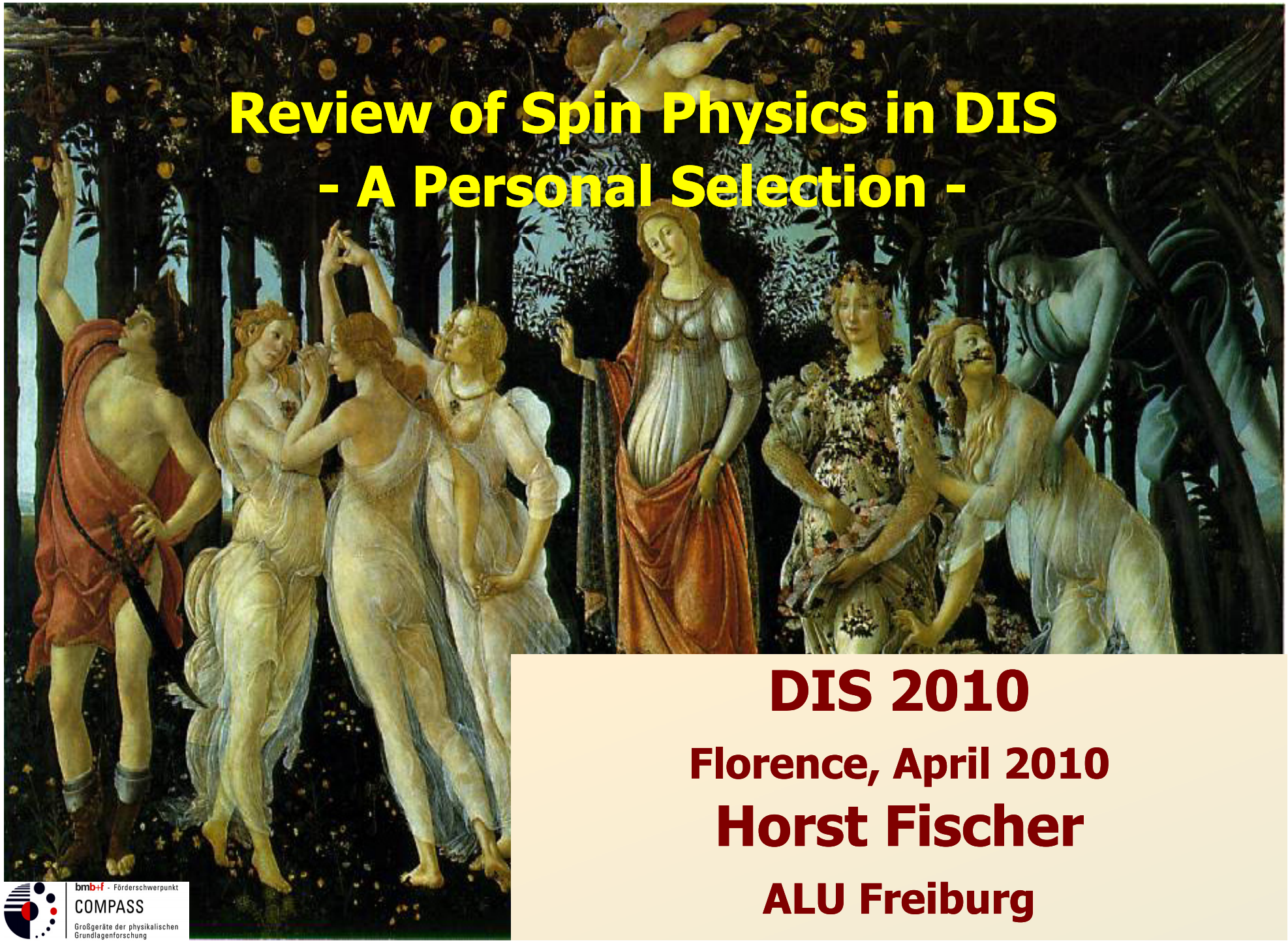
Review of Spin Physics in DIS
- A Personal Selection -



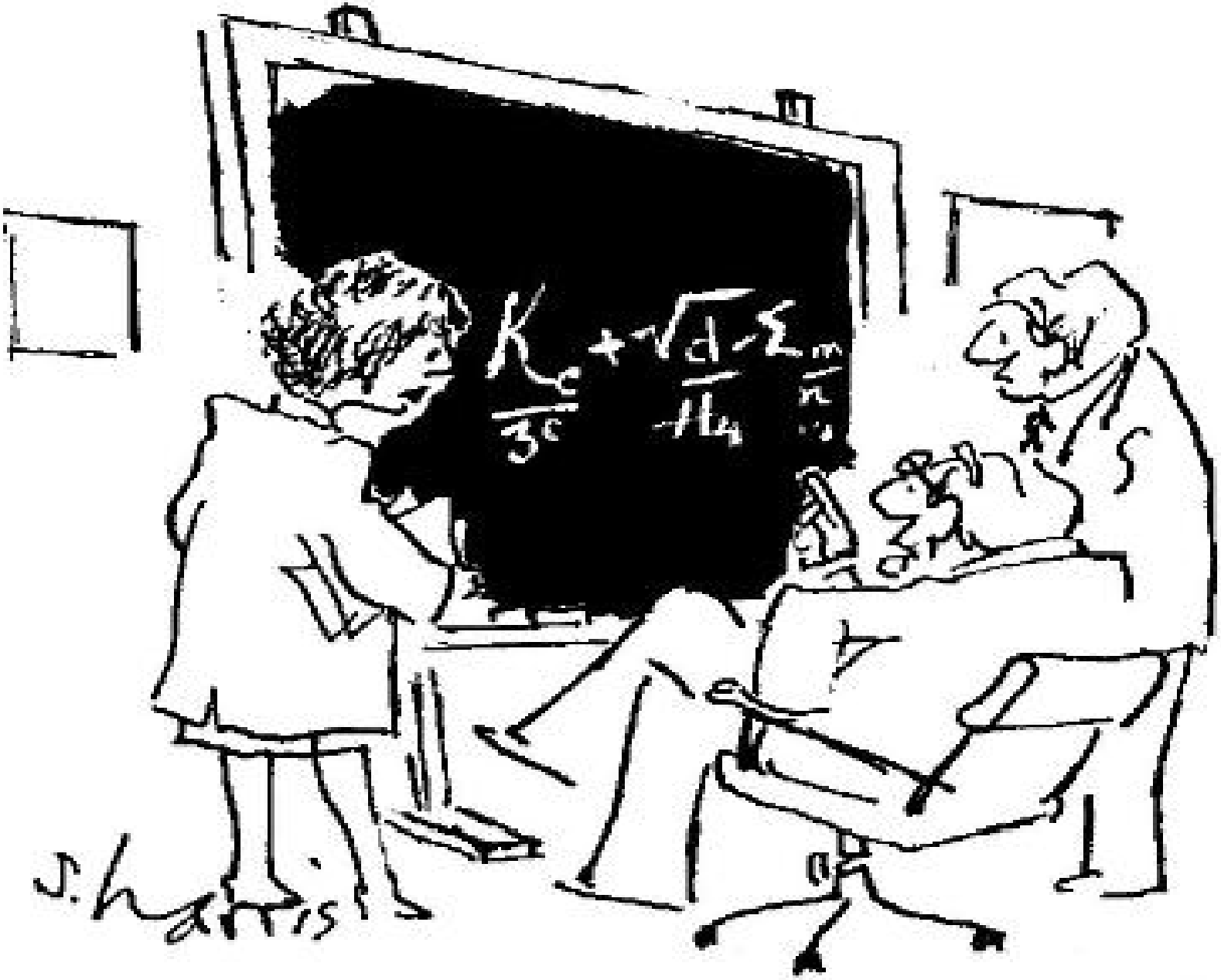
bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung

DIS 2010

Florence, April 2010

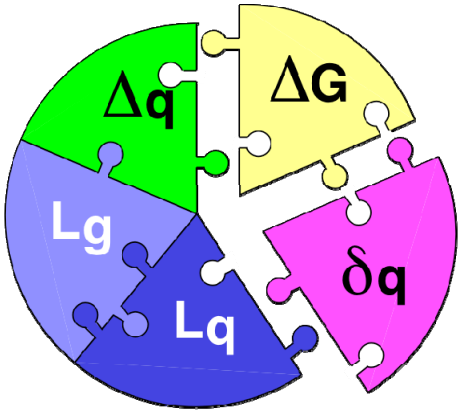
Horst Fischer

ALU Freiburg



"LET'S SEE IF WE COULD PUT A SPIN ON IT AND GET THE PUBLIC INTERESTED."

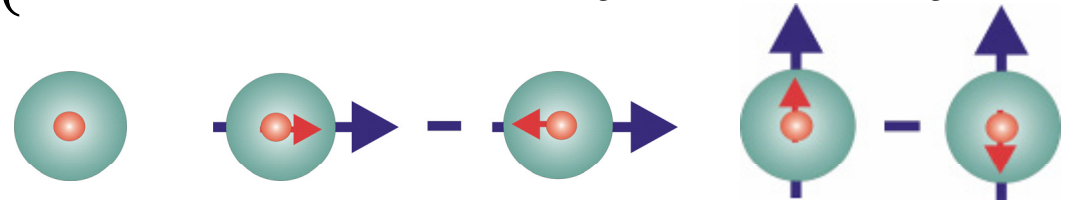
The Spin of the Nucleon



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

All started with EMC (88):
$\Delta\Sigma = 0.12 \pm 0.17$

$$\Phi_{\text{Corr}}^{\text{Tw2}}(x) = \frac{1}{2}\left\{ f_1(x) + S_L\, g_1(x)\gamma_5 + h_1(x)\gamma_5\gamma^1 S_T \right\} n^+$$

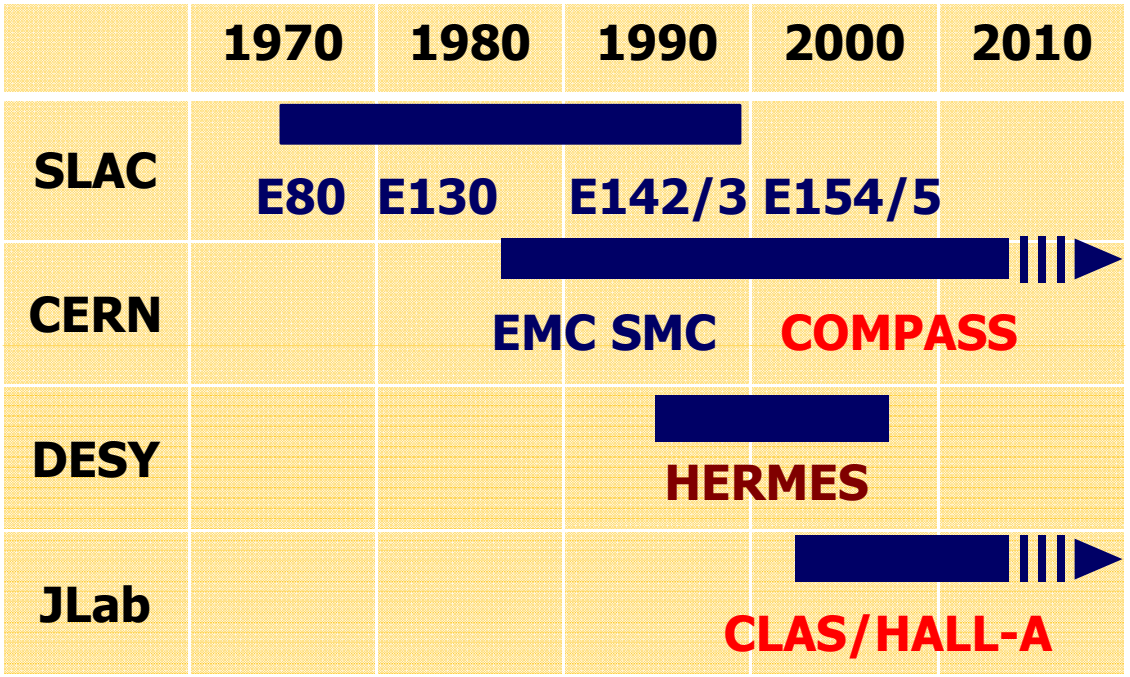


OUTLINE:

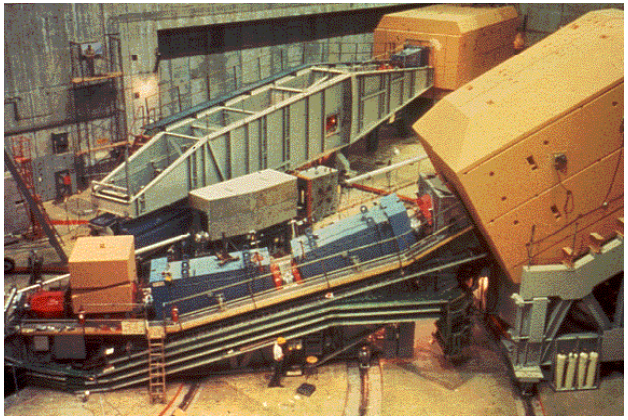
- **Helicity distribution of quarks** $\Delta\Sigma = \Delta u_v + \Delta d_v + \Delta q_s$
- **… and gluons** ΔG
- **Transverse spin phenomena** $h_1, \ldots$

Experiments

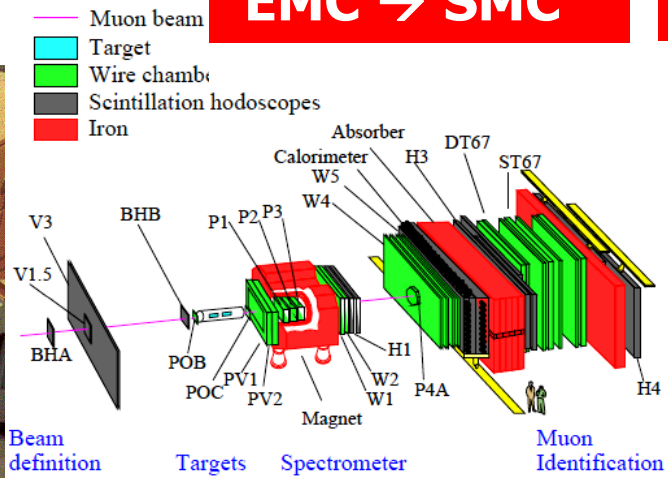
E80, E130	$\vec{e}\,\vec{p}$	≤ 20 GeV
EMC	$\vec{\mu}\,\vec{p}$	100–200 GeV
E142, 143	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	≤ 28 GeV
SMC	$\vec{\mu}\,\vec{p},\vec{d}$	100, 190 GeV
E154, 155	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	≤ 50 GeV
HERMES	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	27.5 GeV
COMPASS	$\vec{\mu}\,\vec{p},\vec{d}$	160 GeV
HALL A	$\vec{e}\,\vec{n}$	6 GeV
CLAS	$\vec{e}\,\vec{p},\vec{d}$	6 GeV



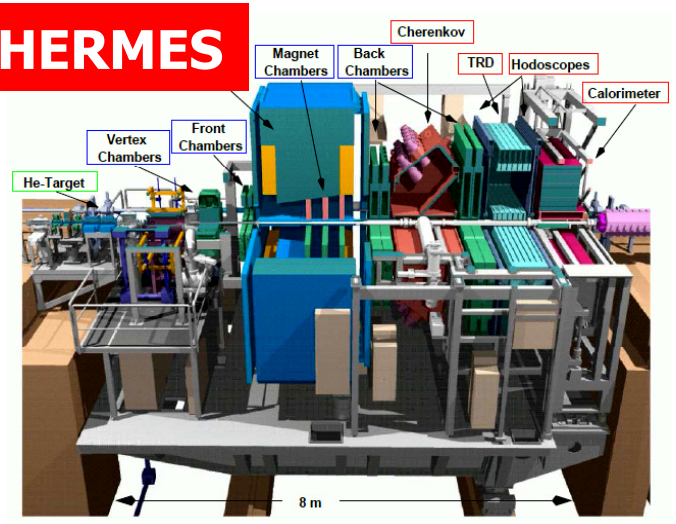
SLAC - End Station A



EMC → SMC



HERMES



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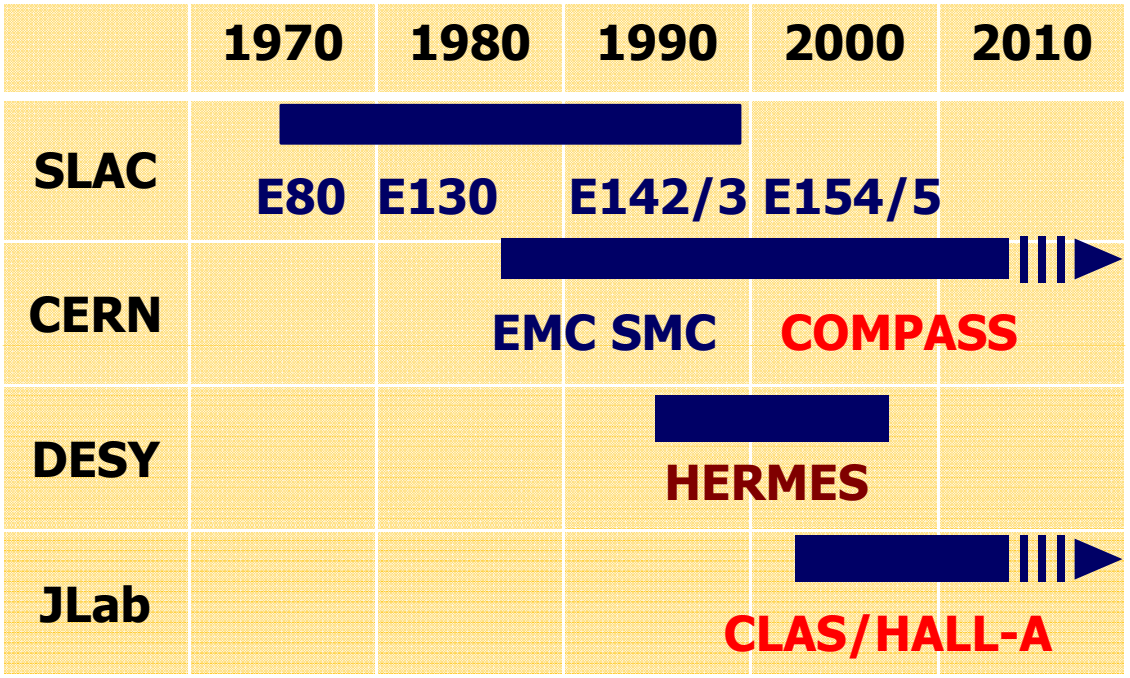
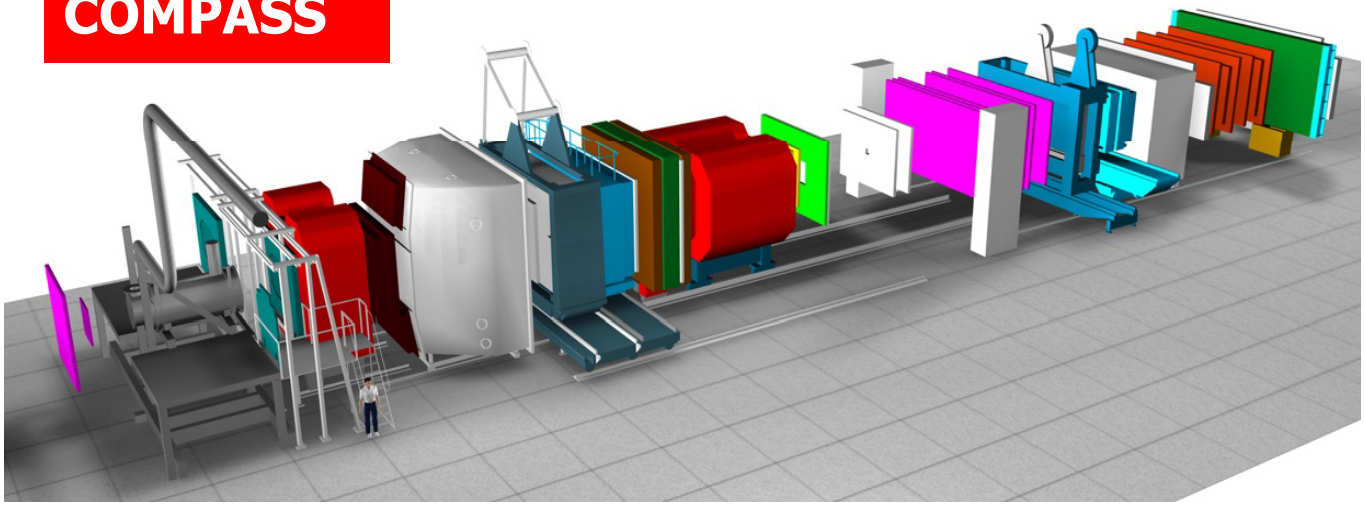
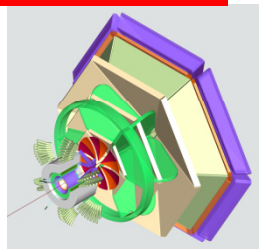
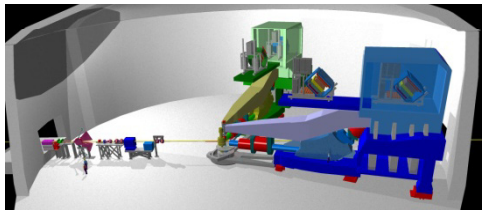


