COMPASS: present and future

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Low x 2012

Paphos, June 27 – 30, 2012

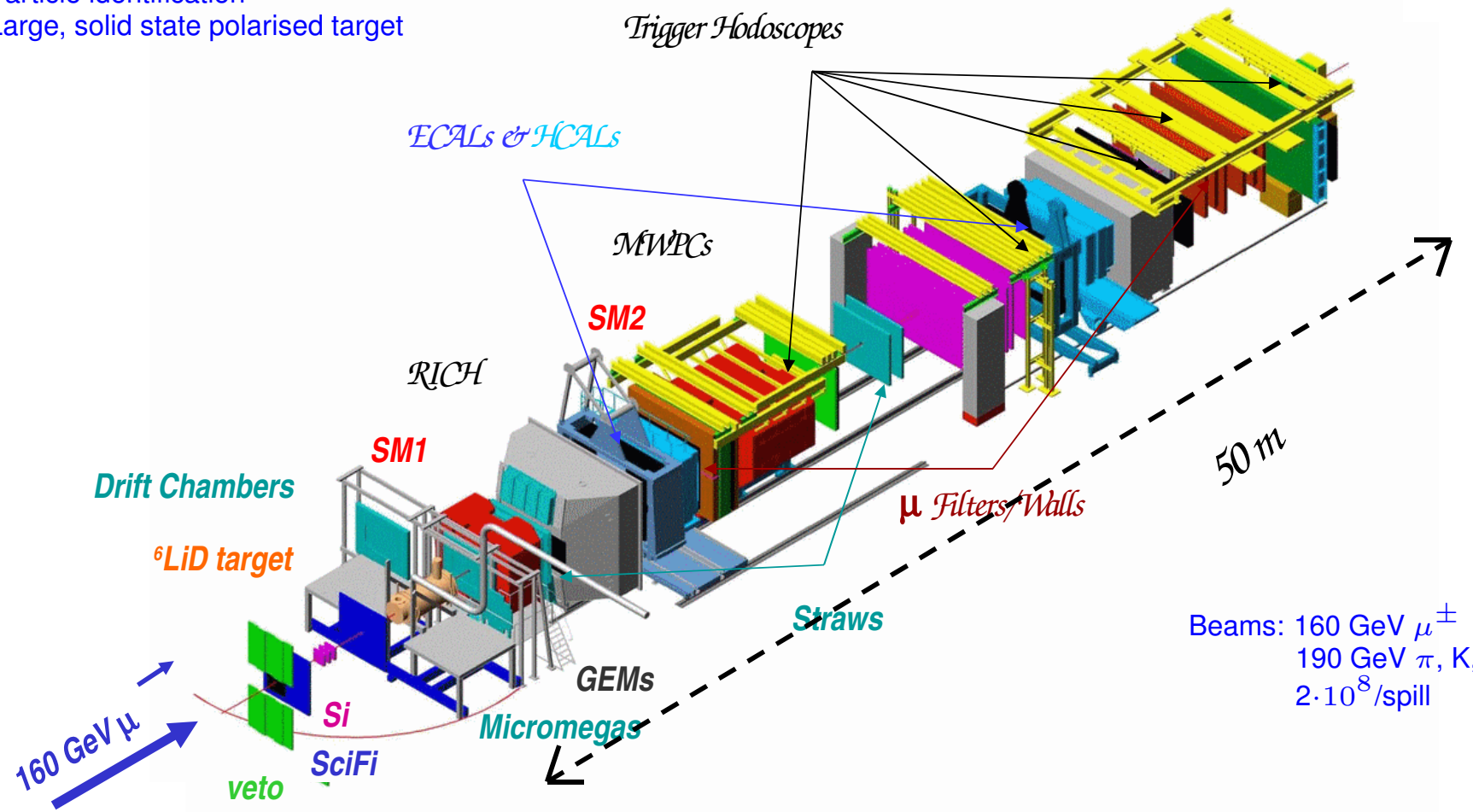
What has COMPASS done so far

- Is taking data since 2002 (2005 break due to SPS shutdown);
- muon and hadron programmes;
- 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 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)

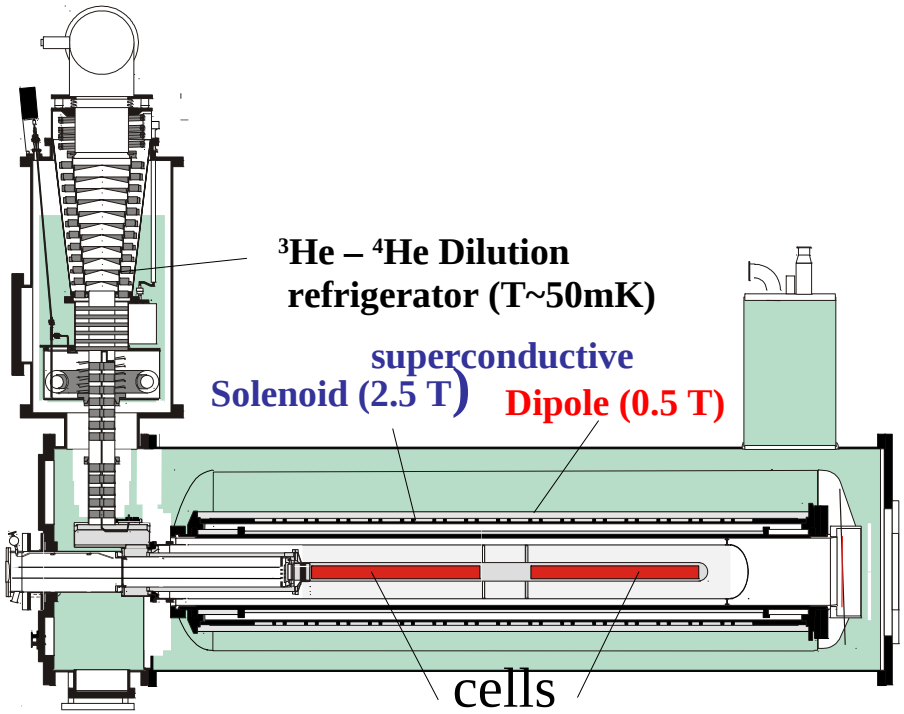
Nucl. Instr. Meth. A577 (2007) 455

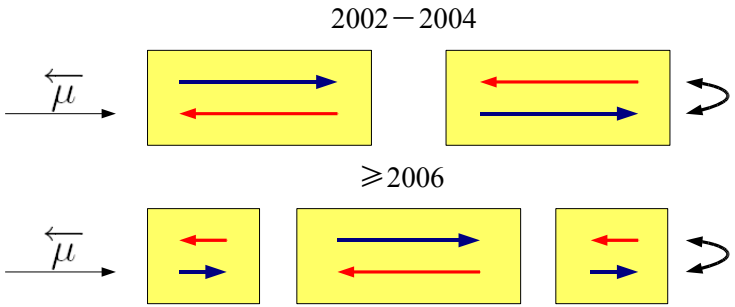
Two stages, $\sim$ 350 planes
Calorimetry
Particle identification
Large, solid state polarised target



