Run Group E

Microscopic studies of meson and baryon hadronization using nuclear targets

ω, f1
Wood,
Soto

π^0, η, η'
Gilfoyle, Joo,
Mineeva, Soto

Λ, Σ, Ξ
El Fassi,
G. Niculescu,
I. Niculescu

π^+, π^-, p
Armstrong,
Hakobyan,
López, Joo

$\bar{p}$
Armstrong,
Dupré, El Fassi,
López

ϕ, $K^\pm$, K^0
El Alaoui, Hicks, Holtrop

$\pi\pi$ *di-hadrons*
Arratia, El Alaoui,
Joo (*new proposal*)

Will Brooks, 25 September 2020

QCD and Hadronization

Hadronization is the process that generates new gravitational mass from energetic quarks and gluons.

It is a fundamental process contained in the QCD Lagrangian that enforces color confinement in dynamical interactions.

In the past:

Theory - too difficult to pose, let alone solve → Effective models.

Experiment - multiplicities, hadron ratios (K/π). No microscopic information available. No significant advances for decades in cold matter studies.

Now:

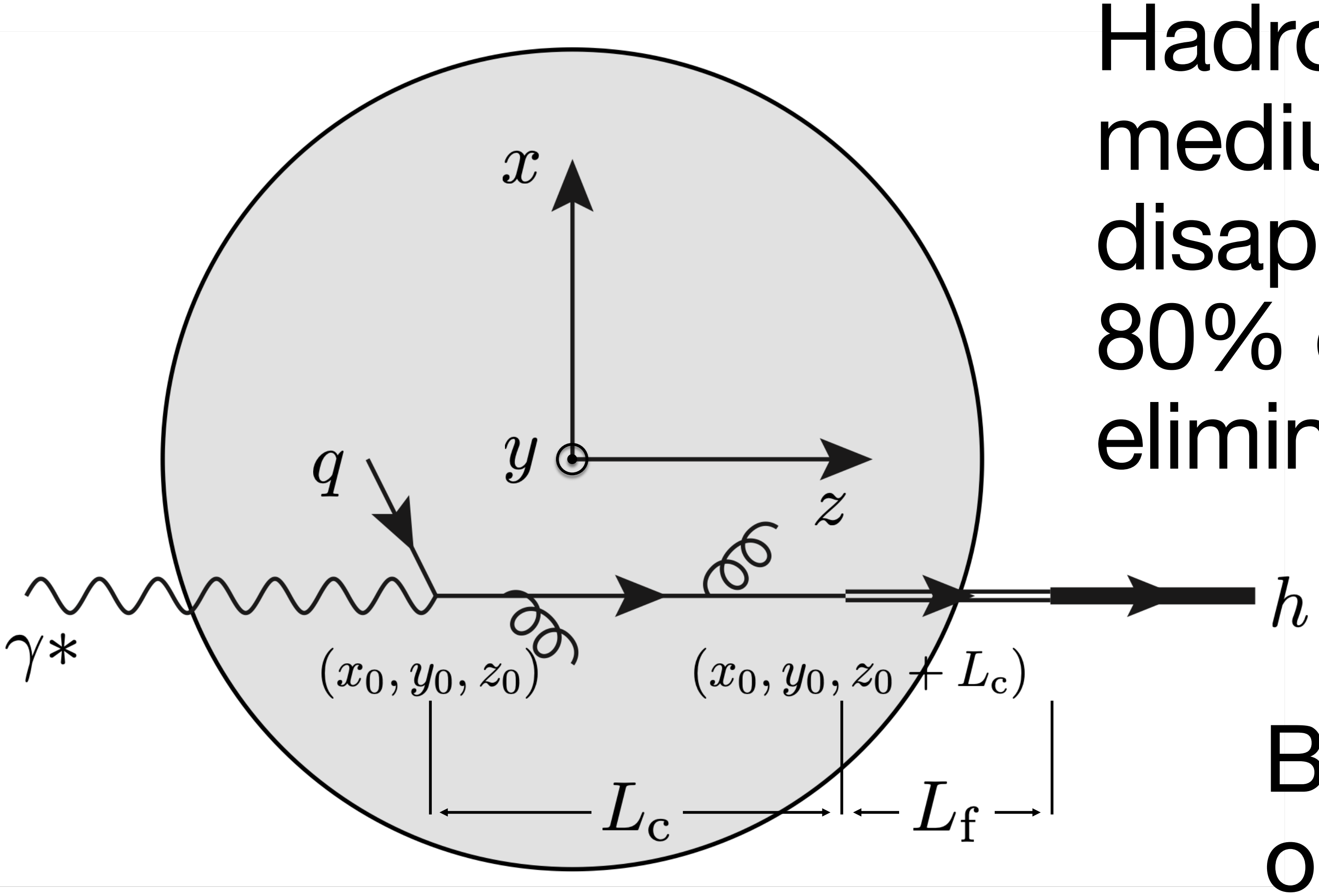
Experiment - Microscopic interactions inside nuclear medium provide access to mechanisms and timescales of the fundamental processes involved.

Theory - the new data are stimulating new phenomenology efforts. New ideas are emerging and being tested and refined.

QCD and Hadronization

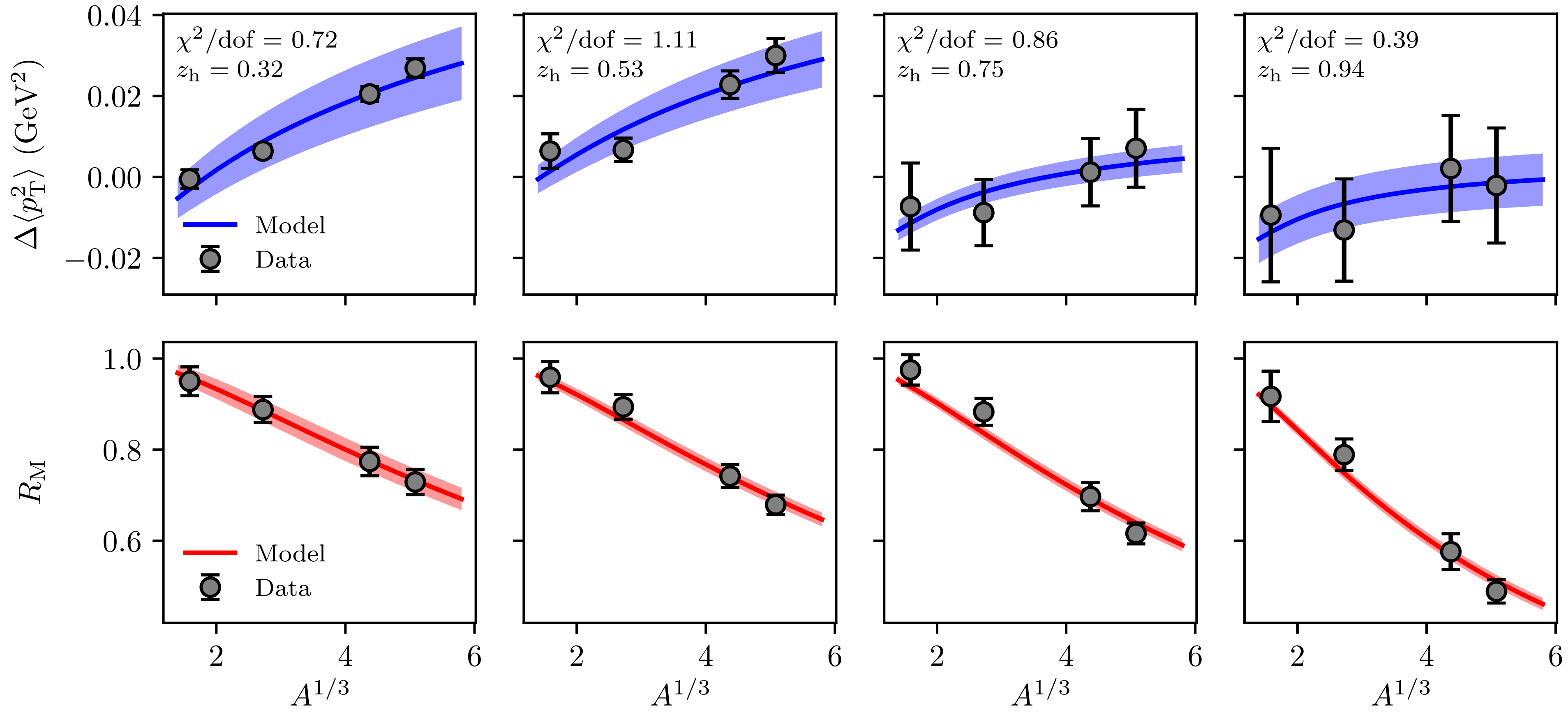
Hadronization inside of nuclei:

