COMPASS
&
The Transverse Momentum Dependent Parton Distribution Functions

Márcia Quaresma, LIP - Lisbon

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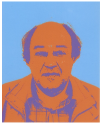
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR
CERN/FIS-NUC/0017/2015

Members of COMPASS group at LIP

Seniors:

Paula Bordalo
Group Leader

Sérgio Ramos
CB member



Catarina Quintans
DY Subgroup Coordinator

Post-docs:

Celso Franco

Luís Silva

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PubCom member

PhD Students:

Márcia Quaresma

Ana Sofia Nunes

Engineer:

Christophe Pires

COMPASS experiment at CERN

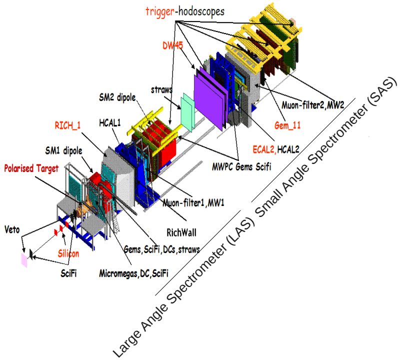
COmmon Muon Proton Apparatus for Structure and Spectroscopy

- Fixed target experiment at the end of M2 SPS beam line
- Around 240 collaborators from 13 countries and 23 institutes
- Data taking since 2002 and approved up to 2018

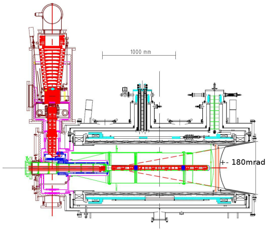
Two main physics programs:

1. DIS programme and Drell-Yan programme: Spin dependent nucleon structure
2. Hadron/Spectroscopy programme: Pion polarizability, hadron spectroscopy, exotic searches.

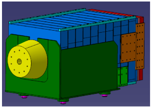
COMPASS setup

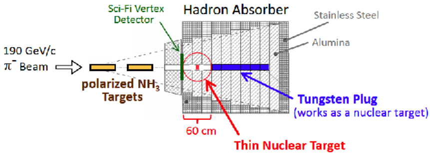


Polarised target



Hadron absorber for DY program





- Two stages spectrometer, wide angular acceptance, ± 180 mrad
- About 350 detector planes
- Particles identification: calorimeters, RICH and μ Filters

LIP group contributions

COMPASS LIP outputs from DY and SIDIS programmes

This talk:

- Multi Dimensional Analysis of the Transversity Data
- Gluon Sivers Asymmetry
- Polarised Drell-Yan measurement

Sofia's talk:

- Gluon Polarisation
- Effects in low x and low Q^2 region
- Multiplicities

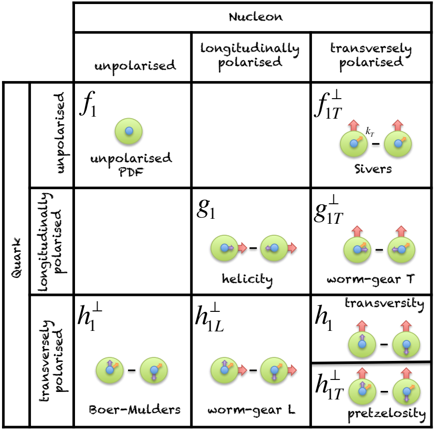
Full LIP responsibility

Christophe's talk:

- Detector Control System

Nucleon structure - TMD PDFs

The nucleon structure in leading order QCD, taking into account k_T, is described by 8 PDFs for each quark flavour.



