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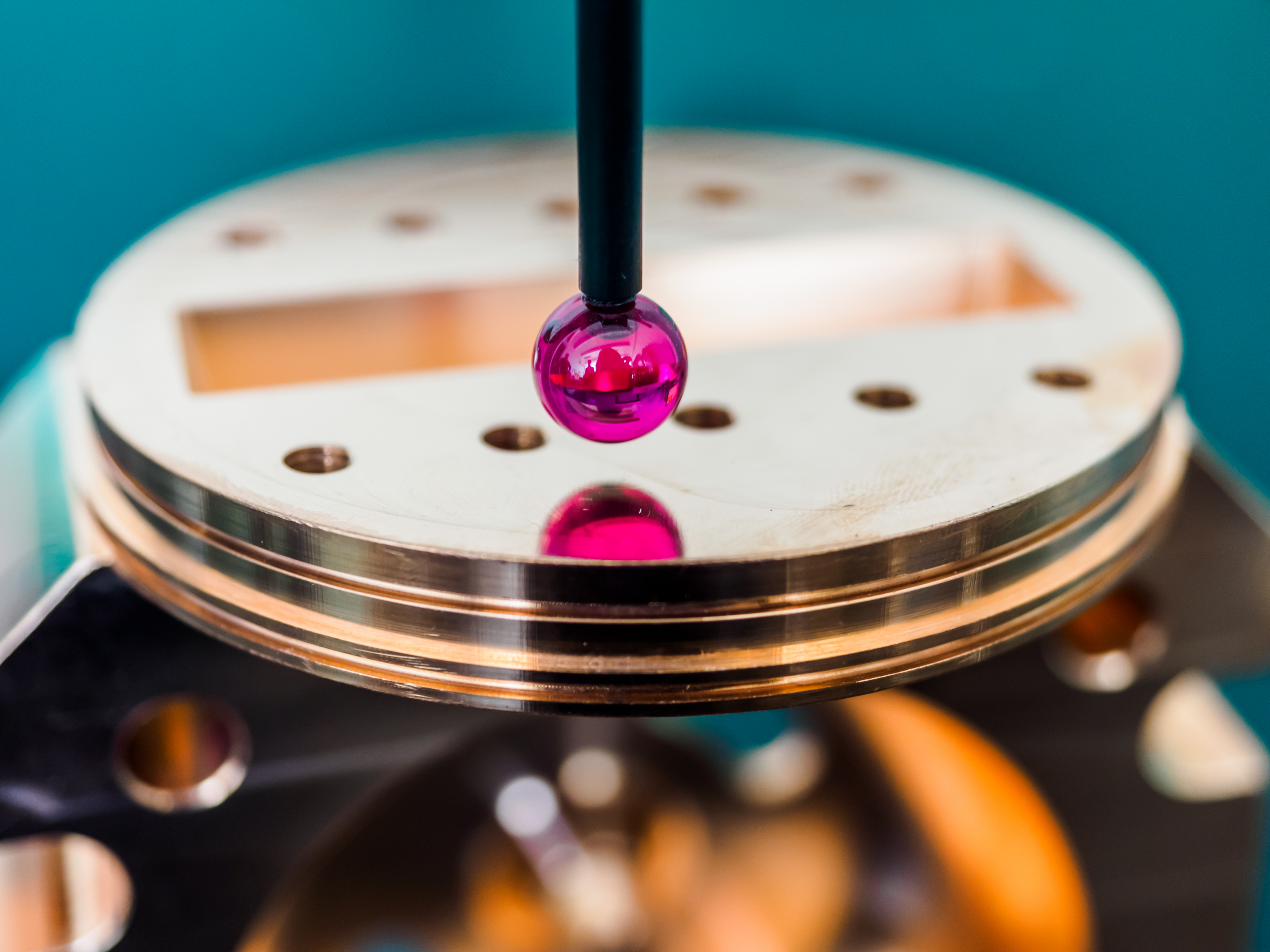
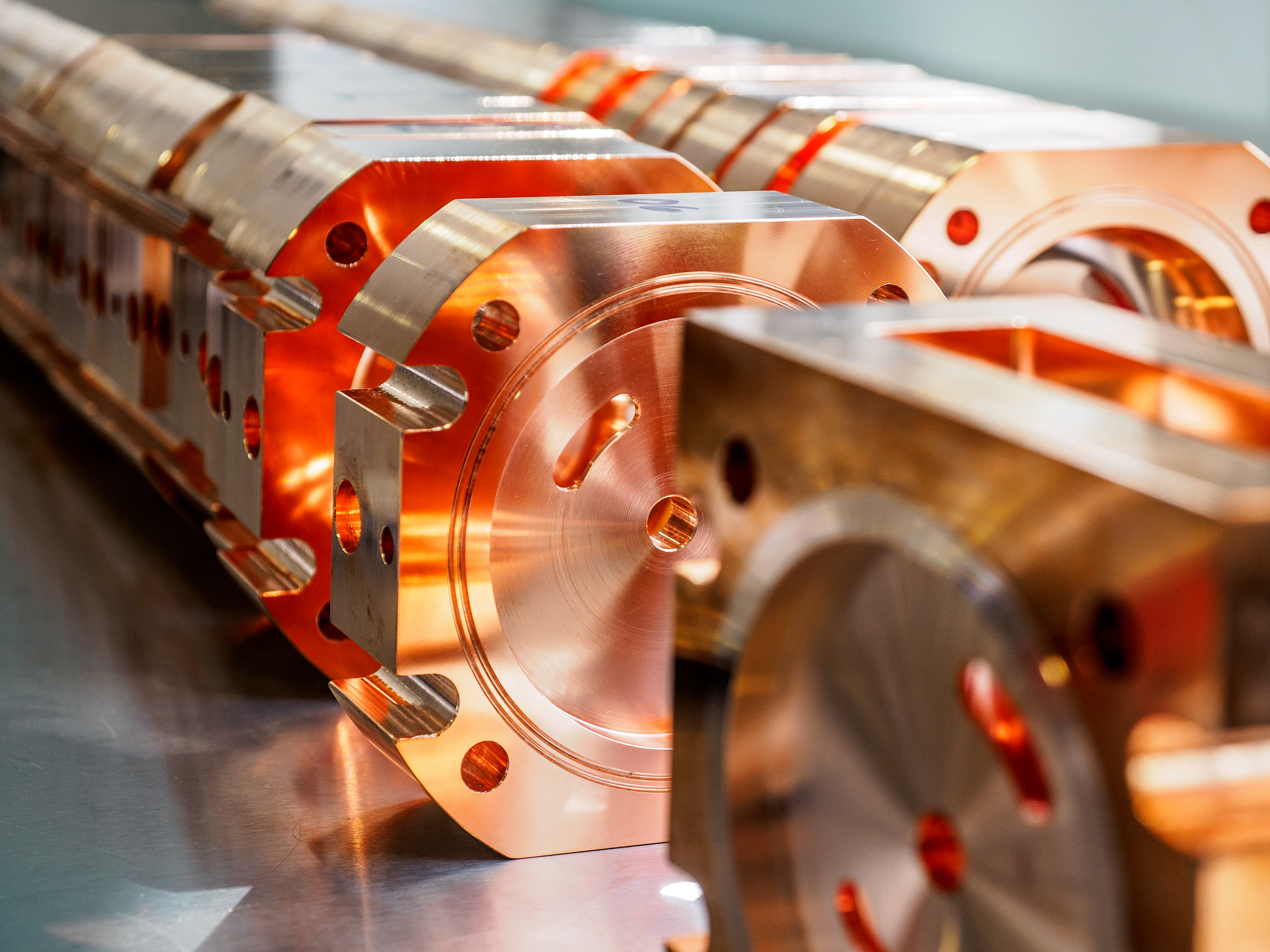
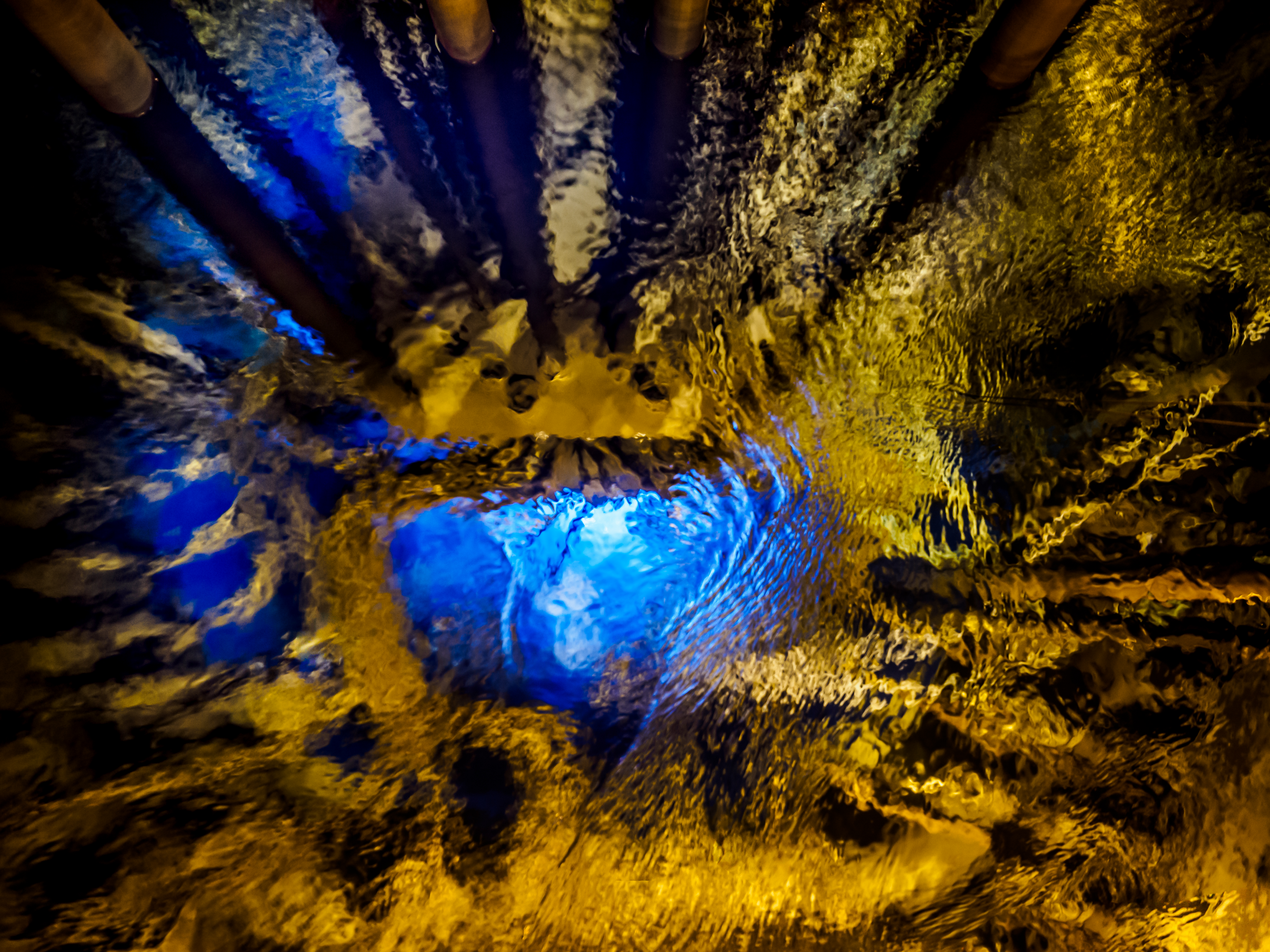






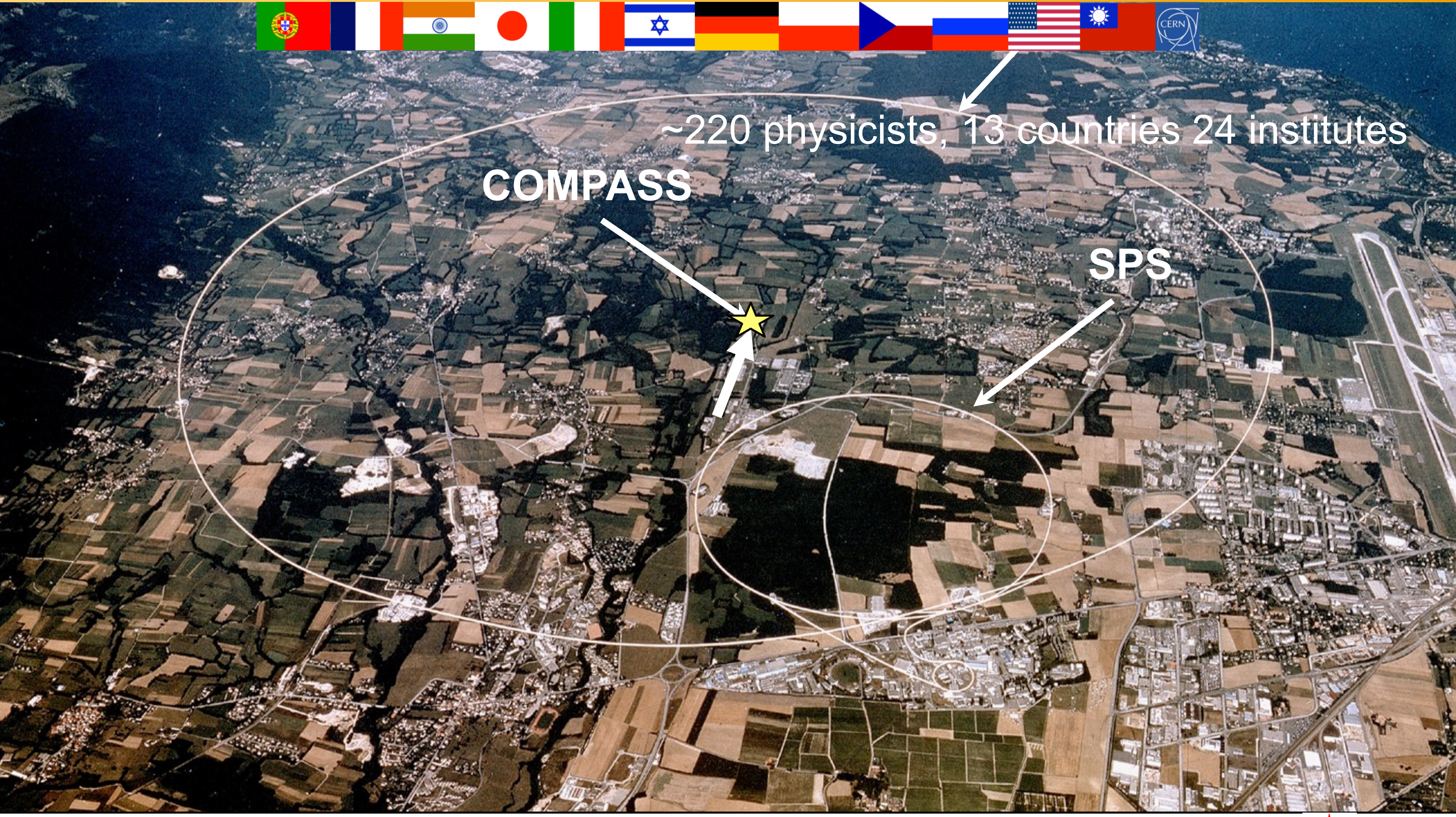
Polarized Gluons and More from COMPASS

Krzysztof Kurek,
National Centre for Nuclear Reserach,
Otwock-Świerk, Poland

COMPASS Collaboration at CERN

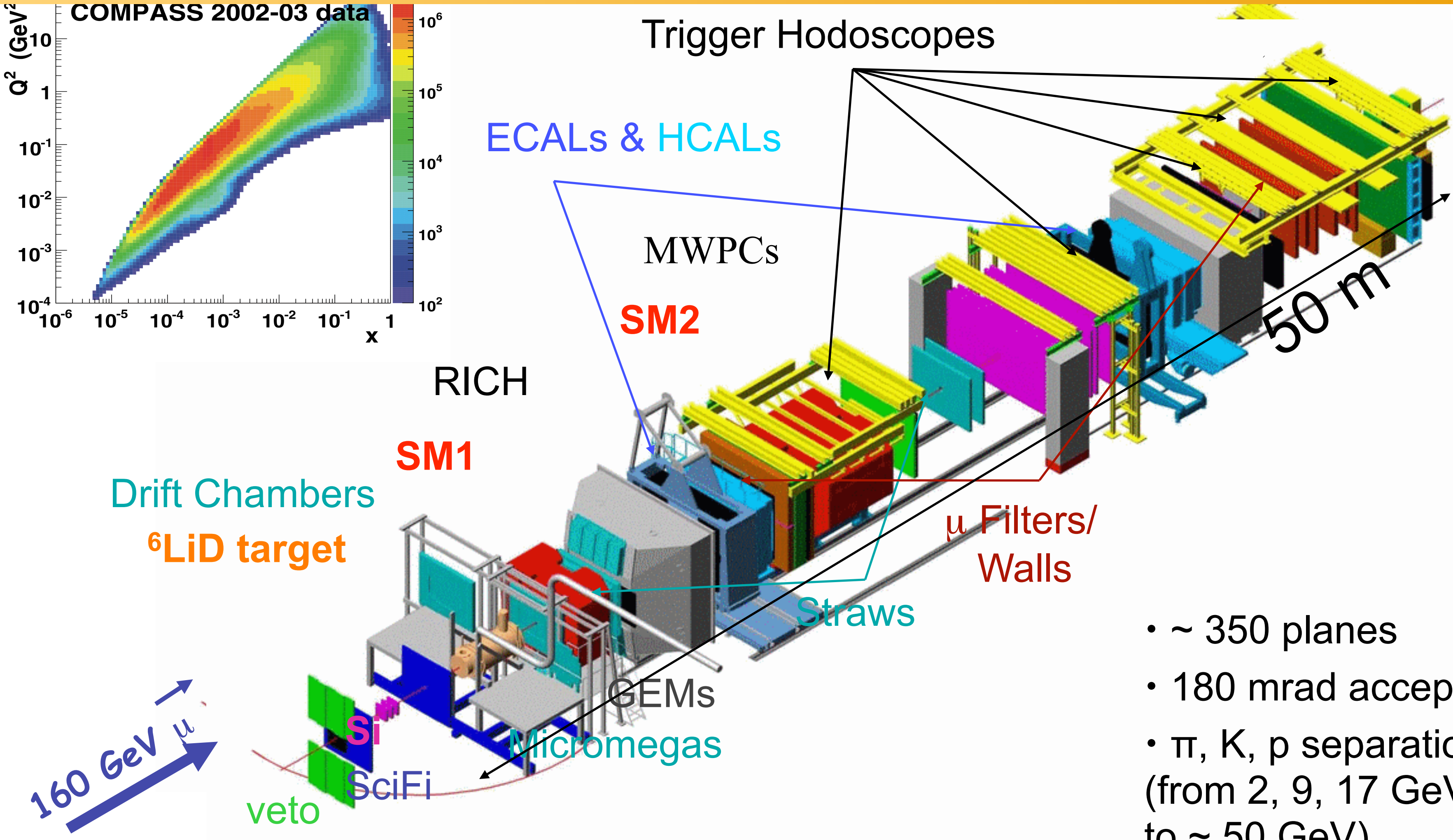
Beam: $2 \cdot 10^8$ μ^+/ spill (4.8s / 16.2s)
Luminosity ~$5 \cdot 10^{32}$ cm^{-2} s^{-1}
Beam polarization: -80%
Beam momentum: 160 & 200 GeV/*c*

