e-A at Large x: Applying Parton Propagation Methods to Investigate QCD Fragmentation, Quantum Fluctuations, and Heavy Quark Energy Loss

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in collaboration with

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Outline

- Exploring cold nuclear matter using colored partonic probes
  - *Fragmentation properties, quantum fluctuations*
- The intensifying puzzle of heavy quark energy loss
  - *EIC role is crucial*
- Suppression of fragmentation hadrons in nuclei: elusive mechanism or hidden duality?
  - *Wide kinematic extremes of EIC will clarify this*

- Goal: study properties of parton propagation and fragmentation in QCD:
  - *Characteristic timescales*
  - *Partonic energy loss*
  - *Quantum interference effects in hadronization*
  - *Current vs. target fragmentation*
  - *Partonic vs. hadronic interactions*
  - *Eventually: hadronization mechanisms*

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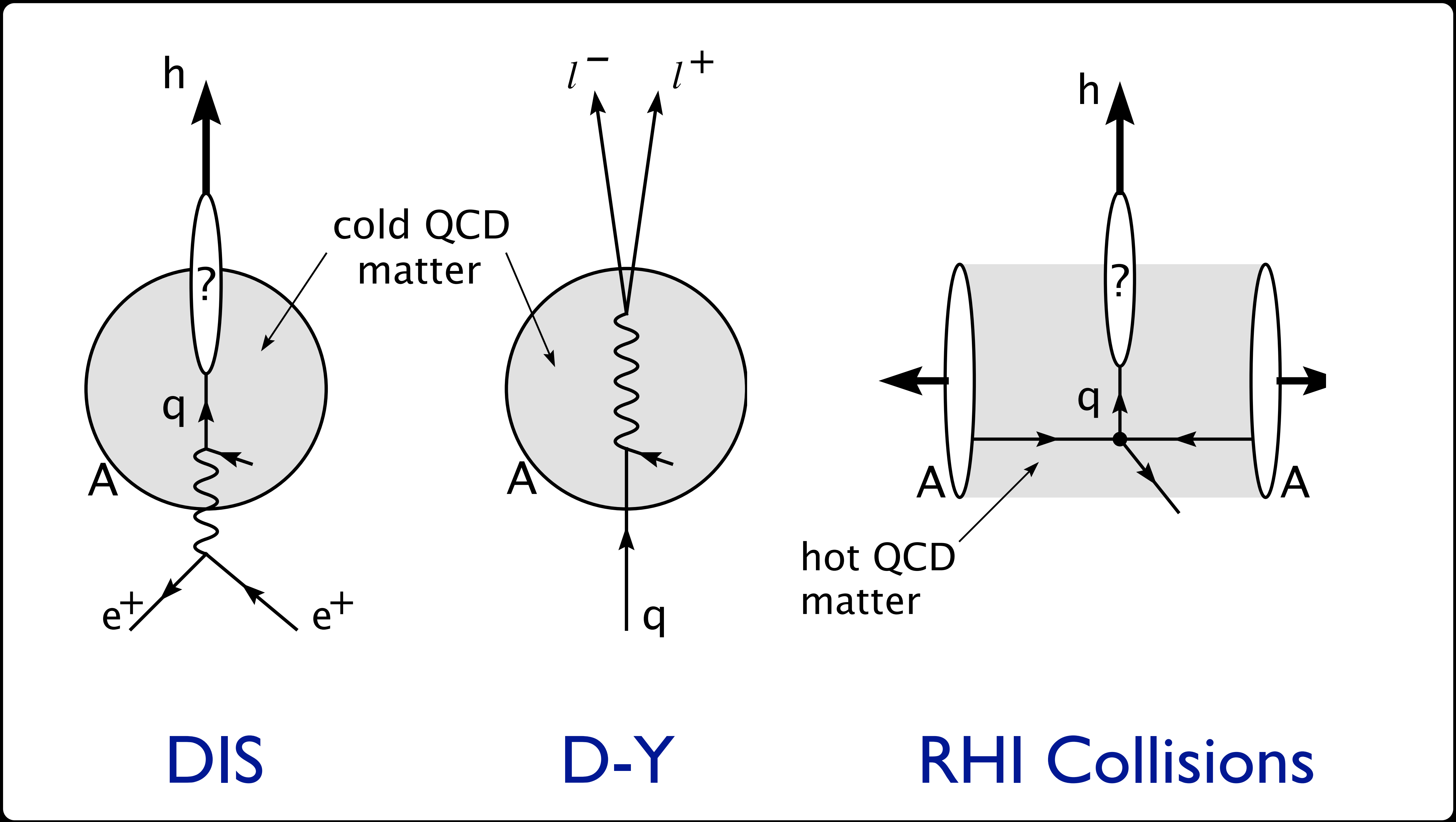
- *Unique kinematic window* at low energies
- *Simpler physical picture* at high energies

Comparison of Parton Propagation in Three Processes



Accardi, Arleo, Brooks, d'Enterria, Muccifora Riv.Nuovo Cim.032:439-553,2010 [arXiv:0907.3534]
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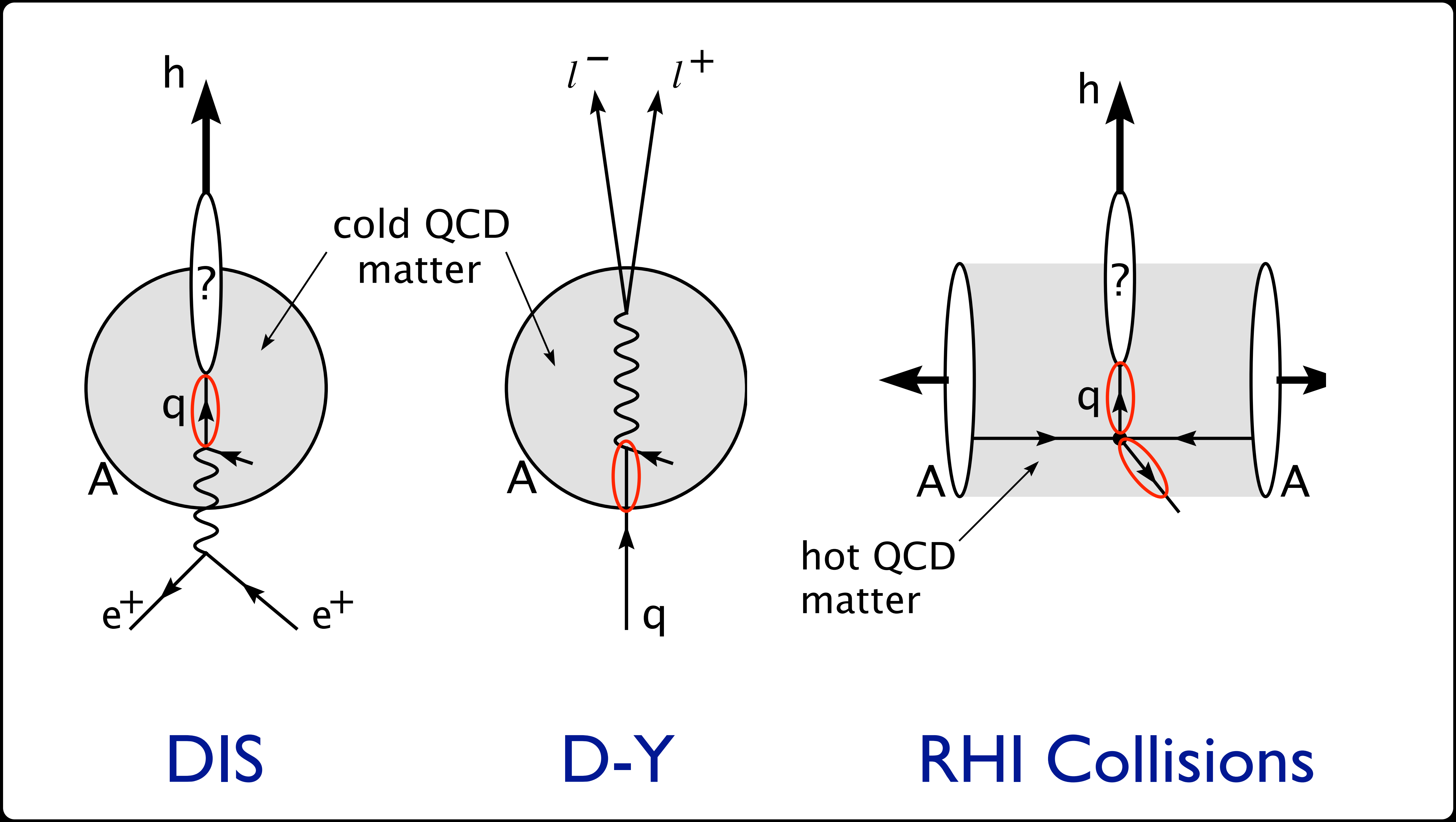

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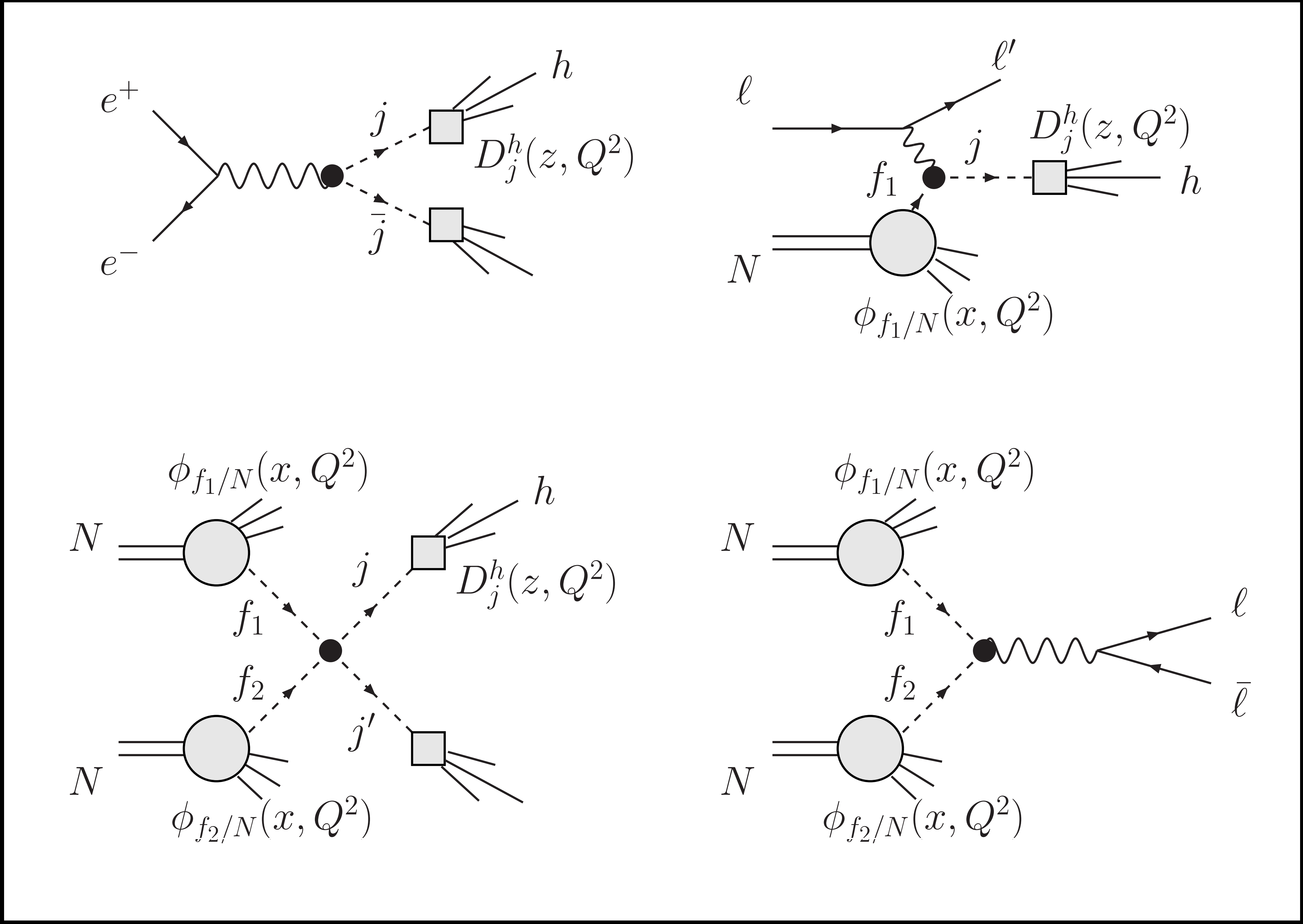
Fundamental ingredients in perturbative picture



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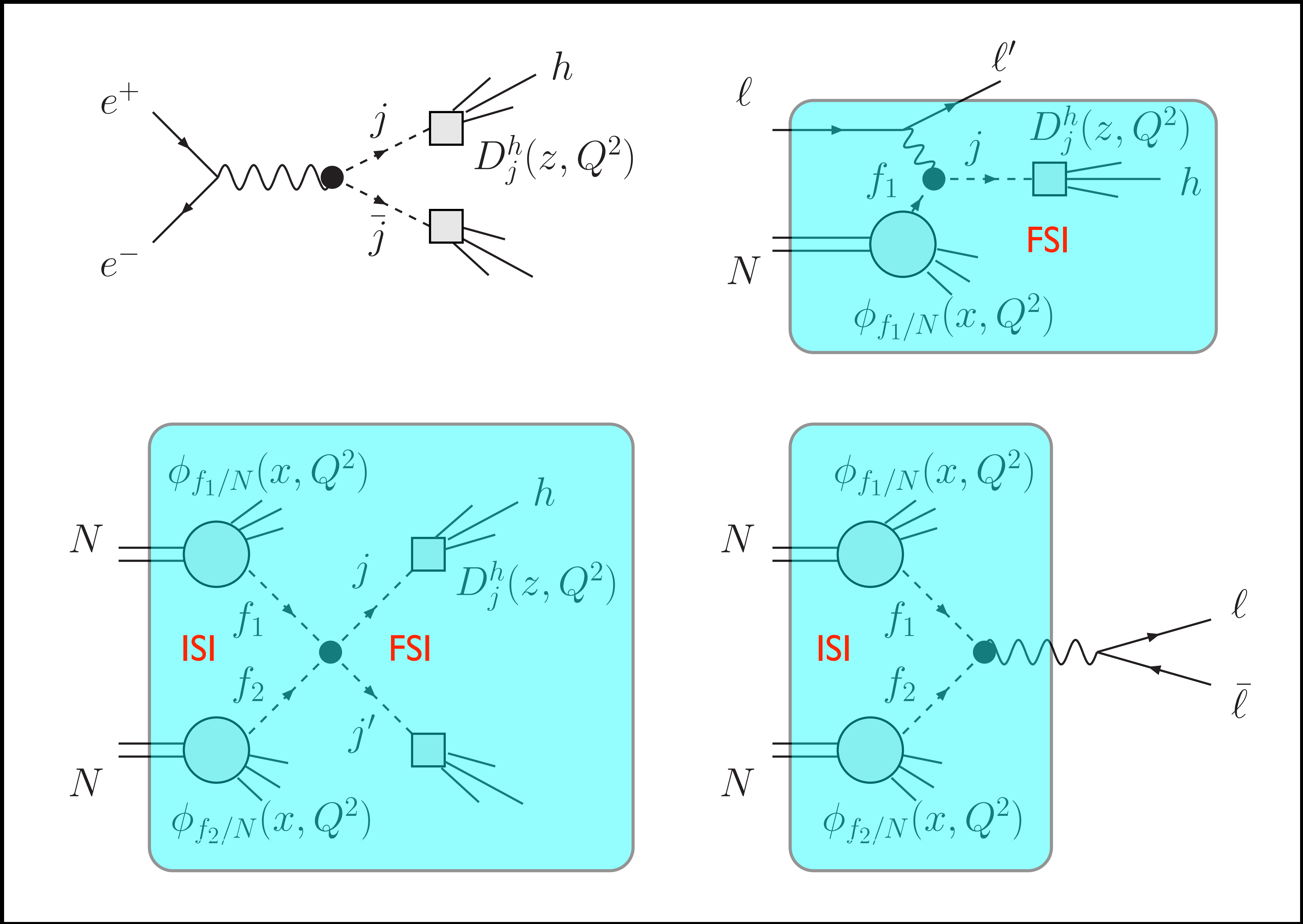
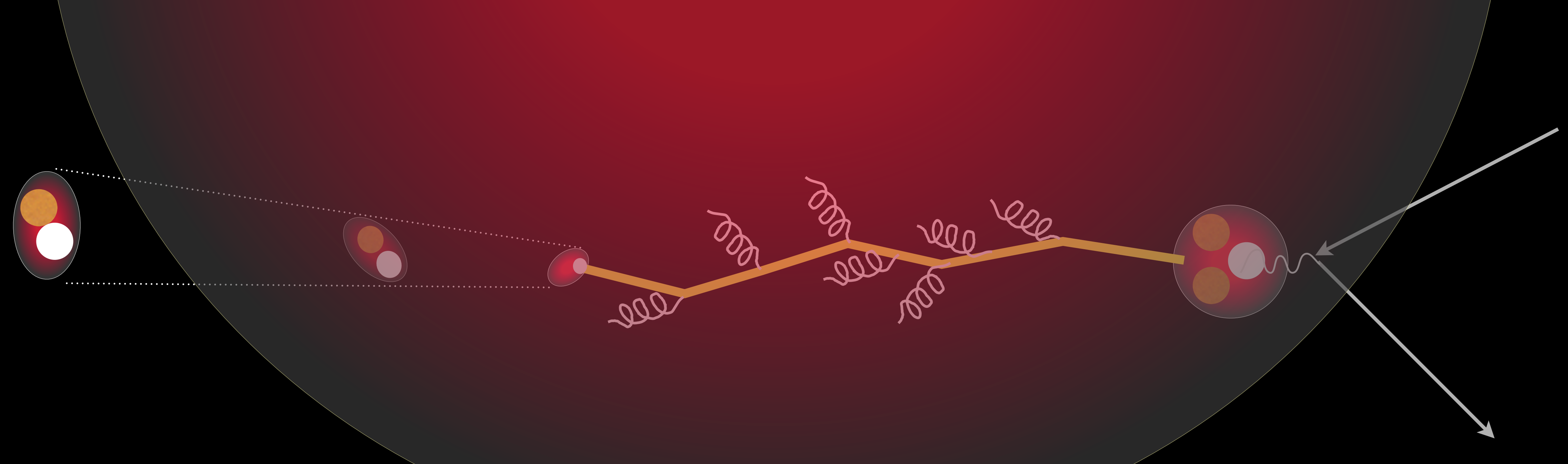
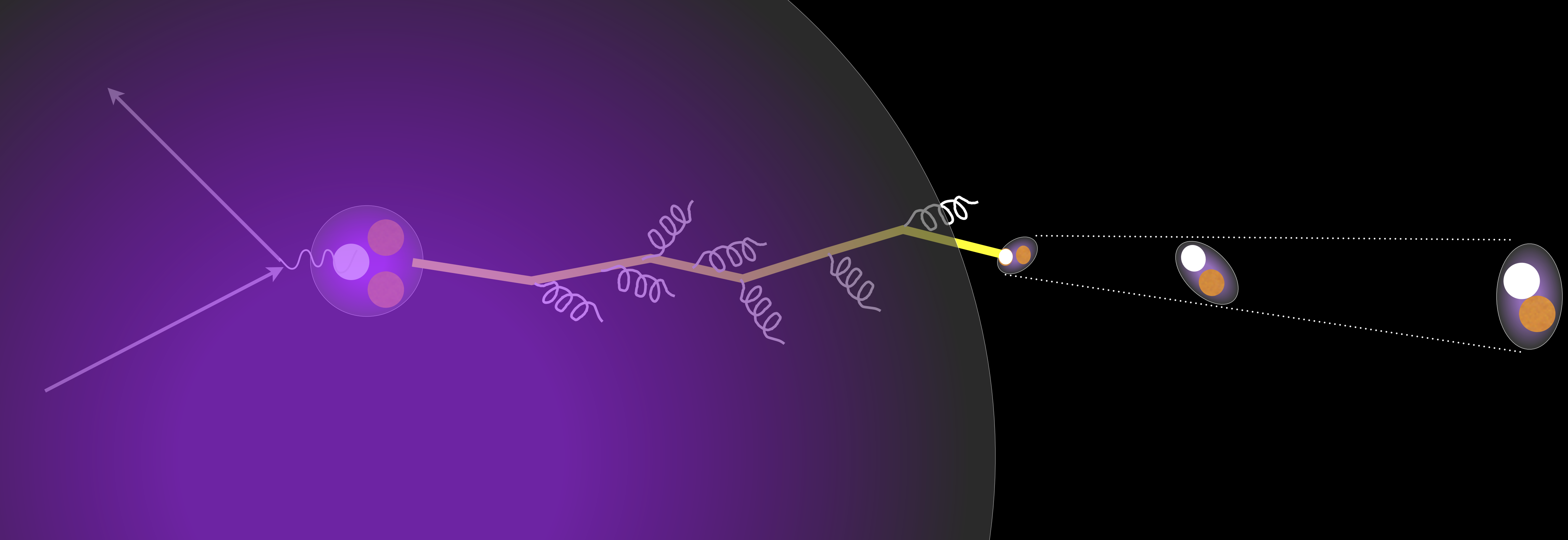




Exploring cold nuclear matter using colored partonic probes

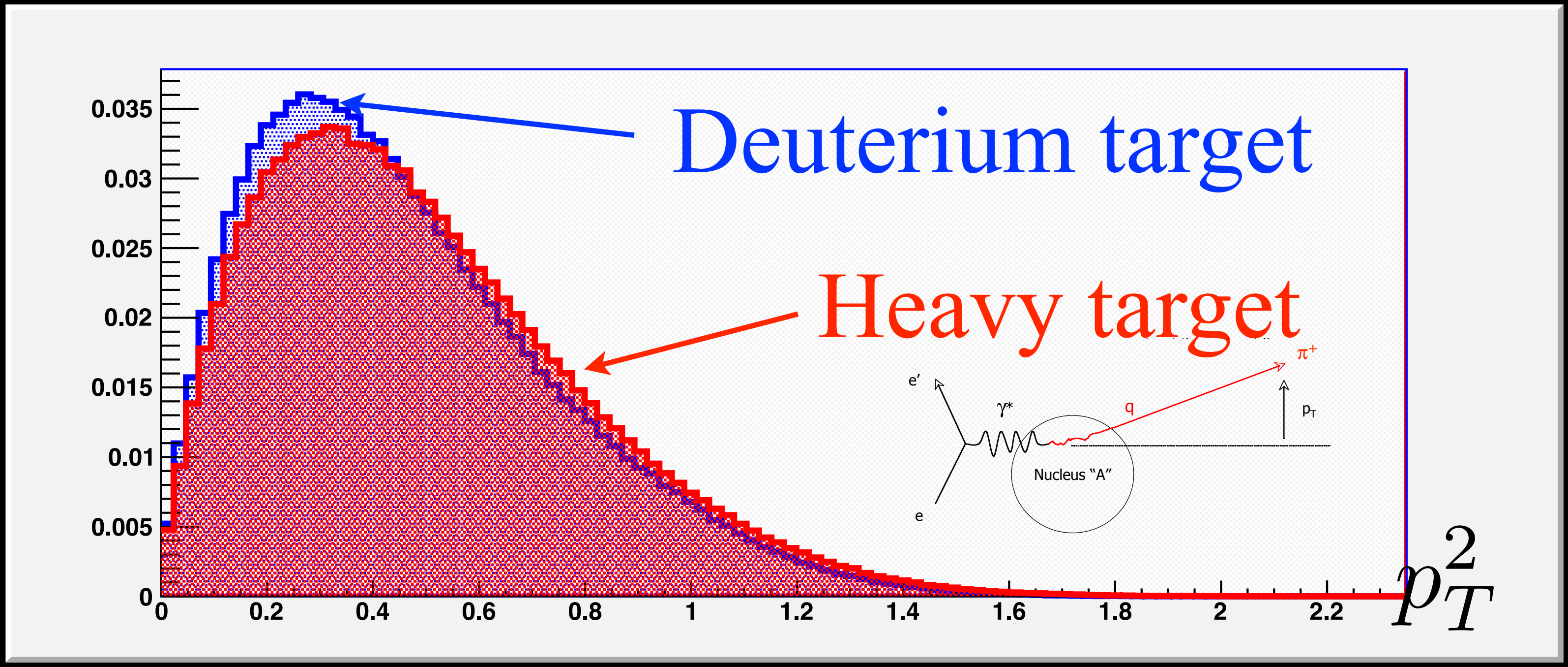


DIS Observables

Transverse momentum broadening:

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

Hadronic multiplicity ratio - defined later



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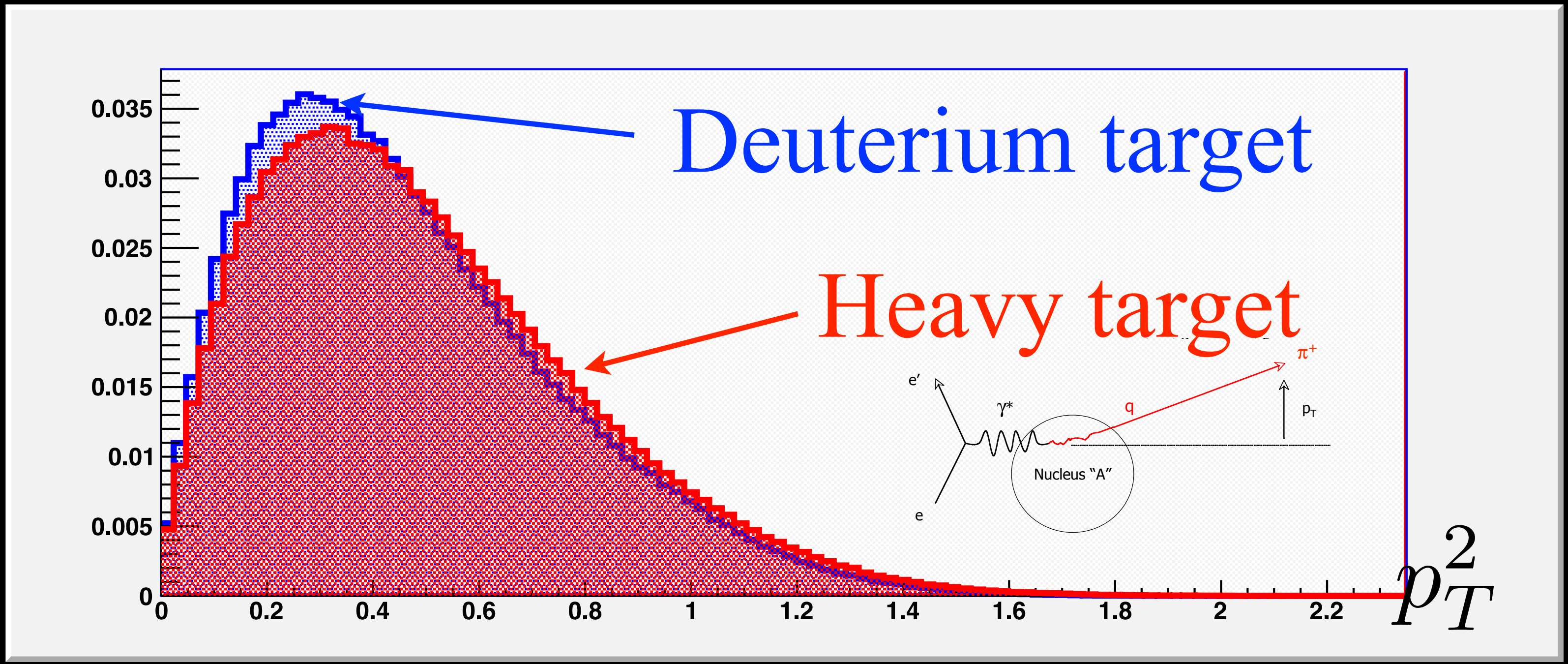


Multi-hadron multiplicity ratios

Hadron-photon correlations

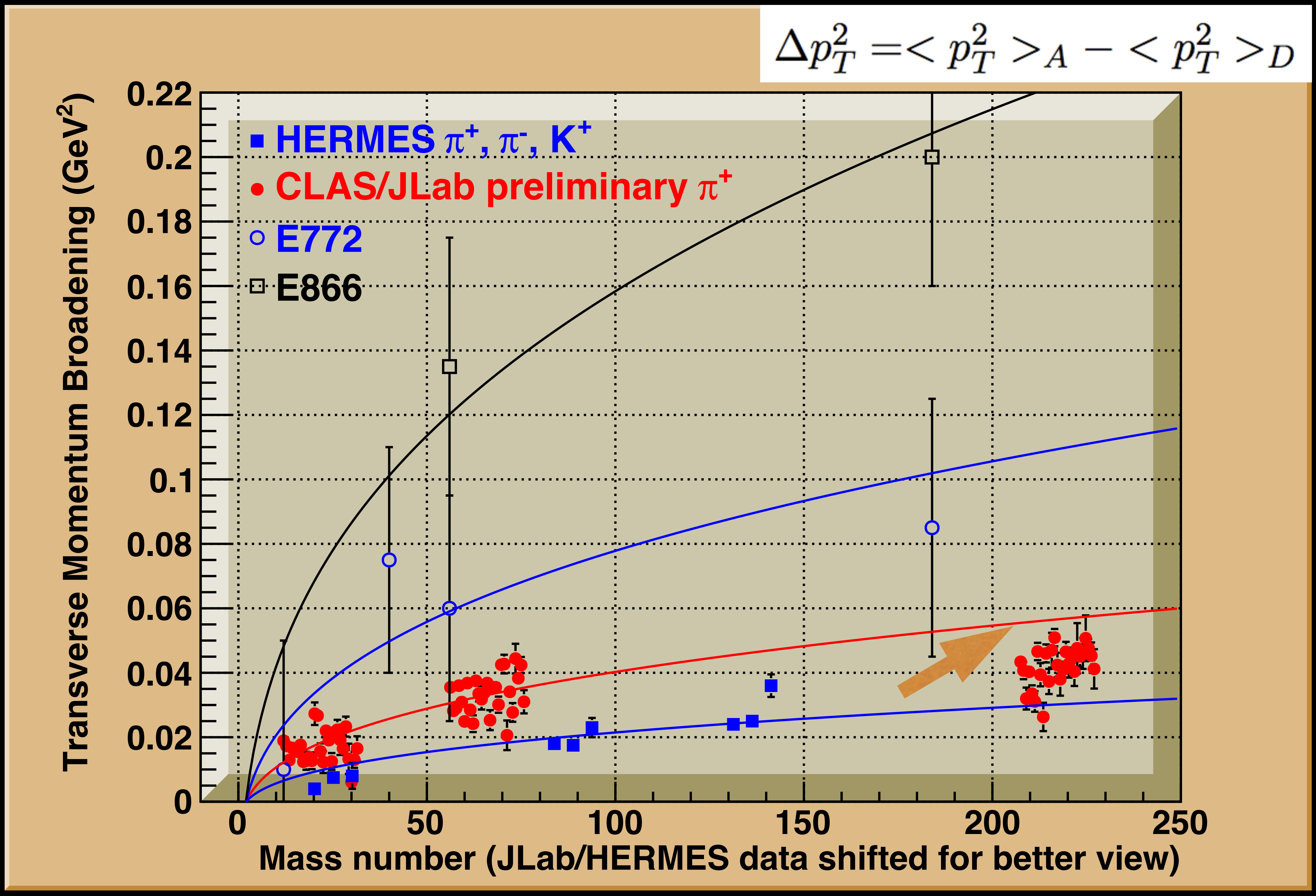
Bose-Einstein correlations

Centrality correlations

more....

not in this talk.....

