Measuring Charge Symmetry Violation in the Nucleon

Precise Measurement of $\frac{pi^+}{pi^-}$ Cross Section Ratio in SIDIS

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On behalf of Shuo Jia

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Introduction

What is Charge symmetry?

Charge symmetry (CS) is a specific rotation in isospin space. It is the invariance with respect to rotation of π about the T2 axis.

$$[H, P_{CS}] = 0 \qquad P_{CS} = \exp(i\pi T2)$$

$$P_{CS}\,|d\rangle = |u\rangle \qquad P_{CS}\,|u\rangle = -\,|d\rangle$$

Low Energy: CS in nuclei

CS operator interchanges neutrons and protons

- pp and nn scattering lengths are nearly the same
- $M_n \simeq M_p$
- $B(n, {}^3He) \simeq B(p, {}^3H)$ and energy levels in other mirror nuclei are equal (to 1%)
- $m({}^3He) \simeq m({}^3H)$

After electromagnetic corrections CS respected down to $\sim$ 1%

QCD: Quark level

- $u^p(x, Q^2) = d^n(x, Q^2)$
  $d^p(x, Q^2) = u^n(x, Q^2)$
- Origin of CS violations:
  $\rightarrow$ Electromagnetic interaction
  $\rightarrow$ $\delta m = m_d - m_u$

Naively, one would expect CSV would be on the order of $(m_d - m_u)/\langle M\rangle$, where $\langle M\rangle$ is roughly $0.5 - 1.0$ GeV
$\rightarrow$ CSV effect about 1%

Motivation

- **Charge symmetry violation** is an important ingredient for pushing the **precision frontier in the partonic structure of the nucleon**
- Charge symmetry is often assumed in extracting PDFs from data – where the data is limited in sensitivity to CS violation
- The validity of charge symmetry is a necessary condition for many relations between structure functions and sum rules
- Flavor symmetry violation extraction $\bar{u}(x) \neq \bar{d}(x)$ relies on the implicit assumption of charge symmetry (in the sea quarks)
- Charge symmetry violation viable part of explanation for the anomalous value of the Weinberg angle extracted by NuTeV experiment
- CSV is related to our understanding of the flavor dependence of the quark masses (one of the key unsolved problems in Physics –
  why is $m_d \sim m_u \neq m_s \neq m_c \neq m_b \neq m_t$)

Upper Limits on CSV

Theoretical Limits

$CSV(x) = \delta d - \delta u$, where

$$\delta d(x) = d^p(x) - u^n(x), \quad \delta u(x) = u^p(x) - d^n(x).$$

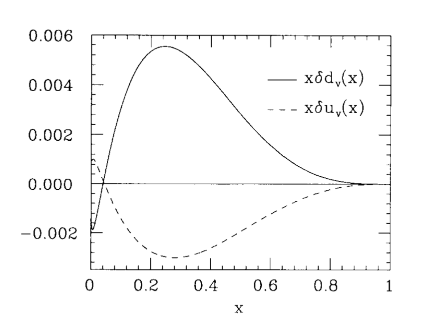
Model by Sather:

$$\delta d(x) \sim 2-3\%, \delta u(x) \sim 1\%$$

$$\delta d_v(x) = -\frac{\delta M}{M}\frac{d}{dx}[x d_v(x)] - \frac{\delta m}{M}\frac{d}{dx}d_v(x)$$

$$\delta u_v(x) = \frac{\delta M}{M}\left(-\frac{d}{dx}[x u_v(x)] + \frac{d}{dx}u_v(x)\right)$$

where M is the n-p mass difference, $\delta M = 1.3MeV$, and $\delta m = m_{dd} - m_{uu} \sim 4MeV$ is the down-up quark mass difference. E. Sather, Phys. Lett. B274, 433 (1992)

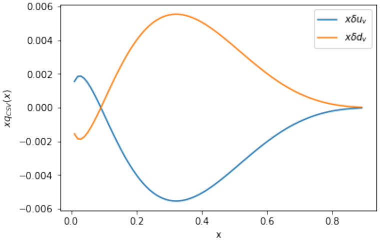


Model by Rodionov, Thomas and Londergan $\delta d(x)$ could reach up to 10% at high x

E. N. Rodionov, A. W. Thomas and J. T. Londergan, Mod. Phys. Lett. A 9, 1799 (1994)

Upper Limits on CSV

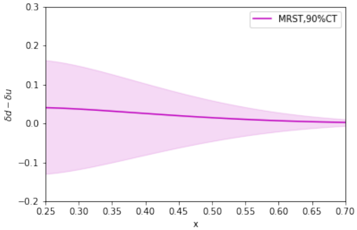
Phenomenological limits



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

Using the uncertainties in PDFs studied by MRST Group, CSV is constrained to less than 9%

