Target Single-Spin Asymmetry in Inclusive Hadron Production

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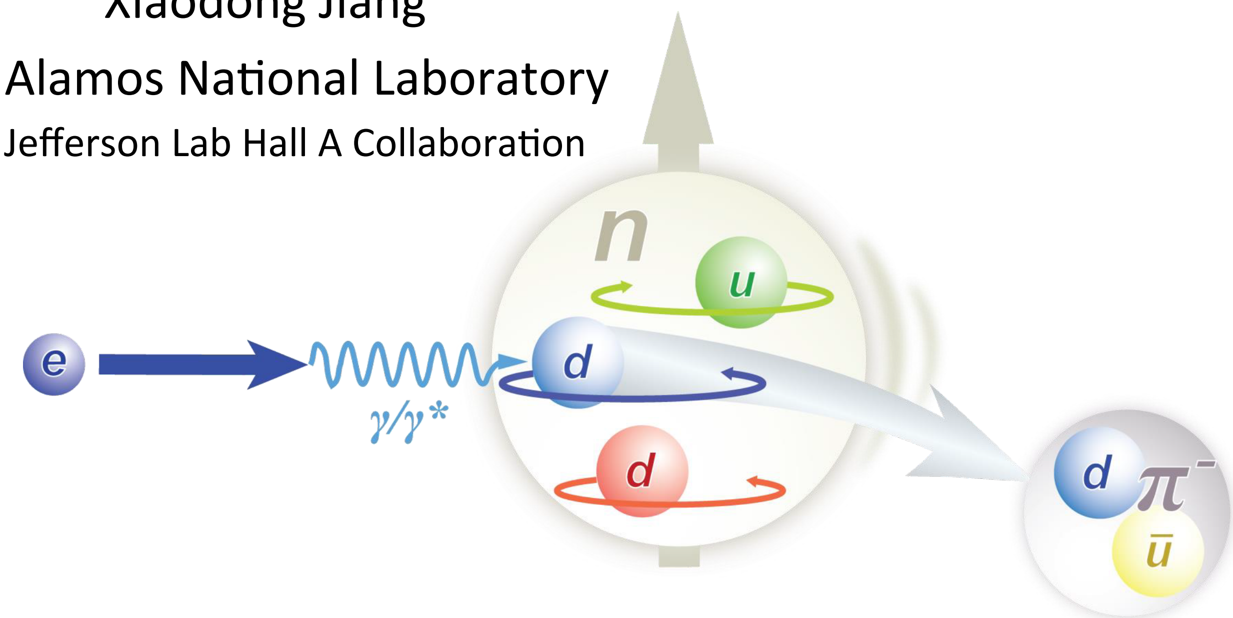
for Jefferson Lab Hall A Collaboration

$$^{3}\text{He}^{\uparrow}(e,h)X$$

$$h = \pi^{+/-}, K^{+/-}$$



Quarks inside a transversely polarized nucleon have a clear left-right bias:

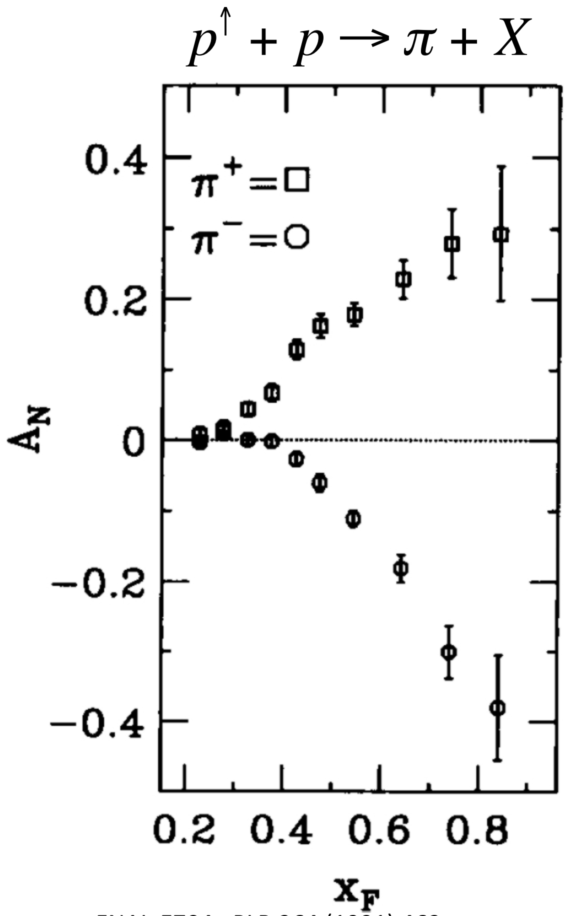
- Inclusive hadron in p↑+p→h+X
- Semi-Inclusive DIS e+N↑ →e'+h+X
- **Inclusive hadron in e+N↑ →h+X**

K. Allada *et al*, Phys. Rev. C 89, 042201(R), 2014

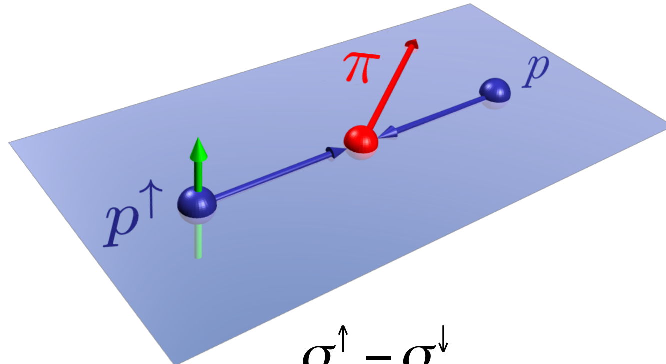
Many surprises in SSA.

Is there a common link ?

Quarks can tell left-right in $p\, p^{\uparrow} \rightarrow \pi X$



FNAL-E704: PLB 264 (1991) 462.



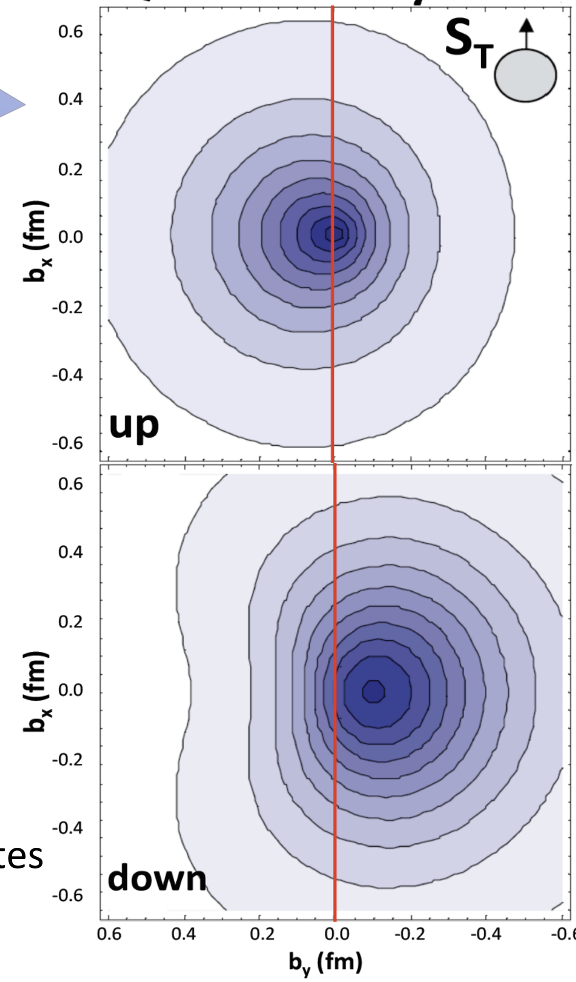
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$\pi^+ \ (u\bar{d})$ favors left

$\pi^- \ (d\bar{u})$ favors right

One explanation (Sivers effect):
quark's transverse motion generates a left-right bias.

Quark Density in 2D



Lattice QCD PRL98:222001,2007.

up-quarks favor left (L_u>0), down-quarks favor right (L_d<0).

Viewing along the polarized proton's momentum direction,

$\pi^+ \ (u\bar{d})$ favors the left-side, $\pi^- \ (d\bar{u})$ favors the right side of the proton spin vector.

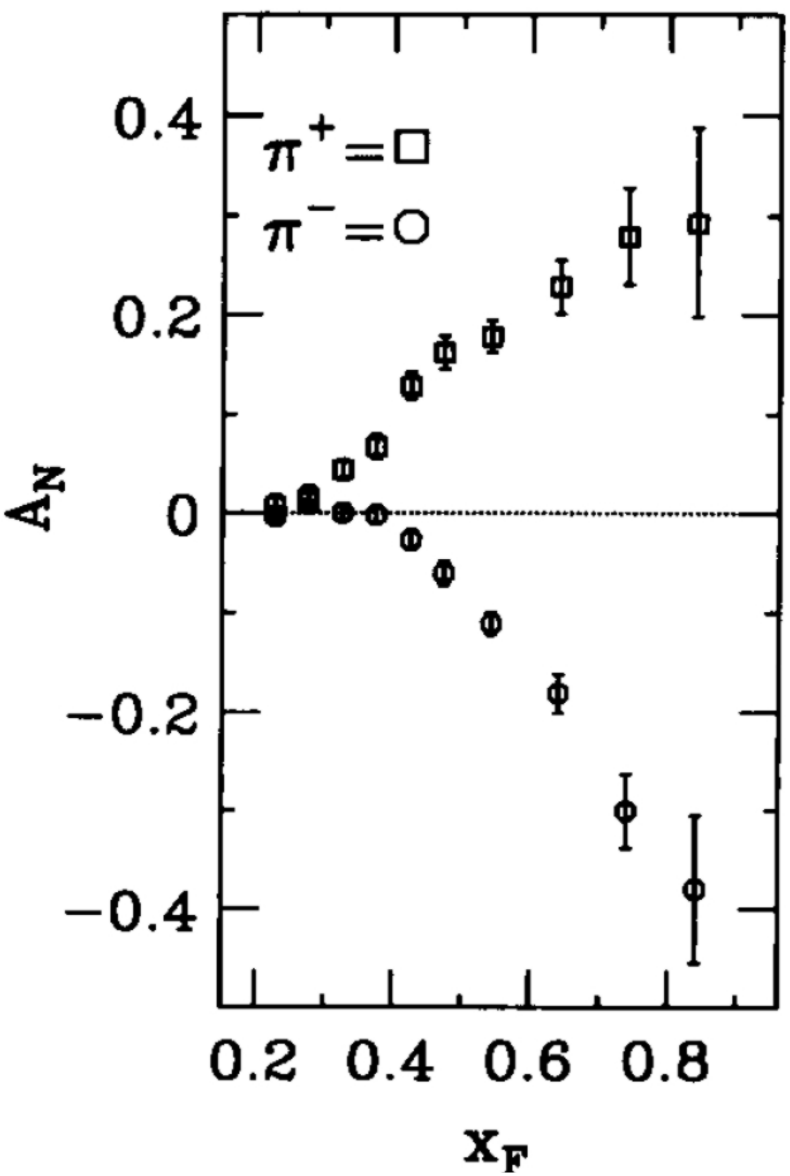
E704 √s =20 GeV.

PLB 264 (1991) 462.

Analyzing power in inclusive π^+ and π^- production at high x_F with a 200 GeV polarized proton beam

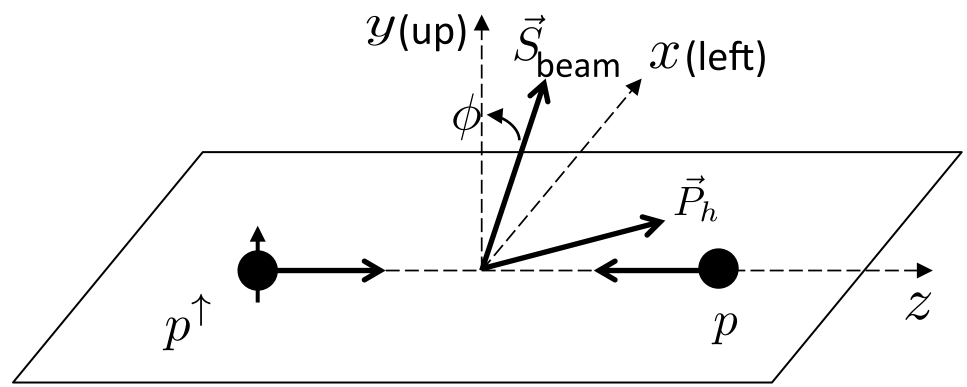
FNAL E704 Collaboration

$$p^{\uparrow} + p \rightarrow \pi + X$$



$$A_N = -\frac{1}{P_B \cos\phi} \frac{N_{\uparrow}(\phi) - N_{\downarrow}(\phi)}{N_{\uparrow}(\phi) + N_{\downarrow}(\phi)},$$

ϕ is the azimuthal angle between the beam polarization direction and the normal to the $\pi^{\pm}$ production plane. $N_{\uparrow(\downarrow)}$ is the number of pions produced for beam spin tagged as positive (negative) normalized to the beam flux. P_B is the average beam polarization. The negative sign in front of the equation is due to the fact that the detection occurred to the right of the beam.



