COMPASS-II: a Facility to study QCD

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY

Long Term Plans for at least 5 years (starting in 2012)

- ✓ 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. PD
- ✓ Drell-Yan with π beams ➔ Transverse Momentum Dependent PDFs — 2014

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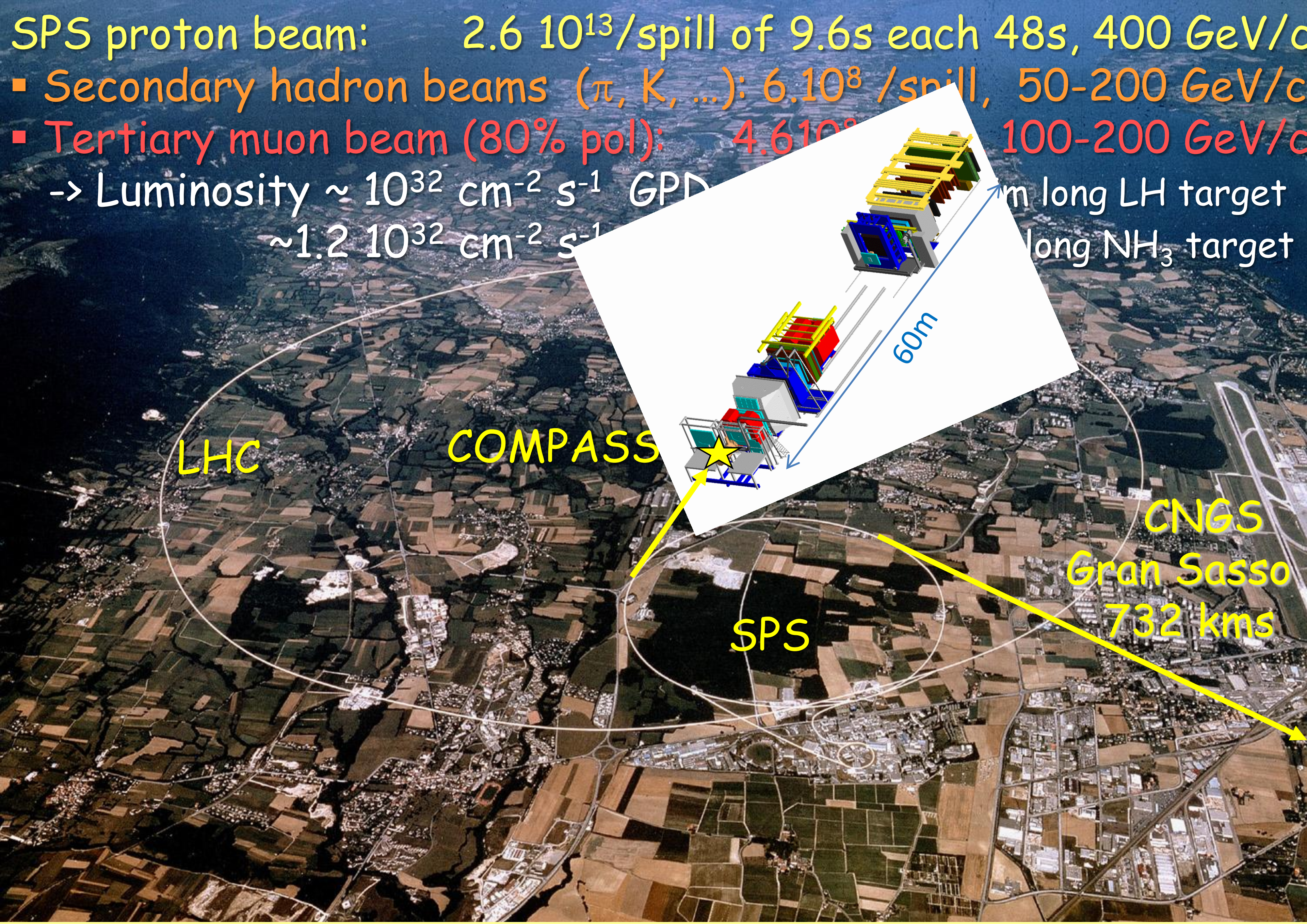
for the COMPASS Collaboration

SPS proton beam: 2.6 10^{13}/spill of 9.6s each 48s, 400 GeV/c

- Secondary hadron beams (π, K, …): 6.10^{8} /spill, 50-200 GeV/c
- Tertiary muon beam (80% pol): 4.6$10^{8}$ … 100-200 GeV/c

-> Luminosity ~ 10^{32} cm^{-2} s^{-1} GPD … m long LH target

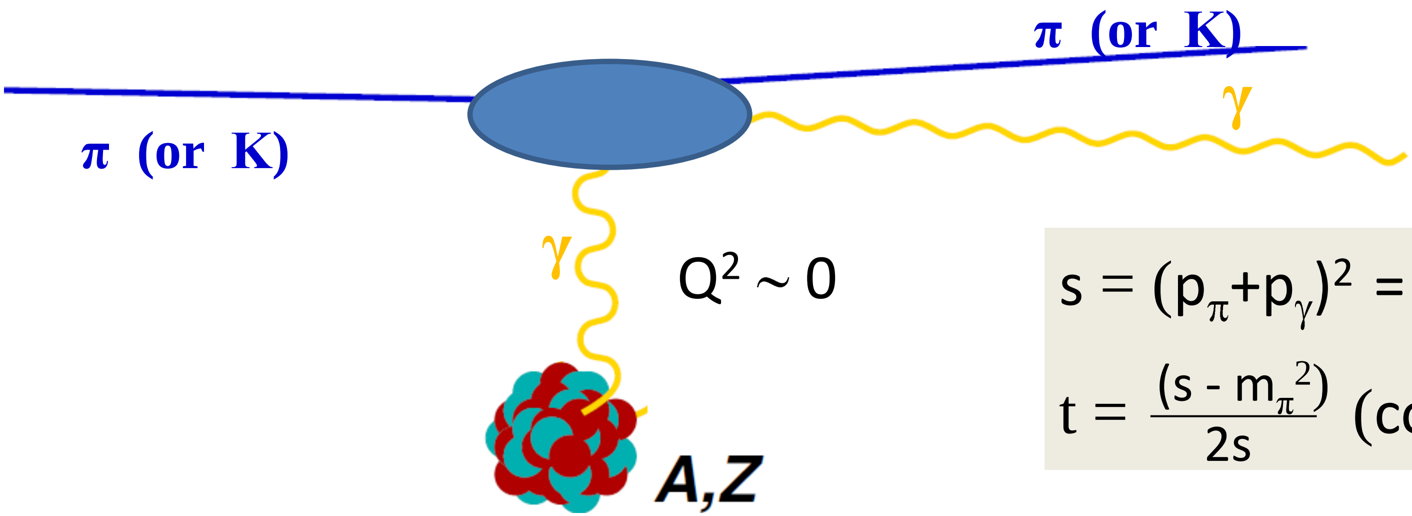
~1.2 10^{32} cm^{-2} s^{-1} … long NH_3 target



high energy beams, broad kinematic range, large angular acceptance

QCD at low energy:

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



$s = (p_\pi + p_\gamma)^2 = (\pi\gamma \text{ CM energy})^2$

$t = \frac{(s - m_\pi^2)}{2s} (\cos \vartheta_{cm} - 1)$

The chiral perturbation theory (ChPT) predicts the low-energy behavior of the cross section with s varying from threshold (m_π^2) to a few m_π^2

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \left[\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}}\right]_{point-like} + C.\frac{(s - m_\pi^2)}{s^2} \cdot \mathcal{P}(\alpha_\pi, \beta_\pi)$$

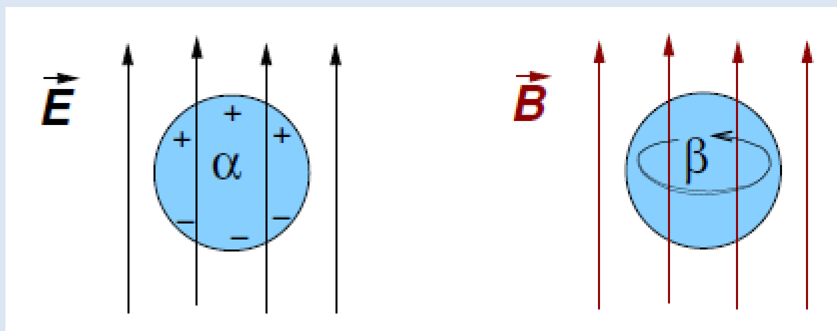
Deviation due to π polarisabilities

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

Pion Polarisabilities and Chiral predictions

The pion: fundamental role for QCD at low-energy
Goldstone boson (spontaneous breaking of chiral symmetry)
lightest quark-gluon bound state system
➔ understanding its internal structure is a fundamental challenge

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



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

2-loop ChPT prediction: $\alpha_\pi + \beta_\pi = (0.2 \pm 0.1)\ 10^{-4}\ \text{fm}^3$

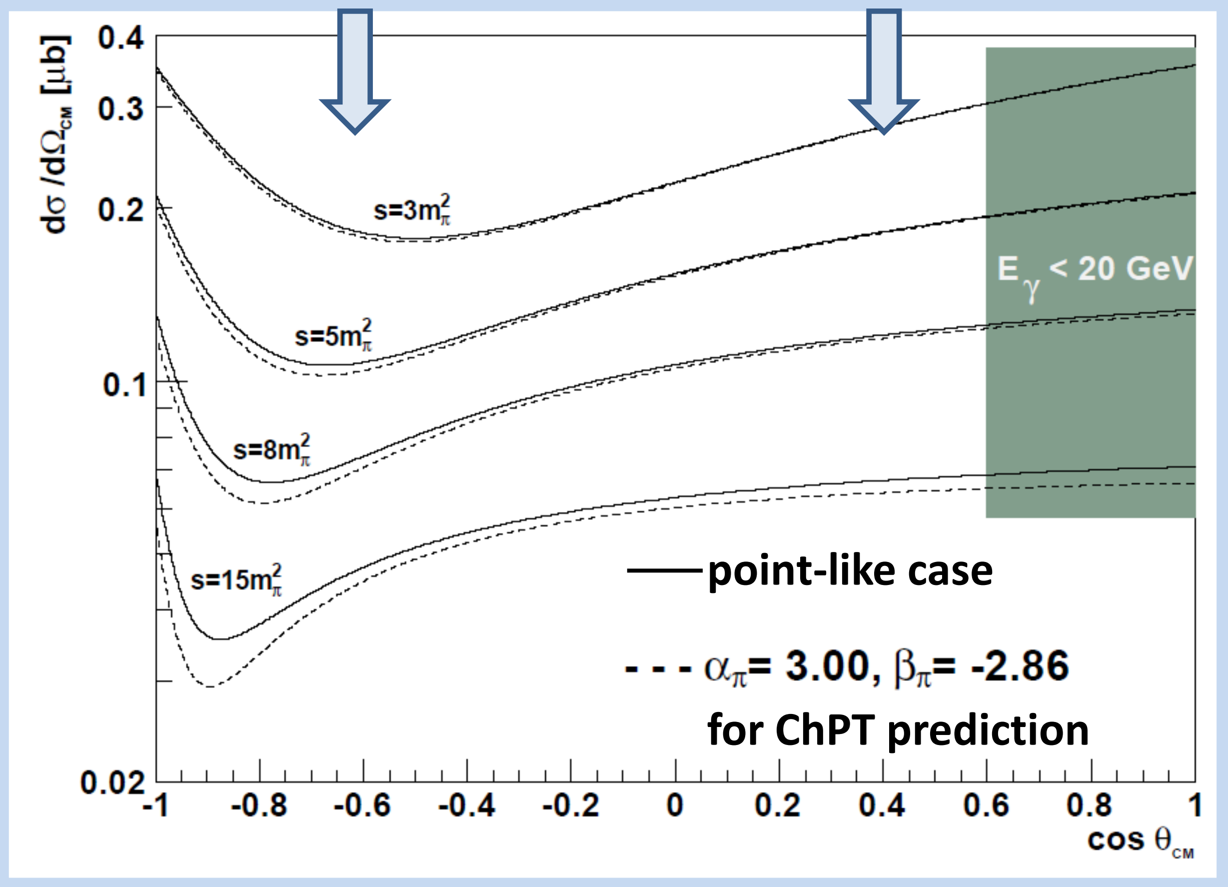
$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0)\ 10^{-4}\ \text{fm}^3$

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

Pion Polarisabilities measurement

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

Polarisability effect with increasing s at backward or forward angle



→The 3 components

$(\alpha_\pi - \beta_\pi)$, $(\alpha_\pi + \beta_\pi)$, $(\alpha_2 - \beta_2)$

can be measured

Summary for Primakoff @ COMPASS

α_π, β_π, $\alpha_2 - \beta_2$ polarisabilities measured for the first time in $\gamma+\pi \rightarrow \pi + \gamma$

