



Jefferson Lab

Charge Symmetry Violation Quark Distributions via Precise Measurement of K^+ / K^- Ratios in Semi-inclusive Deep Inelastic Scattering

E12-09-002 experiment for JLab Hall C

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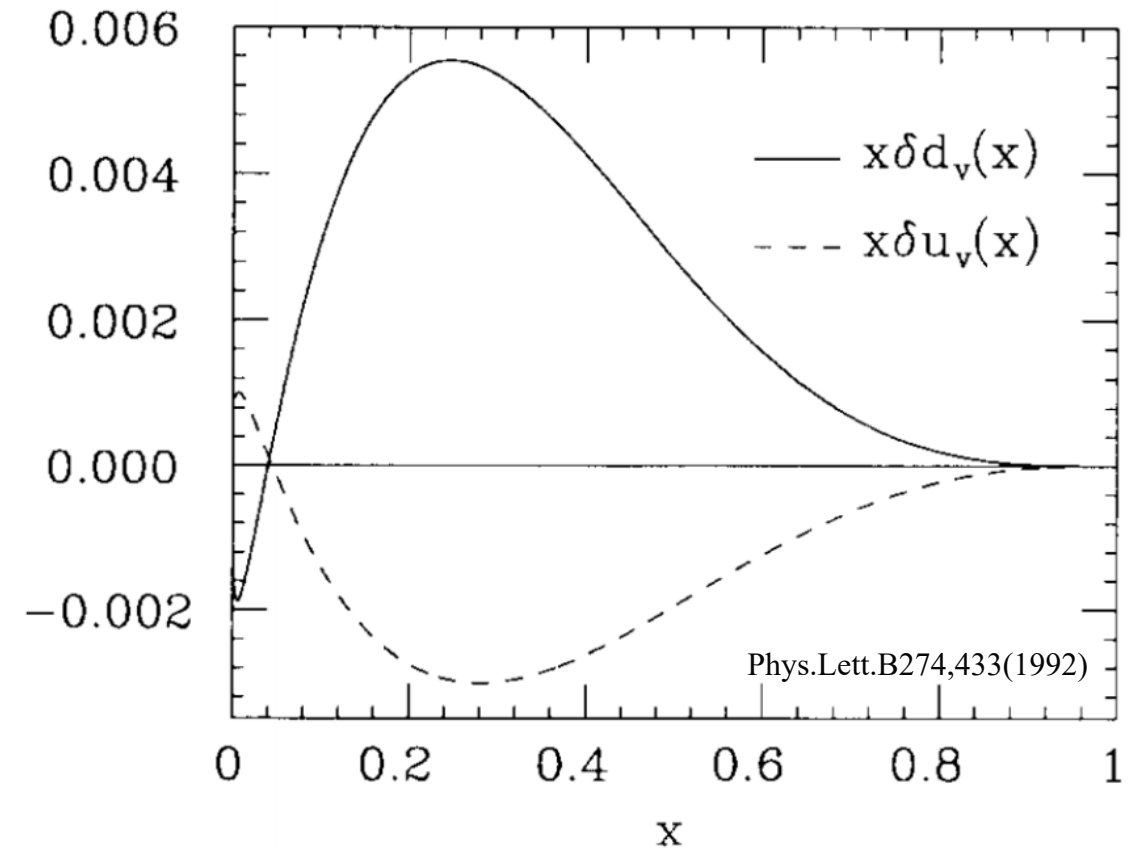
Oct.19, 2026

Wuhan, HuBei

Spicy Gluons (股麻) 2026

Outline

- Introduction
- Experiment Overview
- Data Analysis(PID and correction)
- Summary



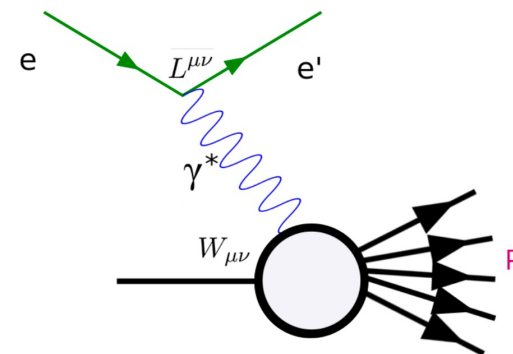
Motivation

DIS: Deep Inelastic Scattering is a scattering process used to probe the insides of hadrons.

$$q = k - k' = (E - E', \vec{k} - \vec{k}')$$

$$Q^2 = -q^2 = 2(EE' - \vec{k} \cdot \vec{k}')$$

$$x_{Bj} \equiv \frac{Q^2}{2P \cdot q}$$



$$l + N \hookrightarrow l' + X$$

SIDIS: Semi-Inclusive Deep Inelastic Scattering measures one or more final state hadrons($\pi^\pm$, $k^\pm$) in coincidence with scattered electrons.

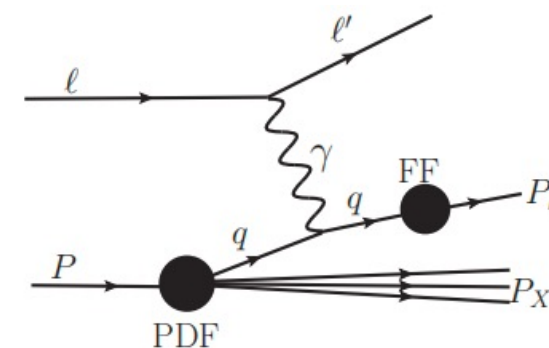
- **Advantage:** Hadron production information links the quark distribution and the fragmentation process.

$$\frac{d\sigma}{dx dz} \propto \sum_i e_i^2 q_i(x) D_{h/i}(z)$$

Scattering cross-section

PDF

FF



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

Motivation

● What is Charge Symmetry (CS) ?

It's one special kind of isospin symmetry, requires invariance with respect to rotation of T_2 axis.

$$[H, P_{CS}] = 0, P_{CS} = \exp(i\pi T_2)$$

For nuclei

CS operator interchanges neutrons and protons

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

Quark level

- $P_{CS}|d\rangle = |u\rangle$
- $P_{CS}|u\rangle = -|d\rangle$
- $u^p(x, Q^2) = d^n(x, Q^2)$
 $d^p(x, Q^2) = u^n(x, Q^2)$
 $s^p(x, Q^2) = s^n(x, Q^2) \equiv s(x, Q^2)$
 $c^p(x, Q^2) = c^n(x, Q^2) \equiv c(x, Q^2)$

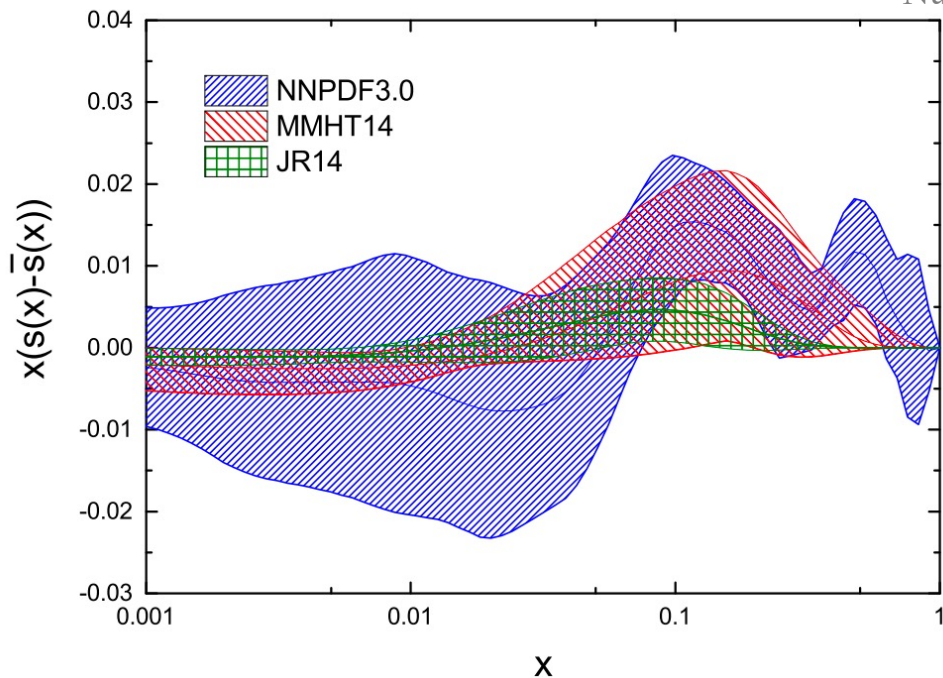
In QCD, CSV arises from electromagnetic interactions and mass differences between quarks. At the quark level, CSV is expected to be approximately $(m_d - m_u)/\langle M \rangle$, where $\langle M \rangle$ is about 0.5-1.0 GeV. **Prog. Part. Nucl. Phys. 41 (1998)**

