



HAWAII 2014, October 7-11, 2014

Session 2WJ: Polarized Drell-Yan Physics at Fermilab

YAMAGATA UNIVERSITY

2WJ.00007

Opportunities with polarized beam & target

Yoshiyuki Miyachi

Yamagata University

- Flavor symmetry violation in the polarized light sea
 - Flavor symmetry violation in the light sea
 - What do we know?
 - Deep Inelastic Scattering
 - W -production at RHIC
- **Transverse Momentum Dependent PDFs** in polarized Drell-Yan
 - TMDs in SIDIS
 - TMDs in Polarized Drell-Yan
- Summary

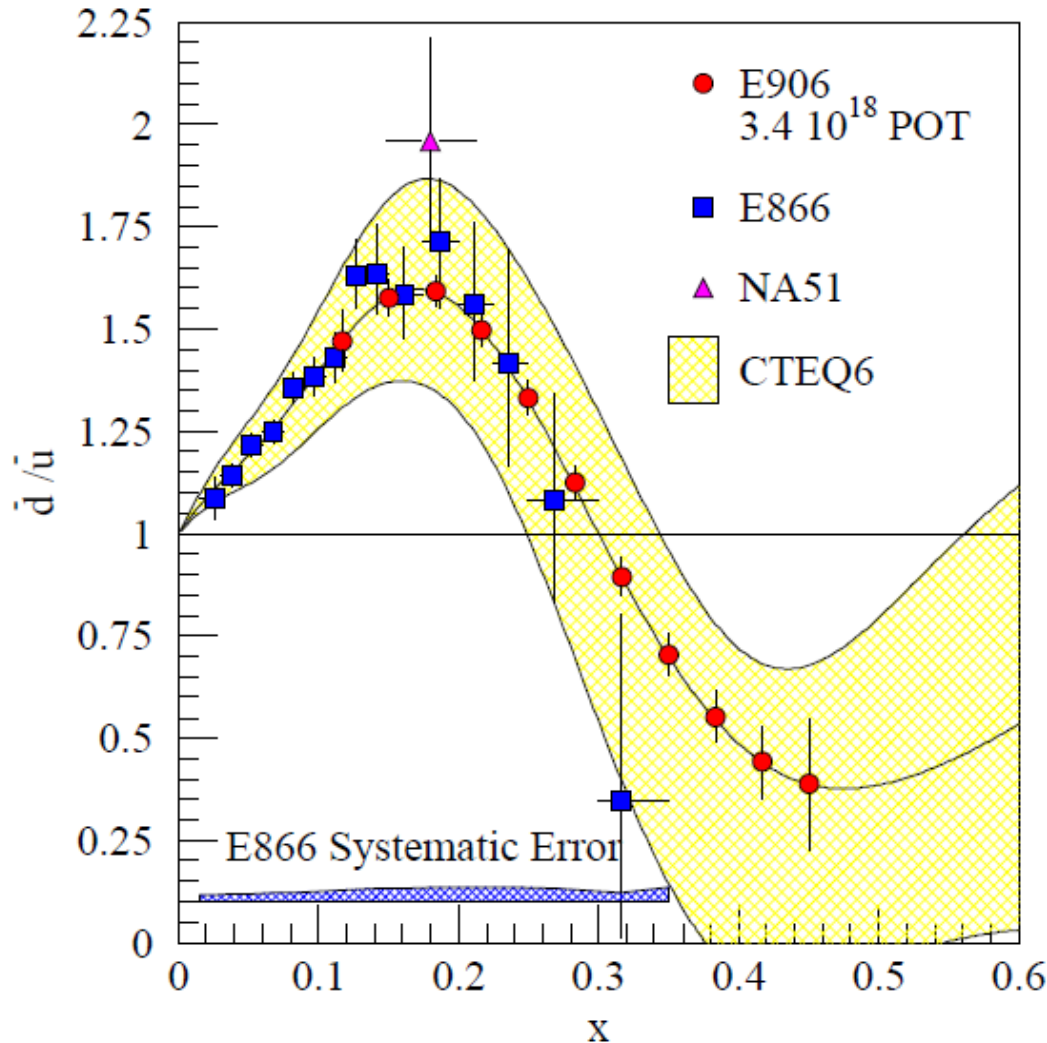


Flavor symmetry violation in the polarized light sea?



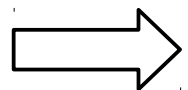
Flavor symmetry violation in the light sea

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Gottfried sum rule violation
 Observed by NMC
 Confirmed and new surprise
 by E866/NeuSea
 E906/SeaQuest will solve
 “Flavor puzzle”

Origin: pion tornado?



Flavor symmetry violation **in the polarized light sea?**

$$\Delta u(x) \neq \Delta d?$$

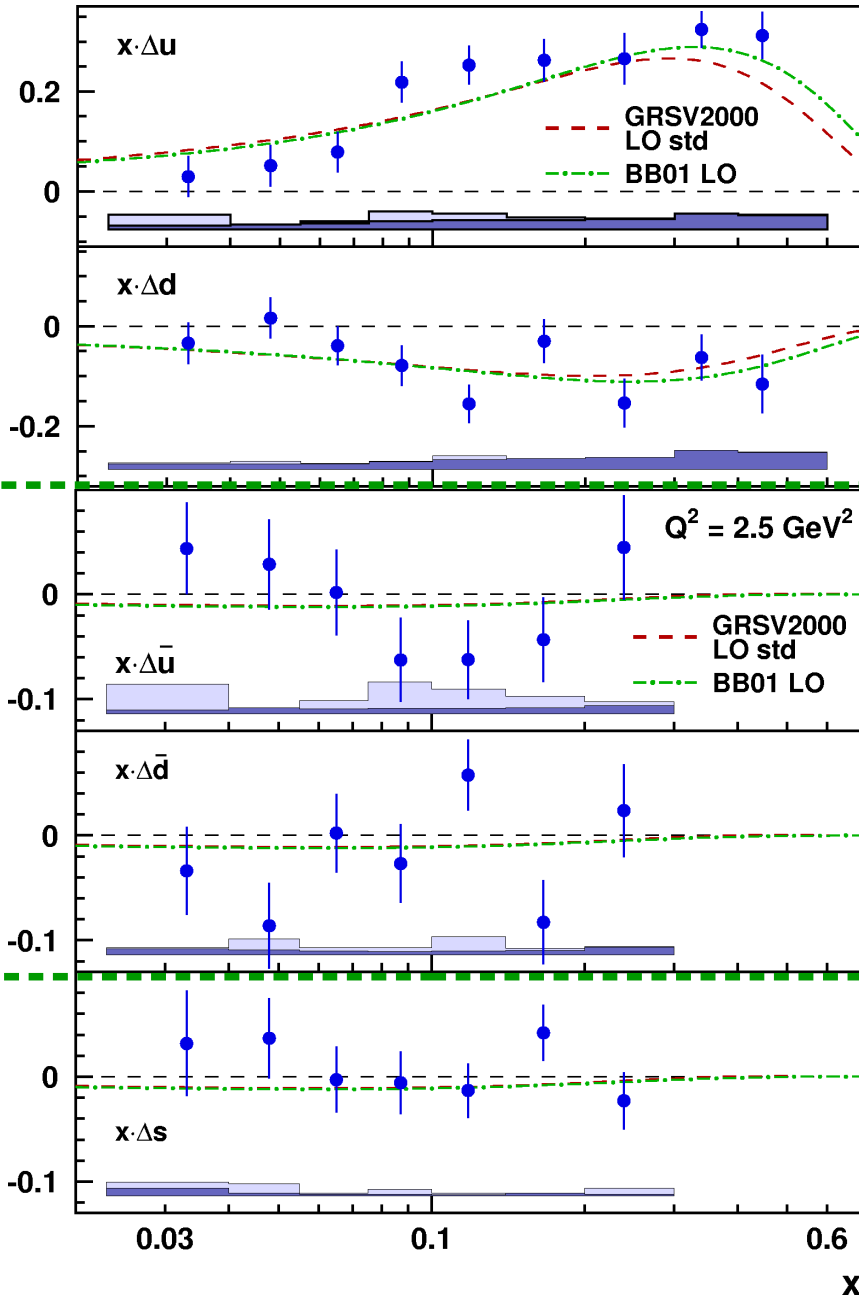


From SIDIS: HERMES

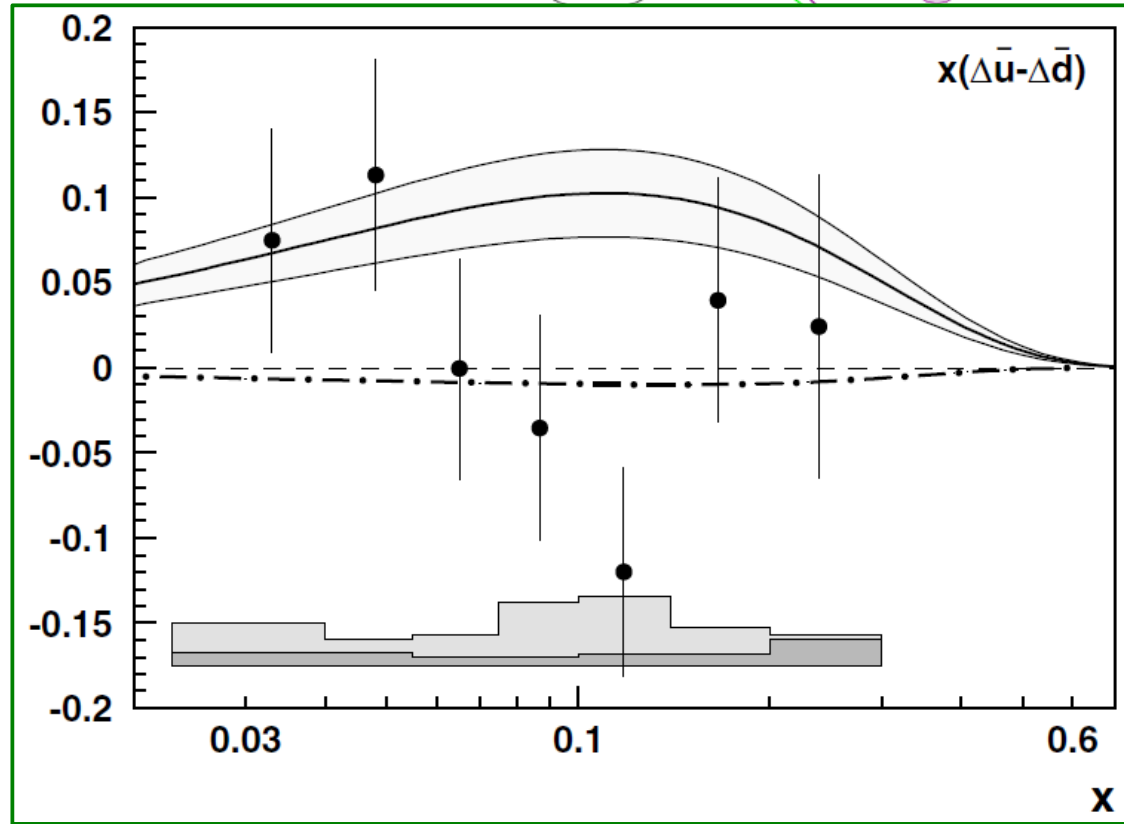
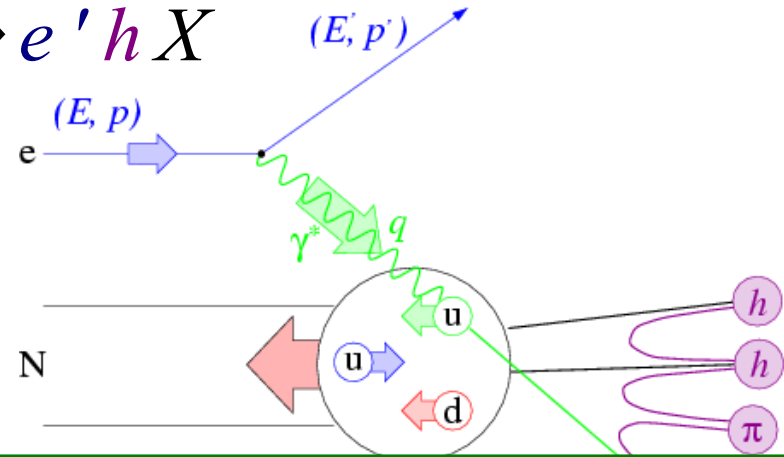
PRD71(2005)012003