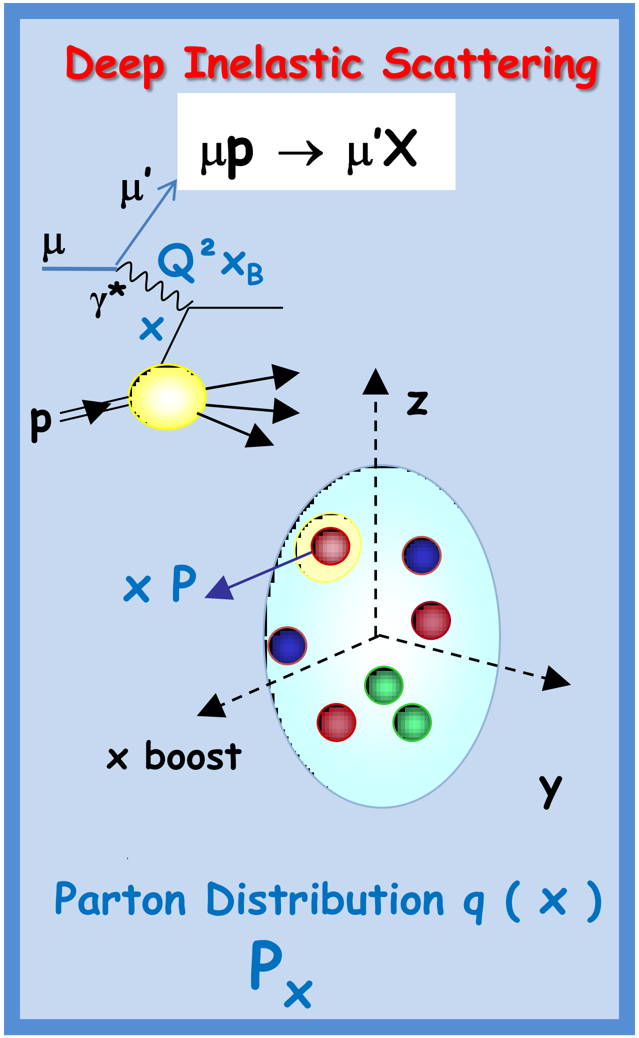
in 120 days 90 days for π beam 30 days for μ beam	$\alpha_\pi - \beta_\pi$ in 10^{-4} fm^3	$\alpha_\pi + \beta_\pi$ in 10^{-4} fm^3	$\alpha_2 - \beta_2$ in 10^{-4} fm^5
2-loop ChPT prediction	5.70 ± 1.0	0.16 ± 0.10	16
experimental accuracy	± 0.66	± 0.025	± 1.94

➔ clear sensitivity to ChPT parameters in COMPASS kinematics

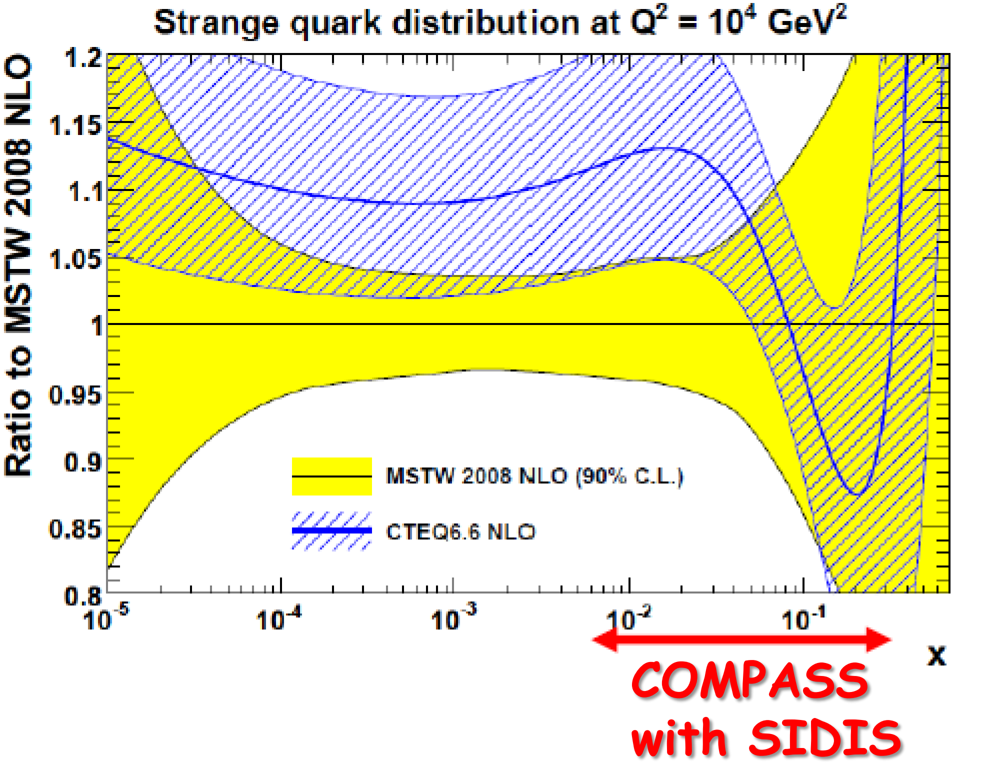
in parallel: chiral anomaly F_3 in $\gamma+\pi \rightarrow \pi + \pi^0$

+ similar reactions induced by kaons

QCD at high energy: Deep Inelastic Scattering



While unpolarised light quark PDF well constrained, strange quark distributions are not so well known



Semi-Inclusive Deep Inelastic Scattering

Semi-Inclusive DIS measurements *during GPD program* with a pure proton target with RICH detector and Calorimeters

Charge separation and identification K^+, K^-, K^0, π^+, π^-, π^0, Λ...

Major progress as compared to previous experiments to improve Unpolarised PDF

Hadron multiplicities at LO

$$\frac{\mathrm{d}N^h(x,z,Q^2)}{\mathrm{d}N^{DIS}} = \frac{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

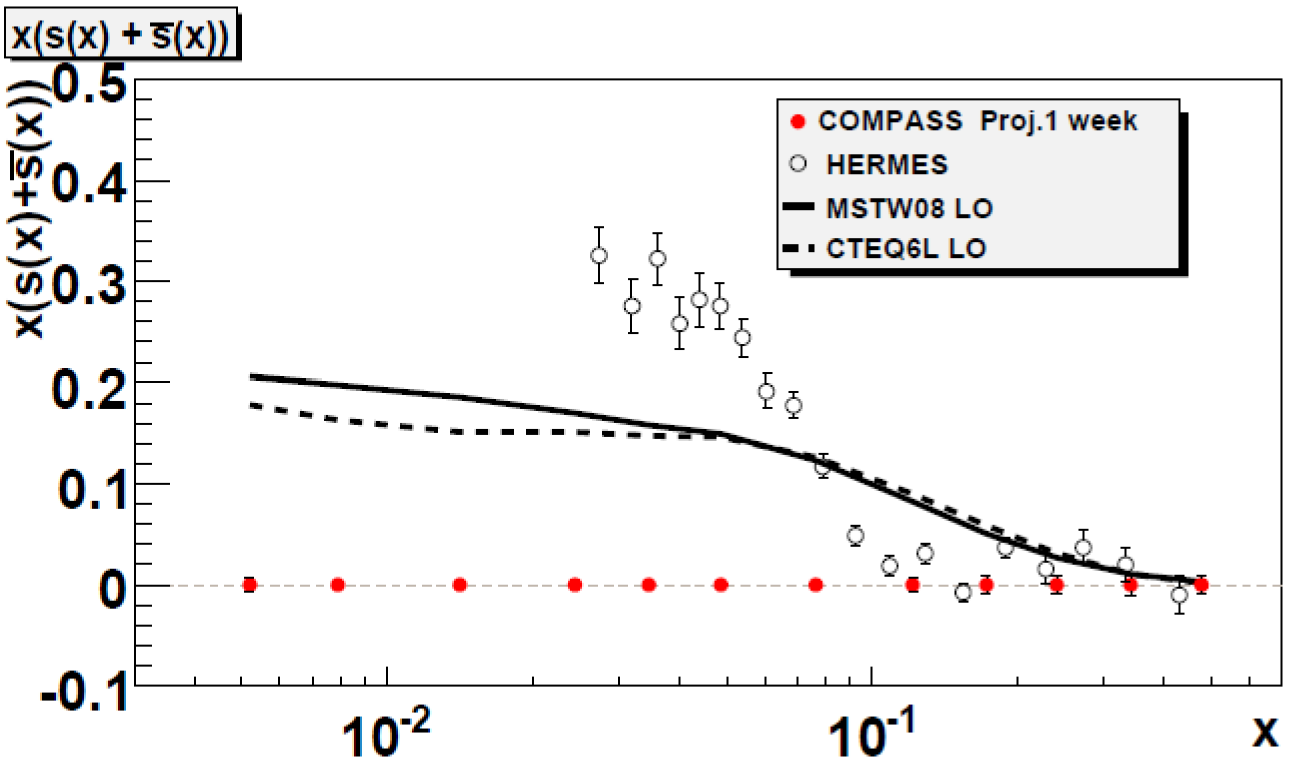
PDF
depend on x

quark Fragmentation Function
depend on z (fraction of energy of the outgoing hadron)

Final goal: extensive measurements (x,z,...) to provide input to NLO global analysis for PDF and FF

Projection of errors for s(x)

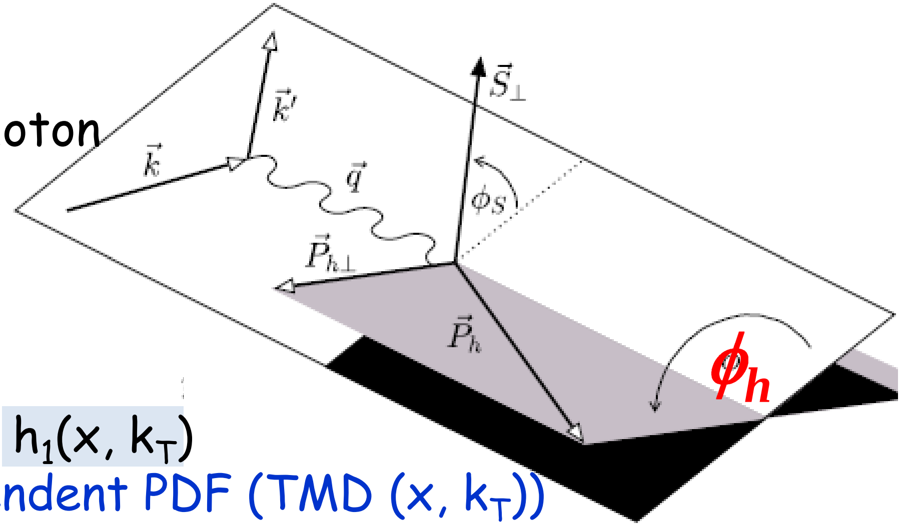
Short term goal: LO analysis from COMPASS data alone integrated over z



Projection for 1 week with 2.5m LH_2 target → high statistics

Semi-Inclusive Deep Inelastic Scattering

Asymmetries in the azimuthal angle ϕ_h
of the outgoing hadron around the virtual photon
can reveal quark transverse spin and
quark transverse momentum (k_T) effects
beyond the collinear approximation

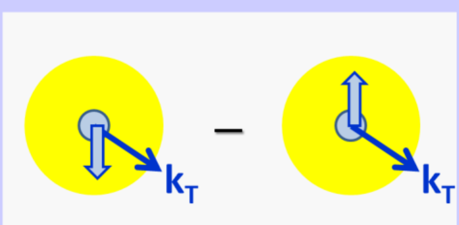


At leading twist, not only $f_1(x, k_T)$, $g_{1L}(x, k_T)$, $h_1(x, k_T)$
but also 5 other Transverse Momentum Dependent PDF (TMD (x, k_T))
which do not survive after integration on k_T

2 examples of TMDs

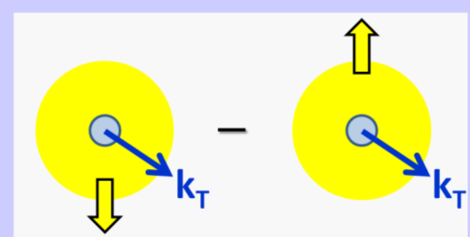
major topic for 2010

The **Boer-Mulders** function



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

The **Sivers** function



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

Semi-Inclusive Deep Inelastic Scattering

Semi-Inclusive DIS measurements *during GPD program* with a pure proton target with RICH detector and Calorimeters

Unpol. cross section:

$$\frac{d\sigma}{dx\,dy\,d\phi_h} = \frac{\alpha^2}{xyQ^2}\frac{1+(1-y)^2}{2}\Big[F_{UU} + \varepsilon_1 \cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon_2 \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + \lambda_\mu \varepsilon_3 \sin\phi_h F_{LU}^{\sin\phi_h}\Big]$$

