Jlab Hall C Current Status and Plans

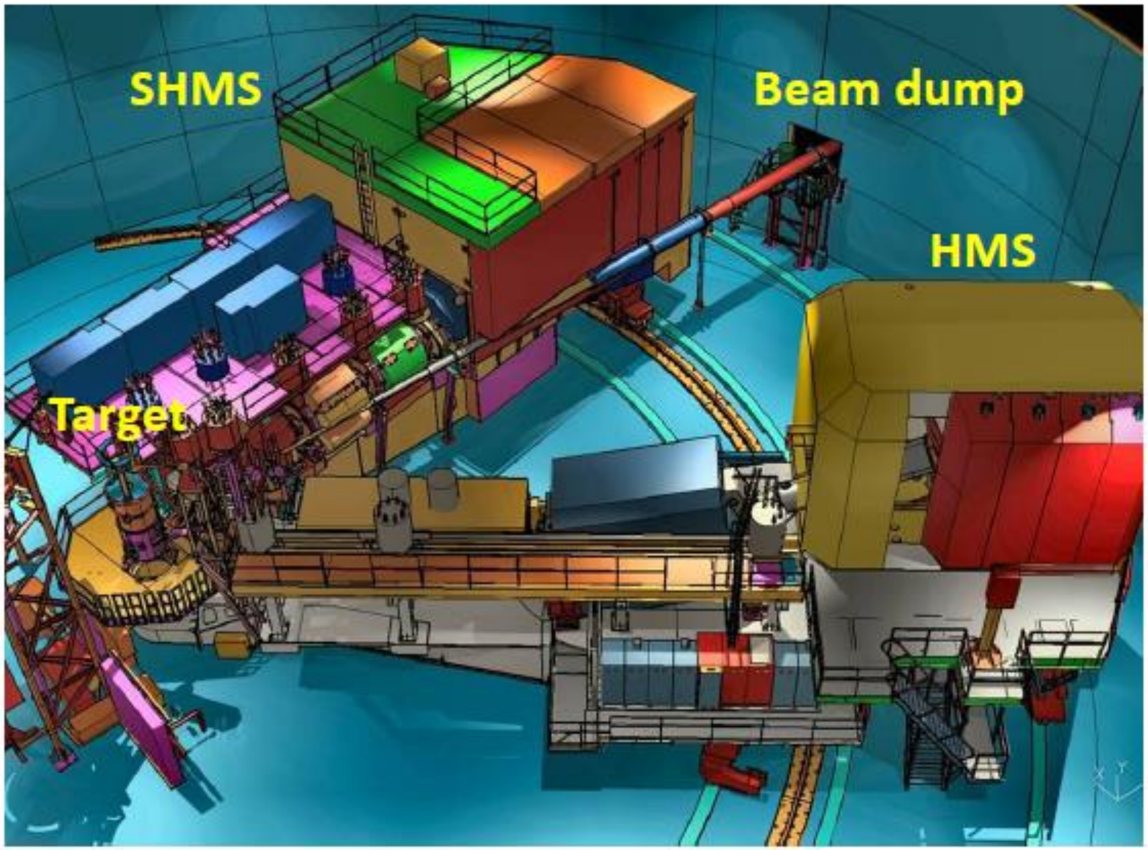
Hamlet Mkrtchyan

ANSL EPD Seminar, 18 Sep 2019

Hall C at CEBAF 12 GeV

12 GeV Hall C base equipment

HMS (old) and SHMS (new) magnetic spectrometers are well suited for (e,e') coincident measurements.



SHMS parameters:
Magnets: (HB)QQQD
P: 2 -- 11 GeV/c
ΔP: (-10% , +22%)
δP: 0.03%-0.08%
θ: 5.5 ° -- 40°
Δ Ω: 4.0 msr

HMS parameters:
Magnets: QQQD
P: 0.5 – 7.5 GeV/c
ΔP: (-10% , +10%)
δP: 0.1%
θ: 12.5 ° -- 90°
Δ Ω: 6.0 msr
L: 10^{38} $cm^{-2}s^{-1}$

Hall C Physics Program at 12 GeV

- Exclusive reactions and form factors
  - Neutron Electric Form Factor
  - d(e,e′p)
  - Pion Form Factor
  - Factorization of exclusive p(e,e′π), p(e,e′K), Kaon FF?
- Semi-Inclusive Deep Inelastic Scattering p,d(e, e′$\pi^{\pm}$)
  - Quark transverse momentum distributions
  - Charge symmetry of parton distributions – $u^p(x) = d^n(x)$?
- Nucleon Structure Functions – Inclusive (e,e′)
  - Unpolarized structure functions, high *x*
  - Neutron spin-structure functions (polarized 3He)
- Nuclear Effects
  - Nuclear transparency, A(e,e′p), A(e,e′π)
  - EMC effect
  - $x>1$(Short Range Correlations, Superfast quarks)
  - ^{4}He(e,e’p)

Outline

- Hall C experimental program: 2018-2019

Fall 2018- Spring 2019

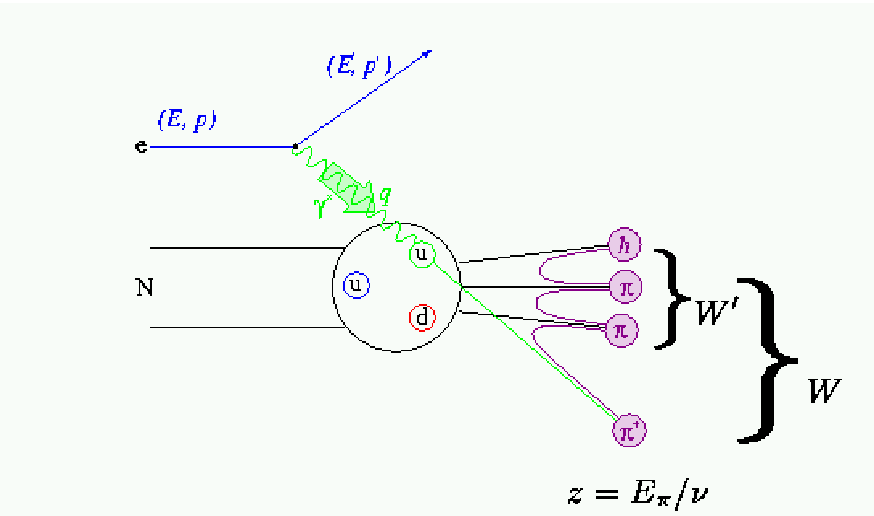
  - E12-09-011: The L-T Separated Kaon Electroproduction Cross section (Kaon L/T)
  - E12-09-017 : Transverse momentum dependence of SI π-Production (Pt-SIDIS)
  - E12-09-002: Charge Symmetry Violating Quark Distributions (SIDIS CSV)
  - E12-16-007: J/ψ photoproduction at Threshold (J/ψ)

Summer-Fall 2019

  - E12-06/101: Pion Form-Factor at High Q^2
  - E12-07-105: Scaling Study of L-T Separated Pion Electroproduction Cross Section
  - E12-15-001: Virtual Compton Scattering
  - E12-06-110: Neutron Spin Asymmetry A1n in the Valence Quark Region
- Detector Calibration and PID
  - HMS Spectrometer: Calorimeter and gas Cerenkov
  - SHMS Spectrometer: Calorimeter, Aerogel and gas Cerenkov
- Preliminary analysis of Pt-SIDIS data taken at Fall 2018
  - Comparison normalized yields from SIMC & Data
- Neutral Particle Spectrometer: ERR, crystals, HV divider, frame design
- The upcoming run preparations: run plans, repairing of the detectors
- The ratio $R = \sigma_L/\sigma_T$ in SIDIS: PAC47 Jeopardy Proposal

Meson electro-production in SIDIS

$$l + N \rightarrow l' + h + X$$



$$\sigma \sim f(x,Q^2)\cdot D(z)$$

$$\sigma_{SIDIS} = \sigma_{DIS}\cdot\sum e_i^2[q_i(x,Q^2)D_i(z)]\cdot b e^{-bp_T^2}$$

$$z = \frac{E_h}{\nu} \qquad x = \frac{Q^2}{2m\nu} \qquad \nu = E - E'$$

$$W^2 = m_p^2 + Q^2\cdot\left(\frac{1}{x} - 1\right)$$

$$W'^2 = m_p^2 + Q^2\cdot(1-z)\cdot\left(\frac{1}{x} - 1\right)$$

- **At high energies SIDIS has been shown to factorize into lepton-quark scattering followed by quark hadronization.** $\sigma \sim f(x,Q^2)\cdot D(z)$
- **At low energies, this factorization ansatz is expected to brake down, due to effects of FSI, resonant nucleon excitations and high twist.**

SIDIS Formalism

General formalism for (e,e'h) reaction with polarized beam:

[A. Bacchetta et al., JHEP 0702 (2007) 093]

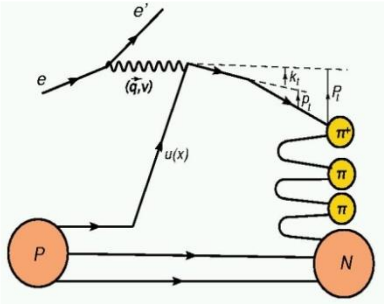
Only surviving terms if unpolarized beam

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} +$$

$$\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos(2\phi_h)} + \lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\Big\}$$

(Y = azimuthal angle of e' around the electron beam axis w.r.t. an arbitrary fixed direction)

Transverse momentum width of quarks with different flavors can be different. Use of polarized beam will provide useful azimuthal beam asymmetry measurements (**F_{LU}**) at low p_T complementing CLAS12 data



Transverse momentum of the detected pion **P_t** arises from convolution of the struck quark transverse momentum **k_t** with the transverse momentum generated during the fragmentation **p_t**. $P_t = p_t + z\,k_t + O(k_t^2/Q^2)$

Hall C SIDIS Program

Why?

Knowledge of $R = \sigma_L/\sigma_T$ in SIDIS is virtually non-existent:

- Does R_{SIDIS} vary with z?
- Is $R_{SIDIS}^{\pi+} = R_{SIDIS}^{\pi-}$?
- Is $R_{SIDIS}^{H} = R_{SIDIS}^{D}$?
- Is $R_{SIDIS}^{K+(-)} = R_{SIDIS}^{\pi+(-)}$?

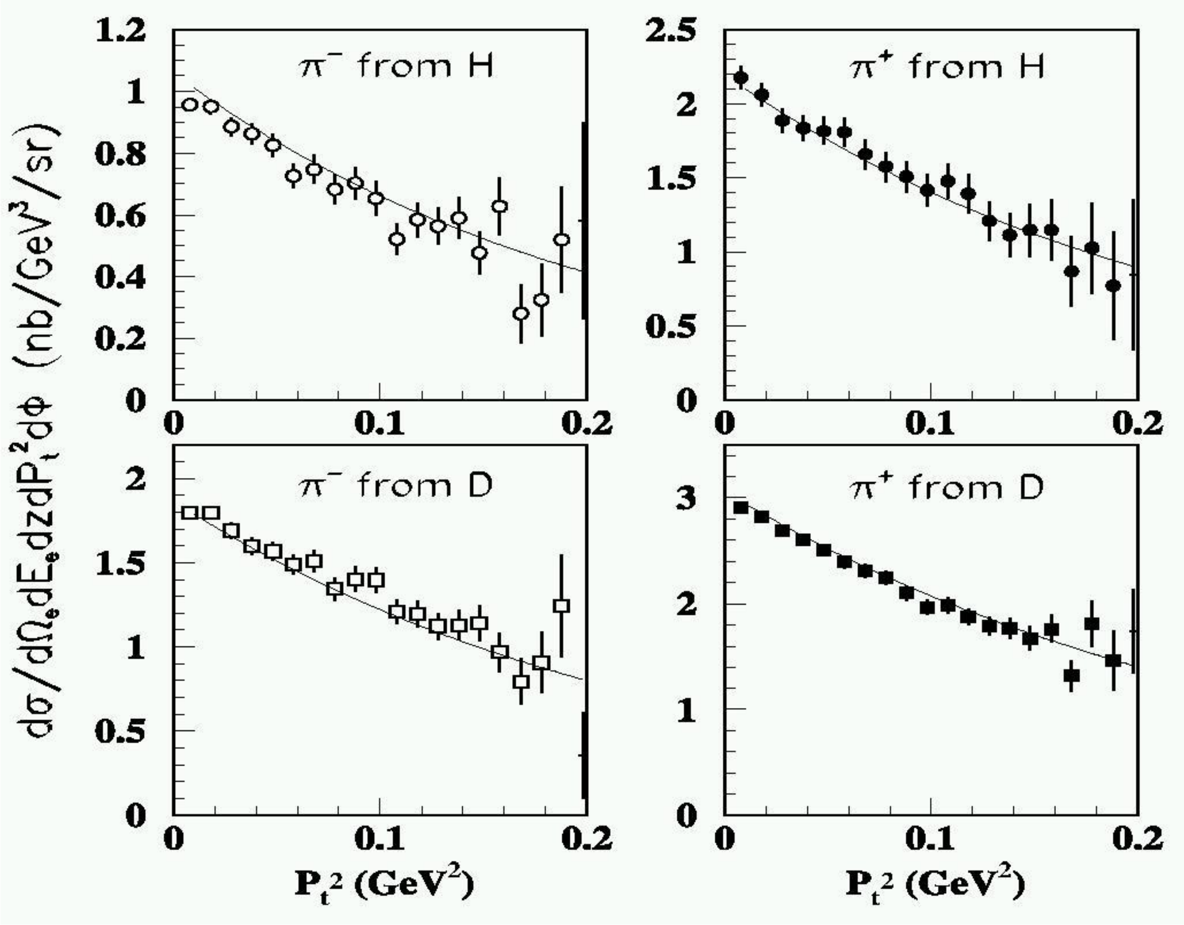
There are both theoretical and experimental indications of a quark flavor distribution dependence on k_T.

Hall C SIDIS program focuses on transverse momentum dependence of unpolarized SIDIS cross sections.

JLab 12GeV goal: Precision 3D momentum imaging of the nucleon, e.g. quark transverse momentum dependence on spin & flavor.

Transverse momentum dependence of SIDIS

E00-108: First SIDIS experiment at JLab (R. Ent, H. Mkrtchyan)



$^{1,2}H(e,e'\pi^{\pm})X$

P_t dependence very similar for proton and deuterium targets, but **deuterium slopes systematically smaller**?

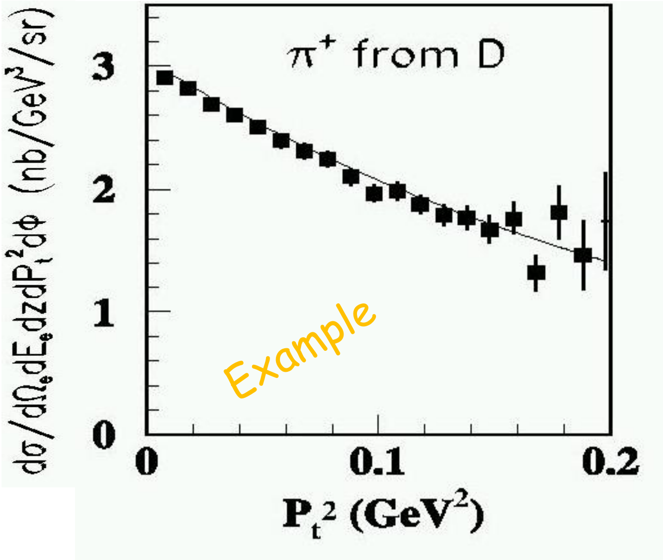
Unpolarized SIDIS – JLab E00-108 data

Constrain k_T dependence of up and down quarks *separately*

1) Probe π^+ and π^- final states

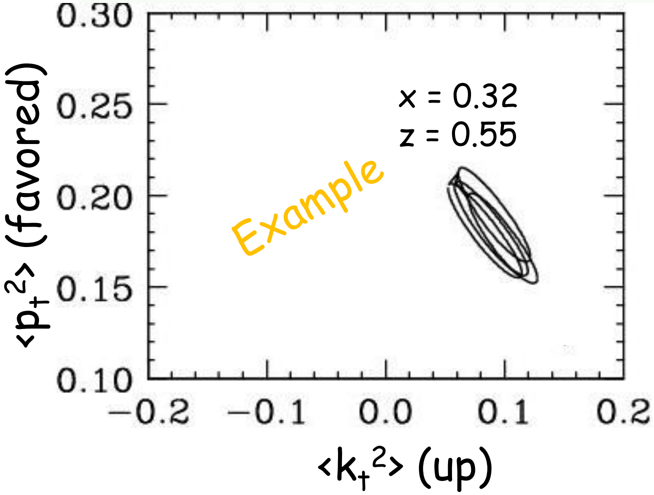
2) Use both **proton** and neutron (**d**) targets

3) Combination allows, in principle, separation of quark width from fragmentation widths



1st example: Hall C, PL B665 (2008) 20

Numbers are close to expectations! But, simple model only with many assumptions (factorization valid, fragmentation functions do not depend on quark flavor, transverse momentum widths of quark and fragmentation functions are Gaussian and added in quadrature, sea quarks are negligible,)**, incomplete cos(f) coverage, uncertainties in exclusive event & diffractive r contributions.**



The P_t^2-dependence of the cross-sections

Assuming: $b \rightarrow b^{\pm}_q$ ($b^{\pm}_u$ and $b^{\pm}_d$)

and : $b^{\pm}_q = (z^2\mu_q^2 + \mu_{\pm}^2)^{-1}$

$\sigma_{SIDIS} \sim \sigma_{DIS}$ (dN/dz) b exp($-bP_t^2$) ➡

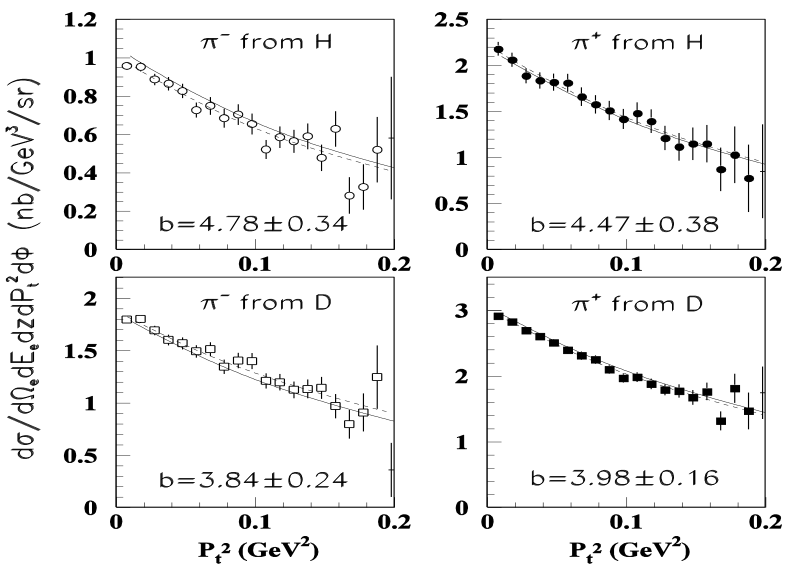
$\sigma_p^{\pi+} = C[4c_1 \cdot \exp(-b^+_u P_t^2) + (d/u)(D^-/D^+)c_2 \cdot \exp(-b^-_d P_t^2)]$

$\sigma_p^{\pi-} = C[4(D^-/D^+)c_3 \cdot \exp(-b^-_u P_t^2) + (d/u)c_4 \cdot \exp(-b^+_d P_t^2)]$

$\sigma_n^{\pi+} = C[4(d/u)c_4 \cdot \exp(-b^+_d P_t^2) + (D^-/D^+)c_3 \cdot \exp(-b^-_u P_t^2)]$

$\sigma_n^{\pi-} = C[4(d/u)(D^-/D^+)c_2 \cdot \exp(-b^-_d P_t^2) + c_1 \cdot \exp(-b^+_u P_t^2)]$

JLab E00-108 data



Fit values:

- $D^-/D^+ = 0.42 \pm 0.01$; $d/u = 0.30 \pm 0.02$
- $\mu_u^2 = -0.01 \pm 0.04$ GeV^2 $\mu_d^2 = 0.26 \pm 0.13$ GeV^2
- $\mu_+^2 = 0.23 \pm 0.04$ GeV^2 $\mu_-^2 = 0.19 \pm 0.04$ GeV^2

The dashed lines are exponential fit to the data. Solid lines are fits with Gaussian width for k_t and p_t

- **Fit results for D^-/D^+ agree with HERMES data , and d/u ratio with LO GRV**
- **Fit tends to larger k_t width for d quarks than for u (as di-quark model)**
- **Fragmentation width μ_+ and μ_- are similar (as predicted by Anselmino)**

E12-09-017: Pt-dependence of SIDIS $\pi^{\pm}$ Production

Spokespersons R. Ent, P. Bosted, H. Mkrtchyan, E. Kinney

- Little is known about ….
- the orbital angular momentum of partons
- PDF dependence on transverse momentum
- Significant orbital angular momentum implies significant transverse momentum of quarks

Transverse momentum of the detected pion $\mathbf{P_t}$ arises from convolution of the struck quark transverse momentum $\mathbf{k_t}$ with the transverse momentum generated during the fragmentation $\mathbf{p_t}$.

