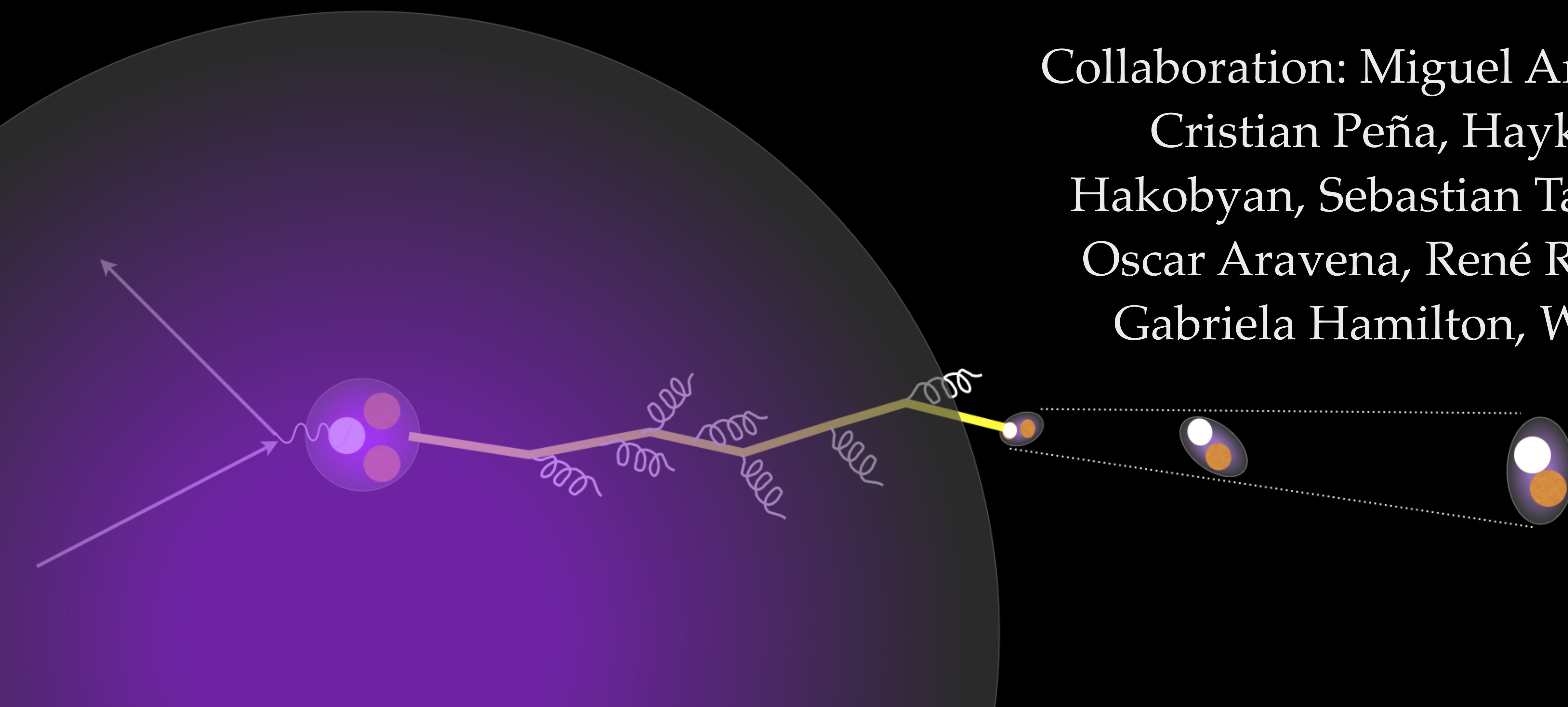


Heavy quarks and fragile mesons similarly suppressed with centrality!



