Signature of Baryon Junctions in SIDIS

Hem Bhatt
Mississippi State University

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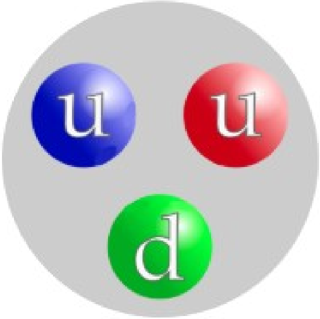
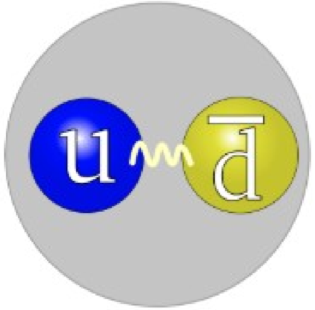
Hadron: Baryons and Mesons



Baryons: 3 quarks
Example: Proton (uud)



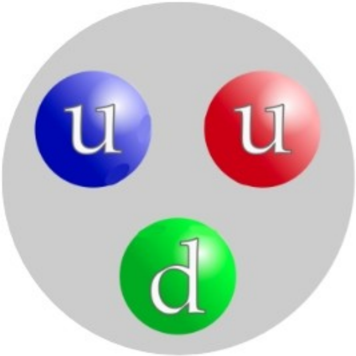
Mesons: 2 quarks
Example: π^+

Hadrons are color neutral

Protons and Neutrons are nucleons, responsible for stable universe

Fundamental Properties of Proton: Mysteries

Property	Value	Internal Structure (Who carries it?)
Mass	938.272 MeV	Shared among quarks and gluons (via interaction energy)
Spin	1/2	Shared among quark spins, gluon spins, and orbital motion
Charge	+1	Sum of fractional charges of quarks
Baryon Number	**+1**	**Conserved quantum number, origin still unclear**

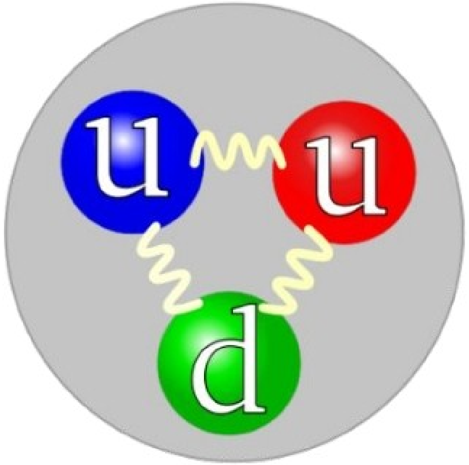


Role of Gluon is significant in nucleon structure.

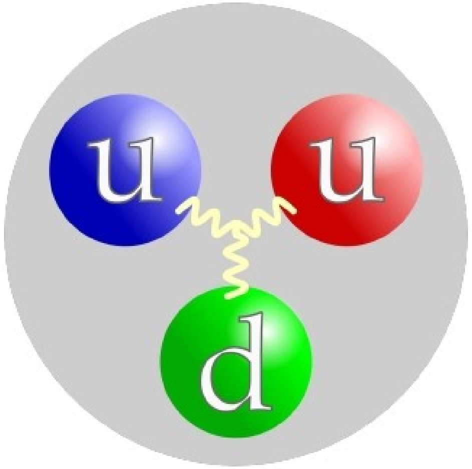
Proton Structure

Very common particle:
hidden mysteries

Mass, spin governed by:
Quarks and Gluons



A

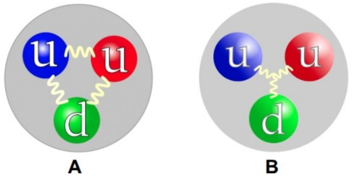


B

Traditional Picture: each quark carry 1/3 of baryon number

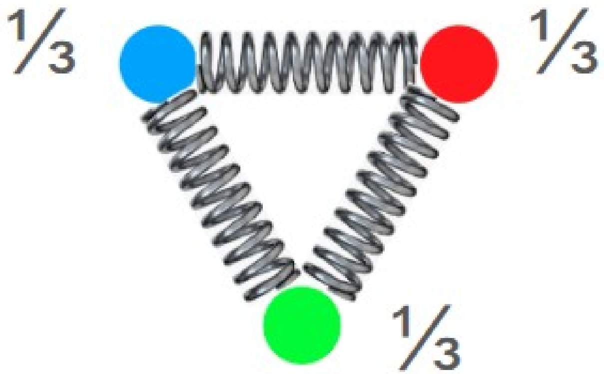
Emerging Picture: A baryon junction : verton, a gluonic configuration-this junction may carry all the baryon number

Proton Image by Frank Wilczek



If A is correct:

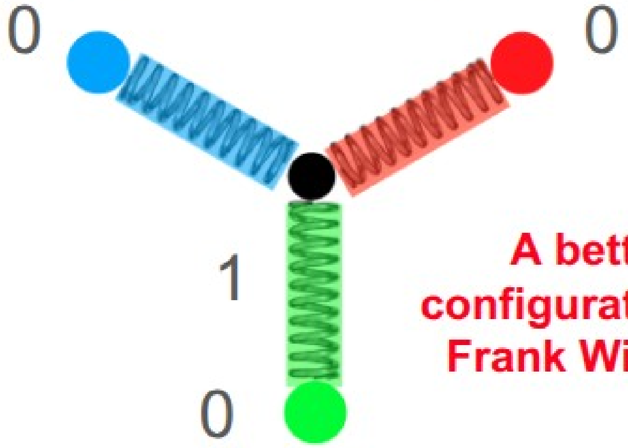
To put back the "3" in color SU(3), we can use U(1) x U(1) x U(1) with an appropriate charge spectrum:



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

If B is correct (Verton):

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



A better configuration by Frank Wilczek

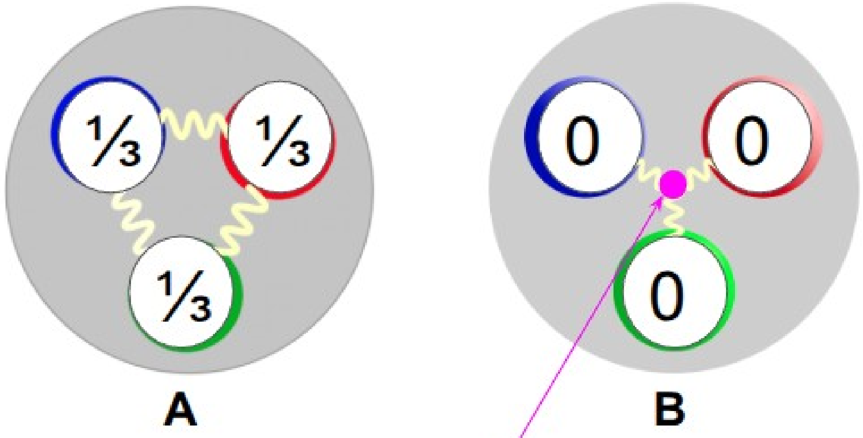
$(1,0,0)$ & $(0,1,0)$ & $(0,0,1)$ + verton $(-1, -1, -1)$

50 Years of Quantum Chromodynamics Seminar Series :

https://indico.cern.ch/event/1276932/contributions/5563300/attachments/2712308/4744769/qcd_ucla_03.pdf

Baryon Number?

