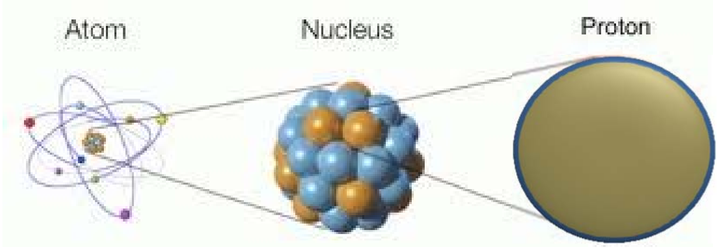
Transverse Momentum Distributions: an experimental update

Luciano L. Pappalardo

INFN & University of Ferrara

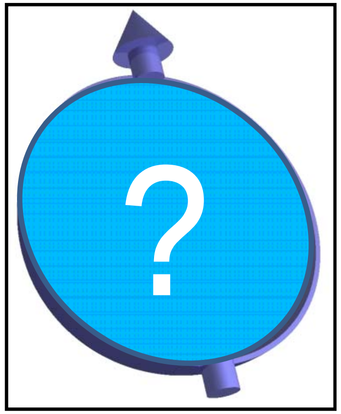
QNP2012 - Palaiseau (France) - April 16-20 2012

Looking deeply into the proton



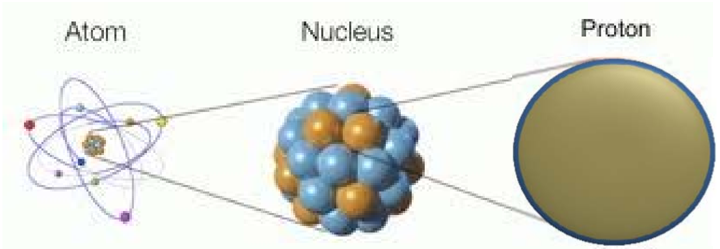
size ≈ 10^{-15} m

< 1960



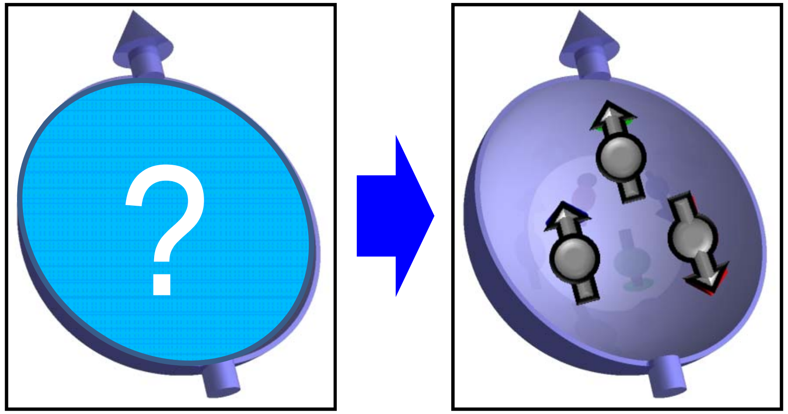
- **Elementary particle?**

Looking deeply into the proton



Internal structure
$\mathbf{10^{-15} \leftrightarrow 10^{-18}}\ \boldsymbol{m}$

< 1960 | 1964



- **Elementary particle?**
- **Quark hypothesis**
  (Gell-Mann - Zweig)

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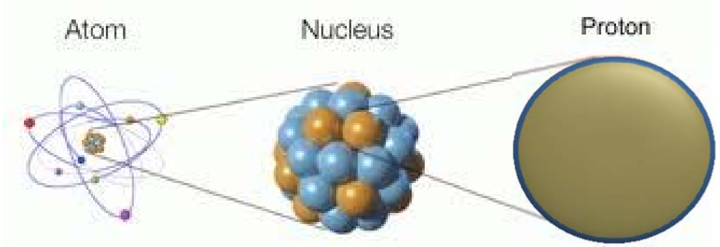

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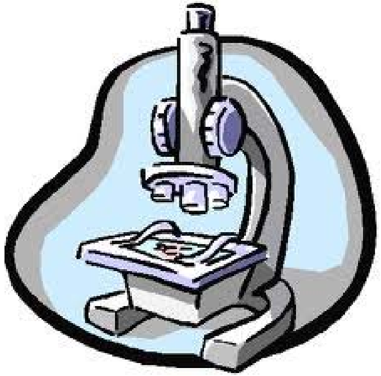

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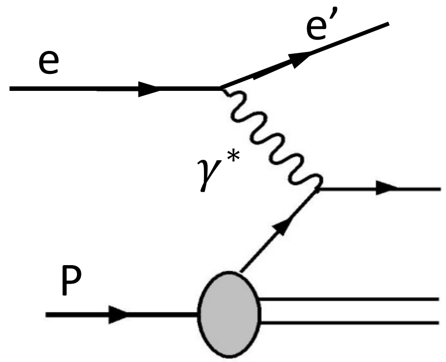
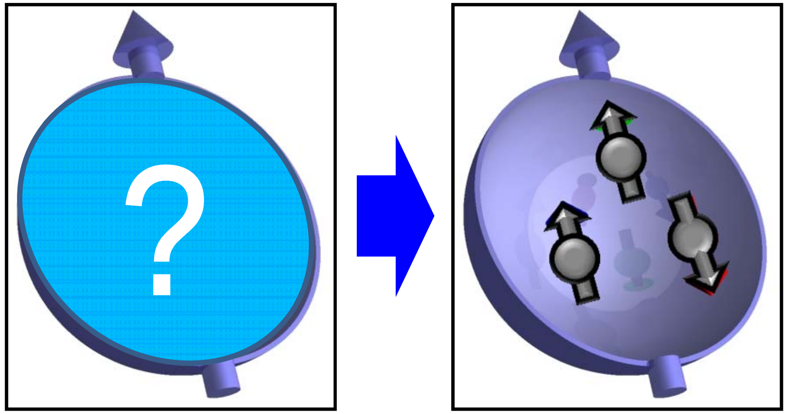


< 1960

1964-1969



- **Elementary particle?**

- **Quark hypothesis** (Gell-Mann - Zweig)
- **Scaling at SLAC** ('69)
- **Parton Model** (Faynman, Bjorken)

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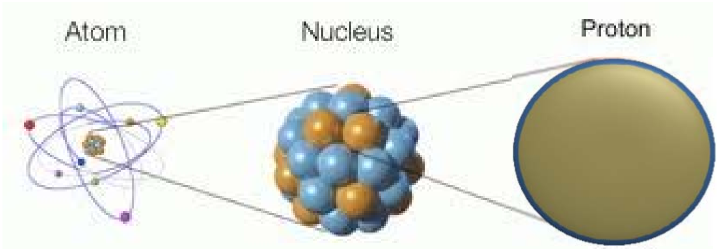

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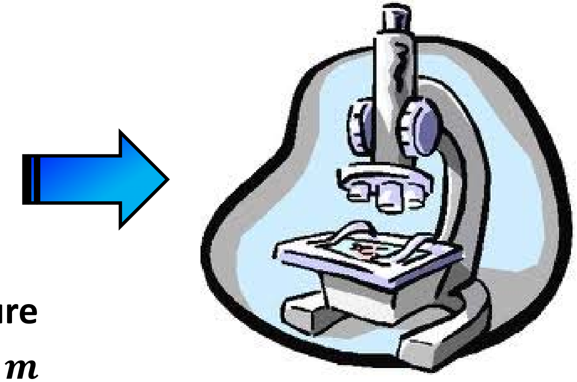

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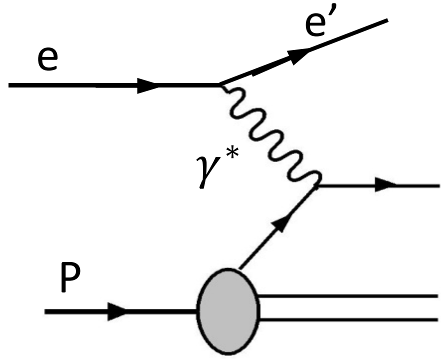
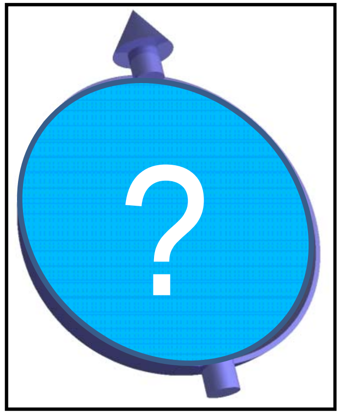
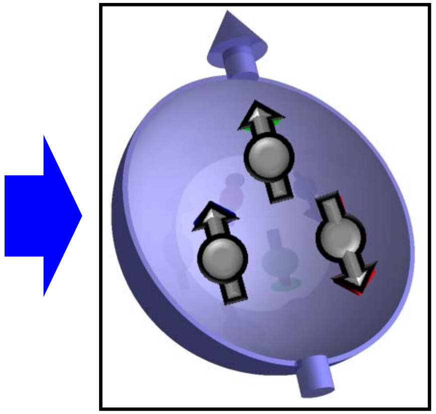
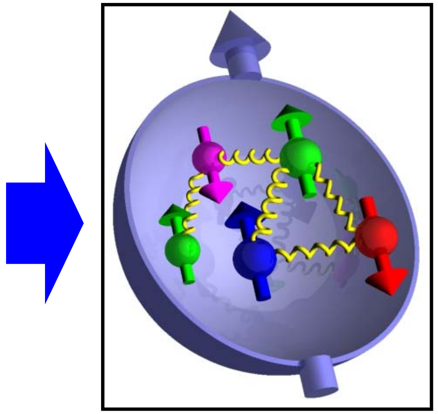


< 1960 | 1964-1969 | 1972-1973







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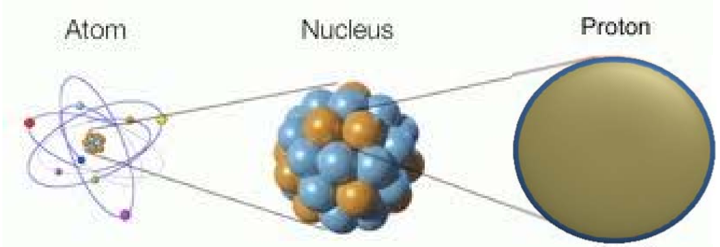
- **Quark hypothesis** (Gell-Mann - Zweig)
- **Scaling at SLAC** ('69)
- **Parton Model** (Faynman, Bjorken)

- **QCD** lagrangian
- **colors**, sea quarks, gluons
- **discovery of gluons** (PETRA '73)

Looking deeply into the proton



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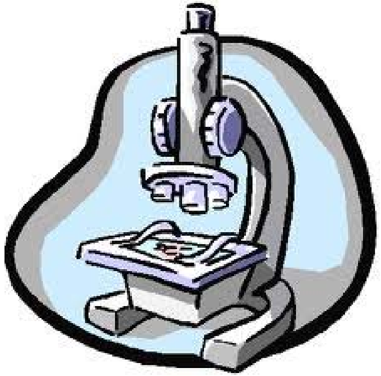

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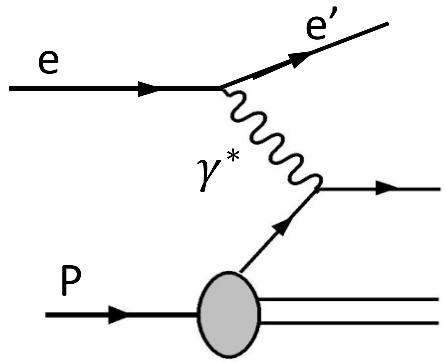

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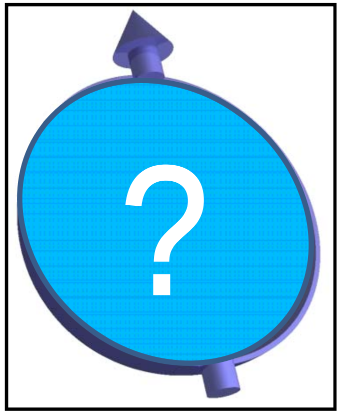

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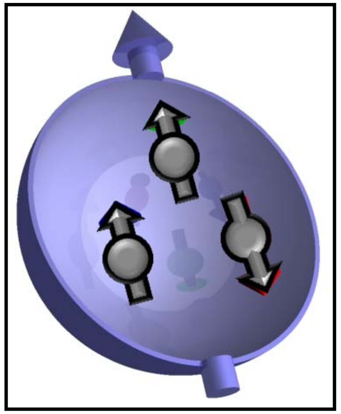

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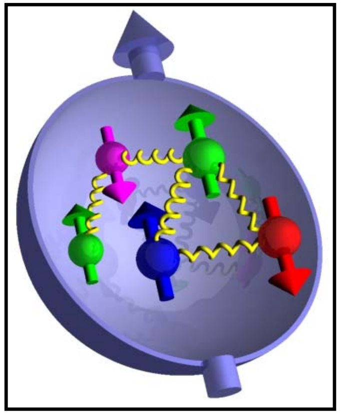

- **QCD** lagrangian
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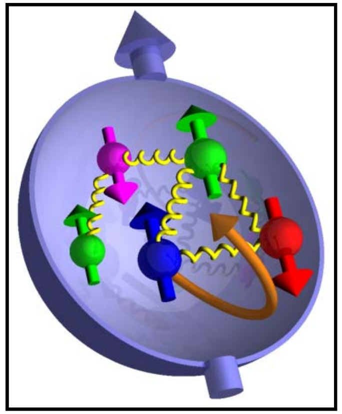
> 1988



- EMC experiment
- the **spin crisis**
  $\frac{1}{2} = \Delta\Sigma + \boldsymbol{\Delta G} + \boldsymbol{L_{q,g}}$
- quest for ΔG & $L_{q,g}$

What is the final goal?

Understand the **full phase-space distribution of the partons**:

- Where are they located ? $\rightarrow x, y, z \equiv r$
- How do they move ? $\rightarrow p_x, p_y, p_z \equiv x, p_T$

$\Bigg\}\; W(x, p_T, r)$ **Wigner function**

...but $\Delta x \Delta p \geq \frac{\hbar}{2}$ $\rightarrow$ no simultaneous knowledge of momentum and position!

$W(x, p_T, r)$

C. Lorce
Session A
Thur. 19

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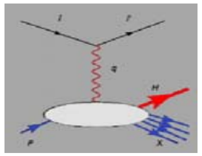
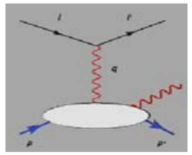
Session A
Thur. 19

$W(x, p_T, r)$

$\int d^3 r$ $\swarrow$ $\qquad$ $\searrow$ $\int d^2 p_T$



TMDs $f(x, p_T)$ $\qquad$ $\mathrm{H}(x, \xi, t)$ GPDs



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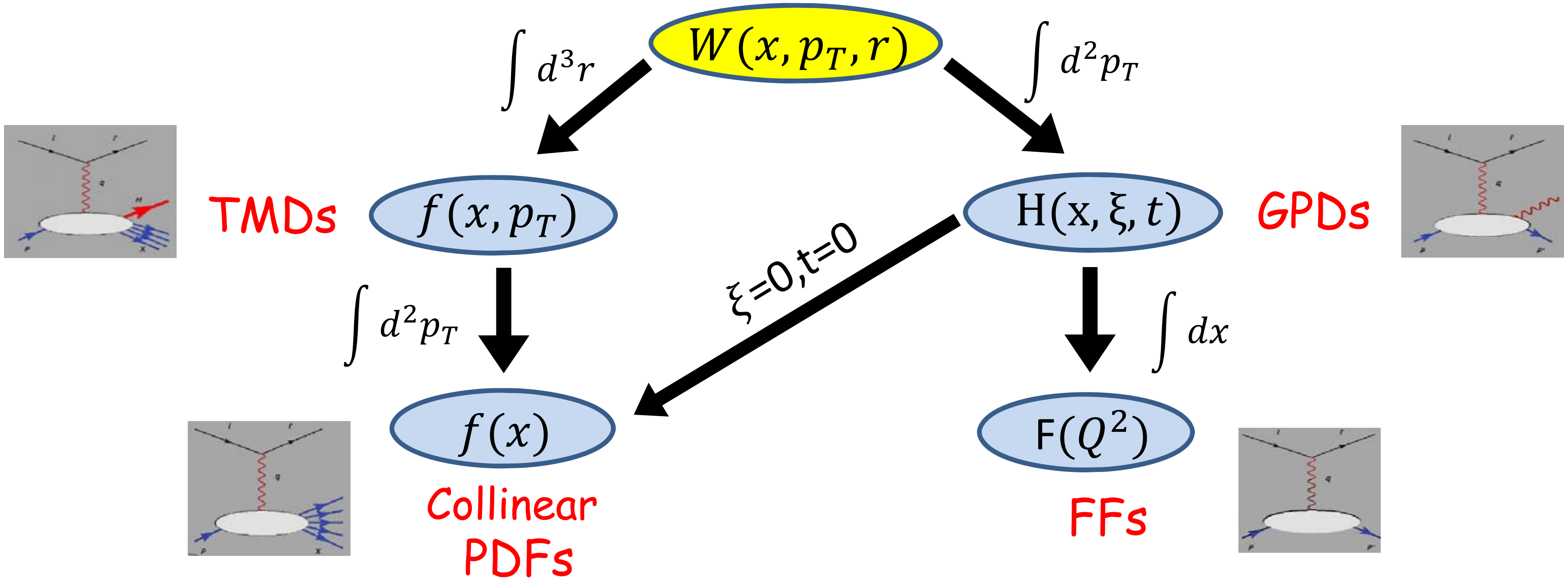

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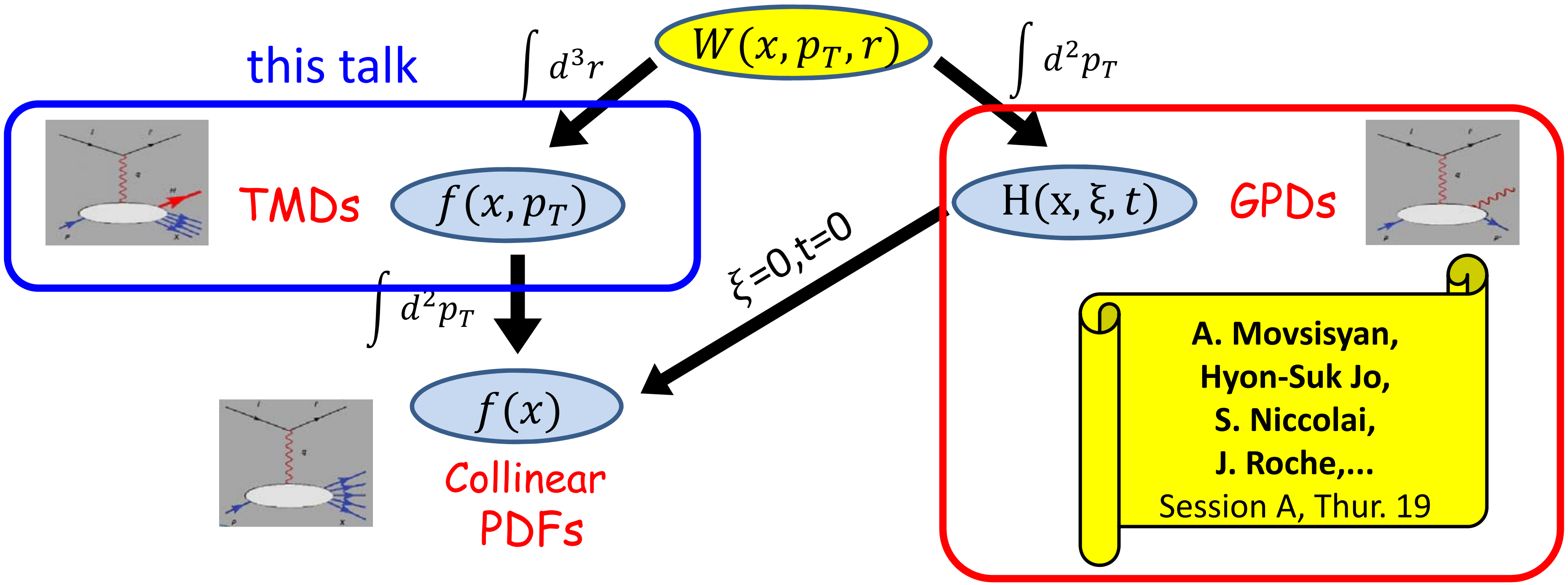
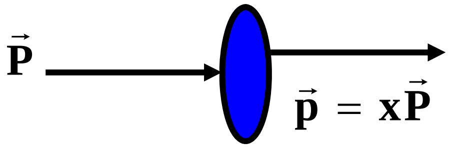


The nucleon **collinear** structure



		quark		
		U	L	T
nucleon	U	f_1		
	L		g_1 -	
	T			h_1 -

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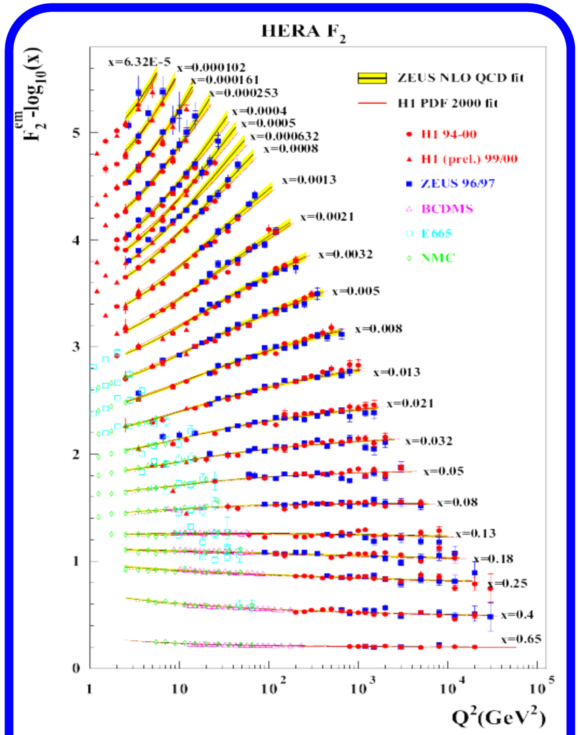

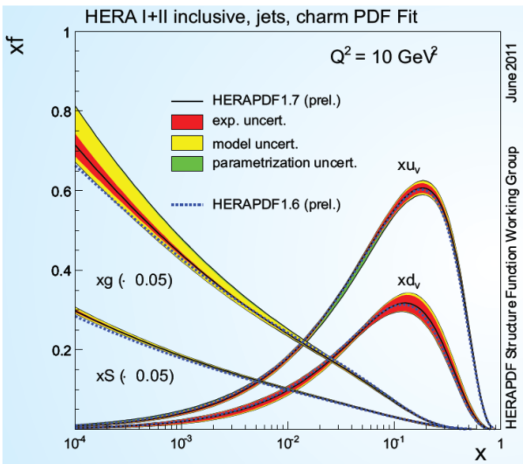

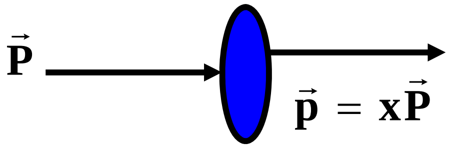

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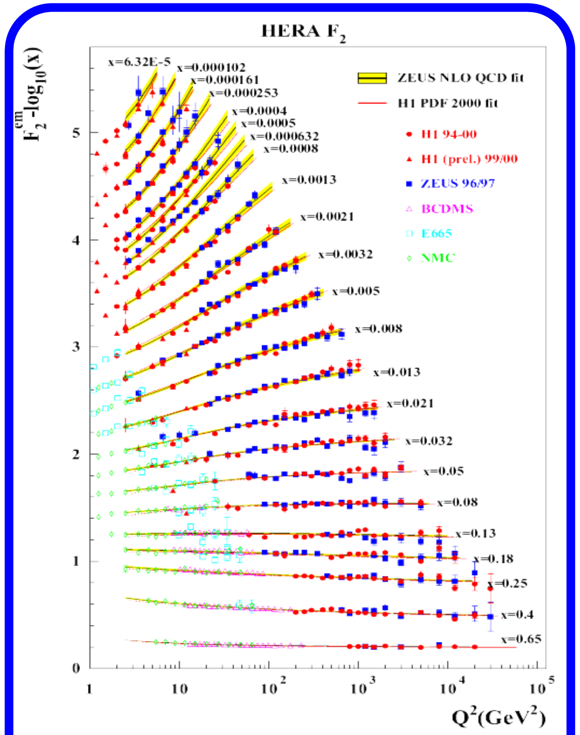

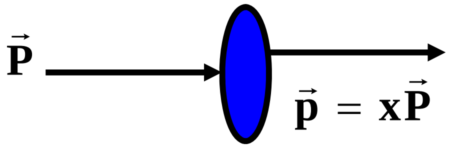

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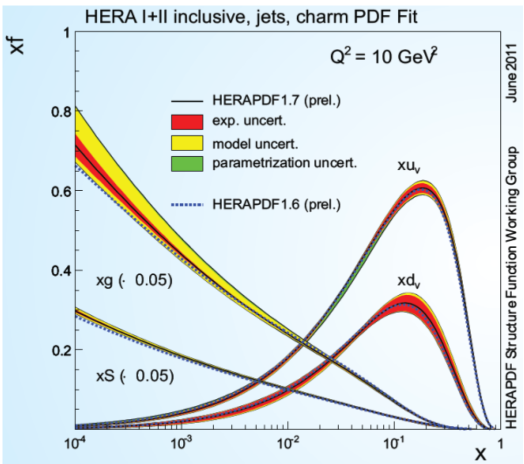

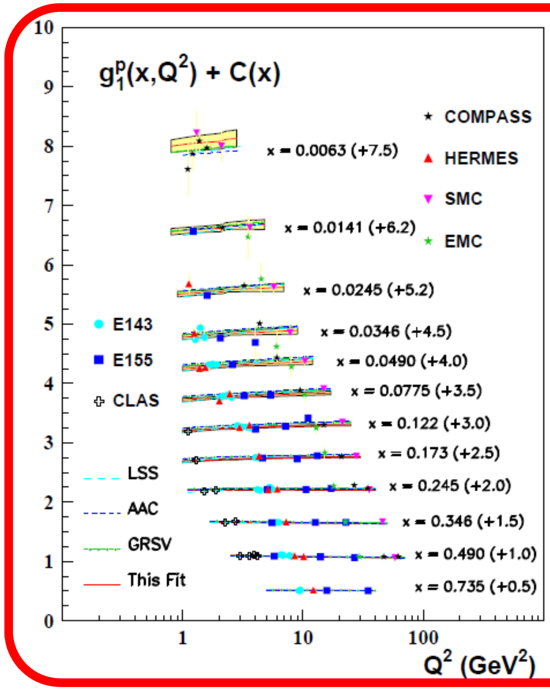

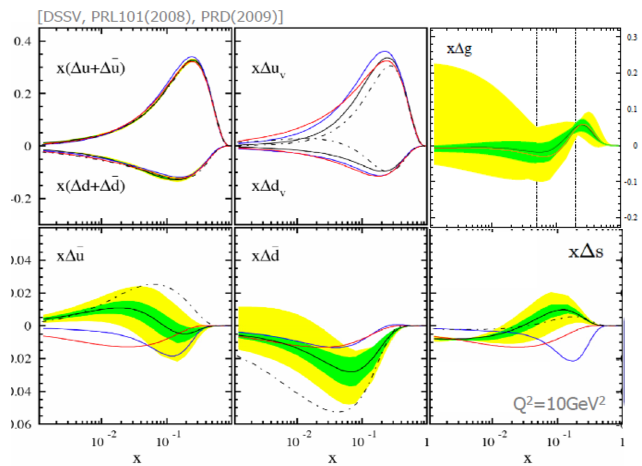

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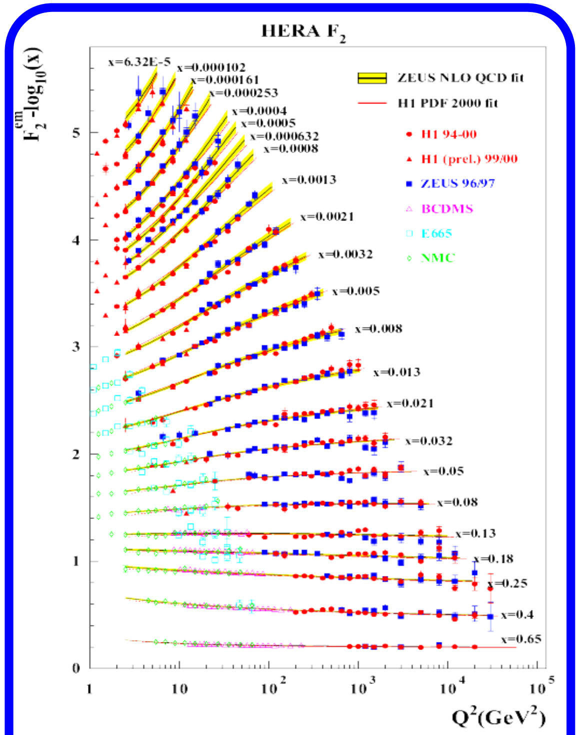

