2nd Part

Single-Spin Asymmetries in High Energy Proton+Proton and Lepton+Nucleon Collisions

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Dec. 25th, 2013. Discussions@PKU

Merry Christmas

Last Time

I will discuss experimental results, physics impacts, interpretations, and the connections of the observed single spin asymmetry (SSA) phenomena in:

- **Inclusive hadron SSA observed in proton-proton collision at Fermilab and RHIC.**
- Target SSA in semi-inclusive deep inelastic scattering (SIDIS).
- New Jefferson Lab results of polarized target SSA in inclusive hadron production e+N->h+X.

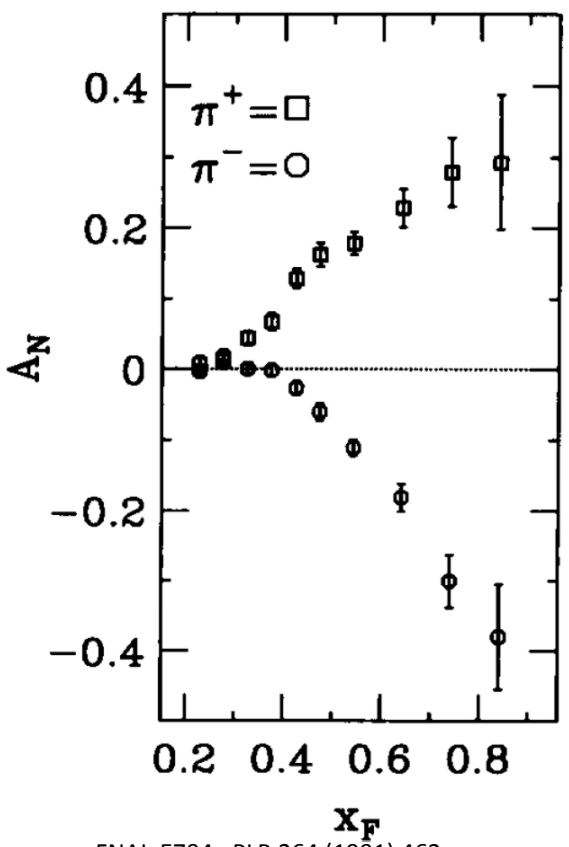
I will also discuss on-going and future experimental efforts, including :

- **Polarized target Drell-Yan experiments at Fermilab (E-1039).**
- Forward jet production asymmetry in p+p with the upgraded PHENIX experiment at RHIC.

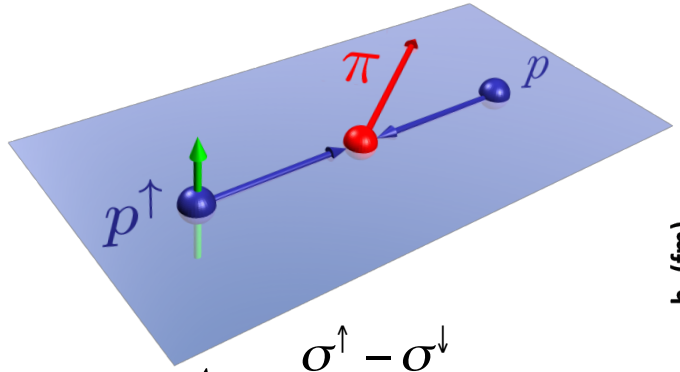
I will raise my own questions to PKU colleagues during the seminar for discussions.

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

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



FNAL-E704: PLB 264 (1991) 462.



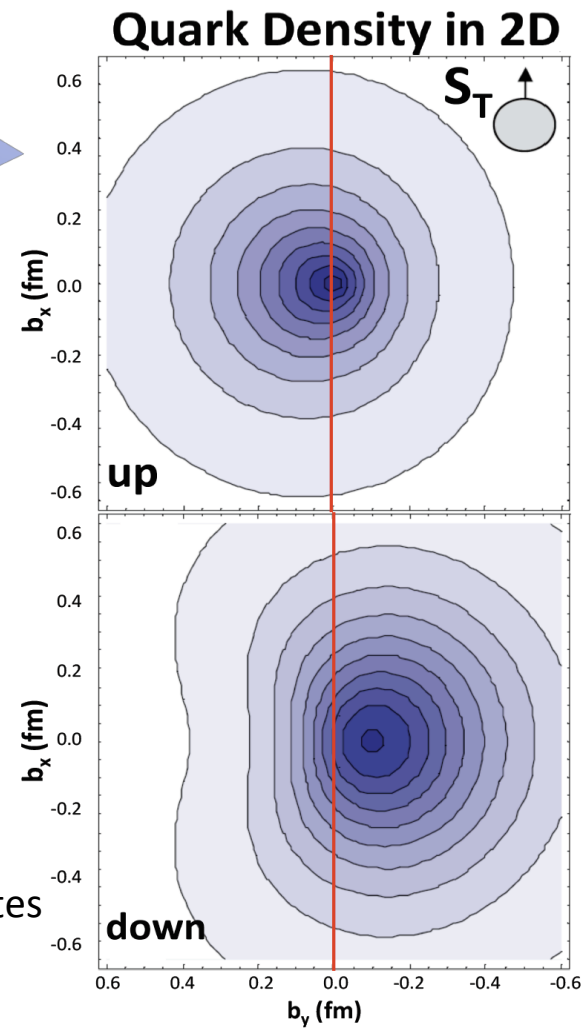
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

π^+ $(u\bar{d})$ favors left

π^- $(d\bar{u})$ favors right

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

Quark Density in 2D



Lattice QCD PRL98:222001,2007.

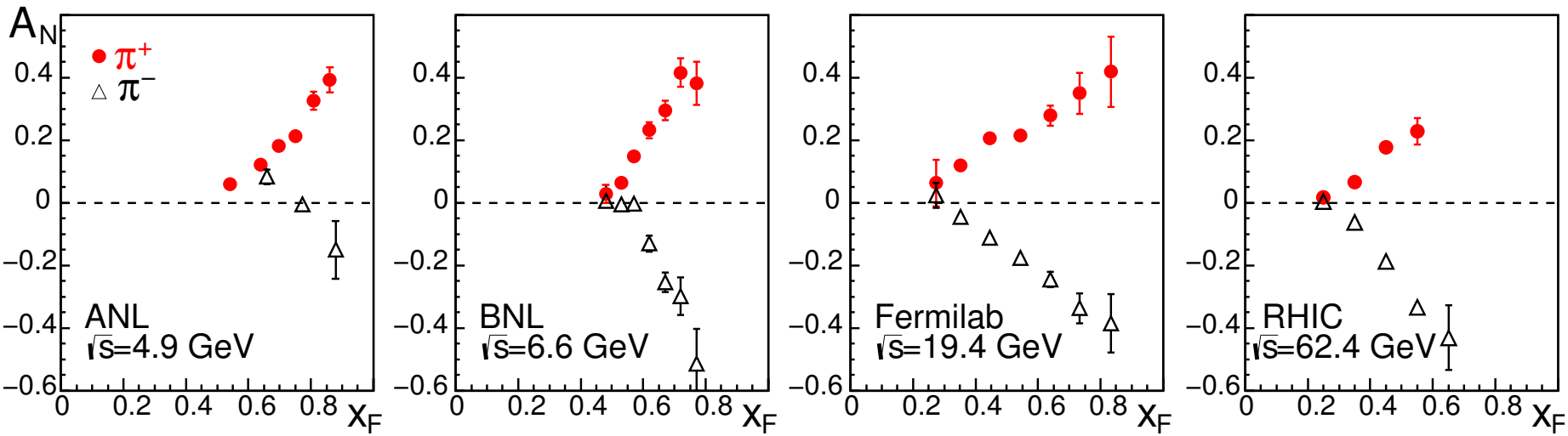
up-quarks favor left (L_u>0), down-quarks favor right (L_d<0).

Viewing along the polarized proton's momentum direction,

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

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

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

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

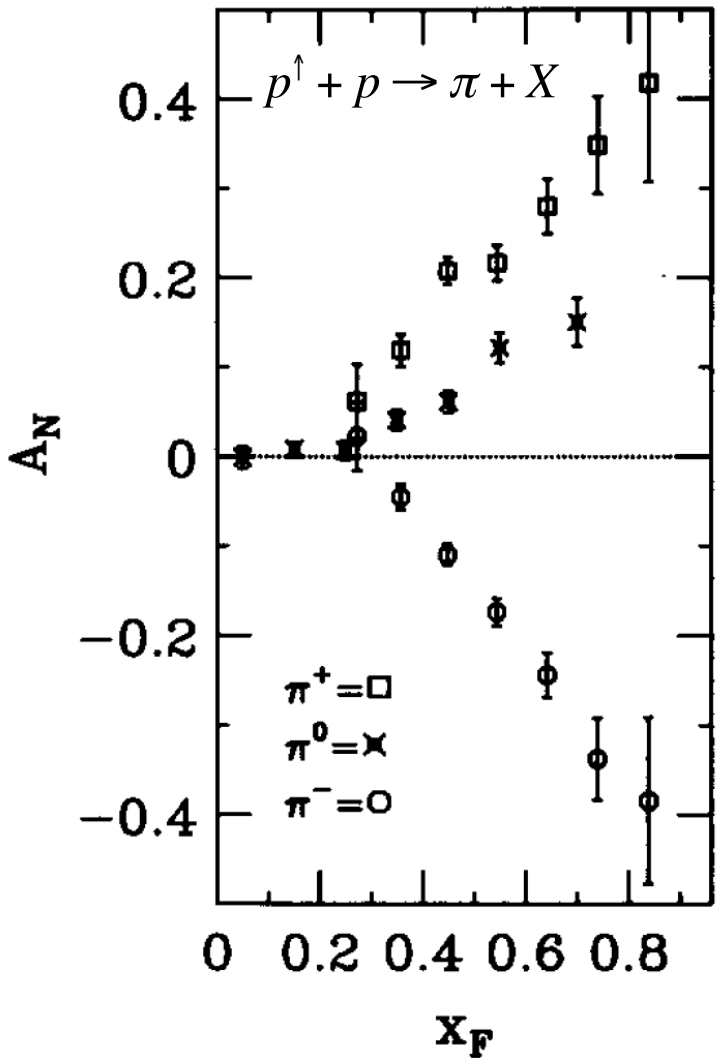
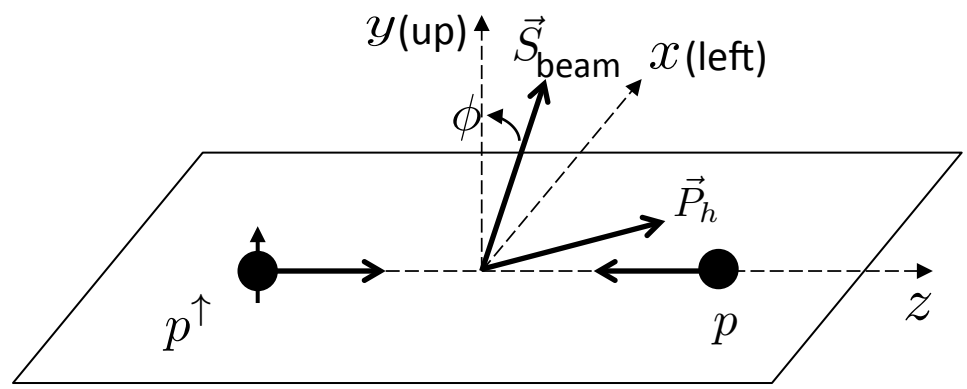


Fig. 4. A_N versus x_F for π^+, π^- and π^0 data.

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

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.



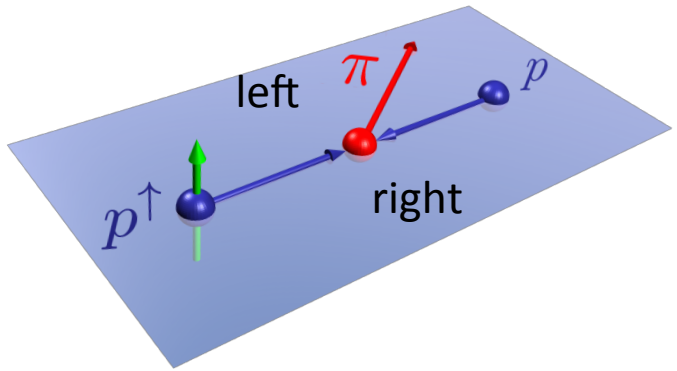
π^+ favors the left side of the polarized proton.

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

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

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.



in p↑+p collisions.

How about in e+p↑ (or l+N↑) collisions ?

(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.