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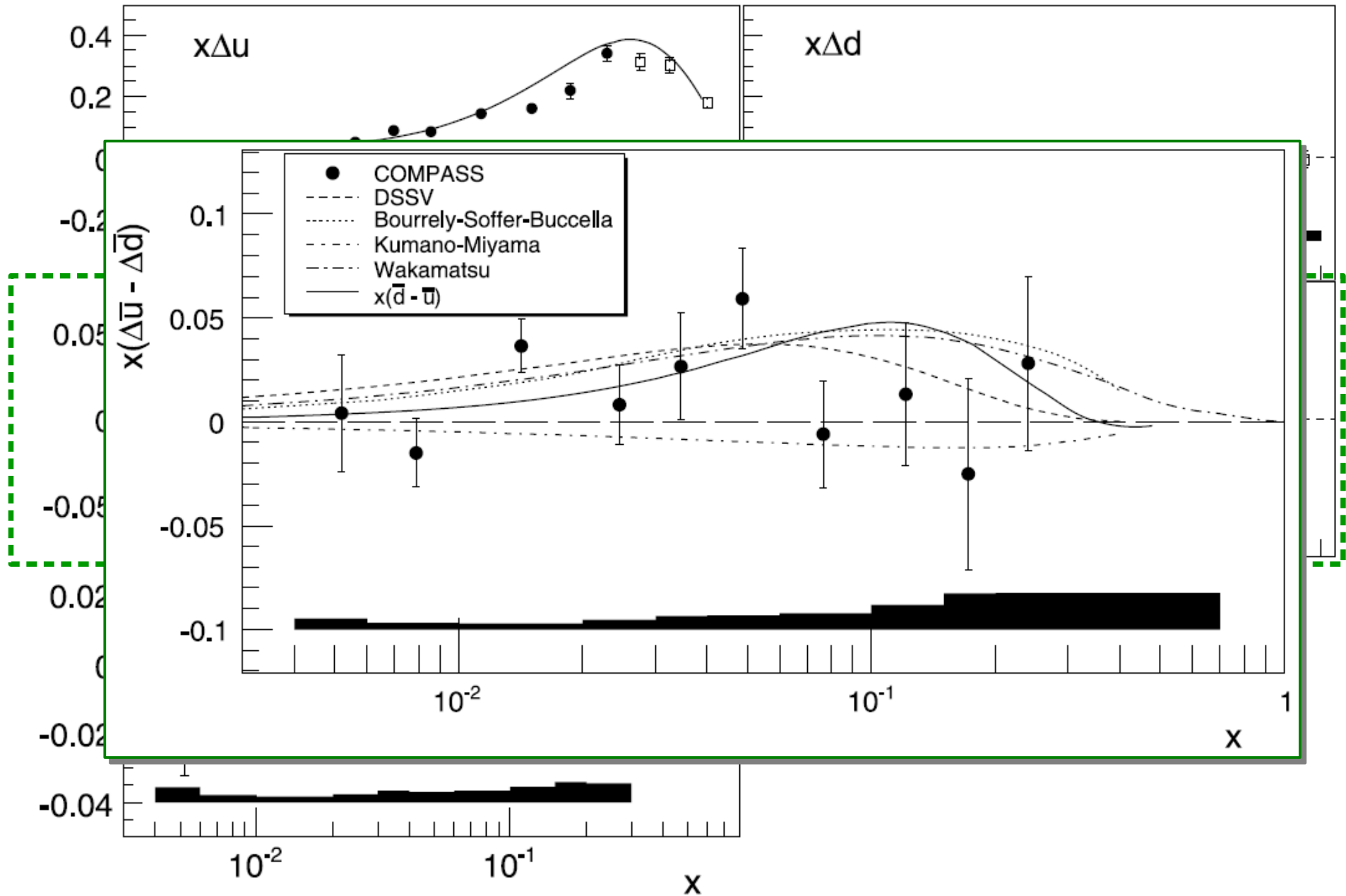
$$e N \rightarrow e' h X$$





From SIDIS: COMPASS

COMPASS PRLB693(2010)227





W± production at RHIC

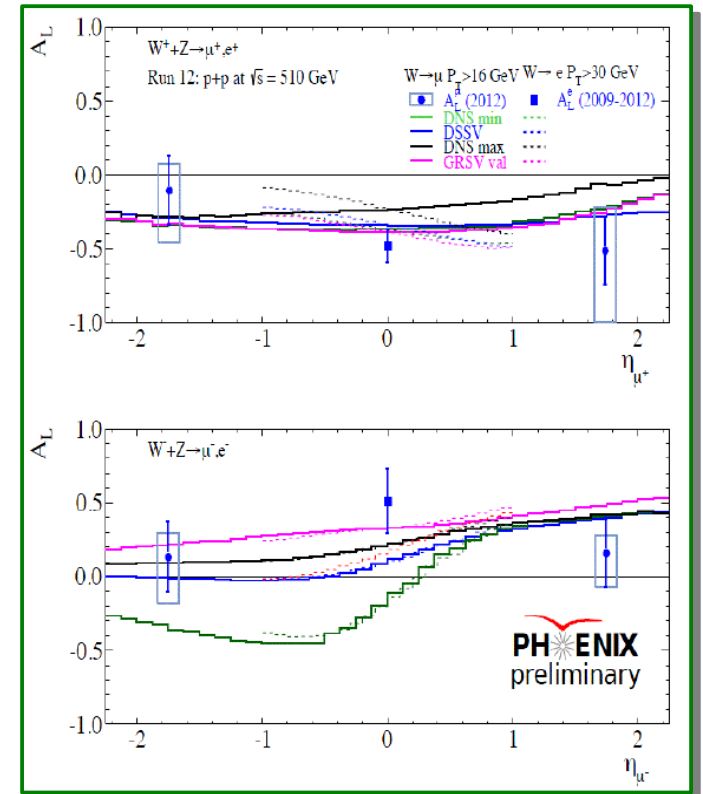
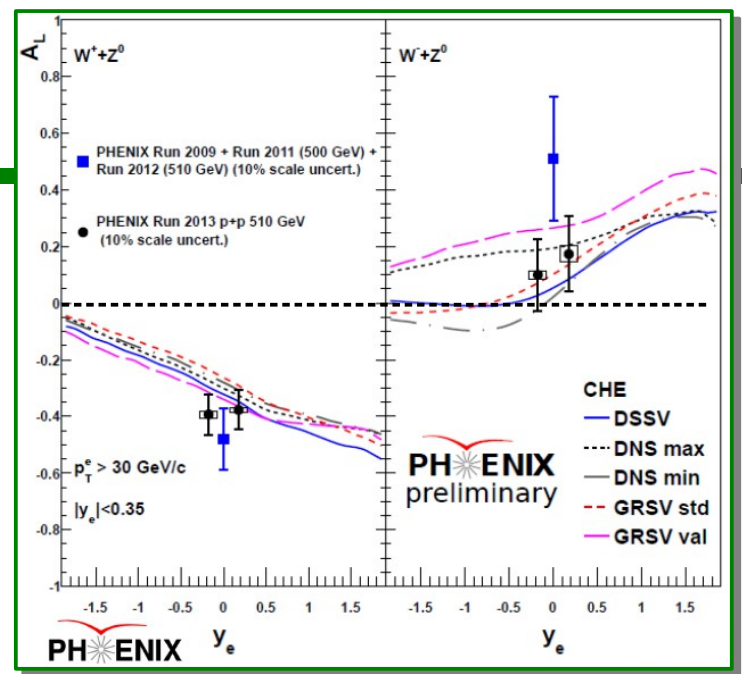
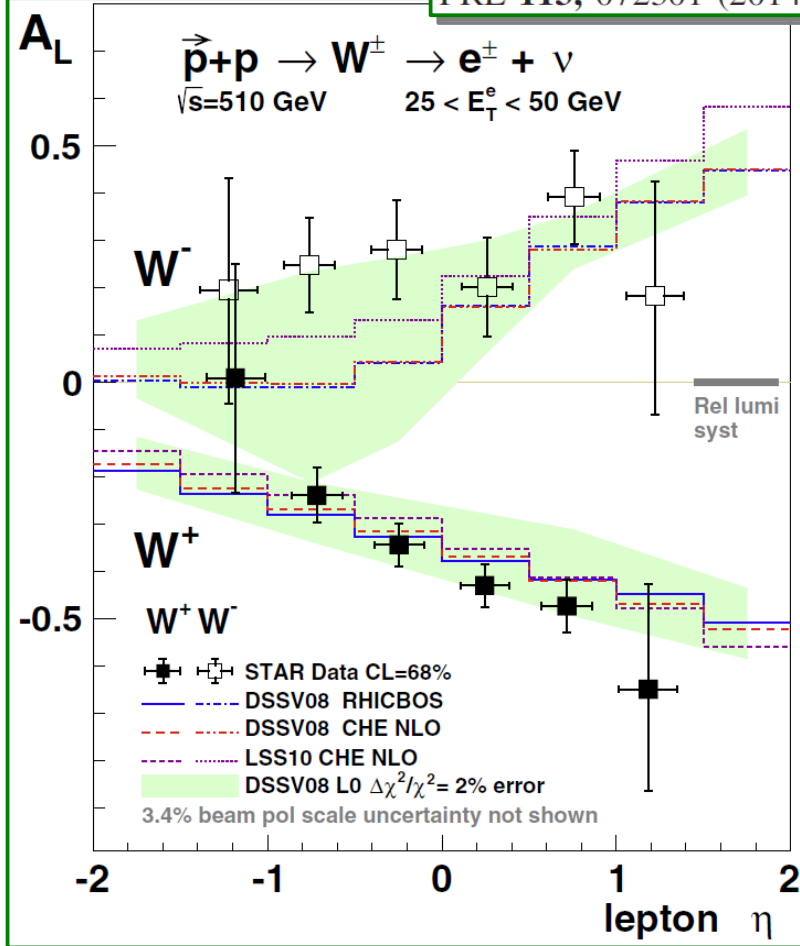
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$$p+p \rightarrow W^\pm + X \quad \sqrt{s}=510 \text{ GeV}$$

$$A_L^{W^-} = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$



PRL 113, 072301 (2014)





