Polarised Drell-Yan Physics at COMPASS

ISMD 2013 – Chicago, 17/09/2013

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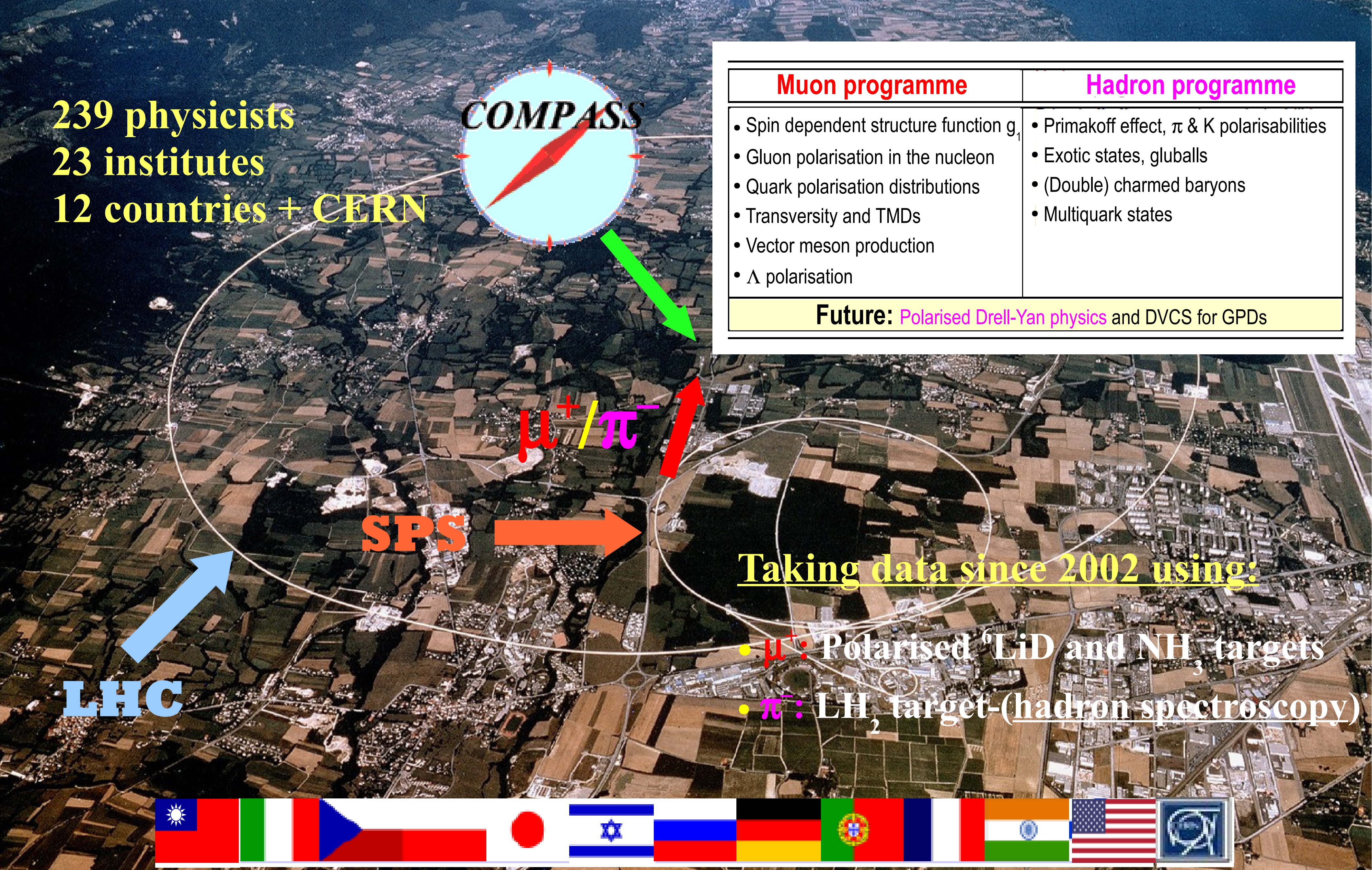
on behalf of the COMPASS collaboration

Common Muon and Proton Apparatus for Structure and Spectroscopy

239 physicists
23 institutes
12 countries + CERN

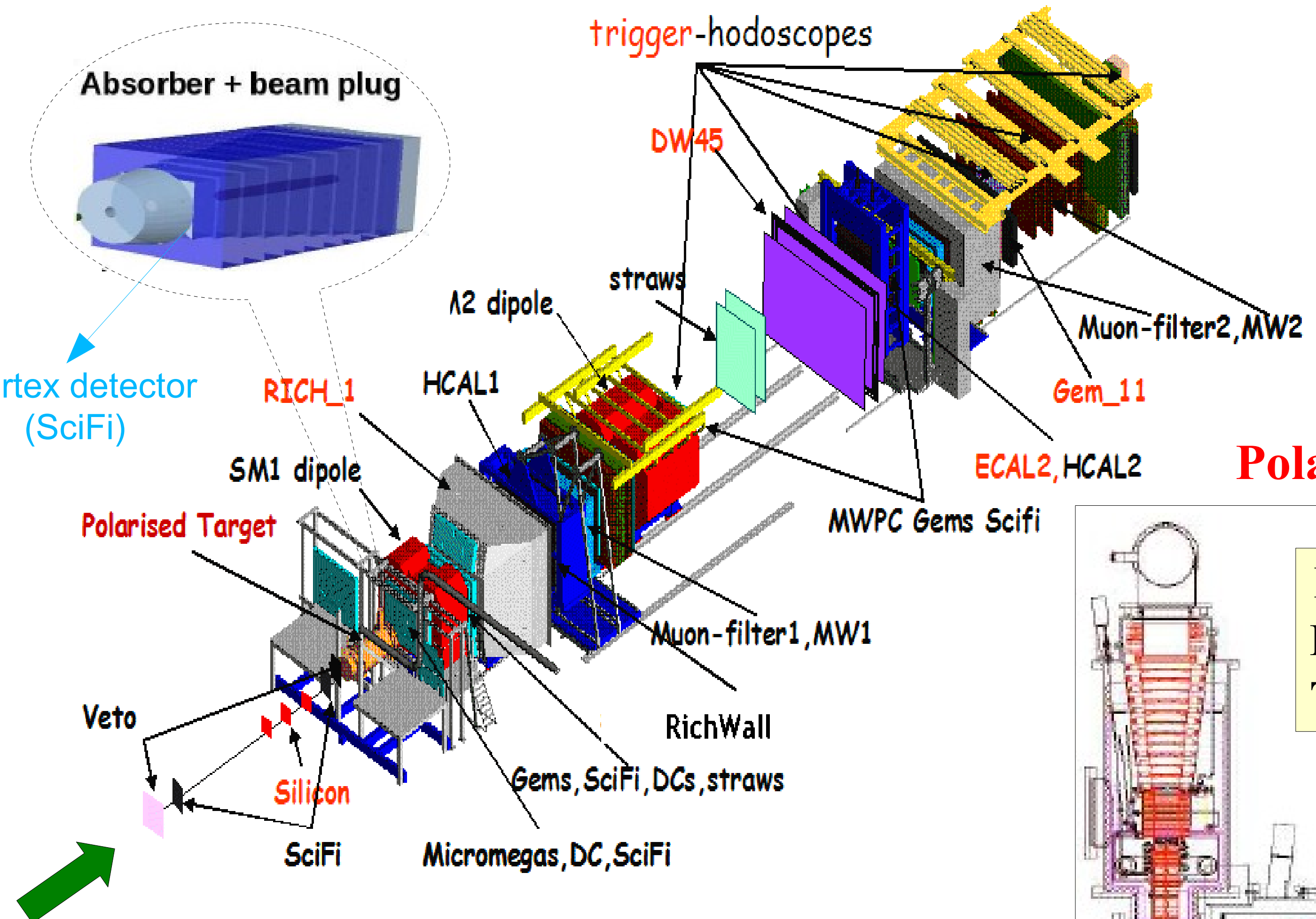
Muon programme	Hadron programme
• Spin dependent structure function g_1	• Primakoff effect, π & K polarisabilities
• Gluon polarisation in the nucleon	• Exotic states, gluballs
• Quark polarisation distributions	• (Double) charmed baryons
• Transversity and TMDs	• Multiquark states
• Vector meson production	
• Λ polarisation	
Future: Polarised Drell-Yan physics and DVCS for GPDs	