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

TODAY

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  HERMES $e+p^{\uparrow}\to h+X$ (arXiv:1310.5070)

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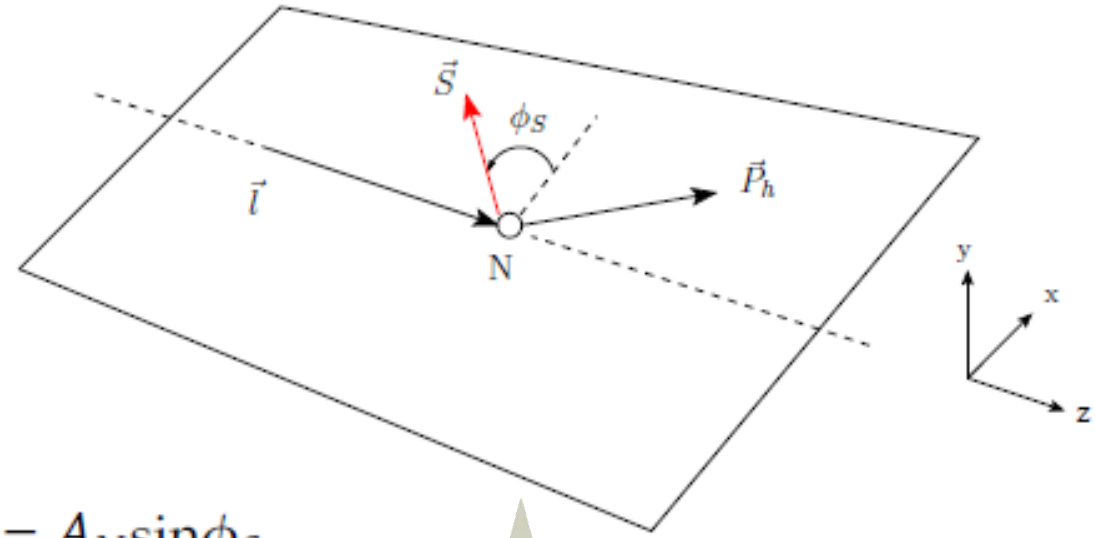
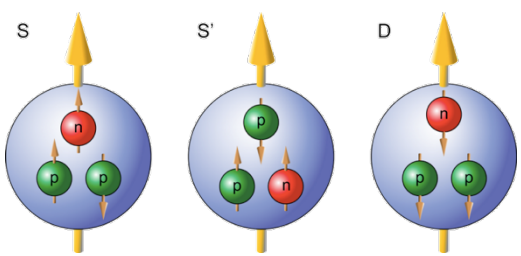
$$^3\mathrm{He}^{\uparrow}(e,h)X$$

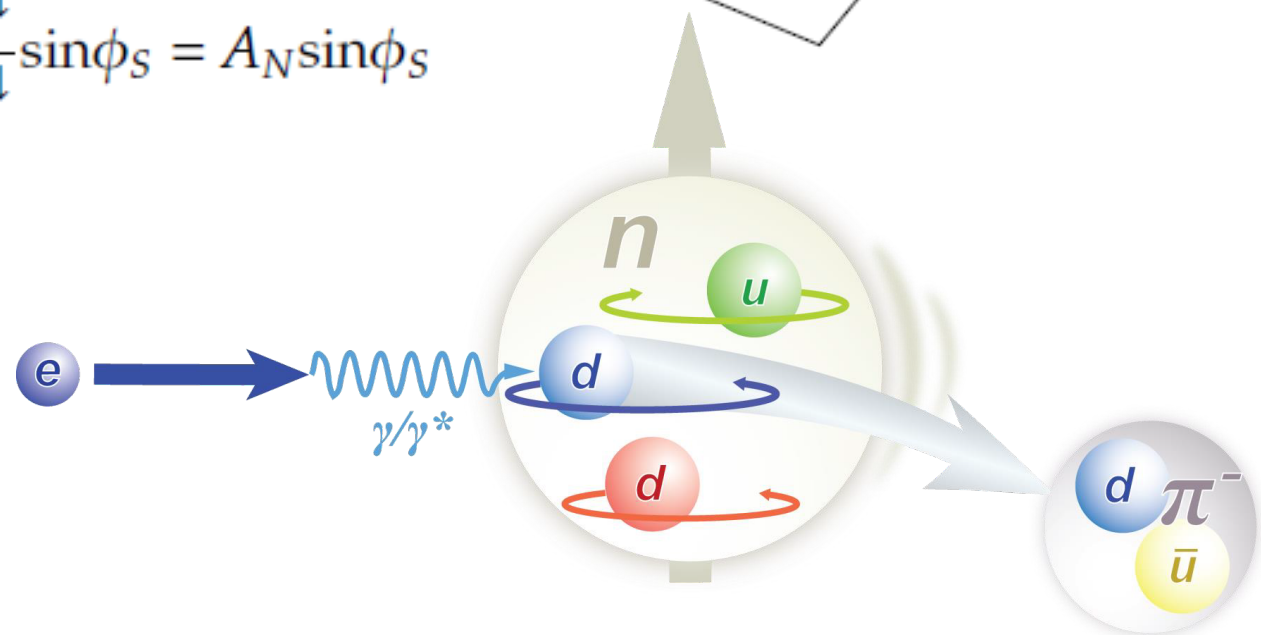
$$h = \pi^{+/-}, K^{+/-}$$



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

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





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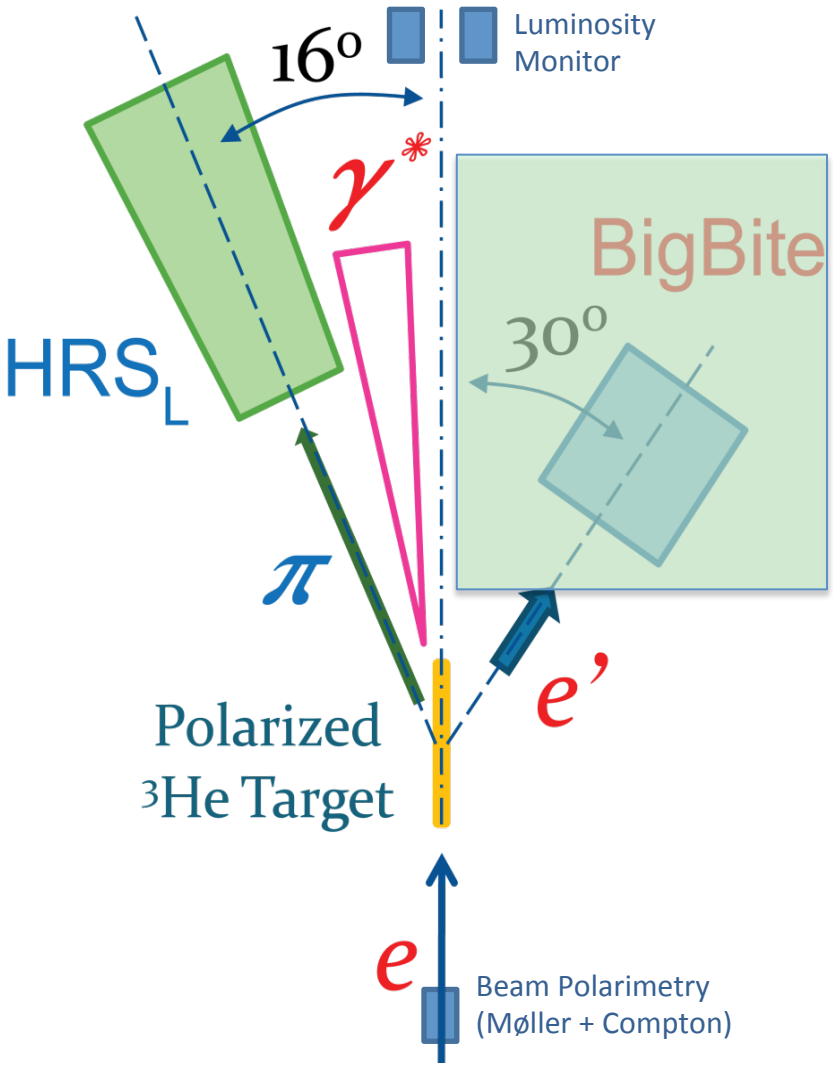
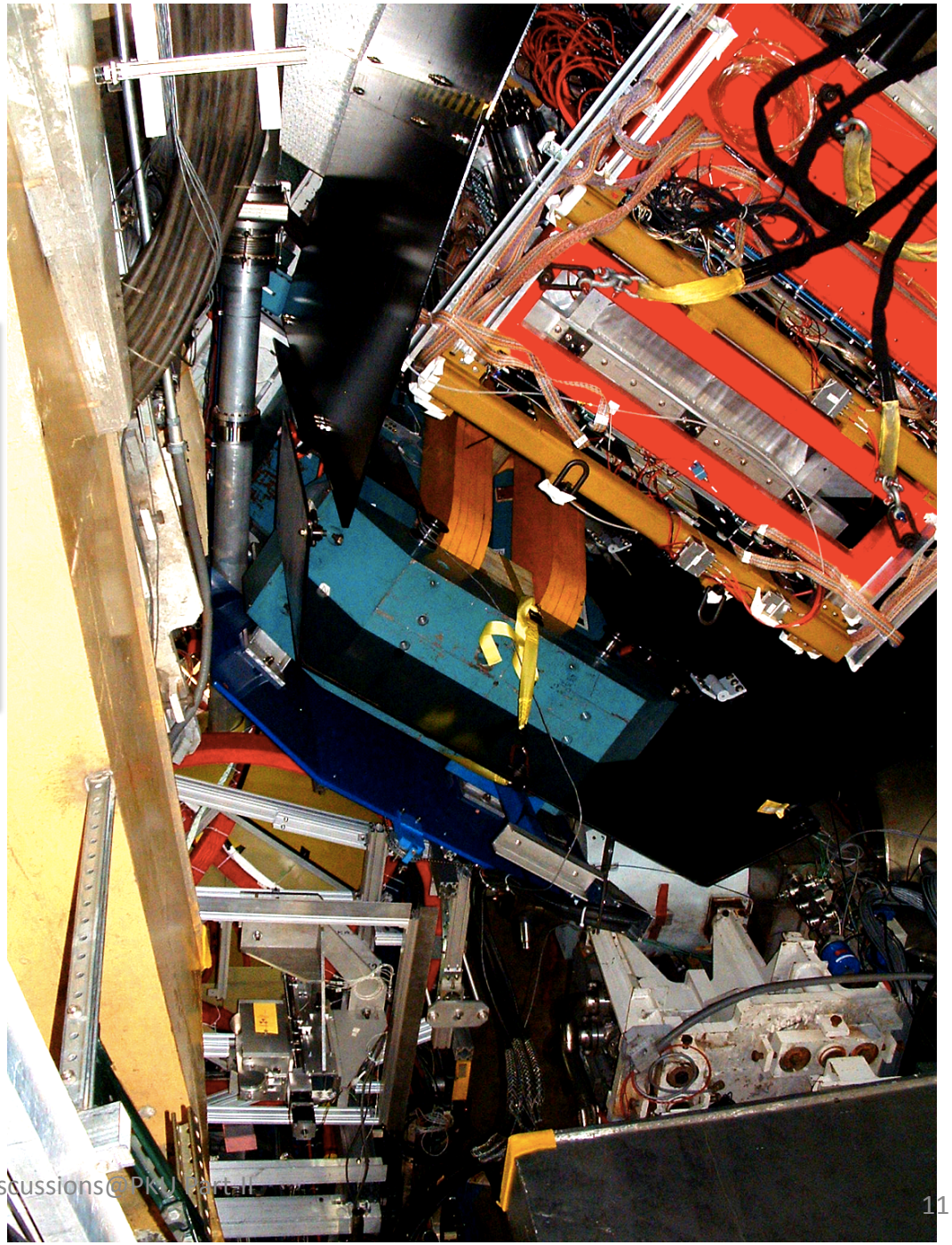
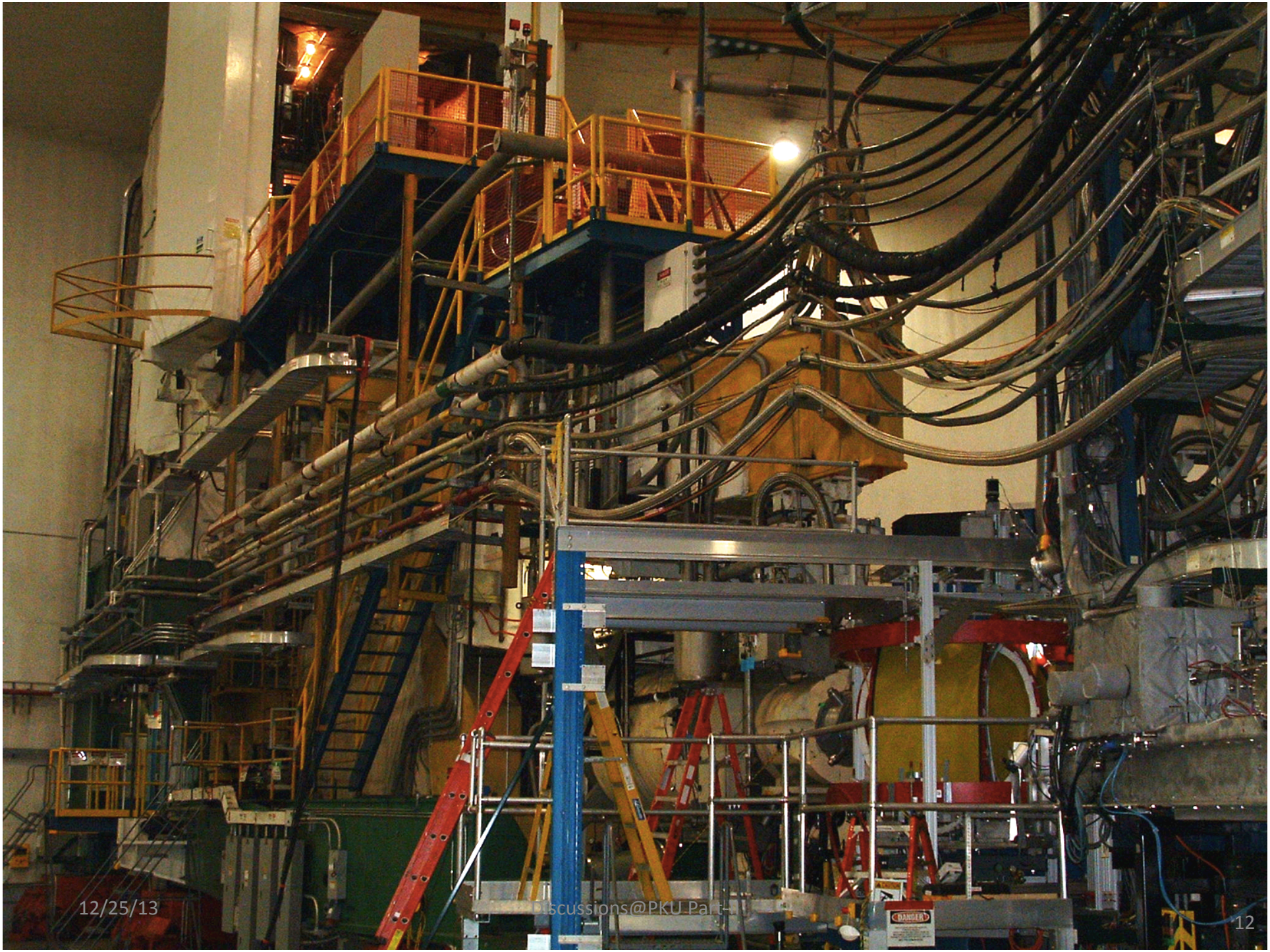
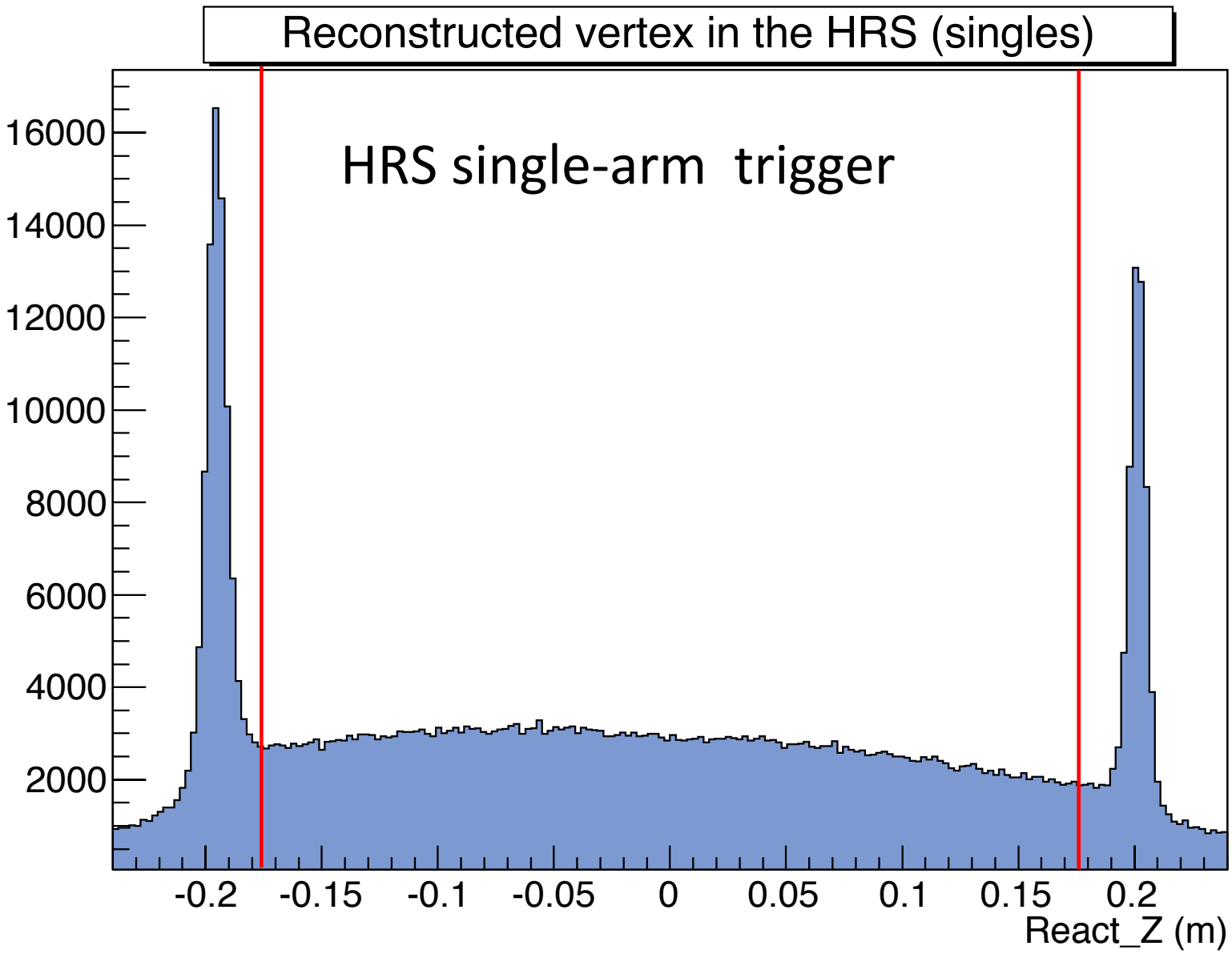




