COMPASS: a Facility to study QCD

A Collaboration of 240 Physicists of 12 countries

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY

Medium and Long Term Plans:

LoI submitted to CERN/SPSC in January 2009
Proposal in preparation

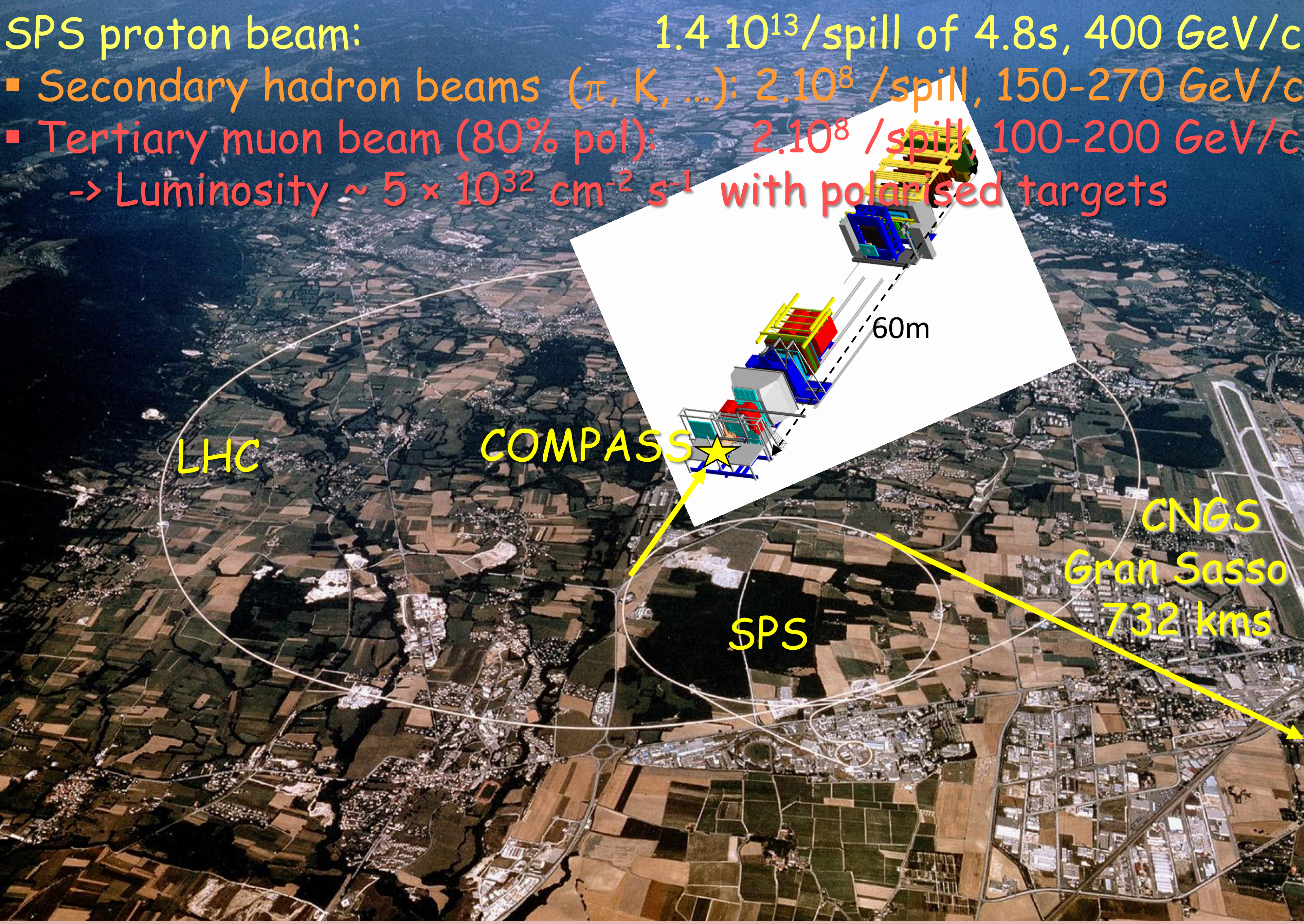
2010-11: Transv. and Long. Nucleon Spin Structure (R. Joosten, E. Kabuss)
with polarised μ and NH_3 (proton) target

≥2012: Hadron Spectroscopy and Primakoff with π, K beam (S. Paul)
Transv. Spatial Distrib. GPDs with DVCS and DVMP with μ beams
Transv. Mom. Distrib. with Drell-Yan with π and in far future $\bar{p}$, K

SPS proton beam: 1.4 10^{13}/spill of 4.8s, 400 GeV/c

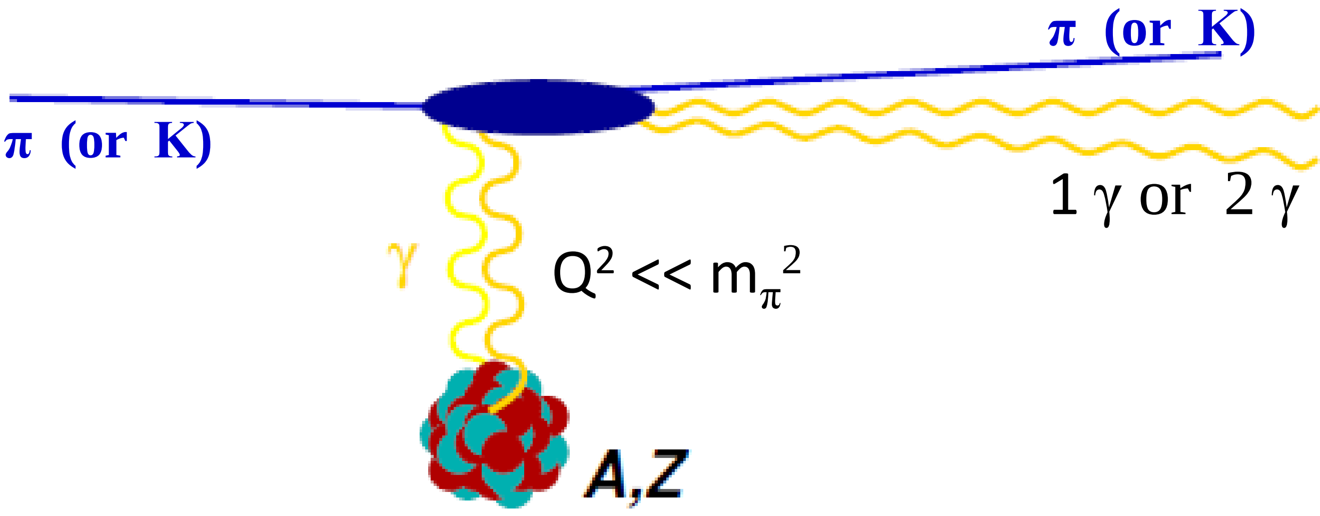
- Secondary hadron beams (π, K, ...): 2.10^{8} /spill, 150-270 GeV/c
- Tertiary muon beam (80% pol): 2.10^{8} /spill, 100-200 GeV/c

-> Luminosity ~ 5 × 10^{32} cm^{-2} s^{-1} with polarised targets



high energy beam(s), broad kinematic range, large angular acceptance

Primakoff experiments with π, K
or inverse Compton Scattering on π, K



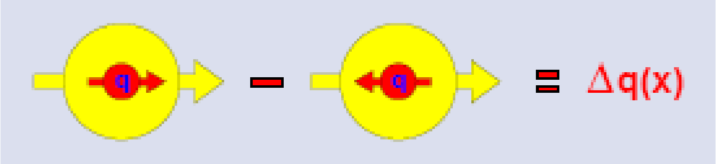
$\pi\,\gamma \rightarrow \pi\,\gamma$ or $K\,\gamma \rightarrow K\,\gamma$: pion (or kaon) polarizabilities
(crucial comparison with (point-like) muon beam)

$\pi\,\gamma \rightarrow \pi\,\pi^0$: chiral anomaly ($F_{\gamma 3\pi}$)

