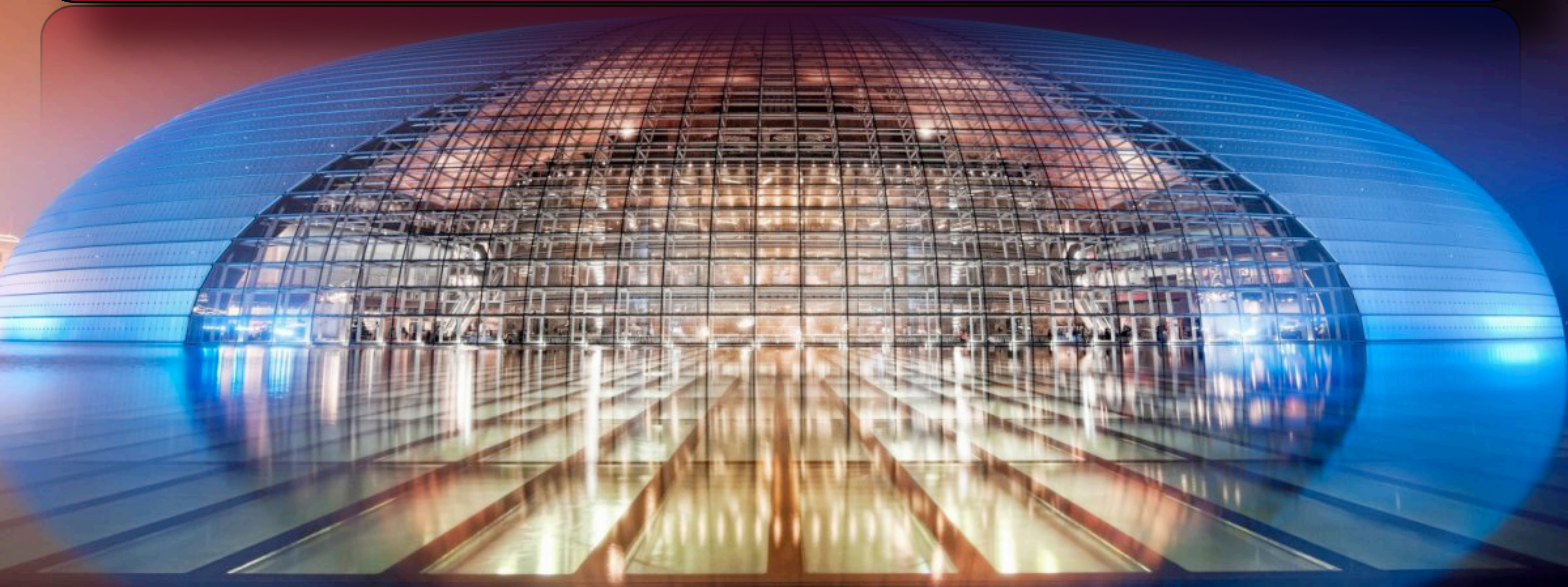
PEKING UNIVERSITY

COMPASS

National Centre for Nuclear Research
Warsaw, Poland

# Gluon Contribution to the Sivers Effect COMPASS Results on Deuteron Target

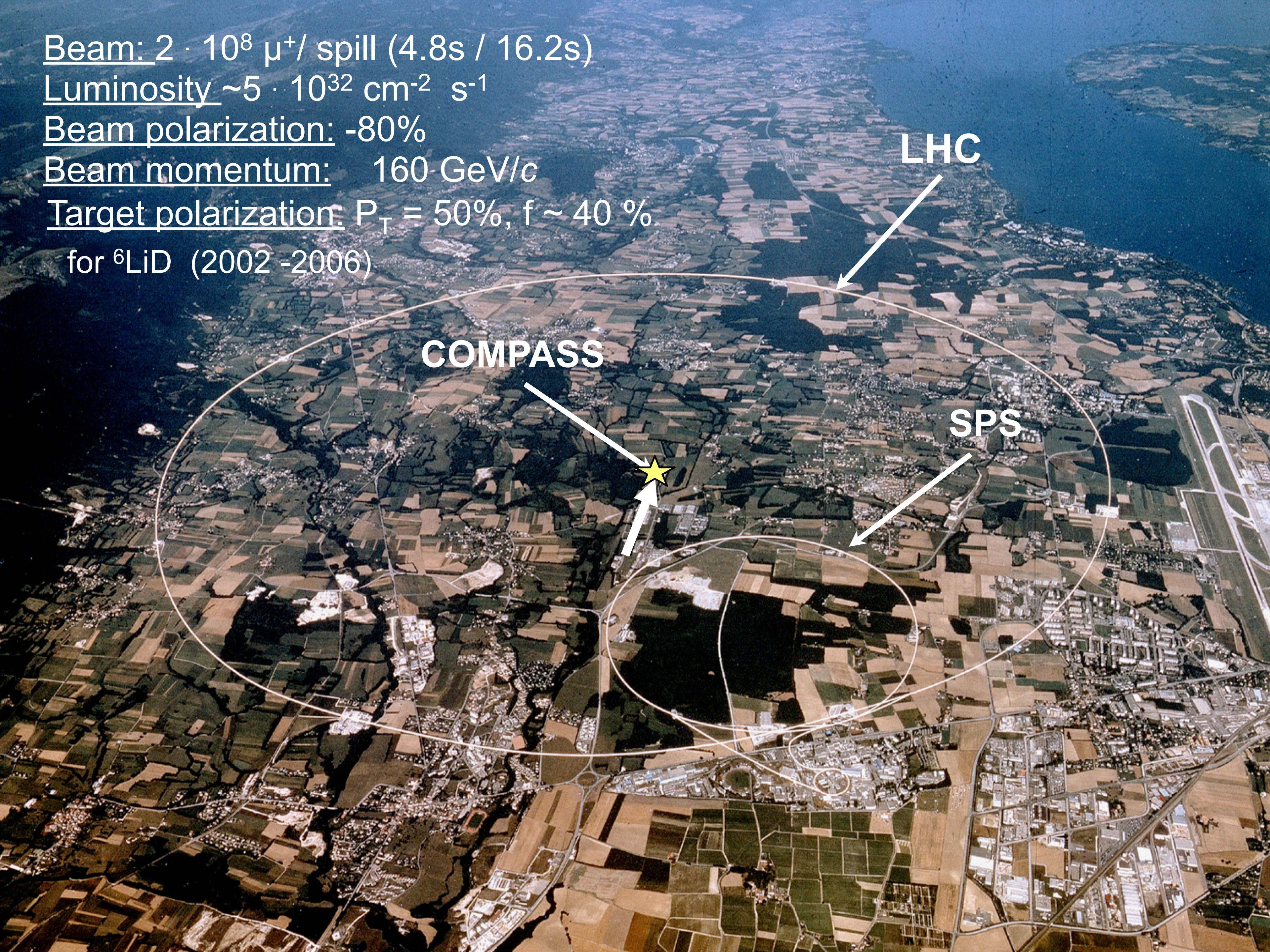

Adam Szabelski
Krzysztof Kurek

**Spin2014**

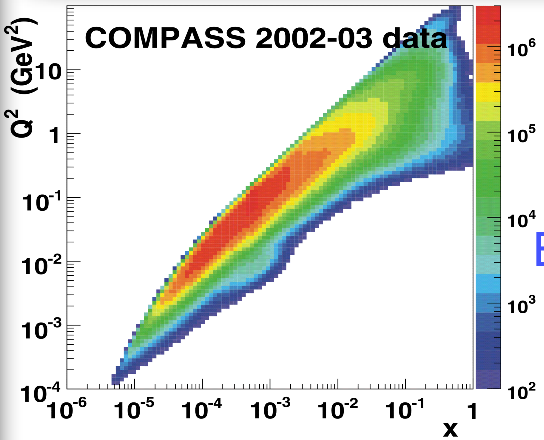
**The 21st International Symposium on Spin Physics**

