Present and Future Exploration of the Nucleon Spin and Structure at COMPASS

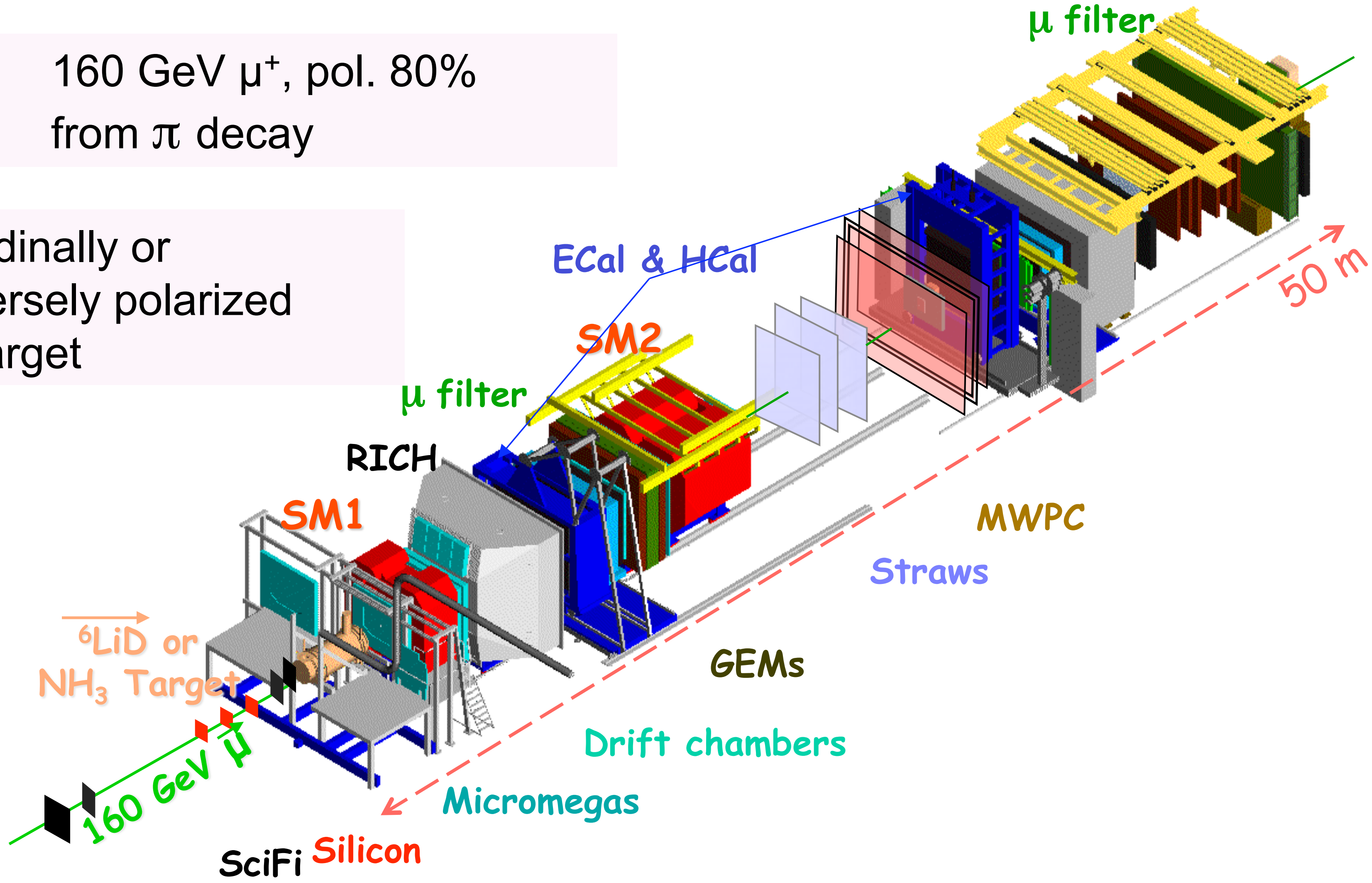
1. Longitudinal spin structure
2. Transverse spin structure
3. Gluon polarization
4. Primakov: pion polarizabilities
5. DY: Transverse Momentum Dependent PDF
6. DVCS: Generalized Parton Distributions

COMPASS phase I

Compass setup 2002-2007

Beam: 160 GeV μ^+, pol. 80% from π decay

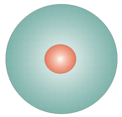
longitudinally or transversely polarized fixed target



Parton distribution functions

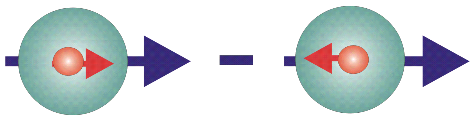
Three leading twist-2 PDFs after integration over k_T

$q(x)$
$f_1^q(x)$



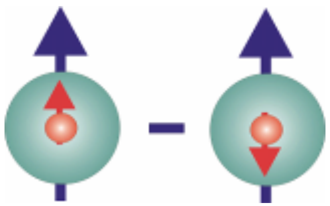
unpolarised PDF
quark with momentum *xP* in a nucleon
well known – unpolarised DIS

$\Delta q(x)$
$g_1^q(x)$



helicity PDF
quark with spin parallel to the nucleon spin in a longitudinally polarised nucleon
known – polarised DIS

$\Delta_T q(x)$
$h_1^q(x)$



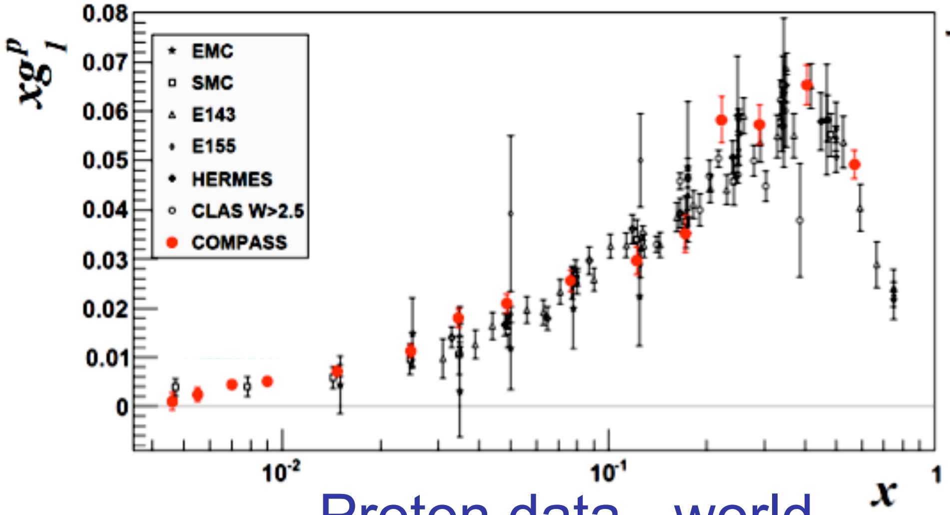
transversity PDF
quark with spin parallel to the nucleon spin in a transversely polarised nucleon
chiral odd, poorly known

Longitudinal Spin structure

Double-spin asymmetries

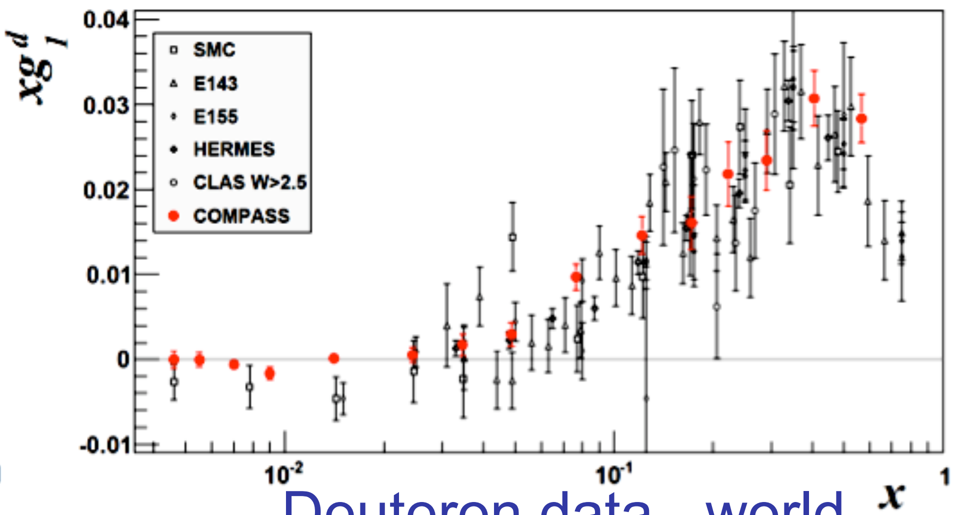
$$A^{\mu} = \frac{1}{P_b P_T f} \frac{N^+ - N^-}{N^+ + N^-}; \; A^{\mu} = D(A_1 + \eta A_2) \qquad g_1 \approx \frac{F_2}{2x(1+R)} A_1$$

Phys. Lett. B 690 (2010) 466



Proton data - world

Phys. Lett. B 647 (2007) 8



Deuteron data - world

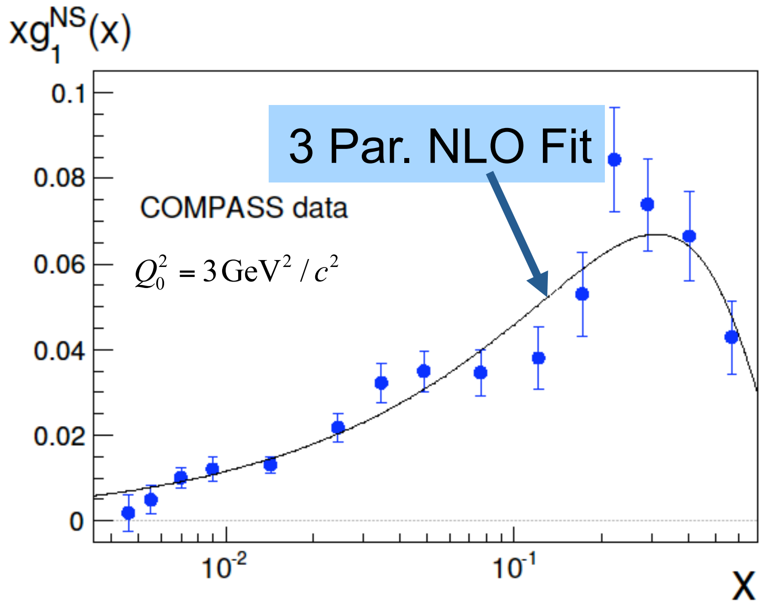
$\Delta\Sigma = a_0 = 0.33 \pm 0.03 \pm 0.05$ (evol. to $Q^2 = \infty$)

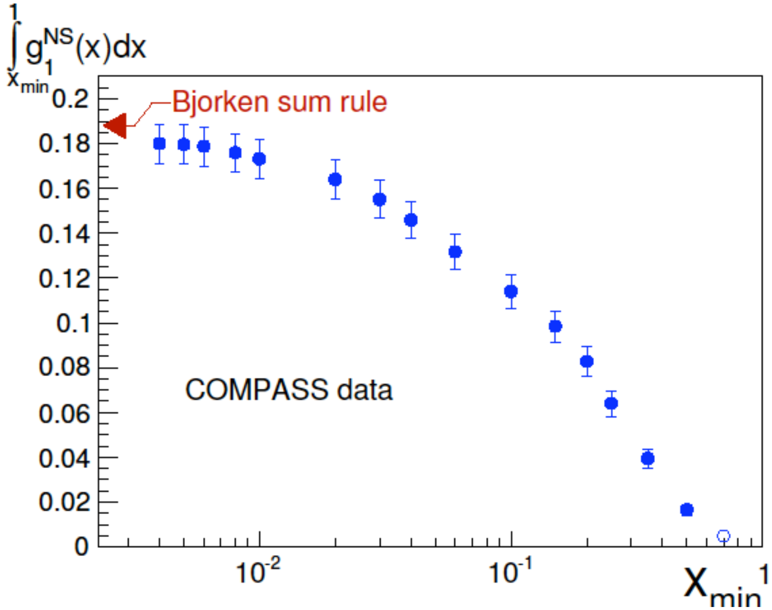
$(\Delta s + \Delta \underline{s}) = 1/3(a_0 - a_8) = -0.08 \pm 0.01 \pm 0.02$