Comparison of p_T broadening data - Drell-Yan and DIS

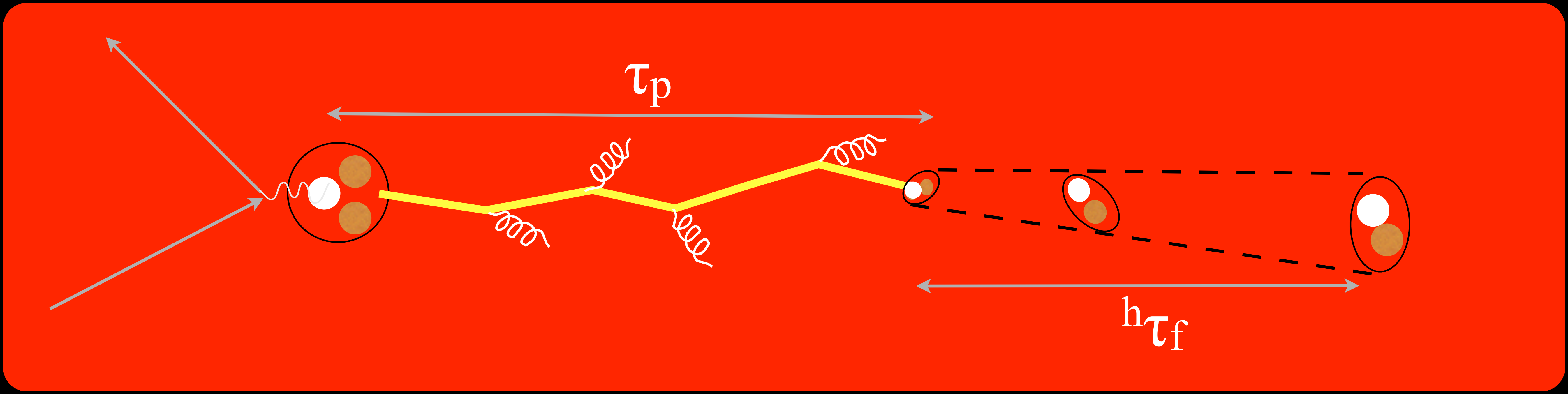


- New, precision data with identified hadrons!
- CLAS π^+: 81 four-dimensional bins in Q^2, ν, z_h, and A

Exploring nuclei with partonic probes

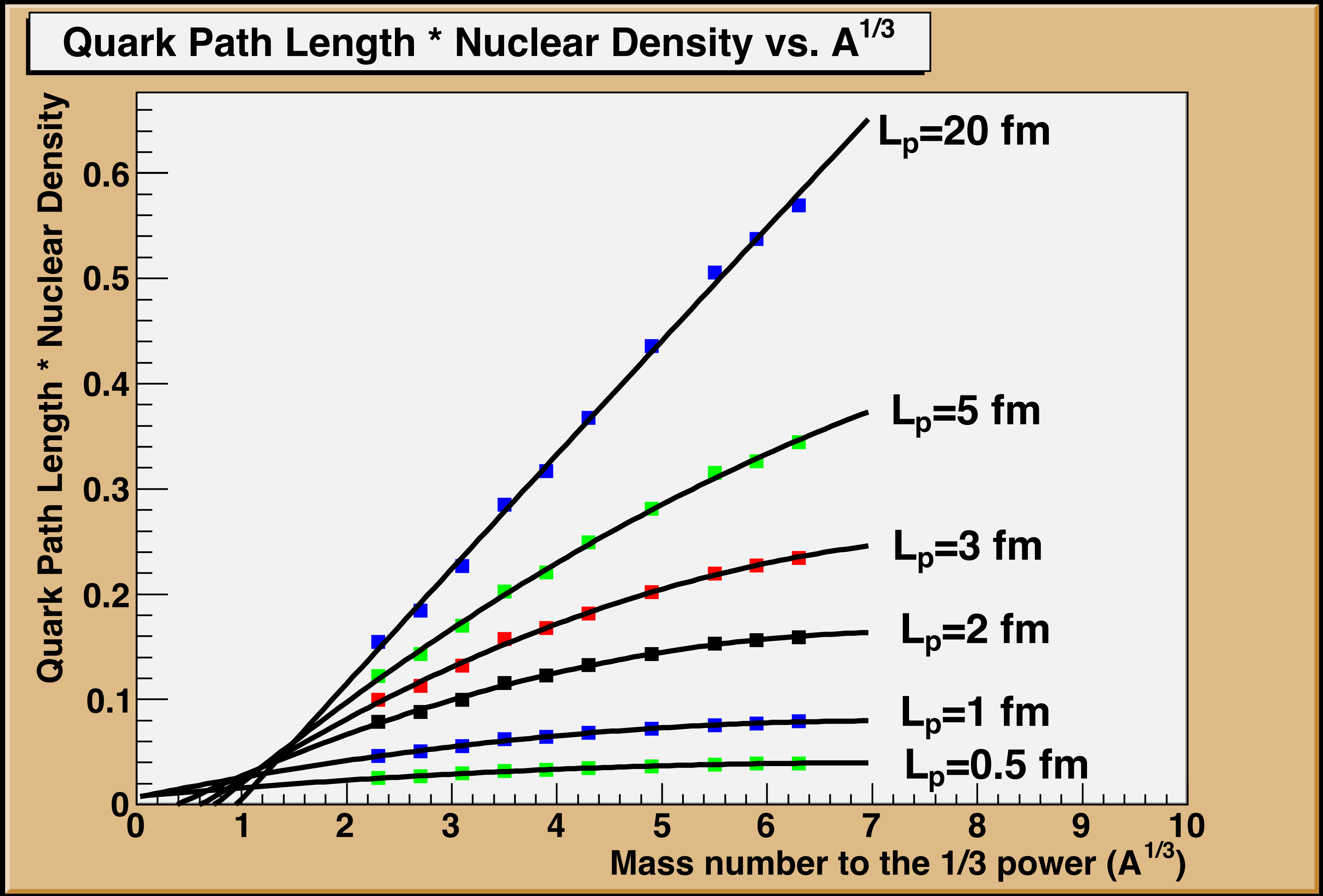
- x>0.1
  - *ensures single quark propagating with initial energy ν*
- p_T broadening tags propagation of colored object
  - *extraction of "production time"/"color neutralization time" at low ν*
- inference of partonic broadening from hadronic broadening
  - *requires factor of z^2*
- systematic studies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

Deep Inelastic Scattering - Vacuum



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

Production Time Extraction - Geometrical Effects



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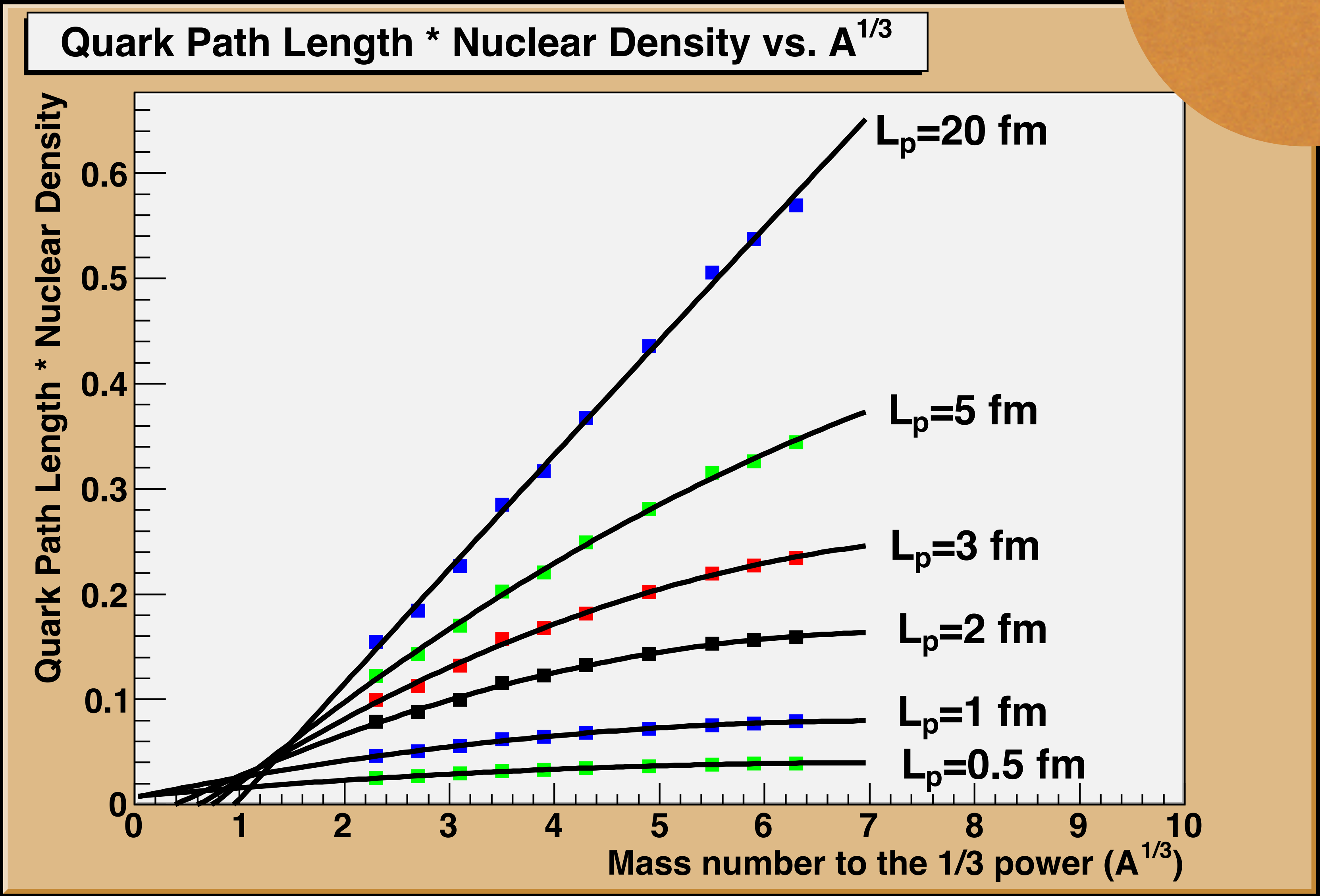

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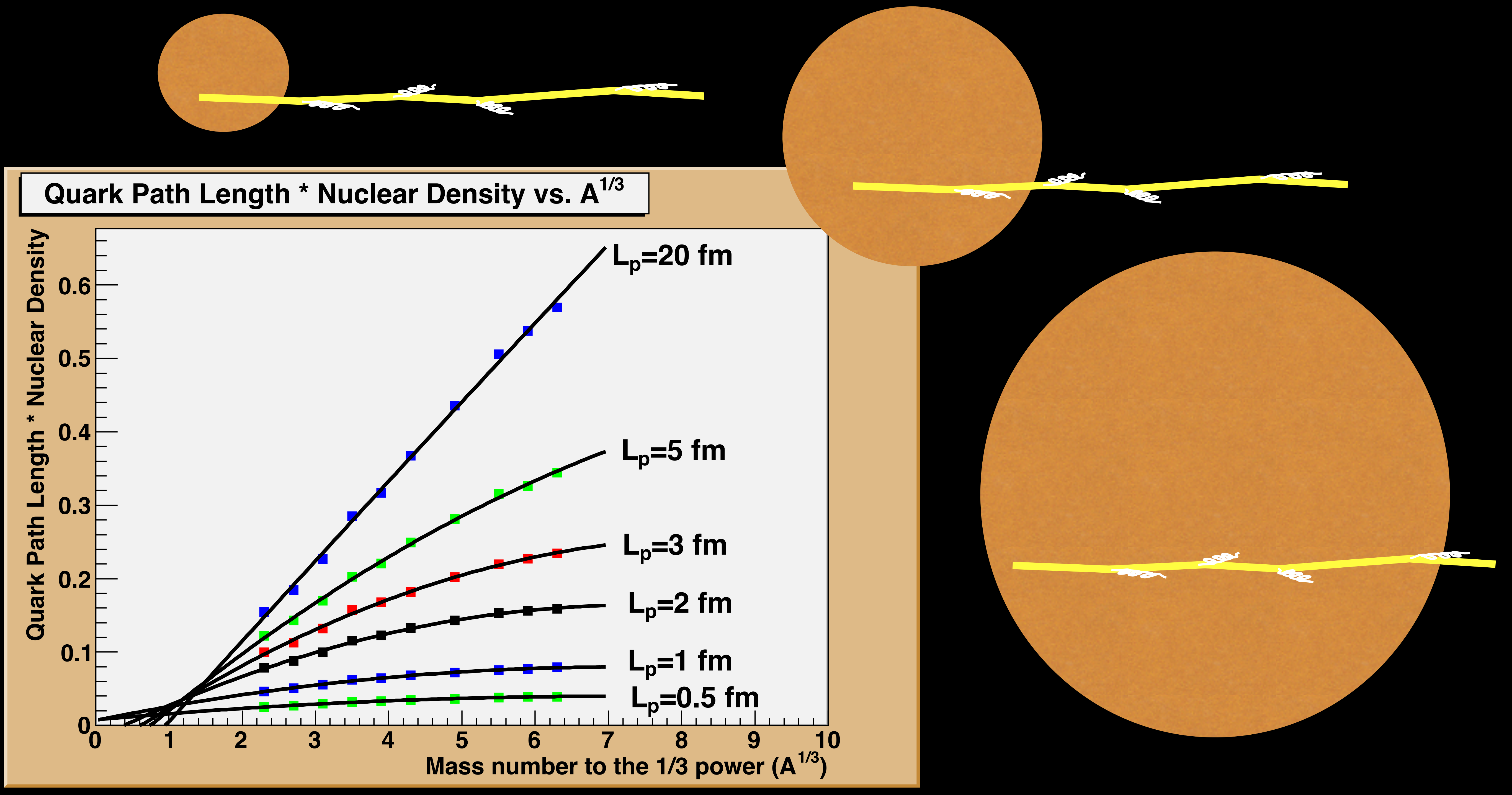

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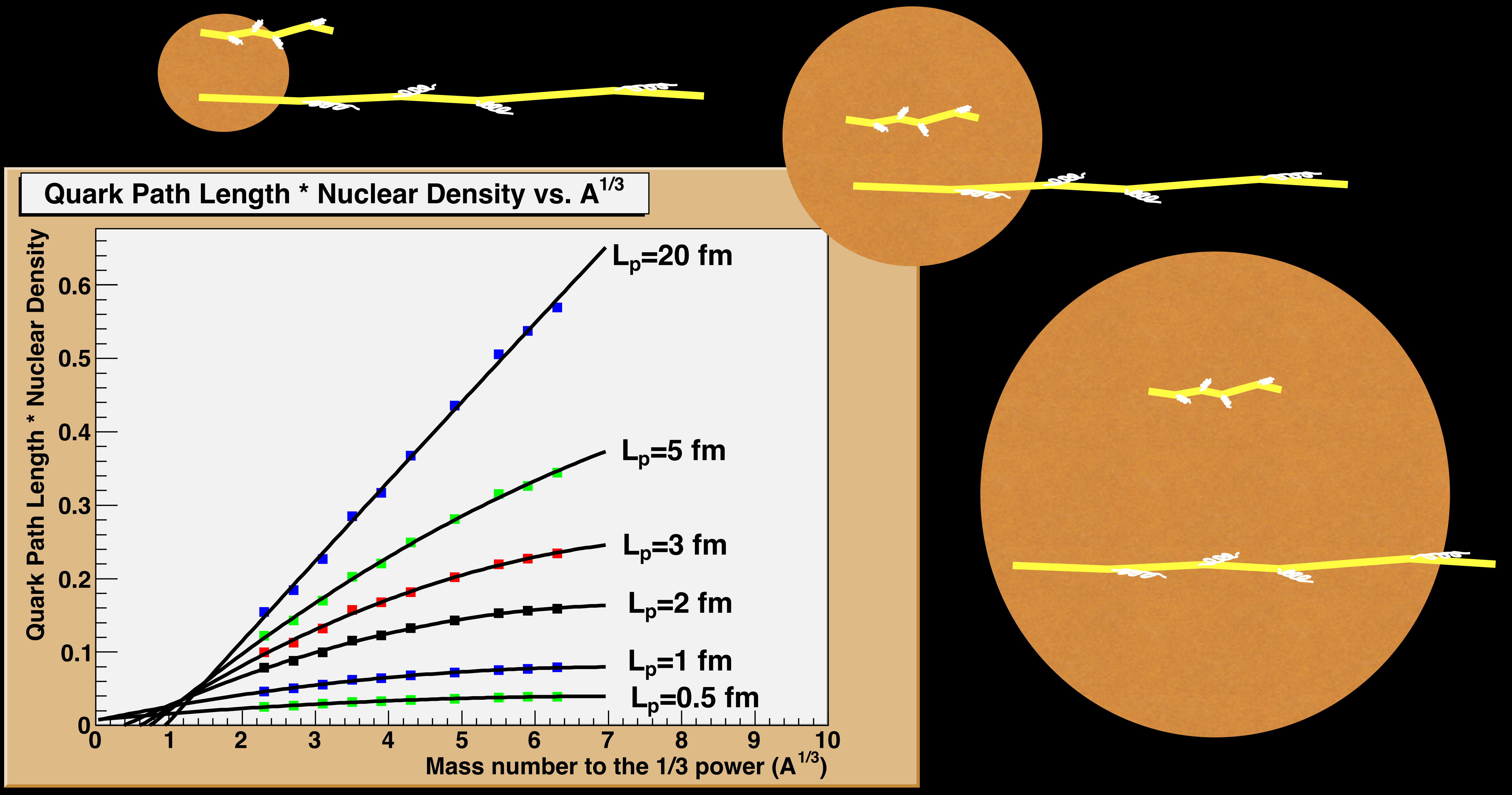

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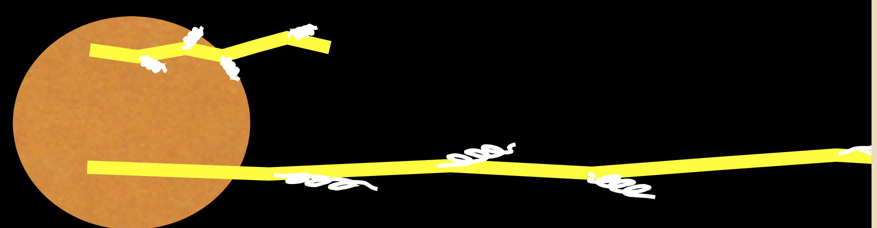
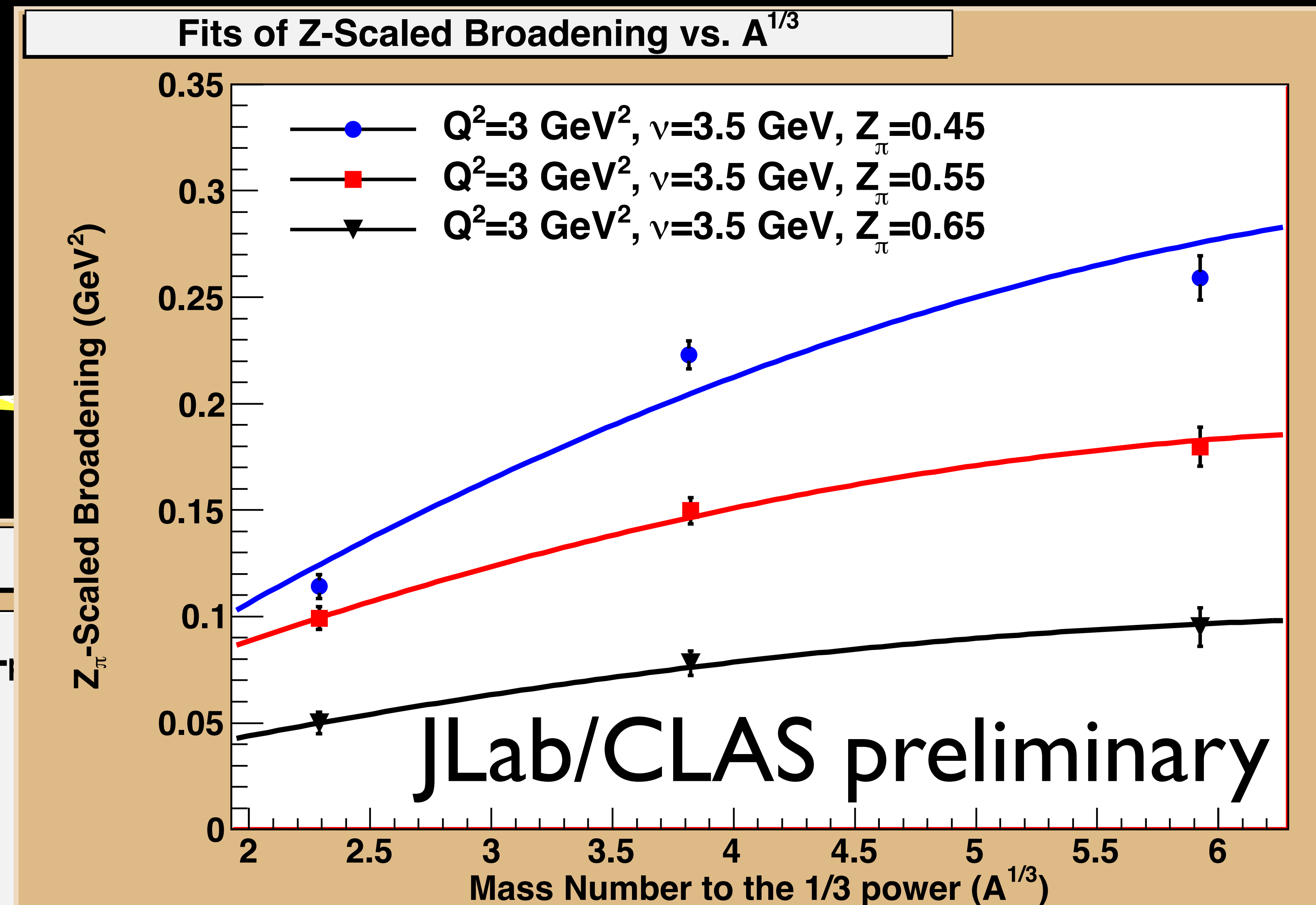
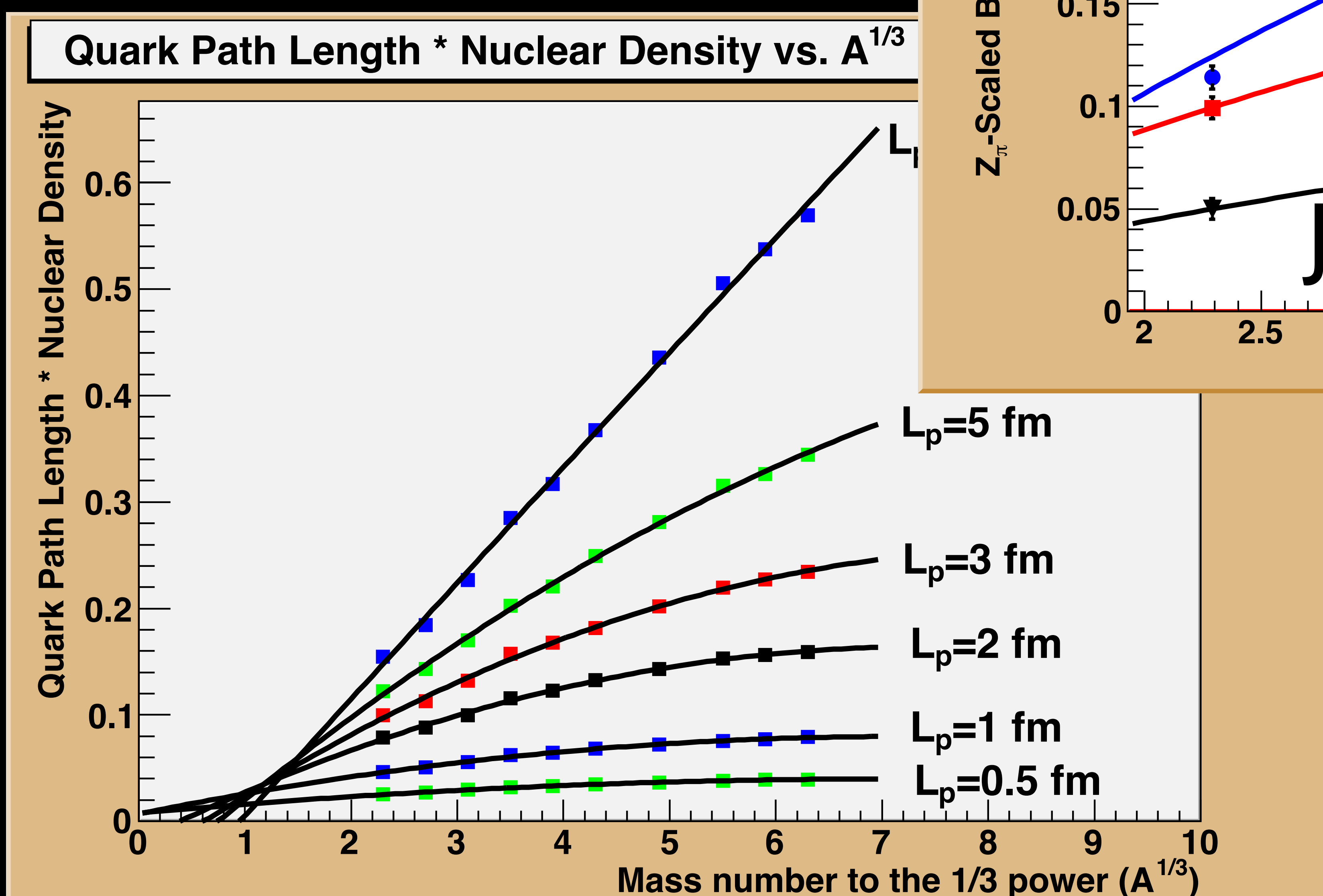
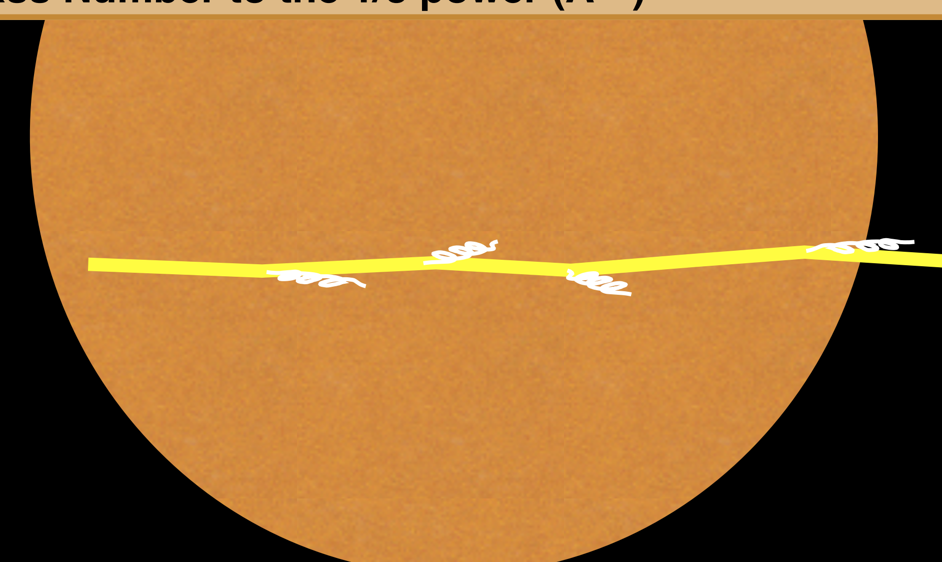