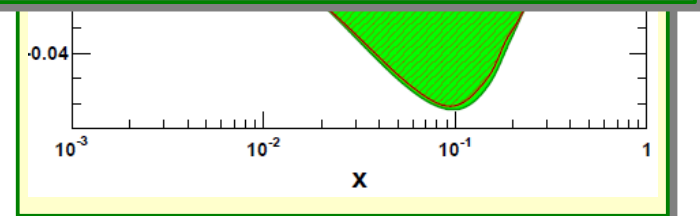
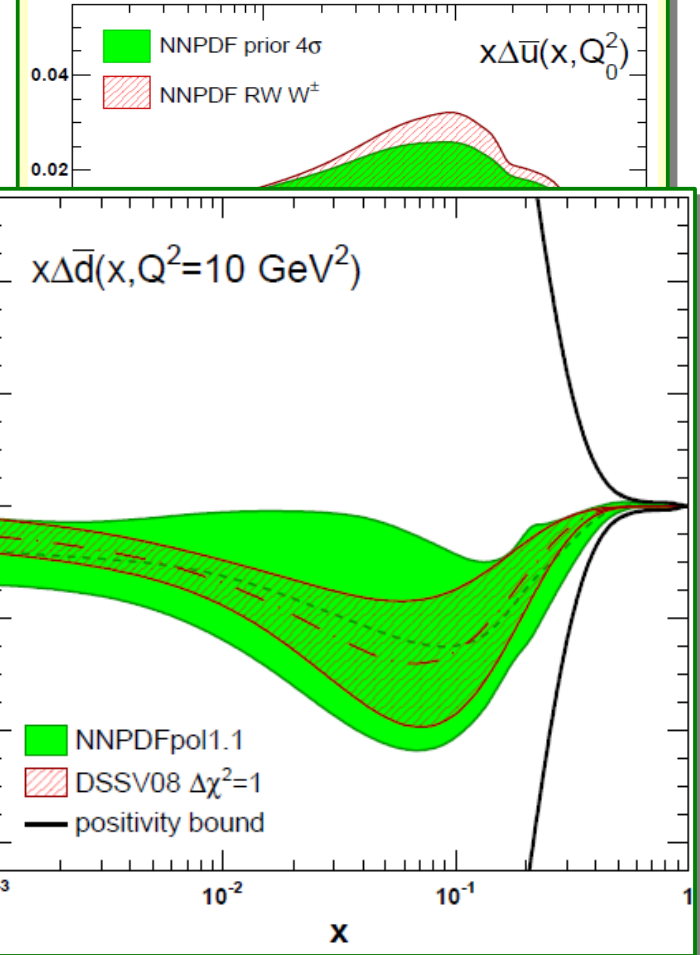
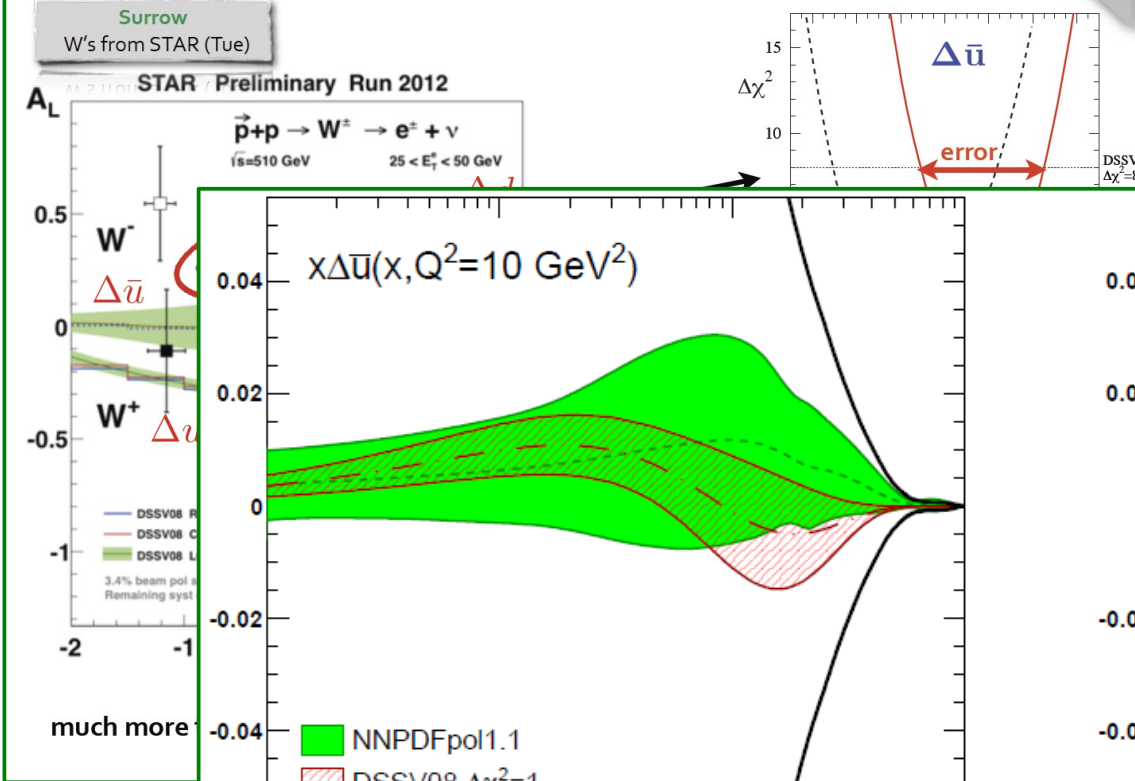
Impact to the helicity distributions

DSSV++

preliminary 2012 STAR data & impact

$\Delta\bar{u}$
 $\Delta\bar{d}$

NNPDF, arXiv:1406.5539



NNPDF: no SIDIS data
DSSV: SIDIS data included

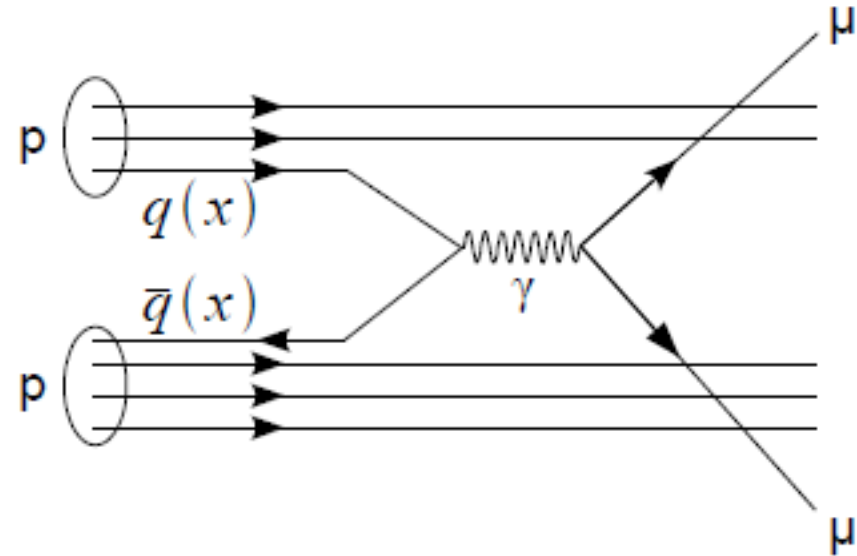


Double polarized Drell-Yan

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Drell-Yan

$$\vec{p} + \vec{p} \rightarrow l^+ + l^- + X$$

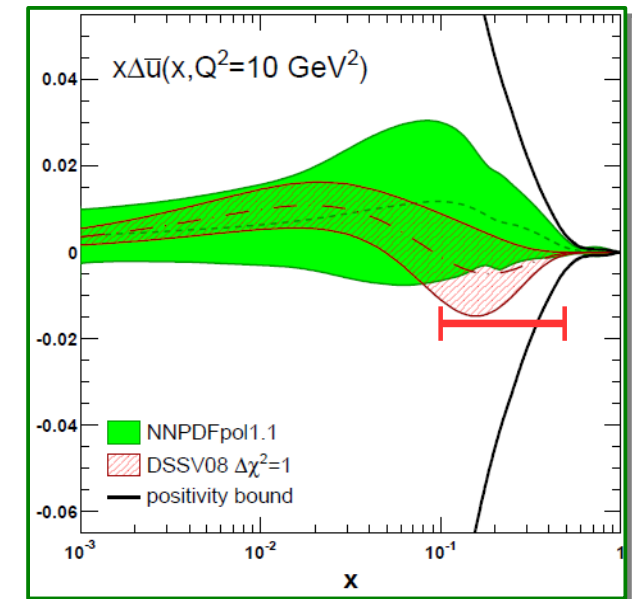
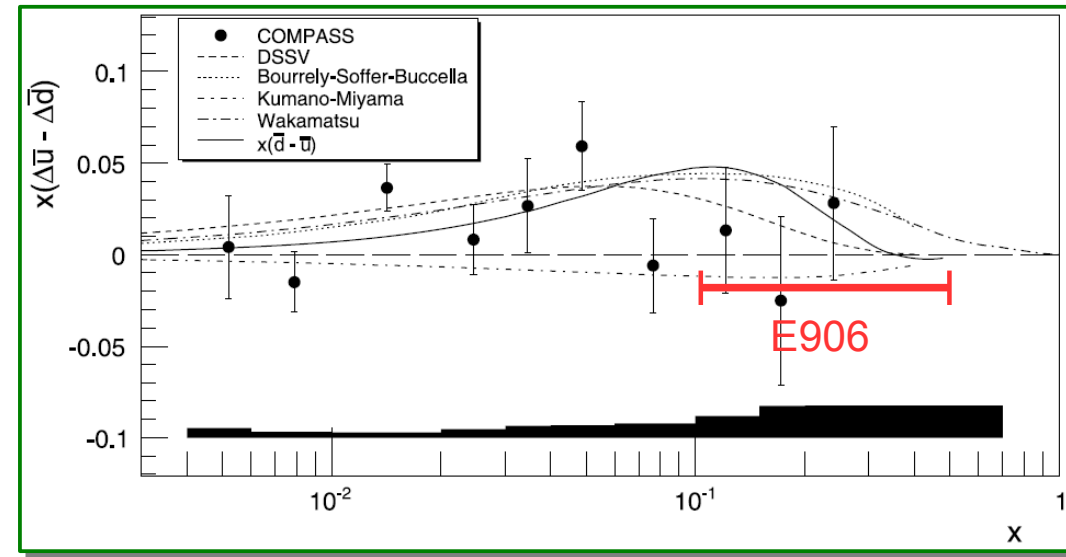


$$A_{LL} \propto \frac{\sum e_q^2 \{ \Delta q(x_1) \Delta \bar{q}(x_2) + \Delta \bar{q}(x_1) \Delta q(x_2) \}}{\sum e_q^2 \{ q(x_1) \bar{q}(x_2) + \bar{q}(x_1) q(x_2) \}}$$

A_{LL} in DY to probe the flavor symmetry violation

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- Drell-Yan with fixed target
 - Sea @ the large x
 - E906/SeaQuest: $x \sim 0.3$
- E1027 with L-pol.
 - Additional spin rotator
- E1034 with L-pol.
 - PT magnet + cryostat modification
 - Proton and deuteron targets
 - Unpol PDF from E906/SeaQuest
- Important input to the global analysis





Doubly polarized

TMDs in Drell-Yan

(Transverse **m**omentum **d**ependent PDF)



Leading twist TMDs

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	<p>f_1 Parton Density</p>	<p>$g_{1L} (= \Delta q)$ Helicity</p>	<p>h_1^\perp Boer-Mulders</p>
	<p>$g_{1L} (= \Delta q)$ Helicity</p>	<p>h_{1L}^\perp Mulders-Kotzinian</p>	<p>h_{1L}^\perp Mulders-Kotzinian</p>
	<p>f_{1T}^\perp Sivers</p>	<p>g_{1T} Worm-gear</p>	<p>$h_{1T} (= \delta q)$ Transversity</p> <hr/> <p>h_{1T}^\perp Pretzelosity</p>



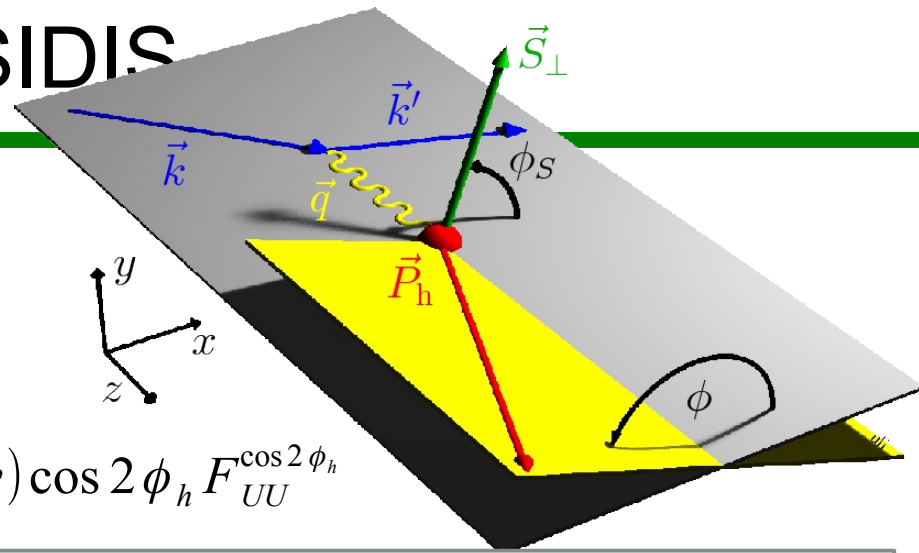
Azimuthal amplitudes in SIDIS

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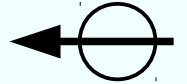


$d\sigma \propto$

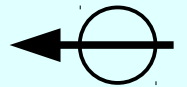
$$\frac{1+(1-y)^2}{2} F_{UU} + (2-y)\sqrt{1-y}\cos\phi_h F_{UU}^{\cos\phi_h} + (1-y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}$$



$$+ S_L \left[(1-y)\sin 2\phi_h F_{UL}^{\sin 2\phi_h} + (2-y)\sqrt{1-y}\sin\phi_h F_{UL}^{\sin\phi_h} \right]$$



$$+ S_L P_z^l \left[\frac{1-(1-y)^2}{2} F_{LL} + y\sqrt{1-y}\cos\phi_h F_{LL}^{\cos\phi_h} \right]$$



$$+ S_T \left[\frac{1+(1-y)^2}{2} \sin(\phi_h - \phi_s) F_{UT}^{\sin(\phi_h - \phi_s)} \right. \\ \left. + (1-y) \left(\sin(\phi_h + \phi_s) F_{UT}^{\sin(\phi_h + \phi_s)} + \sin(3\phi_h - \phi_s) F_{UT}^{\sin(3\phi_h - \phi_s)} \right) \right. \\ \left. + (2-y)\sqrt{1-y} \left(\sin\phi_s F_{UT}^{\sin\phi_s} + \sin(2\phi - \phi_s) F_{UT}^{\sin(2\phi - \phi_s)} \right) \right]$$