Energetic quarks interact gently with the medium, producing an increase in the average transverse momentum of ~0.03 GeV^2.

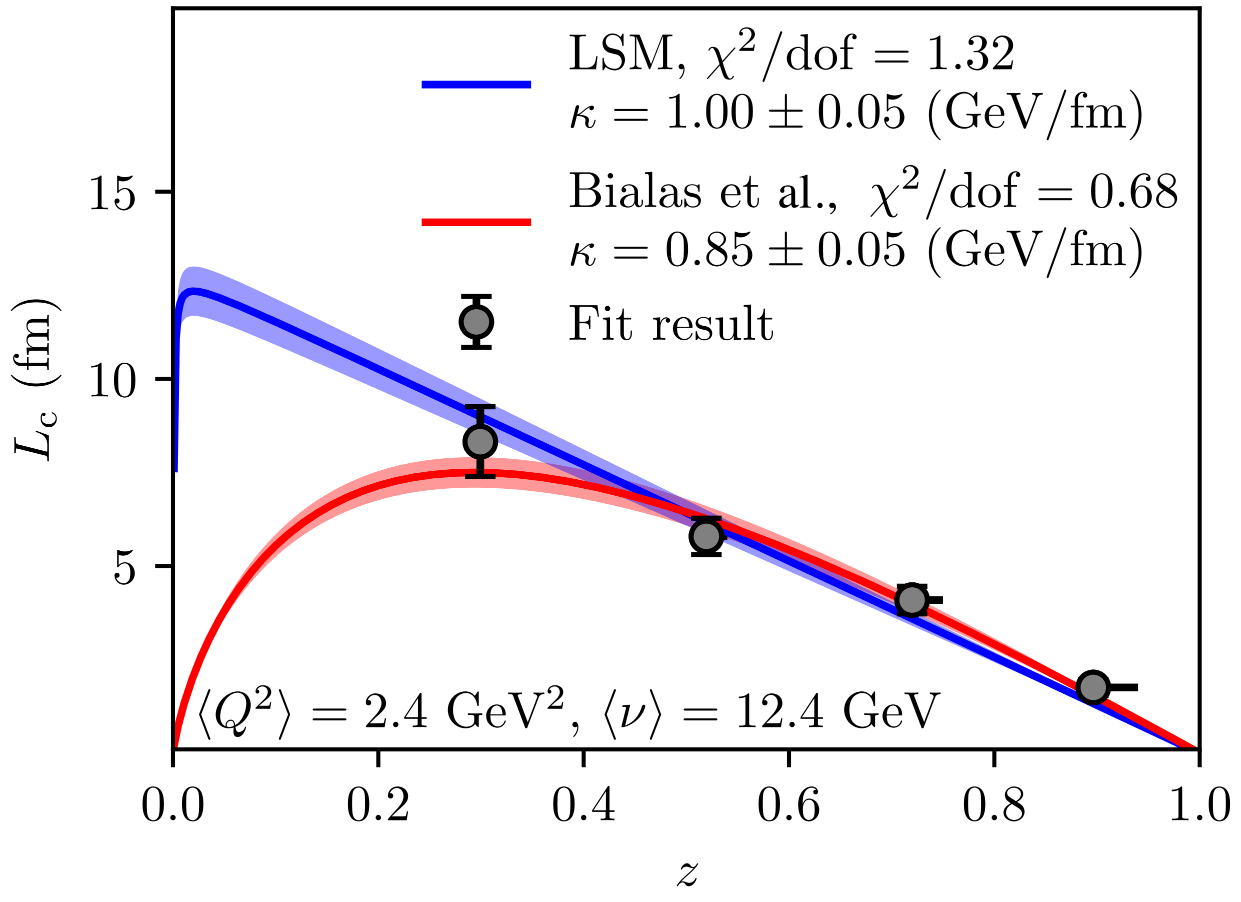


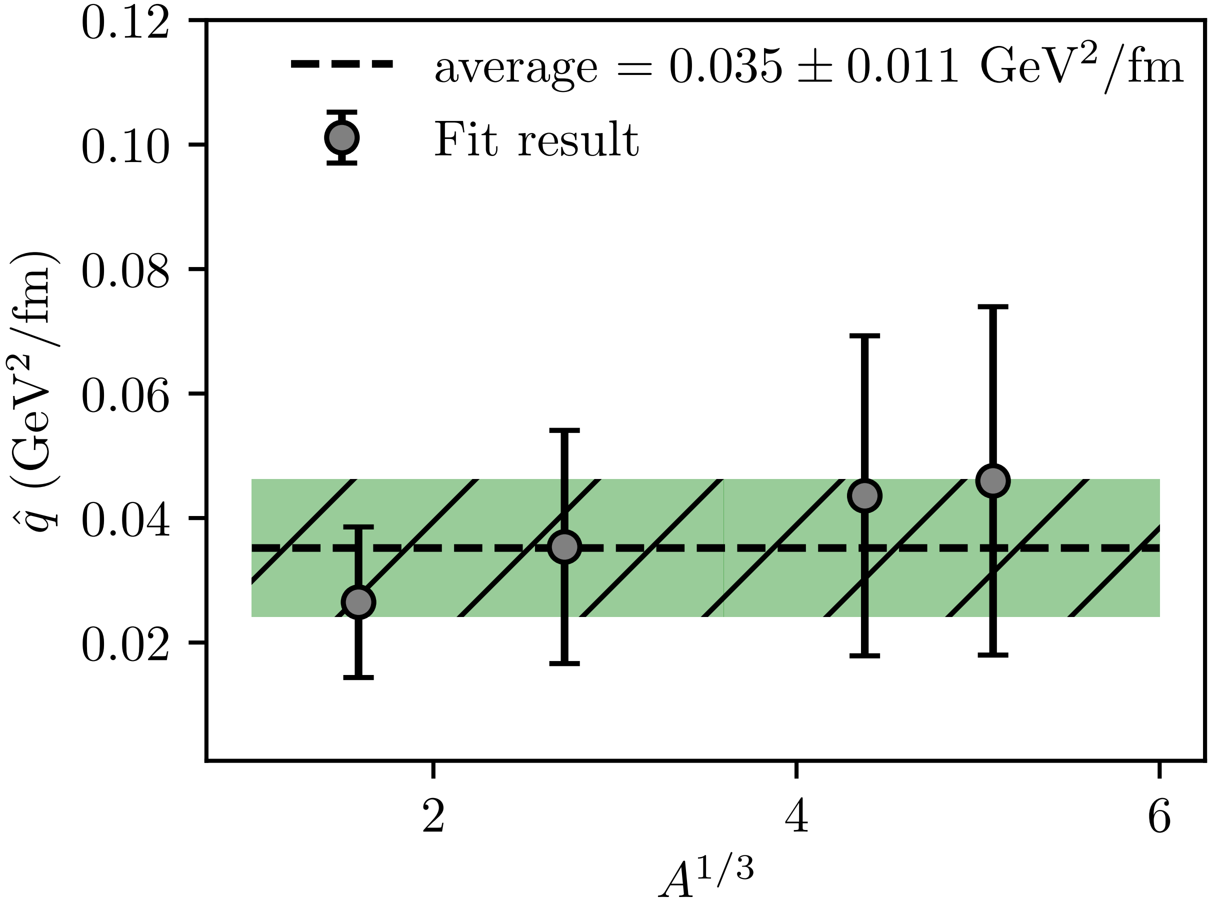
Hadrons that form inside the medium interact very violently, disappearing from the flux. Up to 80% of high-z pions are eliminated in the Pb nucleus.

