Quark Propagation and Fundamental Processes in QCD

- Hadronization
- Quark-gluon dynamics
- Connections to HERMES, LHC/RHIC, and Fermilab
- JLab experiments – present and future

Will Brooks, September 2005, ECT*

Quark Propagation and Fundamental Processes in QCD

Hadronization

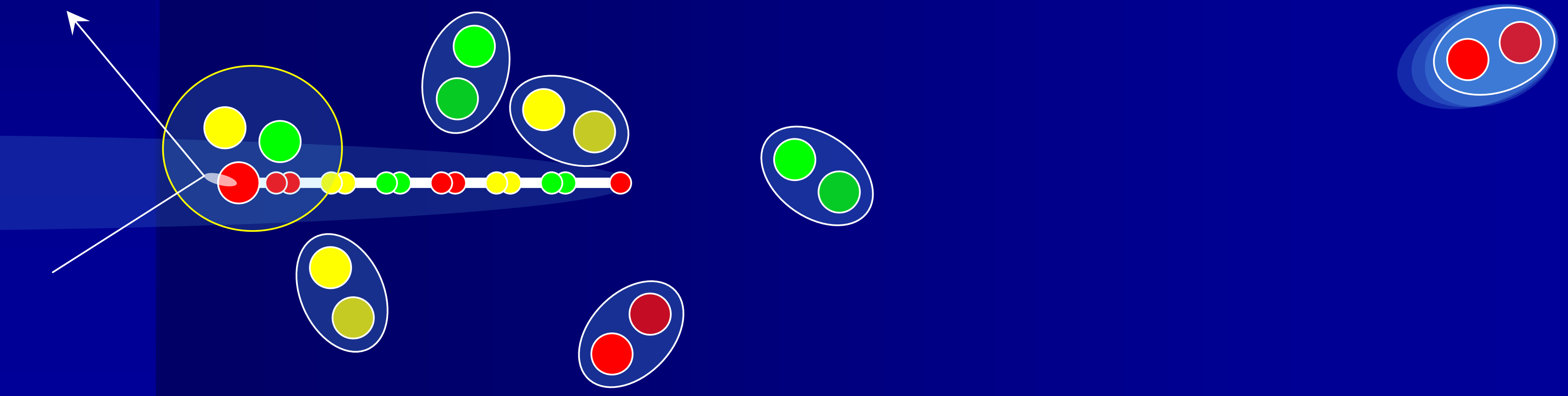
- The transformation of energetic quark in color field into hadron(s)
- Time dependence of restoration of hadron’s local color field

Quark-gluon dynamics

- Partonic energy loss via gluon emission
- Quark-gluon correlations

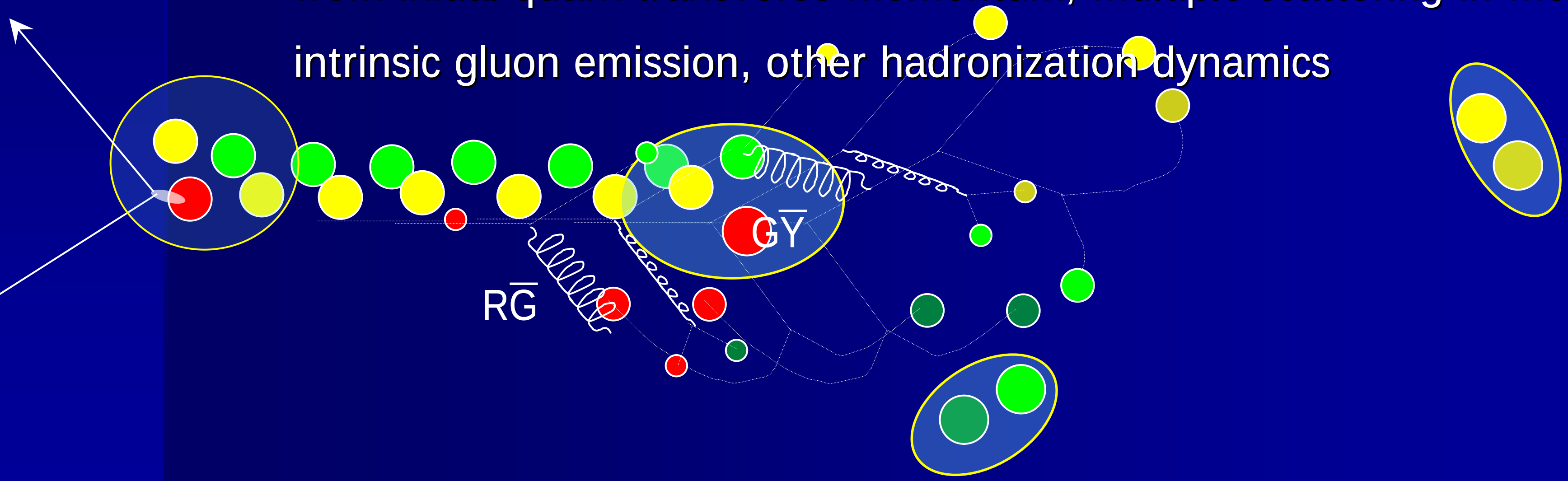
Fascination with Hadronization

- Hadronization is at the heart of the most fascinating feature of QCD: *confinement*



Fascination with Hadronization

ν	energy transferred by the electron (initial energy of struck quark)
Q^2	four-momentum transferred by the electron (initial size of struck quark)
z_h	= E_{hadron}/ν , fraction of struck quark energy carried by hadron; $0<z_h<1$
p_T	quark/hadron momentum transverse to virtual photon direction; results from initial quark transverse momentum, multiple scattering in-medium, intrinsic gluon emission, other hadronization dynamics



Target Frame DIS Kinematics

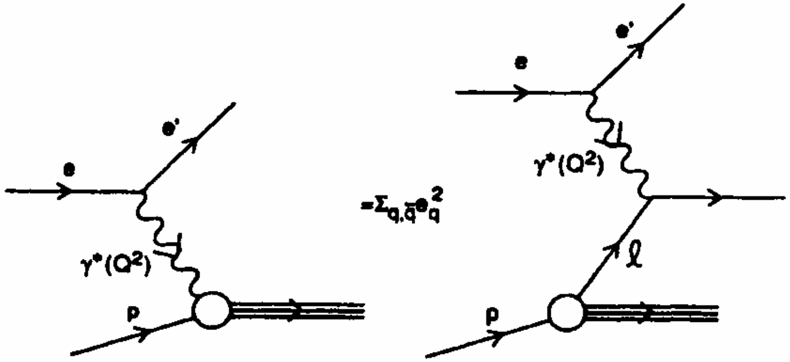
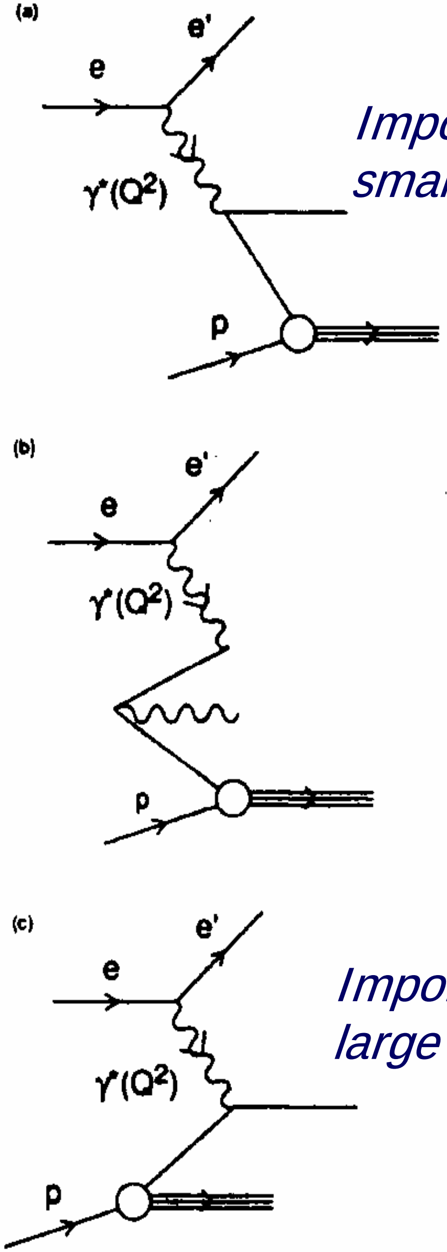


FIG. 1. DIS in the infinite-momentum frame.

See "*Space-time structure of deep-inelastic lepton-hadron scattering*," Del Duca, Brodsky, Hoyer PRD 46 (1992) p. 931



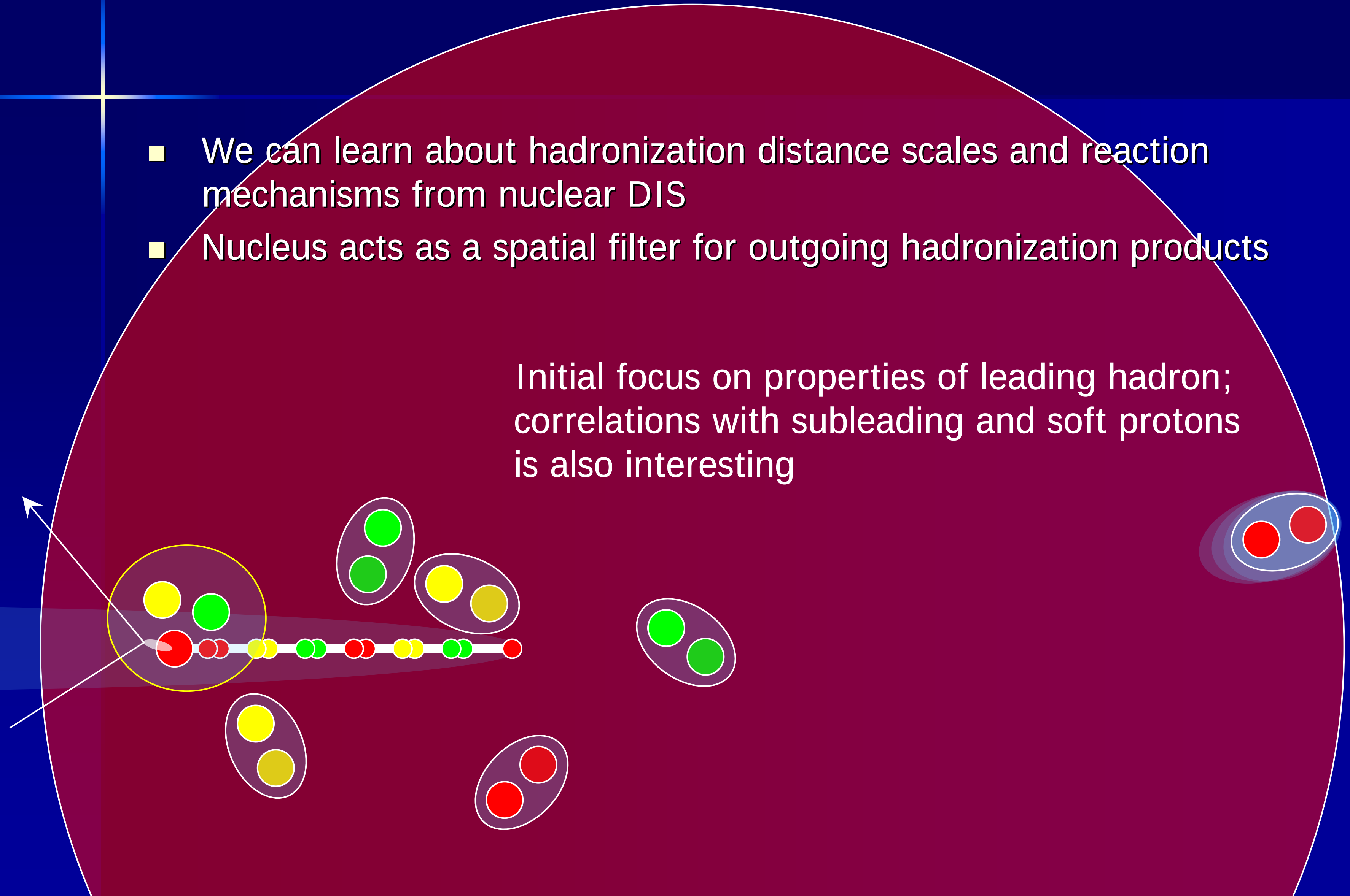
Important at small x

Important at large x

FIG. 2. Time-ordered contributions to DIS in the target rest frame.

Nuclear Deep Inelastic Scattering

- We can learn about hadronization distance scales and reaction mechanisms from nuclear DIS
- Nucleus acts as a spatial filter for outgoing hadronization products



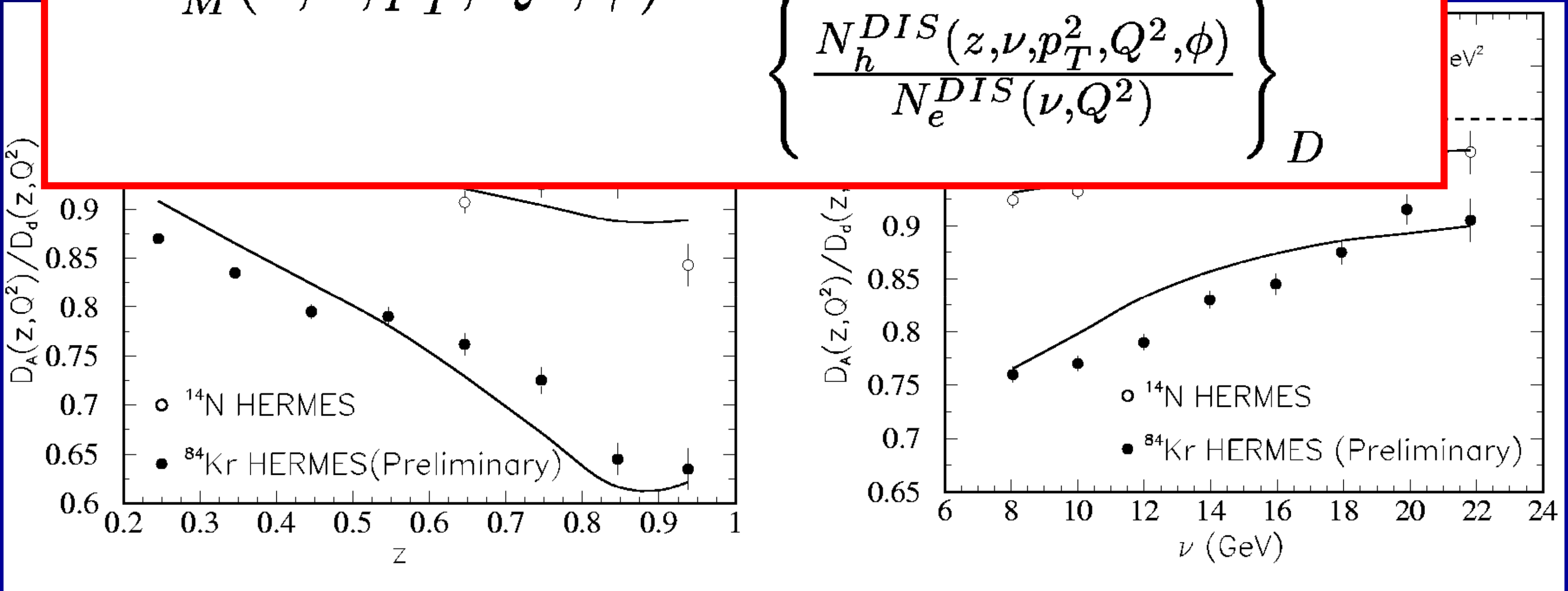
Initial focus on properties of leading hadron; correlations with subleading and soft protons is also interesting

Observables

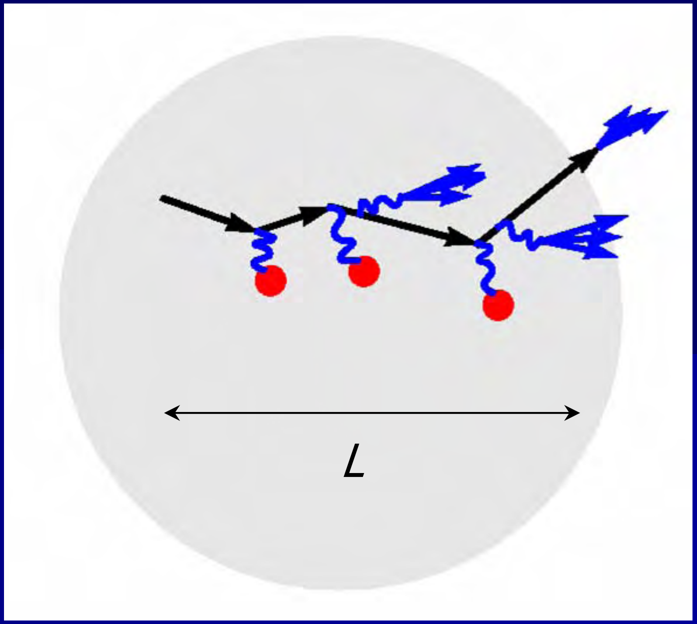
Hadronic multiplicity ratio

$$R_M^h(z,\nu) = \frac{\left\{\frac{N_h(z,\nu)}{N_e^{DIS}(\nu)}\right\}_A}{\left\{N_h(z,\nu)\right.}$$

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



Quark-Gluon Dynamics



- Struck quark emits gluons in vacuum because of confinement
- In nuclear medium, multiple scattering will stimulate *additional* gluon radiation; may vary as L^2 (!) – QCD LPM effect
- Gluon radiation creates dE/dx that can be connected to transverse momentum broadening (an experimental observable):

$$dE/dx \approx \frac{\alpha_s}{\pi} N_c \langle p_T^2 \rangle_L$$

- Indications from models and data suggest dE/dx may be of measurable size, ~ 1 GeV/fm
- There is an associated quark-gluon correlation function (Guo and Qiu, PRD61, 096003, 2000)
- Energy loss is proportional to the *gluon density* of the medium

Drell-Yan: 800 GeV protons on a variety of nuclear targets (McGaughey, Moss, Peng, Ann. Rev. Nucl. Part. Sci. 49, 271 (1999)

Transverse momentum broadening from Fermilab Drell-Yan Experiments

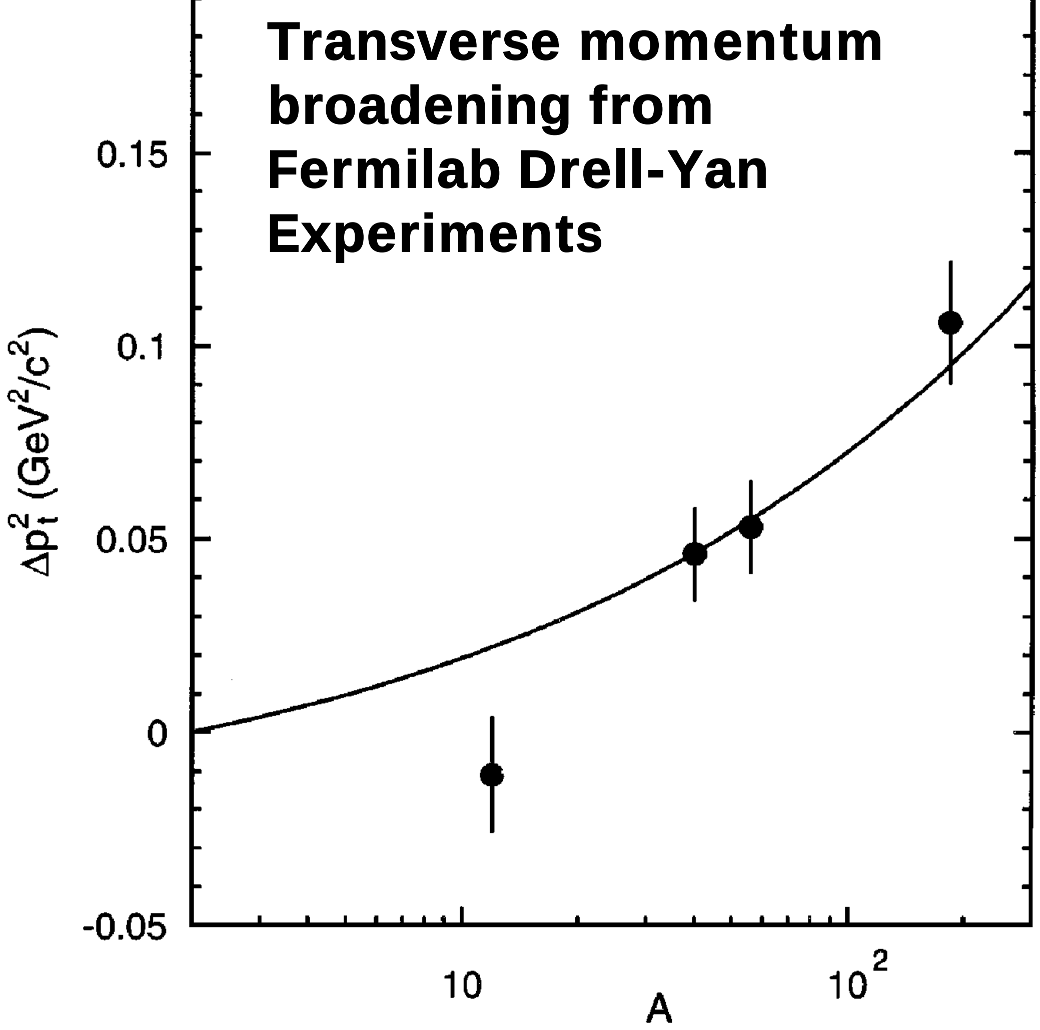


Figure 15 $\boxed{\Delta\langle p_t^2\rangle \equiv \langle p_t^2\rangle(A) - \langle p_t^2\rangle(^2H)}$ versus A for the DY process from E772 (123; PL McGaughey, JM Moss, JC Peng, unpublished data). Solid curve corresponds to $0.027((A/2)^{1/3} - 1)$.