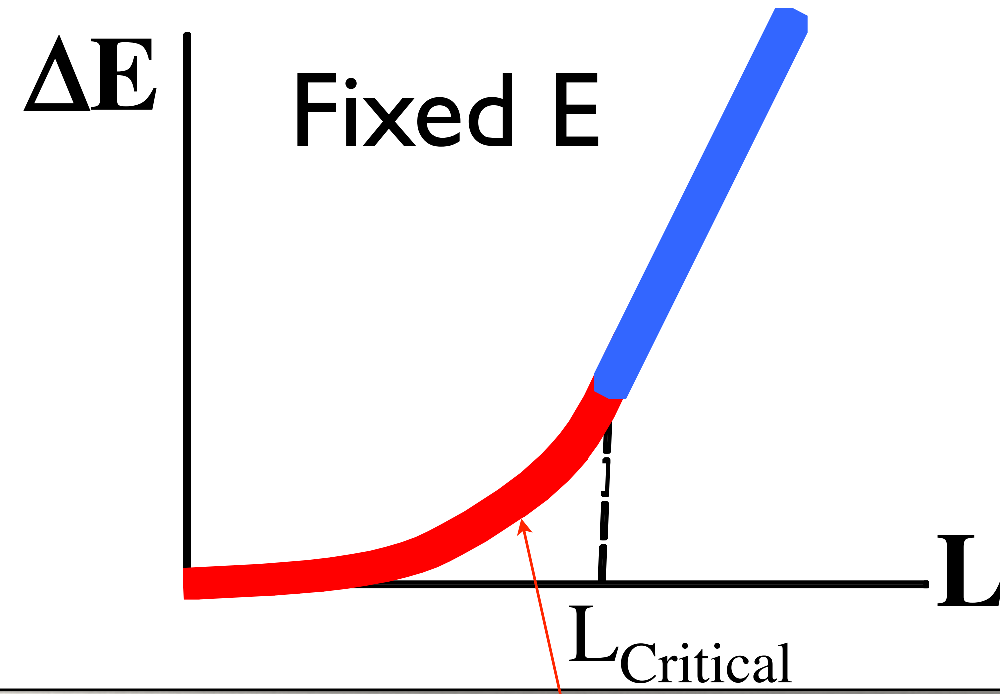
Direct measurement of quark energy loss

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



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

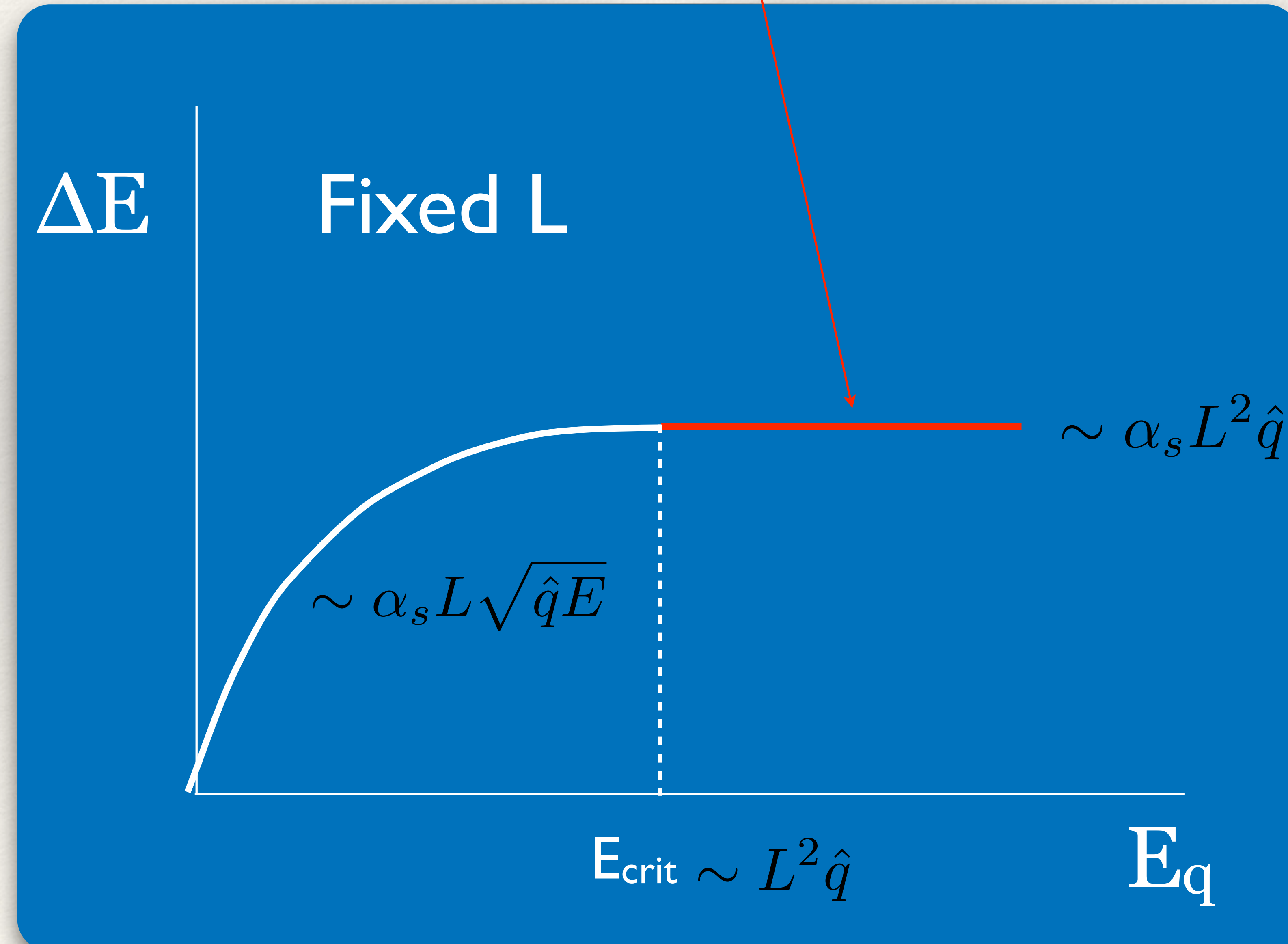
$L > L_{Critical}$ $$-\frac{dE}{dx} \propto \sqrt{E\hat{q}}$$