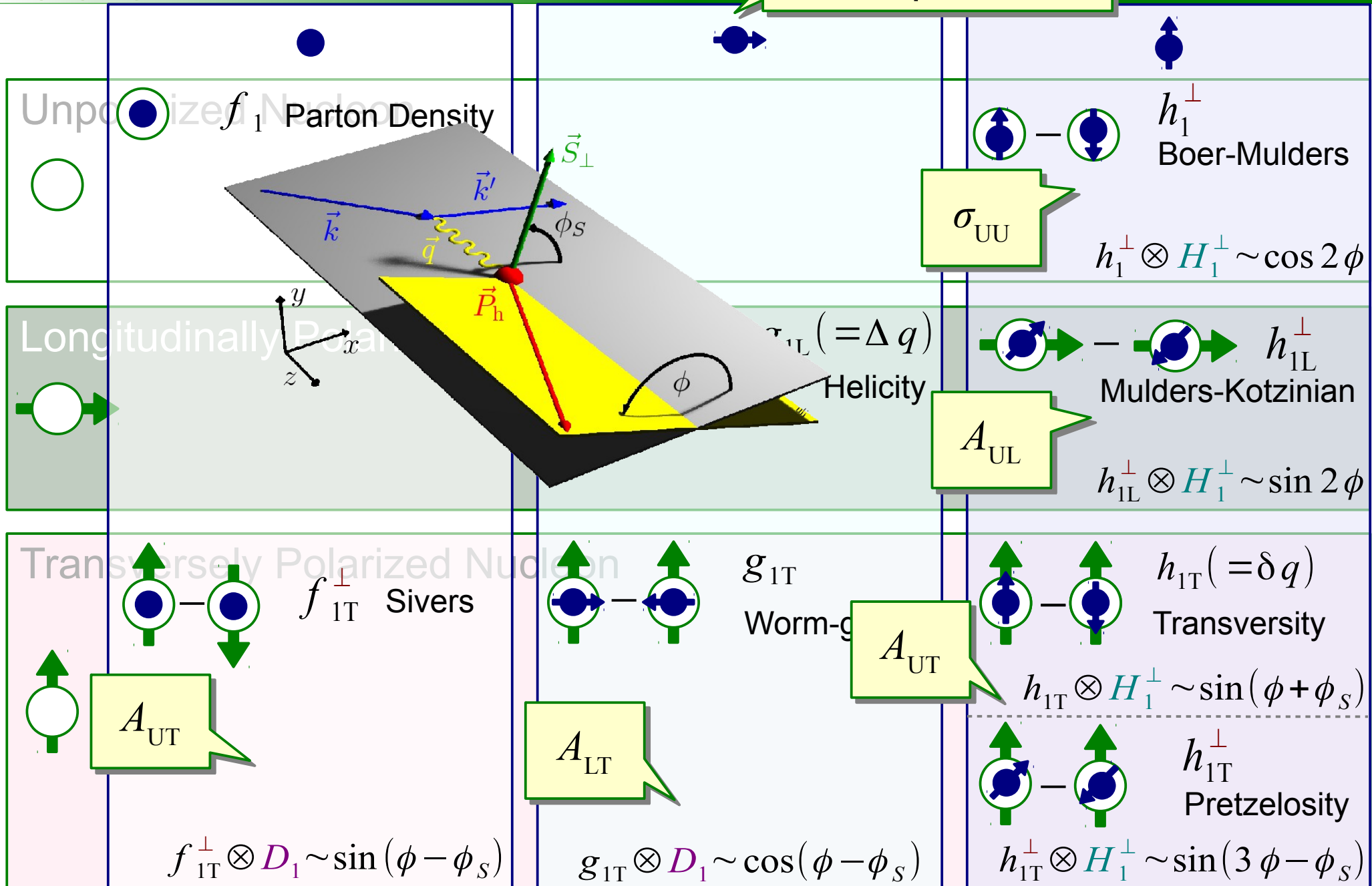


$$+ S_T P_z^l \left[\frac{1-(1-y)^2}{2} \cos(\phi_h - \phi_s) F_{LT}^{\cos(\phi_h - \phi_s)} + y\sqrt{1-y} \left(\cos\phi_s F_{LT}^{\cos\phi_s} + \cos(2\phi - \phi_s) F_{LT}^{\cos(2\phi - \phi_s)} \right) \right]$$



