COMPASS II

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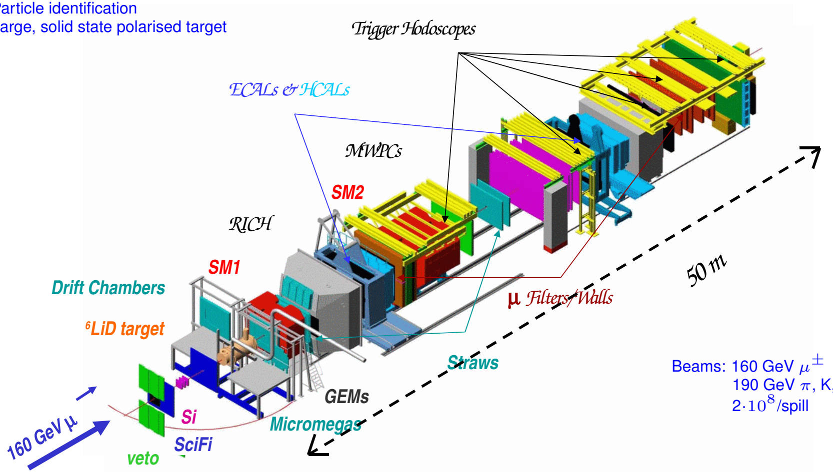
What has COMPASS done so far

- Is taking data since 2002 (2005 break due to SPS shutdown)
- longitudinally polarised muon beam of 160 GeV/c
  off longitudinally and transversely polarised targets: ^{6}LiD (d), NH_3 (p)
- 190 GeV/c hadron beams: π, K, p
  off unpolarised targets: liquid H_2, Pb, Ni, Cu, W
- originally planned until 2009
- addendum 2010-2011: transverse and longitudinal NH_3
- muon and hadron programmes
- muon results: quarks contribute 30% to the nucleon's spin,
  gluons contribution small in the measured x range,
  all 3 leading twist PDF (f_1, g_1, h_1) investigated
- hadron results: search for exotics, hybrids, glueballs;
  measurements of pion polarisabilities.

COMPASS Spectrometer (muon run)

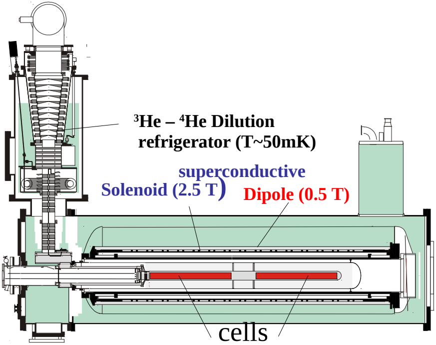
Nucl. Instr. Meth. A577 (2007) 455

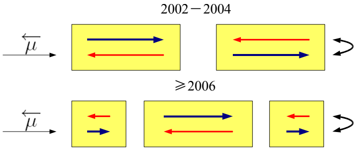
Two stages, $\sim$ 350 planes
Calorimetry
Particle identification
Large, solid state polarised target



Beams: 160 GeV $\mu^{\pm}$
190 GeV π, K, p
$2{\cdot}10^8$/spill

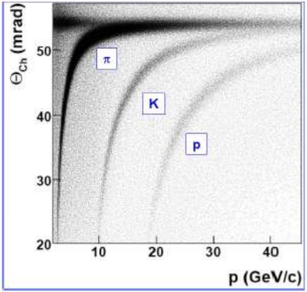
COMPASS polarised targets



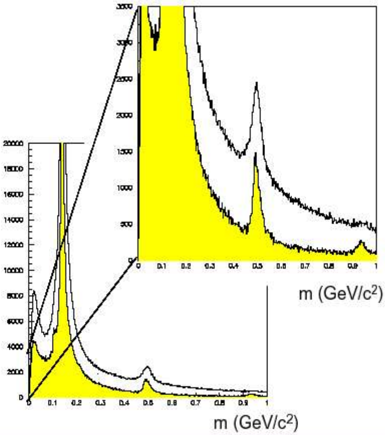


* Two (three) target cells, oppositely polarised
* Polarisation reversed every 8 h (less frequent after 2005) by field rotation
* Material: solid ^{6}LiD (NH_3)
* Polarisation: ~ 50% (~90%), by the Dynamical Nuclear Polarisation
* Dilution: f~0.4 (~0.15)
* Polar acceptance: ~70 mrad (~180 mrad after 2005)