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

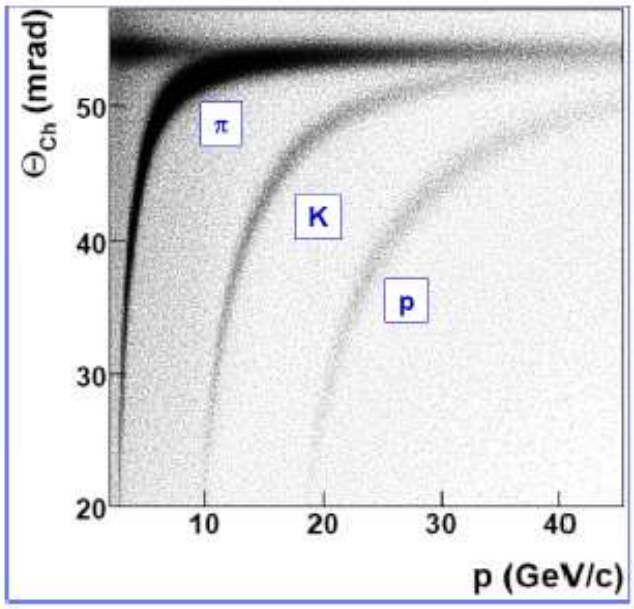
COMPASS polarised targets



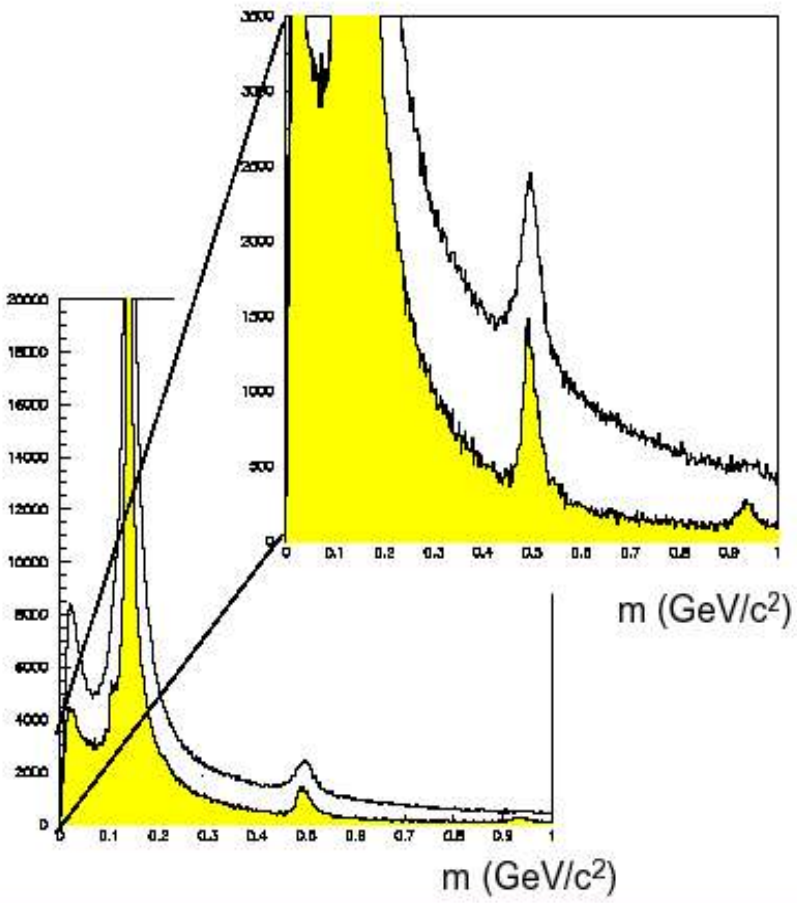


* Two (three) target cells, oppositely polarised
* Polarisation reversed every 8 h (less frequent after 2005) by field rotation
* Material: solid ^{6}LiD (NH_3)
* Polarisation: ~ 50% (~90%), by the Dynamical Nuclear Polarisation
* Dilution: f~0.4 (~0.15)
* Polar acceptance: ~70 mrad (~180 mrad after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

