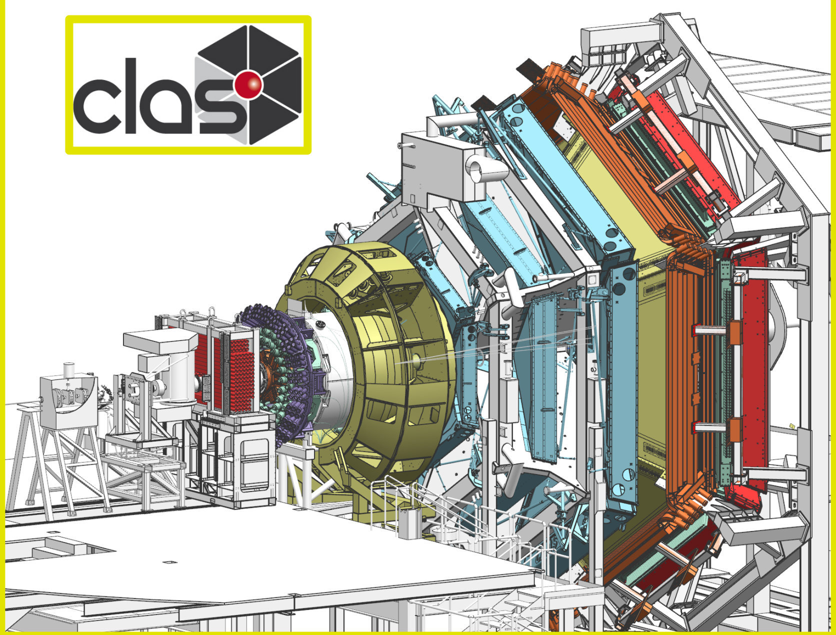
EXCITED NUCLEON SPECTRUM AND STRUCTURE STUDIES WITH CLAS12

FIRST LOOK AT CLAS12 DATA

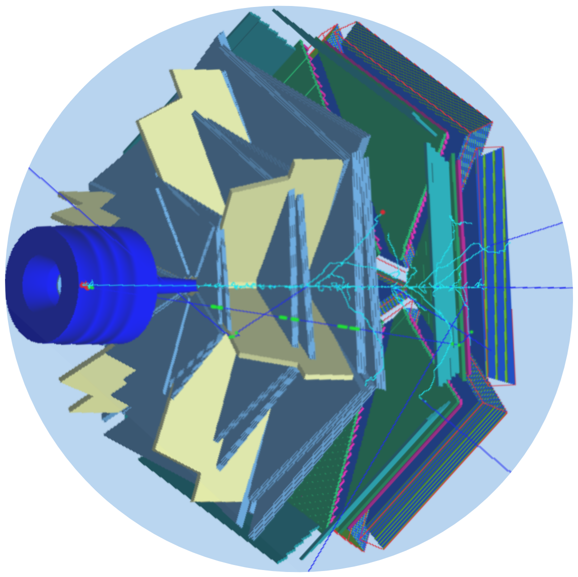


Daniel S. Carman
Jefferson Laboratory

FOR THE CLAS12
HADRON STRUCTURE GROUP

CLAS12 N* Program

The N* program is one of the key physics foundations of Hall B

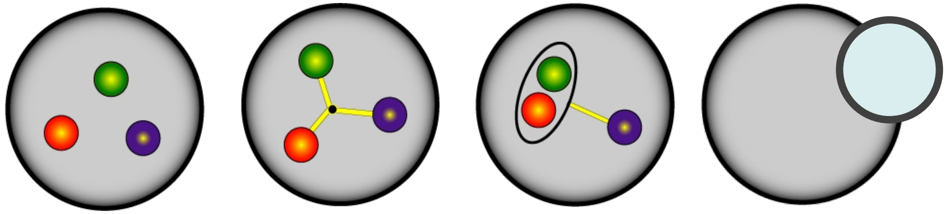


- CLAS12 was designed to measure cross sections and spin observables over a broad kinematic range for exclusive reaction channels:

$$\pi N, \omega N, \phi N, \eta N, \eta' N, \pi\pi N, KY, K^*Y, KY^*$$

- Goal is to probe the *spectrum* of N* states and their *structure*
  - Probe the underlying degrees of freedom of the N* states via studies of the Q^2 evolution of the electroproduction amplitudes
    - N* electroproduction amplitudes do not depend on how they decay but different final states have different hadronic decay parameters and different backgrounds
  - Agreement offers model-independent support for findings
    - Data can unravel the spectrum of contributing states in complementary manner relative to photoproduction

N* degrees of freedom??

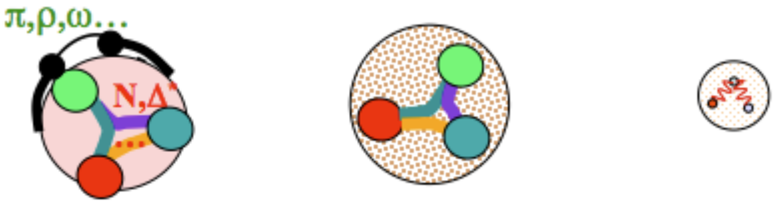


Excited Nucleon Structure

- Nucleon structure is more complex than what can be described accounting for quark degrees of freedom only

  - Low Q^2: ($Q^2 < 2$ GeV^2) — structure well described by adding an external meson cloud to inner quark core

  - High Q^2: ($Q^2 > 5$ GeV^2) — quark core dominates; transition from confinement to pQCD regime



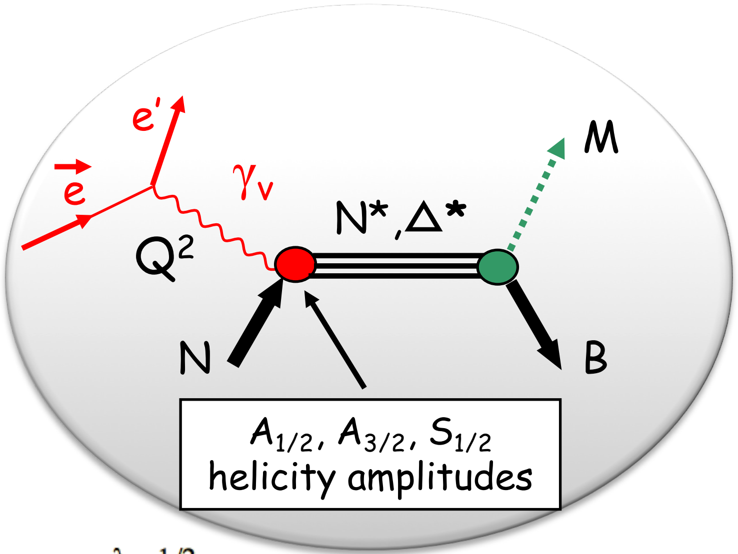
3q core + meson cloud   3q core   pQCD

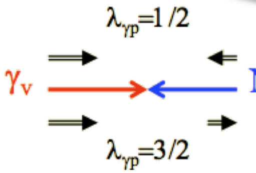
low Q^2 ⟶ high Q^2

- Studies from low to high Q^2 probe the detailed structure of the N* states through the $\gamma_v NN^*$ electrocouplings

  - Elucidate relevant degrees of freedom and their evolution with distance scale

  - Only source of information on many facets of the non-perturbative strong interaction in the generation of different N* states from quarks and gluons