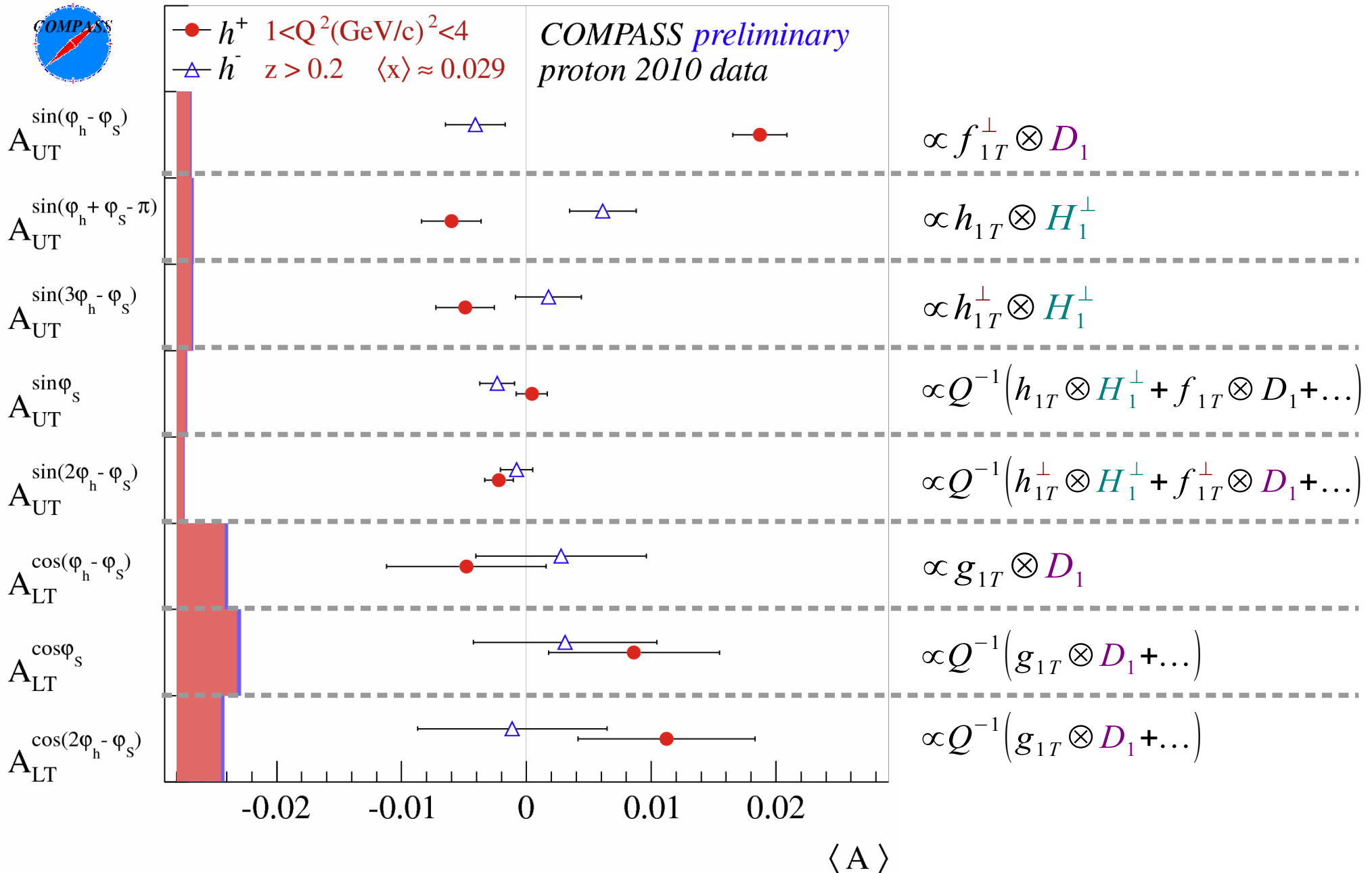
TMDs in SIDIS

With L-pol. beam



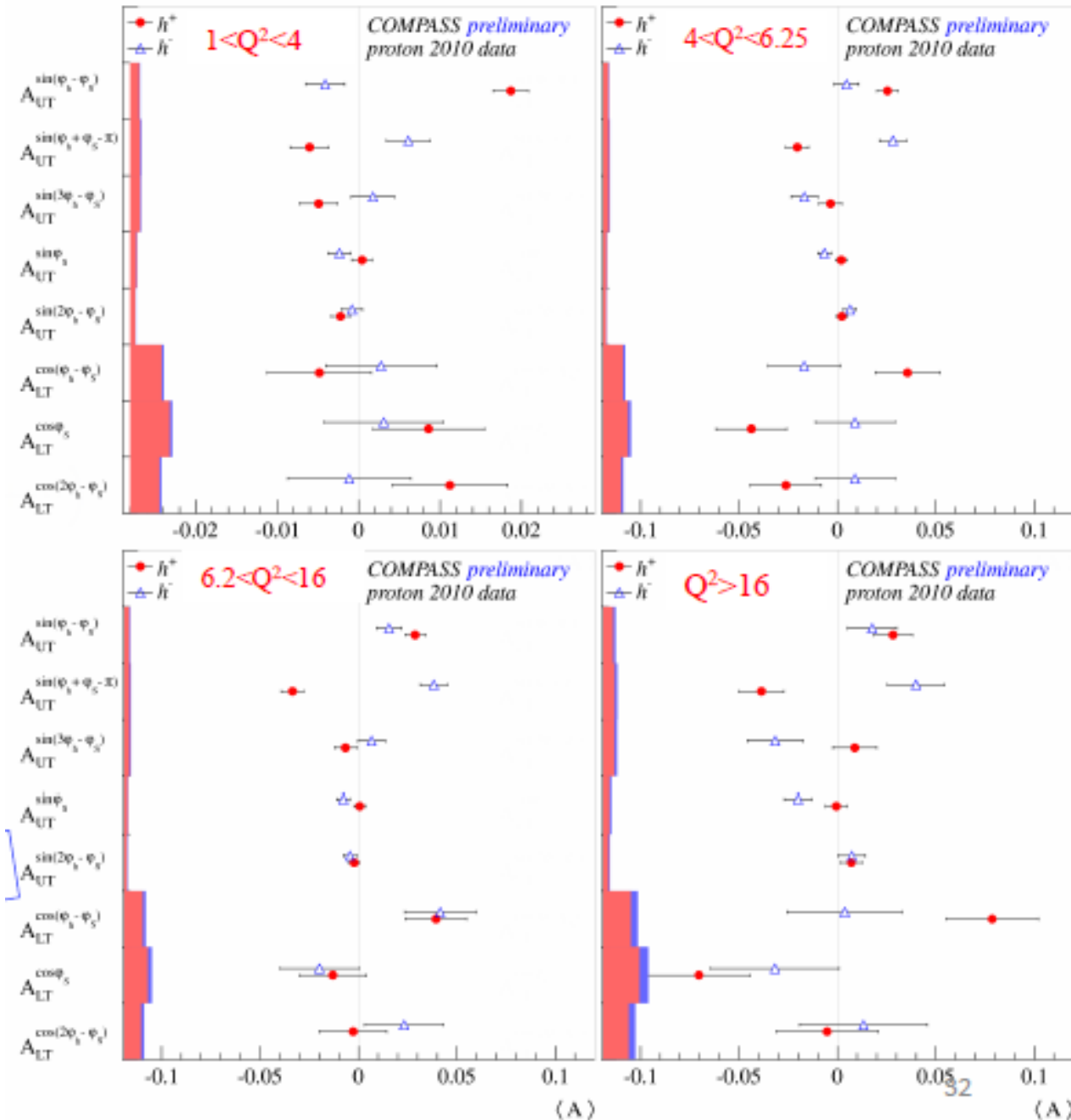


Mean asymmetries

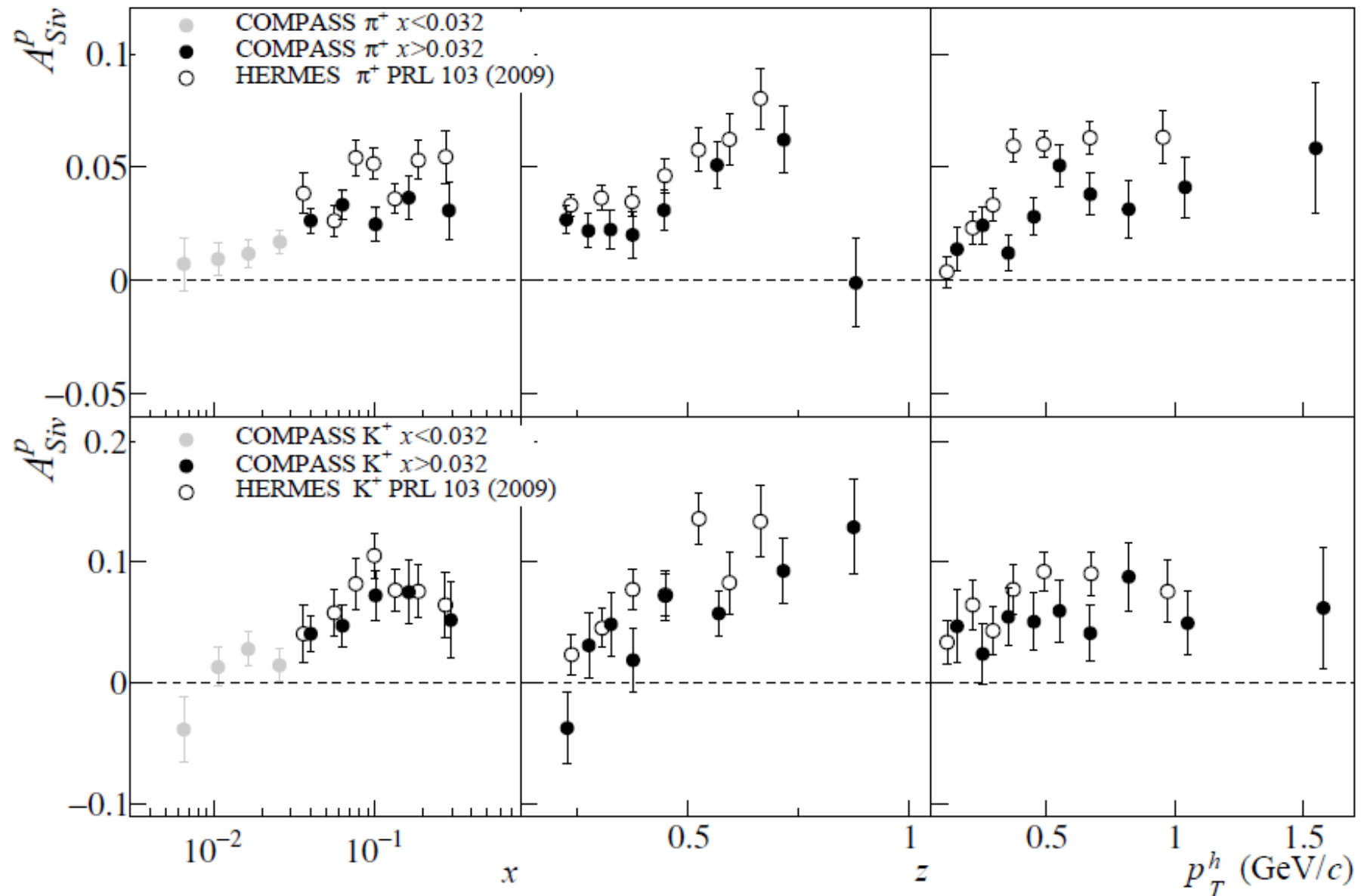




Mean asymmetries



$$f_{1T}^\perp \otimes D_1 \sim A_{UT}^{\sin(\phi - \phi_S)}$$



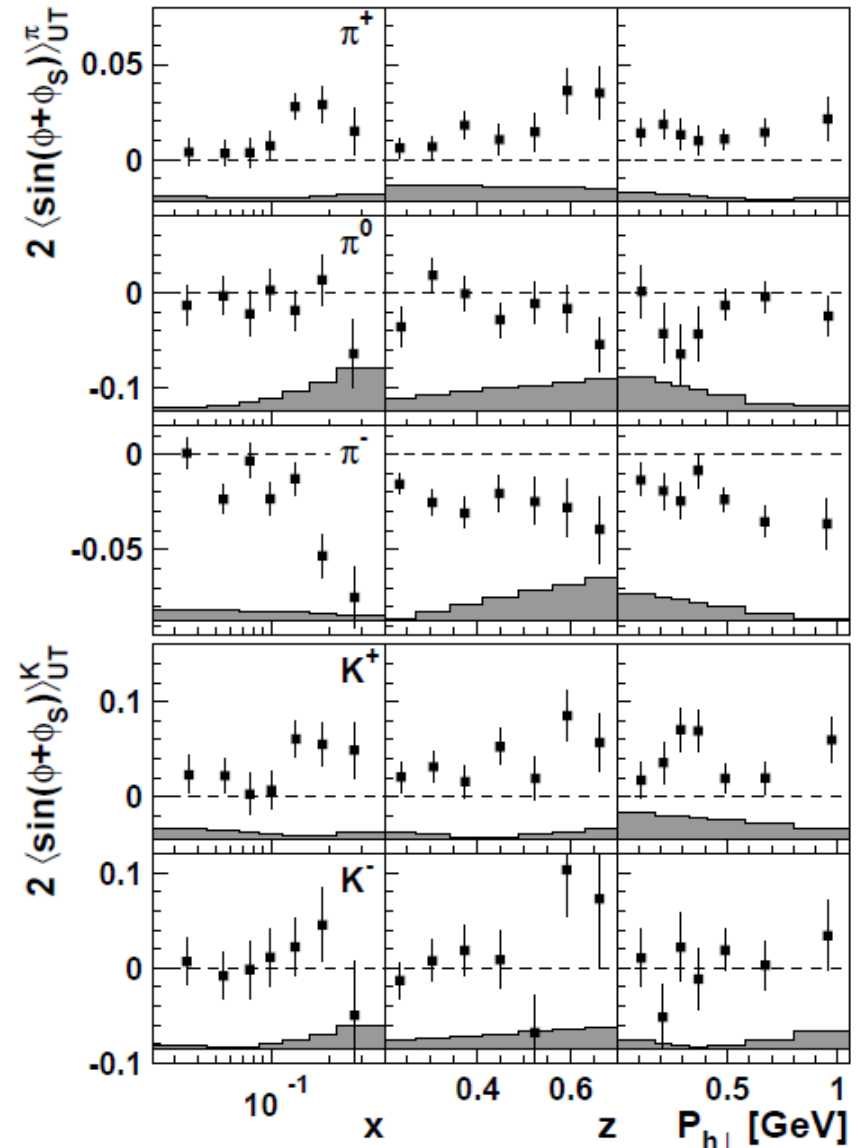
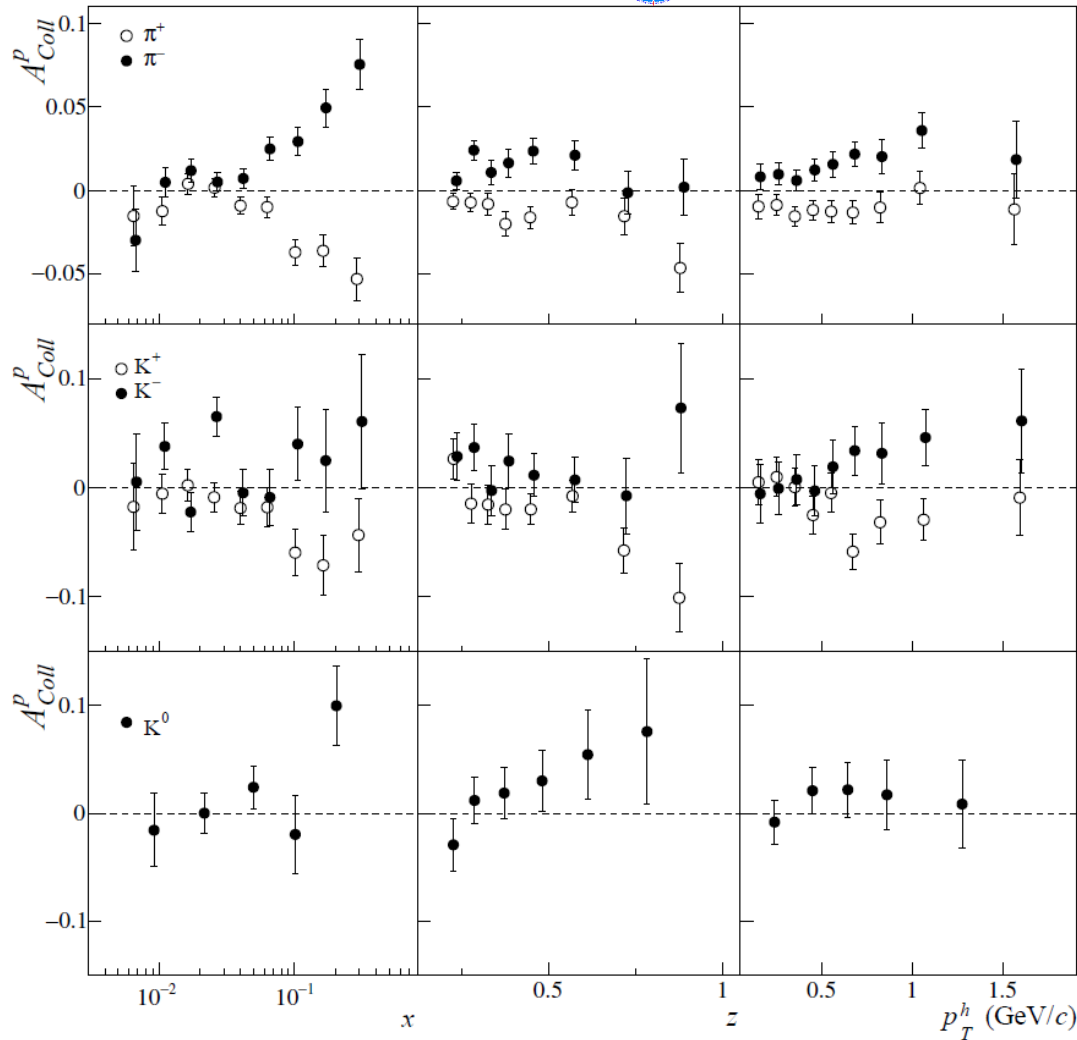
$$h_{1T} \otimes H_1^\perp \sim A_{UT} \sin(\phi + \phi_S)$$



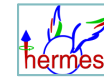
PLB693(2010)



