Probing Charge Symmetry Violation (CSV) in Quark Distributions Using Semi-Inclusive Deep Inelastic Scattering (SIDIS)

Hem Bhatt

Hall C Collaboration Meeting
Jan 28-29, 2021

MISSISSIPPI STATE UNIVERSITY™

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Introduction

Charge Symmetry (CS) in Partons:

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

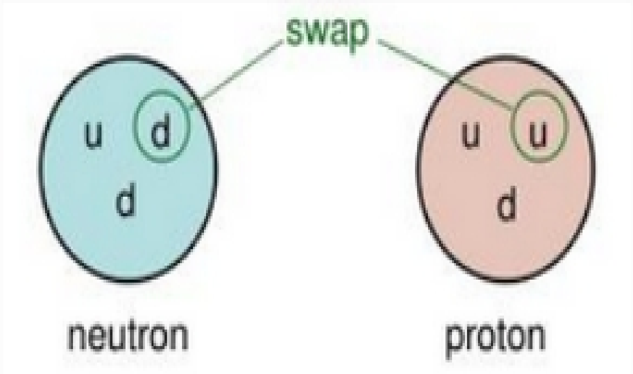
$$d^p(x,Q^2) = u^n(x,Q^2)$$

CS In Nuclei:

nn = pp = np (identical interactions)

Mp ≈ Mn (1%)

After electromagnetic corrections, charge symmetry is expected to be valid to within 1%.



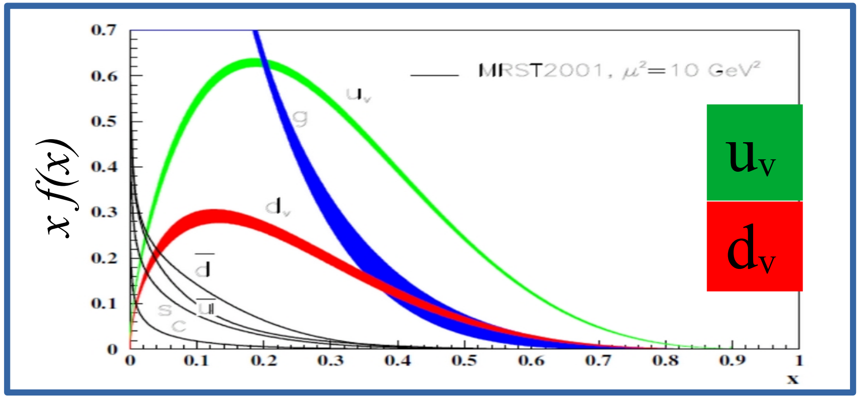
Charge Symmetry Violation (CSV):

(1) $\delta m = m_d - m_u$
(2) Electromagnetic interaction between the quarks

Of these two causes, the significant contribution to CSV is due the mass difference between the quarks.

For partonic systems, CSV = δm/ <M> where, <M> = average expectation value of strong Hamiltonian, with a value roughly 0.5-1.0 GeV => CSV effect of about 1%.

PDFs extracted from fits and Phenomenological Limits on CSV



PDFs extracted from fits to DIS data

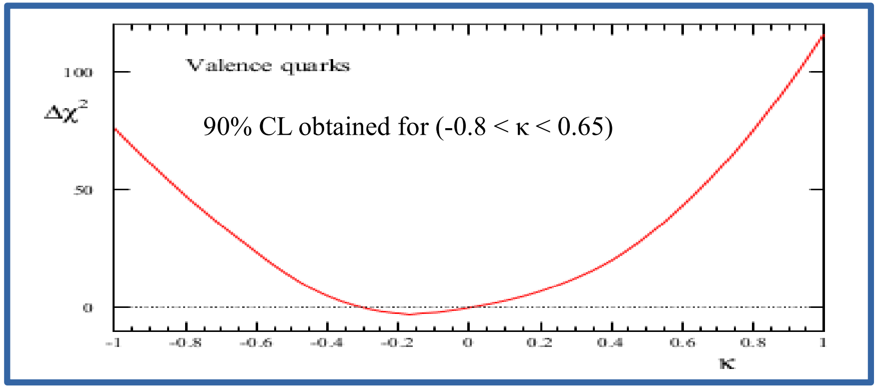
A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne,**(MRST)** Eur. Phys. J. C28 (2003) 455.

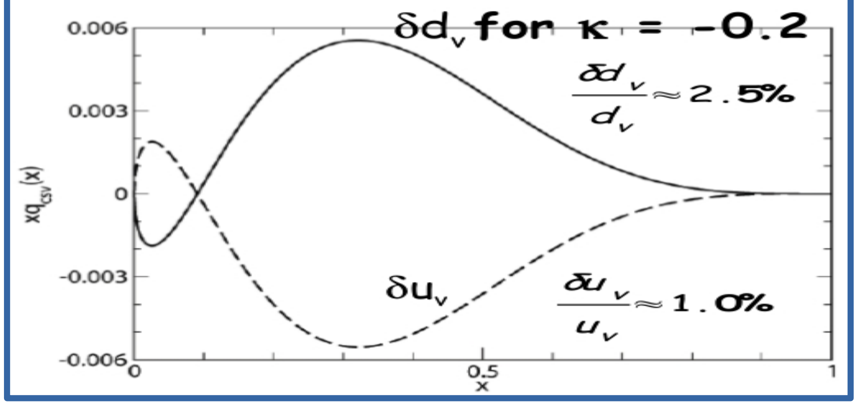
$u^p(x,Q^2) = d^n(x,Q^2)$
$d^p(x,Q^2) = u^n(x,Q^2)$
=> Charge Symmetry

$\delta u_v(x) = u^p(x) - d^n(x)$
$\delta d_v(x) = d^p(x) - u^n(x)$ and
$C(x) = \delta d_v - \delta u_v$ (CSV)

$$\delta u_v = -\delta d_v = \kappa(1-x)^4\, x^{-0.5}\,(x - 0.0909) = \kappa f(x)$$

$\delta d_v(x)$ and $\delta u_v(x)$ distributions for the best fit including CSV

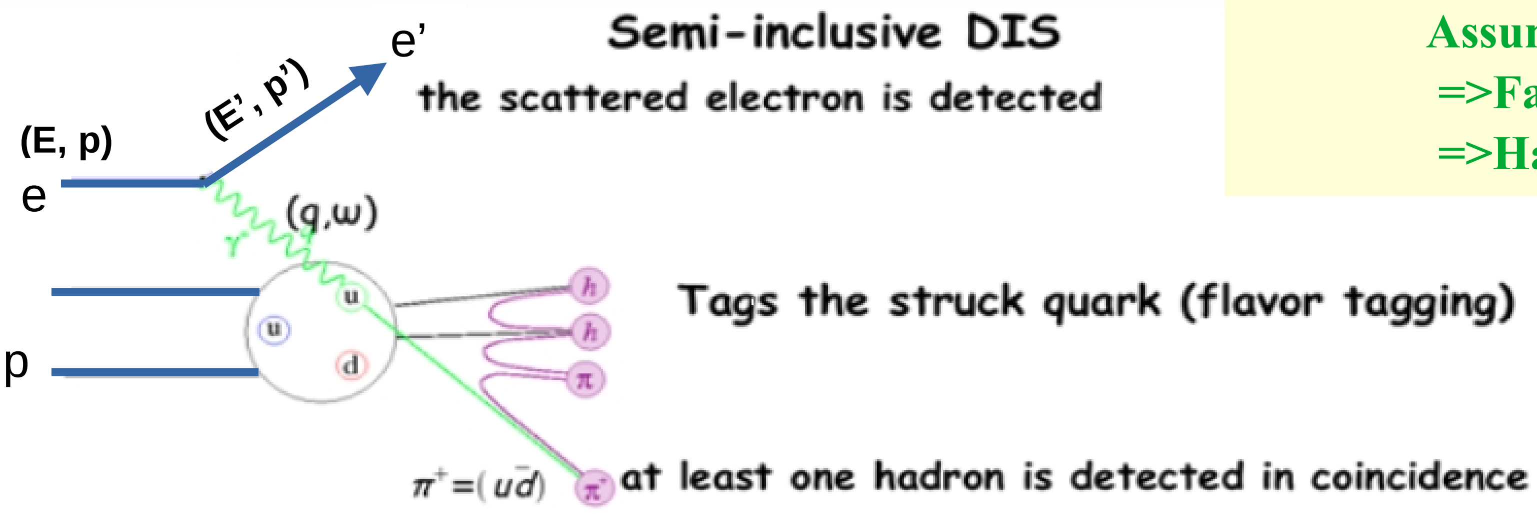




The best fit is obtained for $\kappa = -0.2$ (Eur. Phys. J.35(2004)325)

However, considering the uncertainty in the existing PDF data, at the 2- sigma level, allows upto 9% of CSV.

