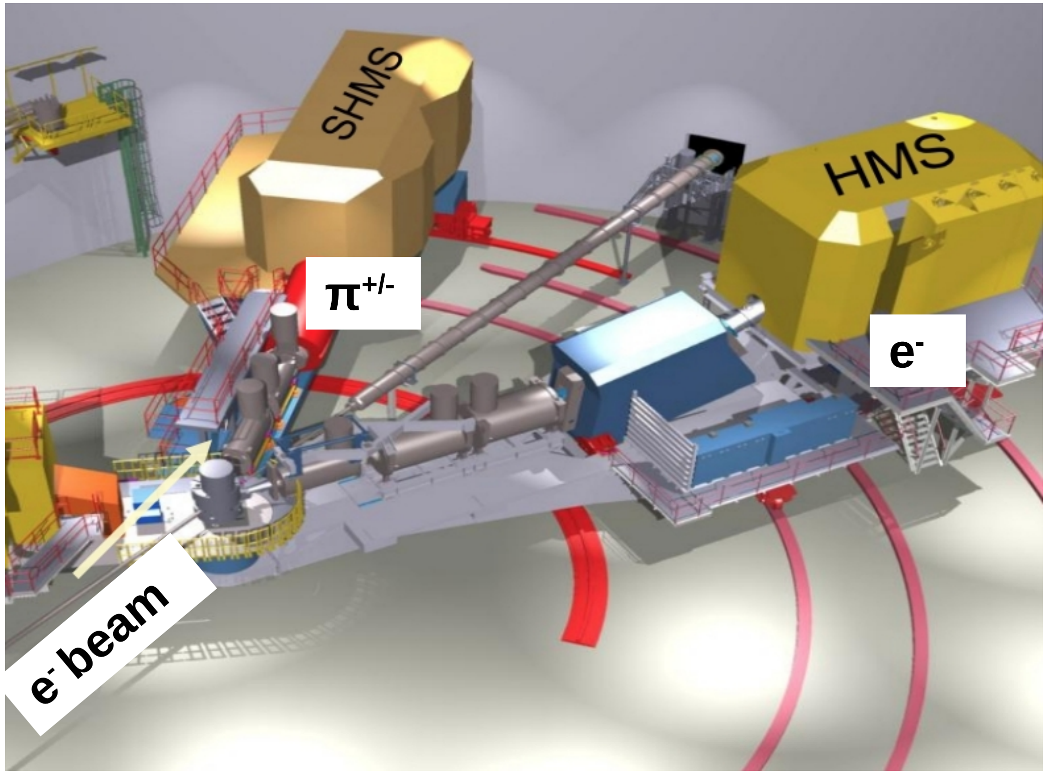
SIDIS Pion and Proton Analysis Update



Hem Bhatt
(on behalf of SIDIS-CSV Collaboration)

Hall C Winter Collaboration Meeting
Jan 13-14, 2025

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Pion SIDIS Analysis Update

Semi-Inclusive Deep Inelastic Scattering

In case of DIS, we detect only the scattered electron, but in SIDIS, we detect at least one hadron, in coincidence with the scattered electron.

Semi-inclusive deep inelastic lepton-nucleon scattering is a key tool to study the internal structure of nucleon in terms of partonic degrees of freedom of QCD.

At least one hadron is detected in coincidence

$$e + p \ (\text{or}\ n) \rightarrow e' + \pi^+ + X$$
$$e + p \ (\text{or}\ n) \rightarrow e' + \pi^- + X$$

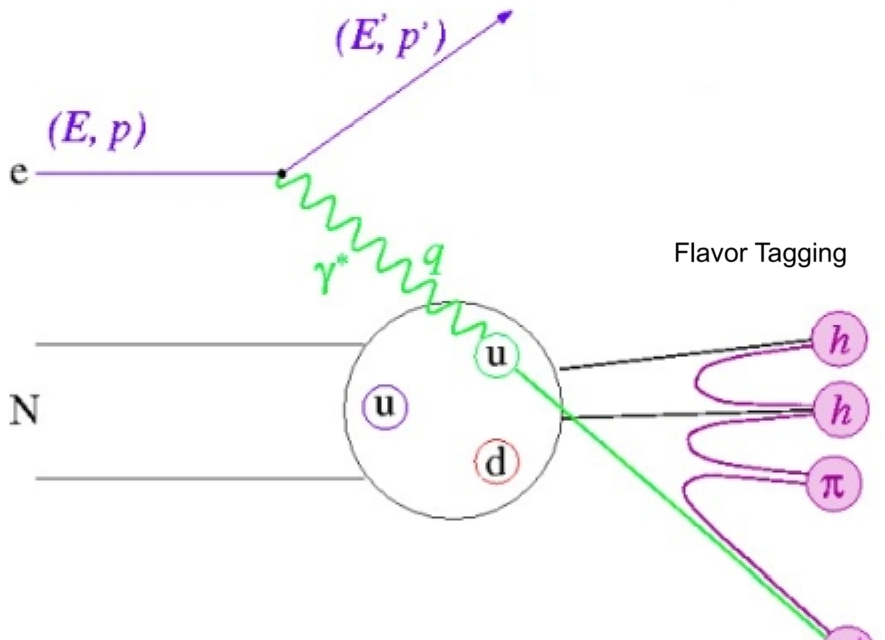


Fig: SIDIS diagram under one photon exchange

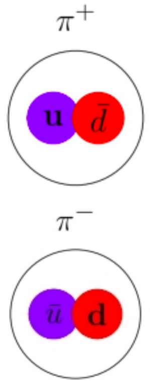
The Pt Integrated SIDIS pion yield:

$$\frac{dN}{dz} \sim \sum_i e_i^2 q_i(x, Q^2) D_{q_i \rightarrow \pi}(z, Q^2)$$

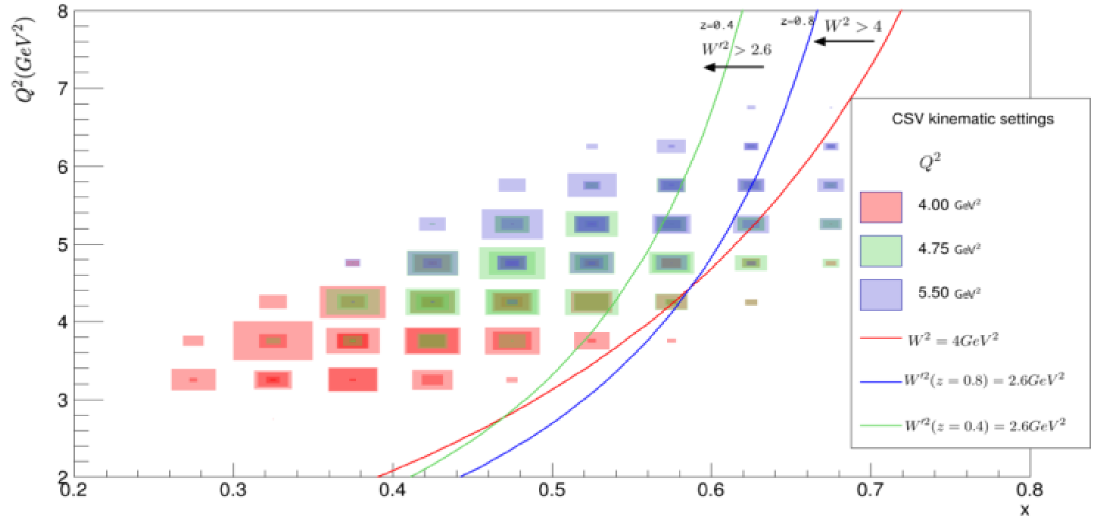
Favored (D+) or Unfavored (D-) Fragmentation: struck quark flavor is same as or different than the quark constituent of detected pion

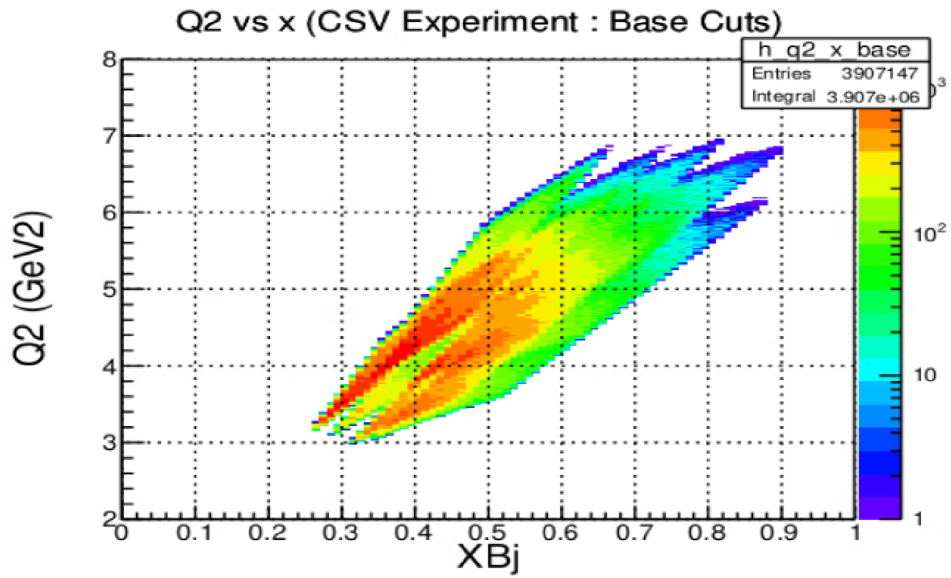
Favored FF: $u \rightarrow \pi^+$, $d \rightarrow \pi^-$

Unfavored FF: $u \rightarrow \pi^-$, $d \rightarrow \pi^+$



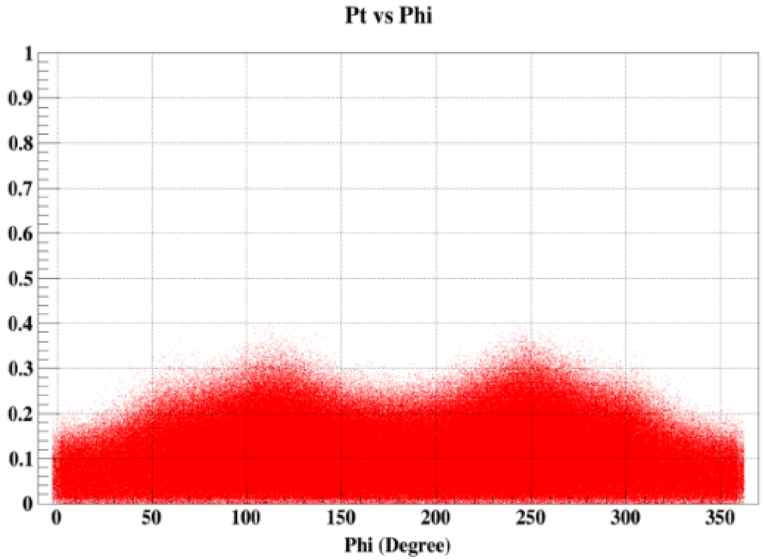
Pion SIDIS-CSV: E12-09-002/E12-09-017

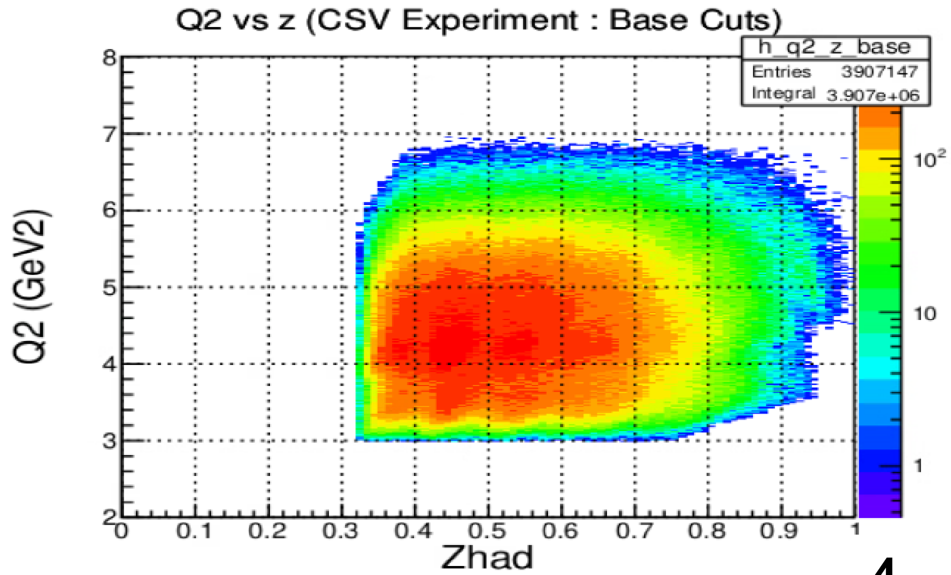




Detected Pion Momentum:
1.9 GeV/c – 4.5 GeV/c

HMS angle:
13-49 Degrees
SHMS angle:
6-30 Degrees
H2, D2, Al targets





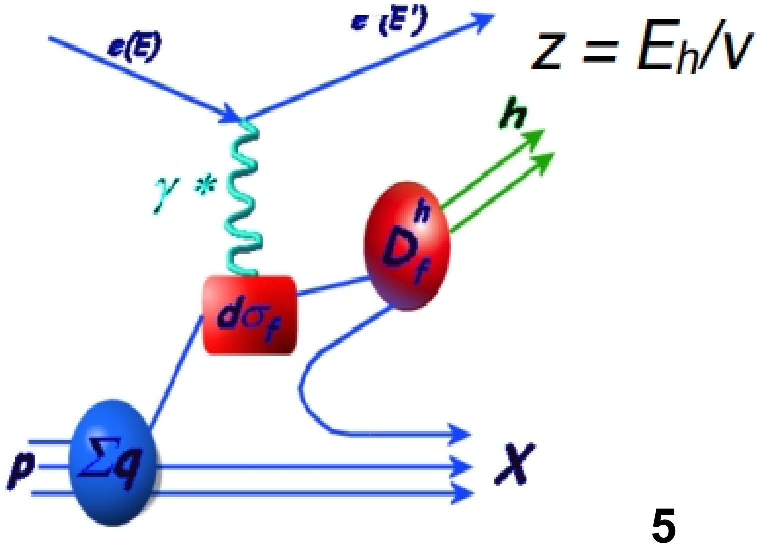
SIDIS Charged Pion Multiplicity: Test of Factorization Assumption

The kinematics for which data were collected on hydrogen and deuterium targets.