Taking data since 2002 using:

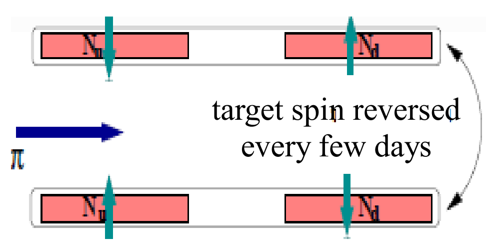
- μ^+: Polarised ^{6}LiD and NH_3 targets
- π^-: LH_2 target (hadron spectroscopy)

The spectrometer and polarised target for the Drell-Yan experiment

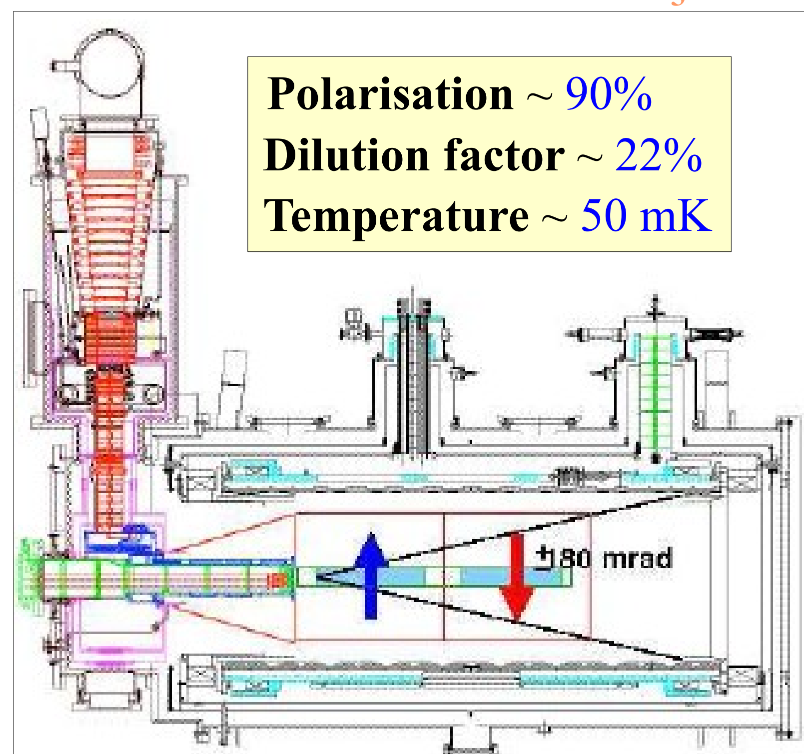


π^- **beam** @190 GeV/c

up to 1× 10^8 π^-/second

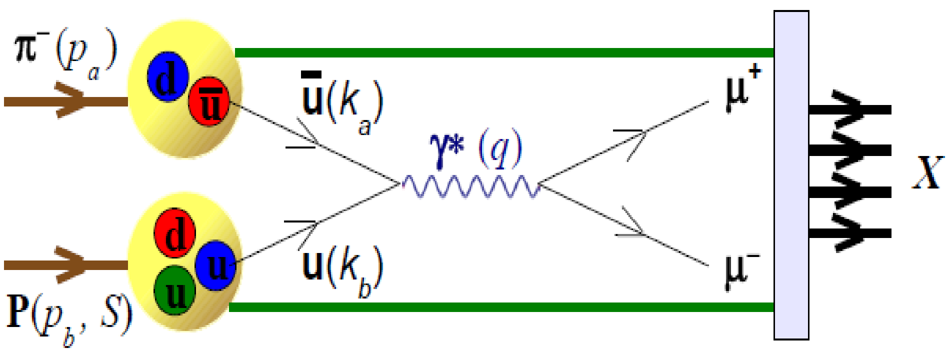


Polarised Target: NH_3



The Drell-Yan (DY) kinematics

Quark-antiquark annihilation with dilepton production



$s = (p_a + p_b)^2$	Total centre-of-mass energy squared
$x_{a\,(b)} = q^2/(2p_{a\,(b)} \cdot q)$	Momentum fraction carried by a quark from the beam (target) hadron
$x_F = x_a - x_b$	Feynman variable
$M_{\mu\mu}^2 = q^2 = s x_a x_b$	Invariant mass squared of the dimuon
$k_{Ta\,(b)}$	Transverse momentum of the quark
$q_T = k_{Ta} + k_{Tb}$	Transverse momentumt of the γ^*

- **The angular distribution of DY events is:**

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1 + \lambda\cos^2\theta + \eta\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

In the collinear hypothesis, i.e., when $k_T = 0$, we have $\lambda = 1, \eta = 0, \nu = 0$. However, past experiments *(NA10 and E615)* have measured a modulation of $\cos 2\phi$ up to 30%

$\Rightarrow$ For a proper study of the nucleon structure, the intrinsic transverse momentum (k_T) of quarks must not be neglected

Leading Order (LO) description of the nucleon structure

(when the intrinsic transverse momentum of quarks, k_T, is also taken into account)

