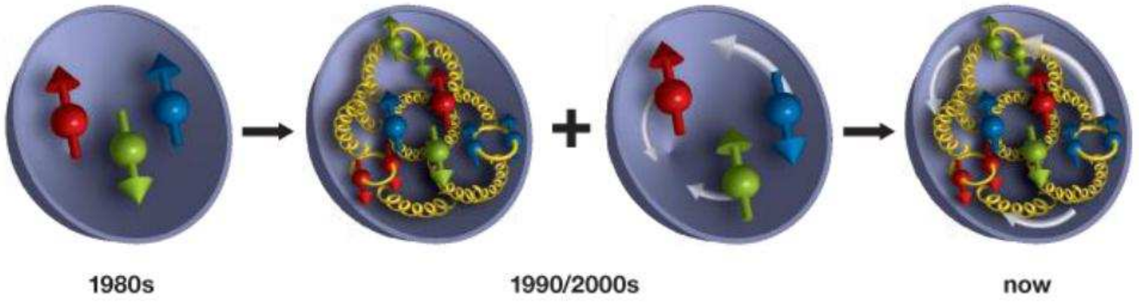
COMPASS II: 3D nucleons

C. Quintans, LIP-Lisbon

21^{st} March 2014, Jornadas LIP 2014



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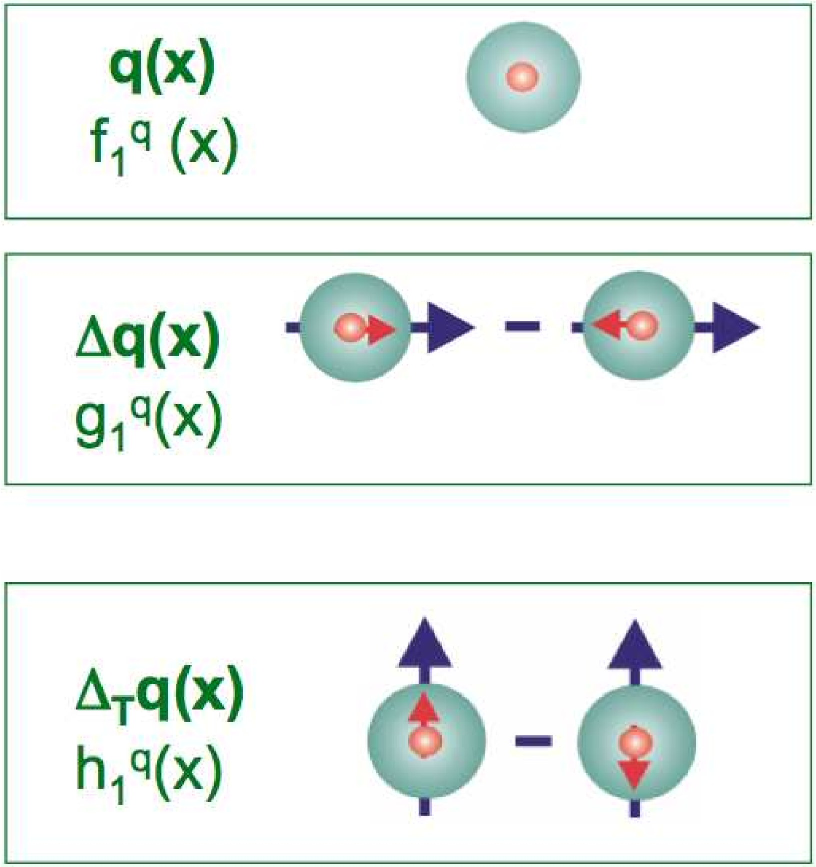
The parton distribution functions (PDFs) give the probability to find a given quark flavour with given fraction of momentum of the nucleon (neglecting transverse motion of the quarks).



To describe the nucleon in terms of its constituents requires 3 PDFs per quark flavour:

- unpolarized PDF $\longrightarrow$ structure function number density f_1,
- longitudinally polarized PDF $\longrightarrow$ helicity g_1,
- transversely polarized PDF $\longrightarrow$ transversity h_1.

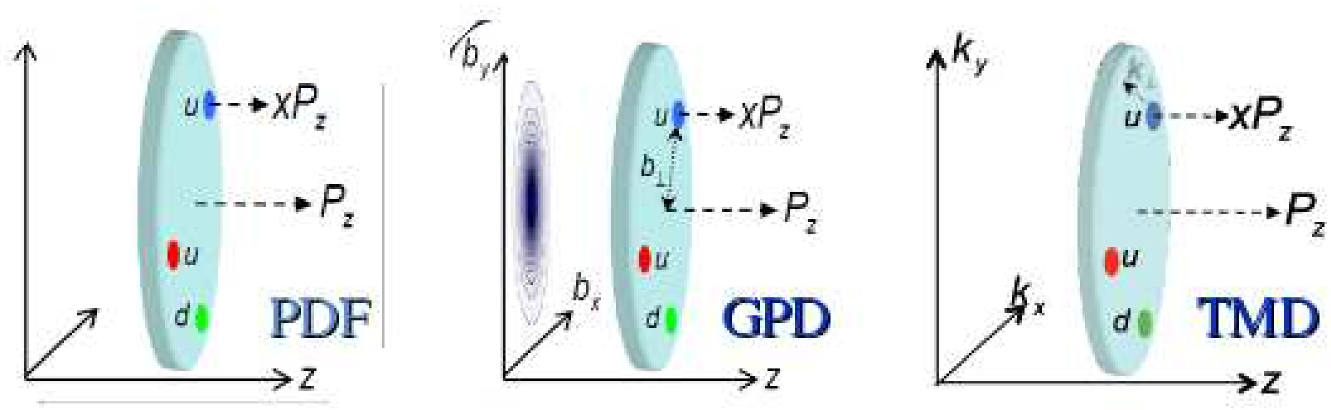
Additionally, gluon helicity also needed.

Towards nucleon tomography

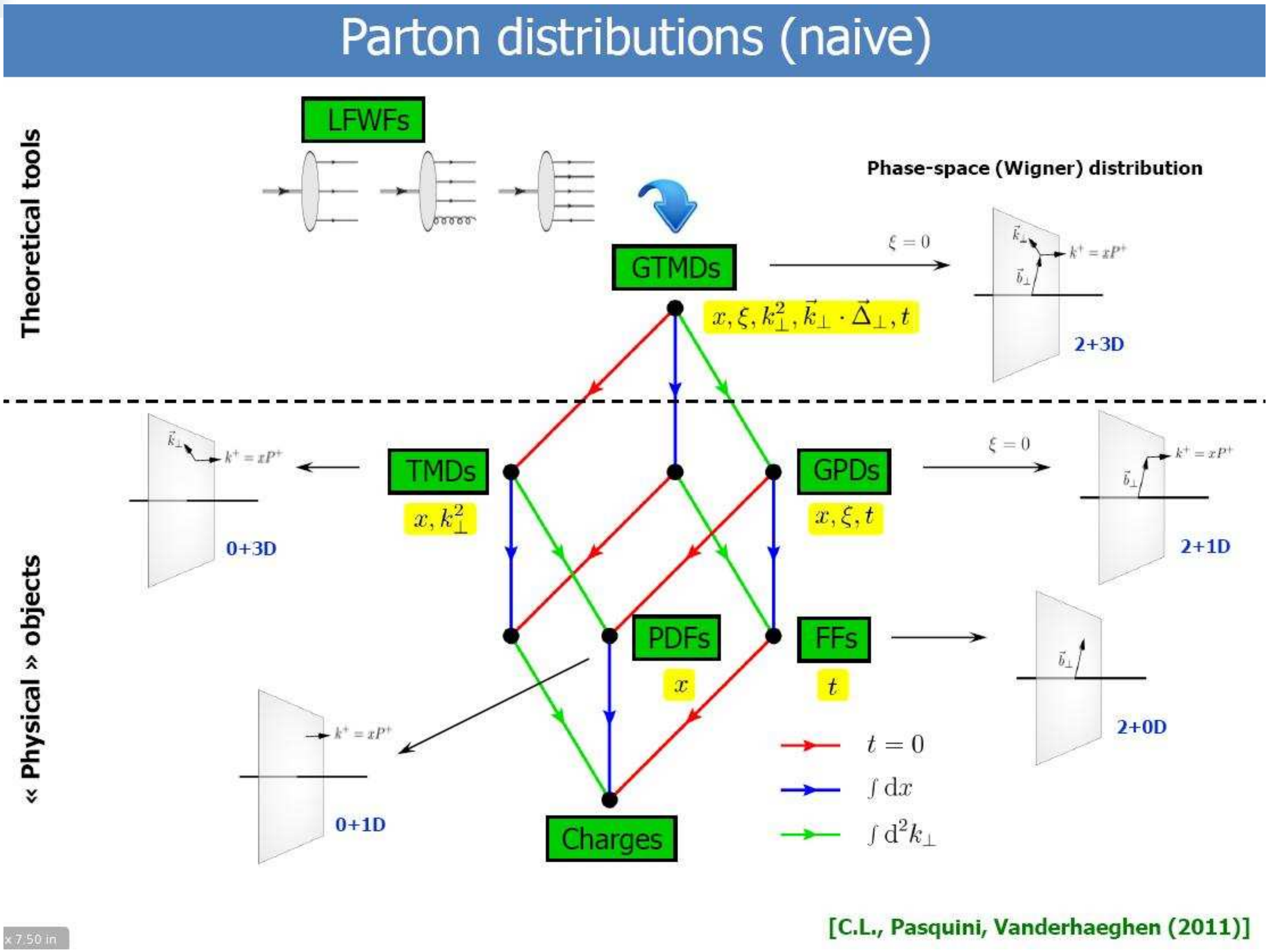
The nucleon world is not 1D! The theory understanding proceeds in 2 complementary ways:

- TMD PDFs: adding information about intrinsic transverse momentum dependence;
- GPDs: adding information about the transverse distance of the constituent quark.

Both address the quarks and gluons orbital angular momentum contribution – although interpretation is difficult.



A theoretical “jungle"

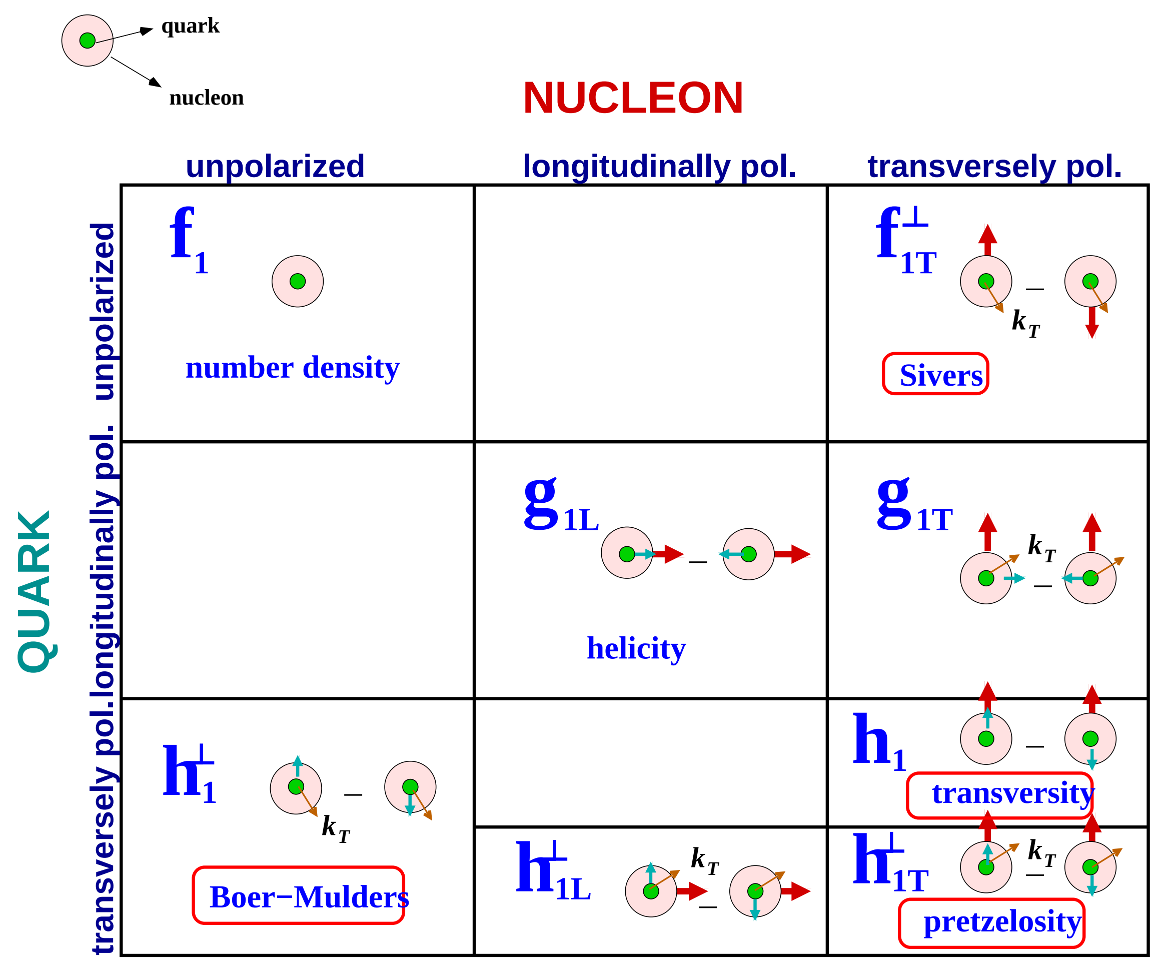


Shown by Cedric Lorcé at INT Workshop 14-55W, Seattle, Feb 2014

Transverse momentum dependent PDFs

M. Stolarski: collinear approximation...

If one takes into account the quarks intrinsic transverse momentum k_T, 8 PDFs are needed to describe the nucleon at leading twist:



COMPASS present and future

COMPASS-II was approved in 2010 and started in 2012, with physics goals that extend those of the COMPASS experiment – following the important theory developments of recent years.

- Access TMD PDFs from polarized Drell-Yan (DY)
  $\hookrightarrow$ 1 dedicated year

  Strong LIP contribution

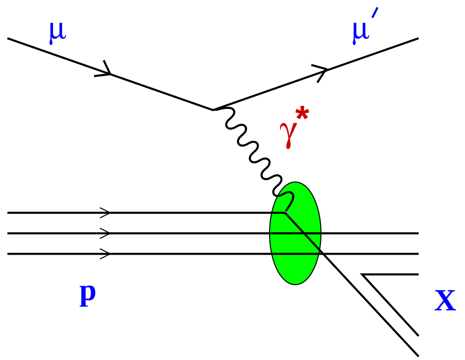
- Access GPDs from exclusive processes like deeply virtual Compton scattering (DVCS)
  $\hookrightarrow$ 2 dedicated years

- Measure the pion and kaon polarizabilities (i.e. the system's response to EM fields – a test of chiral perturbation theory)
  $\hookrightarrow$ Data taken in 2012

Universality of the TMDs

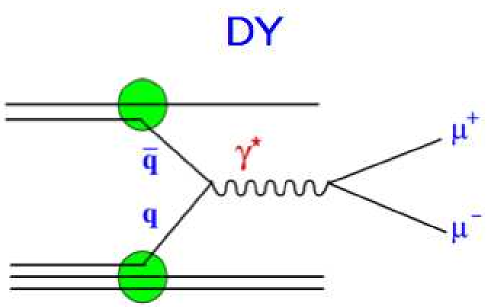
TMD PDFs can be accessed either from a SIDIS process or from a Drell-Yan process (DY).

SIDIS



The spin asymmetry is given by the convolution of structure function with fragmentation function.

DY



The spin asymmetry is proportional to a product of structure functions, one for beam and one for target.