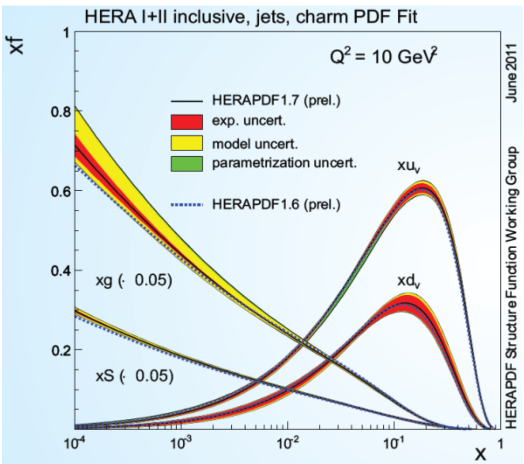

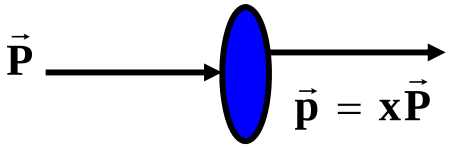

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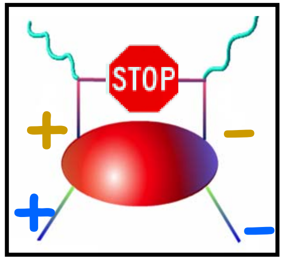
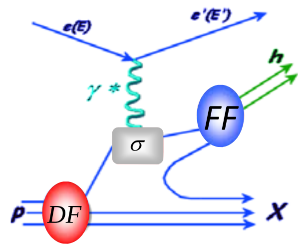
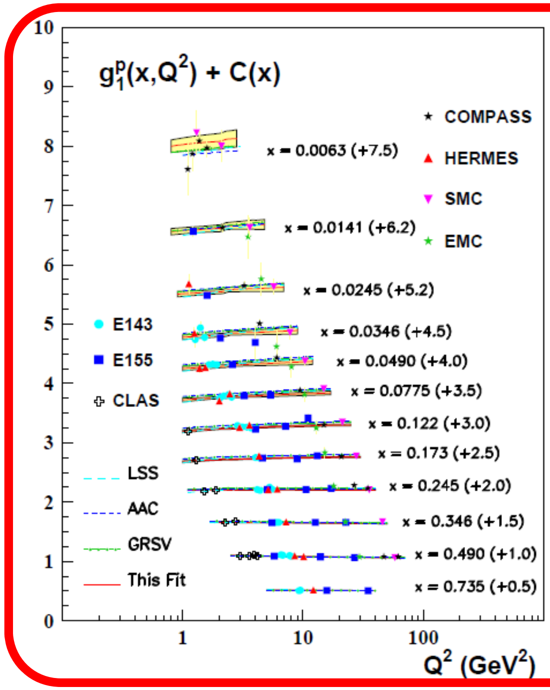
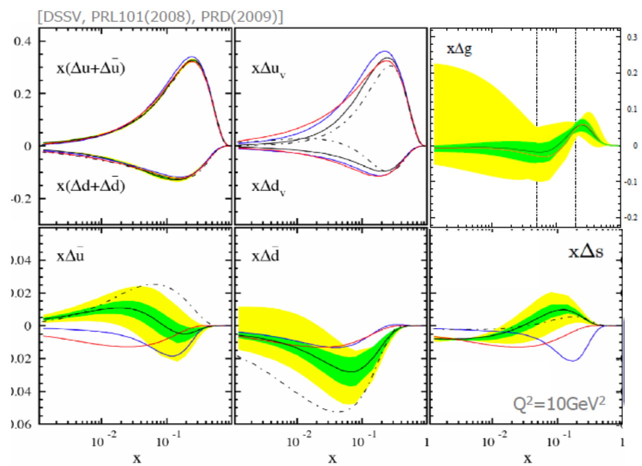


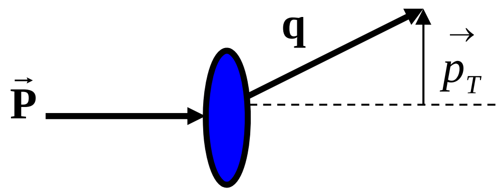


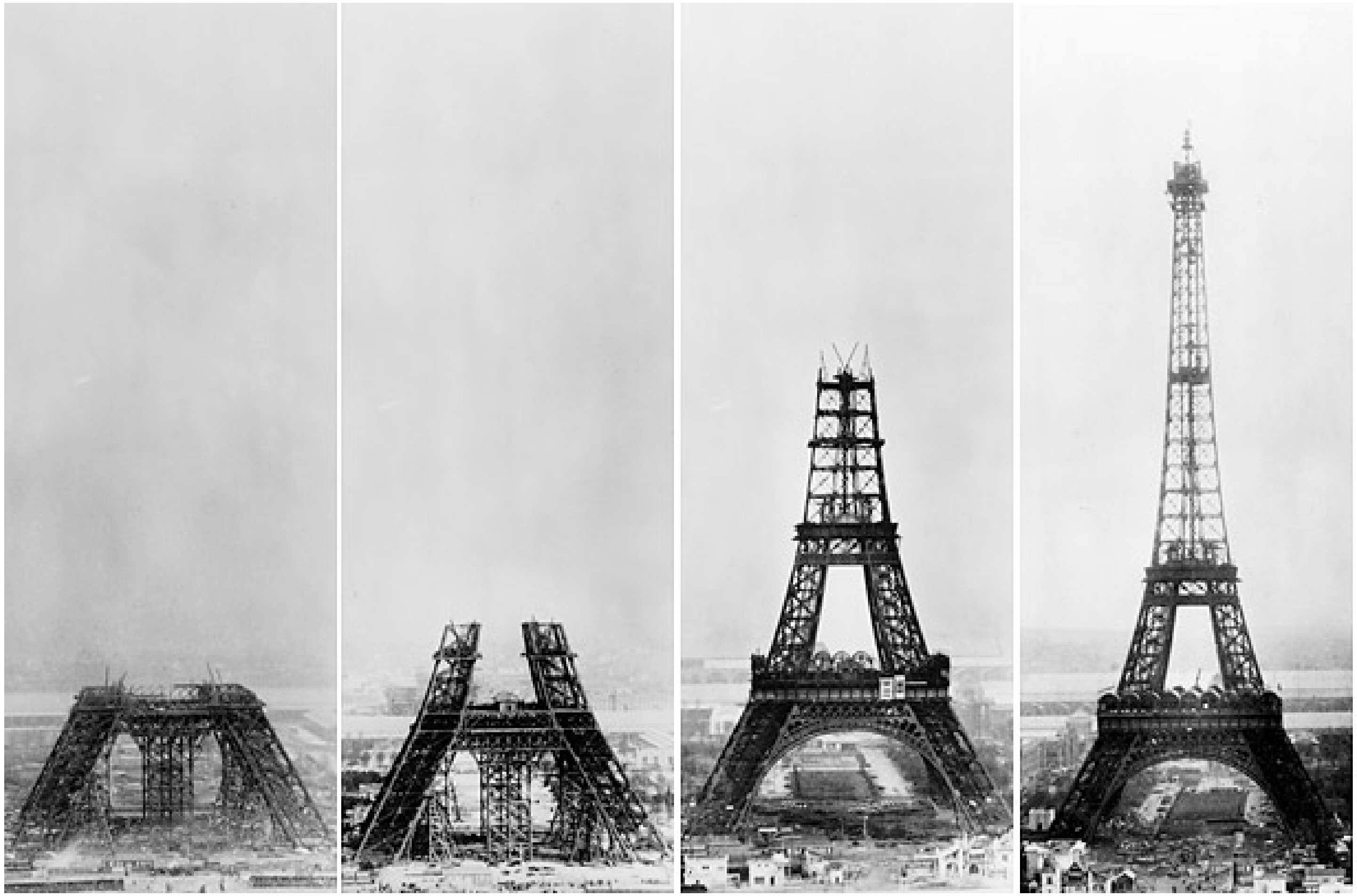
- chiral-odd!
- differs from g_1 due to relativistic effects
- no mix with gluons in spin-$\frac{1}{2}$ the nucleon
- valence object



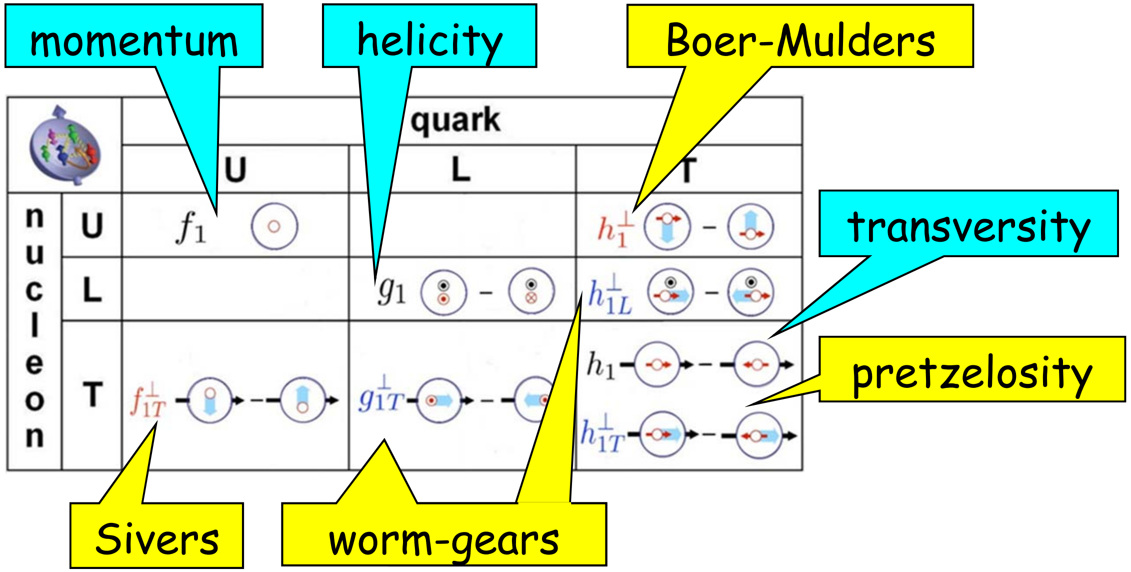


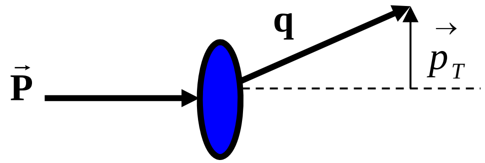
...now let's go transverse!





The **non-collinear** structure of the nucleon





- TMDs depend on p_T
- Vanish when integrated over p_T
- Describe correlations between p_T and quark or nucleon spin (**spin-orbit correlations**)

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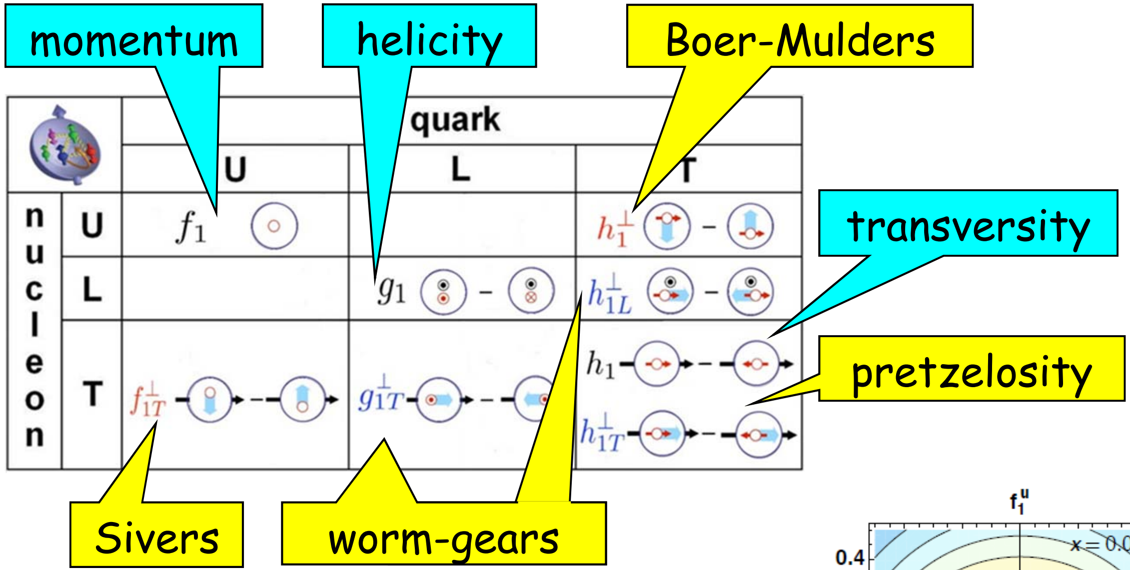

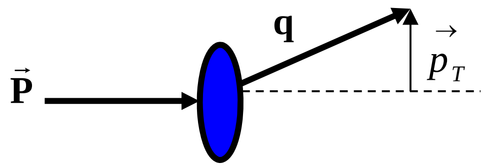

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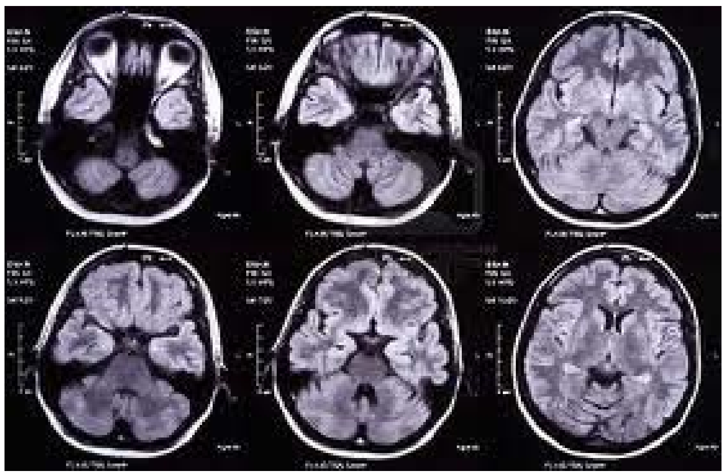
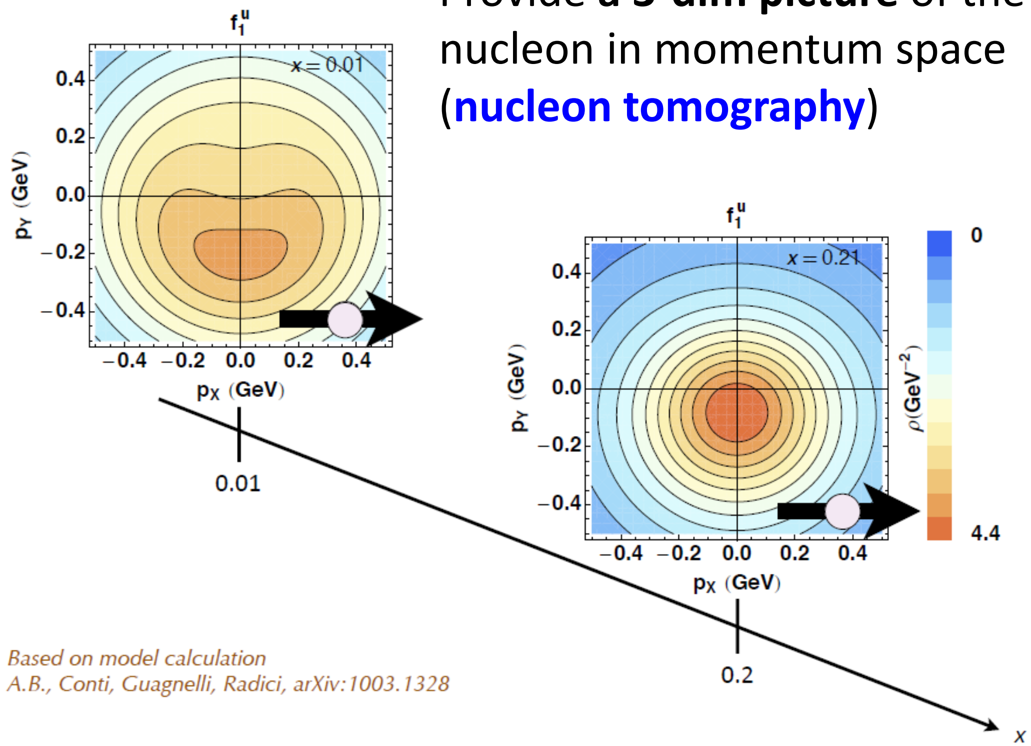


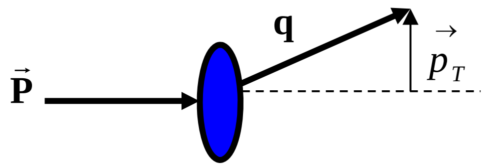


Based on model calculation
A.B., Conti, Guagnelli, Radici, arXiv:1003.1328

The **non-collinear** structure of the nucleon

momentum · helicity · Boer-Mulders · transversity · pretzelosity · Sivers · worm-gears

nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



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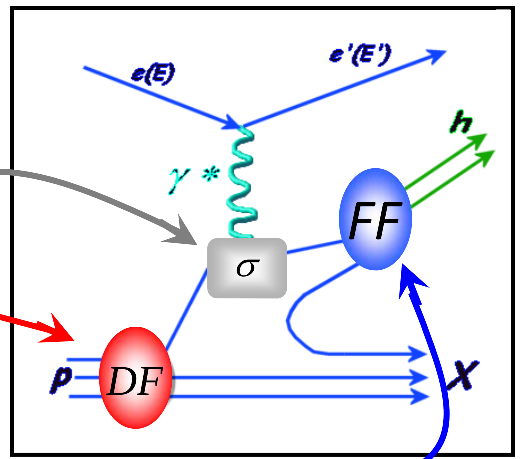
- Provide **a 3-dim picture** of the nucleon in momentum space (**nucleon tomography**)
- Mostly studied in **SIDIS**

Fragmentation Functions (FF)

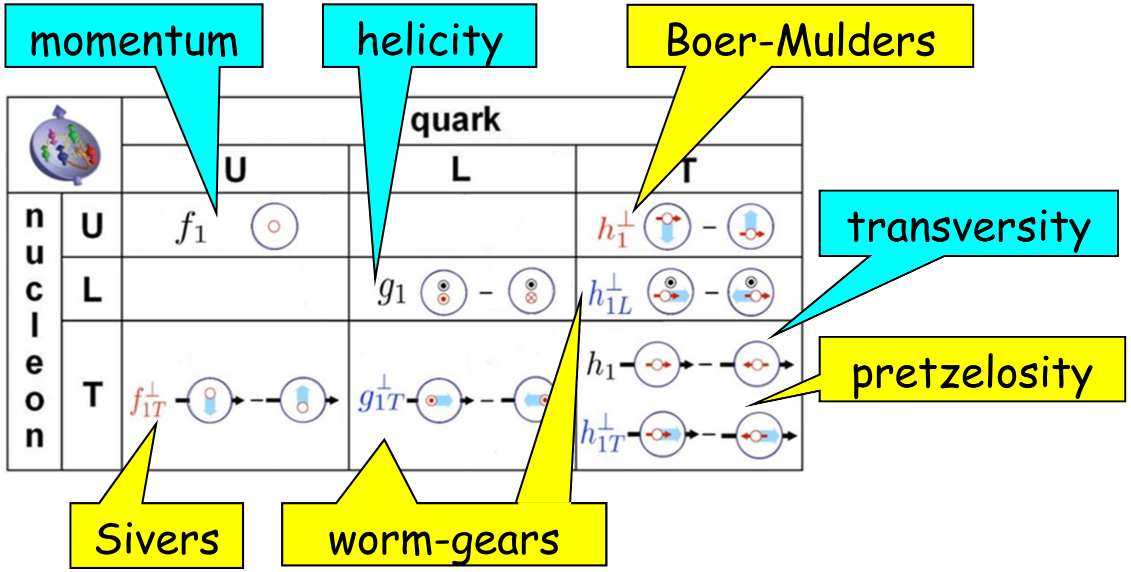
hadron \ quark	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	H_1, $H_{1T}^\perp$

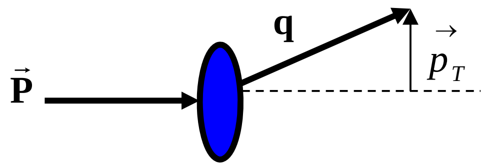
Factorization →
(key result of QCD!)

$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$



The non-collinear structure of the nucleon





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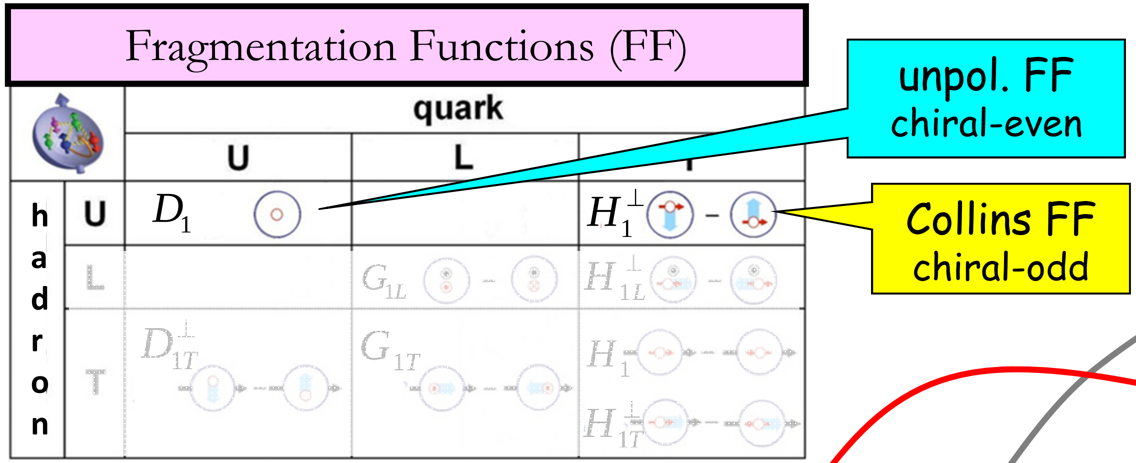

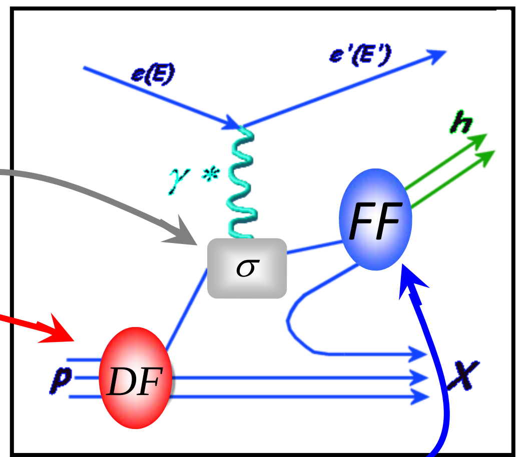

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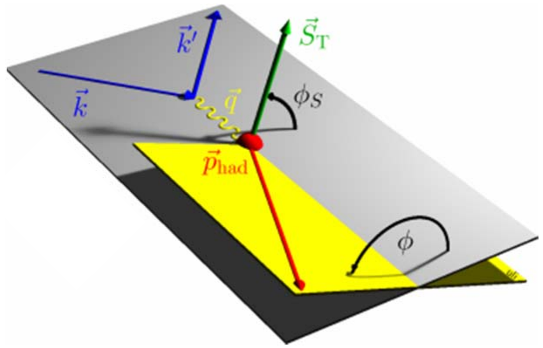
The SIDIS cross-section



$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

The SIDIS cross-section

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \left[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right]$$

unpolarized

$$+ \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{LU}^{\sin(\phi)}\right]$$

beam polarization

$$+ S_L \left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\right]$$

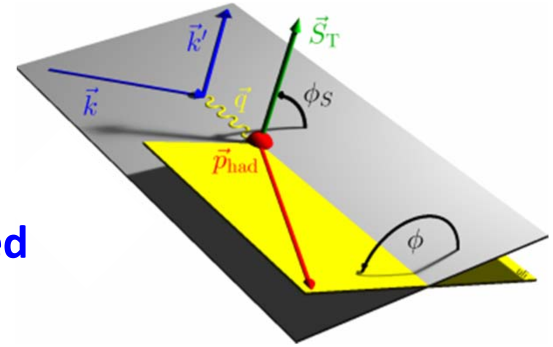
$$+ S_L\,\lambda_l \left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos(\phi)}\right]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

target polarization

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

beam and target polarization



Transversity

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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$$+ \lambda_l \Big[\sqrt{2\epsilon\,(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big]$$

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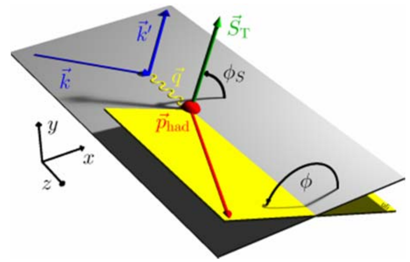
$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$



Describes probability to find transversely polarized quarks in a transversely polarized nucleon

Distribution Functions

		quark		
		U	**L**	**T**
nucleon	**U**	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

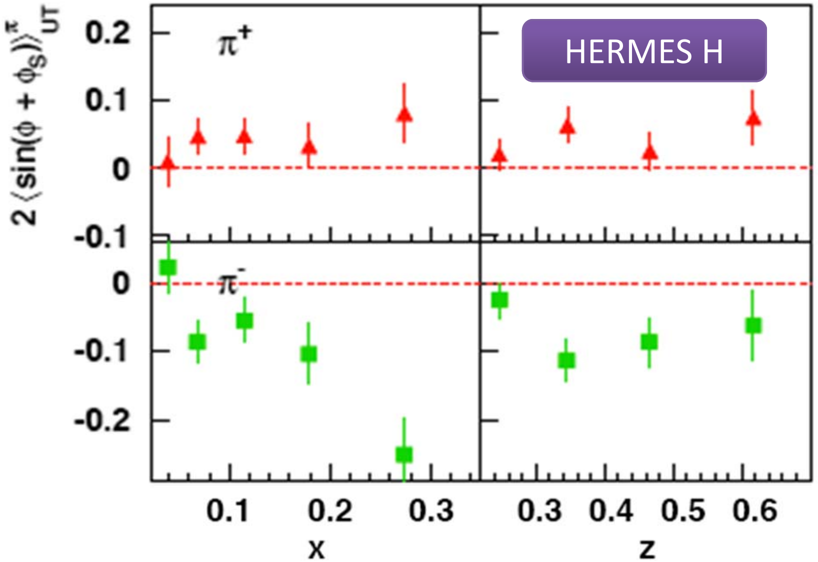
Fragmentation Functions

		quark		
		U	**L**	**T**
h	**U**	D_1		$H_1^\perp$

Transversity

$$A_{UT}^{\sin(\varphi+\varphi_S)} \propto \frac{\sum_q e_q^2\, h_1^q(x,p_T^2)\otimes H_1^{q,\perp}(z,k_T^2)}{\sum_q e_q^2\, f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$

Phys. Rev. Lett. 94 (2005) 012002



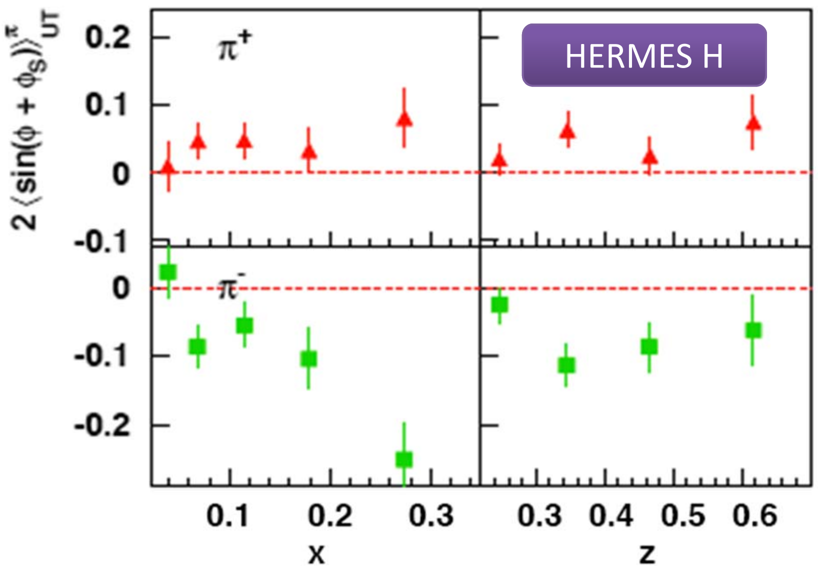
- **First evidence by HERMES (05)**
- Transv. pol. H target
- Limited statistics (2002-2003)
- **Non-zero Collins amplitudes**
- **Non-zero transversity & Collins FF**