By contrasting these two observables, we probe the process ***microscopically***.



Recent fit to HERMES data validates this physical picture for π^+





Simultaneous 3-parameter fit to multiplicity ratio and p_T broadening

https://arxiv.org/abs/2004.07236

The 12 GeV Experiment

First-ever measurement, rare heavy meson hadronization:

$\phi(1019)$, $c\tau$ ~44 fm, $J^P=1^-$, $s\bar{s}$

f1(1285), $c\tau$ ~8 fm, $J^P=1^+$

$\eta'(958)$, $c\tau$ ~1 pm, $J^P=0^-$

First look at GeV-scale meson formation!

First-ever measurement of baryon hadronization of:

$\Lambda(1519)$, ***ud***s, $c\tau$ ~ 13 fm

$\Sigma^+(1189)$, uus, $\Sigma^-(1197)$, dds, S=-1

$\Sigma^0(1193)$ S=-1, ***ud***s

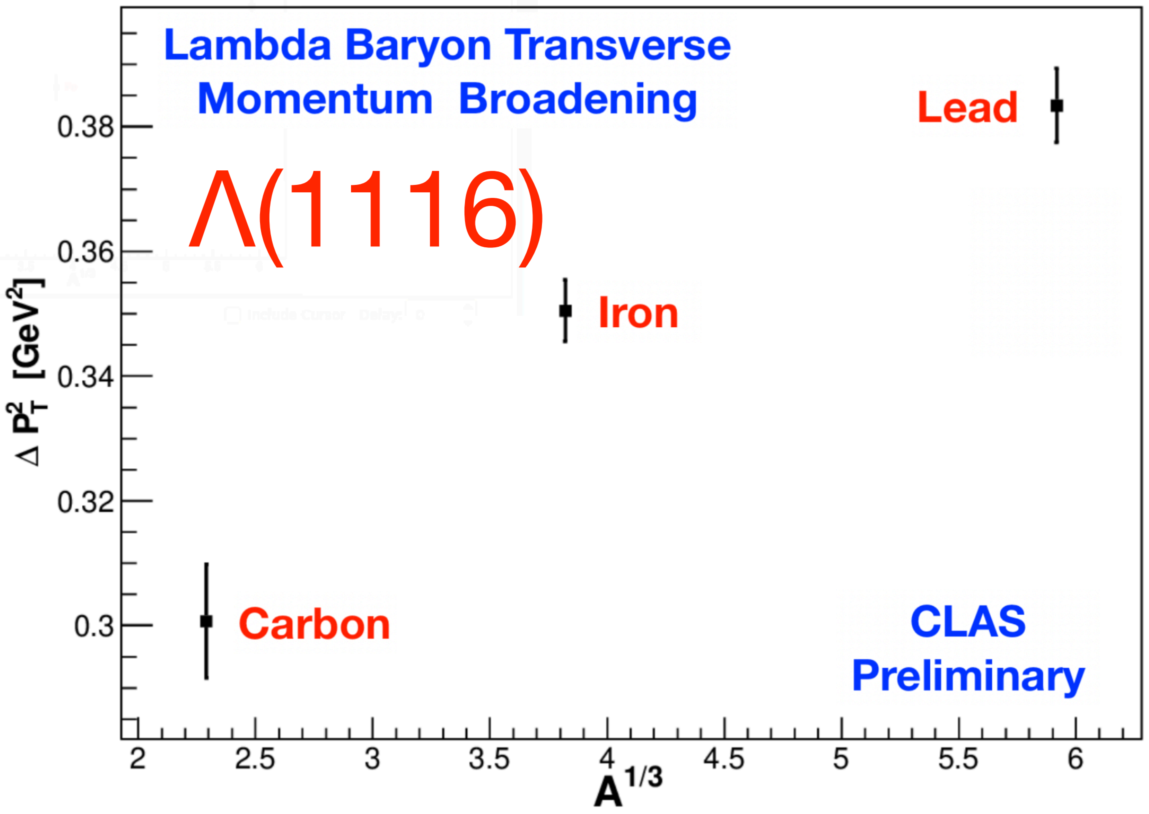
$\Xi^0(1315)$, uss, $\Xi^-(1322)$, dss, S=-2

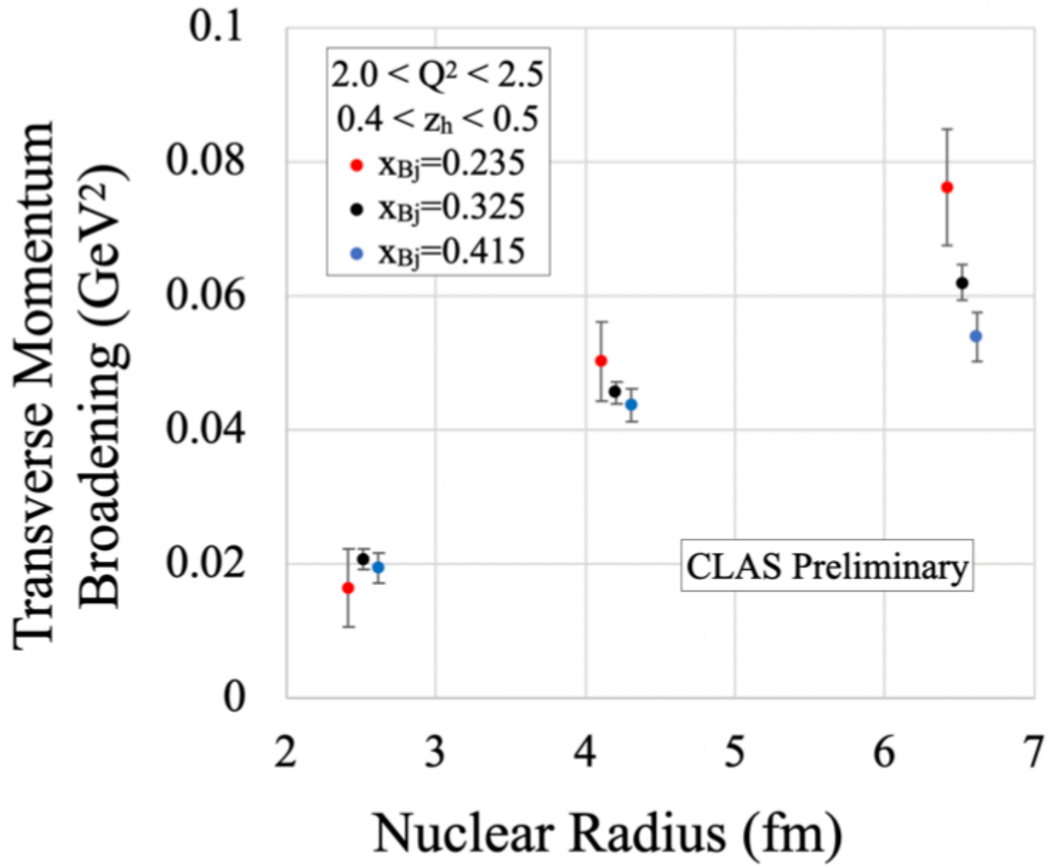
Systematic search for direct scattering of *ud* diquark!