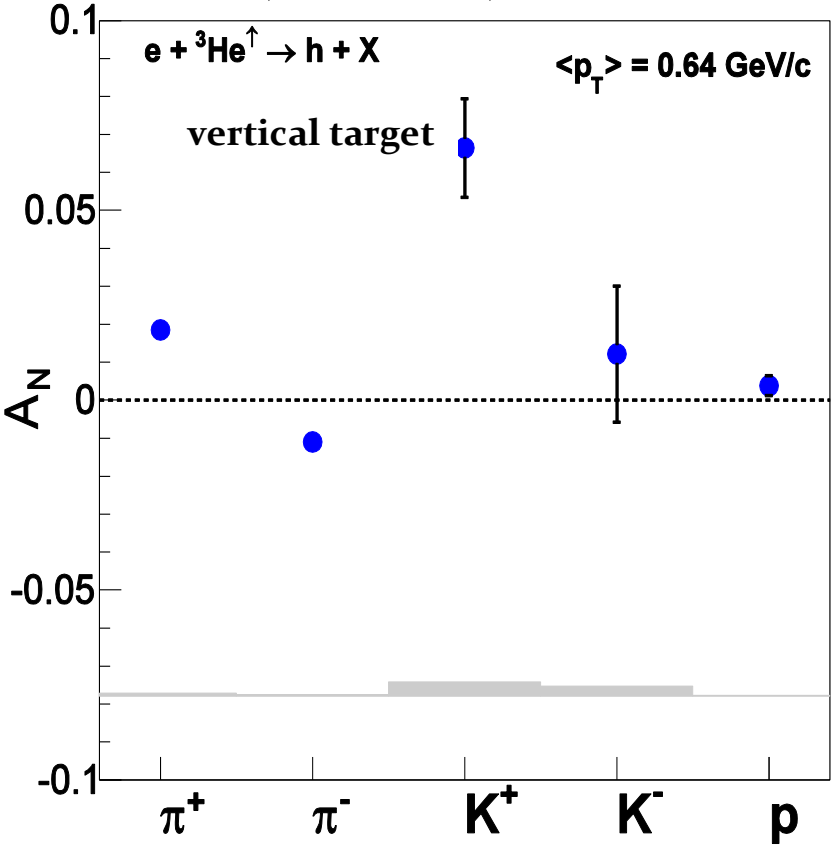

DANGER


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)

Inclusive Hadron SSA

arXiv:1311.1866 **JLab: ^{3}He**

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



Inclusive Hadron SSA

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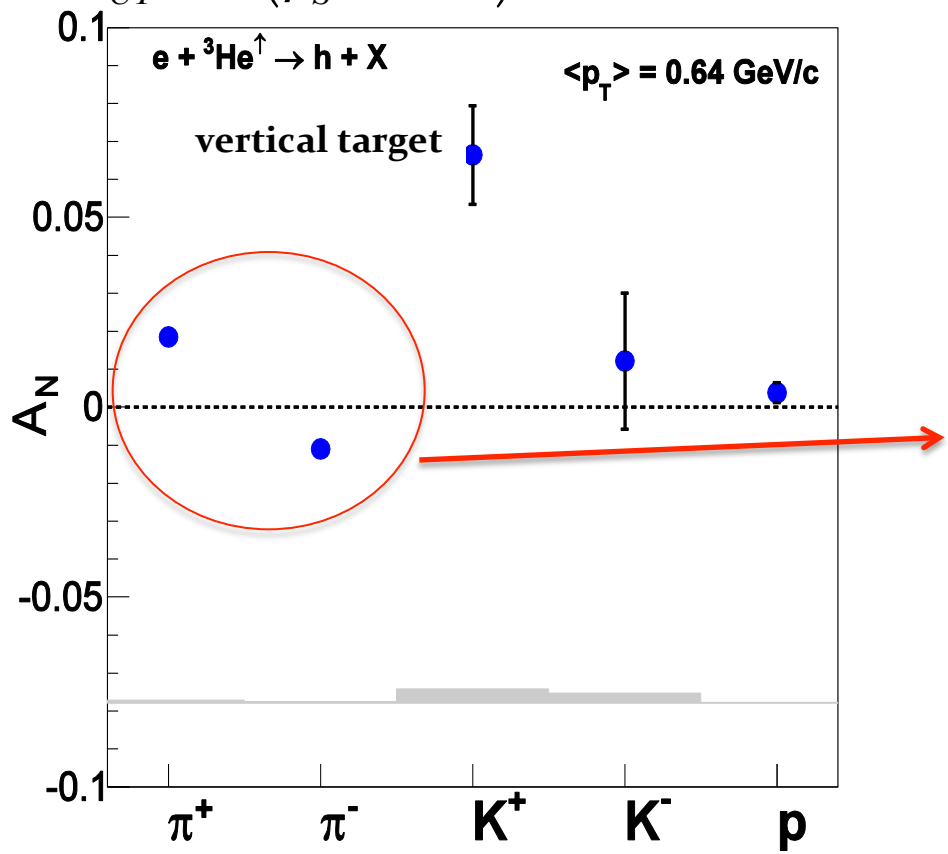
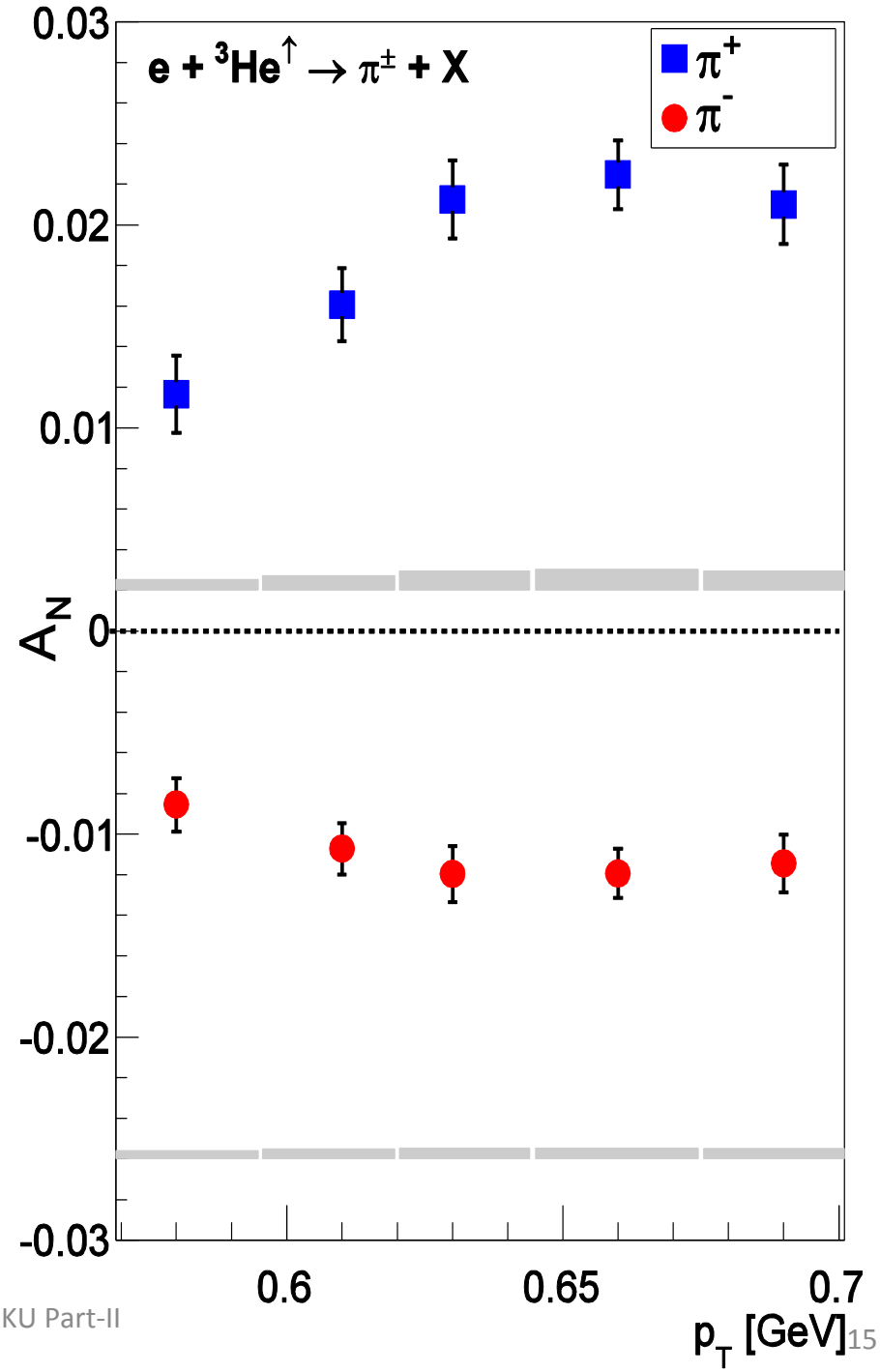
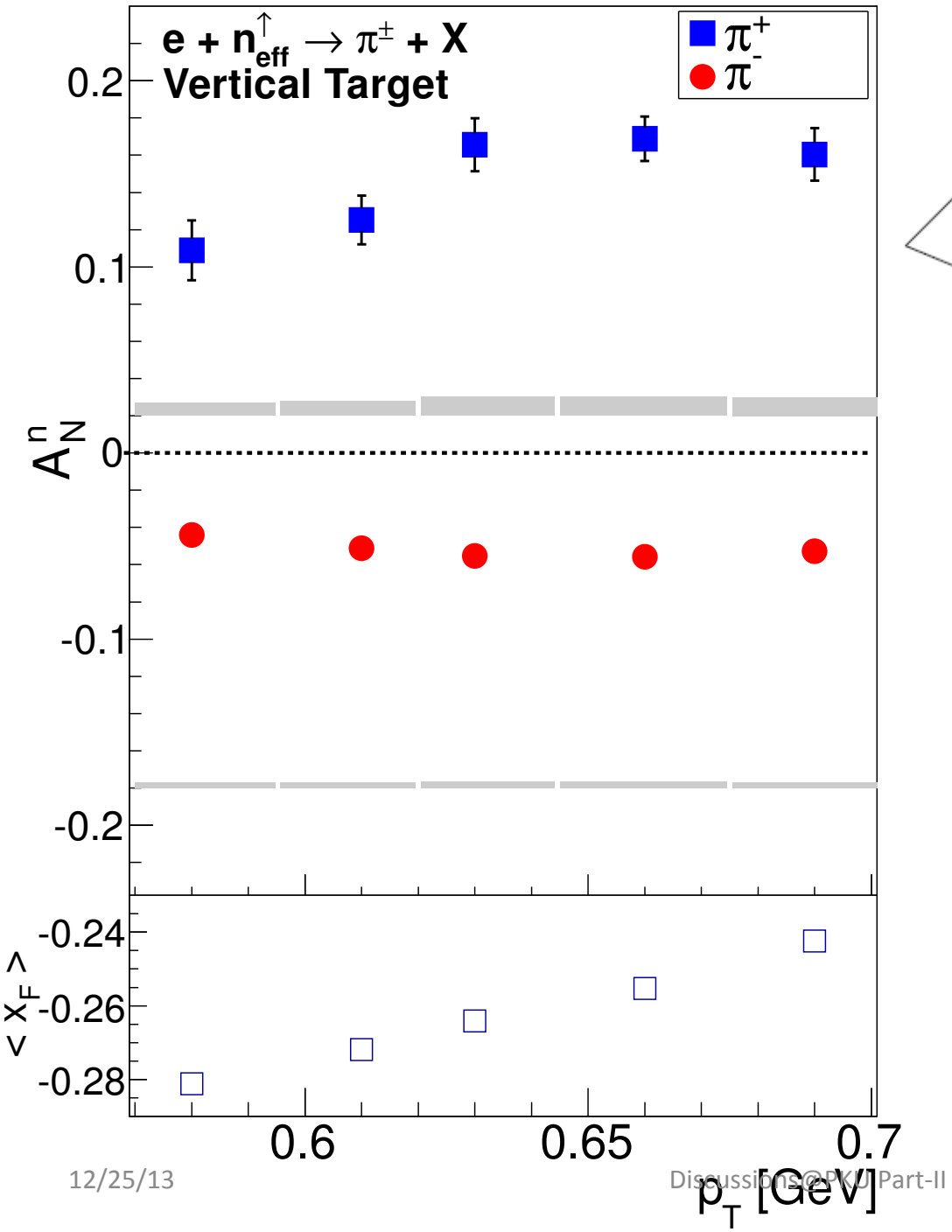
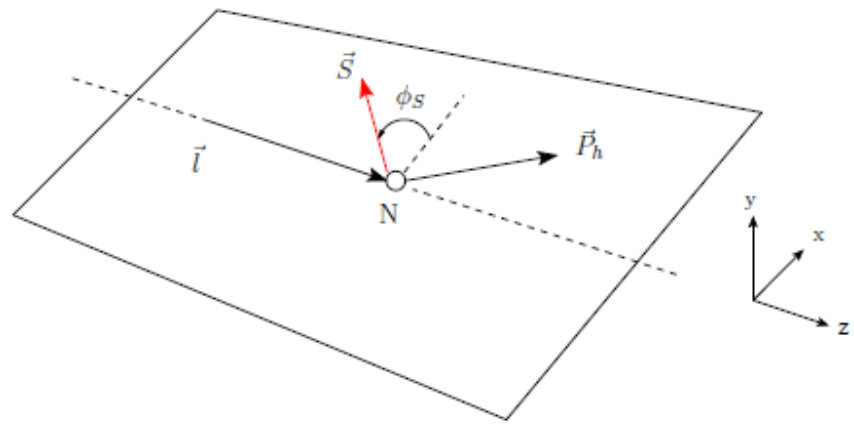


