Status and outlook of COMPASS experiment

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    - with the longitudinally polarized target
    - with the transversely polarized target
- **Outlook** of COMPASS **II**
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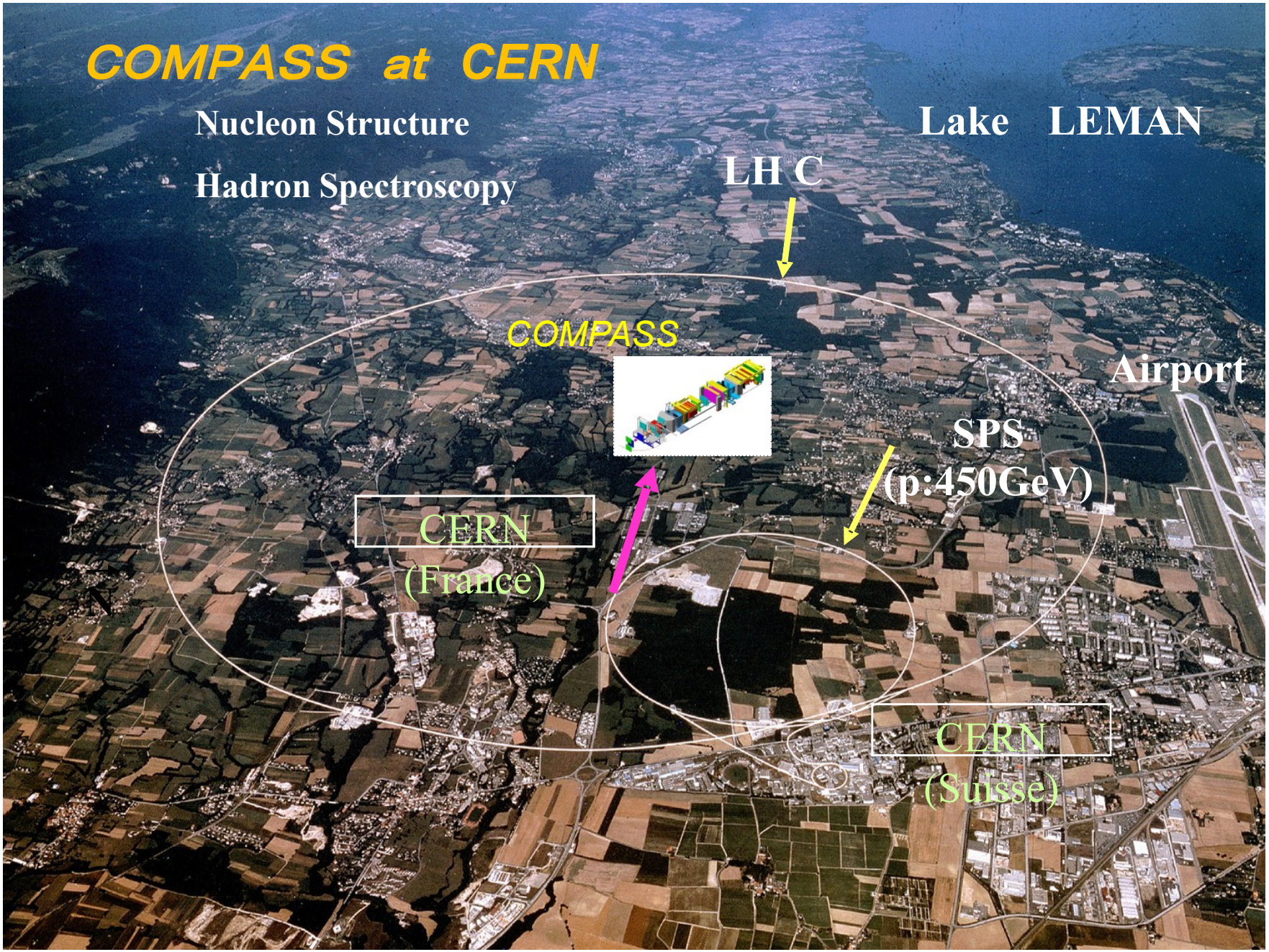
The COMPASS Experiment



COMPASS Spectrometer

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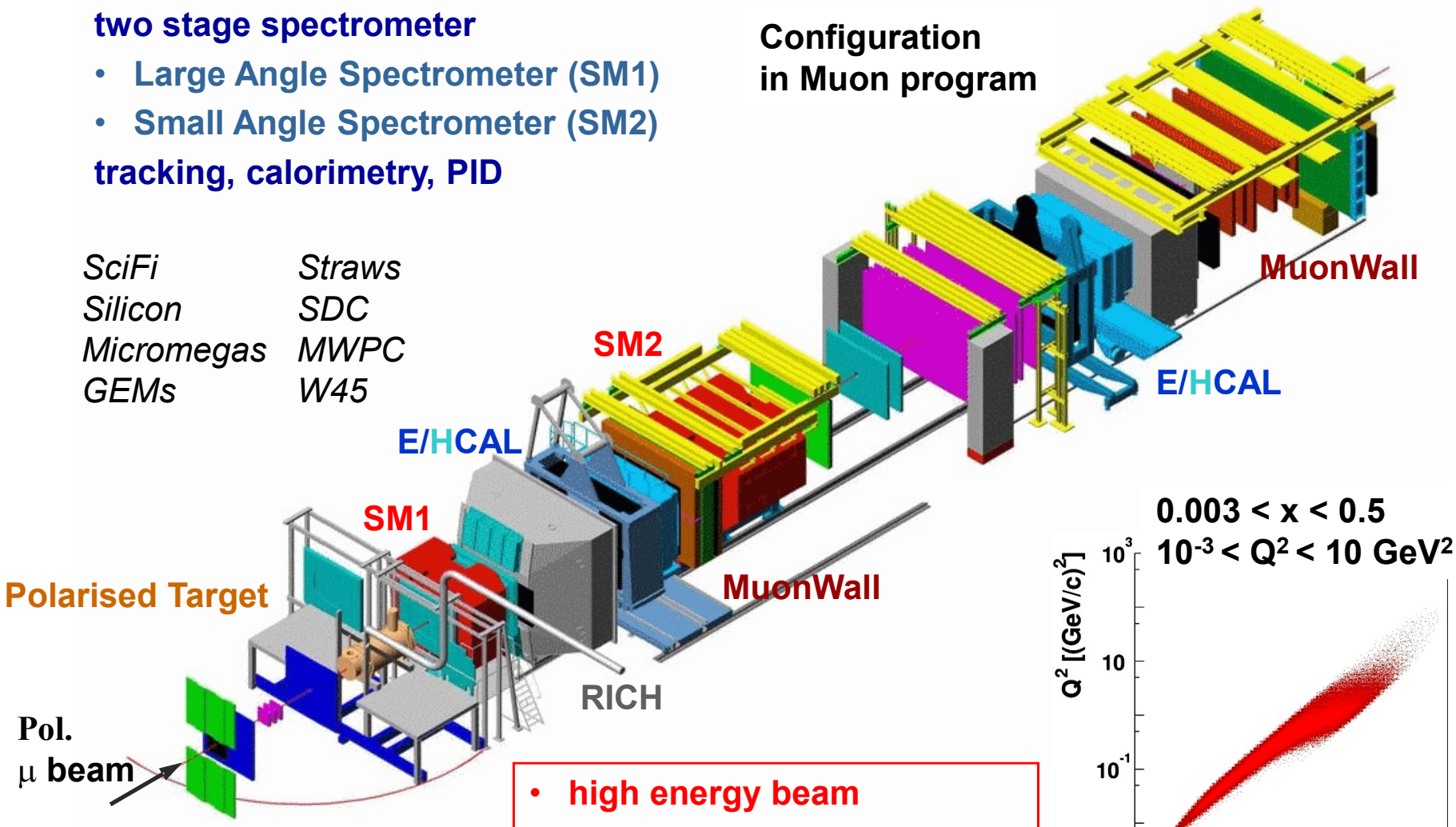
two stage spectrometer

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

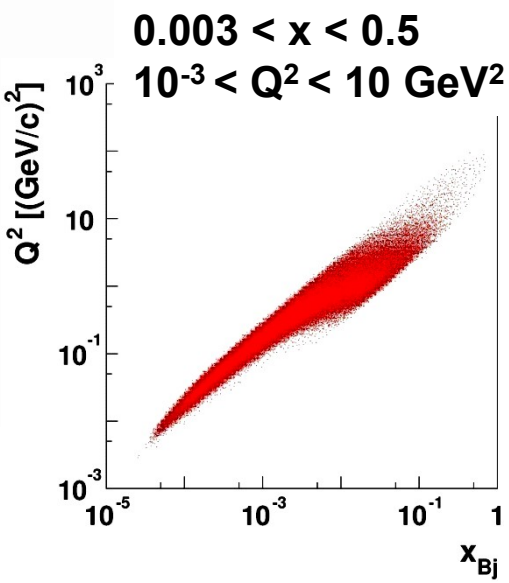
tracking, calorimetry, PID

SciFi	*Straws*
Silicon	*SDC*
Micromegas	*MWPC*
GEMs	*W45*

Configuration in Muon program



- **high energy beam**
- **broad kinematical range**
- **large angular acceptance**



COMPASS Target system

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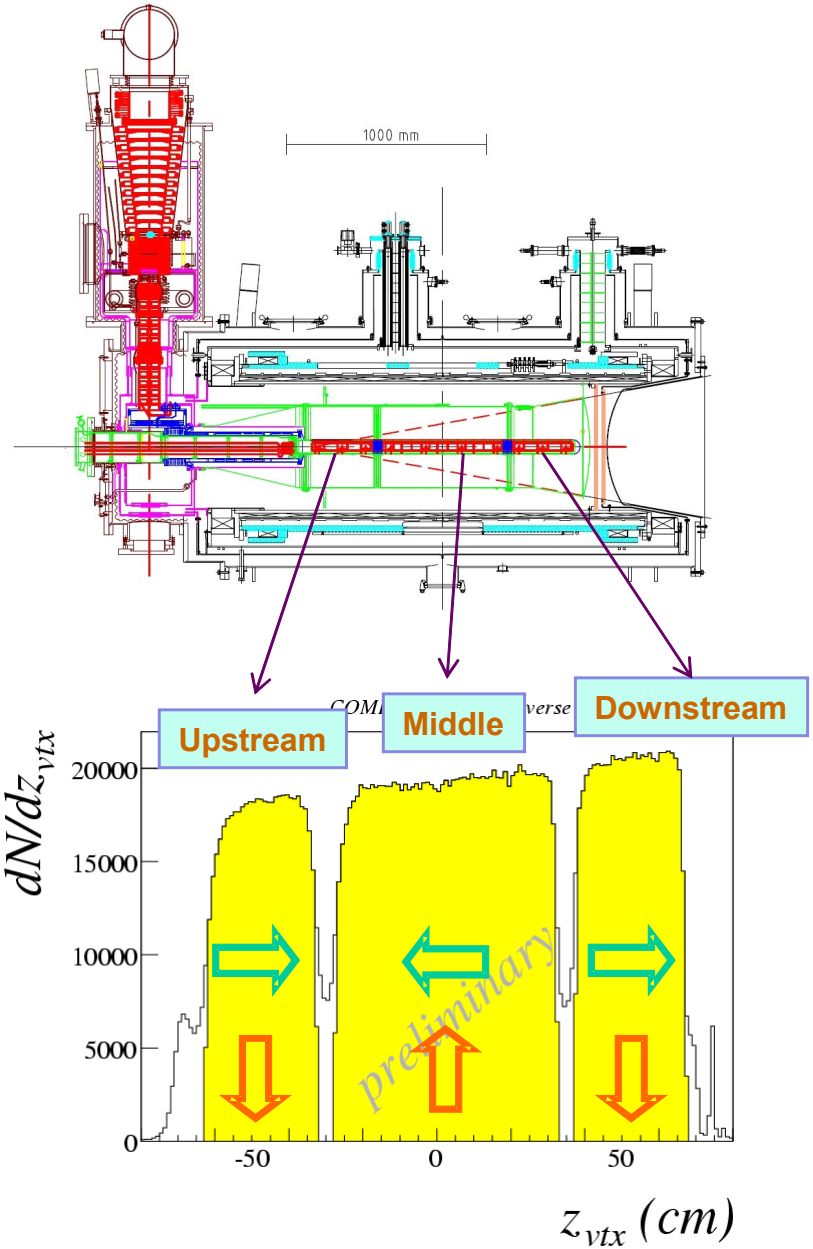
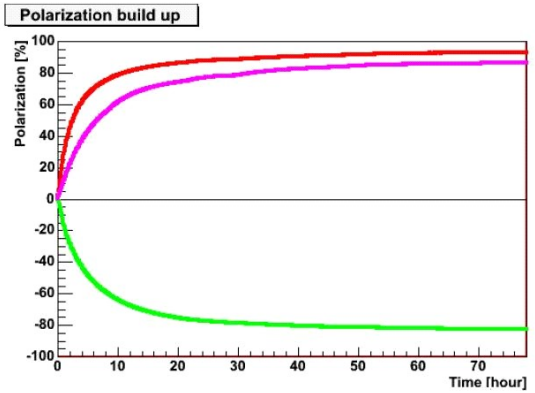


Solid polarized target operated
in ***Dynamic Nuclear Polarization*** technique
with a dilution refrigerator

PT magnet:
→+180~-180 mrad geometrical acceptance

To match larger acceptance:
→3 target cells: reduction of false asymmetries

Target:
→NH_3 for proton , ^{6}LiD for deuteron
→ longitudinal & transverse mode available
→very long relaxation time (~ 4000 h)
→magnetic field rotation without polarization loss
→ Polarization of NH_3 -92%, +88%, -83%



RICH@COMPASS

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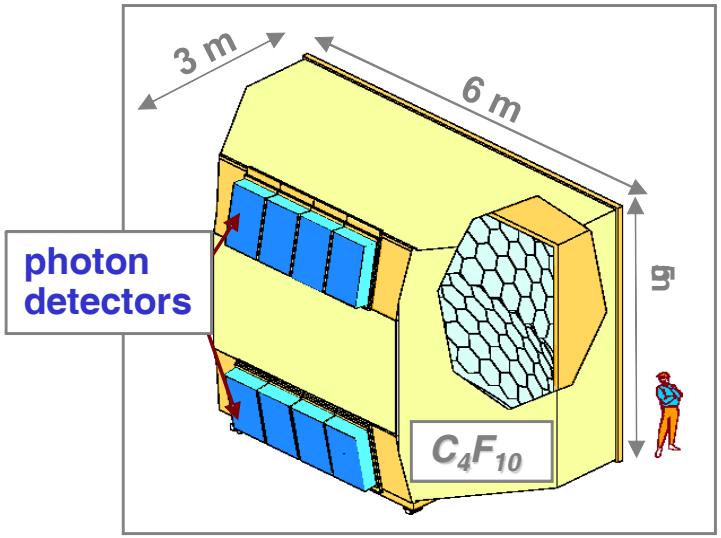
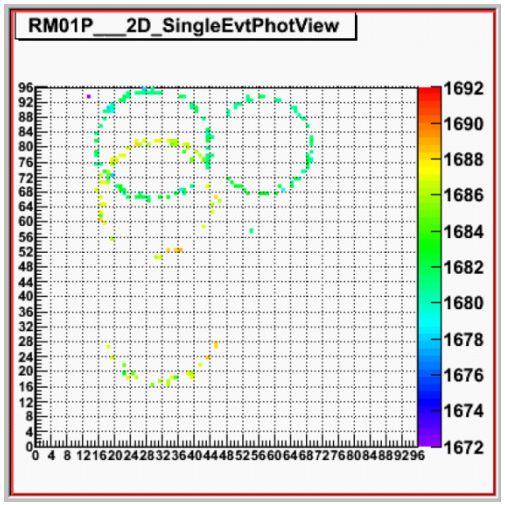
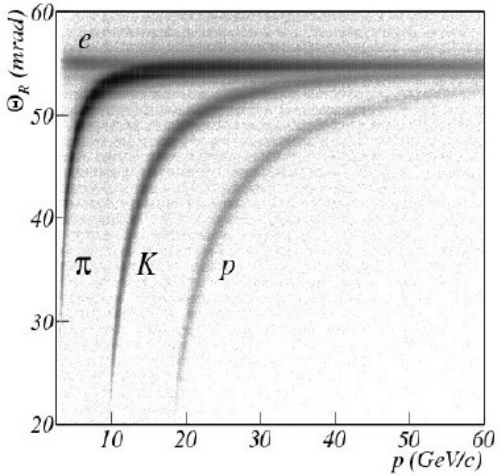
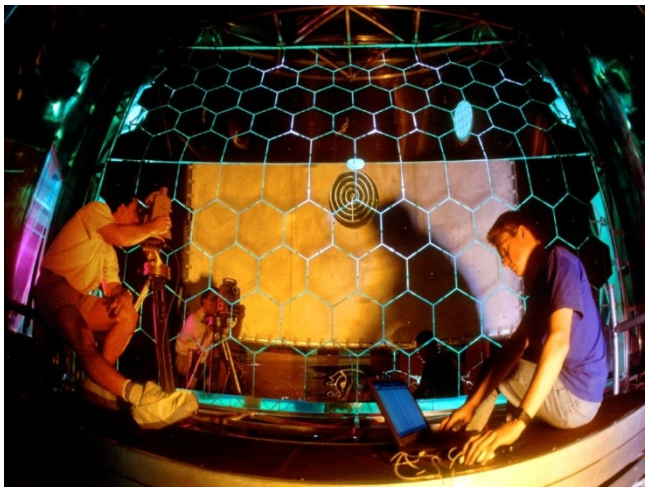