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

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

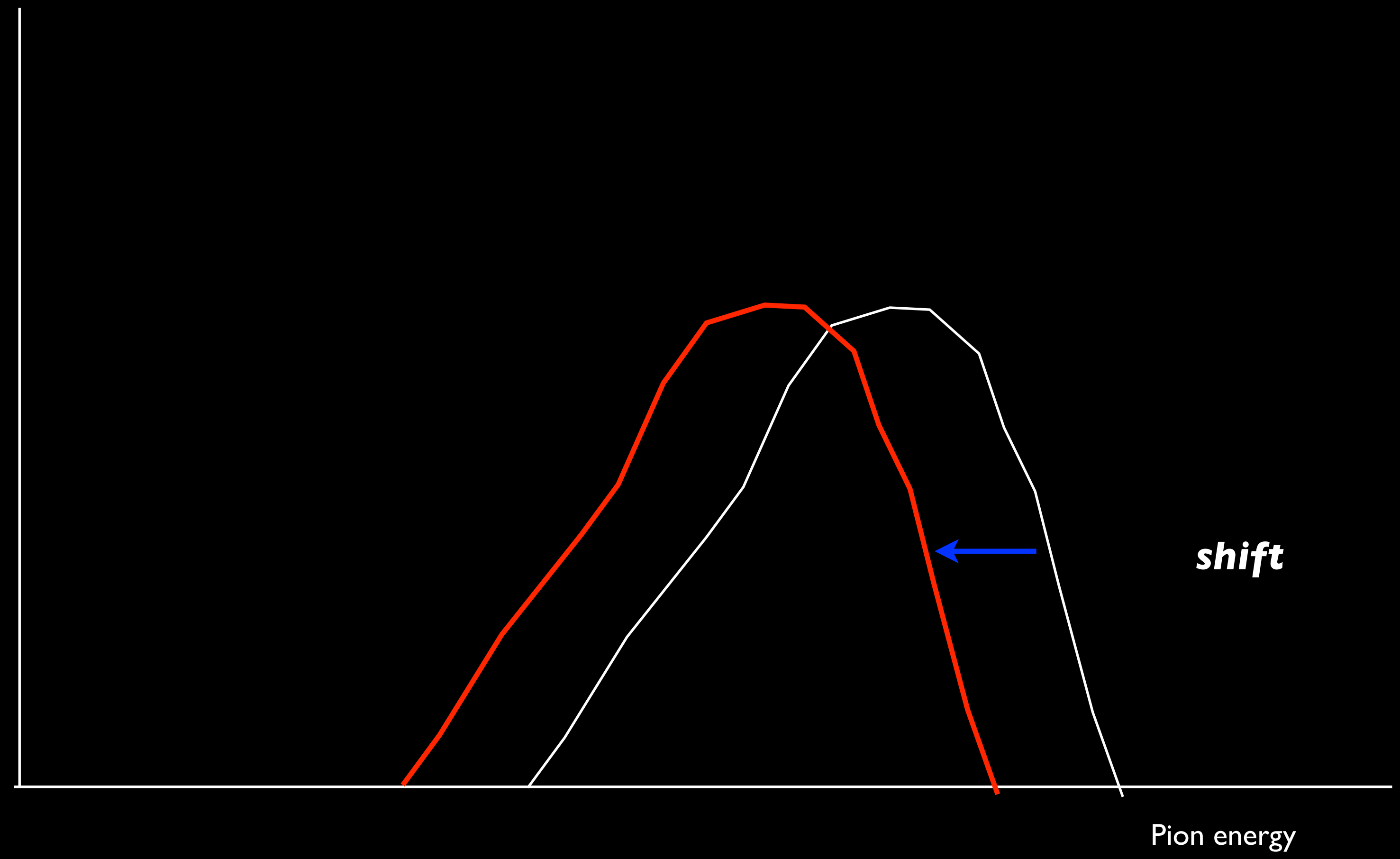
$$E_c \approx 0.4 \cdot \left(\frac{L}{1\ \mathrm{fm}}\right)^2\ \mathrm{GeV}$$