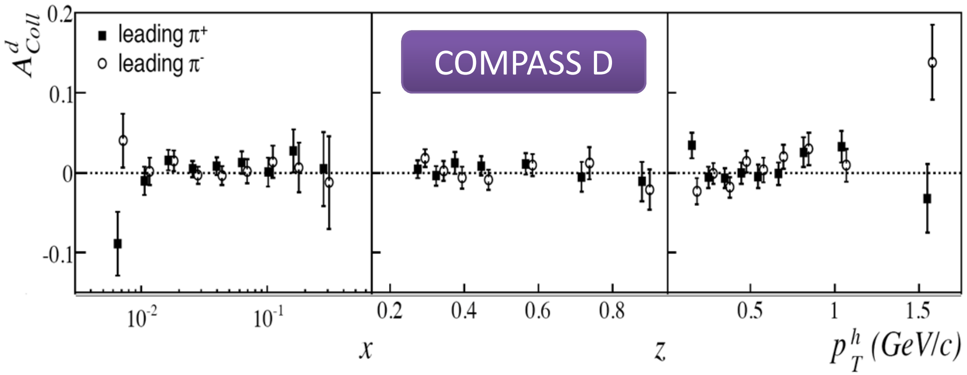
$$H_1^{\perp,\text{unfav}}(z) \approx -H_1^{\perp,\text{fav}}(z)$$

Transversity

$$A_{UT}^{\sin(\varphi+\varphi_S)} \propto \frac{\sum_q e_q^2\; h_1^q(x,p_T^2)\otimes H_1^{q,\perp}(z,k_T^2)}{\sum_q e_q^2\; f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$

Phys. Rev. Lett. 94 (2005) 012002





- **First evidence by HERMES (05)**
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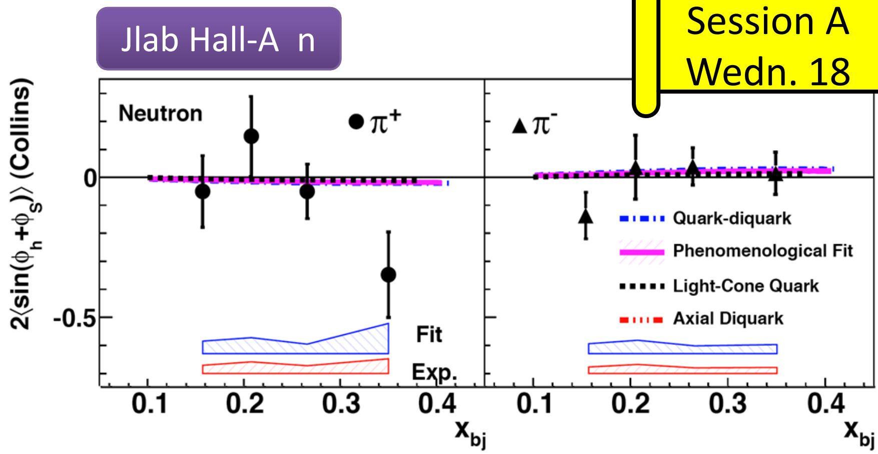
- Limited statistics (2002-2003)
- **Non-zero Collins amplitudes**
- **Non-zero transversity & Collins FF**

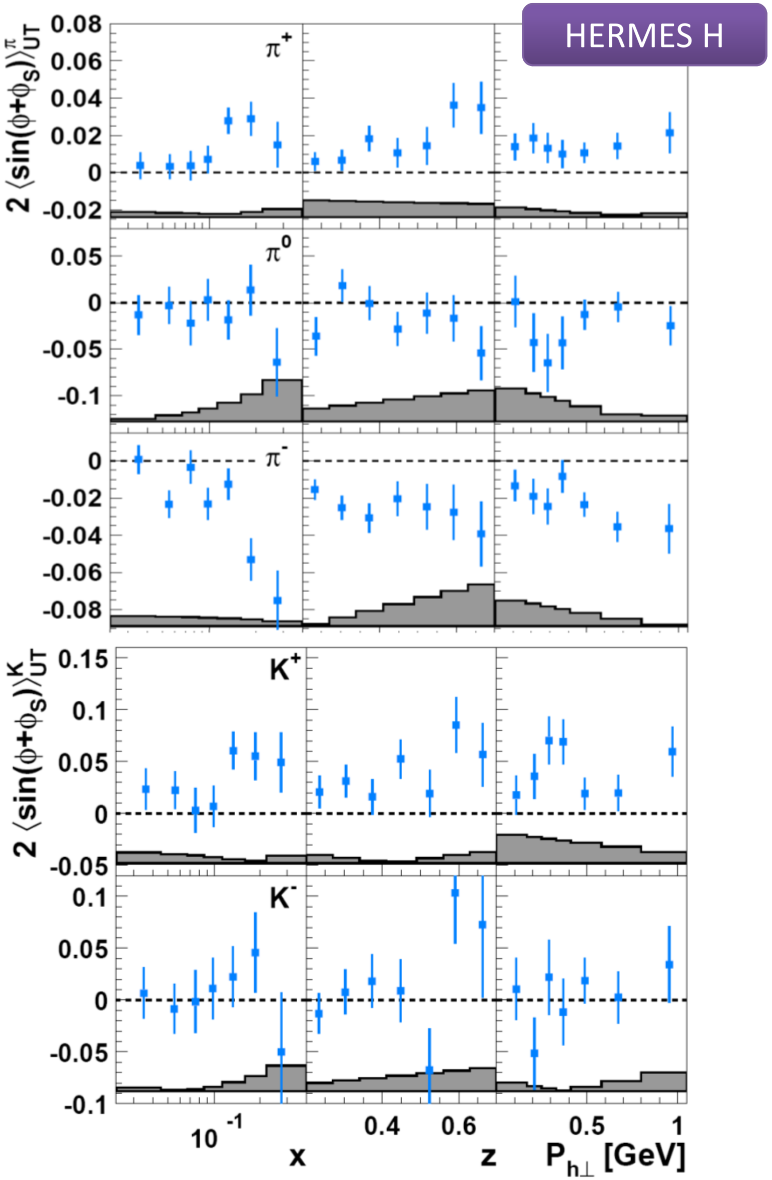
$$H_1^{\perp,\text{unfav}}(z) \approx -H_1^{\perp,\text{fav}}(z)$$

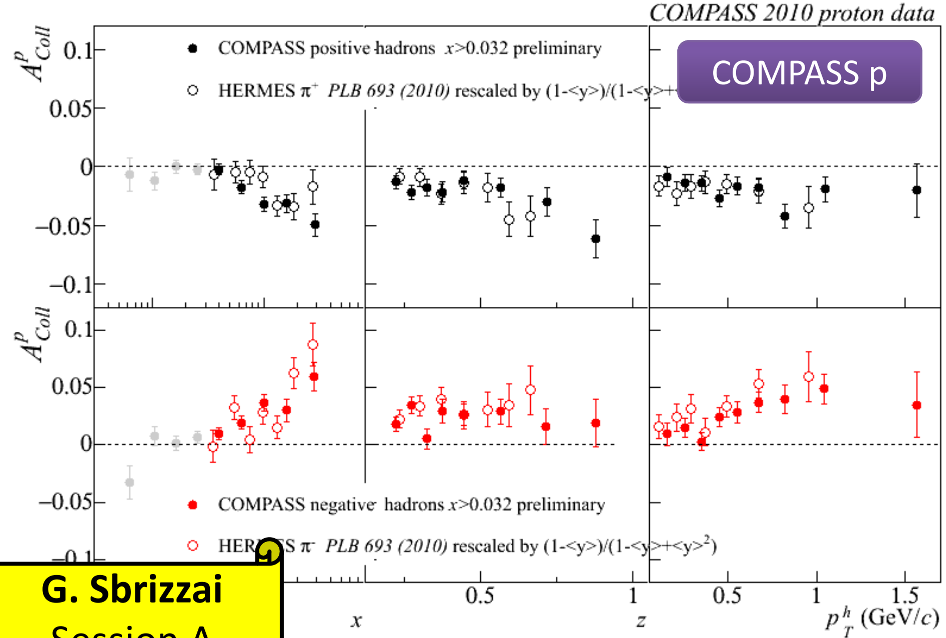
- **Consistent with COMPASS zero amplitude on Deuterium**



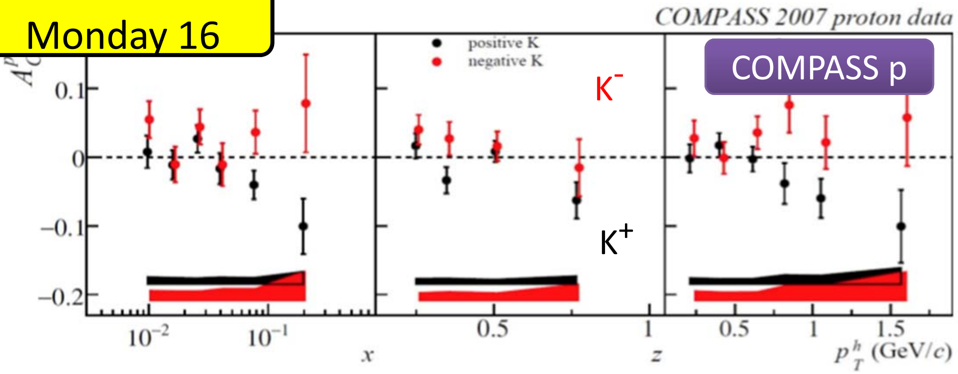
E. Cisbani
Session A
Wedn. 18

Transversity





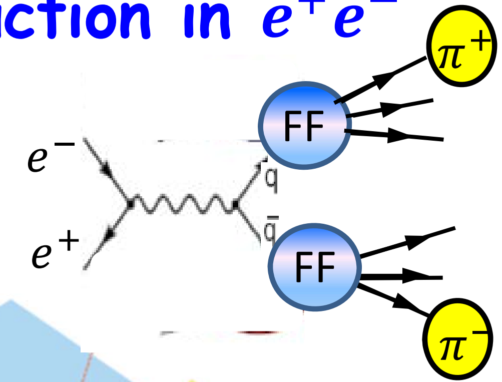
G. Sbrizzai
Session A
Monday 16



COMPASS π results on p consistent with HERMES!

- K^- amplitudes are not in agreement
- statistics for kaons relatively poor
- **Need new data (e.g. from JLab @12Gev)**

Collins FF from inclusive hadron-pair production in e^+e^-

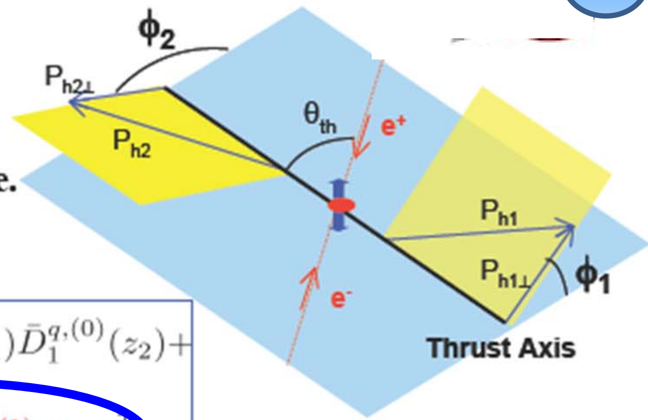


Describes correlation between quark polarization and observed hadron transverse momentum

$\phi_1+\phi_2$ or Thrust RF

θ: angle between the e^+e^- axis and the thrust axis;
$\phi_{1,2}$: azimuthal angles between $P_{h1(h2)}$ and the scattering plane.

All quantities in e+e- center of mass

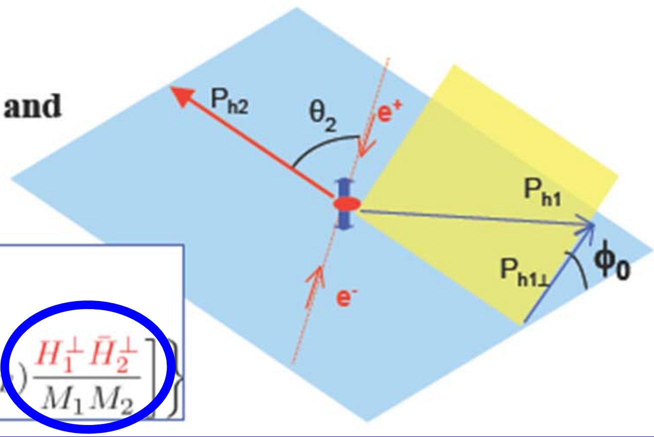


$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2d\phi_1d\phi_2} = \sum_{q,\bar{q}}\frac{3\alpha^2}{Q^2}\frac{e_q^2}{4}z_1^2z_2^2\Big[(1+\cos^2\theta)D_1^{q,(0)}(z_1)\bar{D}_1^{q,(0)}(z_2)+ \sin^2(\theta)\cos(\phi_1+\phi_2)H_1^{\perp,(1),q}(z_1)\bar{H}_1^{\perp,(1),q}(z_2)\Big]$$

$2\phi_0$ or P_{h2} RF

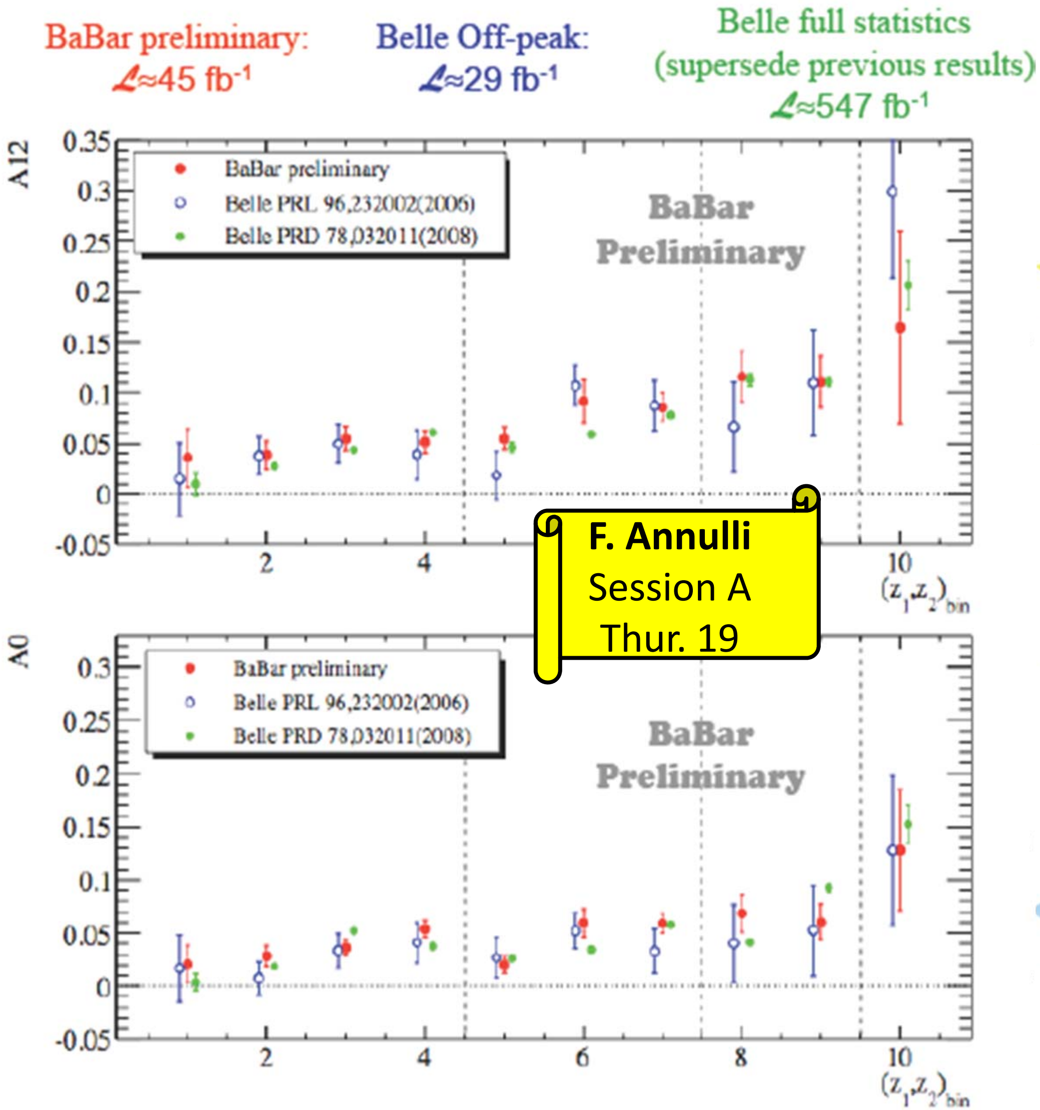
θ_2: angle between the e^+e^- axis and P_{h2};
ϕ_0: angle between the plane spanned by P_{h2} and the e^+e^- axis, and the direction of P_{h1} perpendicular to P_{h2}.

All quantities in e+e- center of mass

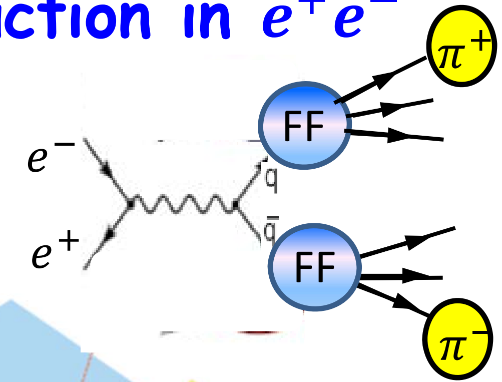


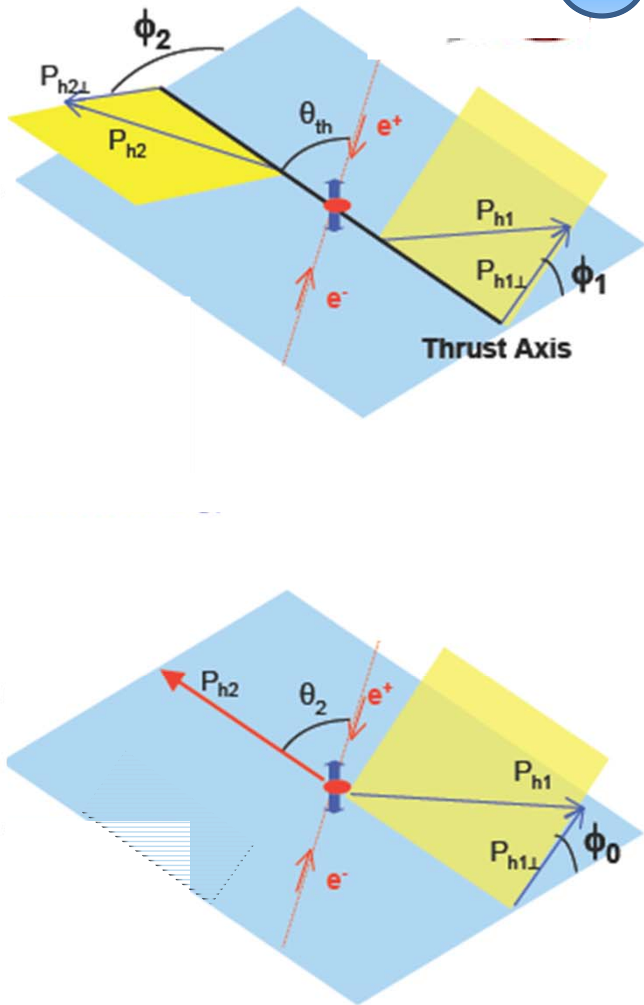
$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2d^2\vec{q}_T} = \frac{3\alpha^2}{Q^2}z_1^2z_2^2\Big\{A(y)\mathcal{F}[D_1\bar{D}_2]+ B(y)\cos(2\phi_0)\mathcal{F}\Big[(2\hat{h}\cdot\vec{k}_T\hat{h}\cdot\vec{p}_T-\vec{k}_T\cdot\vec{p}_T)\frac{H_1^{\perp}\bar{H}_2^{\perp}}{M_1M_2}\Big]\Big\}$$

Collins FF from inclusive hadron-pair production in e^+e^-

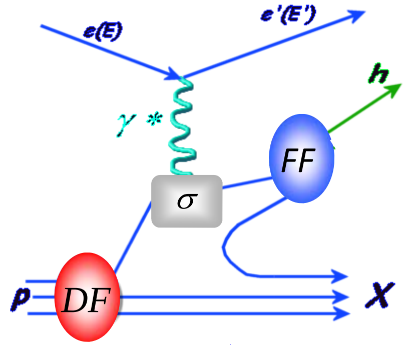


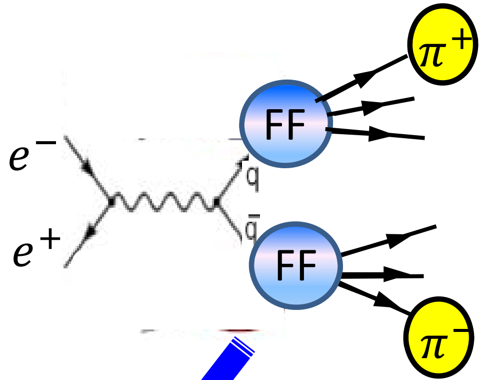
F. Annulli
Session A
Thur. 19





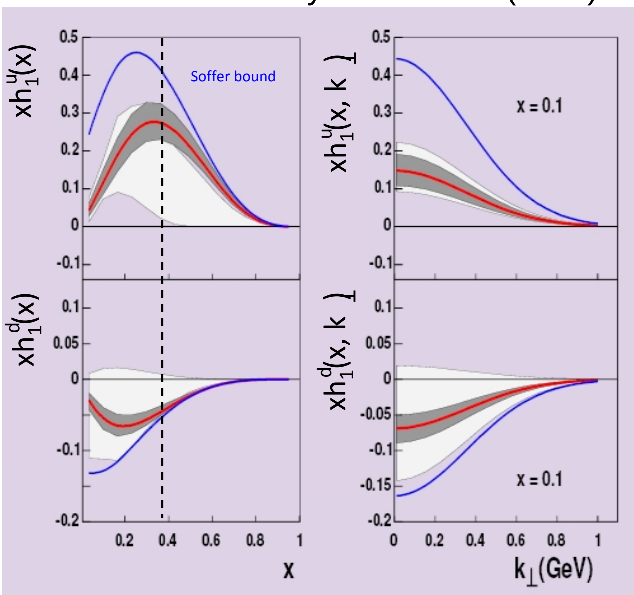
First extraction of Transversity



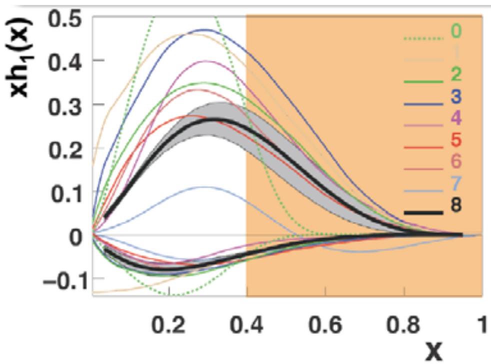


$$A_{UT}^{\sin(\phi+\phi_S)} \propto h_1(x) \otimes H_1^{\perp q}(z)$$

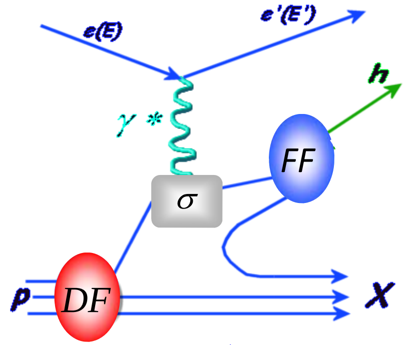
Anselmino et al. Phys. Rev. D 75 (2007)



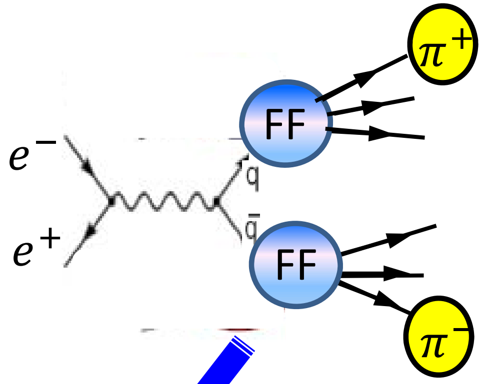
0. chiral color-dielectric model [Barone et al. ,PLB 390 (97)]
1. Soffer bound [Soffer et al., PRD 65 (02)]
2. $h_1 = g_1$ [Korotov et al.., EPJC 18 (01)]
3. Chiral quark-soliton model [Schweitzer et. al., PRD 64 (01)]
4. chiral-quark soloiton model [Wakamatsu, PLB 509 (01)]
5. light-cone constituent quark model [Pasquini et al., PRD 72 (05)]
6. quark-diquark model [Cloet, Bentz, Thomas, PLB 659 (08)]
7. quark-diquark model [Bacchetta, Conti, Radici, PRD 78 (08)]
8. Parametrization [Anselmino et al. , arXiv 0807.0173]



First extraction of Transversity



+

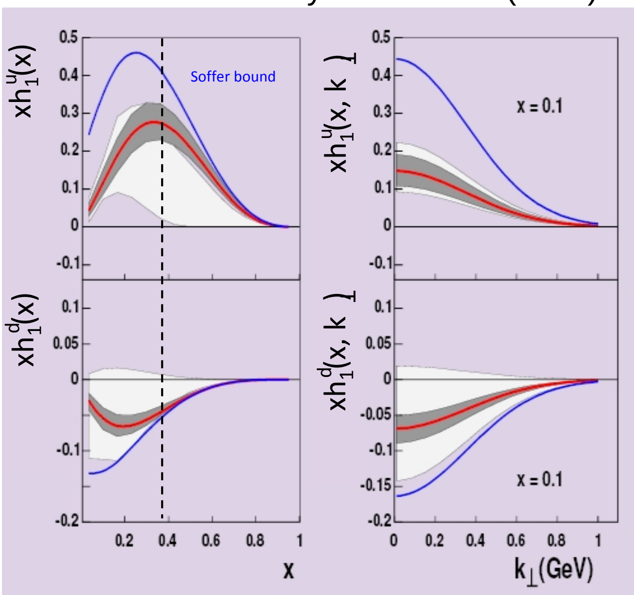


hermes COMPASS

$$A_{UT}^{\sin(\phi+\phi_S)} \propto h_1(x) \otimes H_1^{\perp q}(z)$$

BELLE

Anselmino et al. Phys. Rev. D 75 (2007)



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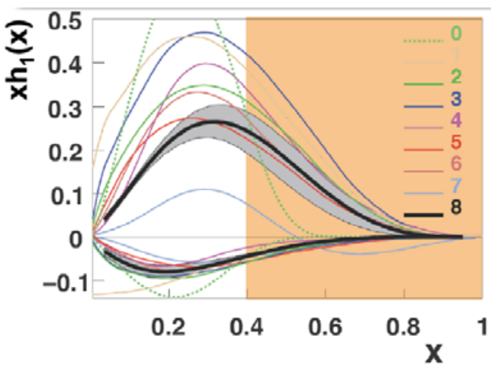
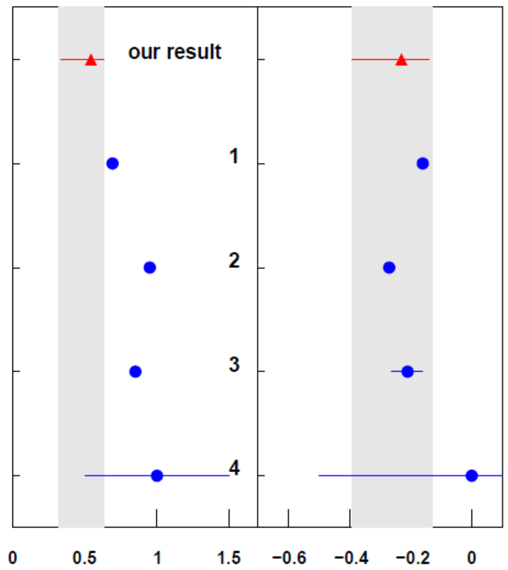