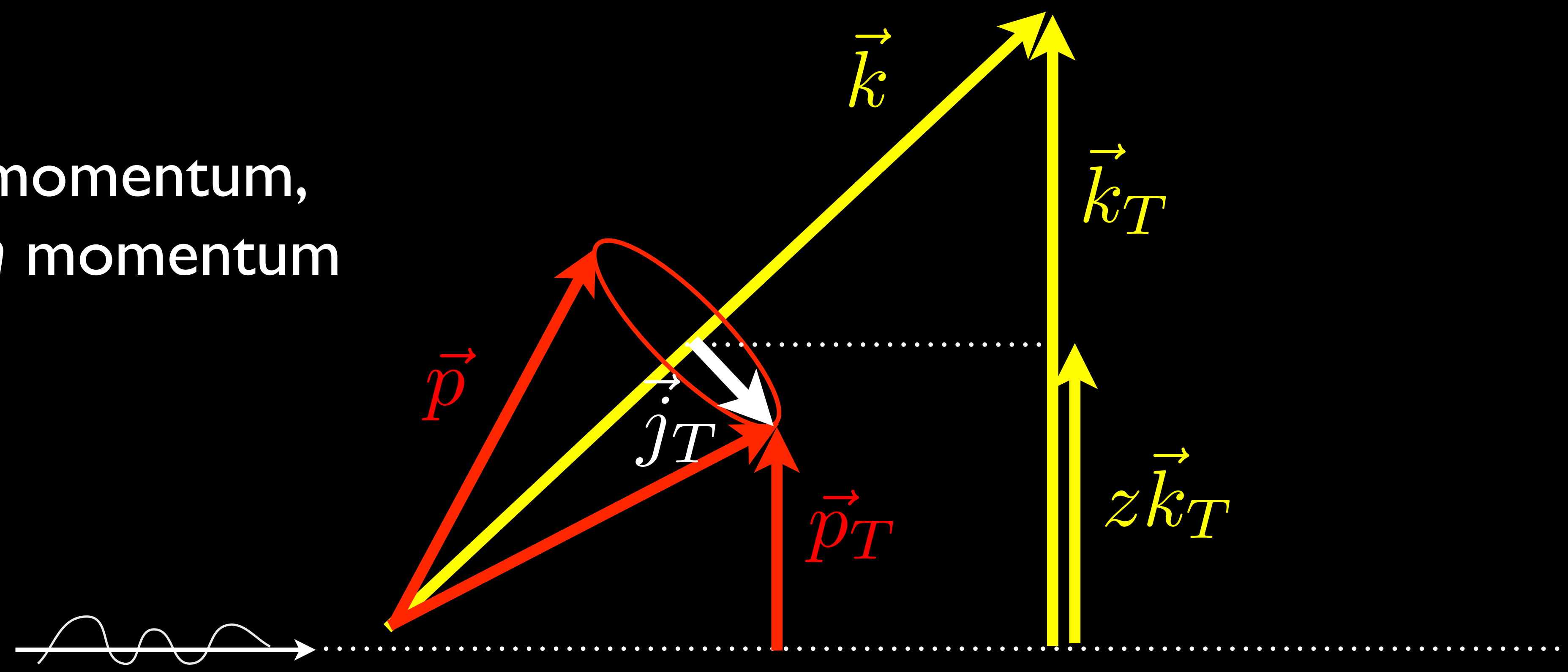




Quark k_T broadening vs. *hadron p_T* broadening

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

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



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

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

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

~0

$$\Delta\langle p_T^2 \rangle \approx z^2 \Delta\langle k_T^2 \rangle$$

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

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

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

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- Universal result in perturbative calculations

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e.g., http://arxiv.org/abs/hep-ph/0006326, http://arxiv.org/abs/1208.0751

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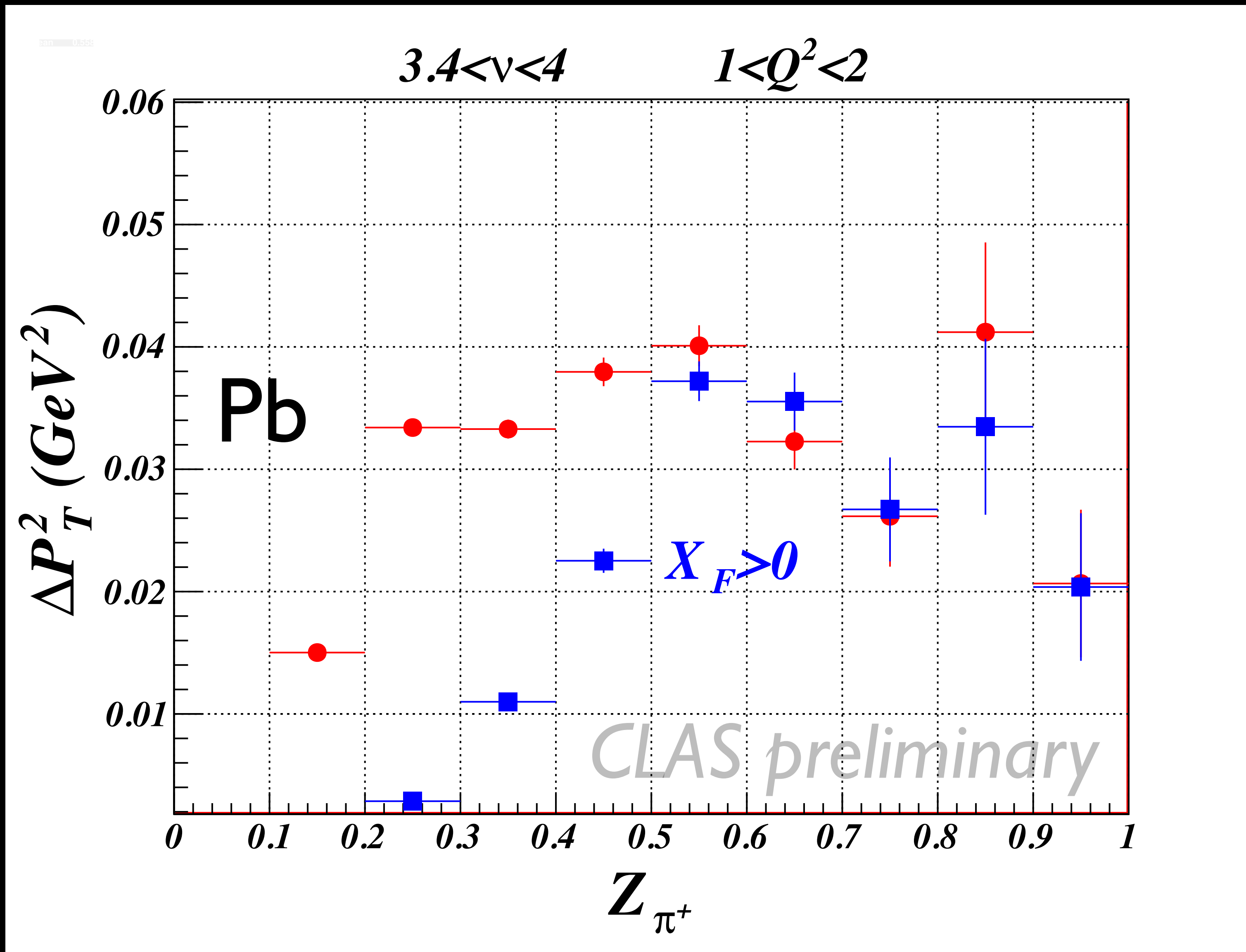
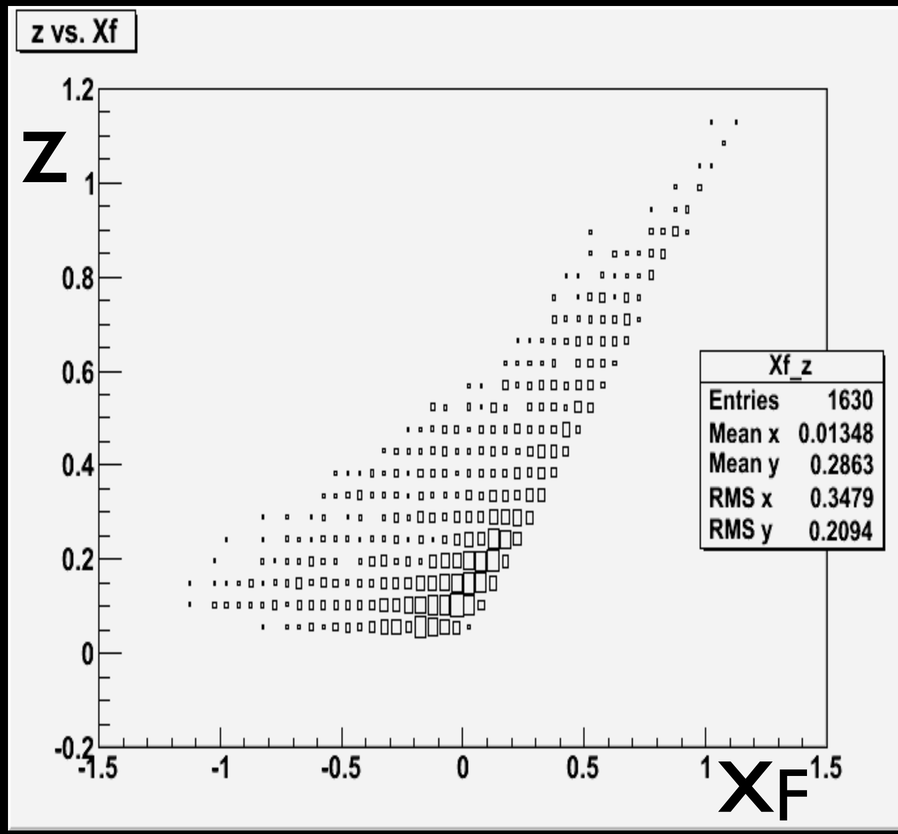
http://arxiv.org/abs/1001.4281

New: 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
- Separate current ($x_F>0$) and target ($x_F<0$) fragmentation
- First observation that *p_T broadening originates in both regimes*

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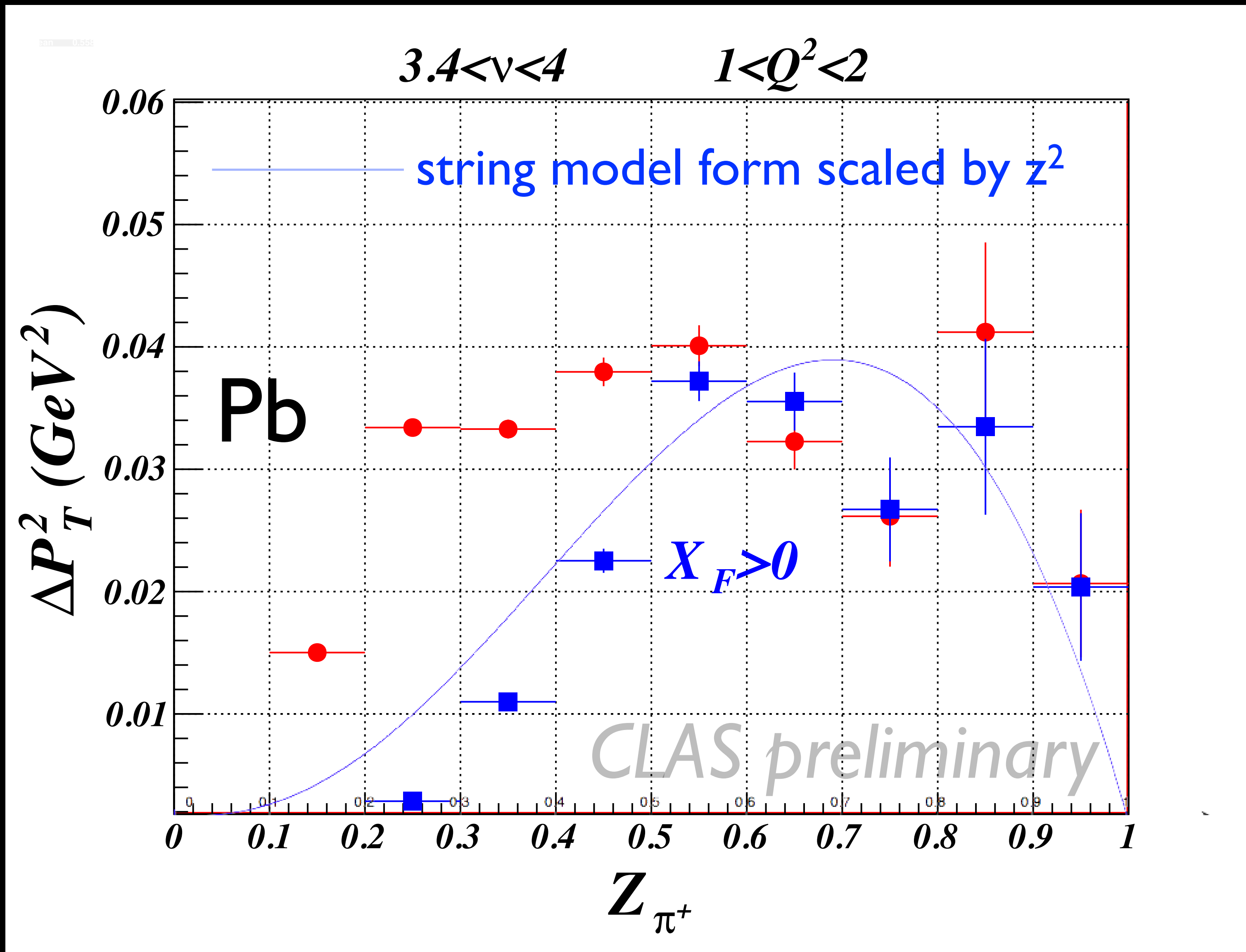

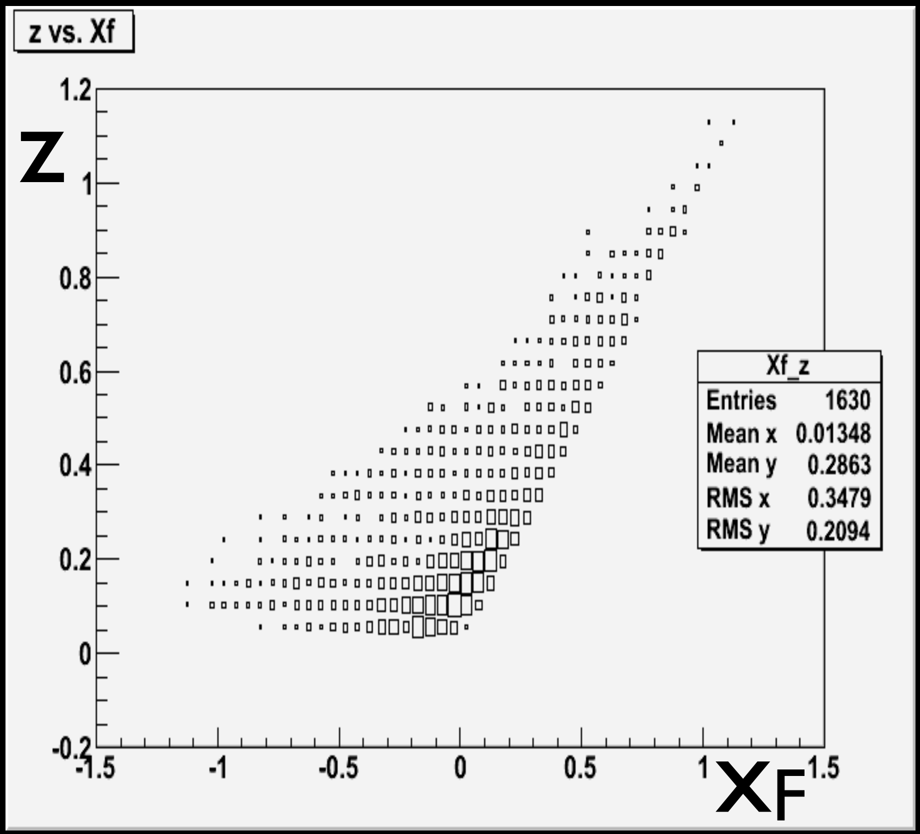

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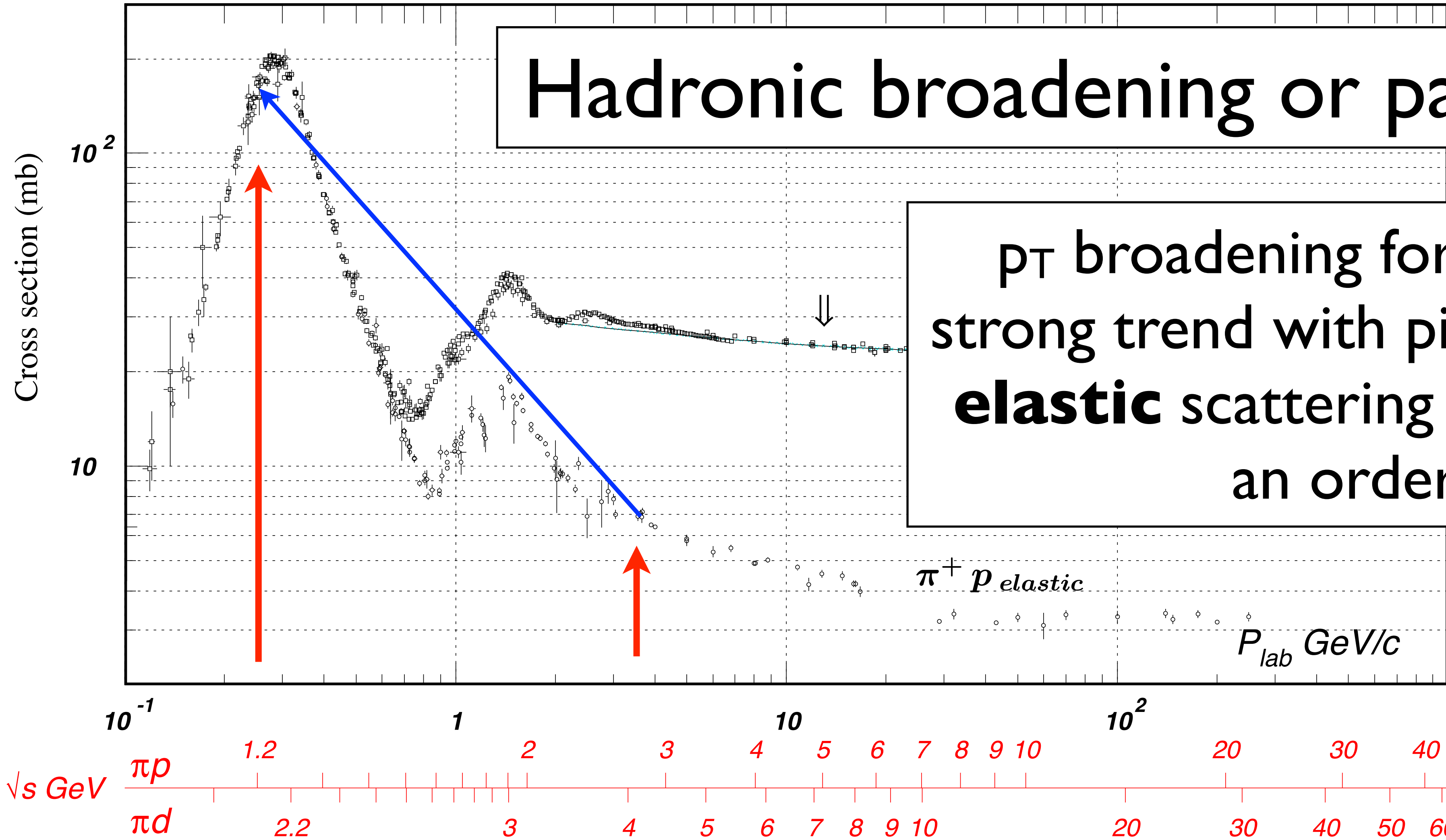
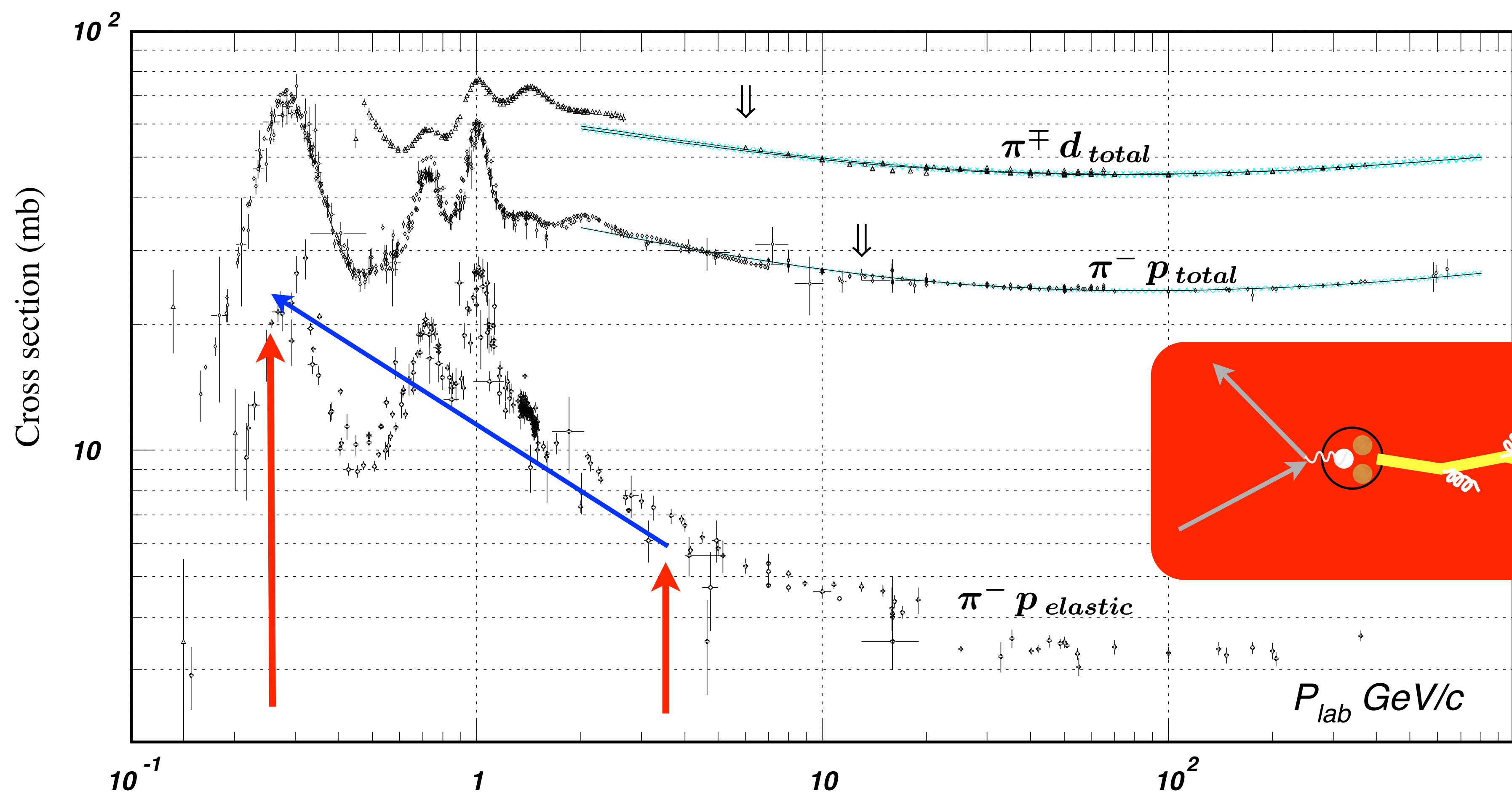
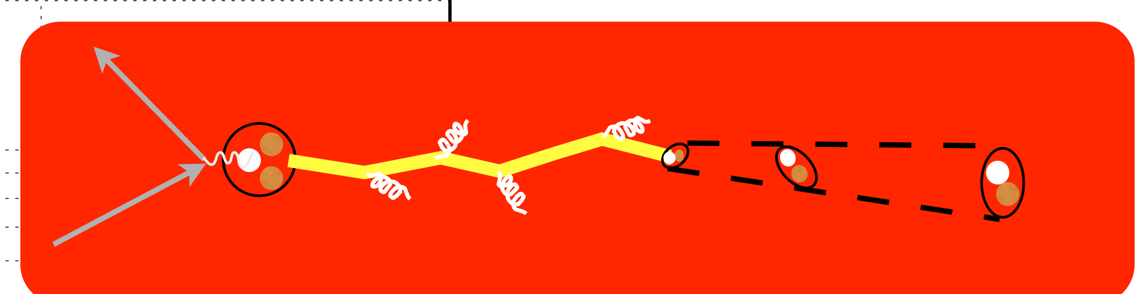
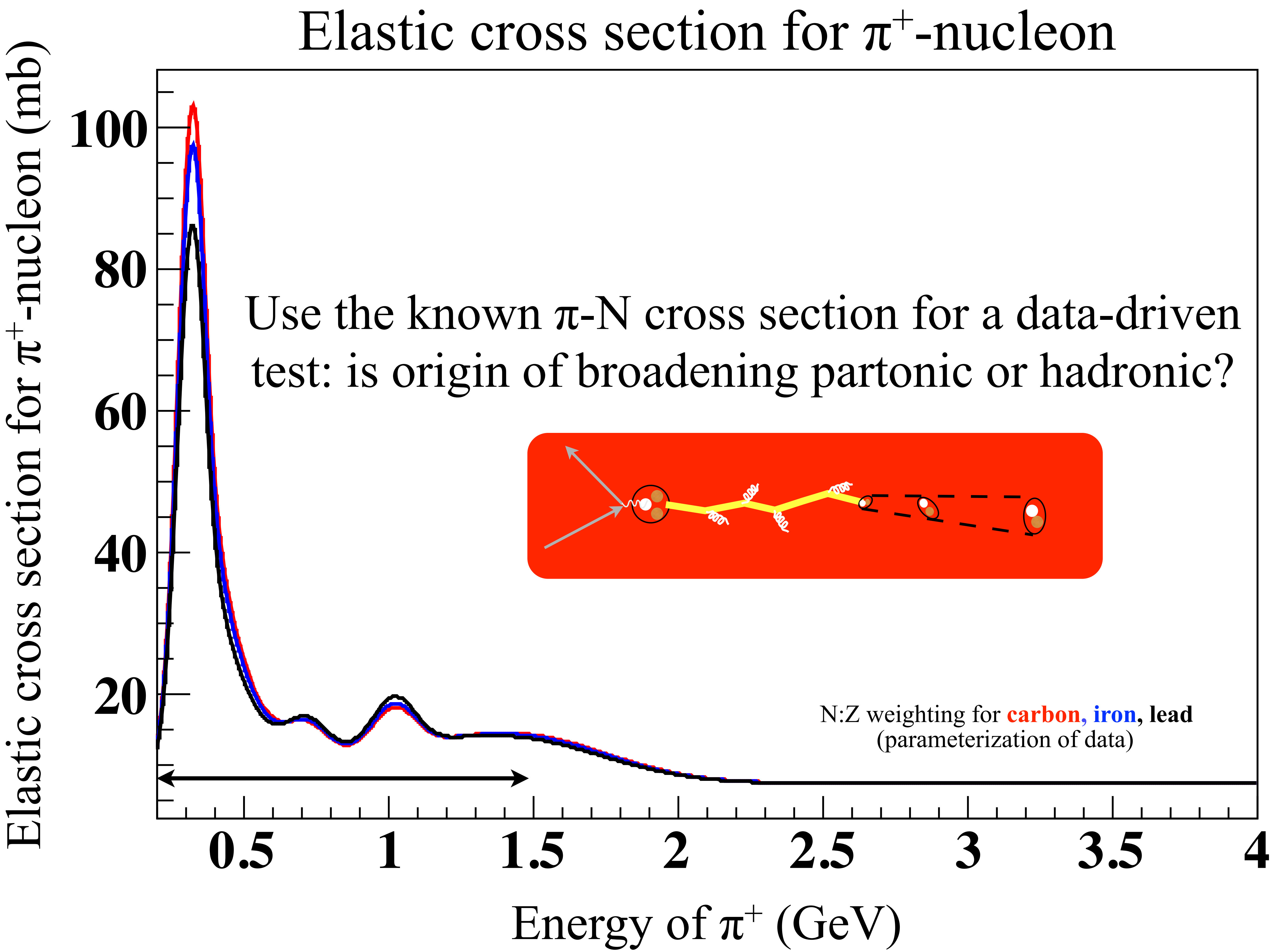
Hadronic broadening or partonic broadening?