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

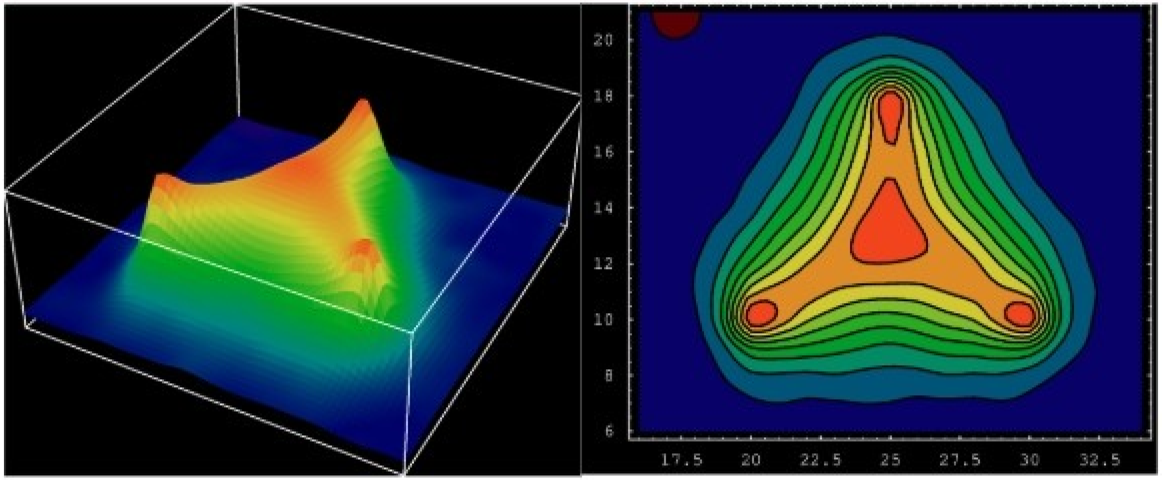


A: implies quark carries fractional baryon number

B: existence of a ***"Junction" like structure*** that potentially carries the baryon number.

Central Questions: 1) Is baryon number an additive property of quarks? Or
2) is it a topological or gluonic feature, concentrated in a baryonic junction

Insights on Baryon Junction: Lattice QCD



->Lattice QCD study on proton wavefunction. *"Baryon Junction is a purely a gluonic field configuration that represents entanglement among quarks and carries baryon number"*

H.Suganuma et al, 2004. https://arxiv.org/pdf/hep-lat/0412026

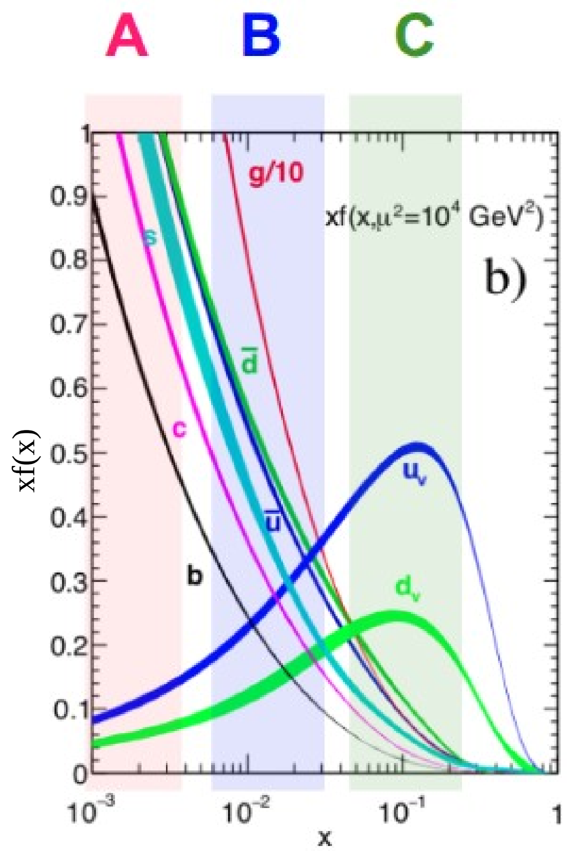
->Baryon Junction was predicted by local gauge invariance of the baryon wave function (1977) *G.C.Rossi, G. Veneziano, Nuclear Physics B, Vol 123, Issue 3, 1977*

->Transport of Baryon number in high energy pp collions (1996)
D. Kharzeev https://arxiv.org/abs/nucl-th/9602027

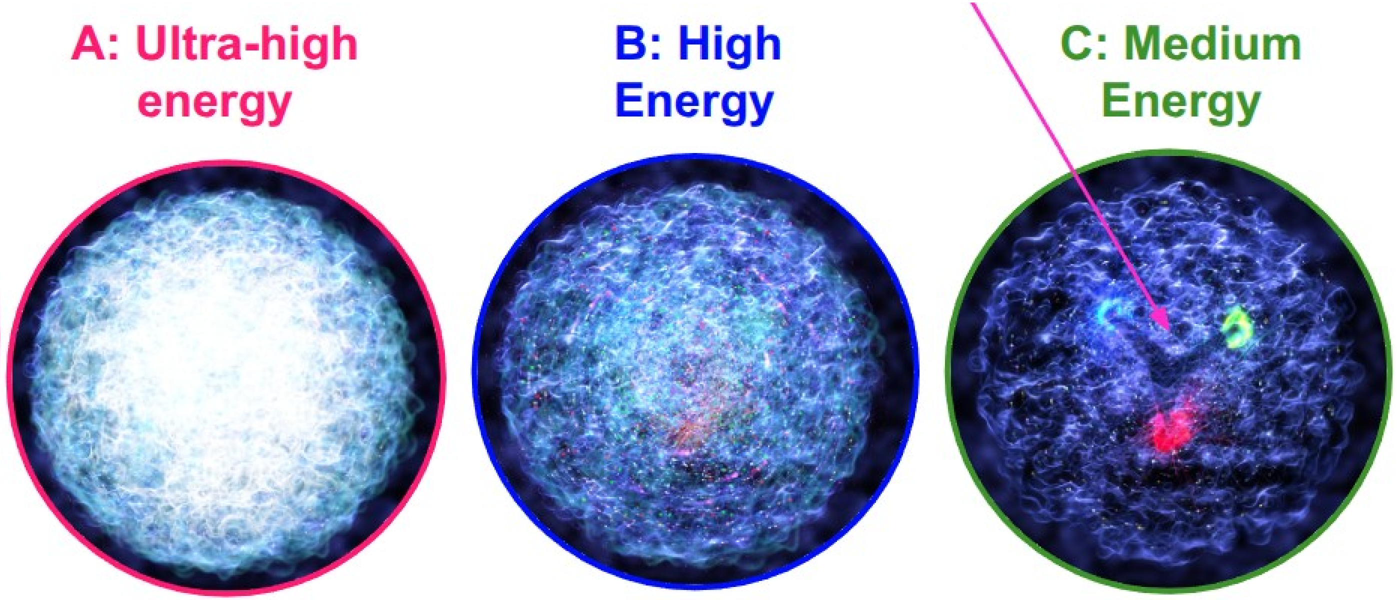
Proton Structure at Different Energy

Nucleon Structure Function:

- Jlab: Valence Quark
- heavy-ion collisions and EIC: quark sea and gluons

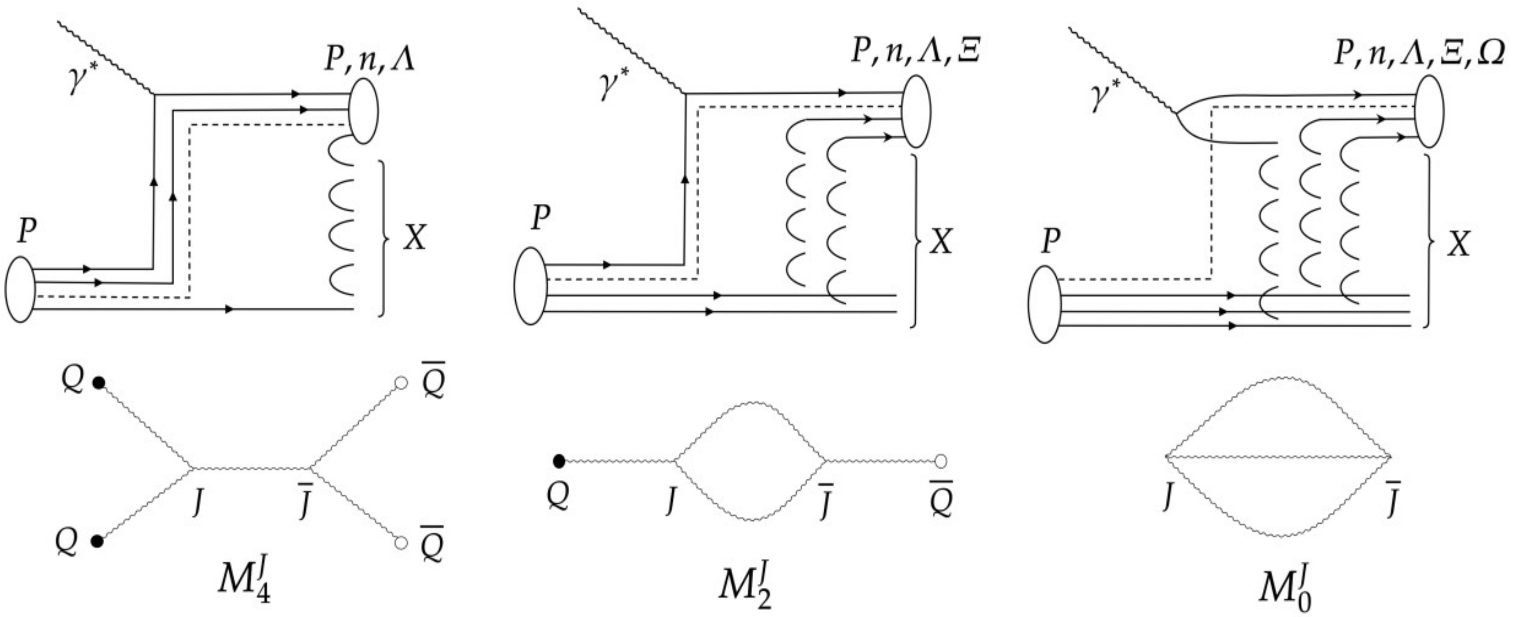


Is this a Junction?



Image/Video credit to JLab and MIT

SIDIS Processes mediated by Baryon Junction e+P->e+baryon+X



dashed line:
Junction

solid lines:
valence quarks

2 valence quarks partcipate and 1 junction is exchanged, accompanied by 1 string fragmentation

1 valence quark partcipates and 1 junction is exchanged, accompanied by 2 string fragmentations

Pure Junction: 0 valence quarks, 1 junction is exchanged, accompanied by 3 string fragmentations

The fewer valence quarks participate in forming final state baryon, the stronger the role of baryon junction.
Detecting such events in SIDIS could reveal gluon-based baryon number transport.

David Frenklakh, Dmitri E. Kharzeev, and Wenliang Li, PLB, 2023, https://arxiv.org/pdf/2312.15039

SIDIS cross-section as a function of rapidity

David Frenklakh, Dmitri E. Kharzeev, and Wenliang Li, PLB, 2023, https://arxiv.org/pdf/2312.15039

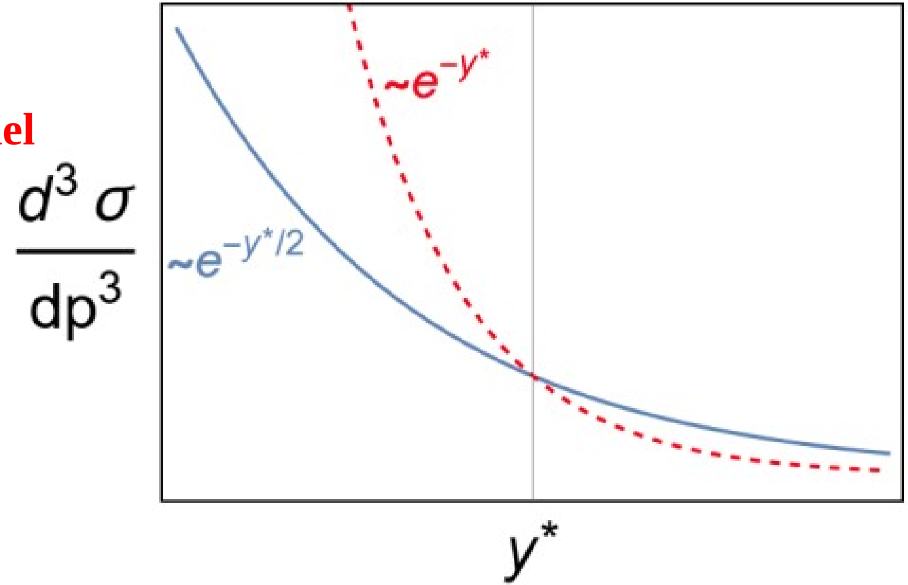
Blue Solid Curve: Baryon Junction Prediction

Red dashed Curve: Conventional valence quark model

$$\mathbf{y}^* = \frac{1}{2}\ln\left(\frac{E^*+p_z^*}{E^*-p_z^*}\right)$$

(Measure of particle's forward motion in CM)

s= CM energy
y* = rapidity
E^* : total energy of the final-state baryon
p_z^* : longitudinal momentum (along beam direction) of the baryon



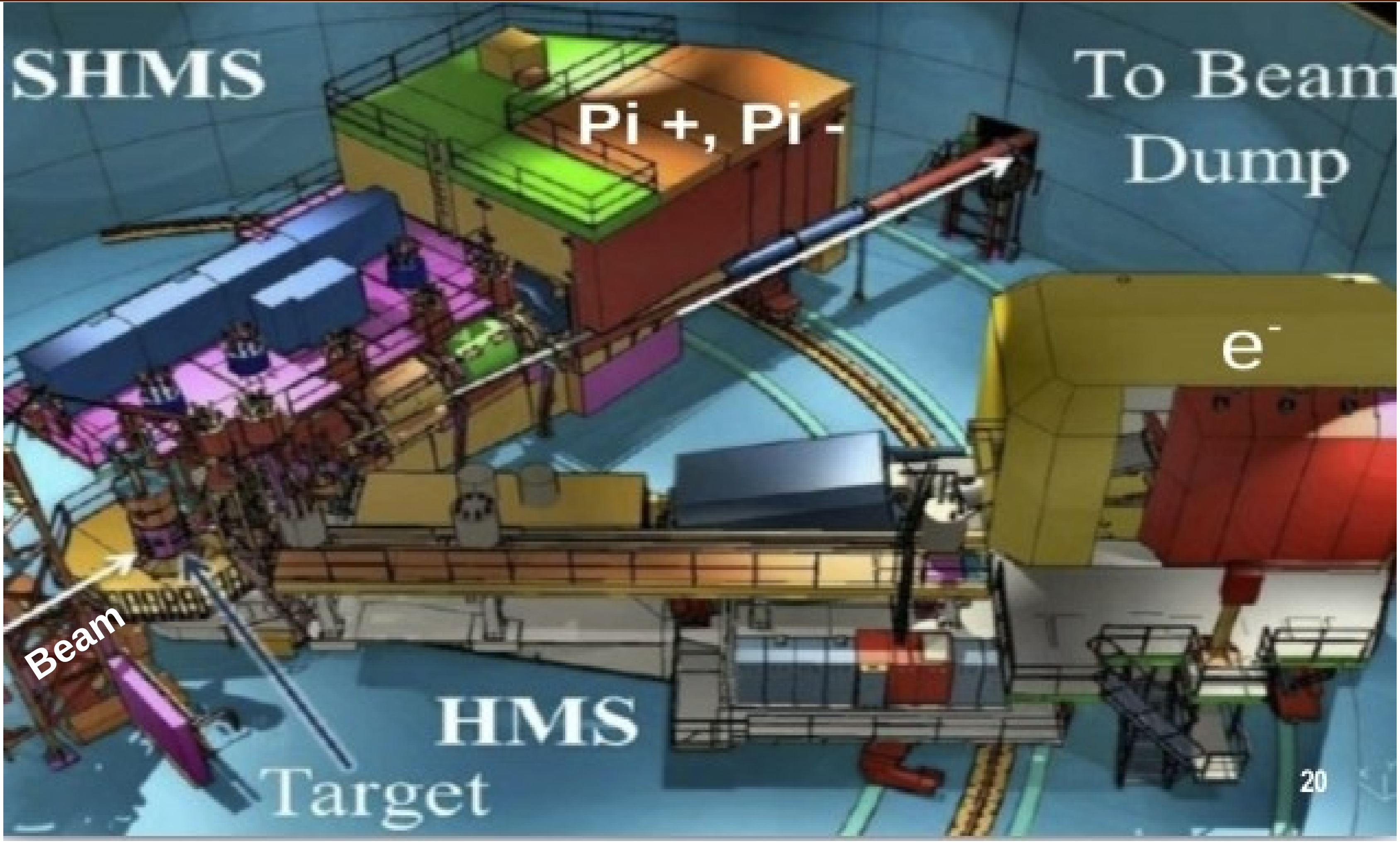
Predicted CS as a function of CMS rapadity.

