Parton propagation and hadron formation in the space-time domain

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Santa Maria University
Valparaiso, Chile

OUTLINE

- Physical picture - reminder
- P_T broadening and space-time confinement parameters
- Hadron attenuation and hadron formation times
- Future prospects

PHYSICS FOCUS

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- *Quark propagation*
  - measure characteristic times for confinement
  - important for nuclear DIS (e^{+-}/ν), Drell-Yan, and RHI

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  - important for nuclear DIS (e^{+-}/ν), Drell-Yan, and RHI
- *Hadron formation*
  - hadron formation times
  - mechanisms of confinement restoration

PHYSICAL PICTURE

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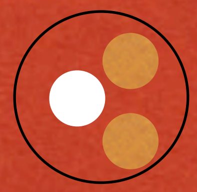

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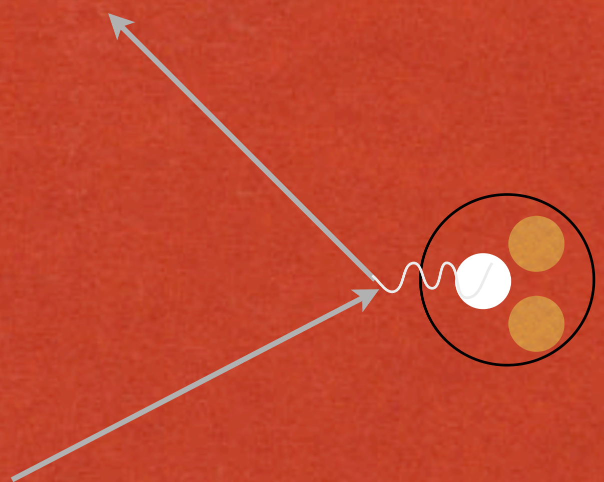

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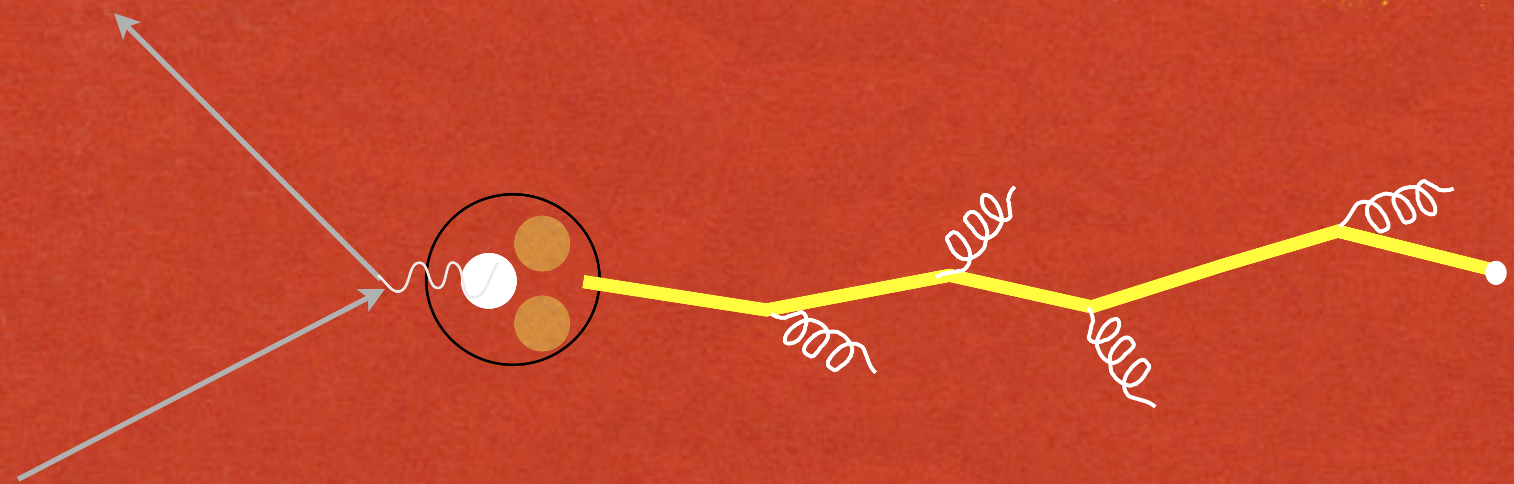

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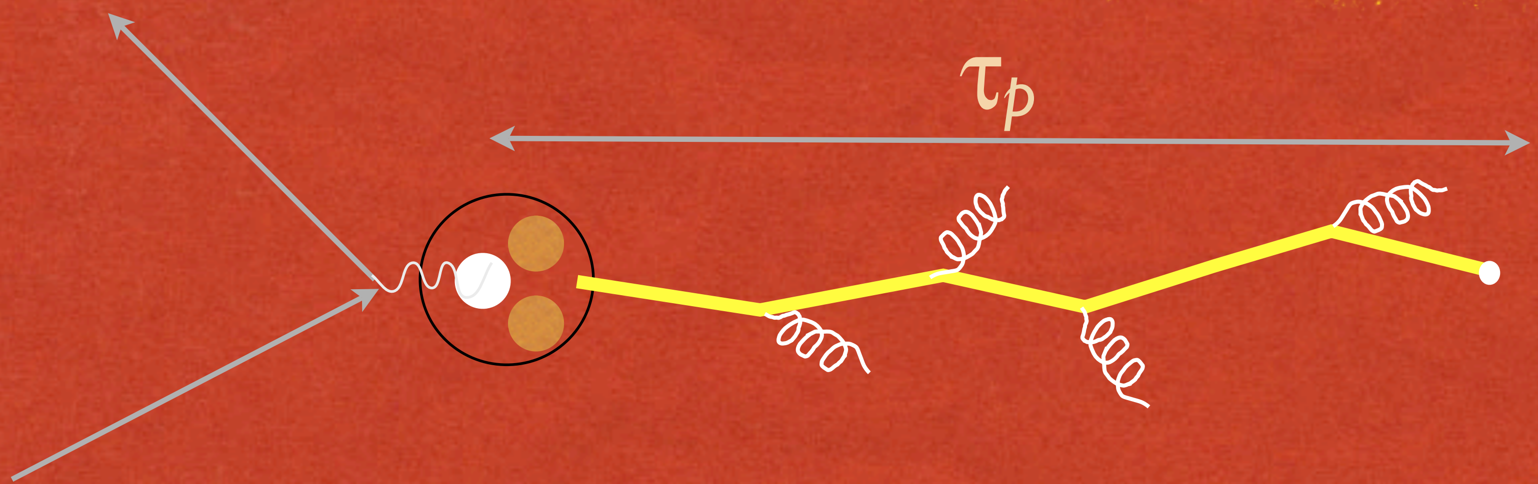

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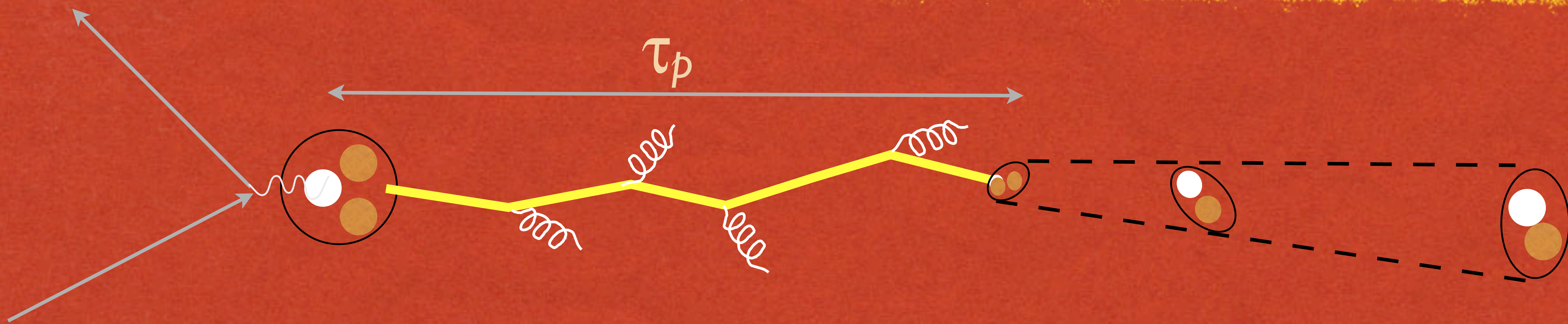

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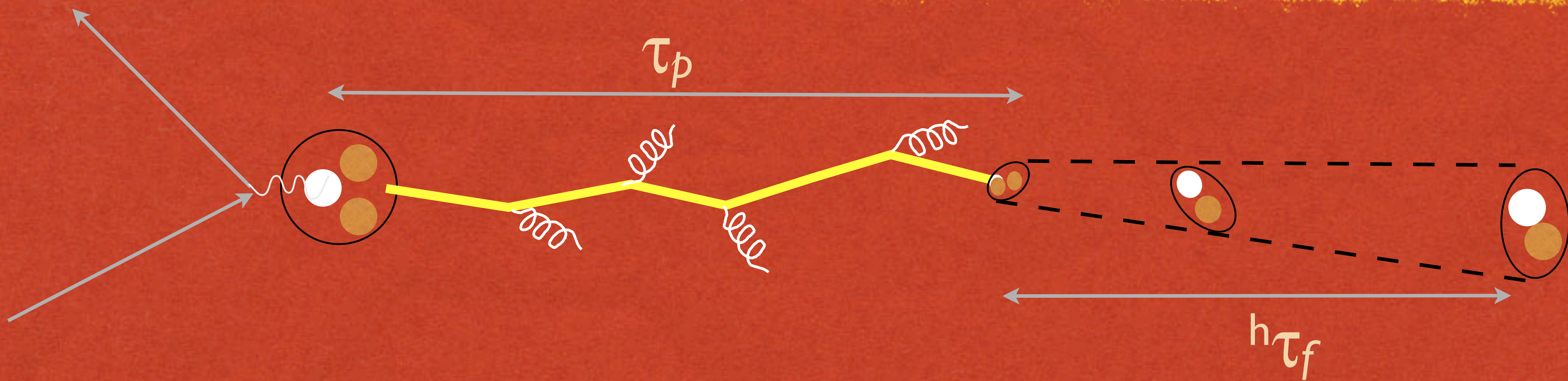

- ***production time*** τ_p is time required to form color singlet pre-hadron; 'lifetime of deconfined quark'; universal(?)
- ***formation time*** $^h\tau_f$ is time required to form full-sized hadron

BACK-OF-ENVELOPE - τ_p

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$$t_p = \frac{\nu}{\left.\frac{dE}{dx}\right|_{vacuum}}(1 - z_h)$$

Energy conservation, time dialation

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If take, e.g., **z** = E_{hadron}/ν = 0.6, ν = 5 GeV, then ***$t_p \sim 2$ fm/c***

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Given hadron of size R_h, can build color field of hadron in its rest frame in time no less than $t_0 \sim R_h/c$. In lab frame this is boosted:

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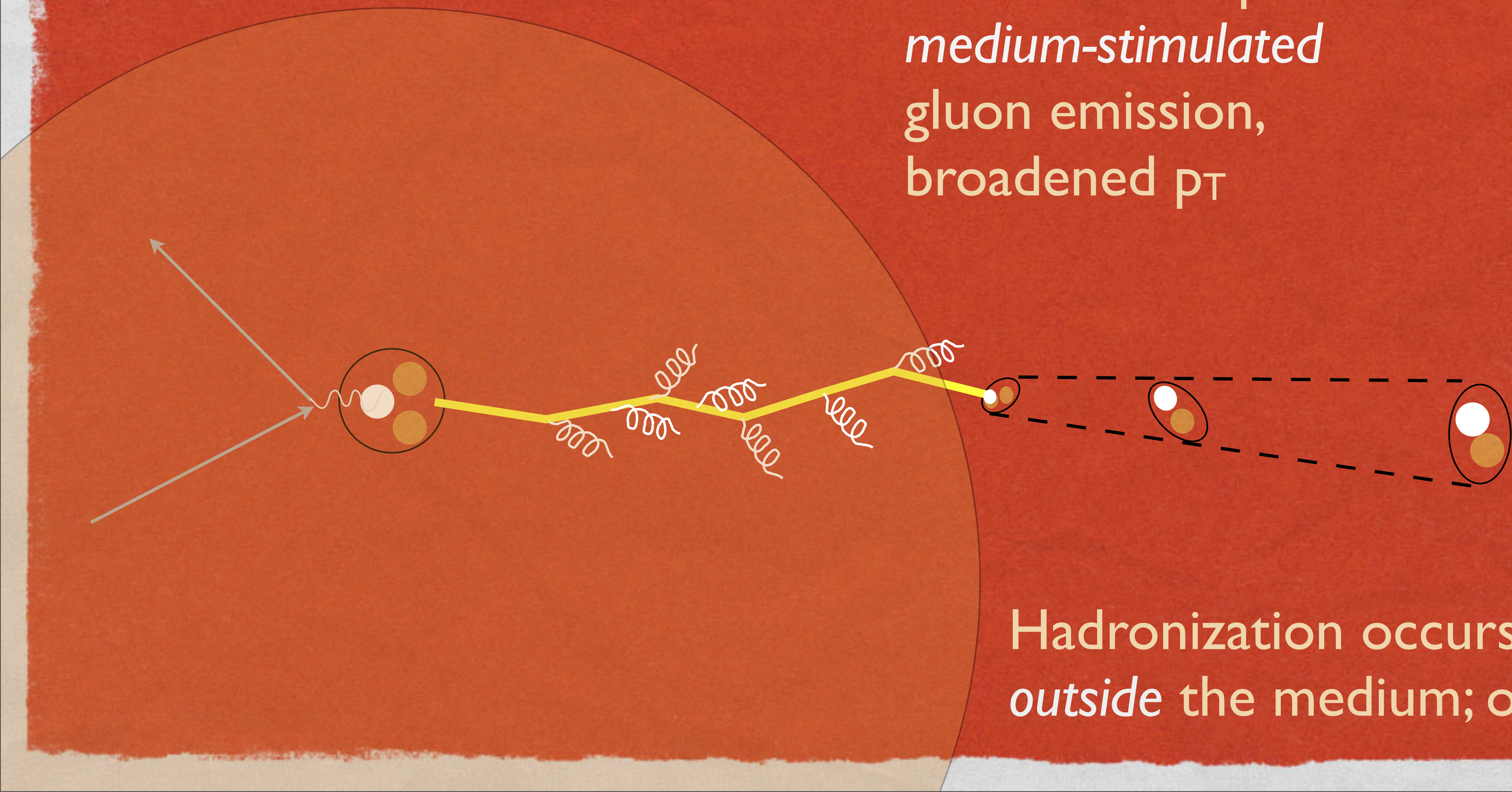
If take, e.g., the pion mass, radius 0.66 fm, E = 4 GeV, then ***$\tau_f \sim 20$ fm/c***.

MEDIUM - DIS

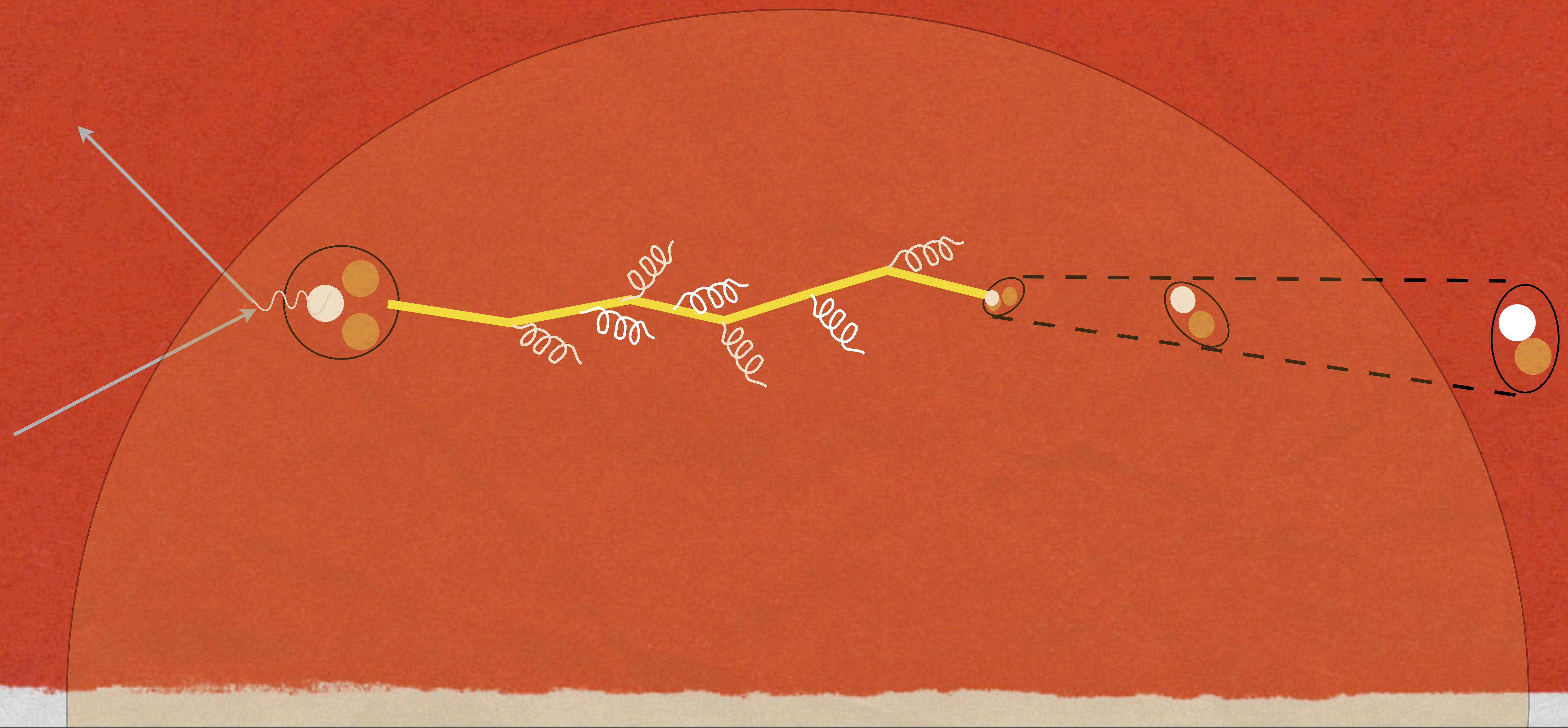
Partonic multiple scattering: *medium-stimulated* gluon emission, broadened p_T



Hadronization occurs *outside* the medium; or....

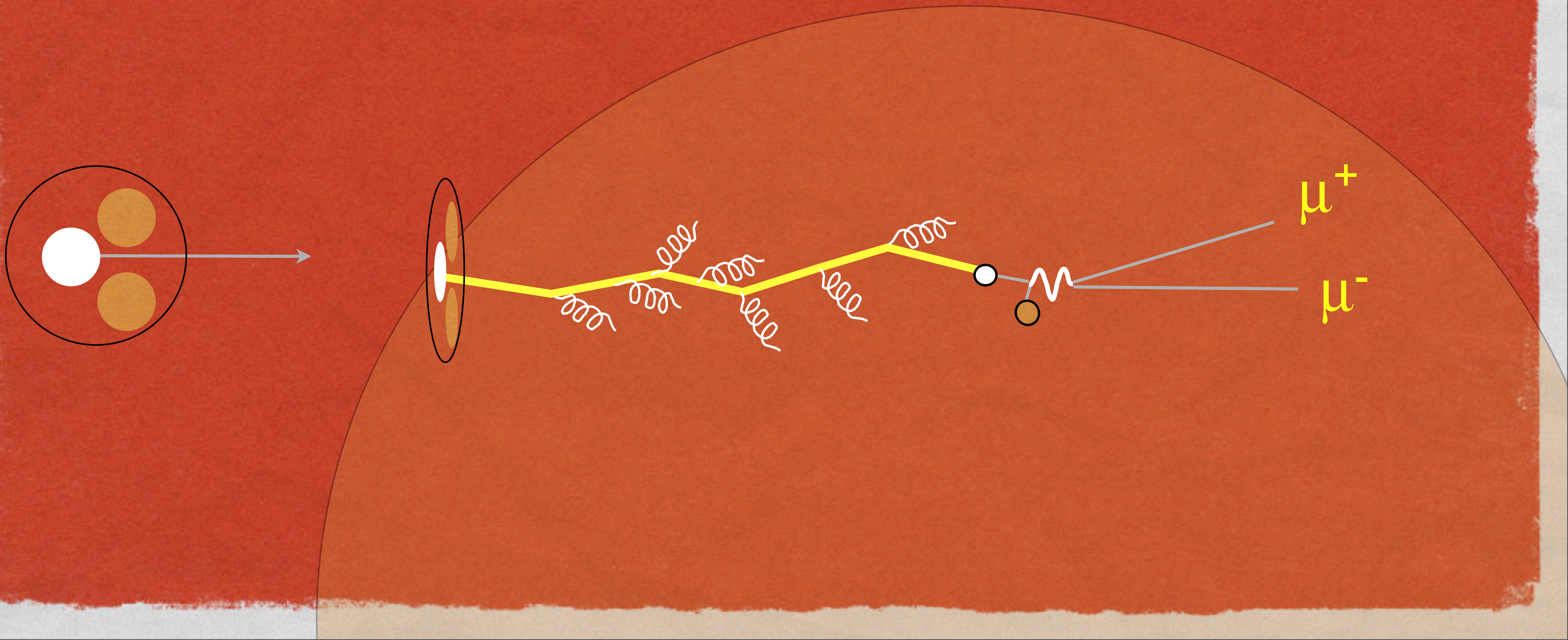
MEDIUM - DIS

Hadronization occurs *inside* the medium; then also have prehadron/hadron interaction

