Hadronization in the Nuclear Medium: Exploring Fundamental QCD Processes Using New Experimental Tools

Will Brooks
UTFSM, Valparaíso, Chile

Fascination with fragmentation

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  - from a classical viewpoint

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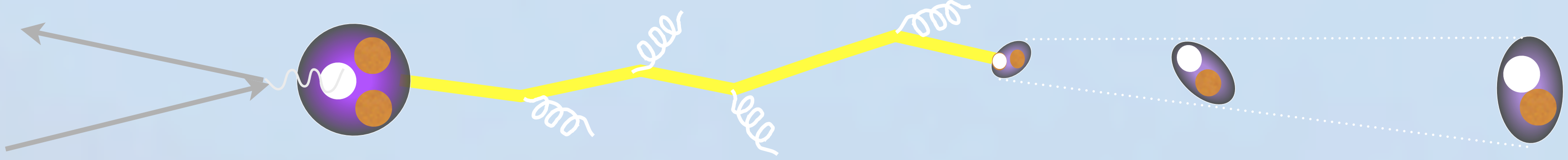

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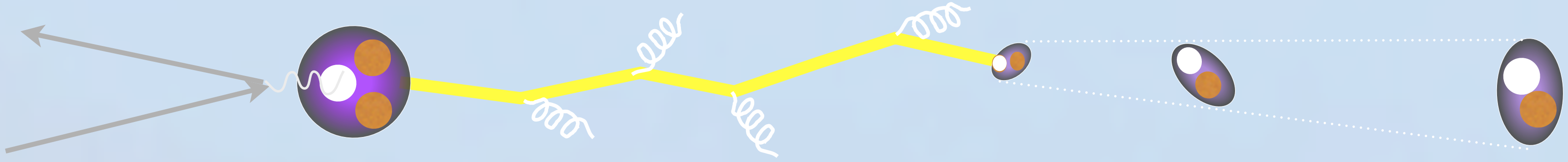

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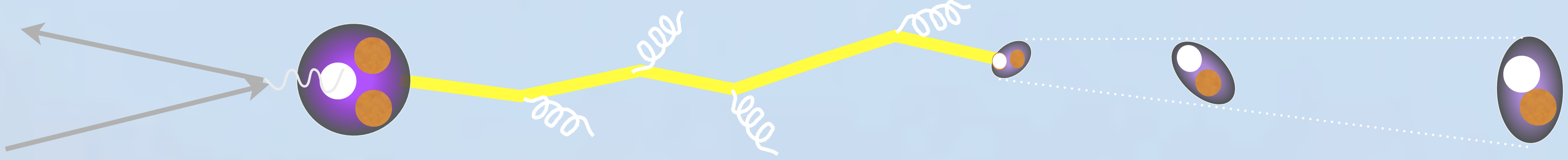

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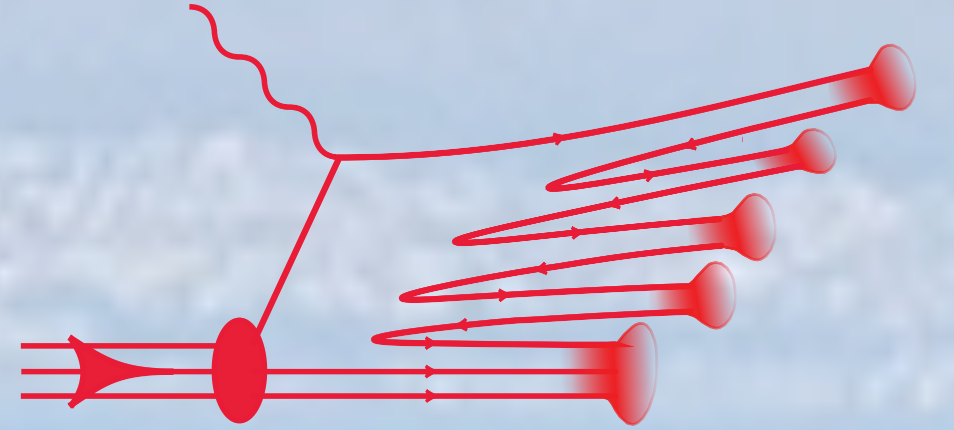

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- ***Timescales***
    - Virtual quark lifetime, hadron formation time

      Measure: p_T *broadening, flavor dependence of hadron attenuation*

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- ***Mechanisms***
  - Hadrons from quarks and gluons? Go beyond the string/cluster dichotomy for QCD cascade? How target baryon wavefunction recovers from losing struck quark? New fragmentation functions for proton and nuclear targets

    Measure: two-hadron correlations, photon-hadron correlations, target fragmentation, hadron yields

Timescales

- **Two distinct stages for struck quark in DIS:**
  - Virtual quark lifetime - “production time” - gluons radiated
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  Overall time, just as in QED: $\frac{k_{||}}{k_{\perp}^2}$
- **Theoretical speculation until now**
  - Interactions with nuclei reveal time/distance scales

  Bose-Einstein correlations too

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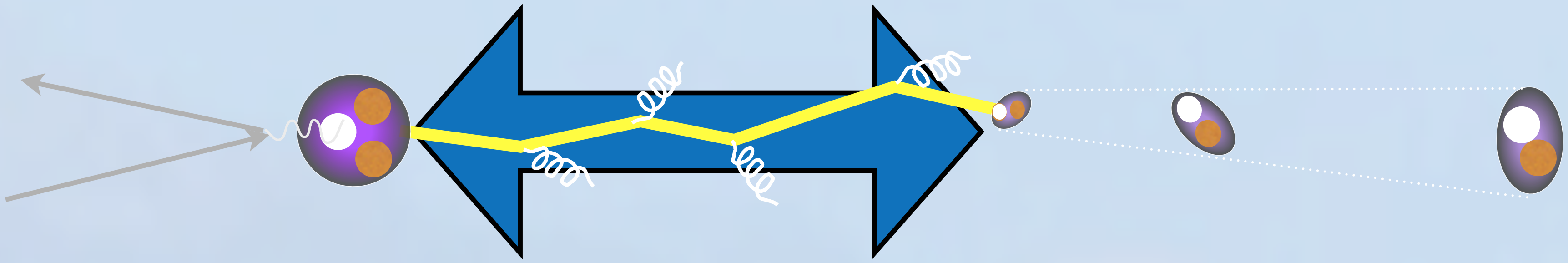

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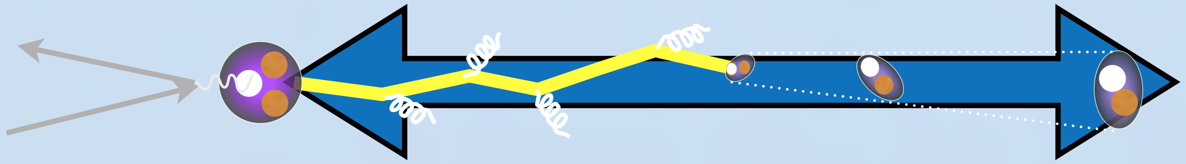
Timescales - how to measure?



- First observable: multiplicity ratio

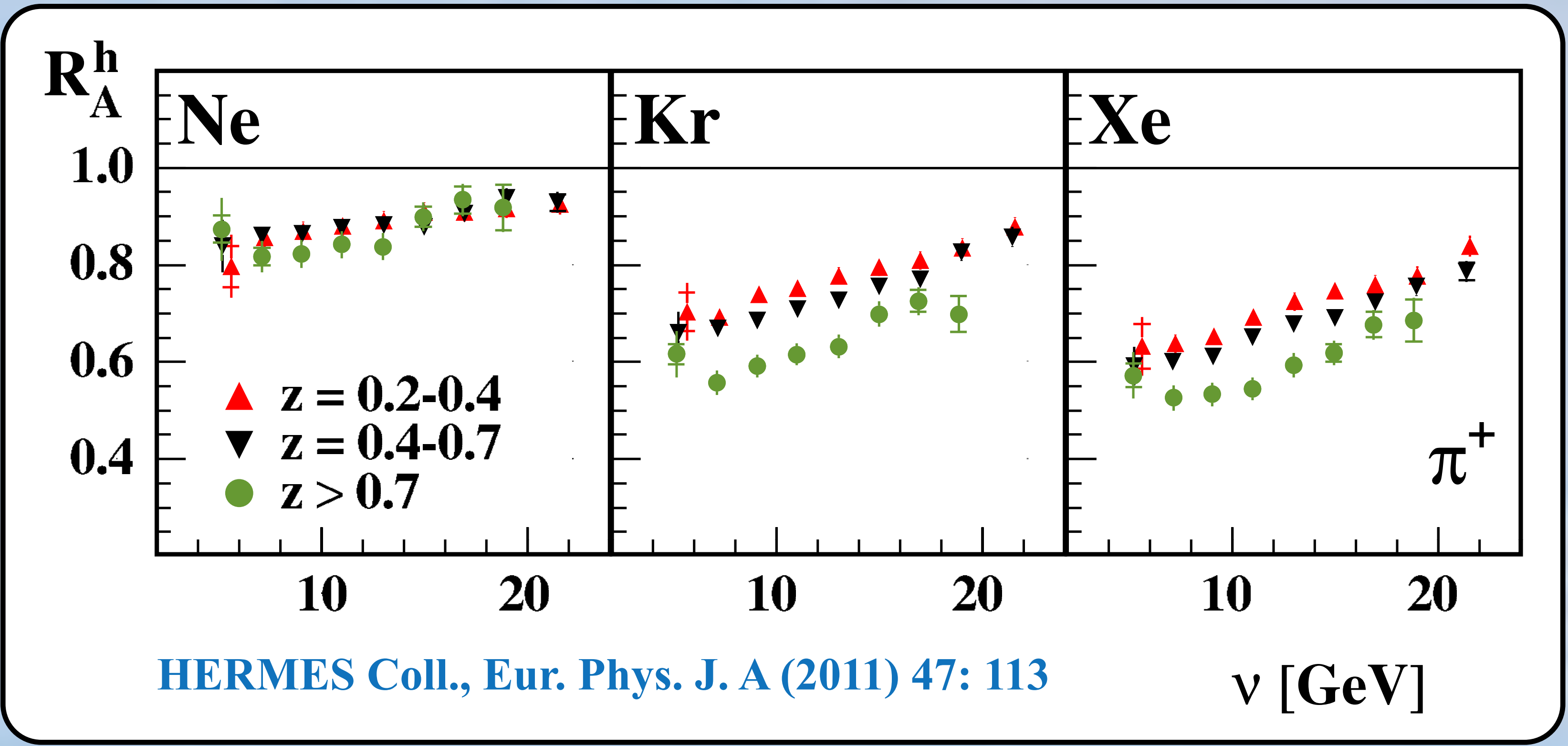
$$R_h = \frac{\frac{1}{N_e^A(Q^2,\nu)} N_h^A(Q^2,\nu,z,p_T,\phi)}{\frac{1}{N_e^D(Q^2,\nu)} N_h^D(Q^2,\nu,z,p_T,\phi)}$$

Expectations: rise→1 at high ν

- **Time dialation**, average pathlength in the medium

$$z \equiv \frac{E_{hadron}}{\nu}$$

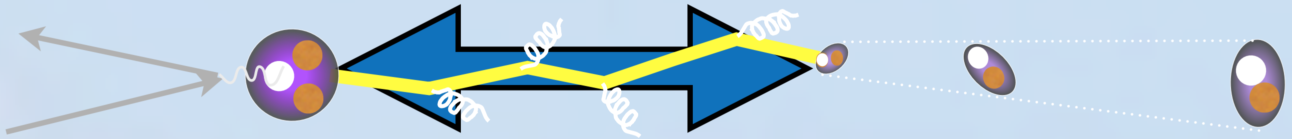
$$0 < z < 1$$



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

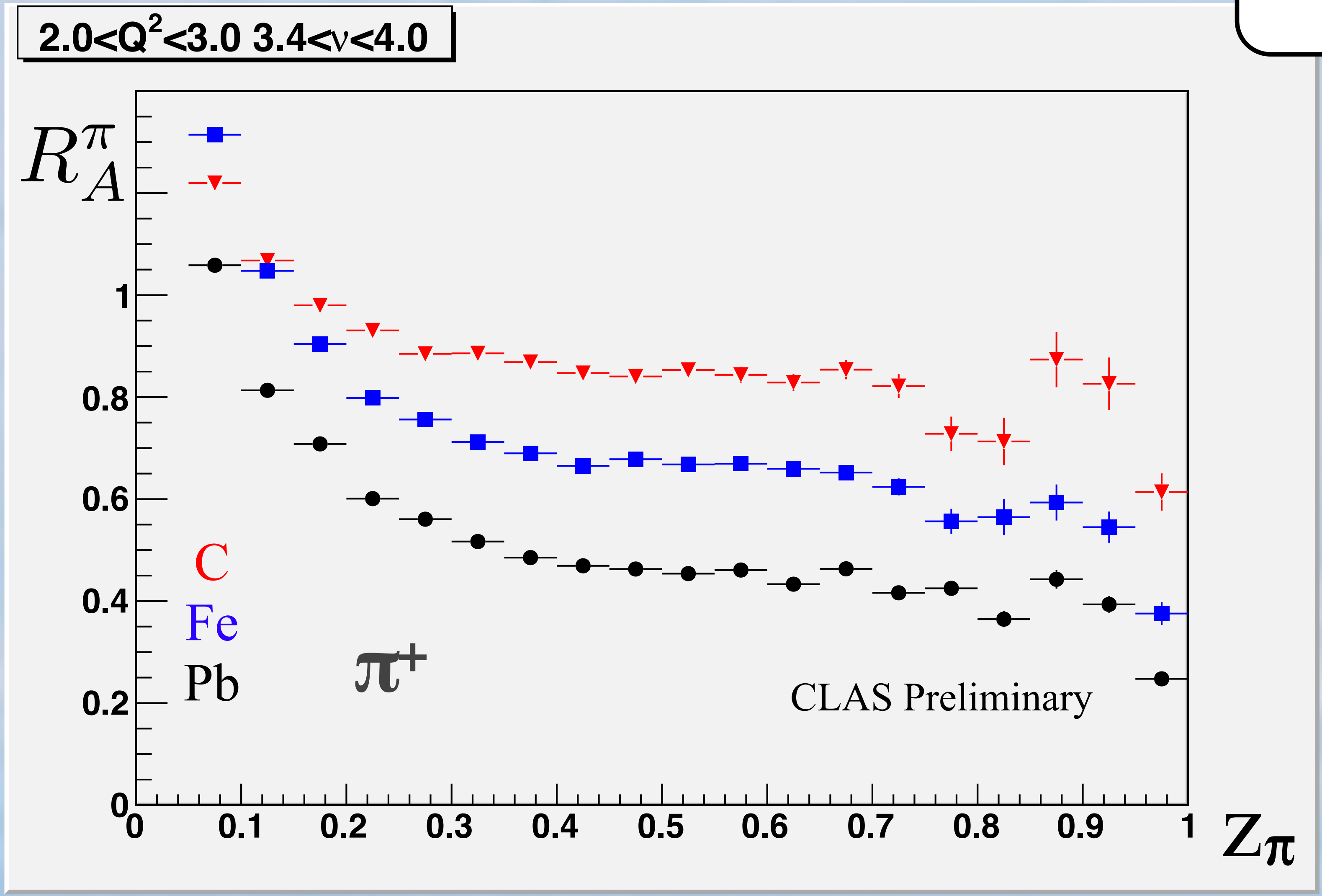
K.Gallmeister, U.Mosel, Nucl.Phys.A801:68-79,2008, arXiv:nucl-th/0701064 , time-based interpretation

Lund string model time estimate



- **Virtual quark lifetime component, light quarks**
- **z dependence**

$$l_p = z\frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$$



Expectation: drop at high z

Expectation: drop at low z, but obscured by other effects for R_A

Maximum lifetime is at intermediate z

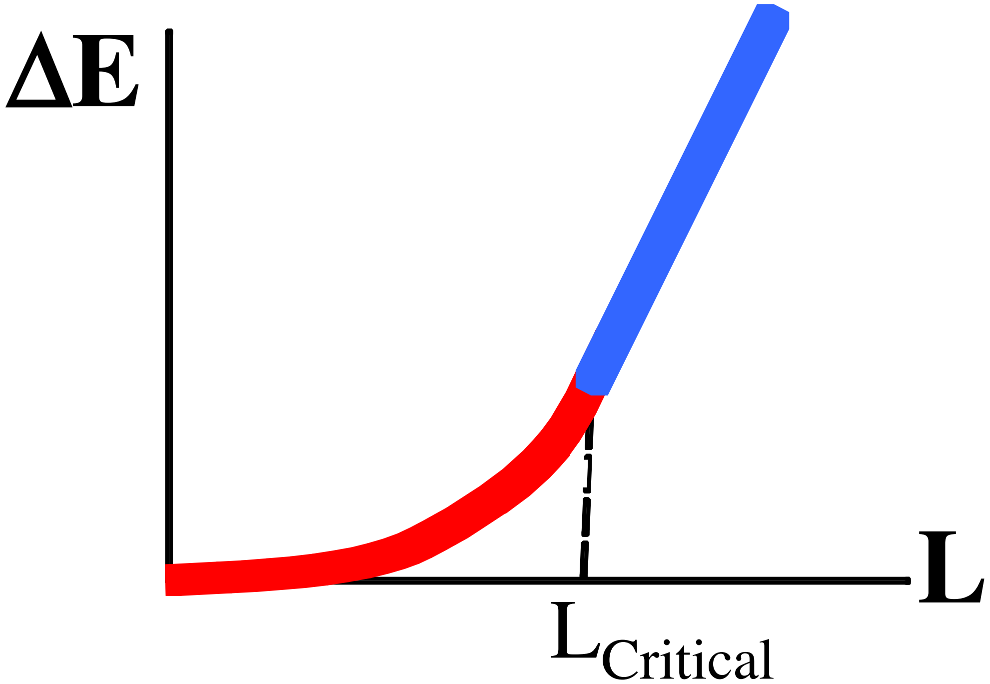
Partonic energy loss in pQCD: L_{crit}

$L < L_{Critical}$

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

$L > L_{Critical}$

$$-\frac{dE}{dx} \propto \sqrt{E\hat{q}}$$



$$\text{at} \quad \mathrm{L} = \mathrm{L_{Critical}}, \quad \mathrm{L\hat{q}} \propto \sqrt{\mathrm{E_q} \cdot \hat{\mathrm{q}}} \;; \quad \mathrm{L_{Critical}} \propto \sqrt{\frac{\mathrm{E_q}}{\hat{\mathrm{q}}}}$$

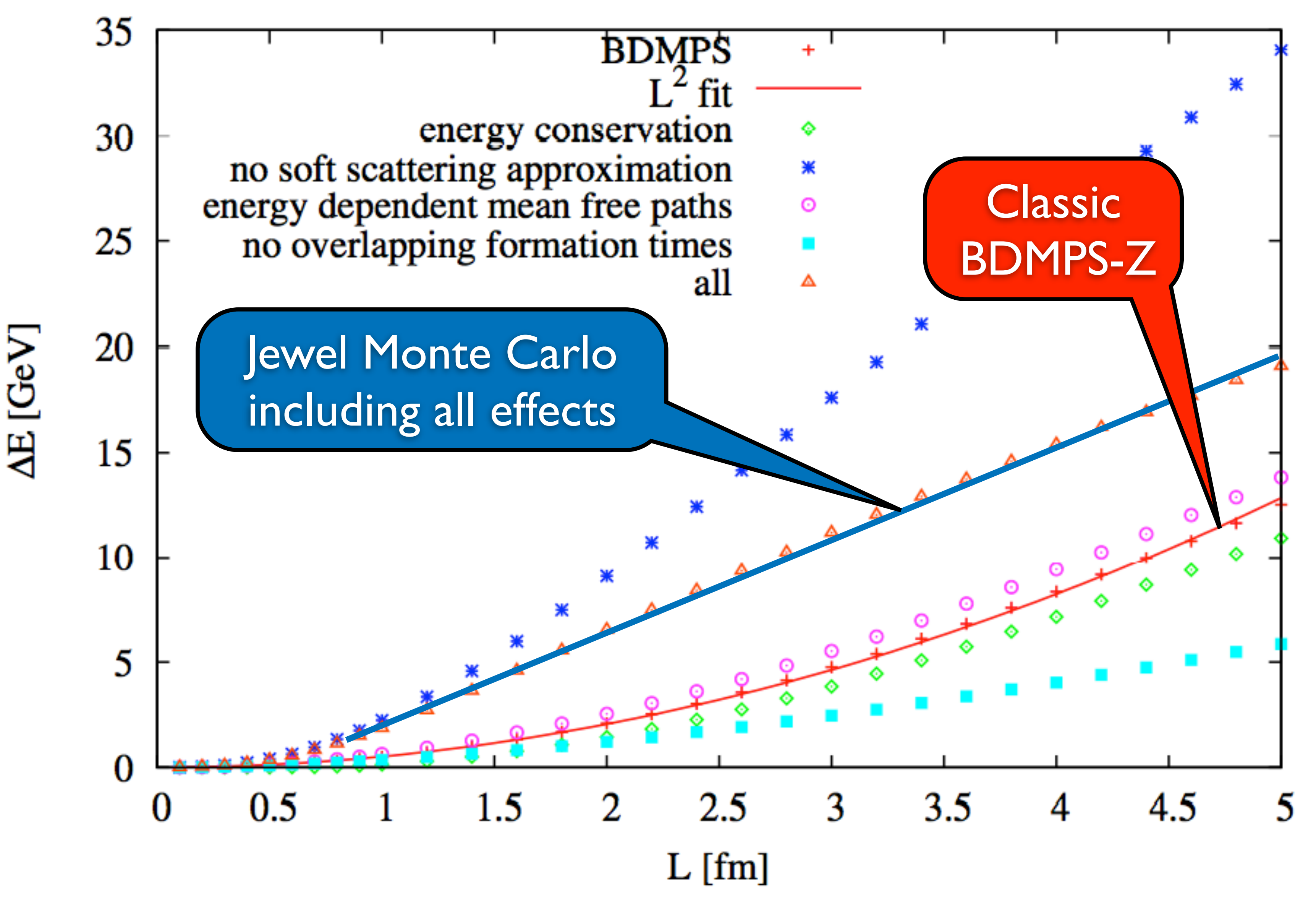
$$\mathrm{E_q} \approx \nu \approx \text{ few GeV}, \ \hat{\mathrm{q}} \approx 0.02 - 0.1 \ \mathrm{GeV^2/fm},$$

$$\longrightarrow \quad \sqrt{\frac{\mathrm{E_q}}{\hat{\mathrm{q}}}} \approx \mathrm{R_{lead}} - \mathrm{R_{carbon}}$$

Connection to p_T broadening observable:

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

Energy loss in *hot dense matter*



Jewel Monte Carlo including all effects

Classic BDMPS-Z

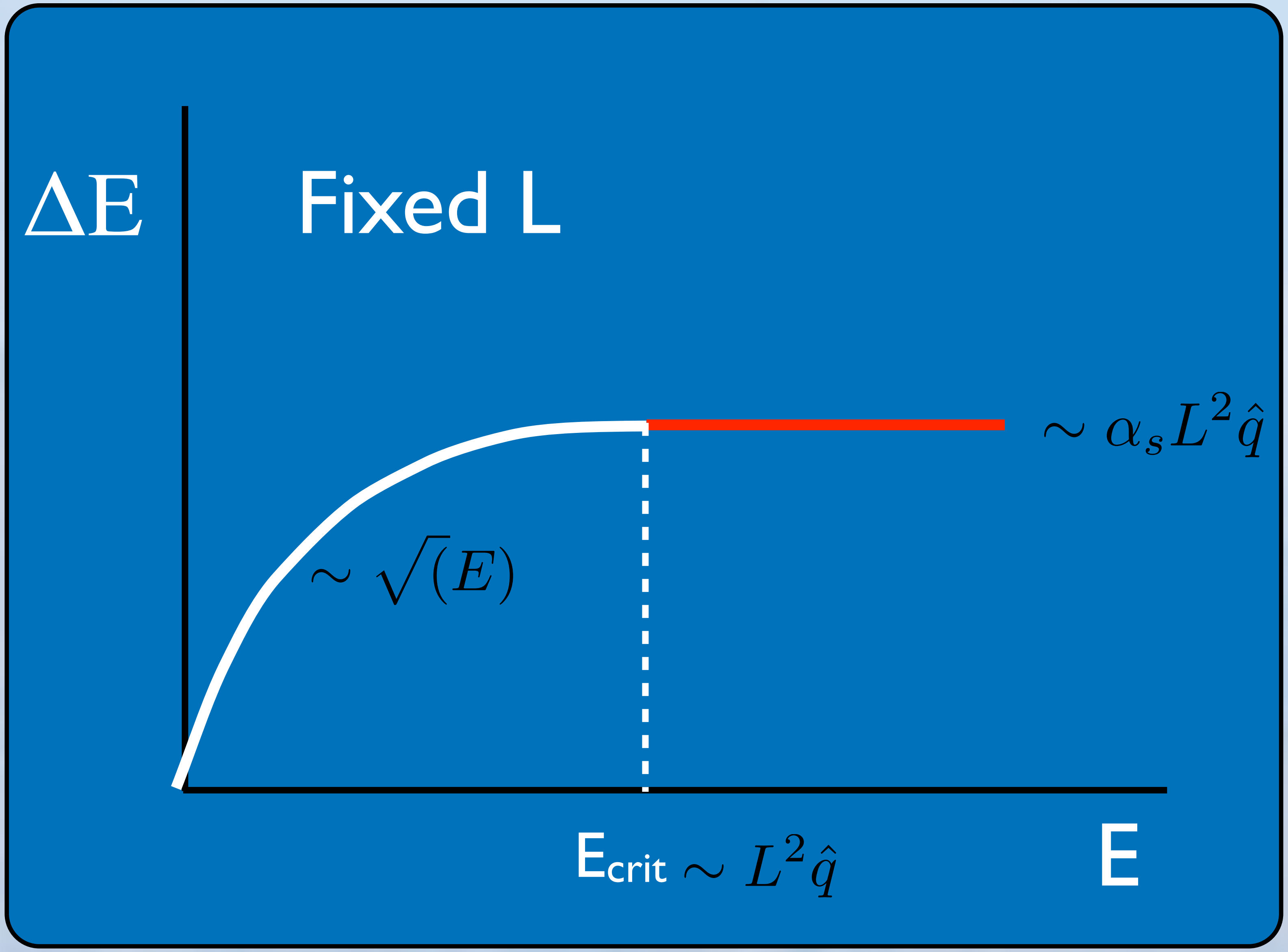
Zapp and Wiedemann find L^2 behavior washed out in realistic Monte Carlo calculation for hot dense matter

also, find more energy loss

arXiv:1202.1192v1 [hep-ph]

arXiv:1311.0048v1 [hep-ph]

Partonic energy loss in pQCD: E_{crit}



BDMPS-Z:

For *fixed* medium length *L* there is a critical energy E_{crit}

$L > L_{crit}$ is equivalent to $E < E_{crit}$

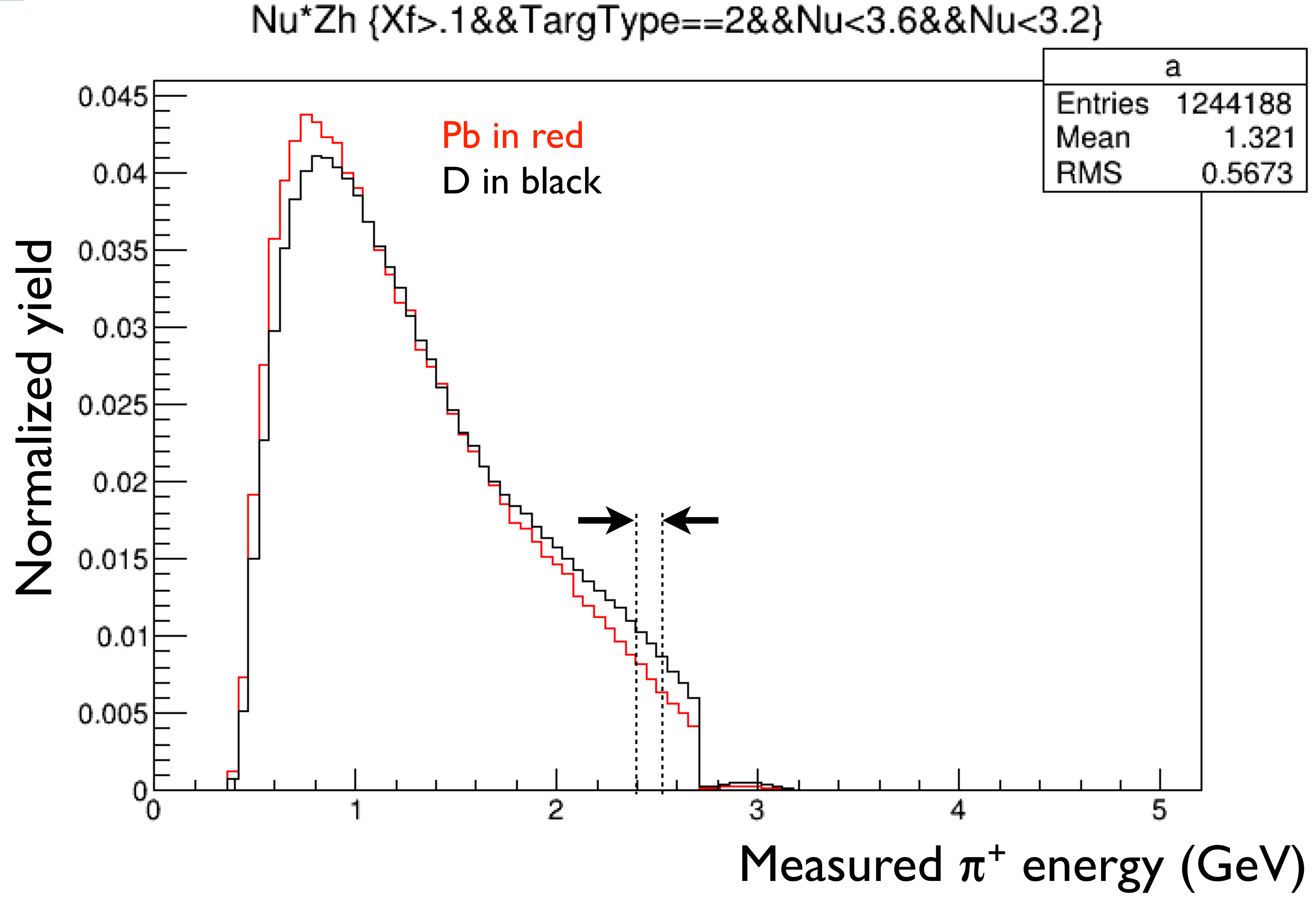
$$E_{crit} \approx 0.4 \cdot (\frac{L}{1\ fm})^2 \quad GeV$$

$$\Delta E \approx \alpha_s L \sqrt{E \hat{q}} \qquad (E << E_{cr})$$

$$\Delta E \approx \alpha_s L^2 \hat{q} \qquad (E >> E_{cr})$$

Carbon: $E_{crit} = \nu =$ 2.5 GeV
Lead: $E_{crit} = \nu =$ 17 GeV
CLAS data in transition region!
CLAS12 will study this

Direct measurement of ΔE?



