EIC: New Scientific and Technology Frontiers for Parton Femtoscopy

Will Brooks
UTFSM, Valparaíso, Chile

Overview

The Electron Ion Collider is the next "QCD machine" proposed in the U.S. -

- will offer outstanding, groundbreaking capabilities to understand gluons and sea/valence quarks in QCD
- Included in 2007 "Long-Range Plan"; 2013 NSAC Facilities Review said it is "...**Absolutely Central** in its ability to contribute to world-leading science in the next decade." ...but needs R&D.....
- Joint community developed "white paper" - 1212.1701 - facility designs by BNL (add e^-) and by JLab (add protons)
- Highly polarized e- and p/D beams; 10^{33}-10^{34} $cm^{-2}s^{-1}$; CM energy 20-100 (150) GeV; ions up to U/Pb
- High luminosity, low x, high polarization → discovery class

Some of the physics topics

- Spin and Three-Dimensional Structure of the Nucleon
  - Δg, g_1
  - TMDs and GPDs
- The Nucleus: A Laboratory for QCD
  - parton propagation and hadronization
  - saturation physics
- Physics beyond the Standard Model

....and much more

http://arxiv.org/abs/arXiv:1212.1701 and references therein

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The Nucleus: A Laboratory for QCD

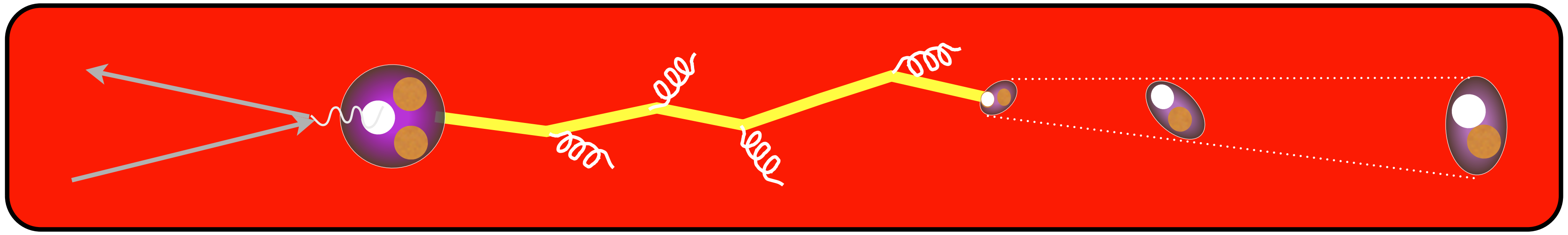
What time scales are involved when partons propagate?

How do hadrons emerge from QCD color?

How large is light and heavy quark energy loss in cold matter?

How big is the QCD saturation scale?

Timescales



- Two distinct stages for struck quark in DIS:
  - Virtual quark lifetime - gluons radiated
  - Hadron formation time
    - Overall time, just as in QED: $\frac{k_{\parallel}}{k_{\perp}^{2}}$
- Theoretical speculation until now
  - Interactions with nuclei reveal time/distance scales
    - Bose-Einstein correlations too

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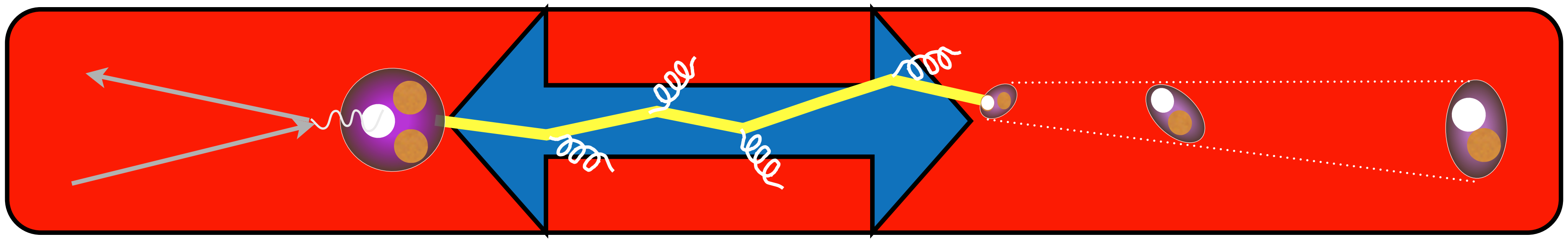

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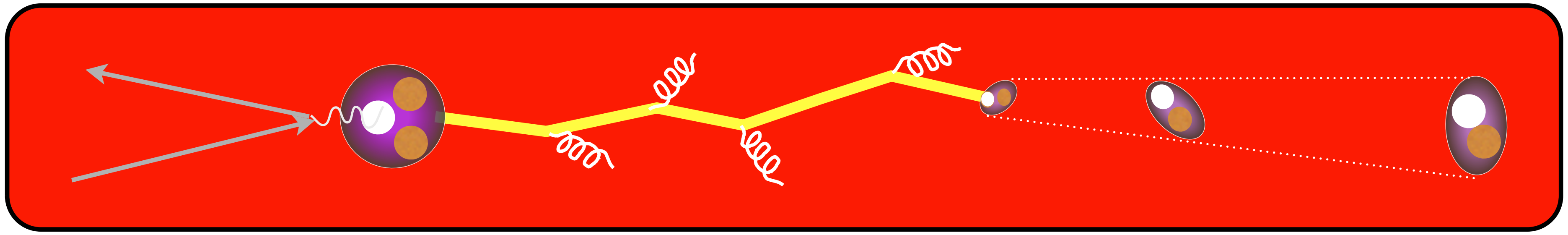

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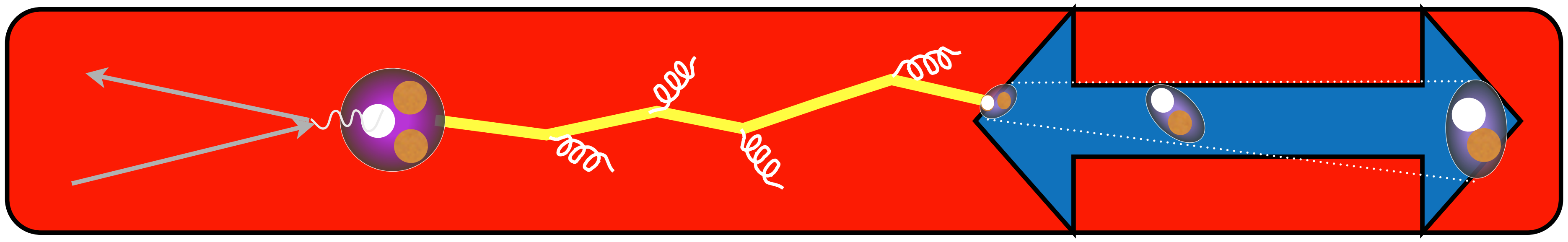

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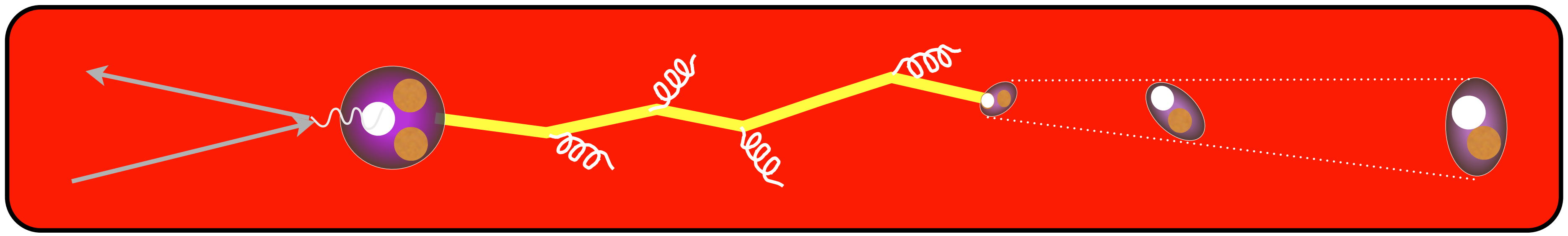

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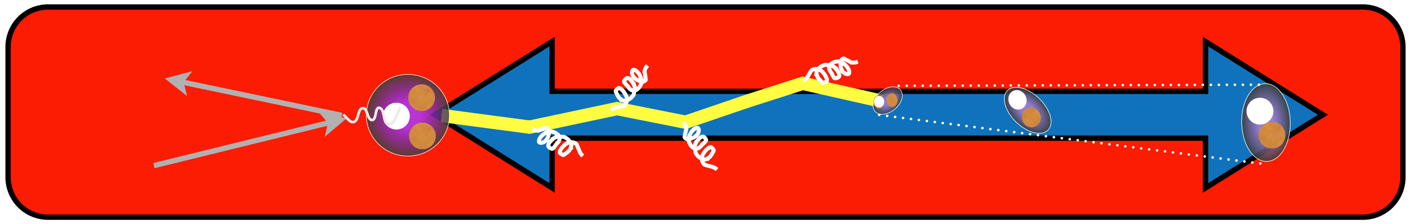
Timescales - how to measure?



- First observable: multiplicity ratio

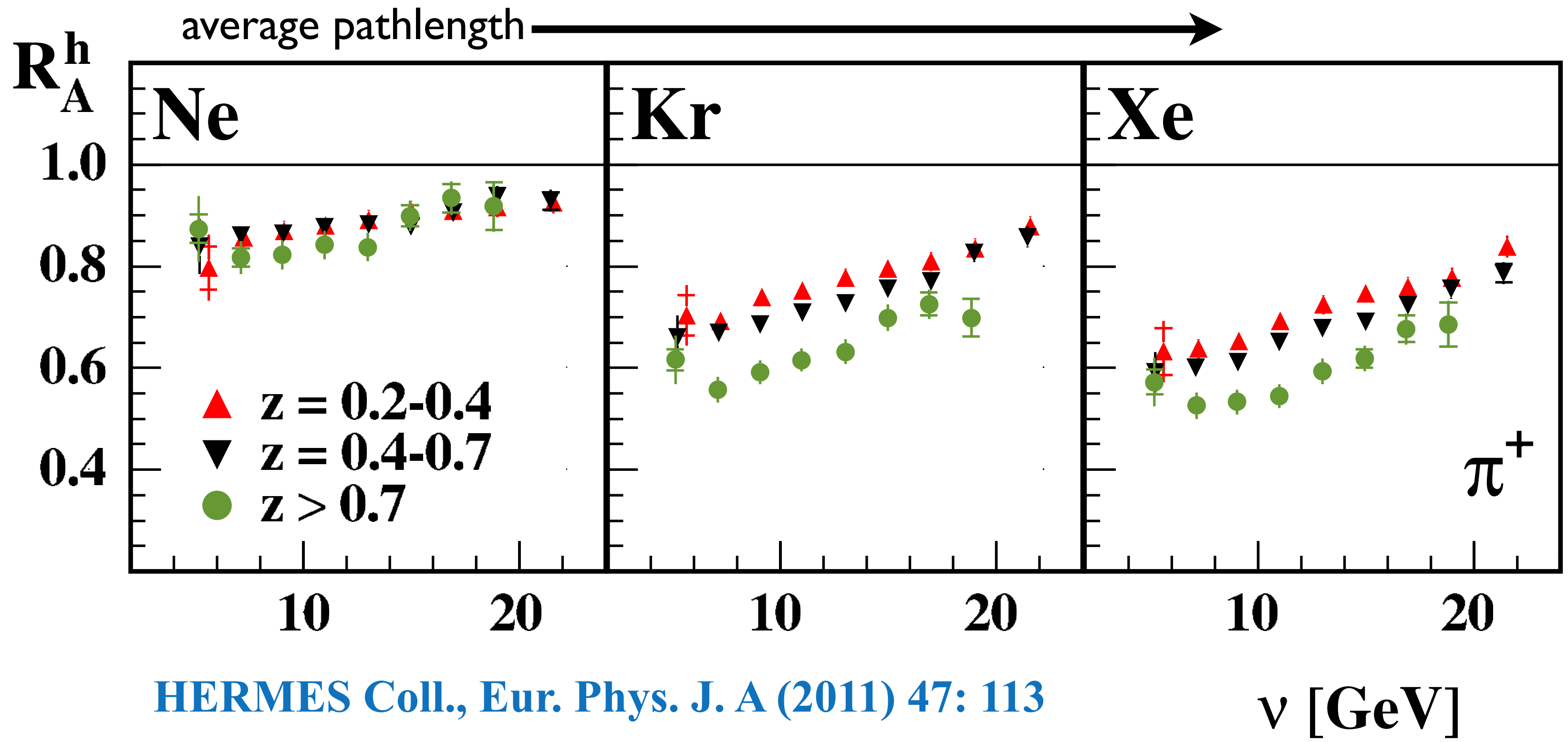
$$R_h = \frac{\frac{1}{N_e^A(Q^2,\nu)} N_h^A(Q^2,\nu,z,p_T,\phi)}{\frac{1}{N_e^D(Q^2,\nu)} N_h^D(Q^2,\nu,z,p_T,\phi)}$$

Expectations: rise→1 at high ν

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

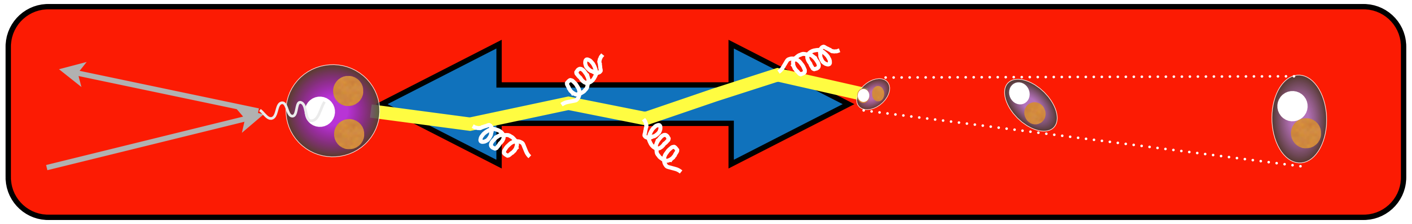
$$z \equiv \frac{E_{hadron}}{\nu}$$

$$0 < z < 1$$



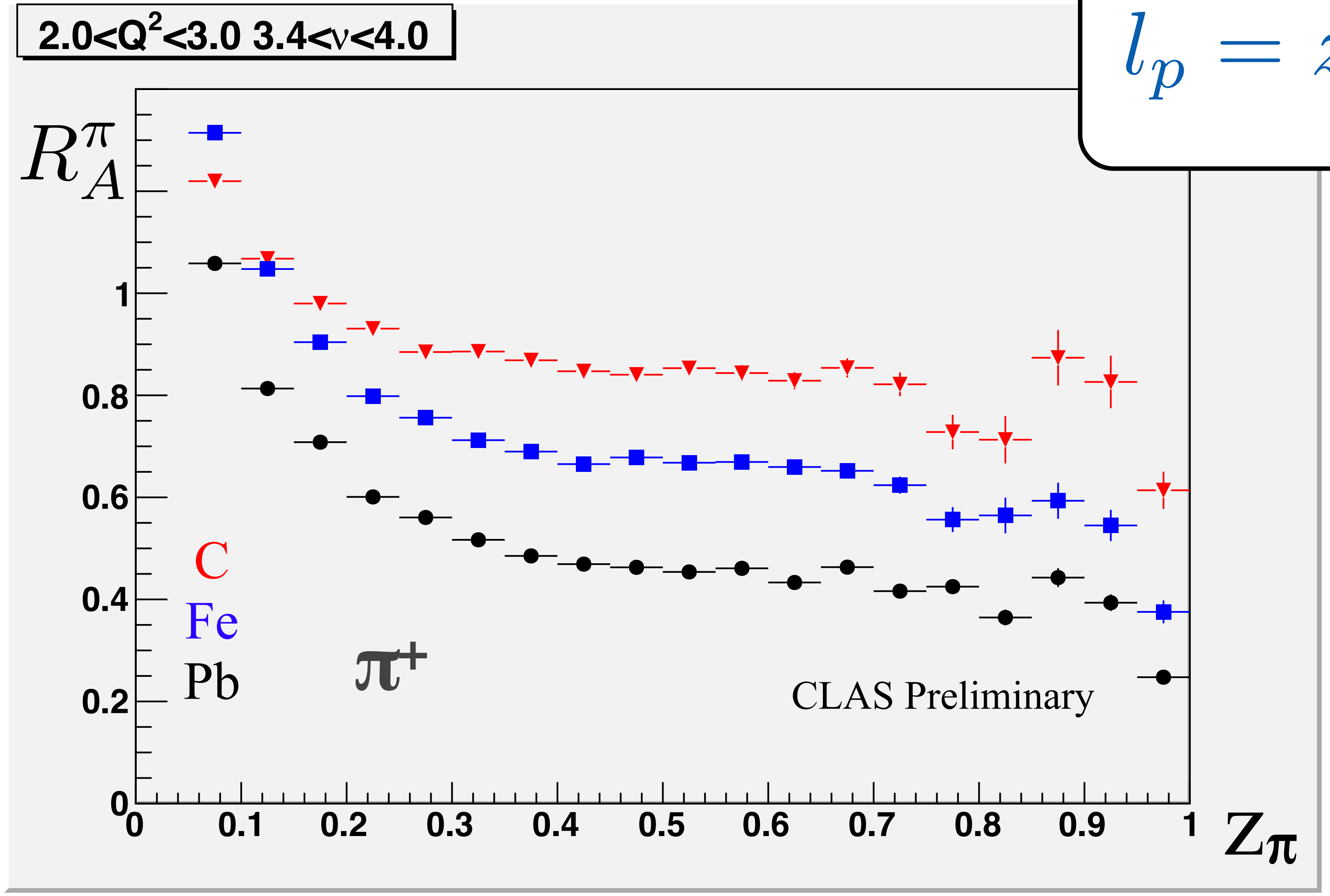
HERMES Coll., Eur. Phys. J. A (2011) 47: 113

Lund string model time estimate



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

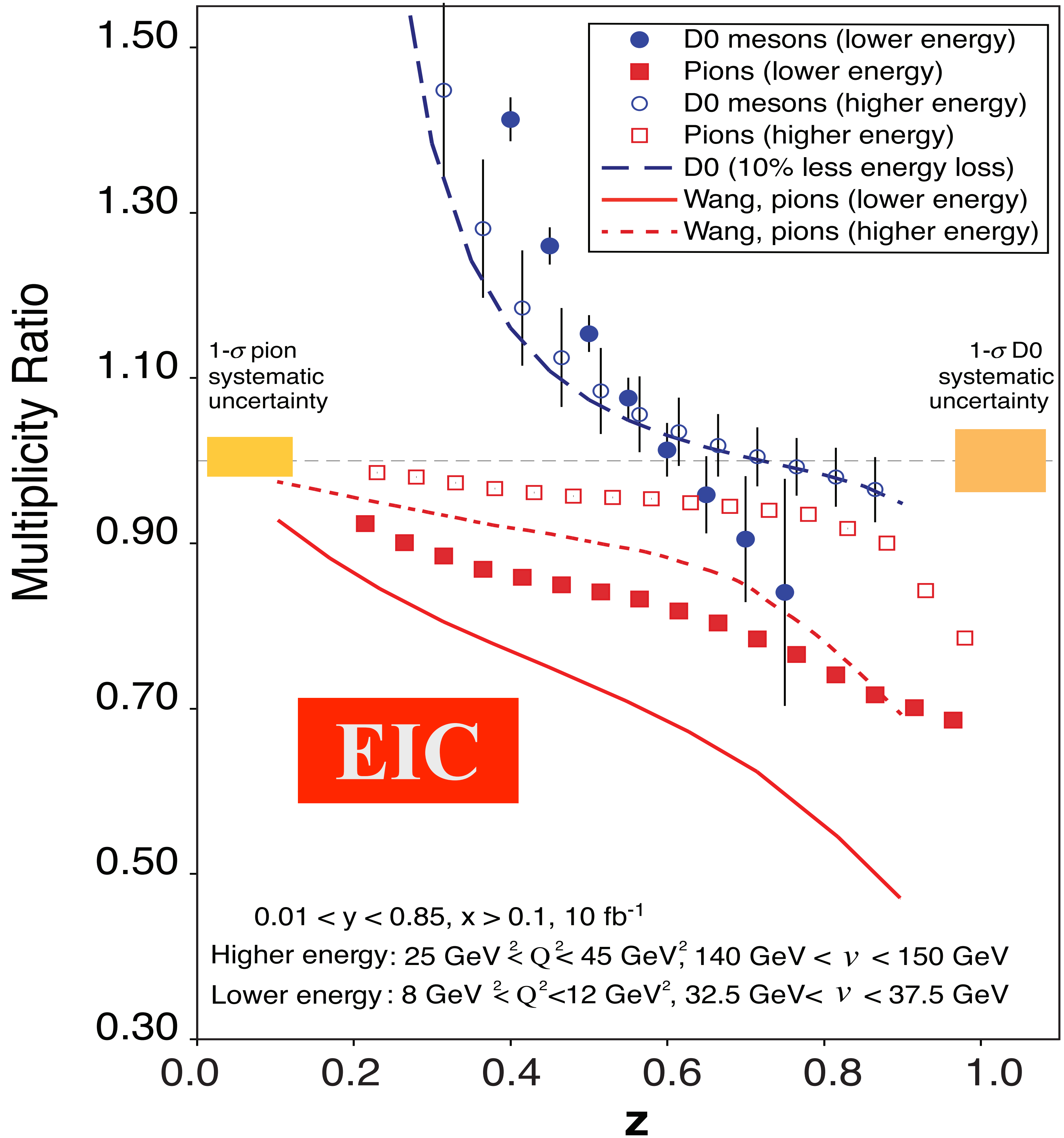
$$l_p = z\frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$$



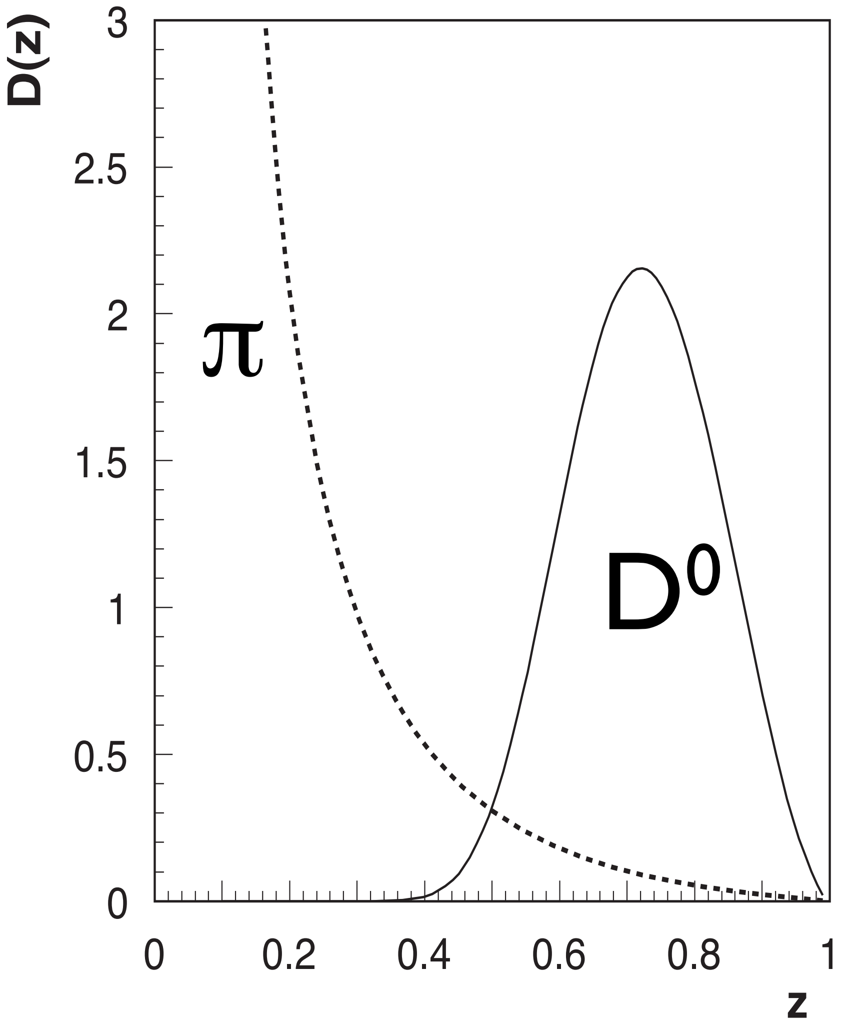
Expectation: drop at high z

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

Maximum lifetime is at intermediate z



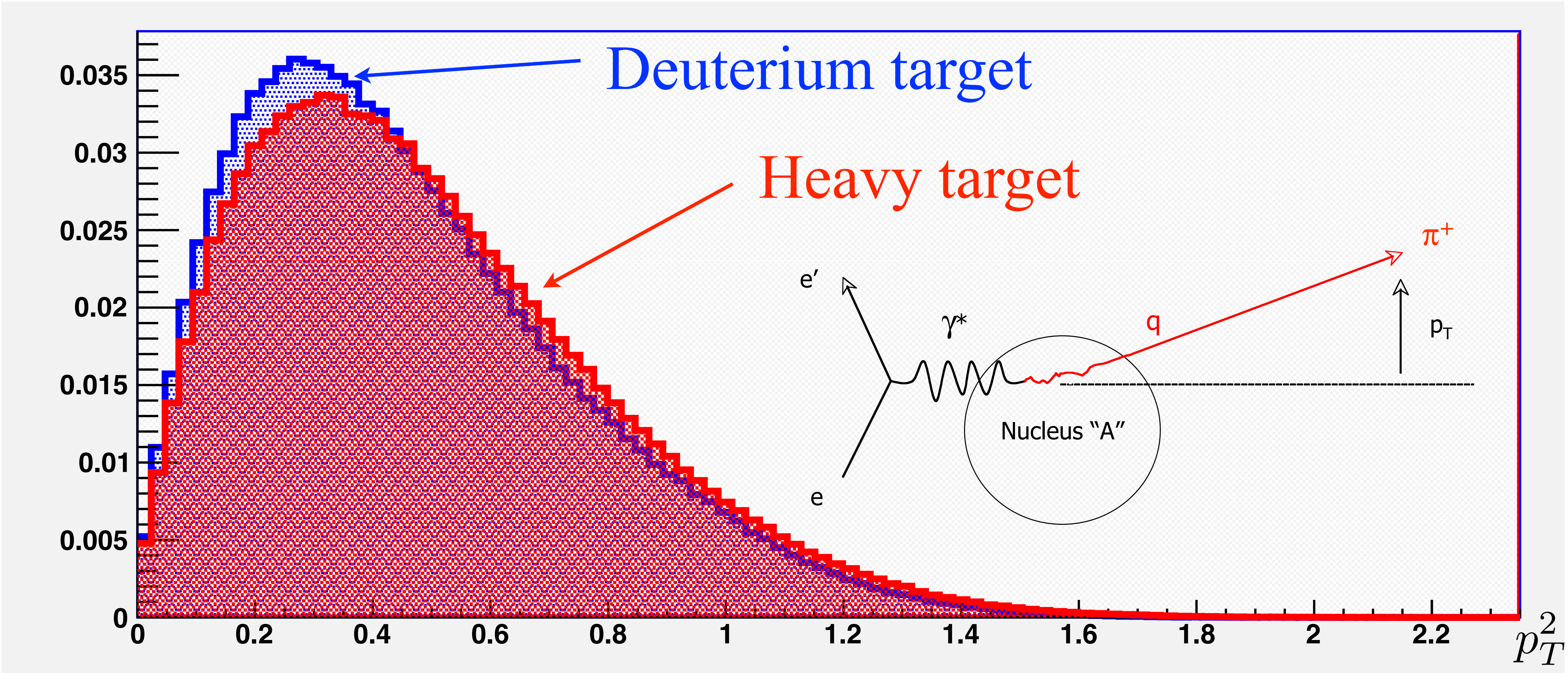
Fragmentation functions



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^+

Observables: Transverse Momentum Broadening

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



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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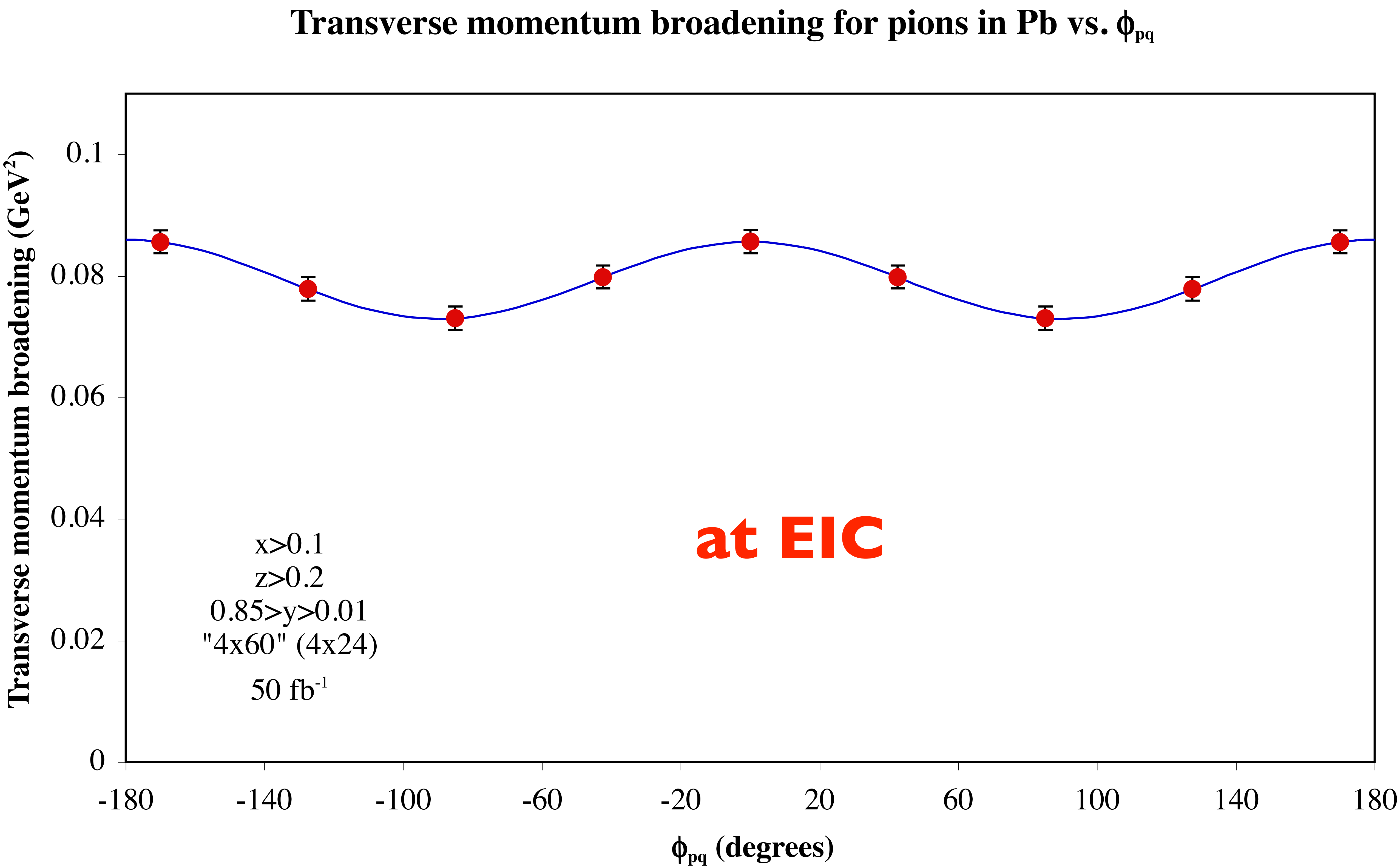
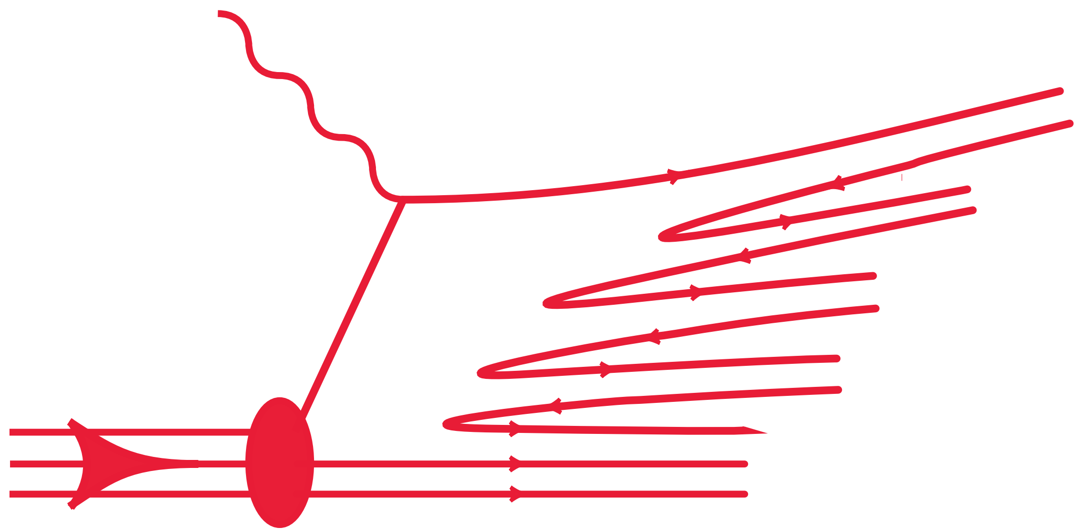
  http://arxiv.org/abs/1001.4281



- Possible p_T broadening measurement at EIC (~speculative:) probing quantum density fluctuations at high energies with partonic multiple scattering
- J/ψ p_T broadening: measure the gluon saturation scale

Mechanisms - phenomenology

- QCD cascade:
  - NLO QCD matrix elements; or
  - Parton shower
- Hadron formation
  - Lund string model



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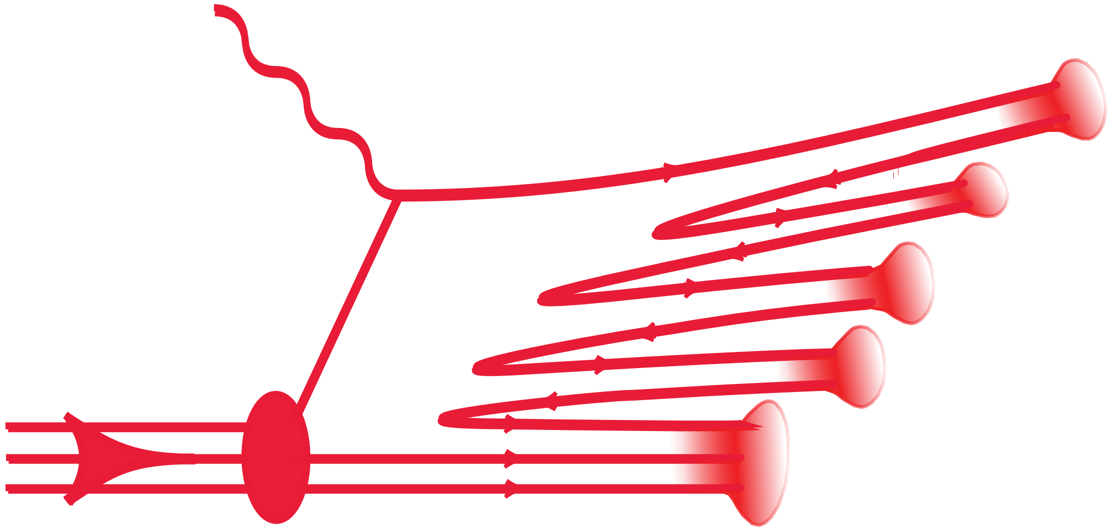

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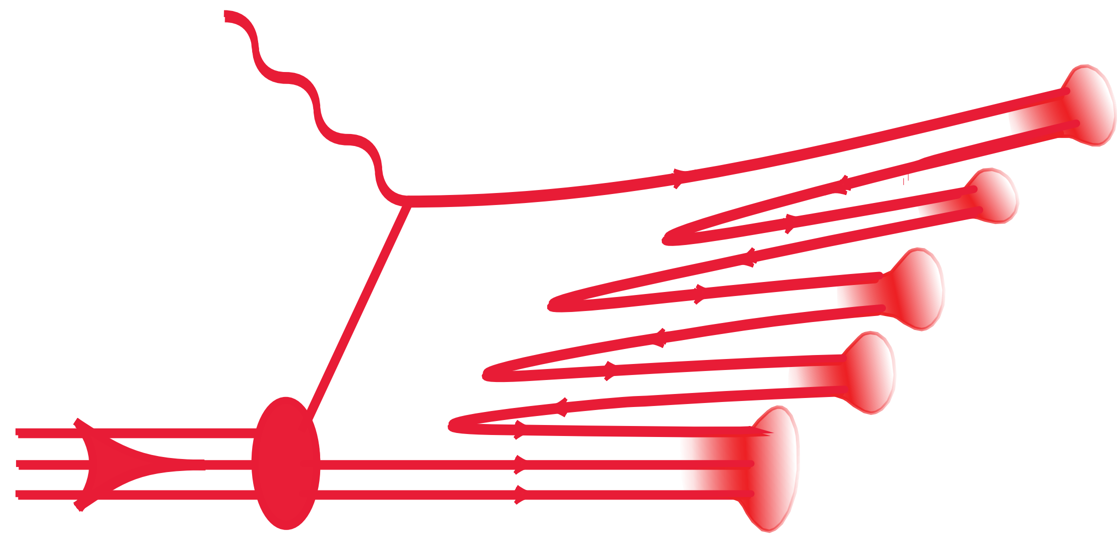

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  - nuclei
  - target fragmentation through forward recoil tagging - measure fracture functions

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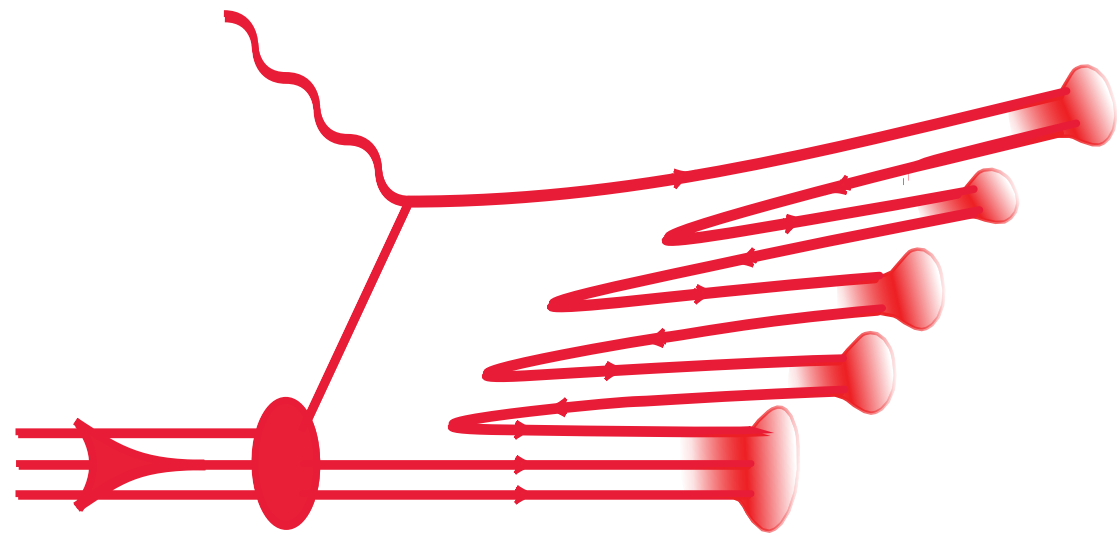

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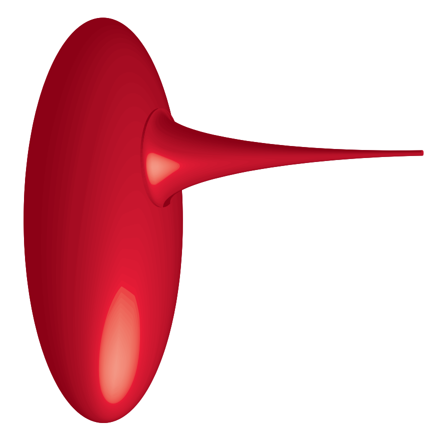


Spin and Three-Dimensional Structure of the Nucleon

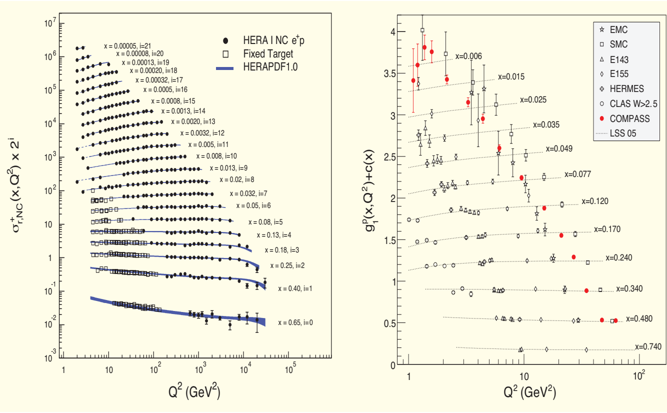
Where does the proton spin come from?