COMPASS



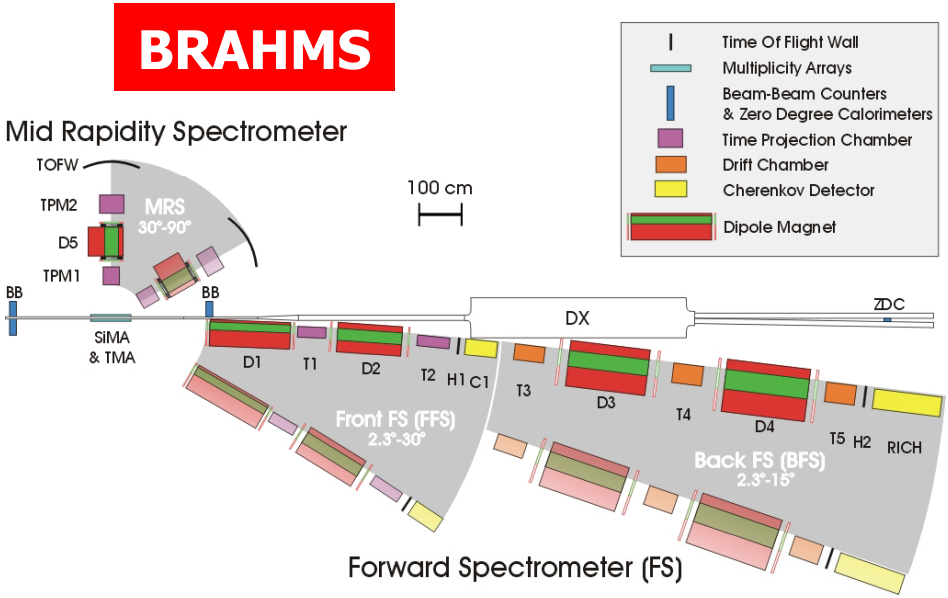
Jlab - CLAS, Hall A



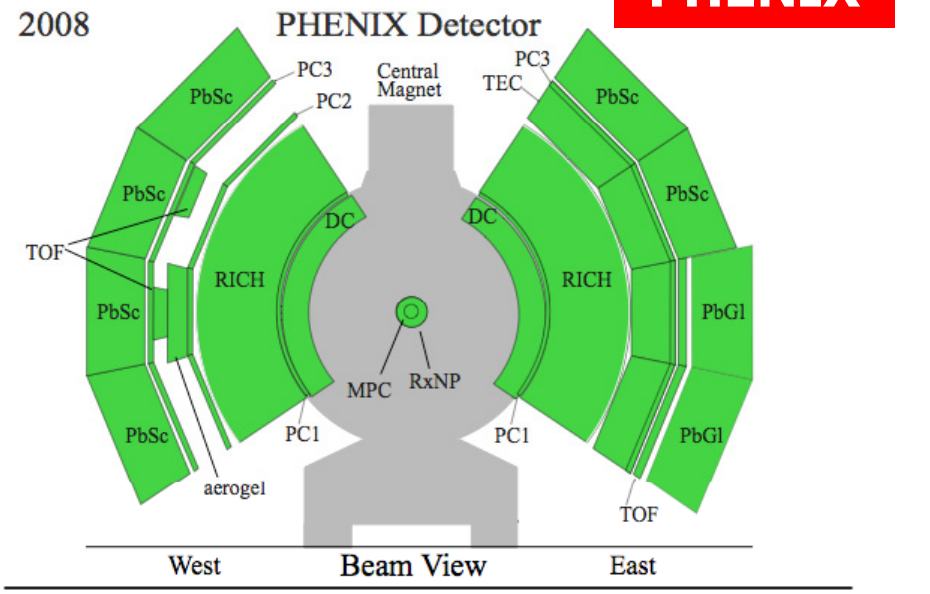


Proton-Proton Scattering Experiments

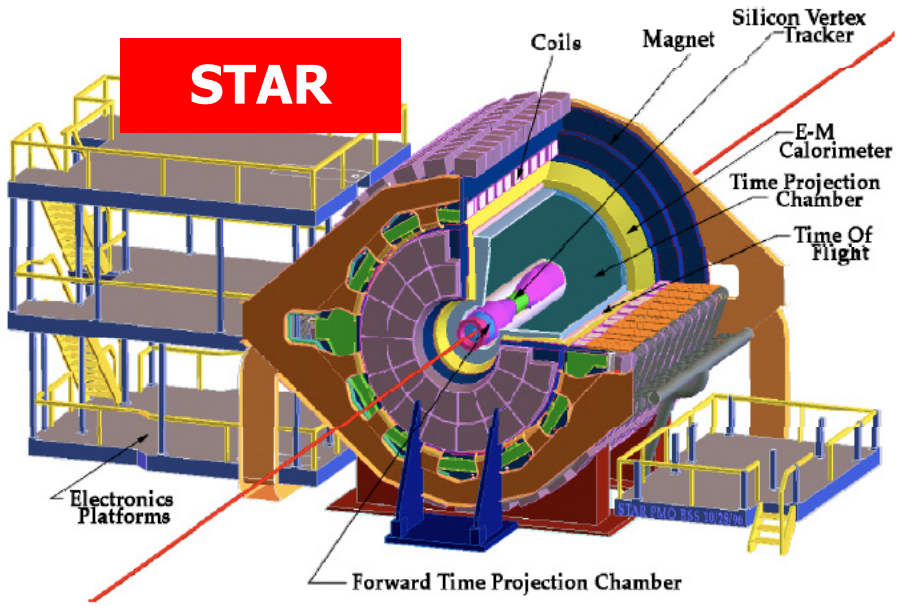
BRAHMS



PHENIX



STAR



RHIC @ BNL: Proton-Proton

√s=200 /500 GeV

~50% polarization

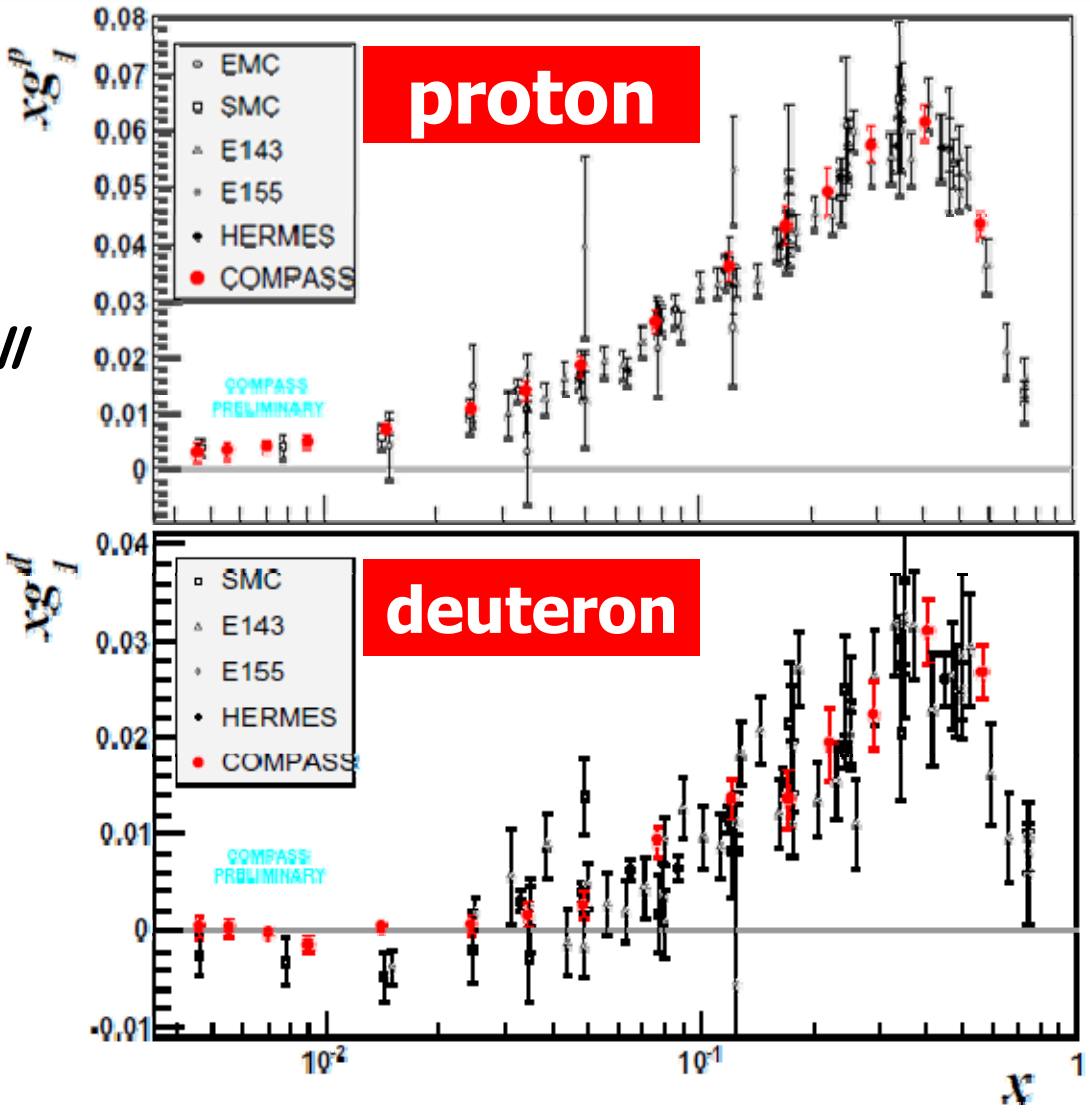
Lumi: L/T 48/18 pb^{-1}

Longitudinal Spin Structure

Spin Structure Function $g_1(x,Q^2)$

$$\sigma_{DIS}^{inclusive} \propto g_1(x) \propto \frac{1}{2}\sum_q e_q^2 \left\{\Delta q(x) + \Delta\bar{q}(x)\right\}$$

- Very precise data
- Good agreement among Experiments
- Large x →extra talk: ***Dave Gaskell***



Deuteron data:

From Γ^1 @ $Q^2 \to \infty$

COMPASS:

- $a_0 = 0.33 \pm 0.03 \pm 0.05$
- $\Delta s + \Delta\bar{s} = 1/3(a_0 - a_8)$
  $= -0.08 \pm 0.01 \pm 0.02$

HERMES:

- $a_0 = 0.330 \pm 0.025 \pm 0.011 \pm 0.028$

Structure Function $g_1(x,Q^2)$

$$\sigma_{DIS}^{inclusive} \propto \ldots + \Delta\bar{q}(x)\}$$

- Ver
- Go

- Large x

Deuteron data:

From Γ^1 @ $Q^2 \to \infty$

COMPASS:

- $a_0 = 0.33 \pm 0.03 \pm 0.05$
- $\Delta s + \Delta\bar{s} = 1/3(a_0 - a_8)$
  $= -0.08 \pm 0.01 \pm 0.02$

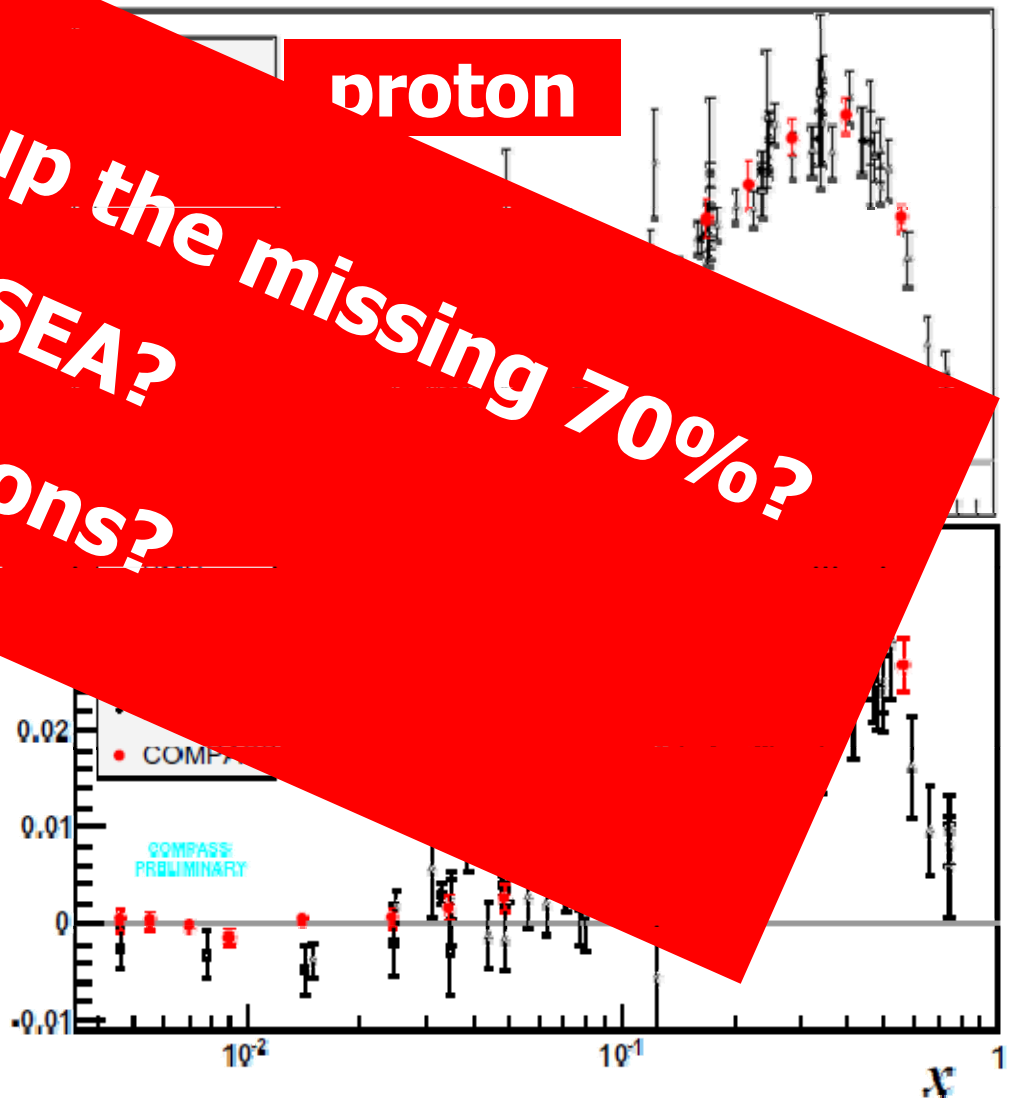
HERMES:

- $a_0 = 0.330 \pm 0.025 \pm 0.011 \pm 0.028$

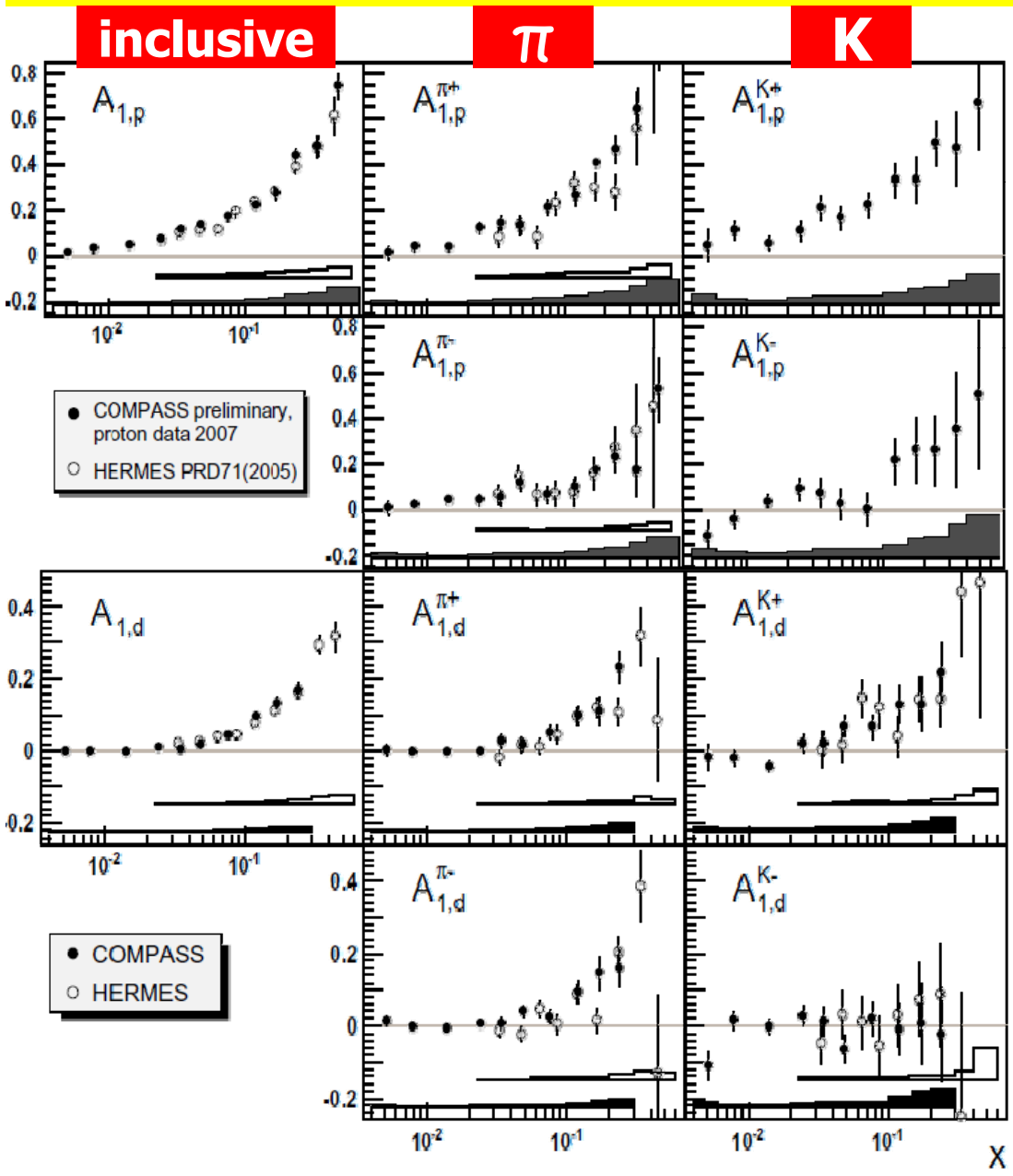
What makes up the missing 70%?