Tensor charge

$$\delta q = \int_0^1 dx \left[h_1^q(x) - \bar{h}_1^q(x)\right]$$



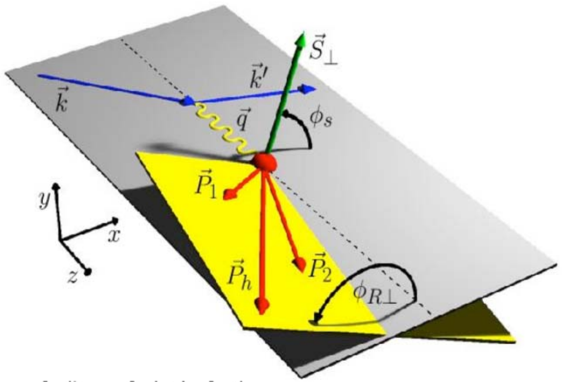
1: Quark-diquark model
2: Chiral quark soliton model
3: Lattice QCD
4: QCD sum rules

$\delta u = 0.54^{+0.09}_{-0.22}$ $\delta d = -0.23^{+0.09}_{-0.16}$

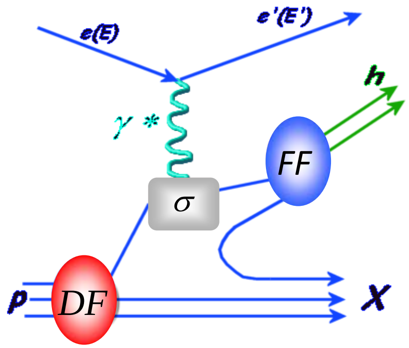
M. Anselmino et al **hep-ph:0812.4366**

Need data in valence region (x > 0.4) -> JLab @ 12 GeV

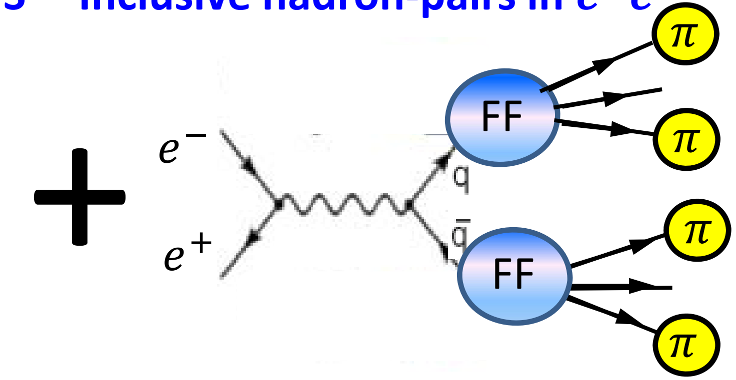
Transversity



2h Semi-Inclusive DIS



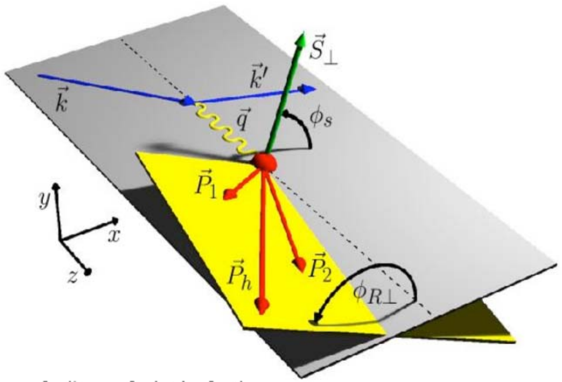
Inclusive hadron-pairs in e^+e^-

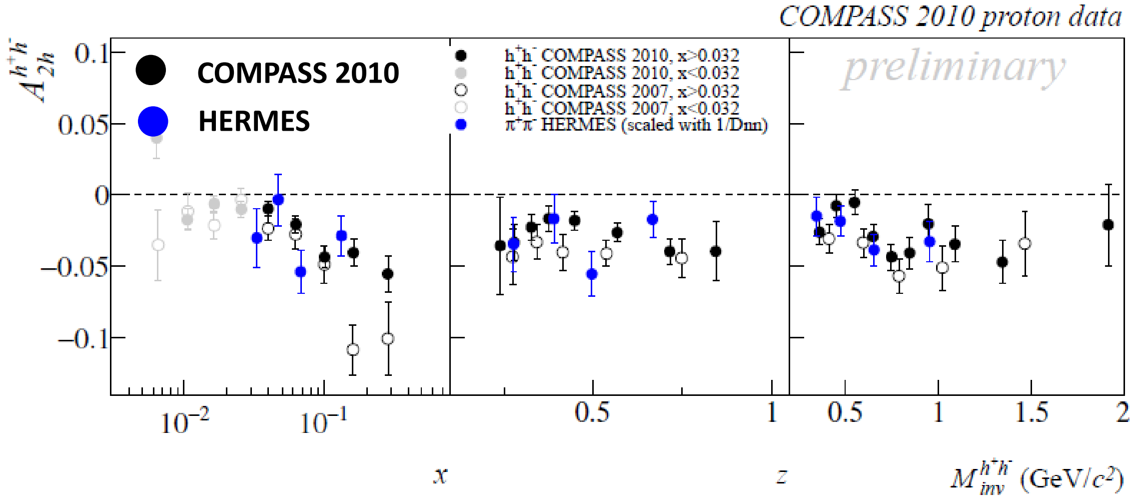


$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta} \propto \frac{\sum_q e_q^2 h_1(x,Q^2) H_1^{\sphericalangle}(z,M_h^2,Q^2)}{\sum_q e_q^2 f_1(x,Q^2) D_1^{\sphericalangle}(z,M_h^2,Q^2)}$$

- Survives integration over transverse momentum
- Collinear factorization (simple product)
- DGLAP evolution

Transversity





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- Survives integration over transverse momentum
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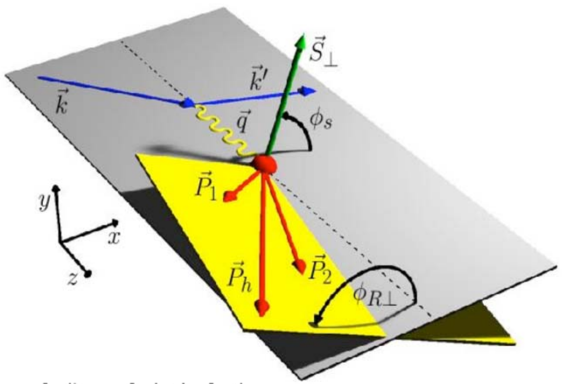
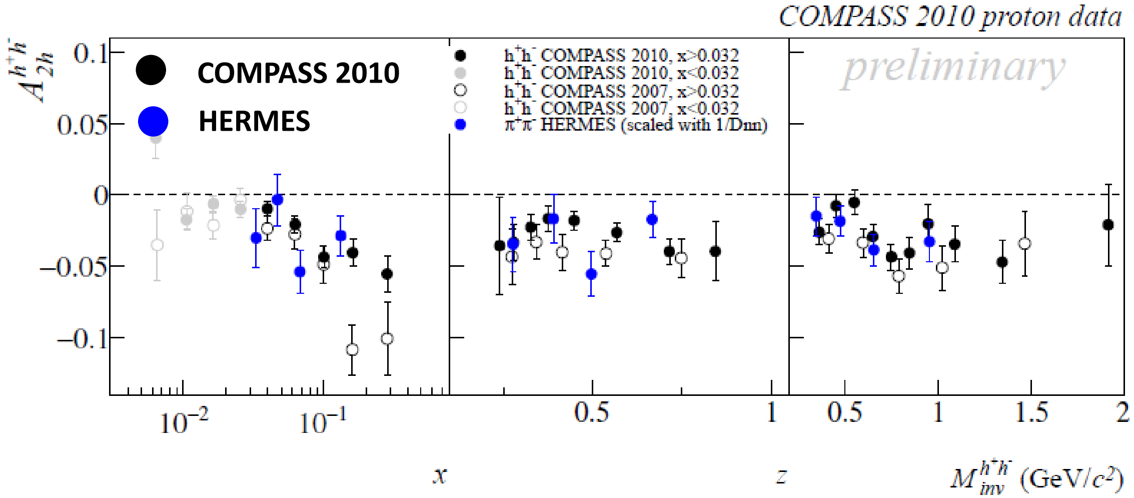
- DGLAP evolution
- **Large asymmetries @ HERMES & COMPASS**

Transversity





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- Survives integration over transverse momentum
- Collinear factorization (simple product)
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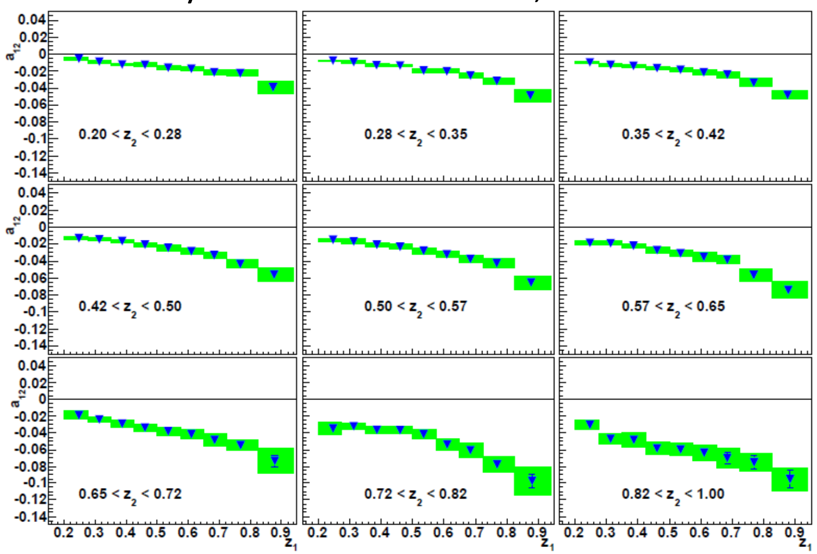
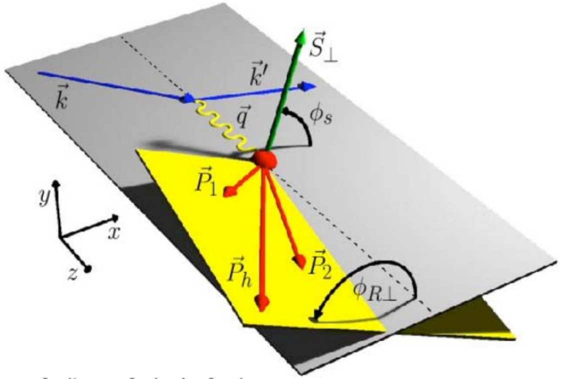
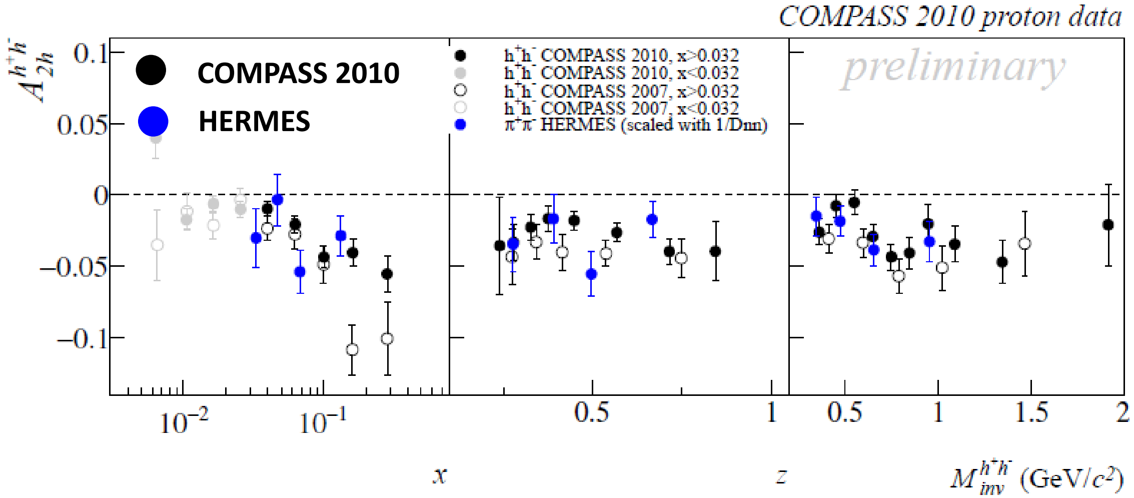
- **Large asymmetries @ HERMES & COMPASS**
- **$H1^{\sphericalangle}$ chiral-odd, measured at BELLE**

Phys.Rev.Lett.107:072004,2011



Transversity





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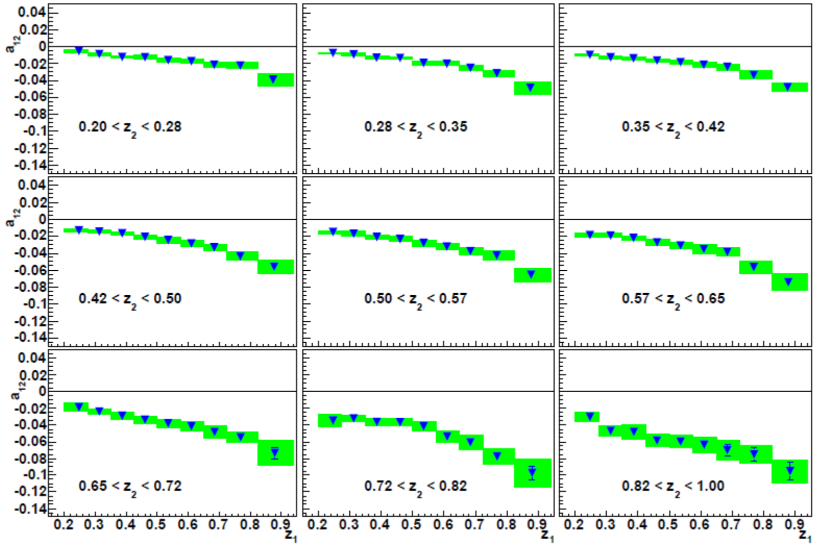
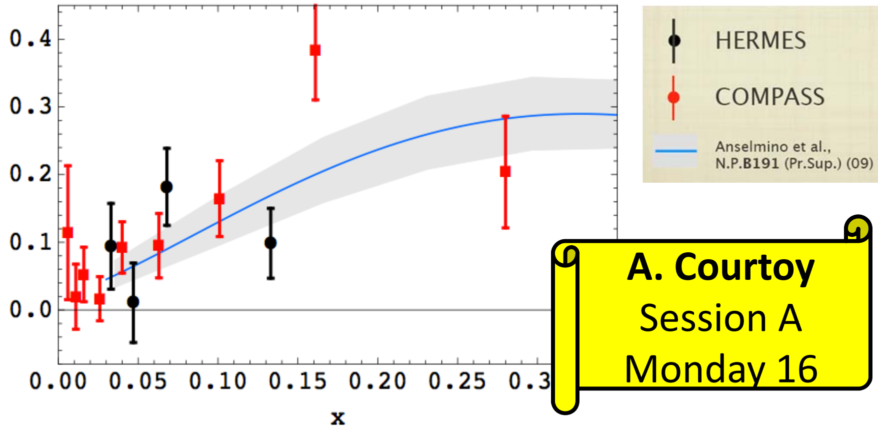
- Survives integration over transverse momentum
- Collinear factorization (simple product)
- DGLAP evolution
- **Large asymmetries @ HERMES & COMPASS**
- **$H1^{\sphericalangle}$ chiral-odd, measured at BELLE**
- **Independent extraction of transversity!**

Phys.Rev.Lett.107:072004,2011



$x\ h_1^u(x) - \frac{x}{4}\ h_1^d(x)$

Bacchetta et al., PRL 107 (11)



A. Courtoy
Session A
Monday 16

Sivers function

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}^2_{h\perp}} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon\,(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

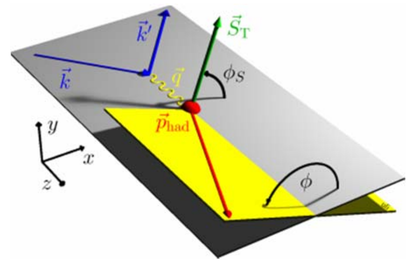
$$+ \lambda_l \Big[\sqrt{2\epsilon\,(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\Big(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon\,(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$



Describes correlation between quark transverse momentum and nucleon transverse polarization

Distribution Functions

nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Fragmentation Functions

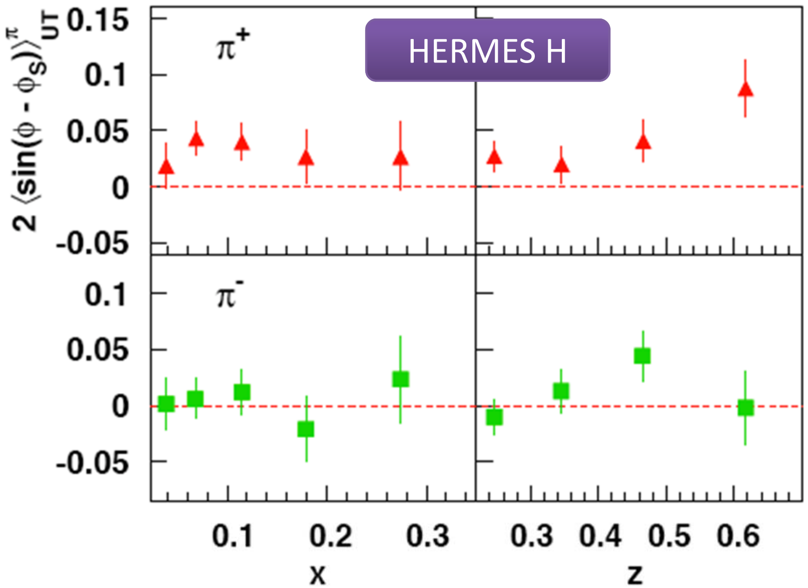
h \ quark	U	L	T
U	D_1		$H_1^\perp$

Sivers function

$$A_{UT}^{\sin(\varphi+\varphi_S)} \propto -\frac{\sum_q e_q^2 \; f_{1T}^{\perp,q}(x,p_T^2)\otimes D_1^q(z,k_T^2)}{\sum_q e_q^2 \; f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$

First evidence by HERMES (2005)

Phys. Rev. Lett. 94 (2005) 012002



- Transv. pol. H target
- Limited statistics (2002-2003)
- **Non-zero Sivers amplitudes for π^+**

  - Non-zero Sivers functon !!

Sivers function

$$A_{UT}^{\sin(\varphi+\varphi_S)} \propto -\frac{\sum_q e_q^2 \; f_{1T}^{\perp,q}(x,p_T^2)\otimes D_1^q(z,k_T^2)}{\sum_q e_q^2 \; f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$

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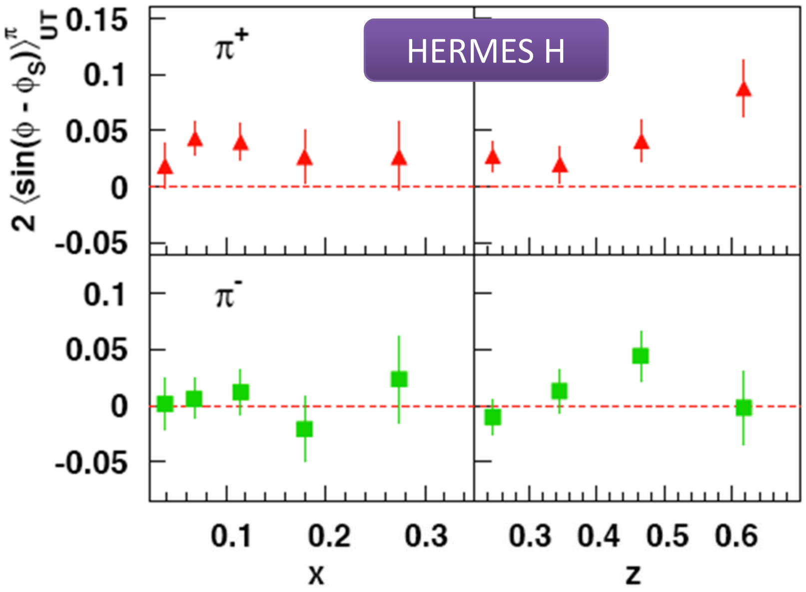

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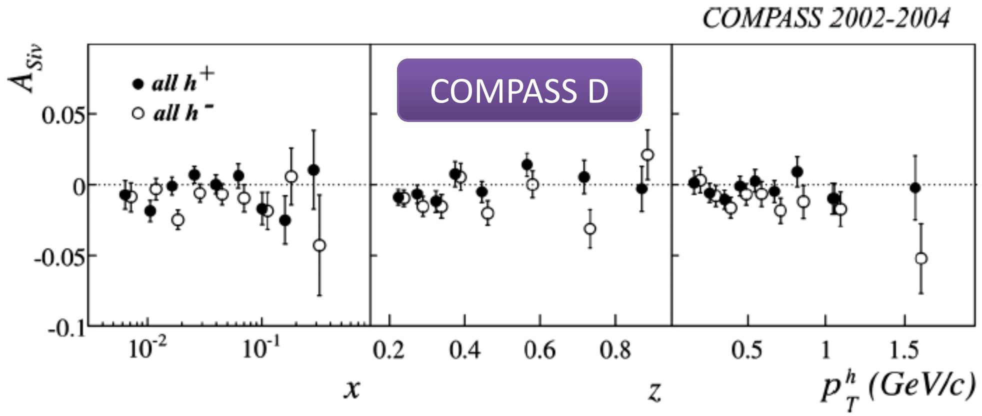
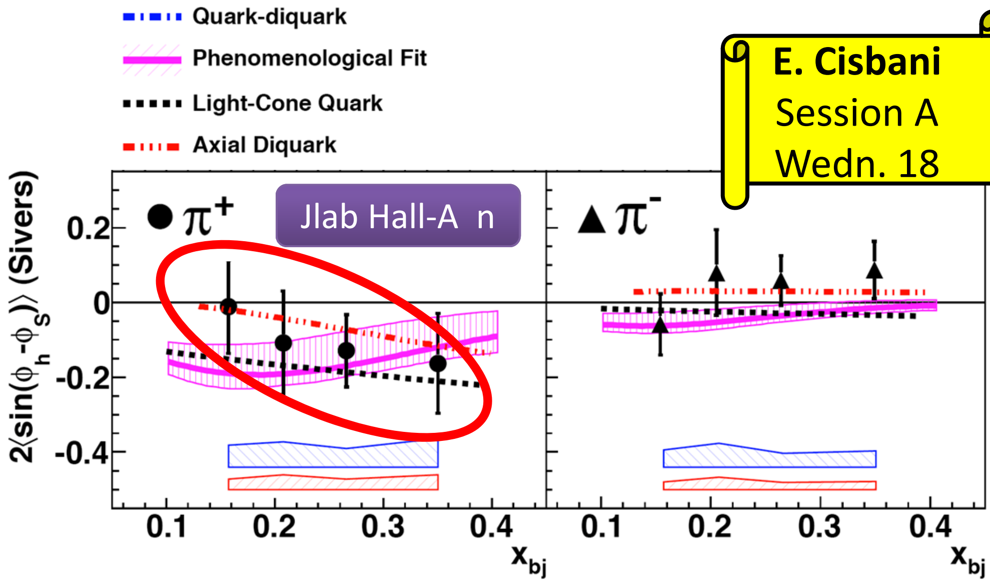
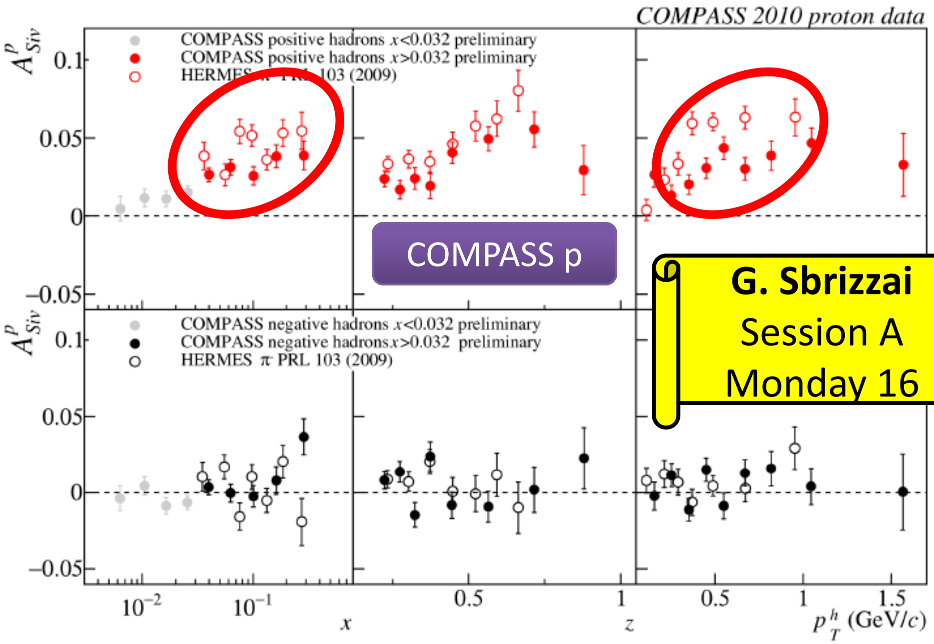




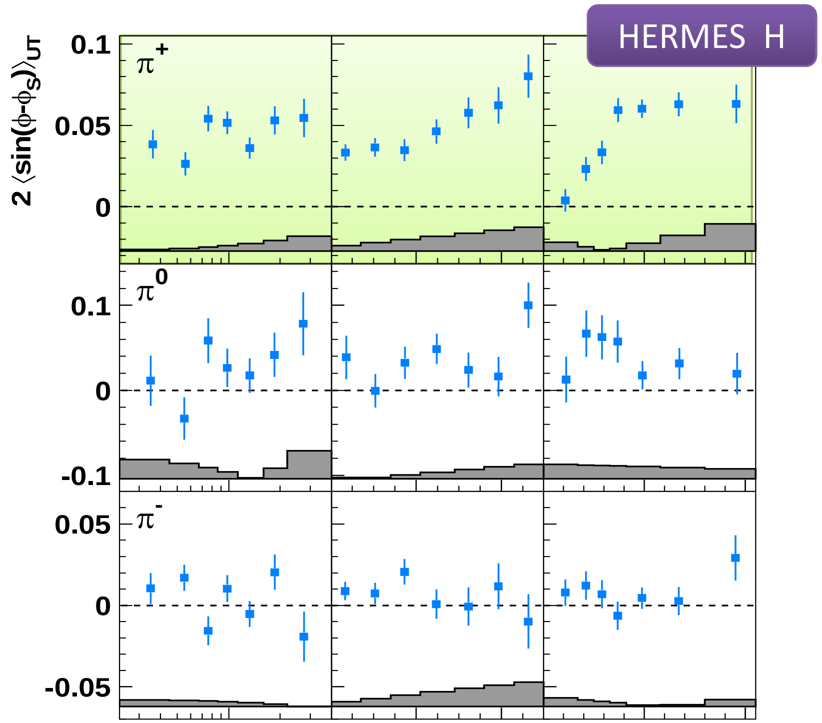
E. Cisbani
Session A
Wedn. 18

Sivers function

- COMPASS amplitudes smaller than HERMES
- New studies: difference reduces substantially in the low y region (0.05<y<0.1)
- TMD evolution? (Anselmino)