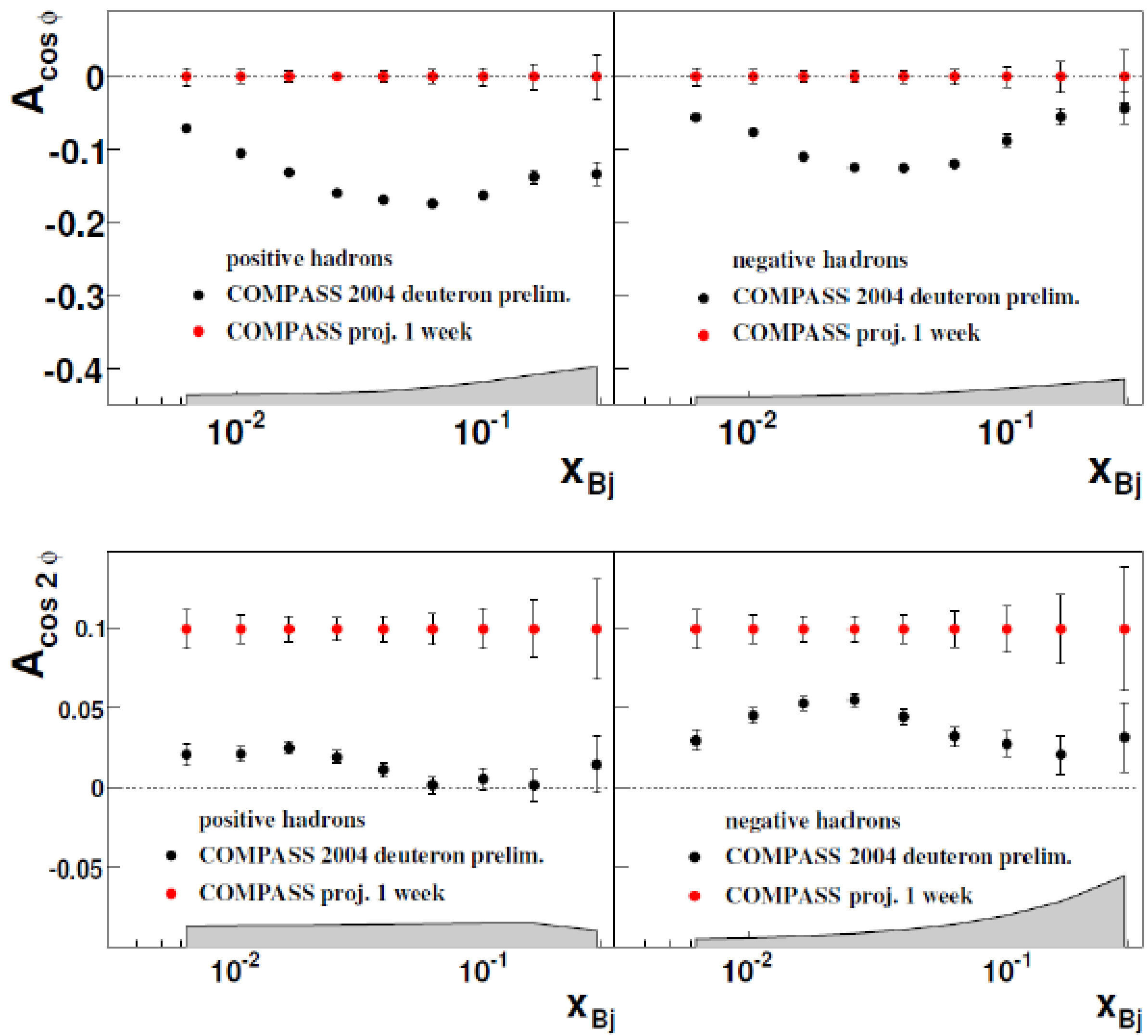
Cahn effect → info on $\langle k_T \rangle$

Boer-Mulders TMD ⊗ Collins FF
+ Cahn effect

measurement of $A^{\cos\phi_h}$ and $A^{\cos 2\phi_h}$
+ knowledge of Collins FF

➔ **Boer-Mulders TMD determination**

Projection of errors for $A^{\cos\phi_h}$ and $A^{\cos 2\phi_h}$



- **Projection proton (LH2) 1 week**
- COMPASS 2004 deuteron 4 weeks

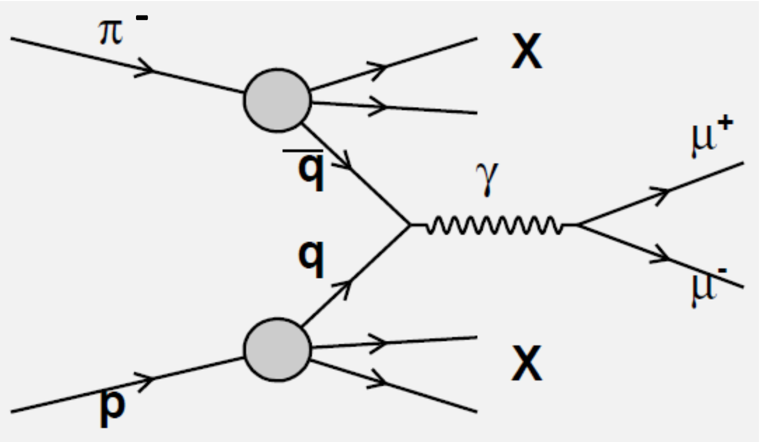
➔ Input for global analysis

\+ flavor separation using RICH particle identification

After SIDIS, Drell-Yan to study TMDs

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

with intense pion beam (up to 10^9 π/spill)
with the transversely polarised NH_3 target
with the COMPASS spectrometer equipped with an absorber



Cross sections:

In SIDIS: convolution of a TMD with a fragmentation function

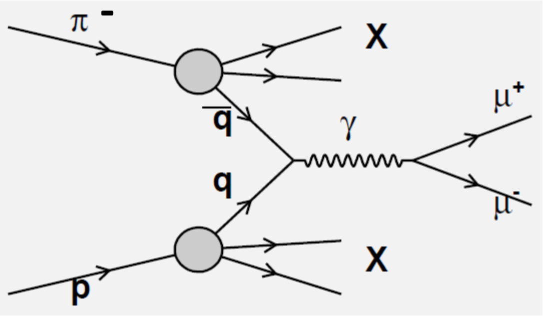
In DY: convolution of 2 TMDs $\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|p}$

→ complementary information and universality test

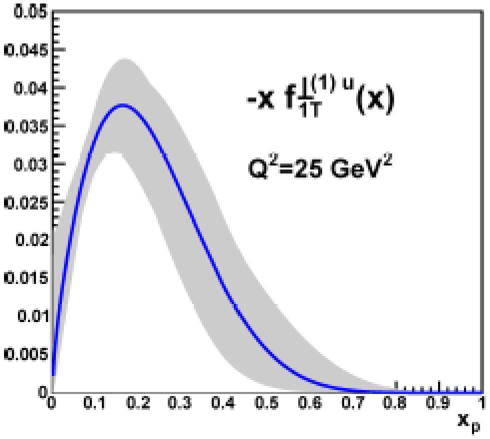
Why DY is very favourable at COMPASS?

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

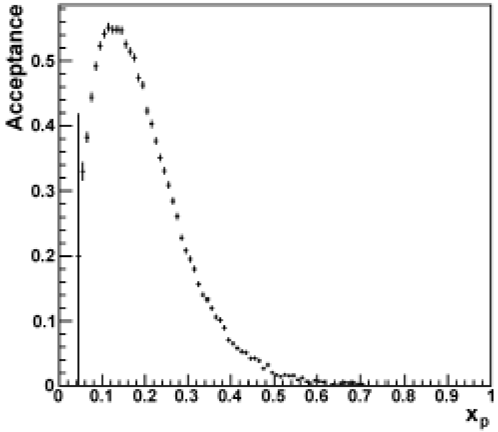
This will be the only such experimental measurement for at least 5-10 years

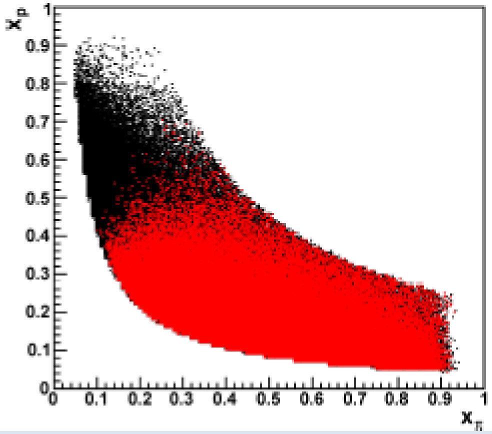


$$\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}$$



1rst moment of Sivers function for u quark





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

The Drell-Yan process in π^- p

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

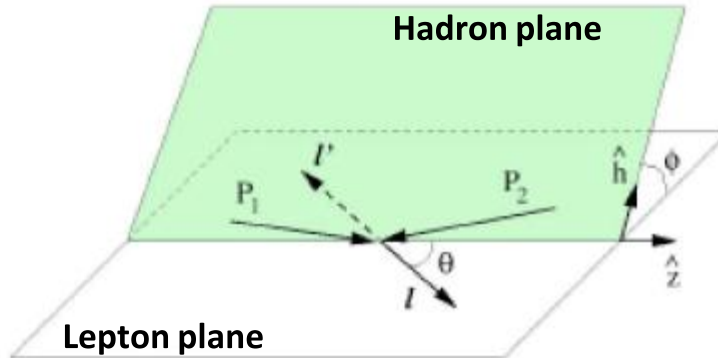
→ Access to TMDs for incoming pion ⊗ target nucleon
TMD as Transversity, Sivers, Boer-Mulders, pretzelosity

Collins-Soper frame (of virtual photon)

θ, ϕ lepton plane wrt hadron plane

target rest frame

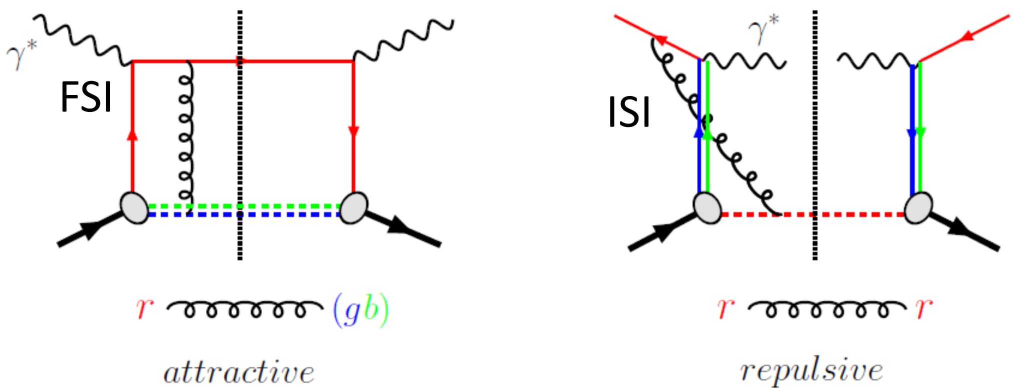
ϕ_S target transverse spin vector /virtual photon



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

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

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



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

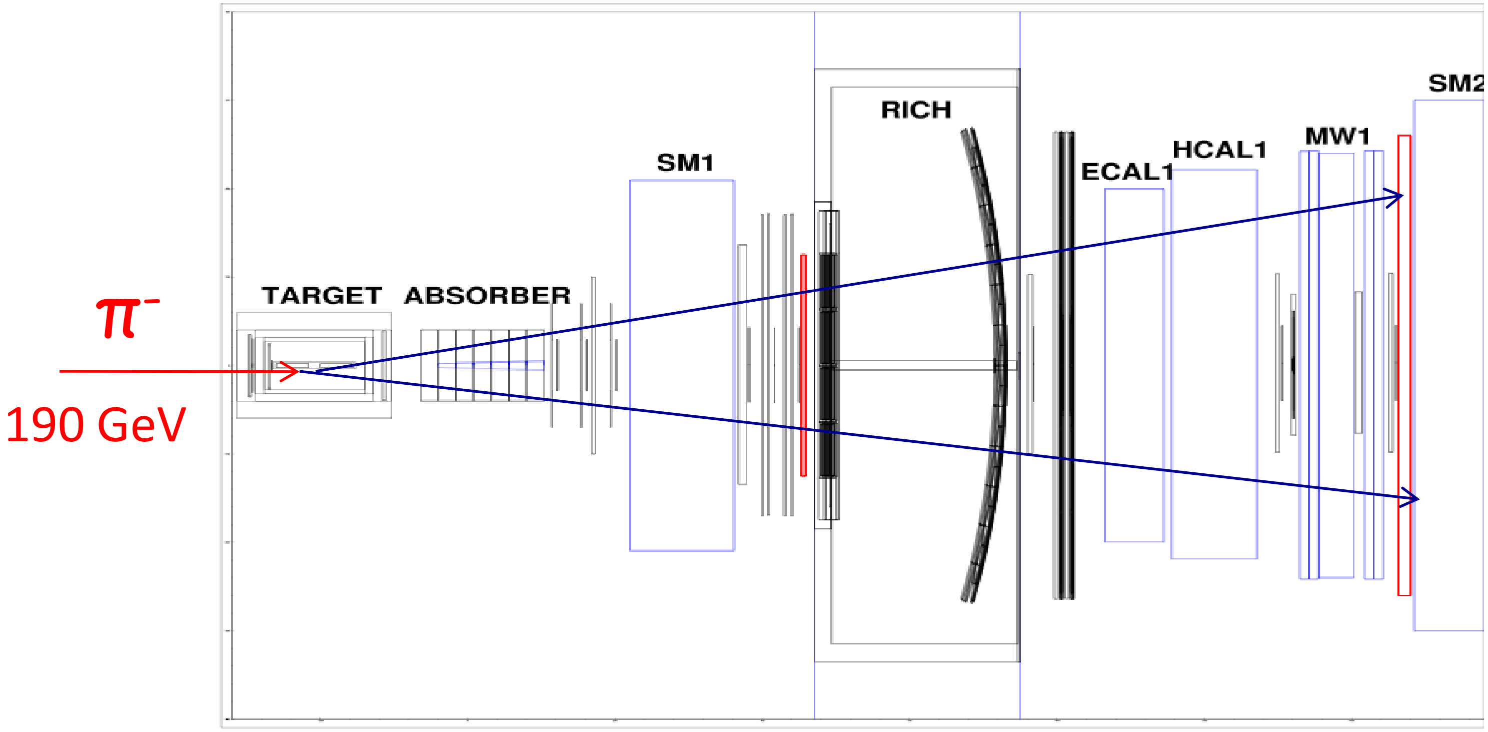
Sivers $f_{1T}^{\perp}(SIDIS) = -f_{1T}^{\perp}(DY)$