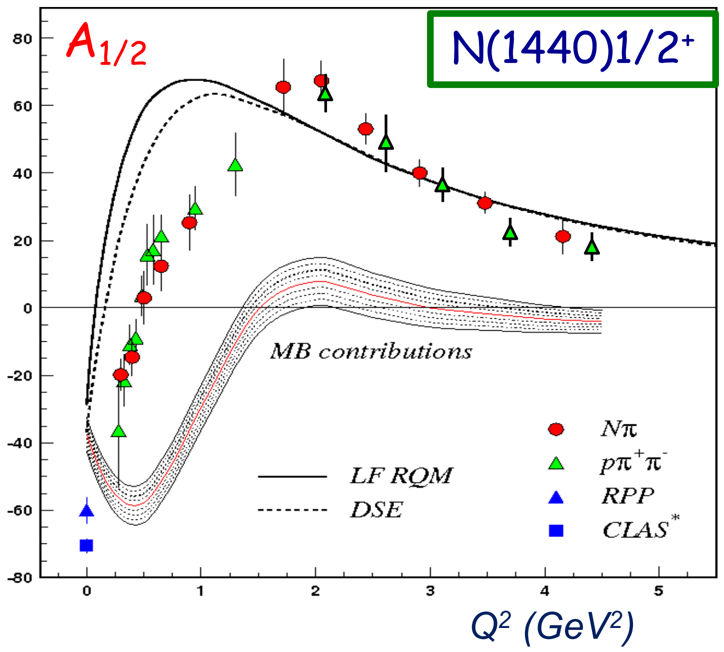


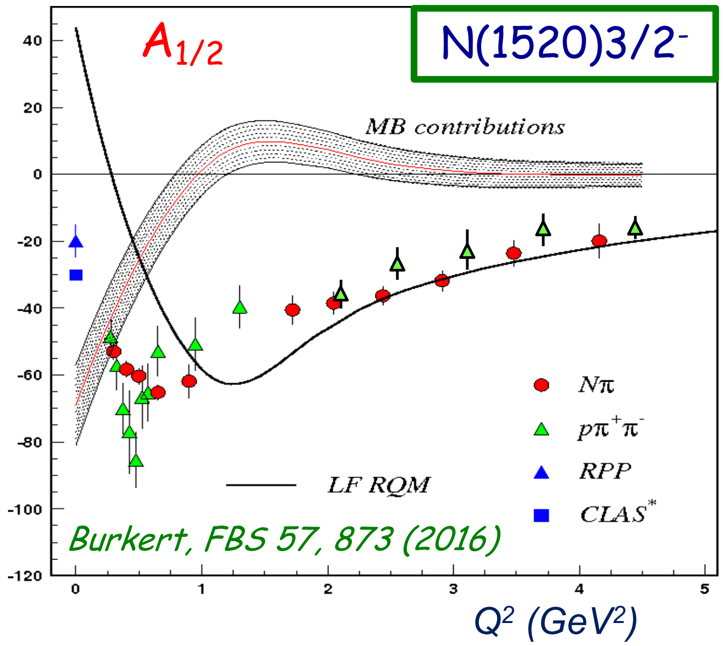


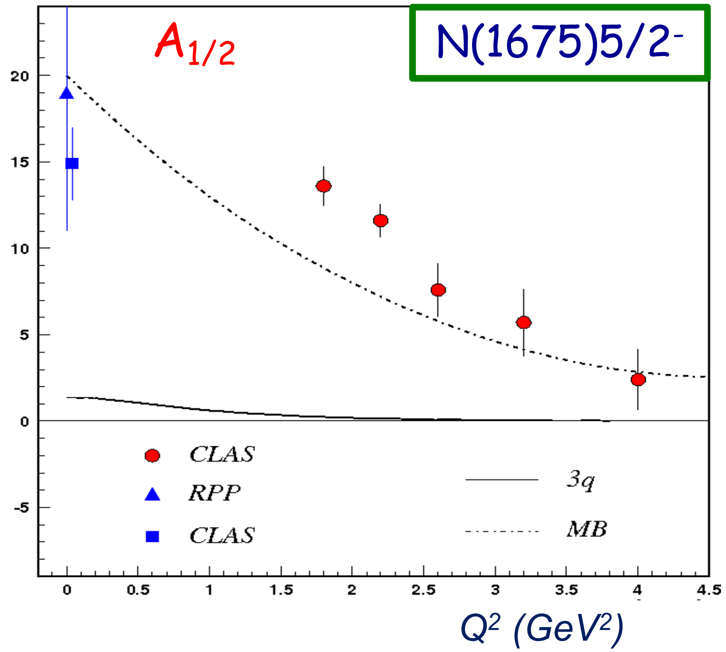
$A_{1/2}$, $A_{3/2}$ – transverse

$S_{1/2}$ - longitudinal

Lower-Lying N* States







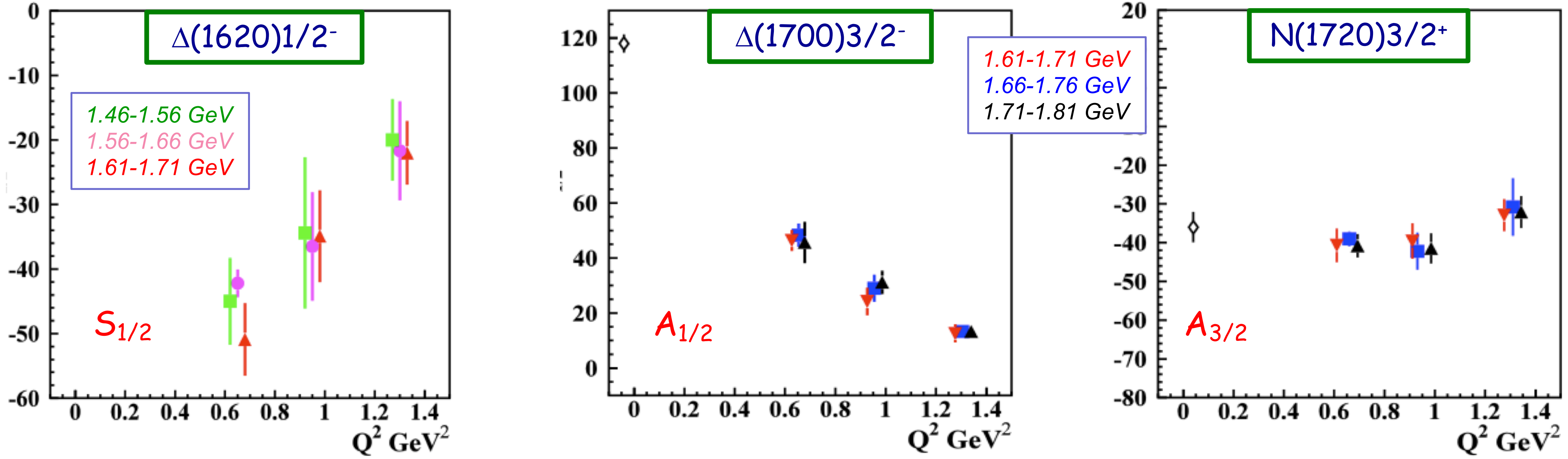
- Electrocouplings reveal different interplay between meson cloud and quark core:
  - *Important to study different N* states vs. distance scale*
- Good agreement of the extracted N* electrocouplings from Nπ and Nππ:
  - *Compelling evidence for the reliability of the results*
  - *Channels have very different mechanisms for the non-resonant background*

Precision studies of N* structure are a key part of the CLAS12 experimental program

Higher-Lying N* States

Nππ channel gave first electrocoupling results on higher-lying states up to 1.8 GeV

Note: Most high-lying N states decay mainly to Nππ with much smaller strength to Nπ*

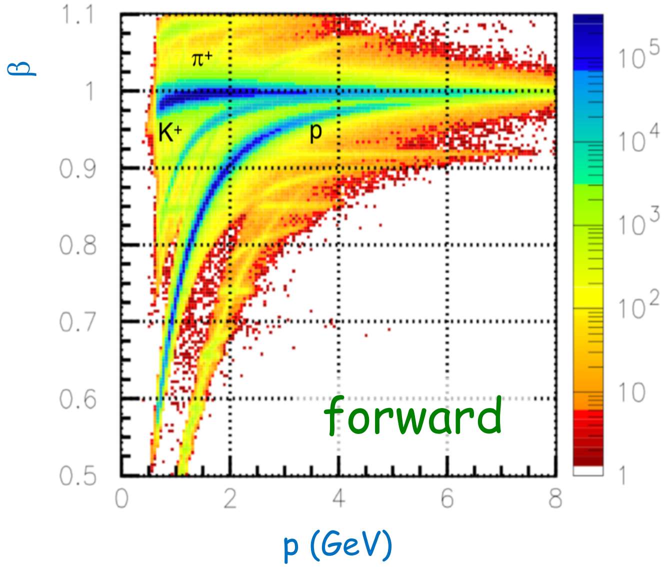


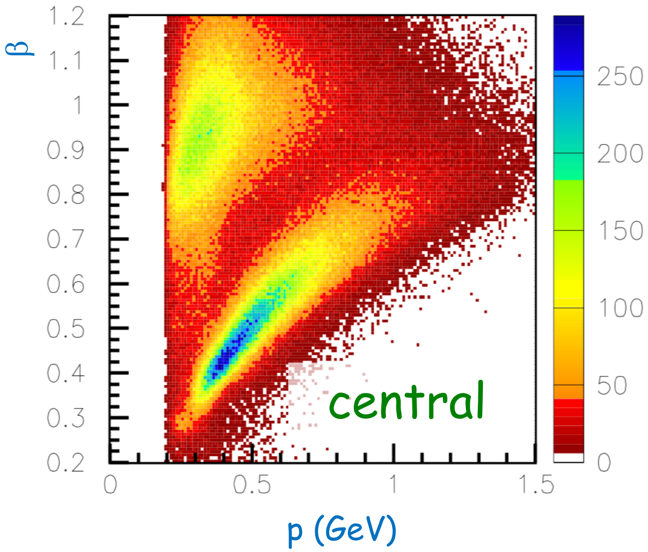
Mokeev, Aznauryan, Int. J. Mod. Phys. Conf. Ser. 26, 1460080 (2014)

Data from the KY channels is critical to provide an independent extraction of the electrocouplings for the higher-lying N* states

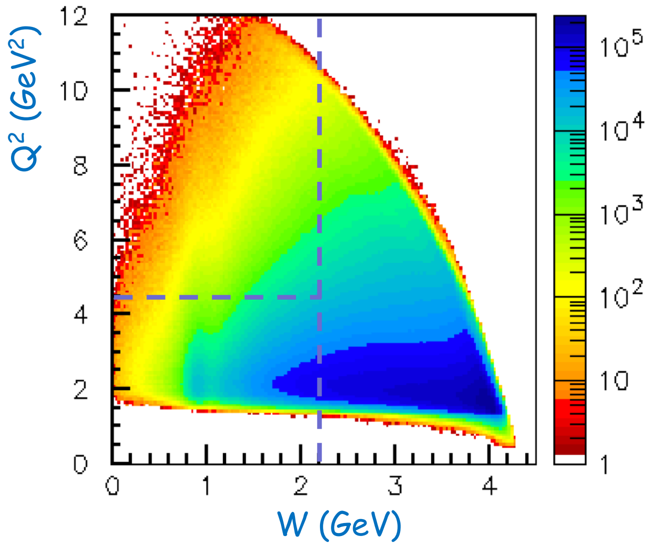
Kinematic Coverage and Particle ID

Run Group	A	K
E_{beam}	10.6 GeV	6.5, 7.5 GeV
Pol. Electrons	85%	
Target	LH_2 (5 cm)	
Data Totals	2 PB, 285 mC	0.35 PB, 45 mC