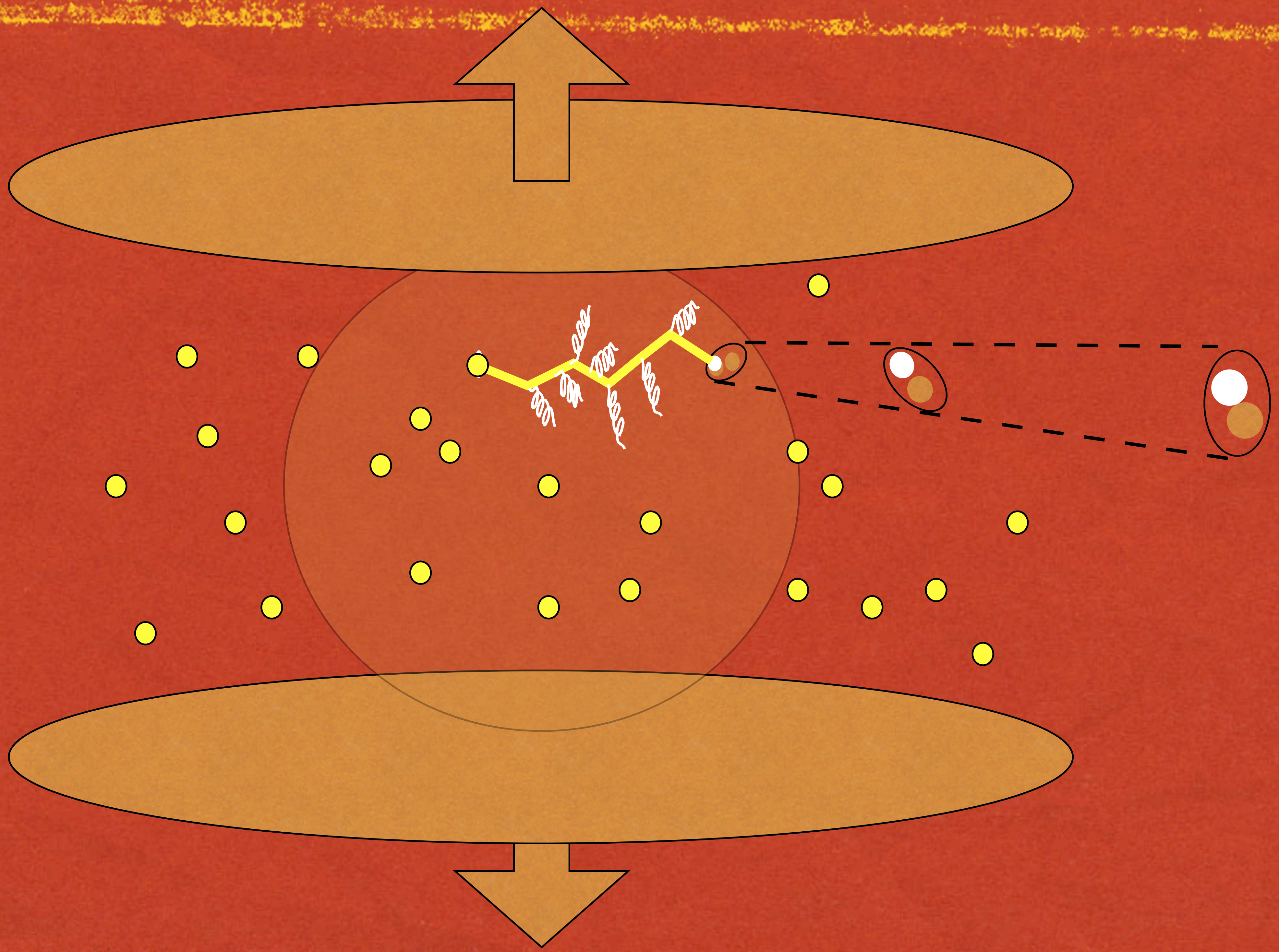


MEDIUM - DRELL-YAN

e.g., 800 GeV protons - no in-medium hadronization - have p_T broadening



MEDIUM - RHIC/LHC



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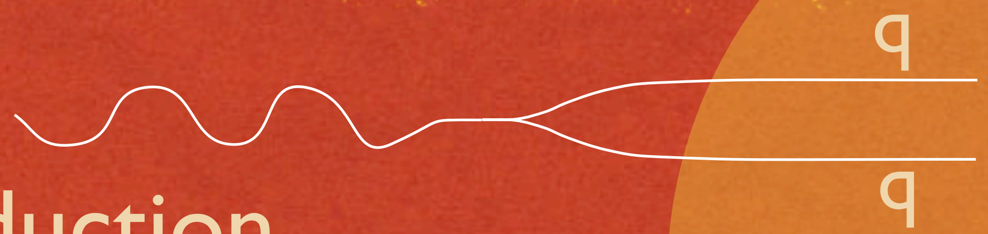
Hadrons interact strongly with nuclear medium
Measure ${}^h\tau_f$ via *hadron attenuation* in nuclei

EXPERIMENTS

- SLAC: 20 GeV e^--beam on Be, C, Cu Sn, PRL 40 (1978) 1624
- EMC: 100-200 GeV μ-beam on Cu, Z.Phys. C52 (1991) 1.
- WA21/59: 4-64 GeV ν-beam on Ne, Z.Phys. C70 (1996) 47.
- Drell-Yan: Fermilab E772, E866, 1990's (**J.C. Peng talk, Friday**)
- HERMES: 27.6 GeV e+(e-) on He, N, Ne, Kr, Xe; five pub's
- CLAS: 5 GeV e^--beam on C, Fe, Pb
- FNAL E906(future) Drell-Yan at 120 GeV
- JLAB12(future): 11 GeV e^- (CLAS12), 9 GeV γ (Hall D)

ASSUMPTIONS - DIS



- $x_{Bj}>0.1$ to avoid quark pair production
- $z_h>\sim0.4$-0.5, struck quark most likely in hadron
- factorization at nucleon level not manifestly broken (z=0.4-0.7)
- contamination (rho, baryon resonance decays) limited
- adequate Q^2, W, W' to define DIS conditions

OBSERVABLES

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$$R_M^h(z,\nu,p_T^2,Q^2,\phi) = \frac{\left\{\frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)}\right\}_A}{\left\{\frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)}\right\}_D}$$

Hadronic multiplicity ratio

OBSERVABLES

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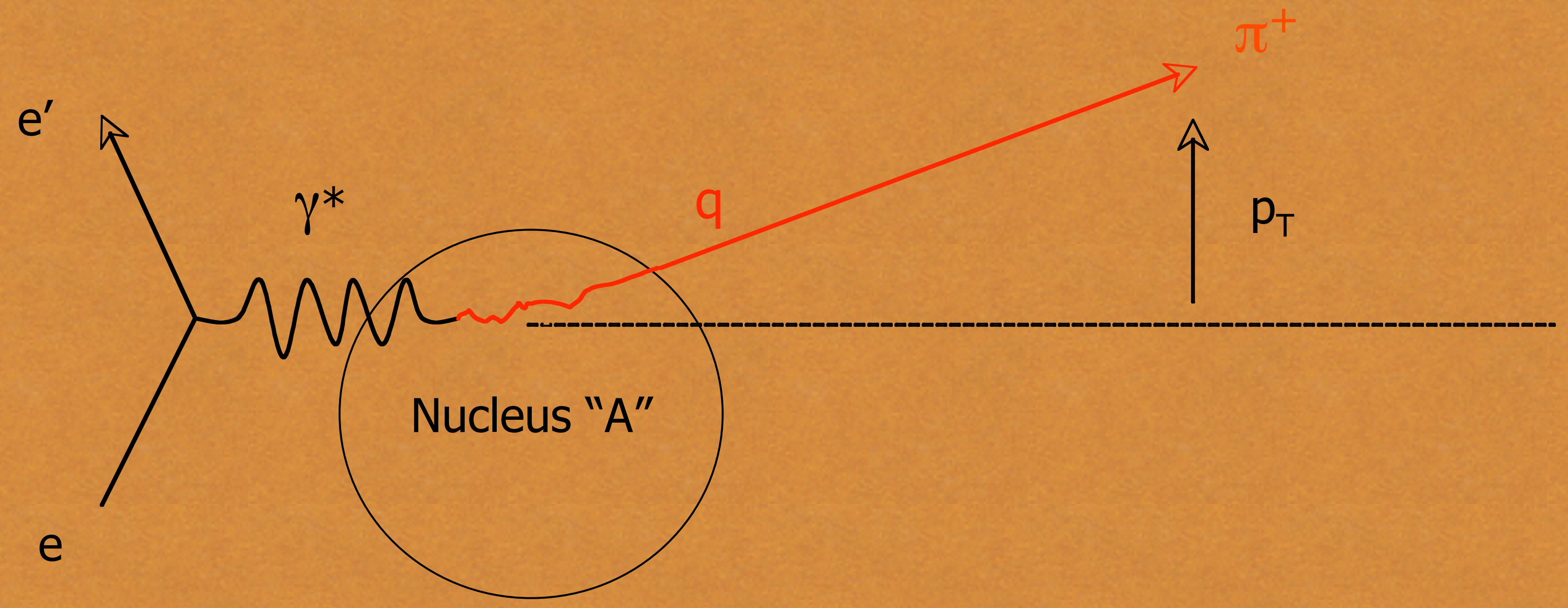
Hadronic multiplicity ratio

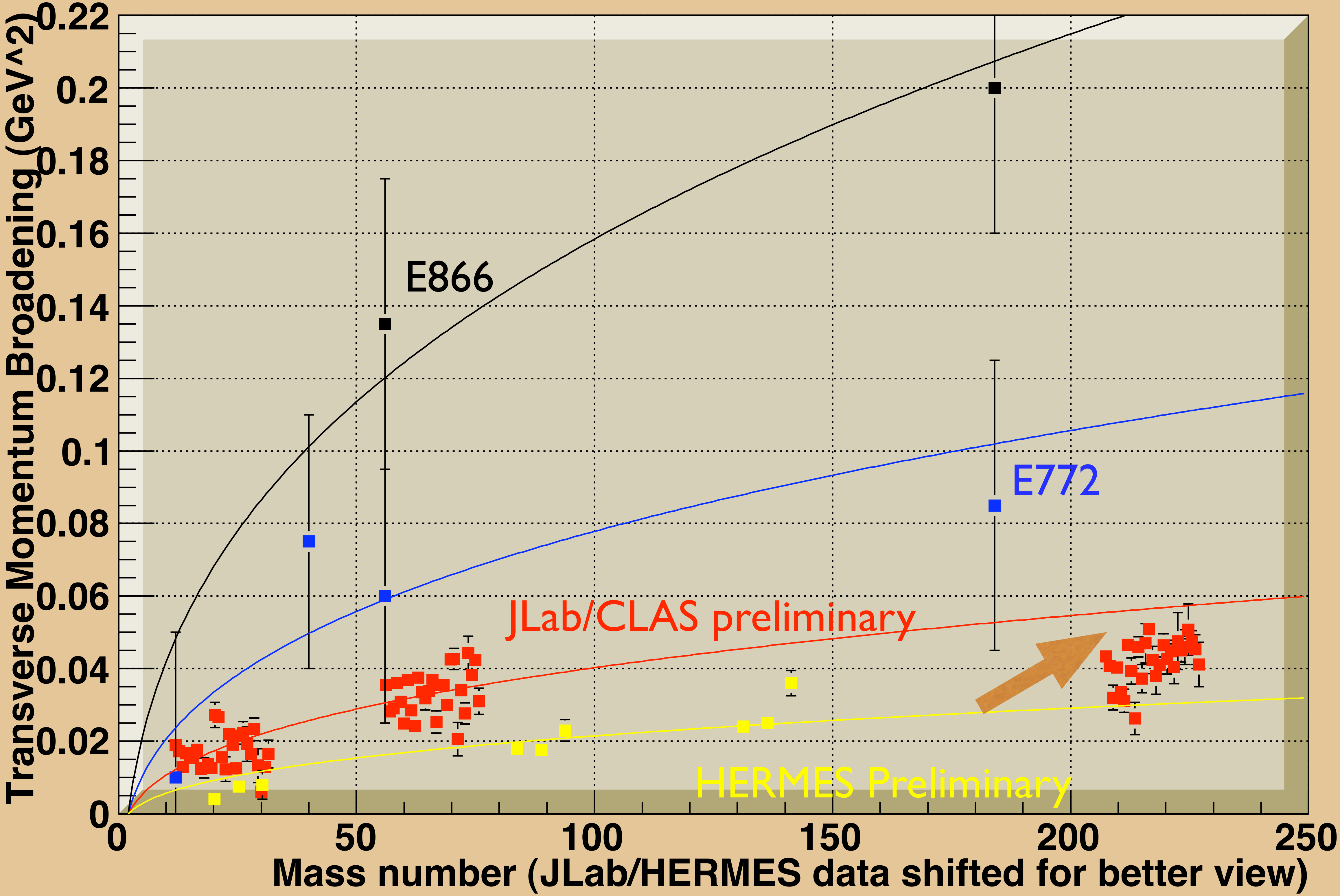
Transverse momentum broadening

p_T *broadening*: $\Delta p_T^2 \equiv \left\langle p_T^2 \right\rangle_A^{DIS} - \left\langle p_T^2 \right\rangle_D^{DIS}$



Comparison of pT broadening data - Drell-Yan and DIS

$$\Delta\langle p_T^2\rangle = D\left[(A/2)^{1/3} - 1\right]$$



PRODUCTION TIME EXTRACTION

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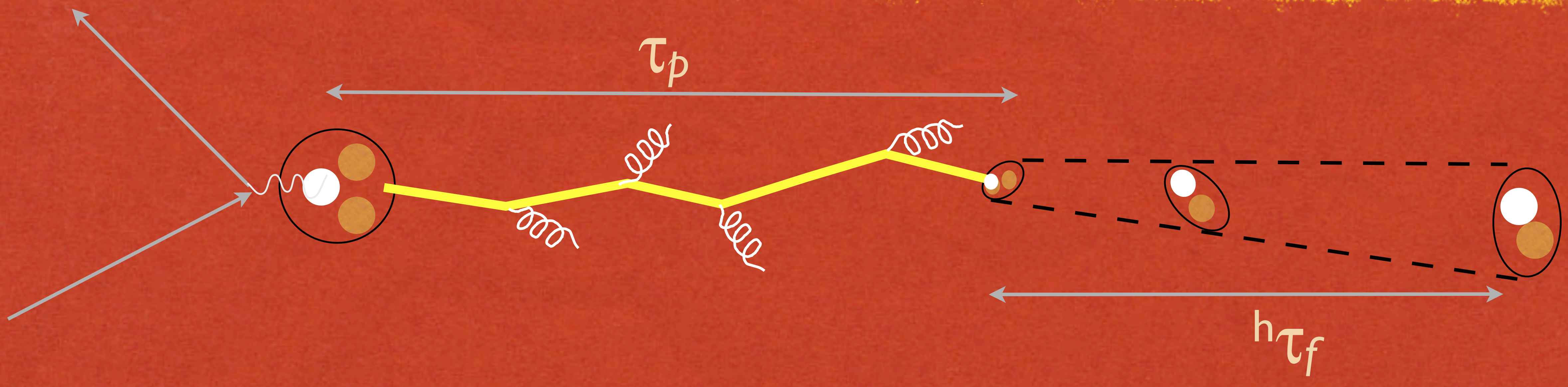

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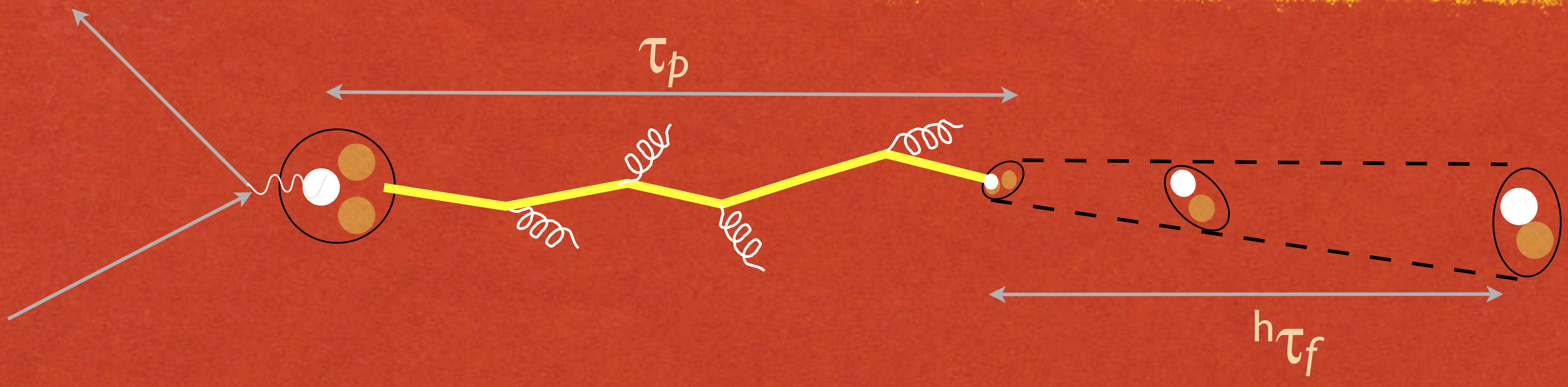
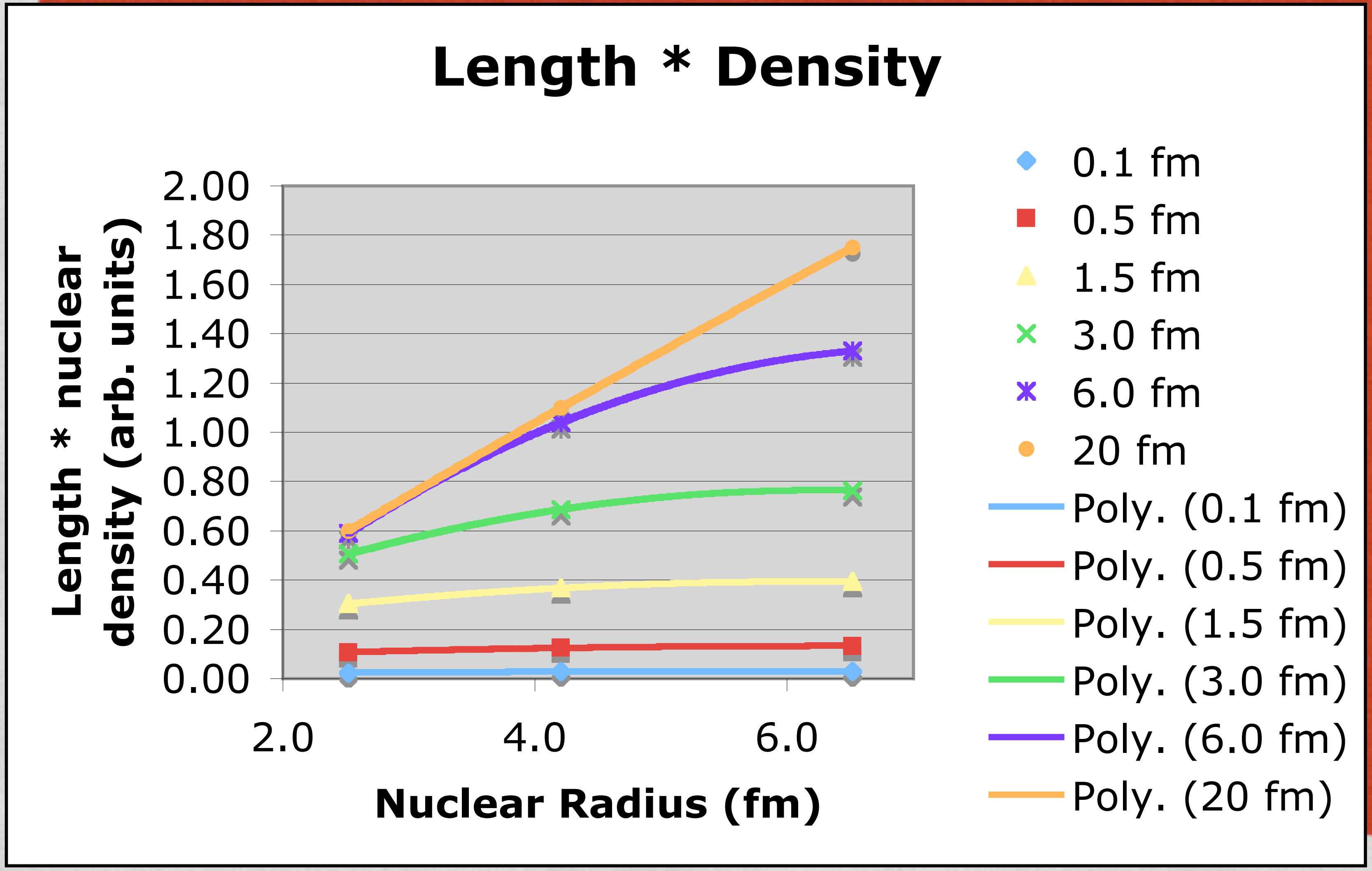


Postulate:

- pT broadening (δp^2_T) only accumulates during production time phase
- ***Shape and magnitude of δp^2_T vs. A is a direct signature of production time - enables extraction of τ_p***

PRODUCTION TIME EXTRACTION: GEOMETRICAL EFFECTS



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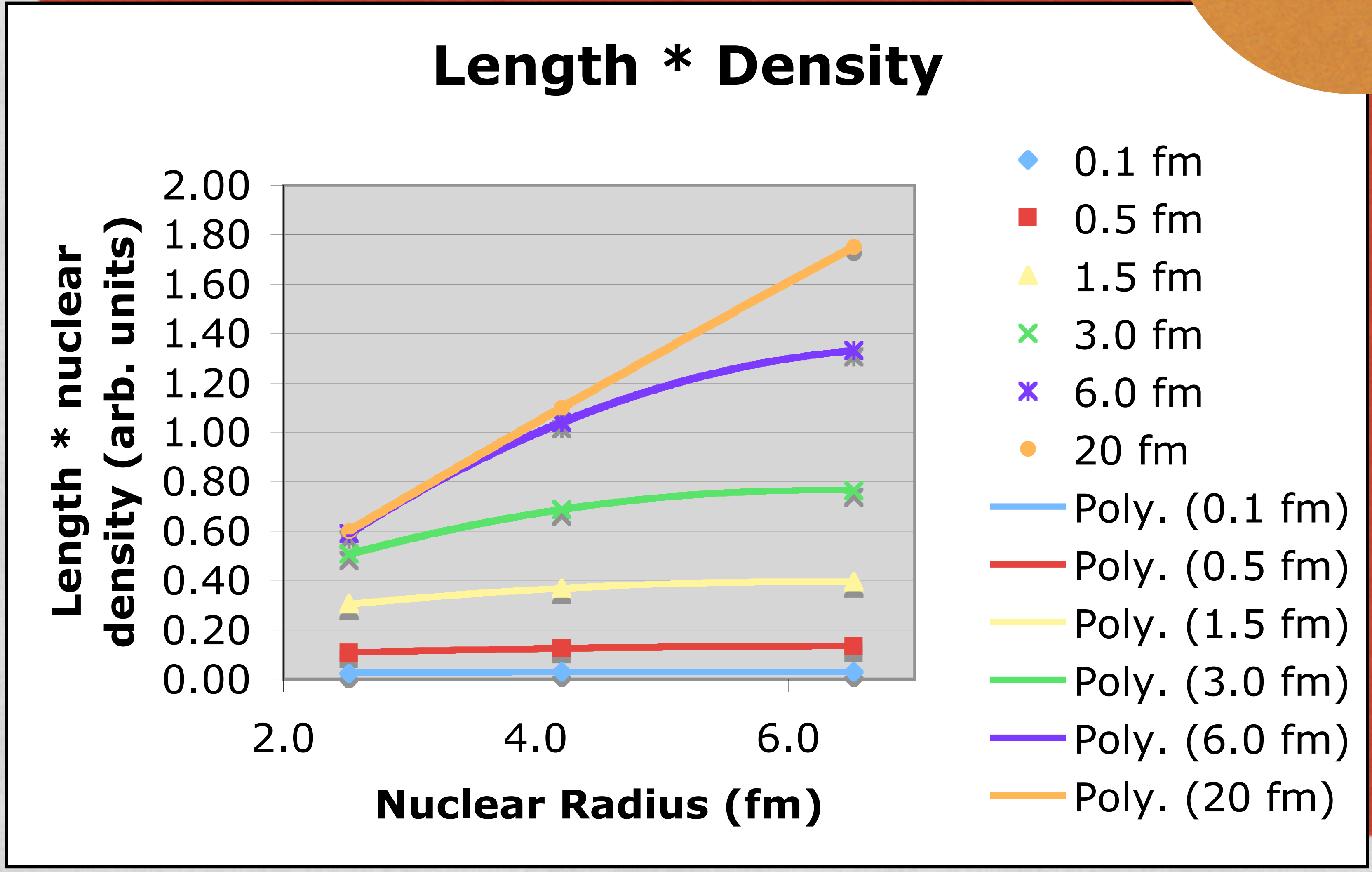