Semi-Inclusive Deep Inelastic Scattering (SIDIS)



Assumptions:
=>Factorization
=>Hadronization

u => π^+
d => π^-

We use SIDIS and the formalism of Londergan et. al. to extract the CSV in valence quark distributions
Londergan, Pang and Thomas PRD54, 3154 (1996)

Few kinematic quantities :

x = $Q^2 / 2M_p\nu$: Fraction of proton's momentum carried by the quark (Bjorken x)

M_p = mass of proton

ν = energy Transfer in lab frame (E - E')

Q^2 = 4 momentum transfer squared = $4EE'\sin^2(\theta/2)$

z = fraction of energy transfer carried by outgoing hadron (pion) = E_h / ν $= \sqrt{(m^2_\pi + p^2_\pi)} / \nu$

Motivations for Direct Measurement of CSV

- Charge symmetry has been universally assumed in extracting PDFs but never been tested experimentally.
- CSV measurements are important on their own as a further step in studying the inner structure of the nucleon.
- CSV could be an explanation for the anomalous value of the Weinberg angle extracted by NuTeV experiment.
- CSV measurements are important for a complete understanding of the strong force.

Jefferson Lab Hall C Experiment : E12-09-002 : 10.6 GeV Electron Beam : Precise Measurement of pi+ / pi- Ratios in Semi-Inclusive Deep Inelastic Scattering

Q^2	x	z
3.9 – 4.0	0.35 – 0.5	0.4 – 0.7
4.75 – 5.0	0.45 – 0.6	0.4 – 0.7
5.50	0.5 – 0.65	0.4 – 0.7

Target : LH2, LD2 and Al Dummy

- HMS Angle = 13 - 21 Degrees
- SHMS Angle = 11 - 21 Degrees
- HMS P = 4.4 - 6.4 GeV/c (electrons)
- SHMS P = 1.7 - 4.5 GeV/c (pi + and pi -)

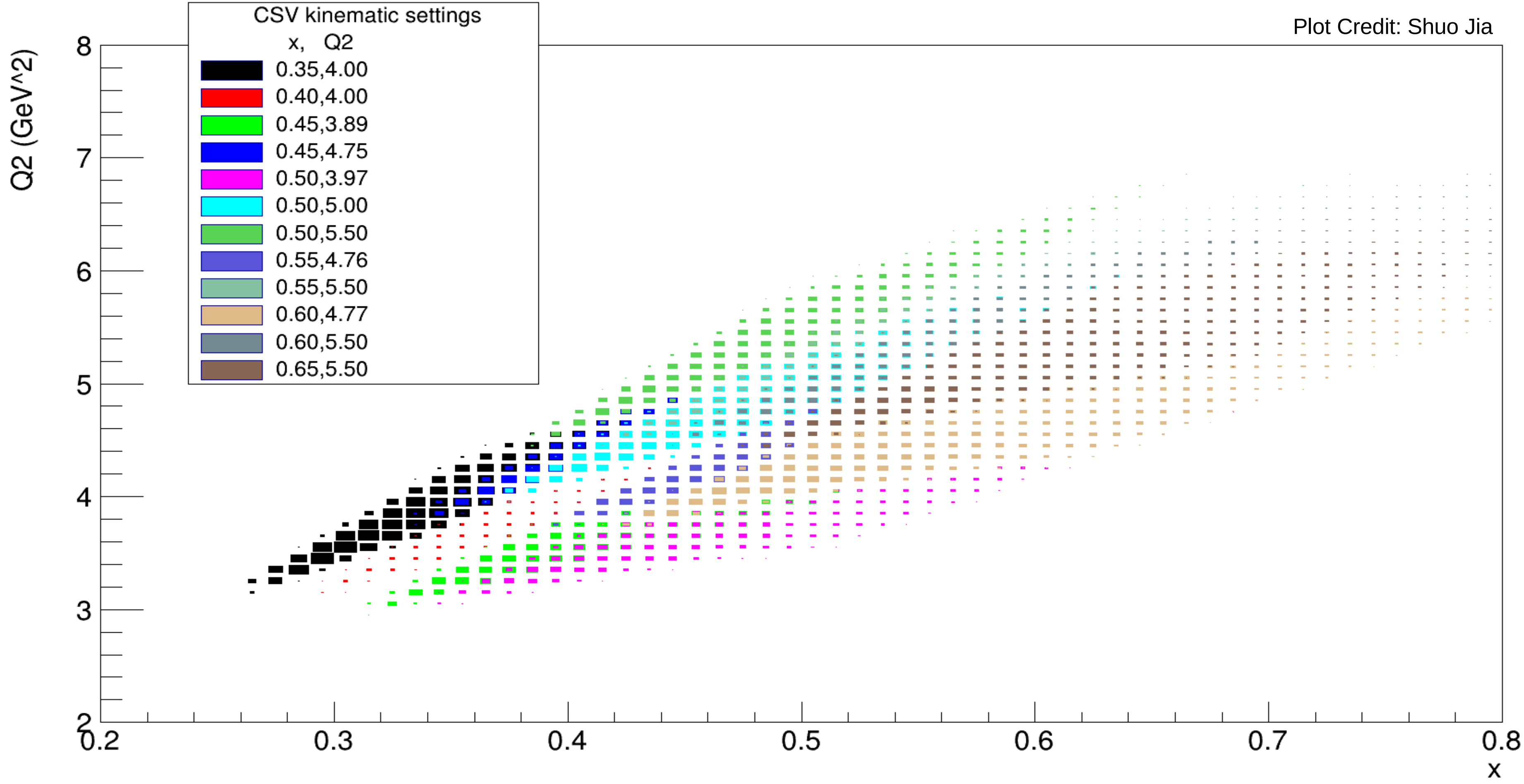
Data Taking completed: March 2019.

LD2: Production

LH2: Factorization Test, Cross-section Measurement

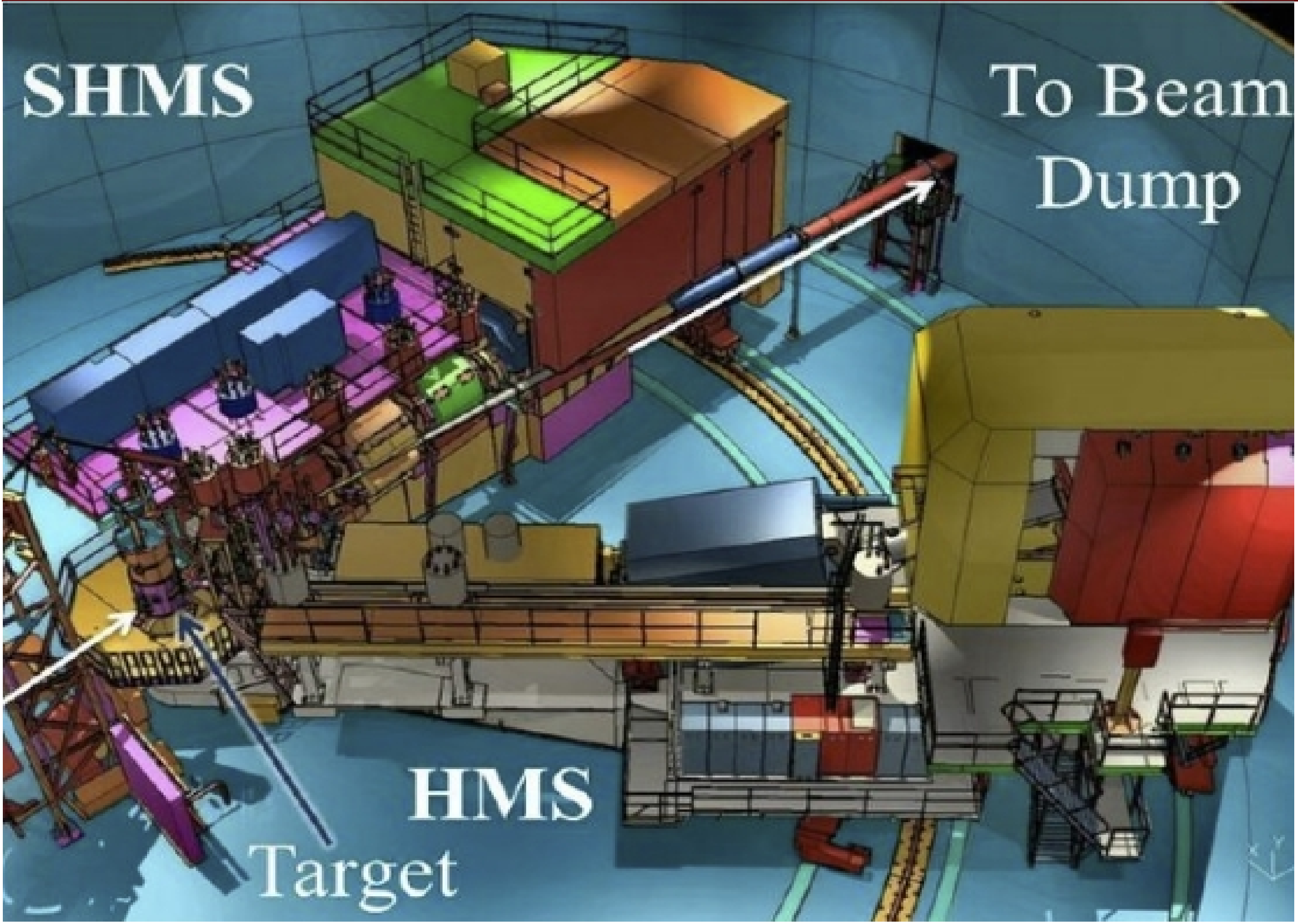
Al dummy: Background subtraction

CSV Kinematics



Plot Credit: Shuo Jia

Jefferson Lab HallC



Super High Momentum Spectrometer(SHMS):

