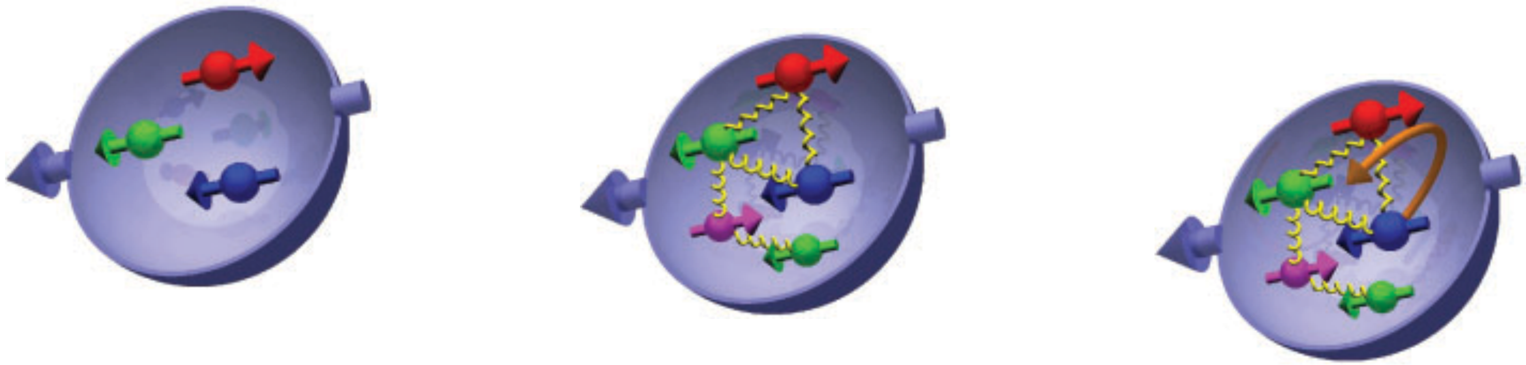
Status of polarized structure functions

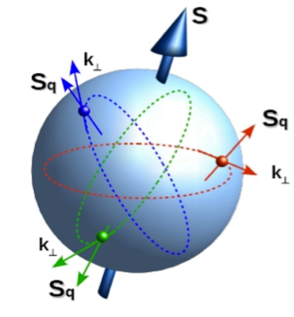
C. Marchand, CEA Saclay



- **Polarized structure functions in longitudinal momentum space: quark and gluon helicities from inclusive, semi-inclusive DIS and pp**

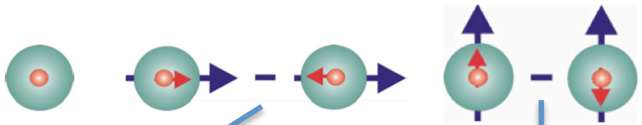
- **Transverse momentum dependent (TMD) distribution functions and relation to OAM from SIDIS, e^+e^- and pp**

The spin of the nucleon

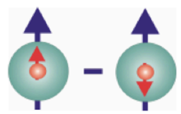


Three twist-2 quark DF's in collinear approximation ($\int dk_\perp$)

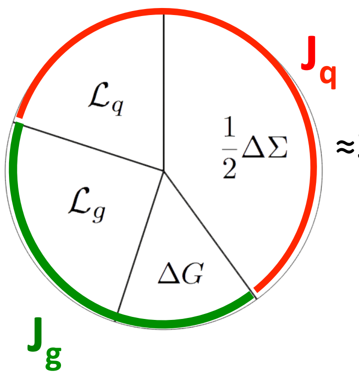
$$\Phi_{Coll}^{Tw-2}(x) = \frac{1}{2}\left\{ q(x) + S_L \gamma_5 \Delta q(x) + S_T \gamma_5 \gamma^1 \Delta_T q(x) \right\} n^+$$



helicity **transversity**

q(x) $f_1^q(x)$	
Δq(x) $g_1^q(x)$	
Δ_Tq(x) $h_1^q(x)$	

$$\frac{S_z^N}{\hbar} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$



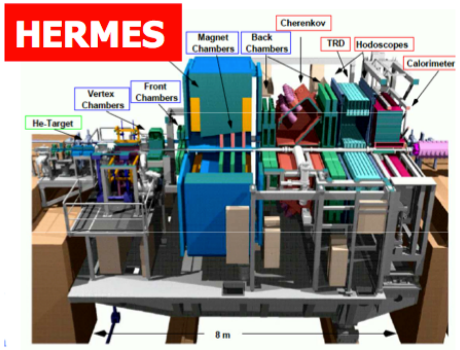
≈30% : **Spin puzzle**

NR limit
[boost, rotat.]=0

➡ $\Delta_T q(x,Q^2) = \Delta q(x,Q2)$

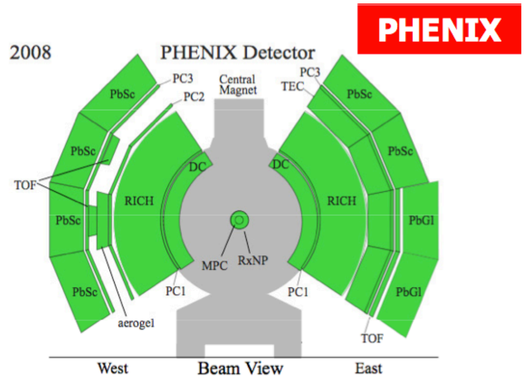
➡ Expect non small Δ_Tq

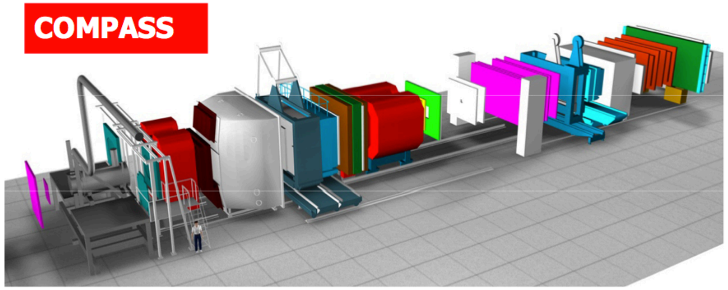
Experiments: e(µ) fixed target, pp collisions

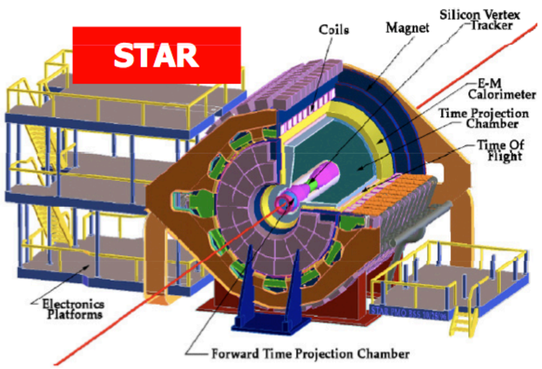


	1970	1980	1990	2000
SLAC	E80	E130	E142/3 E154/5	
CERN		EMC	SMC	COMPASS I
DESY			HERMES	
JLab				CLAS/HALL-A
RHIC				Phenix/Star

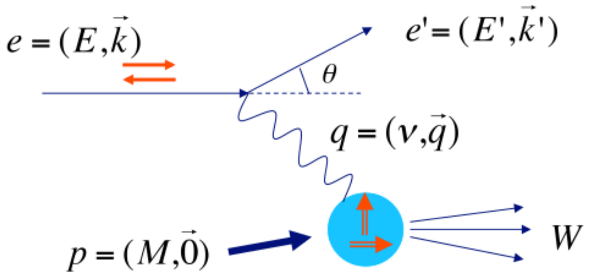
- A worldwide effort since decades







Inclusive DIS polarized structure functions



$$A_{\parallel} = A_{LL} = \frac{1}{P_b P_T f}\frac{\overrightarrow{N} - \overleftarrow{N}}{\overrightarrow{N} + \overleftarrow{N}}$$

$$A_{\perp} = A_{LT} = \frac{1}{P_b P_T f}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

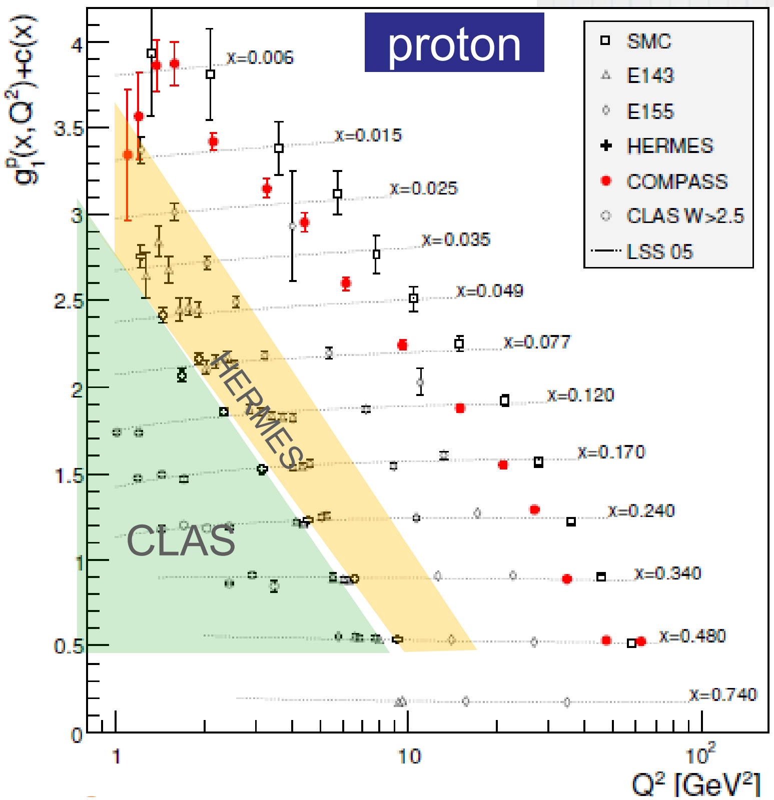
$$A_{\parallel} = D(A_1 + \eta A_2)$$

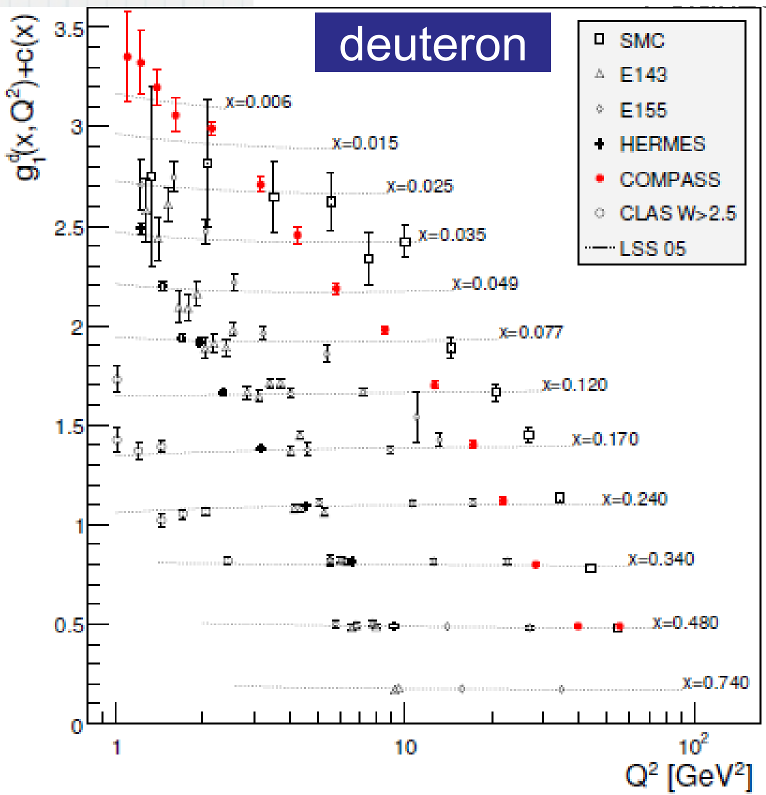
$$A_{\perp} = d(A2 - \xi A1)$$

$$A_1 = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1}$$

$$A_2 = \frac{2\sigma^{LT}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \gamma\,\frac{g_1 + g_2}{F_1}\,.$$

$$g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2 \Delta q(x,Q^2)$$





Inclusive DIS: extraction of quark and gluon helicities

$$g_1^p = \frac{1}{2}\left[\frac{4}{9}\left(\Delta u + \Delta\bar{u}\right) + \frac{1}{9}\left(\Delta d + \Delta\bar{d}\right) + \frac{1}{9}\left(\Delta s + \Delta\bar{s}\right)\right]$$

$$g_1^d = \frac{1}{2}\left[\frac{1}{9}\left(\Delta u + \Delta\bar{u}\right) + \frac{4}{9}\left(\Delta d + \Delta\bar{d}\right) + \frac{1}{9}\left(\Delta s + \Delta\bar{s}\right)\right]$$

$$Singlet : \Delta\Sigma = \left[(\Delta u + \Delta\bar{u}) + +(\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s})\right]$$

$$NS : \Delta q_3 = \left[(\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d})\right]$$

$$NS : \Delta q_8 = \left[(\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) - 2(\Delta s + \Delta\bar{s})\right]$$

$\int g_1 dx$ $\quad \Gamma_1^p = \int_0^1 g_1^p(x)dx;\ \Gamma_1^d = \int_0^1 g_1^p(x)dx$

➡ **Moments** $\Gamma_1^p - \Gamma_1^d = \frac{a_3}{6}(1 + \alpha^2 corr)\ \ (Bjorken\ SR)$

+

$a_3 = \Delta\Sigma_u - \Delta\Sigma_d = F + D = 1.267,$

$a_8 = \Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s = 3F - D \approx 0.58$

from neutron and hyperon decays

$6(\Gamma_1^p - \Gamma_1^n)/(1+\alpha^2\ corr) = 1.28 \pm 0.07 \pm 0.10$

$\Delta\Sigma = a_0 = 0.33 \pm 0.03 \pm 0.05$ (evol. to $Q^2 = \infty$)

$(\Delta s + \Delta\bar{s}) = 1/3(a_0 - a_8) = -0.08 \pm 0.01 \pm 0.02$

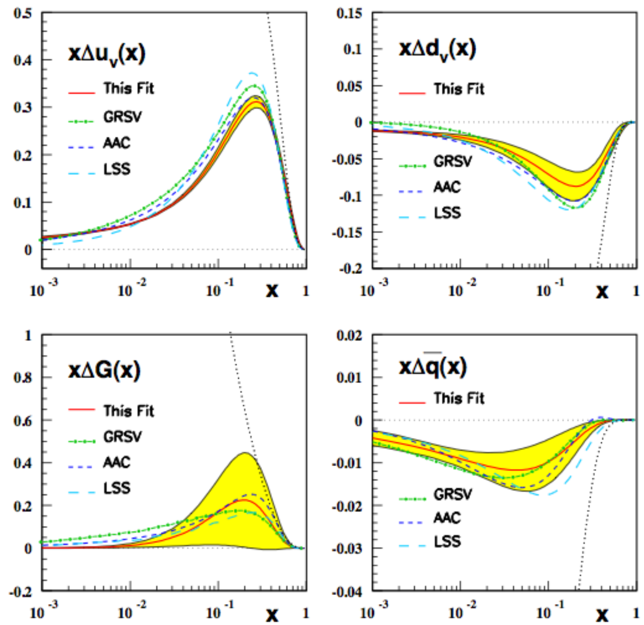
Compass

NLO: DGLAP links q and g

$$\frac{d}{d\ln Q^2}\Delta q_{NS}(x, Q^2) = \frac{\alpha_S(Q^2)}{2\pi} P_{qq}^{NS} \otimes \Delta q_{NS}$$

$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix} = \frac{\alpha_S(Q^2)}{2\pi}\begin{pmatrix}Pqq & P_{qg} \\ P_{gq} & P_{gg}\end{pmatrix} \otimes \begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix}$$

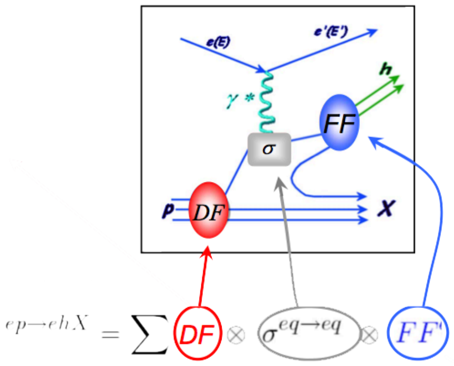
Assume SU(3) flavor symmetry: $\Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s} = \Delta s$