COMPASS RICH



Before upgrade: white distribution
After upgrade: yellow distribution



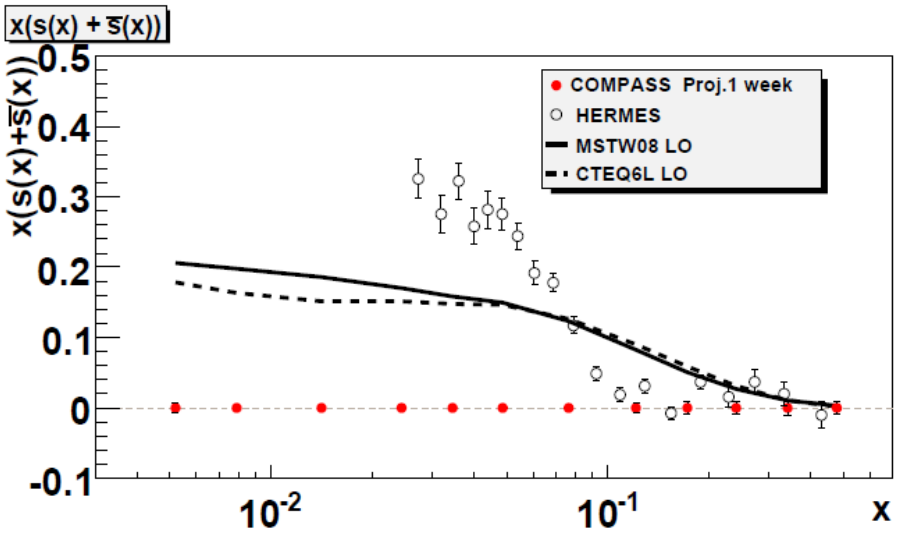
RICH2007 Federica Sozzi 19

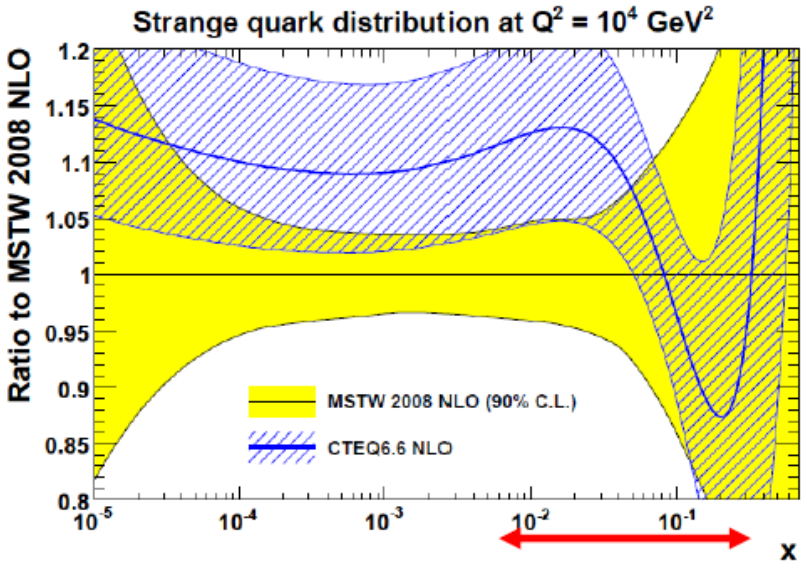
COMPASS II Proposal

- 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

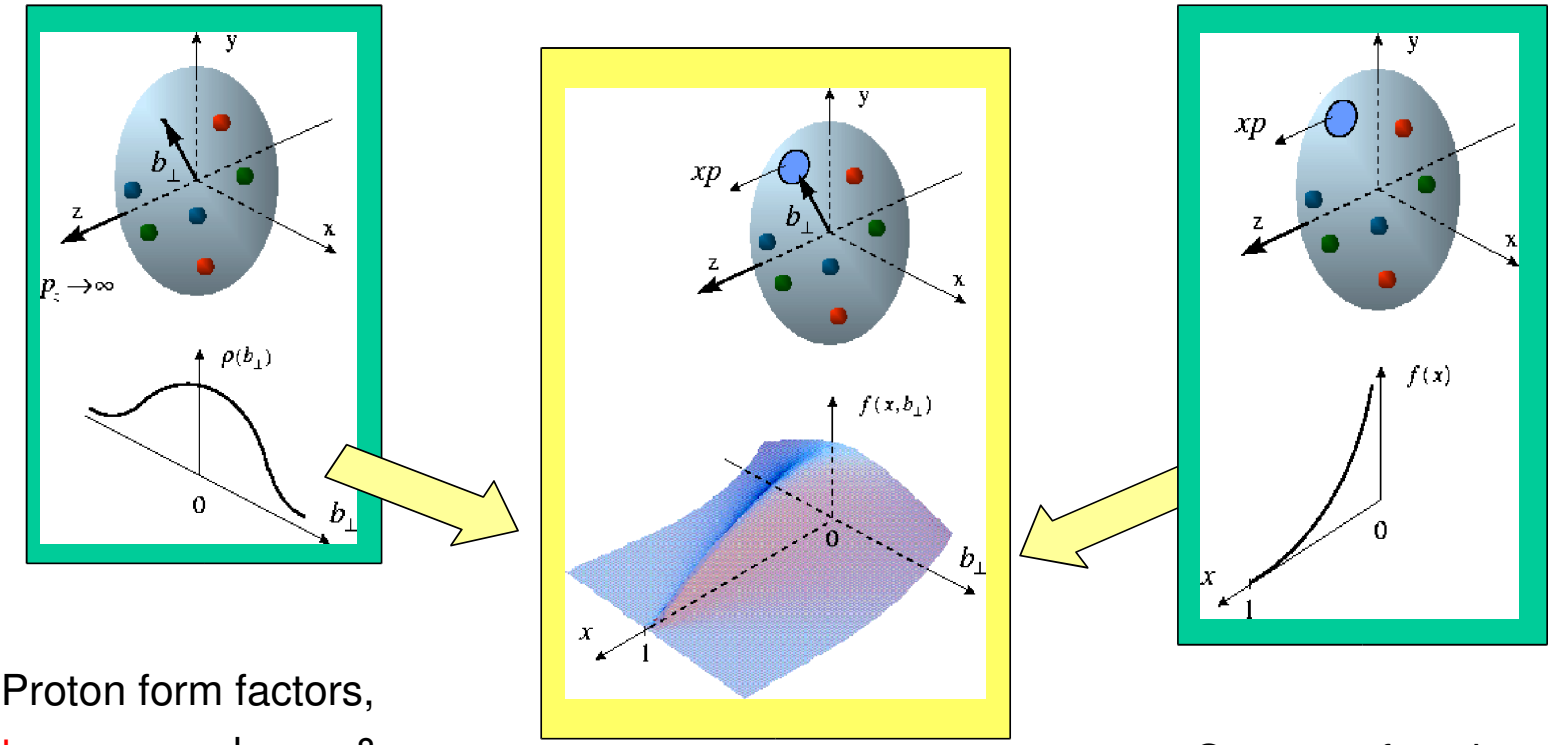
- Spin-averaged SIDIS, $\mu p \to \mu h X$, will be recorded simultaneously with DVCS/DVMP, on a long LH_2 target (NH_3 target from COMPASS I is difficult!)
- Charge and nature of "h" will be determined ($\pi^{\pm}$, π^0, $K^{\pm}$, K^0, Λ, $\bar{\Lambda}$)
- Combined with COMPASS I data on ^{6}LiD $\Longrightarrow$ 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



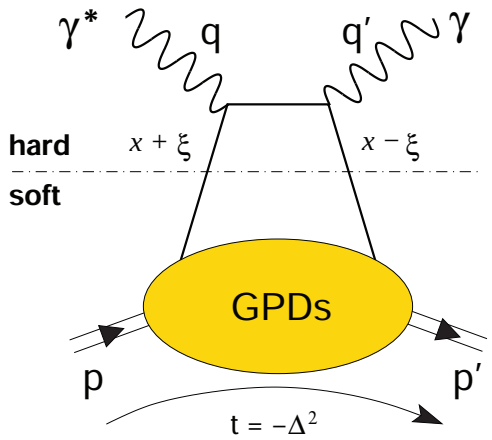
Proton form factors, transverse charge & current densities

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

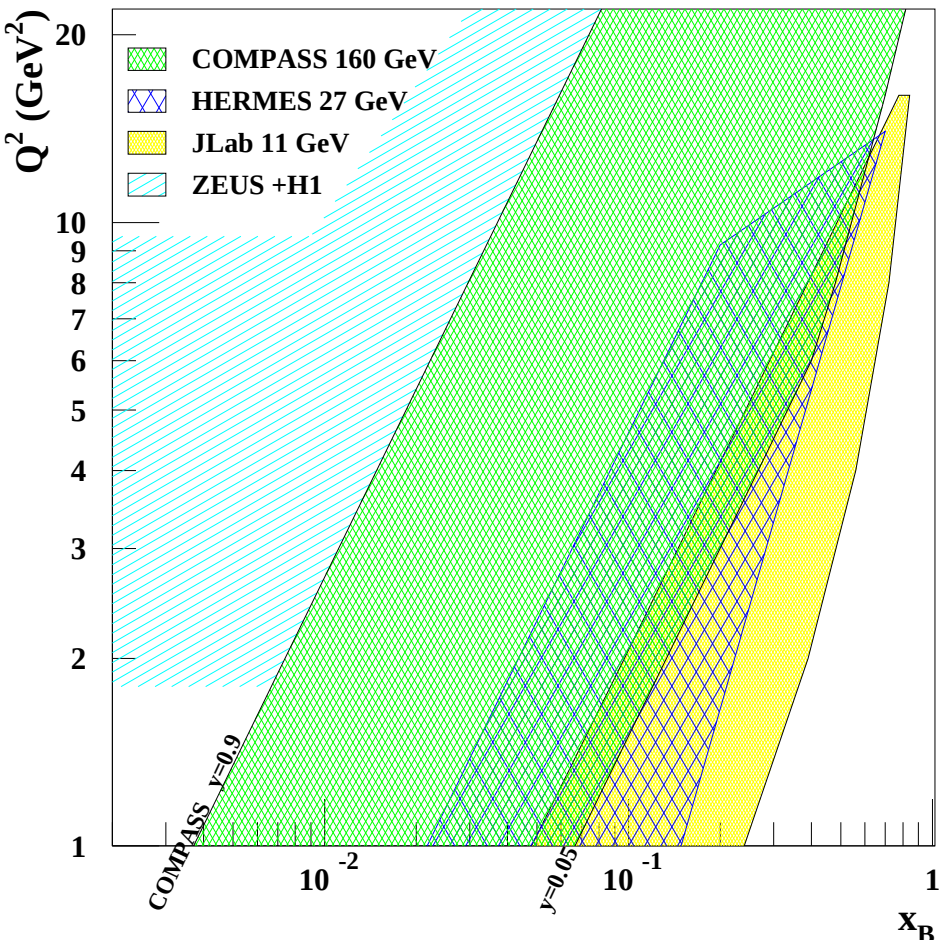


$Q^2 \to \infty$,
fixed $x_B, t \implies |t|/Q^2$ small

- 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
- $H^q(x,0,0) = q(x), \quad \widetilde{H}^q(x,0,0) = \Delta q(x)$

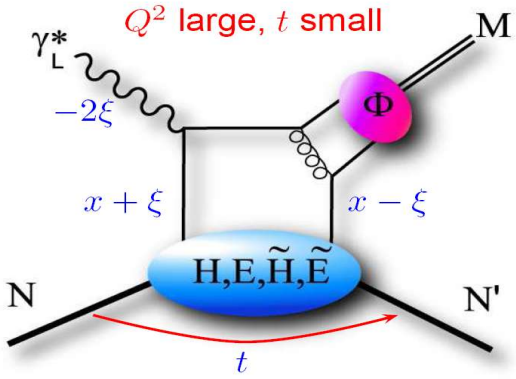
- H, E accessed in vector meson production *via* A_{UT} asymmetries
- $\widetilde{H}, \widetilde{E}$ accessed in pseudoscalar meson production *via* A_{UT} asymmetries
- All 4 accessed in DVCS (γ production) in $A_C, A_{LU}, A_{UT}, A_{UL}$
- Integrals of $H, E, \widetilde{H}, \widetilde{E}$ over x give 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)