The MRST group has included CSV in a phenomenological evaluation of PDFs. They used a wide range of high-energy data to get a global fit of PDFs
Eur. Phys. J.35(2004)325



Upper Limits on CSV

Lattice QCD

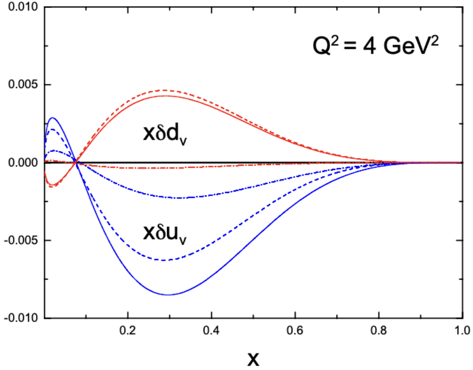
The charge symmetry violation via lattice simulation:

$$\delta U = \int_0^1 dx x \delta u(x) = 0.0023(7)$$

$$\delta D = \int_0^1 dx x \delta d(x) = 0.0017(4)$$

The dash-dotted, dashed and solid curves represent pure QED, pure QCD and the total contributions. The results is comparable to the MRST prediction.

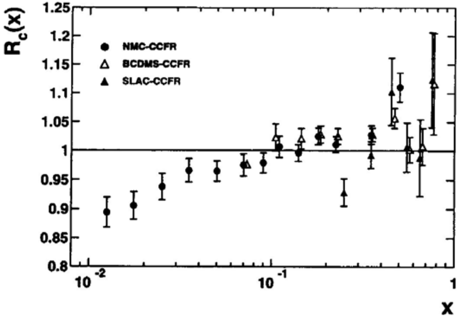
Physics Letters B, 753:595âĂŞ599



Upper Limits on CSV

Experimental Limits

- Upper limit obtained by combining neutral and charged current data on isoscaler targets
- $F_{2\nu}$ by CCFR collaboration at FNAL (Fe data)
- $F_{2\gamma}$ by NMC collaboration using muons (D target)
- $0.1 \leq x \leq 0.4 \rightarrow$ **9% upper limit for CSV effect!**



"Charge Ratio"

$$R_c(x) = \frac{F_2^{\gamma}(x) + x\left[s(x) + \bar{s}(x) - c(x) - \bar{c}(x)\right]/6}{5\bar{F}_2^{W(x)}/18}$$

$$\simeq 1 + \frac{3\left(\delta u(x) + \delta\bar{u}(x) - \delta d(x) - \delta\bar{d}(x)\right)}{10\bar{Q}(x)}$$

$$\bar{Q}(x) = \sum_{u,d,s}\left(q(x) + \bar{q}(x)\right)$$

Formalism

Charge symmetry Violation

$$\delta d(x) = d^p(x) - u^n(x), \delta u(x) = u^p(x) - d^n(x).$$
$$CSV(x) = \delta d - \delta u$$

Londergan, Pang and Thomas PRD54(1996)3154

$$R^D_{meas}(x,z) = \frac{4N^{D\pi^-}(x,z) - N^{D\pi^+}(x,z)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)} = \frac{4R_Y(x,z) - 1}{1 - R_Y(x,z)} \quad (1)$$

where $N^{D\pi^\pm}(x,z)$ is the **measured yield** of $\pi^\pm$ electroproduction on a deuterium target, R_Y is the $N^{D\pi^-}/N^{D\pi^+}$ yield ratio and We rely on

Factorization

$$N^{Nh} = \sum_i e_i^2 q_i^N(x) D_i^h(z)$$

Impulse Approximation

$$N^{D\pi^\pm}(x,z) = N^{p\pi^\pm}(x,z) + N^{n\pi^\pm}(x,z)$$

Formalism

Leading order experimental analysis $\rightarrow$ will need higher order global analysis

Londergan, Pang and Thomas PRD54(1996)3154

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

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

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

$$R(x,z) = \frac{5}{2} + R^D_{meas}$$

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

$$B(x,z) = \tfrac{5}{2} + R^D_{sea\_S}(x,z) + R^D_{sea\_NS}(x)$$

$$R^D_{sea_{NS}}(x) = \frac{5(\overline{u}^p(x) + \overline{d}^p(x)}{[u_v^p(x) + d_v^p(x)]}$$

$$R^D_{sea_S}(x,z) = \frac{\Delta_s(z)[s(x) + \overline{s}(x)]/(1+\Delta(z))}{[u_v^p(x) + d_v^p(x)]}$$