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

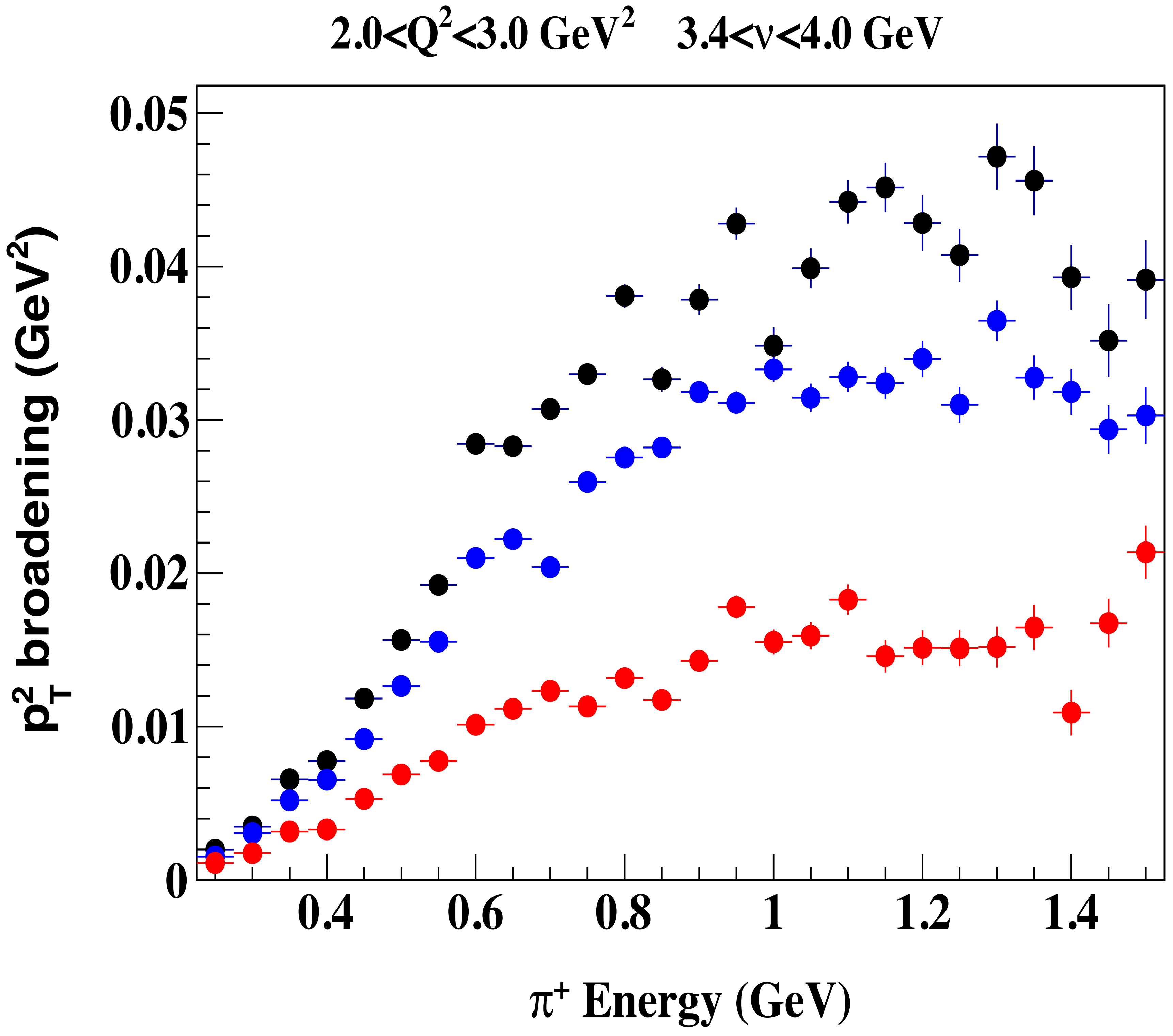







Elastic cross section for π+-nucleon
Elastic cross section for π+-nucleon (mb)
100
80
60
40
20
Use the known π-N cross section for a data-driven test: is origin of broadening partonic or hadronic?
N:Z weighting for carbon, iron, lead
(parameterization of data)
0.5
1
1.5
2
2.5
3
3.5
4
Energy of π+ (GeV)

p_T^2 Broadening vs. Hadron Energy



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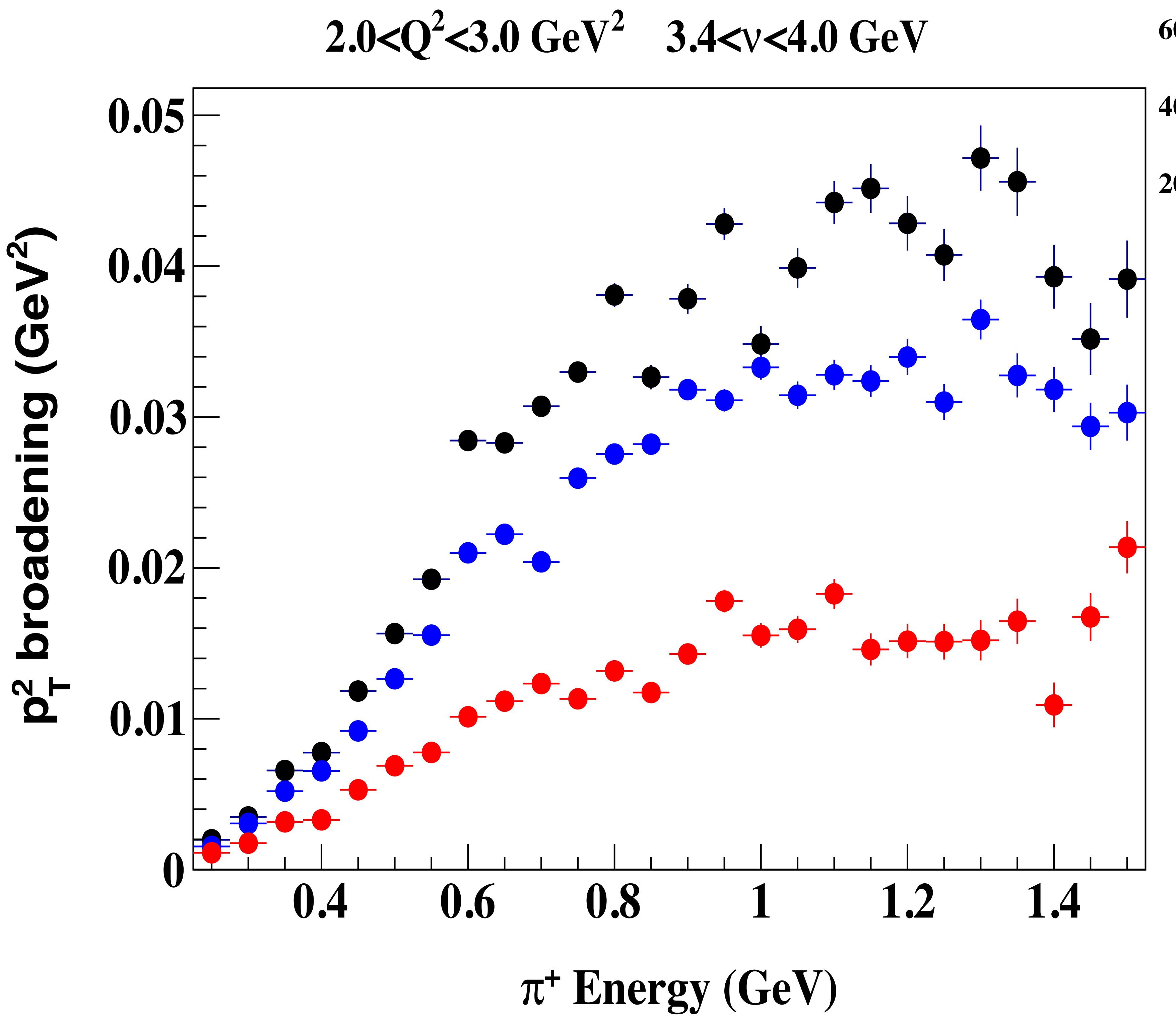

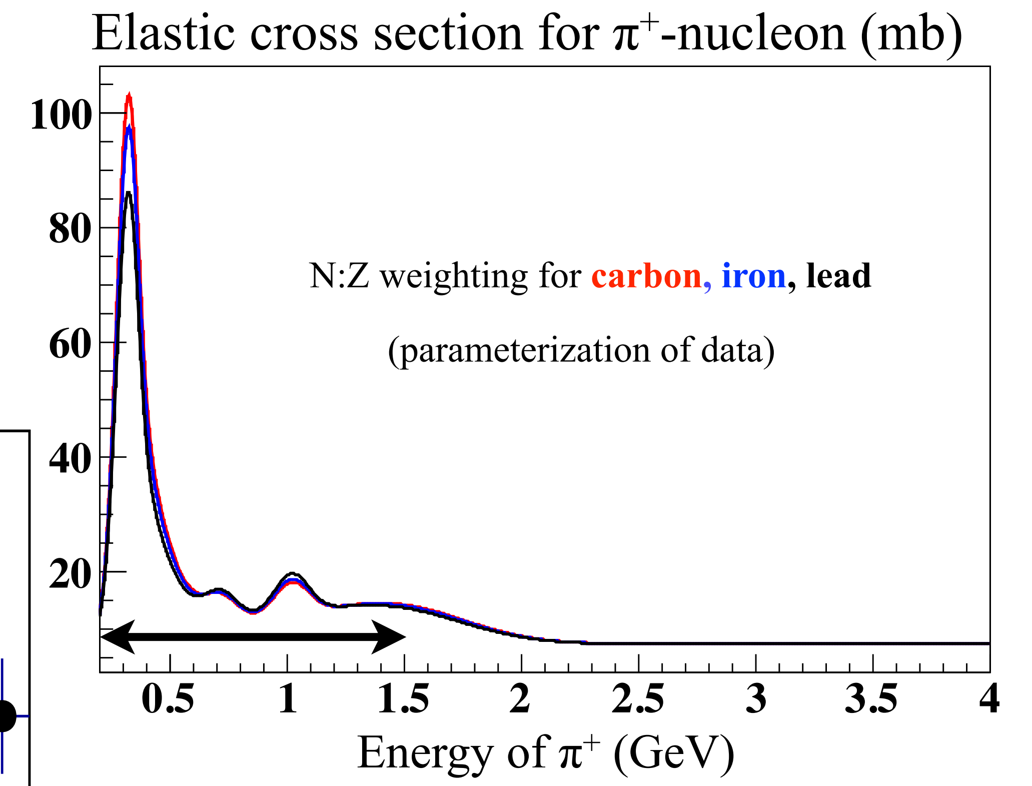

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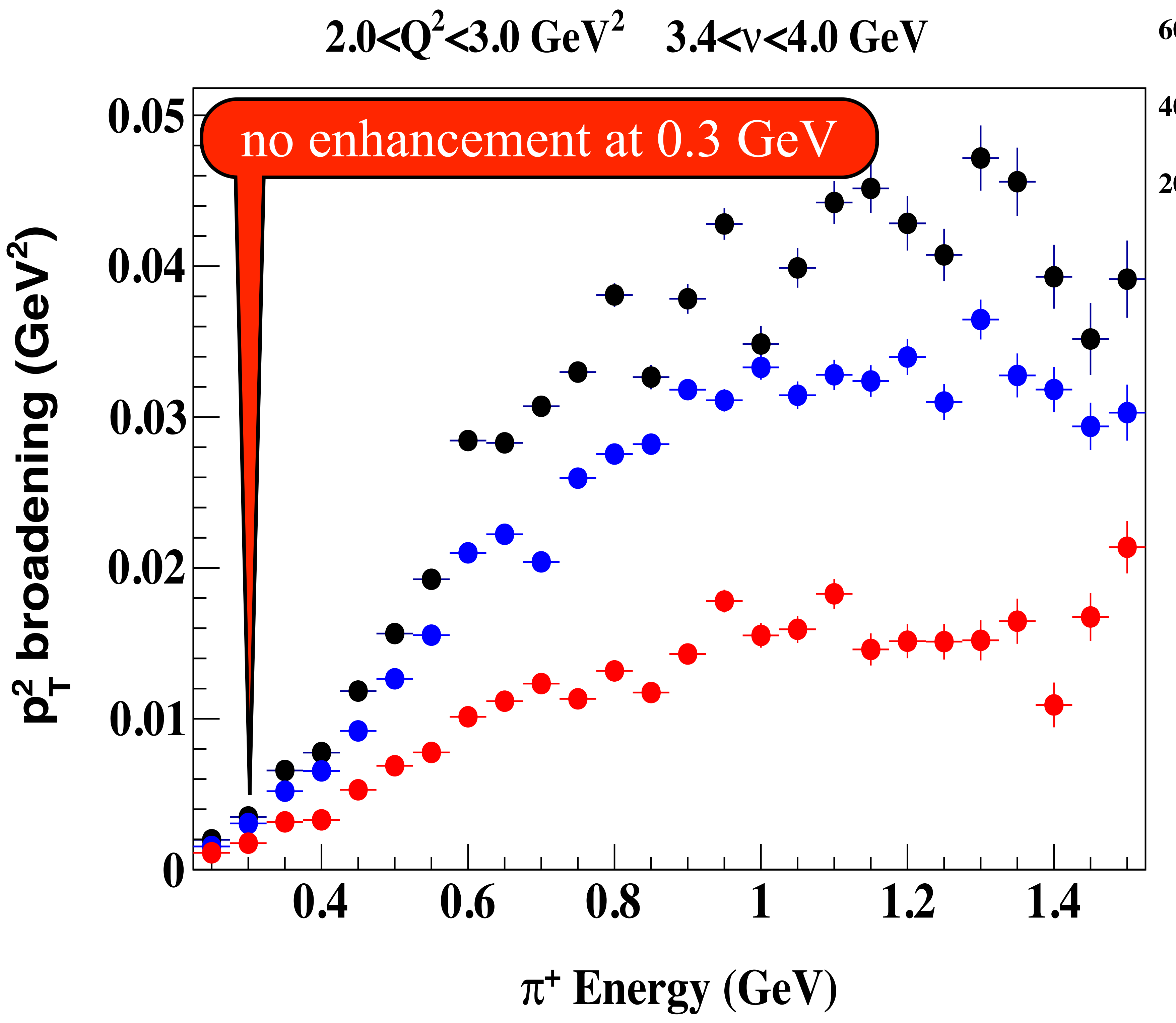

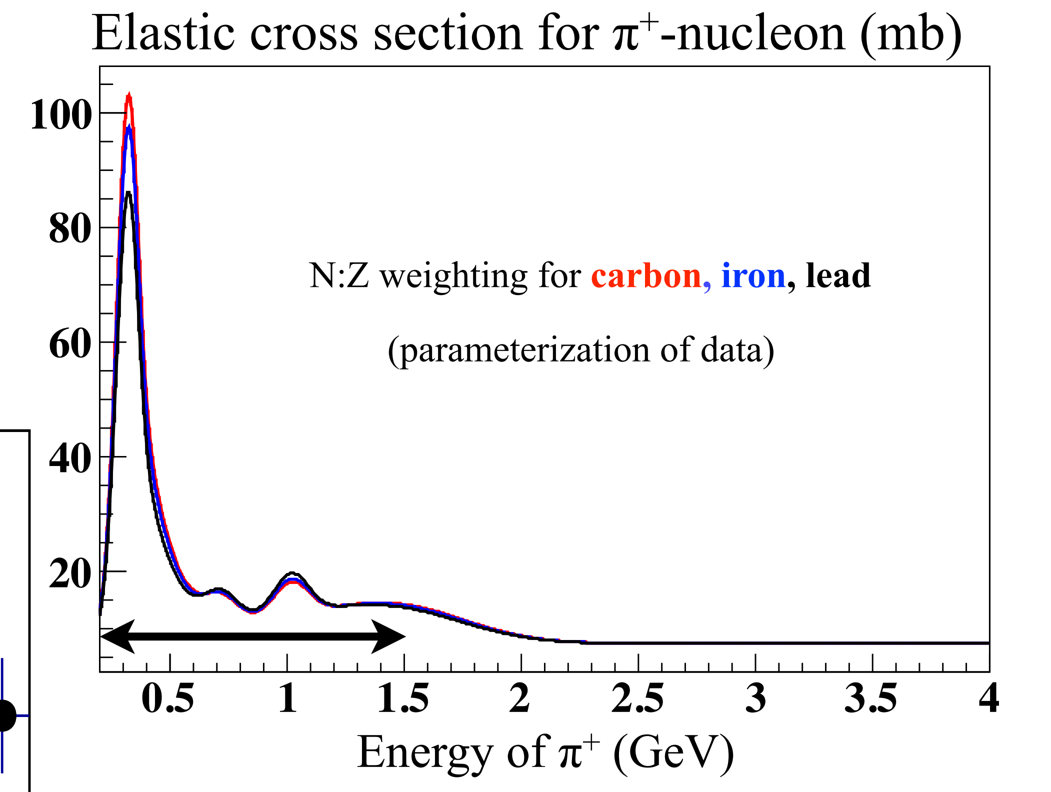

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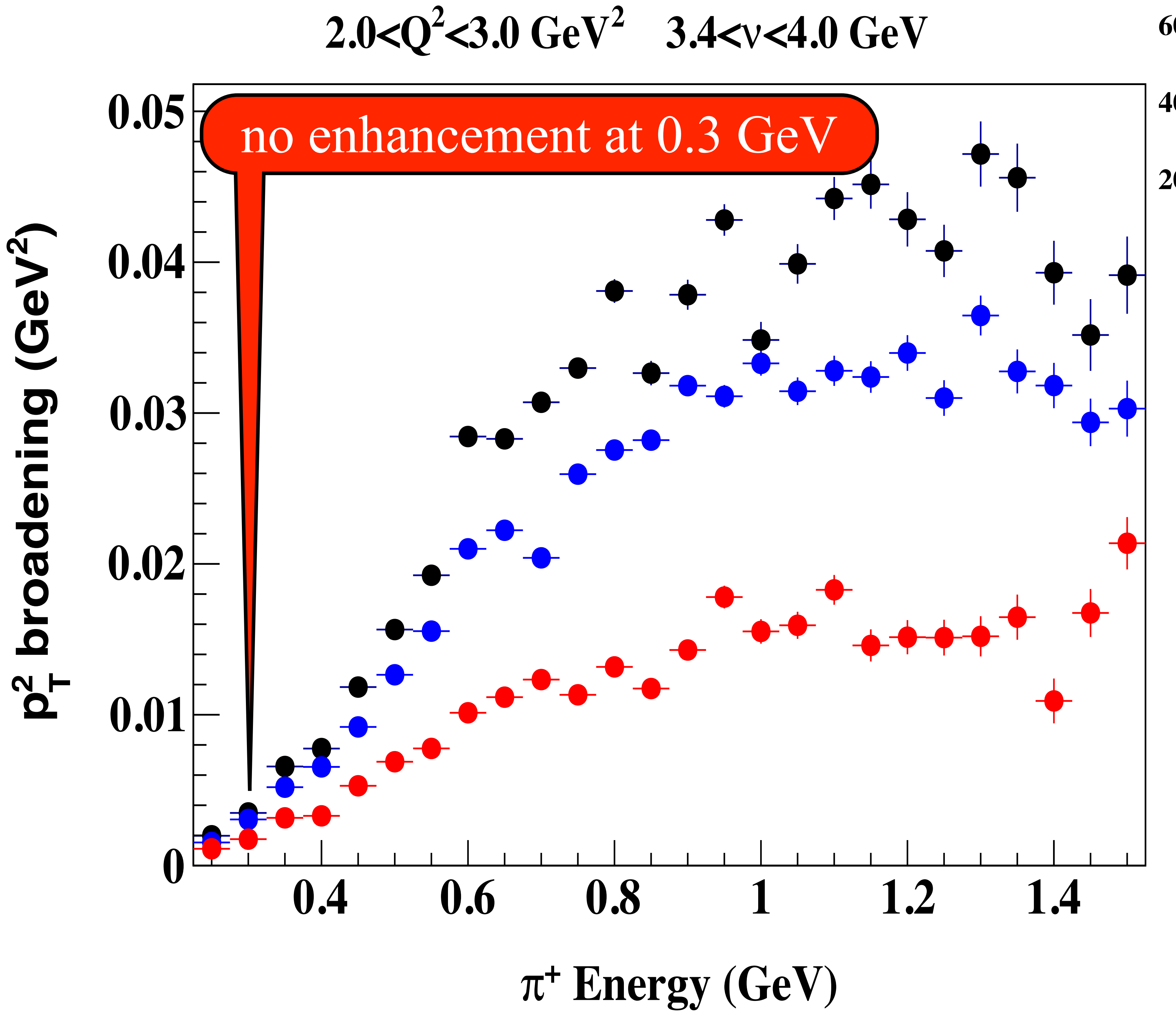
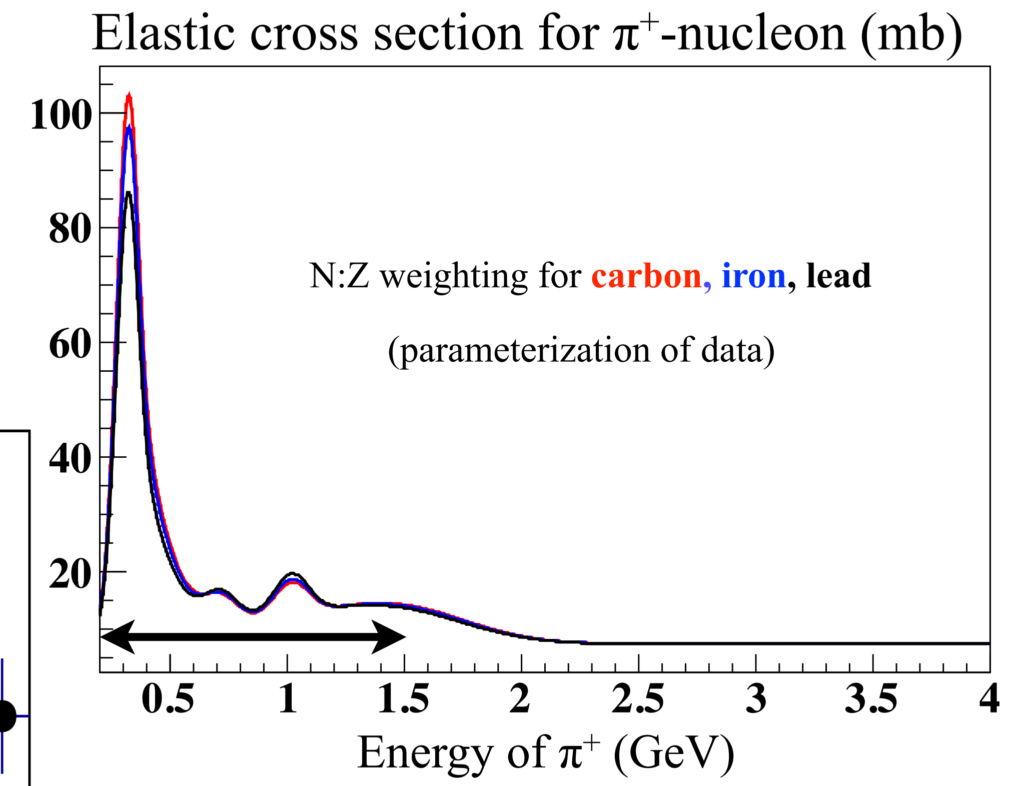
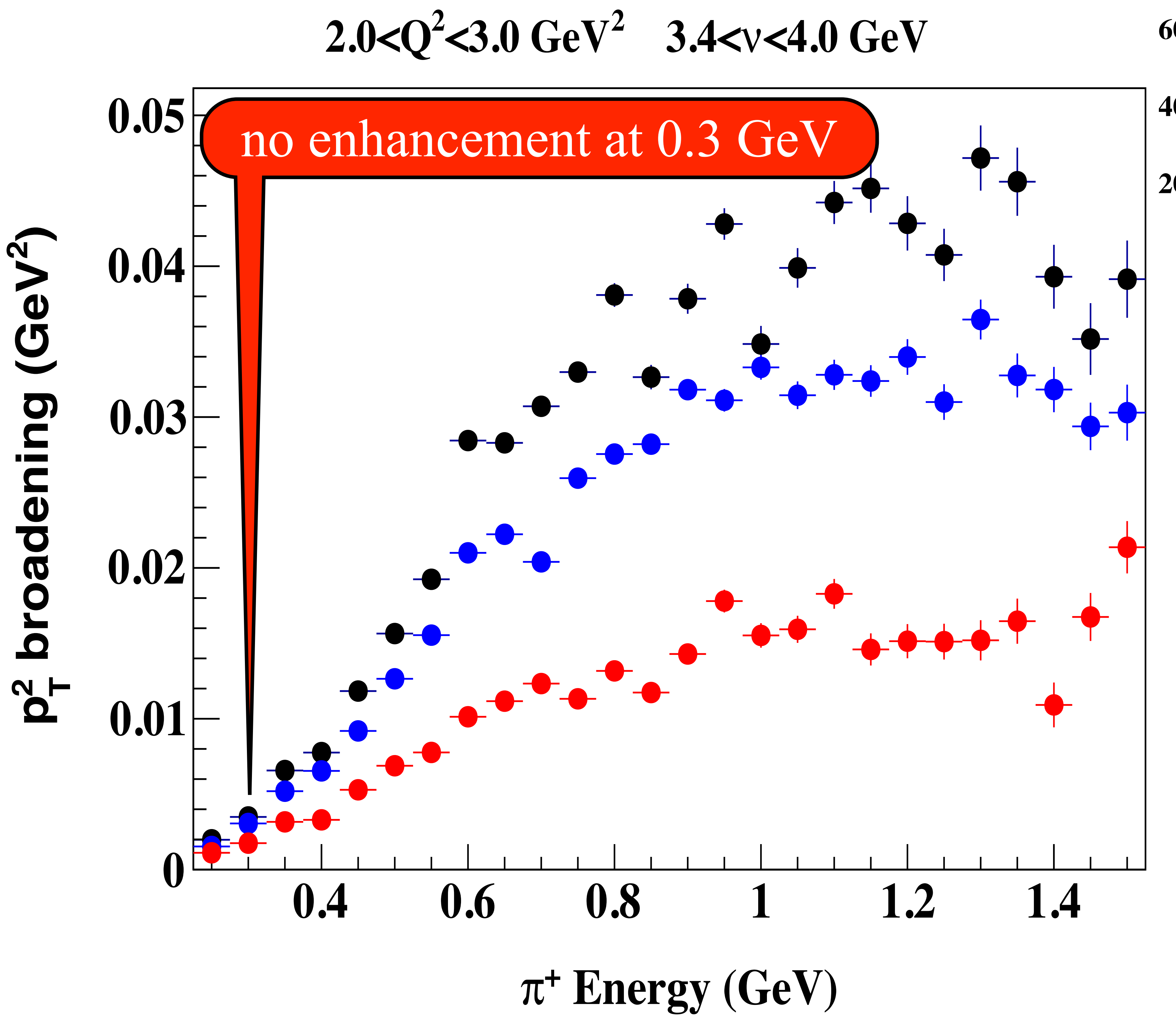
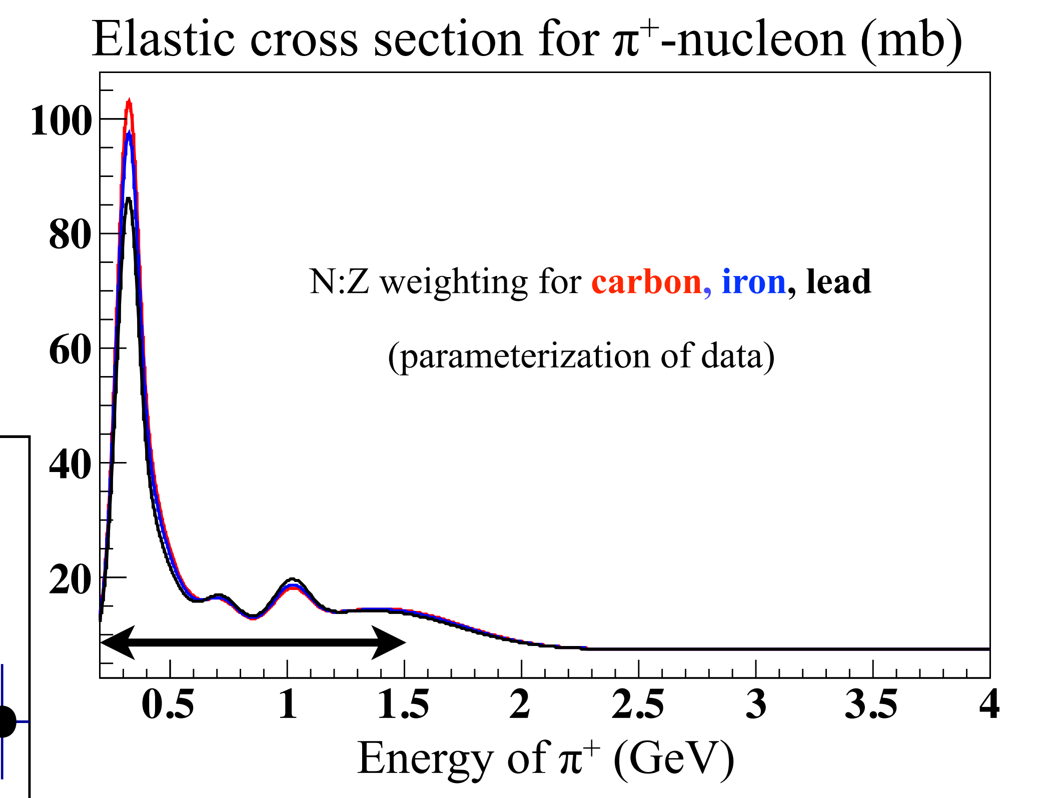