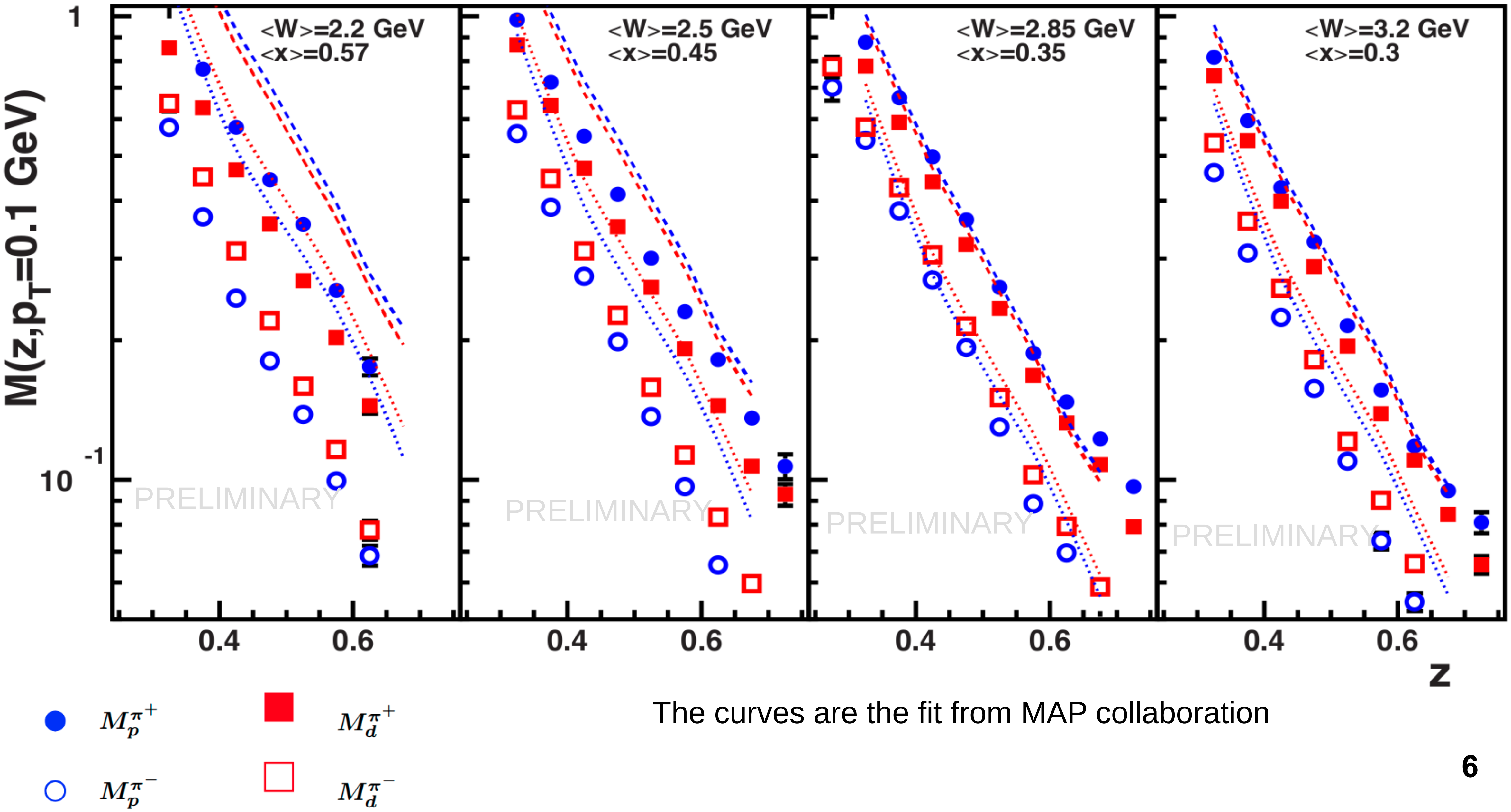
Ebeam (GeV)	E' (GeV/c)	θ_e (deg)	Q^2 (GeV^2)	W (GeV)	x	p_π (GeV/c)	θ_π (deg)
10.2	5.240	18.51	5.5[4.4-6.2]	2.2[2.0-2.5]	0.59[0.44-0.64]	2.219, 2.713, 3.208	17.75
10.6	5.971	15.75	4.8[3.8-5.4]	2.2[2.0-2.5]	0.55[0.39-0.63]	1.838, 2.299, 2.761, 3.223	18.55
10.6	5.971	14.24	3.9[3.0-4.8]	2.4[2.0-2.7]	0.45[0.30-0.60]	1.838, 2.299, 2.761, 3.223	17.04
10.6	5.240	16.30	4.5[3.5-5.1]	2.5[2.3-2.8]	0.45[0.32-0.54]	2.525, 3.363, 5.04	8-26
10.6	4.945	17.26	4.7[3.8-5.8]	2.6[2.1-2.9]	0.44[0.33-0.59]	2.241, 2.804, 3.366, 3.928	14.16
10.6	5.240	13.50	3.1[2.3-3.6]	2.8[2.6-3.1]	0.31[0.20-0.35]	1.956, 2.575, 3.433, 4.79	8-30
10.6	4.483	16.64	4.0[3.2-5.0]	2.9[2.5-9.9]	0.35[0.26-0.46]	2.428, 3.037, 3.646, 4.234	11.61
10.6	3.307	19.70	4.1[3.2-5.0]	3.2[3.0-3.4]	0.30[0.23-0.38]	2.645, 3.393, 4.531, 6.786	8-22

Multiplicity = $\sigma_{SIDIS} / \sigma_{DIS}$

$$M^{\pi^\pm}_{p/d}(x, Q^2, z) = \frac{d\sigma_{ee'\pi X}}{d\sigma_{ee'X}} = \frac{\sum_i e_i^2 q_i^{p/d}(x) D_{q_i \to \pi^\pm}(z)}{\sum_i e_i^2 q_i^{p/d}(x)},$$



Measured Multiplicities of Charged Pions



The curves are the fit from MAP collaboration

SIDIS Charged Pion Multiplicity: Test of Factorization Assumption

Assuming similar Pt dependence for charged pions from both hydrogen and deuterium targets, these multiplicities can be used to form two special (sum and difference) ratios for the test of Factorization in SIDIS:

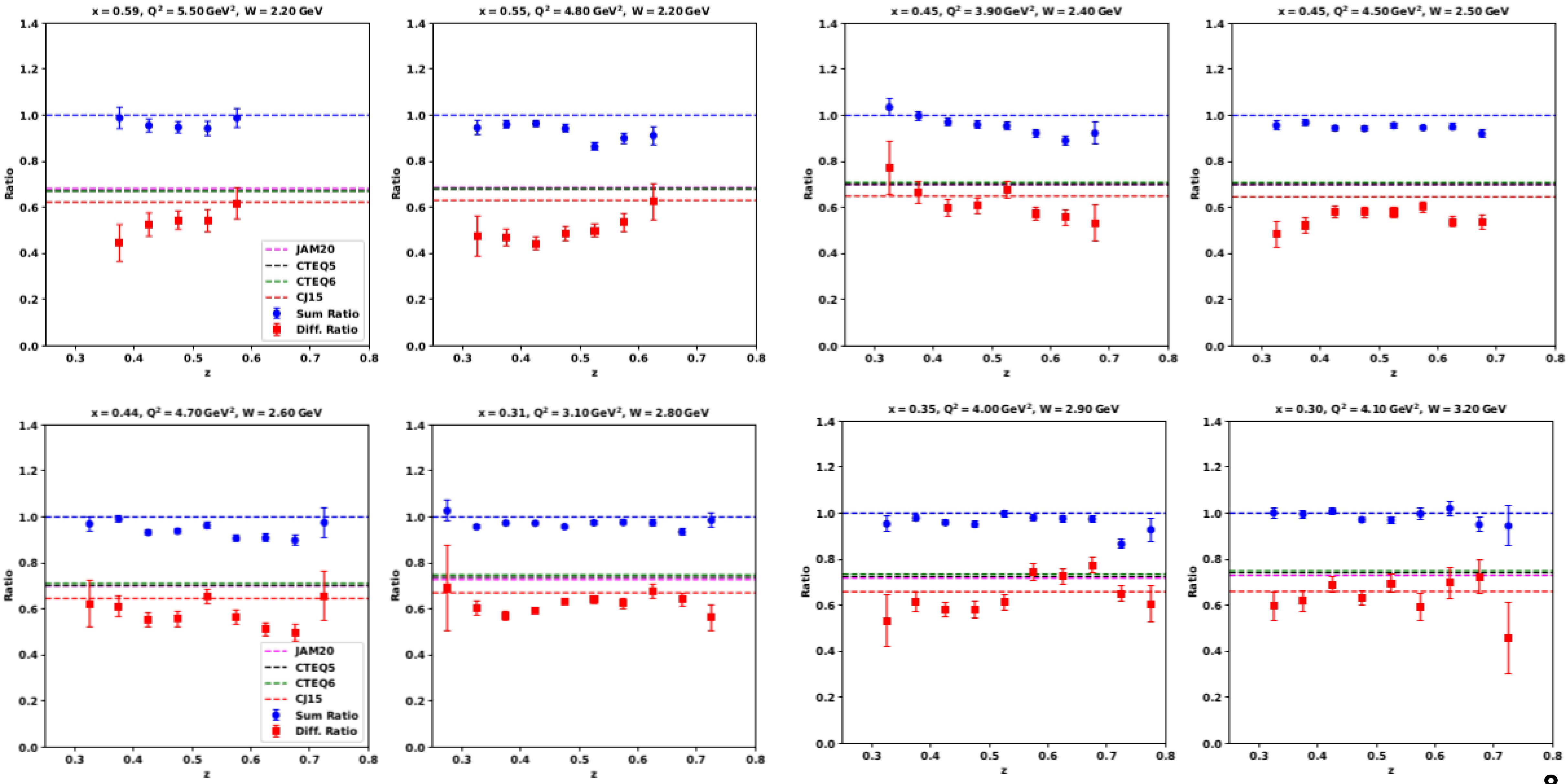
$$R_1(z) = \frac{M_d^{\pi^+}(z) + M_d^{\pi^-}(z)}{M_p^{\pi^+}(z) + M_p^{\pi^-}(z)} = 1$$

$$R_2(z) = \frac{M_d^{\pi^+}(z) - M_d^{\pi^-}(z)}{M_p^{\pi^+}(z) - M_p^{\pi^-}(z)} = \frac{3\,(4u(x) + d(x))}{5\,(4u(x) - d(x))}$$

=> independent of z

Measured Multiplicities of charged pions were used to form two ratios R1(z) and R2(z)

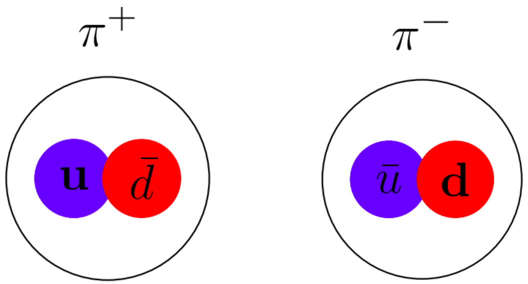
$$R_1(z) = \frac{M_{\rm d}^{\pi^+}(z) + M_{\rm d}^{\pi^-}(z)}{M_{\rm p}^{\pi^+}(z) + M_{\rm p}^{\pi^-}(z)} = 1, \quad R_2(z) = \frac{M_{\rm d}^{\pi^+}(z) - M_{\rm d}^{\pi^-}(z)}{M_{\rm p}^{\pi^+}(z) - M_{\rm p}^{\pi^-}(z)} = \frac{3}{5}\frac{4u(x)+d(x)}{4u(x)-d(x)}$$



Fragmentation Functions (FFs)

FFs describe how the quark and gluons transform into color-neutral hadrons during high-energy scattering processes.

SIDIS on protons and deuterons allow an extraction of flavor dependence of FFs



Charge and isospin symmetry in FFs allow to reduce the 8 FFs into 2 (Favored and Unfavored). The difference between two favored (F^+ and F^-) and two unfavored FFs is an indication of Charge symmetry violation (CSV) in FFs.

$$D_u^+ = D_{\bar{u}}^- = D_{u\pi^+} = F^+ (\text{Fav for } \pi^+),$$

$$D_d^- = D_{\bar{d}}^+ = D_{d\pi^-} = F^- (\text{Fav for } \pi^-),$$

$$D_d^+ = D_{\bar{d}}^- = D_{d\pi^+} = U^+ (\text{Unfav for } \pi^+),$$

$$D_u^- = D_{\bar{u}}^+ = D_{u\pi^-} = U^- (\text{Unfav for } \pi^-).$$

Multiplicity and Fragmentation Functions

$$M_{\mathrm{p/d}}^{\pi^\pm}(x, Q^2, z) = \frac{d\sigma_{ee'\pi X}}{d\sigma_{ee'X}} = \frac{\sum_i e_i^2 q_i^{\mathrm{p/d}}(x) D_{q_i \to \pi^\pm}(z)}{\sum_i e_i^2 q_i^{\mathrm{p/d}}(x)},$$

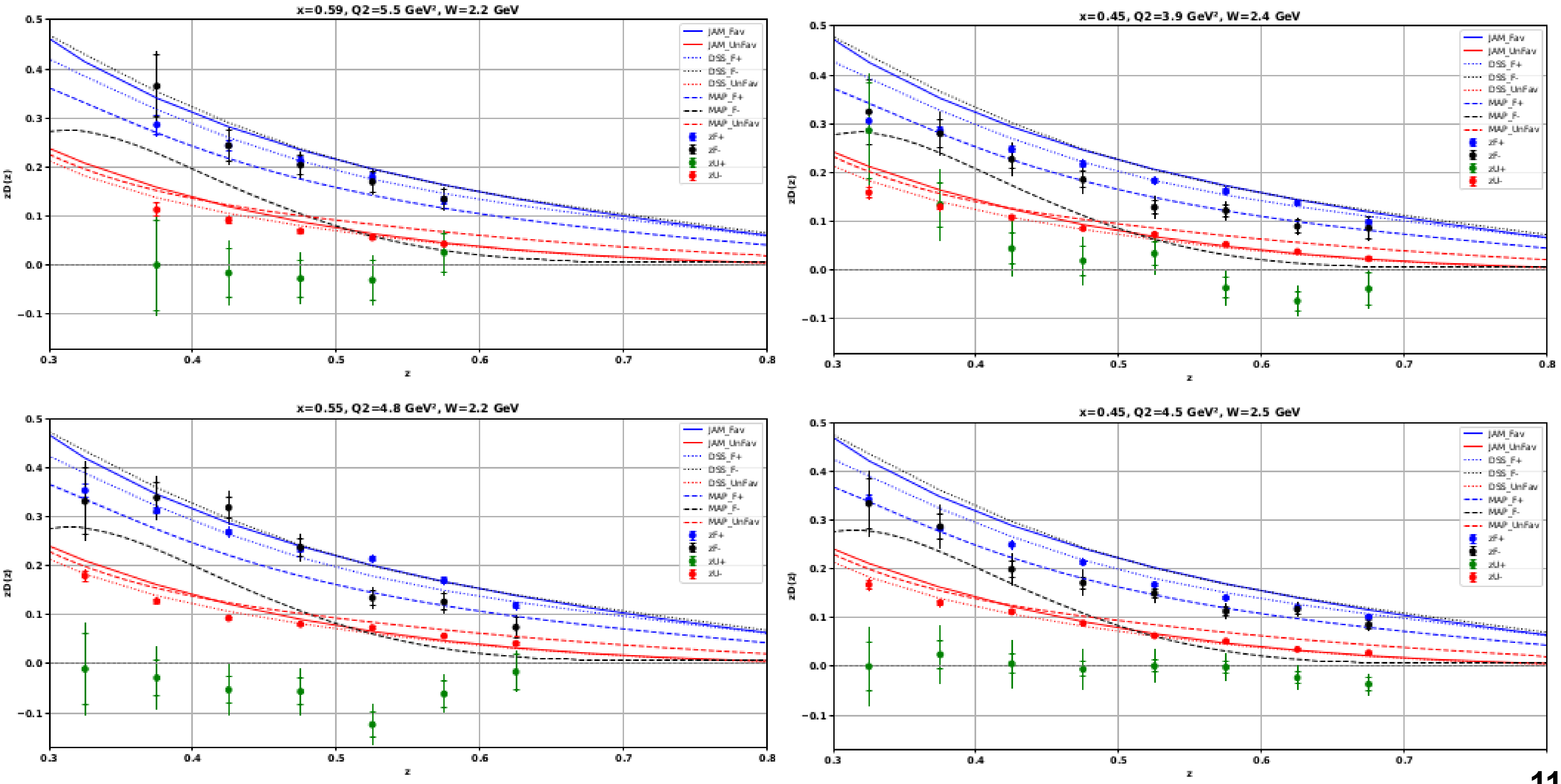
$$M_{\mathrm{p}}^{\pi^+}(x, Q^2, z) = \frac{4u(x)D_{u\pi^+}(z) + \bar{d}(x)D_{d\pi^-}(z)}{4u(x) + 4\bar{u}(x) + d(x) + \bar{d}(x) + 2s(x)} + \frac{d(x)D_{d\pi^+}(z) + 4\bar{u}(x)D_{u\pi^-}(z) + 2s(x)D_{s\pi^+}(z)}{4u(x) + 4\bar{u}(x) + d(x) + \bar{d}(x) + 2s(x)}$$

$$M_{\mathrm{p}}^{\pi^-}(x, Q^2, z) = \frac{4\bar{u}(x)D_{u\pi^+}(z) + d(x)D_{d\pi^-}(z)}{4u(x) + 4\bar{u}(x) + d(x) + \bar{d}(x) + 2s(x)} + \frac{\bar{d}(x)D_{d\pi^+}(z) + 4u(x)D_{u\pi^-}(z) + 2s(x)D_{s\pi^-}(z)}{4u(x) + 4\bar{u}(x) + d(x) + \bar{d}(x) + 2s(x)}$$