By modeling the process as an exchange of exotic trajectories like baryon junction, the cross-section falls off slowly with rapidity:

$$\frac{d^3\sigma}{dp^3} \propto s^{-1/4} e^{-y^*/2}$$

Observing such behavior experimentally would support the Presence of gluon-mediated baryon number exchange.

Pion SIDIS Experiments at Jefferson Lab Hall C (E12-09-002/E12-09-017)



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

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

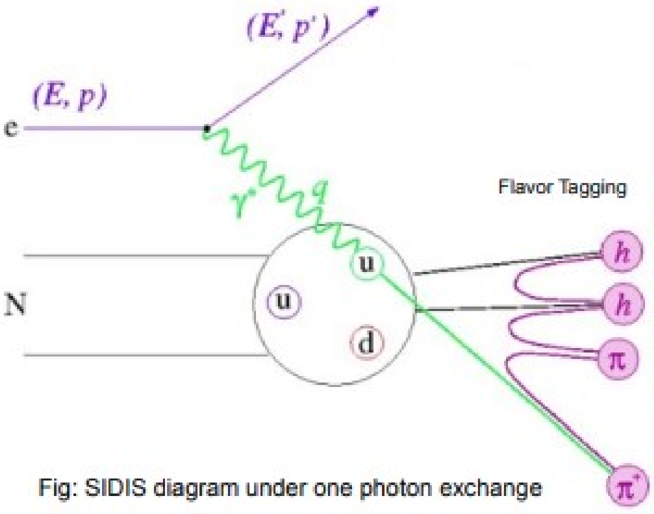


Fig: SIDIS diagram under one photon exchange

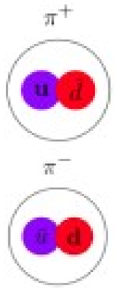
The Pt Integrated SIDIS pion yield:

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

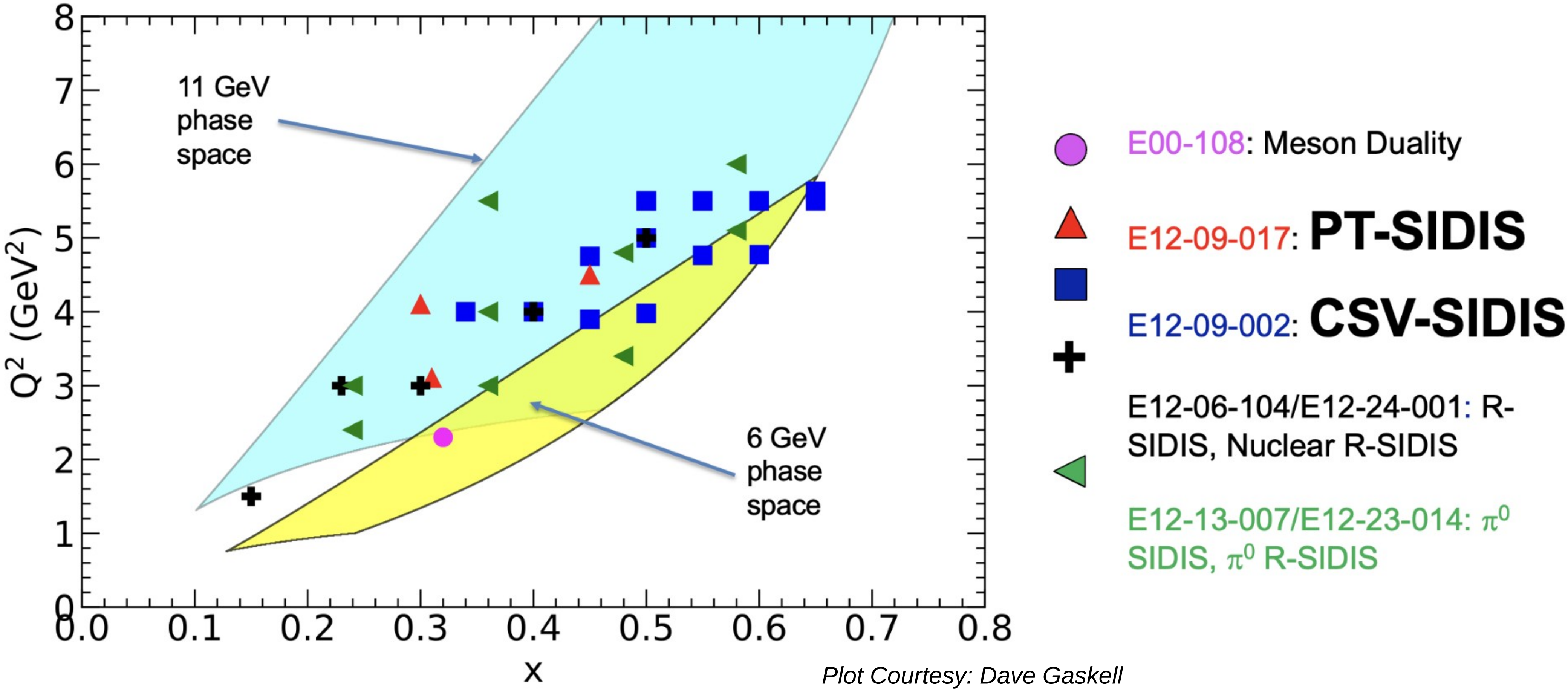
Favored (D^+) or Unfavored (D^-) Fragmentation: struck quark flavor is same as or different than the quark constituent of detected pion

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

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



Hall C SIDIS Kinematics (Charged and Neutral Pions)