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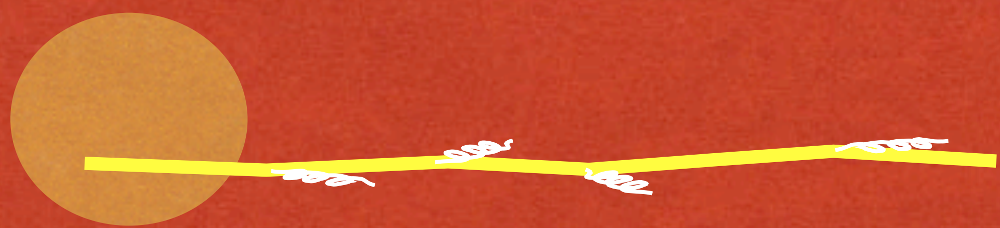

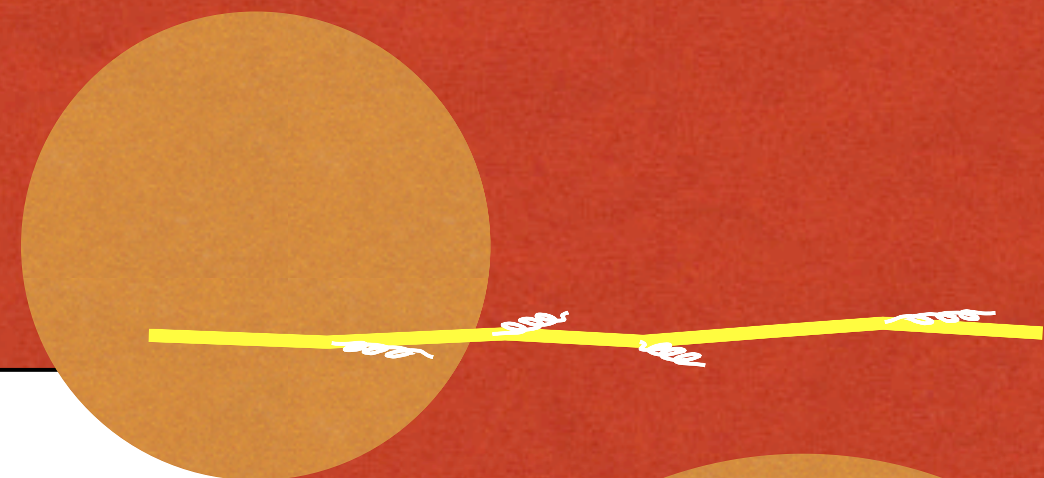

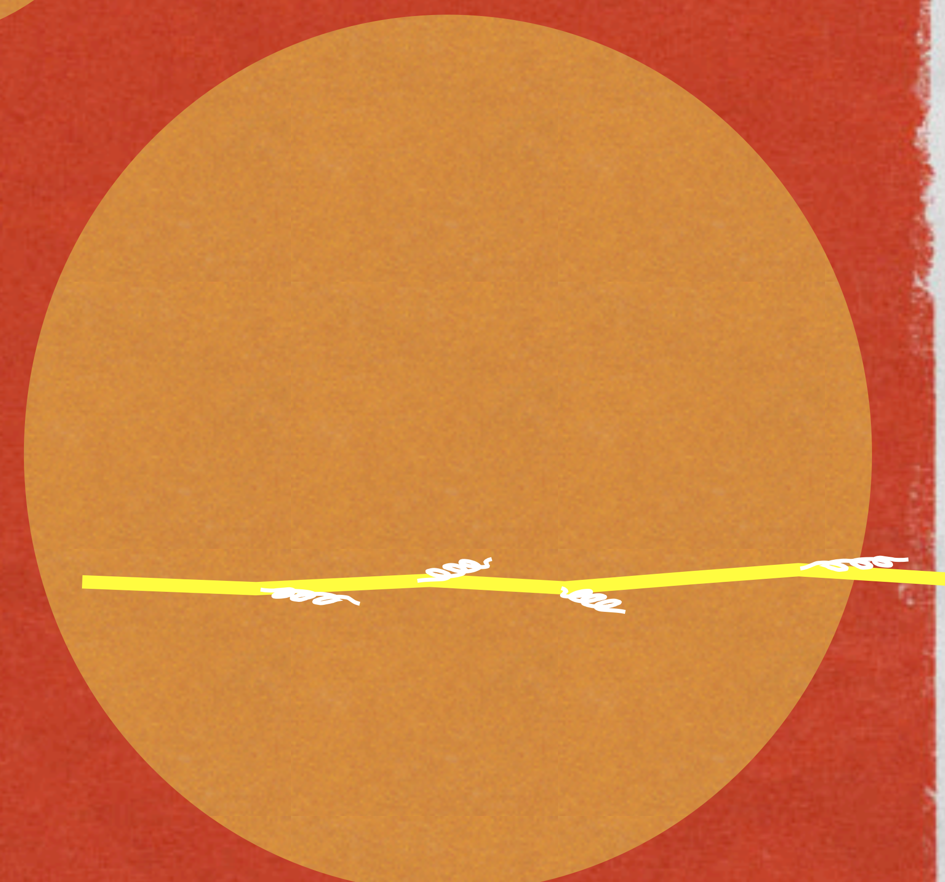

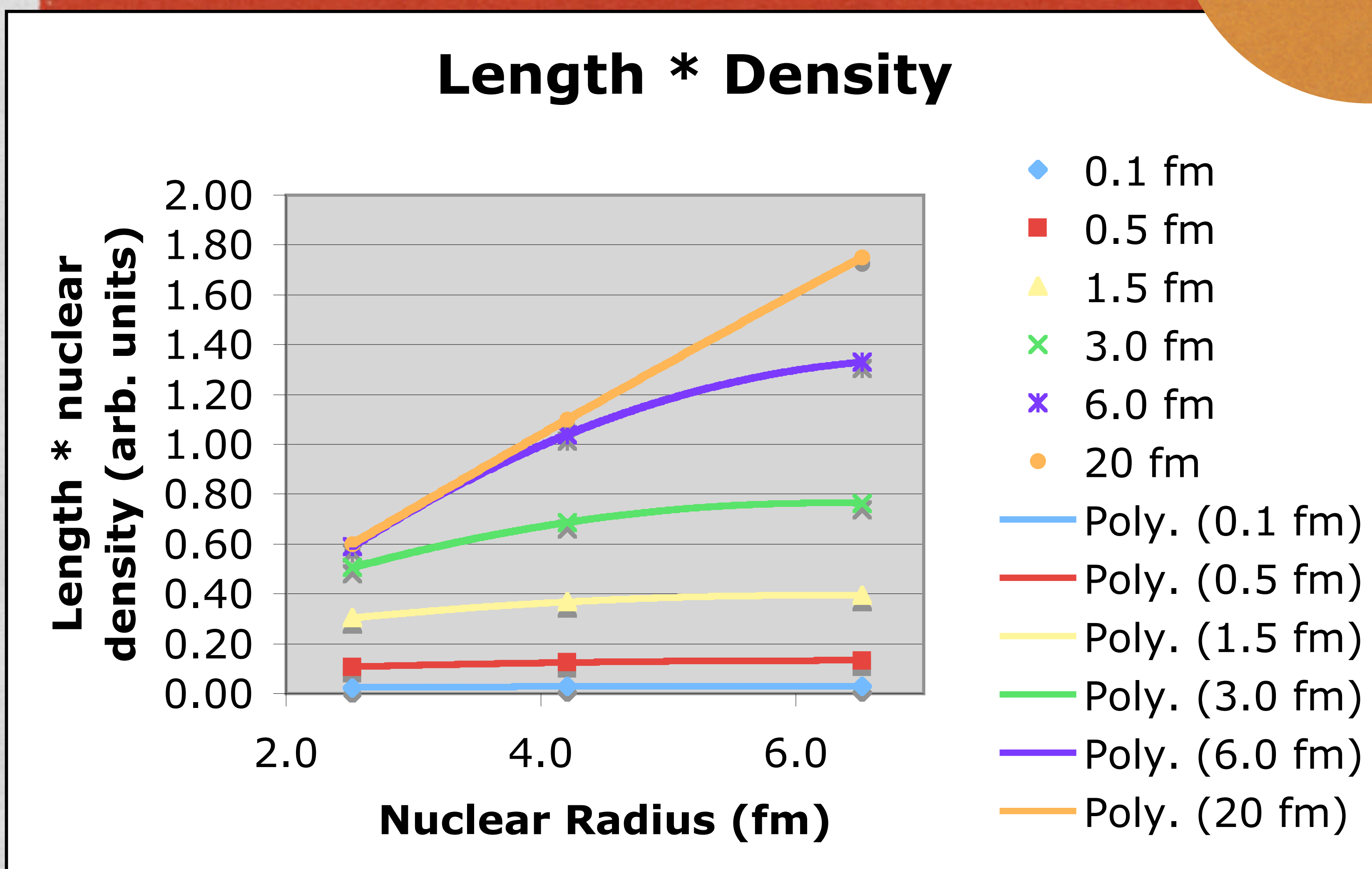

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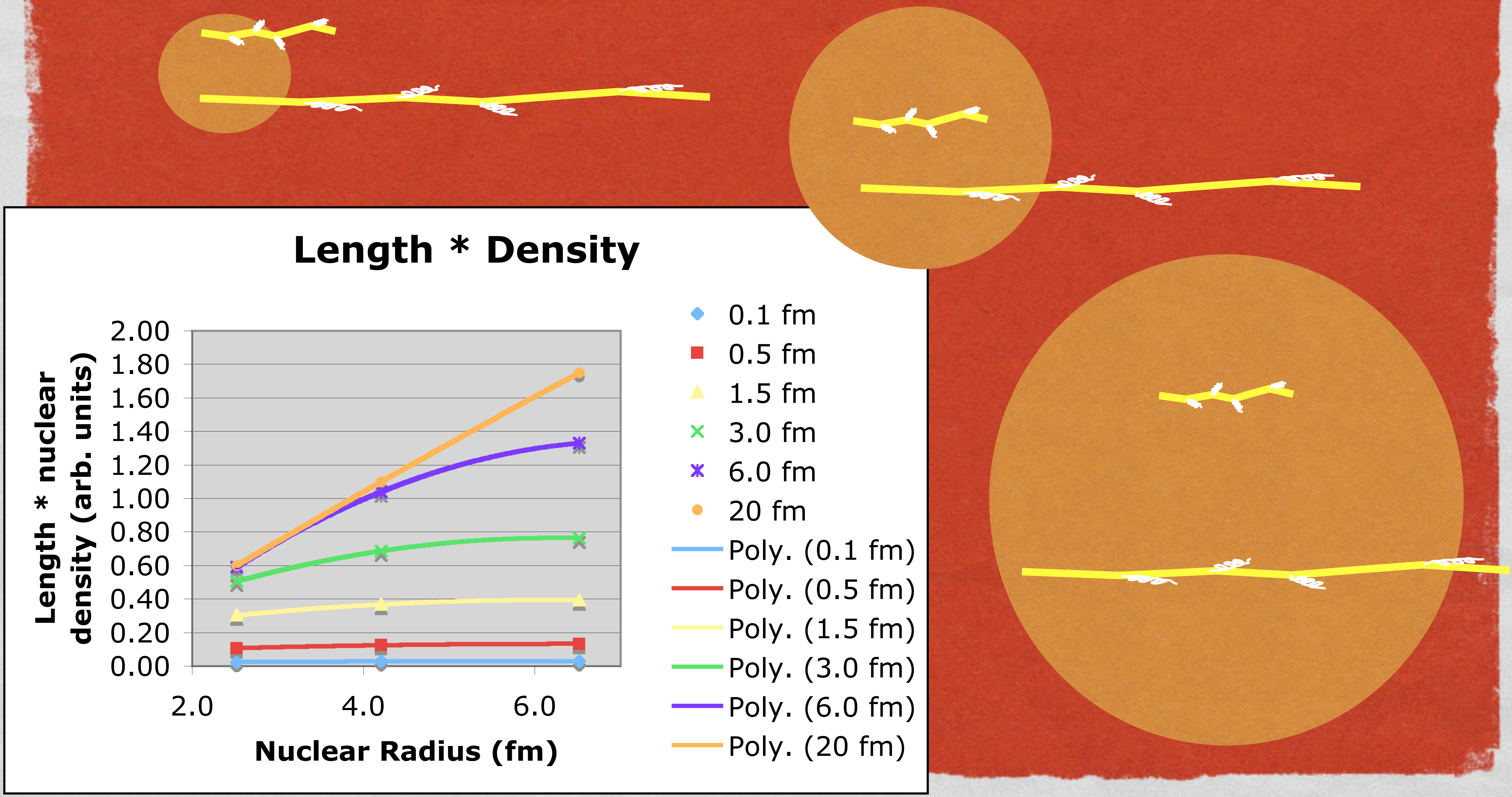


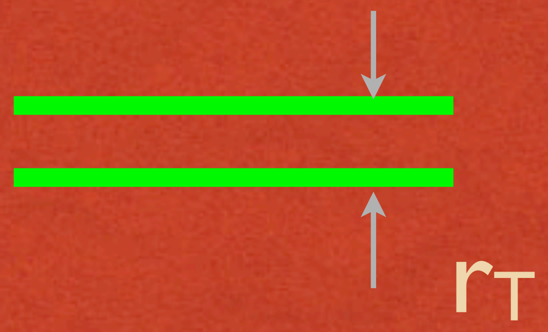
P_T BROADENING - THEORETICAL DESCRIPTIONS

- Color dipole formalism: Kopeliovich
- pQCD: Qiu, Guo, BDMPS, Wang, Majumder
- Jet quenching in hot matter: HT, GRV, AMY, ASW, and alternatives. See:

A. Majumder, arXiv:nucl-th/0702066v1

B.Z.Kopeliovich, I.K.Potashnikova, I. Schmidt, arXiv:0707.4302v1 [nucl-th]

COLOR DIPOLE FORMALISM



- Total cross section, color dipole with nucleon:

$$\sigma_{\bar{q}q}(r_T,s)=C(r,s)r_T^2$$

- At small r_T, C is related to the *proton gluon density*:

$$C(r_T,s)=\frac{\pi^2}{3}G(x,Q^2)$$

- p_T broadening can be expressed in terms of $C(r_T,s)$:

$$\Delta\left\langle k_T^2\right\rangle = 2C\rho_A L = \hat{q}L = \frac{2\pi^2}{3}G(x,Q^2)\rho_A L$$

M. B. Johnson, B. Z. Kopeliovich, and A.V. Tarasov, Phys. Rev. C **63**, 035203 (2001)

$$\Delta \left\langle k_T^2 \right\rangle = 2C\rho_A L = \hat{q}L$$

COLOR DIPOLE FORMALISM

- Energy dependence of $C(r_T=0,s)$ is expected to be small:

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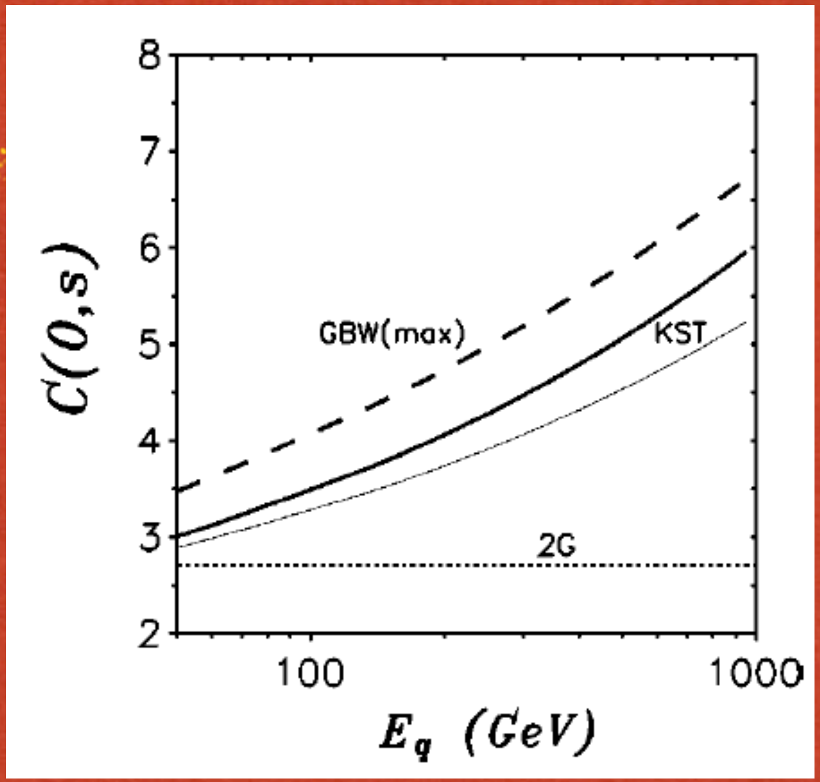

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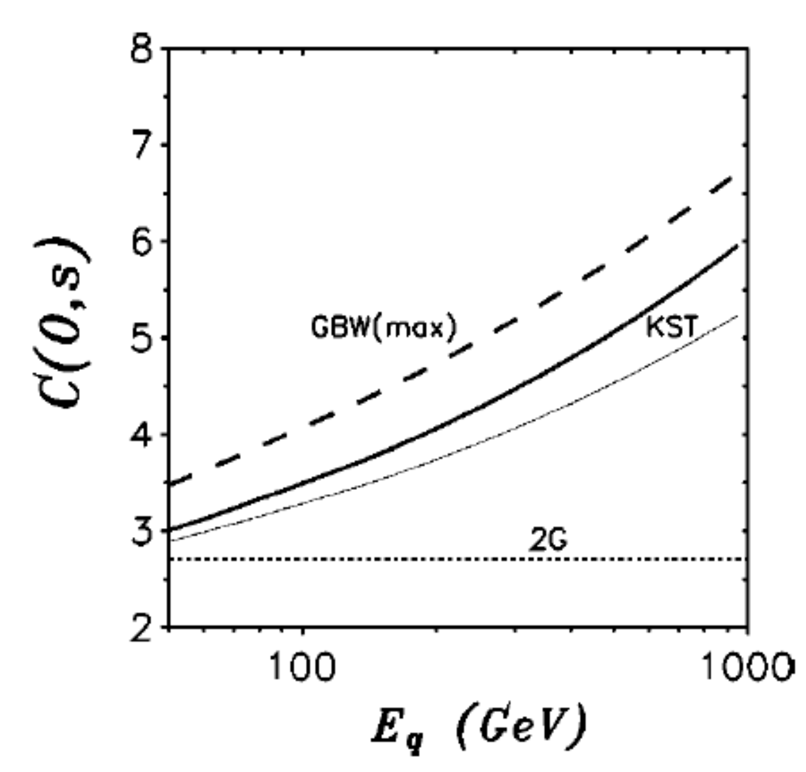
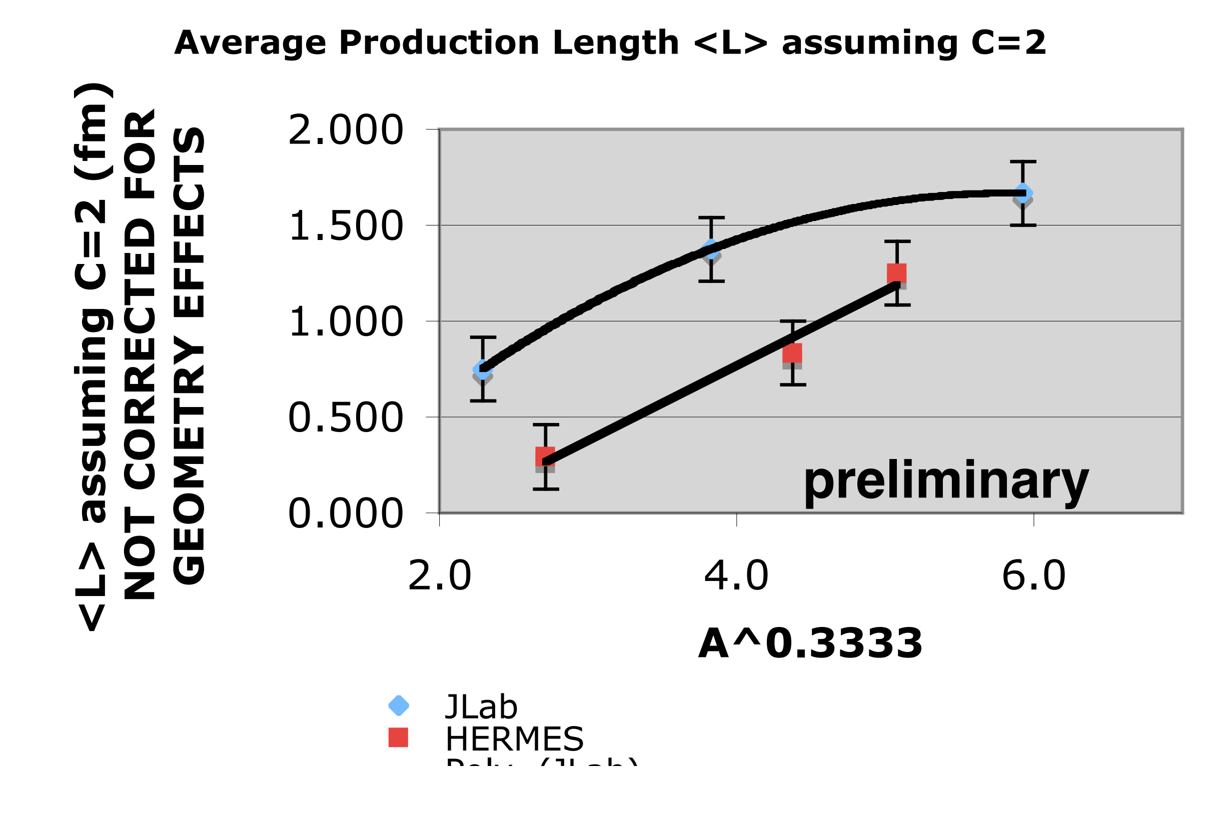


- Can extract production length estimate if assume value of C(0,s):