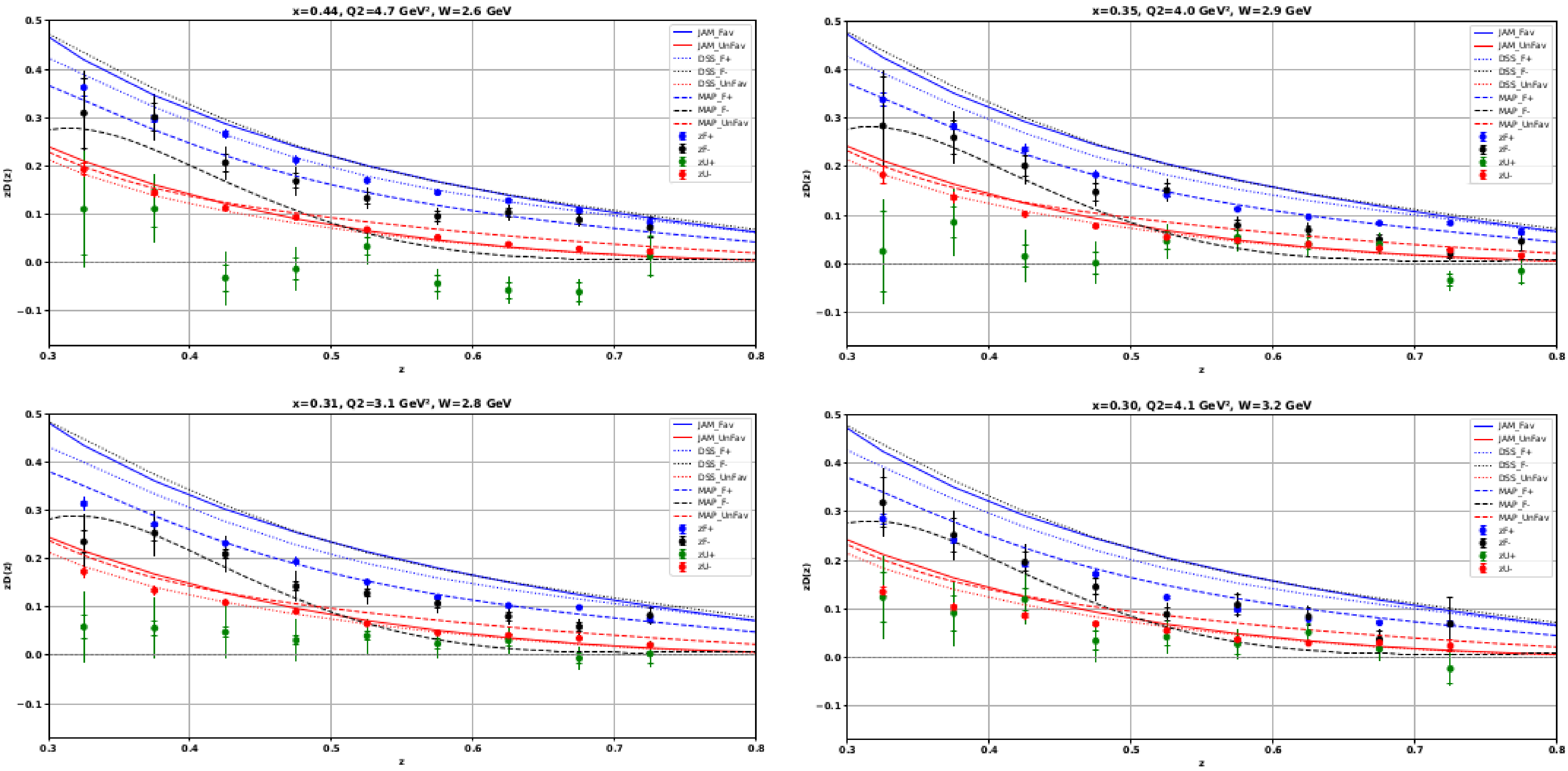
$$M_{\mathrm{d}}^{\pi^+}(x, Q^2, z) = \frac{[4u(x) + 4d(x)]D_{u\pi^+}(z) + [\bar{u}(x) + \bar{d}(x)]D_{d\pi^-}(z)}{5[u(x) + \bar{u}(x) + d(x) + \bar{d}(x)] + 4s(x)} + \frac{[u(x) + d(x)]D_{d\pi^+}(z) + 2s(x)D_{s\pi^+}(z)}{5[u(x) + \bar{u}(x) + d(x) + \bar{d}(x)] + 4s(x)} + \frac{[4\bar{u}(x) + 4\bar{d}(x)]D_{u\pi^-}(z) + 2s(x)D_{s\pi^+}(z)}{5[u(x) + \bar{u}(x) + d(x) + \bar{d}(x)] + 4s(x)}$$

$$M_{\mathrm{d}}^{\pi^-}(x, Q^2, z) = \frac{[4\bar{u}(x) + 4\bar{d}(x)]D_{u\pi^+}(z) + [u(x) + d(x)]D_{d\pi^-}(z)}{5[u(x) + d(x) + \bar{u}(x) + \bar{d}(x)] + 4s(x)} + \frac{[\bar{u}(x) + \bar{d}(x)]D_{d\pi^+}(z) + 2s(x)D_{s\pi^-}(z)}{5[u(x) + d(x) + \bar{u}(x) + \bar{d}(x)] + 4s(x)} + \frac{[4u(x) + 4d(x)]D_{u\pi^-}(z) + 2s(x)D_{s\pi^-}(z)}{5[u(x) + d(x) + \bar{u}(x) + \bar{d}(x)] + 4s(x)},$$

Extracted Fragmentation Functions for Charged Pions (Pt = 0.1 GeV, integrated over Phi)



Extracted Fragmentation Functions for Charged Pions (Pt = 0.1 GeV, integrated over Phi)



Charge Symmetry Violation in Fragmentation Functions

$$D_u^+ = D_{\bar{u}}^- = D_{u\pi^+} = F^+(\text{Fav for } \pi^+),$$

$$D_d^- = D_{\bar{d}}^+ = D_{d\pi^-} = F^-(\text{Fav for } \pi^-),$$

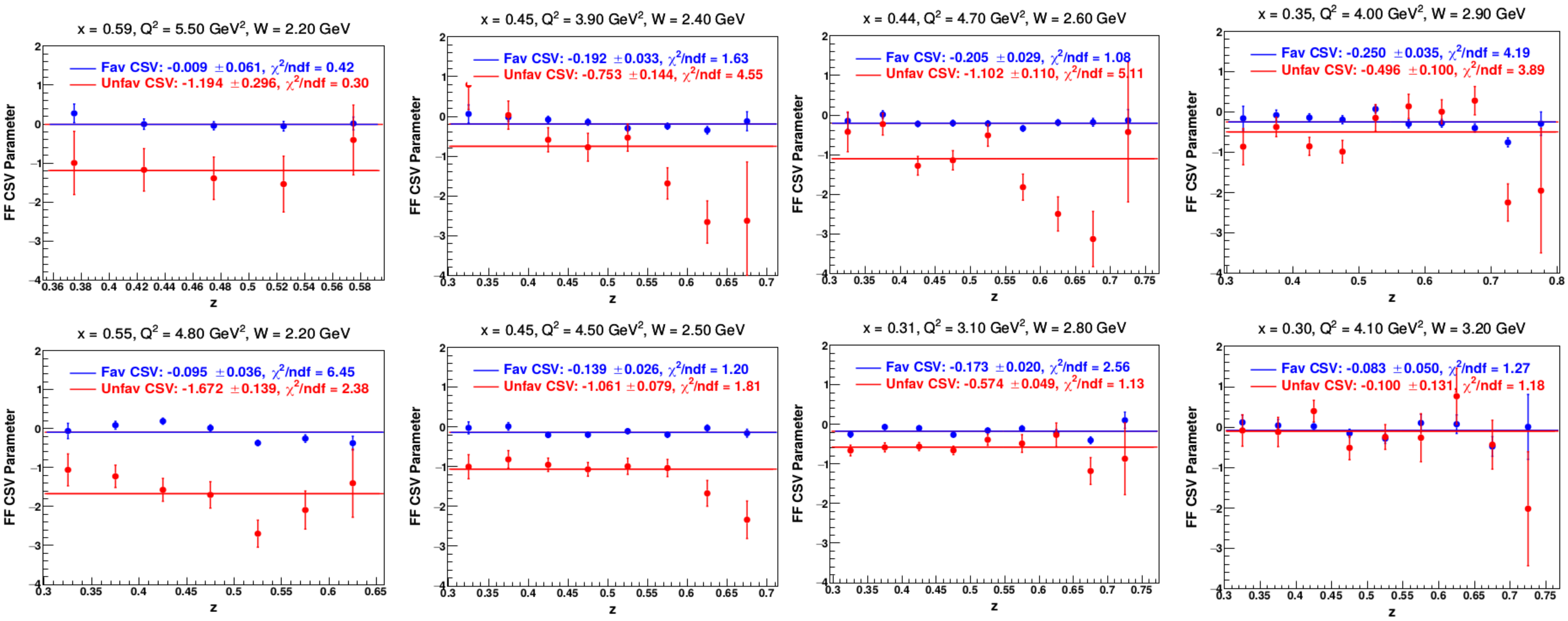
$$D_d^+ = D_{\bar{d}}^- = D_{d\pi^+} = U^+(\text{Unfav for } \pi^+),$$

$$D_u^- = D_{\bar{u}}^+ = D_{u\pi^-} = U^-(\text{Unfav for } \pi^-).$$

$$\text{Fav. FF CSV Parameter} : \delta^f_{\text{CSV}}(z) = \frac{D_{d\pi^-} - D_{u\pi^+}}{D_{u\pi^+}} = \frac{F^- - F^+}{F+},$$

$$\text{Unfav. FF CSV Parameter} : \delta^{uf}_{\text{CSV}}(z) = \frac{D_{d\pi^+} - D_{u\pi^-}}{D_{u\pi^-}} = \frac{U^+ - U^-}{U^-}$$

Charge Symmetry Violation in Fragmentation Functions



Summary

- We have studied the semi-inclusive charged pion electroproduction from hydrogen and deuterium targets at Jefferson Lab.

- Multiplicities of charged pions were extracted.

- The sum-and-difference ratios of multiplicities were used to test the factorization assumption in SIDIS. These ratios satisfy CS/IS at the highest W (3.2 GeV) but steadily deviate from the CS expectation with decreasing W (increasing x). The deviations at lower W may indicate the importance of higher twist contributions to the SIDIS cross-sections.

- The multiplicities were used to quantify the flavor dependence of FFs, they confirm the flavor independence of both the favored and un-favored FF at the highest W.

- Two CSV parameters for favored and unfavored FFs were extracted. The CSV parameter for favored FF agrees with expectation however for unfavoed FFs, it deviates with decreasing W. This may indicate that the fragmentation process could be more complex than is usually assumed. Also, additional observables may be required that can cleanly identify the sources of possible CSV both fragmentation functions.

- The article on the flavor dependence of fragmentation functions has been submitted to PRL.