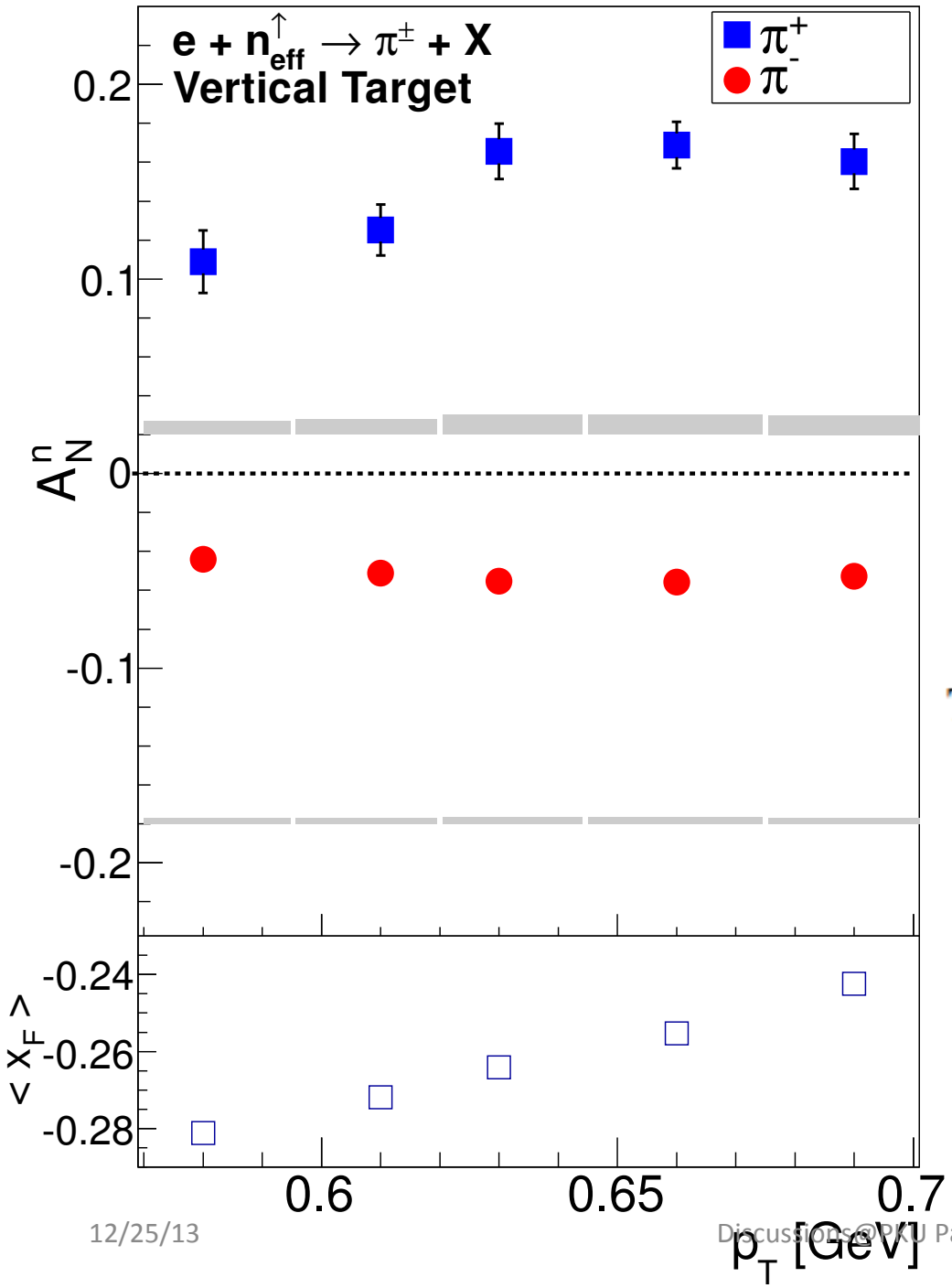






In l+N center-of-mass frame,

viewed along the direction of the neutron's momentum, **π**+ favors the right side of the spin vector, while **π**− favors the left side of the 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 $\kappa_{u/p} = 0.835,\ \kappa_{d/p} = -2.03$

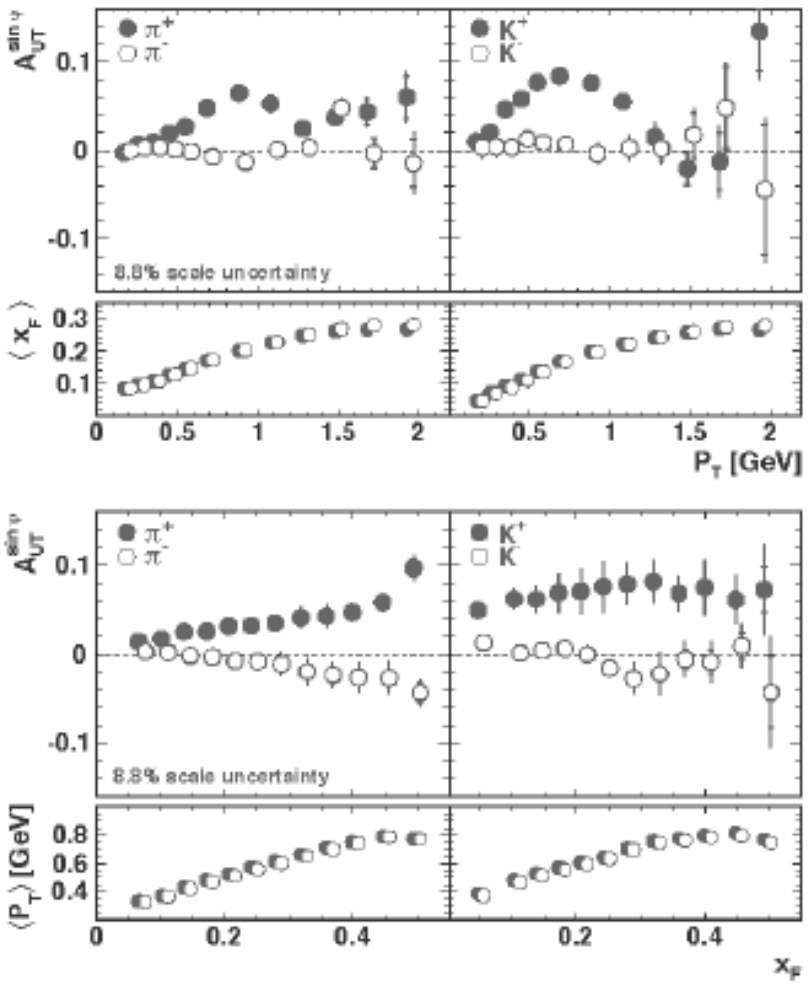
In neutron:
u-quark-term/d-quark-term= 2.43

we observed SSA in size:

π+/π- =2.5 ~ 3.0

Inclusive Hadron SSA

HERMES: proton arXiv:1310.5070



P_T

x_F

In l+p center-of-mass frame,

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

So far, we've seen

Significant single spin asymmetries in :

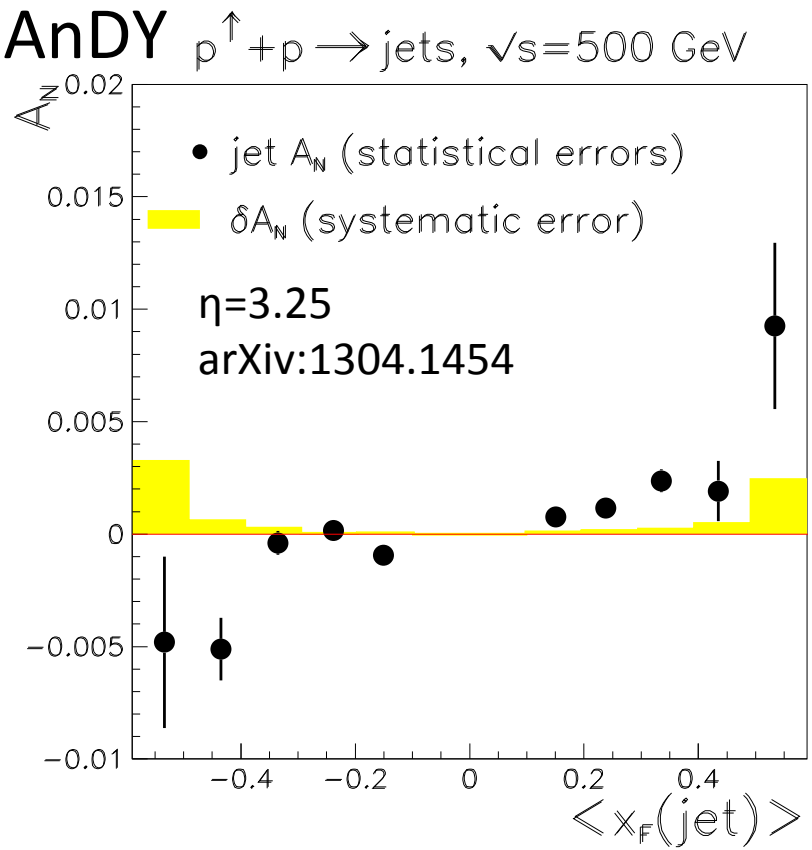
- Inclusive hadron production: **$p^{\uparrow}+p \to h + X$**
- Semi-inclusive deep inelastic scattering: **$e+N^{\uparrow} \to e'+h+X$**
- Inclusive hadron production, JLab on neutron: **$e+n^{\uparrow} \to h+X$**
  HERMES on proton: **$e+p^{\uparrow} \to h+X$**

What happens in a high energy real-photon beam experiment:

$\gamma+p^{\uparrow} \to h+X$???

In addition, there's new data on: **$p^{\uparrow}+p \to$ jet + X**

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



- 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.

In p↑+p center-of-mass frame,

viewed along the direction of the polarized proton's momentum, **jets** favors the left side of the spin vector.

