Results and perspectives on TMDs and GPDs at COMPASS

Nicole d'Hose - *CEA-Saclay – France*
on behalf of the COMPASS Collaboration

COMPASS: a Facility to study QCD

a fixed target experiment at the CERN SPS

~ 250 physicists from 24 Institutions of 13 Countries

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY

Hadron Spectroscopy & **Test of ChPT** with **π, K, p** beams on nuclei **2008-9-12**

Nucleon Structure

SIDIS with **μ** beams with Long or Trans. Polarized Targets

Long. and Transv. Spin structure

↳ **TMDs**

	Polar. Deuteron (Li^6D)	Polar. Proton (NH_3)
Long.	**2002-3-4-6**	**2007-11**
Transv.	**2002-3-4**	**2007-10**

Drell-Yan with **π** beams with Transv. Pol. NH_3 target

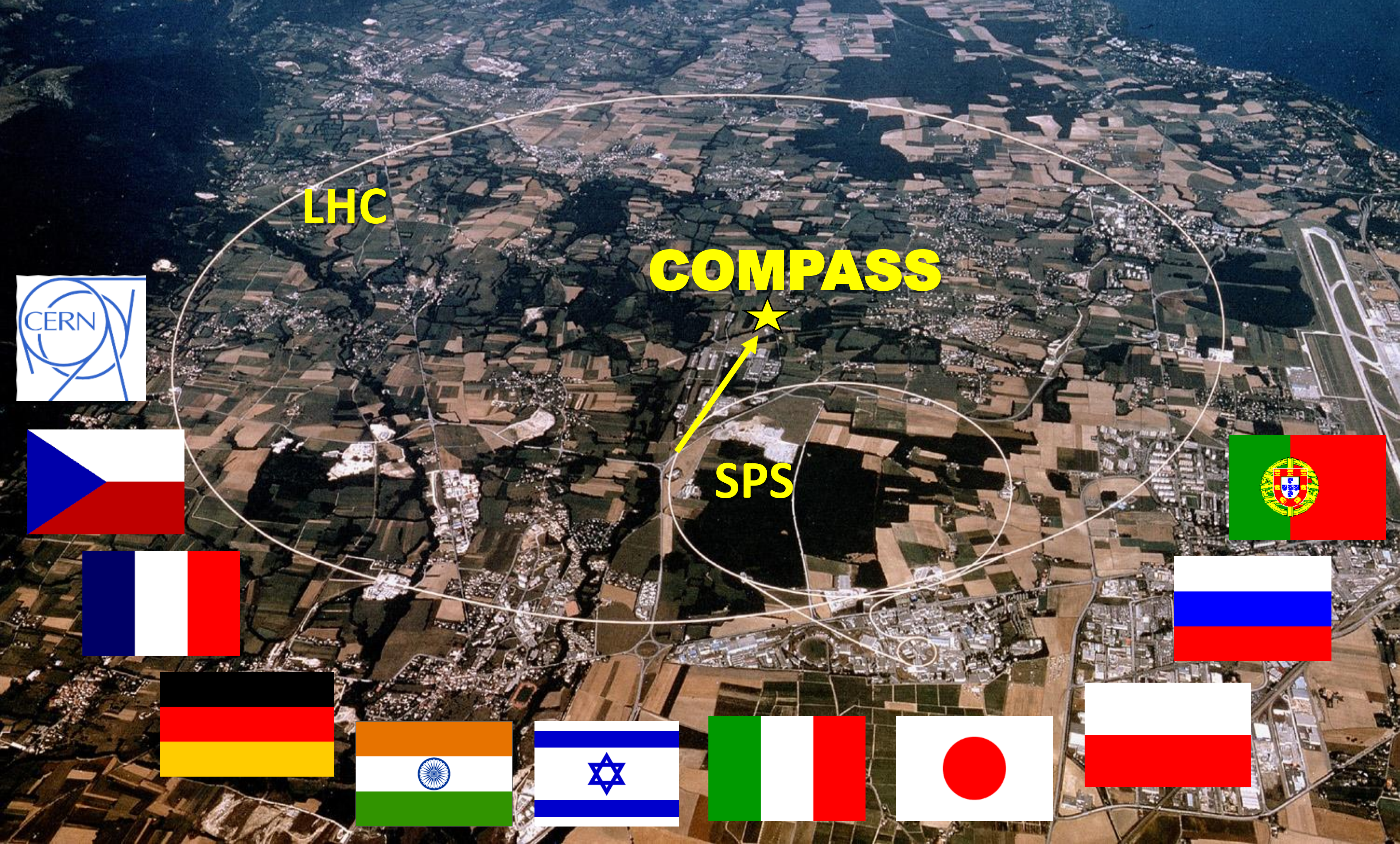
TMDs **2009-2012** (tests) and **2014-15**

Exclusive DVCS & DVMP (+SIDIS) with **μ** beams with LH_2 target

↳ **GPDs (+ TMDs)** **2009-2012** (tests) and **2016-17**

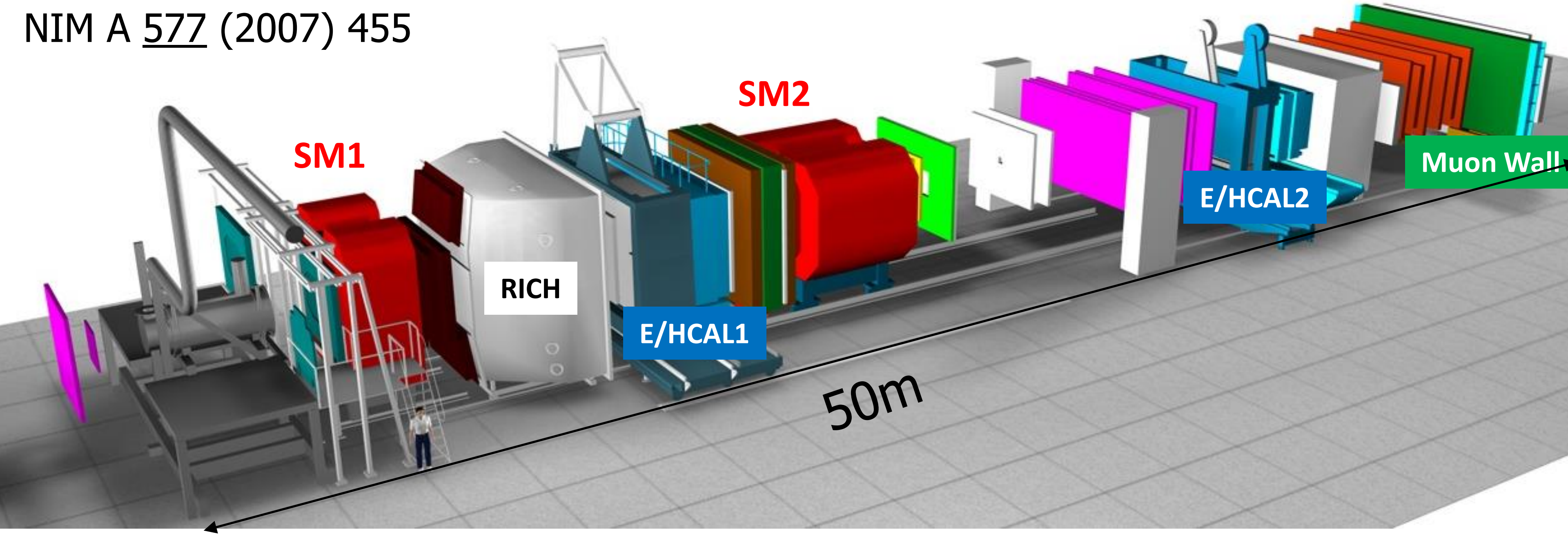
S. Paul (Monday), J.M. Friedrich (Tuesday), J. Bernhard (Wednesday)
K. Klimaneszewski (Monday), G. Sbrizzai (Tuesday), M. Quaresma (Tuesday), W.-D. Nowak (Wednesday)

COMPASS: Versatile facility with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) & lepton (polarized $\mu^{\pm}$) beams of high energy ~200 GeV



The COMPASS setup at CERN

NIM A 577 (2007) 455



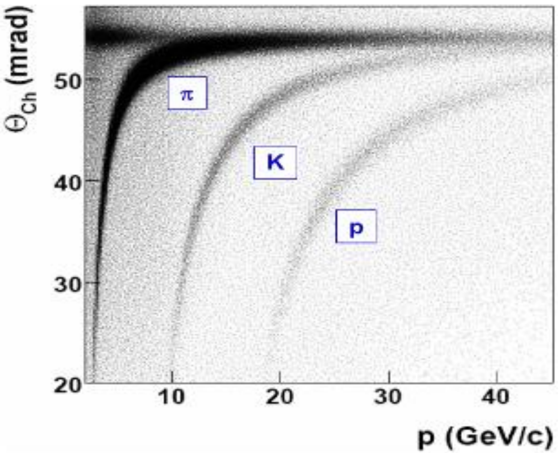
Two stage magnetic spectrometer for **large angular** & **momentum acceptance**

Variety of tracking detectors to cope with all particles from $\theta = 0$ to $\theta \approx 200$mrad

Trackers as SciFi, Silicon, Micromegas, GEM, large DC, Straw, MWPC

Particle identification with:

- Ring Imaging Cerenkov Counter
- Electromagnetic and Hadronic calorimeters
- Hadron absorbers

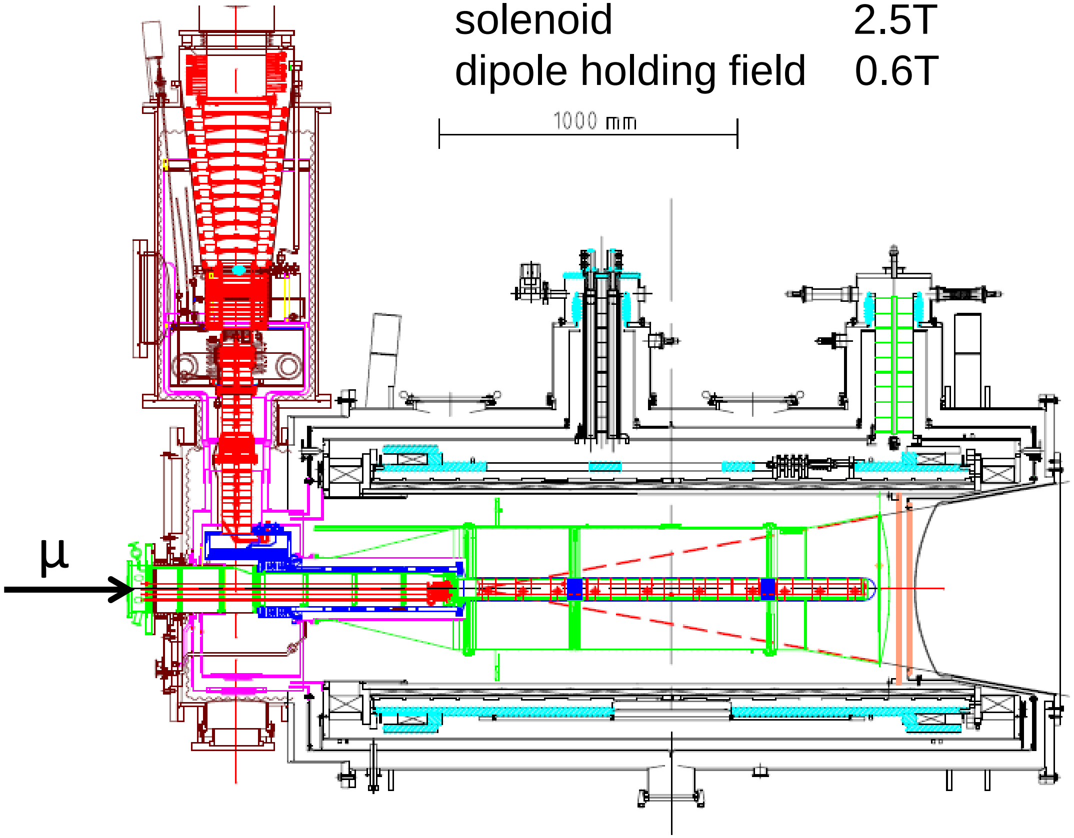


The COMPASS polarized target

solid state target operated in frozen spin mode

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

solenoid 2.5T
dipole holding field 0.6T



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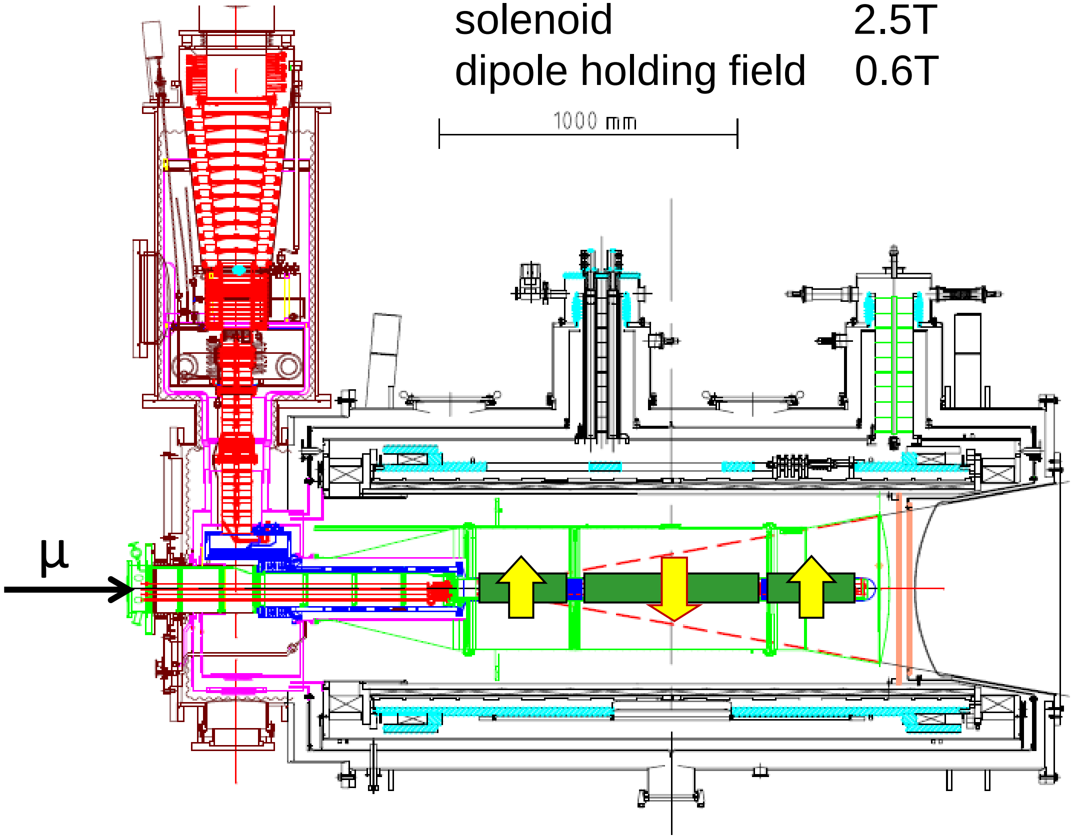

(After 2005)
3 target cells
of 30, 60, 30 cm
with opposite polarization

The COMPASS polarized target

solid state target operated in frozen spin mode

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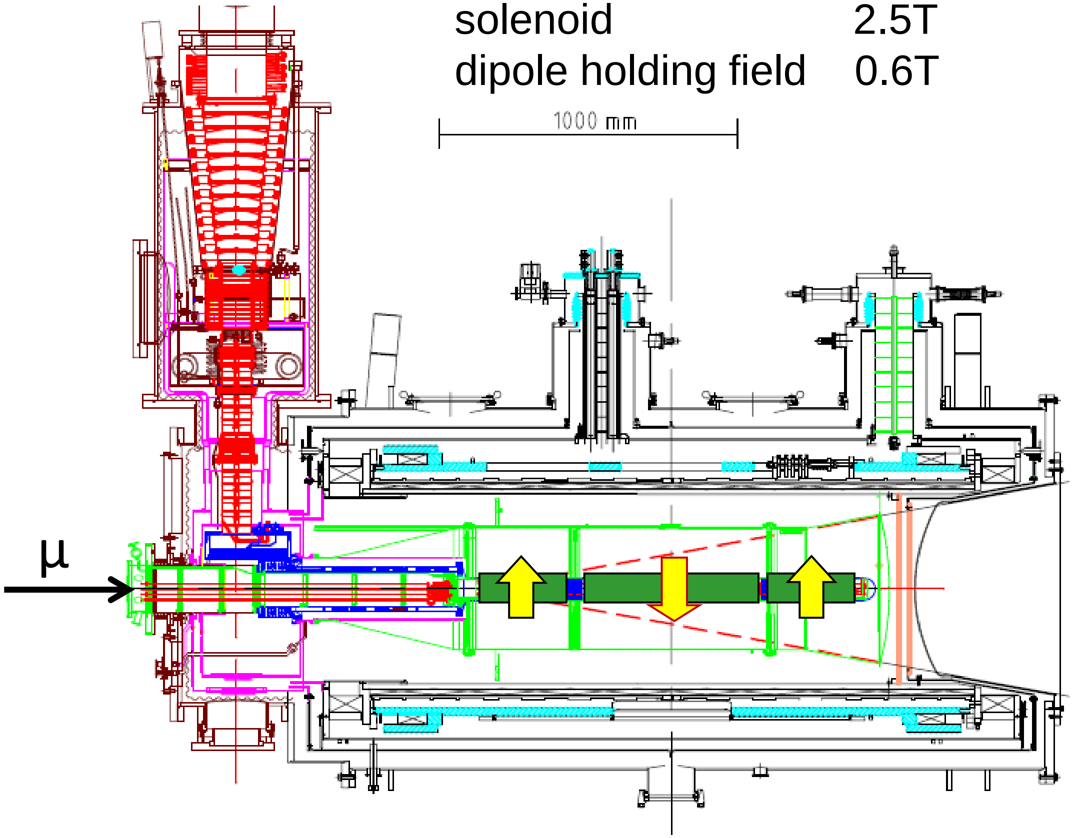
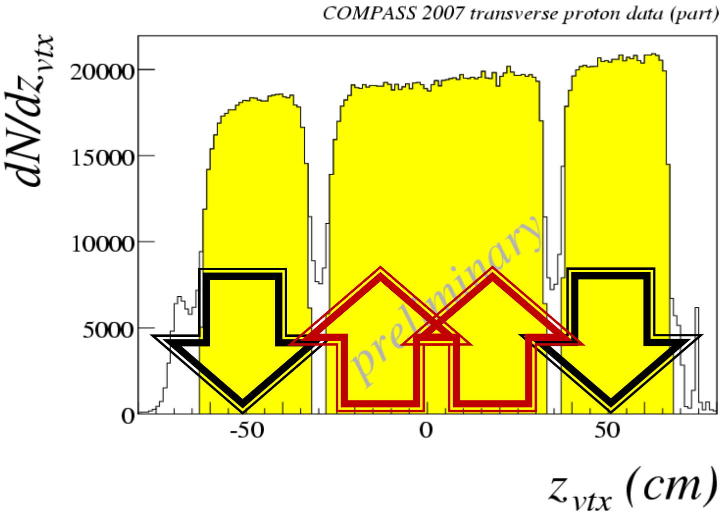
dipole holding field	0.6T