G. Sbrizzai
Session A
Monday 16



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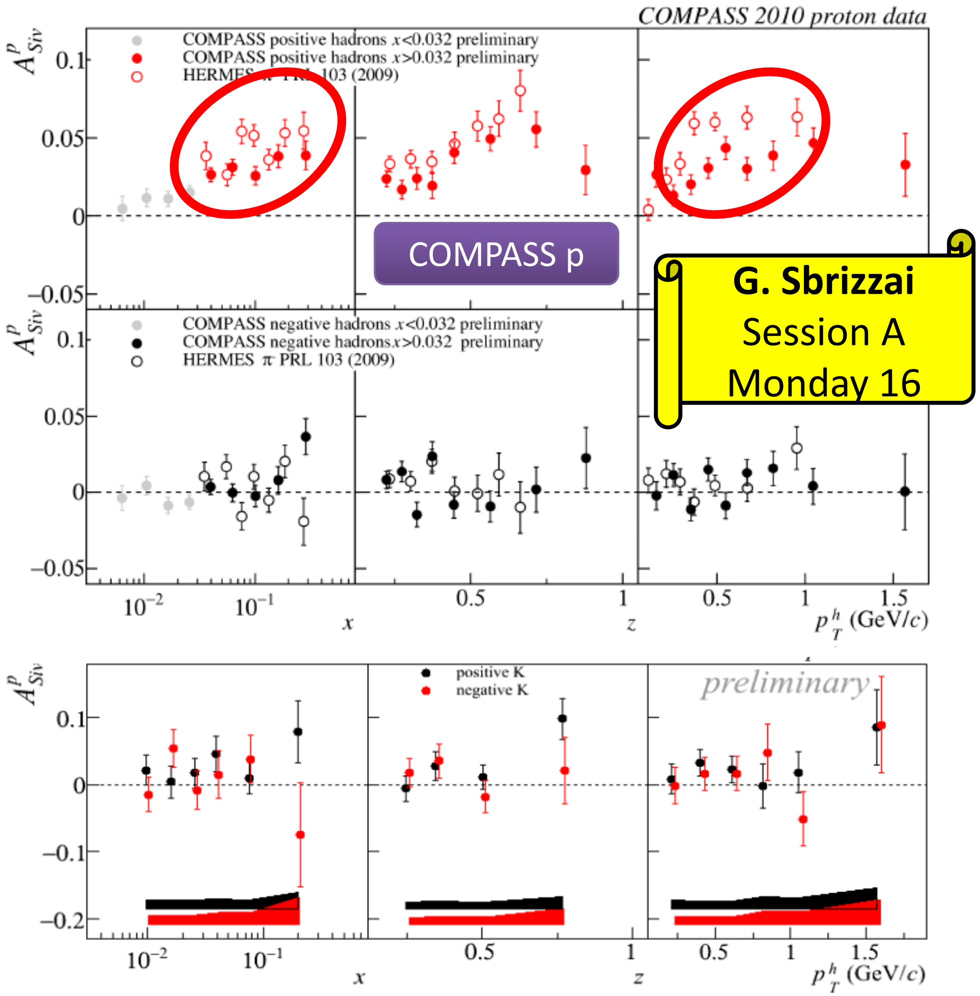
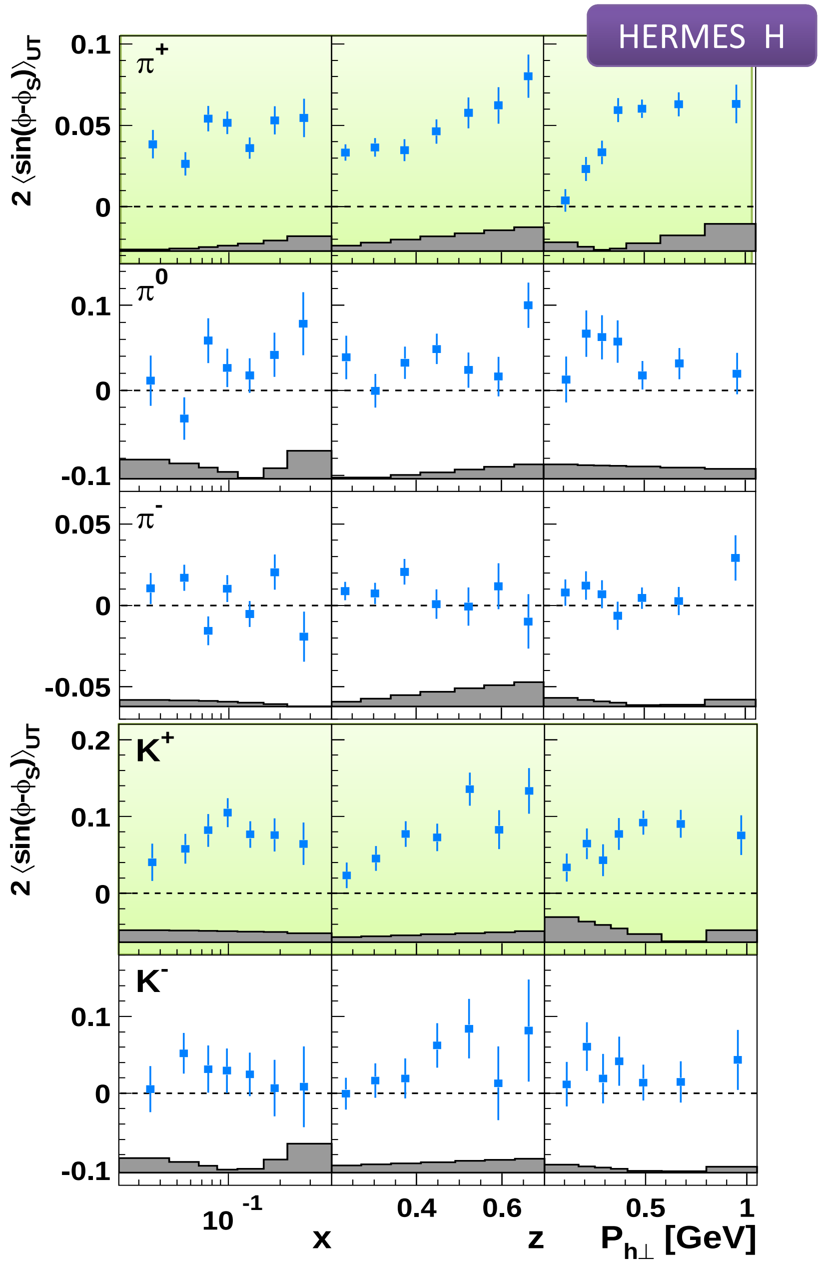




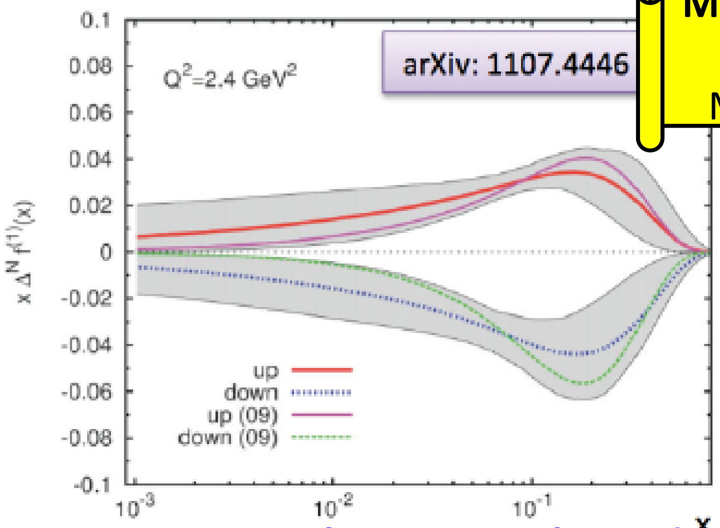
$\pi^+ \equiv |u\bar{d}\rangle,\ K^+ \equiv |u\bar{s}\rangle \rightarrow$ role of sea quarks ?

Extracting the Sivers function

Torino

$$A_{UT}^{\sin(\Phi-\Phi_s)} \propto f_{1T}^{\perp}(x) \otimes D_1^q(z)$$

Fit to Compass d, Hermes p + unpol FF

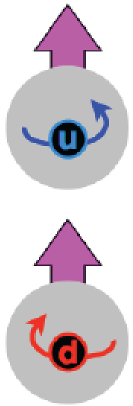


M. Anselmino
Session A
Monday 16

New approach: TMD evolution!

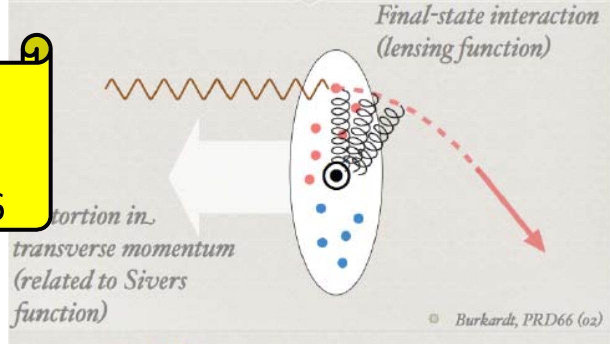
Extraction of Sivers through Bessel weighting avoids convolution!

L. Gamberg
Session A
Monday 16

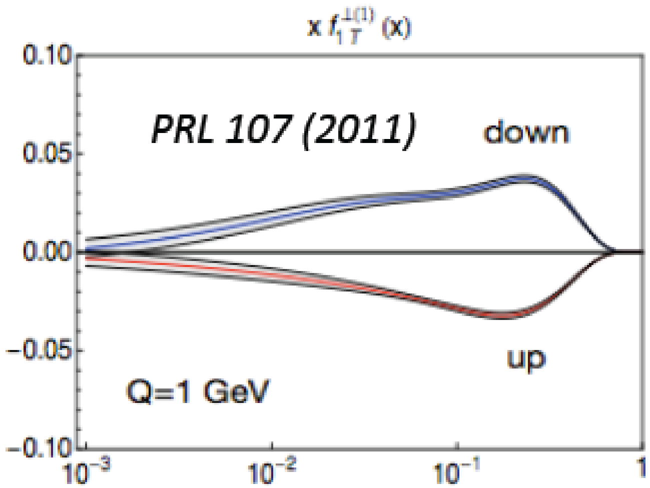


Pavia

M. Radici
Session A
Monday 16

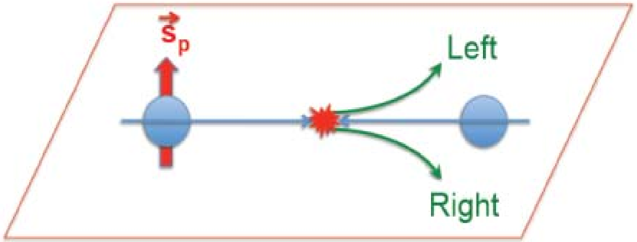


$$f_{1T}^{\perp(0)a}(x;Q_L^2) = -L(x)\,E^a(x,0,0;Q_L^2)$$



Also put constraints on GPD E_q and quark OAM!!

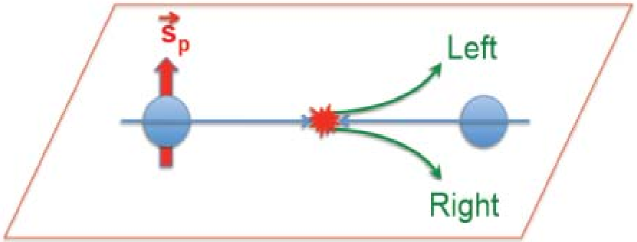
Transversity & Sivers in pp scattering



$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$

Naive (collinear) pQCD predicts $A_N \approx 0$

Transversity & Sivers in pp scattering



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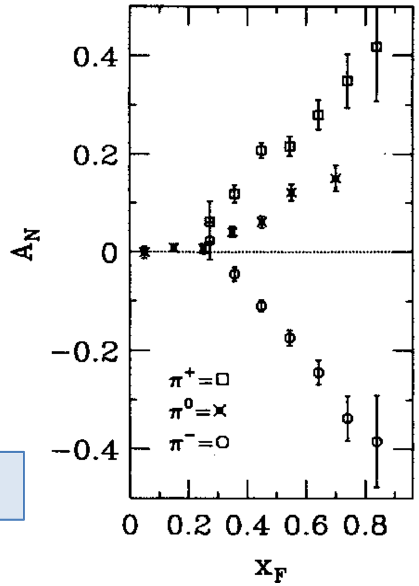


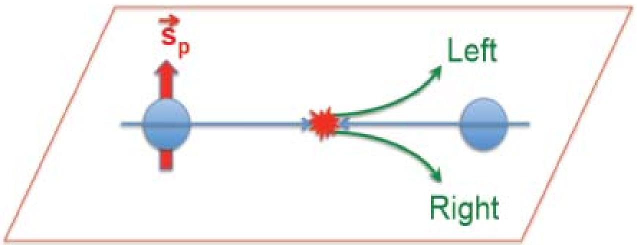
In '90s E-704 exp. @ Fermilab reported large A_N asymmetries (up to 40%!!)

$$x_F \sim \langle z \rangle P_{jet}/P_L$$

Possible explanations:

- **Collins effect** (Transv. x Collins FF)
- **Sivers effect** (orbital motion of quarks)
- **Twist-3** effects
- Combination of above

Transversity & Sivers in pp scattering



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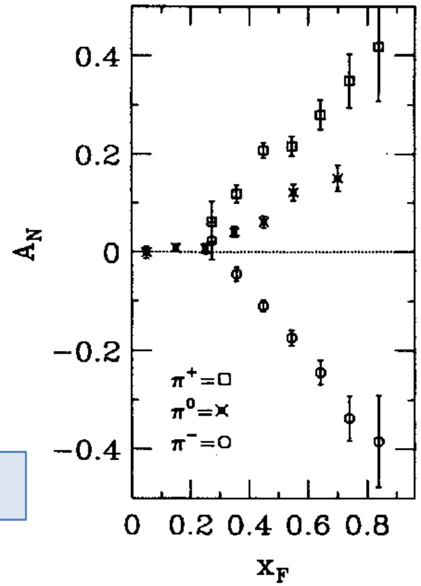

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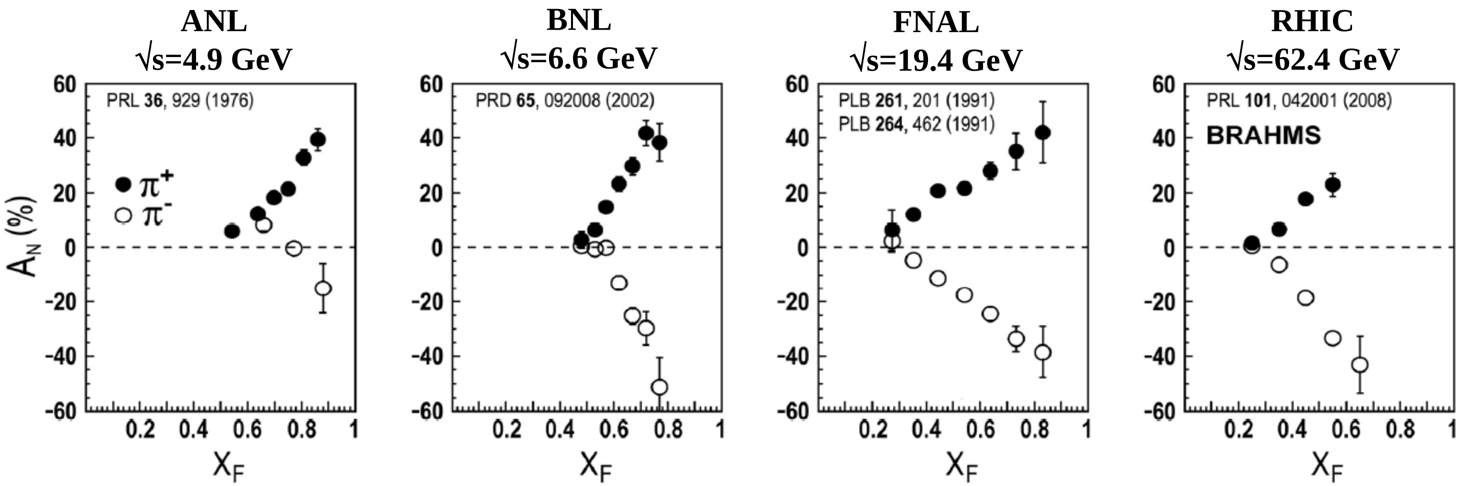
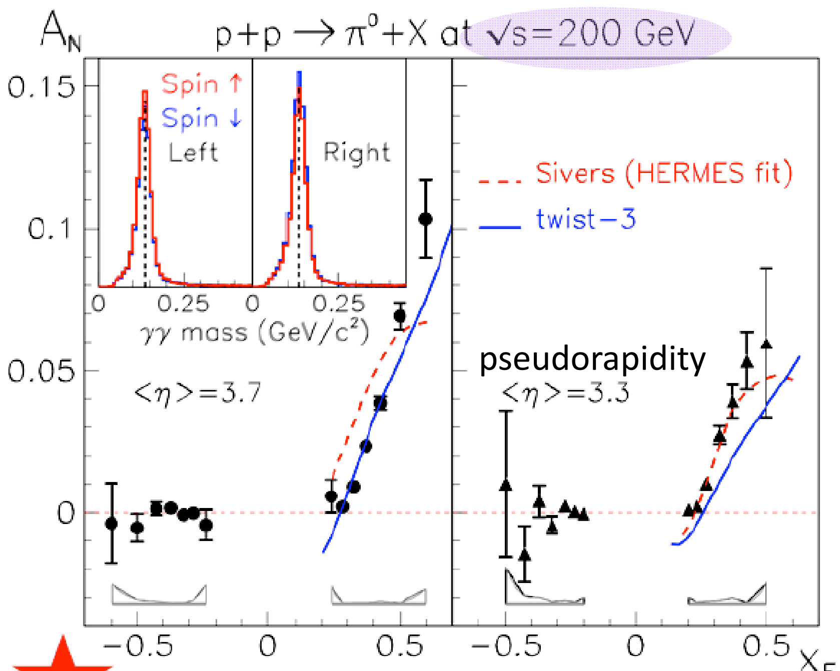
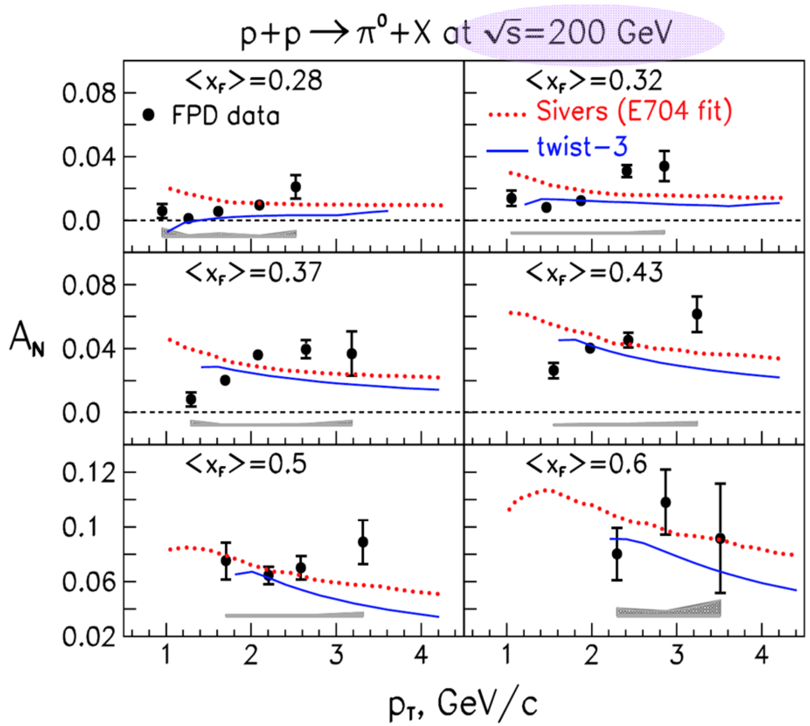


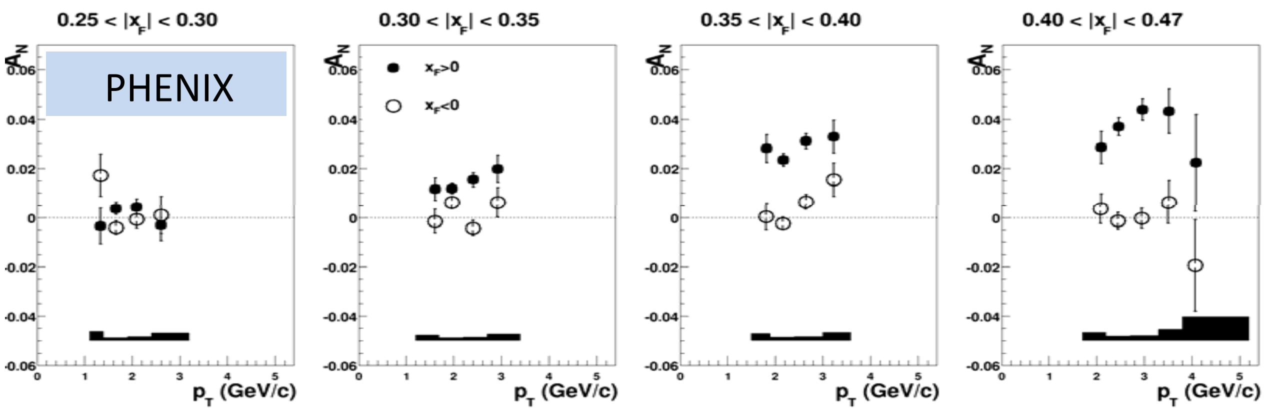
- Reproduced by various exps. over 35 years!
- **persistent with energy!**

Transversity & Sivers in pp scattering: RHIC



STAR Phys. Rev. Lett. 101 (2008) 222001





- **Large asymmetries measured by STAR, PHENIX and BRAHMS**
- **No strong dependence on $\sqrt{s}$ from 19.4 to 200 GeV**
- **Admixture of Transversity, Sivers and Twist-3 effects?**

Boer-Mulders function: DY

$$\frac{d\sigma^{hp\to eeX}}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

$(1-\lambda) - 2\nu = 0$ **Lam-Tung rel.**

Boer-Mulders function: DY

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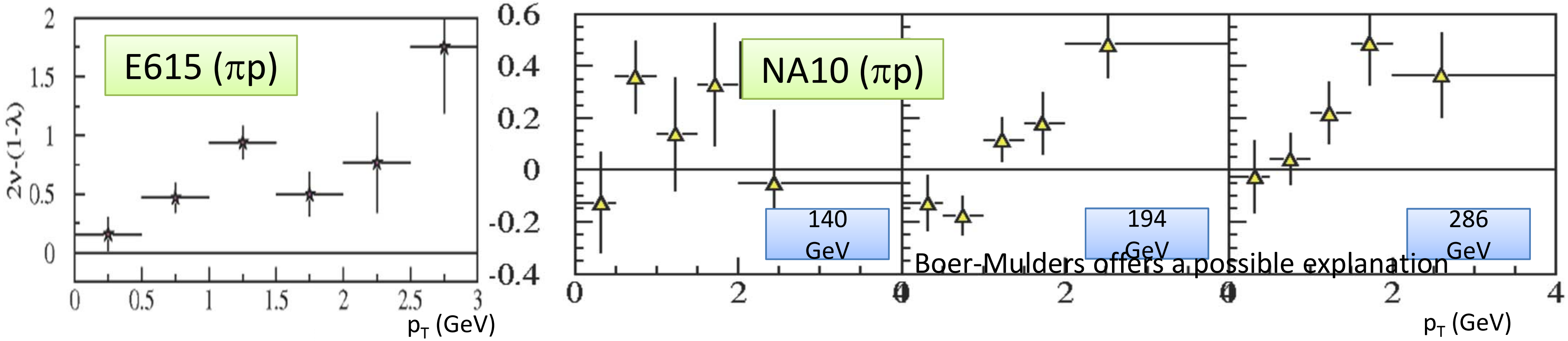
violated in pion-induced DY!



Boer-Mulders offers a possible explanation

Boer-Mulders function: DY

$$\frac{d\sigma^{hp\to eeX}}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

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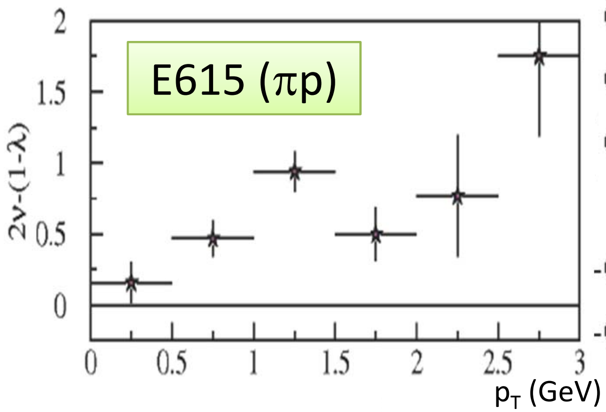
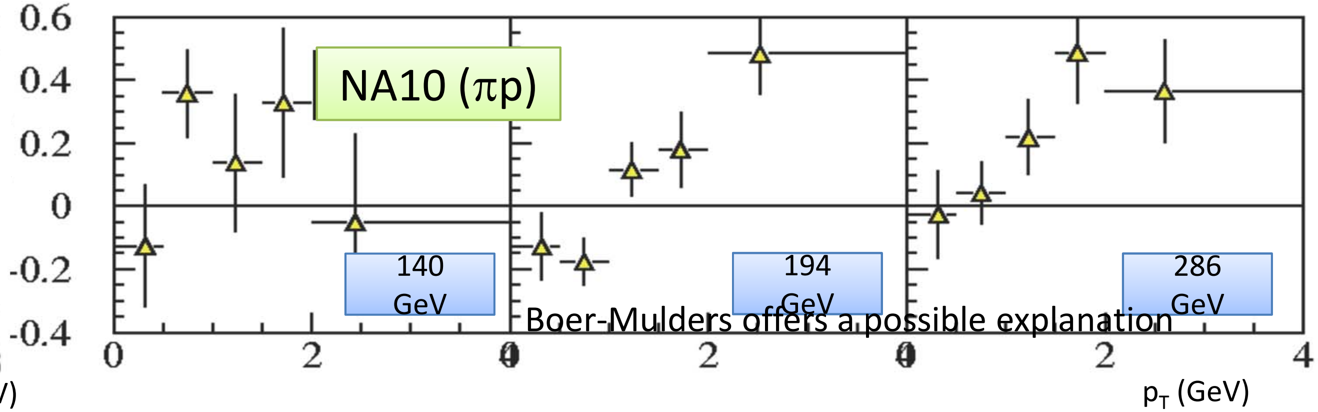
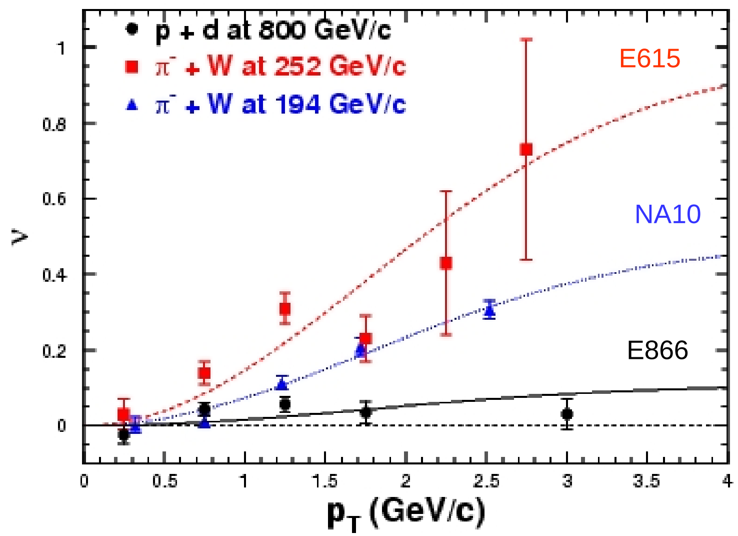




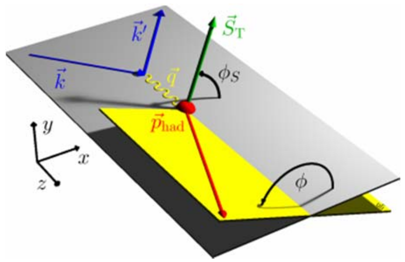
Naive parton model:
$d\sigma/d\Omega \propto 1 + \cos^2\vartheta \Rightarrow \nu \approx 0$

Boer-Mulders effect offers an explanation:

$$\nu \approx h_{1q}^{\perp} \times h_{1\bar{q}}^{\perp}$$



Boer-Mulders function: SIDIS



$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\rm UU,T} + \epsilon F_{\rm UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\rm UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\rm UU}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\rm LU}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\rm UL}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\rm UL}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\rm LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\rm LL}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\Big(F_{\rm UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{\rm UT,L}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S) F_{\rm UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\rm UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\rm UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\rm UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\rm LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\rm LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\rm LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

Describes correlation between quark transverse momentum and transverse spin in unpolarized nucleon

Distribution Functions

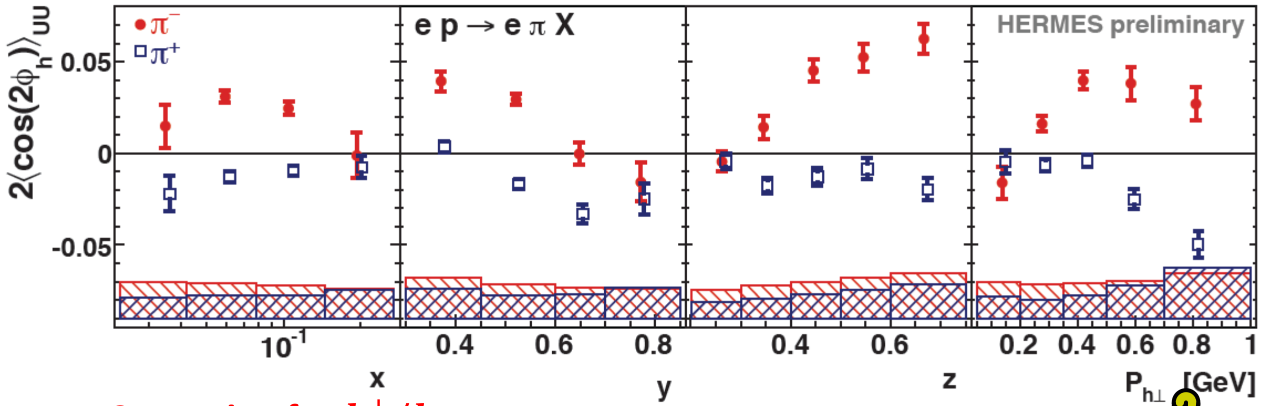
nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Fragmentation Functions

h \ quark	U	L	T
U	D_1		$H_1^\perp$

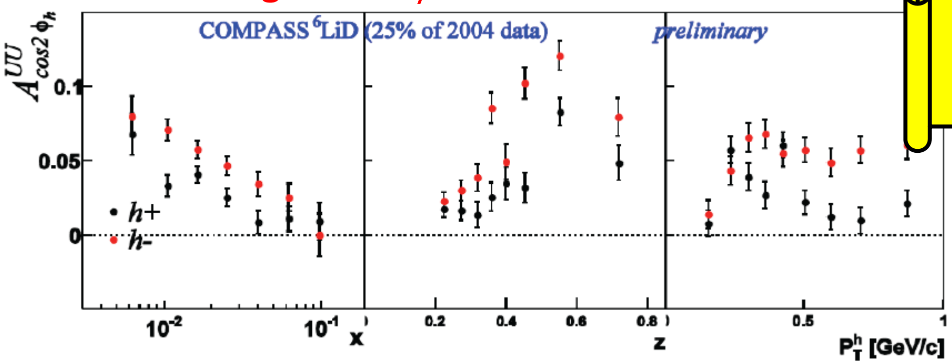
Boer-Mulders function: SIDIS (cos2ϕ)