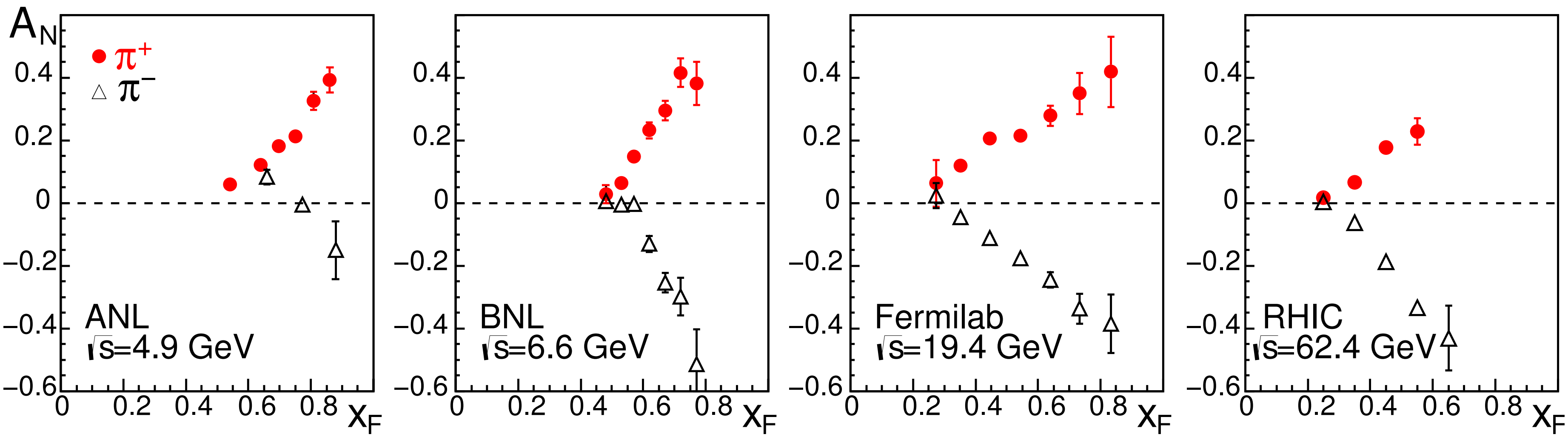
Viewed along the momentum direction of p↑:

π^+ favors the left side of the polarized proton.

π^- favors the right side of the polarized proton.

Inclusive Hadron Single Spin Asymmetries in p↑+p

Large, forward A_N in hadron production in p+p have been measured since the mid 70's



Viewing along the polarized proton's momentum direction:

π^+ $(u\bar{d})$ favors the left-side, π^- $(d\bar{u})$ favors the right side of the proton spin vector.

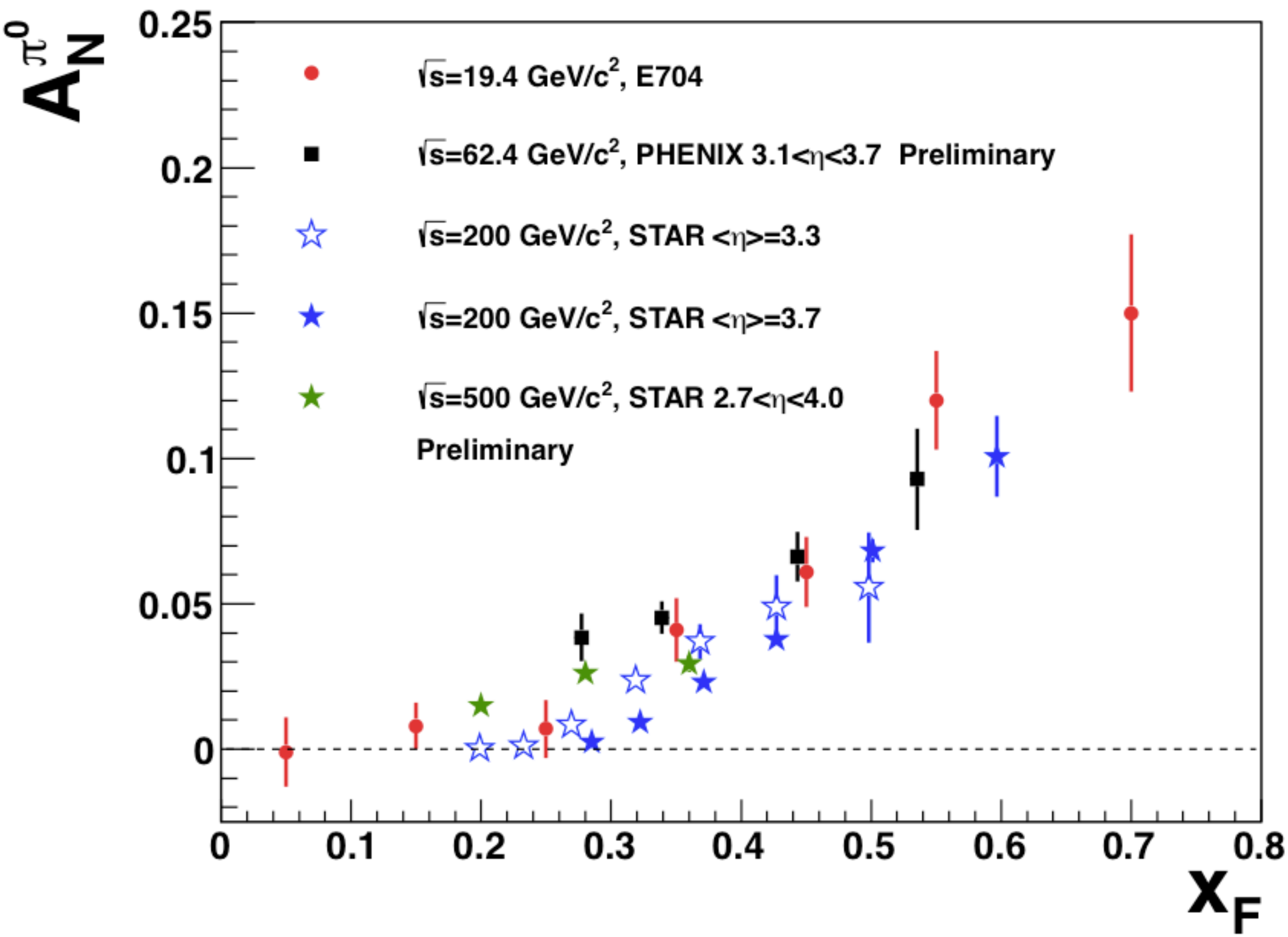
The asymmetries persist from low CM energies to high CM energies.

$$x_F = \frac{2p_L}{\sqrt{s}}$$

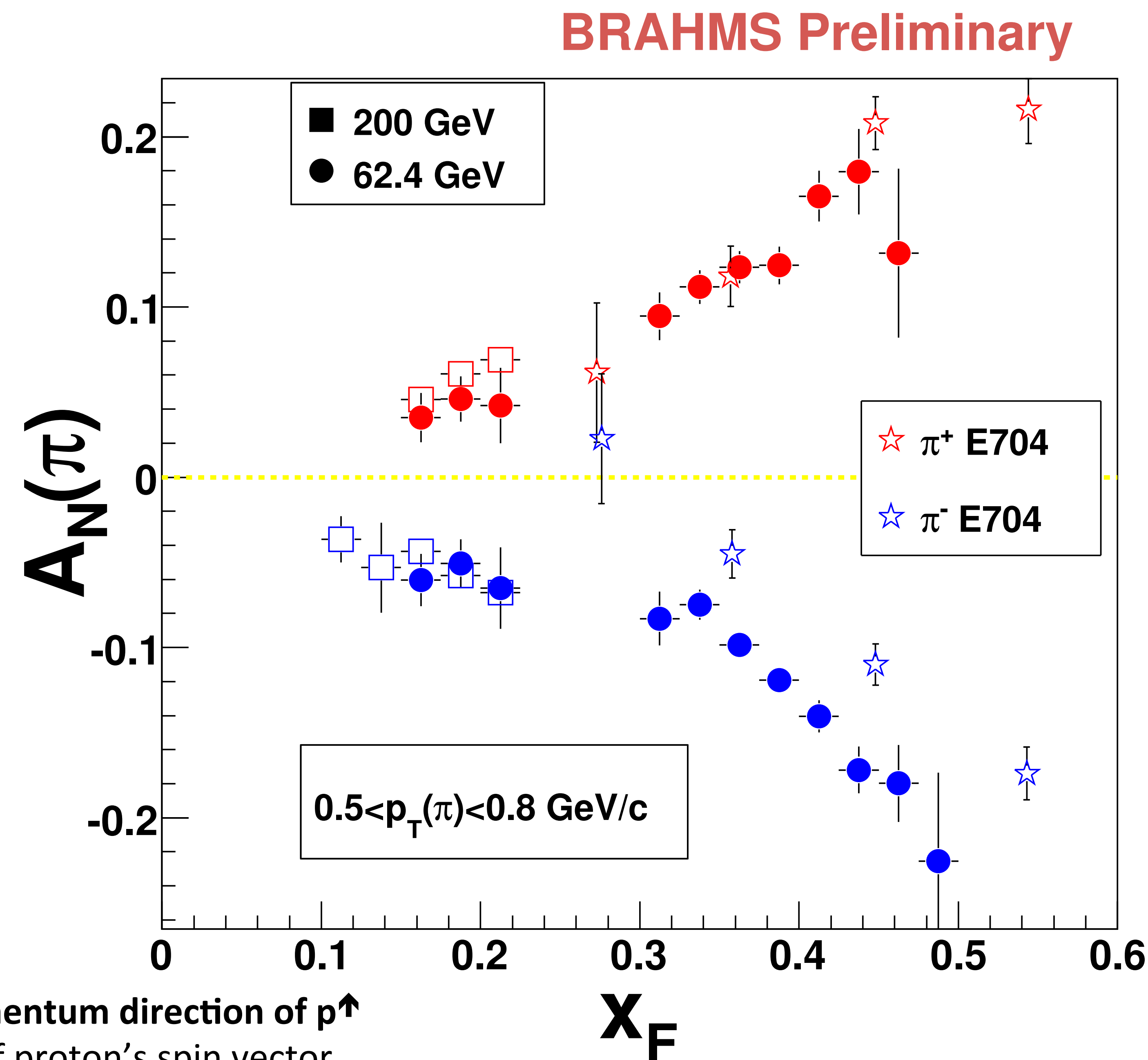
A simple (collinear) pQCD calculation tells us that an A_N can exist, but that it should scale like

$$A_N \approx \frac{m_q \alpha_S}{p_T}$$

π^0 favors the left side of proton spin vector



At 200 GeV



Viewing along the momentum direction of p↑

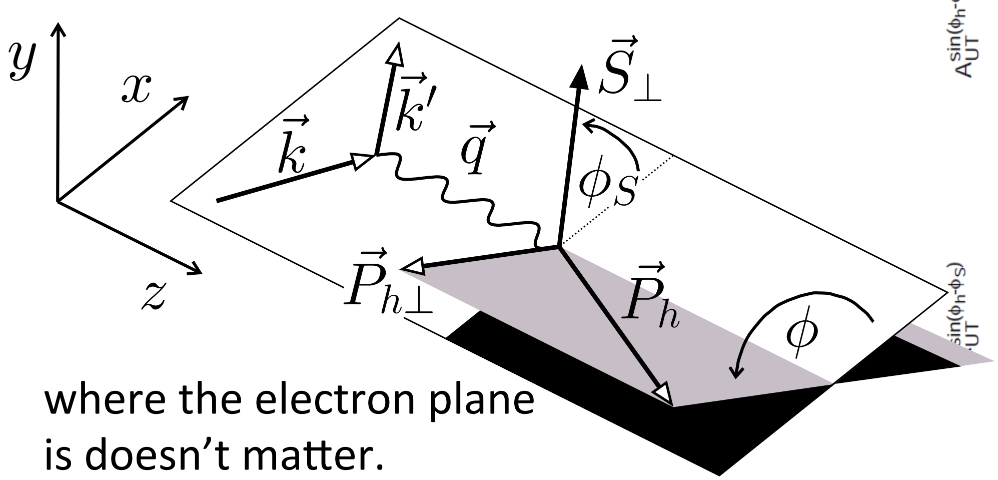
π^+ favors the left side of proton's spin vector.