COMPASS contribution:

- Studying TMD PDFs dependence on several kinematic variables
- Accessing them through two different processes, SIDIS and DY

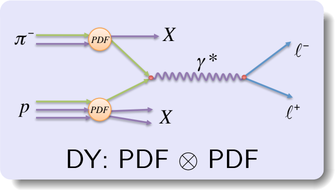
Theoretical prediction of the Sivers and Boer-Mulders sign change when accessed from SIDIS or from DY

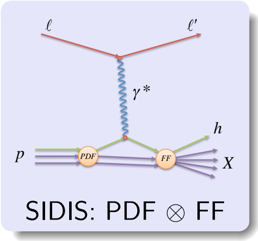
$\Downarrow$

Crucial test of the QCD TMD approach

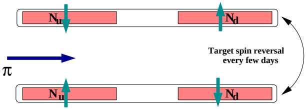
DY and SIDIS processes

The DY and SIDIS cross-sections can be written in terms of angular modulations and the amplitudes of these modulations contain:





Experimental extraction of the amplitudes:

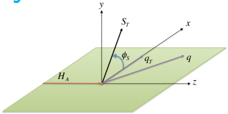


$$\frac{N_u(\phi_S,\phi_h)^{\downarrow} N_d(\phi_S,\phi_h)^{\downarrow}}{N_d(\phi_S,\phi_h)^{\uparrow} N_u(\phi_S,\phi_h)^{\uparrow}}$$

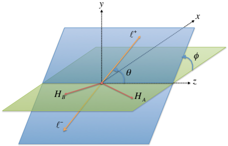
Measurement of the azimuthal angle asymmetries between the 2 transversely and oppositely polarised target cells.

DY and SIDIS cross sections in terms of asymmetries

DY:

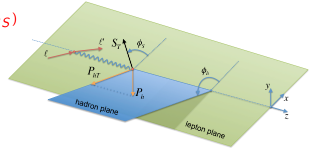


$$\frac{d\sigma}{d^4qd\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \left\{ \left(1 + D_{[\sin^2(\theta)]} A_{UU}^{\cos(2\phi)} \cos(2\phi)\right) + |\vec{S}_T| \left[A_{UT}^{\sin(\phi_S)} \sin(\phi_S) \right.\right.$$
$$\left.\left. + D_{[\sin^2(\theta)]} \left(A_{UT}^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) + A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S)\right)\right]\right\}$$



SIDIS:

$$\frac{d\sigma}{dxdydzd\psi d\phi_h dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)(F_{UU,T}+\varepsilon F_{UU,L}) \times$$
$$\left\{1 + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi_h)A_{UU}^{\cos(\phi_h)} + \varepsilon\cos(2\phi_h)A_{UU}^{\cos(2\phi_h)} + P_l\sqrt{2\varepsilon(1-\varepsilon)}\sin(\phi_h)A_{LU}^{\sin(\phi_h)}\right.$$
$$+S_T\left[\sin(\phi_h-\phi_S)A_{UT}^{\sin(\phi_h-\phi_S)} + \varepsilon\sin(\phi_h+\phi_S)A_{UT}^{\sin(\phi_h+\phi_S-\pi)} + \varepsilon\sin(3\phi_h-\phi_S)A_{UT}^{\sin(3\phi_h-\phi_S)}\right.$$
$$\left. + \sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S)A_{UT}^{\sin(\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)A_{UT}^{\sin(2\phi_h-\phi_S)}\right]$$
$$+S_T P_l\left[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)A_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi_S)A_{LT}^{\cos(\phi_S)}\right.$$
$$\left.\left. + \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)A_{LT}^{\cos(2\phi_h-\phi_S)}\right]\right\}$$



All the asymmetries are extracted together using the Unnbined Maximum Likelihood Method.

DY asymmetries and TMD PDFs

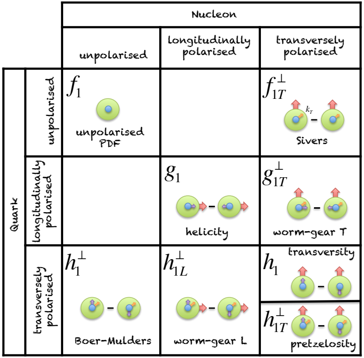
DY:

$$A_{UU}^{\cos(2\phi_{CS})} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q} \quad \text{Boer-Mulders}$$

$$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q} \quad \text{Sivers}$$

$$A_{UT}^{\sin(2\phi_{CS}-\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q} \quad \text{Transversity}$$

$$A_{UT}^{\sin(2\phi_{CS}+\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q} \quad \text{pretzelosity}$$