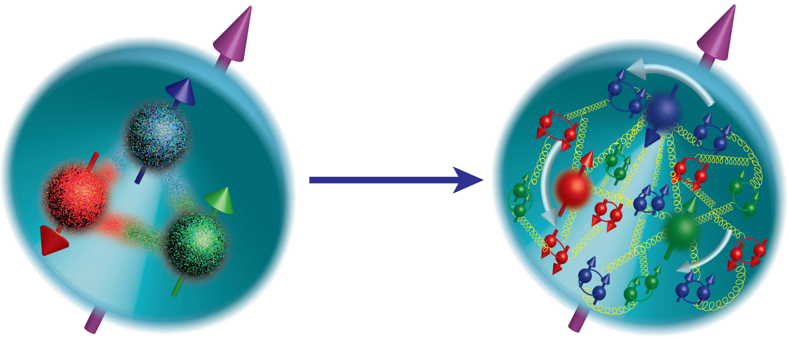
How important is the quark orbital motion?

What is the role of the gluons?

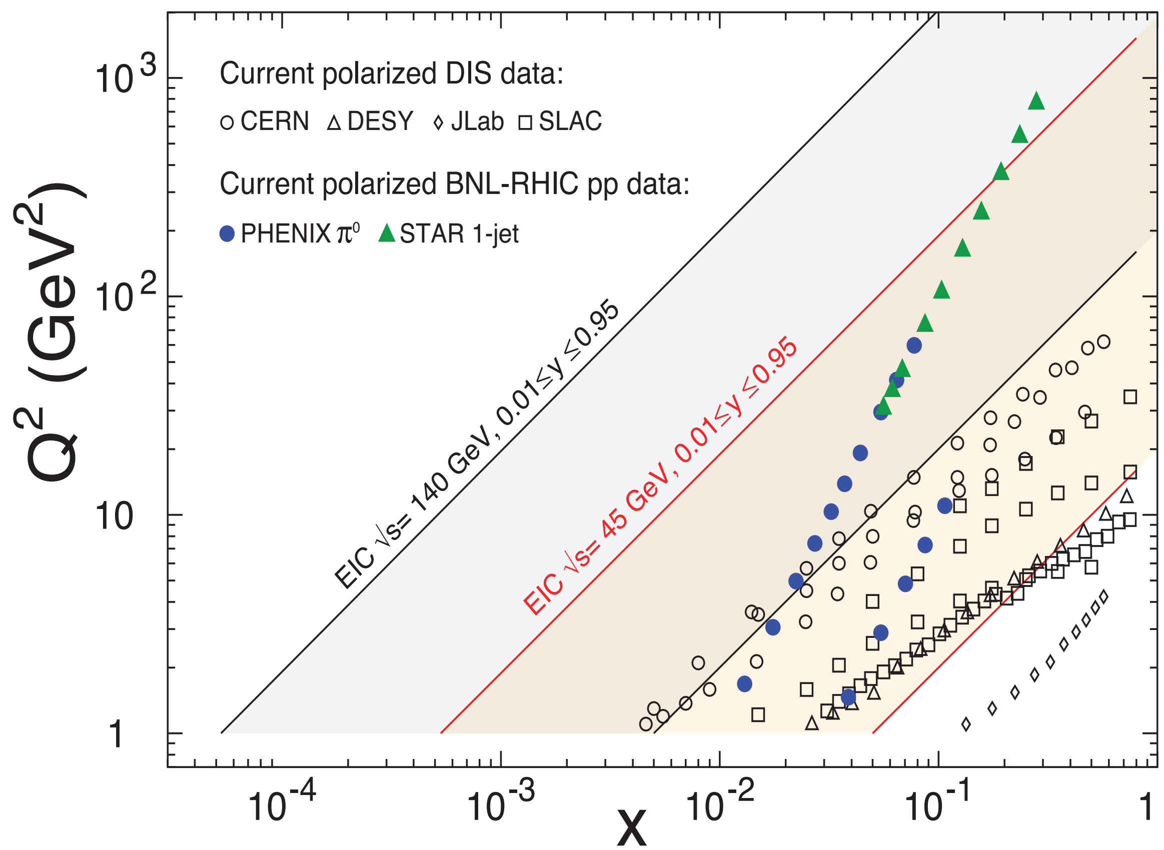
What does the nucleon look like in 3D tomography?

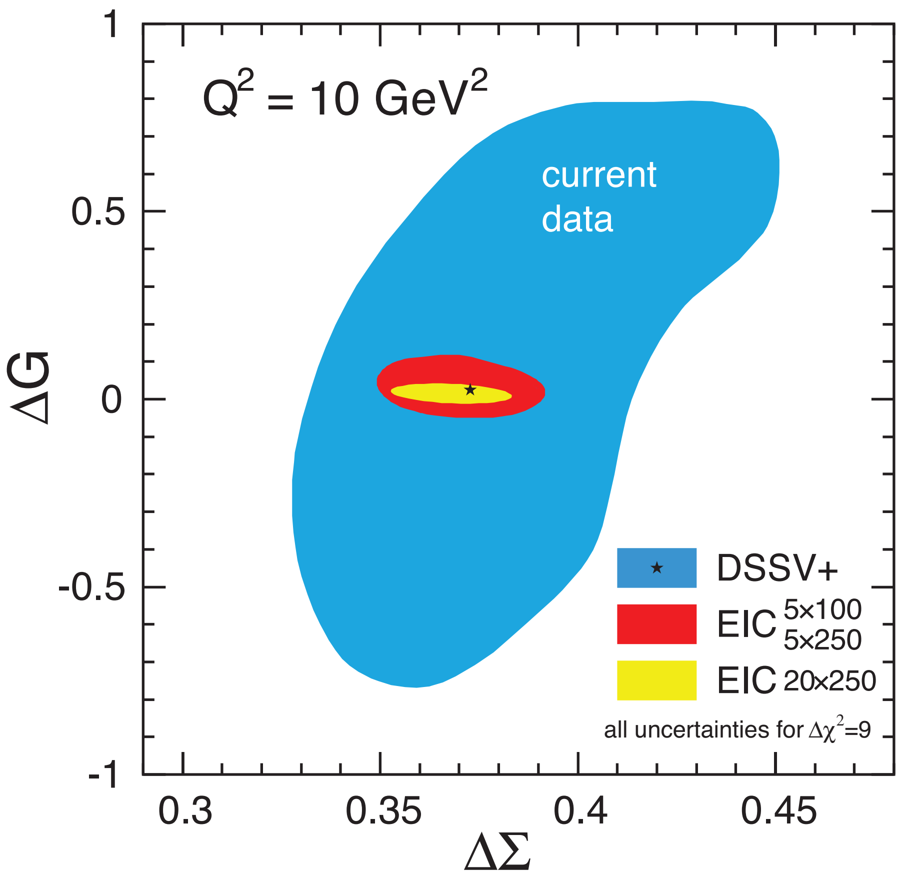
Spin structure of proton and neutron





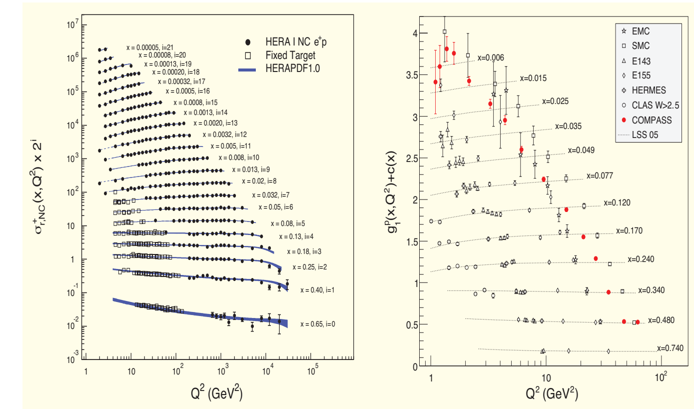
Origin of proton spin is complex
gluon component elusive

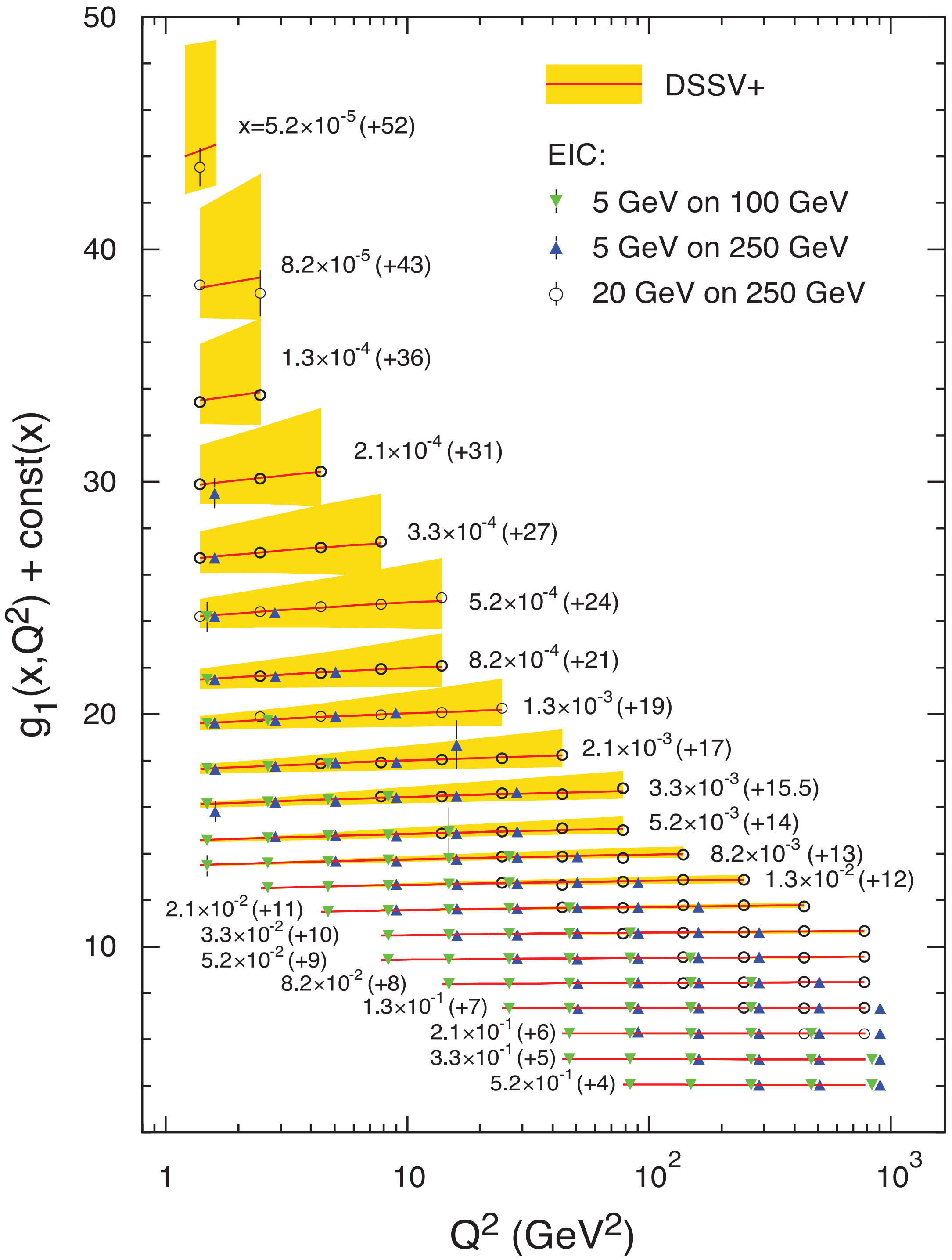




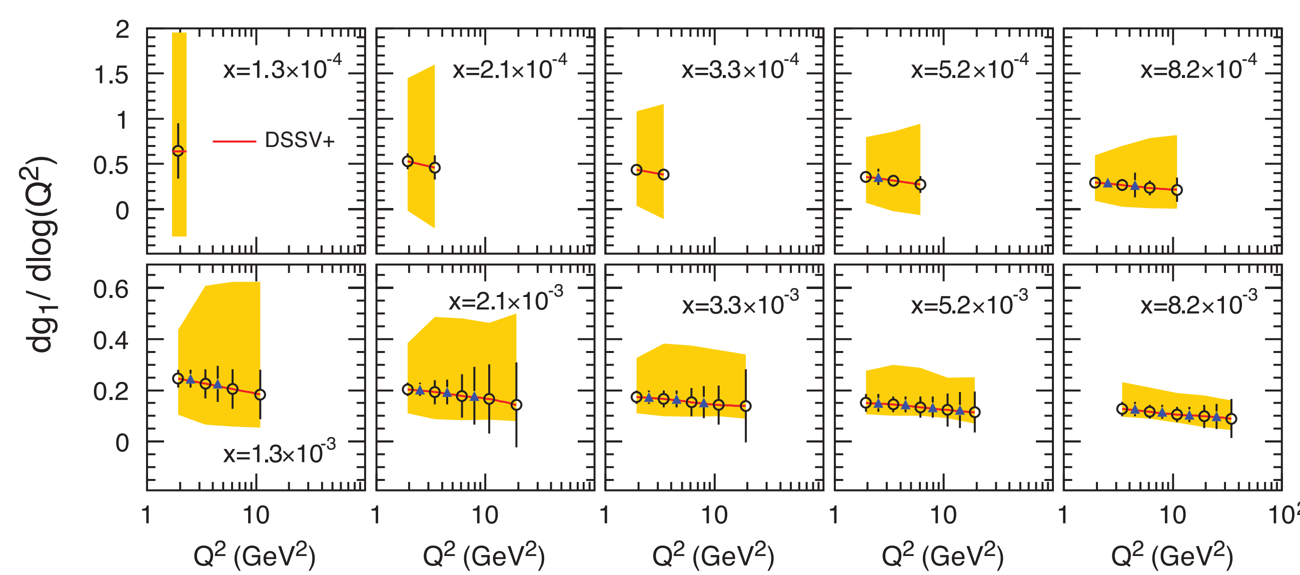
EIC offers much broader kinematics
Crucial for precision determinations of spin contributions

Polarized structure function g_1 at EIC

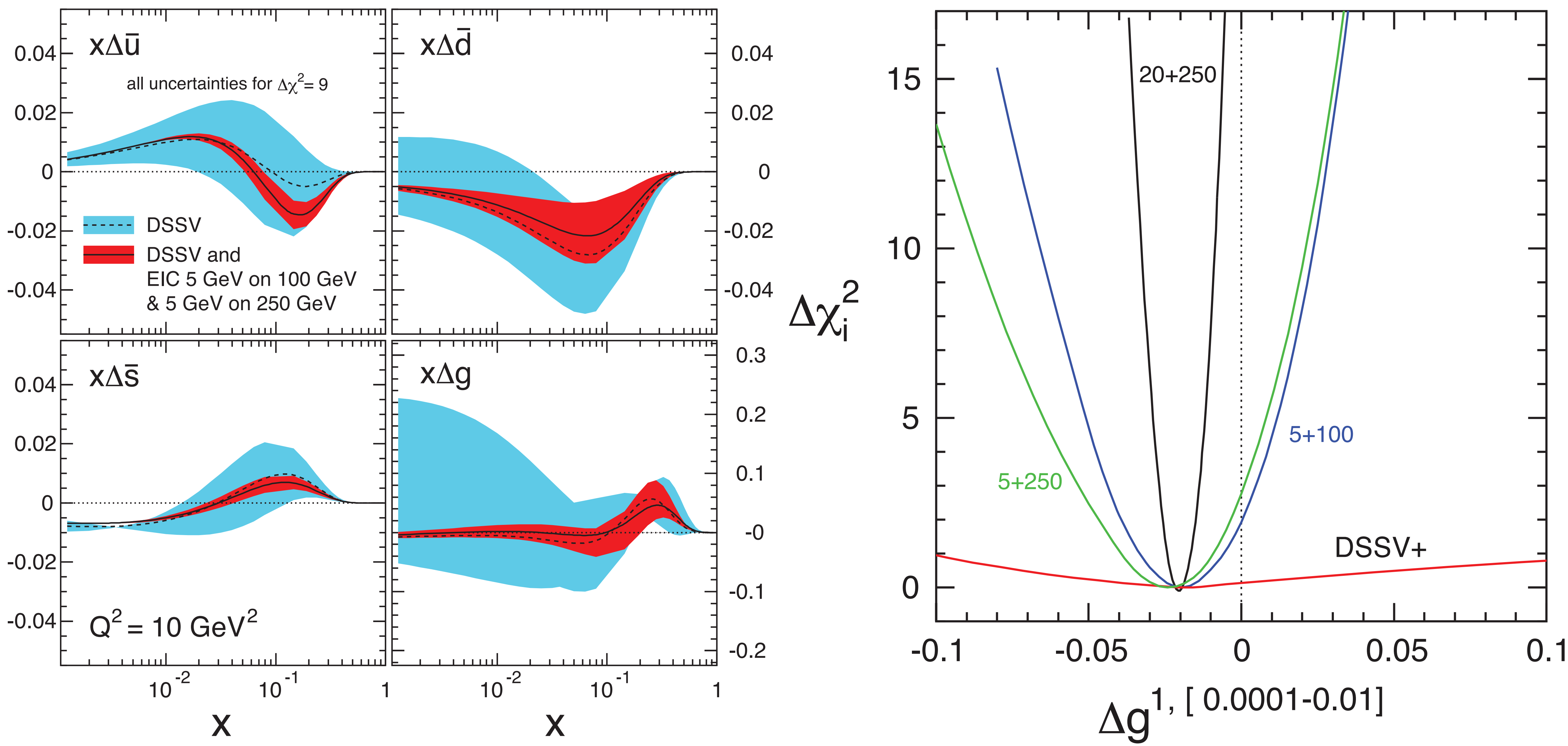




- Enormous improvement relative to present /12 GeV
- Scaling violations well-determined, important for Δg

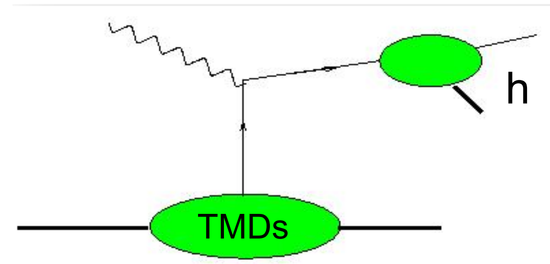


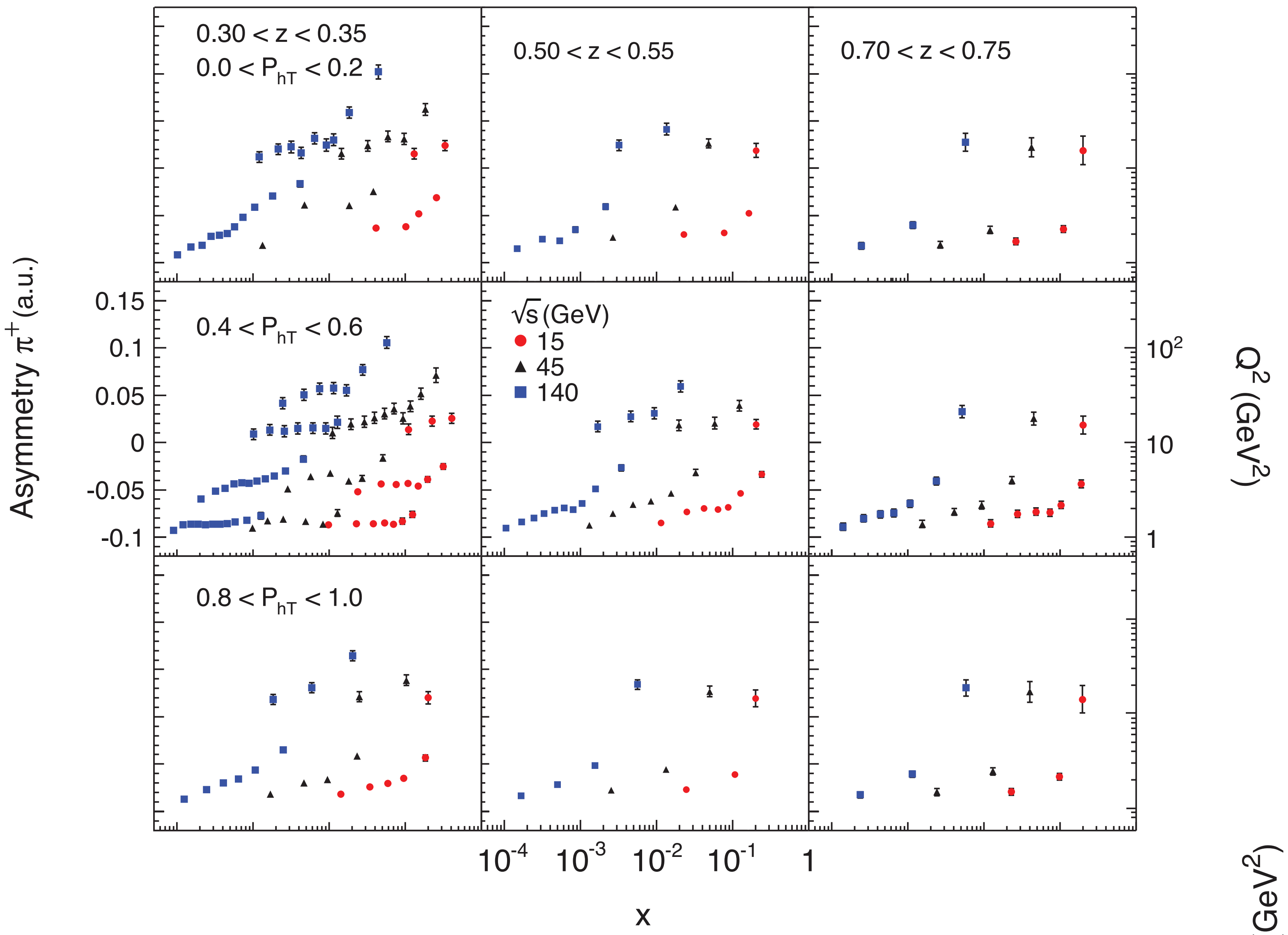
EIC determination of Δg, Δ(sea quarks)

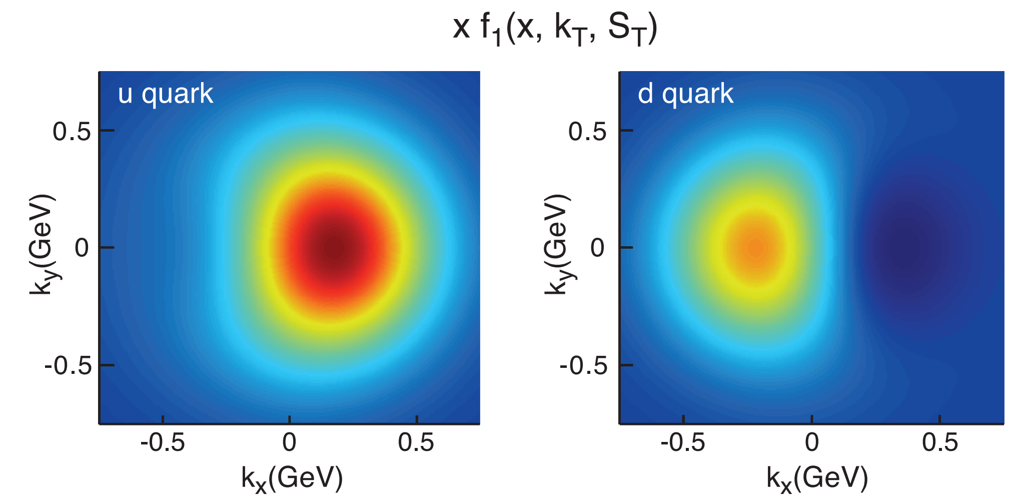


Sensitivity to Δg integral improves with increasing CM energy

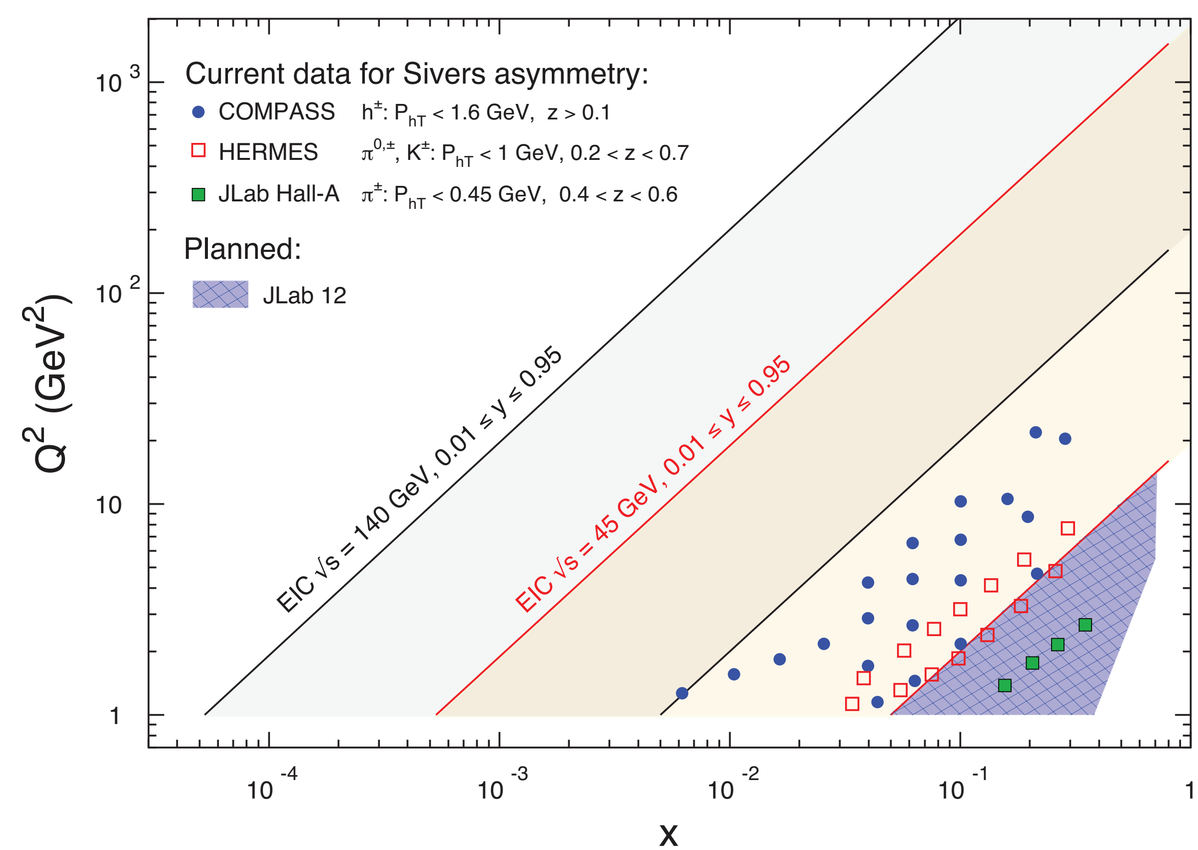
Transverse Momentum Dependent Distributions (TMDs)







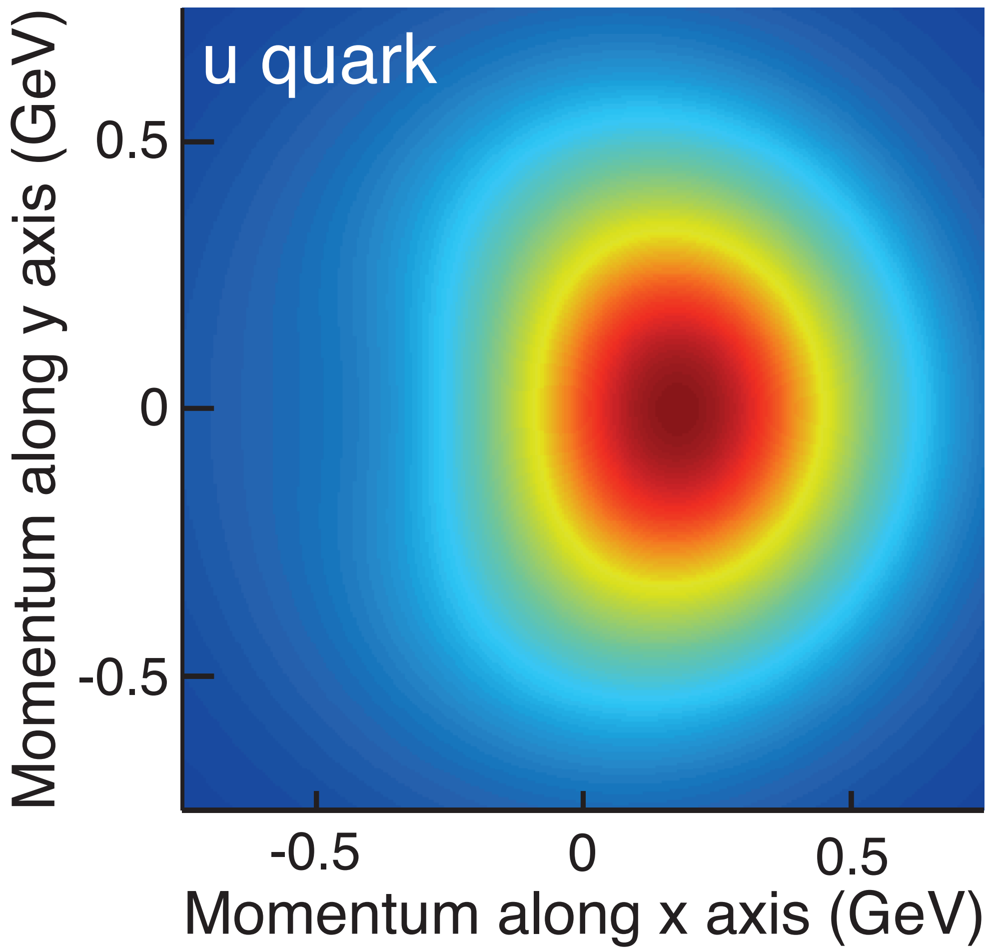
Momentum tomography of the nucleon

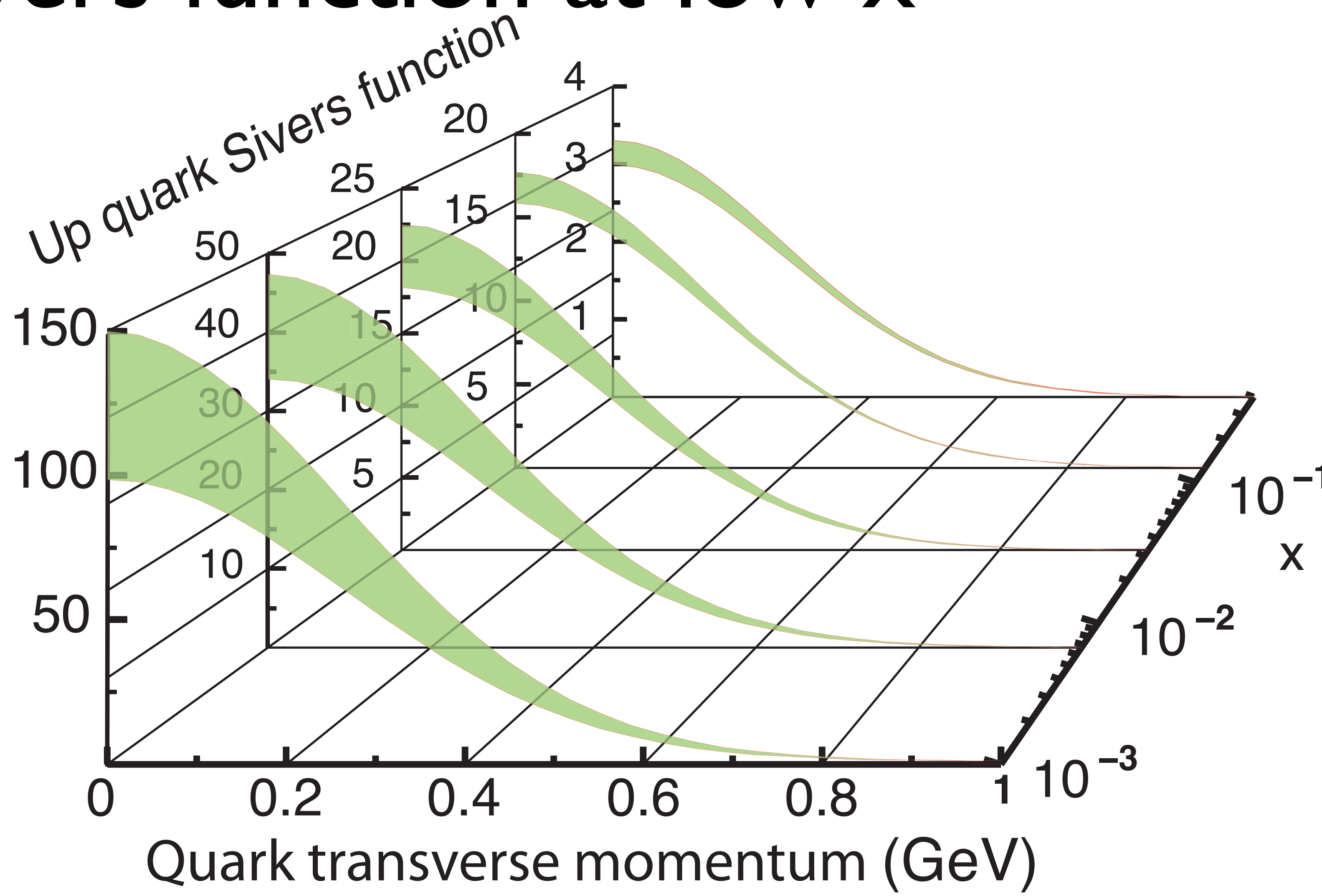


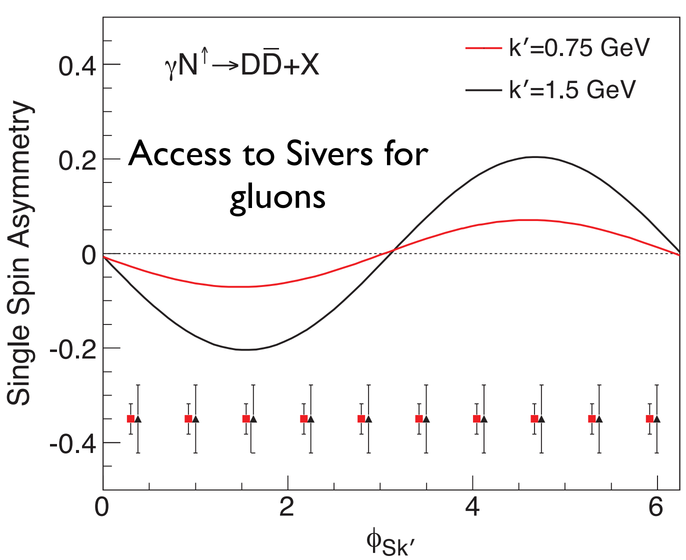
Example: huge kinematic reach for access to Sivers asymmetries in SIDIS

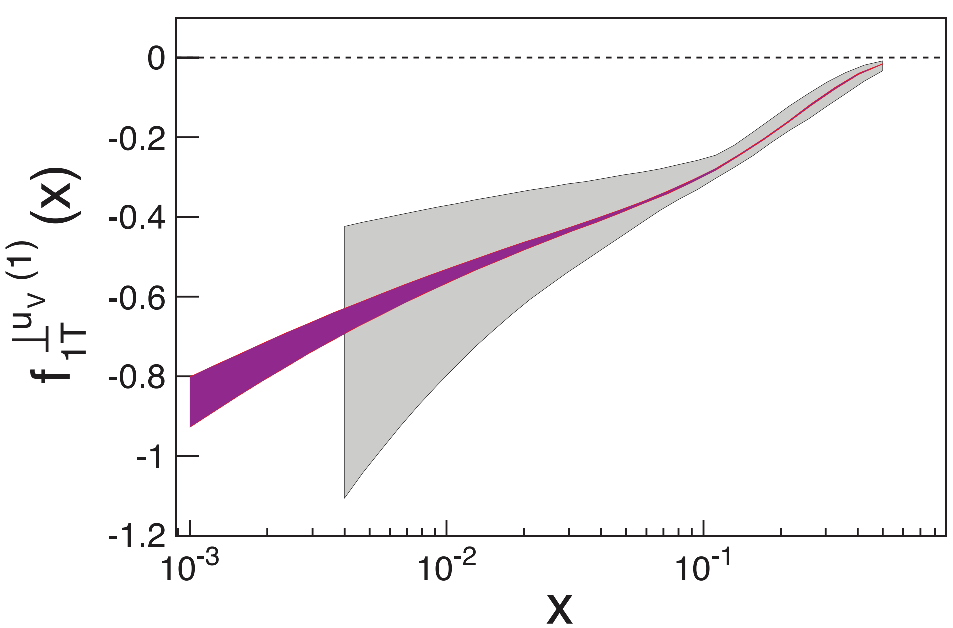
Sivers function: distortion of the momentum distribution of an unpolarized parton *p* when the parent nucleon is transversely polarized.