COMPASS RICH



Before upgrade: white distribution
After upgrade: yellow distribution



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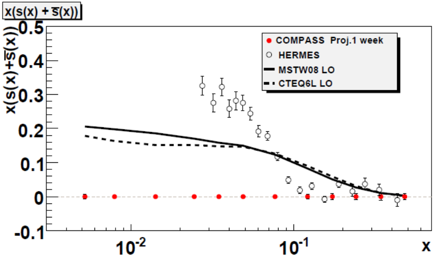
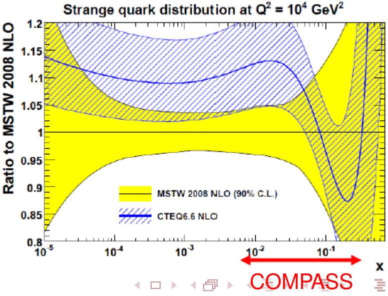
COMPASS II Proposal

- CERN–SPSC–2010–014 (SPSC–P–340) of May 17, 2010
  wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf
- Approved in December 2010 initially 3 years data taking (Phase 1)
- Flavour separation and fragmentation in spin-averaged SIDIS (strange sector !)
- Focus on transverse structure of the nucleon
  - GPD, transverse size and parton orbital angular momentum
  - T-odd TMD (Sivers, Boer-Mulders distributions)
  - Drell-Yan process and TMD sign change SIDIS $\Longleftrightarrow$ DY
- π/K polarisabilities and tests of ChPT
  in the Compton scattering via Primakoff reaction.
- Addendum foreseen (spin-dependent GPD), Phase 2.

Spin-averaged SIDIS

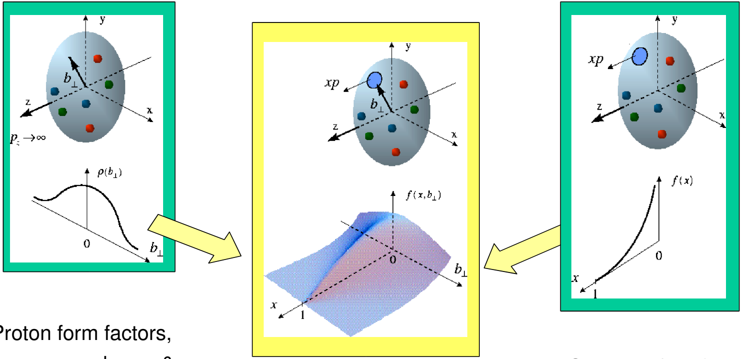
- Spin-averaged SIDIS, $\mu \mathrm{p} \to \mu \mathrm{h X}$, will be recorded simultaneously with DVCS/DVMP, on a long LH_2 target (NH_3 target from COMPASS I is difficult!)
- Charge and nature of "h" will be determined ($\pi^{\pm}$, π^0, $K^{\pm}$, K^0, Λ, $\bar{\Lambda}$)
- Combined with COMAPASS I data on ^{6}LiD $\Longrightarrow$ q_f separation in global QCD fits, constraints on FF (hadron multiplicities) and LO determination of $s(x)$ at $0.001 < x < 0.2$.
- Two years of data taking: dependence on x, Q^2, p_T^2, z and asymmetries $A^{\cos\phi}$, $A^{\cos 2\phi}$, $A^{\sin\phi}$ of hadrons on unpol. proton target.
  They are sensitive to T-odd TMD Boer-Mulders function and Cahn effect.
  Data exist for ^{6}LiD.