π^- favors the right side of proton's spin vector.

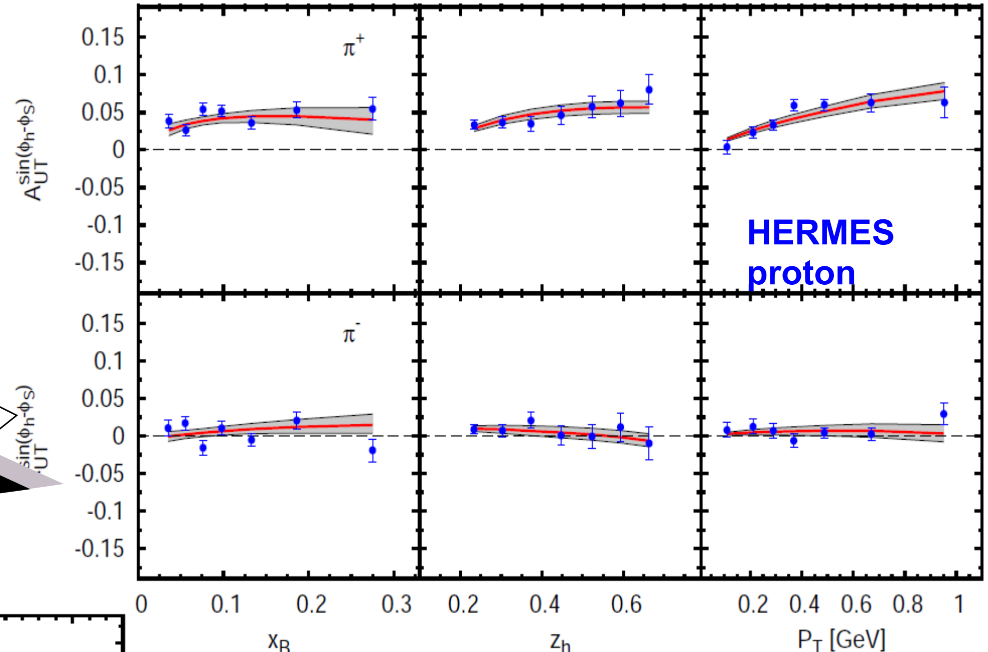
Transverse SSA in SIDIS: A_{UT} Sivers Moments

e + p↑ ⟶ e' + h + X

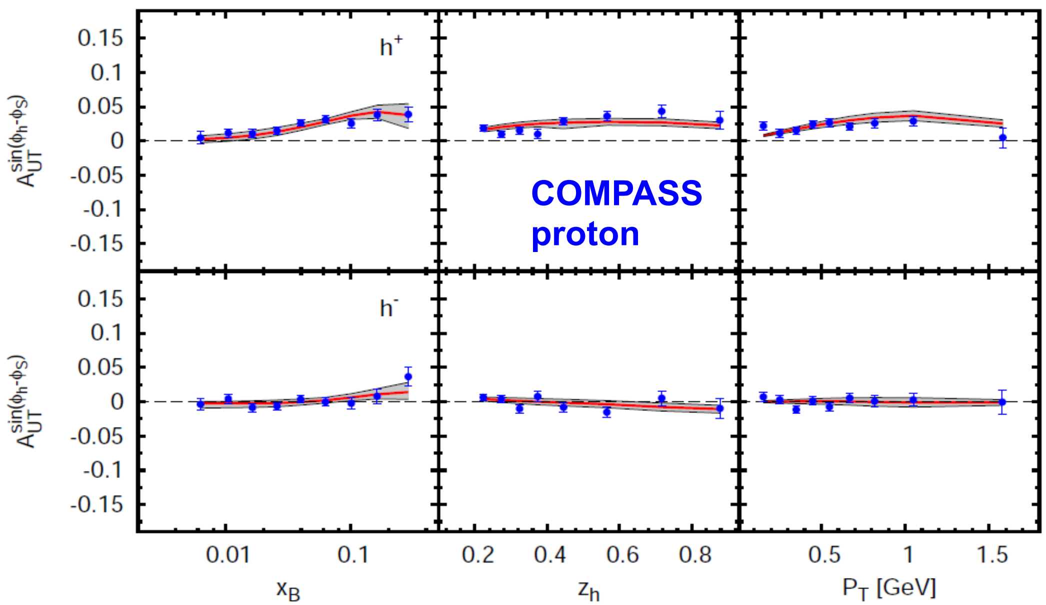
$$\sigma_{UT}^{SIDIS} \propto \sin(\phi_h - \phi_S)\ f_{1T}^{\perp} \otimes D_1$$



where the electron plane is doesn't matter.



Anselmino *et al.* arXiv:1204.1239



Non-vanishing asymmetries for π^+

Viewing along the momentum direction of p↑: **π^+ favors the left side** of proton's spin vector.

(Parity Conserving) Single-Spin Asymmetry

is a left-right asymmetry which always:

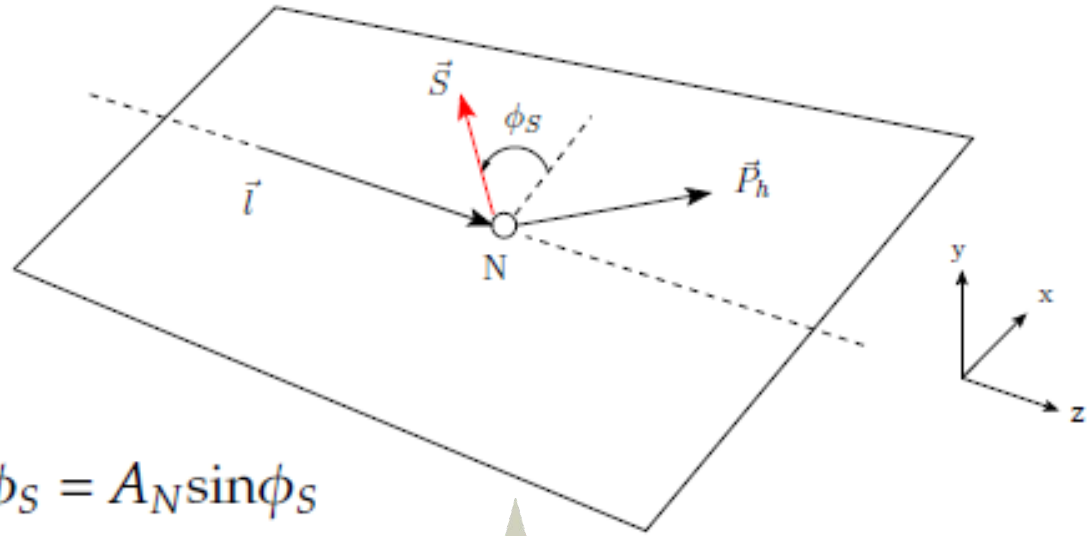
- involves a helicity flip.
- needs two more vectors in addition to the spin vector. Naïve T-Odd.
- relates to the imaginary piece of interference amplitudes. Need a phase difference.

$$A_N \propto (\vec{k}_1 \times \vec{k}_2) \bullet \vec{S}$$

Is there a left-right bias in e+N↑➔h+X ?

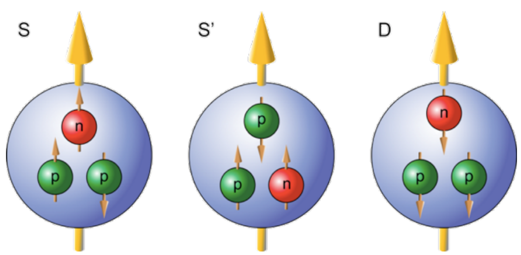
$$^3\mathrm{He}^{\uparrow}(e,h)X$$

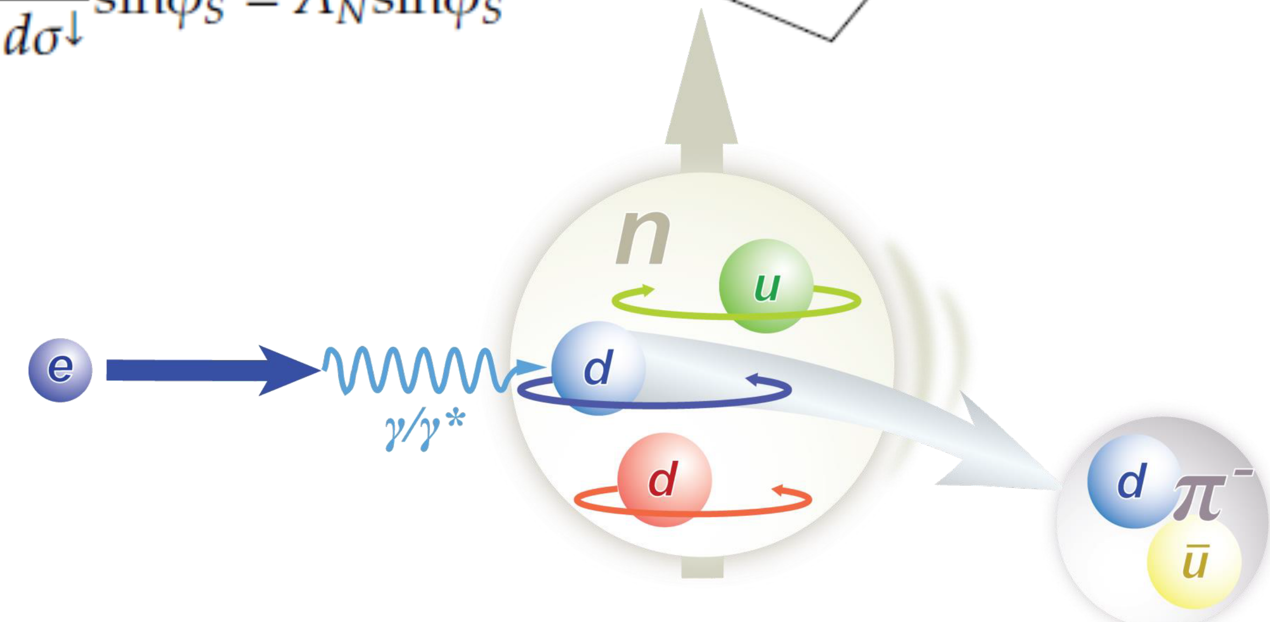
$$h=\pi^{+/-},K^{+/-}$$



$$A_{UT}(x_F,p_T)=\frac{1}{P}\frac{d\sigma^{\uparrow}-d\sigma^{\downarrow}}{d\sigma^{\uparrow}+d\sigma^{\downarrow}}\sin\phi_S=A_N\sin\phi_S$$

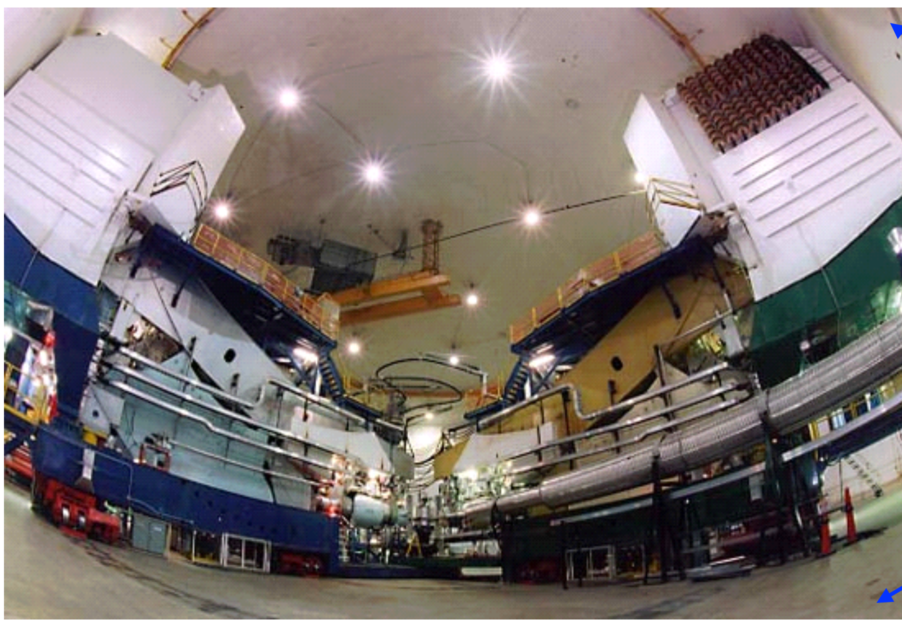
Polarized ^{3}He as an effective polarized neutron target.