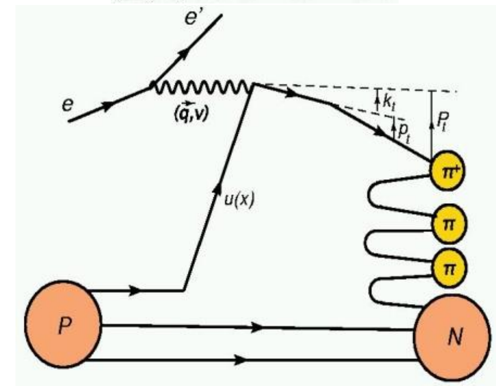
$$P_t = p_t + z\, k_t + O(k_t^2/Q^2)$$

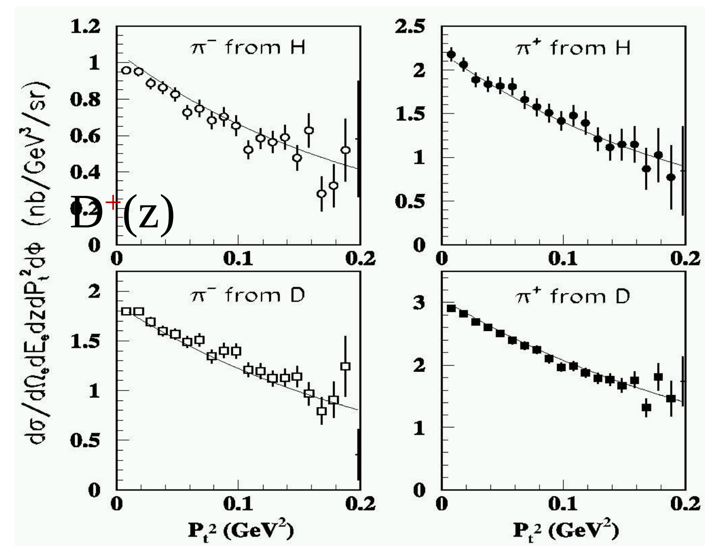
Assuming the width of the quarks $\mathbf{k_t}$ distribution (μ_u, μ_d) and width of the fragmentation functions $\mathbf{p_t}$ distributions (μ_+ μ_-) are Gaussian, and that the these distributions combines quadratically, the total width for each combination can be given by:

$$b_u^{\pm} = (z^2\mu_u^2 + \mu_{\pm}^2)^{-1} \quad \text{and} \quad b_d^{\pm} = (z^2\mu_d^2 + \mu_{\pm}^2)^{-1}$$

Goal: To map the p_T dependence of π^+ and π^- production off proton and deuteron targets to study the k_T dependence of u and d quarks

$$\sum e_q^2\, q(x)\, D_{q \to M}(z)$$





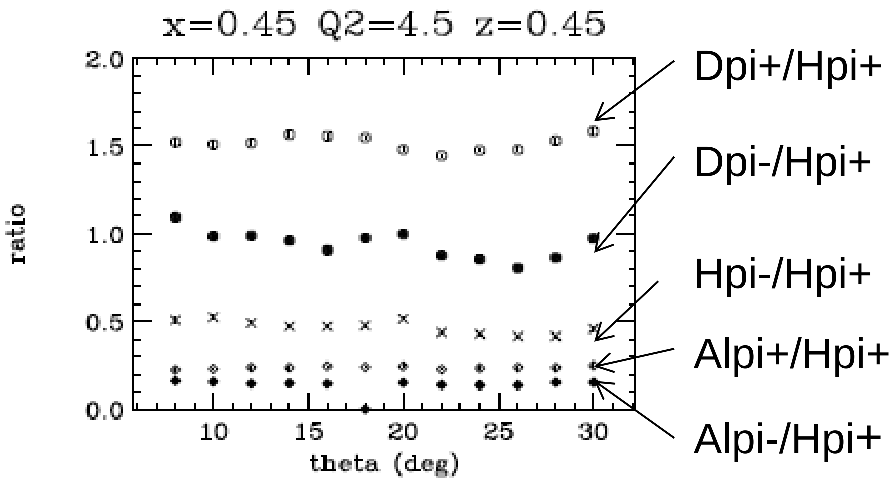
P_t dependence very similar for both targets.
Deuterium slopes systematically smaller?

Choice of E12-09-017 Kinematics

- W^2 = 5.08 GeV^2 and larger (up to 11.38 GeV^2)
- Use SHMS angle down to 5.5 degrees (for p detection)
  HMS angle down to 10.5 degrees (e^- detection)
  separation HMS-SHMS > 17.5 degrees
- $M_X^2 = M_p^2 + Q^2(1/x - 1)(1 - z) > 2.9$ GeV^2 *(up to 7.8 GeV^2)*
- Choice to keep Q^2/x fixed → q_g ~ constant
  - *exception are data scanning Q^2 at fixed x*
- All kinematics both for p^+ (and K^+) and p^- (and K^-), for LH2, LD2 and Al
- Choose z > 0.3 (p_p > 1.7 GeV) to neglect differences in $s(p^+N)$ and $s(p^-N)$

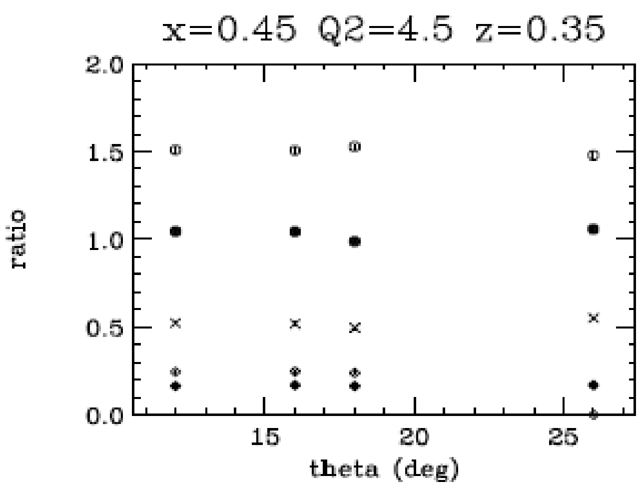
Kin	x	Q^2 (GeV^2)	Z	P_π (GeV)	Θ_π (deg)
I	0.2	2.0	0.3 -0.6	1.7 - 3.3	8.0 - 23.0
II	0.3	3.0	0.3 -0.6	1.7 - 3.4	5.5 - 25.5
III	0.4	4.0	0.3 -0.6	1.7 - 3.4	5.5 - 25.5
IV	0.5	5.0	0.3 -0.6	1.7 - 3.5	8.0 - 28.0
V	0.3	1.8	0.3 -0.6	1.1 - 2.1	8.0 - 30.5
VI	0.3	4.5	0.3 -0.6	2.5 - 5.0	5.5 - 20.5

E12-09-017: First On-line Results



The pion ratios of LD2, LH2 and Al targets relative to pi+ on LH2.

Results look pretty smooth now, at least. $P_t = 0$ is at 15 deg., and 30 deg. for x = 0.45 is $p_t = 0.67$

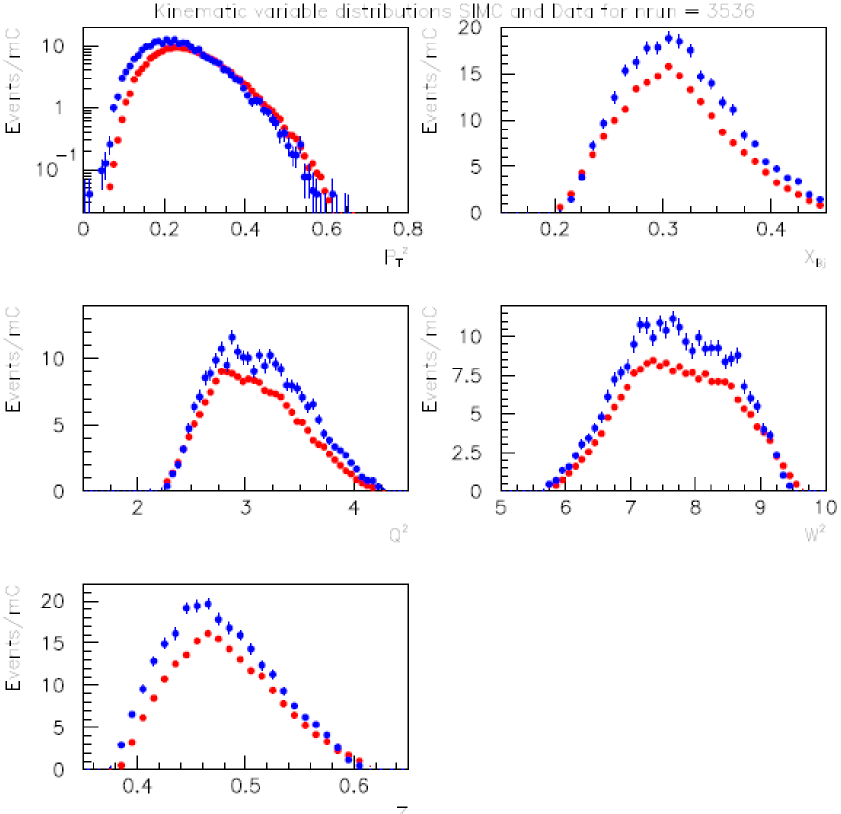


These are just yield ratios of with no target thickness corrections , dummy subtraction, no radiation corrections, etc. Accidentals are subtracted and SHMS tracking efficiency is roughly corrected.

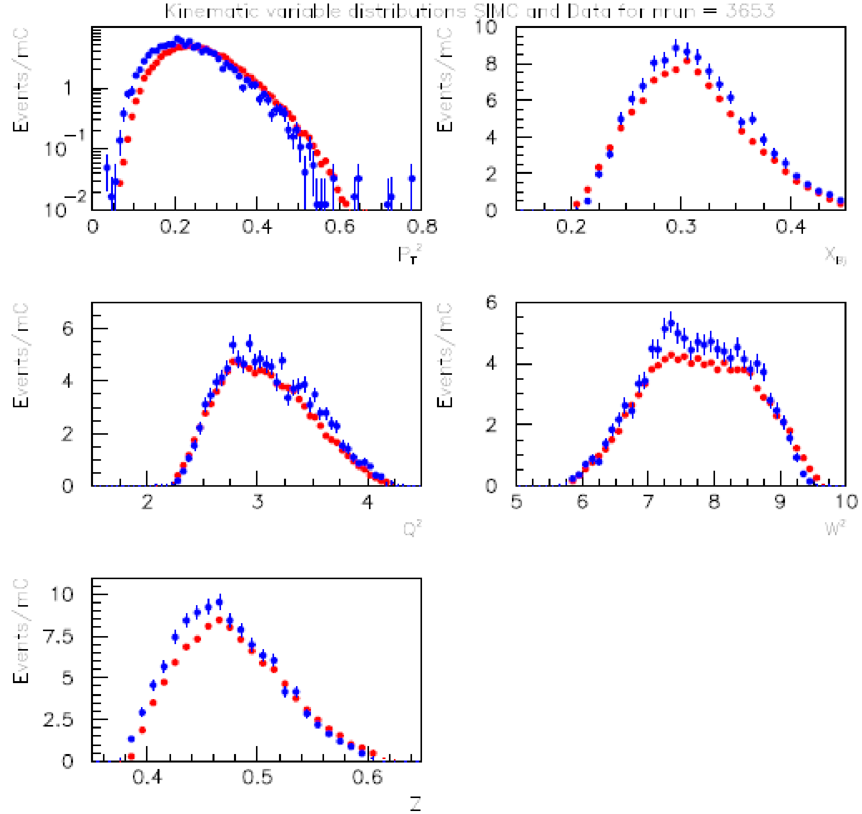
YerPhI group have two other upcoming SIDIS experiments in HALL C: $\pi^{\pm}$ cross section ratios R= σ_L/σ_T in SIDIS and π^o Production in SIDIS

E12-09-017: Normalized Yields from SIMC & Data

π+



π-



$E_{beam'}$ =10.6 GeV, $P_{e'}$ = 2.492 GeV, $\theta_{e'}$ = 13.5 deg, $P_{\pi'}$ = 2.49 GeV, θ_{π} = 24.0 deg.

In first order all look OK, ~10% disagreements between data and SIMC, could be due to physics backgrounds and SIDIS model in MC

E12-09-002: Charge Symmetry Violating (CSV) Quark Distribution via $\pi^{\pm}$ Ratios in SIDIS

What is charge symmetry (CS) ?

CS is a specific case of isospin symmetry (IS) that involves a rotation of 180^{o} in isospin space

Low energy CS in Nuclei

- pp and nn scattering length are nearly the same
- $M_p \approx M_n$ (to 1%)
- $B(^3H) \approx B(^3He)$
- Energy levels in mirror nuclei are equal (t0 1%)

After electromagnetic corrections
CS respected down to ~ 1%

Equality of cross sections for mirror reactions

$$\sigma(n, {}^3He) = \sigma(p, {}^3H)$$

Equality of masses for mirror nuclei

$$m({}^3He) = m({}^3H)$$

QCD CS in quark distributions

- $u^p(x, Q^2) = d^n(x, Q^2)$
- $d^p(x, Q^2) = u^n(x, Q^2)$

Origin of CS violations:

- Electromagnetic interaction
- $\delta m = m_d - m_u$

Naively one would expect that CSV would be of the order of $(m_d - m_u)$ /M, where M ~ 0.5-1 GeV

So, CSV effect → ~ 1%

E12-09-002: CSV Tests in SIDIS

CS in parton distributions almost universally assumed for the past 40 years !

But experimentally never tested !

$$u^p(x,Q^2) \overset{?}{=} d^n(x,Q^2) \qquad \delta u(x) = u^p(x) - d^n(x)$$

$$d^p(x,Q^2) \overset{?}{=} u^n(x,Q^2) \qquad \delta d(x) = d^p(x) - u^n(x)$$

Theoretical predictions

- δd ~2-3% and δu~1% ➔ Sather, PLB 274 (1992) 4333
- δd could reach up to 10% at high x ➔ Thomas et al., Mod. PLA (1994) 1799

$$R^D_{\mathrm{Meas}}(x,z) = \frac{4N^{D\pi^-}(x,z) - N^{D\pi^+}(x,z)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)} \qquad R(x,z) = \frac{5}{2} + R^D_{\mathrm{Meas}}$$

$$D(z)\,R(x,z) + A(x)C(x) = B(x,z)$$

$A(x)$ and $B(x,z)$ are known

$$C(x) = \delta d(x) - \delta u(x)$$

E12-09-002: CSV Tests in SIDIS

Formalism:

Impulse Approximation

$$N^{Dh}(x,z) = N^{ph}(x,z) + N^{nh}(x,z)$$

Factorization

$$N^{Nh}(x,z) = \sum_q e_q^2 q^N(x) D_q^h(z)$$

$$A(x) = \frac{-4}{3(u_v(x) + d_v(x))}$$

$$B(x,z) = \frac{5}{2} + \frac{5\left[\bar{u}(x) + \bar{d}(x)\right]}{u_v(x) + d_v(x)} + \frac{\Delta_s(z)\,[s(x) + \bar{s}(x)]\,/\,[1 + \Delta(z)]}{u_v(x) + d_v(x)}$$

$$\Delta_s(z) = \frac{D_s^{\pi^+}(z) + D_s^{\pi^-}(z)}{D_u^{\pi^+}(z)}$$

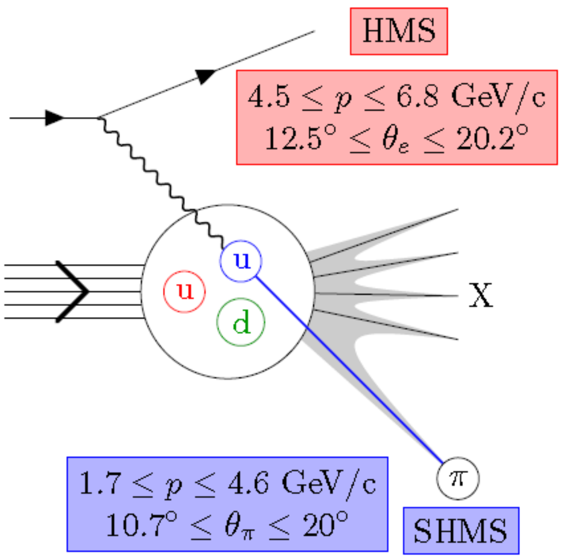
$$D(z) = \frac{1 - \Delta(z)}{1 + \Delta(z)} \qquad \Delta(z) = D_u^{\pi^-} / D_u^{\pi^+}$$

For each Q^2 we have 16 equations and 8 unknowns: $D(z_i)$ and $C(x_i)$

$$D(z)\, R(x,z) + A(x) C(x) = B(x,z)$$

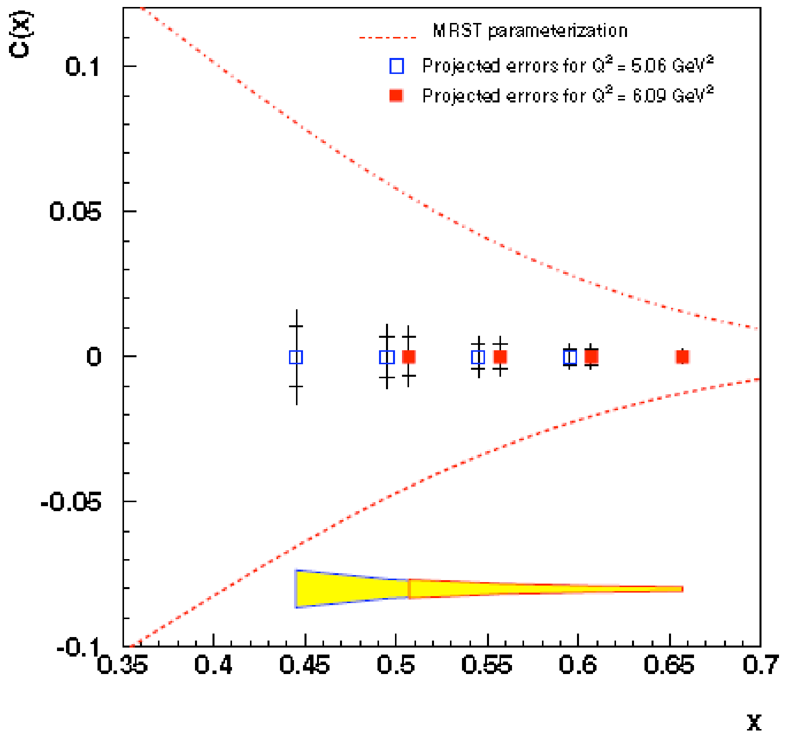
$$\left[\frac{1-\Delta(z)}{1+\Delta(z)}\right]\left[\frac{5}{2} + R^D_{\mathrm{Meas}}\right] + \left[\frac{-4}{3(u_v(x) + d_v(x))}\right]\left[\delta d(x) - \delta u(x)\right] = \frac{5}{2} + \frac{5\left[\bar{u}(x) + \bar{d}(x)\right]}{u_v(x) + d_v(x)} + \frac{\Delta_s(z)\,[s(x) + \bar{s}(x)]\,/\,[1 + \Delta(z)]}{u_v(x) + d_v(x)}$$