No visible evidence of hadronic elastic scattering? Suggests:

p_T^2 Broadening vs. Hadron Energy

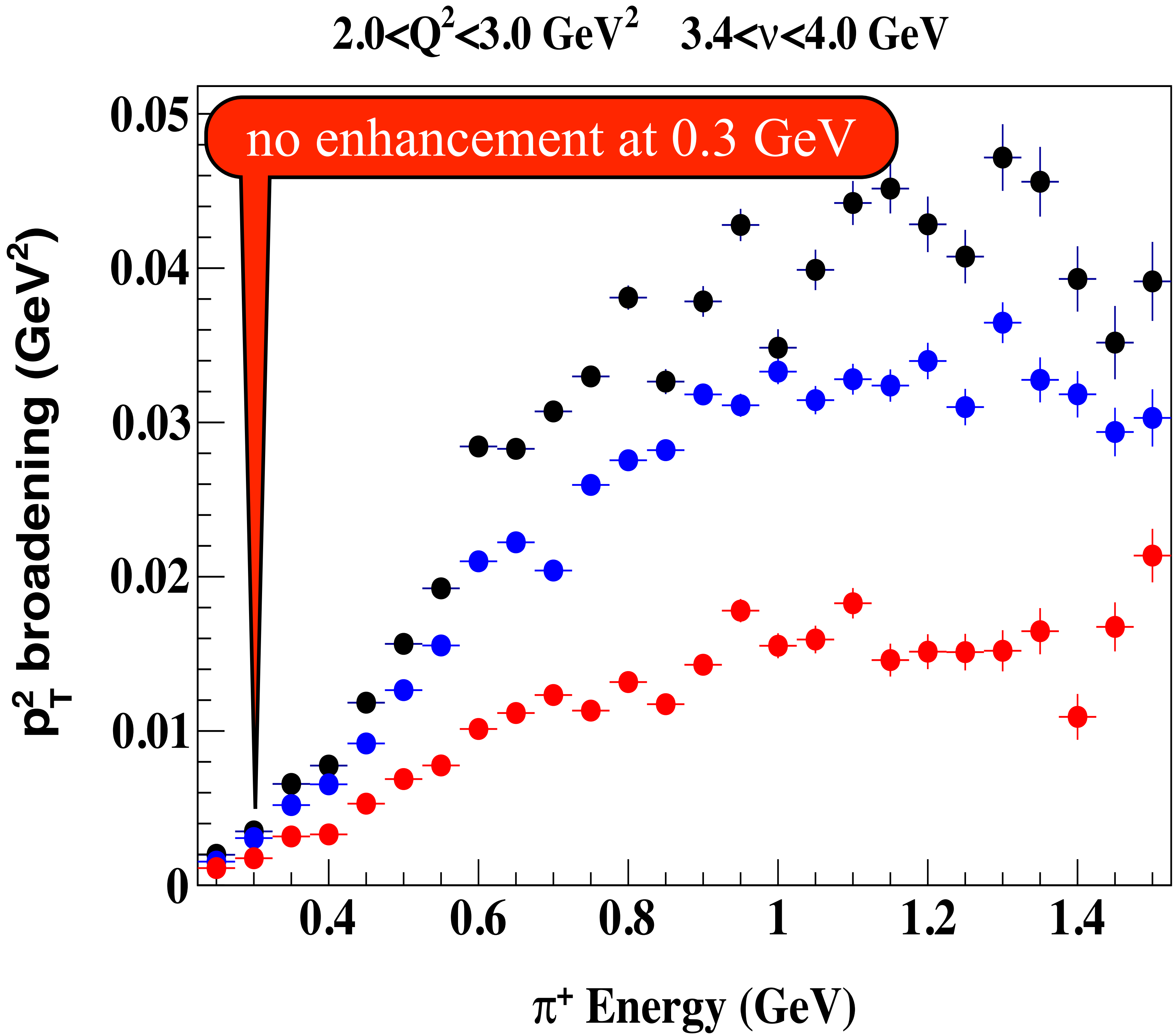


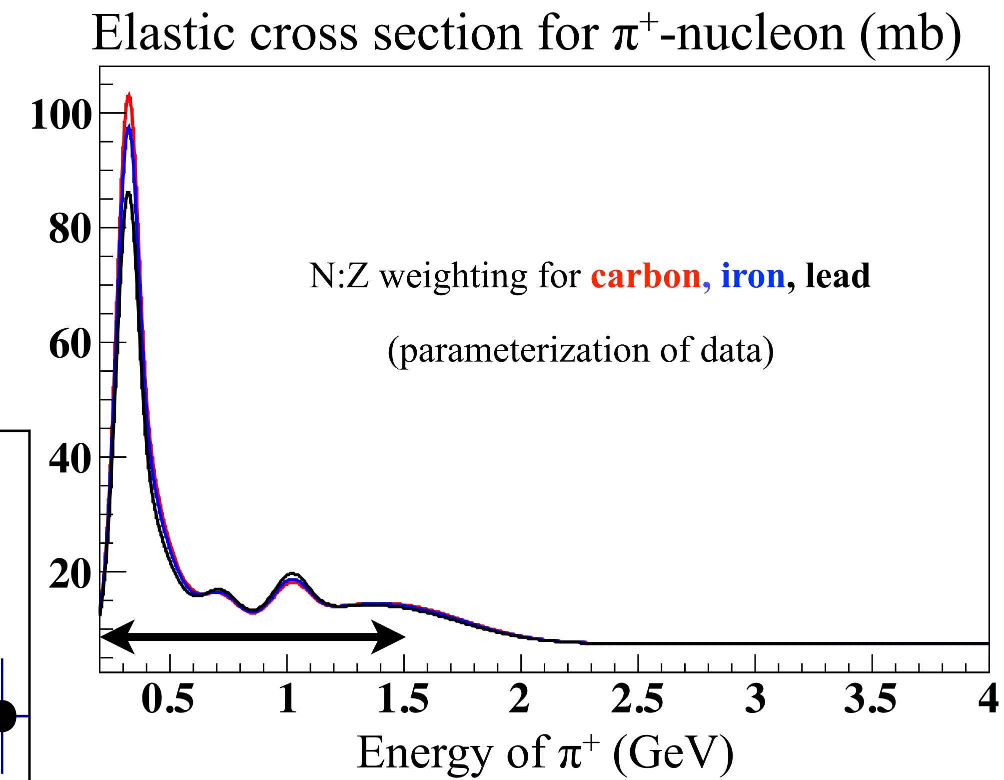


No visible evidence of hadronic elastic scattering? Suggests:

1) formation length is very long

p_T^2 Broadening vs. Hadron Energy





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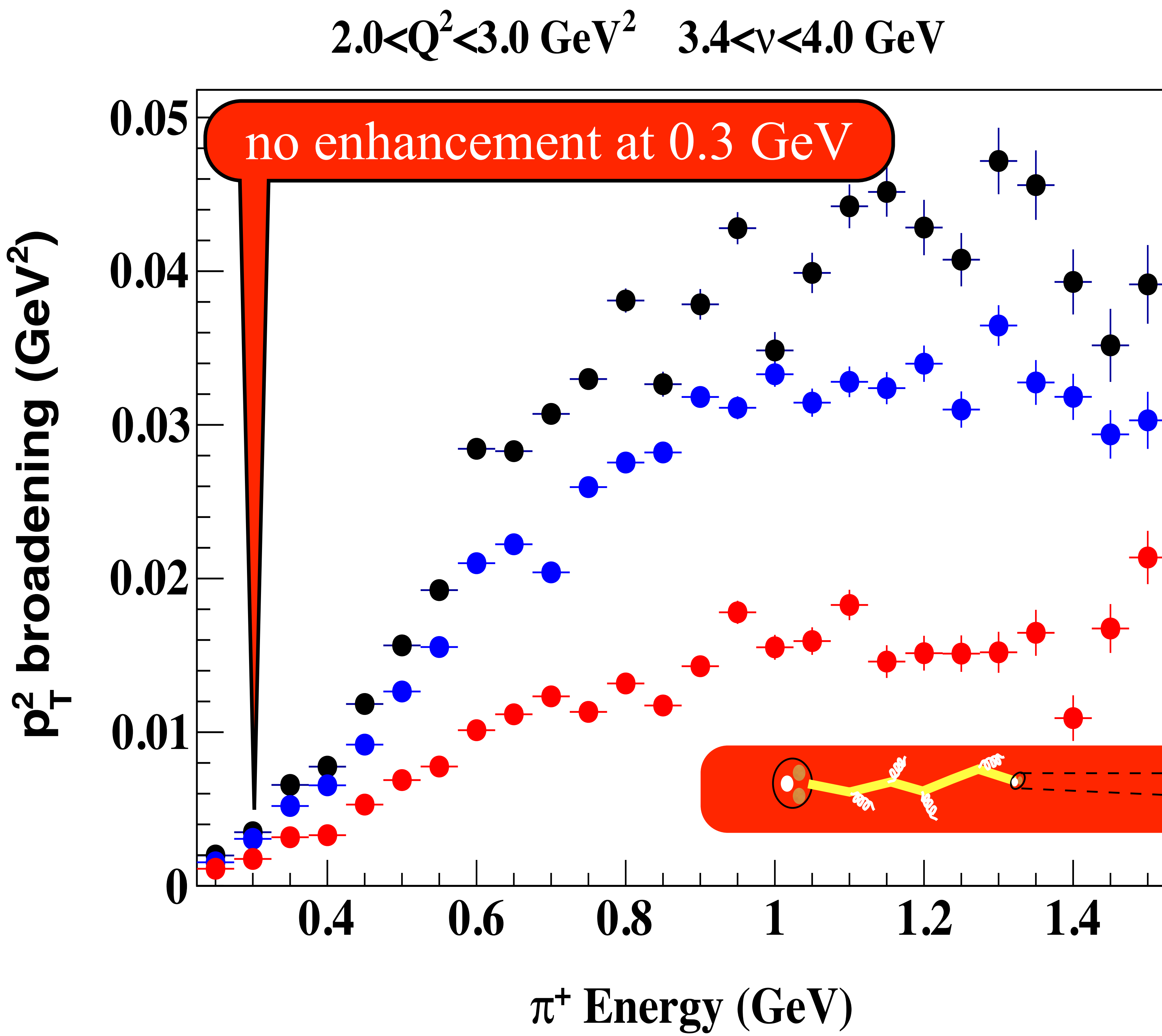
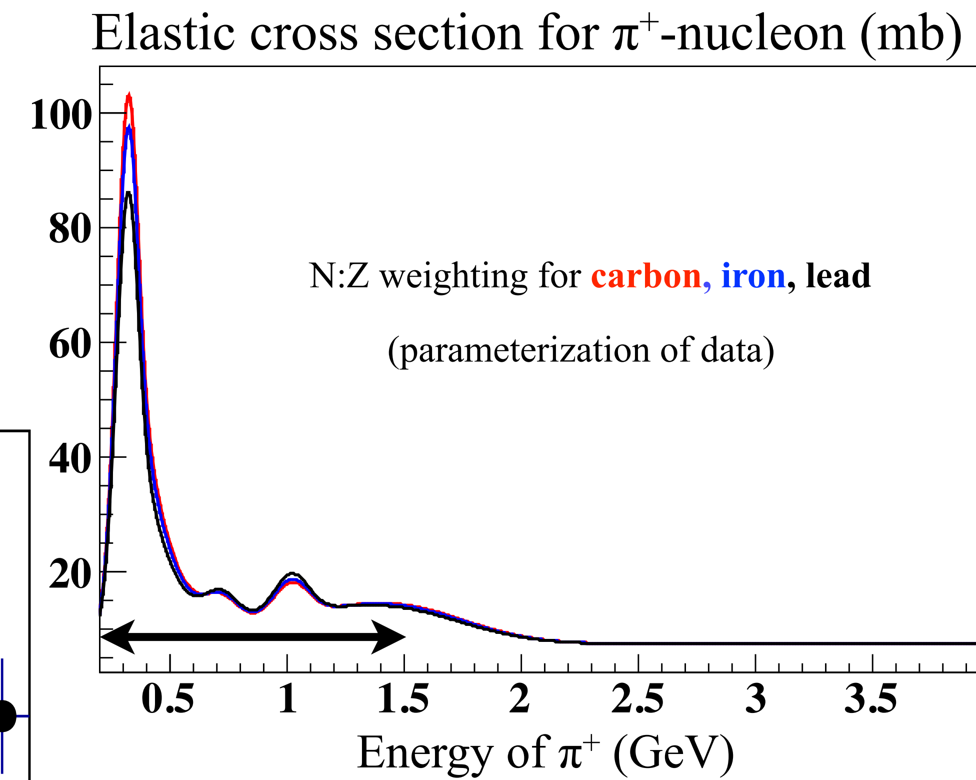
p_T^2 Broadening vs. Hadron Energy





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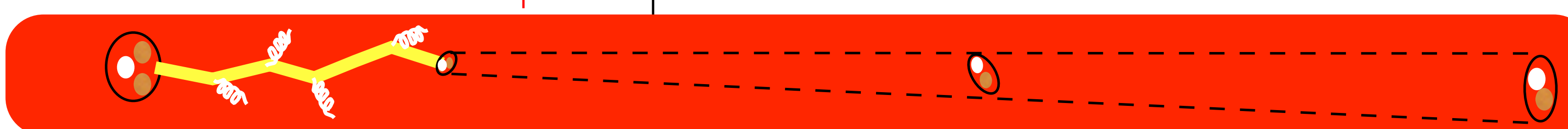

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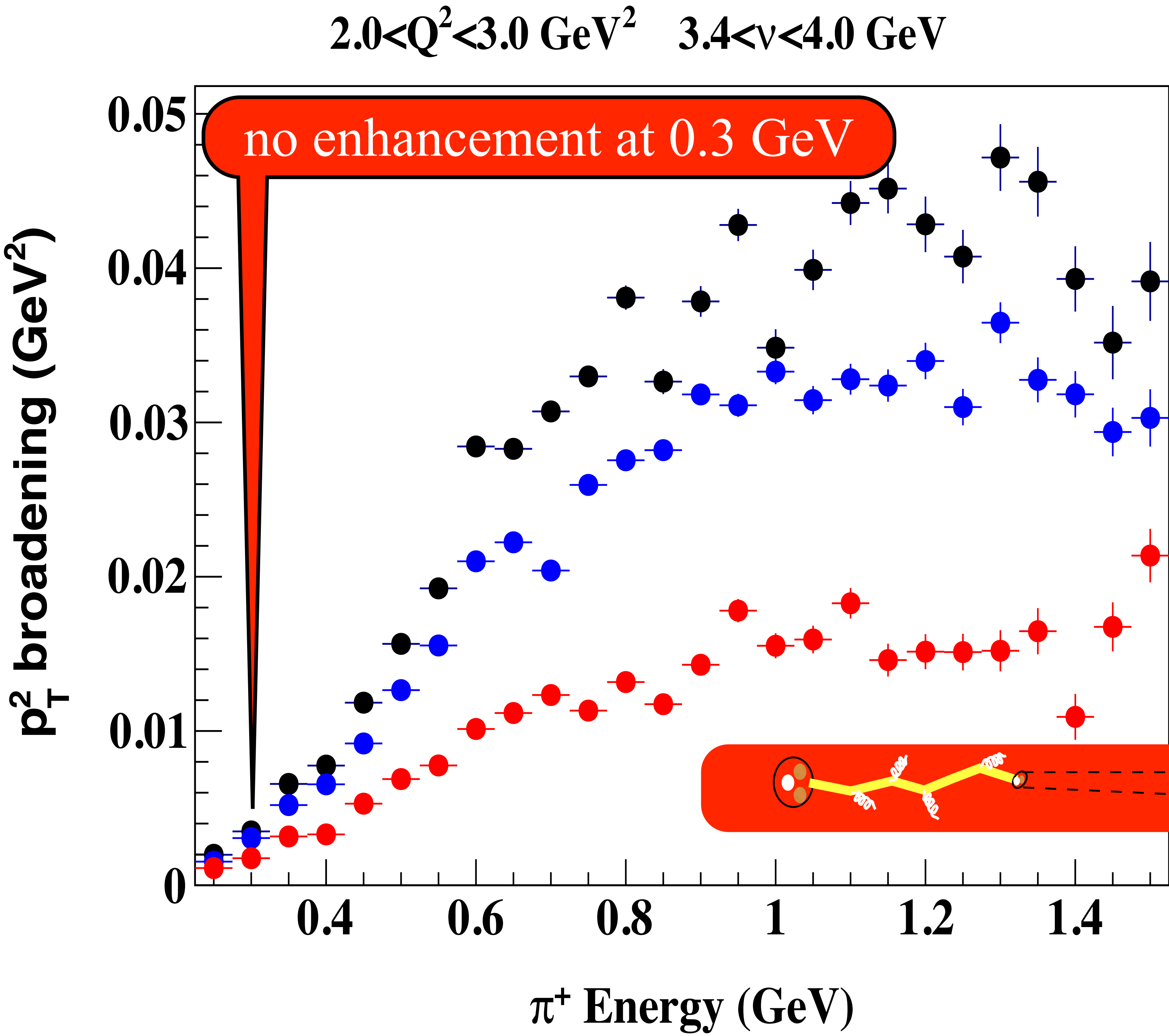
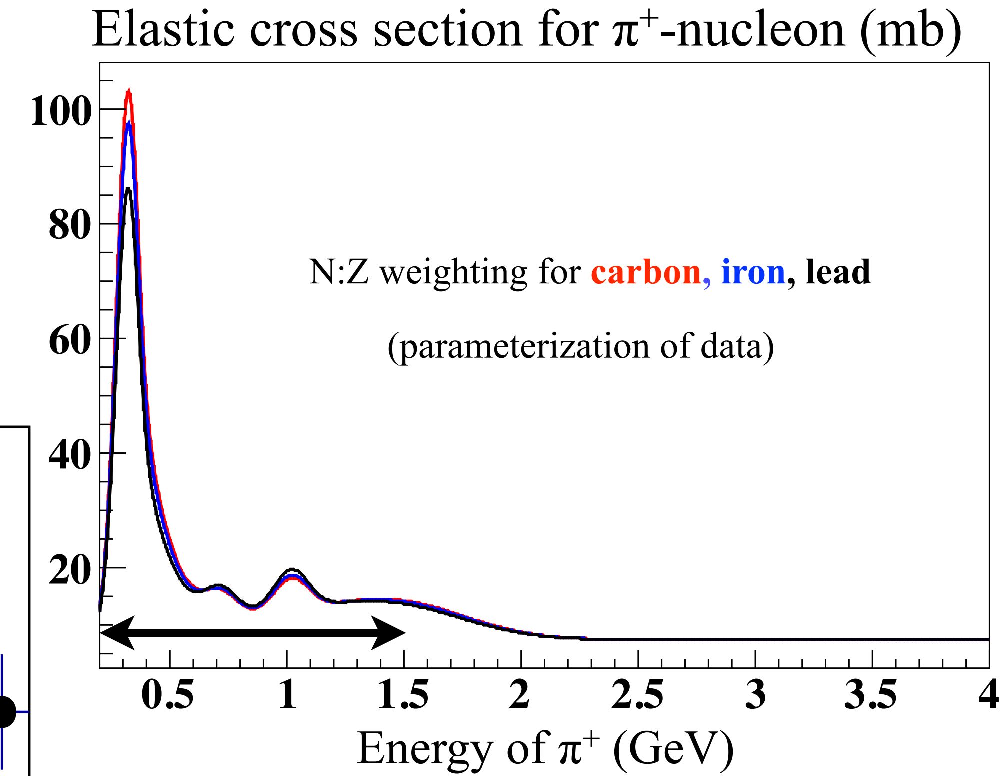
p_T^2 Broadening vs. Hadron Energy





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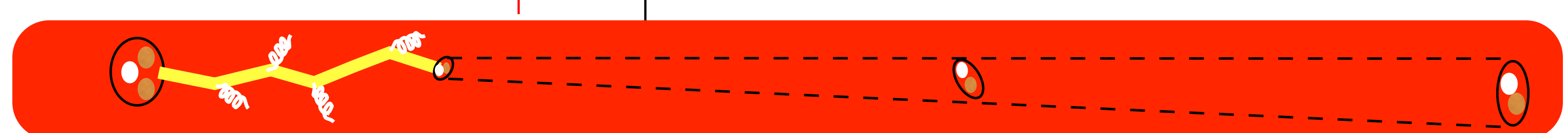

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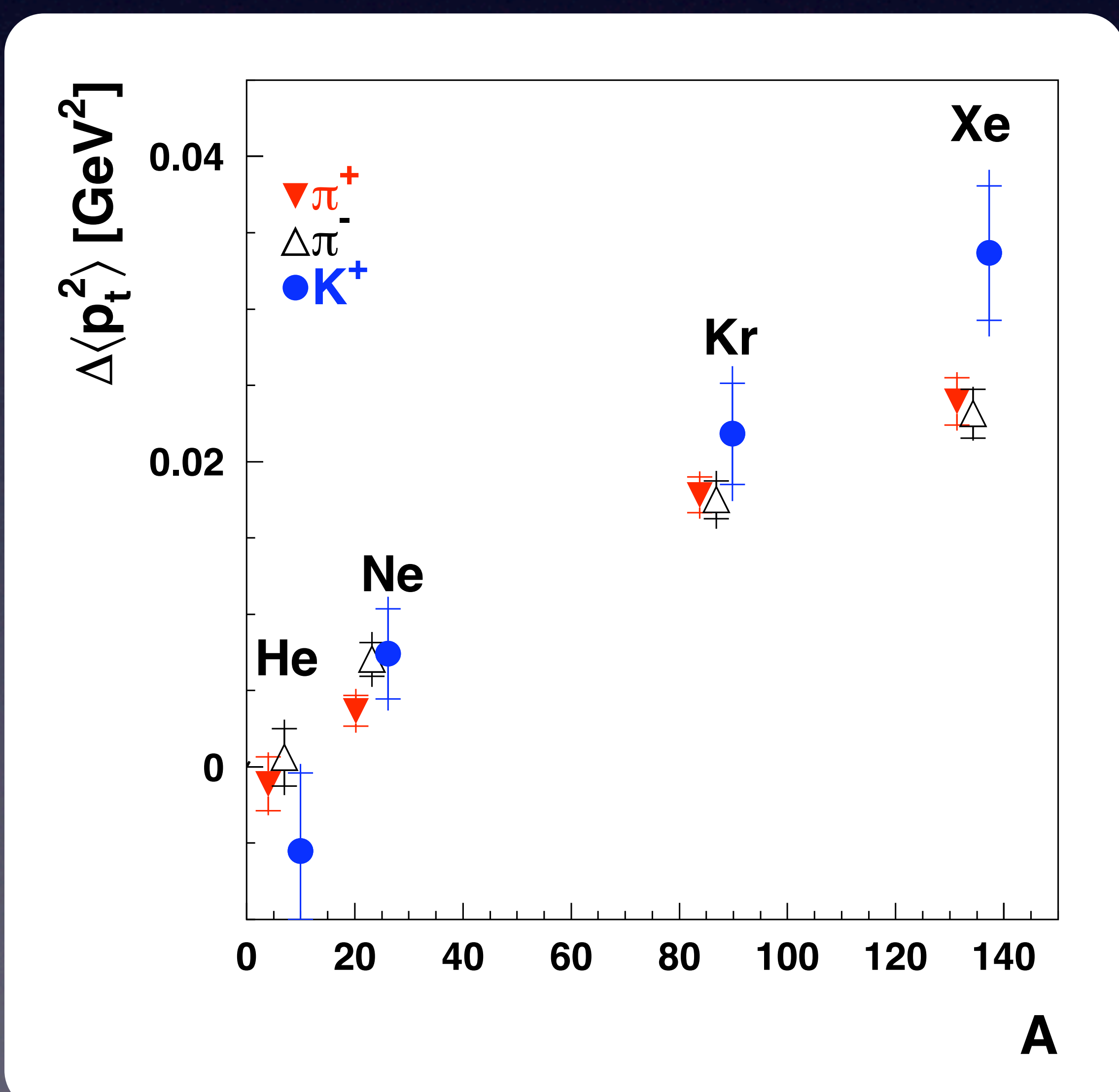
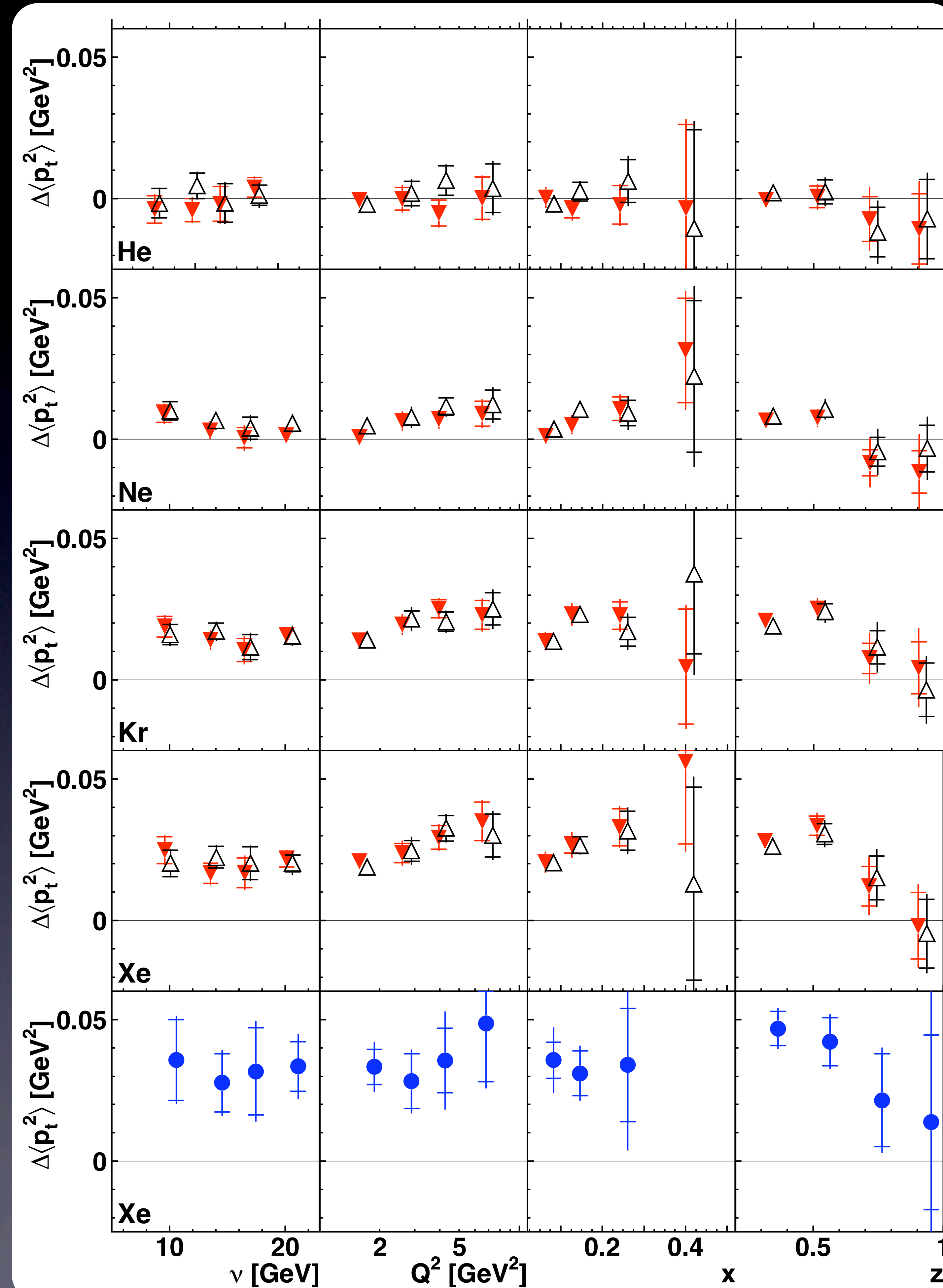
EIC: go to high Q^2, look for enhancement to reappear, indicating shorter formation length