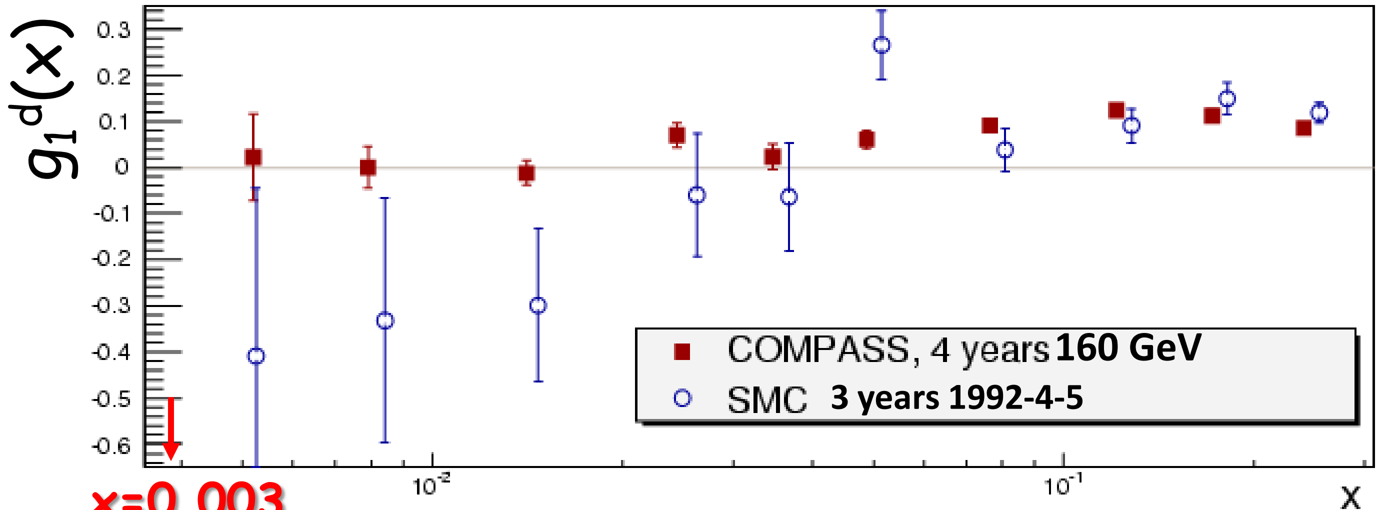
Test of QCD at low energy in π rest frame

Longitudinal Spin Structure Function of the Deuteron

$$g_1(x) = \frac{1}{2}\sum_{q=u,d,s} e_q^2 \Delta q(x) \qquad \Delta q = \vec{\vec{q}} - \overleftarrow{\vec{q}}$$



Inclusive measurements on a longitudinally polarised deuteron target in 2002-3-4-6



- Only place for high energy polarized lepton beams → low x and high Q2
- Precise measurement + impact at small x → systematics from the extrapolation for the unmeasured low x contribution to $\int_0^1 g_1(x)\,dx$ considerably reduced

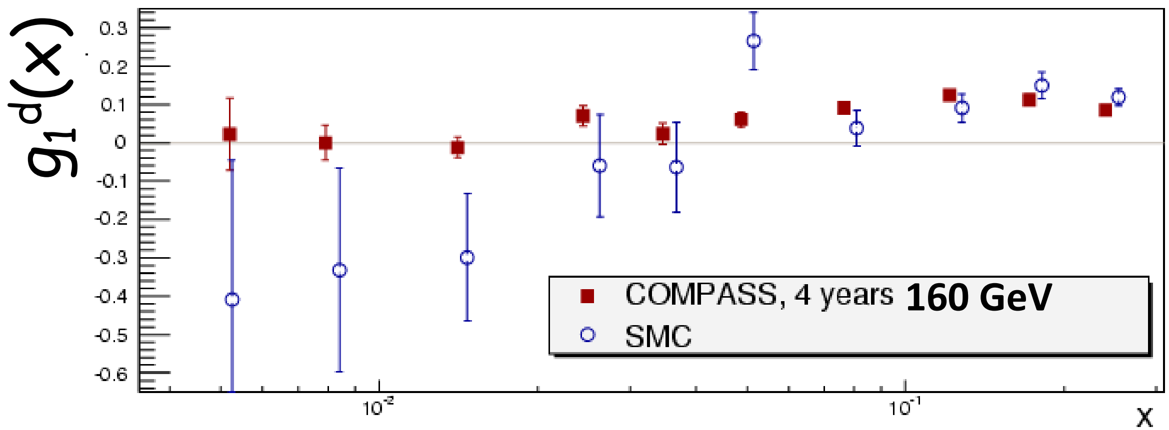
Quark helicity $Q^2=3\ GeV^2$ PLB 647 (2007) 8

$$\Delta\Sigma = \sum_q \int_0^1 \Delta q(x)\,dx = 0.30 \pm 0.01\ (\text{stat}) \pm 0.02\ (\text{extrapolation})$$

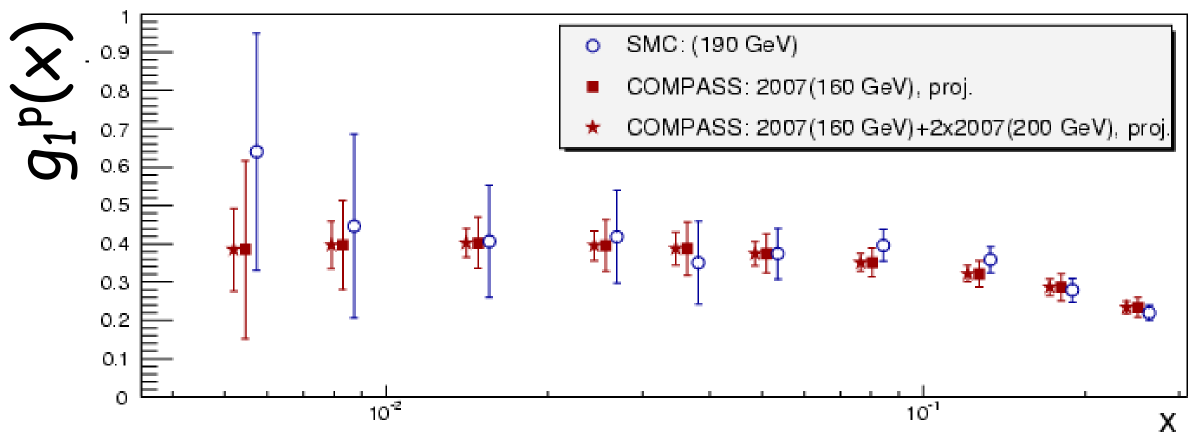
Longitudinal Spin Structure Function of the Proton

Necessity of a balanced statistics between proton and deuteron data

Inclusive measurements on a longitudinally polarised deuteron target in 2002-3-4-6



