COMPASS 

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# Results of the gluon Sivers asymmetry extraction from COMPASS data with transversely polarised targets

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# Outline

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# Nucleon spin decomposition

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

- $\Delta\Sigma \approx 0.3$

  (The COMPASS Collaboration, V.Yu. Alexakhin *et al.*, Phys. Lett. B 647,8 (2007))

- $\Delta g/g$ from COMPASS and $\Delta G$ from global fit to RHIC data suggest small $\Delta G$ contribution

  Marcin Stolarski on behalf of the COMPASS Collaboration, PoS (DIS2014) 211

  The COMPASS Collaboration, C. Adolph *et al.*, Phys. Rev. D 87 (2013) 052018

  D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, Phys.Rev.Lett. 1 113 012001 (2014)

- QCD Lattice calculations show significant but oposite contribution of $L_u$ and $L_d$ LHPC DW, S. N. Sirytsyn et al., arXiv:1111.0718, (2011)

- Nonzero Sivers function of gluon can be related to its orbital motion in a polarized nucleonD. W. Sivers, Phys. Rev. D **41** (1990) 83

# COMPASS experiment

**CO**mmon
**M**uon and
**P**roton
**A**pparatus for
**S**tructure and
**S**pectroscopy

**Fixed target experiment**
**at CERN SPS**
**Data taking since 2002**

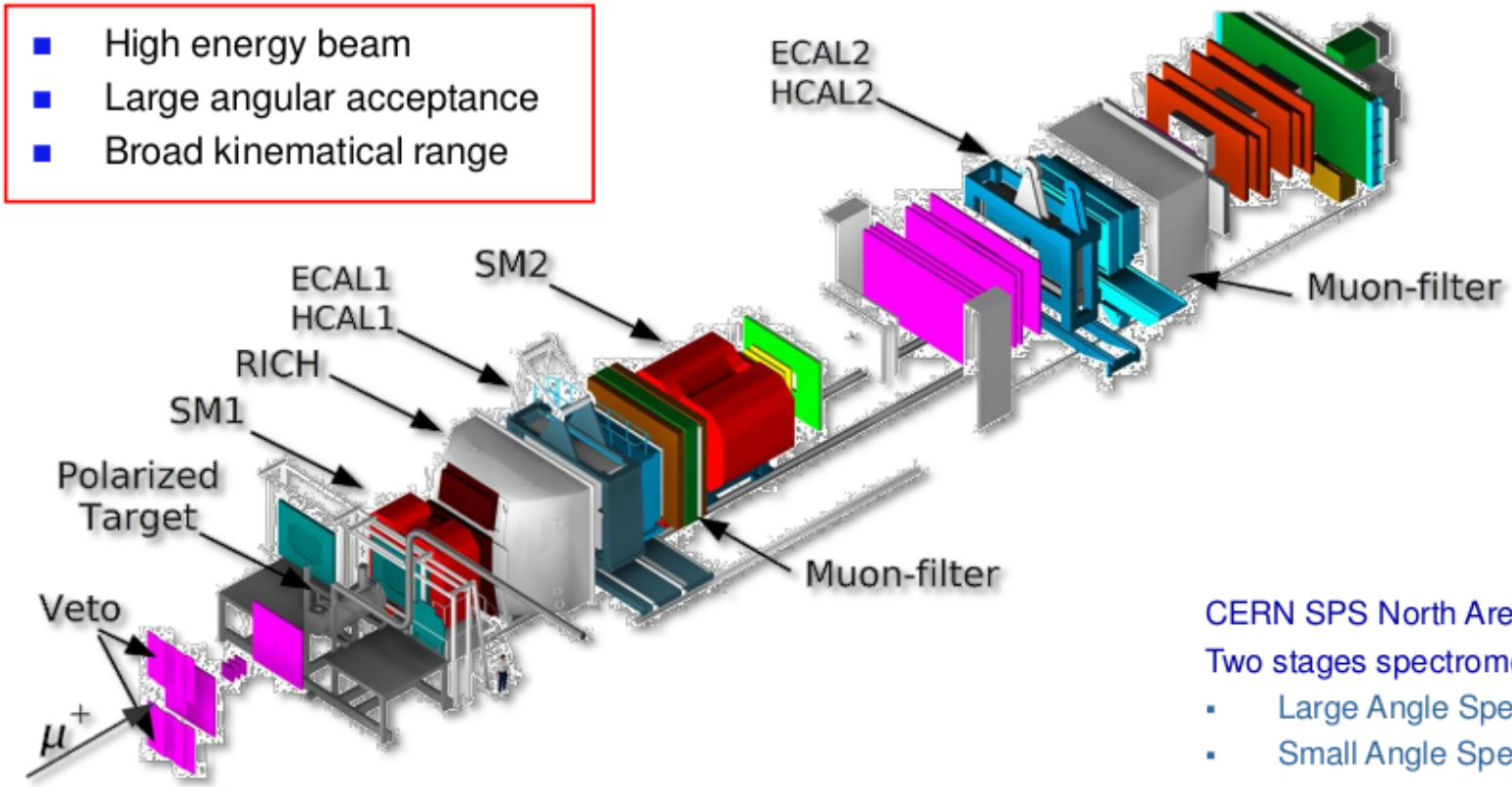

**Nucleon spin structure**
**with high energy muon beams**
**on longitudinally polarized targets:**
- **-gluon polarization**
- **-helicity PDF**

**Transversely polarized targets:**
- **transversity PDF**
- **TMDs**

**Meson and baryon spectroscopy**
**with high energy hadron beam**

# COMPASS spectrometer

- High energy beam
- Large angular acceptance
- Broad kinematical range




**Longitudinally polarized $\mu^+$ beam (160 Gev/c).**

**Longitudinally or Transversely polarized $^6$LiD or $NH_3$ target**

**Momentum, tracking and calorimetric measurements, PID**

CERN SPS North Area.