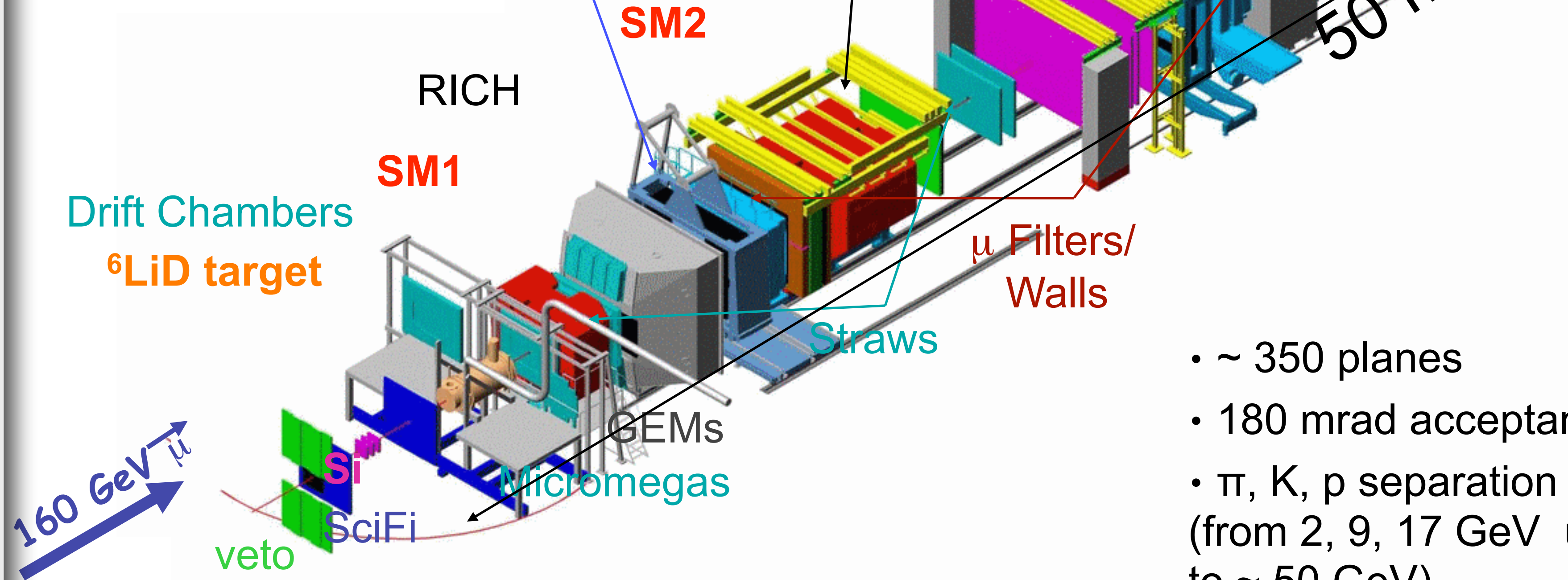
**October 20-24, 2014, Beijing, China**


Beam: $2 \cdot 10^8\ \mu^+$/ spill (4.8s / 16.2s)
Luminosity ~$5 \cdot 10^{32}\ cm^{-2}\ s^{-1}$
Beam polarization: -80%
Beam momentum: 160 GeV/$c$
Target polarization: $P_T$ = 50%, f ~ 40 %
for $^6$LiD (2002 -2006)
LHC
COMPASS
SPS

# The COMPASS spectrometer

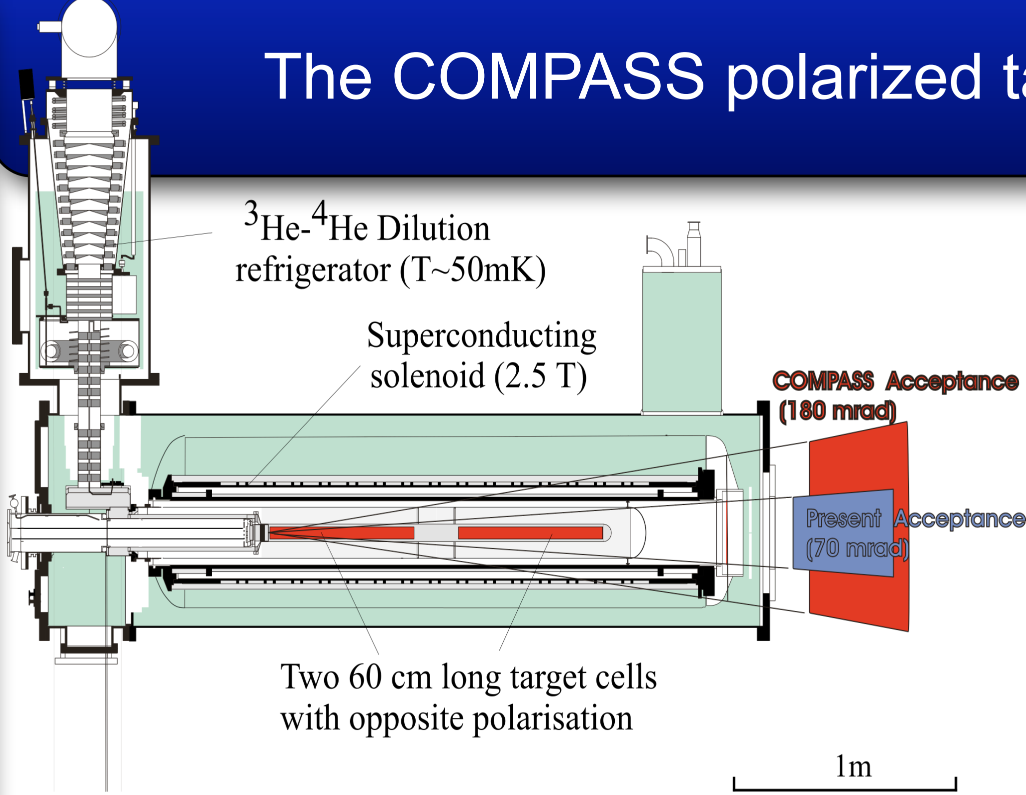
COMPASS in muon run
NIM A 577(2007) 455



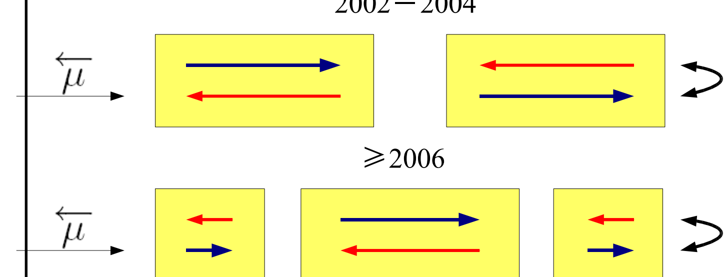

- ~ 350 planes
- 180 mrad acceptance
- π, K, p separation (from 2, 9, 17 GeV up to ~ 50 GeV)

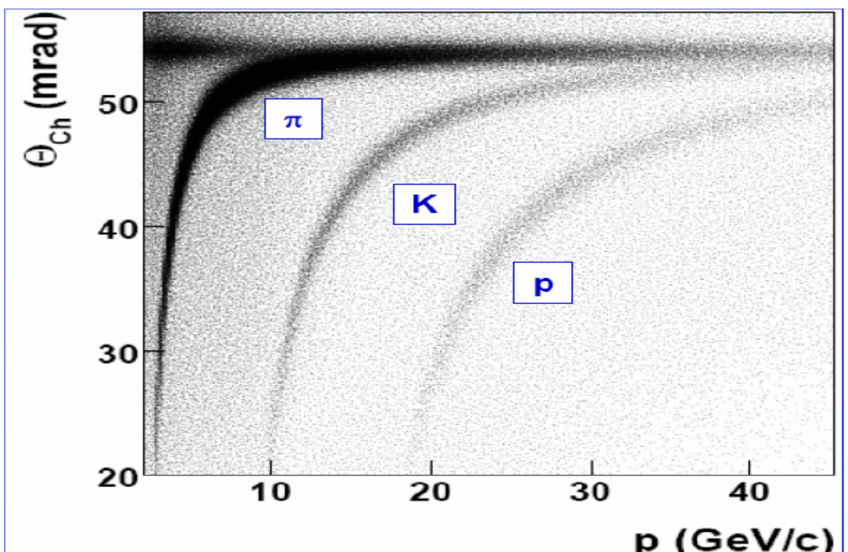
# The COMPASS polarized target and PID




Target material: $^6$LiD
Polarisation: >50%
Dilution factor: ~0.4
Dynamic Nuclear Polarization

2006 - new solenoid
with acceptance 180 mrad
3 target cells
(reduce false asymmetries)