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

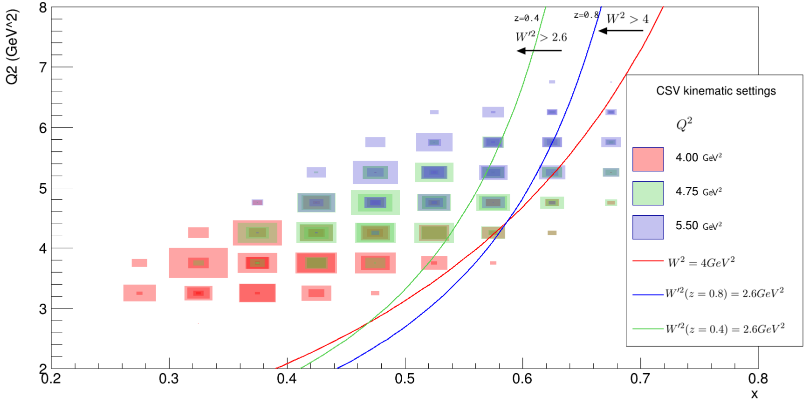
$A(x)$ and $B(x,z)$ are known

CSV

Extract simultaneously D(z) and CSV(x) from each $(Q^2$,x) setting

Experiment

Kinematic Coverage



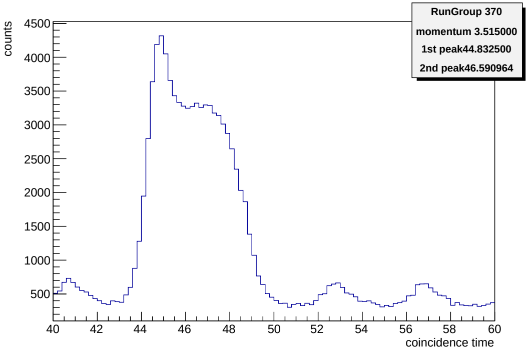
Beam Energy: 10.6 GeV, LD_2(10 cm), LH_2(10 cm), Al-dummy, Fall 2018 and Spring 2019;
HMS: electron, 13-21°, 4.4-6.4 GeV/c SHMS: hadron, 11°-21°, 1.7-4.5 GeV/c

PID coincidence time cut

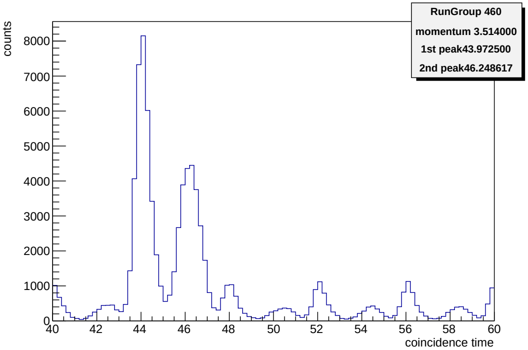
Fall: -2.504 to 2.504

Spring: -1.504 to 1.504

For accidental bgs: left three accidental peaks and right three peaks after proton peak.



One of the fall runs



One of the Spring runs

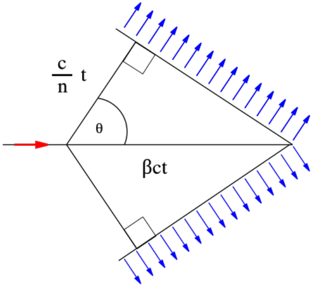
Particle Identification

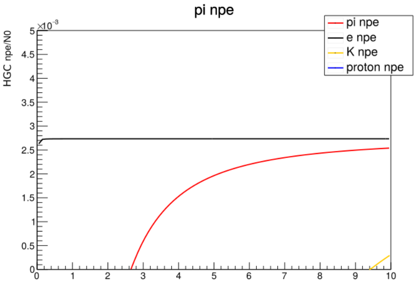
Cherenkov Detector

Cherenkov effect: The charged particle goes faster than the speed of the light in the medium will cause a flash of light. PMTs will measure the photons.

$$v_p \equiv \beta c > \frac{c}{n}, \;\; cos(\theta_c) = \frac{1}{n\beta}$$

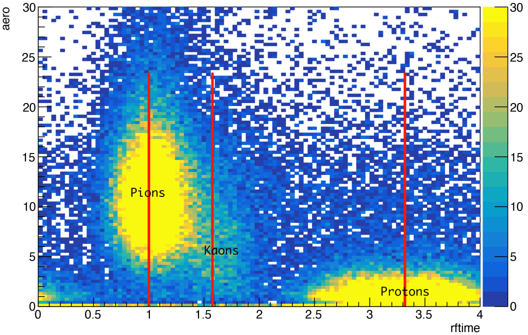
$$N_{p.e.} \approx LN_0 < sin^2\theta >= LN_0(1 - \frac{p^2 + m^2}{n^2 p^2})$$