Proton SIDIS Analysis Update

SIDIS Proton Electroproduction

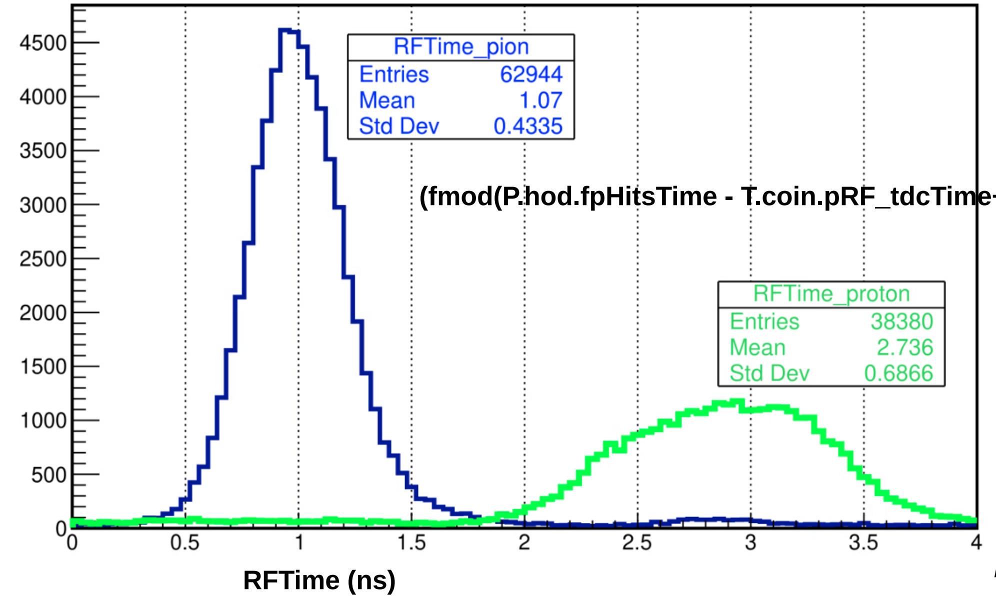
SIDIS pion production

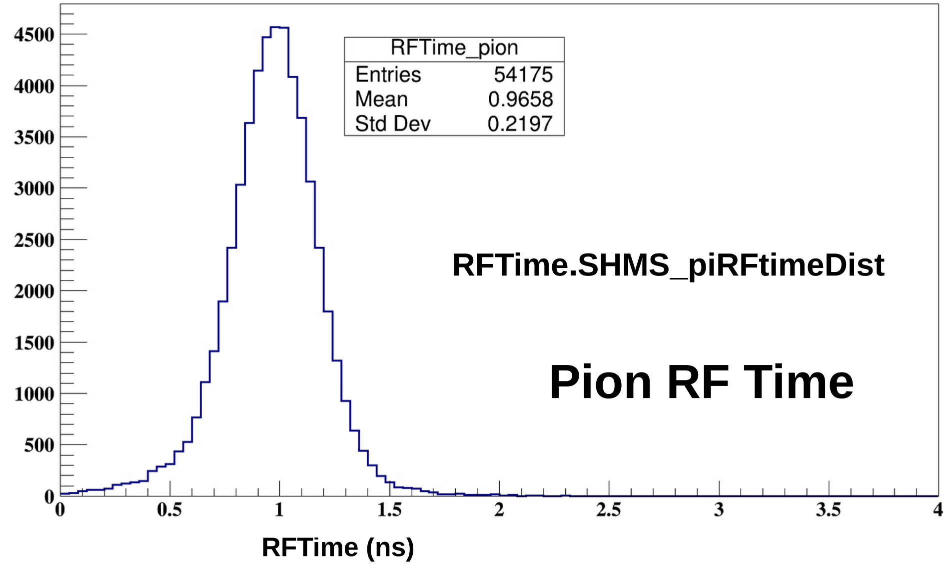
$$e + p\ (\mathrm{or}\ n) \rightarrow e^{'} + \pi^{+} + X$$
$$e + p\ (\mathrm{or}\ n) \rightarrow e^{'} + \pi^{-} + X$$

SIDIS proton production

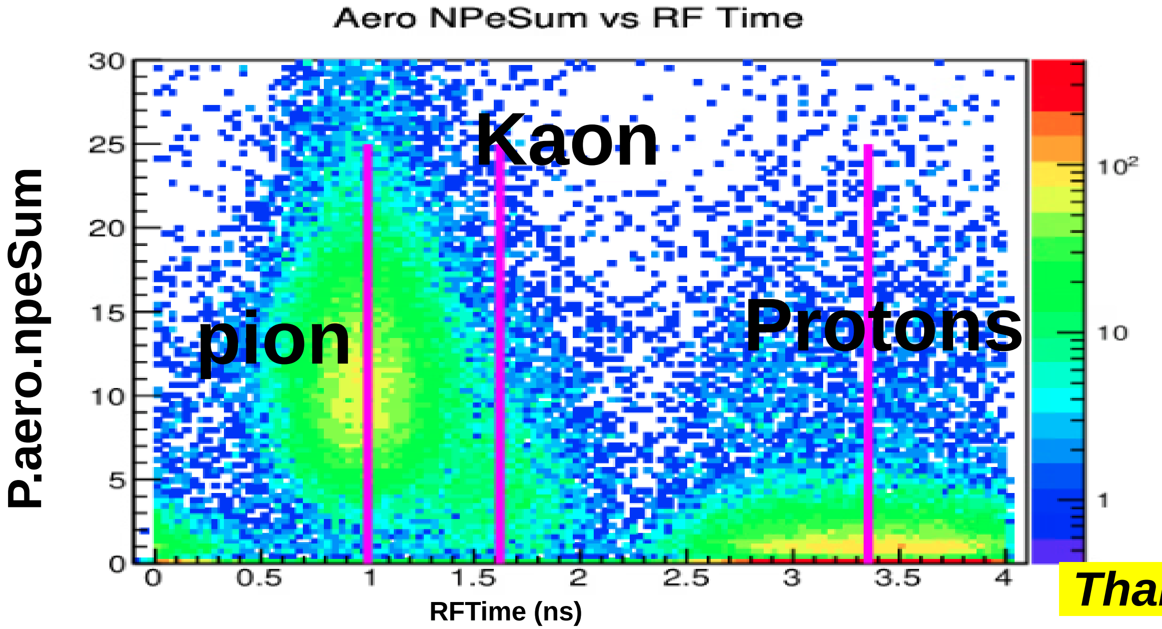
$$e + p\ (or\ n) \rightarrow e^{'} + p + X$$

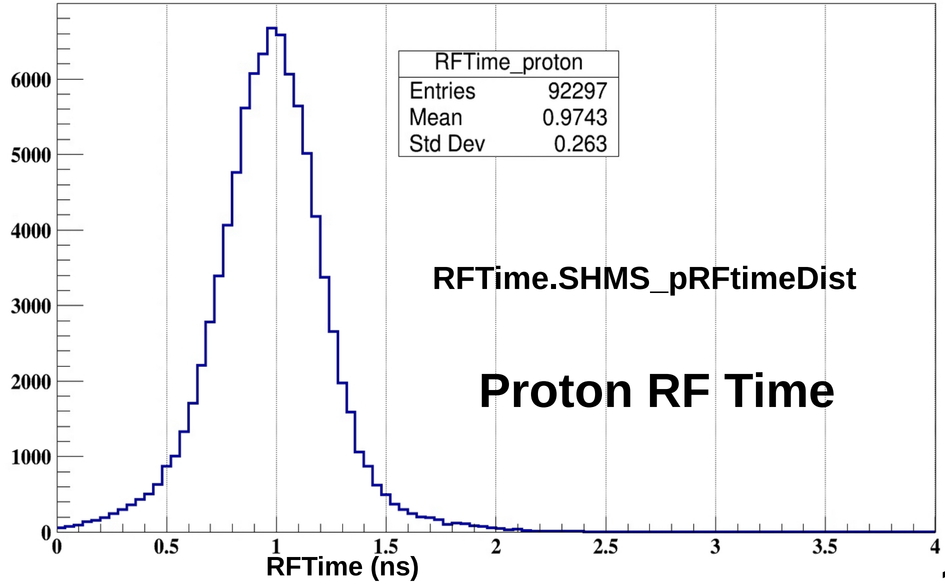
We can select protons using Aerogel, Coincidence Time and RF Time