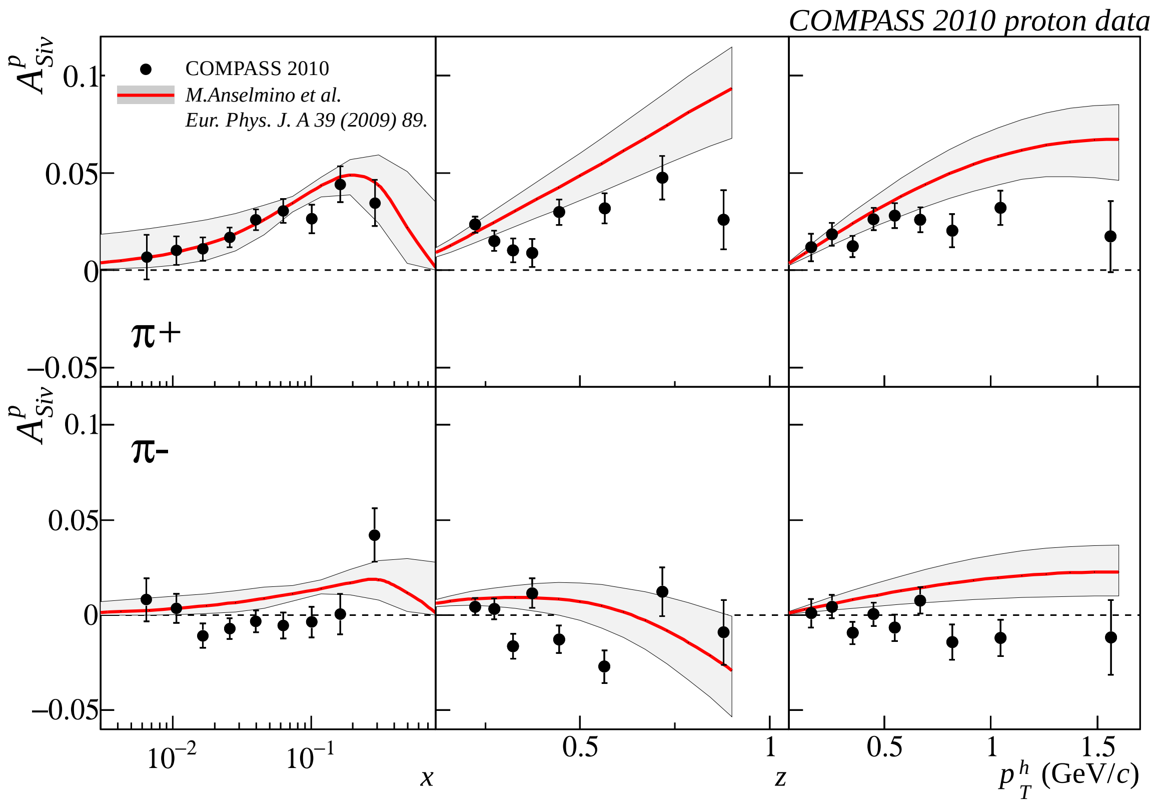
Because Sivers is naive time-reversal odd, it is expected that:

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

Experimental check of this relation is a crucial test of TMD approach.

Sivers PDF

One of the azimuthal modulations that can be extracted from SIDIS is the Sivers effect, arising from the correlation between the quark transverse momentum and the nucleon spin.

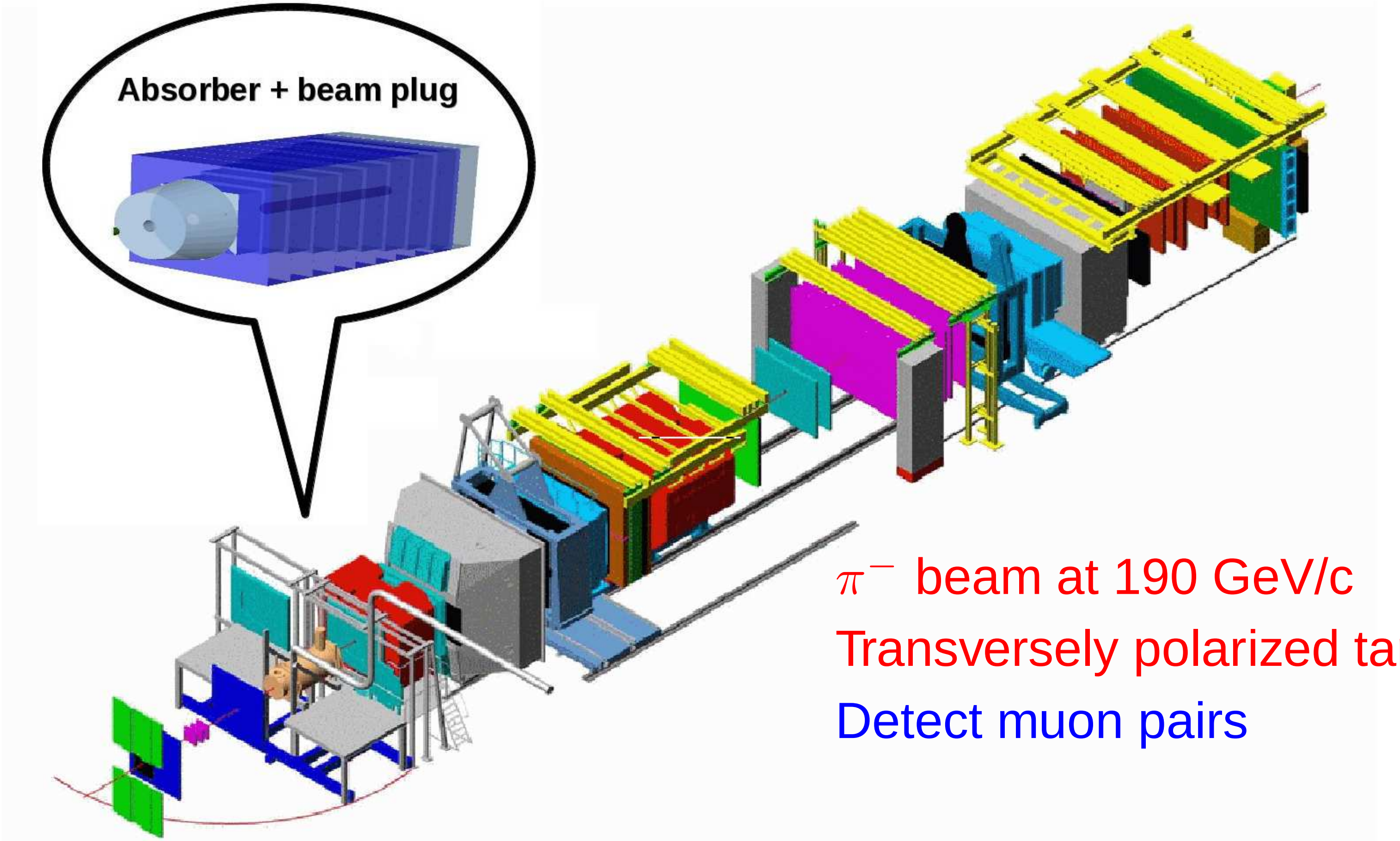


- Non-zero Sivers asymmetry for π^+ (also K^+), on proton target.
- Compatible with zero for π^- (and K^-) on proton target.
- Theory curves using HERMES results overshoot COMPASS data.
- HERMES measures larger asymmetries – interesting physics behind?
- Sivers asymmetry measured on deuteron is compatible with zero.

COMPASS, PLB 717 (2012) 383.