Longitudinal Spin structure

Test of Bjorken sum rule

$$g_1^{NS}(x,Q^2) = g_1^p(x,Q^2) - g_1^n(x,Q^2) \qquad \Gamma_1^{NS}(Q^2) \equiv \int dx\, g_1^{NS}(x,Q^2) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$





C_1^{NS} up to 3rd order in $\alpha_s(Q^2)$: *Larin et al. PLB 404 (1997) 153*

$$\int_{0.004}^{0.7} dx\, g_1^{NS}(x,Q^2) \ \ extrapolated\ to \int_0^1 \ with\ NLO\ fit \rightarrow \left|\frac{g_A}{g_V}\right| = 1.28 \pm 0.07 \pm 0.10$$

$(1.2694 \pm 0.0028 \ \text{ from } \beta \text{ decay})$

Transversity PDF $\Delta_T^0 D_q^h$ or h_1

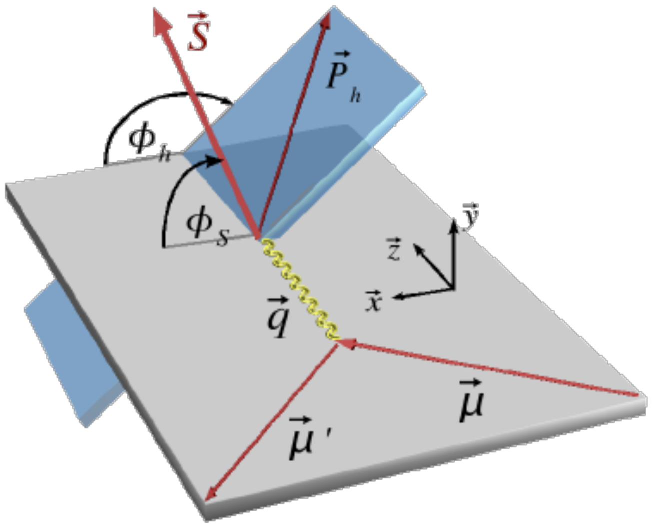
Couple $\Delta_T q$ to chiral odd Collins FF $\Delta_T^0 D_q^h$

$$A_{Coll} = \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 q(x) D_q^h(z, p_T^h)}$$

Azimuthal cross-section asymmetry:

$$\frac{\Delta\sigma}{\sigma} \propto A_{Coll} \sin \Phi_C$$

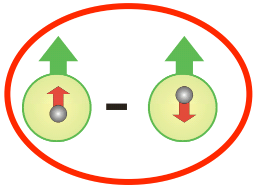
$$\Phi_C = \phi_h + \phi_s - \pi$$

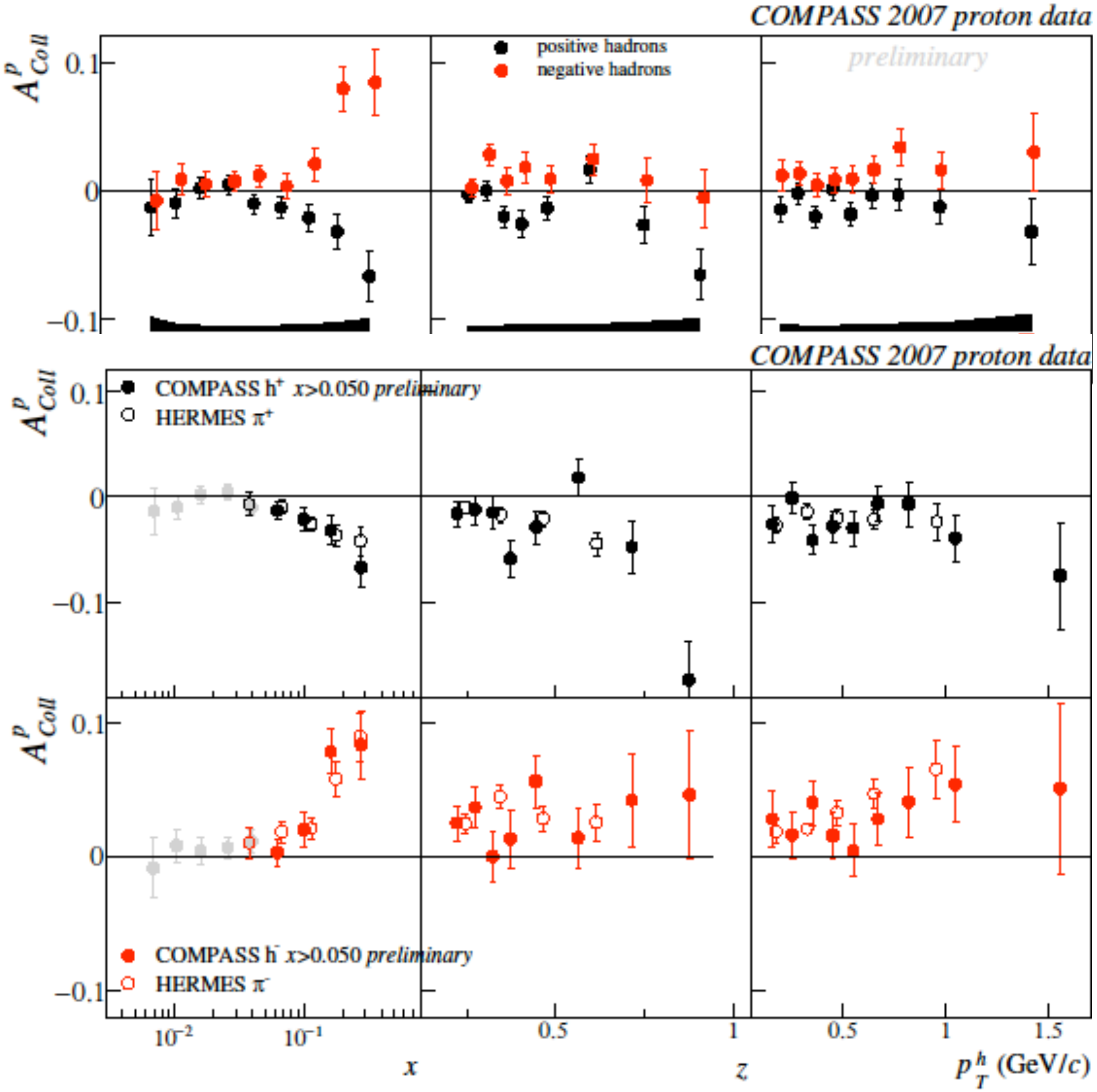


Collins assymetry - proton

Spin dependent fragmentation of transversely polarised quarks into hadrons

$$A_{\mathrm{Coll}} = \frac{A_{\mathrm{T}}^{\mathrm{h},\sin\Phi_{\mathrm{Coll}}}}{D_{\mathrm{NN}} \cdot f \cdot P} = \frac{\sum_q e_q^2 \cdot \Delta_{\mathrm{T}} q \otimes \Delta_{\mathrm{T}} D_q^h}{\sum_q e_q^2 \cdot q \otimes D_q^h}$$





Comparison with HERMES

⇨ COMPASS data with x>0.050

Sub. Phys. Lett. B (hep-ex/1005.5609)

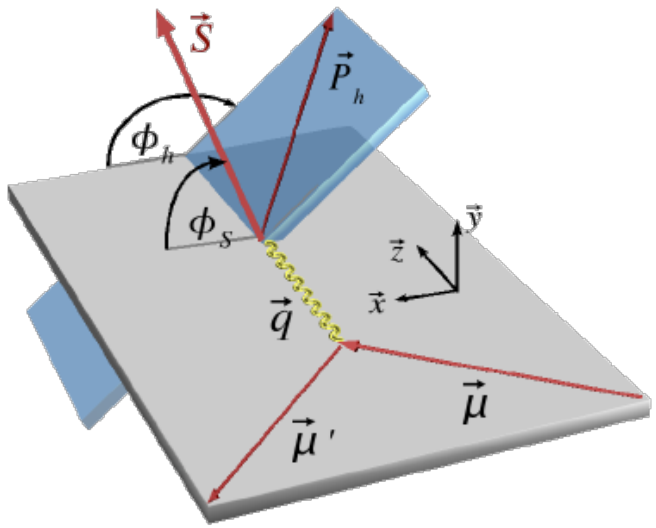
Sievers function $\Delta_0^T q$ or $f_{1T}^{\perp}$

Sivers Asymmetry:

$$A_{Siv} = \frac{\sum_q e_q^2 \Delta_0^T q(x, p_T^h/z) D_q^h(z)}{\sum_q e_q^2 q(x, p_T^h/z) D_q^h(z)}$$

$$\frac{\Delta\sigma}{\sigma} \propto A_{Siv} \sin \Phi_S$$

$$\Phi_S = \phi_h - \phi_S$$

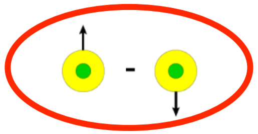


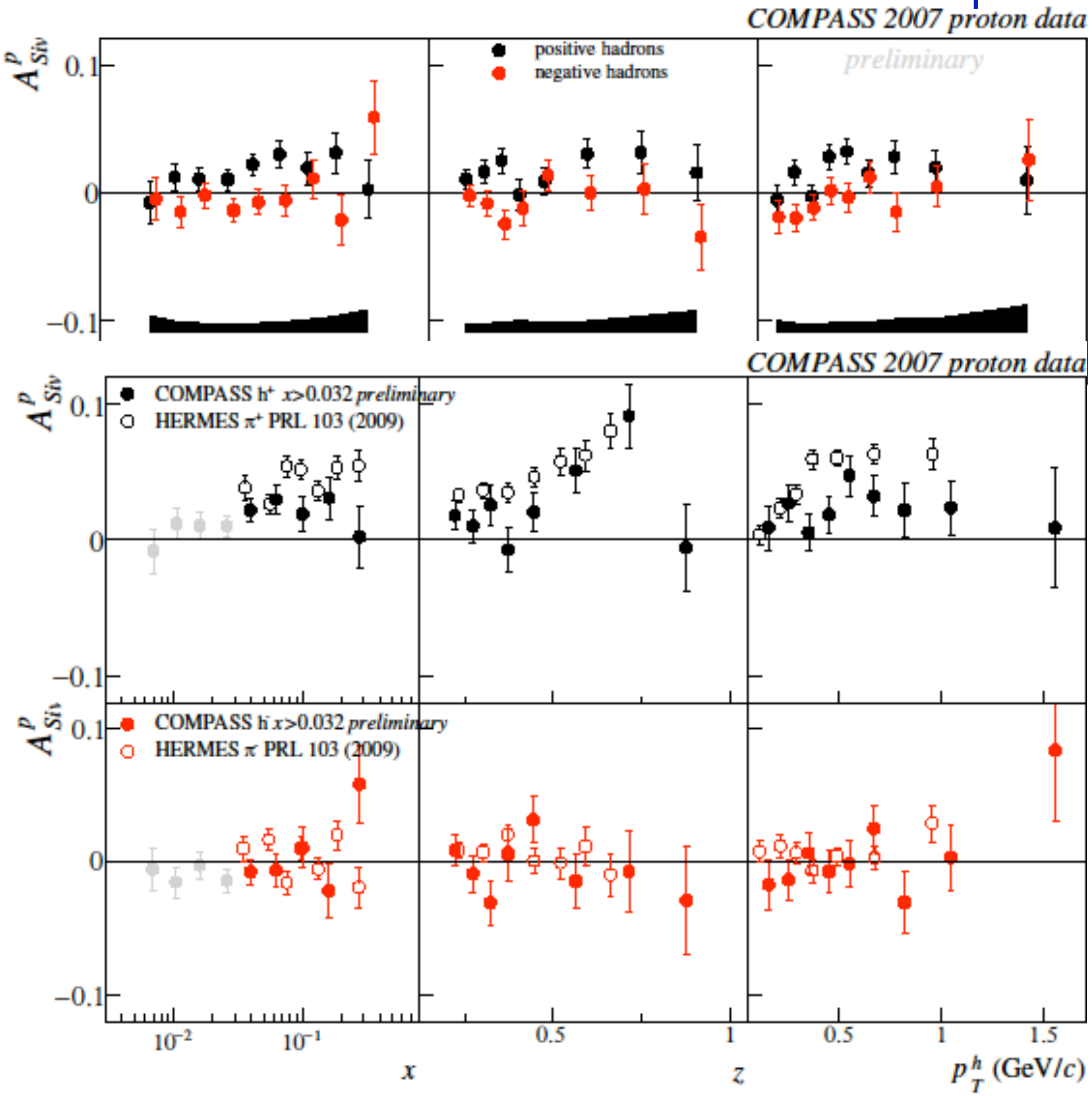
- proposed (1990, Sivers)
- though to vanish (1993, Collins)
- resurrected (2002, Brodsky, Hwang, Schmitt)
- different sign in DY and SIDIS