- **In the Drell-Yan experiment we will access 4 of the TMD PDFs:**

Nucleon \ Quark	Unpolarised	Longitudinal Polarisation	Transverse Polarisation
Unpolarised	f_1 (Number density)		$h_1^\perp$ (Boer Mulders)
Longitudinal Polarisation		g_1 (Helicity)	$h_{1L}^\perp$ (Worm Gear)
Transverse Polarisation	$f_{1T}^\perp$ (Sivers)	g_{1T} (Worm Gear)	h_1 (Transversity) $h_{1T}^\perp$ (Pretzelosity)

May be the cause for the observed cos2ϕ modulation (*i.e.*, $\nu \neq 0$)

Contains information about the Orbital Angular Momentum (OAM) of quarks

Surviving k_T integration

$$\Phi_{Coll}^{Tw-2}(x) = \frac{1}{2}\left\{q(x) + S_L \gamma_5 \Delta q(x) + S_L \gamma_5 \gamma^1 \Delta_T q(x)\right\}$$

Investigated at COMPASS <u>via measurement of spin asymmetries</u>

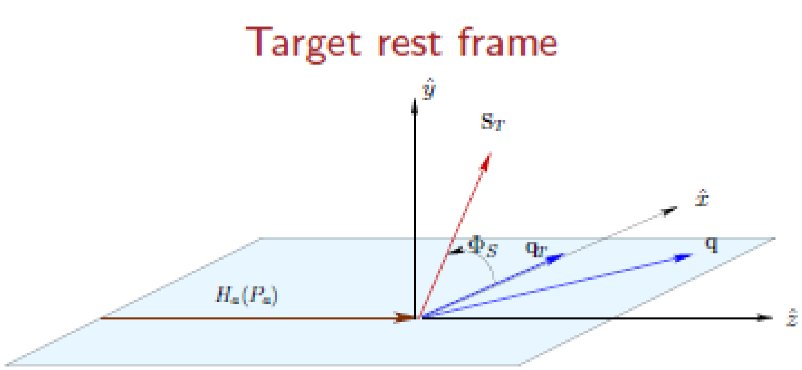
The polarised Drell-Yan cross-section

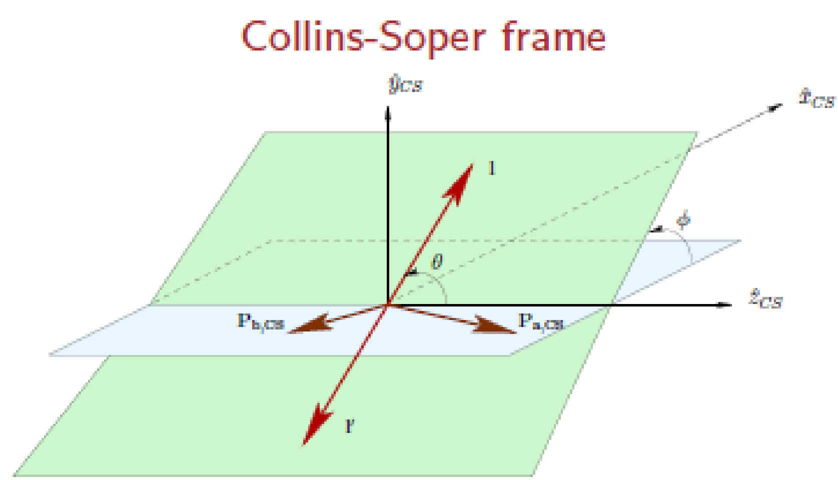
- For a transversely polarised target, one can calculate the cross-sections asymmetry between the 2 spin configurations. Written in terms of azimuthal asymmetries, the DY cross-section for an unpolarised beam and a transversely polarised target is *(in LO)*:

General formula: *S. Arnold et al, Phys.Rev.D79(2009)034005*

$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U\{(1 + D_{[\sin^2\theta]}A_U^{\cos 2\phi}\cos 2\phi) + |\vec{S}_T|[A_T^{\sin\phi_S}\sin\phi_S + D_{[\sin^2\theta]}(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S) + A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S))]\}$$

- **A**: azimuthal asymmetries
- $F = 4\sqrt{(p_a.p_b)^2 - M_a^2 M_b^2}$
- D: depolarisation factor of γ^*
- S_T: target spin components
- $\hat{\sigma}_U$: cross-section surviving integration over ϕ and ϕ_S





Interpretation of the azimuthal asymmetries

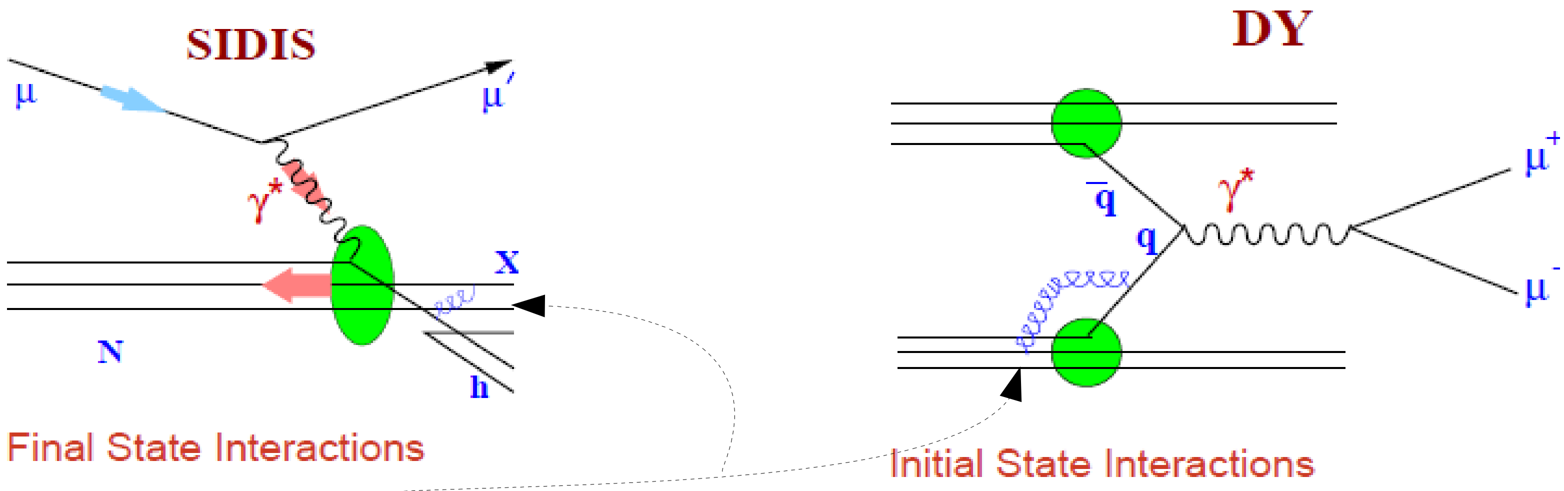
- The 4 asymmetries in the DY cross-section can be measured at COMPASS by fitting the corresponding (ϕ, ϕ_S) distributions. They contain a convolution of 2 PDFs:

  - $A_U^{\cos 2\phi}$: the <u>Boer-Mulders function of both hadrons</u> ($h_1^\perp(\pi) \otimes h_1^\perp(P)$)
  - $A_T^{\sin 2\phi}$: the <u>density number function</u> of the beam hadron with the <u>Sivers function</u> of the target nucleon ($f_1(\pi) \otimes f_{1T}^\perp(P)$)
  - $A_T^{\sin(2\phi+\phi_S)}$: the <u>Boer-Mulders function</u> of the beam hadron with the <u>pretzelosity function</u> of the target nucleon ($h_1^\perp(\pi) \otimes h_{1T}^\perp(P)$)
  - $A_T^{\sin(2\phi-\phi_S)}$: the <u>Boer-Mulders function</u> of the beam hadron with the <u>transversity function</u> of the target nucleon ($h_1^\perp(\pi) \otimes h_1(P)$)

All asymmetries are expected to be large in the valence quark region

(COMPASS $x_p > 0.1$)

Universality of the TMD PDFs: SIDIS vs DY



The resummation of all soft gluons in a k_T dependent PDF is process dependent. This procedure, <u>which is essential to provide the gauge invariance of a PDF</u>, leads to the existence of T-odd functions such as the Sivers and the Boer-Mulders PDFs

⇒ To provide the time invariance, these TMD PDFs need to change sign between SIDIS and DY:

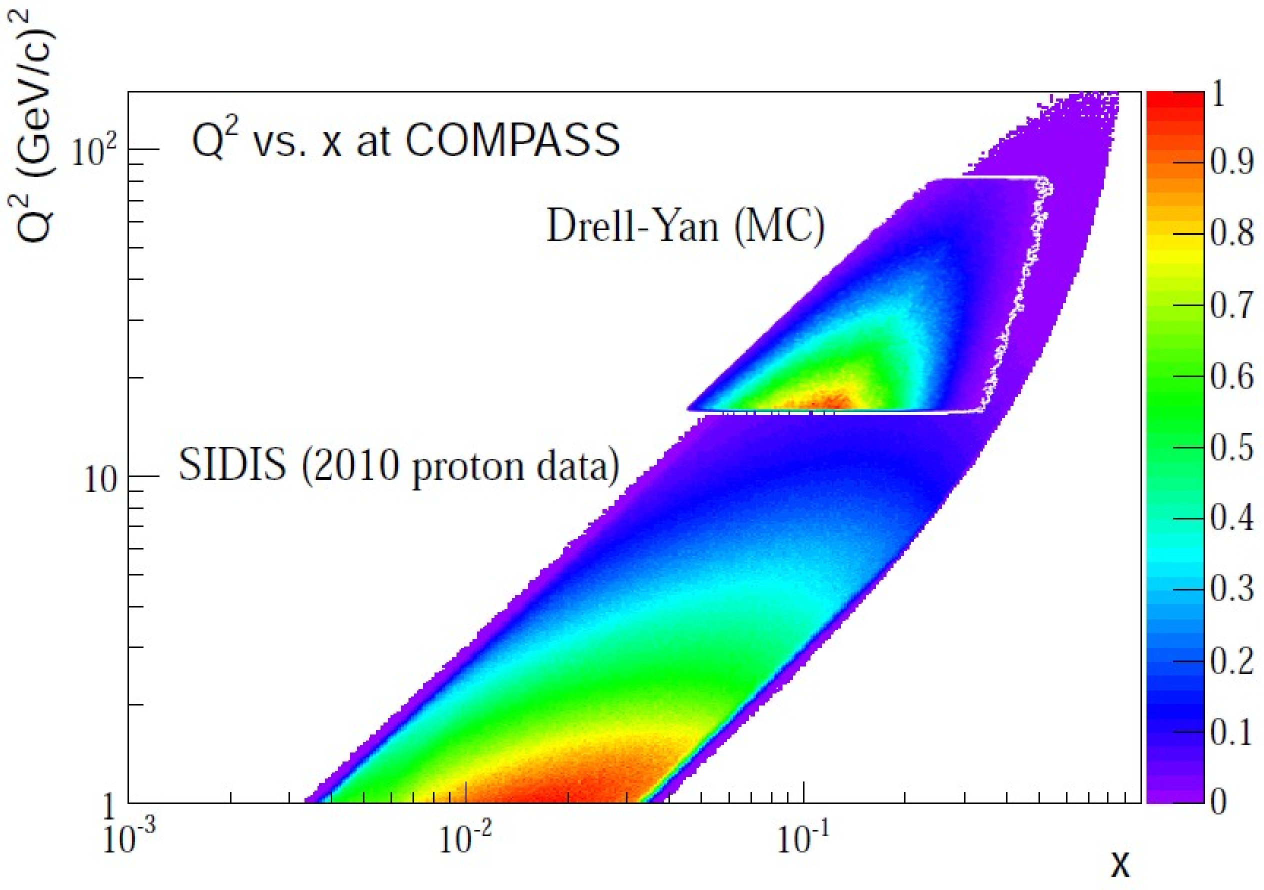
$$f_{1T}^{\perp}(DIS) = - f_{1T}^{\perp}(DY)$$

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

- **The sign change observation is a crucial test of non-perturbative QCD** *(the TMD approach)*
  - By studying both processes, <u>COMPASS has previledged conditions to confirm (or deny) the sign change</u> and also to compare the shape and amplitude of $f_{1T}^{\perp}$ between SIDIS and DY