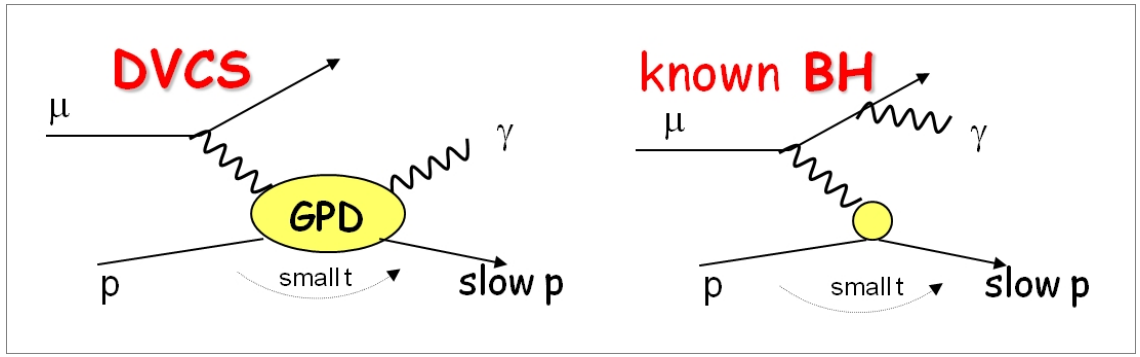
Why GPD at COMPASS ?



- CERN high energy muon beam
  - 100 - 190 GeV
  - 80% polarisation, opposite for μ^+, μ^-
  - $\mu^{+\leftarrow}$ 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: $\mu p \to \mu p \gamma(M)$; what do we measure?

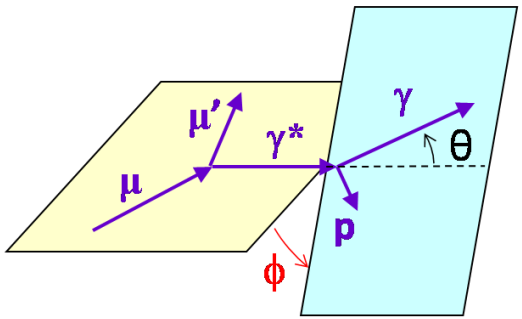




$$\mathrm{d}\sigma^{\mu p\to\mu p\gamma} = \mathrm{d}\sigma^{\mathrm{BH}} + (\mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + P_\mu \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}}) + e_\mu(\mathrm{Re}I + P_\mu \mathrm{Im}I) \qquad 4-\mathrm{dim.}: x_{\mathrm{B}}, Q^2, t, \phi$$

Observables (Phase 1):

- $S_{\mathrm{CS,U}} \equiv \mu^{+\leftarrow} + \mu^{-\rightarrow} = 2\left(\mathrm{d}\sigma^{\mathrm{BH}} + \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + e_\mu P_\mu \mathrm{Im}I\right)$
- $D_{\mathrm{CS,U}} \equiv \mu^{+\leftarrow} - \mu^{-\rightarrow} = 2\left(P_\mu \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}} + e_\mu \mathrm{Re}I\right)$
- $A_{\mathrm{CS,U}} \equiv \dfrac{\mu^{+\leftarrow} - \mu^{-\rightarrow}}{\mu^{+\leftarrow} + \mu^{-\rightarrow}} = \dfrac{D_{\mathrm{CS,U}}}{S_{\mathrm{CS,U}}}$
- 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 $(F_1 H)$

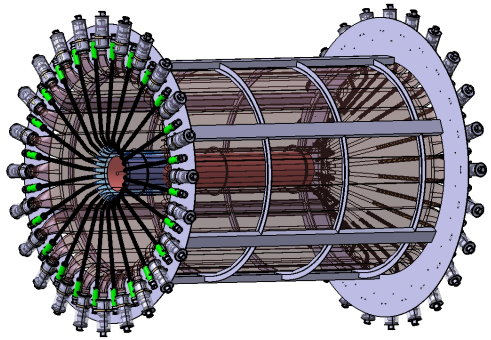


Analogously for transversely polarised target (Phase 2): $S_{\mathrm{CS,T}}, D_{\mathrm{CS,T}}, A_{\mathrm{CS,T}} \Longrightarrow E$

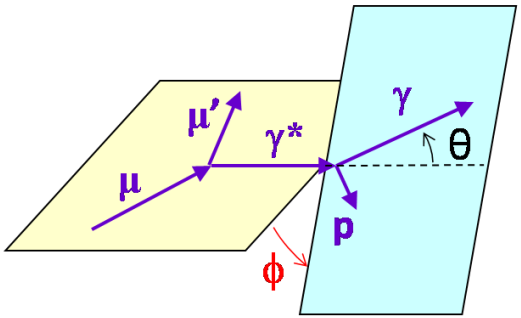
DVCS/DVMP: experimental requirements

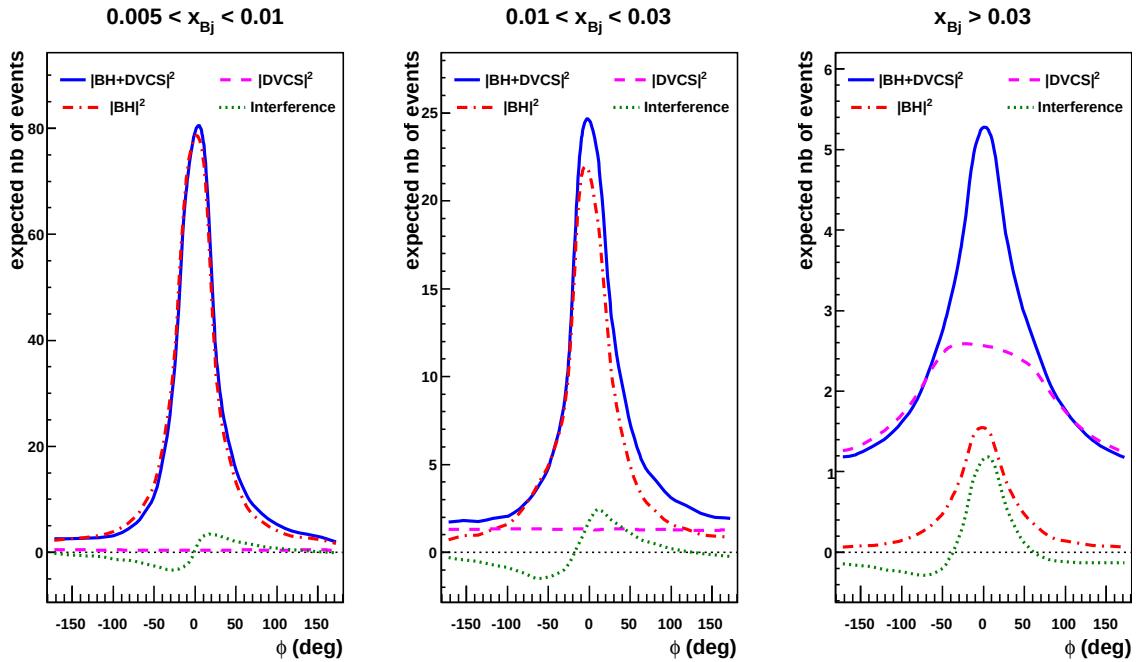
New hardware items needed:

- 2.5 m long liquid H_2 target (LH_2), ready 2012
- 4 m long, tof recoil proton detector (CAMERA), ready 2012, with 2 barrels and a readout of 1GHz digitalisation (Gandalf)
- large angle electromagnetic calorimeter (ECAL0) just downstream target; prototype ready 2012