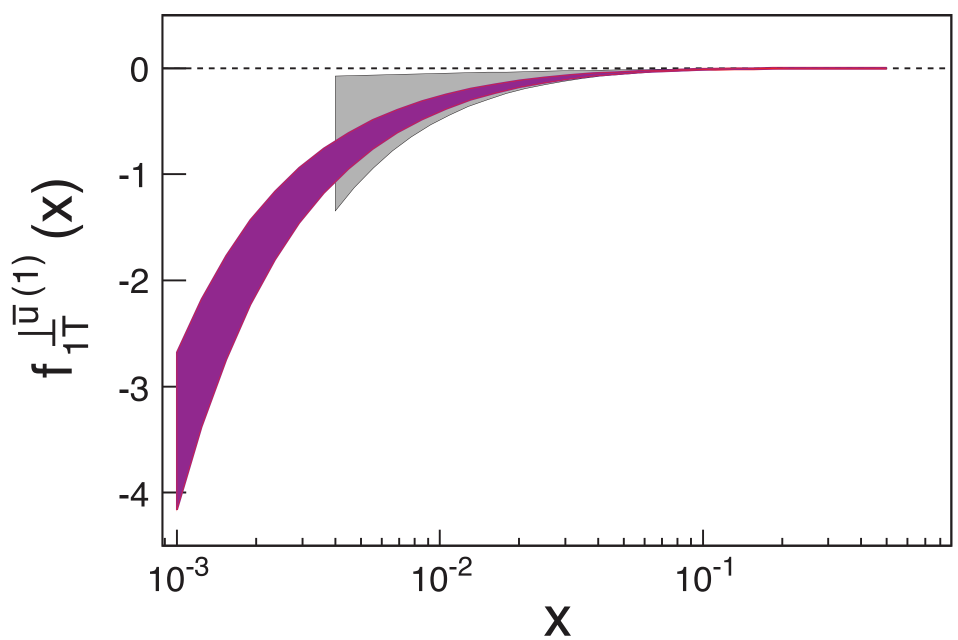
Access to Sivers function at low x





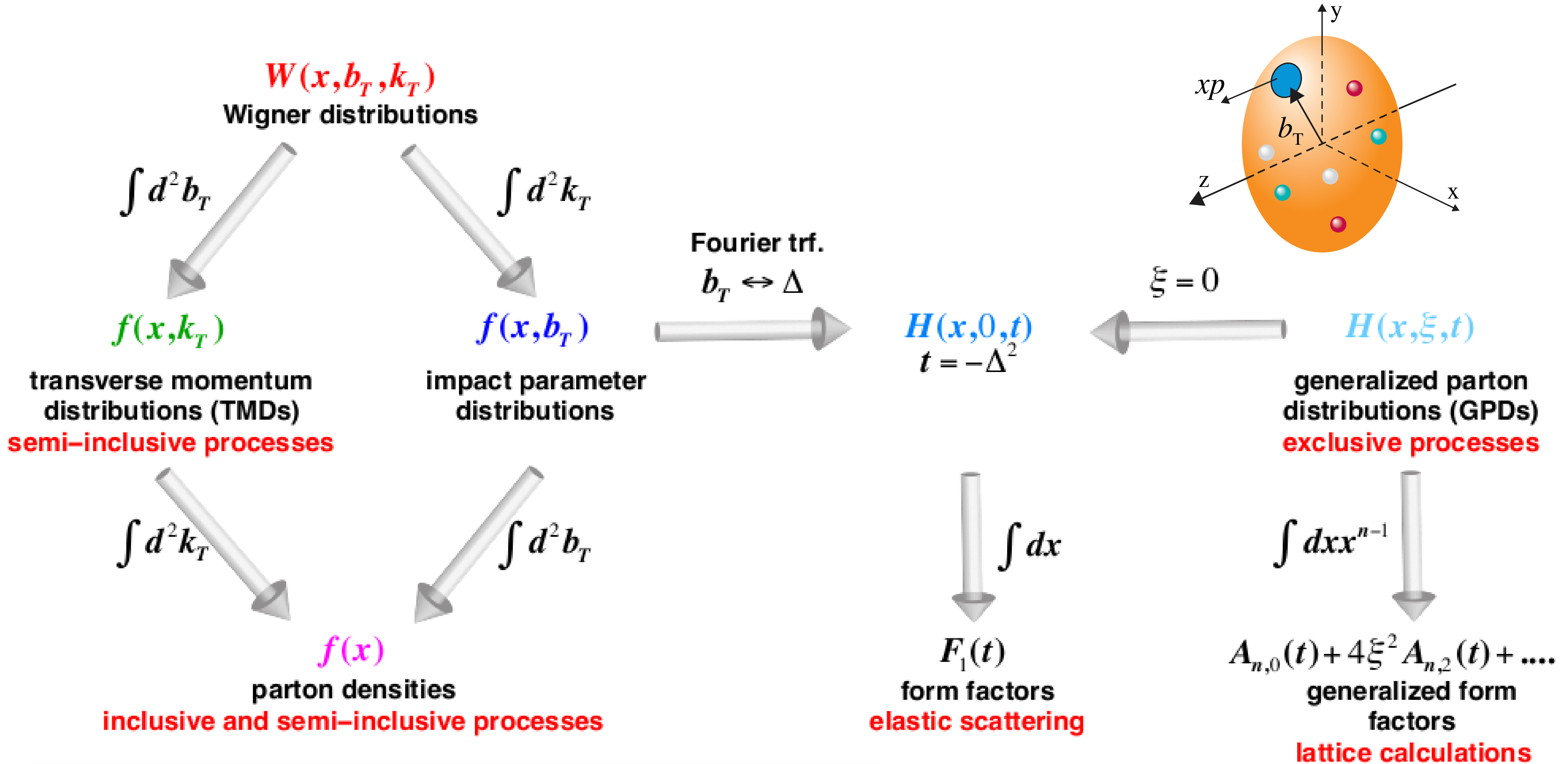




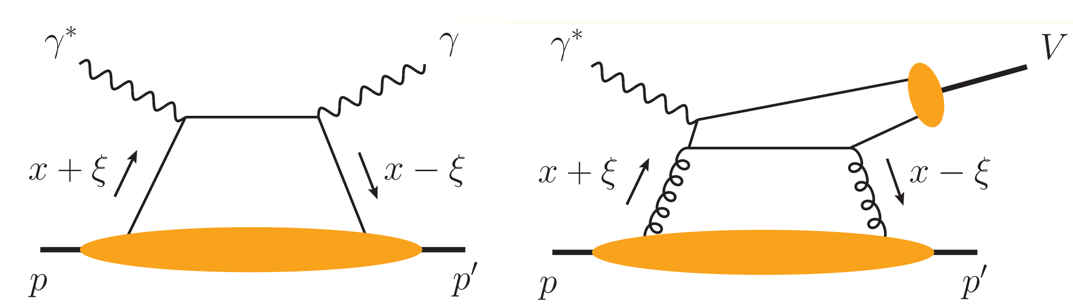


Unprecedented statistical precision and kinematic reach

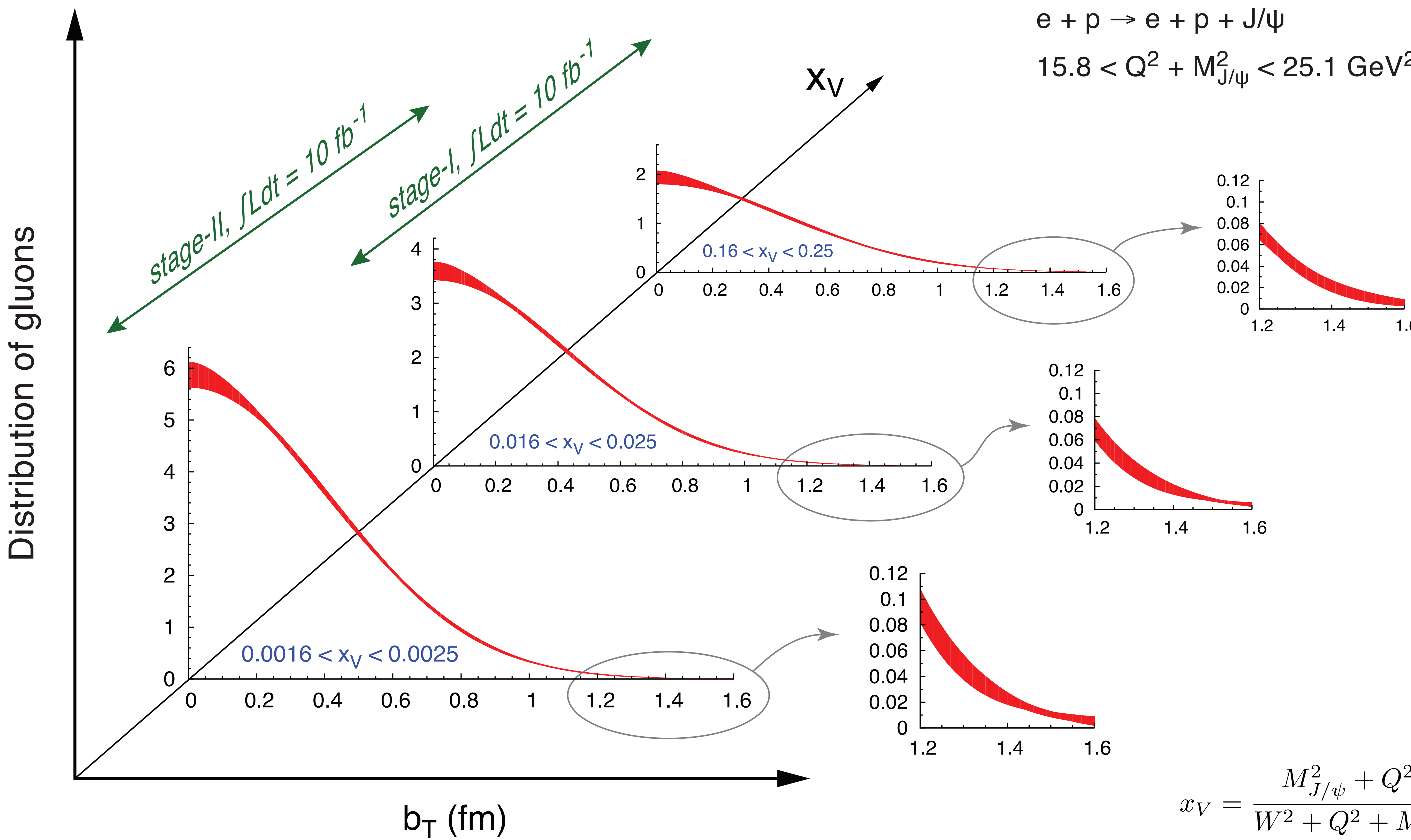
Generalized Parton Distributions (GPDs)



TMDs and GPDs are NOT directly accessible. Their extractions require measurements of cross sections and asymmetries in **a large kinematic domain of x_B, t, Q^2** (GPD) and **x_B, P_T, Q^2, z** (TMD)

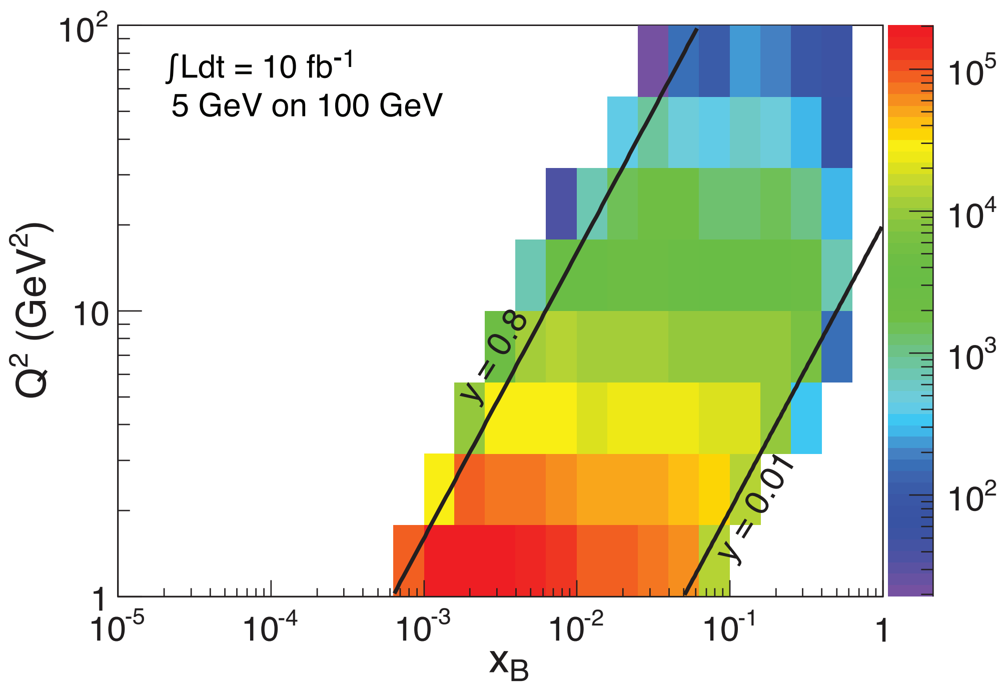


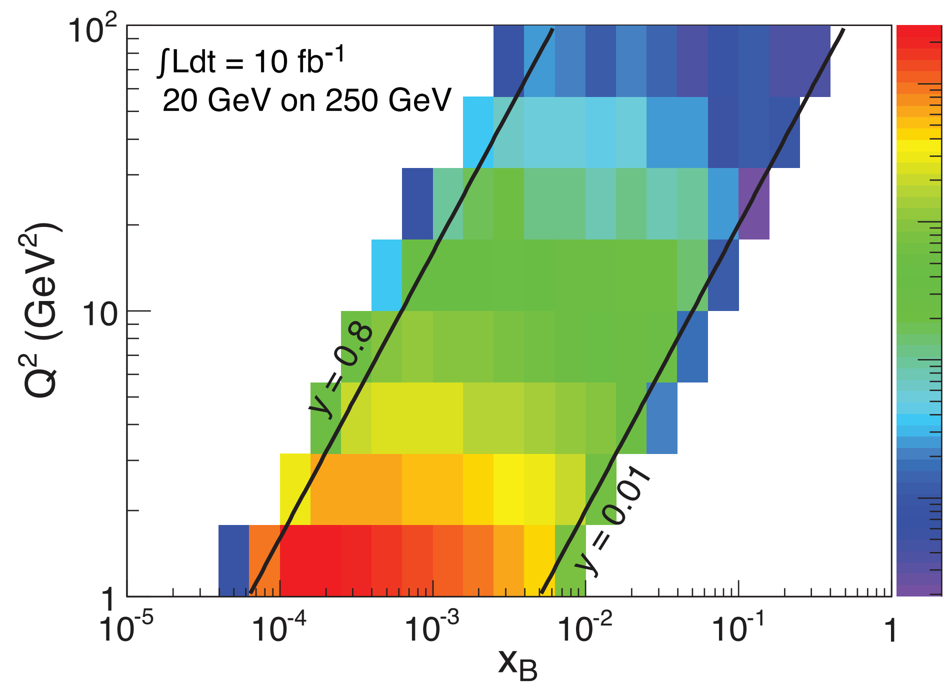
Transverse spatial distributions of gluons - exclusive J/ψ production

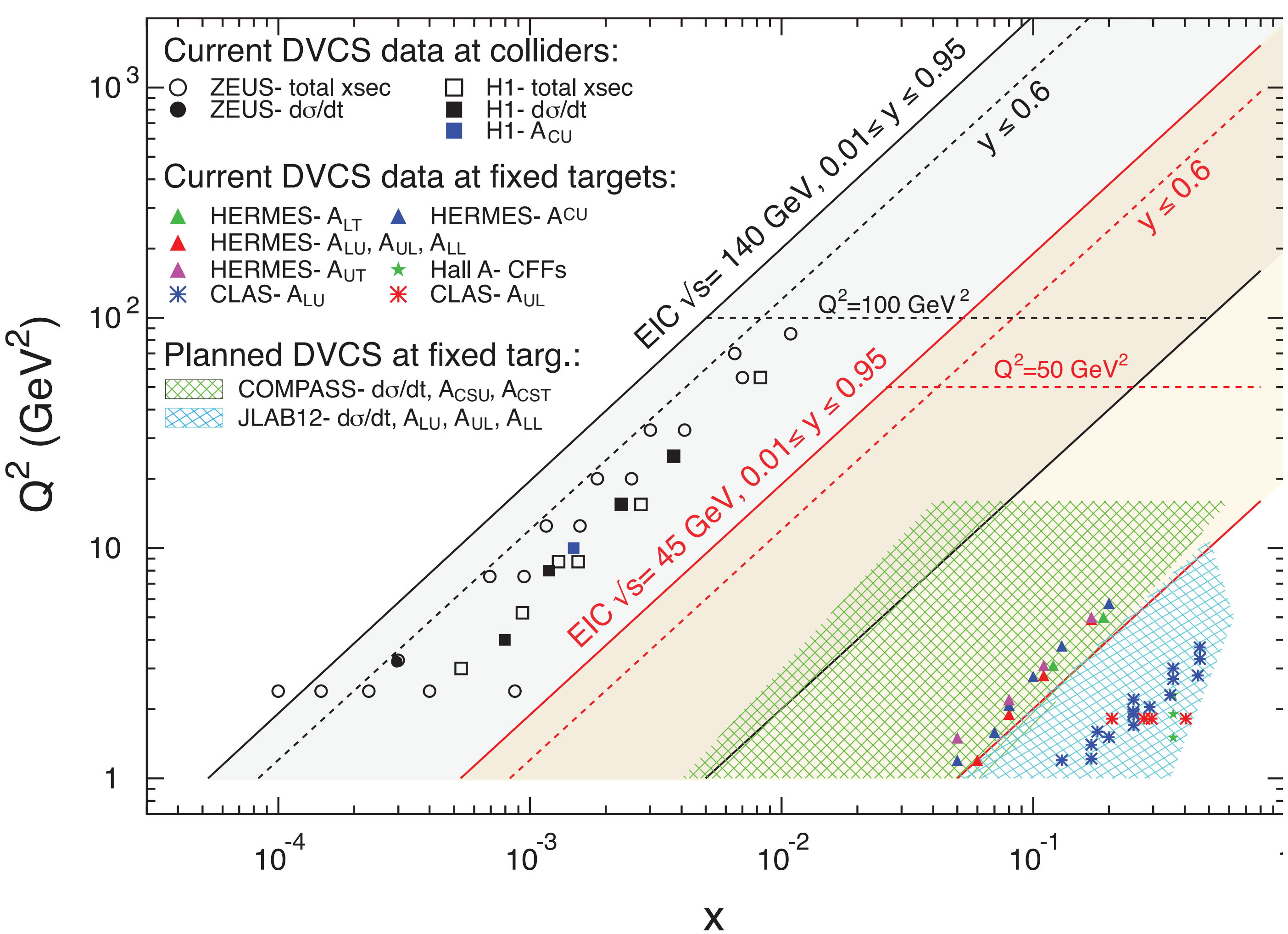


$$x_V = \frac{M^2_{J/\psi} + Q^2}{W^2 + Q^2 + M_N^2}$$

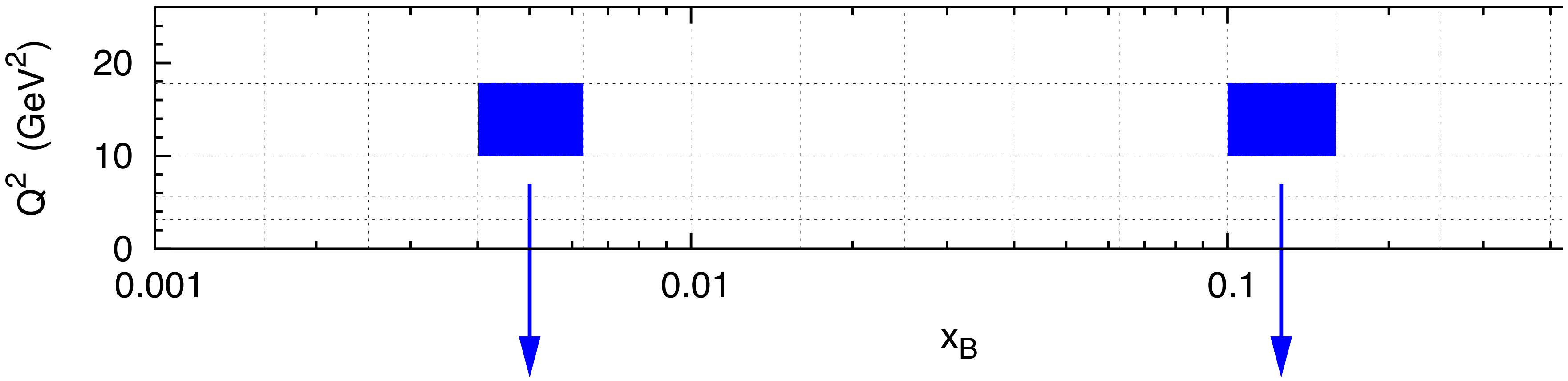
Deeply Virtual Compton Scattering (DVCS)

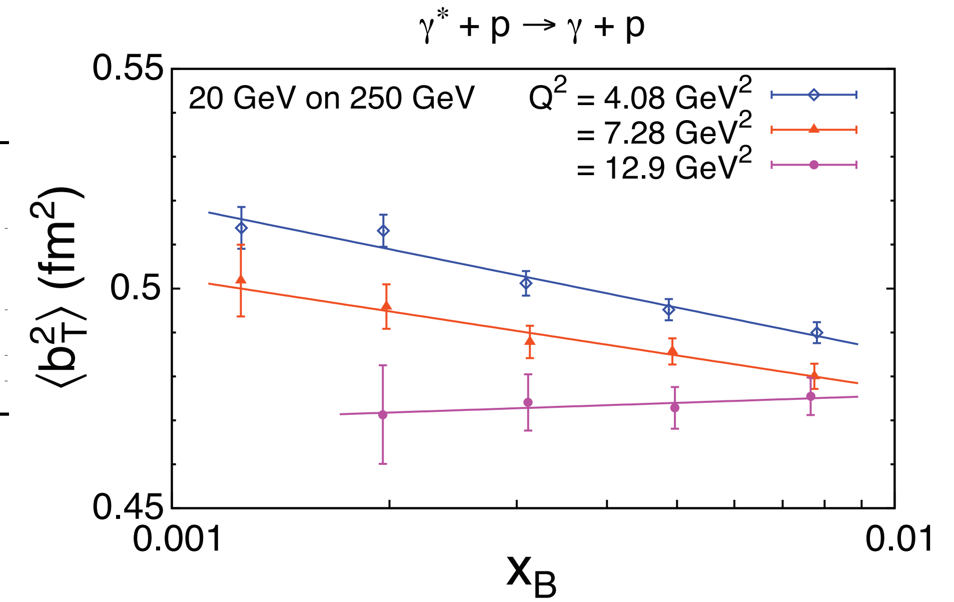


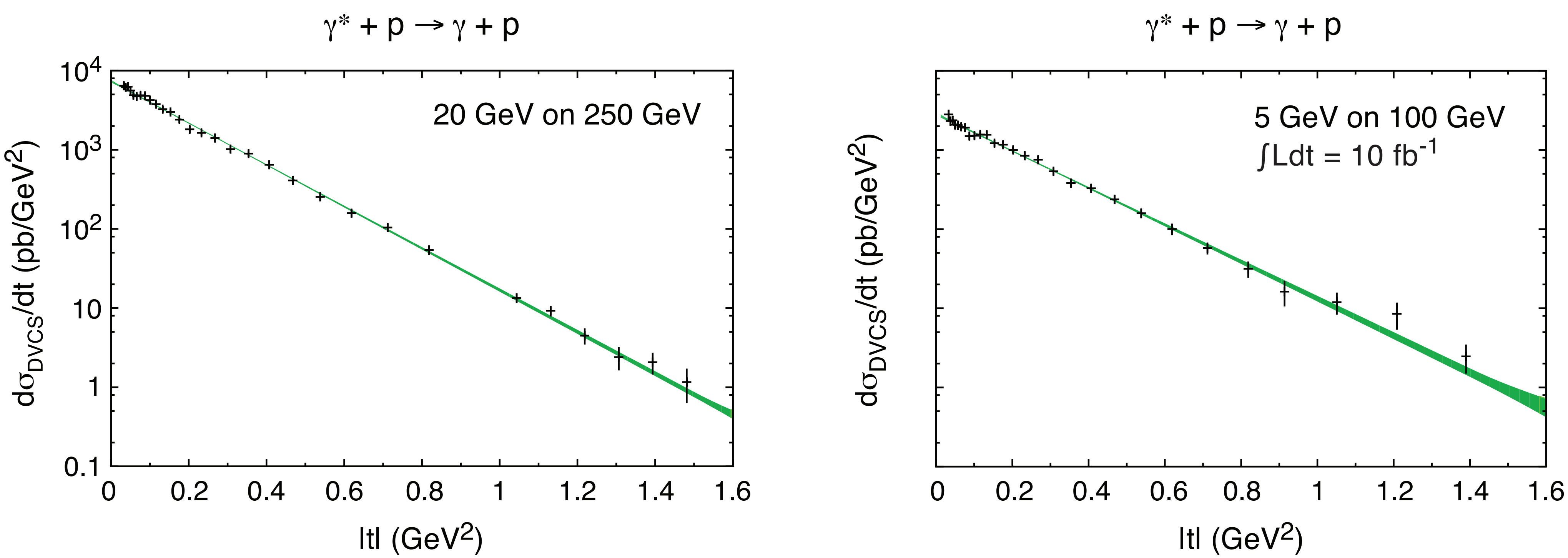




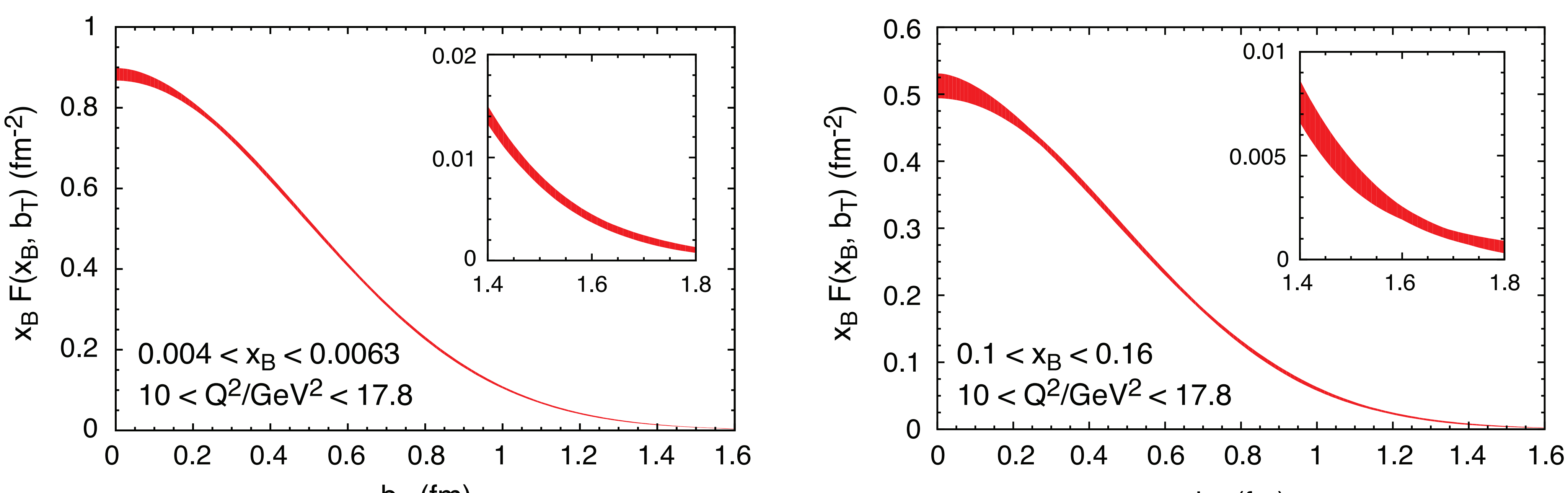
EIC will fill in a large gap in kinematic reach between collider and fixed-target data for DVCS, and increase precision, imposing strong constraints on GPDs





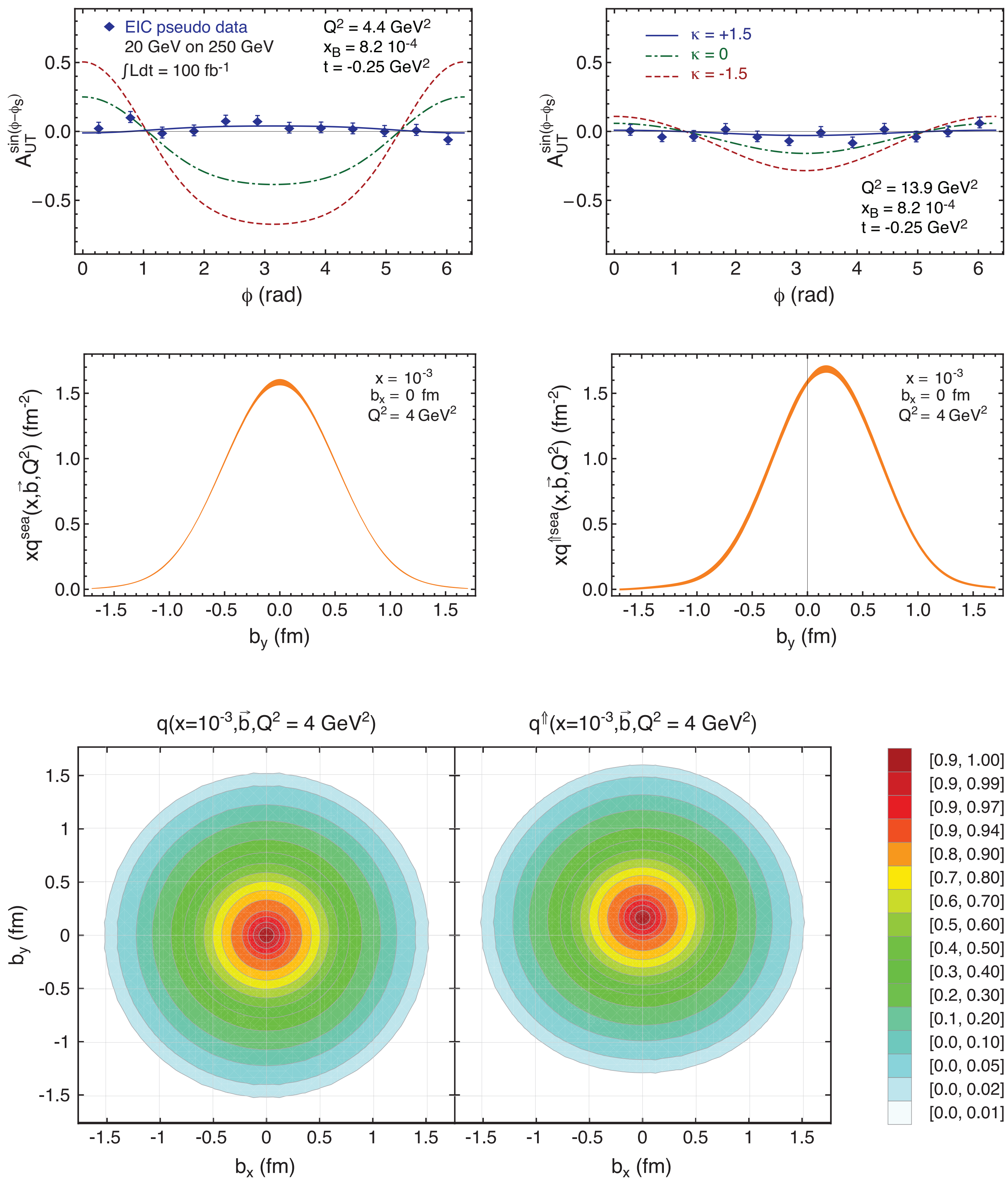


DVCS cross section for two bins in x_B and Q^2.