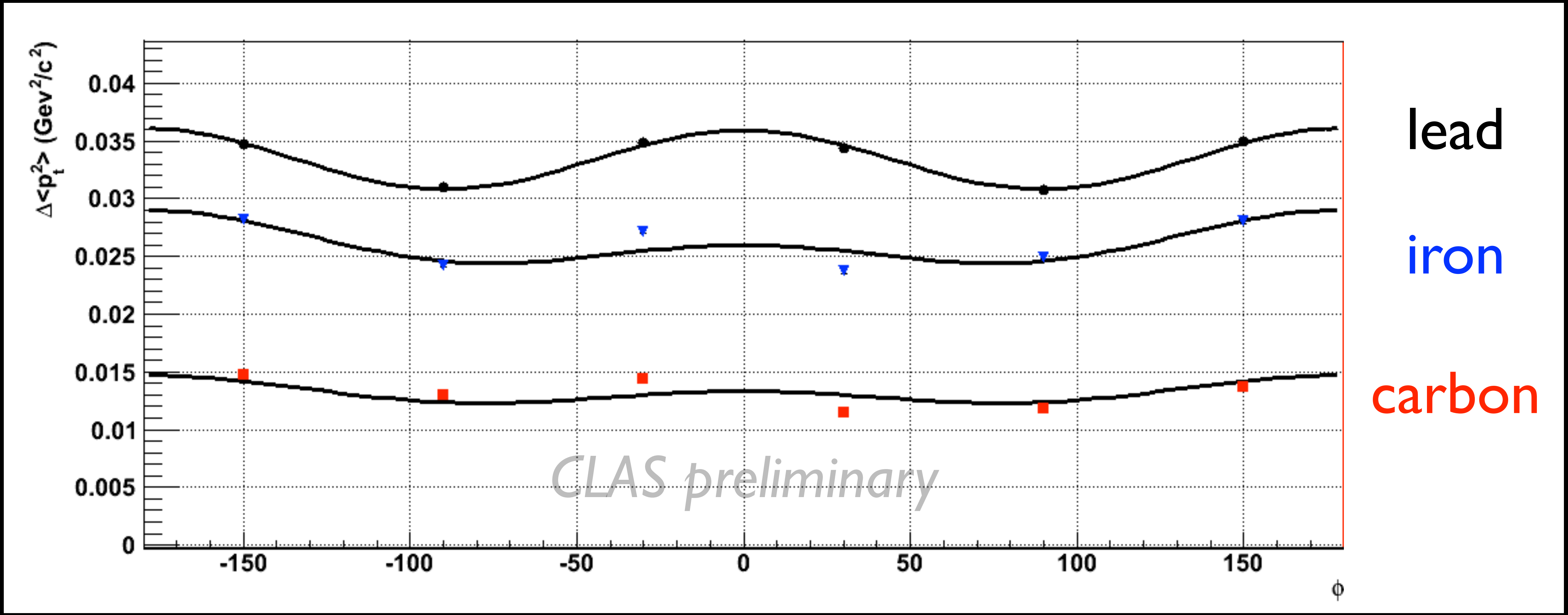
Hermes p_T broadening data

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





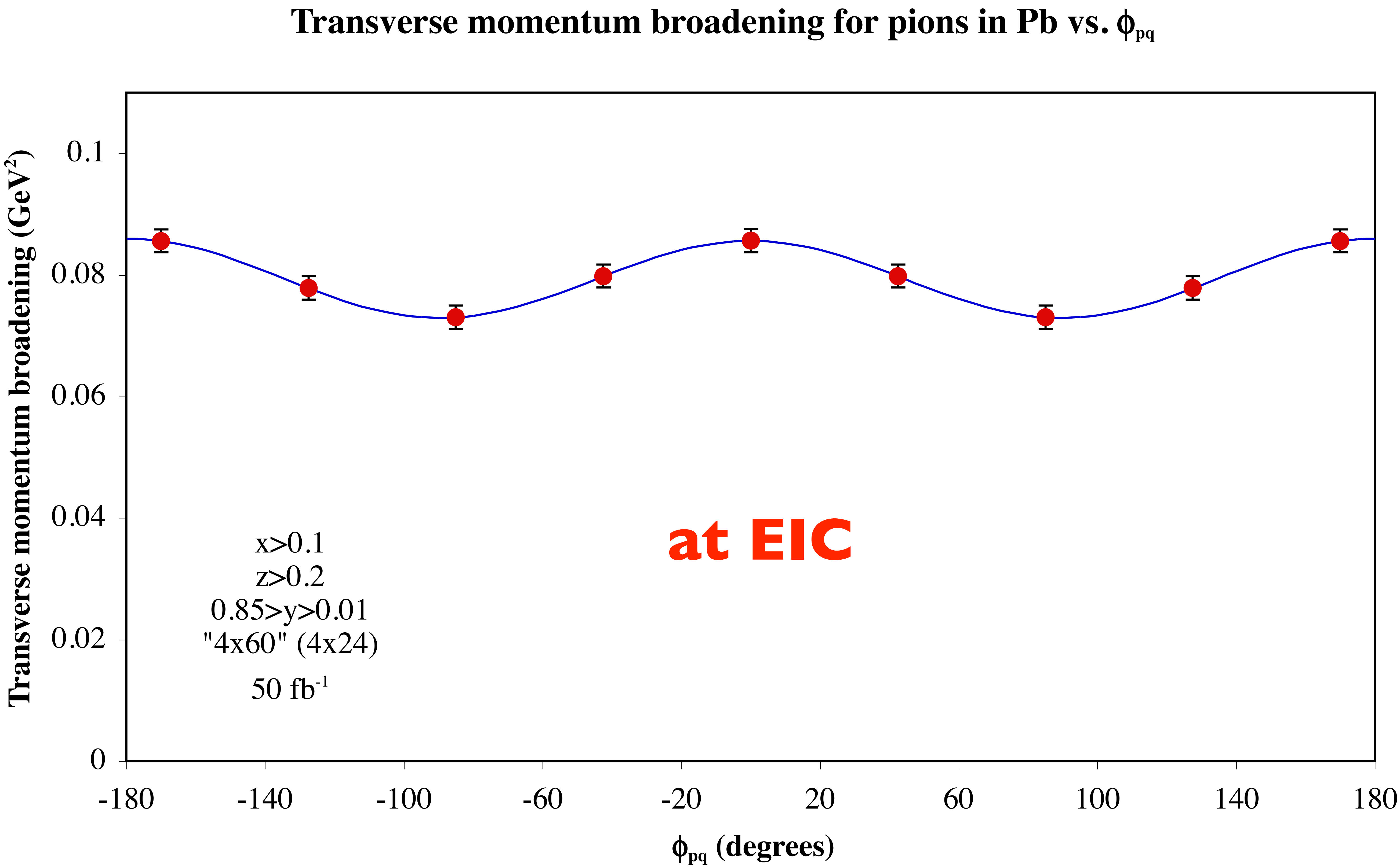
New: dependence of p_T broadening on φ_{pq}



curves shown contain terms in cos(φ_{pq}) and cos(2φ_{pq}) for positive pions
only statistical uncertainties shown

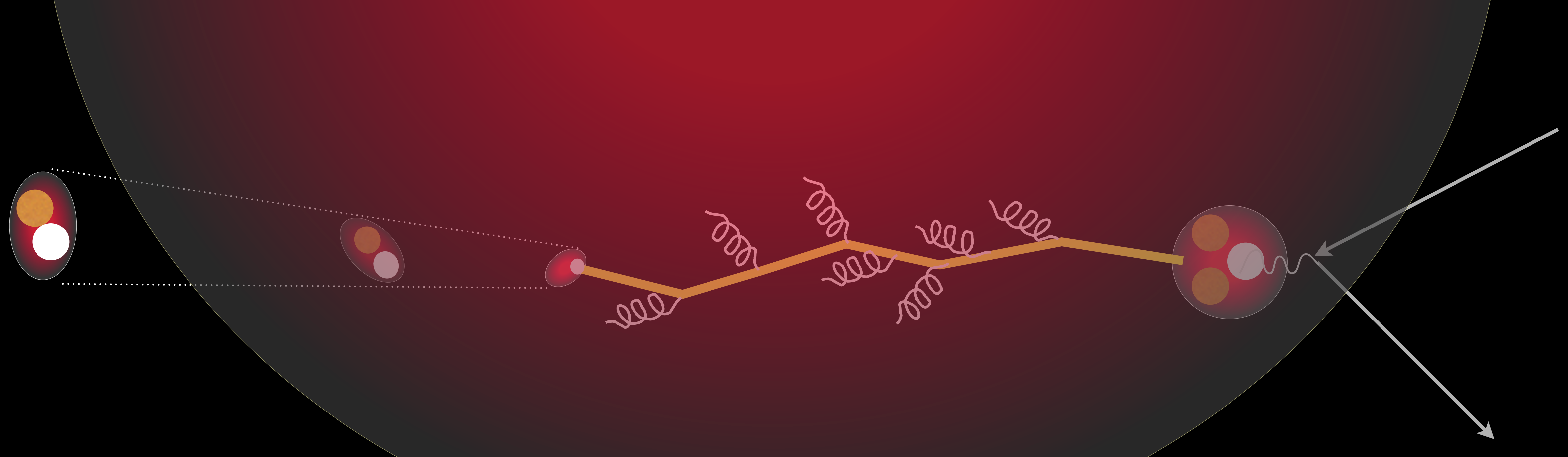
- Expectation within classical picture: any distribution seen in carbon will become more 'washed out' in heavier nuclei
- Not seen! *first observation of quantum effect in p_T broadening*

  - related to parton density fluctuations in larger nuclei? J. Qiu: Boer-Mulders TMD $\otimes D_j^h(z, Q^2)$ in presence of non-vanishing mass dipole moment

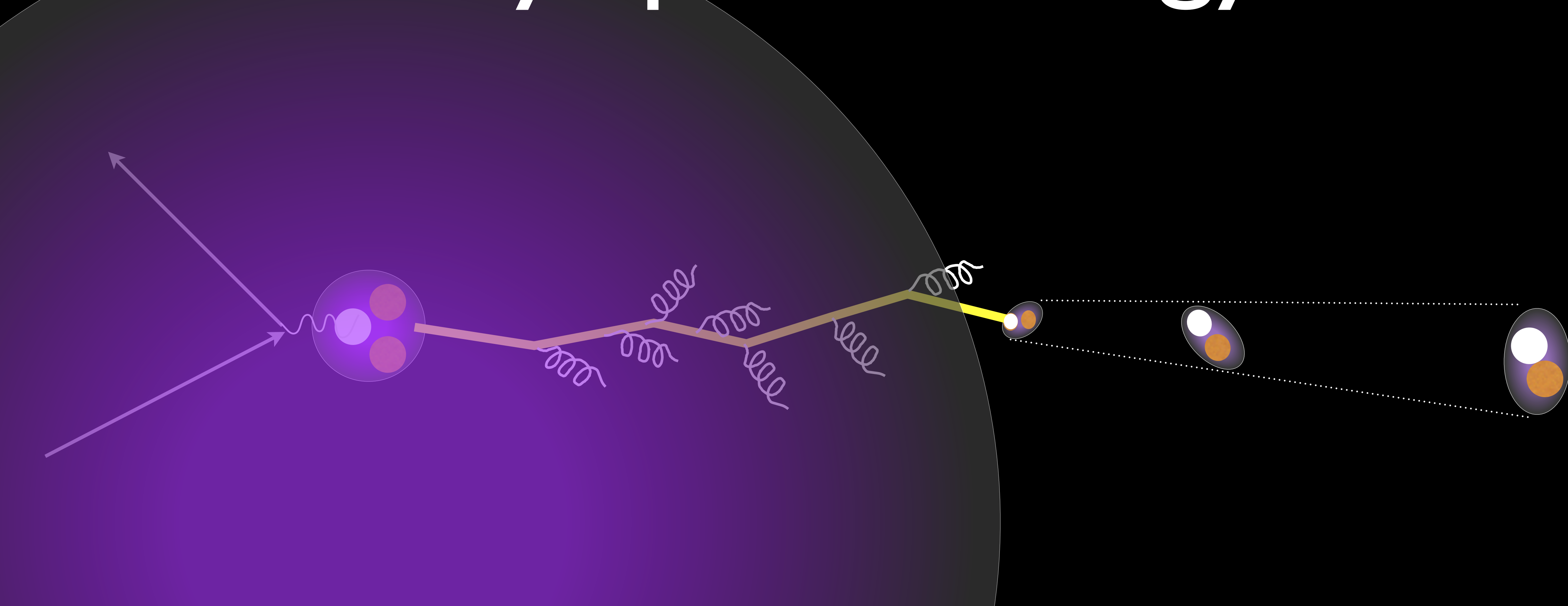


Possible p_T broadening measurement at EIC

(~speculative:) Probing quantum density fluctuations at high energies with partonic multiple scattering!



The intensifying puzzle of heavy quark energy loss

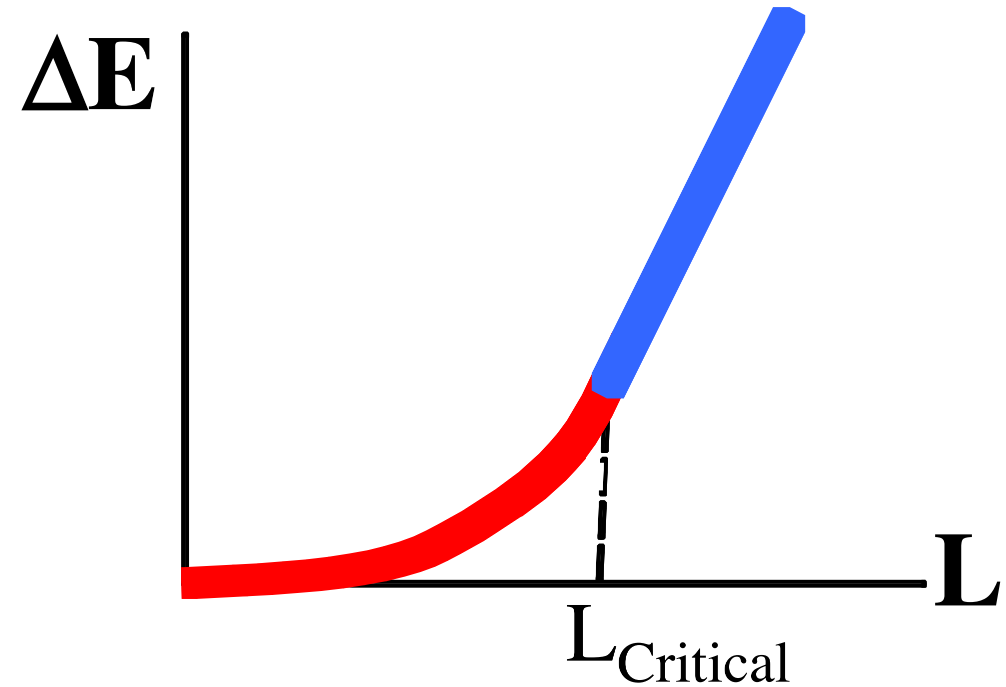


Energy Loss in pQCD

(BDMPS-Z version)

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

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



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

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

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

(multiplied by an unknown prefactor)

Connection to previous topic: $$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta k_T^2$$

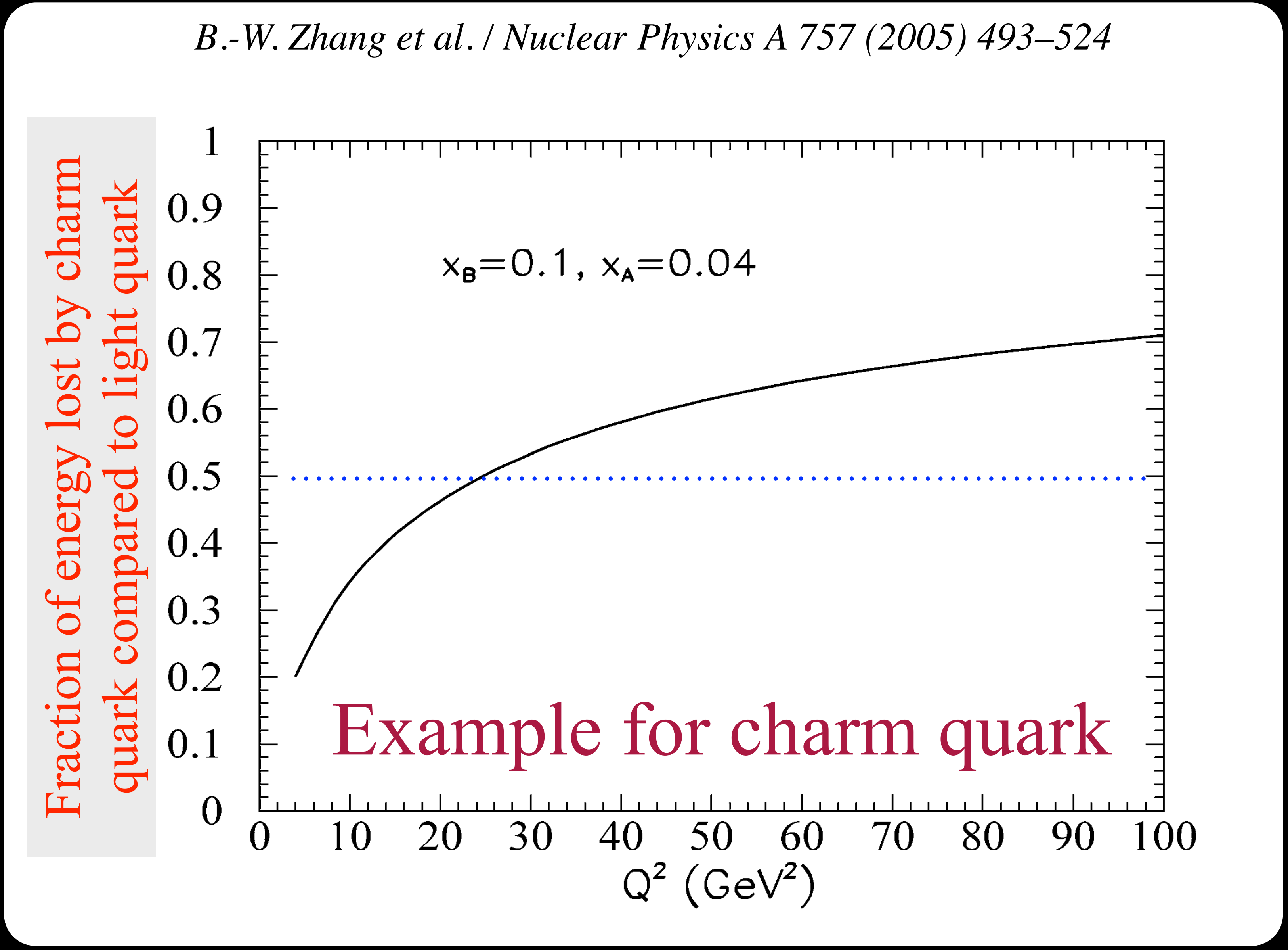
EIC: study partonic energy loss

- Partonic energy loss is a fundamental process in QCD
- Multiplicity ratio a powerful tool to study it, especially at EIC energies -
  - Modification of fragmentation will be minimized, energy loss remains
- Basic pQCD behavior ~ understood, **but**....
  - Heavy quark suppression from RHIC and LHC is showing some puzzling hints

Heavy Quark Energy Loss

Heavy quark radiative energy loss is predicted to be *less* than light quark energy loss

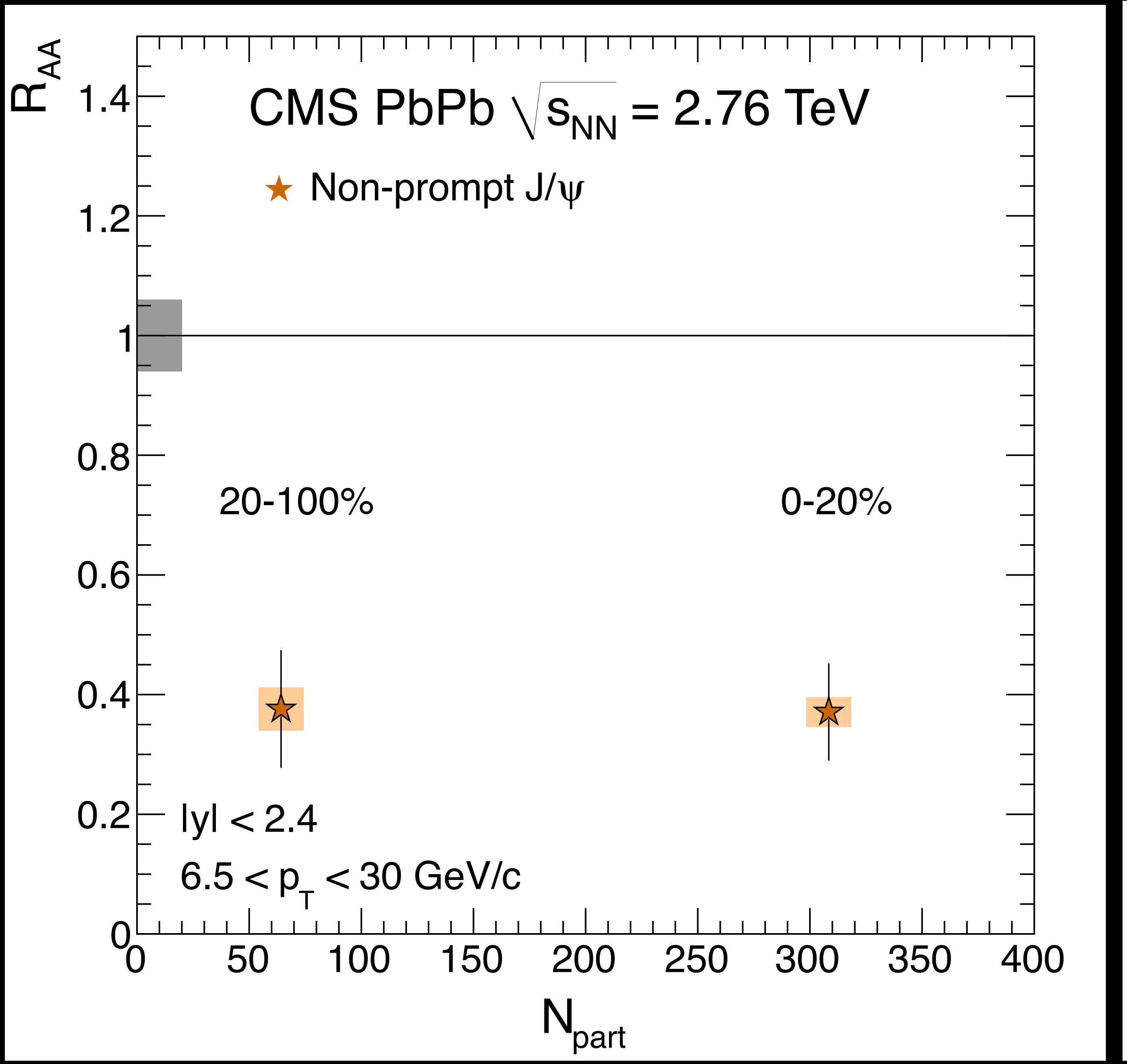
Formalism implies a strict ordering of quark energy loss: u/d, s, c, b