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

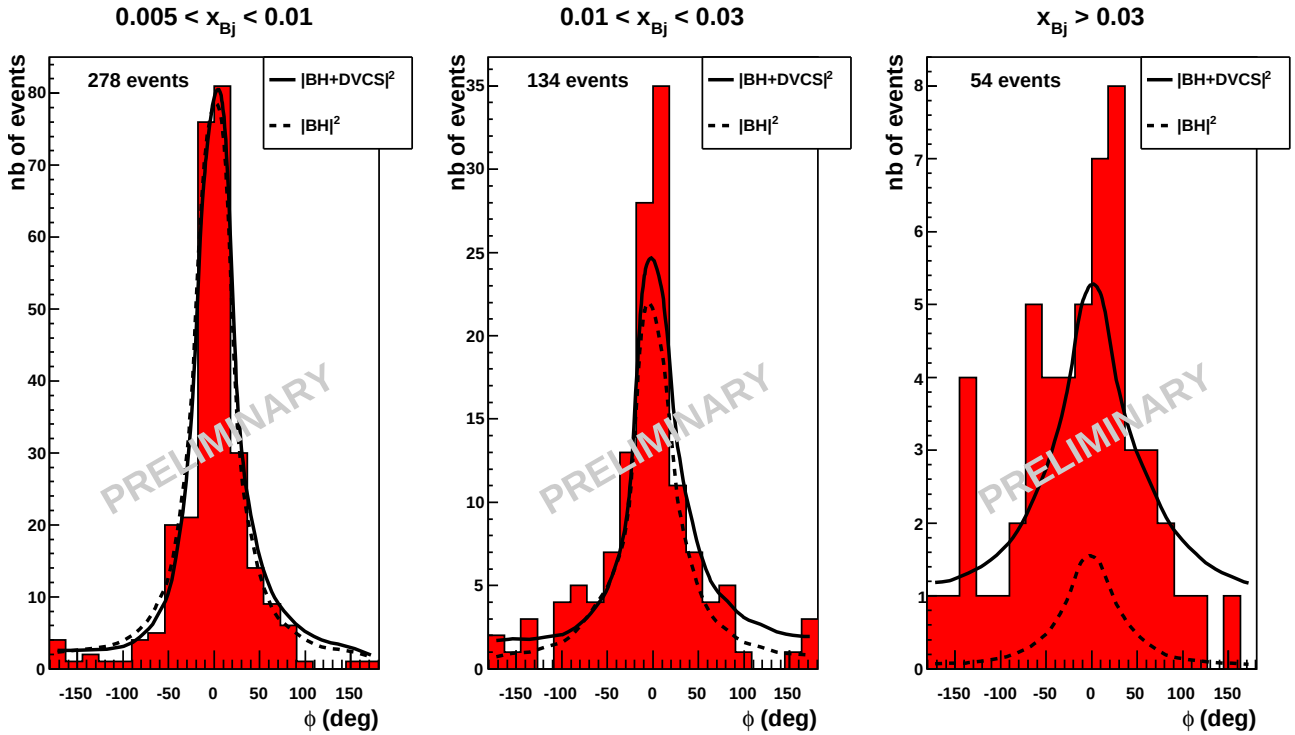




DVCS tests in 2008/2009

- 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, $p_{\rm p} < 1$ GeV/c)
- No ECAL0 (only one γ)

Results for μ^+ beam:

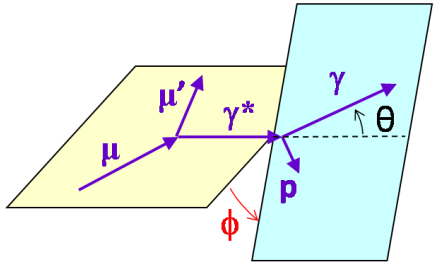


- MC normalised to yield @ low $x_{\rm B}$
- A clear signal of DVCS at $x_{\rm B}$ >0.03

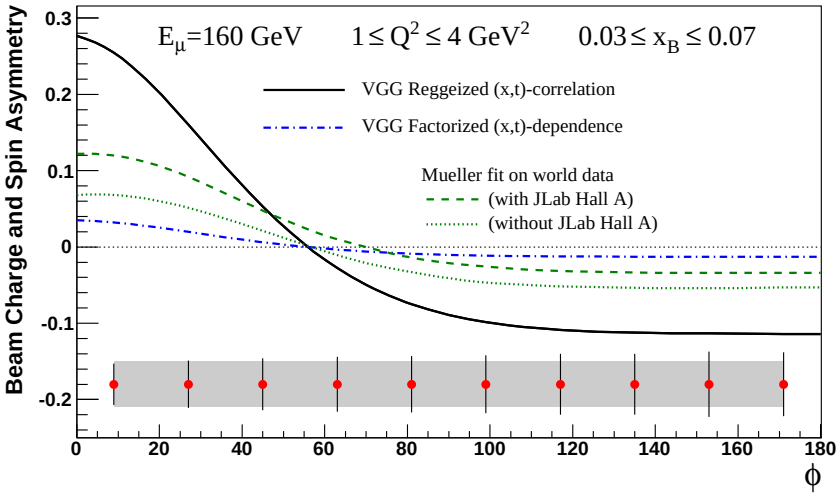
In 2012 $\sim$ 10 x larger statistics!

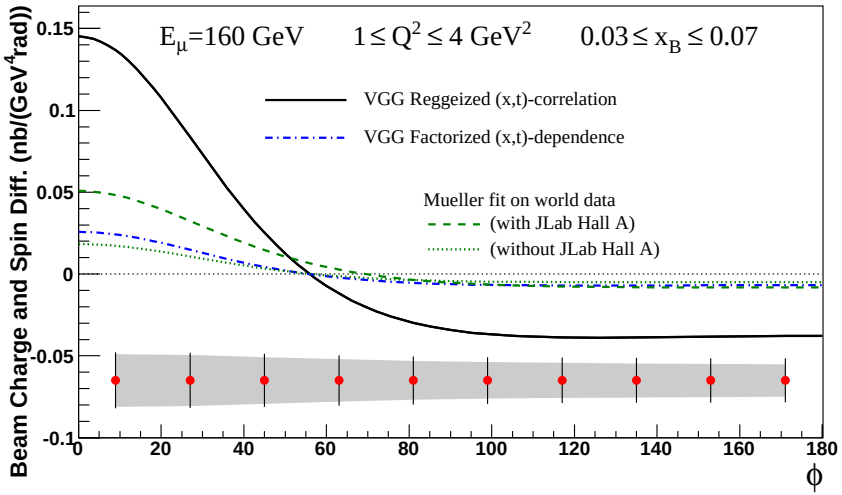
DVCS: projected data sets and results

- 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:

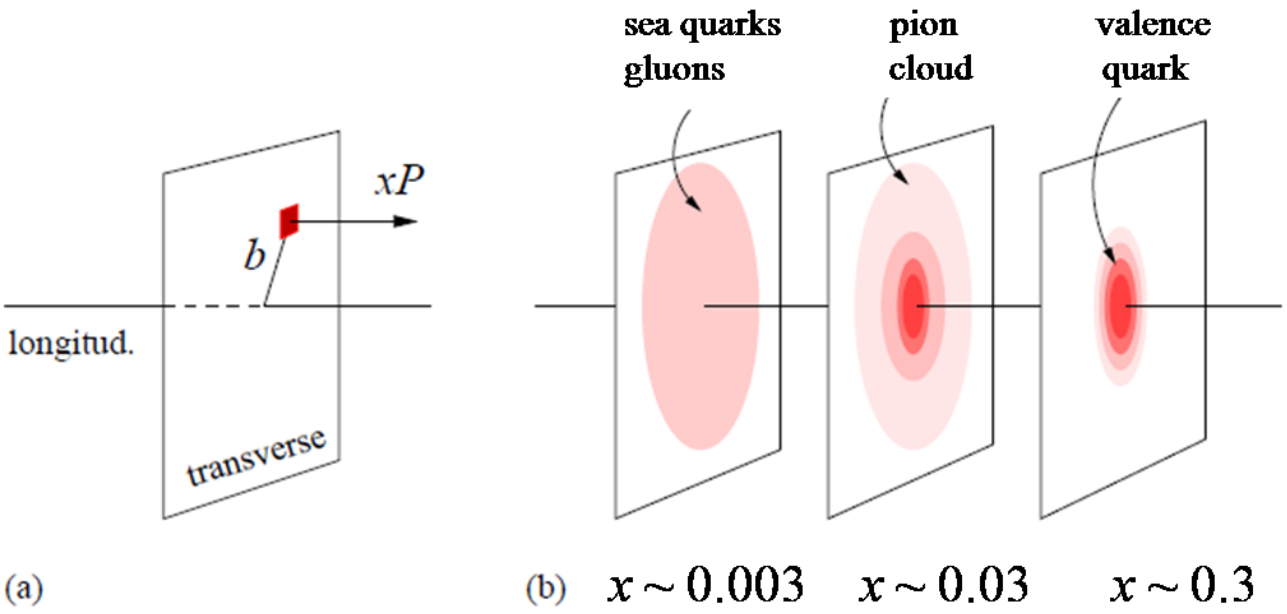




Nucleon transverse structure ("tomography")

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

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

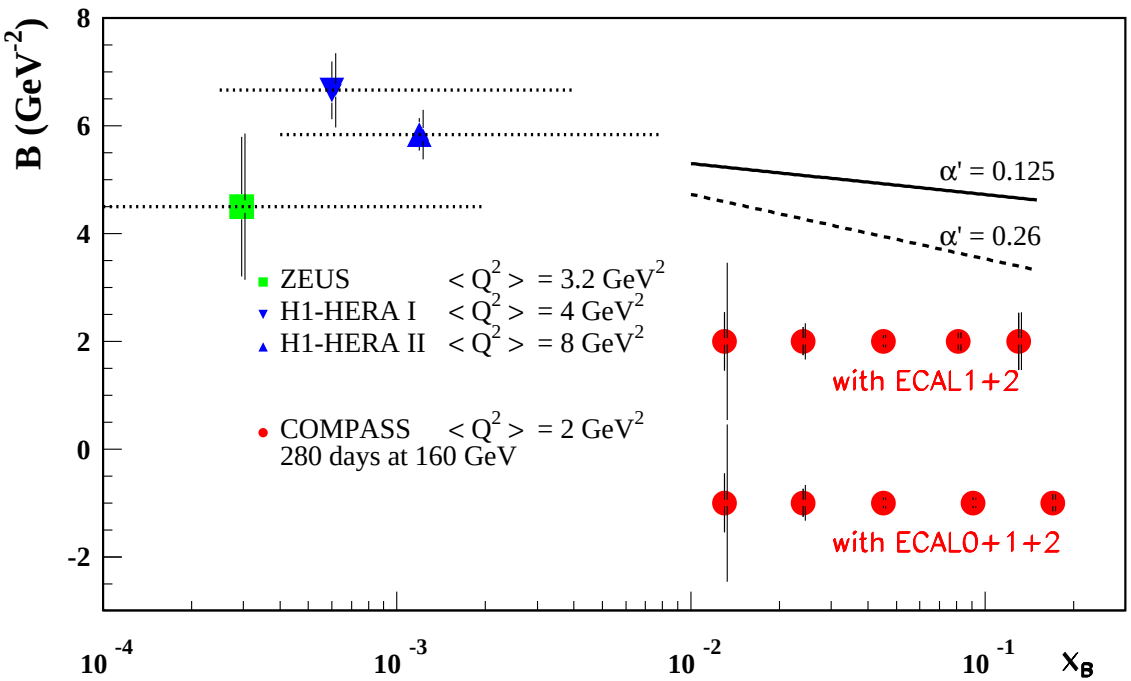


Get the nucleon transverse size as a function of longitudinal momentum fraction

Nucleon transverse structure – projected results

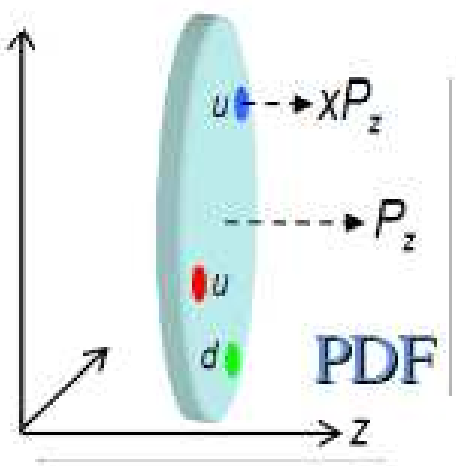
Case $x = \xi$

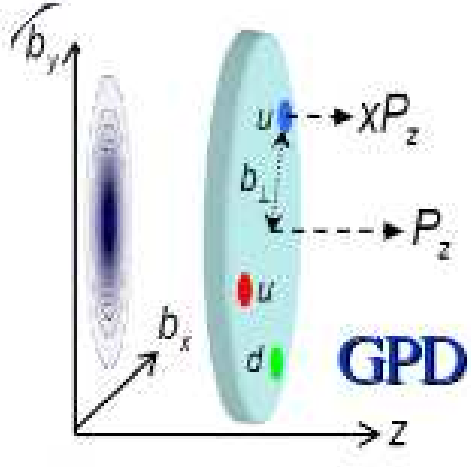
$$\frac{\mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}}}{\mathrm{d}t} \propto e^{-B(x_{\mathrm{B}})|t|} \qquad \text{where at low } x_{\mathrm{B}} : B(x_{\mathrm{B}}) \approx \frac{1}{2}\langle r^2_{\perp}(x_{\mathrm{B}})\rangle$$

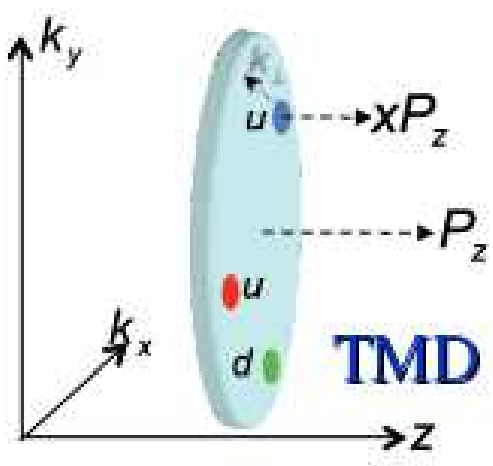


Here a simple ansatz: $B(x_{\mathrm{B}}) = B_0 + 2\alpha' log\frac{x_0}{x_{\mathrm{B}}}$ was assumed.