RICH 2006 upgrade : better PID

MAPMTs in central region

APV electronics in periphery

# Content

# A catalog of PDFs

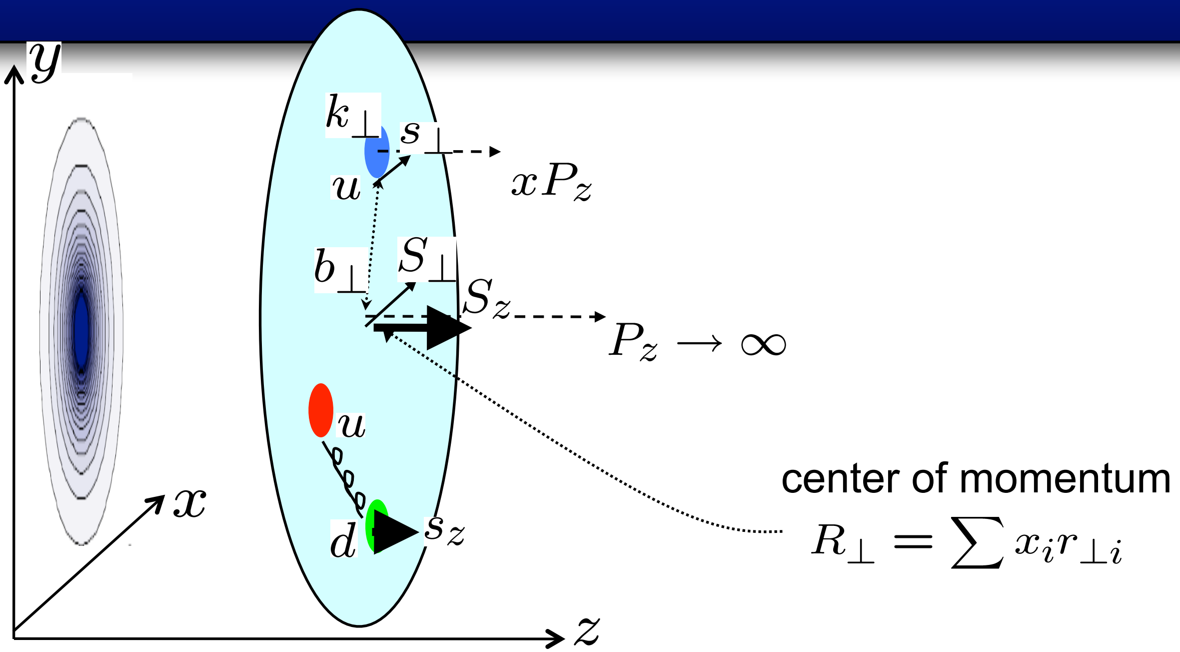
Beyond collinear approximation - $k_T$ dependence

| quark polarization \ nucleon polarization | U | L | T |
|---|---|---|---|
| U | $f_1$ number density | | $f_{1T}^{\perp}$ Sivers T-odd |
| L | | $g_1$ helicity | $g_{1T}$ Worm-gear |
| T | $h_1^{\perp}$ Boer-Mulders T-odd | $h_{1L}^{\perp}$ | $h_1$ transversity<br>$h_{1T}^{\perp}$ Pretzelosity |

LO, twist-2 - 8 independent functions to parameterize structure

# Spatial deformation & GPD

Burhardt,2000



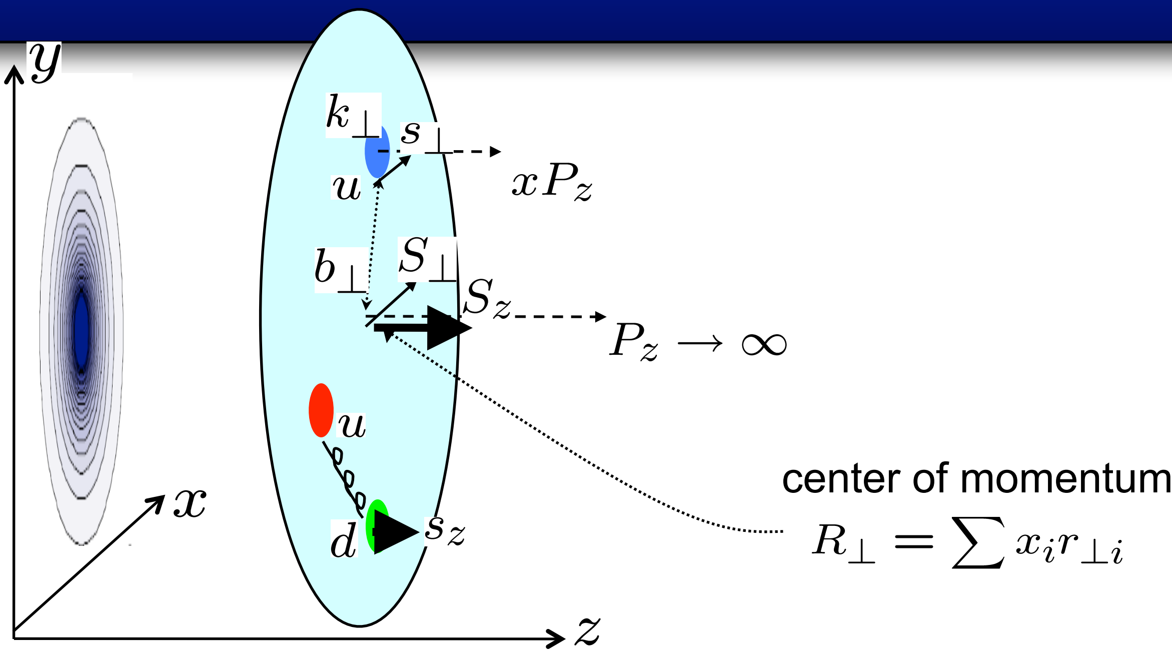

For a transversely polarized nucleon (e.g. polarized in the $+\hat{x}$-direction) the IPD $q_{\hat{x}}(x, \vec{b}_\perp)$ is no longer symmetric due to the non-zero value of the spin-flip GPD $E$. This deformation is described by the gradient of the Fourier transform of $E$:

$$q_{\hat{x}}(x, \vec{b}_\perp) = \mathcal{H}(x, \vec{b}_\perp) - \frac{1}{2M}\frac{\partial}{\partial b_y}\mathcal{E}(x, \vec{b}_\perp).$$

non-zero spin-flip GPD E - existence of non-zero orbital momentum

# Spatial deformation & GPD

Burhardt,2000

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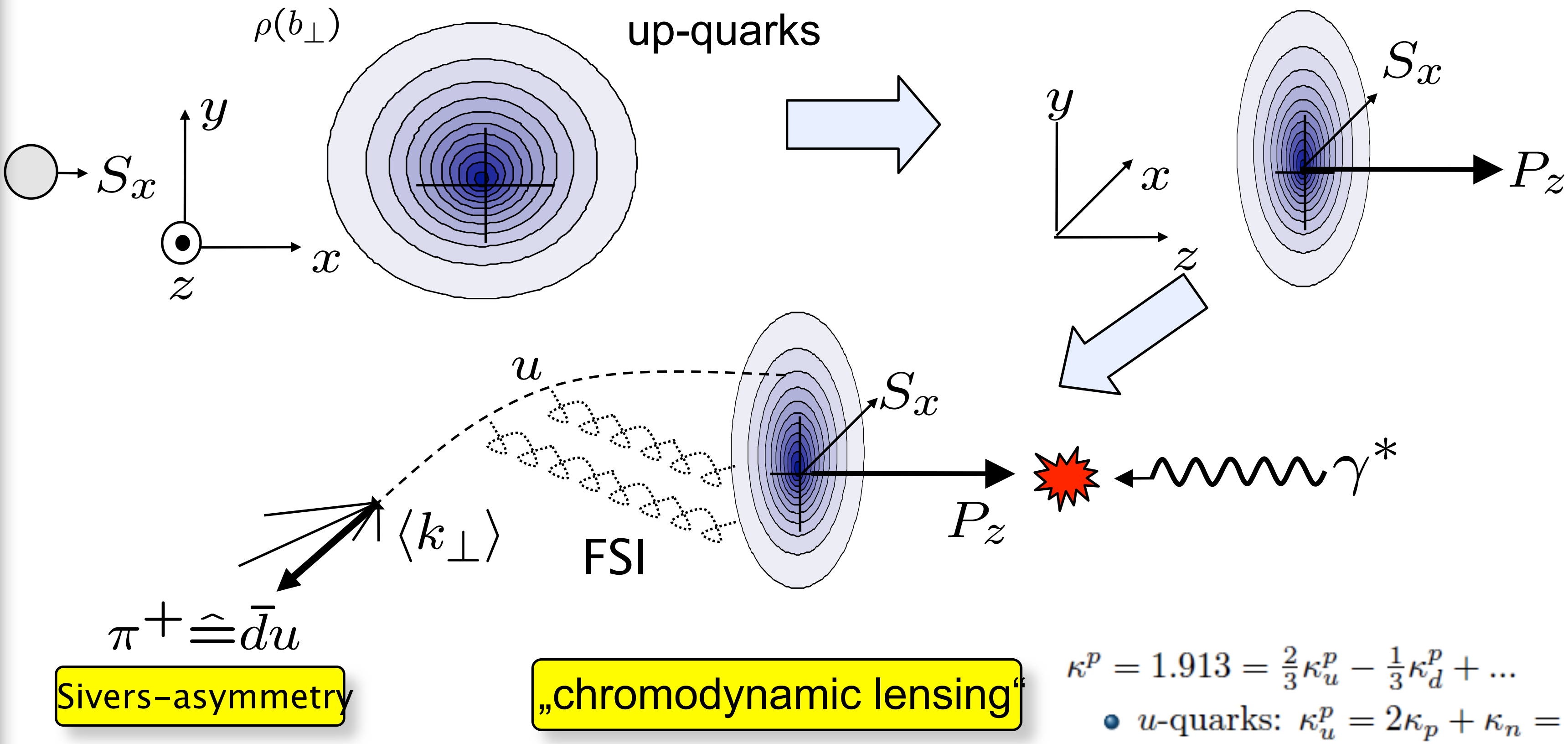
non-zero spin-flip GPD E - existence of non-zero orbital momentum