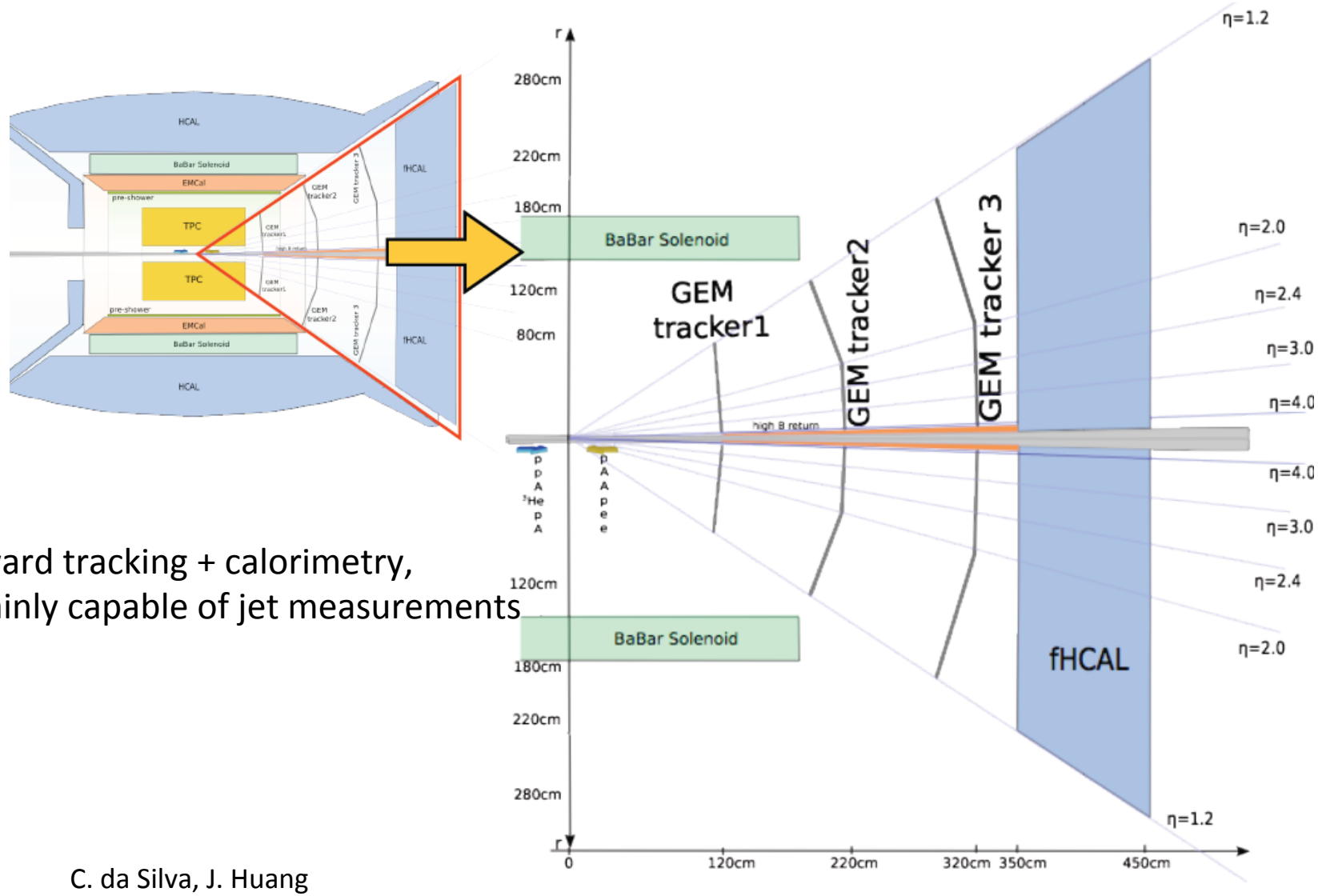
Switching back to high energy p↑+p collisions at RHIC …

At RHIC, PHENIX detector upgrade,

Forward sPHENIX

A physics example **p↑+p-> jet + X**

fsPHENIX Working Concept



Forward tracking + calorimetry, certainly capable of jet measurements

C. da Silva, J. Huang

Physics Discovery Potential of fsPHENIX:

Complementary to EIC

Q: What fsPHENIX physics is crucial and can not be accomplished by EIC alone?

A: one example, forward jet A_N in p+p, to illustrate the discovery potential of fsPHENIX.

fsPHENIX, in combination with EIC, will provide unique opportunities in:

- Detailed studies of nucleon and nucleus structure

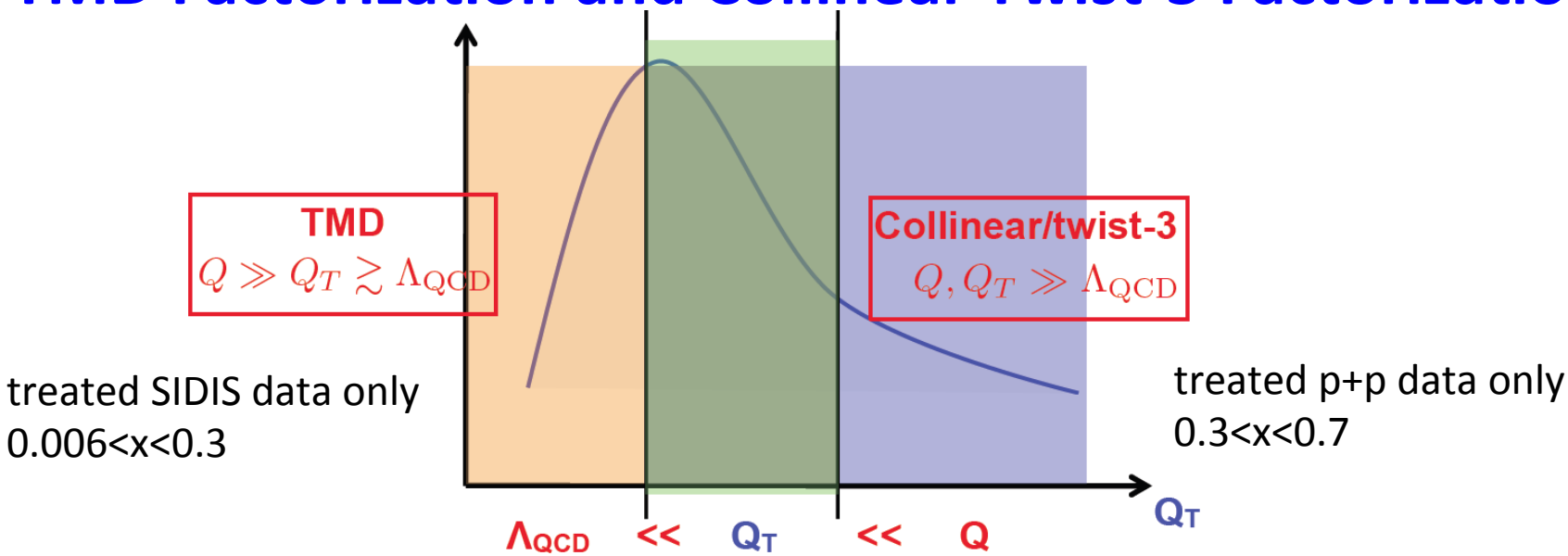
  quark transversity, Sivers distribution (TMDs), un-integrated gluon distributions…

- Test and advance our understandings of strong interaction QCD dynamics, such as confinement, quark energy loss, gluon saturation, and
  - **universality of parton distributions and fragmentation functions.**
  - **gauge invariance properties, such as process dependent PDF.**
  - **connection of TMD factorization and Collinear Twist-3 factorization approaches.**

Can not be addressed by EIC alone !

Two types of theoretical framework to describe SSA phenomena in SIDIS, and in p+p

TMD Factorization and Collinear Twist-3 Factorization



- Transversity
- Sivers distribution
- Collins fragmentation function
- Other spin-dependent frag. func…

linked

- Twist-3 quark-gluon correlation function (ETQS), tri-gluon correlation function …
- Twist-3 fragmentation functions…

One expects consistency of the two approaches, when gauge invariance is accounted:

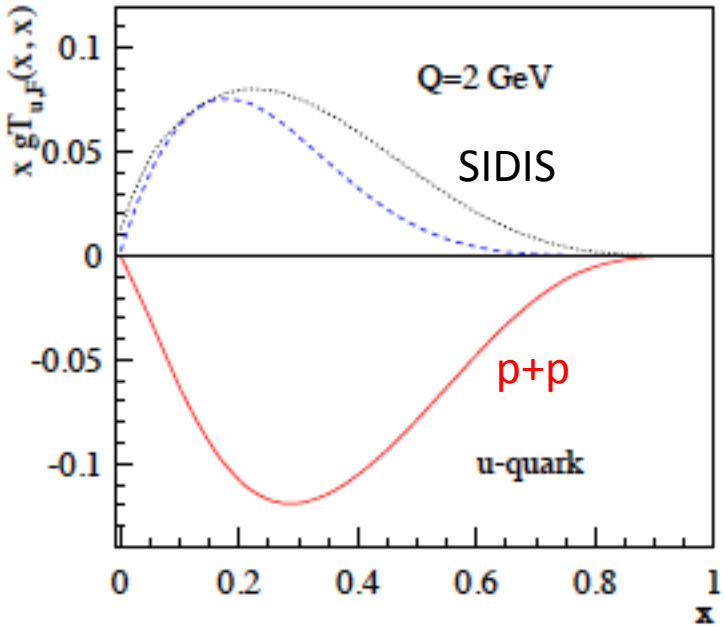
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

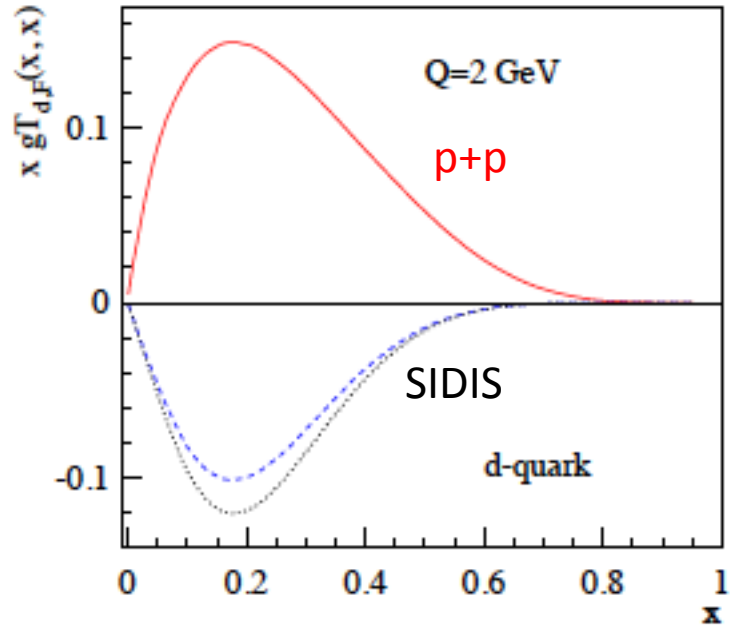
ETQS

Sivers distribution

g: gauge line factor, process dependent

SIDIS vs p+p: Interpretation Disagree





SIDIS: final state interaction only.
p+p: both initial state and final state interactions.

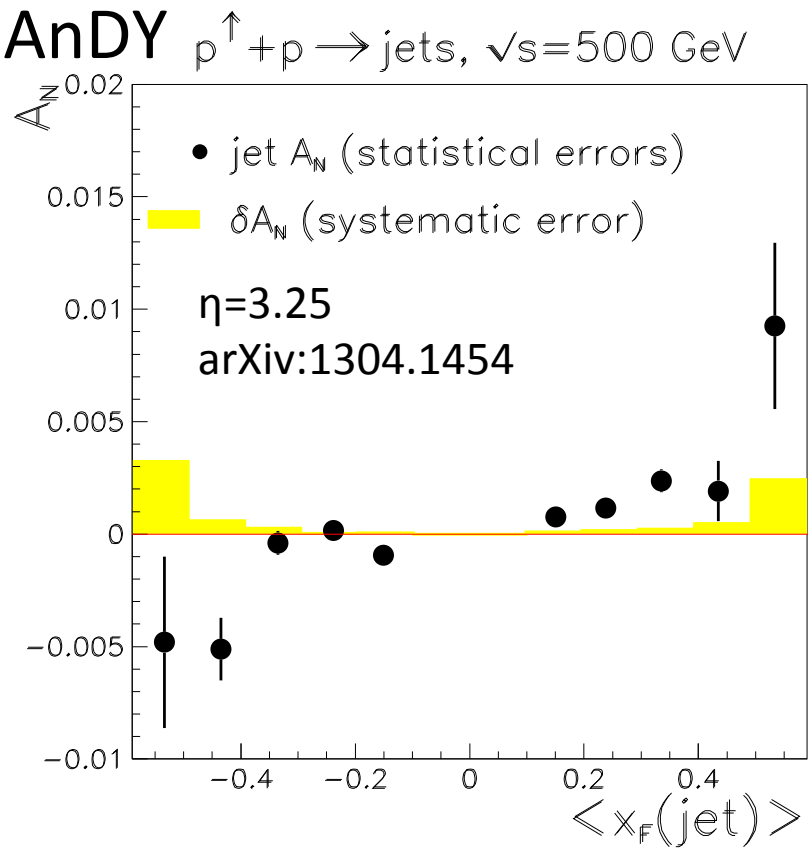
Data covered different x-range. Sivers distribution has a rapid sign change at high-x ?
Major flaws in theory ? Unknown physics ?

fsPHENIX: provide p+p data (0.1<x<0.7) to be compared with JLab-12GeV and EIC.

Inconsistencies and controversies will lead to discoveries.

fsPHENIX is complementary to EIC: Example-1

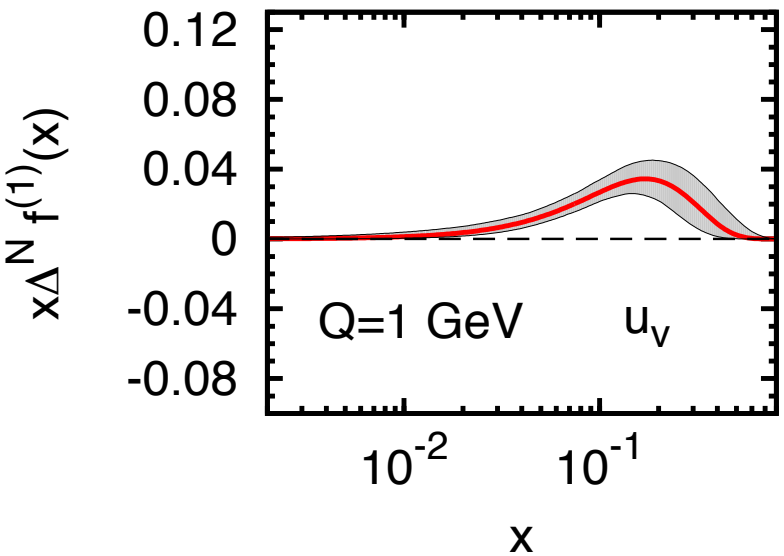
Jet A_N: Left-Right Asymmetry in $p^{\uparrow}+p$

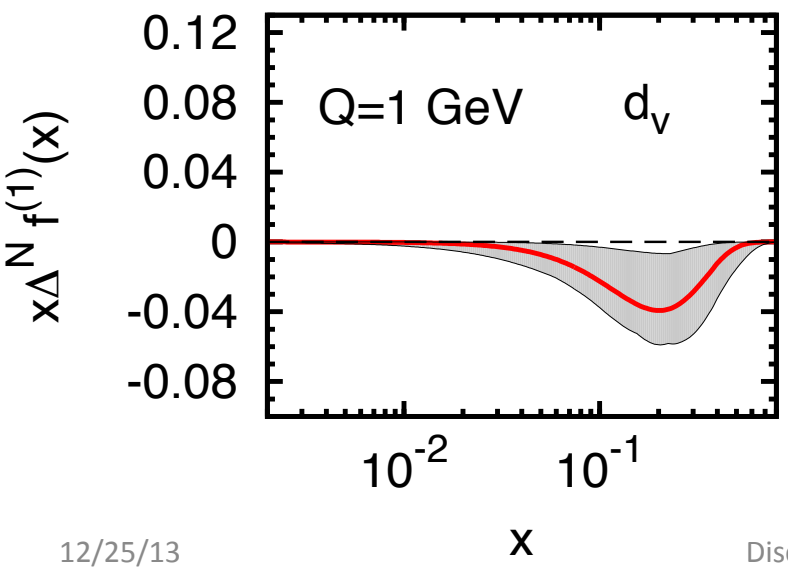


- Jet A_N is sensitive to Sivers-type effect only. Collins-type effect, from polarized quark fragmentation, vanishes when integrating over jet.
- AnDY jets: calorimeter only. Lacking information on particle charge, momentum and details of jet.
- Both initial state and final state interactions contribute.
- Both up and down quarks contribute.