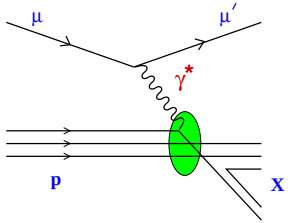
Transverse Momentum Dependent (TMD) distributions



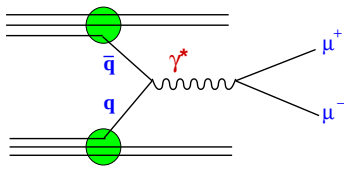




- parton intrinsic k_{T} taken into account
- allow accessing quark L!
- at COMPASS studied in 2 ways:
  - semi-inclusive DIS (polarised muons on unpolarised/transversely polarised target)
  - Drell-Yan process (pion beam on unpolarised/transversely polarised target)



SIDIS

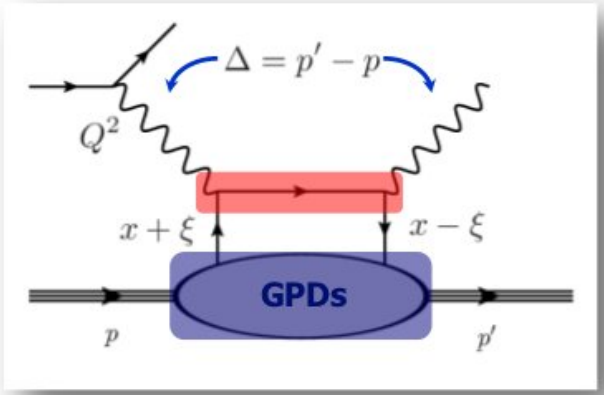


DY

From Cédric Lorcé (Orsay), IWHSS2012

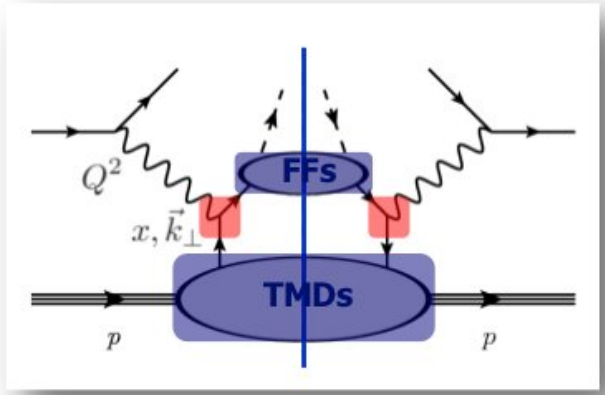
DVCS vs. SIDIS

DVCS



$$x = \frac{k^+}{P+} \qquad -2\xi = \frac{\Delta^+}{P+} \qquad t = \Delta^2$$

SIDIS



Factorization

Compton form factor
Cross section

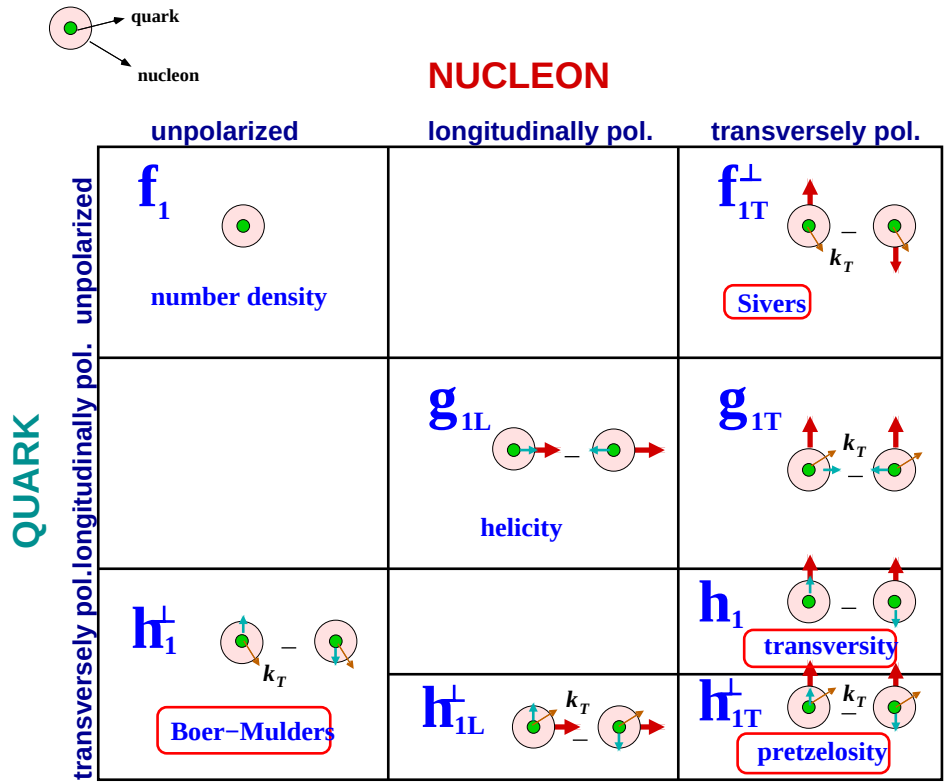
$$= \; \underset{\text{hard}}{H} \; \overset{\mu_F}{\otimes} \; \underset{\text{soft}}{S}$$

- **process dependent**
- **perturbative**

- **« universal »**
- **non-perturbative**

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. $A_{\mathrm{Sivers}} \propto \mathrm{PDF} \otimes \mathrm{FF}$
- DY: e.g. $A_{\mathrm{Sivers}} \propto \mathrm{PDF}^{\mathrm{beam}} \otimes \mathrm{PDF}^{\mathrm{target}}$



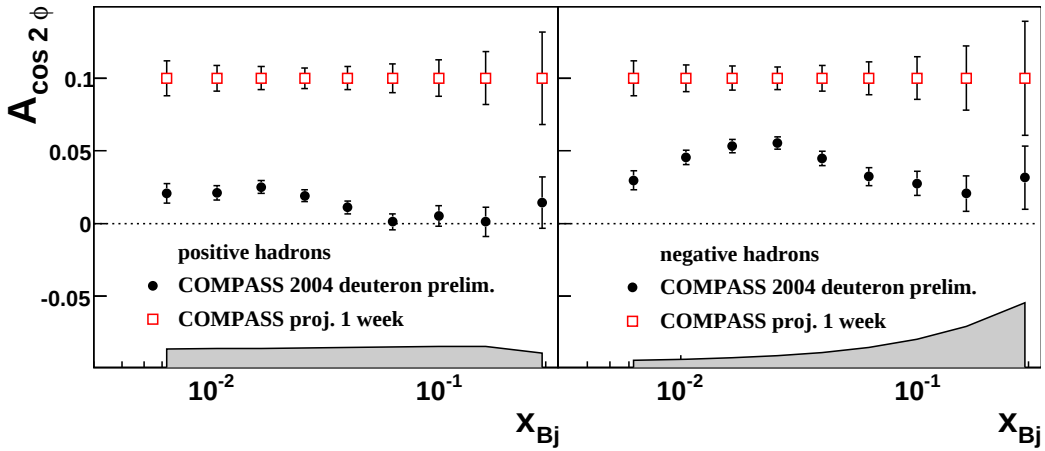
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

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

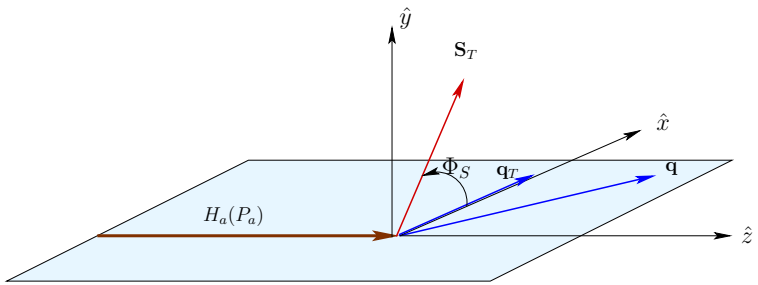
- OBS! transversity PDF is chiral-odd
- Boer-Mulders, Sivers and transversity $(h_1^{\perp}, f_{1\mathrm{T}}^{\perp}, h_1)$ will be measured in COMPASS II