Magnets: HB, Q1, Q2, Q3, Dipole

Characteristics:

Momentum Range: 2-11 GeV/c
Momentum Acceptance: -10% to +22 %
Momentum resolution: dP/P < 0.2
Scattering angle: 5.5 to 40 degrees
Solid Angle Acceptance: > 4 mSr
Beam Capacity: upto 90 μA

High Momentum Spectrometer (HMS):

Magnets: Q1, Q2, Q3, Dipole

Characteristics:
Momentum Range 0.5-7.5 GeV/c
Momentum Acceptance -10% to +10 %
Momentum Resolution: dP/P < 0.1 %
Scattering angle = 12.5 to 90 degrees
Solid Angle Acceptance > 6 mSr
Beam Capacity upto 90 μA

Detector Hut: HMS and SHMS:
Drift Chambers
Hodoscopes
Cerenkovs
Calorimeter

Analysis Workflow

Reference time and timing window
Detector Calibration

- Calorimeter
- Drift Chamber
- Cherenkov
- Hodoscope
- BCM

Efficiency Studies

- Tracking Efficiency
- Computer Dead Time
- Luminosity Scan
- Calorimeter and Aerogel Efficiency
- RF Time
- Heavy Gas Cherenkov Efficiency
- Trigger Efficiency

Comparison of extracted Yield with simulation

Correction/Uncertainty from Diffractive ρ^0 production

Uncertainty from radiative correction

Yield Ratio of Pi+/Pi-

Acceptance Correction

Optics Study

Precise Cross-Section Ratio of Pi+/Pi-

Extraction of C(x) and D(z) using the yield ratio from the full grid of x, z for various Q^2 (x,z).

Factorization Test [H2 data]
Cross-section extraction

We detect charged pions in SHMS in coincidence with electrons in HMS

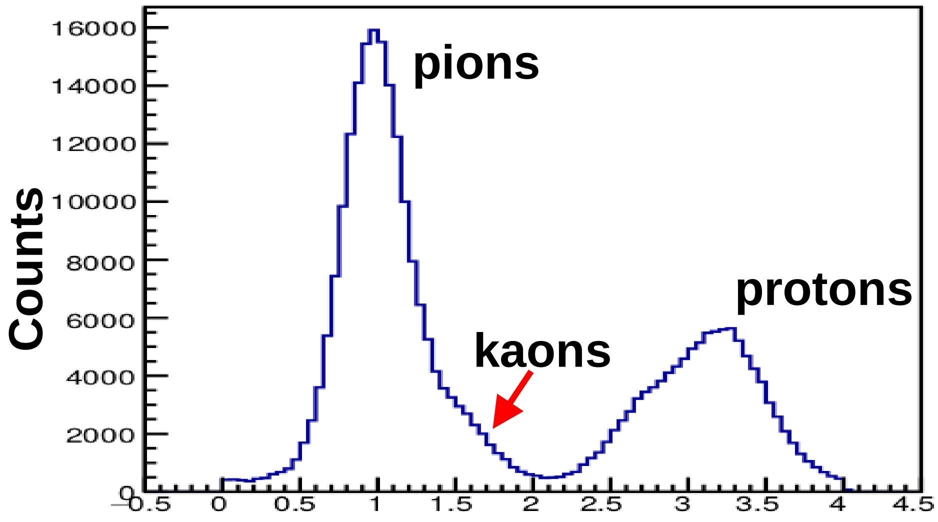
RF Time = time of flight between the target and hodoscope (~ 20 m apart) for beam buckets arriving at the target every 4.008 ns. An offset is added to align the pions at 1.0

RF Timing Signal: To separate pions from kaons or protons

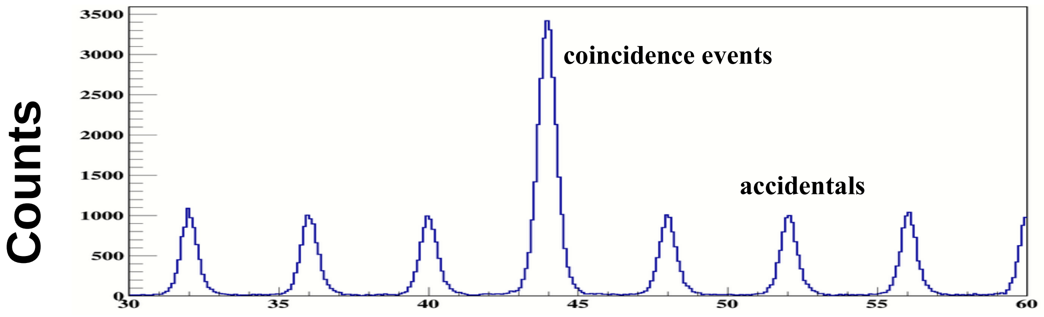
Calorimeter : To separate pions from electrons or positrons

Aerogel Cherenkov : To separate pions from kaons and protons

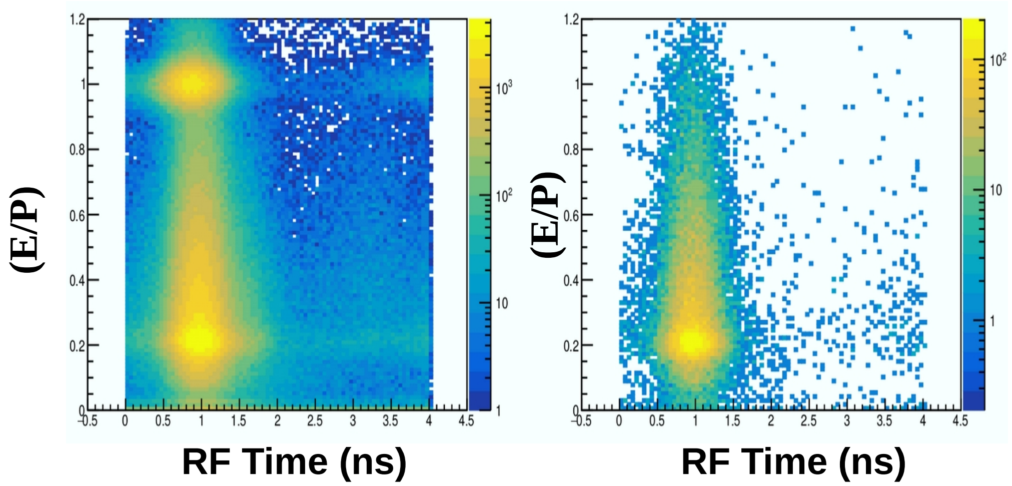
Heavy Gas Cherenkov : To separate pions from kaons



RF Time (ns)