E12-09-002: CSV Tests in SIDIS



Measurements: $D(e, e'\pi^+)$ and $D(e, e'\pi^-)$

Projections



$Q^2 = 4$ GeV^2 $\rightarrow$ x = 0.35, 0.40, 0.45, 0.50

$Q^2 = 5$ GeV^2 $\rightarrow$ x = 0.45, 0.50, 0.55, 0.60

$Q^2 = 6$ GeV^2 $\rightarrow$ x = 0.50, 0.55, 0.60, 0.65

To each x setting corresponds 4 z measu

z = 0.4, 0.5, 0.6, 0.7

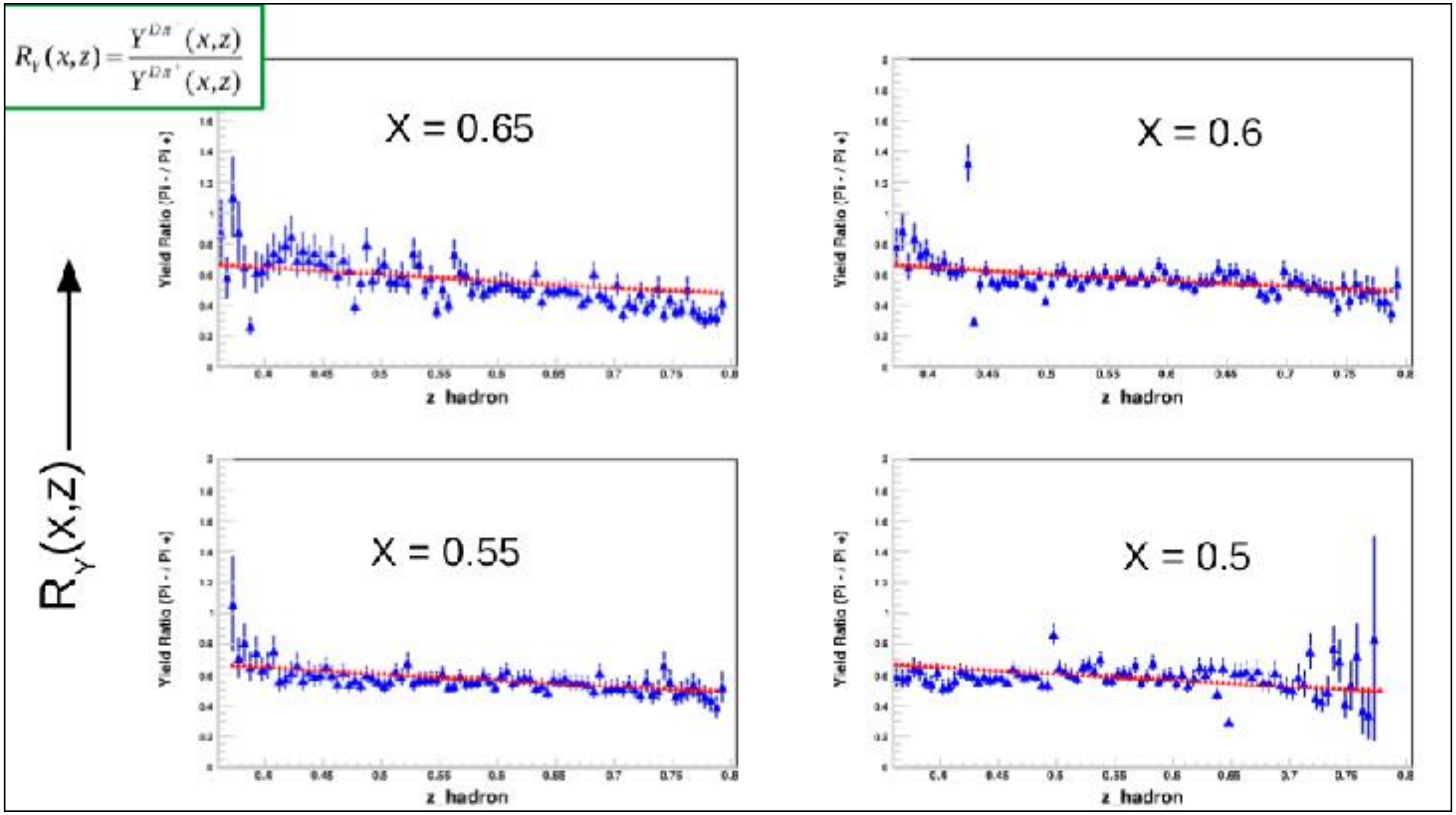
$$R_Y(x,z) = Y^{D\pi^-}(x,z)/Y^{D\pi}(x,z)$$

$$R^D_{\text{Meas}}(x,z) = \frac{4R_Y(x,z)-1}{1-R_Y(x,y)}$$

$$D(z)\,R(x,z) + A(x)C(x) = B(x,z)$$

E12-09-002: CSV Tests in SIDIS

A Very Preliminary Yield Ratio for pi - /pi + for Q2 = 5.5 GeV2

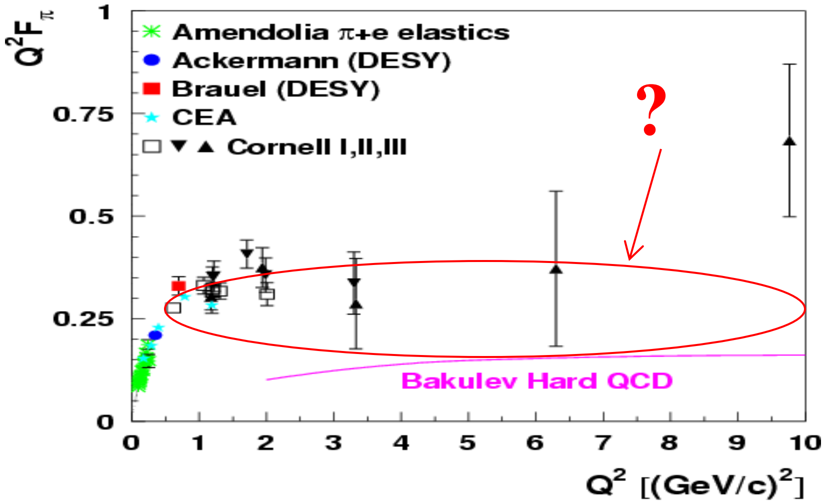


Without the target window correction, efficiency correction and acceptance correction. Red plot is simulation and the blue plot is from the data (100 bins in z from 0.3 to 0.8)

E12-06-101: Pion Form Factor to the highest Q2

Fπ status before Jlab Experiments (1997)

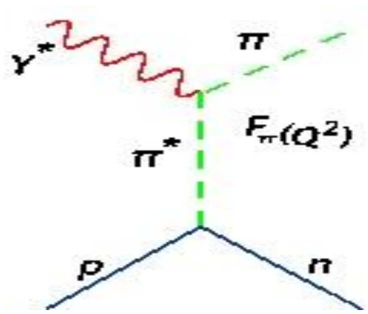
- Pion presents a clean test for our understanding of bound 2-quark systems
- Simple $q\bar{q}$ valence structure
- The pQCD description is expected to be valid at much lower values of Q^2 compared to the nucleon
- The limits on F_π are defined in pQCD and factorized $F_\pi(Q^2) = 8\pi \frac{\alpha_s f_\pi^2}{Q^2} \quad (Q^2 \to \infty)$, where f_π^2 = 93 MeV is the decay constant $\pi^+ \to \mu^+ + \nu_\mu$



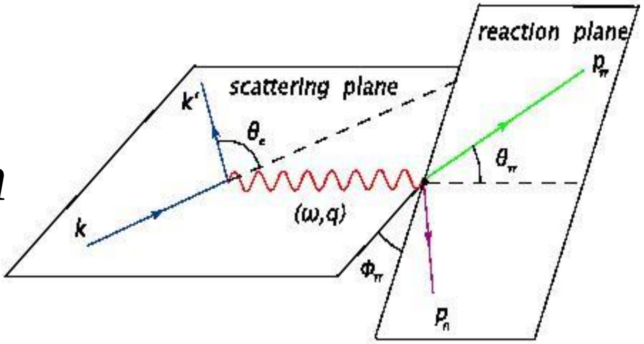
- ➔ F_π is well determined at $Q^2 < 0.3$ GeV^2 from elastic π-e scattering.
- ➔ $F_\pi(Q^2)$ at large Q^2 required the use of pion electroproduction
- ➔ Old F_π data at $Q^2 > 0.6$ GeV^2 have large systematic errors

E12-06-101: Pion Form Factor to the highest Q2

- **The study of F_π is needed for understanding hadronic structure; QCD transition from long to short distance scales**
- ***F_π* is well determined at $Q^2 < 0.3$ (GeV/c)^2 by π-e scattering.**
- **No any real measurements of *F_π* at *$Q^2 > 0.6$ (GeV/c)^2***
- **$F_\pi(Q^2)$ at large Q^2 required the use of pion electroproduction**



$$e + p \rightarrow e' + \pi^+ + n$$

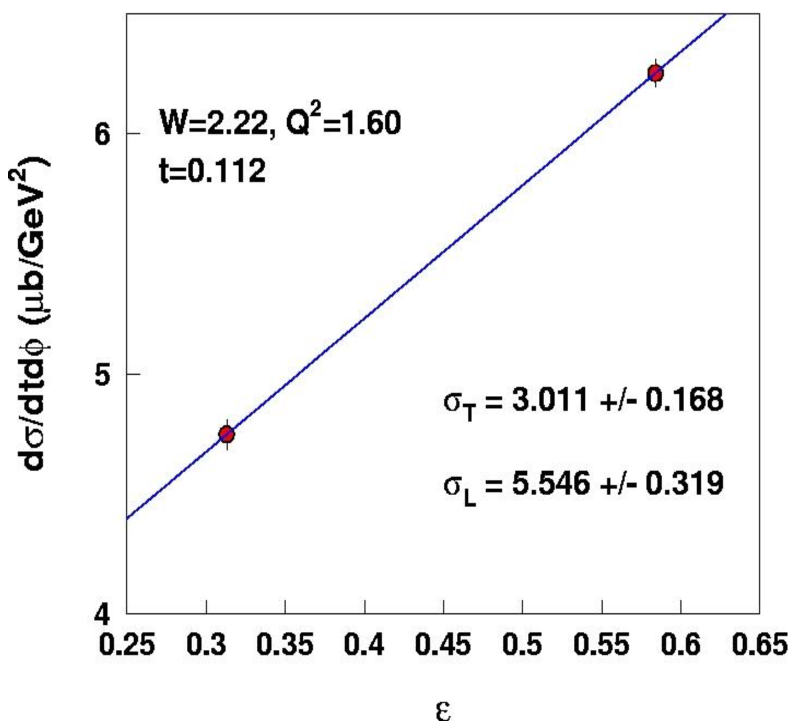


$$\frac{d^2\sigma}{dt\,d\phi} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi)$$

- ***F_π* measurements required extraction σ_L**

E12-06-101: Pion Form Factor to the highest Q^2

"Simple" Longitudinal-Transverse Separation



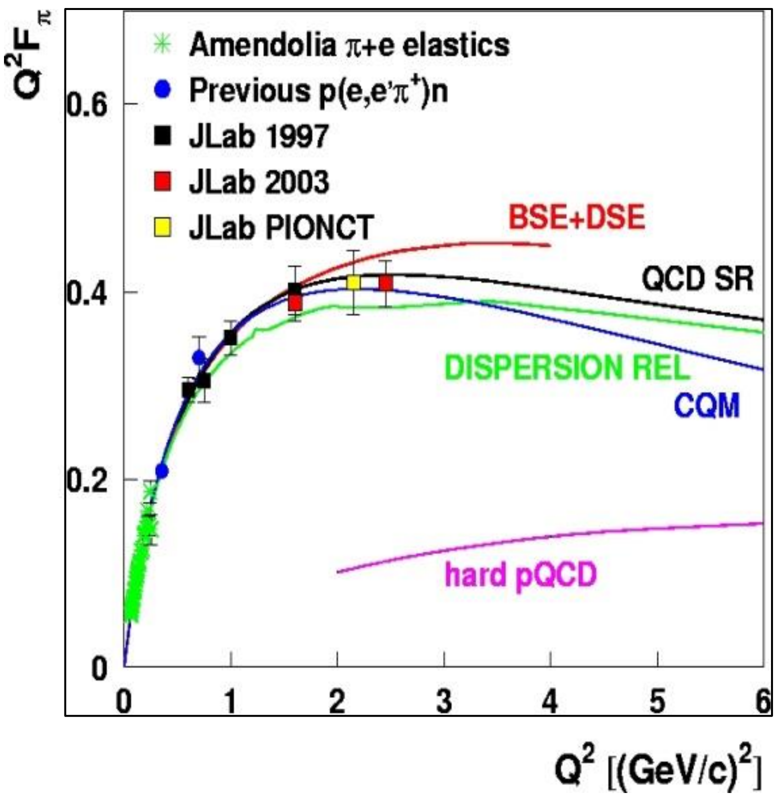
- Determine $\sigma_T + \varepsilon\,\sigma_L$ for high and low ε in each t-bin for each Q^2
- Isolate σ_L, by varying photon polarization, ε
- Effectively integrated out if full 2π coverage in Φ

$$\frac{d^2\sigma}{dt\,d\phi} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi)$$

E12-06-101: Pion Form Factor to the highest Q^2

Hall C F_π Results at CEBAF 6 GeV era

- First precise measurements for F_π in the range Q^2 =0.6-2.5 GeV^2
- Our results extracted from F_π-1 and from πCT data (Q^2=2.15 GeV^2) are consistent with F_π-2
- The F_π data are in relatively good agreement with a QCD sum rule and CQM calculation
- F_π is far from the pQCD prediction: NLO with improved π DA (A.Bakulev et al, Phys. Rev. D70 (2004))
- Data indicate that a maximum value $Q^2 F_\pi$ has been reached ?



Need
New measurements at Q^2>2.5 GeV^2

E12-06-101: Pion Form Factor to the highest Q2

Pion LT publications based on two 6 GeV experiments

6 GeV Pion Experiments:
1997 (phase 1)
2003 (phase 2)

~2000

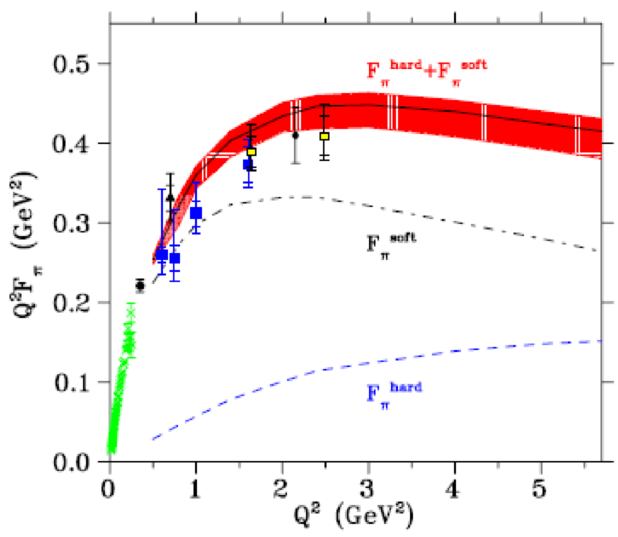
- J. Volmer, et al., Phys. Rev. Lett. **86** (2001) 1713 – **302 citations**
  - Precision F_π results between Q^2=0.60 and 1.60 GeV^2
- T. Horn, D. Gaskell, G. Huber, et al., Phys. Rev. Lett. **97** (2006) 192001 – **232 citations**
  - Precision F_π results at Q^2=1.60 and 2.45 GeV^2
- V. Tadevosyan, et al., Phys. Rev. C**75** (2007) 055205 – **199 citations**
- G. Huber, T. Horn, D. Gaskell, et al., Phys. Rev. C**78** (2008) 045203 – **172 citations**
  - Archival paper of precision F_π measurements at JLab 6 GeV
- G. Huber, T. Horn, D. Gaskell, et al., Phys. Rev. C**78** (2008) 045202 – **99 citations**
  - Archival paper of precision LT separated pion cross sections at JLab 6 GeV
- T. Horn, D. Gaskell, G. Huber, et al., Phys. Rev. C**78** (2008) 058201 – **61 citations**
  - L/T cross sections and F_π at Q^2=2.15 GeV^2, exploratory at Q^2~4.0 GeV^2
- Plus several spin-off papers on, e.g. L/T separations in π and ω production, high-t (2012-present)

2019

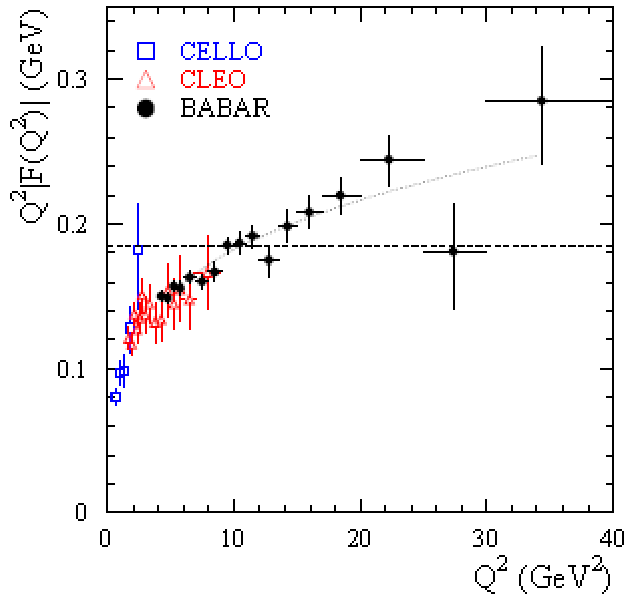
E12-06-101: Charged Pion Form Factor at high Q^2

$$e + p \rightarrow e' + \pi^+ + n$$

- **Pion presents a clean test for our understanding of bound 2-quark systems.** **Simple $q\bar{q}$ valence structure**
- **The pQCD description is expected to be valid at much lower values of Q^2 compared to the nucleon**



Fπ experimental data compared with a LO+NLO calculations. The band around the sum reflects uncertainties from QCD modes.

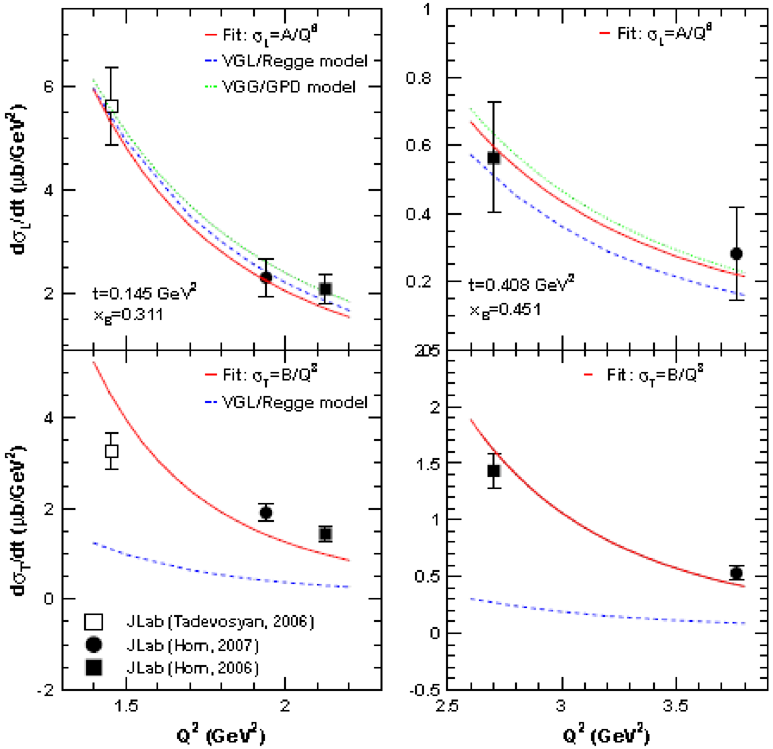


$\gamma\gamma^* \rightarrow \pi^0$ transition form factor from Babar. The dashed line indicates the limit predicted by pQCD. The dotted curve is a power law interpolation of the experimental data.