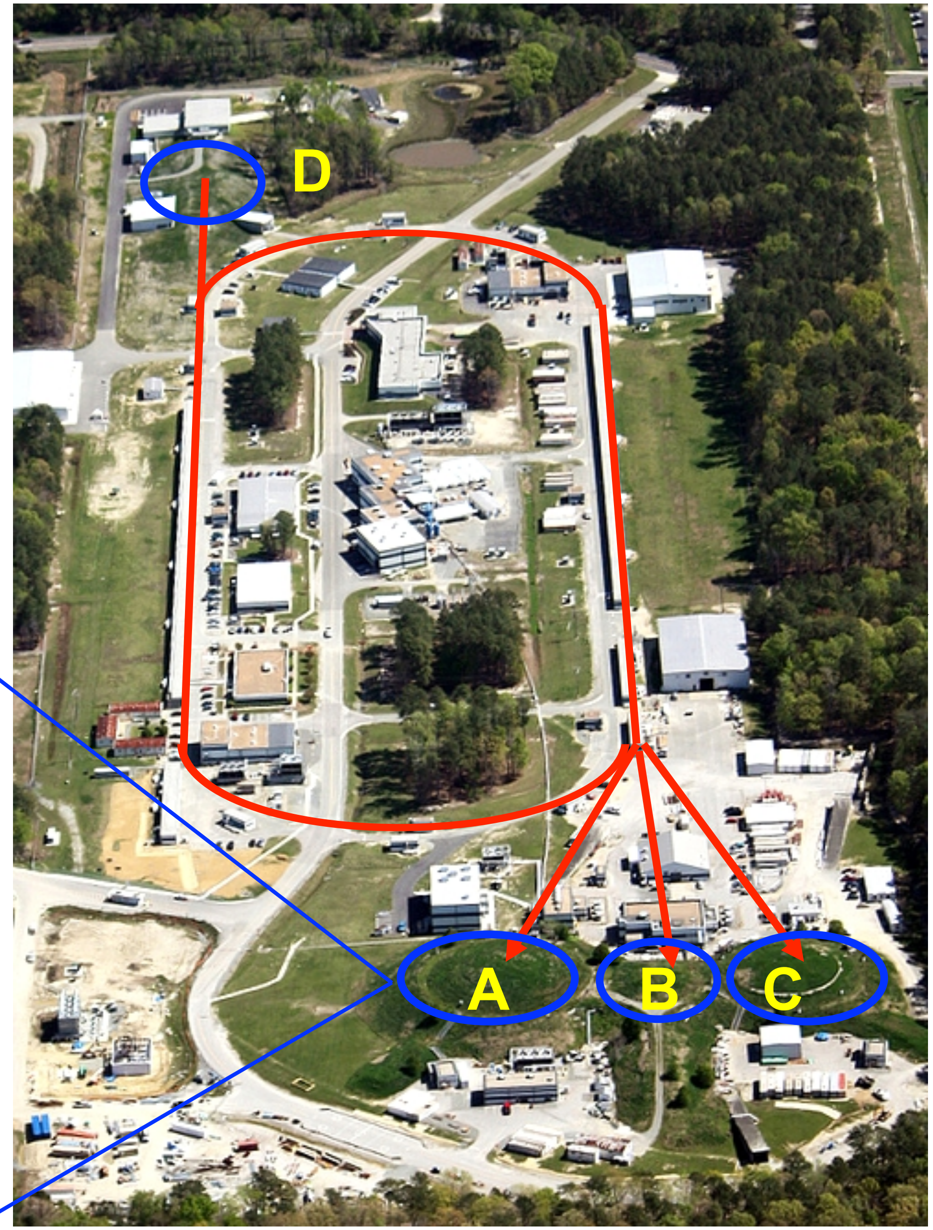




Jefferson Lab

- Run period: Oct. 2008 – Feb. 2009
- Beam energy : 6 GeV
- 40 cm long polarized ^{3}He target
- Average target polarization ~ 55%