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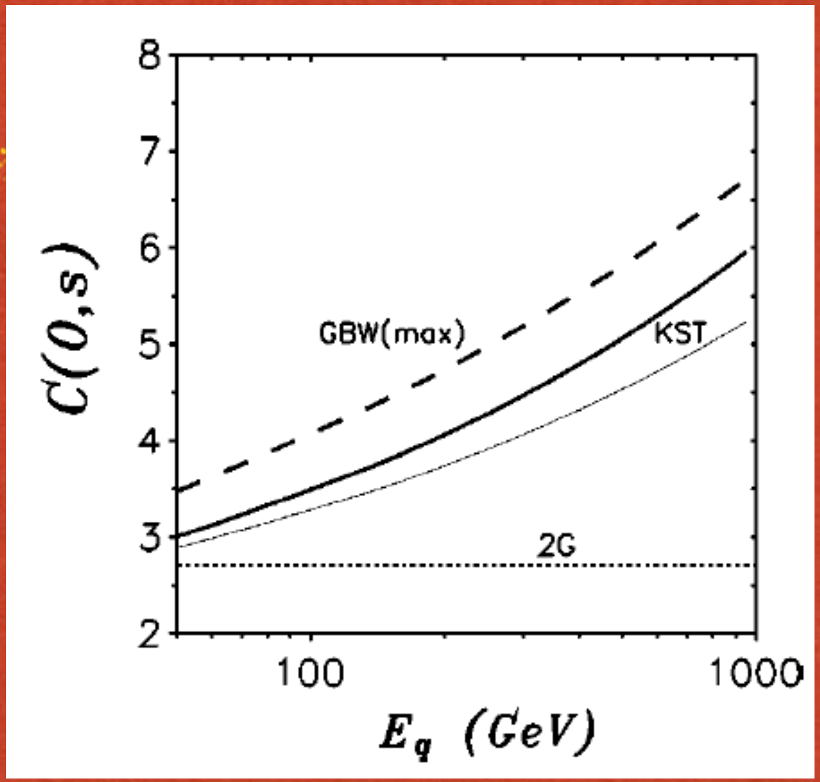

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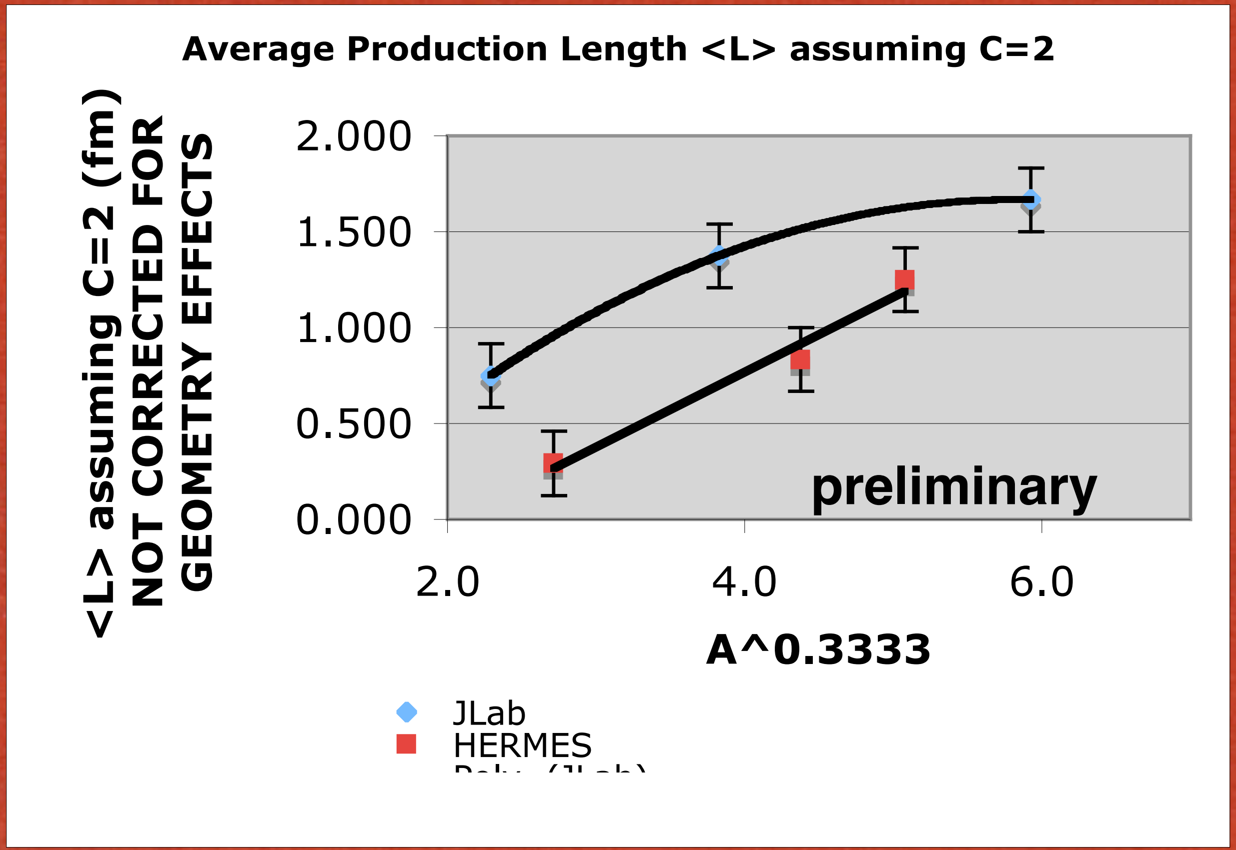
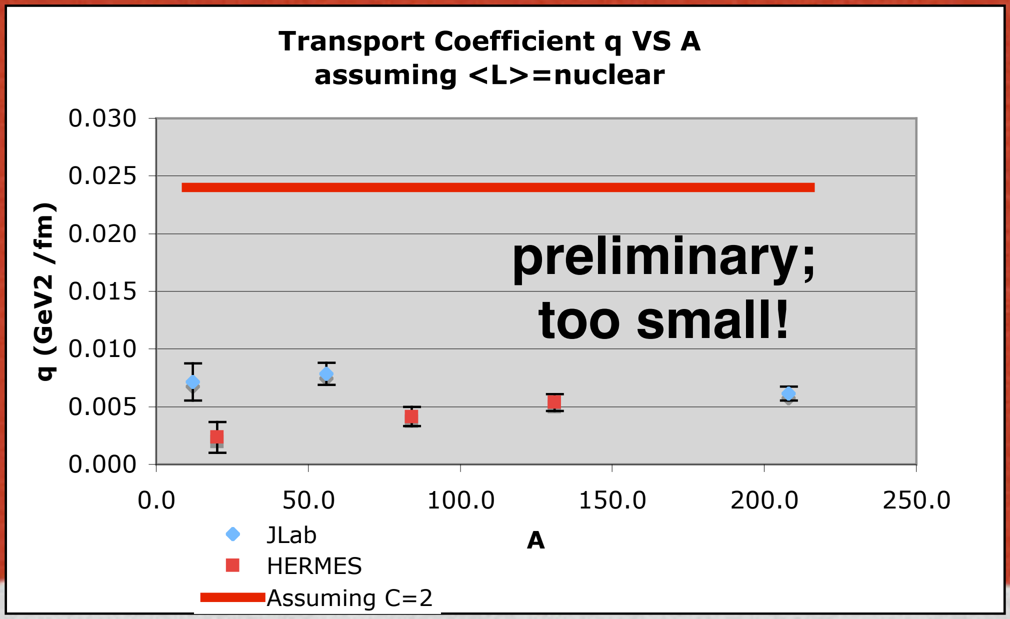


- *Or*, can *assume* production length is >> $R_{nucleus}$, get transport coefficient



QIU AND GUO, PQCD 2000

XIAOFENG GUO AND JIANWEI QIU

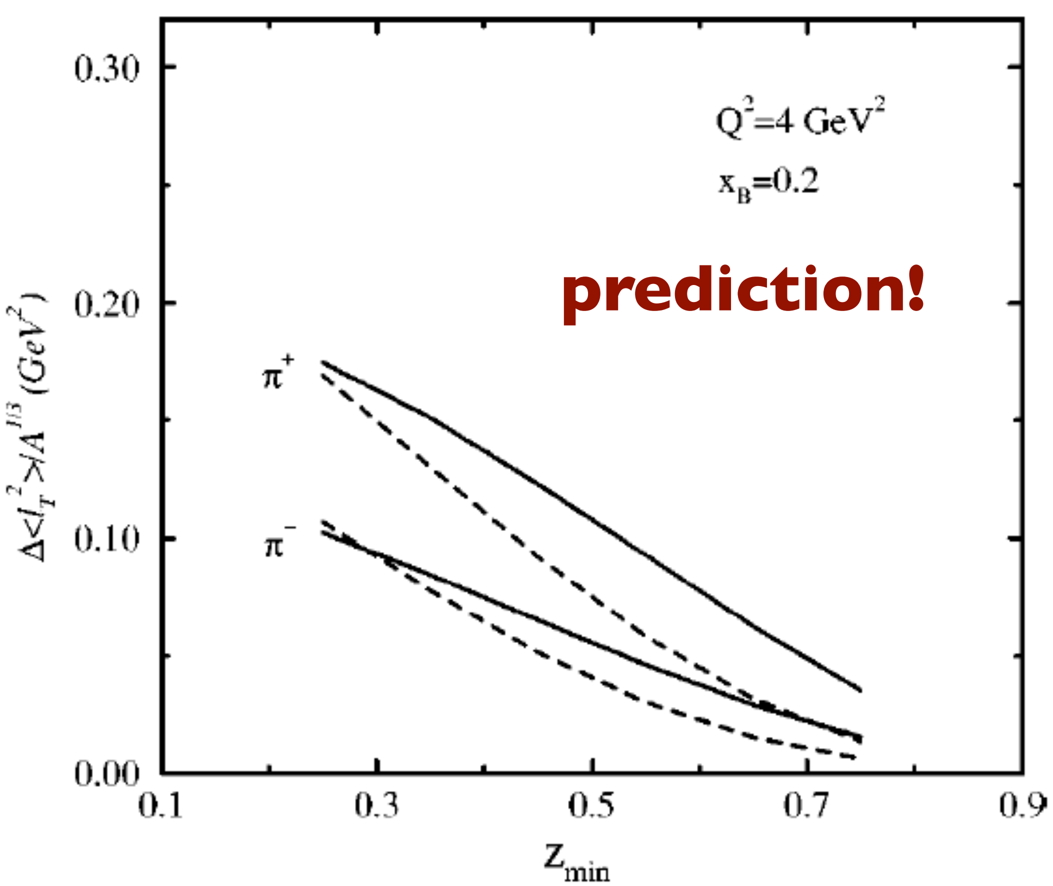
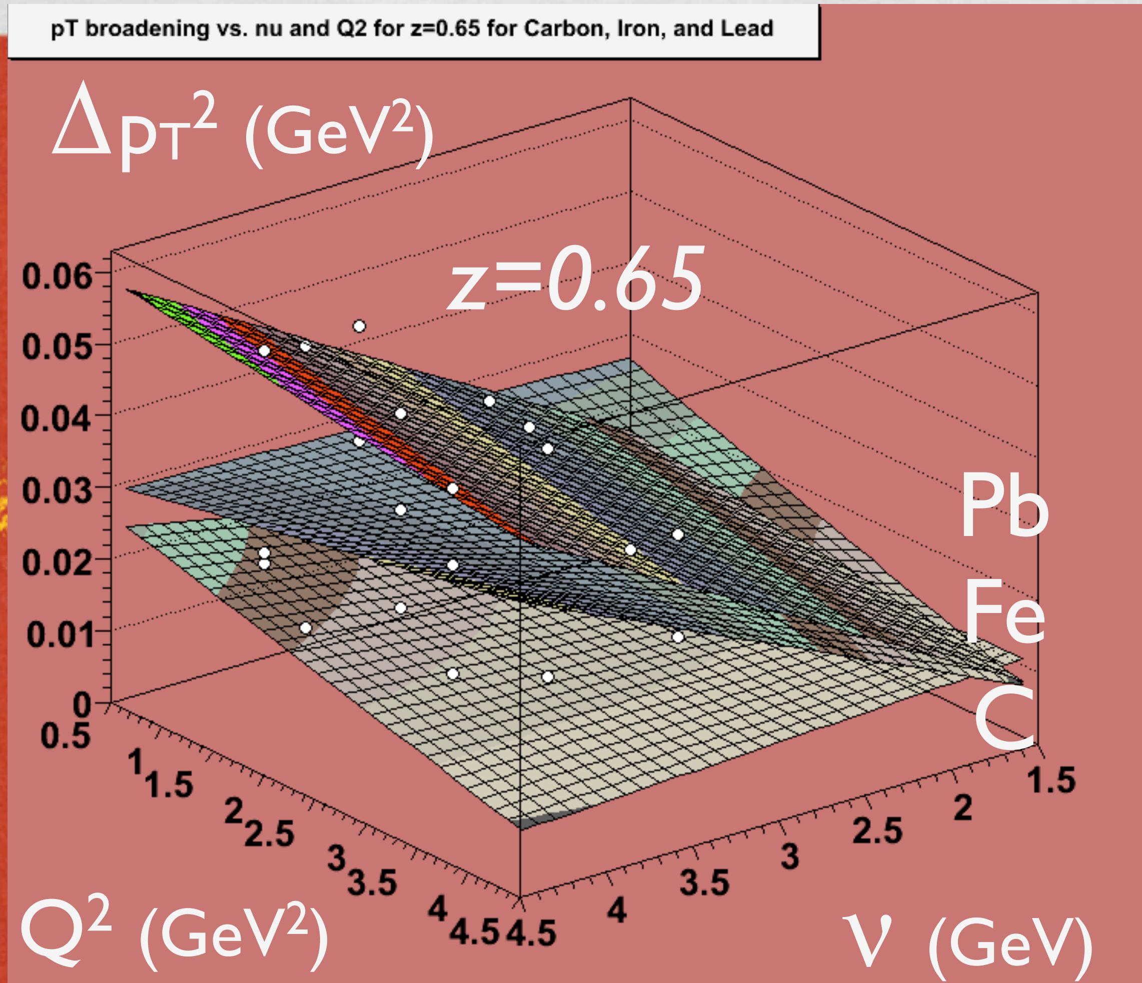


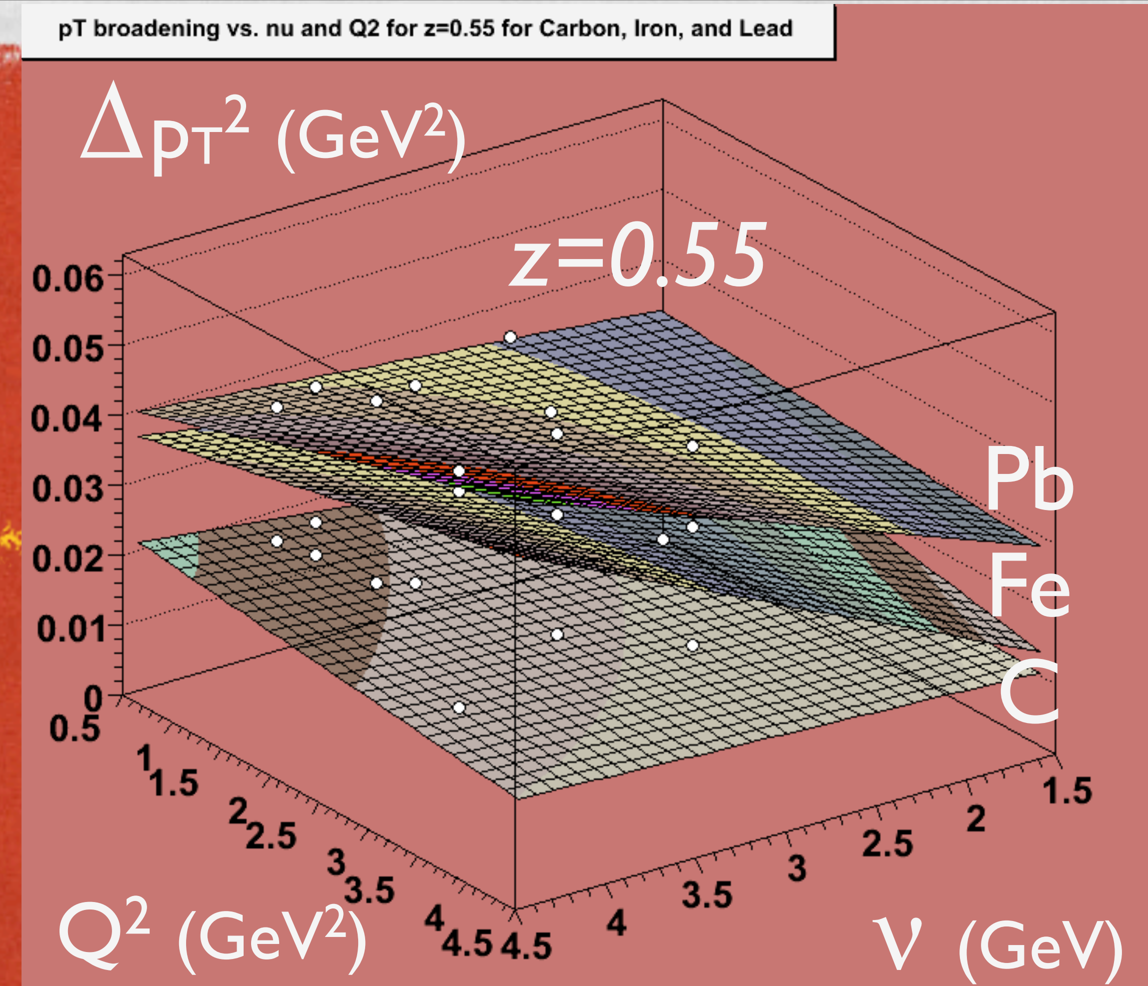
FIG. 8. Transverse momentum broadening of pions, $\Delta\langle l_T^2\rangle_{1/3}^{\pi^\pm}/A^{1/3}$, at $Q^2=4$ GeV^2 and $x_B=0.2$ with different $D_{q\to\pi}(z)$. The solid lines are obtained by using the fragmentation functions of Ref. [26], and the dashed lines are obtained by using the fragmentation functions of Ref. [27].

- pQCD with a model for quark-gluon correlation function assuming λ^2=0.05 GeV^2
- Predicts slow decrease with increasing z, Q^2, ν
- Assumes infinite production time

$$T^A_{qF}(x,Q^2)=\lambda^2 A^{1/3} q^A(x,Q^2)$$

J.-W. Qiu, X.-F. Guo, Phys. Rev. D61, 096003 (2000)