- radiator gas: C_4F_{10}
- mirror wall: 20 m^2 surface
- photon-detectors:
  - outer part (75%) MWPC(pad RO) with CsI cathode
  - inner part(25%) 576 MAPMTs with indiv. telescope

threshold momenta
- p_π = 2 GeV/c
- p_K = 9 GeV/c
- p_P =17 GeV/c

Installed in 2005,
Used in data taking from 2006

Status of COMPASS

Inclusive and Semi-inclusive DIS with

- Longitudinally polarized nucleon target
- Transversely polarized nucleon target

COMPASS Brief History

- 2002 Data taking started

  muon program with 160 GeV polarized muon

- 2002-2006 ^{6}LiD polarized target (pol. deuterons)

  L-mode: 80 / T-mode: 20 , $\Delta G/G$ measurement

  2005 no data taking

- 2007 NH_3 polarized target (pol. protons)

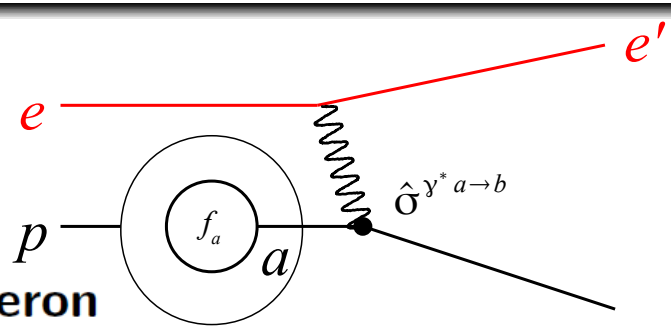
  L-mode: 50 /T-mode: 50

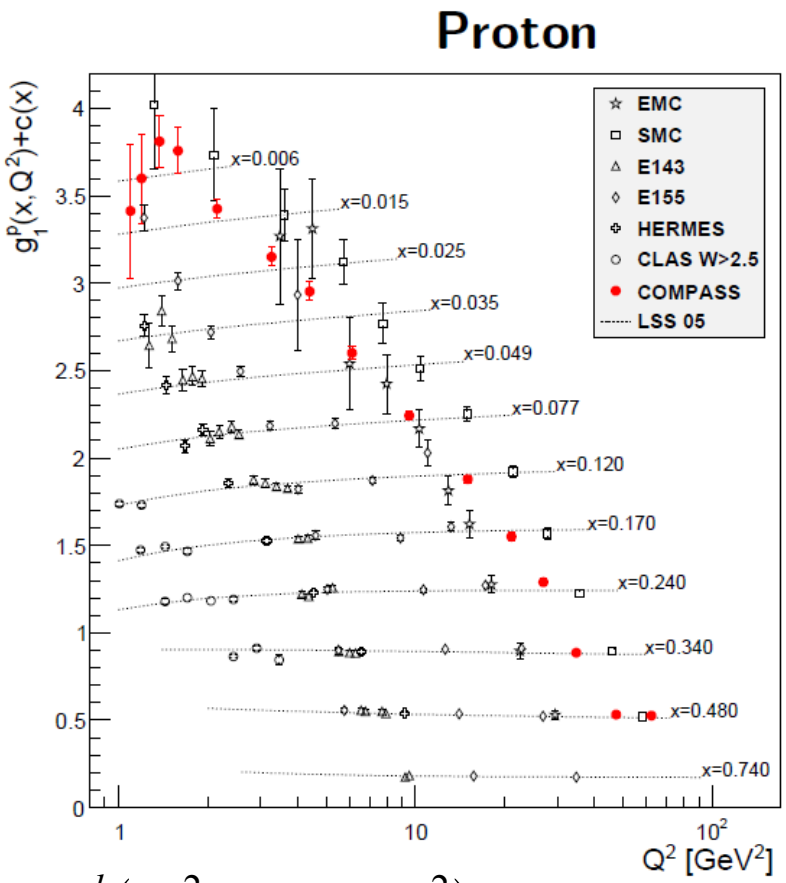
- 2008, 2009 hadron program with hadron beam at 190 GeV
- 2010 NH_3 polarized target (pol. protons) only T-mode
- 2011 ditto only L-mode

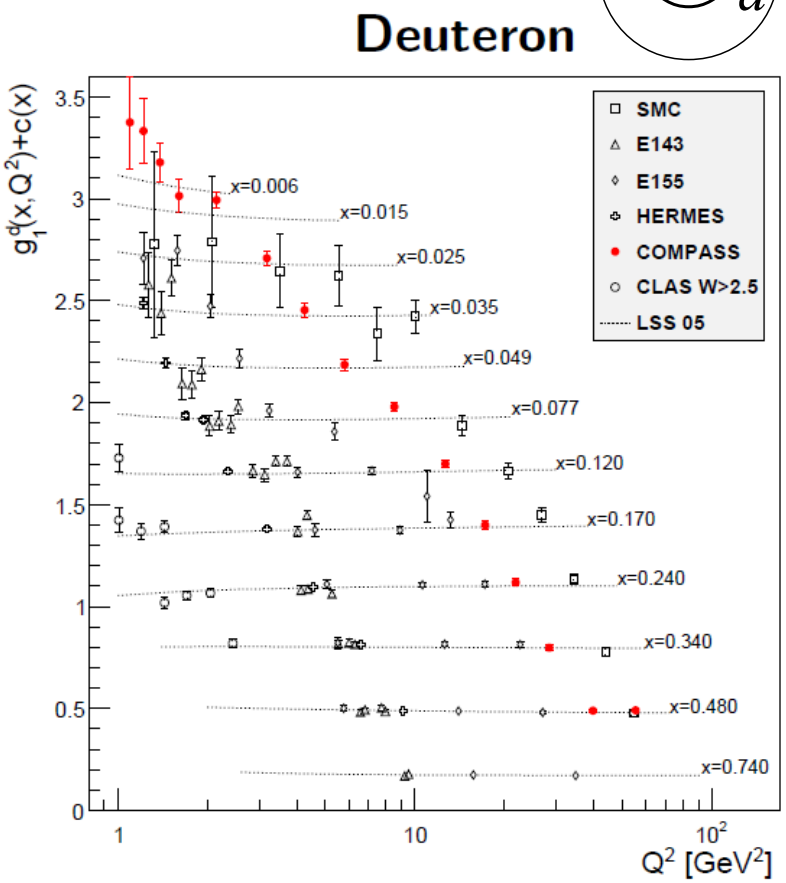
Selected COMPASS results

g_1	The spin-dependent structure function of the proton g_1^p and a Test of the Bjorken Sum Rule,	PLB 690 (2010) 466–472
	Spin asymmetry A_1^d and the spin-dependent structure function g_1^d of the deuteron at low values of x and Q^2,	PLB 647 (2007) 330–340
	The Deuteron Spin-dependent Structure Function g_1^d and its First Moment,	PLB 647 (2007) 8–17
	Measurement of the spin structure of the deuteron in the DIS region,	PLB 612 (2005) 154
Δq	Quark Helicity Distributions from Longitudinal Spin Asymmetries in Muon-Proton and Muon-Deuteron Scattering,	PLB 693 (2010) 227–235
	Flavour Separation of Helicity Distributions from Deep Inelastic Muon-Deuteron Scattering,	PLB 680 (2009) 217–224
	The Polarised Valence Quark Distribution from semi-inclusive DIS,	PLB 660 (2008) 458–465
ΔG	Gluon Polarisation in the Nucleon and Longitudinal Double Spin Asymmetries from Open Charm Muoproduction,	PLB 676 (2009) 31–38
	Gluon polarization in the nucleon from quasi-real photoproduction of high-pT hadron pairs,	PLB 633 (2006) 25–32
SSA	Azimuthal asymmetries of charged hadrons produced by high energy muons off longitudinally polarized deuterons,	EPJC 70 (2010) 39–49
Sivers	Measurement of the Collins and Sivers asymmetries on transversely polarised protons,	PLB 692 (2010) 240–246
Collins	Collins and Sivers asymmetries for pions and kaons in muon-deuteron DIS,	PLB 673 (2009) 127–135
….	A new measurement of the Collins and Sivers asymmetries on a transversely polarised deuteron target,	NP B765 (2007) 31–70
	First measurement of the transverse spin asymmetries of the deuteron in semi-inclusive deep inelastic scattering,	PRL 94 (2005) 202002

Inclusive measurements



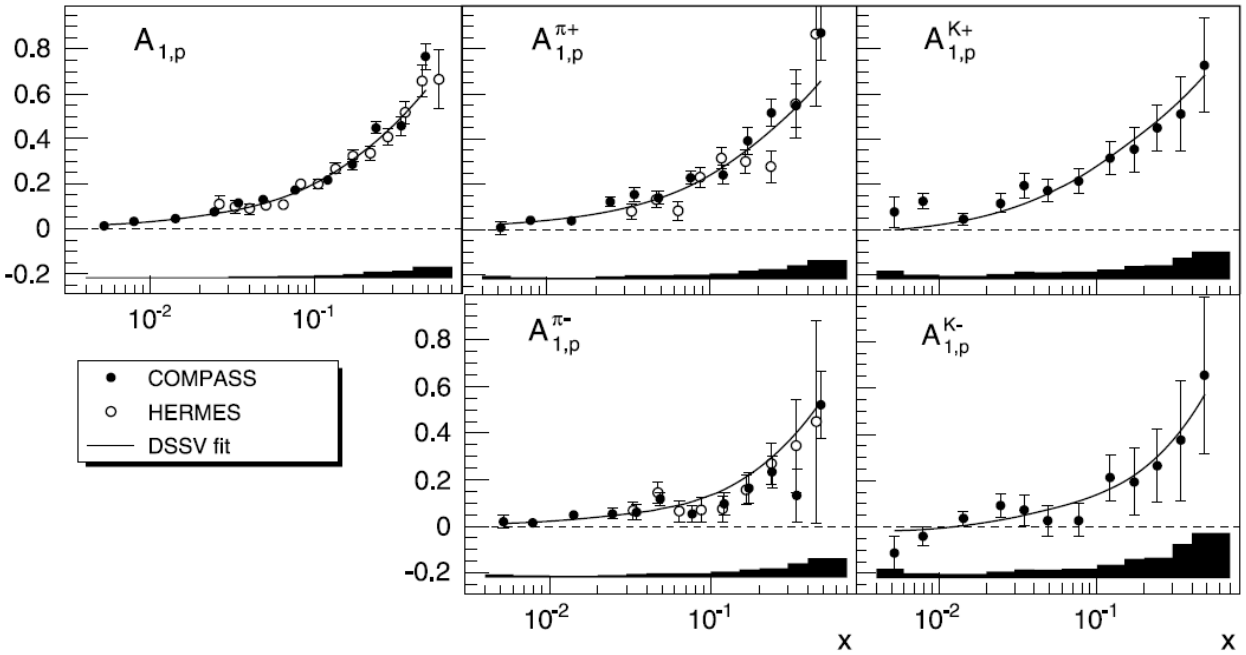


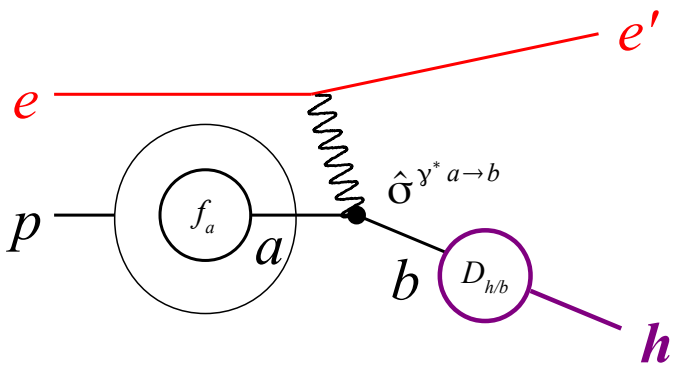


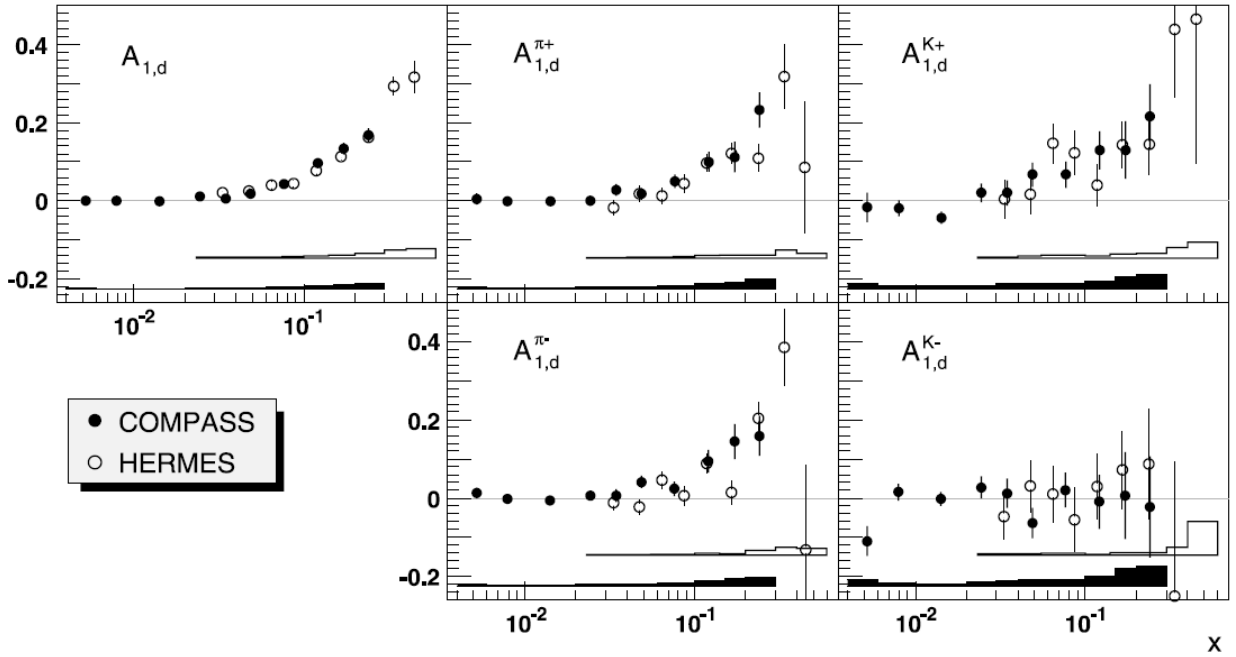
$$\Gamma_1^d\left(Q^2=3\ \mathrm{GeV}^2\right)=0.0502\pm0.028\pm0.020\pm0.051$$

$$\Rightarrow \quad \Delta\Sigma=0.35\pm0.03\pm0.05$$
$$\Delta S=-0.08\pm0.01\pm0.02$$