Sievers assymetry - proton

Intrinsic k_T dependence of the quark distribution correlated to nucleon transverse spin

$$A_{\mathrm{Siv}} = \frac{A_{\mathrm{T}}^{\mathrm{h},\sin\Phi_{\mathrm{Siv}}}}{f \cdot P} = \frac{\sum_q e_q^2 \, \Delta_0^{\mathrm{T}} q \otimes D_q^h}{\sum_q e_q^2 \cdot q \otimes D_q^h}$$





Comparison with HERMES

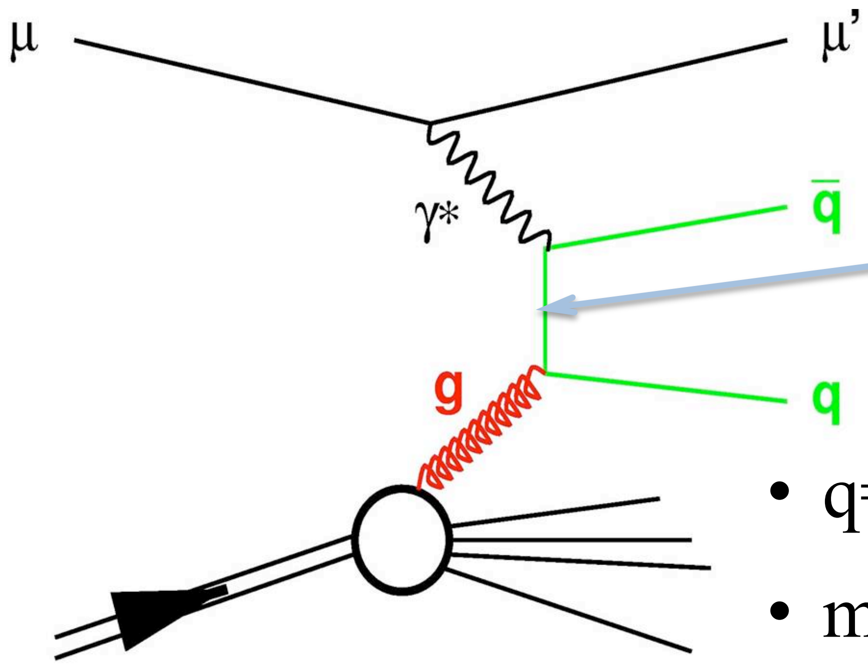
⇨ COMPASS data with x>0.032

Sub. Phys. Lett. B (hep-ex/1005.5609)

Additional data in 2010

Gluon polarization via PGF

Principle: Gluon polarisation enters via photon-gluon fusion (PGF)

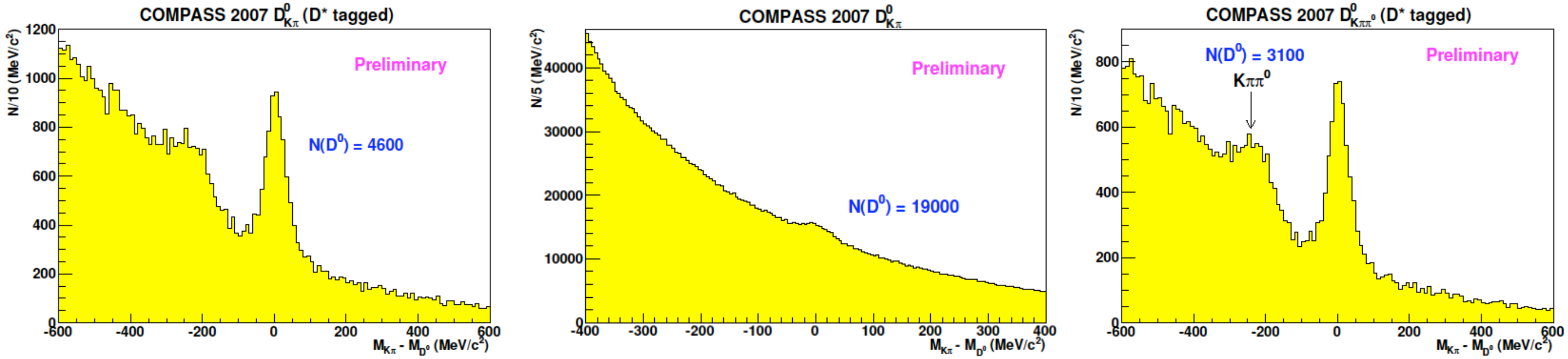


$$A_{LL}^{\mu N} = R^{PGF} a_{LL}^{PGF} \left\langle \frac{\Delta G}{G} \right\rangle$$

- q=c (open charm): no physics bgd
- measure $A_{LL}^{\mu N}$ for events with D°
- calculate R^{PGF}, a_{LL}^{PGF} by MC

Gluon Polarization

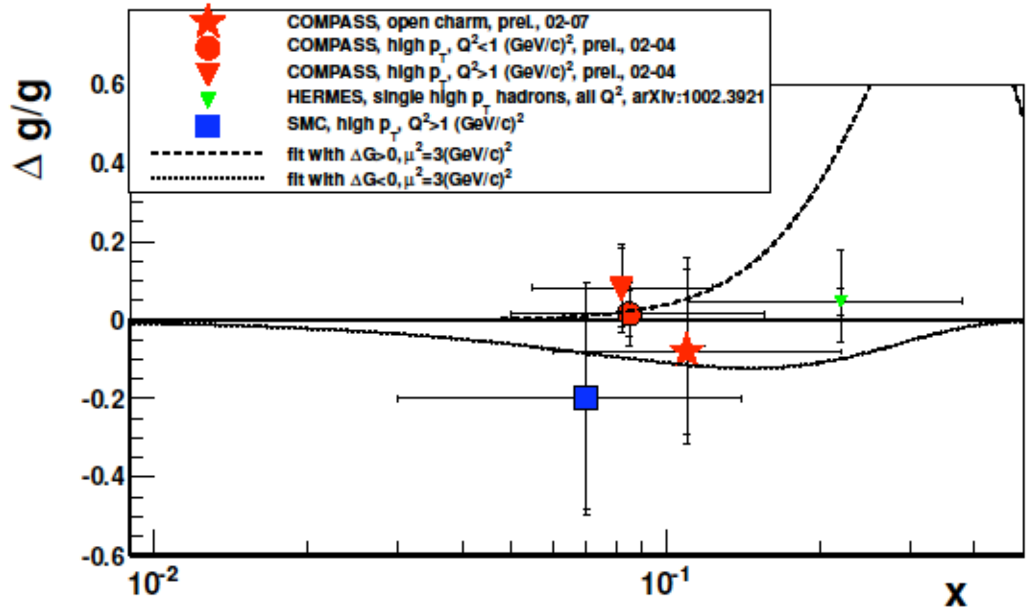
Δ G/G 2002-2007 data



$$D^\circ{}_{K\pi};\ D^\circ{}_{K\pi\pi^\circ};\ D^\circ{}_{K\pi\pi\pi};\ D^\circ{}_{sub(K)\pi}\ \ (all\, D^*\ tagged)$$

$$D^\circ{}_{K\pi}\ \ (untagged)$$

$$2002-2007: proton + deuteron\ data$$



$$\Delta G/G = -0.08 \pm 0.21_{stat} \pm 0.11_{syst}$$

$$\langle x_g \rangle \approx 0.11,\ \mu^2 \approx 13\left(\mathrm{GeV}/c\right)^2$$

COMPASS – II proposal

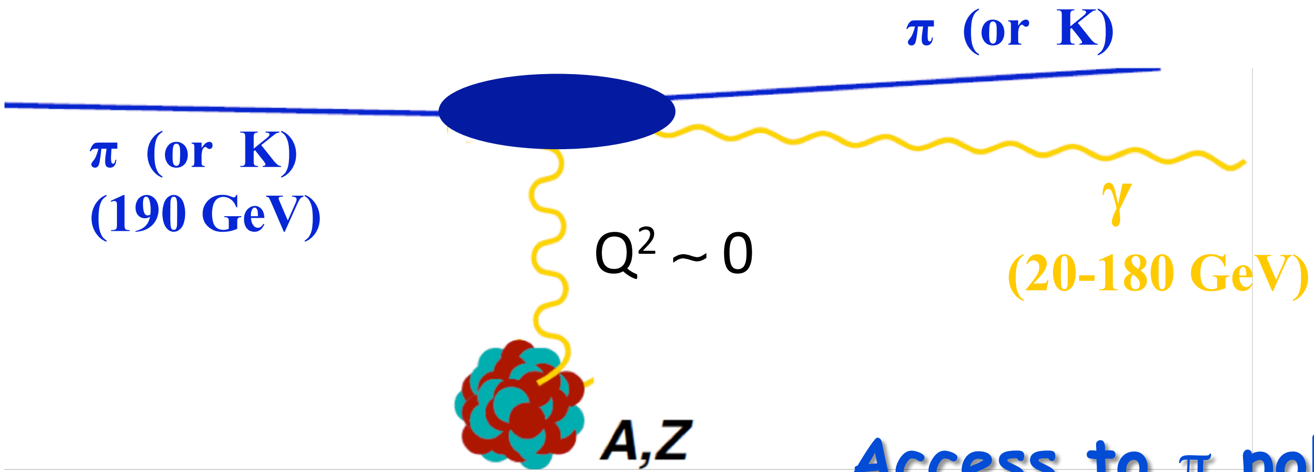
Long Term Plans for at least 5 years (starting in 2012)
Submitted to CERN SPSC commitee June 29

- ✓ Primakoff with π, K beam ➔ Test of Chiral Perturb. Theory 2012
- ✓ DVCS & DVMP with μ beams ➔ Transv. Spatial Distrib. with GPDs 2013
- ✓ SIDIS (with GPD prog.) ➔ Strange PDF and Transv. Mom. Dep. PDFs
- ✓ Drell-Yan with π beams ➔ Transverse Momentum Dependent PDFs 2014