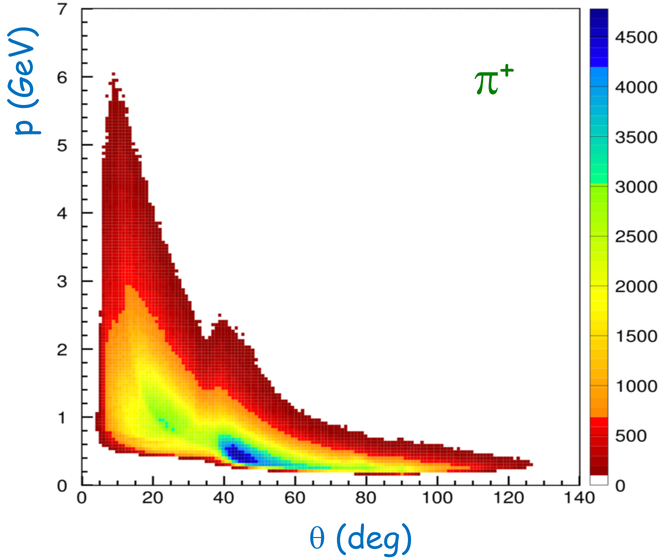


Electron Kinematics



10.6 GeV

Hadron Kinematics & PID



Physics program began Feb. 2018; only a small fraction (<10%) of the data collected is shown here

Analysis Details

Move beyond the current Event Builder PID assignment

Electron ID:

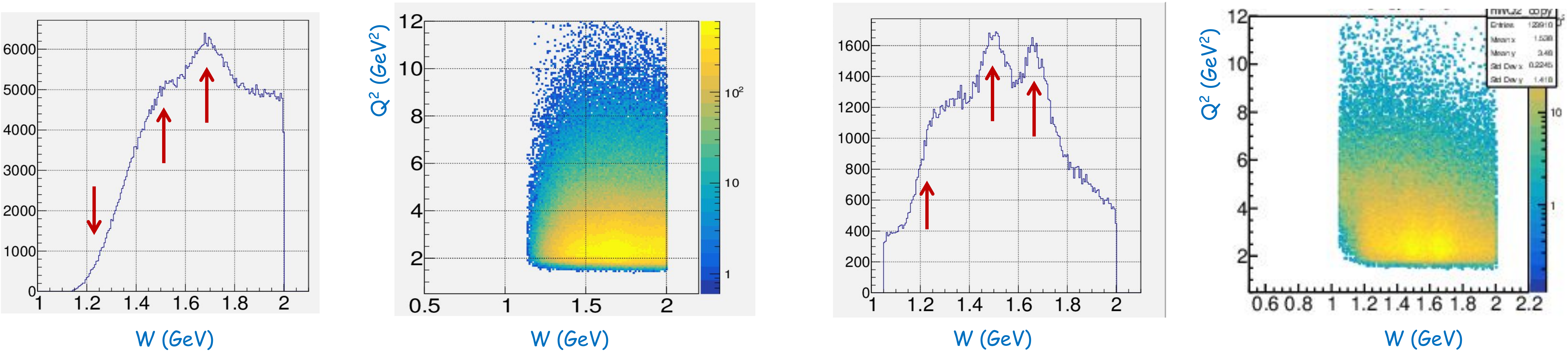
- EB PID=11 (e- in ECAL)
- Cut on tracking status
- $1.5 < p < p_{beam}$
- $t_{min} < TOF_e < t_{max}$
- $-10 < v_{ze} < 5$ cm
- $W^2 > 0$
- 2σ S.F. cut
- UVW ECAL fiducial cut
- χ^2 PID cut
- $N_e=1$

Hadron ID:

- EB PID = ± 211, ± 321, 2212
- Cut on tracking status
- $q \neq 0$
- $p_{min} < p < p_{beam}$
- $t_{min} < TOF_h < t_{max}$
- Cut on $\Delta t_{meas\text{-}calc}$
- $-12 < v_{zh} < 3$ cm
- Tight mass cut for K^+ candidates
- Fwd tracking fiducial cuts
- χ^2 PID cut
- Separate cuts for fwd and cent hadrons

πN Studies

π^+n | 10.6 GeV | π^0p



Arrows mark the 1st, 2nd, and 3rd resonance regions

- Electrocouplings of all prominent resonances will be determined for the first time from combined fit of differential cross sections and polarization asymmetries for $Q^2 > 5.0$ GeV^2
- Initial investigations are focusing on beam spin asymmetries, quantities sensitive to the interference between resonant and non-resonant contributions to the full Nπ amplitudes

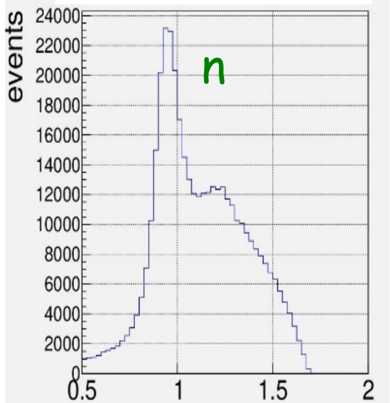
πN Studies

10.6 GeV

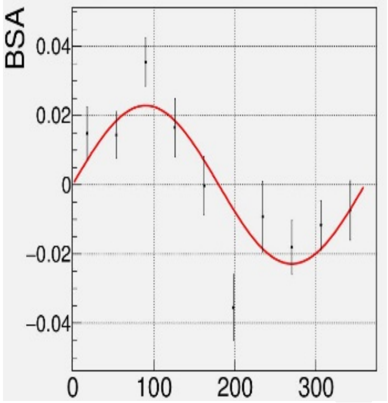
1.1 < W < 2.0 GeV

$\pi^+ n$

Q^2 [1.3:2.4] GeV^2

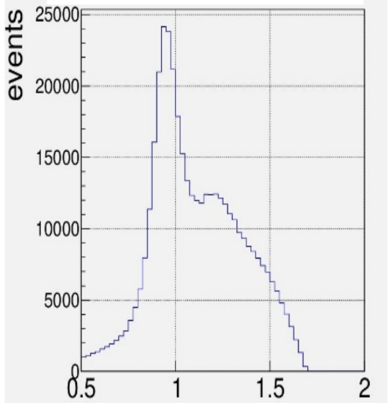


MM (GeV)

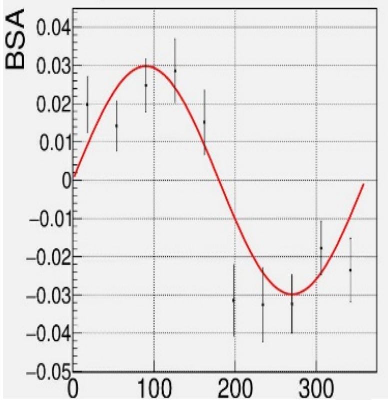


Φ (deg)

Q^2 [2.4:3.1] GeV^2

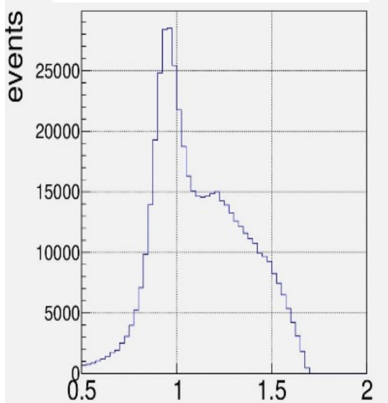


MM (GeV)

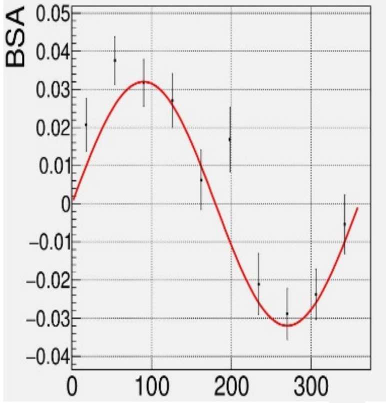


Φ (deg)

Q^2 [3.1:12] GeV^2



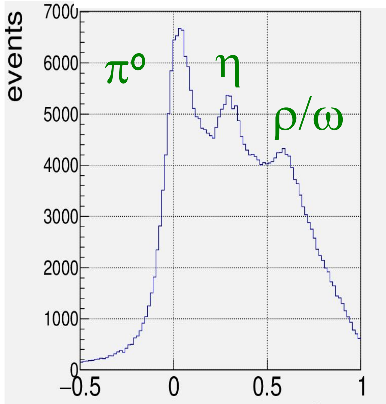
MM (GeV)