The Drell-Yan program

- 2007, 2009, 2012: beam tests
- 2014: 6 weeks pilot run $\longrightarrow$ Starting in October
- 2015: 1 year data taking

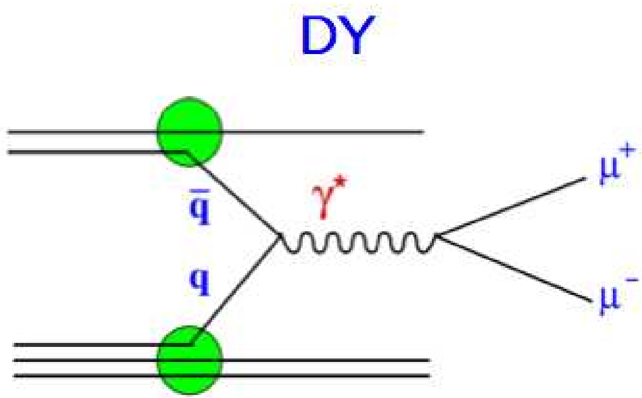


π^- beam at 190 GeV/c

Transversely polarized target

Detect muon pairs

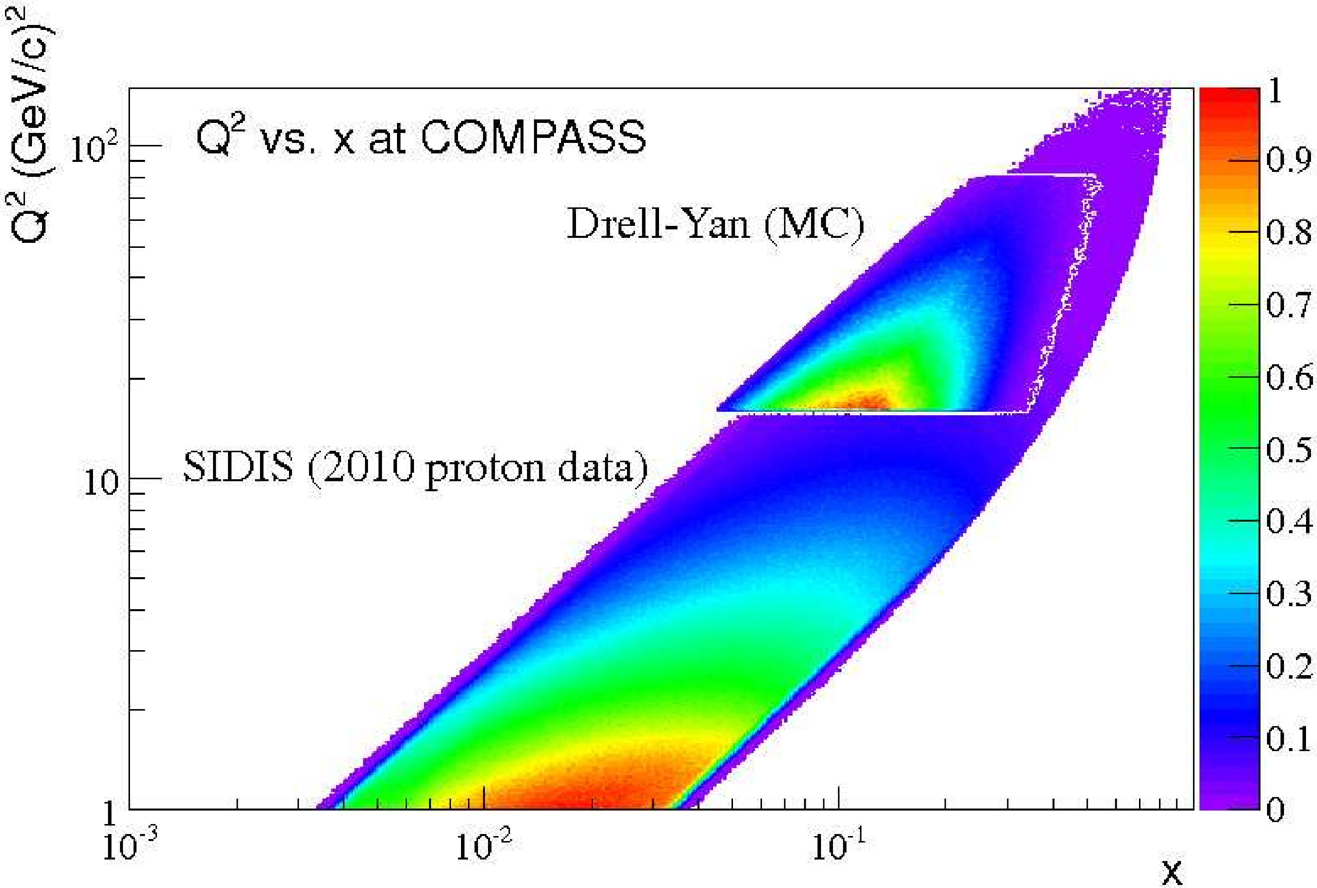
Drell-Yan @ COMPASS



COMPASS has the unique opportunity to study, with the same spectrometer, TMDs both from SIDIS and from polarized Drell-Yan

- Drell-Yan events with $4. < M_{\mu\mu} < 9.$ GeV/c^2, clean signal, no background contributions.
- u-quark dominance, thanks to π^- beam.
- Access the valence quarks region $x_p > 0.1$
- Measure the azimuthal spin asymmetries of DY events from 2 oppositely polarized target cells.

DY and SIDIS measurements

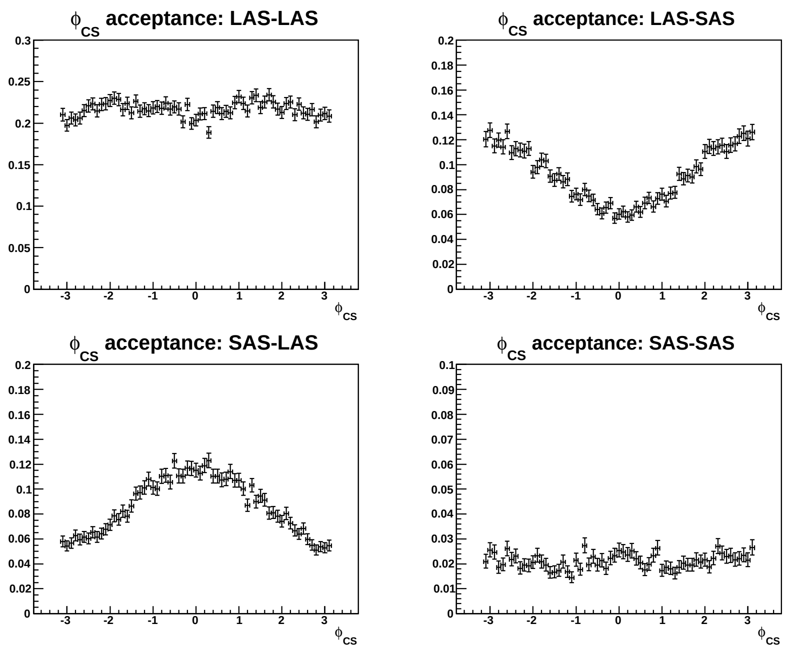


SIDIS and DY measurements have an overlapping region.

$\hookrightarrow$Check the prediction for Sivers and Boer-Mulders sign change when accessed from these 2 processes.

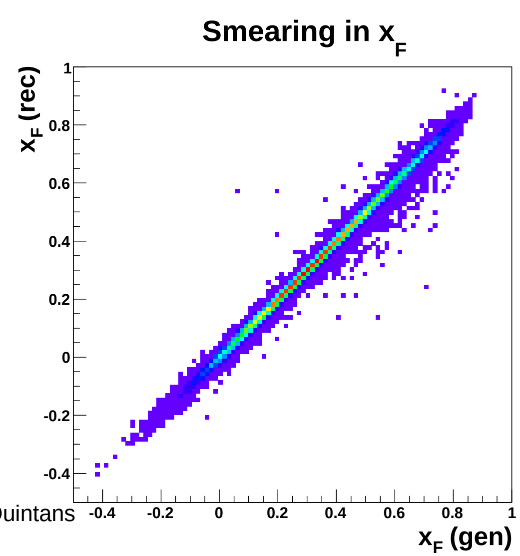
MC simulation: $4 \leq M_{\mu\mu}^{DY} \leq 9$ GeV/c^2

A full MC chain was implemented at LIP, to simulate the Drell-Yan measurement at COMPASS.