Pion polarizabilities

Primakov experiment

Inverse Compton Scattering on π, K



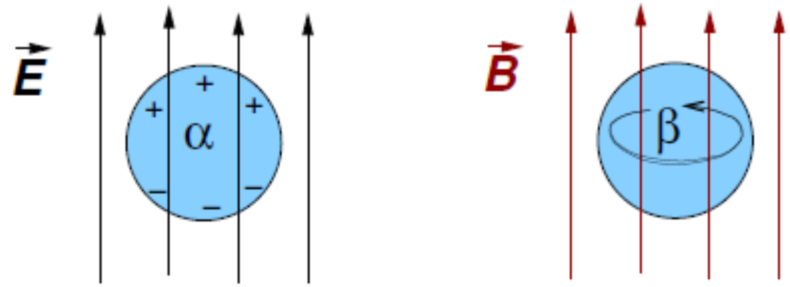
Access to π polarisabilities

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{\rm cm}} = \left[\frac{d\sigma_{\pi\gamma}}{d\Omega_{\rm cm}}\right]_{\rm pt} + C.\frac{(s-m_\pi^2)}{s^2}\cdot\left((1-\cos\theta_{\rm cm})^2(\alpha_\pi-\beta_\pi) + (1+\cos\theta_{\rm cm})^2(\alpha_\pi+\beta_\pi)\frac{s^2}{m_\pi^4} + (1-\cos\theta_{\rm cm})^3(\alpha_2-\beta_2)\frac{(s-m_\pi^2)^2}{24s}\right)$$

the point-like cross section is measured with the muon beam

π polarizability and ChPT

The polarisabilities give the deformation of the pion shape by an EM field



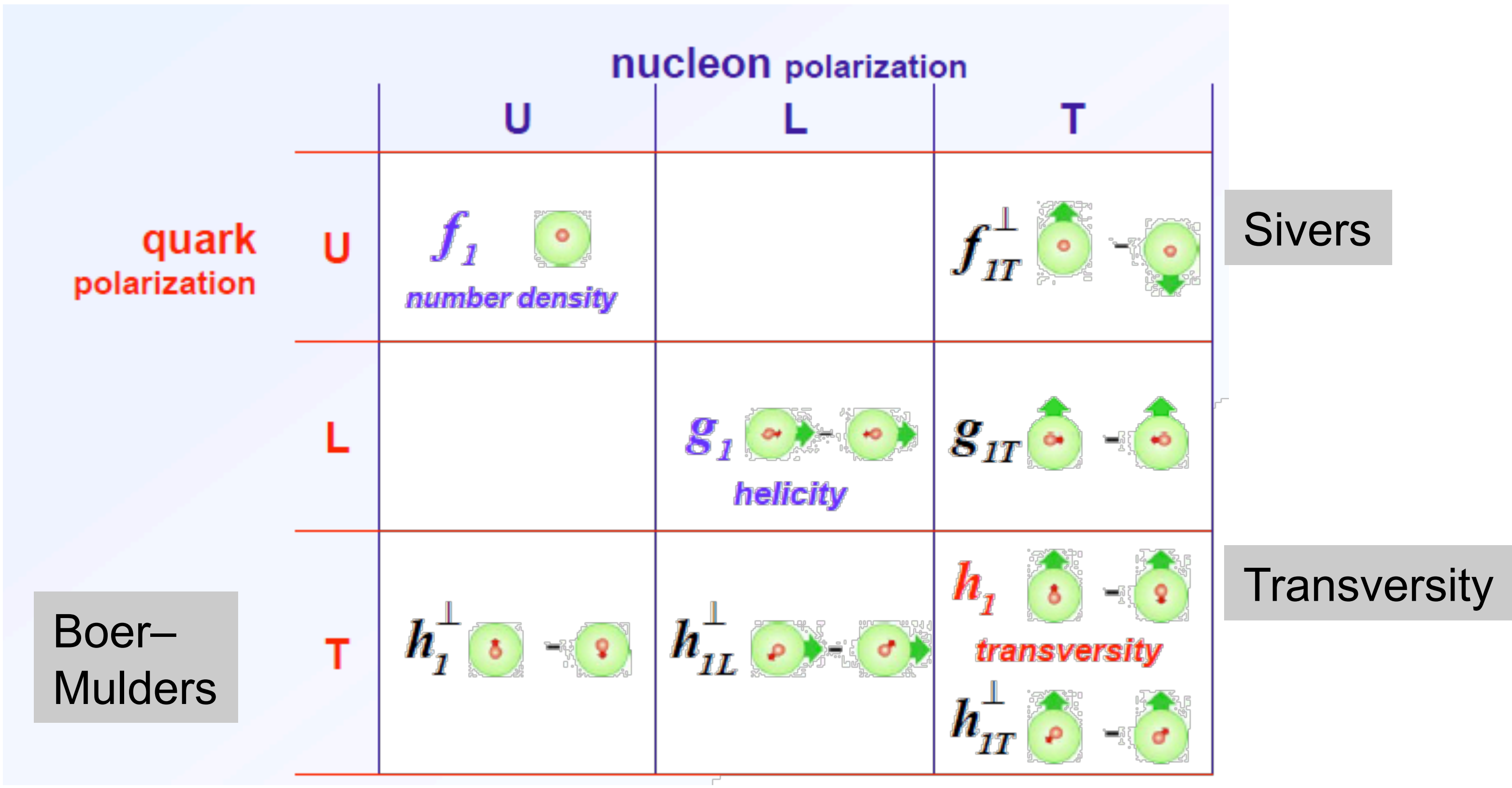
$\alpha_\pi > 0$ S=0 diamagnetic contr. $\beta_\pi < 0$

Present experiments: $\alpha_\pi - \beta_\pi$ from 4 to 14 $.10^{-4}$ fm^3

in 120 days 90 days for π beam 30 days for μ beam	$\alpha_\pi - \beta_\pi$ in 10^{-4} fm^3	$\alpha_\pi + \beta_\pi$ in 10^{-4} fm^3	$\alpha_2 - \beta_2$ in 10^{-4} fm^5
2-loop ChPT prediction	5.70 ± 1.0	0.16 ± 0.10	16
COMPASS accuracy	±0.66	±0.025	±1.94

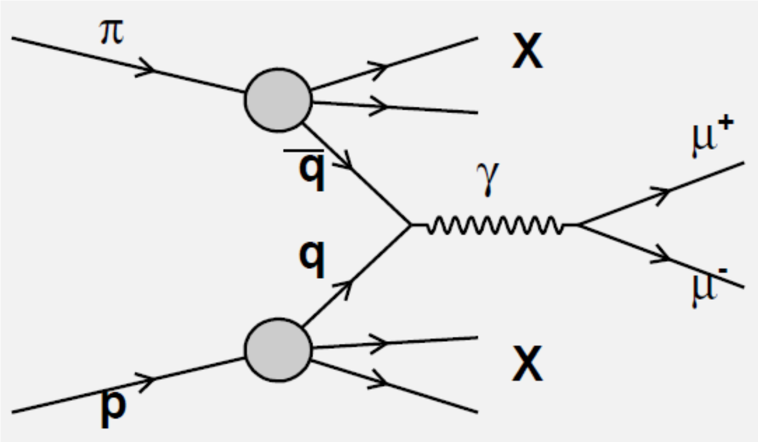
Transverse Mom. Dep. PDF

- 8 intrinsic transverse momentum dependent PDFs at LO
- Asymmetries with different angular dependences on hadron and spin azimuthal angles, Φ_h and Φ_s



Drell-Yann TMDs

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



Pure valence u dominance because of the π^- beam

Cross sections:

In SIDIS: convolution of a TMD with a fragmentation function

In DY: convolution of 2 TMDs $\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|p}$

→ complementary information and universality test

Drell-Yann
TMDs

Drell-Yan cross section at LO

Boer-Mulders

$$d\sigma^{DY} \propto \Big(1+\int d^2k_{1T}\, d^2k_{2T}\, \mathcal{W}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2)\otimes h_1^{\perp}(x_2,k_{2T}^2)\cos 2\phi$$

Sivers

$$+\left|S_T\right|\Big(\int d^2k_{1T}\, d^2k_{2T}\, \mathcal{X}(k_{1T},k_{2T})\, \bar{f}_1(x_1,k_{1T}^2)\otimes f_{1T}^{\perp}(x_2,k_{2T}^2)\sin\phi_S$$

$$+\int d^2k_{1T}\, d^2k_{2T}\, \mathcal{Y}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2)\otimes h_{1T}^{\perp}(x_2,k_{2T}^2)\sin(2\phi+\phi_S)$$

$$+\int d^2k_{1T}\, d^2k_{2T}\, \mathcal{Z}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2)\otimes h_1(x_2,k_{2T}^2)\sin(2\phi-\phi_S)\Big)\Big)$$

The T-odd character of the Boer-Mulders and Sivers function implies that these functions are process dependent

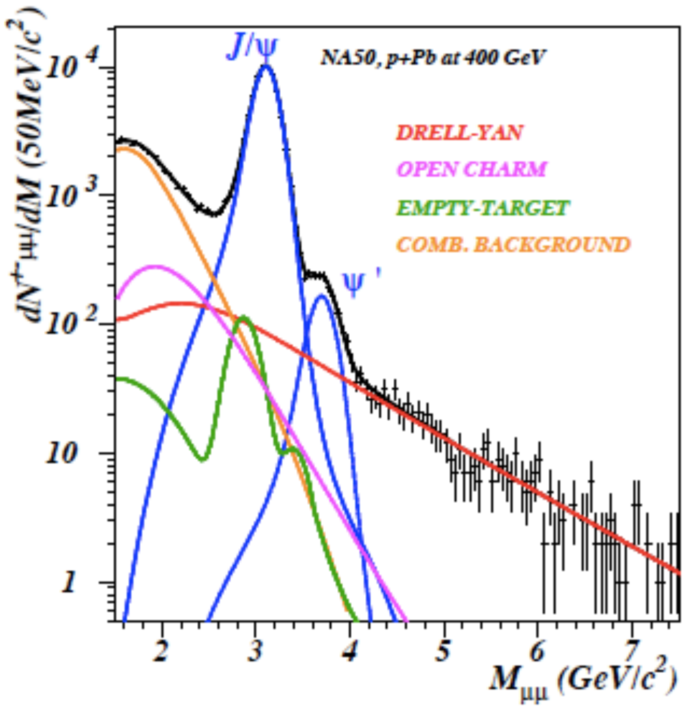
Boer-Mulders

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

Sivers

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

Background estimates



In the dimuon mass spectrum, 2 background sources must be considered:

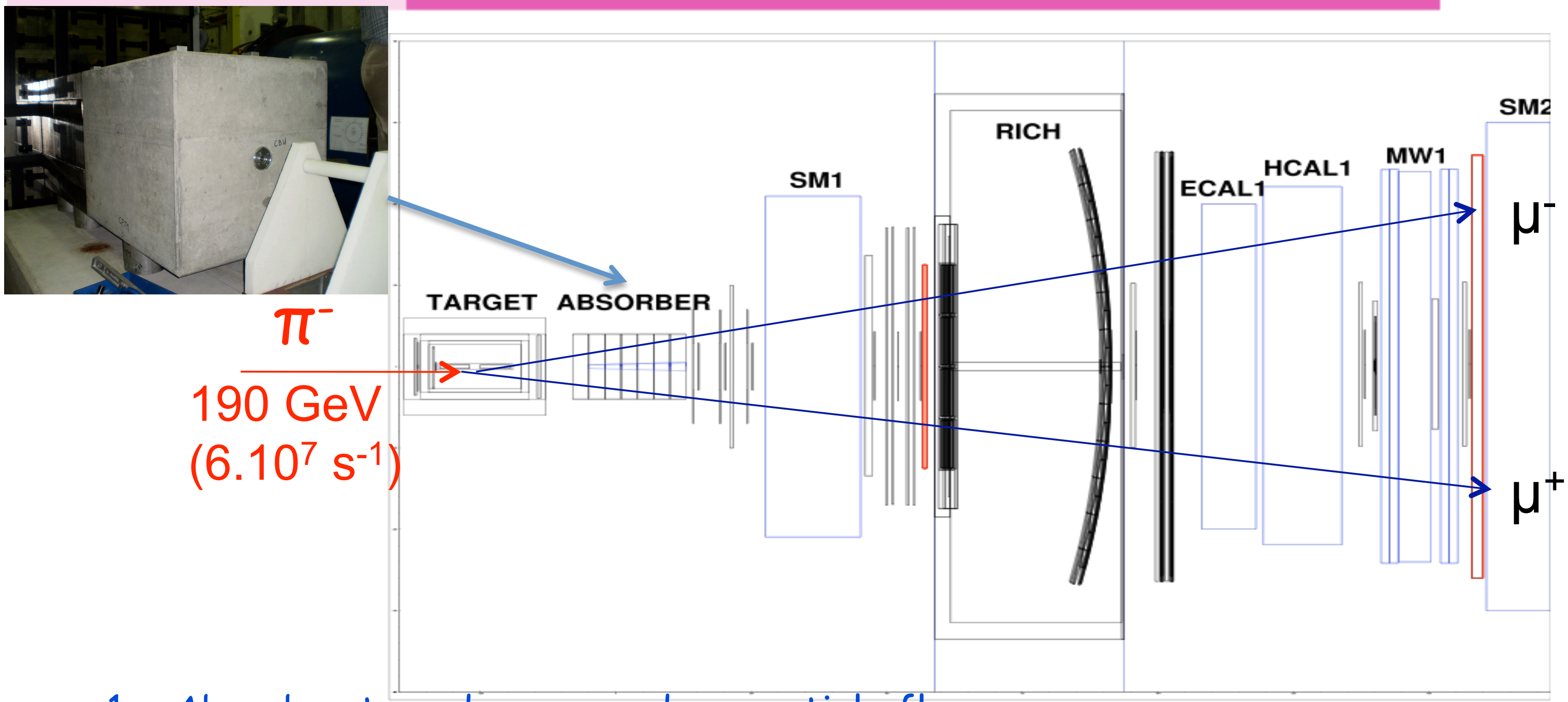
- physics background:
  D and $\bar{D}$ decays to $\mu^{\pm}X$;
  J/ψ and ψ', also a subject of research.
- Combinatorial background
  π and K decaying to $\mu\nu$

The cleanest region to study Drell-Yan is $4. < M < 9.$ GeV/c^2

In the region $2.0 < M < 2.5$ GeV/c^2 there is important contribution from background sources.

Polarized Drell-Yan measurements in COMPASS C. Quintans -

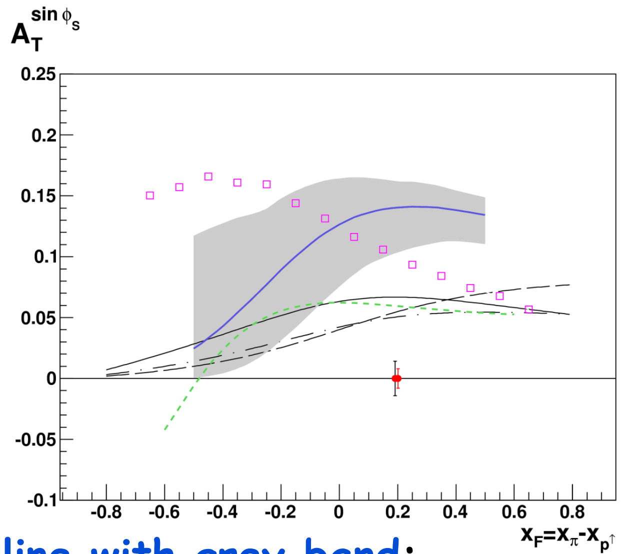
DY COMPASS setup



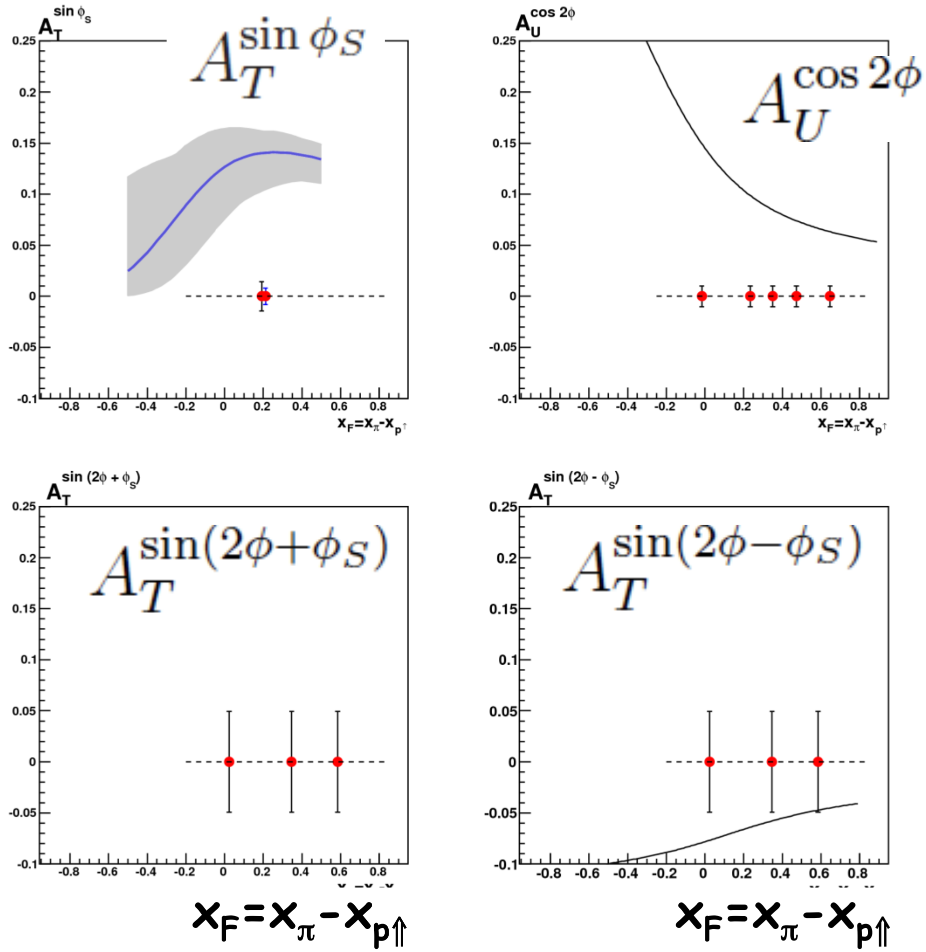
1. Absorber to reduce secondary particle flux
2. COMPASS Polarised Target (2x55cm cells)
3. Tracking system and beam telescope
4. Muon trigger (LAS of particular importance - 60% of the DY acceptance)
5. RICH1, Calorimetry – also important to reduce the background

Drell-Yann
TMDs

DY predictions at COMPASS



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



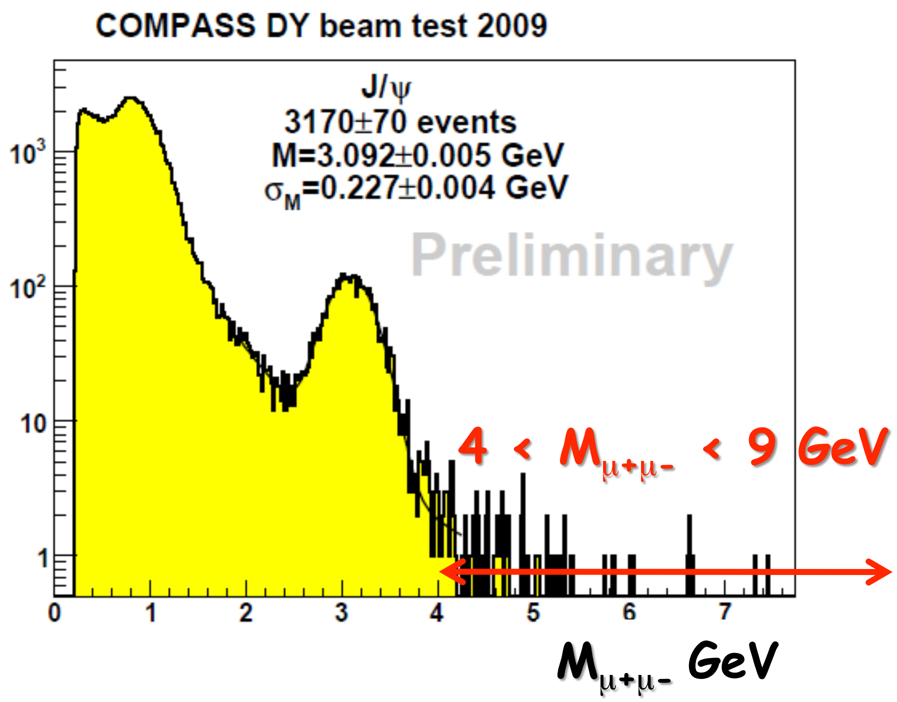
Blue line with grey band:
Anselmino et al., PRD79 (2009)
Black solid and dashed:
Efremov et al., PLB612 (2005)
Black dot-dashed:
Collins et al., PRD73 (2006)
Squares:
Bianconi et al., PRD73 (2006)
Green short-dashed:
Bacchetta et al., PRD78 (2008)

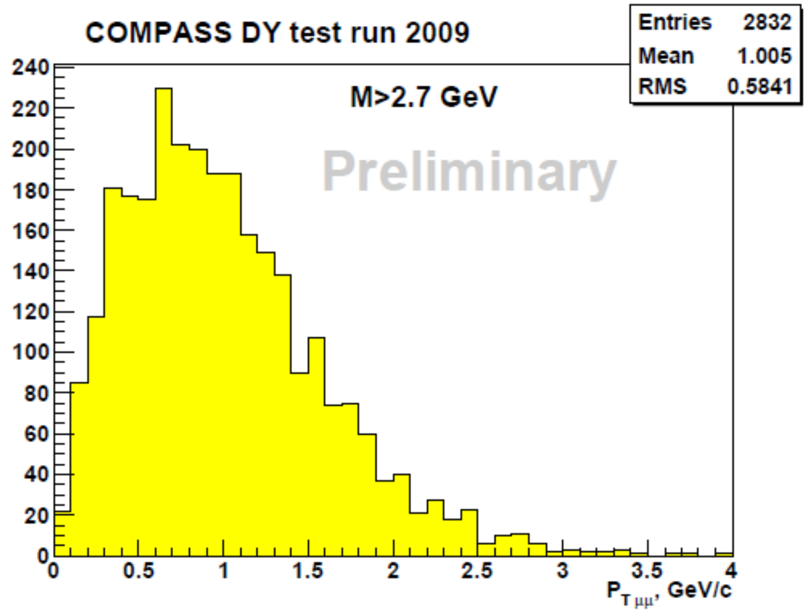
Drell-Yann
TMDs

Results from 2009 DY test

Expected: 3600±600 J/ψ and 110±22 DY

Measured: 3170±70 J/ψ and 84±10 DY





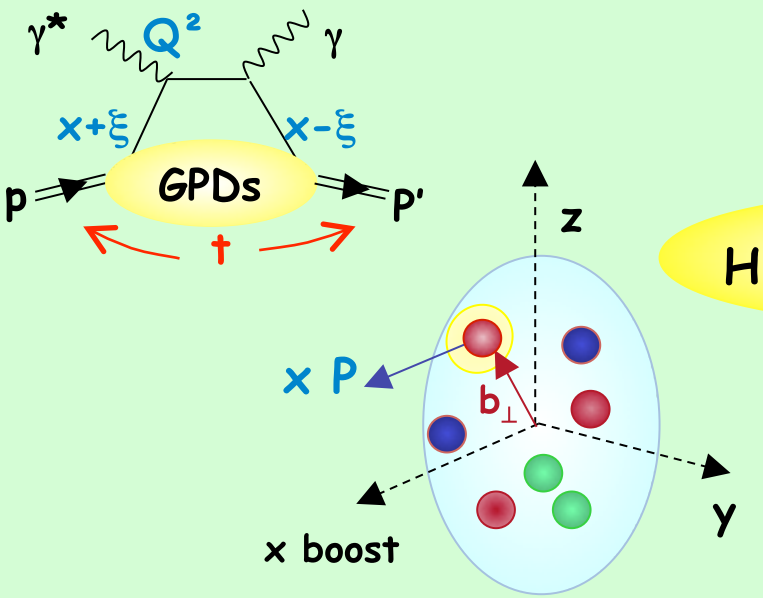
<Pt> = 1 GeV/c

➔ COMPASS sensitive to TMDs

Generalized Parton Dist.