Need experimental verification

Test of consistency of the approach

COMPASS + HERMES have already measured non zero Sivers SSA in SIDIS

DY and COMPASS set-up



Key elements for a small cross section investigation at high luminosity

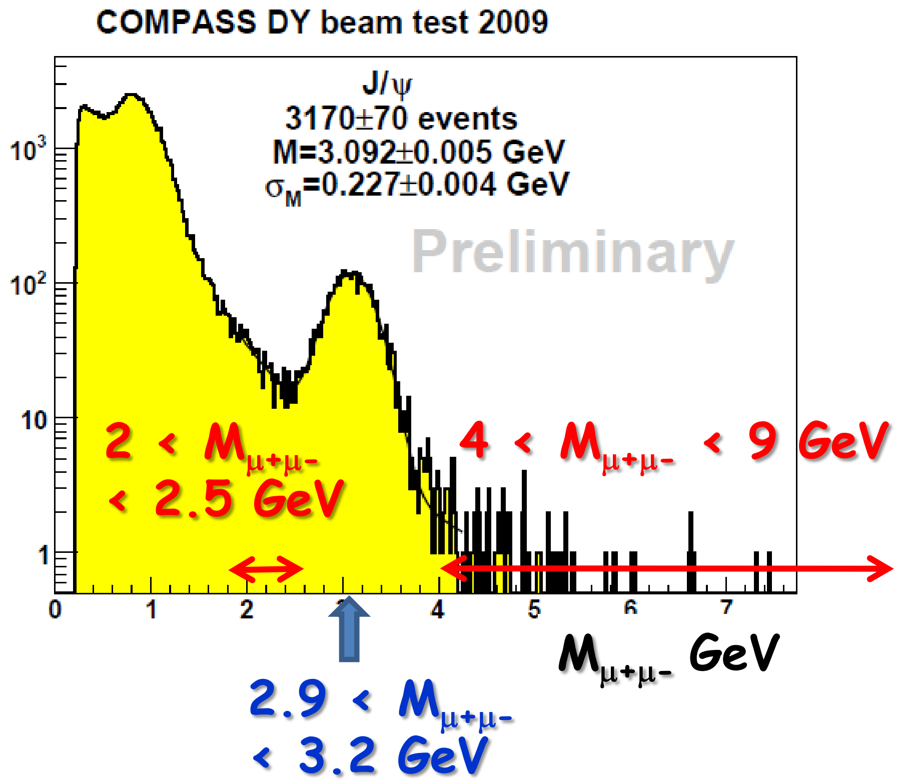
1. Absorber (lesson from 2007-8 tests) to reduce secondary particle flux
2. COMPASS Polarised Target
3. Tracking system and beam telescope
4. Muon trigger (LAS of particular importance - 60% of the DY acceptance)
5. RICH1, Calorimetry – also important to reduce the background

Results from test measurements in 2009

2009 with an absorber up to 1.5 10^8 π/spill (without radioprotection pb)

Expected: 3600±600 J/ψ and 110±22 DY

Measured: 3170±70 J/ψ and 84±10 DY



3 domains of study

1- safe domain for **Drell-Yan**

4 < $M_{\mu+\mu-}$ < 9 GeV

2-reasonable domain for **Drell-Yan**

2 < $M_{\mu+\mu-}$ < 2.5 GeV

Large Combinatorial Background S/B ~ 1

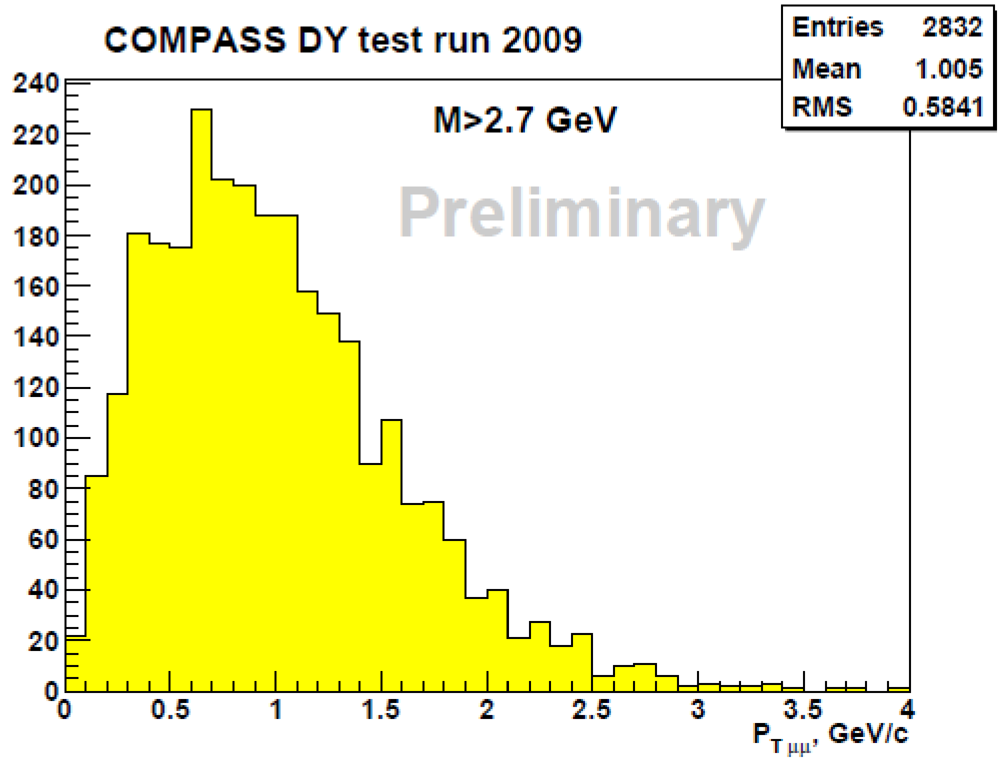
Open charm decays (from D^0) smaller than 15% of signal

3- domain for **J/ψ mechanism**

2.9 < $M_{\mu+\mu-}$ < 3.2 GeV

if q-qbar dominates over g-g fusion Drell-Yan can be considered

Results from test measurements in 2009



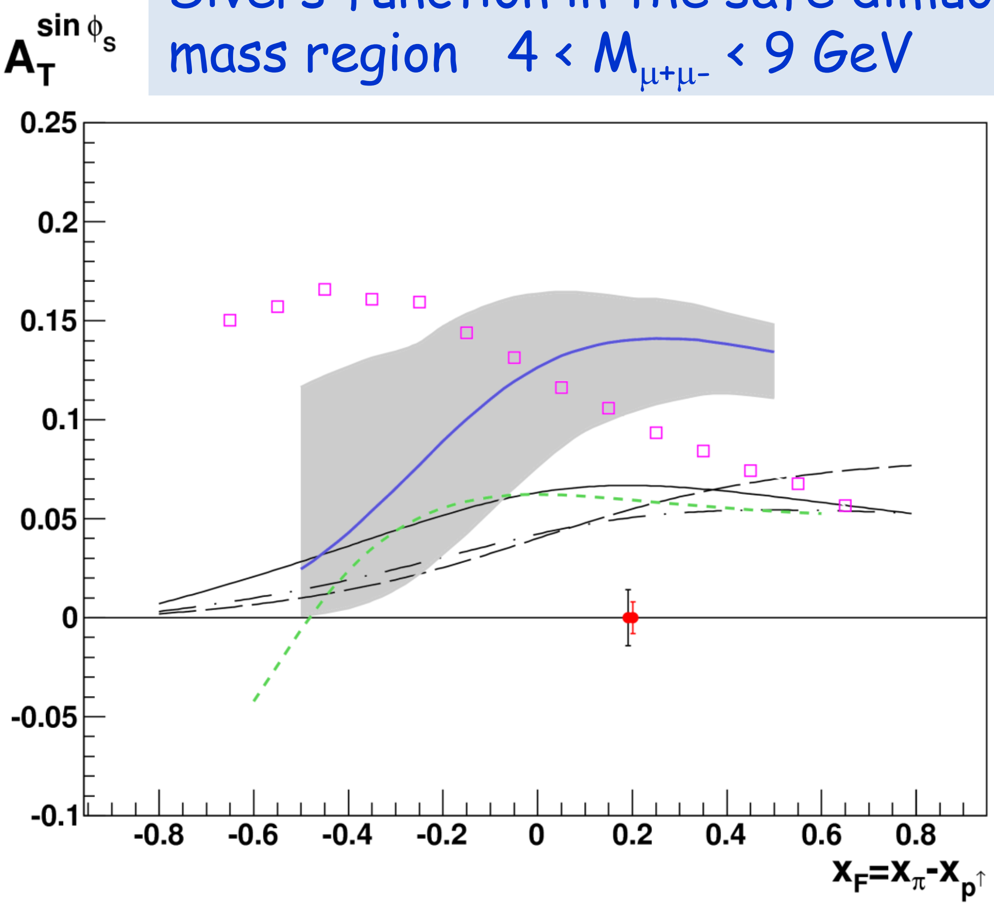
<Pt> = 1 GeV/c

➔ COMPASS sensitive to TMDs

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

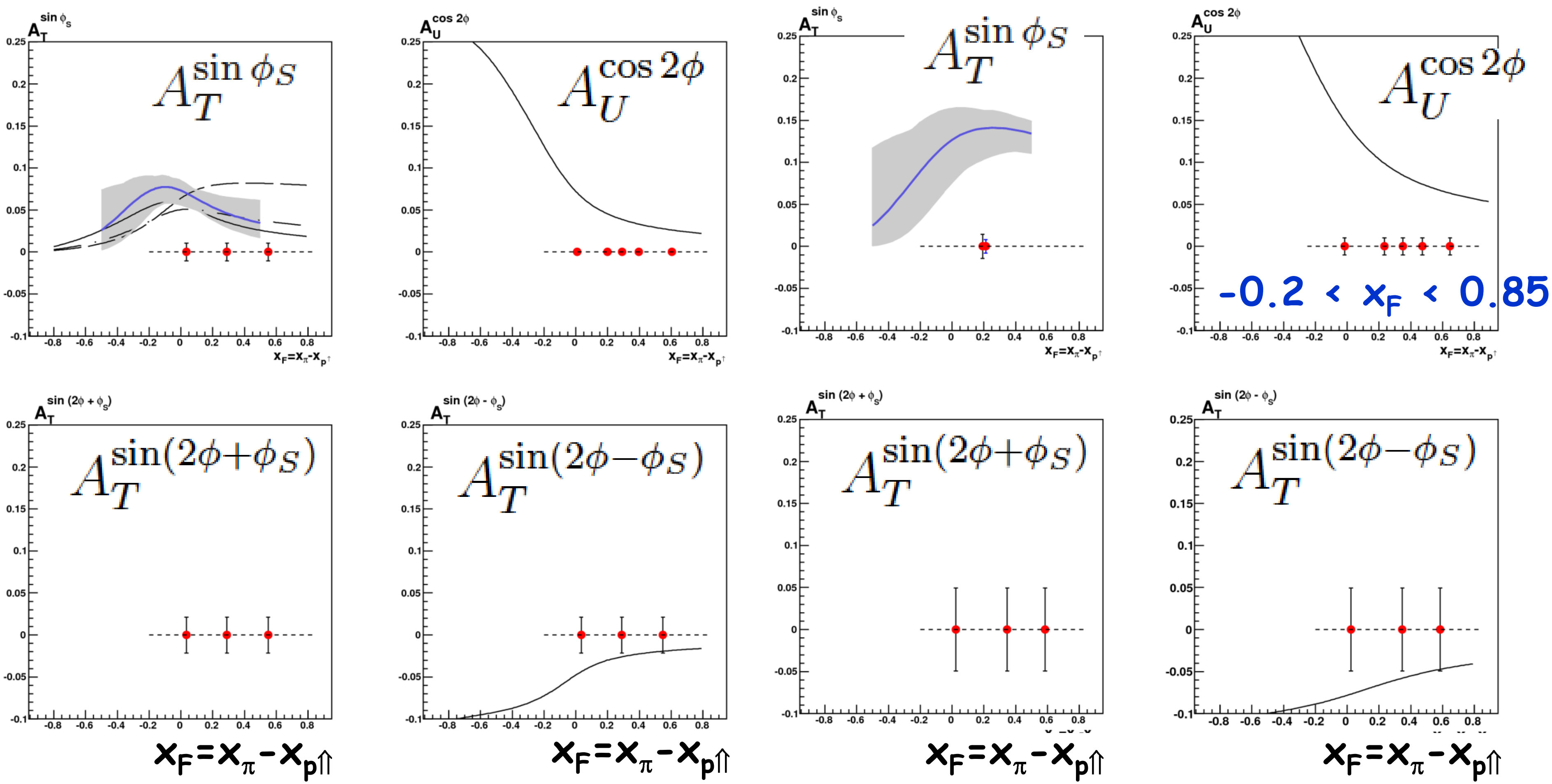


2 years of data
190 GeV pion beam
6 .10^8 π^-/spill (of 9.6s)
1.1 m transv. pol. NH_3 target
Lumi=1.2 10^{32} $cm^{-2}s^{-1}$