Inclusive measurements on a longitudinally polarised proton target in 2007



+ **150 days** (1 year) of SPS beam

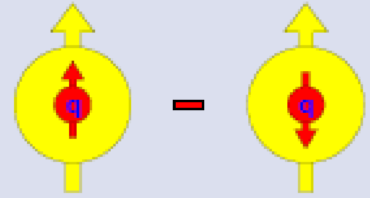
at 200 GeV

COMPASS Projection with 1 additional year of proton

At small x
→precise shape determination
→better extrapolation

Transversity distribution

chiral-odd distribution accessed in SIDIS

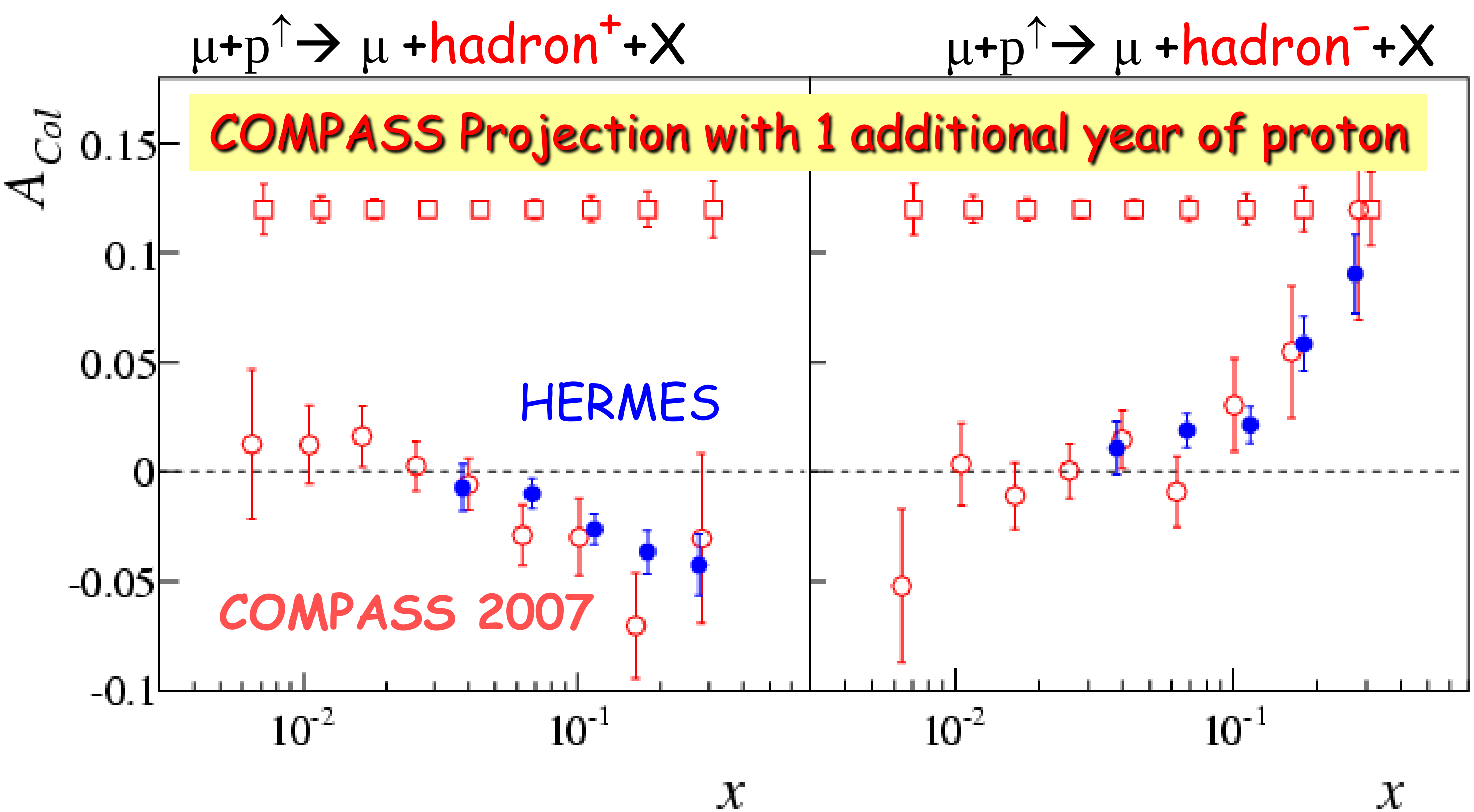


$\equiv \Delta_T q(x) = h_1 = q^{\uparrow\uparrow} - q^{\downarrow\uparrow}$

a quark moving horizontally and polarized upward prefers to emit the leading meson to the left side of the jet

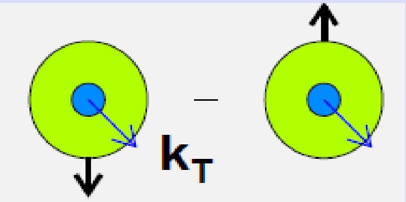
→ left-right asymmetry in the hadronisation of transversely polarised quarks

Collins asymmetry $\propto \Delta_T q(x) \times$ Collins Fragmentation Function in SIDIS



Transverse Momentum Distributions

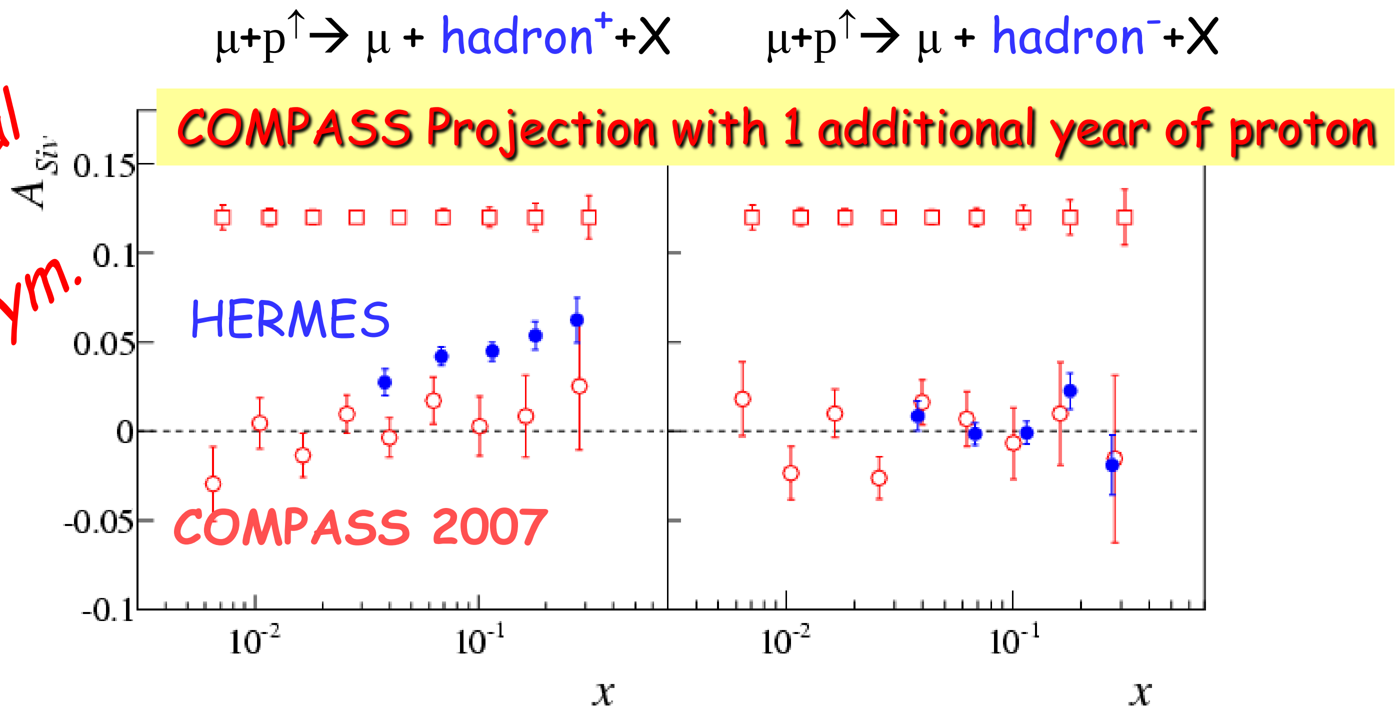
with transv. momentum k_T *of partons* -> 8 TMD PDFs (x, k_T^2)



The most famous: **Sivers** function $\Delta_0^T q(x, k_T^2)$ or $f_{1T}^{\perp}$ correlates the transv. spin of the nucleon to the transv. momentum of the q. (distorsion)

Sivers asymmetry $\propto \Delta_0^T q(x, k_T^2) \times$ Fragmentation Function in SIDIS (requires final state interaction, parton orbital angular momentum)

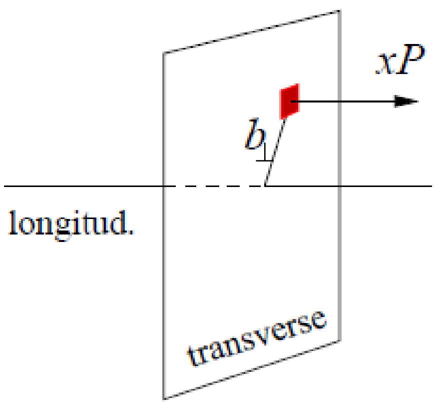
Need of 1 additional year to conclude about Sivers Asym.

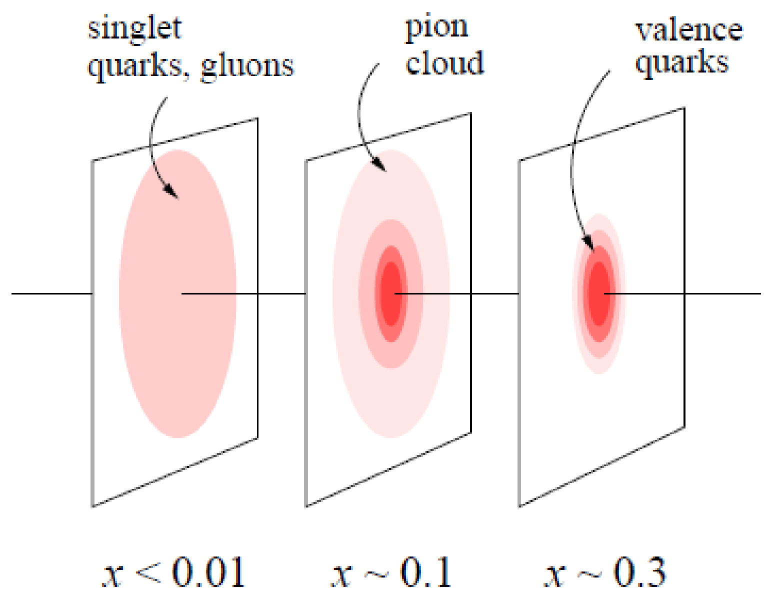


GPDs program @ COMPASS

Generalised Parton Distribution functions ($H, \tilde{H}, E, \tilde{E}$):