The geometrical acceptance is 39%

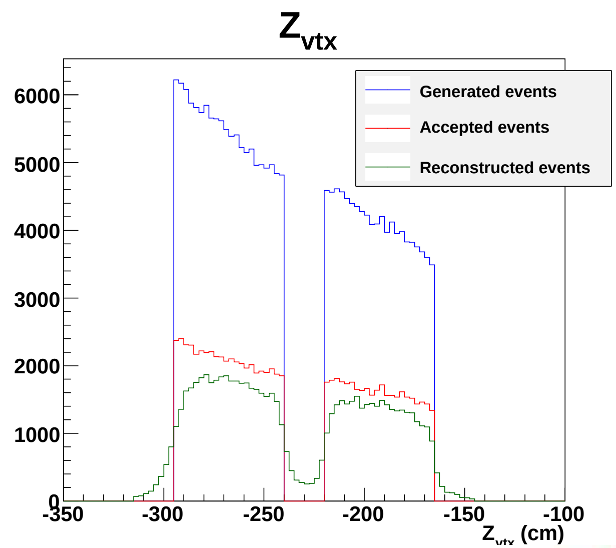
- 2 muons at Large Angle (LAS): 22%
- 2 muons at Small Angle (SAS): 2%
- one muon in LAS, other in SAS: 18%



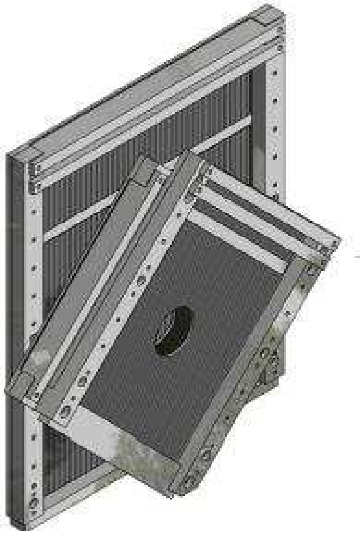
Smearing effects appear, due to the large amount of material along the spectrometer, namely the hadron absorber.

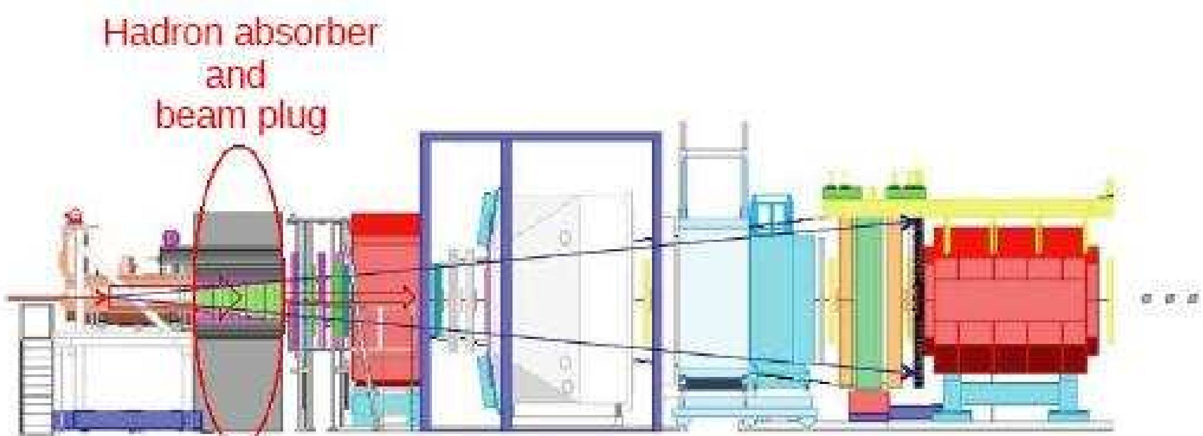
Resolutions and efficiencies

The hadron absorber downstream of the target implied important work of optimization of the vertex reconstruction and dimuon identification – improved from ≈50% to 80% (LIP contribution)



A new vertex detector is placed in the middle of hadron absorber, to help in the vertexing.





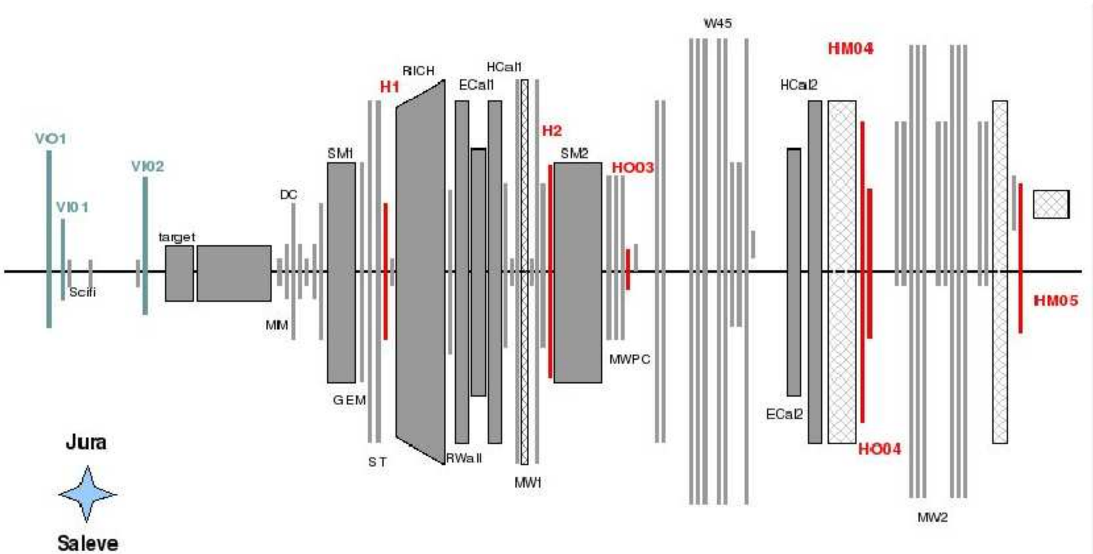
Dimuon trigger

In DIS: the scattered muon is detected mostly at small angle (SAS).
In DY: 2 muons, at least one detected at large angle (LAS).

The MC for the dimuon trigger was done at LIP.

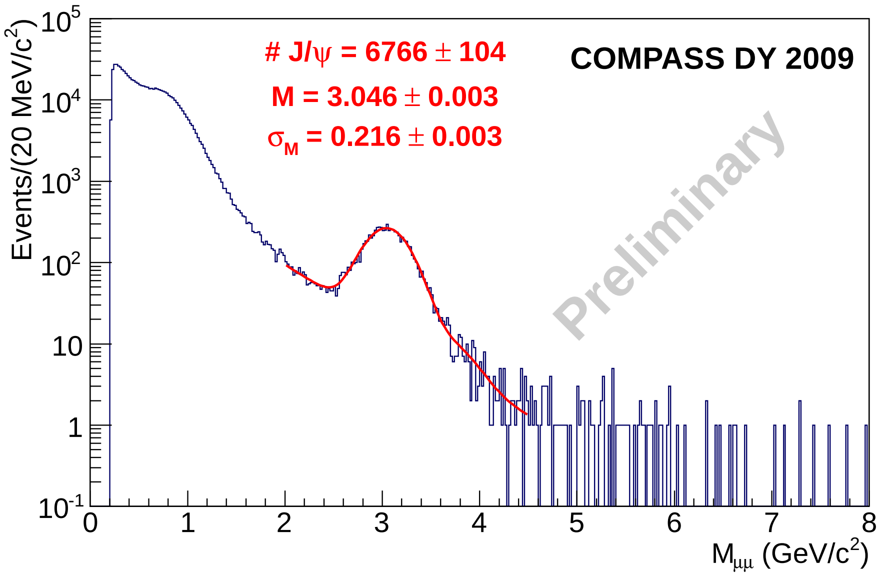
- Simulation of the dimuon trigger
- Optimization of the dimuon trigger, by symmetrizing the SAS trigger system

$\hookrightarrow$ Same coverage for dimuons from trackers and from hodoscopes



Beam test 2009

The feasibility of the measurement was proven by several beam tests. In 2009, a test using a prototype hadron absorber allowed to validate the MC simulations, test the reconstruction program modifications, and check combinatorial background.



Detailed reanalysis of 2009 data: Márcia Quaresma, LIP

With a rough dimuon trigger (calorimeter based, not to be used in the future), and offline quality cuts applied.