Phys. Rep. 194 (1990) 1–116

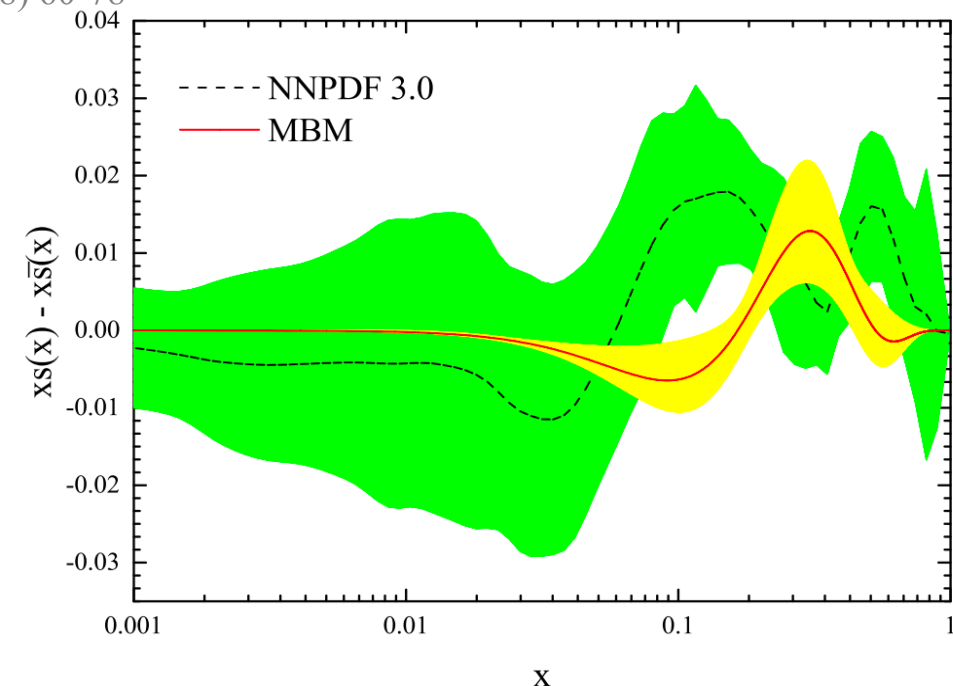
A **percent-level** effect——very **challenging** to measure!

$s-\bar{s}$ Asymmetry

- Three different PDF sets estimate a non-zero $s-\bar{s}$ asymmetry in the proton.
- These results come from global fits to data that **do not assume $s = \bar{s}$** .
- While their uncertainty bands vary, all sets consistently indicate this asymmetry.



- The MBM theoretical prediction **agrees with** the NNPDF3.0 global fit within uncertainties, **supporting $s \neq \bar{s}$** .
- Red solid line (yellow band): without assuming $s = \bar{s}$.
- Black dashed line (green band): assuming $s \neq \bar{s}$



- Test CS experimentally in the strange sector. If $s \neq \bar{s}$, CS is violated in the strange sea——crucial for nucleon structure.

Measure K^+/K^- Ratios

- Measure $\delta s(x)$ (s-quark CSV) via K^+/K^- yield ratios, complementing u/d quark results.

SIDIS: $e+N \rightarrow e'+K^\pm+X$

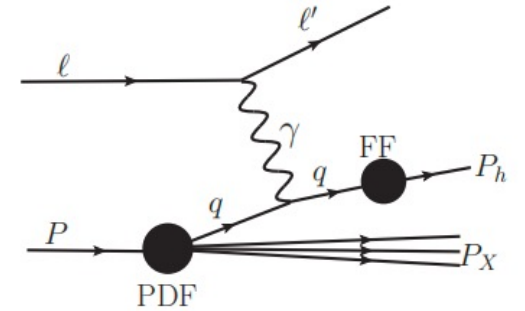
$\bar{s} + u \rightarrow K^+ : \bar{s} \text{ combines with the } u \text{ from the target nucleus}$
 $s + \bar{u} \rightarrow K^- : s \text{ combines with the } \bar{u} \text{ from the target nucleus}$

Extract $\delta s(x)$ $\rightarrow$ Through precision measurement of K^+/K^- yield ratios

CSV : $\delta s(x) = s(x) - \bar{s}(x)$

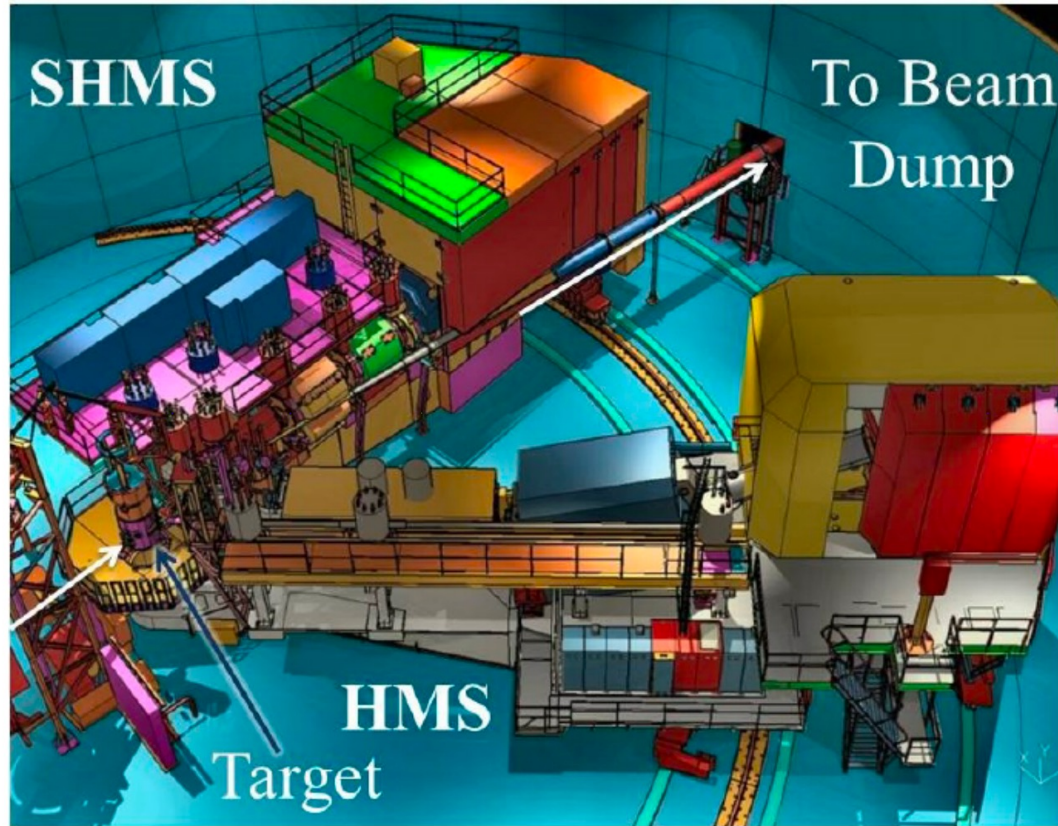
Ratio:
$$\frac{K^+}{K^-} \approx \frac{\frac{4}{9}u(x)D_u^{K^+}(z) + \frac{1}{9}\bar{s}(x)D_{\bar{s}}^{K^+}(z)}{\frac{1}{9}d(x)D_d^{K^-}(z) + \frac{1}{9}s(x)D_s^{K^-}(z)}$$

$D_q^{K^\pm}$: the probability of a quark q fragmenting into a $K^\pm$ meson.