Blümlein, Böttcher arXiv 1101.0052

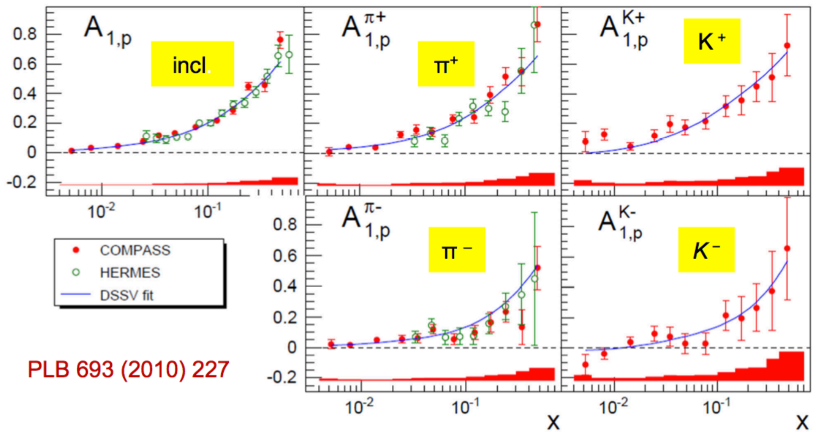
WG6: E. Nocera, A.L. Kataev

Semi-Inclusive DIS: extraction of quark helicities

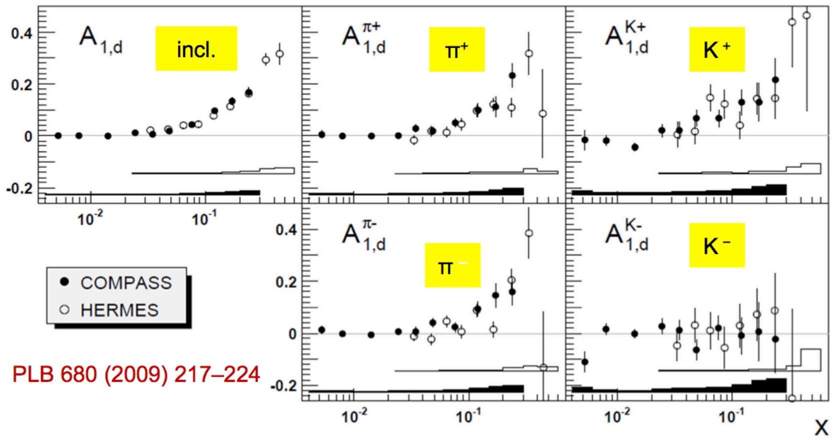


$$A_1^{h\,(p/d)}(x,z,Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}$$

- **Inputs needed for the extraction of $\Delta q(x, Q^2)$:**
  - Unpolarised PDFs ($q(x, Q^2)$) → MRST04
  - $D_q^h(z, Q^2)$ → DSS parameterisation



PLB 693 (2010) 227



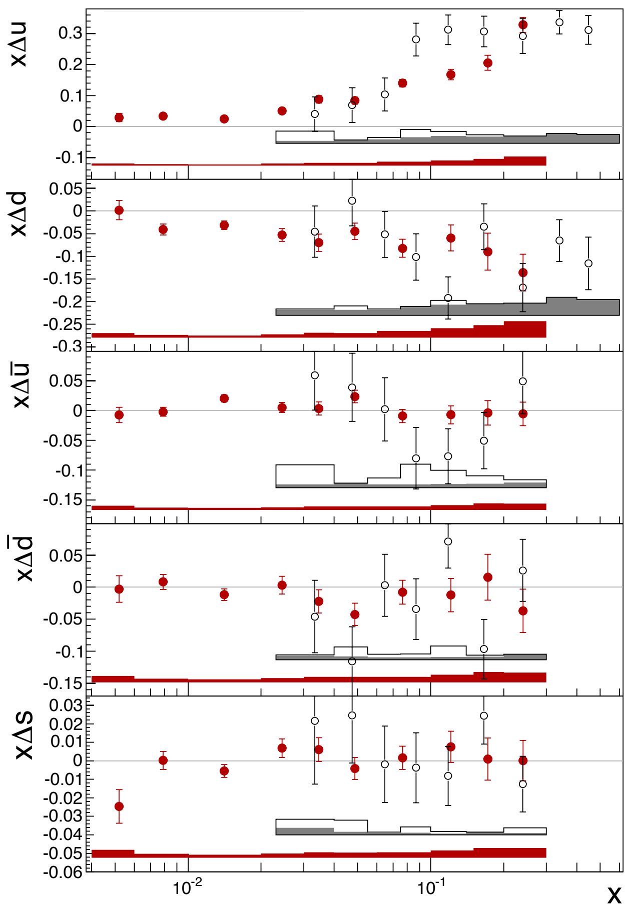
PLB 680 (2009) 217–224

Leading Order (LO) fit of the 10 asymmetries (5d+5p)

Determine 6 flavor separated PDFs $\Delta u,\ \Delta d,\ \Delta\bar{u},\ \Delta\bar{d},\ \Delta s$ and $\Delta\bar{s}$

WG6: M. Stolarski

SIDIS: direct extraction of quark helicity at LO

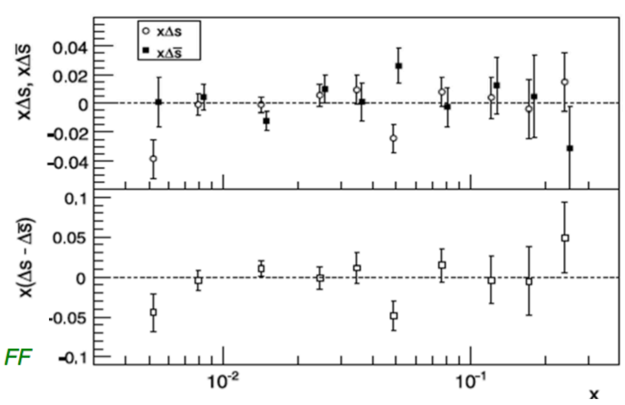


• COMPASS
PLB693(2010)227, using DSS FF
o HERMES
PRD71(2005)012003

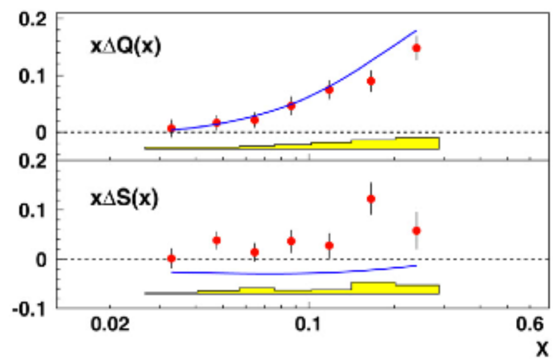
$Q^2 = 3\ GeV^2$

Check the assumption $\Delta s = \Delta\bar{s}$ (a 6 flavors fit)

COMPASS Collaboration / Physics Letters B 693 (2010) 227–235



HERMES: PLB666(2008)446

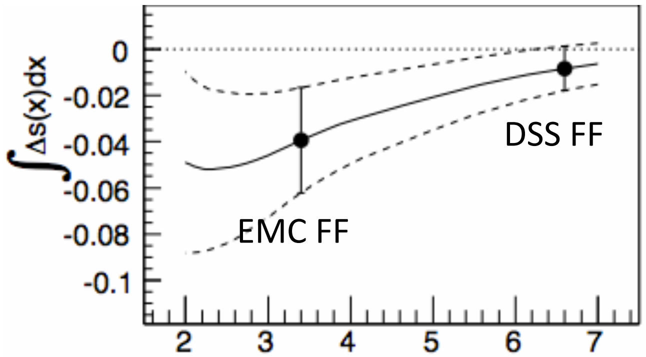


HERMES $\Delta s+\Delta\bar{s}$=0.037 ± 0.019 (stat) ± 0.027 (syst)
COMPASS Δs = - 0.01 ± 0.01 (stat) ± 0.01 (syst), 0.003<x<0.3

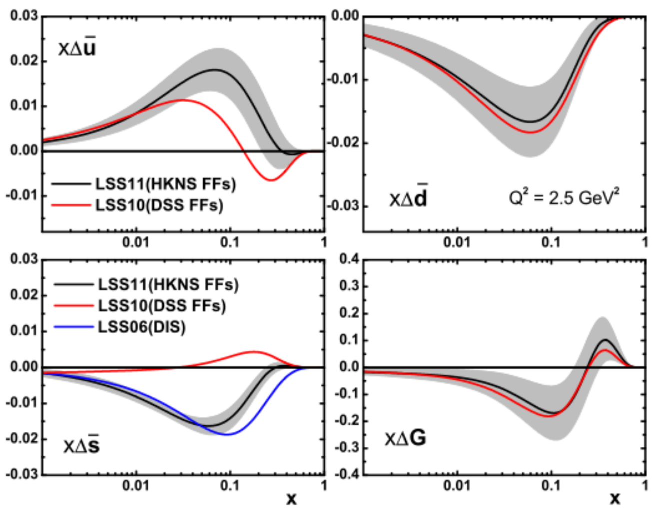
DIS: $(\Delta s+\Delta\bar{s})$ = -0.08 ± 0.01 ± 0.02

Sensitivity of strange quark helicity to FF

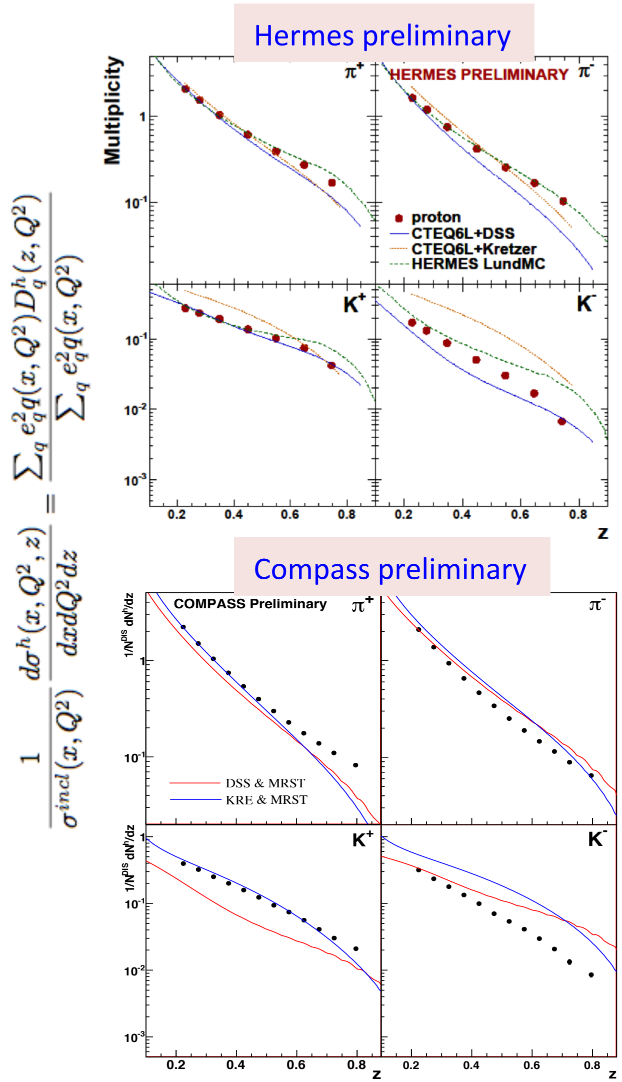
Compass PLB 693 (2010)



$$R_{SF} = D_{\bar{s}}^{K^+} / D_u^{K^+}$$



LSS 1103.5979



LO interpretation

- OK with CTEQ6 pdfs + DSS FF for π^+ and K^+
- OK with CTEQ6 pdfs + Kretzer FF for π^+ and π^-
- poor agreement for K^-

○ Role of unfavored FF
○ Role of NLO term for negative particles

WG4: N. Makke

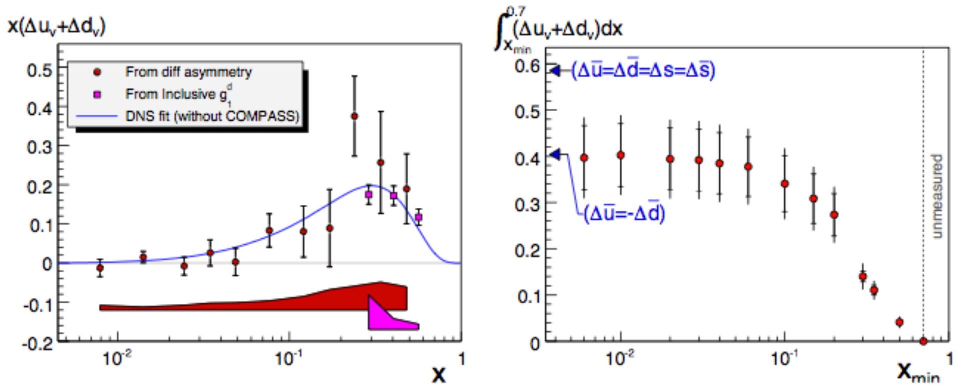
Polarized valence: difference asymmetries SIDIS

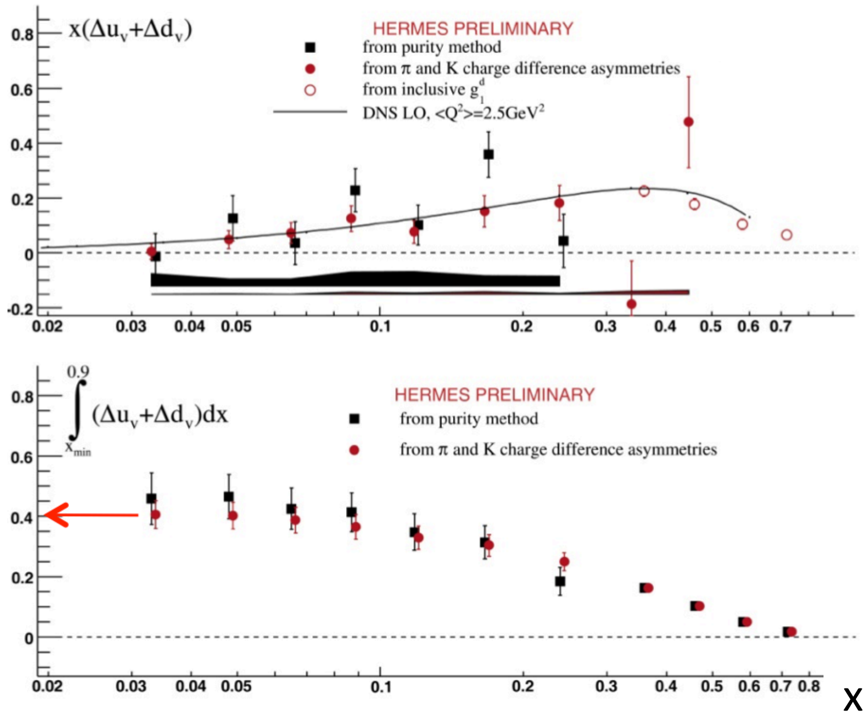
With charge conjugation symmetry in fragmentation $D_{1,q}^{h+} = D_{1,\bar{q}}^{h-}$

$$A_{1d}^{h^+ - h^-} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}(x)$$

K. Rith, Hera Symposium'11

Compass d, PLB 660 (2008) 458





$$\Delta q_v = \Delta q - \Delta\bar{q}$$

$$\Gamma_v = \int_0^1 (\Delta u_v + \Delta d_v)dx = \Sigma_u + \Sigma_v - 2(\Delta\bar{u} + \Delta\bar{d})$$

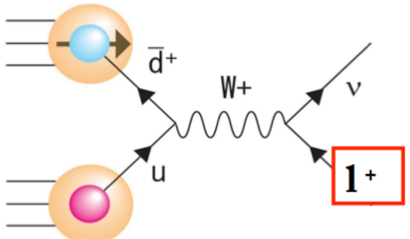
$$a_8 = \Sigma_u + \Sigma_v - 2(\Delta s + \Delta\bar{s})$$

WG6: P. Kravchenko

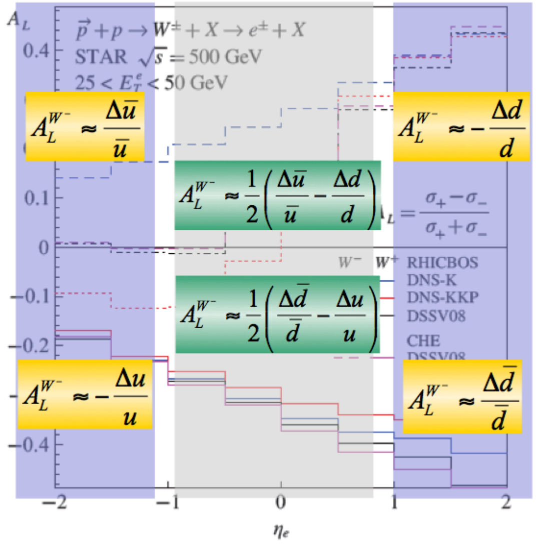
Polarized sea: parity violating W decay

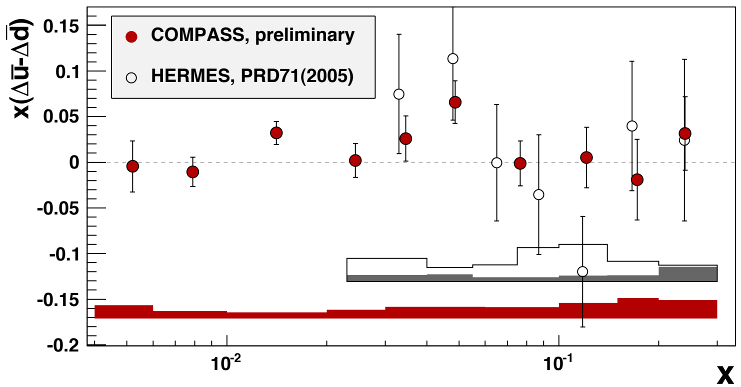
p+p → W± → e±/μ± + ν

- **Parity violating W production:**
  - Fixes quark helicity and flavor
- **No fragmentation involved**
- High Q^2 (set by W mass)