Common Muon and Proton Apparatus for Structure and Spectroscopy



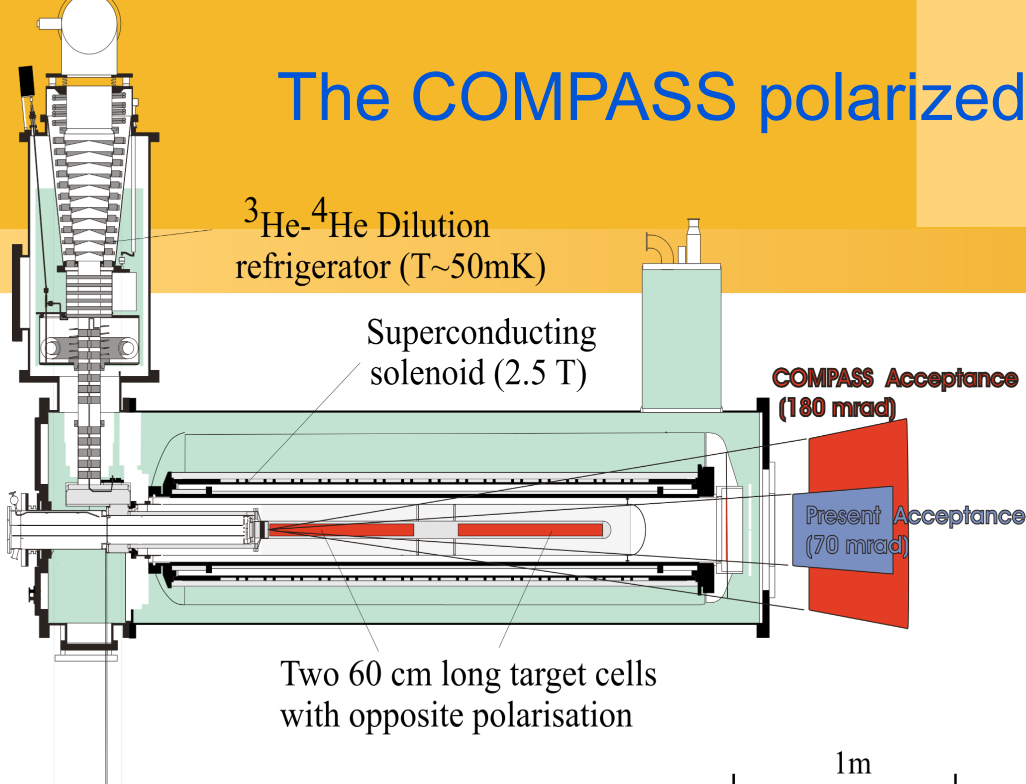
The COMPASS spectrometer

COMPASS in muon run
NIM A 577(2007) 455



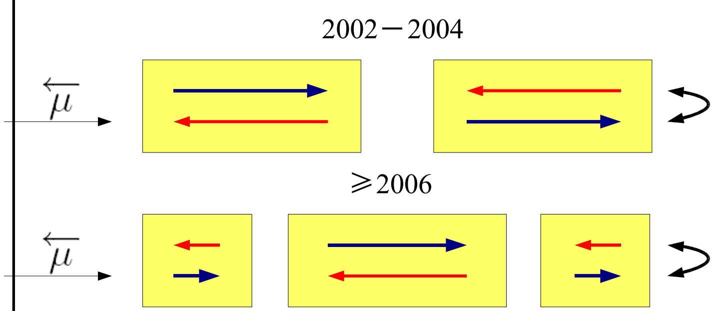
- ~ 350 planes
- 180 mrad acceptance
- π, K, p separation (from 2, 9, 17 GeV up to ~ 50 GeV)

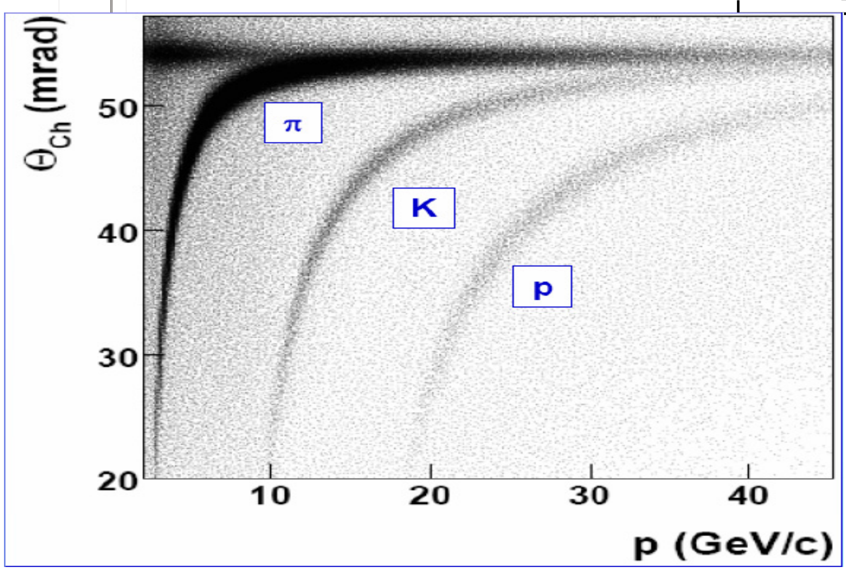
The COMPASS polarized target and PID



Target material: ^{6}LiD NH_3
Polarisation: >50% ~90%
Dilution factor: ~0.4 ~ 0.25
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

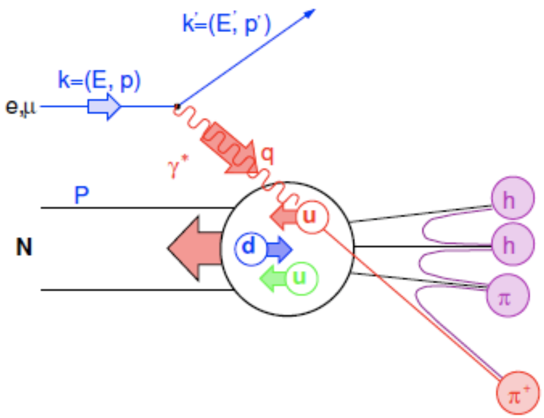
APV electronics in periphery

Contents

- Introduction
- New DIS & SIDIS results from COMPASS
- The determination of gluon polarisation from COMPASS - review and new
- Preliminary result for Sivers asymmetry for gluons on deuteron and proton targets
- Summary

Basic tool: the measurement of inclusive and semiinclusive asymmetry

Inclusive asymmetry:



$$A_1(x,Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2 \, \Delta q(x,Q^2)}{\sum_q e_q^2 \, q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

$$A_1^h(x,z,Q^2) = \frac{\sigma_{\uparrow\downarrow}^h - \sigma_{\uparrow\uparrow}^h}{\sigma_{\uparrow\downarrow}^h + \sigma_{\uparrow\uparrow}^h} \approx \frac{\sum_q e_q^2 \, \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 \, q(x,Q^2) D_q^h(z,Q^2)}$$

Semi-inclusive asymmetry:

Compass g_1 results: deuteron/proton 160 GeV — Phys. Lett. B 647 (2007) 8, 330 (low Q^2)
Phys. Lett. B 690 (2010) 466

proton 200 GeV — M. Wilfert DIS 2014 2016

inclusive and semi-inclusive asymmetry measured on proton and neutron or deuteron allows to full flavour separation

Phys. Lett. B 660 (2008) 458
Phys. Lett. B 680 (2009) 217
Phys. Lett. B 693 (2010) 227
Phys. Lett. B 753 (2016) 18

First moment of g_1 structure functions

Sum rules

first moment $\Gamma_1 = \int g_1(x)dx$

Bjorken s.r. $\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6g_V} C_1^{NS}$

Ellis-Jaffe s.r. $\Gamma_1^{p,n} = \left(\pm a_3 + \frac{a_8}{3}\right)\frac{C_1^{NS}}{12} + a_0 \frac{C_1^S}{9}$

from Y. Goto *et al.*, PRD62 (2000) 034017:
(SU(3)$_f$ assumed for weak decays)
$a_8 = 0.585 \pm 0.025$

$a_3, a_8, g_{A,V}$ measuered in weak β decays (+Su(3)$_f$)

$C_1^{S,NS}$ calculable in pQCD

$$a_0 = \Delta\Sigma = \Delta u + \Delta d + \Delta s$$

Quark contribution to nucleon helicity

MS scheme: a_0 depends on the scale
AB scheme: a_0 does not depend on the scale but now

$$a_0 = \Delta\Sigma - \frac{3}{2}\frac{\alpha_S}{\pi}\Delta G$$

First moment of g_1 structure functions

Compass only

Phys. Lett. B 647 (2007) 8

$$\Gamma_1^N(Q^2) = \frac{1}{9}\left(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2)\right)\left(a_0(Q^2) + \frac{1}{4}a_8\right)$$

$$a_{0|Q_0^2=3(GeV/c)^2} = 0.35 \pm 0.03(stat) \pm 0.05(syst)$$

QCD NLO

$$a_0(Q^2 = 3\,(\mathrm{GeV}/c)^2) = 0.32 \pm 0.02_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}} \pm 0.04_{\mathrm{evol}}$$

2006 data reanalysed
2x statistics
new QCD COMPASS fit

Phys. Lett. B 753 (2016) 18

$$\Gamma_1^N(Q^2) = \frac{1}{9}C_1^S(Q^2)\hat{a}_0 + \frac{1}{36}C_1^{NS}(Q^2)a_8$$

beyond NLO

$$\hat{a}_{0|Q^2\to\infty} = 0.33 \pm 0.03(stat) \pm 0.05(syst)$$

C_1 calculated behind 3 loops app.
S.A.Larin *et al.*,Phys.Lett.B404(1997)153

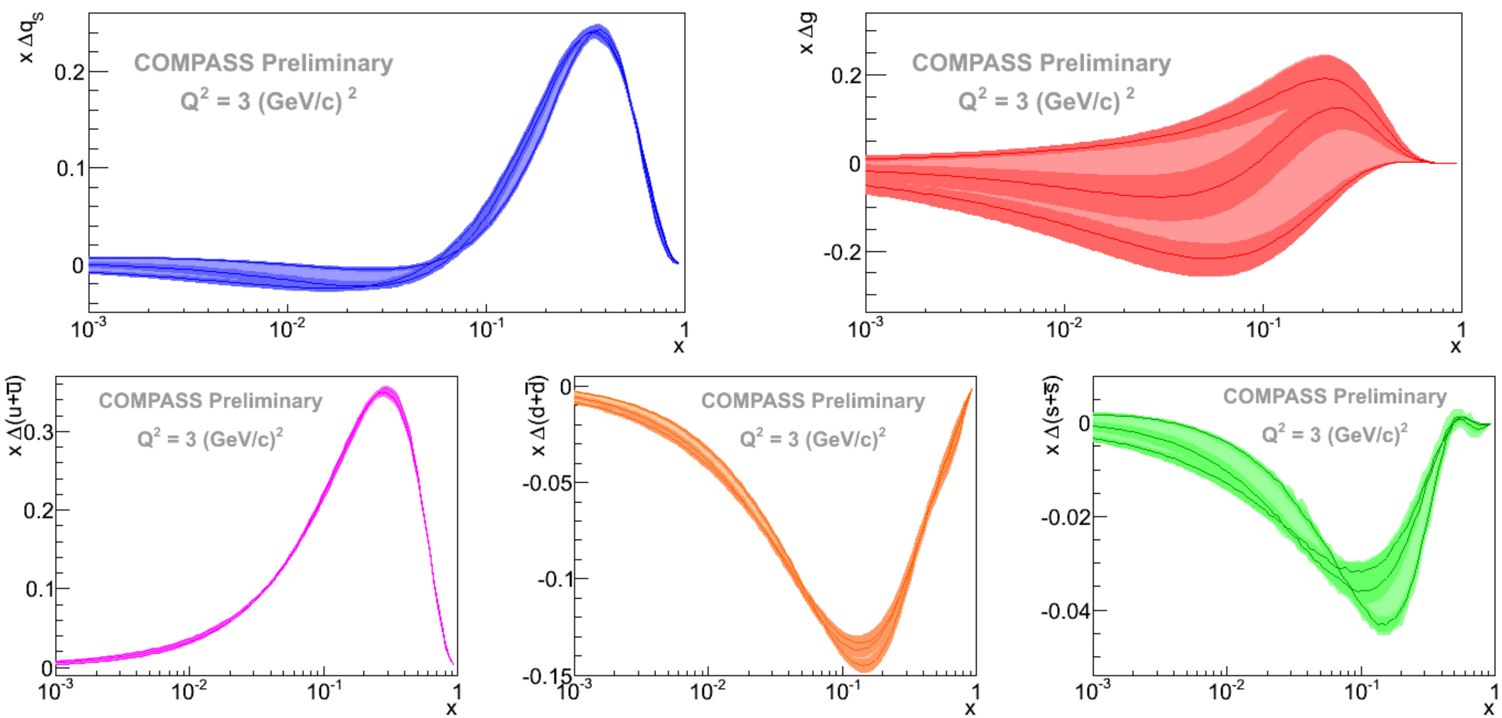
$$(\Delta s + \Delta\bar{s}) = \frac{1}{3}(\hat{a}_0 - a_8) = -0.08 \pm 0.01(stat) \pm 0.02(syst)$$

$$\Delta(s + \bar{s}) = -0.088 \pm 0.007_{\mathrm{stat}} \pm 0.012_{\mathrm{syst}} \pm 0.015_{\mathrm{evol}}$$

New COMPASS NLO QCD fit

Inclusive world data used + new COMPASS

Phys. Lett. B 753 (2016) 18



- Small sensitivity to light sea and gluon polarisation
- Quark polarisation $\Delta\Sigma = \int \Delta q_{Si}(x)\mathrm{d}x \sim 0.3$
- Gluon polarisation $\Delta G = \int \Delta g(x)\mathrm{d}x$ Not well constrained

more details see:
Malte Wilfert, DIS 2016

Test of Bjorken sum rule

Compass data (2011 data & new QCD fit included)

Phys. Lett. B 690 (2010) 466–472

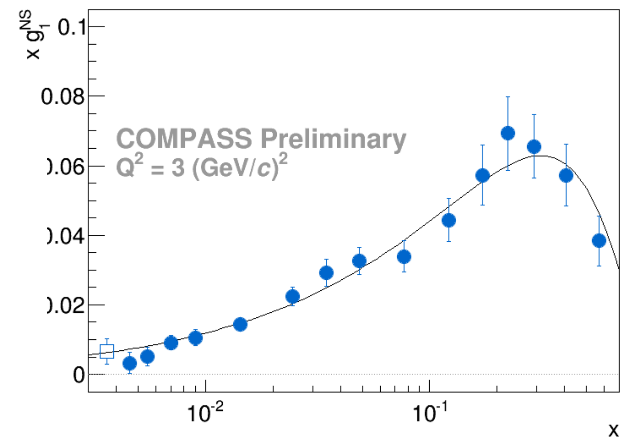
$$\Gamma_1^{NS}(Q^2) = \frac{1}{6}\frac{g_A}{g_V}C_1^{NS}(Q^2)$$

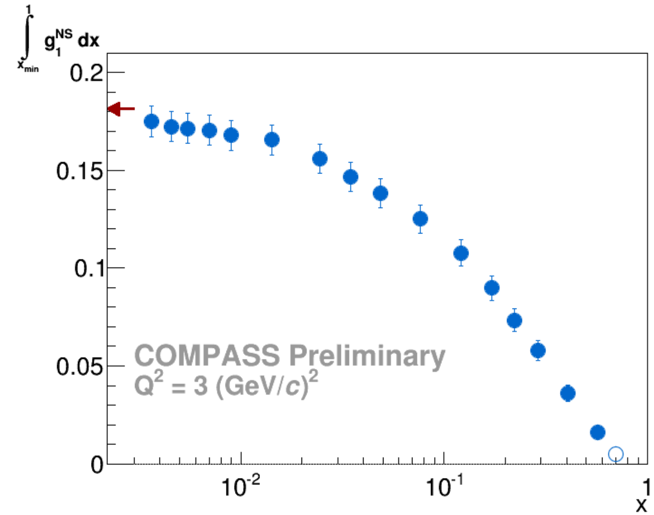
$C^{NS} = 0.89$ $Q^2 = 3\ (\mathrm{GeV}/c)^2$

- Value from the neutron β decay: $|\frac{g_A}{g_V}| = 1.2701 \pm 0.0020$
- Mean Q^2 of the COMPASS data $Q^2 \approx 3\ (\mathrm{GeV}/c)^2$
- $g_A/g_V = 1.220 \pm 0.053\ (\mathrm{stat.}) \pm 0.095\ (\mathrm{syst.})$
  1.28 0.07 0.1
- Verification of the Bjorken sum rule
- Estimate size and direction of NNLO correction
- Use C_1^{NS} in NNLO: $g_A/g_V = 1.256$

$$\Delta(u+\bar{u}) = 0.840 \pm 0.007_{\mathrm{stat}} \pm 0.012_{\mathrm{syst}} \pm 0.015_{\mathrm{evol}}$$
$$\Delta(d+\bar{d}) = -0.429 \pm 0.007_{\mathrm{stat}} \pm 0.012_{\mathrm{syst}} \pm 0.015_{\mathrm{evol}}$$