- Allow for a unified description of form factors and parton distributions
- Allow for transverse imaging (nucleon tomography) and give access to the quark angular momentum (through E)





Impact parameter $b_\perp$

Longitudinal momentum fraction x

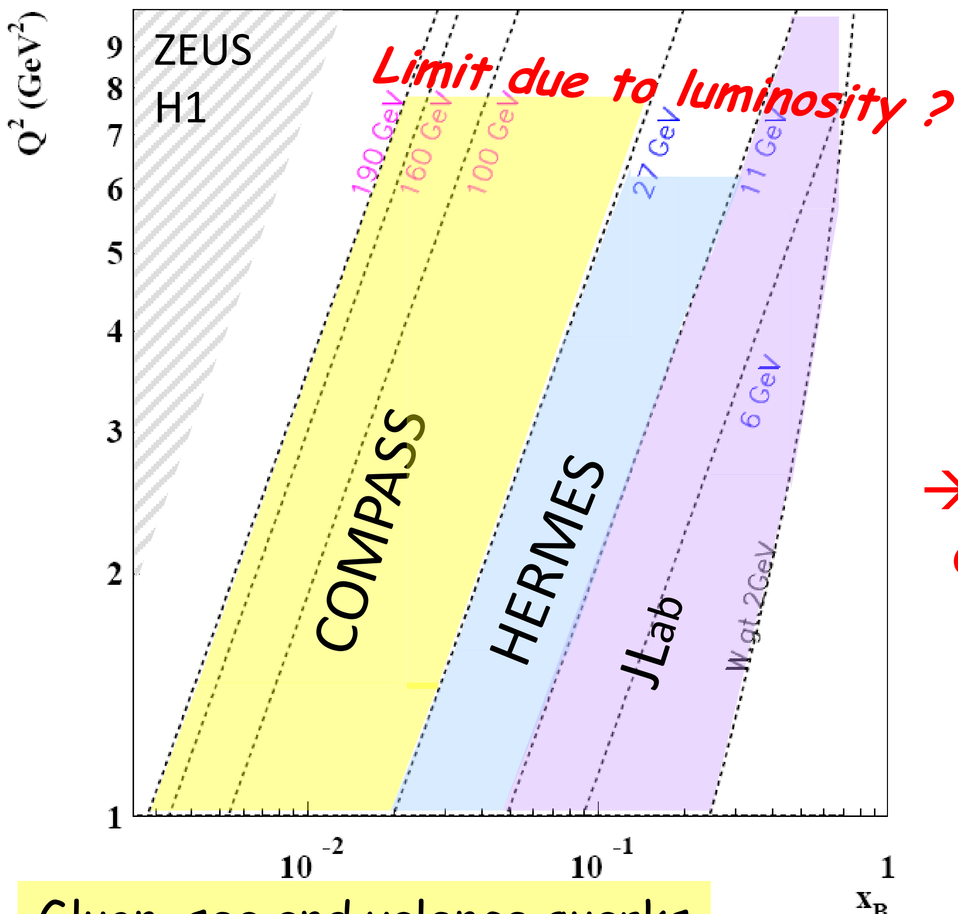
Tomographic parton images of the nucleon

What makes COMPASS a unique case?

1- CERN SPS high energy muon beam 100/190 GeV

Kinematic domain

$10^{-2} < x < 10^{-1}$



Gluon, sea and valence quarks

2- μ+ and μ- with opposite polarisation ±80%

3- with a 2.5m long LH2 target

Lumi= 10^{32} cm^{-2} s^{-1}

(present technology limit for a collider)*

→ Q^2 up to 8 GeV^2

→Any lumi upgrade extents the reach of the proposed measurements

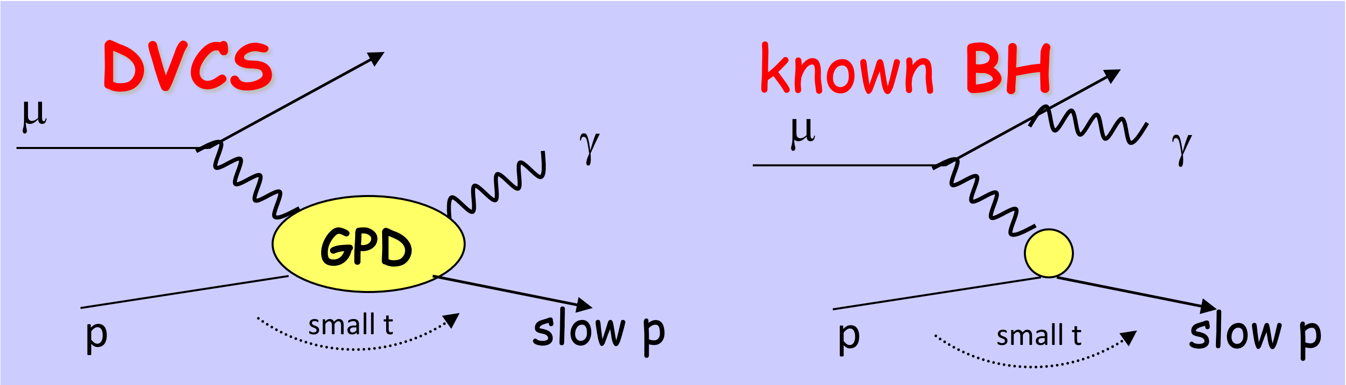
if Lumi × 4 → more comfortable statistics for Q^2 up to 12 GeV^2

**: ENC@FAIR E_p=15GeV E_e=3GeV equivalent to Eμ @ CERN=100GeV*

2 channels studied:

- exclusive meson production ($\rho, \omega, \Phi, J/\psi, \ldots, \pi, \ldots$)
- exclusive single-photon production

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



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

at COMPASS with 160 GeV we can deal with

- ✓ either BH (excellent relative yield)
- ✓ either DVCS
- ✓ or the interference

Deeply Virtual Compton Scattering

Phase 1: DVCS experiment to constrain GPD H

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

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

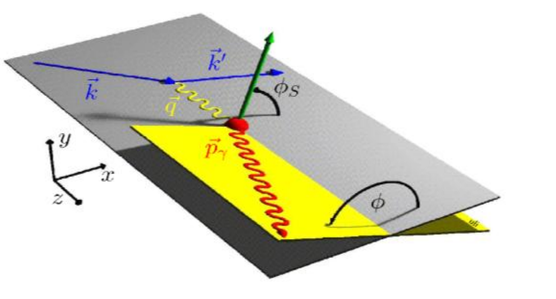
$$\mathcal{S}_{U,CS} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + s_1^{Int}\sin\phi \quad \text{and} \quad s_1^{Int} \sim \mathcal{I}m(F_1\mathcal{H})$$

Using $\mathcal{S}_{U,CS}$ and integration over ϕ and BH subtraction → $d\sigma^{DVCS}/dt$ → *transverse imaging*