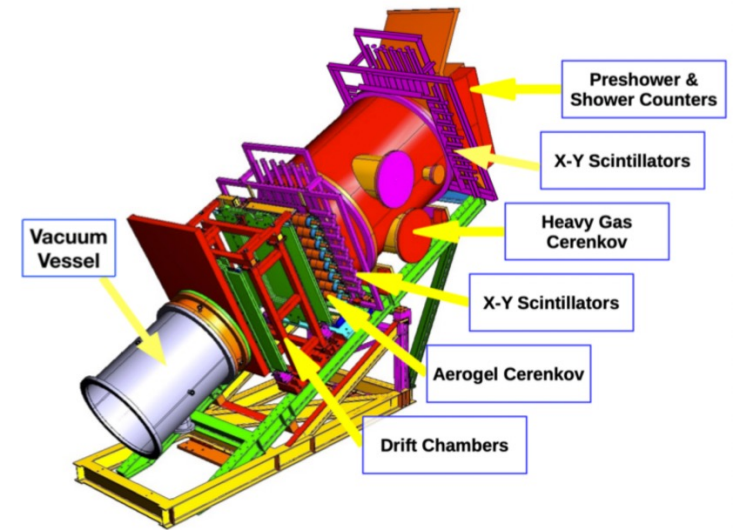
Experiment Overview

10.6 GeV beam, LD₂(10 cm), LH₂(10 cm), Al-dummy, Fall 2018 and Spring 2019

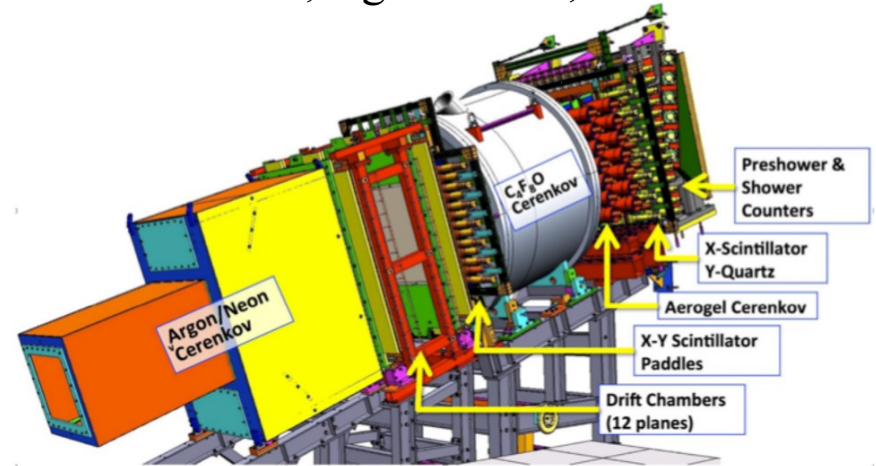


Hall C spectrometers setup

- High-precision measurements require small-angle, high-momentum spectrometers (HMS & SHMS).



HMS: electron, angle 13°-21°, 4.4-6.4 GeV



SHMS: hadron, angle 11°-21°, 1.7-4.5 GeV

Particle Identification

● **Main challenges:** Low kaon yield and difficult kaon-pion separation.

- Basic cuts:
- **HMS Good tracking:** $-10\% < \delta p/p < 10\%$
 - **SHMS Good tracking:** $-10\% < \delta p/p < 22\%$
 - **HMS Cherenkov (Electron):** $N_{pe} > 2$
 - **HMS Calorimeter (Electron):** $E/p > 0.8$
 - **SHMS Calorimeter (Pion):** $E/p < 0.7$

- **SHMS Aerogel Cherenkov :** $N_{pe} > 1.5$
 - **SHMS Heavy Gas Cherenkov :**
 $N_{pe} < 1.0$ (with hole cut)
 - **Coincidence Time Cut:**
 $t_{\text{coin}} = 44.0 - 0.9 \cdot t_{\text{RF}} \ \& \ t_{\text{coin}} = 48.0 - 0.9 \cdot t_{\text{RF}}$
 - **RFtime Cut:** $2.38 < t_{\text{RF}} < 2.61 \text{ ns}$

Kinematic Group 40: Ebeam=10.219 GeV Q2 = 5.5 GeV2, x = 0.55

7808-7809 run P=+3.461GeV

$|t_{\text{kaon}} - t_{\text{pion}}| = 0.6 \text{ ns}$
 $|t_{\text{proton}} - t_{\text{pion}}| = 2.3 \text{ ns}$
 $t = \frac{\text{length} \cdot \sqrt{p^2 + m^2} \cdot 10^9}{c \cdot p}$

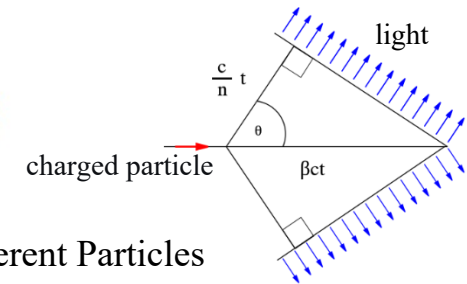
Setting			Kinematics			Spectrometer settings					Good Count Goals		Estimates		Runs	Target SHMS 3/4 (pTRIG1) rates
number	target	lbeam	Q2	x	z	P HMS	th_HMS	P SHMS	th_SHMS	pol	desired	actual	hr:min	charge mC	# runs	kHz
40-1	LD2	50.0	5.5	0.550	0.650	-4.890	19.10	+3.461	15.95	+1	20000	20583/156.6	1:13	217.4	7808-7809	225

PID: Heavy Gas Cherenkov and Aerogel

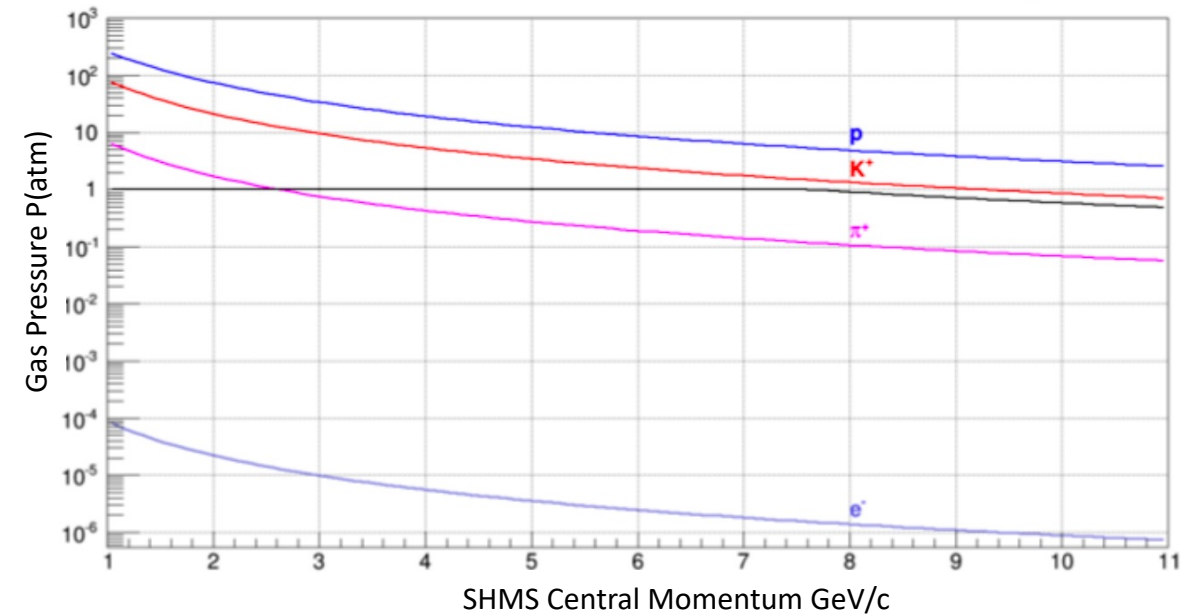
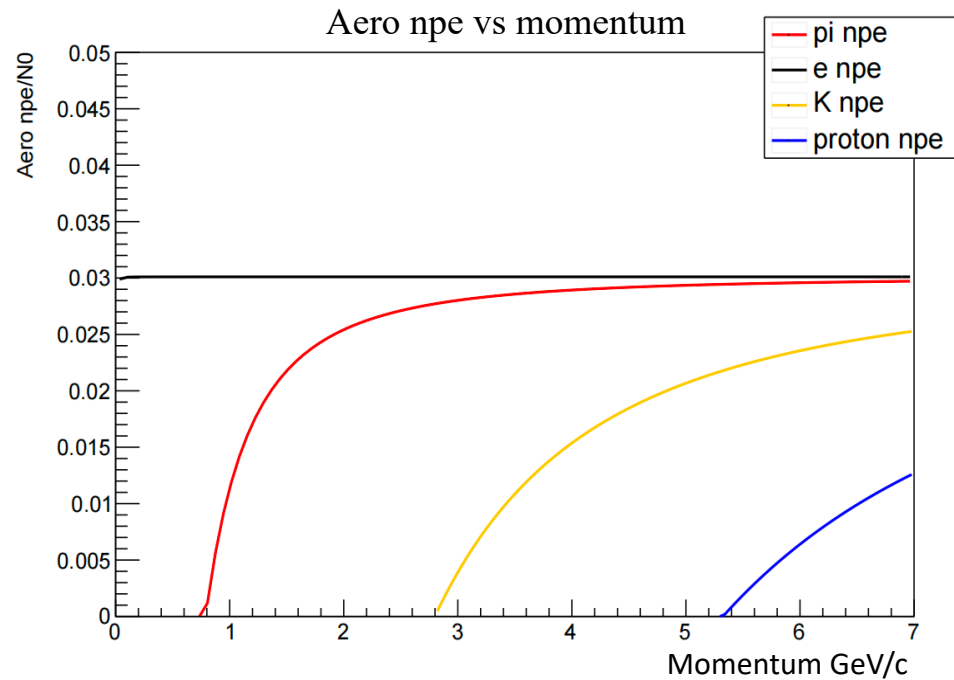
Cherenkov effect :The charged particle going faster than the velocity of the light in the medium will cause a flash of light.