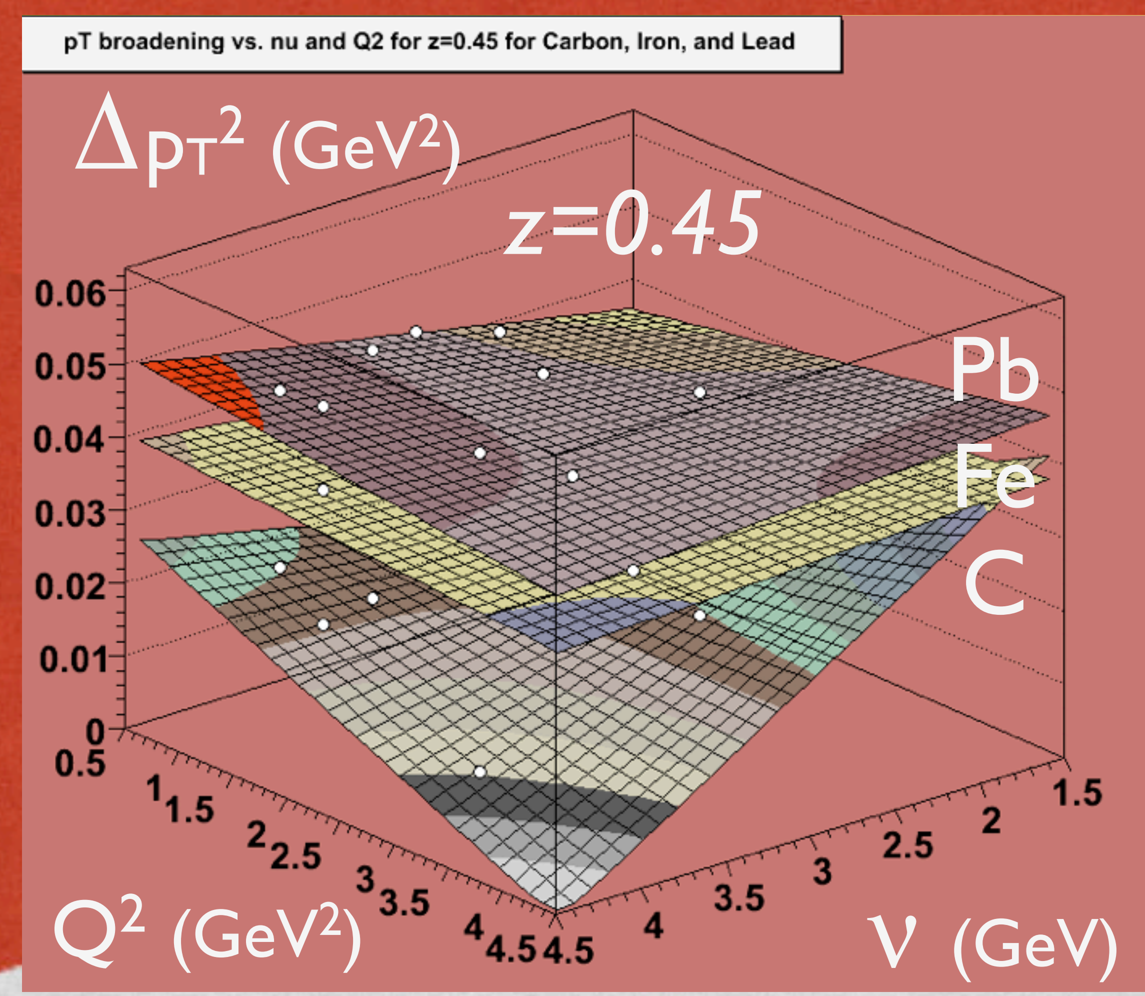


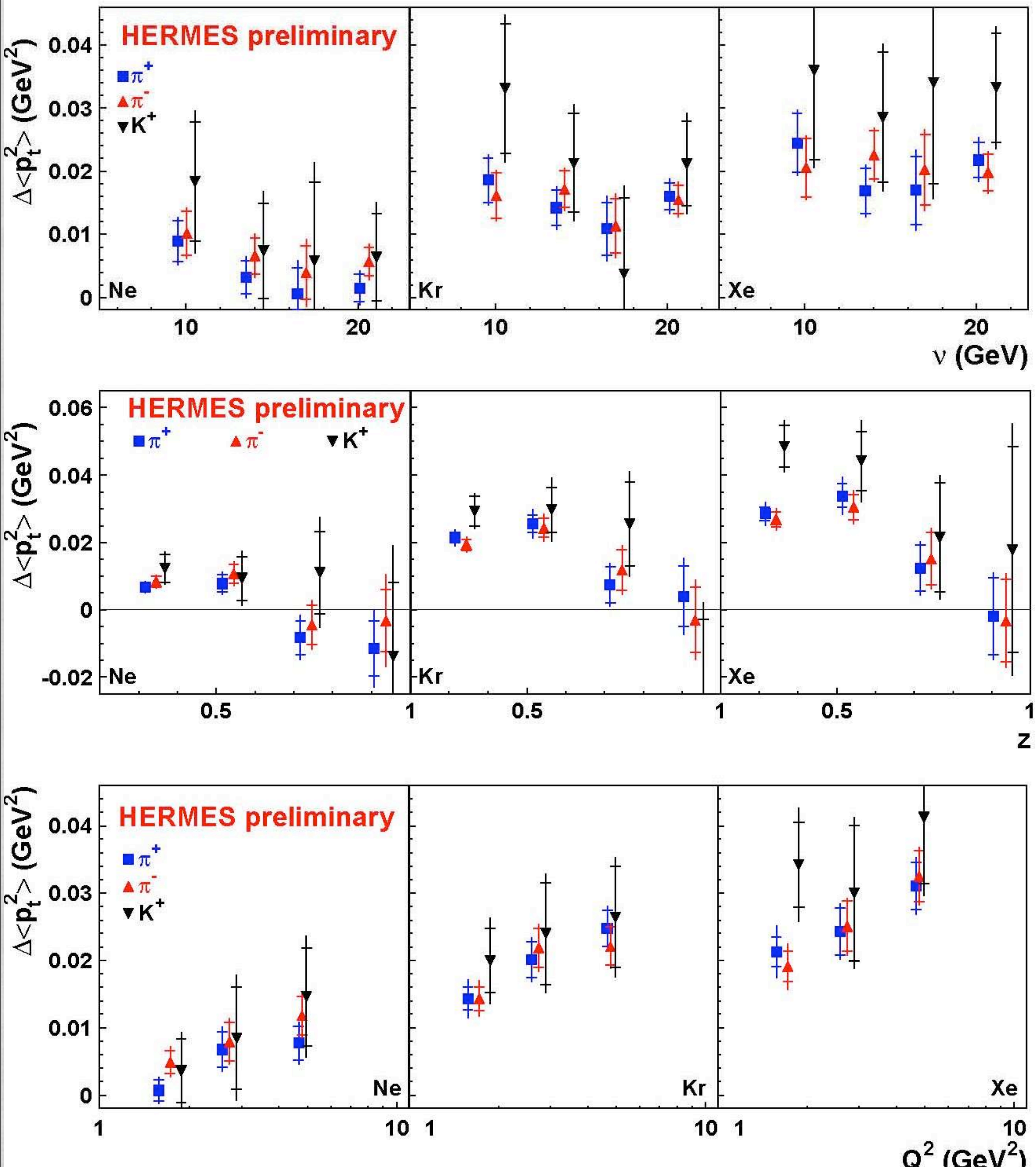


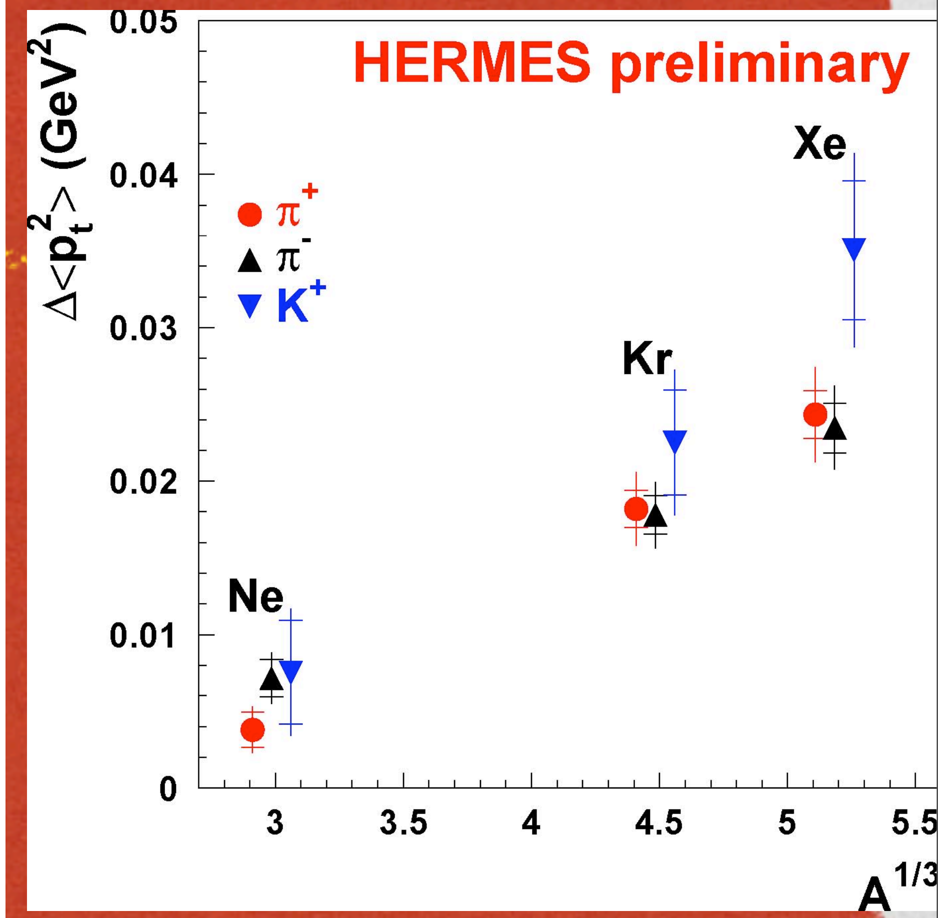
JLAB/CLAS 3-DIMENSIONAL VARIABLE DEPENDENCES
p_T Broadening

E.g., $$\tau \approx \frac{\nu z(1-z)}{Q^2}$$

27 bins in ν, Q^2, z each for 3 nuclei!







Hermes 1-D distributions

ASSOCIATED SLOW PROTONS: TARGET FRAGMENTATION

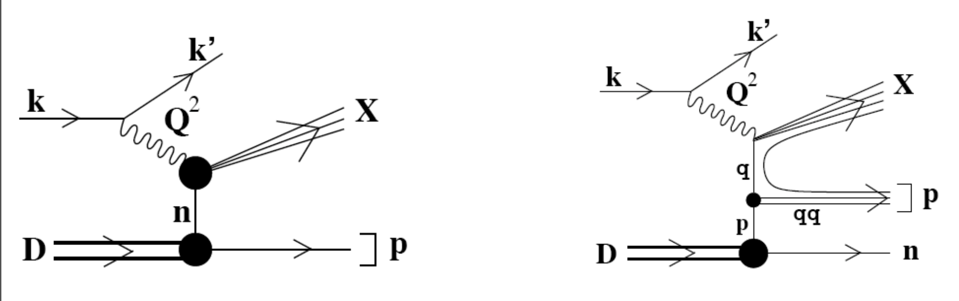
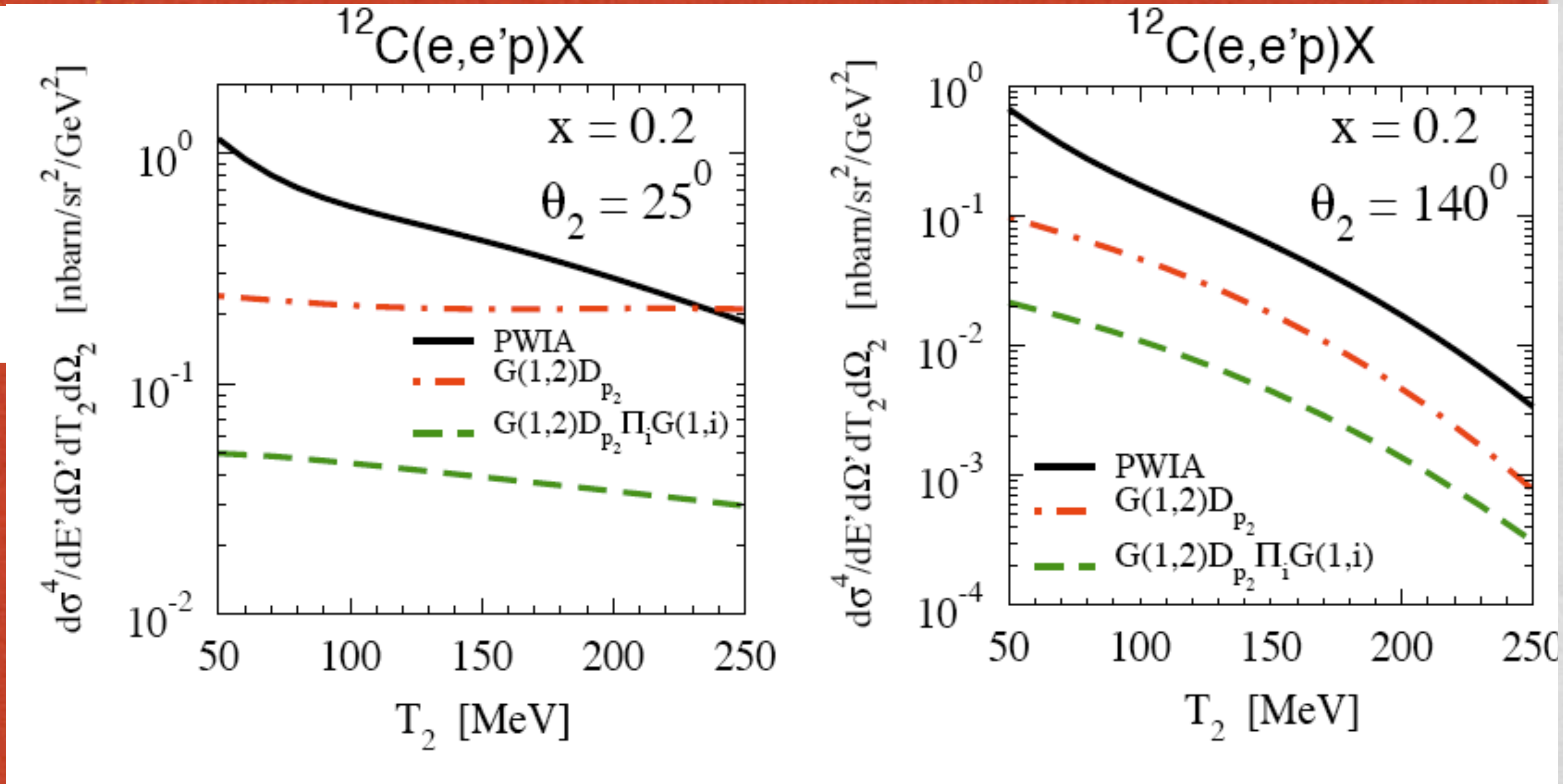


FIG. 1: The Feynman diagrams of the process $D(e,e'p)X$ corresponding to the spectator (left panel) and to target fragmentation (right panel) mechanisms.



Distinguish between spectator mechanism & target fragmentation via slow protons in DIS on nuclei

M. Alvioli, C. Ciofi degli Atti, V. Palli, L.P. Kaptari, arXiv:0705.3617v2 [nucl-th]

SEE ALSO: C. Ciofi degli Atti, B.Z. Kopeliovich, Phys.Lett. B606 (2005) 281-287

SEE ALSO: L. L. Frankfurt and M. I. Strikman, Phys. Rep. 76 (1981) 216; 160 (1988) 235

PHOTON BREMSTRAHLUNG FROM PROPAGATING QUARK

- QED bremsstrahlung from propagating quark

Majumder et al., with no gluon radiation:

- Re-sum higher twist: 2-D diffusion equation: $$\frac{\partial \phi(L^-, \vec{l}_\perp)}{\partial L^-} = D\nabla^2_{l_\perp}\phi(L^-, \vec{l}_\perp),$$
- Average p_T^2 agrees with classical limit
- Relationship between transport coefficient and diffusion constant:

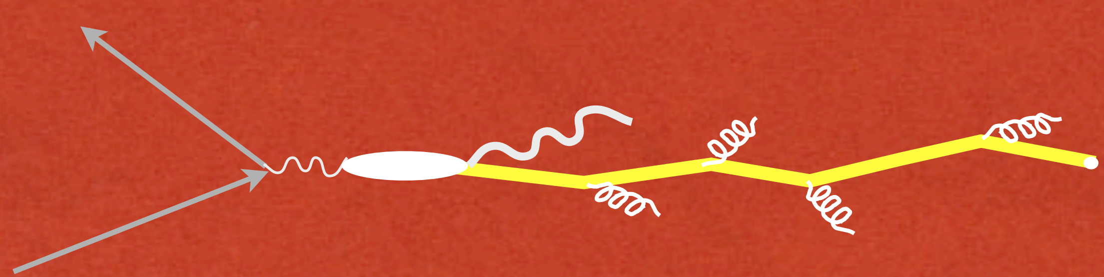
$$\hat{q} = \frac{2\langle l_\perp^2\rangle_{L^-}}{L^-} = 8D = \frac{2\pi^2\alpha_s}{N_c}\rho x_T G(x_T, m^2)|_{x\to 0},$$

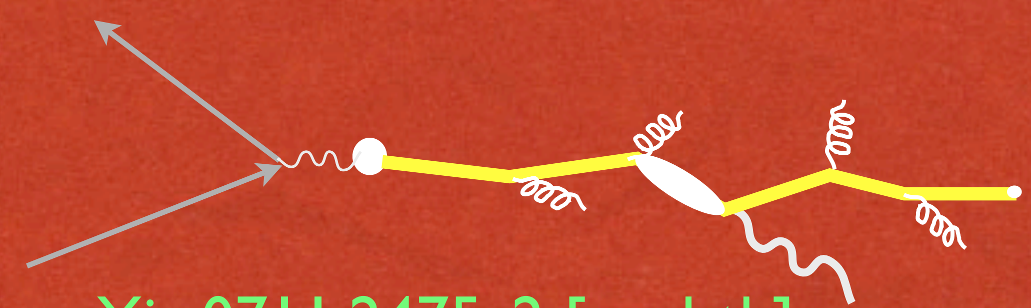
A. Majumder, R. J. Fries, and B. Müller, arXiv:0711.2475v2 [nucl-th]
A. Majumder, B. Müller, arXiv:0705.1147v4 [nucl-th]
V. Del Duca, S. J. Brodsky, P. Hoyer, Phys. Rev. D46, 931 (1992)

PHOTON BREMSTRAHLUNG FROM PROPAGATING QUARK

- Photon spectrum has two undetermined parameters:
- When photon emitted, two interfering amplitudes:
- Connection with off-forward parton distributions

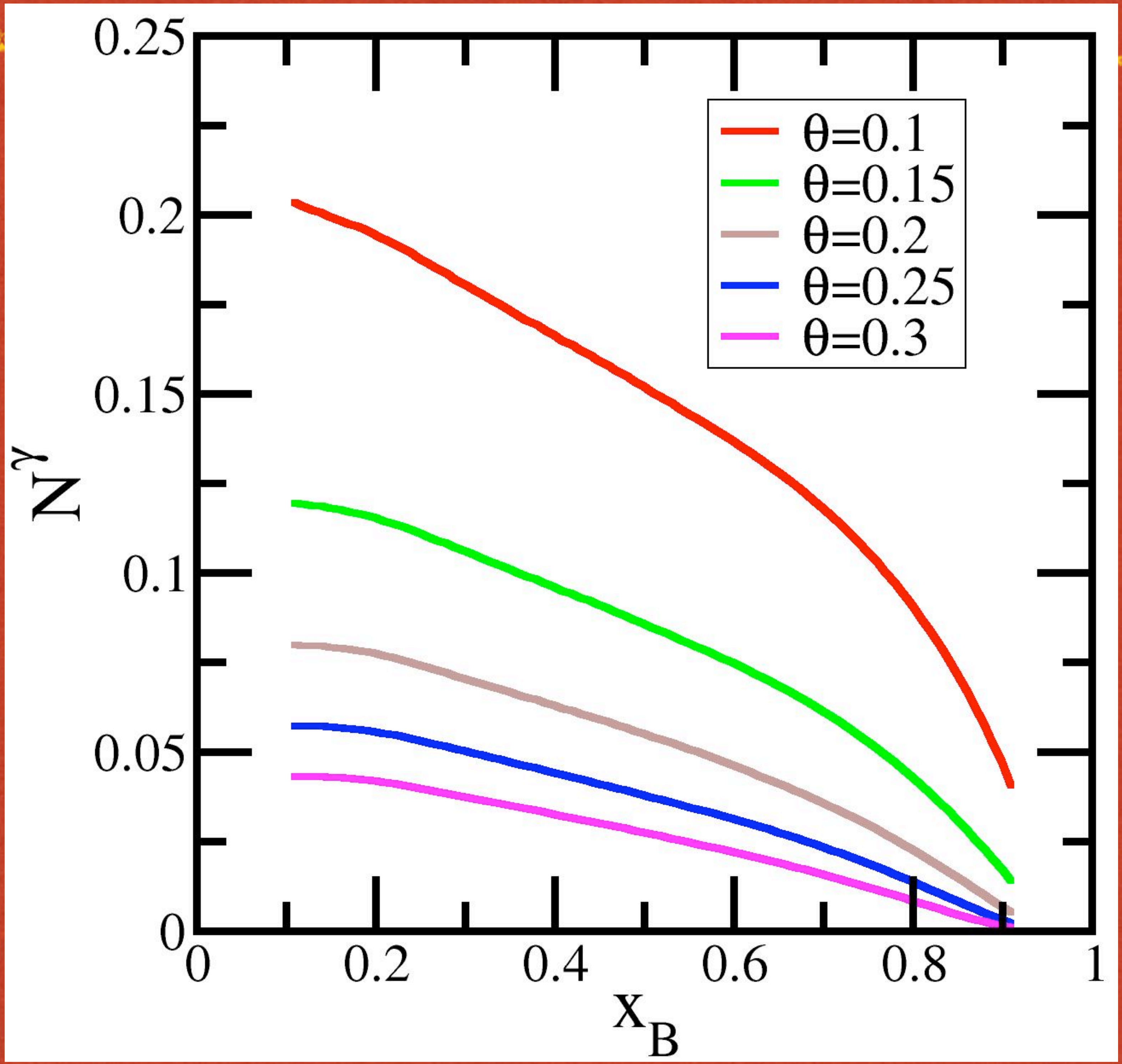
$$
\begin{aligned}
\frac{dW^{A\mu\nu}}{dy\,dl_\perp^2\,d^2l_{q\perp}} &= C_p^A 2\pi \sum_q Q_q^4(-g_\perp^{\mu\nu})\frac{\alpha_{em}}{2\pi}\frac{P_{q\to q\gamma}}{l_\perp^2} \\
&\times \int \frac{dy_0^-}{2\pi} e^{-i(x_B+x_L)p^+y_0^-} F_q(y_0^-) \\
&\times \left[1 + y c_p \frac{\{E^+(x_L)+E^-(x_L)\}}{2DL^-} \right. \\
&\times \left. \frac{l_\perp^2 + \vec{l}_\perp \cdot \vec{l}_{q\perp}}{l_\perp^2} \right] \phi(L^-, l_{q\perp}).
\end{aligned}
$$





A. Majumder, R. J. Fries, and B. Müller, arXiv:0711.2475v2 [nucl-th]
A. Majumder, B. Müller, arXiv:0705.1147v4 [nucl-th]
V. Del Duca, S. J. Brodsky, P. Hoyer, Phys. Rev. D46, 931 (1992)

PHOTON BREMSTRAHLUNG FROM PROPAGATING QUARK

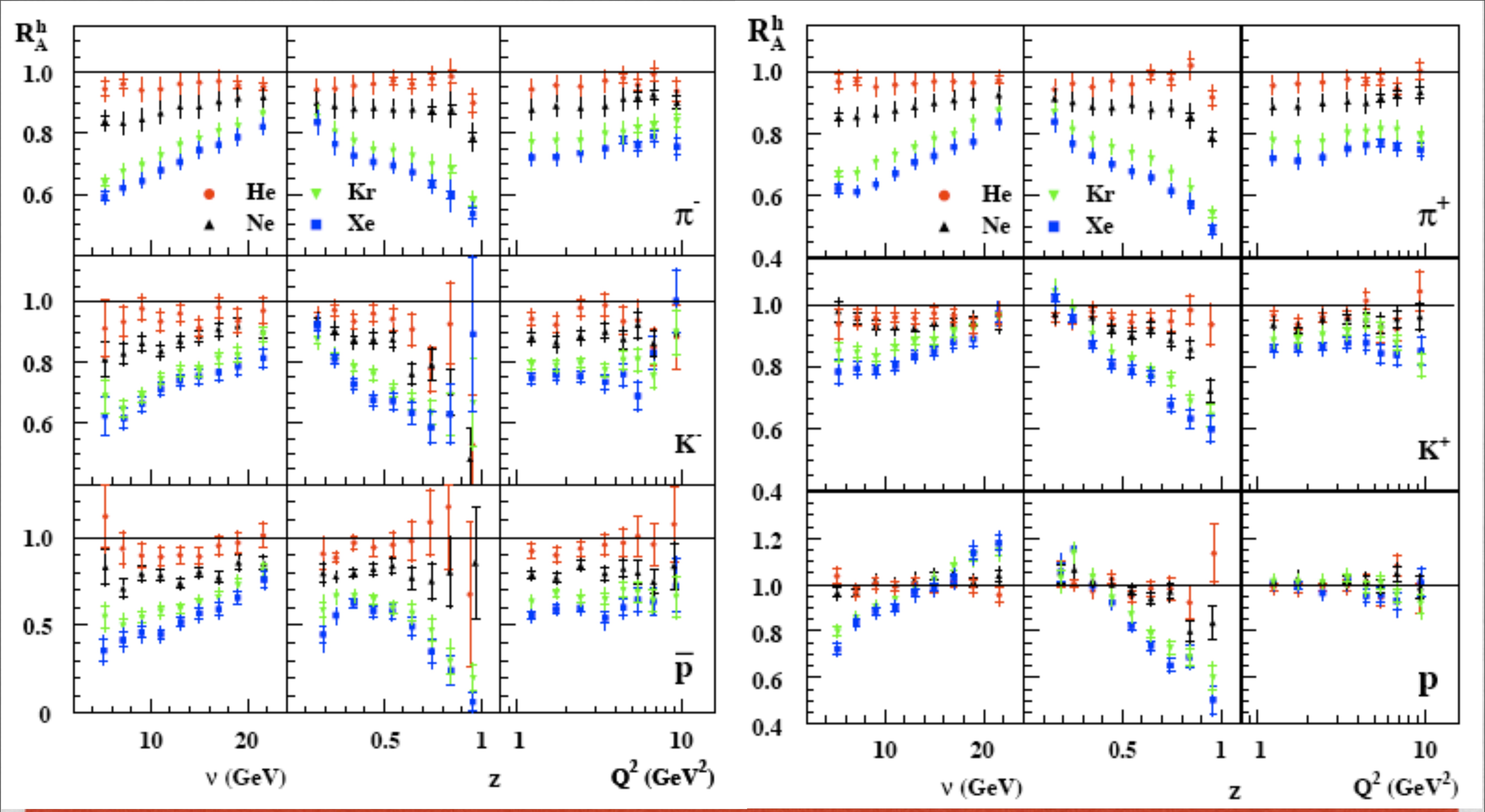


from Abhijit Majumder

P_T BROADENING SUMMARY

- Basic consistency of data, JLab and HERMES
- Some systematic dependences on kinematic variables observed: good test for models
- Color dipole analysis: picture *not clear yet*
  - Transport coefficient for cold nuclear matter is much smaller than expected?
  - Energy dependence greater than expected?
- Quantitative theoretical calculations needed