The diquark argument

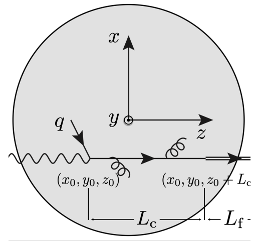
The p_T broadening results from HERMES and from CLAS are very similar for charged pions. Typical values are <0.03-0.05 GeV^2. I think that is quark broadening and it will be seen for production of ordinary hadrons.

For HERMES **protons** and CLAS **protons** and **lambda**, we see something radically different - an order of magnitude larger broadening and/or large multiplicity ratio.





p	$[ud]u$
$\bar{p}$	$[\bar{u}\bar{d}]\bar{u}$
n	$[ud]d$
$\bar{n}$	$[\bar{u}\bar{d}]\bar{d}$
Λ	$[ud]s$
Σ	$[us]u$
Ξ	$[us]s$



A complete description may be found here: https://arxiv.org/pdf/2008.07630.pdf in section 4.2

Theory interest since 2010

Extracting many-body color charge correlators in the proton from exclusive DIS at large Bjorken x.
Adrian Dumitru, Gerald A. Miller, Raju Venugopalan
Phys. Rev. D 98, 094004 (2018)

Transverse momentum broadening in semi-inclusive deep inelastic scattering at next-to-leading order.
Zhong-Bo Kang, Enke Wang, Xin-Nian Wang, and Hongxi Xing
Phys. Rev. D 94, 114024 (2016)

A global extraction of the jet transport coefficient in cold nuclear matter.
Peng Ru, Zhong-Bo Kang, Enke Wang, Hongxi Xing, Ben-Wei Zhang
arXiv:1907.11808 [hep-ph] (2019)

Initial conditions for the modified evolution of fragmentation functions in the nuclear medium
Ning-Bo Chang, Wei-Tian Deng, and Xin-Nian Wang
Phys. Rev. C 89, 034911 (2014)

Spacetime development of in-medium hadronization: Scenario for leading hadrons. Benjamin Guiot and Boris Z. Kopeliovich
arXiv:2001.00974 [hep-ph] (2020)

Quenching of high-pT hadrons: a non-energy-loss scenario.
B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, and I. Schmidt.
EPJ Web Conf., 71:00070 (2014).

Parton transport via transverse and longitudinal scattering in dense media.
Guang-You Qin and Abhijit Majumder
Phys. Rev. C 87, 024909 (2013)

Diquark Correlations in Hadron Physics: Origin, Impact and Evidence
M. Yu. Barabanov, M. A. Bedolla, W. K. Brooks, G. D. Cates, C. Chen, Y. Chen, E. Cisbani, M. Ding, G. Eichmann, R. Ent, J. Ferretti, R. W. Gothe, T. Horn, S. Liuti, C. Mezrag, A. Pilloni, A. J. R. Puckett, C. D. Roberts, P. Rossi, G. Salme, E. Santopinto, J. Segovia, S. N. Syritsyn, M. Takizawa, E. Tomasi-Gustafsson, P. Wein, B. B. Wojtsekhowski
arXiv:2008.07630 [hep-ph] (2020)

The theory and phenomenology of perturbative QCD based jet quenching. A. Majumder and M. van Leeuwen.
Progress in Particle and Nuclear Physics, 66(1):41 – 92 (2011).

Quark energy loss in semi-inclusive deep inelastic scattering of leptons on nuclei. Li-Hua Song and Chun-Gui Duan.
Phys. Rev. C, 81:035207 (2010).

Systematic analysis of the incoming quark energy loss in cold nuclear matter. Li-Hua Song, Chun-Gui Duan, and Na Liu.
Physics Letters B, 708(1-2):68–74 (2012).

Atomic mass dependence of hadron production in semi-inclusive deep inelastic lepton-nucleus scattering. Li-Hua Song, Na Liu, and Chun-Gui Duan.
Chinese Physics C, 37(8):084102 (2013).

Hadron formation in semi-inclusive deep inelastic lepton-nucleus scattering. Li-Hua Song, Na Liu, and Chun-Gui Duan.
Chinese Physics C, 37(10):104102, (2013)

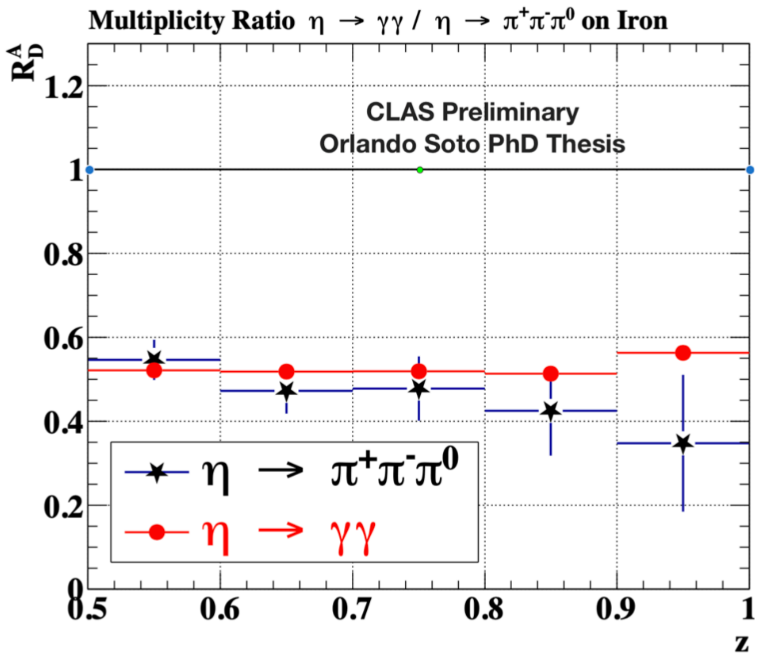
The energy loss and nuclear absorption effects in semi-inclusive deep inelastic scattering on nucleus. Li-Hua Song, Shang-Fei Xin, and Na Liu.
J. Phys., G45(2):025005 (2018).