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)

Predictions for Drell-Yan at COMPASS

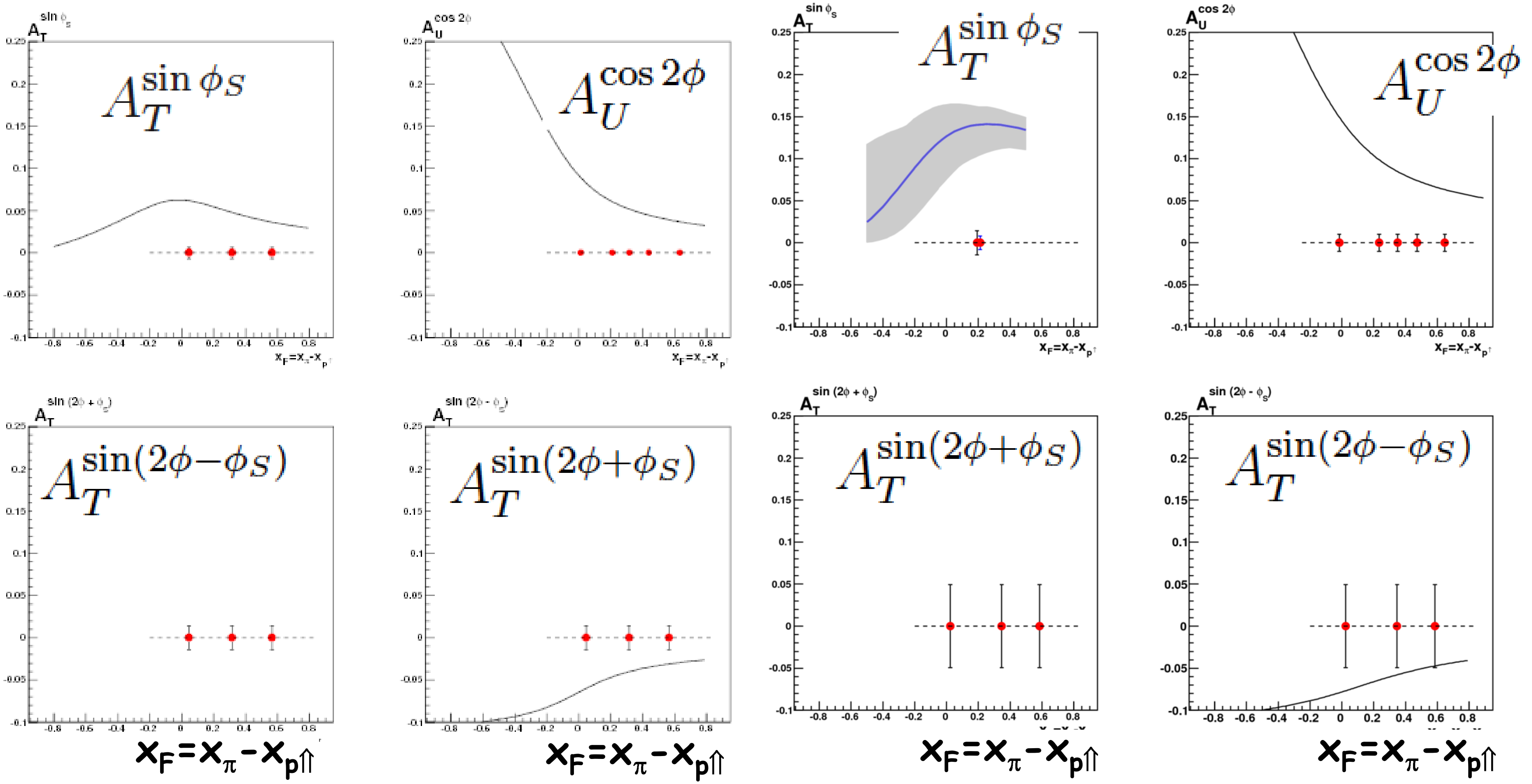
$2.0 \leq M_{\mu\mu} \leq 2.5\ \mathrm{GeV/c^2}$ $\quad$ $4. \leq M_{\mu\mu} \leq 9.\ \mathrm{GeV/c^2}$



Statistical accuracy from 0.01 to 0.02 in two years

Predictions for Drell-Yan at COMPASS

J/ψ: $2.9 \leq M_{\mu\mu} \leq 3.2$ GeV/c^2 $\quad\quad$ $4. \leq M_{\mu\mu} \leq 9.$ GeV/c^2



Statistical accuracy 1÷2% in two years

Summary for Drell-Yan @ COMPASS

First ever polarised Drell-Yan experiment sensitive to TMDs

Pure valence u dominance because of the π^- beam

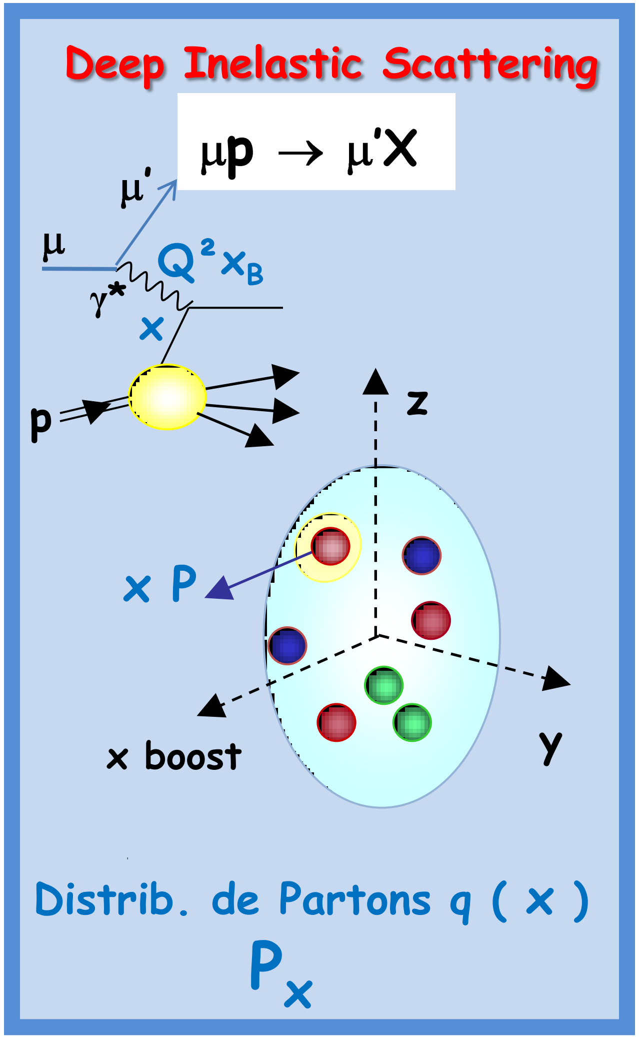
Key measurements:

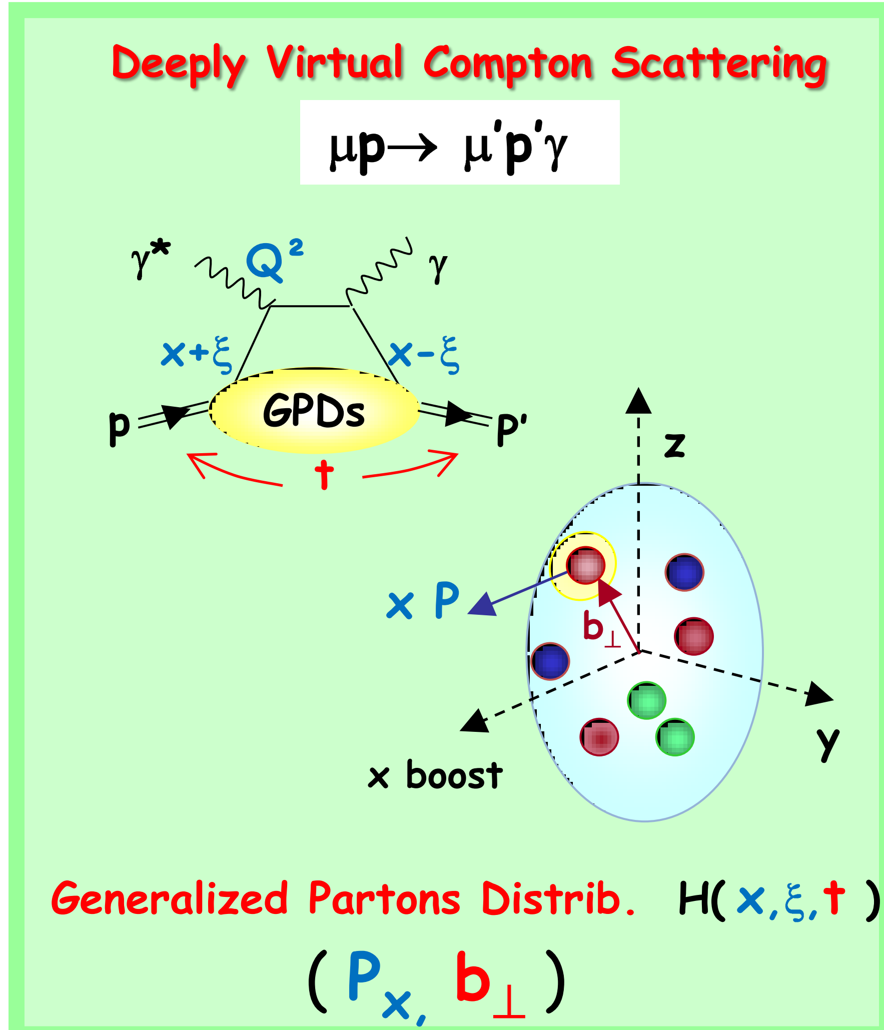
- ✓ TMDs universality SIDIS ←→DY
- ✓ change of sign check from SIDIS to DY for Sivers and Boer-Mulders
- ✓ study of **J/ψ** production mechanism

After a series of beam tests, the feasibility is proven

In a phase 2 (future addendum),
measurement with anti-proton beams will be envisaged

from inclusive reactions to exclusive reactions





Observation of the Nucleon Structure

in 1 dimension **in 1+2 dimensions**

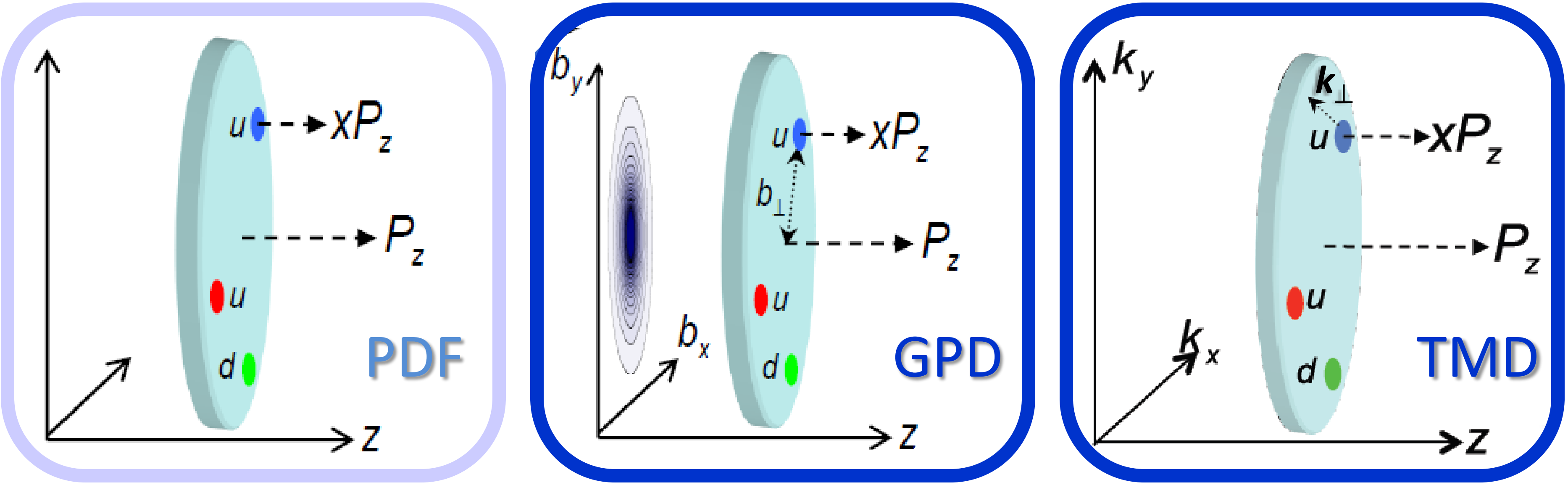
Exploring the 3-dimensional phase-space structure of the nucleon