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

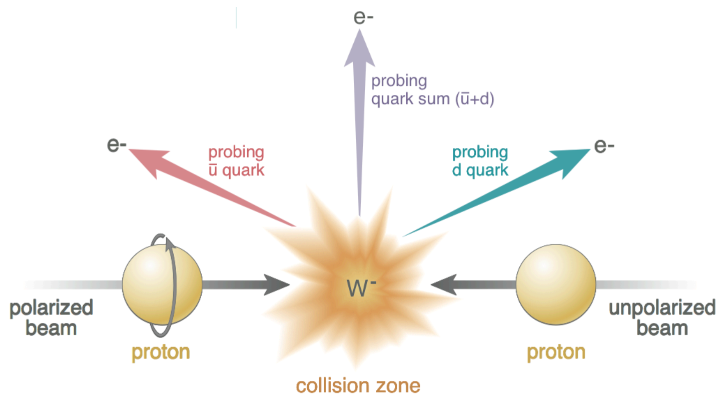




COMPASS @Q^2=3(GeV/c)² : $\int_{0.004}^{0.3}(\Delta\bar{u}-\Delta\bar{d})dx = 0.052 \pm 0.035(\text{stat}) \pm 0.013(\text{syst})$

HERMES @ Q^2=2.5(GeV/c)²: $\int_{0.023}^{0.6}(\Delta\bar{u}-\Delta\bar{d})dx = 0.048 \pm 0.057(\text{stat}) \pm 0.028(\text{syst})$

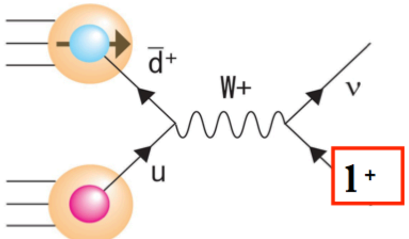
Unpolarized: $\int(\bar{u}-\bar{d})dx = -0.118 \pm 0.012$



Polarized sea: parity violating W decay

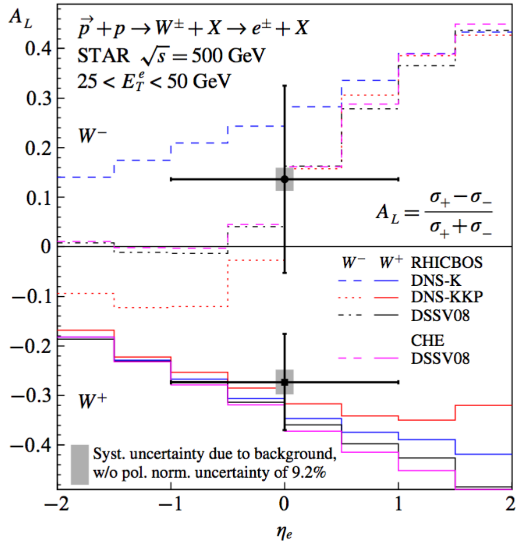
$p + p \rightarrow W^{\pm} \rightarrow e^{\pm}/\mu^{\pm} + \nu$

- **Parity violating W production:**
  - Fixes quark helicity and flavor
- **No fragmentation involved**
- High Q^2 (set by W mass)



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

Present status

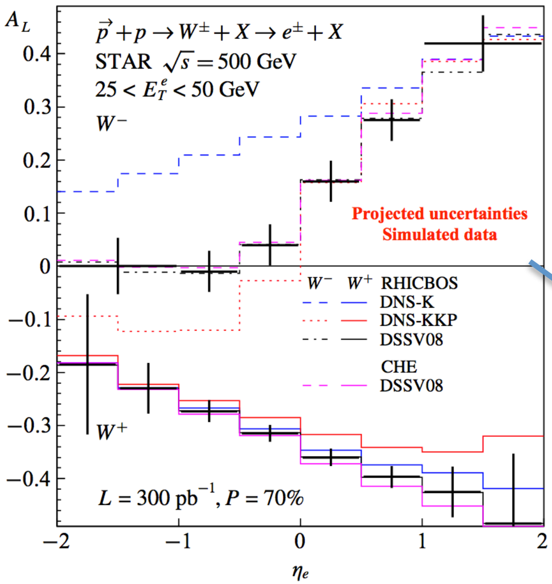


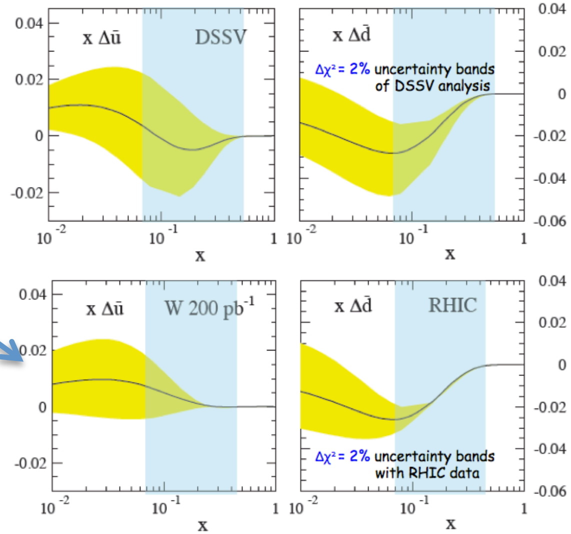
STAR Run 9 Result

$$A_L(W^+) = -0.27 \pm 0.10(stat) \pm 0.02(syst)$$
$$A_L(W^-) = 0.14 \pm 0.19(stat) \pm 0.02(syst)$$

PRL **106**, 062002 (2011)

Projected errors for future

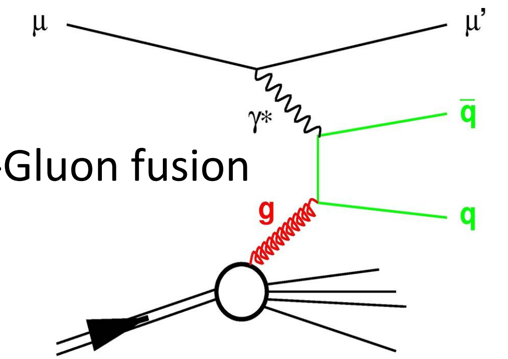




WG6: B. Surrow, Y.J. Kim

Direct measurements of DeltaG/G: Open charm (NLO)

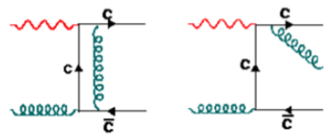
Photon-Gluon fusion



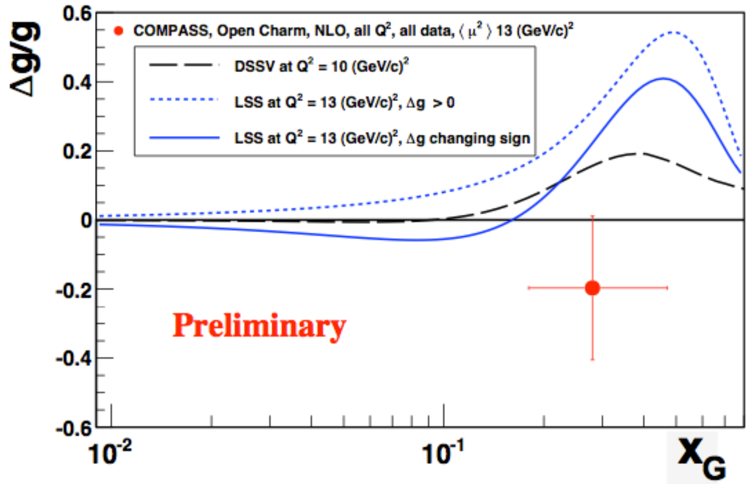
$$A_{LL}^{\mu N(LO)} = R^{PGF} a_{LL}^{PGF} \frac{\Delta g}{g}(x)$$

- **Open Charm production**
  - $\gamma^* g \rightarrow c\bar{c} \;\; \Rightarrow$ reconstruct D^0 mesons
  - Hard scale: $M_c^{\,2}$
  - No intrinsic charm in COMPASS kinematics
  - No physical background
  - Weakly Monte Carlo dependent
  - Low statistics

NLO



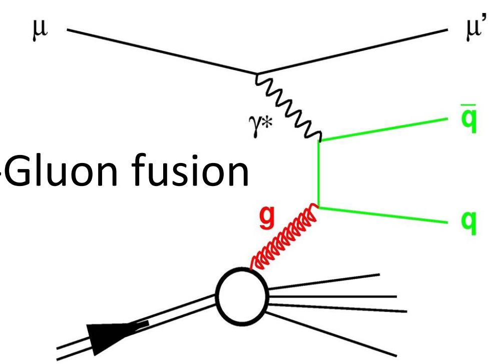
- First extraction of **ΔG at NLO**
- **Constrains ΔG at larger x**
- **Charm result can be included in global NLO fits:** model independent asymmetries $A_{LL}(p_T, E_D)$ available



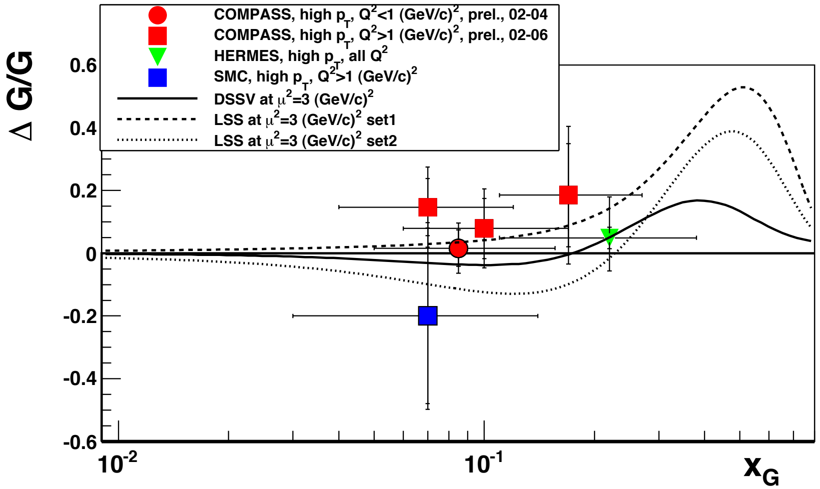
WG6: M. Stolarski

Direct measurements of DeltaG/G: High pT (LO)

Photon-Gluon fusion

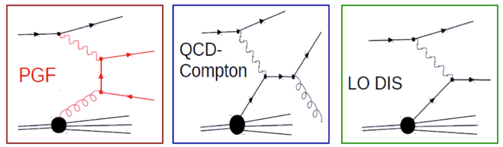


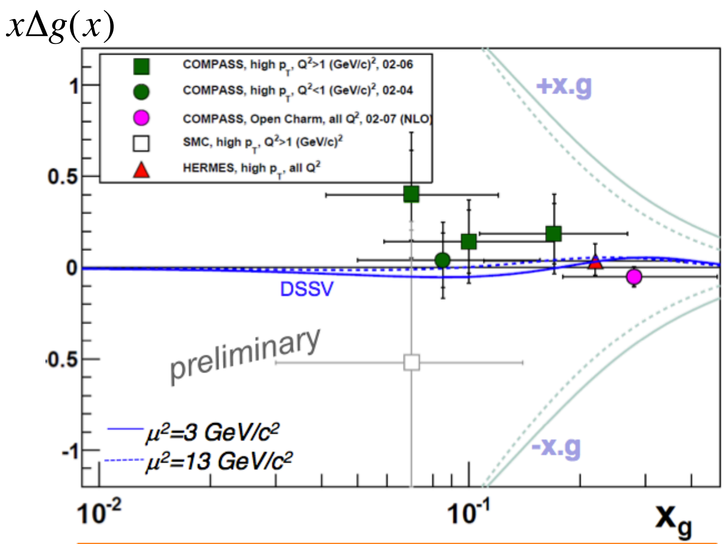
$$A_{LL}^{\mu N(LO)} = R^{PGF} a_{LL}^{PGF} \frac{\Delta g}{g}(x) + ...$$



DSSV: D. de Florian et al., Phys. Rev. D80(2009)034030
LSS: E. Leader, A.V. Sidorov, D.B. Stamenov, arXiv 1010.5742(2010)

- **High-p_T hadron pairs**
  - $\gamma^* g \rightarrow q\bar{q} \Rightarrow$ reconstruct 2 jets or h^+h^-
  - Hard scale: Q^2 or Σp_T^2 [$Q^2 > 1$ or $Q^2 < 1$ (GeV/c)^2]
  - High statistics
  - Physical background
  - Strongly Monte Carlo dependent



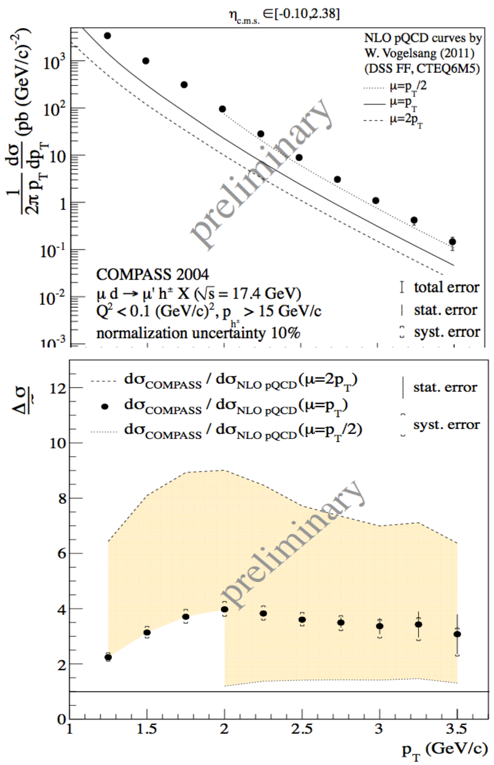


Charm at NLO, all other points at LO

DeltaG/G from hig pT: validity of NLO

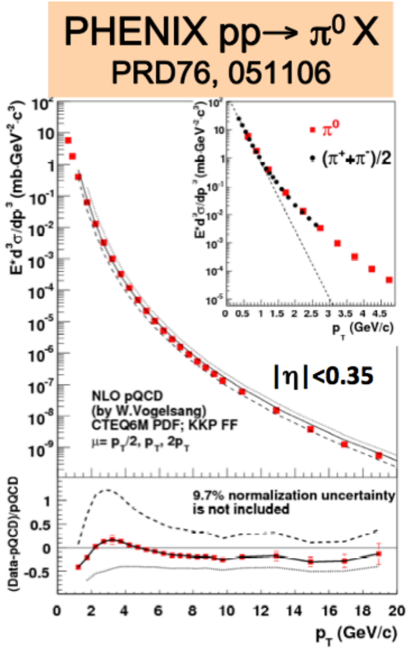
Unpolarized X-section as function of pT

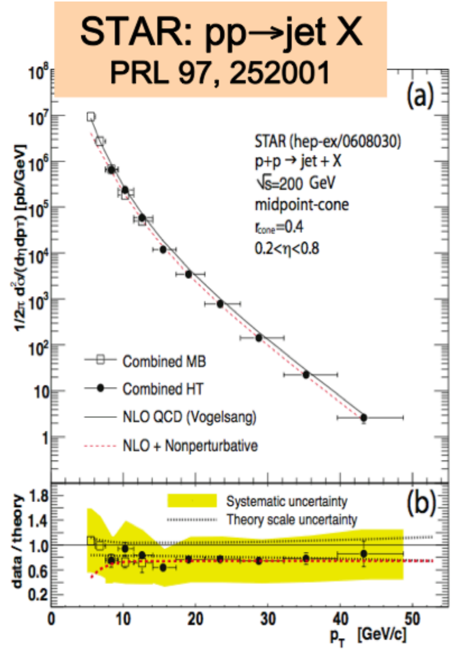
COMPASS <√s>=17 GeV

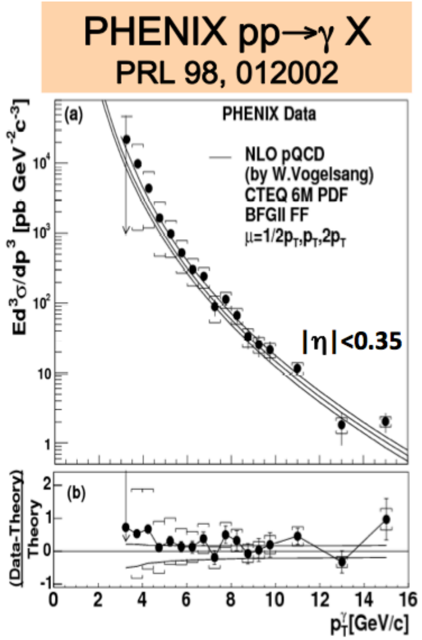


WG6: C. Hoeppner
M. Pfeuffer

RHIC √s = 200 Gev

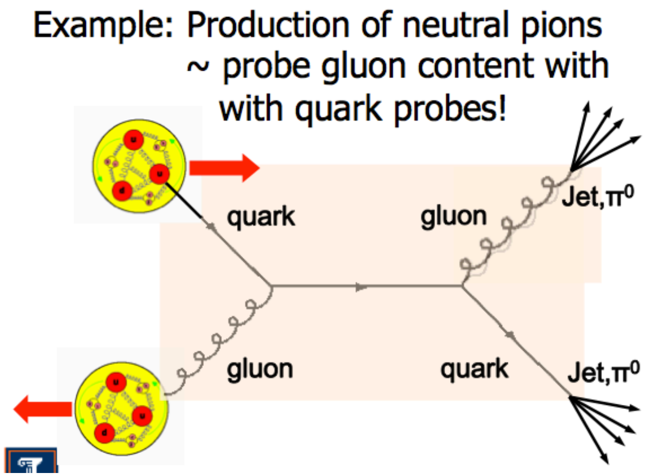






- CERN, HERMES data not included in NLO global fits yet
- RHIC CM energies OK for applicability of NLO to A_{LL}(pT)