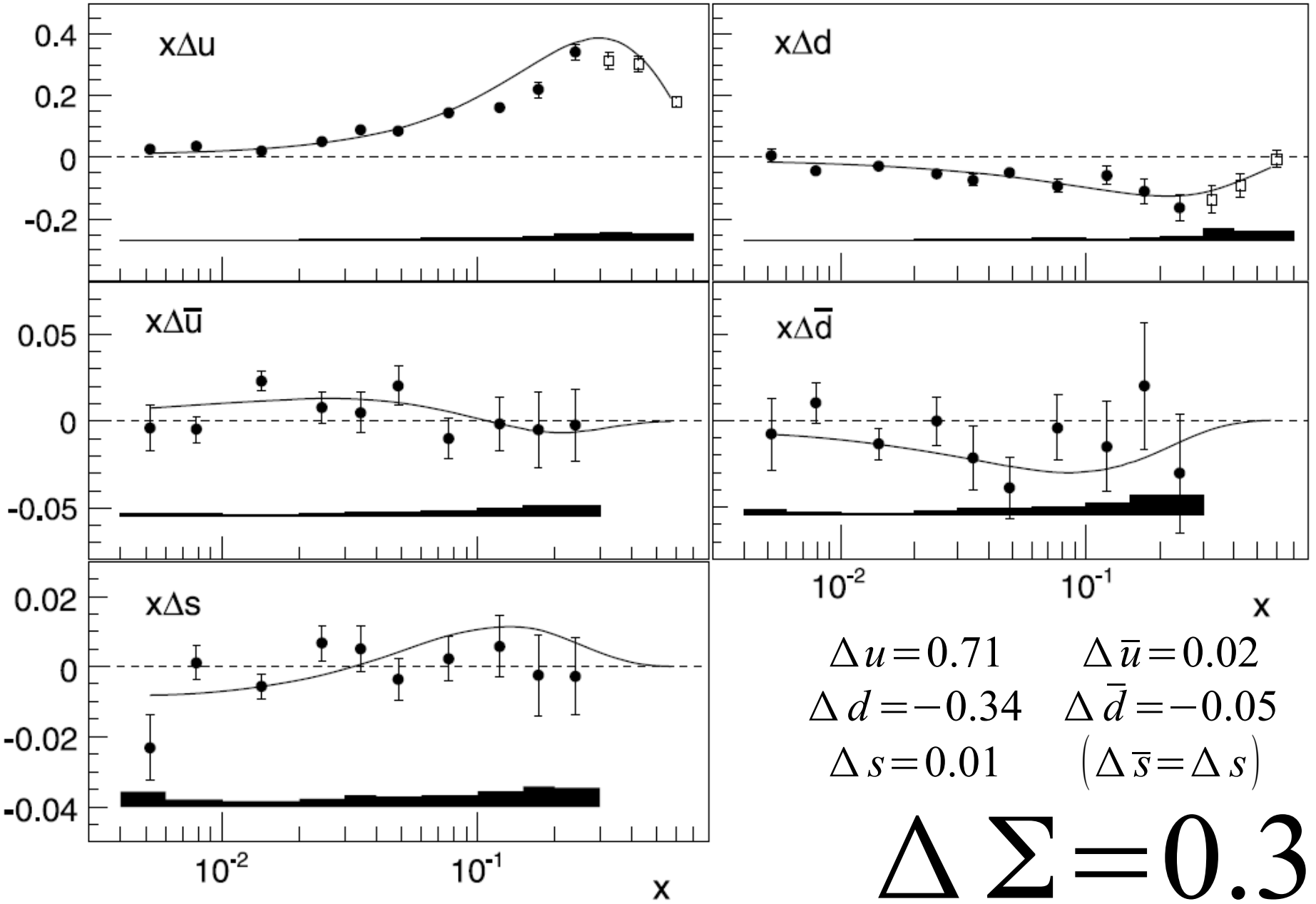
Semi-inclusive measurements: Flavor tagging







Δq: Flavor decomposition

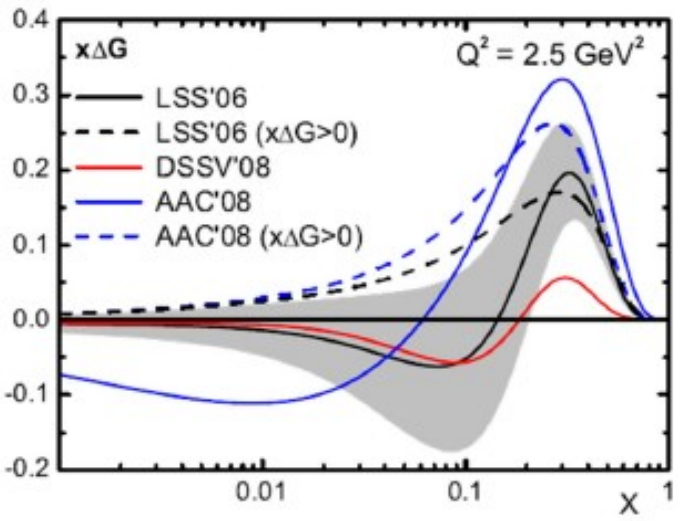


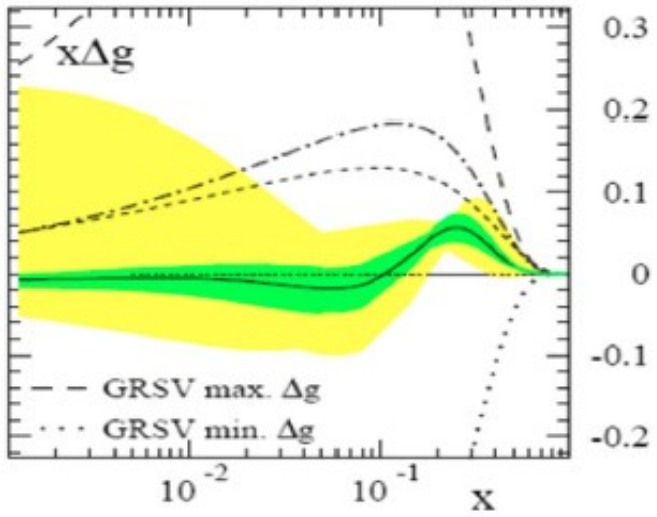
$$\Delta u = 0.71 \qquad \Delta \bar{u} = 0.02$$
$$\Delta d = -0.34 \qquad \Delta \bar{d} = -0.05$$
$$\Delta s = 0.01 \qquad \left(\Delta \bar{s} = \Delta s\right)$$

$$\Delta\Sigma = 0.32$$

Gluon Polarization

From Global Fit

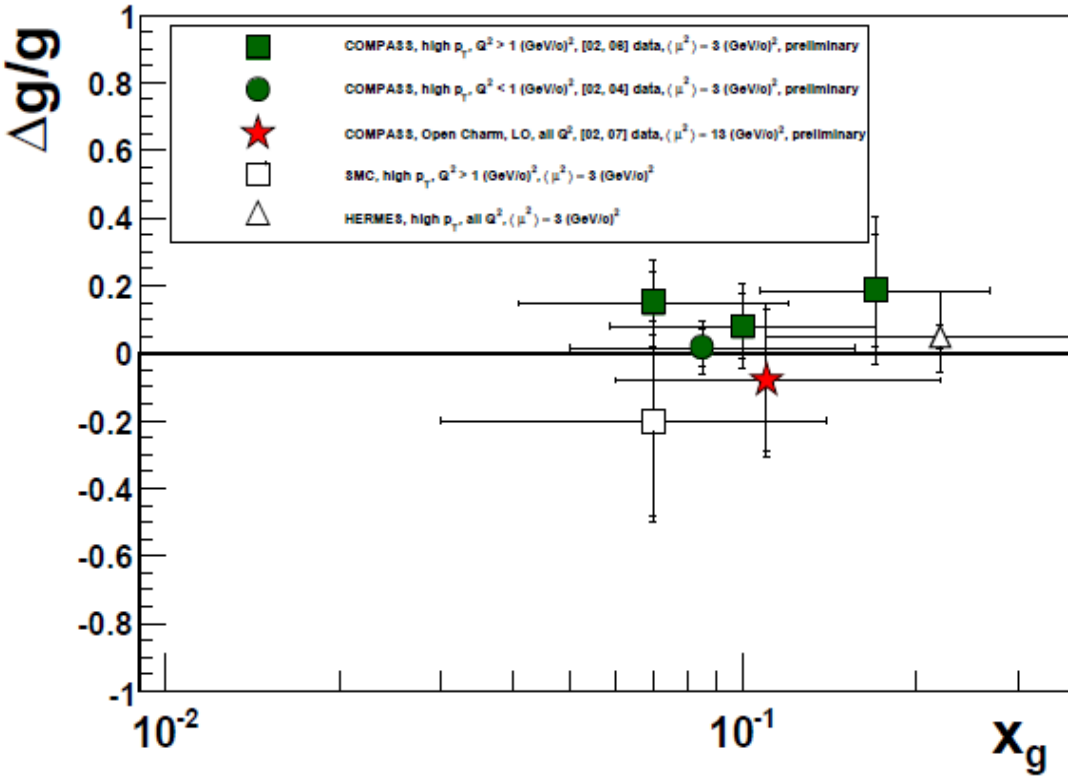




Direct measurements

Open charm

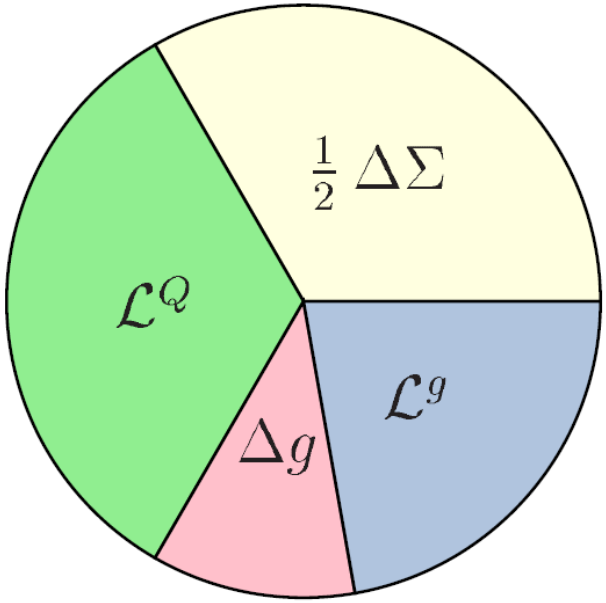
High-pt hadron



Proton spin budget

$$\Delta\Sigma = 0.32$$

$$\frac{1}{2} =$$



$\Delta u = 0.71$ $\quad \Delta\bar{u} = 0.02$

$\Delta d = -0.34$ $\quad \Delta\bar{d} = -0.05$

$\Delta s = 0.01$ $\quad (\Delta\bar{s} = \Delta s)$

$$g_1^d \rightarrow \Delta\Sigma = 0.35$$

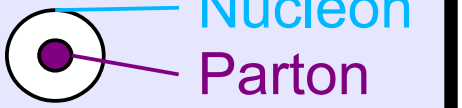
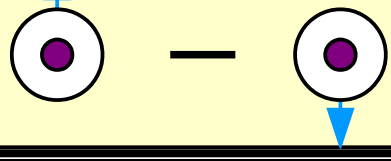
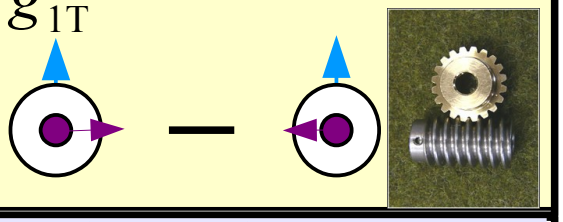
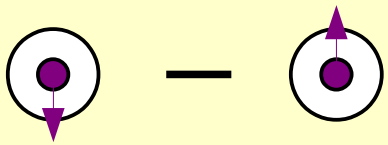
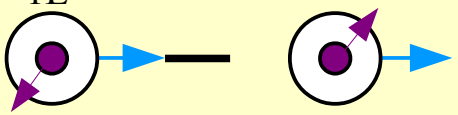
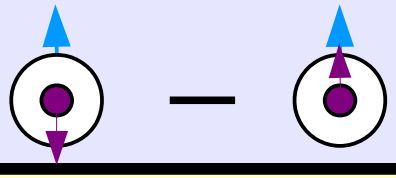
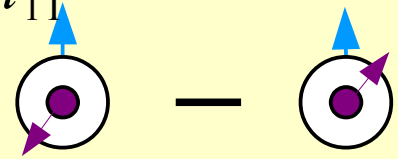
$$|\Delta G| \sim 0.2 - 0.3$$

from Global analysis

$\Longrightarrow$ Becomes larger ?

small (Open charm, high-pt h)

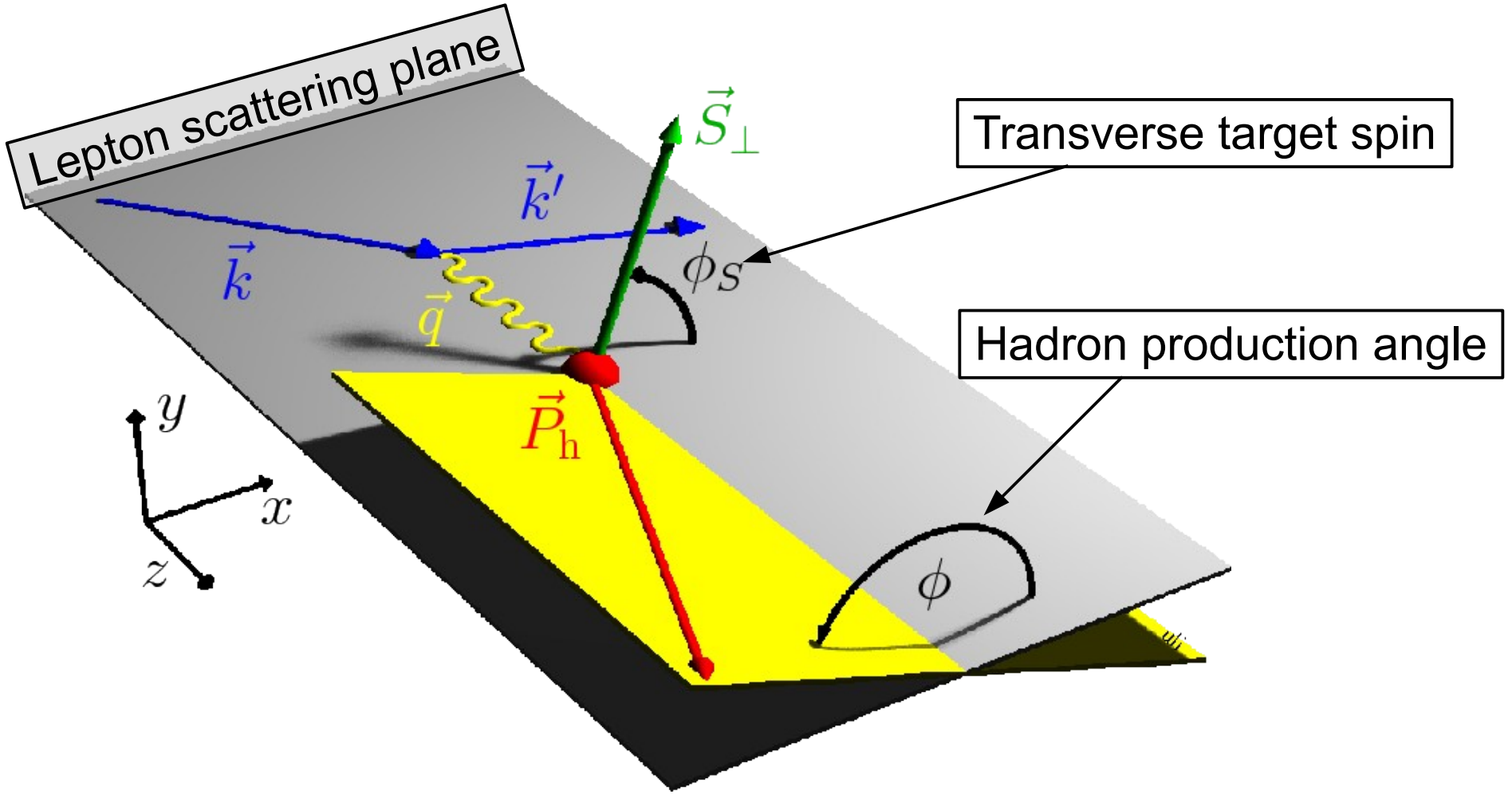
Transverse Momentum Dependent PDF: TMD

Parton \ Nucleon:	Unpolarized	Long. polarized	Trans. polarized
Unpol.	$f_1(=q)$ Number density 		$f_{1T}^{\perp}$ Sivers 
Long. pol.		$g_{1L}(=\Delta q)$ Helicity	g_{1T} Worm-Gear-1 
Trans. polarized	$h_1^{\perp}$  Boer-Mulders	$h_{1L}^{\perp}$ Worm-Gear-2 	$h_{1T}(=\delta q)$ Transversity  $h_{1T}^{\perp}$ Pretzelosity 