Two stages spectrometer

- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

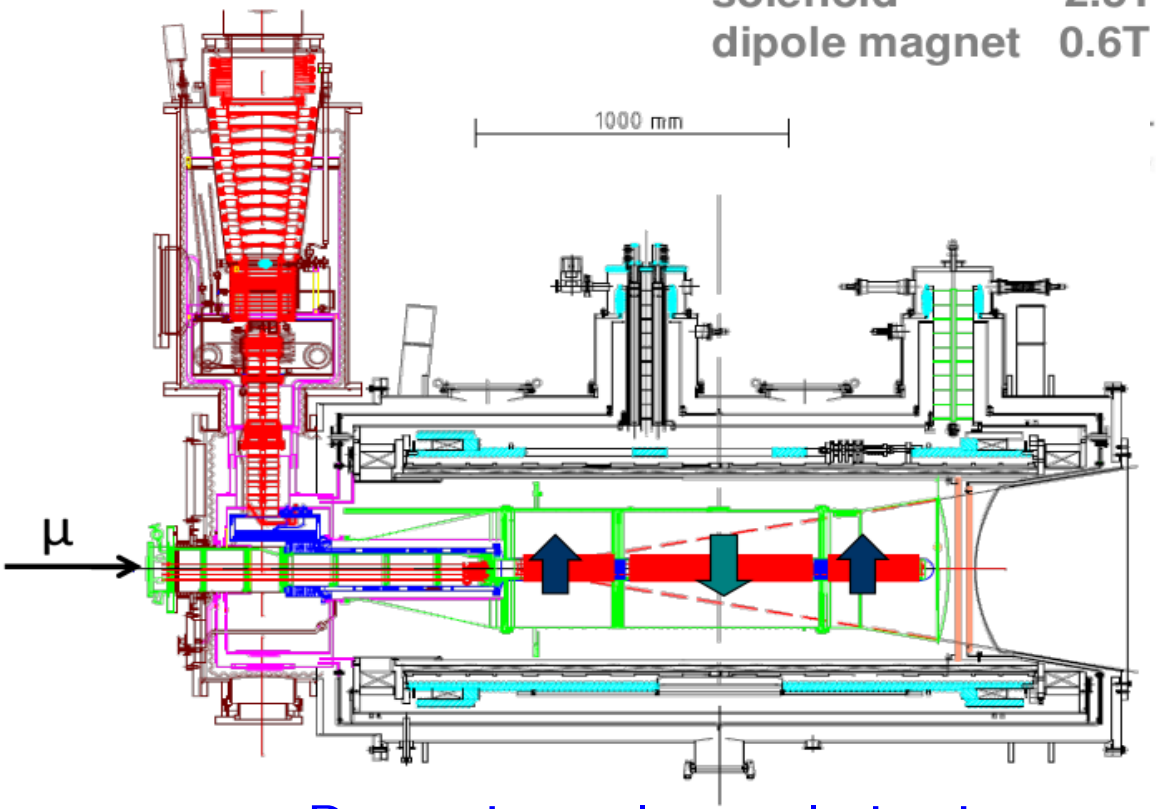
Hadron & Muon high energy beams.

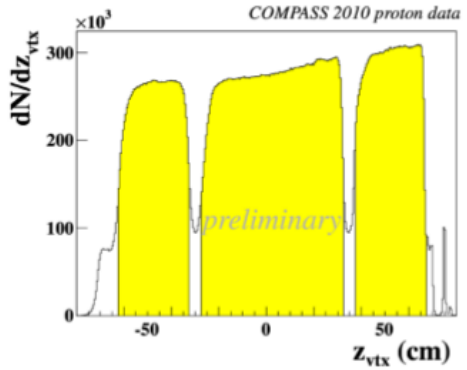
Beam rates: $10^8$ muons/s, $5 \cdot 10^7$ hadrons/s.

# COMPASS polarised target

$^3$He – $^4$He dilution refrigerator (T~50mK)

solenoid 2.5T
dipole magnet 0.6T




acceptance > ± 180 mrad

3 target cells
30, 60, and 30 cm long

opposite polarisation

| | d ($^6$LiD) | p ($NH_3$) |
|---|---|---|
| polarization | 50% | 90% |
| diliution factor | 40% | 16% |

Dynamic nuclear polarisation

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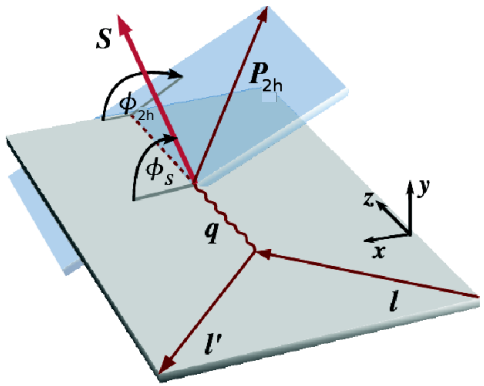
# Sivers Asymmetry

Nonzero Sivers function of gluon can be related to its orbital motion in a polarized nucleon

$$\ell + N \to \ell' + 2h + X$$




$$\mathbf{P}_{2h} = \mathbf{p}_1 + \mathbf{p}_2$$
$$\mathbf{R} = \frac{1}{2}(\mathbf{p}_1 - \mathbf{p}_2)$$

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

$\sigma$- two-hadron cross-section integrated over $\phi_R$; $\quad A_T^{2h}(\phi) = \dfrac{d\sigma^{\uparrow}(\phi) - d\sigma^{\downarrow}(\phi)}{d\sigma^{\uparrow}(\phi) + d\sigma^{\downarrow}(\phi)}$

$$N(\phi) = an\Phi\sigma_0(1 + P_T f A^{\sin(\phi)} \sin(\phi))$$

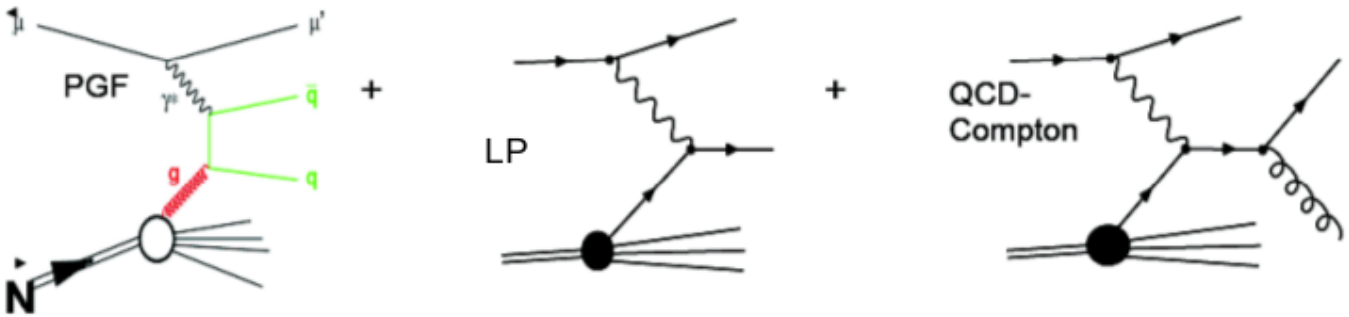
Phys.Rev.Lett.**113**, 062003 (2014), Phys. Rev. D **90**, 074006 (2014)

# 3 processes

photon-gluon fusion (PGF)

Leading process (LP)- main DIS process

QCD Compton




3 processes in the single photon exchange approximation describe well the unpolarised data

# the analysis procedure

The aim is:

- Extraction from measured Sivers asymmetry the asymmetry of the photon gluon fusion (PGF) process (signal) and the asymmetry of the Leading Process (LP) (background 1) and of the QCD Compton process (background 2)

The procedure:

- Selection of a high-$p_T$ hadron pair sample (at least two hadrons with large $p_T$ in event). With this selection:
  - the sample with PGF events is enhanced (too strong cut leads to minimal statistics)
  - correlation between the gluon azimuthal angle and the angle of the sum of two hadrons ($\phi_{2h}$) is stronger (from MC)
- assignment of 3 weights to every event (corresponding to the 3 processes) by neural network (NN) trained on MC data
- Solving the weighted set of equations to obtain asymmetries of the 3 processes

# Weighting method

$$N(\phi) = an\Phi\sigma_0(1 + P_T f A^{\sin\phi} \sin\phi)$$

weight $\omega = \beta/P_T = f \sin\phi$ chosen to optimise statistical and systematic error

$$p_t := \int \omega(\phi) N_t(\vec{x}) d\vec{x} = \int \omega(\phi)\alpha_t(\vec{x}) d\vec{x}$$

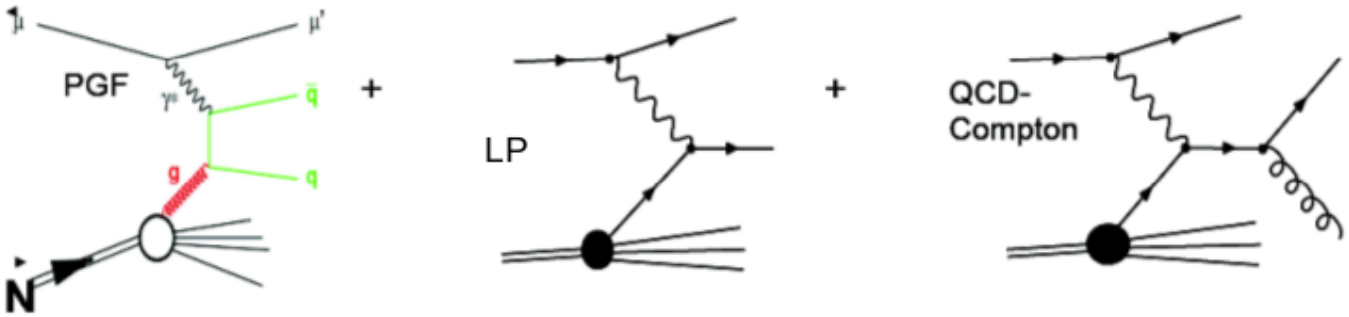
$$+ \int \omega(\phi)\alpha_t(\vec{x})\beta_t(\phi) A_{UT}^{\sin\phi}(\vec{x'}) d\vec{x} \approx \sum_{i=1}^{N_t} \omega_i$$

$\alpha = an\Phi\sigma_0$, $\tilde{\alpha_t} = \int \omega(\phi)\alpha_t(\vec{x})d\vec{x}$, $t = u, d, u', d'$ deuteron; $t = ud, c, ud', c'$ proton

Assuming $A_{UT}^{\sin(\phi)}(x_{Bj})$ dependence is linear and $\langle x_{Bj}\rangle \approx \sum x_{Bj}^i \omega^i \beta^i / \sum \omega^i \beta^i$

$$\sum_{i=1}^{N_t} \omega_i = \tilde{\alpha_t}(1 + \{\beta_t\}_\omega A_{UT}^{\sin(\phi)}(\langle x_{Bj}\rangle)) \qquad \{\beta_t\}_\omega \approx \frac{\sum_{i=1}^{N_t} \beta_t^i \omega_i}{\sum_{i=1}^{N_t} \omega_i}$$

# 3 (single photon exchange) processes




$$A_{UT}^{\sin\phi} = R_{PGF} A_{PGF}^{\sin\phi}(\langle x_g \rangle) + R_{LP} A_{LP}^{\sin\phi}(\langle x_{Bj} \rangle) + R_{QDCD} A_{QCDC}^{\sin\phi}(\langle x_C \rangle).$$

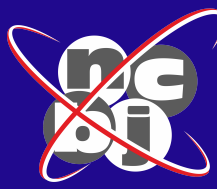
$$\begin{aligned} \omega_{PGF} &\equiv \omega^G = R_{PGF} f \sin\phi = \beta^G / P_T, \\ \omega_{LP} &\equiv \omega^L = R_{LP} f \sin\phi = \beta^L / P_T, \\ \omega_{QCDC} &\equiv \omega^C = R_{QCDC} f \sin\phi = \beta^C / P_T. \end{aligned}$$

$R_{PGF}, R_{LP}, R_{QCDC}$ - from neural network trained on MC data

# Weighting method. 3 processes

$$p_t^j = \sum_{i=1}^{N_t} \omega_i^j = \tilde{\alpha}_t^j \Big( 1 + \{\beta_t^G\}_{\omega j} A_{PGF}^{\sin\phi}(\langle x_g \rangle) + \{\beta_t^L\}_{\omega j} A_{LP}^{\sin\phi}(\langle x_{Bj} \rangle) + \{\beta_t^C\}_{\omega j} A_{QCDC}^{\sin\phi}(\langle x_C \rangle) \Big).$$

Here $j = PGF, LP, QCDC$ and $\frac{\tilde{\alpha}_{ud}^j \tilde{\alpha}_{c'}^j}{\tilde{\alpha}_{ud'}^j \tilde{\alpha}_c^j} = 1$ limits the number of unknowns to 12.


# Data selection

## Kinematic cuts

- DIS cuts: $Q^2 > 1(\mathrm{GeV}/c)^2$; $0.003 < x_{Bj} < 0.7$; $0.1 < y < 0.9$;
- $W > 5\mathrm{GeV}/c^2$ - cuts away resonance production
- $z_1, z_2 > 0.1$ - select current fragmentation region
- $z_1 + z_2 < 0.9$ cuts away exclusive peak
- $p_{T1} > 0.7\mathrm{GeV}/c$; $p_{T2} > 0.4\mathrm{GeV}/c$ - optimized to enhance PGF fraction and $\phi_g, \phi_{2h}$ correlation.