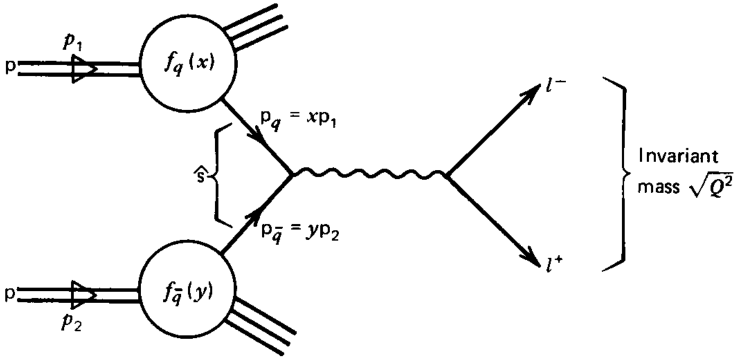
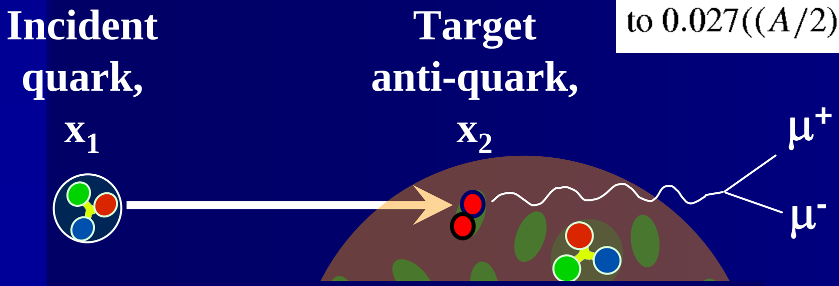


Fig. 11.14 The Drell–Yan process, pp → l^-l^+X.



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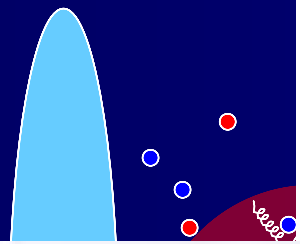
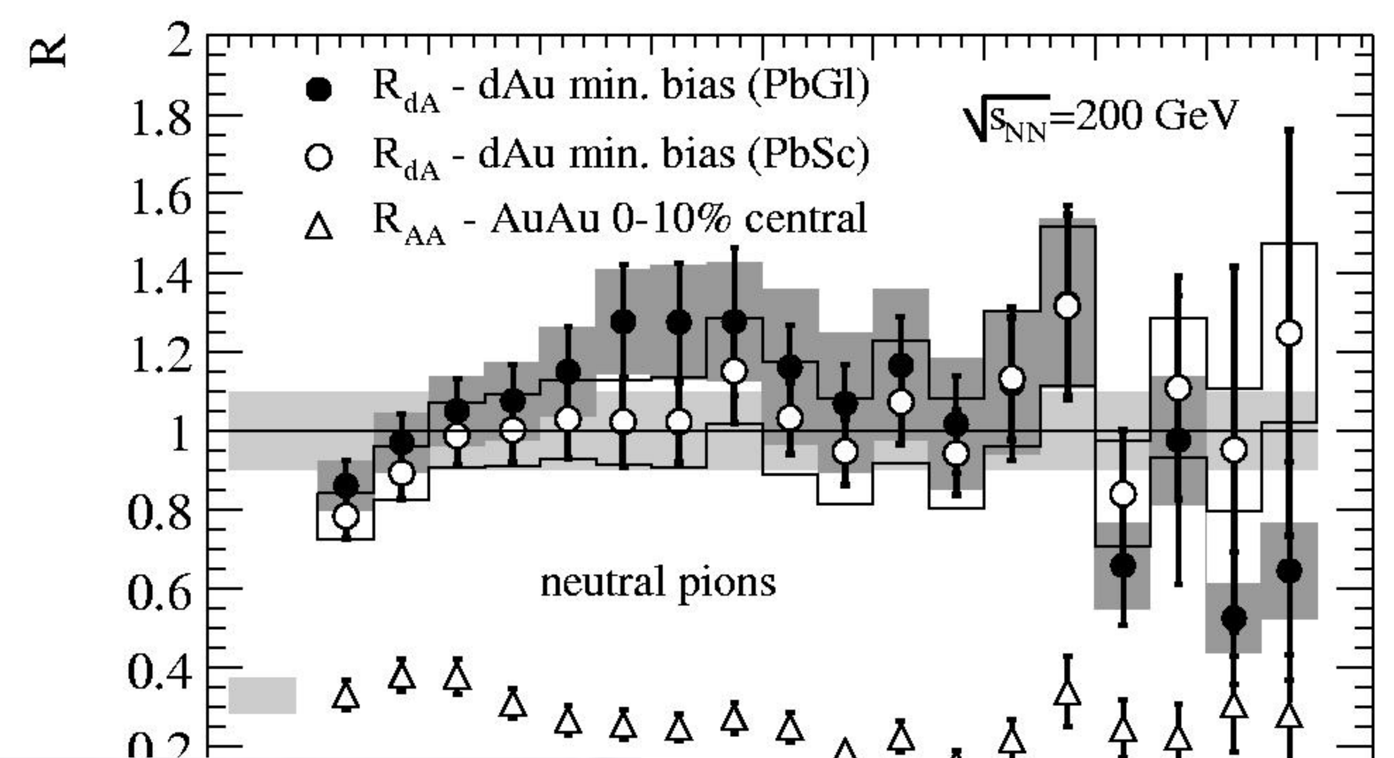
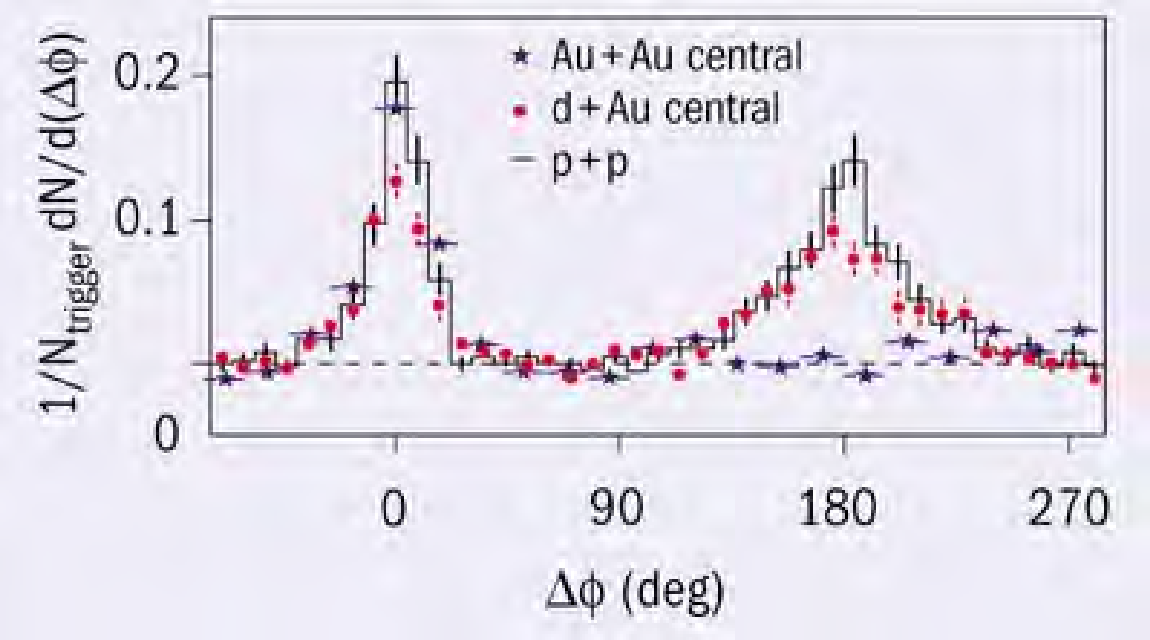
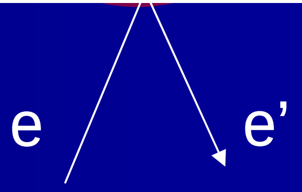
Relativistic He







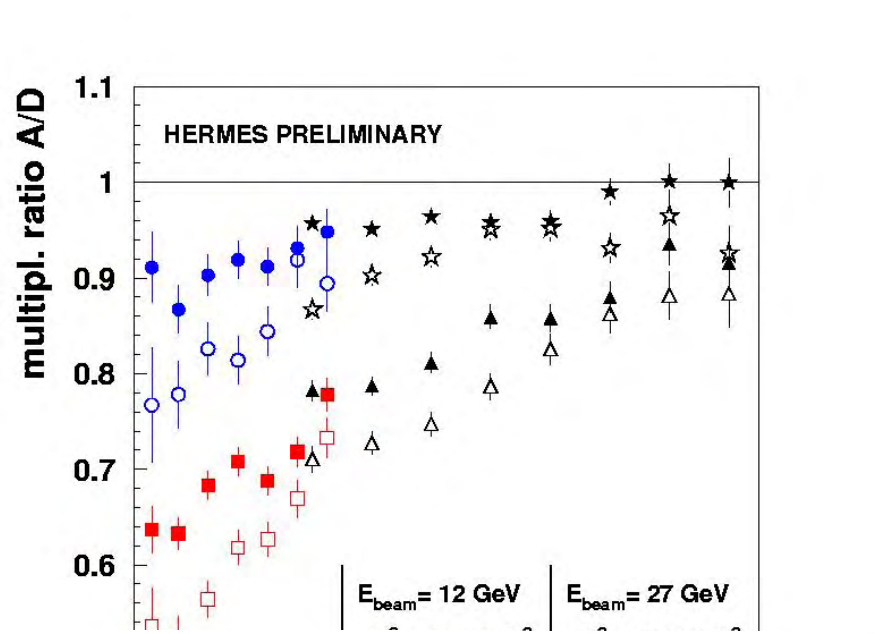


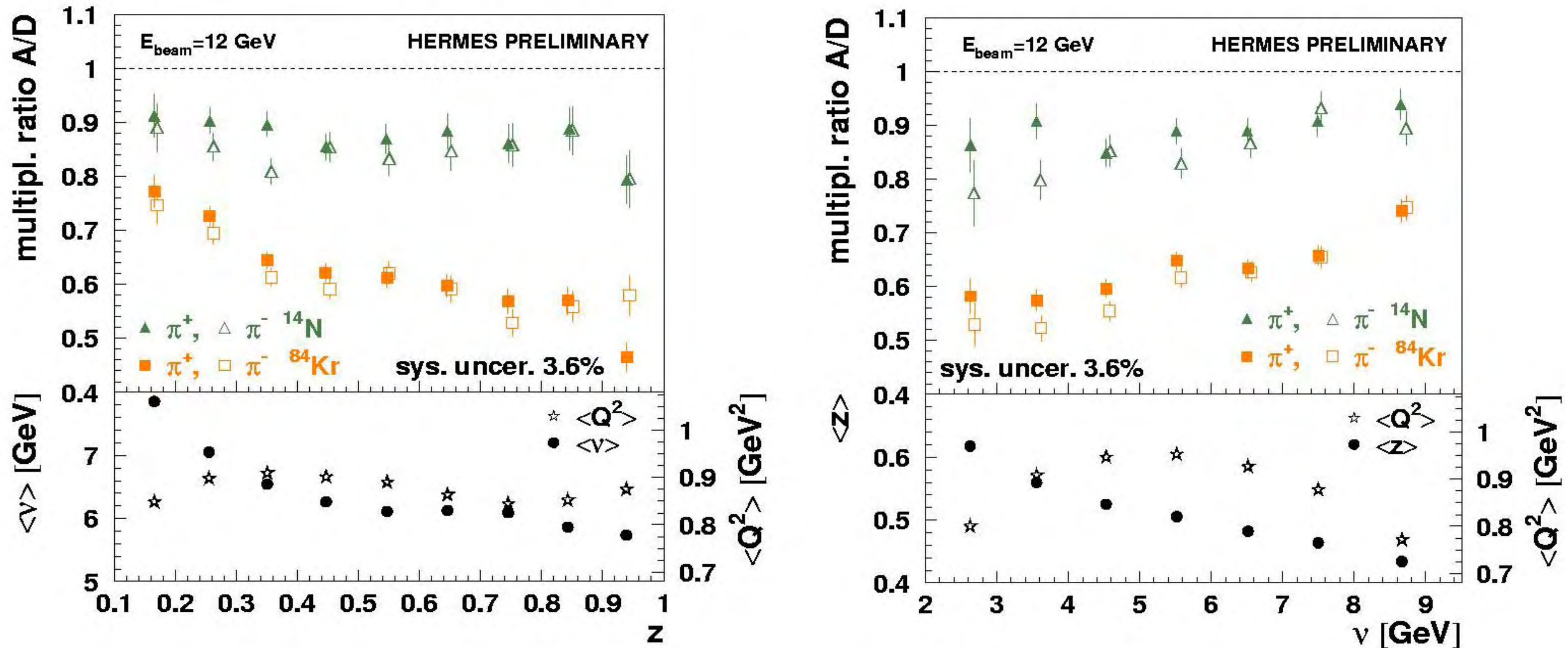
tial quark energy is known
perties of medium are known

HERME

Summary of

- Mostly 27 G





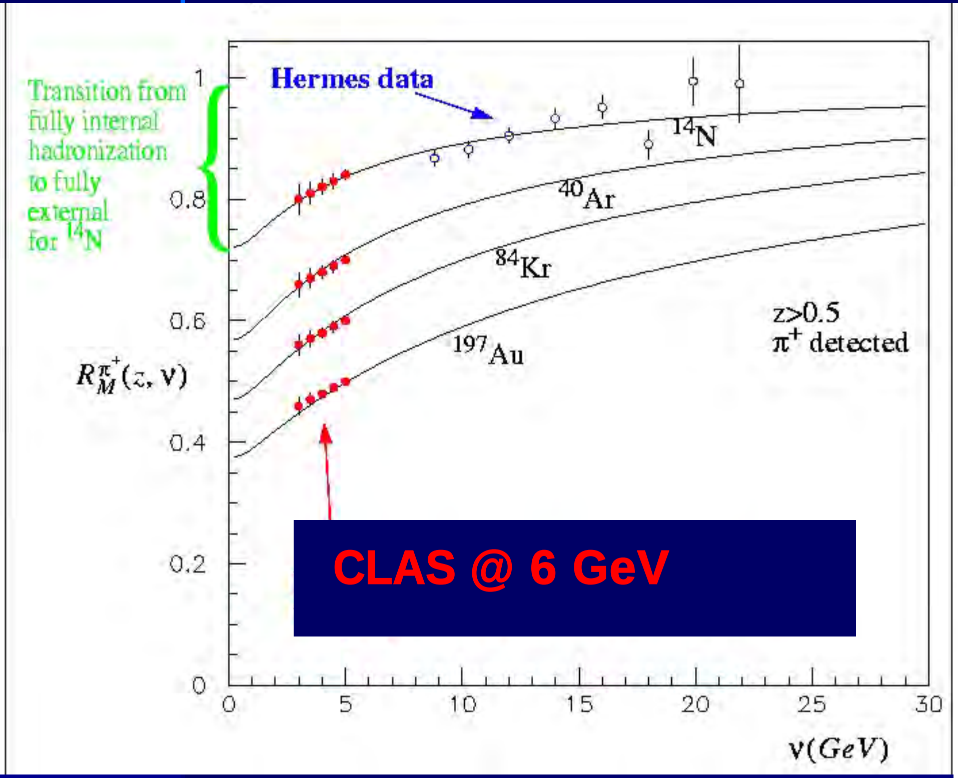
Jefferson Lab Experiments: Next 7 Years

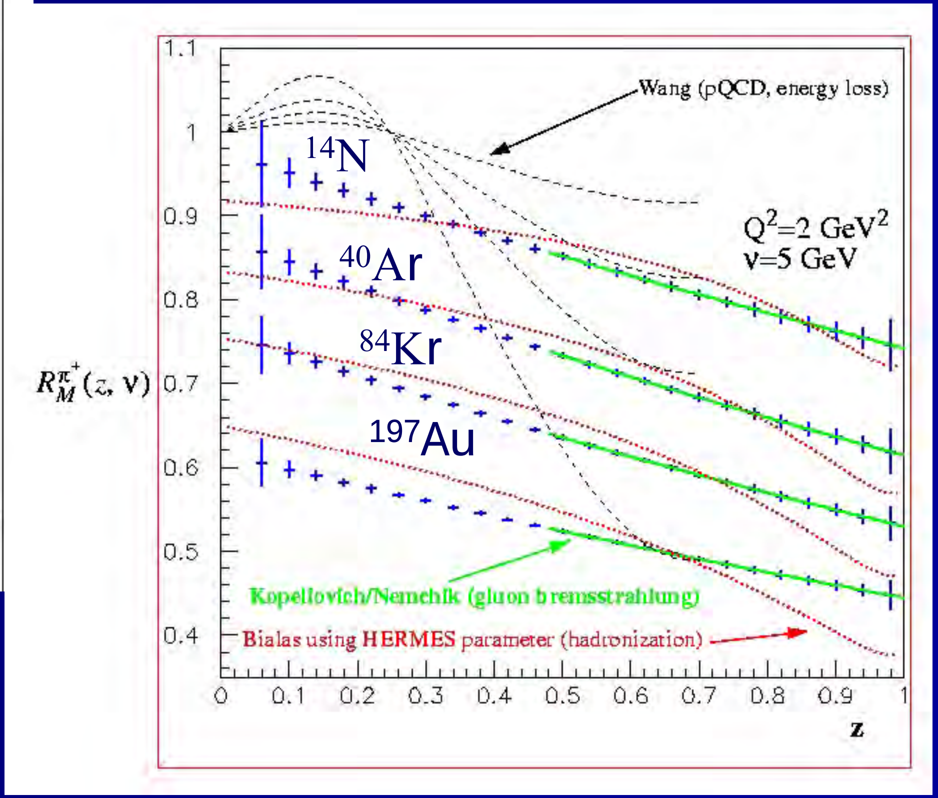
- E02-104 (Brooks, CLAS EG2) in Hall B
  - Took part of data in January-February 2004
  - Hadronization, transverse momentum broadening surveyed over a wide kinematic range