3D picturing of the proton *via* GPD

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



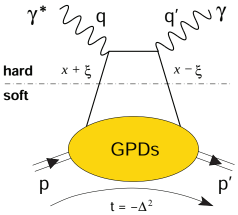
Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Slide from V.D. Volker, LANL 2007

Access GPD through the DVCS/DVMP mechanism

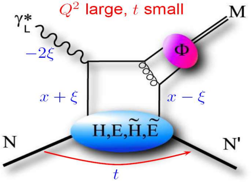


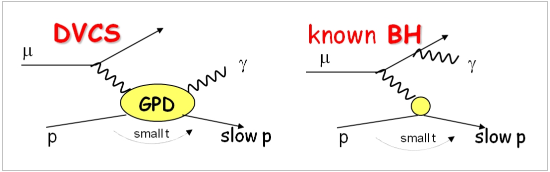
$Q^2 \to \infty$,
fixed $x_B, t \implies |t|/Q^2$ small

- 4 GDPs ($H, E, \widetilde{H}, \widetilde{E}$) for each flavour and for gluons
- Factorisation proven for σ_L only
- All depend on 4 variables: x, ξ, t, Q^2; DIS @ $\xi = t = 0$; Later Q^2 dependence omitted. Careful! Here $x \neq x_B$!
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions
  $\widetilde{H}, \widetilde{E}$ refer to polarised distributions
- $H^q(x,0,0) = q(x), \quad \widetilde{H}^q(x,0,0) = \Delta q(x)$

- H, E accessed in vector meson production *via* A_{UT} asymmetries
- $\widetilde{H}, \widetilde{E}$ accessed in pseudoscalar meson production *via* A_{UT} asymmetries
- All 4 accessed in DVCS (γ production) in $A_C, A_{LU}, A_{UT}, A_{UL}$
- Integrals of $H, E, \widetilde{H}, \widetilde{E}$ over x give Dirac–, Pauli–, axial vector– and pseudoscalar vector form factors respectively.
- Important: $J_z^q = \frac{1}{2} \int dx\, x\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)] = \frac{1}{2}\Delta\Sigma + L_z^q$ (X. Ji)

DVCS/DVMP: $\mu p \to \mu p \gamma (M)$; what do we measure?

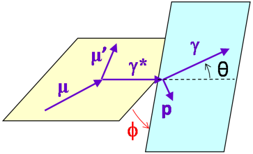




$$d\sigma^{\mu p \to \mu p \gamma} = d\sigma^{BH} + (d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol}) + e_\mu(\mathrm{Re}I + P_\mu \mathrm{Im}I)$$

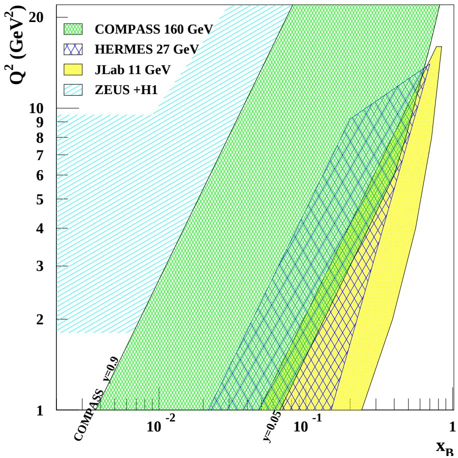
Observables (Phase 1):

- $S_{CS,U} \equiv \mu^{+\leftarrow} + \mu^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}I\right)$
- $D_{CS,U} \equiv \mu^{+\leftarrow} - \mu^{-\rightarrow} = 2\left(P_\mu d\sigma^{DVCS}_{pol} + e_\mu \mathrm{Re}I\right)$
- $A_{CS,U} \equiv \dfrac{\mu^{+\leftarrow} - \mu^{-\rightarrow}}{\mu^{+\leftarrow} + \mu^{-\rightarrow}} = \dfrac{D_{CS,U}}{S_{CS,U}}$
- Each term ϕ-modulated
  If ϕ-dependence integrated over $\Longrightarrow$ twist-2 DVCS contribution;
  if ϕ-dependence analysed: $\Longrightarrow$ Im $(F_1 H)$ and Re $(F_1 H)$



Analogously for transversely polarised target (Phase 2): $S_{CS,T}, D_{CS,T}, A_{CS,T} \Longrightarrow E$

Why GPD at COMPASS ?