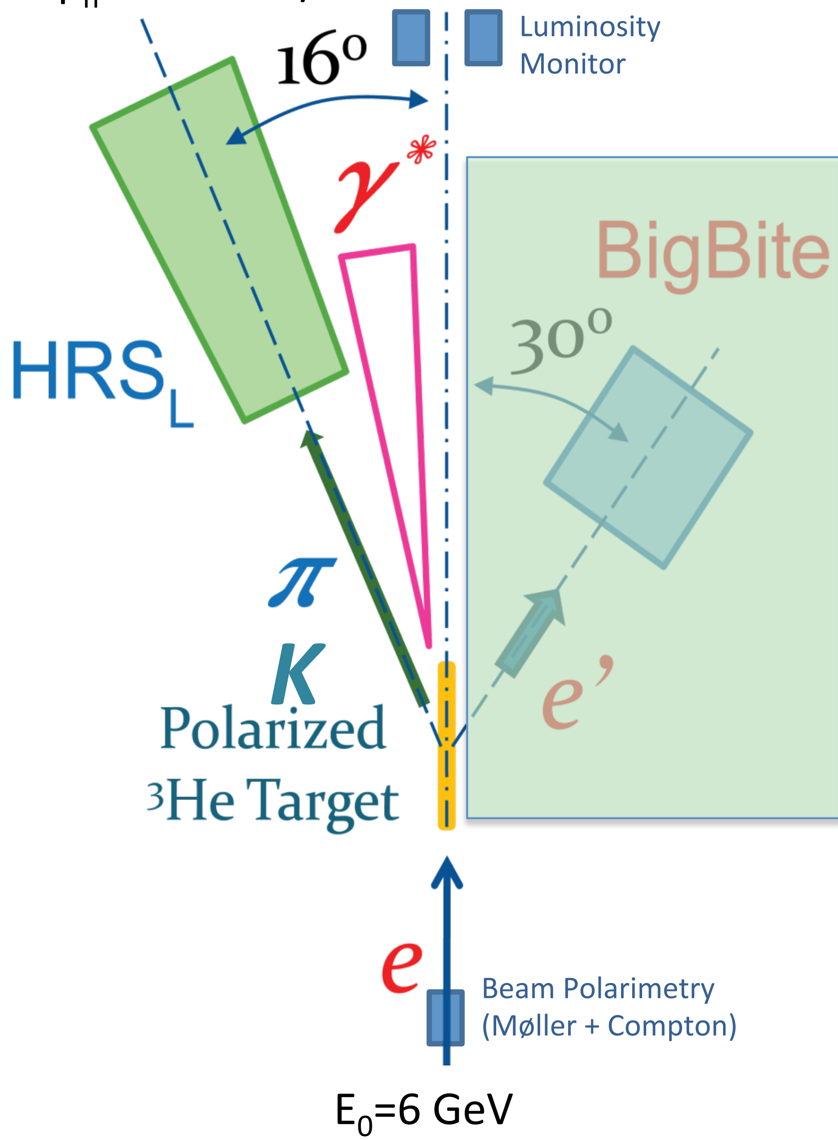


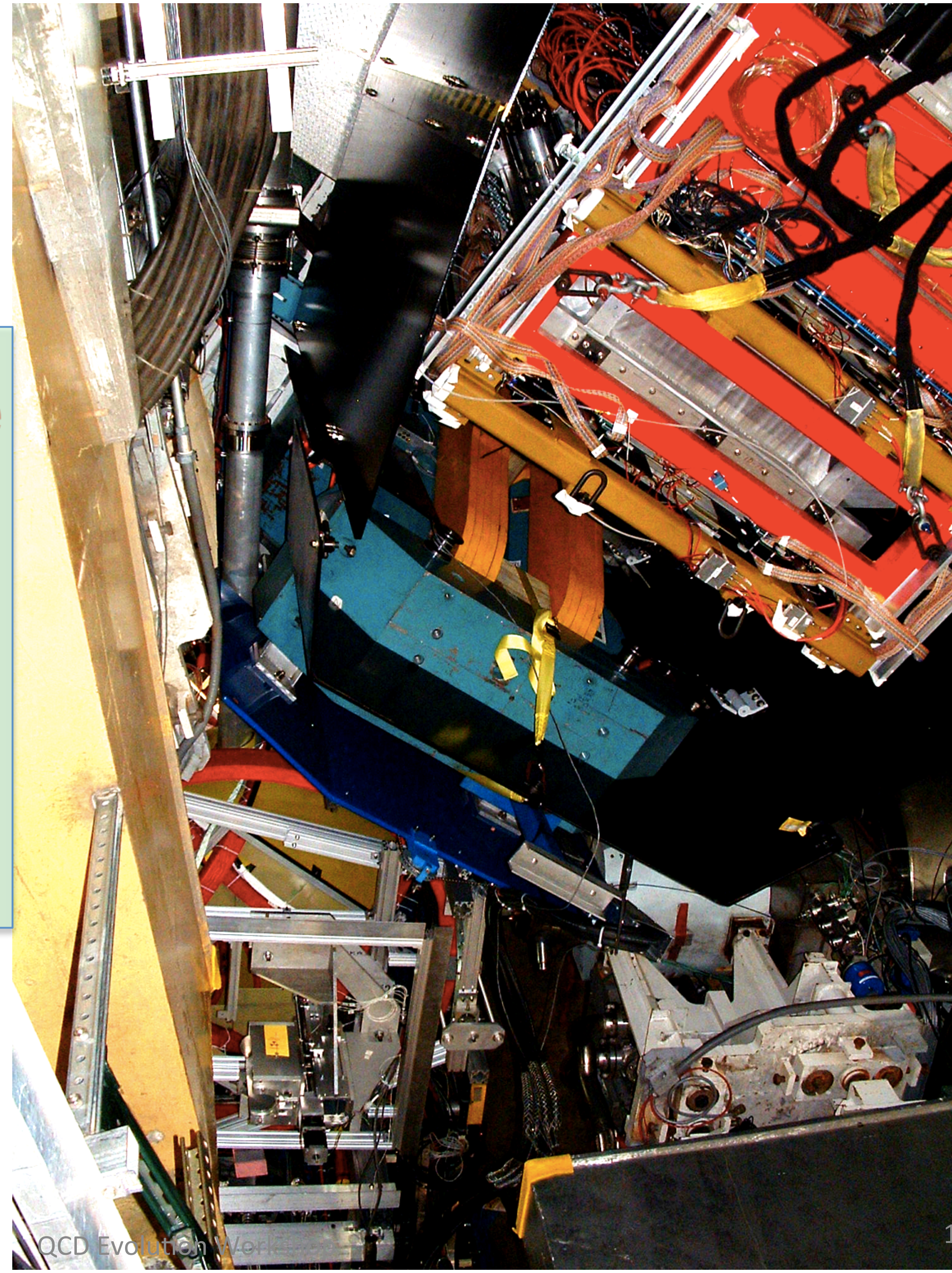


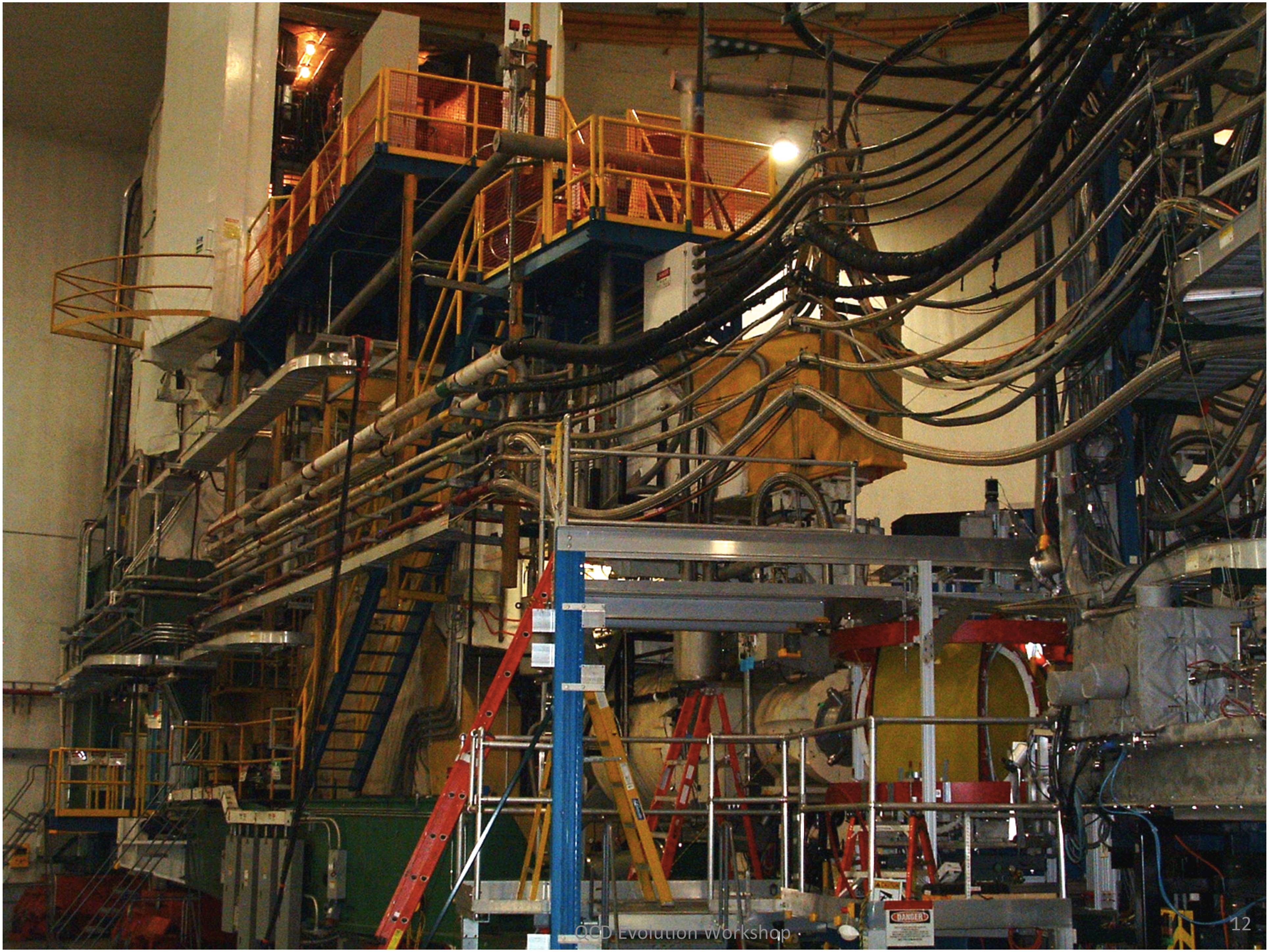
$^{3}He^{\uparrow}(e,h)X$

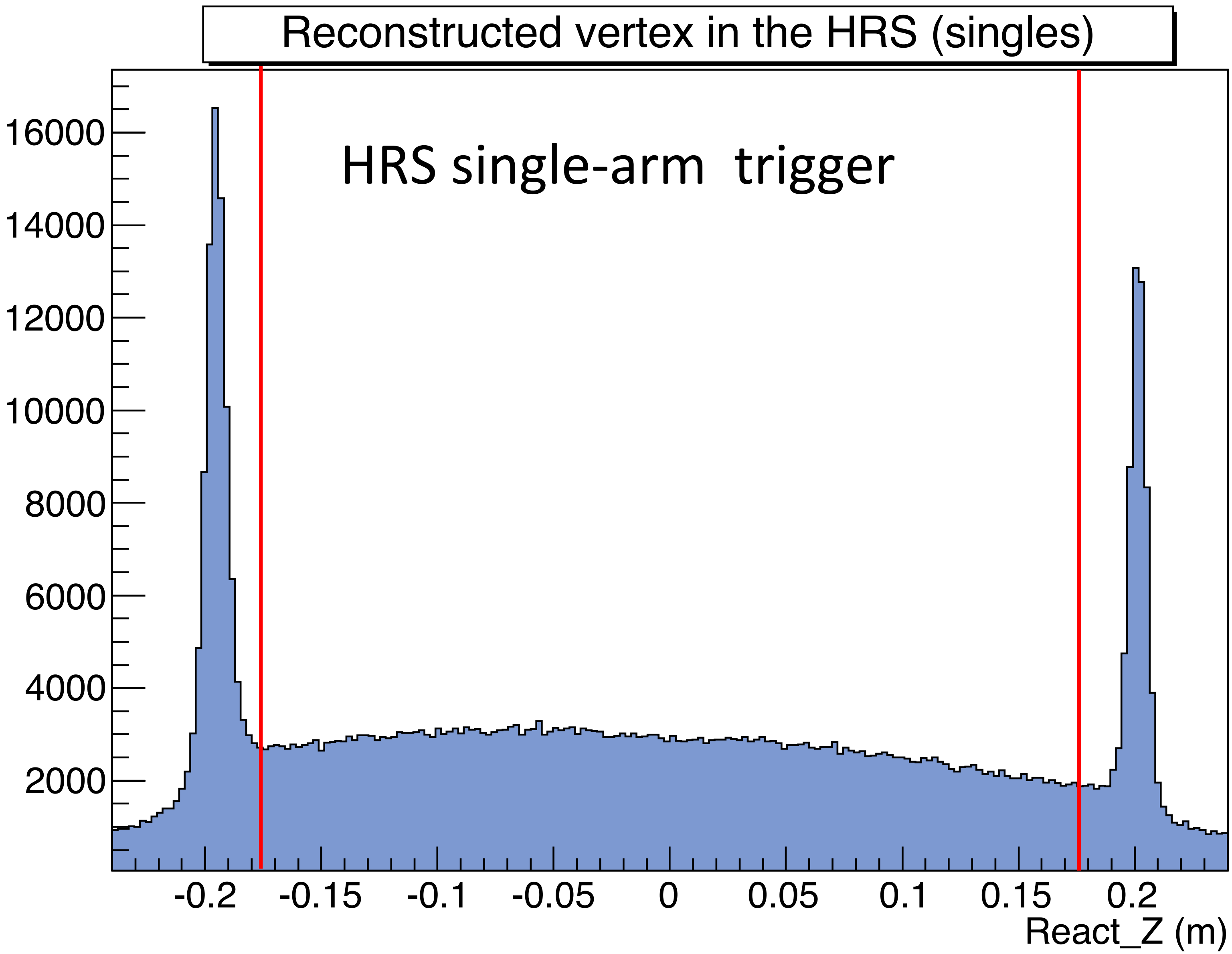
$h = \pi^{+/-}, K^{+/-}$

p_h=2.35 GeV/c





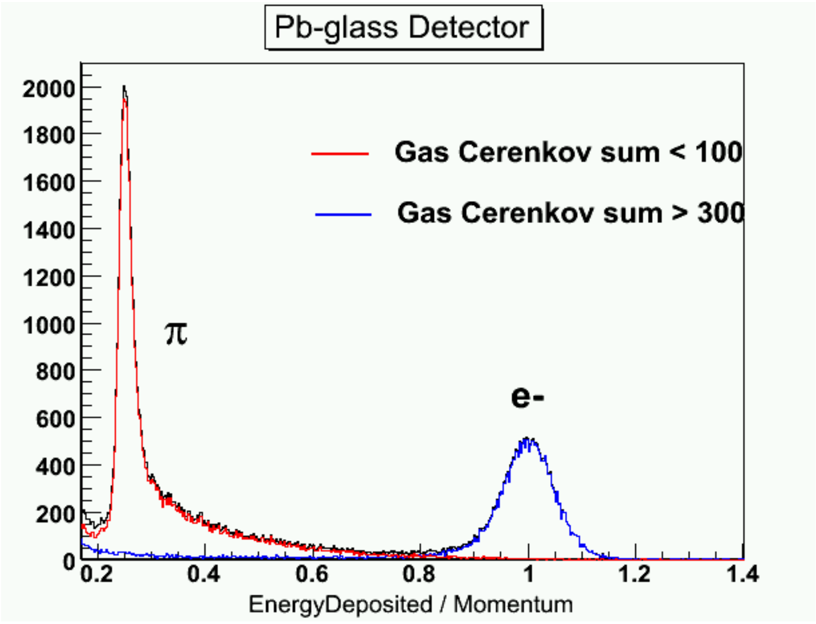


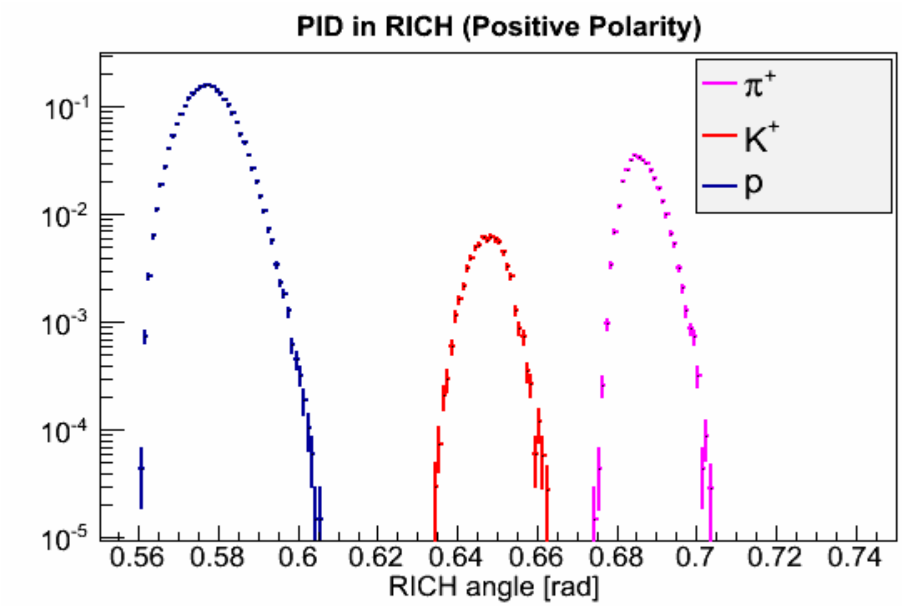

Reconstructed vertex in the HRS (singles)
HRS single-arm trigger
16000
14000
12000
10000
8000
6000
4000
2000
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
React_Z (m)

Hadron Identification in HRS

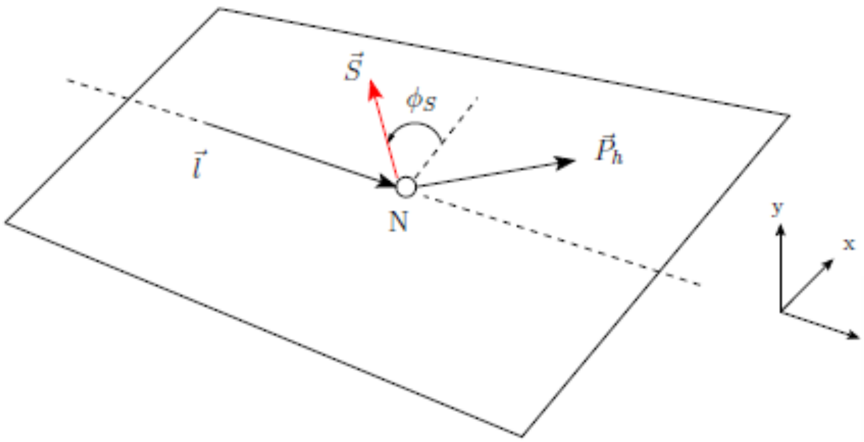
PID detectors:

- Gas Cerenkov: electron
- Aerogel counter (n=1.015): pion
- RICH detector (n=1.30): proton/Kaon/pion
- Lead-glass calorimeter: electron/hadron





Inclusive Hadron SSA: Target Spin **Transverse In-Plane**

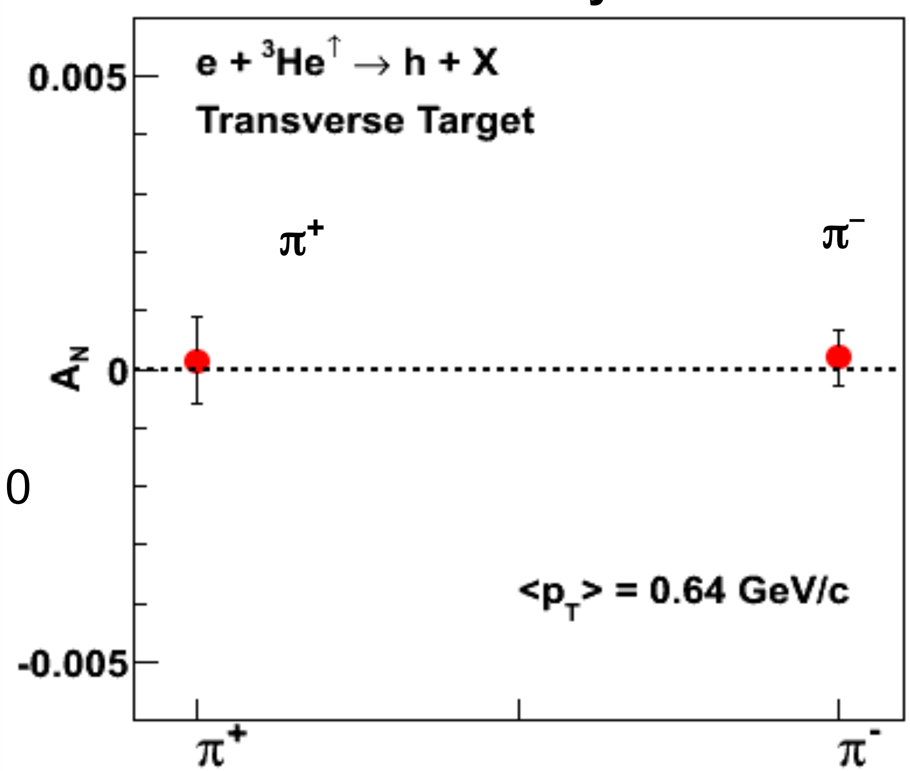


$$(\vec{k}_1 \times \vec{k}_2) \bullet \vec{S} = 0$$

$$A_{UT}^{\sin(\phi_S)}(\phi_S = 0)$$

$$A_{UT}^{\sin(\phi_S)} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

Check False Asymmetries



- Target spin flip every 20 minutes
- Acceptance effects cancels
- Overall systematic check with A_N at ϕ_S= 0
  - **False asymmetry < 0.1%**