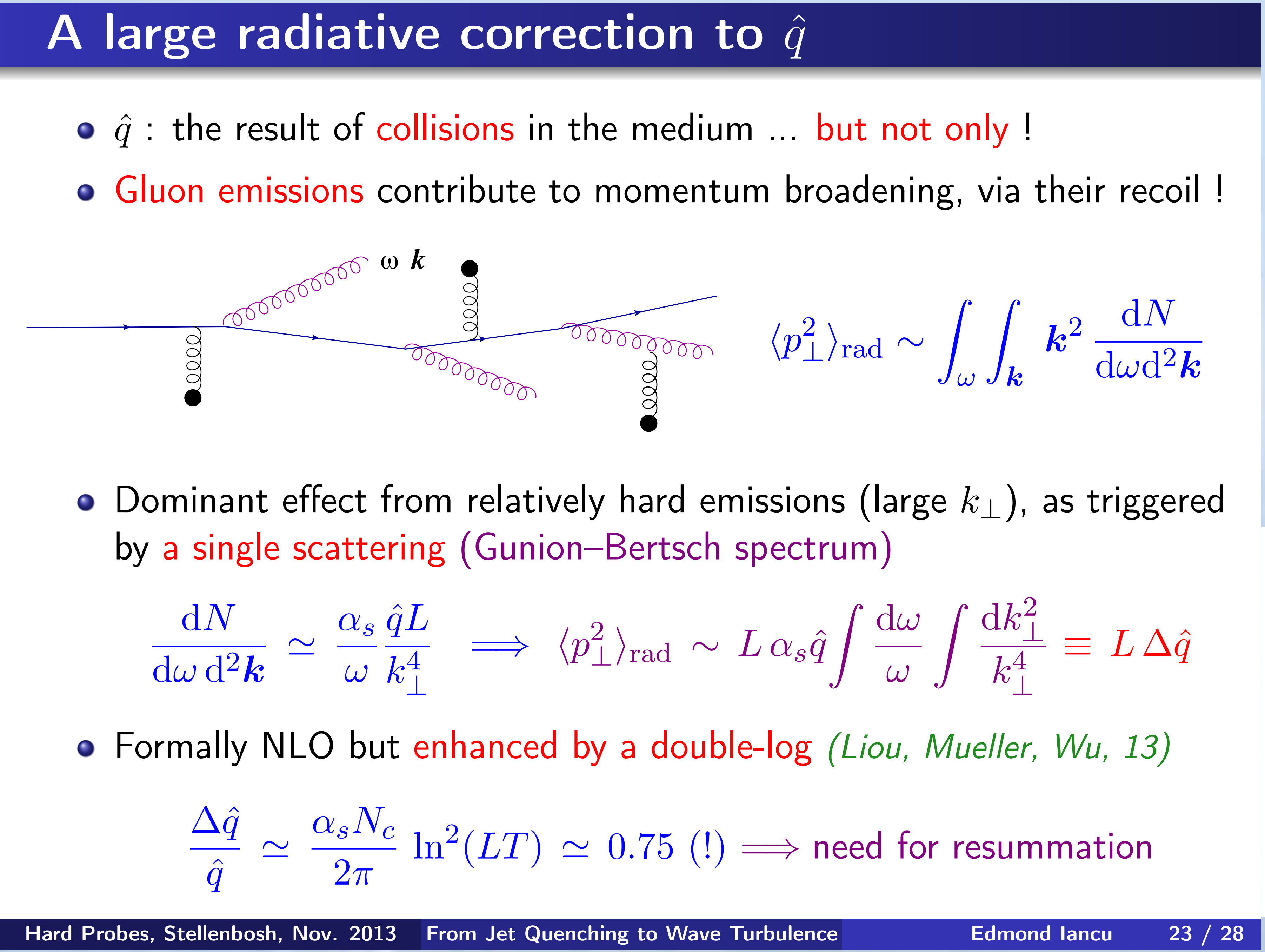
Exploring whether pion energy spectrum shift can be interpreted as direct measurement of ΔE

Feynman x requirement

Modeling of hadronic cascade

- Still in early stages, but ~150 MeV for Pb; consistent
- If correct, can study extensively at 12 GeV - may grow to 0.5-1 GeV shift, easily measured

Energy loss induces *additional* p_T broadening



A large radiative correction to $\hat{q}$

- $\hat{q}$: the result of collisions in the medium ... but not only !
- Gluon emissions contribute to momentum broadening, via their recoil !

$$\langle p_\perp^2 \rangle_{\rm rad} \sim \int_\omega \int_{\boldsymbol{k}} \boldsymbol{k}^2 \frac{{\rm d}N}{{\rm d}\omega {\rm d}^2\boldsymbol{k}}$$

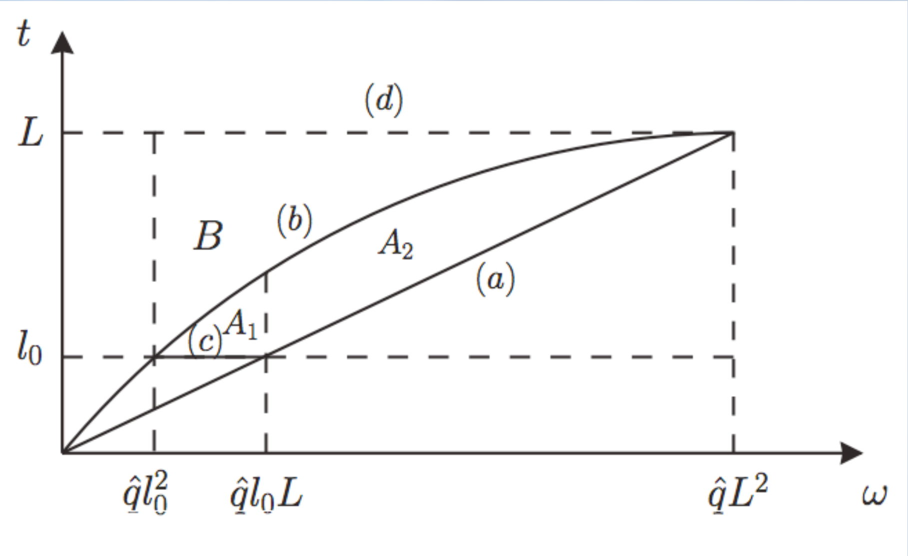
- Dominant effect from relatively hard emissions (large $k_\perp$), as triggered by a single scattering (Gunion–Bertsch spectrum)

$$\frac{{\rm d}N}{{\rm d}\omega\, {\rm d}^2\boldsymbol{k}} \simeq \frac{\alpha_s}{\omega} \frac{\hat{q}L}{k_\perp^4} \Longrightarrow \langle p_\perp^2 \rangle_{\rm rad} \sim L\, \alpha_s \hat{q} \int \frac{{\rm d}\omega}{\omega} \int \frac{{\rm d}k_\perp^2}{k_\perp^4} \equiv L\, \Delta\hat{q}$$

- Formally NLO but enhanced by a double-log *(Liou, Mueller, Wu, 13)*

$$\frac{\Delta\hat{q}}{\hat{q}} \simeq \frac{\alpha_s N_c}{2\pi} \ln^2(LT) \simeq 0.75\ (!) \Longrightarrow \text{need for resummation}$$

Hard Probes, Stellenbosh, Nov. 2013 From Jet Quenching to Wave Turbulence Edmond Iancu 23 / 28



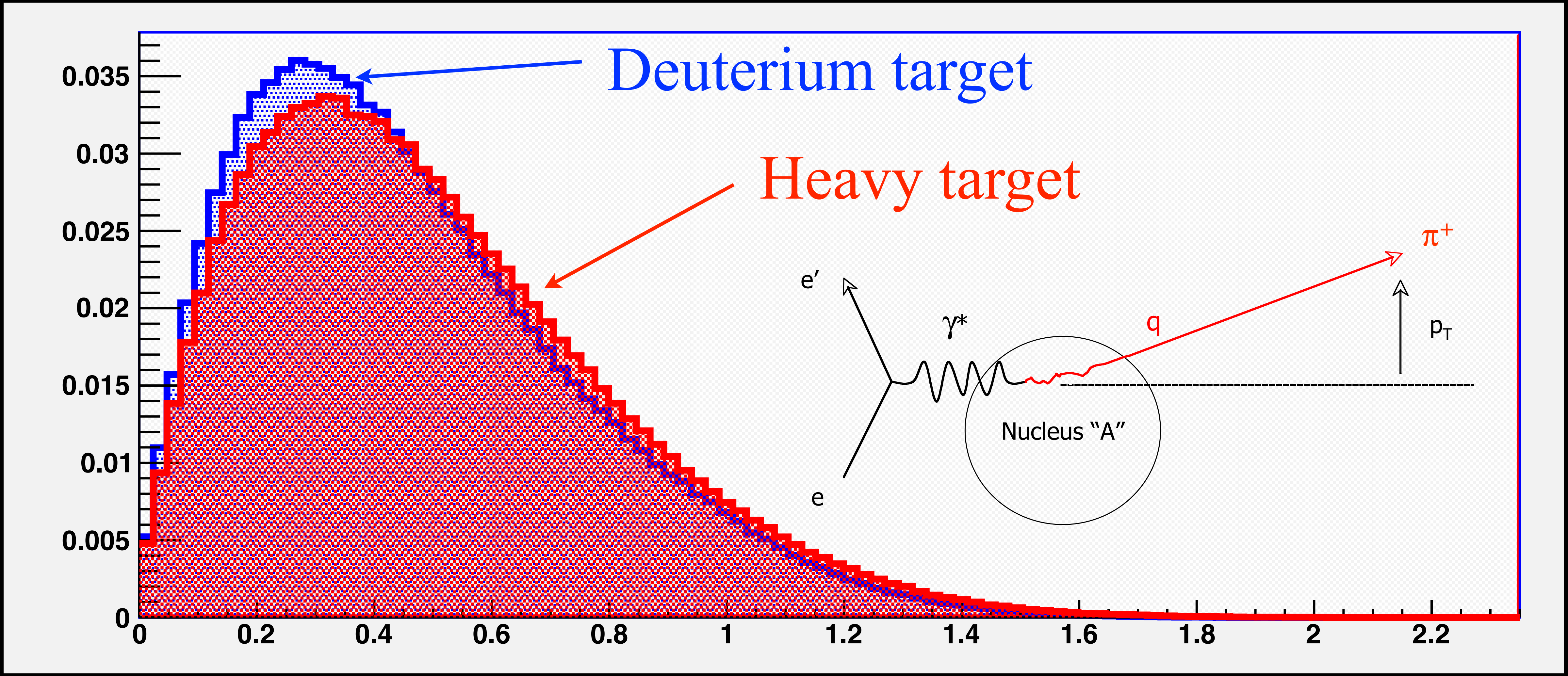
$$\langle p_\perp^2 \rangle = \frac{\alpha_s N_c}{4\pi} \hat{q} L \ln^2 \left(\frac{L}{l_0} \right)^2.$$

Double log enhancement: ~**doubles** the amount of broadening seen, both hot and cold matter. Effect may be visible in CLAS data, see later slides

Tseh Liou, A.H. Mueller, Bin Wu, http://arxiv.org/abs/1304.7677

Observables: Transverse Momentum Broadening

$$\Delta \mathrm{p}_{\mathrm{T}}^2 \equiv \langle \mathrm{p}_{\mathrm{T}}^2 \rangle_{\mathrm{A}} - \langle \mathrm{p}_{\mathrm{T}}^2 \rangle_{\mathrm{D}}$$



No time to discuss other DIS observables: multi-hadron multiplicity ratios, photon-hadron correlations, Bose-Einstein correlations, centrality correlations, more....

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

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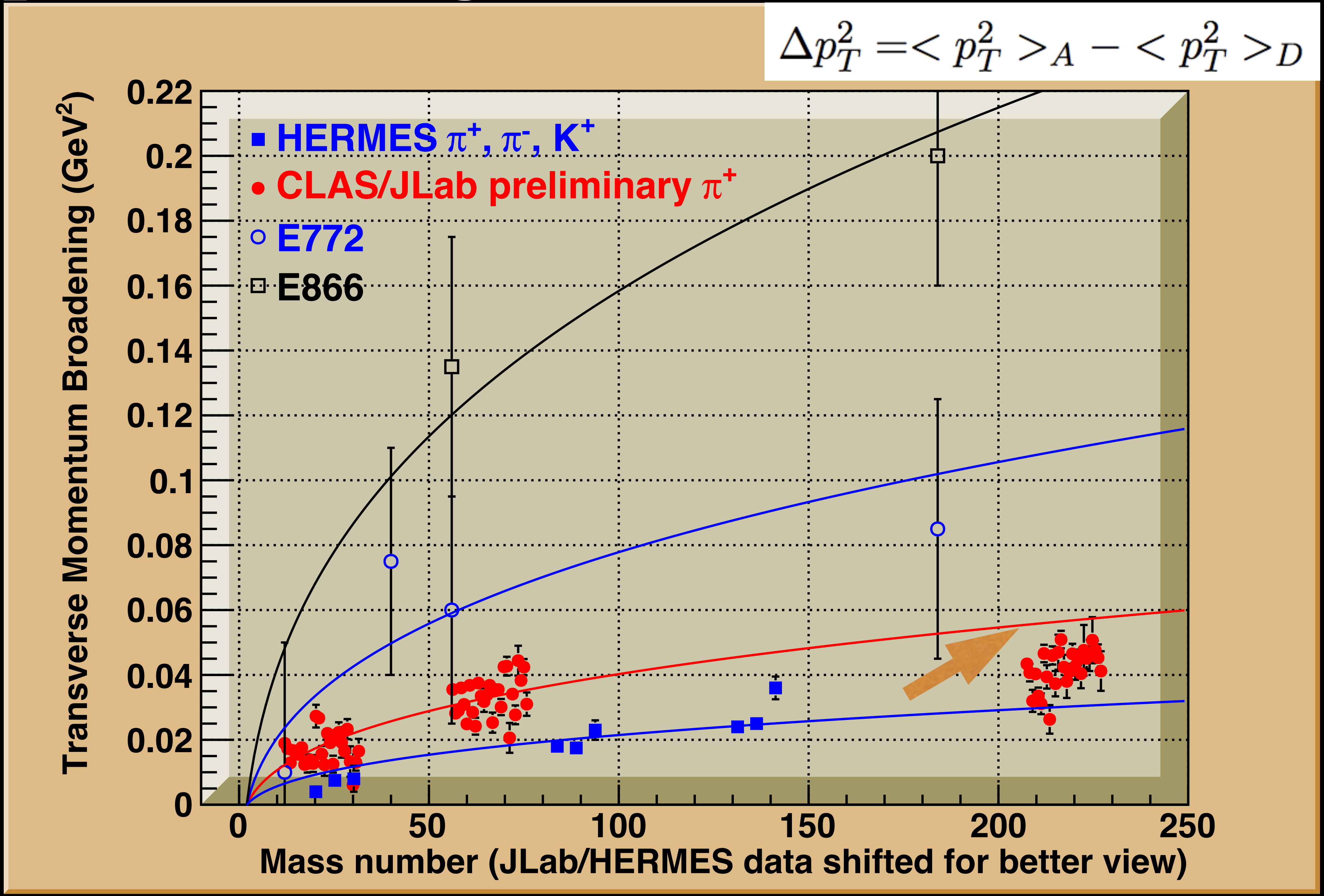
http://arxiv.org/abs/1001.4281

p_T broadening data - Drell-Yan and DIS



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

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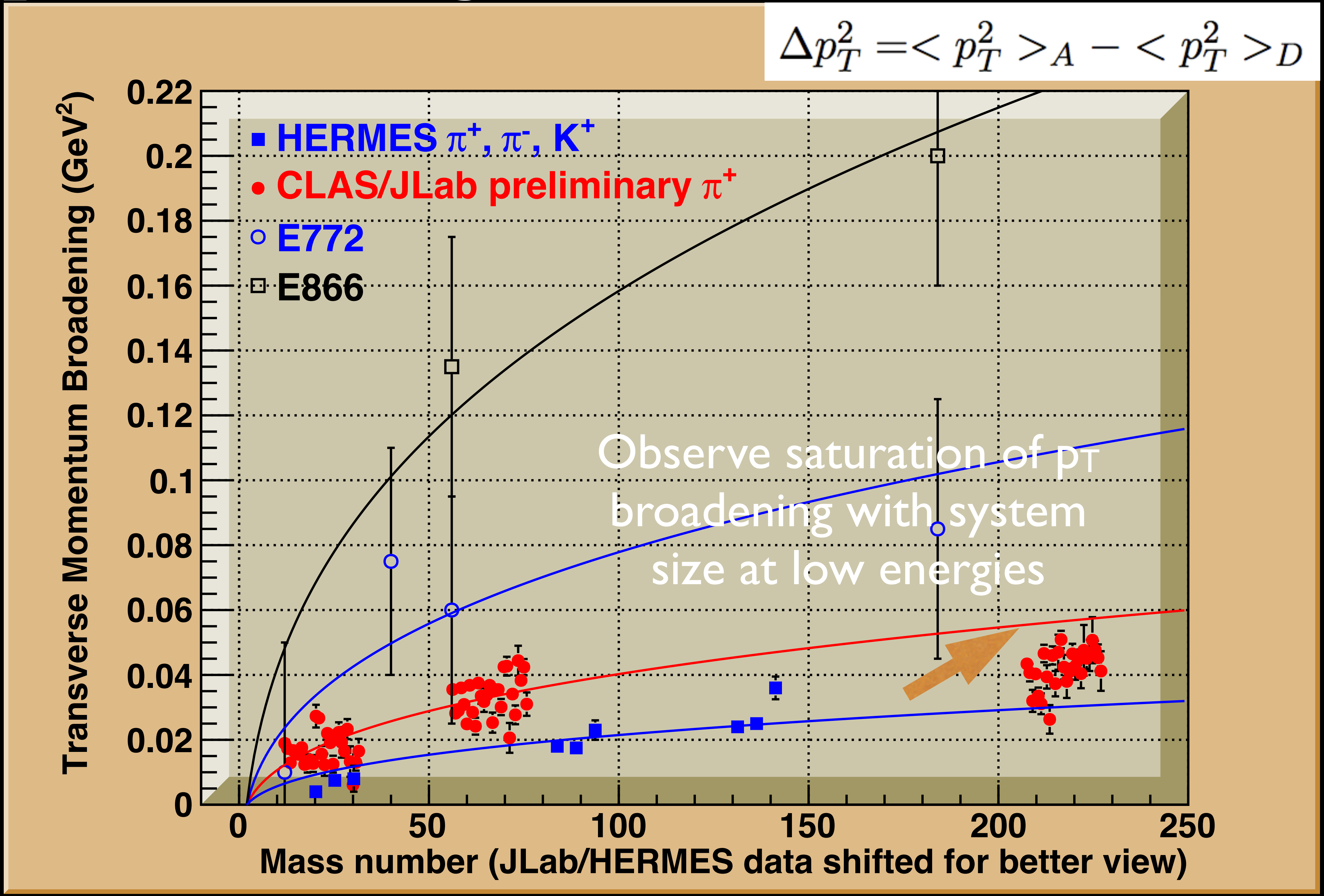

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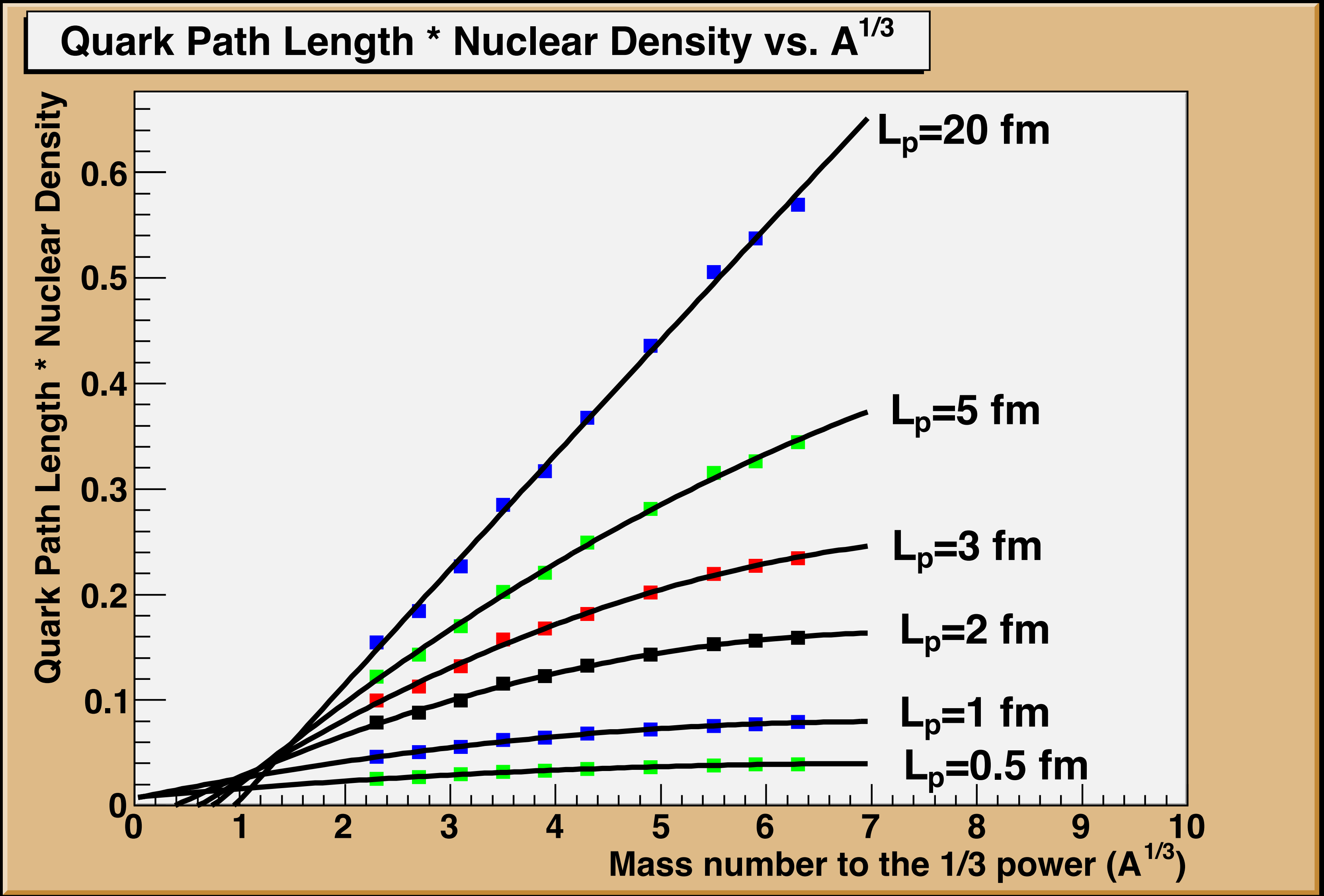
1) Assume saturation is due to shorter production length ℓ : then can *measure* ℓ



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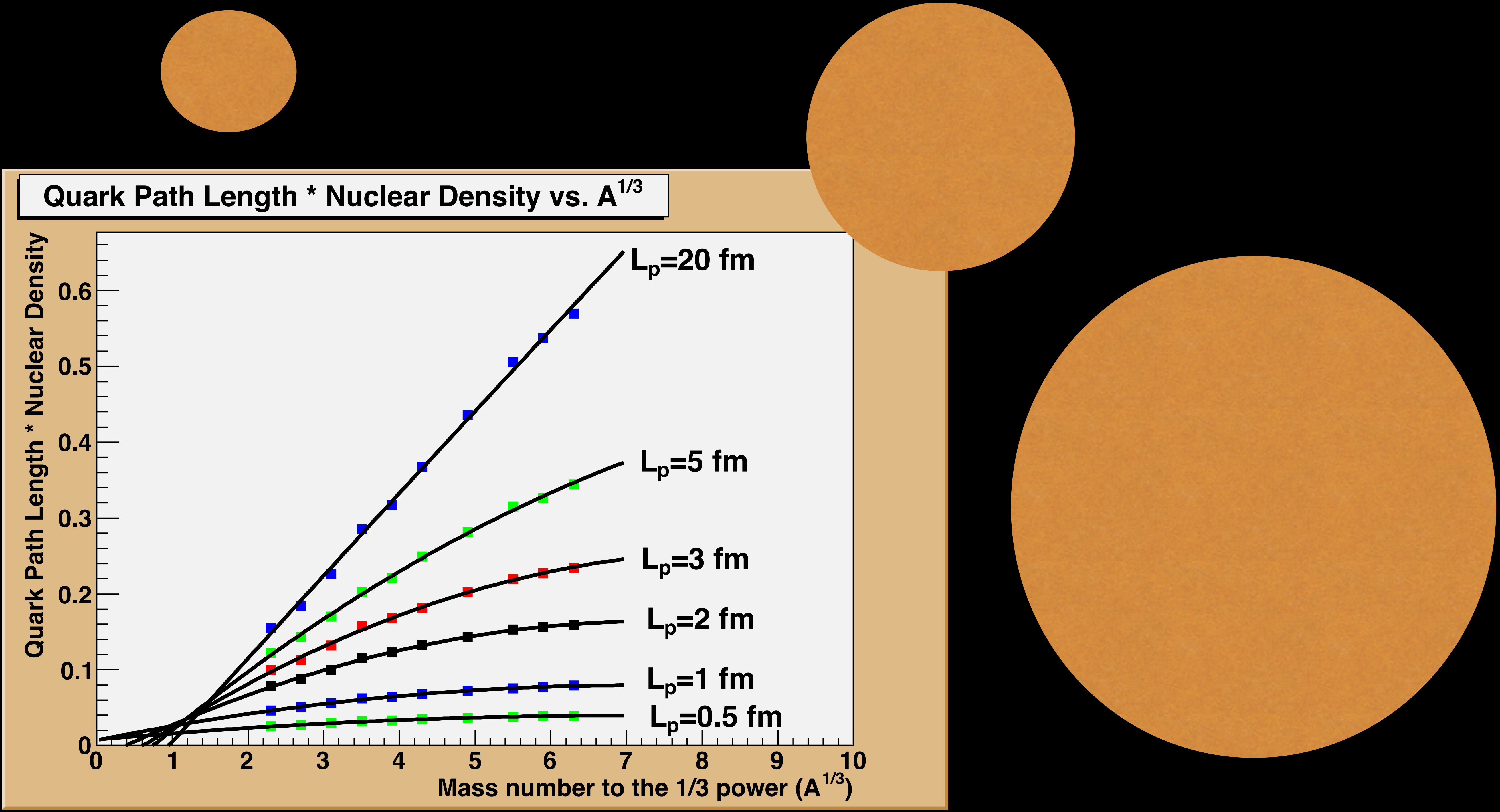

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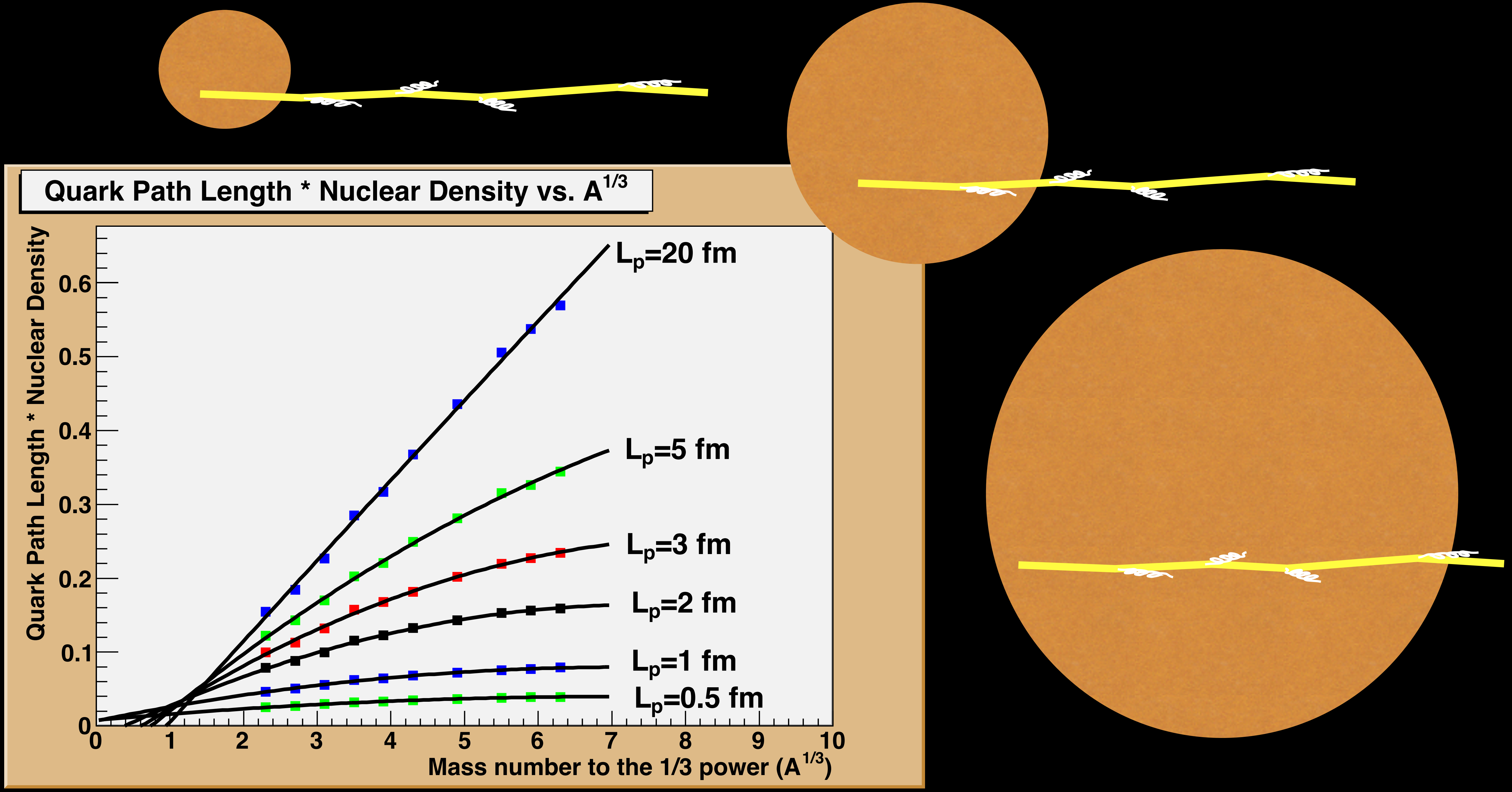