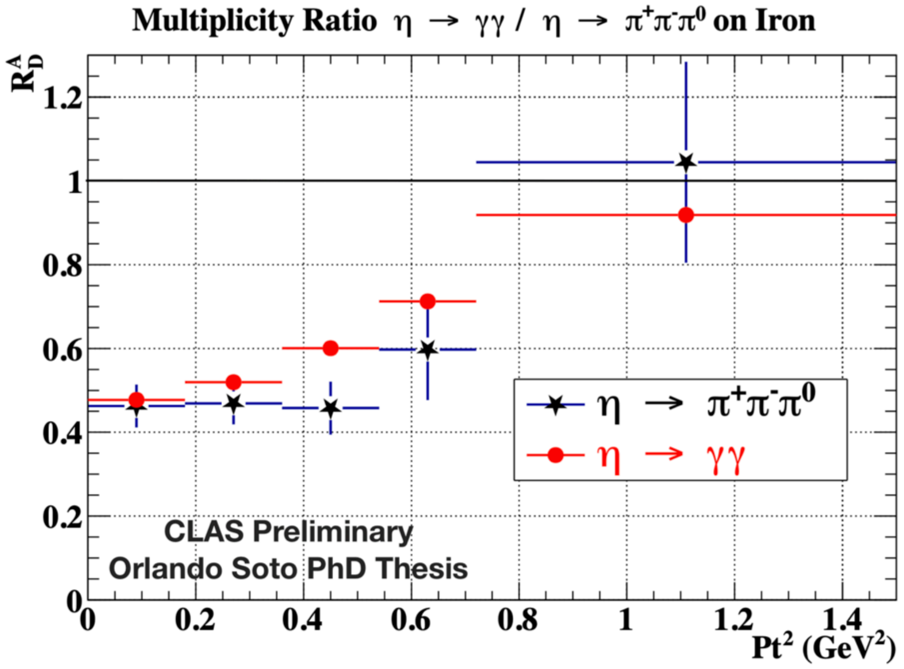
The study of the incoming parton energy loss effect on the NLO nuclear Drell–Yan ratios.
Li-Hua Song, Shang-Fei Xin, and Yin-Jie Zhang.
J. Phys. G: Nuclear and Particle Physics, 47(5):055002, (2020)

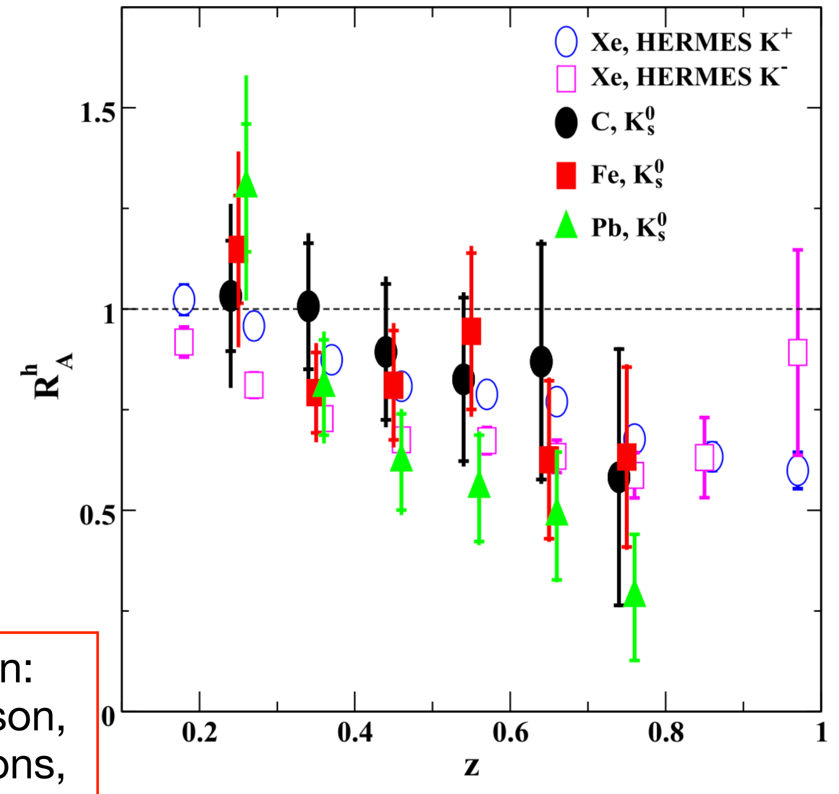
Nuclear geometry effect and transport coefficient in semi-inclusive lepton-production of hadrons off nuclei.
Na Liu, Wen-Dan Miao, Li-Hua Song, and Chun-Gui Duan.
Physics Letters B, 749:88–93 (2015).

Besides theory: pA@LHC, dAu@RHIC, DY@FNAL

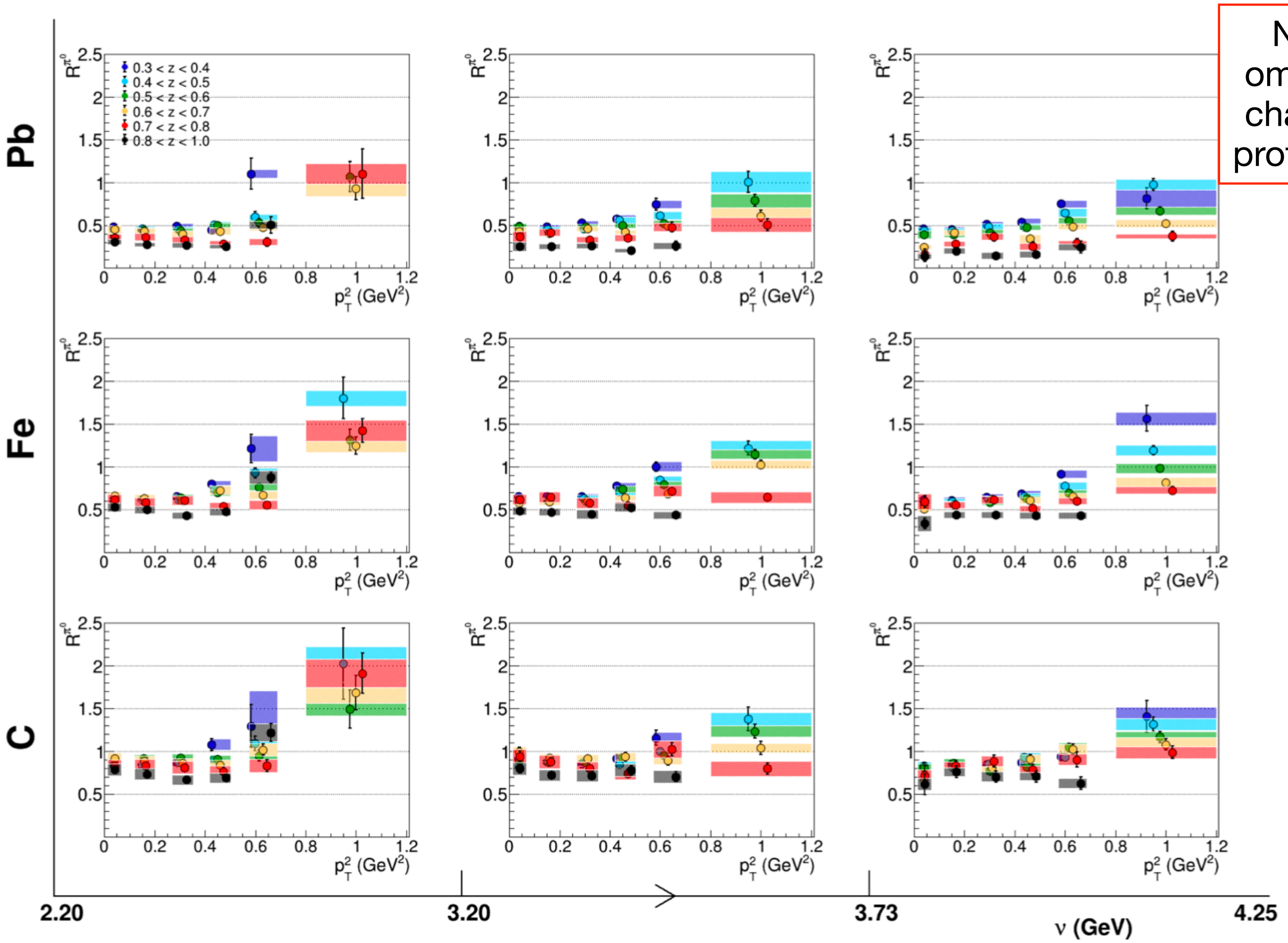
Selected results from 5 GeV CLAS since 2010