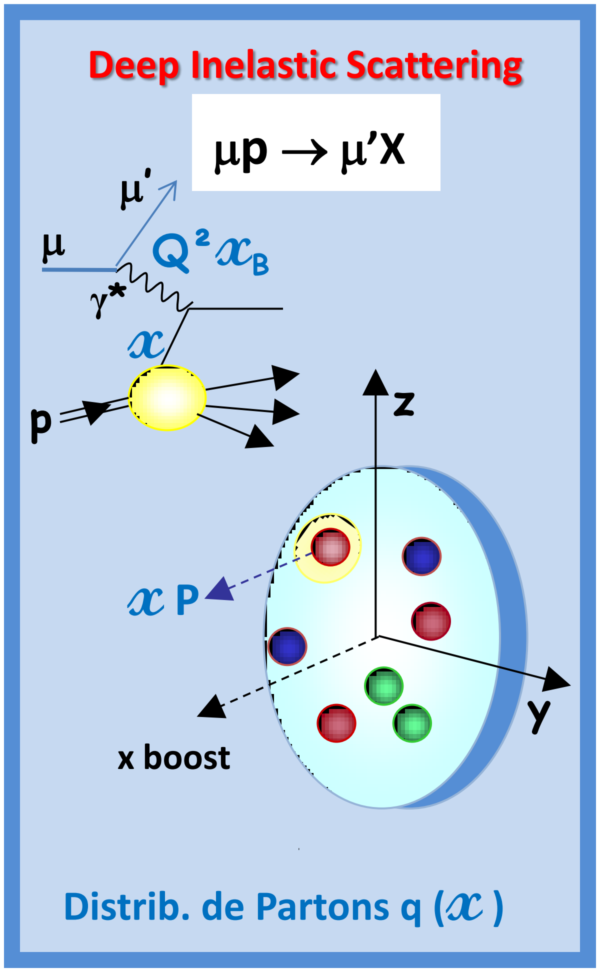
	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
dilution factor	40%	16%

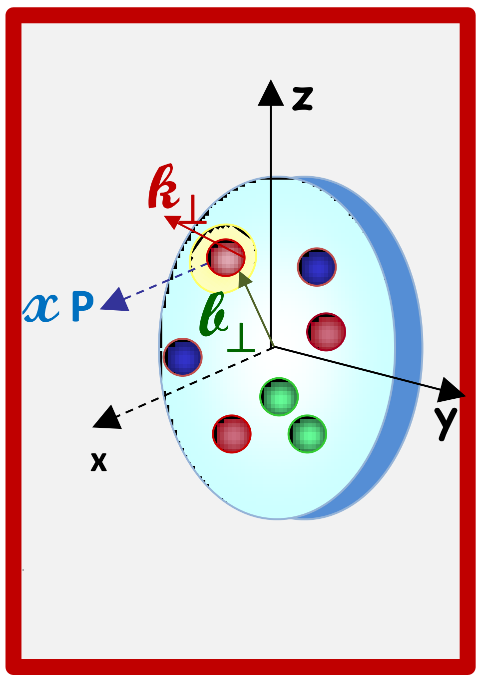
From PDFs to TMDs and GPDs

To reconstruct the **3-dimensional nucleon structure** in momentum and configuration space,

GPD $(x, b_\perp)$: Generalised Parton Distribution
(position in the transverse plane)

TMD $(x, k_\perp)$:Transverse Momentum Distribution
(momentum in the transv. plane)



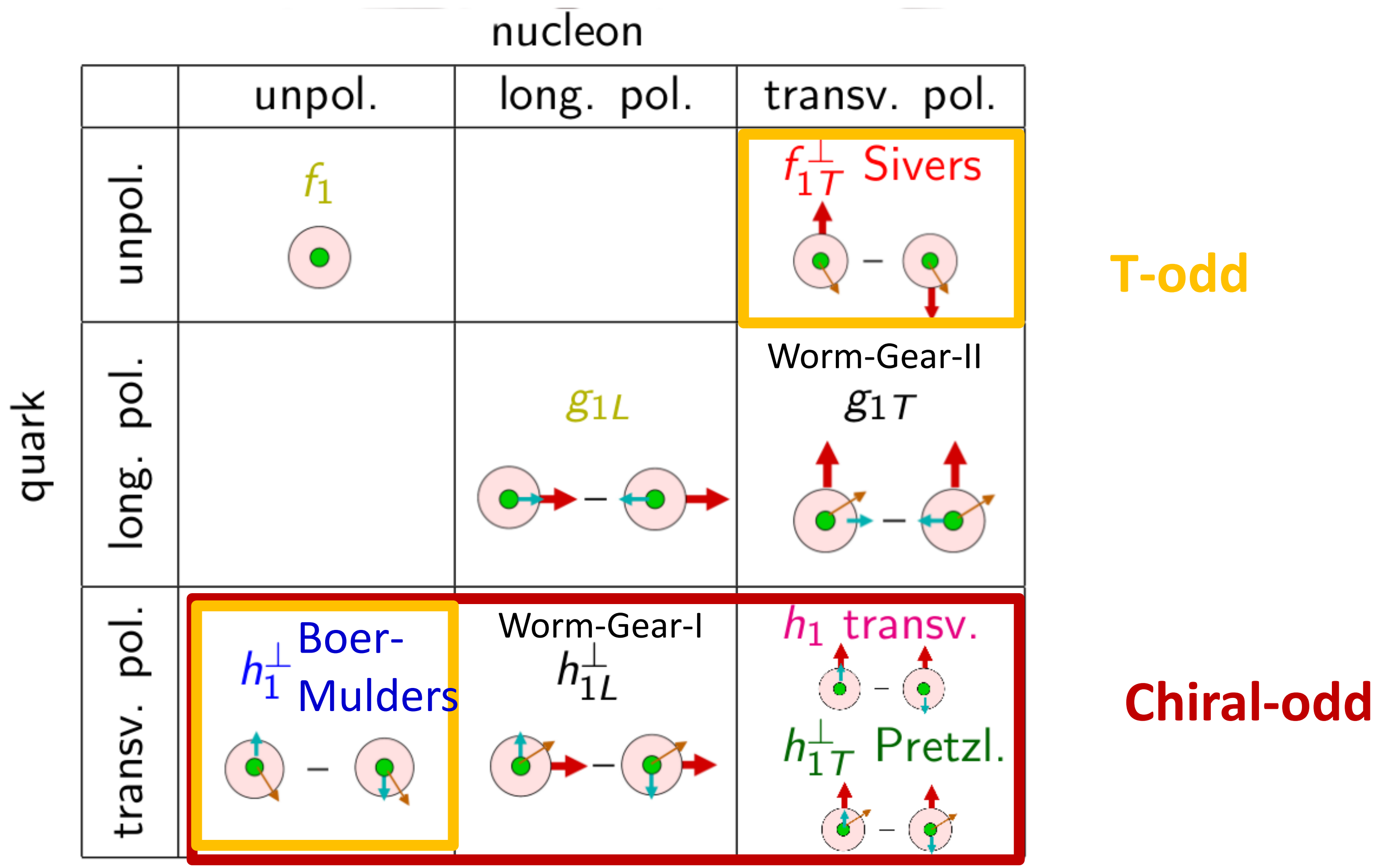


TMD accessible in **SIDIS** and **DY**

GPD in **Exclusive reactions**
DVCS and **DVMP**

Transverse Momentum Dependent PDFs

At leading twist, not only $f_1(x, k_T)$, $g_{1L}(x, k_T)$, $h_1(x, k_T)$
but also 5 **other Transverse Momentum Dependent PDF** or **TMD (x, k_T)**
which do not survive after integration on k_T



SIDIS $\ell\, p^{\uparrow} \rightarrow \ell\, p\, h^{\pm}$ and azimuthal asymmetries

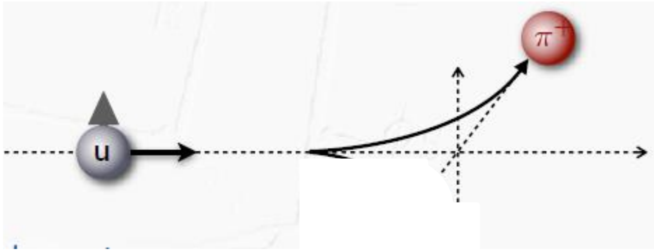
The **transversity** h_1

measures the diff. of density of quarks with spin // and anti// to the transverse spin of the nucleon

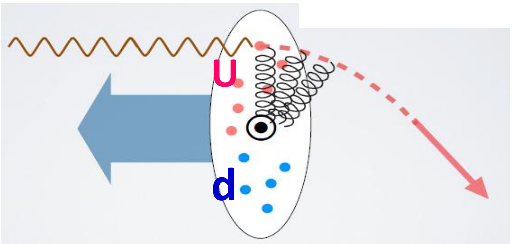
The **Sivers** $f_{1T}^{\perp}$ PDF

correlates the quark k_T and the nucleon transv . spin

Chiral-odd ➔ necessity of the **Collins** FF: $H_{1q}^{\perp}$



Chiral-even and T-odd



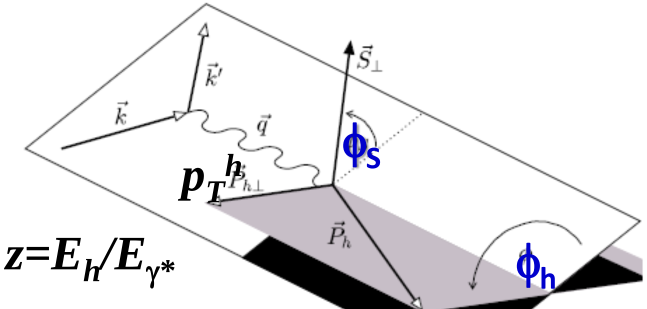
OAM
FSI

$$A_{Coll} \approx \frac{\sum_q e_q^2\, h_1^q(x) \otimes H_{1q}^{\perp h}(z, p_T^h)}{\sum_q e_q^2\, f_1^q(x) \otimes D_{1q}^h(z, p_T^h)}$$

$$A_{Siv} \approx \frac{\sum_q e_q^2\, f_{1T}^{\perp q}(x) \otimes D_{1q}^h(z, p_T^h)}{\sum_q e_q^2\, f_1^q(x) \otimes D_{1q}^h(z, p_T^h)}$$

Collins asymmetry

in sin ($\phi_h+\phi_S-\pi$)



$z=E_h/E_{\gamma*}$

Sivers asymmetry

in sin ($\phi_h-\phi_S$)

The SIDIS cross section

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

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

Boer-Mulders (+Cahn) unpolarized asymmetry

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

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

Sivers asymmetry

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

Collins asymmetry

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

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

Worm-Gear-II asymmetry

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

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

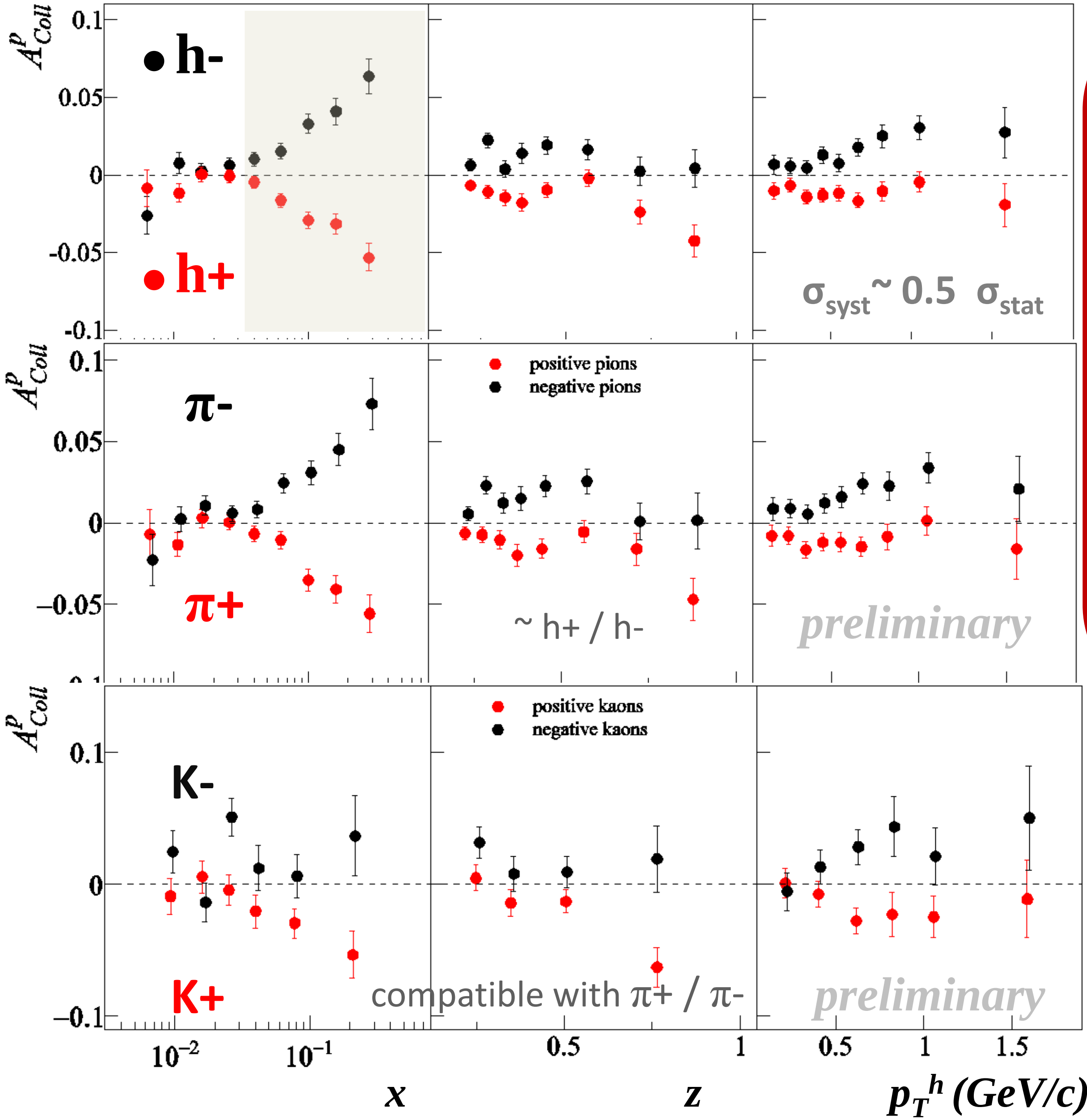
18 structure functions

14=3(u)+3(L)+8(T) indepdt azimuthal modulations

all the 14 amplitudes are being measured in COMPASS

With a transversely polarized target A_{Coll} and A_{Siv} and the 6 other transv. spin asymmetries are measured by fitting the (ϕ_h,ϕ_S) distributions in the different x, z, p_T^h bins

Collins asymmetries on the proton



Charged hadrons:

combined 2007 and 2010 results

2007: PLB 692 (2010) 240

2010: PLB 717 (2012) 376

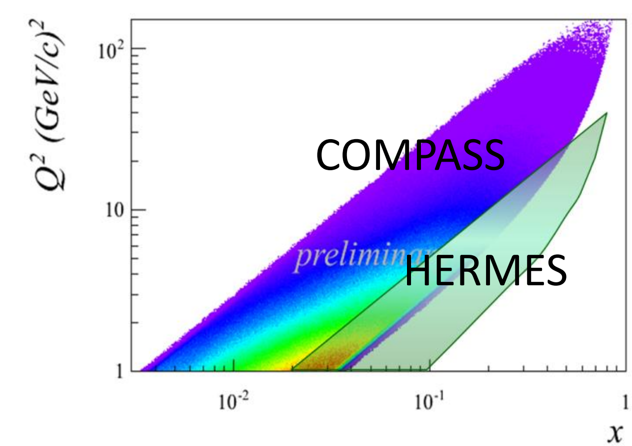
very good agreement between the two independent data sets

Precise measurement

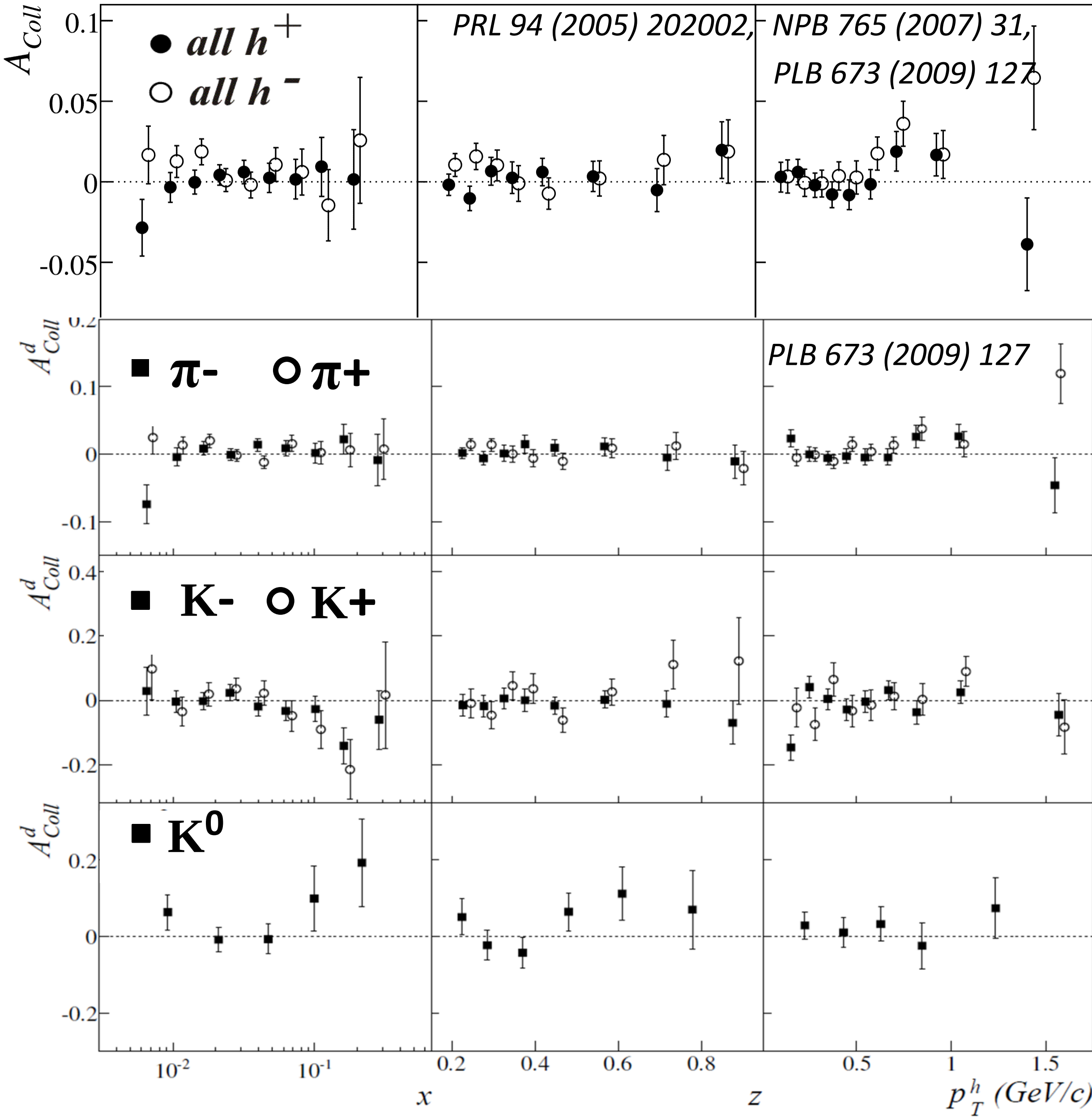
Clear signal at x>0.03, with opposite sign for h+ and h-