Nucleon spin Parton spin

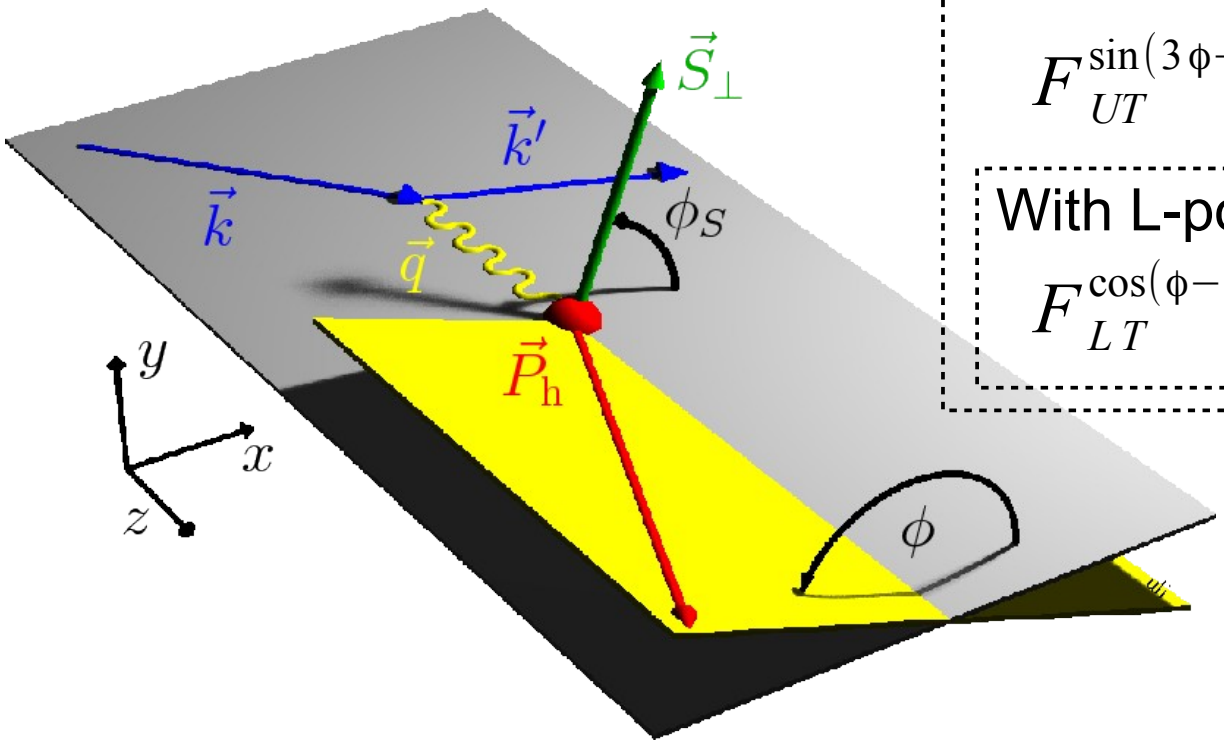
Azimuthal angles in SIDIS

$$l + N \rightarrow l' + h + X$$



Azimuthal dependence of SIDIS cross section

$$F_{UU} \sim (f_1) \otimes (D_1) \qquad F_{UU}^{\cos 2\pi} \sim (BM) \otimes (Collins)$$



With T-pol. target

$$F_{UT}^{\sin(\phi+\phi_S)} \sim (Trans.) \otimes (Collins)$$

$$F_{UT}^{\sin(\phi-\phi_S)} \sim (Sivers) \otimes (D_1)$$

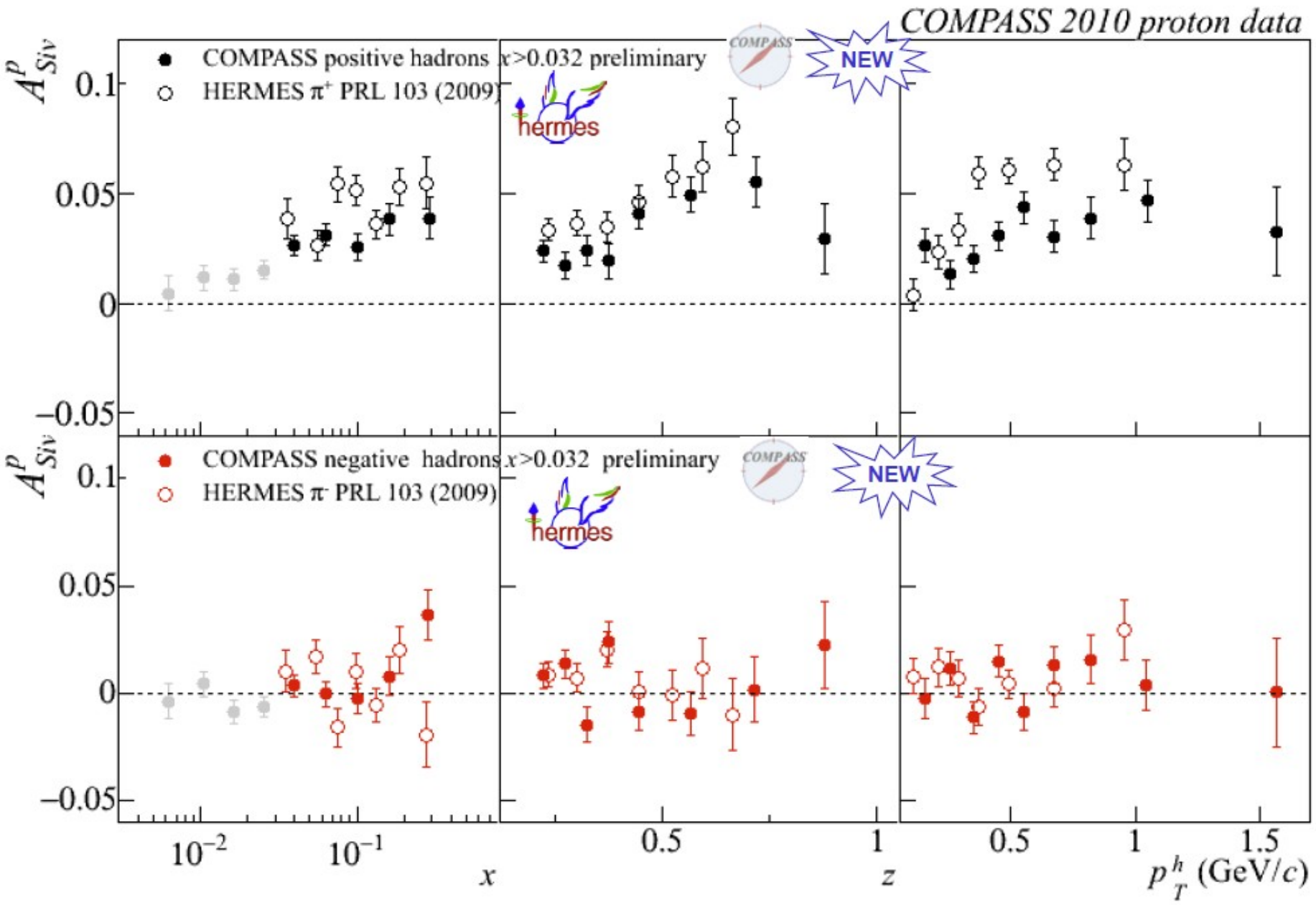
$$F_{UT}^{\sin(3\phi-\phi_S)} \sim (Pretzel.) \otimes (Collins)$$

With L-pol. beam

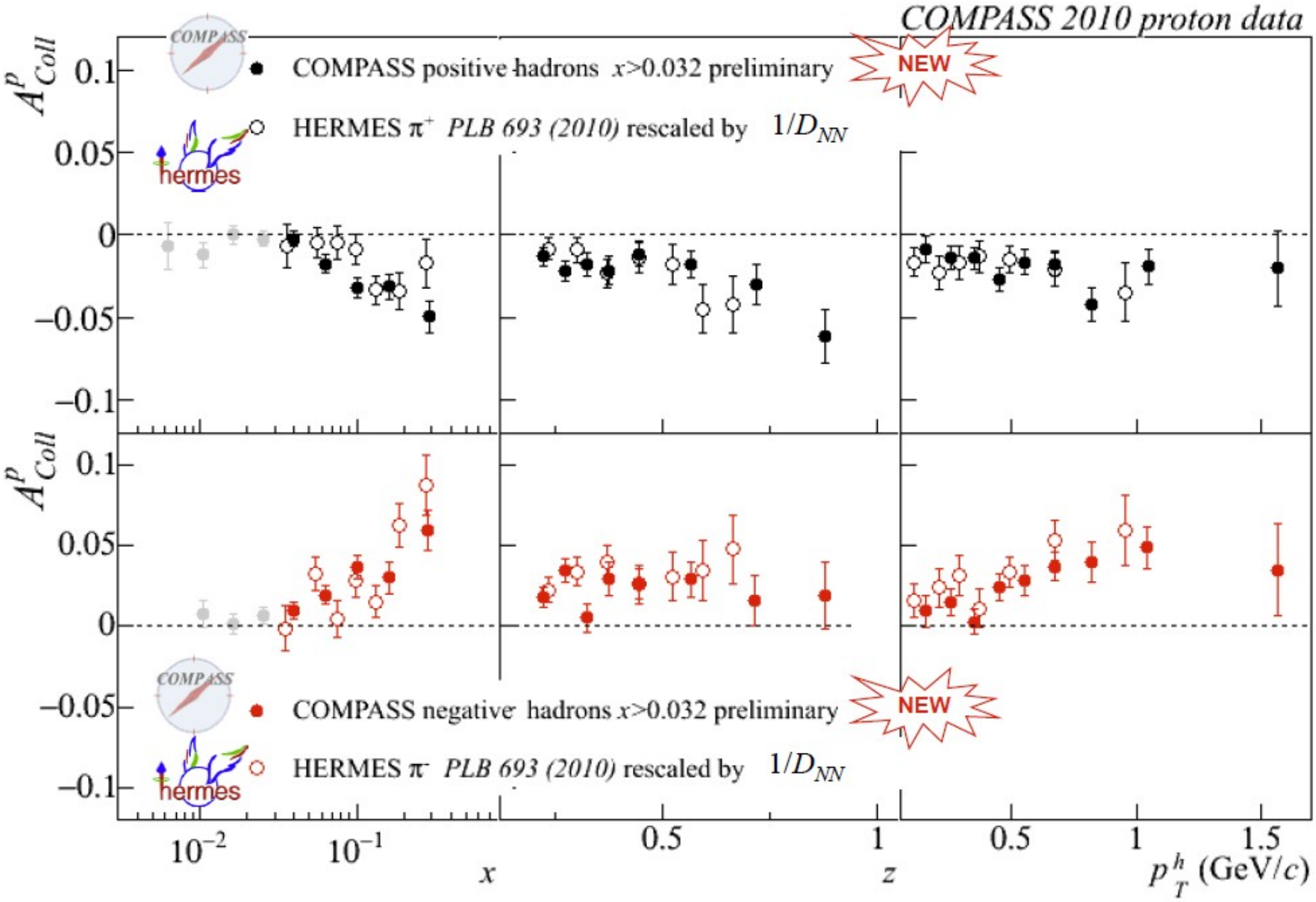
$$F_{LT}^{\cos(\phi-\phi_S)} \sim (WG1) \otimes (D_1)$$

+ others....

Sivers Asymmetry



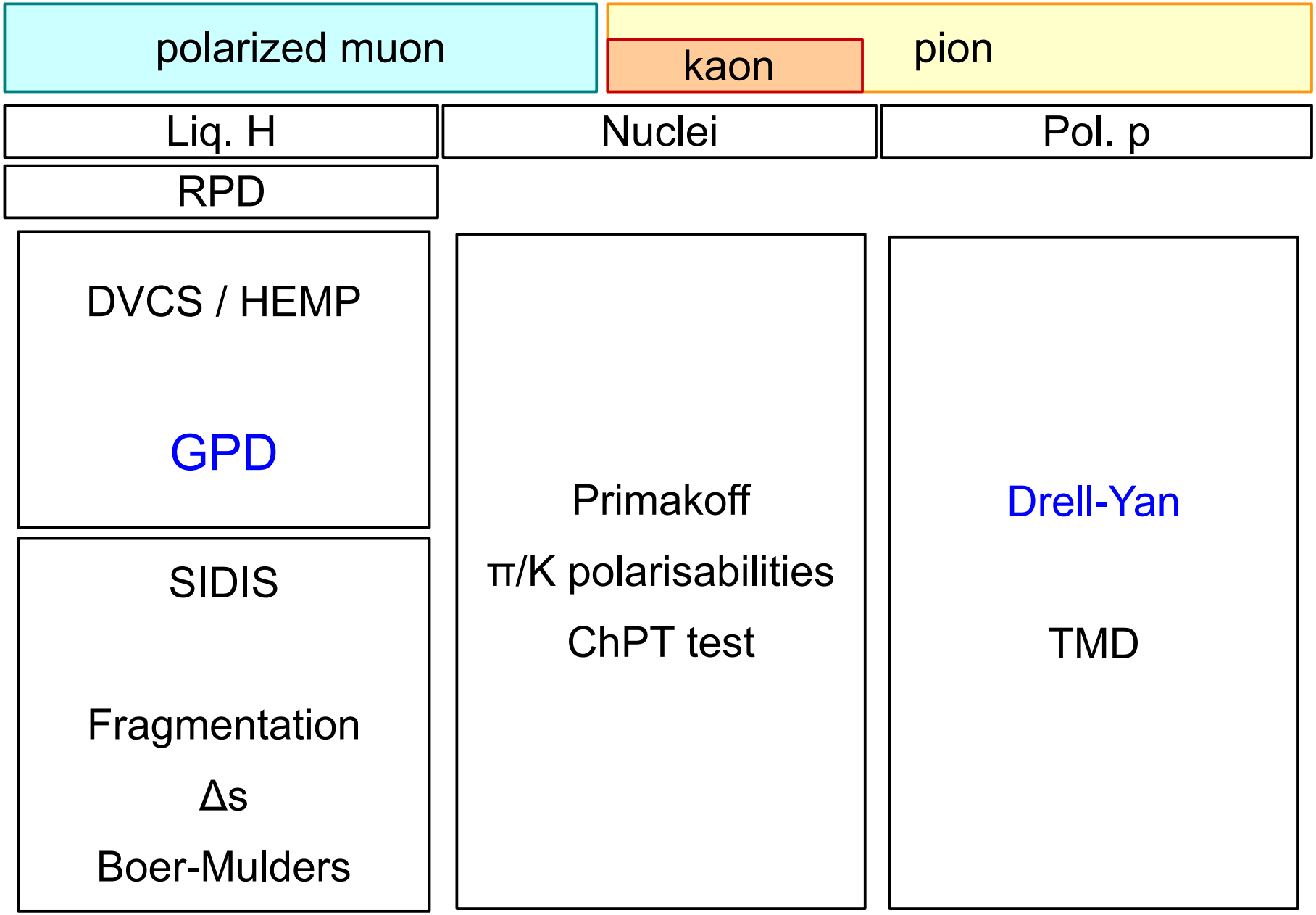
Collins Asymmetry



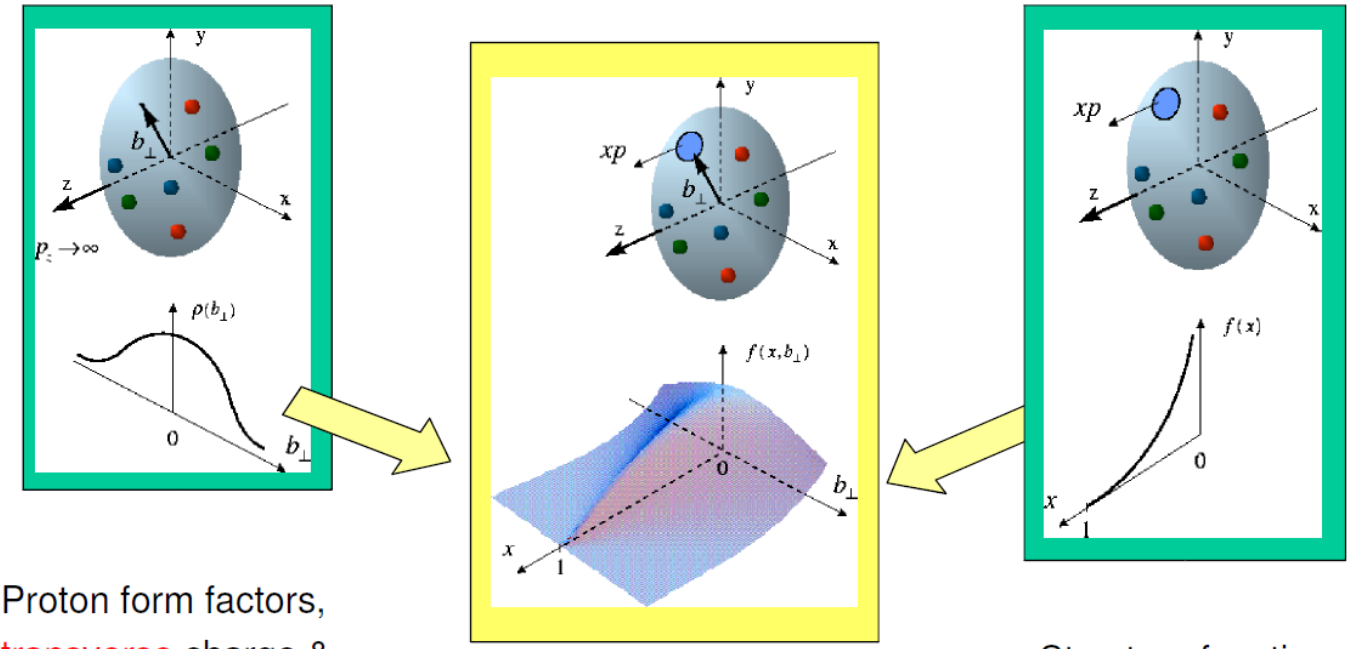
Outlook of COMPASS II

- GPD Program
- Drell-Yan Program

COMPASS II


polarized muon
kaon
pion
Liq. H
Nuclei
Pol. p
RPD
DVCS / HEMP
GPD
SIDIS
Fragmentation
Δs
Boer-Mulders
Primakoff
π/K polarisabilities
ChPT test
Drell-Yan
TMD