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$



- Opposite signs for π^+/π^-
- Similar results on H & D target → same sign for u and d?
- K^+/K^- amplitudes are larger and of same sign

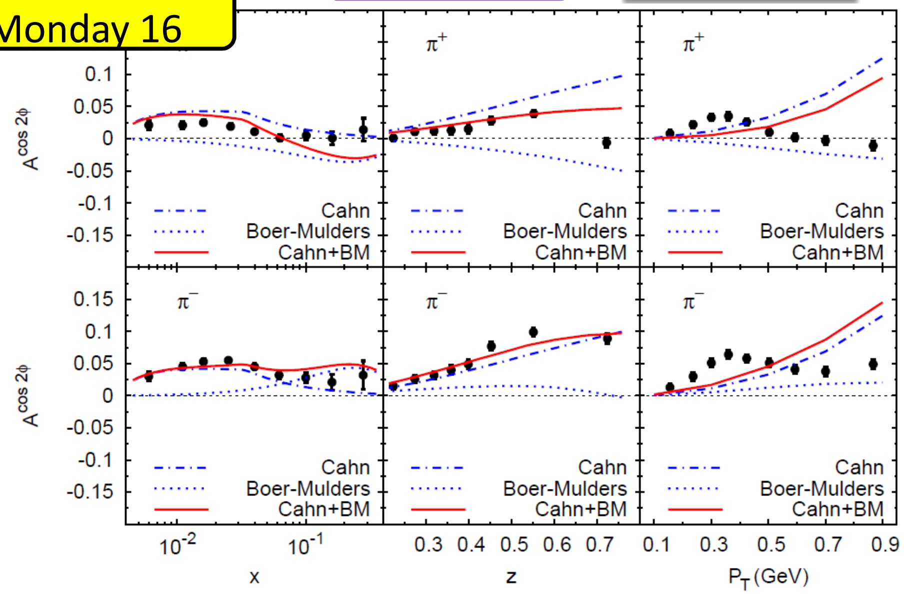
- Same sign for h^+/h^-



G. Sbrizzai
Session A
Monday 16

COMPASS D

arXiv: 0912.5194



- **Amplitudes are significant**
- **Clear evidence of BM effect**
- **Strong dependence on kinematic variables**
- Issue on data consistency for h^+
- New 2-dim extraction from COMPASS!
- Discrepancy with theory: uncert. on Chan + HT

Worm-gear $h^{\perp}{}_{1L}$

$$\frac{d\sigma^{h}}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}^2_{h\perp}} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon\,(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

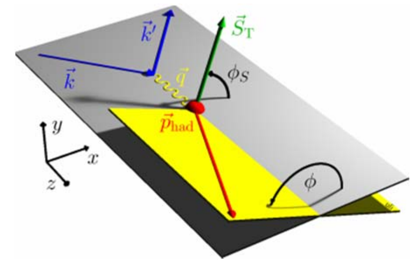
$$+ \lambda_l \Big[\sqrt{2\epsilon\,(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\Big(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon\,(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon\,(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon\,(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$



Describes the probability to find transversely polarized quarks in a longitudinally polarized nucleon

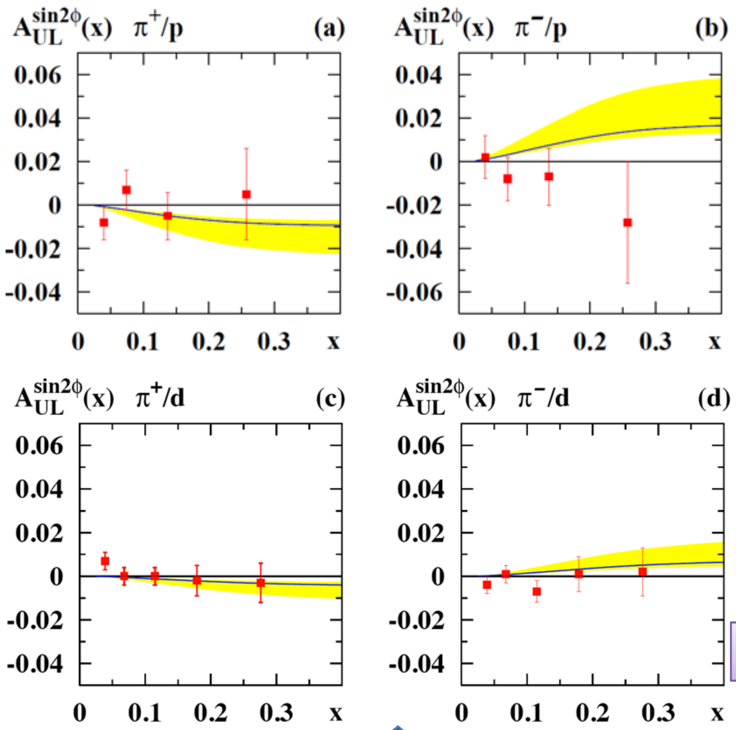
Distribution Functions

		quark U	quark L	quark T
nucleon	U	f_1		$h_1^{\perp}$
	L		g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

Fragmentation Functions

		quark U	quark L	quark T
h	U	D_1		$H_1^{\perp}$

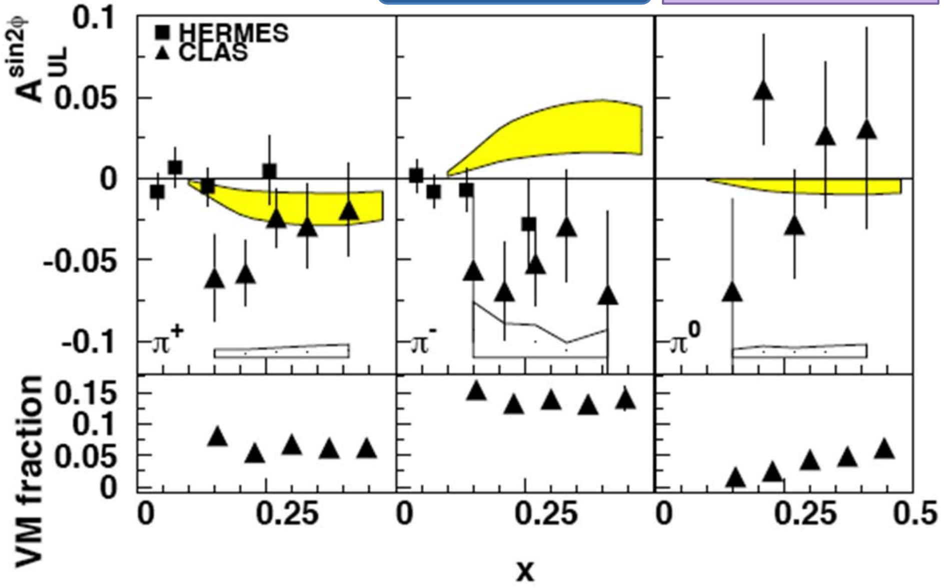
Worm-gear $h^{\perp}_{1L}$



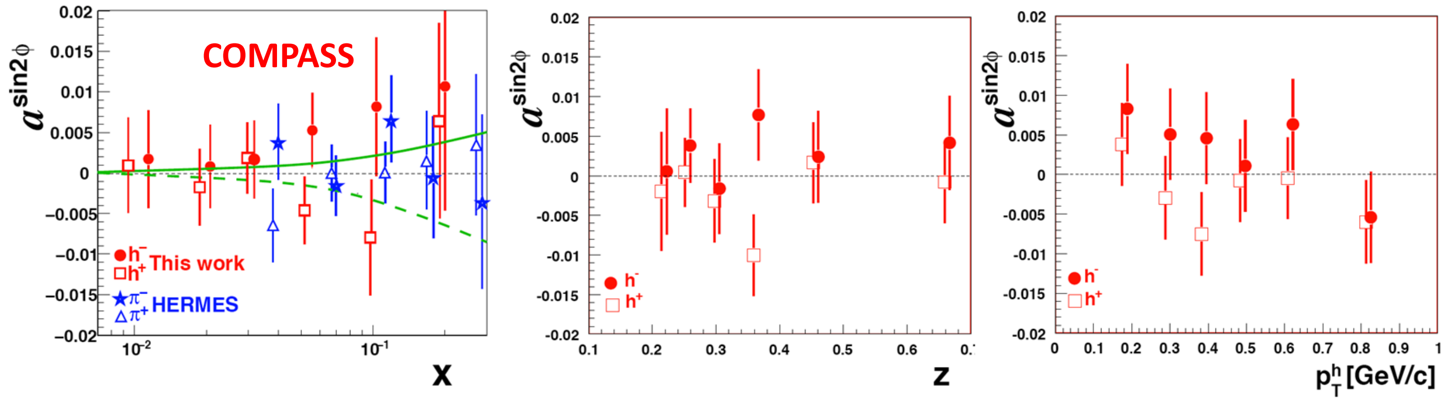
arXiv: 0902.0689

Proton

arXiv: 1007.1562



- Consistent with zero @ HERMES & COMPASS
- **Significant amplitude @ CLAS!**



Deuteron

arXiv: 1003.4549

G. Sbrizzai
Session A
Monday 16

Worm-gear $g^{\perp}_{1T}$

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}^2_{h\perp}} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F^{\cos(\phi)}_{\mathrm{UU}} + \epsilon\cos(2\phi)F^{\cos(2\phi)}_{\mathrm{UU}}\Big]$$

$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F^{\sin(\phi)}_{\mathrm{LU}}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F^{\sin(\phi)}_{\mathrm{UL}} + \epsilon\sin(2\phi)F^{\sin(2\phi)}_{\mathrm{UL}}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F^{\cos(\phi)}_{\mathrm{LL}}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F^{\sin(\phi-\phi_S)}_{\mathrm{UT,T}} + \epsilon F^{\sin(\phi-\phi_S)}_{\mathrm{UT,L}}\right) + \epsilon\sin(\phi+\phi_S)F^{\sin(\phi+\phi_S)}_{\mathrm{UT}} + \epsilon\sin(3\phi-\phi_S)F^{\sin(3\phi-\phi_S)}_{\mathrm{UT}} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F^{\sin(\phi_S)}_{\mathrm{UT}} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F^{\sin(2\phi-\phi_S)}_{\mathrm{UT}}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F^{\cos(\phi-\phi_S)}_{\mathrm{LT}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F^{\cos(\phi_S)}_{\mathrm{LT}} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F^{\cos(2\phi-\phi_S)}_{\mathrm{LT}}\Big]\Big\}$$

Describes the probability to find longitudinally polarized quarks in a transversely polarized nucleon!

- The only TMD that is both chiral-even and naïve-T-even
- requires interference between wave funct. components that differ by 1 unit of OAM

Distribution Functions

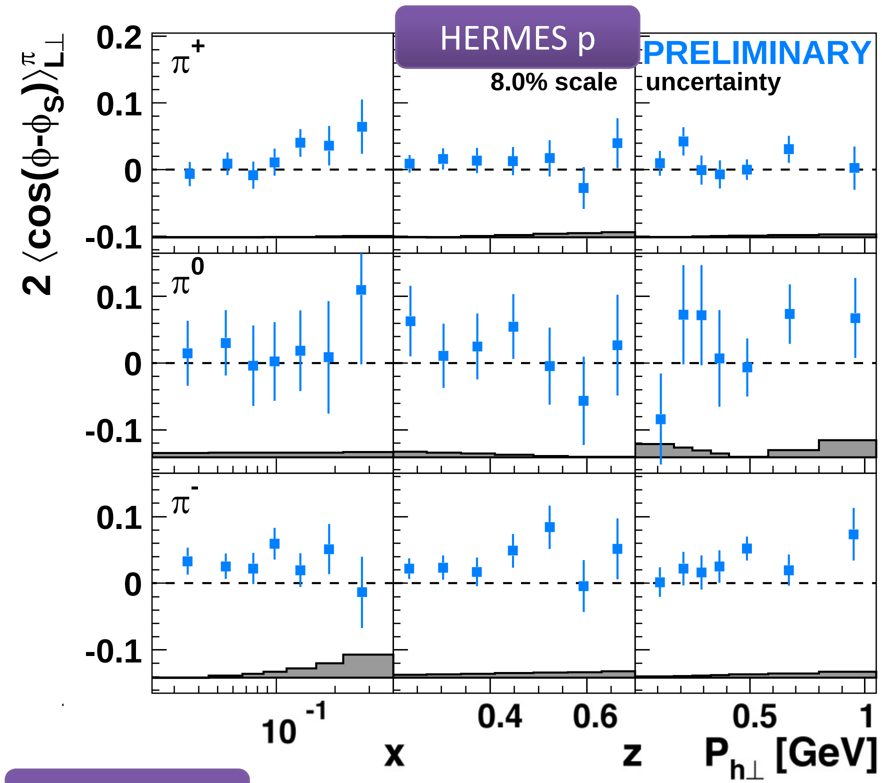
nucleon \ quark	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

Fragmentation Functions

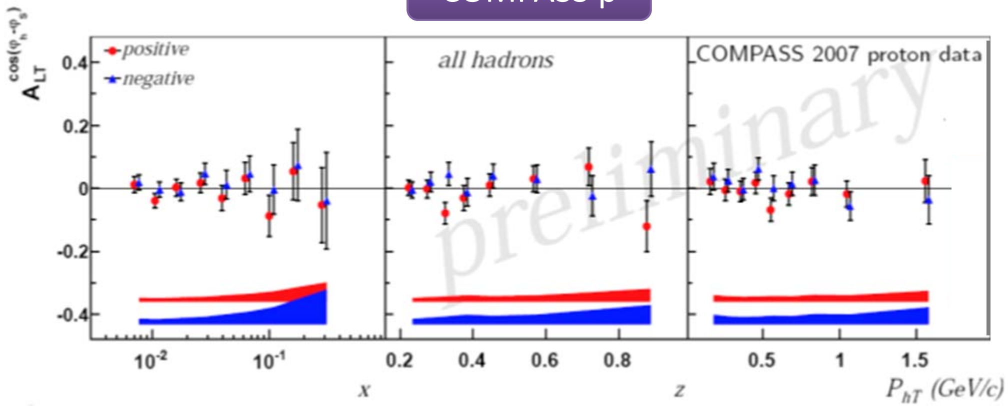
h \ quark	U	L	T
U	D_1		$H_1^{\perp}$

Worm-gear $g^{\perp}_{1T}$

HERMES p



COMPASS p



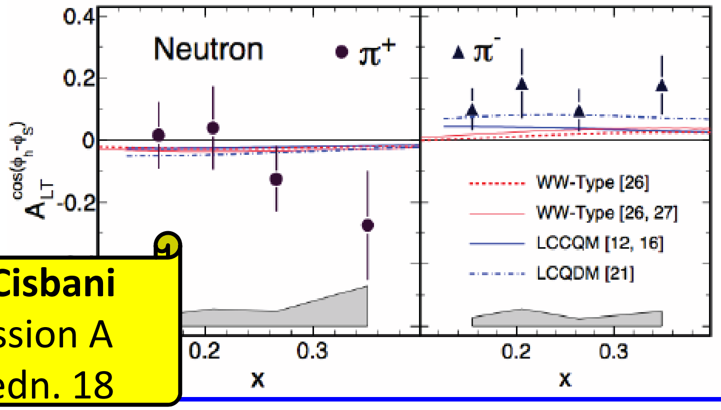
Statistics not enough to investigate relations supported by many theoretical models:

$$g_{1T}^{q} = -h_{1L}^{\perp q}$$ (supported by Lattice QCD and first data)

$$g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x \int_x^1 \frac{dy}{y} g_1^q(y)$$ (Wandura-Wilczek type approximation)

Jlab Hall-A n

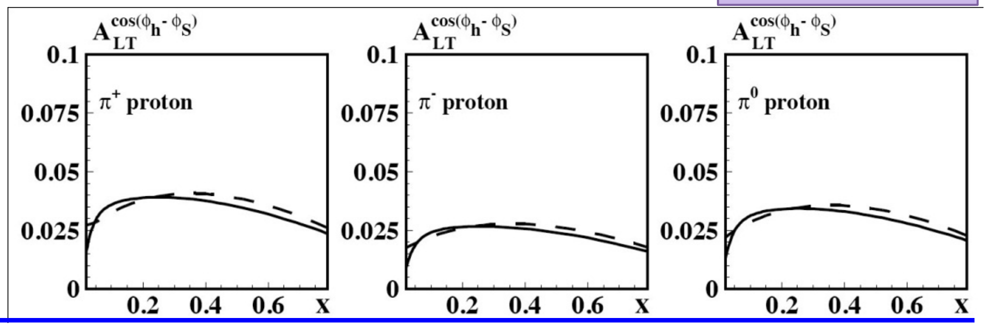
Jlab n, PRL108(2012)



E. Cisbani
Session A
Wedn. 18

From constituent quark model:

arXiv: 0903.1271



Pretzelosity

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}^2_{h\perp}} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\right]$$

$$+ S_L \left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\right]$$

$$+ S_L\,\lambda_l \left[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\right]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)}$$
$$+ \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

Describes correlation between quark transverse momentum and transverse spin in a transversely pol. nucleon

- Sensitive to the D-wave component
- Sensitive to **non-spherical shape** of the nucleon
- Kinematically suppressed w.r.t. Collins and Sivers by a factor ${P_{h\perp}}^2$

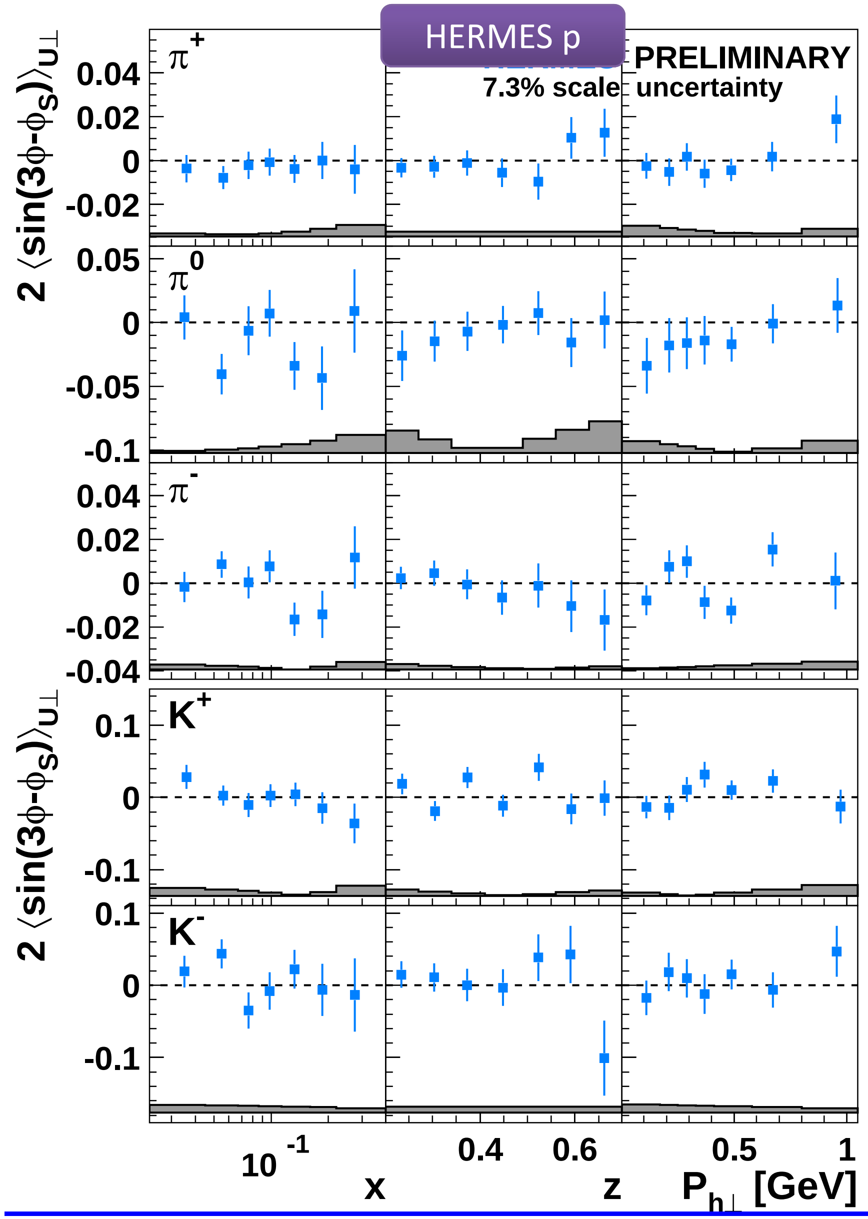
Distribution Functions

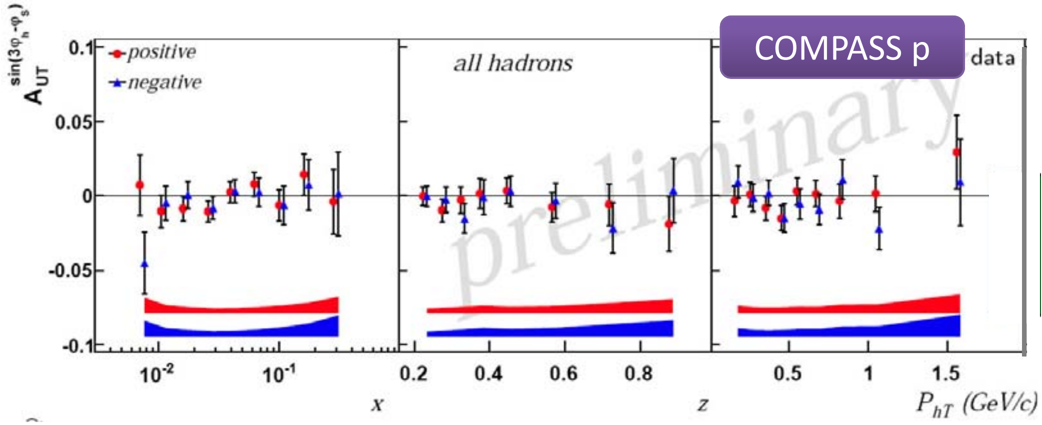
		quark U	quark L	quark T
nucleon	U	f_1		$h_1^\perp$ -
	L		g_1 -	$h_{1L}^\perp$ -
	T	$f_{1T}^\perp$ -	$g_{1T}^\perp$ -	h_1 - ; $h_{1T}^\perp$ -

Fragmentation Functions

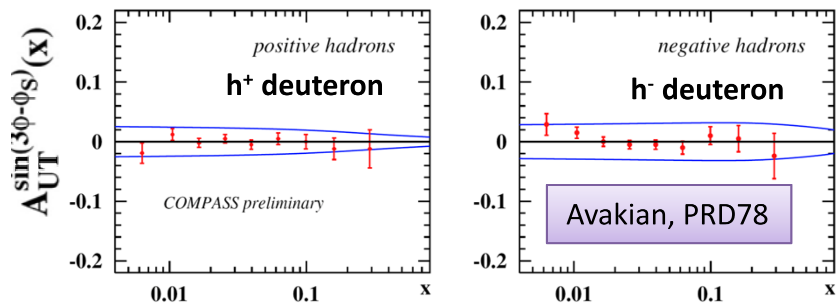
		quark U	quark L	quark T
h	U	D_1		$H_1^\perp$ -

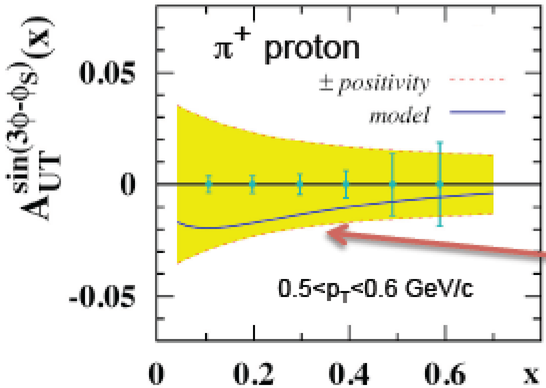
Pretzelosity





- Proton and deuteron data consistent with zero
- Statistical power of existing data is not enough to observe significant signals

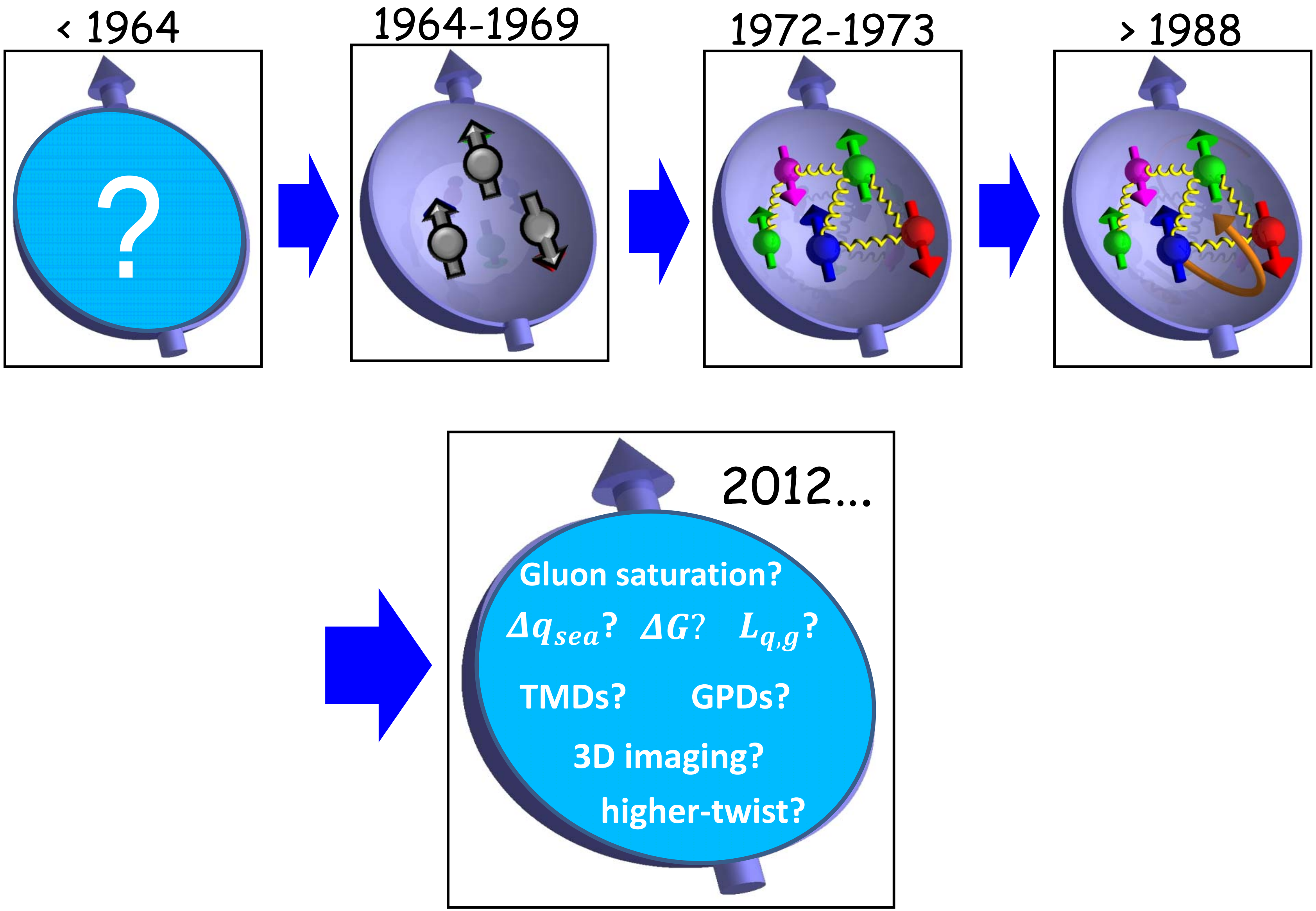




arXiv: 0812.3246

Few % signal expected at Jlab from covariant model

Looking deeply into the proton



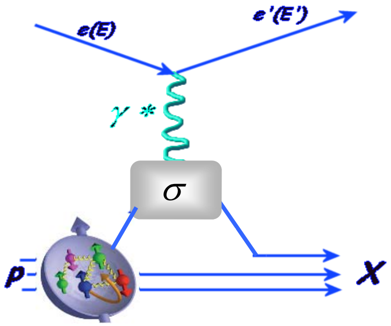
The treasure map!