# MC used for NN training

Full chain MC with LEPTO generator, GEANT with COMPASS setup and reconstruction package

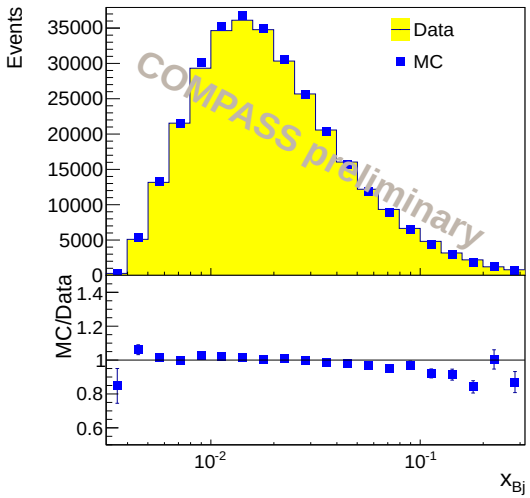
The MC settings:

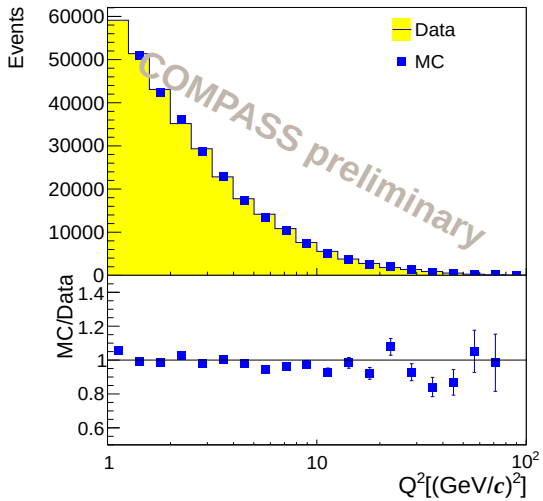
- COMPASS (high-$p_T$) tuning
- MSTW08 PDFs
- FLUKA for secondary interactions
- Parton Shower on
- $F_L$ on

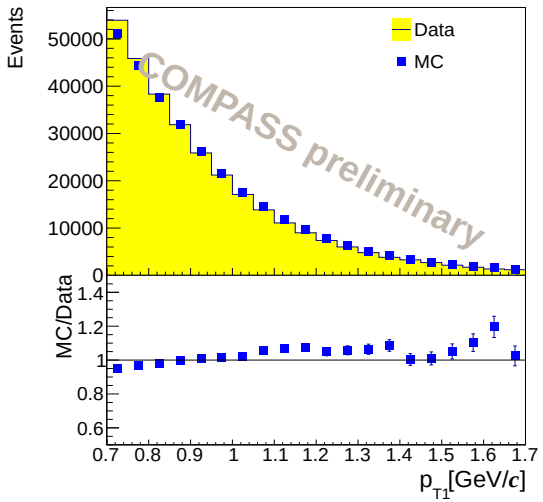
6 kinematic variables as an input of NN: $p_{T1}, p_{T2}, p_{L1}, p_{L2}, Q^2, x_{Bj}$

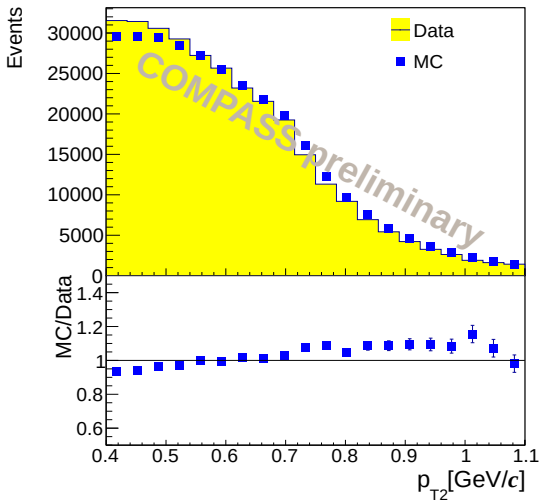
good agreement between MC and data for distribution of these variables needed