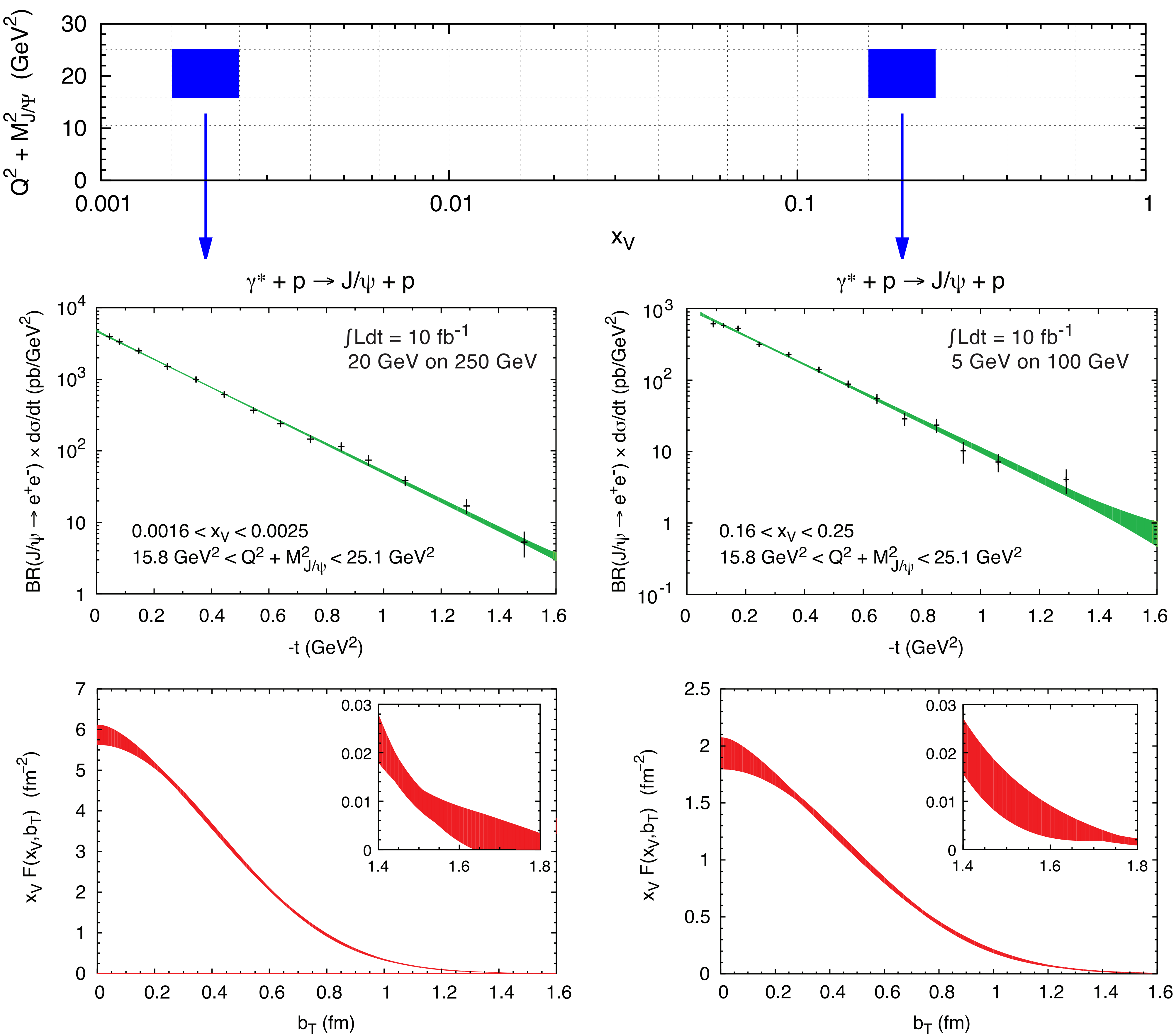


Precise quark impact parameter distributions extracted

DVCS Polarization Asymmetry A$_{UT}$



Exclusive J/ψ production accesses gluon distributions

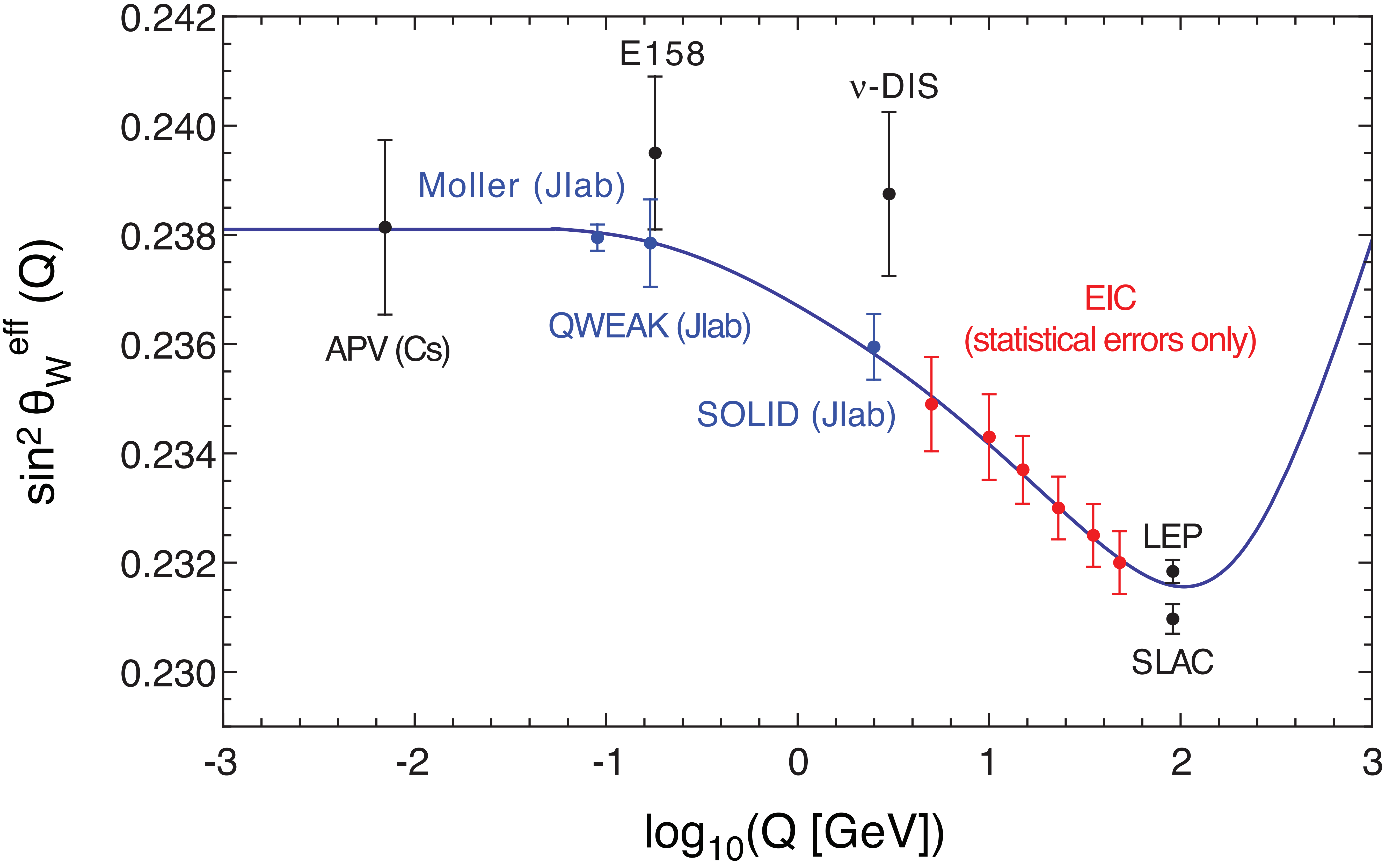


DVMP cross section for two bins in x_B and Q^2.

Precise gluon impact parameter distributions extracted

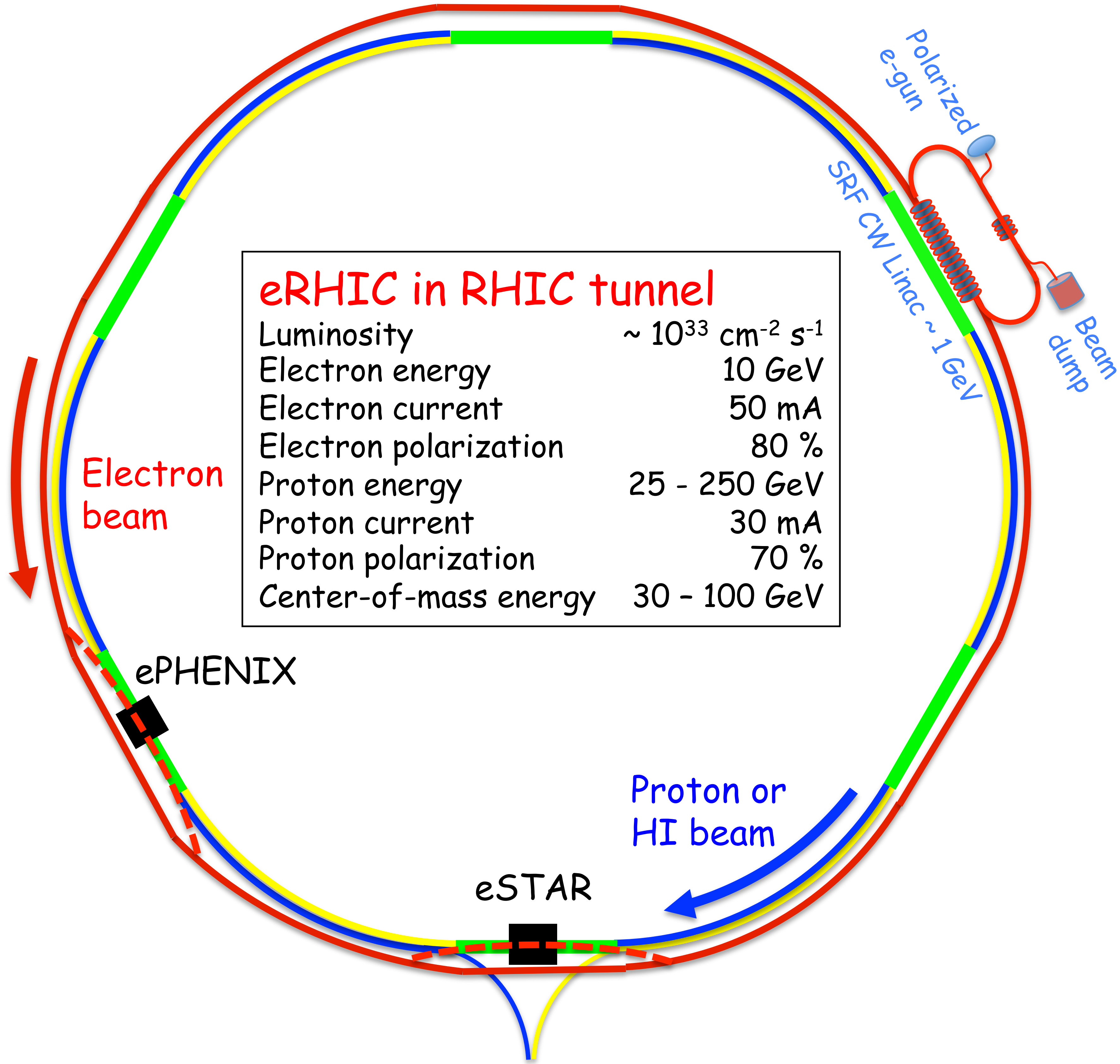
Physics Beyond the Standard Model

New precise measurements of Weinberg angle



The Accelerator Designs and Challenges

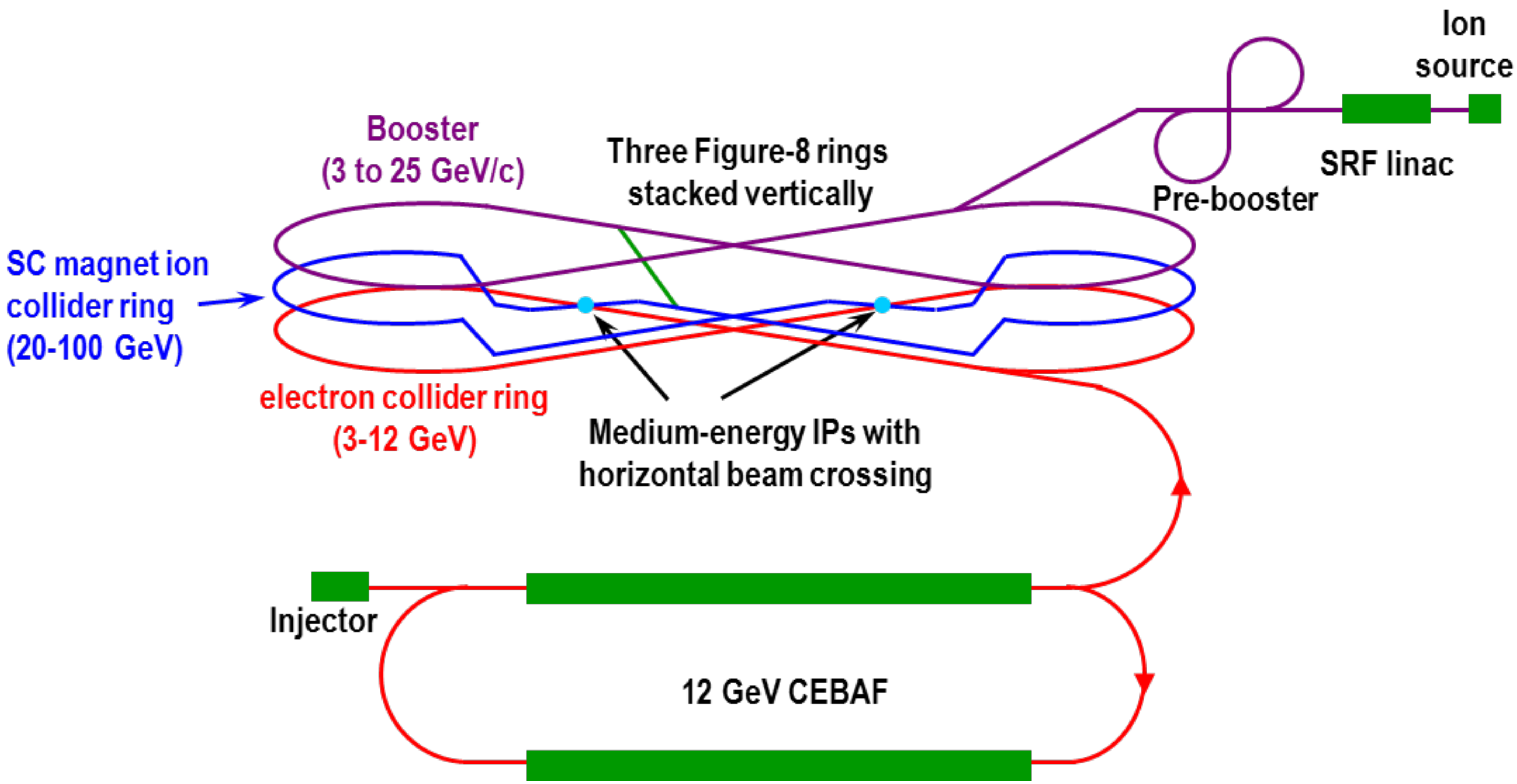
Basic eRHIC configuration



eRHIC in RHIC tunnel

Luminosity	~ 10^{33} cm^{-2} s^{-1}
Electron energy	10 GeV
Electron current	50 mA
Electron polarization	80 %
Proton energy	25 - 250 GeV
Proton current	30 mA
Proton polarization	70 %
Center-of-mass energy	30 – 100 GeV

JLab MEIC design

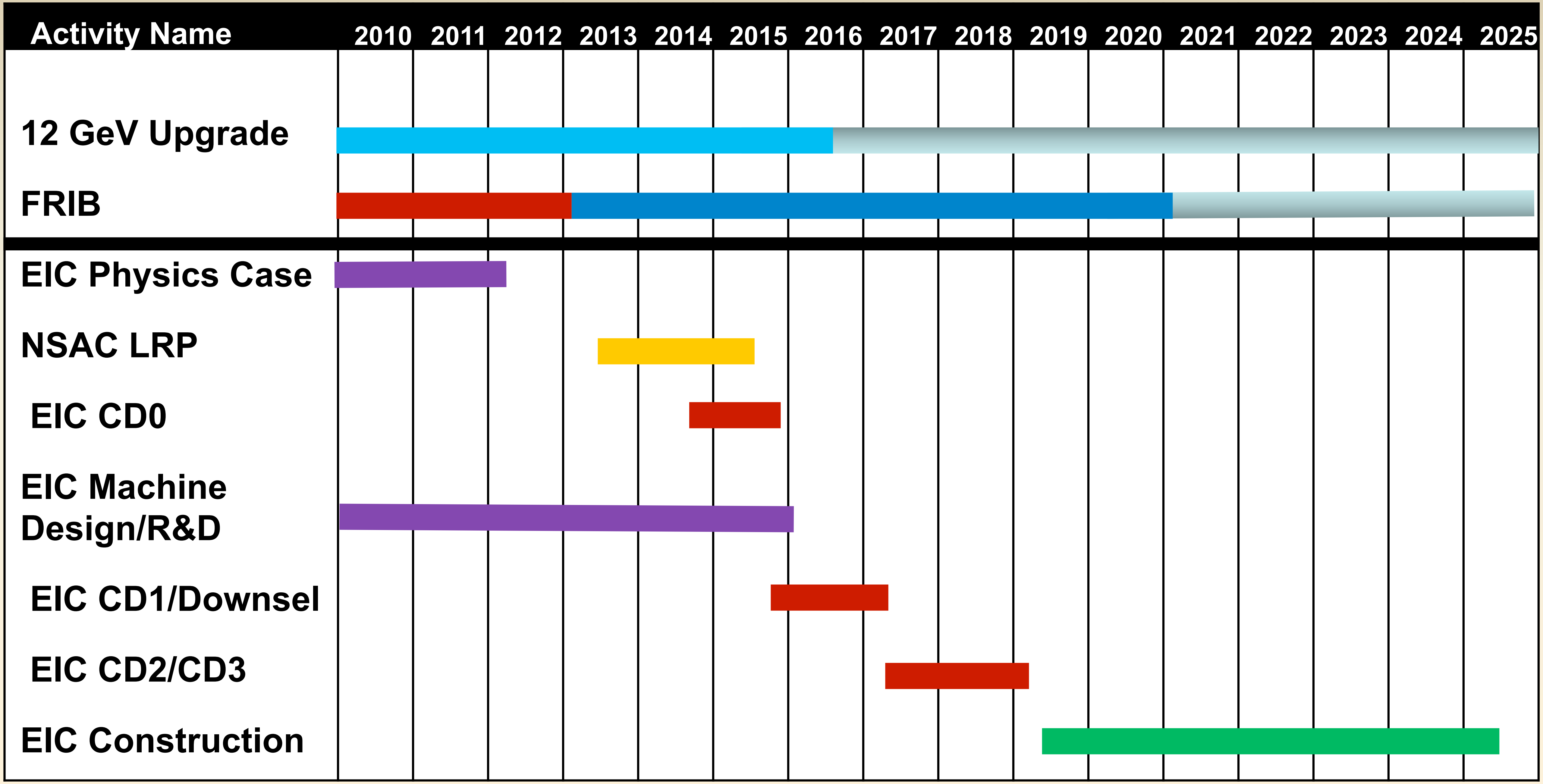


- 3-11 GeV on 20-100 GeV ep/eA collider fully-polarized, L and T
- Luminosity: up to few x 10^{34} e-nucleons cm^{-2} s^{-1}

- Upgradable to higher energies: 250 GeV protons + 20 GeV electrons

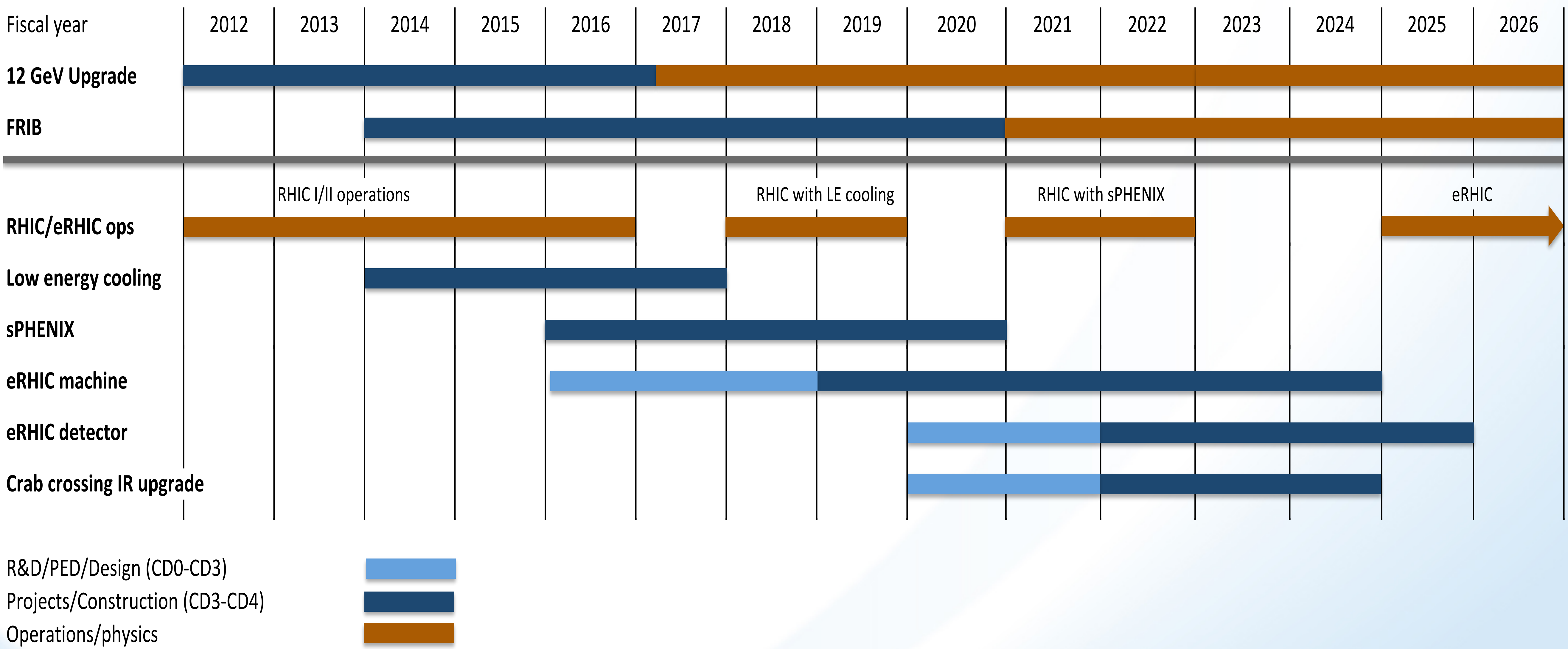
Schedules

EIC Realization Imagined



Assumes endorsement for an EIC at the next NSAC Long Range Plan
Assumes relevant accelerator R&D for down-select process done around 2016

Notional eRHIC schedule



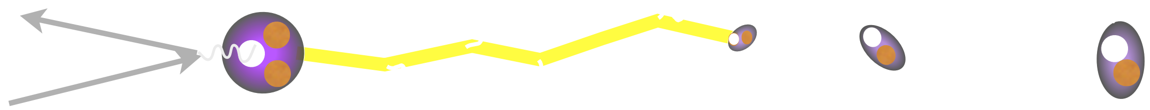
Berndt Mueller, October 2013

Conclusions

- EIC will offer a wide spectrum of new measurements with groundbreaking impact
  - parton propagation and hadronization
  - spin structure and 3D imaging of proton, neutron, nuclei
  - many other topics
- Now is the time for a united effort supporting this new and exciting facility!
  - science case
  - technical implementation

Backup Slides

Time estimates - basic expectations



- Light quarks:

$$\tau_{q\rightarrow hadron}^{formation} \approx \frac{E_q}{m_q} R_{hadron} \approx E_q R_{hadron}^2$$

$$\approx \nu R_{hadron}^2 \qquad x > 0.1, \text{ struck quark in hadron}$$

  - Bigger hadrons form much slower
  - Virtual photon energy ν=10 GeV, R(EM)=0.6 fm, τ=18 fm/c

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  - e.g., mass suppression for D0/pi is factor ~4

- **Reality:** mass dependence + flavor dependence + mechanism

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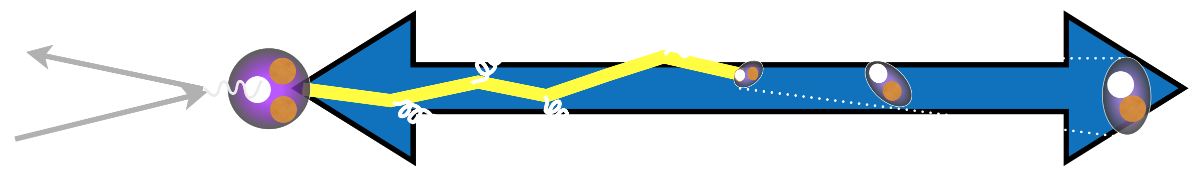

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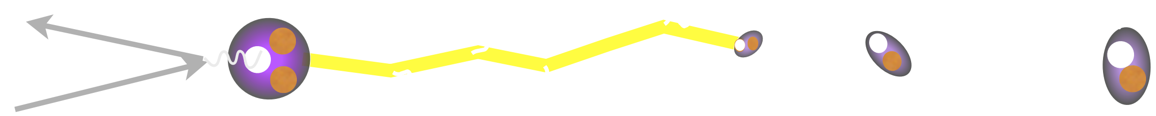

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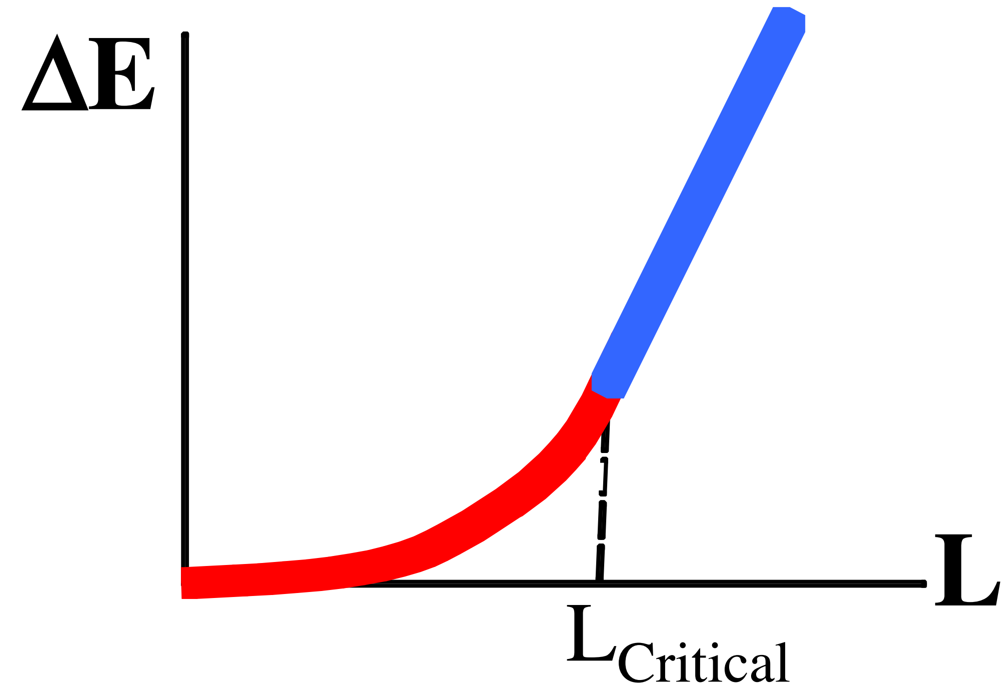
Partonic energy loss in pQCD

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

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



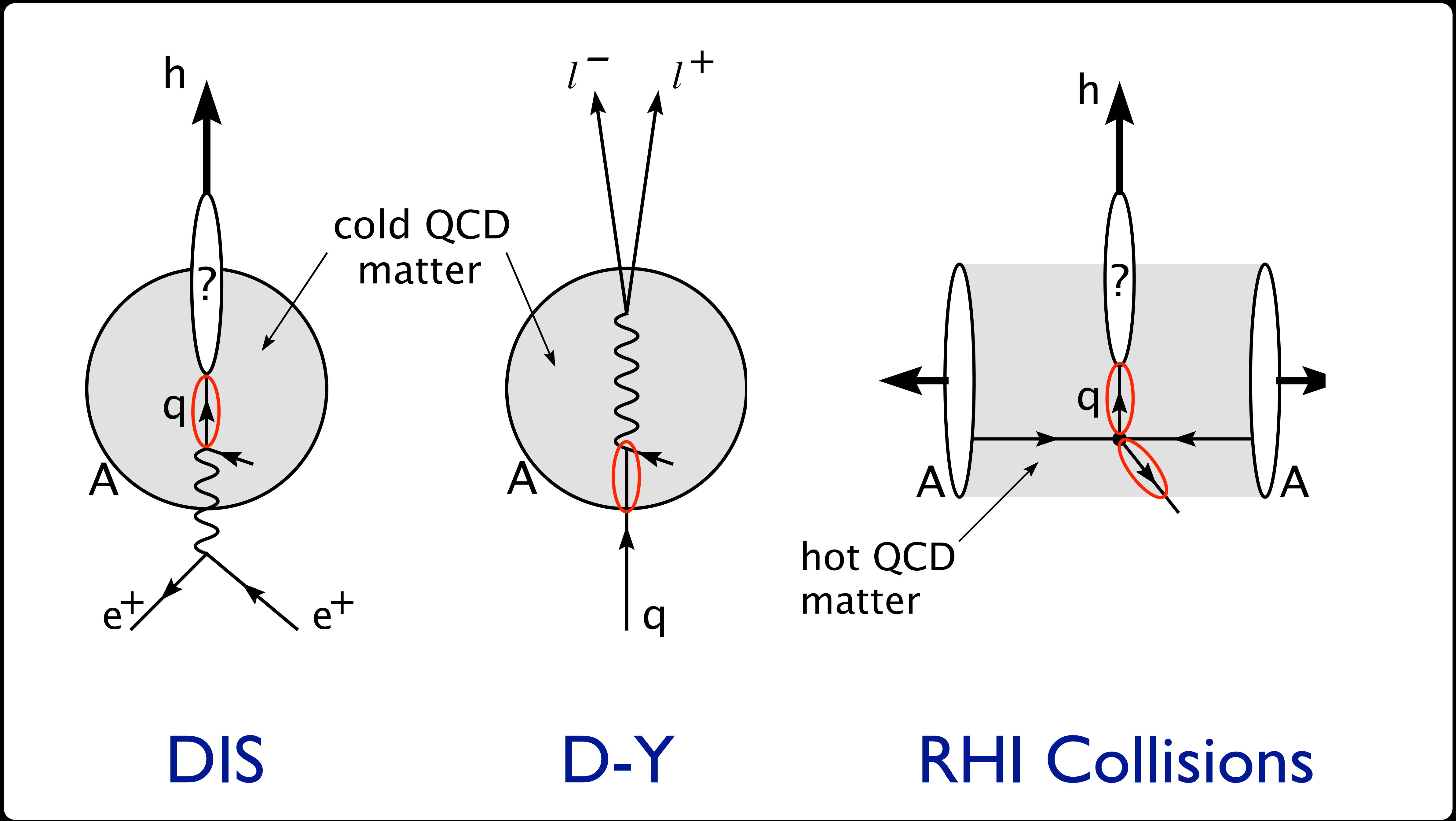
$$\text{at} \quad L = L_{Critical}, \quad L\hat{q} \propto \sqrt{E_q \cdot \hat{q}} \;\; ; \quad L_{Critical} \propto \sqrt{\frac{E_q}{\hat{q}}}$$

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

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

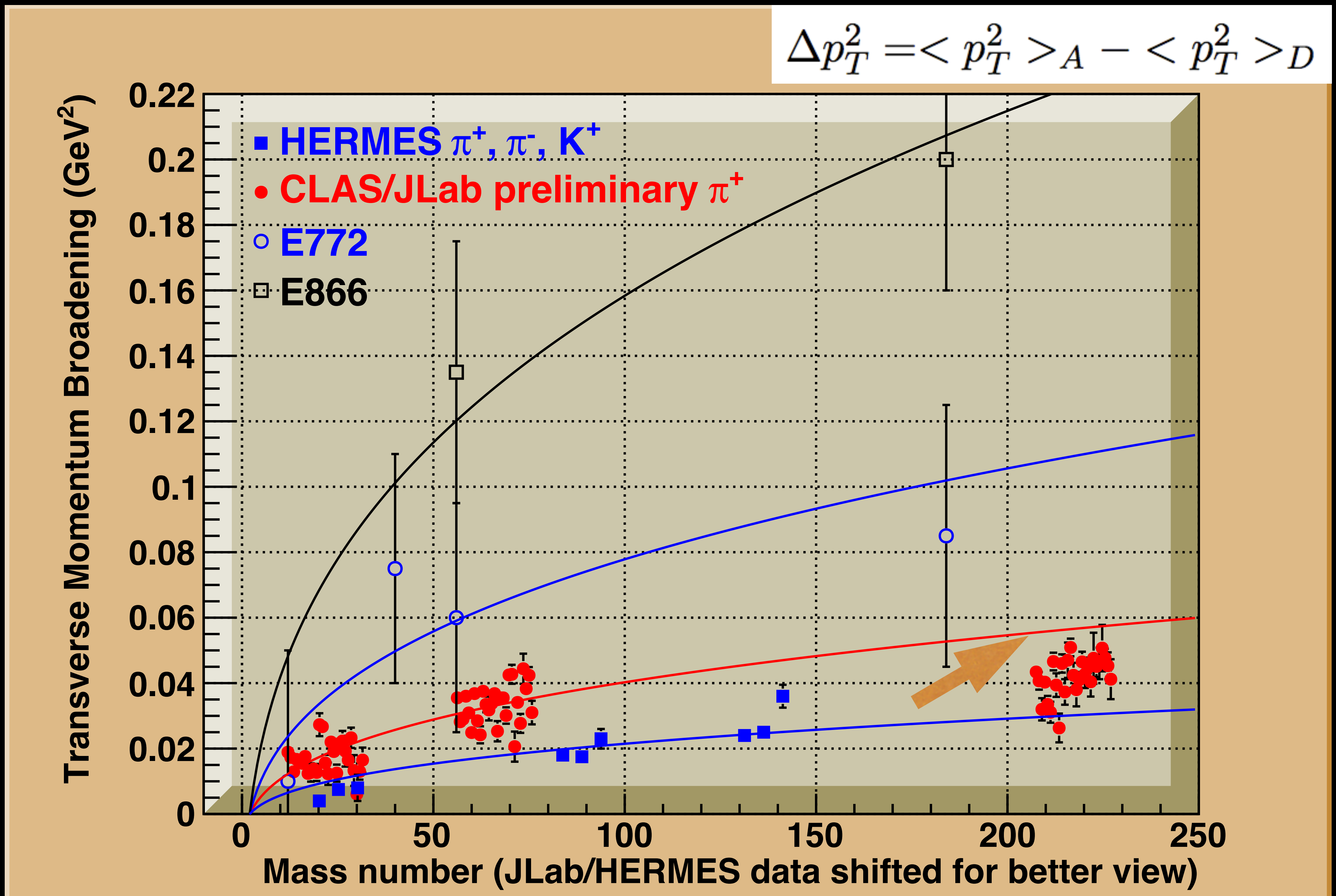
Connection to p_T broadening observable: $-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta k_T^2$

Parton Propagation in Three Processes



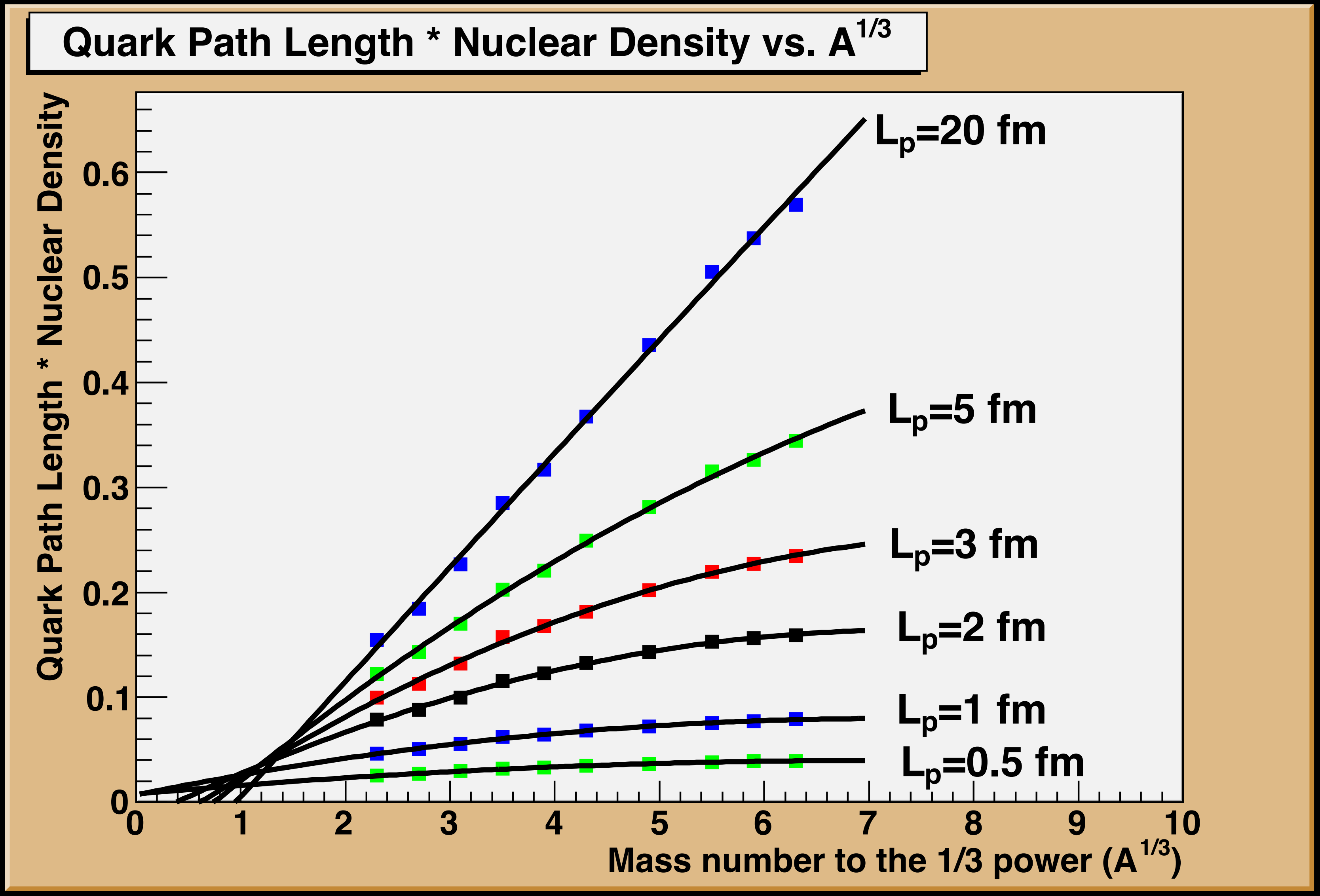
Accardi, Arleo, Brooks, d'Enterria, Muccifora Riv.Nuovo Cim.032:439-553,2010 [arXiv:0907.3534]
Majumder, van Leuween, Prog. Part. Nucl. Phys. A66:41, 2011, arXiv:1002.2206 [hep- ph]
S. Peigne, A.V. Smilga, Phys.Usp.52:659-685, 2009, arXiv:0810.5702v2 [hep-ph]