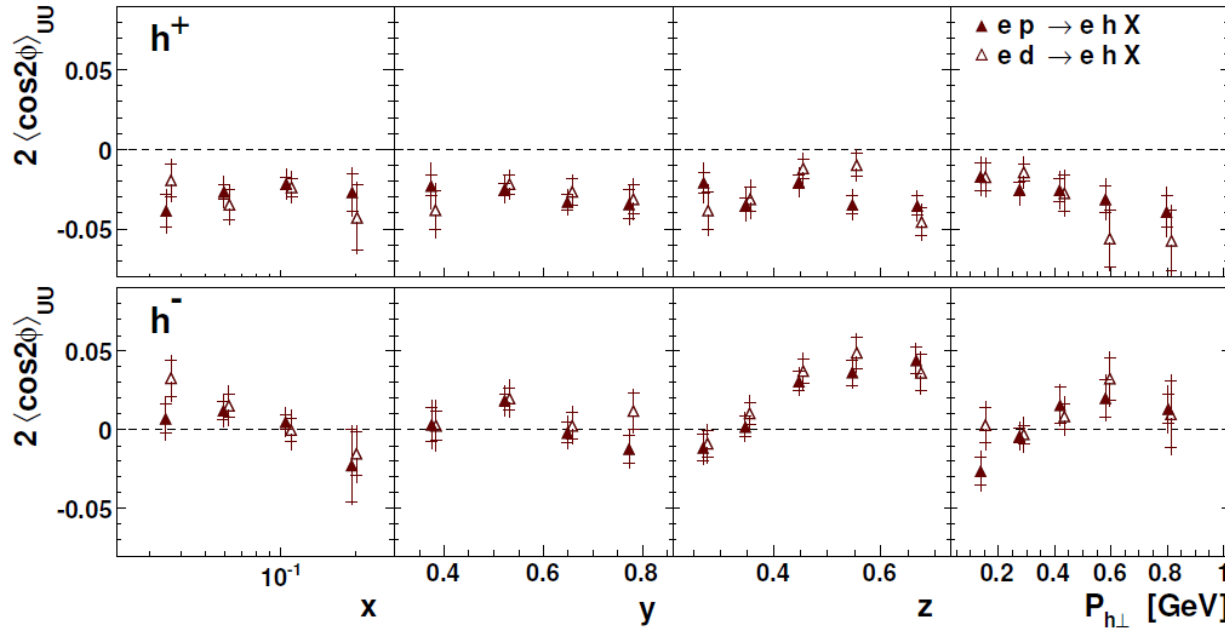
arXiv:1408.4405



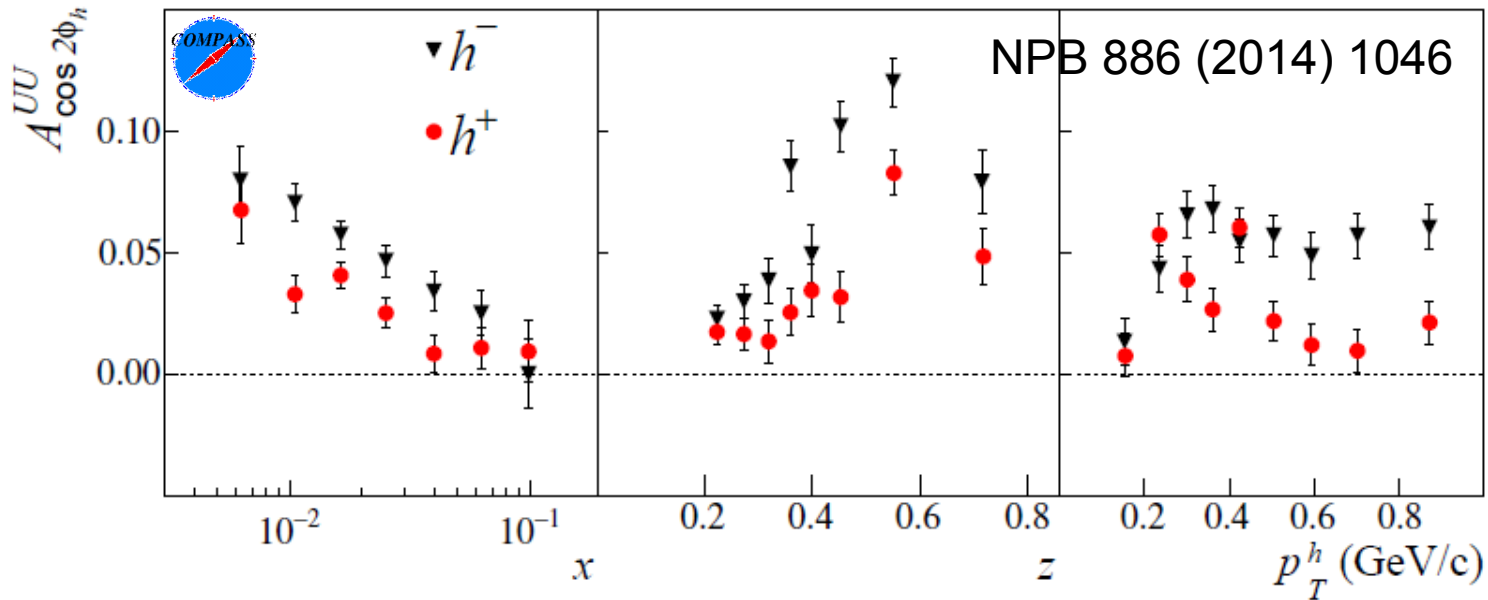
$$h_1^\perp \otimes H_1^\perp \sim F_{UU}^{\cos 2\phi}$$



PRD87(2013)012010



Li⁶D target

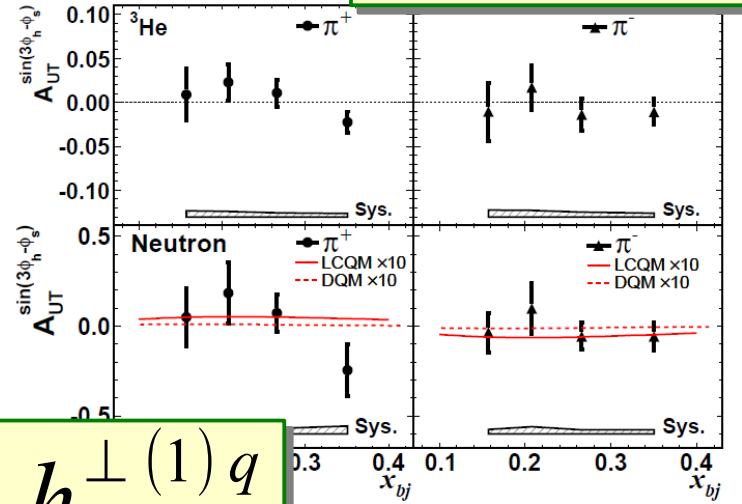
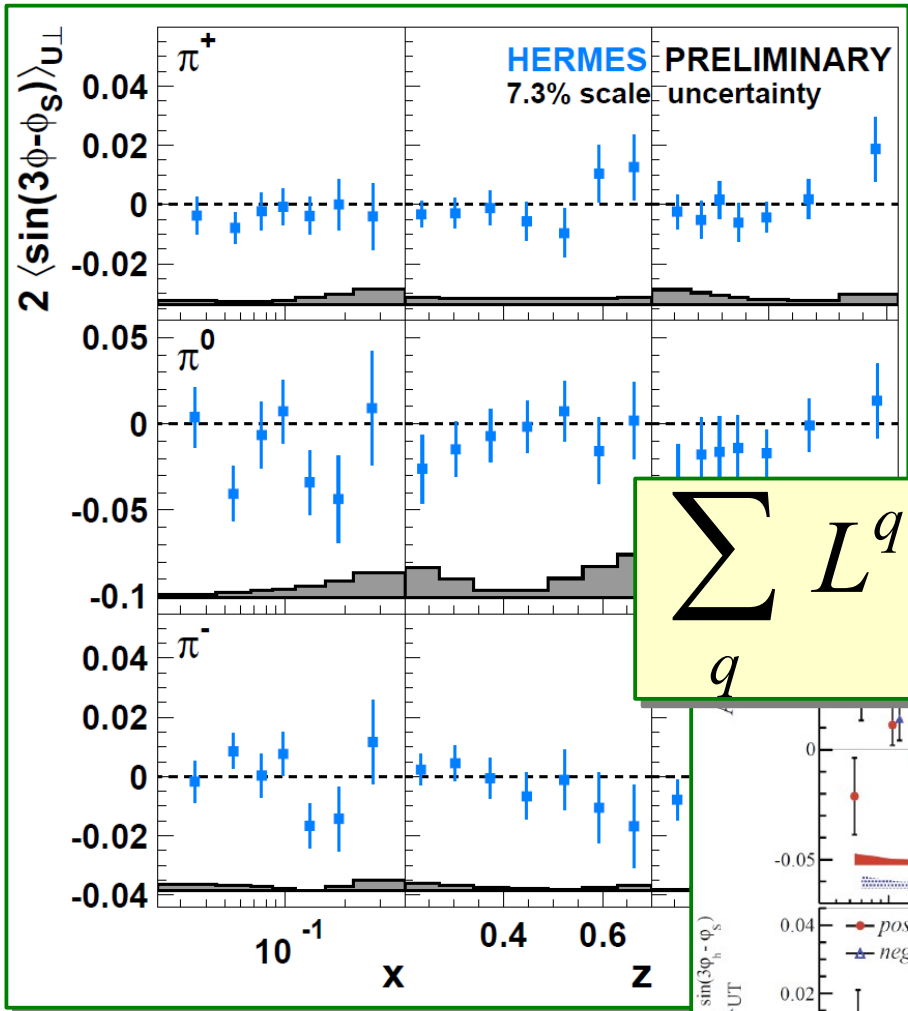