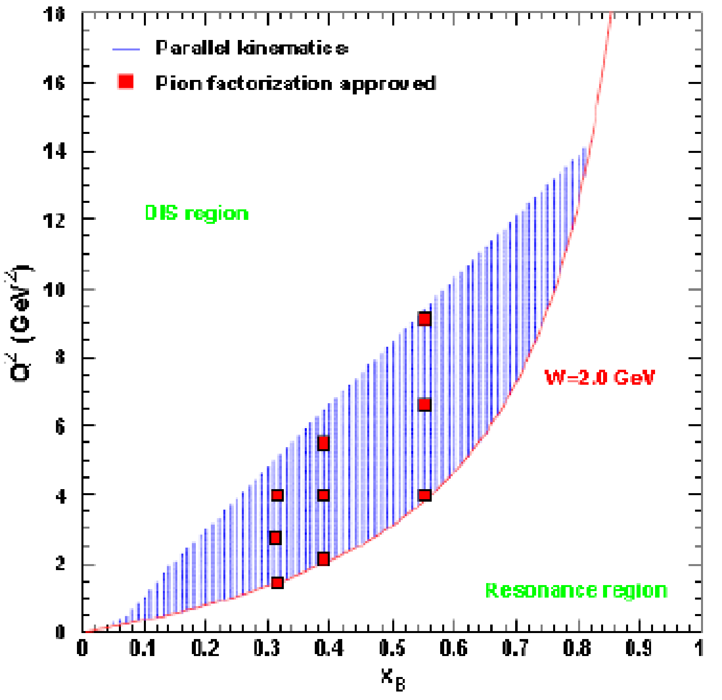
E12-07-105: L-T Separated Pion Electroproduction

Main goal:

- To measure separated p(e,e'pi+)n cross sections, test the dominance of the longitudinal cross section and its Q^2 dependence in hard exclusive processes.
- This measurement is of particular interest for our understanding of hadronic structure in terms of quark-gluon degrees of freedom in transition region from hadronic to the partonic regime for Q^2 up to 10 GeV^2



Q^2 dependence of the separated cross sections. The red, solid curve a fit of Q^{-6} for σ_L, and Q^{-8} for σ_T. The green dotted and blue dashed lines are GPD & VGL/Reggand calculation.



Q^2 versus xb phase space available for L-T separation in Hall C at 11 GeV energy using SHMS+HMS combination.

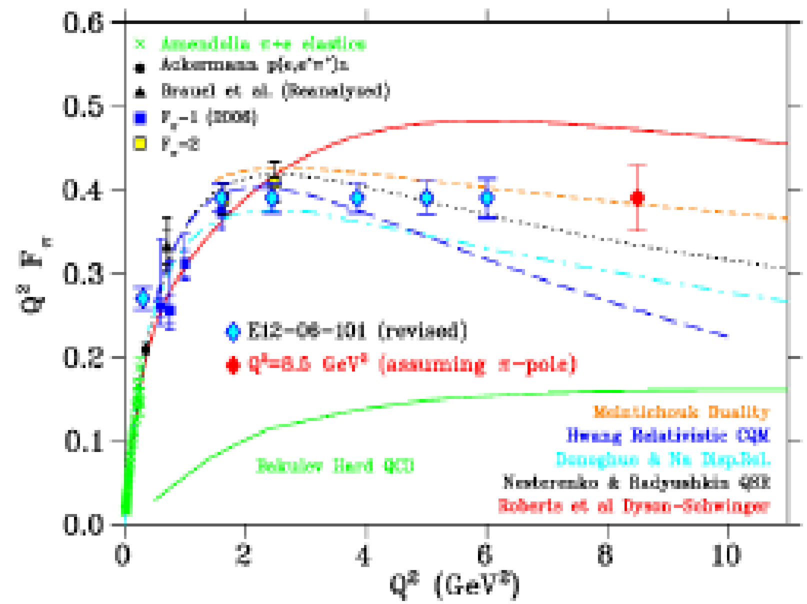
E12-06-101: Pion Form Factor to the highest Q^2

The JLab 12 GeV π^+ experiments:

- ❑ ***E12-06-101***: determine F_π up to Q^2=6 GeV^2 in a dedicated experiment
  - ➢ Require t_{min}<0.2 GeV^2 and $\Delta\varepsilon$>0.25 for L/T separation
  - ➢ Approved for 52 PAC days with "A" rating, high impact
- ❑ ***E12-07-105***: probe conditions for factorization of deep exclusive measurements in π^+ data to highest possible Q^2~9 GeV^2 with SHMS/HMS
  - ➢ Potential to extract F_π to the highest Q^2~9GeV^2 achievable at Jlab 12 GeV
  - ➢ Approved for 36 PAC days with "A-" rating

Experimental studies include:

- ➢ Check consistency of model with data
  - o F_π values seem robust at larger -t (>0.2) – increased confidence in applicability of model to the kinematic regime of the data
- ➢ Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
  - o R_L (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance
- ➢ Extract F_π at several values of t_{min}

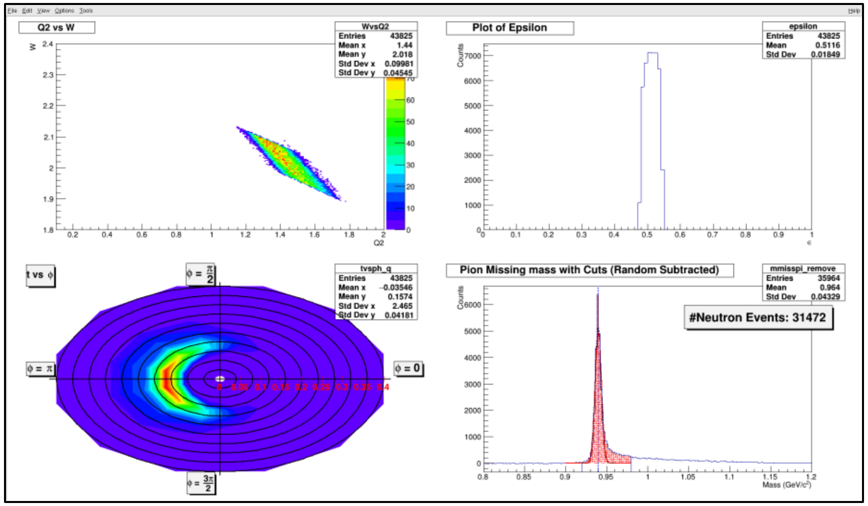


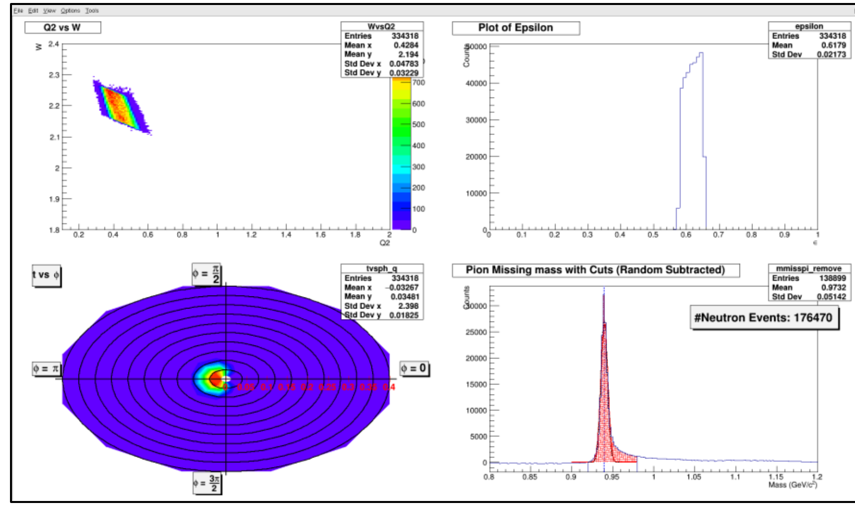
Main Goals:

- **F_π extraction to the highest Q^2**
- **Cross sections measurement over a range Q^2, x and t**
- **Separated cross sections σ_L and σ_T as a function of Q^2 at x=0.3, 0.4 & 0.5 to test reaction mechanism**

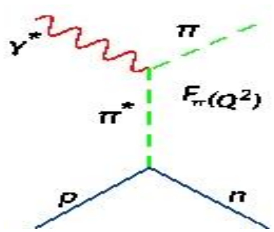
E12-06-101: Pion Form Factor to the highest Q^2

Examples of On-Line analysis plots





Low ε **Middle ε**



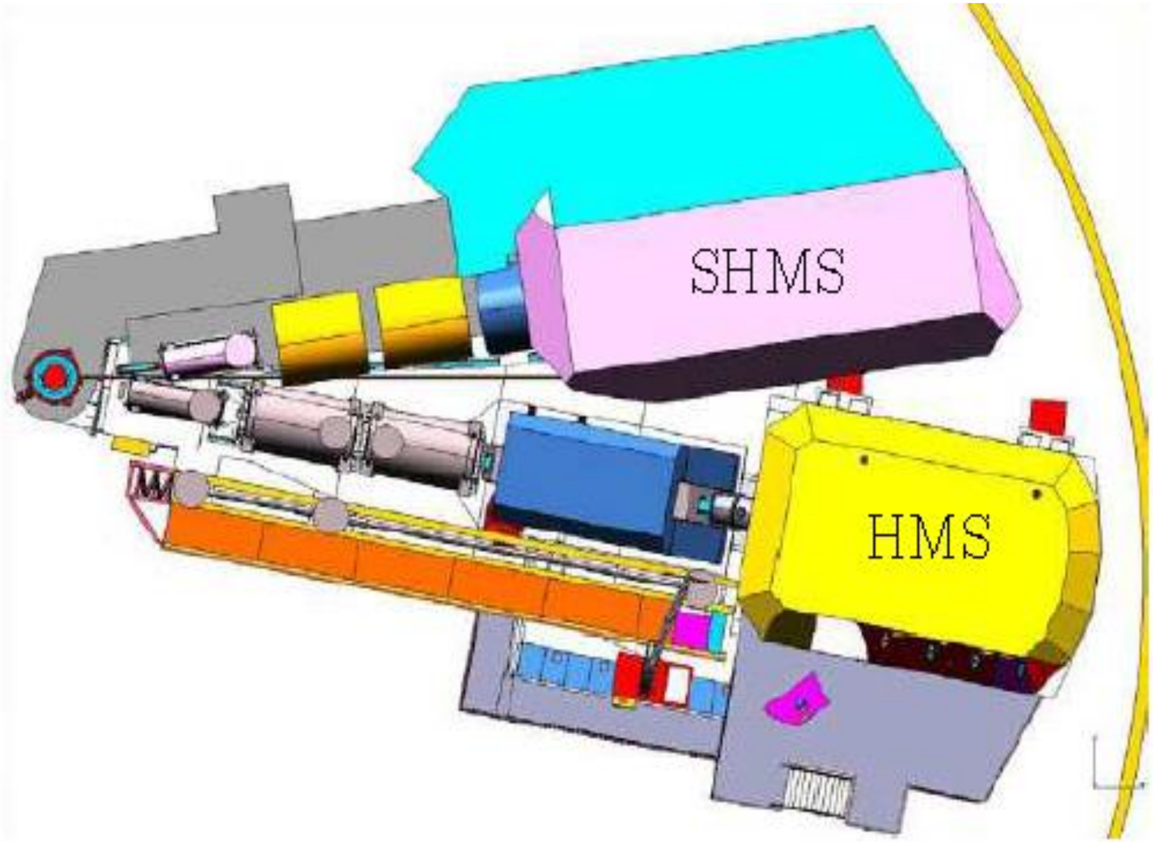
$$\frac{d^2\sigma}{dt\,d\phi}=\frac{d\sigma_T}{dt}+\epsilon\frac{d\sigma_L}{dt}+\sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{TL}}{dt}\cos(\phi)+\epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi)$$

F_π measurements required extraction σ_L

Hall C at CEBAF 12 GeV

12 GeV Hall C base equipment

HMS (old) and SHMS (new) magnetic spectrometers are well suited for (e,e') coincident measurements.



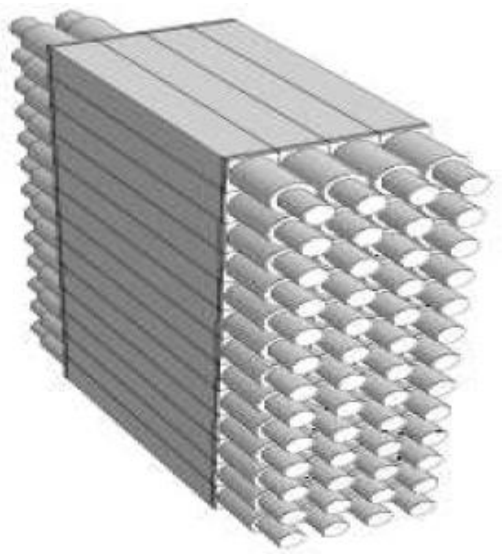
SHMS parameters:
Magnets: (HB)QQQD
P: 2 -- 11 GeV/c
ΔP: (-10% , +22%)
δP: 0.03%-0.08%
θ: 5.5 ° -- 40°
Δ Ω: 4.0 msr

HMS parameters:
Magnets: QQQD
P: 0.5 – 7.5 GeV/c
ΔP: (-10% , +10%)
δP: 0.1%
θ: 12.5 ° -- 90°
Δ Ω: 6.0 msr
L: 10^{38} $cm^{-2}s^{-1}$