From Wigner phase-space-distributions (Ji, PRL 2003, Belitsky, Ji, Yuan PRD 2004)
We can build « mother-distributions » (Meissner, Metz, Schlegel, JHEP 0908:056 2009)

$$\mathcal{W}(x, b_\perp, k_\perp)$$

and derive

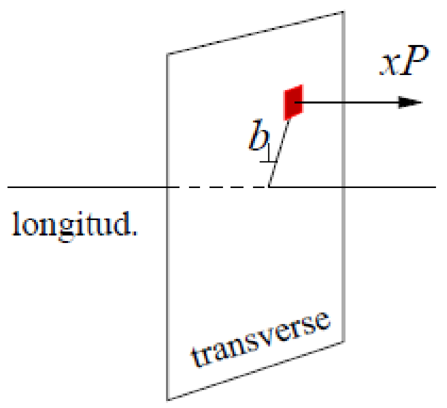
- ✓ GPD: Generalised Parton Distribution (position in the transverse plane)
- ✓ TMD: Transverse Momentum Distribution (momentum in the transv. plane)



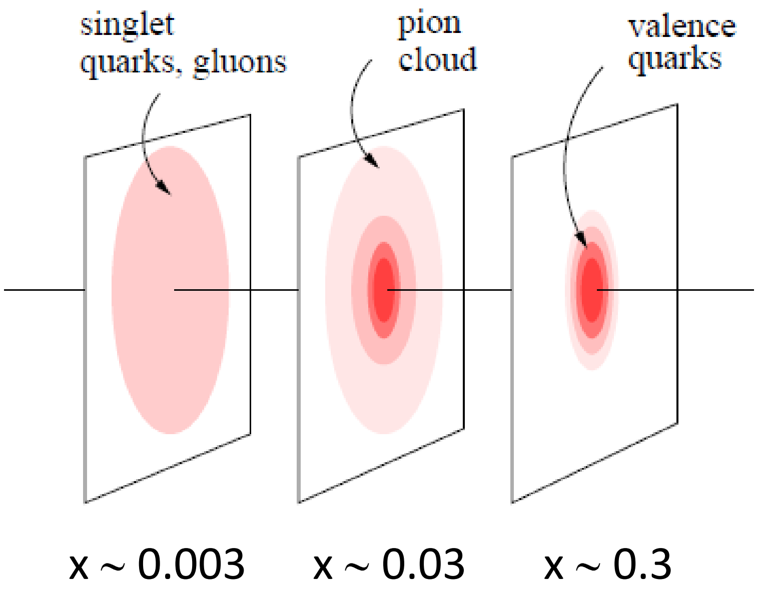
New research fields

Generalized Partons Distributions (H,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)

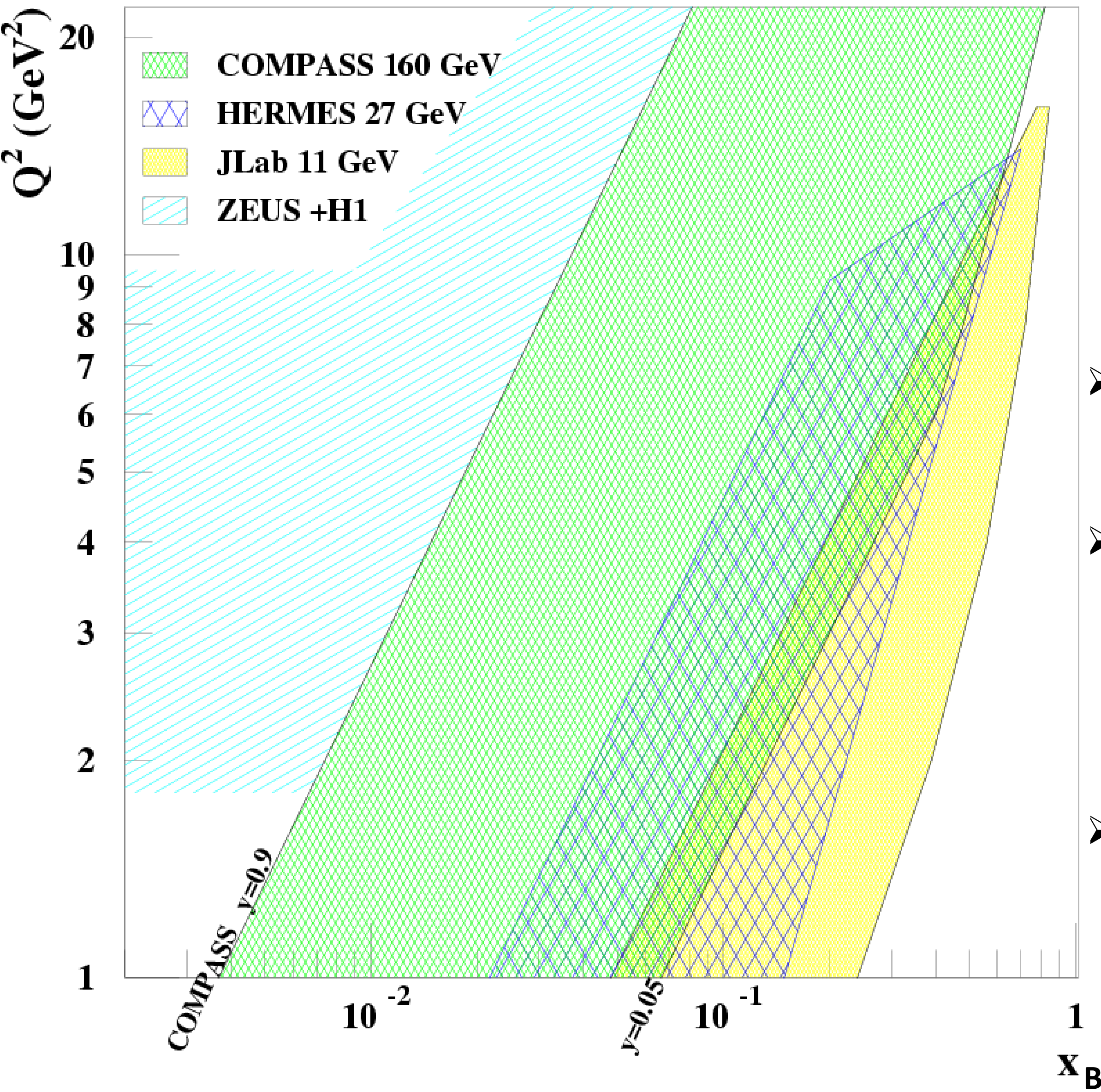


Impact parameter $b_\perp$
Longitudinal momentum fraction x



Tomographic parton images of the nucleon

What makes COMPASS unique for GPDs?



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
- Transverse structure at $x \sim 10^{-2}$ essential input for phenemenology of high-energy pp collision (LHC)

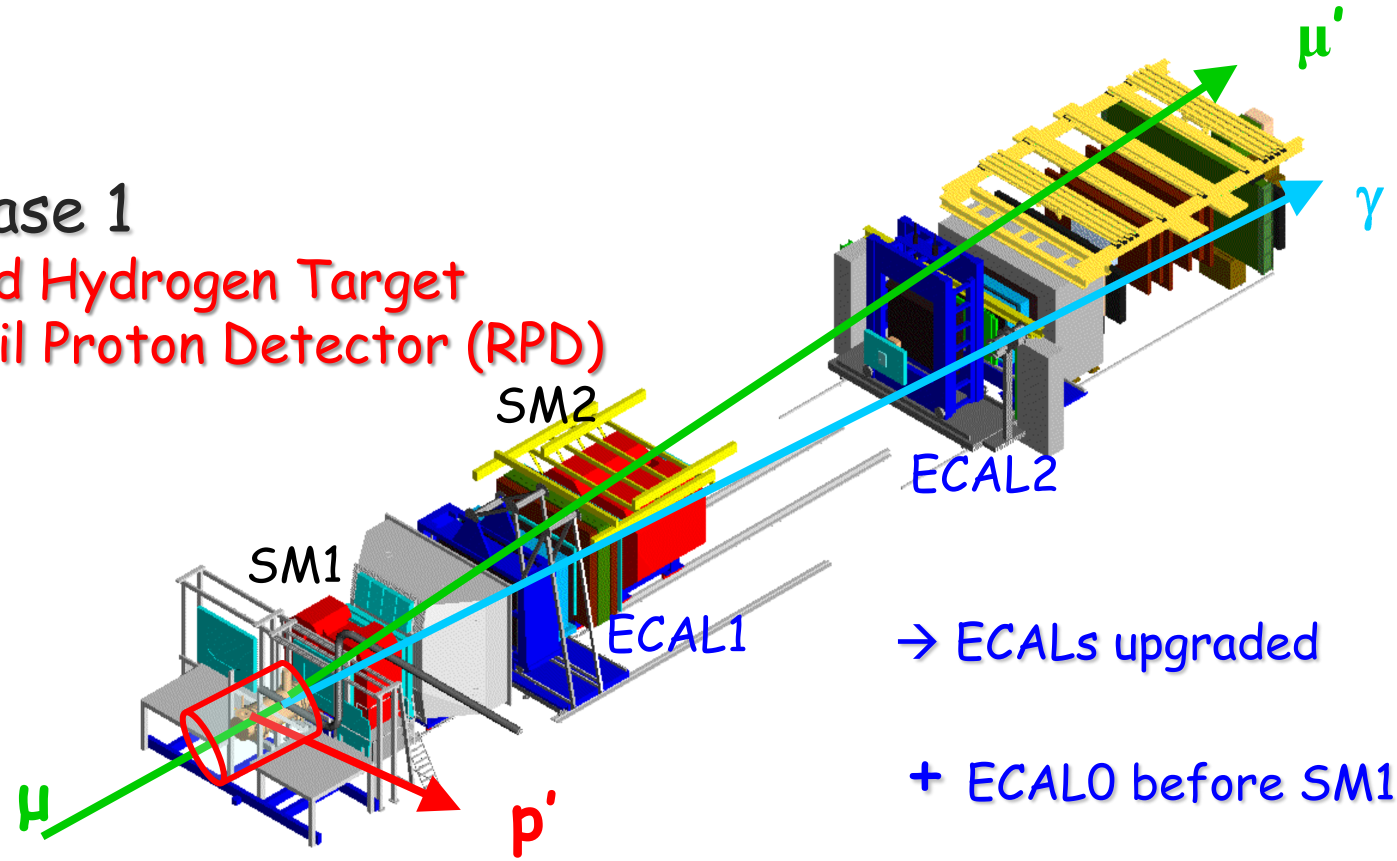
Experimental requirements for DVCS

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

Phase 1

~ 2.5 m Liquid Hydrogen Target

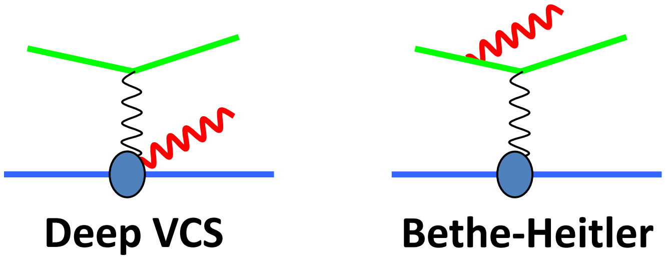
~ 4 m Recoil Proton Detector (RPD)