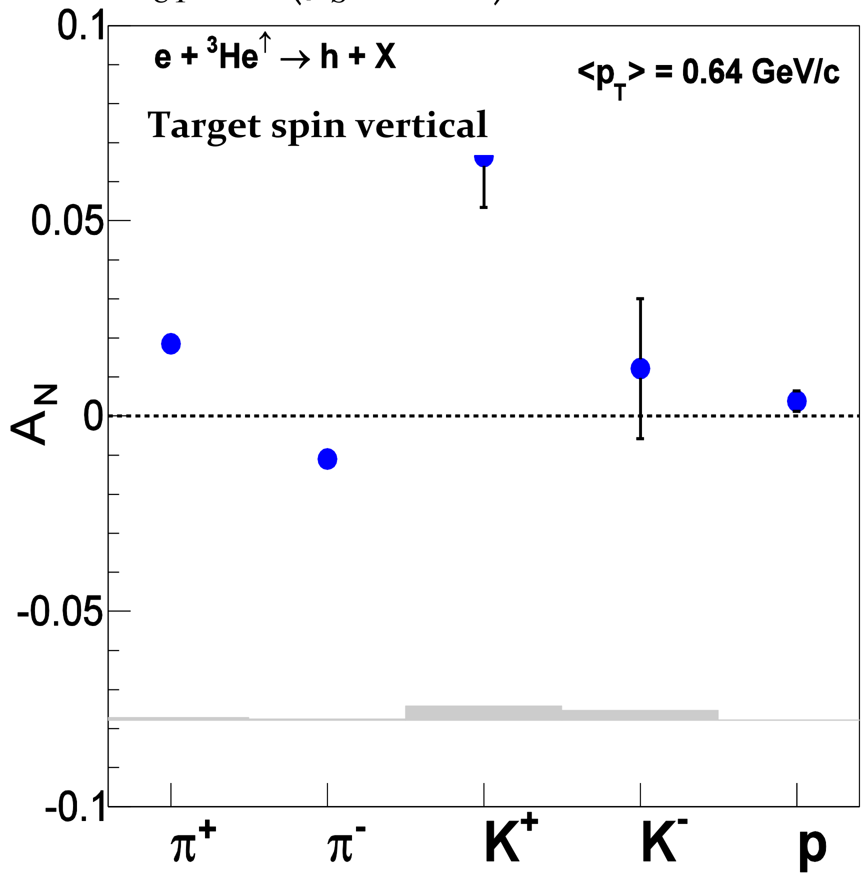
Parity conserving SSA:

$$A_N \propto (\vec{k}_1 \times \vec{k}_2) \bullet \vec{S}$$

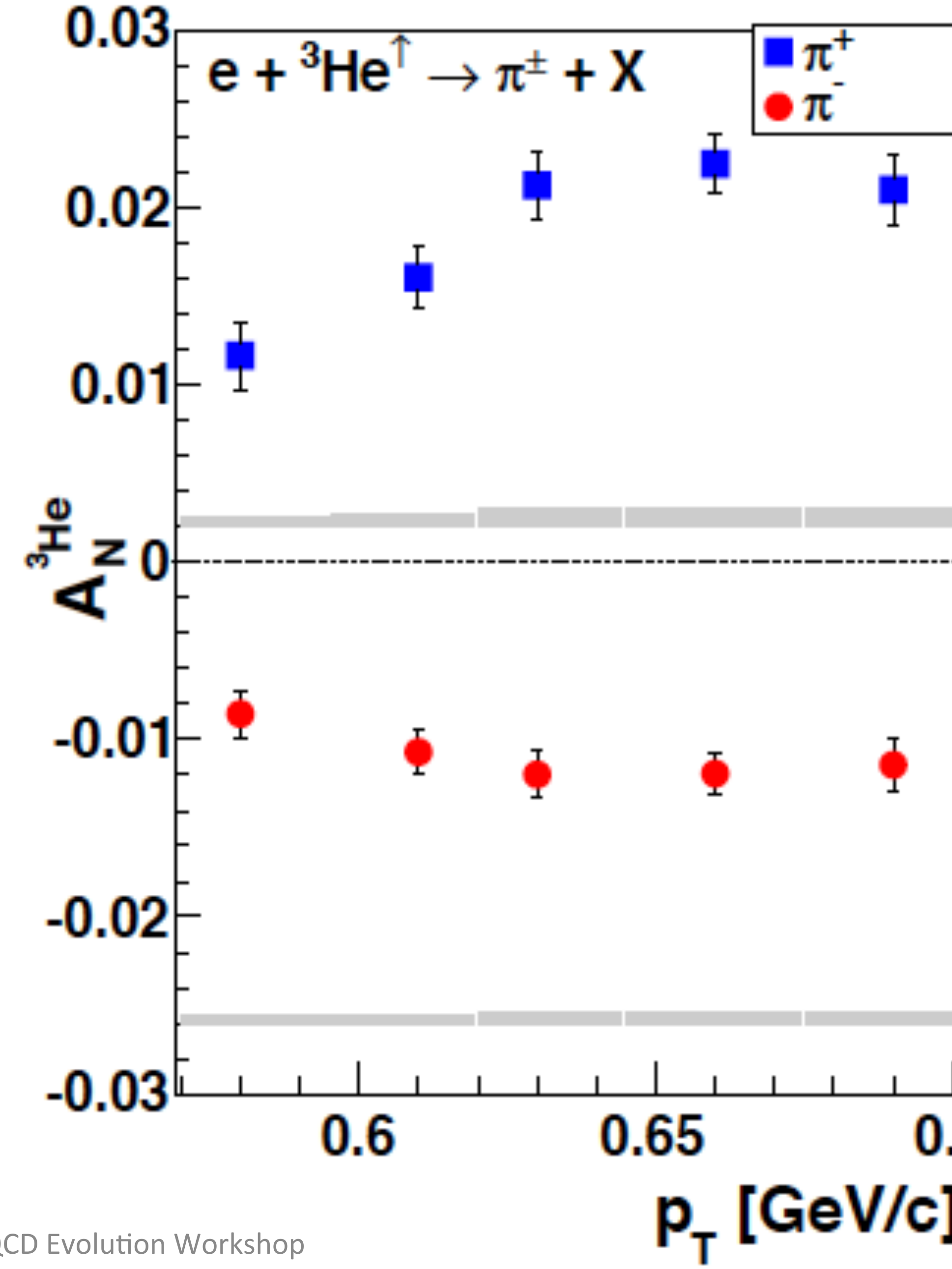
Inclusive Hadron SSA: Target Spin Vertical

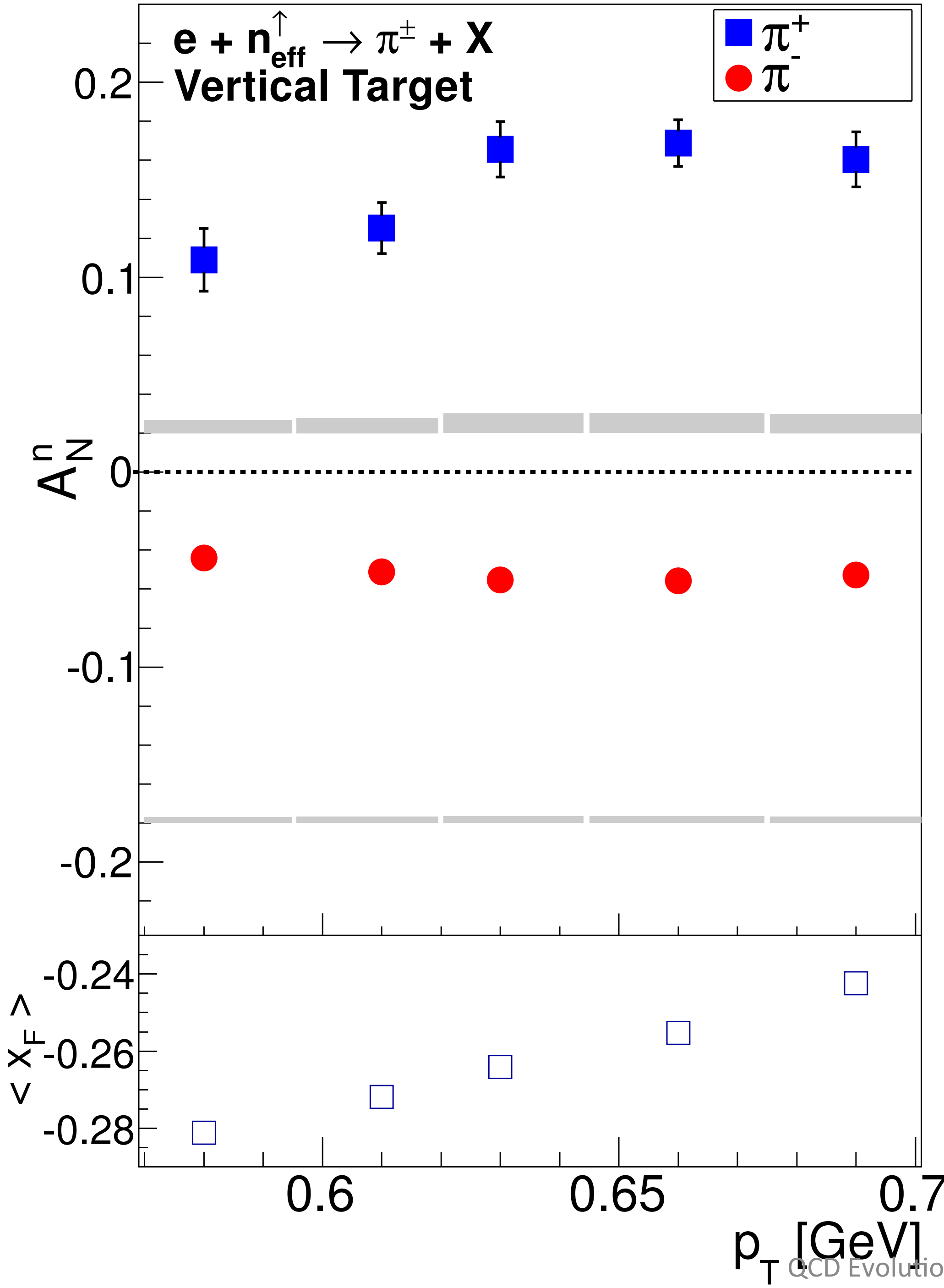
$$(\vec{k}_1 \times \vec{k}_2) \bullet \vec{S} \neq 0$$