Spring 2019 Production Run 6550

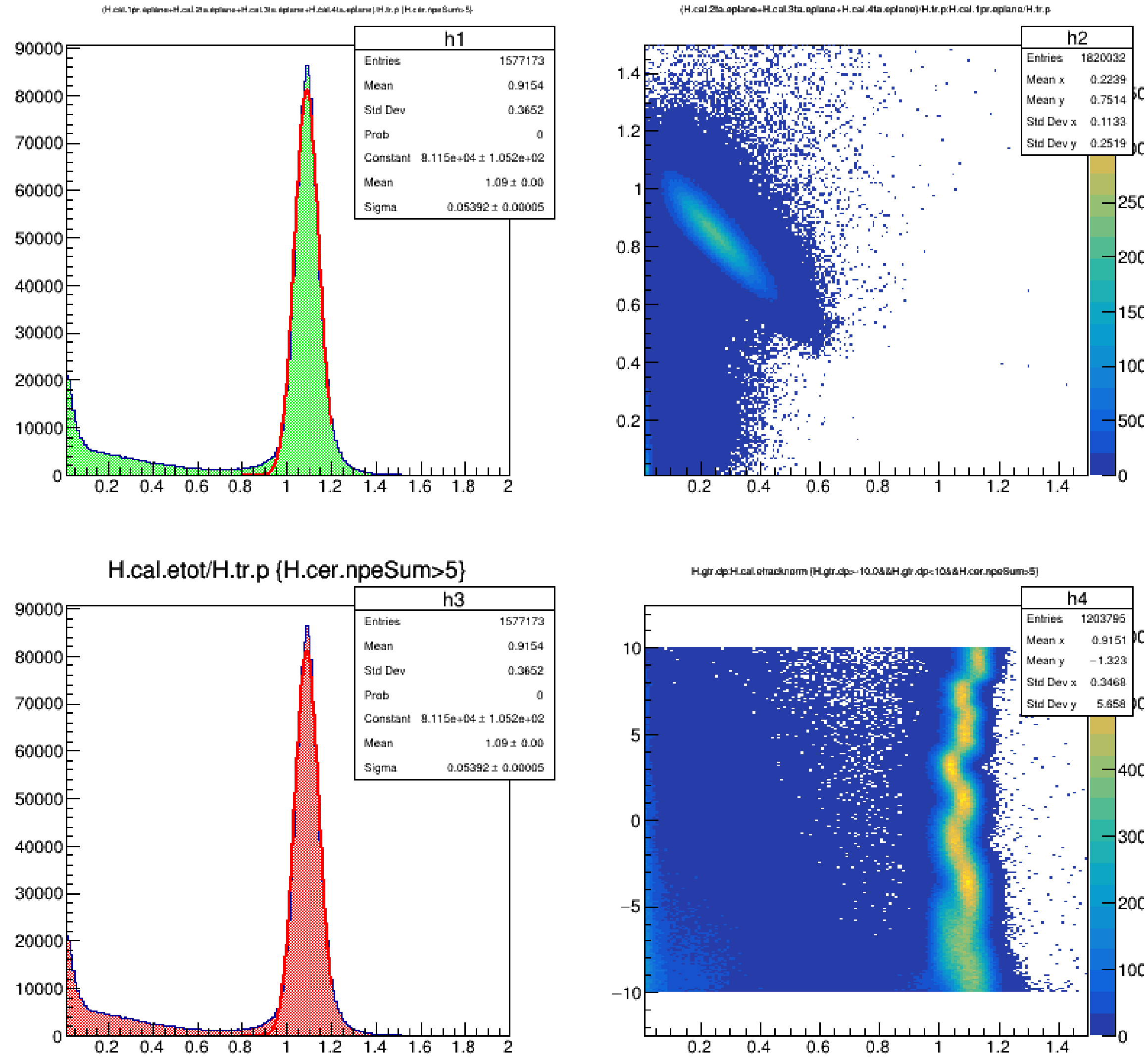
HMS Calorimeter Before Calibration

HMS Calorimeter



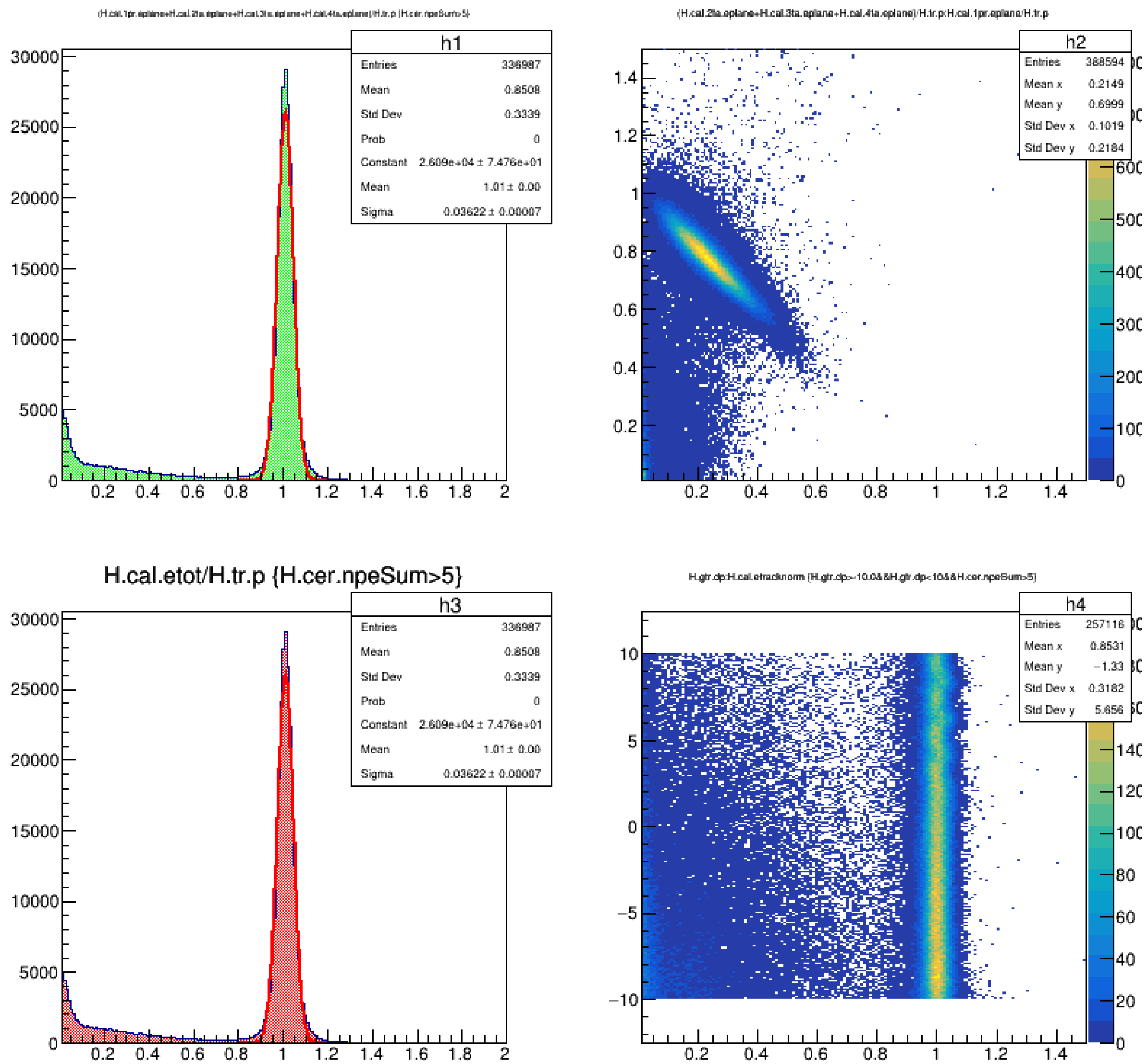
4x13➔52 TF-1 Blocks
2x26+2x13➔78 XP3462

Spring 2019 data



Note, HMS Calorimeter have been designed and build by YerPhI group

HMS Calorimeter After Calibration



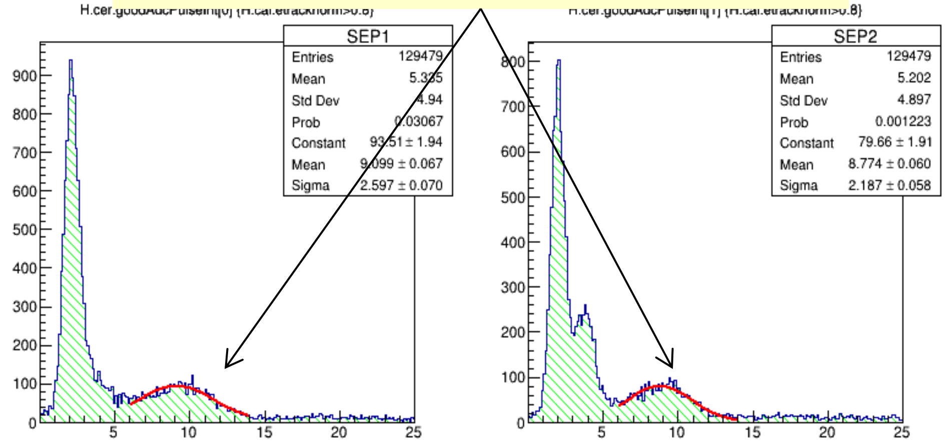
Spring 2019 data

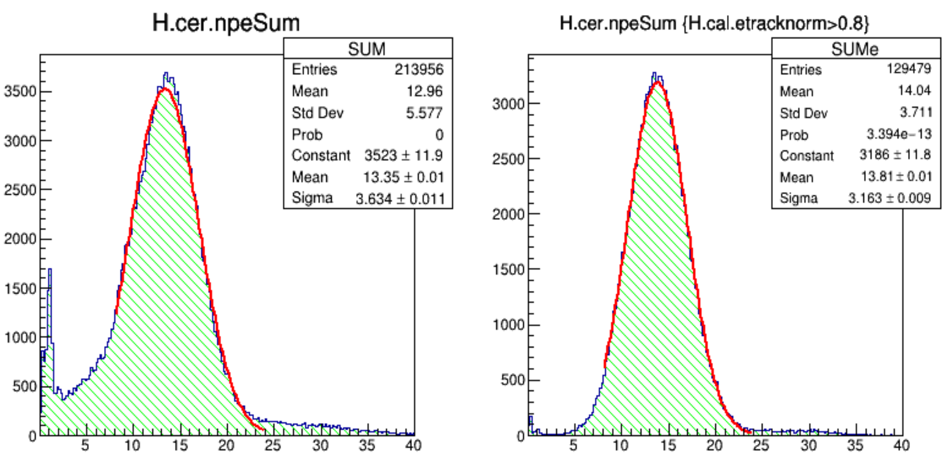
Calorimeter analysis and Calibration codes have been developed by V. Tadevosyan

HMS Gas Cerenkov Detector Calibration

Cerenkov radiation threshold for particles (1-β) < (n-1)

PMTs Pulse Integral distributions from fADC have been used to localize SEP





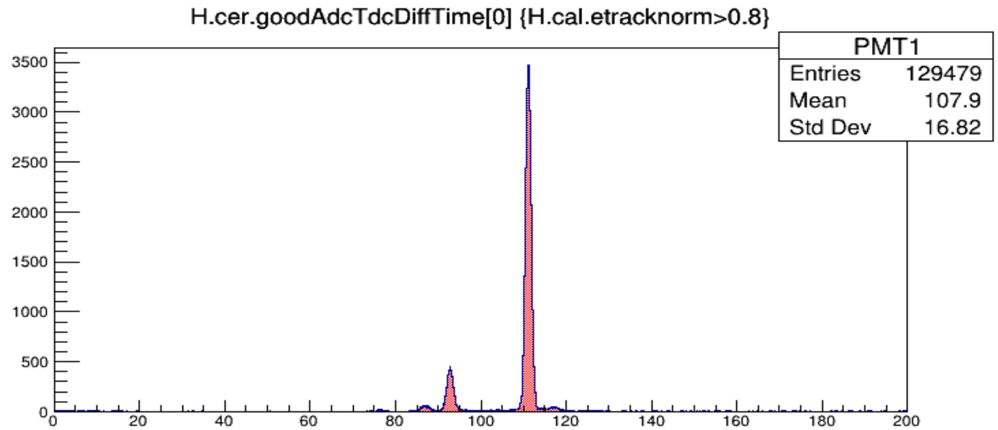
HMS Cerenkov: 2R = 150 cm, L=165cm

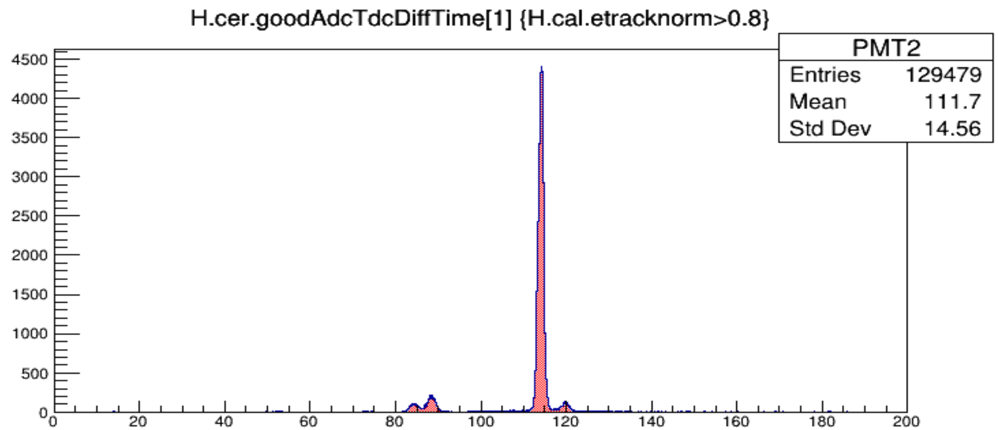
- Filled C_4F_8O (octafluorotetrahydrofuran) at 0.42 atm, n=1.0006, (n=1.0014 at 1 atm)
- Pion threshold momentum ~4.0 GeV/c
- 2 mirrors and 2 PMTs (5" Burle 8854 coated with WLS to improve efficiency

Sum of Photoelectrons before and after PID cut

HMS Gas Cerenkov Detector Calibration

The "H.cer.goodAdcTdcDiffTime" distributions for PMT1 and PMT2



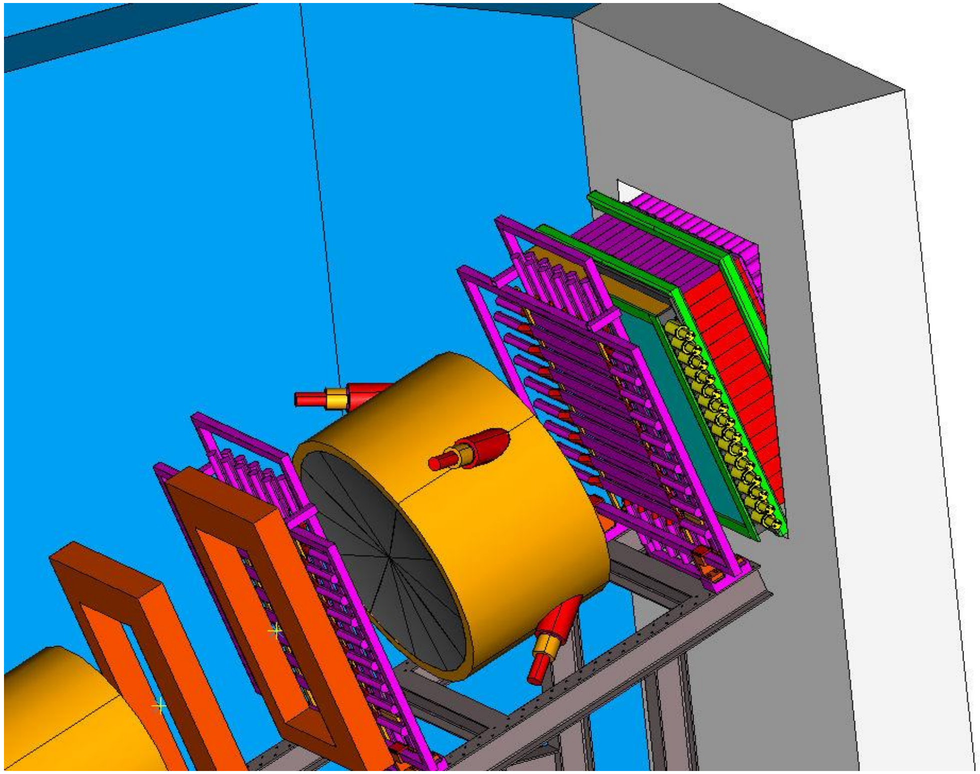


Spring 2019 data

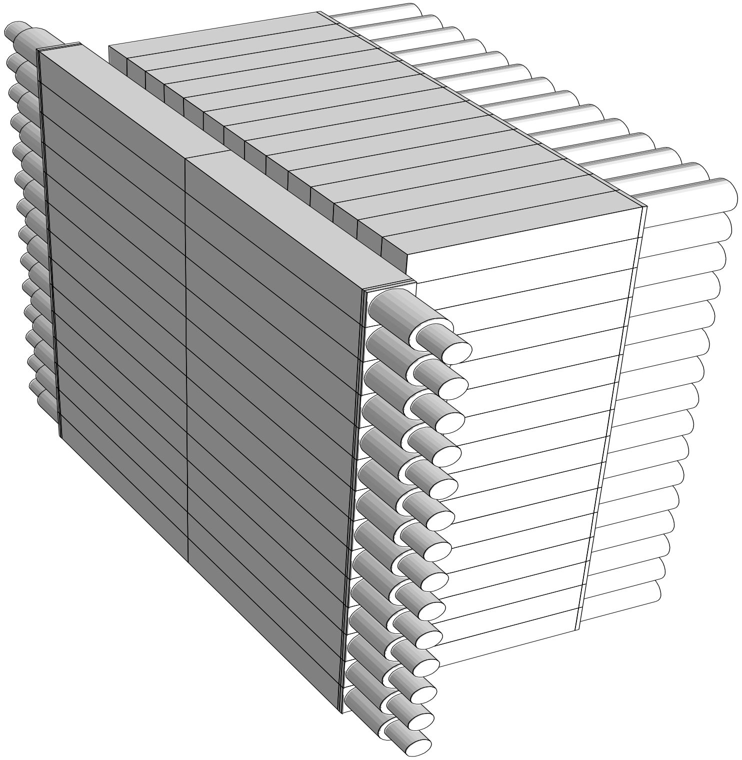
- First calibration was done with wide open cuts on hcer_adcTimeWindow (-1000, 1000).
- Changing timing window position of SEP and sum of photoelectrons are not changing.

Super High Momentum Spectrometer (SHMS)

Detector Hut

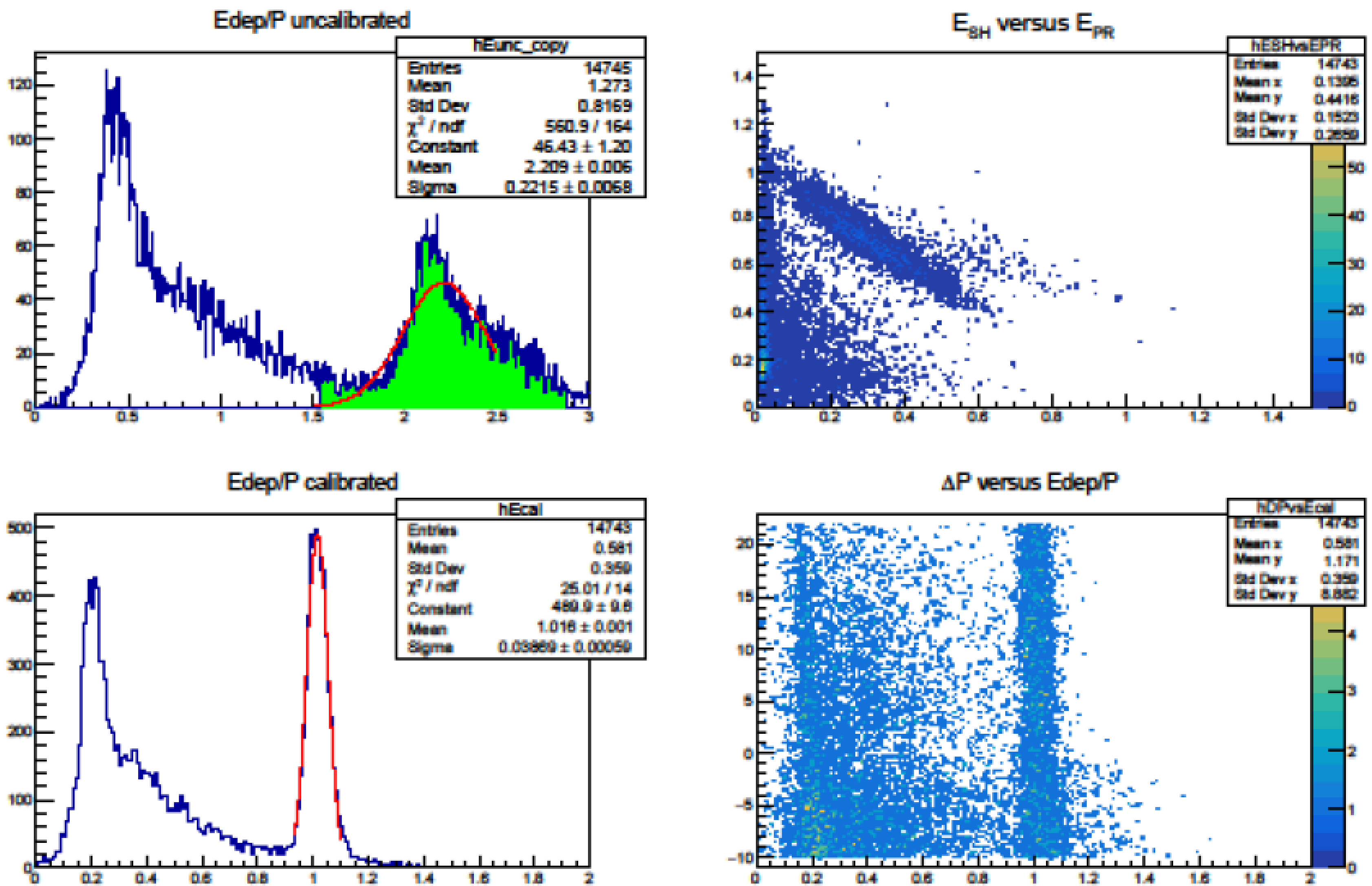


Calorimeter



- Calorimeter is situated at the very end of SHMS detector stack
- With effective area 120cm x 140cm, it will cover SHMS acceptance
- π/e rejection 200:1 with Preshower & Shower (at 99.5% e^- efficiency)
- Preshower consists of 28 modules (TF-1) stacked back to back
- Shower part consists of 224 modules (F-101) from HERMES detector

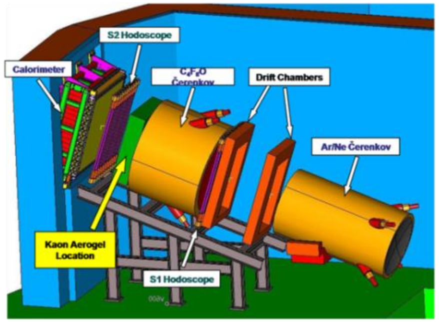
SHMS Calorimeter Calibration



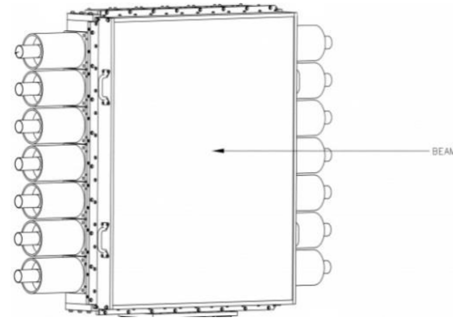
Note, SHMS Calorimeter have been designed and build by YerPhI group