Flavor separation: Phys. Lett. B 647 (2007) 8 & 690 (2010) 466
Difference asymmetry Phys. Lett. B 660 (2008) 458





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Phys. Lett. B 690 (2010) 466–472

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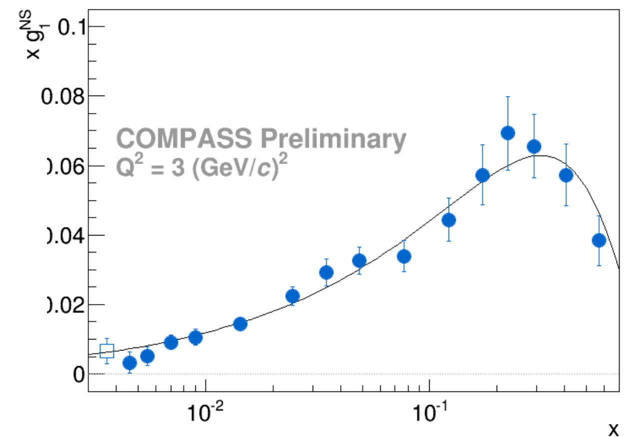

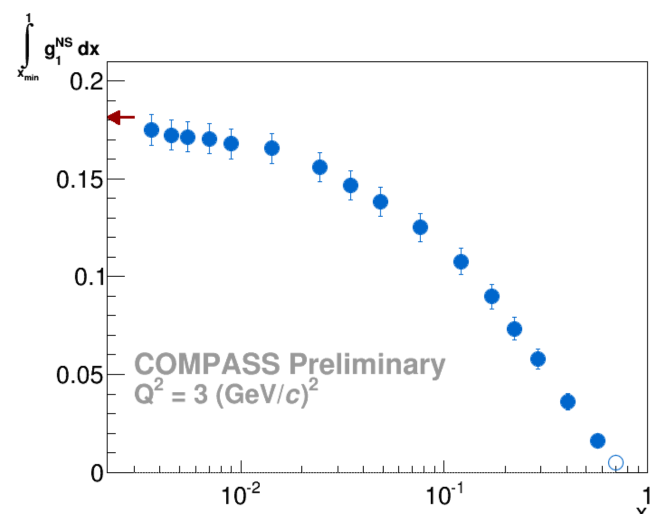

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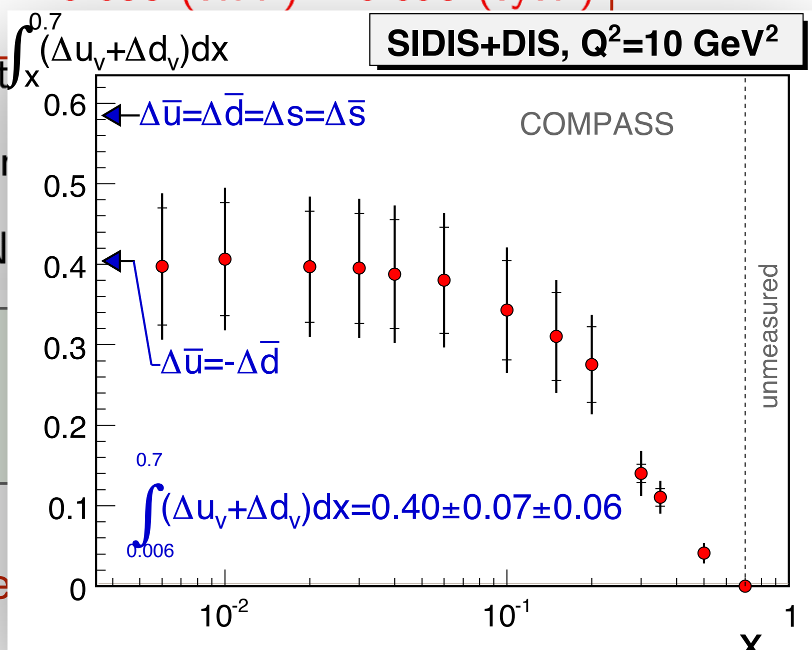
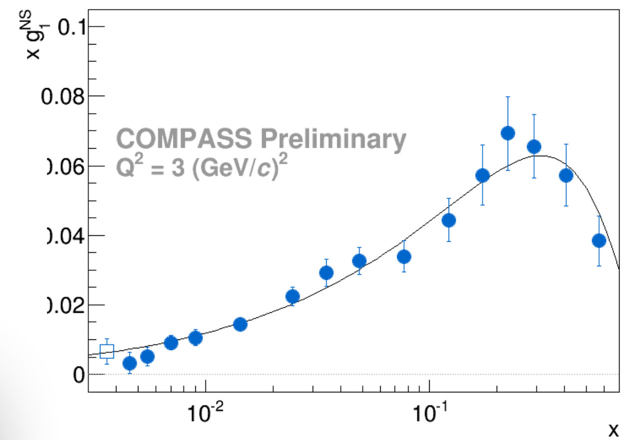
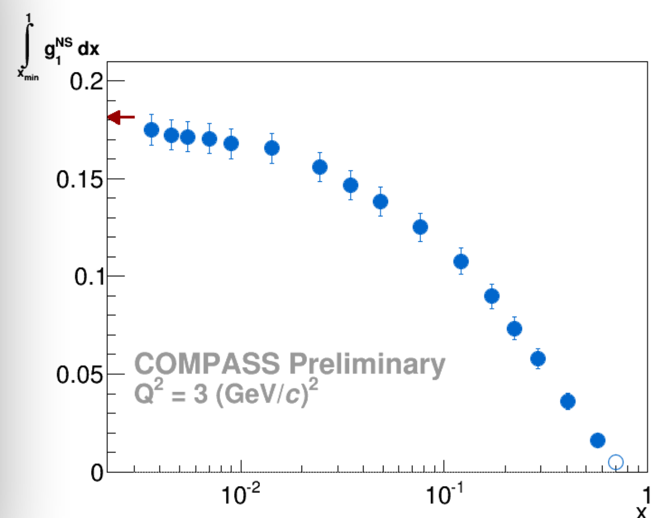
  1.28
- Verification of t
- Estimate size a
- Use C_1^{NS} in NN

$\Delta(u+\bar{u})$ =
$\Delta(d+\bar{d})$ =

Flavor separation:
Difference asymme

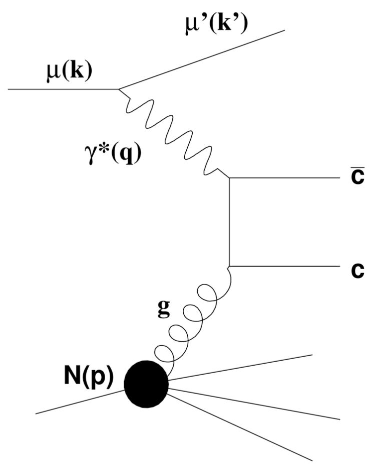






Direct gluon polarisation measurement via tagging PGF process

Non direct measurement of gluon polarisation - QCD fits



To select PGF process two methods are used @COMPASS:

- **Open-charm D meson production:**
  charm quark pairs produced in PGF, "clean" channel however with huge combinatorial background, low statistics but analysis less MC dependent

- **High transverse momentum hadron pairs production:**
  light quark pairs produced, high statistics but physical background; strongly model and MC dependent analysis, requires a very good agreement between data and MC

$$\sigma^{PGF} = G \otimes \hat{\sigma}^{PGF} \otimes H$$

$$\Delta\sigma^{PGF} = \Delta G \otimes \Delta\hat{\sigma}^{PGF} \otimes H$$

R.D.Carlitz, J.C.Collins and A.H.Mueller, Phys.Lett.B 214, 229 (1988)
Revisited by A.Bravar,D.von Harrach and A.Kotzinian, Phys.Lett.B 421, 349 (1998)
Applied by SMC, HERMES and COMPASS

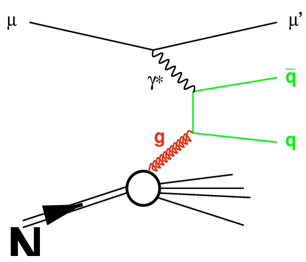
from MC

$$A \approx \frac{\Delta G}{G}(\bar{x}_G) < \hat{a}_{LL}^{PGF} >_G$$

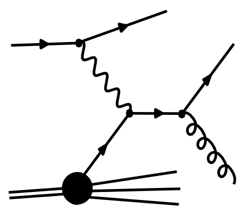
signal asymmetry from data

Large Q^2 : $Q^2 > 1\ (\mathrm{GeV}/c)^2$

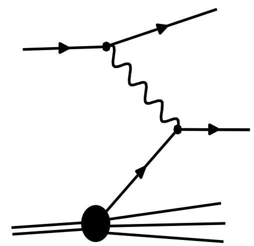
Physical model: three processes (LO QCD)



PGF



QCD-Compton



LO-DIS

$$A_{LL}^{2h}(x_{Bj}) \approx \frac{\Delta G}{G}(x_G)\,\hat{a}_{LL}^{PGF} R_{PGF} + A_1^{LO}(x_C)\,\hat{a}_{LL}^{C} R_C + A_1^{LO}(x_{Bj})\, D R_L$$

$$A_1^{LO} \equiv \frac{\sum_i e_i^2 \Delta q_i}{\sum_i e_i^2 q_i}$$

Same decomposition for inclusive sample to determine A_1^{LO}

Optimization needed : “clean” (more PGF, “pure”) sample with limited statistics or less PGF populated but larger sample

ex: MC vs Data (sample: 2004) gluon polarization result

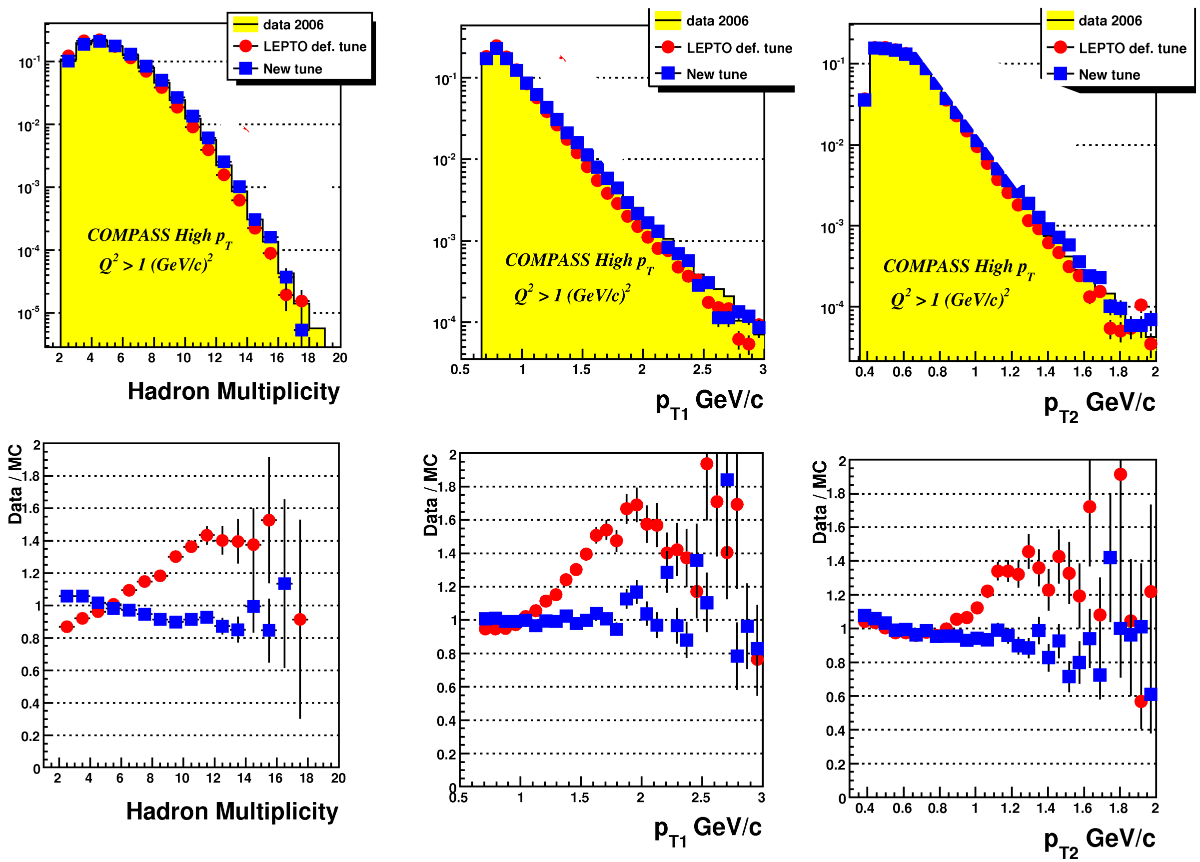
Effect of tuning clearly visible

Phys. Lett. B 718 (2013) 922

	1st point	2nd point	3rd point
ΔG/G	0.15 ± 0.09 ± 0.09	0.08 ± 0.10 ± 0.08	0.19 ± 0.17 ± 0.14
$<x_g>$	$0.07^{+0.05}_{-0.03}$	$0.10^{+0.07}_{-0.04}$	$0.17^{+0.10}_{-0.06}$

$$\frac{\Delta G}{G} = 0.125 \pm 0.060 \pm 0.063$$

$$x_G = 0.09^{+0.08}_{-0.04} \qquad \langle \mu^2 \rangle = 3.4 (GeV/c)^2$$



$\delta(\Delta G/G)_{NN}$	0.010
$\delta(\Delta G/G)_{MC}$	0.045
$\delta(\Delta G/G)_{false}$	0.019
$\delta(\Delta G/G)_{f,Pb,Pt}$	0.004
$\delta(\Delta G/G)_{A1}$	0.015
$\delta(\Delta G/G)_{formula}$	0.035
Total	0.063

MC

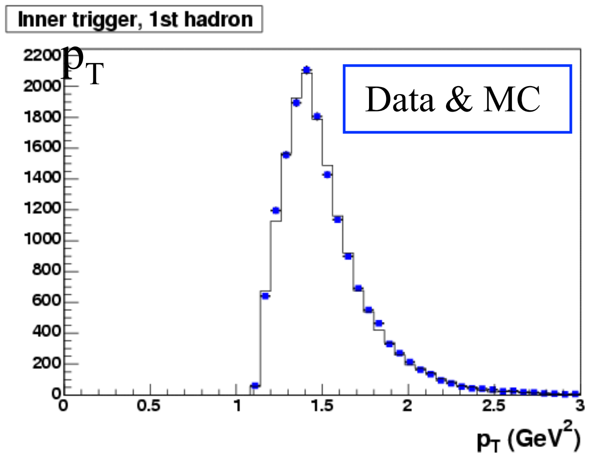
Results for low Q^2 : $Q^2 < 1\ (GeV/c)^2$

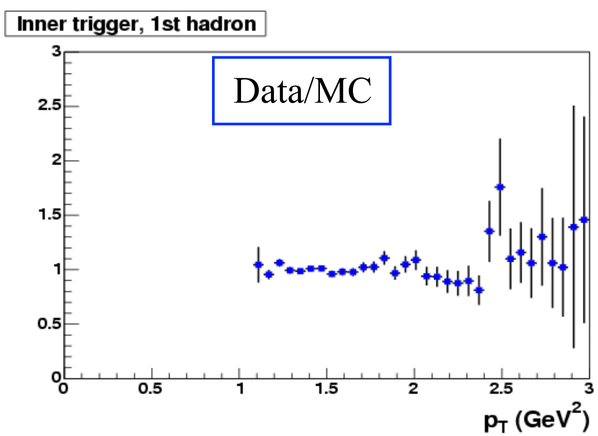
Cuts used – cut on $\Sigma p_T^2 > 2.5\ (GeV/c)^2$

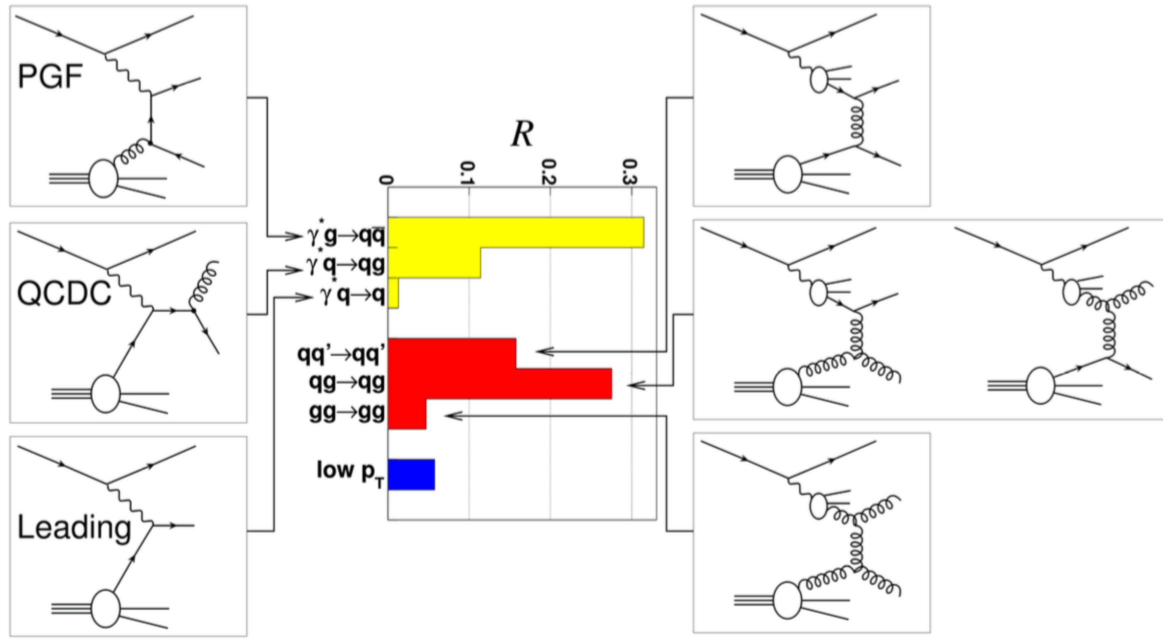
2002-03 results published: Phys. Lett. B 633 (2006) 25

90% of statistics!