SEA?

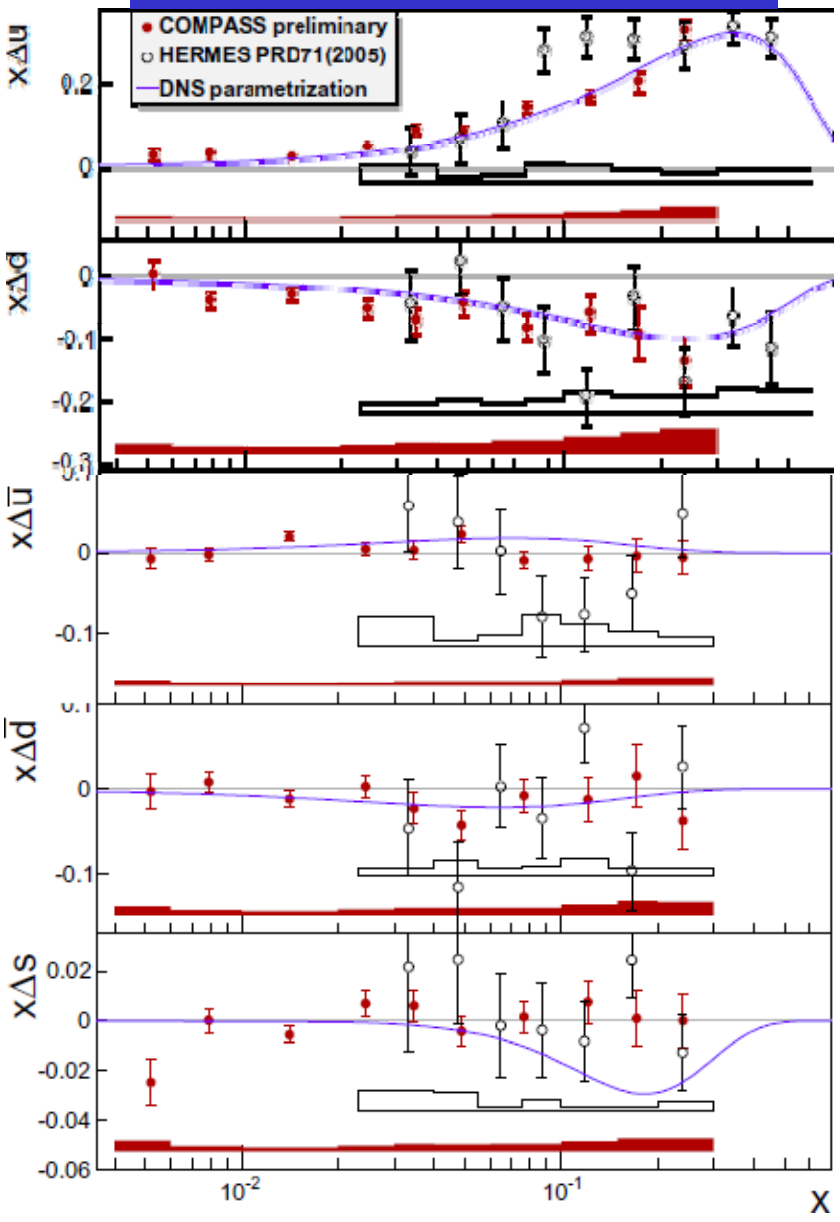
Gluons?



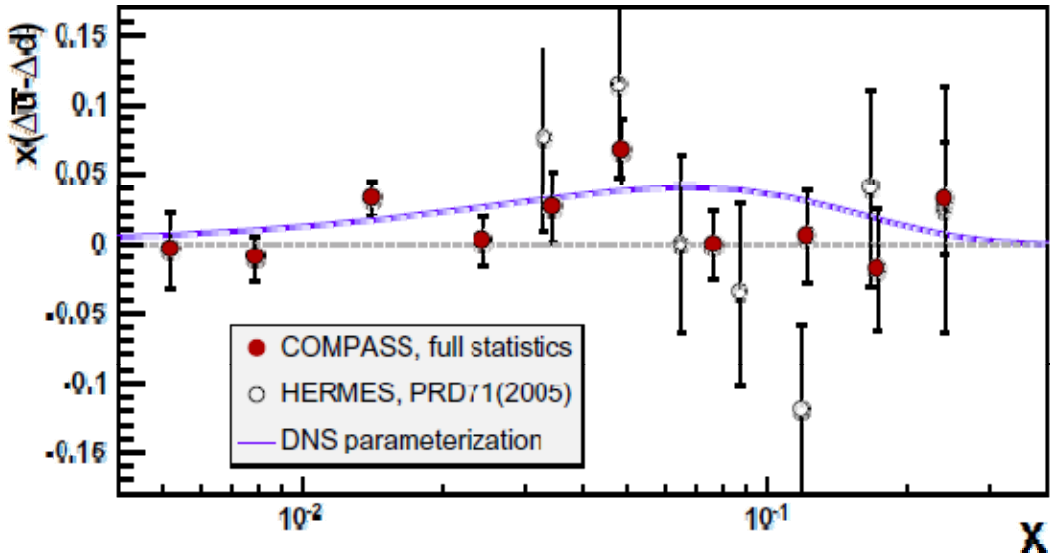
SIDIS Photon-Nucleon Asymmetries



Leading order analysis



Flavor symmetry breaking $\Delta\bar{u} - \Delta\bar{d}$



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

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

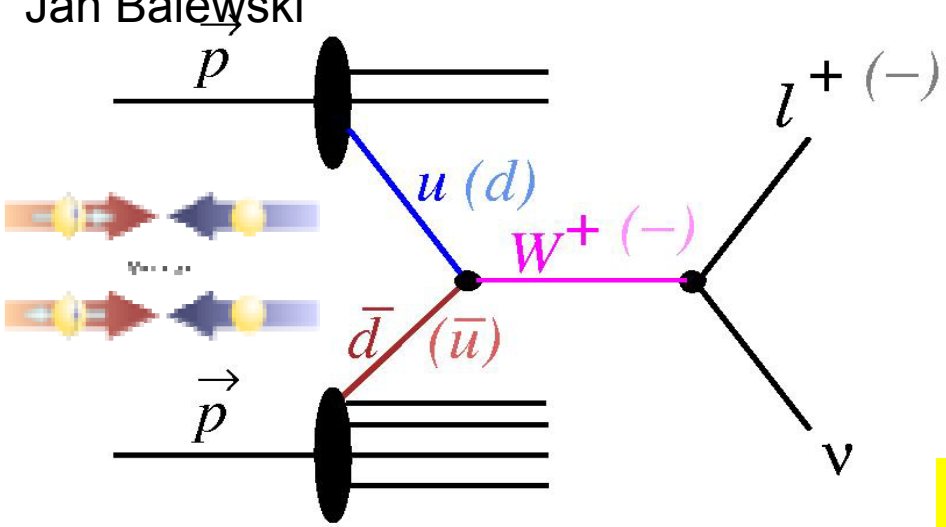
- Presently only accessible in SIDIS
- Considerable asymmetry in the unpolarized case

$$\int(\bar{u}-\bar{d})\mathrm{d}x = -0.118 \pm 0.012$$

- Model predicts naturally symmetry breaking for polarized case

W Production at STAR

Bernd Surrow
Jan Balewski



STAR measures $W^{\pm}$ through their $e^{\pm}$ decays:

$$u + \bar{d} \rightarrow W^{+} \rightarrow e^{+} + \nu$$

$$\bar{u} + d \rightarrow W^{-} \rightarrow e^{-} + \bar{\nu}$$

- **No fragmentation uncertainty**

- Measure the parity-violating, single-spin helicity asymmetry

$$A_L = (\sigma^{+} - \sigma^{-})/(\sigma^{+} + \sigma^{-})$$

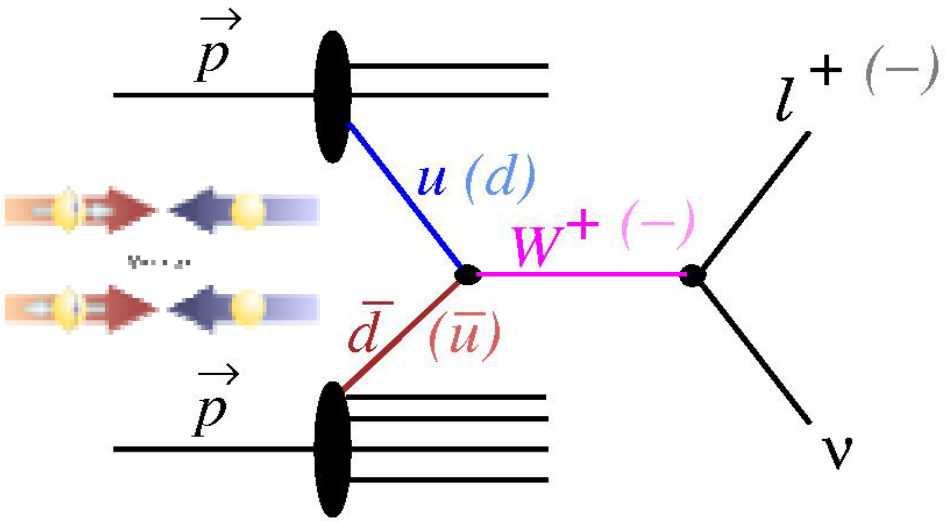
- At LO:

$$A_L^{W^+} \propto -\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2) \quad \mathbf{<0}$$

$$A_L^{W^-} \propto -\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2) \quad \mathbf{>0}$$

Expectations:
using pol. PDFs (DSSV) & universality

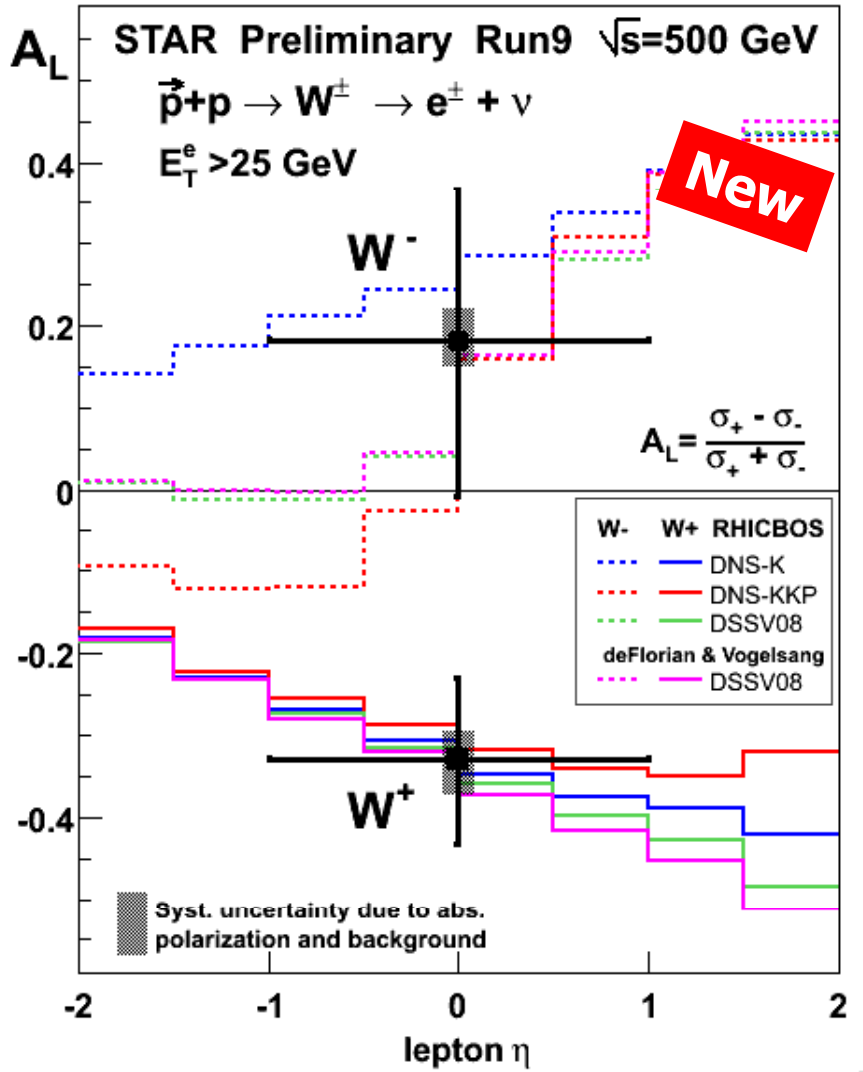
W Production at STAR - Asymmetries



STAR Preliminary Run 9 (p+p √s=500 GeV)

$$A_L(W^+) = -0.33 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.})$$

$$A_L(W^-) = 0.18 \pm 0.19(\text{stat.}) \; {}^{+0.04}_{-0.03}(\text{syst.})$$

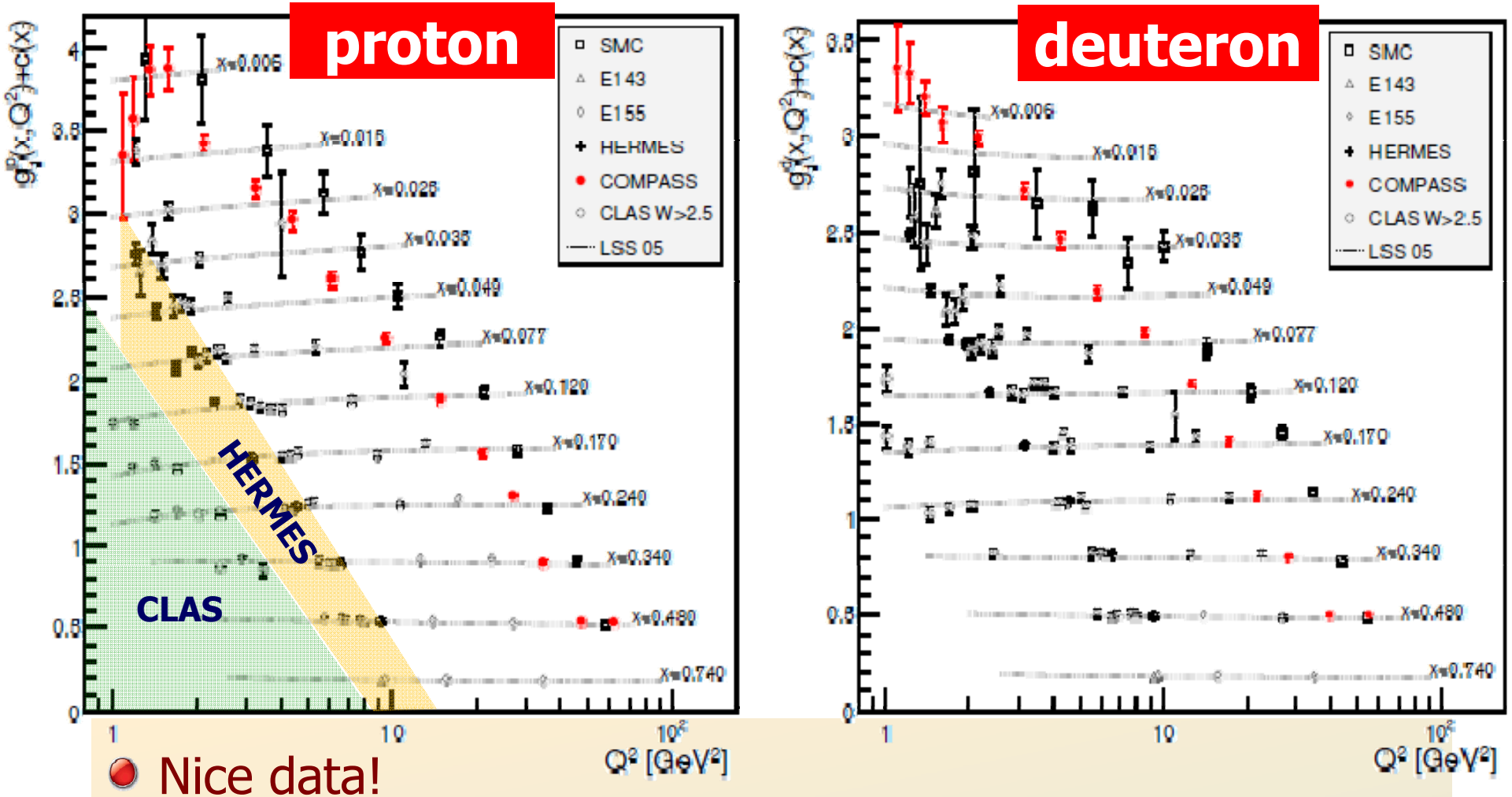


$$A_L^{W^+} \propto -\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2) \quad <0 \quad (3.3\ \sigma)$$

$$A_L^{W^-} \propto -\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2) \quad >0$$