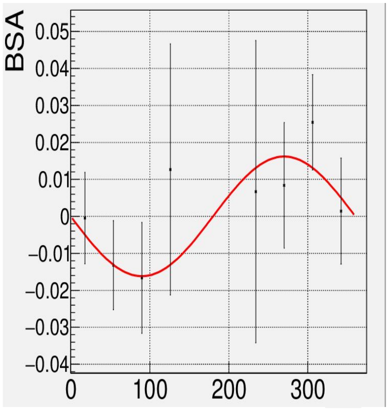
Φ (deg)

$\pi^0 p$

Q^2 [1.3:2.4] GeV^2

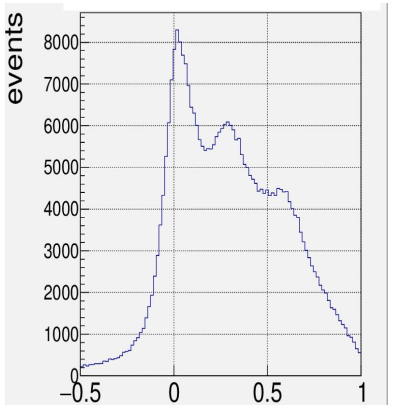


MM^2 (GeV^2)

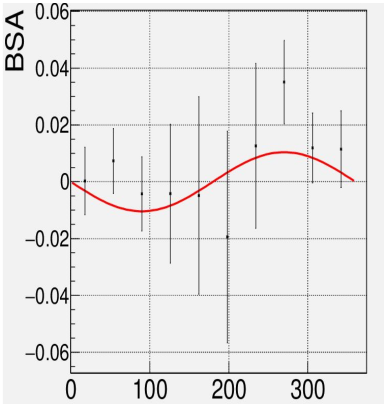


Φ (deg)

Q^2 [2.4:3.1] GeV^2

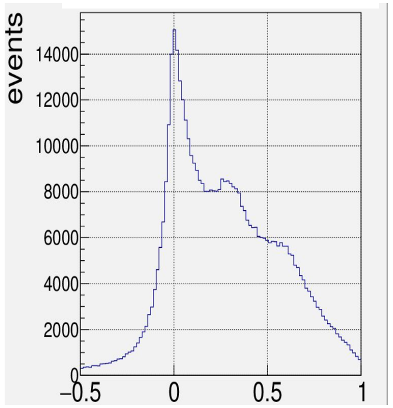


MM^2 (GeV^2)

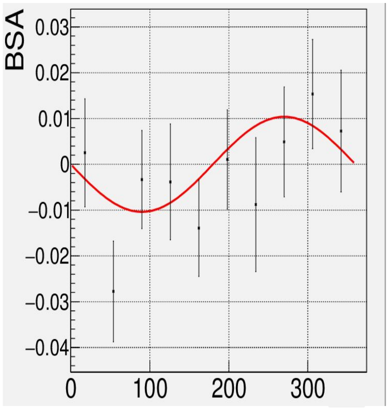


Φ (deg)

Q^2 [3.1:12] GeV^2



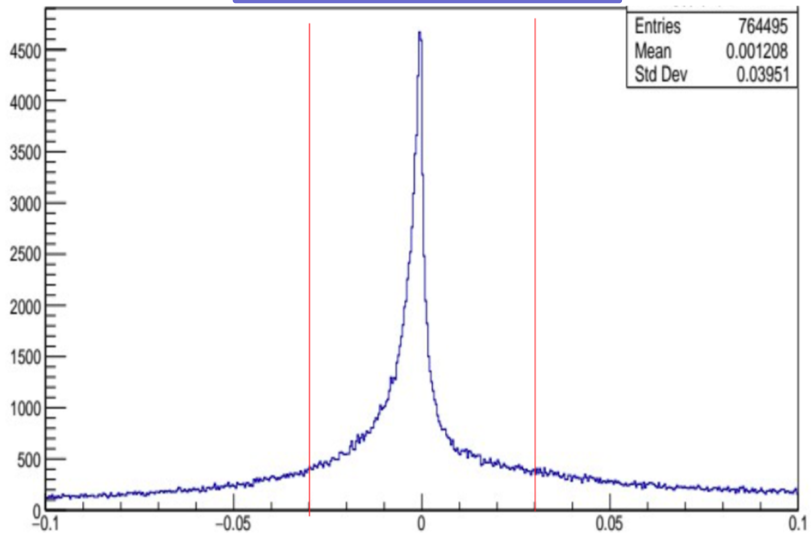
MM^2 (GeV^2)



Φ (deg)

$\pi^+\pi^-p$ Studies

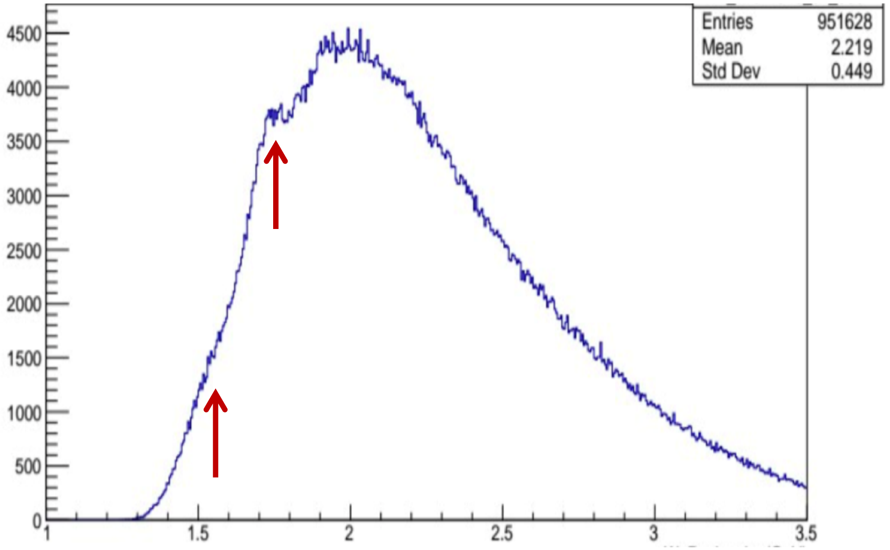
$ep \rightarrow e'\pi^+\pi^-p'X$



MM^2 (GeV^2)

7.5 GeV

Arrows mark the 2nd and 3rd resonance regions



W (GeV)

- The $\pi\pi N$ final state dominates the cross section at W > 1.6 GeV; this channel is promising for searches of "missing" and hybrid-baryons
- Electrocouplings of all prominent resonances will be obtained for the first time from fits of the differential cross sections binned in W and Q^2 for Q^2 up to 10-12 GeV^2
- Consistent results on electrocouplings obtained from independent studies of the πN, $\pi^+\pi^-p$, and K^+Y electroproduction will validate the extraction in a nearly model-independent way.

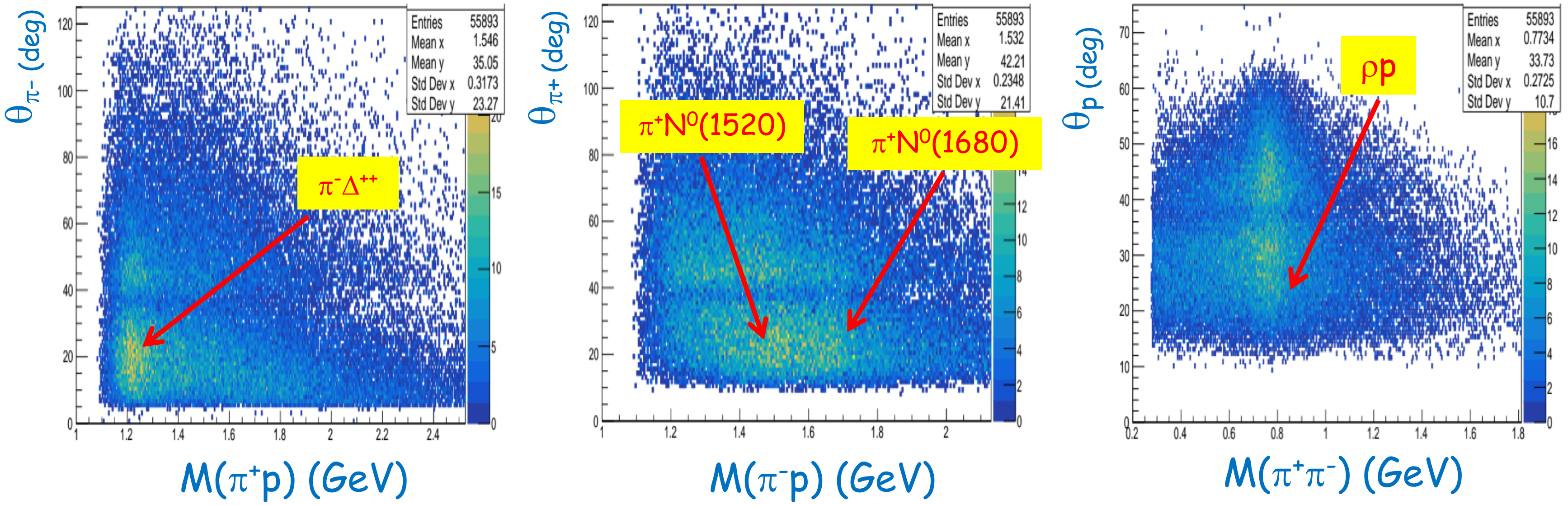
$\pi^+\pi^-p$ Studies

Data shows contributions:

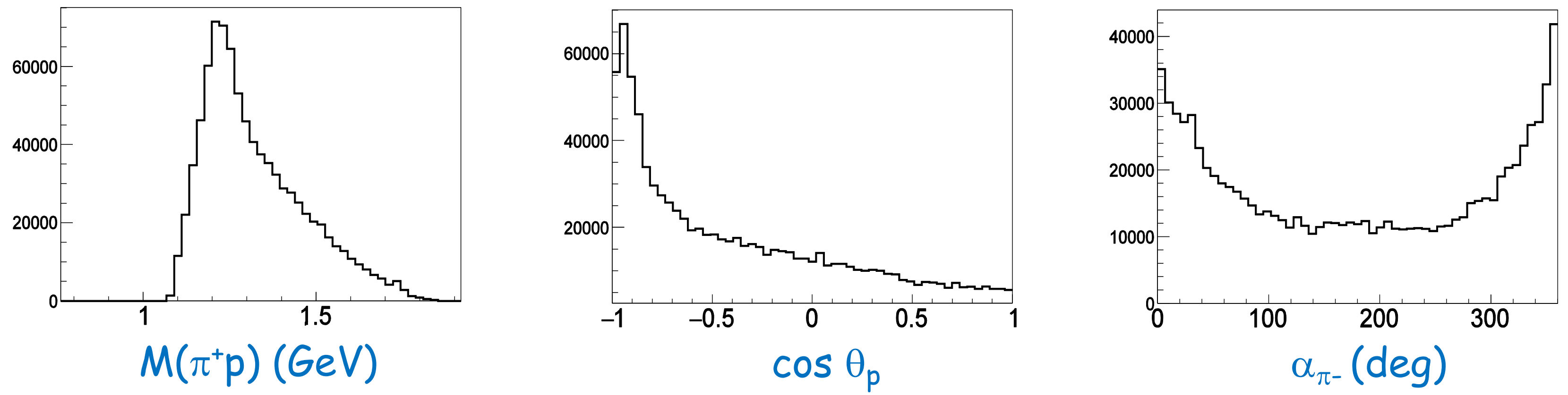
- ❑ $\theta(\pi^-)$ vs. $M(\pi^+p)$
  - $\gamma_v p \to \pi^-\Delta^{++}$
- ❑ $\theta(\pi^+)$ vs. $M(\pi^-p)$
  - $\gamma_v p \to \pi^+N^0(1520)3/2^-$
  - $\gamma_v p \to \pi^+N^0(1680)5/2^+$
- ❑ $\theta(\pi^+)$ vs. $M(\pi^+\pi^-)$
  - $\gamma_v p \to \rho p$

1.2 GeV < W < 2.0 GeV

7.5 GeV

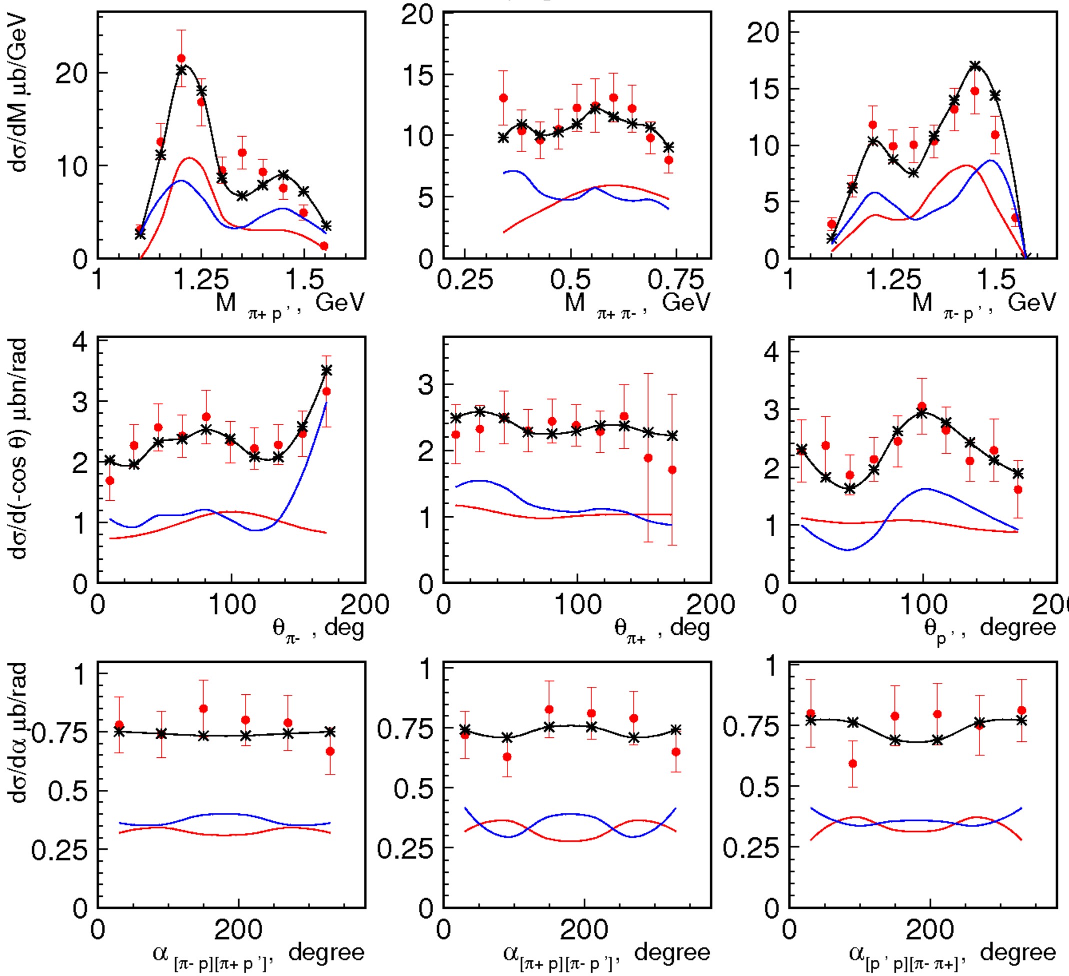


Examples of acceptance-corrected yields



$\pi^+\pi^-p$ Studies

W=1.71 GeV, Q^2=3.2 GeV^2



Description of nine 1-fold differential cross sections within JM17 model:

Full JM17

Non-resonant contributions

Resonant contributions

Analysis approach is to extract the 9 1-fold differential cross sections in bins of Q^2, W

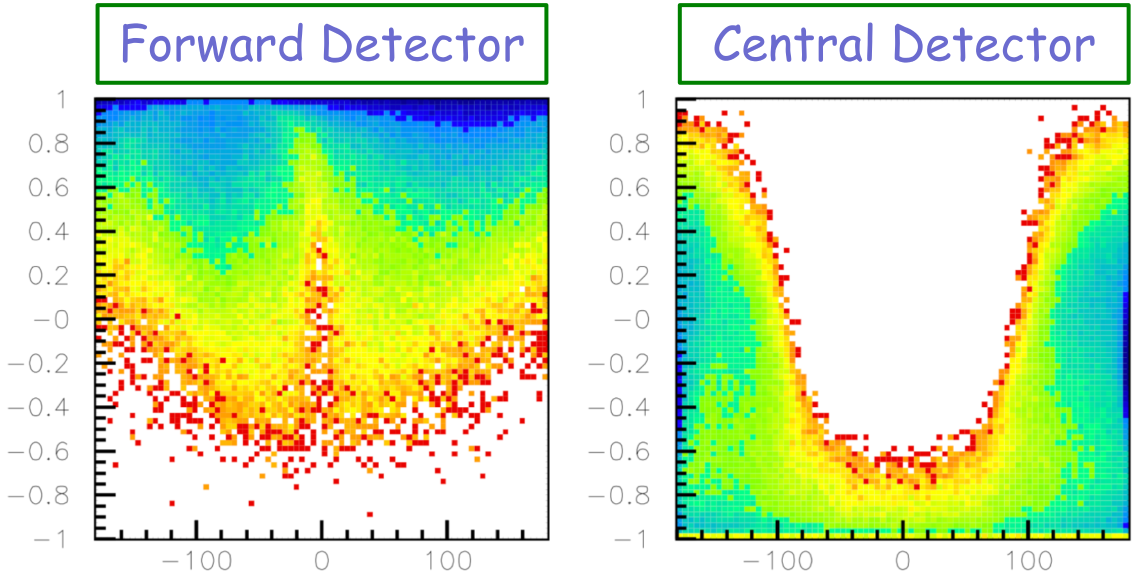
E.L. Isupov et al., Phys. Rev C 96, 025209 (2017)

K^+Y Studies

$$\frac{d\sigma}{d\Omega} = (\sigma_T + \epsilon\sigma_L) + \epsilon\sigma_{TT}\cos 2\Phi + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\Phi + h\sqrt{\epsilon(1-\epsilon)}\sigma_{LT'}\sin\Phi$$