Phase 2: DVCS experiment to constrain GPD E

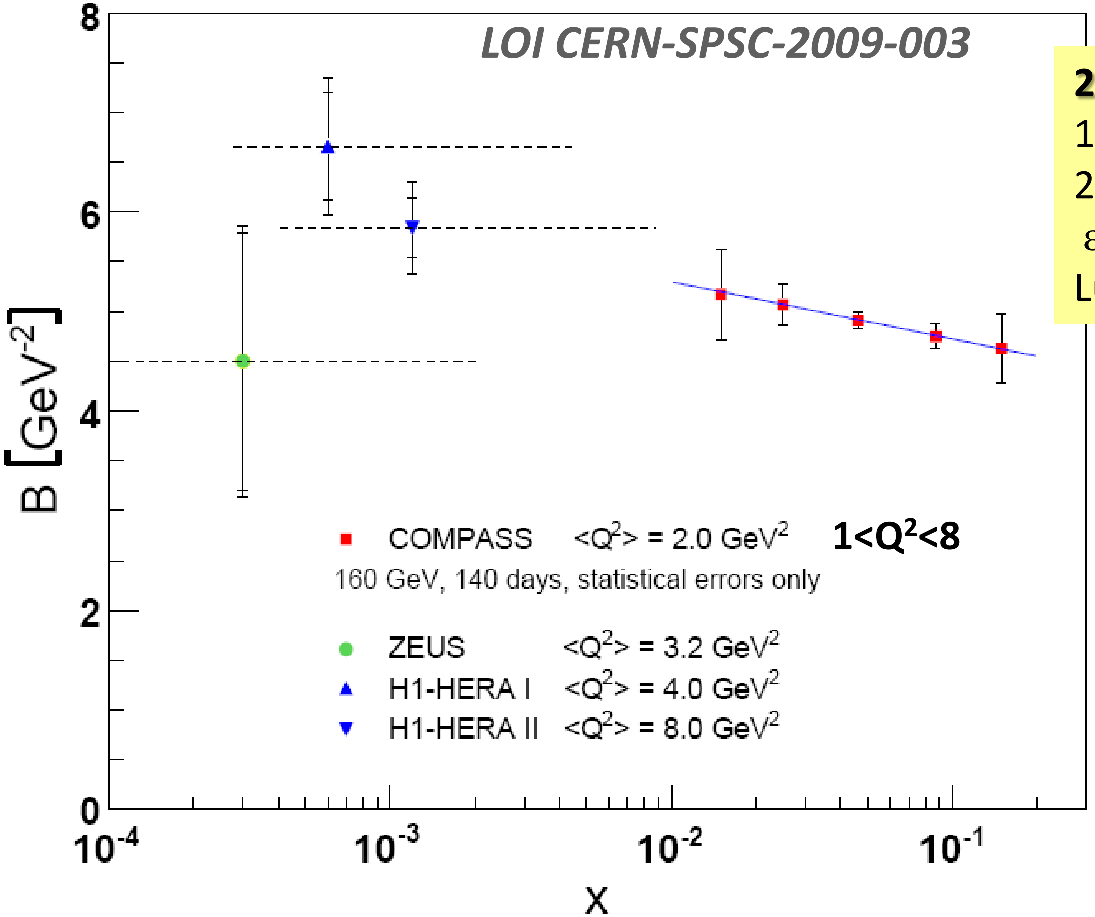
with μ^{+} and transversely polarized NH3 (proton) target

$$d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S+\pi) \propto \mathcal{I}m(F_2\mathcal{H} - F_1\mathcal{E})\sin(\phi - \phi_S)\cos\phi$$



Transverse imaging at COMPASS

Using $\mathcal{S}_{U,CS}$ and integration over ϕ and BH subtraction $\longrightarrow$ $d\sigma_{DVCS}/dt \sim \exp(-B|t|)$



2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%,
Lumi=1222pb^{-1}

$B(x) \sim \frac{1}{2} \langle b_\perp^2 \rangle$ at a given x

ansatz at small x:

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

α' =0.125 GeV^{-2} in FFS model

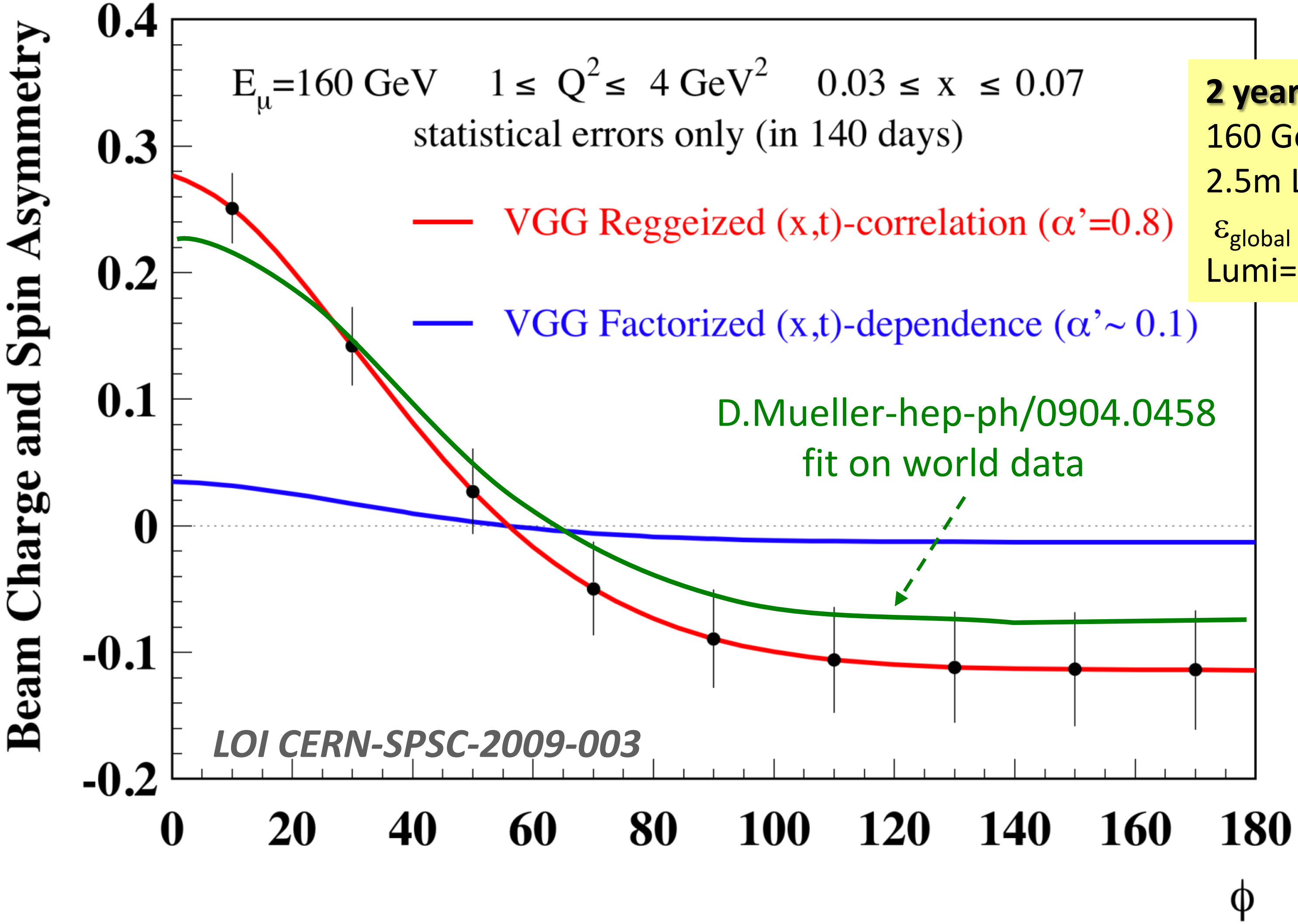
for valence quark $\alpha' \sim 1\ GeV^{-2}$ to reproduce FF $\cong$ meson Regge traj.

for gluon $\alpha' \sim 0.164\ GeV^{-2}$ (J/Ψ at Q^2=0) « $\alpha' \sim 0.25\ GeV^{-2}$ for soft Pomeron

$\alpha' \sim 0.02\ GeV^{-2}$ (J/Ψ at Q^2=2-80 GeV^2)

Using $\mathcal{D}_{U,CS}$ / $\mathcal{S}_{U,CS}$: Beam Charge and Spin Asymmetry