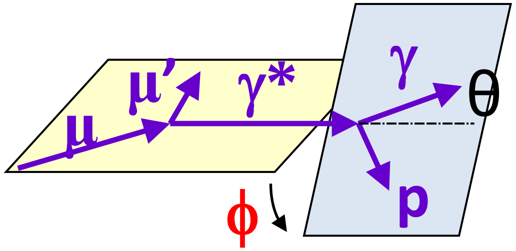


→ ECALs upgraded

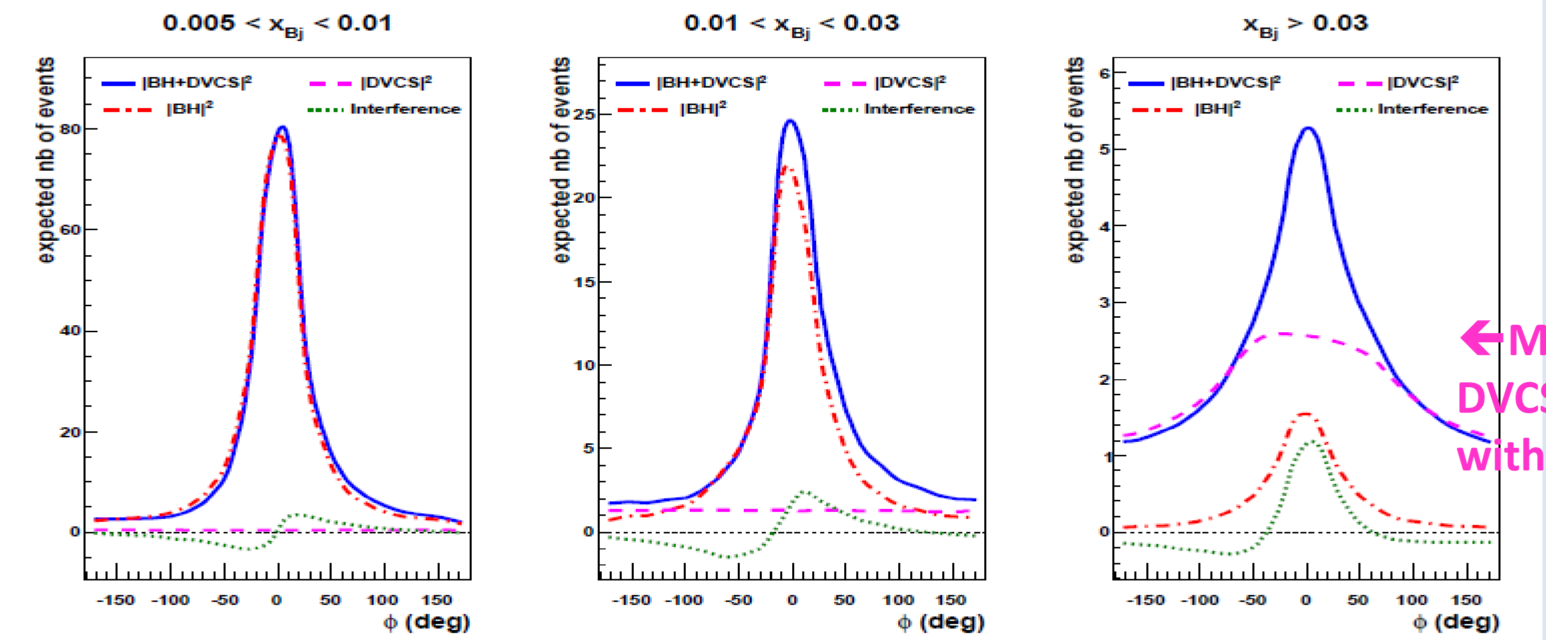
+ ECAL0 before SM1

Contributions of DVCS and BH at E_μ=160 GeV





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



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

← Missing DVCS acceptance without ECAL0

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

Deeply Virtual Compton Scattering

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

Phase 1: DVCS experiment to study the transverse imaging

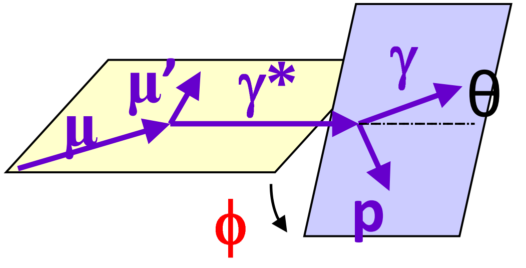
with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

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

$\downarrow$

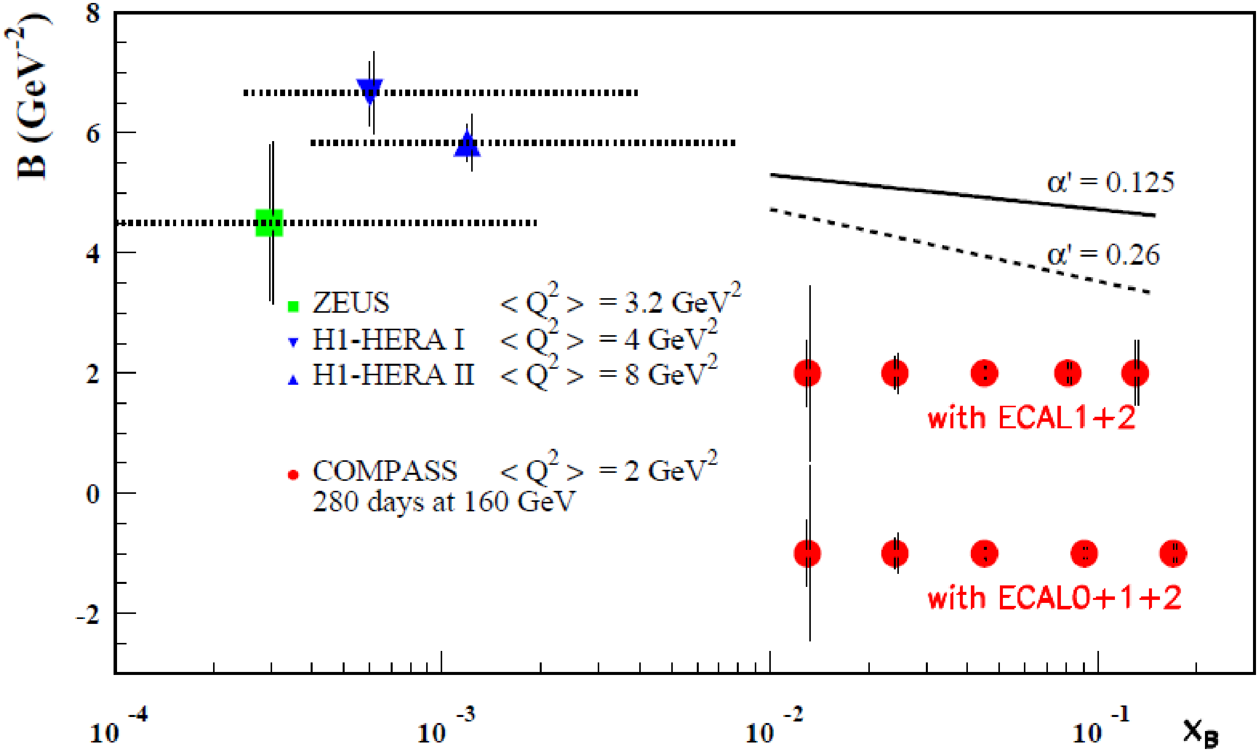
Using $S_{CS,U}$ and integration over ϕ and BH subtraction

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



DVCS: Transverse imaging at COMPASS

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



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

without any model we can extract $B(x_B)$

$$B(x_B) = \frac{1}{2} \langle r_\perp^2(x_B) \rangle$$

$r_\perp$ is the transverse size of the nucleon

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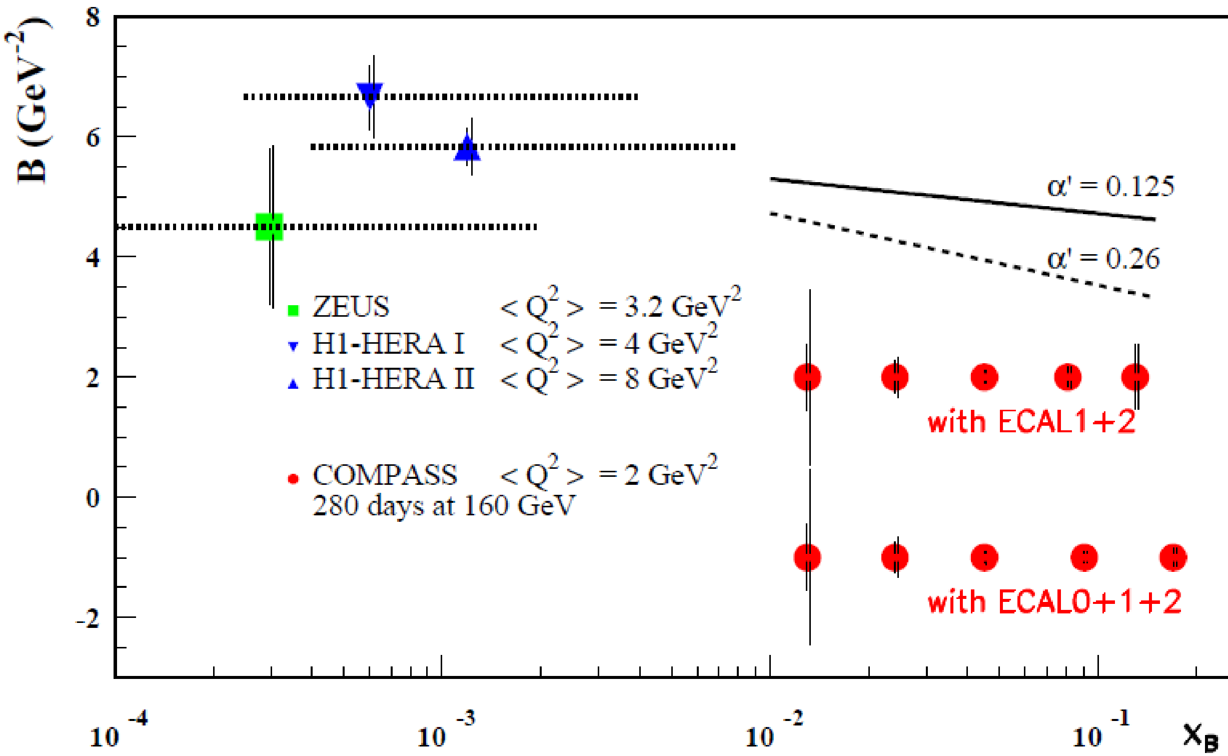
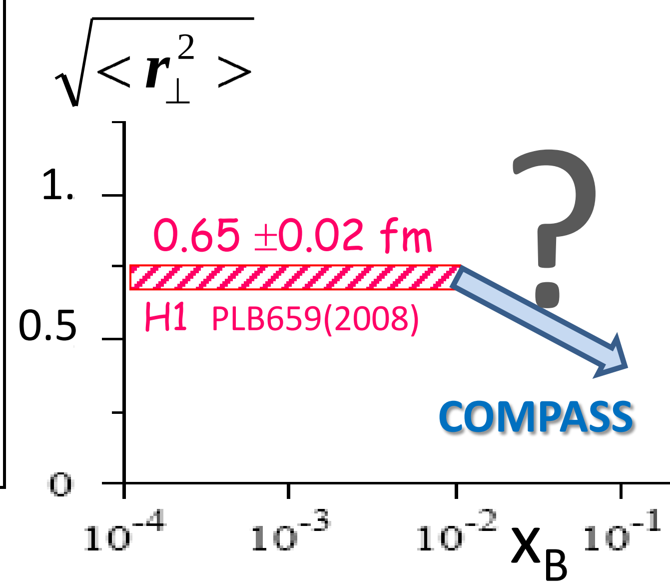