Compatibility for x>0.03 between COMPASS & HERMES

No strong Q^2 dependence



Collins asymmetries on the deuteron



Charged hadrons
2002-2003-2004 data

Charged π, K and neutral K^0
2003-2004 data

The only existing data

Asymmetries compatible with 0
understood as u - d cancellation

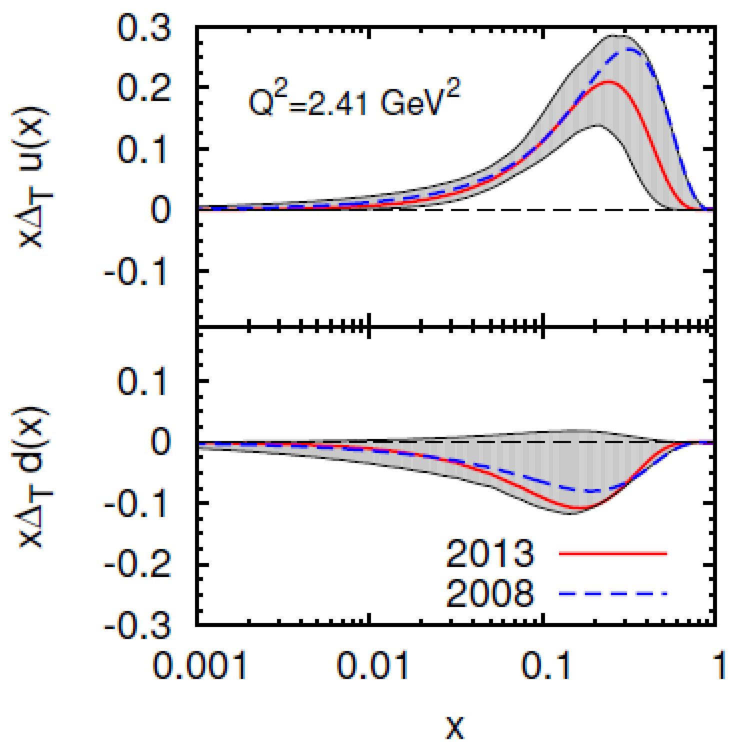
Transversity and Collins FF

Global fit from Anselmino at al., arXiv:1303.3822

Using HERMES p, COMPASS p and d, Belle e+e- data

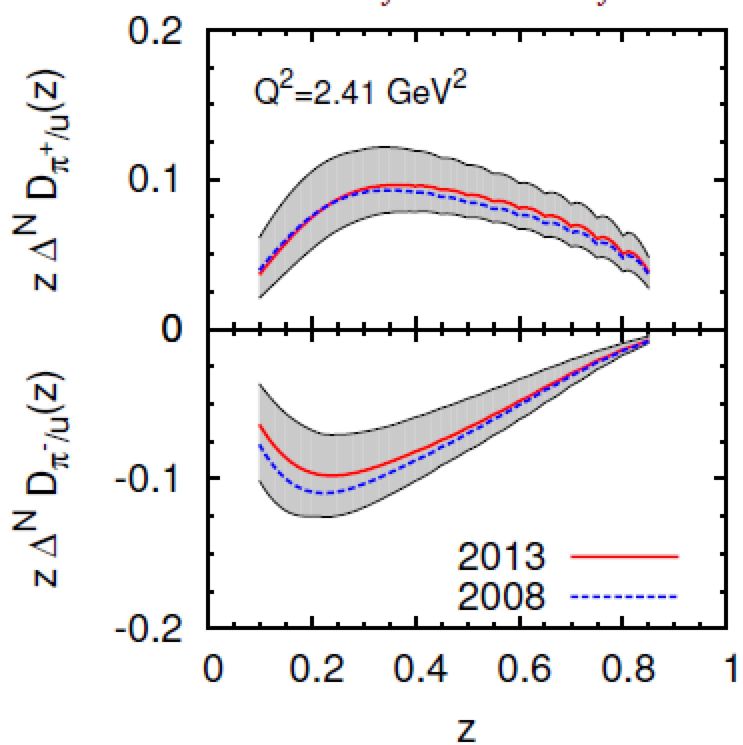
Assuming independent measurements in x, z, p_T^h

Transversity functions h_1^u **and** h_1^d

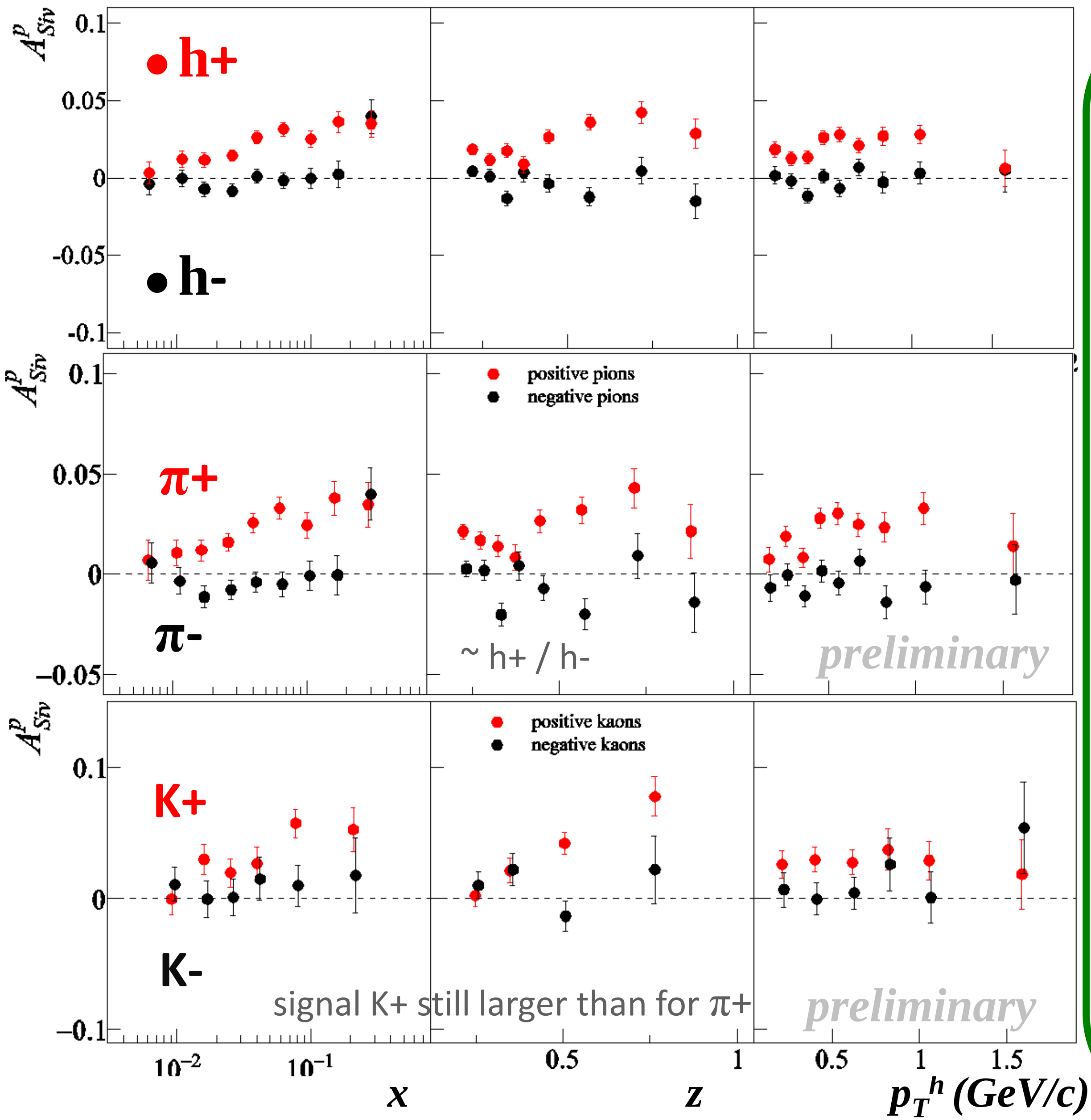


Favoured and Unfavoured Collins FF

$$H_{1\,unf}^{\perp q} \simeq -H_{1\,fav}^{\perp q}$$



Sivers asymmetries on the proton



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Results on HEPDATA

For h+, π+, K+:

- **Clear signal down to low x** in the previously unmeasured region
- In the region of overlap, agreement with HERMES **but clear indication that the strengh decreases.**

Q^2 dependence?

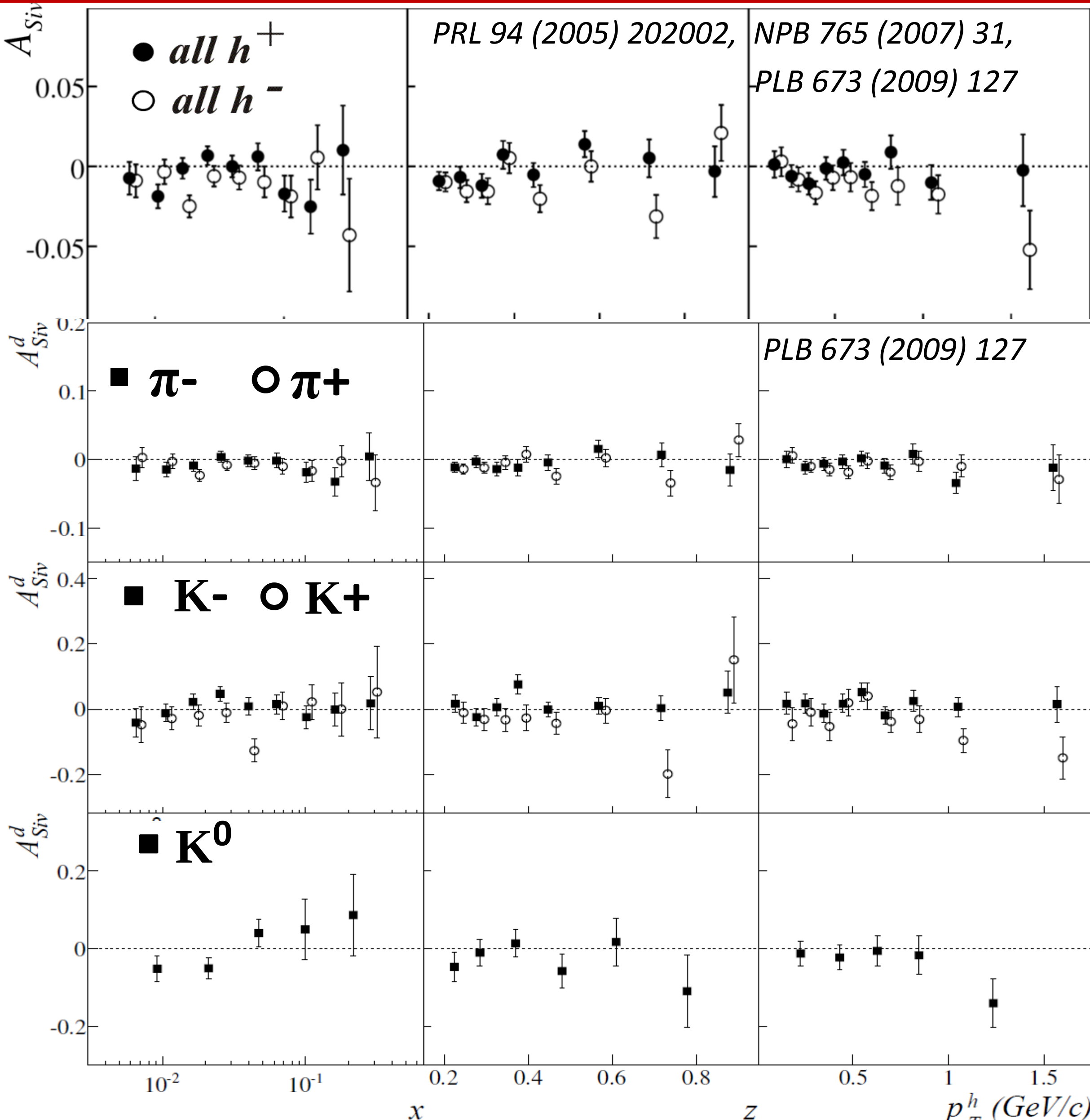
Large theoretical activities:

Aybat, Produkin, Rogers: PRL108 (2012)

Anselmino, Boglione, Melis: 2012): arXiv:1204.1239

Sun, Yuan (2013): arXiv:201308. 5003

Sivers asymmetries on the deuteron



Charged hadrons
2002-2003-2004 data

Charged π, K and neutral K^0
2003-2004 data

The only existing data

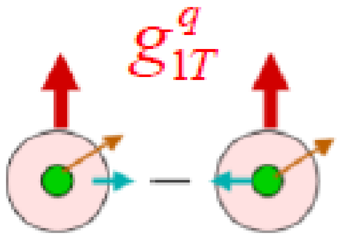
Asymmetries compatible with 0
understood as u - d cancellation

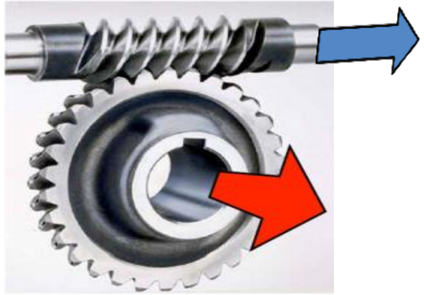
beyond 'Collins and Sivers' transverse spin asymmetries

$A_{UT}^{\sin(3\varphi_h-\varphi_s)}$, $A_{UT}^{\sin\varphi_s}$, $A_{UT}^{\sin(3\varphi_h-\varphi_s)}$, $A_{LT}^{\cos(\varphi_h-\varphi_s)}$, $A_{LT}^{\cos\varphi_s}$ & $A_{LT}^{\cos(2\varphi_h-\varphi_s)}$

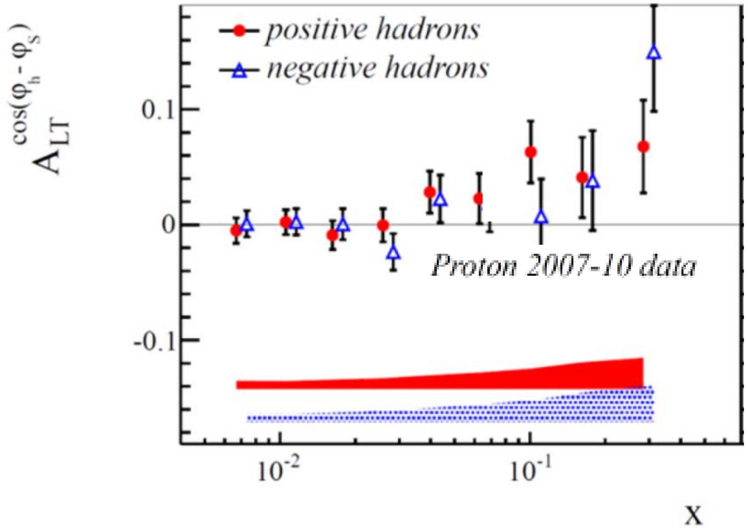
Non –zero Worm-Gear-II

$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$





Transv. Pol. of the nucleon
Longit. Pol. of the quark



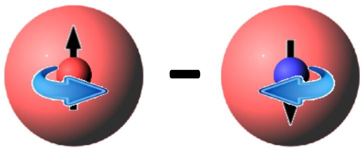
Agreement with theoretical predictions

A. Kotzinian, B. Parsamyan, A. Prokudin Phys.Rev.D73:114017 (2006)
S. Boffi, A.V. Efremov, B. Pasquini and P. Schweitzer PRD79:094012(2009)

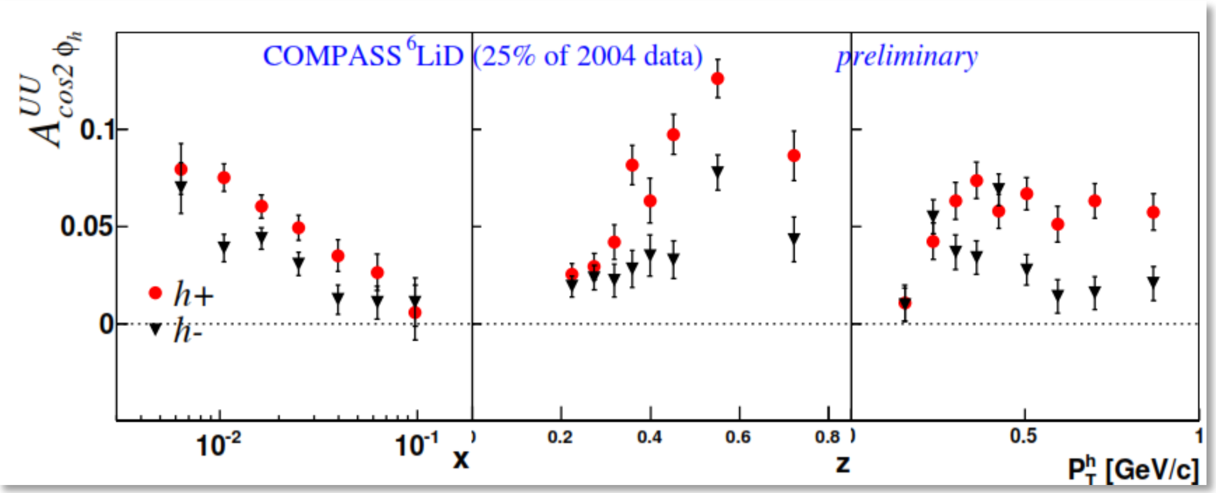
with unpolarized asymmetries

$$A^{UU}_{\cos 2\phi_h} = \mathrm{BM} + \frac{1}{Q^2}\,\mathrm{Cahn}$$

Boer-Mulders (T-odd and Chiral odd)