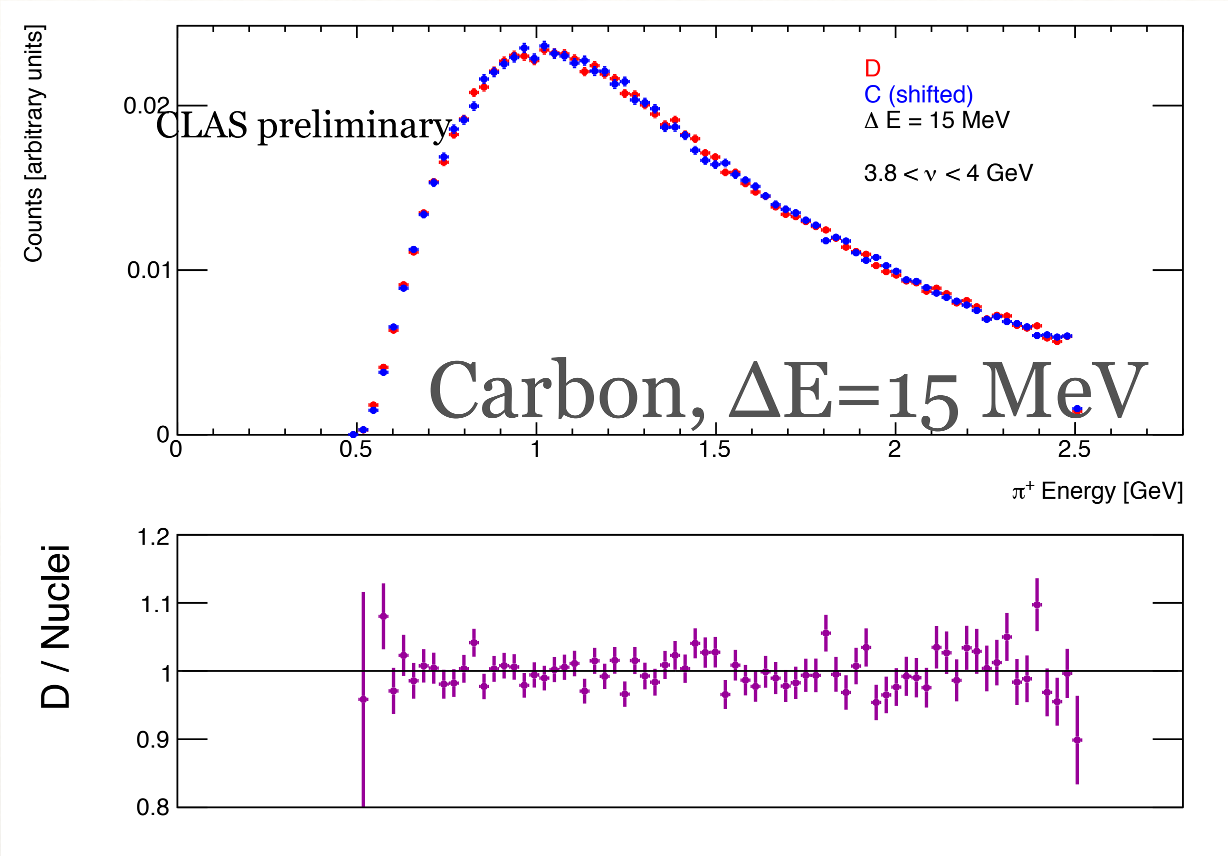


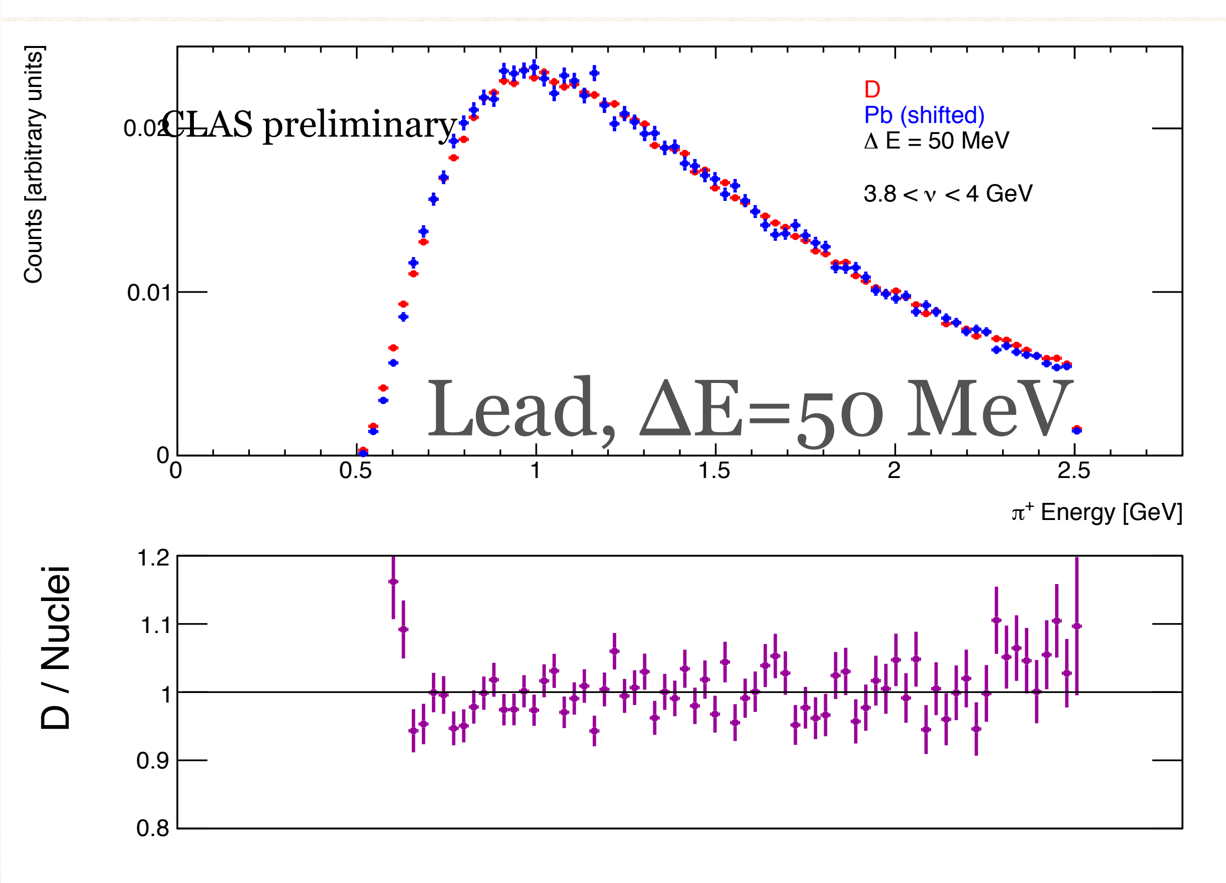
$$-\Delta E_q = \frac{\alpha_s}{4} \Delta k_T^2 \cdot L = \frac{\alpha_s}{4} \hat{q} \cdot L^2$$