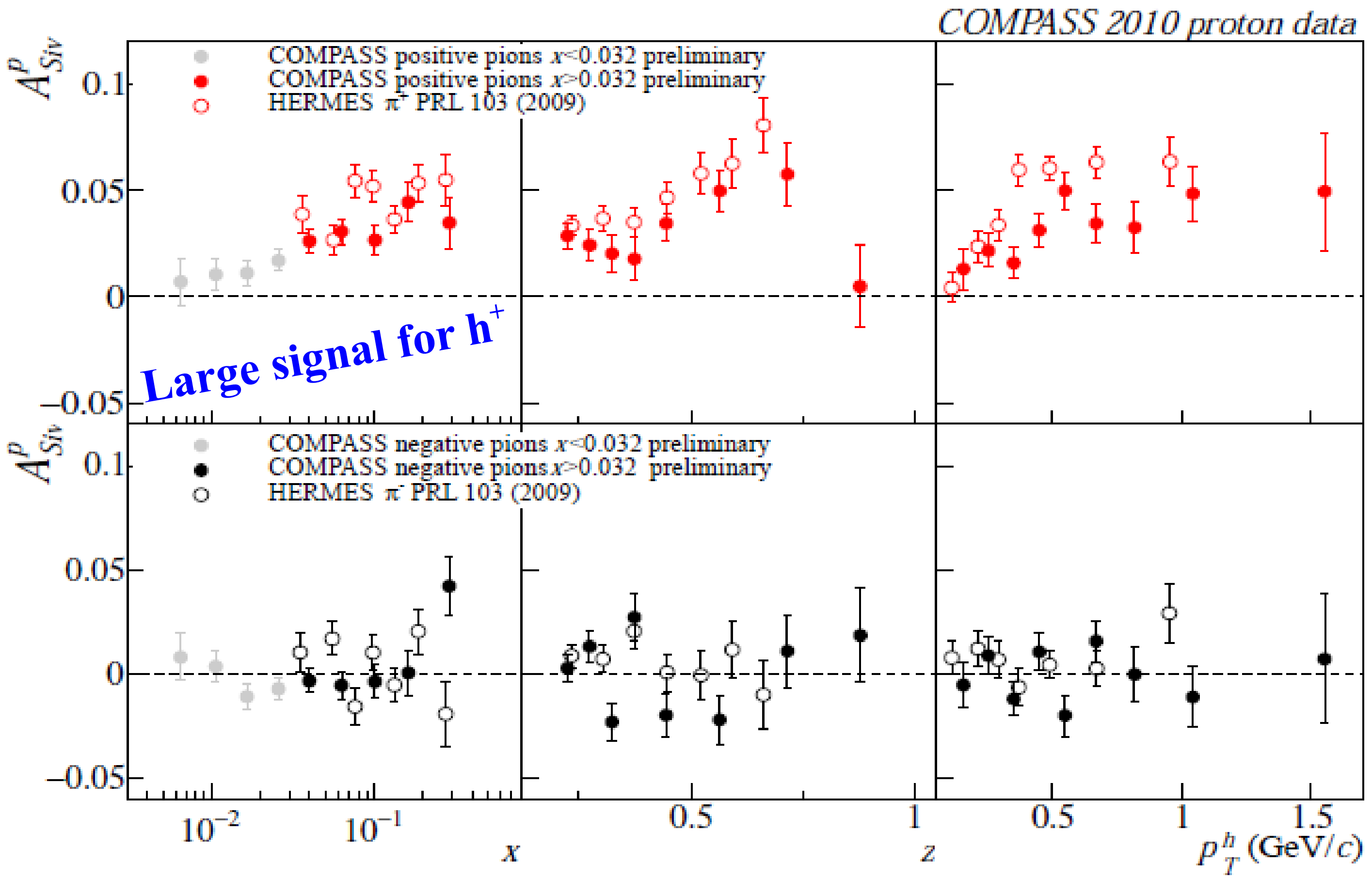
SIDIS and Drell-Yan at COMPASS

- In COMPASS we have the unique opportunity to perform, using the same spectrometer and transversely polarised target, both the SIDIS and the DY measurements:



There is a phase space overlap between the two measurements!

COMPASS result on the Sivers asymmetry from SIDIS



- Interpretation of the Sivers asymmetry in SIDIS and in DY:

Requires knowledge on fragmentation functions to extract $f_{1T}^{\perp}$

SIDIS

$$A_{Sivers} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp(1)}(x) D_q^h(z)}{\sum_q e_q^2 f_1(x) D_q^h(z)}$$

DY

$$A_{Sivers} \propto 2\frac{\sum_q e_q^2 \bar{f}_{1q}(x_1) f_{1Tq}^{\perp(1)}(x_2)}{\sum_q e_q^2 f_{1q}(x_1) f_{1q}(x_2)}$$

J/ψ studies

The following studies will be performed at COMPASS:

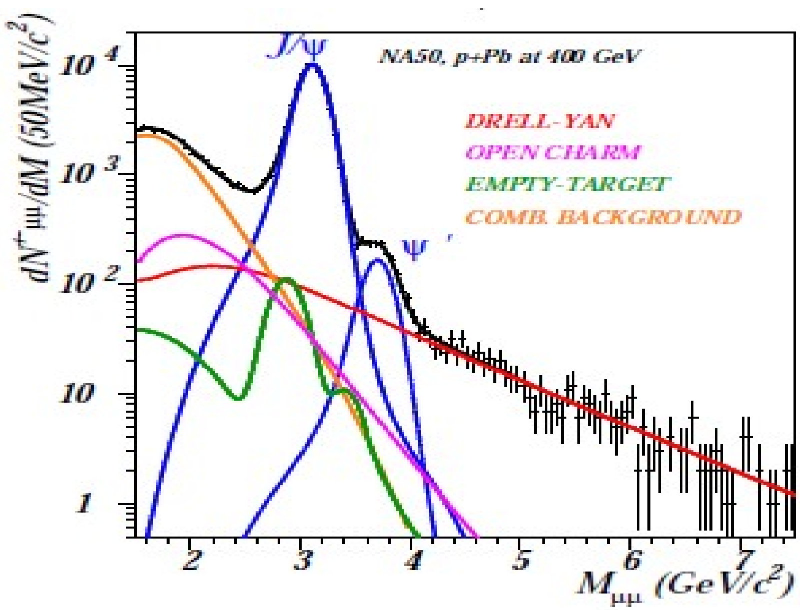
- Verify the duality hypothesis, i.e., J/ψ ↔ DY → Study if the gg fusion mechanism of the J/ψ production is dominated by the $q\bar{q}$ annihilation mechanism *(@ COMPASS kinematics)*

$$\pi^- p^\uparrow \to J/\Psi\, X \to \mu^+ \mu^+ X \quad \leftrightarrow \quad \pi^- p^\uparrow \to \gamma^* X \to \mu^+ \mu^+ X$$

- In case of duality, one can also perform:
  - The study of the polarised J/ψ cross-section
  - The extraction of TMD PDFs with much larger statistics

- Study the J/ψ production mechanisms by varying the beam energy *(from 100 GeV to 280 GeV)*, i.e., the $q\bar{q}$ annihilation vs gg fusion:
  - It may provide the possibility to study the gluon Sivers function → related to the gluons orbital angular momentum

Signal and background



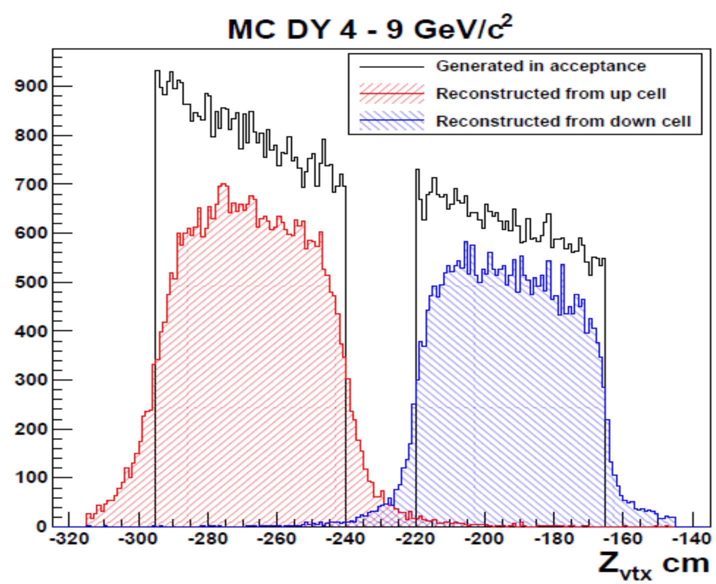
- Despite the sharp drop of σ_{DY} with $M_{\mu\mu}$, dimuons with $4 \leq M_{\mu\mu} < 9$ GeV/c^2 are the ideal sample to study TMD PDFs, due to negligible background contamination