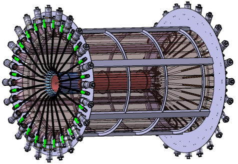


- CERN high energy muon beam
  - 100 - 190 GeV
  - 80% polarisation
  - $\mu^{+\leftarrow}$ and $\mu^{-\rightarrow}$ beams
- Kinematic range
  - between HERA and HERMES/JLab12
  - intermediate x (sea and valence)
- Separation
  - pure B-H @ low x_B
  - predominant DVCS @ high x_B
- Plans
  - DVCS
  - DVMP
- Goals
  - from unpolarised target: H (Phase 1)
  - from $\perp$ polarised target: E (Phase 2)

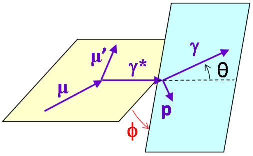
DVCS/DVMP: experimental requirements

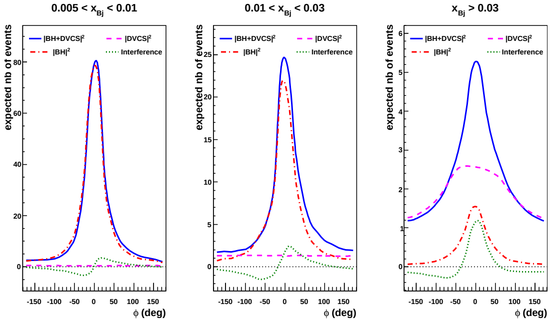
New hardware items needed:

- 2.5 m long liquid H_2 target (LH_2)
- 4 m long, time-of-flight recoil proton detector (RPD) with 2 barrels and a readout of 1GHz digitalisation (Gandalf)
- large angle electromagnetic calorimeter (ECAL0) just downstream target



Simulations @ 160 GeV and present setup (no ECAL0); normalisation of BH @ small x_B

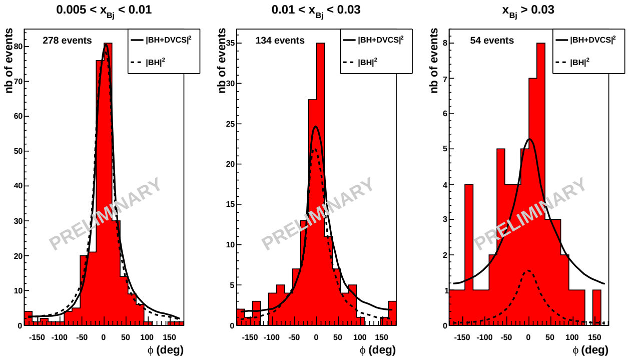




DVCS tests in 2008/2009

- Data taken at 160 GeV with μ^+ and μ^- (flux (μ^+)/flux (μ^-) = 3 at this energy)
- 40 cm long H_2 target (one vertex with μ, μ')
- Short recoil proton detector (one proton, $p_p < 1$ GeV/c)
- No ECAL0 (only one γ)

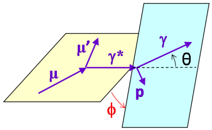
Results for μ^+ beam:



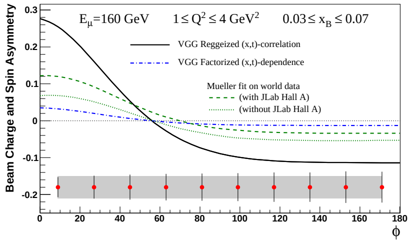
- MC normalised to yield @ low x_B
- A clear signal of DVCS at x_B >0.03

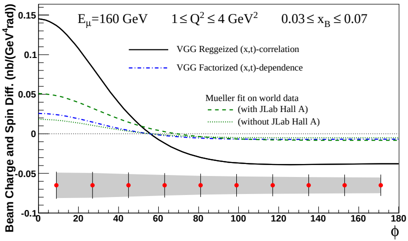
DVCS: projected data sets and results

- Simulations for:
  - 2 years of data taking
  - 10% global efficiency
  - L = 1222 pb^{-1}