Azimuthal spin asymmetries

The single polarized Drell-Yan cross-section can be written as:

$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U \mathcal{A}\Big\{\left(1 + A_U^1 \cos^2\theta + D_{[\sin 2\theta]} A_U^{\cos\phi} \cos\phi + D_{[\sin^2\theta]} A_U^{\cos 2\phi} \cos 2\phi\right)$$

$$\pm |\vec{S}_T| \Big[(D_{[1]} A_T^{\sin\phi_S} + D_{[\cos^2\theta]} \tilde{A}_T^{\sin\phi_S}) \sin\phi_S$$

$$+ D_{[\sin 2\theta]} (A_T^{\sin(\phi+\phi_S)} \sin(\phi+\phi_S) + A_T^{\sin(\phi-\phi_S)} \sin(\phi-\phi_S))$$

$$+ D_{[\sin^2\theta]} (A_T^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) + A_T^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S)) \Big] \Big\}$$

- A: azimuthal asymmetries
- D: depolarization factors
- S: target spin component

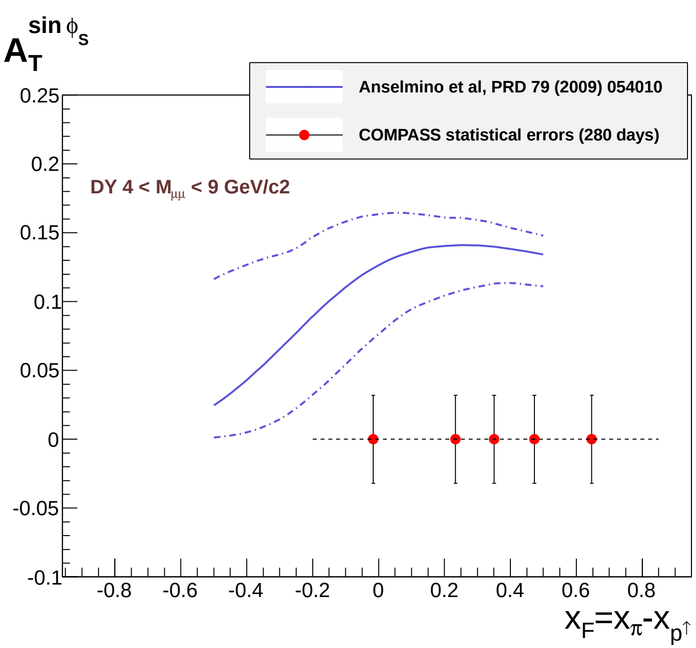
- $F = 4\sqrt{(P_a \cdot P_b)^2 - M_a^2 M_b^2}$
- $\hat{\sigma}_U$: cross-section surviving integration over ϕ and ϕ_S.
- $\mathcal{A}$: acceptance function

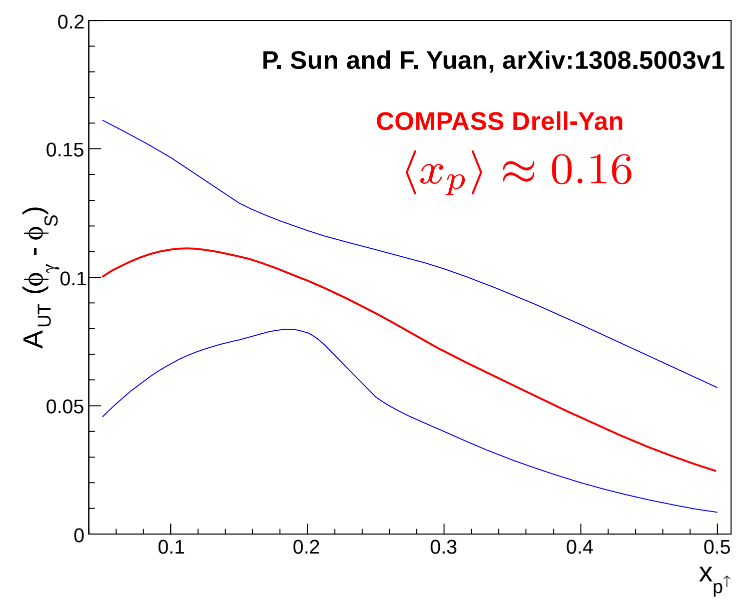
$\hookrightarrow$ 8 azimuthal modulations measured simultaneously

Expected accuracy

DY cross-section in the high mass region is low (fractions of nanobarn). In order to have enough statistics, one needs high luminosity: $I_{beam} = 10^8\ \pi^-$/s.

- 900 events/day from DY in $4 \leq M_{\mu\mu} < 9$ GeV/c^2





Prediction from Anselmino et al, 2010.

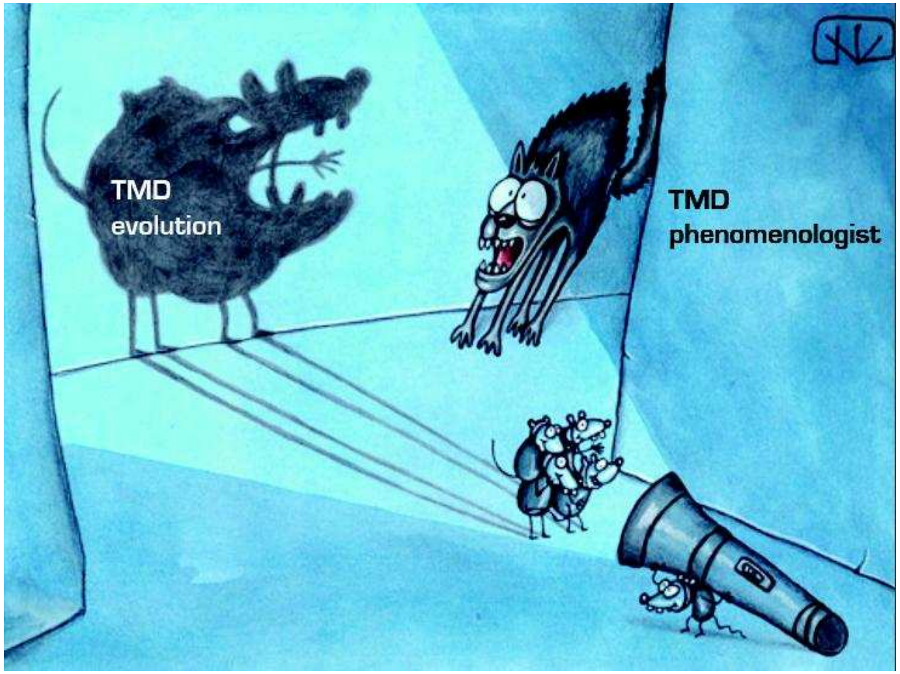
No TMD evolution included.

Prediction from Sun and Yuan, 2013, with (a) TMD evolution included.

Testing the TMD approach

The PDFs dependence on Q^2 is governed by the DGLAP equations. But what about TMDs?

- A breakthrough in 2011: consistent TMD formalism by J. Collins
  "Foundations of Perturbative QCD",Cambridge Univ. Press, 2011
- Very recent develoments on the TMDs evolution
- SIDIS and DY results will be the ultimate answer to validate the TMD approach and clarify type of evolution.



shown by A. Bacchetta,
INT Workshop 14-55W, Seattle 2014

Some conclusions

COMPASS II started data-taking in 2012, for a Primakoff measurement that will lead to the extraction of pion and kaon polarizabilities. Also in 2012, a pilot run for the DVCS measurement was done.

After the long LHC/SPS shutdown at CERN, we are expected to have beam by mid October, for a period of 6 weeks, when the Drell-Yan measurement will start. DY data-taking will proceed during the full 2015 Run.

- First ever polarized Drell-Yan measurement.
- Check of Sivers function sign change between DY and SIDIS.
- Measurement of 8 azimuthal spin asymmetries.
- J/ψ polarization studies.
- ...

Some conclusions

Strong participation of the LIP group in the COMPASS 2nd phase:

- optimization of the spectrometer and dimuon trigger;
- adapting and improving the reconstruction program;
- analysing the beam test data;
- preparing the MC for signal and background studies;
- full responsability of the Detector Control System.