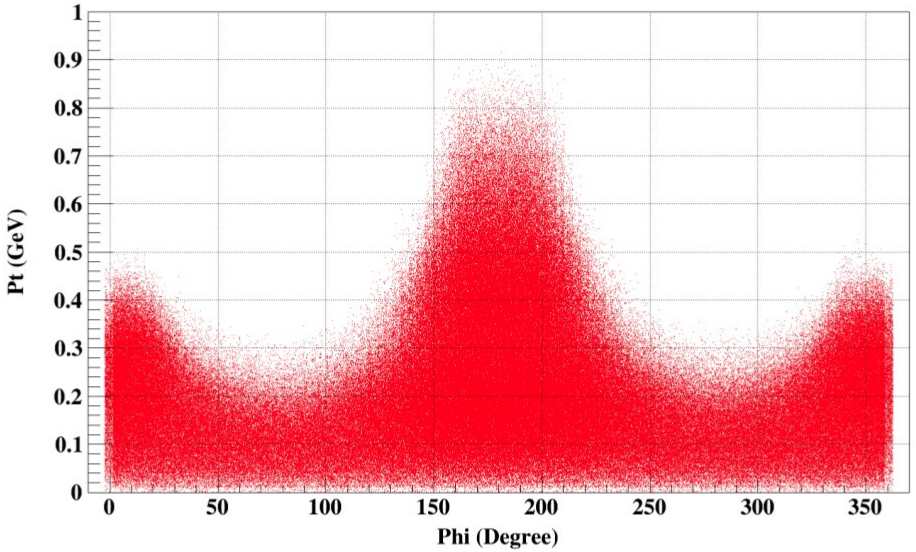


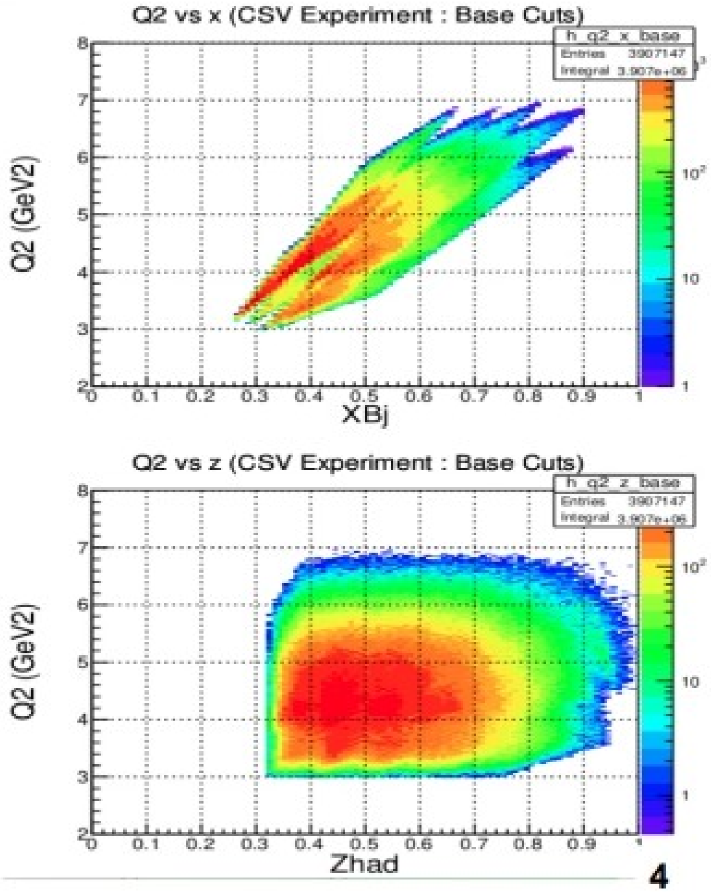
Plot Courtesy: Dave Gaskell

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

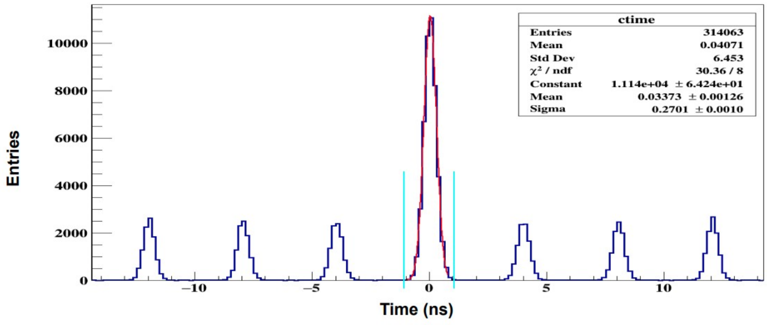
Detected Pion Momentum:
1.9 GeV/c – 4.5 GeV/c

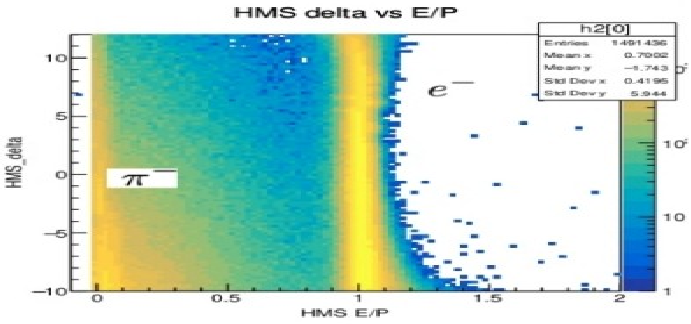
HMS angle:
13-49 Degrees
SHMS angle:
6-30 Degrees
H2, D2, Al targets