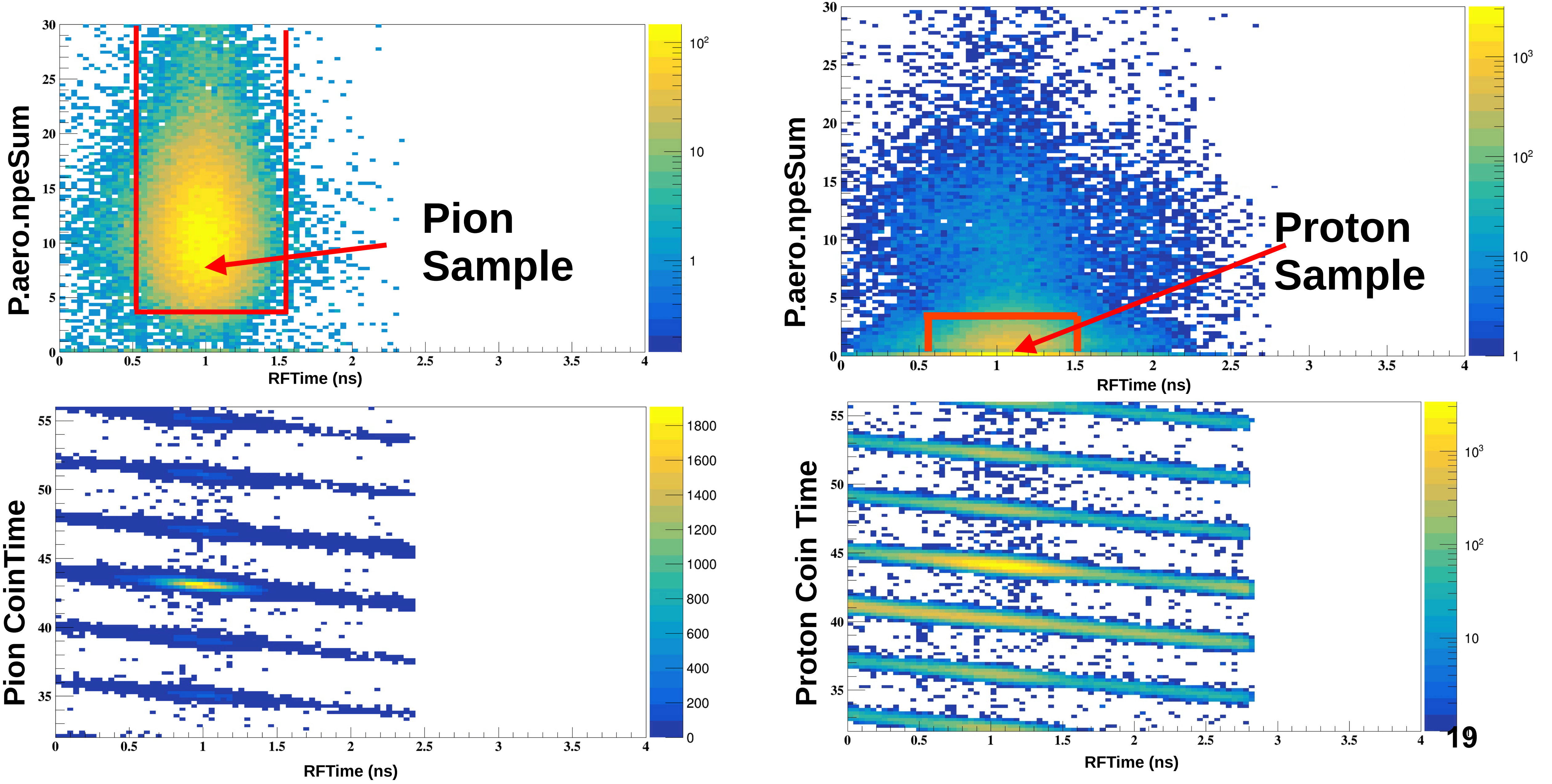
hcana updated



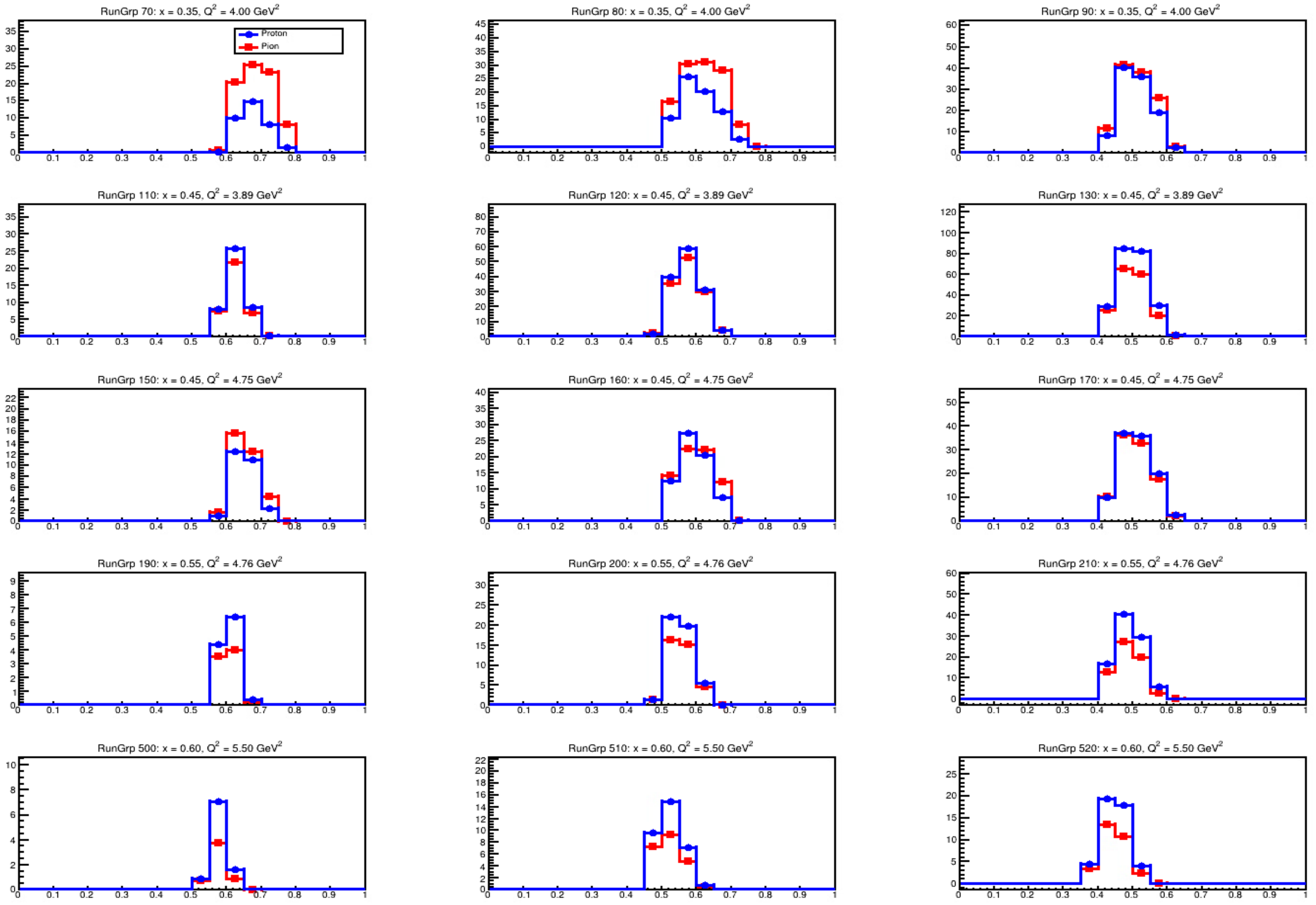


Thanks to Stephen Kay for adding RFTime leaf in hcana

We can select protons using Aerogel, Coincidence Time and RF Time

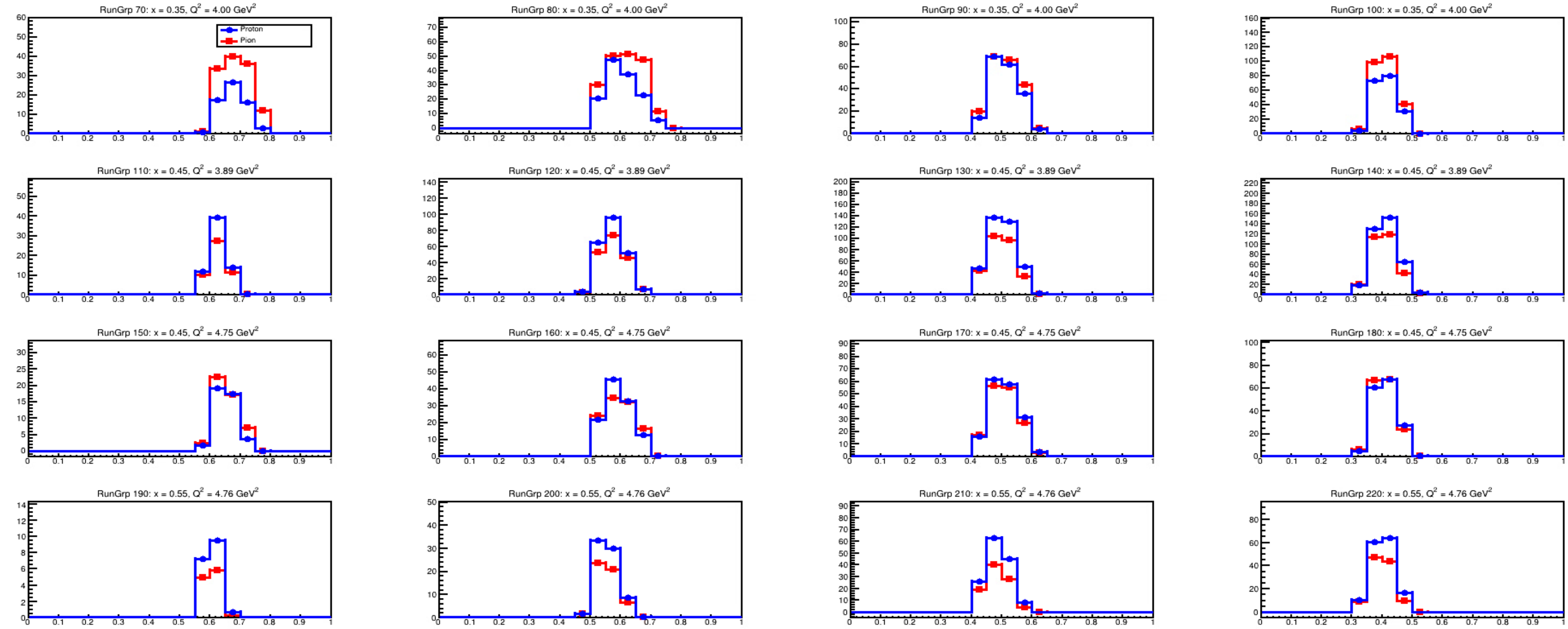


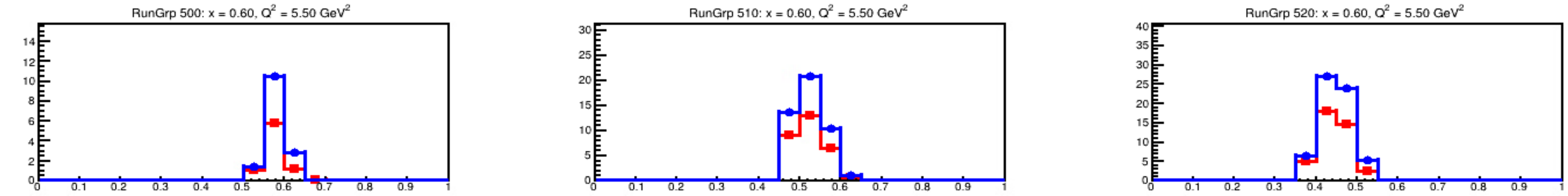
Pion SIDIS Yield vs Proton SIDIS Yield (H2 Target) : Significant Statistics



Yield (counts/mc) vs z for Pi+ from Hydrogen vs P from Hydrogen

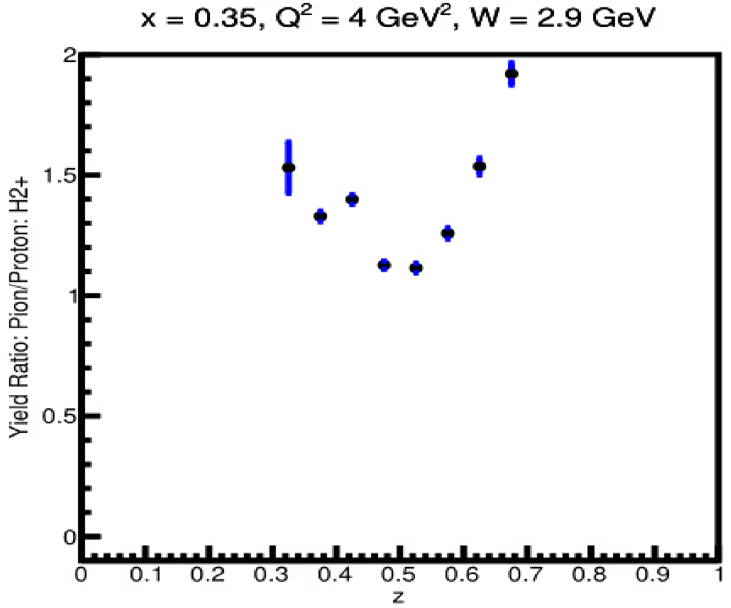
Pion SIDIS Yield vs Proton SIDIS Yield (D2 Target) : Significant Statistics

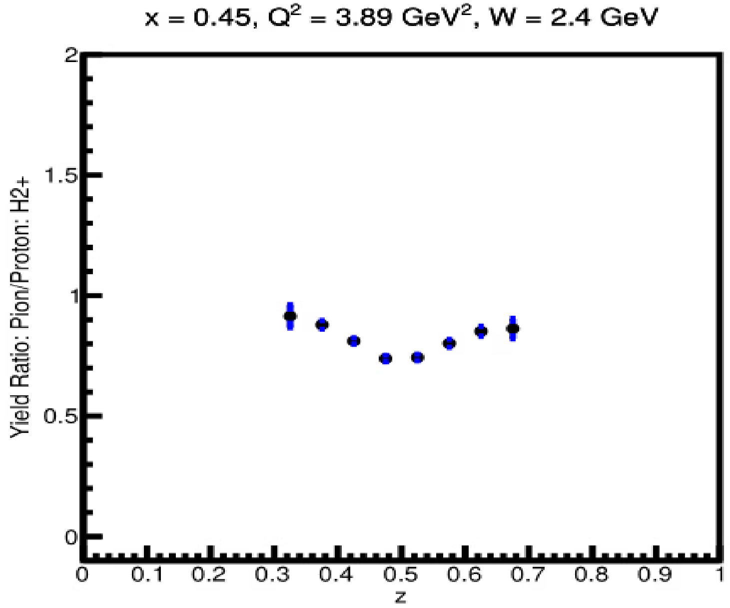


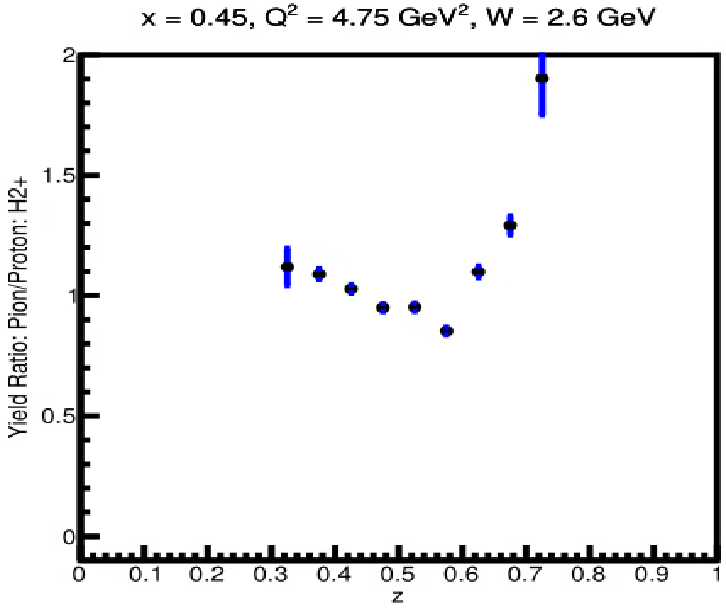


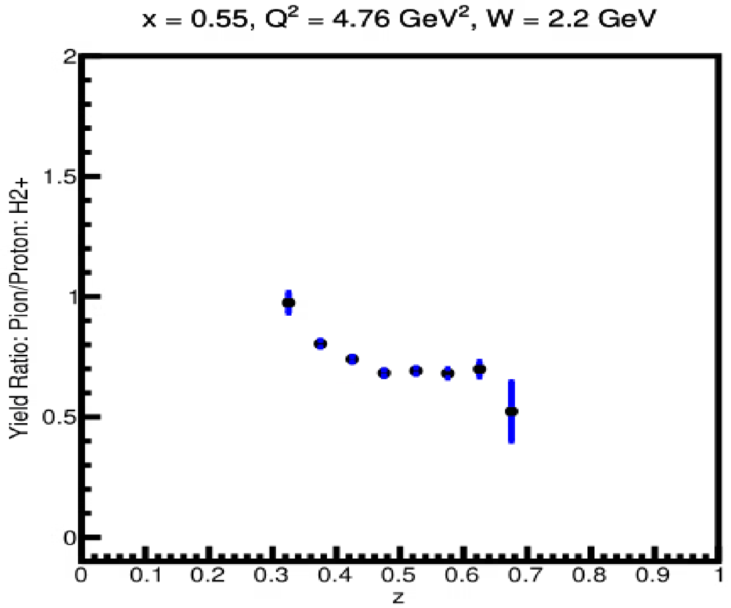
Yield (counts/mc) vs z for Pi+ from Deuterium vs P from Deuterium

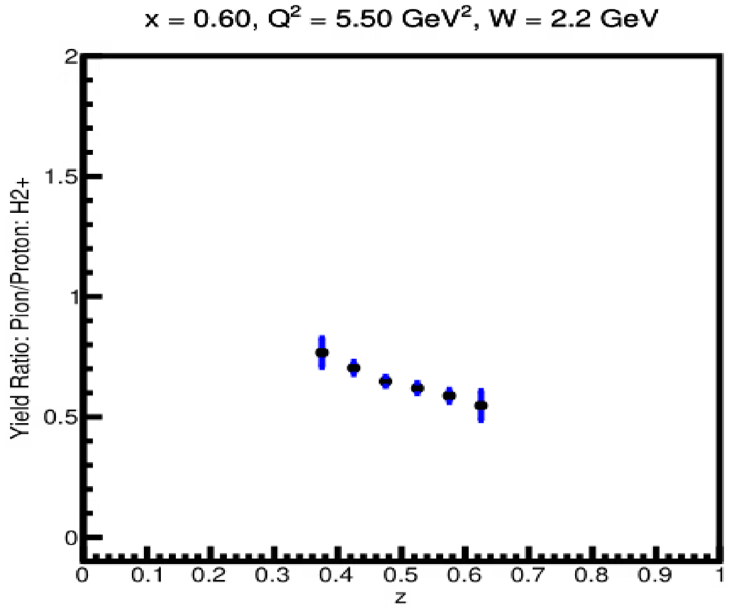
Pion SIDIS Yield / Proton SIDIS Yield : (H2 Target)



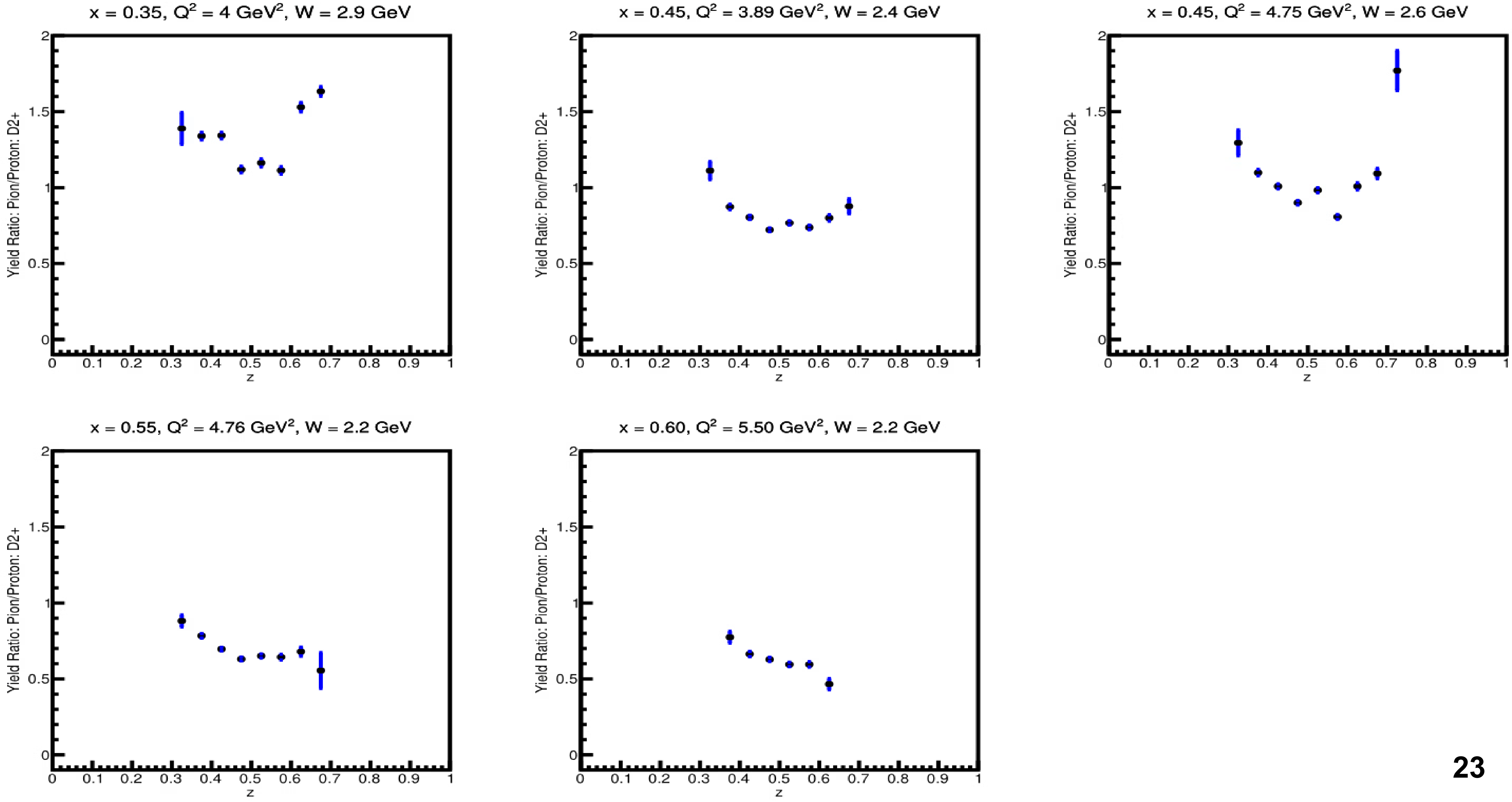








Pion SIDIS Yield / Proton SIDIS Yield : (D2 Target)



Summary

- We have Significant Proton data which can be cleanly separated from positive pions using RFTiming information, Coincidence Time and Aerogel detector.

- The SIMC model for proton SIDIS is under development, starting from the existing pion SIDIS Model (decay off).

- Study of Factorization in SIDIS proton electroproduction.

- Pt-and Phi dependence of SIDIS proton cross-section.