$$A_{UT}^{\sin(\varphi_S)}\left(\varphi_S = 90^0\right)$$



K. Allada *et al*, Phys. Rev. C 89, 042201(R), 2014



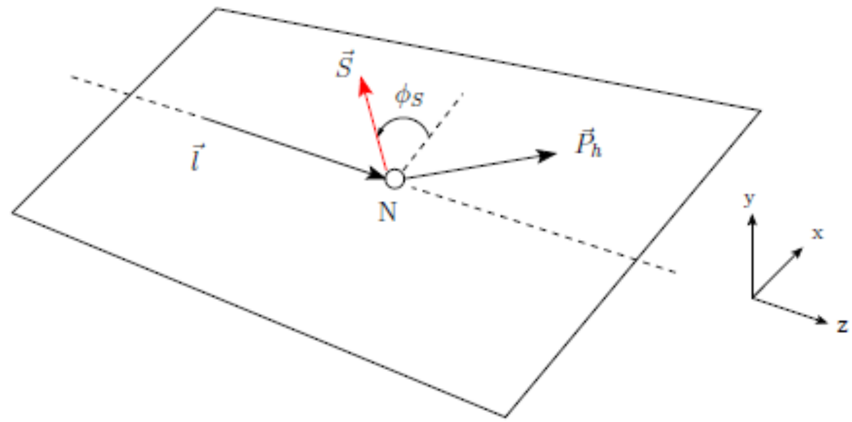


Translated into "effective neutron" SSA

$$A_{3He} = P_n * (1 - f_p) * A_n + P_p f_p A_p$$

$$P_n = 0.86^{+0.036}_{-0.02} \quad and \; P_p = -0.028^{+0.009}_{-0.004}$$

$$f_p = \frac{2\sigma_p}{\sigma_{3\text{He}}}$$

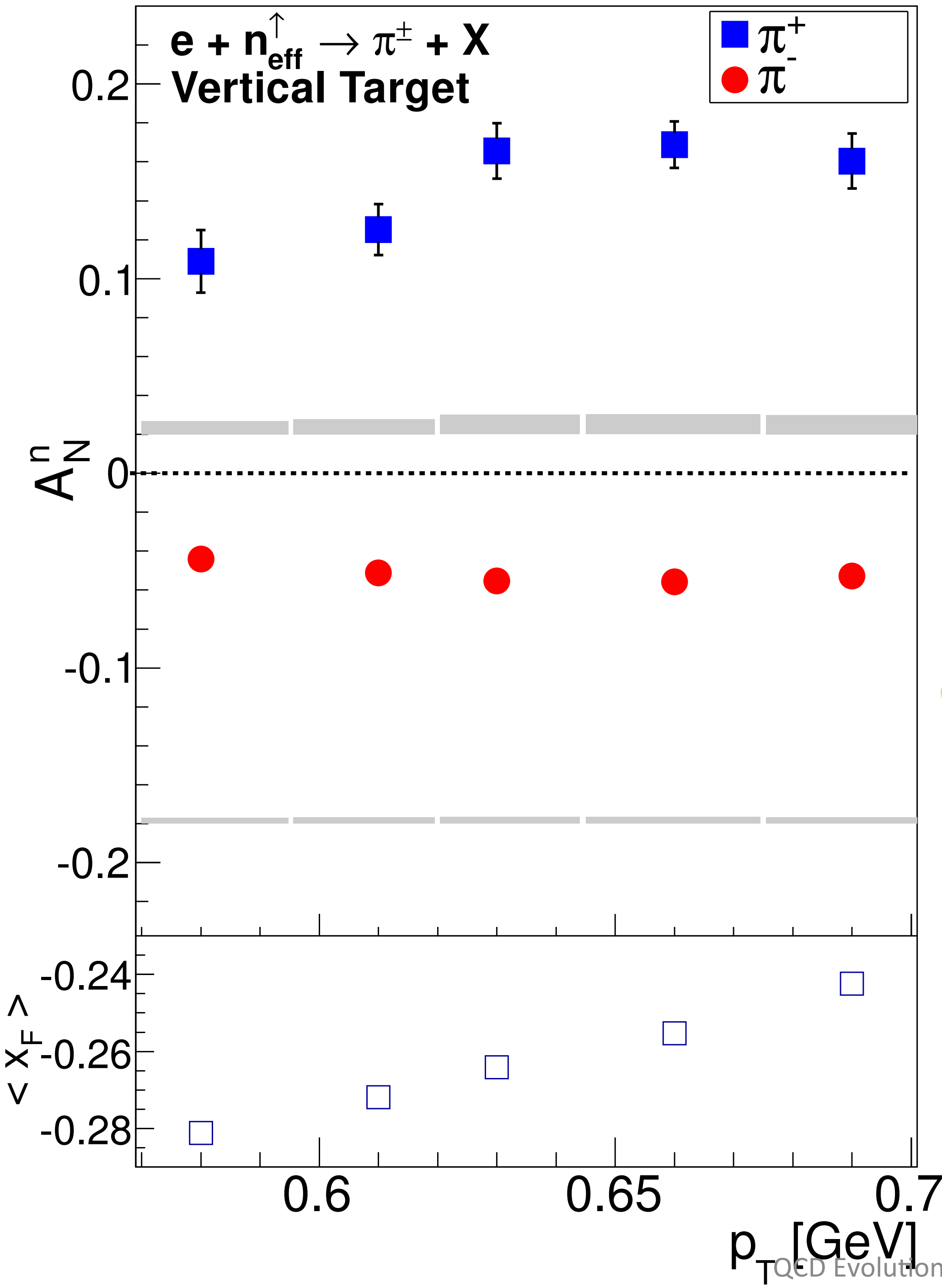


in e+n↑ center-of-mass frame,

viewed along n↑ momentum direction

π+ favors the right side of spin vector,

π− favors the left side of spin vector.



Consider the valence quarks' contribution to nucleon's anomalous magnetic moments:

Z. Lu and I. Schmidt, Phys. Rev. D 75**, 073008 (2007).**

$$\kappa_p = 1.79,\ \kappa_n = -1.91$$

$$\kappa_p = (2)(2/3)\kappa_{u/p} + (-1/3)\kappa_{d/p},$$

$$\kappa_n = (2)(-1/3)\kappa_{u/p} + (2/3)\kappa_{d/p}.$$

Thus one has $\kappa_{u/p} = 0.835,\ \kappa_{d/p} = -2.03$

we notice that for neutron:
1st-term/2nd-term= 2.43

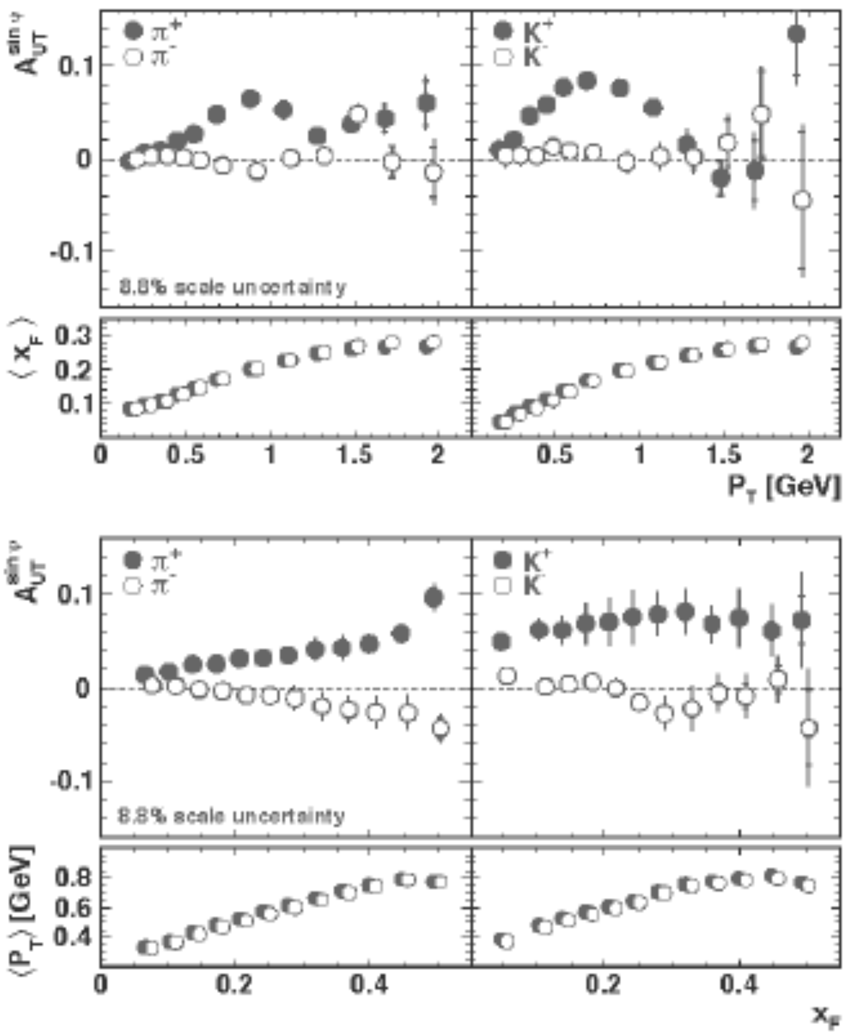
and we happened to observe SSA:

(SSA π+)/(SSA π-) =2.5 ~ 3.0

accidental coincidence ?

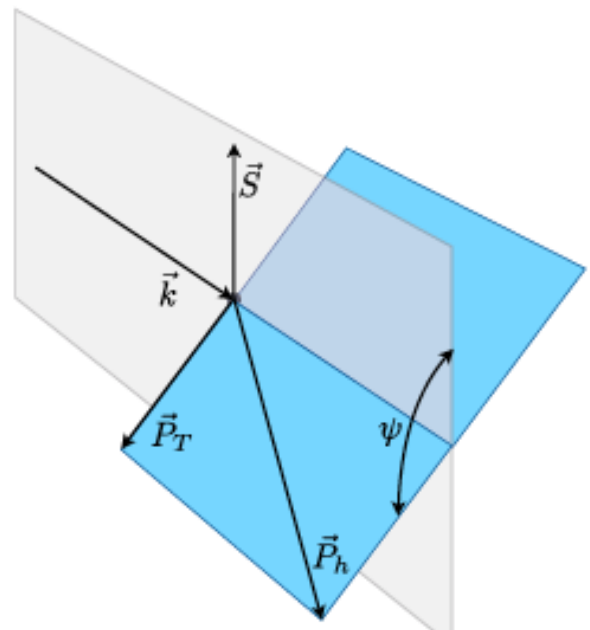
Left-Right Bias in e+p↑➔h+X

HERMES: proton PL B728 (2014) 183



P_T

x_F



$$A_N \equiv \frac{\int_{\pi}^{2\pi} d\psi\, d\sigma - \int_0^{\pi} d\psi\, d\sigma}{\int_{\pi}^{2\pi} d\psi\, d\sigma + \int_0^{\pi} d\psi\, d\sigma} = -\frac{2}{\pi} A_{UT}^{\sin\psi}$$

In e+p↑ center-of-mass frame,

viewed along the momentum direction of p↑

π+ favors the left side of proton's spin vector,
π− favors the right side of proton's spin vector.

We've observed left-right bias:

Significant single spin asymmetries in :

- Inclusive hadron production: **p↑+p-> h + X**
- Semi-inclusive deep inelastic scattering: **e+p↑->e'+h+X**
- Inclusive hadron production, JLab on neutron: **e+n↑->h+X**
  HERMES on proton: **e+p↑->h+X**

p↑

viewed along the momentum direction of p↑
π+ favors the left side of proton's spin vector,
π− favors the right side of proton's spin vector.

n↑

viewed along n↑ momentum direction
π+ favors the right side of neutron's spin vector,
π− favors the left side of neutron's spin vector.

Obviously, there's a common connection among these SSA phenomena.

What exactly is the connection ?

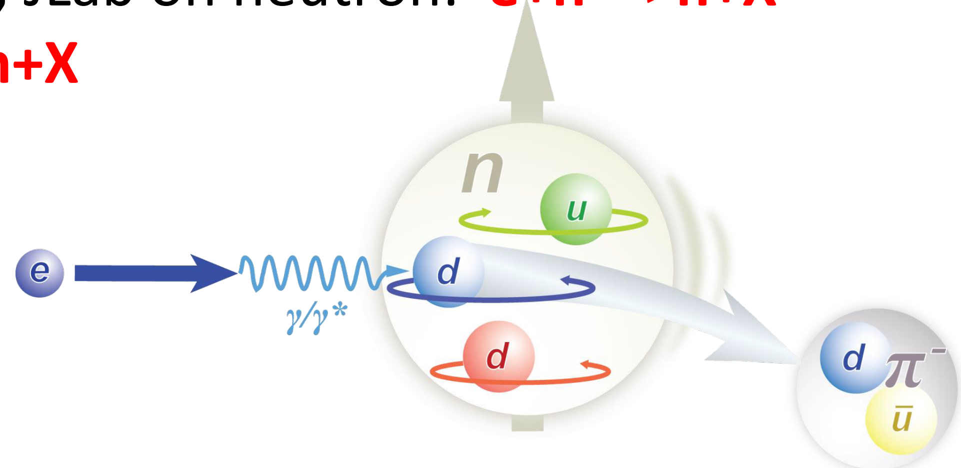
So far, we've observed left-right bias:

Significant single spin asymmetries in :

- Inclusive hadron production: **p↑+p-> h + X**
- Semi-inclusive deep inelastic scattering: **e+p↑->e'+h+X**
- Inclusive hadron production, JLab on neutron: **e+n↑->h+X**
  HERMES on proton: **e+p↑->h+X**

What happens in a high energy real-photon reaction:

γ+p↑->h+X ?