Cahn effect: kinematic effect proportional to the quark k_T



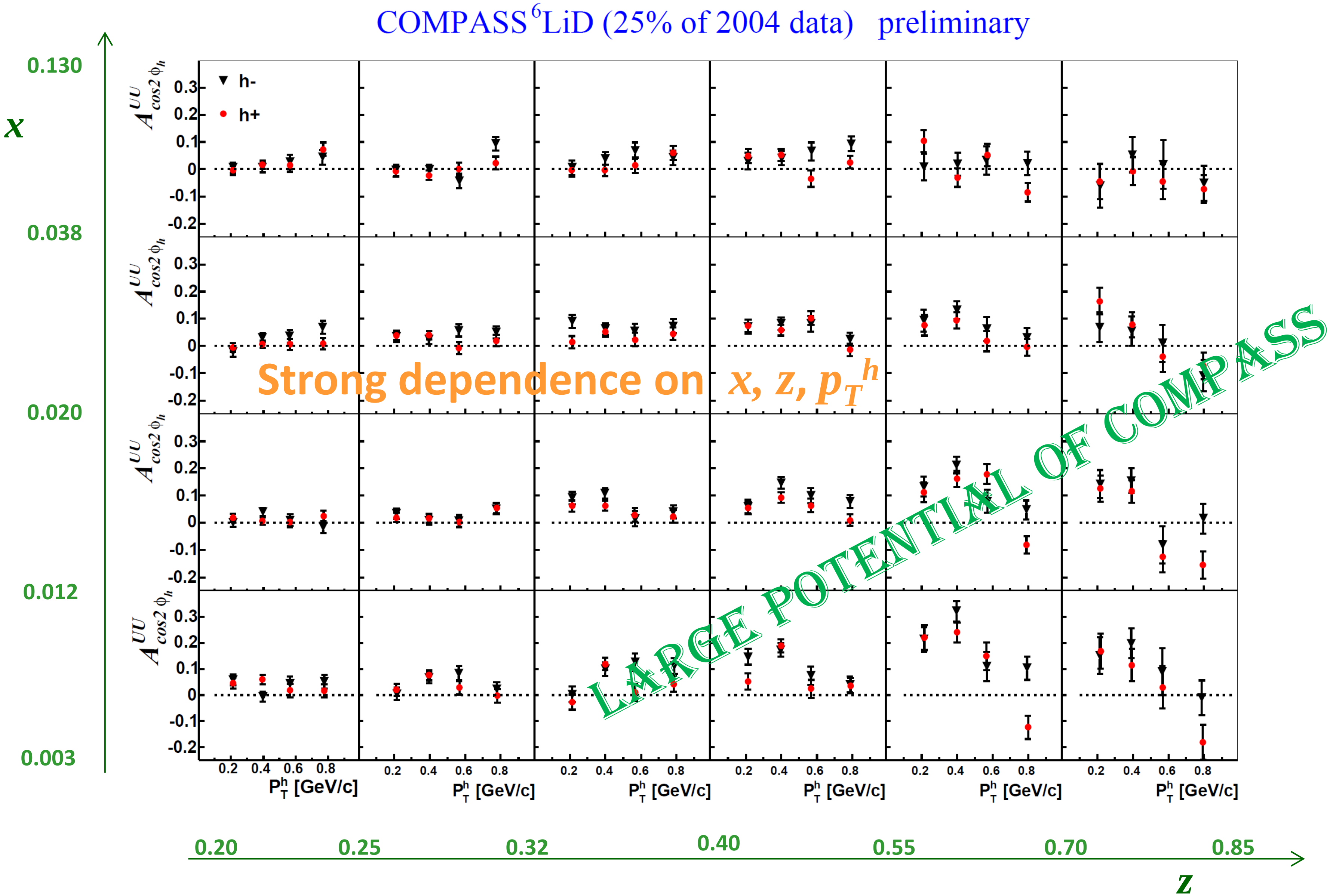
Large signal at small x

Different effect for h+ and h-

Strong dependence on x, z, $p_T{}^h$

Not well understood theoretically

with unpolarized asymmetries



SIDIS perspectives

Soon:

Multidimensional analysis in (x, z, p_T^h)

for of Collins and Sivers with **trans. polarized μ p↑**

for **Multiplicities** and Azimuthal asymmetries with **unpolarized μ d**

In few years 2016-17:

Precise Measurements with **unpolarized μ p** (in // with DVCS)

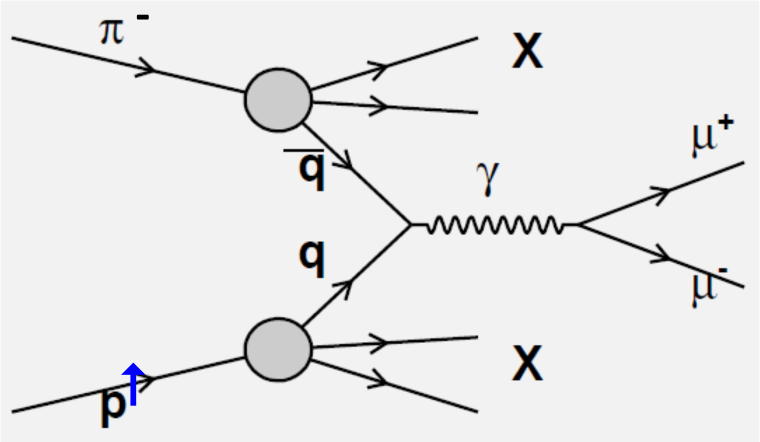
Later on:

Precise Measurements with **transversely polarized μ d**?

See Giulio Sbrizzai: Measurement of TMD observables at COMPASS (Nucleon Structure III on Tuesday at 14:30)

Alternatively, polarized Drell-Yan to study TMDs

Drell –Yan **$\pi^- p^\uparrow \rightarrow \mu^+\mu^- X$**



Cross sections:

In SIDIS: convolution of a TMD with a fragmentation function

In DY: convolution of 2 TMDs

the simplest: negative pion + proton $\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|p}$

the best: anti-proton + proton (investigation for the future)

→ SIDIS/DY: complementary information and universality test

The polarized Drell-Yan process in $\pi^- p$

$$
\begin{aligned}
d\sigma^{DY} \propto & \Big(1+\int d^2k_{1T}\, d^2k_{2T}\, \mathcal{W}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2)\otimes h_1^{\perp}(x_2,k_{2T}^2)\cos 2\phi \Big)\\
& +|S_T|\Big(\int d^2k_{1T}\, d^2k_{2T}\, \mathcal{X}(k_{1T},k_{2T})\, \bar{f}_1(x_1,k_{1T}^2)\otimes f_{1T}^{\perp}(x_2,k_{2T}^2)\sin\phi_S\\
& +\int d^2k_{1T}\, d^2k_{2T}\, \mathcal{Y}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2)\otimes h_{1T}^{\perp}(x_2,k_{2T}^2)\sin(2\phi+\phi_S)\\
& +\int d^2k_{1T}\, d^2k_{2T}\, \mathcal{Z}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2)\otimes h_1(x_2,k_{2T}^2)\sin(2\phi-\phi_S)\Big)
\end{aligned}
$$

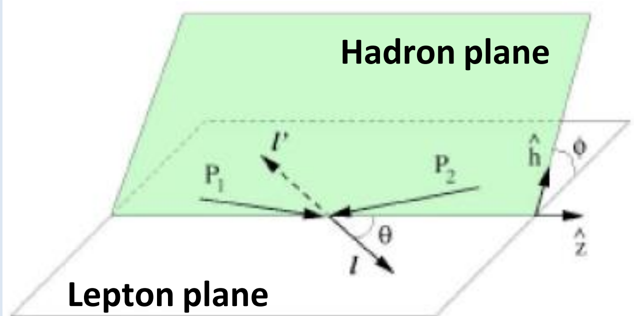
➔ Access to TMDs for incoming pion $\otimes$ target nucleon
TMD as Transversity, Sivers, Boer-Mulders, pretzelosity

Collins-Soper frame (of virtual photon)

θ, ϕ lepton plane wrt hadron plane

target rest frame

ϕ_S target transverse spin vector /virtual photon

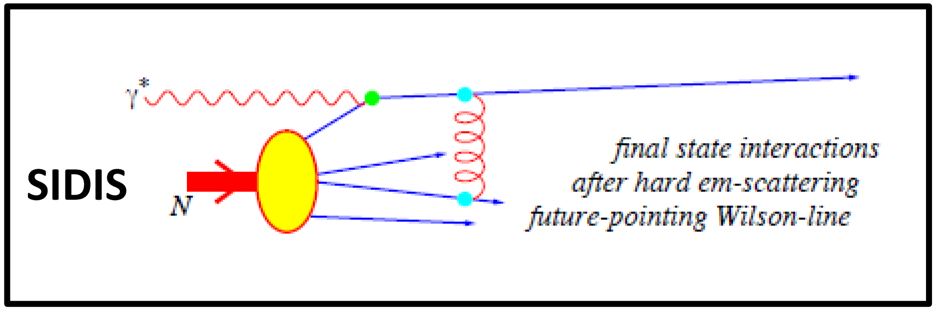


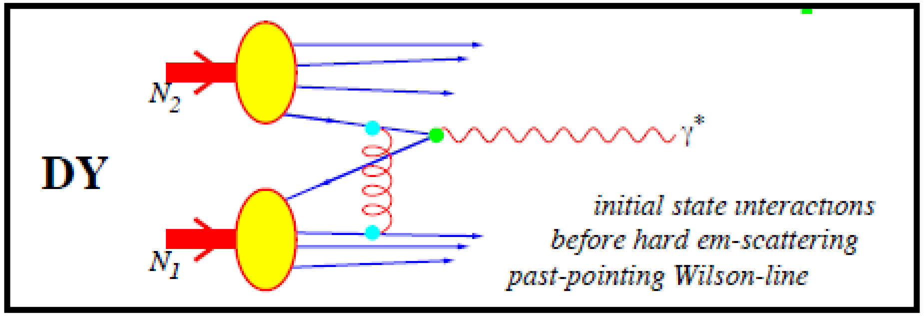
Experimental check of the change of sign of TMDs confronting Drell-Yan and SIDIS results

T-odd character of the Boer-Mulders and Sivers functions

In order not to be forced to vanish by time-reversal invariance
the SSA requires an interaction phase generated by
a rescattering of the struck parton in the field of the hadron remnant

Time reversal





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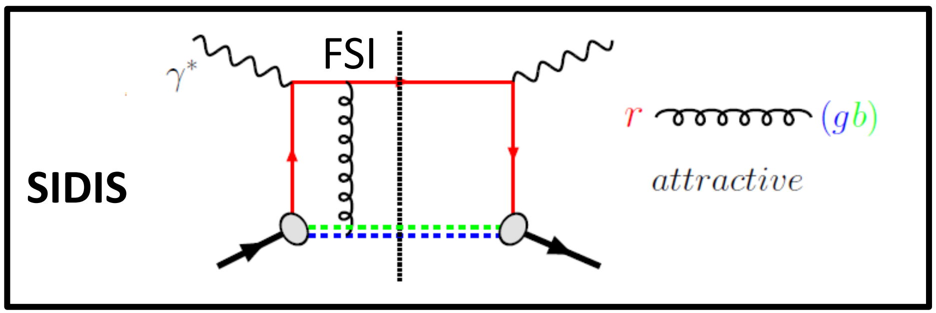
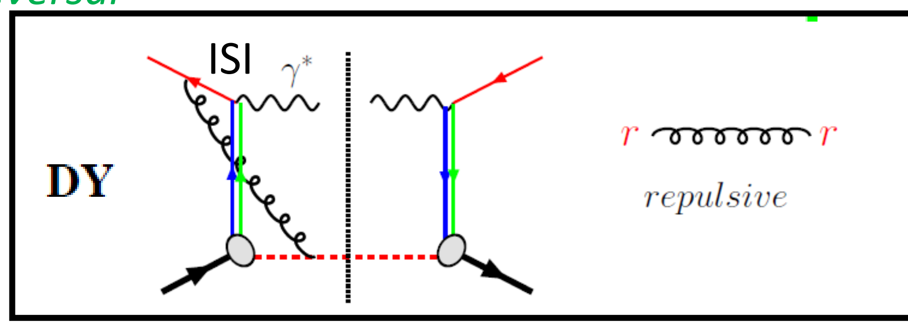




Boer-Mulders

$$h_1^{\perp}(SIDIS) = -h_1^{\perp}(DY)$$

Sivers

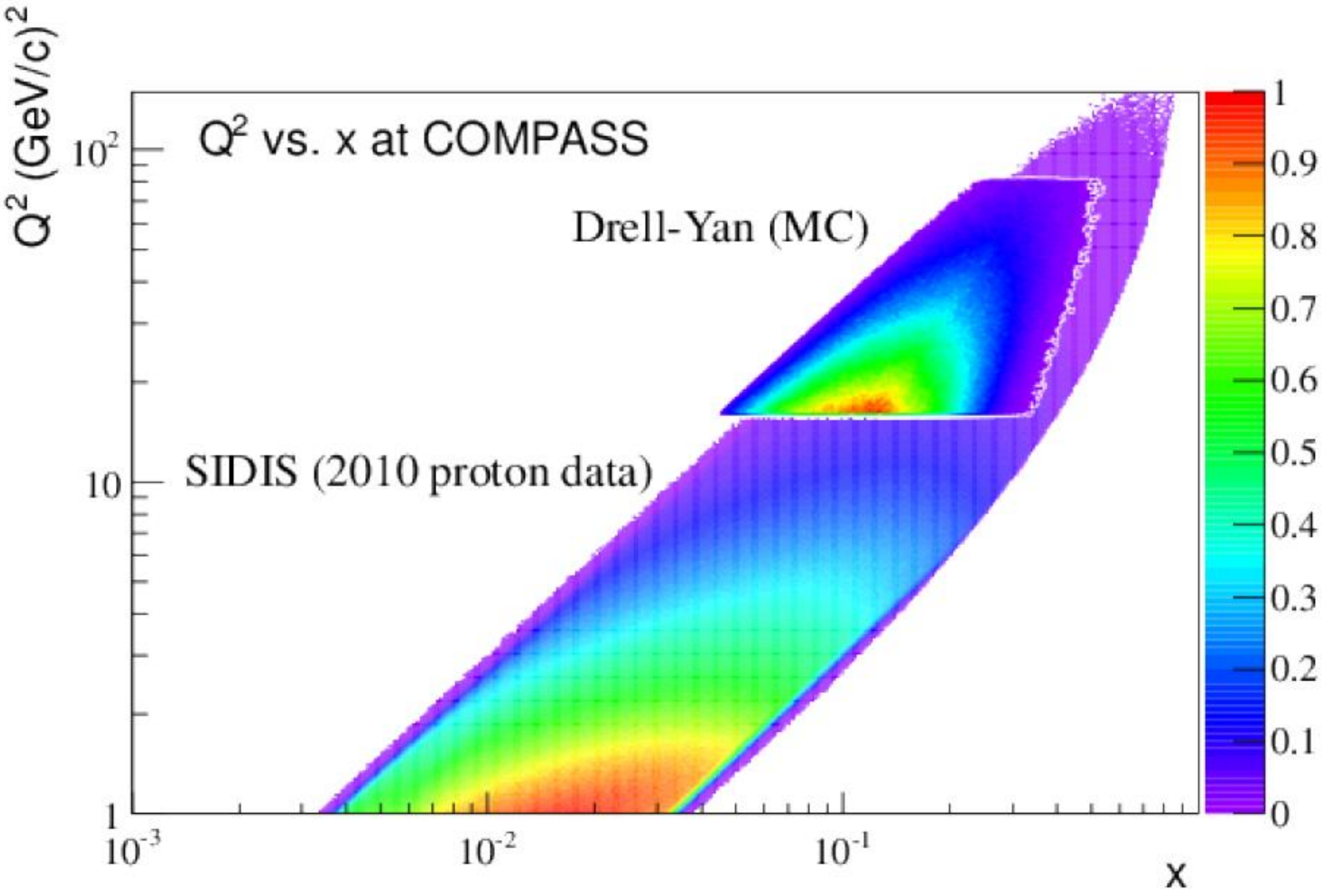
$$f_{1T}^{\perp}(SIDIS) = -f_{1T}^{\perp}(DY)$$

NEED EXPERIMENTAL VERIFICATION
SIGN + AMPLITUDE + SHAPE

TEST OF CONSISTENCY
OF THE APPROACH

These functions are process dependent, restricted universality

Q^2 vs x phase space at COMPASS



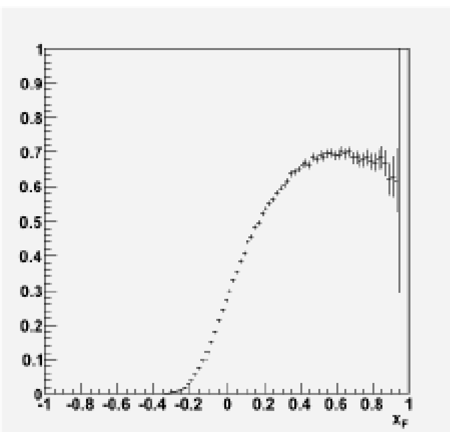
The phase spaces of the two processes overlap at COMPASS

➔ Consistent extraction of TMDs in the same region

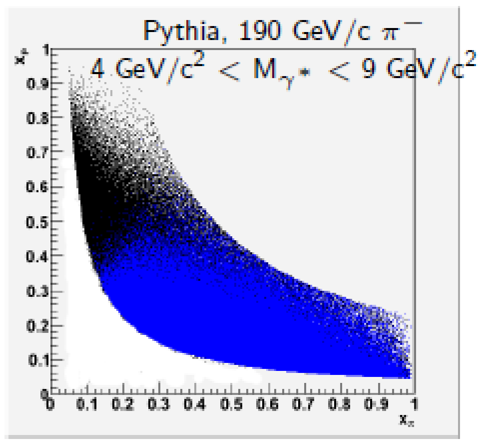
Why DY $\pi^{\pm} p^{\Uparrow}$ is very favourable at COMPASS?