HADRON ATTENUATION



HERMES data for He, Ne, Kr, Xe: π^{+-}, K^{+-}, p, antiproton

pions act similarly, K^+ vs. K^-, proton vs. antiproton

MODELS ADDRESSING HERMES DATA - ***2 PICTURES***

Models based on partonic energy loss

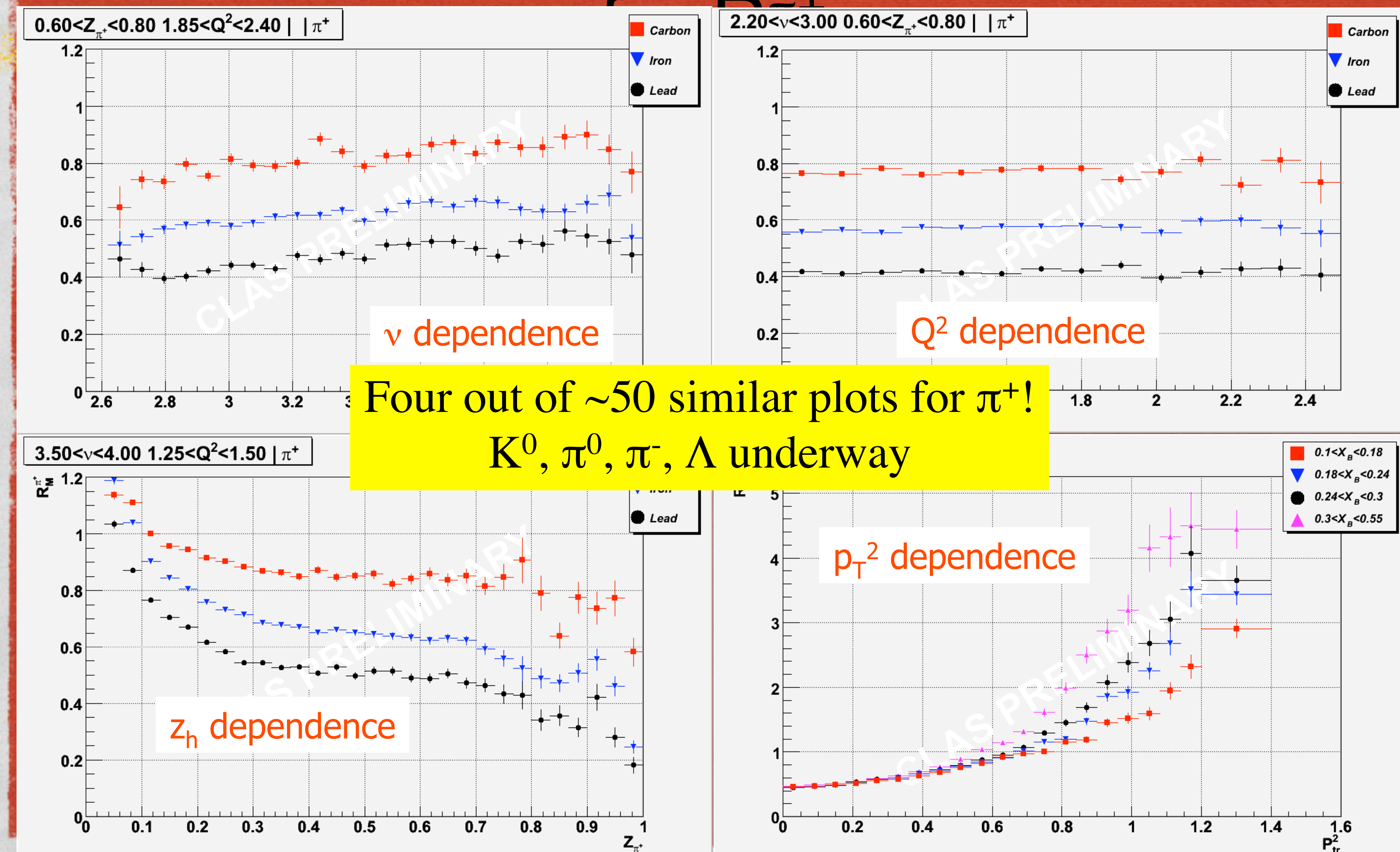
X.N. Wang et al. (PRL 89, 162301 (2002))
F. Arleo et al. (EPJ C 30, 213 (2003))

Models based on (pre)-hadronic interaction

B. Z. Kopeliovich, J. Nemchik, et al. (e.g., NPA 740, 211 (2004))
T. Falter et al. (e.g., PLB 594 (2004) 61)
A. Accardi et al. (e.g., NPA 720, 131 (2003); NPA 761, 67 (2005))
N. Akopov et al. (Eur.Phys. J 44(2005) 219)
H.J. Pirner et al. (e.g., NPA761 (2005), NPA720 (2003) 131-156)
K.Gallmeister, U. Mosel (nucl-th/0701064; nucl-th/07122200)

NO conclusive resolution from the HERMES 1-D data

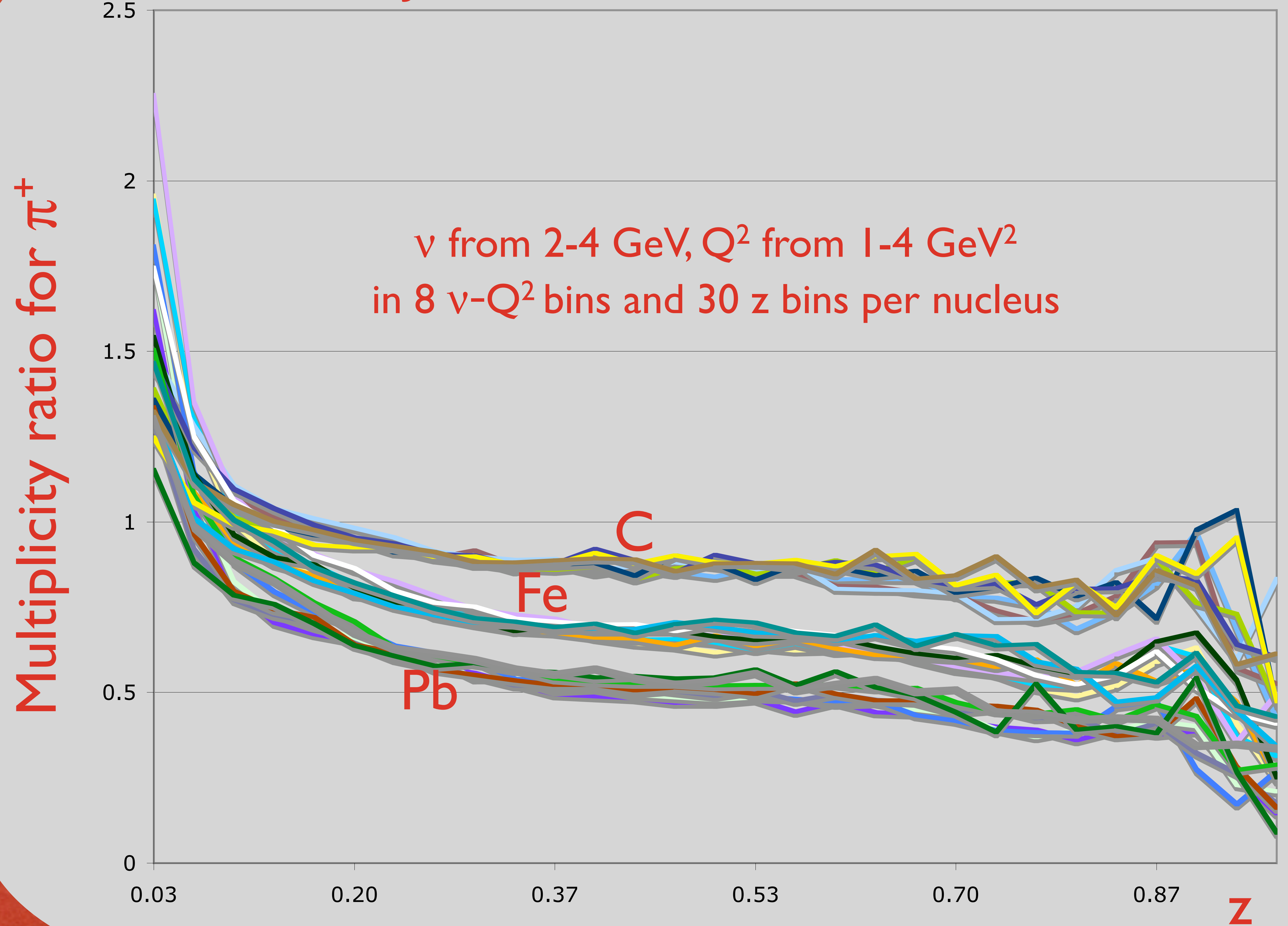
Examples of multi-variable slices of preliminary CLAS 5 GeV data



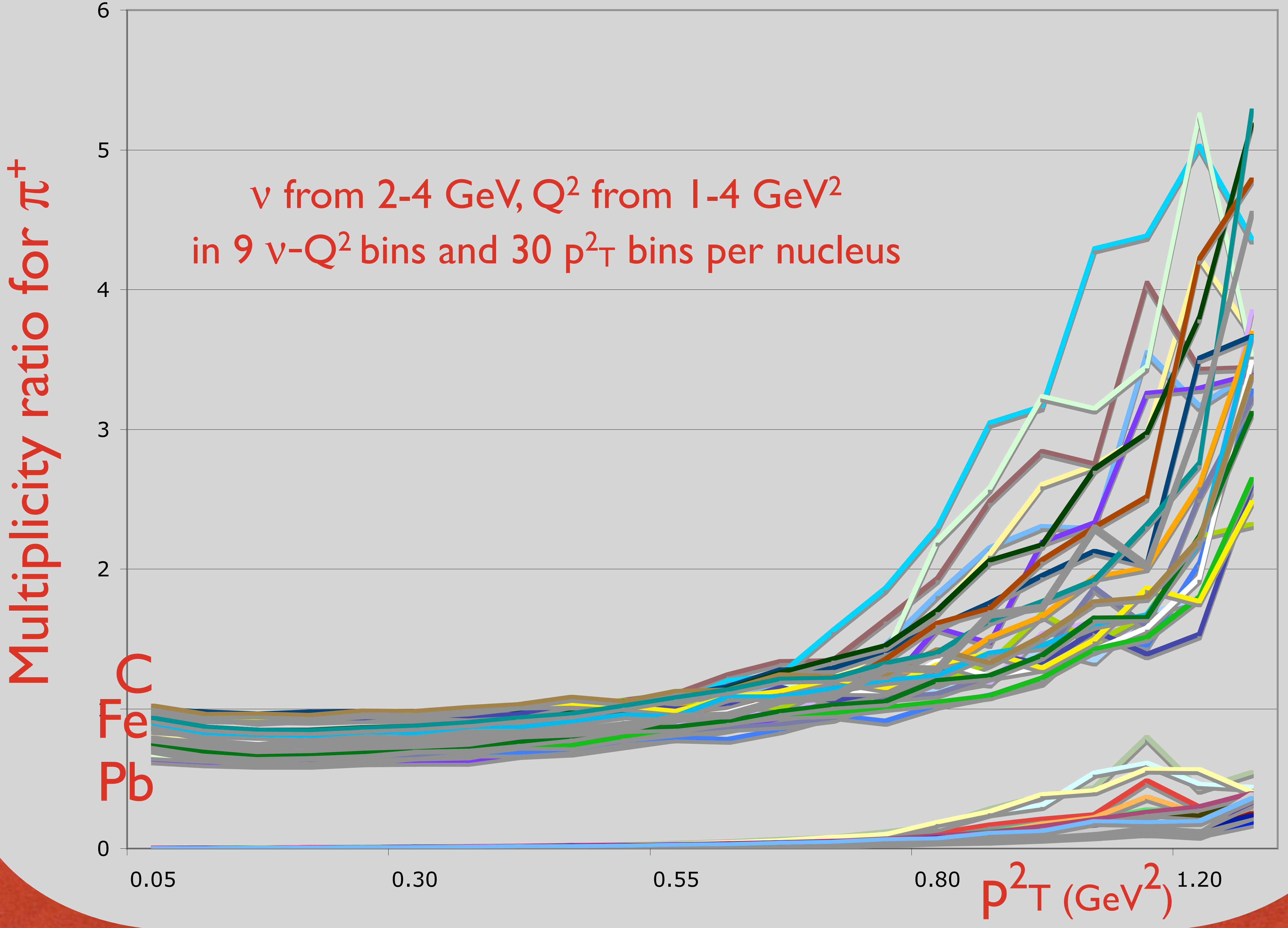
Four out of ~50 similar plots for π^+!

K^0, π^0, π^-, Λ underway

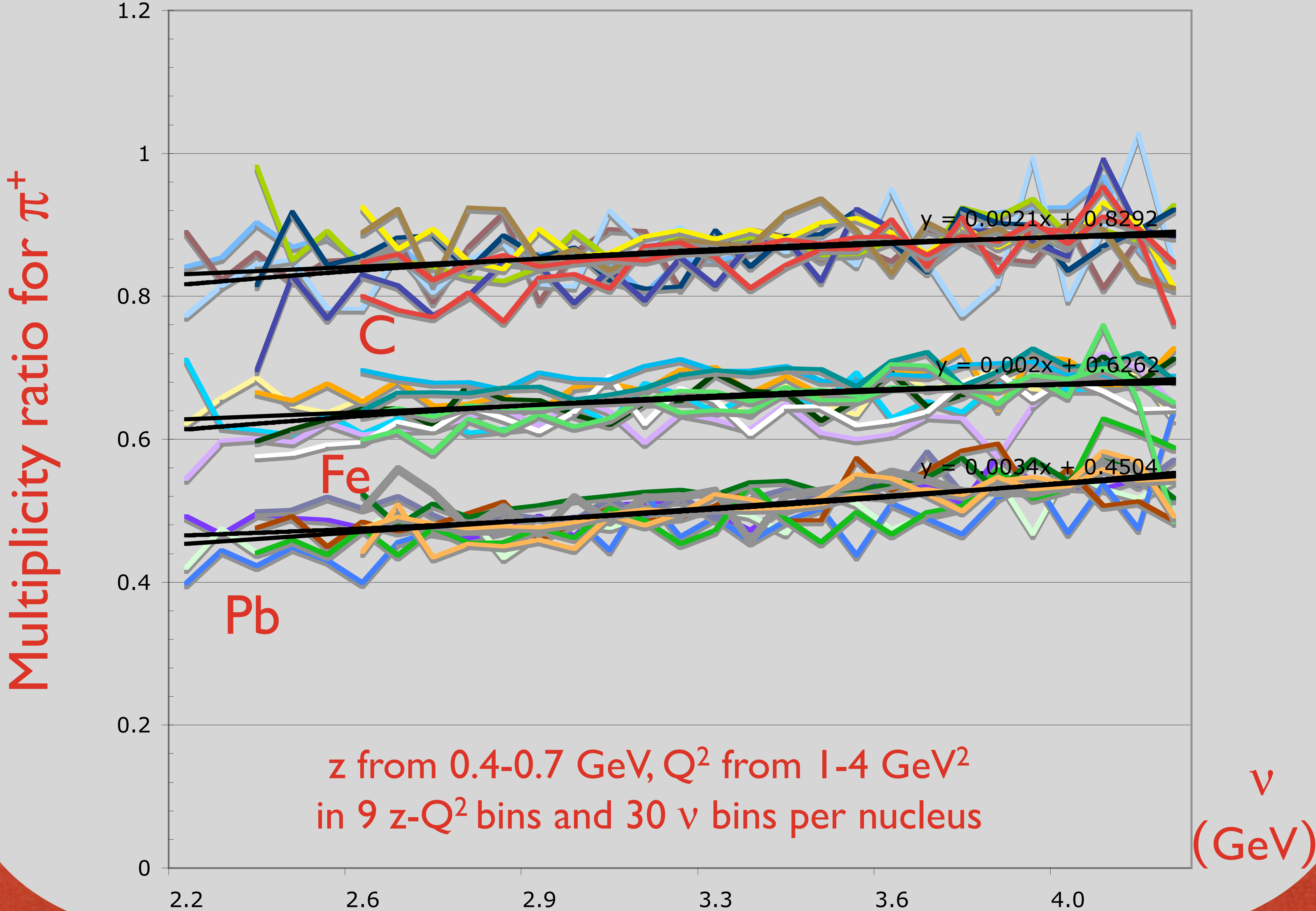
JLab/CLAS data for C, Fe, Pb



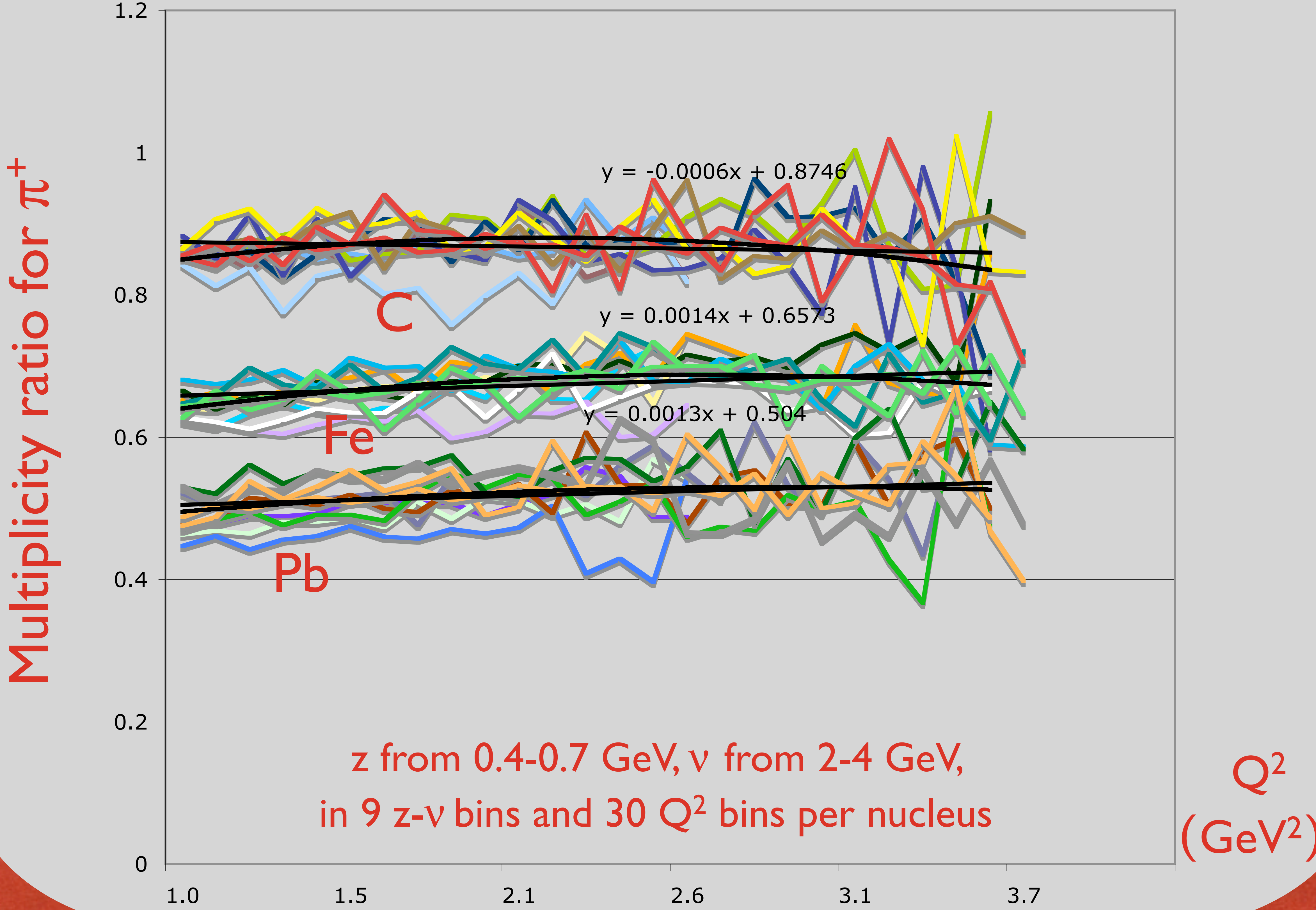
JLab/CLAS data for C, Fe, Pb



JLab/CLAS data for C, Fe, Pb



JLab/CLAS data for C, Fe, Pb



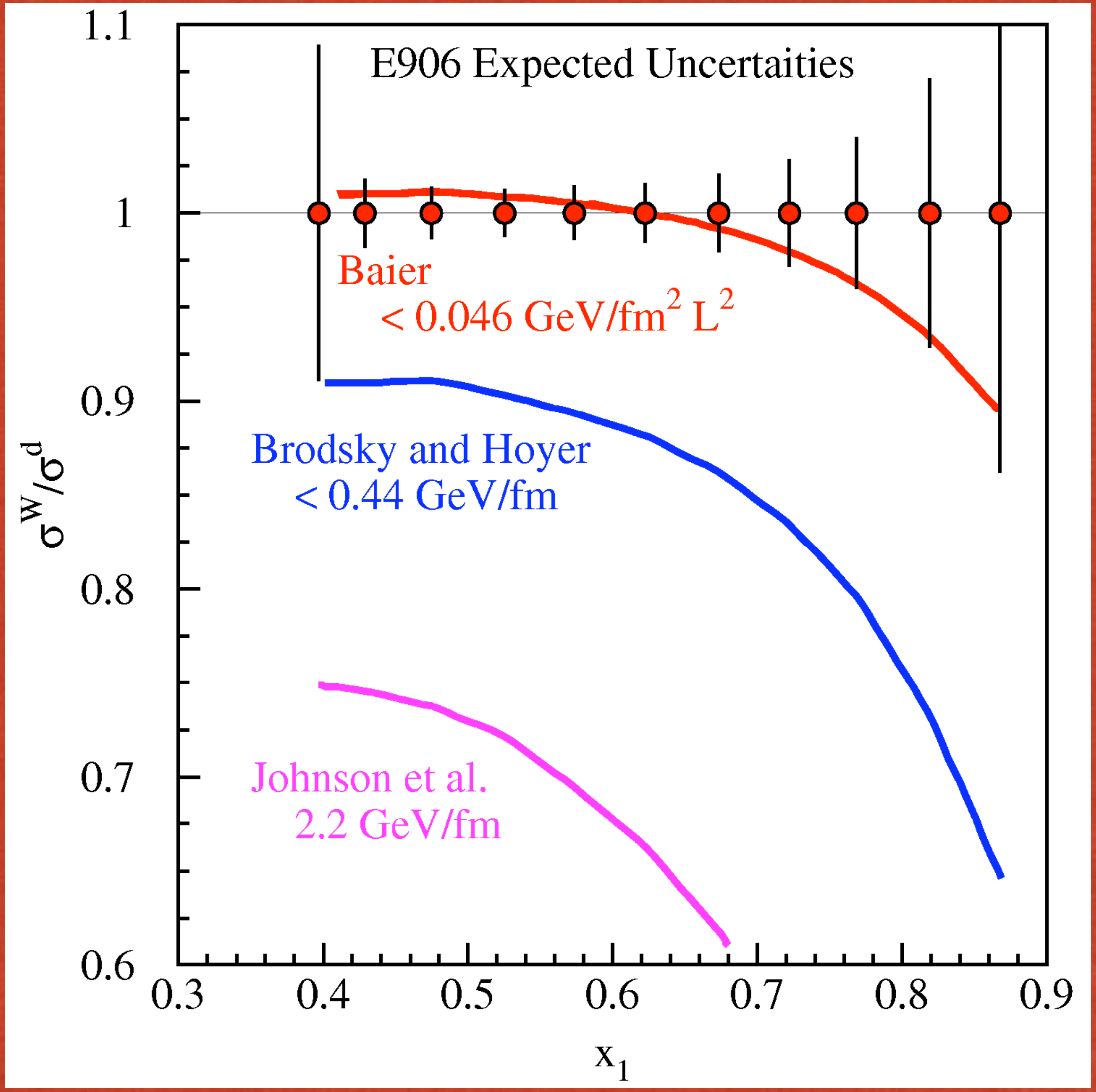
HADRON ATTENUATION SUMMARY

- Good consistency of data from HERMES and CLAS
- Hermes data: landmark study
- Models do not discriminate between two basic proposed mechanisms from HERMES data; need better data (higher luminosity, more channels)
- Exploratory 3-variable study performed with JLab/ CLAS data, provides quite stringent test for models