GPD and Proton 3D structure

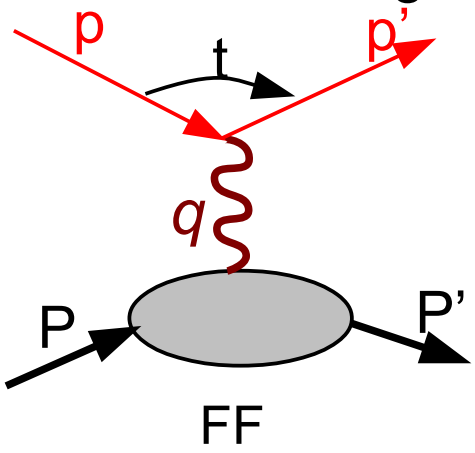


Proton form factors, transverse charge & current densities

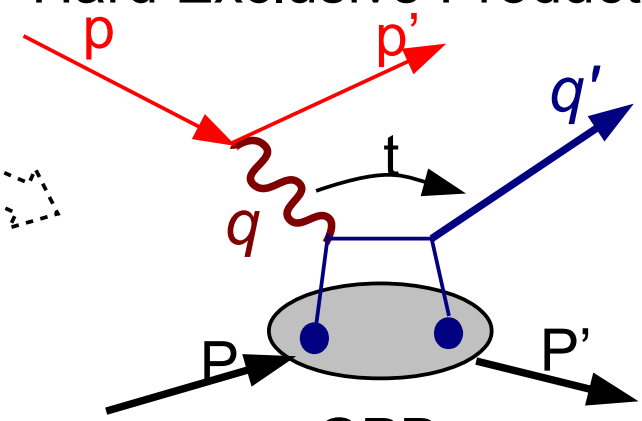
Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

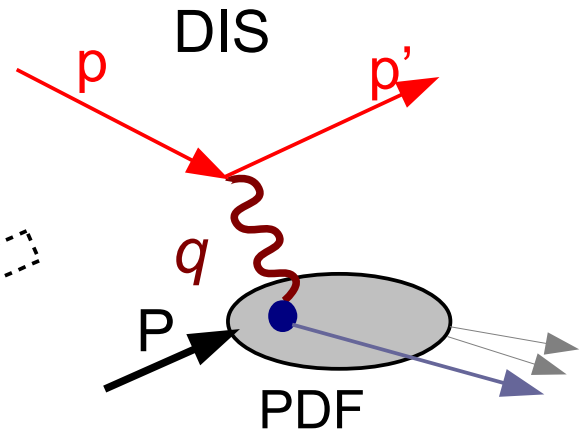
Elastic scattering



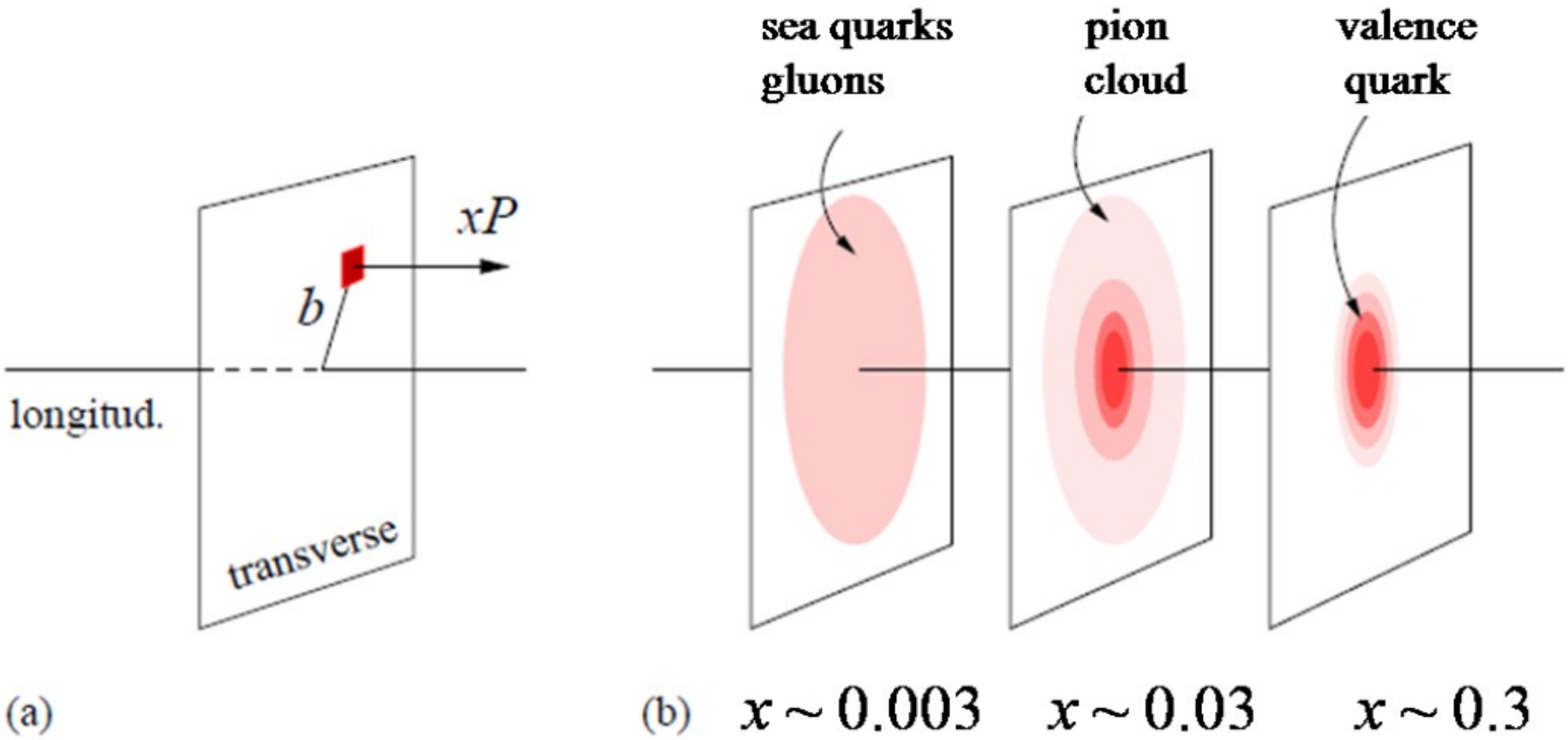
Hard Exclusive Production



DIS



GPD and Nucleon tomography

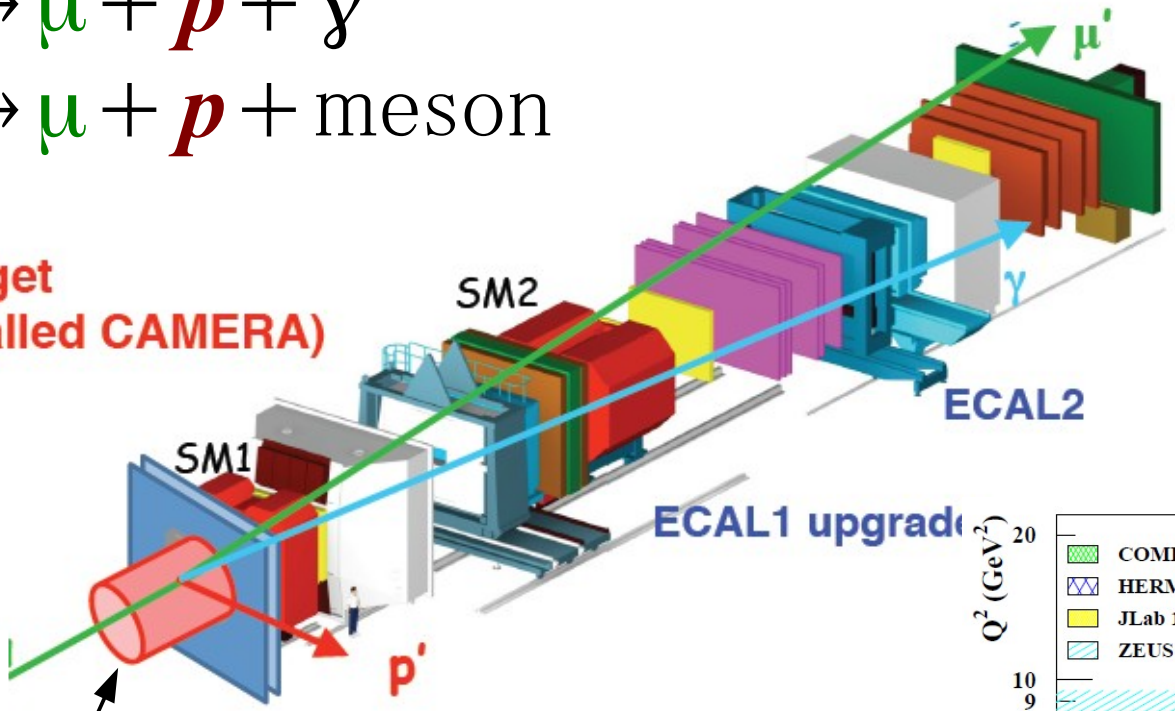


$$q^f(x, \boldsymbol{b}_\perp) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} H^f(x, 0, -\boldsymbol{\Delta}_\perp^2).$$

COMPASS II: GPD

$$\mu + p \rightarrow \mu + p + \gamma$$
$$\mu + p \rightarrow \mu + p + \text{meson}$$

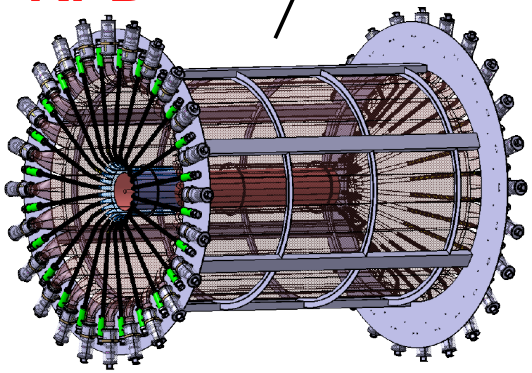
2.5m LH2 target
+ 4m RPD (called CAMERA)

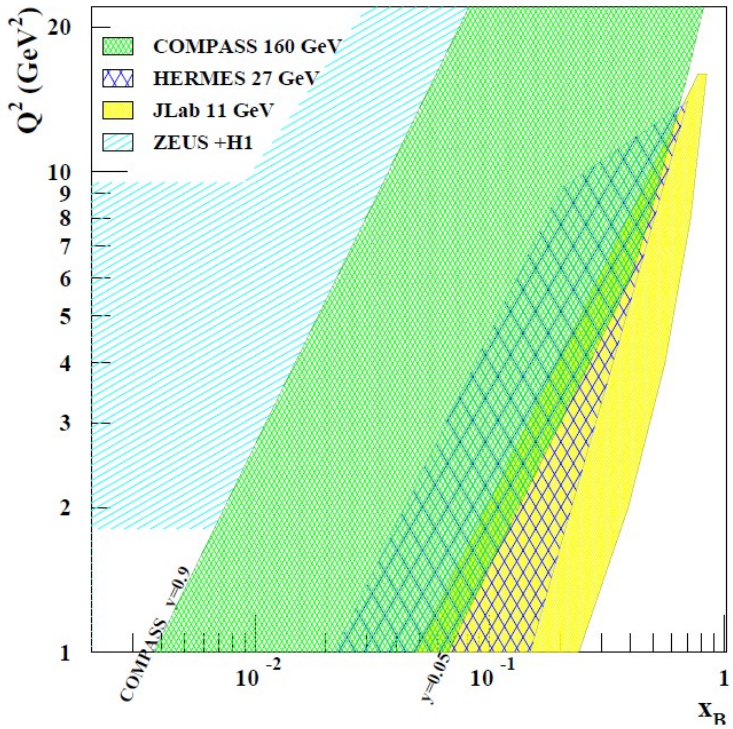


pol. μ^+, μ^-

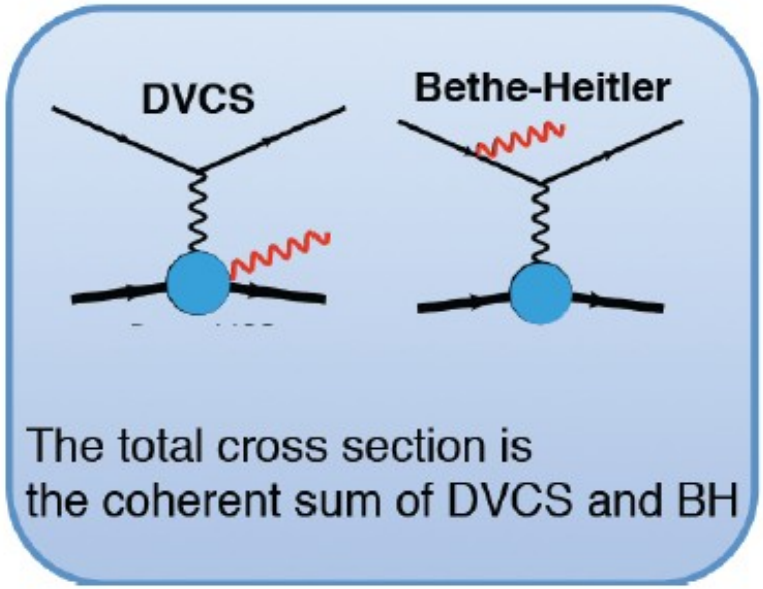
+ ECAL0 before SM1
(for higher acceptance in large X_B)

RPD

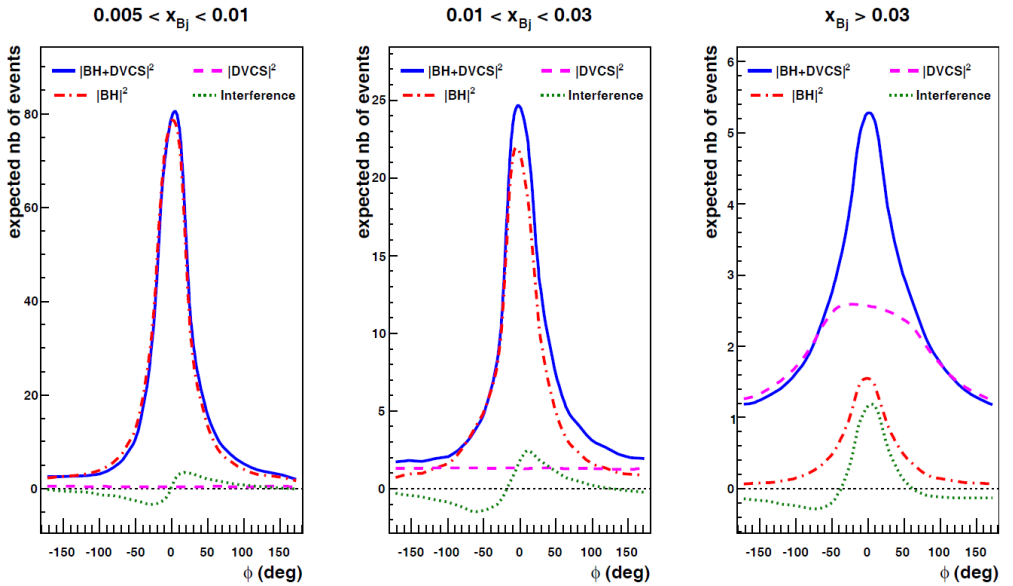


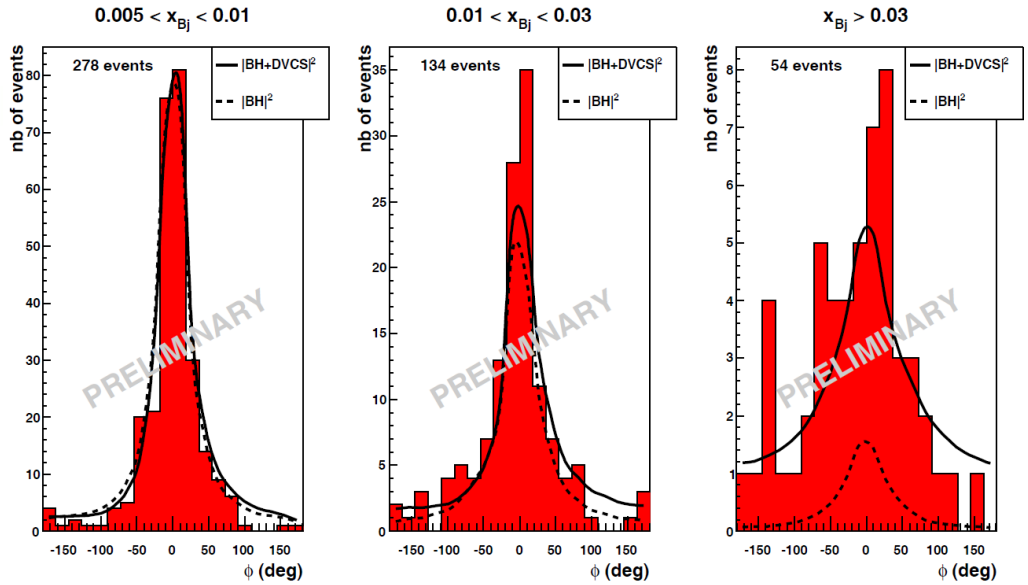


DVCS @ COMPASS II



$$d\sigma(\mu N \to \mu N \gamma) \propto |\mathcal{A}_{BH}|^2 + |\mathcal{A}_{DVCS}|^2 + \underbrace{\mathcal{A}_{BH}\mathcal{A}^*_{DVCS} + \mathcal{A}^*_{BH}\mathcal{A}_{DVCS}}_{I}.$$