- E04-002 (Chen, Norum, Wang) in Hall A
  - Hadronization in narrow kinematic bins with good particle ID for charged K and π
  - Waiting to get on the schedule

- Interest in Hall C (Ent, Gaskell, Keppel, Kinney)
  - Transverse momentum broadening in narrow kinematic bins with good particle ID for charged K and π
  - Proposal under discussion

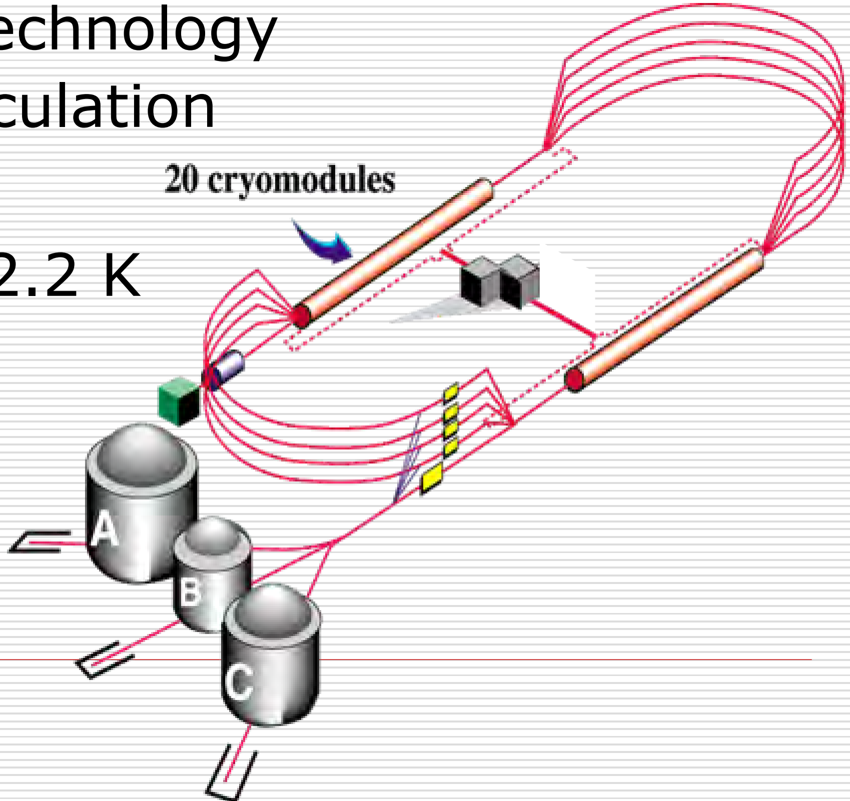
Sample of Anticipated 6 GeV Data



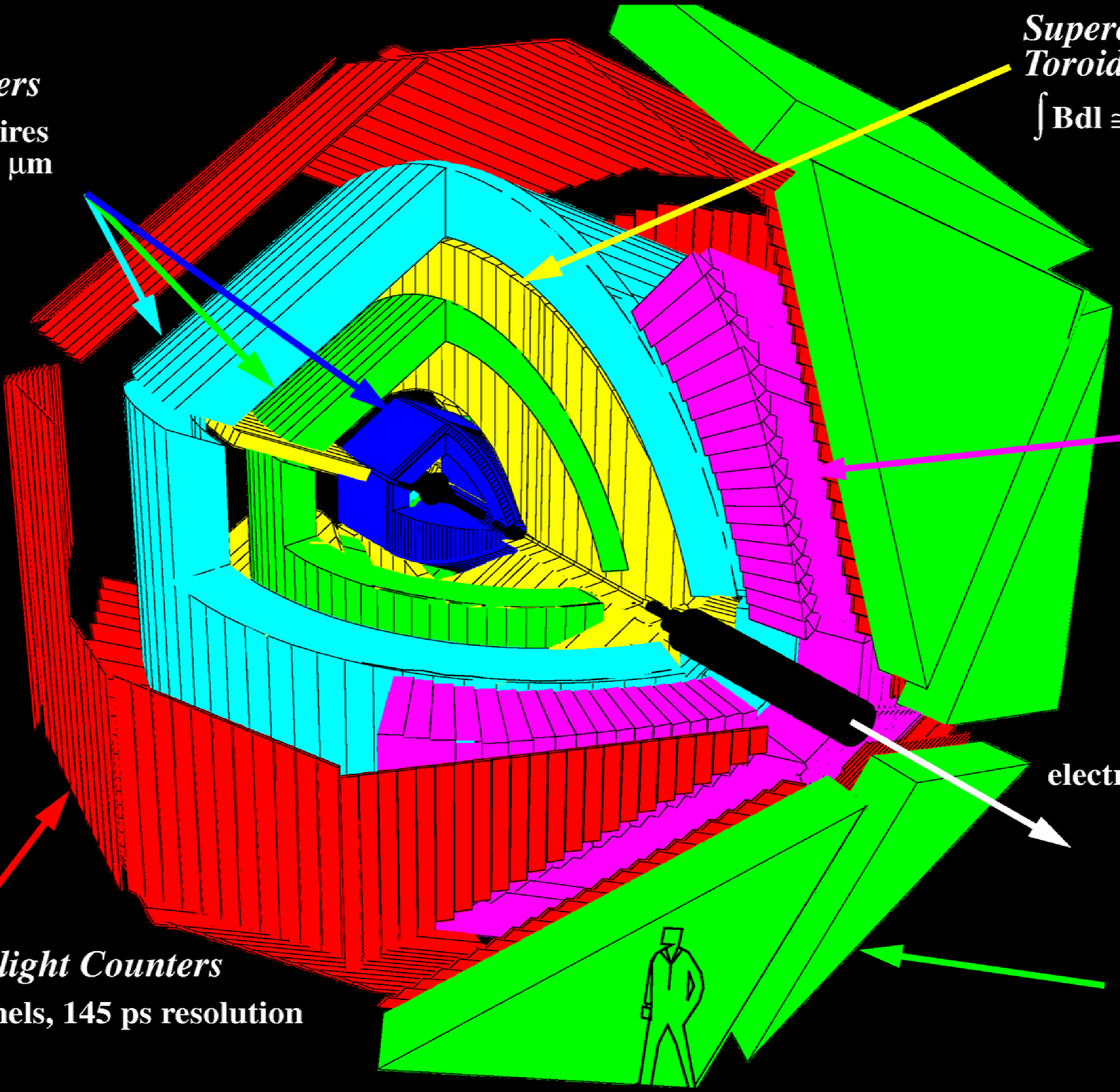


CEBAF at Jefferson Lab

- A high intensity, continuous electron beam recirculating accelerator
- Innovations
  - Superconducting RF technology
  - Multi-pass beam recirculation
- Cavities:
  - 338 5-cell cavities at 2.2 K
  - 1497 MHz, ≤12 MV/m
  - $Q_0>5\times10^9$



CLAS – the CEBAF Large Acceptance Spectrometer



Drift Chambers

35,000 wires
$\sigma_R = 350\ \mu m$

Superconducting Toroidal Magnet

$\int B dl \cong 1.7$ T-m

Cerenkov Counters

216 channels
99.5% efficient
over 50 m^2 area

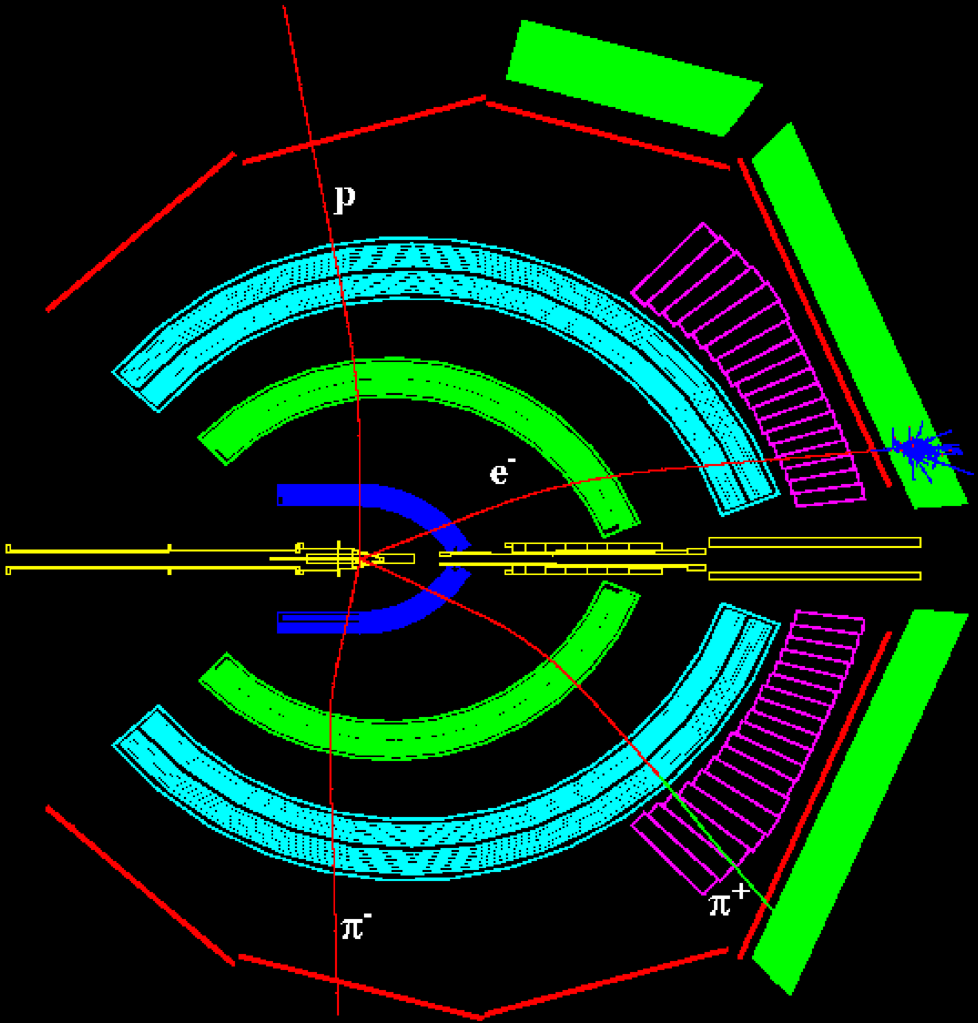
electron beam direction

Electromagnetic Shower Calorimeters

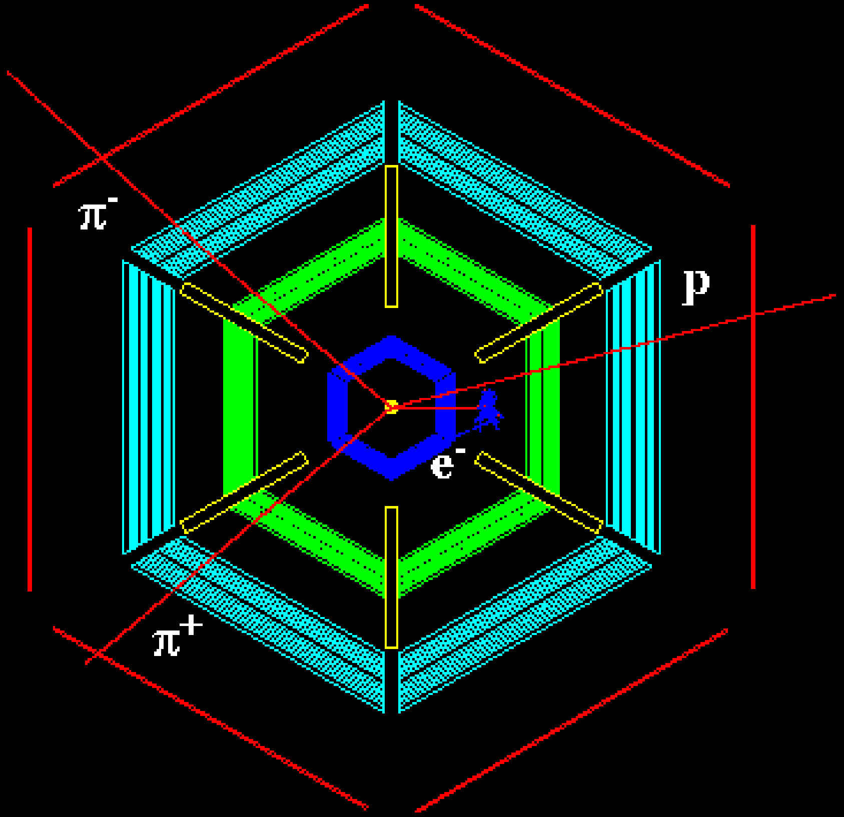
1700+ channels
$\sigma/E = 10\%/E^{0.5}$

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^+

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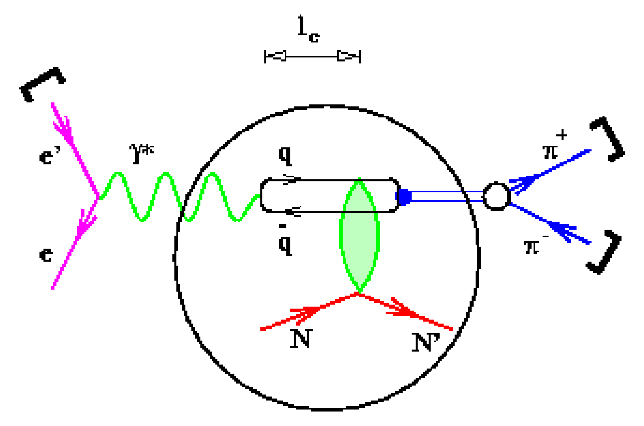
CLAS EG2

Physics Focus

Search for Color Transparency

Measure rho absorption vs. Q^2 at fixed coherence length

Compare absorption in deuterium, carbon, aluminum, and iron

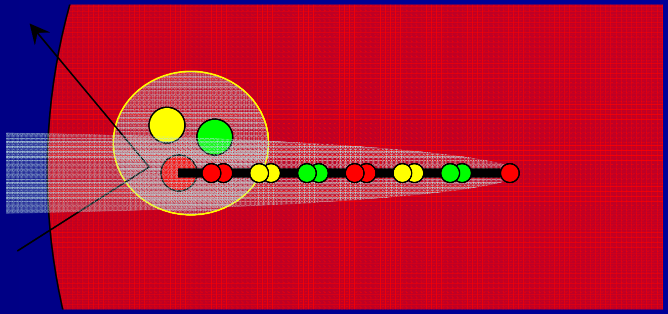


E02-110

Quark Propagation through Nuclei

Measure attenuation and transverse momentum broadening of hadrons (π, K) in DIS kinematics

Compare absorption in deuterium, carbon, iron, tin, and lead

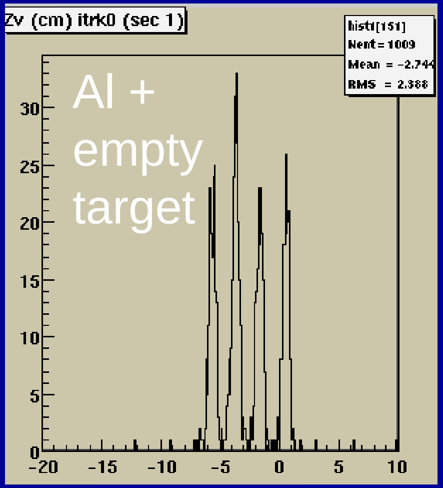


E02-104

CLAS EG2

Targets

- *Two* targets in the beam simultaneously
- 2 cm LD2, upstream
- Solid target downstream
- Six solid targets:
  - -Carbon
  - -Aluminum (2 thicknesses)
  - -Iron
  - -Tin
  - -Lead



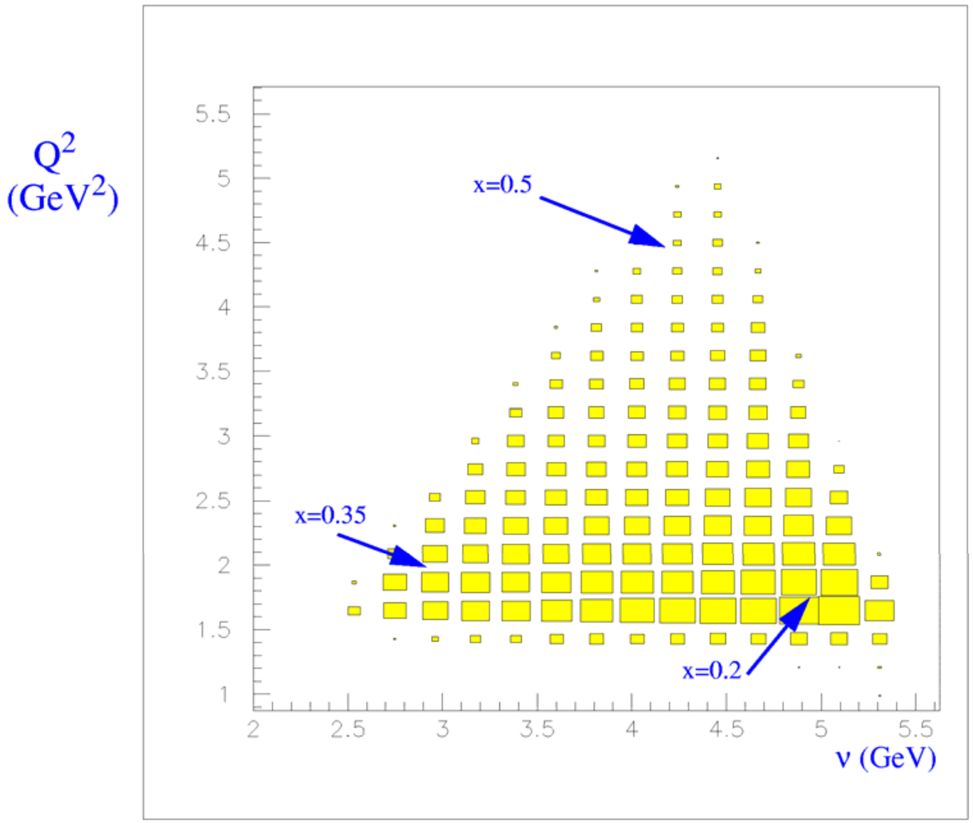
Al + empty target

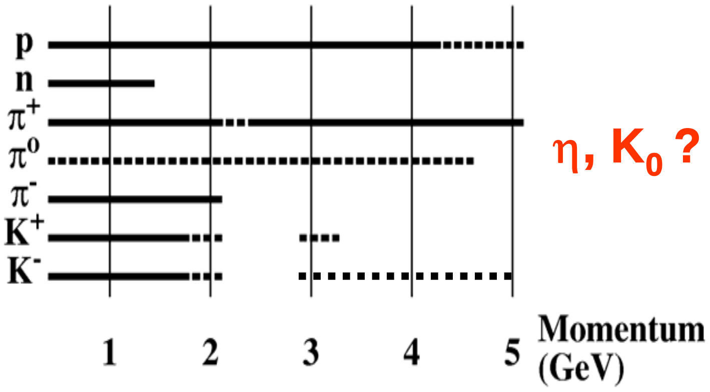
CLAS EG2

Running Conditions

- Beam energies: 4 GeV (7 day) and 5 GeV (50 days)
- Luminosity: 1.9-2.0 E34 (D+Fe), 1.3 E34 (D+Pb)
- Data taking:
  - DC occupancy < 3%,
  - deadtime 7% (D+Pb) and 14% (D+Fe)
- Number of triggers:
  - 0.6 billion (D+Fe, 4 GeV)
  - 2 billion (D+Fe, 5 GeV)
  - 1.5 billion (D+Pb, 5 GeV)
  - Anticipate ~1 billion (D+C, 5 GeV)
- Primary challenges:
  - Beam current stability
  - Beam profile
  - DAQ stability (December 2003 – January 2004)
  - DC gas (summer 2003) and temperature (December 2003)

CLAS Kinematic Coverage and Particle Identification at 6 GeV

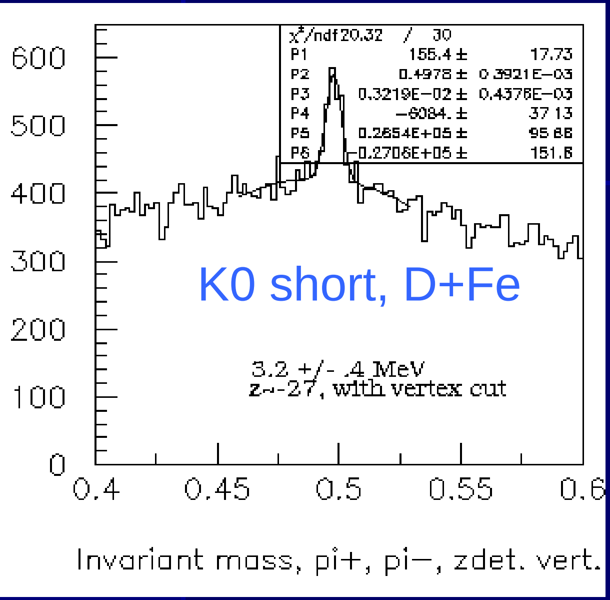




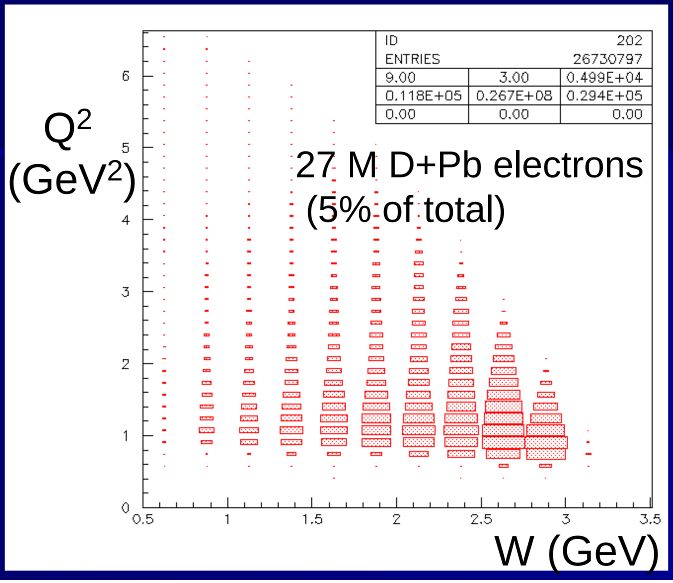
η, K_0 ?