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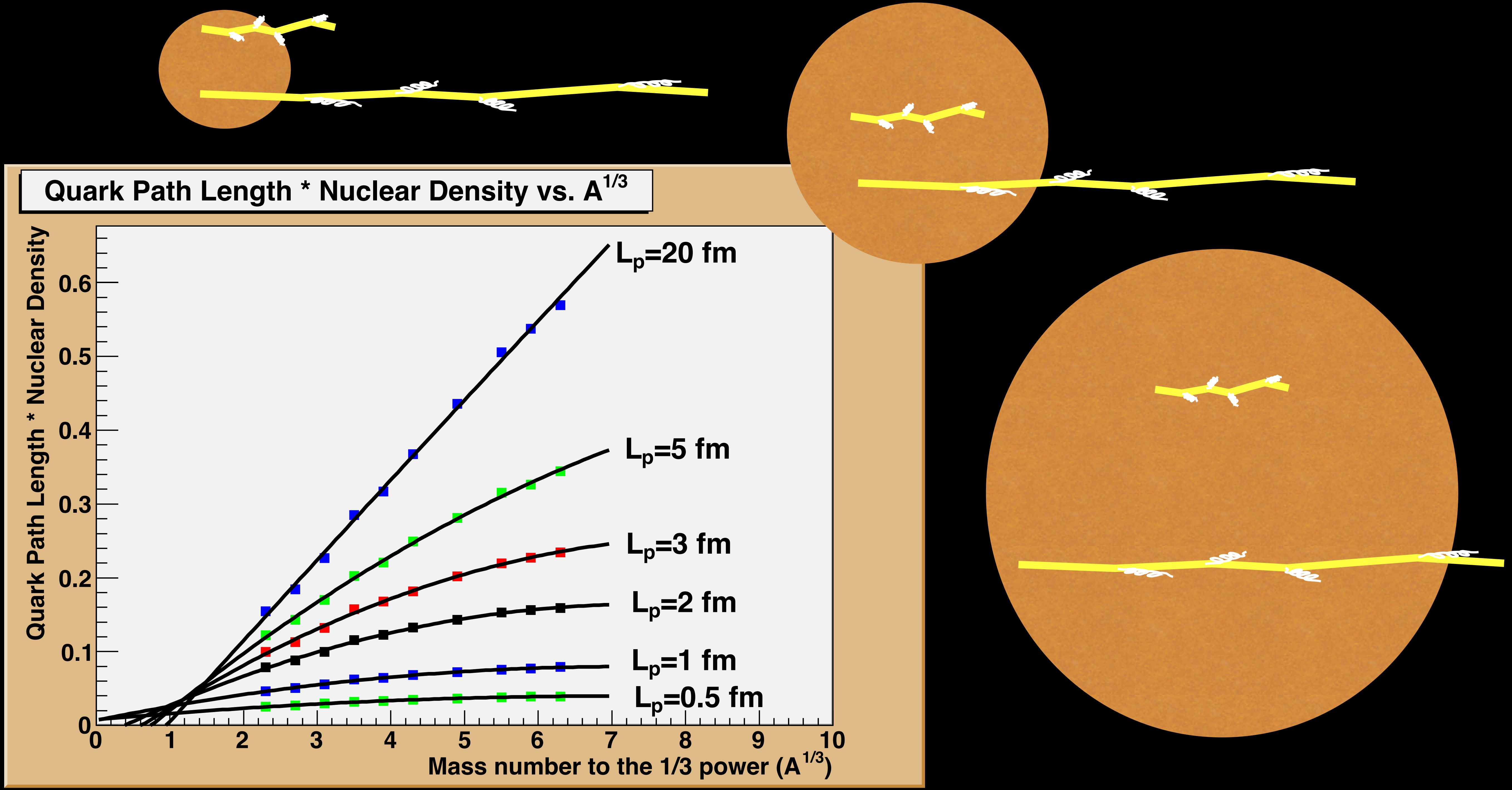

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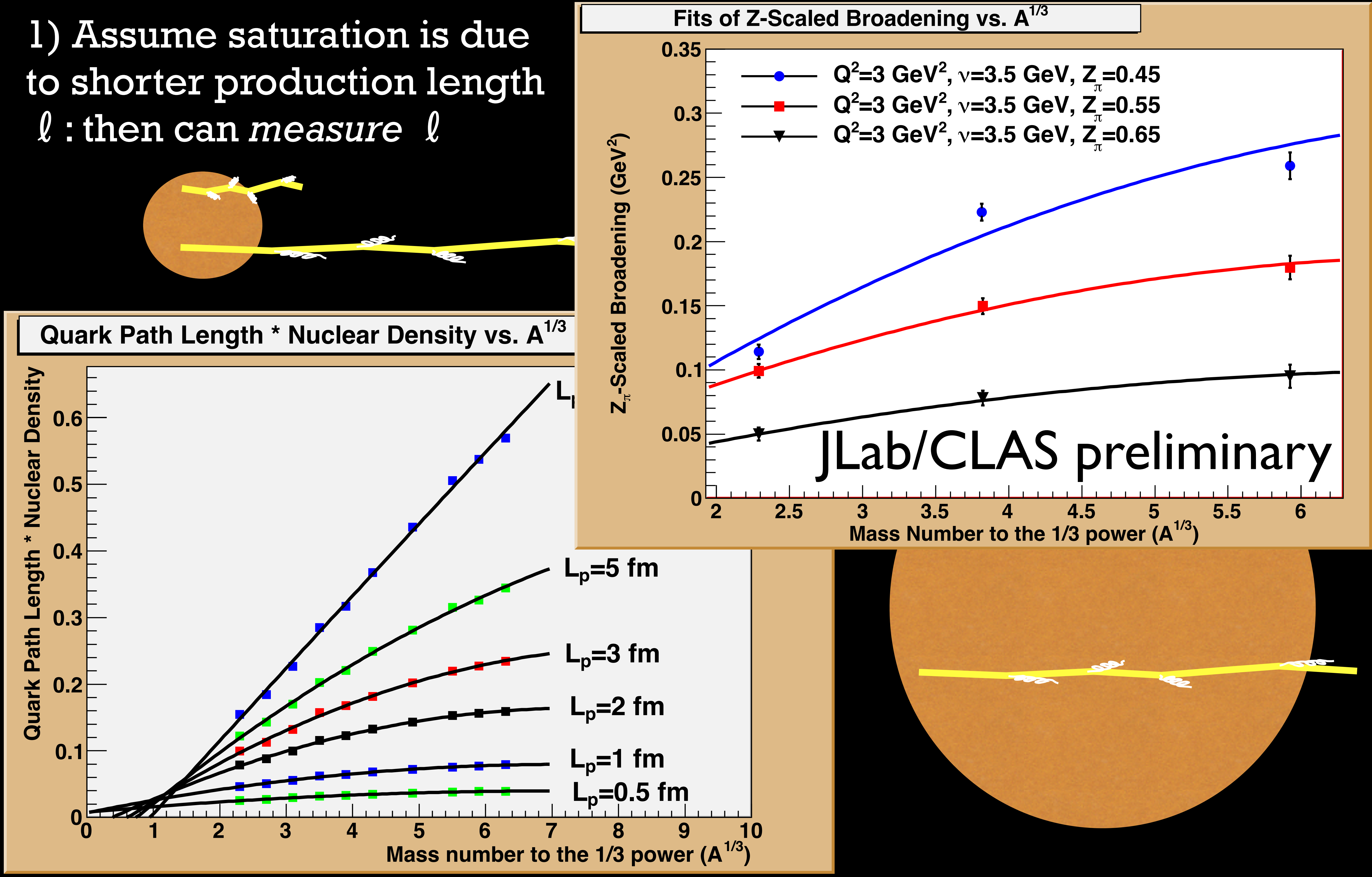
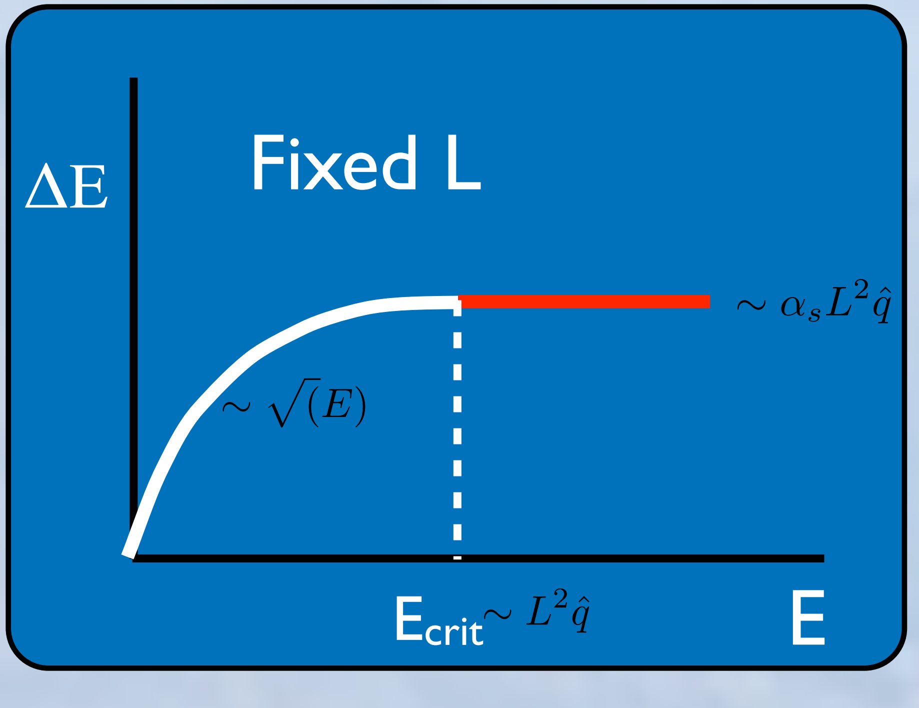


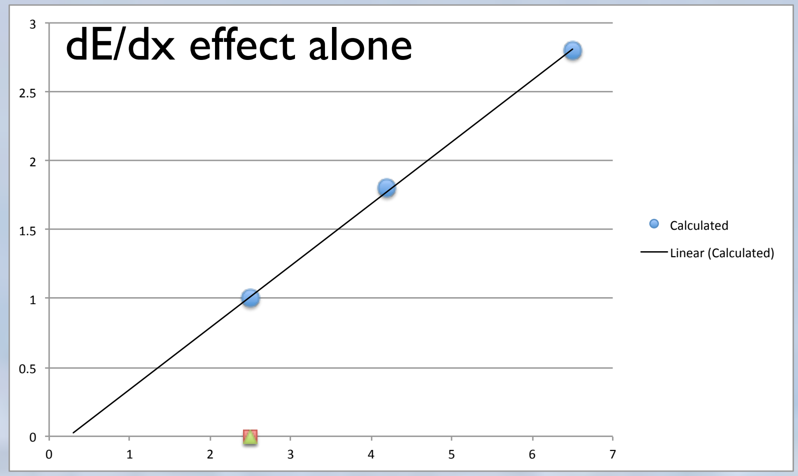
Quark dE/dx effects

2) Assume saturation is due to two effects: (a) dE/dx behavior *plus* (b) stimulation of additional broadening by gluon emission



	Carbon	Iron	Lead
E$_{crit}$ (GeV)	2.5	7.1	17
<ΔE> ratio to C	1	1.8	2.8

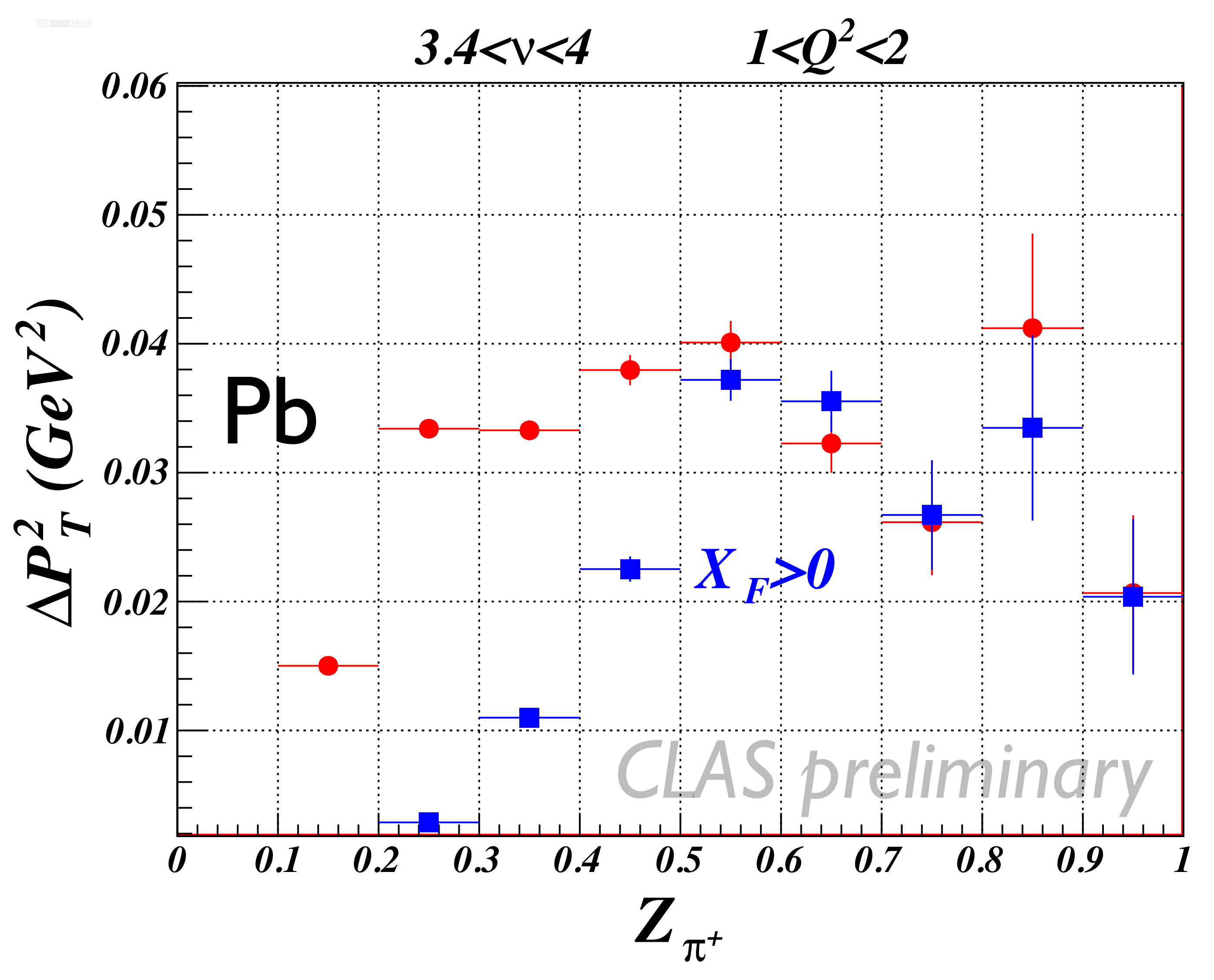
$$E_{crit} \approx 0.4 \cdot (\frac{L}{1\ fm})^2\ \ GeV$$

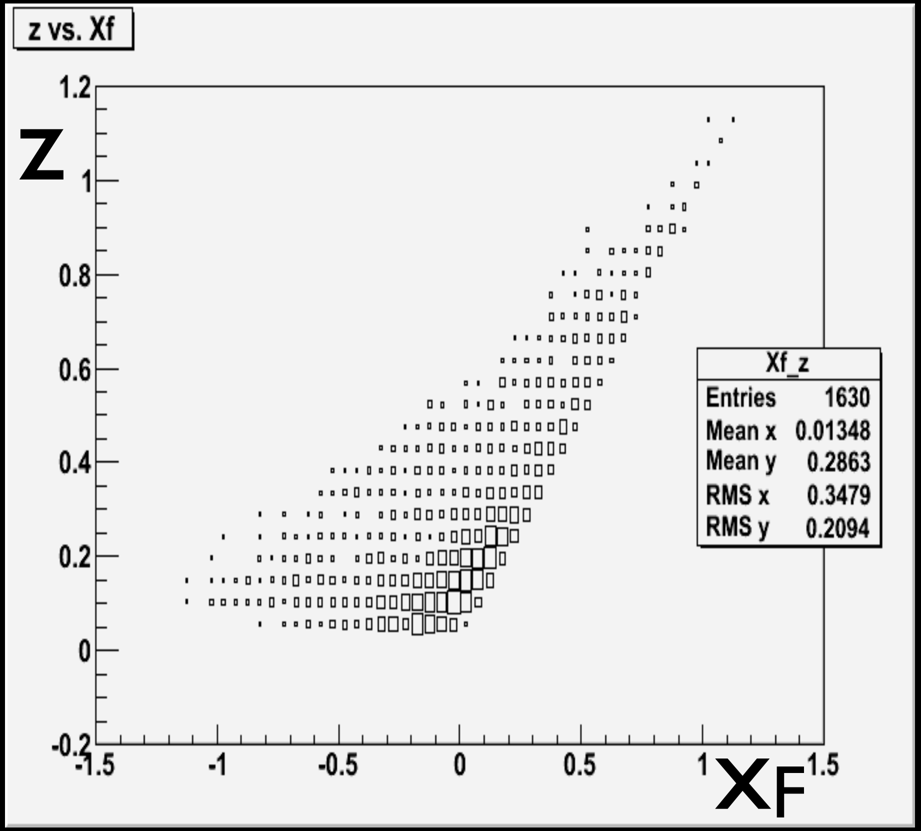


The two mechanisms (time dialation and dE/dx effects) should be separable with 12 GeV JLab

Small effect in the right direction visible from this toy calculation. Offset also moves in correct direction. Stimulation of additional broadening will amplify this effect.

Dependence of p_T broadening on Feynman x





- x_F and z_h are partially correlated

- Feynman x is the fraction ${}^{\pi}p_L/\max\{{}^{\pi}p_L\}$ in the γ*-N CM system
- Emphasizes current ($x_F>0$) vs. target ($x_F<0$) fragmentation
- First observation that *p_T broadening originates in both regimes*

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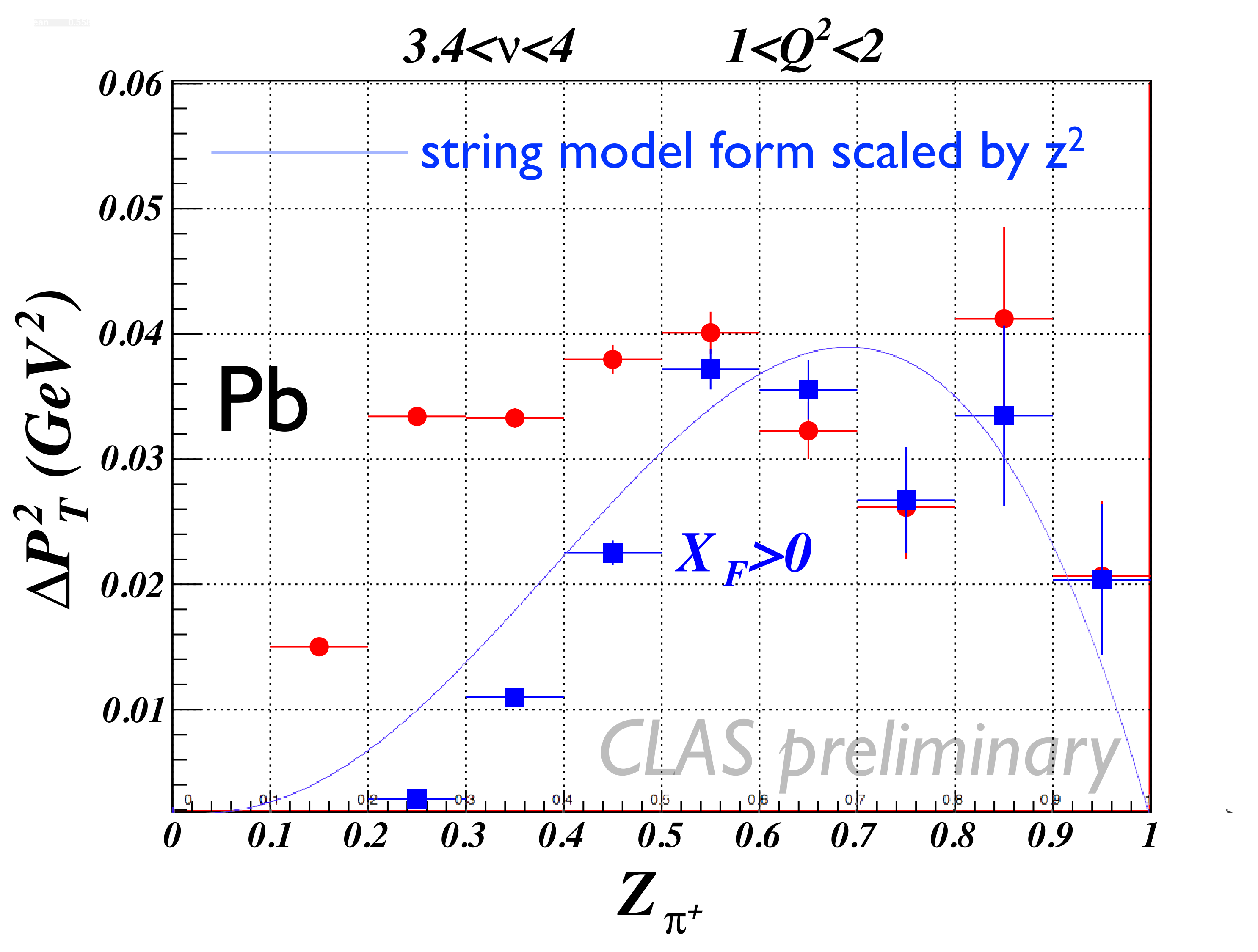

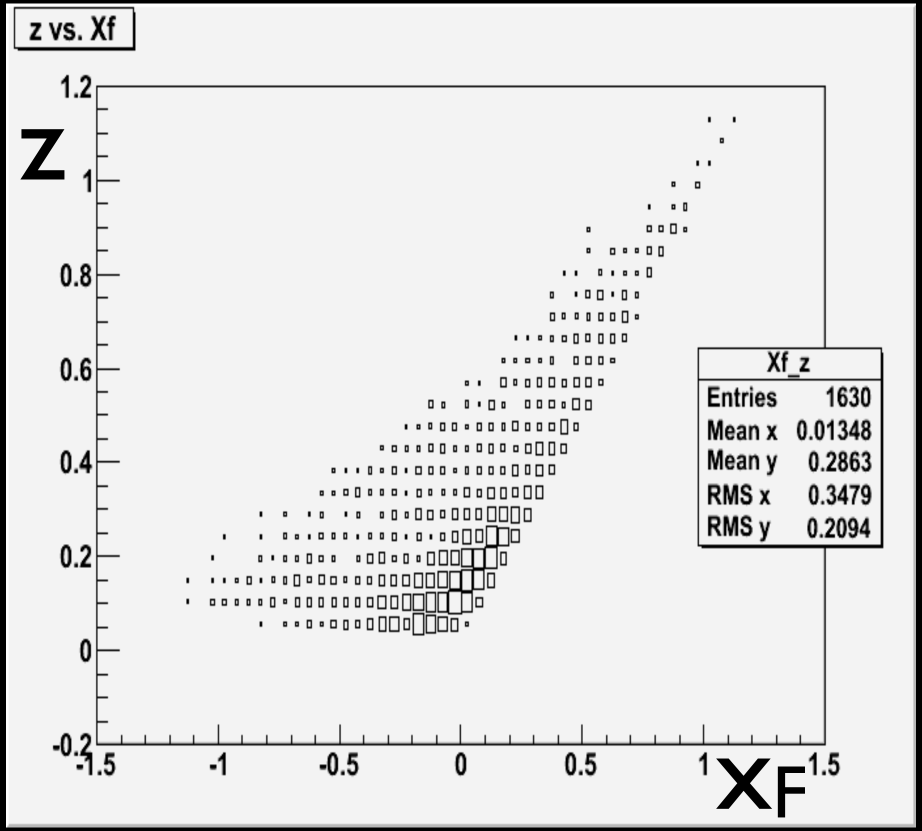

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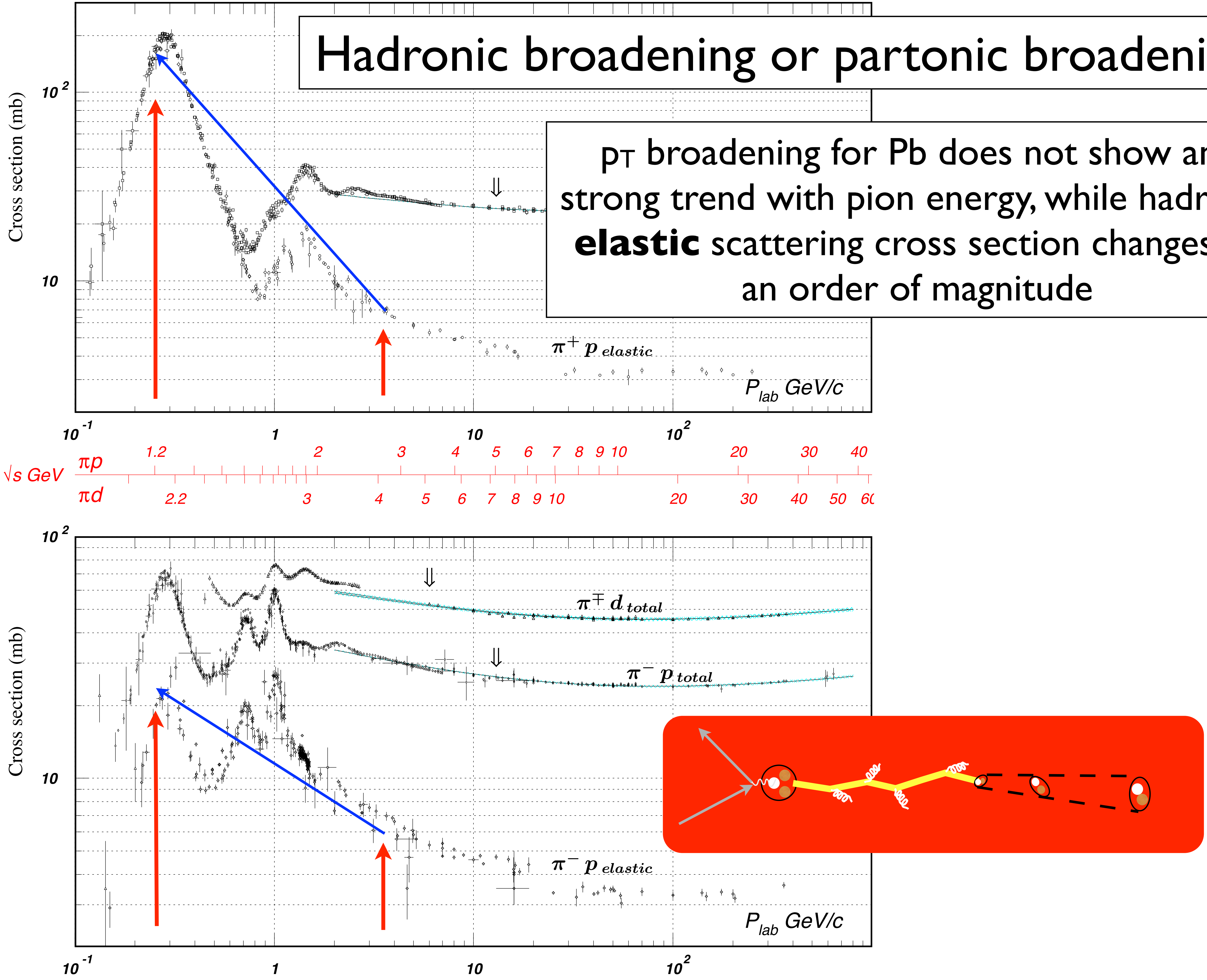
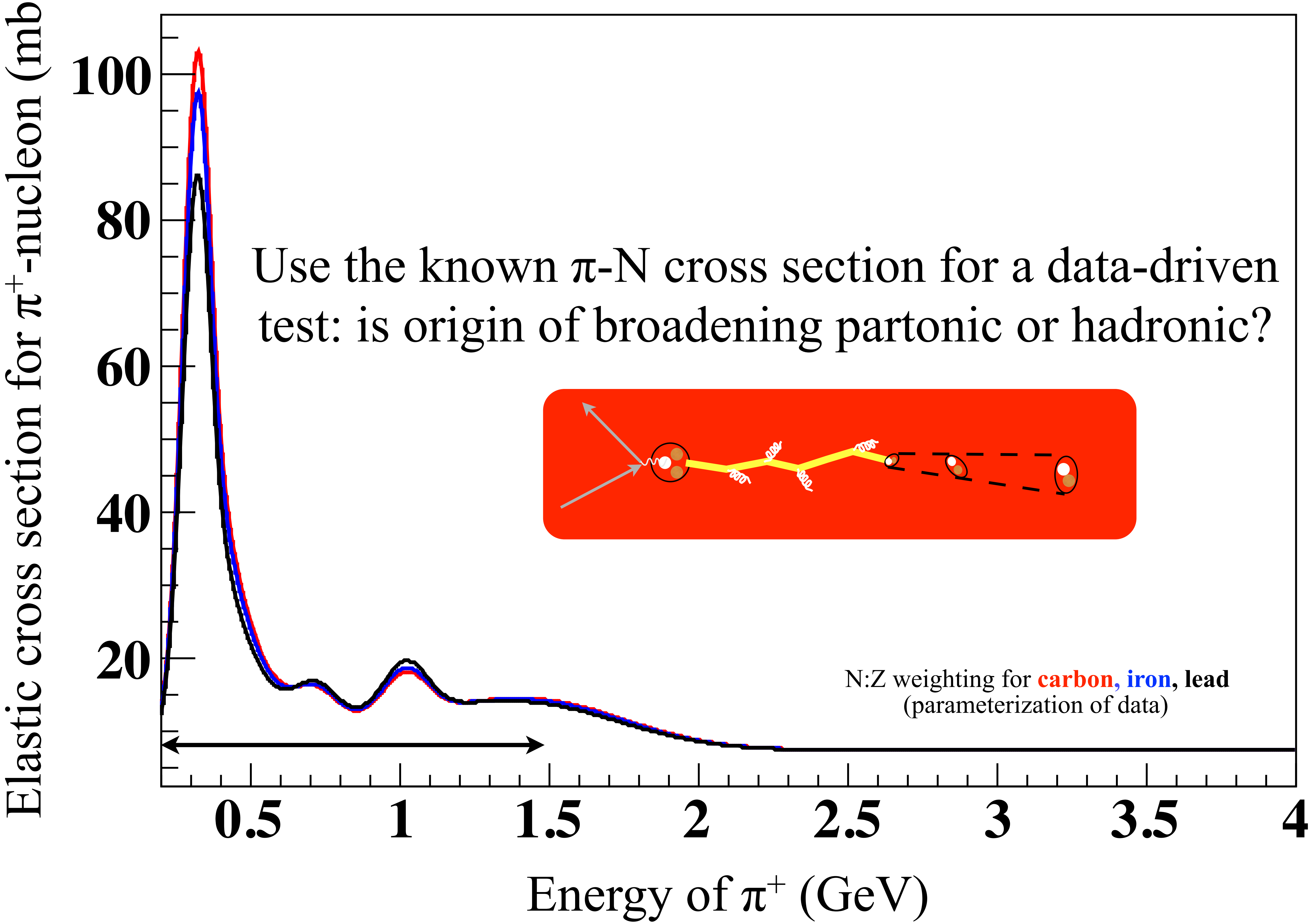
Hadronic broadening or partonic broadening?