- $S_{\mathrm{CS,U}}, D_{\mathrm{CS,U}}, A_{\mathrm{CS,U}}$ measured in 6 $x_{\mathrm{B}} \times$ 4 Q^2 bins as function of ϕ
- Azimuthal dependence $A_{\mathrm{CS,U}}$ and $D_{\mathrm{CS,U}}$ compared to models:

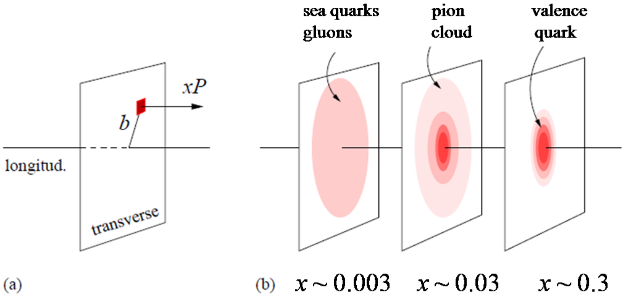




Nucleon transverse structure (“tomography”)

In the GPD limiting case ξ = 0, $t \equiv -\mathbf{\Delta^2} = -\mathbf{\Delta}_\perp^2$ and

$$q^f(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{\Delta}_\perp \cdot \mathbf{b}_\perp} H^f(x, 0, -\mathbf{\Delta}_\perp^2)$$

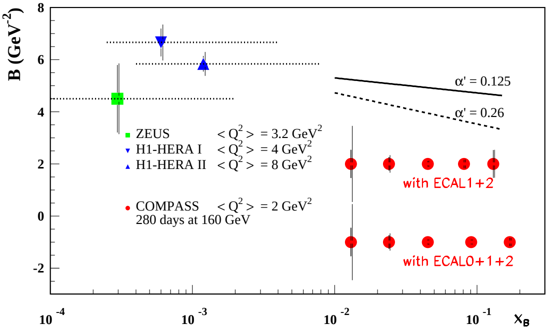


Get the nucleon transverse size as a function of longitudinal momentum fraction

Nucleon transverse structure – projected results

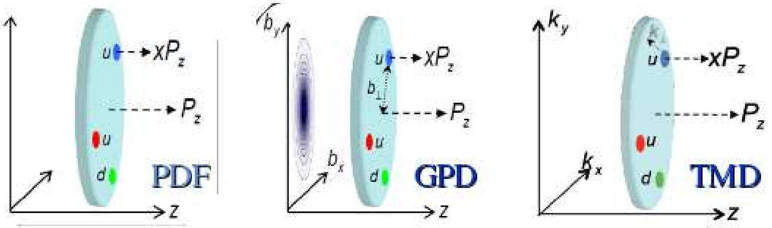
Case $x = \xi$

$$\frac{d\sigma^{\mathrm{DVCS}}}{dt} \propto e^{-B(x_B)|t|} \quad \text{where at low } x_B : B(x_B) \approx \frac{1}{2}\langle r_\perp^2(x_B)\rangle$$

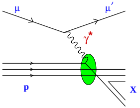


Here a simple ansatz: $B(x_B) = B_0 + 2\alpha' log \frac{x_0}{x_B}$ was assumed.

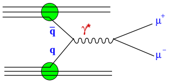
Transverse Momentum Dependent (TMD) distributions



- parton intrinsic k_{T} taken into account
- allow accessing quark L!
- at COMPASS studied in 2 ways:
  - semi-inclusive DIS (polarised muons on unpolarised/transversely polarised target)
  - Drell-Yan process (pion beam on unpolarised/transversely polarised target)