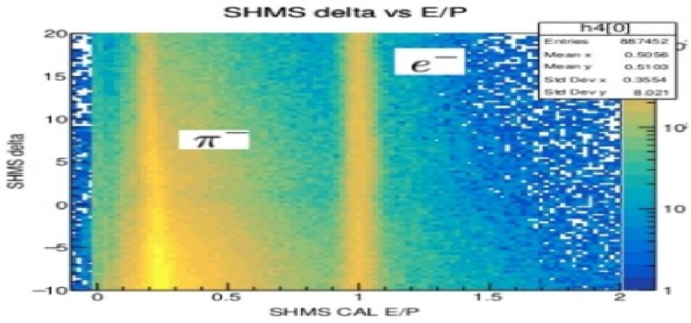


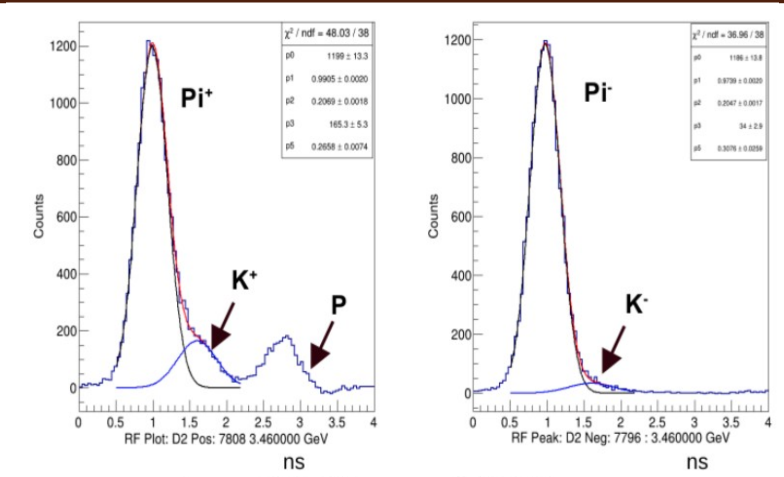


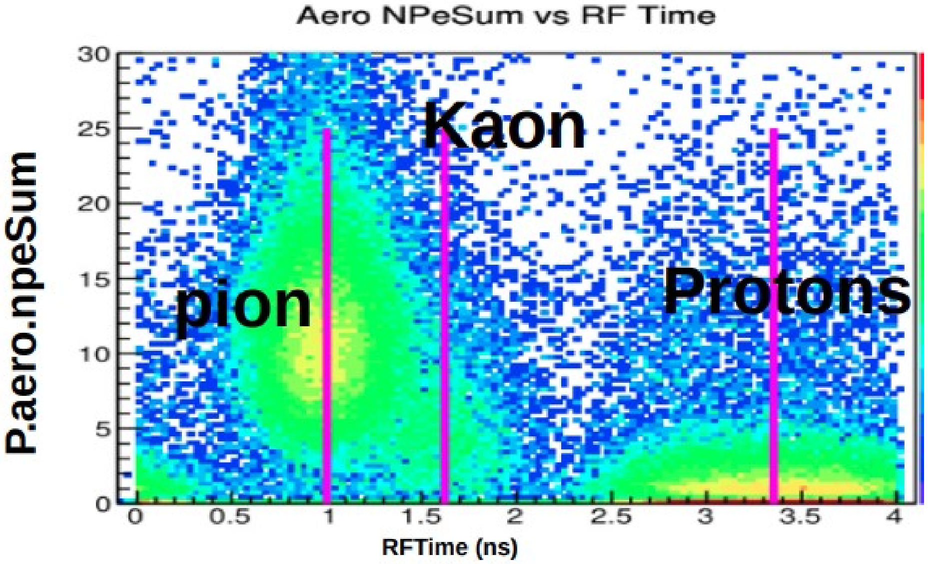
Precise Particle Identification





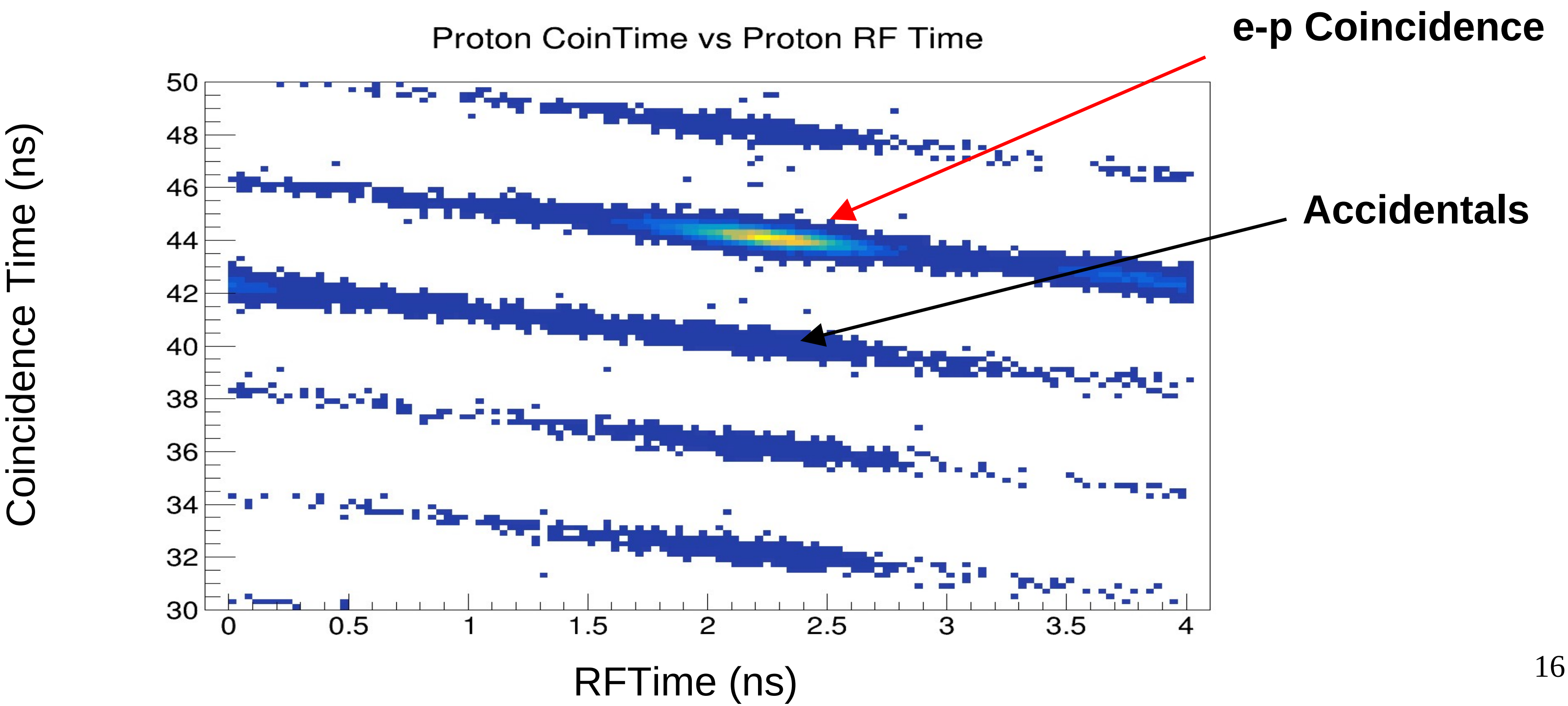






Electron-Proton Coincidence

$$e + P \rightarrow e' + P + X$$



Does SIDIS protons play role for Signature of Baryon Junction?

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi^*\,dP_T^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}(1+\frac{\gamma^2}{2x})$$
$$\left\{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi^*)F_{UU}^{\cos(\phi^*)} + \epsilon\cos(2\phi^*)F_{UU}^{\cos(2\phi^*)}\right\}$$

$$\mathbf{e} + \mathbf{P} \rightarrow \mathbf{e}' + \mathbf{P} + \mathbf{X}$$

where $F_{UU,T}$, $F_{UU,L}$, etc., are structure functions, ϵ is the virtual photon polarization, $\gamma = \frac{2Mx}{Q}$, $y = \frac{\nu}{E}$, ϕ^* is the azimuthal angle, and Q^2 is the four-momentum transfer squared.

Unlike pion SIDIS, the proton in SIDIS may not originate from quark fragmentation but from target fragmentation or baryon junction mechanisms.

$$\frac{d\sigma}{dP_T^2} = C \cdot \exp\left(-\frac{P_T^2}{\langle P_T^2\rangle}\right)$$

To study the transverse momentum dependence of SIDIS protons, we integrate over all other kinematics except P_T^2, and extract $\frac{d\sigma}{dP_T^2}$. The exponential slope of this distribution may be sensitive to nonperturbative baryon transport mechanisms such as baryon junctions.

Summary

- Exploring whether baryon number can be transported via gluonic junctions.

- Junction exchange predicts slow fall-off in forward baryon rapidity.

- SIDIS protons offer a probe of non-valence baryon number transport.

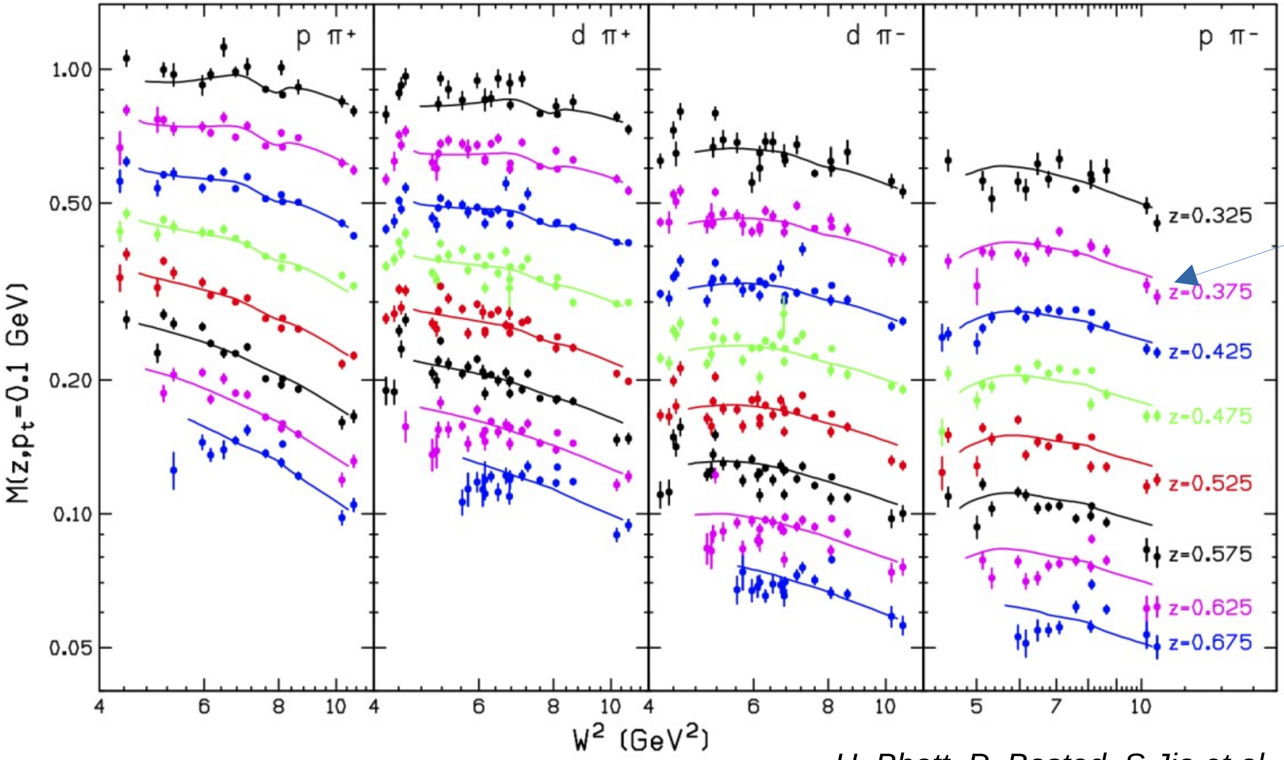
- Ongoing analysis tests these predictions using Jefferson Lab Hall C data.