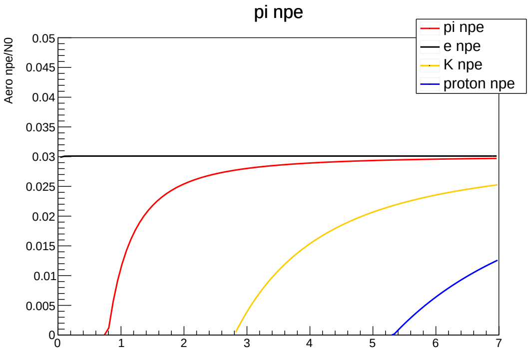




Hadron Particle Identification

Aerogel Cherenkov Detector



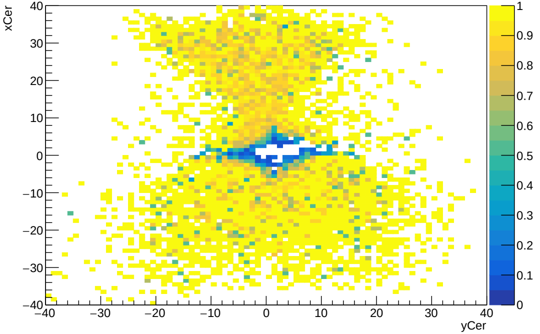


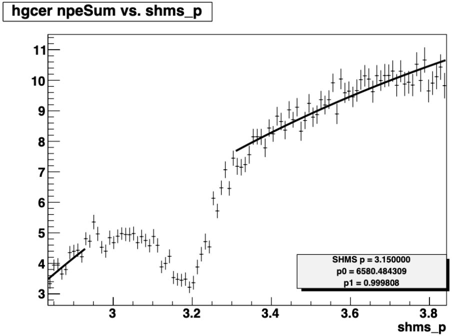
Protons are below threshold, however, there are knock-on electrons. So the aerogel Npe is greater than 4 photoelectrons.

A pol0 fit on aero eff vs. SHMS momentum, the result is 96.86% and the uncertainty is 0.03%

Hadron Particle Identification

Heavy Gas Cherenkov detector





A gap in the mirrors of the HGC causes a pion detection inefficiency and a region of poor K/π separation.

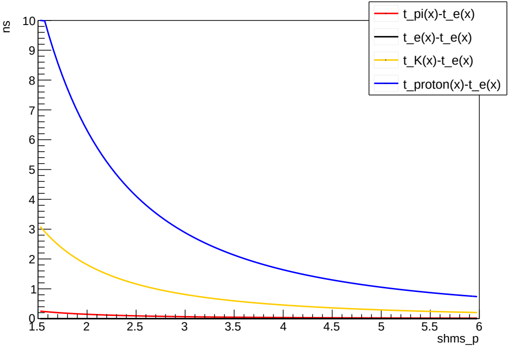
$$N_{p.e.} = p_0(1 - \frac{p^2 + m^2}{(p_1 n)^2 p^2})$$

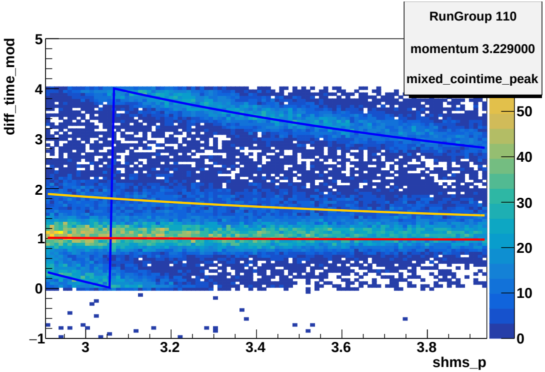
Hadron particle identification

RF time based time-of-flight PID

RF time: hodoscope hit time relative to a reference clock time from accelerator's RF signal → provides best ToF measurement RF clock is much lower than 250 MHz (electron bunches sent every 4 ns) so useful information is contained in (RFtime mod 4 ns). Pion peak moved to 1

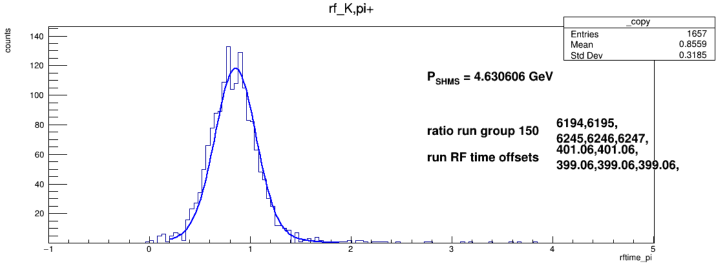
$$t = \frac{\text{length} \cdot \sqrt{p^2 + m^2} \cdot 10^9}{c \cdot p}$$