# Sivers function and spatial deformation



M.Burhardt 2002/2003

Dynamical origin of quark transverse momentum




$\kappa^p = 1.913 = \frac{2}{3}\kappa_u^p - \frac{1}{3}\kappa_d^p + \ldots$

- $u$-quarks: $\kappa_u^p = 2\kappa_p + \kappa_n = 1.673$

$\hookrightarrow$ shift in $+\hat{y}$ direction

- $d$-quarks: $\kappa_d^p = 2\kappa_n + \kappa_p = -2.033$

$\hookrightarrow$ shift in $-\hat{y}$ direction

- $\langle b_y^q \rangle = \mathcal{O}(\pm 0.2 fm)$ !!!!

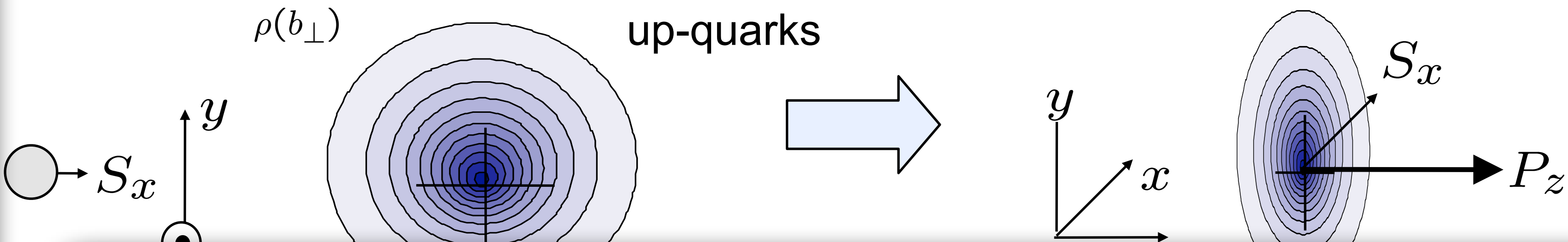
Deformation details are model-dependent but the size and directions is determined by anomalous magnetic moments of proton and neutron.

# Sivers function and spatial deformation



M.Burhardt 2002/2003

Dynamical origin of quark transverse momentum




Q: Is gluon's spacial distribution in transverse plane also deformed?


Sivers–asymmetry

„chromodynamic lensing"

Deformation details are model-dependent but the size and directions is determined by anomalous magnetic moments of proton and neutron.

$\kappa^p = 1.913 = \frac{2}{3}\kappa_u^p - \frac{1}{3}\kappa_d^p + ...$

- $u$-quarks: $\kappa_u^p = 2\kappa_p + \kappa_n = 1.673$

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- $\langle b_y^q \rangle = \mathcal{O}(\pm 0.2 fm)$ !!!!

# Sivers for gluons @ COMPASS



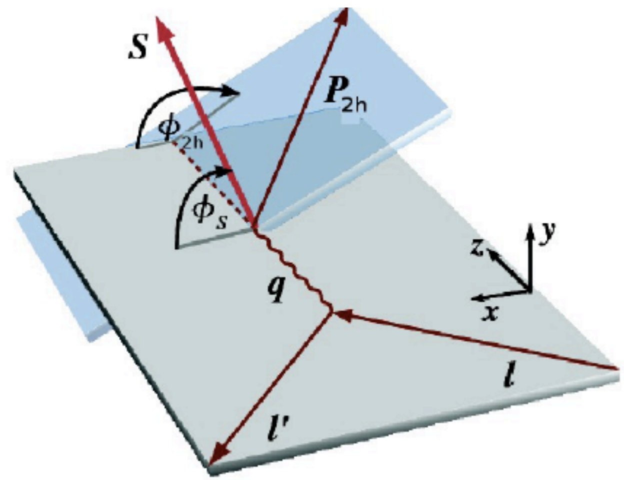
The idea: selection of high-$p_T$ hadron pairs to increase photon-gluon fusion (PGF) similar to Δg determination with longitudinally polarised target.

difficulties comparing to Δg
- asymmetry in azimuthal angle
- gluon „simulated” from pair of hadrons from PGF
- Sivers effect due to final interactions (no analyzing powers)

Single-spin asymmetry is measured:

$$A_T^h \sim \frac{d^6\sigma^\uparrow - d^6\sigma^\downarrow}{d^6\sigma^\uparrow + d^6\sigma^\downarrow}.$$

8 asymmetries; concentrated on Sivers




$\mathbf{P}_{2h} = \mathbf{p}_1 + \mathbf{p}_2$

Sivers angle:

$\phi = \phi_{2h} - \phi_S$

The statistically weighted method was used, similar to open-charm and all-$p_T$ methods used in Δg determination

J.Pretz, J-M Le Goff NIM A 602 (2009) 594

COMPASS open-charm: Phys. Rev. D (2013) 052018

# The weighted method

The number of events:

$$n_c(\vec{x}) = \alpha_c(\vec{x})(1 + \beta_c(\vec{x}) A_{UT}^{\sin(\phi_{2h}-\phi_s)}(\vec{x}))$$

Every event is weighted by the weight ω

$$p_c := \int \omega(\vec{x}) n_c(\vec{x}) d\vec{x} = \int \omega(\vec{x}) \alpha_c(\vec{x}) d\vec{x}$$

$$+ \int \omega(\vec{x}) \alpha_c(\vec{x}) \beta_c(\vec{x}) A_{UT}^{\sin(\phi_{2h}-\phi_s)}(\vec{x}) d\vec{x} \approx \sum_{i=1}^{N_c} \omega_i,$$

$$\sum_{i=1}^{N_c} \omega_i = \tilde{\alpha}_c (1 + \{\beta_c\}_\omega \{A_{UT}^{\sin(\phi_{2h}-\phi_s)}\}_{\omega\beta_c}),$$

where

$$\tilde{\alpha}_c = \int \omega(\vec{x}) \alpha_c(\vec{x}) d\vec{x},$$

$$\{A_{UT}^{\sin(\phi_{2h}-\phi_s)}\}_{\omega\beta_c} = \frac{\int A_{UT}^{\sin(\phi_{2h}-\phi_s)}(\vec{x}) \omega(\vec{x}) \beta_c \alpha_c(\vec{x}) d\vec{x}}{\int \omega(\vec{x}) \beta_c \alpha_c(\vec{x}) d\vec{x}},$$

$$\{\beta\}_\omega = \frac{\int \beta(\vec{x}) \omega(\vec{x}) \alpha_c(\vec{x}) d\vec{x}}{\int \omega(\vec{x}) \alpha_c(\vec{x}) d\vec{x}} \approx \frac{\sum_i \beta_i \omega_i}{\sum_i \omega_i}.$$

where:

$$\vec{x} = (x_{Bj}, y, t, \phi, \ldots)$$

$$\alpha_c(\vec{x}) = a_c \Phi n_c \sigma ,$$

$$\beta_c(\vec{x}) = P_T f \sin(\phi_{2h} - \phi_s)$$

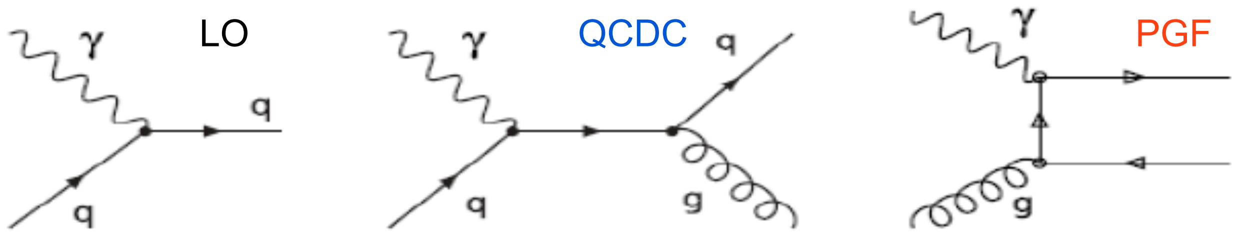
c= $u, d, u', d'$

$$\omega(\vec{x}) = \frac{\beta(\vec{x})}{P_T} = f \sin(\phi_{2h} - \phi_s)$$

Gluon „Sivers effect" measured at COMPASS

# The weighted method

## Physical model: three basic processes @LO




$$A_{UT}^{\sin(\phi_{2h}-\phi_s)} = R_{PGF} A_{PGF}^{\sin(\phi_{2h}-\phi_s)}(< x_G >) + R_{LP} A_{LP}^{\sin(\phi_{2h}-\phi_s)}(< x_{Bj} >)$$
$$+ R_{QDCD} A_{QCDC}^{\sin(\phi_{2h}-\phi_s)}(< x_C >)$$

$$\omega_{PGF} \equiv \omega^G = R_{PGF} f \sin(\phi_{2h} - \phi_s) = \frac{\beta^G}{P_T},$$
$$\omega_{LP} \equiv \omega^L = R_{LP} f \sin(\phi_{2h} - \phi_s) = \frac{\beta^L}{P_T},$$
$$\omega_{QCDC} \equiv \omega^C = R_{QCDC} f \sin(\phi_{2h} - \phi_s) = \frac{\beta^C}{P_T}.$$

# The weighted method

## Physical model: three basic processes @LO

leads to 12 eqs.:

$$p_c^j = \sum_{i=1}^{N_c} \omega_i^j = \tilde{\alpha}_c^j (1 + \{\beta_c^G\}_{\omega^j} A_{PGF}^{\sin(\phi_{2h}-\phi_s)}(\langle x_G \rangle) + \{\beta_c^L\}_{\omega^j} A_{LP}^{\sin(\phi_{2h}-\phi_s)}(\langle x_{Bj} \rangle) + \{\beta_c^C\}_{\omega^j} A_{QCDC}^{\sin(\phi_{2h}-\phi_s)}(\langle x_C \rangle)) = \tilde{\alpha}_c^j \left(1 + A_{PGF}\{\beta^G\}_{\omega^j} + A_{LP}\{\beta^L\}_{\omega^j} + A_{QCDC}\{\beta^C\}_{\omega^j}\right)$$

with 15 unknows: (3 asymmeries + 12 acceptances) but thanks to $\frac{\tilde{\alpha}_u^j \tilde{\alpha}_{d'}^j}{\tilde{\alpha}_d^j \tilde{\alpha}_{u'}^j} = 1,$ it is reduced to 12. *Here j stands for LO, QCDC and PGF, respectively

To determine asymmetries the minimalizatiion procedure has been used:

$$\chi^2 = (\vec{N_{exp}} - \vec{N_{obs}})^T Cov^{-1} (\vec{N_{exp}} - \vec{N_{obs}})$$

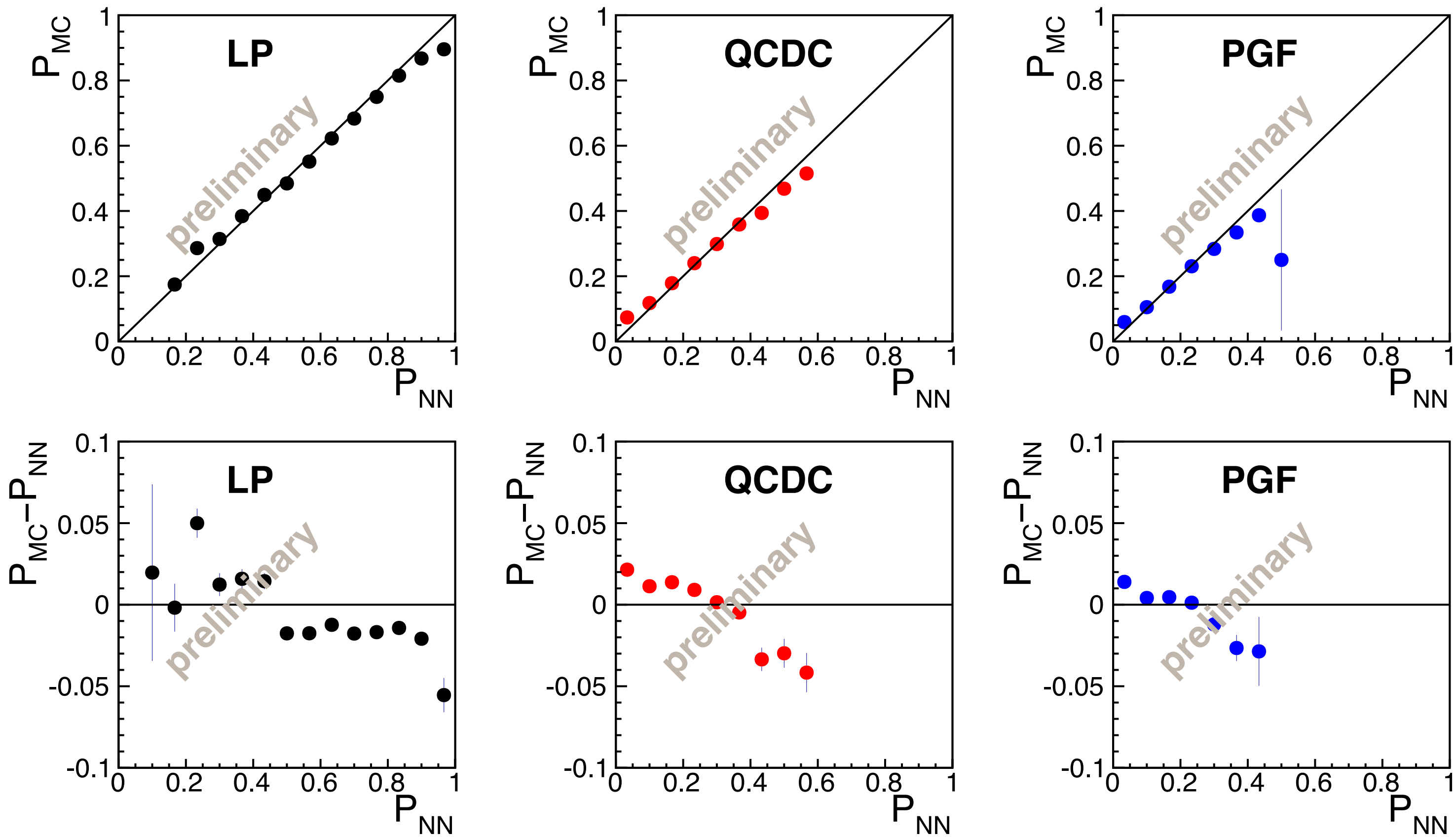
$Cov \sim \sum_{N_c} \omega_x \omega_y.$

$$\vec{N_{obs}} = \left(\sum_{i=0}^{N_u} \omega_i^G, \ldots, \sum_{i=0}^{N_{d'}} \omega_i^C\right),$$

$$\vec{N_{exp}} = (N_{exp,G}^u, \ldots, N_{exp,C}^{d'}), \qquad N_{exp,j}^c = \tilde{\alpha}_c^j \left(1 + A_{PGF}\{\beta^G\}_{\omega^j} + A_{LP}\{\beta^L\}_{\omega^j} + A_{QCDC}\{\beta^C\}_{\omega^j}\right)$$