$$v_p \equiv \beta c > \frac{c}{n}, \cos(\theta_c) = \frac{1}{n\beta}, p > \frac{m}{\sqrt{n^2 - 1}}$$

$$N_{p.e.} \approx LN_0 \langle \sin^2 \theta \rangle = LN_0 \left(1 - \frac{p^2 + m^2}{n^2 p^2}\right)$$



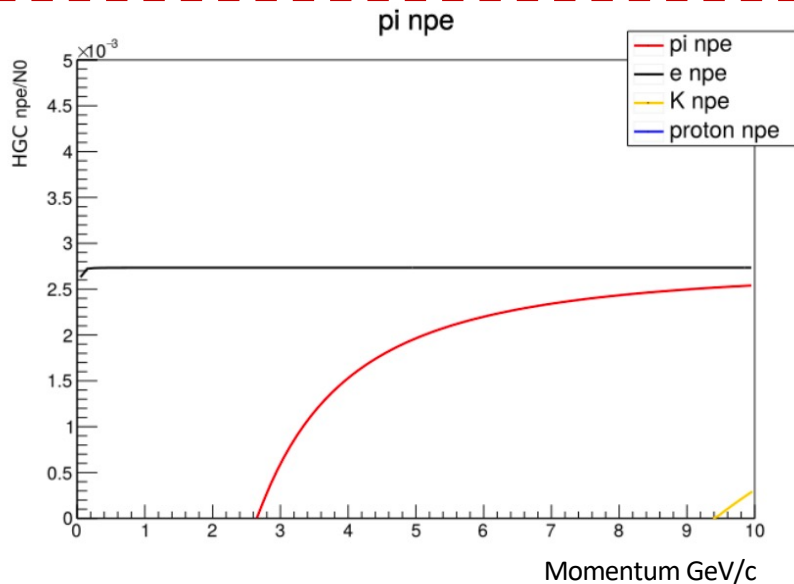
Cherenkov Radiation Threshold Pressure for Different Particles



- The high refractive index of **Aerogel** makes **kaons** and **pions** are always above its emission threshold.

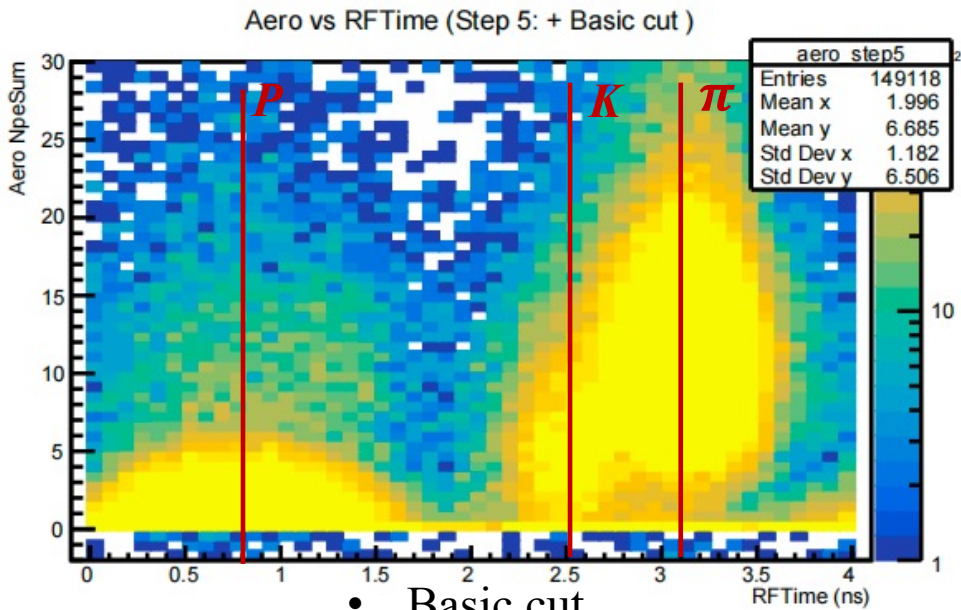
- The **HGC** refractive index is precisely tuned via gas pressure to keep **kaons** below its emission threshold.

PID: Heavy Gas Cherenkov and Aerogel



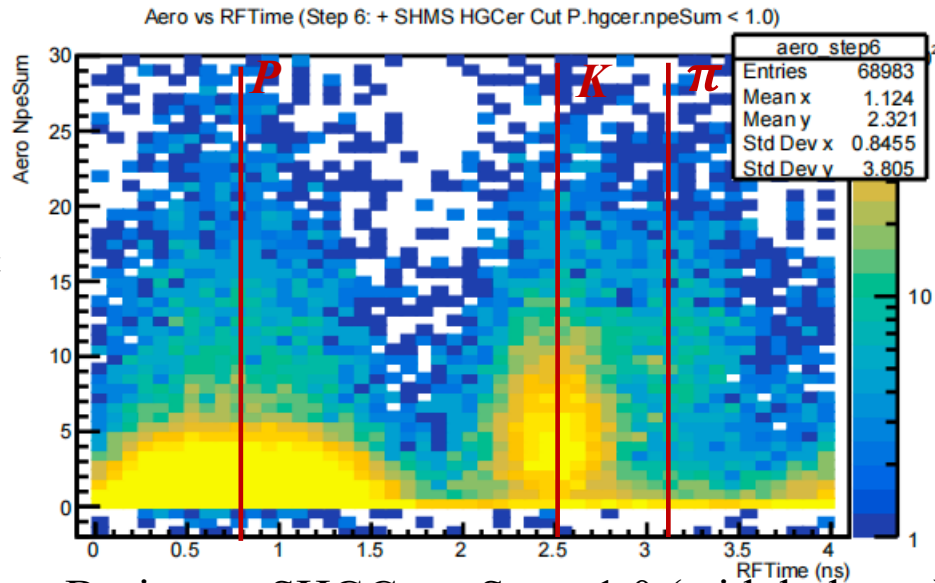
Detector	Medium	Refractive Index (n)	Kaon Behavior
SHGC	C ₄ F ₈ O Gas	~1.00137 (adjustable)	$P_{th} \approx 9.4$ GeV/c NO Light
Aerogel	Silica Aerogel	1.015 (fixed)	$P_{th} \approx 2.8$ GeV/c YES Light

- By tuning the refractive index of the gas in the SHGC, pions radiate Cherenkov light while kaons do not.



- Basic cut

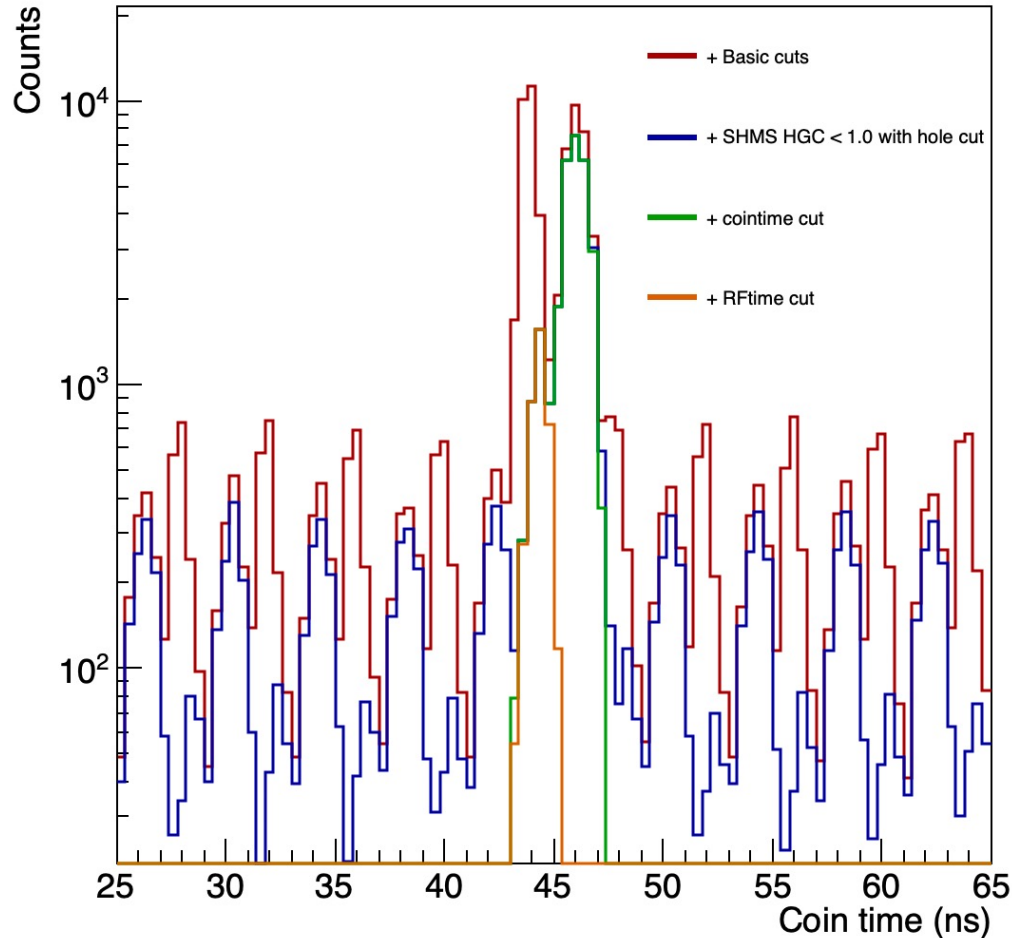
+SHGC cut



- Basic cut+SHGC npeSum<1.0 (with hole cut)