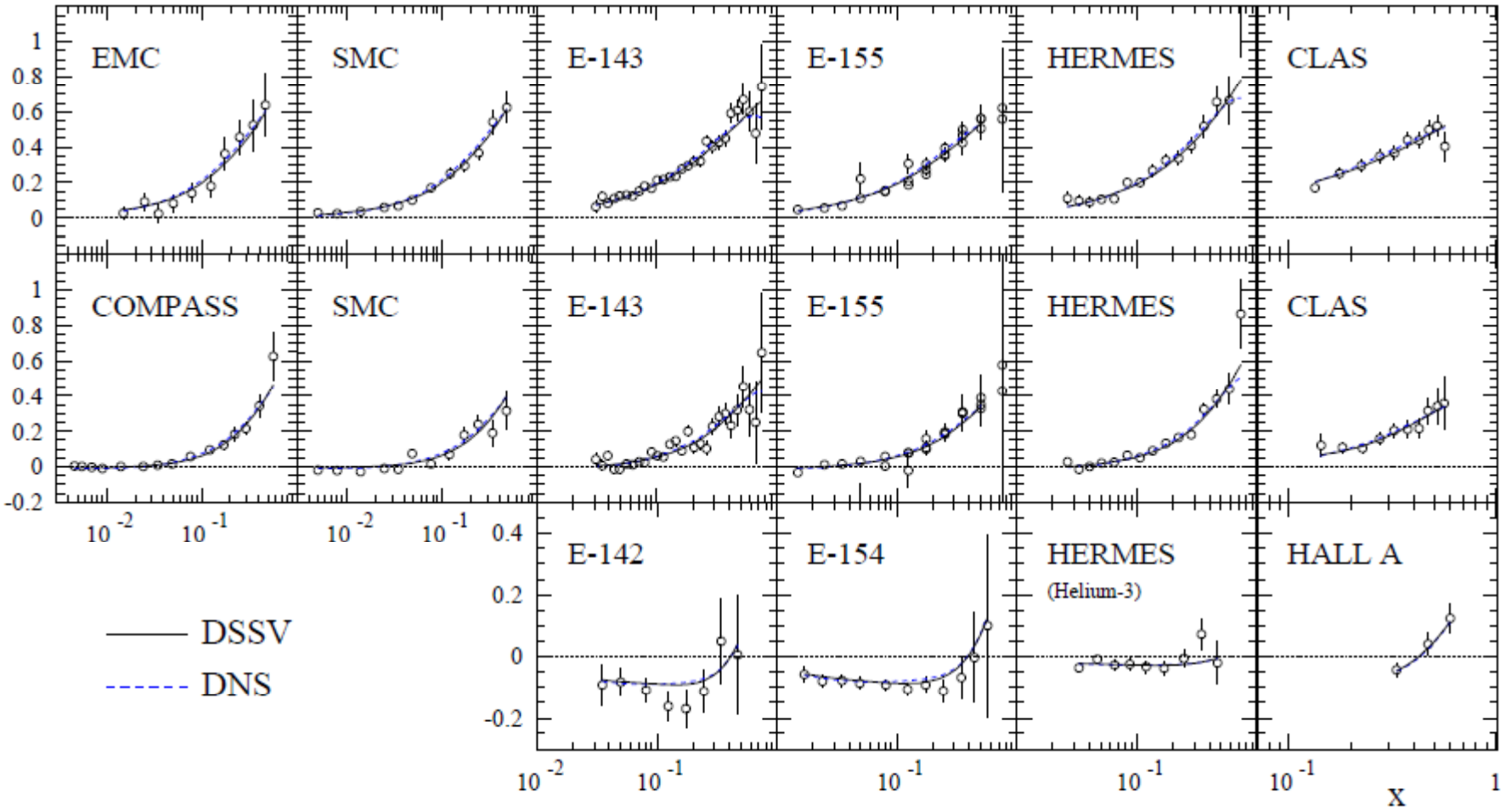
Bernd Surrow
Jan Balewski

Global NLO QCD Analysis



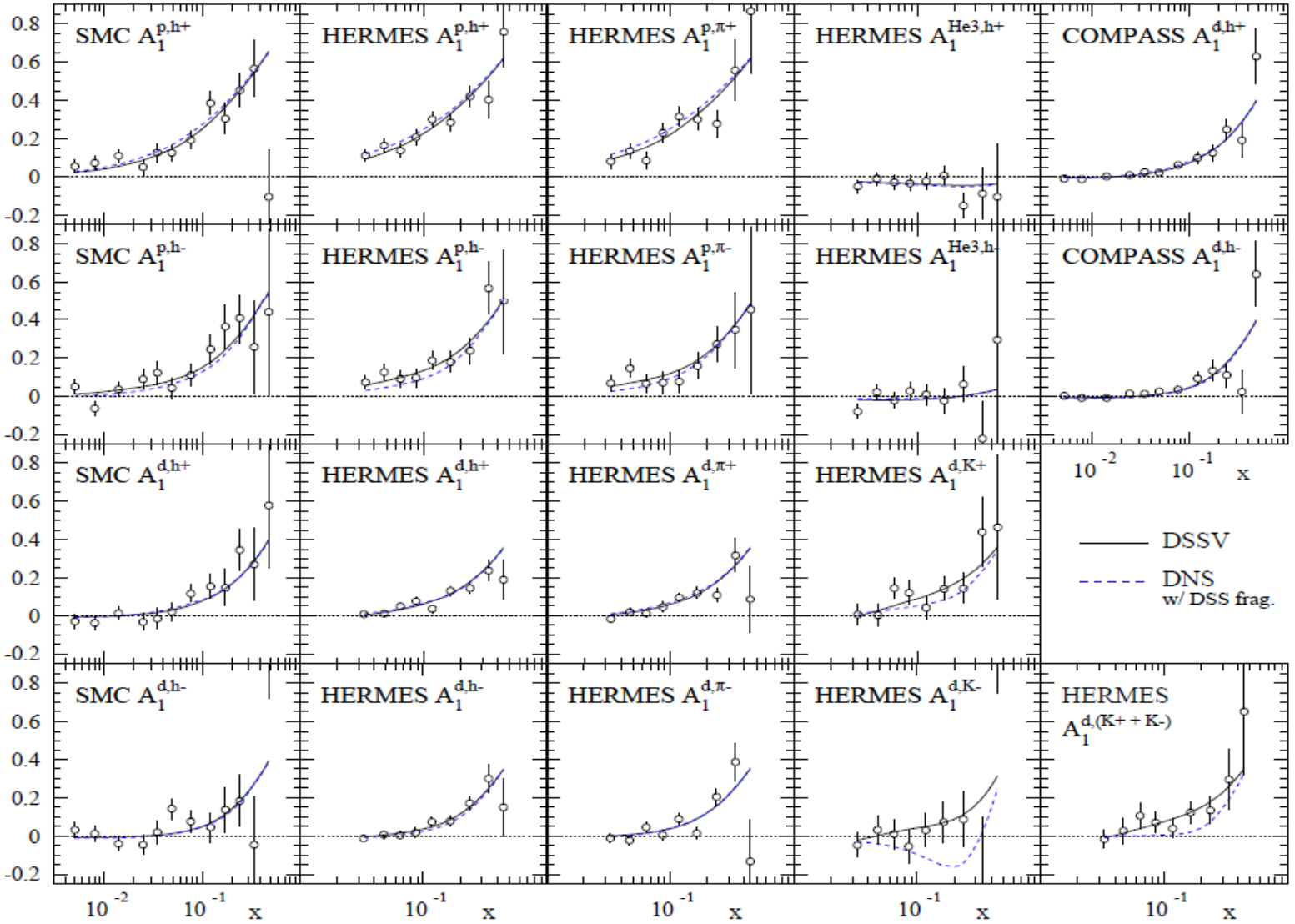
- Nice data!
- Q^2 dependence of g_1 data described in QCD
- Limited kinematic range (c.f. Collider)

Inclusive World data



CERN | SLAC | DESY | JLab

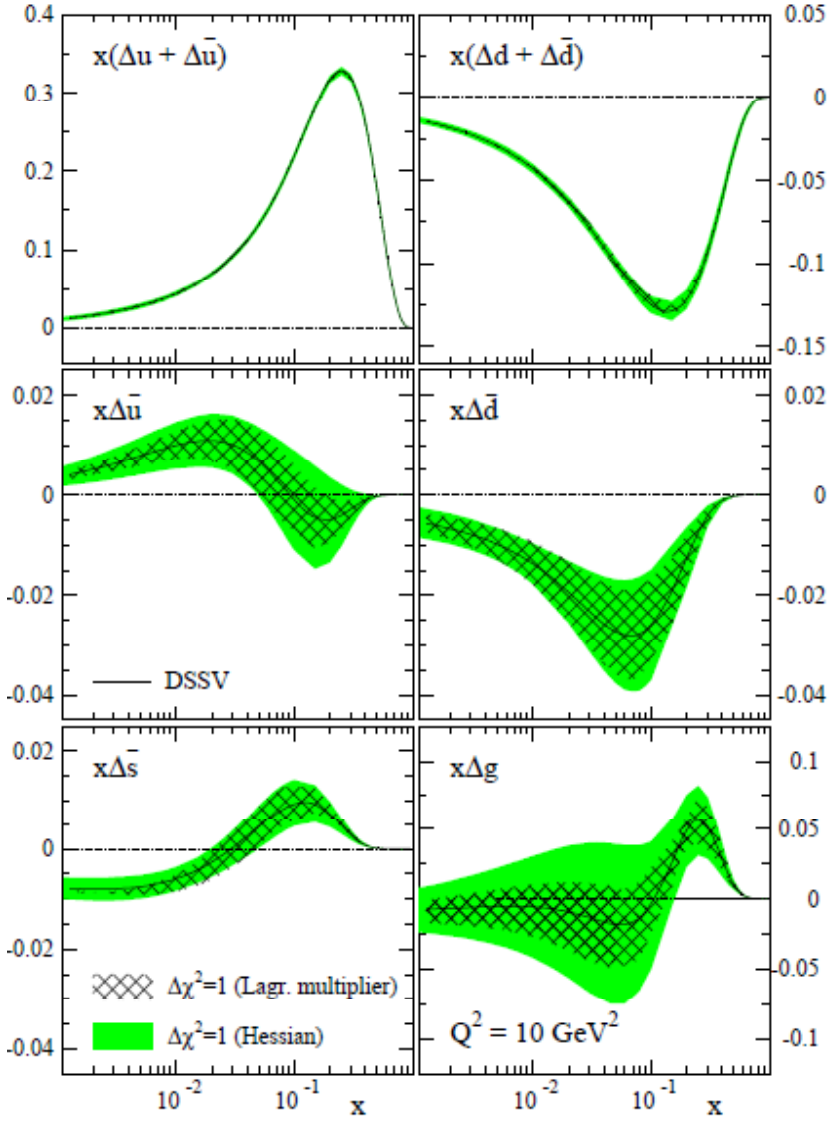
Semi-Inclusive World Data



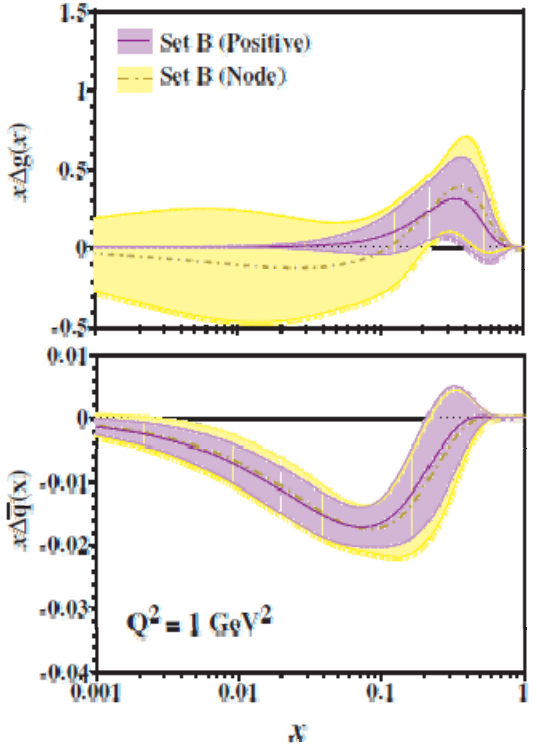
CERN & DESY

Selected Results from two Global Fits

DSSV

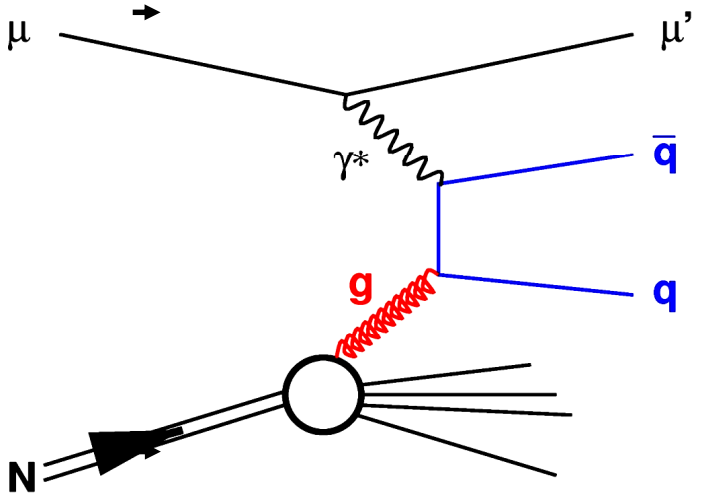


Hirai, Kumano, Saito



- Quark distributions well determined
- Possibility of a node @ x=0.1 in Δg(x)
- SIDIS prefer Δs>0 (x>0.01)
  Incl. data require Δs<0 (SU3)
  Fits give indication for a node

Direct Access to the Gluon Polarization (SIDIS)



- Direct measurement of $\Delta G/G$ in **Photon-Gluon-Fusion**

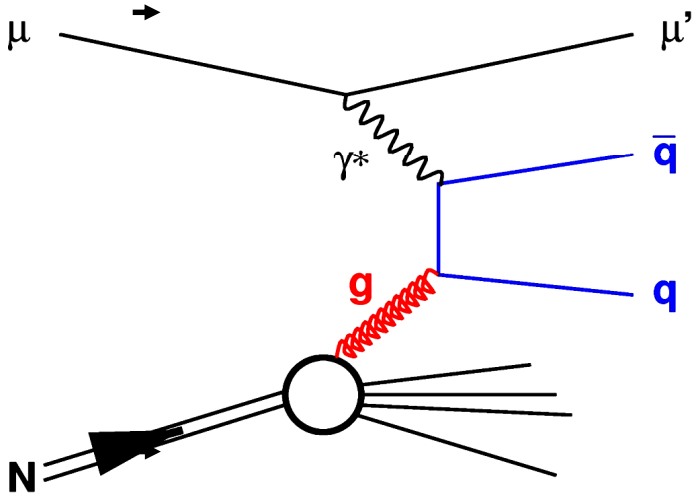
$$A_{\parallel} = R_{pgf} \langle \hat{a}_{pdf} \rangle \left\langle \frac{\Delta g}{g} \right\rangle$$

Strategies to suppress background:

- **q = c**
  - **charm fragmentation:**
    - **D^0, D^* (60%)**
    - **D^+ (20%)**
    - **D^+_s, Λ^+_c (10% each)**
- **Hadrons with large p_T**
  - **q = u, d, s**

- single charmed meson
  - quasi-real photons
  - AROMA,RAPGAP
- high-p_T hadron pairs (no ID of π, K)
  - $Q^2 > 1$ GeV^2
  - LEPTO
  - $Q^2 < 1$ GeV^2 / unmeas.
  - PYTHIA
- high-p_T single hadron
  - small Q^2 / unmeasured
  - PYTHIA

Direct Access to the Gluon Polarization (SIDIS)



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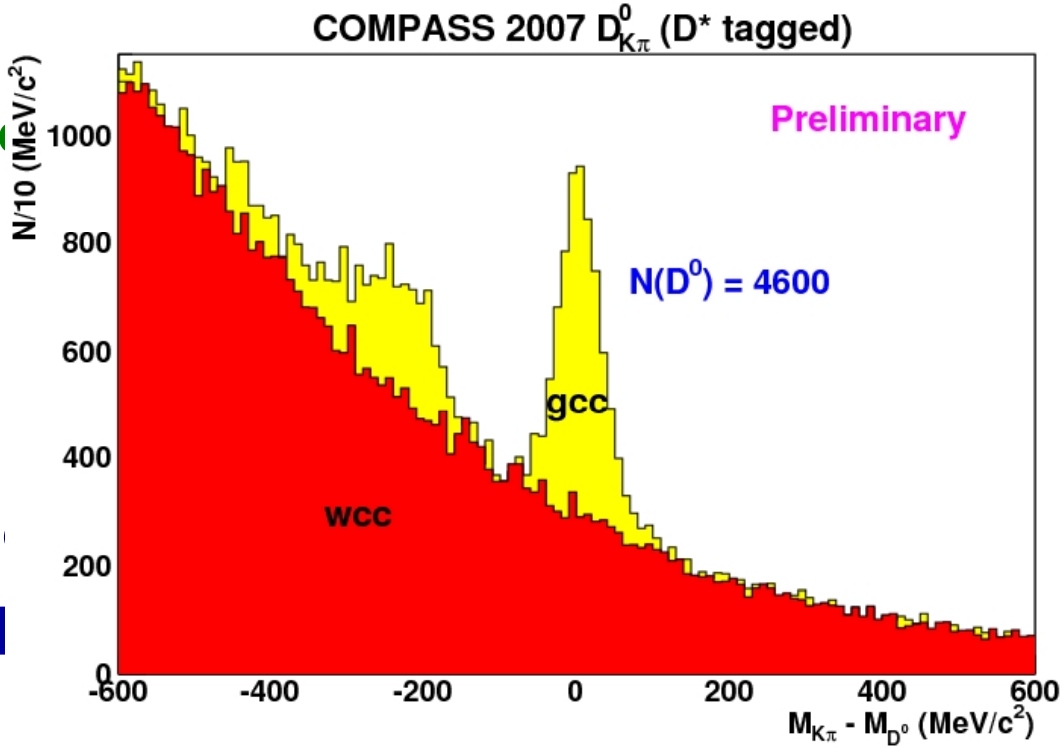
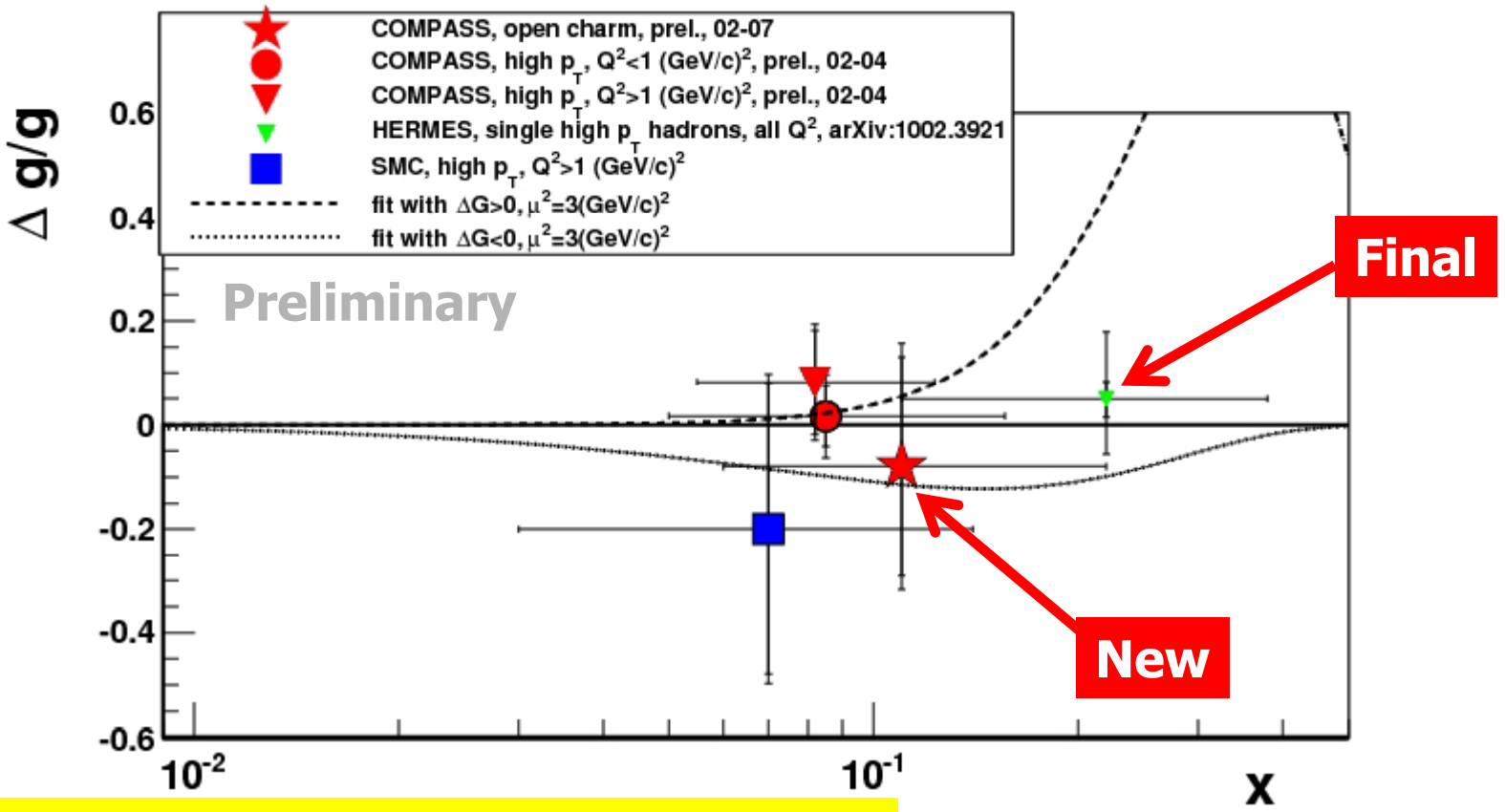
    - **D^+ (20%)**
    - **D^+_s, Λ^+_c (10% ea**
- **Hadrons with large p**
  - **q = u, d, s**