σ^{DY} dominated by the annihilation of a valence anti-quark from the pion and a **valence** quark from the polarised proton

$$\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}$$



x_F acceptance plot



x_p vs x_π scatter plot: in black all generated events, in blue events in acceptance

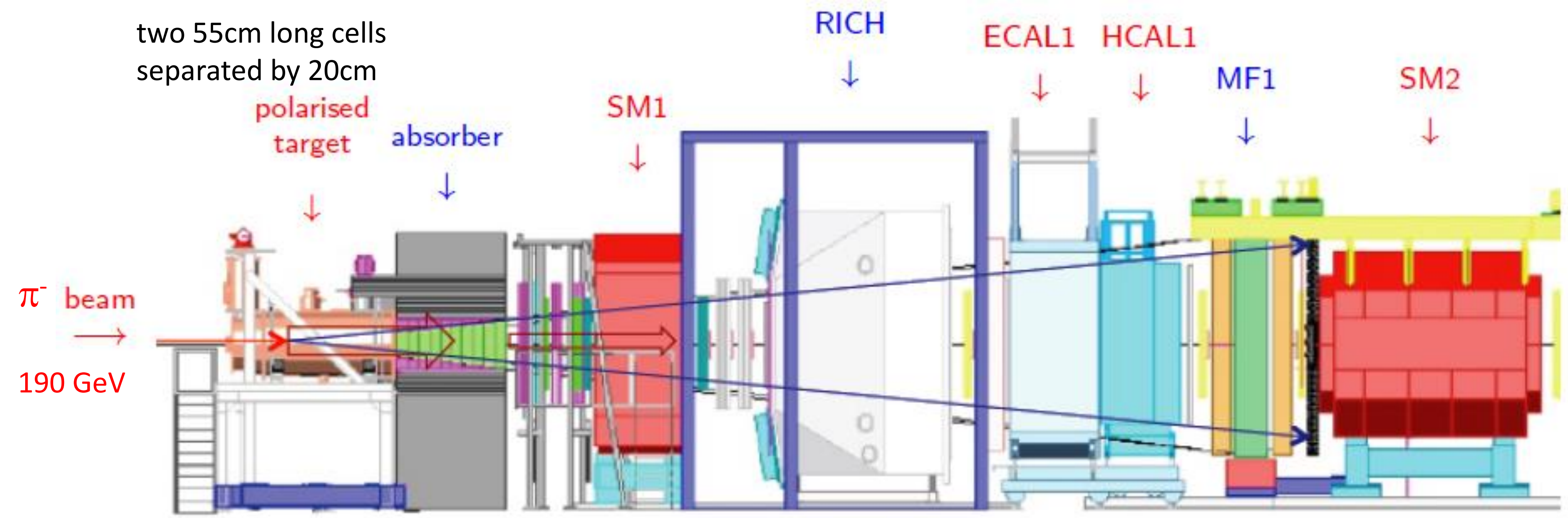
large acceptance of COMPASS
in the valence quark region for p and π
where SSA are expected to be larger

Competitive experiments at:

Fermilab fixed target (2015) (sea quark domain)	$pH^{\Uparrow\Rightarrow}$
Fermilab fixed target	$p^{\Uparrow\Rightarrow} H$
RHIC (STAR, PHENIX) collider	$p^{\Uparrow} p$
J-PARC fixed target	$pp^{\Uparrow}$, $\pi p^{\Uparrow}$
FAIR (PAX) collider	$\bar{p}^{\Uparrow} p^{\Uparrow}$
NICA collider	$p^{\Uparrow} p^{\Uparrow}$, $d^{\Uparrow} d^{\Uparrow}$

COMPASS has the chance to start in 2014 to be the first single polarized DY experiment

DY $\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$ and COMPASS set-up

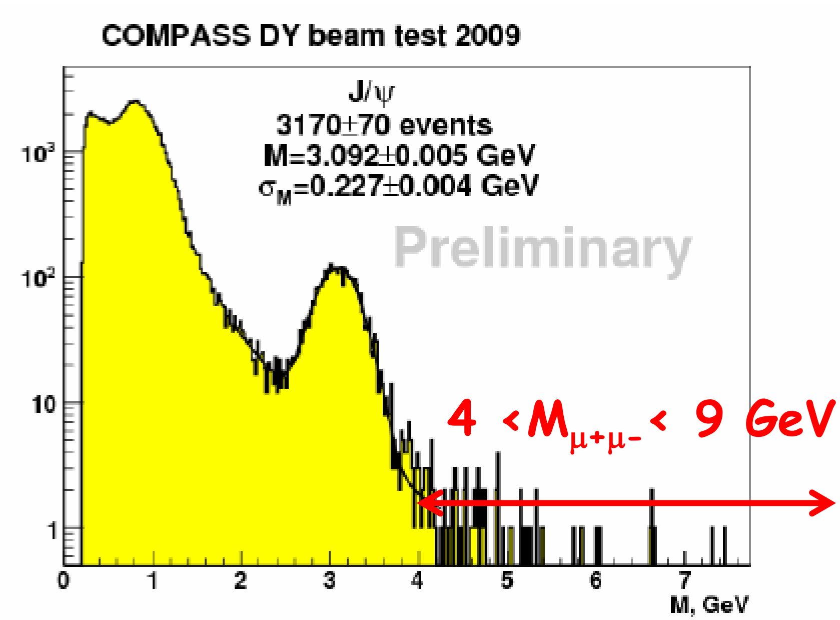


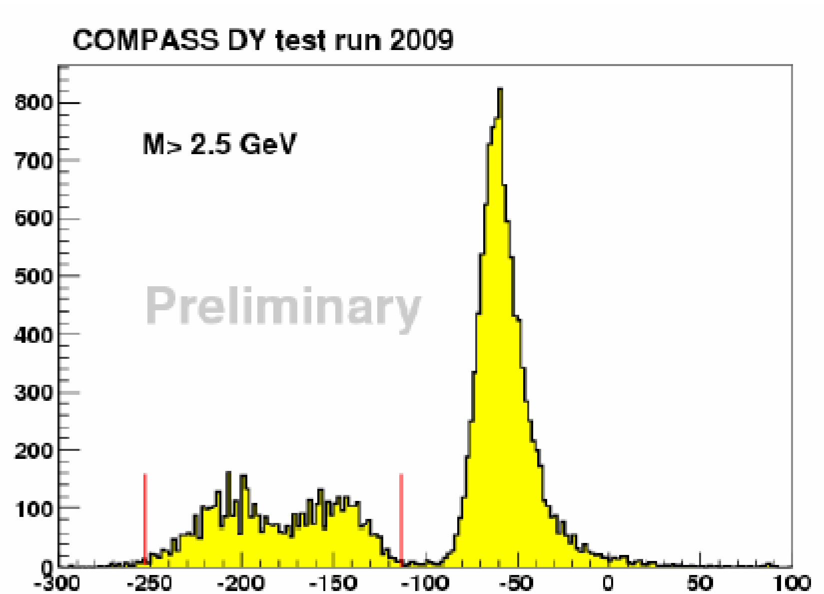
Key elements for a small cross section investigation at high luminosity

1. high intensity pion beam 10^8 π^- per second on a thick target (~1 interaction length)
2. a **hadron absorber** to stop secondary particles and
   a beam plug to stop the non-interacting beam
3. rearrangement of the target area to place the absorber
   - a **new di-muon trigger** in the first stage spectrometer (60% of the DY acceptance)
   - a **vertex detector (SciFi)** to improve the cell separation
4. RICH1, Calorimetry – also important to reduce the background

Results from DY tests in 2007-8-9 and 2012

The J/ψ peak and DY events were observed as expected
and the two cells were distinghished.





Distributions of primary vertexes along beam axis

→ a vertex detector has been proposed

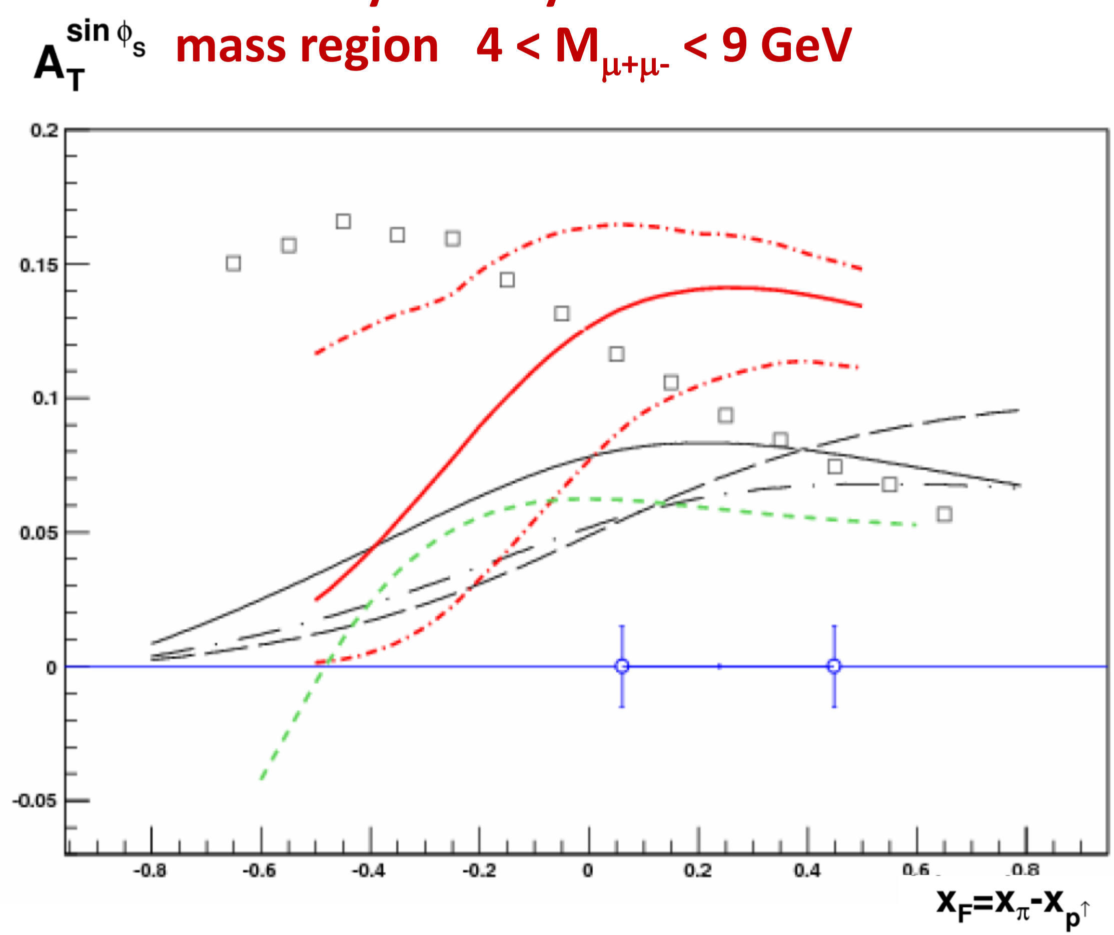
Recent test done in the condition of the future measurement with the hadron absorber.

- Target temperature OK
- Detector occupancies OK
- Radioprotection limits respected

Predictions for Drell-Yan at COMPASS

$$A_T^{\sin\phi_S}(x_a, x_b) = \frac{2}{f\,|S_T|} \frac{\int d\phi_S d\phi \frac{dN(x_a,x_b,\phi,\phi_S)}{d\phi\, d\phi_S} \sin\phi_S}{N(x_a, x_b)}$$

Sivers asymmetry in the safe dimuon mass region $4 < M_{\mu+\mu-} < 9$ GeV



2 years of data
190 GeV pion beam
6 .10^8 π^-/spill (of 9.6s)
1.1 m transv. pol. NH_3 target
Lumi=1.2 10^{32} $cm^{-2}s^{-1}$

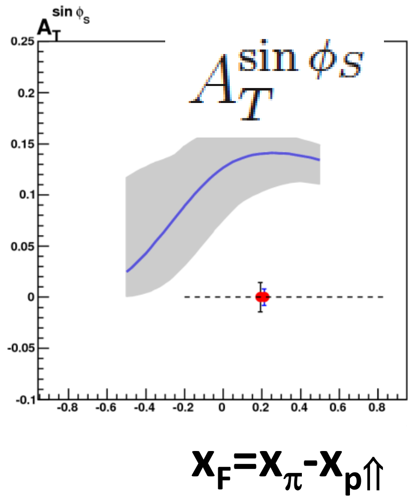
Red solid and dod-dashed line
Anselmino et al., PRD79 (2009)
Black solid and dashed:
Efremov et al., PLB612 (2005)
Black dot-dashed:
Collins et al., PRD73 (2006)
Squares:
Bianconi et al., PRD73 (2006)
Green short-dashed:
Bacchetta et al., PRD78 (2008)

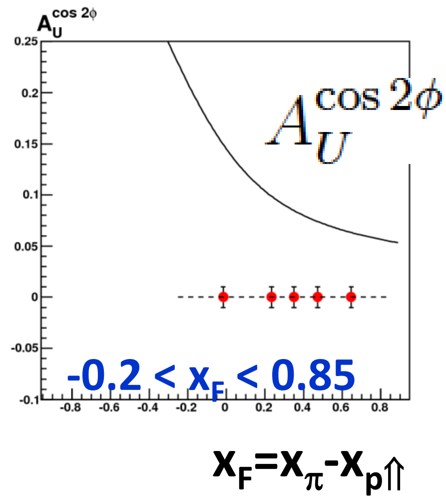
Predictions for Drell-Yan at COMPASS

$$4. \leq M_{\mu\mu} \leq 9.\ \mathrm{GeV}/c^2$$

Sivers

M. Anselmino et al, Phys. Rev. D 79, 054010 (2009)





Boer-Mulders

B. Zhang et al, Phys. Rev. D 77, 054011 (2008)

The first ever polarised Drell-Yan experiment sensitive to TMDs

end of 2014: 2 months with the complete setup

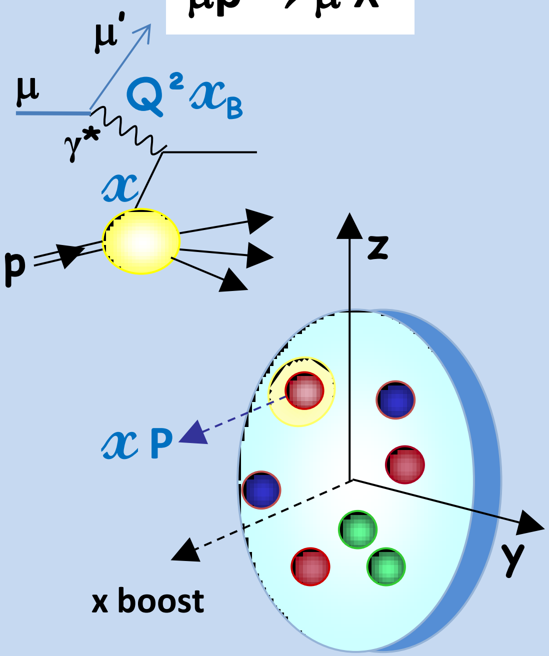
2015: a full year dedicated to the polarized Drell-Yan at COMPASS

See Marcia Quaresma: Study of TMD from Polarized Drell-Yan at COMPASS (Nucleon Structure IV on Tuesday at 17:00)

from inclusive reactions
to exclusive reactions

Deep Inelastic Scattering

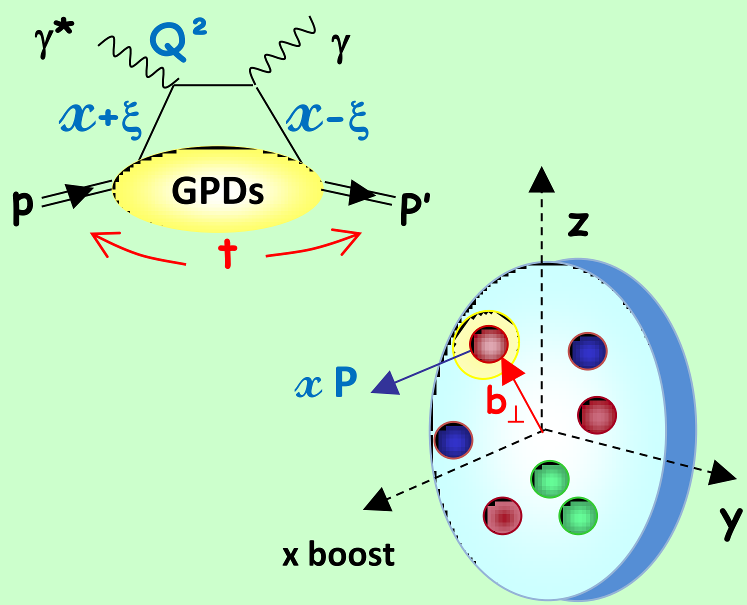
$\mu p \to \mu' X$



Distrib. de Partons q (x)

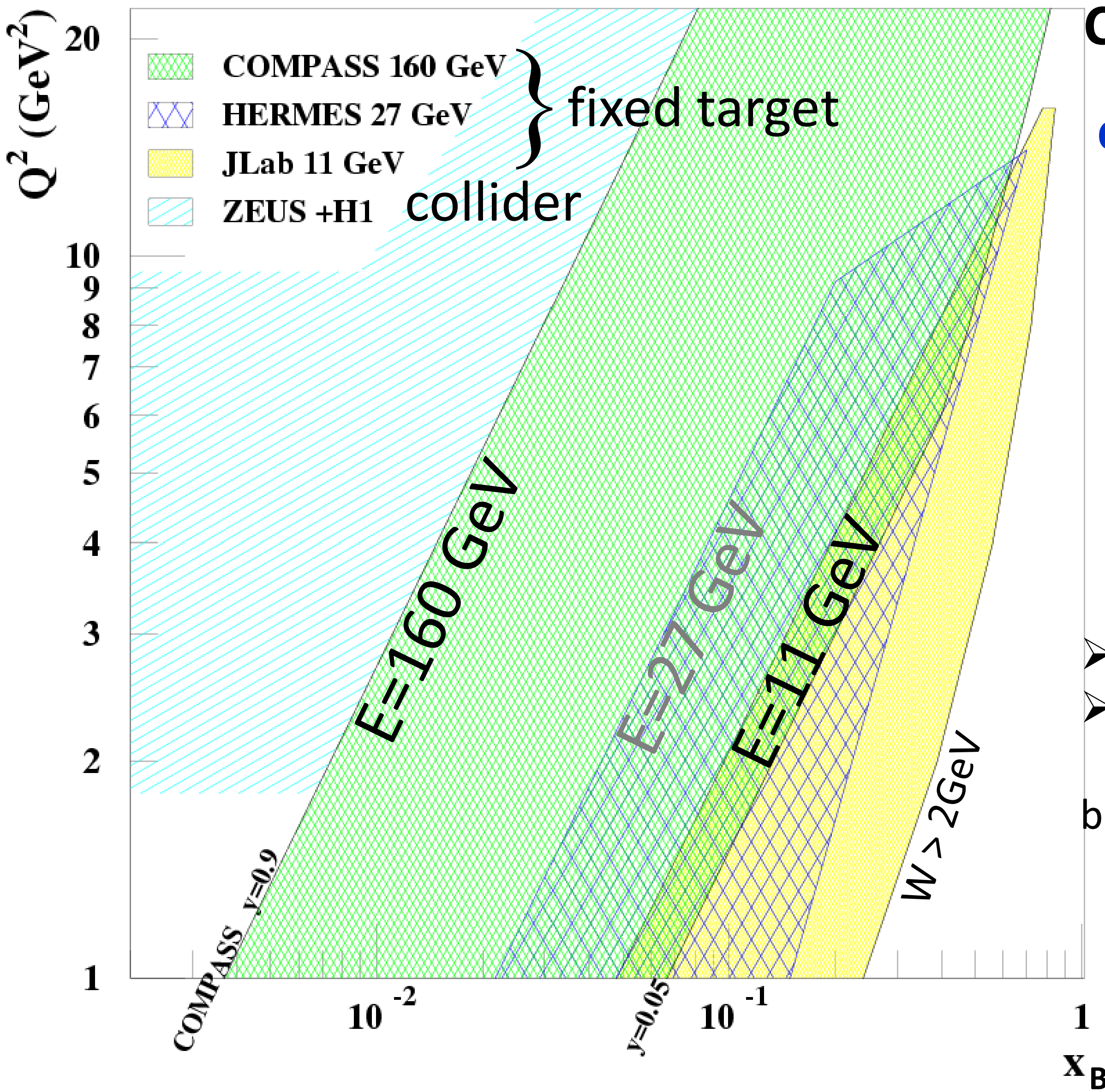
Deeply Virtual Compton Scattering

$\mu p \to \mu' p' \gamma$



Generalized Partons Distrib. $H(x,\xi,t)$

Kinematic domain (Q^2, x_B) for GPDs



COMPASS unique for GPDs

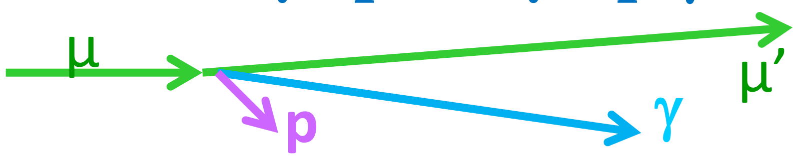
CERN High energy muon beam

- ✓ $\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ available
- ✓ 80% Polarisation with opposite polarization
- ✓ 4.6 10^8 μ^+
  ➔ Lumi= 10^{32} cm^{-2} s^{-1} with 2.5m LH2 target