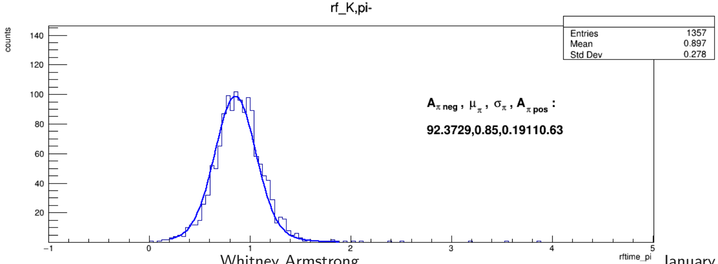




Pion event selection with HGC

Events with > 1 photoelectrons provide pure pion sample



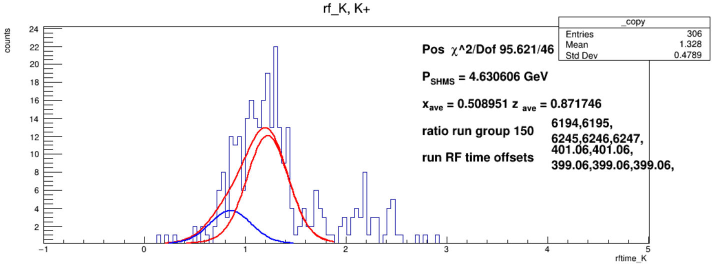


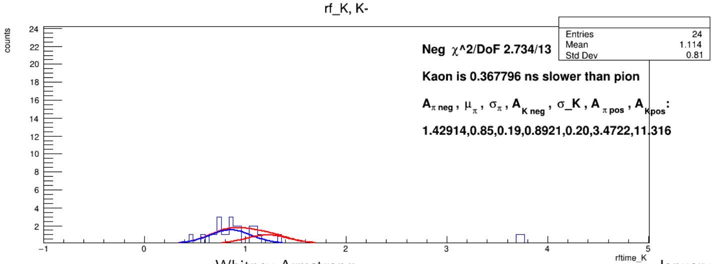
The pion peaks are plotted at the Kaon corrected rftime spectrum. Both pi^- and π^+ peaks are fitted simultaneously. From the fitting ,we can get pion μ and σ.

By integration, we could get $N^{\pi+}_{withHGC}$ and $N^{\pi-}_{withHGC}$

Kaon event selection with anti-HGC

Events < 1 photoelectrons provides a mixture of π and K





The pion μ and σ is fixed by the pions rf_pi spectrum from the last slides. The free parameter would be the amplitude of the π^+ and π^- peak, the amplitude of both K^+ and K^- and the σ for kaons peak.

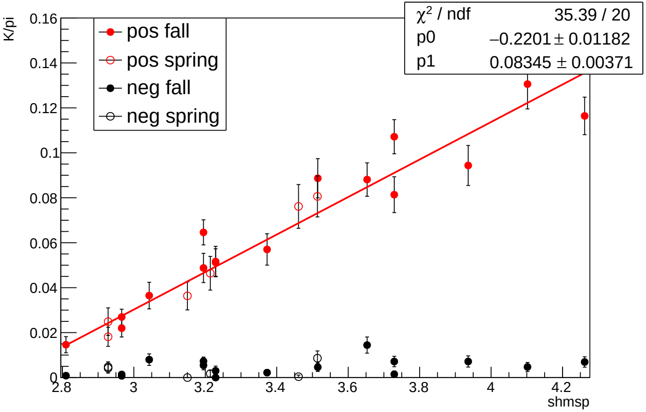
By integration, we could get

$$N^{\pi+}_{antiHGC}, N^{\pi-}_{antiHGC}$$
$$N^{K+}_{antiHGC}, N^{K-}_{antiHGC}$$

Kaon/Pion Ratio

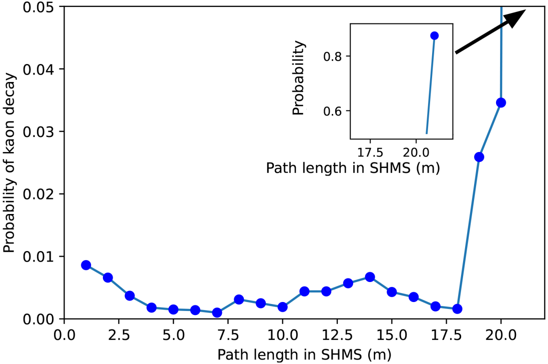
$$R_{K/pi} = \frac{N^{K}_{antiHGC}}{N^{\pi}_{withHGC} + N^{\pi}_{antiHGC}}$$

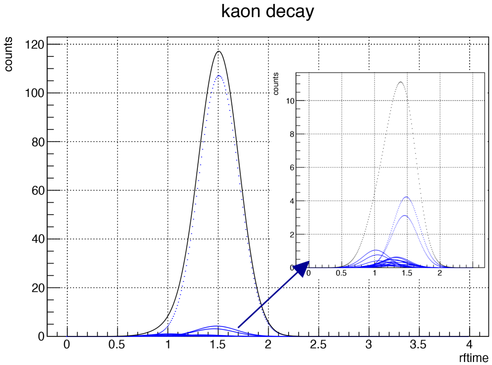
One point for each Run-group, plotted as a function of momentum. The kaon to pion ratio increases with high momentum, which is higher z. There are more K^+ than K^-