FUTURE

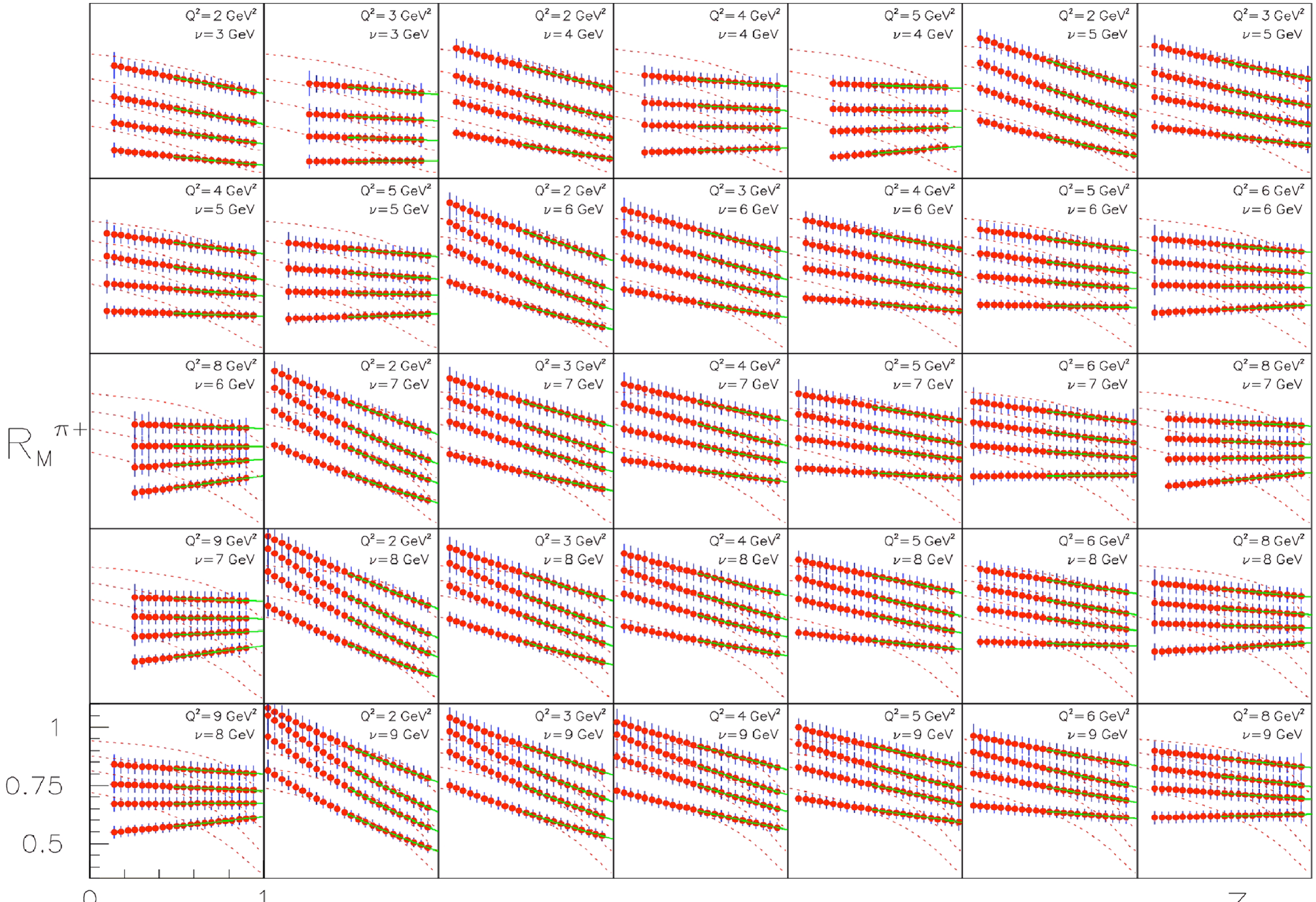
FNAL E906

- Drell Yan at 120 GeV
- Remove analysis ambiguity between shadowing and energy loss
- See J.C. Peng's talk on Friday



Paul Reimer, EINN 2005

Examples of Experimental Data and Theoretical Predictions



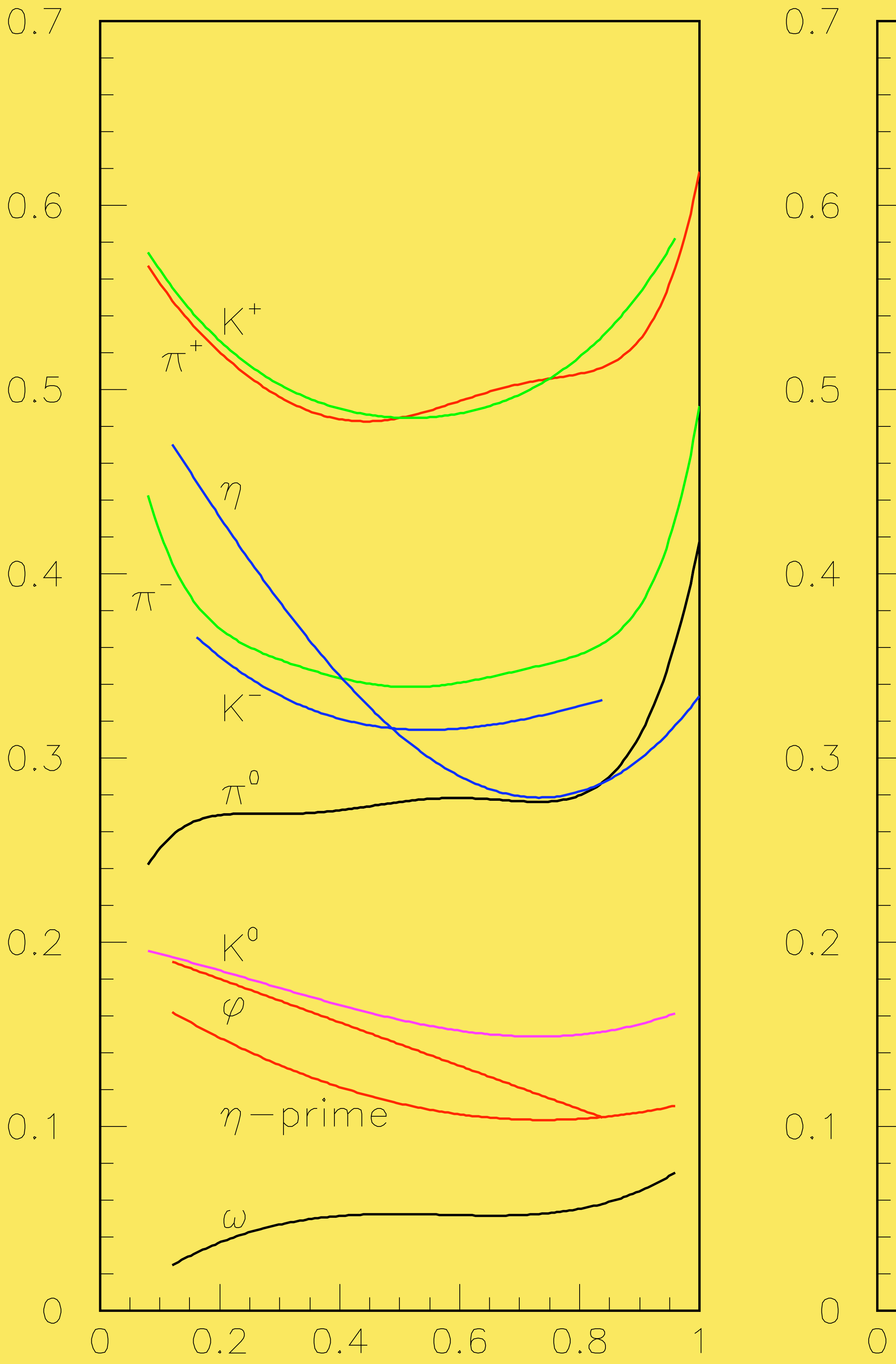
ν=3-9 GeV, Q²=2-8 GeV²

CLAS12 Multiplicity Ratio vs. Z_h, π^+

CLAS12 Hadrons

hadron	$c\tau$	mass (GeV)	flavor content	detection channel	Production rate per 1k DIS events
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	$\gamma\gamma$	1100
π^+	7.8 m	0.14	$u\bar{d}$	direct	1000
π^-	7.8 m	0.14	$d\bar{u}$	direct	1000
η	0.17 nm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	$\gamma\gamma$	120
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\pi^0$	170
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\eta$	27
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	K^+K^-	0.8
$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	$\pi\pi\pi\pi$	-
K^+	3.7 m	0.49	$u\bar{s}$	direct	75
K^-	3.7 m	0.49	$\bar{u}s$	direct	25
K^0	27 mm	0.50	$d\bar{s}$	$\pi^+\pi^-$	42
p	stable	0.94	ud	direct	530
$\bar{p}$	stable	0.94	$\bar{u}\bar{d}$	direct	3
Λ	79 mm	1.1	uds	$p\pi^-$	72
$\Lambda(1520)$	13 fm	1.5	uds	$p\pi^-$	-
Σ^+	24 mm	1.2	us	$p\pi^0$	6
Σ^0	22 pm	1.2	uds	$\Lambda\gamma$	11
Ξ^0	87 mm	1.3	us	$\Lambda\pi^0$	0.6
Ξ^-	49 mm	1.3	ds	$\Lambda\pi^-$	0.9

CLAS12 Geometric Acceptances for Mesons and Baryons



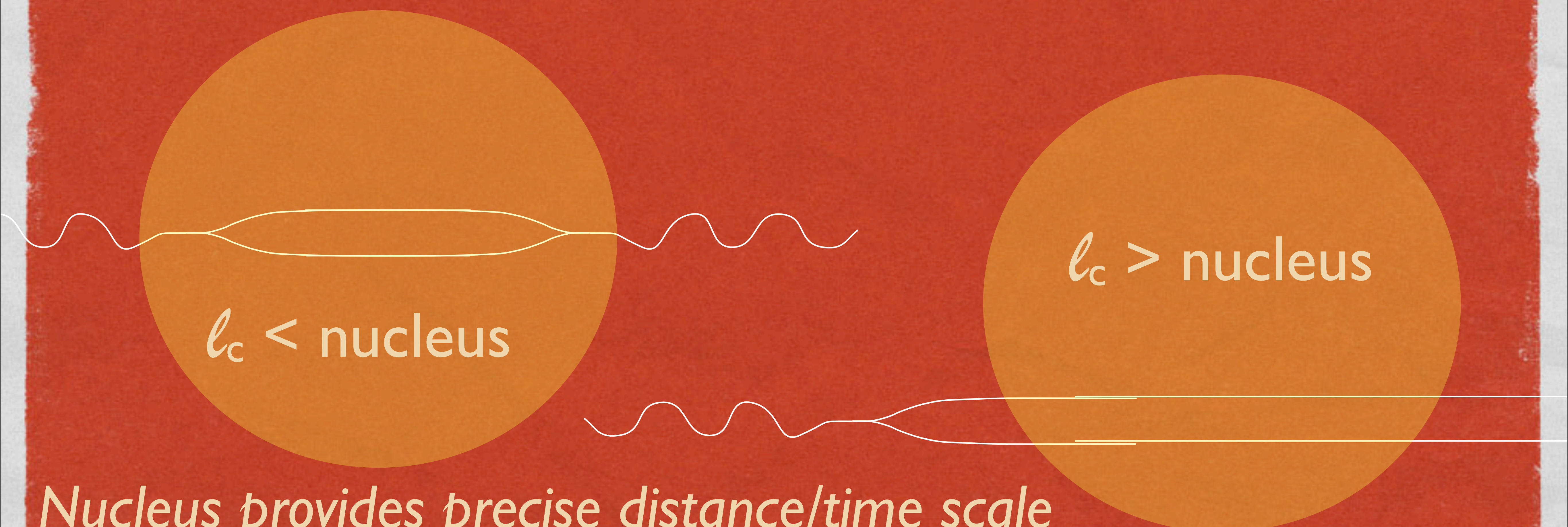
CLAS12 Acceptance for Mesons

CLAS12 Acceptance for Baryons

HALL D: INVESTIGATE PREHADRONS SEPARATELY

Vacuum process:

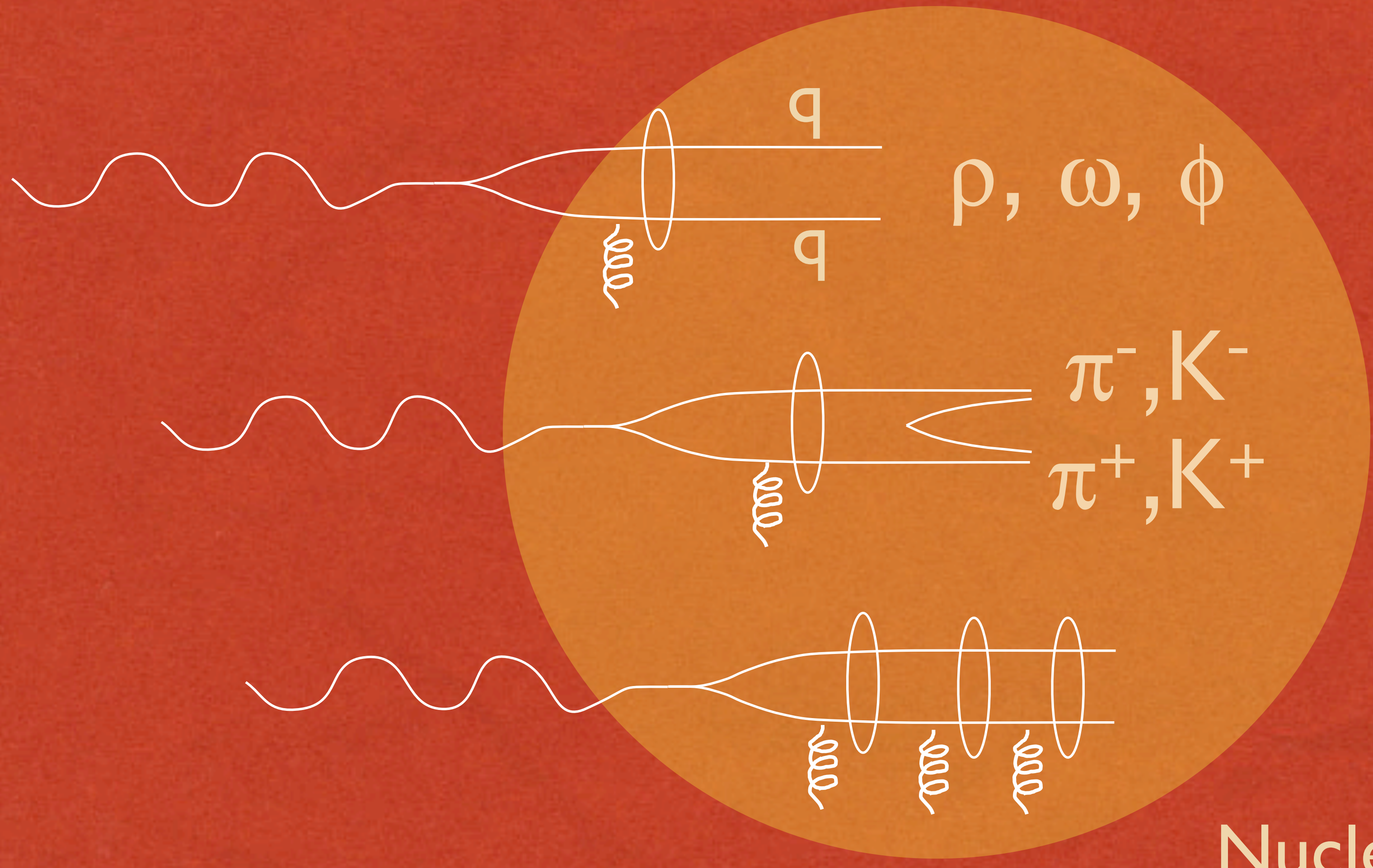
Lifetime of fluctuation: coherence length $\ell_c = 2E_\gamma/M^2_{qq}$



Nucleus provides precise distance/time scale

HALL D PT BROADENING MEASUREMENTS

Processes in-medium:



Color-neutral
2-gluon exchange

In-medium **broadening of (transverse) dipole momentum**
(ρ, ω, ϕ, π, K)

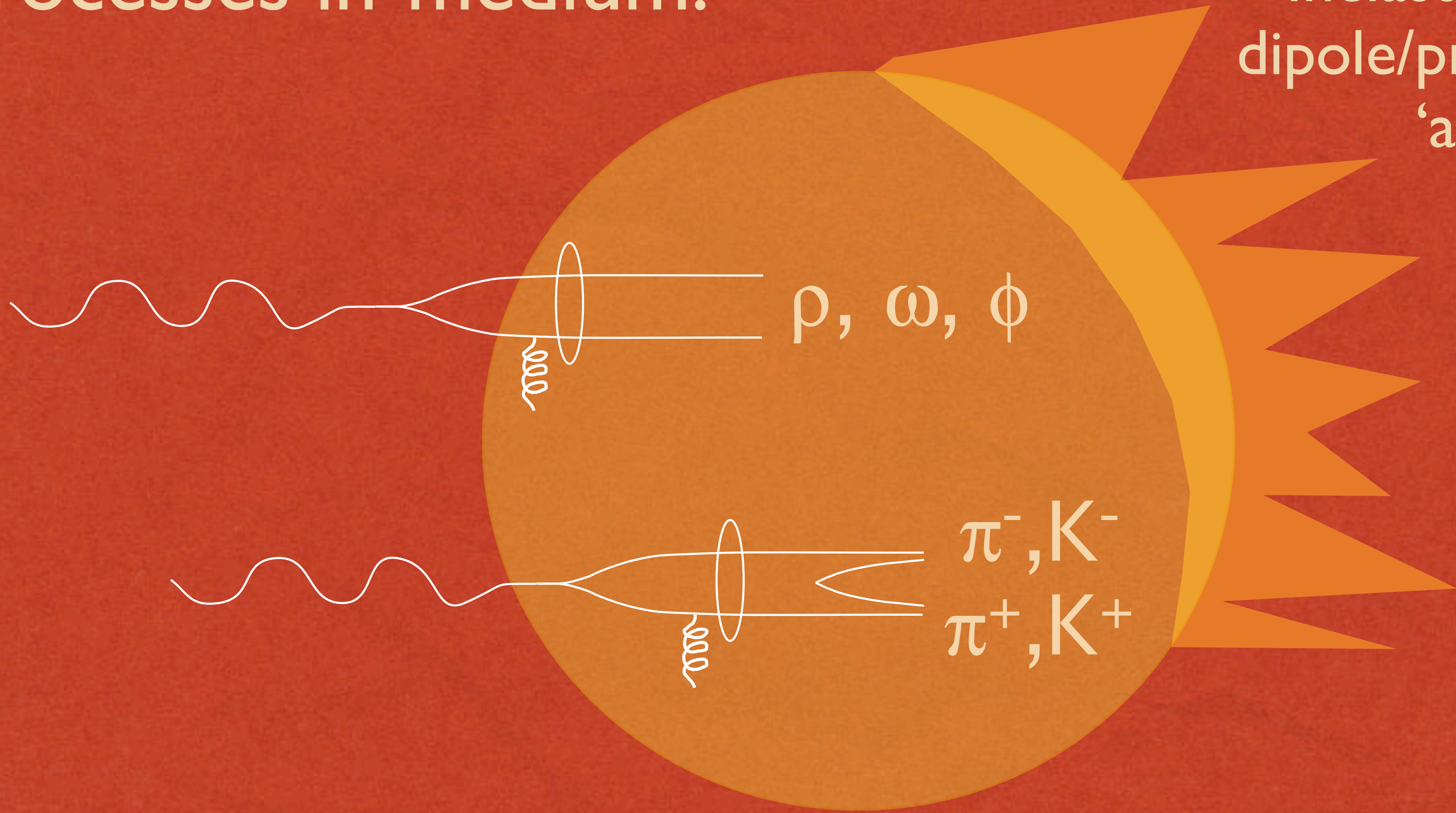
Nucleus not excited: coherent

Nucleus excited/breaks up: incoherent

HALL D ABSORPTION MEASUREMENTS

Processes in-medium:

Inelastic interaction of dipole/prehadron/meson - ‘attenuation’