Planned measurements: (W, Q^2, $\cos\theta_K^{cm}$, Φ)

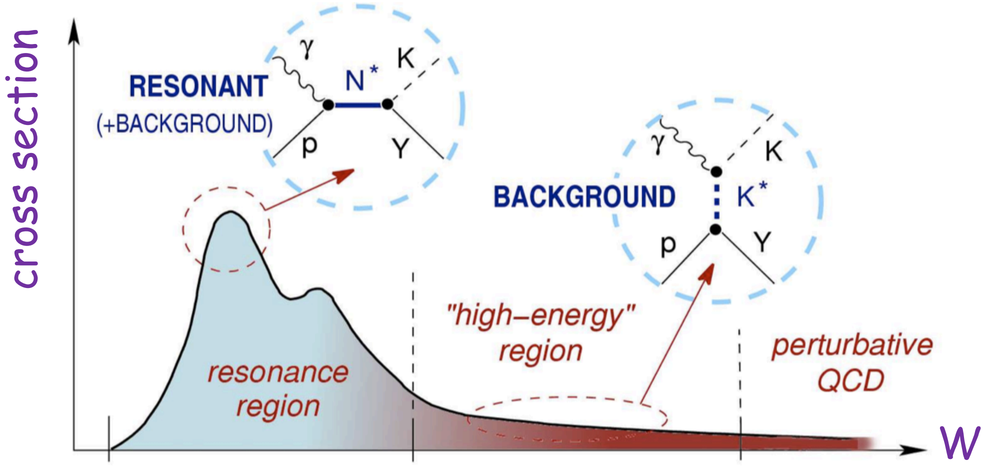
- Differential cross sections
- Separated structure functions
- Recoil and beam-recoil polarization



$\cos\theta_K^{cm}$ vs. Φ

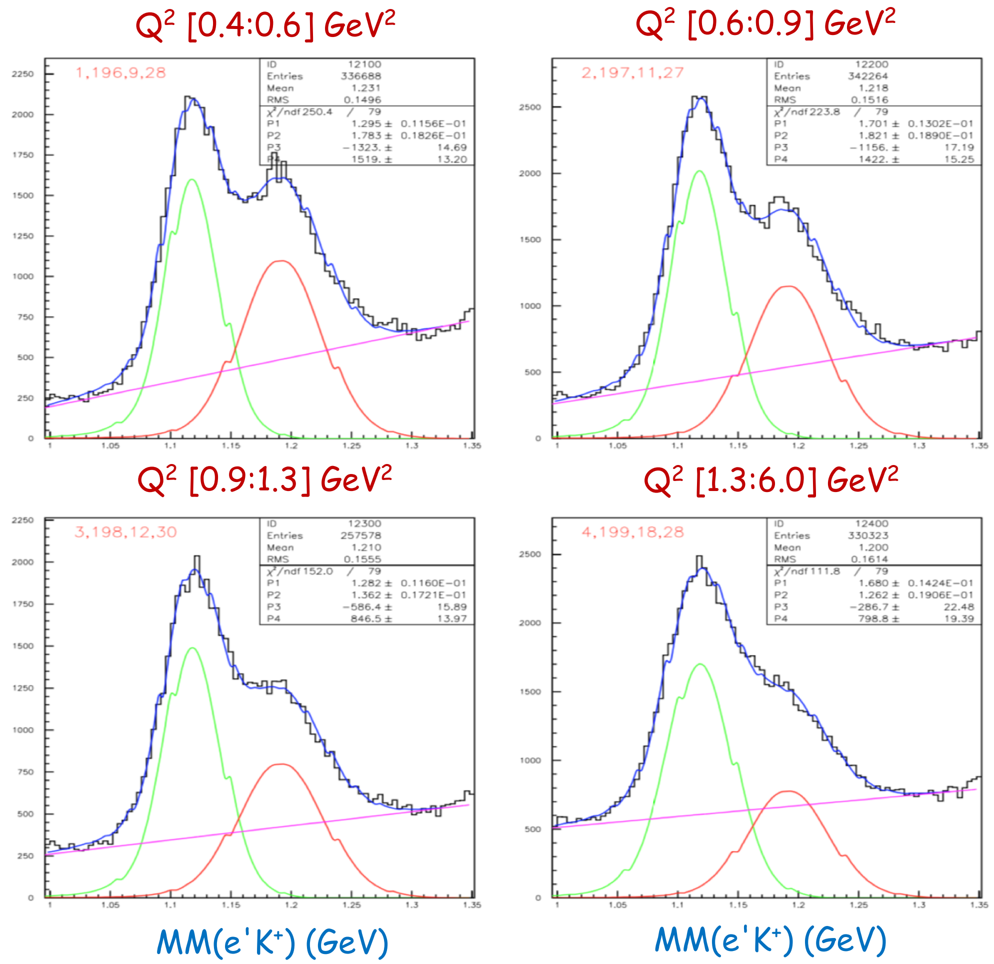
Key Physics:

- Structure studies have advanced due to results from independent analyses of different final states
  - e.g. $N^* \to \pi N$, $N^* \to \pi^+\pi^- N$, $N^* \to K^+Y$
  - Channels have different non-resonant backgrounds
- New N^* states have been claimed in $\gamma p \to K^+Y$ photoproduction data; electroproduction data provides complementary technique to cross-check

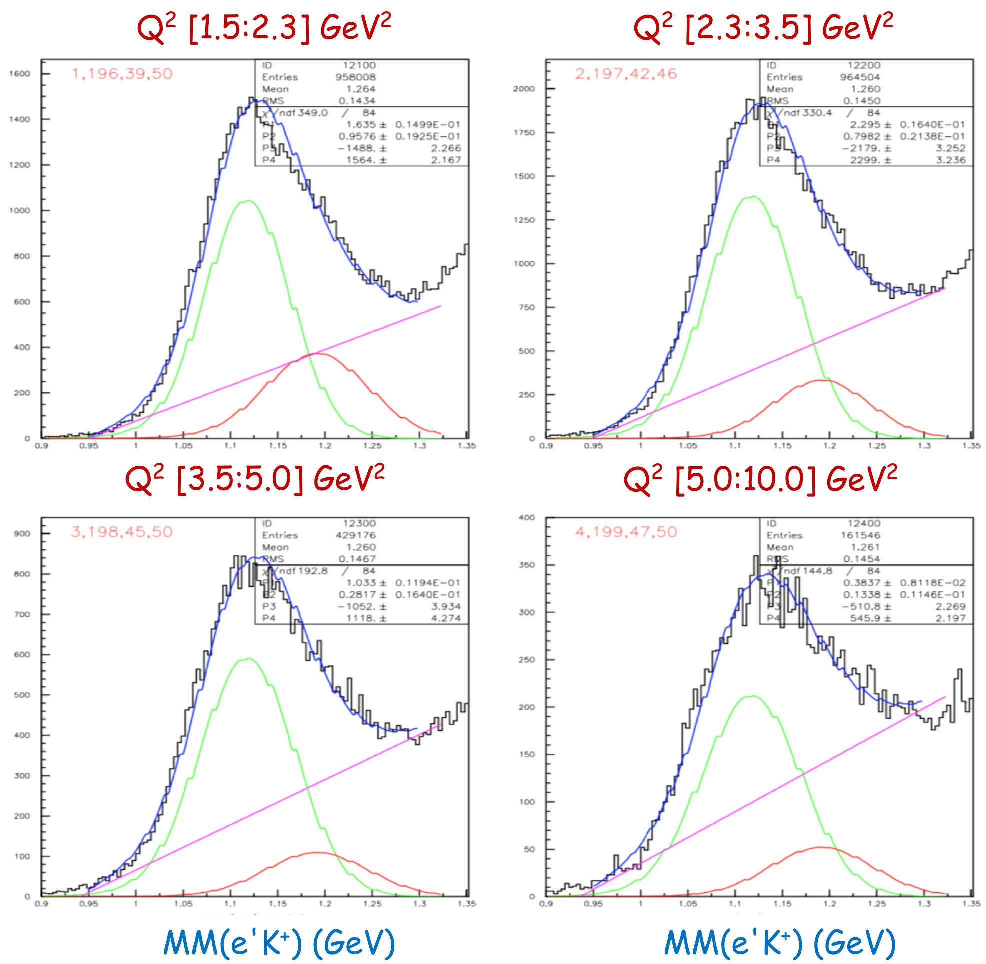


K^+Y Studies

7.5 GeV



10.6 GeV



Current MM resolution is limited by momentum resolution (B-field, alignment, reconstruction, calibration)