SIDIS:

$$A_{UU}^{\cos(\phi_h)} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots\right)$$

$$A_{UU}^{\cos(2\phi_h)} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots\right)$$

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$A_{UT}^{\sin(\phi_S)} \propto Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

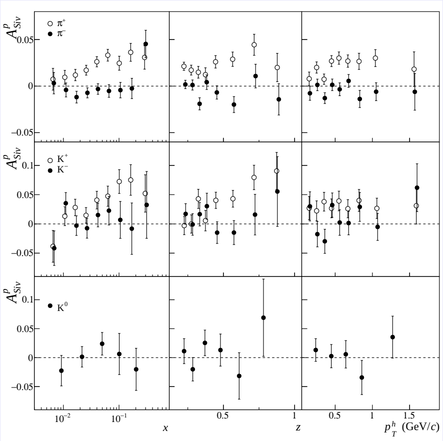
$$A_{UT}^{\sin(2\phi_h-\phi_S)} \propto Q^{-1}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

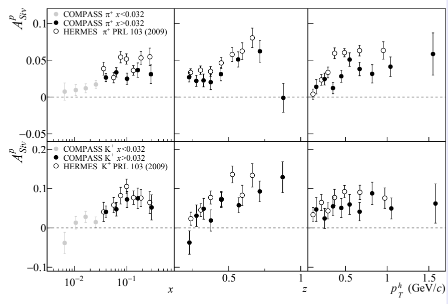
$$A_{LT}^{\cos(\phi_S)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

$$A_{LT}^{\cos(2\phi_h-\phi_S)} \propto Q^{-1}\left(g_{1T}^q \otimes D_{1q}^h + \ldots\right)$$

COMPASS results on Sivers asymmetry

COMPASS proton data from 2007 and 2010 (*Phys.Lett. B744 (2015) 250*)





COMPASS : $\langle Q^2 \rangle = 8.7$ GeV$/c^2$

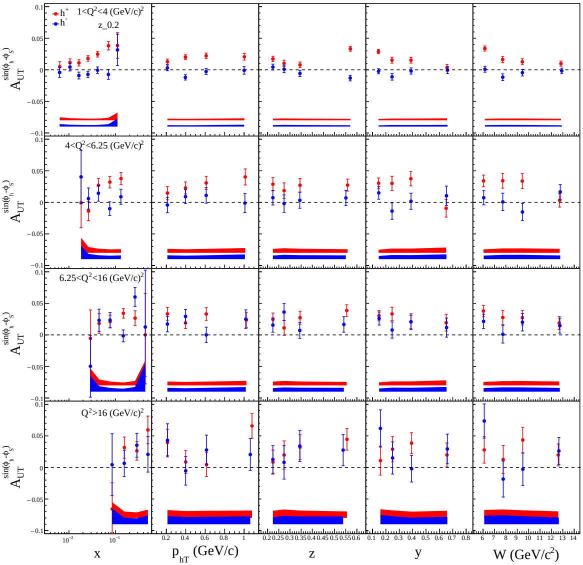
HERMES : $\langle Q^2 \rangle = 2.4$ GeV$/c^2$

The experiments point to some Q^2 evolution

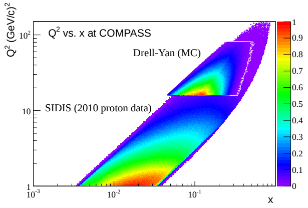
Multi-Dimensional Analysis

Marcia's contribution

2D analysis: 4 Q^2 bins and for each several bins in x, p_{Th}, z, y or W (also a 3D analysis was performed)