- **"Conspiracy cancellation" between up and down quarks makes A_N small.**
- **Process dependency leads to very different interpretations.**

SIVERS FUNCTION - DGLAP





Using the same Sivers functions from a global fit to SIDIS data

Anselmino et al. updated 2012.

- **Predict jet A_N with and without consideration of Sivers function's process dependency.**
- **Break into contributions from up and down quarks.**

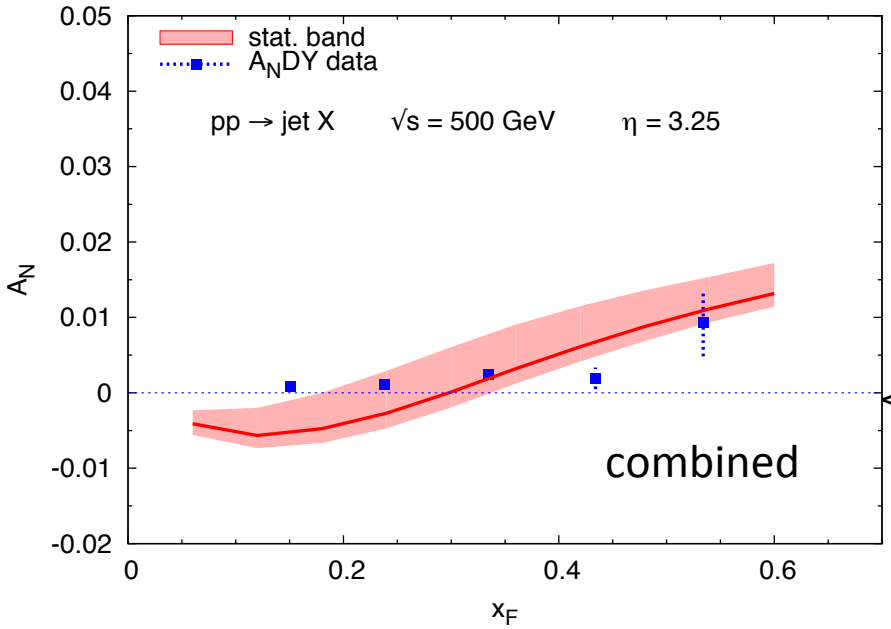
Without process dependency:
Anselmino et al. 2013.

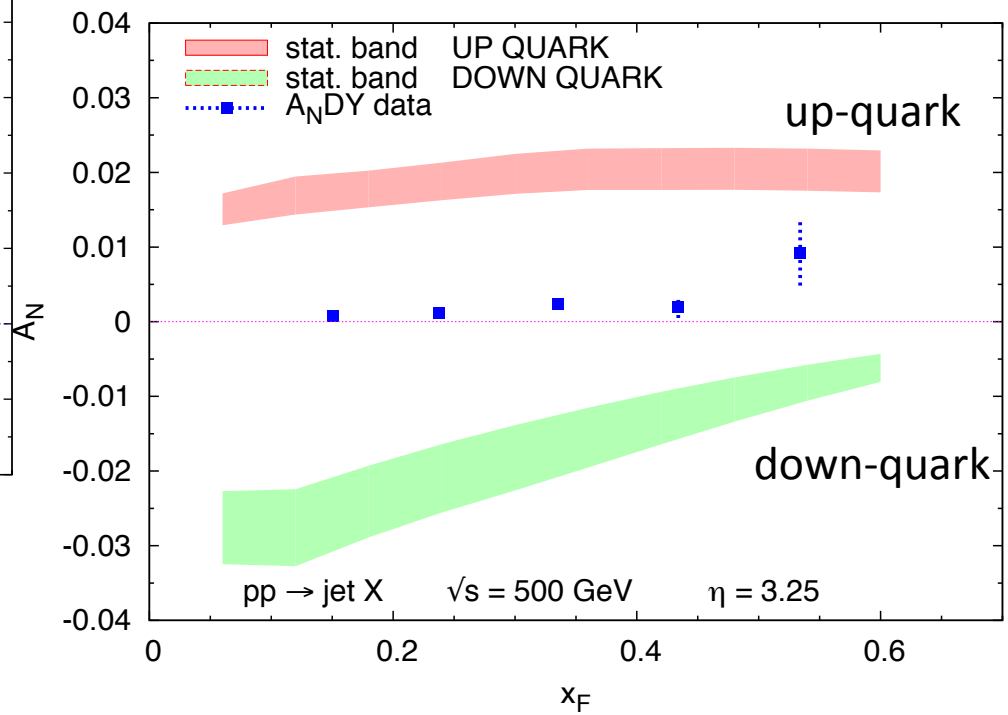
With process dependency:
Kang et al. 2013.

Not considering "process dependency" of Sivers function

Anselmino et al. 2013.

Directly use Sivers function from SIDIS fit





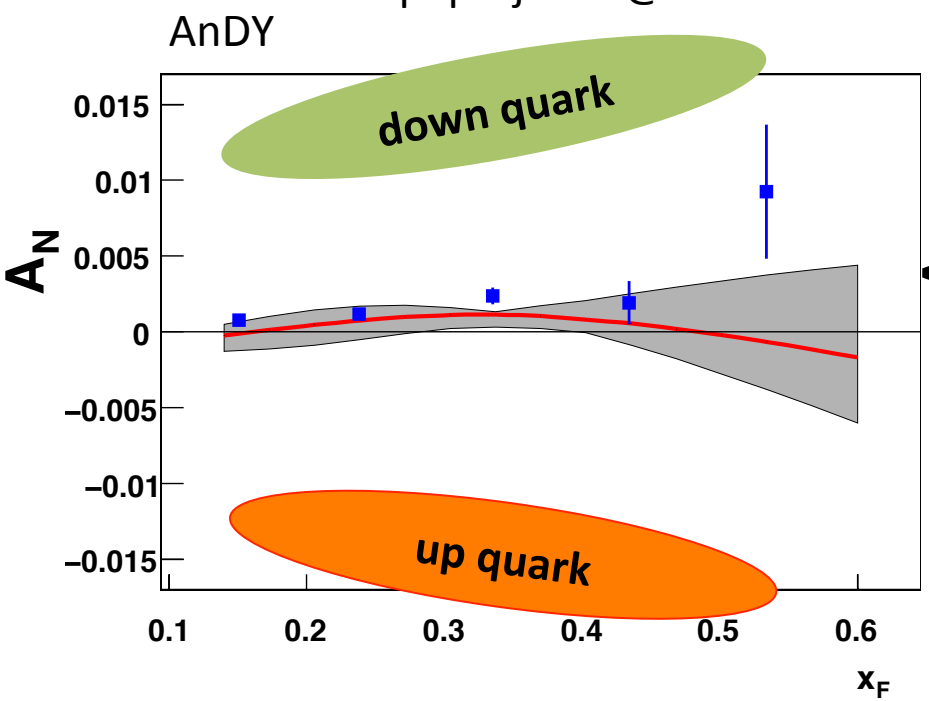
Jets with more up-quark contributions ➔more positive A_N

Jets with more down-quark contributions ➔more negative A_N

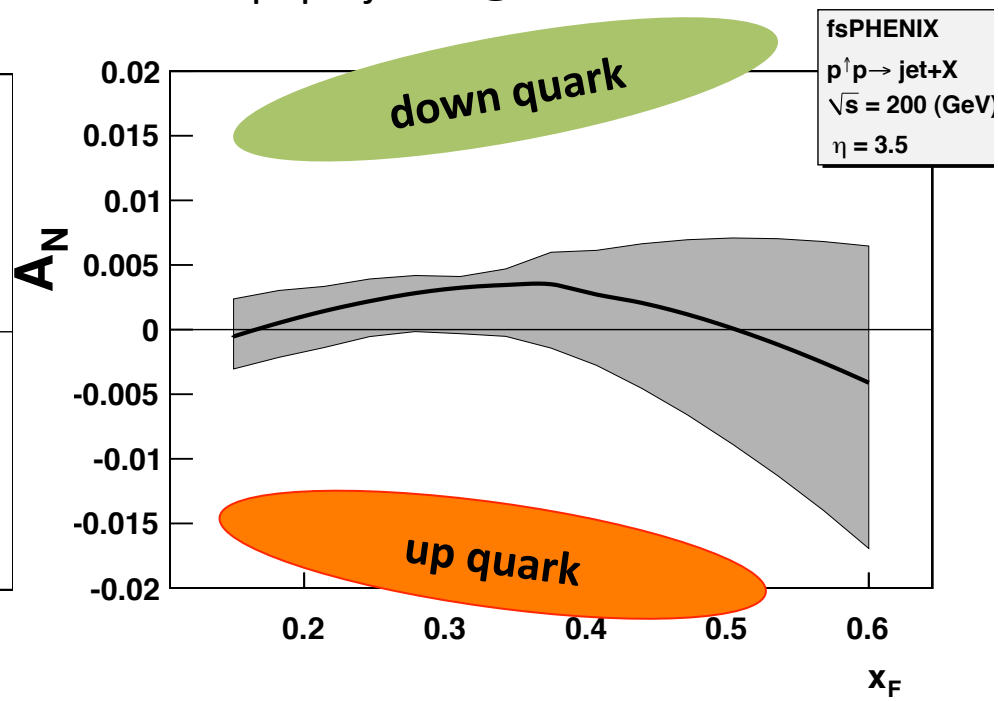
Consider "Process Dependency" of Sivers function

Sivers functions in Jet A_N have opposite signs to that of SIDIS. Kang et al. 2013

p+p➔jet+X @500 GeV



p+p➔jet+X @200 GeV

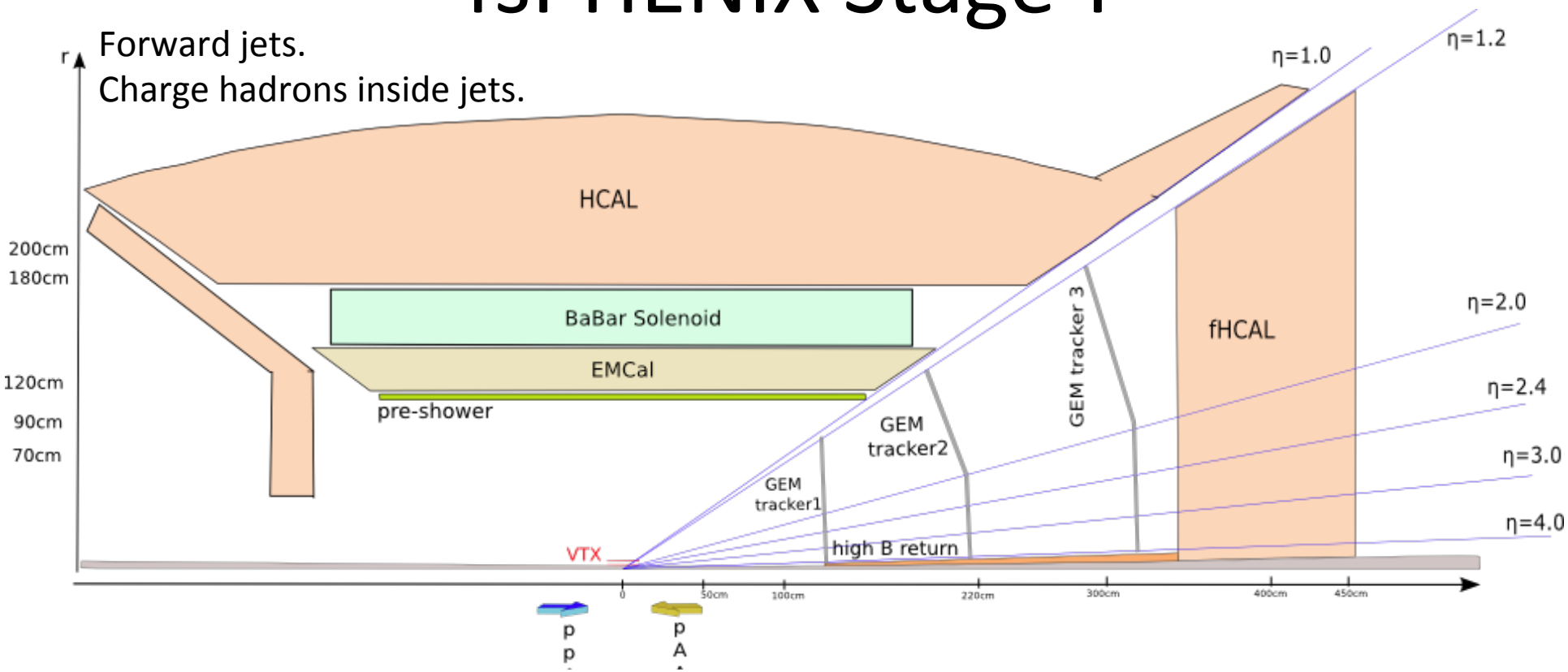


up-quark's contribution is negative, down-quark's contribution is positive.
(Plots will be updated with separated bands of up and down quarks)