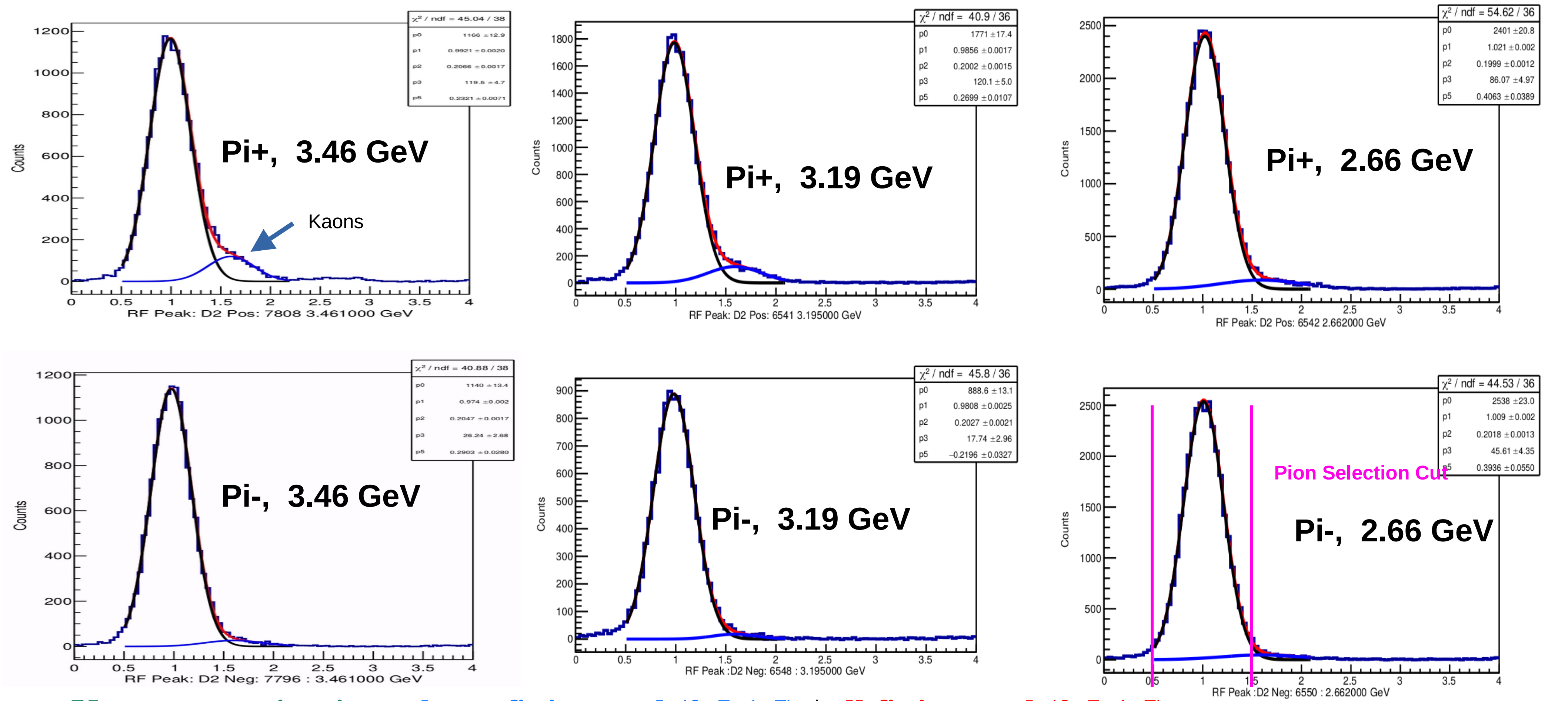


Coincidence Time (ns)



SHMS Calorimeter E/P vs RF Time (ns)

We use RF Timing Peak to separate Kaons from Pions : Cut Used: 0.5 to 1.5. (AeroNpeSum > 4)

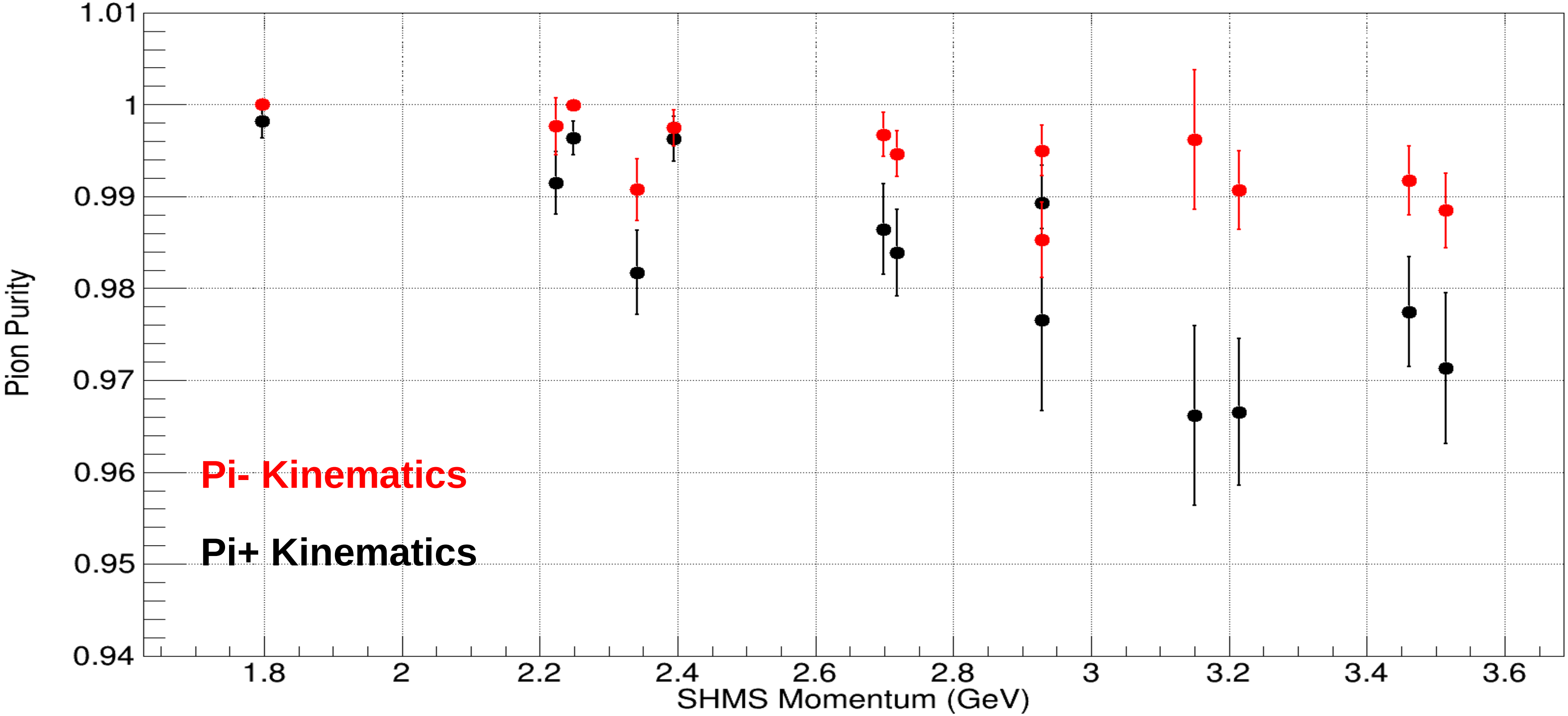


Kaon contamination = kaon fit integral (0.5-1.5) / all fit integral (0.5-1.5)

Pion Purity = 1 – kaon contamination

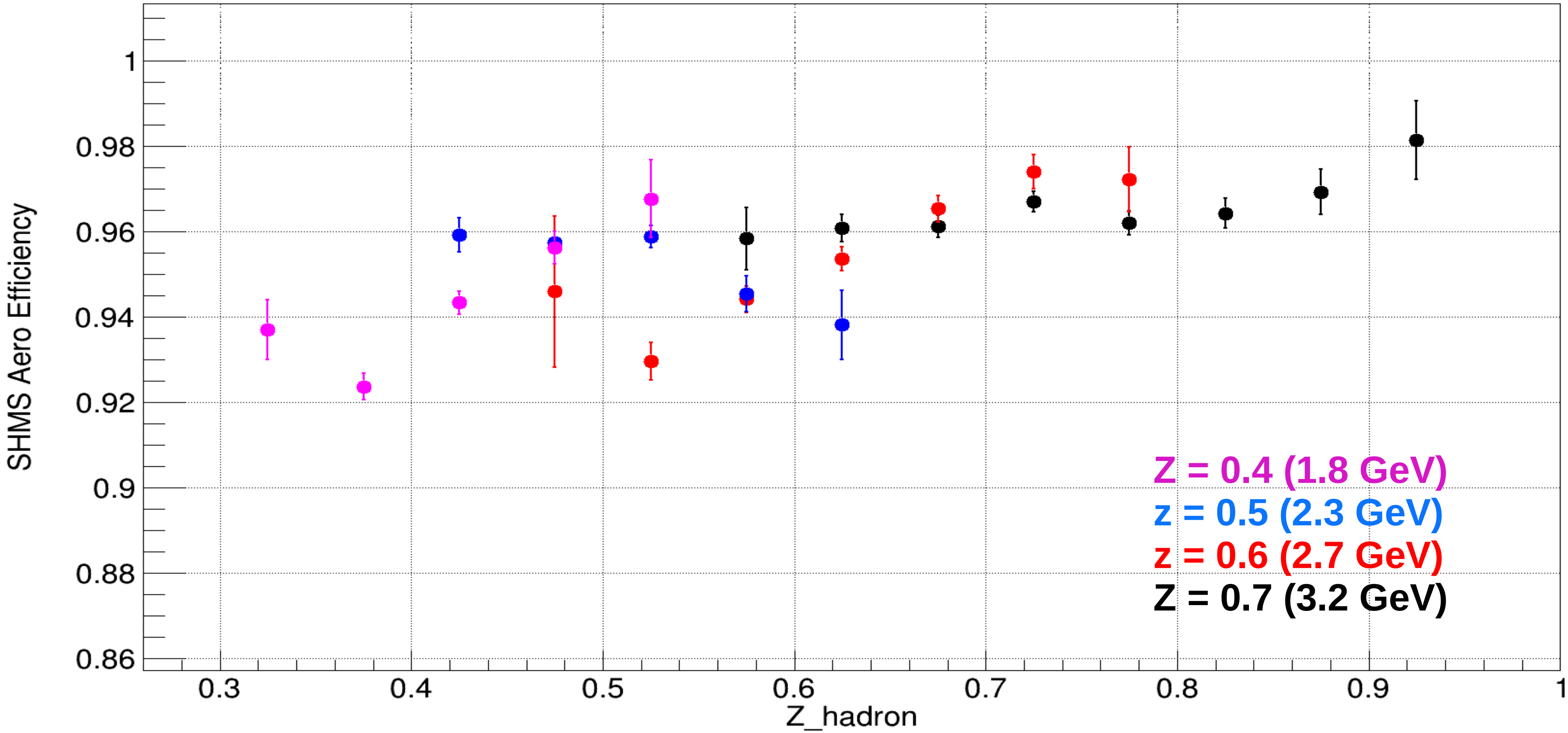
Higher the particle momentum, more will be kaon contamination. Also, more kaons are at positive Polarity (Production of K+ > K-)