Comparison to different models



2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%,
Lumi=1222pb^{-1}

Experimental requirements for DVCS

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

Phase 1

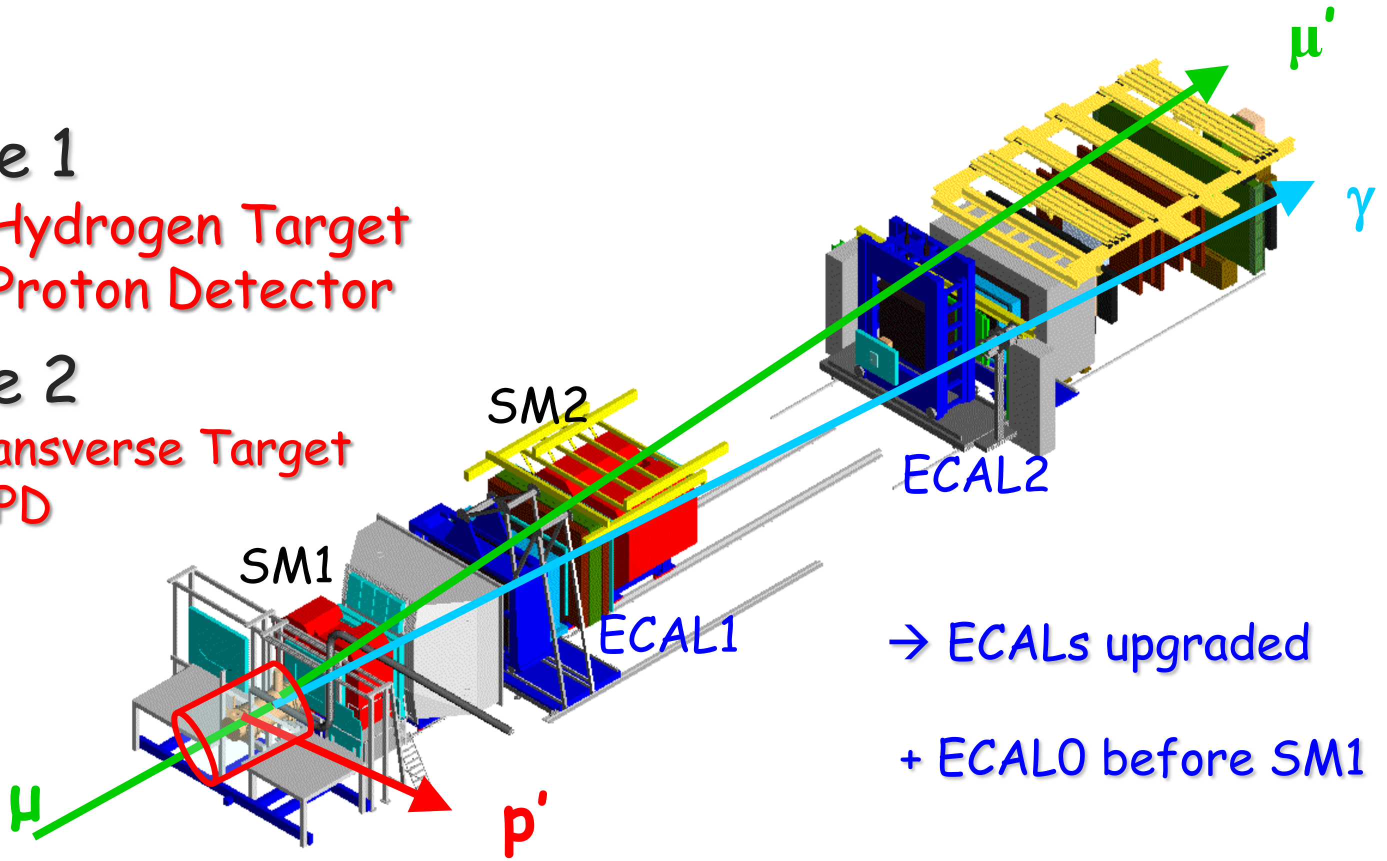
~ 2.5 m Liquid Hydrogen Target

~ 4 m Recoil Proton Detector

Phase 2

Polarised Transverse Target

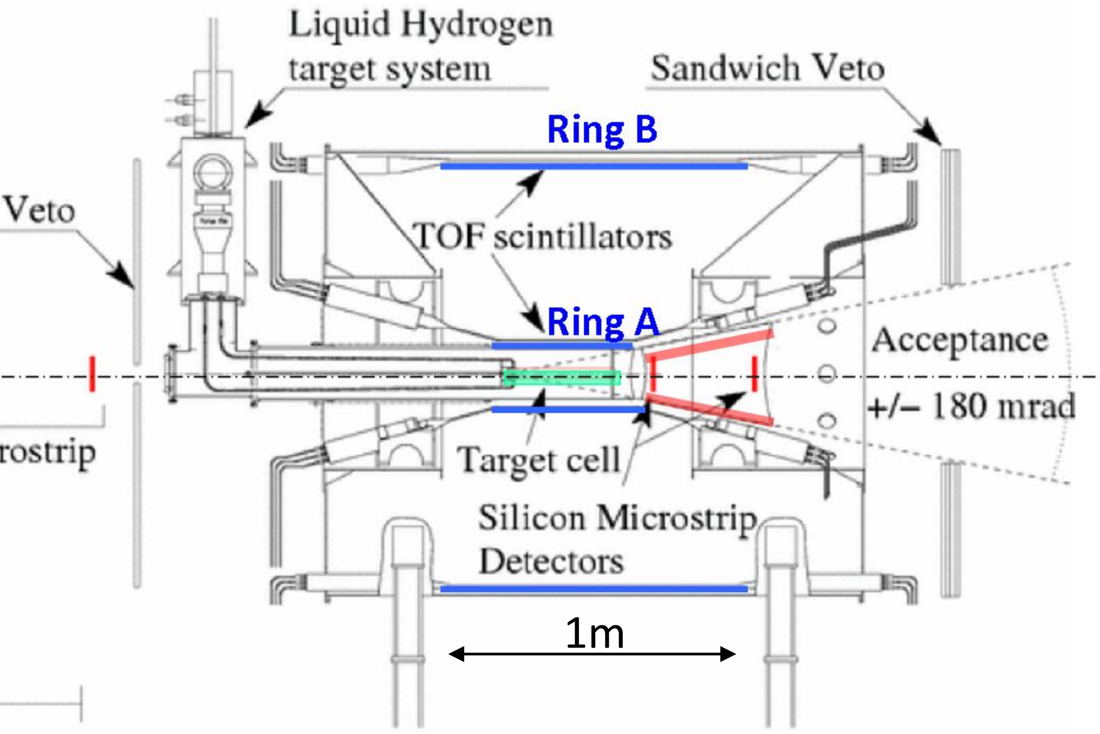
Associated RPD

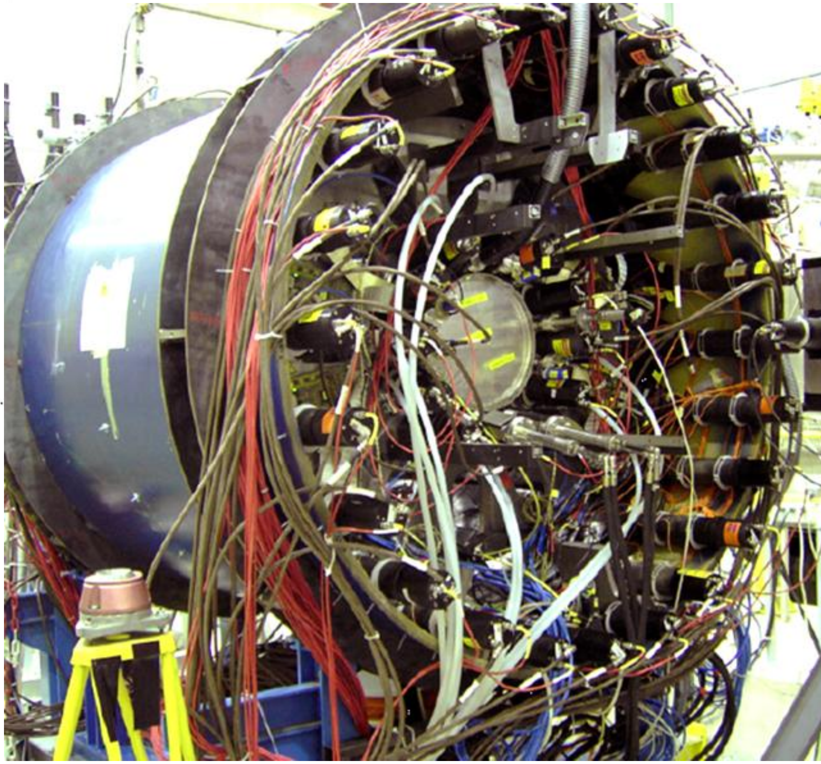


→ ECALs upgraded

+ ECAL0 before SM1

2008-2009: a small 1m Recoil Proton Detector and a 40cm LH2 target during the hadron program





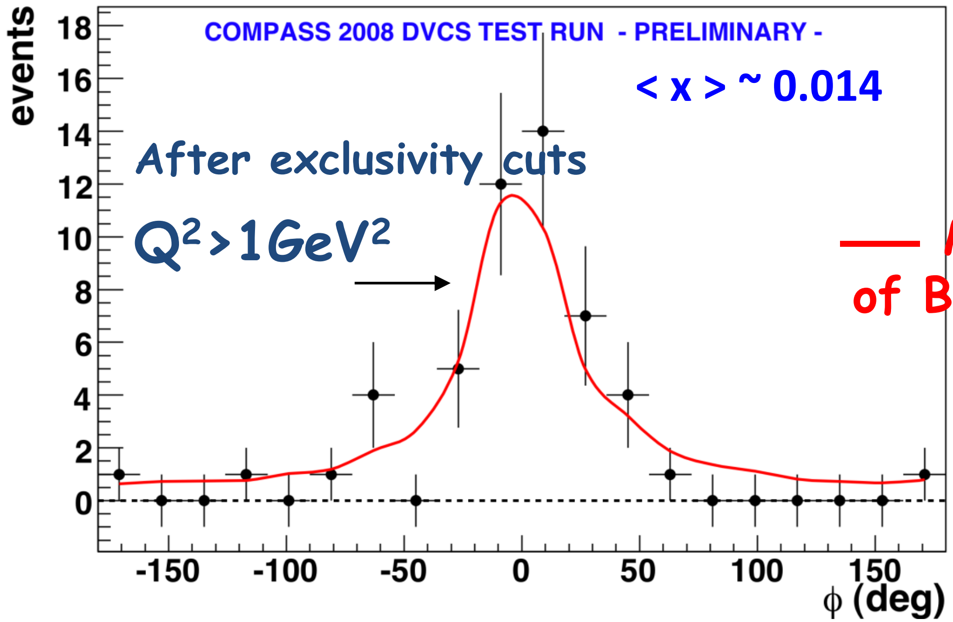
Selection of single photon production (DVCS test 2008)