Summary Gluon Polarization

Presently all Analysis in LO only



COMPASS Open Charm:

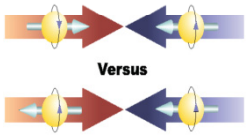
$\Delta G/G$=-0.08+- 0.21(stat) +- 0.11(sys.)
(Systematic error still under investigations)

(Value supersedes previous publication)

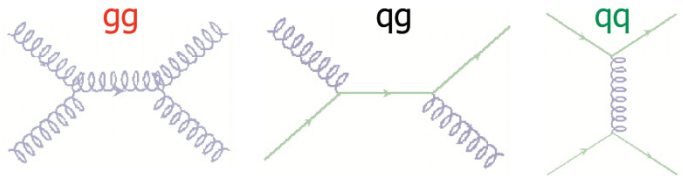
C.Franco

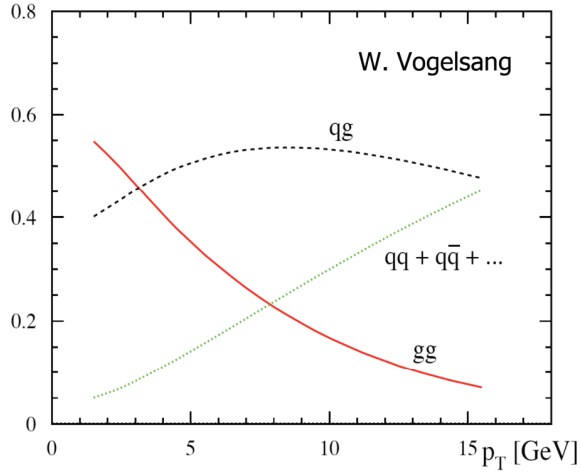
Gluon Polarization from RHIC

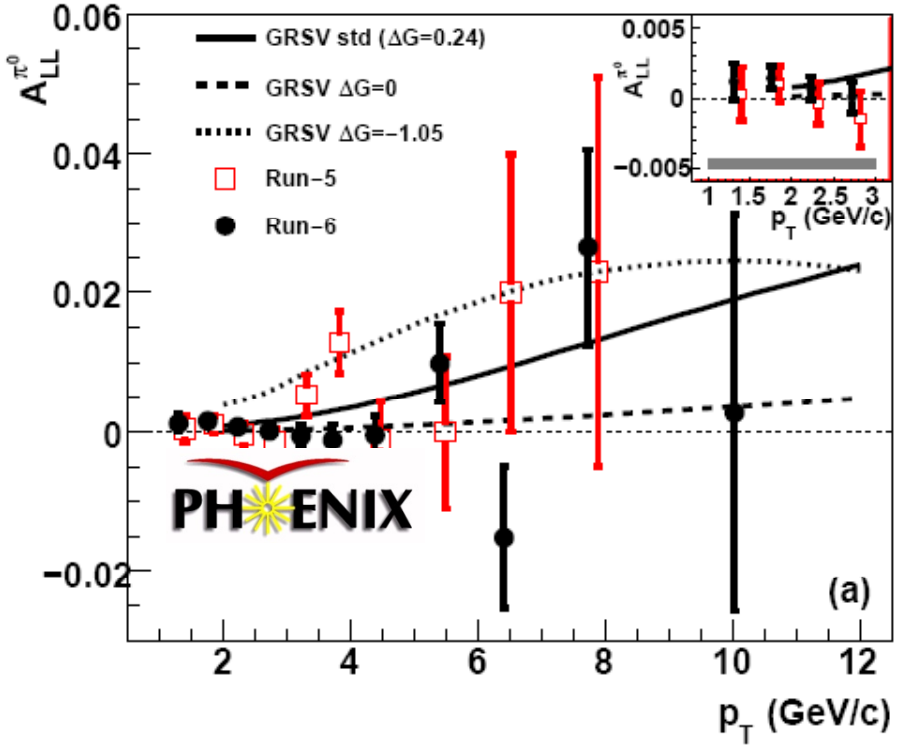
One example from PHENIX & STAR:

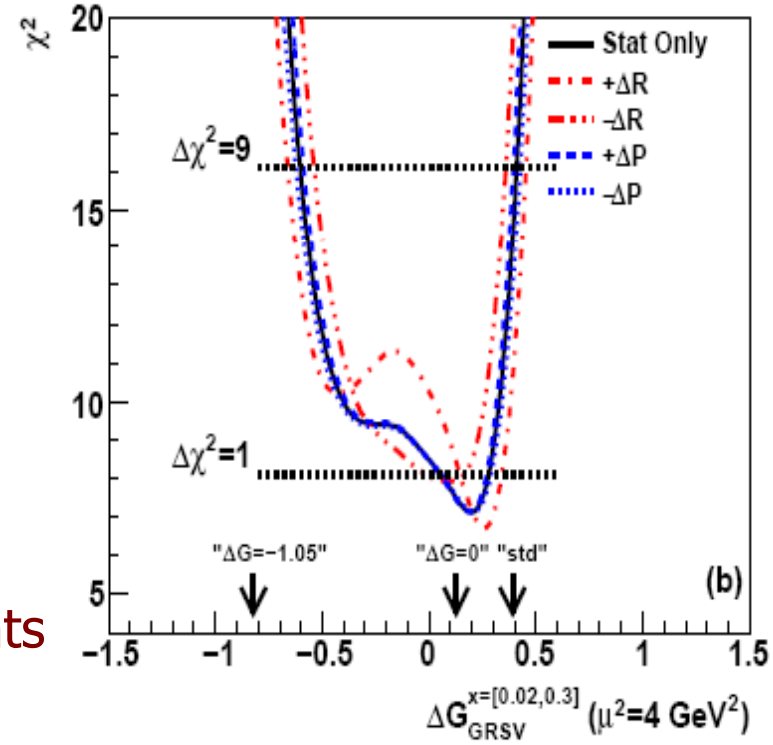


$$p^{\uparrow}p^{\uparrow} \rightarrow \pi^0 X$$









- Confirmation of lepton scattering experiments
- Impact on extraction of Δg(x) in QCD-fits

Transverse Spin Structure

Single Hadron Production Cross Section

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h-}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+P_{beam}\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+\,P_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+\,P_L P_{beam}\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$$+\,|\boldsymbol{P}_T|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

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

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

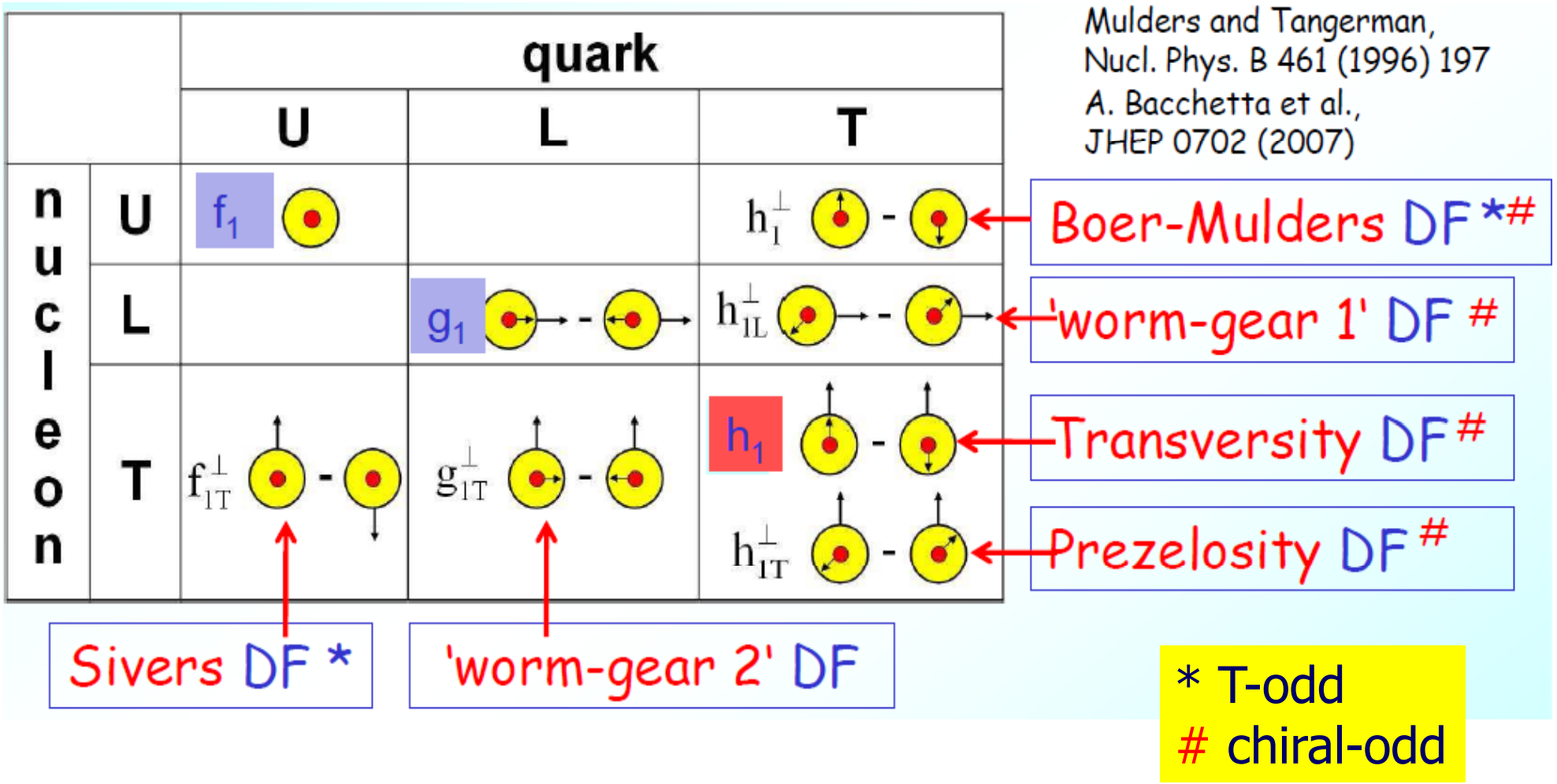
$$+\,|\boldsymbol{P}_T|P_{beam}\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

- **General expression**
- **Valid for**
  - ☑ **SIDIS**
  - ☑ **exclusive reactions**
- **for entire phase space (TFR, CFR)**

A.Kotzinian NPB 441 (1995) 234
Bacchetta et al, JHEP 0702:093,2007

Transverse Momentum Dependent PDFs

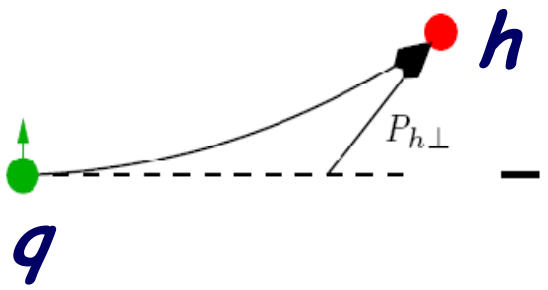


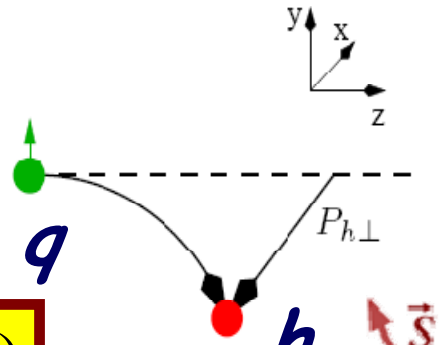
- Only f_1 and g_1 measurable in inclusive DIS, all others in SIDIS

Transversity DF & Collins FF

- The Collins FF $H_1^{\perp q}(z, p_T)$ correlates the transverse spin of the fragmenting quark and the transverse momentum $P_{h\perp}$ of the produced hadron h

N/q	U	L	T	
U	f_1		$h_1^\perp$	
L		g_1	$h_{1L}^\perp$	
T	$f_{1T}^\perp$	g_{1T}	h_1	$h_{1T}^\perp$

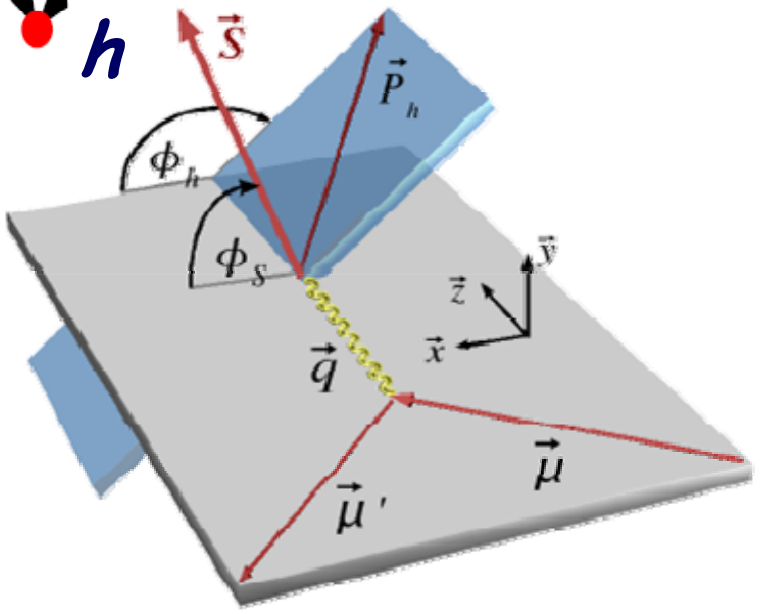




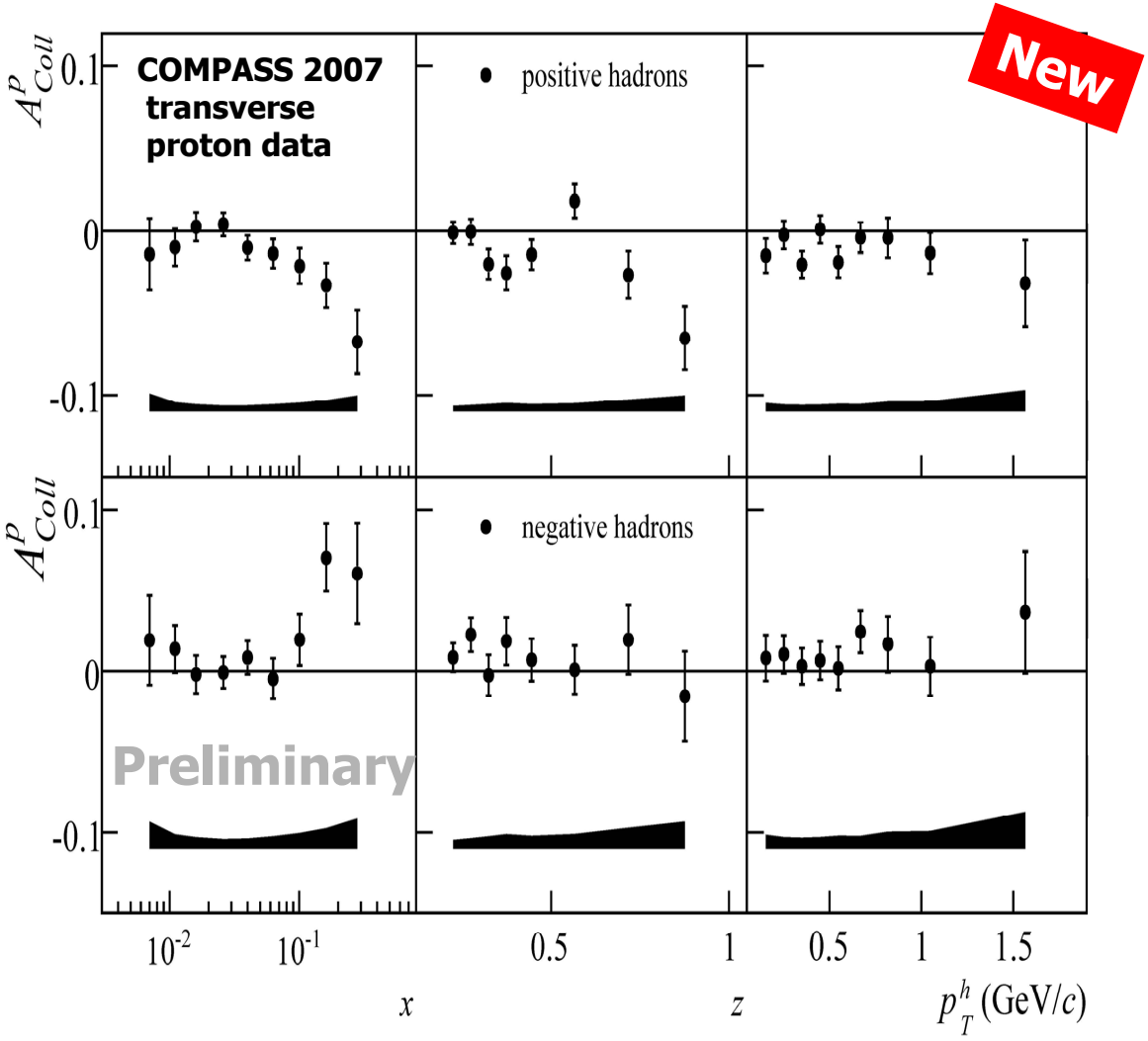
$$A_{\text{Coll}} \propto \frac{\sum_q e_q^2 \; h_1^q(x) \cdot H_1^{\perp q}(z, p_T)}{\sum_q e_q^2 \; f^q(x) \cdot D_q^h(z)}$$