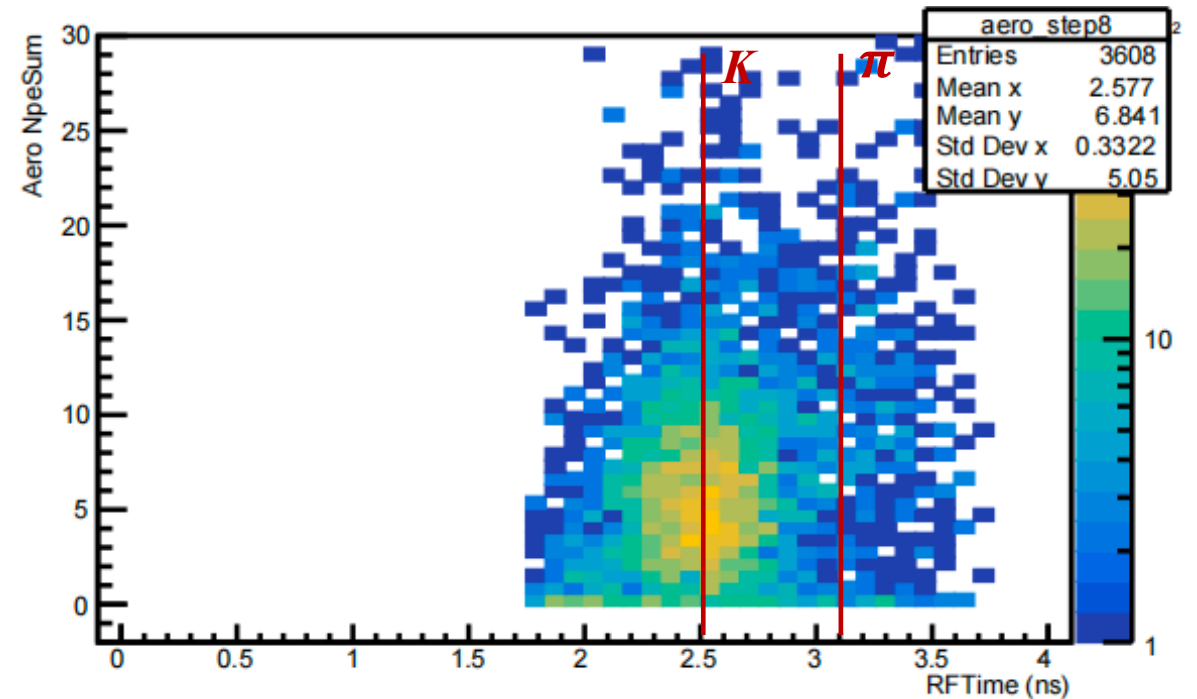
PID: Coincidence time and Rftime cut

- The coincidence time determines whether two particle detected within the same time window originate from the same beam bunch.



- Rftime identifies particles via their mass-dependent time-of-flight relative to the beam.

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



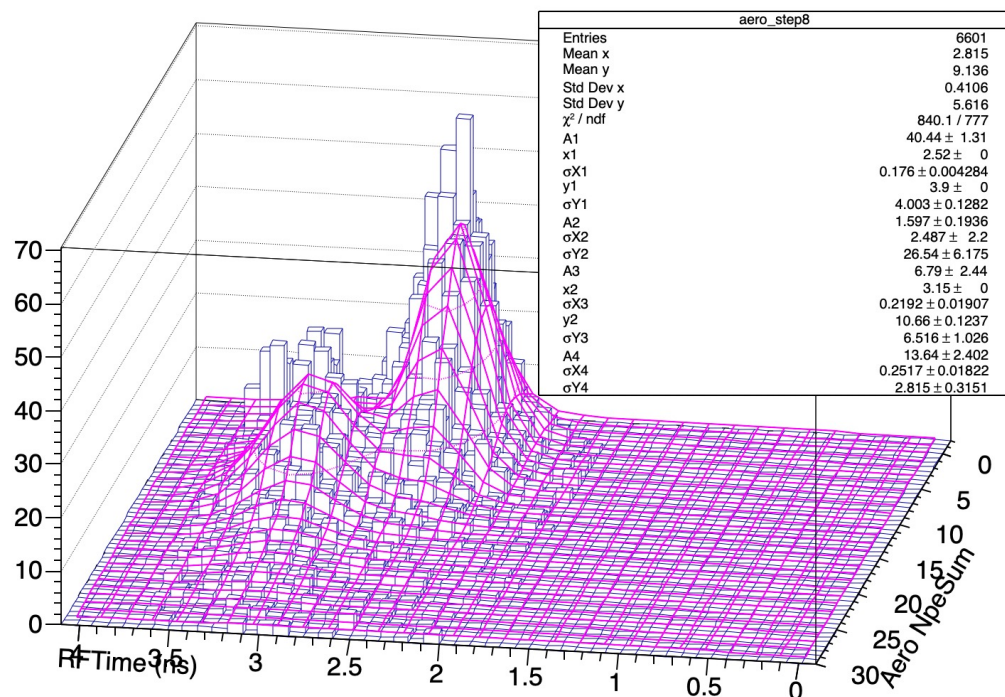
- Basic cut+SHGC npeSum<1.0 (with hole cut)
+Coincidence time cut+Rftime cut

2D fit-To further separate K , π separation

- Fitting function:

$$f(x, y) = A_1 \exp\left(-\frac{(x - \mu_{x1})^2}{2\sigma_{x1}^2} - \frac{(y - \mu_{y1})^2}{2\sigma_{y1}^2}\right) + A_2 \exp\left(-\frac{(x - \mu_{x1})^2}{2\sigma_{x2}^2} - \frac{(y - \mu_{y1})^2}{2\sigma_{y2}^2}\right) \\ + A_3 \exp\left(-\frac{(x - \mu_{x2})^2}{2\sigma_{x3}^2} - \frac{(y - \mu_{y2})^2}{2\sigma_{y3}^2}\right) + A_4 \exp\left(-\frac{(x - \mu_{x2})^2}{2\sigma_{x4}^2} - \frac{(y - \mu_{y2})^2}{2\sigma_{y4}^2}\right)$$

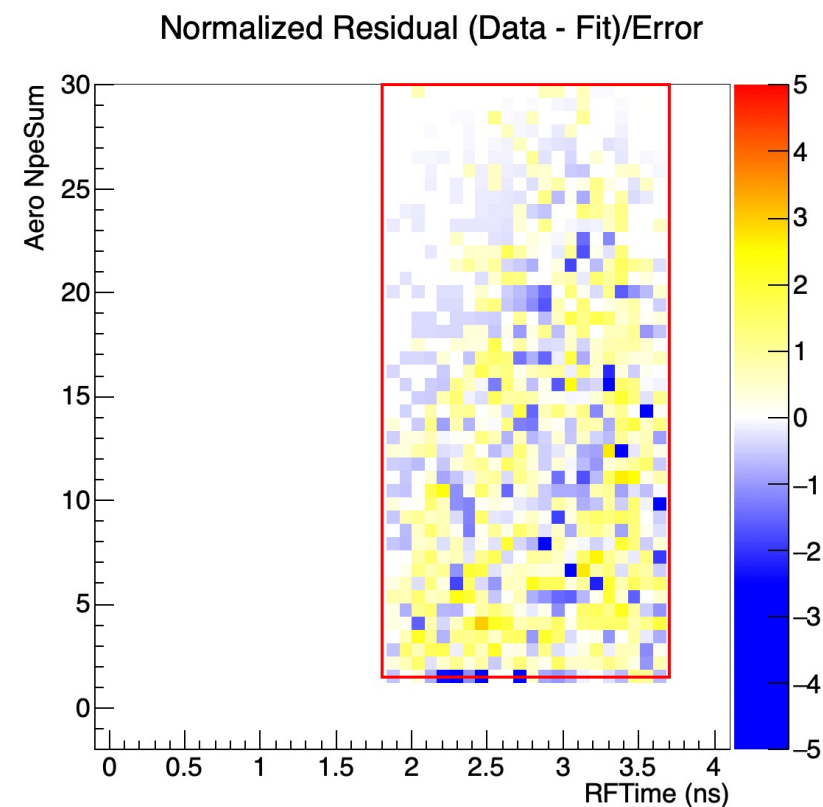
- The first two Gaussians share center coordinates
- The last two Gaussians share center coordinates