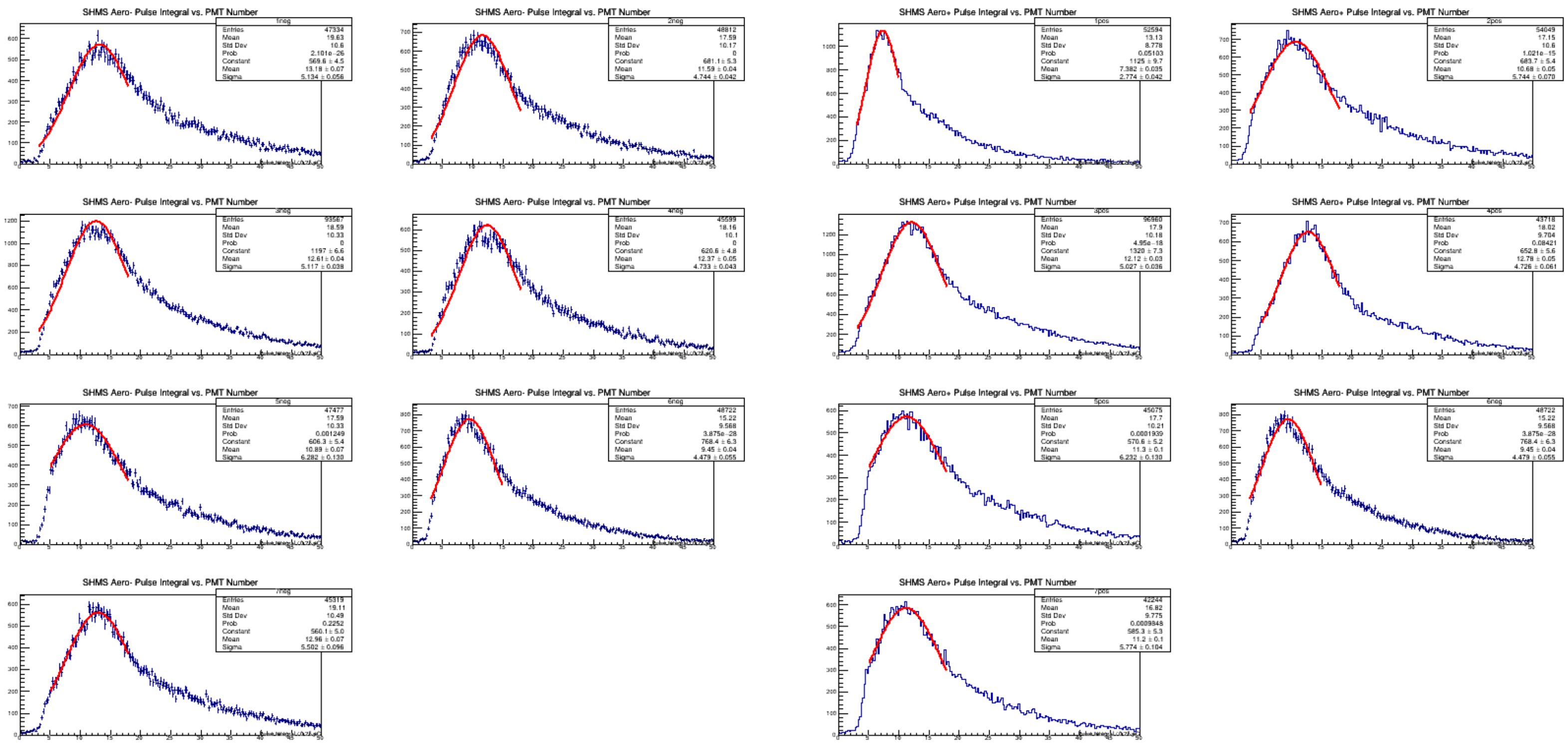
SHMS Aerogel Cerenkov PMTs Calibration

Cerenkov radiation threshold for particles (1-β) < (n-1)



14 PMTs, 5" XP4572
4 exchangeable tray:
n=1.030, n=1.020
n=1.015 and n=1.011

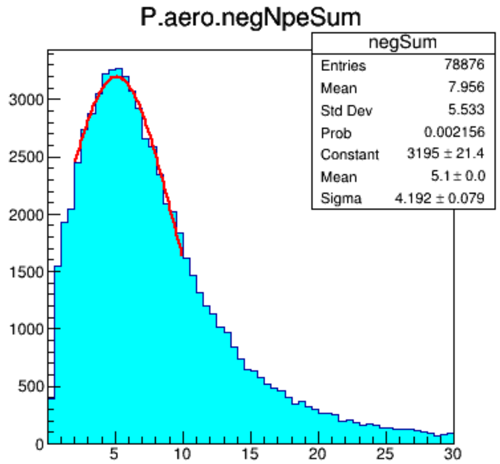


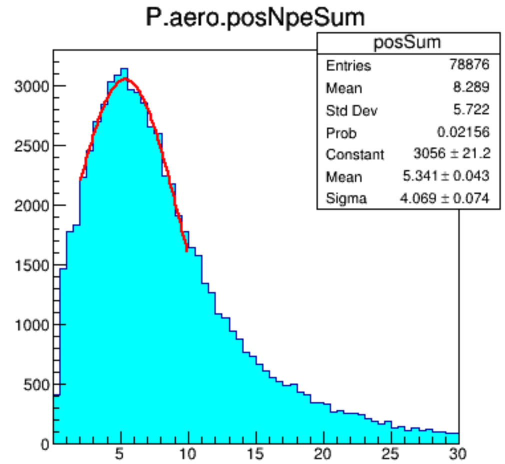


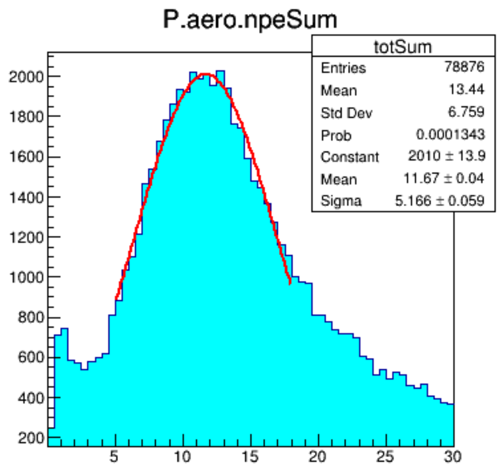
SHMS Aerogel detector PMTs SEP distributions.

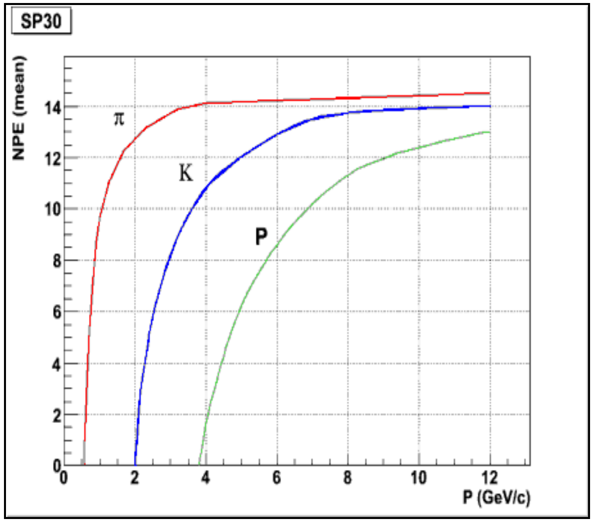
SHMS Aerogel Cerenkov NPE Sums

Spring 2019 SIDIS Run. LH2 Target, Pshms=-3.043 GeV/c









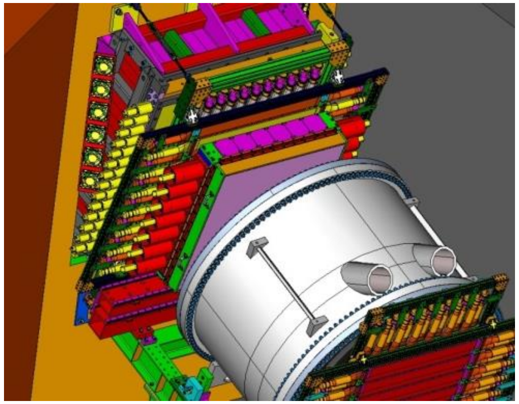
π/K/P separation with Aerogel Cherenkov

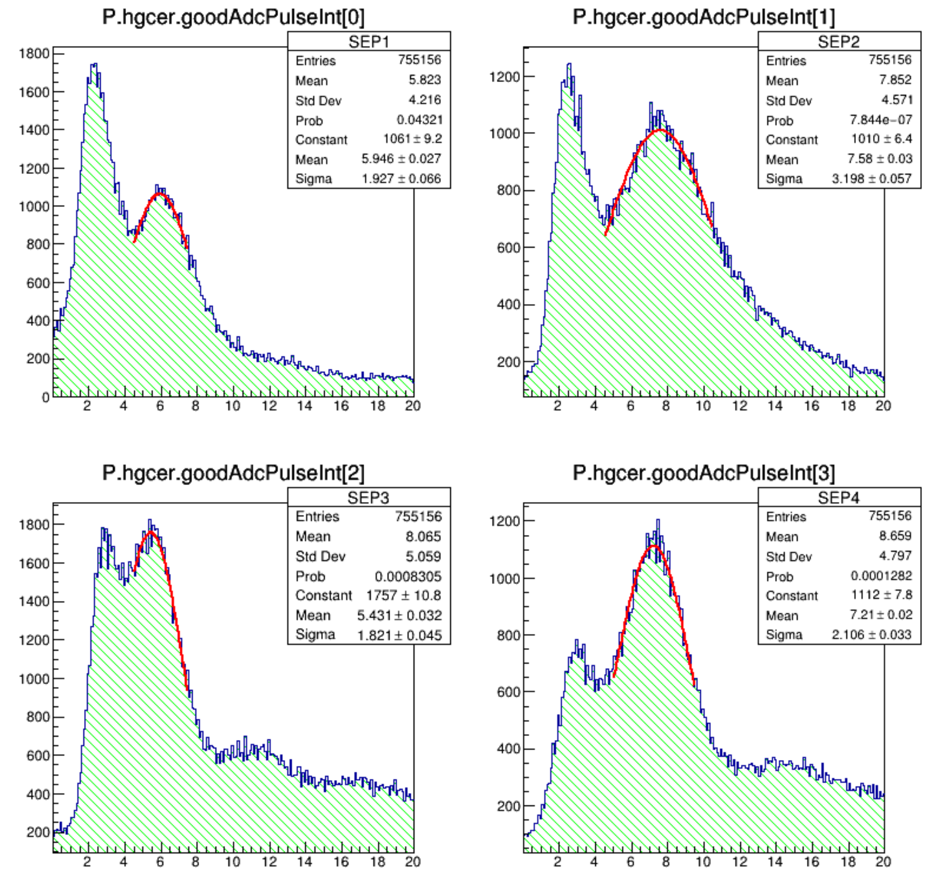
Type of Particle	P_{th} in n=1.030	P_{th} in n=1.015	P_{th} in n=1.010	P_{th} in n=1.006
μ	0.428	0.608	0.746	0.963
π	0.565	0.803	0.984	1.272
K	2.000	2.840	3.482	4.500
P	3.802	5.397	6.618	8.552

Note, SHMS Aerogel detector have been designed and build by YerPhI & CUA

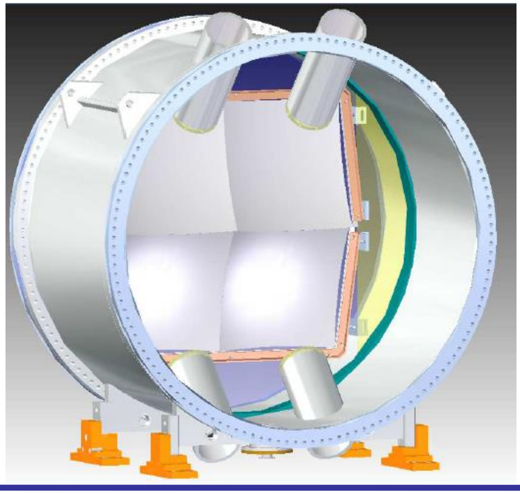
SHMS HG Cerenkov Calibration

Cerenkov radiation threshold for particles $(1-\beta) < (n-1)$





- Filled with C_4F_8O (octafluorotetra-hydrofuran) n=1.0014 at 1 atm
- 4 mirrors and 4 PMTs (Hamamatsu)

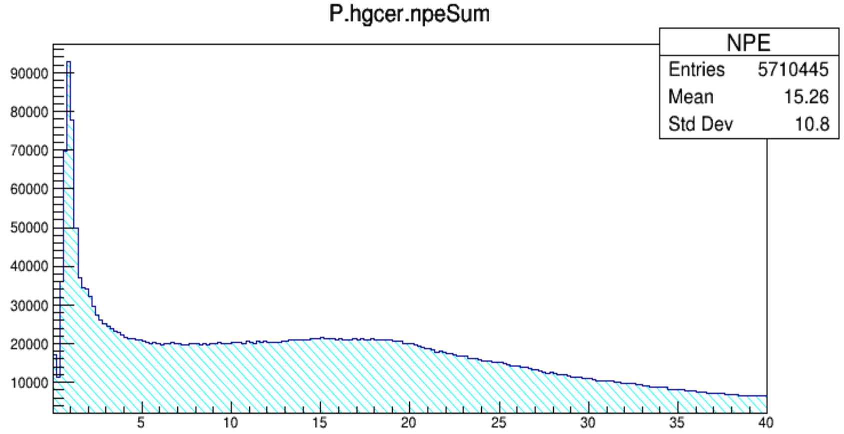


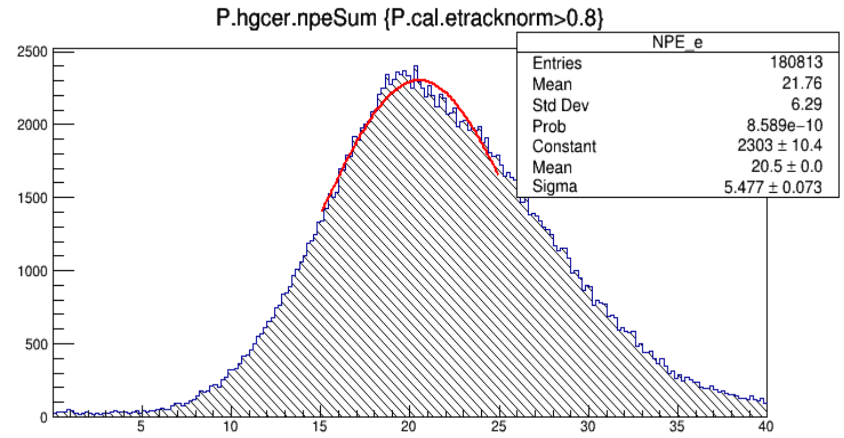
- HG Cerenkov PMTs SEP positions from run-to-run are stable.
- In some cases the 2 electron peak also can be seen.

SHMS HG Cerenkov Calibration

Momentum (GeV/c)	n_e (0.5 MeV/c^2)	n_π (139.57 MeV/c^2)	n_K (493.67 MeV/c^2)	n_{Proton} (938.27 MeV/c^2)
3	1.01435	1.00108	1.01345	1.04778
5	1.00519	1.00039	1.00486	1.01745
7	1.00265	1.00020	1.00248	1.00894
9	1.00160	1.00012	1.00150	1.00542
11	1.00107	1.00008	1.00101	1.00363

Total sum of photoelectrons without and with PID cut (requiring electrons in CAL).



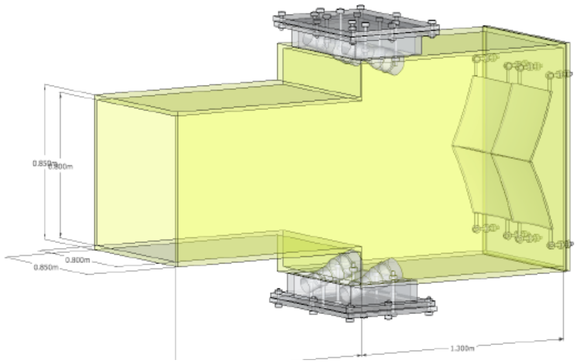


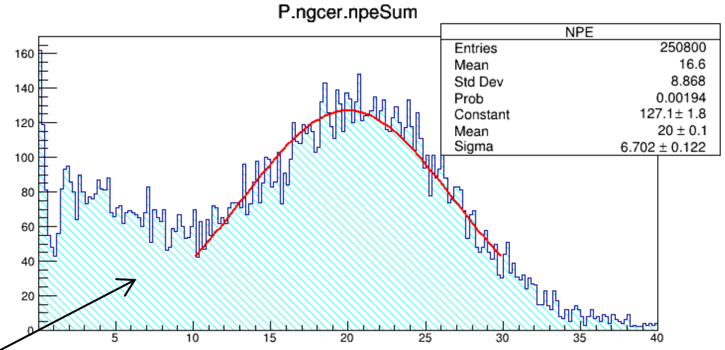
- For electrons we expect npeSum ~20.

SHMS NG Cerenkov Calibration

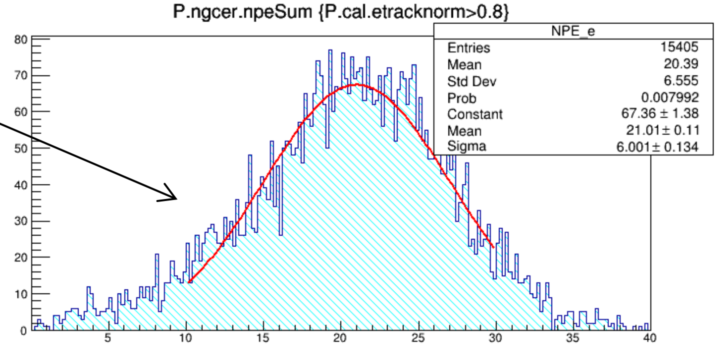
Cerenkov radiation threshold for particles (1-β) < (n-1)

- Filled with Ar or Ne (at 1 atm)
- n =1.001233 for Ar
- n = 1.001205 for Ne
- 4 mirrors and 4 PMTs (5" Hamamatsu R1584, coated with WLS to improve QE)





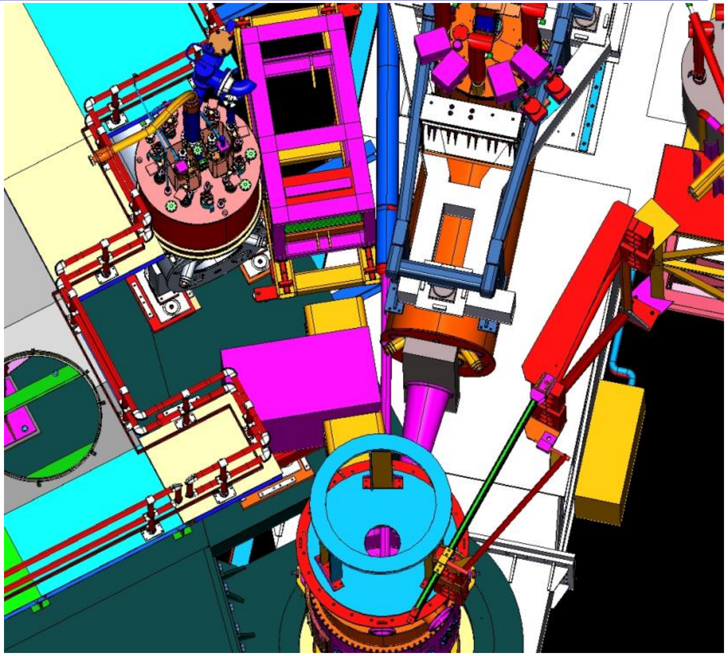
Number of photoelectrons without and with electron-PID requirement



- For electrons we expect npeSum ~20.

Neutral Particle Spectrometer (NPS)

A Neutral Particle Spectrometer (NPS) is required to carry out the JLab 12 GeV Hall C program of precision cross section measurements and L/T separations, extending the charged-particle (p, $\pi^{+/-}$, $K^{+/-}$) measurements to neutral particles (γ and π^0). It will open new opportunities in Hall C, utilizing the well-understood HMS and the new SHMS infrastructure.



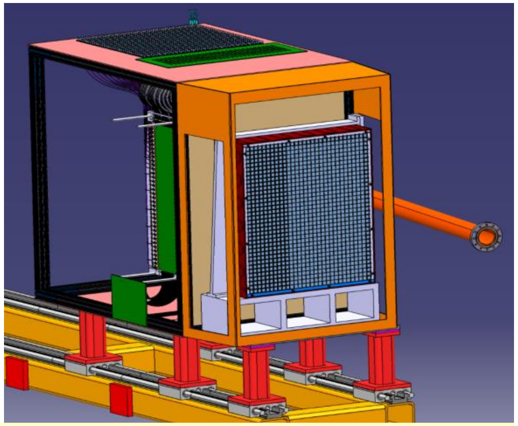
Proposals benefitting from the NPS facility, so far:

- E12-13-007, Measurement of Semi-Inclusive π^0 Production as Validation of Factorization. (25 days, PAC40 approved, A- rating, running with E12-13-010).
- E12-13-010, Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C. (53 days, PAC40 approved, A rating).
- E12-14-003, Wide-angle Compton scattering at 8 and 10 GeV photon energies. (18 days, PAC42 approved, A rating).
- E12-14-005, Wide Angle, Exclusive Photoproduction of π^0 Mesons. (18 days, PAC42 approved, B rating).