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

Production Time Extraction - Geometrical Effects



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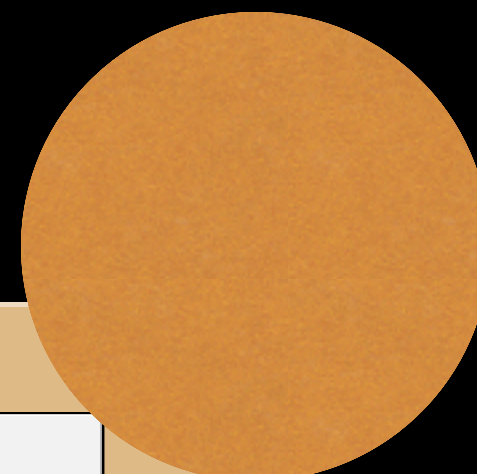

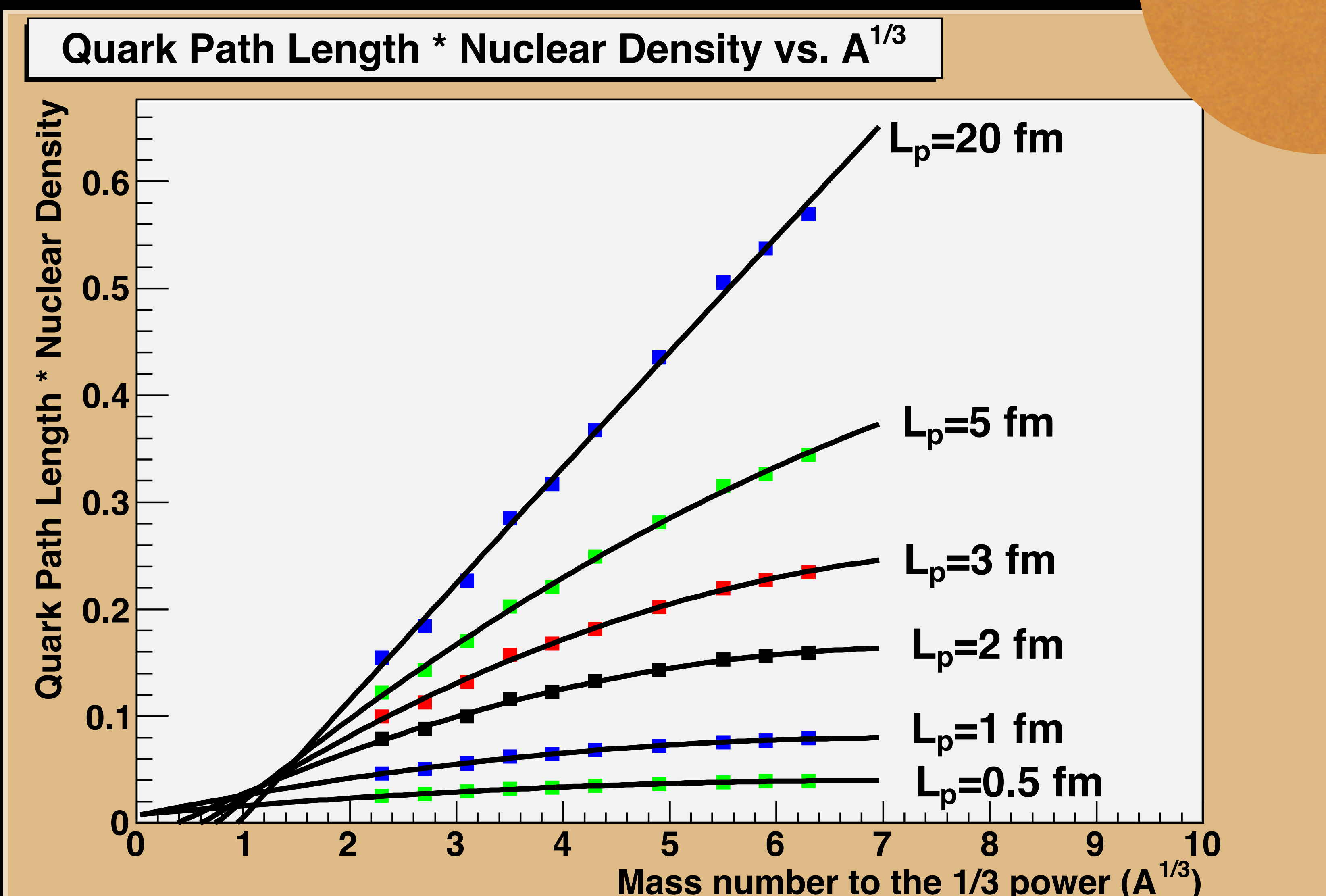

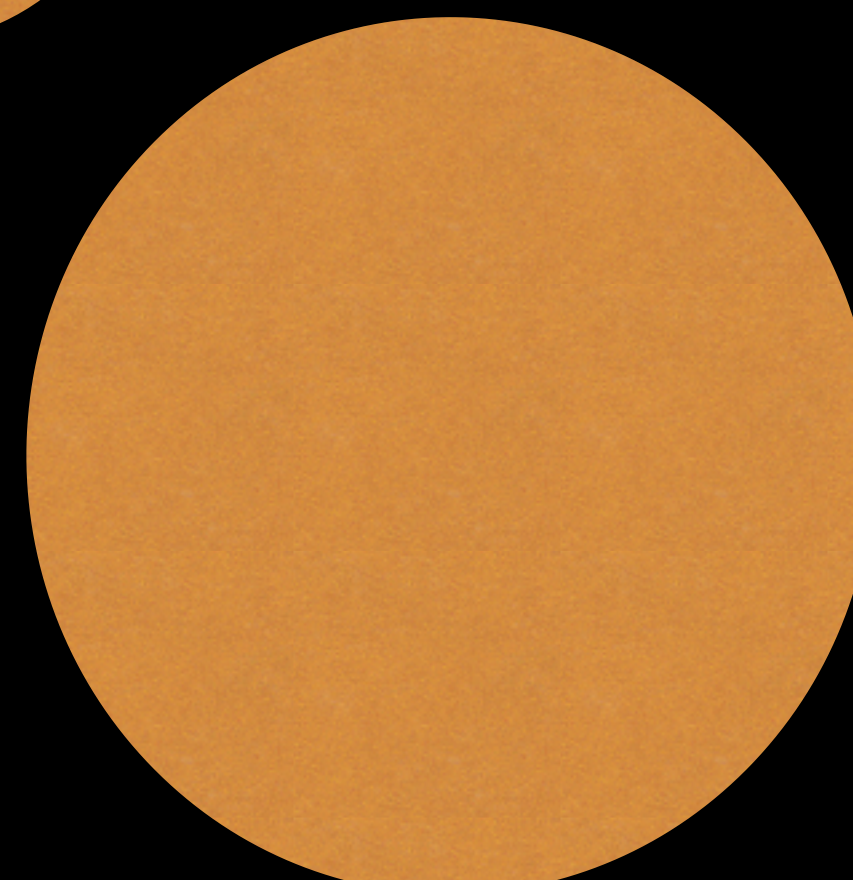

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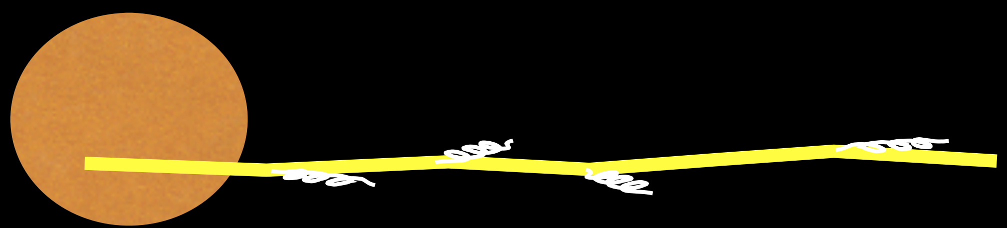

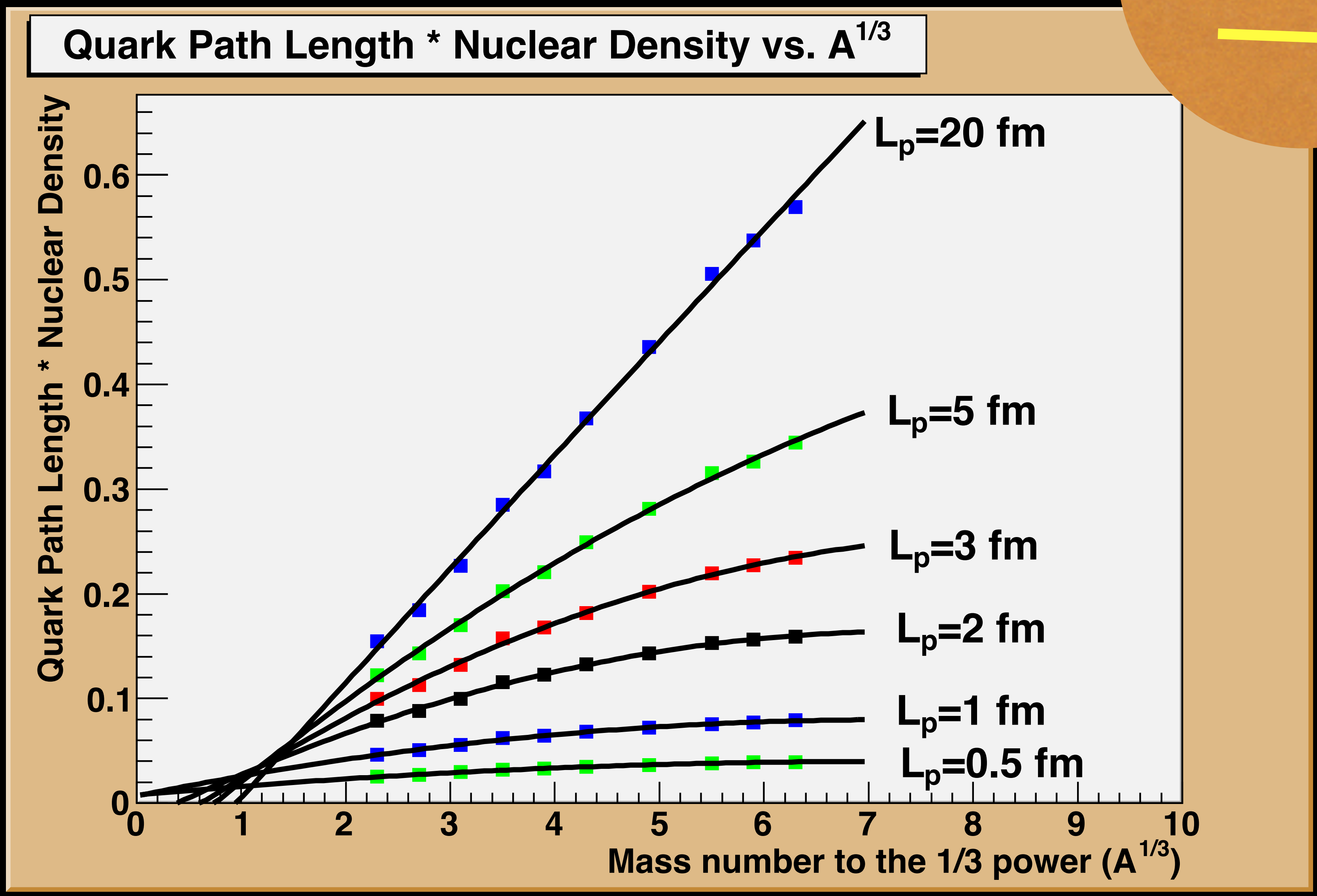

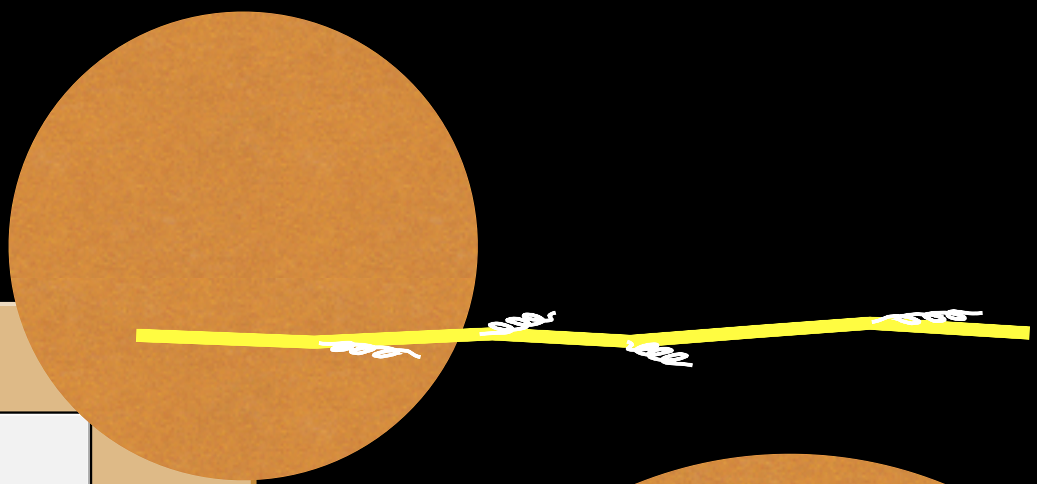

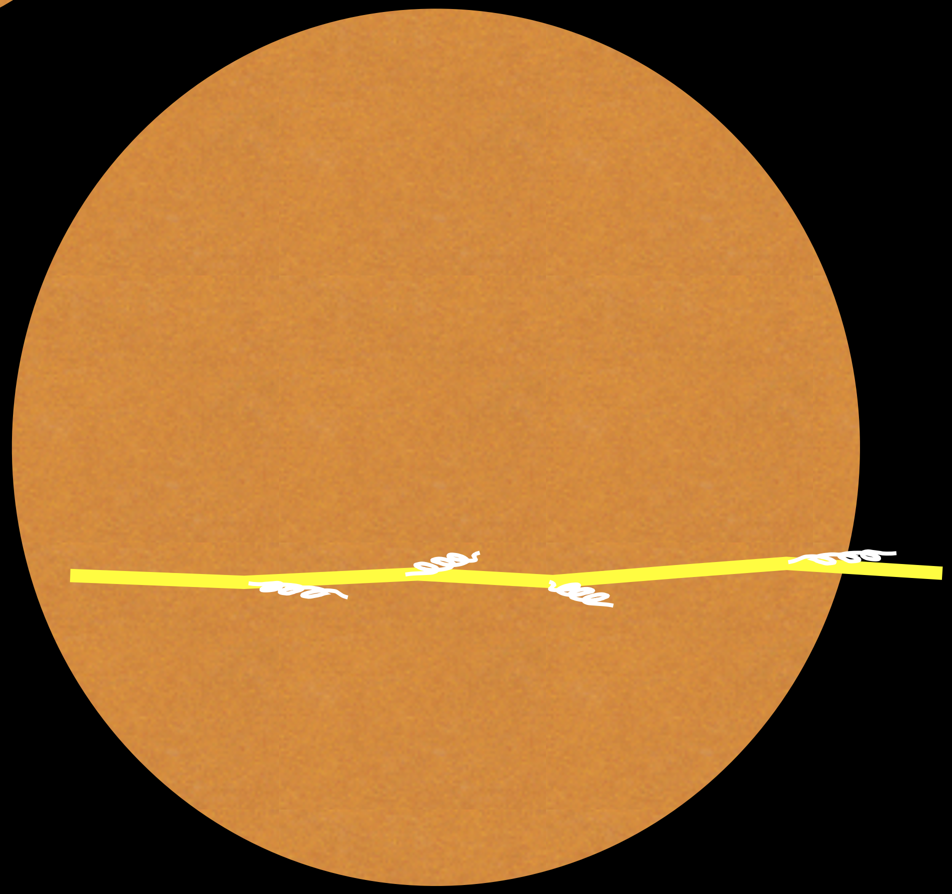

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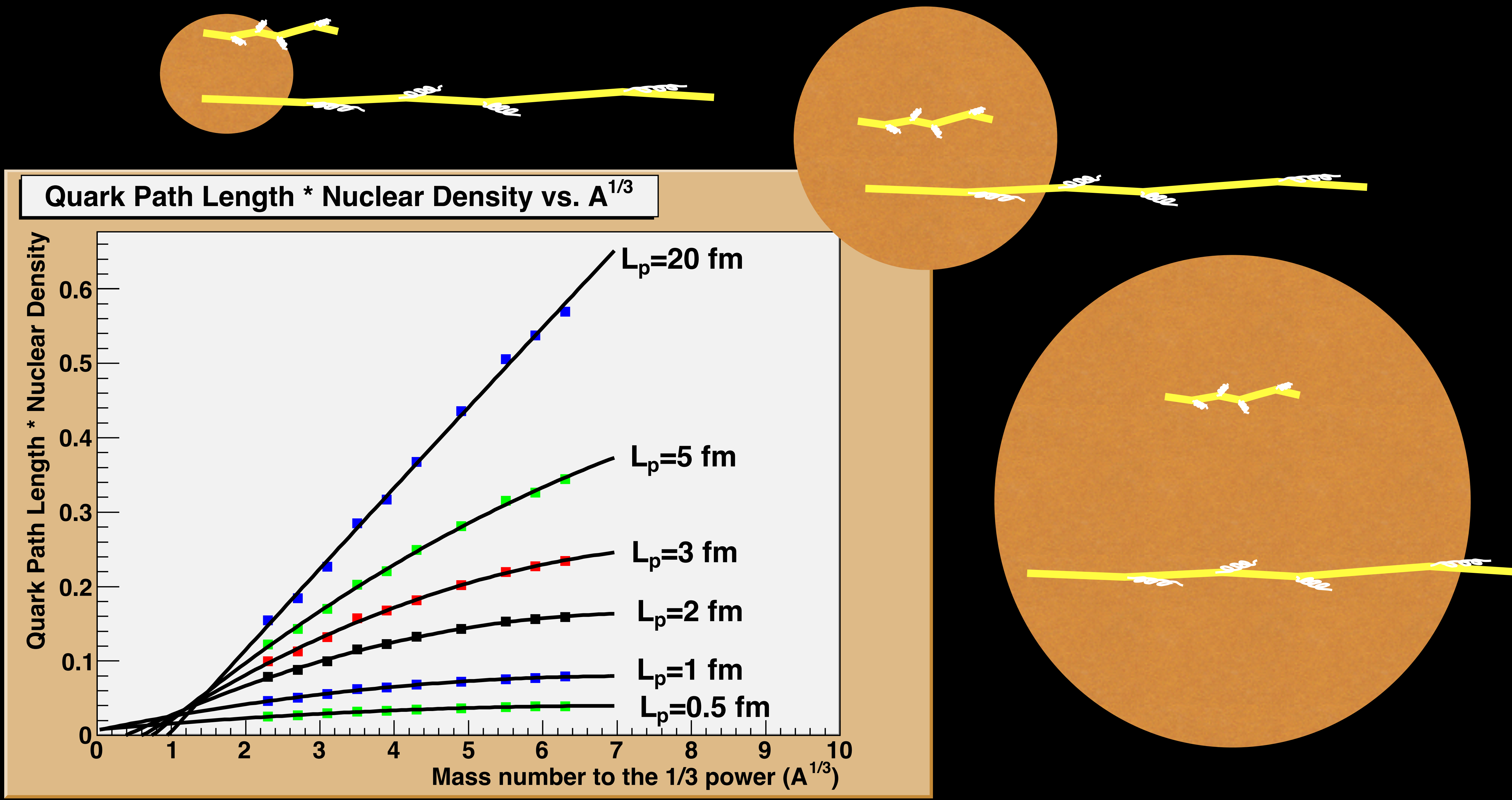

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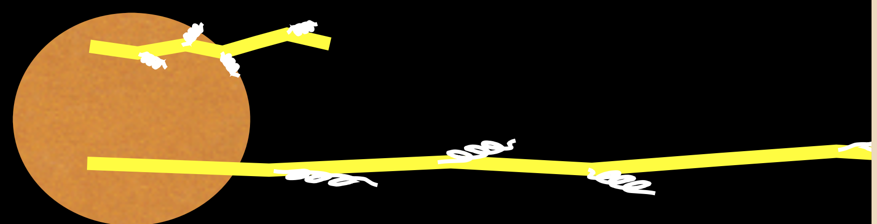
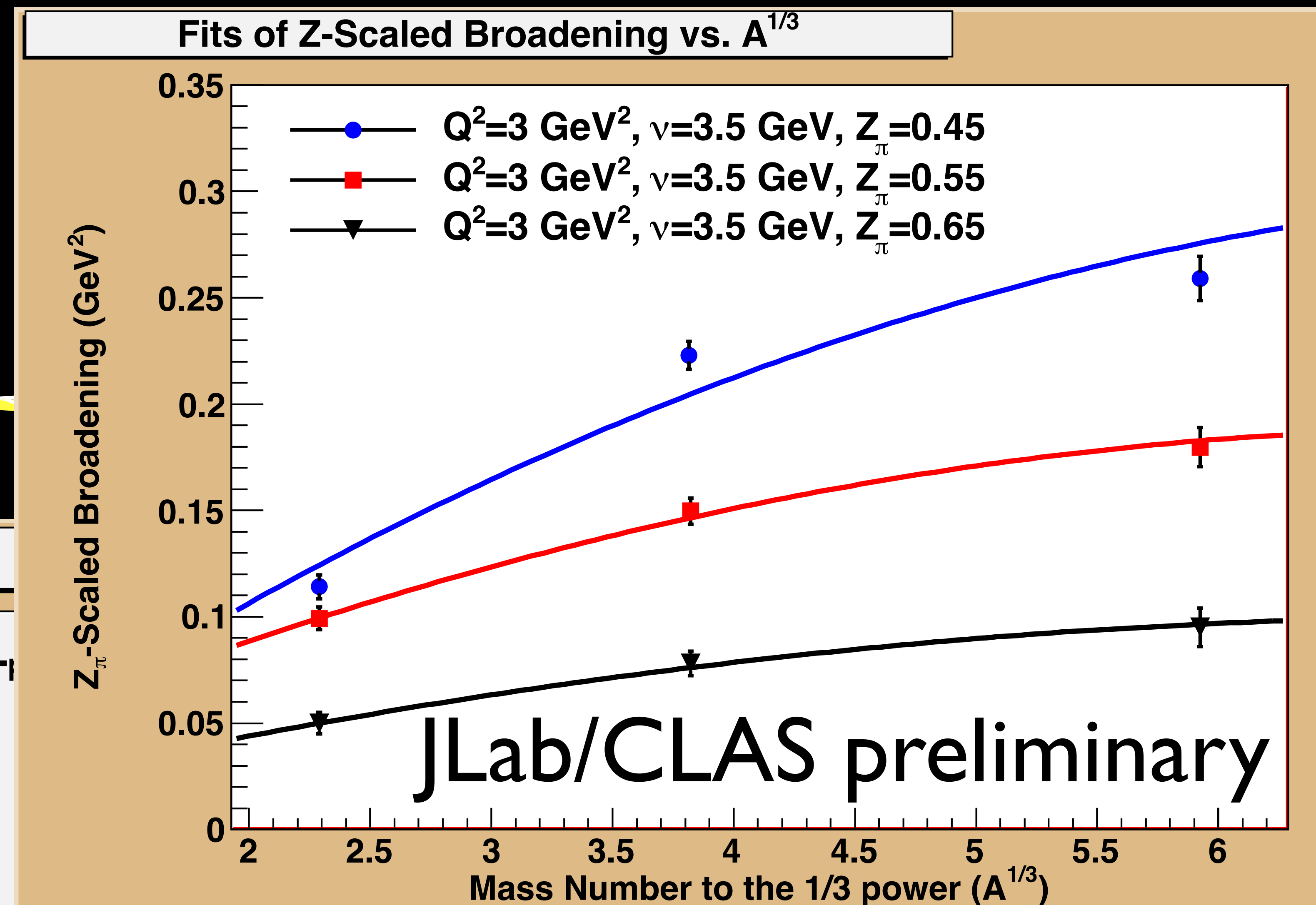
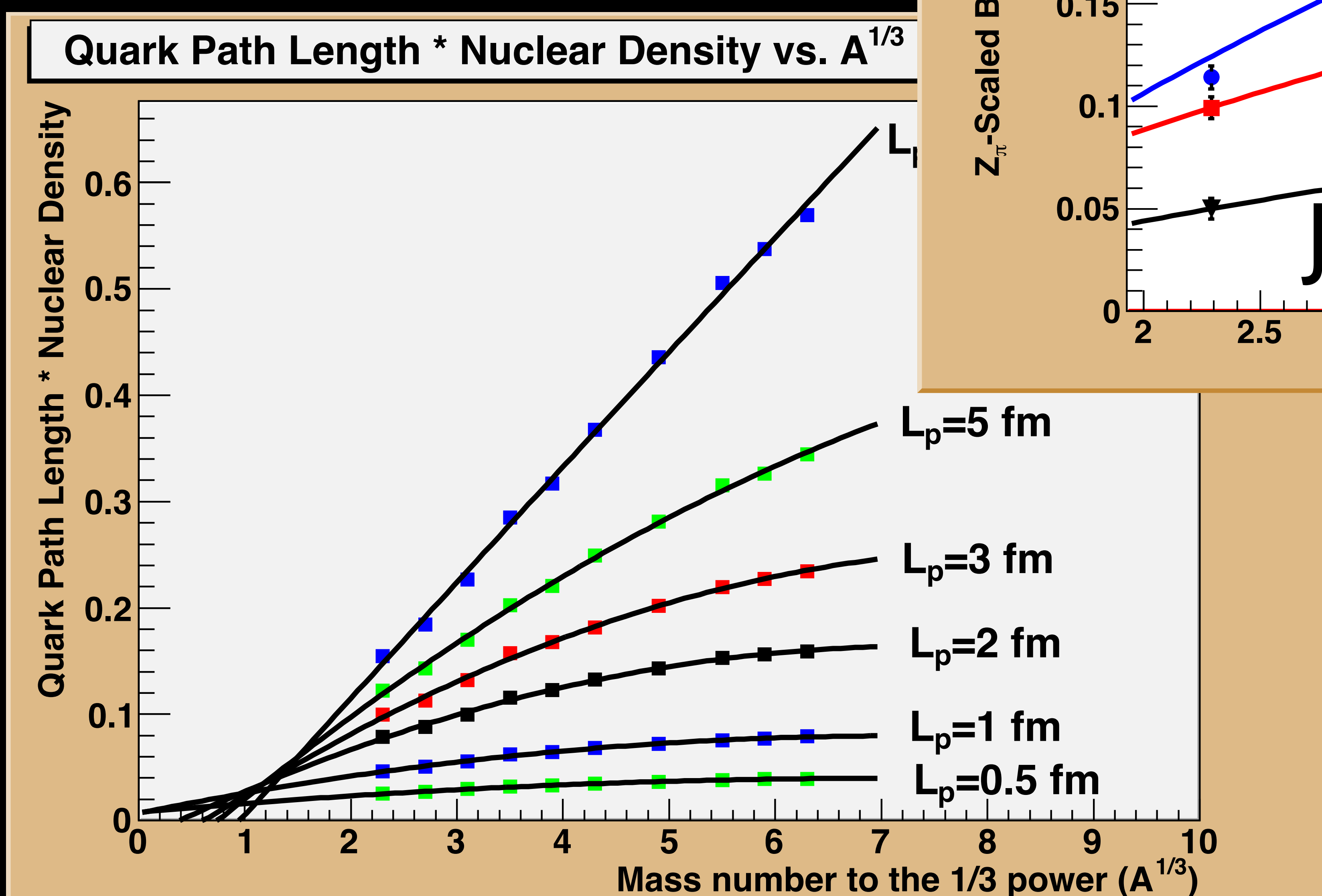
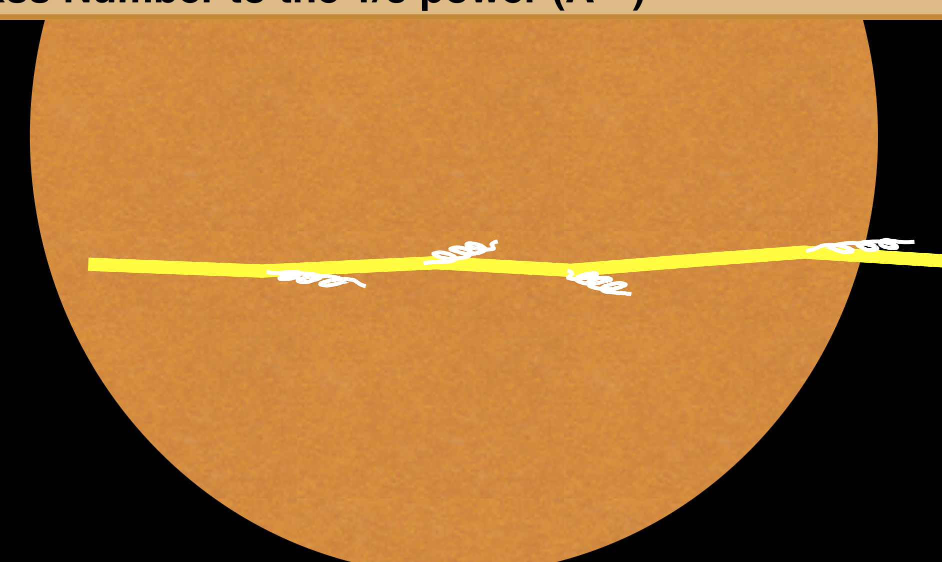
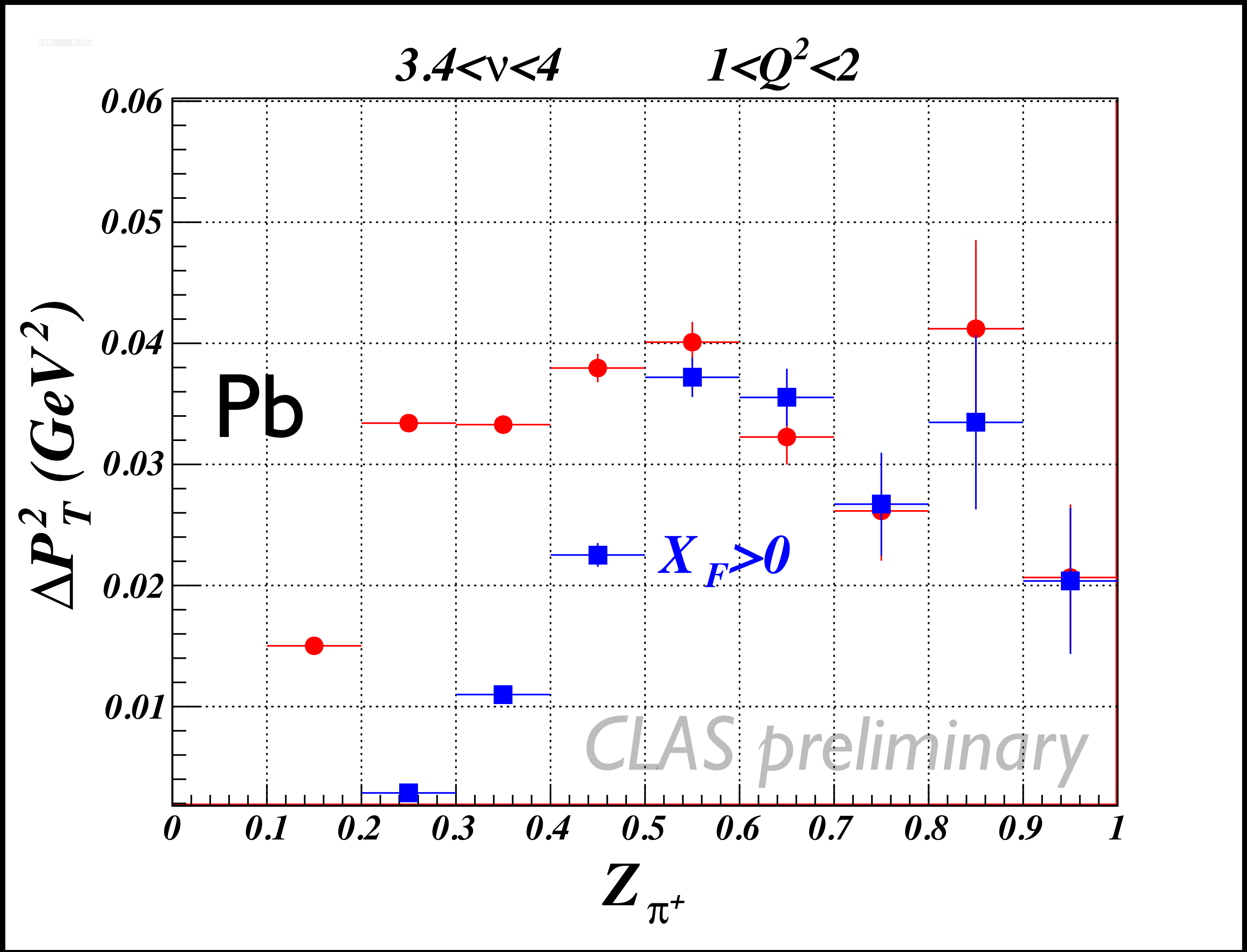