- Fitting range: Aero: (1.5, 30), RFTIME: (1.8, 3.7) ns

- Pion background entering the kaon cut P_π :**

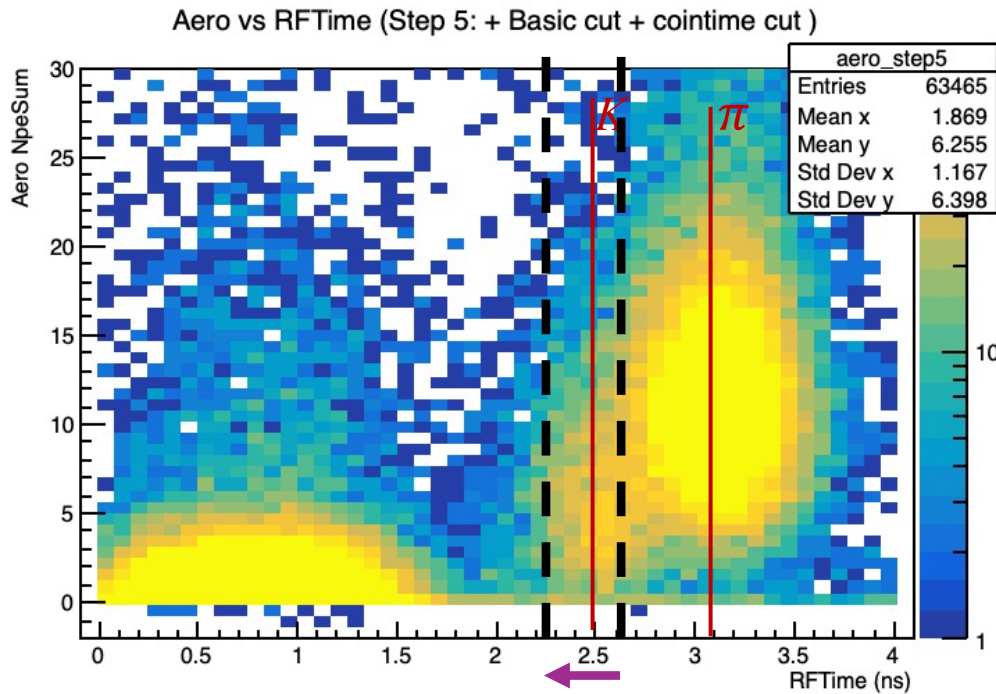
$$7.69374 \pm 0.448724\%$$



Detection Efficiency vs RTime Cut Width and SHGC Cut

(Positive run)

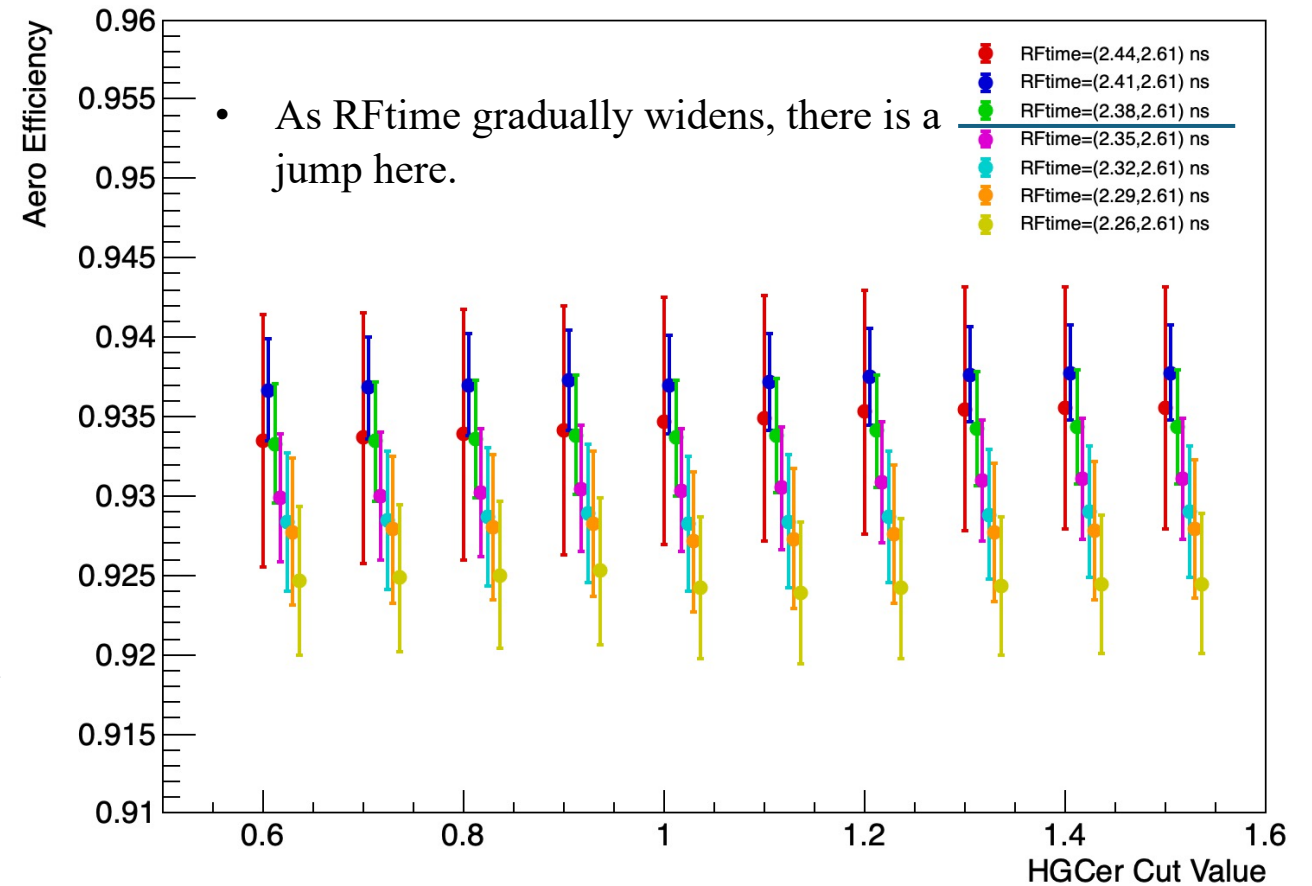
Using Basic cut+cointime cut



- Fix the right boundary(2.61 ns) of RTime and cut it to the left to 2.26 ns
- SHGC npeSum < 0.6, 0.7, 0.8 ... 1.5

- The **two-dimensional** variation of Aero efficiency with **both RTime and SHGC cuts**.

Aero Efficiency vs HG Cer Cut (Fully Correlated Errors)



- As RTime gradually widens, there is a jump here.

- RTime=(2.38, 2.61) ns, SHGC npeSum < 1.0
This contains the relatively pure intervals of kaon.

SHMS HGC Efficiency correction for Kaon

- To estimate the proton and the pion, and then do an efficiency correction

- to Calculate the proton efficiency.

(0.736 ± 0.010)

$$\varepsilon = P_k \varepsilon_k + P_p \varepsilon_p + P_\pi \varepsilon_\pi$$

(0.687 ± 0.011) (0.895 ± 0.01)