Jets with more up-quark contributions ➔more negative A_N
Jets with more down-quark contributions ➔more positive A_N

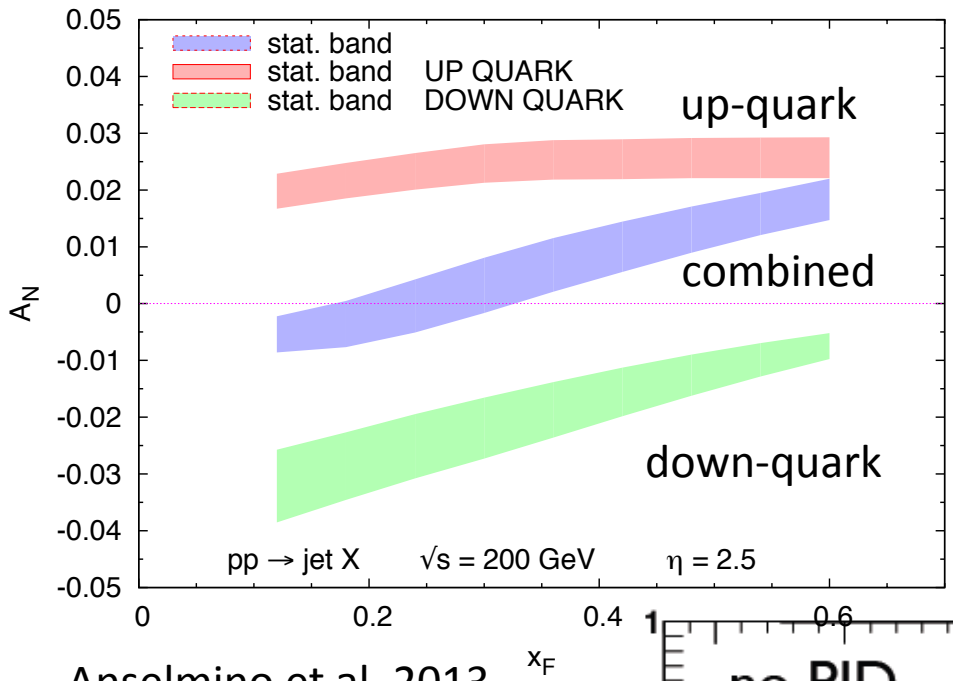
fsPHENIX Stage-I

Forward jets.
Charge hadrons inside jets.

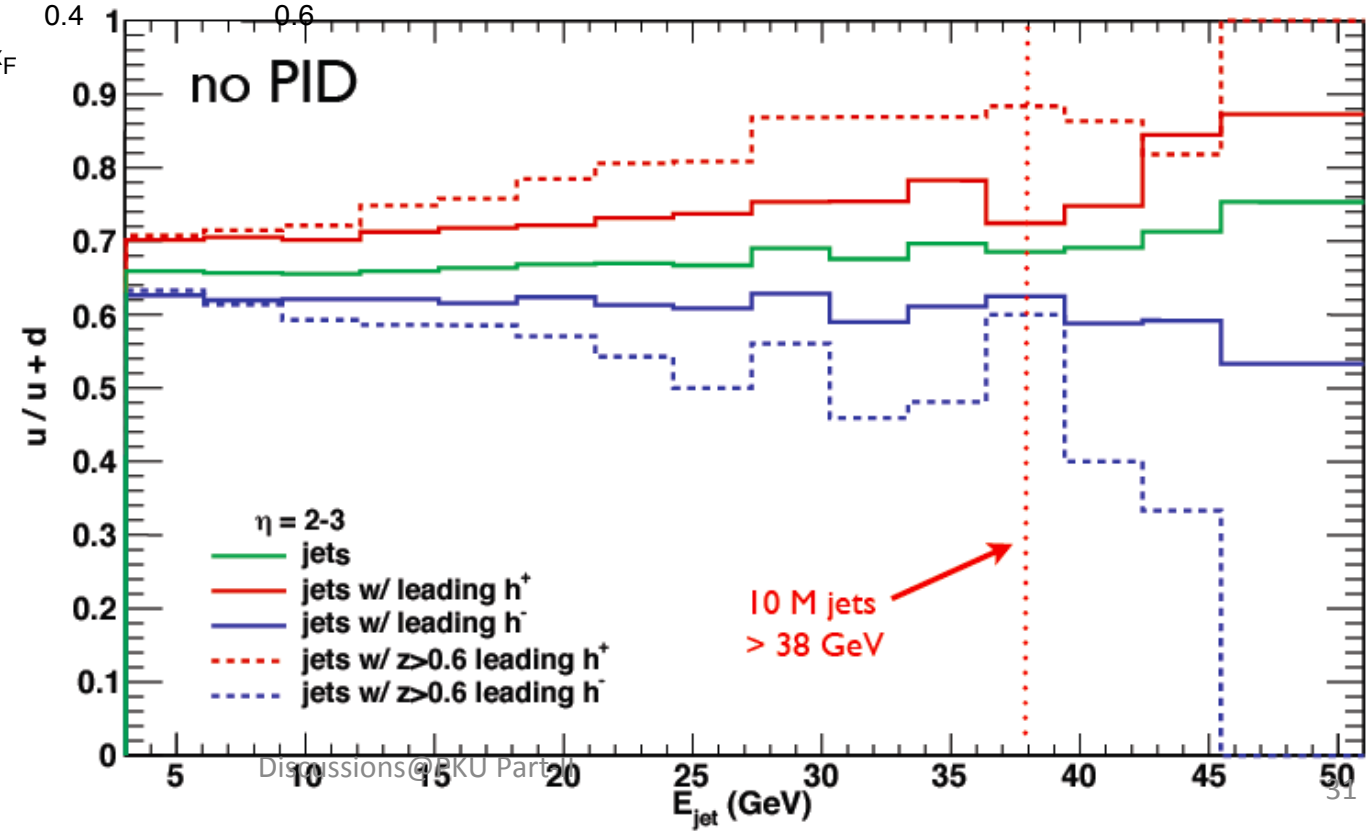


	Observable	Physics	Detectors Required						Costs
			FVTX	GEMTr	hPID	EMCal	HCal	MuID	
$p^{\uparrow}+p^{\uparrow}$	incl. A_N^{Jet}	Quark Sivers	×	×	×	×	√	×	
200 GeV	$A_N^{h^{\pm}-Jet}$	Collins $\delta q(x)$	×	√	×	×	√	×	
50 pb^{-1}	Interf. A_N^{2h}	Transv. $\delta q(x)$	×	√	×	×	√	×	
	$\Lambda^{\uparrow}$ pol.	Transv. $\delta q(x)$	×	√	×	×	√	×	
$p^{\uparrow}+A$	$A_N^{h^{\pm}-Jet}$	Collins in Nucl.	×	√	×	×	√	×	
200 GeV	A_N^{h+}, A_N^{h-}	Saturation	×	√	×	×	√	×	
50 pb^{-1}	incl. R_{pA}^{Jet}	CNM	×	×	×	×	√	×	

Jet A_N for fsPHENIX



Anselmino et al. 2013.

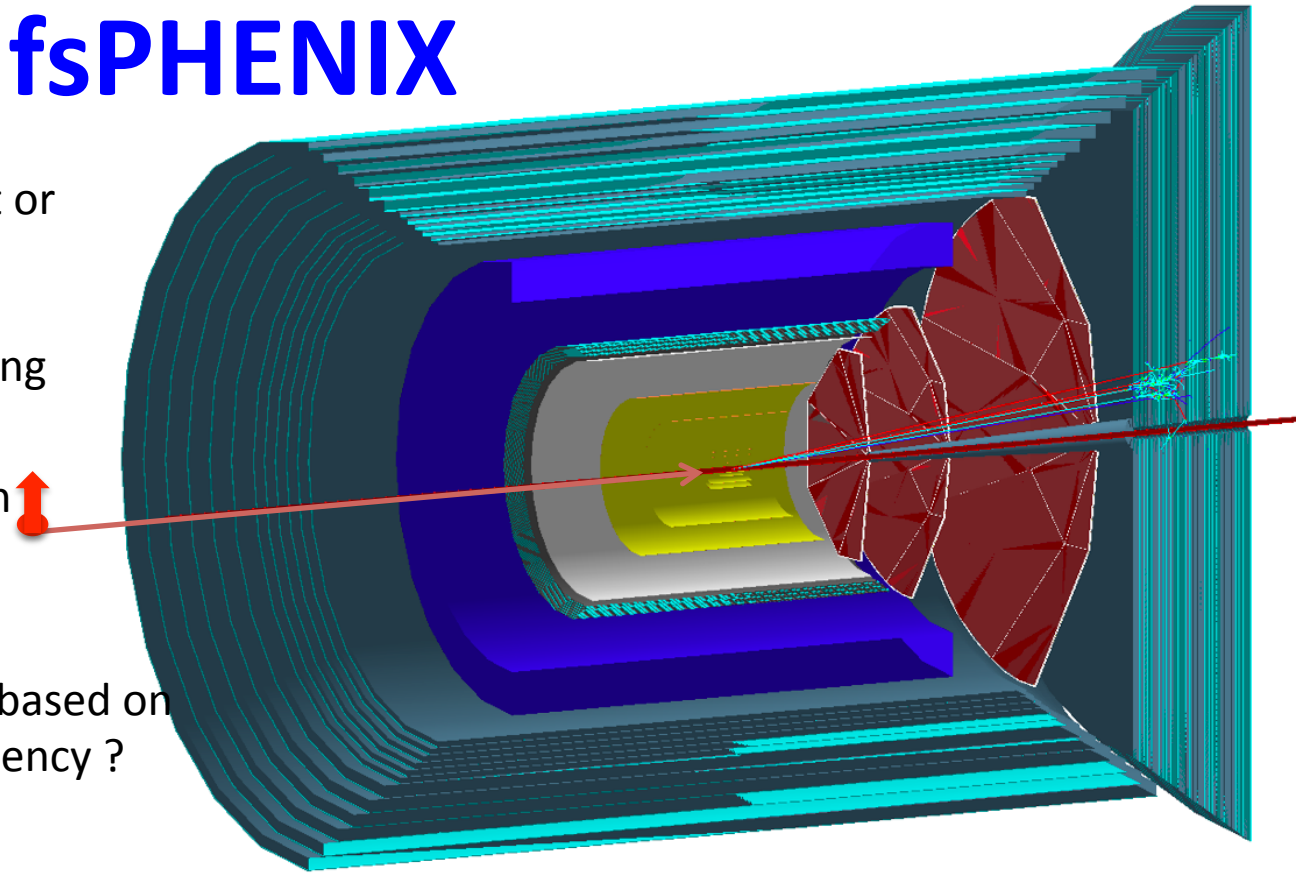


Mike's simulation
Fraction of up-quark jets with different selections.

to enhance one flavor of quark jets.

Jet A_N with fsPHENIX

- Which side a jet favors, left or right of the spin vector ?
- Does it matter when selecting different types of jet ?



- Consistent with predictions based on SIDIS data + process dependency ?

Can only be done with fsPHENIX at RHIC, the world's only polarized p+p collider. Not at a fixed target experiment. Not at EIC.

fsPHENIX is complementary to EIC: Example-2, Example-3, Example-4, Example-5 … at Stage-I

	Observable	Physics	
			Transversity*(Chiral-Odd Frag. Func.)
$p^{\uparrow} + p^{\uparrow}$	incl. A_N^{Jet}	Quark Sivers	
200 GeV	$A_N^{h^{\pm}-Jet}$	Collins $\delta q(x)$	Transversity*(Collins Frag. Func.)
50 pb^{-1}	Interf. A_N^{2h}	Transv. $\delta q(x)$	Transversity*(2h_Interf. Frag. Func.)
	$\Lambda^{\uparrow}$ pol.	Transv. $\delta q(x)$	Transversity*(spin_transf. Frag. Func.)
$p^{\uparrow} + A$	$A_N^{h^{\pm}-Jet}$	Collins in Nucl.	
200 GeV	A_N^{h+}, A_N^{h-}	Saturation	
50 pb^{-1}	incl. R_{pA}^{Jet}	CNM	

Can only be done with fsPHENIX at RHIC, the world's only polarized p+p collider. Not at a fixed target experiment. Not at EIC.

Summary

Significant single spin asymmetries have been observed in :

- Inclusive hadron production: **$p^{\uparrow}$+p-> h + X**
- Semi-inclusive deep inelastic scattering: **e+$N^{\uparrow}$->e'+h+X**
- Inclusive hadron production, JLab on neutron: **e+$n^{\uparrow}$->h+X**
  HERMES on proton: **e+$p^{\uparrow}$->h+X**
- Inclusive jet production at RHIC (AnDY): **$p^{\uparrow}$+p-> jet + X**

We are pushing for the next generation SSA experiments:

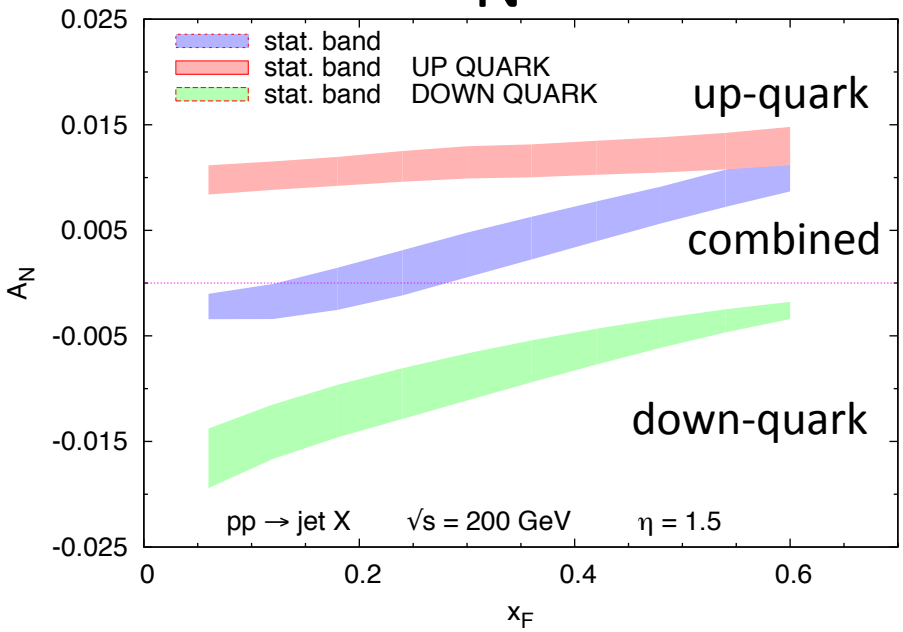
- Target SSA with real photon beam Hall-D@JLab12: **γ+$p^{\uparrow}$->h+X**
  (E_{γ}=9.0~11.0 GeV, can by polarized, linearly or circularly. p_{Th}=0~2.0 GeV/c)
- Polarized target Drell-Yan E-1039@FNAL: **p+$p^{\uparrow}$-> $\mu^{+}\mu^{-}$ + X**
- Forward jet asymmetry fsPHENIX@RHIC: **$p^{\uparrow}$+p-> jet + X**
  (with "charge selected" jets to favor up or down quark)
  (Can also use jet1+jet2+X, γ+jet+X channels etc.)