p_T broadening for Pb does not show any strong trend with pion energy, while hadronic **elastic** scattering cross section changes by an order of magnitude

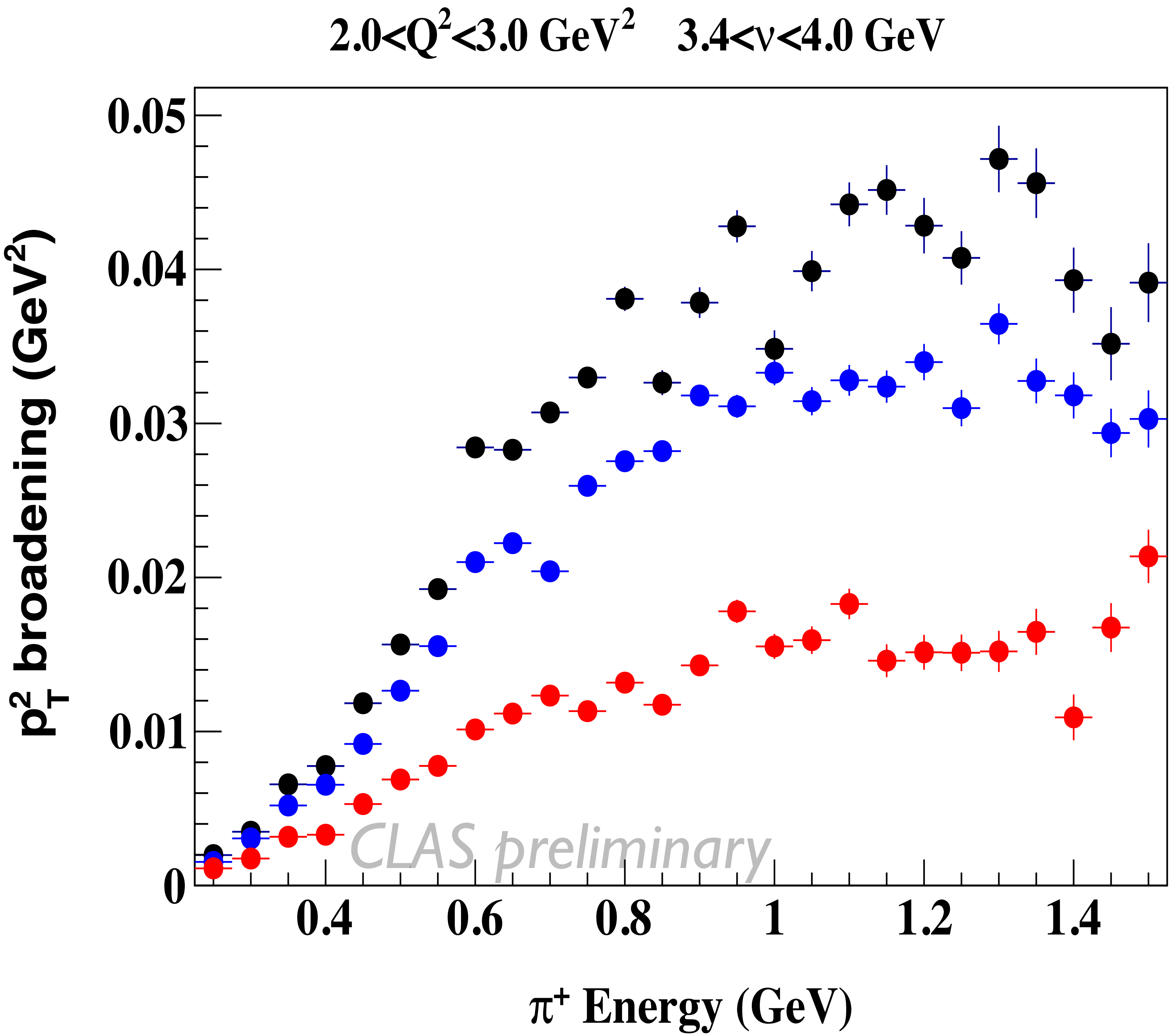


Elastic cross section for π^+-nucleon



Use the known π-N cross section for a data-driven test: is origin of broadening partonic or hadronic?

p_T^2 Broadening vs. Hadron Energy



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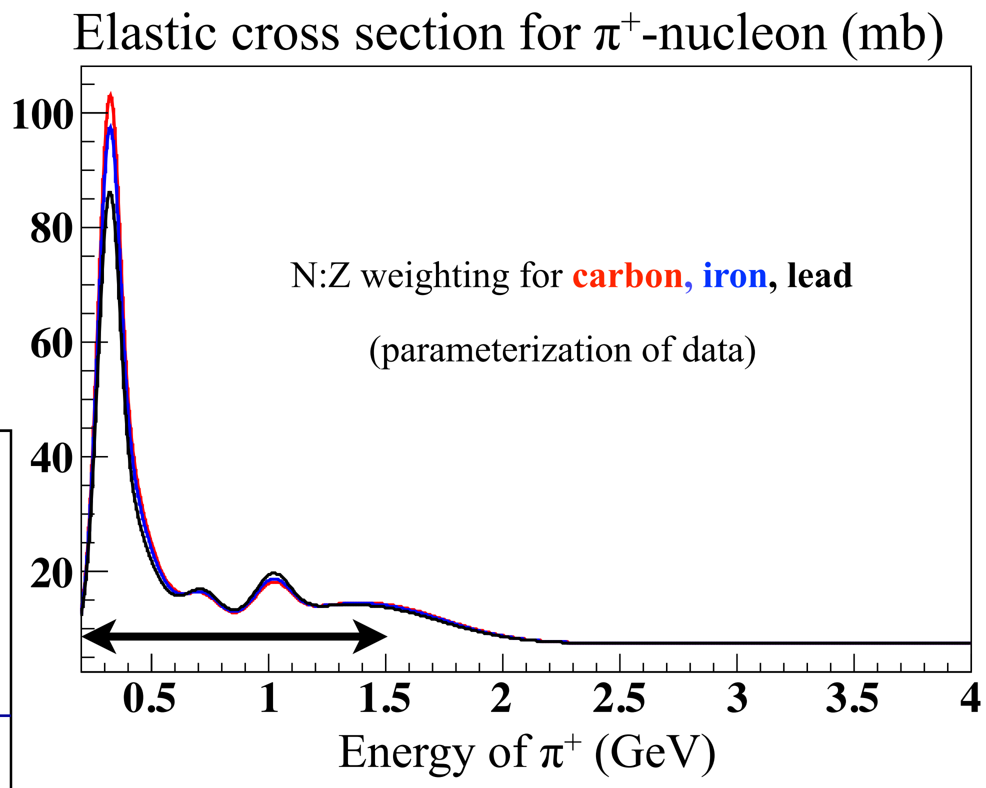
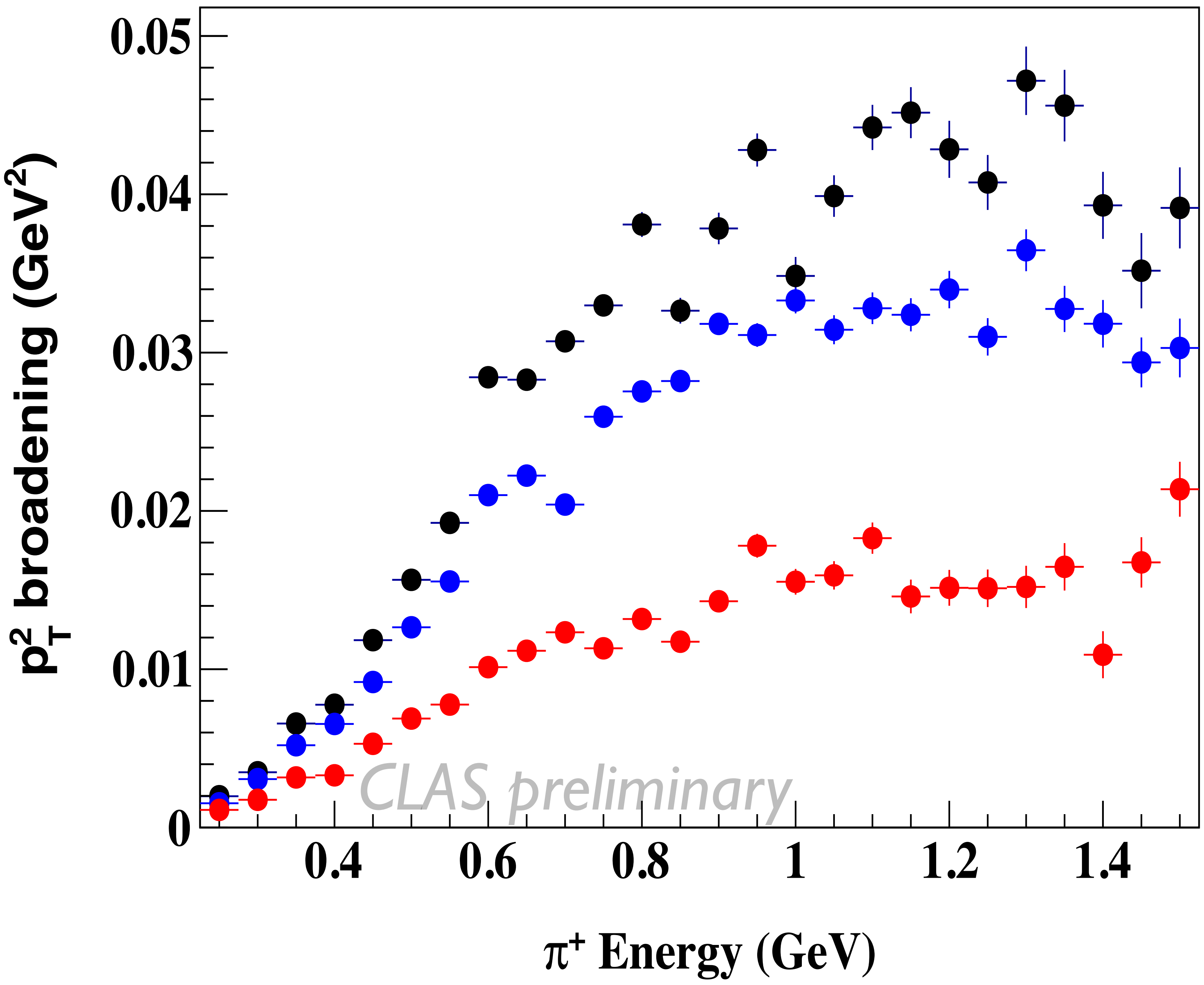


$2.0<Q^2<3.0$ GeV^2 $3.4<\nu<4.0$ GeV



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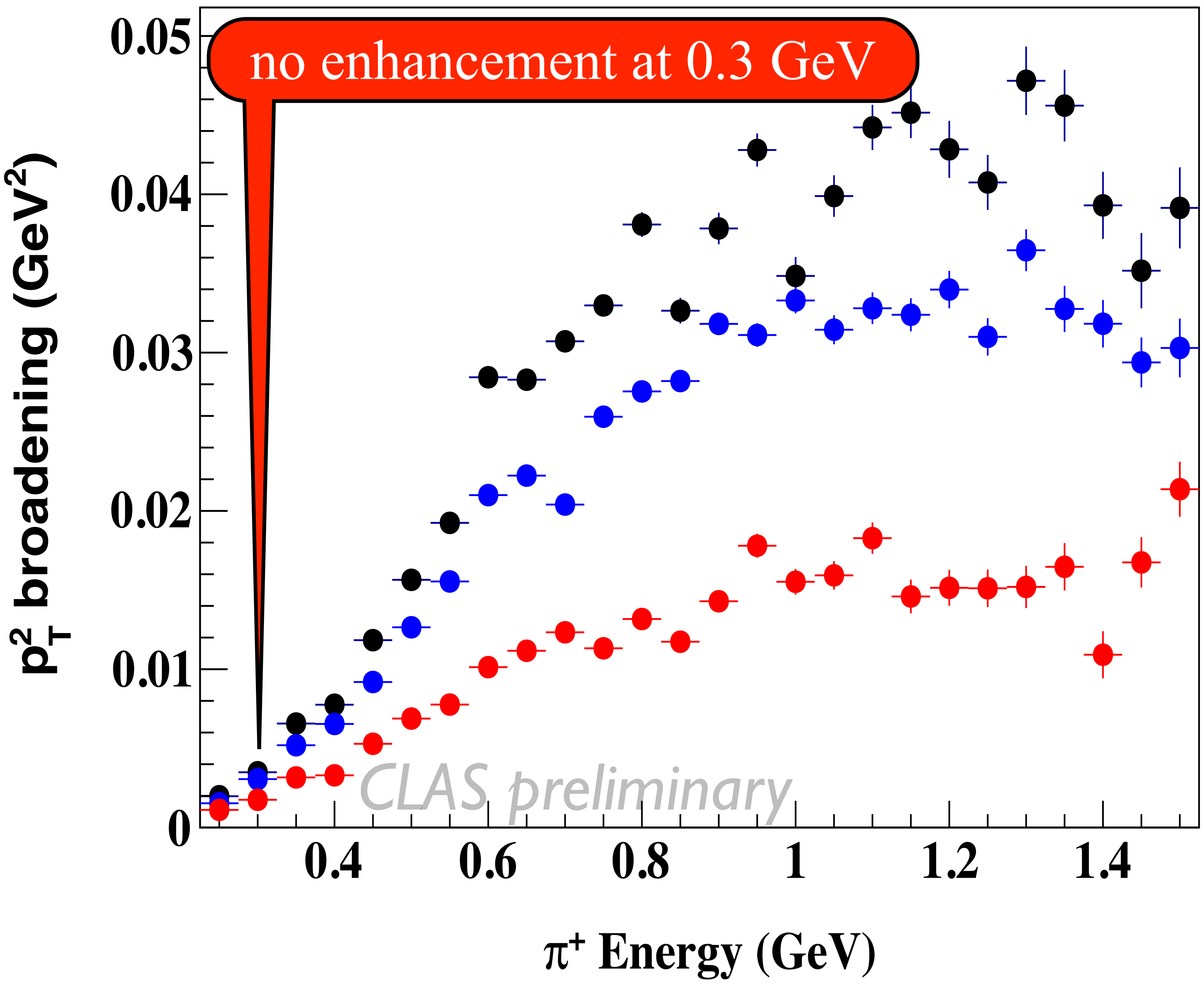
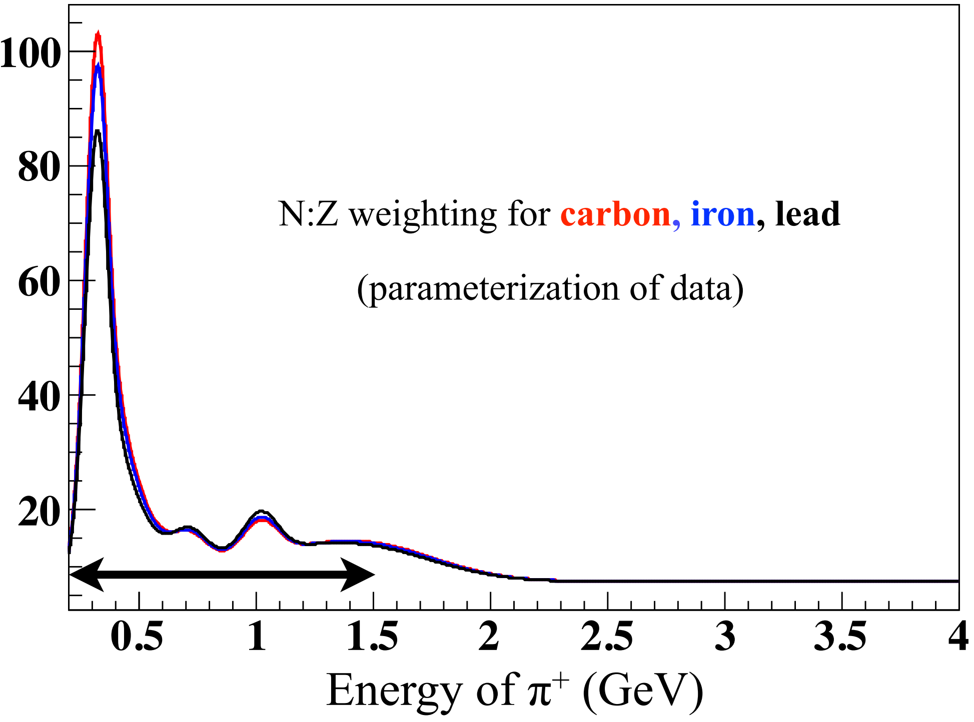
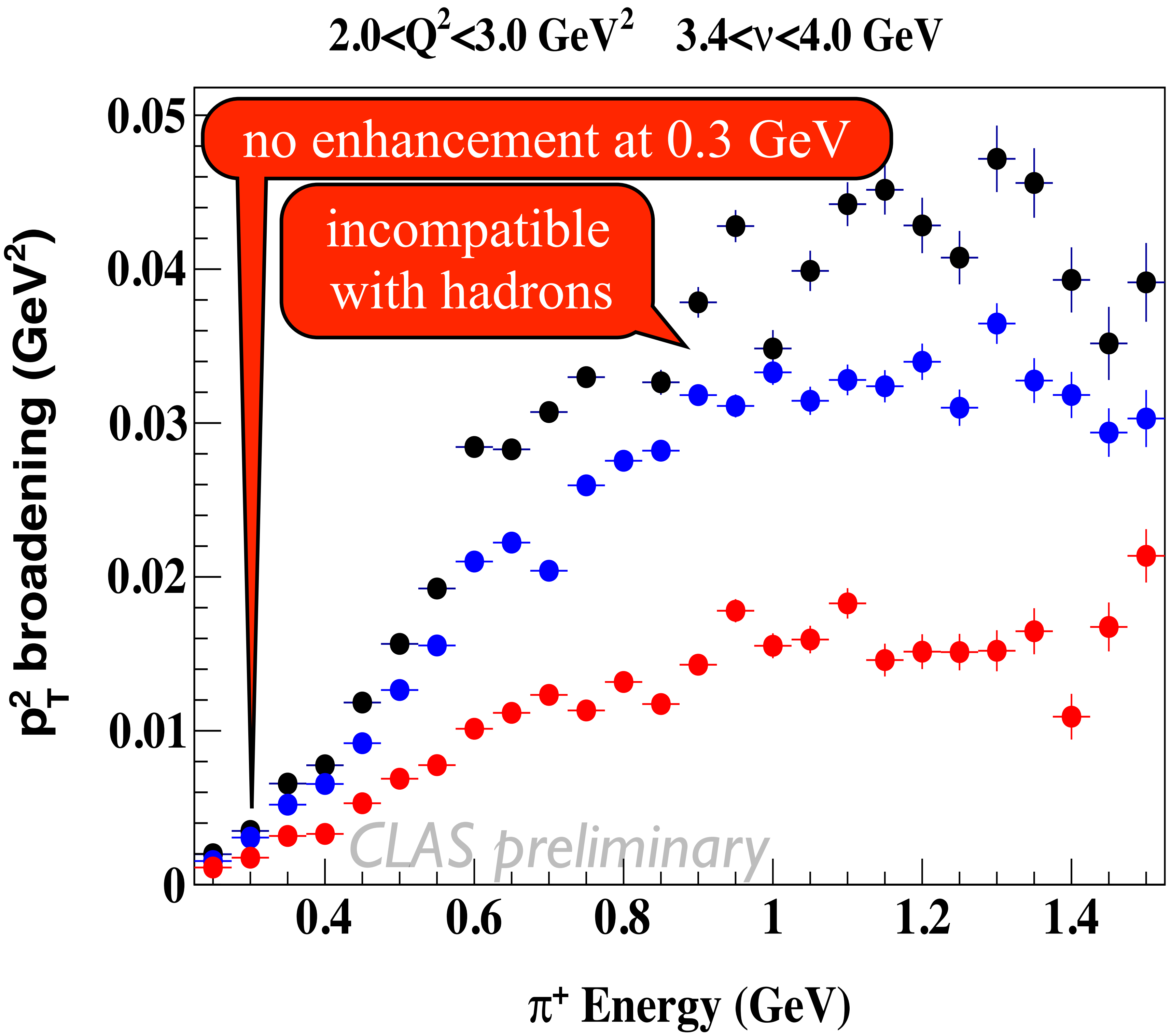

no enhancement at 0.3 GeV

Elastic cross section for π^+-nucleon (mb)


N:Z weighting for **carbon**, **iron**, **lead**

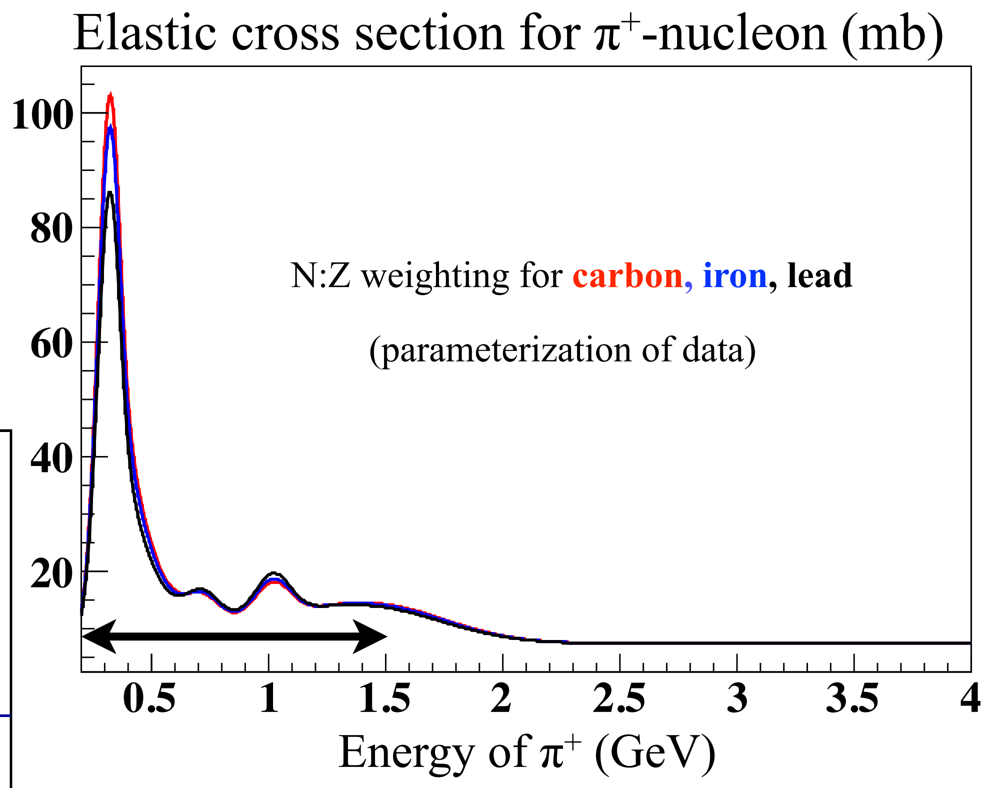
(parameterization of data)

p_T^2 Broadening vs. Hadron Energy



no enhancement at 0.3 GeV

incompatible with hadrons



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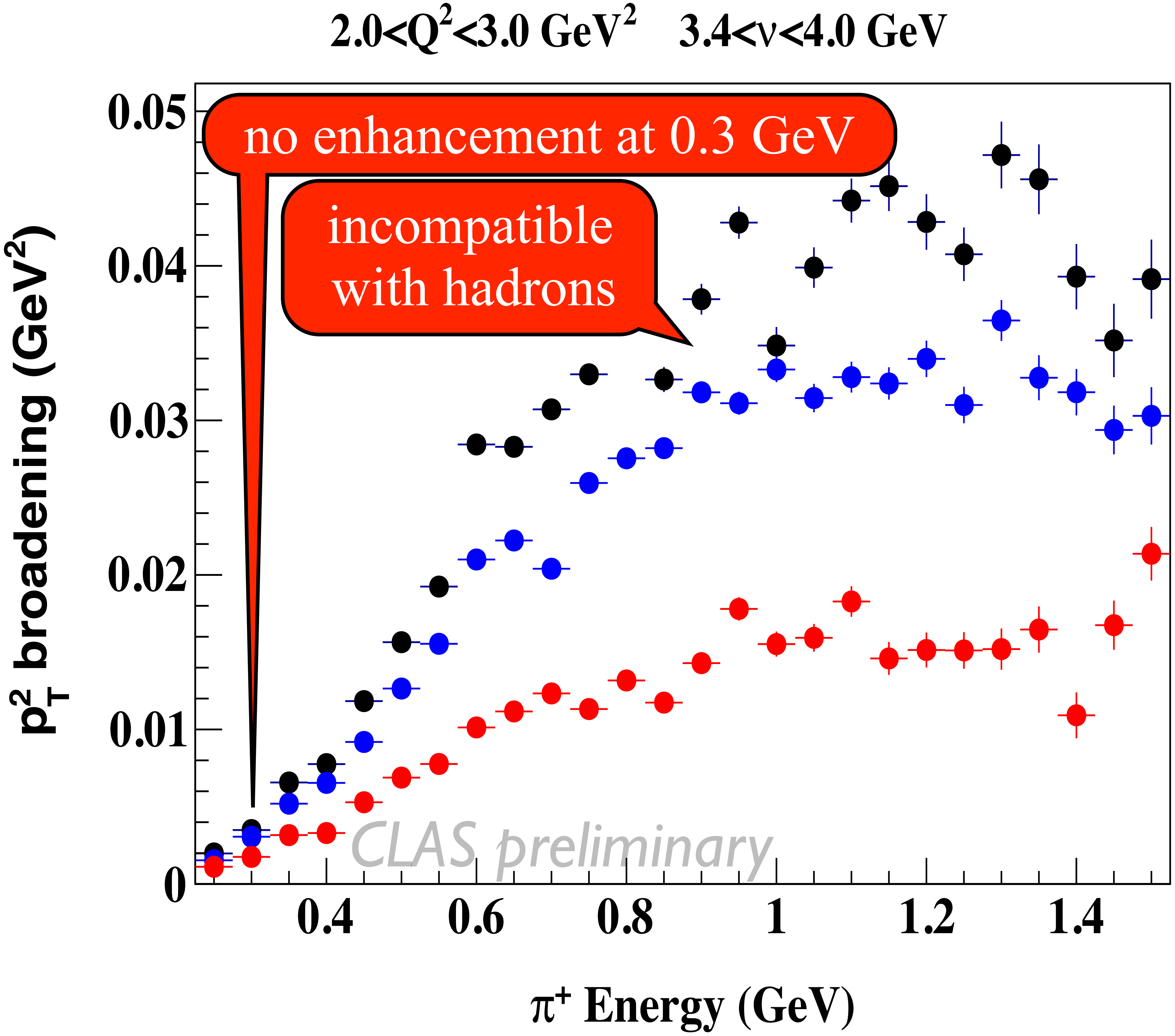
$2.0<Q^2<3.0$ GeV^2 $3.4<\nu<4.0$ GeV