PYTHIA generator for low Q² + spectrometer simulation







Data	(ΔG/G)	stat	exp.syst	MC.syst	resolved
02-03	0.024	0.089	0.014	0.052	0.018
02-04	0.016	0.058	0.014	0.052	0.013

New asymmetries (1h) for low Q^2 2006 and 2011 data included

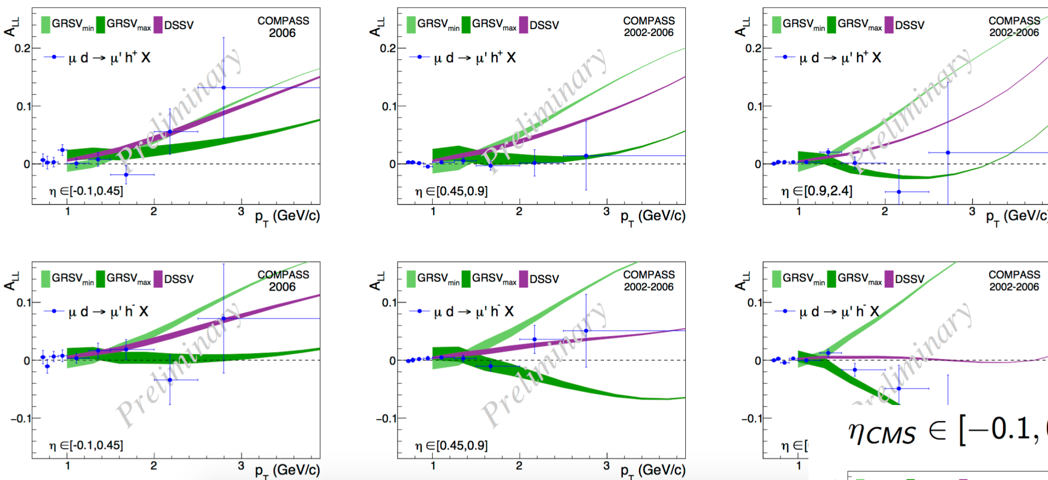
NLO calculations M. Stratmann, B Jager, W. Vogelsang EPJC 44(2005) 533

COMPASS: potentially discriminated power on gluon polarisation

$\eta_{CMS} \in [-0.1, 0.45]$ $\eta_{CMS} \in [0.45, 0.9]$ $\eta_{CMS} \in [0.9, 2.4]$

h^+

h^-



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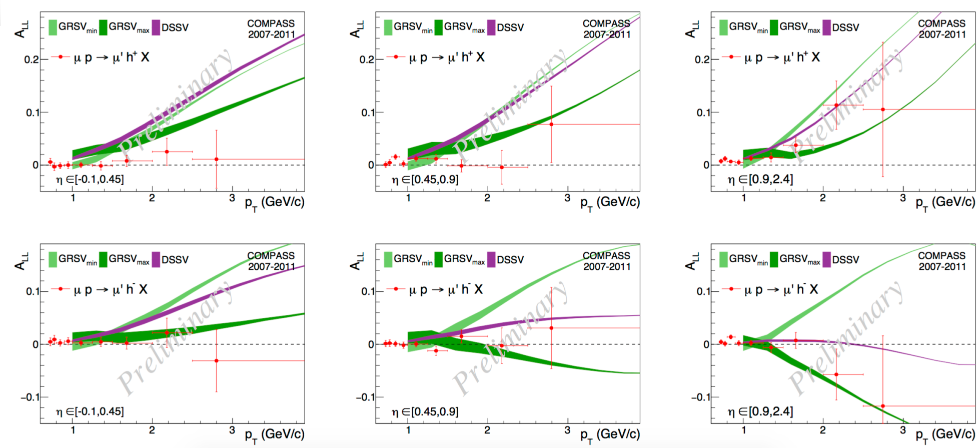

Discrepancy on the level of cross section!
gluons resummation needed?

COMPASS Phys.Rev. D 88 (2013) 091101

calculations Phys. Rev. D 88 (2013) 014024

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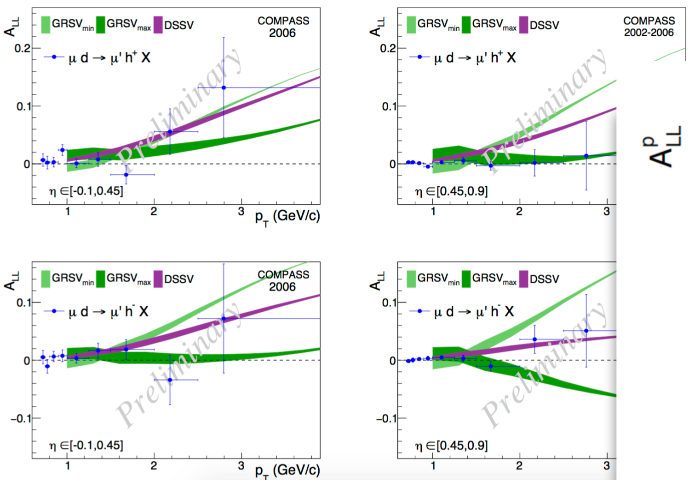
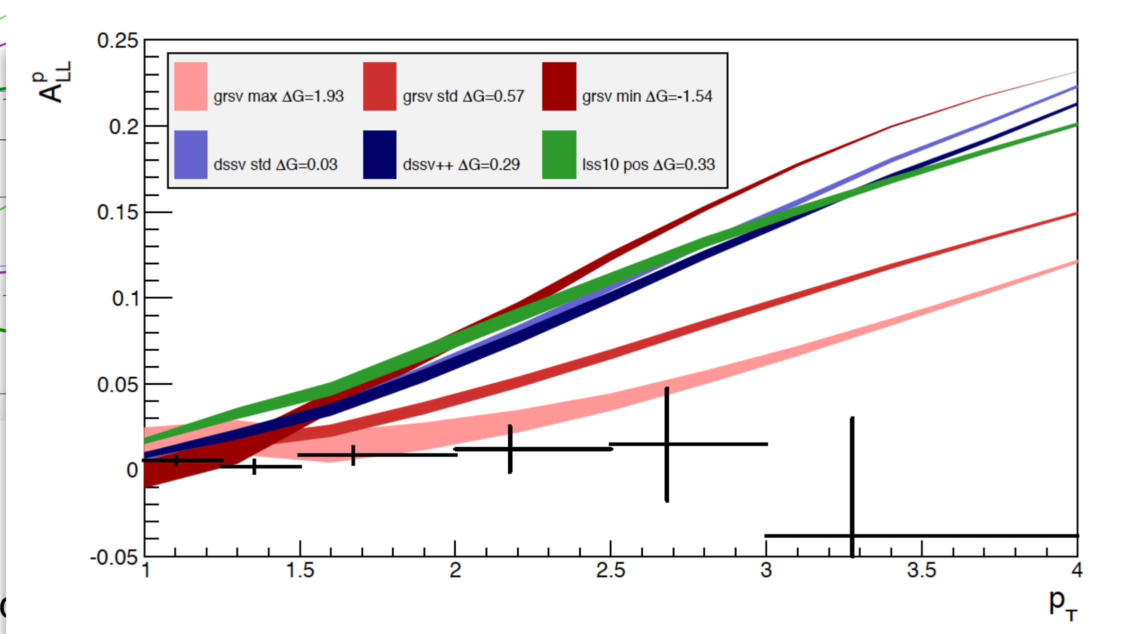
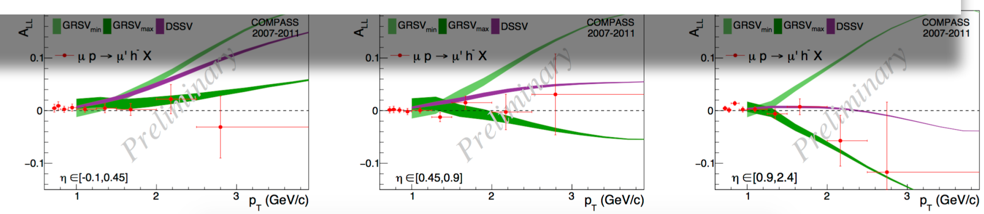




Discrepancy on the level of cross sec… gluons resummation needed?



COMPASS Phys.Rev. D 88 (2013) 091101

calculations Phys. Rev. D 88 (2013) 014024

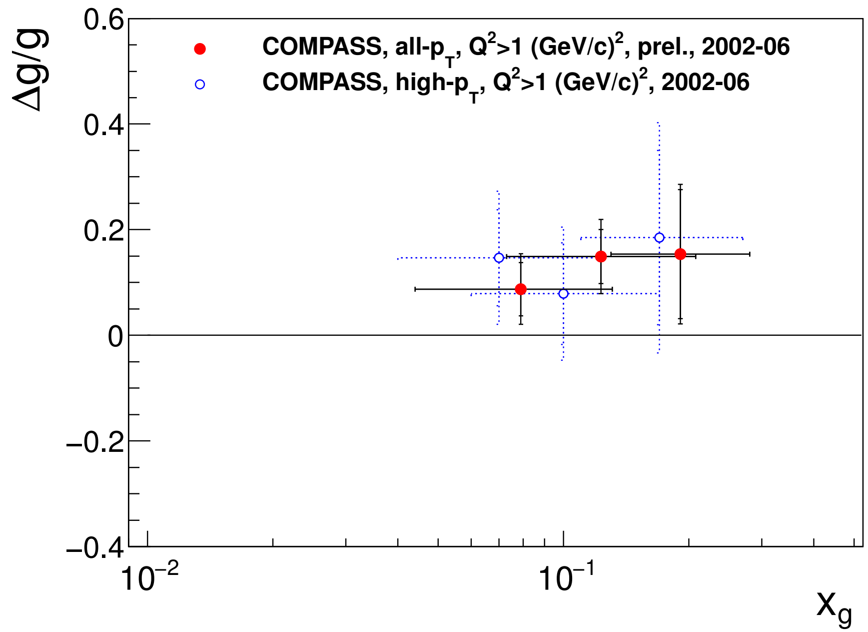
New analysis - all-p_T method results $Q^2 > 1$ GeV^2

Minimalization procedure and covariant matrix is used for error estimation; simultaneously A_1^{LO} and $\Delta g/g$ is fitted; 1 hadron in the final state, no p_T cut!

- $w_{new} \sim a_{LL}^{PGF} R_{PGF}$
- $w_{old} \sim a_{LL}^{PGF} R_{PGF} - a_{LL}^{incl,PGF} R_{PGF}^{incl} \left(\frac{R_{LP} + R_{QCDC} a_{LL}^{QCDC}/D}{R_{LP}^{incl}} \right)$

$$\Delta g/g = 0.113 \pm 0.038 \pm 0.035 \quad \text{(Preliminary)}$$

- the scale, $\mu^2 = < Q^2 > \approx 3$ (GeV/c)^2, and $< x_g > \approx 0.10$
- the result obtained under the assumption: $A_1^{QCDC}(x_C) = A_1^{LP}(x_{Bj})$ for $x_C = x_{Bj}$



comparing to

$$\frac{\Delta G}{G} = 0.125 \pm 0.060 \pm 0.063$$

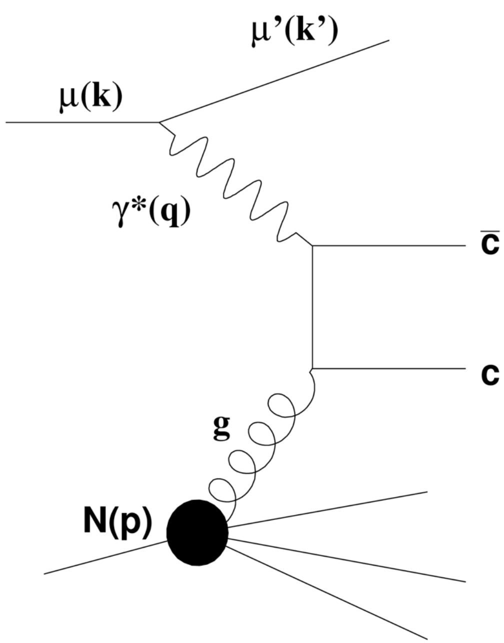
$$x_G = 0.09^{+0.08}_{-0.04} \qquad \langle \mu^2 \rangle = 3.4 (GeV/c)^2$$

significantly reduced statistical and systematics erros

D^0 meson production

Low statistics! Huge combinatorial background

Phys. Lett. B 676 (2009) 31 Phys.Rev. D 87 (2013) 052018



Open-charm production@COMPASS -
Photon-Gluon Fusion (PGF) - the only process in LO QCD.

$$\sigma^{PGF} = G \otimes \hat{\sigma}^{PGF} \otimes H$$

$$\Delta\sigma^{PGF} = \Delta G \otimes \Delta\hat{\sigma}^{PGF} \otimes H$$

assumption: $$\frac{\Delta G}{G}(x) \approx a(x - \overline{x}) + b$$

from MC

$$A \approx \frac{\Delta G}{G}(\overline{x}_G) < \hat{a}_{LL}^{PGF} >_G$$

signal asymmetry from data

notice:

$$A^{measured} = f P_T P_b \left(\frac{S}{S+B} A^{signal} + \frac{B}{S+B} A^B\right)$$

The method similar to all-p_T

Total number of events:

$$\frac{\mathrm{d}^k N}{\mathrm{d}m\,\mathrm{d}X} = a\phi n(s+b)\left[1 + P_t P_\mu f\left(\frac{s}{s+b}A^{\mu\mathrm{N}\to\mu'\mathrm{D}^0\mathrm{X}} + \frac{b}{s+b}A_\mathrm{B}\right)\right].$$

two weights:

$$w_\mathrm{S} = P_\mu f D \frac{s}{s+b},$$
$$w_\mathrm{B} = P_\mu f D \frac{b}{s+b}.$$

Every event is weighted by these weights and asymmetries for signal and background in $(p_\mathrm{T}^{\mathrm{D}^0}, E_{\mathrm{D}^0})$ intervals are simultaneously extracted.
Gluon polarisation from signal asymmetry is then estimated.

Another way: extract gluon polarisation directly event-by event basis using weights with analyzing power:

$$w = f\,P_B\,\frac{S}{S+B}\,a_{LL}$$

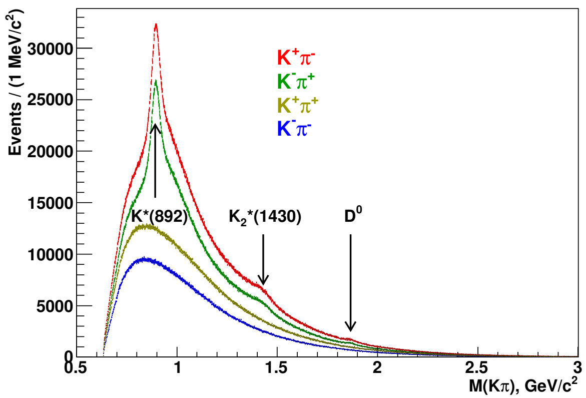
calculation/MC dependent

Statistically optimised determination of gluon polarisation;
takes into account anticorrelation between analyzing power and signal strength

D^0 meson data selection

Considered events:

- $D^0 \to K\pi$ *(BR: 4%)*
- $D^* \to D^0\pi_s$ *(30% D^0 tagged with a D^*)*
  - $D^0 \to K\pi$
  - $D^0 \to K\pi\pi^0$ *(BR: 13%)* → **not directly reconstructed**
  - $D^0 \to K\pi\pi\pi$ *(BR: 7.5%)*
  - $D^0 \to sub(K)\pi$ → **no RICH ID for Kaons** *($p < 9$ GeV/c)*

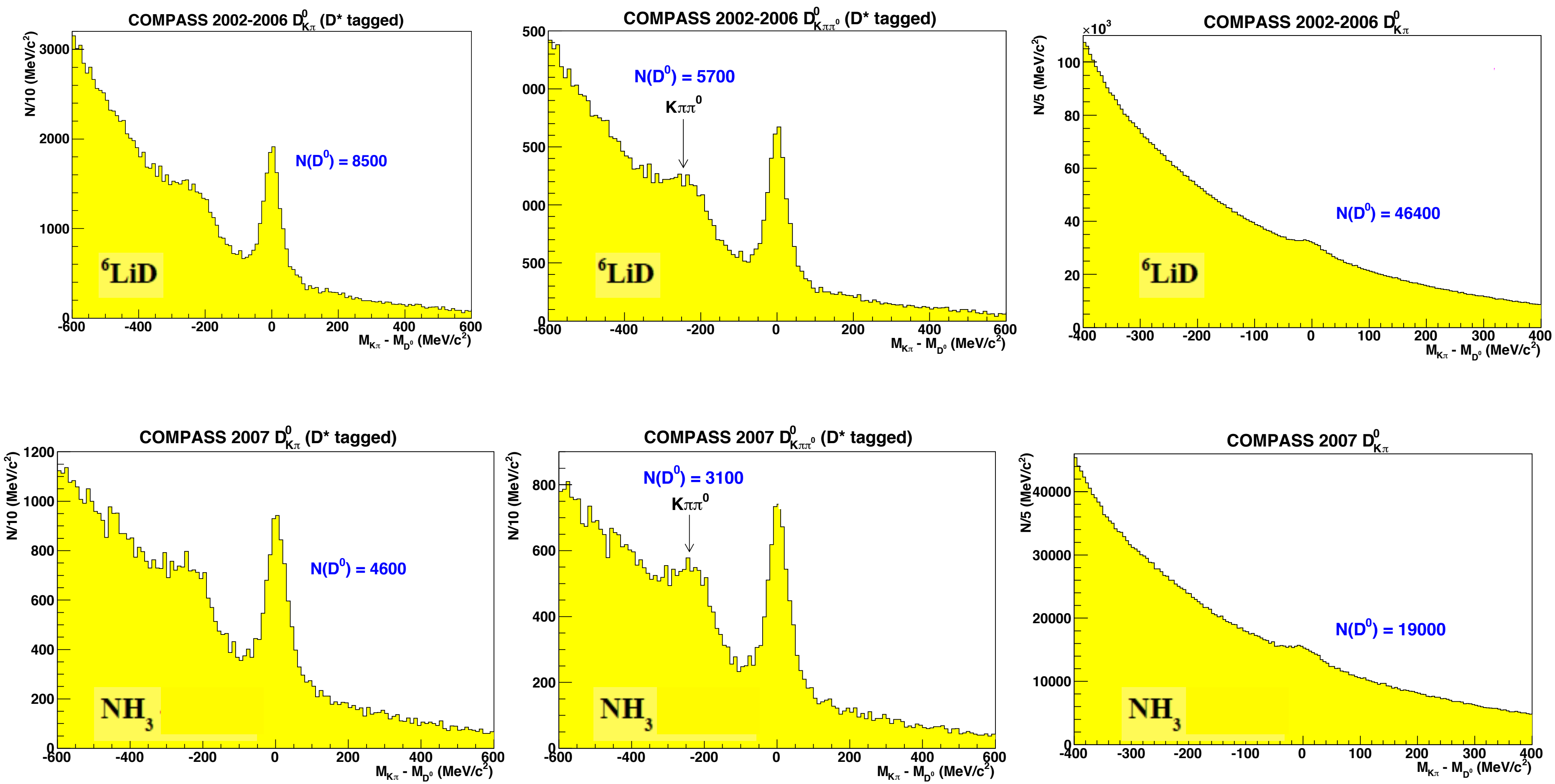


Selection to reduce the combinatorial background

- **Kinematical cuts:** Z_D and D^0 decay angle *(to reject colinear events with γ^* coming from the nucleon fragmentation)*, K and π momentum
- **RICH identification:** K and π ID + electrons rejected from the π_s sample
- Mass cut for the D^* tagged channels *($M[K\pi\pi_s] - M[K\pi] - M[\pi]$)*
- Neural Network qualification of events