$$A_{Coll} = \frac{A_{UT}^{\sin\phi}}{D_{NN} \cdot f \cdot P}$$

$$\Phi_C = \phi_h - \phi_s - \pi$$



Transversity



- **Collins FF and Transversity distribution function are sizeable**
- **π^- asymmetries unexpectedly large**
- **Indication for large contribution from unfavoured FF**

$$H_1^{\perp q}{}_{unf} \simeq -H_1^{\perp q}{}_{fav}$$

Two Hadron Interference FF

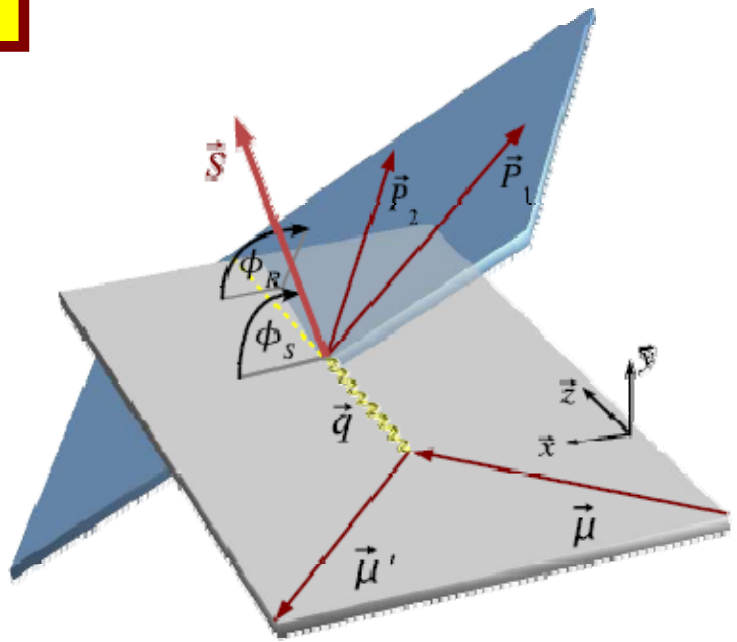
Alternative: couple $h_1^{\mathrm{q}}(x)$ to chiral odd 2-hadron interference FF $H_1^{\sphericalangle}$

$$A_{\mathrm{Coll}} \propto \frac{\sum_q e_{\mathrm{q}}^2 \; h_1^{\mathrm{q}}(x) \cdot H_1^{\sphericalangle \mathrm{q}}(z, M_{\mathrm{T}}^2)}{\sum_q e_{\mathrm{q}}^2 \; f^{\mathrm{q}}(x) \cdot D_{\mathrm{q}}^{\mathrm{h}}(z, M_{\mathrm{T}}^2)}$$

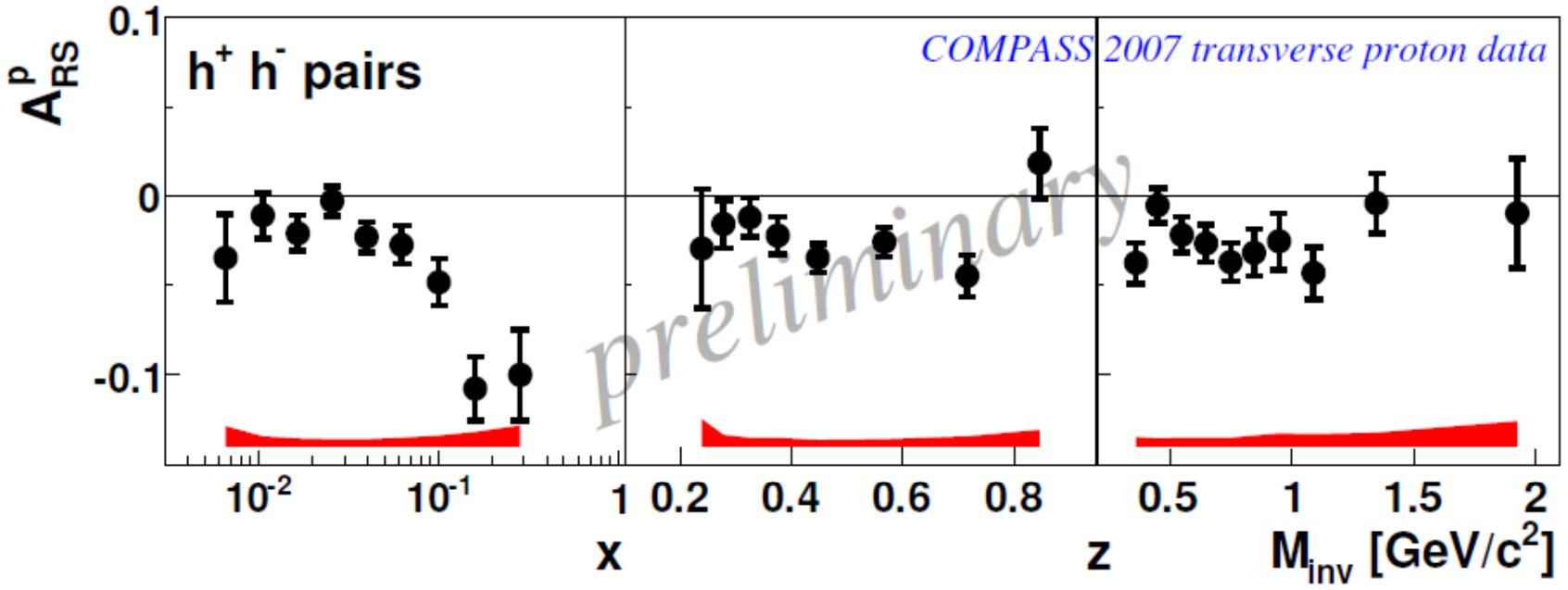
cross-section asymmetry:

$$\frac{\Delta\sigma}{\sigma} \propto A_{RS} \sin\phi_{RS} \sin\theta$$

$$\phi_{RS} = \phi_R + \phi_S - \pi; \quad \sin\theta \simeq 1$$



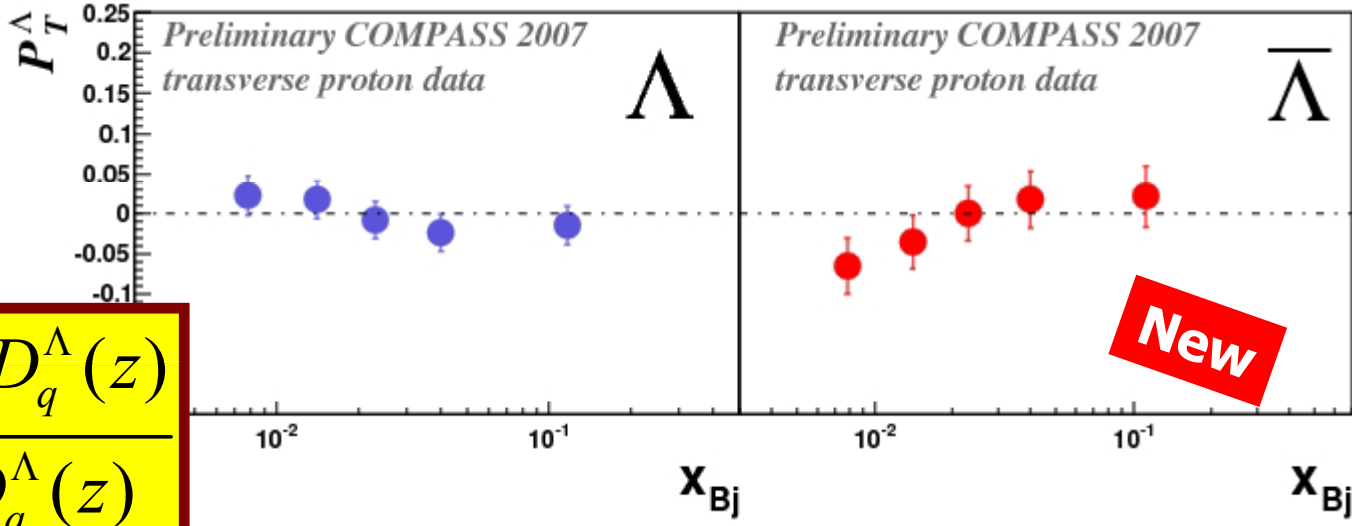
Two Hadron Interference FF



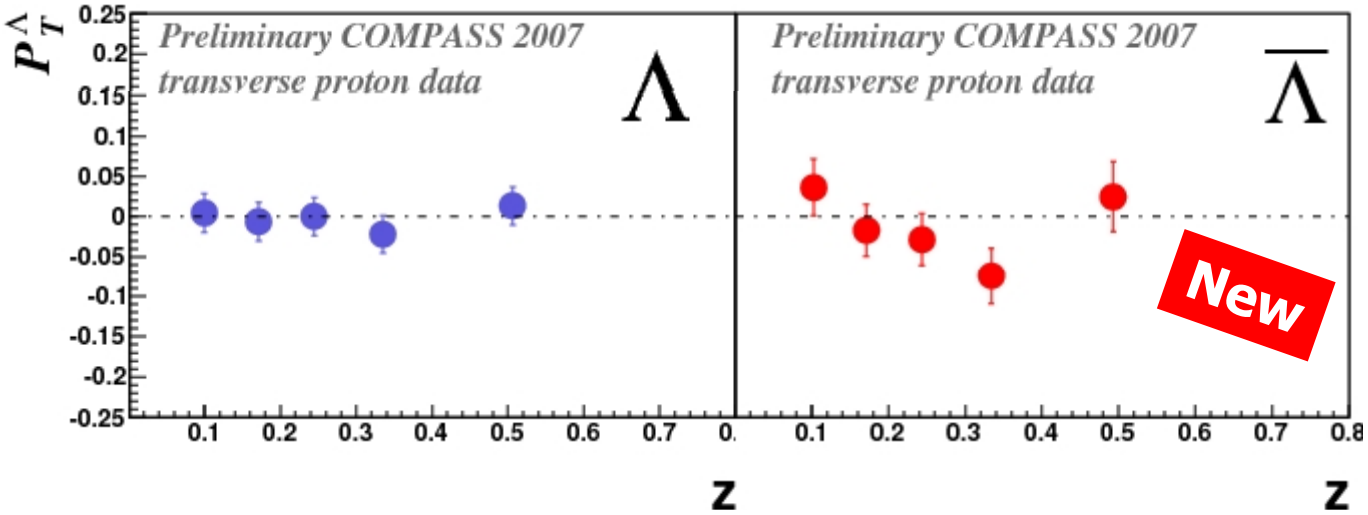
- large asymmetries
- interference FF and transversity sizable

Transversity from Λ polarization

$$P_\Lambda \propto \frac{\sum_q e_q^2 h_1^q(x)\Delta_T D_q^\Lambda(z)}{\sum_q e_q^2 f^q(x) D_q^\Lambda(z)}$$

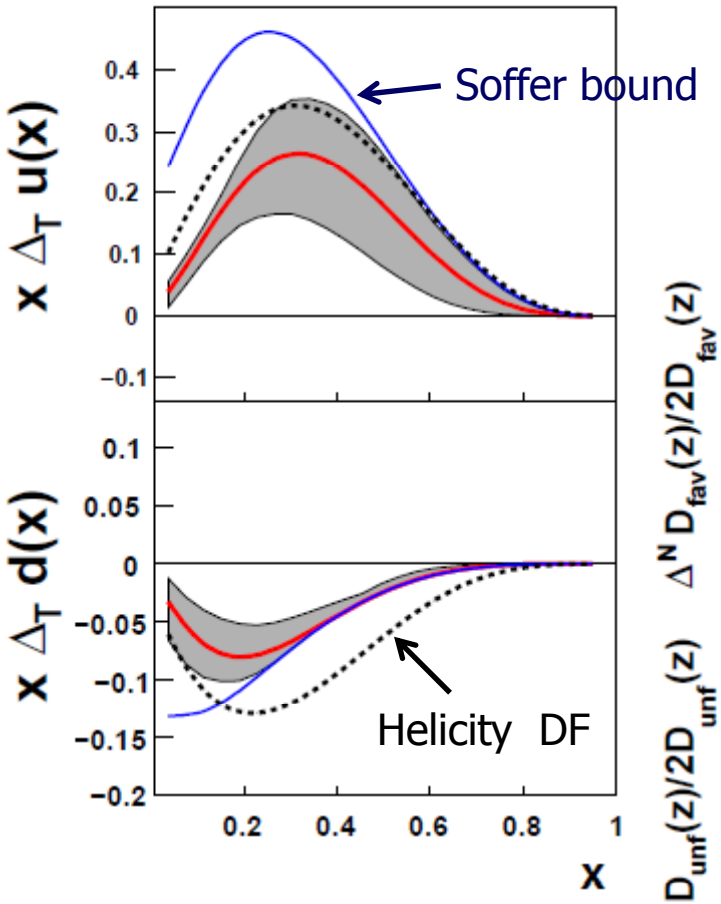


- Indication that $\Delta_T D_q^\Lambda(z)$ might be small



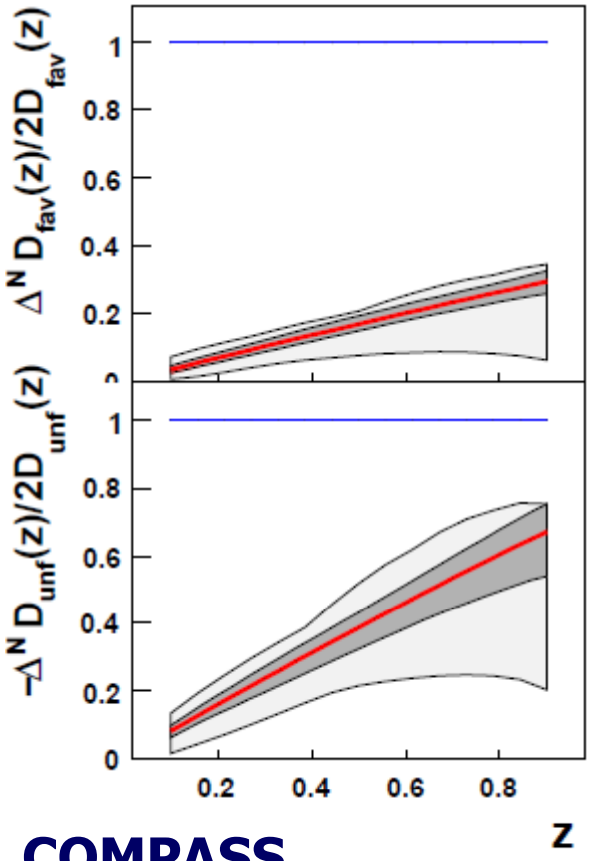
Systematic error: $\sigma_{sys.} \leq 0.74\sigma_{stat.}$

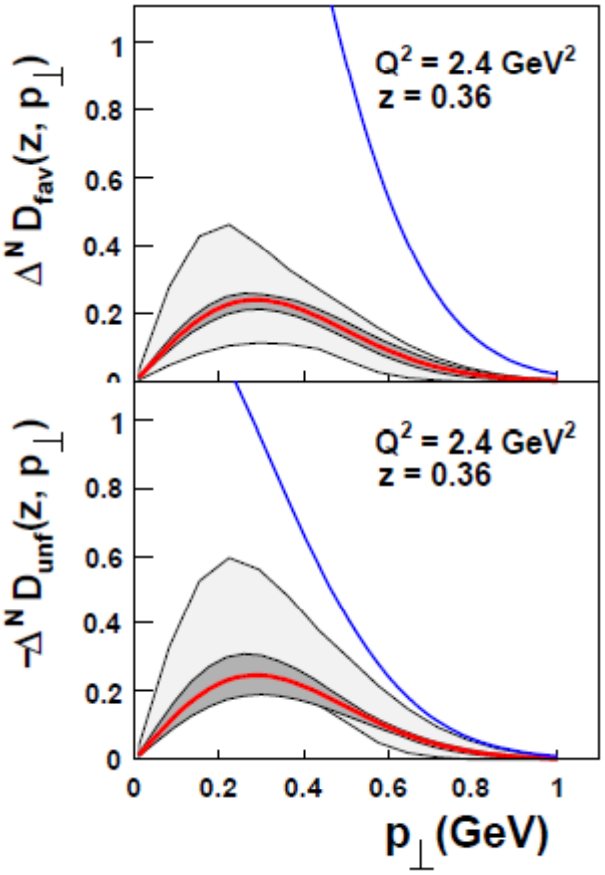
Transversity DF and Collins FF from a Global Fit



- **Indication for large contribution from unfavoured FF**

$$H_1^{\perp q}{}_{unf} \simeq -H_1^{\perp q}{}_{fav}$$





- **Extraction from Belle, COMPASS, HERMES data @ Q²=2.4 (GeV/c)²**

Anselmino et al.