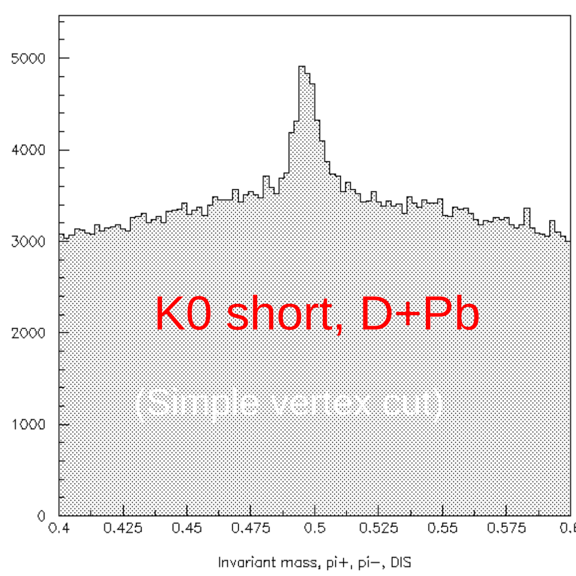
CLAS EG2

Online Physics Results

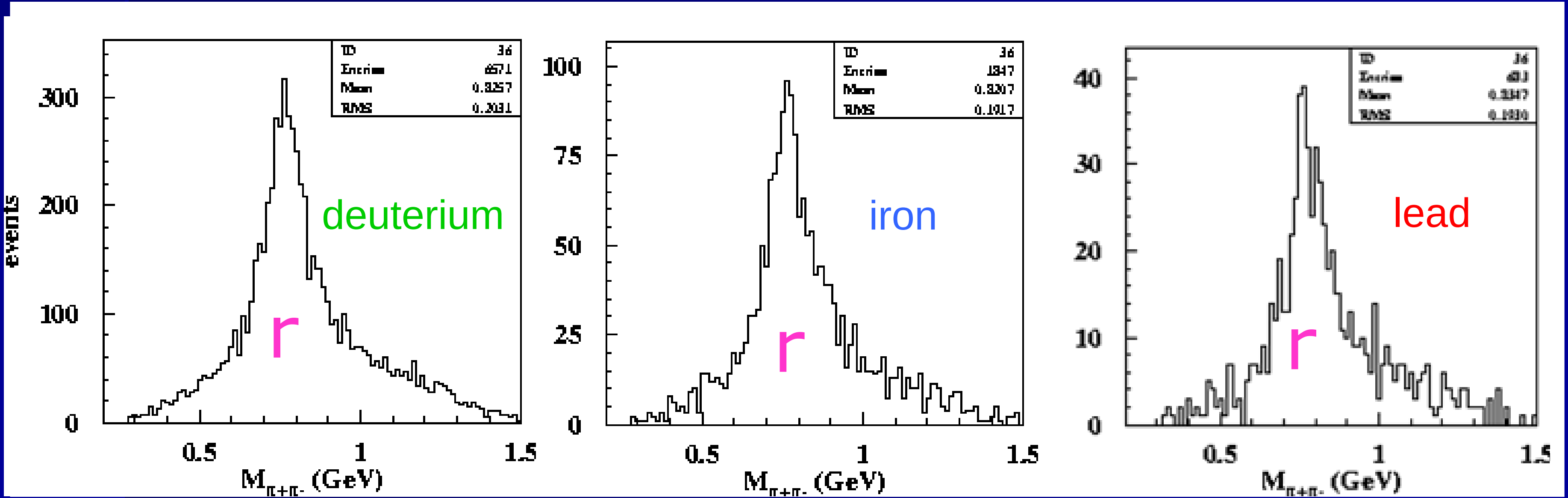

K0 short, D+Fe

3.2 +/- .4 MeV
z~-27, with vertex cut


27 M D+Pb electrons
(5% of total)


K0 short, D+Pb

(Simple vertex cut)


deuterium

iron

lead

Examples of studies that can be performed with CLAS high-luminosity data

- Multi-dimensional analysis – dependence on A, z, ν, p_T^2, Q^2, ϕ of
  - Hadronic multiplicity ratio
  - p_T^2 broadening
- Correlations
  - Between leading and next-to-leading hadron
  - Between leading hadron and soft transverse protons
- Others?
  - Hoping for more ideas from this workshop!

Preliminary Results from EG2

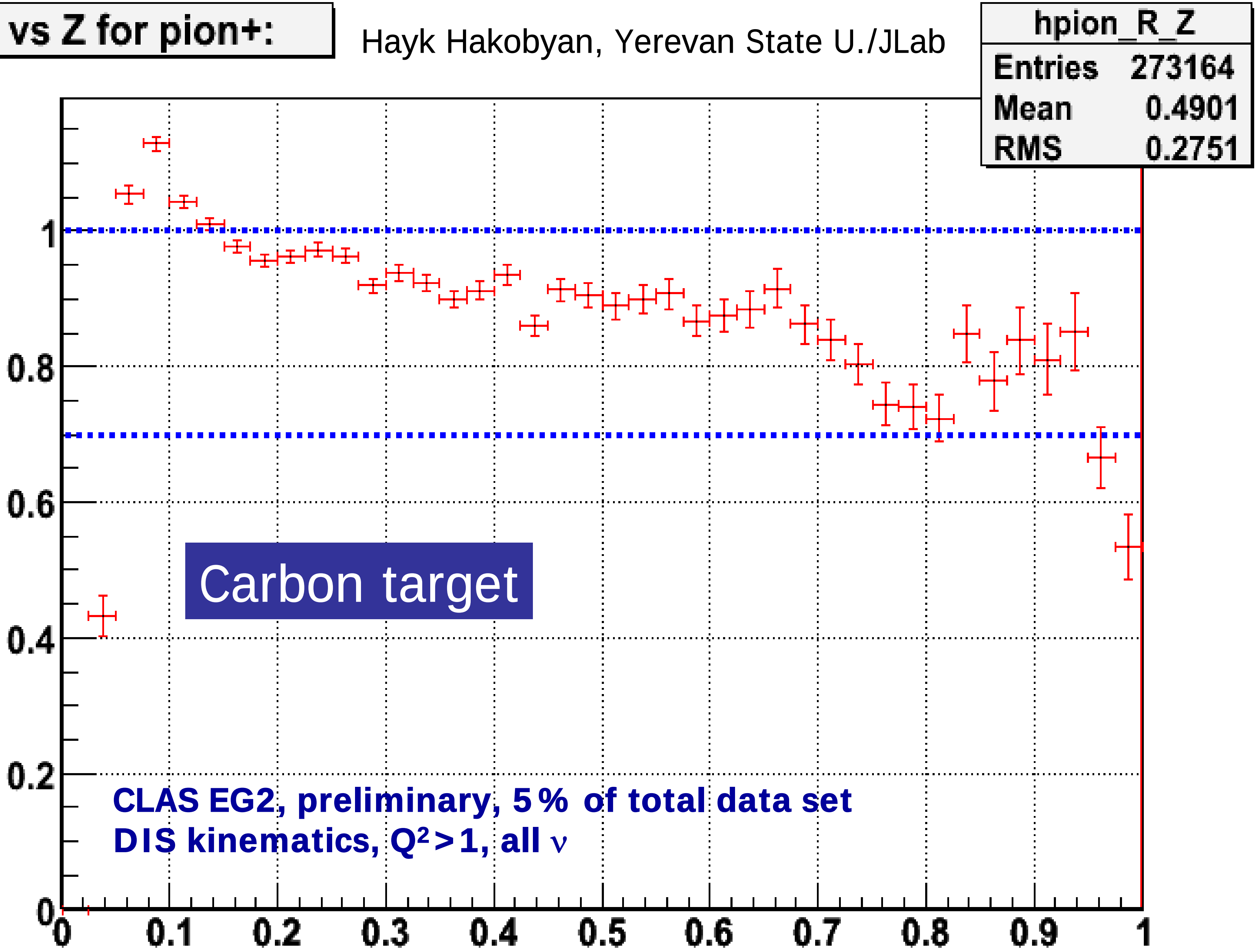
- Based on 5% of data with preliminary calibrations
- Disclaimers and caveats:
  - No acceptance correction (small, two targets in the beam)
  - Not final calibrations (should be nearly irrelevant, bins are huge)
  - No fiducial cuts (probably ok, two targets in beam)
  - No radiative correction (effect primarily cancels in ratios)
  - No correction for rho contribution of pi+ (need full statistics to correct for this)***
  - Few-percent kaon contamination in region 2-2.7 GeV
  - No isospin correction for heavy targets(~5%?)
  - No x_F cuts
- These disclaimers apply to all CLAS data in this talk!

Preliminary results: hadronic multiplicity ratio for leading π^+

$$\boxed{R_M^h(z,\nu) = \frac{\left\{\dfrac{N_h(z,\nu)}{N_e^{DIS}(\nu)}\right\}_A}{\left\{\dfrac{N_h(z,\nu)}{N_e^{DIS}(\nu)}\right\}_D}}$$

R vs Z for pion+:

Hayk Hakobyan, Yerevan State U./JLab

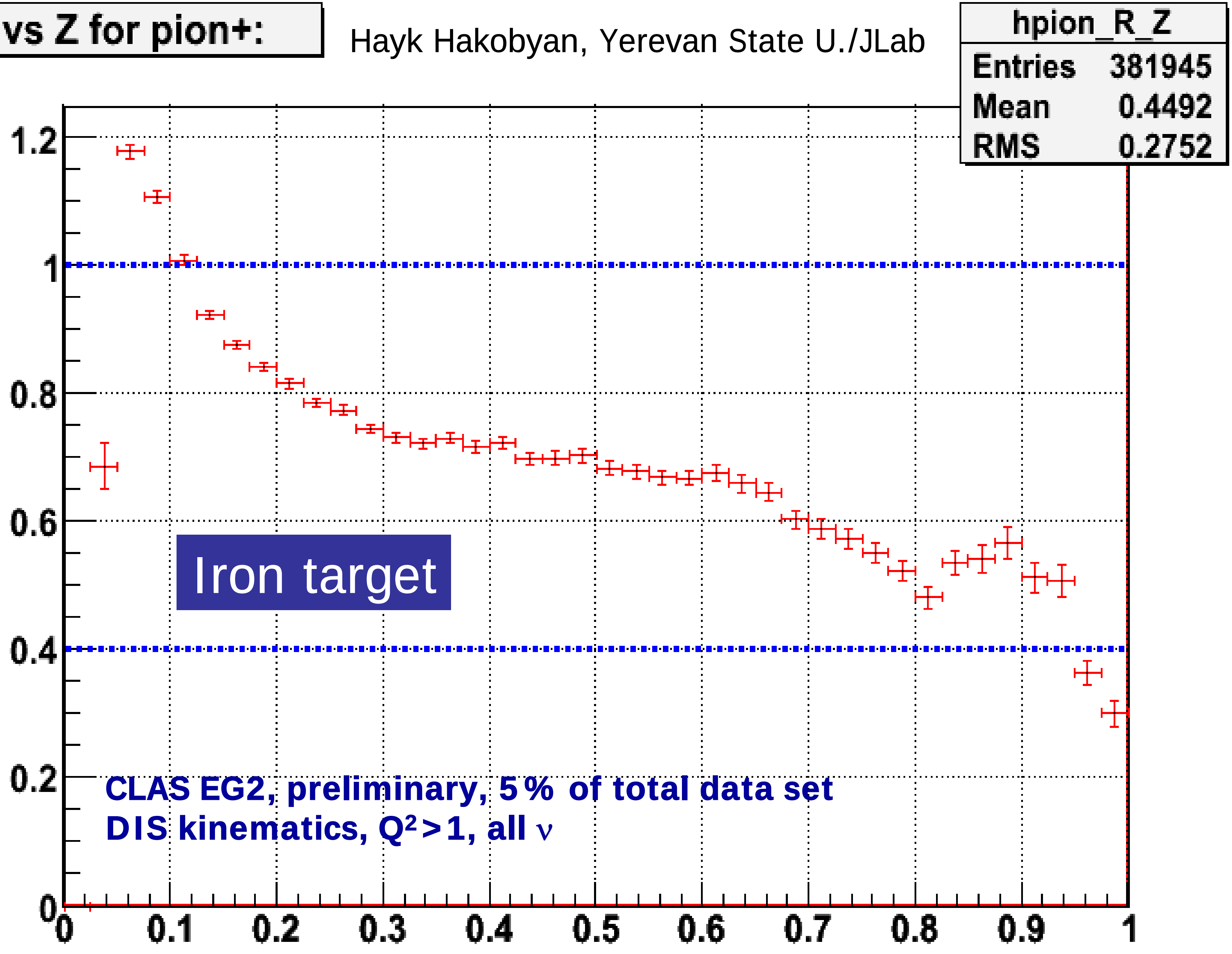


Carbon target

CLAS EG2, preliminary, 5% of total data set
DIS kinematics, $Q^2>1$, all ν

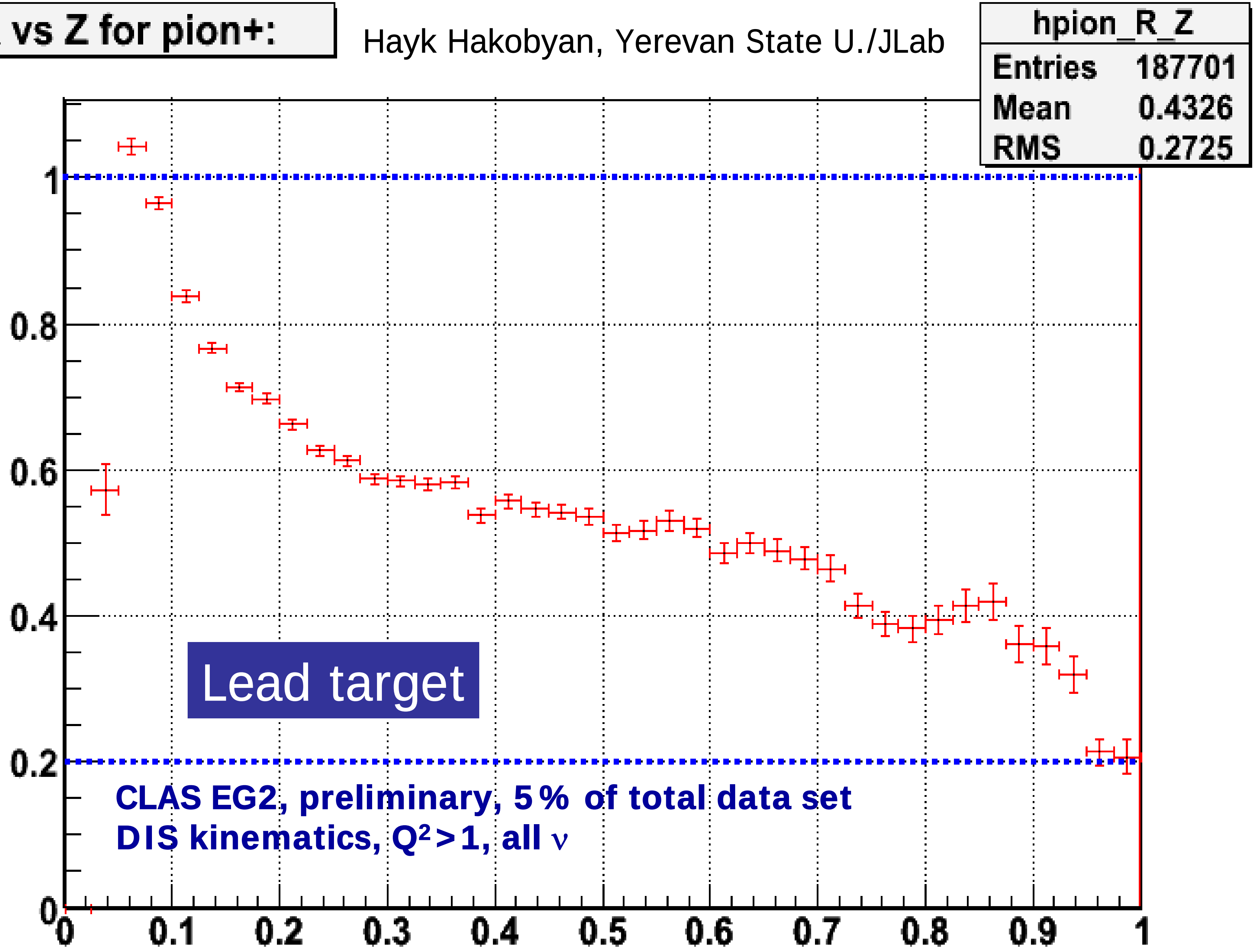
R vs Z for pion+:

Hayk Hakobyan, Yerevan State U./JLab



R vs Z for pion+:

Hayk Hakobyan, Yerevan State U./JLab

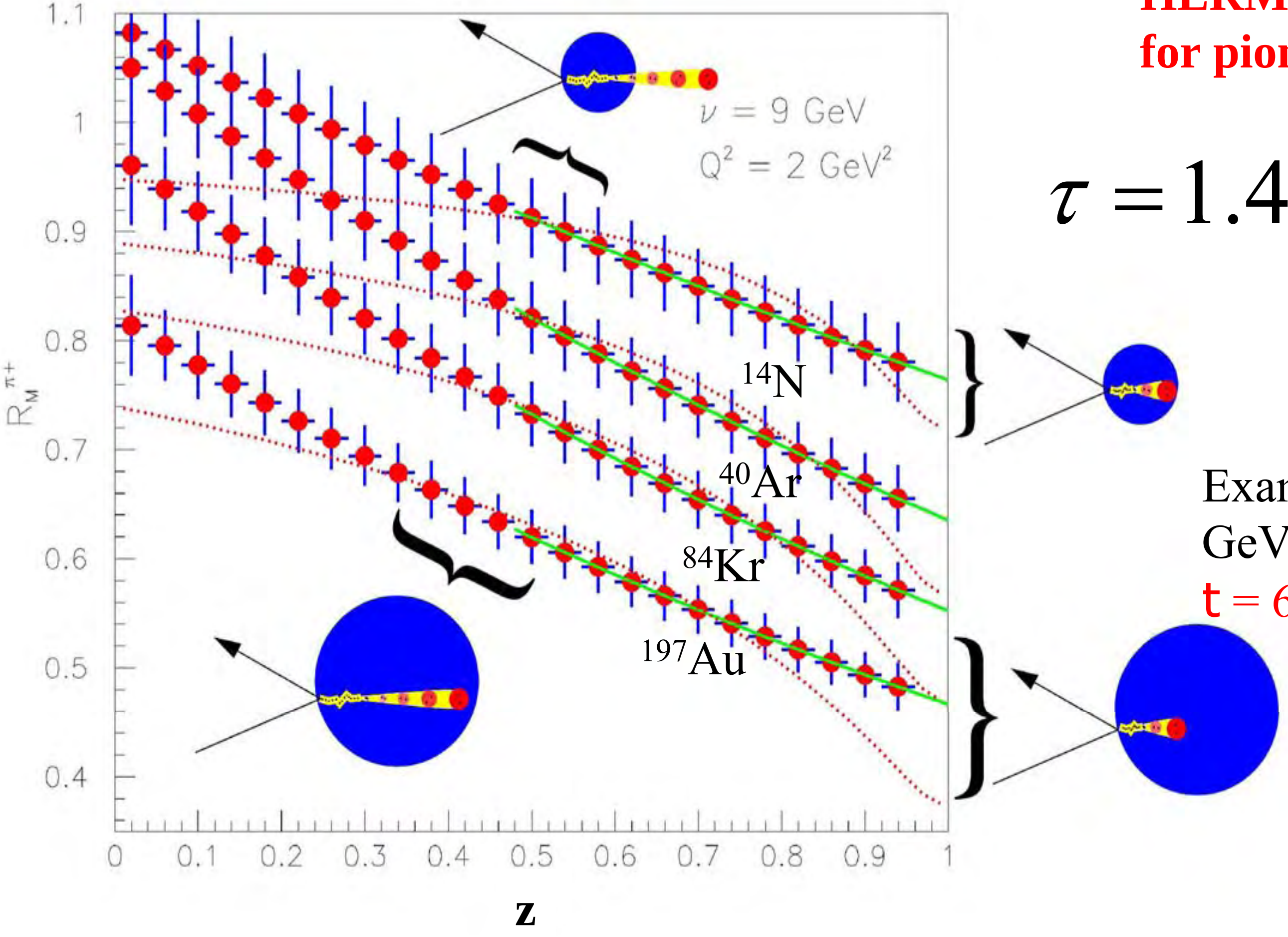


Lead target

CLAS EG2, preliminary, 5 % of total data set
DIS kinematics, $Q^2 > 1$, all ν

Interpretation of Hadronic Multiplicity Ratio

(concrete example in hadronization picture)



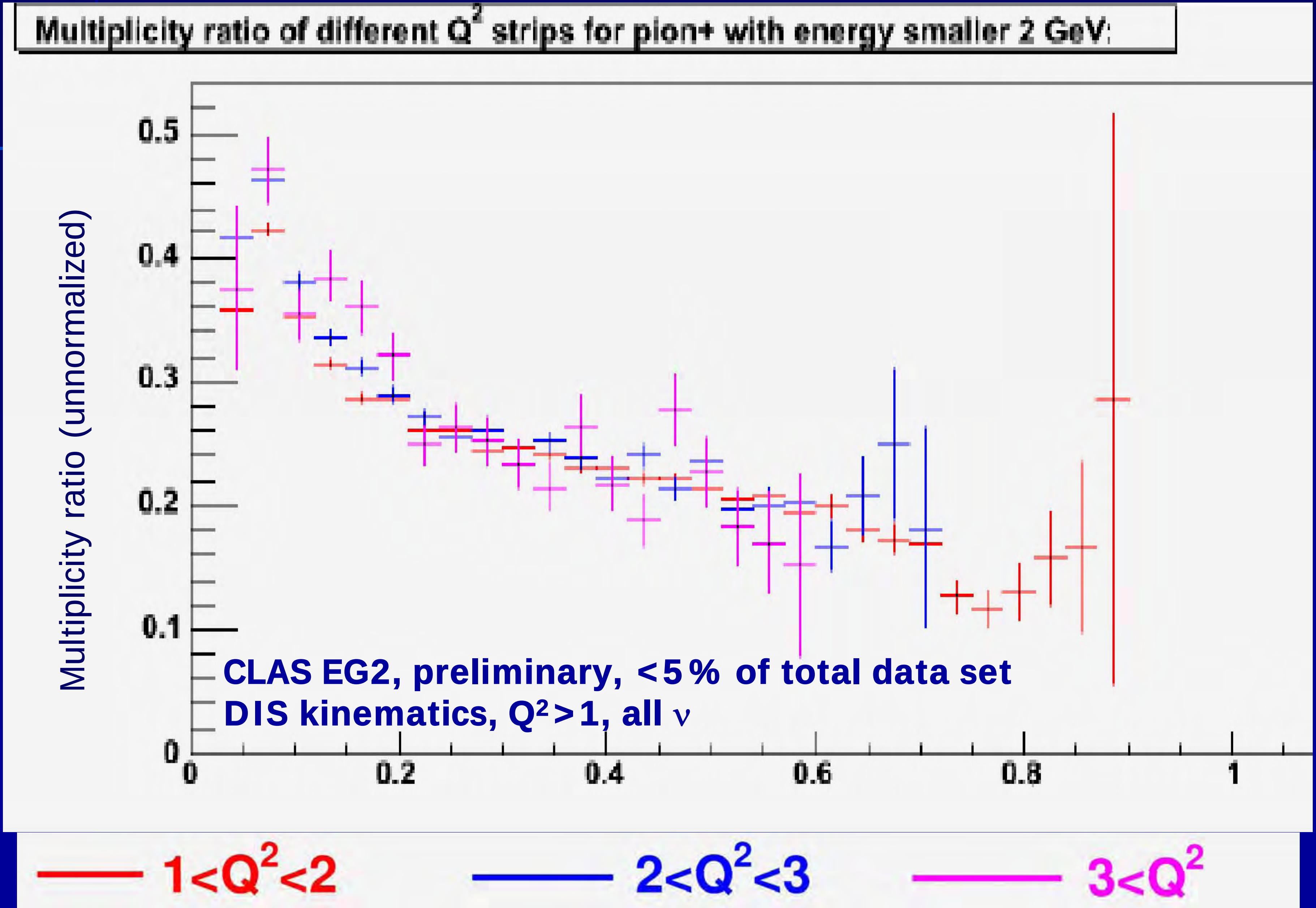
HERMES parameterization for pion formation length:

$$\tau = 1.4 \cdot \nu \cdot (1 - z)\ fm$$

Example: z = 0.5, n = 9 GeV,

t = 6.3 fm, ~ radius Pb

No strong Q^2 dependence seen

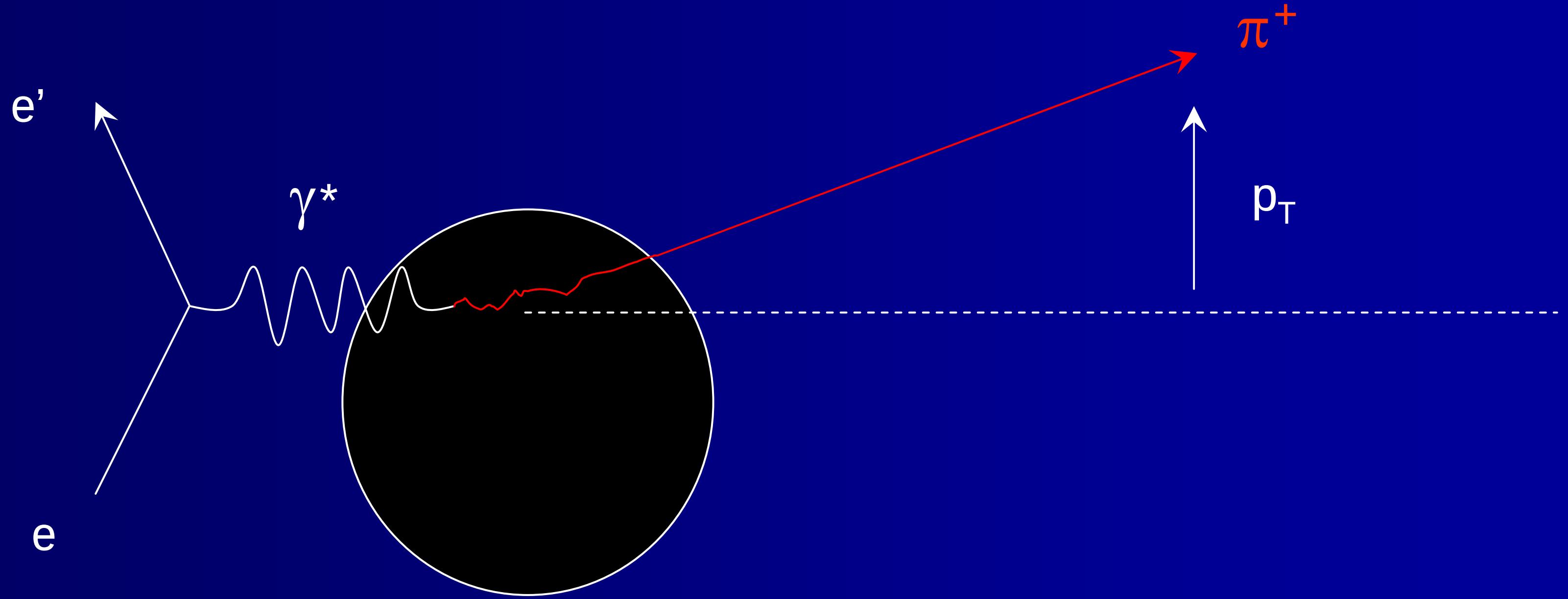


CLAS EG2, preliminary, <5% of total data set

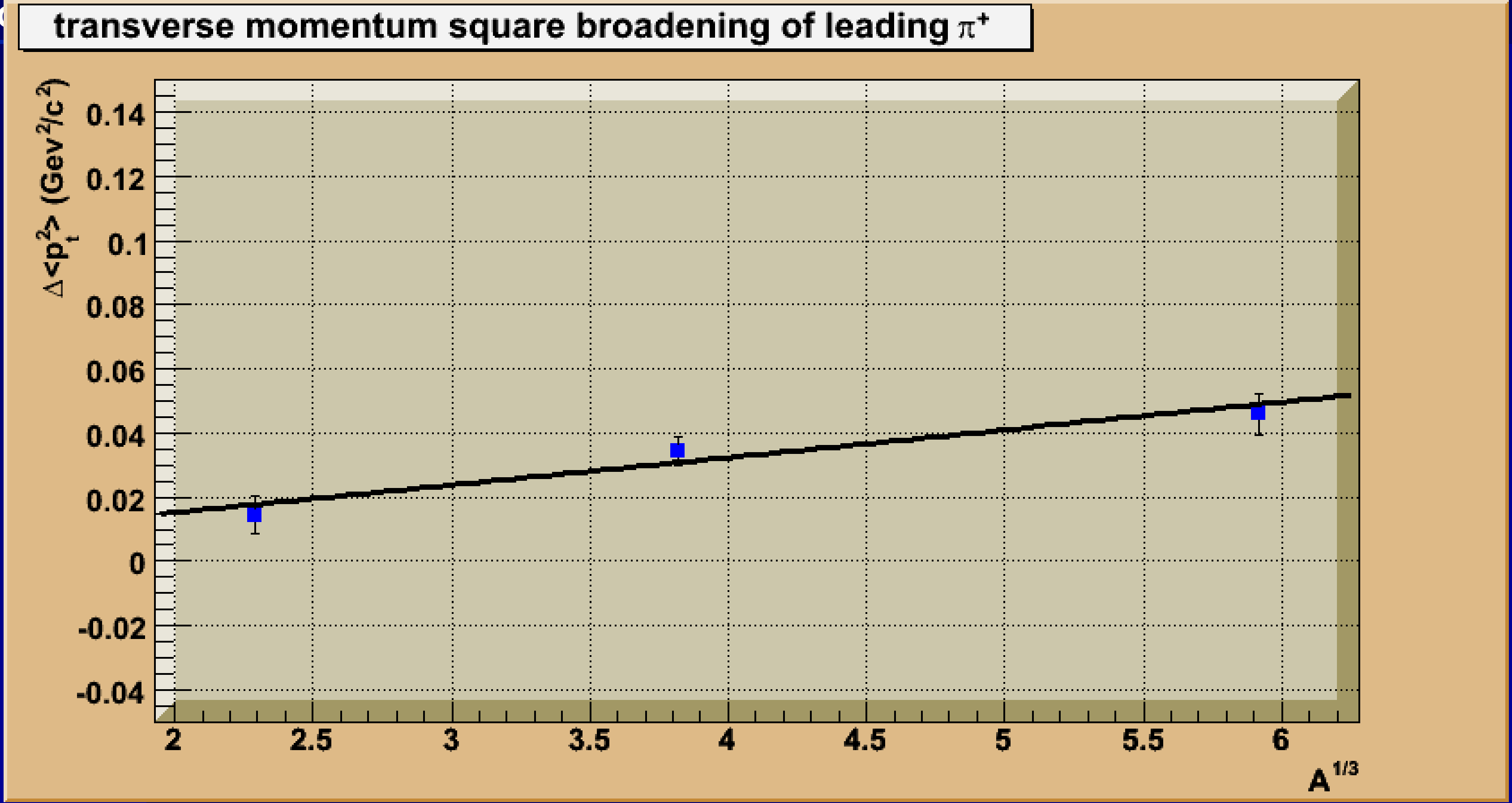
DIS kinematics, $Q^2>1$, all ν

Preliminary results: p_T^2 broadening for leading π^+

$$\Delta(p_T^2) = p_T^2(A) - p_T^2(^2H)$$

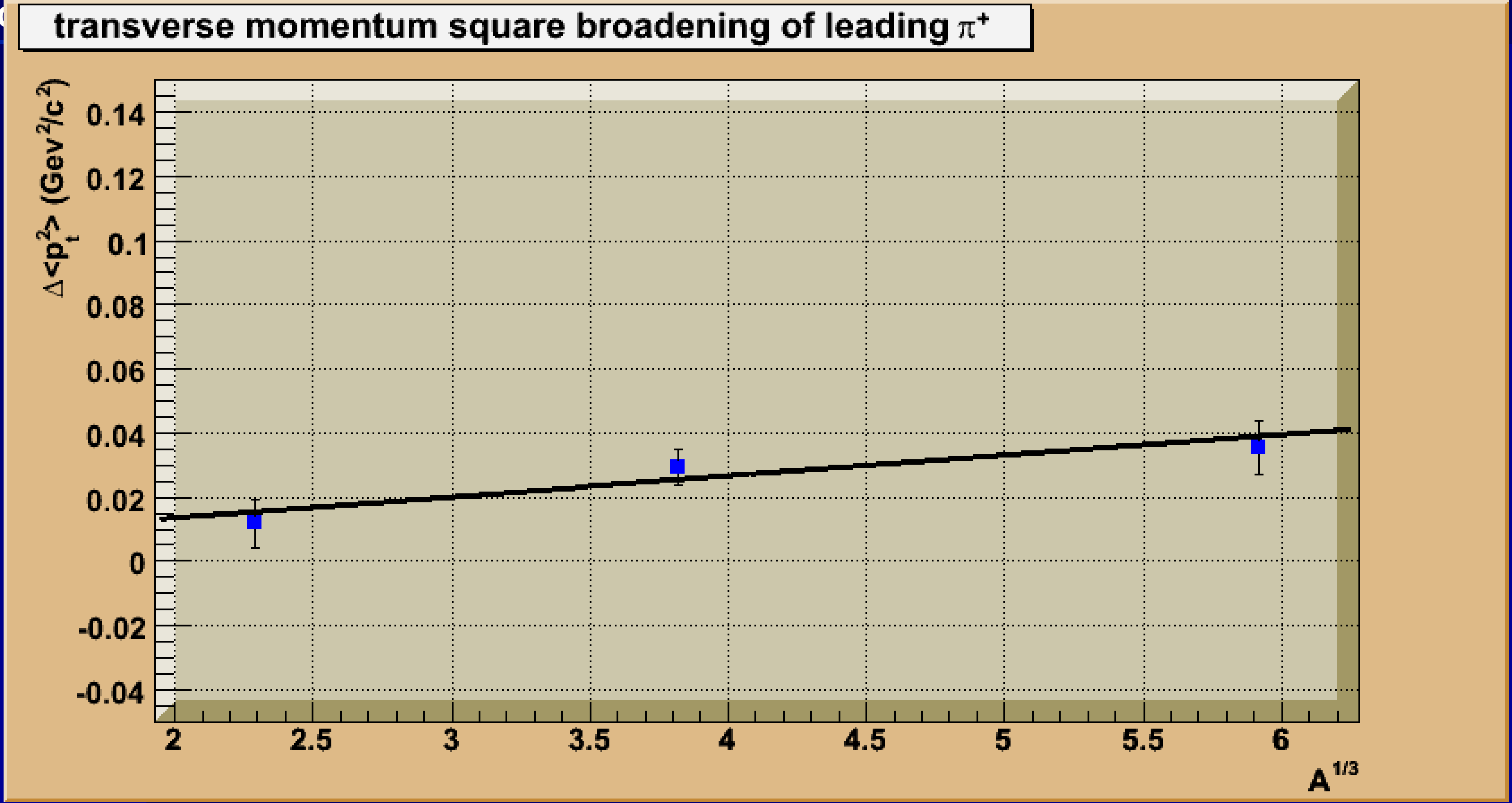


1 < Q2 < 2; 2 < nu < 3; 0.5 < Z < 0.6



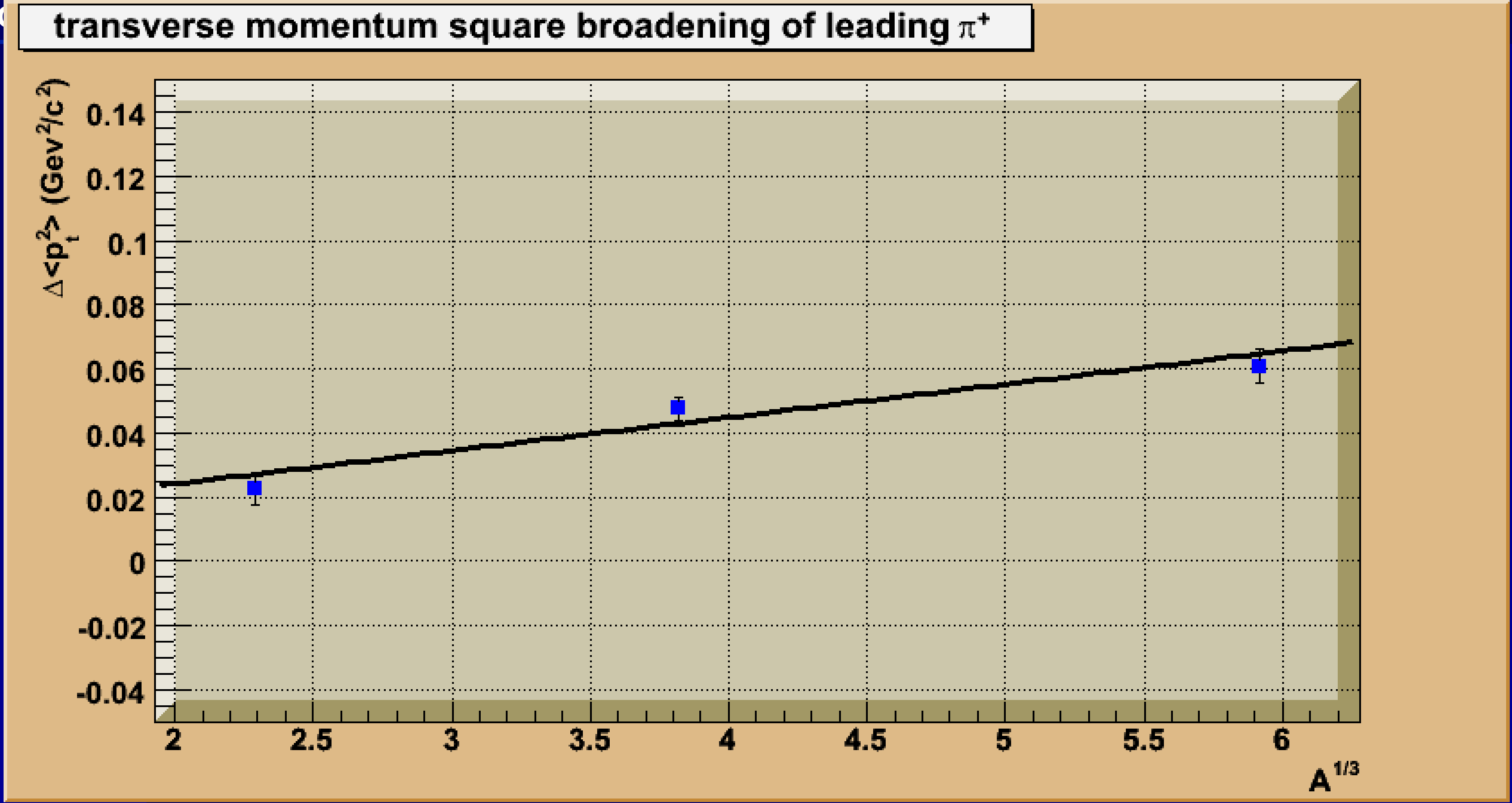
CLAS EG2 Preliminary
5 % of data

1 < Q2 < 2; 2 < nu < 3; 0.6 < Z < 0.7



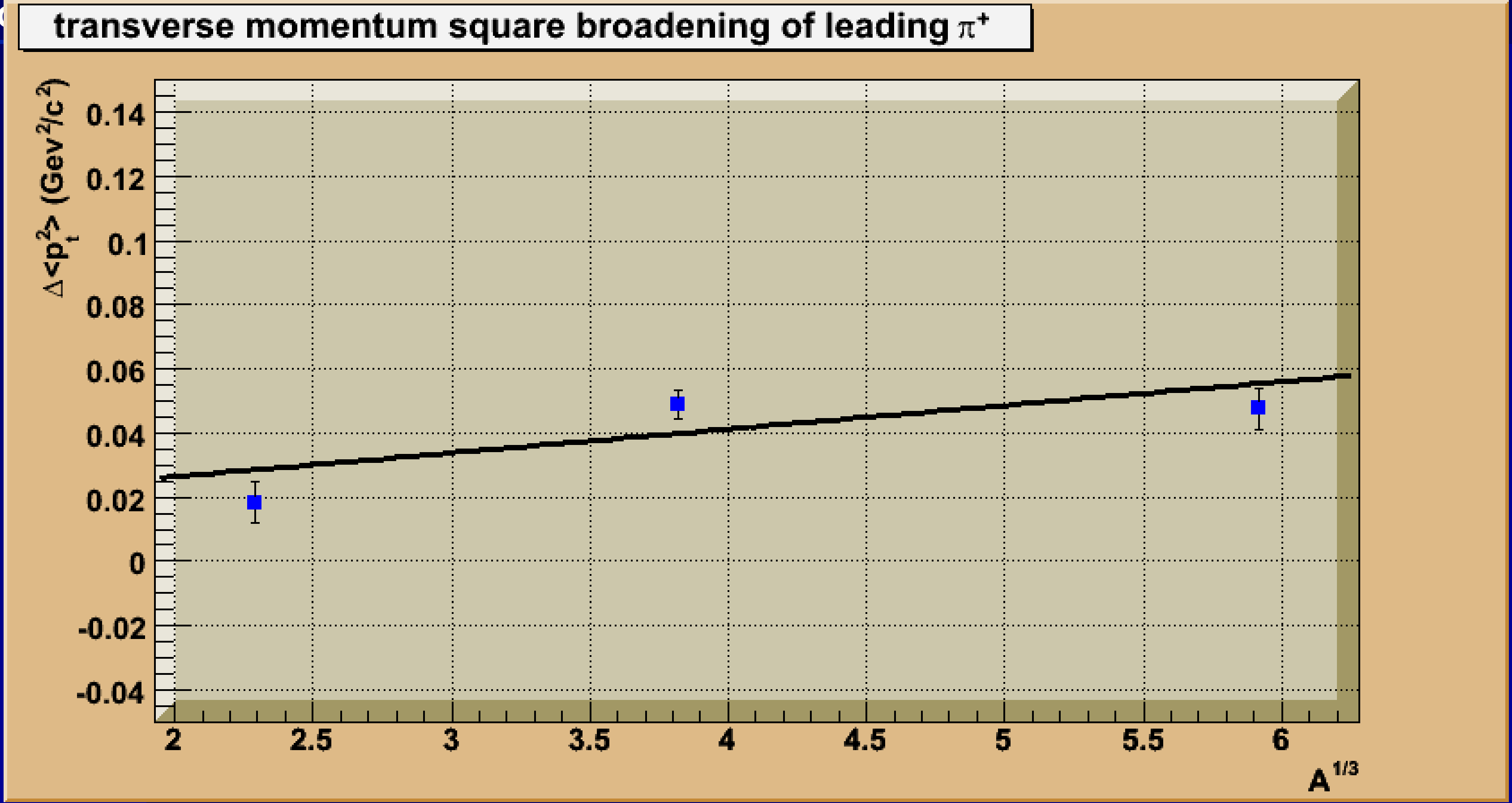
CLAS EG2 Preliminary
5 % of data

1 < Q2 < 2; 3 < nu < 4; 0.5 < Z < 0.6



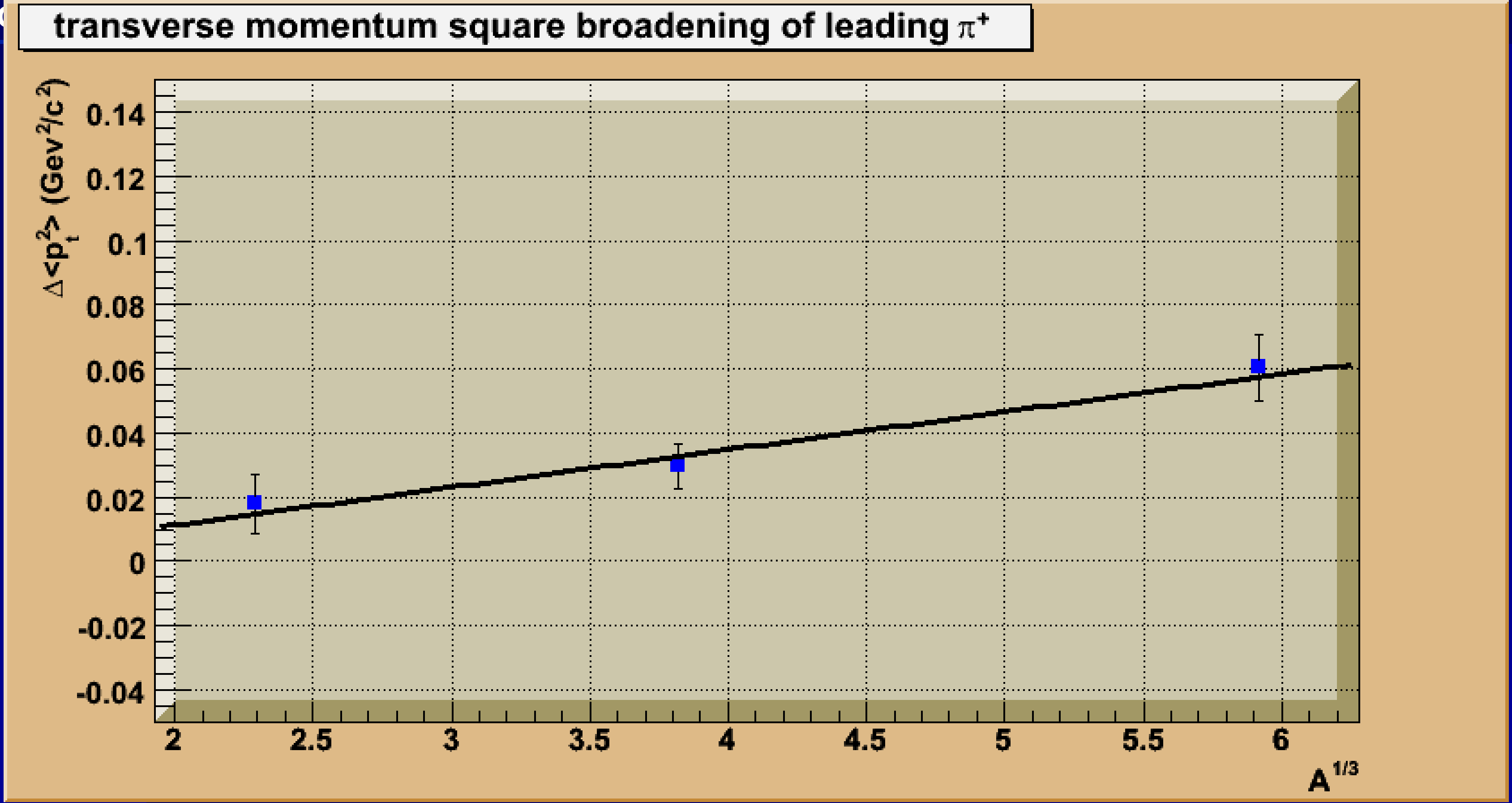
CLAS EG2 Preliminary
5 % of data

1 < Q2 < 2; 3 < nu < 4; 0.6 < Z < 0.7



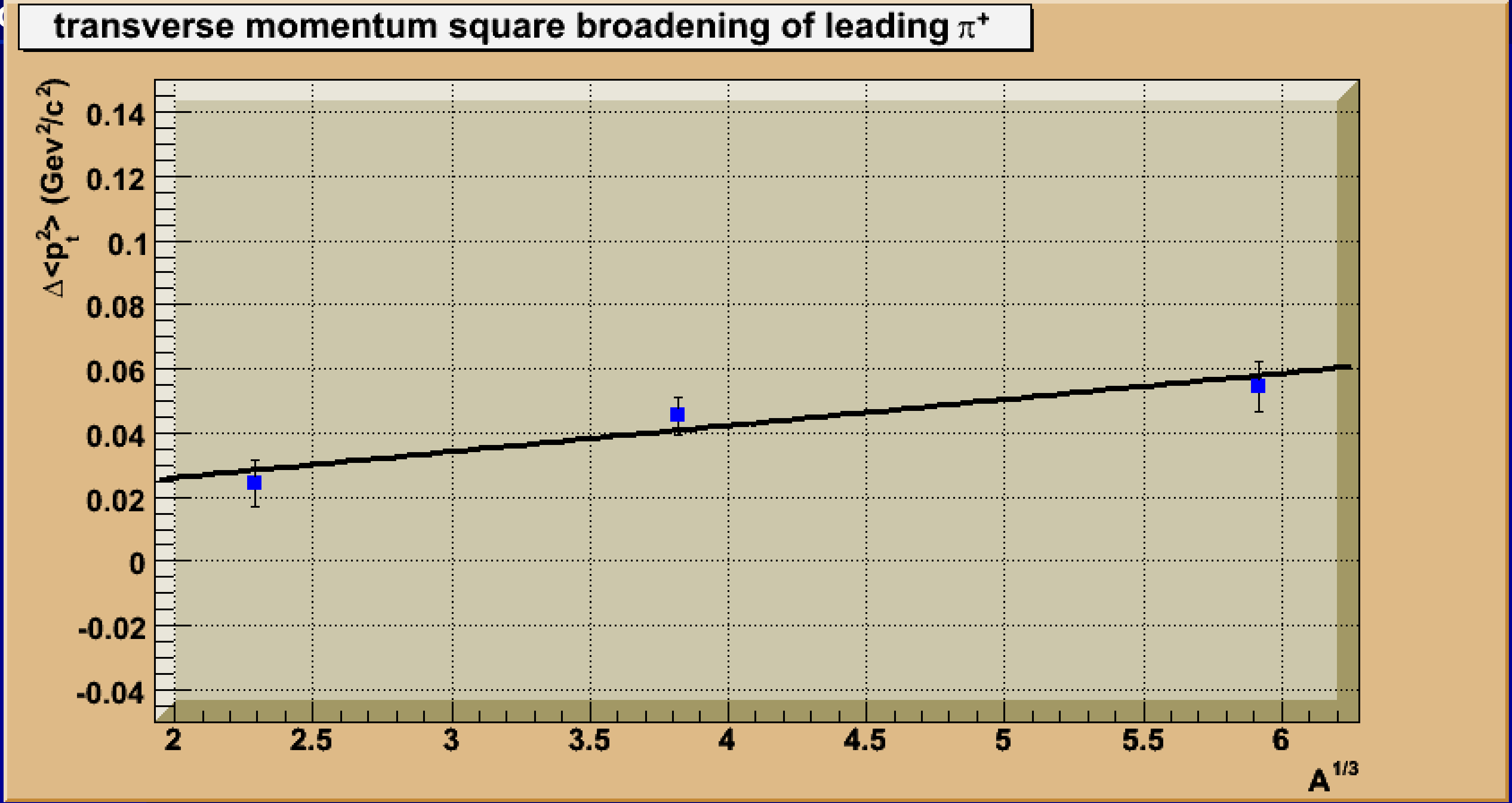
CLAS EG2 Preliminary
5 % of data

2 < Q2 < 3; 3 < nu < 4; 0.6 < Z < 0.7



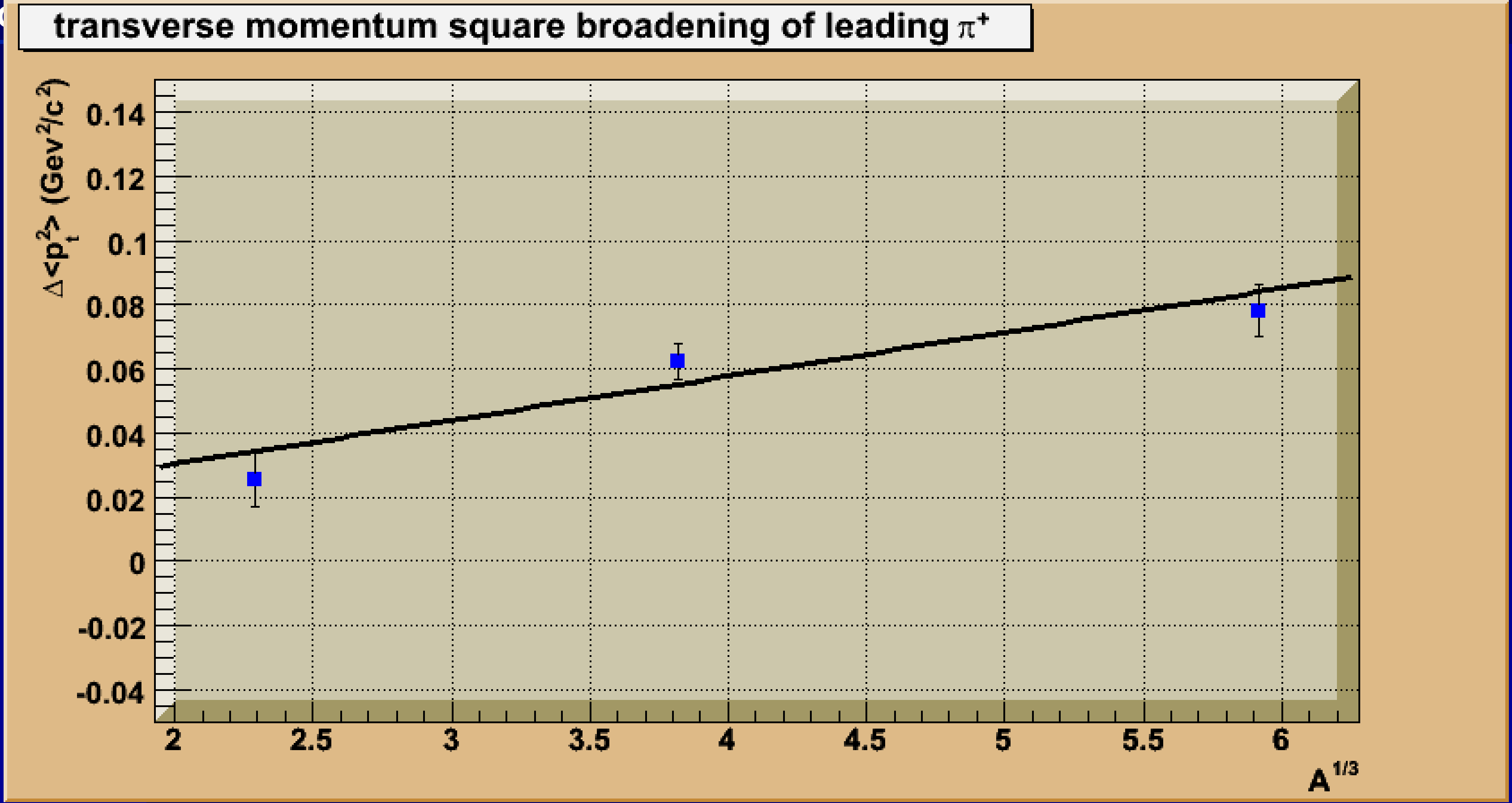
CLAS EG2 Preliminary
5 % of data