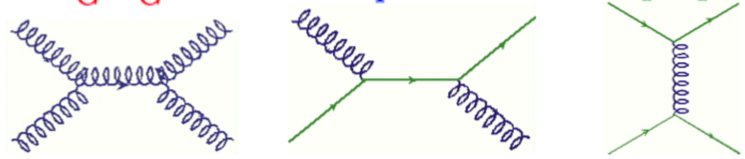
Direct measurements of DeltaG/G with pp->jets

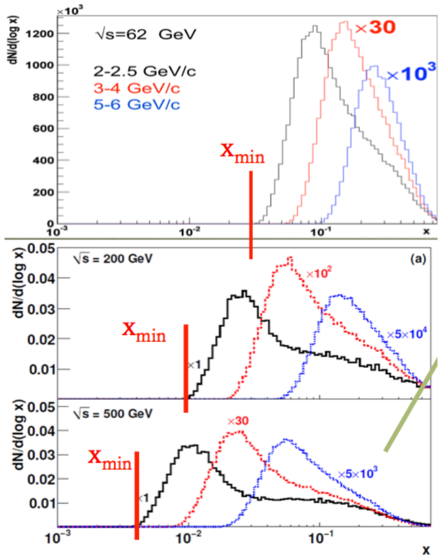


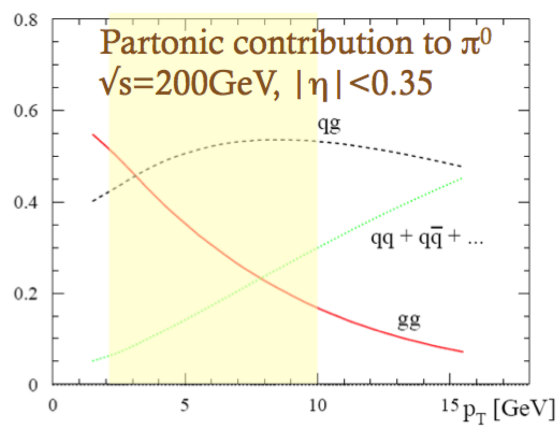
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Δf: polarized parton distribution functions

$\frac{\Delta G}{G}\frac{\Delta G}{G}$ $\frac{\Delta q}{q}\frac{\Delta G}{G}$ $\frac{\Delta q}{q}\frac{\Delta q}{q}$

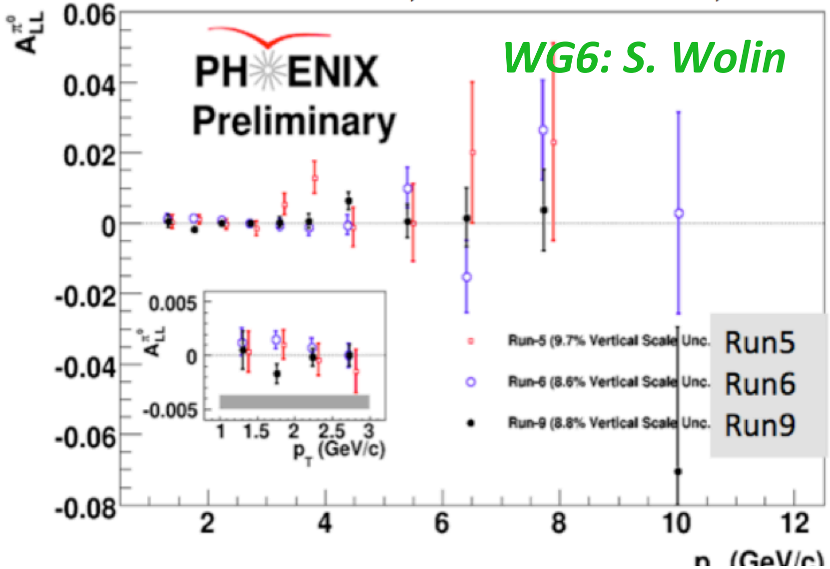




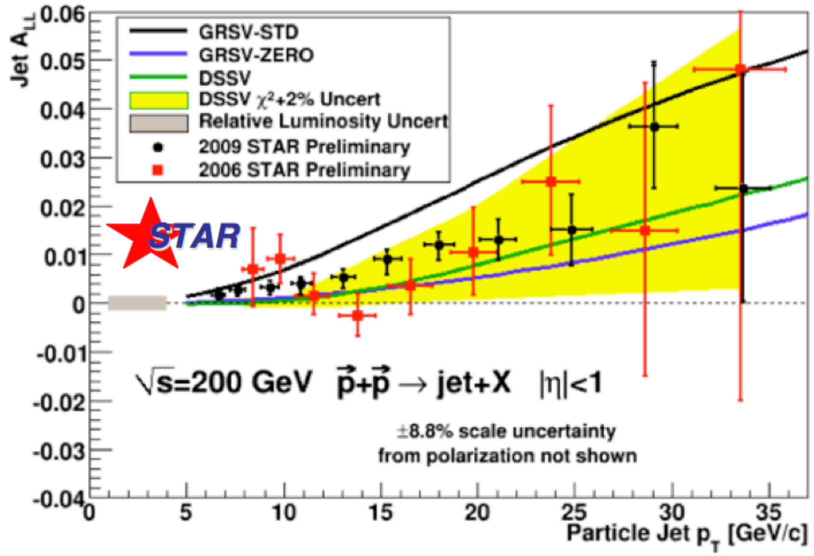


Direct measurements of DeltaG/G with pp-> jets

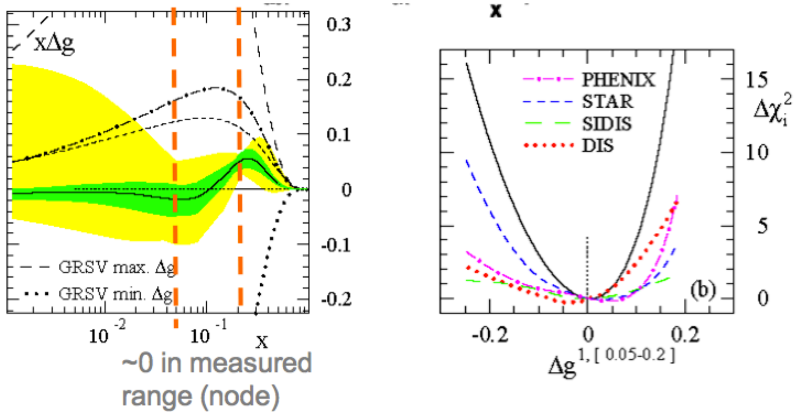
Kensuke Okada, for the PHENIX collaboration, DIS2011



Pibero Djawotho, for the STAR collaboration, DIS2011

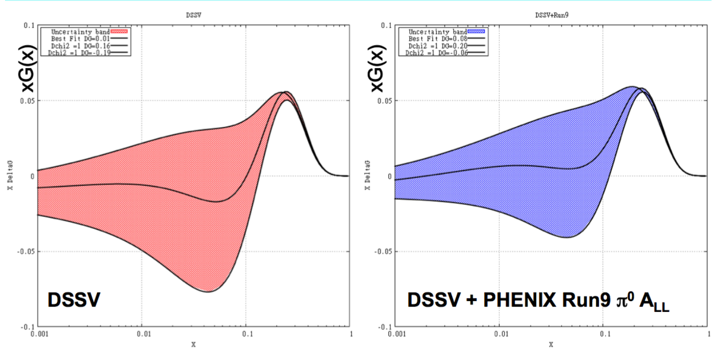


DSSV Phys. Lett. 101 (2008)



Global Fit Including PHENIX Run9 π^0 A_{LL}

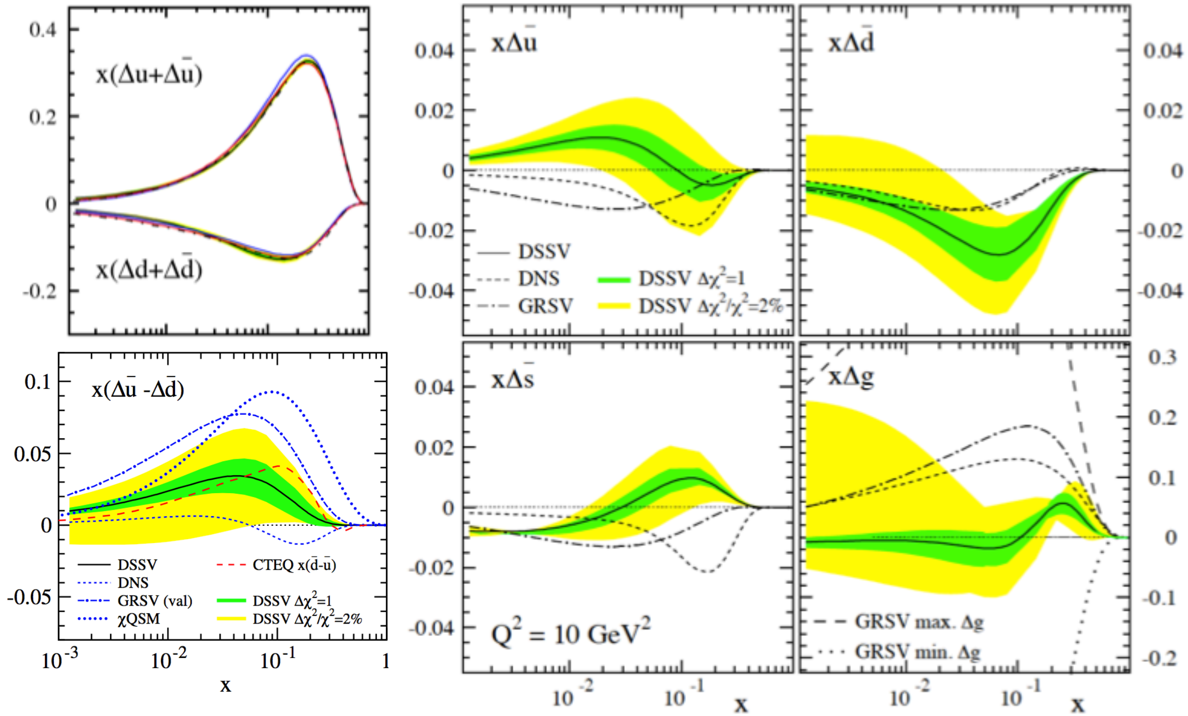
By S.Taneja et al (DIS2011) based on code from DSSV



$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.005^{+0.051}_{-0.058} (\Delta\chi^2 = 1); \int_{0.05}^{0.2} \Delta g(x)\,dx = 0.005^{+0.129}_{-0.164} (\Delta\chi^2/\chi^2 = 2\%)$$

DIS+SIDIS+pp: global fit to extract q and g helicity

DSSV Phys. Lett. 101 (2008)



Experiment	Process	N_{data}	χ^2
EMC [2]	DIS (p)	10	3.9
SMC [3]	DIS (p)	12	3.4
SMC [3]	DIS (d)	12	18.4
COMPASS [4]	DIS (d)	15	8.1
E142 [5]	DIS (n)	8	5.6
E143 [6]	DIS (p)	28	19.3
E143 [6]	DIS (d)	28	40.8
E154 [7]	DIS (n)	11	4.5
E155 [8]	DIS (p)	24	22.6
E155 [9]	DIS (d)	24	17.1
HERMES [10]	DIS (He)	9	6.3
HERMES [11]	DIS (p)	15	10.5
HERMES [11]	DIS (d)	15	16.9
HALL A [12]	DIS (n)	3	0.2
CLAS [13]	DIS (p)	10	5.9
CLAS [13]	DIS (d)	10	2.5
SMC [14]	SIDIS (p, h^+)	12	18.7
SMC [14]	SIDIS (p, h^-)	12	10.6
SMC [14]	SIDIS (d, h^+)	12	7.3
SMC [14]	SIDIS (d, h^-)	12	14.1
HERMES [15]	SIDIS (p, h^+)	9	6.4
HERMES [15]	SIDIS (p, h^-)	9	4.9
HERMES [15]	SIDIS (d, h^+)	9	11.4
HERMES [15]	SIDIS (d, h^-)	9	4.5
HERMES [10]	SIDIS (He, h^+)	9	4.7
HERMES [10]	SIDIS (He, h^-)	9	6.9
HERMES [15]	SIDIS (p, π^+)	9	9.6
HERMES [15]	SIDIS (p, π^-)	9	4.9
HERMES [15]	SIDIS (d, π^+)	9	9.4
HERMES [15]	SIDIS (d, π^-)	9	19.5
HERMES [15]	SIDIS (d, K^+)	9	6.2
HERMES [15]	SIDIS (d, K^-)	9	5.8
HERMES [15]	SIDIS (d, $K^+ + K^-$)	9	3.4
COMPASS [16]	SIDIS (d, h^+)	12	6.2
COMPASS [16]	SIDIS (d, h^-)	12	12.0
PHENIX [22]	pp (200 GeV, π^0)	10	14.2
PHENIX [23]	pp (200 GeV, π^0)	10	7.1 [13.8][a]
PHENIX [24]	pp (62 GeV, π^0)	5	3.1 [2.8][a]
STAR [25]	pp (200 GeV, jet)	10	8.8
STAR (prel.) [26]	pp (200 GeV, jet)	9	6.9
TOTAL:		467	392.6

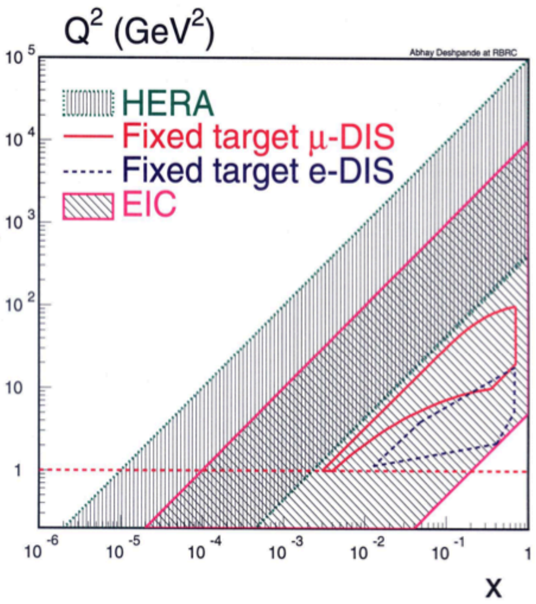
$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.005^{+0.051}_{-0.058} (\Delta\chi^2 = 1); \int_{0.05}^{0.2} \Delta g(x)\,dx = 0.005^{+0.129}_{-0.164} (\Delta\chi^2/\chi^2 = 2\%)$$

$$\int_{0}^{1} \Delta g(x)\,dx = 0.013^{+0.106}_{-0.120} (\Delta\chi^2 = 1); \int_{0}^{1} \Delta g(x)\,dx = 0.013^{+0.702}_{-0.314} (\Delta\chi^2/\chi^2 = 2\%)$$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g = 0.16 + \Delta G + L_z^q + L_z^g$$