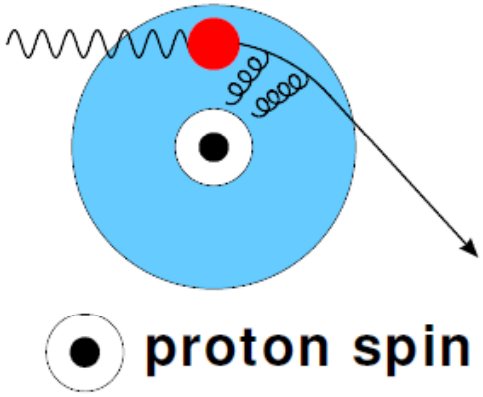
Sivers

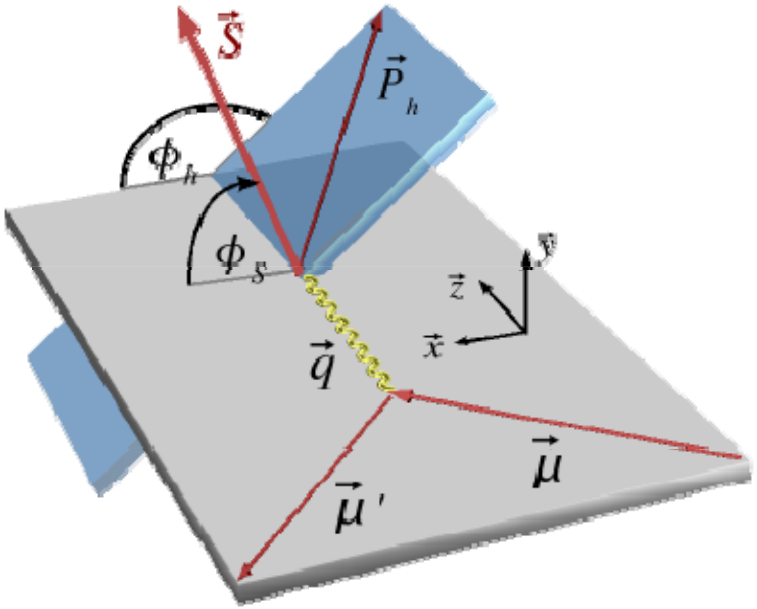
$$A_{Siv} \propto \frac{\sum_q e_q^2 \, f_{1T}^{\perp q}(x, p_T^h/z) \cdot D_q^h(z)}{\sum_q e_q^2 \, f^q(x, p_T^h/z) \cdot D_q^h(z)}$$

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

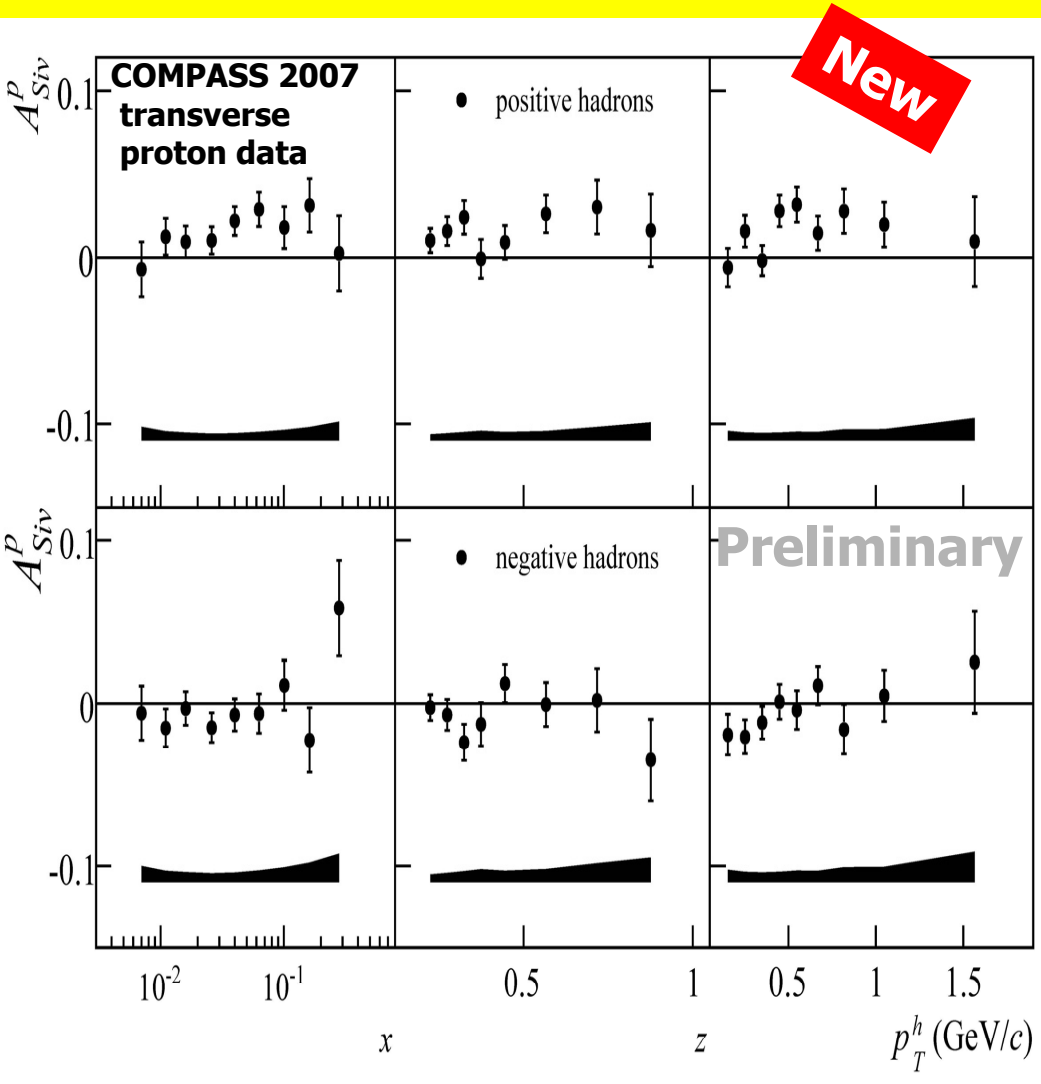
$$\frac{\Delta\sigma}{\sigma} \propto A_{Siv} \sin\Phi_S$$

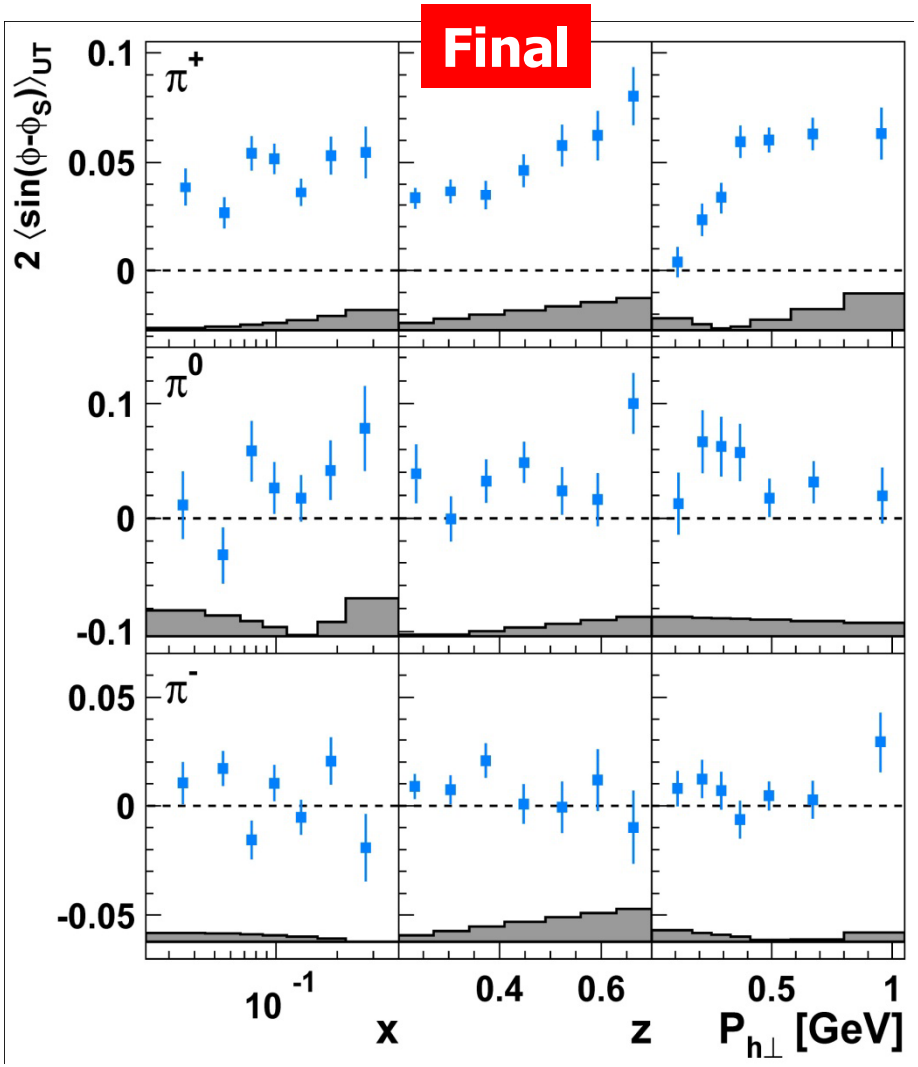
$$\Phi_S = \phi_h - \phi_S$$





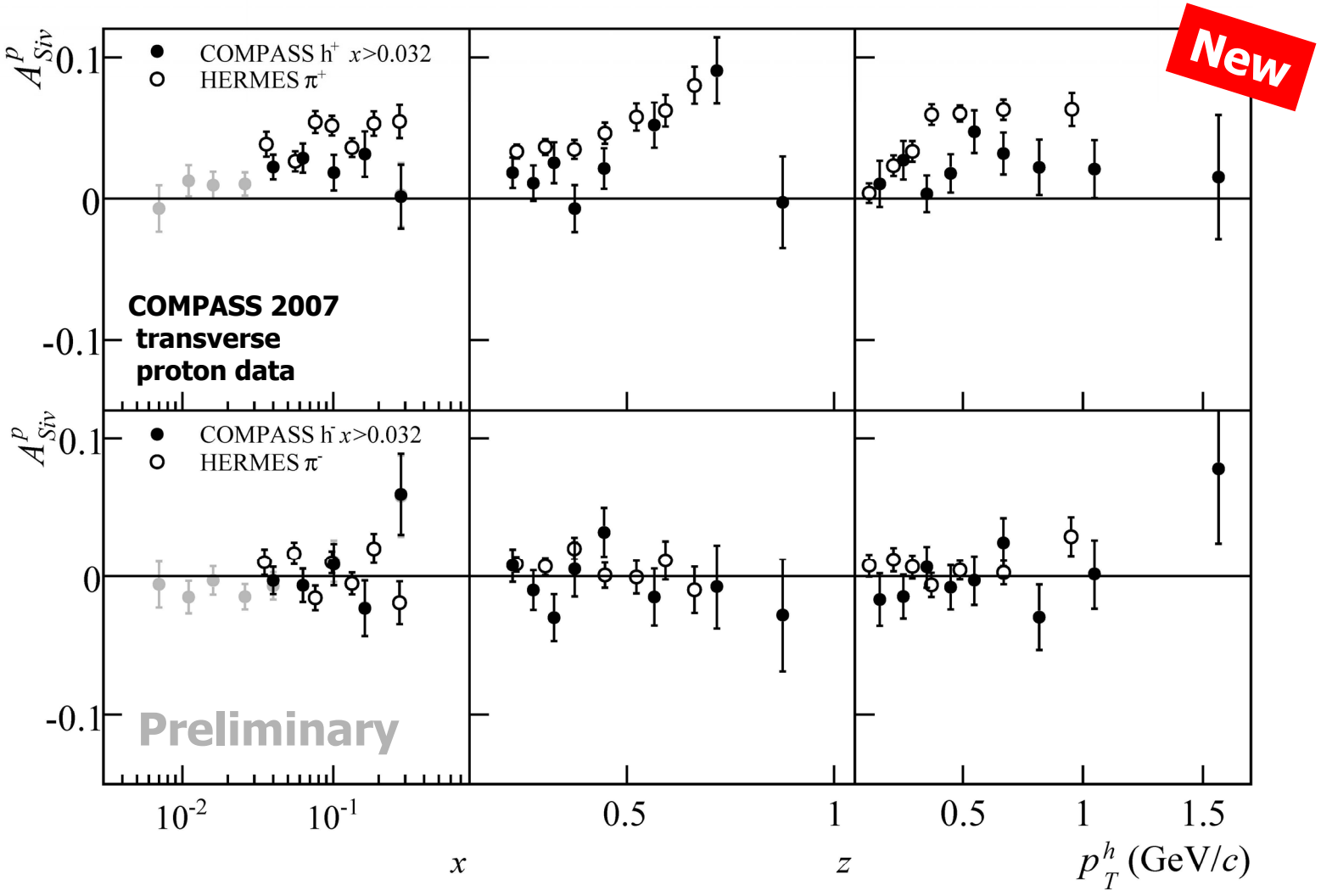
Sivers Asmmetries





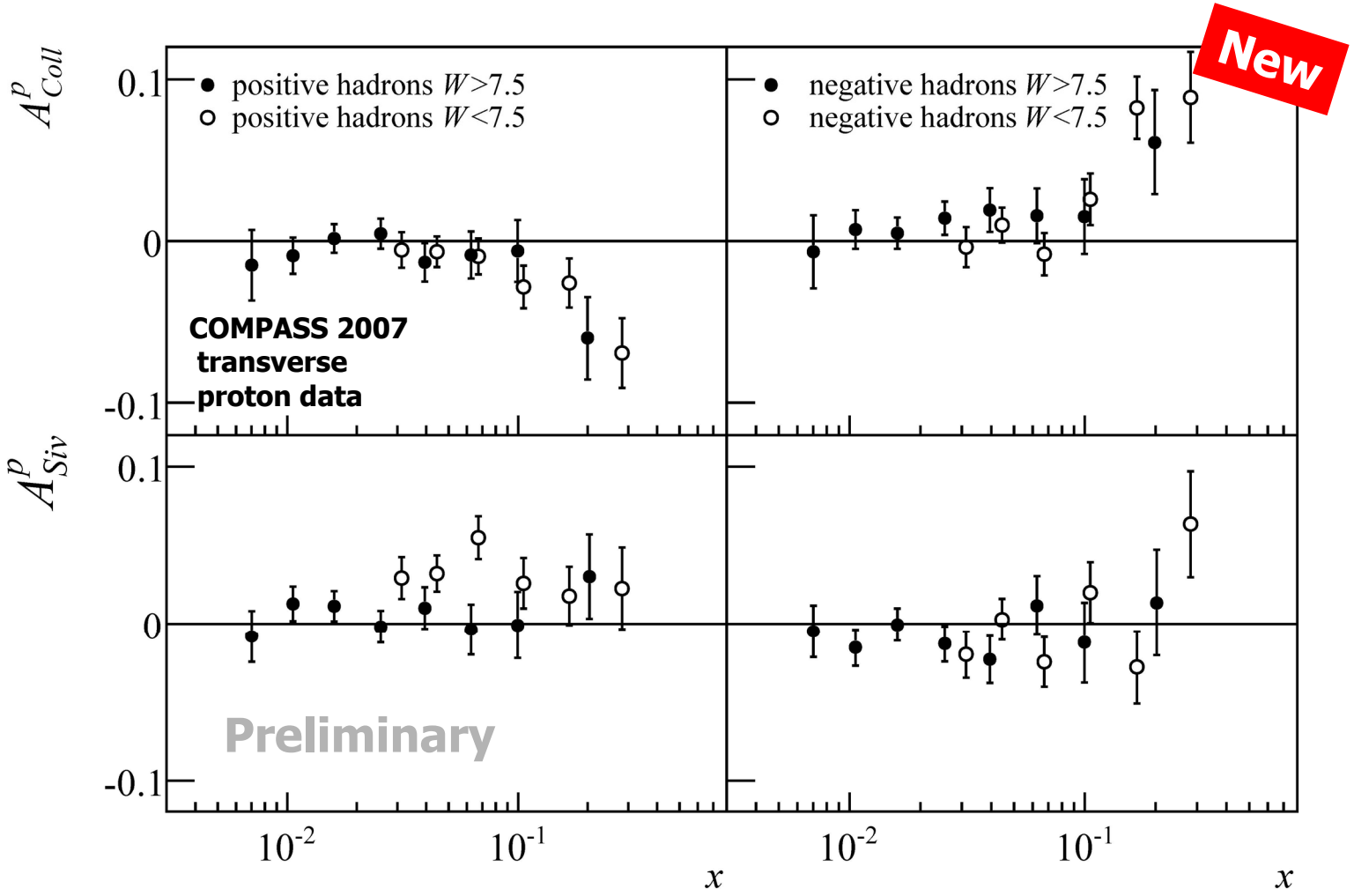
- **Experimental evidence for orbital momentum of the quarks**

Sivers Asymmetries

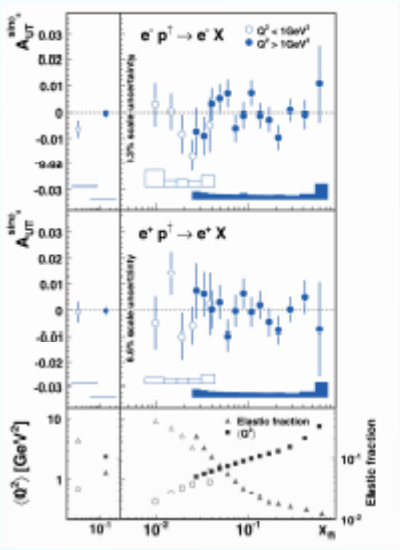


Systematic error - h^+:$\sigma=0.8\sigma_{stat}$; h^+:$\sigma=0.4\sigma_{stat}$; ±0.01 scale (abs)

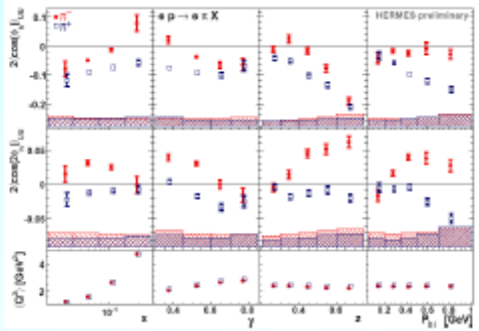
Kinematic Effects



- ff



2-γ exchange

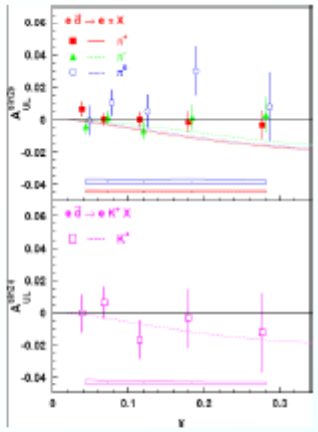


Boer-Mulders DF Cahn

nucleon \ quark	U	L	T
U	f_1		$h_1^\perp$ - ○ ← Boer-Mulders DF *#
L		g_1 → ○ - ○	$h_{1L}^\perp$ → ○ - ○ ← worm-gear 1' DF #
T	$f_{1T}^\perp$ ○ - ○	$g_{1T}^\perp$ ○ - ○	h_1 ○ - ○ ← Transversity DF #
			$h_{1T}^\perp$ ○ - ○ ← Prezelosity DF #

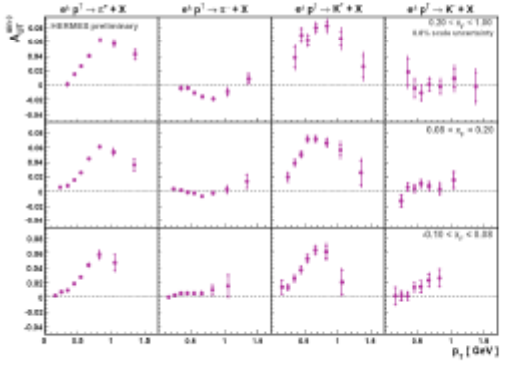
Sivers DF * | 'worm-gear 2' DF

Mulders and Tangerman, Nucl. Phys. B 461 (1996) 197
A. Bacchetta et al., JHEP 0702 (2007)