- Explore the intermediate x_{Bj} region
- Uncovered region between ZEUS+H1 & HERMES **+ Jlab** before new colliders may be available

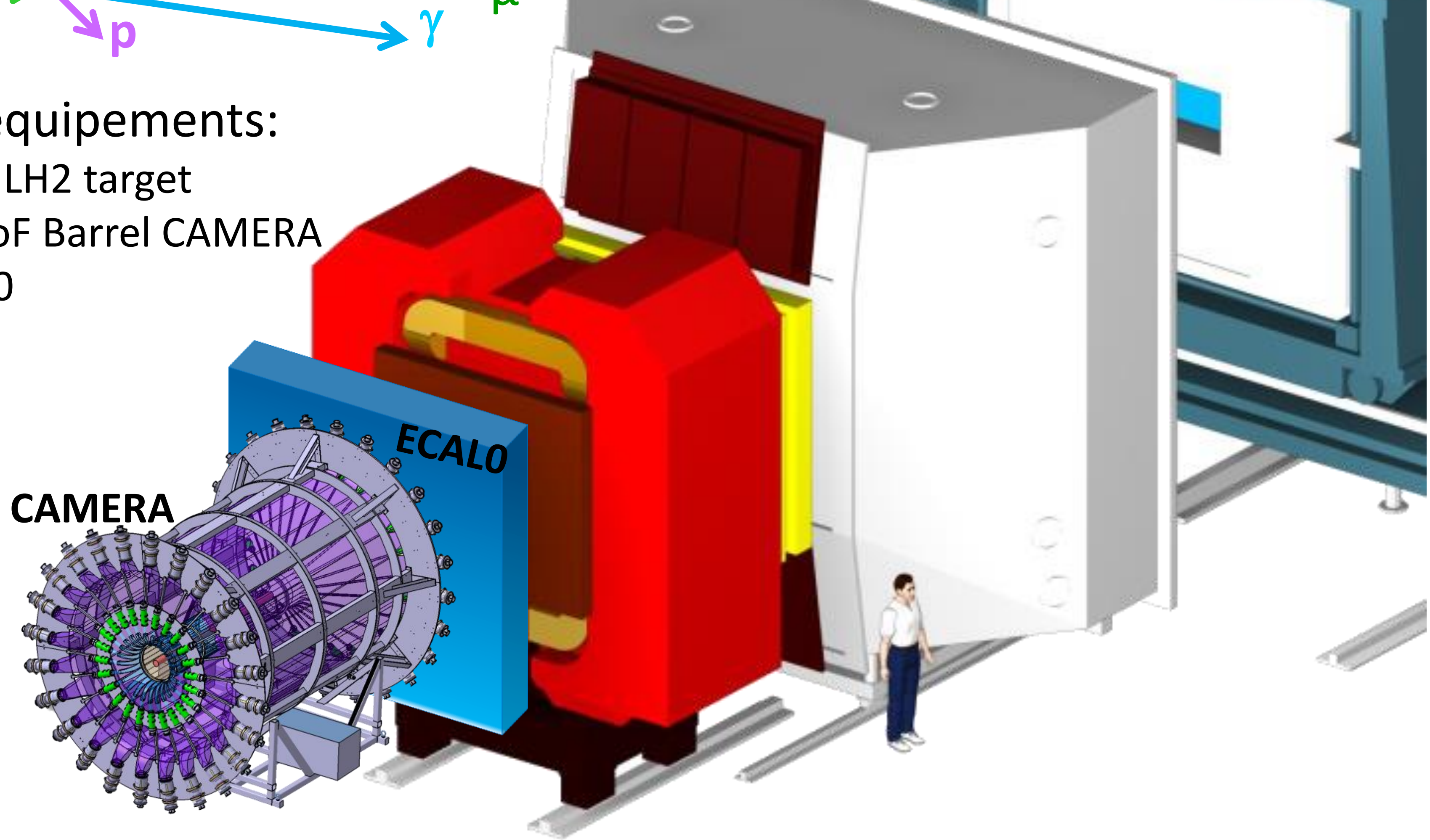
Upgrades of the COMPASS spectrometer

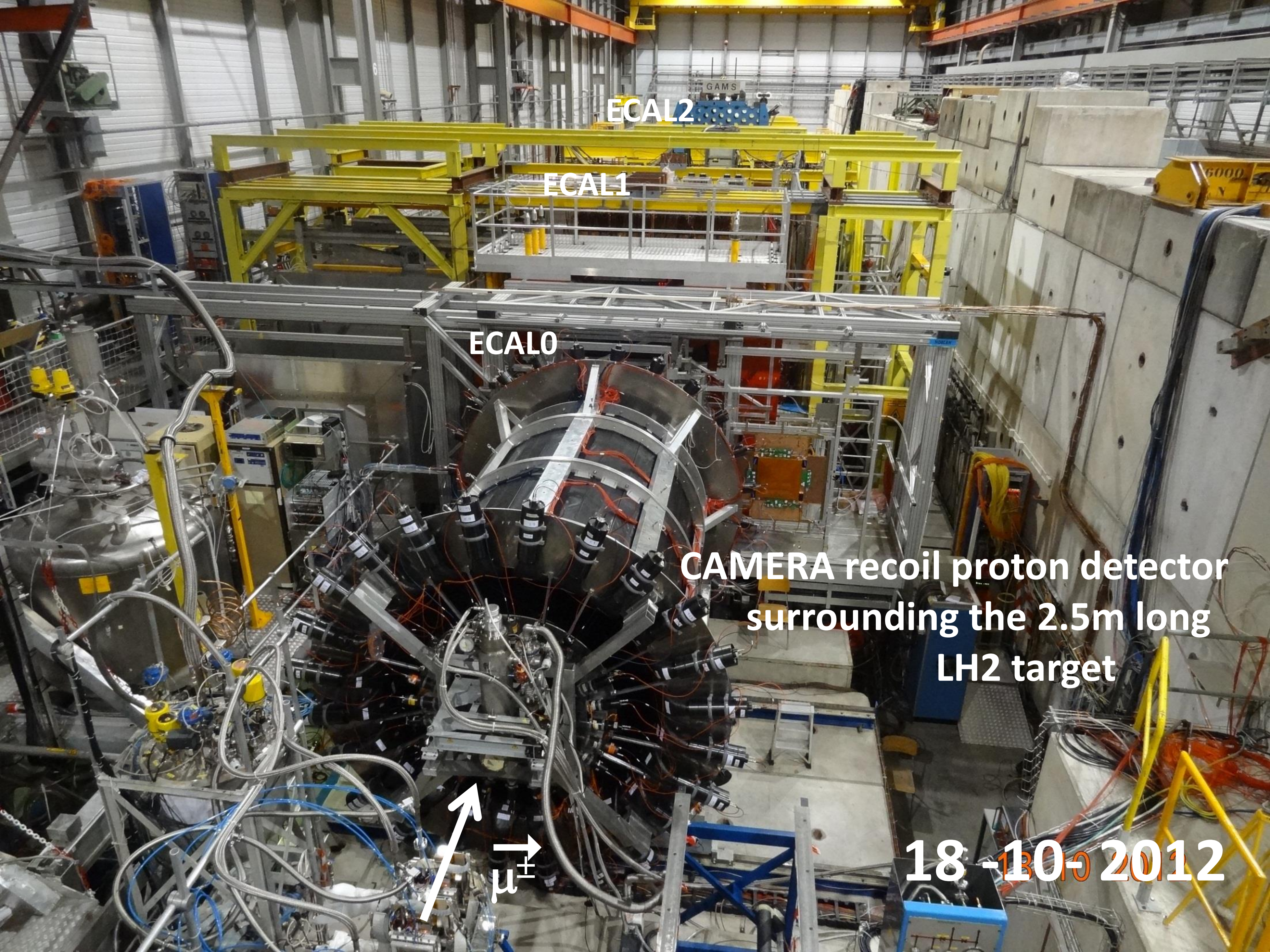
DVCS : μ p → μ' p γ



New equipements:

- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECAL0



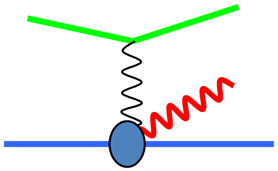

GAMS
ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
μ±
18 -10- 2012

Constraints on the GPD H

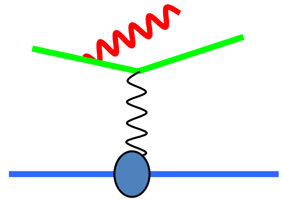
with hydrogen target and recoil proton detection

- Very first tests in 2008-9
- 1 month in november 2012
- 2 years in 2016-17

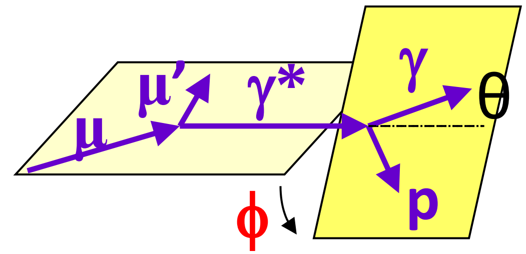
Contributions of DVCS and BH at E_{μ}=160 GeV



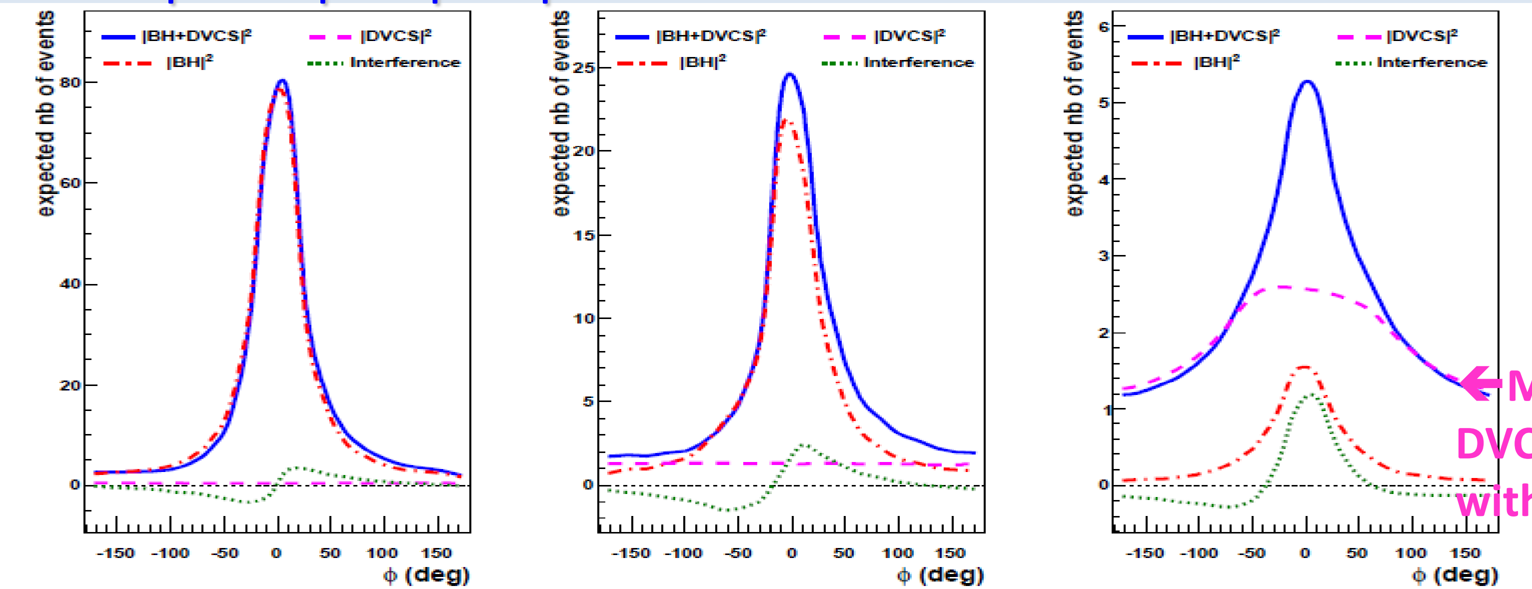
Deep VCS



Bethe-Heitler



$d\sigma \;\alpha\; |T^{DVCS}|^2 + |T^{BH}|^2$ + Interference Term

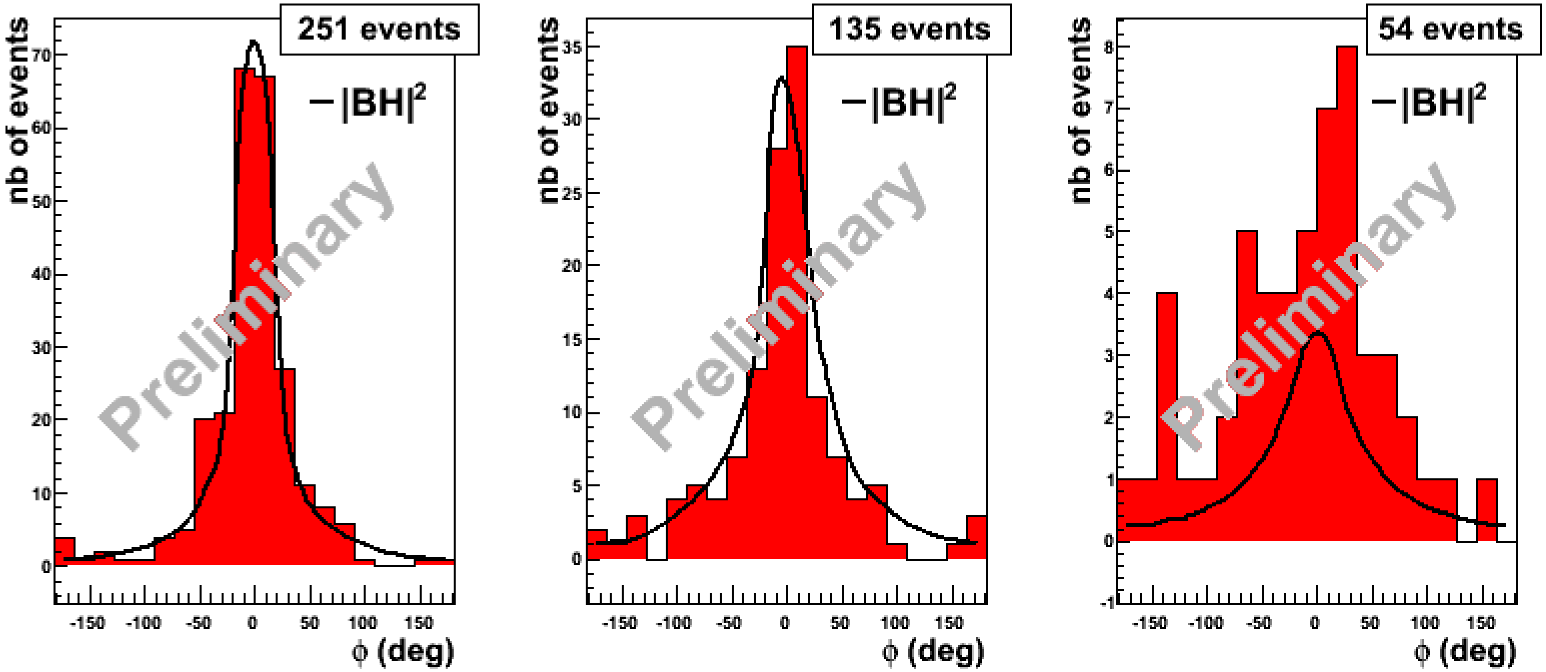


Monte-Carlo Simulation for COMPASS set-up with only ECAL1+2

Missing DVCS acceptance without ECAL0

$0.005 < x_B < 0.01$	$0.01 < x_B < 0.03$	$0.03 < x_B$
BH dominates	**study of Interference**	**DVCS dominates**
excellent reference yield	→ Re T^{DVCS} or Im T^{DVCS}	study of $d\sigma^{DVCS}/dt$ → Transverse Imaging

2009 DVCS test run (10 days, short RPD+target)



0.005 < x_B < 0.01 0.01 < x_B < 0.03 0.03 < x_B

$\epsilon_{\mu p \rightarrow \mu' \gamma p} \approx 35\%$

$\times\ (0.8)^4$ for SPS + COMPASS avail. + trigger eff + dead time

$\varepsilon_{global} \approx 0.14$ confirmed $\varepsilon_{global} = 0.1$
as assumed for COMPASS II predictions

54 evts = 20 BH
+ about 22 DVCS
& about 12 γ from π^0

Deeply Virtual Compton Scattering

cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

$$d\sigma_{(\mu p \to \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol} + e_\mu\, a^{BH}\, \mathcal{Re}\, A^{DVCS} + e_\mu P_\mu\, a^{BH}\, \mathcal{Im}\, A^{DVCS}$$