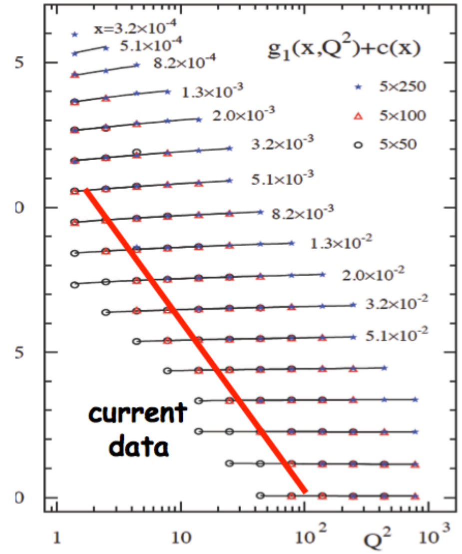
WG6: W. Vogelsang

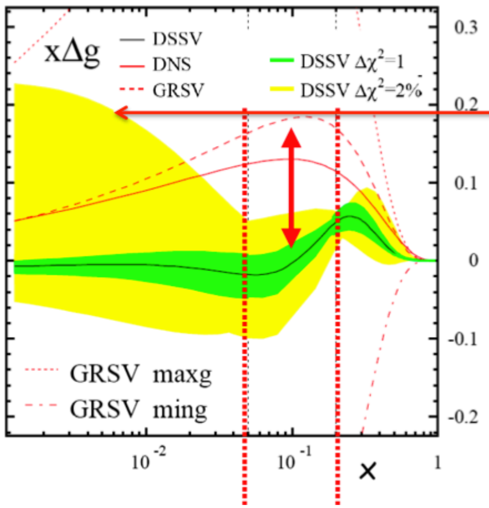
Constrain gluon helicity at future EIC

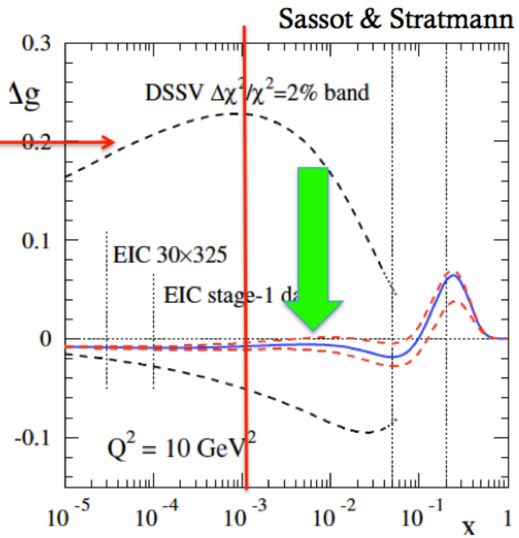


- E_e: 5-30 GeV
- E_p: 50-325 GeV
- √s: 30-200 GeV
- $x_{min} = 10^{-4}$; $Q^2_{max}=10^4$ GeV^2
- Polar: ~70% (e,p,3He,D)
- Lumi: >10^{33} cm^{-2}s^{-1}

$$\frac{dg_1(x,Q^2)}{d\ln Q^2} \propto -\Delta g(x,Q^2)$$







WG6+7: M. Stratmann

g2 structure function

$$A_2 = \frac{2\sigma^{LT}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \gamma \frac{g_1 + g_2}{F_1}$$

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2)$$

$$g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 g_1(y, Q^2)\frac{dy}{y}$$

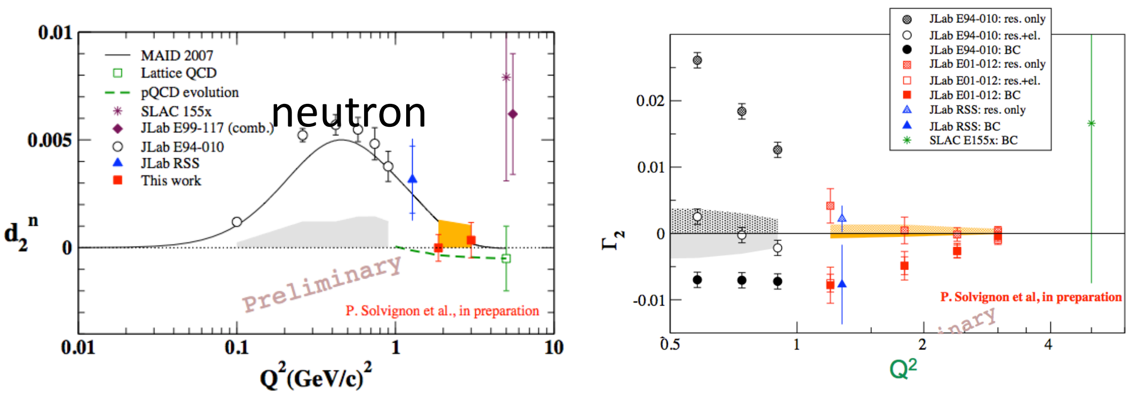
Higher TW: quark-gluon correlations

$$d_2(Q^2) = 3\int_0^1 x^2 \bar{g}_2(x, Q^2)\,dx$$

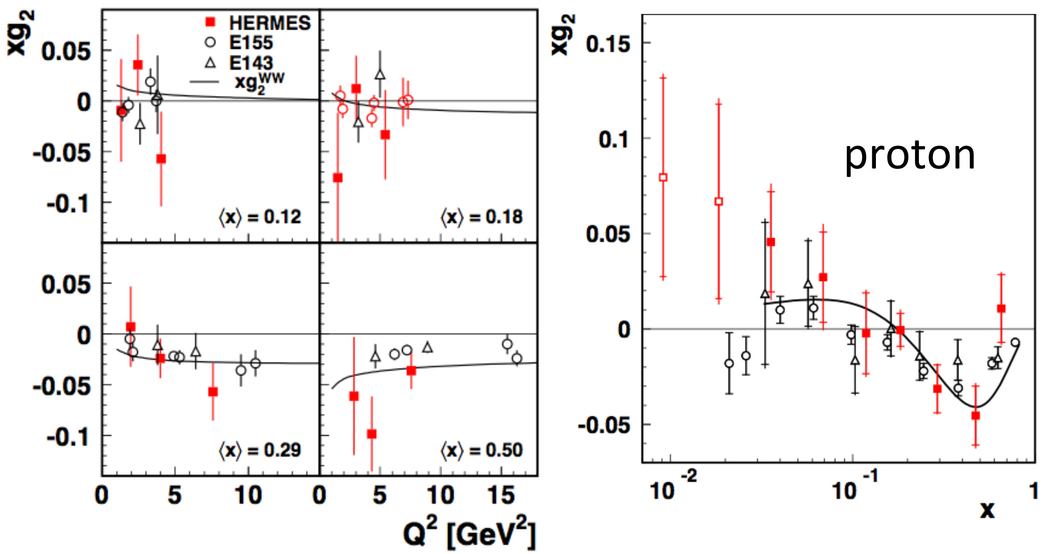
Burkhardt-Cottingham Sum Rule

$$\int_0^1 g_2(x, Q^2)dx = 0$$

JLAB Hall A



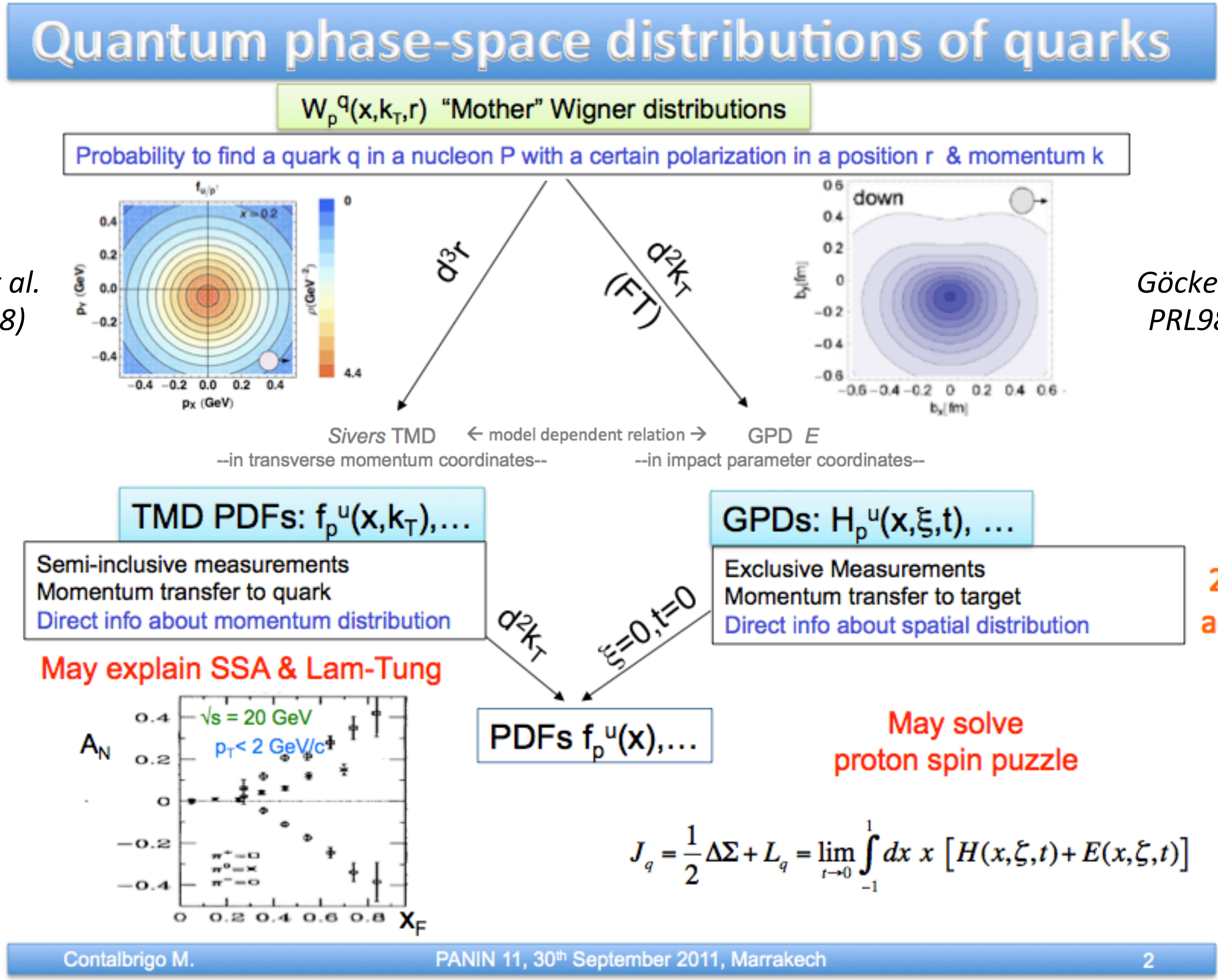
Hermes arXiv 1112.5584



$$d_2^p\left(Q^2 = 5GeV^2\right) = 0.0148 \pm 0.0096(stat) \pm 0.0048(syst)$$

$$\int_{0.023}^{0.9} g_2^p\left(x, Q^2 = 5GeV^2\right) = 0.006 \pm 0.024(stat) \pm 0.017(syst)$$

Quark distributions in nuclei: 3D picture



Transverse Momentum Dependent (TMD) DF

Twist-2 DF

N/q	U	L	T
U	f_1 Number Density		$h_1^{\perp}$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^{\perp}$ Worm-gear
T	$f_{1T}^{\perp}$ Sivers	$g_{1T}^{\perp}$ Worm-gear	h_1 Transversity $h_{1T}^{\perp}$ Pretzelosity

h1 ≠ g1 : relativistic effects and no mix with gluons in spin ½ nucleon

Survive k_T integration

Twist-3 DF

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

Sivers & BM: Naive T-odd elements:
-contain information about OAM
-sign change between SIDIS and DY

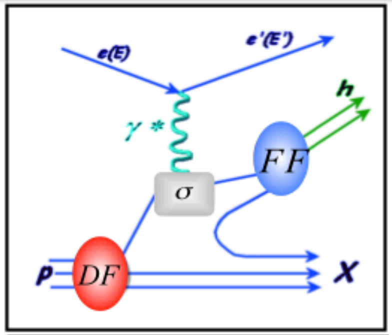
Fragmentation Functions (FF)

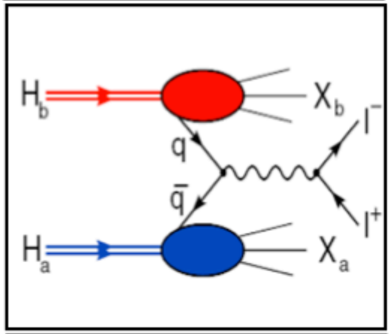
		quark U	quark L	quark T
had.	U	D_1 Unpol. FF		$H_1^{\perp}$ Collins FF

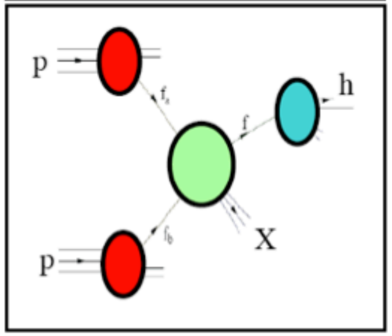
Chiral-Odd TMD ($\gamma_5\gamma^1$)

Possible ways to access TMD's

Physics reactions







SIDIS: rich phenomenology, the most explored so far

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

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

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

DY: challenging for experiments (only unpolarized so far)

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

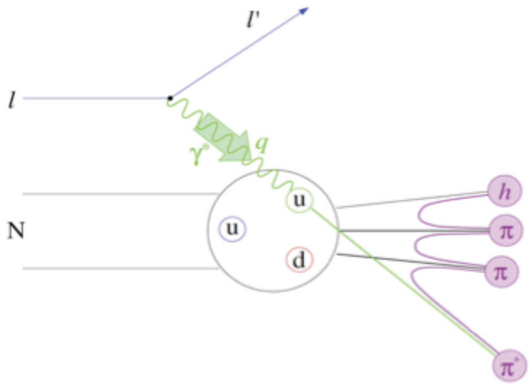
Hadron reactions: challenging for theory (ISI + FSI)

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

WG6: Y. Makdisi

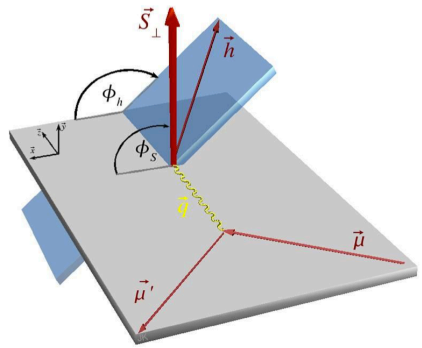
Contalbrigo M. PANIN 11, 30th September 2011, Marrakech 4

TMD formalism in SIDIS



WG6: P. Mulders, J.W. Qui

Courtesy: Jiang, Wehai'11



$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$

Unpolarized

$$\{F_{UU,T} + \ldots$$

$$+\,\varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

Polarized Target — **SSA**

$$+\,S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$

$$+\,S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+\,\sin(\phi_h-\phi_S)\cdot(F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$

$$+\,\varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

Polarized Beam and Target — **DSA**

$$+\,S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$

$$+\,S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

S_L, S_T: Target Polarization; λ_e: Beam Polarization

Collins and Sivers TMD's

Courtesy: N. Makins, PANIC'11

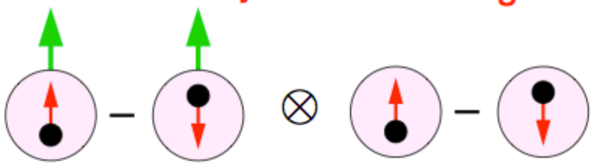
The "Collins Effect"

$\sin(\Phi_h + \Phi_S)$

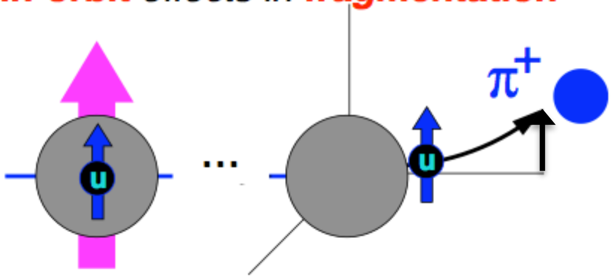
Angle of hadron / initial quark spin

$h_1(x) \otimes H_1^{\perp}(z, p_T)$

Transversity   Collins Frag Func^n



*sensitive to **transversity** and **spin-orbit** effects in **fragmentation***



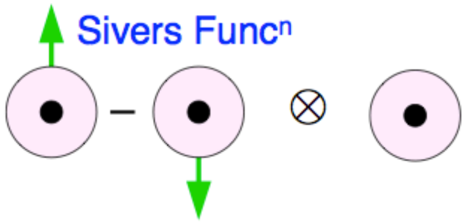
The "Sivers Effect"