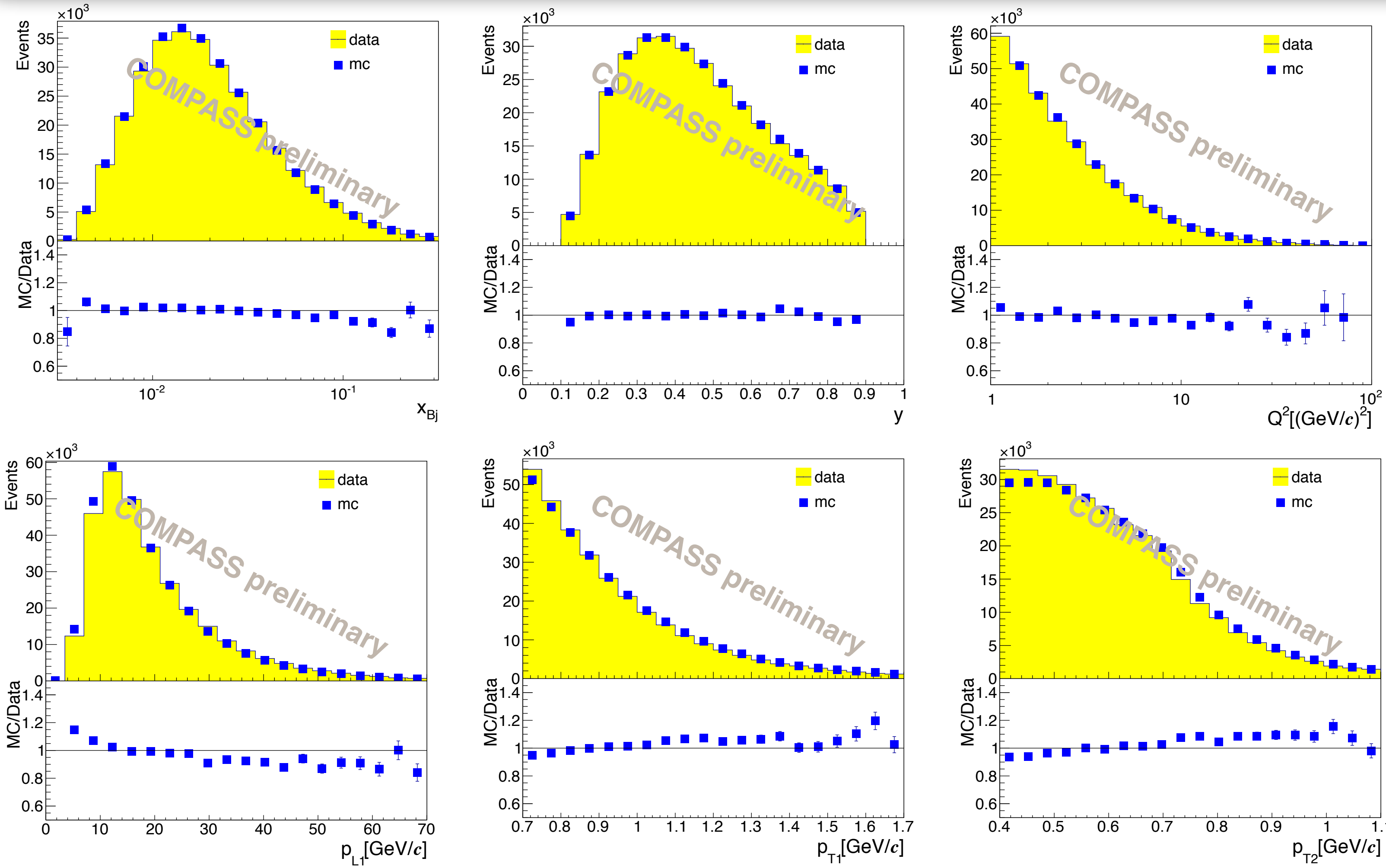
# Artificial Neural Network approach - validation

To find R's (fractions or probabilities of three processes) the ANN approach has been used (as in longitudinal high-$p_T$ analysis for gluon polarisation measurement, see: Phys. Lett. B 718 (2013) 922 )




training vector: $p_T, p_L, x_{Bjk}, Q^2$

# Data-MC comparison




good agreement (COMPASS tuning high-$p_T$)

# Validation of the method



- MC (LEPTO + COMGEANT, high-$p_T$ tuning) events have no azimuthal asymmetries therefore we weight every event by $1+A\sin(\phi_{2h} - \phi_S)$.

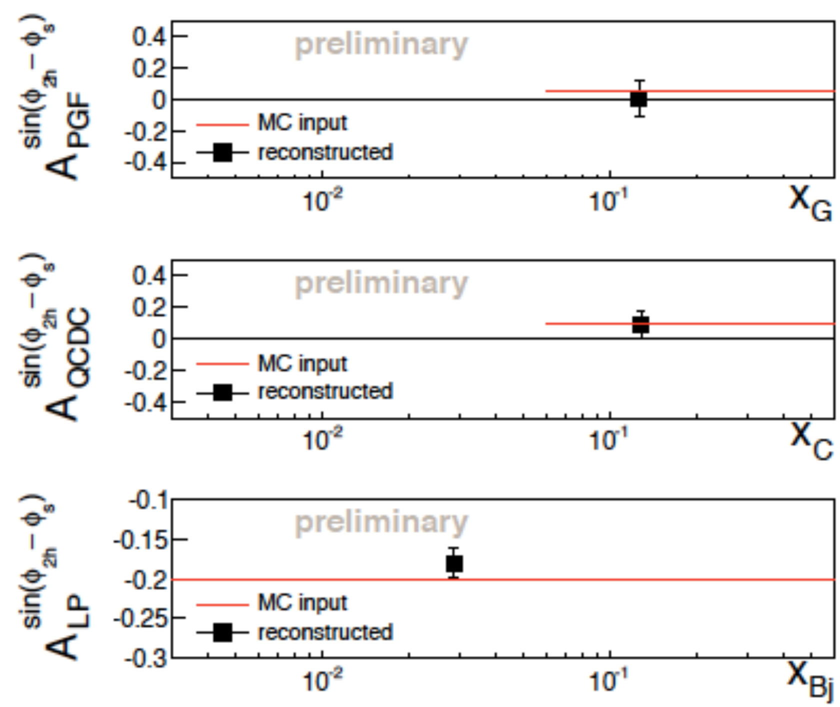
  $\phi_{2h}$- azimuthal angle of the vector sum of the 2 leading hadron momenta.

A - assumed asymmetry for LO, QCDC and PGF

- For each MC event we get

  $R_{LP}$, $R_{QCDC}$, $R_{PGF}$ and $x_C$, $x_G$ from NN

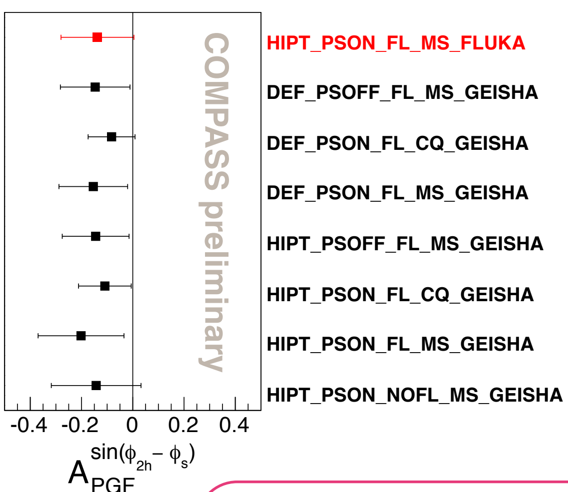
Sivers Asymmetry



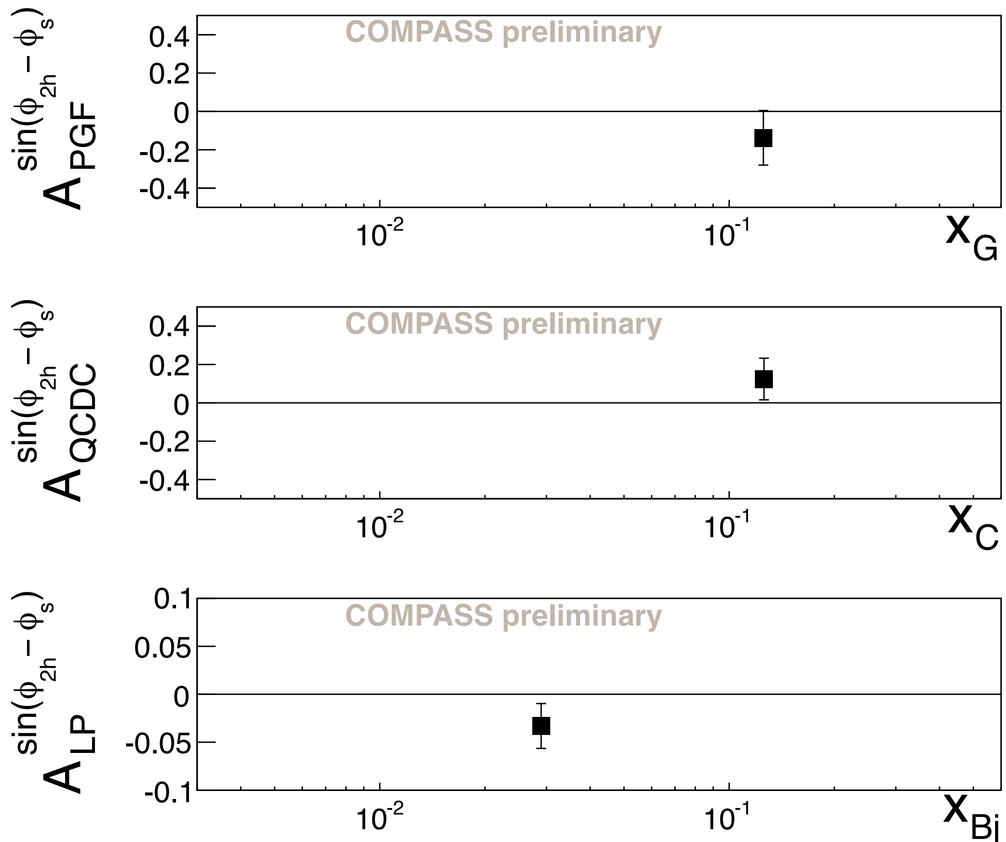
# Data selection & preliminary results

## COMPASS 2003-2004 data taken on deuteron polarised target

- Inclusive cuts:
  - $Q^2 > 1 (GeV/c)^2$
  - $0.003 < x_{Bj} < 0.7$
  - $0.1 < y < 0.9$
- hadronic cuts
  - $p_{T1} > 0.7$ GeV/$c$
  - $p_{T2} > 0.4$ GeV/$c$
  - $z_1 > 0.1$
  - $z_2 > 0.1$