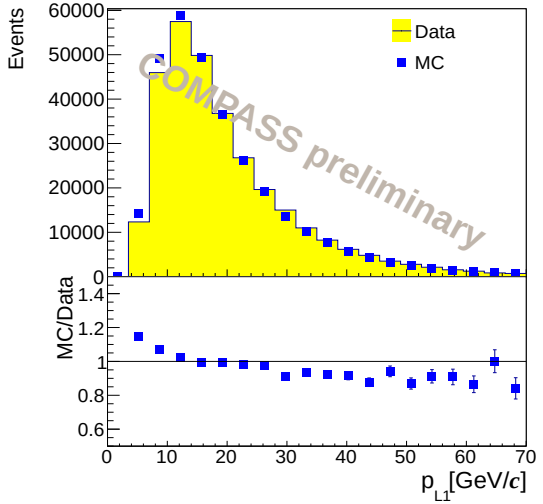
# MC vs data. Deuteron

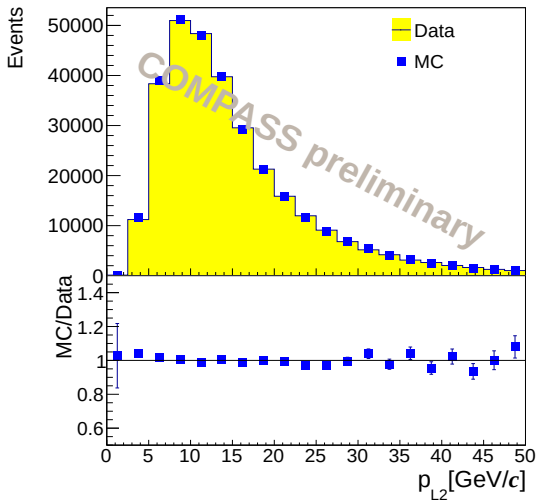


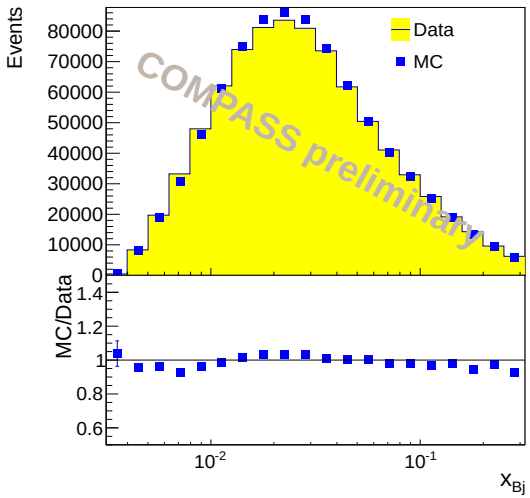



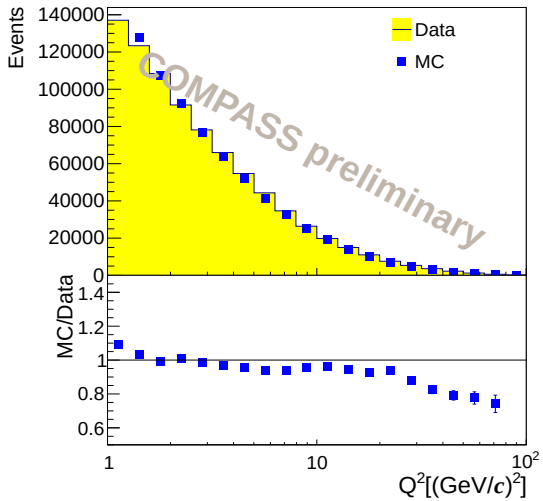



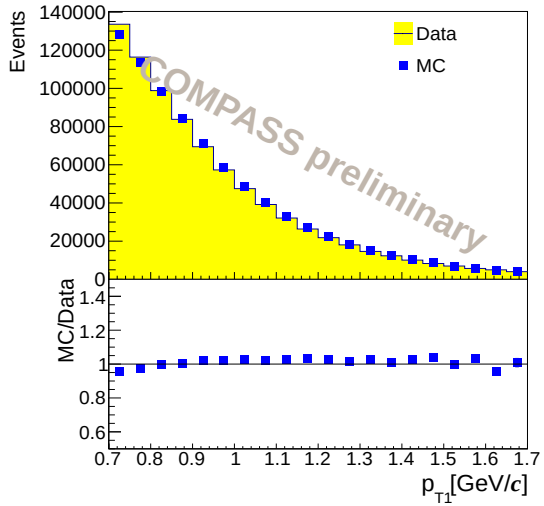



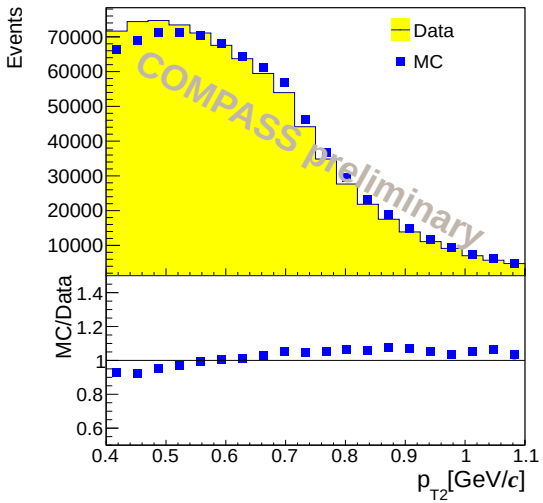



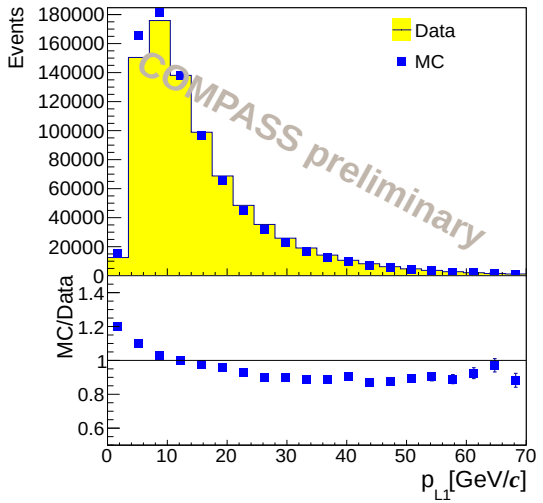
# MC vs data. Proton

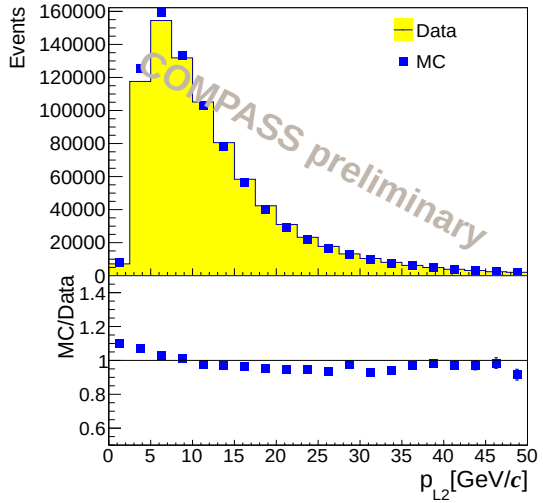


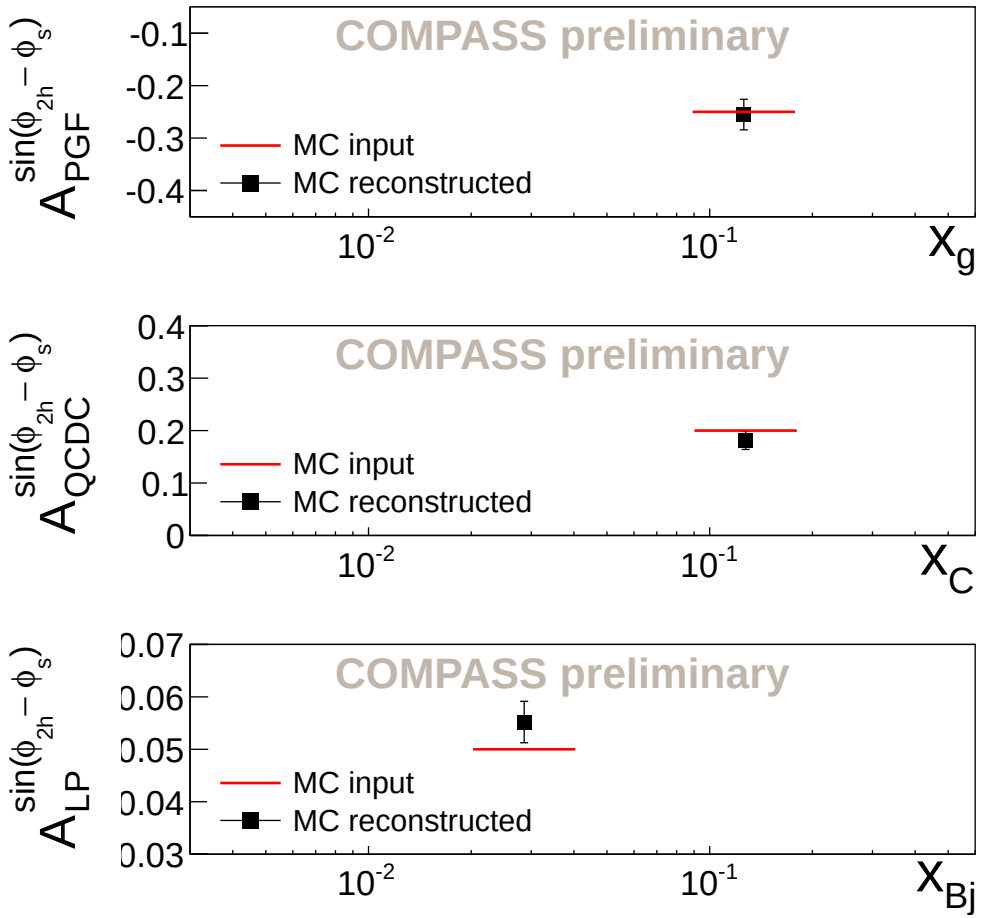



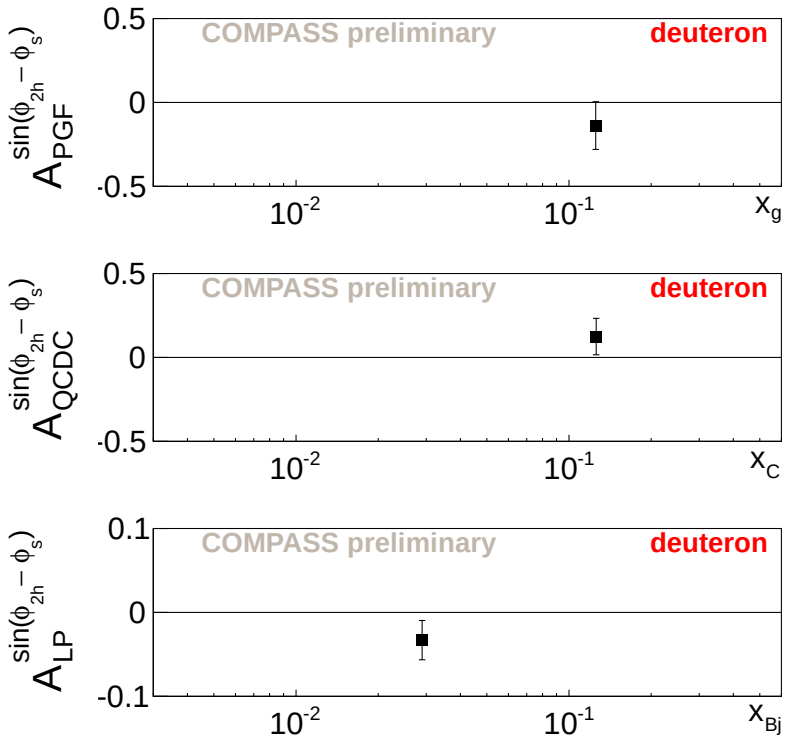



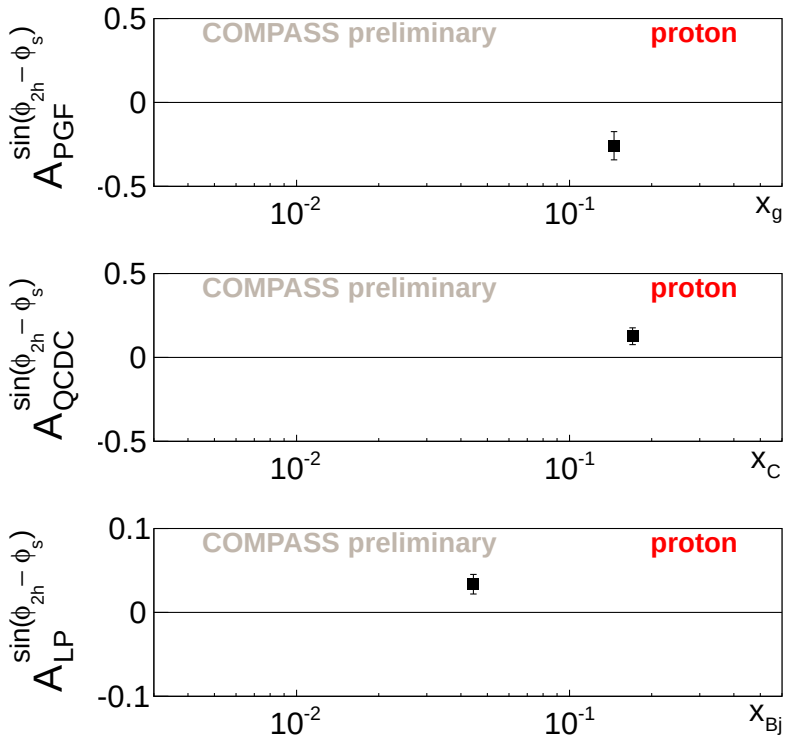



# Method Validation



# Results


COMPASS preliminary
deuteron
$\sin(\phi_{2h}-\phi_s)$ $A_{PGF}$
$x_g$
$\sin(\phi_{2h}-\phi_s)$ $A_{QCDC}$
$x_C$
$\sin(\phi_{2h}-\phi_s)$ $A_{LP}$
$x_{Bj}$


COMPASS preliminary
proton
$\sin(\phi_{2h}-\phi_s)$ $A_{PGF}$
$x_g$
$\sin(\phi_{2h}-\phi_s)$ $A_{QCDC}$
$x_C$