- **I_{beam} ≤ 10^8 π^-/s** ~ <u>10× lower than in NA50</u>

  => Background (∝ I_{beam}^2) ~ 100× lower than in NA50

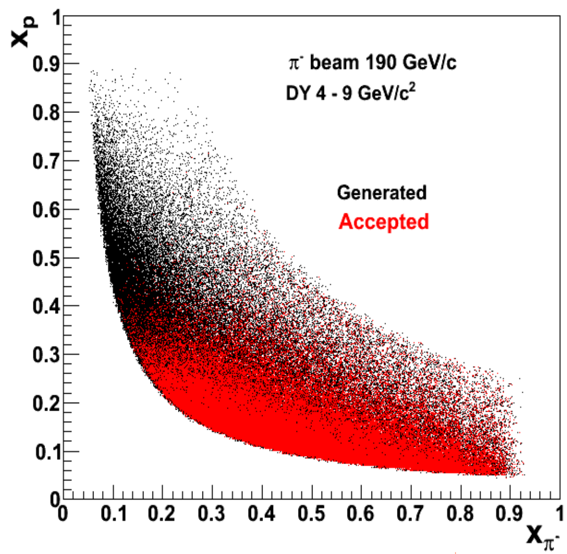
  => Possibility to use the regions of $2 \leq M_{\mu\mu} < 2.5$ GeV/c^2 and J/ψ (*<u>J/ψ ↔ DY duality</u>*) for TMDs

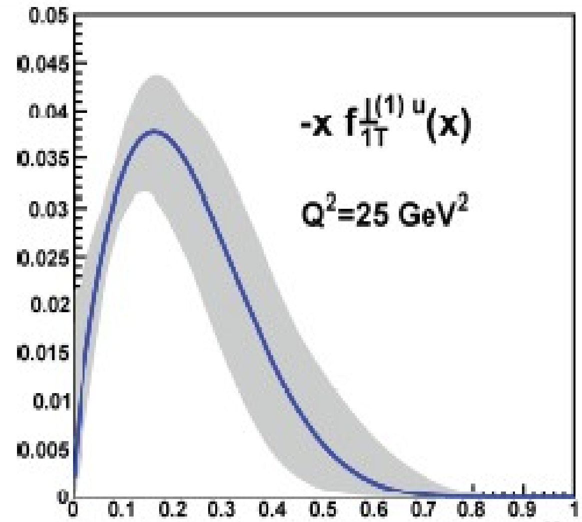
- **The combinatorial background is suppressed by the use of a hadron absorber with low Z material** *(Al_2O_3)*: minimises the muon multiple scattering and maximises the hadrons stopping

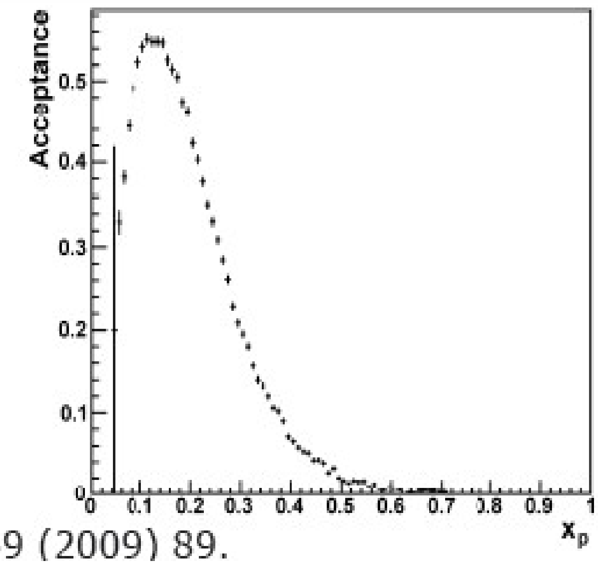


Very good reconstruction of DY events at COMPASS (Monte Carlo)