want to get

From the shuo's analysis

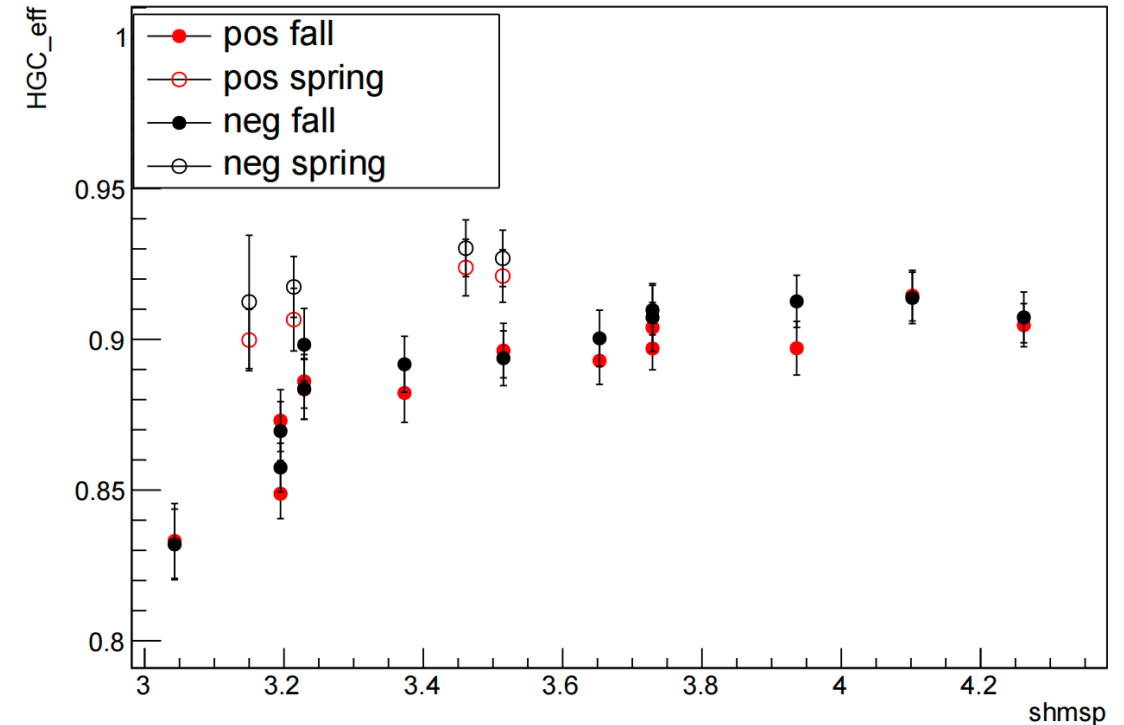
P_k, P_p, P_π : **from 2D fit**

P_k : 92.128% $\pm$ 1.49627%

P_p : 0.178278 $\pm$ 0.0658796%

P_π : 7.69374 $\pm$ 0.448724%

- $\varepsilon_k = 0.670 \pm 0.012$
- This efficiency correction is essential for extracting the true kaon yield.



Summery and Outlook

Summery:

- Charge symmetry, universally assumed in PDF extraction, has never been experimentally tested.
- Charge Symmetry Violation (CSV) is crucial for understanding fundamental symmetries and nucleon structure.
- Measure $\delta s(x)$ (s-quark CSV) via K^+/K^- yield ratios, complementing u/d quark results (via π^+/π^- yield ratios).
- JLab Hall C E12-09-002: 10.6 GeV beam, LD₂/LH₂/Al dummy; HMS primarily detects electrons; SHMS primarily detects hadrons.
- Main challenge: low kaon yield and K/π separation.

Multi-PID: Heavy Gas Cherenkov, Aerogel, Calorimeter, Coincidence time, RFtime.

Outlook:

- Obtain the preliminary K^+/K^- yield ratio.
- Extract $\delta s(x) = s(x) - \bar{s}(x)$ from the K^+/K^- yield ratio.



Jefferson Lab

Thank you for your attention!

Oct.19, 2026

Wuhan, HuBei

Spicy Gluons (胶麻) 2026

Back up

Charge Symmetry

• T_2 :

- The T_2 axis in abstract isospin space (where T_3 is charge).
- Rotation of 180° around T_2 interchanges protons/neutrons and u/d quarks.

• $P_{CS}=\exp(i\pi T_2)$

- Standard quantum rotation operator for $\theta=\pi$ around T_2 .
- The minus sign ($P_{CS}|u\rangle=-|d\rangle$) comes from the SU(2) Pauli matrix σ_2 properties for fermions.

•If $[H,P_{CS}]=0$, why does CSV exist?

- The commutation is an **approximation** assuming $m_u=m_d$ and no EM interactions.
- In reality, $m_d\neq m_u$ and EM interactions break it, making $[H,P_{CS}]\neq 0$ at the $\sim 1\%$ level.

•Isospin Symmetry vs. Charge Symmetry

- Isospin symmetry: invariant under **all** rotations in isospin space ($[H,T]=0$).
- Charge Symmetry: invariant under **only** 180° **rotation about** T_2 .
- CS is a weaker condition, thus better conserved in strong interactions.

Meson-Baryon Model

- The core idea is that the proton's wavefunction is not simply three valence quarks. It contains **non-perturbative fluctuations** into virtual **meson-baryon Fock states**, such as:

$$p \longrightarrow K^+ + \Lambda^0 \quad K^+ = u\bar{s}, \quad \Lambda^0 = uds$$

- In such a state, the strange quark (s) resides in the baryon, while the anti-strange quark ($\bar{s}$) is in the meson (K^+)
- Their **different momentum distributions** within the proton lead to an overall asymmetry between $s(x)$ and $\bar{s}(x)$.
- The model calculates this asymmetry using **light-cone momentum convolution**:

$$dP = \frac{g^2}{(16\pi^2)^{N-1}(N-2)!} \prod_{j=1}^N dx_j \delta\left(1 - \sum_{j=1}^N x_j\right) \int_{s_0}^{\infty} ds \frac{(s-s_0)^{N-2}}{(s-m_0^2)^2} |F(s)|^2$$

Nucl.Phys. A973 (2018) 60-78

Coincidence Time

- **Coincidence Time** defined as the time difference between the arrival of a charged pion at the SHMS detector and the scattered electron at the HMS detector, after accounting for path length corrections.
- This quantity determines whether two particles detected within the same beam pulse originate from the same electron-nucleon deep inelastic scattering (DIS) event.

$$t_{\text{coinc}} = (t_{\text{SHMS, corr}} - t_{\text{HMS, corr}})$$

$$t_{\text{corr}} = t_{\text{raw}} - \text{TOF}_{\text{calc}}$$

t_{Raw}: Precise timing from when particles trigger the first hodoscope planes is recorded via Time-to-Digital Converters (TDCs)

TOF_{calc}: Using the particle's reconstructed momentum p and geometric path length L from the interaction target to the detector, along with an **assumed particle rest mass** m

$$v = \frac{pc}{\sqrt{p^2 + m^2c^2}}$$

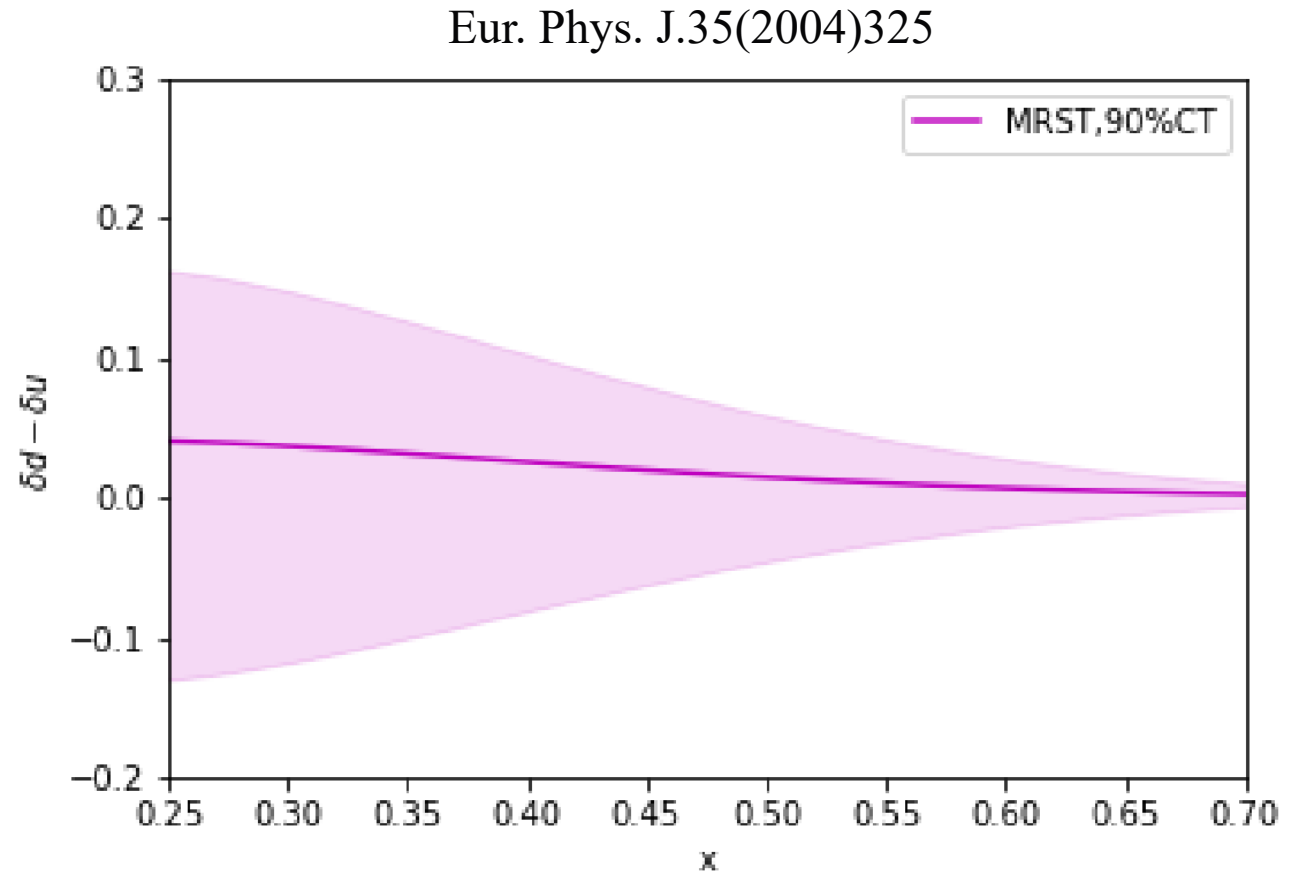
$$\text{TOF}_{\text{calc}} = \frac{L}{v}$$