Deeply Virtual Compton Scattering

$\mu p \rightarrow \mu' p' \gamma$

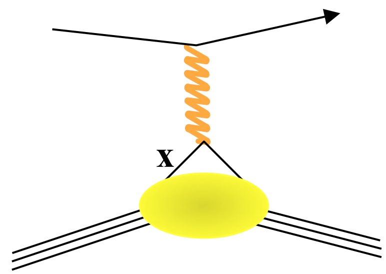


Generalized Partons Distrib. $H(x, \xi, t)$

$(P_x, b_\perp)$

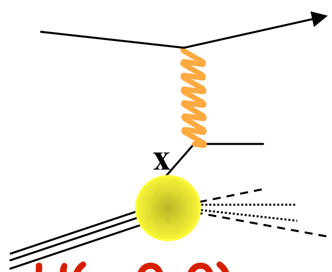
$H, \tilde{H}, E, \tilde{E}\ (x, \xi, t)$

Elastic Form Factors



$\int H(x,\xi,t)dx = F(t)$

"ordinary" parton density



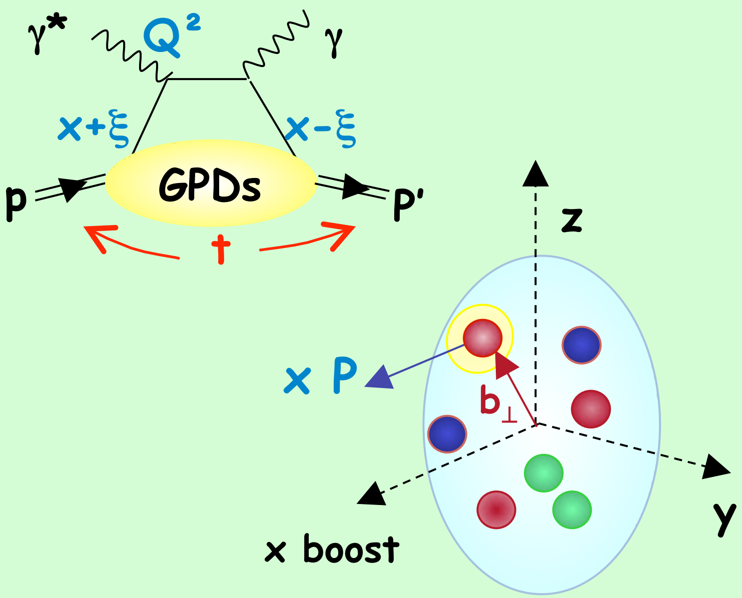
$H(x,0,0) = q(x)$

$\tilde{H}(x,0,0) = \Delta q(x)$

Generalized Parton Dist.

Deeply Virtual Compton Scattering

$\mu p \rightarrow \mu' p' \gamma$



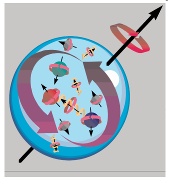
Generalized Partons Distrib. $H(x,\xi,t)$

$(P_{x},\ b_{\perp})$

Ji's sum rule

$$2J_q = \int x(H+E)(x,\xi,0)dx$$

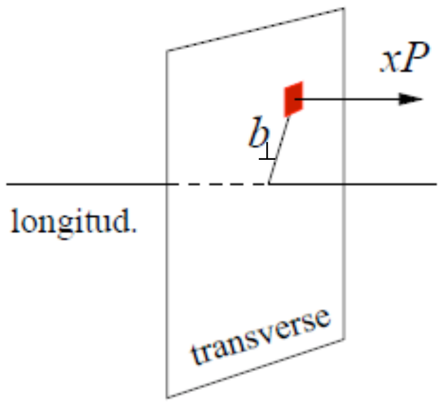
$$1/2 = \underbrace{1/2\ \Delta\Sigma + Lq}_{} + \Delta G + Lg$$



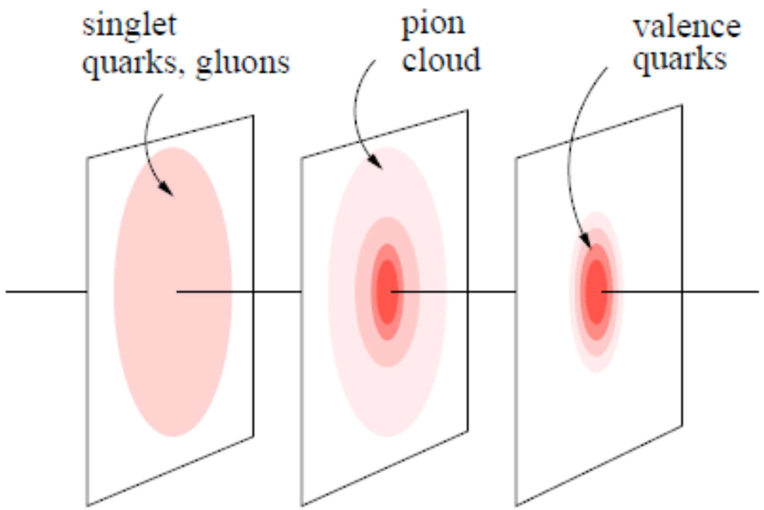
DVCS
GPDs

Nucleon tomography

GPDs allow simultaneous measurement of longitudinal momentum and transverse spatial structure



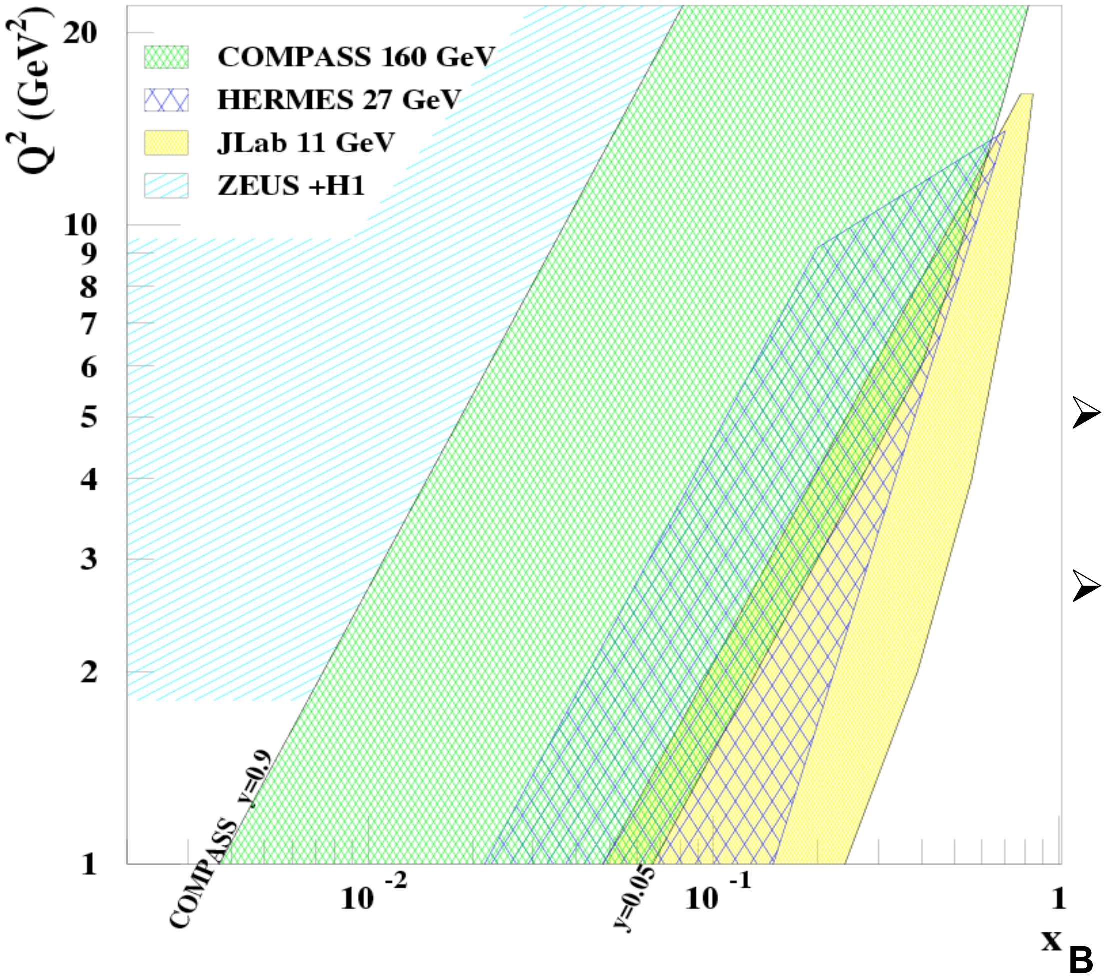
Impact parameter $b_\perp$
Longitudinal momentum fraction x



x ~ 0.003 x ~ 0.03 x ~ 0.3

Tomographic parton images of the nucleon

Kinematical domain



CERN High energy muon beam

- ✓ 100 - 190 GeV
- ✓ μ^+ and μ^- available
- ✓ 80% Polarisation with opposite polarization