Can be measured very well at JLab Hall-D

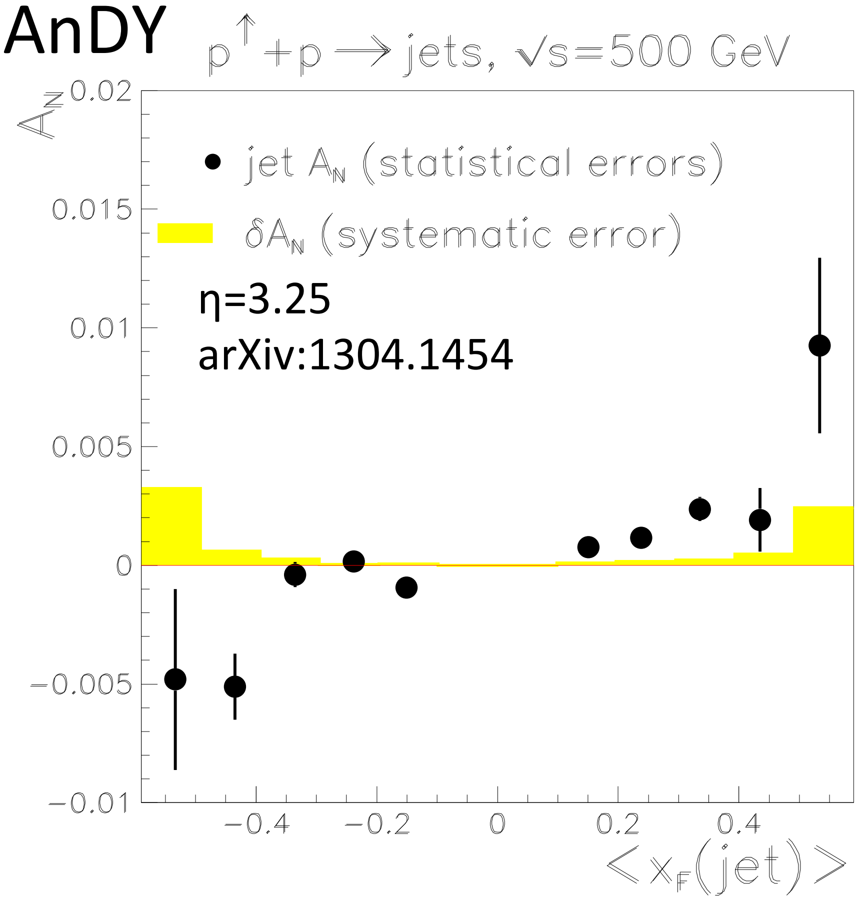
Does it matter which type of particle hits the polarized nucleon ?
$\pi^{\pm}$, $K^{\pm}$, ρ, ω, φ, J/Ψ ? Or ν, ν ?

In addition, we also have: **p↑+p-> jet + X**

In addition, we also have

Jet A_N: Left-Right Bias in p↑+p-> jet+X

AnDY



- Jet A_N is sensitive to Sivers-type effect only. Collins-type effect, from polarized quark fragmentation, vanishes when integrating over jet.
- Both up and down quarks contribute, with up quarks dominate jet production in p↑+p

In p↑+p center-of-mass frame,

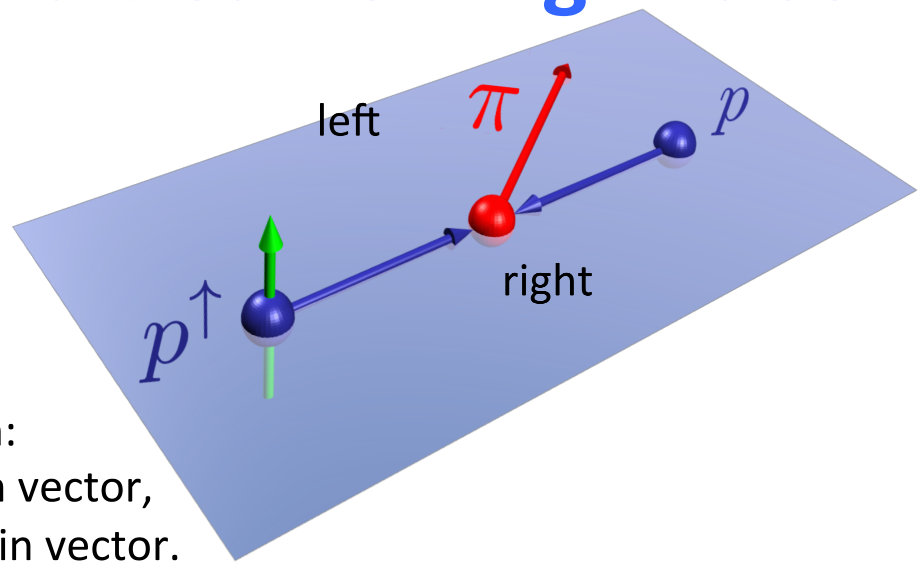
viewed along the momentum direction of p↑ jets favors the left side of the proton's spin vector.

Summary

Valence quarks inside a transversely polarized proton have a clear left-right bias.

$\pi^+ (u\bar{d})$

$\pi^- (d\bar{u})$



p↑

viewed along p↑ momentum direction:
π+ favors the left side of proton's spin vector,
π− favors the right side of proton's spin vector.

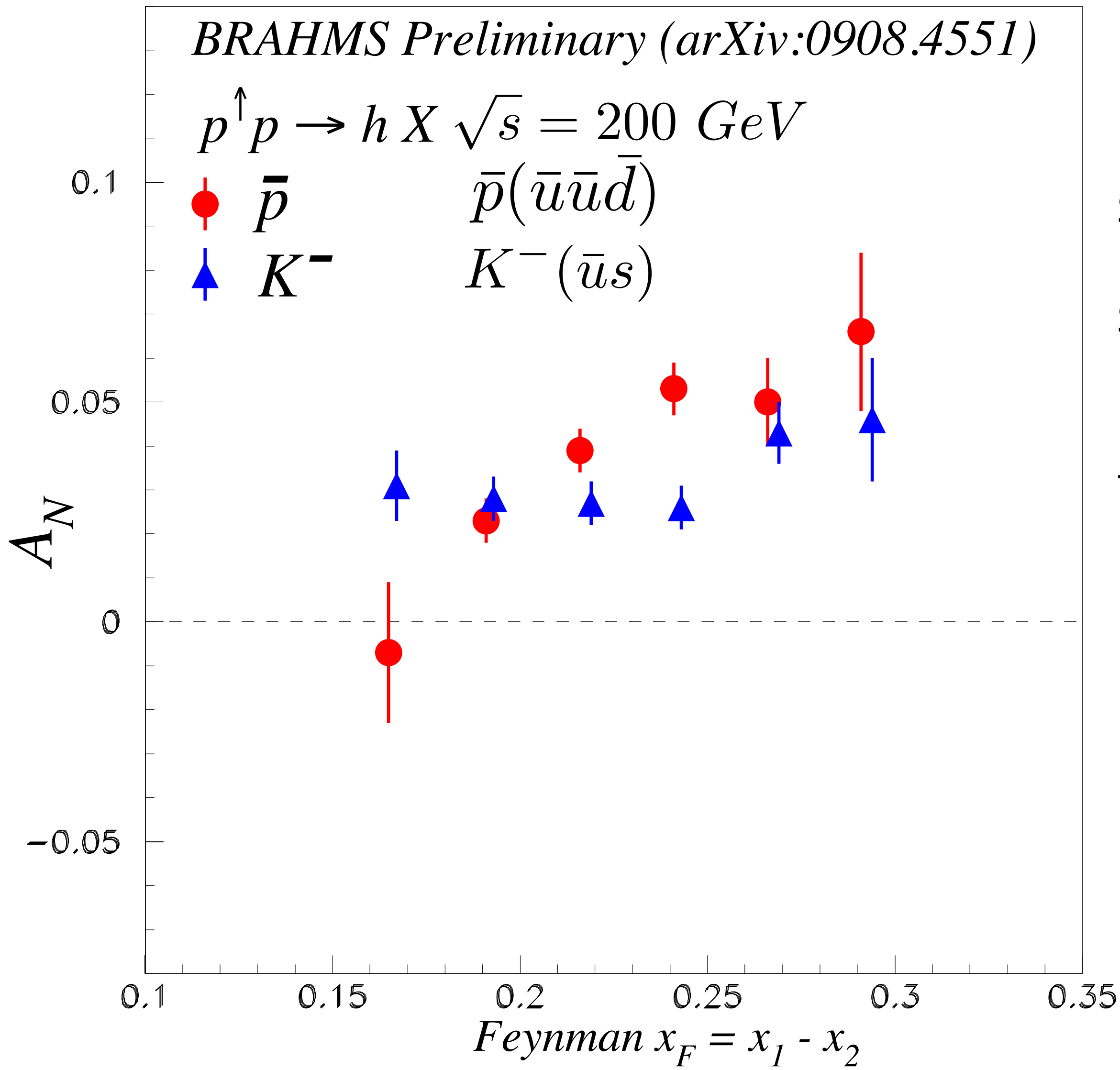
n↑

viewed along n↑ momentum direction:
π+ favors the right side of neutron's spin vector,
π− favors the left side of neutron's spin vector.

Is there a common link among these SSA phenomena ?

Left-right bias from sea quarks ?
Left-right bias from strange quarks ?

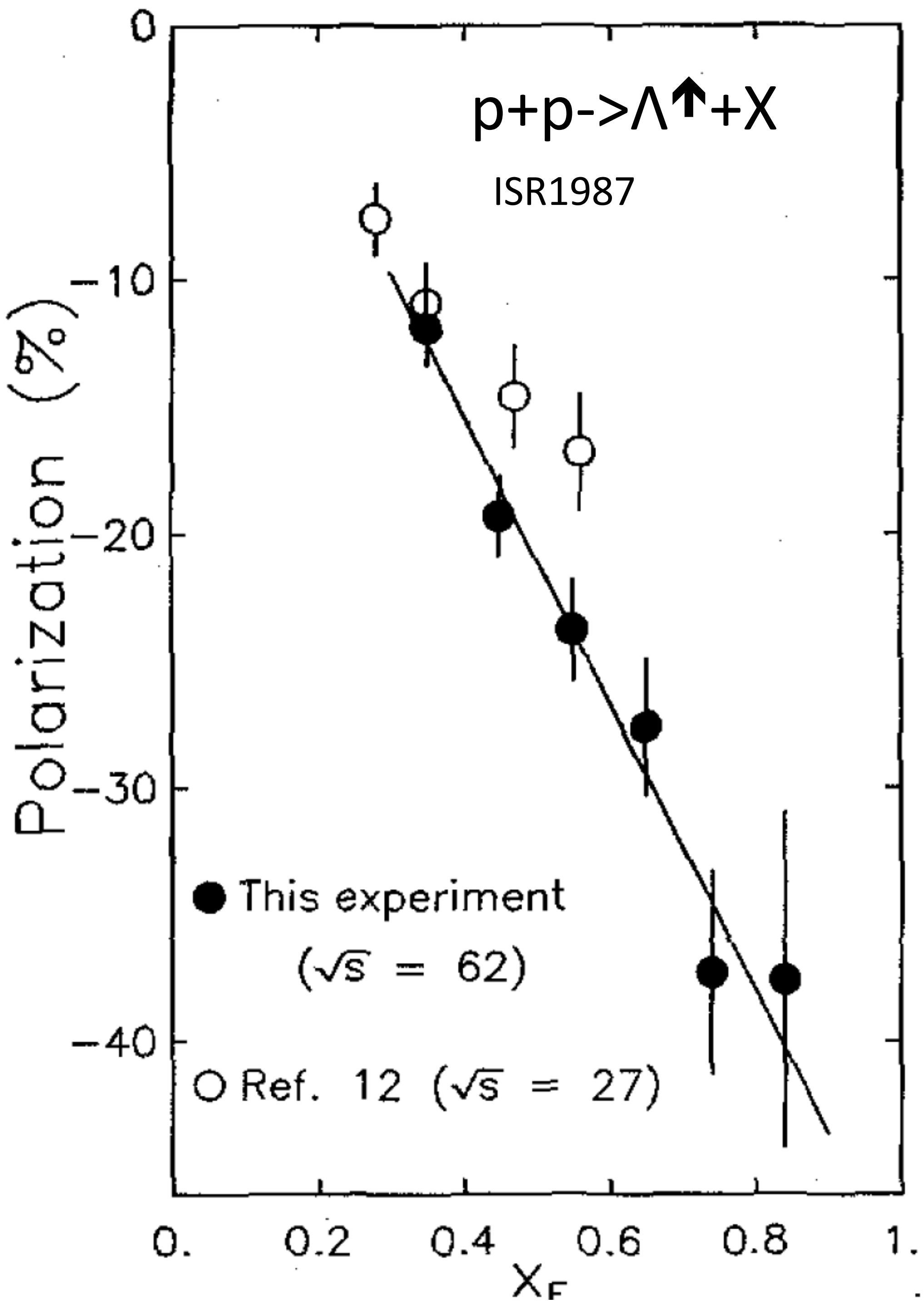
Evidence of Sea Quark's Left-Right Bias ?



Sea quark generates left-right bias ?

Secondary string-breaking ?

Left-right bias generated through fragmentation process ?


p+p->Λ↑+X
ISR1987
Polarization (%)
0
−10
−20
−30
−40
0.
0.2
0.4
0.6
0.8
1.
X_F
This experiment
(√s = 62)
Ref. 12 (√s = 27)

Backup Slides