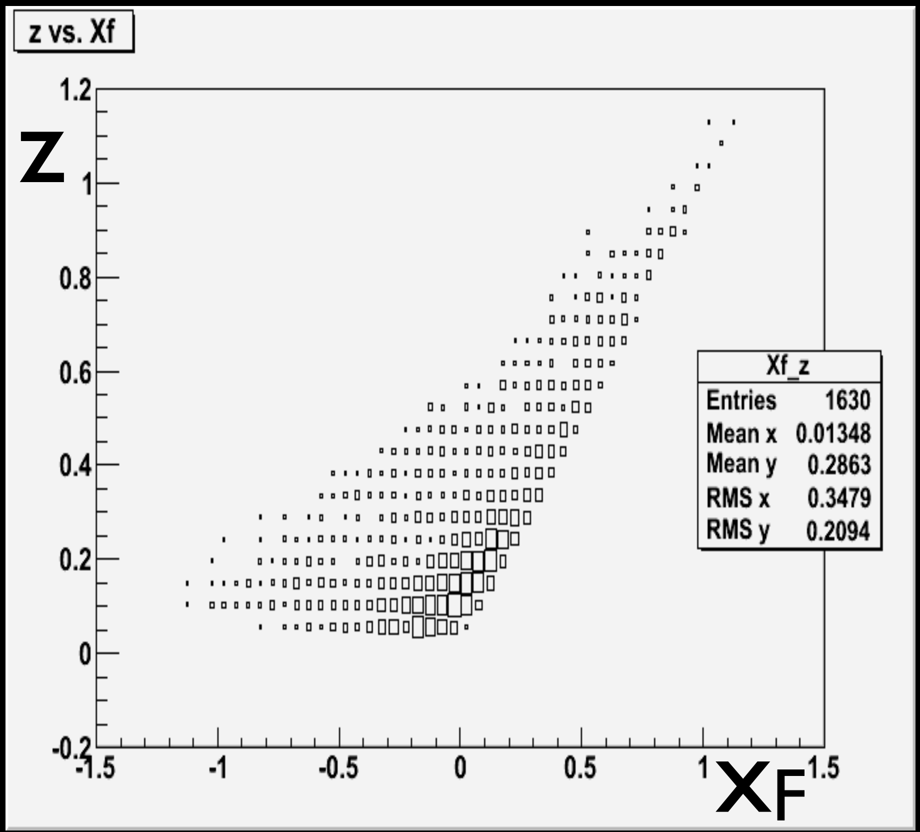






Dependence of p_T broadening on Feynman x





- 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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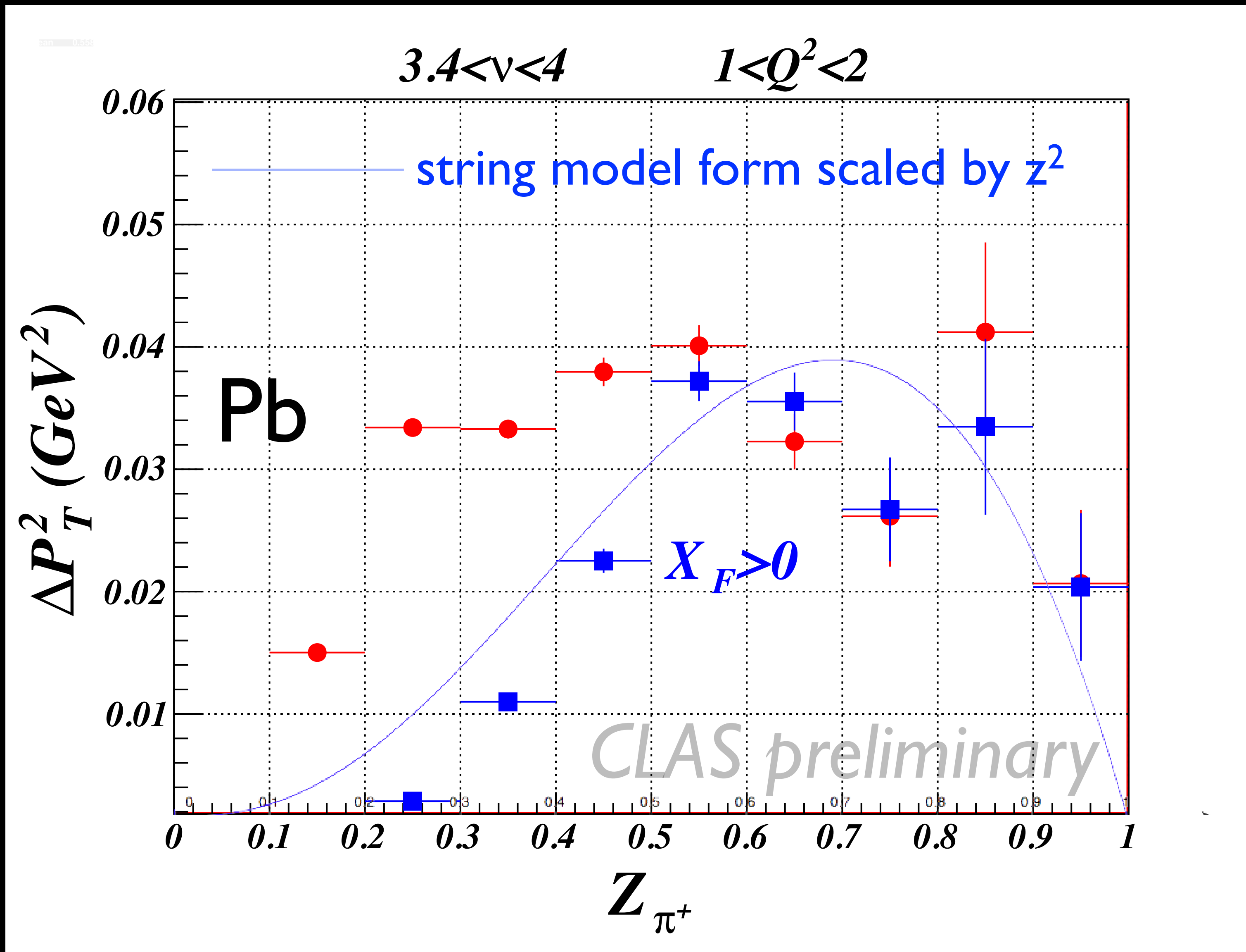

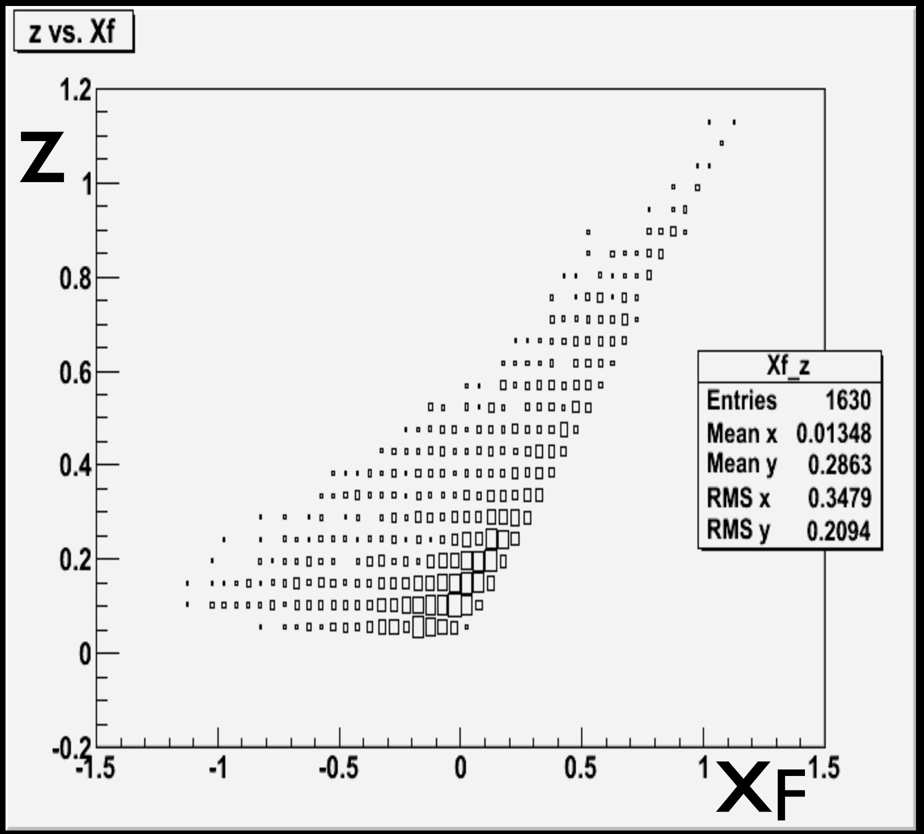

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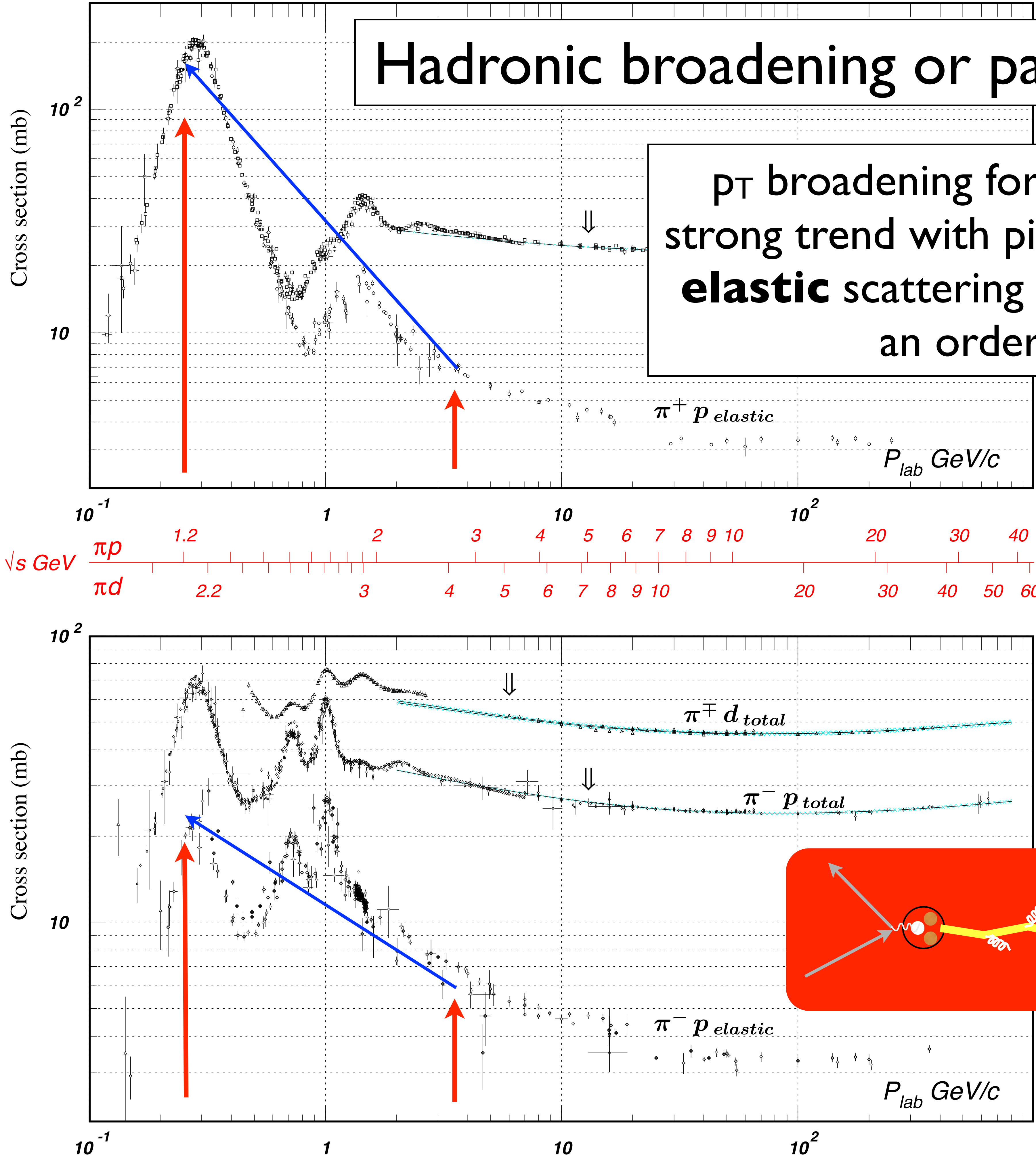
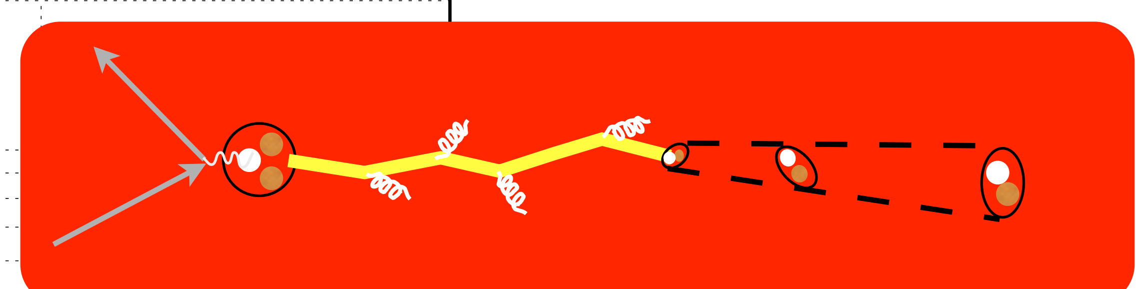
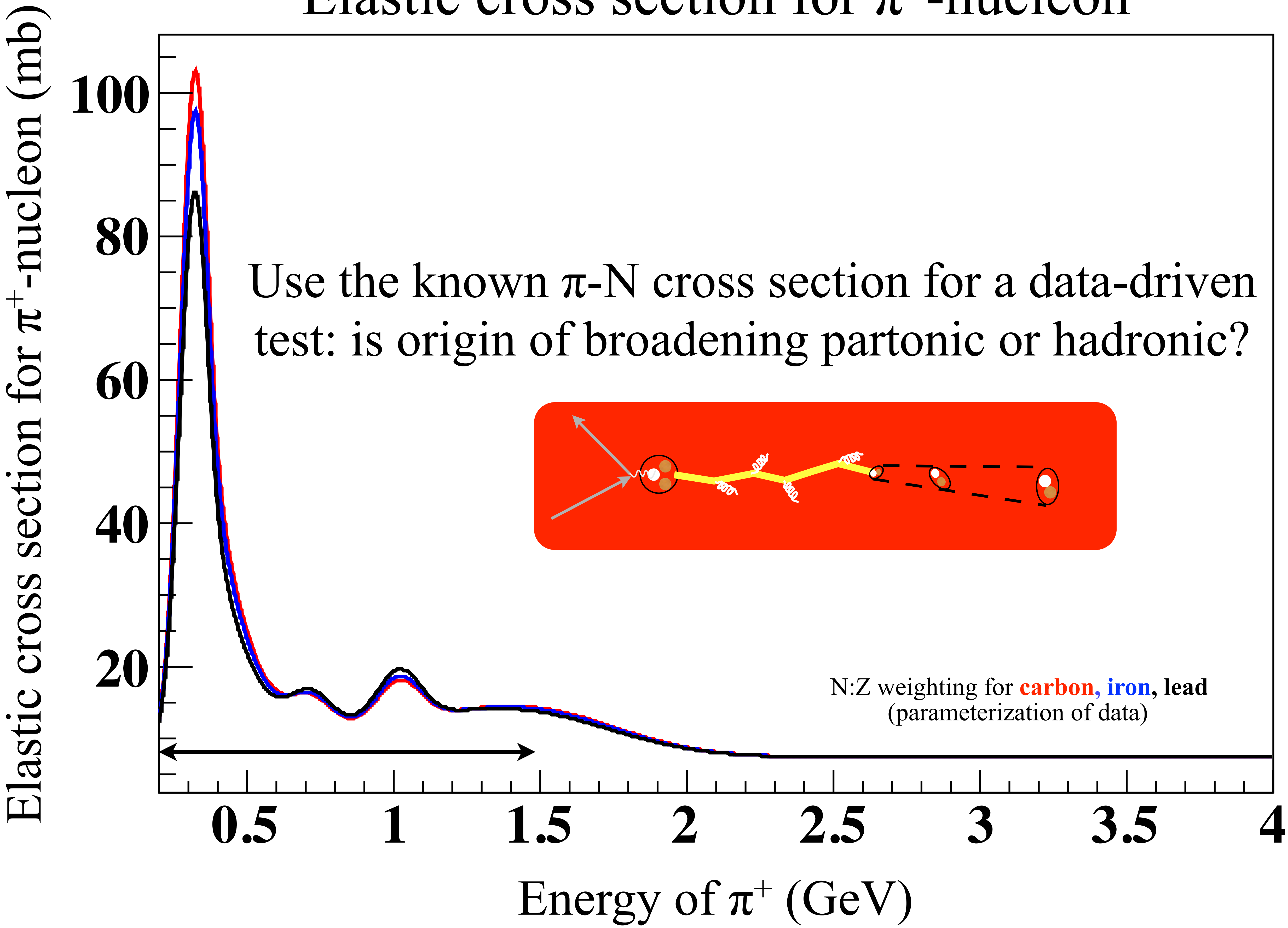
Hadronic broadening or partonic broadening?

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

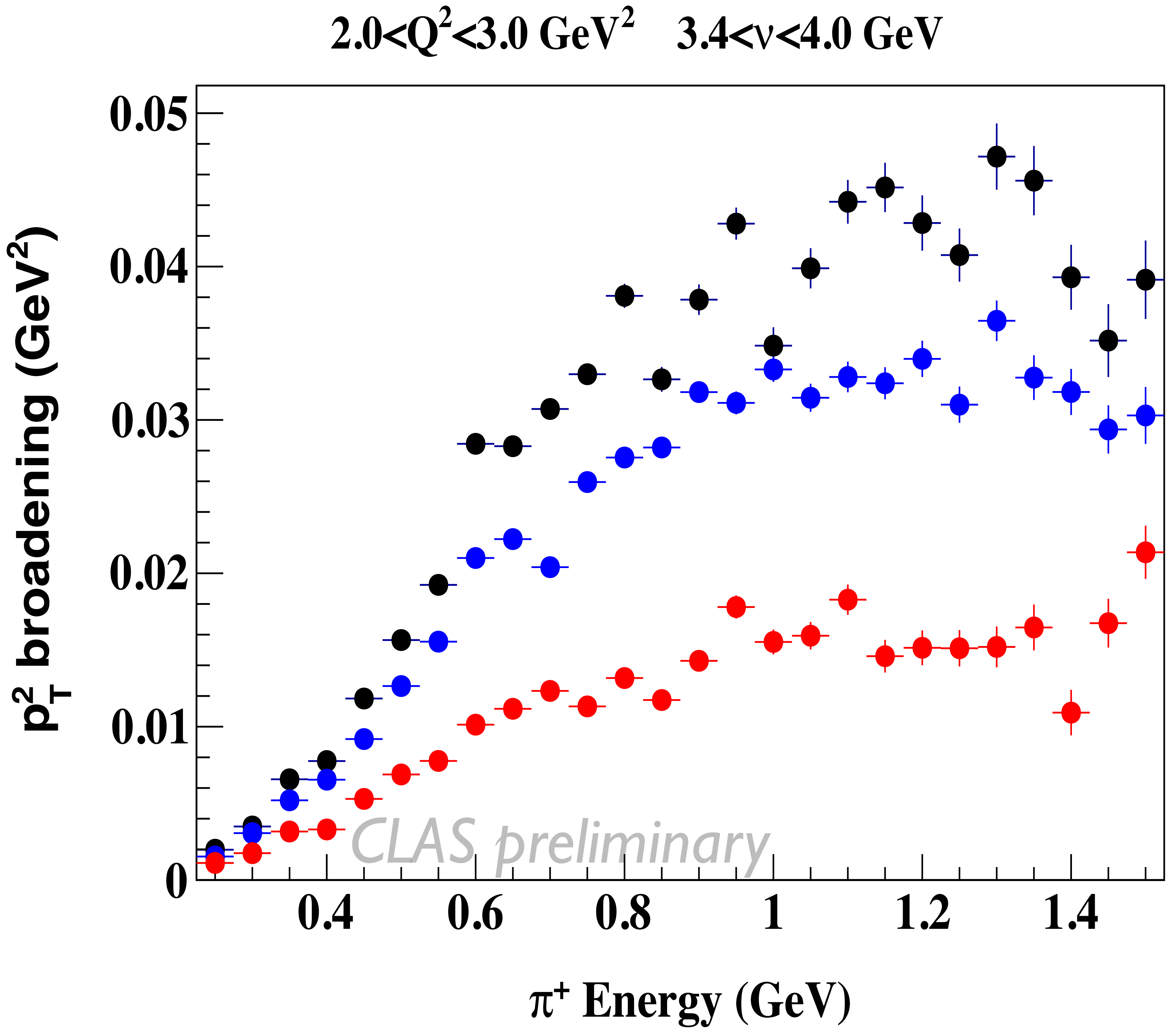




Elastic cross section for π^+-nucleon



p_T^2 Broadening vs. Hadron Energy



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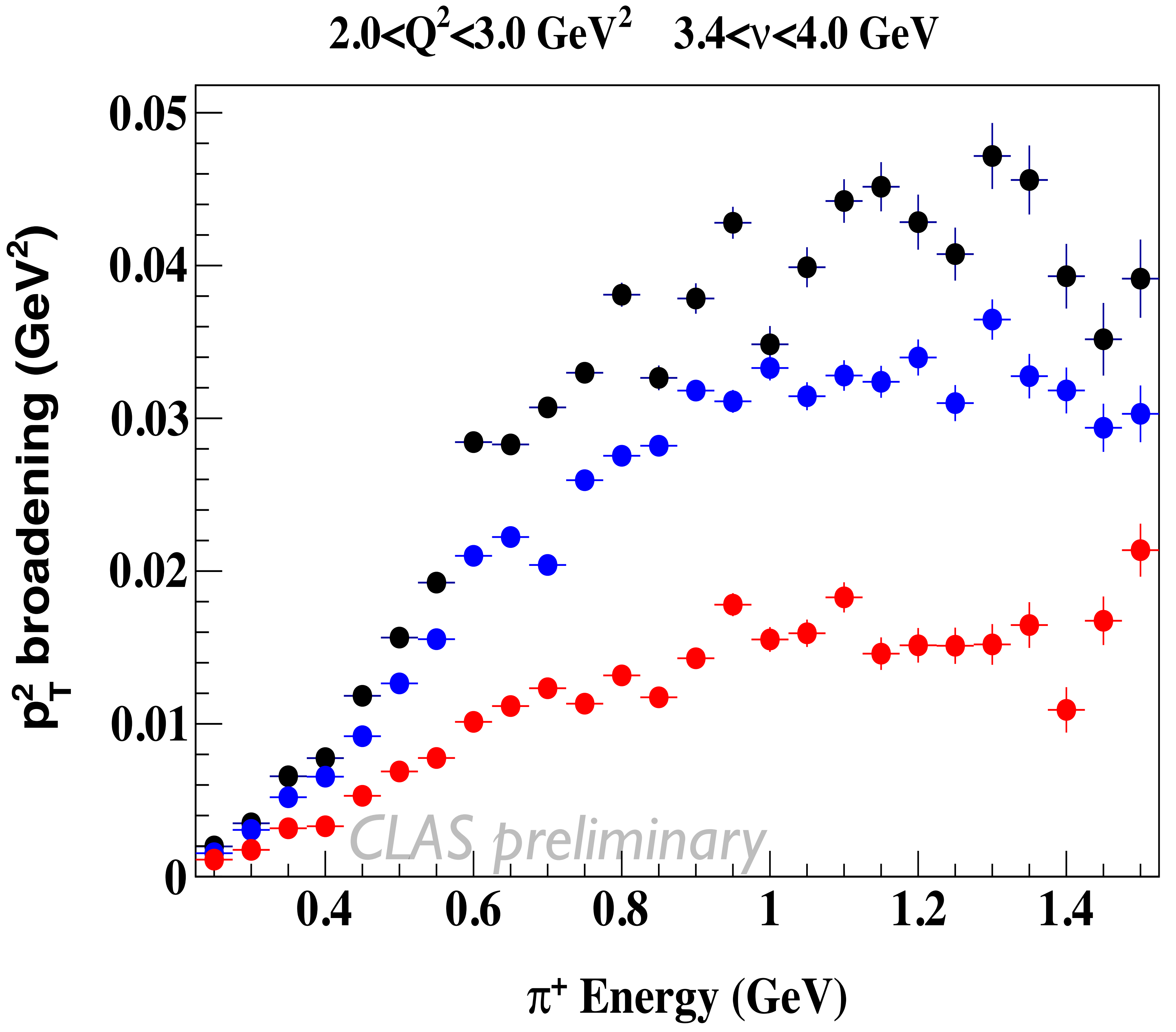

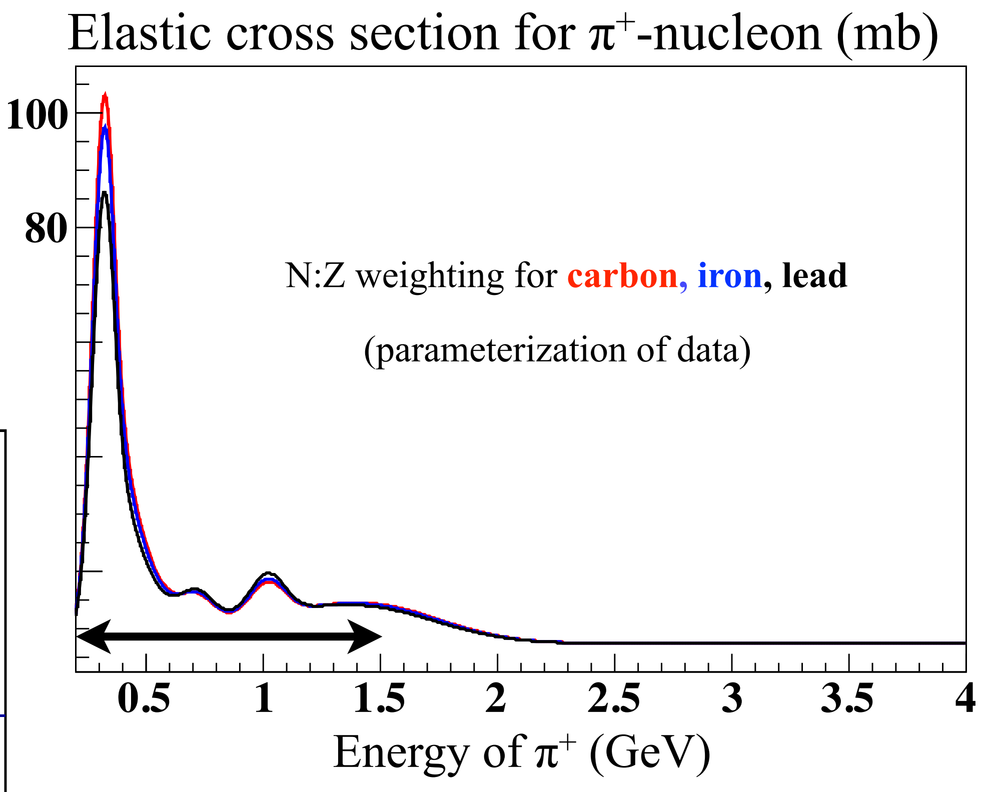

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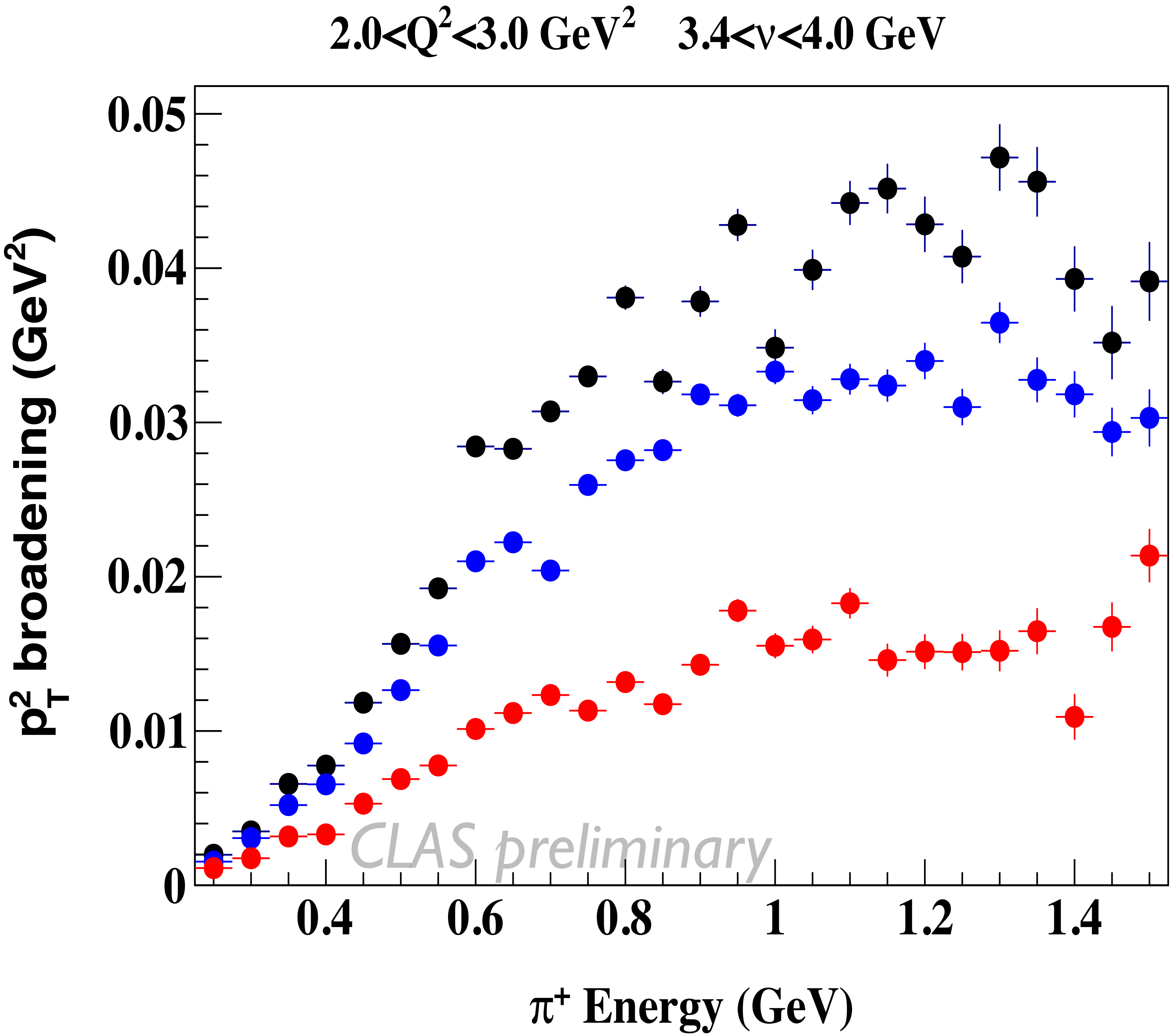

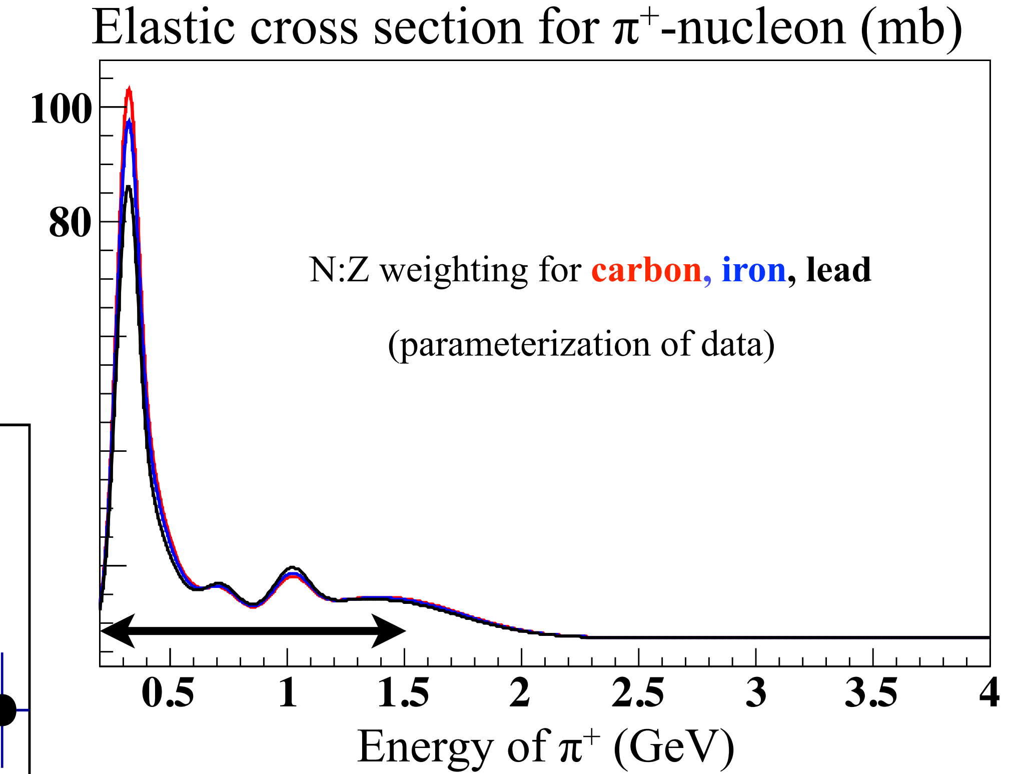

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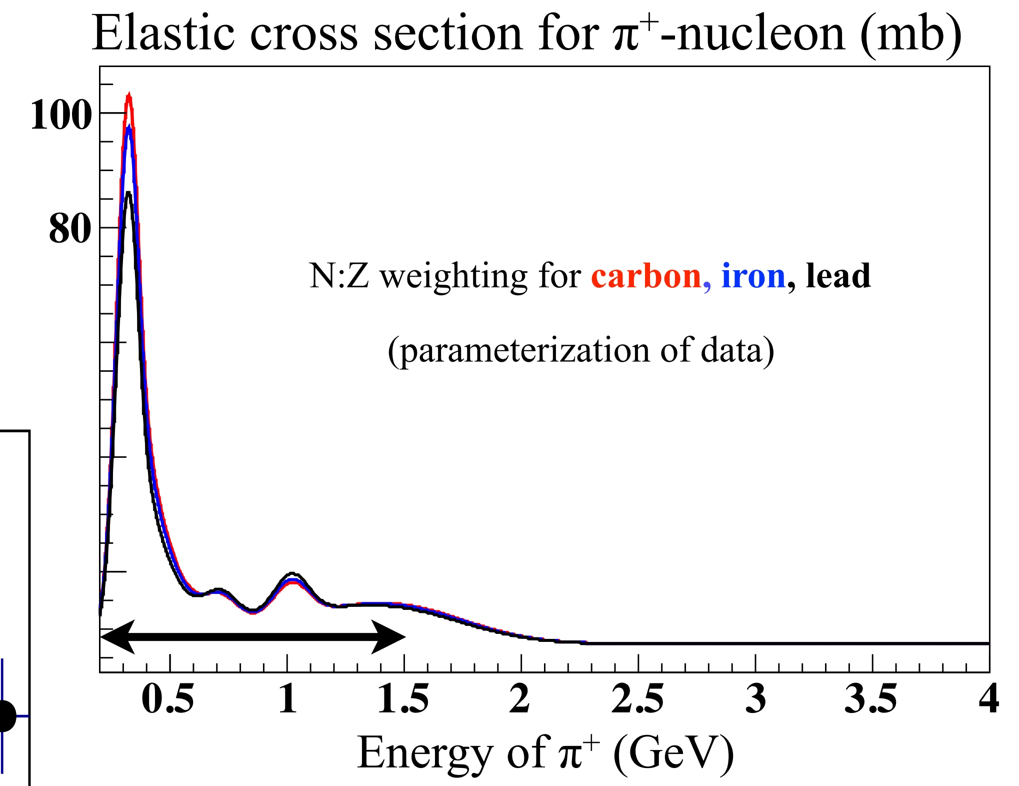