➢ Will explore the intermediate x_{Bj} region

➢ Uncovered region between ZEUS+H1 and HERMES+Jlab

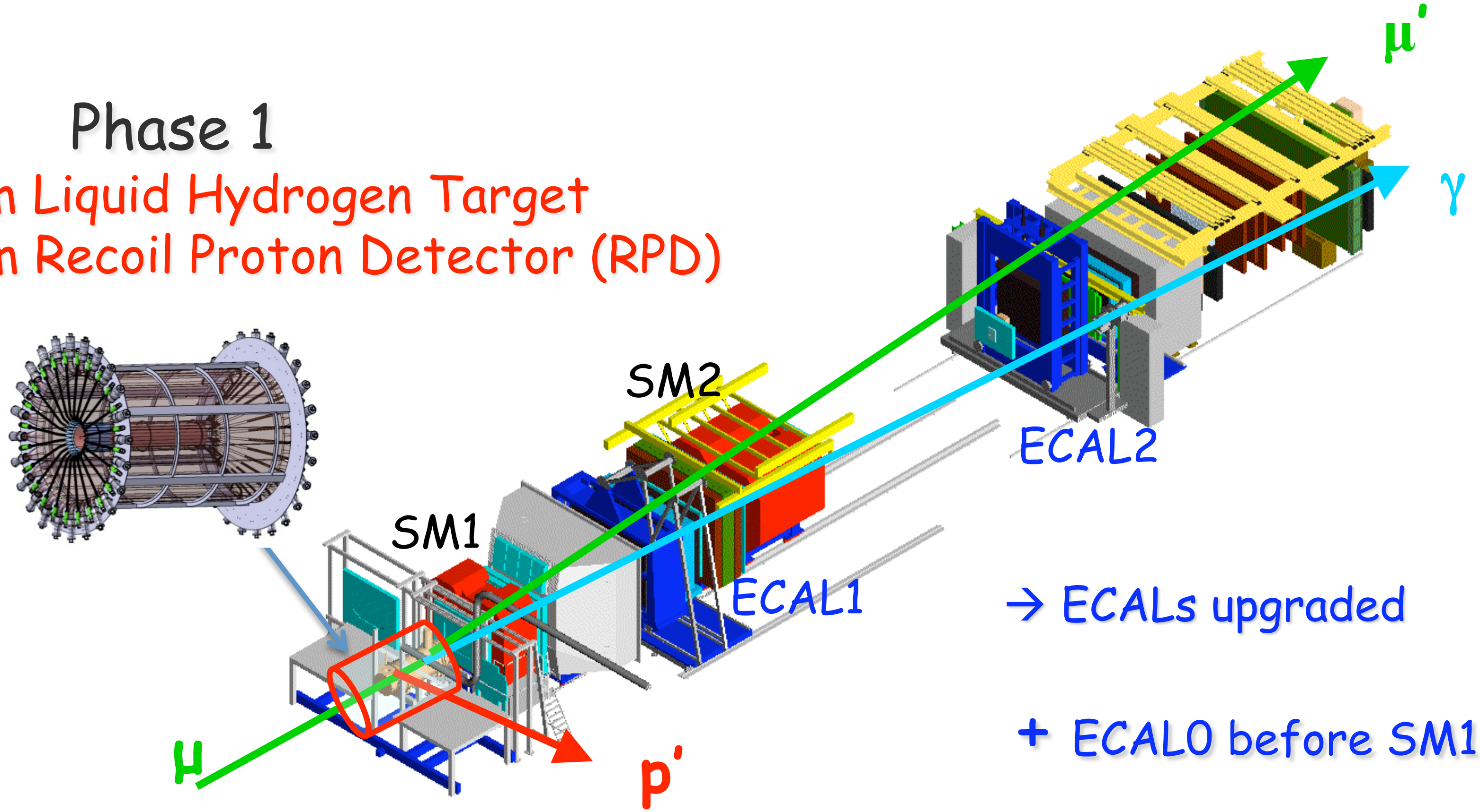
before new colliders may be available

Experimental setup

Phase 1

~ 2.5 m Liquid Hydrogen Target

~ 4 m Recoil Proton Detector (RPD)



→ ECALs upgraded

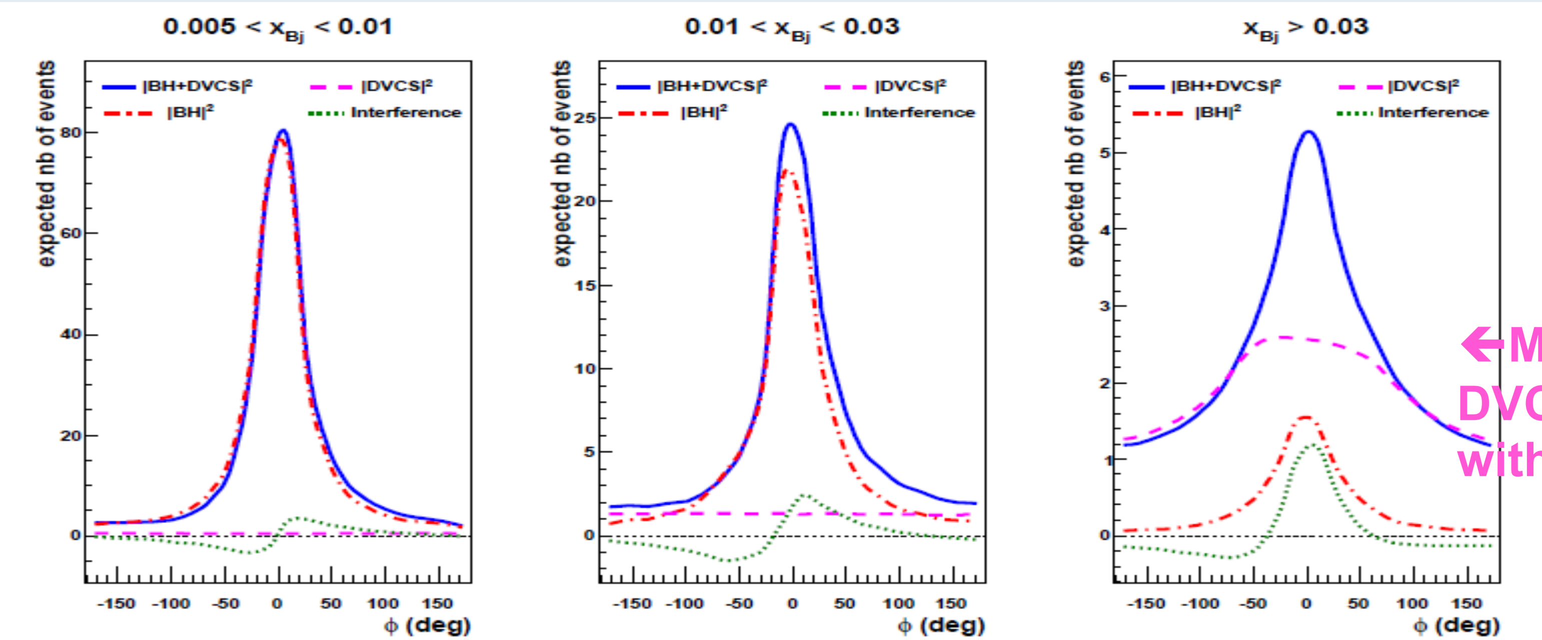
+ ECAL0 before SM1

DVCS
GPDs

Interferences DVCS - BH

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

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



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

← Missing DVCS acceptance without ECAL0

BH dominates

excellent
reference yield

study of Interference

→ Re A^{DVCS}
or Im A^{DVCS}

DVCS dominates

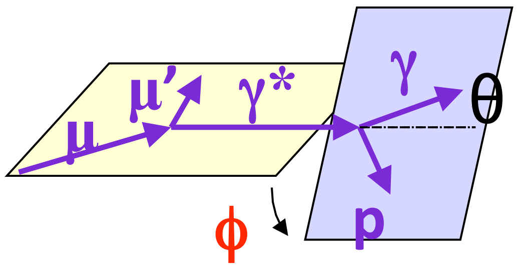
study of $d\sigma^{DVCS}/dt$
→ Transverse Imaging

Beam charge and spin sum

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

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

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



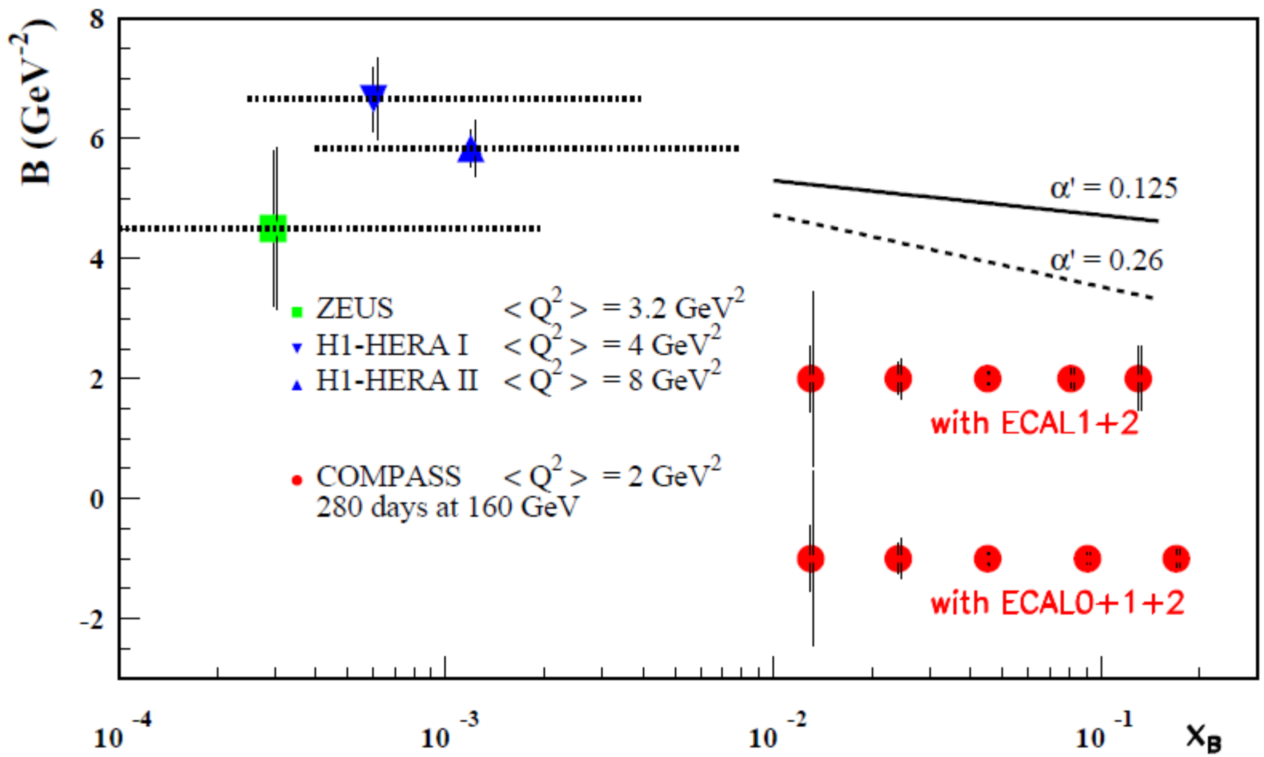
$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$

Transverse imaging

$s_1^{Int} \sim Im(F_1 \mathcal{H})$

Transverse imaging

Integrating $\mathcal{S}_{CS,U}$ over Φ and substracting BH → $d\sigma^{DVCS}/dt \sim \exp(-B|t|)$



$B(x_B) = \frac{1}{2} < r_\perp^{\,2}(x_B) >$

$r_\perp = b_\perp/(1-x)$
(0.65 fm at low x)

2 years of data
160 GeV muon beam
2.5m LH_2 target
$\varepsilon_{global} = 10\%$

ansatz at small x_B:

$B(x_B) = b_0 + 2\ \alpha'\ \ln(x_0/x_B)$

- determination of B with 0.1 GeV^{-2} accuracy, α′ with 2.5σ acc. if α′ ≥0.12
- no model dependence