Pion Purity vs SHMS Momentum (AeroNpeSum > 4)

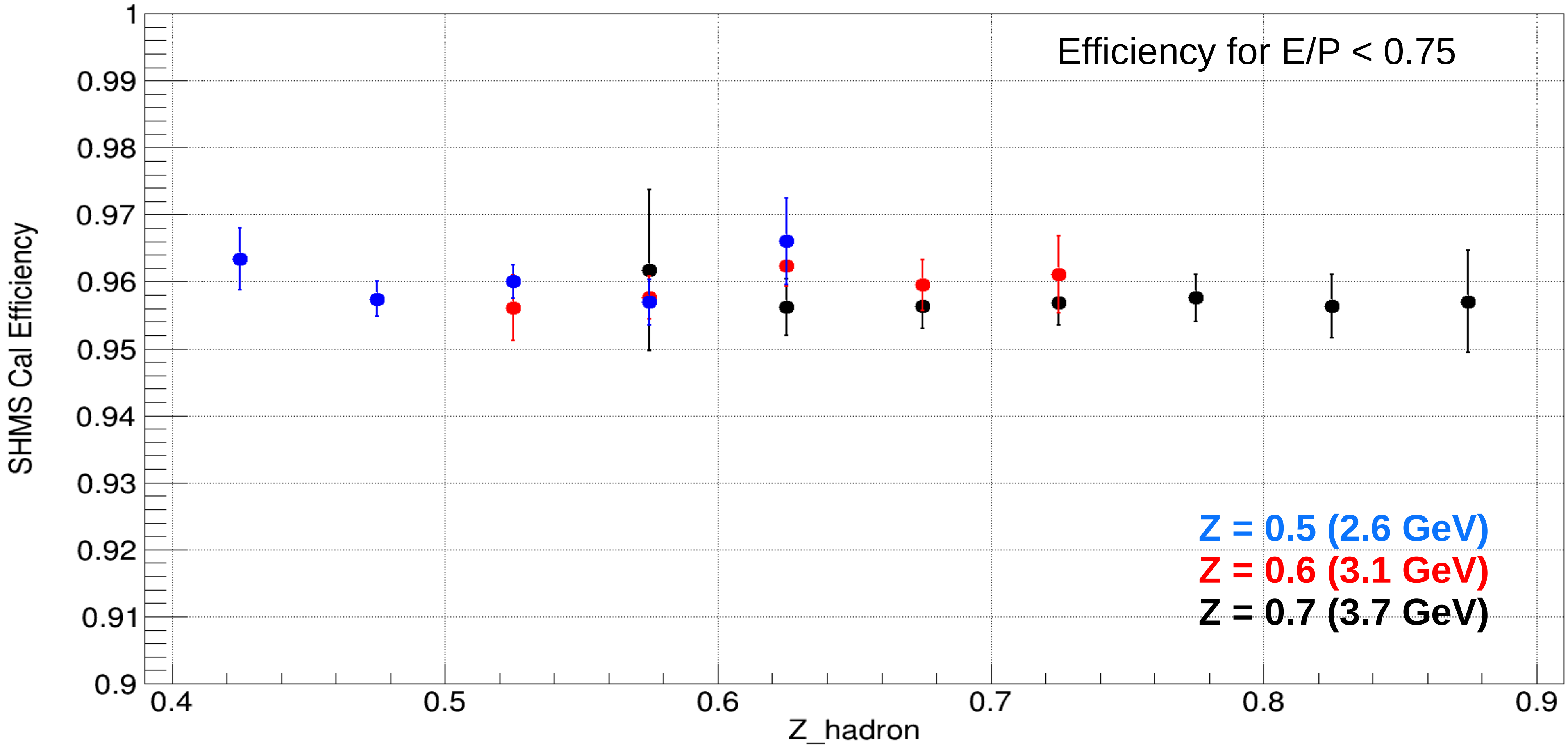


Kaon contamination = kaon fit integral (0.5-1.5) / all fit integral (0.5-1.5)
Pion Purity = 1 – kaon contamination

Aerogel Efficiency (overlap between 4-z settings) (AeroNpeSum > 4)



SHMS Calorimeter Efficiency vs z (showing the kinematic overlap between 3-z regions)



The Standard Hall C Monte Carlo (SIMC)

Features:

=> Optics (COSY), spectrometer apertures and all material

=> Radiative Corrections, multiple scattering, ionization energy loss, particle decay

=> Coulomb corrections, off-shell corrections

=> Parameterization of SIDIS cross-sections from HERMES experiment and Preliminary Jlab Hall C measurements at 12 GeV.

Reactions:

=> $H(e,e'\pi^{+})n$, $A(e,e'\pi^{+/-})$ (exclusive: quasifree or coherent)

=> $H(e,e'\pi^{+/-})X$, $D(e,e'\pi^{+/-})X$ (semi-inclusive)

=> $H(e,e'\Delta)$, $D(e,e'\Delta)$ (Delta production)

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

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

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

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

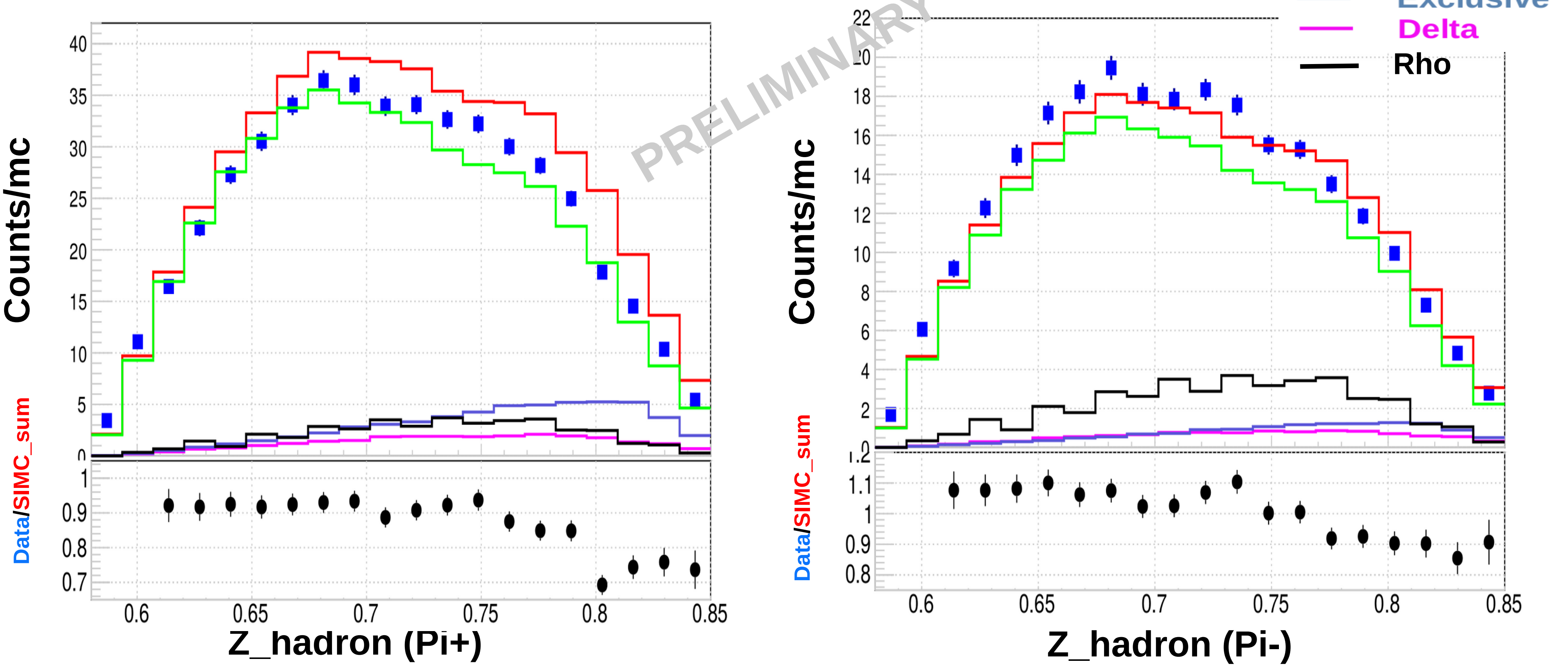
=> $H(e,e'\rho)$, $D(e,e'\rho)$ (Rho production)

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

Peter Bosted and Dave Gaskell are working on improving SIDIS model, Delta Production, and Exclusive model.