COMPASS acceptance for Drell-Yan events

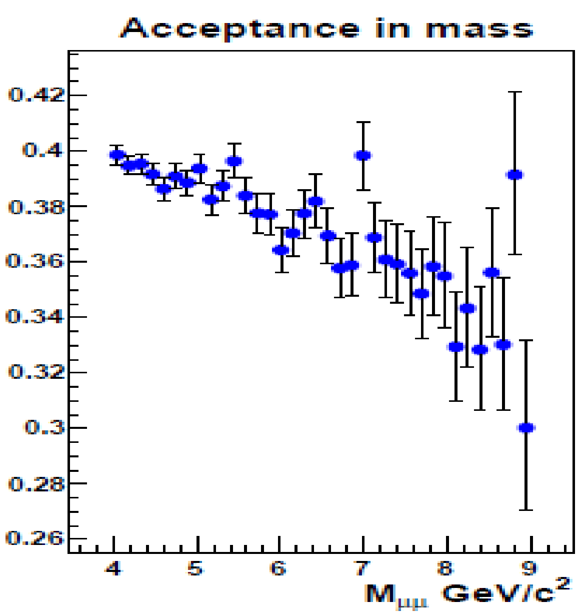


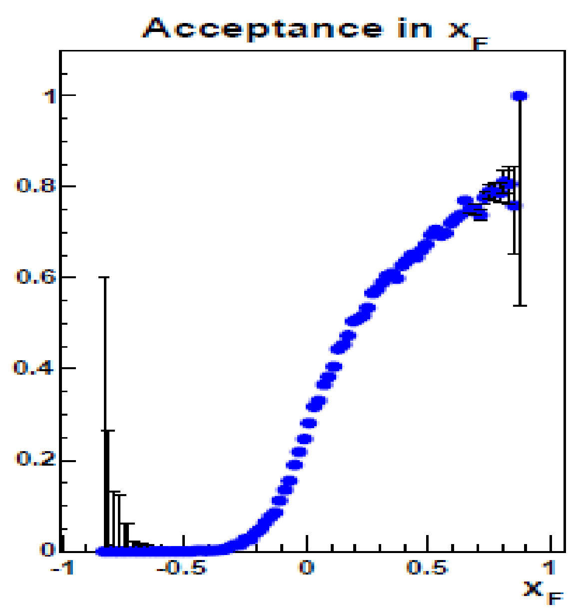


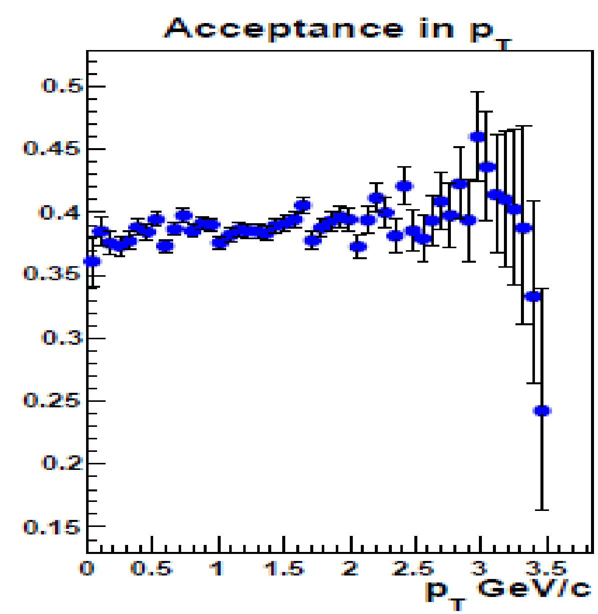


M. Anselmino et al., Eur. Phys. J. A39 (2009) 89.

Large acceptance in the proton valence region where large spin asymmetries are expected







Expected rates and statistical precision

- With a beam intensity of $I_{beam} = 6 \times 10^7\ s^{-1}$, a luminosity $L = 1.2 \times 10^{32}\ cm^{-2}s^{-1}$ can be obtained. With this luminosity, we expect:
  - 900 events/day *(≈ 250000 events/year)* from DY in $4 \leq M_{\mu\mu} < 9\ GeV/c^2$
  - 4300 events/day *(≈ 1.2×10^6 events/year)* from DY in $2 \leq M_{\mu\mu} < 2.5\ GeV/c^2$
  - 22500 events/day *(≈ 6.3×10^6 events/year)* from DY+J/Ψ in $2.9 \leq M_{\mu\mu} < 3.2\ GeV/c^2$

- **The expected statistical error in the asymmetries is:**

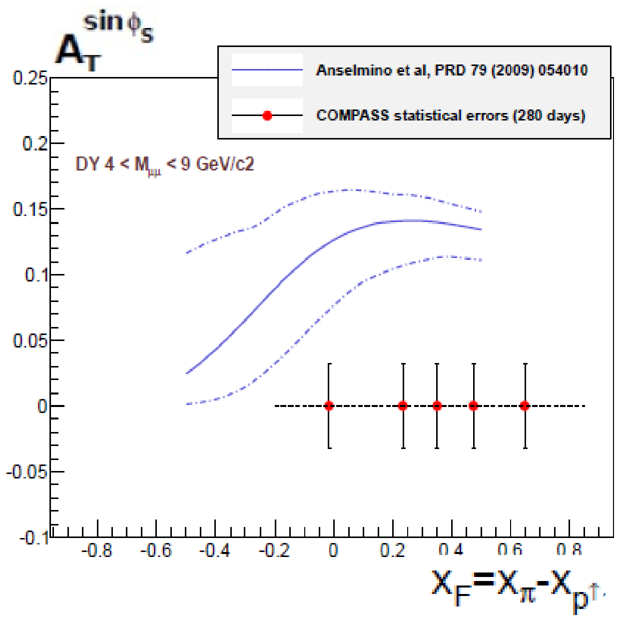
Asymmetry uncertainty	Dimuon mass (GeV/c^2)		
	$2 < M_{\mu\mu} < 2.5$	J/ψ region	$4 < M_{\mu\mu} < 9$
$\delta\, A_U^{\cos 2\phi}$	0.0026	0.0014	0.0056
$\delta\, A_T^{\sin \phi_S}$	0.0065	0.0036	0.0142
$\delta\, A_T^{\sin(2\phi+\phi_S)}$	0.0131	0.0073	0.0284
$\delta\, A_T^{\sin(2\phi-\phi_S)}$	0.0131	0.0073	0.0284

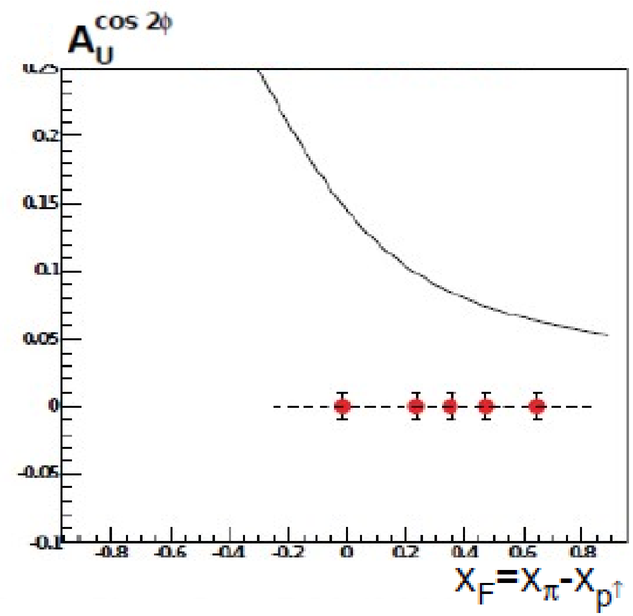
Comparison of the asymmetries with theory predictions

(Theory update is needed to take into account the Q^2 evolution)