Thank You

Pion-SIDIS Analysis

Charged Pion Multiplicities (SIDIS/DIS) from proton and deuterium

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



Empirical fits

Low P_t (< 0.25), integrated over ϕ

H. Bhatt, P. Bosted. S.Jia et al, Phys.Lett.B 865 (2025), 139485

Factorization in SIDIS pion electroproduction

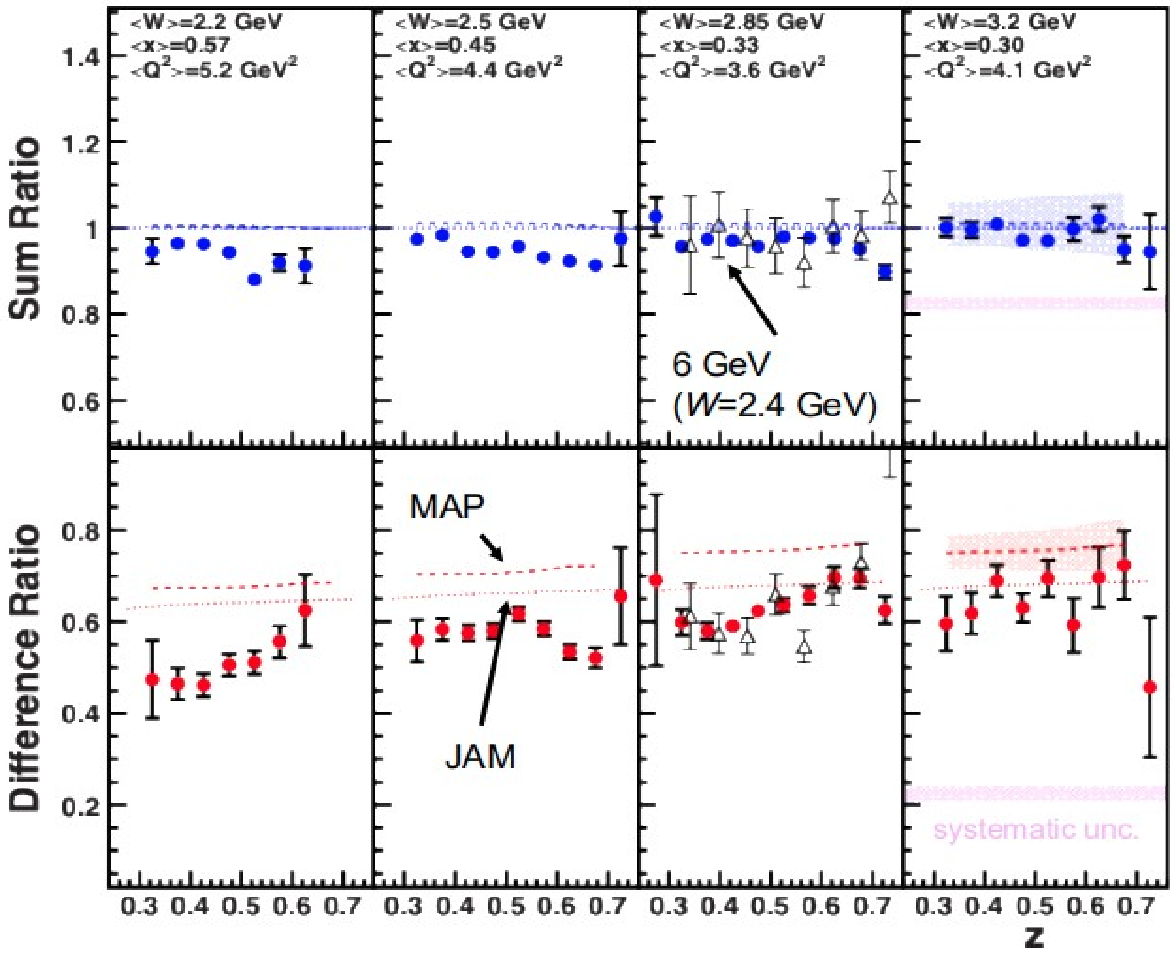
Assuming:
a)Charge symmetry in PDFs

b)symmetric sea quark contributions

c)Pt dependence is same for Pi+ and Pi- from both H2 and D2

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

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



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Flavor Dependent Fragmentation Functions

Under charge and isospin symmetry: 8 FFs => 2 FFs

$$D^{+} = D_{u}^{\pi^{+}} = D_{d}^{\pi^{-}} = D_{\bar{u}}^{\pi^{-}} = D_{\bar{d}}^{\pi^{+}}$$ → Favored fragmentation function

$$D^{-} = D_{u}^{\pi^{-}} = D_{d}^{\pi^{+}} = D_{\bar{u}}^{\pi^{+}} = D_{\bar{d}}^{\pi^{-}}$$ → Unfavored fragmentation function

Under charge symmetry in PDFs, but not in FFs: 8 FFs => 2 FFs

$$D_{fav}^{+} = D_{u}^{\pi^{+}} = D_{\bar{u}}^{\pi^{-}} \qquad D_{fav}^{-} = D_{d}^{\pi^{-}} = D_{\bar{d}}^{\pi^{+}}$$ → 2 favored FFs

$$D_{unf}^{+} = D_{d}^{\pi^{+}} = D_{\bar{d}}^{\pi^{-}} \qquad D_{unf}^{+} = D_{d}^{\pi^{+}} = D_{\bar{d}}^{\pi^{-}}$$ → 2 unfavored FFs

Flavor Dependent Fragmentation Functions

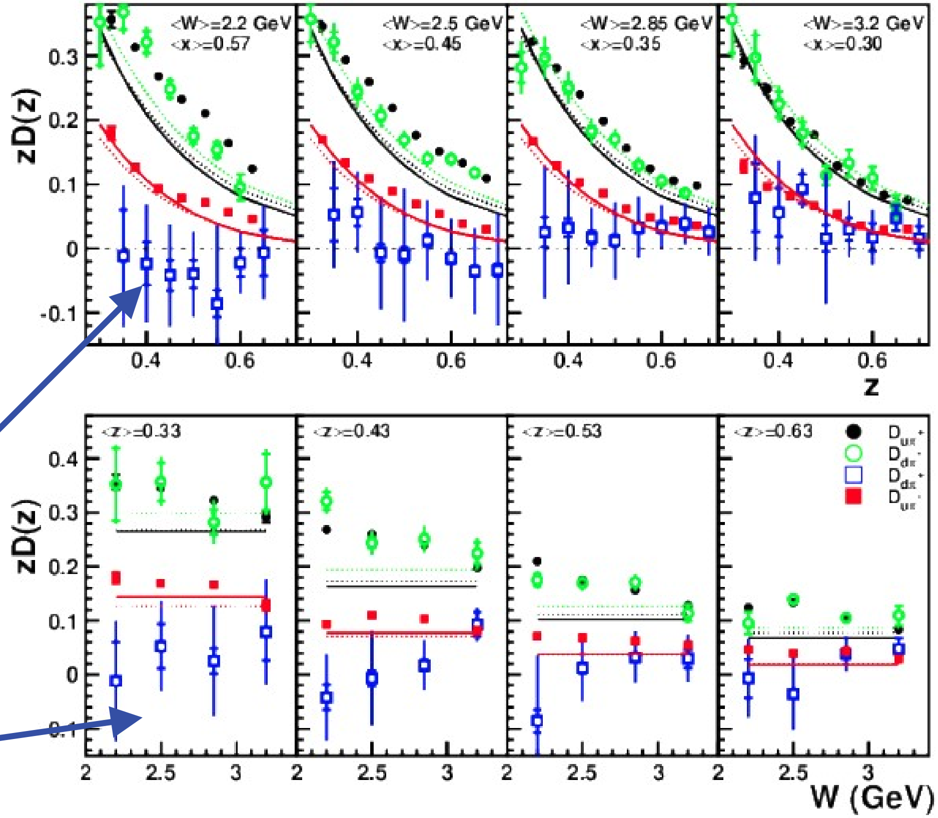
4 multiplicities for pi+ and pi- from proton and deuteron are used to extract 4 FFs

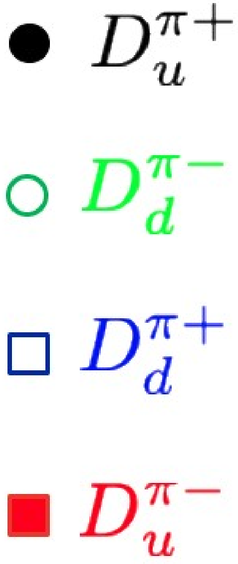
Pt < 0.25 GeV (on average 0.1 GeV).