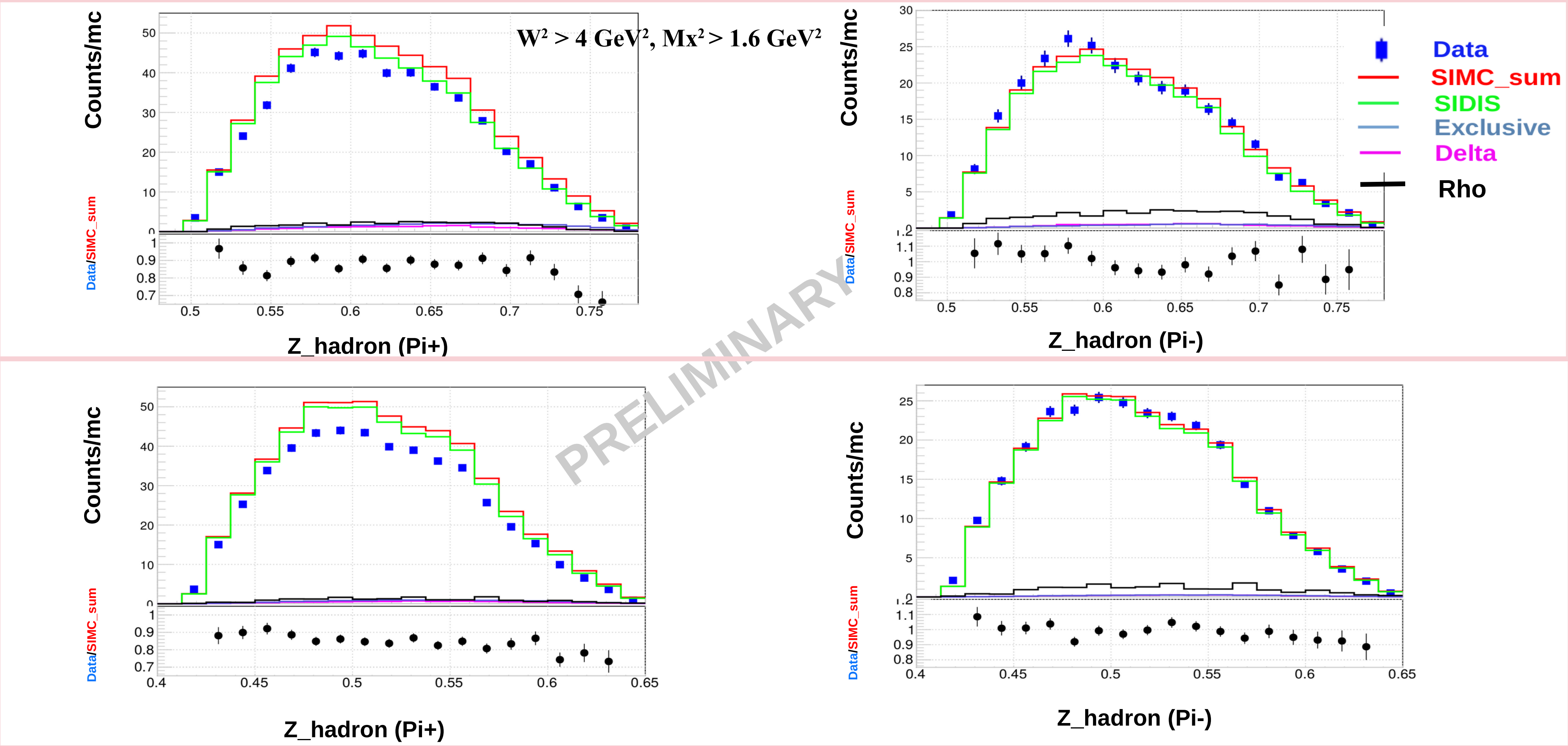
Data and Simulation (SIMC) Yields (x = 0.4 , z = 0.7, Q^2 = 4.0 GeV^2)

$W^2 > 4\ GeV^2$, $Mx^2 > 1.6\ GeV^2$



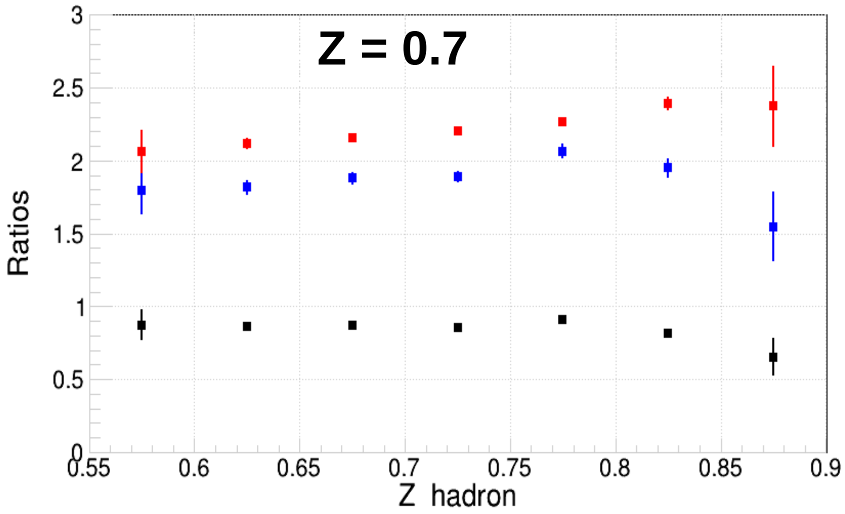
SIMC_sum = (Inclusive + Exclusive + Delta) Pion-Production using SIMC

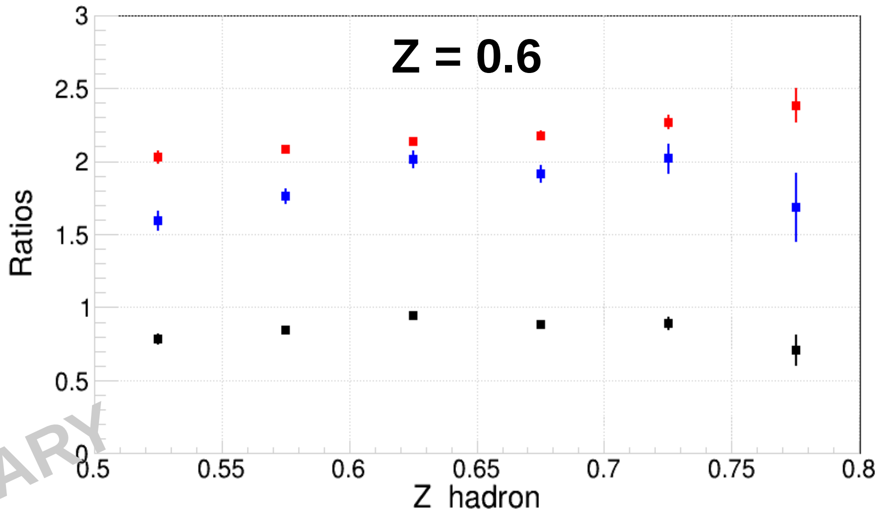
Data and Simulation (SIMC) Yields: $x = 0.4$, $z = 0.6$ (top), and $z = 0.5$(bottom), $Q^2 = 4.0$ GeV^2



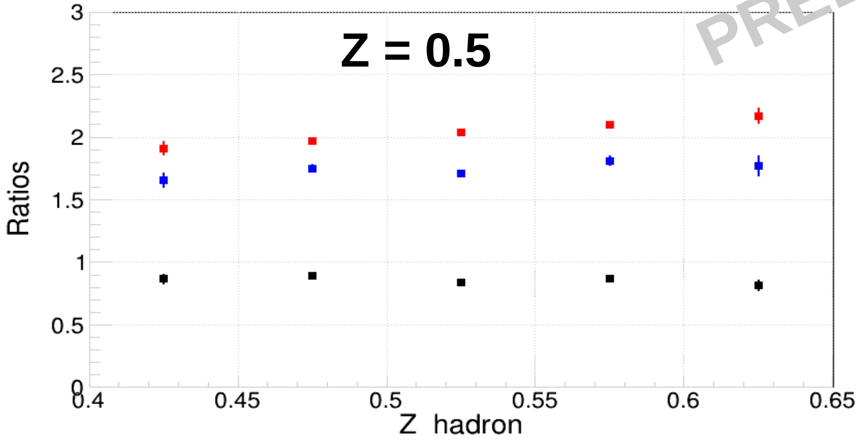
SIMC_sum = (Inclusive + Exclusive + Delta) Pion-Production using SIMC