Back-up

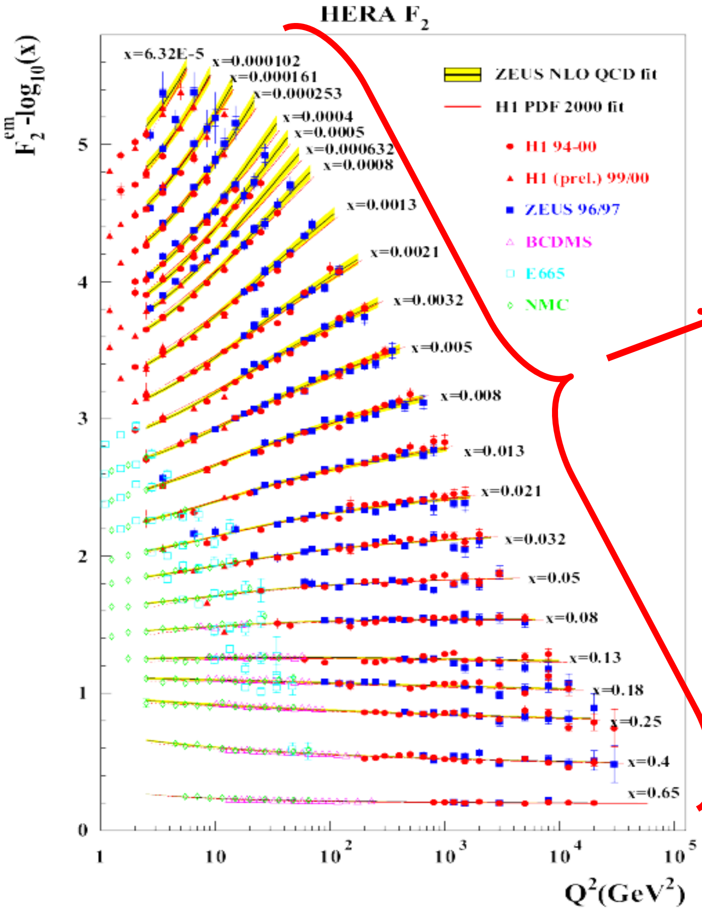
The nucleon **collinear** structure: **momentum**

	U	L	T
U	f_1		
L			
T			

$f_1(x) = q^+(x) + q^-(x)$

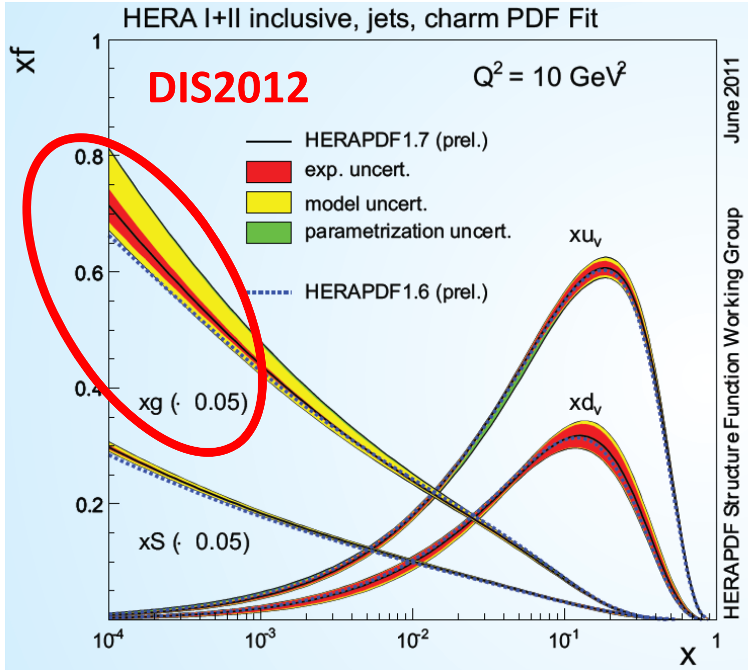


- 40 years of **inclusive DIS** experiments
- fixed target exp. & HERA collider
- **very precise data!**
- wide kinematic range in x and Q^2
- prediction of Q^2 dependence $\rightarrow$ triumph of QCD!



4 orders of magnitude in x!

5 orders of magnitude in Q^2!



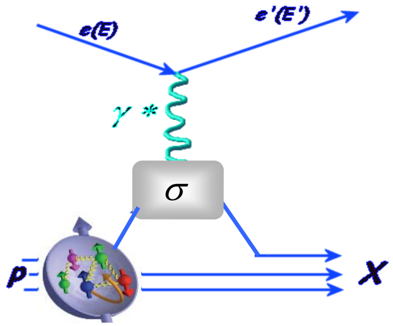
very good knowledge of longitudinal momentum structure of the nucleon!

...but gluons should saturate!

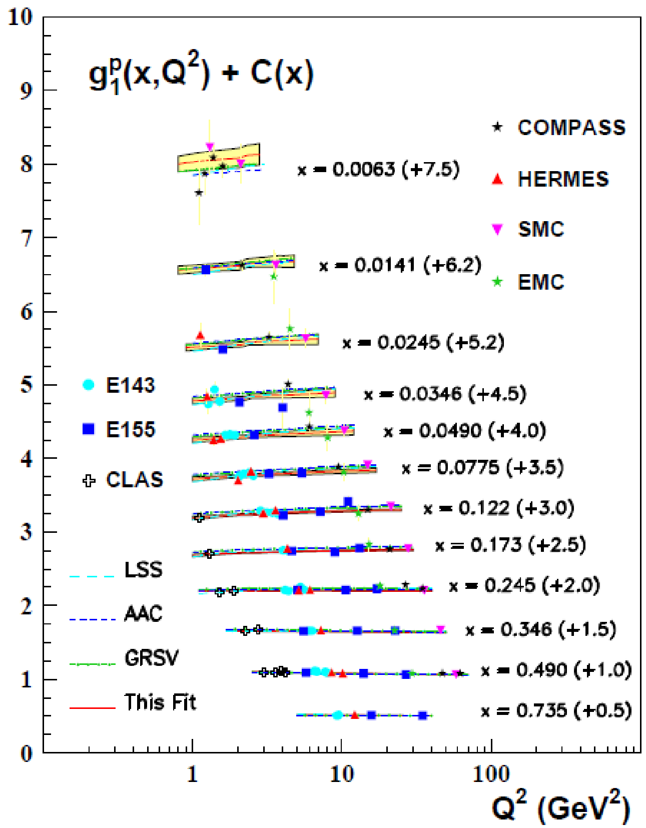
The nucleon **collinear** structure: **helicity**

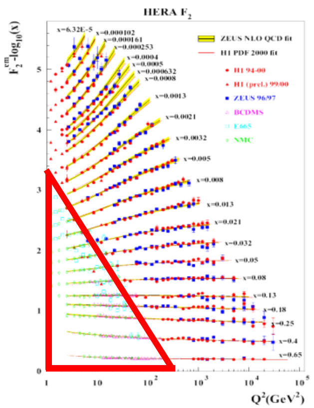
	U	L	T
U			
L		g_{1L}	
T			

$$g_1(x) = q^+(x) - q^-(x)$$



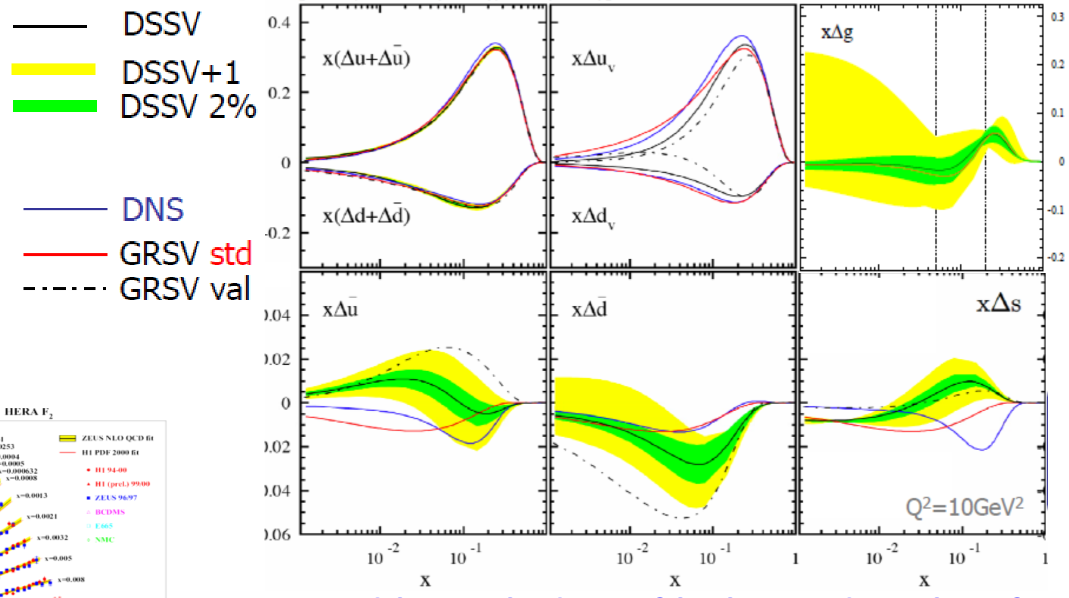
- **inclusive DIS** (+ semi-inclusive → flavor tagging)
- Fixed target experiments
- polarized beams and target → challenging
- relatively limited kinematic coverage in x and Q^2





global NLO fit of helicity distributions

[DSSV, PRL101(2008), PRD(2009)]



good knowledge of helicity distrib. of valence quarks

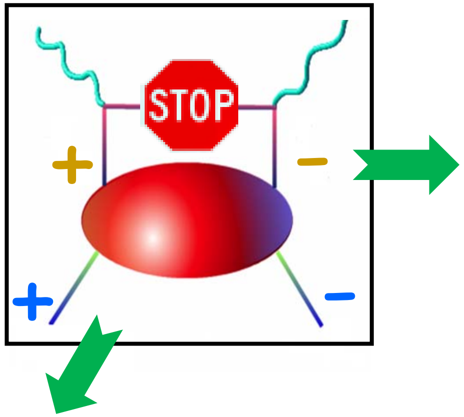
Sea quarks and gluon helicity still poorly constrained...

The nucleon **collinear** structure: **transversity**

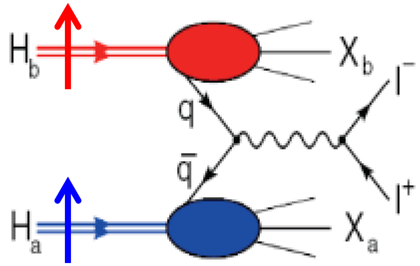
	U	L	T
U			
L			
T			h_1,

$h_1(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$

Chiral-odd!!!



Double-polarized DY



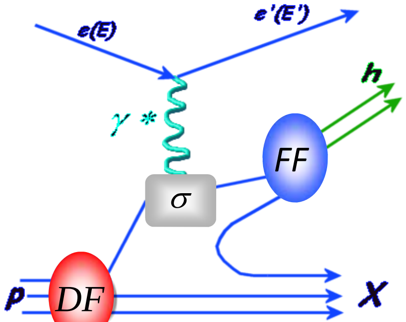
Golden process!

...but challenging:

- very small X-section
- huge background
- polarizing $\bar{p}$ beams

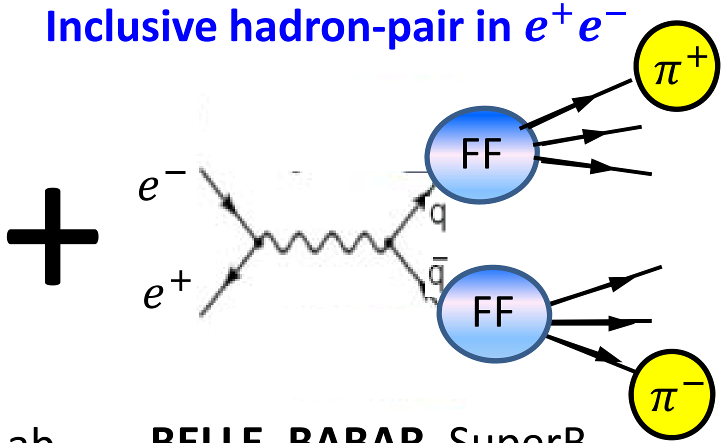
Future exp. RHIC, CERN,FAIR

Semi-Inclusive DIS

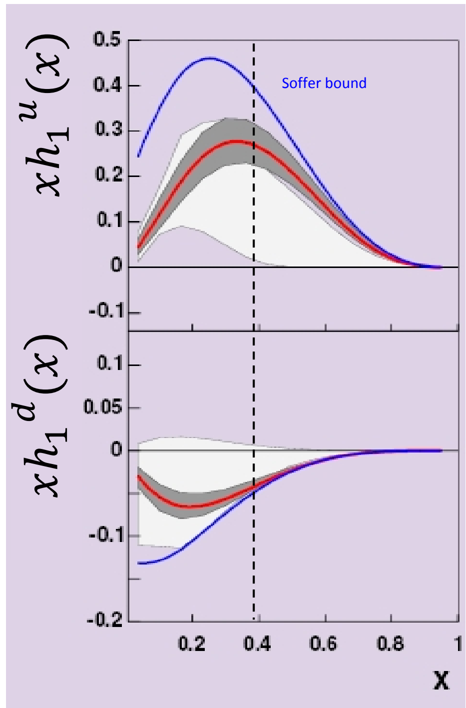


HERMES, COMPASS, JLab,...

Inclusive hadron-pair in e^+e^-

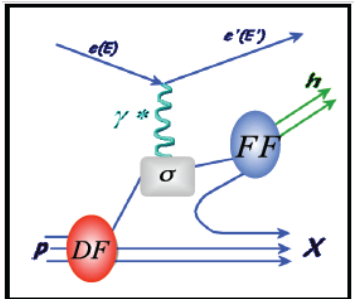


BELLE, BABAR, SuperB,...



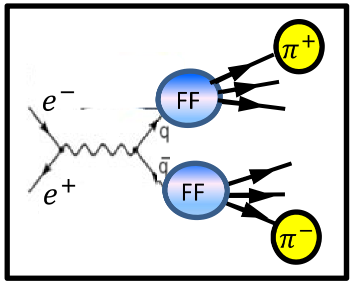
- Very recent: first evidence (2005), first extraction (2007)!
- limited coverage in x (< 0.4)
- more data in valence region (JLab) to constrain tensor charge
- sea quark transversity completely unconstrained

Reactions and experiments



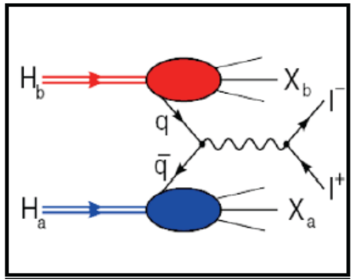
SIDIS: rich phenomenology, the most explored so far

SIDIS $\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$



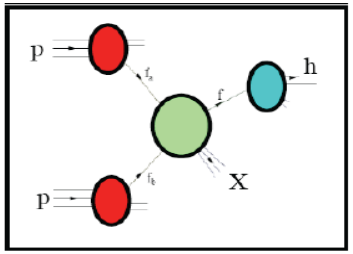
e⁺e⁻: B-factories as powerful fragmentation laboratories

e^+e^- $\sigma^{ee\to hhX} = \sum_q \sigma^{qq\to ee} \otimes FF \otimes FF$



DY: challenging for experiments (only unpolarized so far)

DY $\sigma^{pp\to eeX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to ee}$



Hadron reactions: challenging for theory (ISI + FSI)

pp $\sigma^{pp\to hX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to qq} \otimes FF$

Boer-Mulders function: SIDIS

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h dP_{h\perp}} \propto \left\{ F_{UU,T} + \varepsilon F_{UU,L} + 2\sqrt{\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos 2\phi_h F_{UU}^{\cos 2\phi_h} \right\}$$

Twist-2:

$$d\sigma_{UU}^{Cos2\phi} \propto \cos 2\phi \cdot \sum_q e_q^2 I\left[\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T) - \vec{k}_T\cdot\vec{p}_T}{MM_h} h_1^{\perp} H_1^{\perp q}\right]$$

Boer & Mulders PRD 57 (1998)

Boer-Mulders effect

Pure kinematic effect due to transverse momentum of partons in the nucleon

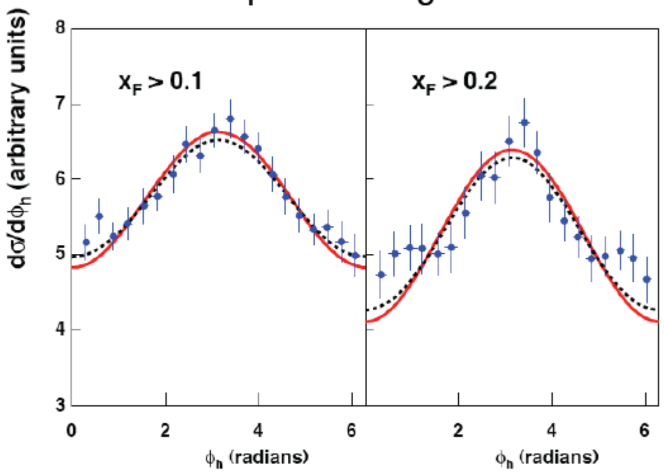
Cahn effect

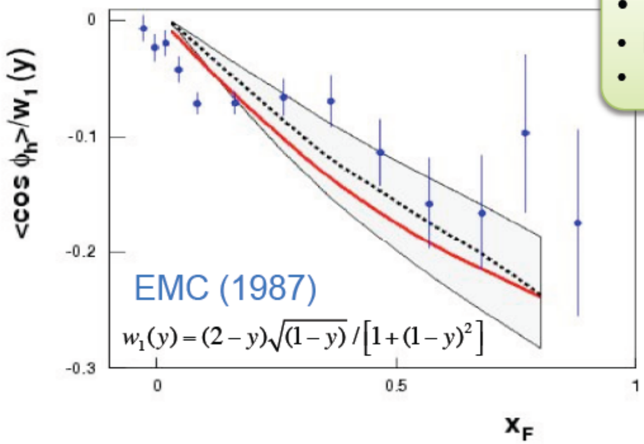
Cahn PLB 78 (1978)

Twist-3:

$$d\sigma_{UU}^{Cos\phi} \propto \cos\phi \cdot \sum_q e_q^2 \frac{2M}{Q} I\left[-\frac{(\hat{P}_{h\perp}\cdot\vec{p}_T)}{M_h} x\, h_1^{\perp} H_1^{\perp q} - \frac{(\hat{P}_{h\perp}\cdot\vec{k}_T)}{M} x\, f_1 D_1 + \ldots\right]$$

Till 2008: qualitative agreement with Cahn expectations

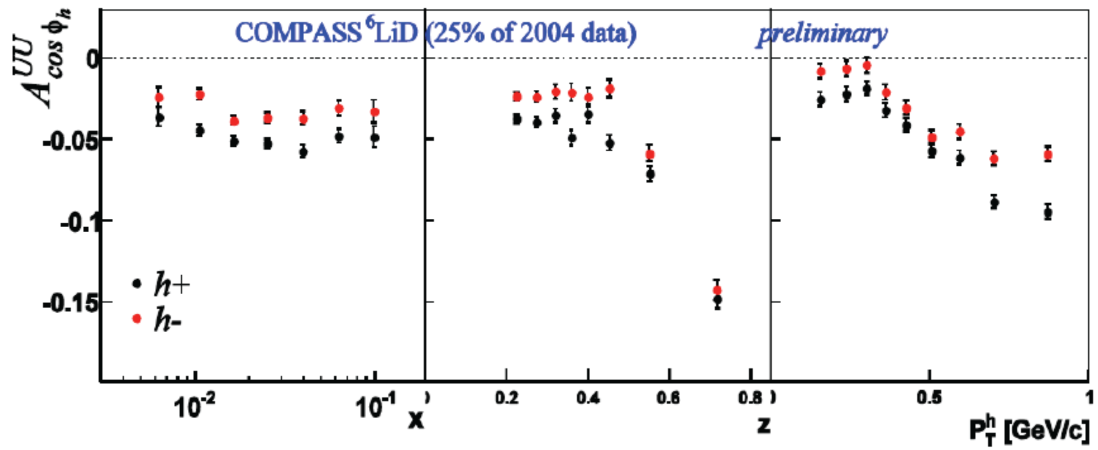




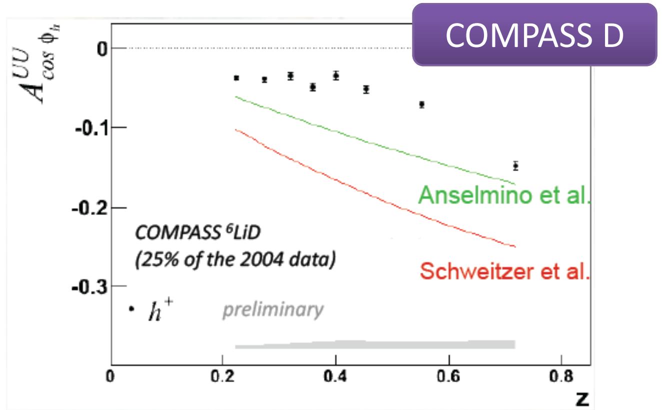
- No hadron identification
- No charge separation
- Poor statistics for cos2ϕ

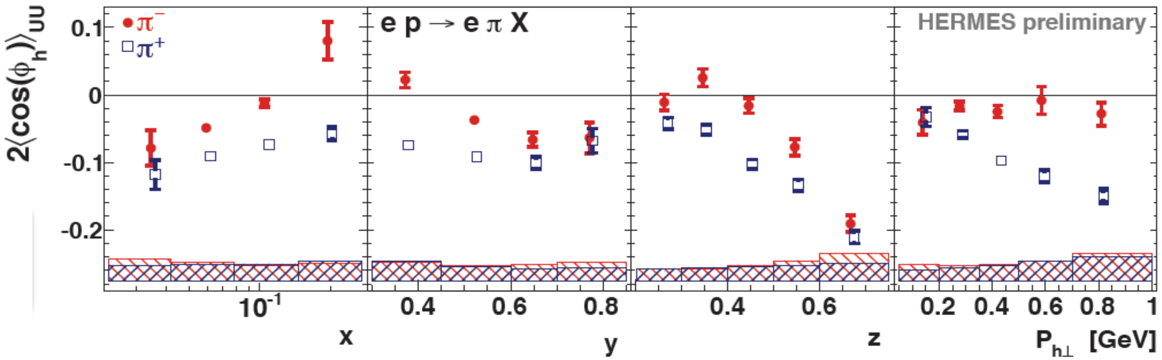
Boer-Mulders function: SIDIS (cosϕ)

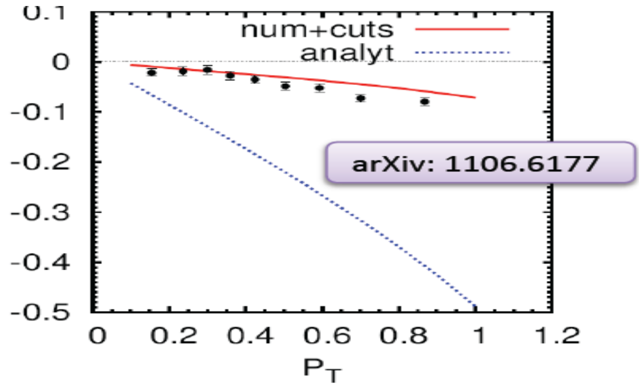
$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} + \ldots \right] / Q$$



- No dependence on hadron charge is expected
- Difference between h^+/h^- due to Boer-Mulders term
- Predictions overestimate data
- BM or twist-3?







Unpolarized TMDs

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \left[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right]$$

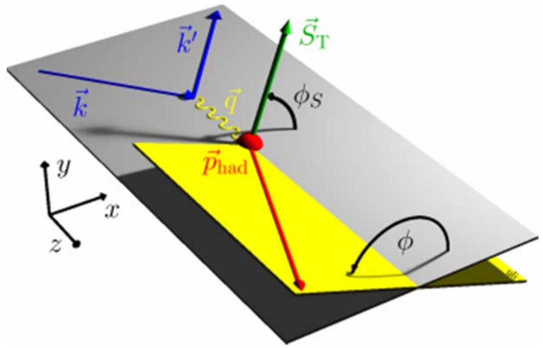
$$+ \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{LU}^{\sin(\phi)}\right]$$

$$+ S_L \left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\right]$$

$$+ S_L\,\lambda_l \left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos(\phi)}\right]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$



Distribution Functions

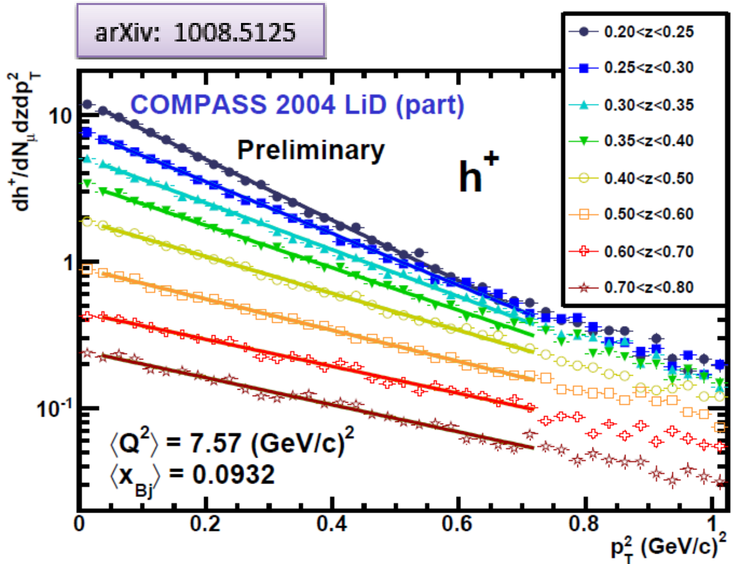
nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Fragmentation Functions

h \ quark	U	L	T
U	D_1		$H_1^\perp$

Unpolarized TMDs: $P_{h\perp}$-unintegrated distributions

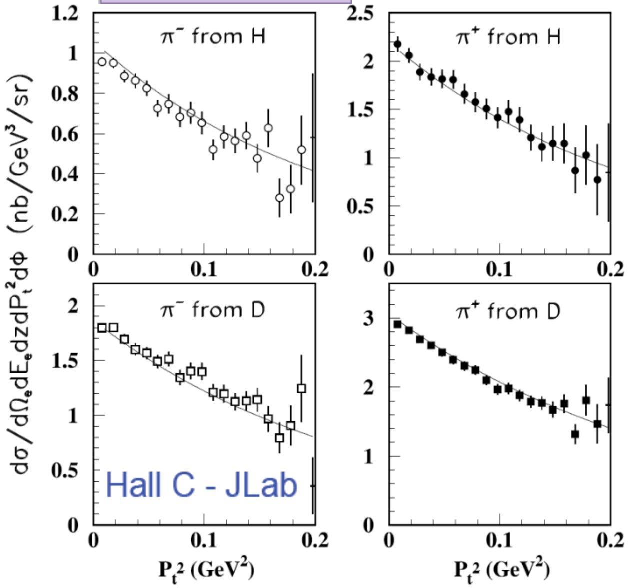
arXiv: 1008.5125



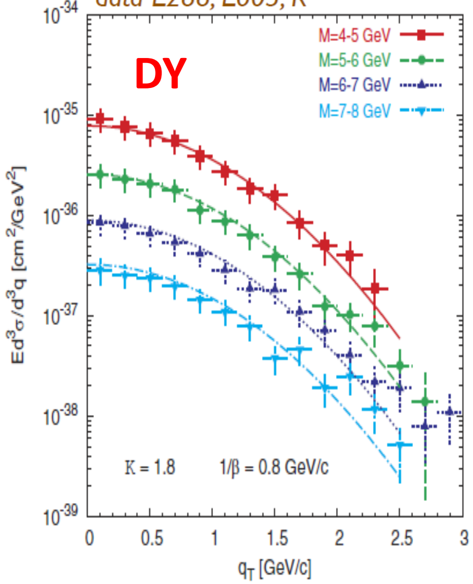
$$M_N^h = \frac{1}{N_N^{DIS}(Q^2)} \frac{dN_N^h(z,Q^2)}{dz} = \frac{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2)}$$

disentangling the z and $P_{h\perp}$ dependencies allows to access intrinsic transverse momenta p_T and k_T: $\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$ $\rightarrow$ 3D analysis $(x, z, P_{h\perp})$