Access to GPD

The beam charge & spin sum of cross sections

$$\mathcal{S}_{CS,U} \equiv \mathrm{d}\sigma^{\overleftarrow{+}} + \mathrm{d}\sigma^{\overrightarrow{-}} = 2(\mathrm{d}\sigma^{BH} + \mathrm{d}\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\ I)$$

$$\Rightarrow\ s_1^I \sin\phi + s_2^I \sin 2\phi$$

$$s_1^I \propto \mathrm{Im}(F_1, \mathcal{H})$$

The beam charge & spin difference of cross sections

$$\mathcal{D}_{CS,U} \equiv \mathrm{d}\sigma^{\overleftarrow{+}} - \mathrm{d}\sigma^{\overrightarrow{-}} = 2(P_\mu \mathrm{d}\sigma^{DVCS}_{pol} + e_\mu \mathrm{Re}\ I)$$

$$\Rightarrow\ c_0^I + c_1^I \cos\phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi$$

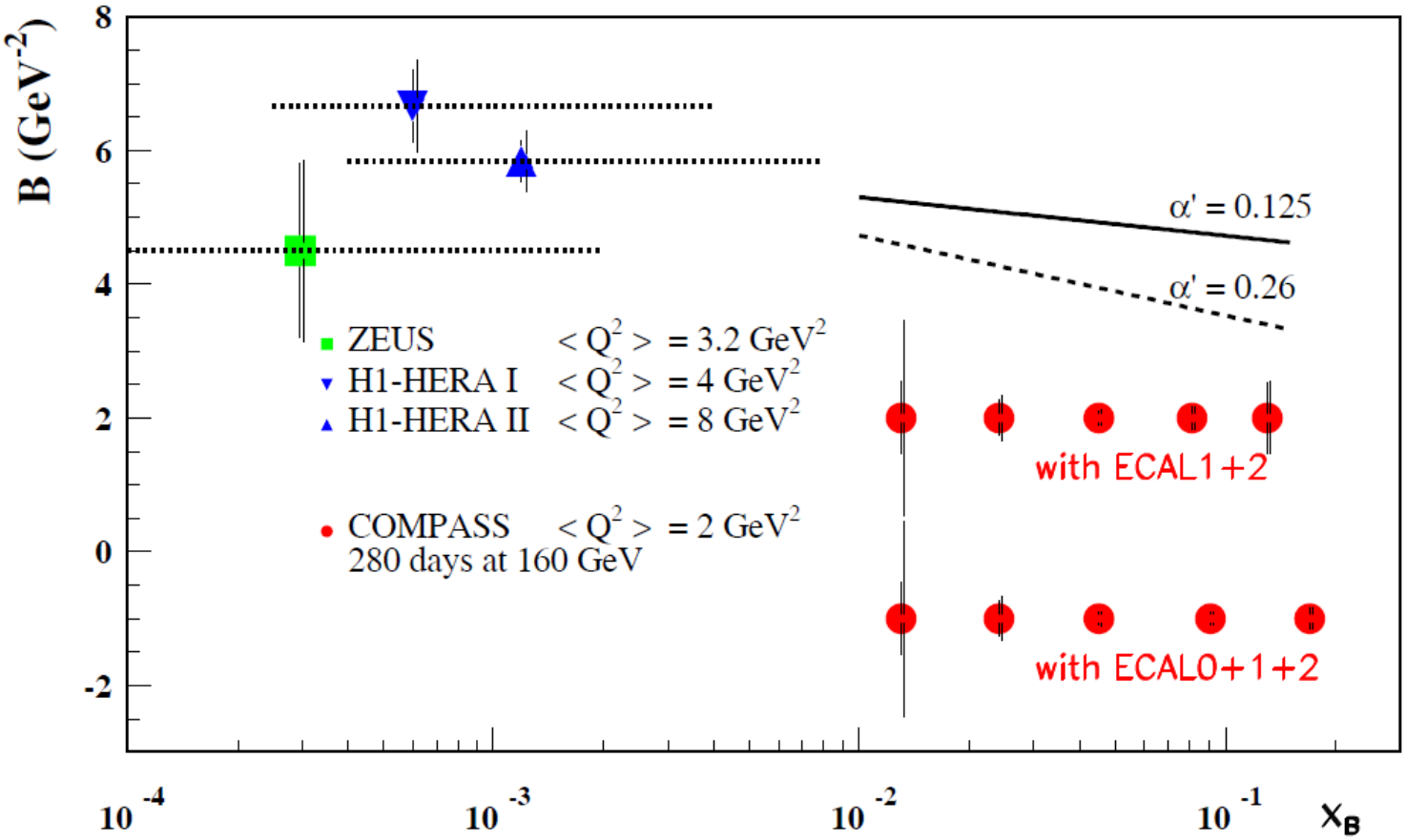
$$c_1^I \propto \mathrm{Re}(F_1, \mathcal{H})$$

The beam charge & spin asymmetry of cross sections

$$\mathcal{A}_{CS,U} \equiv \frac{\mathrm{d}\sigma^{\overleftarrow{+}} - \mathrm{d}\sigma^{\overrightarrow{-}}}{\mathrm{d}\sigma^{\overleftarrow{+}} + \mathrm{d}\sigma^{\overrightarrow{-}}} = \frac{\mathcal{D}_{CS,U}}{\mathcal{S}_{CS,U}}$$

Transverse imaging

$$d\sigma/dt \propto \exp\left(-B(x_B)|t|\right) \qquad B(x_B) = B_0 + 2\,\alpha' \log\left(\frac{x_0}{x_B}\right)$$

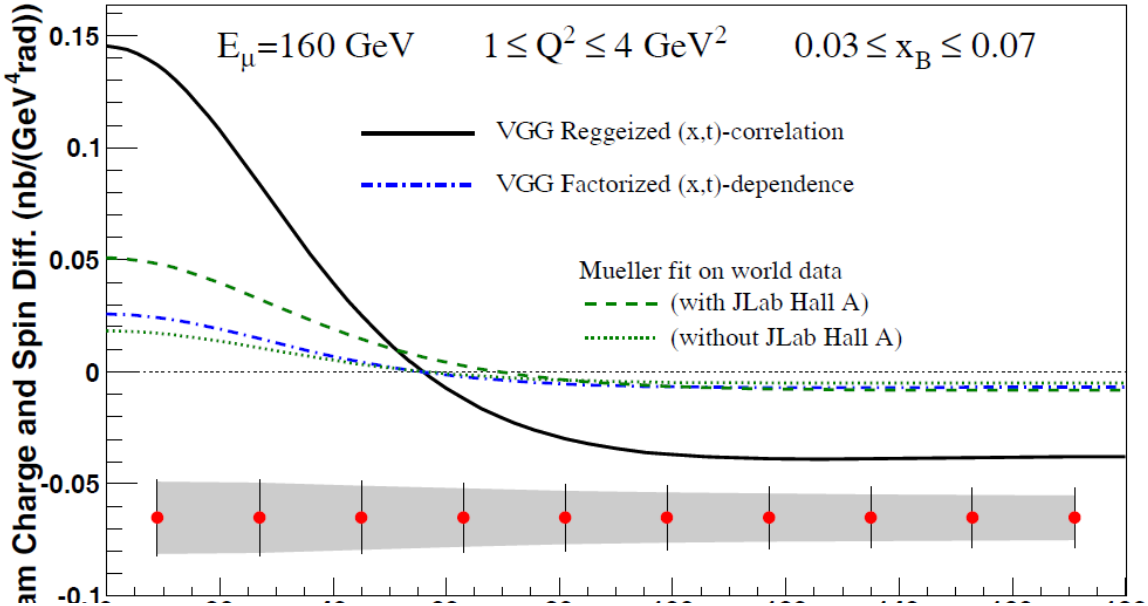


$$\Rightarrow \quad \left\langle r_\perp^2(x_B) \right\rangle \sim 2 \cdot B(x_B)$$

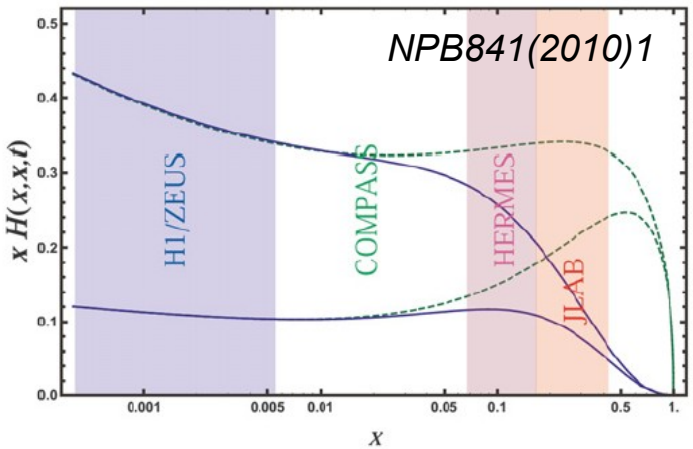
Projection of the azimuthal distributions

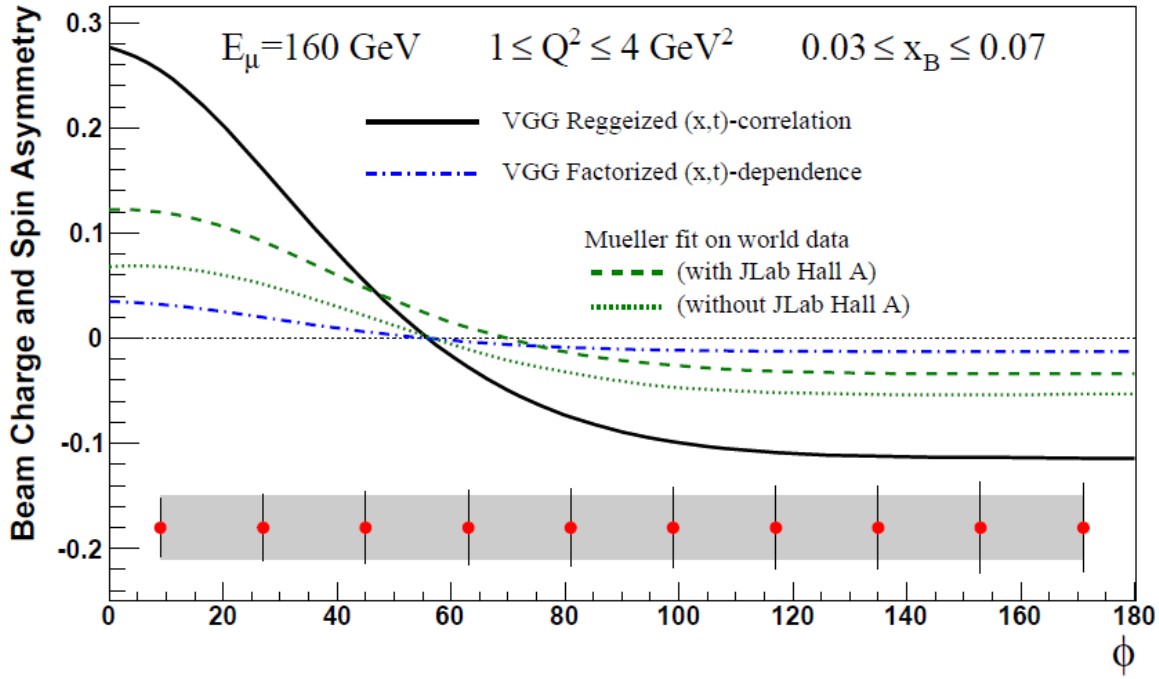
$$\mathcal{D}_{CS,U} \equiv \mathrm{d}\sigma^{\overleftarrow{+}} - \mathrm{d}\sigma^{\overrightarrow{-}}$$

$$c_1^I \propto \mathrm{Re}(F_1, \mathcal{H})$$



$$\mathcal{A}_{CS,U} \equiv \frac{\mathrm{d}\sigma^{\overleftarrow{+}} - \mathrm{d}\sigma^{\overrightarrow{-}}}{\mathrm{d}\sigma^{\overleftarrow{+}} + \mathrm{d}\sigma^{\overrightarrow{-}}}$$





SIDIS data from the COMPASS GPD run

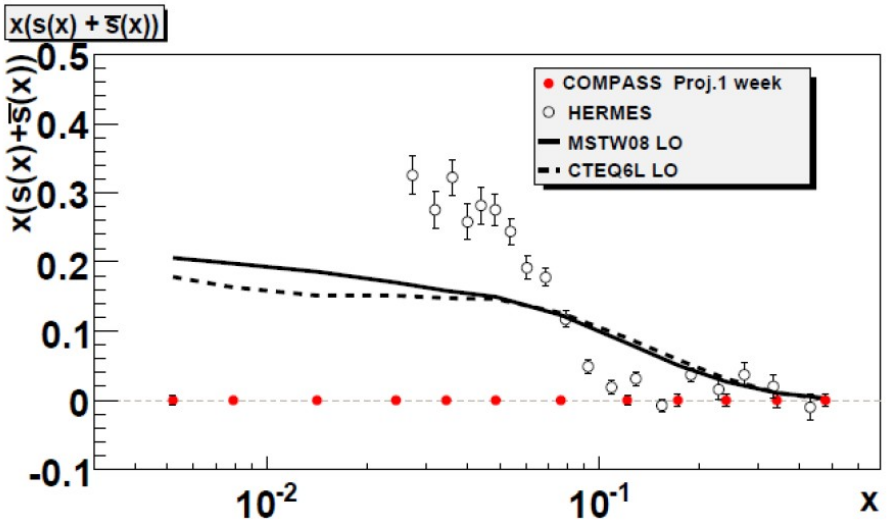
SIDIS measurements is possible with the GPD setup.