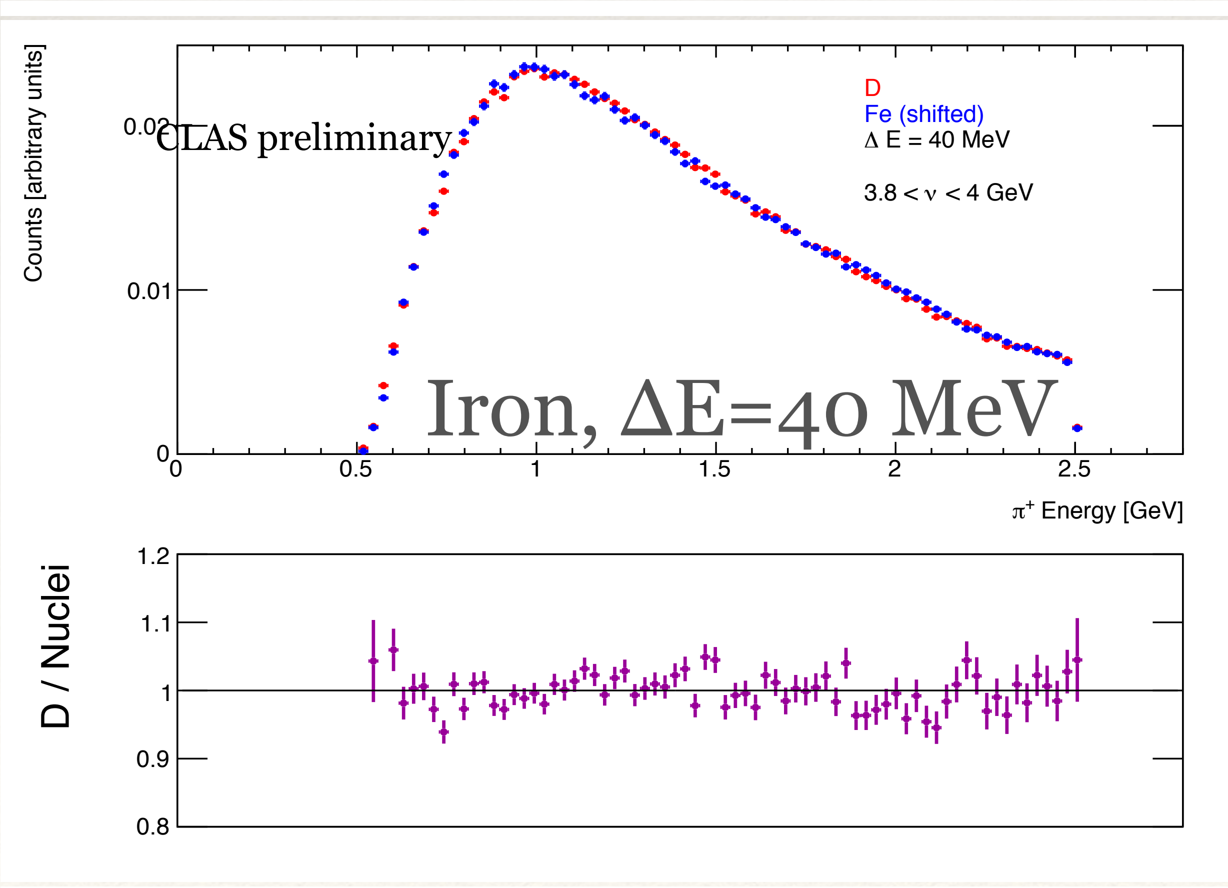
How to *directly* measure quark energy loss?