$f_{1T}^{\perp}(x, k_T) \otimes D_1(z)$

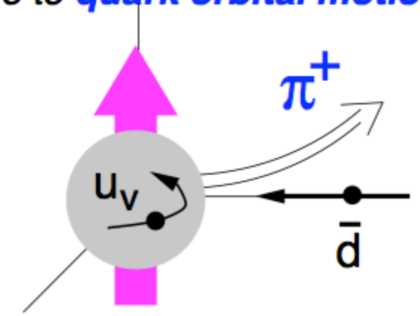
$\sin(\Phi_h - \Phi_S)$

Angle of hadron / final quark spin

Sivers Func^n



*sensitive to **quark orbital motion***



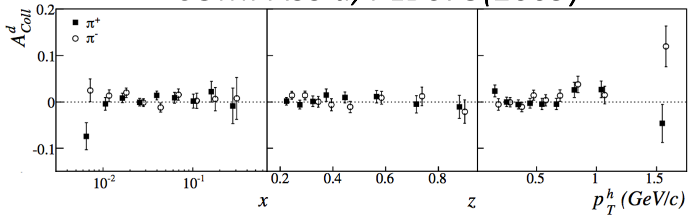
$\otimes$ denotes **convolution** over intrinsic quark k_T & fragmentation p_T

- correlation between parton transverse polarization in a transversely polarized nucleon and transverse momentum of the produced hadron

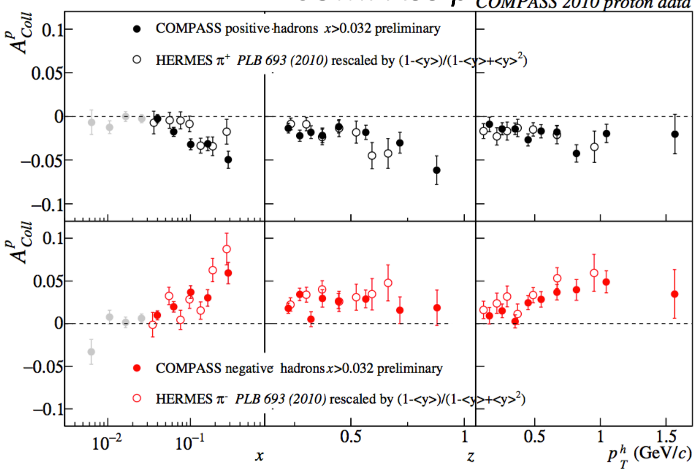
- correlation between parton transverse momentum and nucleon transverse polarization
- requires orbital angular momentum

TMD: Collins SIDIS & pp SSA for π

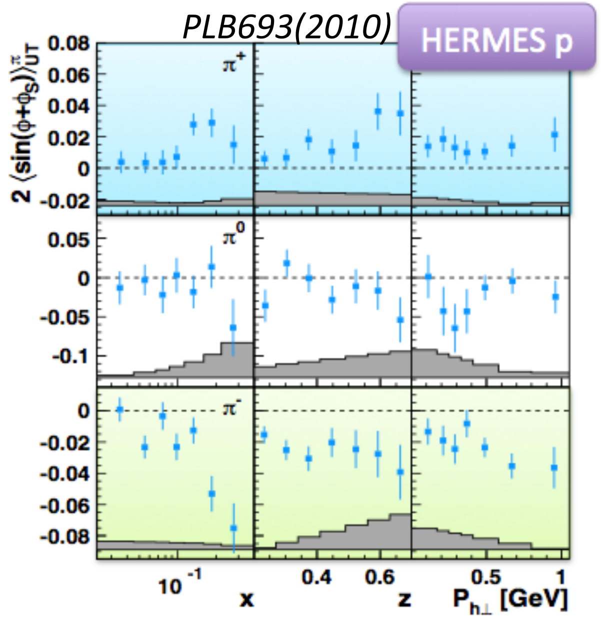
COMPASS d, PLB673(2009)



COMPASS p



PLB693(2010)



- positive amplitude for π^+
- compatible with zero amplitude for π^0
- large negative amplitude for π^-
- increase in magnitude with x
  - transversity mainly receives contribution from valence quarks
- increase with z
  - in qualitative agreement with BELLE results
- positive for π^+ and negative for π^-
  - role of disfavored Collins FF:

$$H_1^{\perp,disfav} \approx -H_1^{\perp,fav}$$

$$u \Rightarrow \pi^+; \qquad d \Rightarrow \pi^-(fav)$$

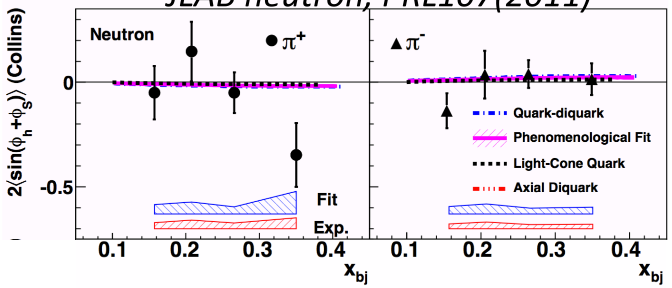
$$u \Rightarrow \pi^-; \qquad d \Rightarrow \pi^+(disfav)$$

$$h_1^u > 0$$

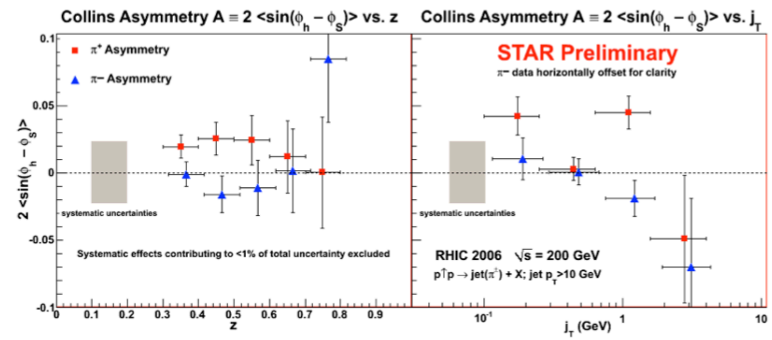
$$h_1^d < 0$$

WG6: C. Adolf

JLAB neutron, PRL107(2011)

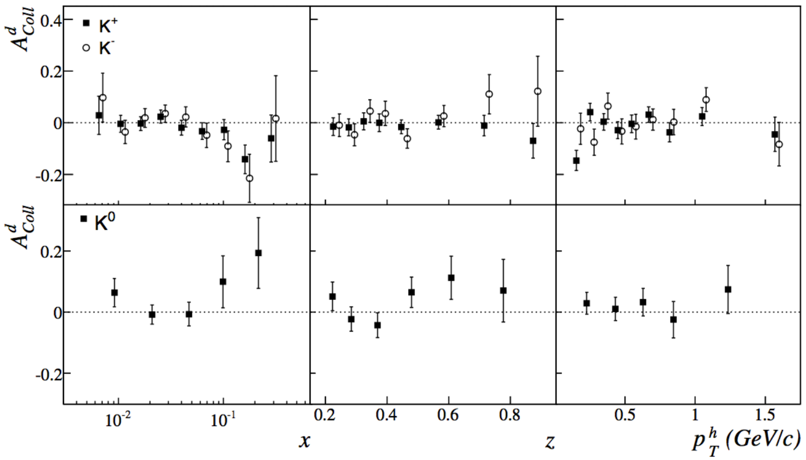


STAR pp, mid rapidity

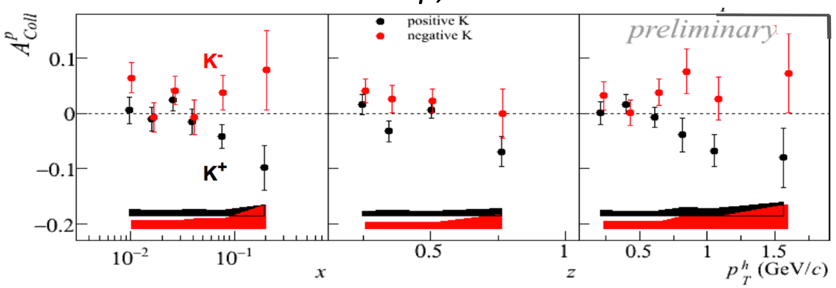


TMD: Collins SIDIS SSA for K

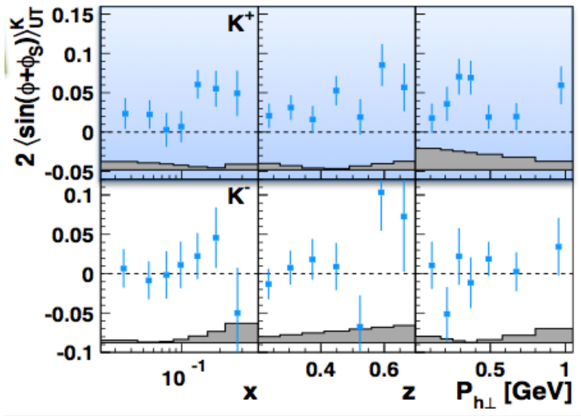
COMPASS d, PLB673(2009)



COMPASS p, 2007 data



Hermes p, PLB693(2010)



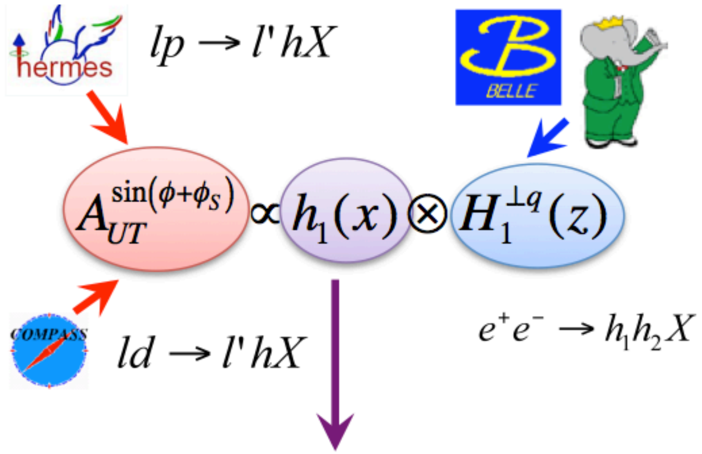
K^+

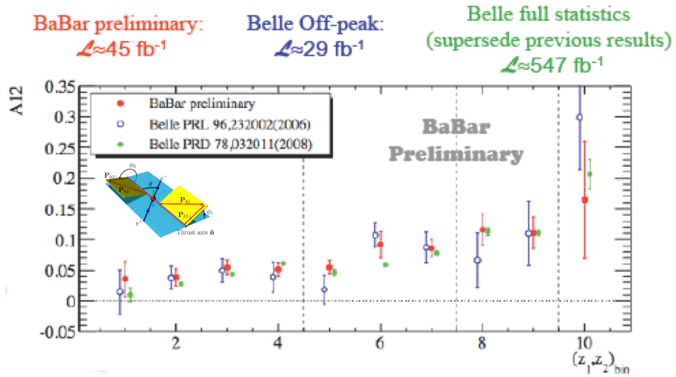
- K^+ amplitudes are similar to π^+ as expected from the u-quark dominance
- K^+ are larger than π^+

K^-

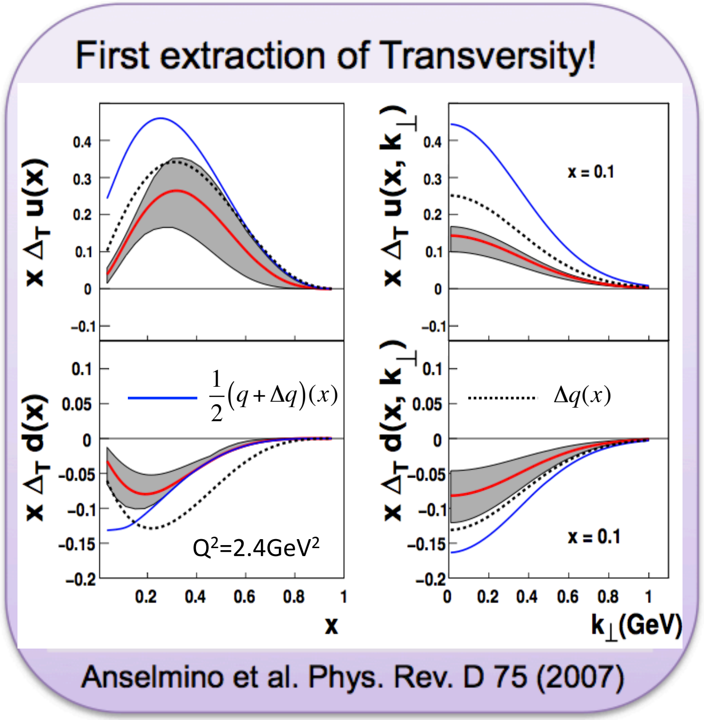
- consistent with zero amplitudes
- K^- $(\bar{u}s)$ is all see object

TMD: Global fits to Collins 1h



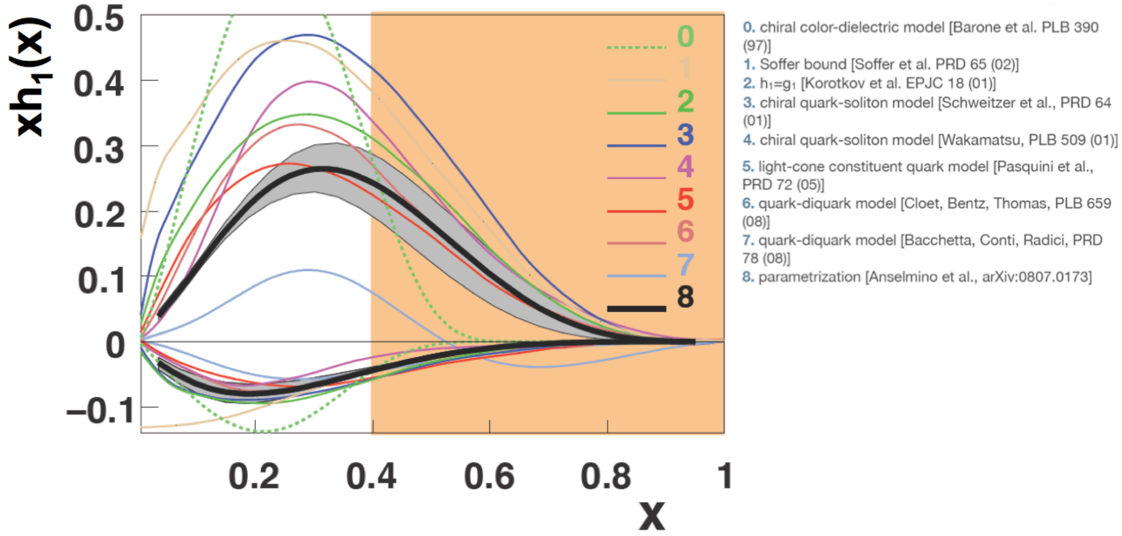


WG6: M. Leitgab

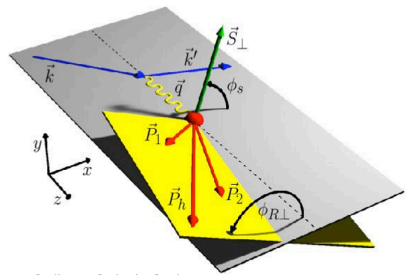


Anselmino et al. Phys. Rev. D 75 (2007)

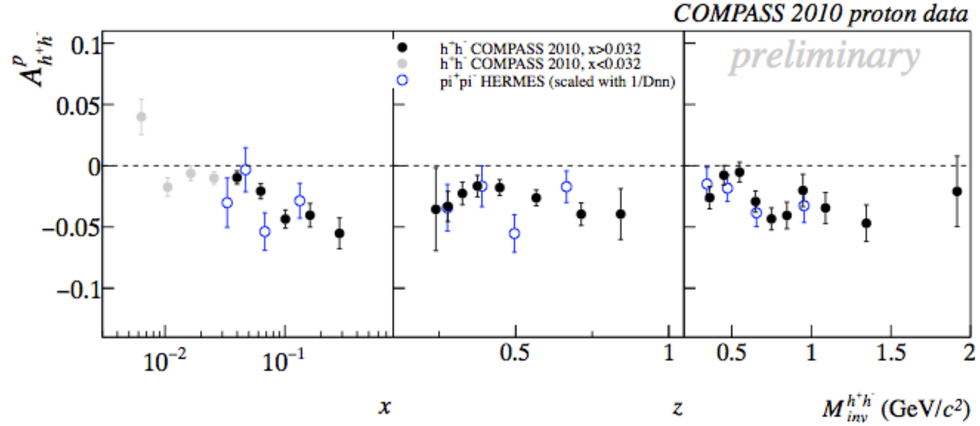
- Fit to Compass d + Hermes p (no Compass p in fit yet)
- $h_1^{u,d}$ slightly smaller than $g_1^{u,d}$ ($\Delta u, \Delta d$)



TMD: Collins asymmetry 2 h SIDIS



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



$$x h_1^{u_v}(x,Q^2) - \frac{1}{4} x h_1^{d_v}(x,Q^2) \approx -\frac{A_{UT}^{\sin(\phi_R+\phi_S)\,\sin\theta}(x,Q^2)}{C_y} \frac{n_u(Q^2)}{n_u^{\uparrow}(Q^2)} \sum_{q=u,d,s} \frac{e_q^2 N_q}{e_u^2} x f_1^{q+\bar{q}}(x,Q^2)$$

hermes data (+ COMPASS)