no enhancement at 0.3 GeV

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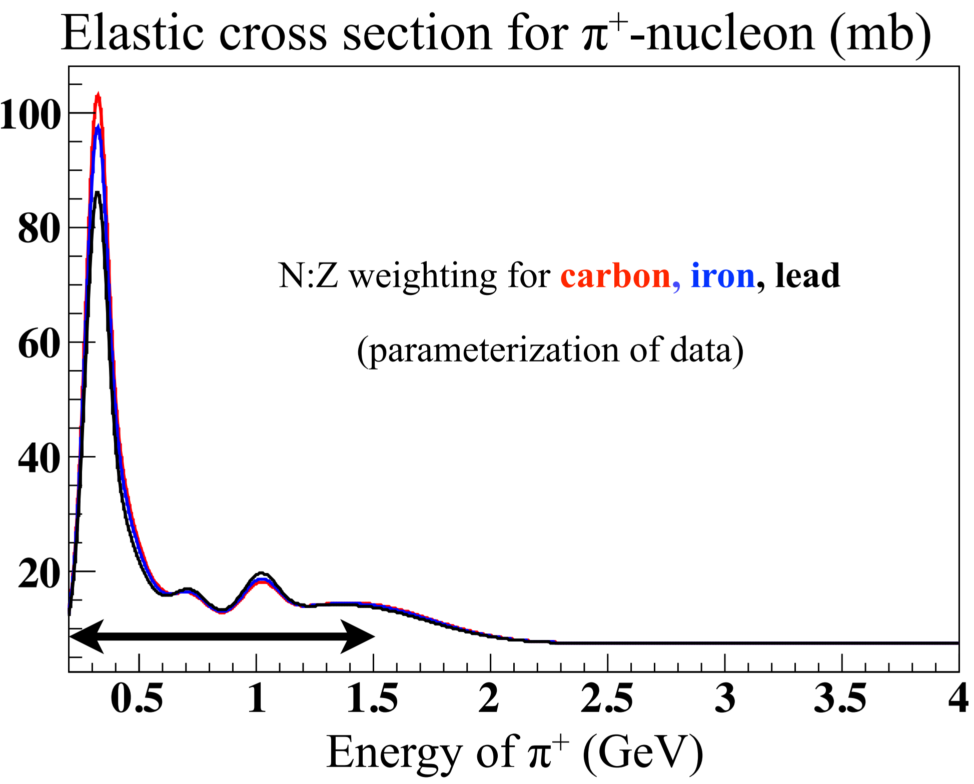
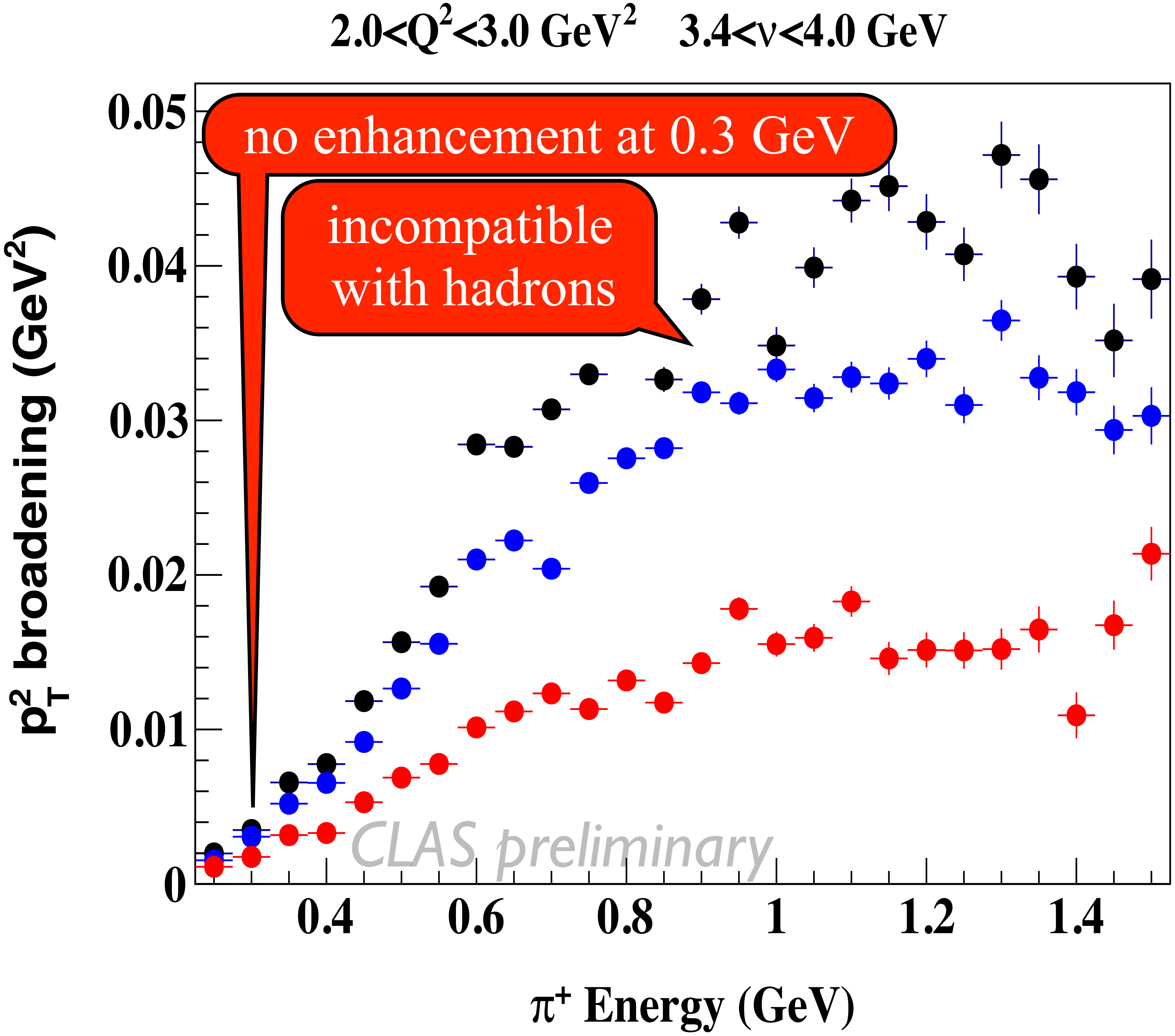

Elastic cross section for π^+-nucleon (mb)

N:Z weighting for **carbon**, **iron**, **lead**

(parameterization of data)

No visible evidence of hadronic elastic scattering?
Suggests:

p_T^2 Broadening vs. Hadron Energy



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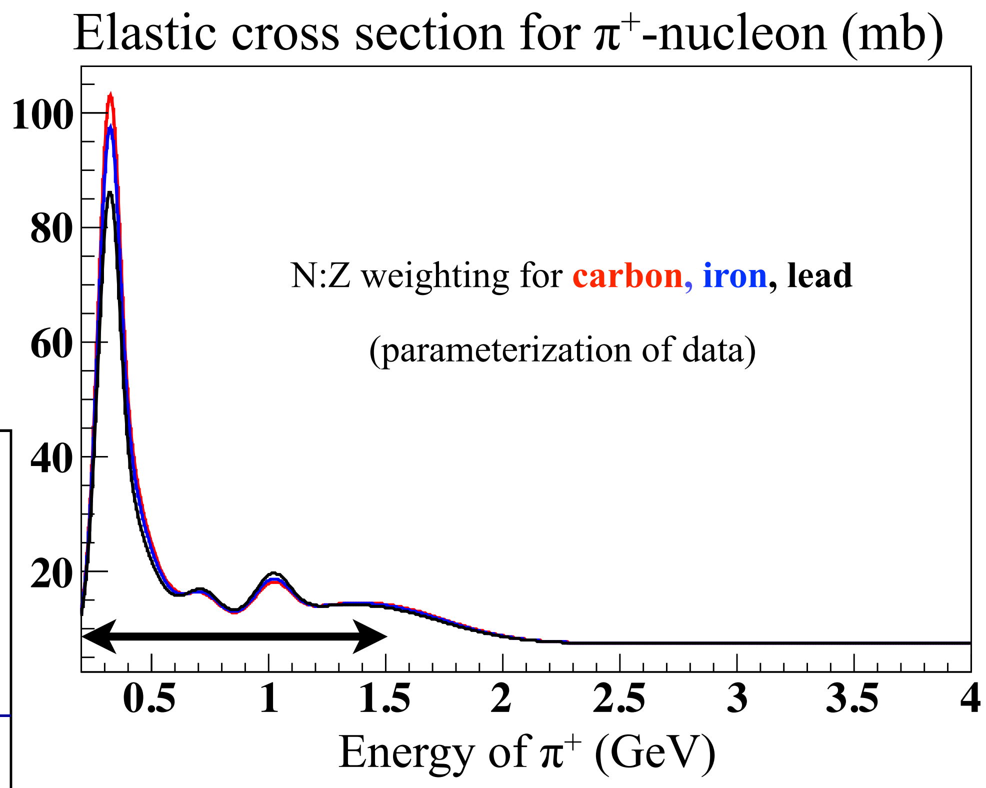
incompatible with hadrons



No visible evidence of hadronic elastic scattering? Suggests:

1) formation length is very long

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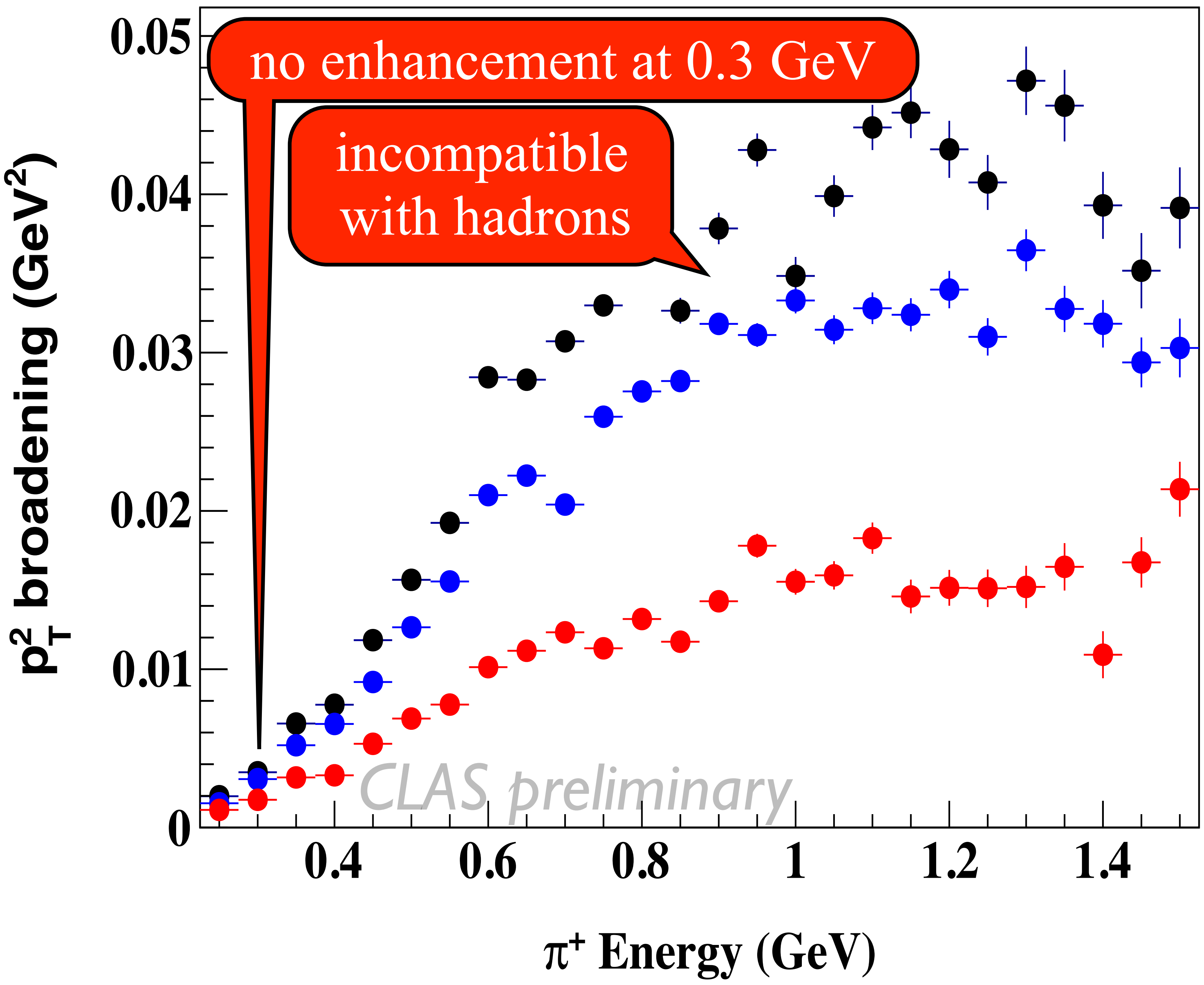

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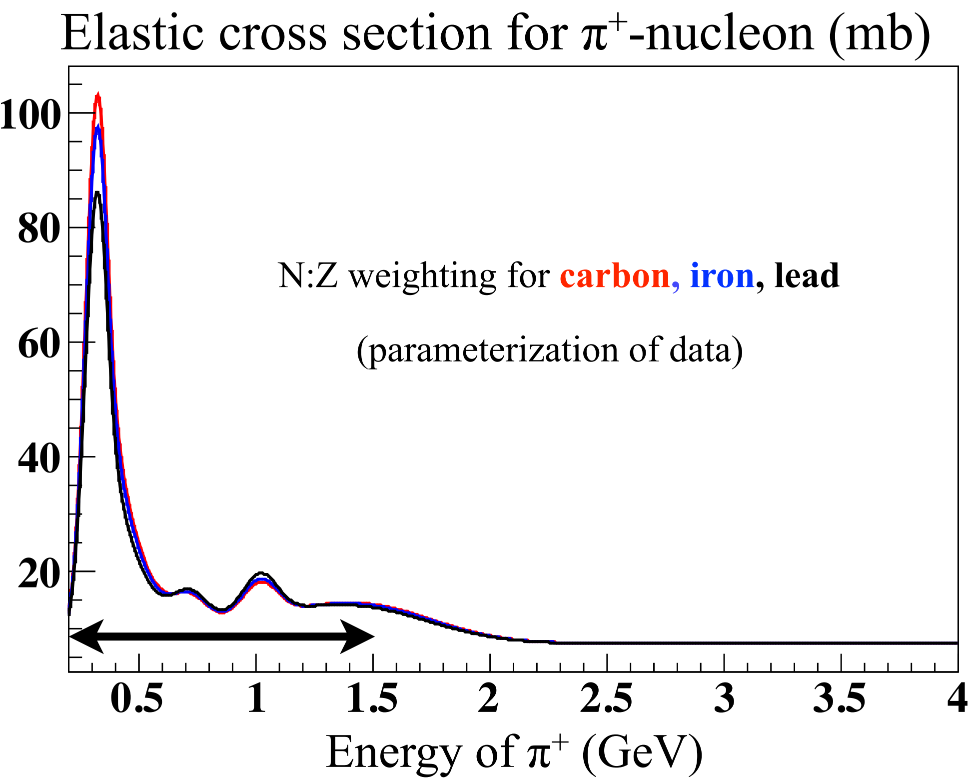

N:Z weighting for **carbon**, **iron**, **lead**

(parameterization of data)

No visible evidence of hadronic elastic scattering? Suggests:

1) formation length is very long

2) broadening is purely partonic

p_T^2 Broadening vs. Hadron Energy

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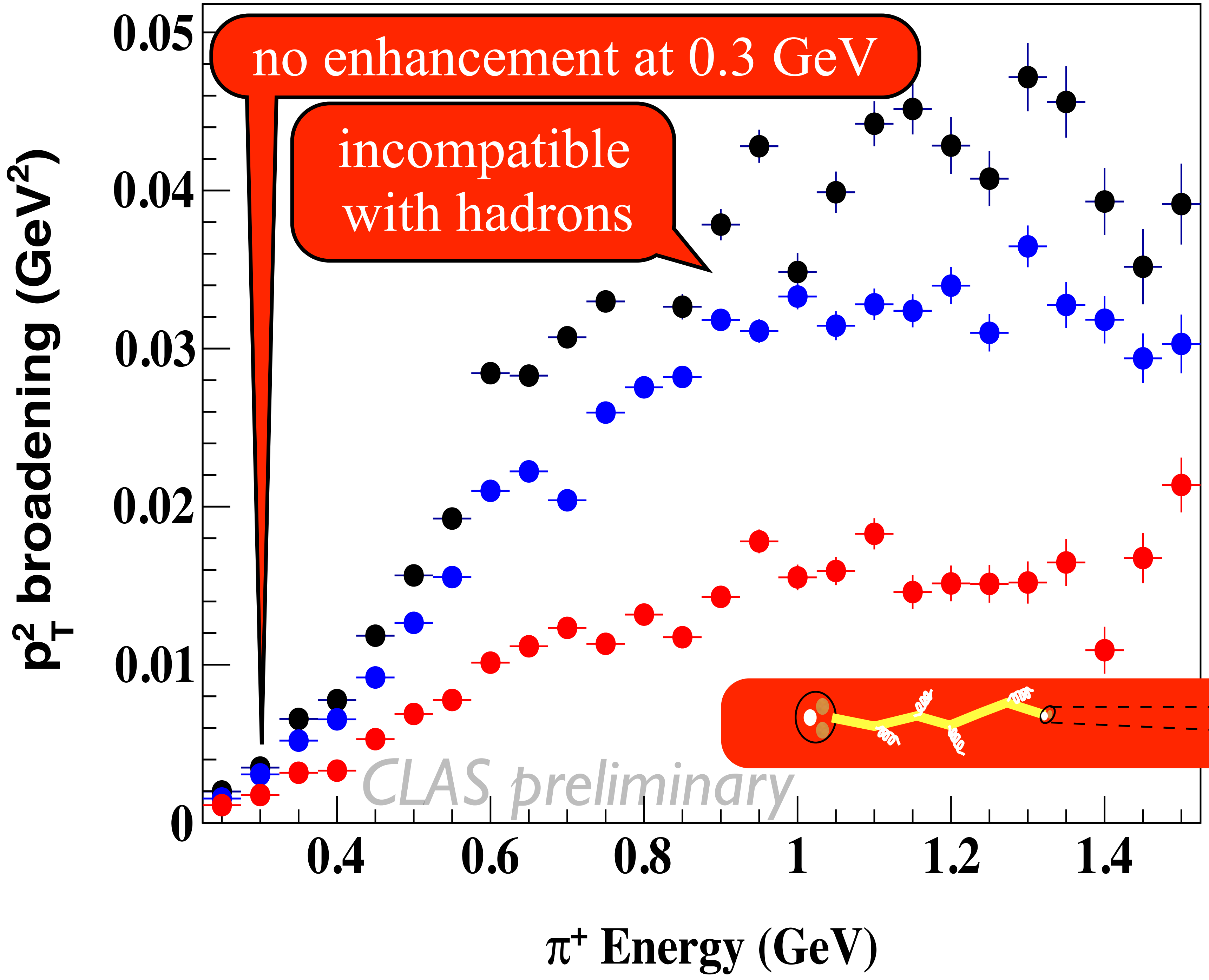

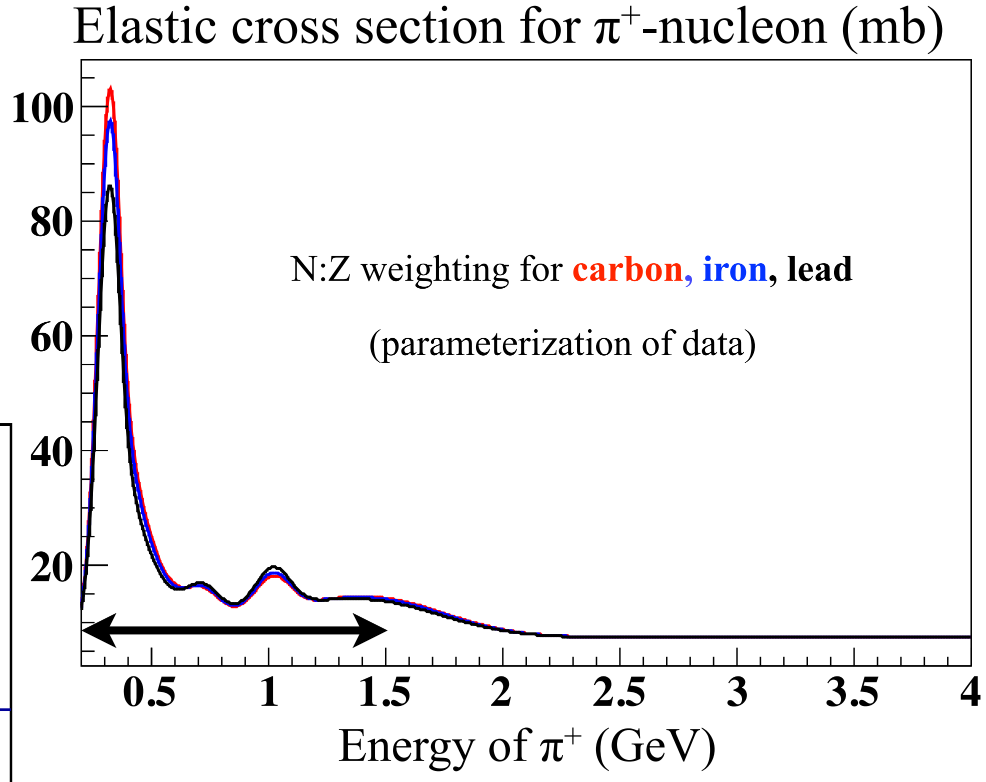

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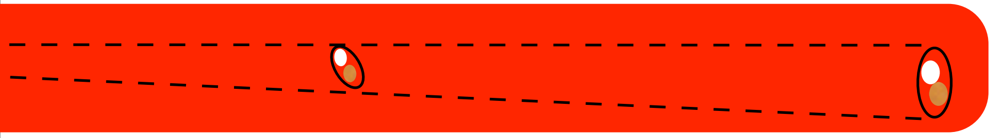

2) broadening is purely partonic

Strangeness@12 GeV - what will it bring?

- Crucially important information on mass dependence of hadron formation in two-quark systems
- Answer the question: is production length hadron independent?
- First look at p_T broadening in 2-quark system of 1 GeV mass (ϕ meson). Terra incognita. Can't do omega or eta broadening. Strangeness is crucial here.
- Probe fragmentation mechanism for leading vs. non-leading particles (K^+ vs. K^-) via p_T broadening in nuclei. (less broadening for K^-? overall string shorter)
- Cleaner access to high momentum identified hadrons, crucial for needed kinematic reach

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

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

meson	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$
π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$
η’	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$
$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$
K^0	27 mm	0.50	$d\bar{s}$
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$

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baryon	cτ	mass	flavor content
p	stable	0.94	ud
$\bar{p}$	stable	0.94	$\overline{ud}$
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
Ξ^-	49 mm	1.3	ds

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

○ Actively underway with existing 5 GeV data

meson	cτ	mass	flavor content
○ π^0	25 nm	0.13	$u\bar{u}d\bar{d}$
○ π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$
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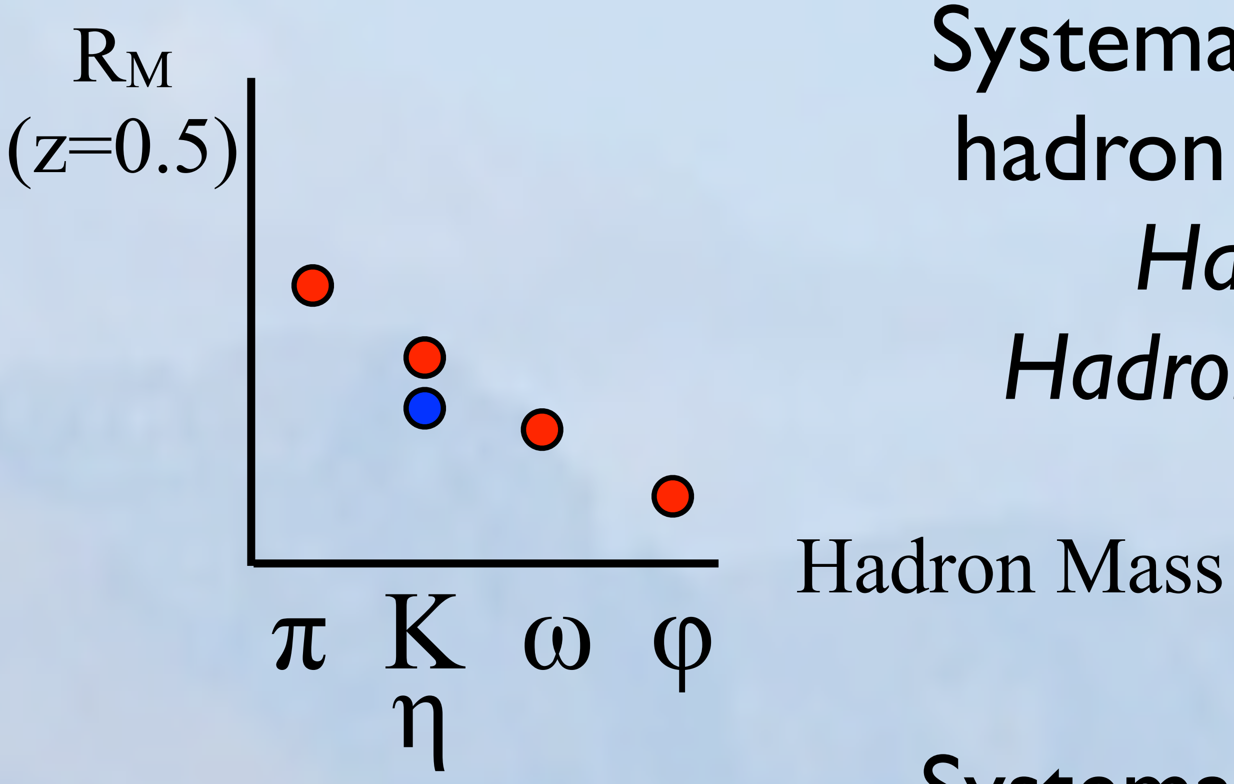
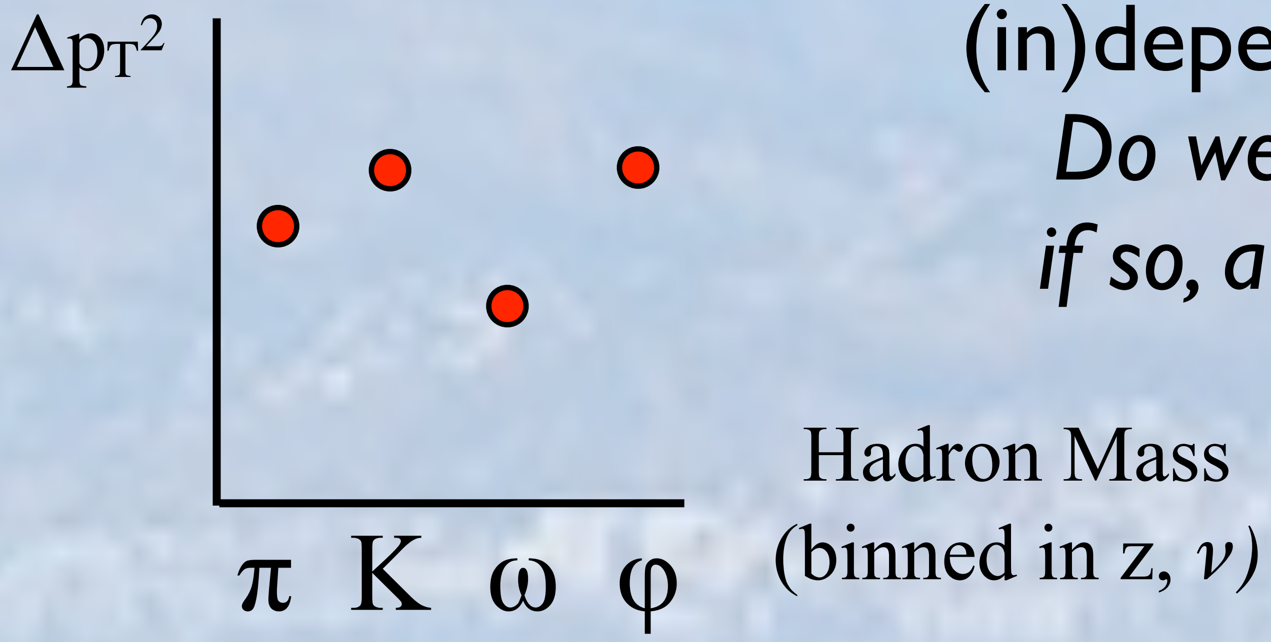
Strangeness@12 GeV - what will it bring?



Systematic study of attenuation vs. hadron mass for 2-quark systems

Hadron formation lengths

Hadron suppression mechanisms



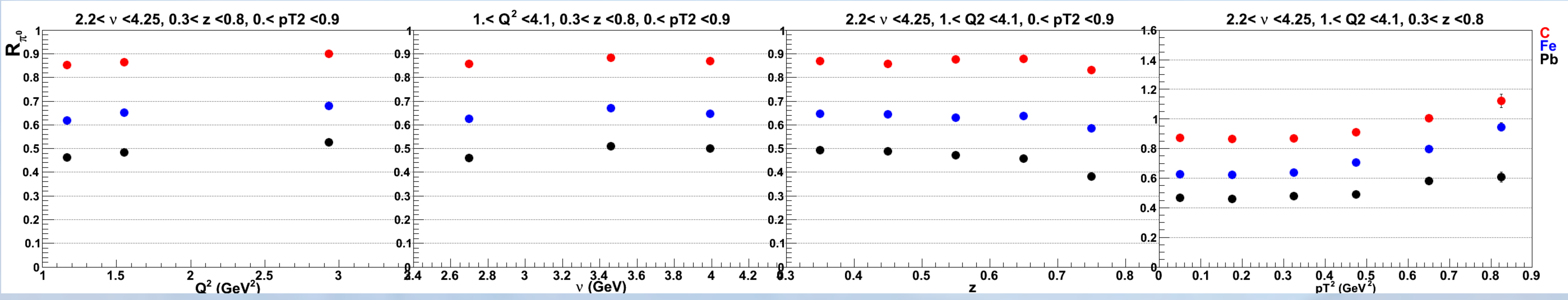
Systematic study of hadron species (in)dependence of p_T broadening

Do we have a partonic probe?