- 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







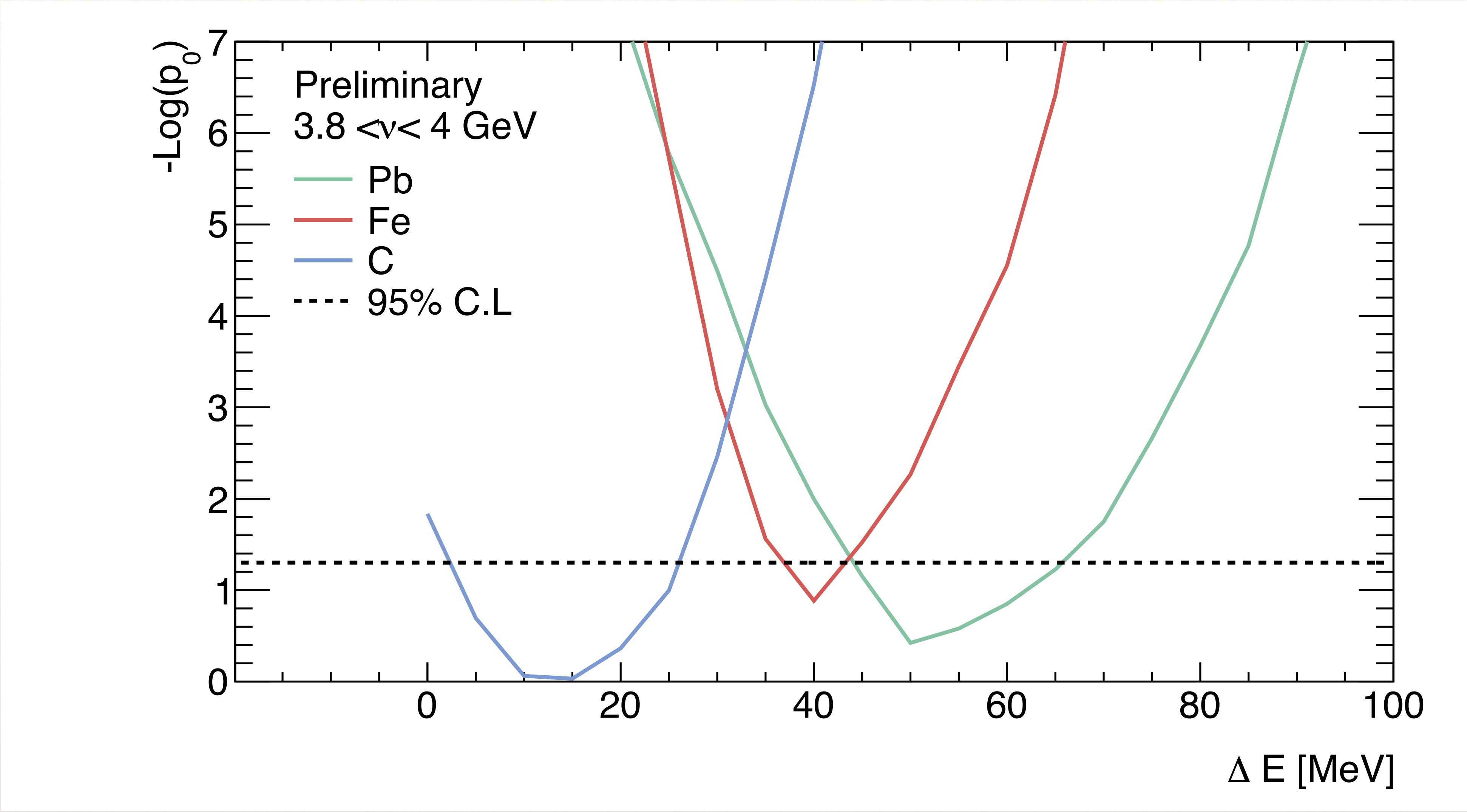


Energy spectrum of π^+ produced in C, Fe, Pb compared to that of deuterium, normalized to unity, with energy shifted by ΔE.