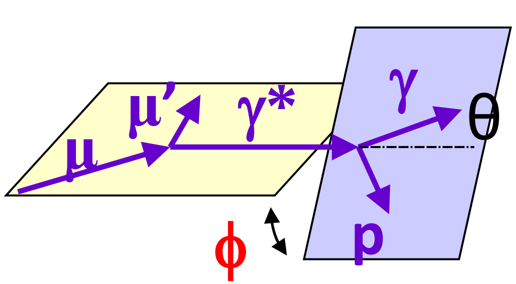
in only 1 day

with 1/3 nominal μ intensity, 1/6 target length

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

angular distribution in ϕ





Monte-Carlo simulation of BH (dominant) and DVCS

$\varepsilon_{global} = 13\% \pm 5\%$

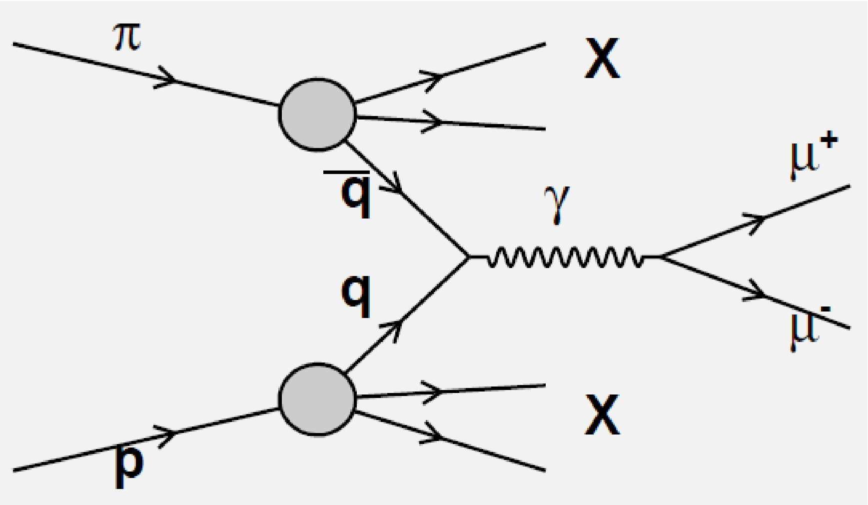
- clear signature of BH events (about 100 events)

- DVCS events are expected with a flat distribution

Looks encouraging, **2 weeks measurements now in 2009** to get about 1000 BH and 100 (DVCS+ Int)

Drell-Yan to study TMD

Phase 1: Drell –Yan $\pi^- p^\uparrow \rightarrow \mu^+\mu^- X$
with intense pion beam
with the transversely polarised NH_3 target



Cross sections:
In SIDIS: convolution of a DPF with a fragmentation function
In DY: convolution of the PDFs from the 2 hadrons
→ complementary information

The Drell-Yan process in π^- p

Unpolarised

$$d\sigma^{DY} \propto \bar{h}_1^{\perp}(x_1, k_{T1}^2) \otimes h_1^{\perp}(x_2, k_{T2}^2) \cos 2\phi$$

↑ Boer-Mulders ↑

Target transversely polarised

$$d\sigma^{DY} \propto \bar{f}_1(x_1, k_{T1}^2) \otimes f_{1T}^{\perp}(x_2, k_{T2}^2) \sin(\phi - \phi_{S2}) +$$

↑ Sivers

$$+ \bar{h}_1^{\perp}(x_1, k_{T1}^2) \otimes h_1(x_2, k_{T2}^2) \sin(\phi + \phi_{S2}) +$$

↑ Boer-Mulders ↑ Transversity

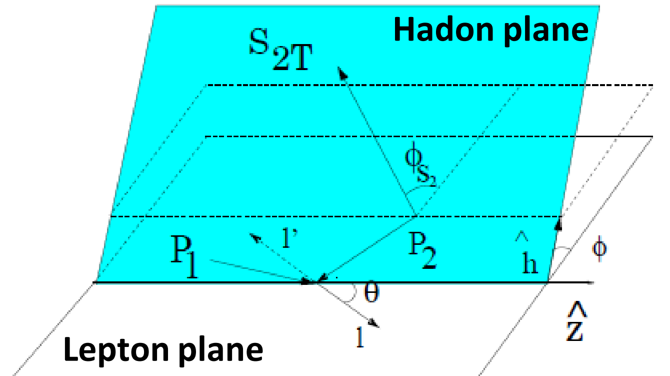
$$+ \bar{h}_1^{\perp}(x_1, k_{T1}^2) \otimes h_{1T}^{\perp}(x_2, k_{T2}^2) \sin(3\phi - \phi_{S2})$$

↑ Boer-Mulders ↑ Pretzelosity

Collins-Soper frame

θ, ϕ lepton plane wrt hadron plane

ϕ_{S2} target transverse spin vector S_{2T} wrt lepton plane



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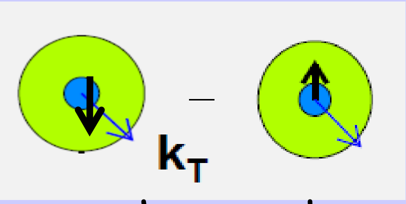
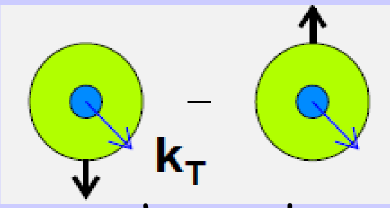
The **Boer-Mulders** function



correlates the quark transverse spin and the quark k_T (unpol N)

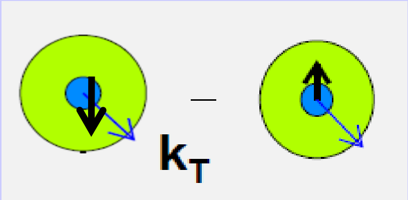
The **Sivers** function



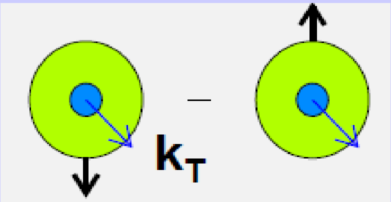
correlates the nucleon spin and the quark k_T (transv. Pol. N)

Important tests of non-perturbative QCD

The **Boer-Mulders** function



The **Sivers** function



Confronting Drell-Yan and SIDIS results

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

Boer-Mulders

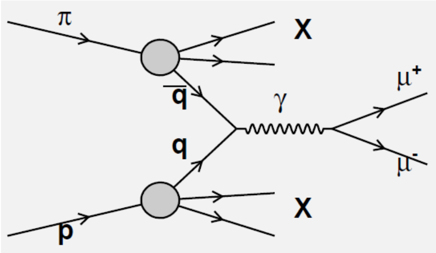
$$h_1^{\perp}(DY) = -h_1^{\perp}(SIDIS)$$

Sivers

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

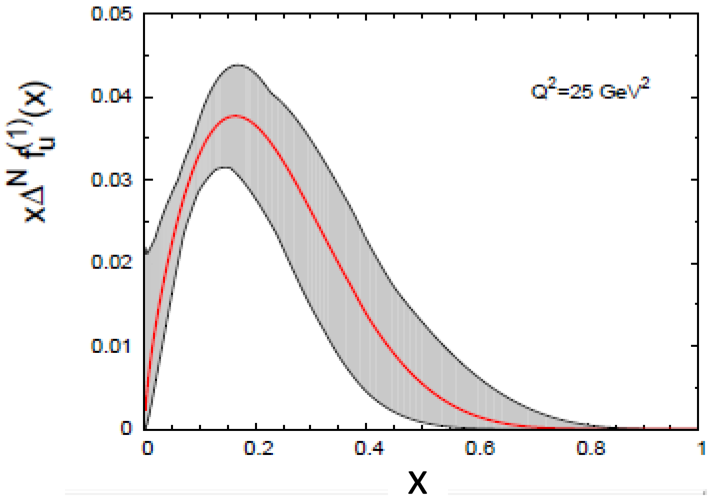
Why Drell-Yan at COMPASS ?