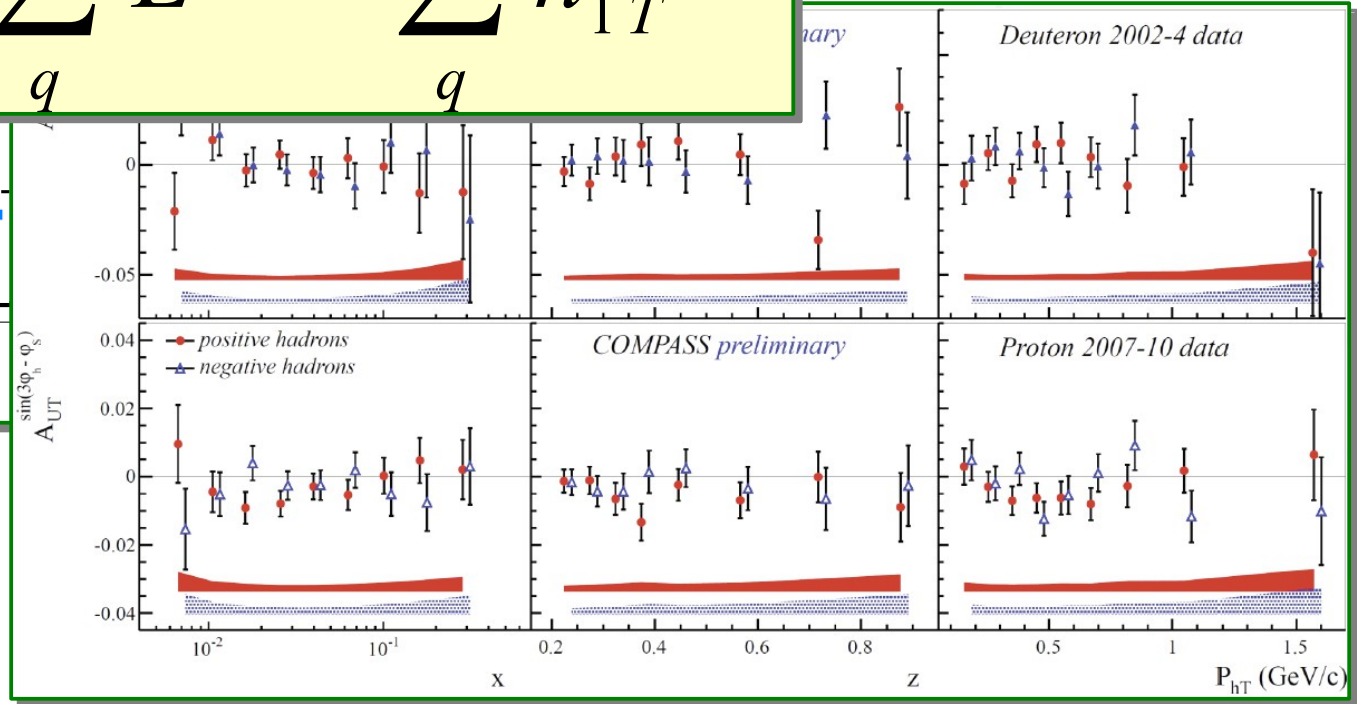
Pretzelosity

$$h_{1T}^\perp \otimes H_1^\perp \sim A_{UT}^{\sin(3\phi - \phi_s)}$$

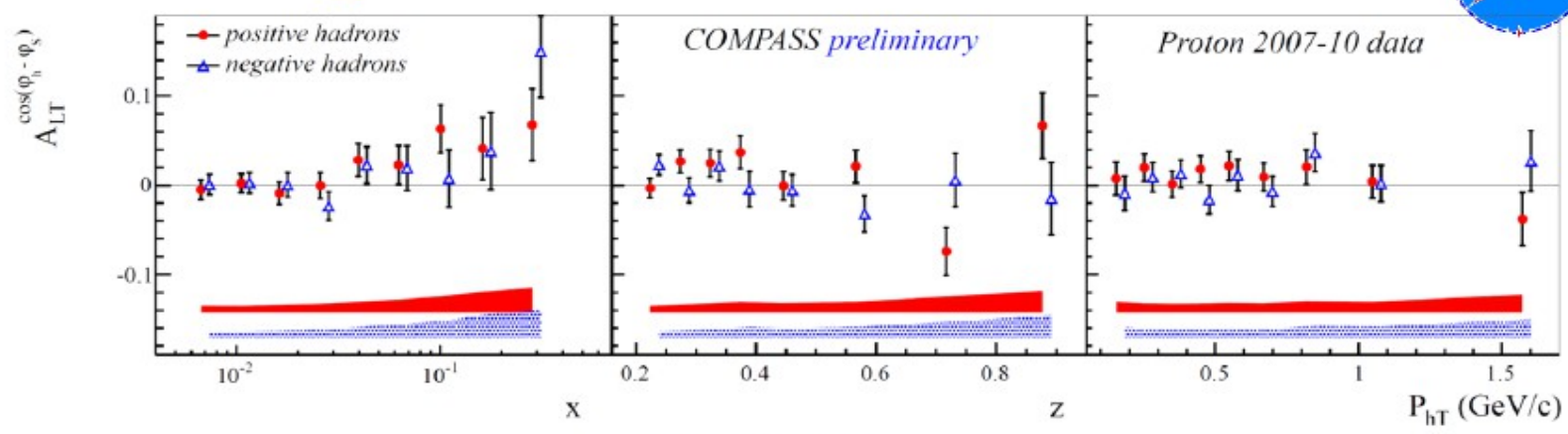
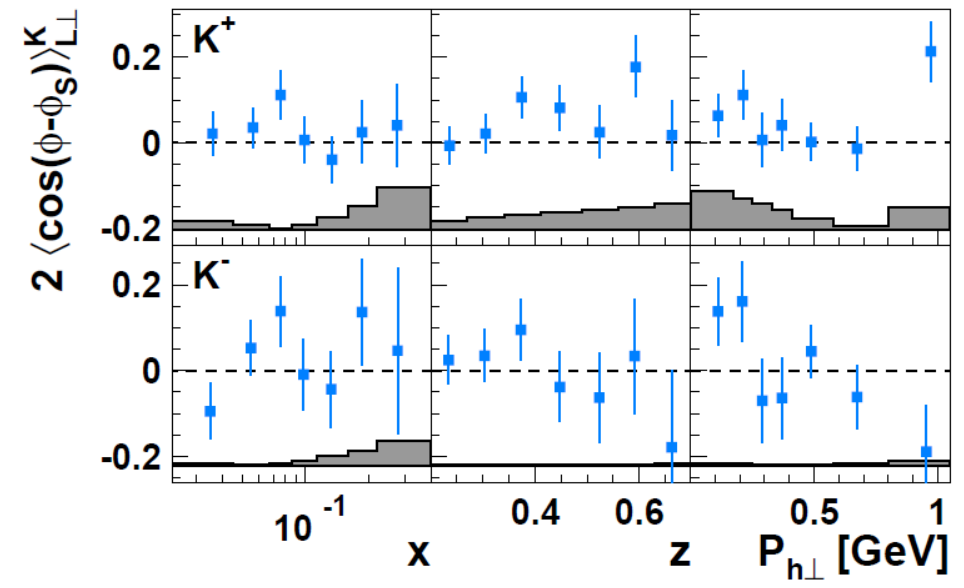
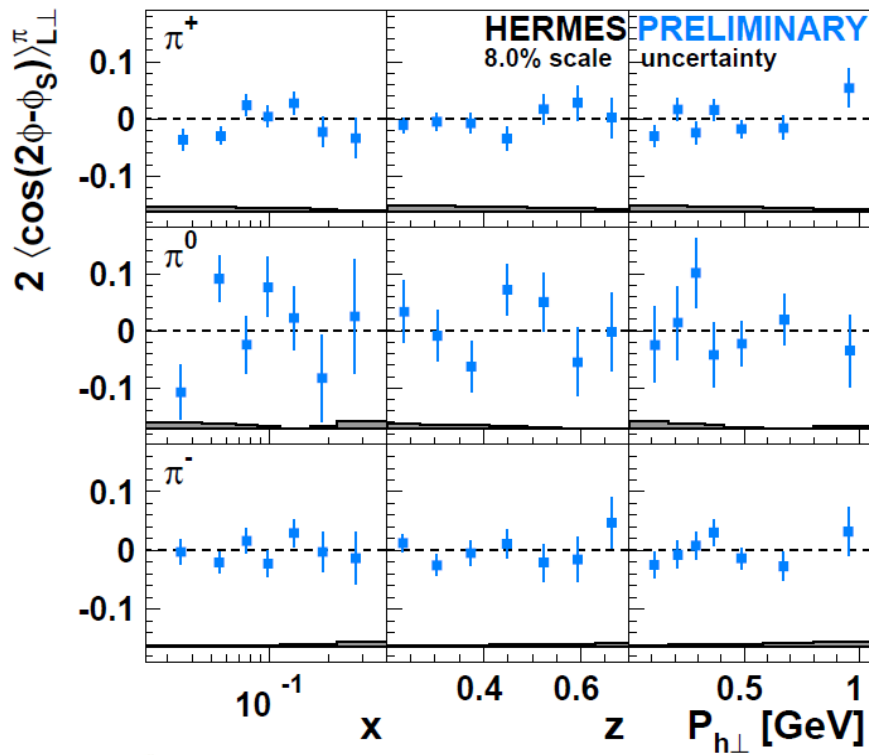
JLab, arXiv:1312.3047



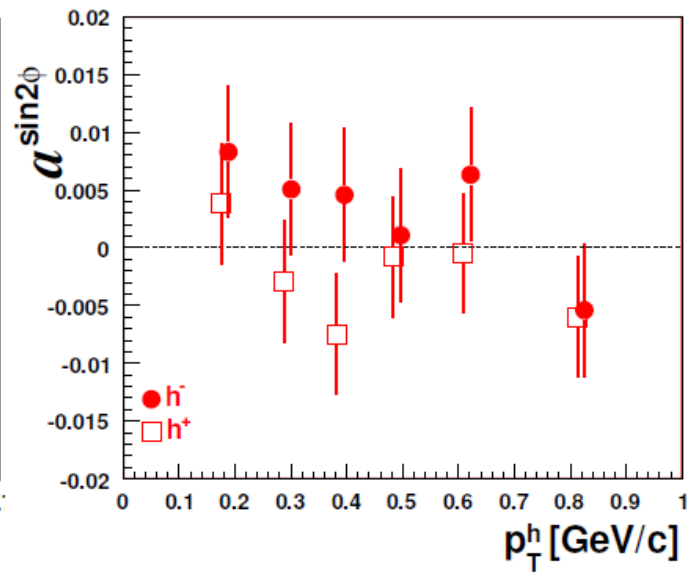
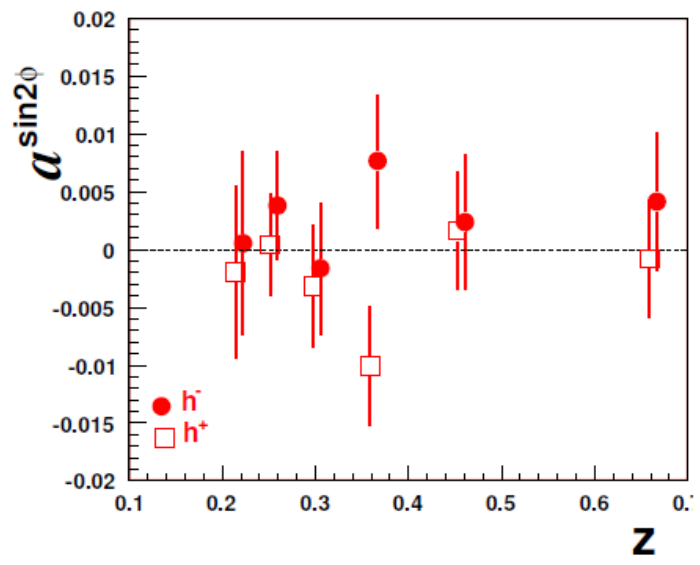
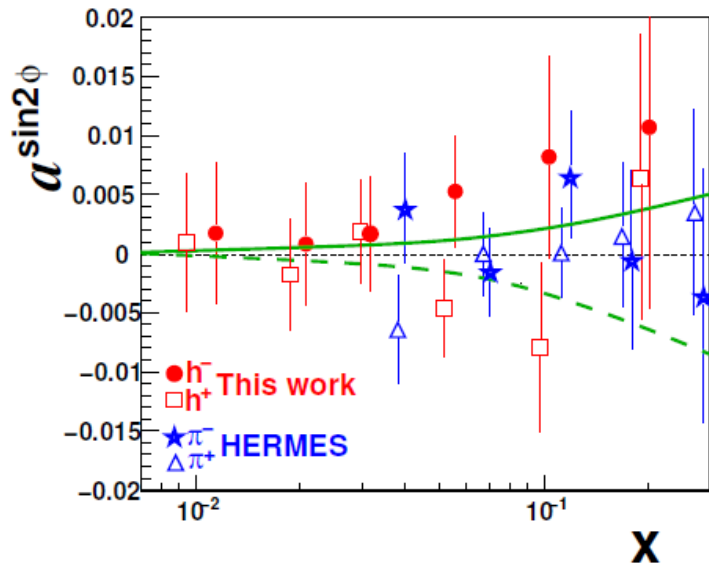
$$\sum_q L^q = - \sum_q h_{1T}^\perp(1) q$$