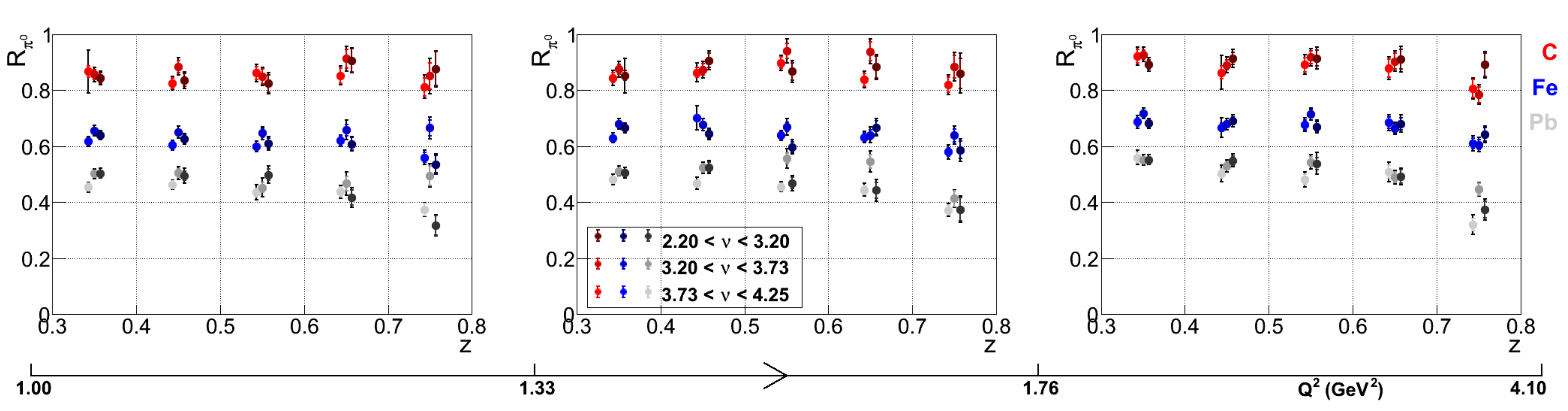
if so, a vast program of studies!

New π^0 hadron multiplicity ratios from CLAS

PhD thesis of Taisiya Mineeva



Integrated to 1 dimension

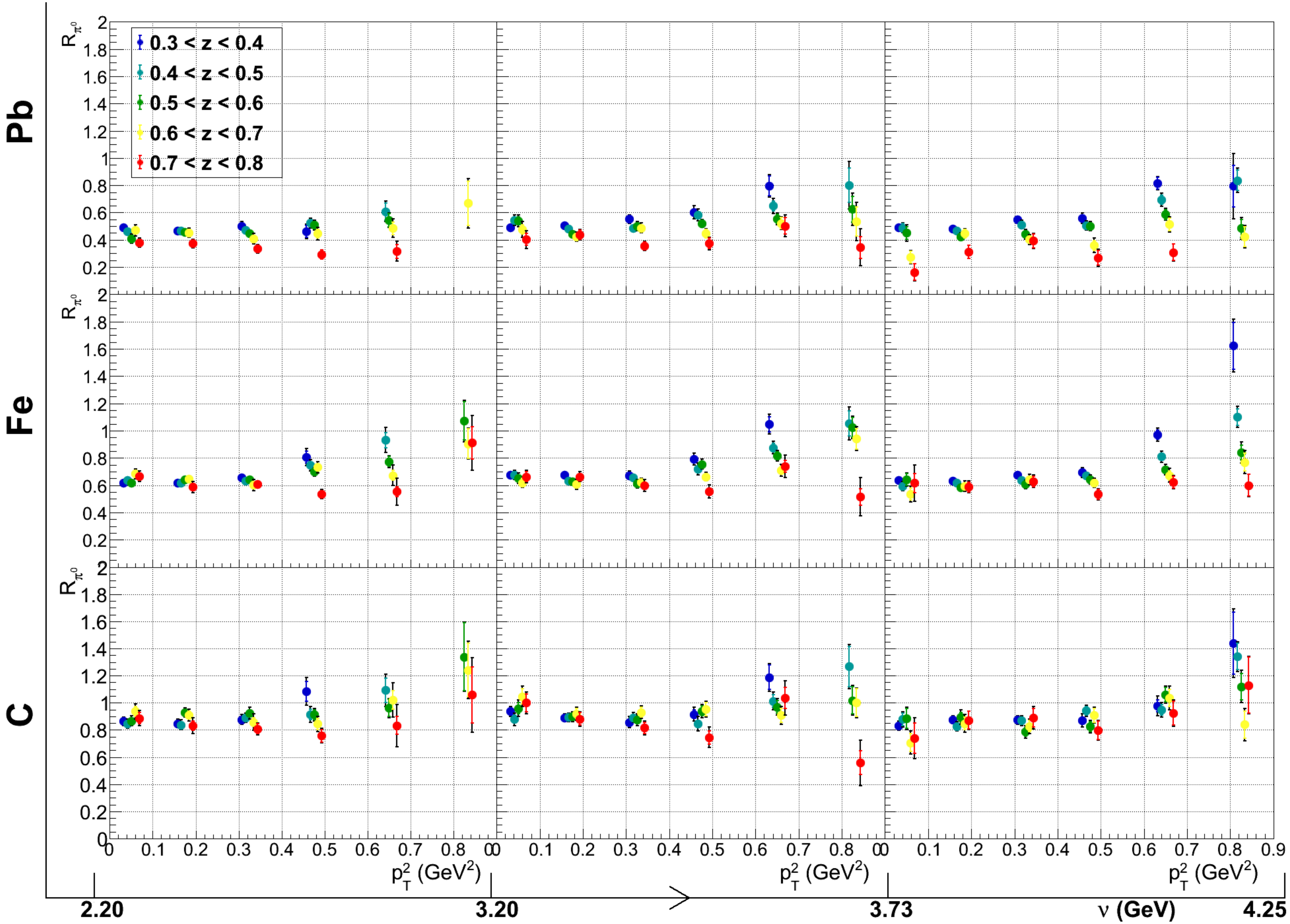


3-fold differential, z dependence vs. *ν* and Q^2

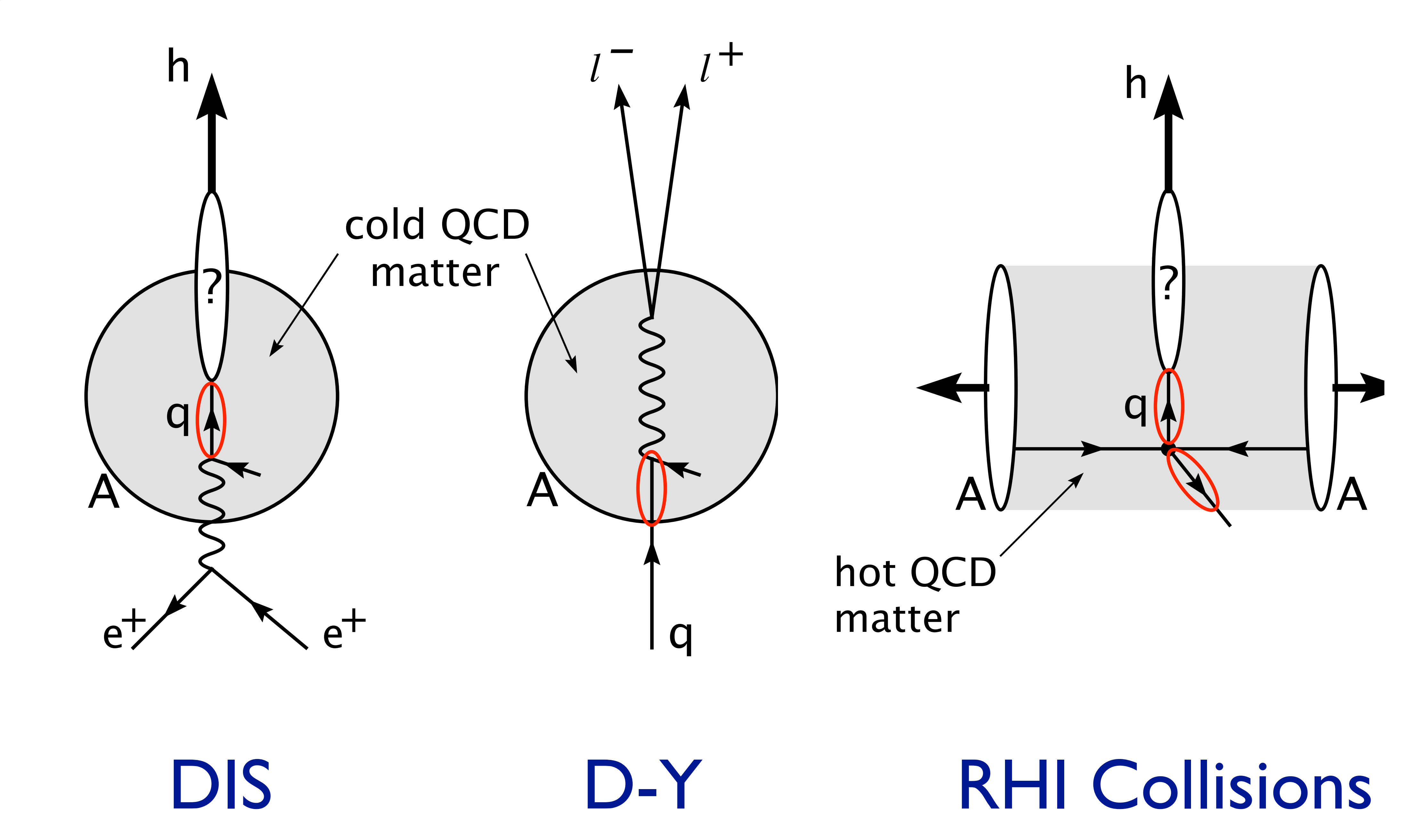
New π^0 hadron multiplicity ratios from CLAS, pg 2/2

PhD thesis of Taisiya Mineeva

3-fold differential, p_T dependence vs. ν and z



Parton Propagation in Three Processes

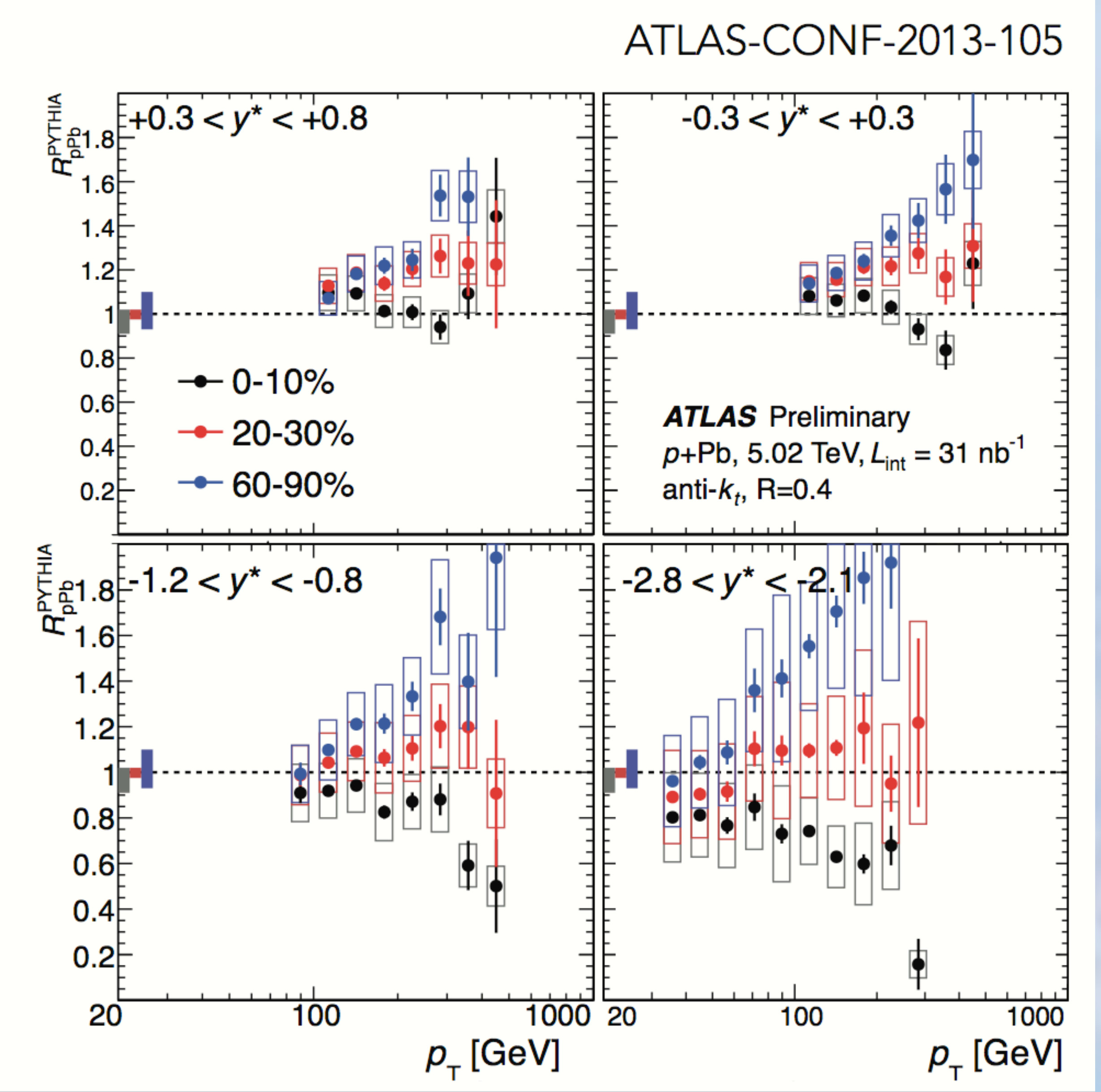


Accardi, Arleo, Brooks, d'Enterria, Muccifora Riv.Nuovo Cim.032:439-553,2010 [arXiv:0907.3534]
Majumder, van Leuween, Prog. Part. Nucl. Phys. A66:41, 2011, arXiv:1002.2206 [hep- ph]
S. Peigne, A.V. Smilga, Phys.Usp.52:659-685, 2009, arXiv:0810.5702v2 [hep-ph]

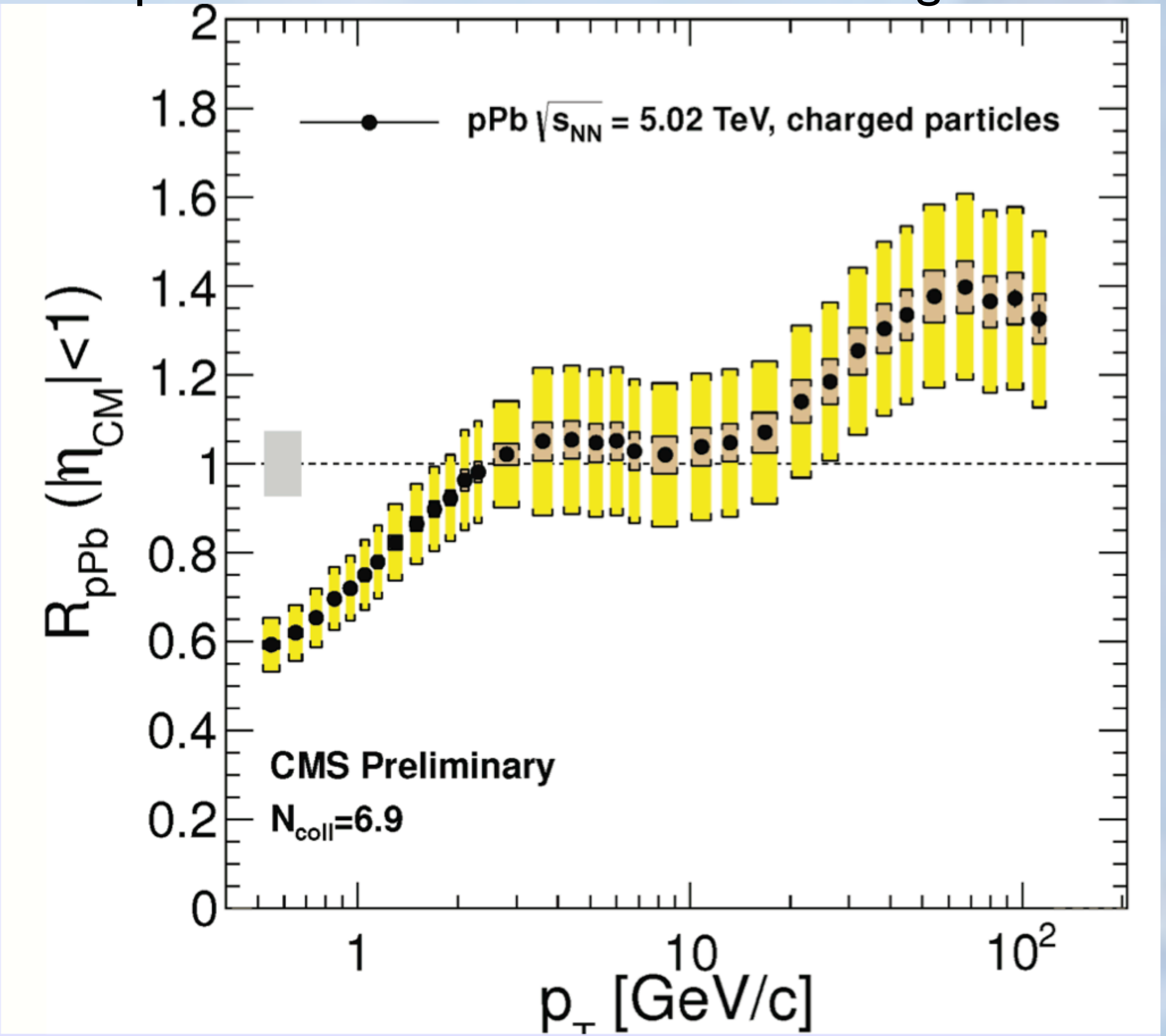
More mysteries of parton propagation at 5 TeV from Hard Probes 2013

Just released last week by ATLAS and CMS, p+Pb collisions at 5 TeV cm energy

Centrality dependence of jets *inverted*



Unexpected nuclear modification of charged tracks

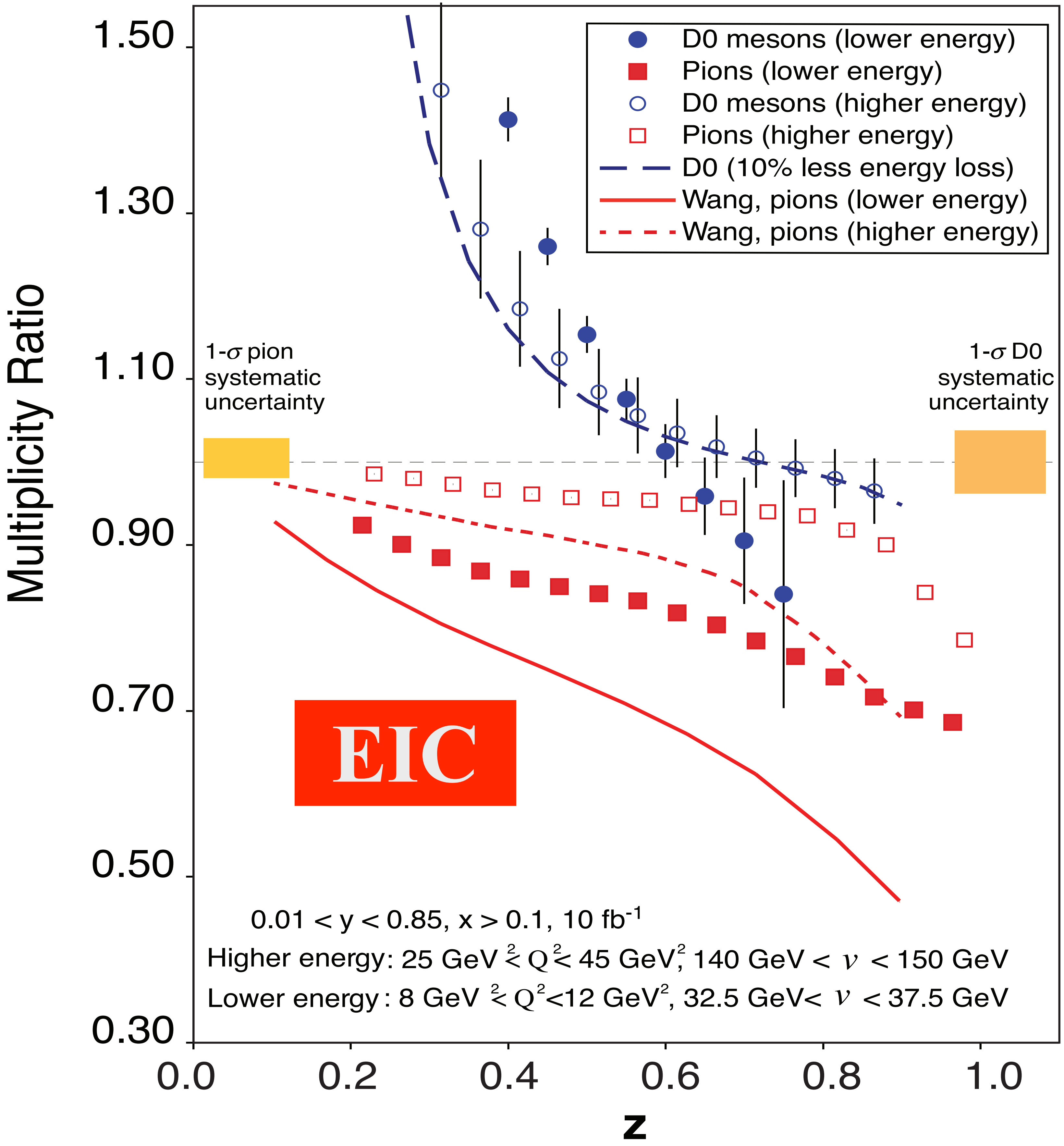


Nuclei do not get simpler at higher energies!

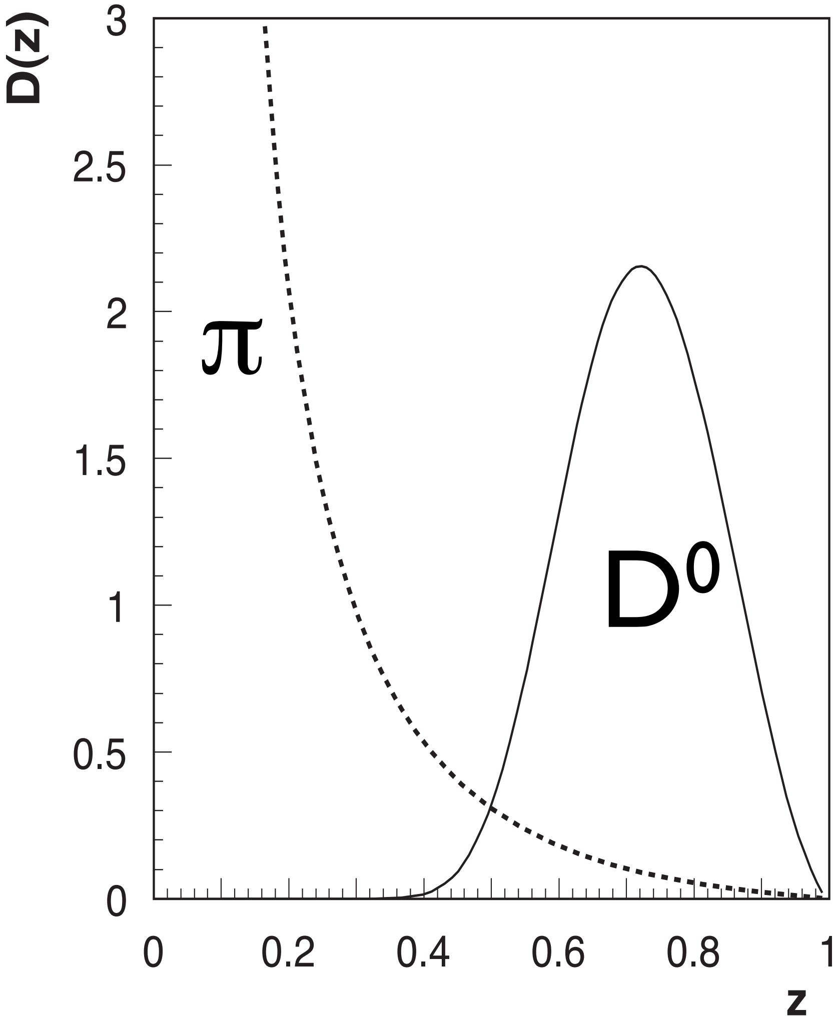
Conclusions

- Rich program of measurements with the long-term goal of understanding parton propagation and hadron formation in QCD, a fundamental sector of the theory
  - in stage now of developing an understanding of the tools
- Enhancement from K and ϕ bring profound and conclusive impact
  - hadron formation lengths
  - degree to which p_T broadening characterizes a hadron-independent partonic probe
- 12 GeV program, and the future EIC, will close the book on timescales and coherence in QCD fragmentation (vacuum, cold medium). And, perhaps on fragmentation mechanisms!

Backup Slides

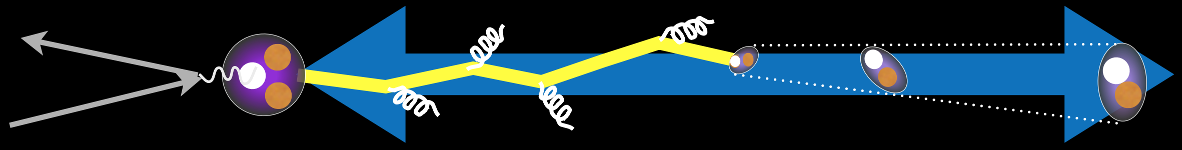


Fragmentation functions

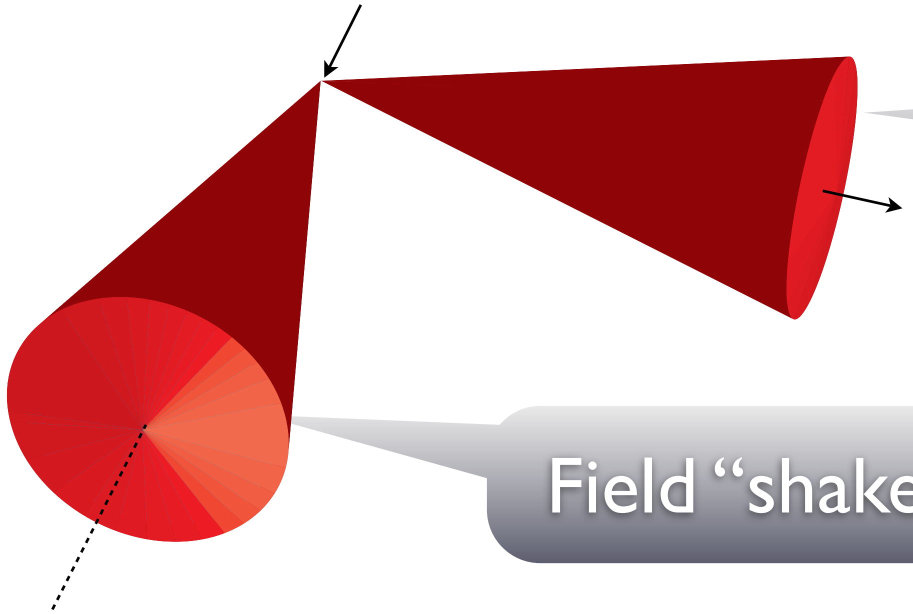


Access to very strong, unique light quark energy loss signature via D^0 heavy meson. Compare to s and c quark energy loss in D_s^+

Formation zone - QCD and QED



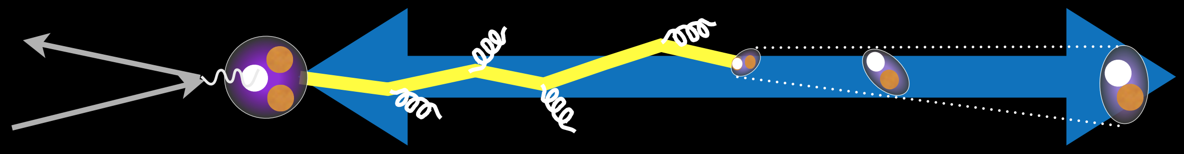
- Truncated field following hard interaction
- Quark/prehadon ‘protected’ from interaction for a long time
- Radiation (gluons and photons) into two cones



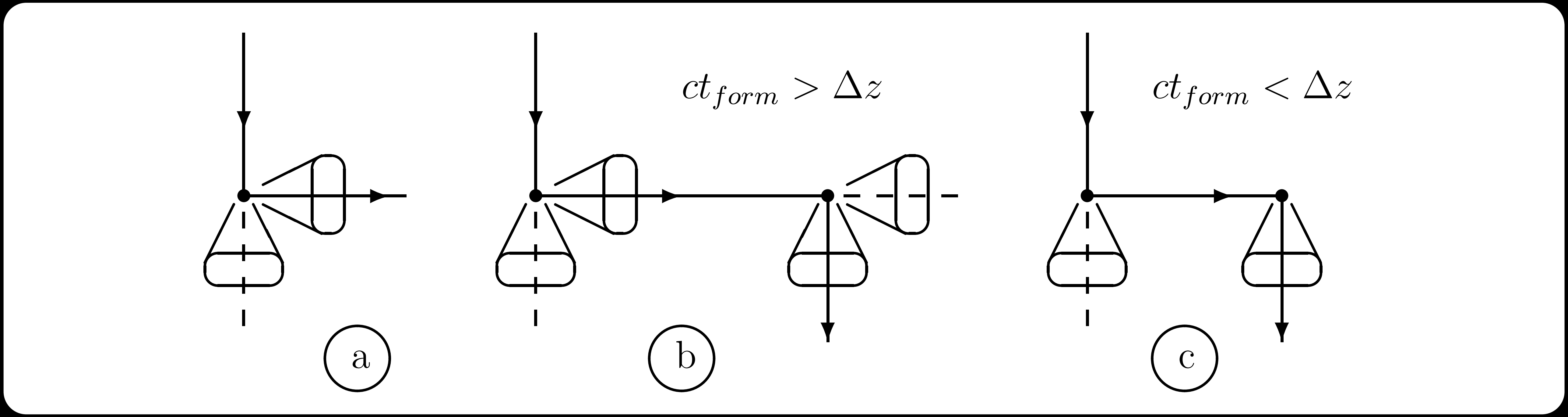
Regenerated “private field” of electron or quark