$\sin(\phi_{2h}-\phi_s)$ $A_{LP}$
$x_{Bj}$

# Systematics summary. Proton target

| source | value | % $\sigma_{stat}(= 0.085)$ | estimated uncertainty |
|---|---|---|---|
| Monte Carlo | 0.054 | 64% | 0.054 |
| False asymmetries | 0.032 | 38% | 0.032 |
| cut on hadron charges $q_1 \cdot q_2 = -1$ | 0.038 | 45% | 0.038 |
| radiative corrections | 0.018 | 21% | 0.018 |
| large $Q^2$ | 0.014 | 16% | 0.014 |
| $x_{Bj}$ binning | 0.011 | 13% | 0.011 |
| all asyms vs only Sivers | 0.005 | 6% | 0.005 |
| ML vs Weighted | 0.004 | 5% | 0.004 |
| target polarisation | 0.0043 | 5% | 0.0043 |
| dilution factor | 0.0017 | 2% | 0.0017 |
| total $\sqrt{\sum \sigma_i^2}$ | | 92% | 0.078 |

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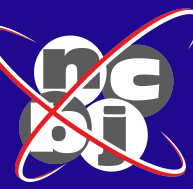
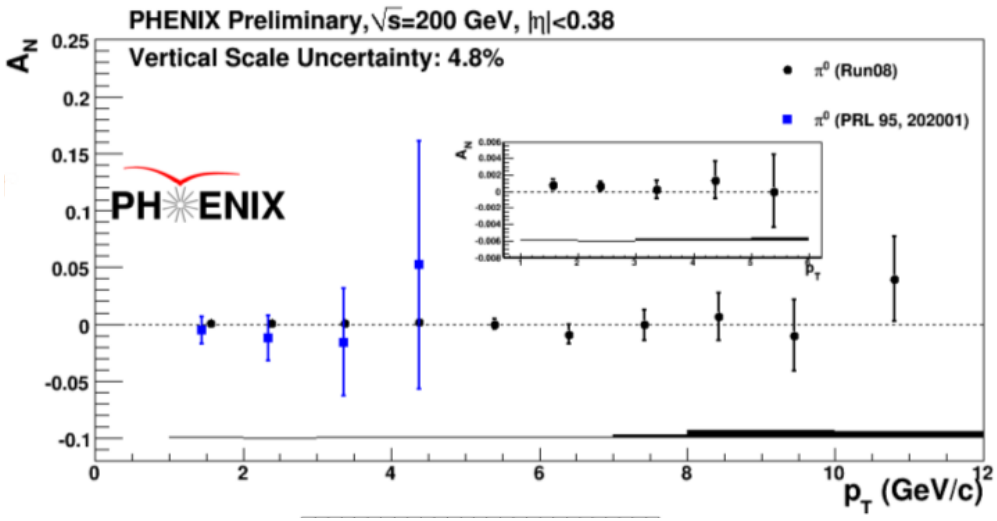
# Summary