$$g_{1T} \otimes D_1 \sim A_{LT}^{\cos(\phi - \phi_S)}$$



$$h_{1L}^\perp \otimes H_1^\perp \sim \sin 2\phi$$



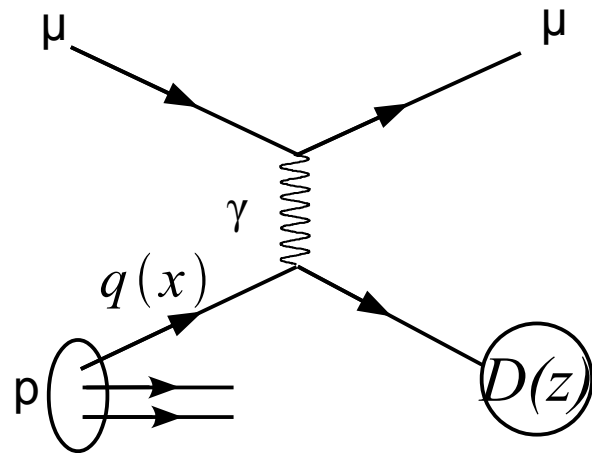
EPJC70(2010)39

PLB562(2003)182



SIDIS

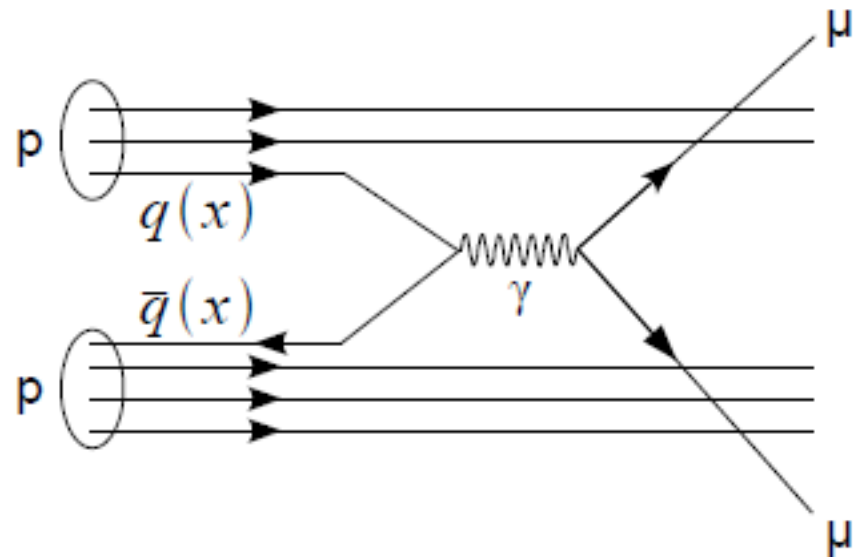
$$e + N \rightarrow e' + h + X$$



$$d\sigma \propto \sum e_q^2 q(x) D(z)$$

Drell-Yan

$$h + h \rightarrow l^+ + l^- + X$$

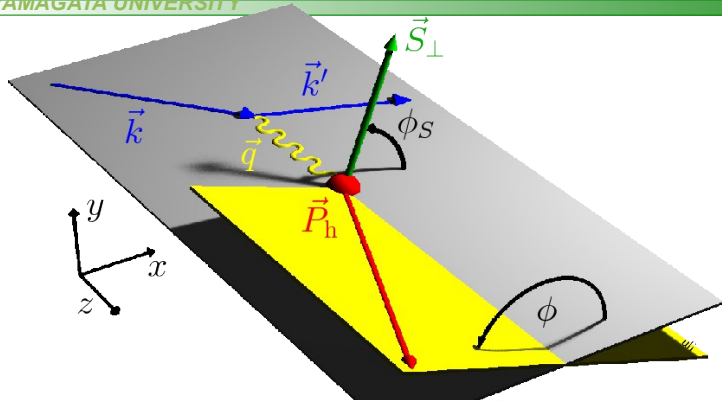


$$d\sigma \propto \sum e_q^2 \{ q(x_1) \bar{q}(x_2) + \bar{q}(x_1) q(x_2) \}$$



Azimuthal angles in DY

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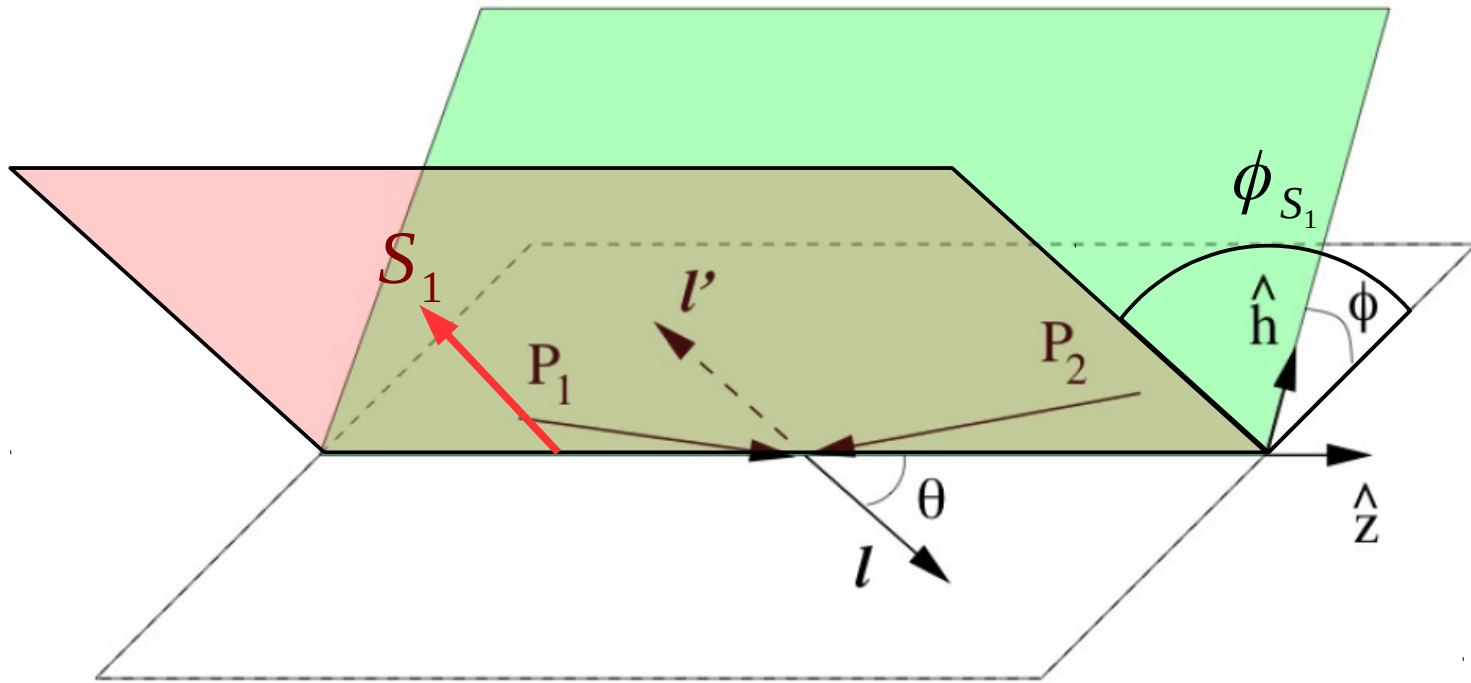


ϕ

hadron and lepton planes

$\phi_{S_{1,2}}$

polarization and lepton planes



lepton plane (cm)

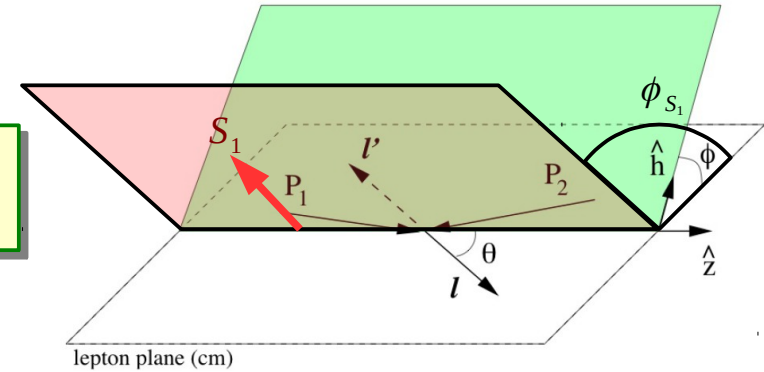
Collins-Soper Reference Frame



Azimuthal amplitudes and TMDs in DY

$$h_1 + h_2 \rightarrow l^+ + l^- + X$$

$$[f\bar{f}] \propto \sum_q e_q^2 \{ f(x_a)\bar{f}(x_b) + \bar{f}(x_a)f(x_b) \}$$



$$F_{UU}^1 \propto \begin{bmatrix} f_1 & f_1 \end{bmatrix}$$

$$F_{UU}^{\cos 2\phi} \propto \begin{bmatrix} h_1^\perp & \bar{h}_1^\perp \end{bmatrix}$$

} E906/SeaQuest

$$F_{TU}^{\sin(\phi - \phi_{s_1})} \propto \begin{bmatrix} f_{1T}^\perp & \bar{f}_1 \end{bmatrix}$$

$$F_{TU}^{\sin(\phi + \phi_{s_1})} \propto \begin{bmatrix} h_{1T} & \bar{h}_1^\perp \end{bmatrix}$$

$$F_{TU}^{\sin(3\phi - \phi_{s_1})} \propto \begin{bmatrix} h_{1T}^\perp & \bar{h}_1^\perp \end{bmatrix}$$

} E1027

$$F_{UT}^{\sin(\phi - \phi_{s_2})} \propto \begin{bmatrix} f_1 & \bar{f}_{1T}^\perp \end{bmatrix}$$

$$F_{UT}^{\sin(\phi + \phi_{s_2})} \propto \begin{bmatrix} h_1^\perp & \bar{h}_{1T} \end{bmatrix}$$

$$F_{UT}^{\sin(3\phi - \phi_{s_2})} \propto \begin{bmatrix} h_1^\perp & \bar{h}_{1T}^\perp \end{bmatrix}$$

} E1039

U	f_1	\bar{h}_1^\perp
L	g_{1L}	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}
		h_{1T}^\perp



Azimuthal amplitudes and TMDs in DY

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$$h_1 + h_2 \rightarrow l^+ + l^- + X$$

E1027 + E1039

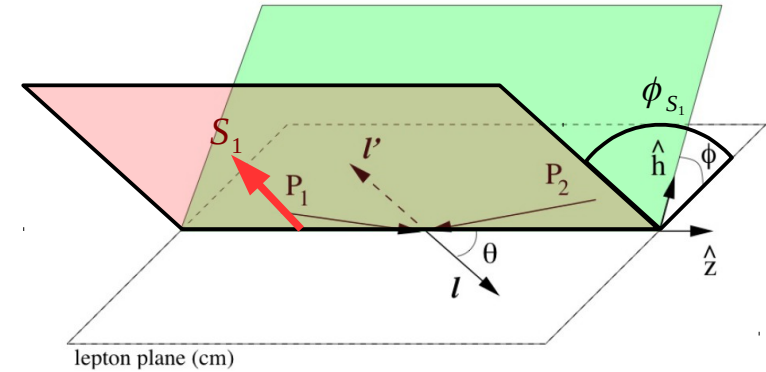
$$F_{TT}^{\cos(\phi_{S_1} - \phi_{S_2})} \propto [f_{1T}^\perp \bar{f}_{1T}^\perp + g_{1T} \bar{g}_{1T}]$$

$$F_{TT}^{\cos(\phi_{S_1} + \phi_{S_2})} \propto [h_{1T} \bar{h}_{1T}]$$

$$F_{TT}^{\cos(2\phi - \phi_{S_1} - \phi_{S_2})} \propto [f_{1T}^\perp \bar{f}_{1T}^\perp - g_{1T} \bar{g}_{1T}]$$

$$F_{TT}^{\cos(2\phi - \phi_{S_1} + \phi_{S_2})} \propto [h_{1T}^\perp \bar{h}_{1T}^\perp]$$

$$F_{TT}^{\cos(2\phi + \phi_{S_1} - \phi_{S_2})} \propto [h_{1T} \bar{h}_{1T}^\perp]$$



U	f_1	\bar{h}_1^\perp
L	g_{1L}	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}
		h_{1T}^\perp



Azimuthal amplitudes and TMDs in DY

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$$h_1 + h_2 \rightarrow l^+ + l^- + X$$

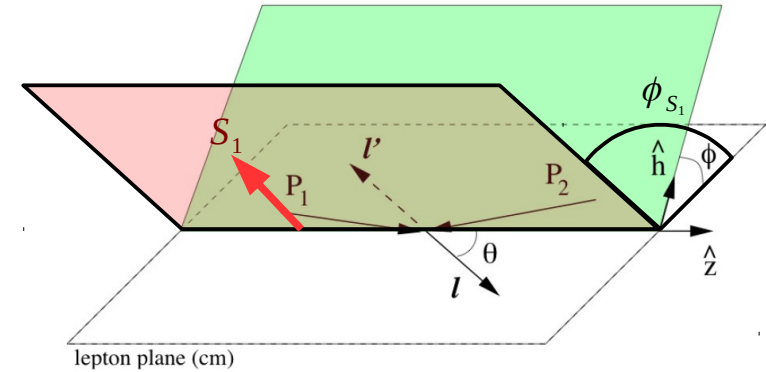
L-pol., L.-target

$$F_{LU}^{\sin 2\phi} \propto [h_{1L}^\perp \bar{h}_1^\perp]$$

$$F_{UL}^{\sin 2\phi} \propto [h_1^\perp \bar{h}_{1L}^\perp]$$

$$F_{LL}^1 \propto [g_{1L} \bar{g}_{1L}]$$

$$F_{LL}^{\cos 2\phi} \propto [h_{1L}^\perp \bar{h}_{1L}^\perp]$$



U	f_1	\bar{h}_1^\perp
L	g_{1L}	h_{1L}^\perp
T	f_{1T}^\perp	h_{1T} h_{1T}^\perp



Azimuthal amplitudes and TMDs in DY

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$$h_1 + h_2 \rightarrow l^+ + l^- + X$$

$$F_{LT}^{\cos(\phi - \phi_{S_2})} \propto [g_{1L} \bar{g}_{1T}]$$

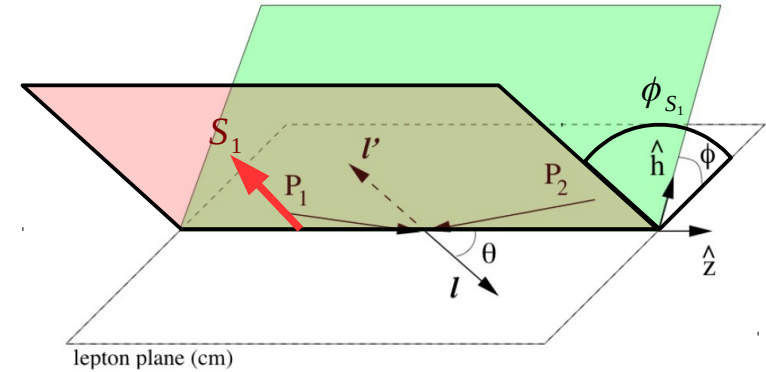
$$F_{LT}^{\cos(\phi + \phi_{S_2})} \propto [h_{1L}^\perp \bar{h}_{1T}]$$

$$F_{LT}^{\cos(3\phi - \phi_{S_2})} \propto [h_{1L}^\perp \bar{h}_{1T}^\perp]$$

$$F_{TL}^{\cos(\phi - \phi_{S_1})} \propto [g_{1T} \bar{g}_{1L}]$$

$$F_{TL}^{\cos(\phi + \phi_{S_1})} \propto [h_{1T} \bar{h}_{1L}^\perp]$$

$$F_{TL}^{\cos(3\phi - \phi_{S_1})} \propto [h_{1T}^\perp \bar{h}_{1L}^\perp]$$



U	f_1	\bar{h}_1^\perp
L	g_{1L}	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}
		h_{1T}^\perp



	Beam	Target	\sqrt{s} (GeV)	
E906/SeaQuest	p	p, d, A	16	RUNNING
E1027	p [↑]	p		
E1039	p	p [↑]		
COMPASS	π	p [↑]	17	RUNNING
PANDA	\bar{p}	p [↑]	6	
SPAS-CHARM	π	p [↑]	8	
AFTER	p	p [↑] , d [↑]	115	
RHIC	p ^(↑→) p ^(↑→)		250, 510	
NICA-SPD	p ^(↑) p ^(↑) , p ^(↑) d ^(↑) , d ^(↑) d ^(↑)		10 - 26	
PAX	p [↑] , \bar{p} [↑]		14	

- Polarized Drell-Yan is a unique tool to study nucleon structure
 - FF does not involved
 - Longitudinal double spin asymmetry, A_{LL} , with proton and deuteron targets:
 - Flavor symmetry violation in the polarized sea
 - Important input to the global analysis
- E906, E1027, E1039
 - Boer-Mulder, Sivers, Transversity, Pretzelosity
- E1027 + E1039: Worm-Gear g_{1T}
- With L-pol beam, L-pol targets: h_{1L}^{\perp}