Field “shaken off” (radiated photon or gluon)

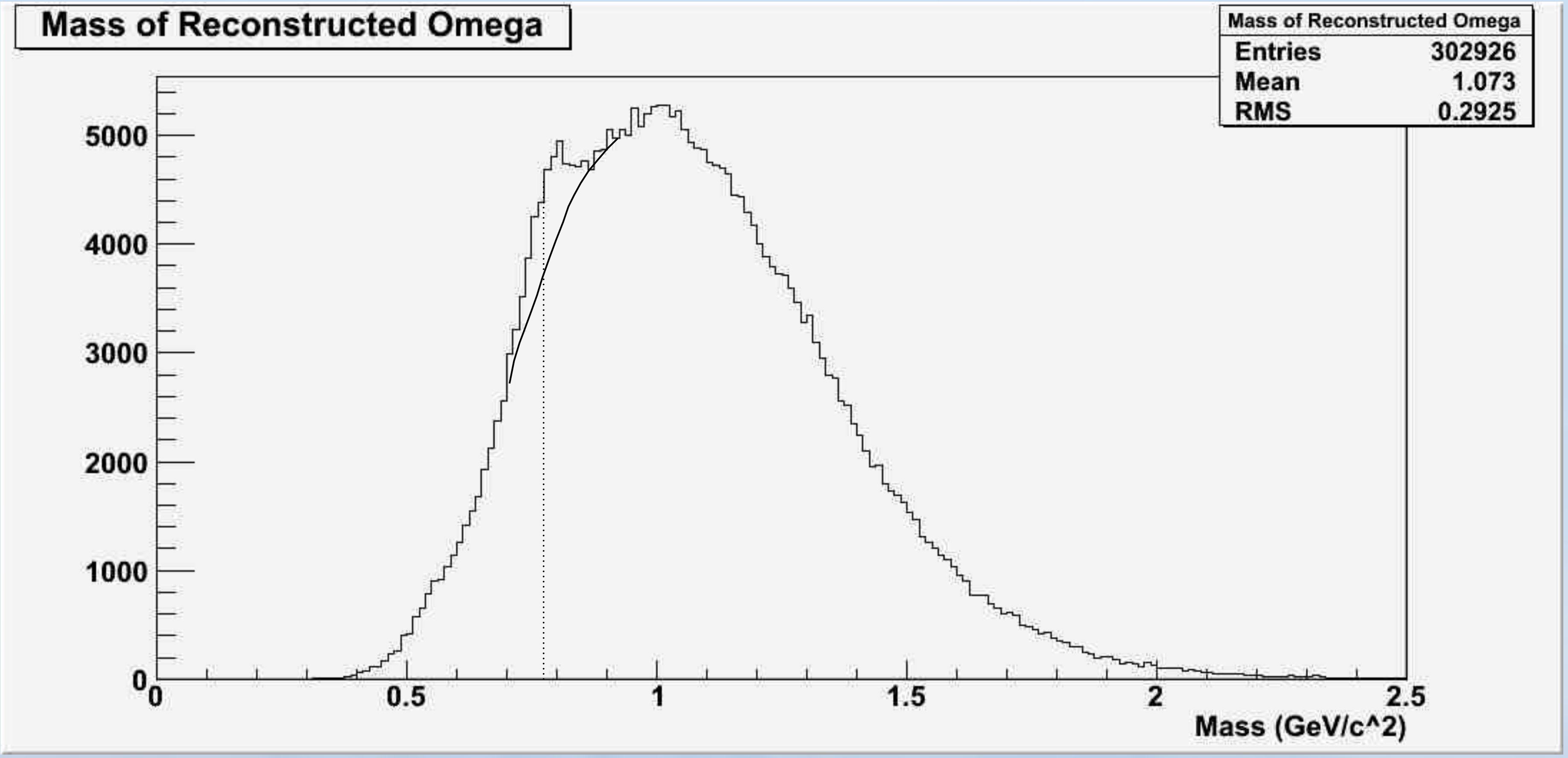
Multiple scattering and interference

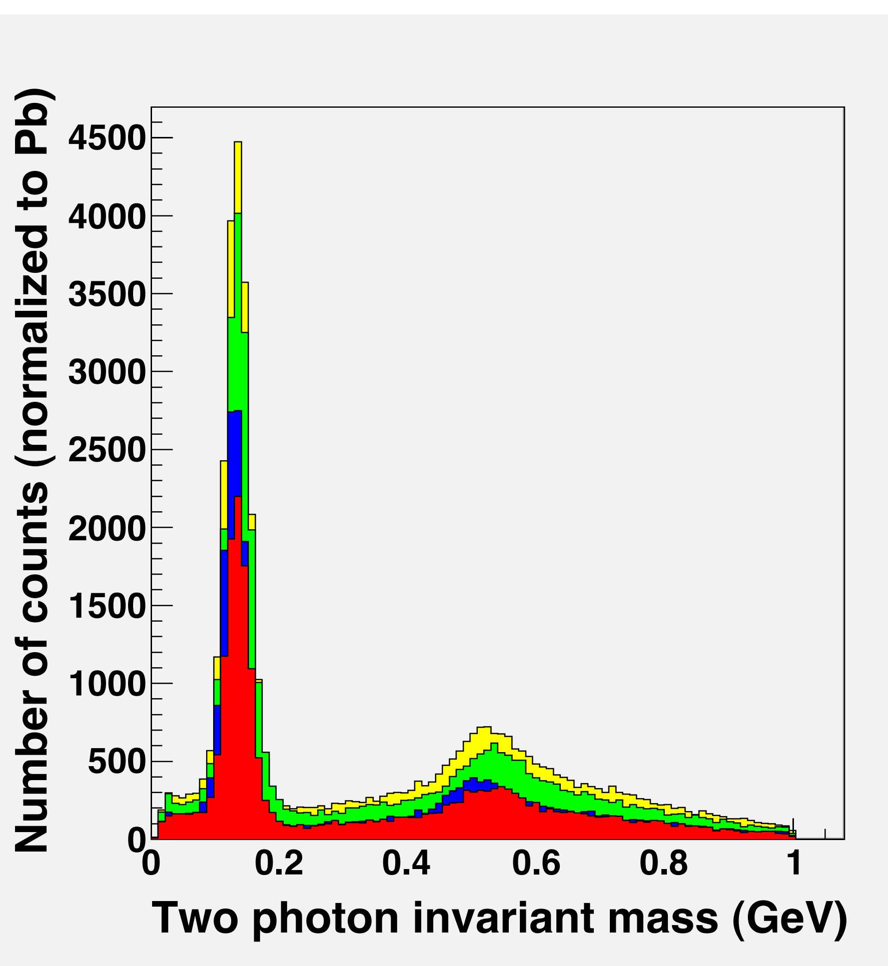


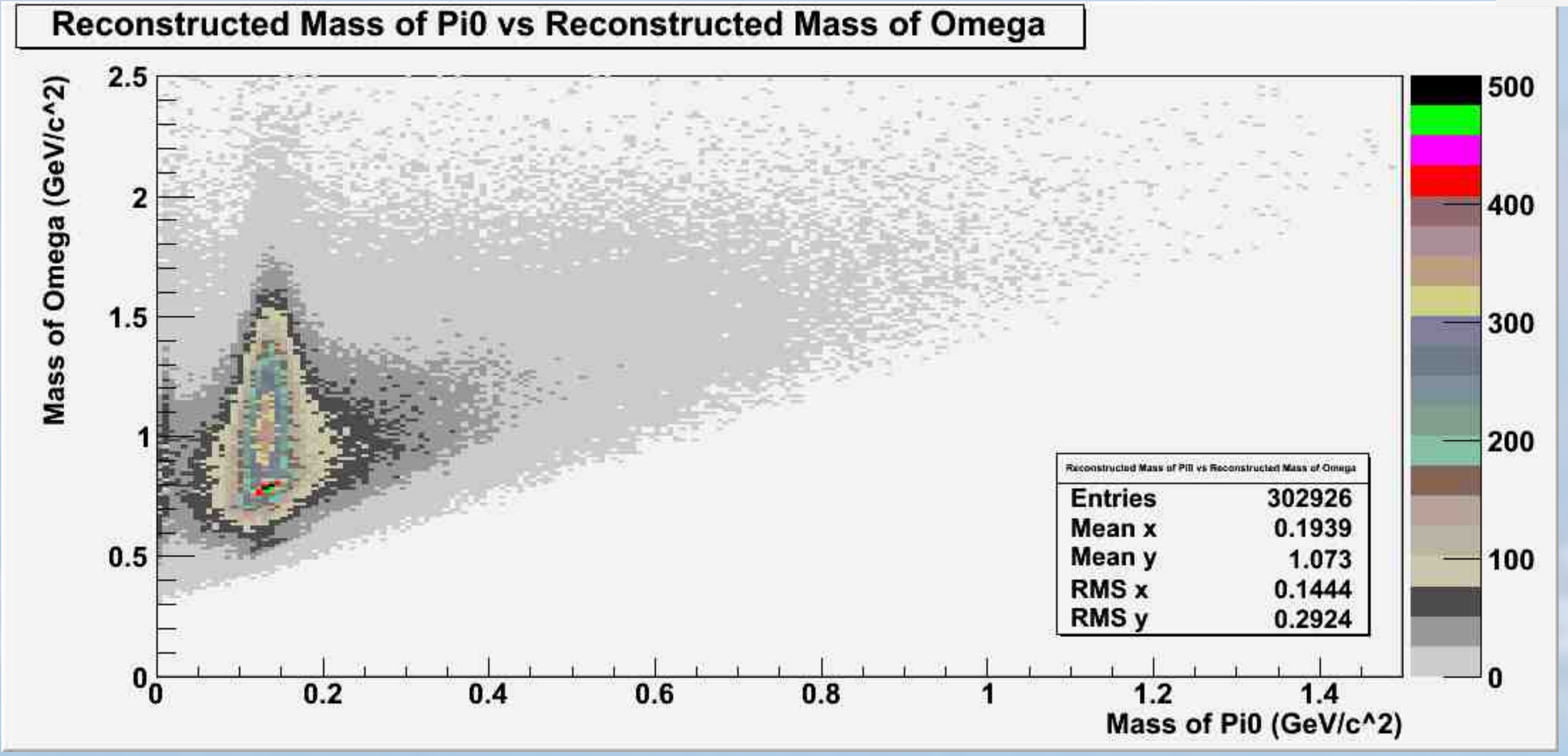
- Landau-Pomeranchuk-Migdal (LPM) effect (QED and QCD)



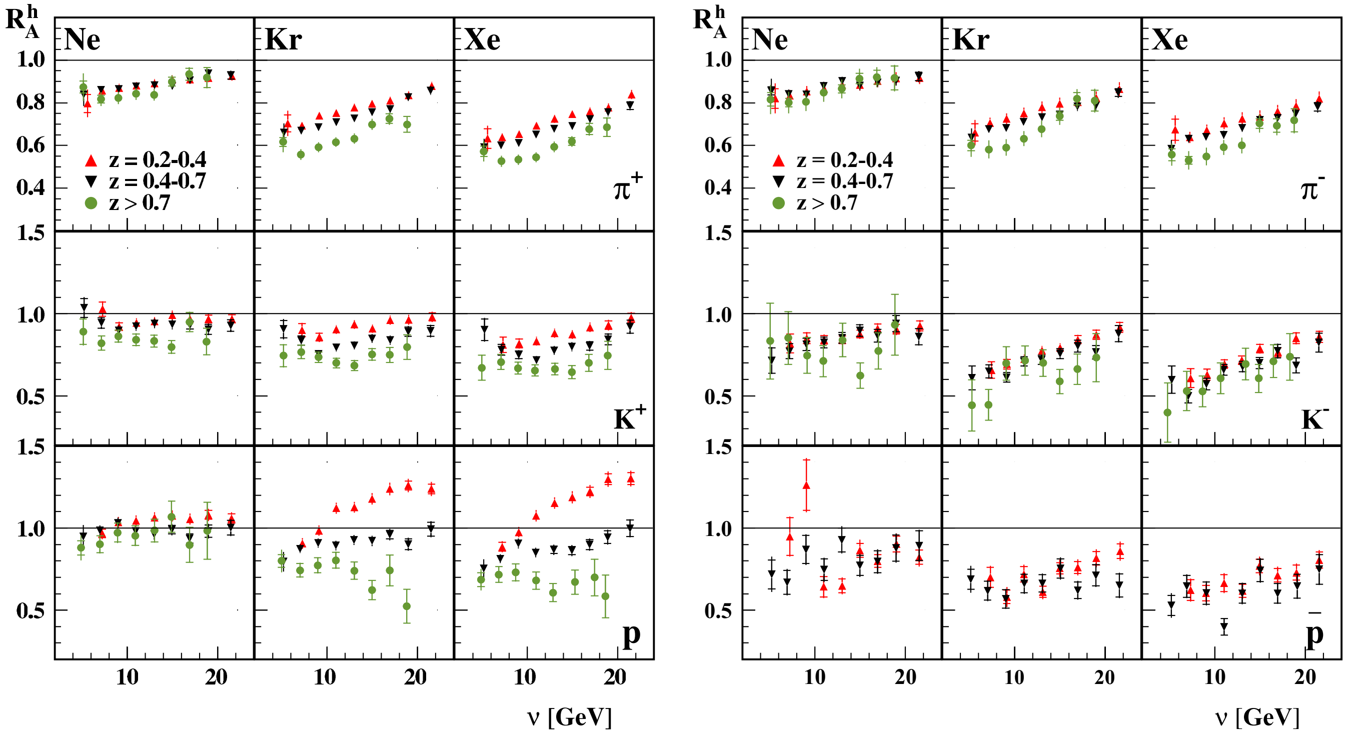
- Subsequent radiation suppressed if gluon not fully formed
- Resulting energy loss proportional to path length L or L^2

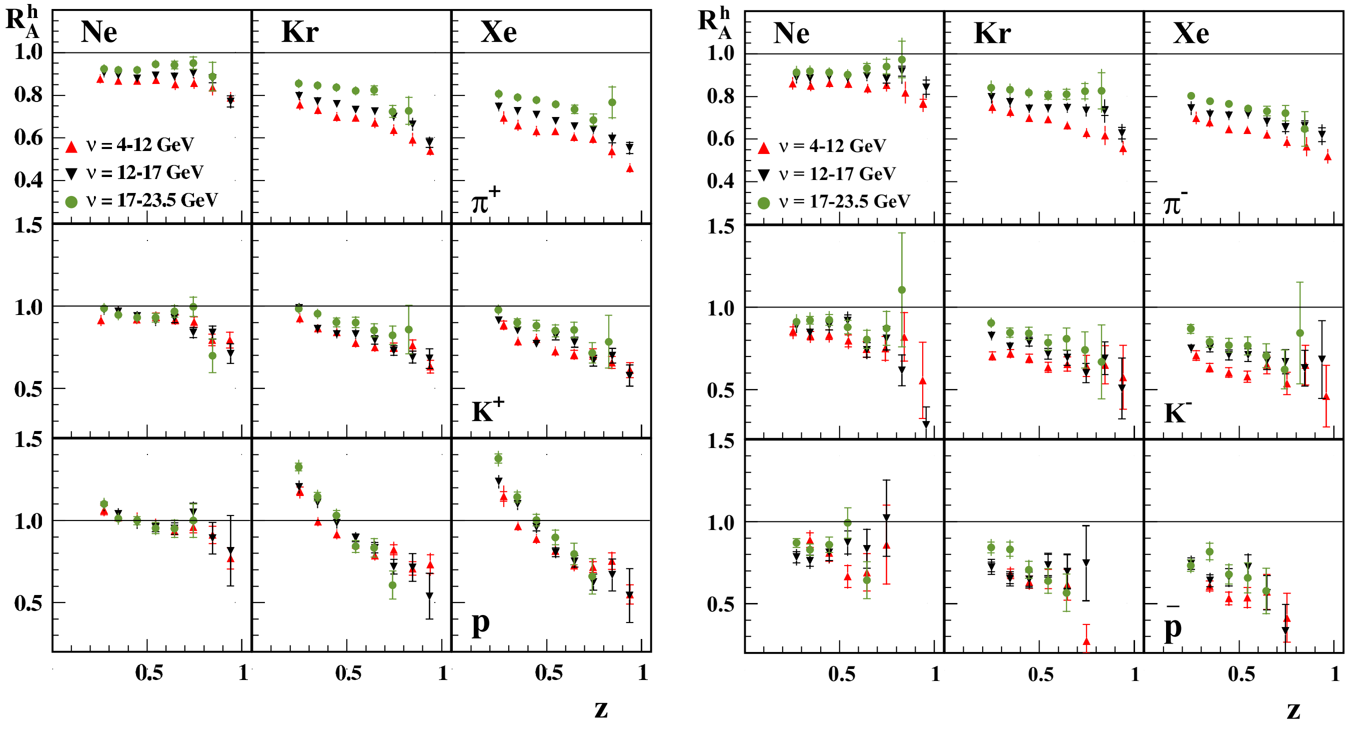


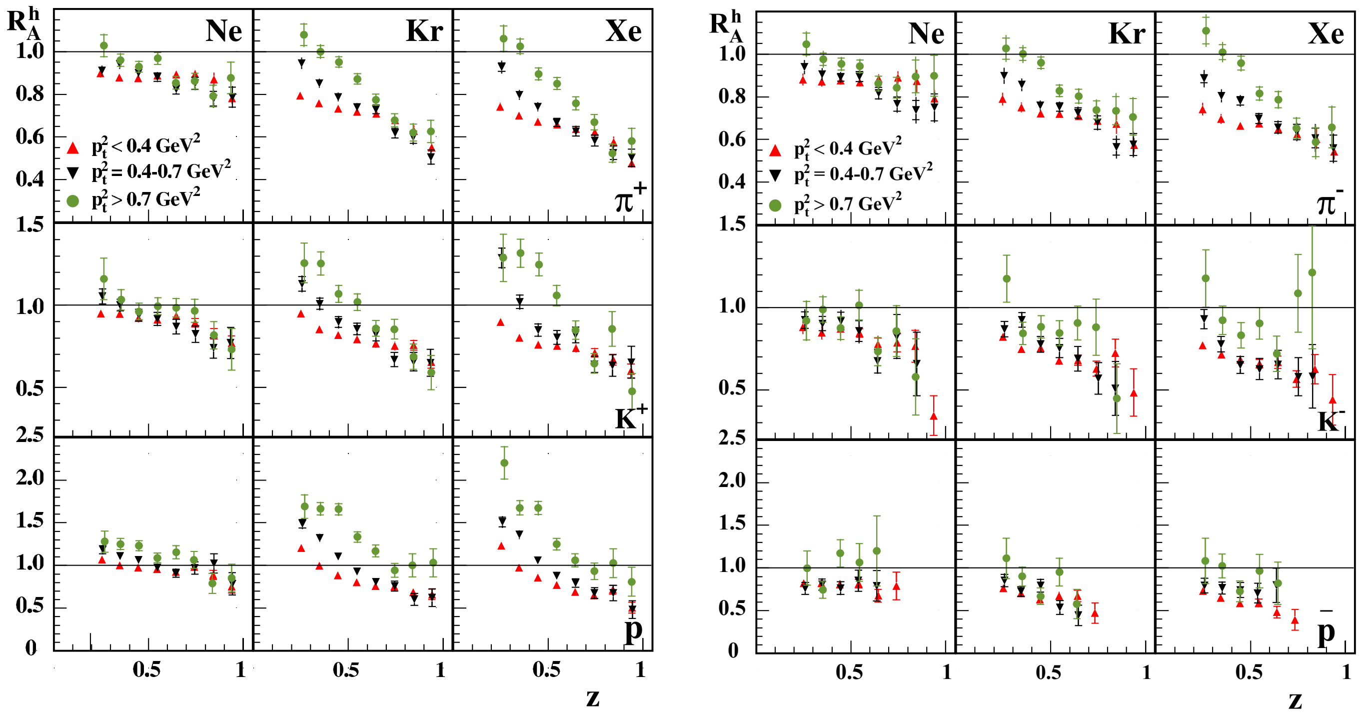


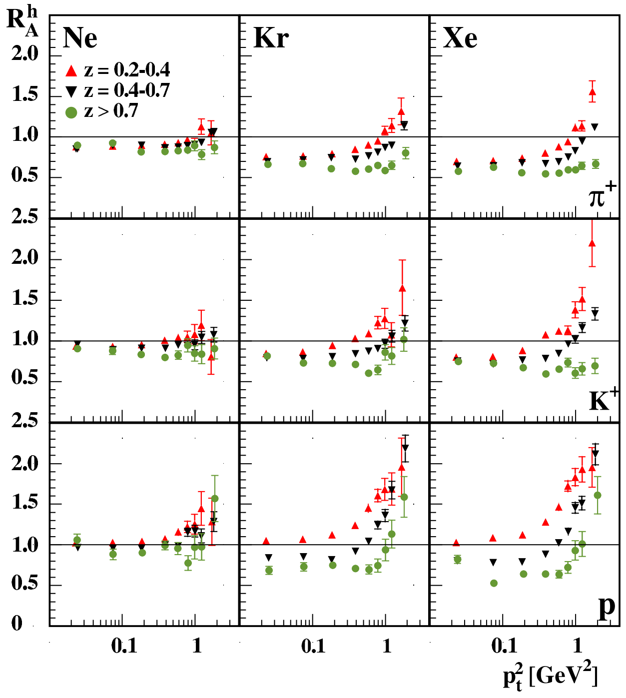


Omega and eta mesons in CLAS data on nuclear targets D, C, Fe, Pb







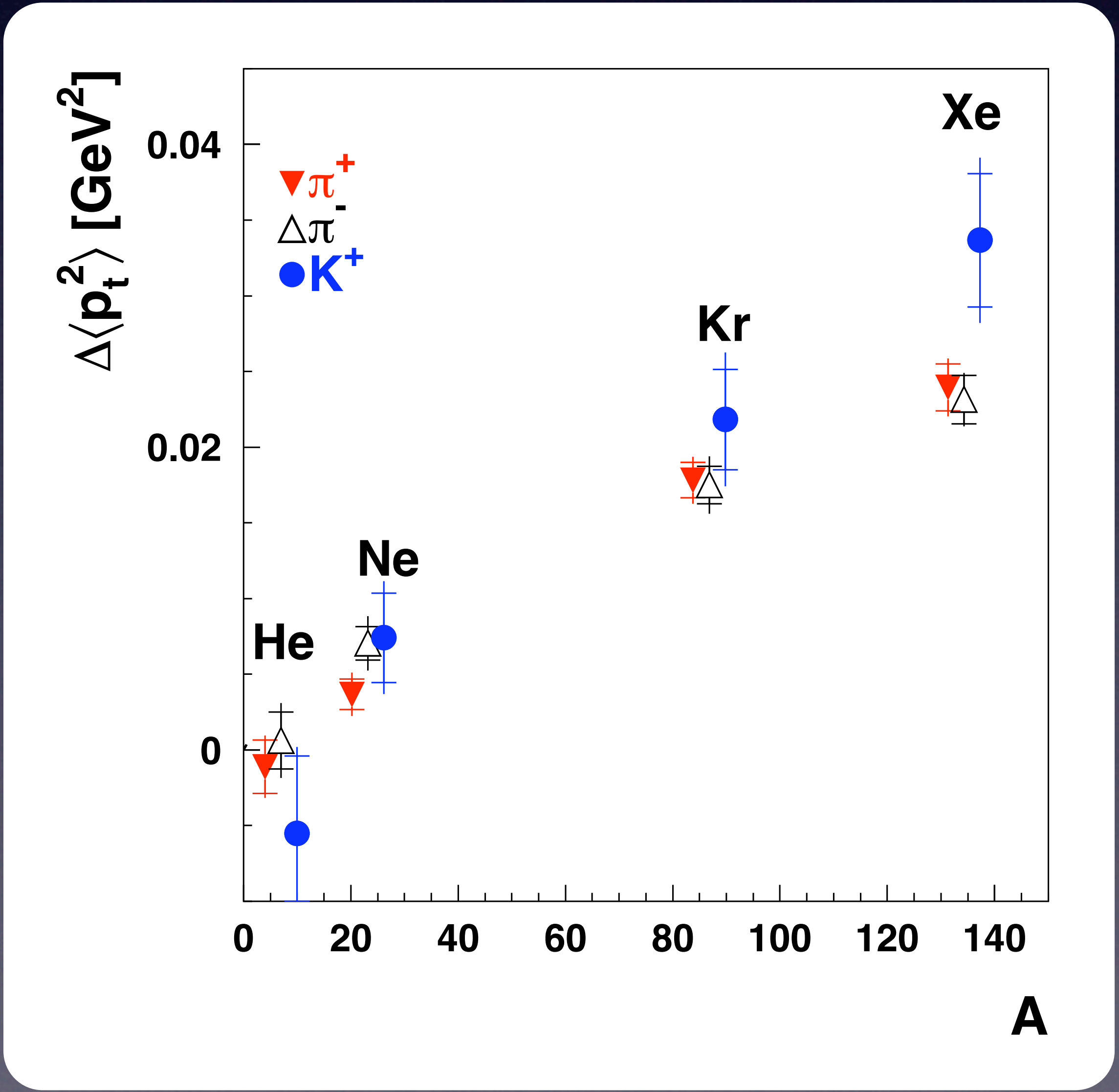


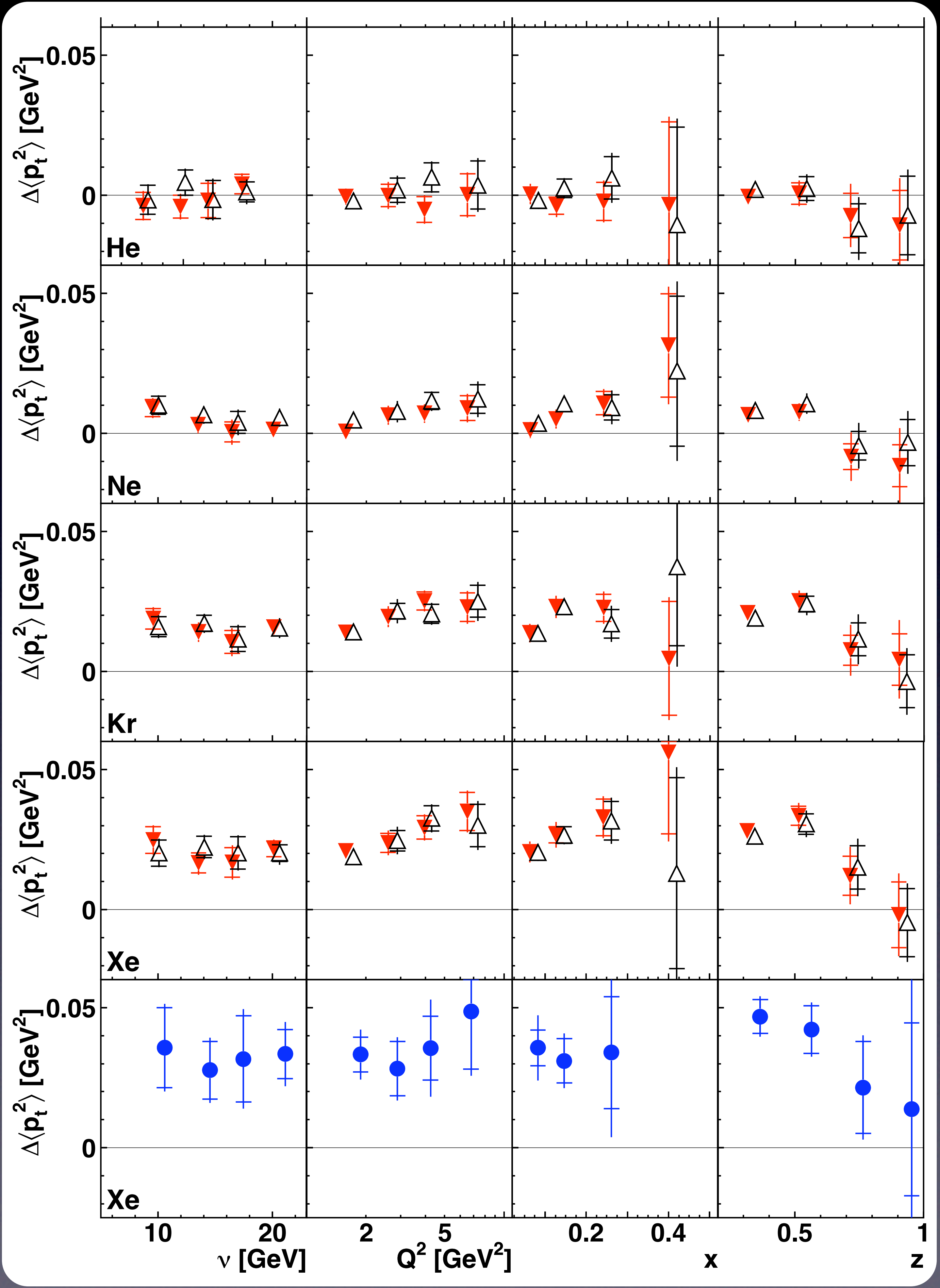
Hermes 2-D studies of multiplicity ratios for **π**,K,p