Acknowledgments

Dipangkar Dutta, Dave Gaskell, Peter Bosted, Shuo Jia, Whitney Armstrong, Hamlet Mkrtchyan, Rolf Ent, Wenliang Bill Li, and the Jefferson Lab Hall C Collaboration.

H. Bhatt, P. Bosted, S. Jia, W. Armstrong, D. Dutta, R. Ent, D. Gaskell, E. Kinney, H. Mkrtchyan, S. Ali, R. Ambrose, D. Androic, C. Ayerbe Gayoso, A. Bandari, V. Berdnikov, D. Bhetuwal, D. Biswas, M. Boer, E. Brash, A. Camsonne, J. P. Chen, J. Chen, M. Chen, E. M. Christy, S. Covrig, S. Danagoulian, M. Diefenthaler, B. Duran, M. Elaasar, C. Elliot, H. Fenker, E. Fuchey, J. O. Hansen, F. Hauenstein, T. Horn, G. M. Huber, M. K. Jones, M. L. Kabir, A. Karki, B. Karki, S. J. D. Kay, C. Keppel, V. Kumar, N. Lashley-Colthirst, W. B. Li, D. Mack, S. Malace, P. Markowitz, M. McCaughan, E. McClellan, D. Meekins, R. Michaels, A. Mkrtchyan, G. Niculescu, I. Niculescu, B. Pandey, S. Park, E. Pooser, M. Rehfuss, B. Sawatzky, G. R. Smith, H. Szumila-Vance, A. S. Tadepalli, V. Tadevosyan, R. Trotta, H. Voskanyan, S. A. Wood, Z. Ye, C. Yero, X. Zheng

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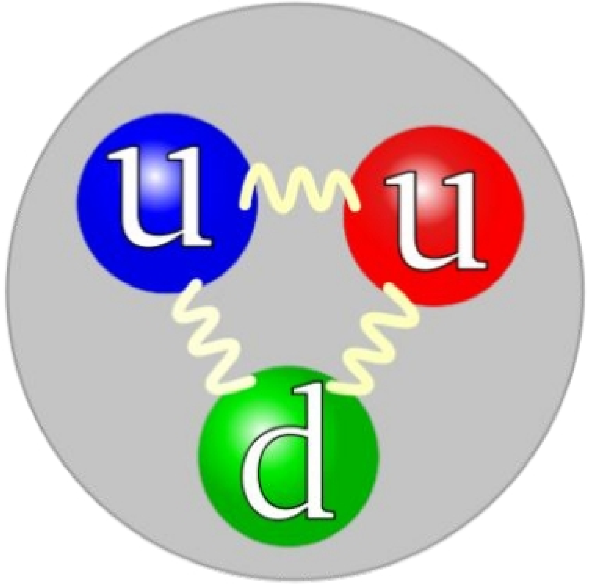
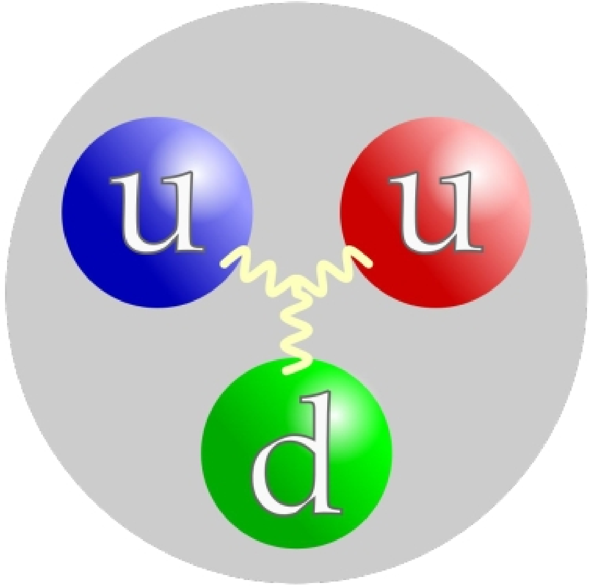
Backup Slides

Which picture is correct?

- **Proton internal structure: which of the following picture is correct?**



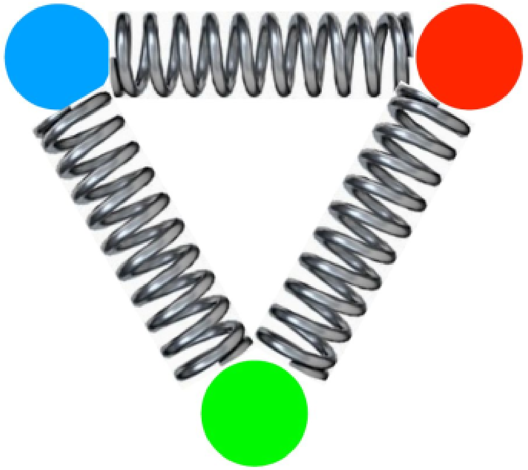
A



B

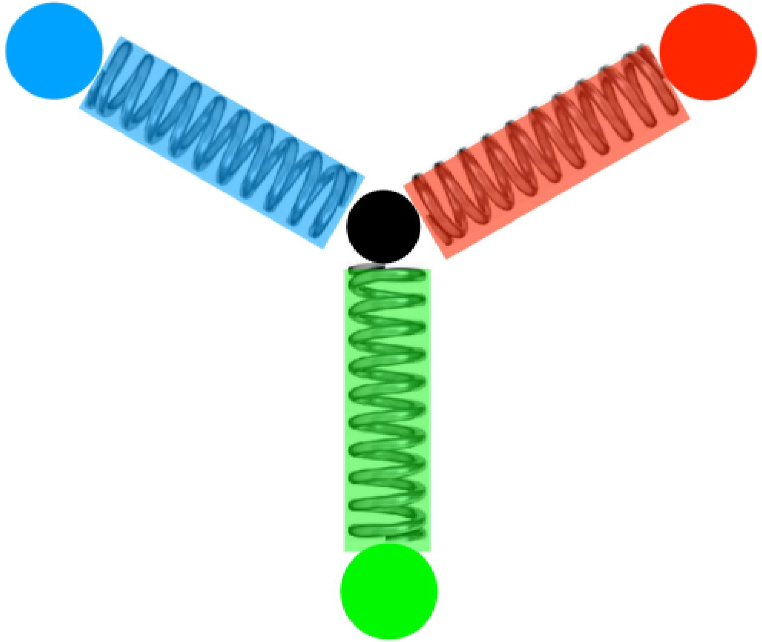
Proton Image by Frank Wilczek

To put back the "3" in color SU(3), we can use U(1) x U(1) x U(1) with an appropriate charge spectrum:



$(1, -1, 0)$ & $(-1, 0, 1)$ & $(0,1, -1)$

Or, likely best of all in this vein: just U(1), unit charged quarks and a charge -3 verton.

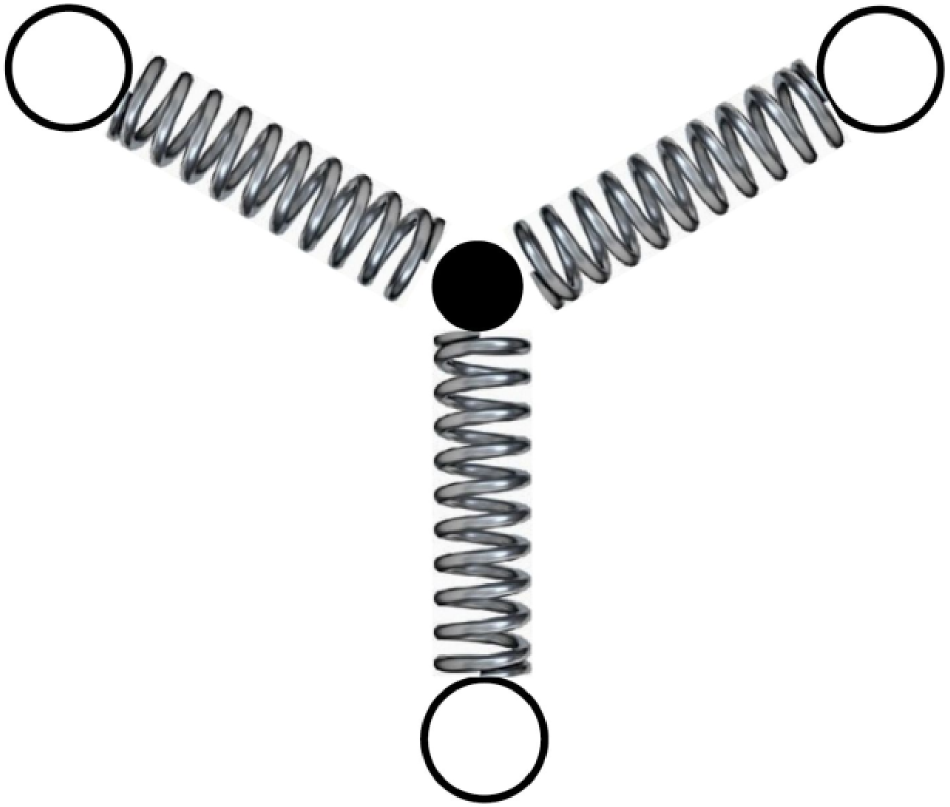


$(1,0,0)$ & $(0,1,0)$ & $(0,0,1)$ + verton $(-1, -1, -1)$

A better configuration by Frank Wilczek

50 Years of Quantum Chromodynamics Seminar Series :
https://indico.cern.ch/event/1276932/contributions/5563300/attachments/2712308/4744769/qcd_ucla_03.pdf

A New Concept: “Verton”



1 & 1 & 1 + verton – 3

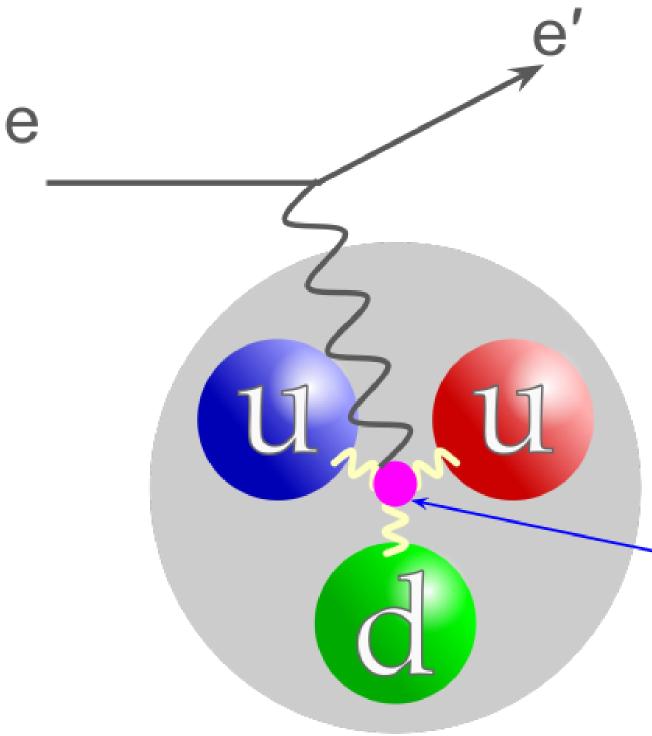
A “**verton**” concept: **ver**tex of par**ton**

mathematically by introducing a scalar field that carries the appropriate charges.

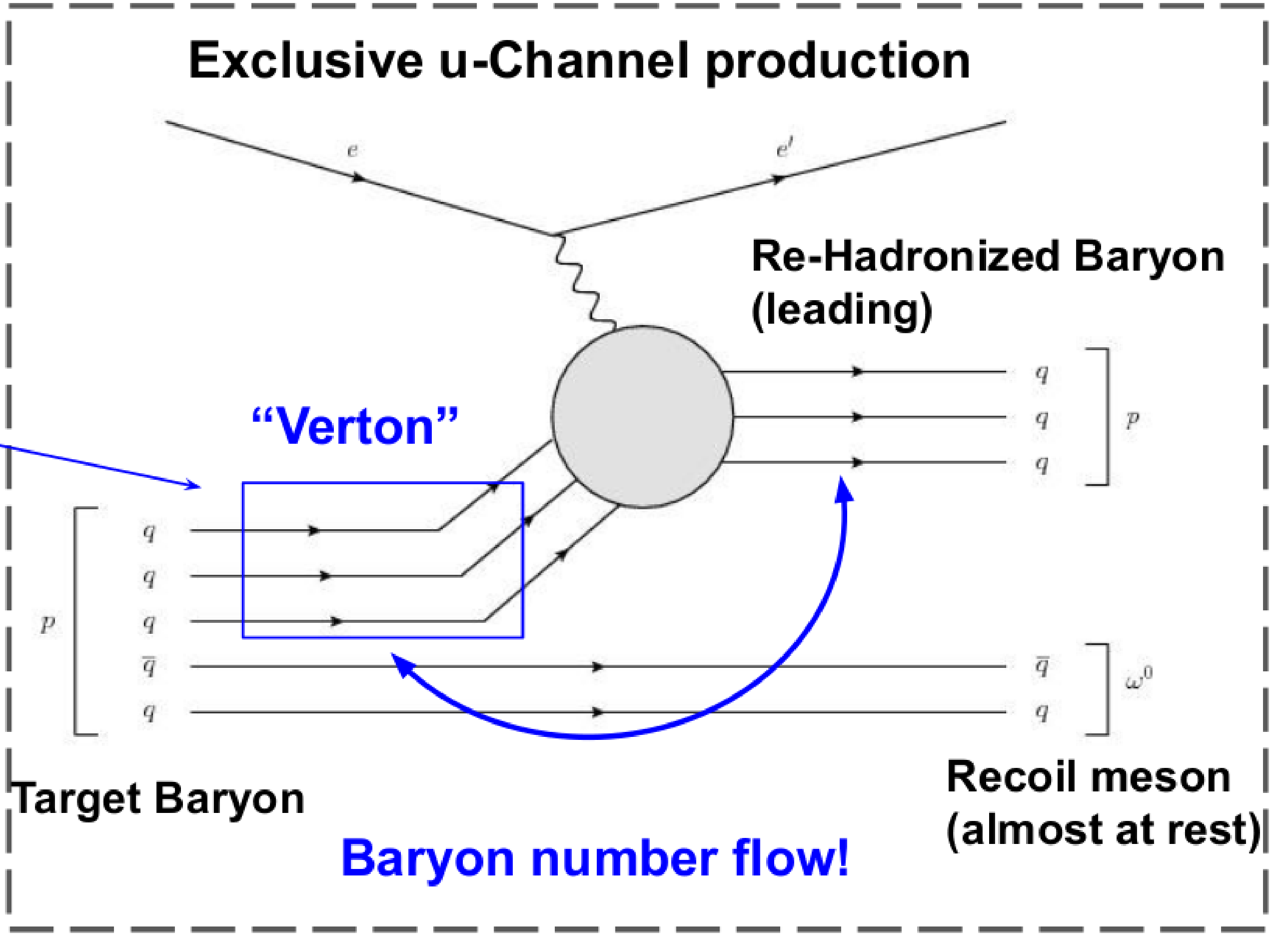
This adds a parameter or two (i.e., the verton mass and self-interaction) while it raises many interesting possibilities like “nuclei”, “glueballs”, “exotics”, condensation …