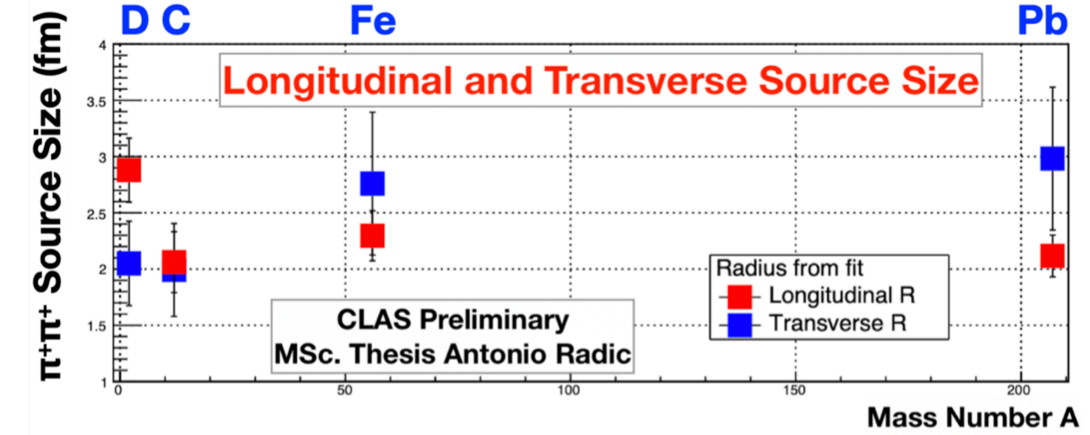


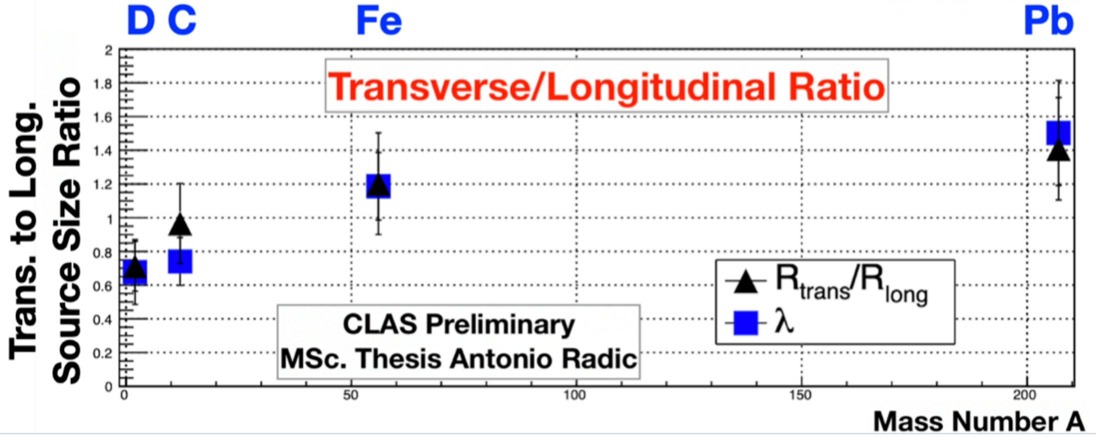


Not shown:
omega meson,
charged pions,
protons, lambda



BOSE-EINSTEIN Correlations for $\pi^+\pi^+$





Comments from Theory TAC

“Color propagation and hadron formation are fundamental properties of QCD dynamics, and are critically important for understanding the emergence of hadrons and the neutralization of color.”

“Understanding the color propagation and hadron formation is also one of the fundamental physics goals of the future Electron-Ion Collider.”

“this proposed experiment is timely and very important”

“This experiment will bridge JLab 6 experiments, where formation times are smaller and hadrons can be formed inside the medium, to the EIC kinematics”

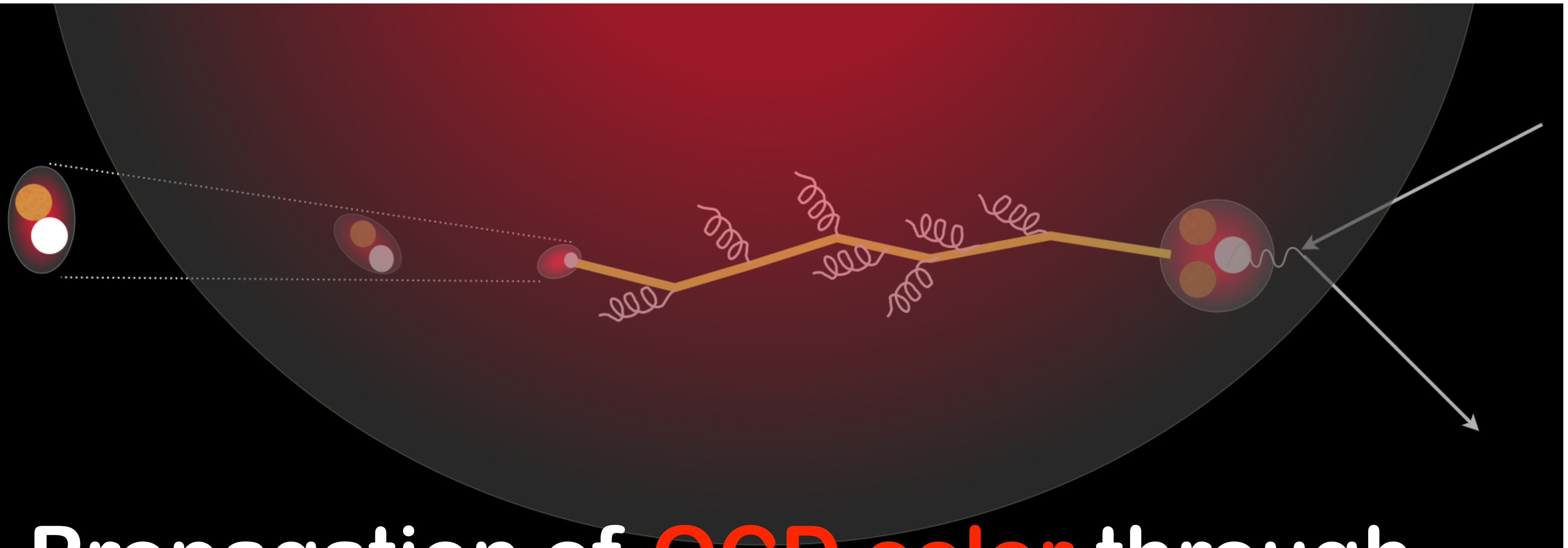
“In summary, the results of this run group proposal…will thus be fundamental to help us addressing one of the key fundamental questions of the strong interactions - how hadrons emerge from colored quarks and gluons.”