$0.2 \le z \le 1$

$0.5 \le M_h \le 1$ $\quad 0.28 \le M_h \le 1.2$ [GeV]

$Q^2(\langle x \rangle) \sim 2.5$ [GeV²]

fitting (BELLE)

from a PDF param.
ex: MSTW08LO
not sensitive to other choices

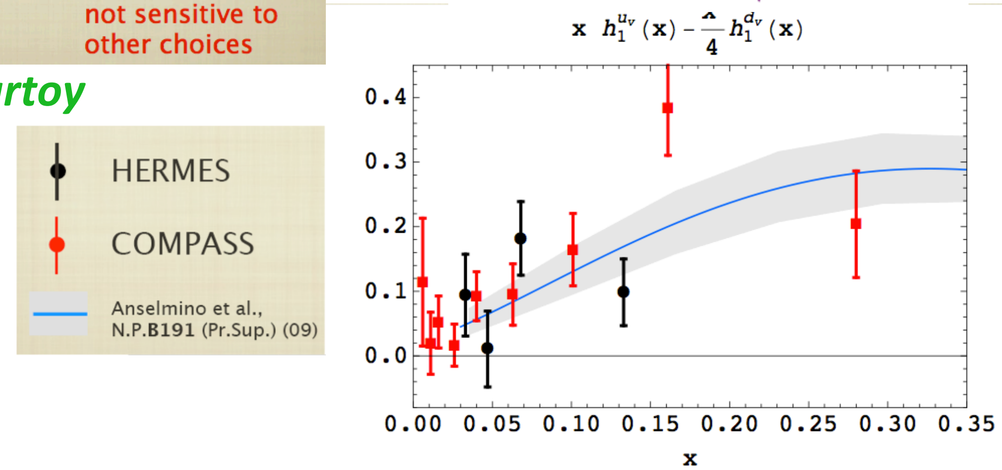
WG6: A. Courtoy

$lp \to l'\pi^+\pi^- X$

WG6: C. Braun

hermes, COMPASS

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)} \propto \sin\vartheta\, h_1(x) \otimes H_1^{\sphericalangle q}(z)$$

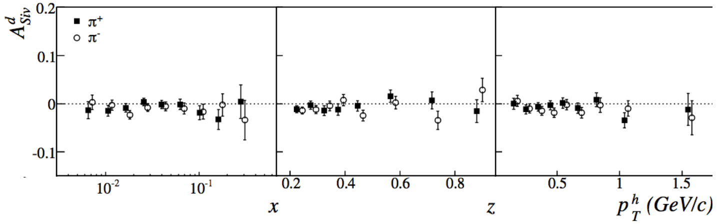


- Independent access to h_1^q
- Combining p+d → h_1^u, h_1^d

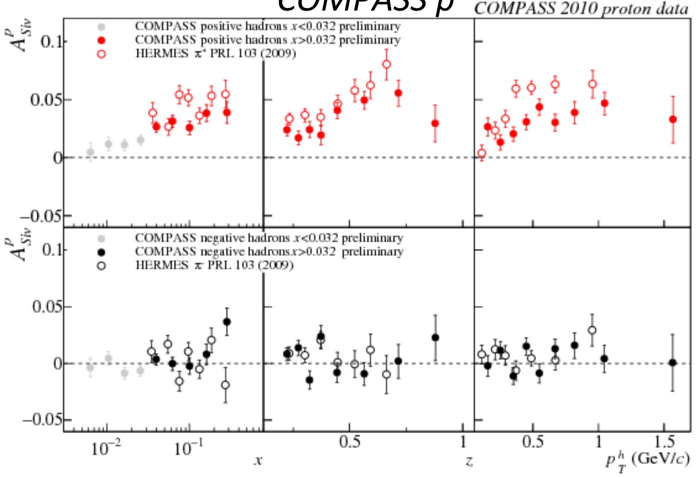
(not shown here)

TMD: Sivers SIDIS SSA for π

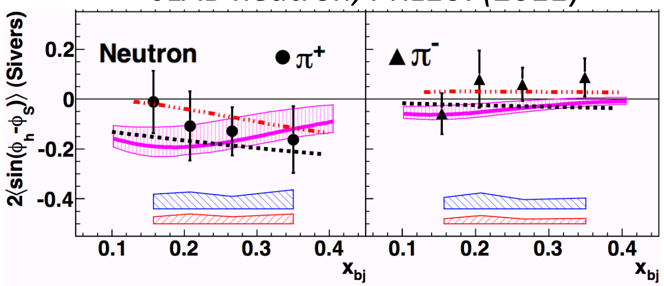
COMPASS d, PLB673(2009)



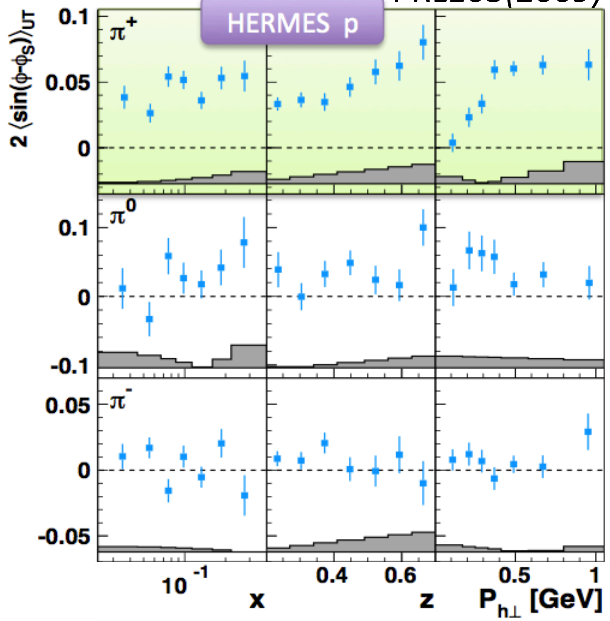
COMPASS p



JLAB neutron, PRL107(2011)



PRL103(2009)



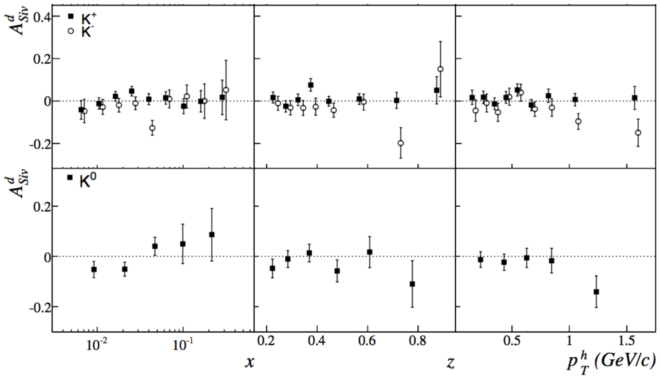
- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- slightly positive
- consistent with zero

Compass confirms Hermes with 2010 new data set

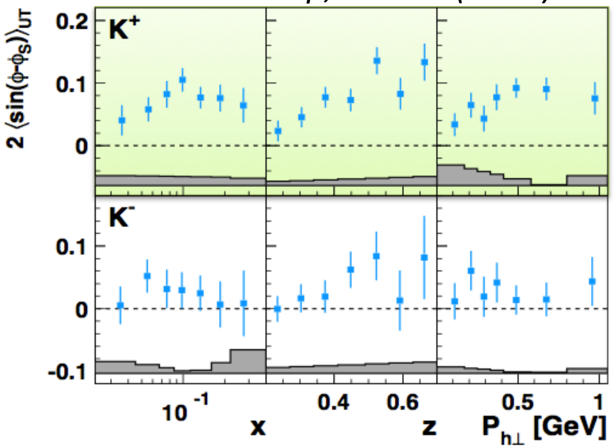
WG6: V. Sulkovsky

TMD: Sivers SIDIS SSA for K

COMPASS d, PLB673(2009)



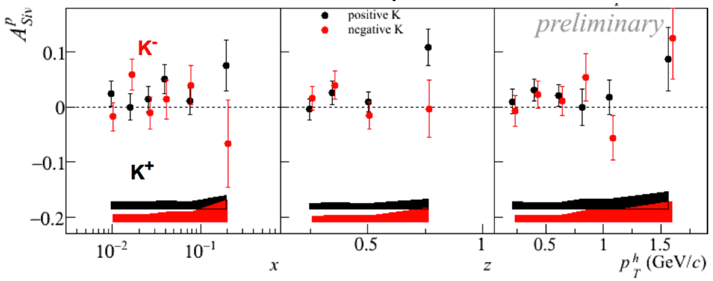
Hermes p, PRL103(2009)



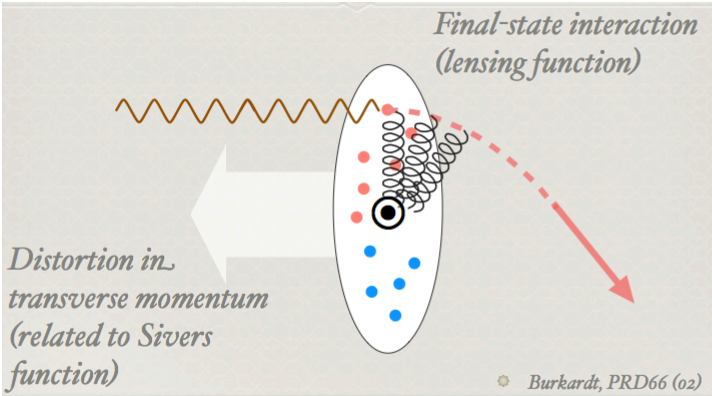
[Airapetian *et al.*, Phys. Rev. Lett. 103 (2009) 152002]

- significantly positive
- clear rise with z
- rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- slightly positive

COMPASS p, 2007 data



Sivers asymmetry SIDIS and OAM



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

Sivers TMD *Lensing function*

Use SIDIS Sivers asymmetry data to constrain shape

hermes COMPASS Jefferson Lab

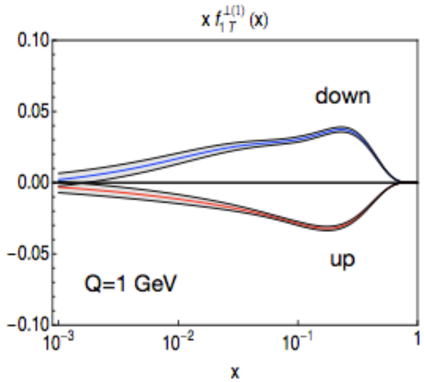
$$\kappa^p = \int_0^1 \frac{dx}{3}\left[2E^{u_v}(x,0,0) - E^{d_v}(x,0,0) - E^{s_v}(x,0,0)\right]$$

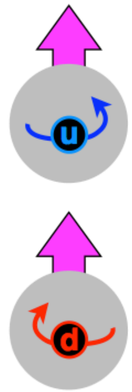
$$\kappa^n = \int_0^1 \frac{dx}{3}\left[2E^{d_v}(x,0,0) - E^{u_v}(x,0,0) - E^{s_v}(x,0,0)\right]$$

Use anomalous magnetic moments to constrain integral

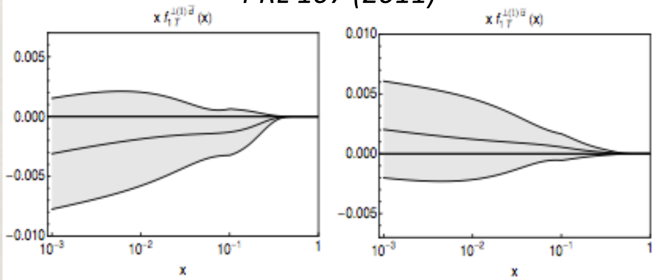
Courtesy Bacchetta, PINAN'11

Pavia



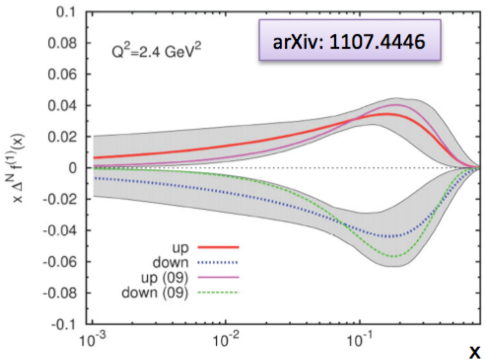


PRL 107 (2011)



WG6: A. Bacchetta
M. Boglione

Torino



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

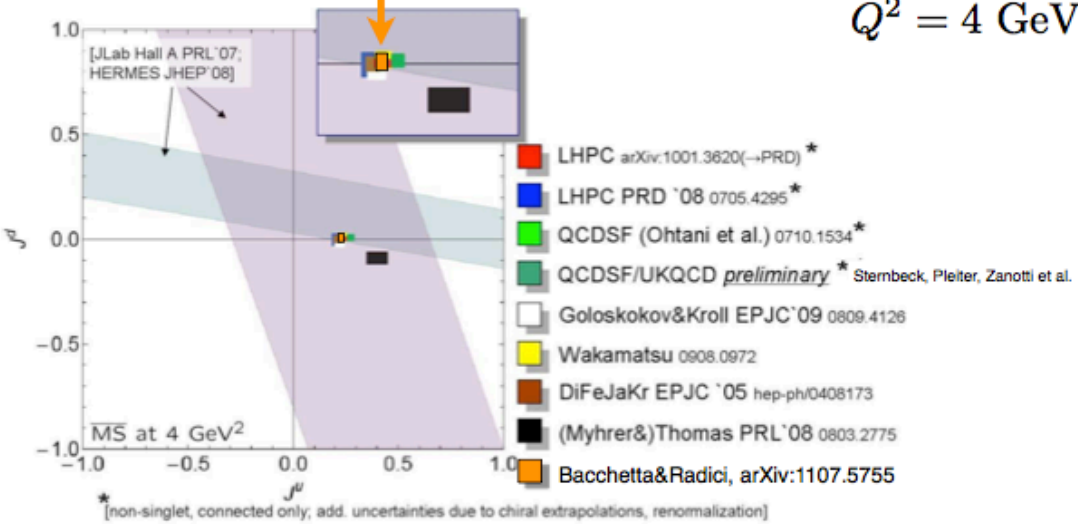
Fit to Compass d, Hermes p + unpol FF

Sivers asymmetry SIDIS and quark OAM

Courtesy Bacchetta, PINAN'11

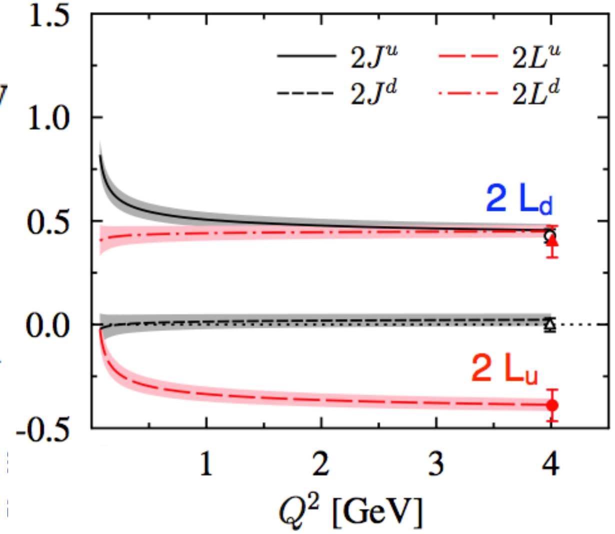
$$J^u = 0.233 \pm 0.002^{+0.008}_{-0.012}, \quad J^{\bar{u}} = -0.019 \pm 0.003^{+0.002}_{-0.001},$$
$$J^d = -0.003 \pm 0.002^{+0.020}_{-0.005}, \quad J^{\bar{d}} = 0.026 \pm 0.003^{+0.002}_{-0.001},$$
$$J^s = 0.011 \pm 0.000^{+0.000}_{-0.007}, \quad J^{\bar{s}} = 0.010 \pm 0.000^{+0.001}_{-0.007}$$

$Q^2 = 4$ GeV



WG6: S. Collins

Lattice: Wakamatsu, EPJA44(2010)

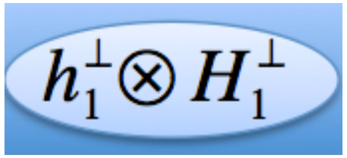


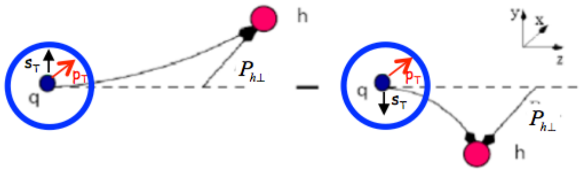
- *INT writeup, Boer et al., arXiv:1108.1713 (fig. 4.3)*