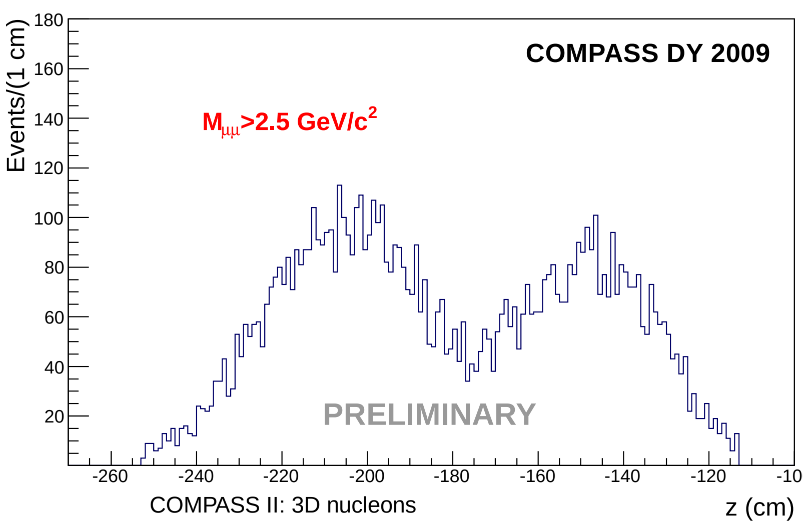
Results expected very soon!

SPARES

SPARE: More on the DY 2009 test

This beam test used 2 polyethylene target cells (40 cm each), a concrete $+$ steel absorber ($1+1$ m, 66 radiation lengths), and a calorimeter-based dimuon trigger.

- Dimuon trigger efficiency: 45 ± 2%
- Dimuon trigger purity: 5.3 ± 0.2% (2 muons at large angle)
- J/ψ signal/Bkg: 9.5 ± 0.4
- Dimuon reconstruction efficiency: 79 ± 1% (from J/ψ MC)



No vertex detector included in this test.

Prototype absorber much more massive than the one for future measurement.

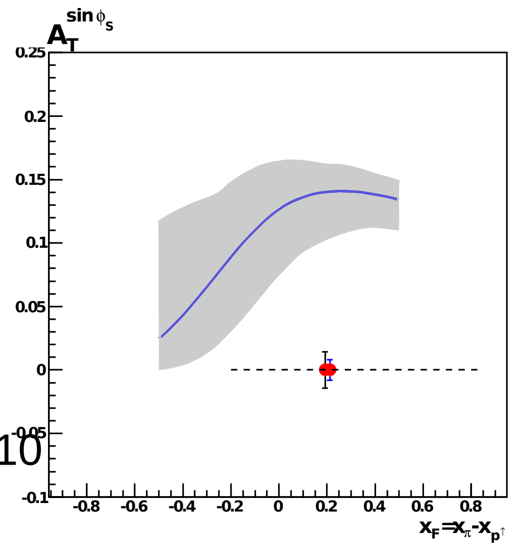
SPARE: DY – Comparing with predictions

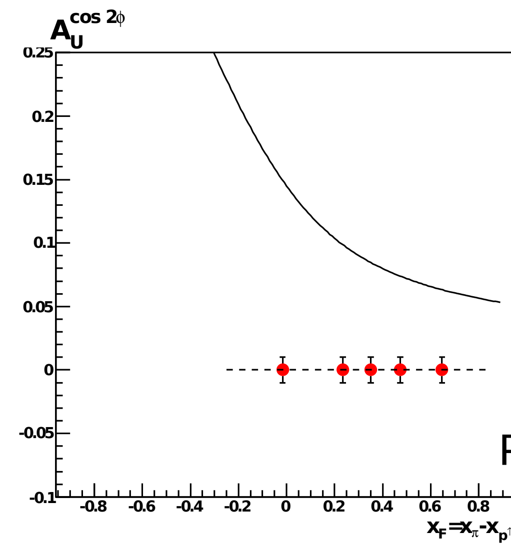
...but: Q^2 evolution not properly accounted for in the predictions...

DY: $4 < M_{\mu\mu} < 9$ GeV/c^2

Sivers

Anselmino et al, PRD79(2009)054010

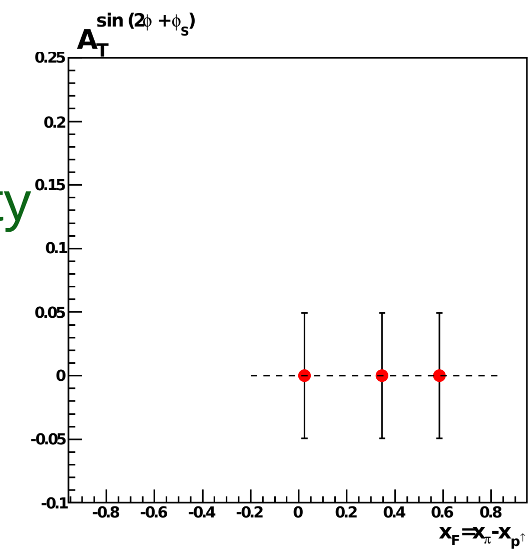


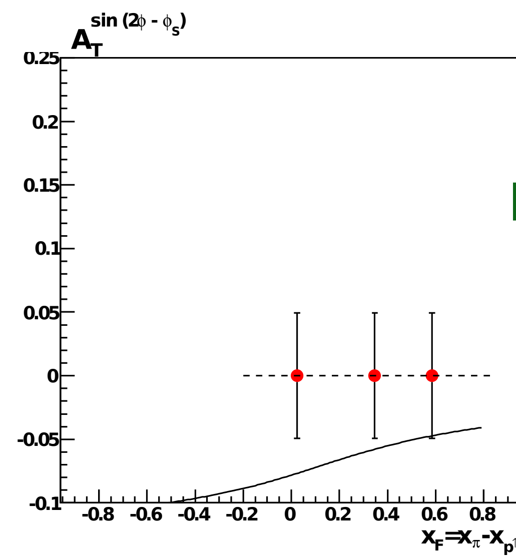


Boer-Mulders

B. Zhang et al, PRD77(2008)054011

BM $\otimes$ pretzelosity





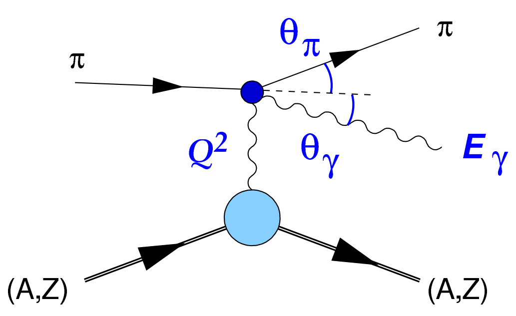
BM$\otimes$transversity

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

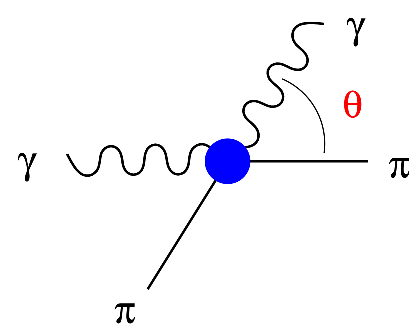
SPARE: Testing ChPT

Chiral Perturbation Theory predicts the strong interaction dynamics of Goldstone bosons.

$\hookrightarrow$ the internal structure of the pion is revealed by its response in presence of an electromagnetic field, i.e. pion polarizabilities.



Primakoff



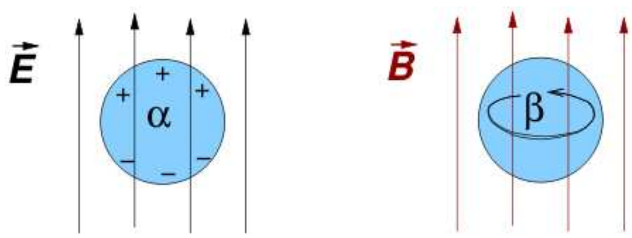
Inverse Compton

π polarizabilities can be measured from the π induced Primakoff reaction and the embedded inverse Compton scattering – check of ChPT prediction.