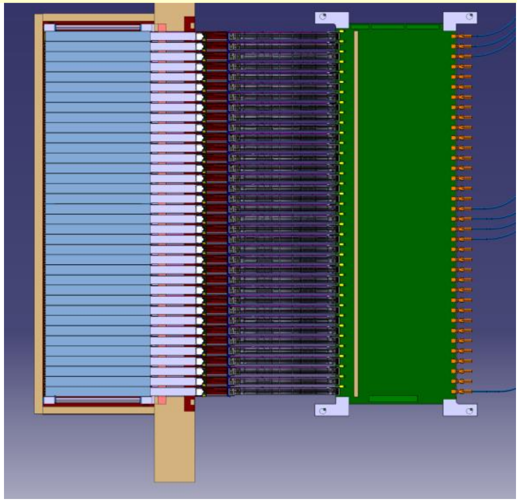
Neutral Particle Spectrometer (NPS)

NPS ERR (Experiment Readiness Review) – 15 May 2019

- Magnet assembled and tested with software control
- Hall-probe mapper were used to measure three-axis field in 1 cm intervals
- 560 Crystals onsite (460 from SICCAS+100 from Crytur)
- Calorimeter frame design completed
- Full assembling scheduled – Fall 2020
- First experiment WACS preliminary scheduled -2021



PbWO Crystal Calorimeter



Vendor	Samples	Delivered
SICCAS	460	FY 2017
CRYTUR	100	FY 2018

Sweep magnet

Summary and Outlook

Collaboration with JLab Hall C started in early 90's. Its effective and productive

In CEBAF 6 GeV era YerPhI group main contributions are:

- ✓ Design and construction LG calorimeters for HMS and SOS spectrometers
- ✓ Design construction of Aerogel detector for HMS spectrometer
- ✓ Participation in ~50 experiments installation, data taking and analysis
- ✓ Participation in development of physics program at 6 GeV
- ✓ YerPhI group first proposed and lead first SIDIS experiment at JLab

In CEBAF 12 GeV era YerPhI group main contributions are:

- ➢ Design and construction Shower and Preshower Calorimeter for SHMS
- ➢ Design and construction Aerogel detector for SHMS (in collaboration with CUA)
- ➢ Development 3 physics proposals related to SIDIS at 12 GeV energy
- ➢ Development Neutral Particle Spectrometer (NPS) program and PbWO crystal based multichannel calorimeter for upcoming approved experiments
- ➢ Development of TCS project (currently under preparation)

- ❖ **Future effective continuation required support from AANSL and SC**
- ❖ **Need students & PhD to cover all our responsibilities and program**

BACKUP SLIDES

YerPhI group have two other upcoming SIDIS experiments in HALL C: $\pi^{\pm}$ cross section ratios $R = \sigma_L/\sigma_T$ in SIDIS and π^{o} Production in SIDIS

The ratio $R = \sigma_L/\sigma_T$ in Semi-Inclusive Deep Inelastic Scattering

(E12-06-104, Spokespersons: P. Bosted, R. Ent, E. Kinney, and H. Mkrtchyan)

- This experiment will make precise measurements of R in charged π and K SIDIS on H and D targets as a function of Q^2, fractional hadron momentum z, and hadron transverse momentum p_T
- Standard technique to measure R: Vary the virtual photon polarization ε by using different incident beam and electron scattering angles, while keeping the Q^2, x, z, and p_T constant. Will use the two magnetic

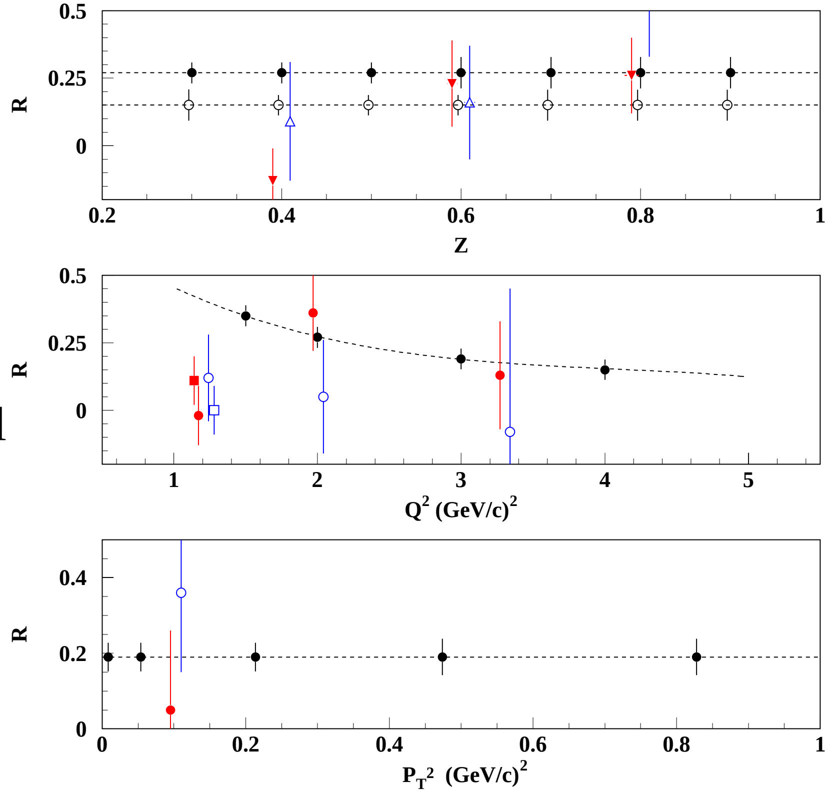
$$\sigma = \Gamma(\sigma_T + \varepsilon\sigma_L + \varepsilon\cos(2\phi)\sigma_{TT} + [\varepsilon(\varepsilon+1)/2]^{1/2}\cos(\phi)\sigma_{LT})$$

$$\varepsilon = \left[1 + 2\left(\frac{Q^2}{4M^2x^2}\right)\tan\frac{\theta}{2}^2\right]^{-1}$$

$R = \sigma_L/\sigma_T$ is a basic aspect of the photon-parton interaction

- First DIS evidence that quarks had spin ½ (R→0 as $Q^2 \rightarrow \infty$)
- Almost no experimental knowledge of R in SIDIS

Projections for E12-06-104 vs existing Cornell Data (projections assume $R_{SIDIS} = R_{DIS}$) Comparable 1.6% systematic uncertainties not indicated



Projections: Solid Black H, Open Black D π Cornell:
Top panel: solid red (open blue) π^+ (π^-) on LH_2
Middle : solid red (open blue) dots are π^+ (π^-) on LH_2
solid red (open blue) squares are π^+ (π^-) on LD_2
Bottom : solid red (open blue) dots are for π^+ (π^-) on

The ratio $R = \sigma_L/\sigma_T$ in Semi-Inclusive Deep Inelastic Scattering

- An essential measurement in understanding SIDIS in LO factorized form at these energies

$$\sim \Sigma e_q^2 q(x)\, D_q^{\pi}(z$$

  - ➢ Previous JLab cross section experiments experiments suggest this factorized picture is valid at JLab energies at appropriate final hadronic state energies

$$R_{SIDIS} = R_{DIS}?$$

$$R_{SIDIS}^{\pi^+} = R_{SIDIS}^{\pi^-}? \qquad R_{SIDIS}^{H} = R_{SIDIS}^{D}? \qquad R_{SIDIS}^{\pi^+} = R_{SIDIS}^{K^+}?$$

- Important for determining spin structure function g_1 (need term $(1 + \varepsilon R)$ to get g_1/F_1 from $A_{\parallel}$)
- At low z, expect DIS Q^2 behavior ($\sim 1/Q^2$), but as z→ 1, expect Deep-Exclusive Q^2 behavior ($\sim Q^2$)
- Completely unknown p_T behavior, which might impact on TMD analyses

Measurement of Semi-Inclusive π^0 Production as Validation of Factorization

PAC-40 Proposal PR12-13-007

Spokespersons Rolf Ent, Tanja Horn, Hamlet Mkrtchyan & Vardan Tadevosyan

- Essential ingredient of basic (e,e'π) cross section measurements to lay a solid foundation for the SIDIS program at a 12-GeV JLab.

JLab Theory Group Report (Prokudin & Radyushkin):

> The physical goal of the experiment is to check so called factorization of SIDIS cross section into quark distribution $f(x)$ for the initial nucleon and final pion fragmentation function $D(z)$. The precision of such a factorization is crucial for experimental determination of fragmentation functions and applications of QCD theory to meson production experiments. The accuracy of factorization is expected to increase with energy, and an important question is to which extent it is settled at JLab energies. The use of neutral pions for this purpose has several advantages, in particular, absence of contamination from pion generated from diffractively produced ρ mesons, and reduced nucleon resonance contribution.

Beam Time Request: 25 days* at 11.0 GeV

(not including setup and checkout time as this depends on scheduling)

*fully overlapping the PR12-13-010 beam time request

Hall C SIDIS Program – basic (e,e'π) cross sections

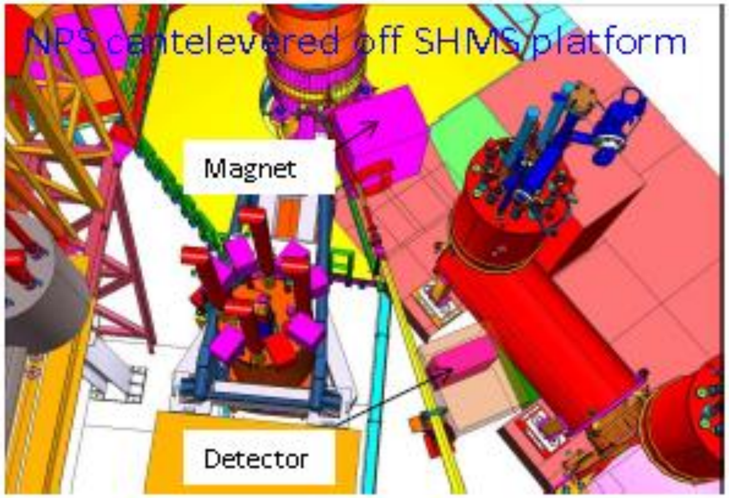
Low-energy (x,z) factorization, or possible *convolution in terms of quark distribution and fragmentation functions*, at JLab-12 GeV must be well validated to substantiate the SIDIS science output. Many questions at intermediate-large z (~0.2-1) and low-intermediate Q^2 (~2-10 GeV^2) remain.

Why need for $(e,e'\pi^0)$ beyond $(e,e'\pi^{+/-})$?

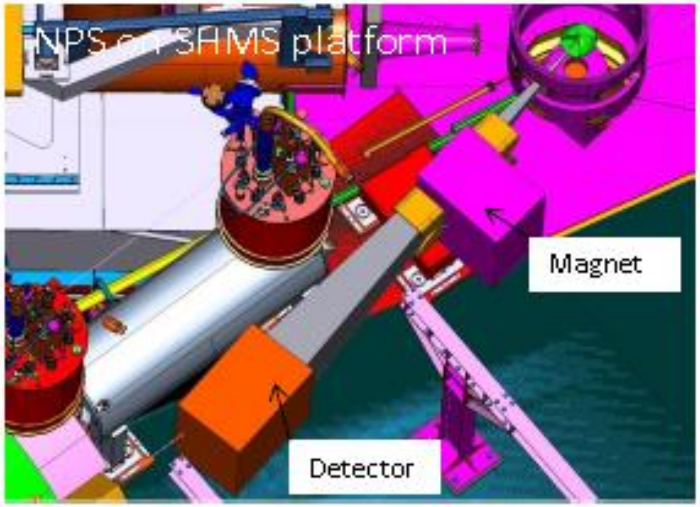
- No diffractive ρ contributions
- Smaller radiative tail
  - no pole contributions
- Less resonance region contributions
  - for example, compare with $ep \rightarrow e\pi^- \Delta^{++}$
- Proportional to average fragmentation function
  - easier to disentangle quark and fragmentation functions

The Neutral-Particle Spectrometer (NPS)

The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ, π^0).



NPS angle range: 5.5 – 30 degrees



NPS angle range: 25 – 60 degrees

The need for such a device can be exemplified by the submitted program to PAC40:

PR12-13-007 – Measurement of Semi-inclusive π^0 production as Validation of Factorization

PR12-13-010 – Exclusive Deeply Virtual Compton and Neutral Pion Cross Section Measurements in Hall C

(PR12-13-007 & PR12-13-010 can run as one run group – unique in Hall C)

PR12-13-009 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies

LOI12-13-003 – Large Center-of-Mass Angle, Exclusive Photoproduction of π^0 Mesons at Photon Energies of 5-11 GeV

The Neutral-Particle Spectrometer (NPS)

- a ~25 msr neutral particle detector consisting of 1116 PbWO4 crystals in a temperature-controlled frame – use PRIMEx crystals or more likely new.

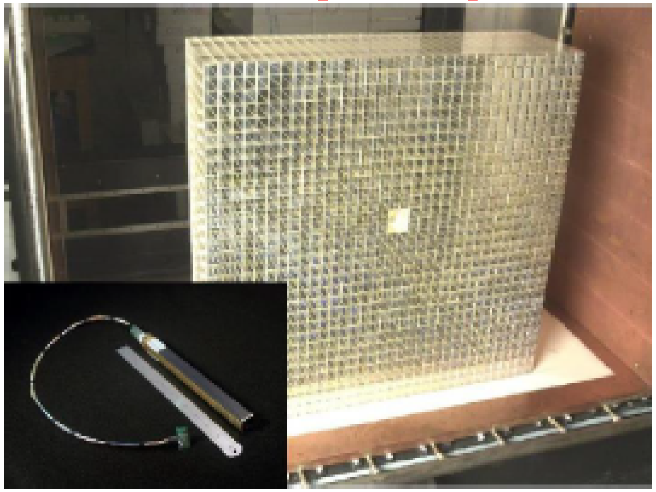
- HV distribution bases with built-in amplifiers for operation in a high-rate environment – new

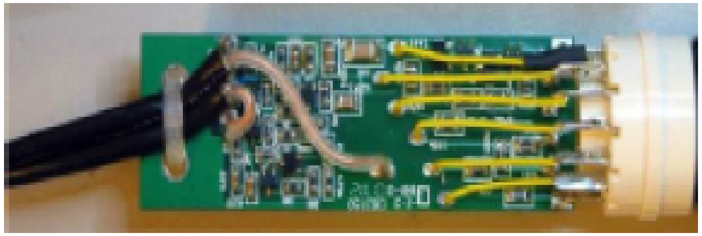
- essentially deadtime-less digitizing electronics to independently sample the entire pulse form for each crystal – JLab-developed Flash ADCs

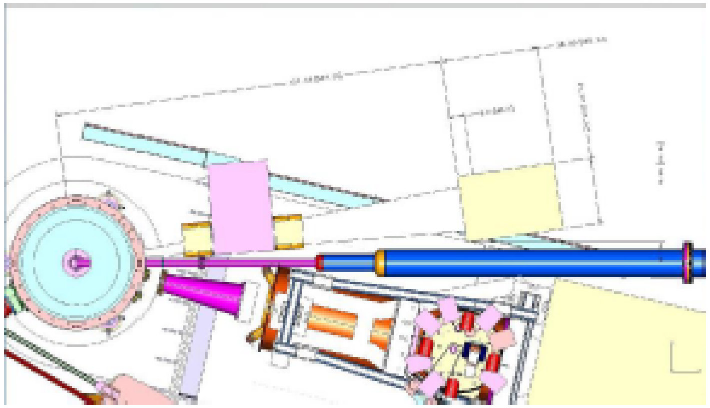
- Two sweeping magnets, one horizontal bending with ~0.3 Tm field strength, and one vertical bending with ~0.6 Tm field strength for larger angles/WACS. Both designed to use an existing power supply – new

- Cantelevered platforms off the SHMS carriage to allow for remote rotation (in the small angle range), and platforms to be on the SHMS carriage (in the large angle range) – new

- A dedicated beam pipe with as large critical angle as possible to reduced beamline-associated backgrounds – further study has shown only a small section needs modification (JLab/Hall C)



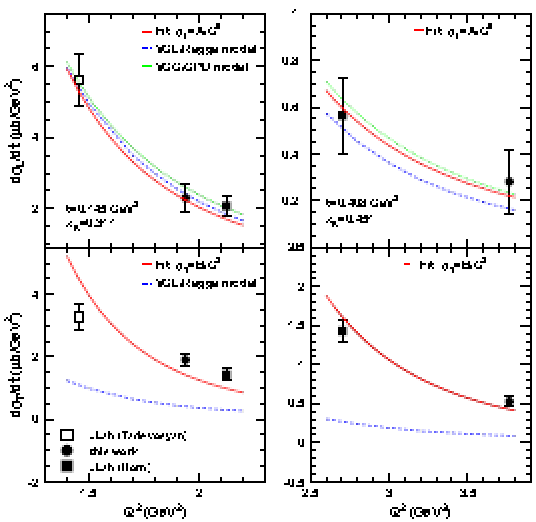




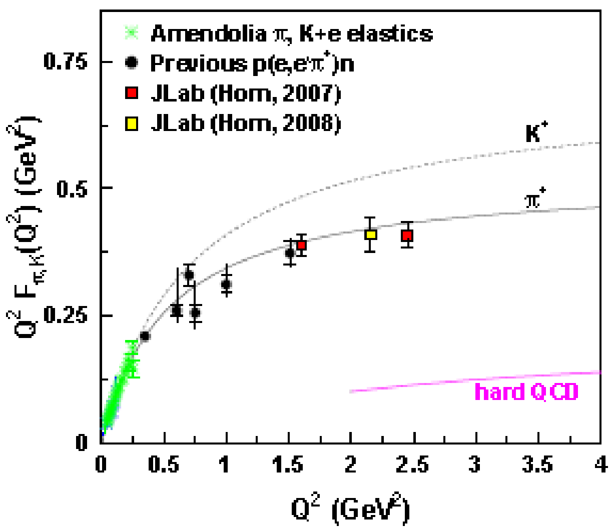
HV and cabling is assumed from JLab, and similar as for BigCal

E12-09-011: L-T Separated Kaon Electroproduction

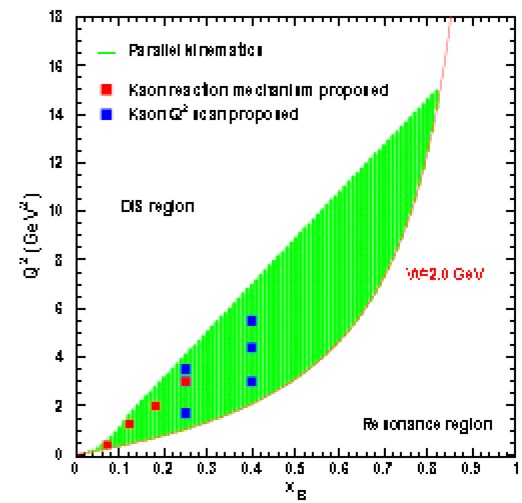
- $p(e,e'K^+)\Lambda$ and $p(e,e'K^+)\Sigma^0$ reactions are important tools to study of hadron structure
- There are no L/T separated data for exclusive K^+ production above the resonances
- Separated $p(e,e'K^+)\Lambda,\Sigma^0$ cross sections allow investigation of the transition from hadronic to partonic degrees of freedom in exclusive process
- A direct comparison of the scaling properties of π^+ & K^+ separated cross will provide a study of scaling in strange system.
- The results from the proposed measurement will help to identify missing elements in existing theoretical calculations.
- If these studies indicate K^+ pole dominance at low –t, the data would be use to extract K^+ form factor, as has been done for the π^+.