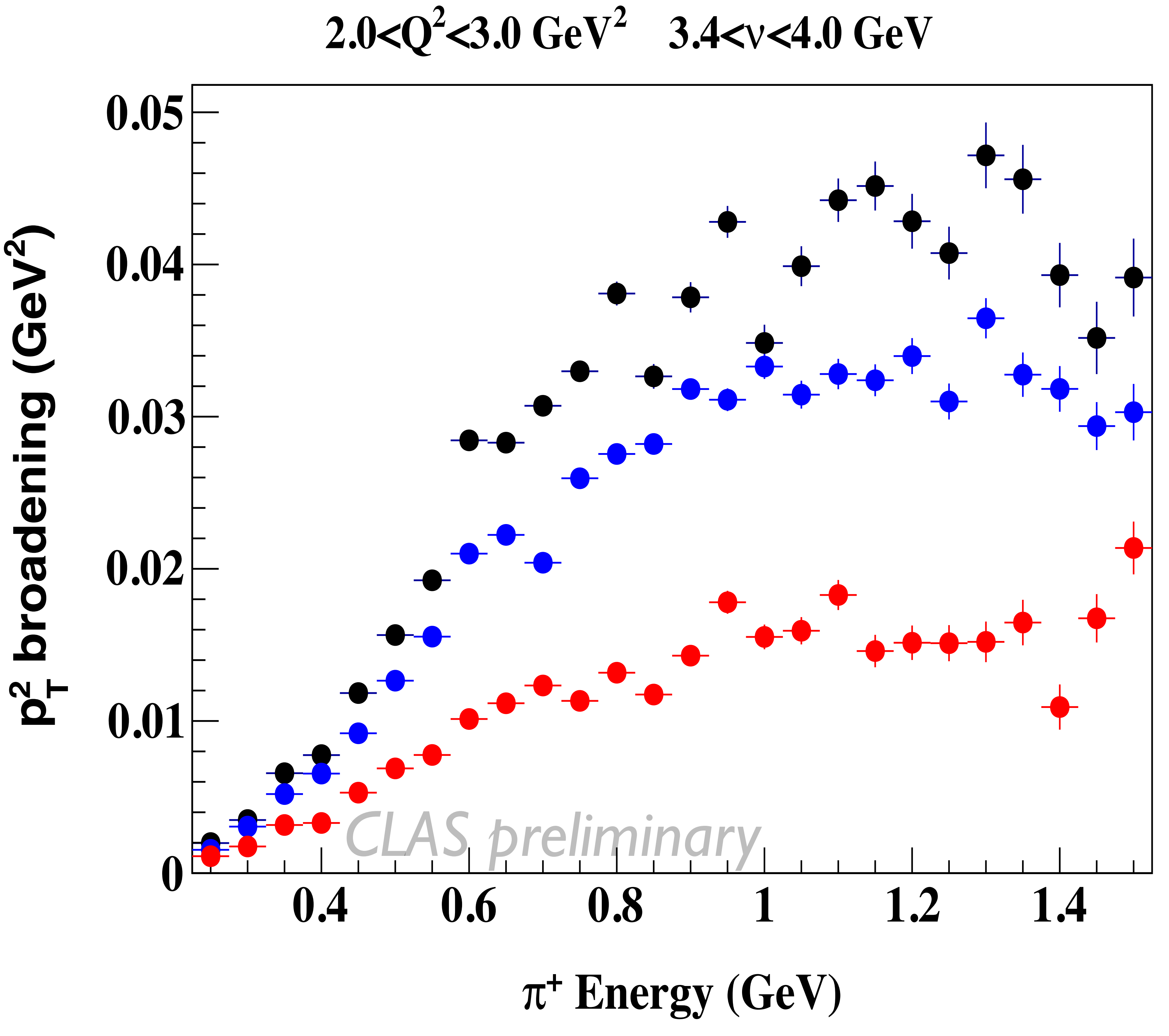

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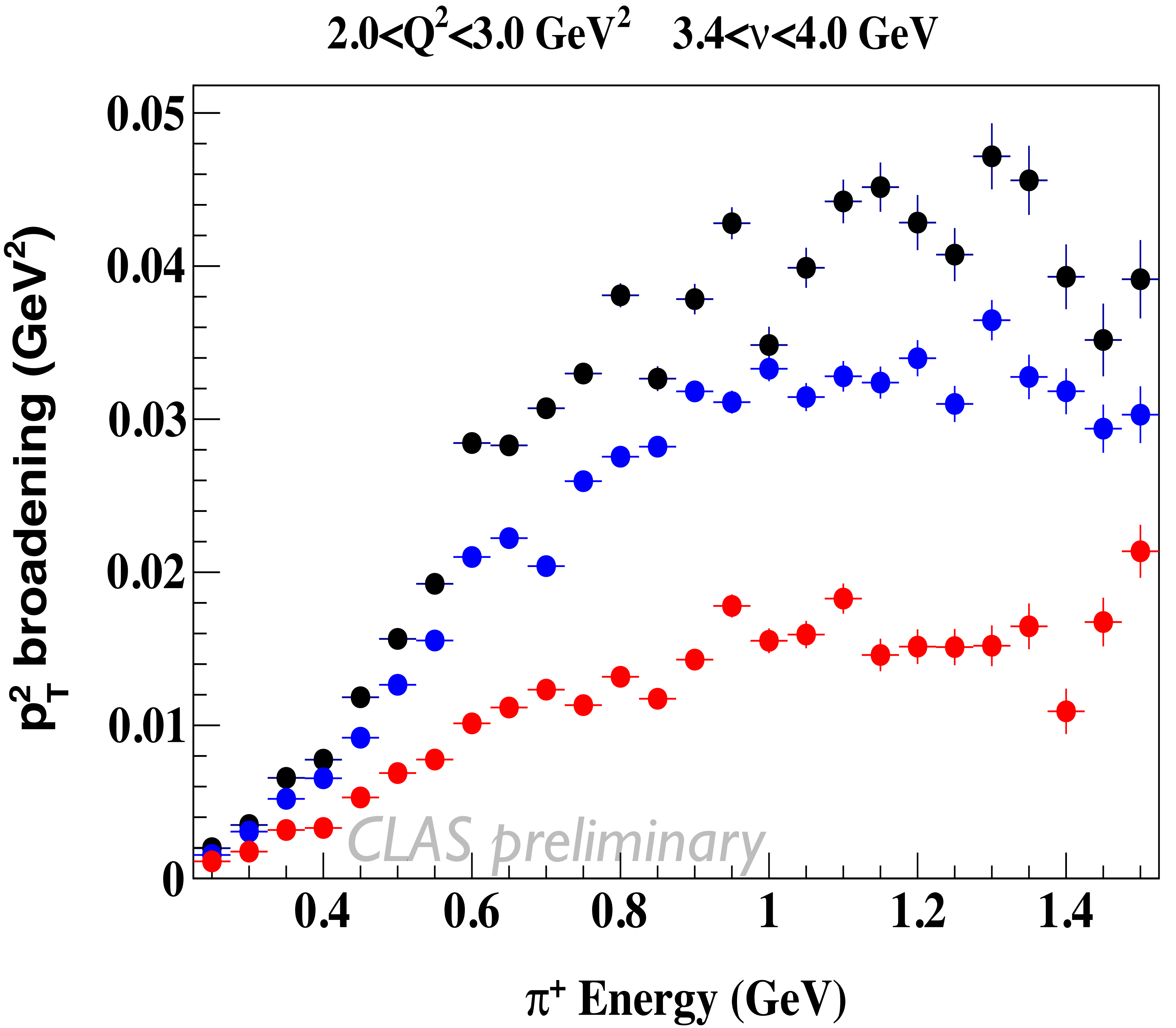
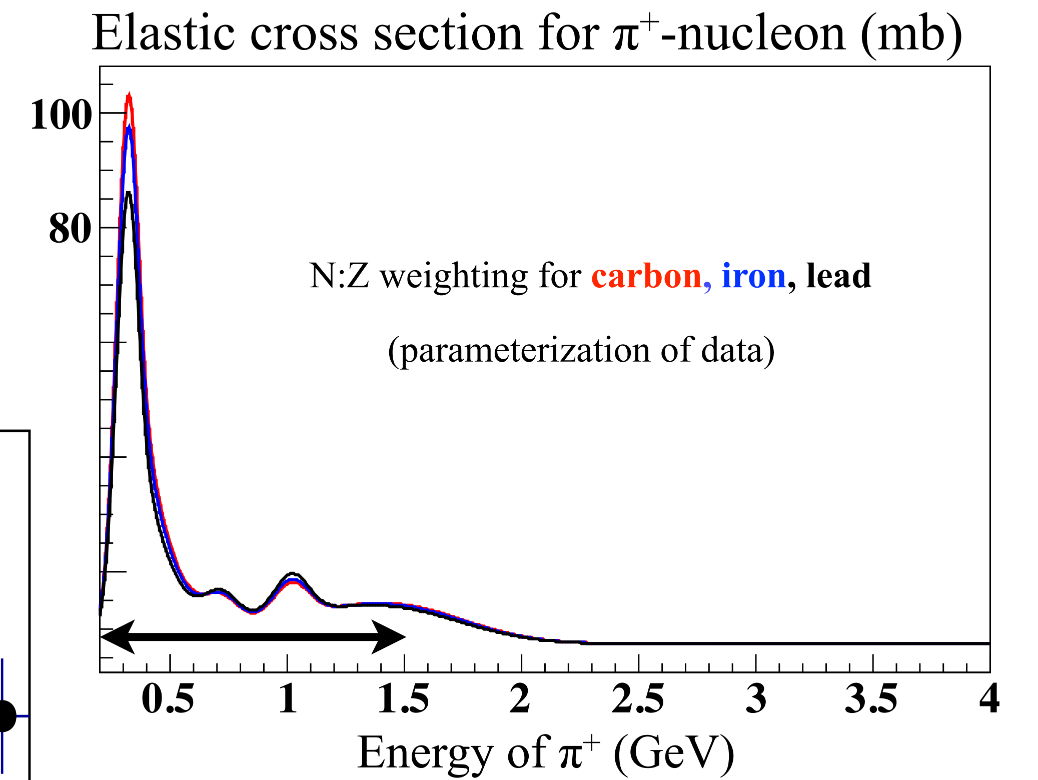
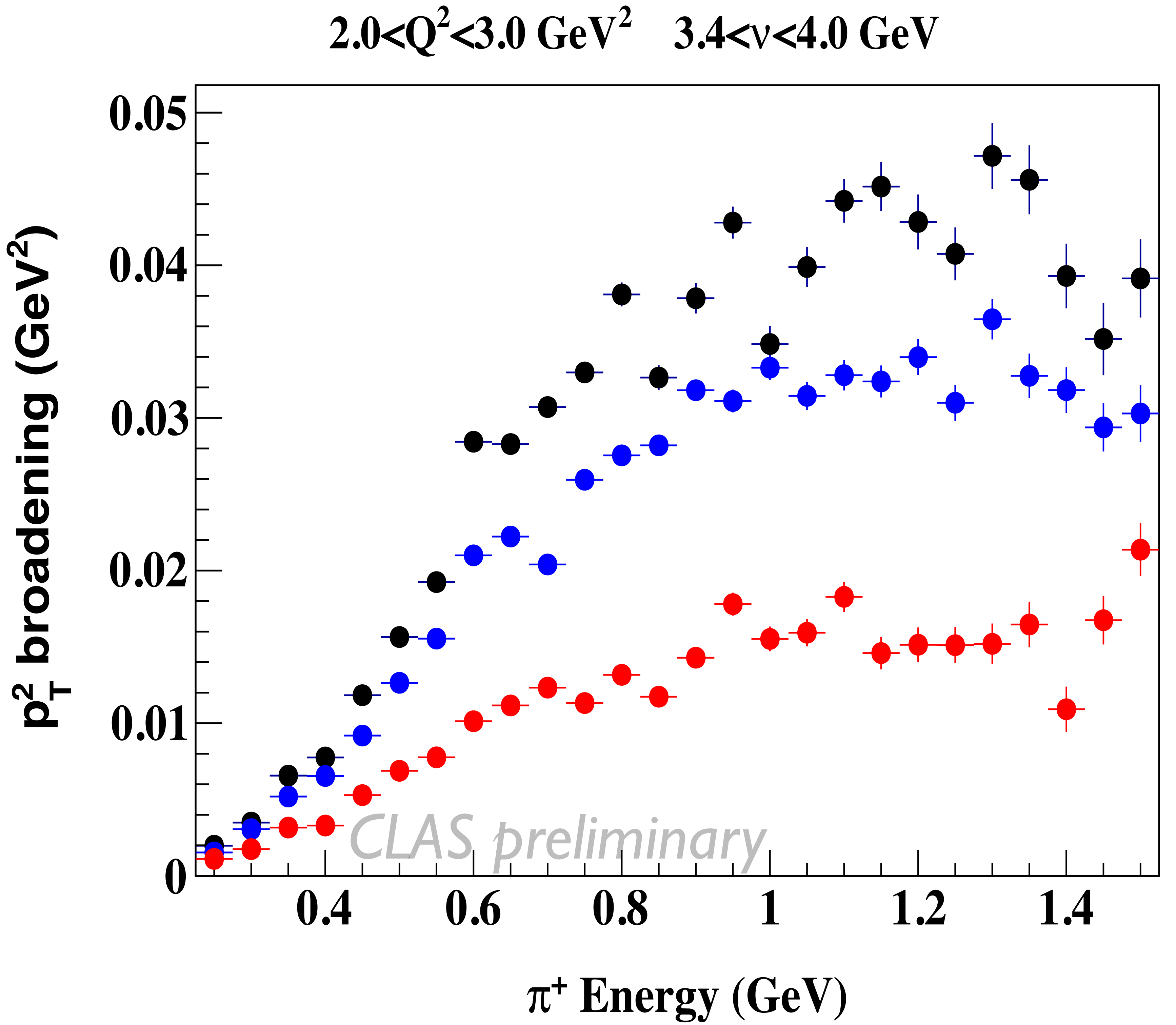
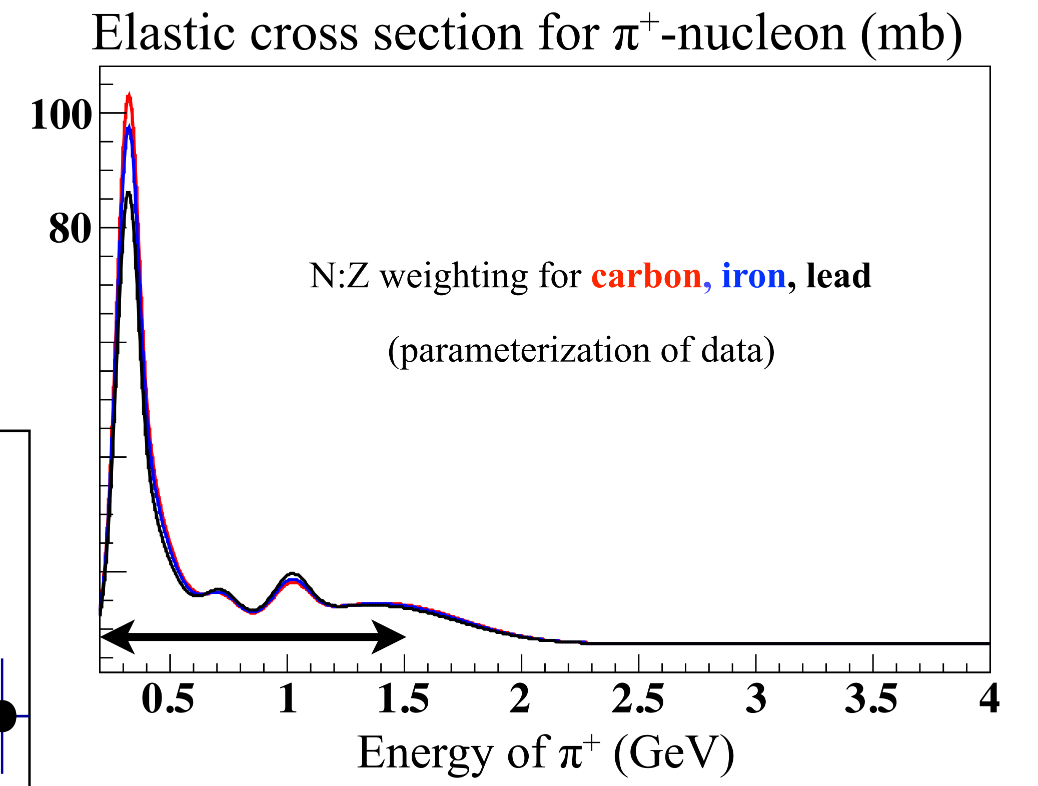




No visible evidence of hadronic elastic scattering?
Suggests:

p_T^2 Broadening vs. Hadron Energy





No visible evidence of hadronic elastic scattering? Suggests:

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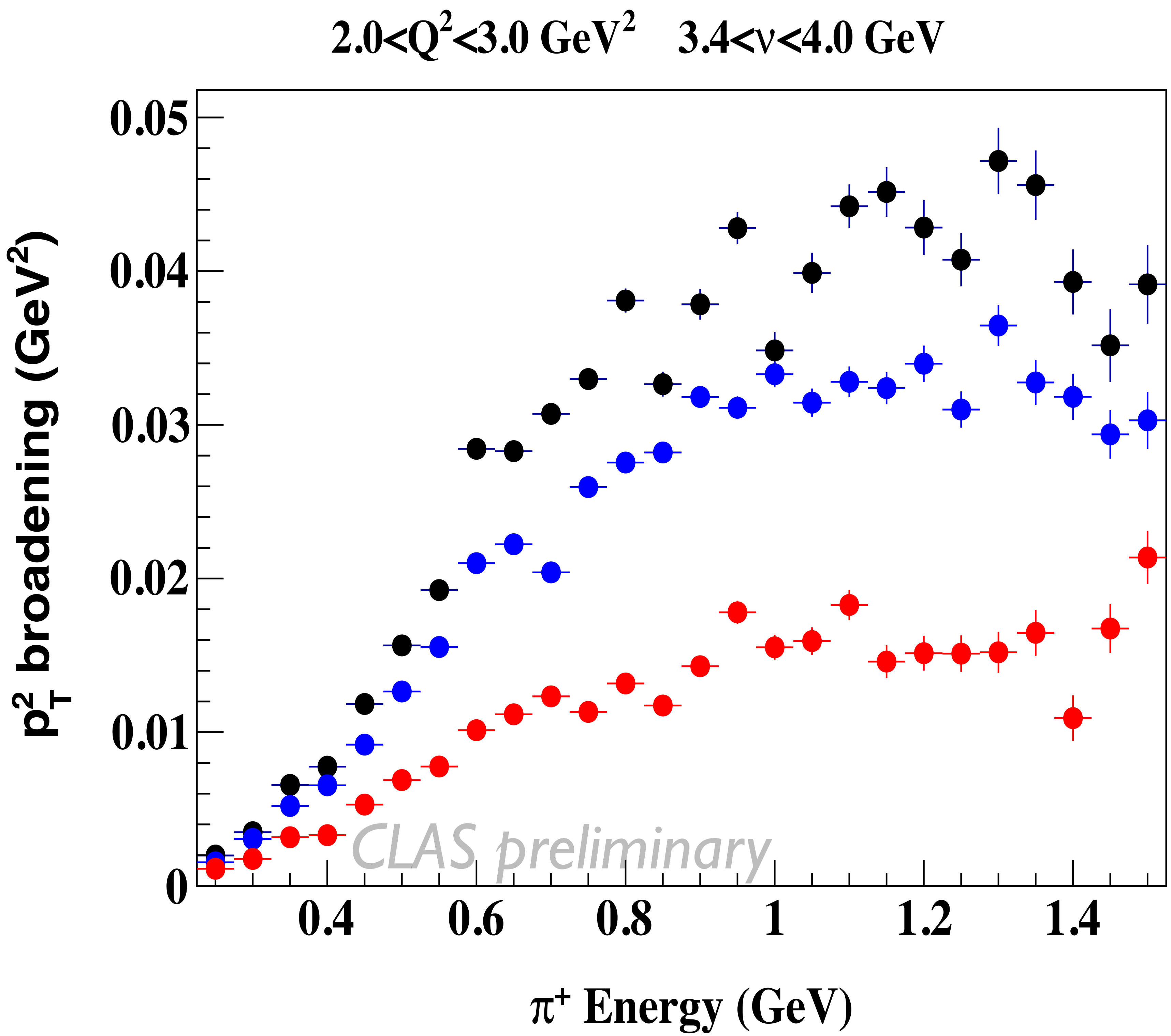
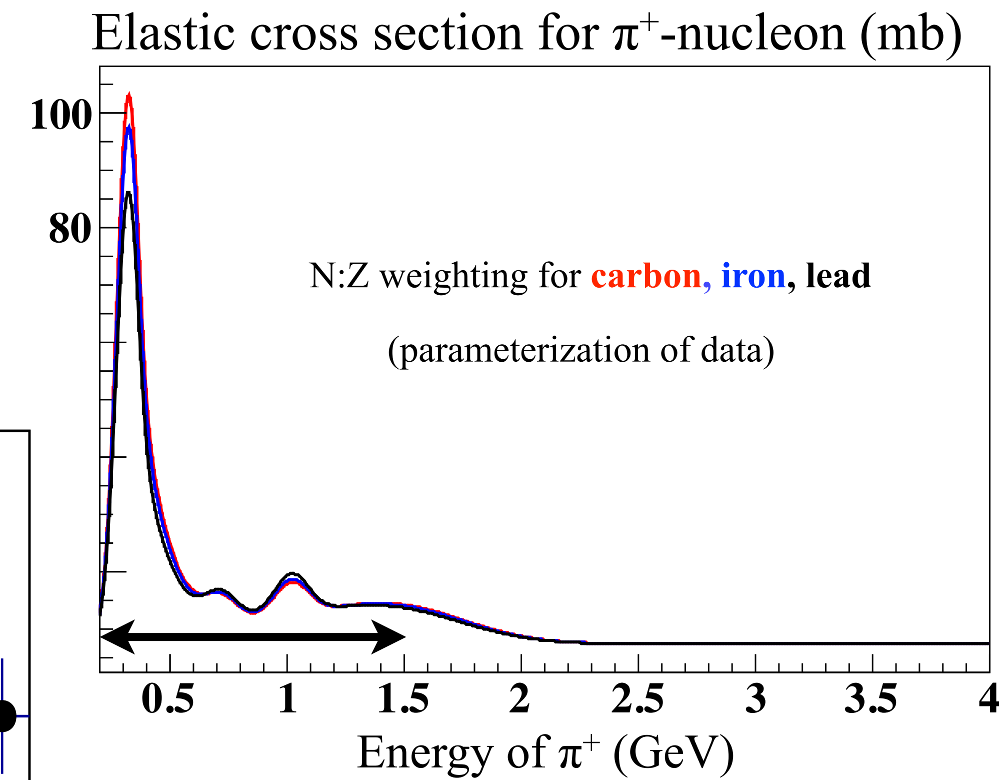
p_T^2 Broadening vs. Hadron Energy





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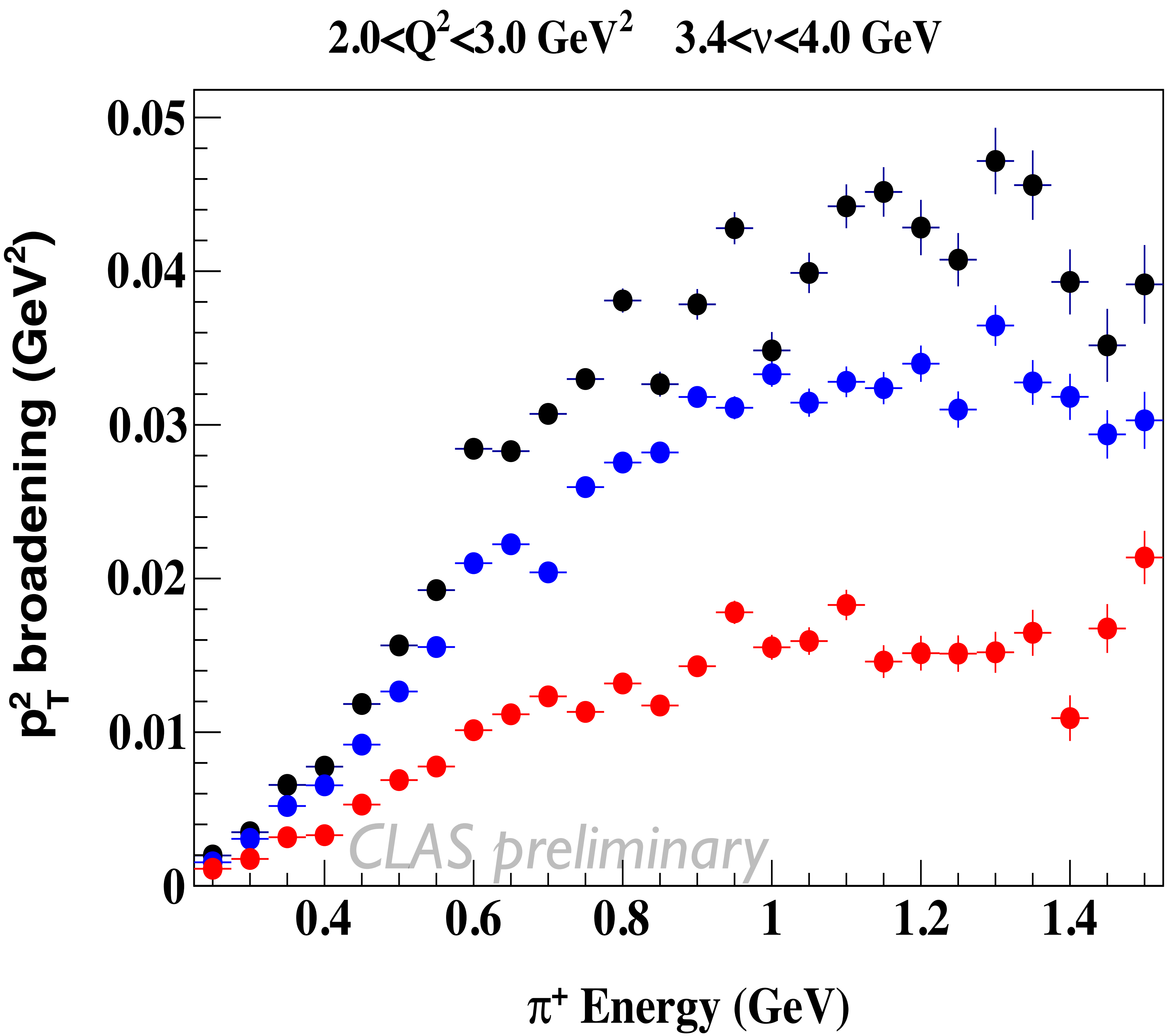
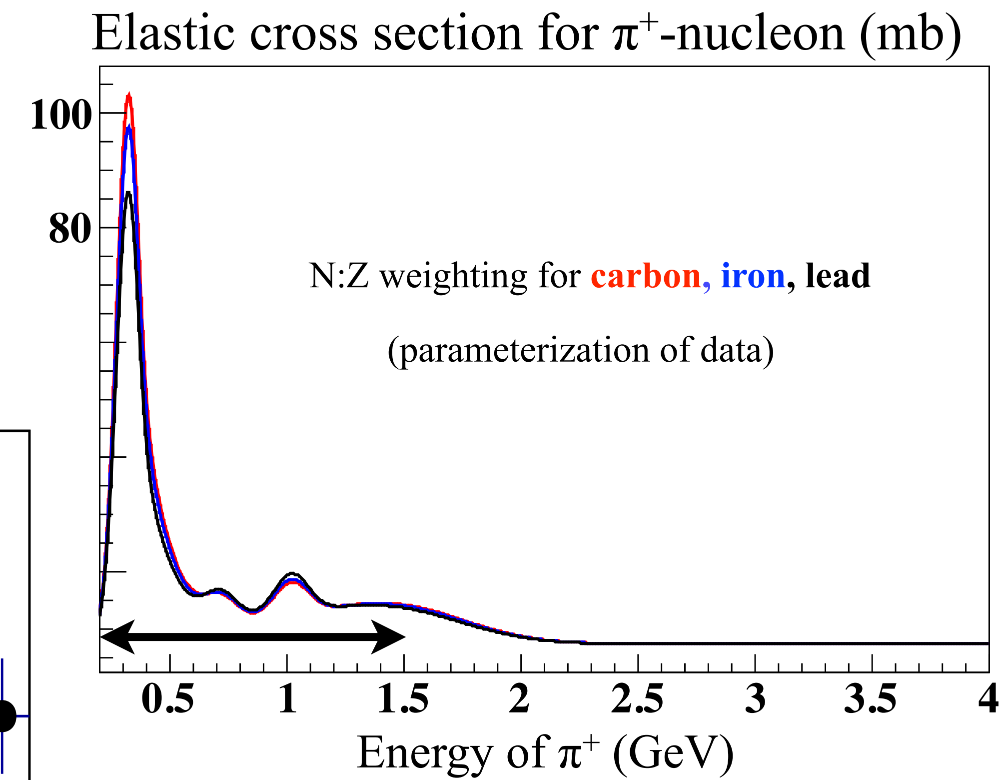
p_T^2 Broadening vs. Hadron Energy





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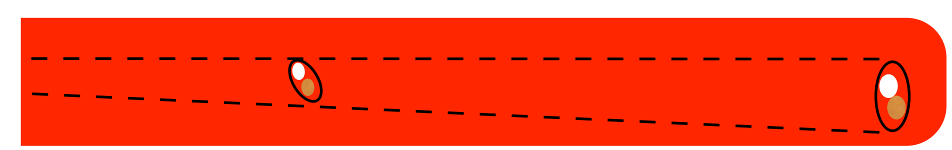

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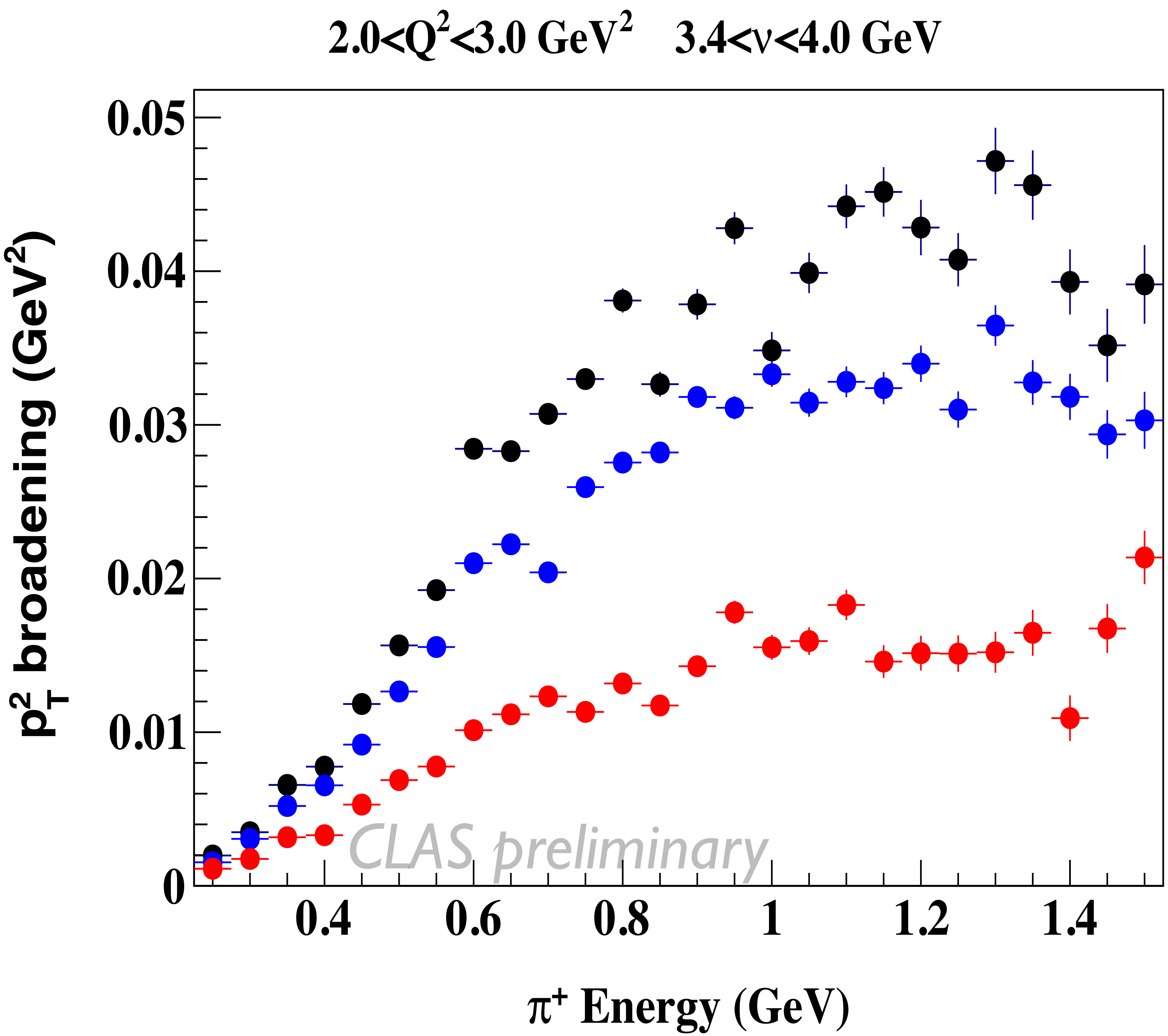
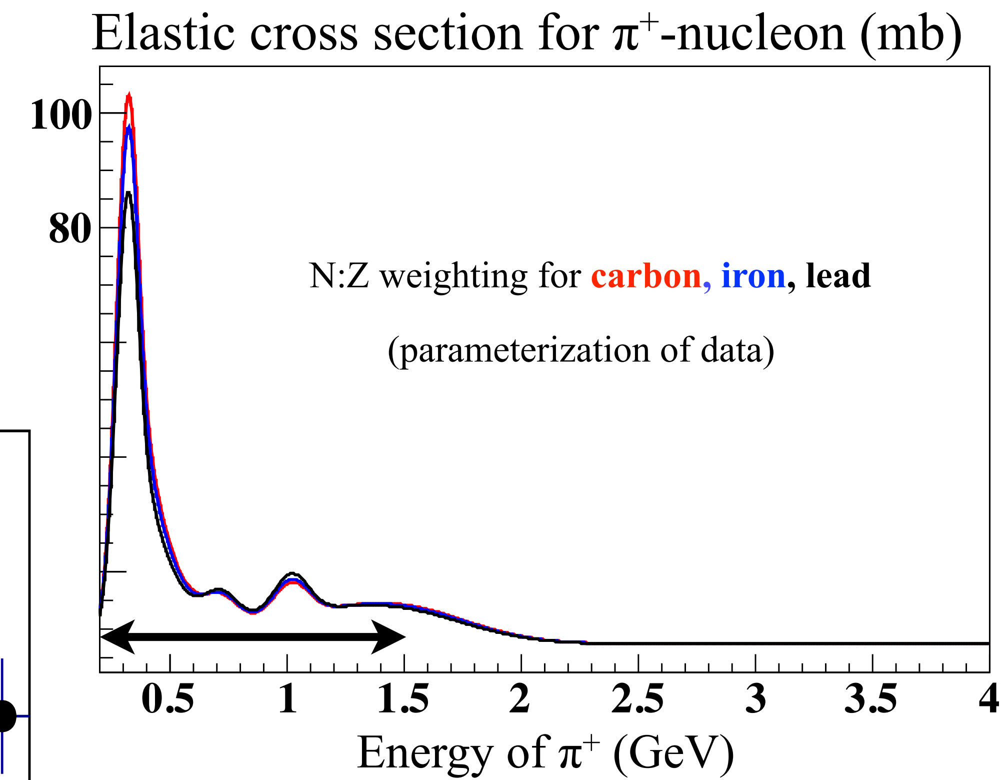
p_T^2 Broadening vs. Hadron Energy





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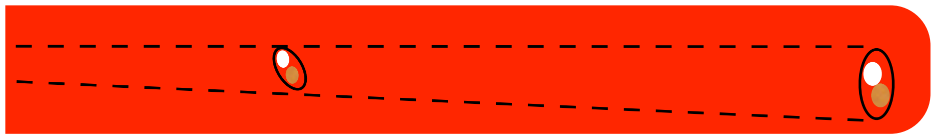
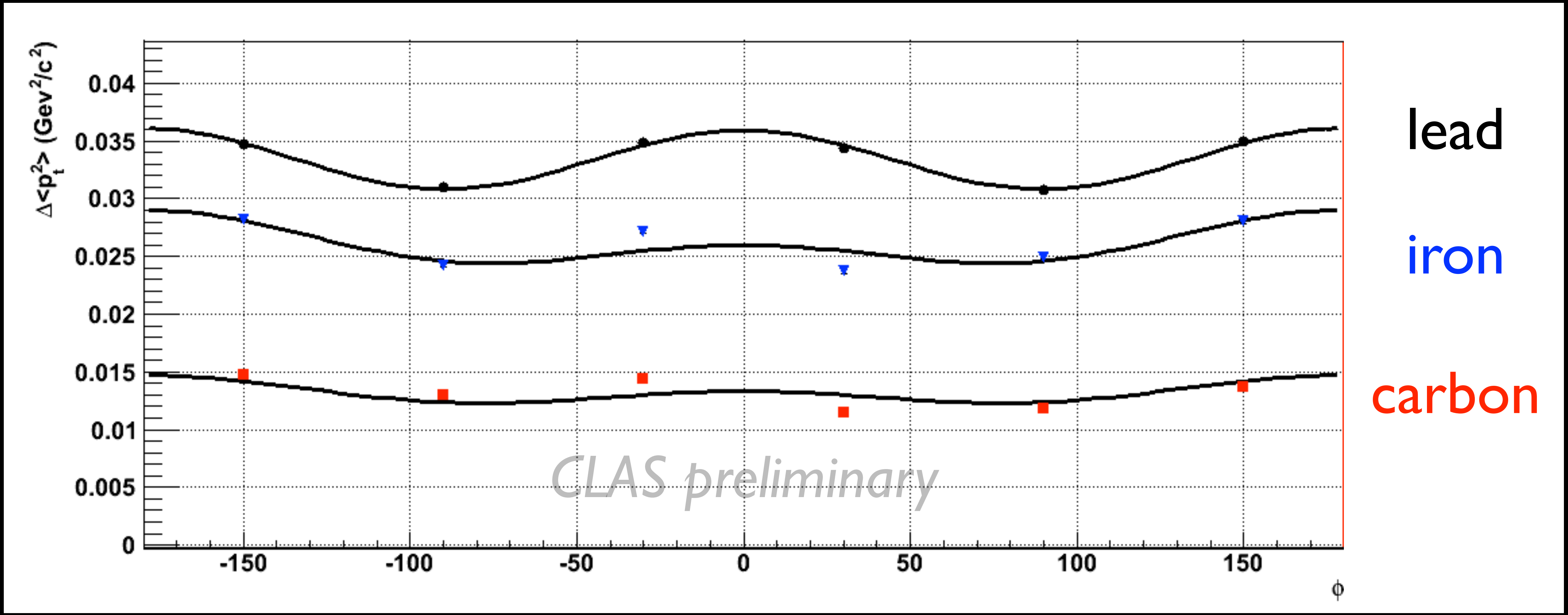