Data and SIMC Yield Ratios: x = 0.4, Q^2 = 4.0 GeV^2 , z = 0.7, 0.6, and 0.5





PRELIMINARY

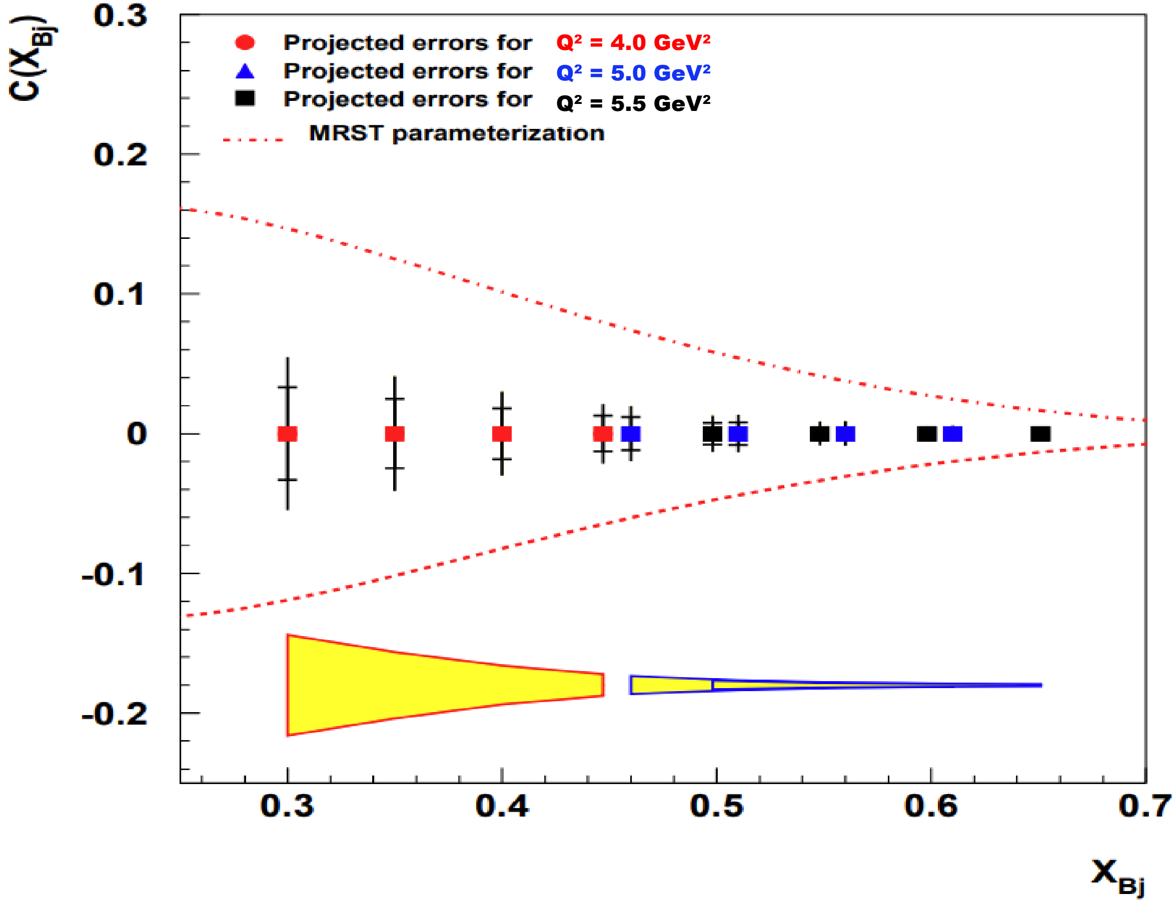


Red Points are Pi+/Pi- Yield Ratio From SIMC

Blue Points are Pi+/Pi- Yield Ratio From Data

Black Points are Pi+/Pi- SuperYield Ratio
i.e Data Yield Ratio/ SIMC Yield Ratio

Projected Uncertainties from the Proposal



Predicted uncertainties for the charge symmetry violating quark distributions

Summary

This Experiment will:

→ Extract the precise ratio of charged pion electro production using semi-Inclusive deep inelastic scattering from deuterium.

→ Constrain the strength of charge symmetry violation in valence PDFs for the first time.

→ Constrain the x-dependence of charge symmetry violating valence PDF

Completed: Detector calibrations, live time study, tracking efficiency, target boiling study.

In Progress: PID study, Detector efficiency study, optics study, comparison of extracted yield with simulation, radiative correction, uncertainty from diffractive ρ^0 production.

Plan : Obtain the precise cross-section ratio : π^+/π^- and extraction of CSV.

Acknowledgments

I would like to acknowledge to my advisors Dr. James Dunne, Dr. Dipangkar Dutta and Dr. Dave Gaskell for their continuous support. Many thanks to Dr. Peter Bosted, Dr. Whitney Armstrong, Dr. Arun Tadapalli, Shuo Jia and the Hall C Collaboration.

This work is supported by U.S. DOE Grant Number: DE-FG02-07ER41528

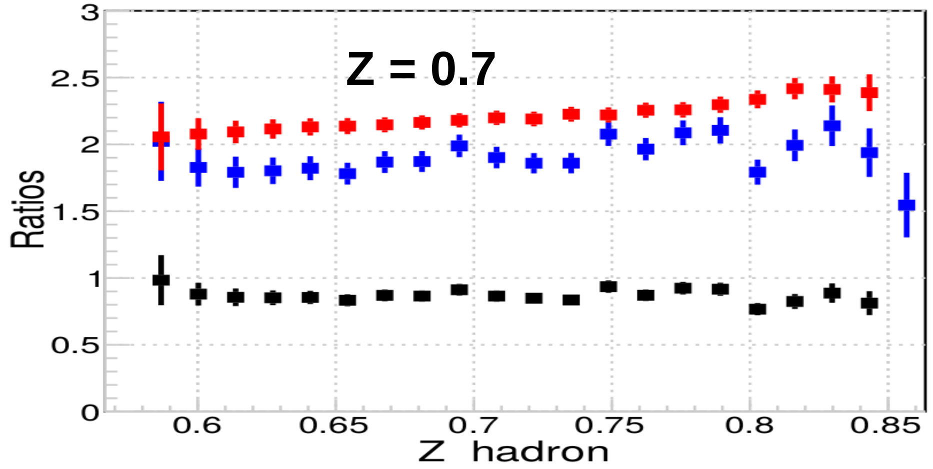
Thank You

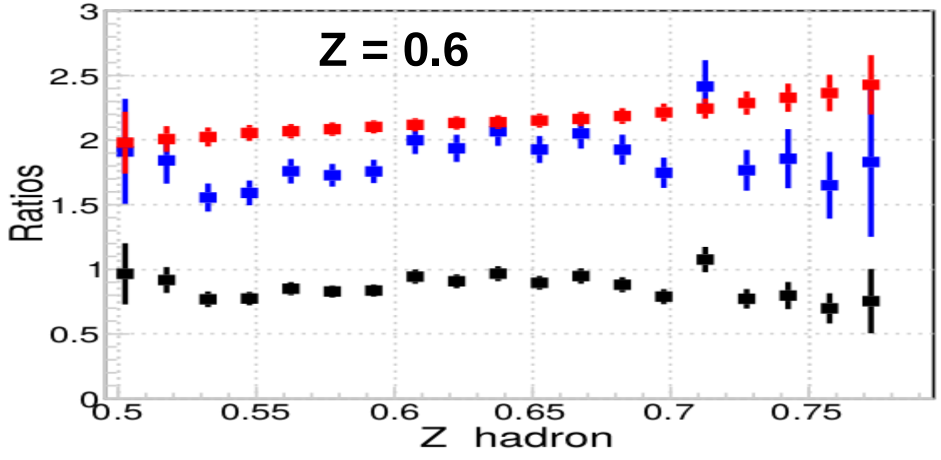
Back Up Slides

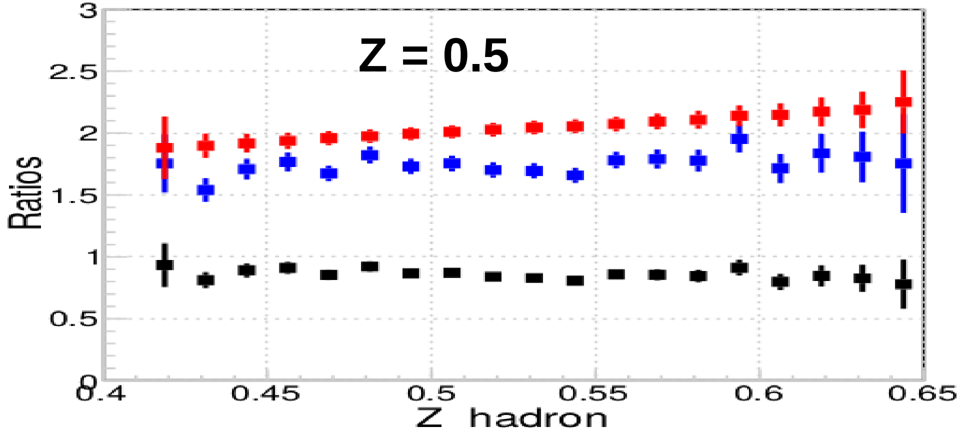
CUTS

Pdelta = (-10 to 20)
Hdelta = (-8 to 8)
Hcal E/P > 0.75
Event type > 3 (all coincidence events)
Dipole Exit ==1 (Inside of the diplole)
GoodHosdostart =1
RF time = peak +/- 0.5 (total 1 ns width)
Coin Time = +/- 2 ns (for fall or even +/- 2.2 ns, depends) and +/- 1.5 ns (Spring)
Aero > 4
HGCER not used so far.
Pcal E/P < 0.75
HCER not used so far.
HMS Xptar (H.gtr.th) = (-0.060 to + 0.060)
HMS Yptar (H.gtr.ph) = (-0.025 to + 0.025)
SHMS Xptar (P.gtr.th) = (-0.045 to + 0.045)
SHMS Yptar (P.gtr.th) = (- 0.028 to + 0.028)
W2 > 4 GeV2, Mx2 > 1.6 GeV2 (for data, simc Yield)
Current cut > 3 (or 5) uA