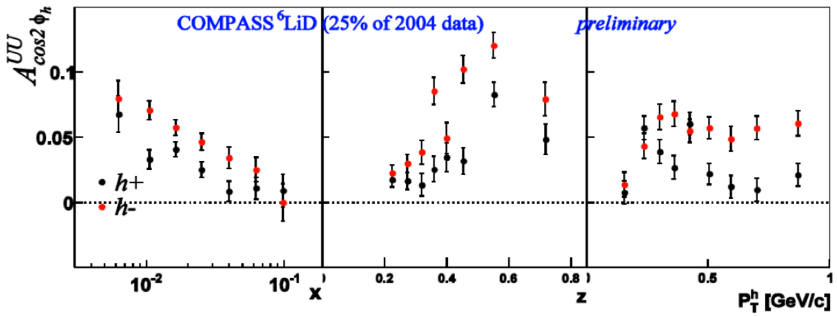
$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\ x\left[H(x,\xi,t) + E(x,\xi,t)\right]$$

WG6: F. Yuan

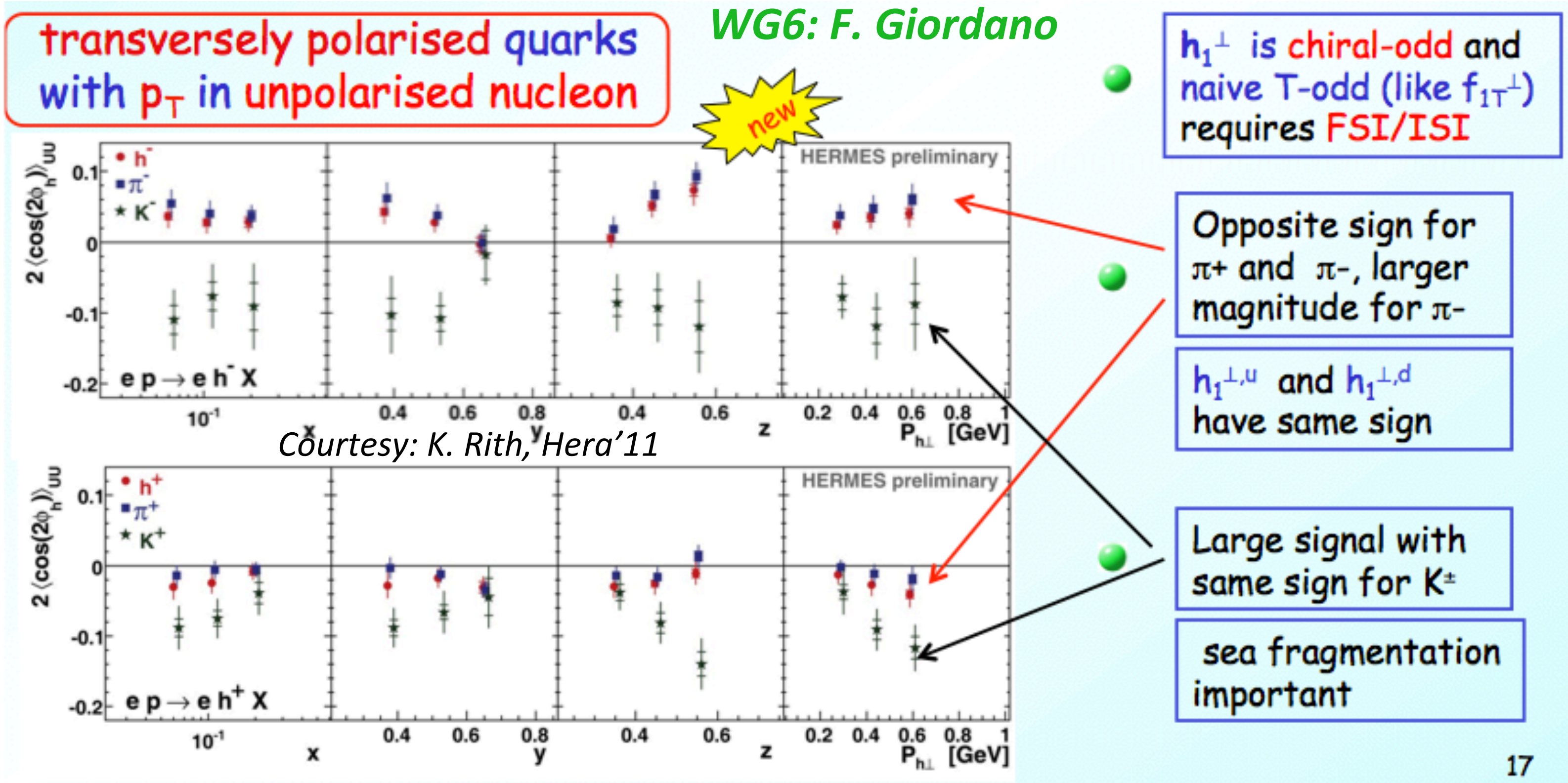
TMD: Boer-Mulders in SIDIS





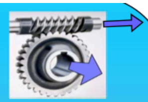


WG6: F. Giordano



TMD: Worm-Gear in SIDIS

Worm-gear



$\propto g_{1T}^{\perp}(x, p_T^2) \otimes D_1(z, k_T^2)$

- describes the probability to find longitudinally polarized quarks in a transversely polarized nucleon (→ "**trans-helicity**")
- accessible in LT DSAs through the leading-twist $\cos(\phi - \phi_S)$ Fourier component

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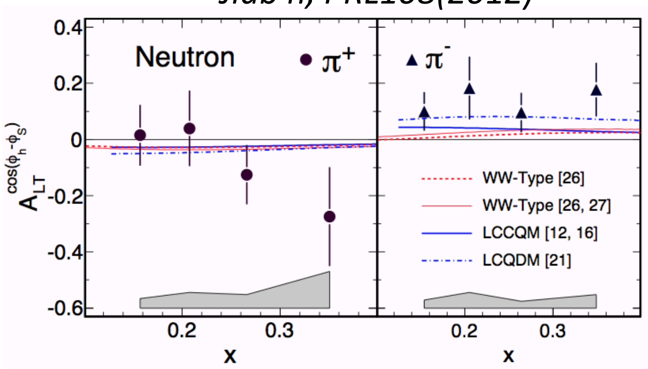
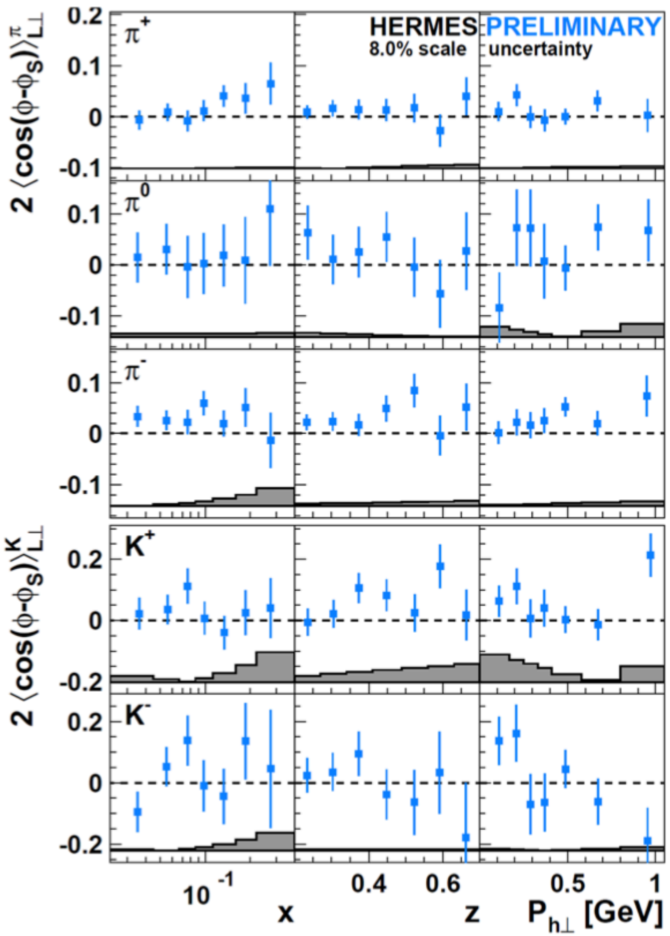
Jlab n, PRL108(2012)



The only TMD that is both chiral-even and naïve-T-even

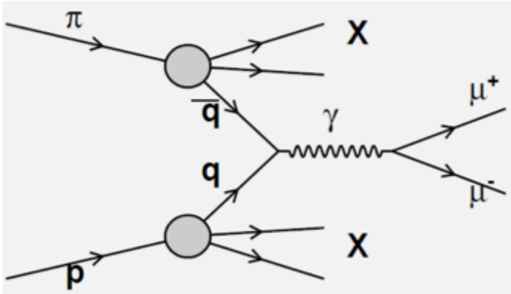
requires interference between wave funct. components that differ by 1 unit of OAM

- Many models support simple relations among $g_{1T}^{\perp}$ and other TMDs:
- $g_{1T}^{q} = -h_{1L}^{\perp q}$ (also supported by Lattice QCD and first data)
- $g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x \int_x^1 \frac{dy}{y} g_1^q(y)$ (Wandzura-Wilczek appr.)



consistent positive signal for π+ on p,n

TMD: Sivers (&BM) asymmetry DY (future)



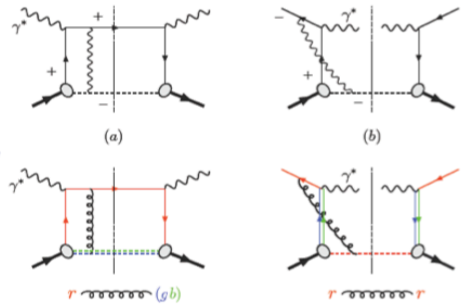
$$\sigma^{pp\to eeX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to ee}$$

Crucial role of gauge-links in TMDs

Brodsky, Hwang, Schmidt; Collins; Belitsky, Ji, Yuan; Boer, Mulders, Pijlman

process-dependence of Sivers functions

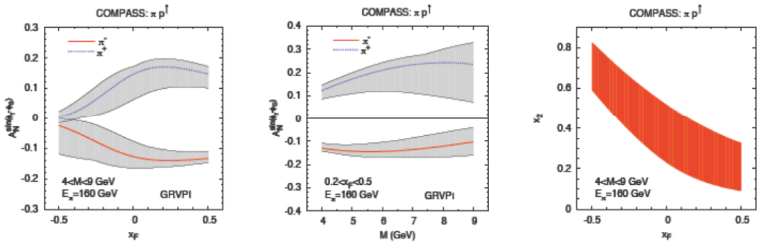
DIS: "attractive"



D-Y: "repulsive"

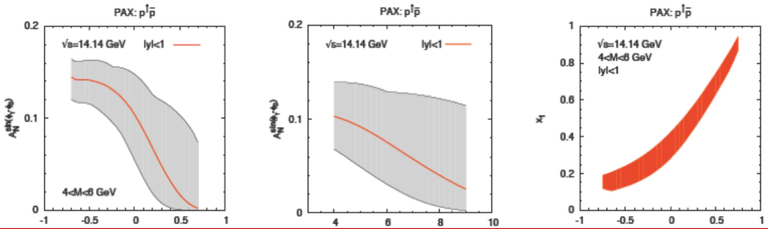
$$[f_{1T}^{q\perp}]_{\mathrm{SIDIS}} = -[f_{1T}^{q\perp}]_{\mathrm{DY}}$$

Test of TMD factorization at QCD level

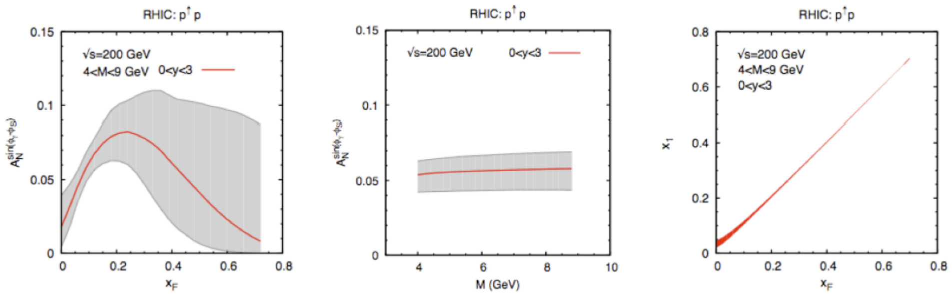


Fixed target mode
$\sqrt{s}$ = 17.4 GeV
$x_F = x_1 - x_2$
Large-x_2 region explored at negative x_F values

M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin,Phys. Rev. D79 (2009) 054010



Collider mode
$\sqrt{s}$ = 14.4 GeV
$x_F = x_1 - x_2$
Large-x_2 region explored at positive x_F values



M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, Phys. Rev. D79 (2009) 054010

$\sqrt{s}$ = 200 GeV
$x_F = x_1 - x_2$
X_1 region explored extends to larger values than that explored in SIDIS

M. Anselmino et al., Phys.Rev.D79:054010,2009

WG7: G. Mallot, K. Boyle, M. Lamont

Summary & Outlook

- **Helicity distributions for quark and gluons:**
  - -Valence Δu_v,Δd_v quite well known, but $\Sigma(\Delta q)$ only 33% of nucleon spin
  - -Separated Δq,$\Delta\overline{q}$ obtained, but still issues with sea polarization
  - -$\Delta G/G(x)$ from direct measurements, but still limited in x range

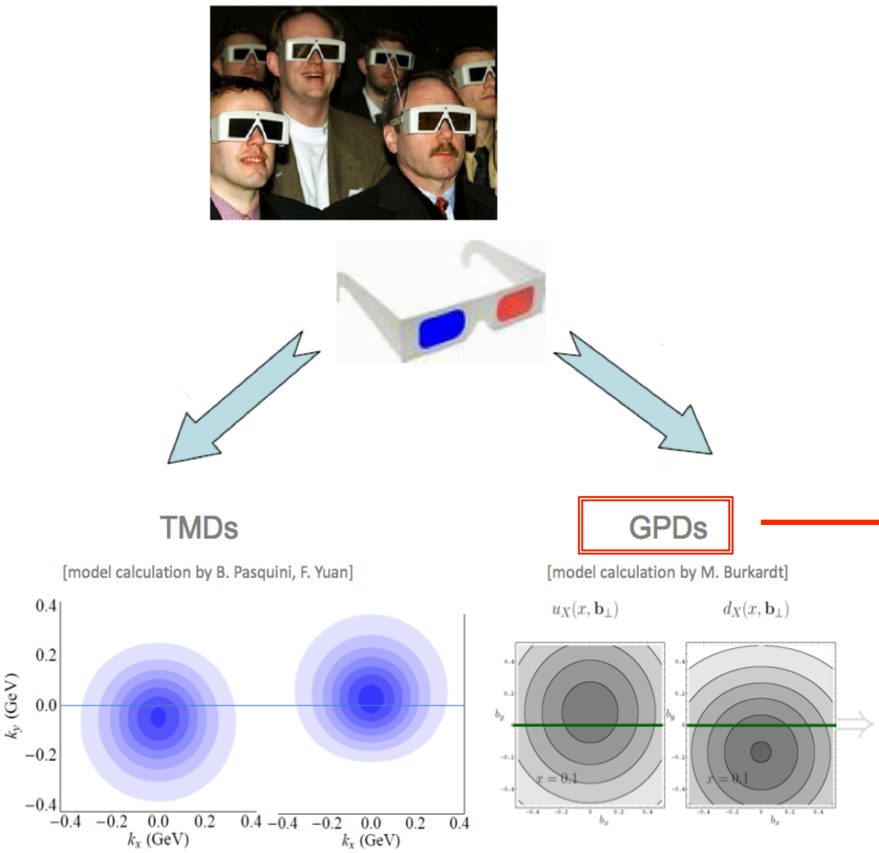
- **Transverse momentum dependent DF for quarks:**
  - -Transversity (Collins): clean opposite signals for π^+,π^-, $\Delta_T q \leq \Delta q$
  - -T-odd Sivers: confirmed signal≠0 for π^+, =0 for π^- on p, relation to OAM
  - -Many other SSA and SSA measured, more to come

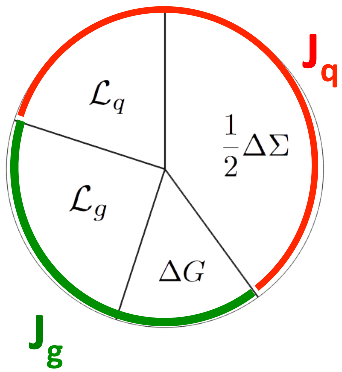
- **Expected improvements for future:**
  - -Gluon sector: RHIC, EIC
  - -Quark sector (helicity, TMD-DY, GPD): COMPASS, JLAB12, RHIC, EIC, ….

WG7: G. Mallot, H. Wollny (COMPASS)
K. Griffioen, K. Allada (JLAB12)
K. Boyle, M. Lamont (RHIC)
A. Bazilewski (EIC)
WG6+7: F. Yuan, M. Stratmann (EIC)

Stay tuned for further « surpises »

3D imaging of nucleon and OAM





Theory:
WG6: F. Yuan, S. Liuti, J. Wagner
WG2+6: M. Diehl
WG6+7: D. Mueller

Experimental:
WG6+7: S. Fazio
WG2+6: H. Moutarde, M. Murray
D. Sokhan