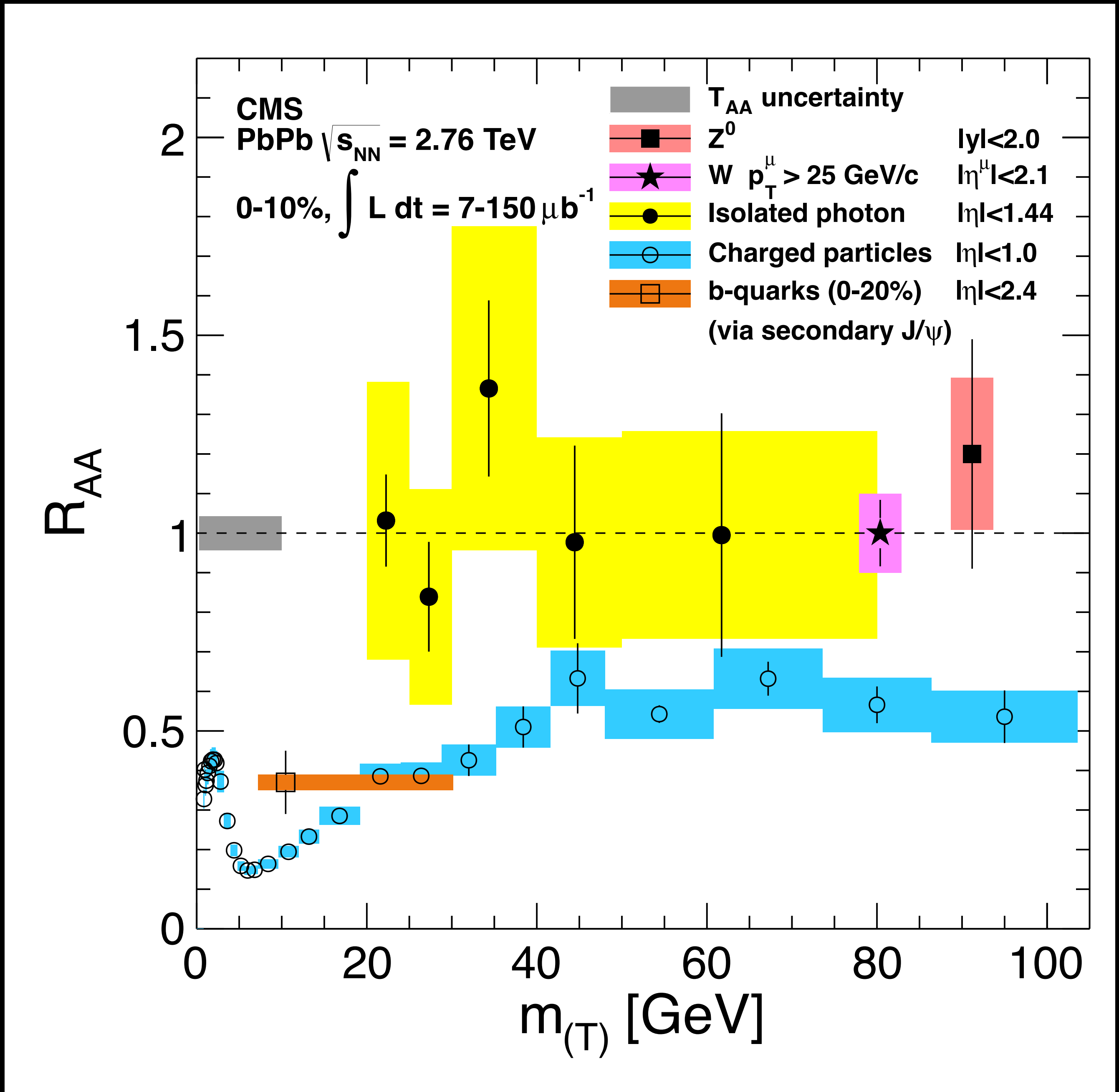


$$\frac{Q_H(k_T)}{Q_L(k_T)} \approx \exp[\frac{16\alpha_s C_F}{9\sqrt{3}} \cdot L \cdot (\frac{\hat{q} M^2}{M^2 + k_T^2})^{1/3}]$$

http://arxiv.org/abs/0810.5702, http://arxiv.org/abs/0907.1918

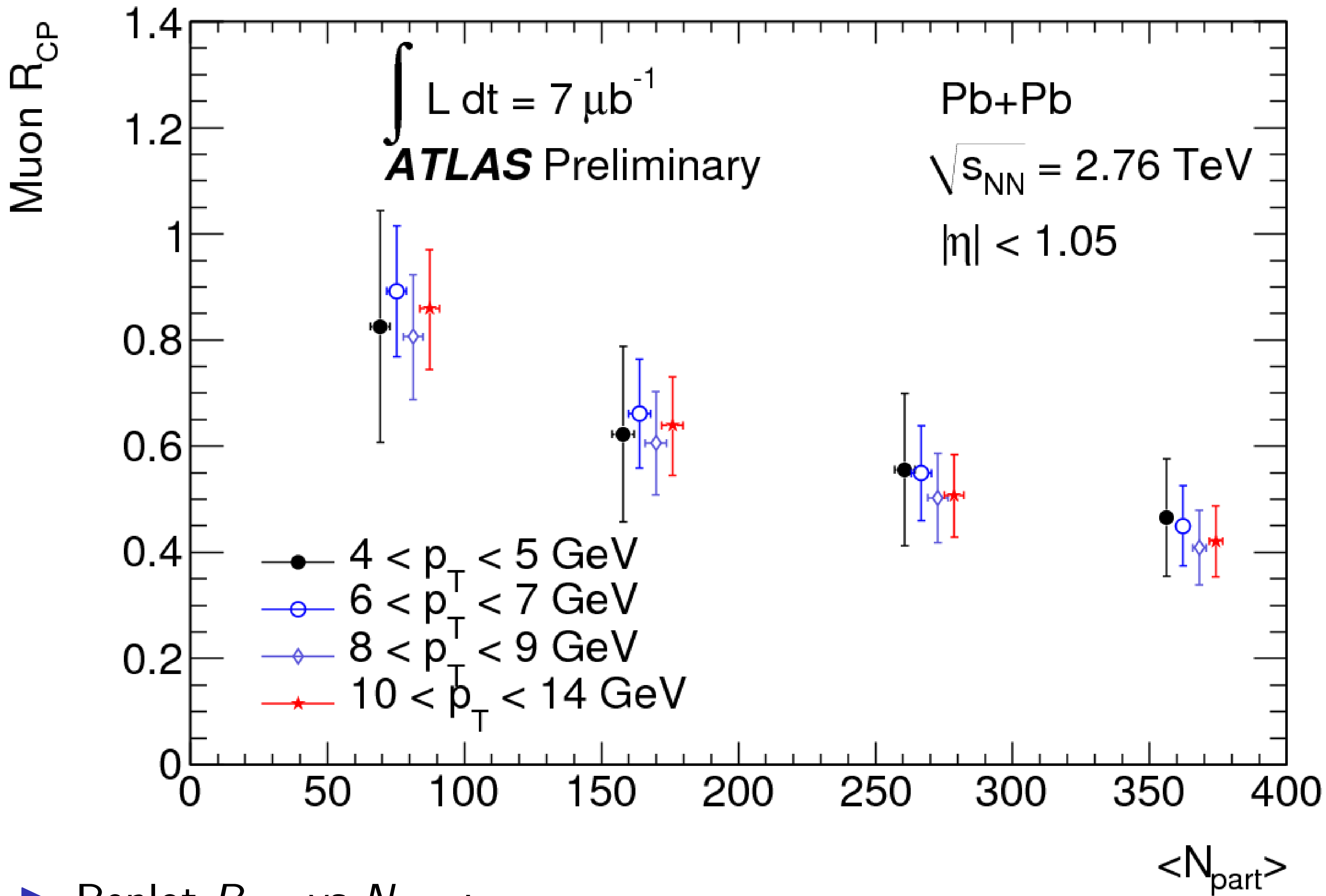
R_{AA} from CMS for PbPb collisions - Puzzles





- Assuming non-prompt J/ψ represents b-quarks sampling the medium, a lack of centrality dependence is very surprising.
- Suppression is comparable to that of light quarks, but should be much less suppressed (previous slide showed *charm* quark)

Results: $R_{\mathrm{CP}}(N_{\mathrm{part}})$ from heavy flavor decays



- Replot R_{CP} vs N_{part}:
  - $\Rightarrow$ suppression evolves smoothly with centrality.
  - $\Rightarrow$ similar N_{part} dependence at all p_{T}.

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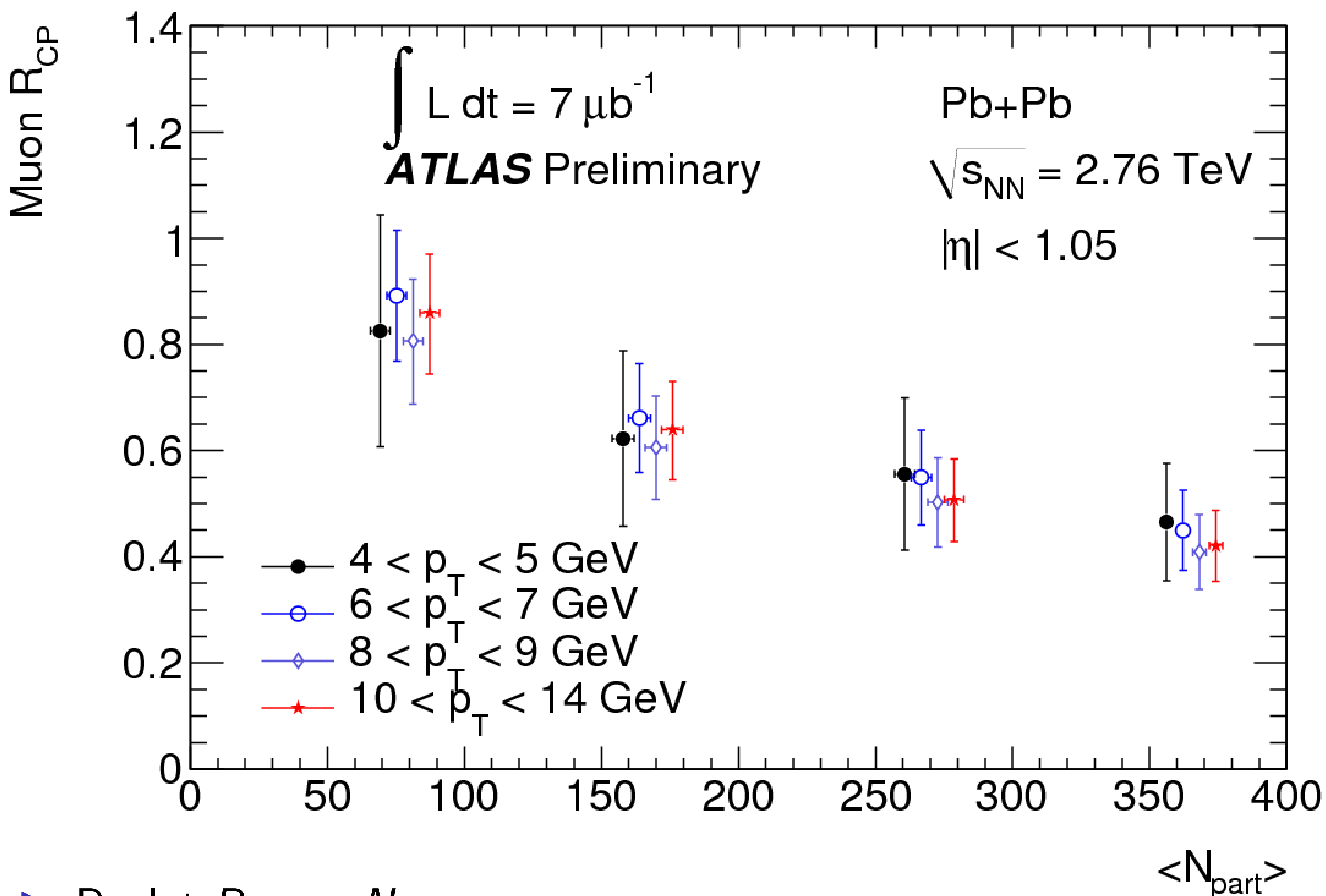
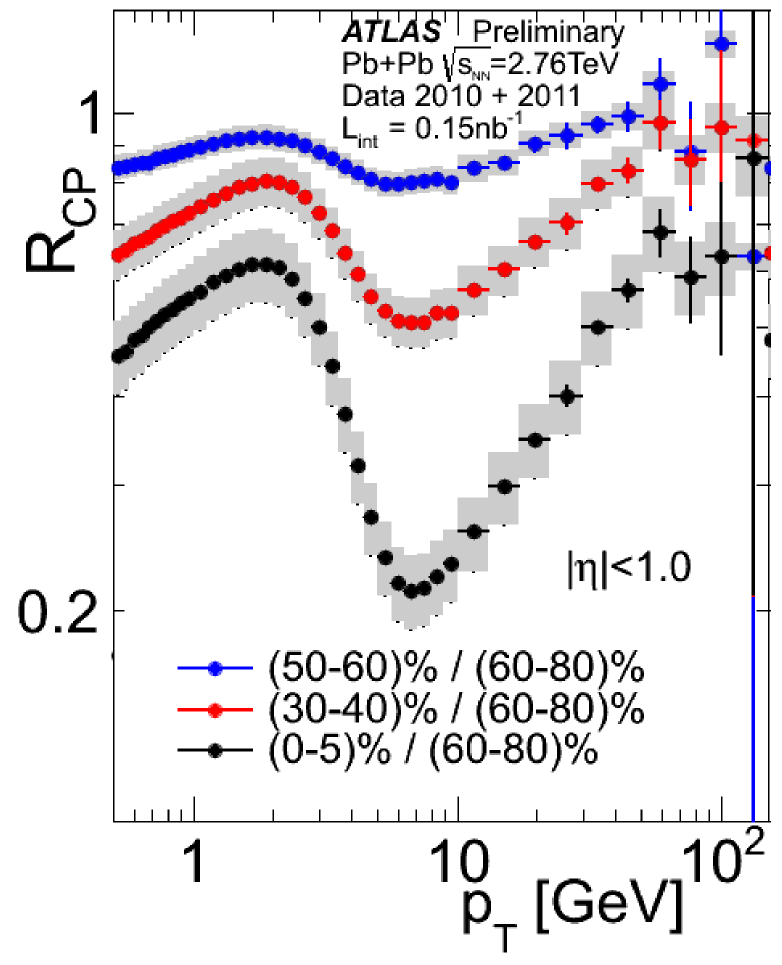
Results: $R_{\rm CP}(N_{\rm part})$ from heavy flavor decays





- Replot $R_{\rm CP}$ vs $N_{\rm part}$:
  - ⇒ suppression evolves smoothly with centrality.
  - ⇒ similar $N_{\rm part}$ dependence at all $p_{\rm T}$.

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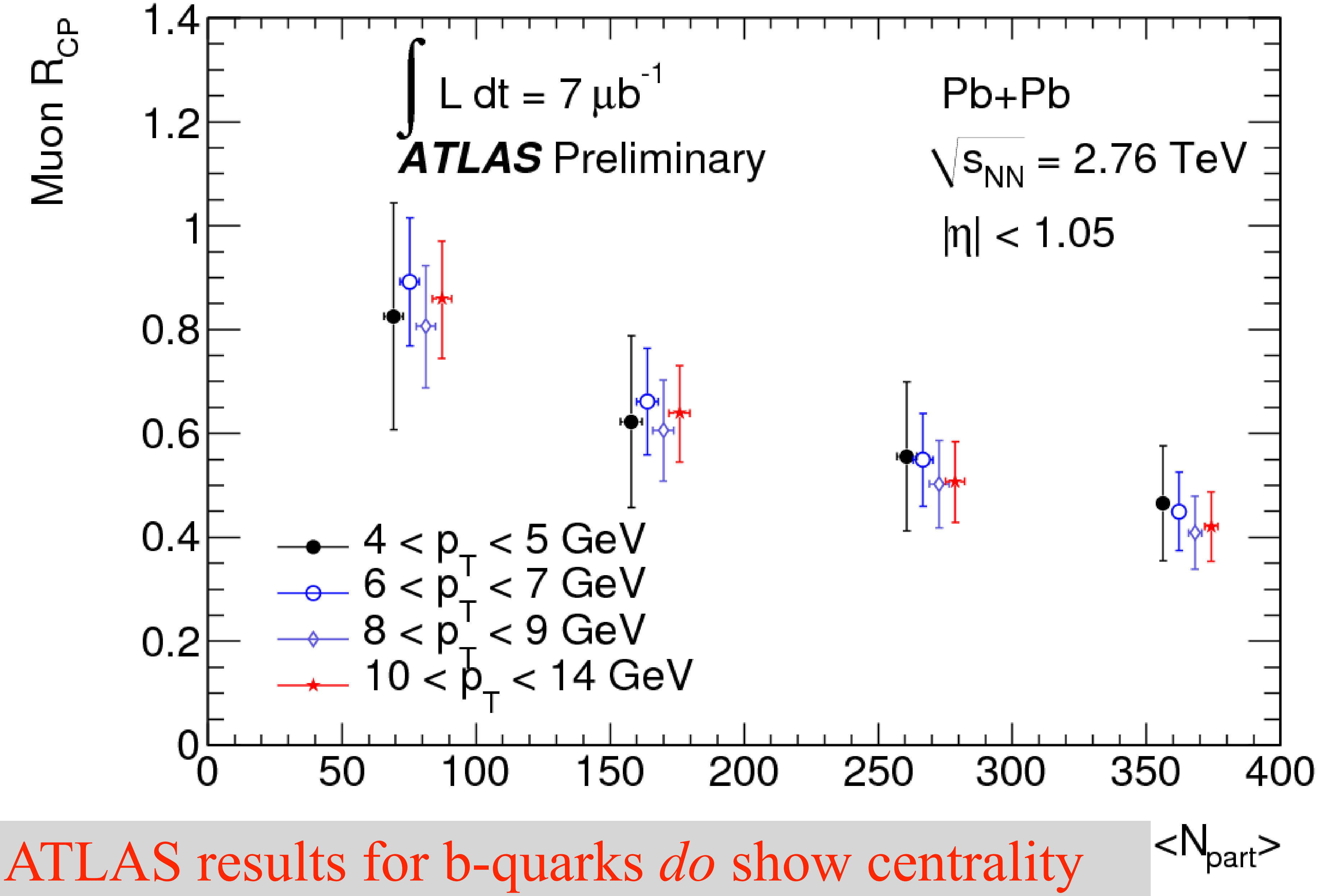
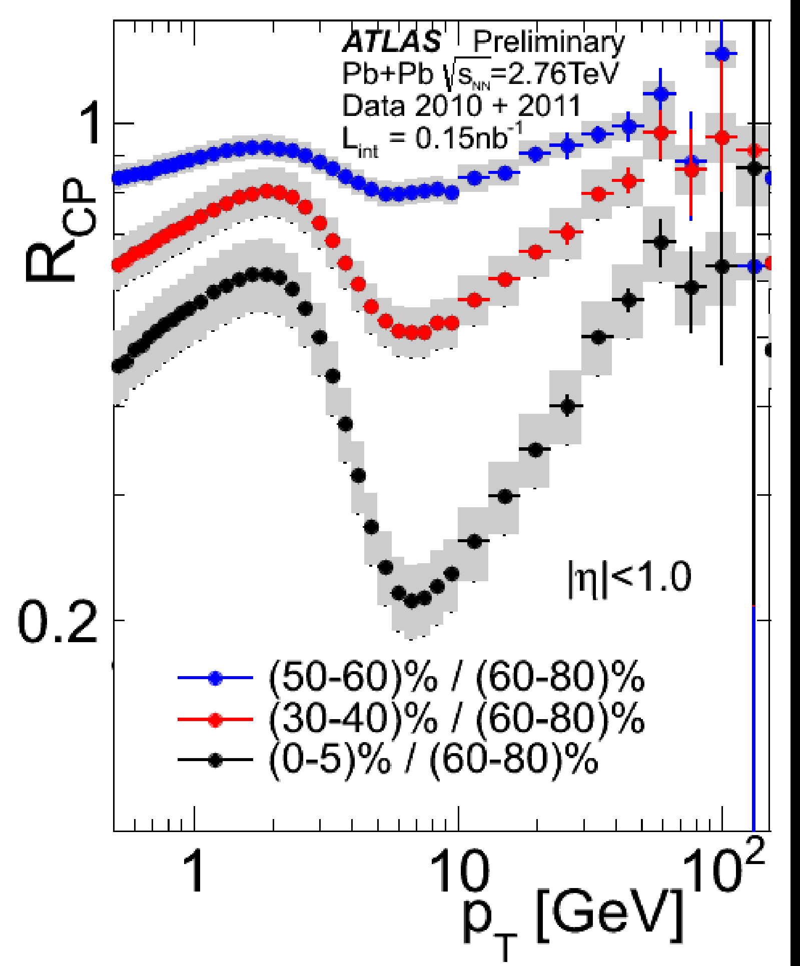


ATLAS μ-tagged Open Heavy Flavor



ATLAS results for b-quarks *do* show centrality dependence (μ-tagged open heavy flavor), but similar suppression for central collisions as CMS

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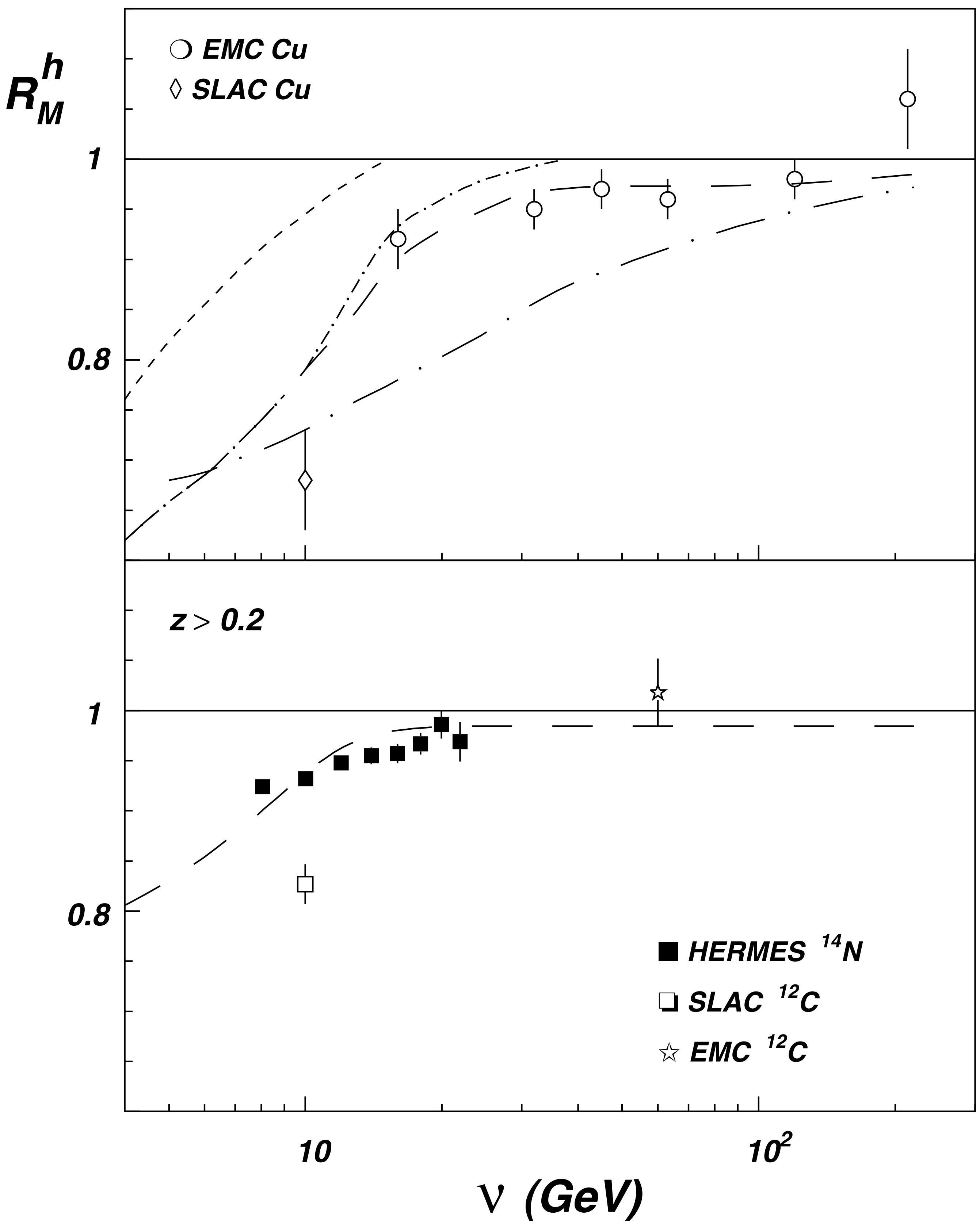
Nuclear fragmentation effects do not disappear at high energies!
(not at EIC, probably not even at LHeC)

http://arxiv.org/abs/hep-ph/0501260



$$R_M^h = R_A^h = \frac{\frac{1}{N_e^A} N_h^A}{\frac{1}{N_e^D} N_h^D}$$

See Anna Stasto's talk tomorrow

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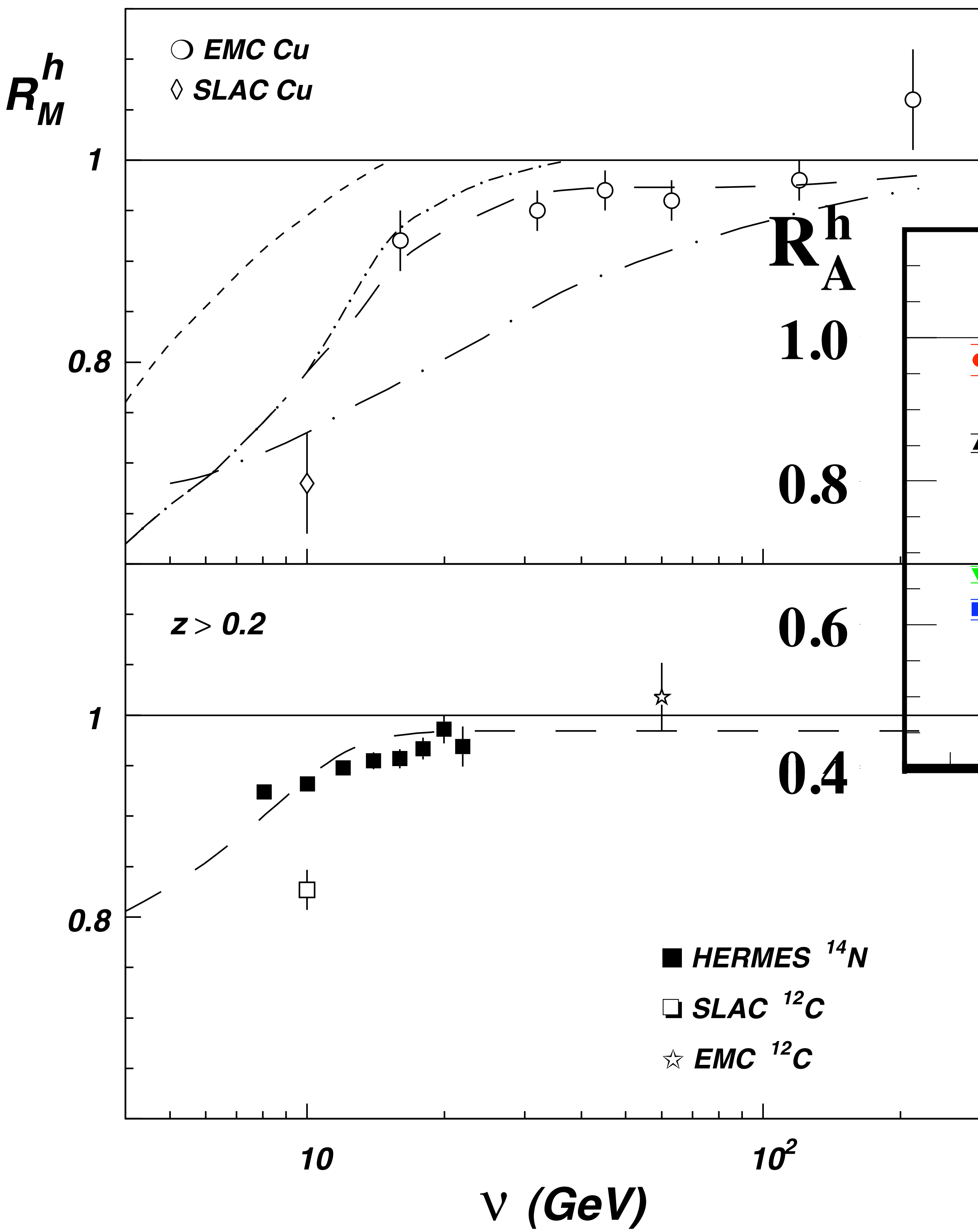