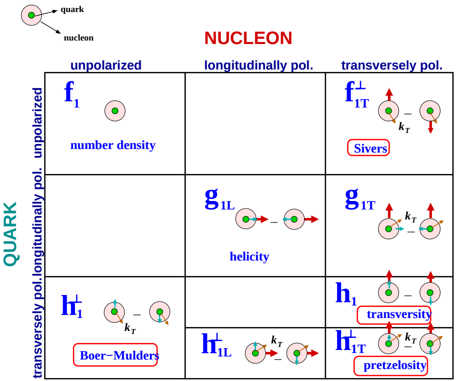


SIDIS



DY

TMD distributions...cont'd



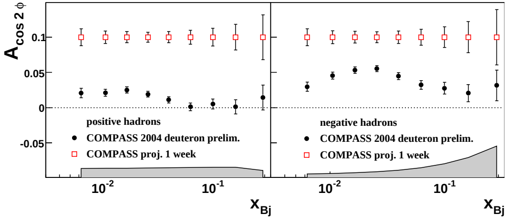
- In LT and considering k_{T},
  8 PDF describe the nucleon
- QCD-TMD approach valid $k_{\mathrm{T}} \ll \sqrt{Q^2}$
- After integrating over k_{T}
  only 3 survive: f_1, g_1, h_1
- TMD accessed in SIDIS and DY
  by measuring azimuthal asymmetries
- SIDIS: e.g. $A_{\mathrm{Sivers}} \propto$ PDF $\otimes$FF
- DY: e.g. $A_{\mathrm{Sivers}} \propto$ PDF$^{\mathrm{beam}} \otimes$ PDF$^{\mathrm{target}}$
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY}) \qquad f_{1\mathrm{T}}^{\perp}(\mathrm{SIDIS}) = -f_{1\mathrm{T}}^{\perp}(\mathrm{DY})$$

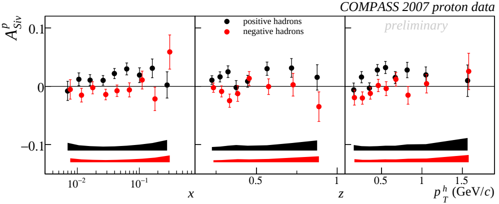
- OBS! transversity PDF is chiral-odd
- Boer-Mulders, Sivers and transversity $(h_1^{\perp}, f_{1\mathrm{T}}^{\perp}, h_1)$ will be measured in COMPASS II

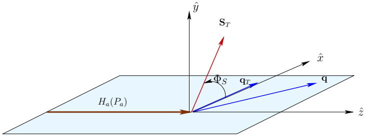
Boer-Mulders ($h_1^{\perp}$) and Sivers ($f_{1T}^{\perp}$) DF in SIDIS

- Boer–Mulders asymmetry, $A_{\cos 2\phi} \equiv A_{\rm LU}^{\cos 2\phi}$, was found $\neq 0$ on deuteron
- can be measured on the proton together with DVCS



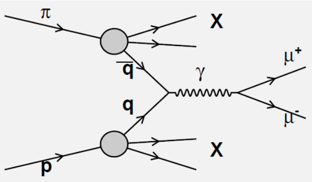
- Sivers asymmetry, $A^{\rm p}_{\rm Siv} \equiv A_{\rm LT}^{\sin \phi_{\rm S}}$, measured on d and p targets
- Found positive for h^{+} on proton but less strong than in HERMES