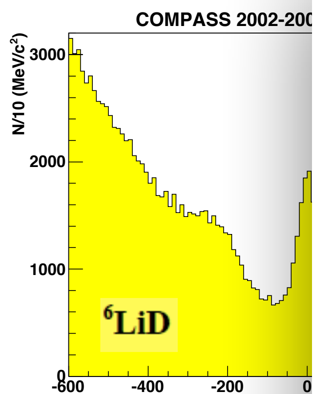
D^0 meson reconstruction

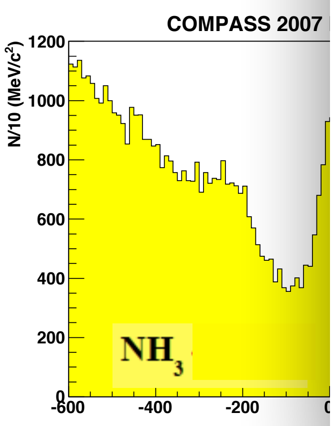
Artificial Neutral Network qualification of events



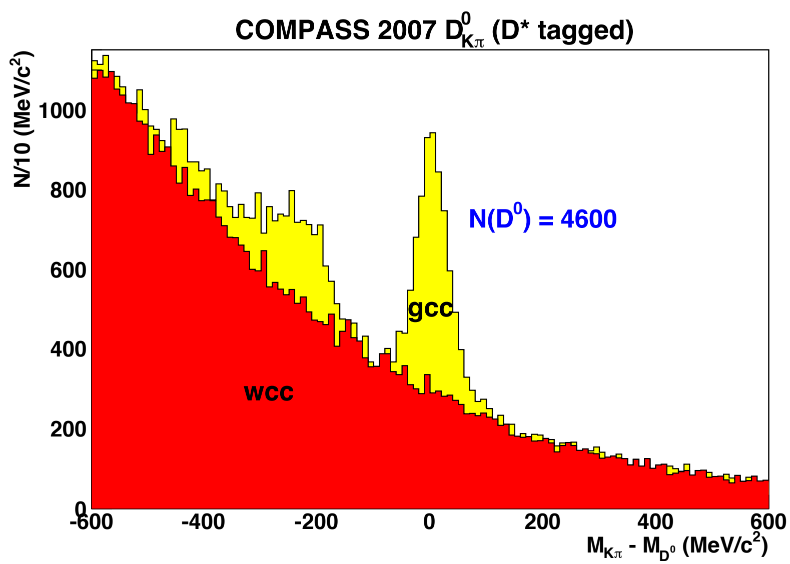
D^0 meson reconstruction

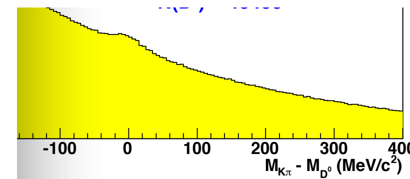
Artificial Neutral Network qualification of events

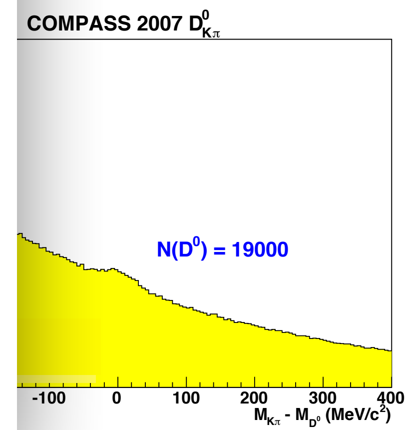




- Assuming background model to be good **Neural Network** is able to find some differences between samples: *S+B* and *B*.
- This way the signal probability *S/(S+B)* is constructed event-by-event







Gluon polarization @ LO

Final gluon polarization result from open-charm in LO QCD

$$\left\langle \frac{\Delta g}{g} \right\rangle = -0.10 \pm 0.22\ (\mathrm{stat.}) \pm 0.09\ (\mathrm{syst.}) \quad \left\langle \frac{\Delta g}{g} \right\rangle = -0.06 \pm 0.21\ (\mathrm{stat.}) \pm 0.08\ (\mathrm{syst.})$$

from asymmetries $\langle x_G \rangle = 0.11^{+0.11}_{-0.05}$ $\mu^2 \approx 13 \frac{GeV^2}{c^2}$ Statistically optimised

Source	$\delta(\langle \Delta g/g \rangle)$	Source	$\delta(\langle \Delta g/g \rangle)$
Beam polarisation P_μ	0.005	$s/(s+b)$	0.007
Target polarisation P_t	0.005	False asymmetry	0.080
Dilution factor f	0.002	a_{LL}	0.015
Assumption, Eq. (9)	0.025	Depolarisation factor D	0.002
Total uncertainty	0.086		

More details and asymmetries in bins - see:
Phys.Rev. D 87 (2013) 052018

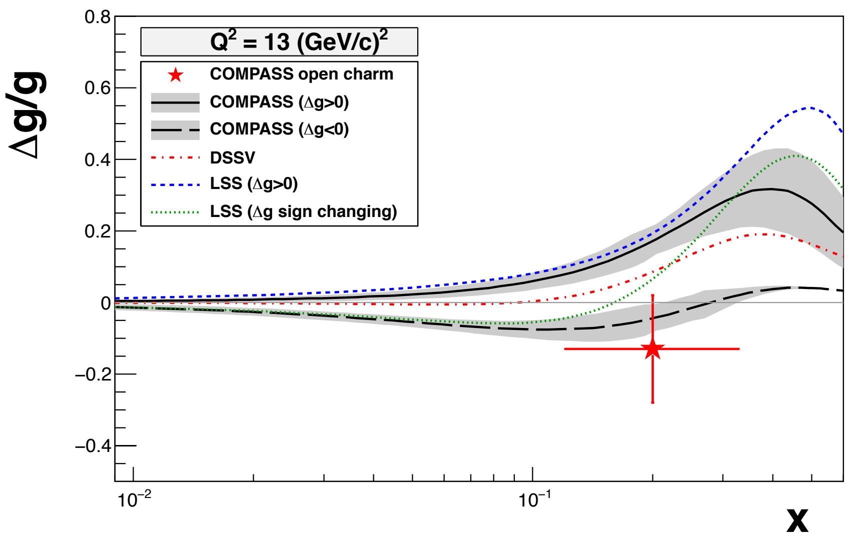
Source	$\delta(\langle \Delta g/g \rangle)$	Source	$\delta(\langle \Delta g/g \rangle)$
Beam polarisation P_μ	0.003	$s/(s+b)$	0.004
Target polarisation P_t	0.003	a_{LL}	0.005
Dilution factor f	0.001	False asymmetry	0.080
Assumption, Eq. (9)	0.025		
Total uncertainty	0.084		

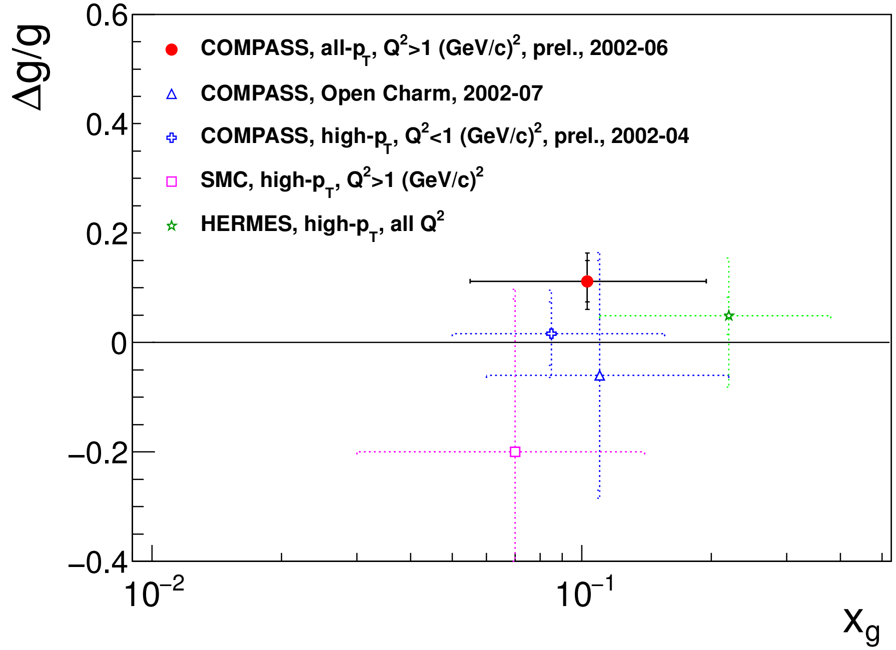
Result on gluon polarisation @LO & NLO QCD

I.Bojak, M.Stratmann, Nucl.Phys.B 540 (1999) 345, I.Bojak, PhD th.

Phys.Rev. D 87 (2013) 052018

J.Smith, W.L.Neerven, Nucl.Phys.B 374 (1992)36),
W.Beenakker, H.Kuijf, W.L.Neerven,,J.Smith, Phys.Rev.D40(1989)54





Source	$\delta(\langle\Delta g/g\rangle)$	Source	$\delta(\langle\Delta g/g\rangle)$
Beam polarisation P_μ	0.006	$s/(s+b)$	0.009
Target polarisation P_t	0.006	a_{LL}	0.119
Dilution factor f	0.003	False asymmetry	0.080
Assumption, Eq. (9)	0.025	Depolarisation factor D	0.002
Total uncertainty 0.146			

$$\left\langle \frac{\Delta g}{g} \right\rangle^{\text{NLO}} = -0.13 \pm 0.15 \ (\text{stat.}) \pm 0.15 \ (\text{syst.})$$

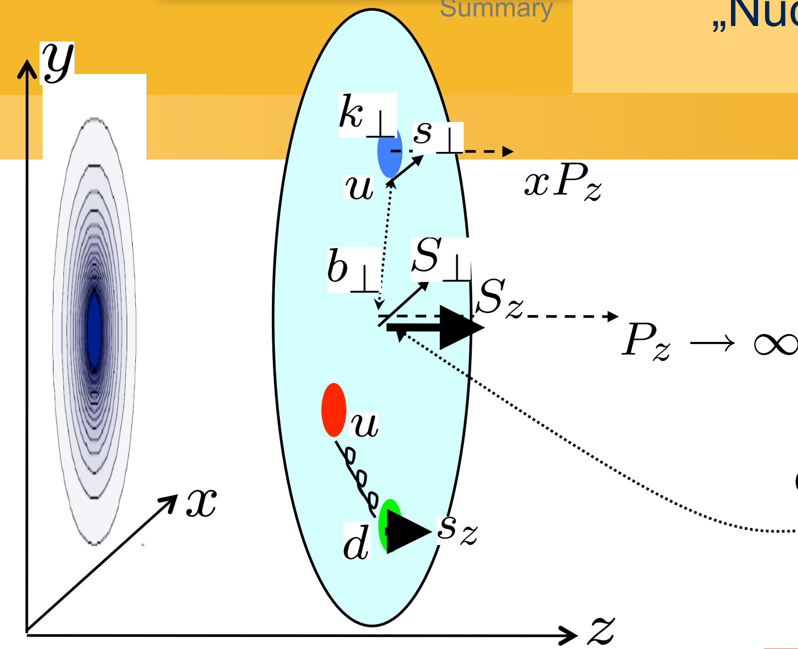
Beyond collinear approximation - k_T dependence

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

nucleon polarization (columns) / **quark polarization** (rows)

	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; $h_{1T}^{\perp}$ Pretzelosity

GPD and Impact Parameter PDFs
„Nucleon tomography"

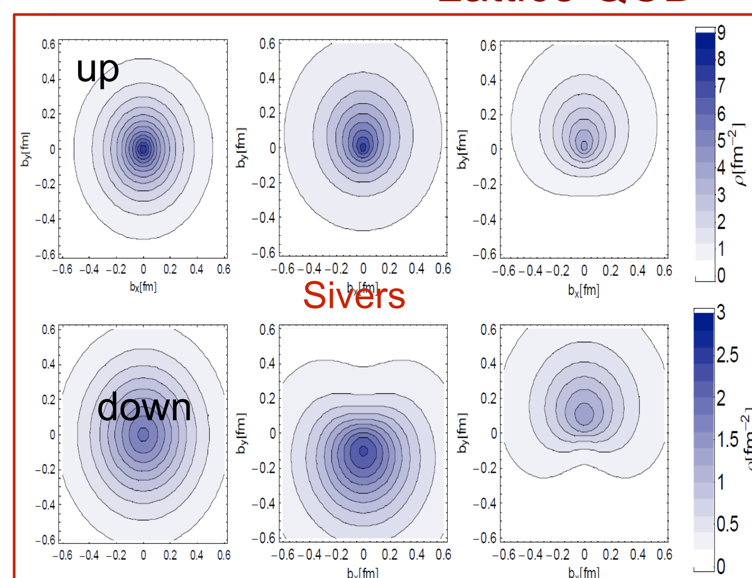


TMD's - 3-Dimensional image of nucleon in momentum space

center of momentum

$$R_\perp = \sum x_i r_{\perp i}$$

Lattice QCD



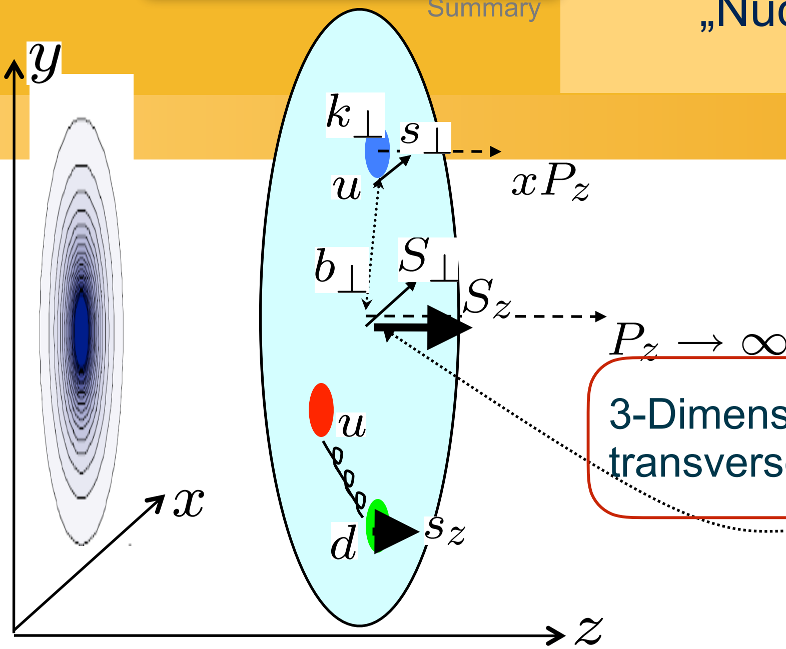
$$\mathcal{H}(x,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{2\pi} e^{i\vec{\Delta}_\perp . \vec{b}_\perp} H(x,0,-\vec{\Delta}_\perp^2).$$

$$\tilde{\mathcal{H}}(x,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{2\pi} e^{i\vec{\Delta}_\perp . \vec{b}_\perp} \tilde{H}(x,0,-\vec{\Delta}_\perp^2),$$

$$\mathcal{E}(x,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{2\pi} e^{i\vec{\Delta}_\perp . \vec{b}_\perp} E(x,0,-\vec{\Delta}_\perp^2).$$

3-Dimensional image of nucleon in the mixed transverse plane-longitudinal momentum space

GPD and Impact Parameter PDFs
„Nucleon tomography”



TMD’s - 3-Dimensional image of nucleon in momentum space

3-Dimensional image of nucleon in the mixed transverse plane-longitudinal momentum space

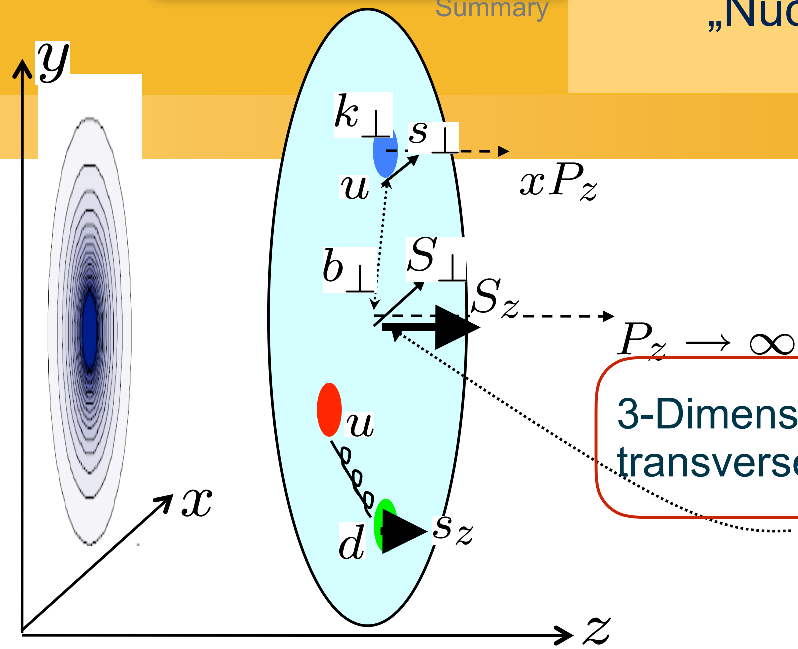
center of momentum

$$R_\perp = \sum x_i r_{\perp i}$$

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:

$$q_{\hat{x}}(x, \vec{b}_\perp) = \mathcal{H}(x, \vec{b}_\perp) - \frac{1}{2M} \frac{\partial}{\partial b_y} \mathcal{E}(x, \vec{b}_\perp). \qquad (7.12)$$