Unpolarised PDF ⊗ Sivers

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

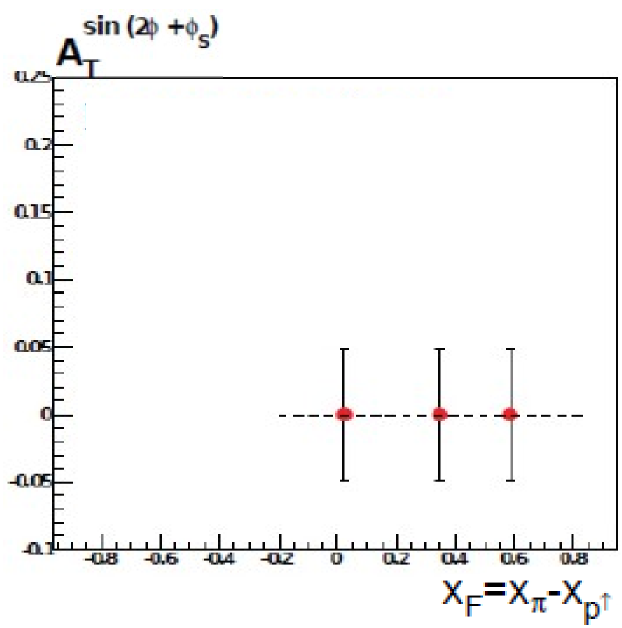


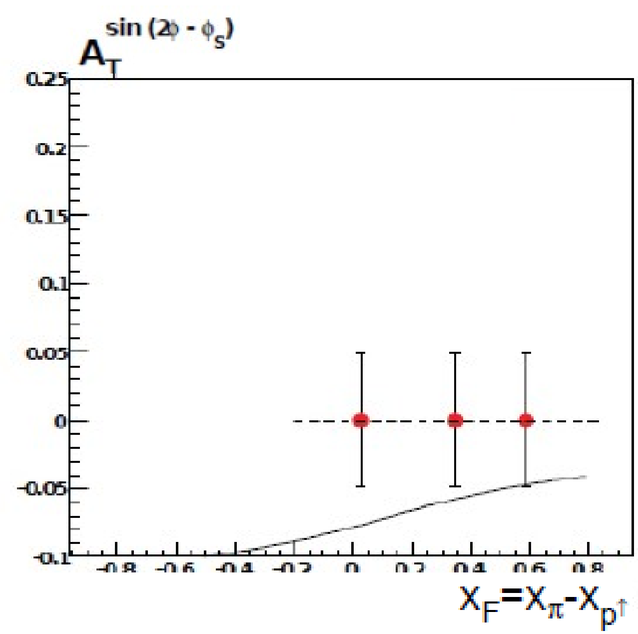


Boer-Mulders ⊗ Boer-Mulders

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

Boer-Mulders ⊗ Pretzelosity



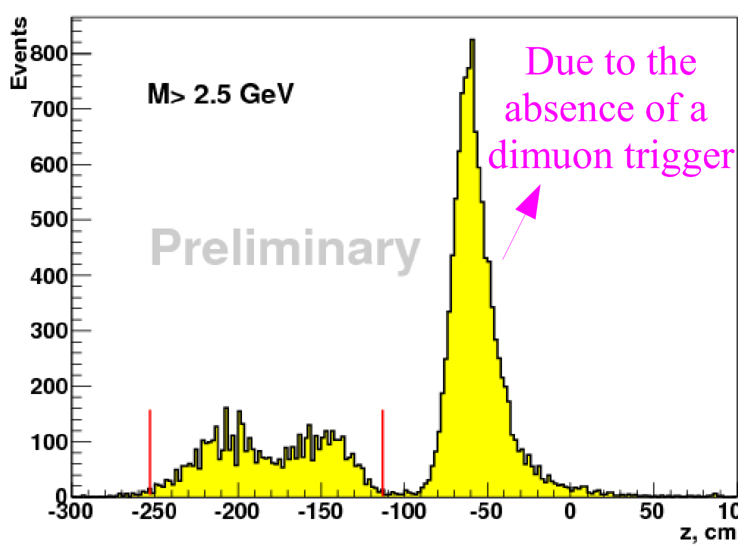


Boer-Mulders ⊗ Transversity

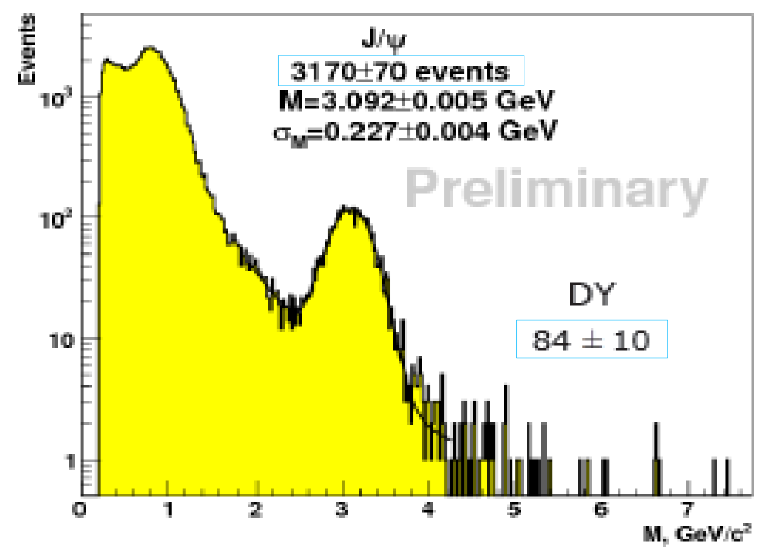
A. N. Sissakian *et al*, Phys. Part. Nucl. 41: 64-100, 2010

Feasibility of the measurement

- The feasibility of the measurement was proved by several beam tests:
  - Verification of the absorber effect and spectrometer response *(including the $\mu^+\mu^-$ trigger)* ✓
  - Verification of the radiation doses ✓
  - Validation of the expected J/Ψ yields *(2009)* ✓ → 3 days of data taking using a π^- beam of 190 GeV/c on an unpolarised 2-cells polyethylene target. The setup included a prototype absorber made of concrete + stainless steel and a beam plug made of steel discs



Reasonable Zvertex separation, allowing to distinguish the 2 target cells and the absorber



The expected number of J/Ψ and DY events from Monte-Carlo was confirmed:
expected J/Ψ: 3600 ± 600
expected DY: 110 ± 22

Competition and complementarity

- **Worldwide plans to study TMD PDFs via the polarised DY process:**

Facility	type	s (GeV^2)	timeline
RHIC (STAR, PHENIX)	collider, $p^{\uparrow}p$	200^2	> 2016
J-PARC	fixed target, $p^{\rightarrow\uparrow}$ D	60 – 100	> 2018
FAIR (PAX)	collider, $\bar{p}^{\uparrow}$ $p^{\uparrow}$	200	> 2018
NICA	collider, $p^{\uparrow}$ $p^{\uparrow}$, $D^{\uparrow}$ $D^{\uparrow}$	676, 144	> 2018
COMPASS	fixed target, $\pi^{\pm}$ $H^{\rightarrow\uparrow}$, $\pi^{\pm}$ $D^{\rightarrow\uparrow}$	357	2014

COMPASS aims to perform the first polarised DY experiment in the world

Summary

- The opportunity to study, with the same spectrometer, the TMD PDFs from both SIDIS and Drell-Yan processes is unique at COMPASS
  - In particular, the sign change in the Sivers and Boer-Mulders functions when measuring in Drell-Yan or in SIDIS will be checked *(crucial for our current understanding of TMD PDFs in non-perturbative QCD)*
- The experimental acceptance of COMPASS covers the valence quarks region, where TMD effects are expected to be sizable
- The feasibility of the measurement was proven after a series of beam tests
- The polarised Drell-Yan measurement will start by the end of 2014 with a short beam test. The physics run will take place in 2015. A second year of data-taking is also planed, possibly in 2018
  - With 2 years of data it will be possible to study the TMD PDFs as a function of x_F and p_T