1. A method of simultaneous extraction of asymmetries of three contributing processes has been proposed.
2. the value of gluon Sivers asymmetry for proton is:
   $A_{PGF}^{\sin(\phi_{2h}-\phi_s)} = -0.26 \pm 0.09(stat.) \pm 0.08(syst.)$ at $\langle x_G \rangle = 0.15$
3. the value of gluon Sivers asymmetry for deuteron is:
   $A_{PGF}^{\sin(\phi_{2h}-\phi_s)} = -0.14 \pm 0.15(stat.) \pm 0.06(syst.)$ at $\langle x_G \rangle = 0.13$
4. The result on deuteron is compatible with zero but the central value is negative with large error.
5. 2010 proton data show a value which is negative, 3 $\sigma$ bellow zero and does not contradict the result obtained on deuteron.
6. PHENIX results from proton-proton collisions with $\sqrt{s} = 200$GeV for the observable $A_N$ sensitive to the gluon Sivers function give values compatible with zero.

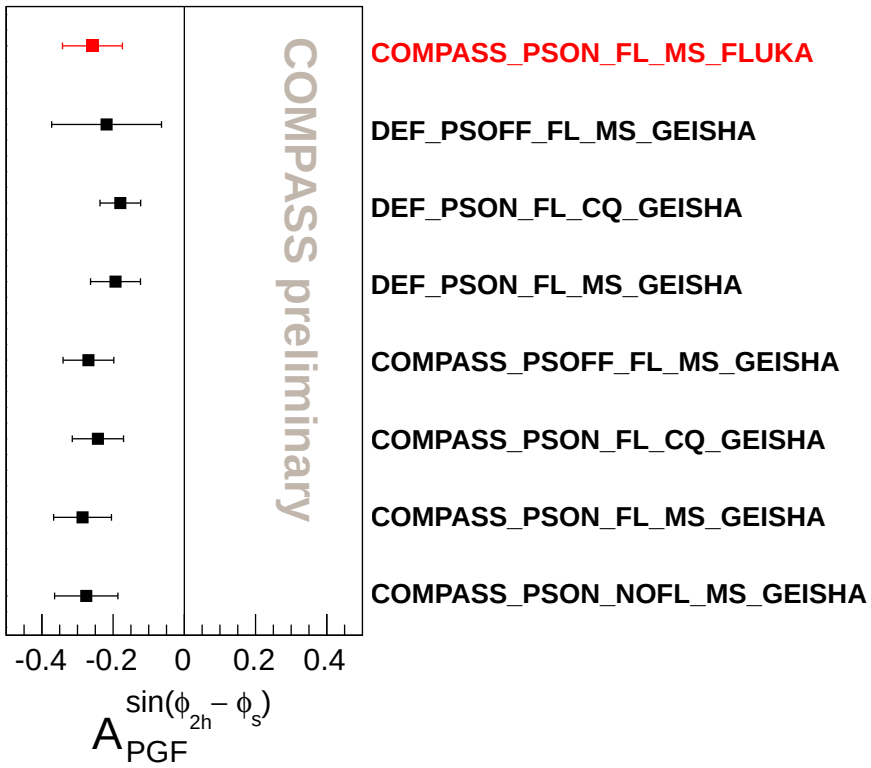
COMPASS 


ncbj 

# Backup slides

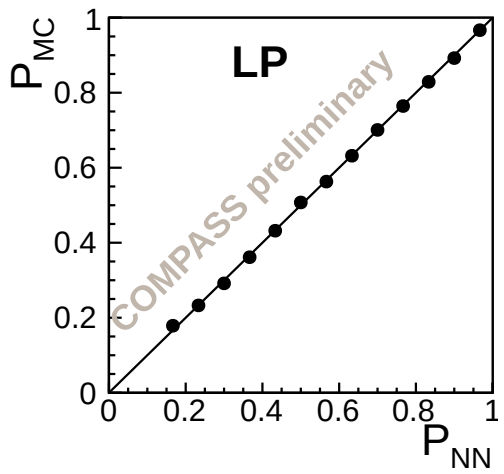

PHENIX Preliminary, √s=200 GeV, |η|<0.38
Vertical Scale Uncertainty: 4.8%
π⁰ (Run08)
π⁰ (PRL 95, 202001)
PHENIX
A_N
p_T (GeV/c)