Kaon decay into muons and pions

The kaons decay anytime during the SHMS path, the probabilities are simulated by SIMC for ten momenta. From Peter Bosted



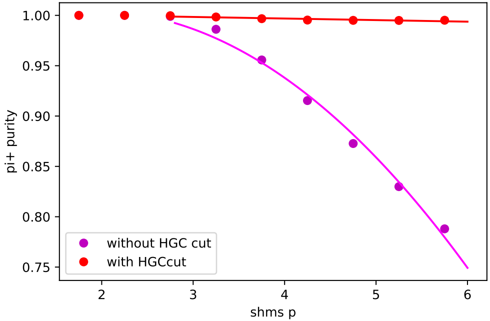


Among all the kaons that we detected, 1% decay at $0m$ at the target chamber, 1% decay at $12.5m$ at the middle, 4% decay at the $20m$ in detector hut, and 80% doesn't decay. For each meter, a function for pion/muons is assumed

Pion Purity

$$\pi_{\text{purity}} = \left(1 - R_{K/\pi} P_K\right)\Big|\text{RFtimecut}$$
$$N^{\pi}_{true} = N^{\pi}_{raw} \cdot \pi_{\text{purity}}$$

The purity as a function of momentum for one setting is plotted here. The red line is for with HGC cut case, the not decayed kaon will be completely removed by the HGC cut, but the decayed kaon remains. But it's small, less than 1%

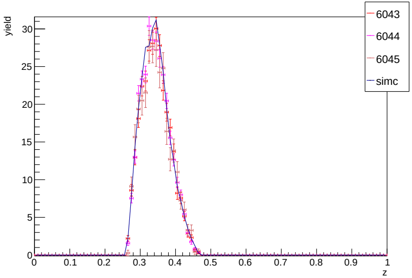


Fixed RFtimecut 0.2 to 1.54 ns

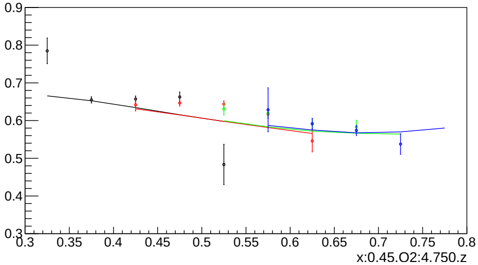
Corrections

- Tracking efficiency: Drift chambers inefficiency of tracking due to too busy or not enough tracks
- Live time:The inefficiency come from Data Acquisition DAQ system, determined by Electronics Dead Time Monitoring (EDTM) system.
- FADC deadtime: 100 ns intrinsic deadtime in the FADCs that block the reference time pulse from the trigger.
- Rate dependent $\rightarrow$ tried to run with similar $\pm$ trigger rates

Consistency check



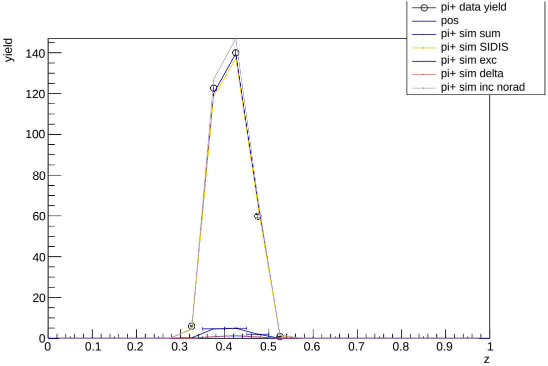
Compare different runs in Run Group



Check yield ratio as function of z for different $\langle z \rangle$ setting

Results

$$\langle x\rangle = 0.35, \langle Q^2\rangle = 4GeV^2, \langle z\rangle = 0.4$$



Data yield

$$Y^D_{corr}(x,z) = \frac{N_{\text{pions}}}{Q\,\varepsilon_{\text{t}}\,\varepsilon_{\text{LT}}\,\varepsilon_{\text{PID}}}$$

Backgrounds from SIMC:

Y_{exc}: Exclusive radiative backgrounds $D(e,e'\pi^{\pm})n(p)\gamma$

Y_{delta}: Delta radiative backgrounds $D(e,e'p)\pi$

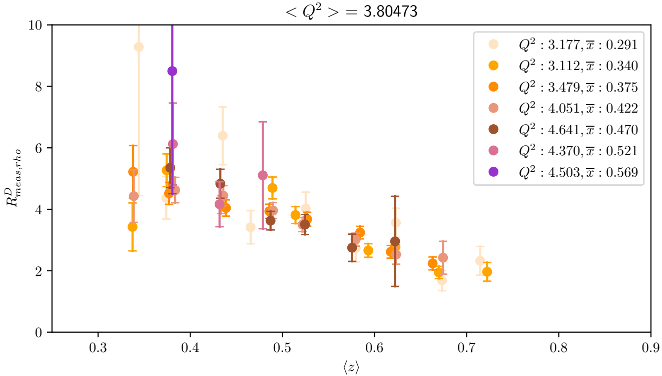
Y_{ρ}: Diffractive ρ $D(e,e'\rho\to\pi^+\pi^-)$