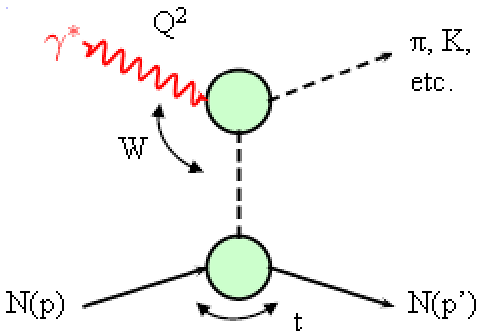
(a) The Q^2 dependence of σ_L and σ_T.



(b) The Q^2 dependence of the pion form factor.



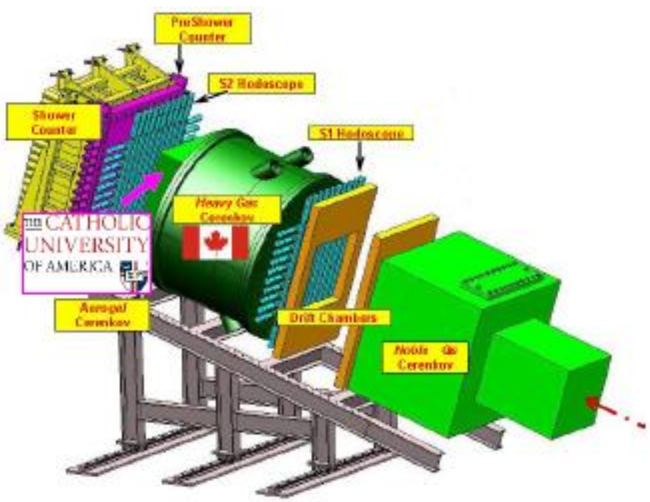
E12-09-011: L-T Separated Kaon Electroproduction

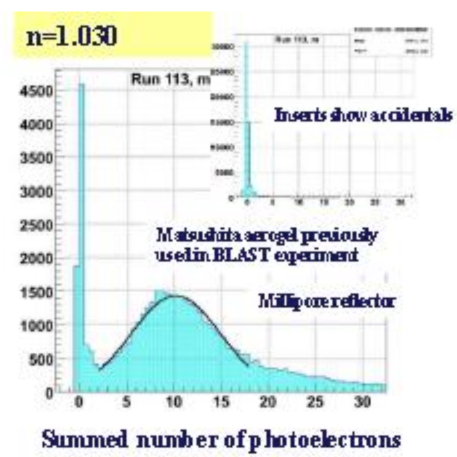


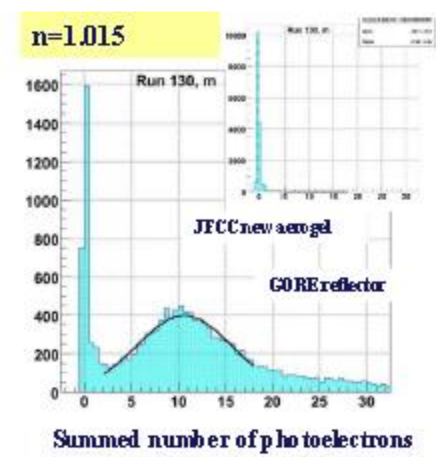
t-channel process

- In the limit of small $-t$, meson production can be described by the t-channel meson exchange (pole term)
  - Spatial distribution described by form factor

$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$







E12-16-007: J/ψ Photo-production at Hall C

<u>*Main goal:*</u>

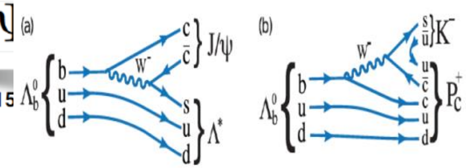
- To measure the photo-production cross section of J/ψ near threshold
- Search for the LHCb Charmed Pentaquark in J/ψ Photo-production

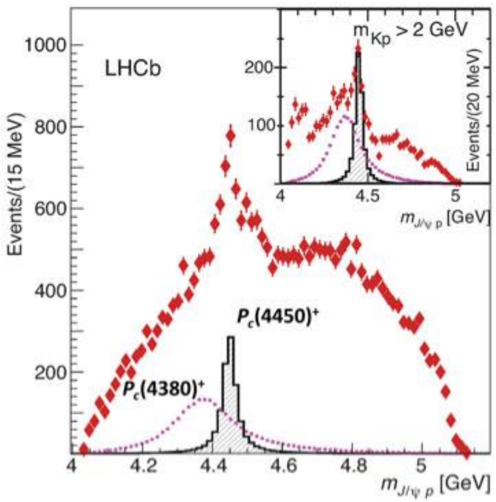
<u>*Note:*</u>

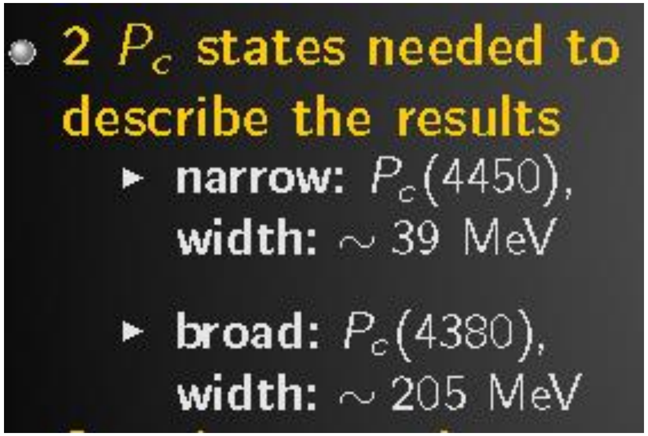
- LHCb observed charm resonances $P_c(4380)$ and $P_c(4450)$ consisted with "pentaquarkks"
- They looked for pentaquark states by examining the decay of Λb baryon into J-psi, proton and charged kaon. Studying the spectrum of masses of the J/ψ and proton revealed intermediate states $P_c(4380)$ and $P_c(4450)$. Since 2015 there are about 700 citations

$$\Lambda_b \rightarrow K^- p J/\psi$$

Aaij, R, et. al (LHCb) PRL 115-7 (2015

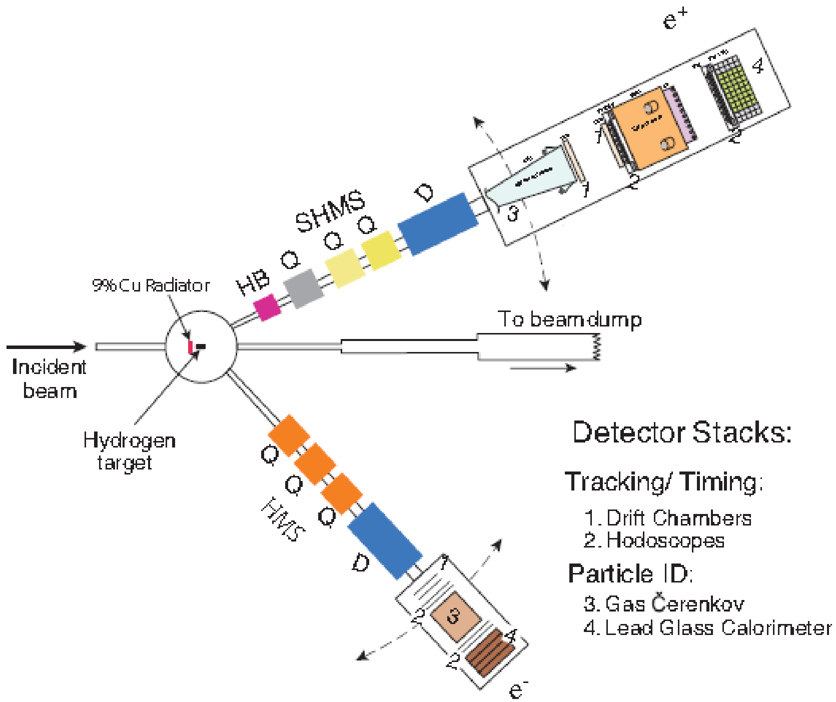






Observation of these resonances in photo-production is important to differentiate the true resonance nature of these states

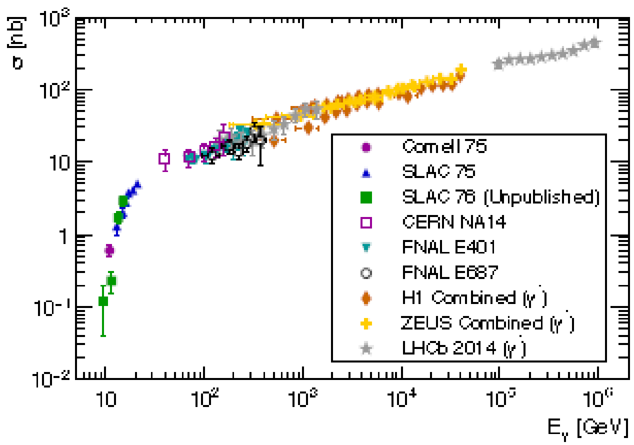
E12-16-007: J/ψ Photo-production at Hall C

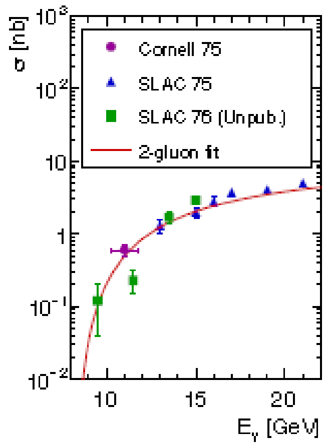


E12-16-007 SETTINGS

- t channel (BG) Setting 1: low $E\gamma$, low t
- precise determination of the t channel background
- HMS: 4.95 GeV, 19.1°
- SHMS: 4.835 GeV, 17°

- t channel (BG) Setting 2: high $E\gamma$, low t
- precise determination of the t channel background
- HMS: 4.08 GeV, 19.9°
- SHMS: 3.5 GeV, 20.1°





E12-15-001: Proton's Generalized Polarizabilities in VCS

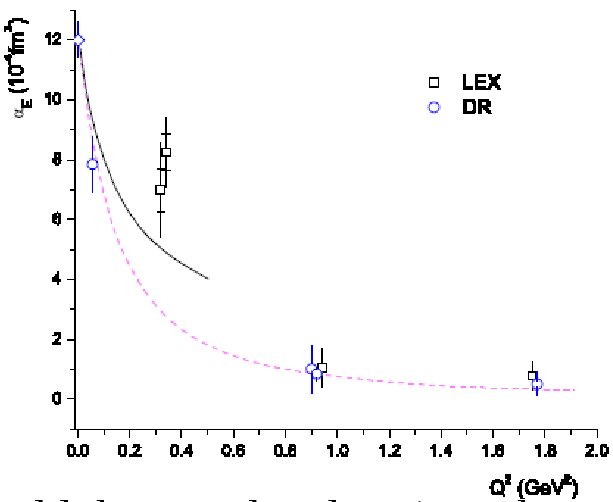
Main goal: ▪ Extract the two scalar Generalized Polarizabilities of the proton in the region of Q^2 = 0.3-0.75 GeV^2 using Virtual Compton Scattering reaction.

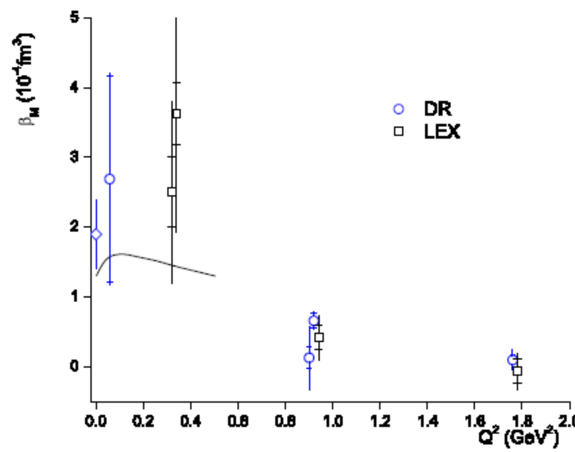
What is Polarizability ?

▪ A nucleon in an electric field **E** and a magnetic field **H** obtains an electric dipole moment **d** and magnetic dipole moment **m** given by:

$$\mathbf{d} = 4\pi\alpha\mathbf{E} \text{ and } \mathbf{m} = 4\pi\beta\mathbf{H}$$

▪ The proportionality constants α and β are defined as the electric and magnetic polarizabilities. Electric polarizability is the relative tendency of a charge distribution to change under external electric field. Magnetic polarizability defines by spin interaction of nucleon.

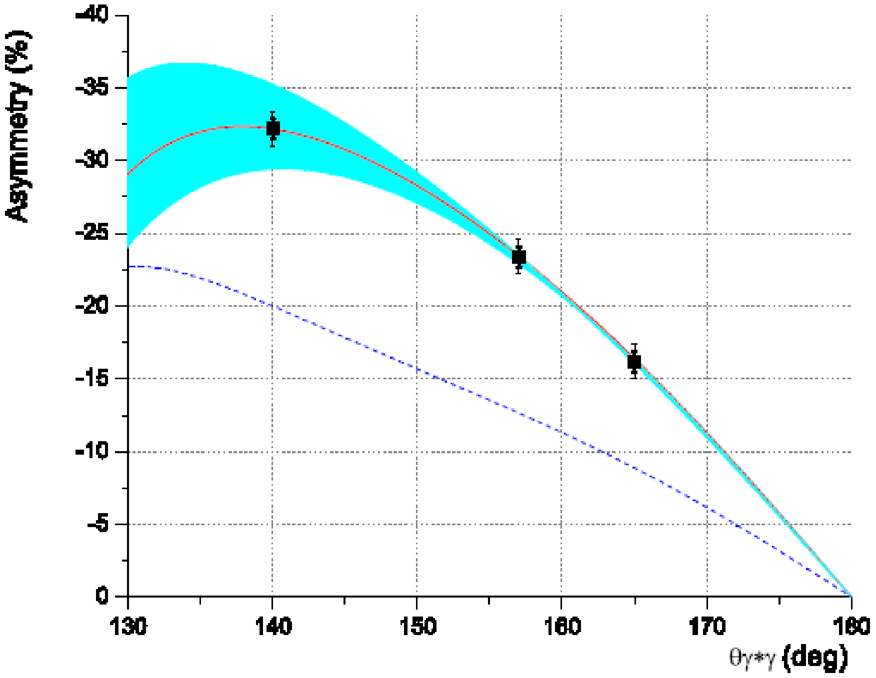




World data on the electric and magnetic Generalized Polarizabilities (GPs) of Proton

E12-15-001: Proton's Generalized Polarizabilities in VCS

- Virtual Compton Scattering off the proton (ep➔epγ) below pion threshold allows access to generalized polarizabilities of the proton.
- Experiment will measured at ϕγγ* =0° and ϕγγ* = 180°
- This will allow to extract polarizabilities without extracting absolute cross sections.



$$A_{(\phi_{\gamma*\gamma}=0,\pi)} = \frac{\sigma_{\phi_{\gamma*\gamma}=0} - \sigma_{\phi_{\gamma*\gamma}=180}}{\sigma_{\phi_{\gamma*\gamma}=0} + \sigma_{\phi_{\gamma*\gamma}=180}}$$

E12-06-110: Neutron Spin Asymmetry A1n

Main goal:

- Precision measurements of the neutron spin asymmetry A_1^n in the deep inelastic scattering region 0.3 < x < 0.77 and 3 < Q^2 < 10 GeV^2.
- Use polarized ^{3}He target with SHMS (or HMS) spectrometer to study Q^2 dependence of A_1^n and test predictions of various theoretical models.

Interest in spin structure of the nucleon become prominent in 1980's when experiments at CERN and SLAC showed that the total spin carried by quark was very small which was in contrast to the simple relativistic quark model prediction.

Quark distribution inside nucleon are described by four structure functions: functions F_1, F_2 (cross section), and spin structure functions g_1, g_2 (polarization observables).

Current understanding of the nucleon spin is that the total spin is distributed among valence quarks, quark-antiquark sea, their orbital angular momenta, and gluons.

$$S_z^N = S_z^q + L_z^q + J_z^g = \frac{1}{2}$$

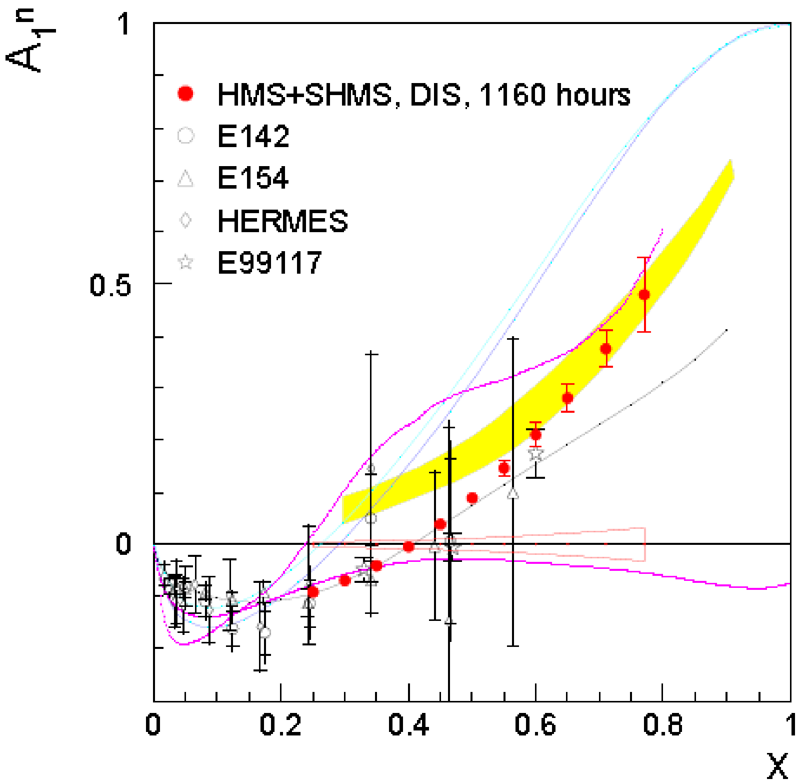
In Quark-Model, we can write F_1 and g_1 in terms of helicity dependent quark distribution $F_1(x) = \frac{1}{2}\sum e_i^2 (q_i^+ + q_i^-)$ and $g_1(x) = \frac{1}{2}\sum e_i^2 (q_i^+ - q_i^-)$, and $g_2(x) = -g_1(x) + \int_x^1 g_1(y, Q^2) y dy$

The conventional approach to extract g_1 and g_2 is to measure an asymmetry instead of the cross section difference. Two asymmetries are usually measured, with $\theta_N = 0$ (beam parallel to target field) and $\theta_N = \pi/2$.

E12-06-110: Neutron Spin Asymmetry A1n

The spin asymmetries A_1 and A_2 are related to virtual photon absorption cross sections for photon helicities +1, -1 and 0:

$$A_1 = \frac{\sigma_{1/2}^T - \sigma_{3/2}^T}{\sigma_{1/2}^T + \sigma_{3/2}^T} = \frac{1}{F_1}(g_1 - \gamma^2 g_2) \qquad A_2 = \frac{2\sigma_{LT}}{\sigma_{1/2}^T + \sigma_{3/2}^T} = \frac{\gamma}{F_1}(g_1 + g_2)$$



The raw asymmetries can be extracted from helicity-dependent yield as

$$A_{raw} = \frac{N^+/(Q^+\eta_{LT}^+) - N^-/(Q^-\eta_{LT}^-)}{N^+/(Q^+\eta_{LT}^+) + N^-/(Q^-\eta_{LT}^-)}$$

Then the neutron asymmetry A_1^n is extracted from A_1 of ^3He as

$$A_1^n = \frac{F_2^{^3He}\left[A_1^{^3He} - 2\frac{F_2^p}{F_2^{^3He}} P_p A_1^p \left(1 - \frac{0.014}{2P_p}\right)\right]}{P_n F_2^n \left(1 + \frac{0.056}{P_n}\right)}$$

Due to Pauli principle, the two protons in ^3He are in an antisymmetric spin state. Total spin of ^3He is carried by the neutron. Measurement of the ^3He asymmetry is a measurement of the neutron asymmetry.