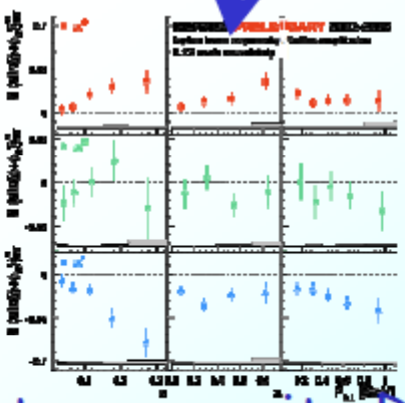


Worm-gear DF

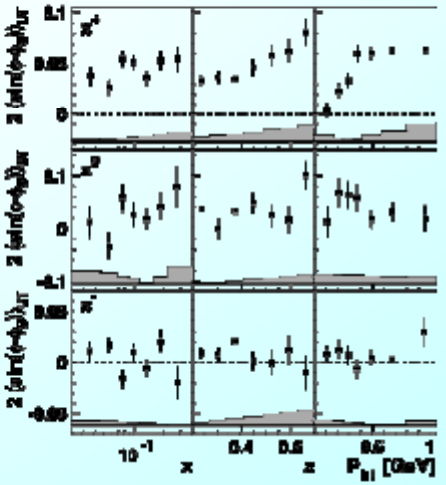
hermes



Inclusive hadron TSA



transversity DF



Sivers DF

K.Rith

Outlook

- Goals: Precise determination of $\Delta g(x)$
  Generalized parton distributions (GPD)
  Orbital angular momentum

- Experimental prospects:

  - Short term: More lepton data from COMPASS & Jlab
    More hadron data from RHIC

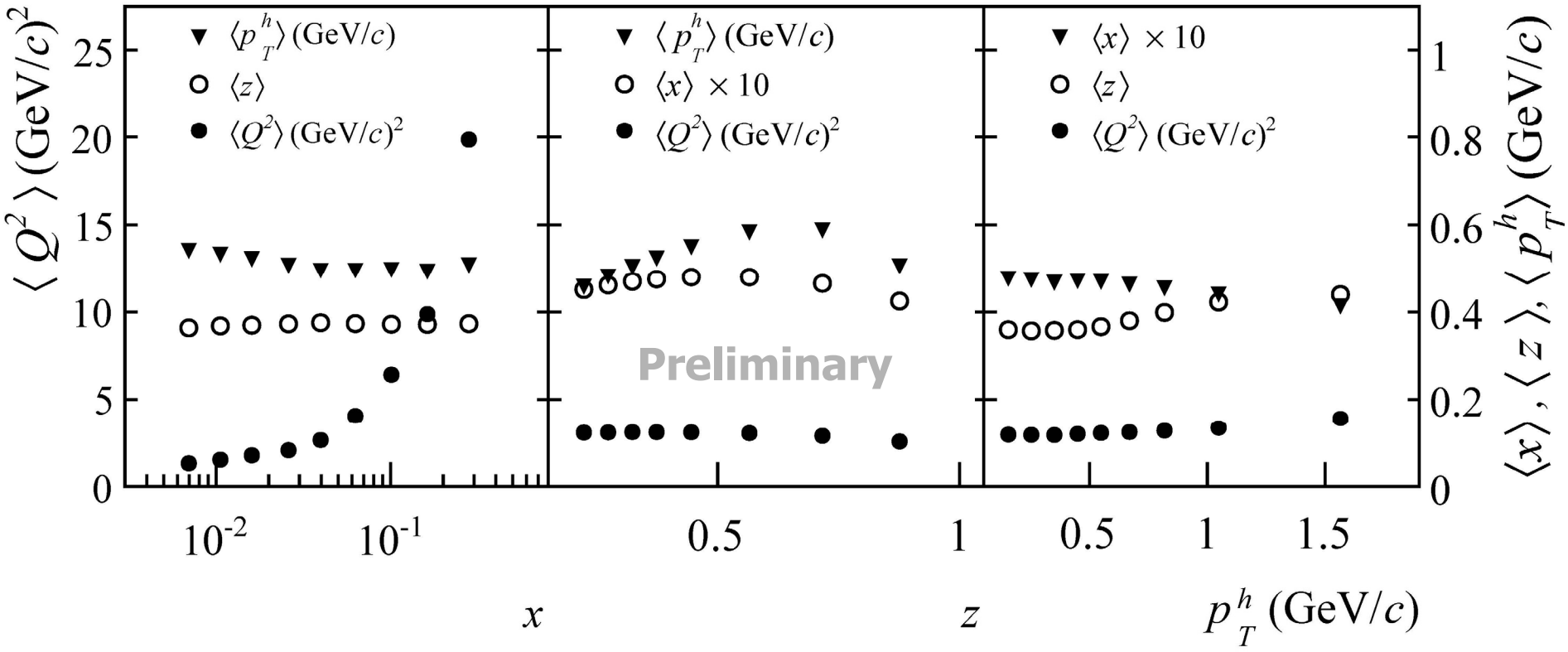
  - Longer term: COMPASS GPD & DY programme
    RHIC upgrade
    JLab 12 GeV

  - Long term: Electron-Ion Colliders: eRHIC, ELIC, ENC

... now you may practice during lunch break

Backup

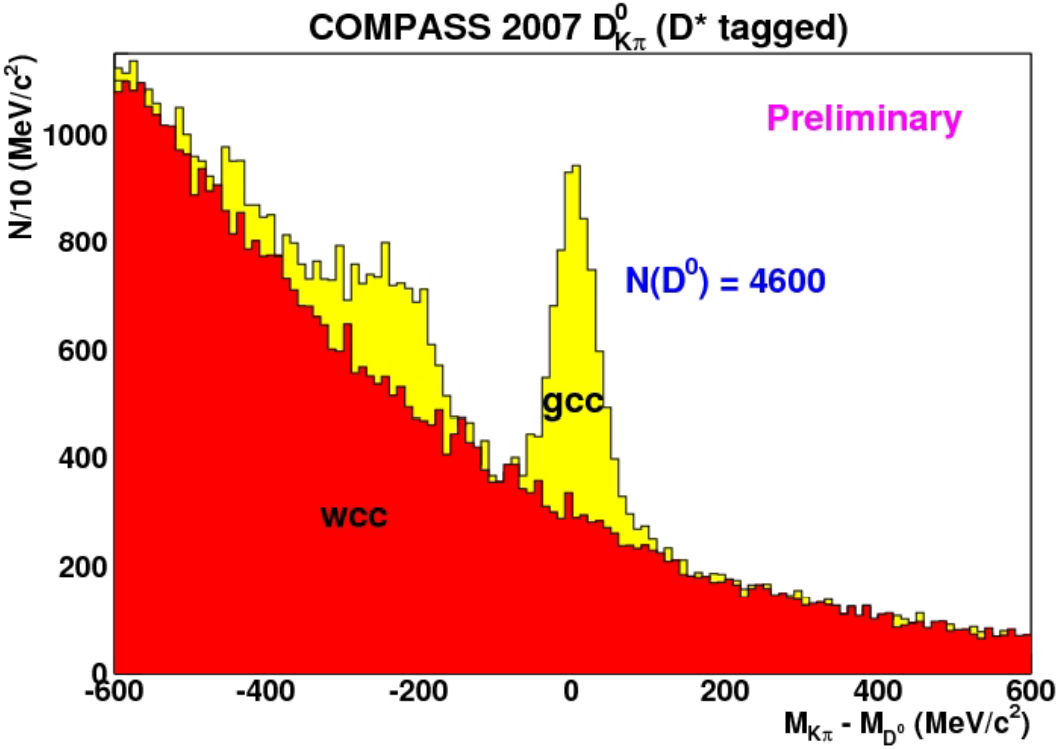
Kinematic Correlation in Sivers Data@ COMPASS



COMPASS 2007 transverse proton data

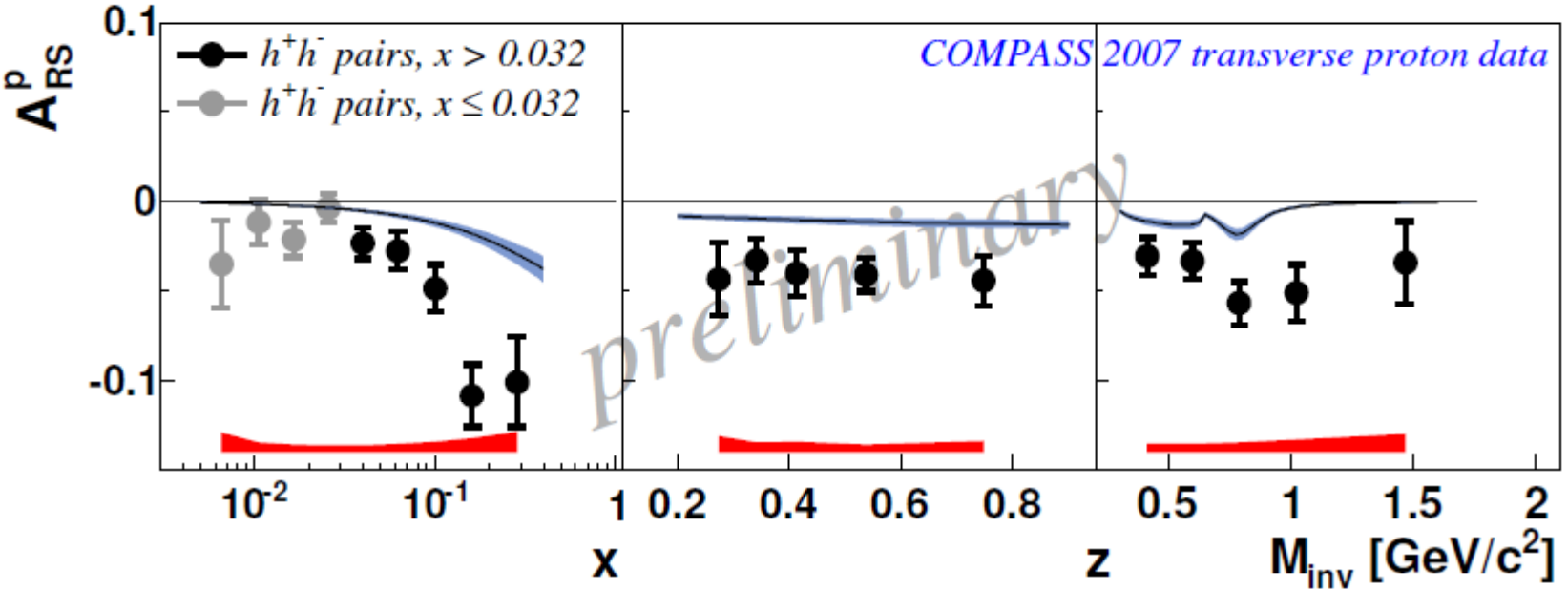
Open Charm

- Little physics background (LO, QCDC)
- Statistics limited, $D \to \pi K$ (BR ~ 4%)
- Large combinatorial background, drastically reduced in D^* channel with slow π_S
- All deuteron data
- new channels in D^* sample
  - sub-threshold kaons
  - 3-body decay with non-observed π^0 (bump)



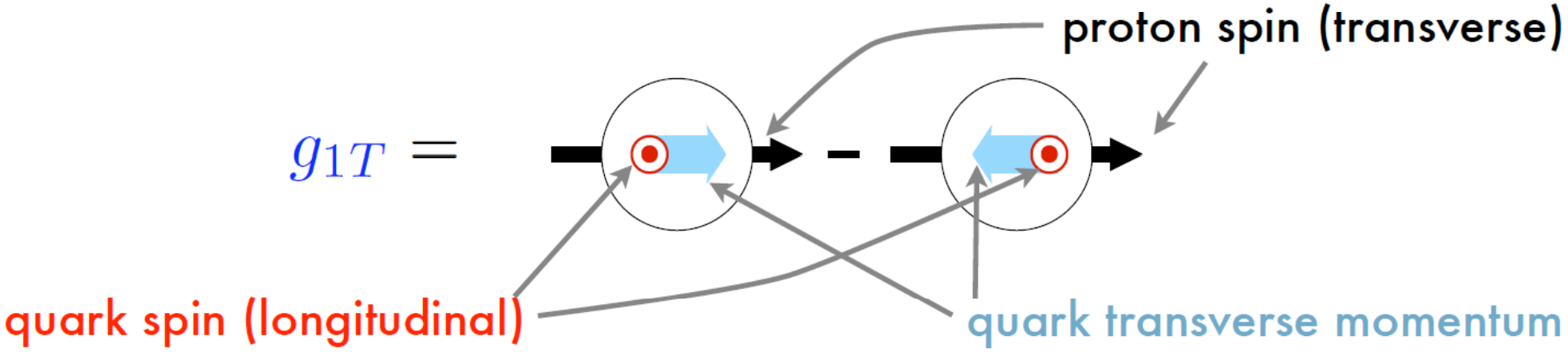
Two Hadron Interference

- Recent fit (dominated by HERMES, COMPASS *p* not yet in)

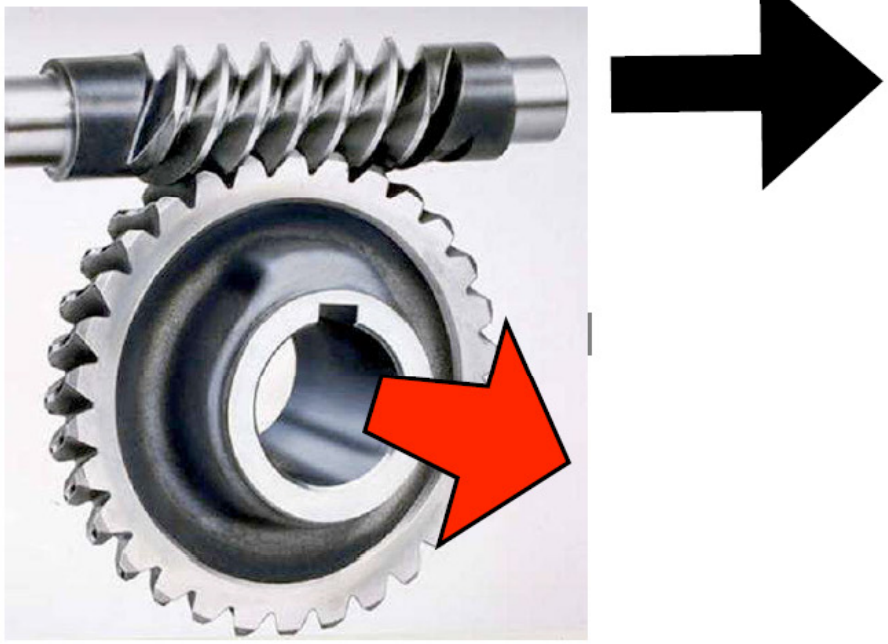


Very recent prediction (Bacchetta, Radici Phys.Rev.D79:034029,2009)

Worm Gear on the Lattice

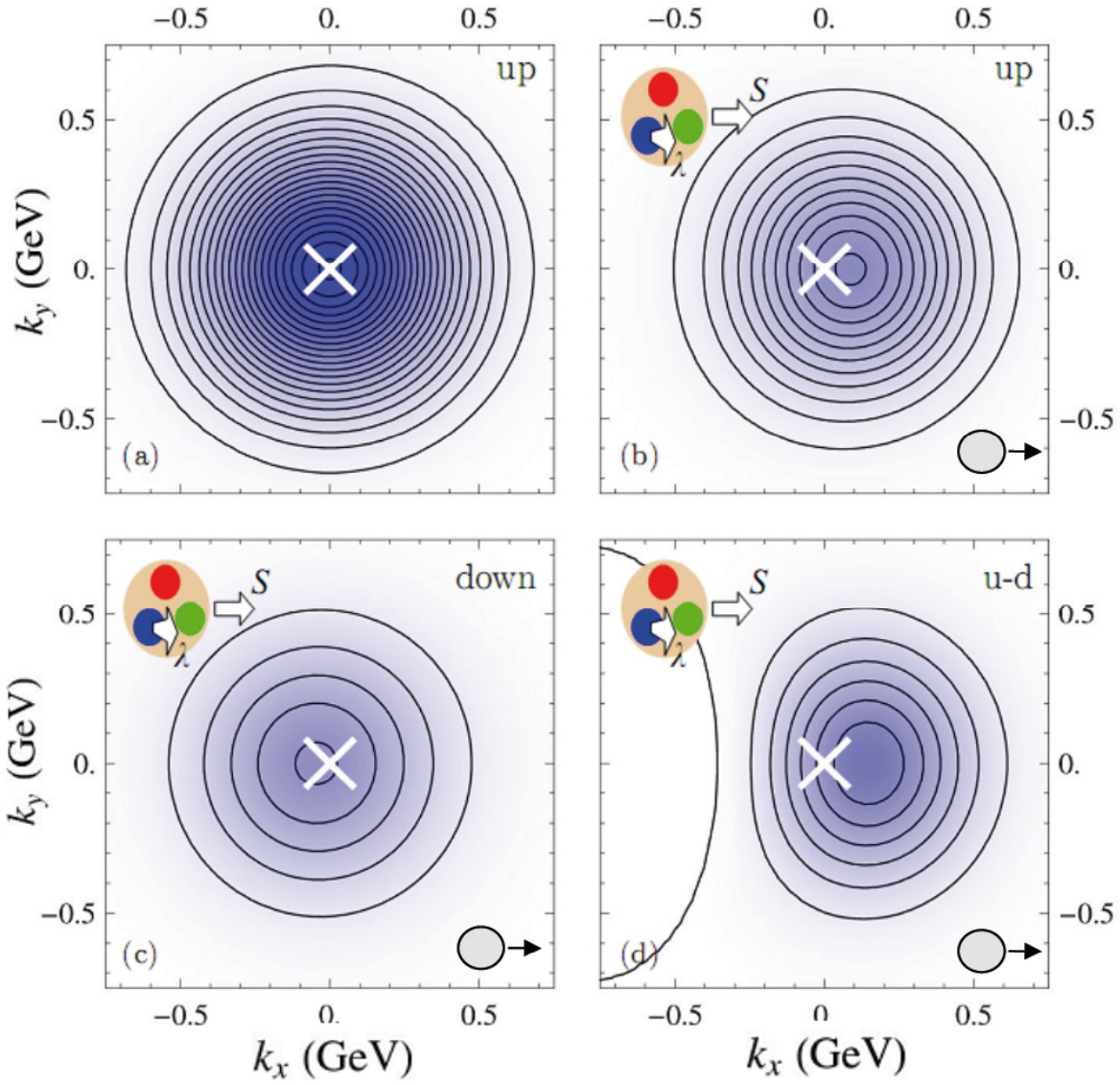


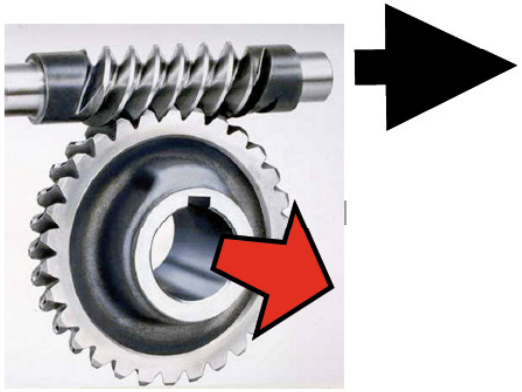
A worm gear



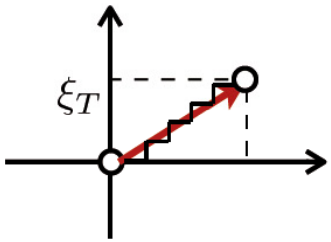
A. Bacchetta

Worm Gear on the Lattice





Caveat: gauge link!



A. Bacchetta