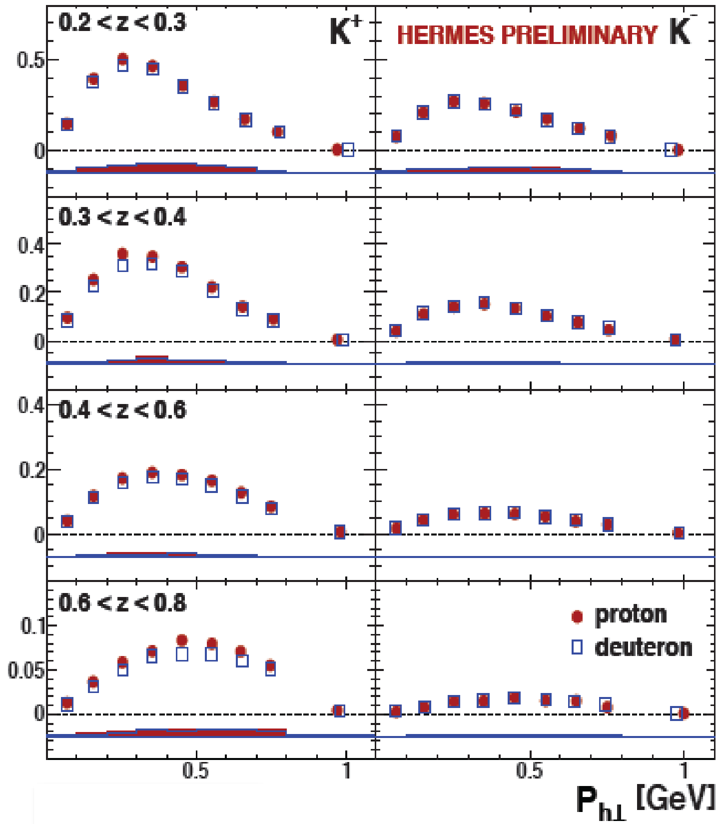
arXiv: 0709.3020



D'Alesio, Murgia, PRD70 (04)
data E288, E605, R



Hadron multiplicities

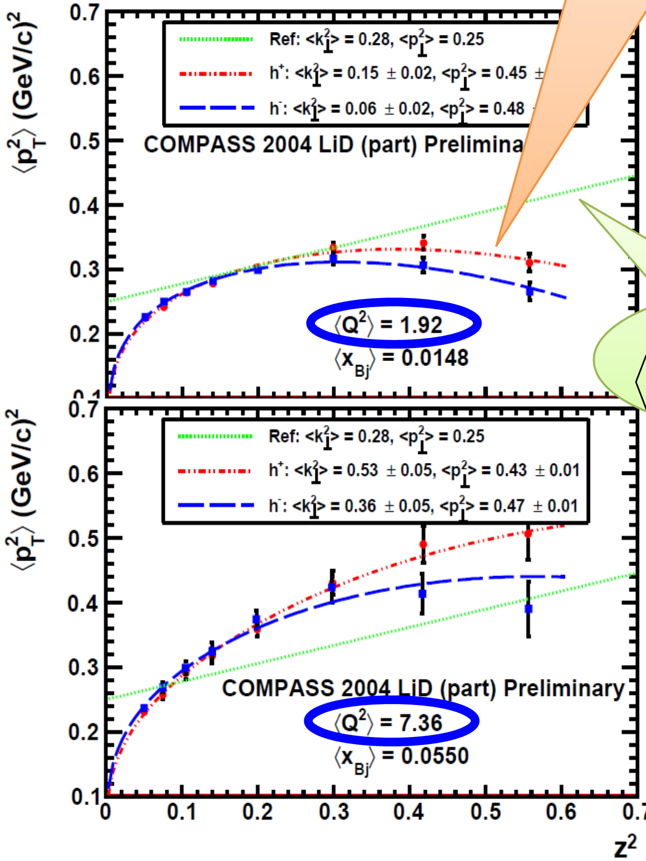


Unpolarized TMDs: *energy dependence & evolution*

Is p_T independent of z ?

$$\langle P_{h\perp}^2\rangle = z^2\langle k_T^2\rangle + z^\alpha(1-z)^\beta\langle p_T^2\rangle$$

arXiv: 1008.5125

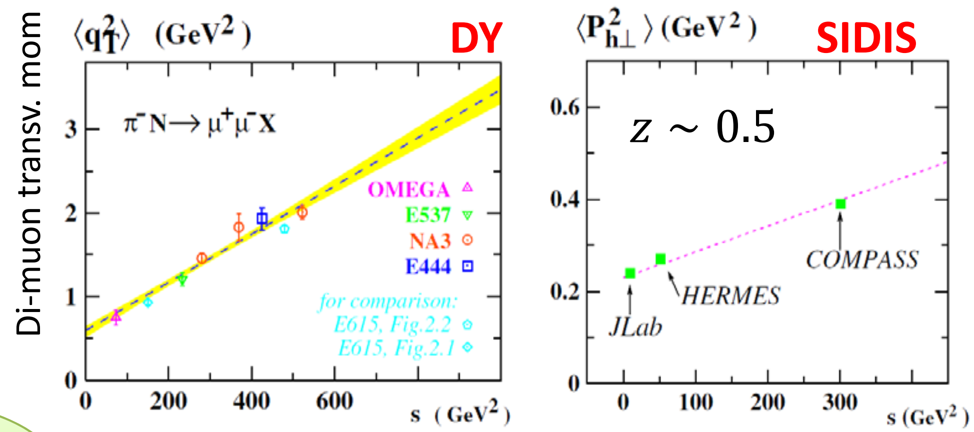


Gaussian ansatz

$$\langle P_{h\perp}^2\rangle = z^2\langle k_T^2\rangle + \langle p_T^2\rangle$$

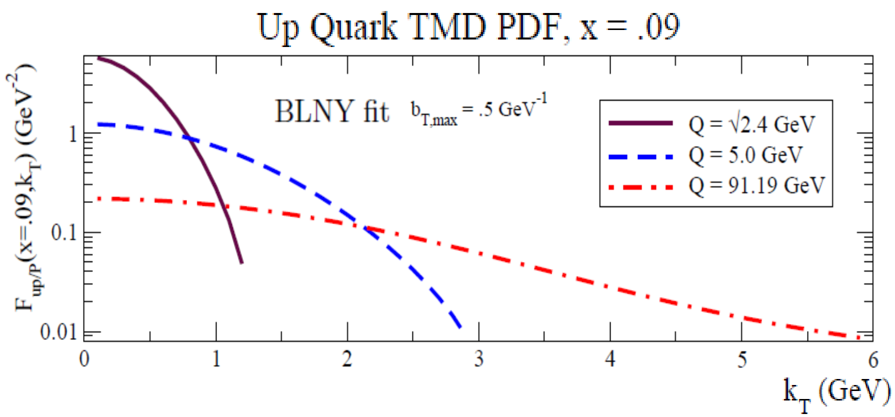
- **Hint of z-dependence**
- **Hint of flavour dependence**
- **Q^2-dependence**

P. Schweitzer, T. Teckentrup, A. Metz, PRD81(10)



Transverse-momentum broadening in SIDIS & DY

Available data suggest that intrinsic p_T in $f_1(x, p_T)$ are compatible in SIDIS and DY → **universality!**



S.M. Aybat & T.C. Rogers arXiv: 1101.5057v2

"QCD evolution has a strong quantitative effect on TMDs"

Helicity TMDs

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\Big]$$

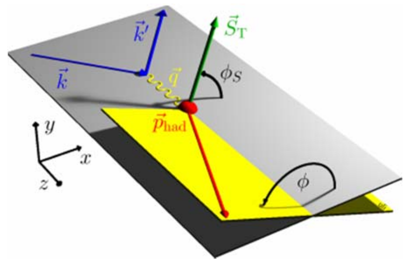
$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{LU}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\Big(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$



Describes probability to find longitudinally polarized quarks in a longitudinally polarized nucleon

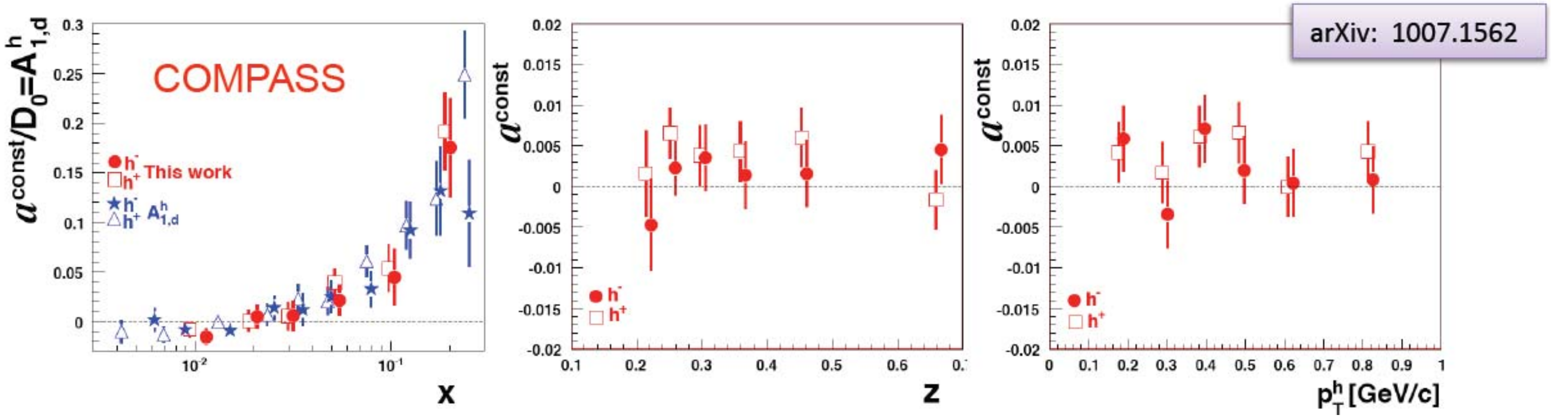
Distribution Functions

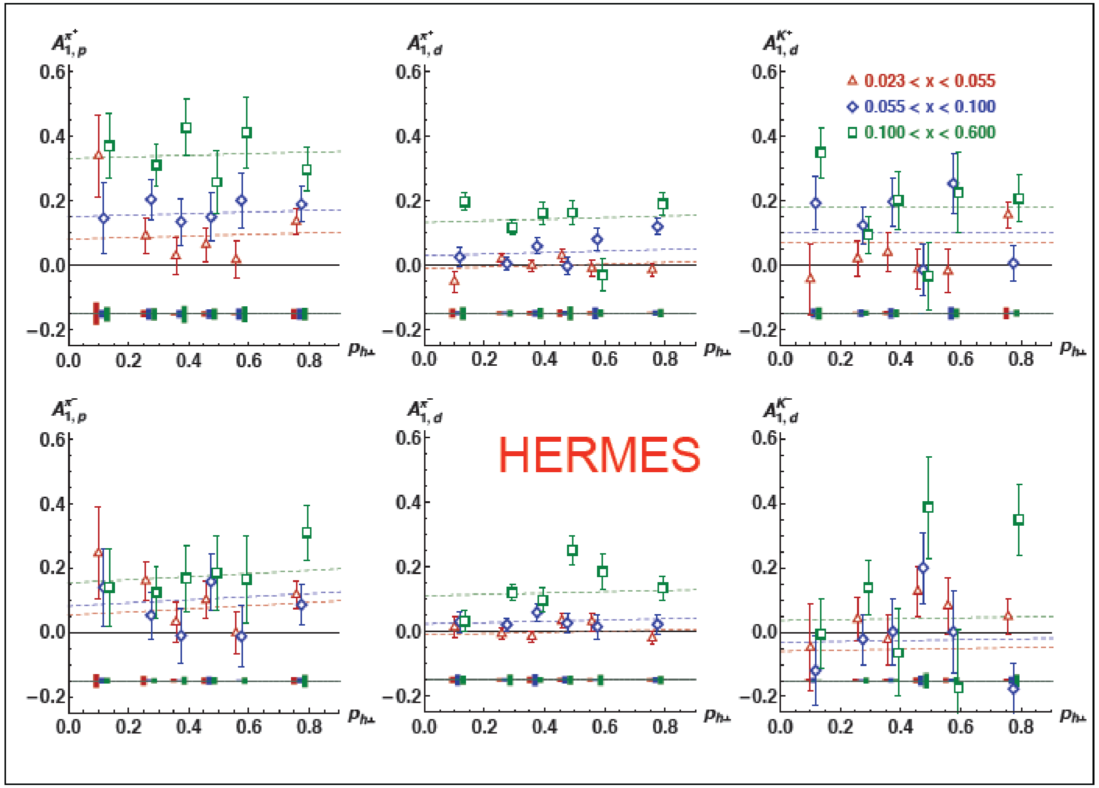
nucleon \ quark		U	L	T
nucleon	U	f_1		$h_1^\perp$ -
	L		g_1 -	$h_{1L}^\perp$ -
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

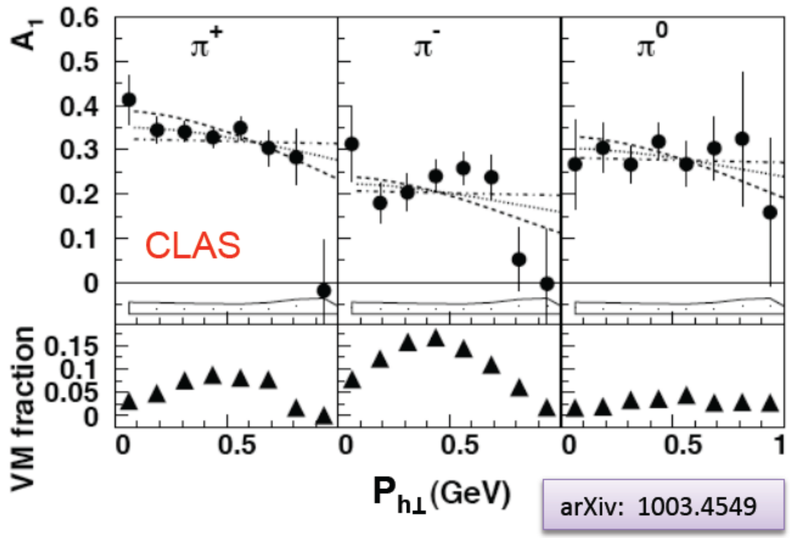
Fragmentation Functions

		U	L	T
h	U	D_1		$H_1^\perp$ -

Helicity TMDs: $P_{h\perp}$-unintegrated A_{LL} DSAs







Only a weak dependence on $P_{h\perp}$ is observed

Higher-twist

$$\sigma_{LU}^{\sin(\varphi)} \propto [e \otimes H_1^{\perp} + g^{\perp} \otimes D_1 + \ldots]/Q$$

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\Big]$$

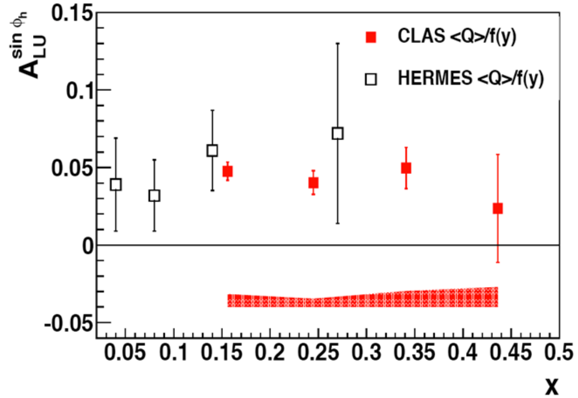
$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{LU}^{\sin(\phi)}\Big]$$

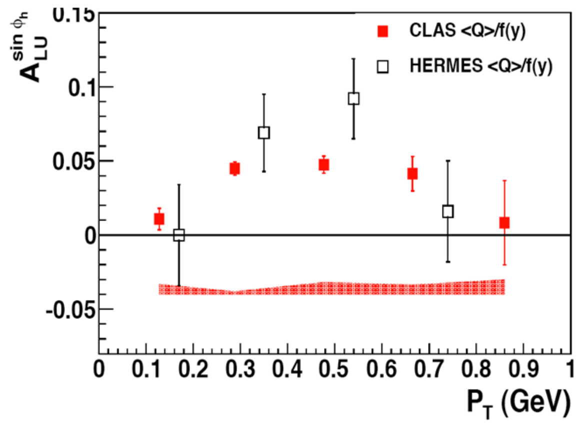
$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\Big]$$

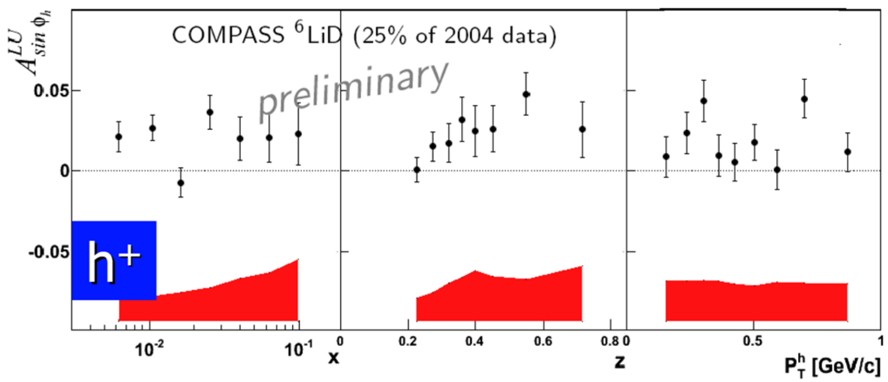
$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]$$







Higher-twist

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{\mathrm{UU}}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

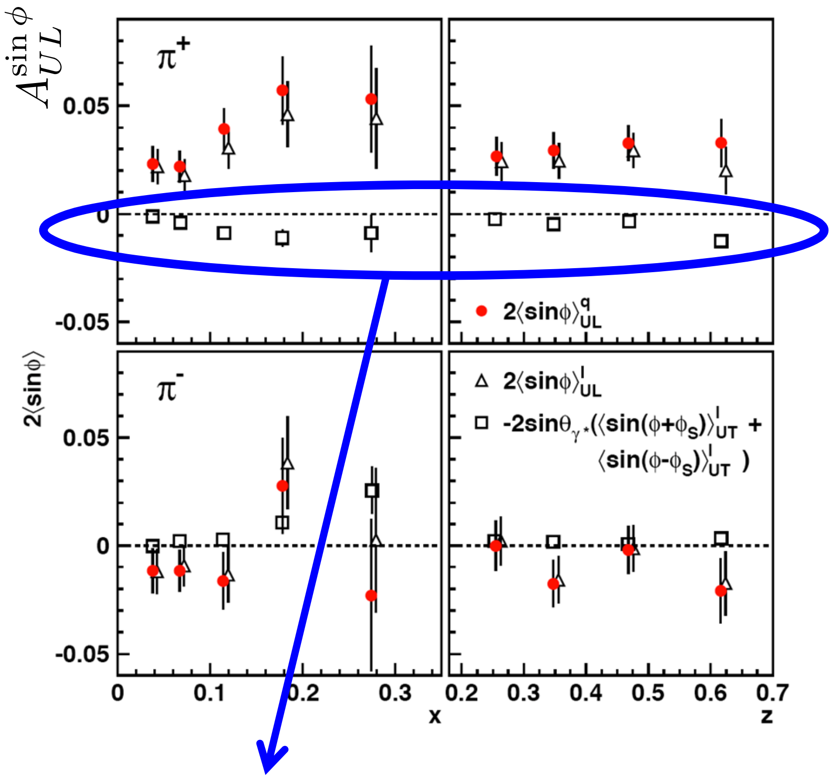
$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{\mathrm{UL}}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)}$$
$$+ \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

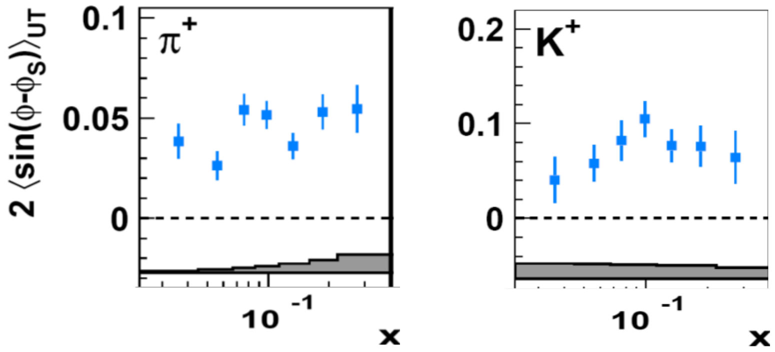
$$\sigma_{UL}^{\sin(\varphi)} \propto [h_L \otimes H_1^{\perp} + f_L^{\perp} \otimes D_1 + \ldots]/Q$$

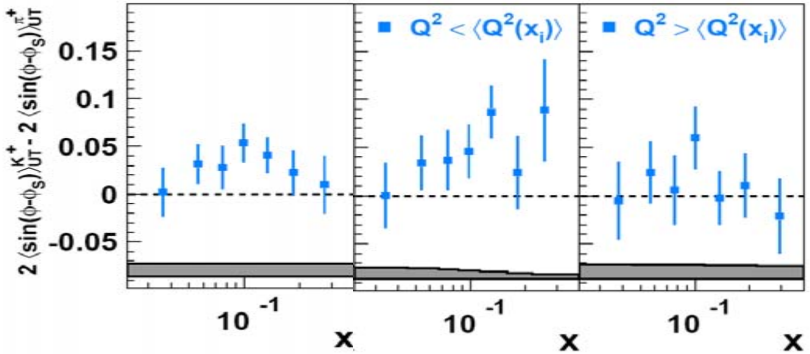


Collins and Sivers contributions are small
→ **Measured asymmetry is a genuine higher-twist effect**

Sivers kaons amplitudes: open questions

π^+/K^+ production dominated by u-quarks, but:

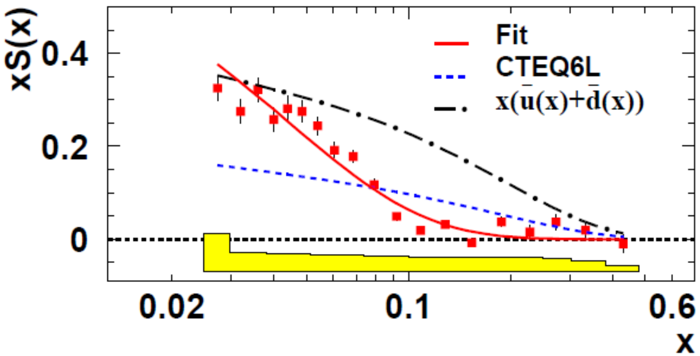


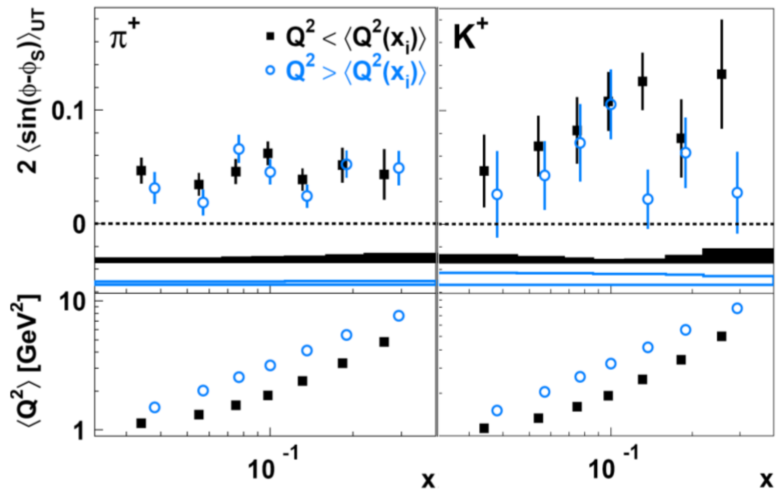


only in low-Q^2 region significant (90% C.L.) deviation is observed

$$\pi^+ \equiv |u\bar{d}\rangle,\ K^+ \equiv |u\bar{s}\rangle \ \rightarrow$$

different role of various sea quarks ?

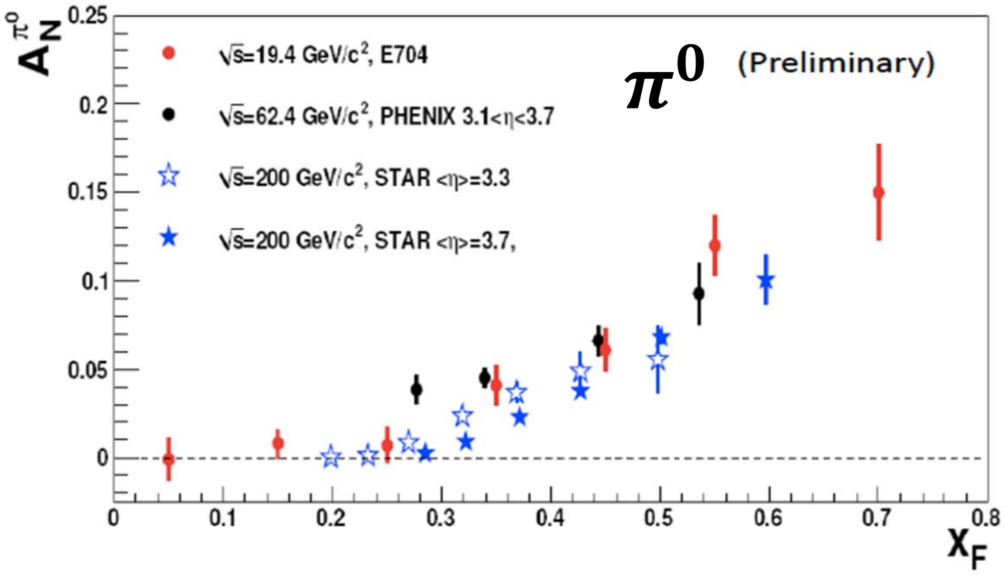


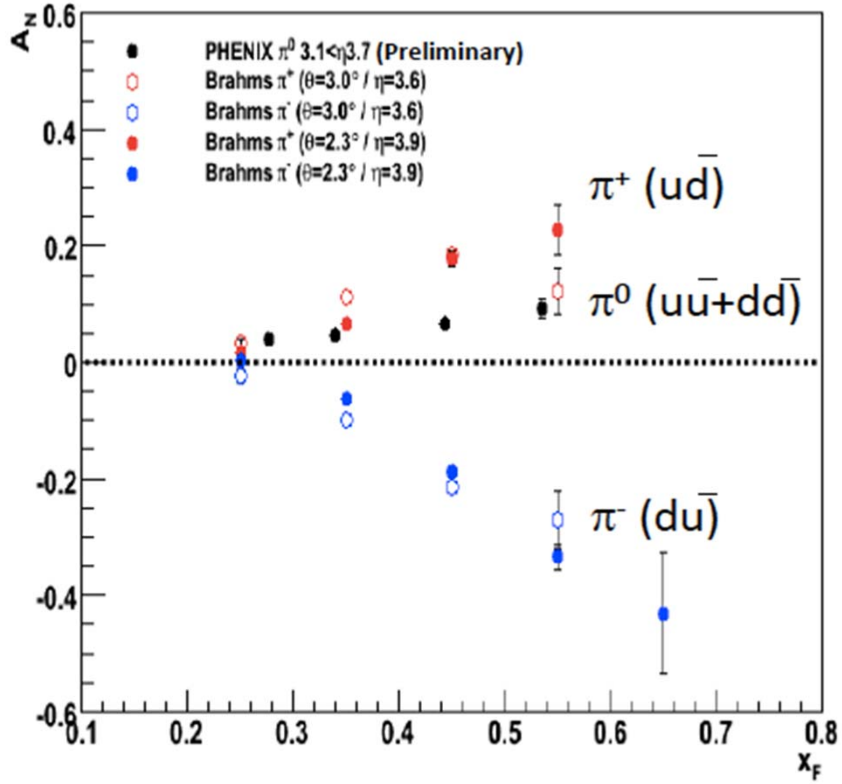


impact of different k_T dependence of FFs in the convolution integral

Each x-bin divided into two Q2 bins
Higher-twist contrib. for kaons?

Transversity & Sivers in pp scattering: RHIC





- **Large asymmetries measured by STAR, PHENIX and BRAHMS**
- No strong dependence on $\sqrt{s}$ from 19.4 to 200 GeV
- Spread of data probably due to different acceptance in pseudorapidity and/or p_T
- **Could be due to admixture of Transversity, Sivers and Twist-3 effects**