DY and SIDIS phase-space overlap at large Q^2

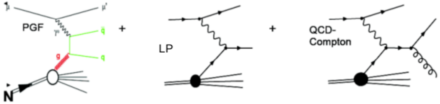


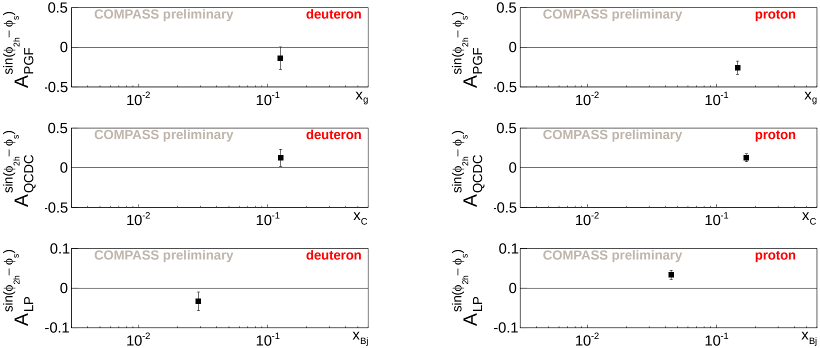
Gluon Sivers Asymmetry

Luis' contribution

Nucleon spin decomposition:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$





$$A_{PGF,\ d}^{\sin(\phi_{2h}-\phi_S)} = -0.14 \pm 0.15(stat) \pm 0.06(syst)$$

$$at\ \langle x_G \rangle = 0.13$$

$$A_{PGF,\ p}^{\sin(\phi_{2h}-\phi_S)} = -0.26 \pm 0.09(stat) \pm 0.08(syst)$$

$$at\ \langle x_G \rangle = 0.15$$

The results are compatible, nevertheless Sivers asymmetry is compatible with zero for deuteron and negative for proton

LIP Contributions to DY experiment

Open and asymmetric COMPASS spectrometer ⇒ DIS measurement

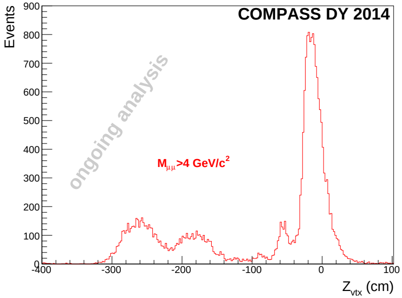
New philosophy for the DY experiment:

- Inclusion of a hadron absorber ⇒ Closed spectrometer
  - Absorber design ⇒ length and material
- Detection of muon pairs ⇒ Symmetrisation
  - Symmetrisation of the old very forward spectrometer hodoscopes
- Design of two large trigger hodoscopes
- Redefinition of the trigger matrices
- New vertex reconstruction philosophy
- MC simulations ⇒ Estimates of event rates
- Detector planes efficiency per wire

Drell-Yan measurement - 2014 pilot run

Marcia's and Catarina's contributions

- NH_3 target **not polarised**, also Al and W targets
- A vertex detector, but not fully operational
- $\mathbf{I_{beam} \sim 7 \times 10^7 \pi/s}$
- 17 days of stable data taking used for the analysis
- **Alignment** of the spectrometer trackers - Marcia's responsibility



Clear signal from all the targets: Ammonia, aluminum and tungsten.

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Reasonable Z_{vtx} resolution

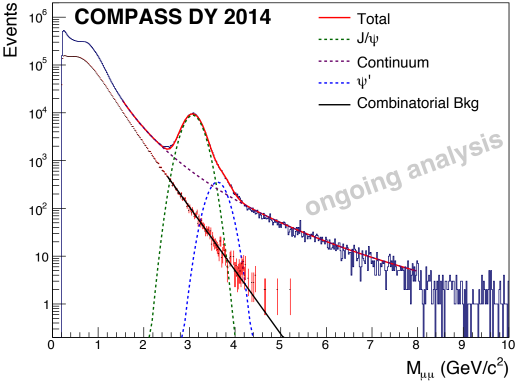
For 2015 data $\Rightarrow$ The vertex reconstruction philosophy was completely changed to give priority to the muon pairs

$\hookrightarrow$ Developed by Celso

DY 2014 pilot run - Results

Marcia's and Catarina's contributions

- First COMPASS unpolarised high mass DY data
- Clear J/ψ signal
- $M_{\mu\mu} > 4$ GeV$/c^2$ $\sim$ **7000** $\mu^+\mu^-$ **pairs** from NH_3 target