2) broadening is purely partonic

EIC: explore this with broad kinematic range

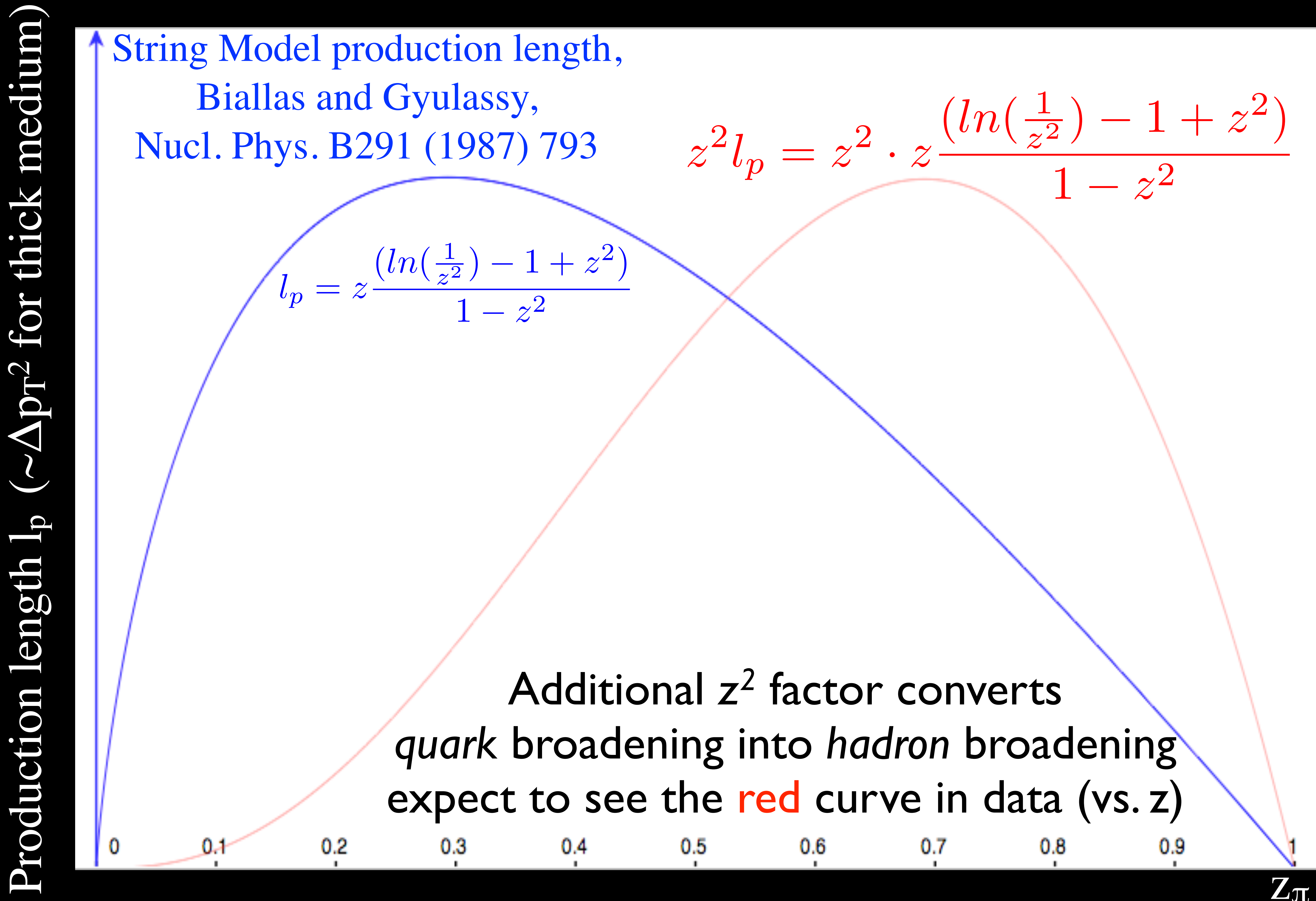
Dependence of p_T broadening on ϕ_{pq}



curves shown contain terms in cos(φ_{pq}) and cos($2\varphi_{pq}$) 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! *quantum effect in p_T broadening?*

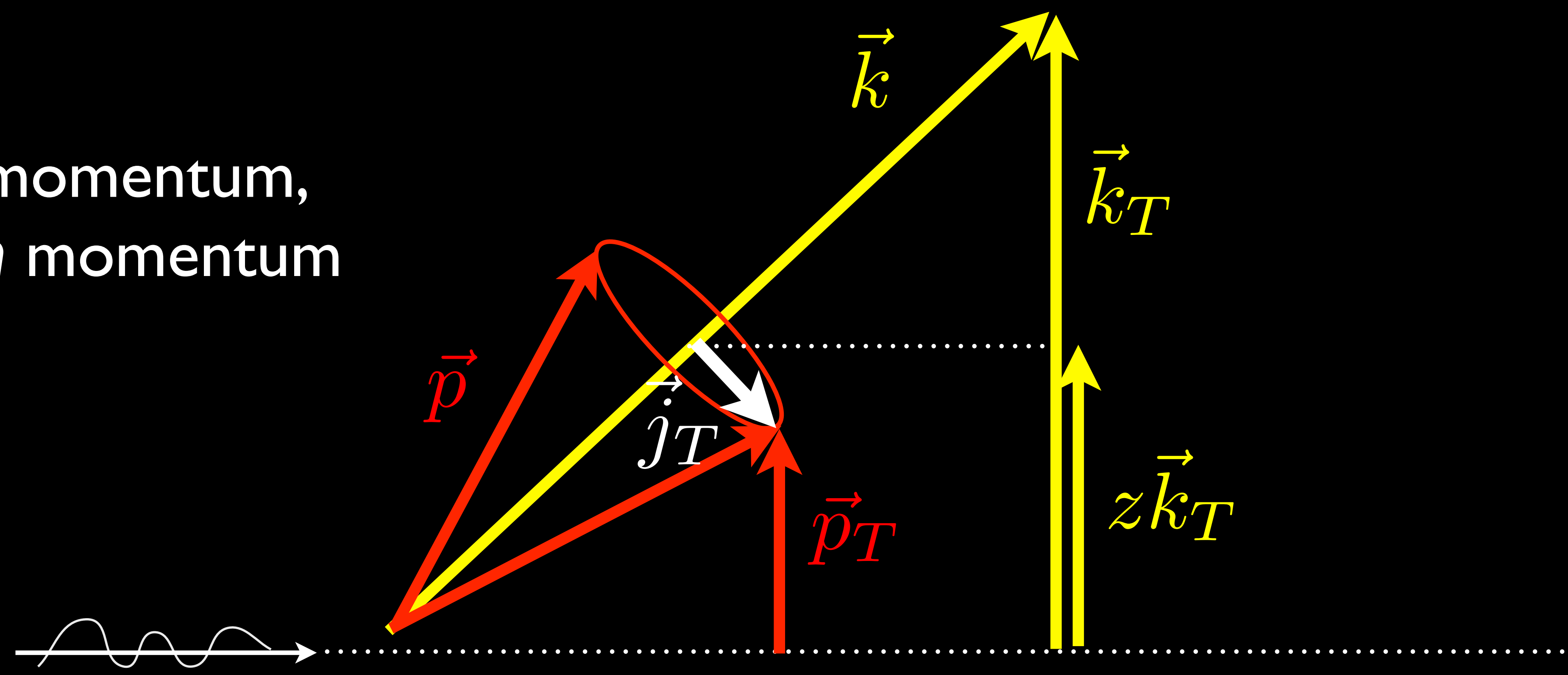
  - related to parton density fluctuations in larger nuclei? J. Qiu: Boer-Mulders TMD $\otimes D_j^h(z, Q^2)$ in presence of non-vanishing mass dipole moment


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)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Production length l_p ($\sim \Delta p_T^2$ for thick medium)
z_π

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

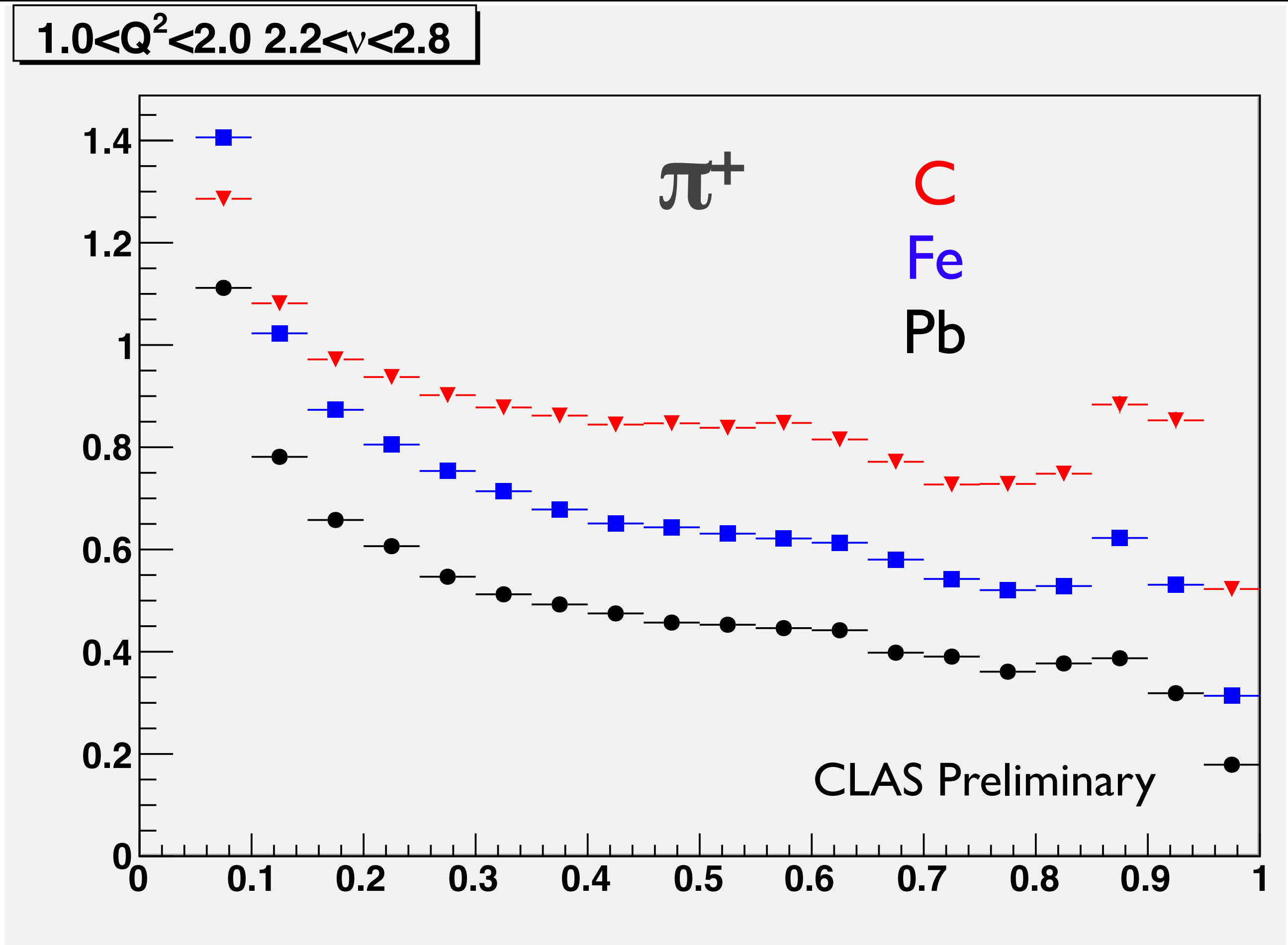
Basic questions at low energies:

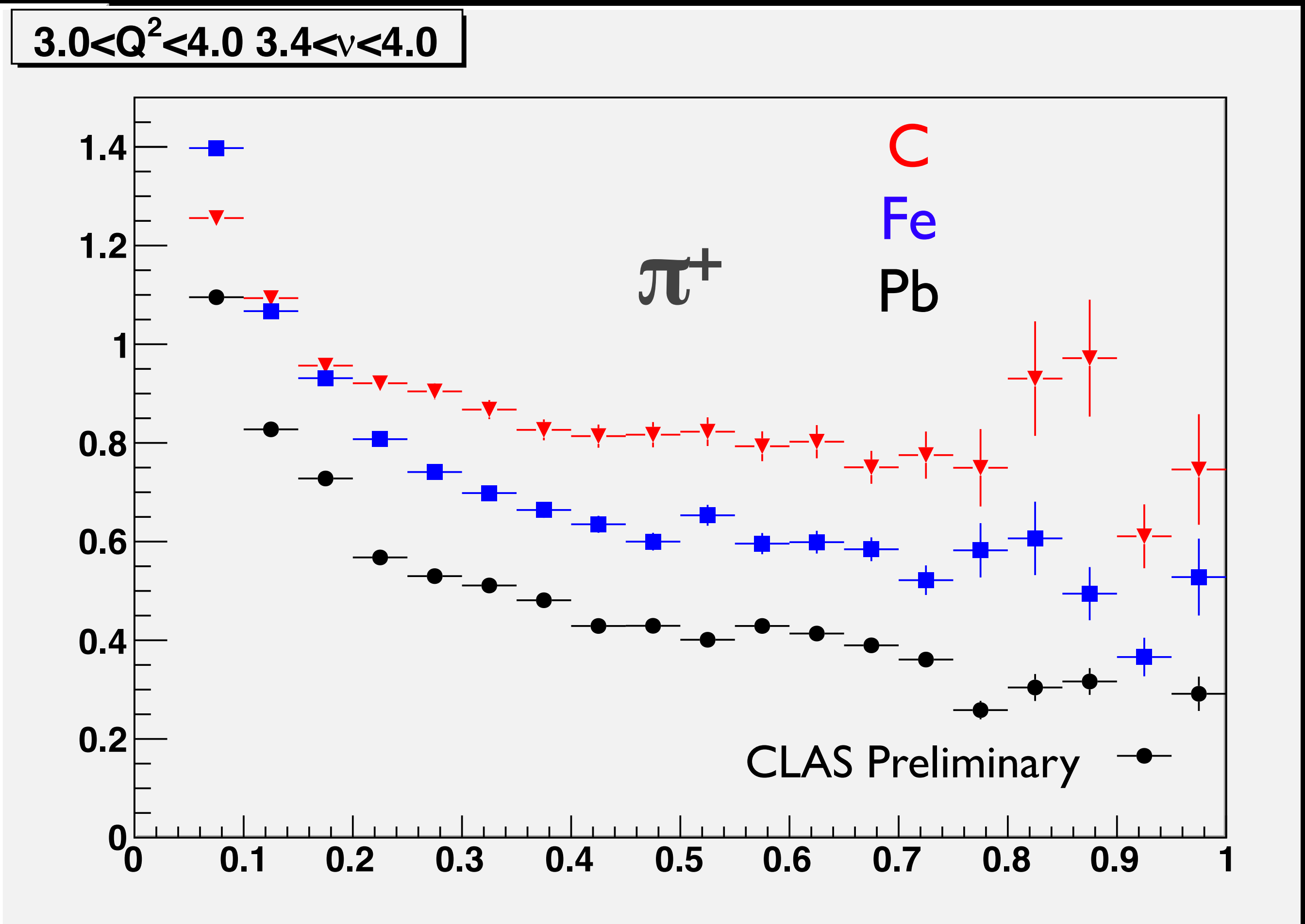
Partonic processes dominate, or hadronic? in which kinematic regime? classical or quantum?

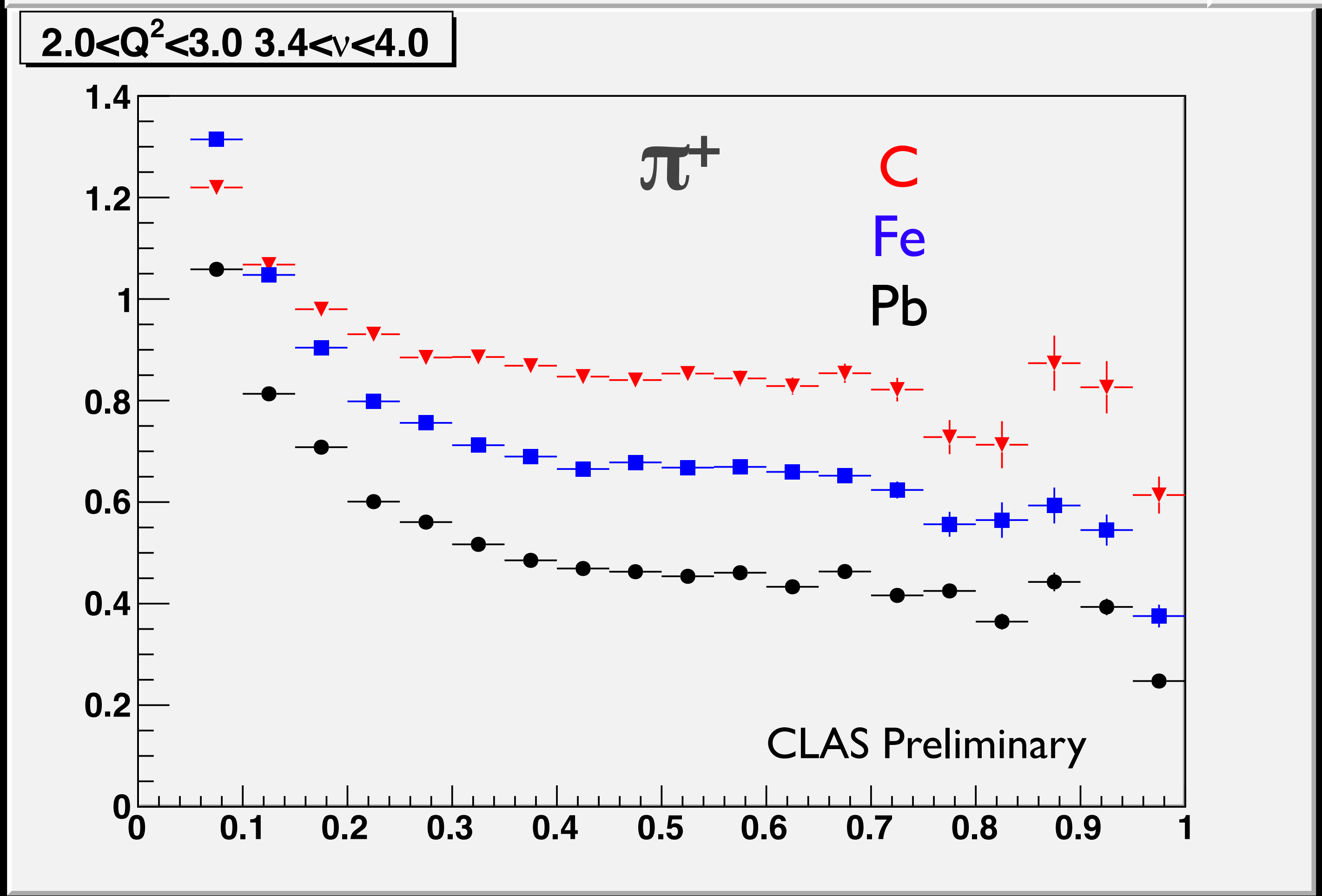
Can identify dominant hadronization mechanisms, uniquely? what are the roles of flavor and mass?

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

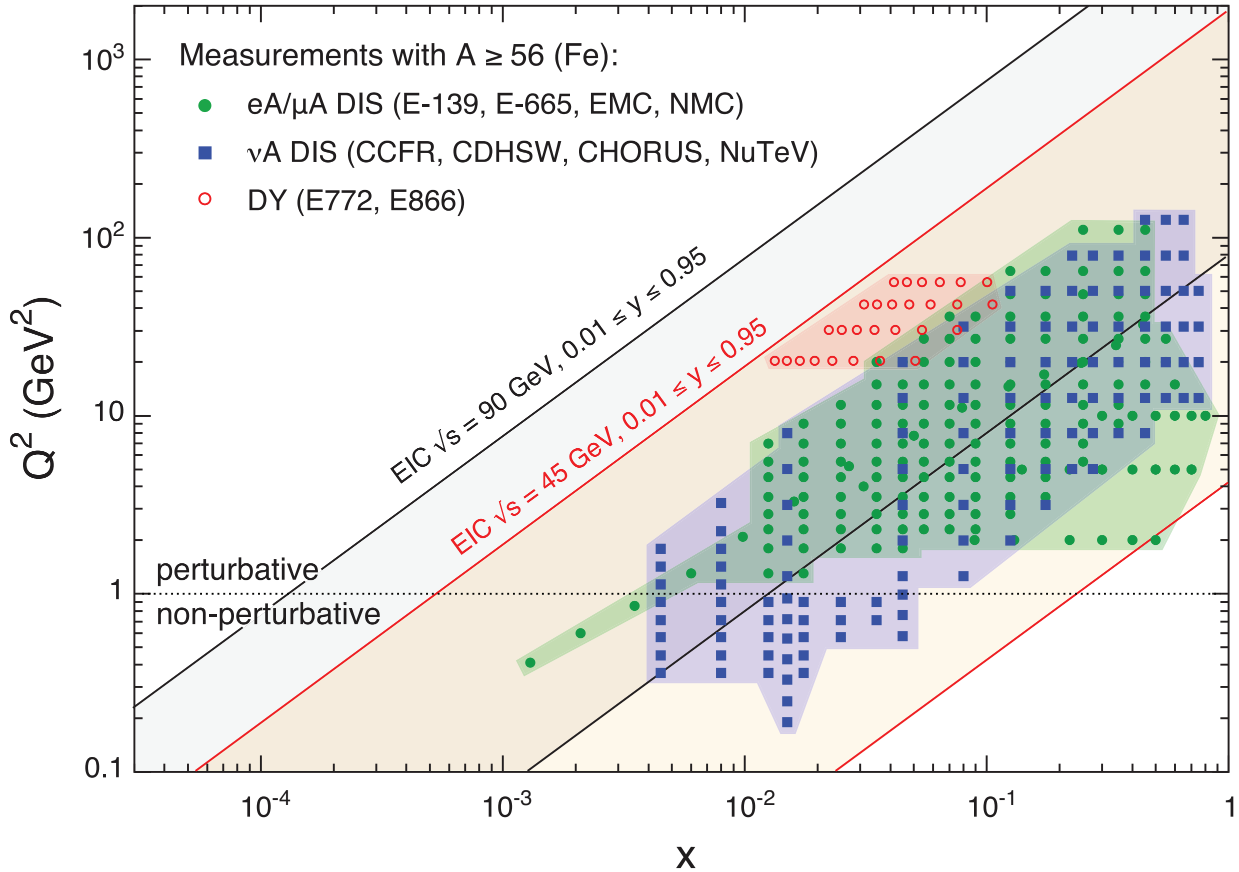


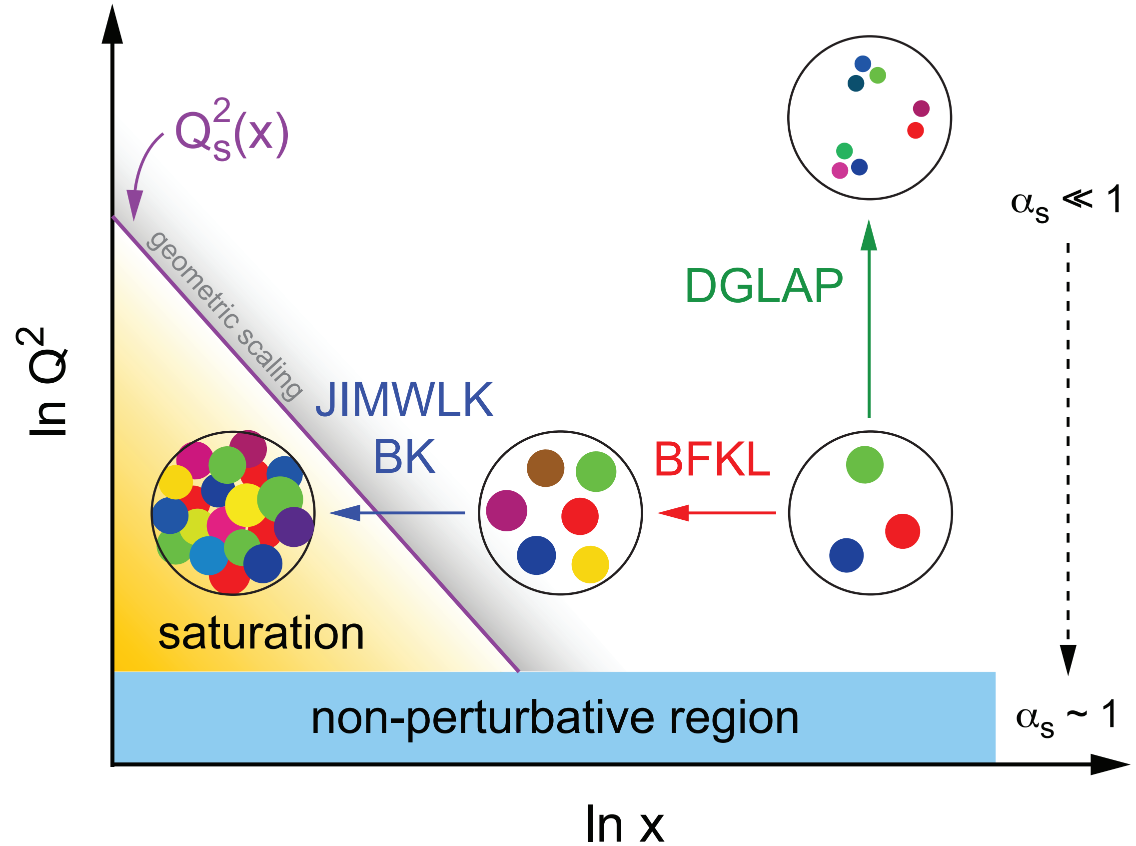


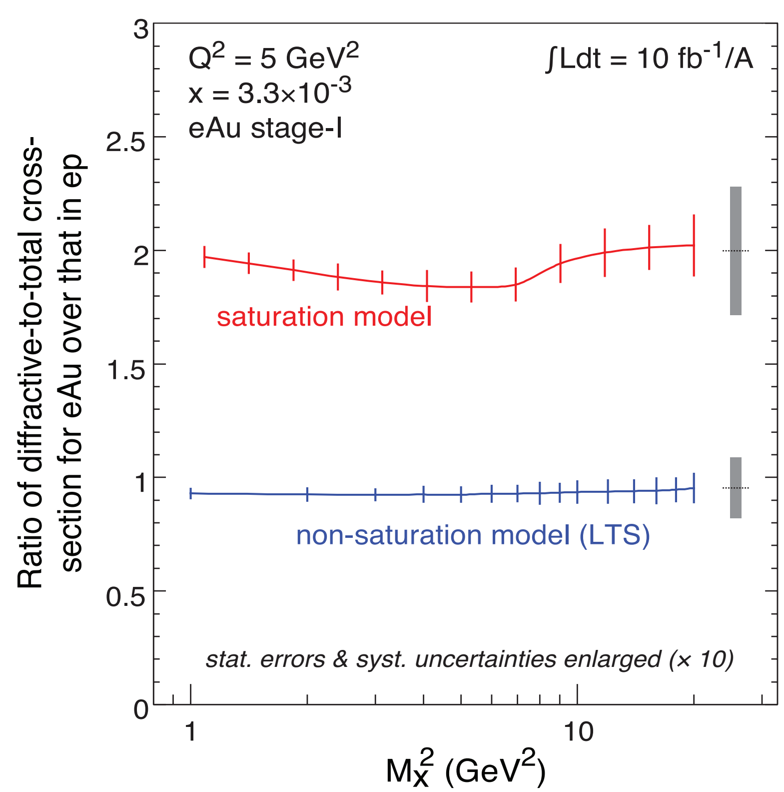


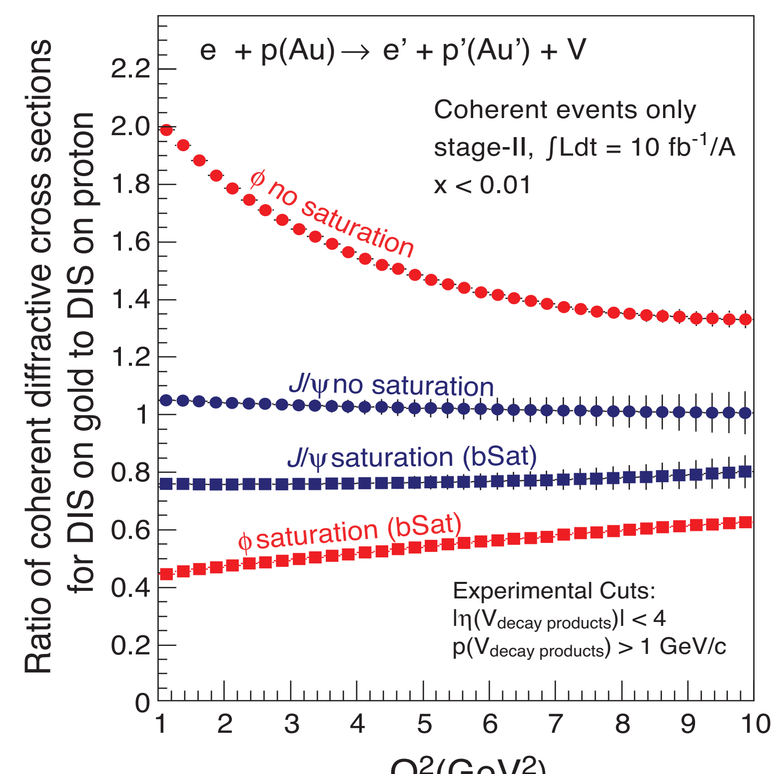
3-dimensional CLAS multiplicity ratios, fully corrected for radiative processes and acceptance, normalized to target thicknesses; C, Fe, Pb (3 of many such plots) also, K^0, π^0, π^-

Saturation physics

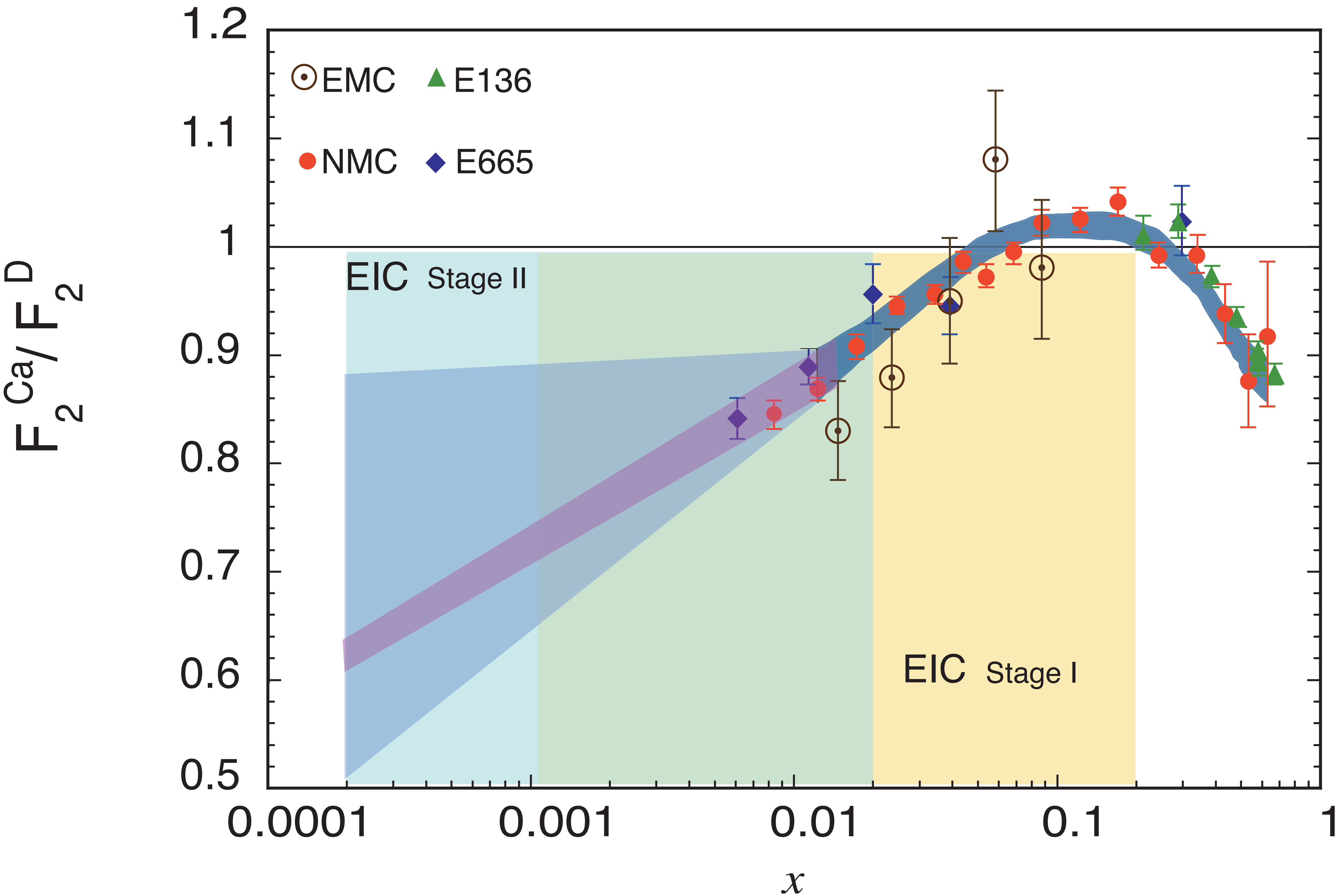








Nuclear PDFs to very low x



Transverse Momentum Dependent Distributions for Quarks

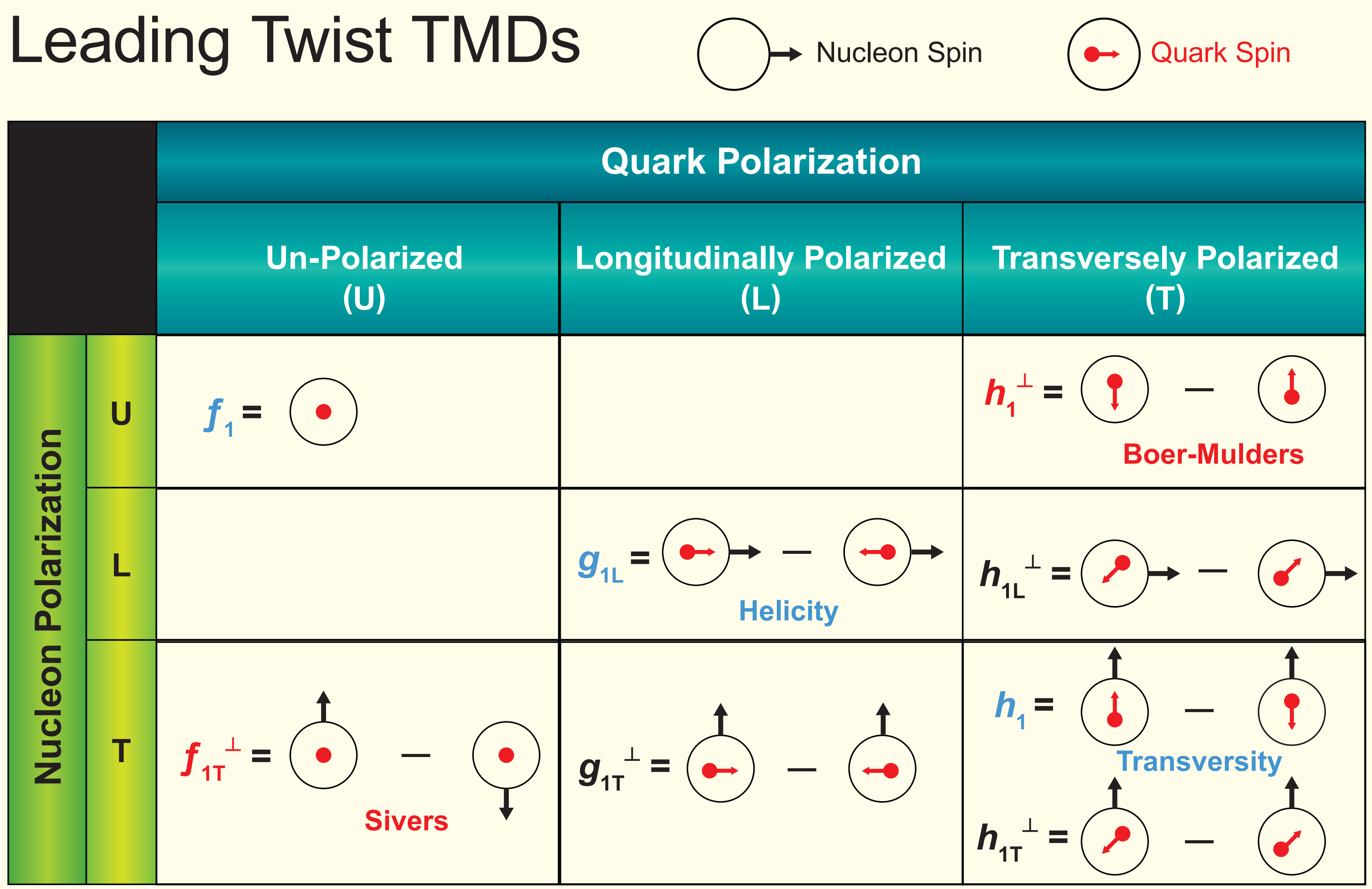


Figure 2.12: Leading twist TMDs classified according to the polarizations of the quark (f, g, h) and nucleon (U, L, T). The distributions $f_{1T}^{\perp,q}$ and $h_1^{\perp,q}$ are called naive-time-reversal-odd TMDs. For gluons a similar classification of TMDs exists.