GPD and Impact Parameter PDFs
„Nucleon tomography"



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3-Dimensional image of nucleon in the mixed transverse plane-longitudinal momentum space

center of momentum

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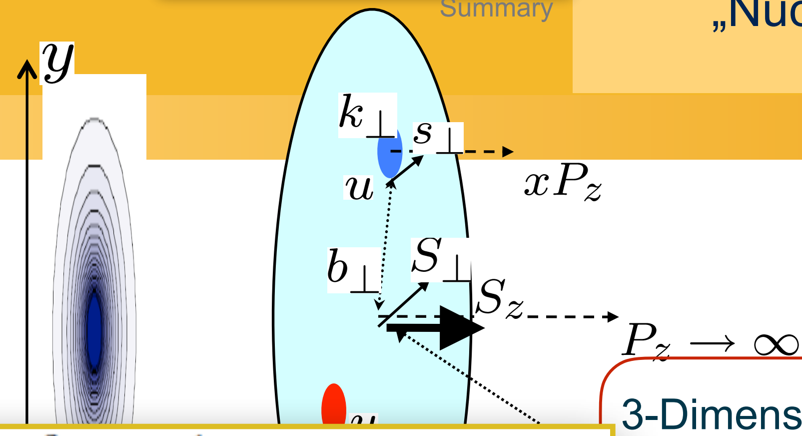
GPD and Impact Parameter PDFs „Nucleon tomography"



TMD's - 3-Dimensional image of nucleon in momentum space

3-Dimensional image of nucleon in the mixed transverse plane-longitudinal momentum space

center of momentum

$$R_\perp = \sum x_i r_{\perp i}$$

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

- 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

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

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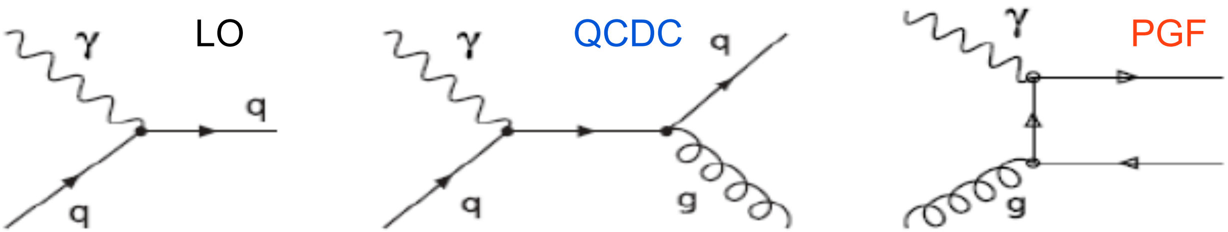
Sivers asymmetry for gluons

Physical model: three basic processes @LO



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

$$\omega_{PGF} \equiv \omega^G = R_{PGF} f \sin(\phi_{2h} - \phi_s)$$

$$\omega_{LP} \equiv \omega^L = R_{LP} f \sin(\phi_{2h} - \phi_s)$$

$$\omega_{QCDC} \equiv \omega^C = R_{QCDC} f \sin(\phi_{2h} - \phi_s)$$

$$A_{PGF}^{\sin(\phi_{2h}-\phi_s)} = -0.14 \pm 0.15(stat.) \pm 0.06(syst.) \text{ at } \langle x_G \rangle = 0.13$$ deuteron

$$A_{PGF}^{\sin(\phi_{2h}-\phi_s)} = -0.26 \pm 0.09(stat.) \pm 0.08(syst.) \text{ at } \langle x_G \rangle = 0.15$$ proton !!

Summary

- The review of some updated and new results for longitudinal spin physics has been presented
- New results on gluon polarisation @ LO QCD approximation from high-p_T hadrons measurement has been shown in “all-p_T method”
- The determination of gluon polarisation @ LO as well as NLO QCD approximation from COMPASS open-charm data has been presented
- New results on gluon polarisation from new COMPASS QCD fits have been shown
- Preliminary result for Sivers asymmetry for gluons on deuteron and proton targets have been shown

Spares

Input parametrisation

- Reference scale $Q_0^2 = 1\ (\mathrm{GeV}/c)^2$
- Functional form are given at the reference scale Q_0^2

  $\Delta q_{Si}(x|Q_0^2) = \eta_s x^{\alpha_s}(1-x)^{\beta_s}(1+\gamma_s x)/N_s$

  $\Delta g(x|Q_0^2) = \eta_g x^{\alpha_g}(1-x)^{\beta_g}(1+\gamma_g x)/N_g$

  $\Delta q_3(x|Q_0^2) = \eta_3 x^{\alpha_3}(1-x)^{\beta_3}/N_3$

  $\Delta q_8(x|Q_0^2) = \eta_8 x^{\alpha_8}(1-x)^{\beta_8}/N_8$
- $\eta_3 = F + D = g_A/g_V$

  $\eta_8 = 3F - D$

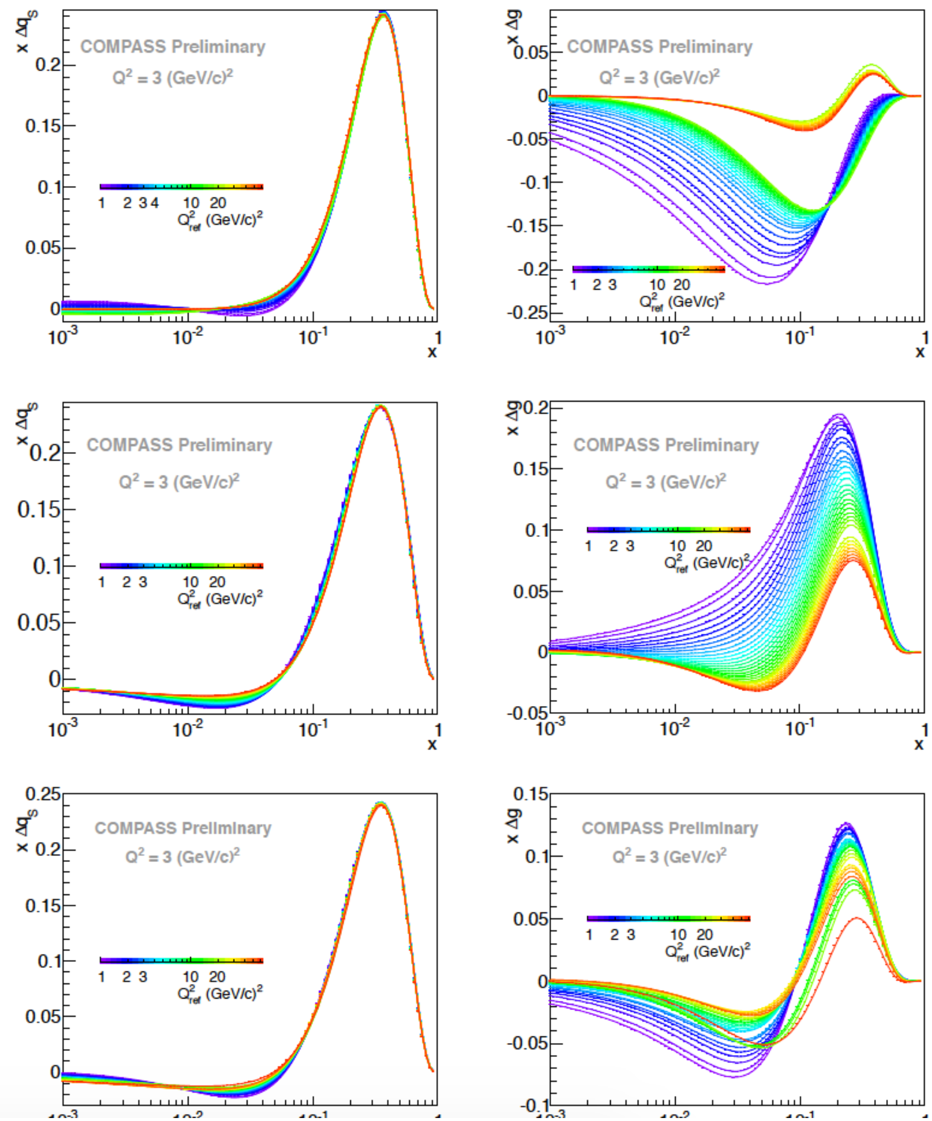
  β_g is fixed
- Using the DGLAP equations:
- Obtain $\Delta q_{Si}(x, Q^2), \Delta g(x, Q^2), \Delta q_3(x, Q^2), \Delta q_8(x, Q^2)$ at any scale Q^2

- $\chi^2 = \sum_{n=1}^{N_{exp}} \left[\sum_{i=1}^{N_n^{data}} \left(\frac{g_1^{fit} - \mathcal{N}_n g_{1,i}^{data}}{\mathcal{N}_n \sigma_i} \right)^2 + \left(\frac{1-\mathcal{N}_n}{\delta \mathcal{N}_n} \right)^2 \right] + \chi^2_{positivity}$
- Positivity: $|\Delta g(x)| < |g(x)|$ and $|\Delta(s(x) + \bar{s}(x))| < |s(x) + \bar{s}(x)|$
- Input: g_1^p, g_1^n, g_1^d and our $\Delta g/g$ measurement (Open Charm @ NLO)
- MSTW2008
- Overall: 28 free parameters and 679 data points

Systematic studies

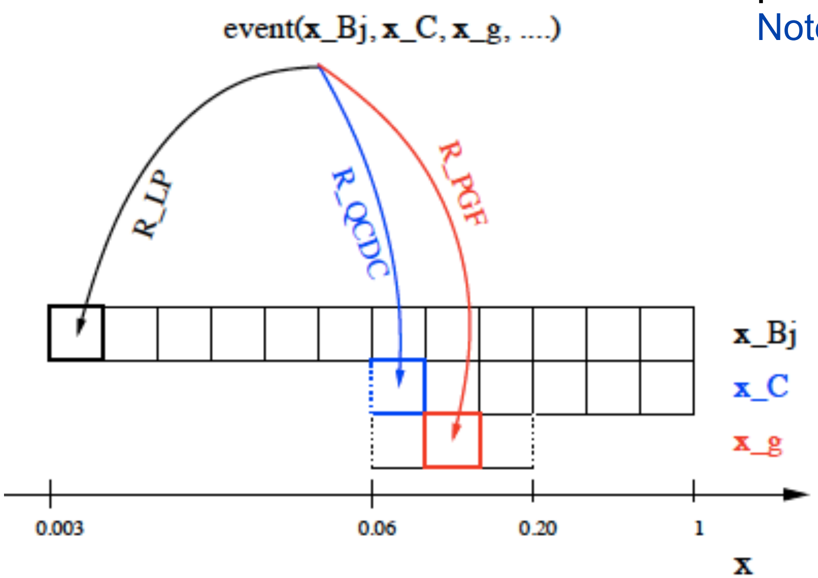
- Remarks on the previously published fit:
  - Only 2 parametrisations
  - No systematic uncertainties
- Study impact of:
  - Different parametrisations
  - Reference scale Q_0^2
- χ^2 very stable

$\rightarrow$ Larger uncertainty compared to statistical one



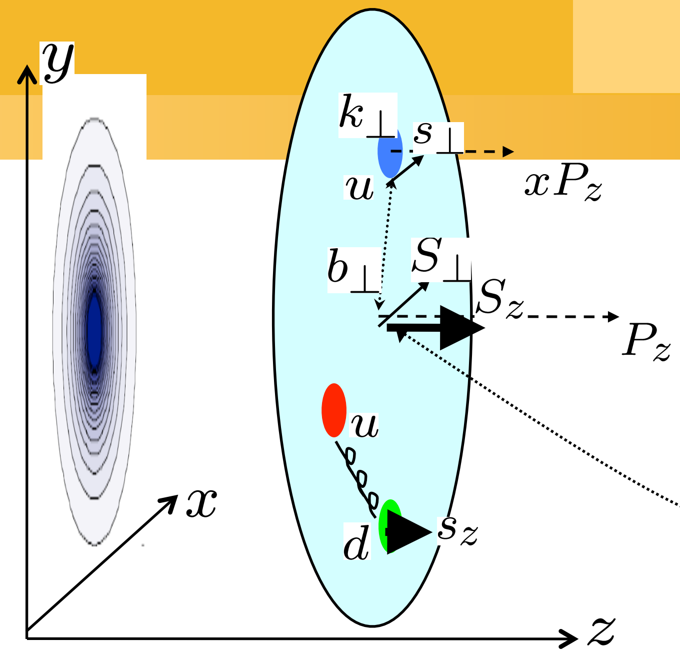
$$A_1^{QCDC}(x_C) = A_1^{LP}(x_{Bj}) = A_1^{LO}(x);\ \text{for } x_C = x_{Bj}$$

It can be verified equality of the two asymmetries by performing χ^2 test and select the best MC tuning ;
Note that statistical weight is constructed on the MC basis



	name	χ^2
1	HIPT_PSON_MS_FLUKA	8.1
2	HIPT_PSON_MS	8.8
3	HIPT_PSOFF_MS	3.9
4	HIPT_PSON_CQ	10.1
5	HIPT_PSON_MS_NOFL	6.9
6	DEF_PSON_CQ	13.1
7	DEF_PSON_MS	10.7
8	DEF_PSOFF_MS	9.9

Data selection:
standard DIS cut on inclusive variables (large Q^2)
at least one charged hadron detected - no high-p_T cut !
for ANN information from one, leading hadron only is used



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

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

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:

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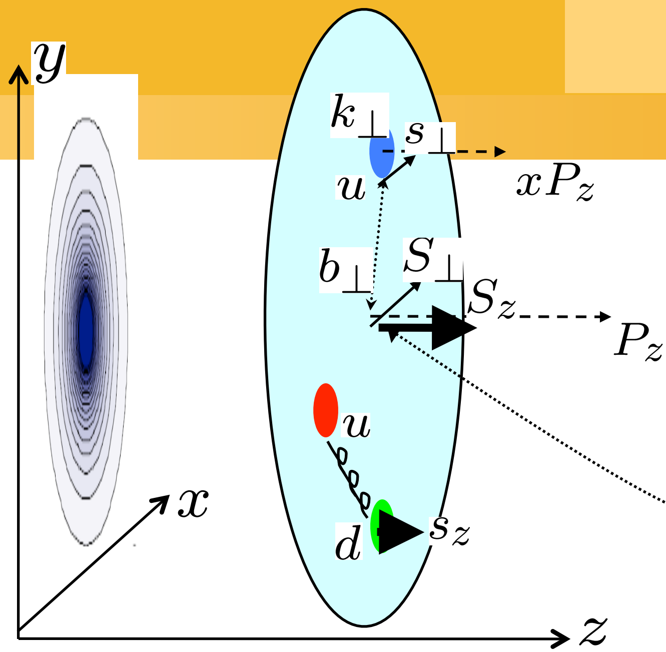
non-zero spin-flip GPD E - existence of non-zero orbital momentum



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

Sea flavour helicity asymmetry Δū - Δđ

COMPASS data   Phys.Lett.B 693 (2010) 227

Δū ≥ Δđ ?

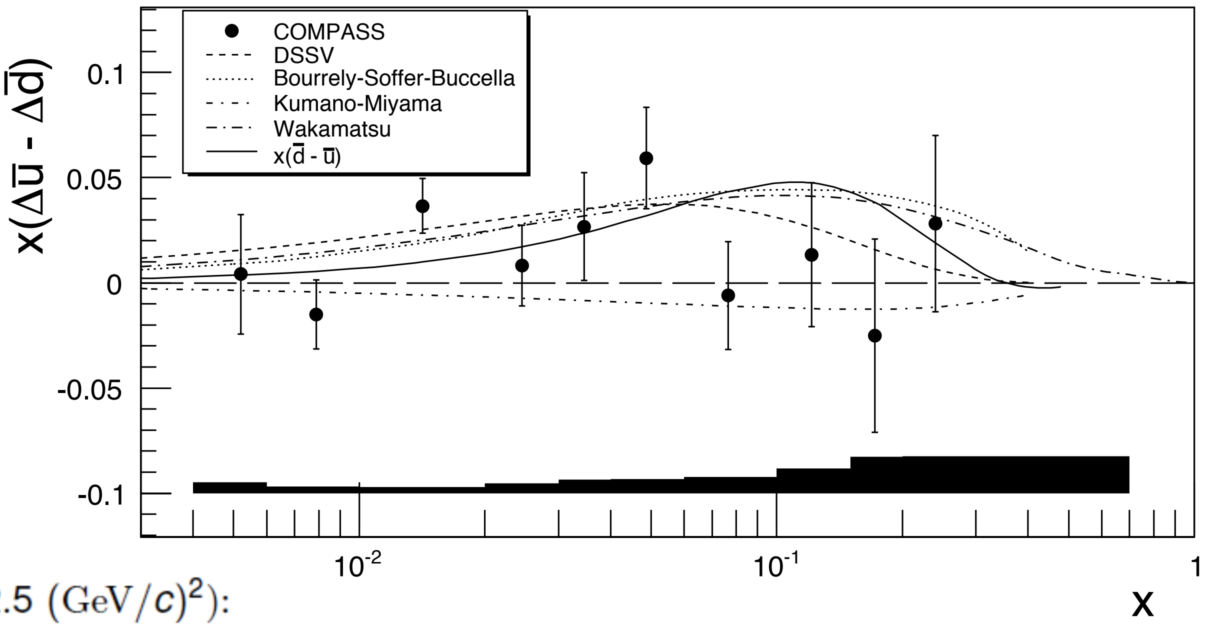
Phys. Rev. Lett. 18, (1967) 1174

Pauli exclusion principle, Δ resonance etc.