Conclusions

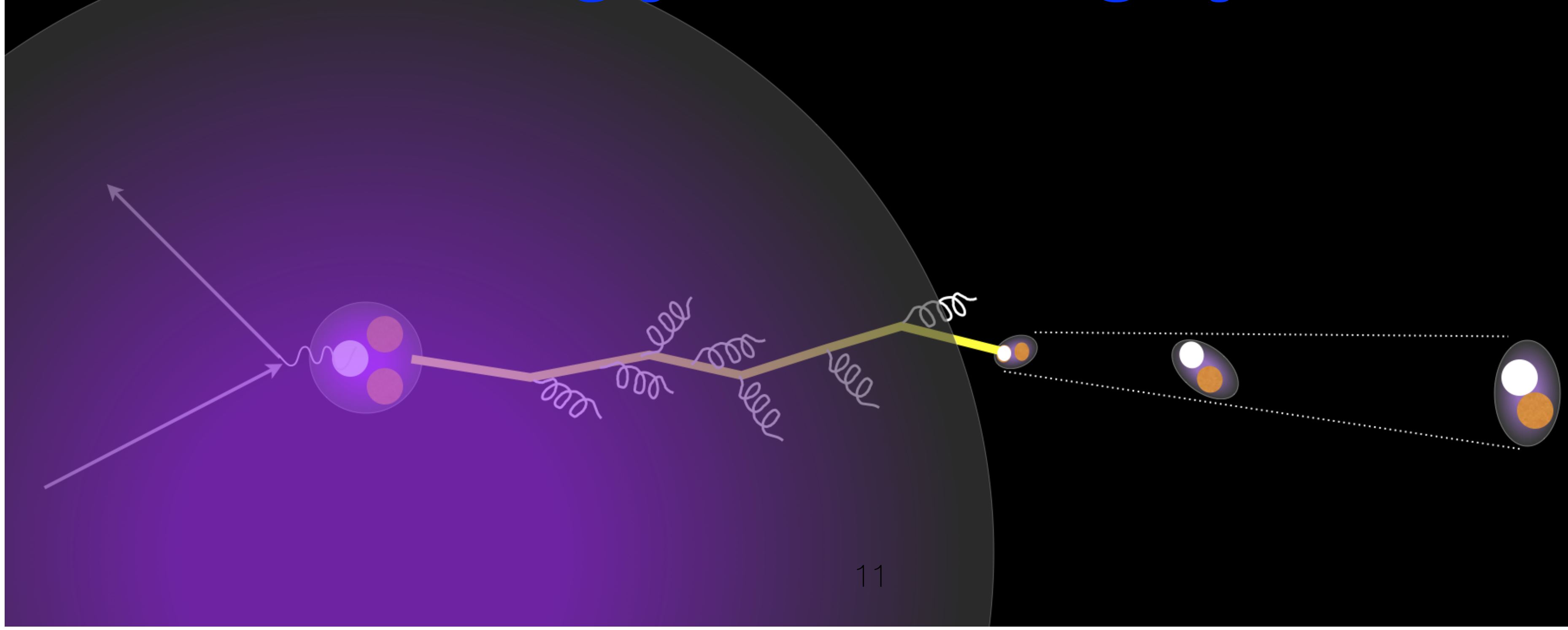
“Is there any new information that would affect the scientific importance or impact of the experiment since it was originally proposed?”

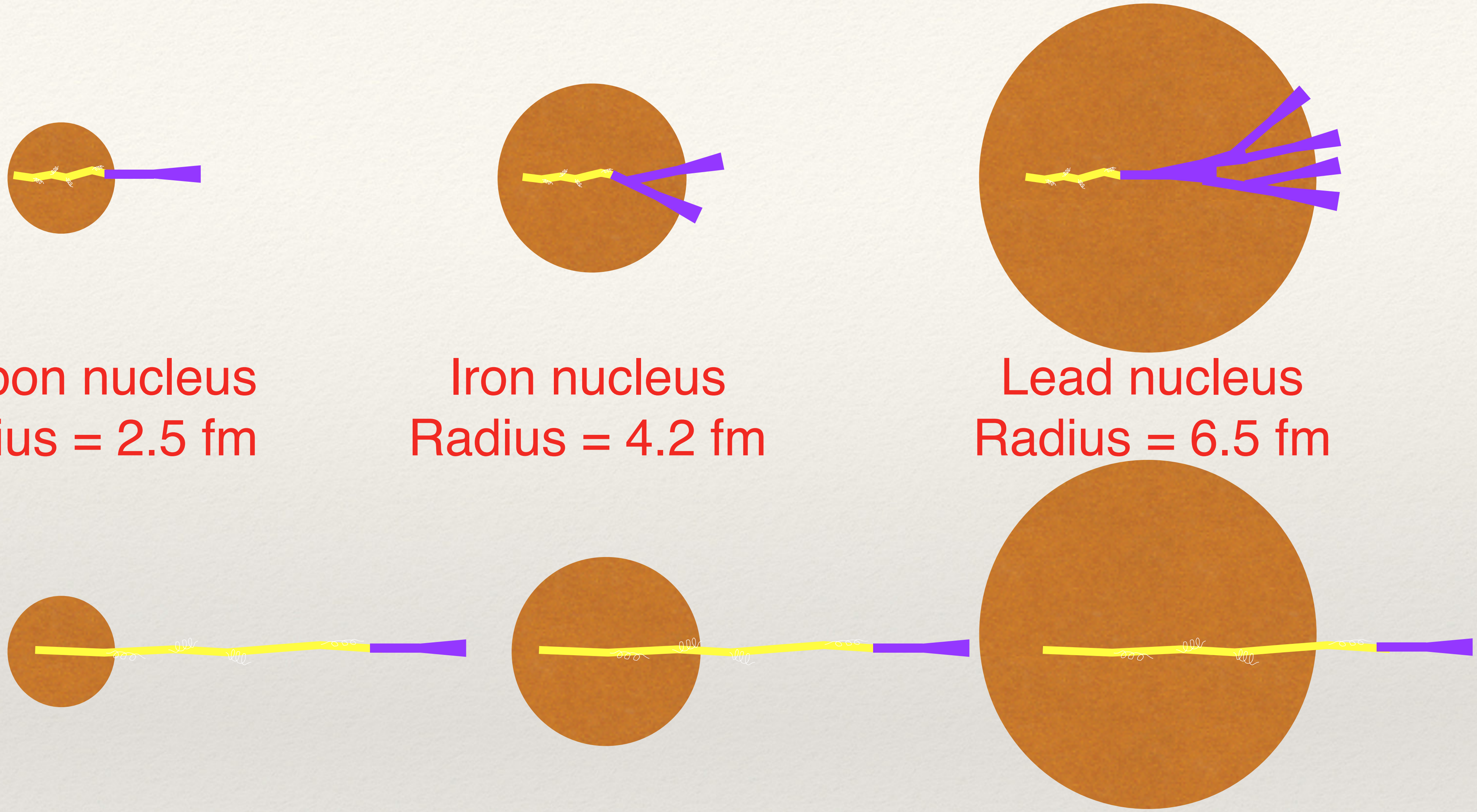
- US EIC CD-0 approval. Chinese EicC HIAF stage being built; e-A the new international priority in the field. CLAS12 nuclear target data will chart the path for EIC measurements.
- Visible acceleration of theory work to understand nuclear environment in DIS.
- Important new theory work on di-quark correlations in hadrons.

“Beam time allocation”: Important channels such as the phi meson and anti-proton are statistics-limited.