Similar Pt dependence for pions from proton and deuteron

At high x, and low W, there is more deviation in two unfavored FFs

The uncertainties for $D_d^{\pi+}$ are larger due to small differences in flavor dependent multiplicities





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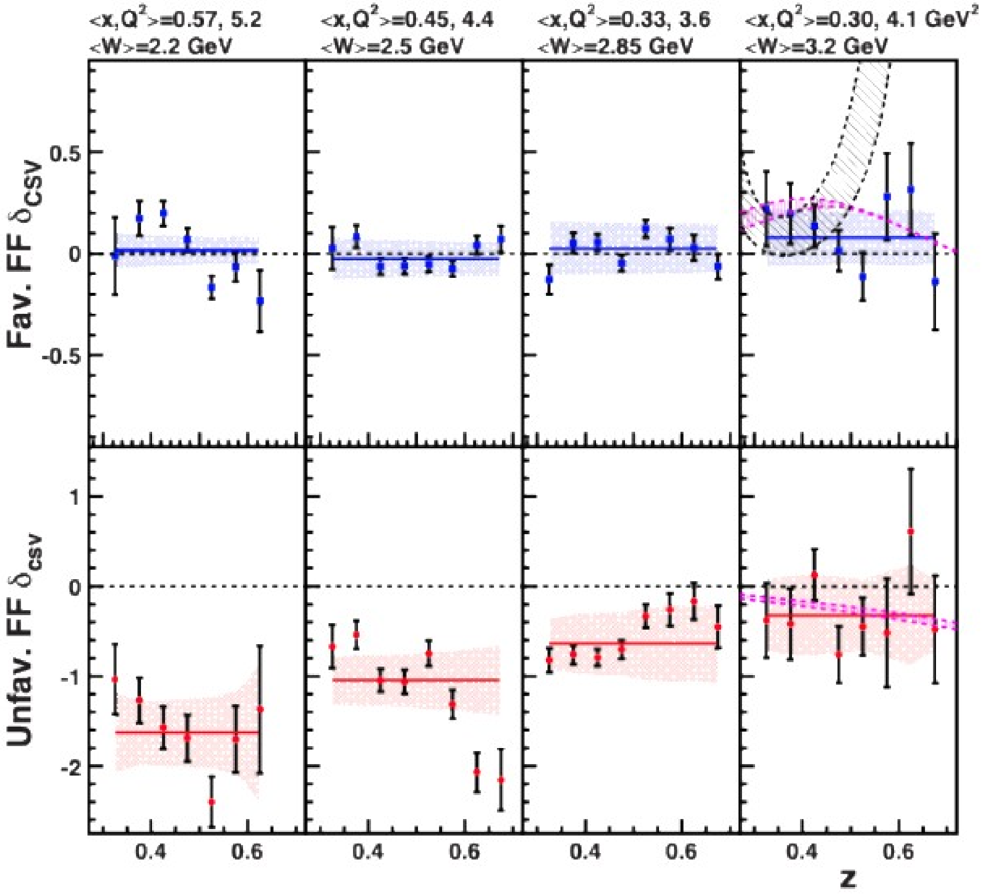
CSV in Fragmentation Functions

For better vizualization of charge symmetry violation in Ffs, we can define two CSV parameters for favored and unfavored Ffs as:

$$\delta^{f}_{\rm CSV}(z) = \frac{D_{d\pi^-} - D_{u\pi^+}}{D_{u\pi^+}}$$

$$\delta^{uf}_{\rm CSV}(z) = \frac{D_{d\pi^+} - D_{u\pi^-}}{D_{u\pi^-}}$$

Favored CSV parameter is consistent with zero, while unfavoed CSV parameter shows significant deviation at lower W (larger x).
=>At low W: the fragmentation is more complex process.



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Rapidity (y^*)

The rapidity of the produced baryon in the γ*-p center of mass frame is given by:

$$\mathbf{y}^* = \frac{1}{2}\ln\left(\frac{E^*+p_z^*}{E^*-p_z^*}\right)$$

E^*: total energy of the final-state baryon in the γ*-p center-of-mass frame,

p_z^*: longitudinal momentum (along beam direction) of the baryon in the same frame.

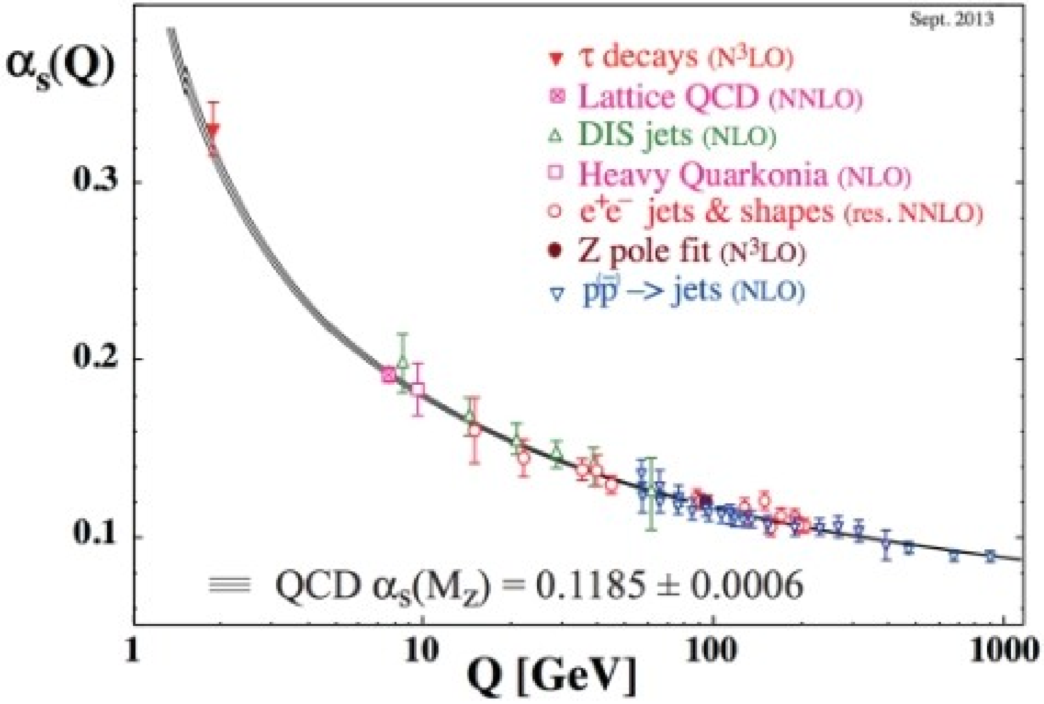
Rapidity describes the rate at which a particle is moving with respect to a choosen reference point situated on the line of motion.

$$y^* = \tanh^{-1}\left(\frac{p_z}{E}\right)$$

https://www.phenix.bnl.gov/WWW/publish/erichard/tutorials/abbotkinematics.pdf

Strong Coupling Constant

Q: Momentum exchange between the probe and the struck parton, similar to the resolving power.



Higher Q (shorter distances), the strong force becomes weaker, this phenomenon is called asymptotic freedom.

Higher Q: More complex internal substructure.