Data and SIMC Yield Ratios: x = 0.4, $Q^2 = 4.0\ GeV^2$, z = 0.7, 0.6, and 0.5







Red Points are Pi+/Pi- Yield Ratio From SIMC

Blue Points are Pi+/Pi- Yield Ratio From Data

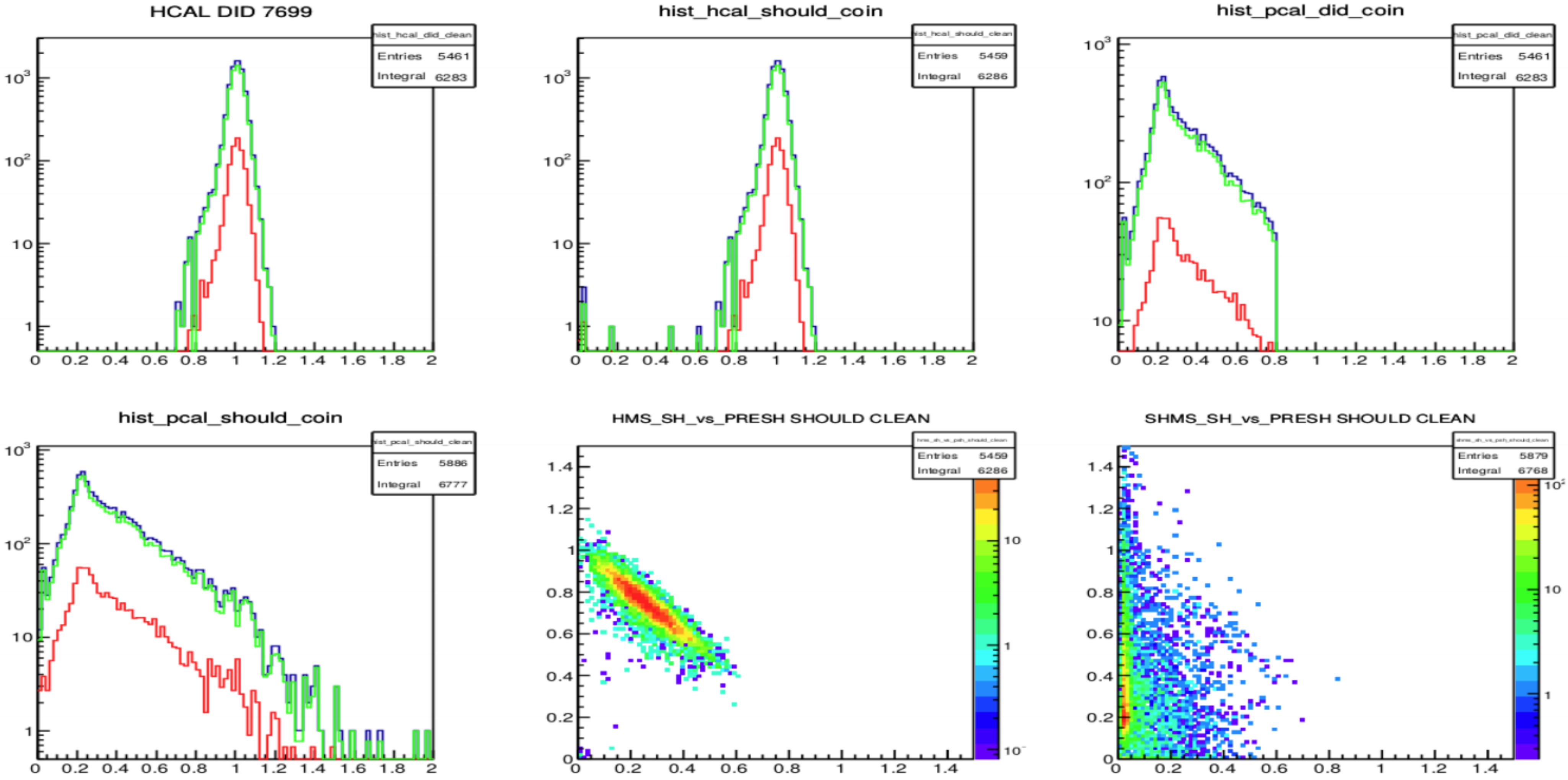
Black Points are Pi+/Pi- SuperYield Ratio
i.e Data Yield Ratio/ SIMC Yield Ratio

Ratio Plots from Page 14-15, with same number of bins as in the z distribution

HMS CAL Plots: hcer > 10, Aero > 8, xptar, yptar Cuts

Blue: All, Red = Acc. , Green = Acc Subtracted

Hcal Eff = 0.999
Pcal Eff = 0.927



Formalism by Londergan, Pang and Thomas PRD54, 3154 (1996)

Get this ratio : $R_Y(x,z)$ = Yield ratio = $Y_{\pi+}(x,z) / Y_{\pi-}(x,z)$: from the data

$$R^D_{Meas}(x,z) = (4 - R_Y(x,z)) / (R_Y(x,z)-1)$$

$$R(x,z) = (5/2) + R^D_{Meas}(x, z)$$

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

Goal: By using the measured yield ratio of Pi+ over Pi- for different Q^2 at various x and z, we will extract **C(x)** and **D(z)**

D(z) = Function of ratio of fragmentation function

$R(x,z) = (5/2) + R^D_{Meas}(x, z)$: from Experiment

A(x) = Function of Valence quark PDFs (known)

C(x) = CSV parameter = $\delta d_v - \delta u_v$

B(x,z) = Function of sea quark PDFs (known from the Global Fit)

Formalism by Londergan, Pang and Thomas PRD54, 3154 (1996)

$$\Delta(z) = D_u^{\pi^-} / D_u^{\pi^+}$$

where Δ(z) is the ratio of the unfavored to the favored quark fragmentation functions;

$$D(z) = \frac{1-\Delta(z)}{1+\Delta(z)}$$

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

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

$$R(x,z) = (5/2) + R^D_{Meas}(x, z)$$

$$C(x) = \text{CSV parameter} = \delta d_v - \delta u_v$$

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

NuTeV anomaly and CSV

In 2001 NuTeV collaboration, using ν DIS, measured:

$\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$

G. P. Zeller et al. Phys. Rev. Lett. 88, 091802 (2002)

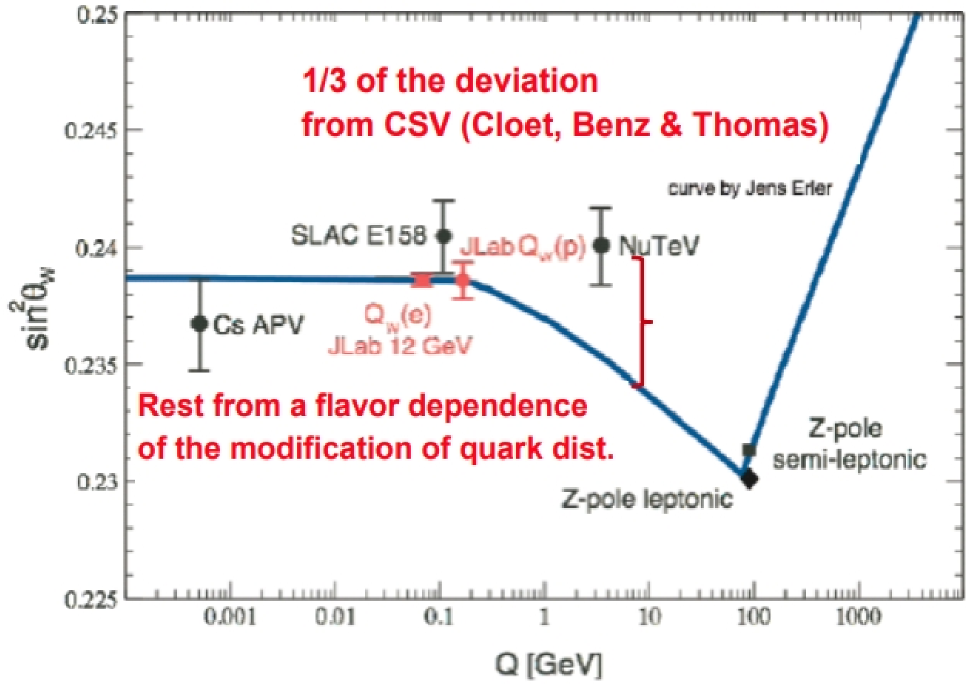
Θ_W = weak mixing angle

World average (not including NuTeV):

$\sin^2\theta_W = 0.2227 \pm 0.0037$

D. Abbaneo et al., , CERN Report CERN-EP/2001-098, arXiv:hep-ex/0112021.

3 σ discrepancy!!! ⇒ "NuTeV anomaly"



CSV corrections reduces the anomaly by about ∼30% (1σ)

Fig: $\sin^2\theta_W$ vs Q

J.T.Londergan, Possible Explanations for The NuTeV Weinberg Angle Measurement

https://arxiv.org/pdf/hep-ph/0408243.pdf

Huge amount of theoretical and experimental interests:
One of the Highly Cited Topic

Talk: Ian C. : INT Program: Low Energy Precision Electroweak Physics in the LHC Era, 4th Nov, 2008