Transverse size of the nucleon



without any model we can extract $B(x_B)$

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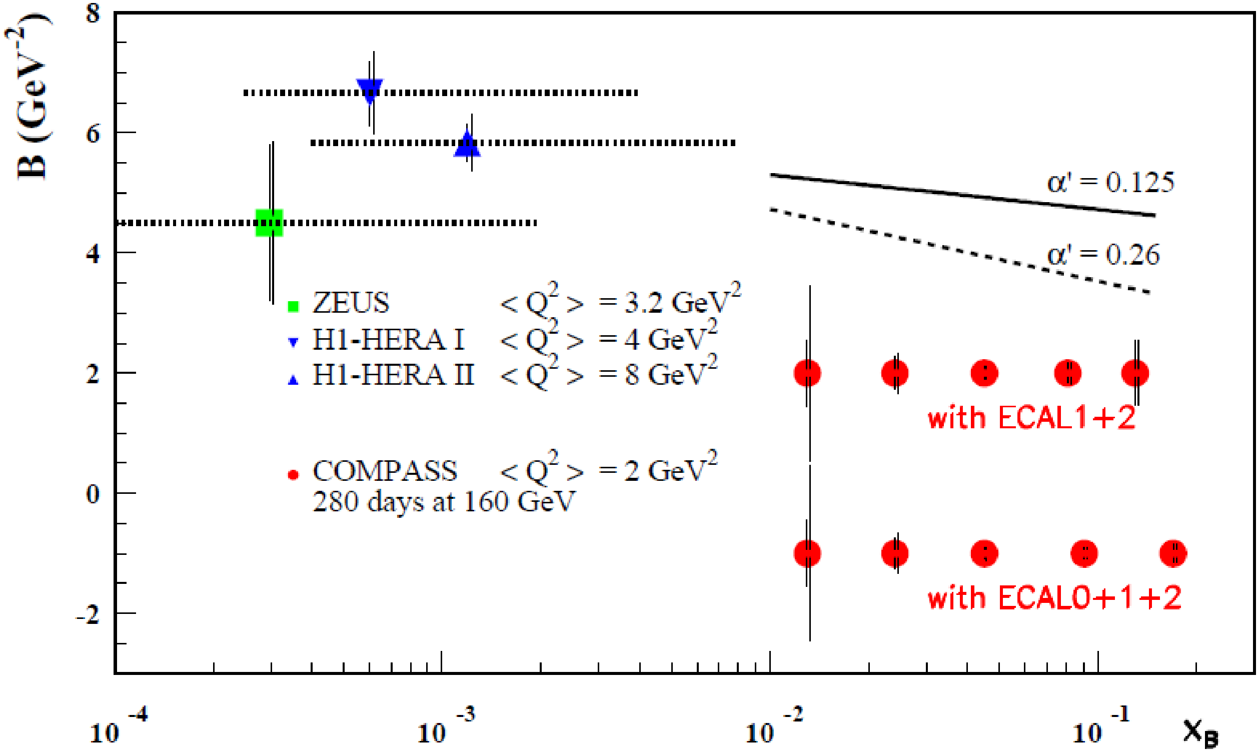


ansatz at small x_B inspired by Regge Phenomenology:

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

α' slope of Regge traject

with the projected uncertainties we can determine :

- B with an accuracy of 0.1 GeV^{-2}
- α' with an accuracy $\geq 2.5\,\sigma$
  if $\alpha' \geq$ **0.26** with ECAL1+2
  if $\alpha' \geq$ **0.125** with ECAL0+1+2

Deeply Virtual Compton Scattering

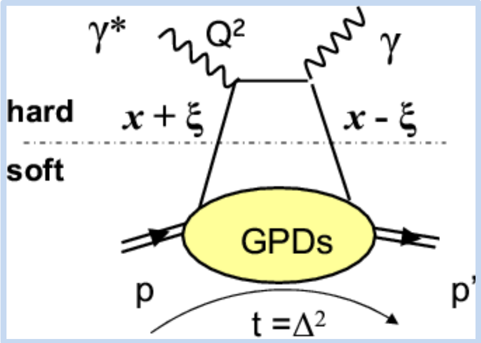
$$d\sigma_{(\mu p\to\mu p\gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol} + e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} + e_\mu\, P_\mu\, a^{BH}\, \mathcal{I}m\, A^{DVCS}$$

Phase 1: DVCS experiment to constrain GPD H

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

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

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

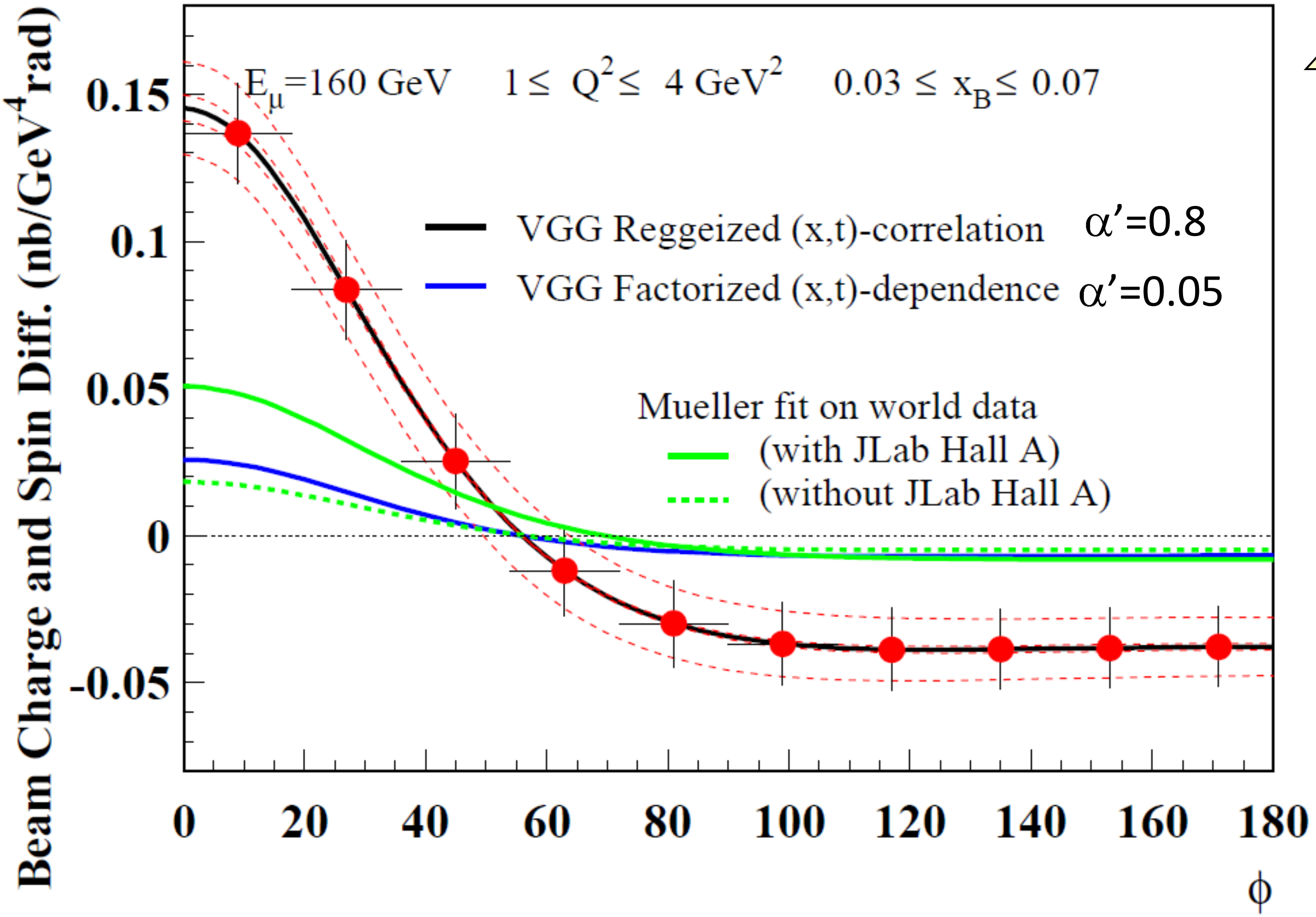


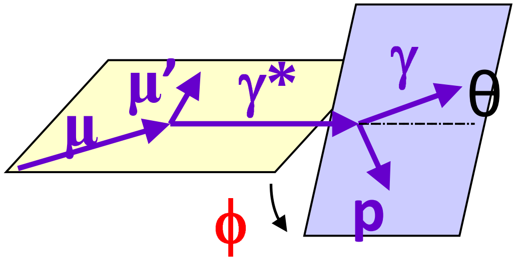
$\xi \sim x_B / (2-x_B)$

- $\mathcal{I}m\, \mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$
- $\mathcal{R}e\, \mathcal{H}(\xi,t) = \mathcal{P}\int dx\, H(x,\xi,t)\,/(x-\xi)$

Beam Charge and Spin Difference (using $\mathcal{D}_{cs,u}$)

Comparison to different models





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

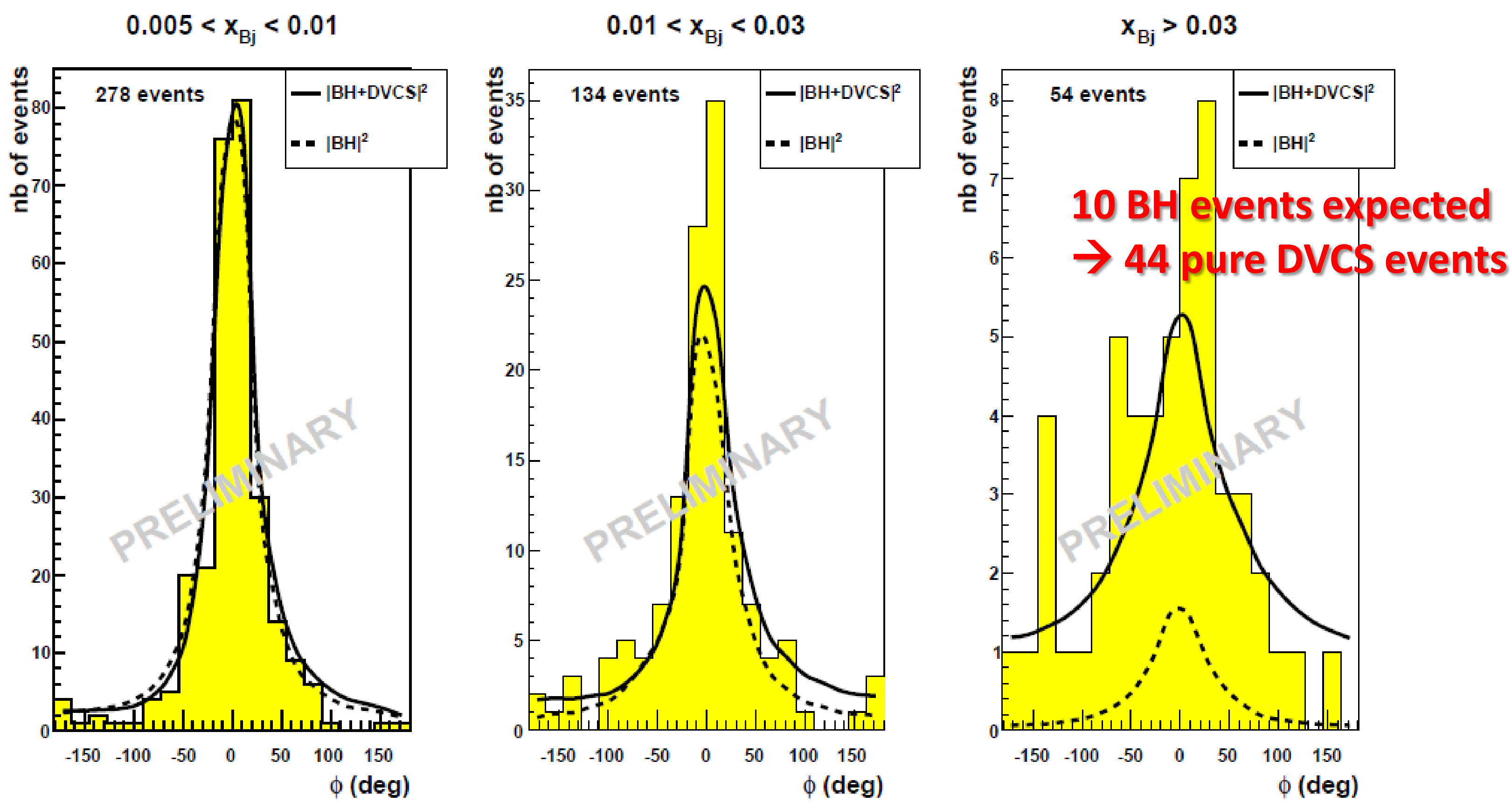
Systematic error bands assuming a 3% charge-dependent effect between μ+ and μ- (control with inclusive evts, BH…)

2008-9 tests: observation of BH and DVCS events

During the hadron program with 1m long recoil proton detector (RPD) and 40cm long LH2 target and the 2 existing ECAL1 and ECAL2

2008: observation of exclusive single photon production,
ε_{global} = 0.13 +/- 0.05 ➔ confirmed ε_{global} = 0.1 as assumed for simulations

2009: observation of BH and DVCS events



Summary for GPD @ COMPASS

GPDs investigated with Hard Exclusive Photon and Meson Production

- the t-slope of the DVCS cross section ……………… LH_2 target + RPD……phase 1
  → transverse distribution of partons
- the Beam Charge and Spin Sum and Difference and Asymm…………….phase 1
  → Re T^{DVCS} and Im T^{DVCS} for GPD H determination

- the Transverse Target Spin Asymm………polarised NH_3 target + RPD……phase 2
  → GPD E and angular momentum of partons (future addendum)

NEW HARDWARE:

- Recoil Proton Detector and Liquid Hydrogen Target
- Complete angular hermiticity for ECAL1-2 + a new ECAL0

Conclusions

A new proposal COMPASS-II has been submitted.

The main topics are:

- GPD with DVCS and DVMP
- TMD with DY and SIDIS
- precise unpolarised PDF measurements
- Chiral perturbation theory - soft QCD
- Hadron Spectroscopy (talk by B. Ketzer)

For the next 10 years, before ENC, EIC, eRHIC, or LHeC, COMPASS@CERN can be a major player in QCD physics using its unique high energy hadron and polarised muon beams

Promising discussions with potential new collaborators:
Bonn, Argonne and Illinois