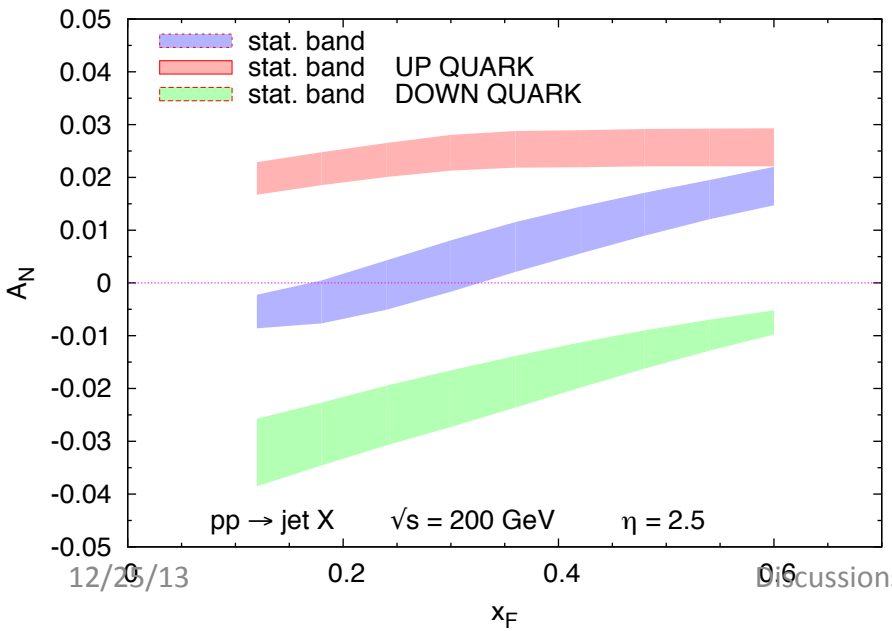
If RHIC has polarized ^{3}He beam in the future: **$^{3}He^{\uparrow}$+p-> jet + X**
To observe SSA sign flip due to valence up_quark <-> down_quark.

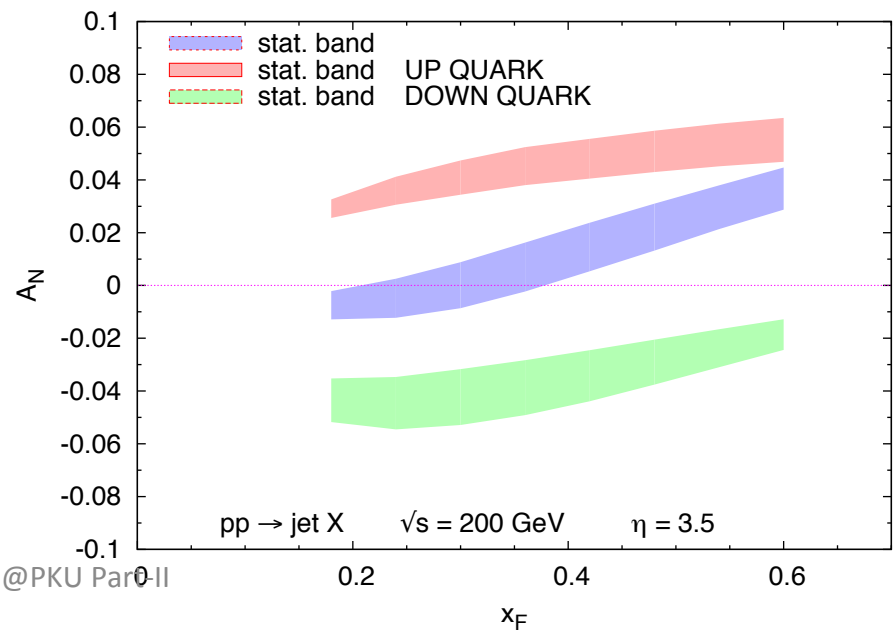
Backup Slides

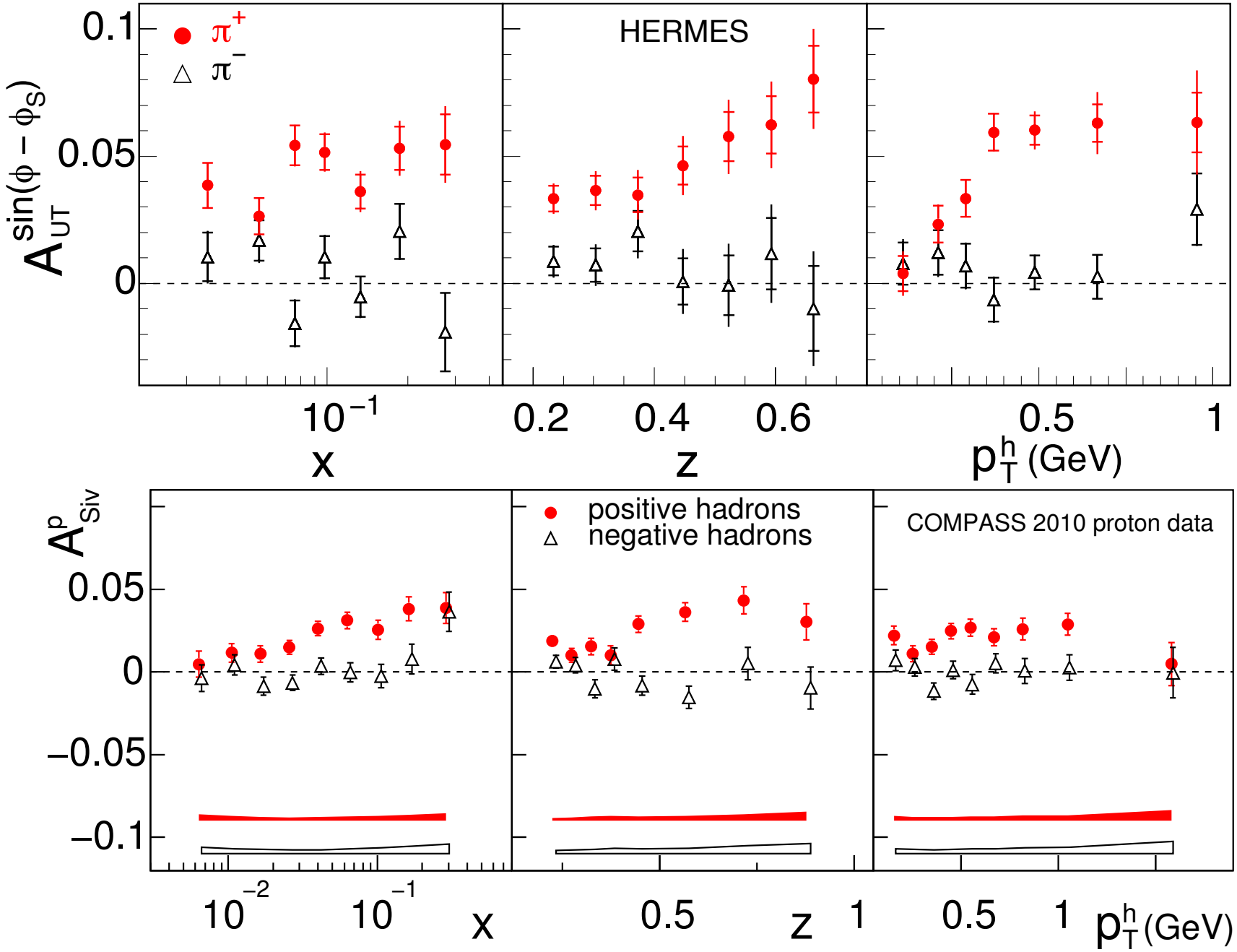
Jet A_N Predictions for fsPHENIX

Anselmino et al. updated 2012.



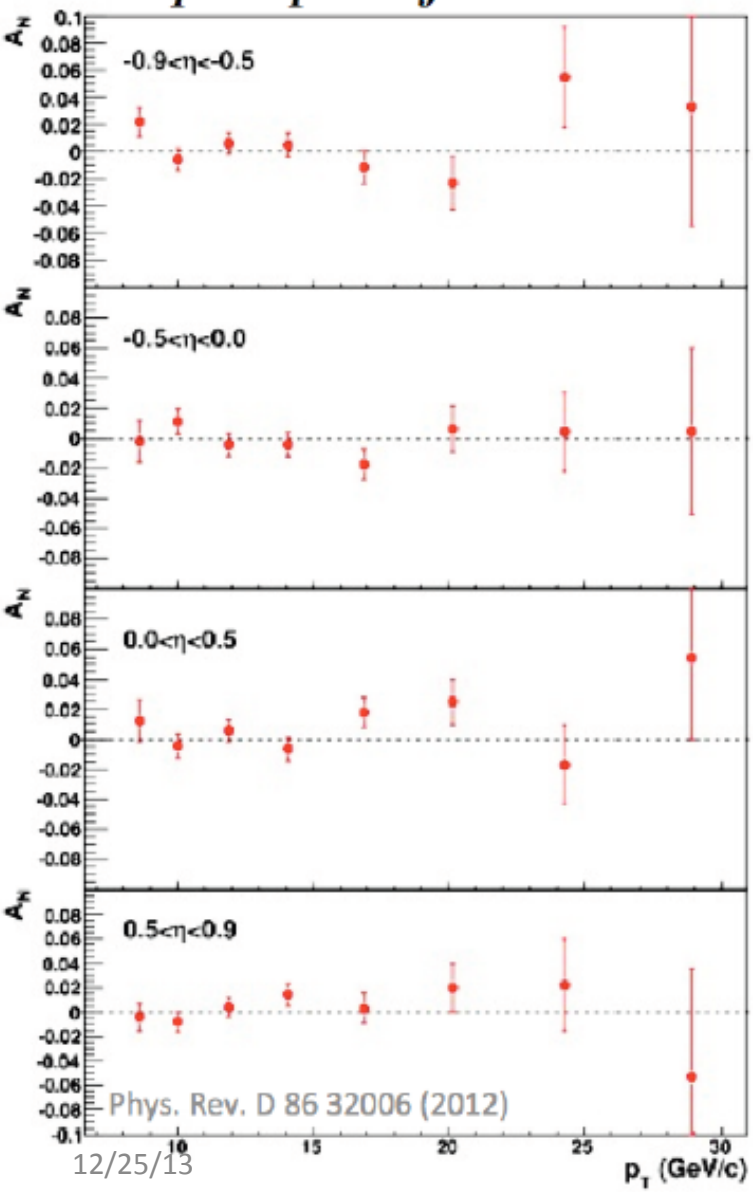


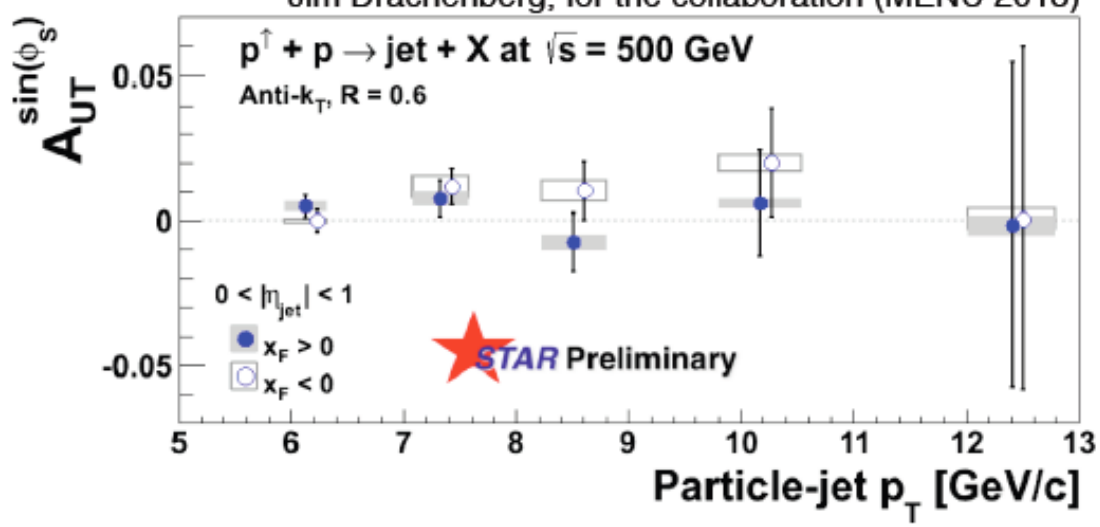



HERMES
π^+
π^-
$A_{UT}^{\sin(\phi-\phi_S)}$
0.1
0.05
0
10^{-1}
x
0.2
0.4
0.6
z
0.5
1
p_T^h (GeV)
COMPASS 2010 proton data
positive hadrons
negative hadrons
A_{Siv}^p
0.05
0
−0.05
−0.1
10^{-2}
10^{-1}
x
0.5
z
1
0.5
1
p_T^h (GeV)

STAR Transverse Spin Phenomena - Sivers Effect

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



- *2006 mid-central rapidity data at √s = 200 GeV: no evidence for Sivers effect to %-level precision, qualitatively consistent with STAR's Sivers di-jet measurement, Phys. Rev. Lett **99** (2007) 142003.*
- *2011 mid-central rapidity data at √s = 500 GeV qualitatively confirm smallness at mid-rapidity.*

Jim Drachenberg, for the collaboration (MENU 2013)