2 < Q2 < 3; 3 < nu < 4; 0.5 < Z < 0.6



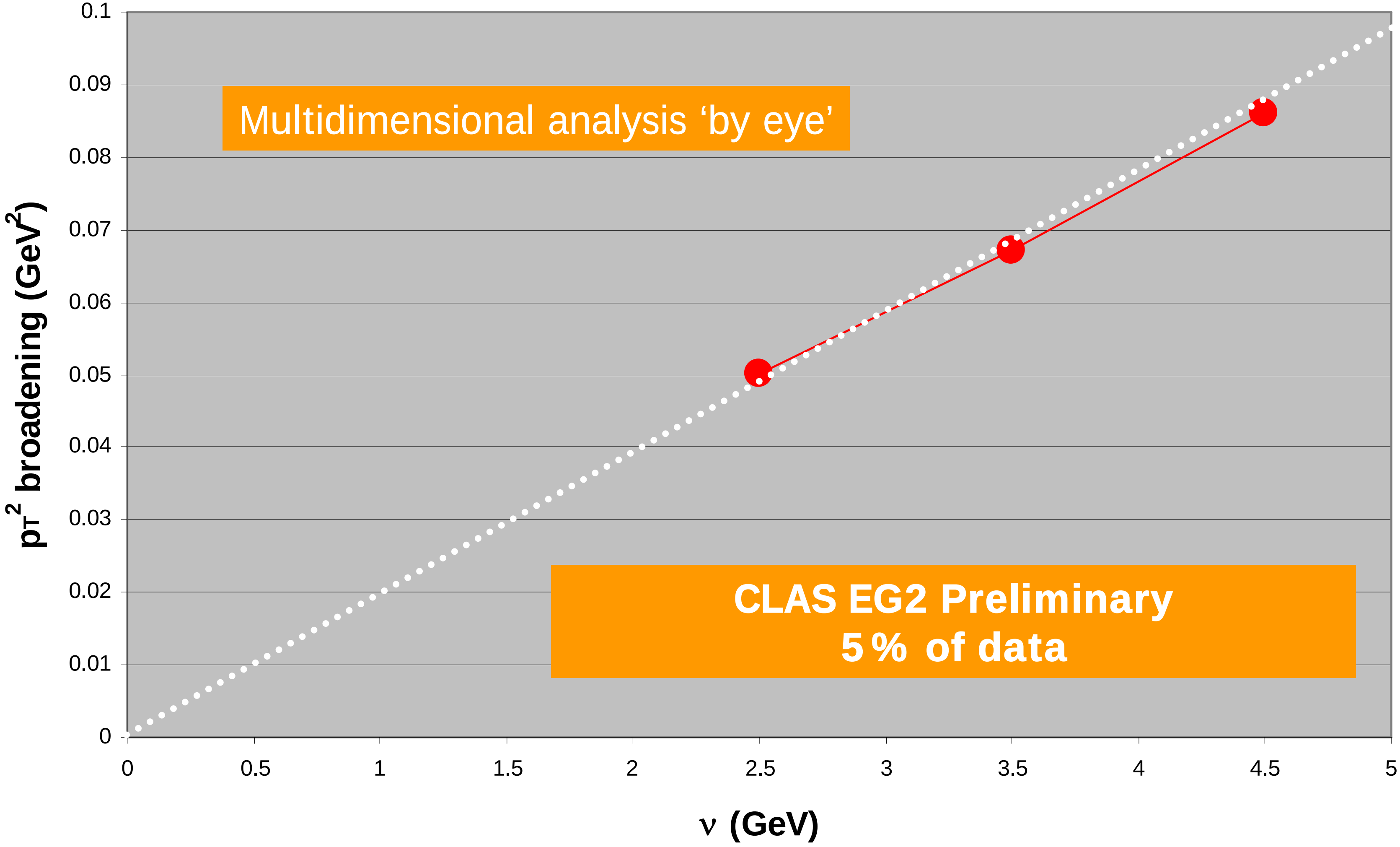
CLAS EG2 Preliminary
5 % of data

1 < Q2 < 2; 4 < nu < 5; 0.5 < Z < 0.6



CLAS EG2 Preliminary
5 % of data

p_T^2 broadening vs. ν for $1<Q^2<2$ GeV^2 and $0.5<z<0.6$, $A^{1/3}=6$

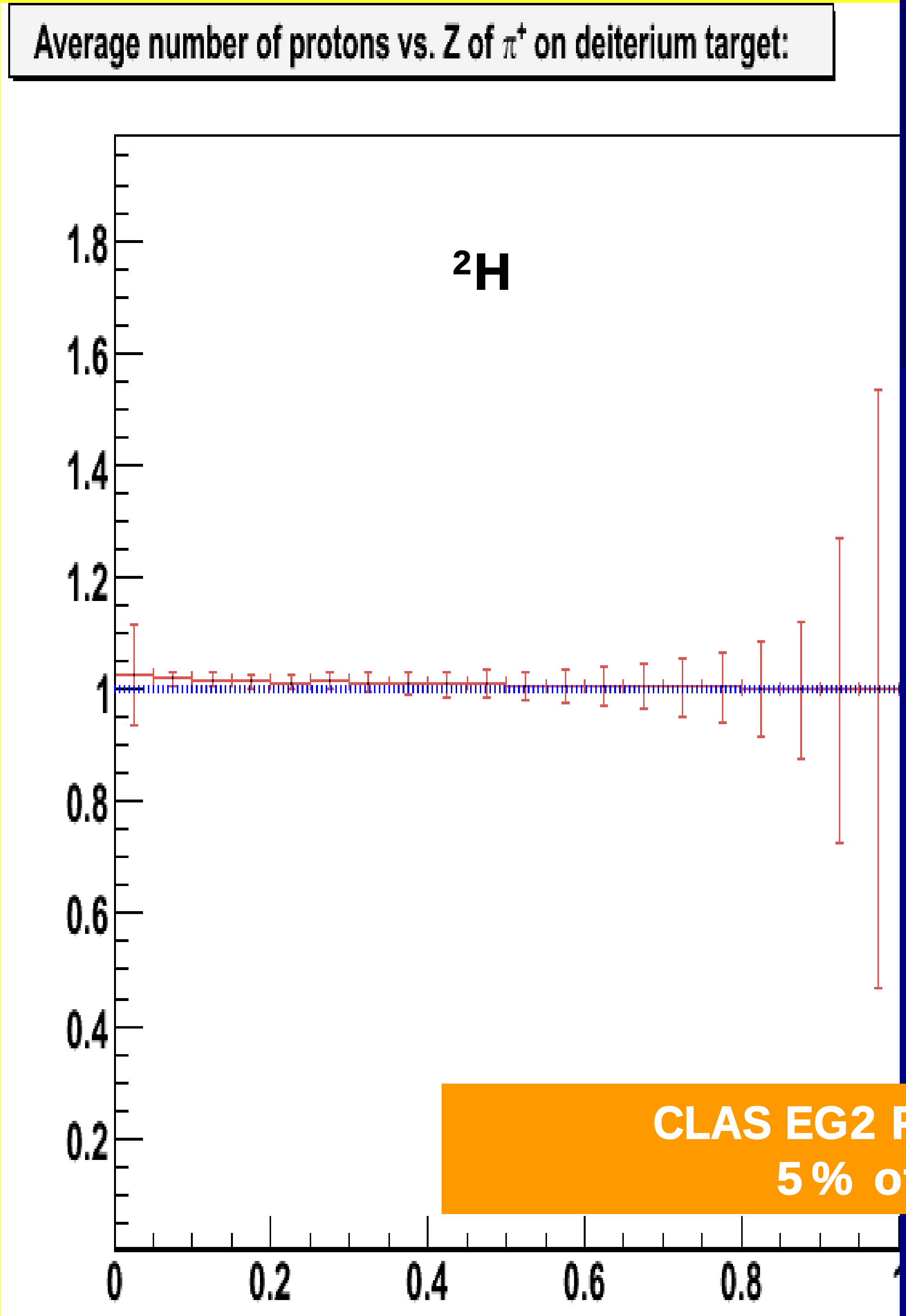


Multidimensional analysis ‘by eye’

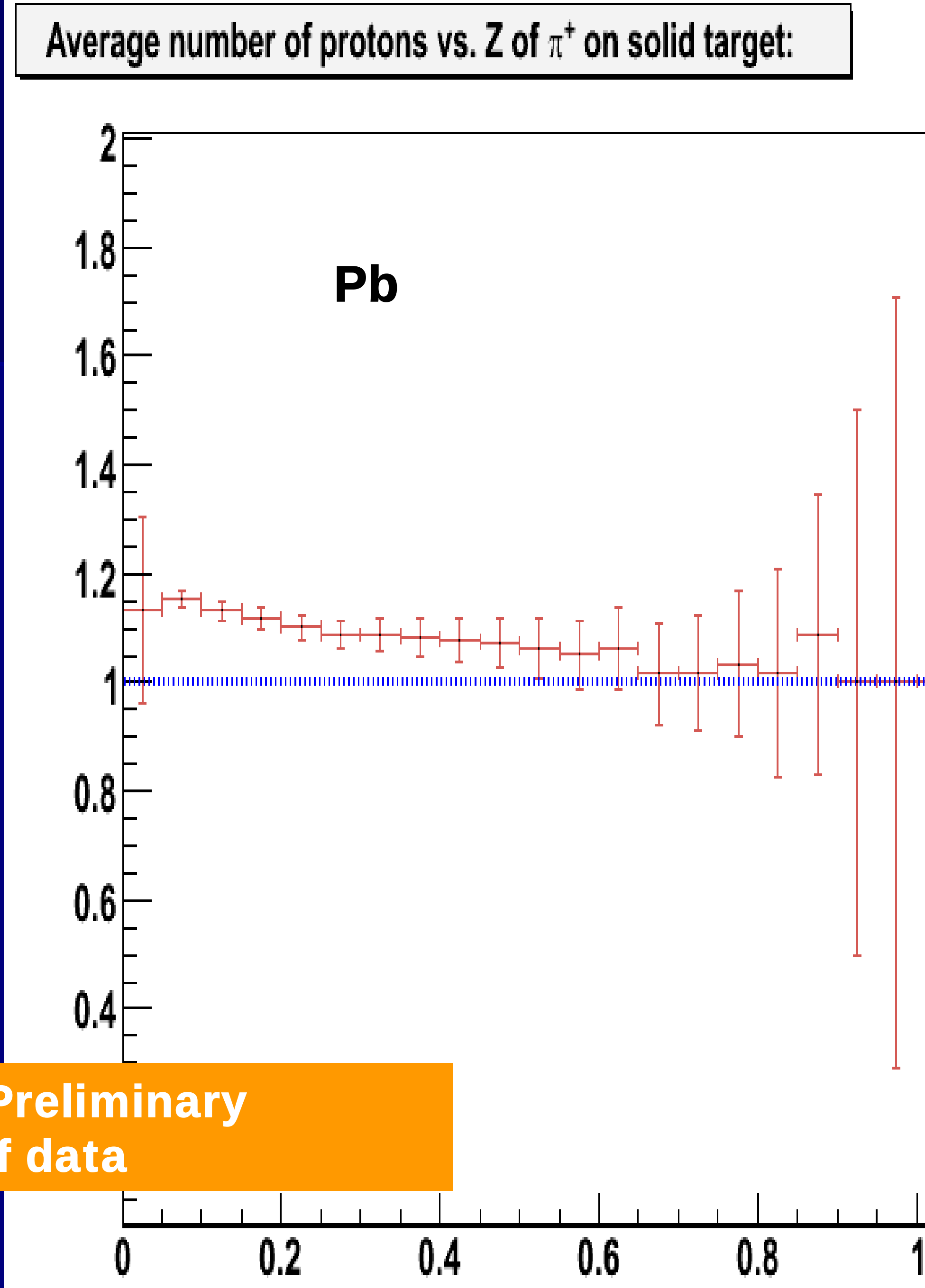
CLAS EG2 Preliminary
5% of data

Correlations: protons accompanying leading π^+

- For DIS events with a leading π^+ and at least one proton detected, calculate the average number of protons vs. z and p_T
- Results shown for Pb and deuterium
- Low energy, large angle protons also studied, show much smaller effect



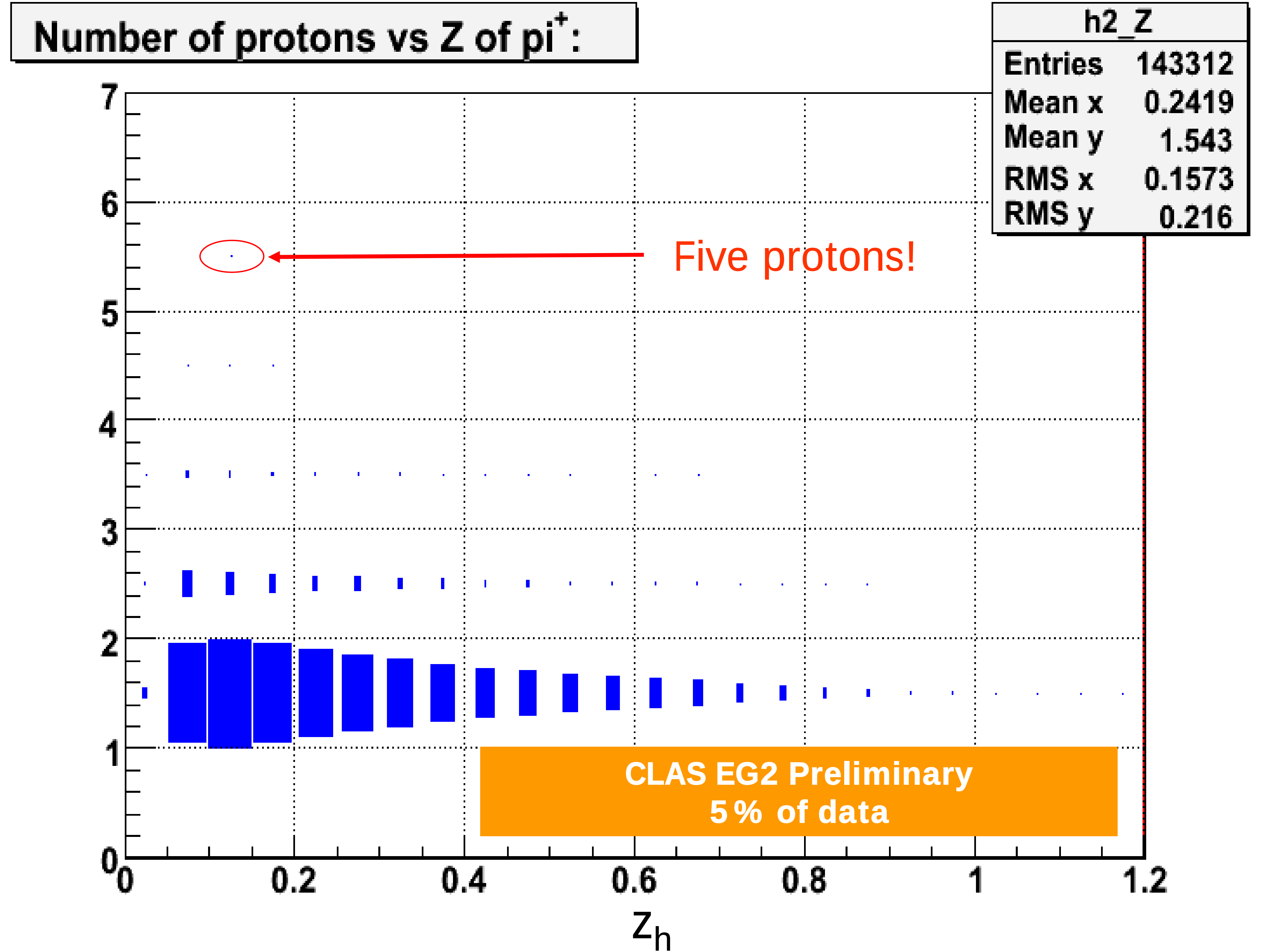
Average number of protons vs. Z of π^+ on deiterium target:



Average number of protons vs. Z of π^+ on solid target:

CLAS EG2 Preliminary
5% of data

Number of protons vs Z of pi$^+$:

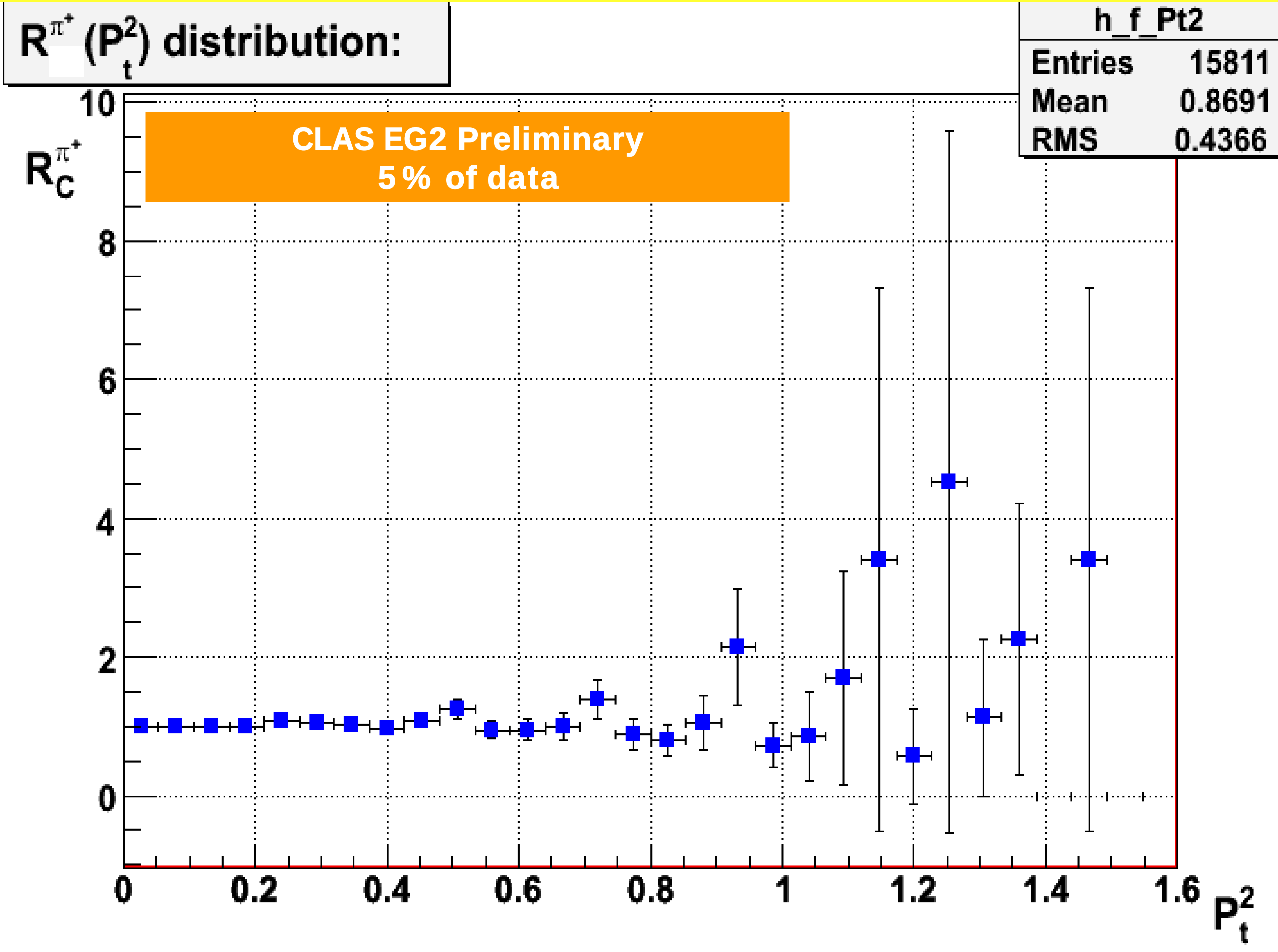


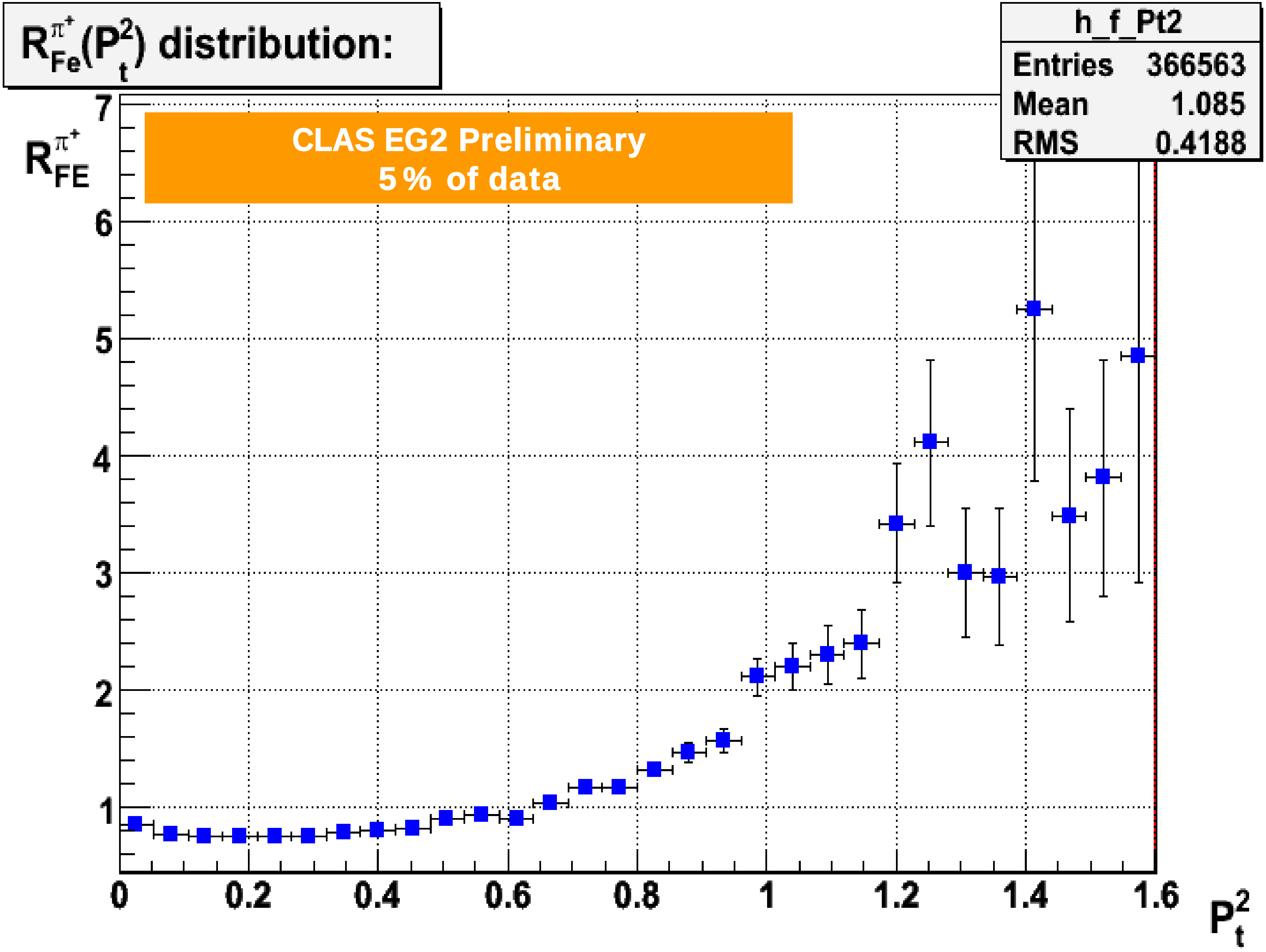
Five protons!