NMC,E866

unpolarized asymmetry:

$$\int_0^1 (\bar{d} - \bar{u})dx = 0.118 \pm 0.012$$



HERMES $(Q^2 = 2.5\ (\mathrm{GeV}/c)^2)$:

$$\int_{0.023}^{0.3} (\Delta\bar{u} - \Delta\bar{d})dx = 0.048 \pm 0.057(\mathrm{stat.}) \pm 0.028(\mathrm{syst.})$$

COMPASS $(Q^2 = 3\ (\mathrm{GeV}/c)^2)$:

$$\int_{0.004}^{0.3} (\Delta\bar{u} - \Delta\bar{d})dx = 0.06 \pm 0.04\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{syst.})$$

The data disfavour models predicting $\Delta\bar{u} - \Delta\bar{d} \gg \bar{d} - \bar{u}$

Flavour separation analysis

Compass data

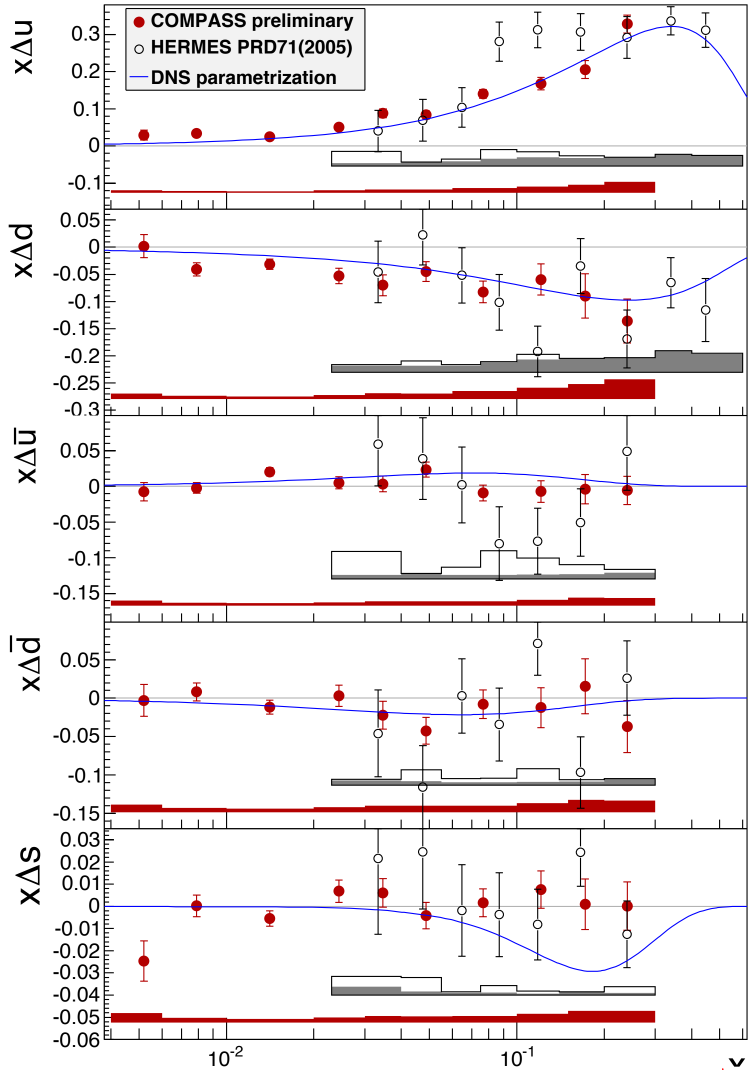
- **SIDIS**

$$A_1^h = \frac{\sum e_q^2[\Delta q(x) \int D_q^h(z)dz + \Delta\bar{q}(x) \int D_{\bar{q}}^h(z)dz]}{\sum e_q^2[q(x) \int D_q^h(z)dz + \bar{q}(x) \int D_{\bar{q}}^h(z)dz]}$$

- $D_q^h \neq D_{\bar{q}}^h$ yields quark and antiquark separation
- **measured:** $A_1^d, A_{1d}^{K\pm}, A_{1d}^{\pi\pm}, A_1^p, A_{1p}^{K\pm}, A_{1p}^{\pi\pm}$
- **determined:** $\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}, \Delta s \equiv \Delta\bar{s}$
- system of linear equations in LO
- **input:** MRST04 unpolarised PDFs, DSS parametrisation of FFs (e^+e^-, DIS, hadron-hadron)

$$\int_{0.004}^{0.3} \Delta s(x)dx = -0.01 \pm 0.01 \pm 0.01$$

DNS: De Florian, Navarro, Sassot, Phys. Rev. D71, 2005



Flavour separation analysis

Compass data

Phys. Lett. B 647 (2007) 8   Phys. Lett. B 690 (2010) 466

- **SIDIS**

$$A_1^h = \frac{\sum e_q^2[\Delta q(x) \int D_q^h(z)dz + \Delta\bar{q}(x) \int D_{\bar{q}}^h(z)dz]}{\sum e_q^2[q(x) \int D_q^h(z)dz + \bar{q}(x) \int D_{\bar{q}}^h(z)dz]}$$

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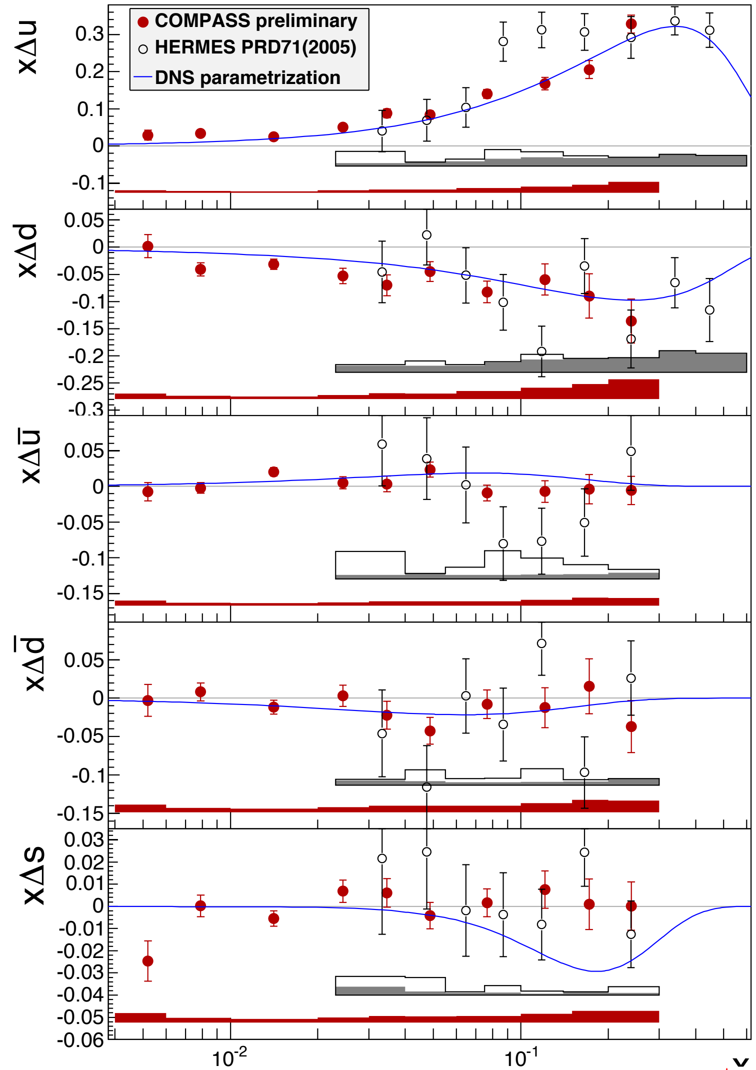


Systematic studies & results

Phys. Lett. B 718 (2013) 922

- Neural Network stability
- MC
- False Asymmetries
- δP_b ,δP_t ,δf
- A_1 parametrisation
- Simplification of the Formula for ΔG/G

$\delta(\Delta G/G)_{NN}$	0.010
$\delta(\Delta G/G)_{MC}$	0.045
$\delta(\Delta G/G)_{false}$	0.019
$\delta(\Delta G/G)_{f,Pb,Pt}$	0.004
$\delta(\Delta G/G)_{A1}$	0.015
$\delta(\Delta G/G)_{formula}$	0.035
Total	0.063

$$\frac{\Delta G}{G} = 0.125 \pm 0.060 \pm 0.063$$

$$x_G = 0.09^{+0.08}_{-0.04} \qquad \langle \mu^2 \rangle = 3.4 (GeV/c)^2$$

	1st point	2nd point	3rd point
ΔG/G	0.15 ± 0.09 ± 0.09	0.08 ± 0.10 ± 0.08	0.19 ± 0.17 ± 0.14
$\langle x_g \rangle$	$0.07^{+0.05}_{-0.03}$	$0.10^{+0.07}_{-0.04}$	$0.17^{+0.10}_{-0.06}$

These 3 points show no x_G dependence (within errors)

Difference asymmetry

Compass only

COMPASS: Phys.Lett.B 660 (2008) 458

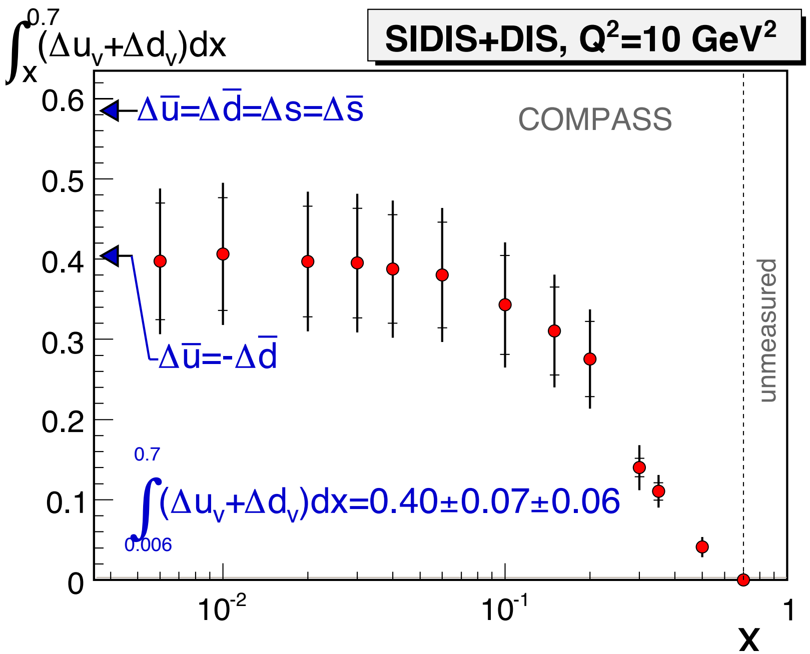
Idea: Phys.Lett.B230(1989)141,
SMC:Phys.Lett.B369(1996)93,

$$A^{+-} = \frac{(\sigma_{\uparrow\downarrow}^{h^+} - \sigma_{\uparrow\downarrow}^{h^-}) - (\sigma_{\uparrow\uparrow}^{h^+} - \sigma_{\uparrow\uparrow}^{h^-})}{(\sigma_{\uparrow\downarrow}^{h^+} - \sigma_{\uparrow\downarrow}^{h^-}) + (\sigma_{\uparrow\uparrow}^{h^+} - \sigma_{\uparrow\uparrow}^{h^-})}$$

$$A_d^{\pi^+-\pi^-}(x) = A_d^{K^+-K^-}(x) = \frac{\Delta u_v(x) + \Delta d_v(x)}{u_v(x) + d_v(x)}$$

→ Only valence quarks!

Fragmentation functions cancell out in LO and under the assuption of independent fragmentation.



$$\Delta\bar{u} = \Delta\bar{d} = \Delta s = \Delta\bar{s}$$ symmetric

$$\Delta\bar{u} = -\Delta\bar{d}$$ asymmetric

→ scenario

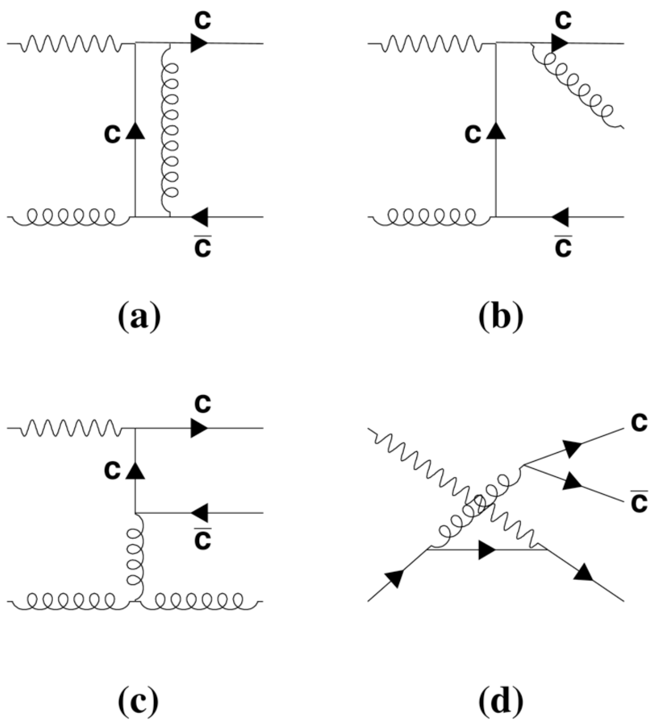
$$\Gamma_v = \int_0^1 (\Delta u_v(x) + \Delta d_v(x))dx$$

$$\Delta\bar{u} + \Delta\bar{d} = 3\Gamma_1^N - \tfrac{1}{2}\Gamma_v + \tfrac{1}{12}a_8 = (\Delta s + \Delta\bar{s}) + \tfrac{1}{2}(a_8 - \Gamma_v)$$

Gluon polarisation @ NLO QCD

I.Bojak, M.Stratmann, Nucl.Phys.B 540 (1999) 345, I.Bojak, PhD th.

J.Smith, W.L.Neerven, Nucl.Phys.B 374 (1992)36),
W.Beenakker, H.Kuijf, W.L.Neerven,,J.Smith, Phys.Rev.D40(1989)54



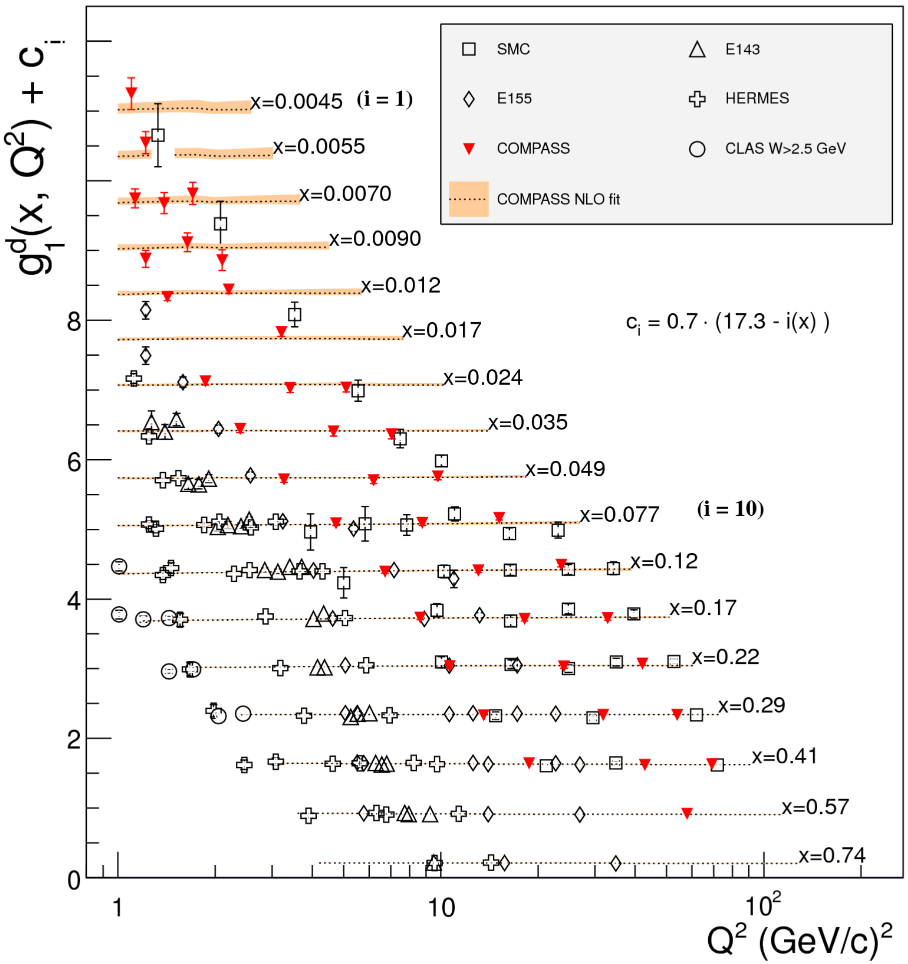
Procedure for NLO calculations:

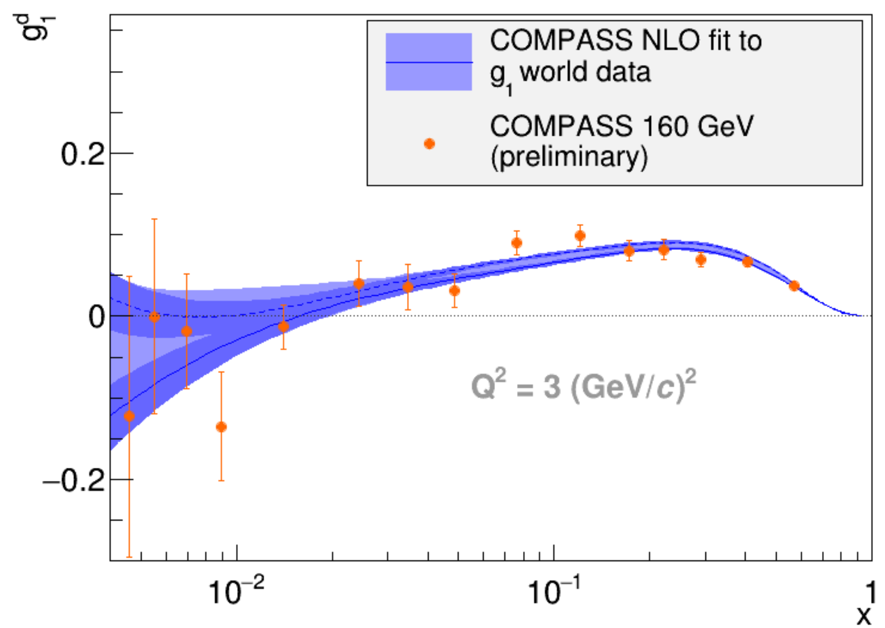
1. *Aroma* MC generator with Parton Shower-on describes COMPASS data very well
2. PS simulates phase space for NLO correction - a_{LL} can be calculated event-by-event basis from theoretical formulas (as in LO case)
3. light quark correction ~ A_1 which is taken directly from data
4. Asymmetries in bins used (rebinned in $p_T^{D^0}$ bins only)

g1 structure function for deuteron

Compass data 2002-2006 and world data

2002-2004 published in Phys. Lett. B 647 (2007) 8





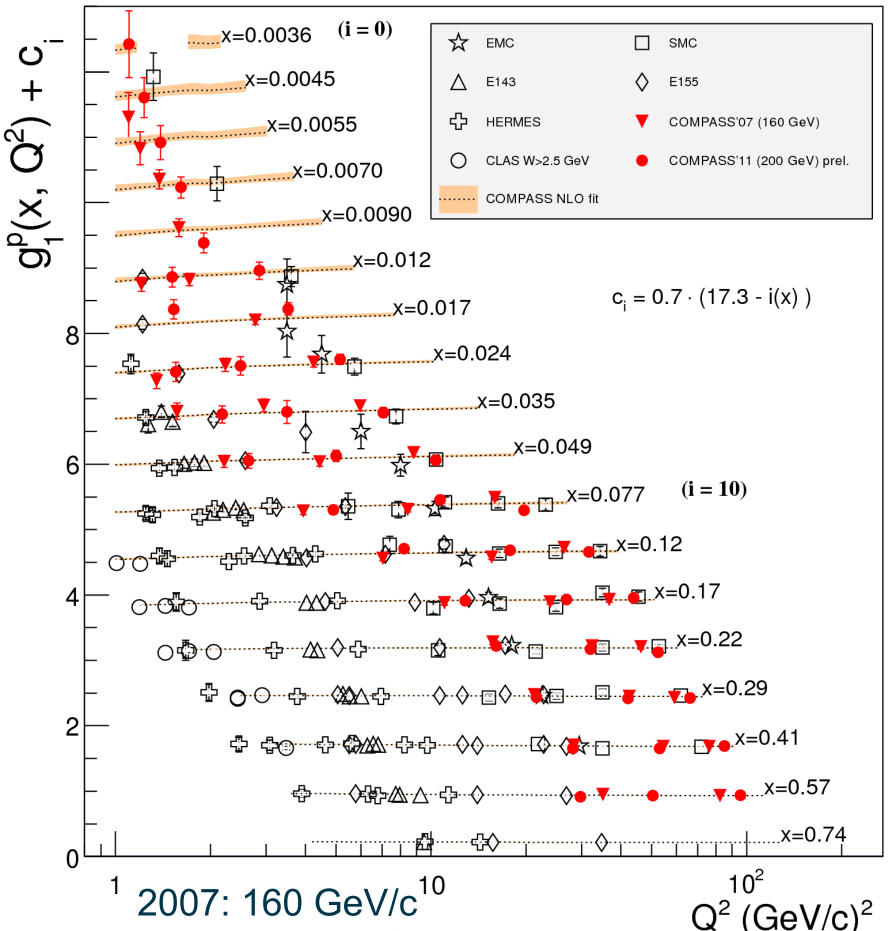
2006 reanalysed, new NLO COMPASS fit

Phys. Lett. B 753 (2016) 18

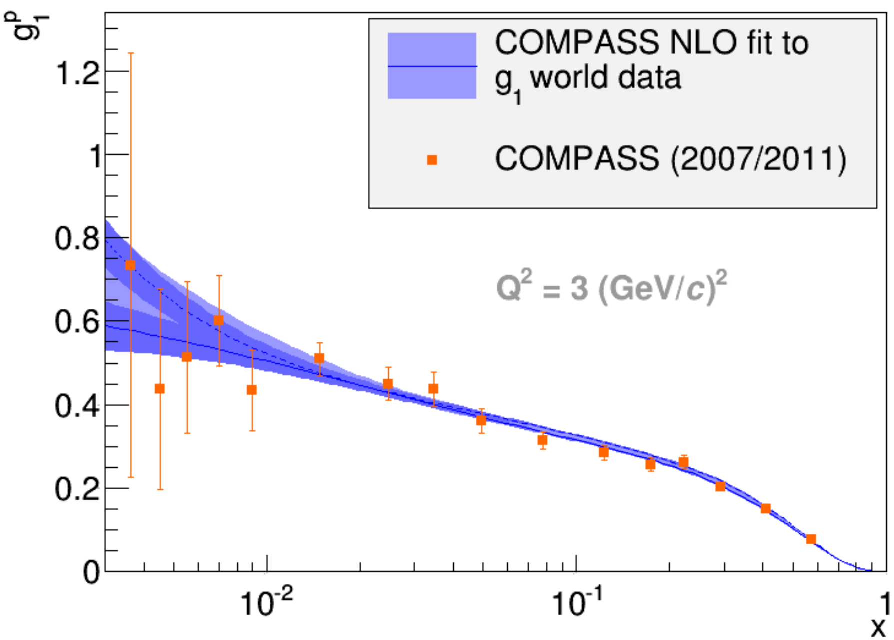
g1 structure function for proton

Compass data 2007 & 2011 and world data

Phys. Lett. B 690 (2010) 466–472



2007: 160 GeV/c
2011: 200 GeV/c



New 2011 proton data &
new COMPASS NLO QCD fit

Phys. Lett. B 753 (2016) 18

Master formula for determination ΔG statistical weighting & ANN approach

$$\frac{\Delta G}{G}(x_G) = \frac{A_{LL}^{2h}(x_{Bj}) + A^{corr}}{\beta}$$

$$\beta = a_{LL}^{PGF} R_{PGF} - a_{LL}^{PGF,incl} R_{PGF}^{incl} \left(\frac{R_L}{R_L^{incl}} + \frac{R_C}{R_L^{incl}} \frac{a_{LL}^C}{D}\right)$$

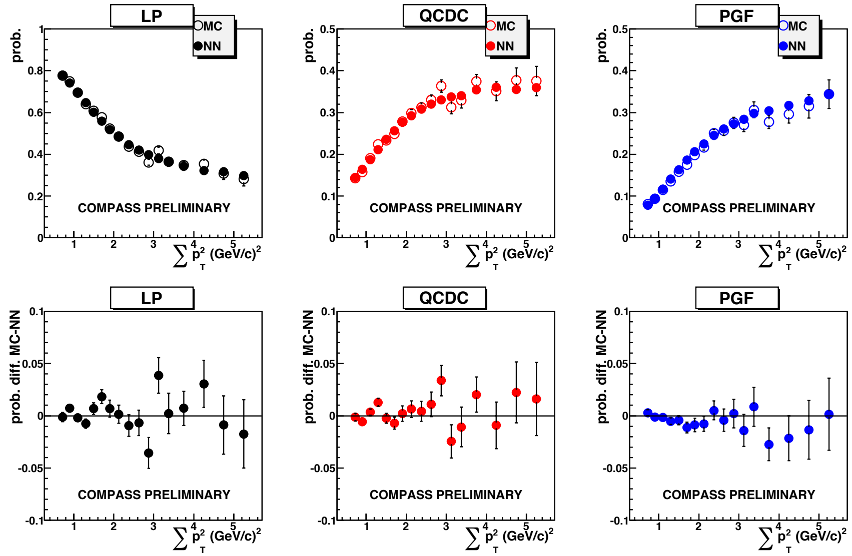
$$A^{corr} = -A_1(x_{Bj}) D \frac{R_L}{R_L^{incl}} - A_1(x_C)\beta_1 + A_1(x'_C)\beta_2$$

R's are fractions of the sub-processes (LO,PGF, QCDC) in high-p_T and inclusive samples, respectively;

a_{LL} are so-called analyzing powers
D is a depolarization factor.

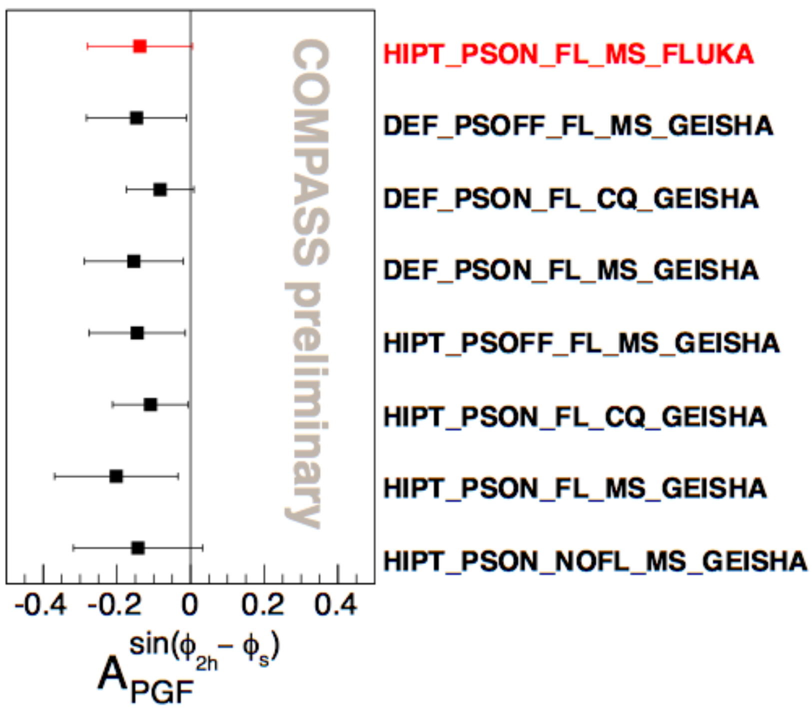
$$\beta_1 = \frac{1}{R_L^{incl}} \left(a_{LL}^C R_C - a_{LL}^{C,incl} R_C^{incl} \frac{R_L}{R_L^{incl}}\right) \qquad \beta_2 = a_{LL}^{C,incl} \frac{R_C R_C^{incl}}{(R_L^{incl})^2} \frac{a_{LL}^C}{D}$$

- f,D,P_b can be directly obtained from data
- Remaining factors have to be obtained from MC
- ANN trained on MC samples, then used on real data
- Input variables for ANN trainning:
  - inclusive case: x_{Bj} and Q^2
  - high-p_T: x_{Bj}, Q^2, $p_{L1,2}$, $p_{T1,2}$
- Weight used: $fDP_b\,\beta$
- Good data description with MC is a „key point" of the analysis

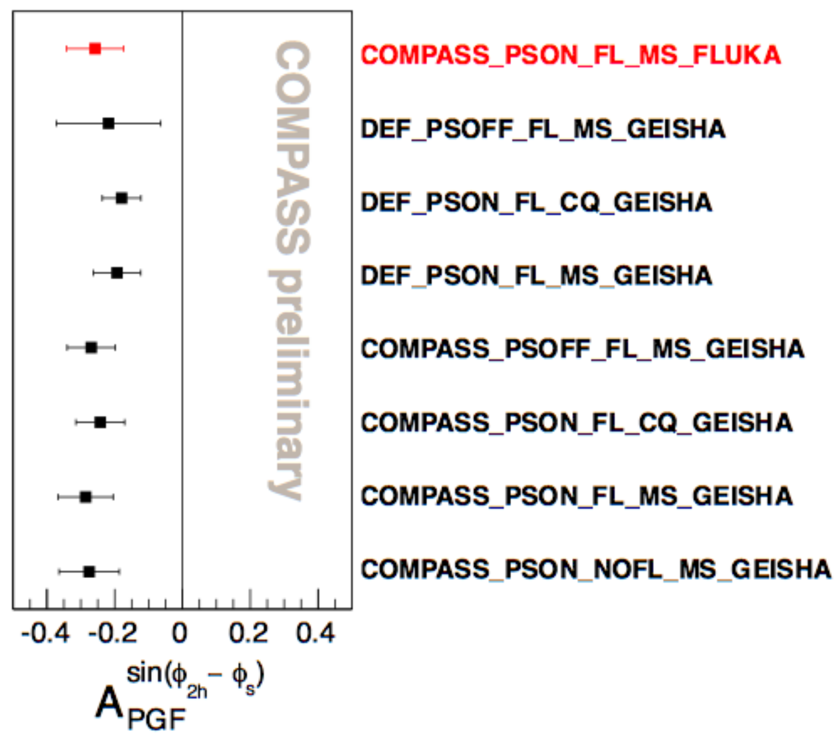


Systematics Studies

deuteron target



proton target



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:

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

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

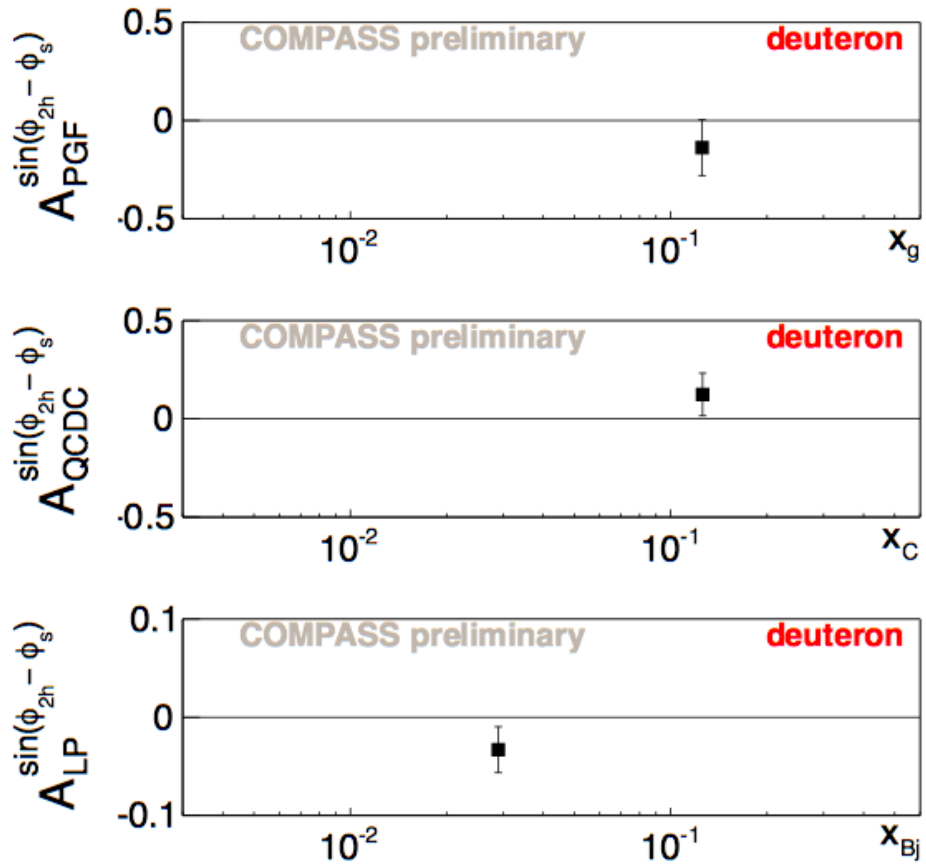
$$\vec{N_{obs}} = \left(\sum_{i=0}^{N_u} \omega_i^G, \ldots, \sum_{i=0}^{N_{d'}} \omega_i^C\right),$$

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

Data selection & preliminary results

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

  $z_1 + z_2 < 0.9$



$$A_{PGF}^{\sin(\phi_{2h}-\phi_s)} = -0.14 \pm 0.15(stat.) \pm 0.06(syst.) \text{ at } \langle x_G \rangle = 0.13$$

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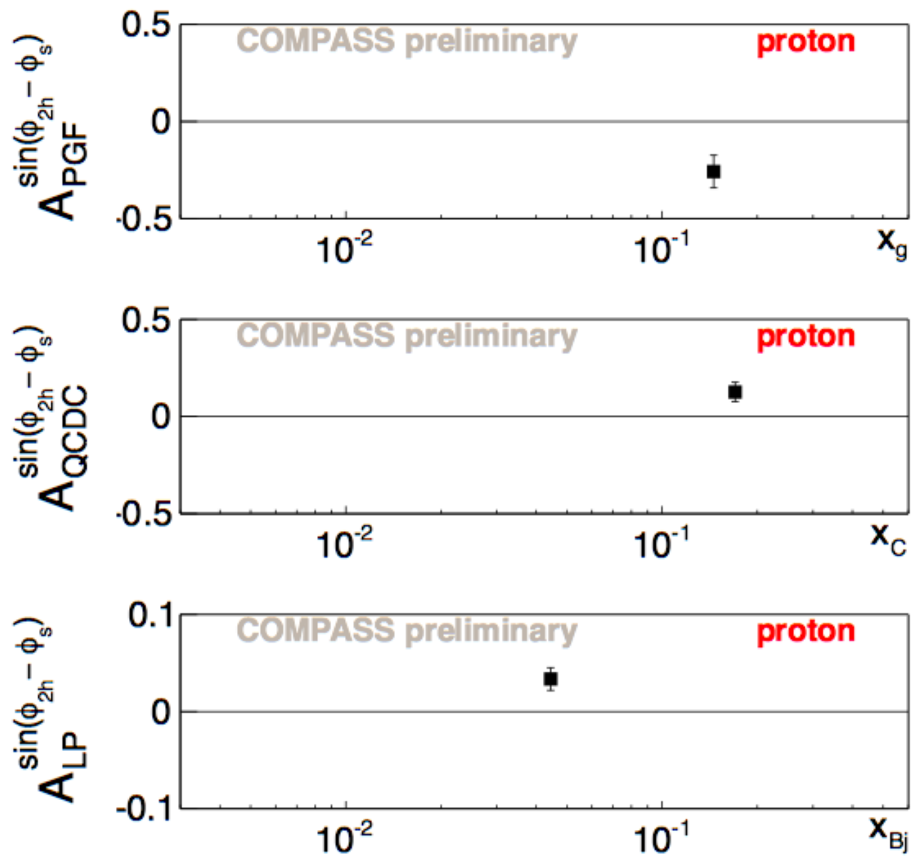
$z_1 + z_2 < 0.9$



$$A_{PGF}^{\sin(\phi_{2h}-\phi_s)} = -0.26 \pm 0.09(stat.) \pm 0.08(syst.) \text{ at } \langle x_G \rangle = 0.15$$