Acceptance corrected

Cut on X_F >0.1 is applied

Consistent with simple energy shift + unchanged fragmentation

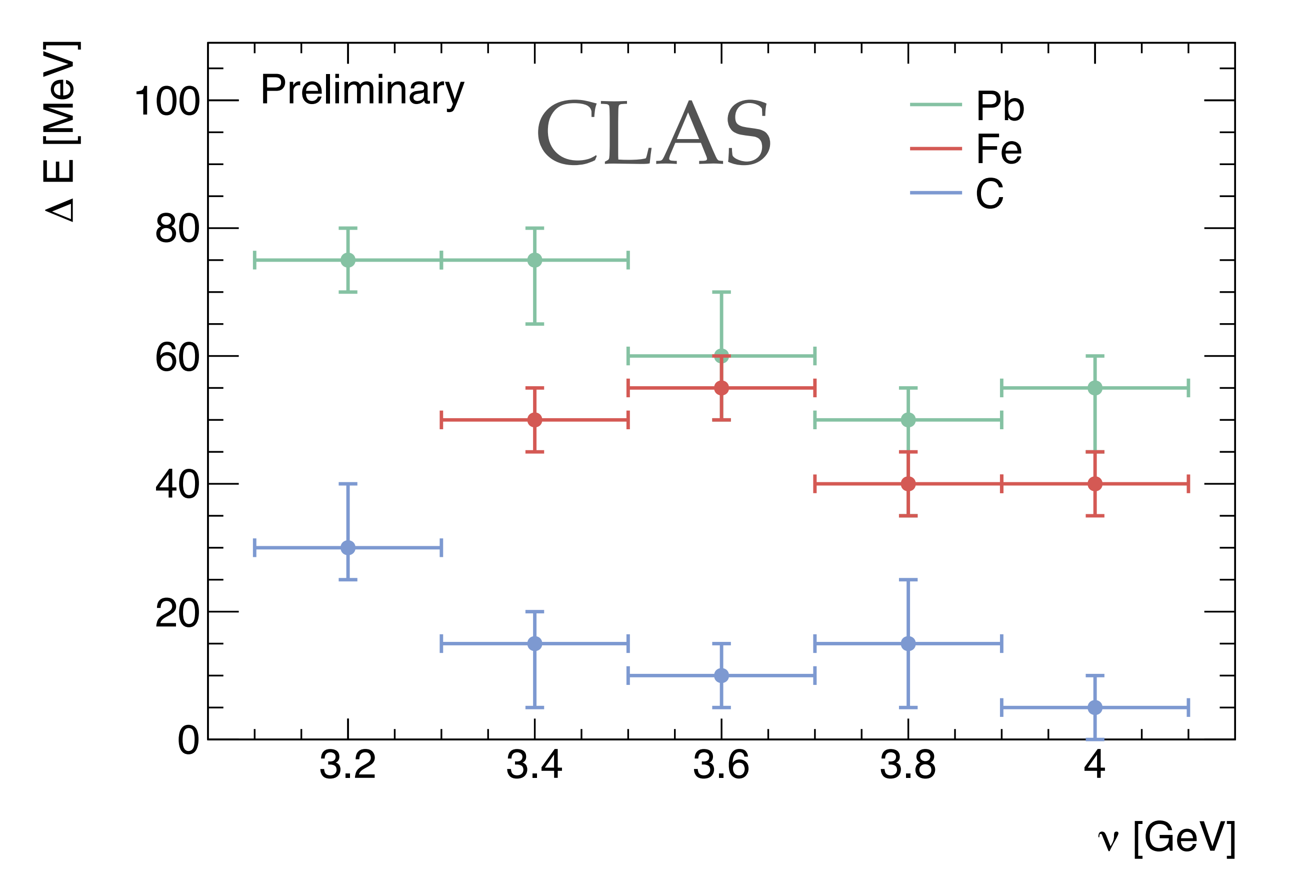


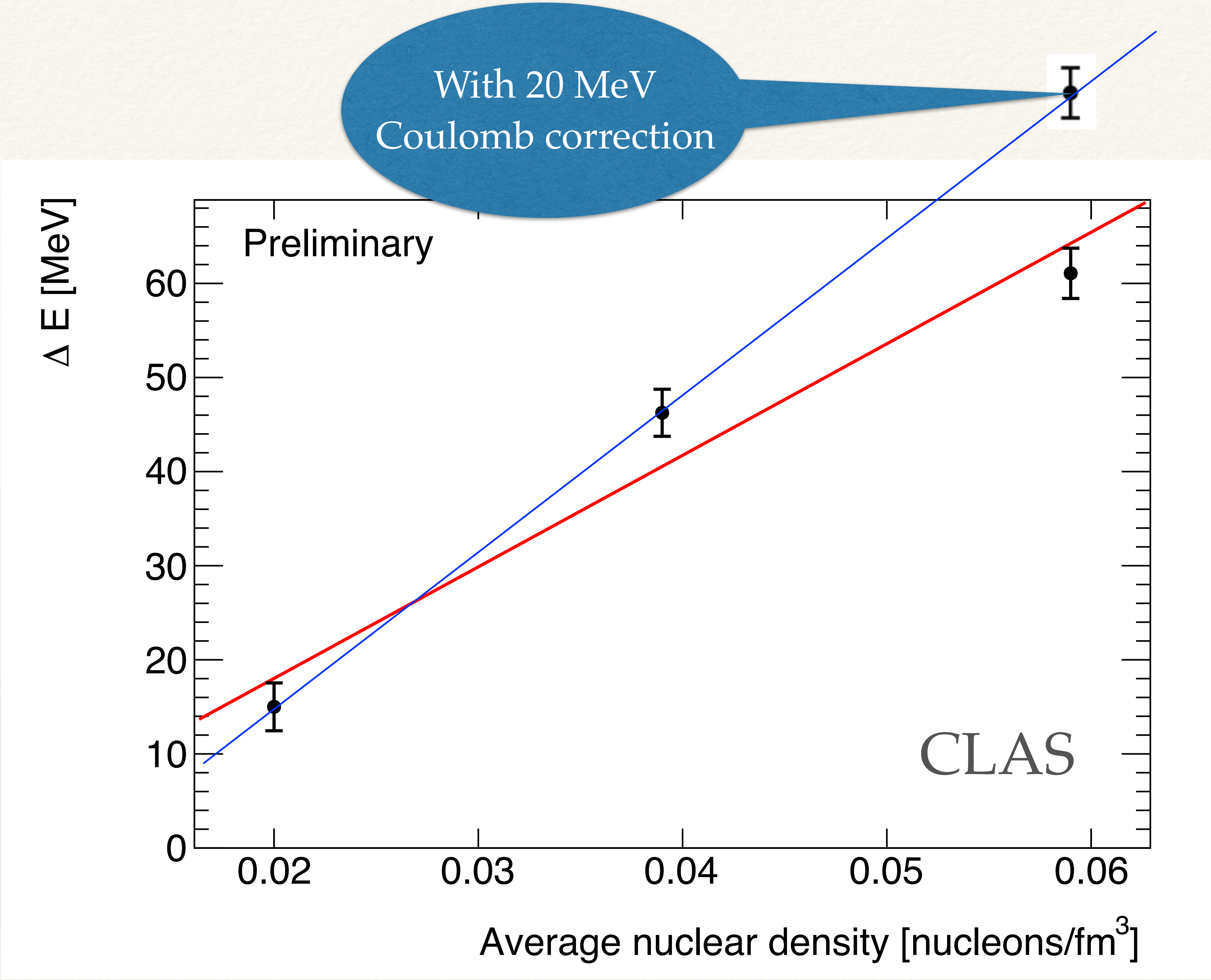
Log of p-values of Kolmogorov-Smirnov test as a function of energy shift ΔE: carbon, iron, lead.

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

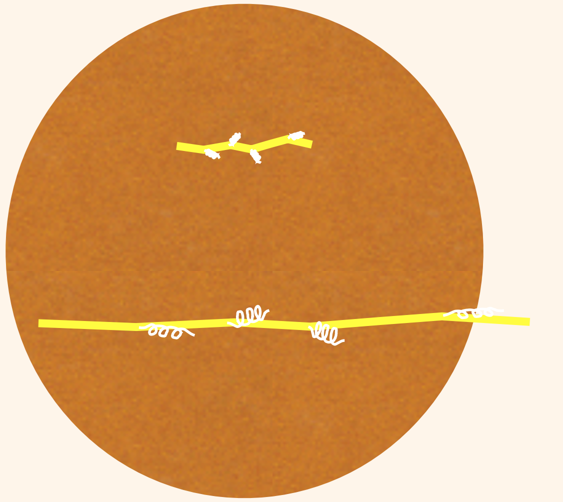
Range of possible energy shift in MeV obtained by Kolmogorov-Smirnov test in ν intervals