K⁺Y Studies

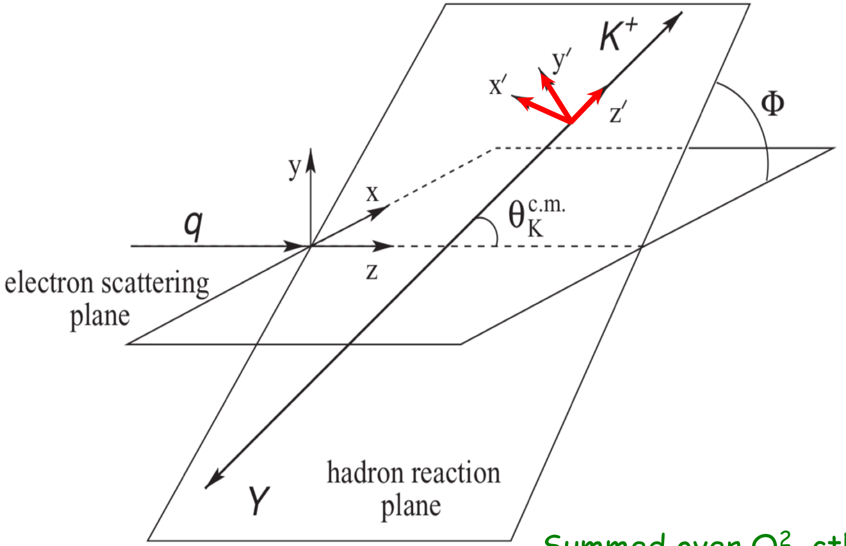
$$A = \frac{N^+ - N^-}{N^+ + N^-} = \alpha_\Lambda P_b \mathcal{P}'_\Lambda \cos\theta_p^{RF}$$

$\mathcal{P}'_{x'}$	$K_I c_0 R_{TT'}^{x'0}$
$\mathcal{P}'_{y'}$	0
$\mathcal{P}'_{z'}$	$K_I c_0 R_{TT'}^{z'0}$