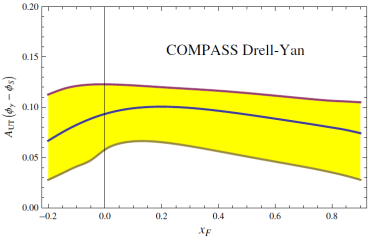
Comparison data <> MC ongoing $\Rightarrow$ Detectors Efficiency per plane and per wire
$\hookrightarrow$ Implemented in the reconstruction of the MC events $\Rightarrow$ Implemented by Luis

Polarised Drell-Yan measurement - 2015 run

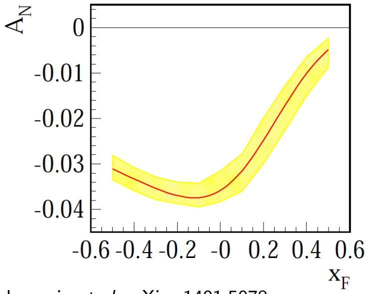
Marcia's, Catarina's, Celso's and Luis' contributions

1st World Experiment

- NH_3 **polarised** target (plus Al and W targets)
- $\boldsymbol{I_{beam} \sim 10^8 \pi/s}$ - very high intensity
- The analysis of these data is ongoing $\Rightarrow$ **One period already produced**
- $M_{\mu\mu} > 4$ GeV$/c^2$ $\sim$ **80000** $\boldsymbol{\mu^+\mu^-}$ **pairs** expected from polarised target
- $\delta A_{UT}^{\sin(\phi_S)} \sim 2.8\%$ $\Rightarrow$ Models predict $A_{UT}^{\sin(\phi_S)}$ from 5% to 10%



P. Sun and F. Yuan, PRD 88, 114012



Echevarria *et al*, arXiv: 1401.5078, $x_F = x_p - x_\pi$

BACKUP SLIDES

COMPASS Experimental Programme

COMPASS - I	2002 - 2004 2006	2007	2008 - 2009 2012	2010	2011
DIS Nucleon Spin Structure: $g_1, h_1, \Delta q, \Delta_T q$ LIP	**^{6}LiD** – Polarised **L** & **T** μ^+(160 GeV)	**NH_3** – Polarised **L** μ^+ (160 GeV)		**NH_3** – Polarised **T** μ^+ (160 GeV)	**NH_3** – Polarised **L** μ^+ (200 GeV)
Hadron Spectroscopy: Exotics,hybrids, π polarisability			Several targets non - polarised π^- (190 GeV)		

COMPASS - II	2015	2016 - 2017
DY Nucleon Spin Structure: TMDs: $h_1, h^T_1, h^T_{1T}, f^T_{1T}$ LIP	**NH_3** – Polarised **T** π^- (190 GeV) First world exp.	
DVCS GPDs - 3D Nucleon picture		**LH_2** non-polarised target μ^+ (160 GeV)

Collaboration in the COMPASS CERN experiment

Short and mid-term Programme

- **2015 ➔**
  - LIP leading role in the analysis of the dimuon high mass (4-9 GeV/c^2) **DY** region:
    - Measurement of azimuthal asymmetries, giving access to TMD PDFs
    - Check of the QCD prediction that TMDs functions, although universal, change sign between SIDIS and DY processes

- **2016/2017 ➔**
  - Unpolarised Deep Virtual Compton Scattering (**DVCS**) programme (tri-dimensional nucleon structure functions – Generalized Parton Distributions, GPDs)
  - Study of hard exclusive processes:
    - DVCS and HEMP (Hard Exclusive Meson Production), using muons impinging on an unpolarised liquid hydrogen target
    - Extraction of unpolarised GPDs, aiming to the nucleon's 3-dimensional description

- **2019 ?**
  - Data taking relative to the measurement of the polarised Drell-Yan physics (TMD PDFs characterization) − statistics improvement

- **2020 ?**
  - Data taking for polarised DVCS and HEMP physics