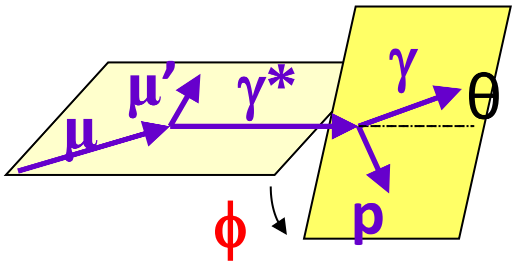
Charge & Spin Sum:

$$S_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K.s_1^{Int} \sin\phi$$

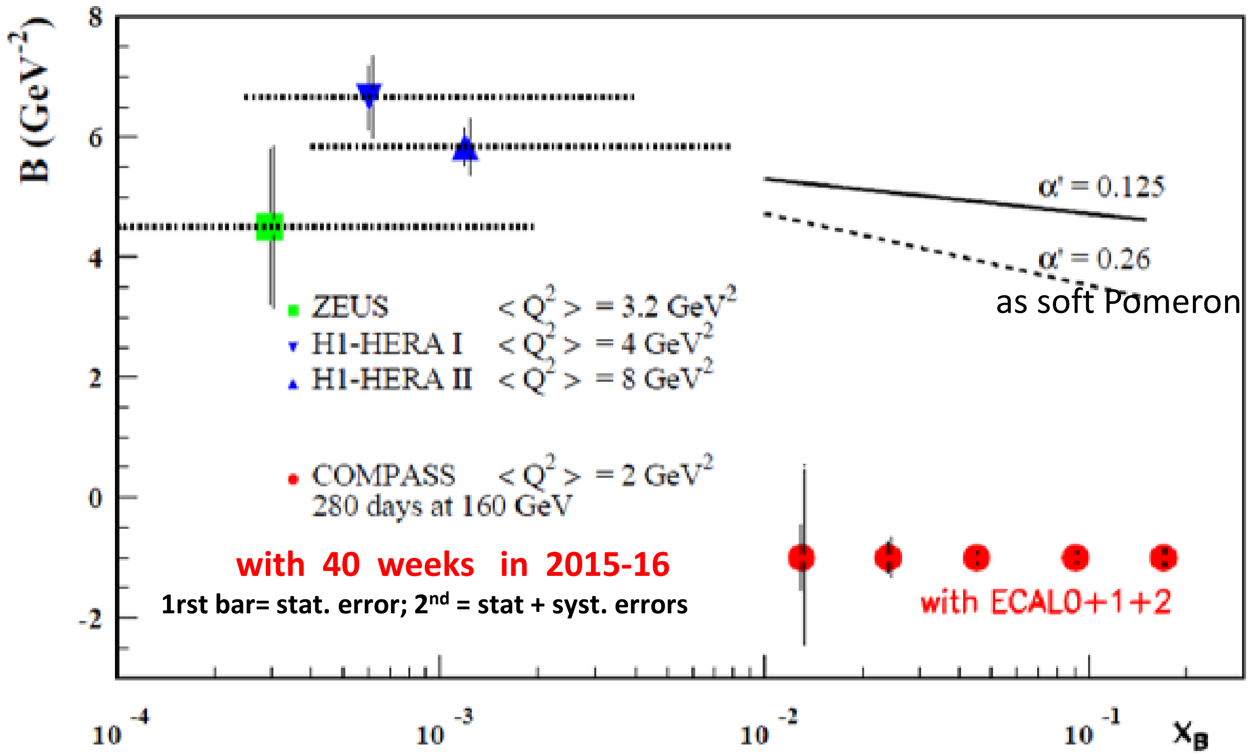
$\downarrow$

Using $S_{CS,U}$ and BH subtraction and integration over ϕ

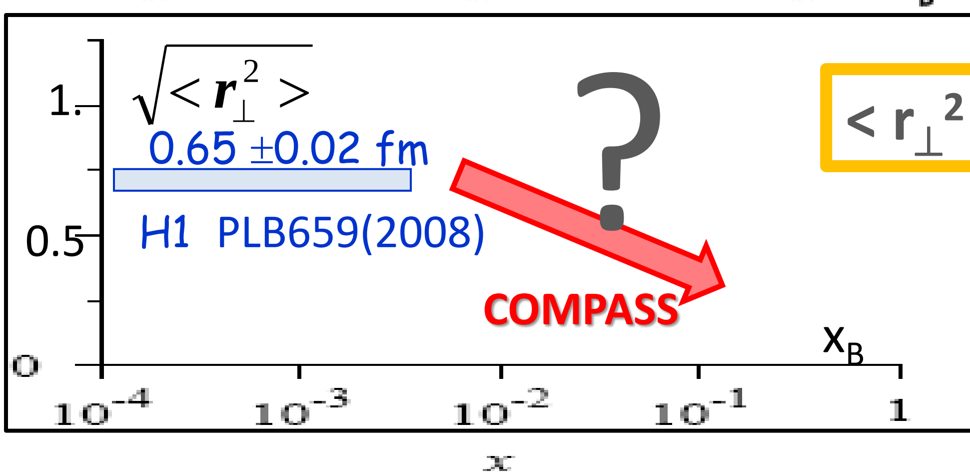
$$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$$



Transverse imaging at COMPASS
$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$



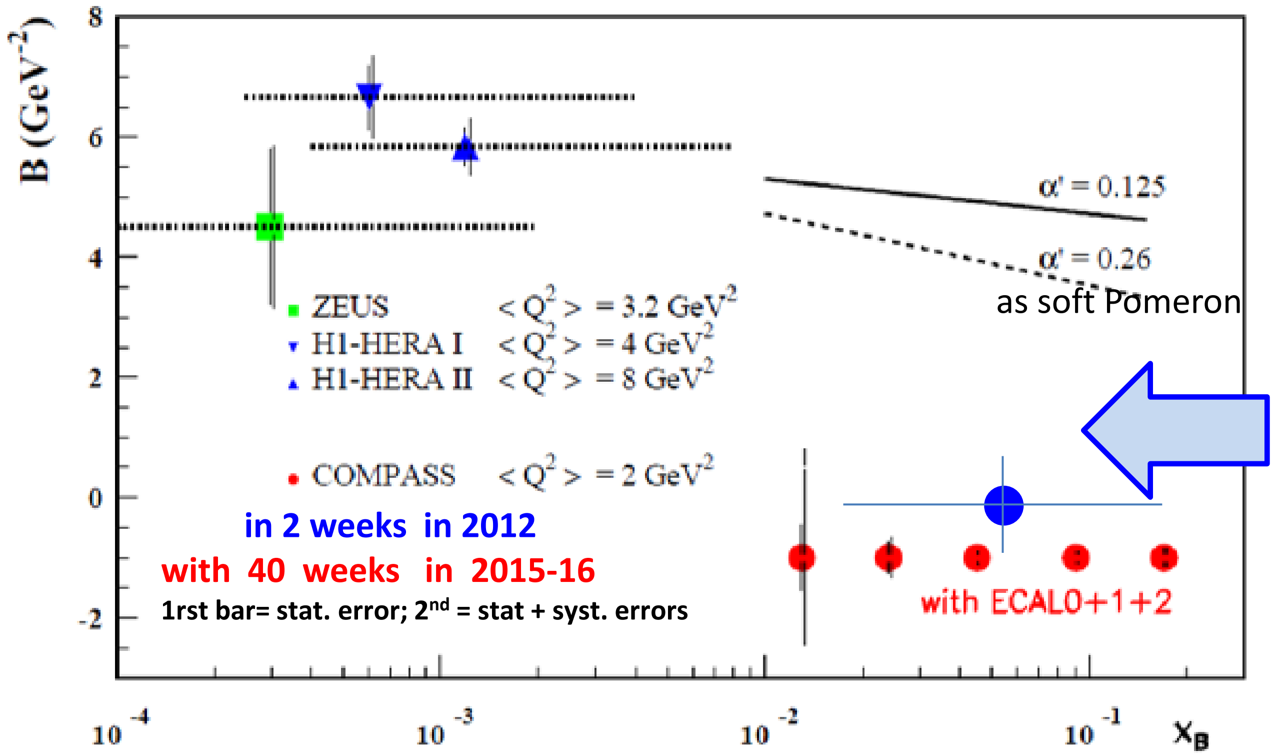
2 years of data = 40 weeks
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%



$< r_\perp^2(x_B) > \approx 2\, B(x_B)$

Transverse imaging at COMPASS

$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$



DVCS test in 2012

With 2 weeks
Using the 4m long RPD
+ the 2.5m long LH2 target

1/20 of the complete statistics

2012: we can determine one mean value of B in the COMPASS kinematic range

Deeply Virtual Compton Scattering

cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ& P_μ)

$$d\sigma_{(\mu p \rightarrow \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu \, d\sigma^{DVCS}_{pol} + e_\mu \, a^{BH} \, \mathcal{Re} \, A^{DVCS} + e_\mu \, P_\mu \, a^{BH} \, \mathcal{Im} \, A^{DVCS}$$

Charge & Spin Difference and Sum:

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int} \cos\phi$$ and $c_{0,1}^{Int} \sim F_1 \, \mathcal{Re}\,\mathcal{H}$

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int} \sin\phi$$ and $s_1^{Int} \sim F_1 \, \mathcal{Im}\,\mathcal{H}$

Deeply Virtual Compton Scattering

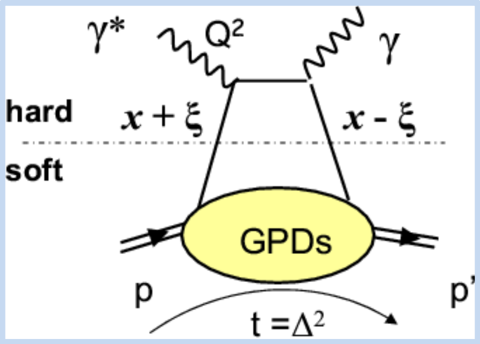
cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

$$d\sigma_{(\mu p \to \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu \, d\sigma^{DVCS}_{pol} + e_\mu \, a^{BH} \, \mathcal{R}e \, A^{DVCS} + e_\mu \, P_\mu \, a^{BH} \, \mathcal{I}m \, A^{DVCS}$$

Charge & Spin Difference and Sum:

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int} \cos\phi \quad \text{and} \quad c_{0,1}^{Int} \sim F_1 \, \mathcal{R}e \, \mathcal{H}$$

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int} \sin\phi \quad \text{and} \quad s_1^{Int} \sim F_1 \, \mathcal{I}m \mathcal{H}$$



$\xi \sim x_B / (2 - x_B)$

Note: dominance of **H** at COMPASS kinematics

$$\mathcal{I}m \, \mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$$

$$\mathcal{R}e \, \mathcal{H}(\xi,t) = \mathcal{P}\int dx \, \frac{H(x,\xi,t)}{x-\xi} = \mathcal{P}\int dx \, \frac{H(x,x,t)}{x-\xi} + \mathcal{D}(t)$$

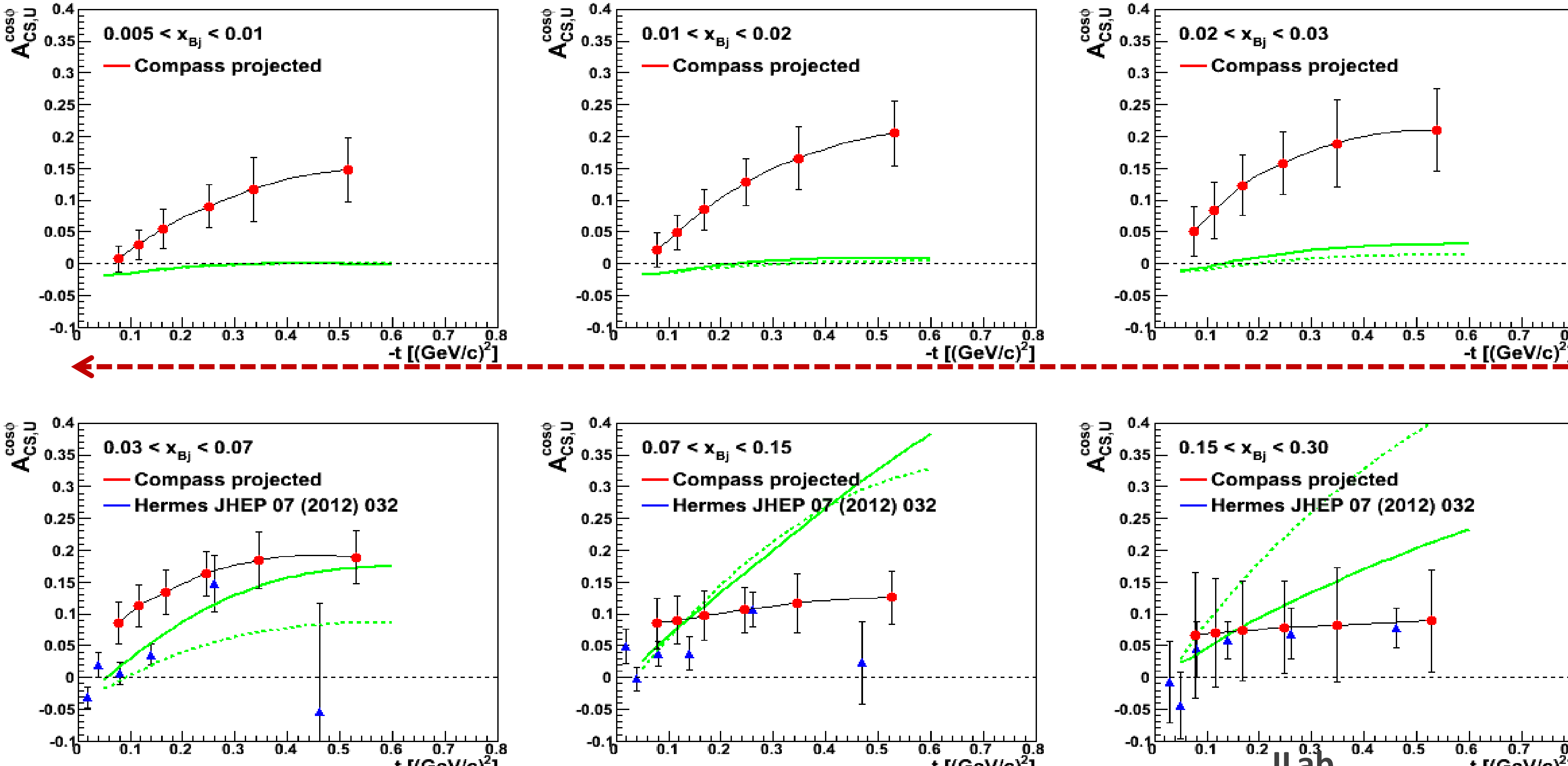
Re part of the *Compton Form Factors* linked to the *D term*

$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int} \cos\phi$ and $c_{0,1}^{Int} \sim F_1 \,\mathcal{R}e\, \mathcal{H}$

$A_{CS,U}^{\cos\phi}$ related to c_1^{Int}

Predictions with
VGG and D.Mueller

$\mathcal{R}e\,\mathcal{H}$ > 0 at H1
< 0 at HERMES/JLab
Value of x_B for the node?



JLab

HERMES 10 years of data

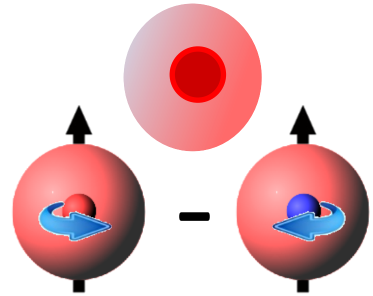
COMPASS 2 years of data Eμ= 160 GeV 1 < Q^2 < 8 GeV^2 With ECAL2 + ECAL1 + ECAL0

Other GPDs

Chiral-even

$H \longleftrightarrow q$

$E \longleftrightarrow f_{1T}^{\perp}$



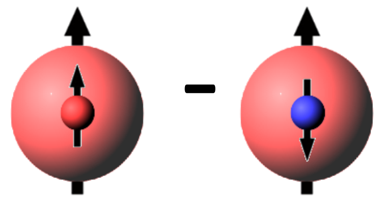
Sivers: quark k_T
and nucleon transv. Spin

the Holy Grail: to reveal OAM

Ji: $2J^q = \int x\,(H^q(x,\xi,0) + E^q(x,\xi,0))\,dx$

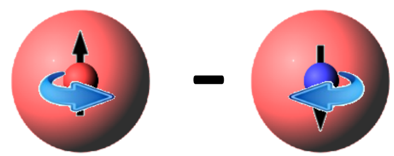
Chiral-odd

$H_T \longleftrightarrow h_1$



Transversity: quark spin
and nucleon transv. spin

$\bar{E}_T = 2\tilde{H}_T + E_T \longleftrightarrow h_1^{\perp}$



Boer-Mulders: quark k_T
And quark transverse spin

With transversely polarized target :

- with recoil detector: to be investigated for the future
- without recoil detector: Deeply vector meson production
  (deuteron data 2002-3-4 and proton data 2007-10)

See Wolf-Dieter Nowak: Transverse Target Spin Asymmetries in exclusive ρ production
(Nucleon Structure VI on Wednesday at 16:00)

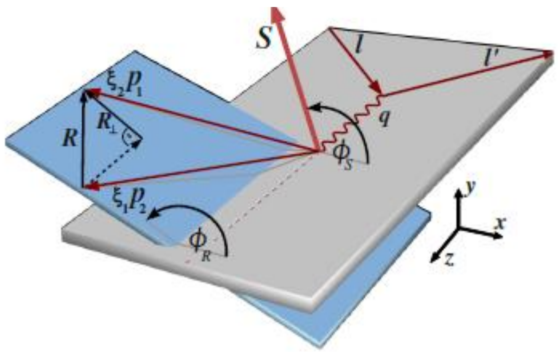
For the next 10 years,
COMPASS@CERN can be a major player in QCD physics
using its unique high energy (~200 GeV) hadron
and polarised positive and negative muon beams