Hadron multiplicities

→ fragmentation functions

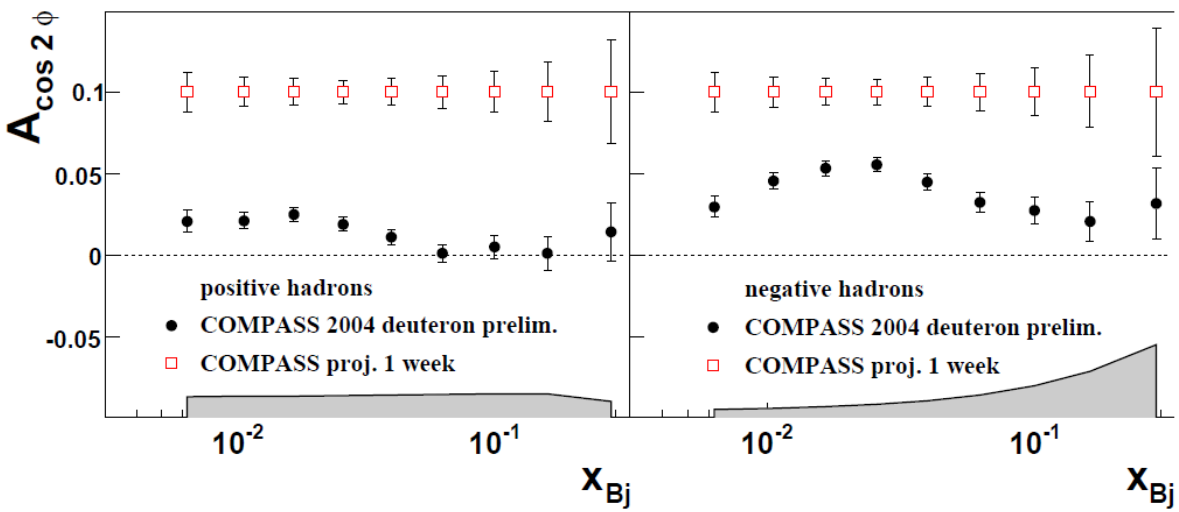
→ strange quark distribution

$$F_{UU} \sim (f_1) \otimes (D_1)$$

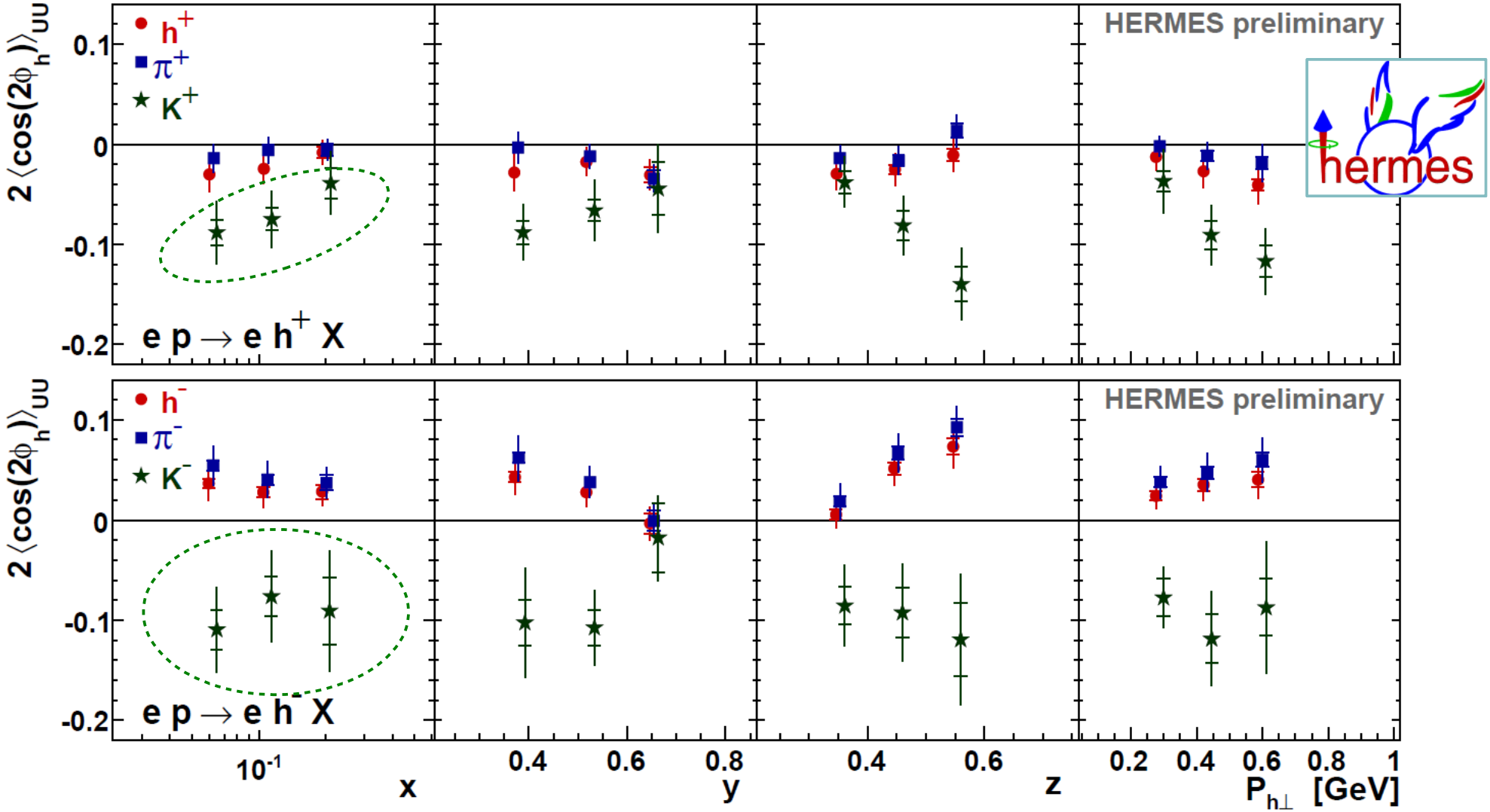


Boer-Mulders functions

$$F_{UU}^{\cos 2\pi} \sim (BM) \otimes (Collins)$$



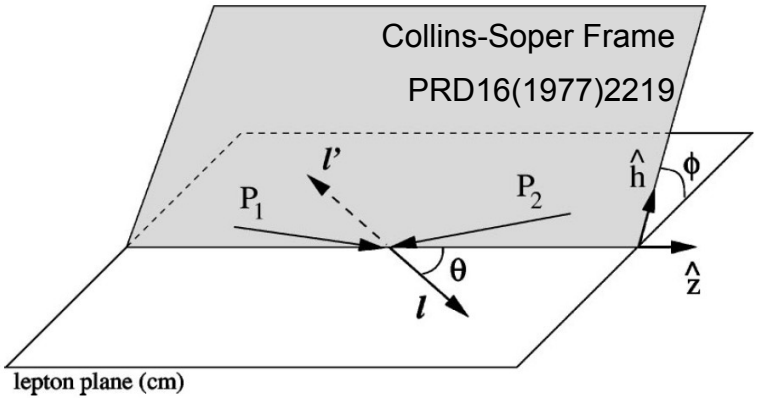
Kaon cos 2ϕ @ HERMES

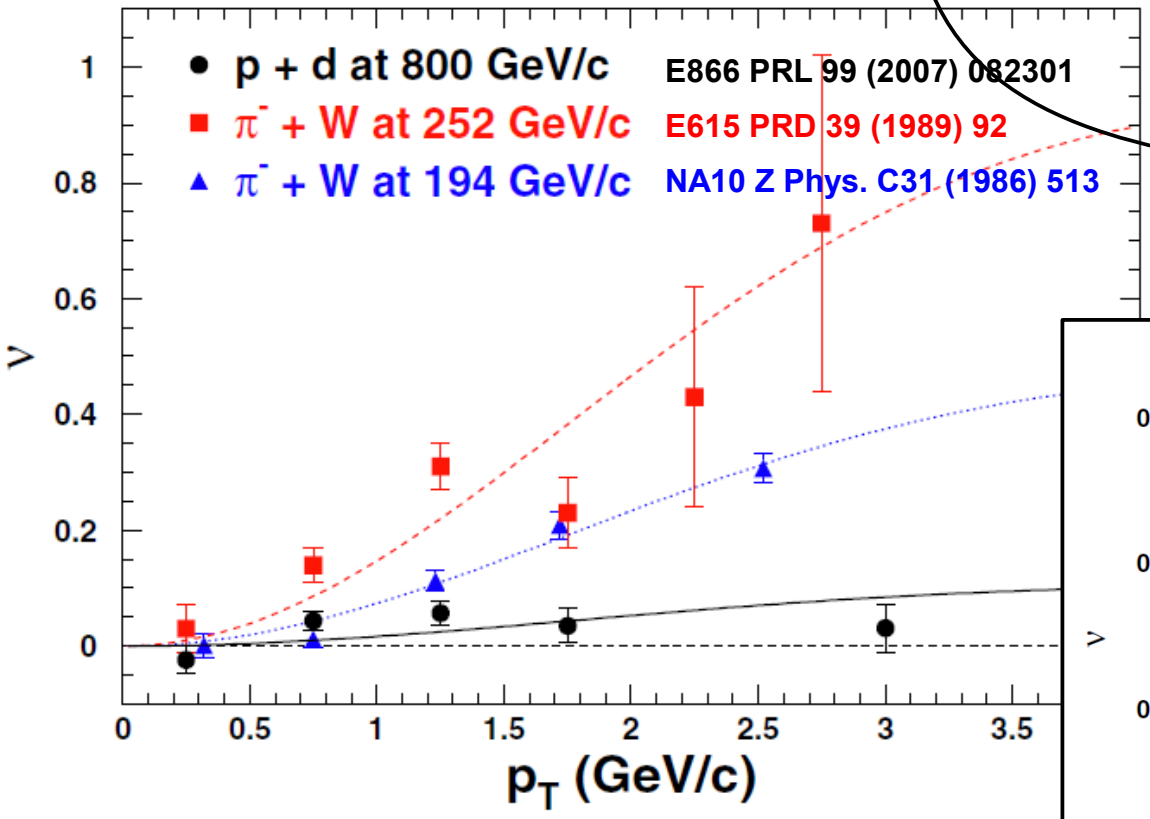


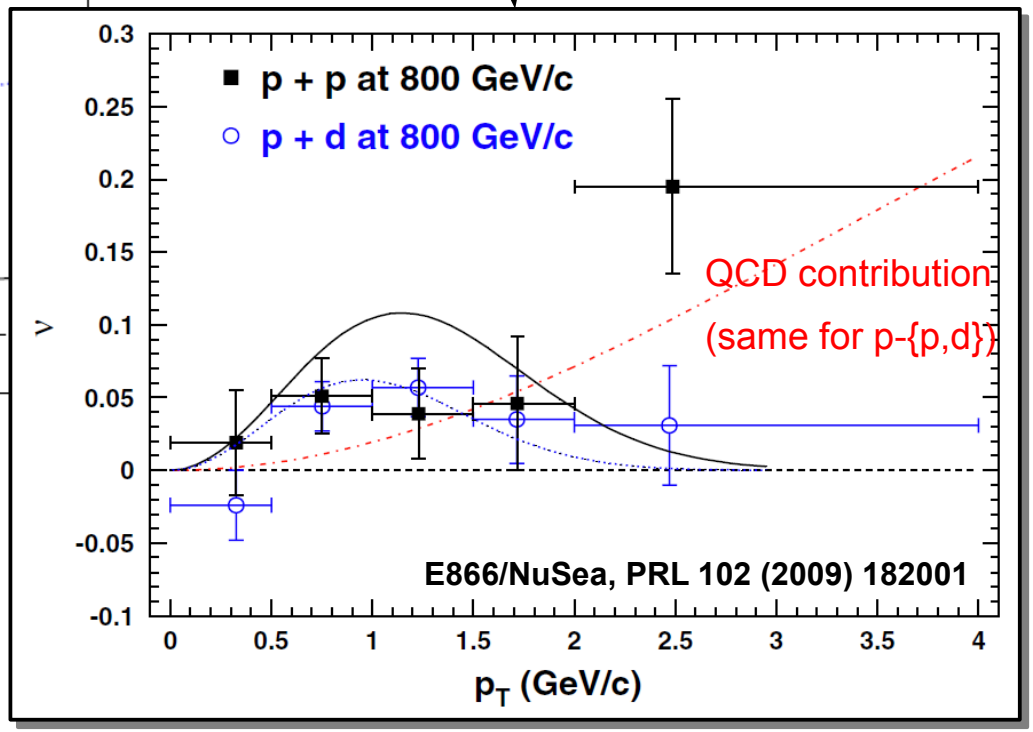
To be checked in COMPASS II

Boer-Mulders in Drell-Yan

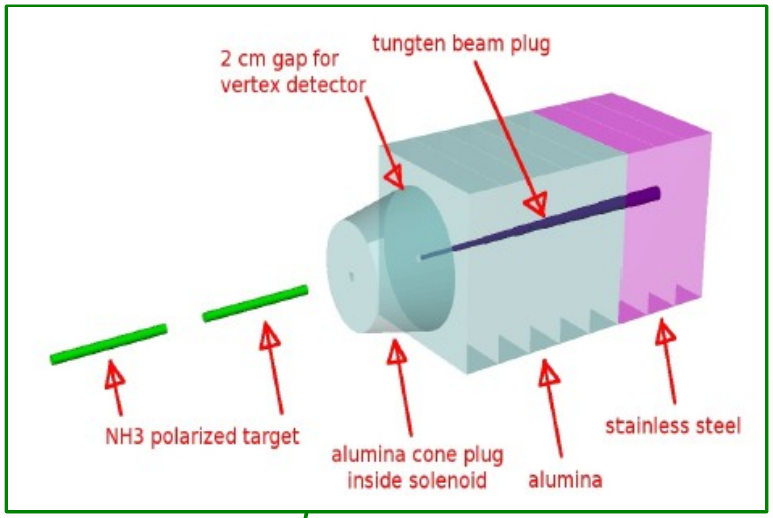
$$d\sigma \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \underbrace{\frac{\nu}{2} \sin^2\theta \cos 2\phi}$$