Radiative correction: $\mathrm{RC} = \frac{Y_{SIMC,noradia}}{Y_{SIMC,radia}+Y_{exc}+Y_{delta}+Y_{\rho}}$

$$Y_D(x,z) = \mathrm{RC}(Y^D_{\text{corr}} - 0.245 Y_{\text{Dummy}})$$

R^D_{meas} from data

$$D(z)\ R(x,z) + A(x)CSV(x) = B(x,z), R(x,z) = \frac{5}{2} + R^D_{meas}(x,z)$$

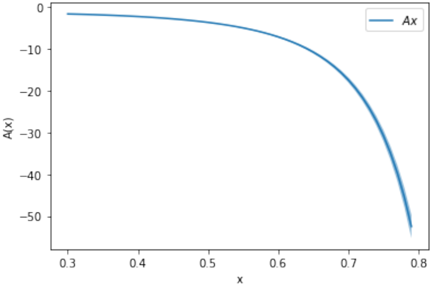


$R^D_{meas}(x,z)$ for $\langle Q^2 \rangle = 4GeV^2$ projected on z axis.
All variables are bin center corrected.
For each of (Q^2,x,z), weighted average are taken for the overlap of the different group of runs

$$R^D_{meas}(x,z) = \frac{4N^{D\pi^-}(x,z) - N^{D\pi^+}(x,z)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)} = \frac{4R_Y(x,z) - 1}{1 - R_Y(x,z)}$$

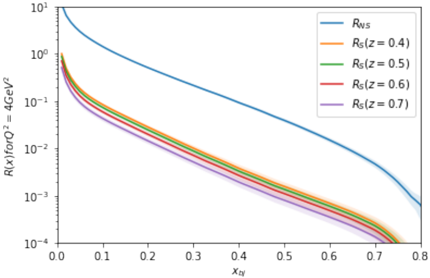
Model Inputs

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



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

JAM20 PDF



$$B(x,z) = \frac{5}{2} + R^D_{sea\_S}(x,z) + R^D_{sea\_NS}(x)$$

cteq6 PDf and JAM20FF

Calculate CSV from different Fragmentation Functions

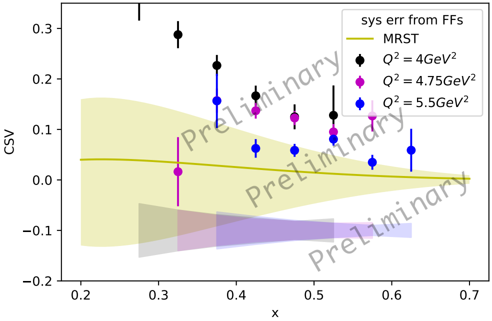
$$D(z)\ R(x,z) + A(x)CSV(x) = B(x,z)$$

$$CSV(x) = \frac{B(x,z) - D(z)\ R(x,z)}{A(x)}$$

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

Fragmentation Functions:

- JAM20SIDIS
- DSS LO
- DSS NLO



Extract simultaneously

Fragmentation ratio and CSV extraction

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

$$\Delta(z) \equiv \frac{D_u^{\pi^-}(z)}{D_u^{\pi^+}(z)} = z^\alpha(1-z)^\beta$$

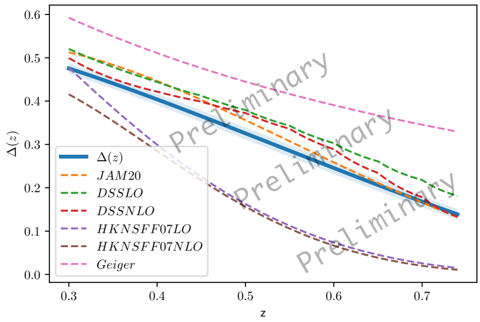
$$CSVx \equiv \delta d - \delta u = x^a(1-x)^b(x-c)$$