DVCS
GPDs

Beam charge and spin diff

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

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

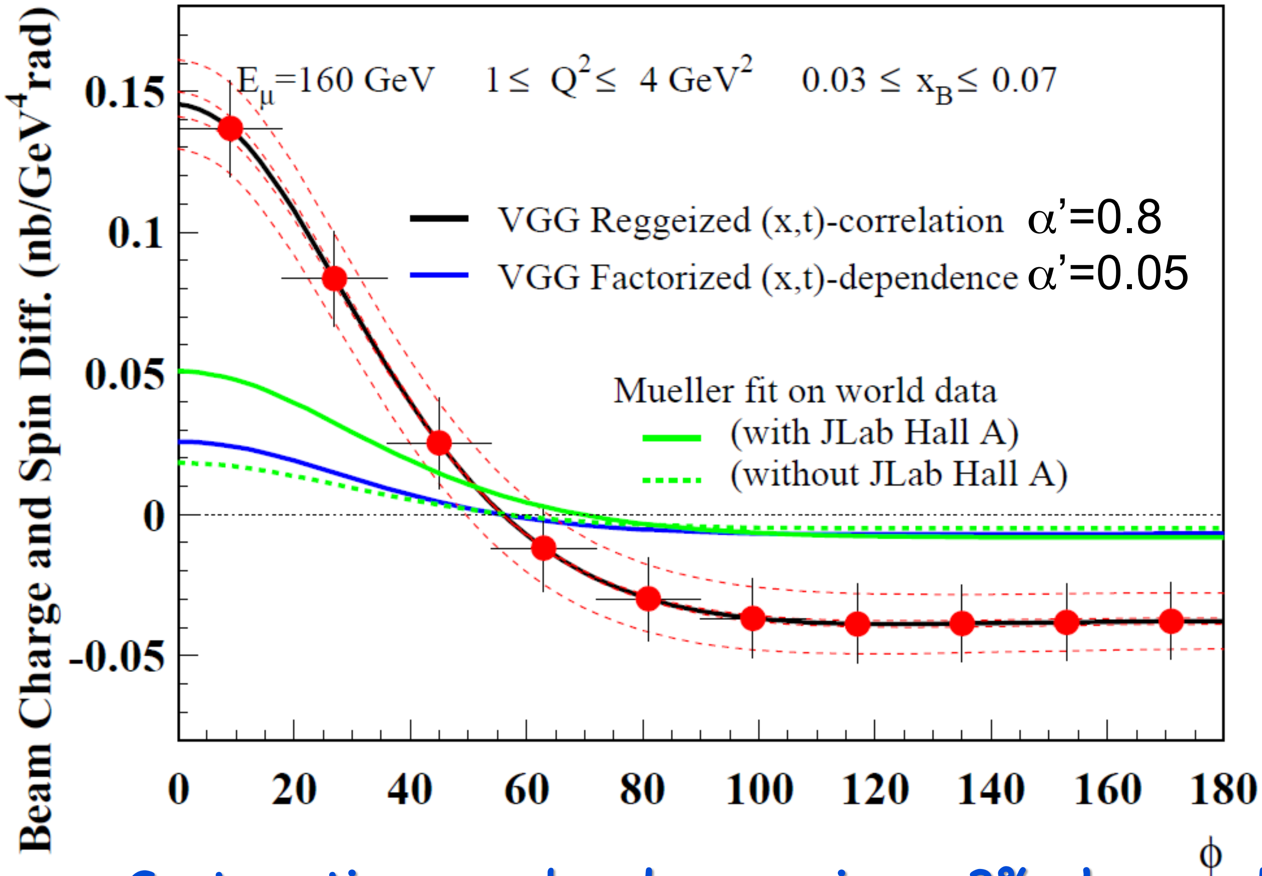
Advantage: BH contribution cancels
Difficulty: needs control of absolute X-section at few % level

Alternative: Beam charge and spin asymmetry

$$\mathcal{A}_{CS,U} = \frac{d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow})}{d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow})}$$

DVCS
GPDs

Beam charge and spin diff



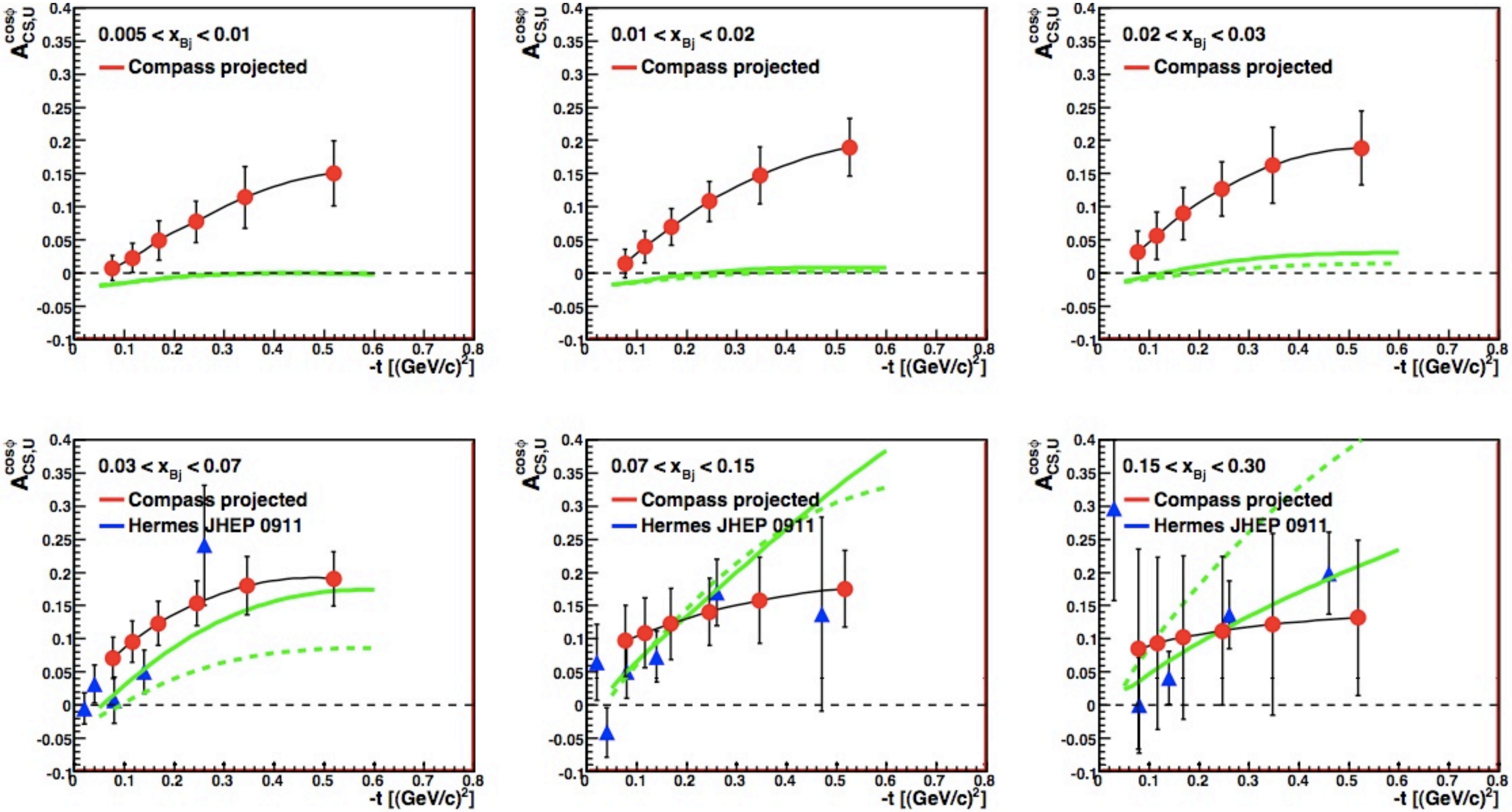
$$\ldots . + c_1^{Int} \cos\varphi + \ldots$$

=> $\mathcal{R}e\,(F_1\mathcal{H})$

2 years of data
160 GeV muon beam
2.5m LH_2 target
$\varepsilon_{global} = 10\%$

Systematic error bands assuming a 3% charge-dependent effect between μ+ and μ- (control with inclusive evts, BH…)

Beam charge and spin asym

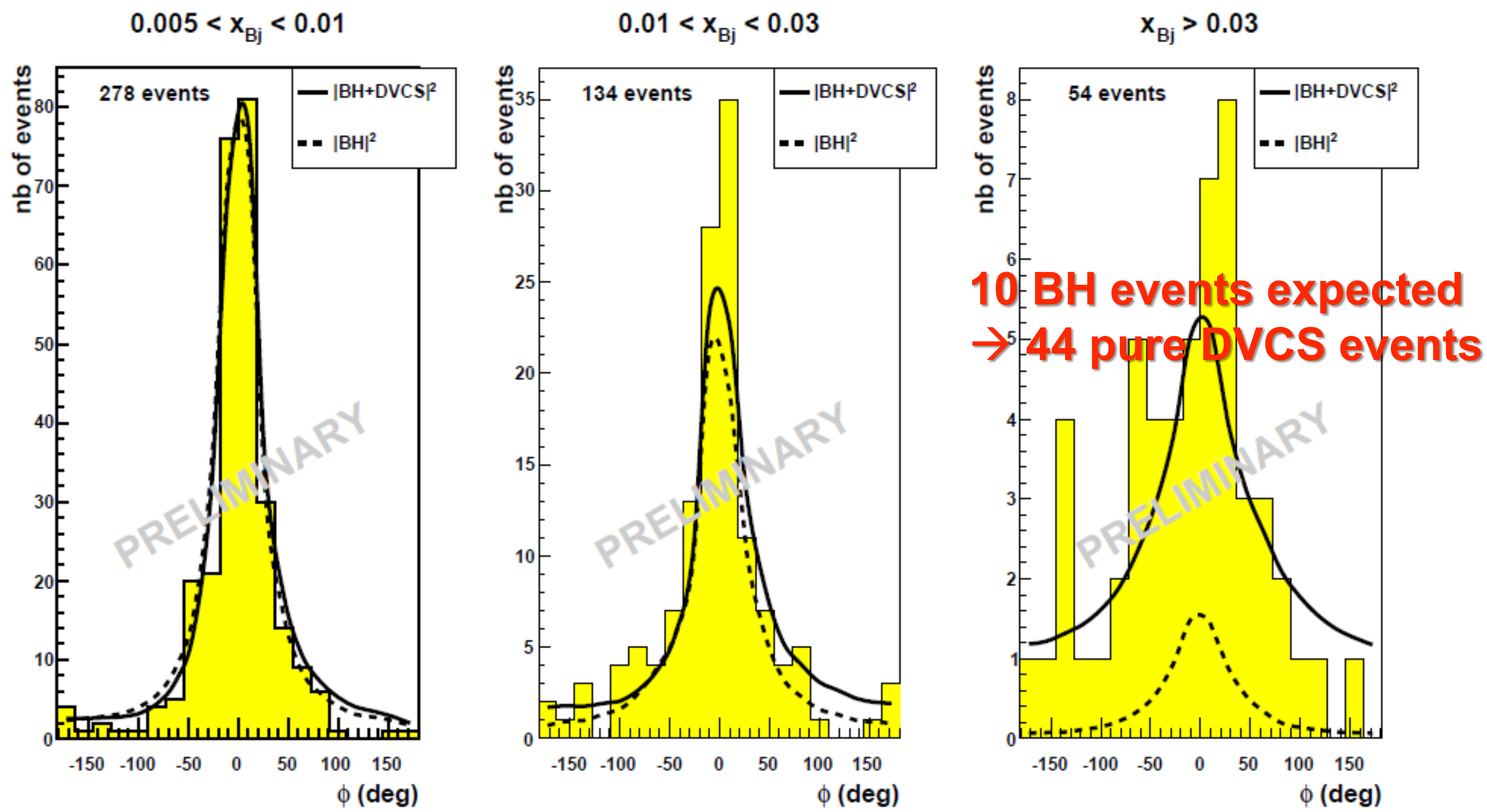


Projection with VGG model (Regge Ansatz) compared to HERMES data

Results from 2009 DVCS test

1m long recoil proton detector (RPD) and 40cm long LH2 target

Selection of events: vertex with μ and μ' (no other charged track)
one high energy photon
proton in RPD + exclusivity cuts



Conclusions

•New results for spin structure:

-precise test of Bjorken sum rule

-non zero transverse spin and momentum effects

-constraints on gluon polarization

•Future program (2012…) submitted to CERN SPSC:

-Primakov: ChPT tests and π polarizabilities

-DY: TMD PDFs and univerality DY-SIDIS

-DVCS: constrain GPD H, dσ/dt → tranverse imaging
(phase 2: GPD E, needs transv. pol. target + RPD)

→ New groups welcome to join COMPASS