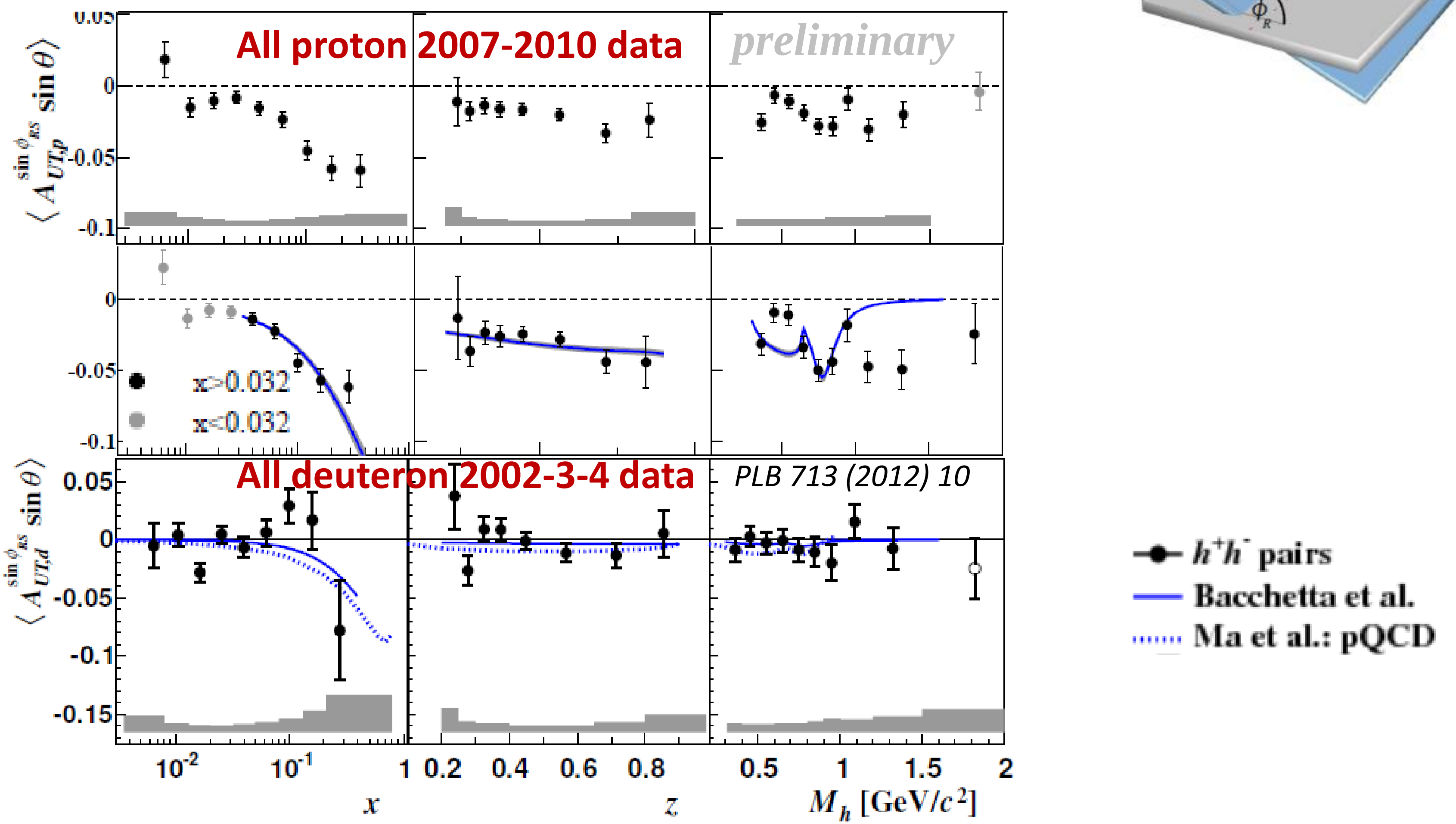
Hadron Pair Asymmetry: alternative to access transversity

couple $h_1^q(x)$ to chiral odd 2-hadron

$$A_{UT}^{\sin\phi_{RS}} = \frac{|\boldsymbol{p_1} - \boldsymbol{p_2}|}{2M_h} \frac{\sum_q e_q^2 \, h_1^q(x) \, H_{1,q}^{\sphericalangle}(z, M_h^2, \cos\theta)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1,q}(z, M_h^2, \cos\theta)}$$

$$\phi_{RS} = \phi_R - \phi_{S'} = \phi_R + \phi_S - \pi$$





Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p \to \mu p \gamma)} = \sout{d\sigma^{BH}} + \sout{d\sigma^{DVCS}_{unpol}} + P_\mu \, d\sigma^{DVCS}_{pol}$$

$$+ e_\mu \, a^{BH} \, \mathcal{Re}\, A^{DVCS} \quad + e_\mu \, P_\mu \, \sout{a^{BH} \, \mathcal{Im}}\, A^{DVCS}$$

<u>Phase 1</u>: **DVCS experiment to constrain GPD H**

with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int} \cos\phi \quad \text{and} \quad c_{0,1}^{Int} \sim \mathcal{Re}(F_1 \mathcal{H})$$

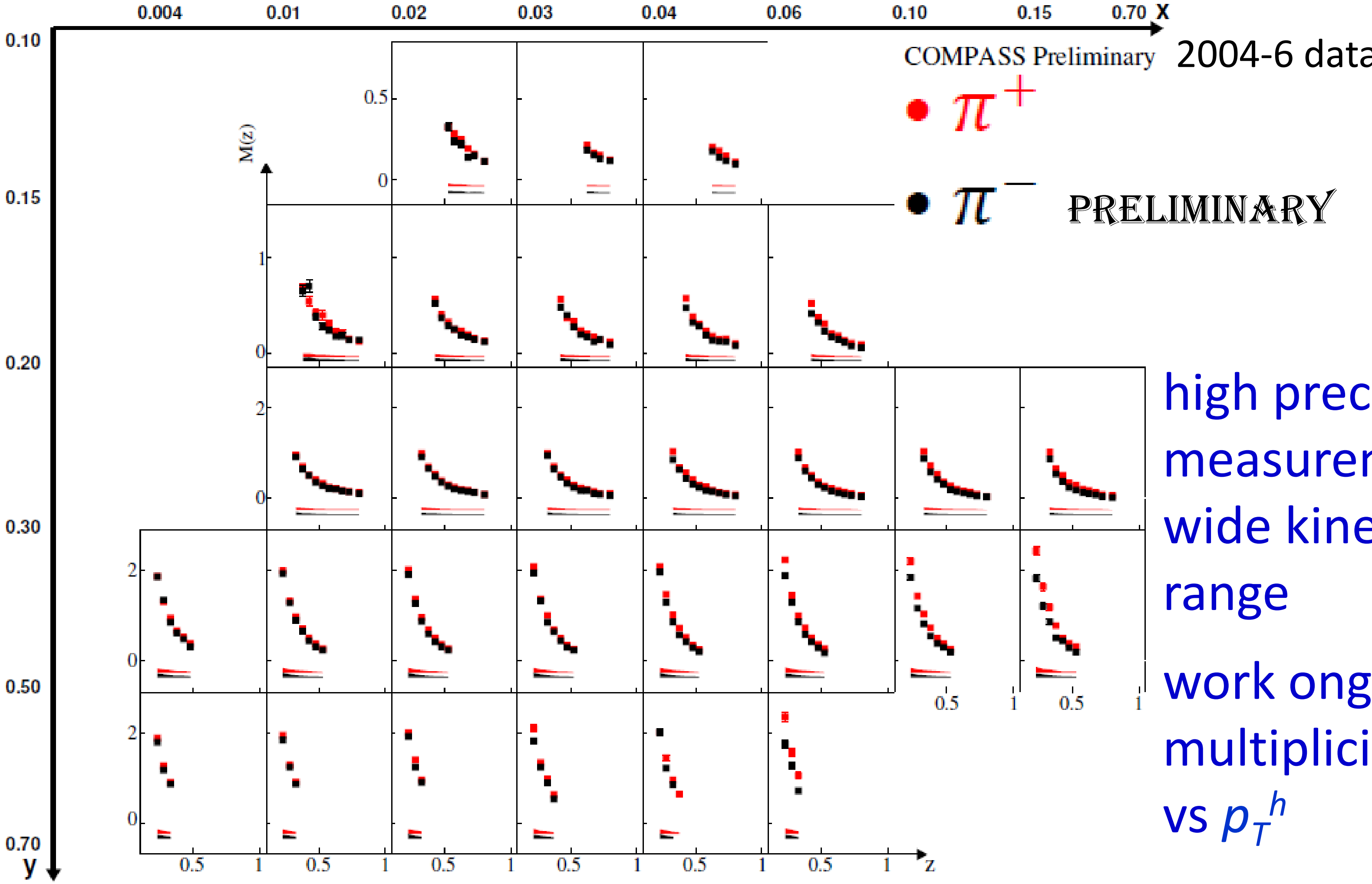
$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int} \sin\phi \quad \text{and} \quad s_1^{Int} \sim \mathcal{Im}(F_1 \mathcal{H})$$

Angular decomposition of **sum** and **diff** of the **DVCS cross section** will provide umambiguous way to separate the *Re* and *Im* of the *Compton Form Factors* from higher twist contributions

D term related to the energy momentum tension
To the radial distribution of pressure inside the proton
+ shear forces or surface tension

SIDIS and multiplicities

Charged π^+ and π^- multiplicities vs z in (x,y) bins

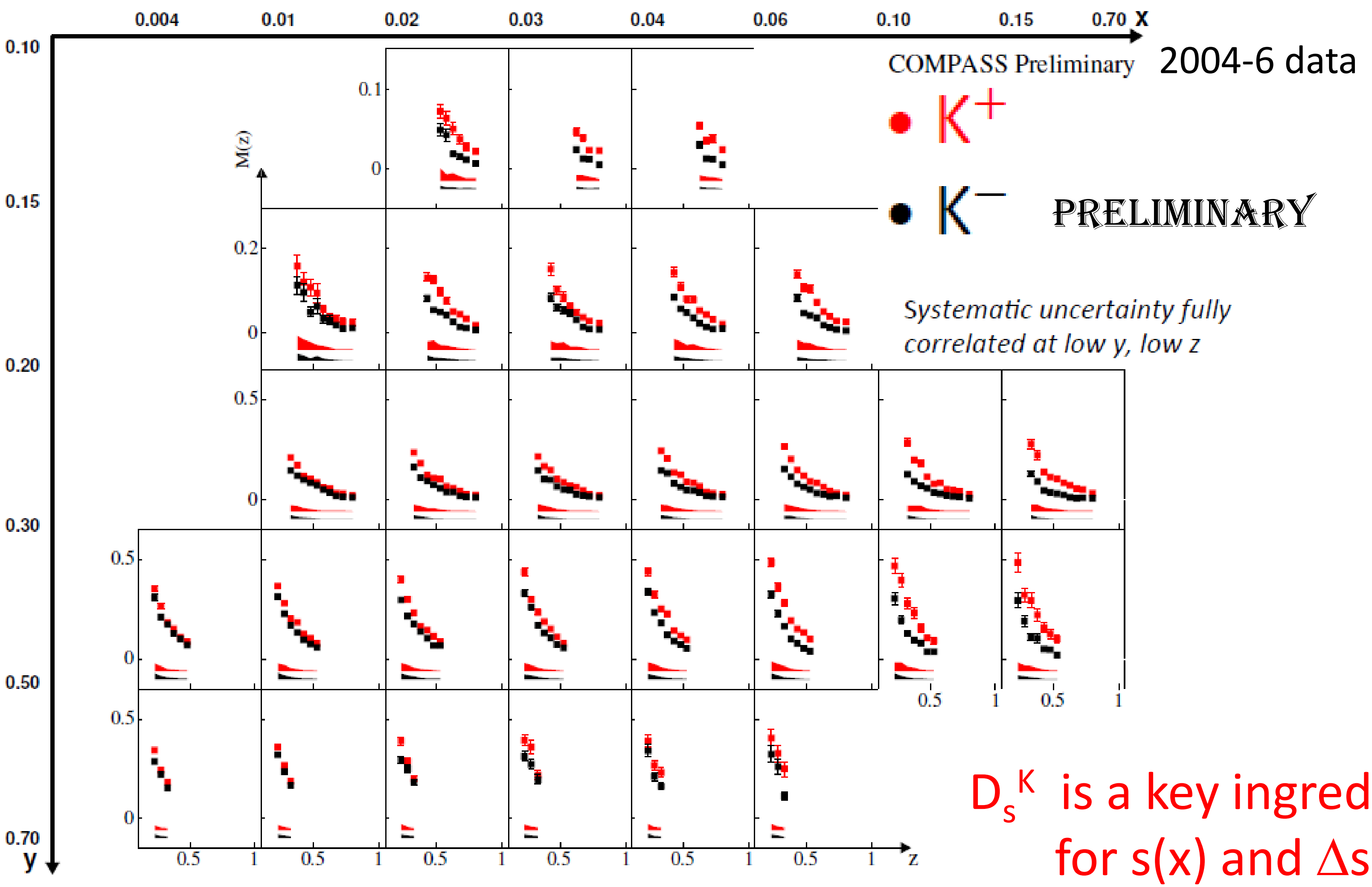


high precision measurement in wide kinematic range

work ongoing for multiplicity studies vs p_T^h

SIDIS and multiplicities

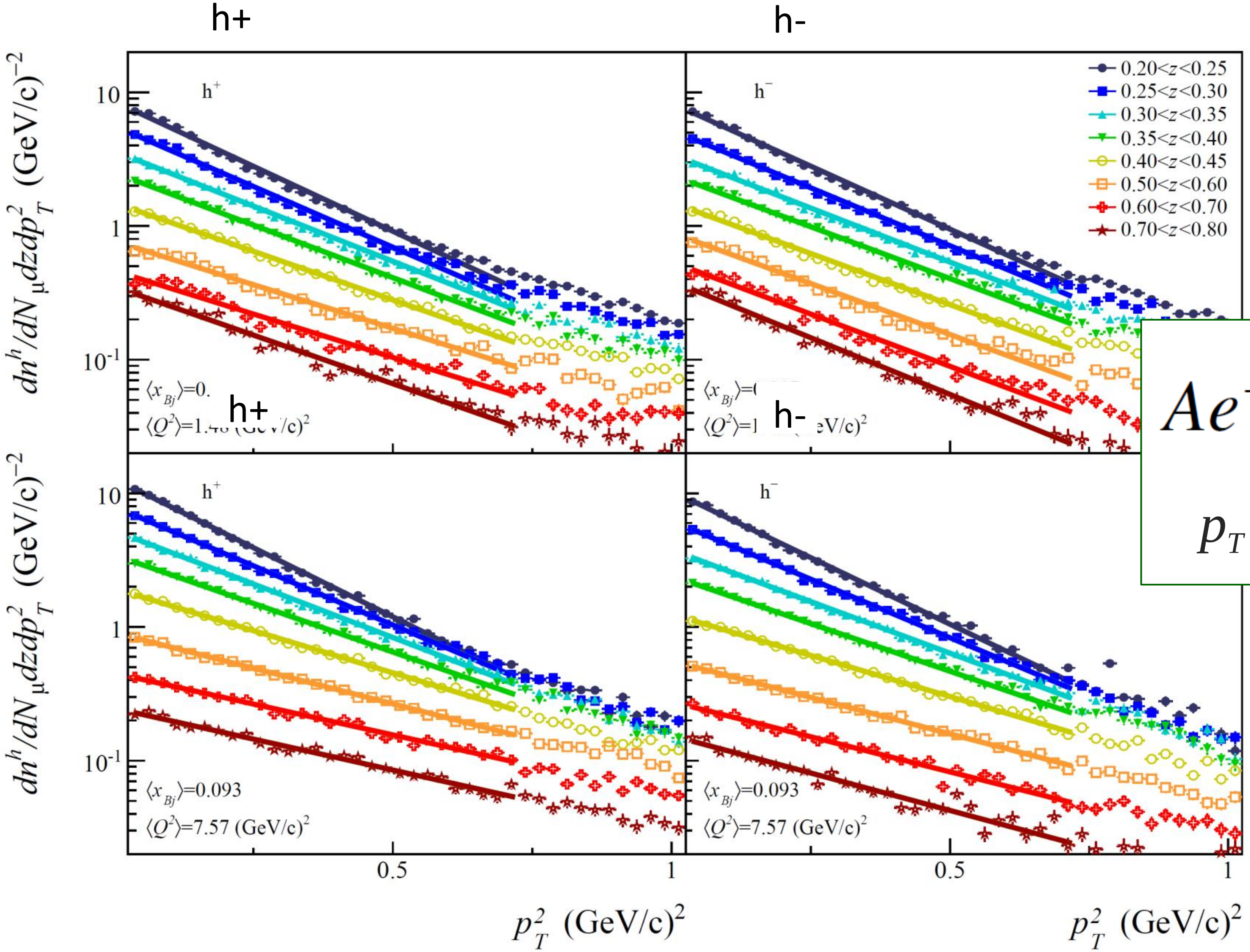
Charged K^+ and K^- multiplicities vs z in (x,y) bins



D_s^K is a key ingredient for for s(x) and $\Delta s(x)$

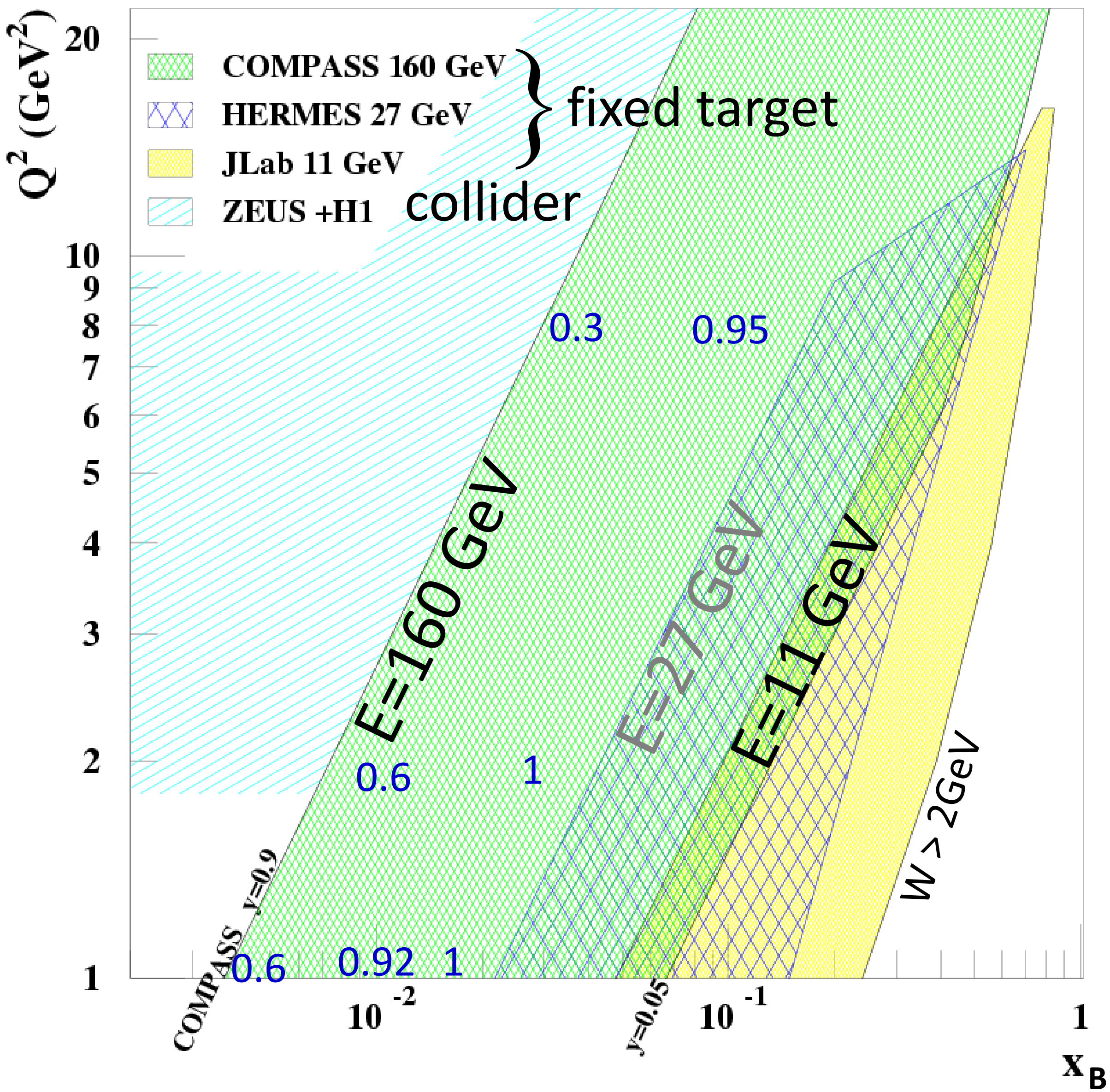
SIDIS and multiplicities

Hadron multiplicities vs p_T^2



$$Ae^{-p_T^2/\langle p_T^2 \rangle}$$

p_T < 0.85 GeV/c



Epsilon value