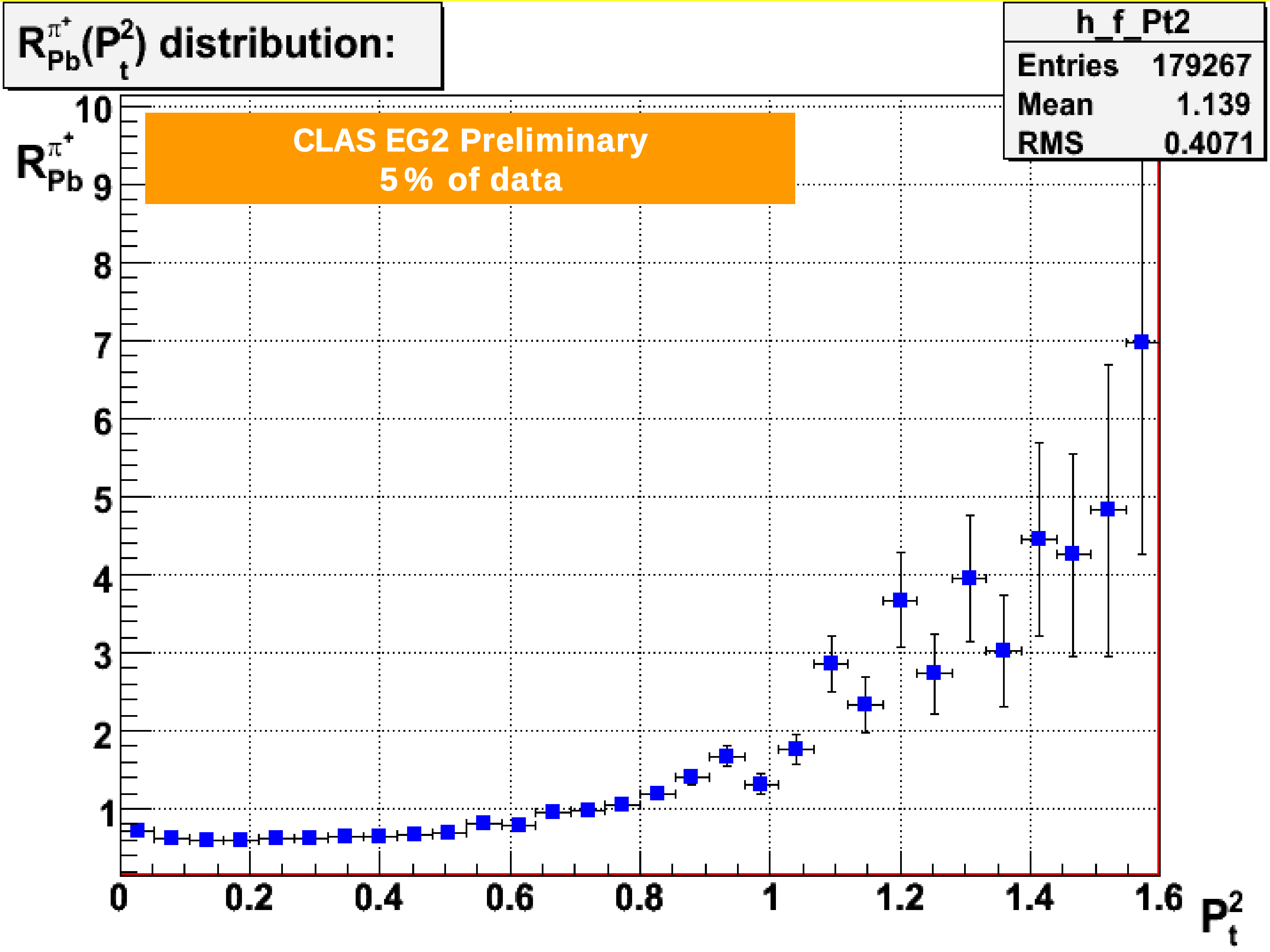
CLAS EG2 Preliminary
5% of data

‘Cronin effect’

$R^{\pi^+}(P_t^2)$ distribution:

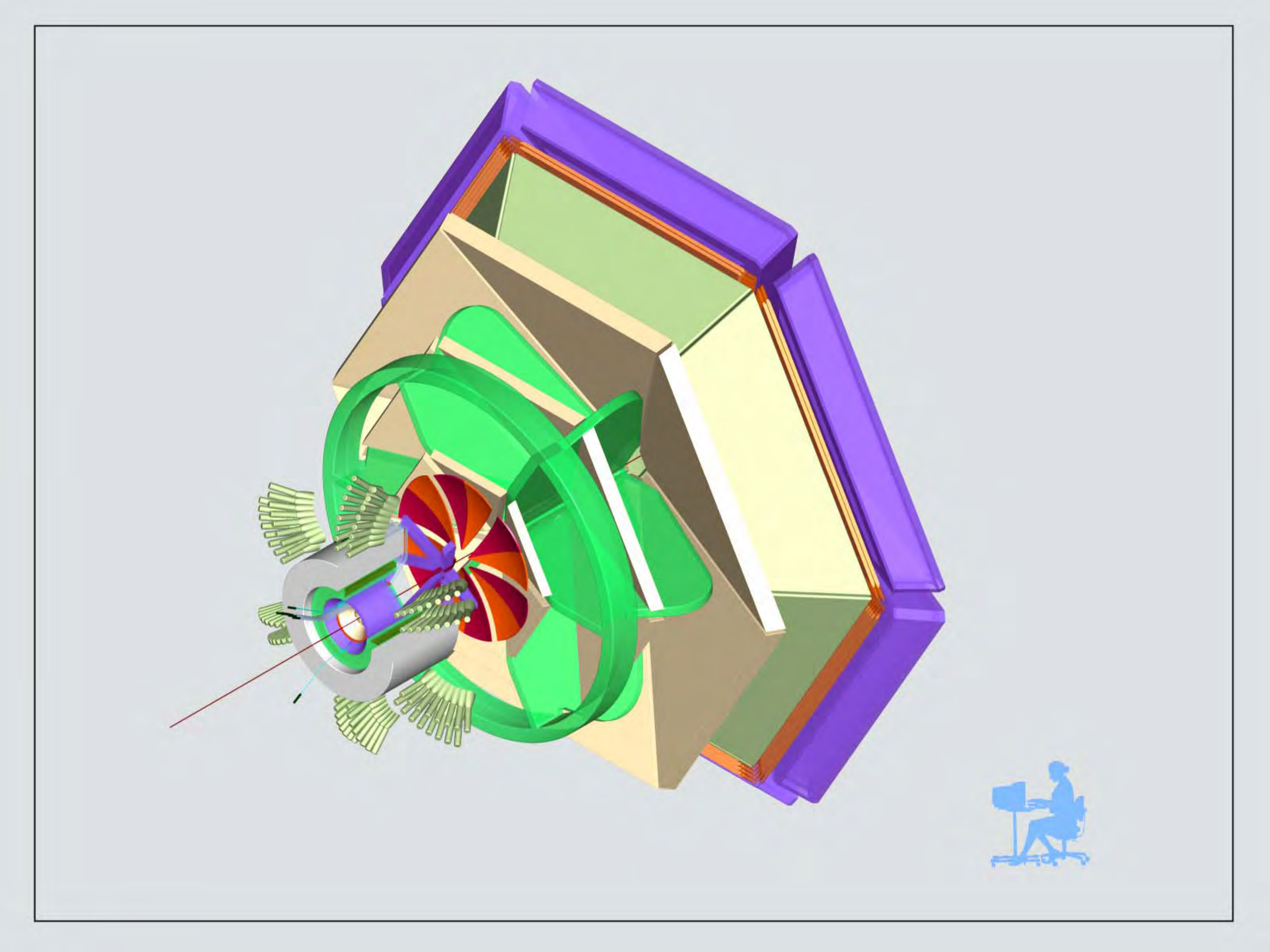



$R^{\pi^+}_{Fe}(P_t^2)$ distribution:
h_f_Pt2
Entries 366563
Mean 1.085
RMS 0.4188
CLAS EG2 Preliminary
5 % of data
$R^{\pi^+}_{FE}$
1
2
3
4
5
6
7
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
P_t^2



CLAS EG2 Preliminary
5 % of data

Capabilities after the 12 GeV upgrade



Comparison to HERMES Data

- ☐ Mostly 27 GeV positron beam, some 12 GeV beam
- ☐ Targets include D, He, N, Kr, Xe
- ☐ Excellent PID (RICH) except for early nitrogen targets
  - ➢ identify $\pi^{+/-/o}$, $K^{+/-}$, proton and antiproton
- ☐ Pioneering measurements of high quality
  - ➢ Some limitations: luminosity, gas targets → typically 1-D binning, lower Q^2, $A<140$

With JLab at 12 GeV (~2013-2015), will have:

nearly three orders of magnitude more luminosity:

→ do multi-dimensional binning

→ reach high Q^2

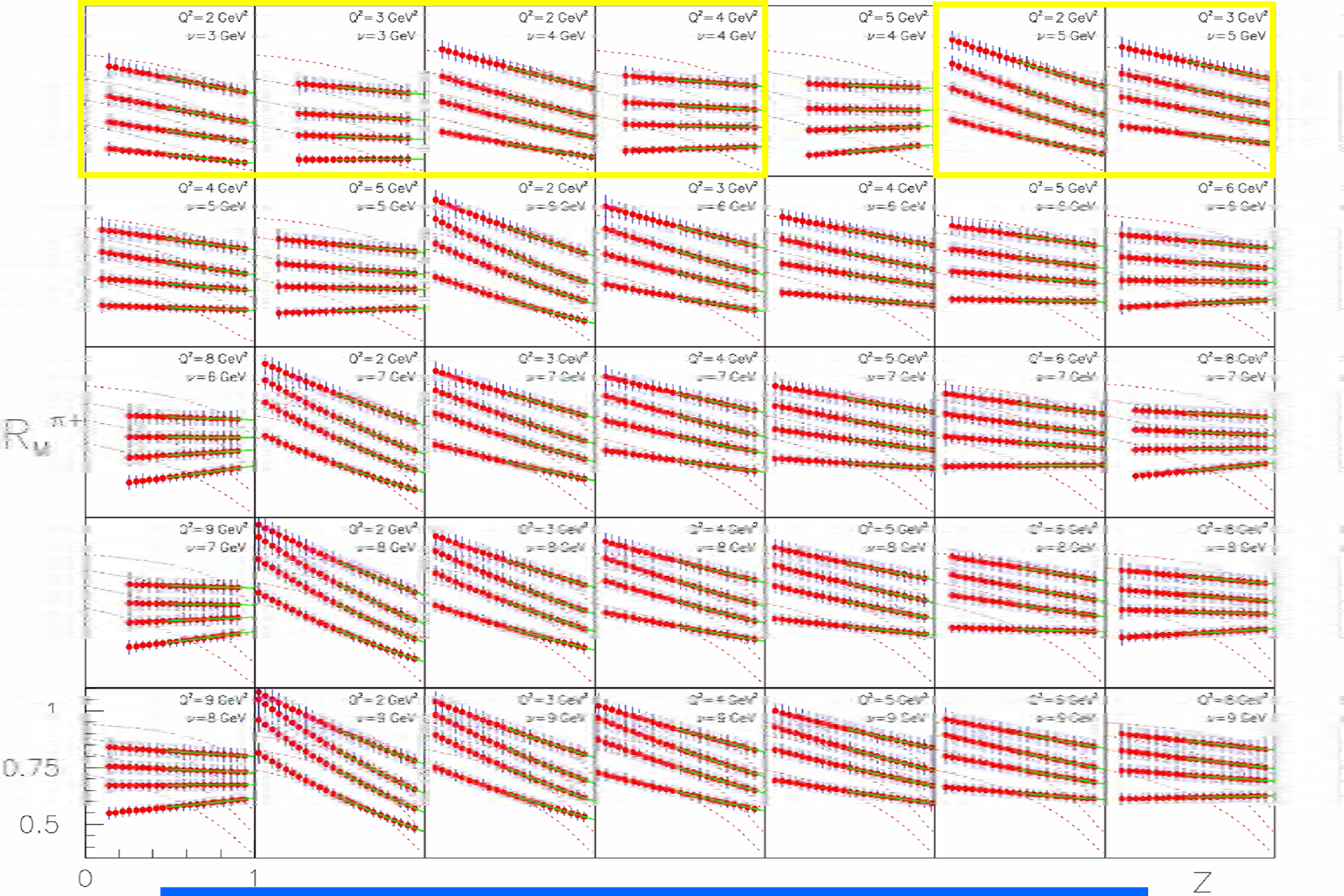
→ study multi-particle correlations

capability of solid targets:

→ study largest nuclei

Examples of Experimental Data and Theoretical Predictions

12 GeV Anticipated Data



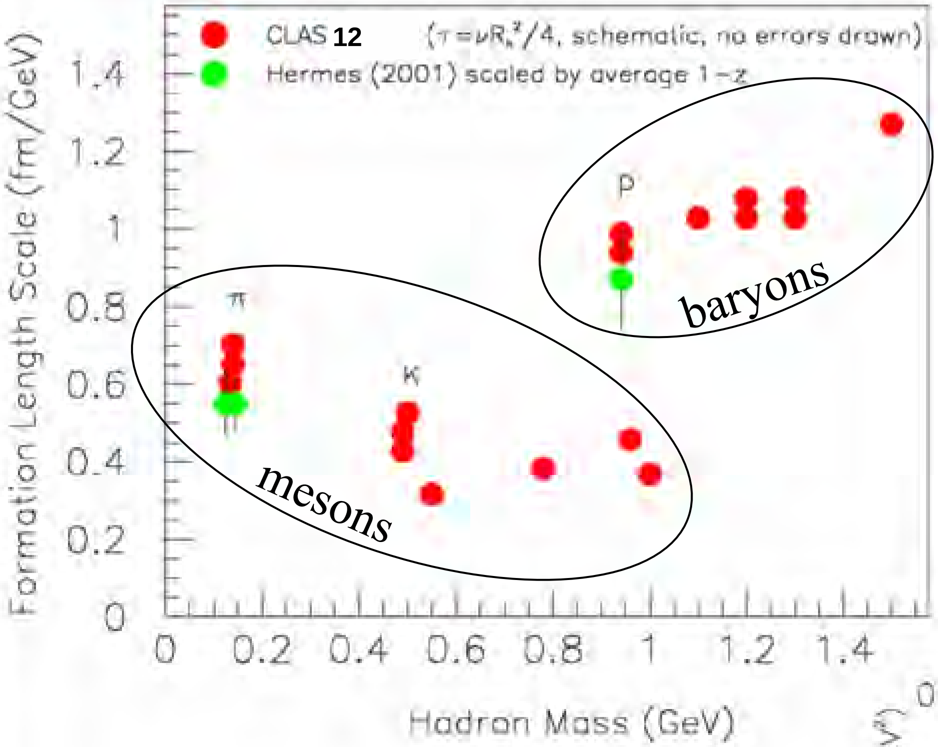
Bins in yellow are accessible at 6 GeV

Accessible Hadrons (12 GeV)

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
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	1100
$\bar{p}$	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

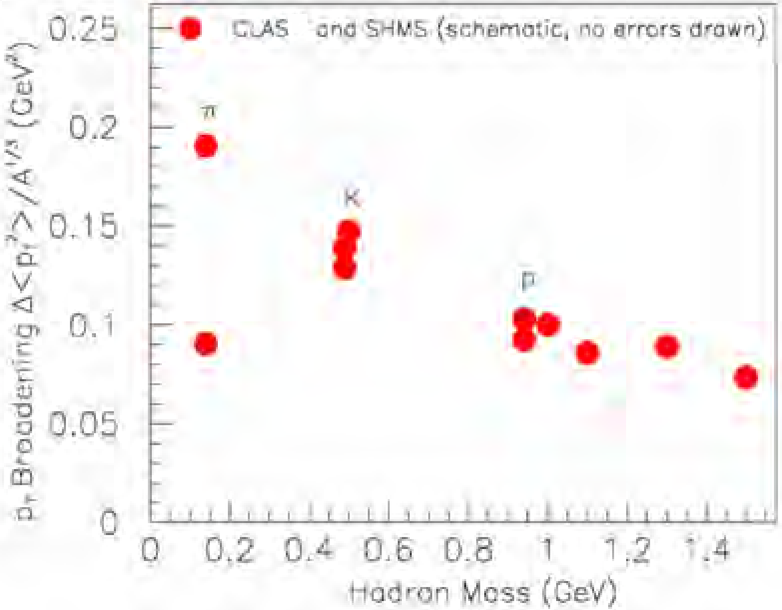
12 Γες Αντιχιπατεδ Δατα

Schematic Examples of Analysis Results



- Formation lengths for a wide variety of hadrons using data from CLAS**12** and SHMS

- Transverse momentum broadening for a number of hadrons using data from CLAS**12** and SHMS, for a particular Q^2, ν.



Conclusions

- The birth of a new class of experiments
- Exciting opportunity to gain new insight into two fundamental QCD processes – hadronization and gluon bremsstrahlung
- The Next Seven Years – new data from all three halls at Jefferson Lab will break new ground
- 12 GeV experiments will be even better

Potential issues

- Extent to which factorization applies
- Resonances in the residual system
- Distinguish target from current fragmentation?