The same can be done using kaon induced Primakoff reaction
$\hookrightarrow$ access kaon polarizabilities for the first time.

SPARE: Pion polarizabilities

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



Polarizability:

$$\mathcal{P} = (1-\cos\theta_{cm})^2\,(\alpha_\pi-\beta_\pi) + (1+\cos\theta_{cm})^2\,(\alpha_\pi+\beta_\pi)\,\frac{s^2}{m_\pi^4} + (1-\cos\theta_{cm})^3\,(\alpha_2-\beta_2)\,\frac{(s-m_\pi^2)^2}{24s}$$

In 120 days (90 with π, 30 with μ beams)	$\alpha_\pi-\beta_\pi$ (10^{-4} fm^3)	$\alpha_\pi+\beta_\pi$ (10^{-4} fm^3)	$\alpha_2-\beta_2$ (10^{-4} fm^5)
2-loop ChPT prediction	5.7 $\pm$ 1.0	0.16 $\pm$ 0.10	16
COMPASS sensitivity	$\pm$ 0.66	$\pm$ 0.025	$\pm$ 1.94

Measurement with muon beam to cross-check systematics.

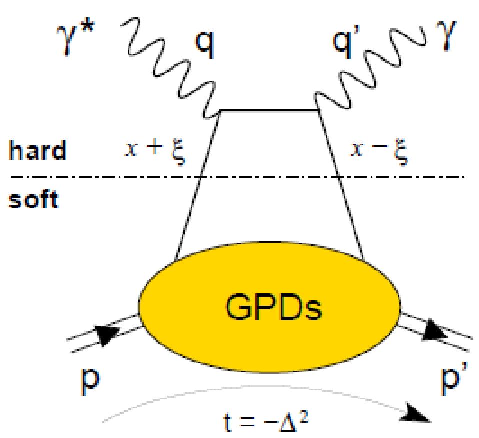
Up to now, experiments measured $\alpha_\pi-\beta_\pi$ from 4 to 14 $\times 10^{-4}$ fm^3.

Measurements in 2009 and 2012. Results expected soon!

SPARE: DVCS in COMPASS

Study of muon induced exclusive processes started with a pilot Run in 2012.

Deeply Virtual Compton Scattering (DVCS): $\mu p \to \mu' p \gamma$



$$\frac{d\sigma}{dt} \approx e^{-Bt} \qquad B \approx \langle r_\perp^2 \rangle / 2$$

- Main priority is DVCS.
- Deeply Virtual Meson Production (DVMP): $\mu p \to \mu' p \rho$ will be studied in parallel.
- 2 competing processes: DVCS and Bethe-Heitler
  - Low x_B: BH;
  - High x_B: DVCS;
  - intermediate x_B: interference DVCS-BH.
- BH is well-known: used as reference process.

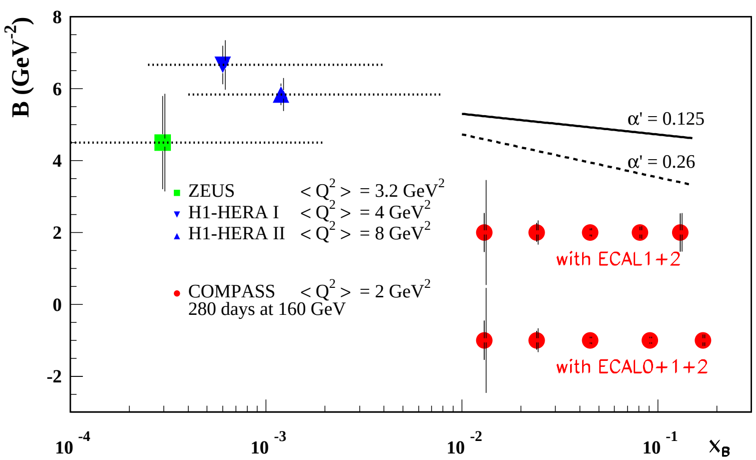
Phase 1: $\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ beams off a 2.5m unpolarized liquid H_2 target $\Rightarrow$ GPD H.

Phase 2: $\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ beams off a transversely polarized NH_3 target $\Rightarrow$ GPD E.

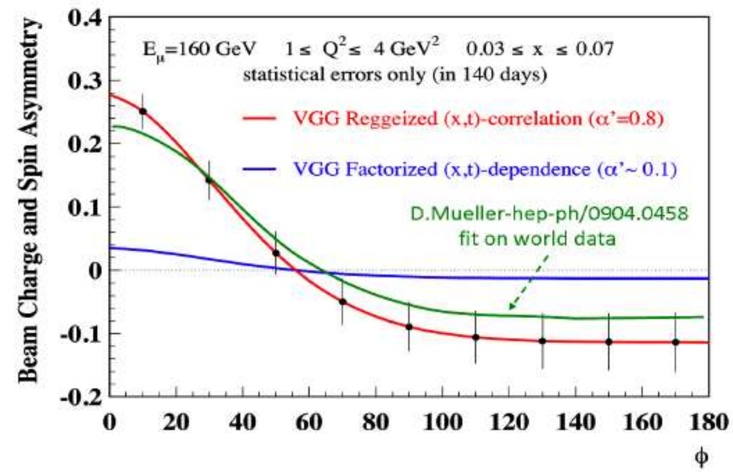
SPARE: Projections for DVCS

Measure the modulations given by the sum and difference of "spin and charge" dependent DVCS cross-sections. Amplitudes are proportional to $\mathcal{I}m(F_1 H)$ and $\mathcal{R}e(F_1 H)$.

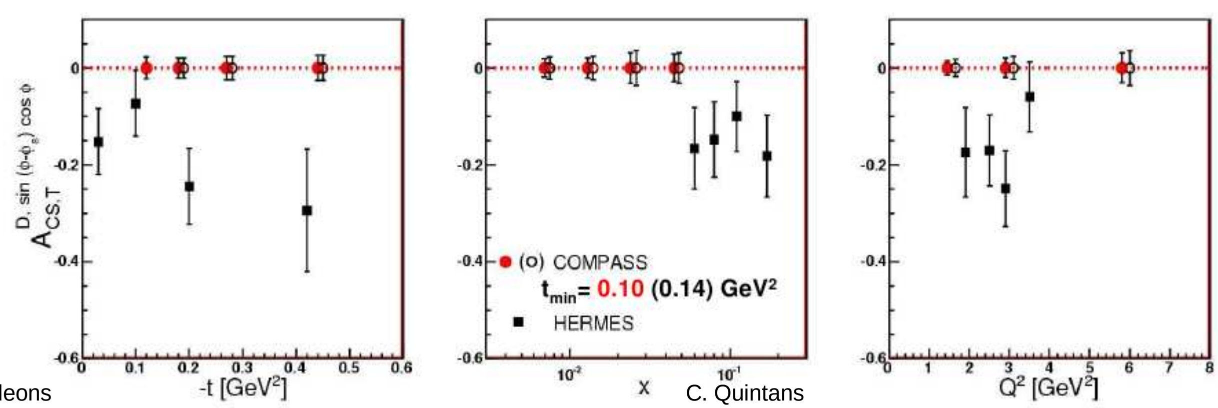
Phase 1: B=$\langle r_\perp^2 \rangle$/2



$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow})$$



Phase 2: Azimuthal asymmetries



SPARE: Long term future

Important COMPASS results in nucleon structure and spectroscopy studies obtained up to now, and more are expected in the near future.

Much more can be done later on, after the LHC/SPS shutdown in 2018:

Run type	physics goals	key aspects
Hadron	glueballs	280 GeV beam, high intens., π, K, $\bar{p}$ separation
DVCS	GPD E	transversely polarized p target
SIDIS	h_1^d (same accur. as h_1^u)	transv. polarized D target
	$f_1^\perp$ evolution	100 GeV beam, transv. polarized p target
DY	TMDs shape, K TMDs	transv. polarized p target (higher stats)
	flavor separation	transv. polarized D target
	test of Lam-Tung relation	unpolarized H target
	EMC effect	different nuclear targets