Propagation of QCD color through strongly interacting systems





Short color lifetime

Long color lifetime

Carbon nucleus
Radius = 2.5 fm

Iron nucleus
Radius = 4.2 fm

Lead nucleus
Radius = 6.5 fm

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

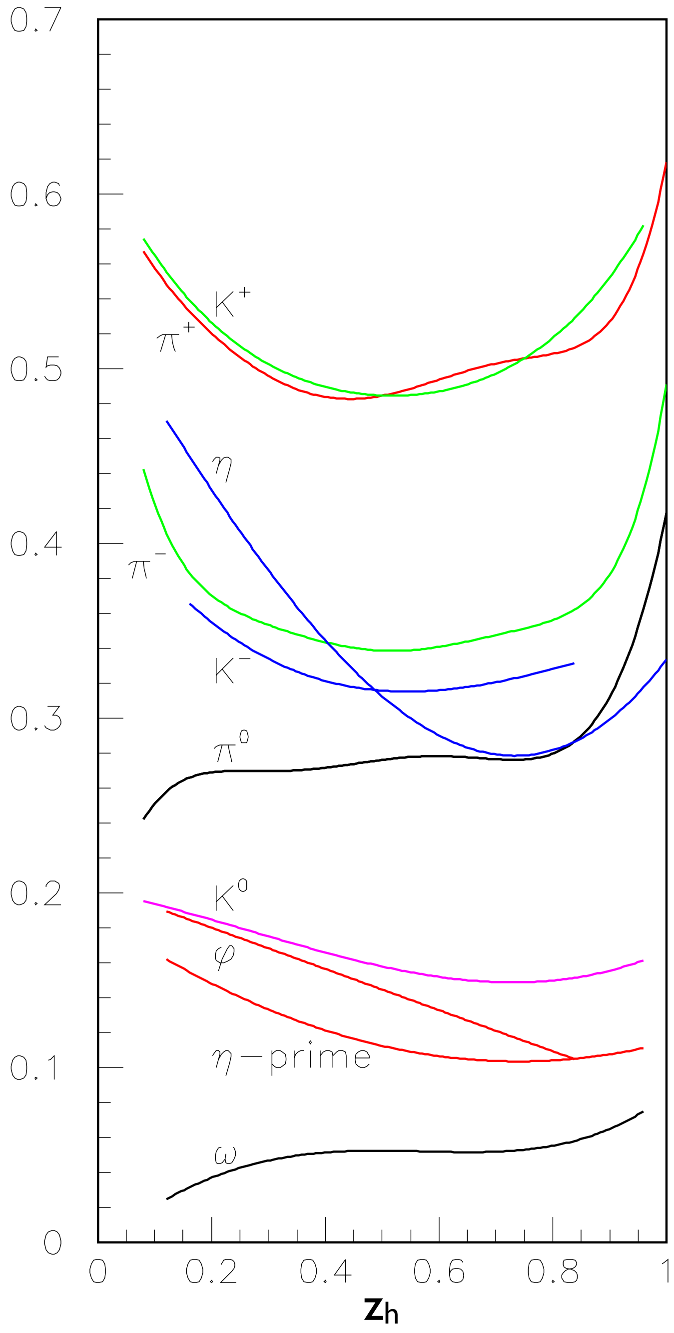
Quark Propagation and Hadron Formation with 11 GeV Beam

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	uūdd̄	5.7% (sys)
π^+, π^-	7.8 m	0.14	ud̄, dū	3.2% (sys)
η	170 pm	0.55	uūdd̄ss̄	6.2% (sys)
ω	23 fm	0.78	uūdd̄ss̄	6.7% (sys)
η'	0.98 pm	0.96	uūdd̄ss̄	8.5% (sys)
ϕ	44 fm	1	uūdd̄ss̄	5.0% (stat)*
f1	8 fm	1.3	uūdd̄ss̄	-
K^0	27 mm	0.5	ds̄	4.7% (sys)
K^+, K^-	3.7 m	0.49	us̄, ūs	4.4% (sys)
p	stable	0.94	ud	3.2% (sys)
$\bar{p}$	stable	0.94	ūd̄	5.9% (stat)**
Λ	79 mm	1.1	uds	4.1% (sys)
$\Lambda(1520)$	13 fm	1.5	uds	8.8% (sys)
Σ^+	24 mm	1.2	us	6.6% (sys)
Σ^-	44 mm	1.2	ds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	us	16% (stat)*
Ξ^-	49 mm	1.3	ds	7.8% (stat)*

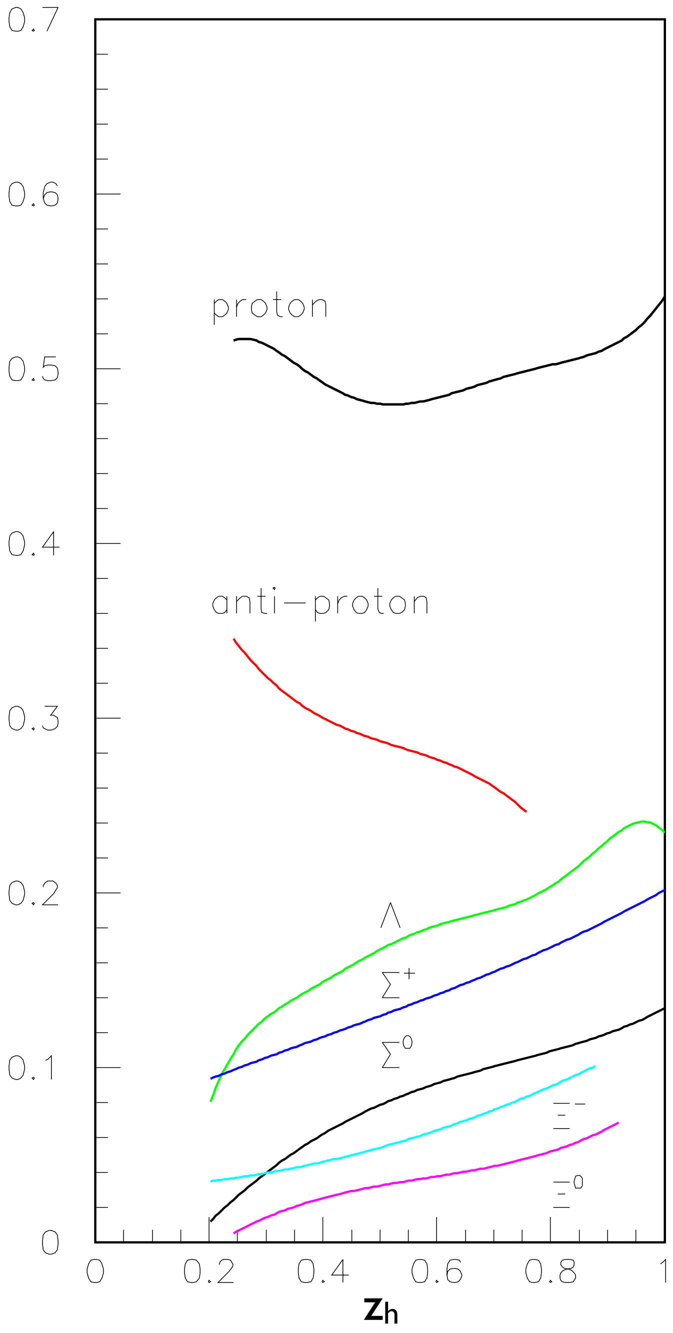
*in a bin in z from 0.7-0.8, integrated over all ν, p_T, ϕ_{pq}, and Q^2>5 GeV^2

**in a bin in z from 0.6-0.7, integrated over all ν, p_T, ϕ_{pq}, and Q^2>5 GeV^2

Dependency of observables (and thus derived quantities, such as production time, formation times, transport coefficient, in-medium cross section, etc.) on mass, flavor, and number of valence quarks



CLAS12 Acceptance for Mesons



CLAS12 Acceptance for Baryons