Phenomenological limits

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

- 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

Using the uncertainties in PDFs studied by MRST Group, CSV is constrained to **less than 9%**
(Shuo's PhD Dissertation)

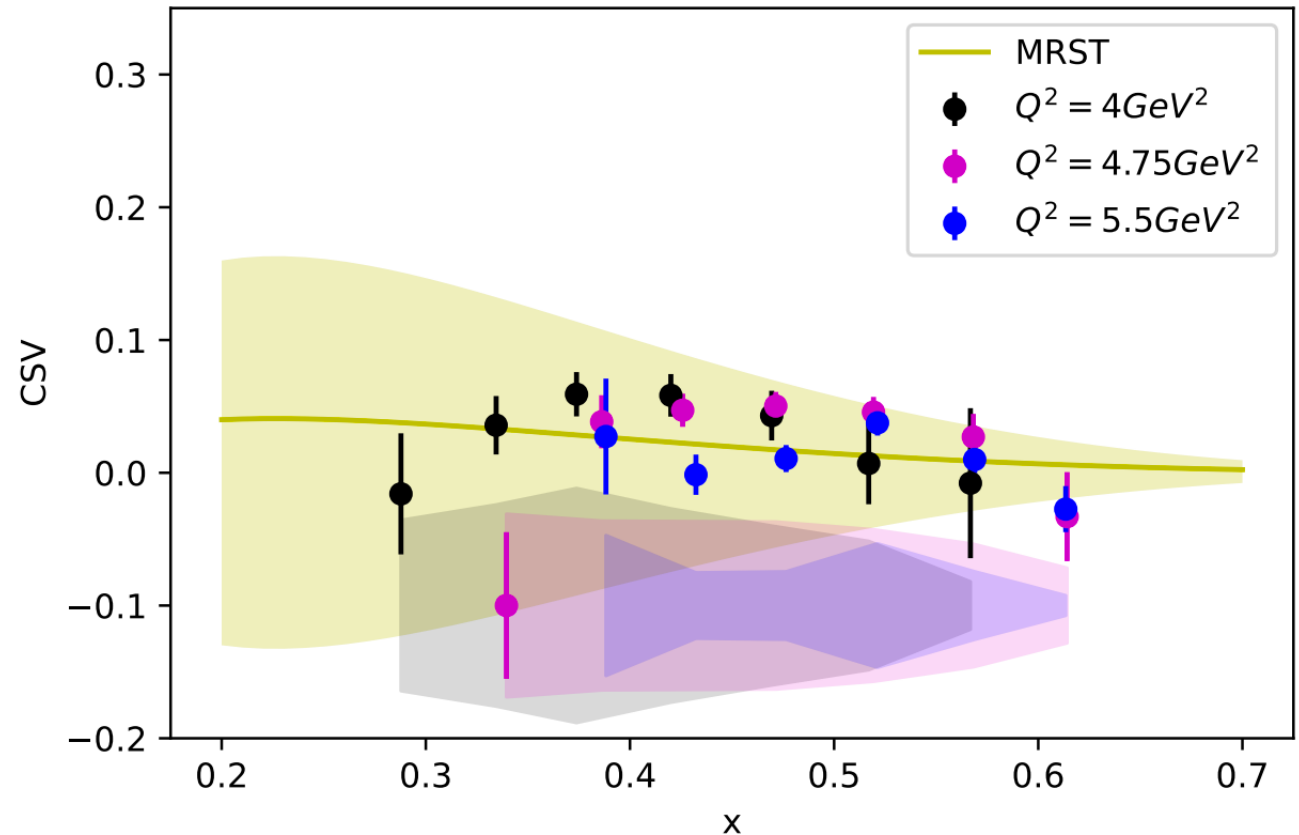


CSV results by measuring π^+/π^- Ratios

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

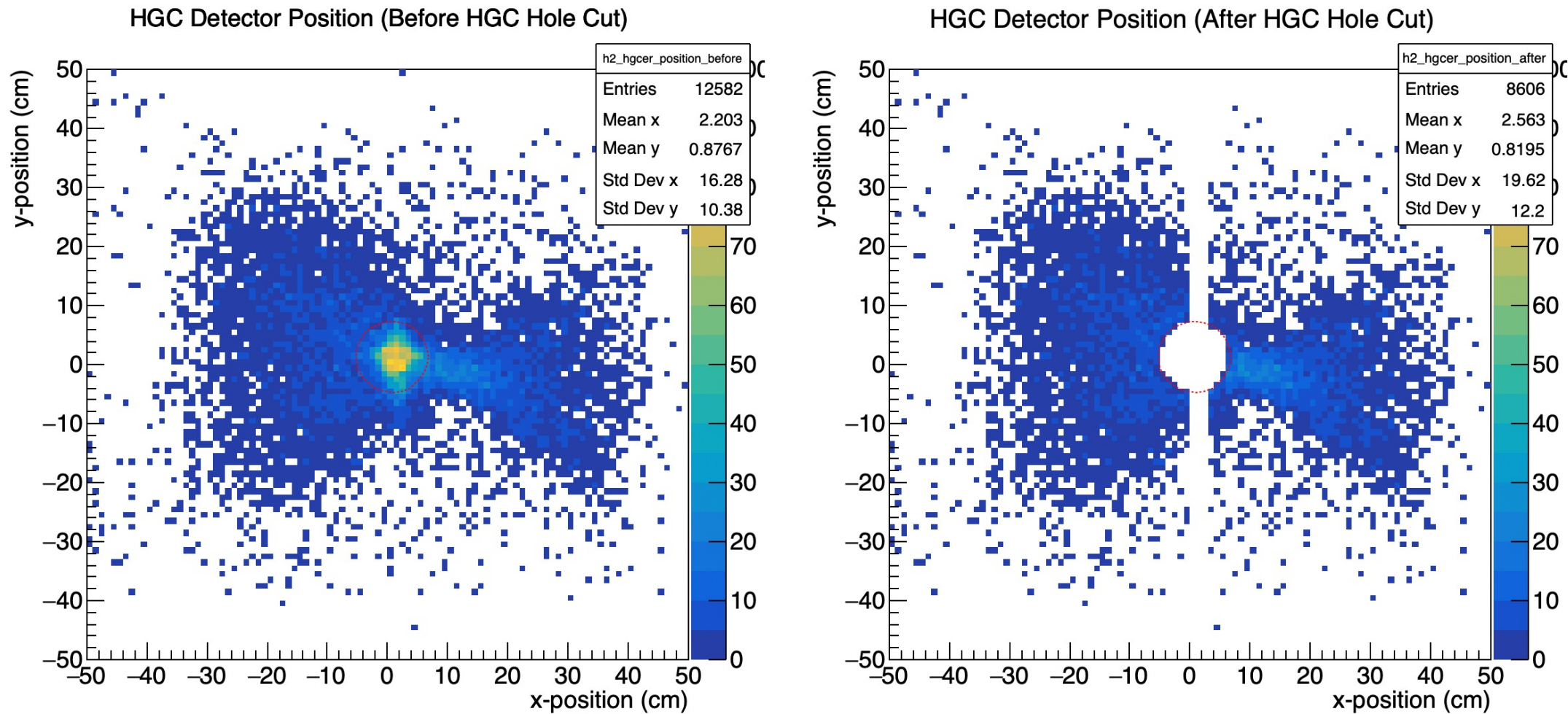
- **CSV** : the value and uncertainty of CSV under different x values.
- **Model Stability**: Minimal sensitivity to PDF/FF choices, demonstrating experimental stability.
- **QCD Validation**: Matches theoretical predictions confirming CSV mechanisms.

Shuo's PhD Dissertation



The CSV results from all different cases.

SHMS Heavy Gas Cherenkov Hole Cut



- y-position (cm) vs. x-position (cm) at HGC showing an inefficient region of the Cherenkov detector at the center of acceptance (left) and after removing this region (right)