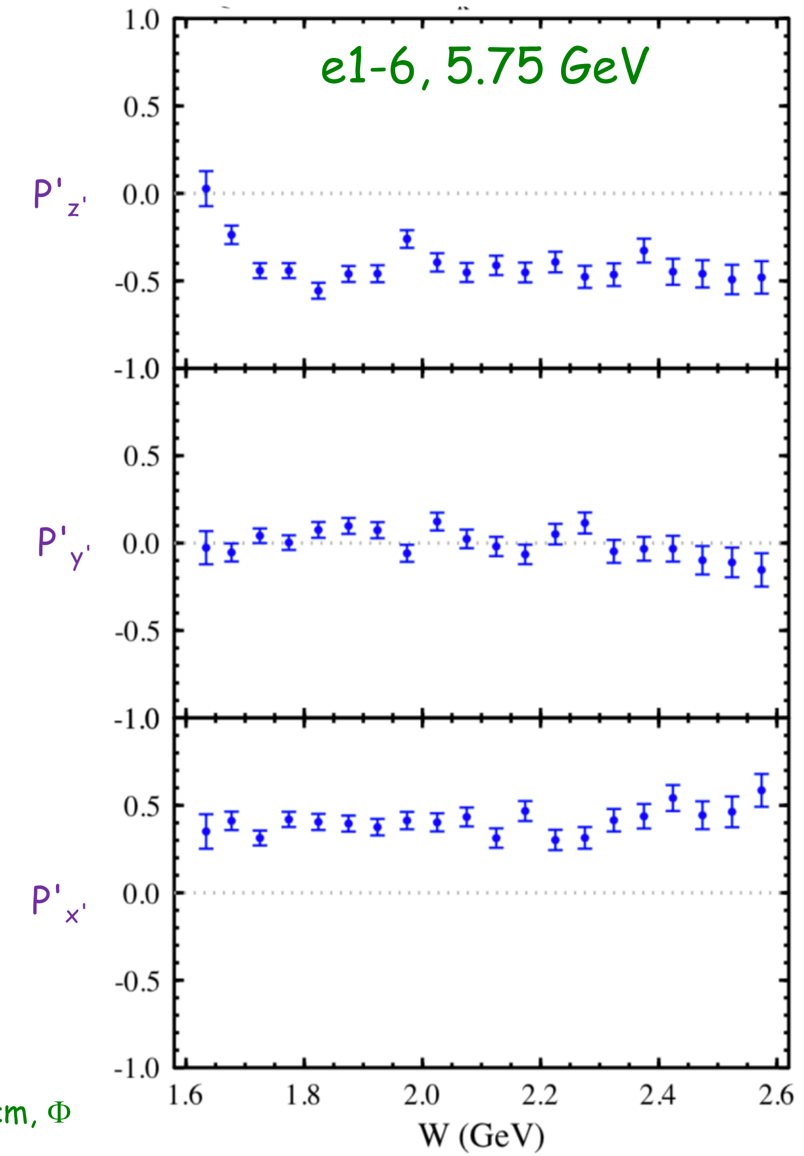
$$c_0 = \sqrt{1-\epsilon^2}$$

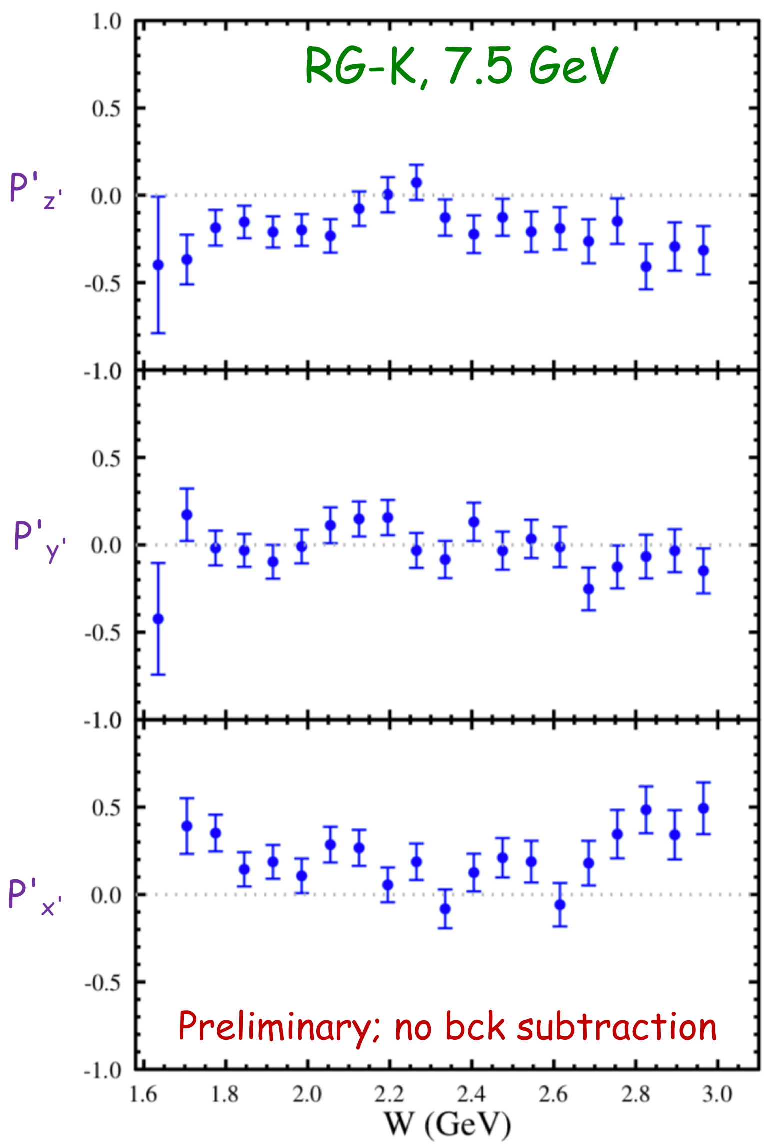
c_0 different @ 5.75/7.5 GeV

$$K_I = \frac{|\vec{q}_K|}{k^*_\gamma} \cdot \frac{1}{\sigma_0}$$

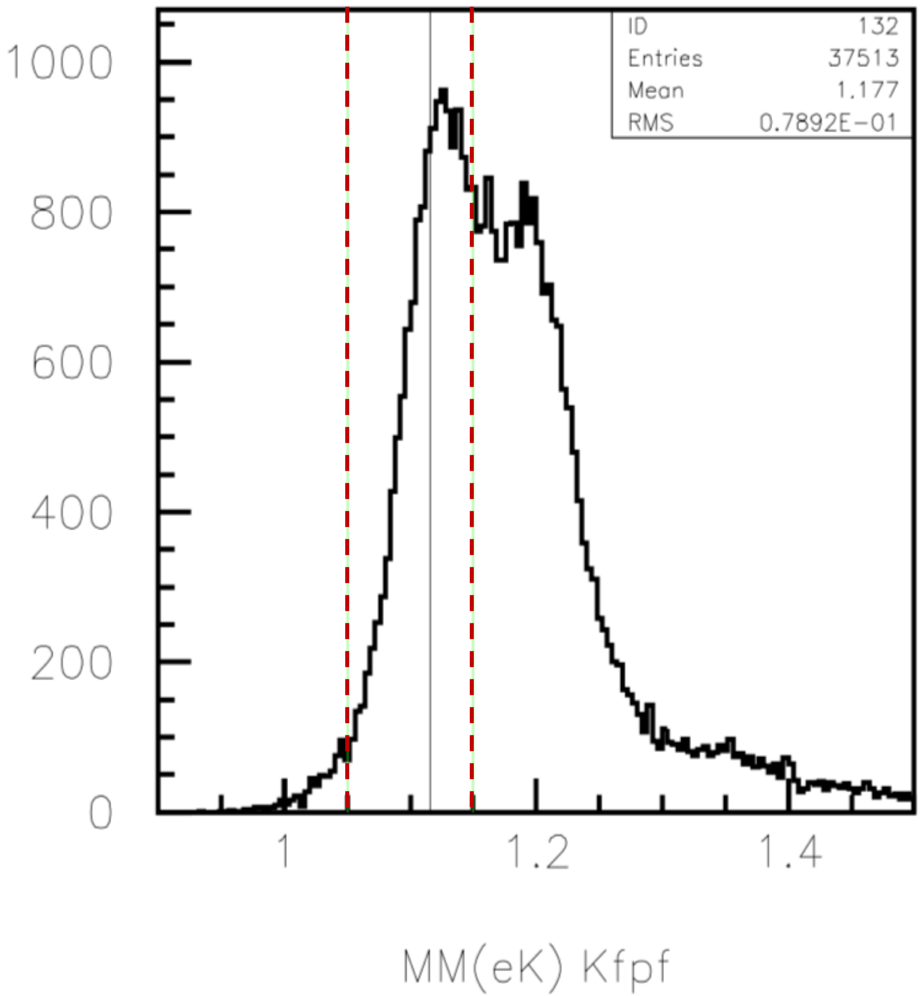


Summed over Q², cthkcm, Φ

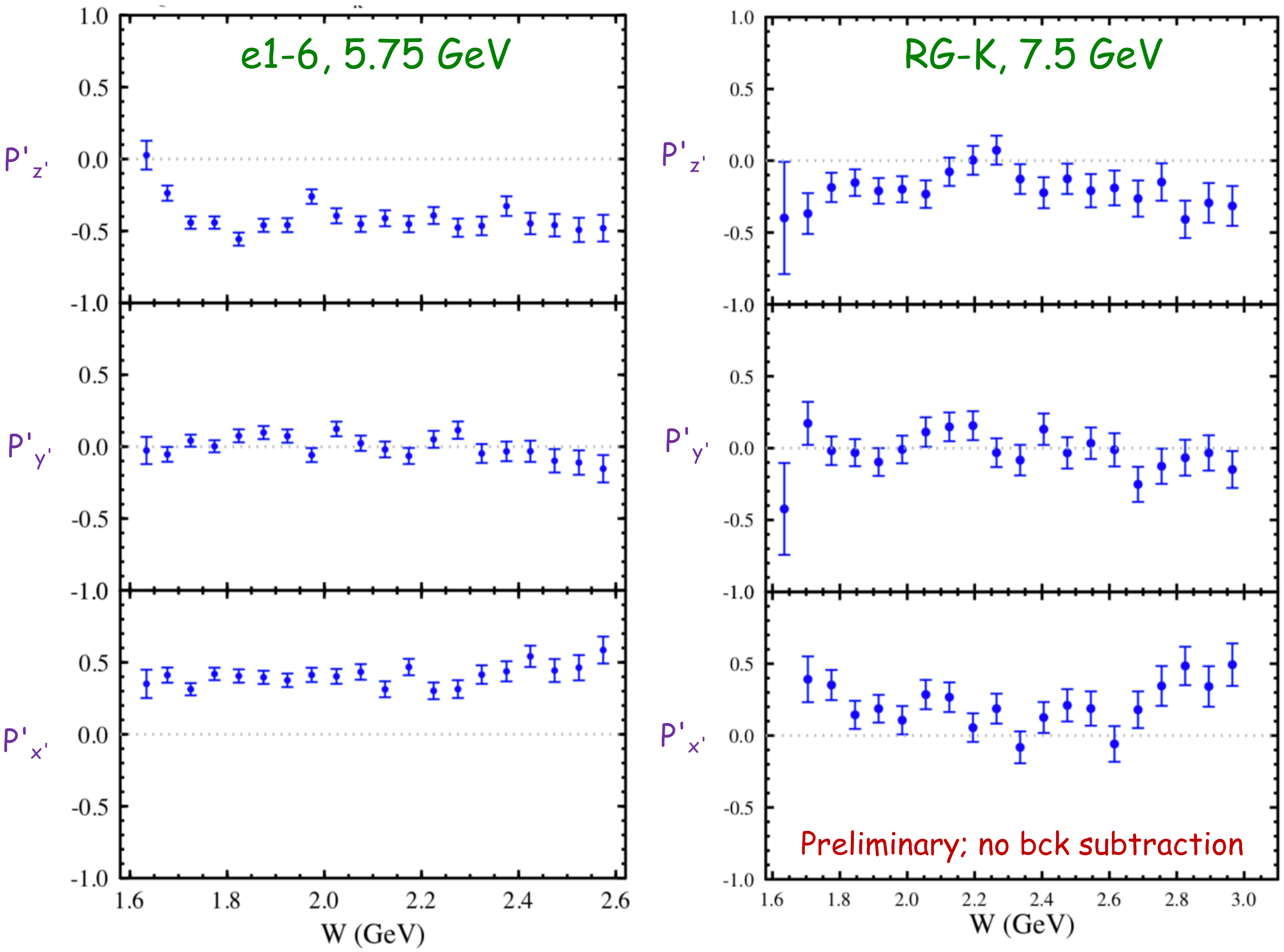




K+Y Studies



ID 132
Entries 37513
Mean 1.177
RMS 0.7892E−01
1000
800
600
400
200
0
1
1.2
1.4
MM(eK) Kfpf



e1-6, 5.75 GeV
RG-K, 7.5 GeV
P'z'
P'y'
P'x'
1.0
0.5
0.0
-0.5
-1.0
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
W (GeV)
Preliminary; no bck subtraction

QCD2019 Workshop

- Pre-workshop Symposium "Synergies in Hadron Physics between J-PARC and JLab"
- Workshop aimed to develop plans and to facilitate the future synergistic efforts between experimentalists, phenomenologists, and theorists working on studies of hadron spectroscopy and structure with the goal to connect the properties of hadrons and atomic nuclei available from data to the strong QCD dynamics underlying their emergence from QCD.
- *As a part of the Workshop we had a special session honoring the outstanding scientific achievements and the inspiring leadership of Volker Burkert for more than 30 years of his research at JLab.*

90 registered participants!

https://www.jlab.org/conference/QCD2019

QCD2019 Workshop Summary

- Last workshop: The Nature of Hadron Mass and Quark-Gluon Confinement from JLab Experiments in the 12-GeV Era: 1-4 July 2018, South Korea
- Remarkable progress in the intervening 16 months
- Inspiration found in many areas, especially, perhaps, in:
  - Commencement of JLab12 era
  - Physics Beyond Colliders initiative at CERN
  - Prospects for constructing EIC

*next workshop in this series to be held in Nanjing in early 2021

- No single approach/experiment can solve this problem alone
- Different data sets from experiments with EM probes in the N* and DIS-regions offer an excellent opportunity to gain insight into strong QCD underlying the hadron generation from quarks and gluons
- Success being delivered by amalgam of Experiment … Phenomenology …Theory
- Continue to exploit the synergies we have found and to develop more, including practitioners from other fields, *e.g.* imaging.

Summary: Craig Roberts (Nanjing University), Victor Mokeev (JLab)

Concluding Remarks

- The study of N* spectrum/structure is one of the foundations of the Hall B physics program:
  - The CLAS12 N* program is an important extension of the CLAS N* program that allows for an increase of Q^2_{max} from 5 to 12 GeV^2
- Data from the first beam runs with CLAS12 is now calibrated and work is underway to advance the data analysis while working to understand and improve the systematics
- Main program goals:
  - Provide insight into the strong interaction dynamics of dressed quarks and their confinement in baryons over a broad Q^2 range
  - Address the most challenging problems of the Standard Model on the nature of hadron mass, confinement, and the emergence of N* states
- Successful QCD2019 workshop to bring community together – experimentalists, phenomenologists, theorists (N*, DIS, GPD, EIC) – to map out the future toward understanding strong QCD from hadrons to nuclei

Backup Slides

Connecting to Electrocoupling Amplitudes

- Cross sections of resonance r of mass M_r and width $\Gamma_{tot}(M_r) = \Gamma_r$ and spin J_r:

$$\sigma^r_{L,T}(W,Q^2) = \frac{\pi}{q_\gamma^2} \sum_{N^*,\Delta^*} (2J_r+1) \frac{M_r^2 \Gamma_{tot}(W) \Gamma_\gamma^{L,T}(M_r)}{(M_r^2 - W^2)^2 + M_r^2 \Gamma_{tot}^2(W)} \frac{q_\gamma}{K}$$

- with the following kinematic definitions:

$$q_\gamma = \sqrt{Q^2 + E_\gamma^2}, \quad E_\gamma = \frac{W^2 - Q^2 - M_N^2}{2W}, \quad K = \frac{W^2 - M_N^2}{2W}$$

- The electromagnetic decay widths at the resonance point $W=M_r$ are given by:

$$\Gamma_\gamma^L(M_r,Q^2) = 2\frac{q_{\gamma,r}^2(Q^2)}{\pi} \frac{2M_N}{(2J_r+1)M_r} |S_{1/2}(Q^2)|^2$$

$$\Gamma_\gamma^T(M_r,Q^2) = \frac{q_{\gamma,r}^2(Q^2)}{\pi} \frac{2M_N}{(2J_r+1)M_r} (|A_{1/2}(Q^2)|^2 + |A_{3/2}(Q^2)|^2)$$