## Sivers Asymmetry




$$A_{PGF}^{\sin(\phi_{2h}-\phi_s)} = 0.14 \pm 0.15(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})$$

$$\langle x_G \rangle = 0.126.$$

# Summary

- For the first time preliminary result for Sivers asymmetry for gluons has been obtained from COMPASS deuteron target data:

$$\mathbf{A_{PGF}^{\sin(\phi_{2h}-\phi_S)} = 0.14 \pm 0.15(stat.) \pm 0.06(syst.)}$$

The result is compatible with zero.
S.J.Brodsky & S. Gardner,Phys.Lett. B643 (2006) 22-28

- Analysis on proton data (more interesting, much larger statistics) is ongoing

# Thank you for your attention

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COMPASS

Gluon Contribution to the Sivers Effect
COMPASS Results on Deuteron Target

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**Spin2014**

**The 21st International Symposium on Spin Physics, October 20-24, 2014, Beijing, China**

# Backup slides

# A catalog of PDFs

## SIDIS cross section decomposition LO

$$
\begin{aligned}
\frac{d\sigma}{xdyd\phi_S d\phi_h dz_h dP_{hT}^2} &= \frac{e^4}{32\pi^2 x Q^2}\frac{y}{1-\varepsilon}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon\ F_{UU,L} + \varepsilon\ cos(2\phi_h) F_{UU}^{cos2\phi_h} \\
&+ \sqrt{2\varepsilon(1-\varepsilon)}\left(cos\phi_h F_{UU}^{cos\phi_h} + h_l sin\phi_h F_{LU}^{sin\phi_h}\right) \\
&+ S_{\parallel}\left[\sqrt{2\varepsilon(1+\varepsilon)} sin\phi_h F_{UL}^{sin\phi_h} + \varepsilon\ sin(2\phi_h) F_{UL}^{sin2\phi_h}\right] \\
&+ S_{\parallel} h_l \left[\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} cos\phi_h F_{LL}^{cos\phi_h}\right] \\
&+ |S_\perp|\Big[sin(\phi_h-\phi_S)\left(F_{UT,T}^{sin(\phi_h-\phi_S)} + \varepsilon\ F_{UT,L}^{sin(\phi_h-\phi_S)}\right) \\
&\qquad + \varepsilon\ sin(3\phi_h-\phi_S) F_{UT}^{sin(3\phi_h-\phi_S)} + \varepsilon\ sin(\phi_h+\phi_S) F_{UT}^{sin(\phi_h+\phi_S)} \\
&\qquad + \sqrt{2\varepsilon(1+\varepsilon)}\left(sin\phi_S F_{UT}^{sin\phi_S} + sin(2\phi_h-\phi_S) F_{UT}^{sin(2\phi_h-\phi_S)}\right)\Big] \\
&+ |S_\perp| h_l \Big[\sqrt{1-\varepsilon^2} cos(\phi_h-\phi_S) F_{LT}^{cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\varepsilon(1-\varepsilon)}\left(cos\phi_S F_{LT}^{cos\phi_S} + cos(2\phi_h-\phi_S) F_{LT}^{cos(2\phi_h-\phi_S)}\right)\Big]\Big\},
\end{aligned}
$$

# A catalog of PDFs

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\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\phi_S\,d\phi_h\,dz_h\,dP_{hT}^2} = \frac{e^4}{32\pi^2 x Q^2}\frac{y}{1-\varepsilon}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ & F_{UU,T} + \varepsilon\, F_{UU,L} + \varepsilon\, cos(2\phi_h) F_{UU}^{cos2\phi_h} \\
& + \sqrt{2\varepsilon(1-\varepsilon)}\left(cos\phi_h F_{UU}^{cos\phi_h} + h_l sin\phi_h F_{LU}^{sin\phi_h}\right) \\
& + S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)} sin\phi_h F_{UL}^{sin\phi_h} + \varepsilon\, sin(2\phi_h) F_{UL}^{sin2\phi_h}\right] \\
& + S_\parallel h_l\left[\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} cos\phi_h F_{LL}^{cos\phi_h}\right] \\
& + |S_\perp|\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) \\
& \quad + \varepsilon\, sin(3\phi_h-\phi_S) F_{UT}^{sin(3\phi_h-\phi_S)} + \varepsilon\, sin(\phi_h+\phi_S) F_{UT}^{sin(\phi_h+\phi_S)} \\
& \quad + \sqrt{2\varepsilon(1+\varepsilon)}\left(sin\phi_S F_{UT}^{sin\phi_S} + sin(2\phi_h-\phi_S) F_{UT}^{sin(2\phi_h-\phi_S)}\right)\Big] \\
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\end{aligned}
$$

Cahn & Boer-Mulders

unpolarised target

# A catalog of PDFs

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$$+\sqrt{2\varepsilon(1-\varepsilon)}\left(cos\phi_h F_{UU}^{cos\phi_h} + h_l sin\phi_h F_{LU}^{sin\phi_h}\right)$$

Cahn & Boer-Mulders

unpolarised target

$$+ S_{\parallel}\left[\sqrt{2\varepsilon(1+\varepsilon)} sin\phi_h F_{UL}^{sin\phi_h} + \varepsilon\, sin(2\phi_h) F_{UL}^{sin2\phi_h}\right]$$

$$+ S_{\parallel} h_l \left[\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} cos\phi_h F_{LL}^{cos\phi_h}\right]$$

longitudinaly polarised target

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

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

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

$$+ |S_\perp| h_l \Big[\sqrt{1-\varepsilon^2} cos(\phi_h-\phi_S) F_{LT}^{cos(\phi_h-\phi_S)}$$

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

# A catalog of PDFs

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$$+\sqrt{2\varepsilon(1-\varepsilon)}\left(cos\phi_h F_{UU}^{cos\phi_h} + h_l sin\phi_h F_{LU}^{sin\phi_h}\right)$$

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

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$$+ |S_\perp| h_l\Big[\sqrt{1-\varepsilon^2} cos(\phi_h-\phi_S) F_{LT}^{cos(\phi_h-\phi_S)}$$

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

Cahn & Boer-Mulders

unpolarised target

longitudinaly polarised target

transversely polarised target

Sivers
Collins
Pretzelosity
Worm Gear

# A catalog of PDFs

Spares

## SIDIS cross section decomposition LO

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,d\phi_h\,dz_h\,dP_{hT}^2} = \frac{e^4}{32\pi^2 x Q^2}\frac{y}{1-\varepsilon}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon\, F_{UU,L} + \varepsilon\, cos(2\phi_h) F_{UU}^{cos2\phi_h}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\left(cos\phi_h F_{UU}^{cos\phi_h} + h_l sin\phi_h F_{LU}^{sin\phi_h}\right)$$

$$+S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)} sin\phi_h F_{UL}^{sin\phi_h} + \varepsilon\, sin(2\phi_h) F_{UL}^{sin2\phi_h}\right]$$

Cahn & Boer-Mulders

unpolarised target

$$F_{UU,T} \sim \sum_q e_q^2 \cdot f_1^q \otimes D_q^h, \qquad F_{LT}^{cos(\phi_h-\phi_S)} \sim \sum_q e_q^2 \cdot g_{1T}^q \otimes D_q^h,$$