by F. Wilczek

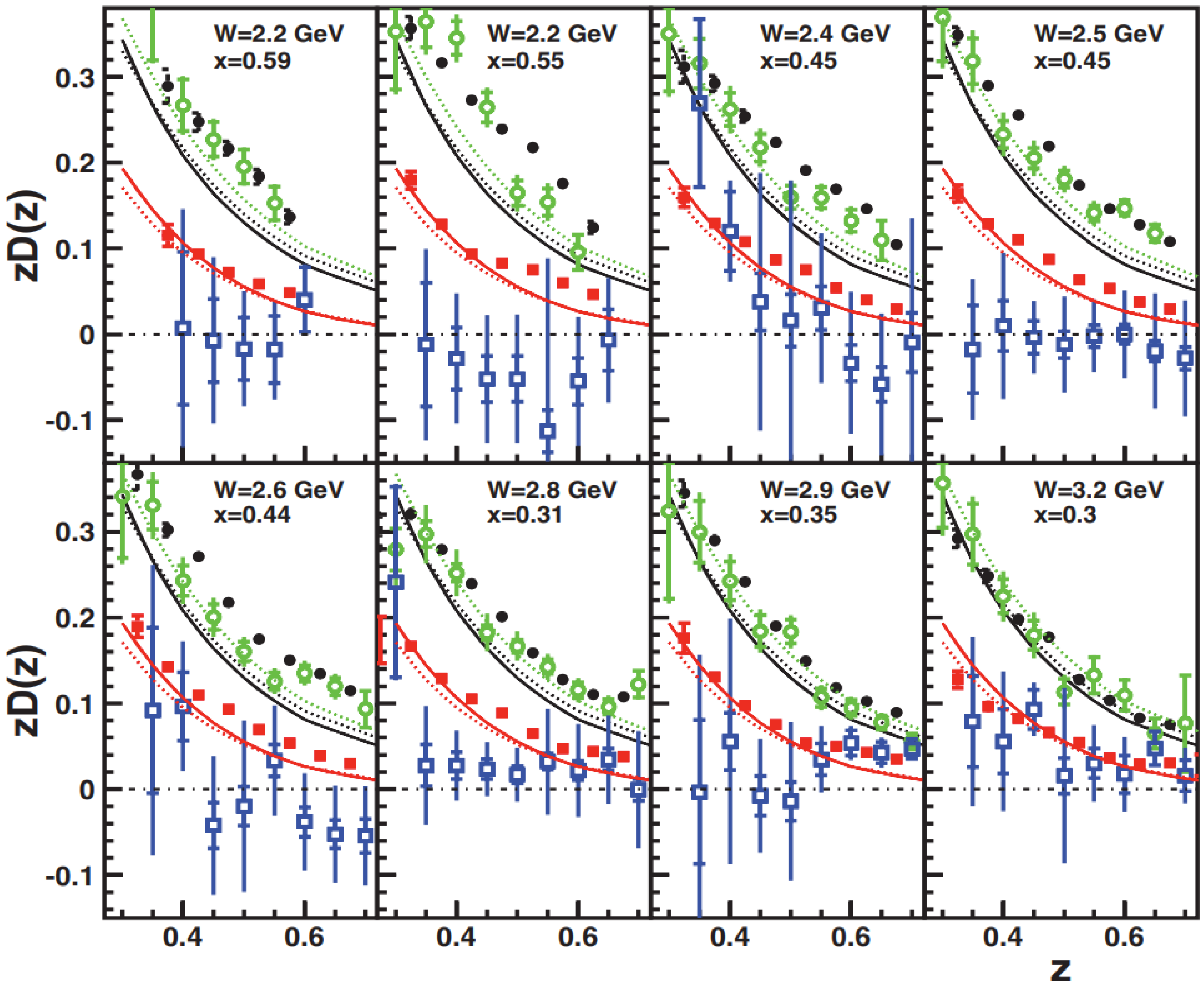
Looking for Verton via Exclusive u-Channel Processes



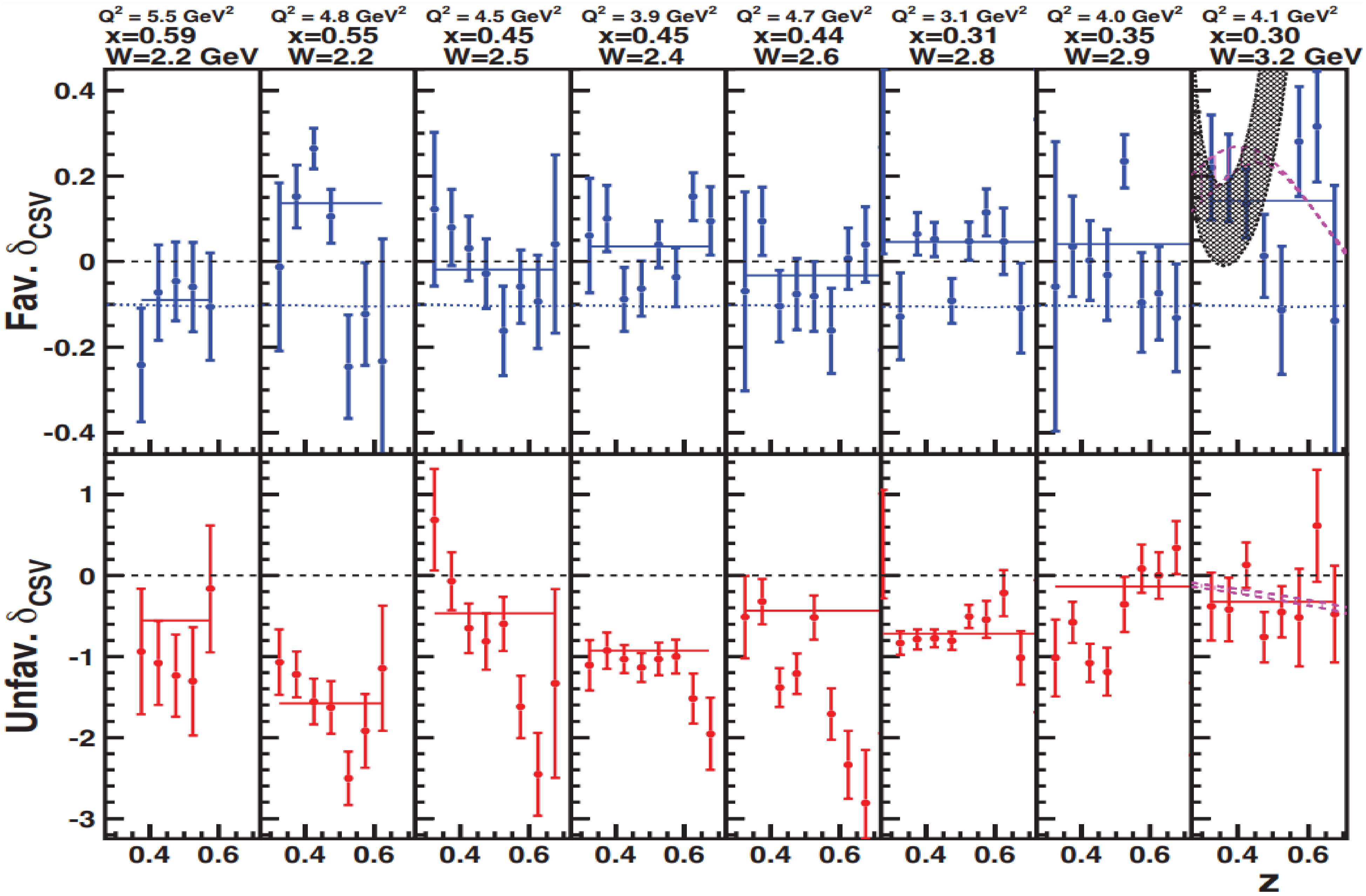
- **Probing verton JLab 12 GeV?**
  - knocking a proton out of a proton process



Fragmentation Functions Extractions



CSV in FFs for 8 kinematics



Systematic Uncertainty

Table 3.9: Systematic uncertainty of the multiplicities.

Source	Scale Uncertainty (%)	Point-to-Point Uncertainty (%)	Correlated Uncertainty (%)
Charge	-	0.45	-
Target density ^{2}H (^{1}H)	0.6 (0.7)	-	-
Target boiling correction	-	0.3	-
Target end cap subtraction	0.1	-	-
Tracking efficiency	-	0.1	-
Live time	-	0.04	-
Particle identification	0.8	-	-
Background subtraction			
ρ^0	-	0.1 - 0.6	0.1- 1.4
Δ	-	0 - 0.15	0.03 - 0.3
Exclusive	-	0 - 0.05	0.05 - 0.7
Contamination			
Kaon	-	0.1 - 0.2	-
Proton	-	0 - 0.05	-
Electron	-	0 - 0.05	-
Spectrometer Acceptance	1	0.45	-
Kinematics	-	0.2	-
Radiative correction	1	0.5	-
Inclusive cross-section	2	-	-
FADC rate dependence	-	0.9	-
Total	2.65	1.27 - 1.42	0.1-1.6
Total systematic uncertainty added in quadrature = 2.94 to 3.4 %			

The Experiment: E12-09-002

$$Yield = \frac{e - \pi \text{ coincidence counts}}{Q \ . \ \epsilon}$$

$$\text{Yield} = Y_{data} - Y_{rho} - Y_{delta} - Y_{excl}$$

Y_{data} = Yield after contributions from the accidental backgrounds and target end caps are subtracted.

Multiplicity = $\sigma_{SIDIS} / \sigma_{DIS}$

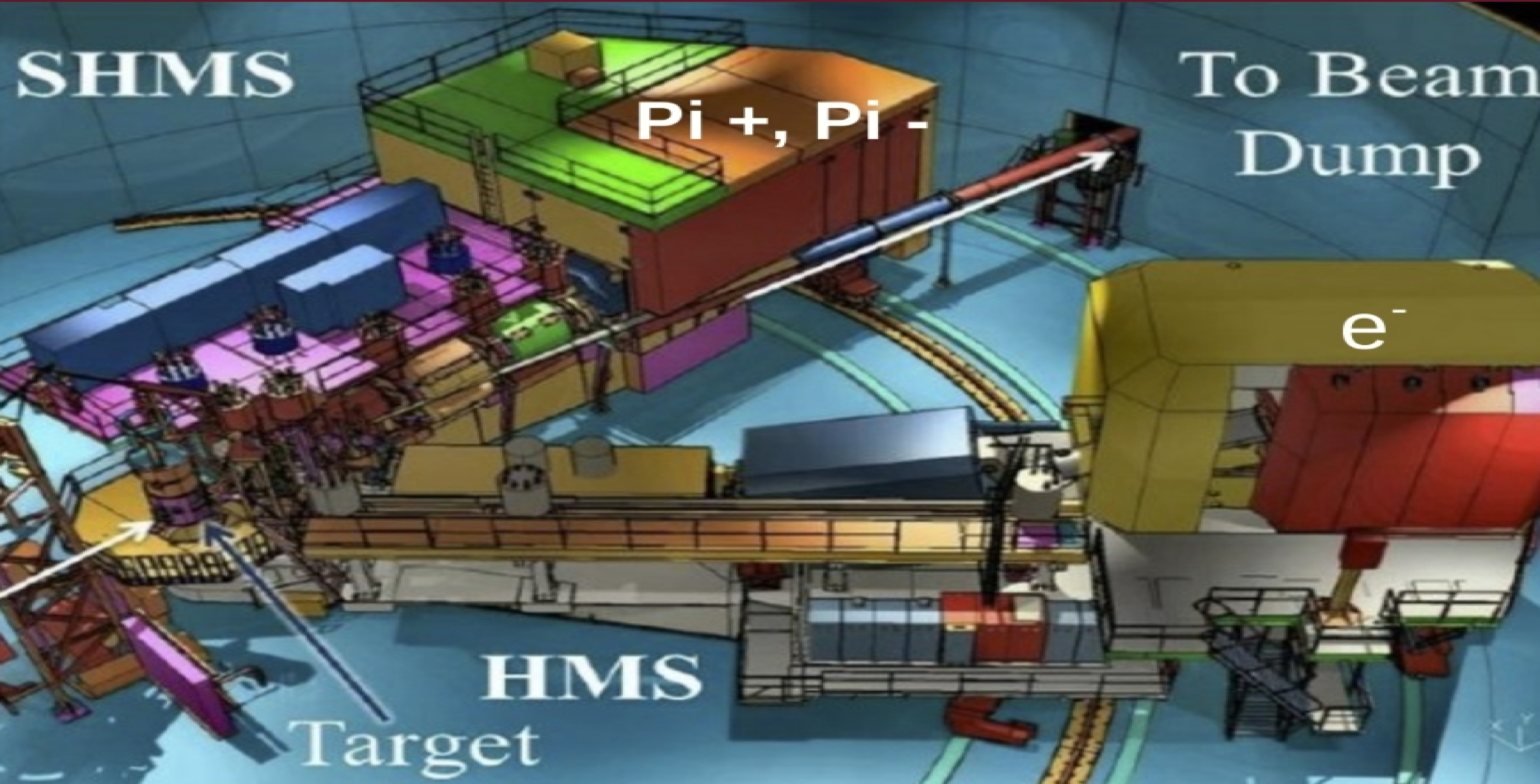
$$M = \left(\frac{Y_{data}}{Y_{SIMC}}\right) \times M_{model}$$

$$M = \frac{1}{\sigma_N(x)} \frac{d\sigma_N^h(x,z)}{dz} = \frac{\sum_i e_i^2 q_i^N(x) D_i^h(z)}{\sum_i e_i^2 q_i^N(x)}$$

Here, M_{model} is the multiplicity calculated based on a well-defined model for the kinematics (x, Q^2, z, P_T = 0.1 GeV) of interest. Data collected simultaneously from Hydrogen and Deuterium target allows us to extract 4 FFs:

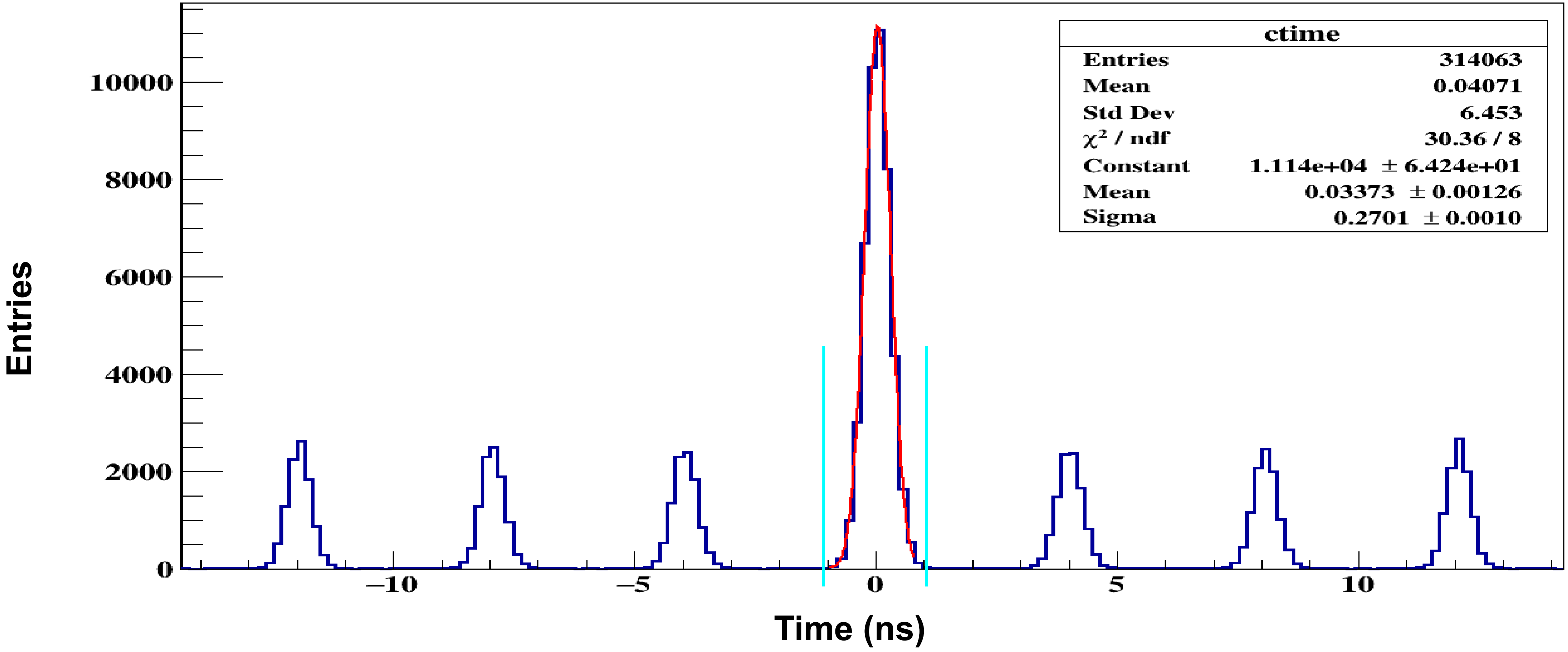
From above definition of multiplicities, We get 4 types of FFs for Pi^+ and Pi^-

The Hall C Spectrometers



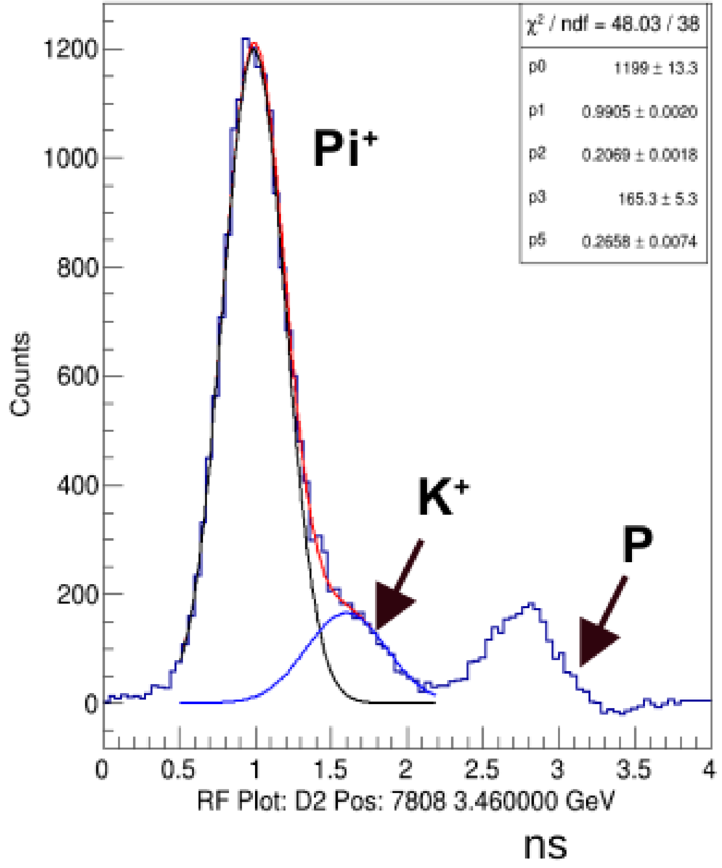
Coincidence Time

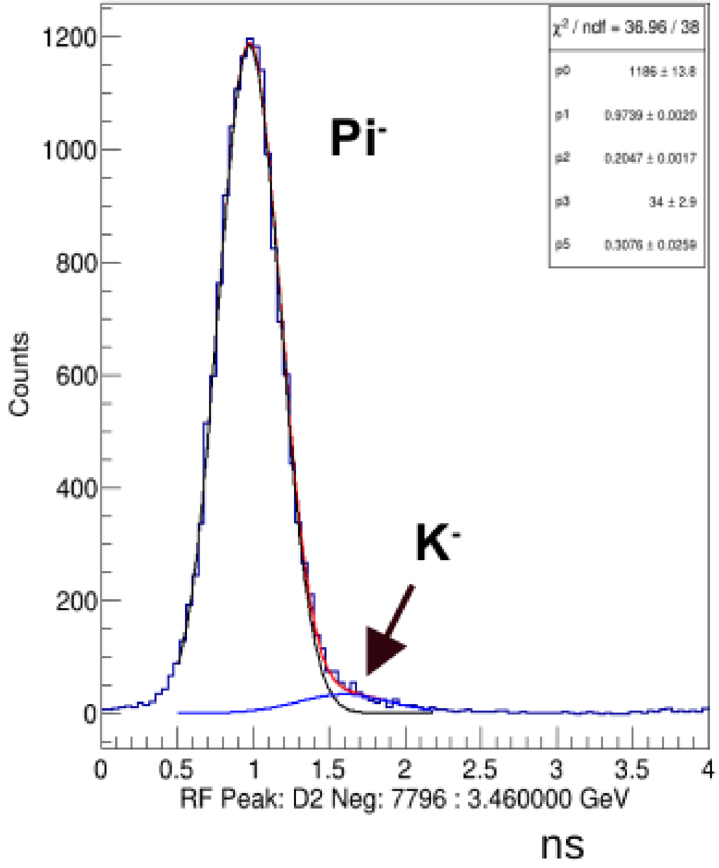
Coincidence Time is the difference between ¾ hodoscope trigger time in the HMS (electron arm) and SHMS (pion arm) corrected for the exact particle trajectory. The pronounced peak is for the electron-pion coincidence events from the same beam bunch. For accidental events, the electrons and pions originate from different beam bunches.The accidental events under the main peak has to be removed while calculating experimental yield.



RF Time as a PID: Pion-Kaon-Proton separation

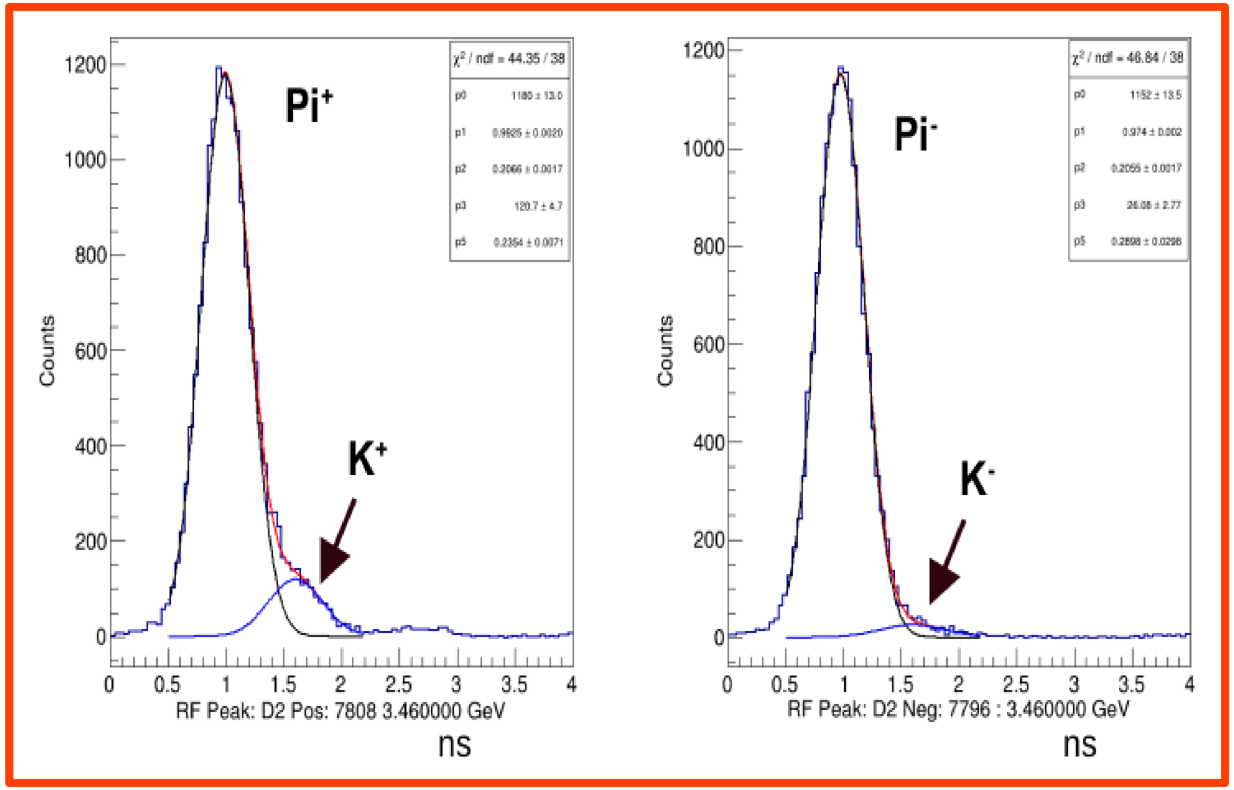
The accelerator provides an RF pulse that defines the time structure of the beam buckets that are delivered to the Hall C. Timing information in spectrometer can be compared to RF signal, essentially yielding Time of Flight (TOF) information relative the bunch arrival at target. The timing information is corrected for the pathlength of the particle in the spectrometers. A spectrum of particles' arrival time at the SHMS hodoscope relative to the RF pulse are shown below:

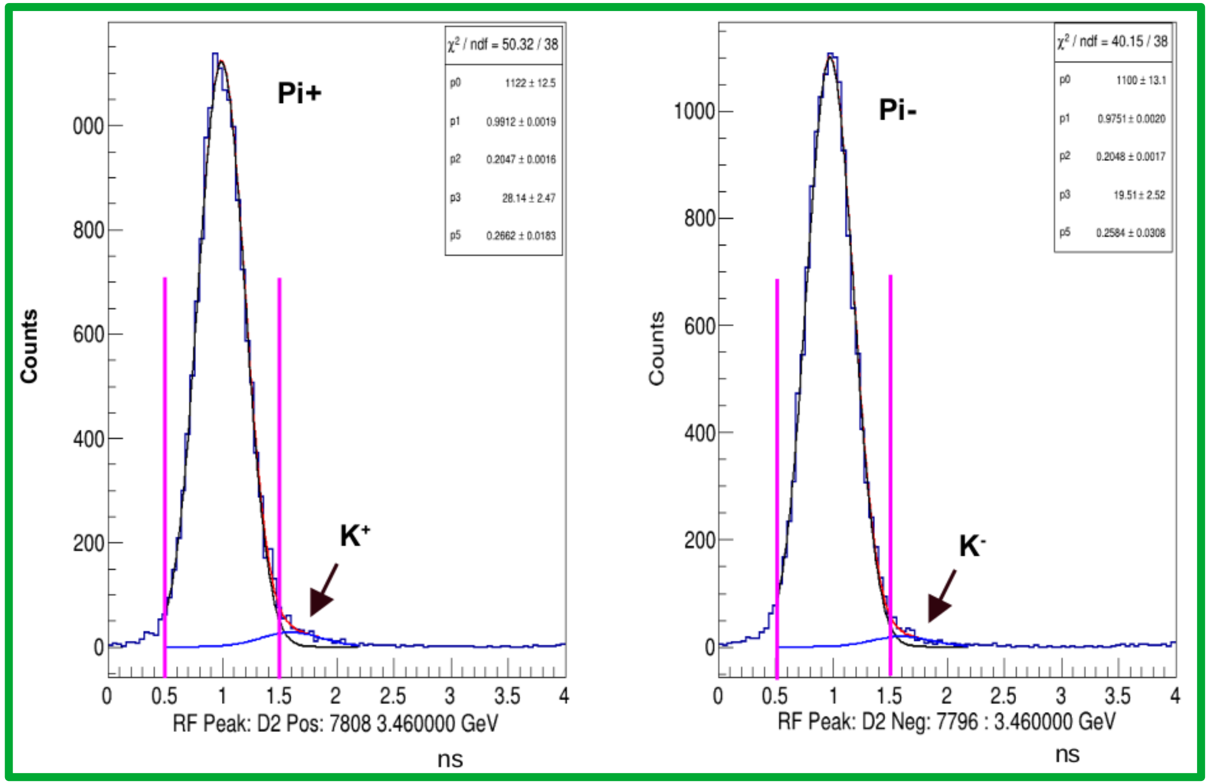




RF Time distribution for positive (left) and negative (right) charged hadrons with acceptance and other PID cuts but not the Aerogel and Heavy Gas Cherenkovs.

RF Time as a PID: Pion-Kaon-Proton separation: contd.





After applying additional Aerogel Cherenkov detector (left pannel) and Aerogel plus HGCER (right pannels). For pions with central momentum above 2.9 GeV/c, HGCER detector can be used whereas Aerogel can be used for momenta upto 5 GeV/c.

RF time information can be used to select the events of interest at any hadron momentum.

Simulation Package (SIMC)

- Simulates exclusive and semi-inclusive reactions involving protons, pions, kaons, ρ^0 mesons, the delta resonance, and other hadrons in the final state
- Includes validated models of the Hall C magnetic spectrometers and detectors along with trajectory reconstruction to the target vertex.
- The spectrometers are modeled by a set of magnetic optics transport matrices that project the charged particles passing through the spectrometer to all its major apertures and to its magnetic focal plane.
- Simulates radiative effects, coulomb corrections, multiple scattering, ionization energy loss, and particle decay.

SIDIS: $H(e,e^{'}\pi^{\pm})X$, $D(e,e^{'}\pi^{\pm})X$

$e + p \text{ (or } n) \rightarrow e^{'} + \pi^{+} + X$

$e + p \text{ (or } n) \rightarrow e^{'} + \pi^{-} + X$

Backgrounds from Exclusive Pion Production:

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

$e + n \rightarrow e^{'} + \pi^{-} + n$

Backgrounds from Diffractive Rho production:

$e + p \rightarrow e^{'} + \rho^{0} + p$

$e + n \rightarrow e^{'} + \rho^{0} + n$

$\rho^{0} \rightarrow \pi^{+}\pi^{-}$

Backgrounds from Delta Pion Production:

$e + N \rightarrow e^{'} + \Delta$

The Δ particles could be $\Delta^{++}, \Delta^{+}, \Delta^{0}$ or Δ^{-}

$\Delta^{++} \rightarrow \pi^{+} + p$

$\Delta^{+} \rightarrow \pi^{+} + n$

$\Delta^{0} \rightarrow \pi^{-} + p$

$\Delta^{-} \rightarrow \pi^{-} + n$