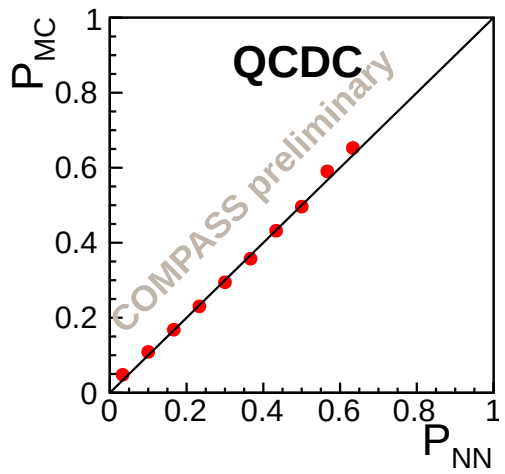
# NNs final

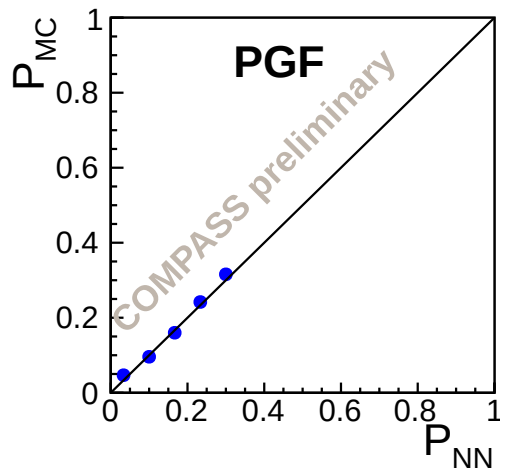


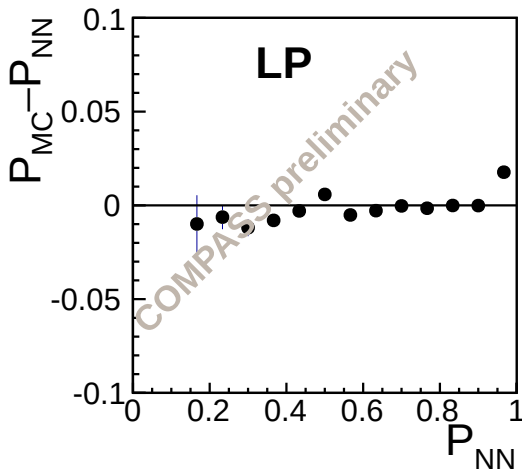

RMS : 0.040; min : -0.300; max : -0.193; (max-min)/2 = 0.054

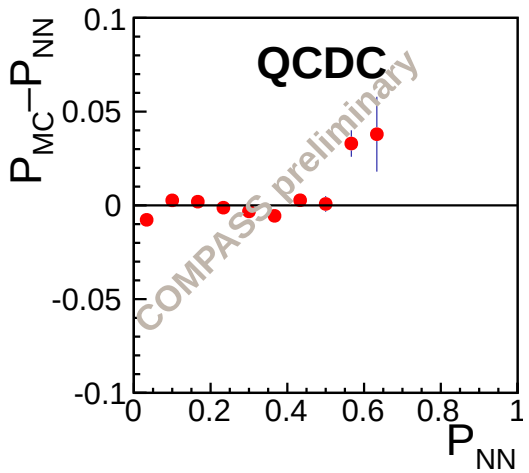
# NN training validation

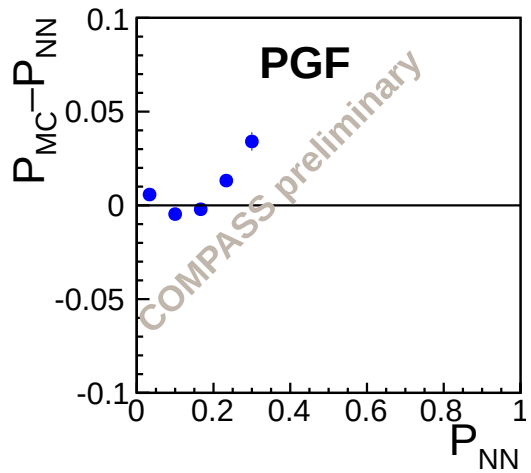


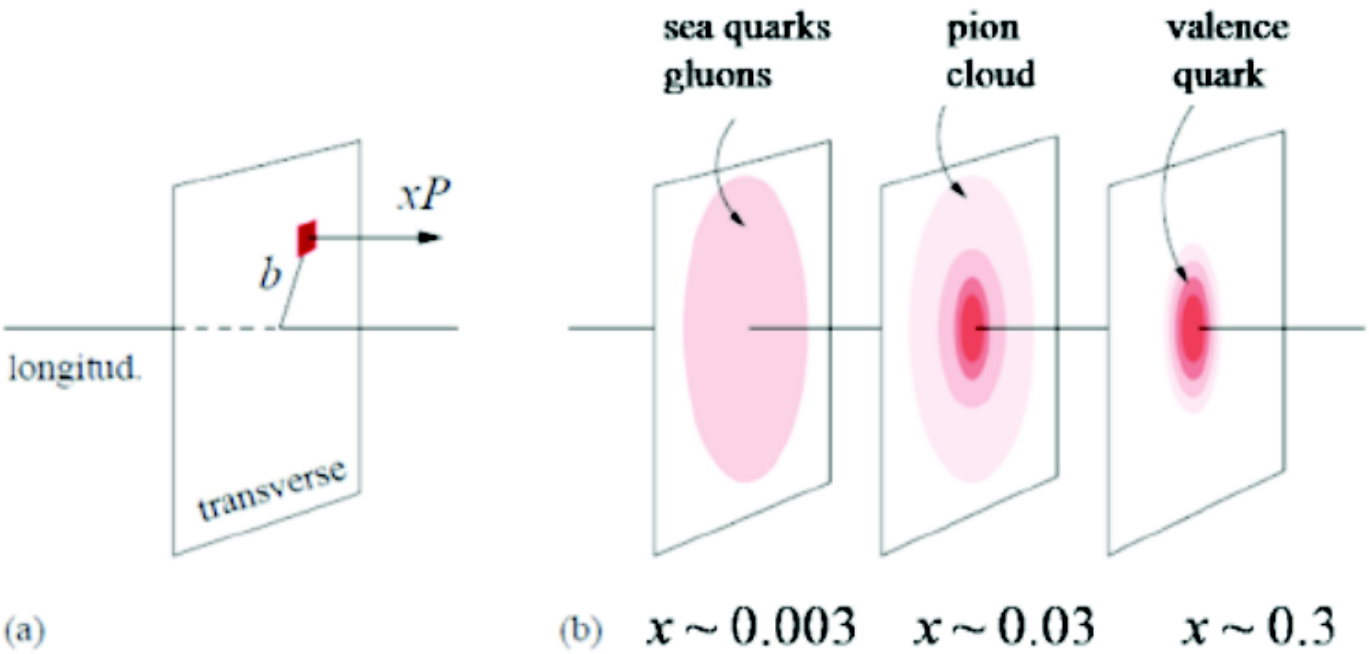



# Nucleon "tomography"

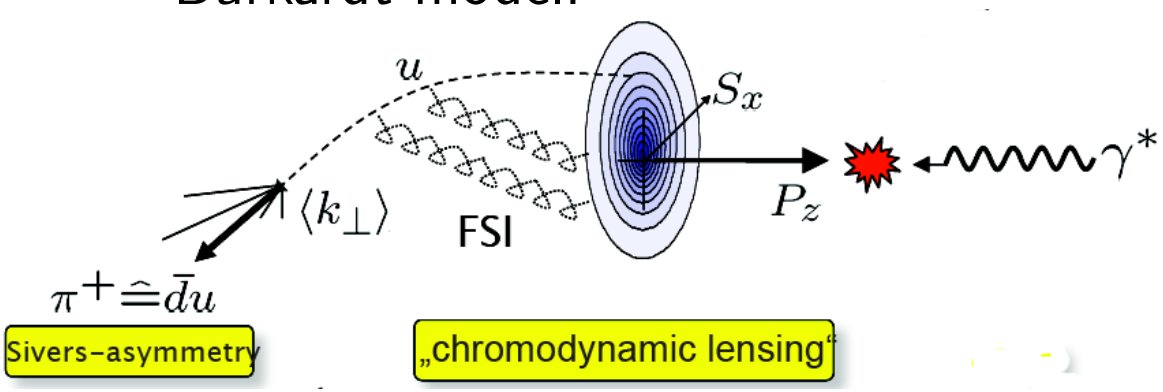
TMD: longitudinal momentum x and trasverse momentum $\vec{k}_T$(3D)

alternatively: GPDs gives simultaneous distribution of quarks w.r.t.: longitudinal momentum xP and transverse position $\vec{b}_\perp$ - impact parameter (3D)



# Chromodynamic lensing

Burkardt model:




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

$\mathcal{H}$ - unpolarised GPD function (symmetric)

$\mathcal{E}$ - spin-flip function, when nonzero $\Rightarrow$ nonzero OAM

M. Burkardt, Int. J. Mod. Phys. A 18 (2003) 173; Nucl. Phys. A 735 (2004) 185; Phys. Rev. D 69 (2004) 074032