Eur. Phys. J. A (2011) 47: 113

Hermes pT broadening data

World's first comparison between pion and K^+ pT broadening



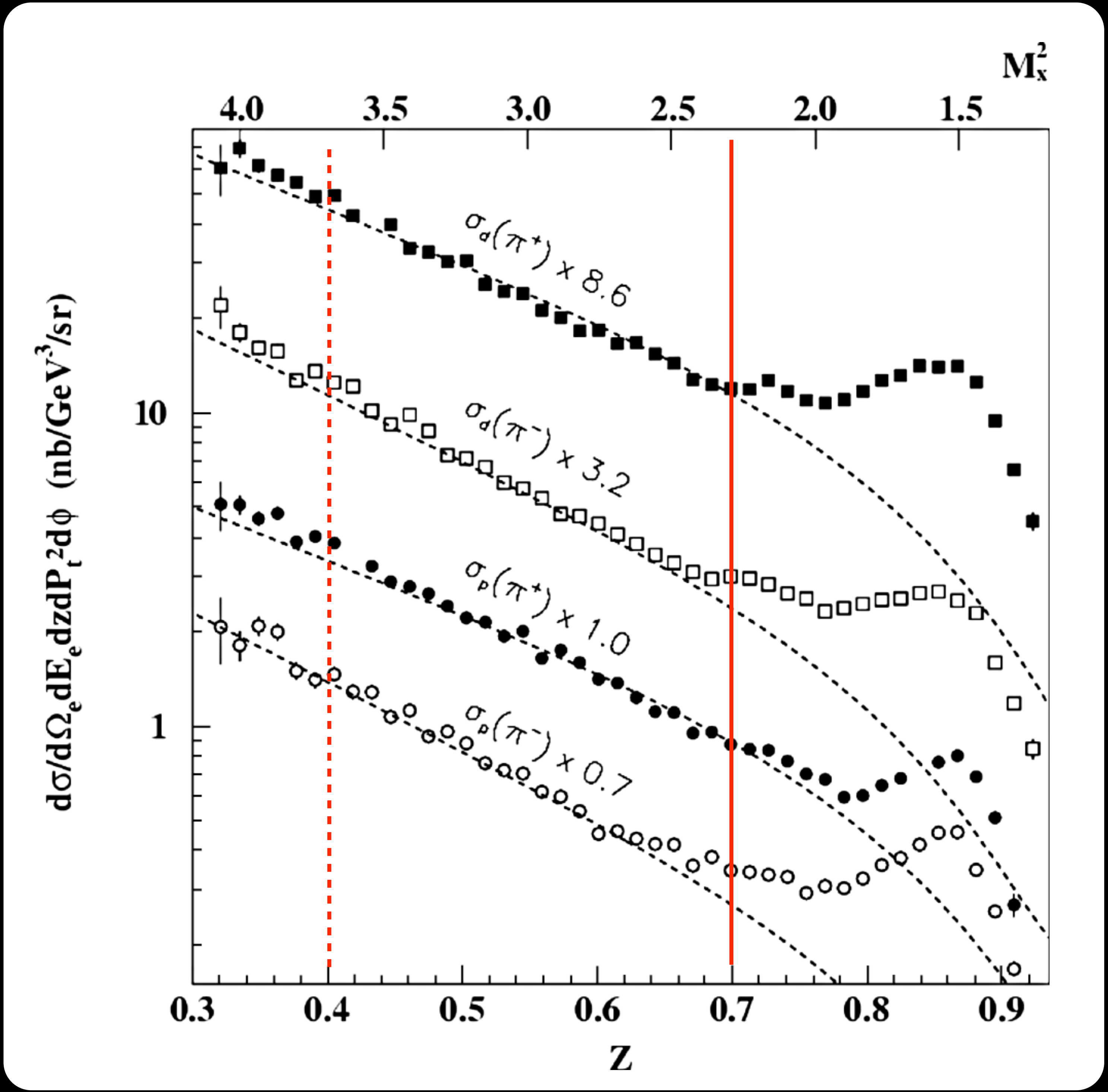


Factorization and interpretability

Hall C data

Precocious factorization

Limited deviation

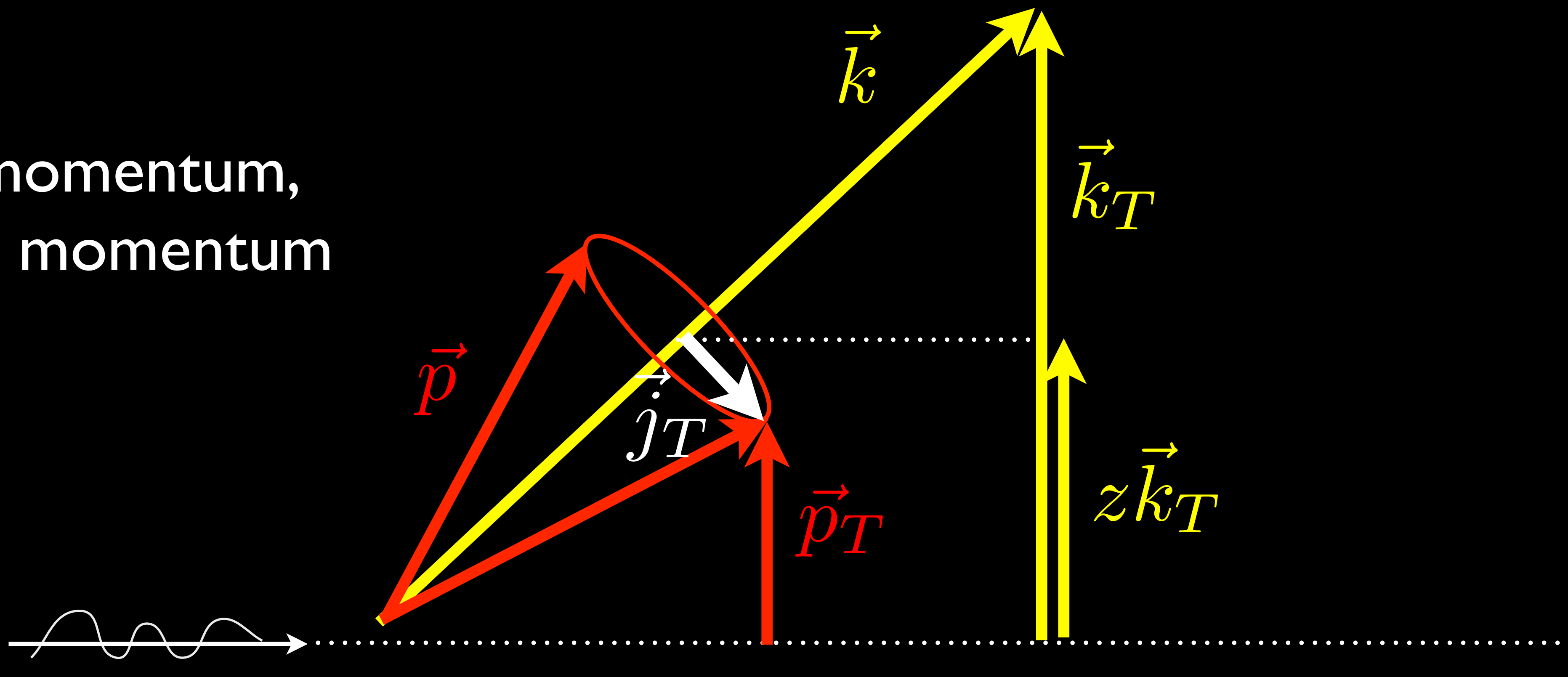


T. Navasardyan, et al., PRL 98, 022001 (2007)

Quark k_T broadening vs. *hadron* p_T broadening

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

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



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

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

$$\Delta\langle p_T^2\rangle = \Delta\langle z^2 k_T^2\rangle + \cancelto{\sim 0}{\Delta\langle j_T^2\rangle}$$

$$\boxed{\Delta\langle p_T^2\rangle \approx z^2\Delta\langle k_T^2\rangle}$$

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

Basic questions at low energies:

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

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

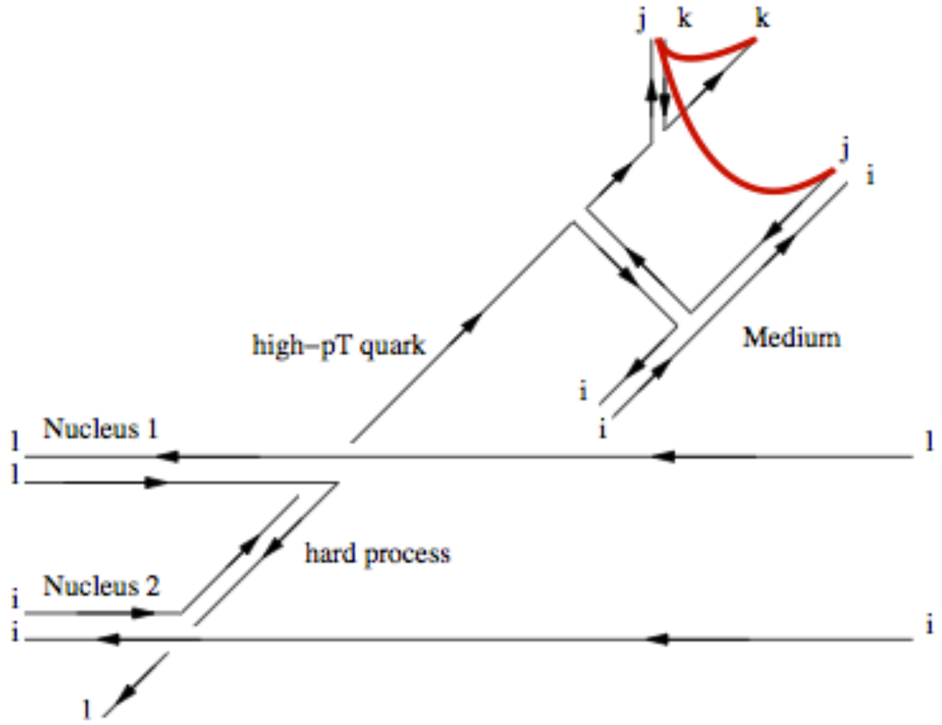
What can we infer about fundamental QCD processes by observing the interaction with the nucleus?

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

Color correlations versus kinematics

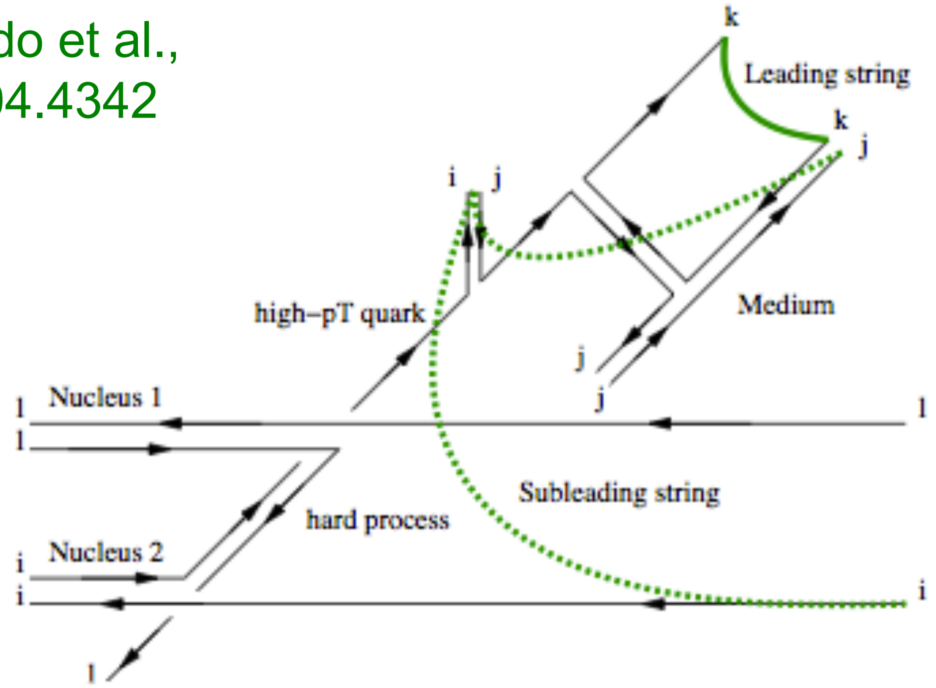
Even if hadron forms outside medium, it may form from modified color connection

- Vacuum-like hadronization
  (q & g contribute to leading hadron)



- Medium-modified hadronization
  (glue cannot contribute to leading hadron)

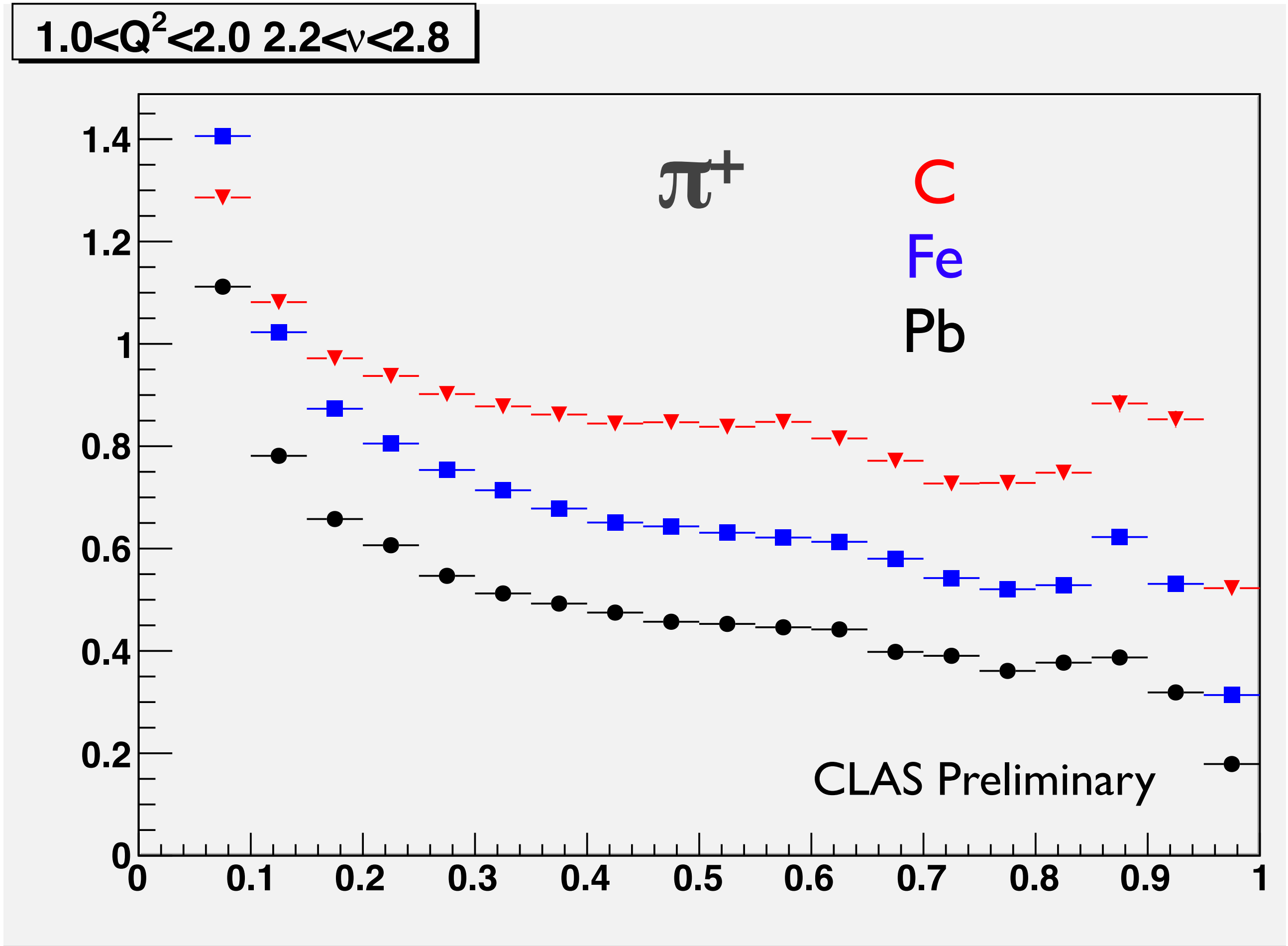
A. Beraudo et al.,
arXiv:1204.4342

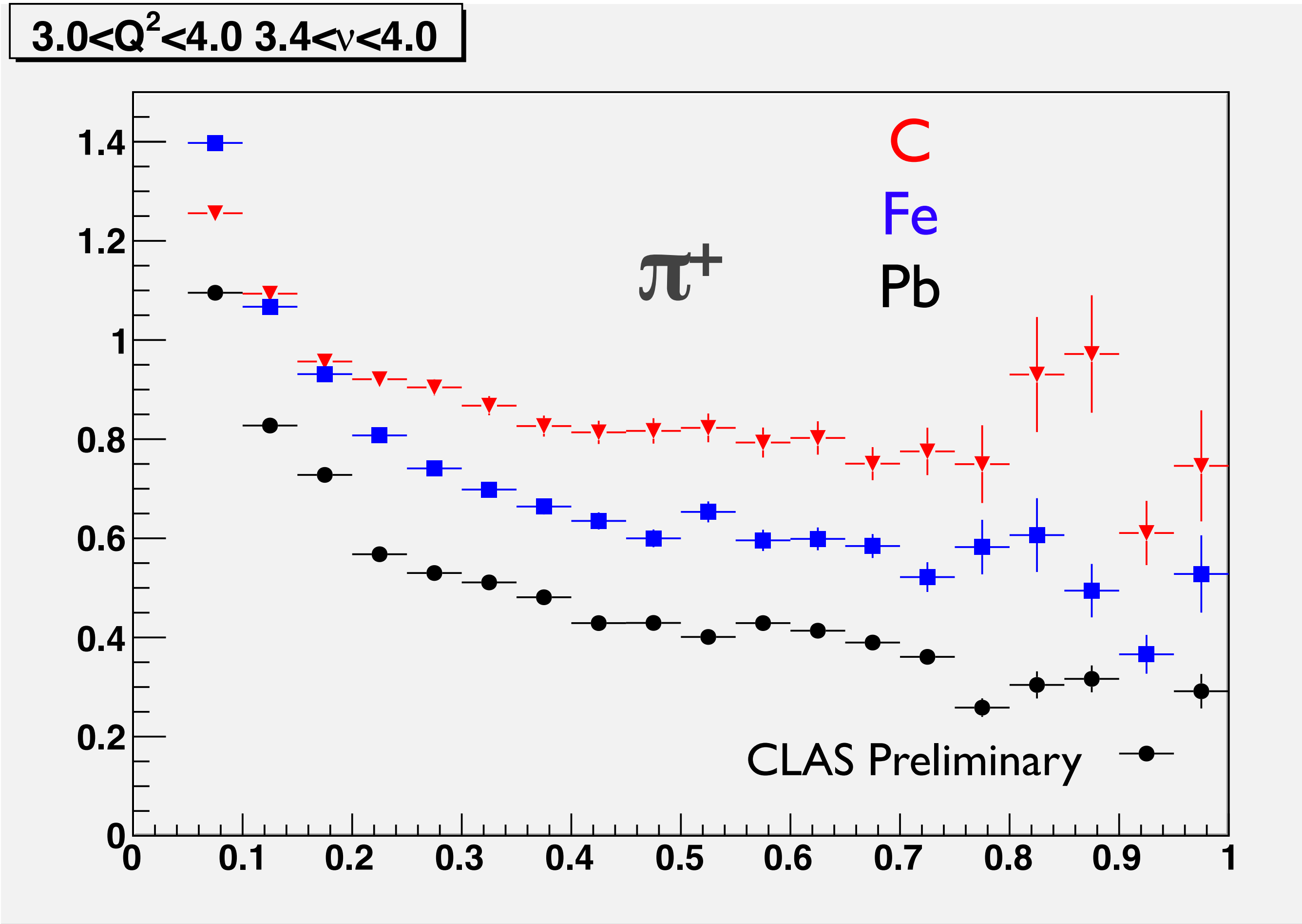


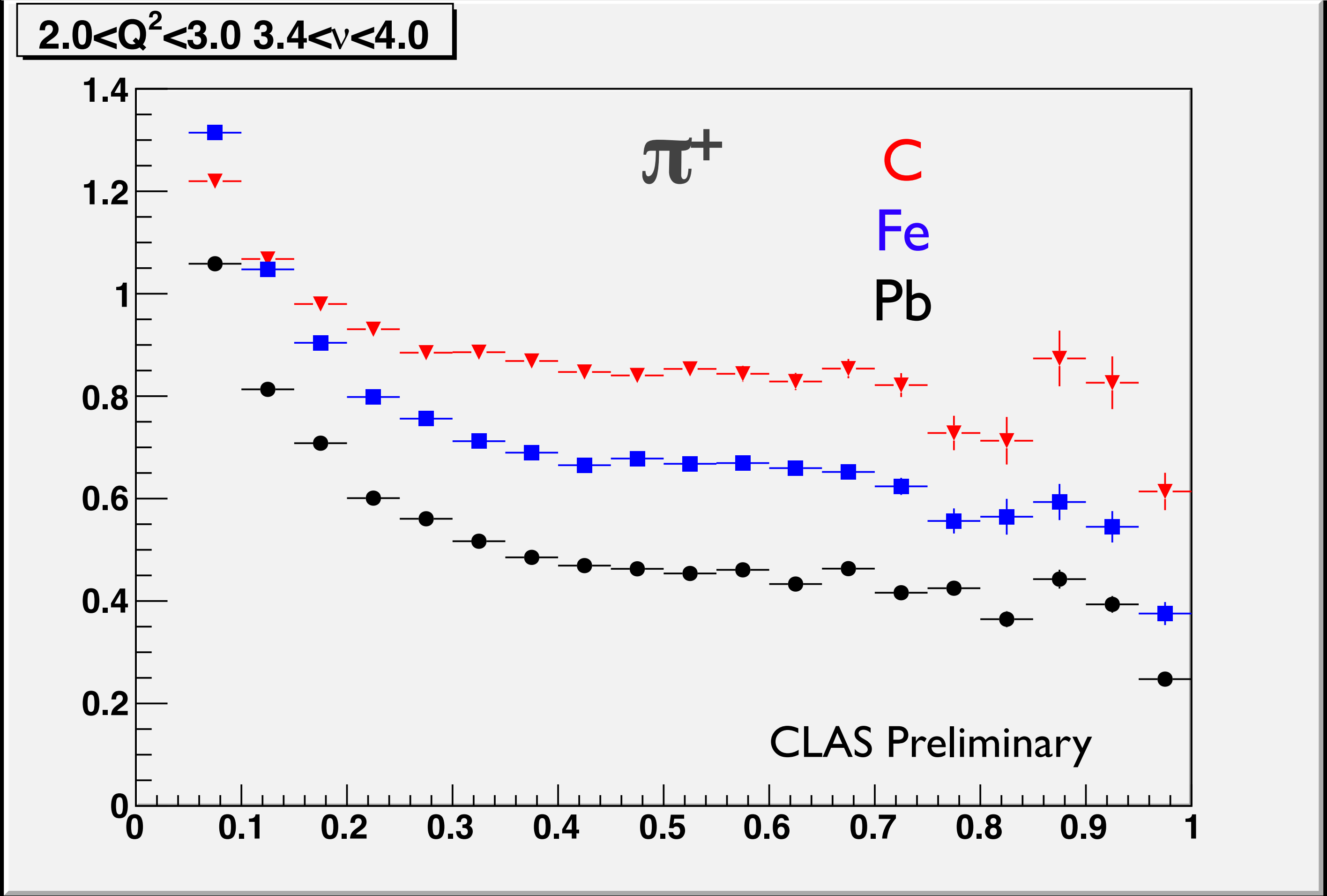
- Subleading string hadronizes separately
  -> enhanced soft multiplicity
- Leading string hadronizes vacuum-like
  but with reduced E_T

- Color connection between medium and probe
  also relevant for Quarkonium suppression

U.A.Wiedemann talk at QM2012







3-dimensional CLAS multiplicity ratios, fully corrected for radiative processes and acceptance, normalized to target thicknesses; C, Fe, Pb (3 of many such plots)

also, K^0, π^0, π^-

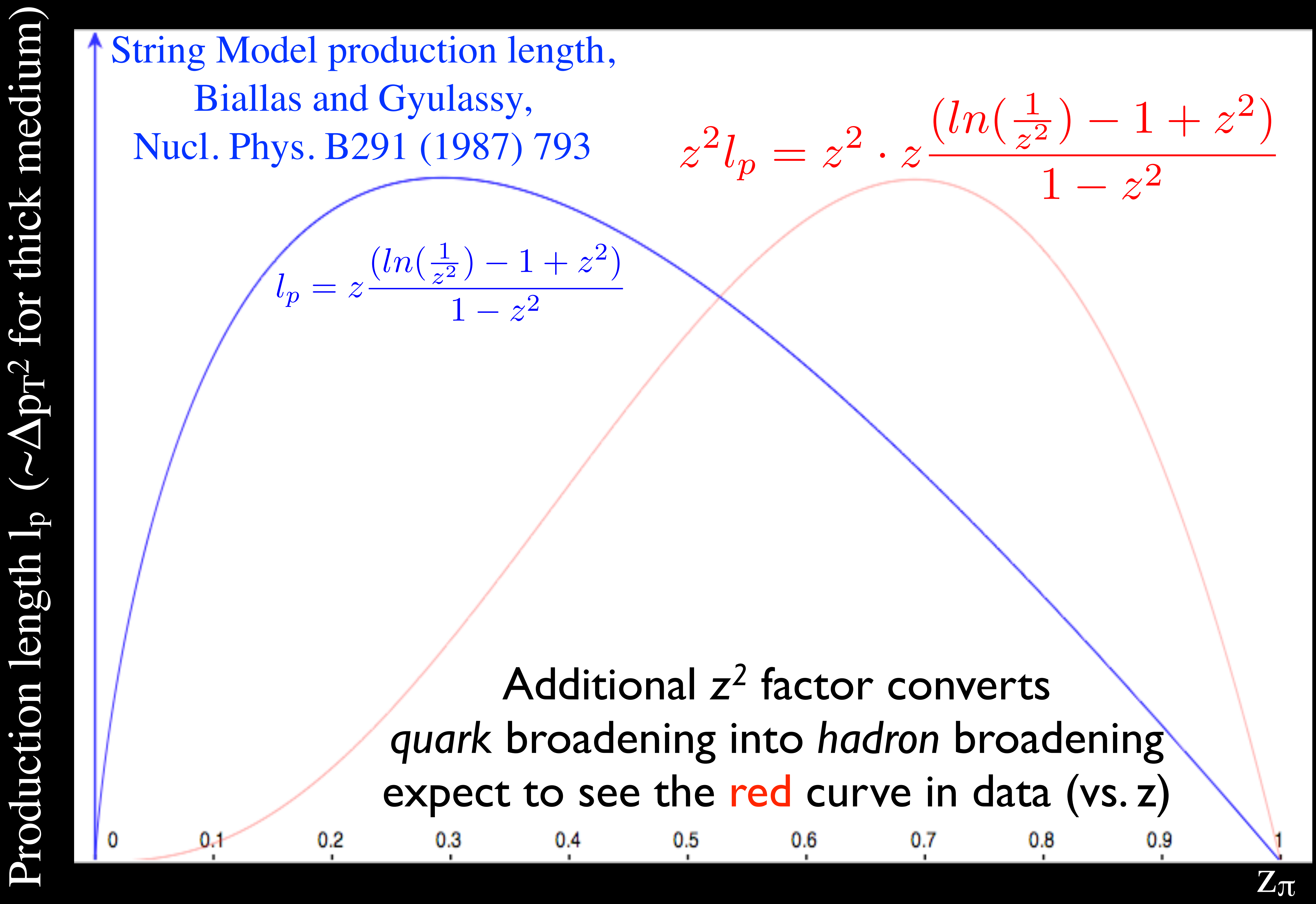
HERMES, JLAB6, JLAB12, p-A, EIC

- Two different explanations for HERMES data, no definitive differentiation yet

- parton energy loss, pre-hadron interaction with medium

- Models based on one view or the other, or a mixture, all describe the data at a similar level of quality

- EIC important to make a clear separation between hadronic and partonic effects



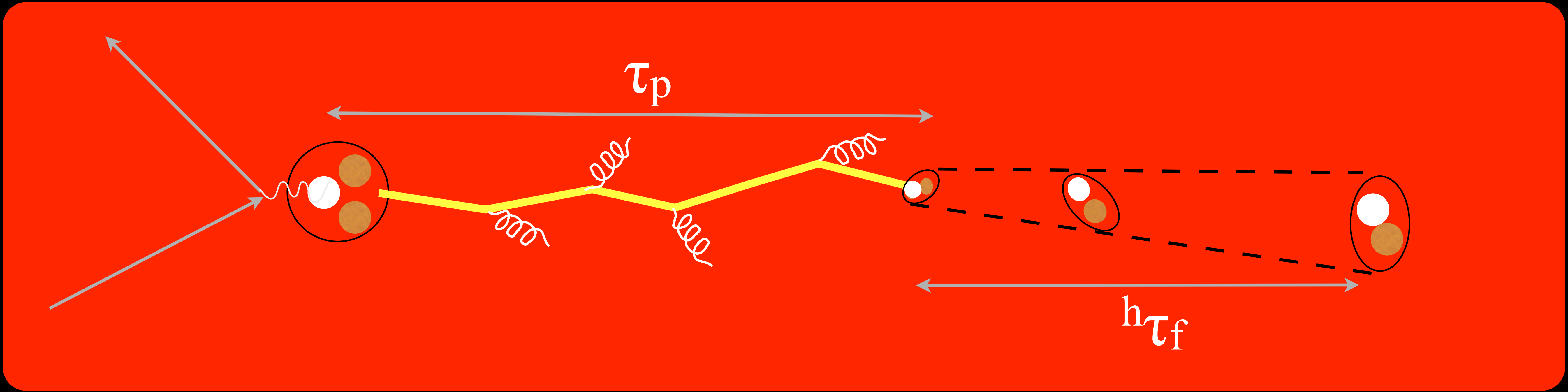
String Model production length,
Biallas and Gyulassy,
Nucl. Phys. B291 (1987) 793

$$l_p = z\frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$$

$$z^2 l_p = z^2 \cdot z\frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$$

Additional z^2 factor converts
quark broadening into *hadron* broadening
expect to see the red curve in data (vs. z)

Deep Inelastic Scattering - Vacuum



- *production time* t_p - propagating quark
- *formation time* ^ht_f - dipole grows to hadron
- *partonic energy loss - dE/dx via gluon radiation in vacuum*

Exploring nuclei with partonic probes

- $x>0.1$
  - *ensures single quark propagating with initial energy ν*
- p_T broadening tags propagation of colored object
  - *extraction of "production time"/"color neutralization time" at low ν*
- inference of partonic broadening from hadronic broadening
  - *requires factor of z^2*
- systematic studies needed to understand properties of the probe, currently ongoing
  - *HERMES, JLab6, JLab12 provide the foundation for EIC studies*