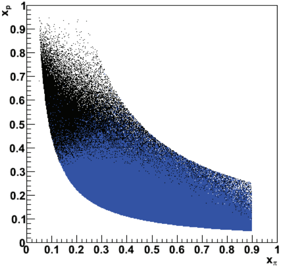




Drell-Yan process: $\pi^- p^\uparrow \to \mu^+ \mu^- X$ @ COMPASS

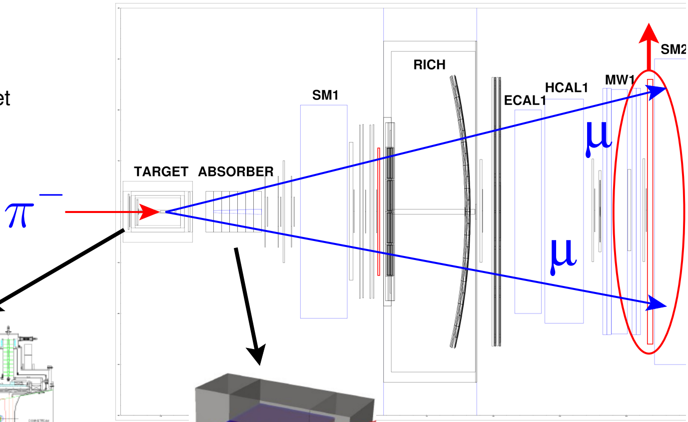
- Clean partonic process
- No fragmentation functions involved!
- Convolution of two Parton Distribution Functions
  $\sigma^{\rm DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|\rm p}, \quad \sigma^{\rm DY} = \sigma^{\rm DY}(x_\pi, x_{\rm p})$
- Gives an access to azimuthal modulations of 4 PDF: transversity, pretzelosity, Boer–Mulders and Sivers.
- Ideal: $\bar{\rm p}{\rm p}$; good compromise: $\pi^-{\rm p}$
- Here dominated by annihilation of valence $\bar{u}$ from π^- and valence u from p
- COMPASS has large acceptance in the valence region of p and π (large SSA expected).
  Example of covered kinematics (in blue):
  π^- beam, 190 GeV/c, NH_3 target, $\perp$ polarised
  dimuon mass range: 4 – 9 GeV/c^2 (low bckg.)
- QCD TMD approach justified by:
  $M_{\mu\mu} \gg p_{\rm T}^{\mu\mu} \approx$ 1 GeV

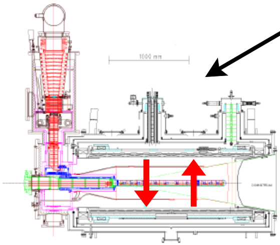


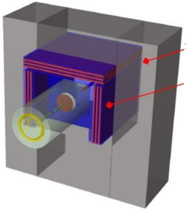


Drell–Yan @ COMPASS: experimental requirements

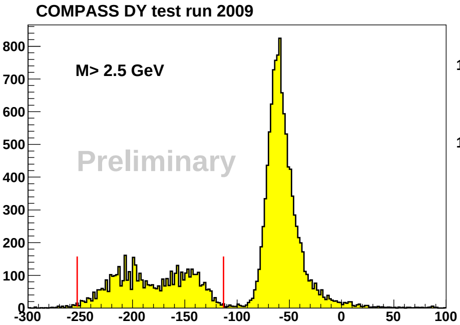
- intense π beam (up to 10^9/spill)
- hadron absorber downstream target
- di-muon trigger

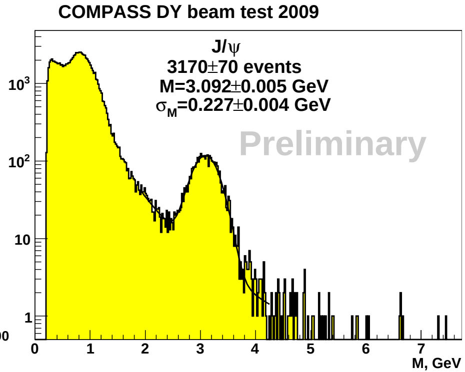






Drell–Yan @ COMPASS: Results from 2009 beam test

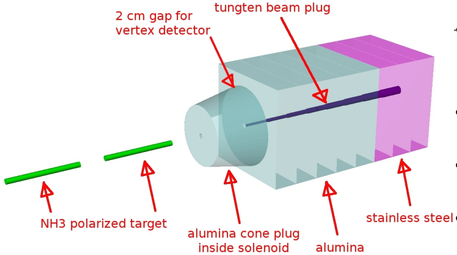


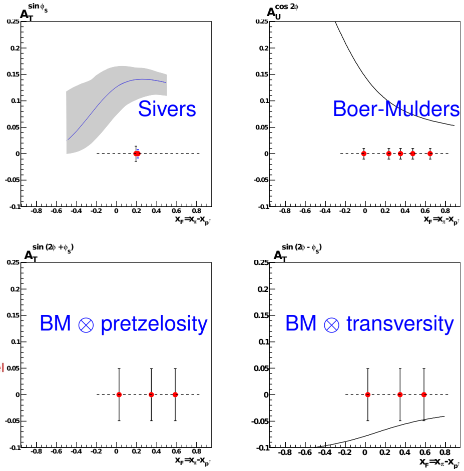


- 3 days of data taking
- $8{\cdot}10^7 \pi^-$/9.6 s spill
- 2 cells of CH_2 of 40-20-40 cm
- temporary absorber
- simple trigger