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

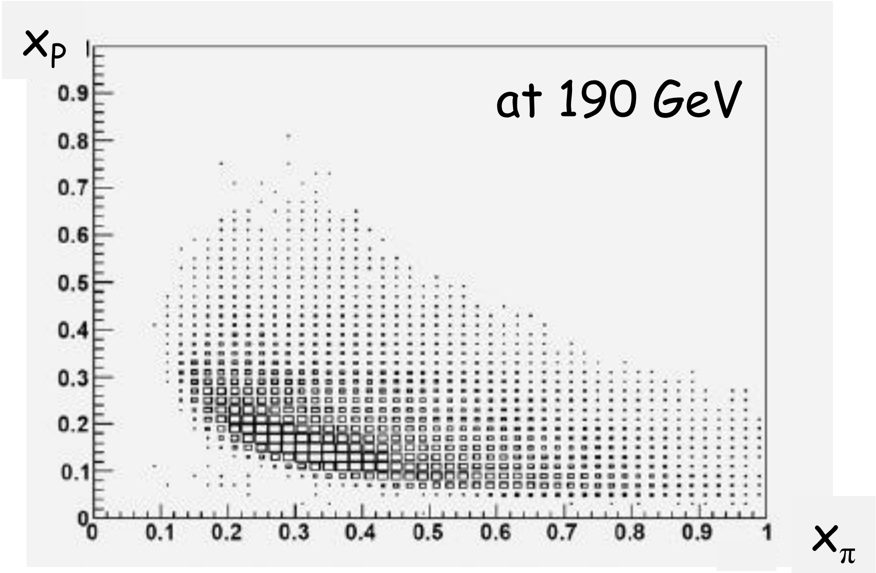


$$\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}$$

where $f = h_1^\perp, f_1, f_{1T}^\perp, h_1, h_{1T}^\perp$

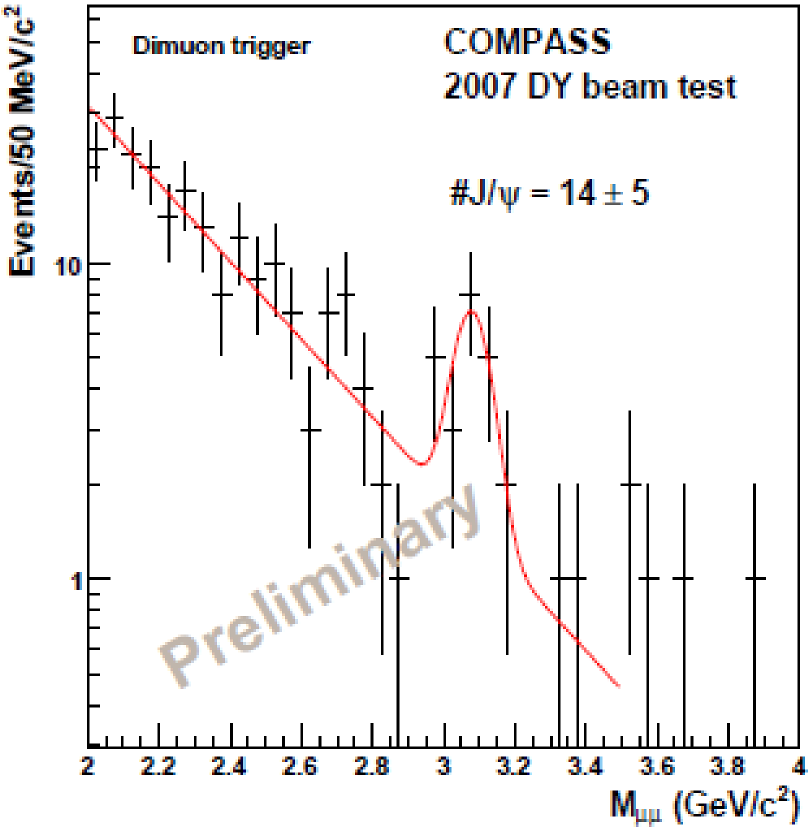


1^{rst} moment of Sivers function for u quark (at Q^2=25 GeV^2)



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

Results from test measurements in 2007



- 12h of data taking in 2007

-160 GeV π^- beam on NH3 target

- expected J/ψ = 20 $\pm$ 8

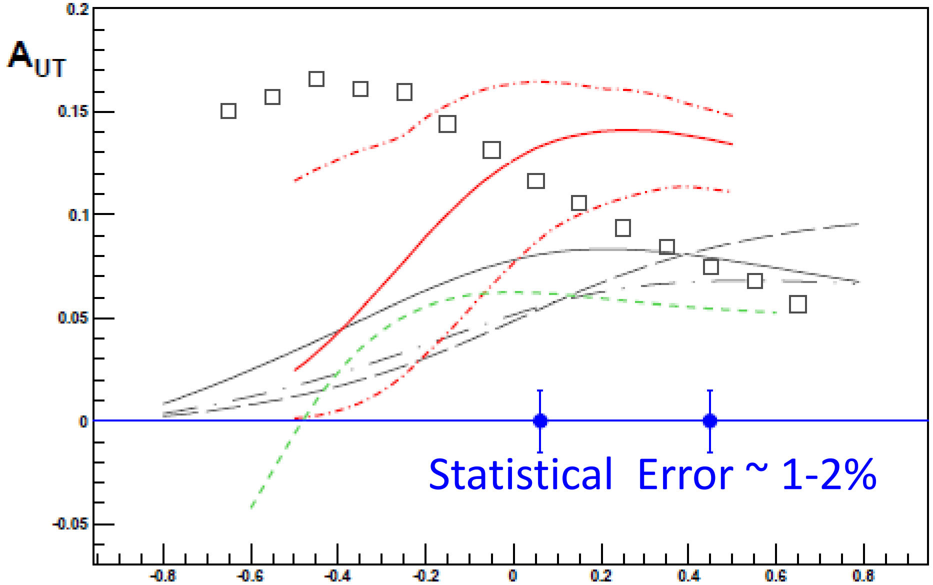
domain for J/ψ and ψ' production
Large background from D→ $\mu^\pm$ X

save domain for Drell-Yan
4 < $M_{\mu+\mu-}$ < 9 GeV

Prediction for Drell-Yan at COMPASS

To access Sivers function, we propose to measure in the safe dimuon mass region $4 < M_{\mu+\mu-} < 9$ GeV :

$$A_{UT}^{\sin(\phi_{S2}-\phi)} = \frac{\int_0^{2\pi}(d\sigma^{\uparrow} - d\sigma^{\downarrow})\sin(\phi_{S2}-\phi)d\phi}{\frac{1}{2}\int_0^{2\pi}(d\sigma^{\uparrow} + d\sigma^{\downarrow})d\phi}$$



2 years of data
190 GeV pion beam
$6 \cdot 10^7$ π^-/s
1.2m transv. pol. NH_3 target
Lumi=1.7 10^{33} $cm^{-2}s^{-1}$

Theoretical predictions from Anselmino, Bachetta, Bianconi, Collins, Efremov

Experimental Requirements

Phase 1:
- Hadron absorber downstream of polarised target
- New trigger system for μ+ μ- pairs

Phase 2: For the Longer Term:

RF separated $\bar{p}$ / K^- beam of 5.10^7 $\bar{p}$/spill for 10^{13} ppp with 50% purity

$(\bar{p}, p\uparrow)$ $\bar{p}$: $(\bar{u}\bar{u}\bar{d})$ p: (uud) $f_{\bar{u}|\bar{p}} = f_{u|p}$

$$\sigma^{DY} \propto f_{u|p} f_{u|p}$$

$(K^-, p\uparrow)$ K^-: $(\bar{u}s)$

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

Conclusions

COMPASS is preparing to tackle new central issues:

- Transverse Momentum Distributions with DY
- Transverse Spatial Distributions GPD with DVCS and DVMP

For the next 10 years, CERN is a major actor in QCD physics with the unique high energy polarized muon and hadron beams

In future, luminosity and energy upgrades will open a large window on uncovered territories

- intense H^- source and linac4 (2008-2014),
- PS replaced by PS2 50 GeV (2012-2018),
- SPS upgrade
  → higher energy, higher intensity, higher duty cycle