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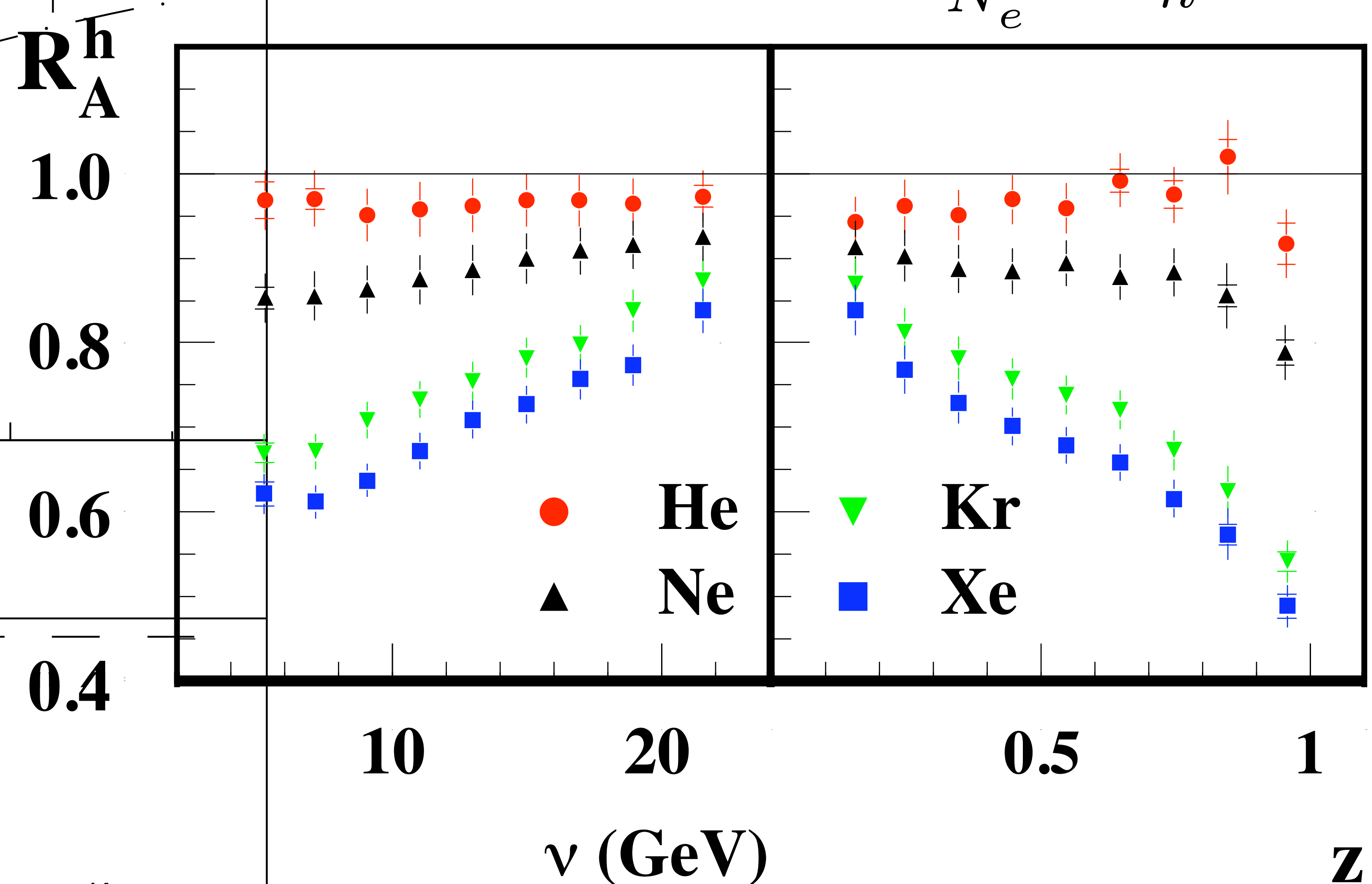
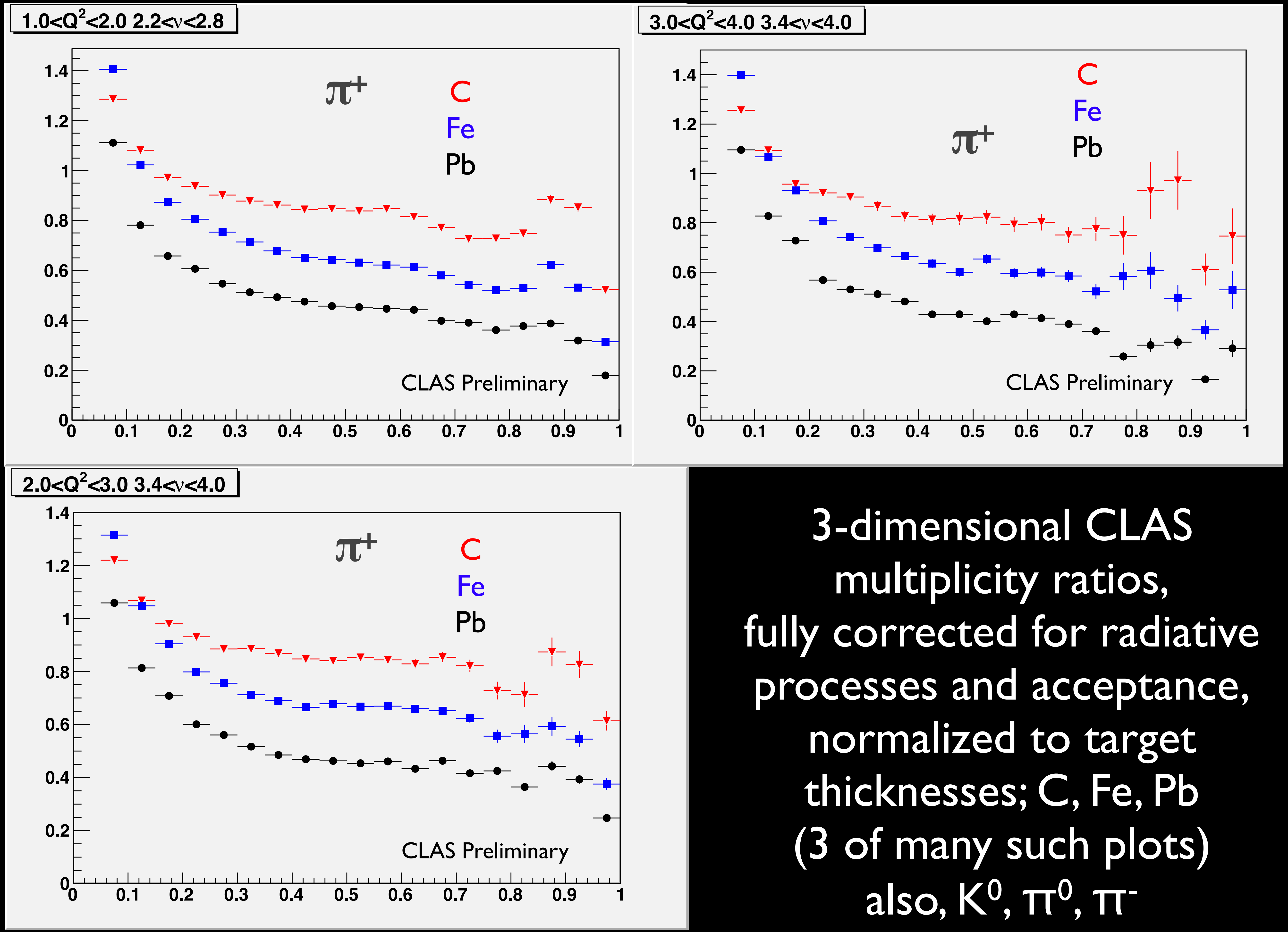
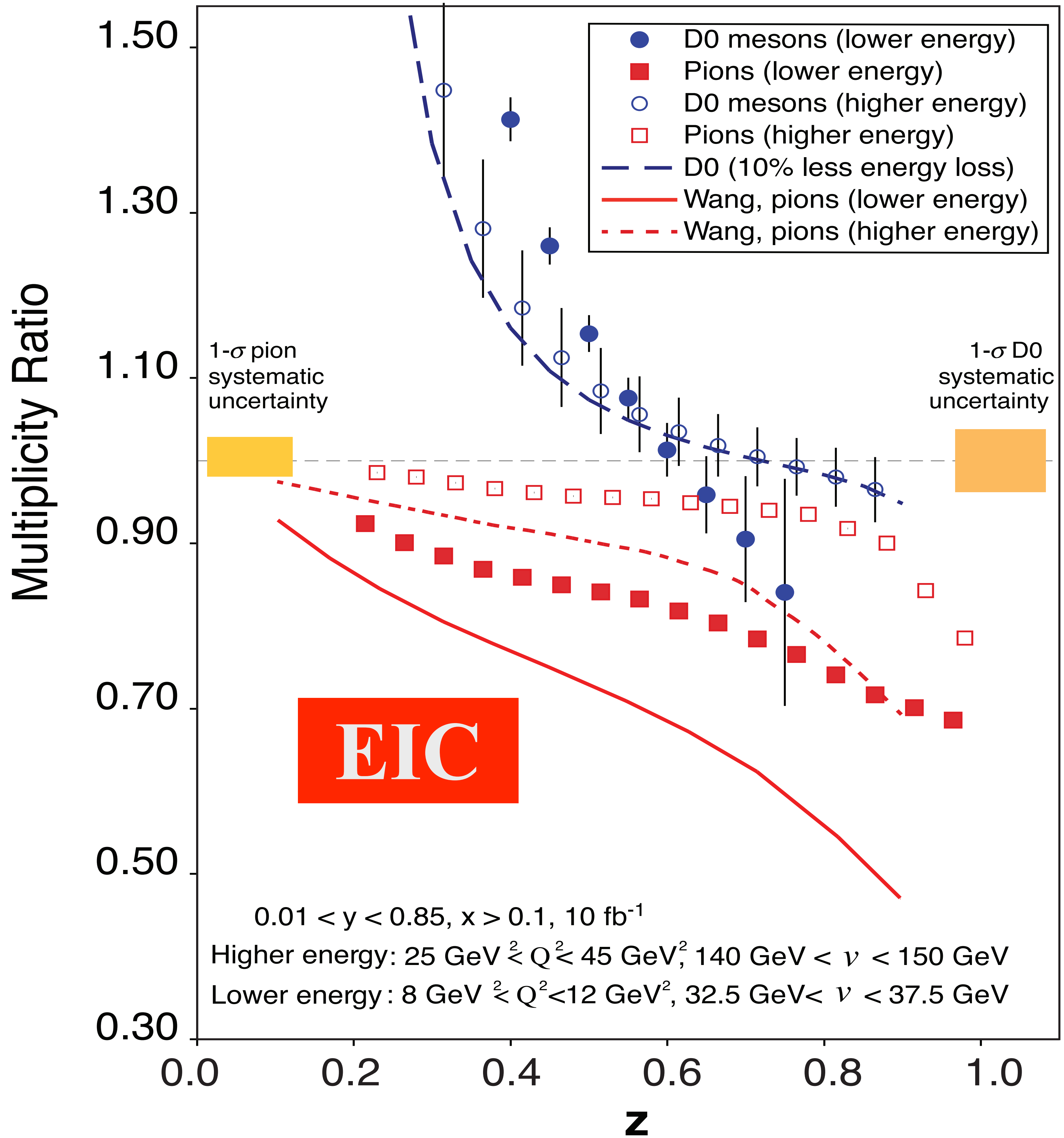


Persistent effects for large nuclei at high z

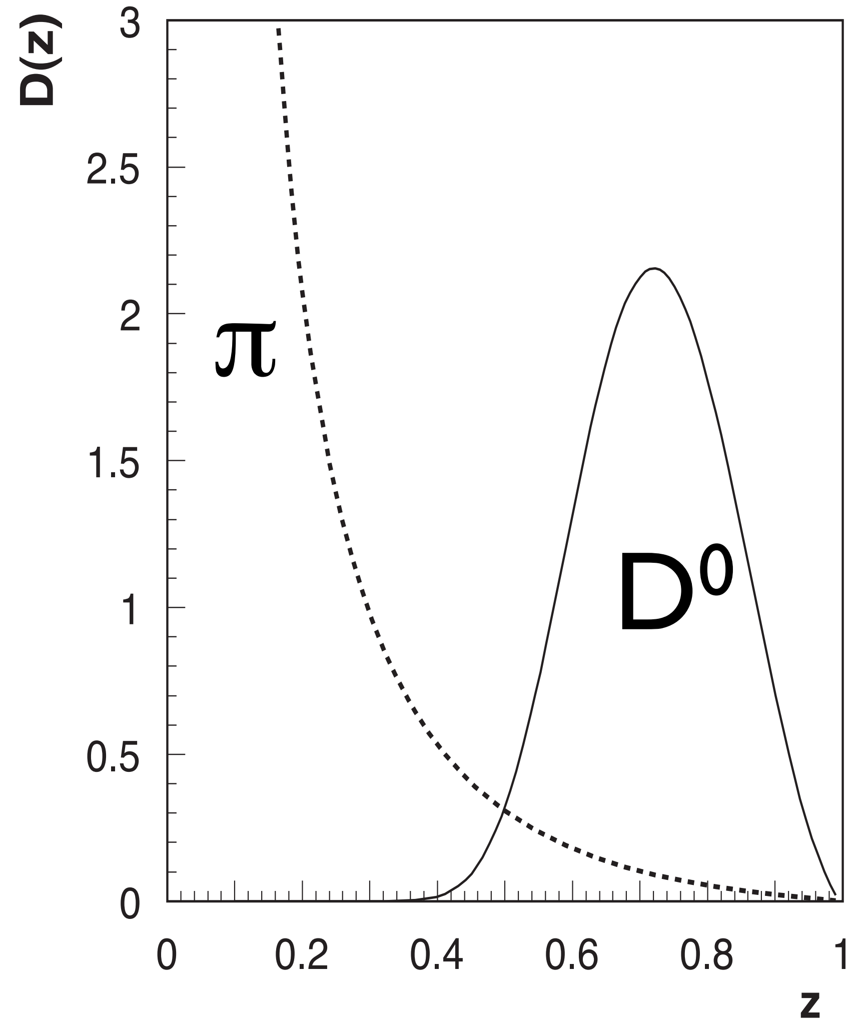
See Anna Stasto's talk tomorrow



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^-



Fragmentation functions



Access to very strong, unique energy loss signature for charm quarks
Substantial suppression for pions, despite high energy! (baryons too)

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
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
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Actively underway with existing 5 GeV data

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K^0	27 mm	0.50	$d\bar{s}$	Ξ^0	87 mm	1.3	us
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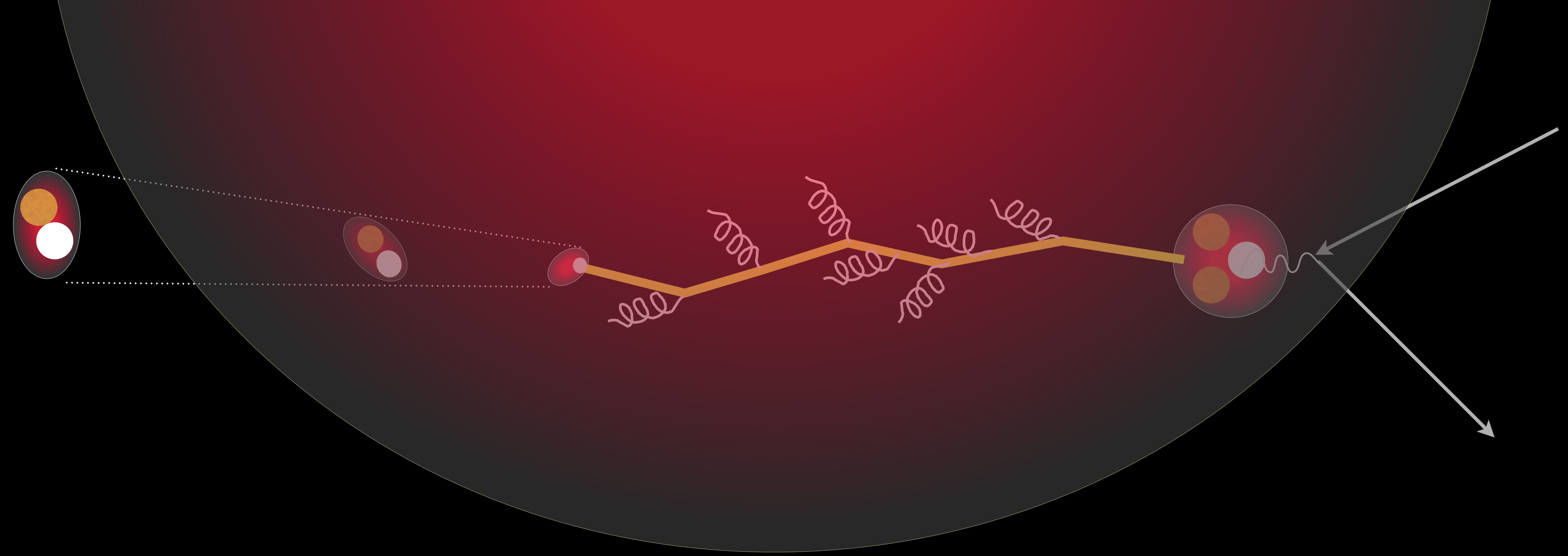
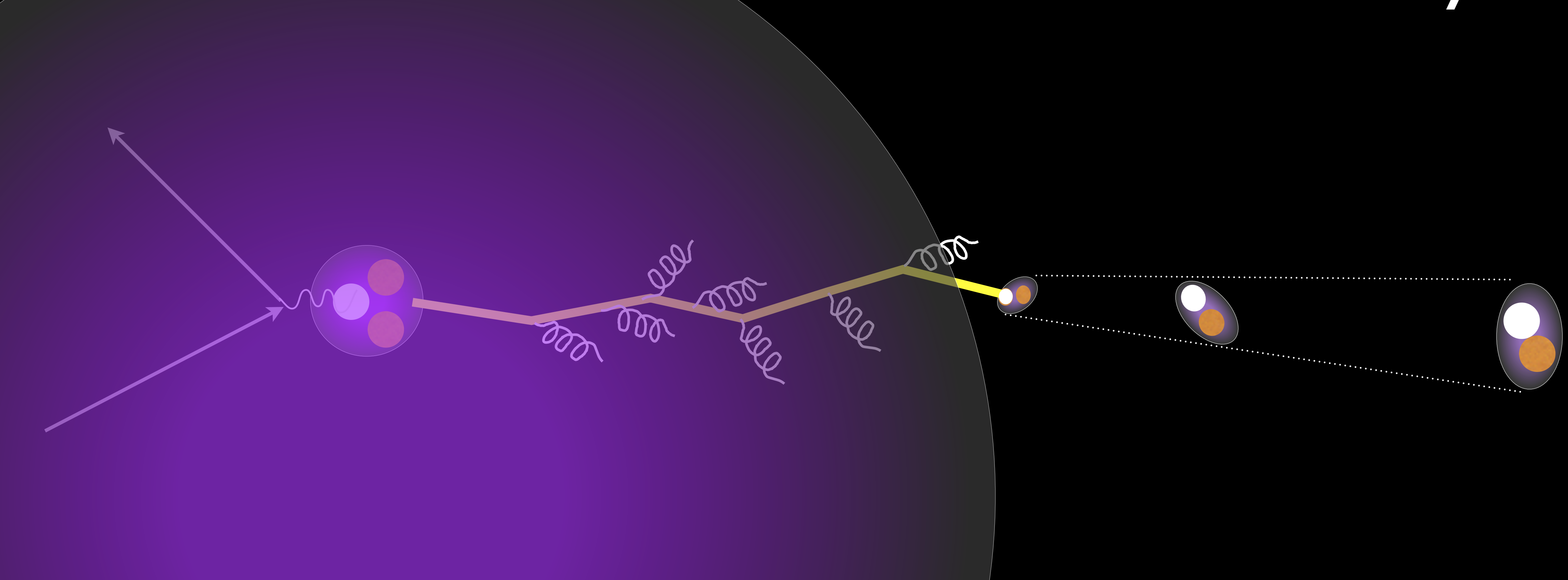
EIC too!



Suppression of fragmentation hadrons in nuclei: elusive mechanism or hidden duality?



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

Conclusions

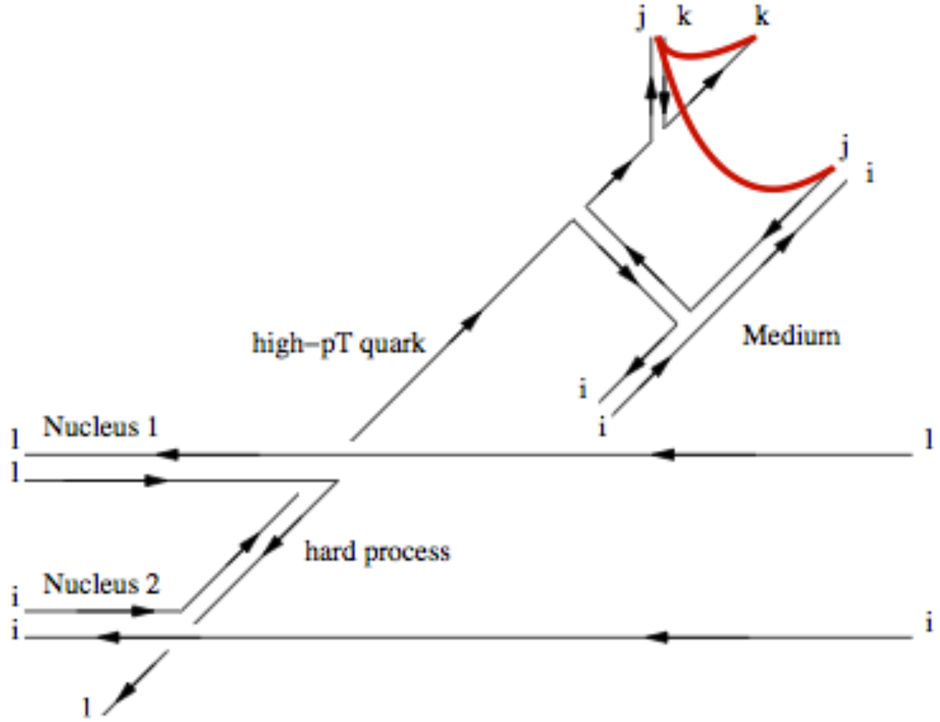
- Exploring cold nuclear matter using colored partonic probes
  - *Much recent progress, foundation for EIC*
- The intensifying puzzle of heavy quark energy loss
  - *EIC role is crucial to clarify this issue, as well as many other mysteries from heavy ion collisions*
- Suppression of fragmentation hadrons in nuclei: elusive mechanism or hidden duality?
  - *Wide kinematic extremes of EIC will clarify this*

Backup slides

Color correlations versus kinematics

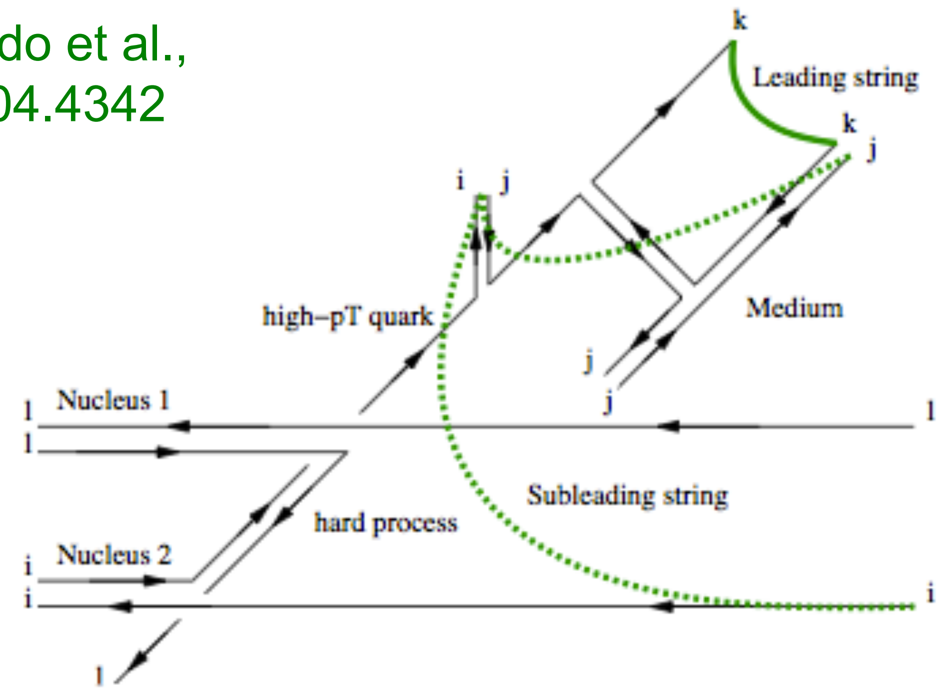
Even if hadron forms outside medium, it may form from modified color connection

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



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

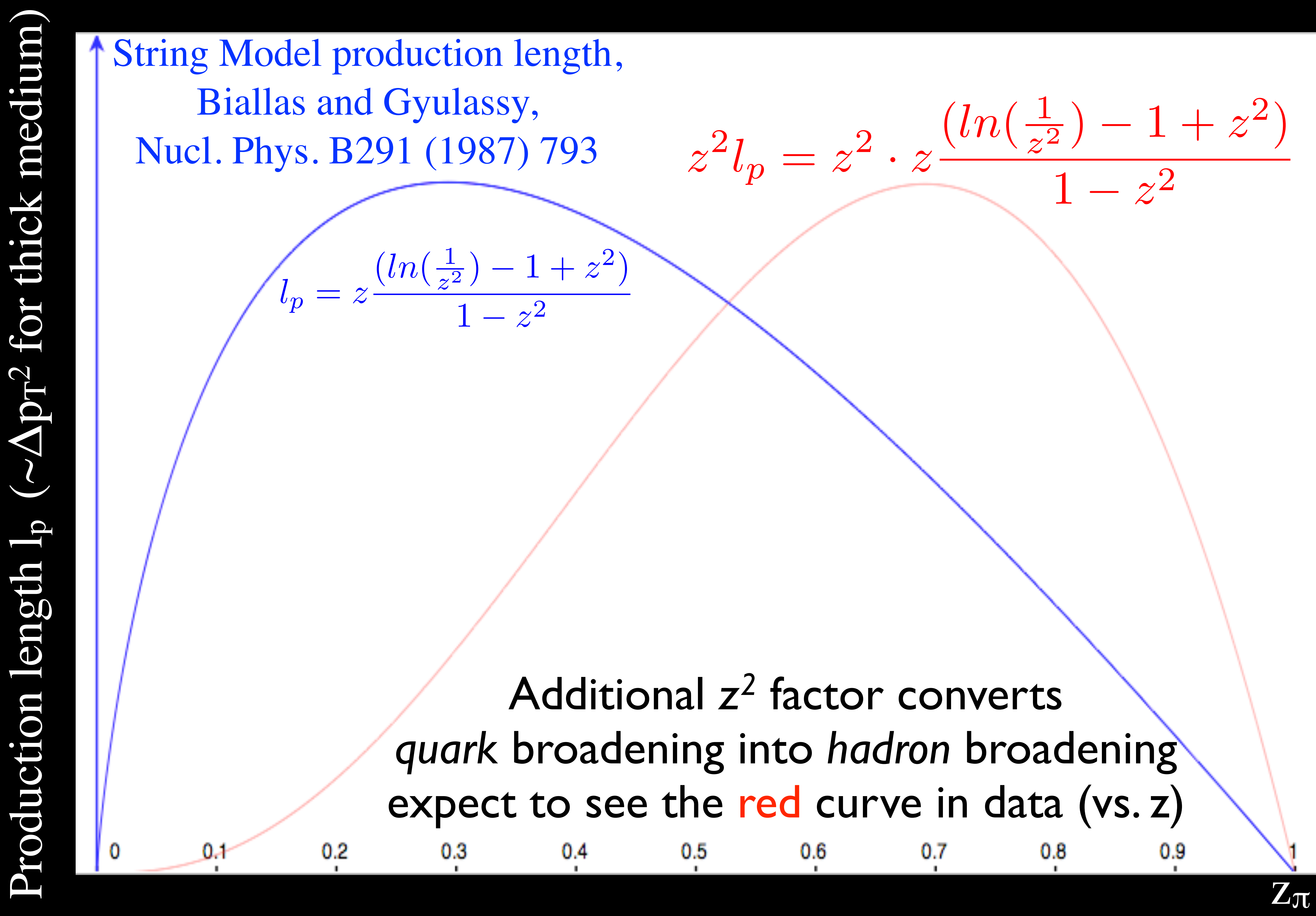
A. Beraudo et al., arXiv:1204.4342



- 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



String Model production length,
Biallas and Gyulassy,
Nucl. Phys. B291 (1987) 793
$z^2 l_p = z^2 \cdot z \frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$
$l_p = z \frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$
Additional z^2 factor converts
quark broadening into *hadron* broadening
expect to see the red curve in data (vs. z)
Production length l_p (~Δp_T^2 for thick medium)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z_π