Drell–Yan @ COMPASS: Projections for azimuthal asymmetries

- projections for 4 GeV/$c^2 < M_{\mu\mu} <$ 9 GeV/c^2
- 2 years of data taking
- $6 \cdot 10^8$ pions /9.6 s spill
- 1.1 m long, polarised NH_3 target





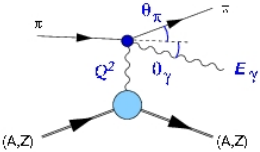
Goals: change of sign between DIS and SIDIS in $h_1^\perp$,
J/Ψ production mechanism,...

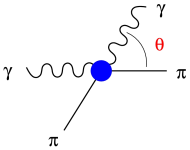
Future Drell–Yan experiments

Facility	Type		s (GeV^2)	Time-line
RHIC (STAR, PHENIX)	collider,	$p^{\Uparrow}p^{\Uparrow}$	200^2, 500^2	> 2014
RHIC (internal target)	fixed target,	$p^{\Uparrow}p^{\Uparrow}$	500	> 2015
RHIC (AnDY)	collider,	$p^{\Uparrow}p^{\Uparrow}$	500^2	> 2013
E906 (Fermilab)	fixed target,	pp	226	> 2010
J-PARC	fixed target,	$pp^{\Uparrow}$	$60 \div 100$	> 2015
GSI (PAX)	collider,	$\overline{p}^{\Uparrow}p^{\Uparrow}$	200	> 2017
GSI (Panda)	fixed target,	$\overline{p}p$	30	> 2016
NICA	collider,	$p^{\Uparrow}p^{\Uparrow}$, $d^{\Uparrow}d^{\Uparrow}$	676	> 2014
COMPASS II	fixed target,	$\pi^-p^{\Uparrow}$	300÷400	> 2012

Studies of Chiral Perturbative Theory

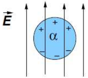
Primakoff ($\pi^- Z \to \pi^- Z\gamma$) and Compton ($\pi\gamma \to \pi\gamma$) processes

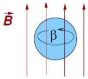




- Breaking of chiral symmetry $\Longrightarrow$ Goldstone bosons (pions, kaons)
- ChPT predicts *e.g.* pion electromagnetic polarisabilities
  $\Longrightarrow$ deviations of $\sigma(\pi\gamma \to \pi\gamma)$ from QED from point-like, spin 0 object

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

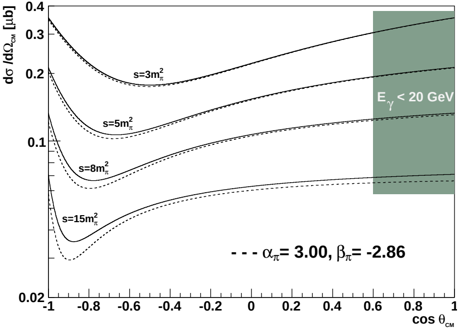




$$P(\alpha_\pi, \beta_\pi) =$$
$$(1-\cos\theta_{cm})^2(\alpha_\pi - \beta_\pi) + (1+\cos\theta_{cm})^2(\alpha_\pi + \beta_\pi)f_1(s) + (1-\cos\theta_{cm})^3(\alpha_2 - \beta_2)f_2(s)$$

Studies of Chiral Perturbative Theory,...cont'd

- 2-loop ChPT prediction: $\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \cdot 10^{-4}$ fm^3
- Measurements: $\alpha_\pi - \beta_\pi = (4 - 14) \cdot 10^{-4}$ fm^3
- COMPASS II: measurements of both pion and kaon polarisabilities!



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

Tentative time table

- 2012 setup and tests: Primakoff 18 weeks, GPD 6 weeks
- 2013 SPS shutdown;
  polarised target movement and installation
- 2014 Drell-Yan
- 2015 GPD
  2016 GPD
- $\geq$ 2016 Addendum ?