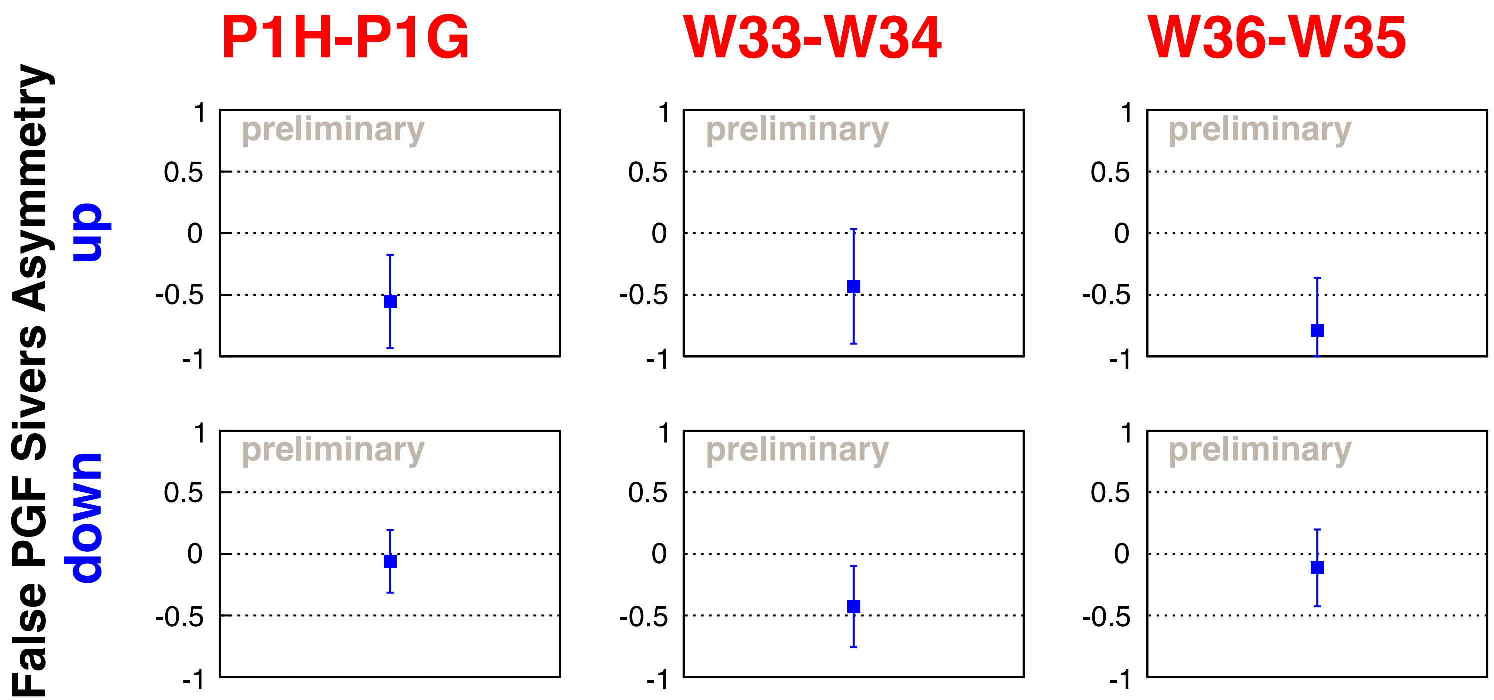
$$F_{LL} \sim \sum_q e_q^2 \cdot g_{1L}^q \otimes D_q^h, \qquad F_{UT,T}^{sin(\phi_h-\phi_S)} \sim \sum_q e_q^2 \cdot f_{1T}^{\perp q} \otimes D_q^h,$$

$$F_{UU}^{cos2\phi_h} \sim \sum_q e_q^2 \cdot h_1^{\perp q} \otimes H_1^{\perp q}, \qquad F_{UT}^{sin(\phi_h+\phi_S)} \sim \sum_q e_q^2 \cdot h_1^q \otimes H_1^{\perp q},$$

$$F_{UL}^{sin2\phi_h} \sim \sum_q e_q^2 \cdot h_{1L}^{\perp q} \otimes H_1^{\perp q}, \qquad F_{UT}^{sin(3\phi_h-\phi_S)} \sim \sum_q e_q^2 \cdot h_{1T}^{\perp q} \otimes H_1^{\perp q}.$$

get

# Falses

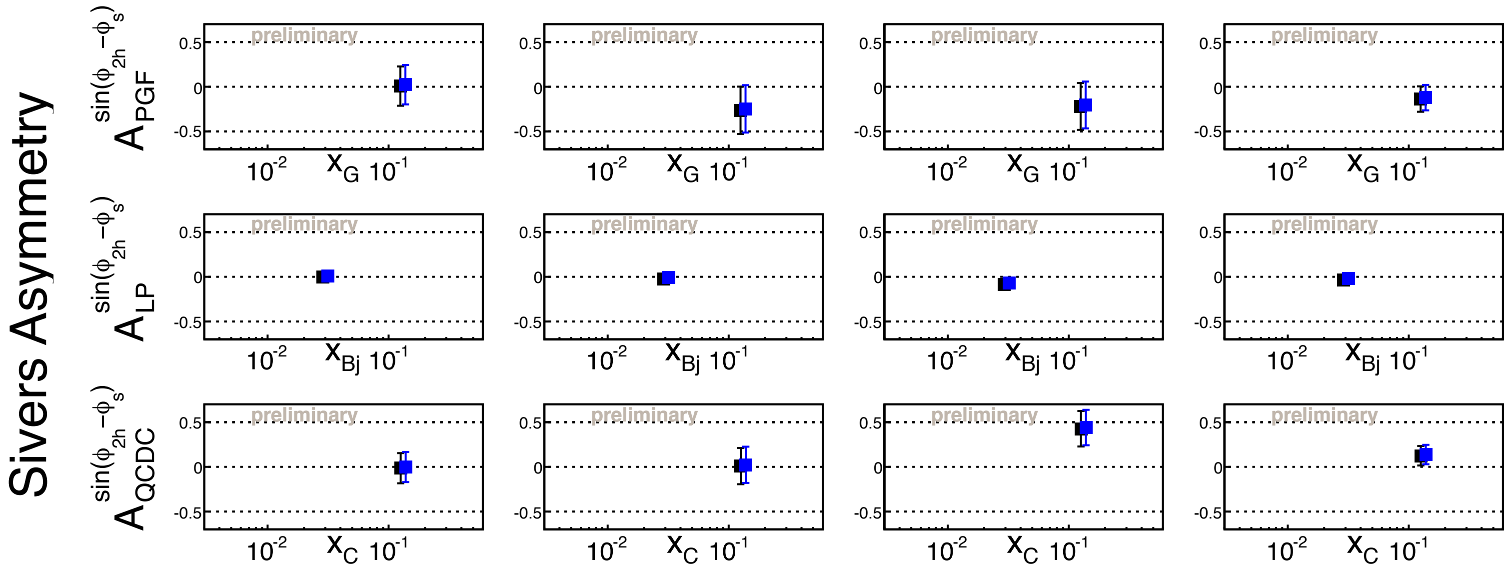

P1H-P1G
W33-W34
W36-W35
False PGF Sivers Asymmetry
up
down
preliminary
1
0.5
0
-0.5
-1

# 1% false test for asymmetry



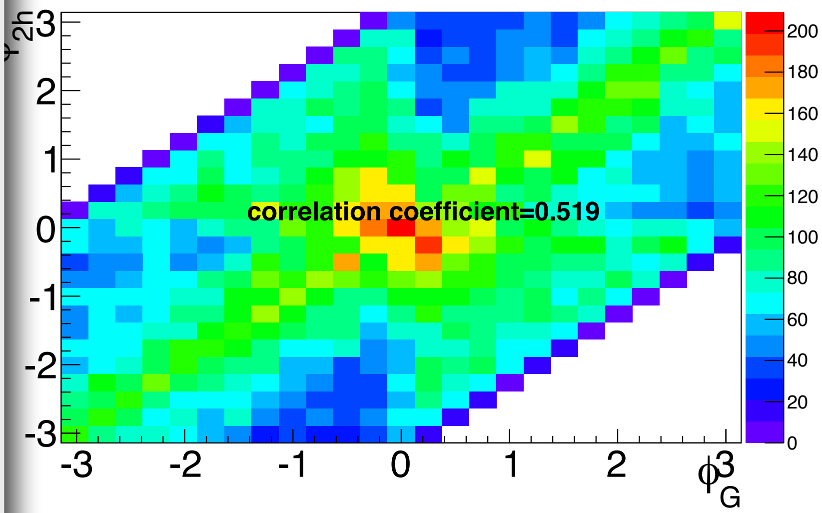
**standard** **1% false**

**P1H-P1G** **W33-W34** **W36-W35** **final**



# Correlations

no $p_T$ cut




$p_{T1}$>0.7[GeV/c], $p_{T2}$>0.4[GeV/c]