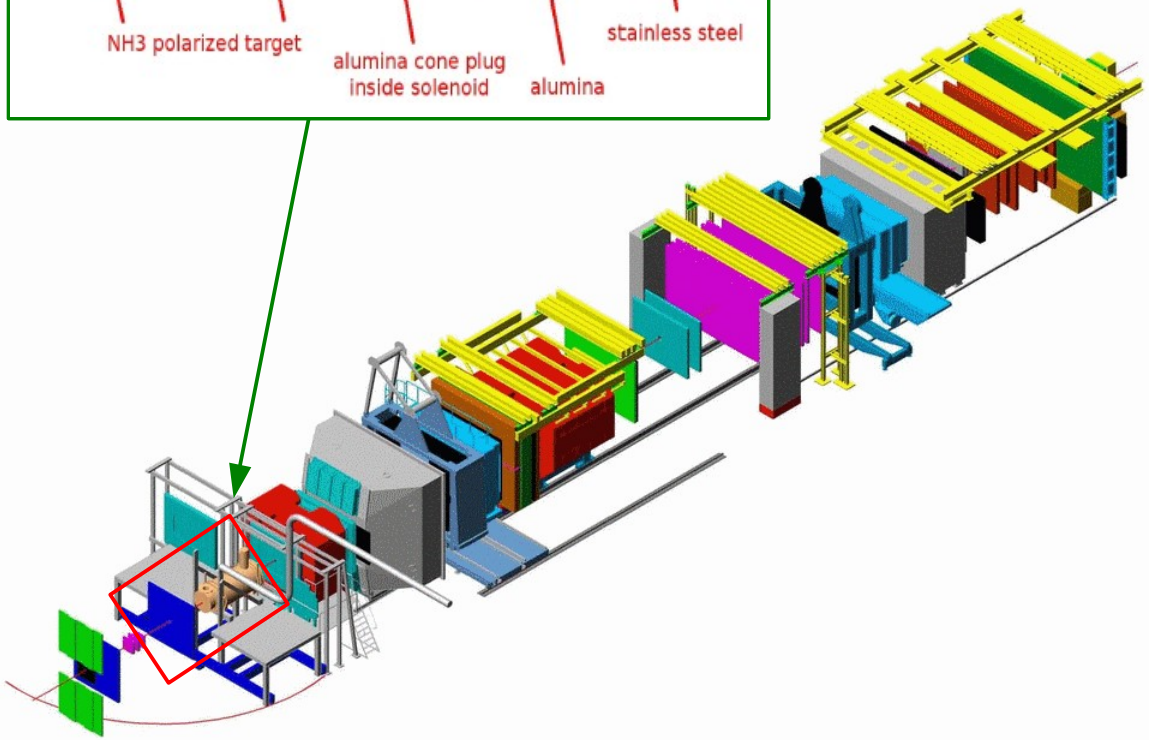






COMPASS II: Drell-Yan



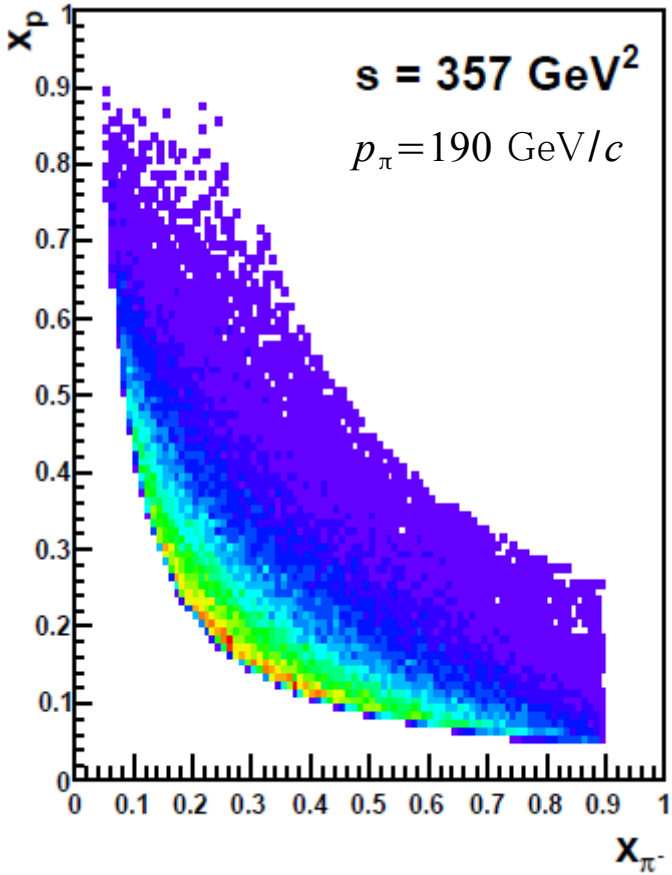


190 GeV/c pion beam

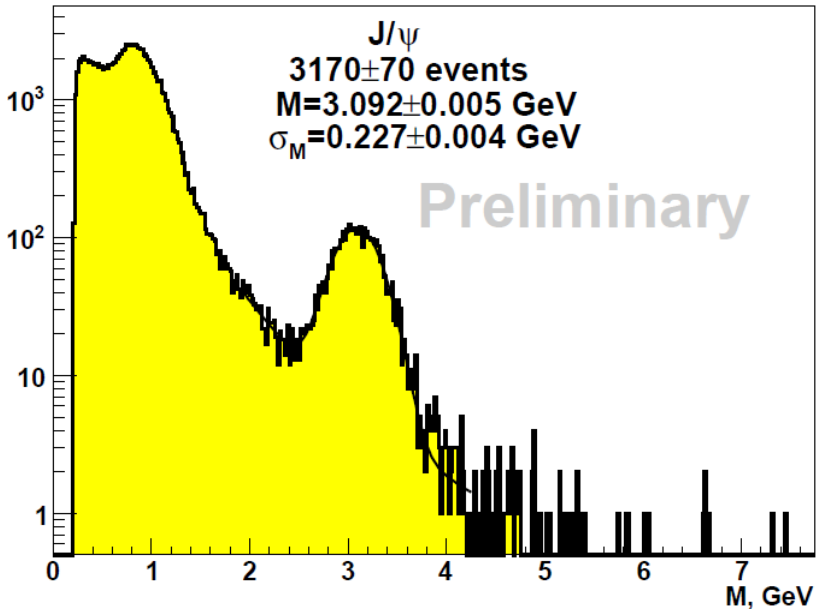
Pol. NH3

Single polarized

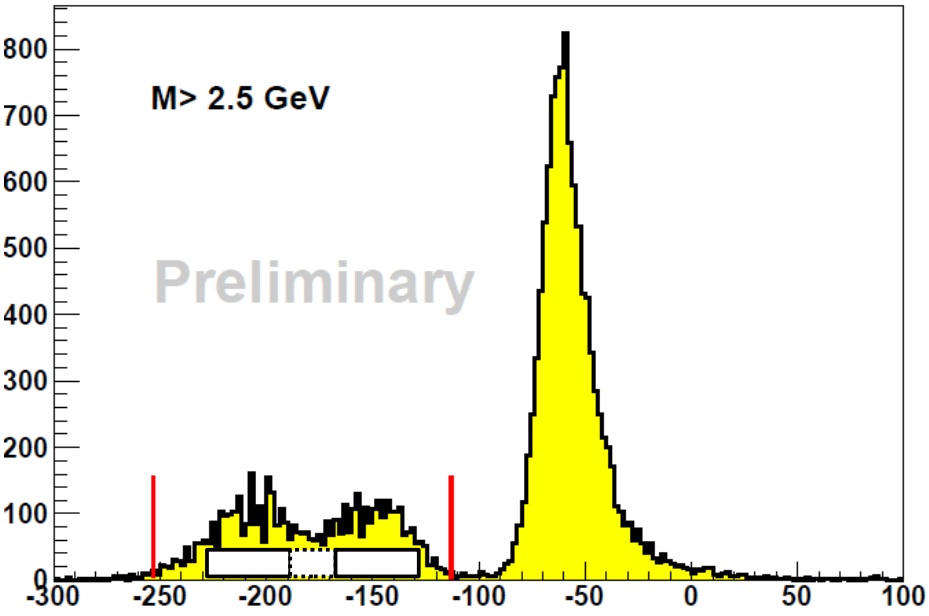
π-p Drell-Yan



The results from 2009 beam test



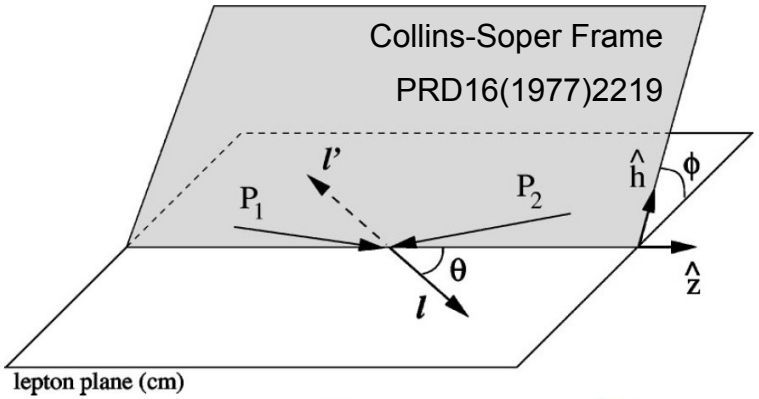
Reconstructed vertex z distribution



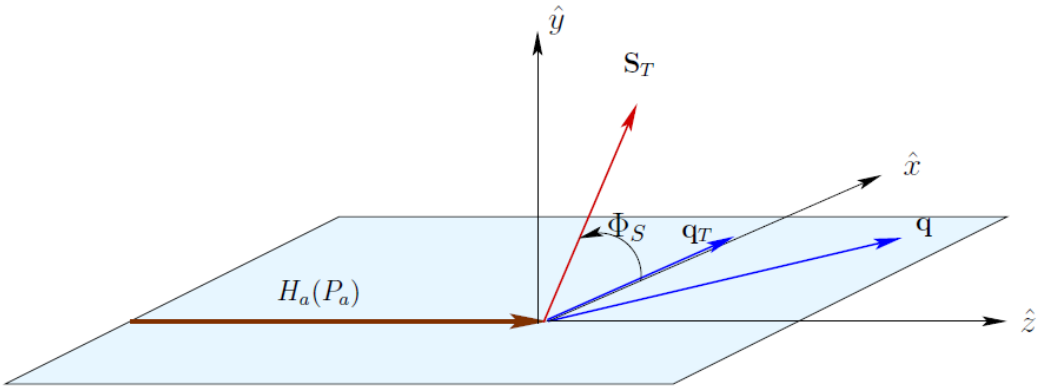
	Expected	Found
J/ψ	3600±600	3170±70
DY M>4 GeV	110±22	84±10

- 3 days of data taking
- $8 \cdot 10^7 \pi^-$/9.6 s spill
- 2 cells of CH_2 of 40-20-40 cm
- temporary absorber
- simple trigger

Single Polarized Drell-Yan cross section



+



$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\,\mathrm{d}\Omega} \overset{\mathrm{LO}}{=} \frac{\alpha_{em}^2}{F\,q^2}\hat{\sigma}_U\Big\{\Big(1 + D_{[\sin^2\theta]}\,A_U^{\cos 2\phi}\cos 2\phi\Big) + |\mathbf{S}_T|\Big[A_T^{\sin\phi_S}\sin\phi_S + D_{[\sin^2\theta]}\Big(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S) + A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\},$$

$$A_T^{\sin\phi_S} \to \left(f_1\right)_\pi \otimes \left(Sivers\right)_p$$

$$A_U^{\cos 2\phi} \to \left(BM\right)_\pi \otimes \left(BM\right)$$

$$A_T^{\sin(2\phi+\phi_S)} \to \left(BM\right)_\pi \otimes \left(Pretz.\right)_p$$

$$A_T^{\sin(2\phi-\phi_S)} \to \left(BM\right)_\pi \otimes \left(Trans.\right)_p$$

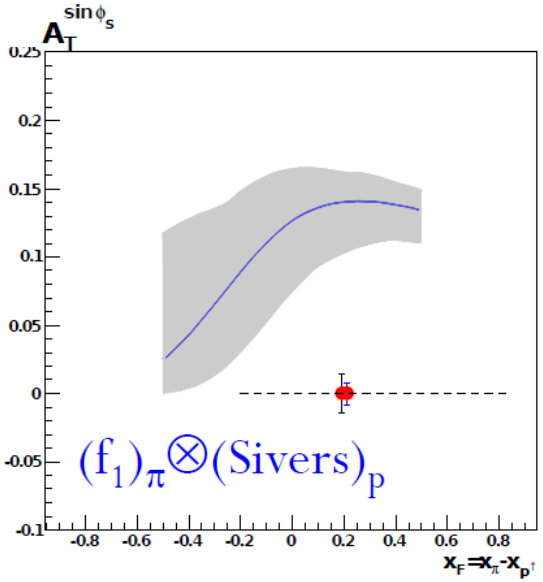
Projections for azimuthal asymmetries

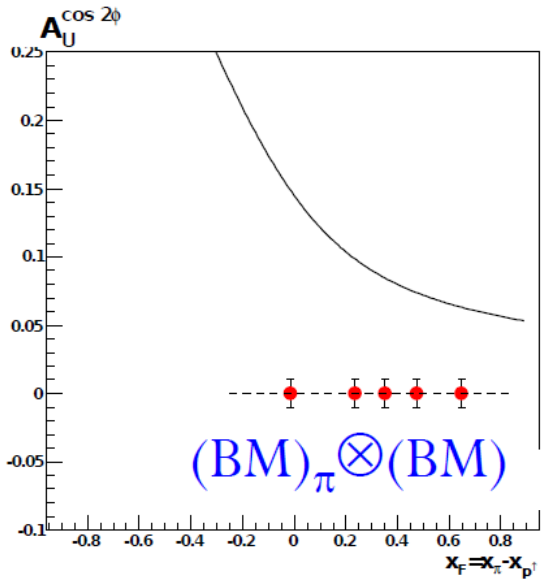
projections with
2 years of data
$6 \cdot 10^8$ π spill (9.6 s)
1.1 m pol. NH_3

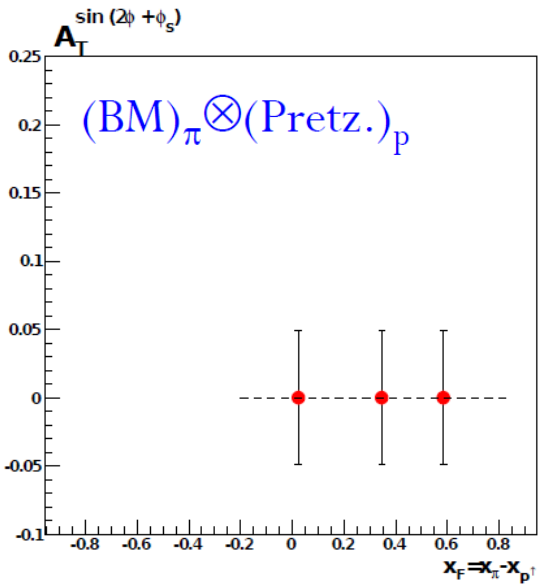
$$p_\pi = 190 \text{ GeV}/c$$

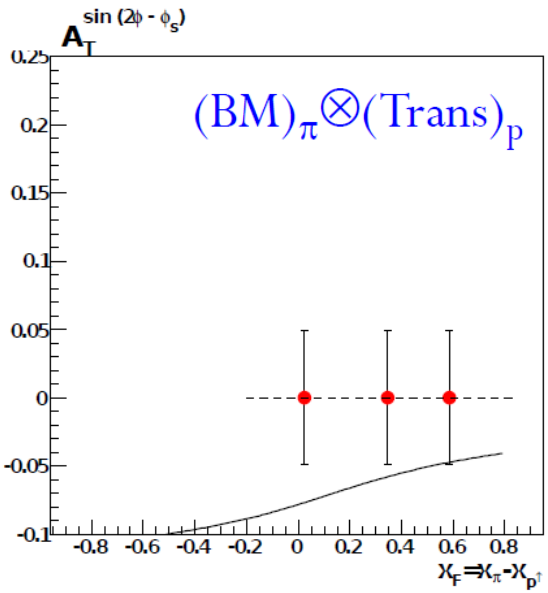
$$4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$$

Asymmetry	Dimuon mass (GeV/c^2)		
	$2 < M_{\mu\mu} < 2.5$	J/ψ region	$4 < M_{\mu\mu} < 9$
$\delta A_U^{\cos 2\phi}$	0.0020	0.0013	0.0045
$\delta A_T^{\sin \phi_S}$	0.0062	0.0040	0.0142
$\delta A_T^{\sin(2\phi+\phi_S)}$	0.0123	0.008	0.0285
$\delta A_T^{\sin(2\phi-\phi_S)}$	0.0123	0.008	0.0285









Universality of TMD

DIS

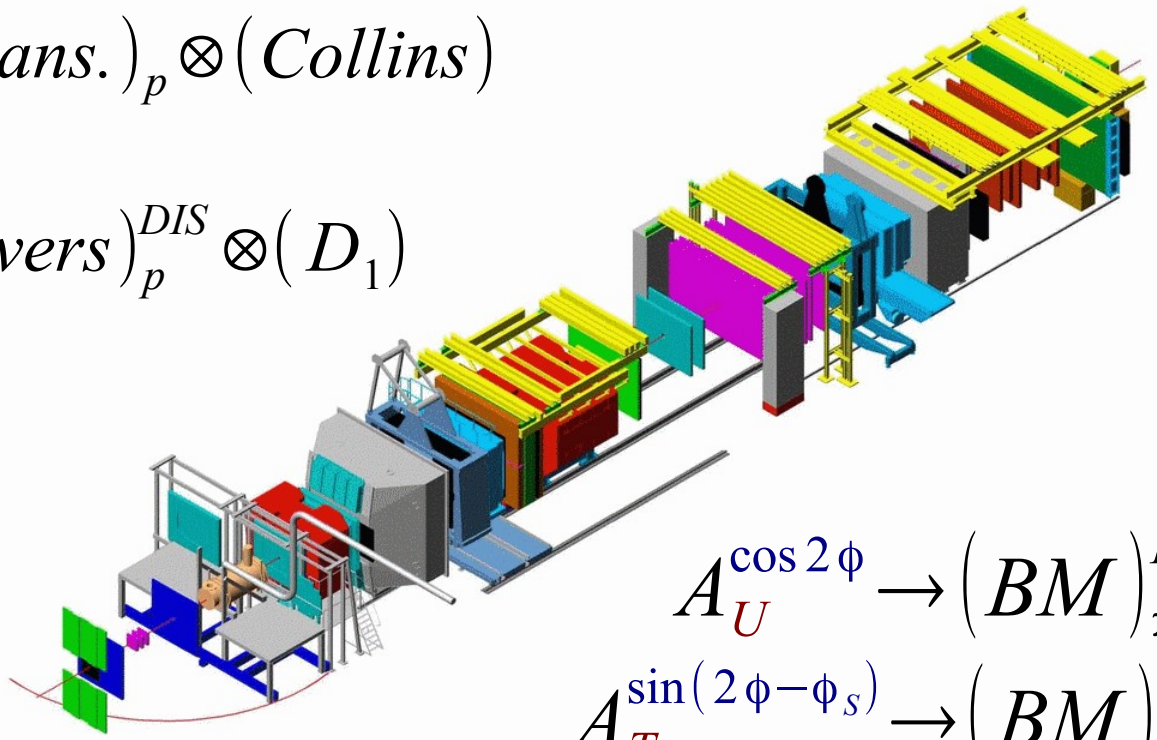
$$A_{UU}^{\cos 2\pi} \rightarrow \left(BM\right)_p^{DIS} \otimes \left(Collins\right)$$

$$A_{UT}^{\sin(\phi+\phi_S)} \rightarrow \left(Trans.\right)_p \otimes \left(Collins\right)$$

$$A_{UT}^{\sin(\phi-\phi_S)} \rightarrow \left(Sivers\right)_p^{DIS} \otimes \left(D_1\right)$$

COMPASS

Unique to measure TMD in SIDIS and DY with the same spectrometer



DY

$$A_U^{\cos 2\phi} \rightarrow \left(BM\right)_\pi^{DY} \otimes \left(BM\right)^{DY}$$

$$A_T^{\sin(2\phi-\phi_S)} \rightarrow \left(BM\right)_\pi^{DY} \otimes \left(Trans.\right)_p$$

$$A_T^{\sin\phi_S} \rightarrow \left(f_1\right)_\pi \otimes \left(Sivers\right)_p^{DY}$$

$(\text{Sivers})^{\text{DIS}} = -\ (\text{Sivers})^{\text{DY}}$

$(\text{BM})^{\text{DIS}} = -\ (\text{BM})^{\text{DY}}$?

Schedule

2012 Promakoff (18 weeks), **GPD** (6 weeks)

2013 SPS shutdown

2014 **Drell-Yan**

2015 **GPD**

2016 **GPD**

201? GPD with Pol. target...

Summary

- COMPASS has studied the proton spin structure
  - with long. and trans. polarized nucleon target
  - $\Delta\Sigma \sim 0.3$, small ΔG
  - Sivers & Collins asymmetries agree with HERMES
- COMPASS II: 2012 - 2015
  - GPD to reveal the 3D structure with DVCS, HEMP
    - SIDIS measurements will be done at the same time
      - the hadron multiplicity, Boer-Mulders
  - Pion induced polarized Drell-Yan
    - TMD: Boer-Mulders, Sivers, Pretzel., and Transversity without Fragmentation process
    - Test of the TMD universality
  - Phase 2: Pol. target and RPD: access to GPD E