Nucleus excited/breaks up: incoherent

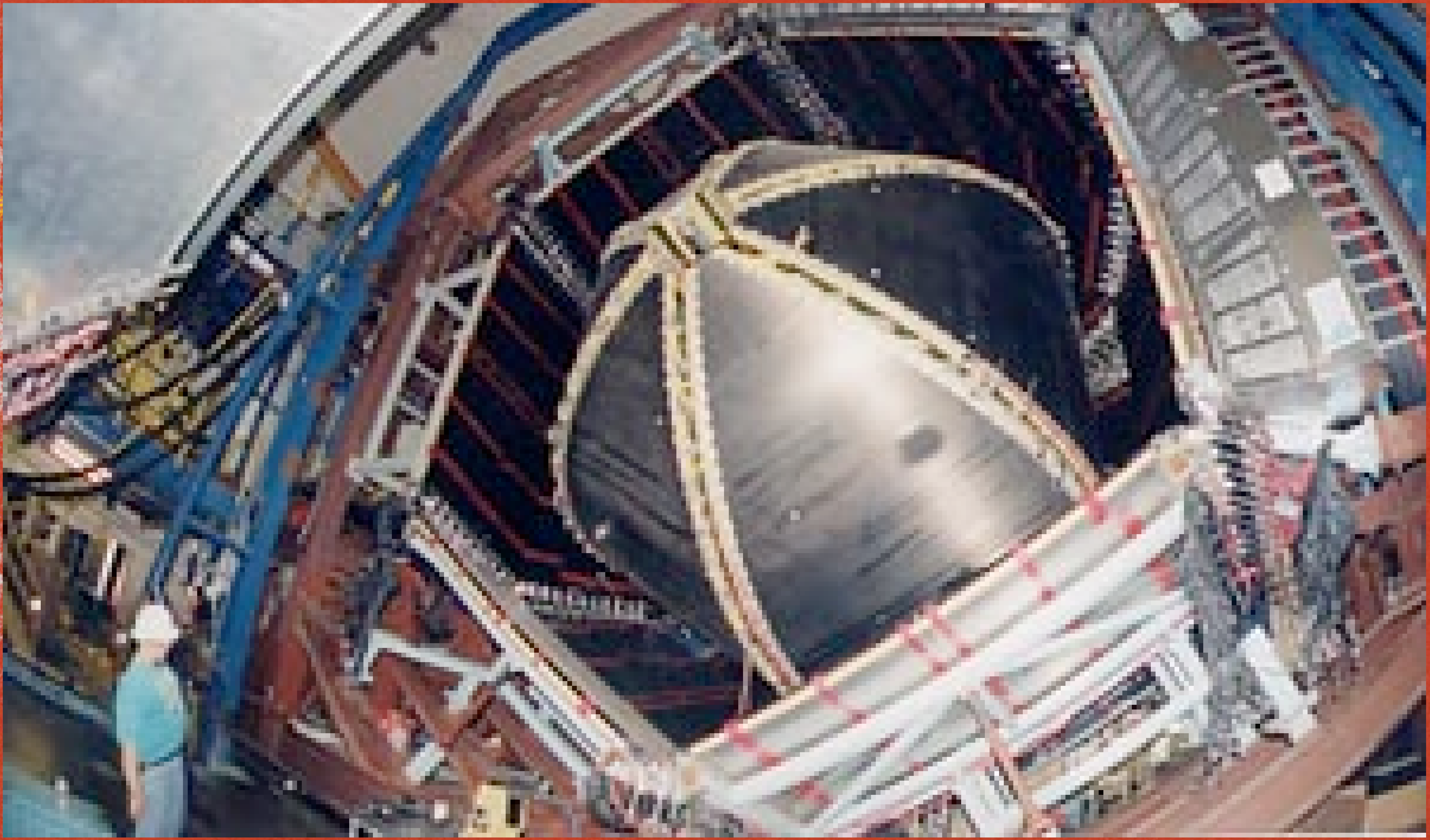
CONCLUSIONS

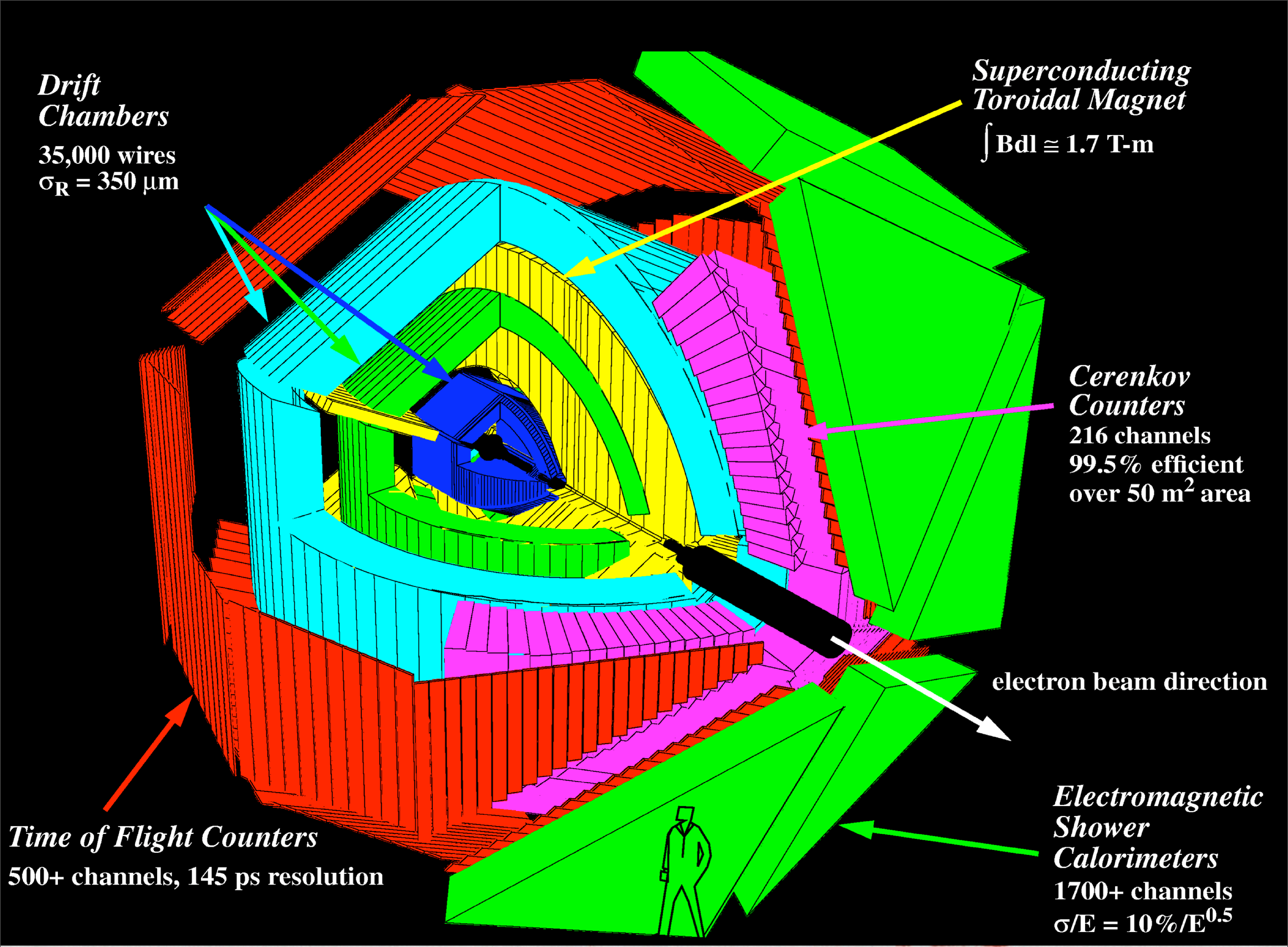
- Good consistency among diverse data sets
- 3D analysis of huge JLab data sample
- Controversies remain, wide potential impact
- Need theoretical framework for τ_p, ${}^h\tau_f$ extraction
- Future: FNAL: E906 Drell-Yan at 120 GeV
- Future: JLab@12 GeV - CLAS12 and Hall D

ADDITIONAL SLIDES

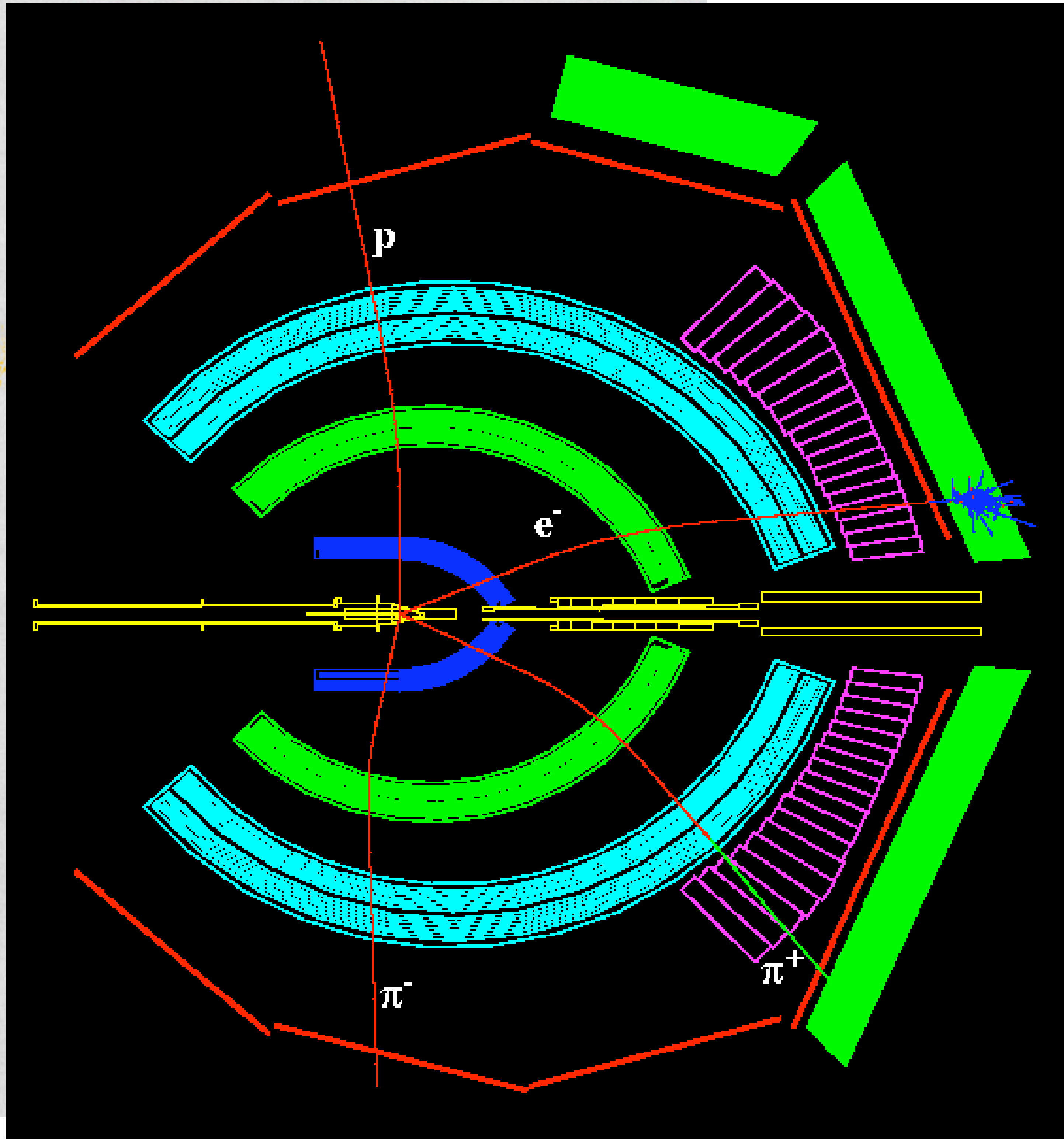
COMPARISON: HERMES AND 6 GEV CLAS

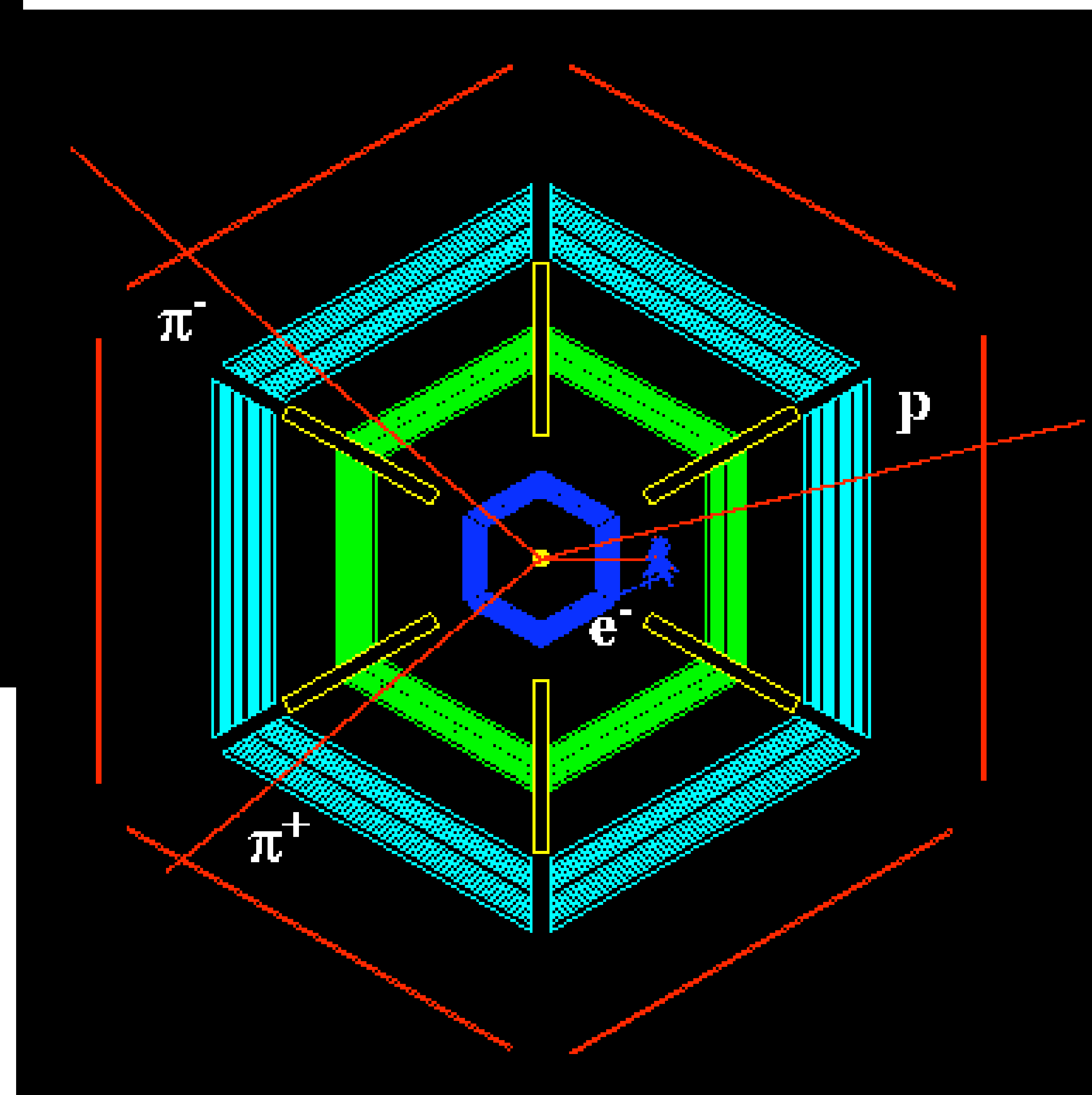
- HERMES
  - More hadrons: all pions, protons, antiprotons, K^+, K^-
  - More ν (8-20 GeV vs. 2-4 GeV) and W_{max} (3 vs. 7)
- JLab
  - More luminosity (x100): 3D vs. 1D distributions
  - Heaviest targets (not limited to gas targets)



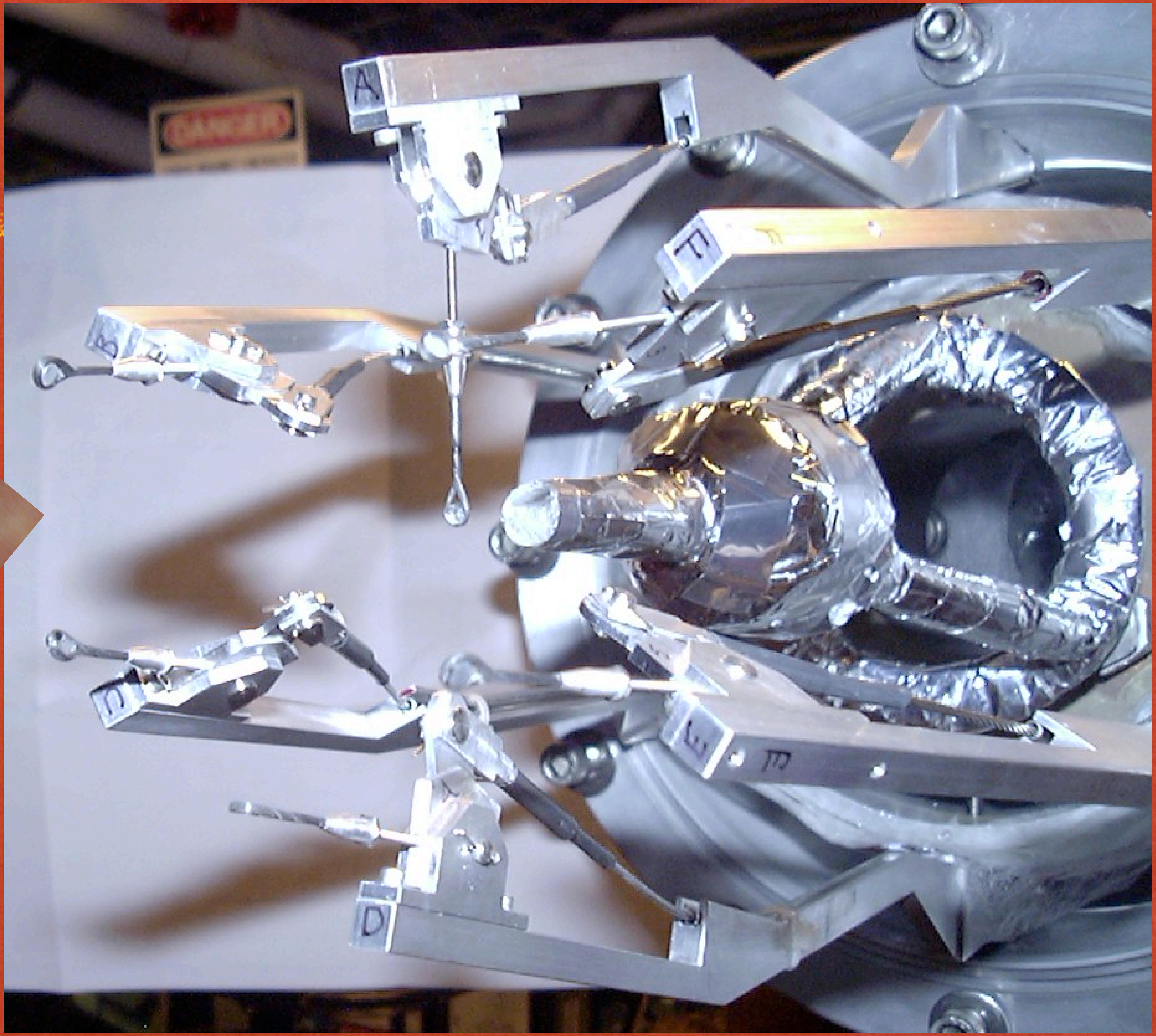

Drift Chambers
35,000 wires
σR = 350 μm
Superconducting Toroidal Magnet
∫Bdl ≅ 1.7 T-m
Cerenkov Counters
216 channels
99.5% efficient
over 50 m2 area
electron beam direction
Electromagnetic Shower Calorimeters
1700+ channels
σ/E = 10%/E0.5
Time of Flight Counters
500+ channels, 145 ps resolution

- Charged particle angles 8° - 144°
- Neutral particle angles 8° - 70°
- Momentum resolution ~0.5% (charged)
- Angular resolution ~0.5 mr (charged)
- Identification of p, π^+/π^-, K^+/K^-, e^-/e^+



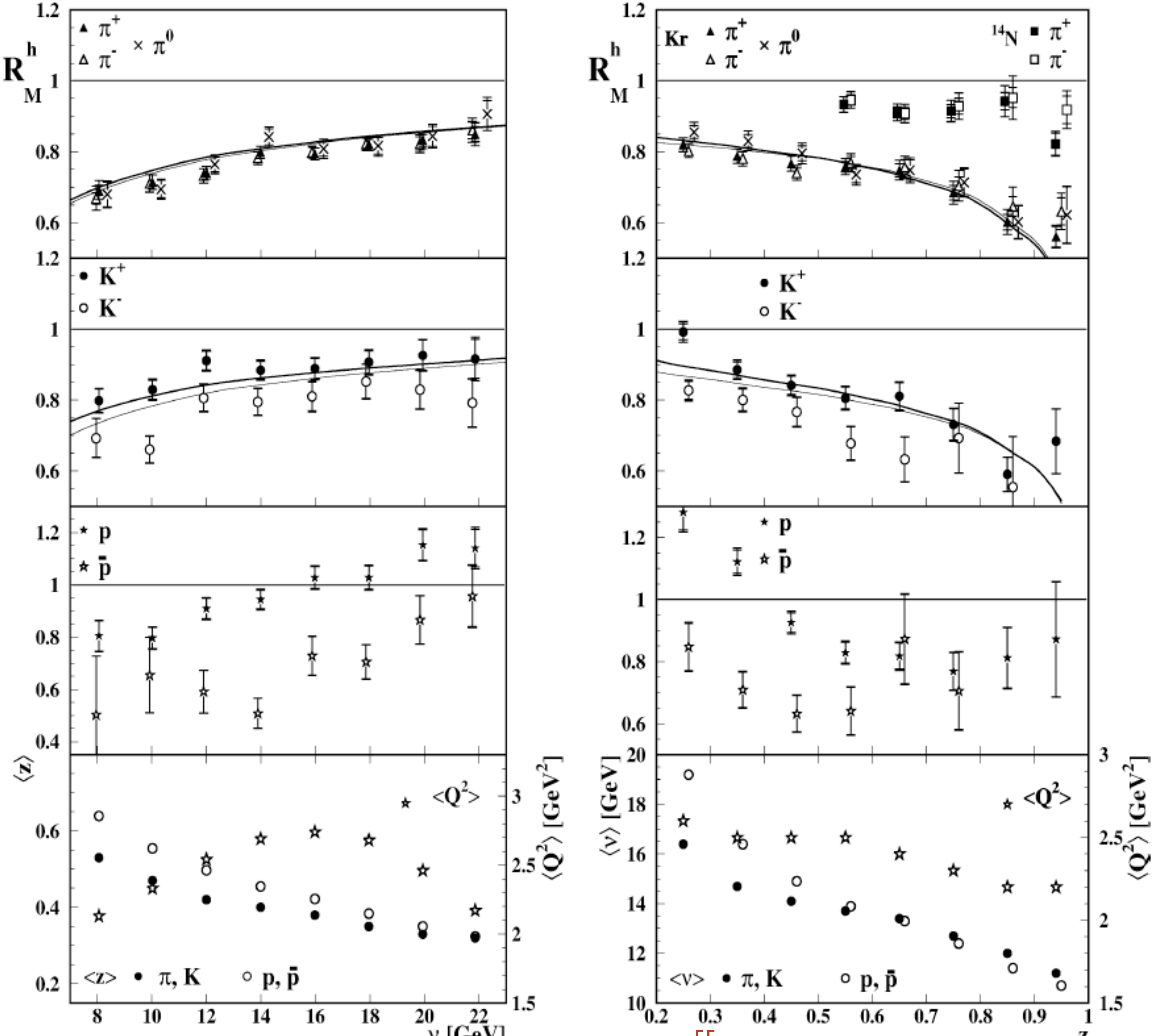


CLAS EG2 Targets



HERMES, CLAS6, CLAS12

- HERMES took data 1997-2005, 7 nuclear targets, most of data with RICH.
  - 231 pb^{-1} on He+Ne+Kr+Xe at 27 GeV
- CLAS took data 2003, 4 primary nuclear targets
  - ~25,000 pb^{-1} on C+Fe+Pb, at 5.0 GeV
- CLAS12: approved experiment, ~10x CLAS luminosity



HERMES

Krypton Target (mostly)