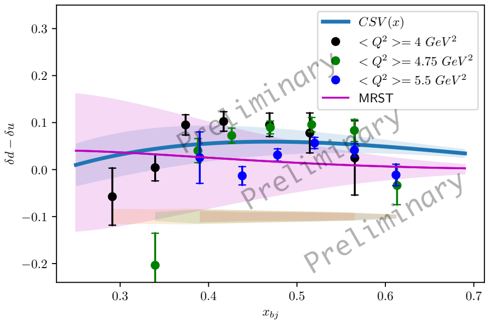
Constraint: $\int_0^1 CSV(x)dx = 0$

$$c = \frac{\int_0^1 x^{(a+1)}(1-x)^b}{\int_0^1 x^a(1-x)^b} = \frac{B(a+2,b+1)}{B(a+1,b+1)}, B(x,y) = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)}$$

$$R_{fit}^D(x,z) = \frac{B(x,z) - A(x)CSV(x)}{D(z)} - \frac{5}{2}$$

Results after standard ρ background subtraction





$$\Delta(z) \equiv D_u^{\pi^-}(z)/D_u^{\pi^+}(z) = z^\alpha(1-z)^\beta \qquad CSVx \equiv \delta d - \delta u = x^a(1-x)^b(x-c)$$

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

From the fitting result $\Delta(z)$, CSV can be calculated for each kinematic point. Weighted average are taken for overlap

Summary

- Conducted precision semi-inclusive measurements of the π^-/π^+ ratio on a deuterium target
- Extracted the CSV parton distribution and fragmentation function ratio for a range of x... Q2 and z...
- Using different FF models input suggests a CSV contribution from the fragmentation functions should be considered in a global analysis
- Results for the CSV parton distribution are consistent with MRST limits.
- Some CSV in the fragmentation functions improves shapes of fits and leads to good agreement with nominal ρ BG subtraction

Future

- Study ρ production data to finalize background subtraction
- Write paper and publish CSV sensitive data (ratios)
- Ultimately, these results should be included in a large global analysis which includes CSV in parton distributions and fragmentation functions
- Some more H_2 data have been already taken and more data are expected. Analysis of the full set of data on H_2 might help determine CSV in the quark distributions or in the fragmentation functions.

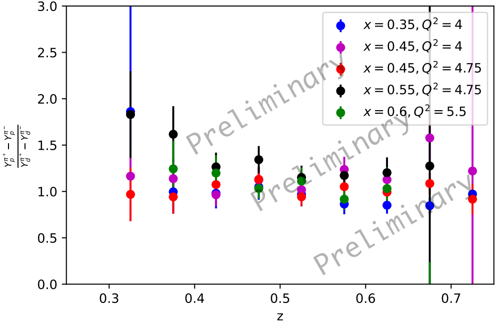
Thank you!

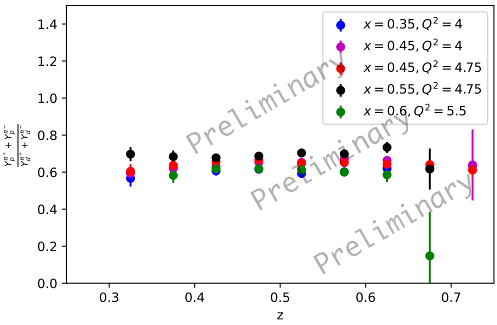
Backups

H_2 runs results

H_2 runs are taken for some kinematic to test the assumption of factorization.

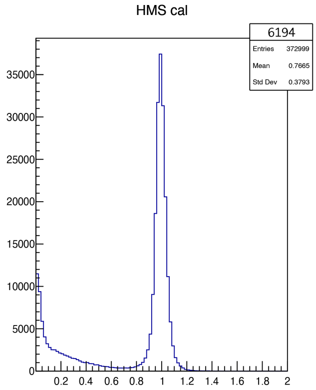
$$\frac{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}} = \frac{4u_v - d_v}{3(u_v + d_v)} \qquad \frac{\sigma_p^{\pi^+} + \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} + \sigma_d^{\pi^-}} = \frac{4u + 4\overline{u} + d + \overline{d}}{5(u + \overline{u} + d + \overline{d})}$$





Particle Identification by electromagnetic calorimeter

Calorimeters are made of lead glass where the particles deposit their energy in electromagnetic showers. The electron deposit all of the energy by ionization and Bremsstrahlung, the E/p would be 1. Hadrons deposit part of its energy, E/p is less than 1.



Electron PID: HMS calorimeter E/p cut greater than 0.8

RFtime mass correction

Rftime is corrected by the particle mass and SHMS δp

$$\mathrm{Preal} = (dp + 100) \times \mathrm{Pcentral}/100$$
$$\mathrm{rf}_{\pi} = \mathrm{rf}_{\mathrm{raw}} + t_{\pi}(\mathrm{Preal}) - t_{\pi}(\mathrm{Pcentral})$$
$$\mathrm{rf}_{K} = \mathrm{rf}_{raw} + t_{K}(\mathrm{Preal}) - t_{K}(\mathrm{Pcentral})$$
$$\mathrm{rf}_{\mathrm{proton}} = \mathrm{rf}_{\mathrm{raw}} + t_{P}(\mathrm{Preal}) - t_{P}(\mathrm{Pcentral})$$