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

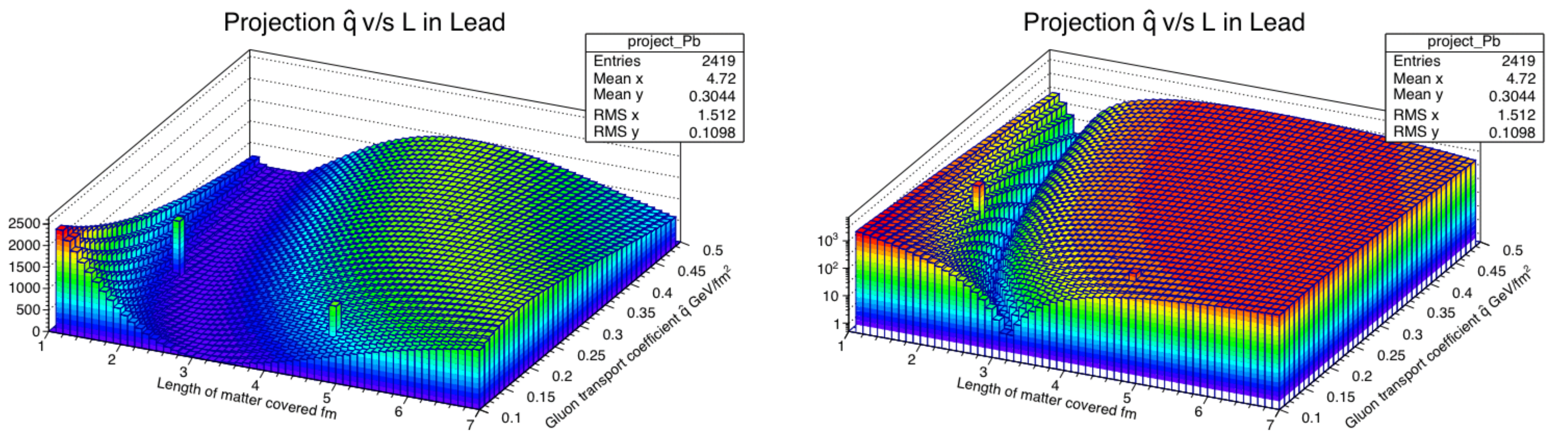
Direct Measurement of Quark Energy Loss in CLAS: Conclusions



- 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)	$\chi^2_{/dof}$	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

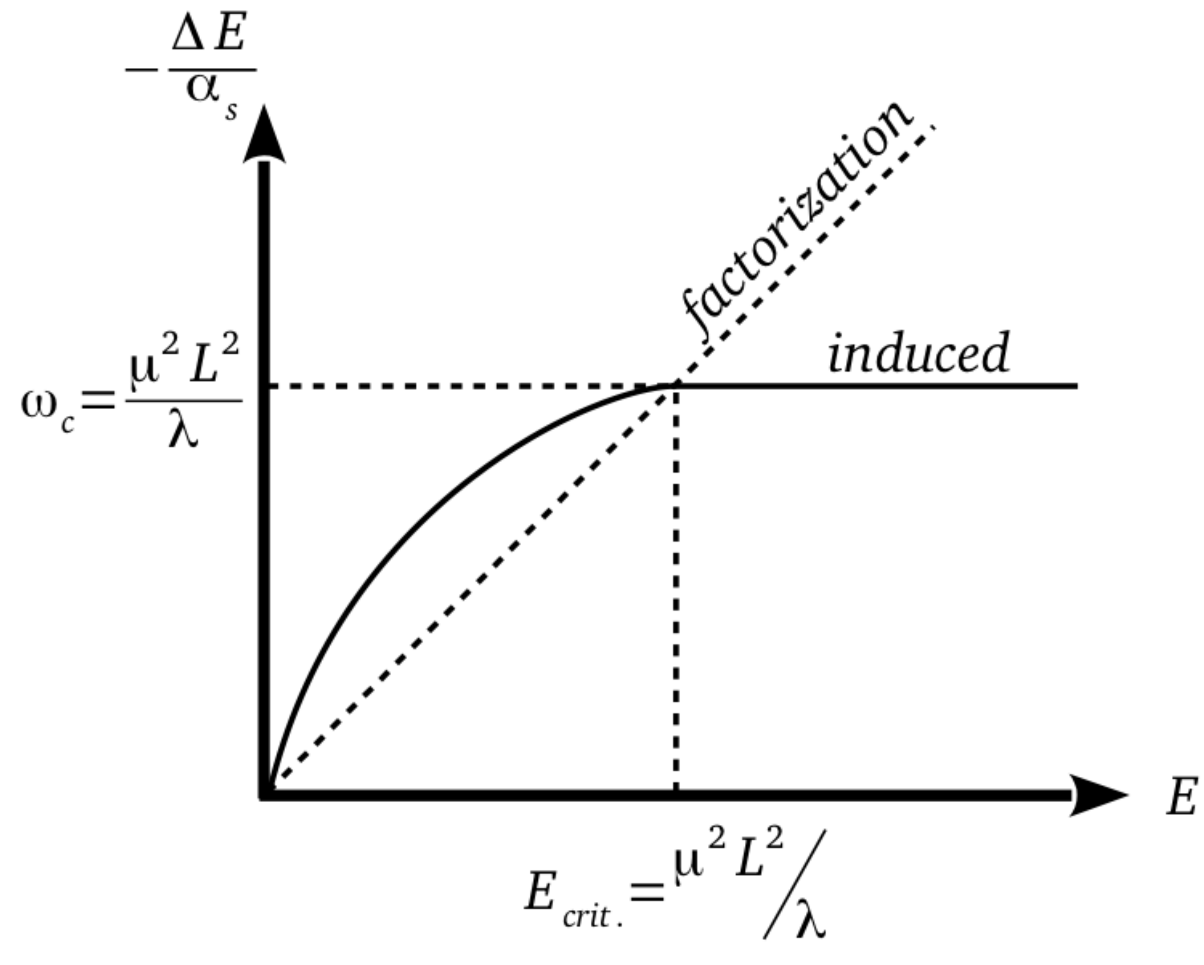


Figure 3.4: Schematic representation of total induced energy loss as a function of the parton energy E (left) and total induced energy loss as a function of the medium size L (right).

λ = mean free path for multiple scattering

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

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  - HERMES data - we measure the production time, and independently obtain the Lund string constant of *1 GeV/fm*

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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