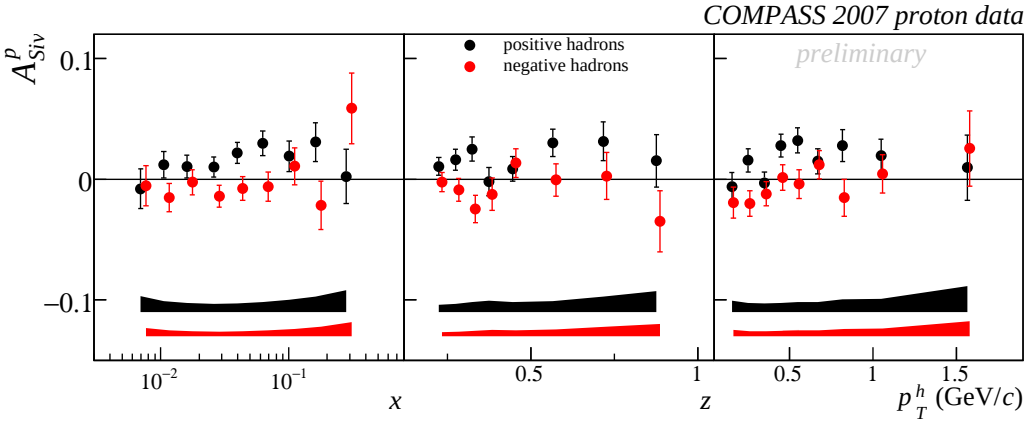
Boer-Mulders ($h_1^\perp$) and Sivers ($f_{1\mathrm{T}}^\perp$) DF in SIDIS

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



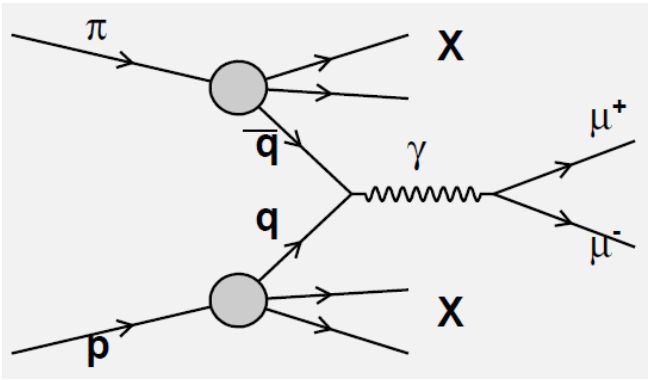
- Sivers asymmetry, $A_{\mathrm{Siv}}^{\mathrm{p}} \equiv A_{\mathrm{LT}}^{\sin \Phi_{\mathrm{S}}}$, measured on d and p targets
- Found positive for h^+ on proton but less strong than in HERMES

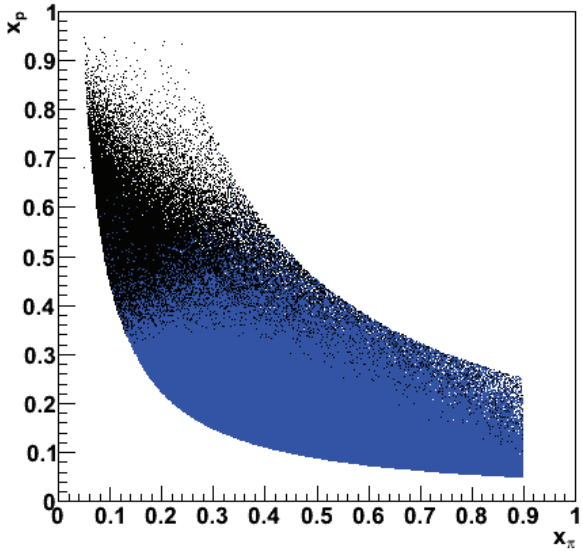




Drell-Yan process: $\pi^- p^\uparrow \to \mu^+\mu^- X$ @ COMPASS

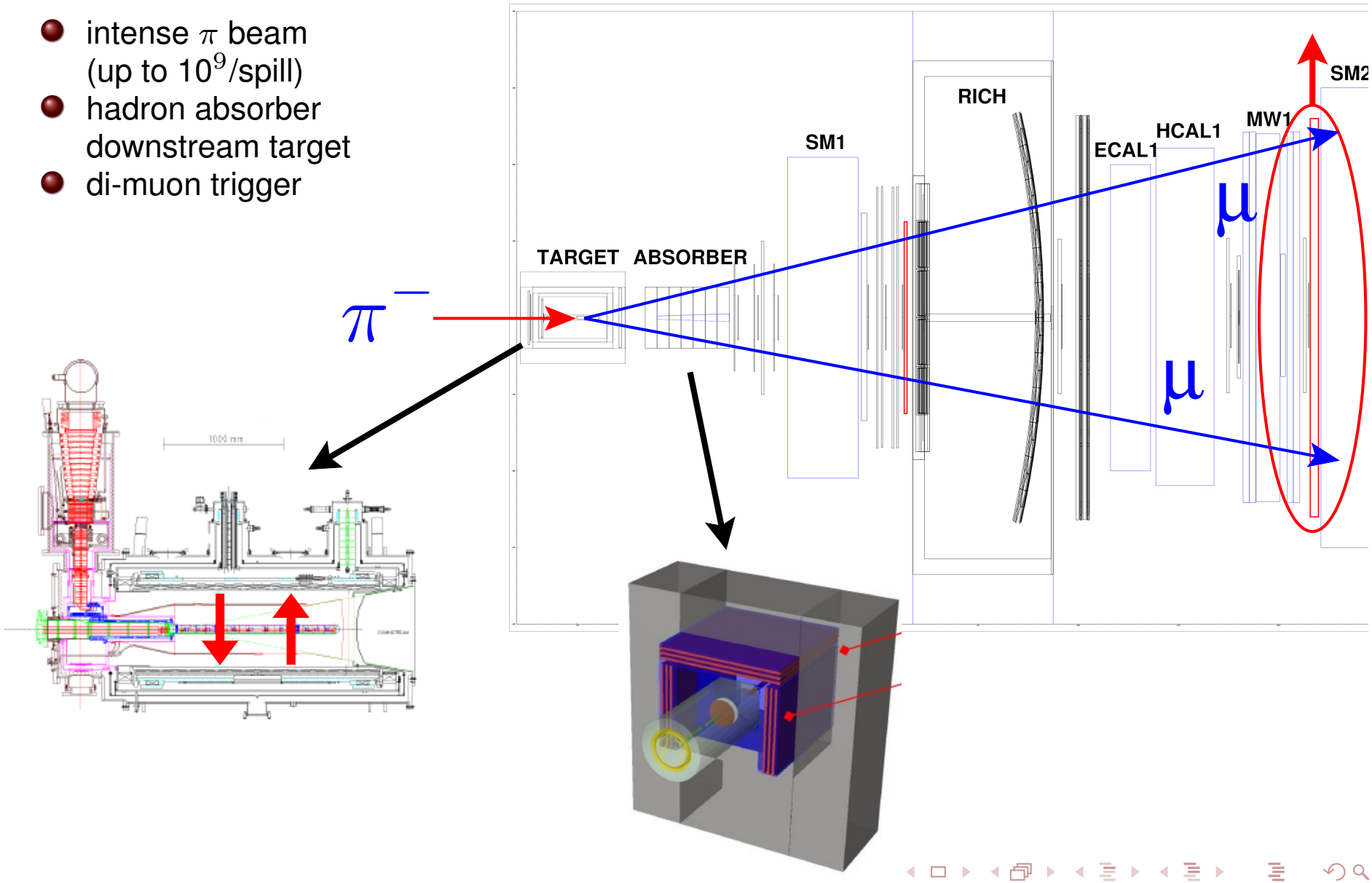
- Clean partonic process
- No fragmentation functions involved!
- Convolution of two Parton Distribution Functions
  $\sigma^{\mathrm{DY}} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|\mathrm{p}}, \quad \sigma^{\mathrm{DY}} = \sigma^{\mathrm{DY}}(x_\pi, x_\mathrm{p})$
- Gives an access to azimuthal modulations of 4 PDF: transversity, pretzelosity, Boer–Mulders and Sivers.
- Ideal: $\bar{\mathrm{p}}\mathrm{p}$; good compromise: $\pi^-\mathrm{p}$
- 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: $M_{\mu\mu} \gg p_{\mathrm{T}}^{\mu\mu} \approx 1$ GeV



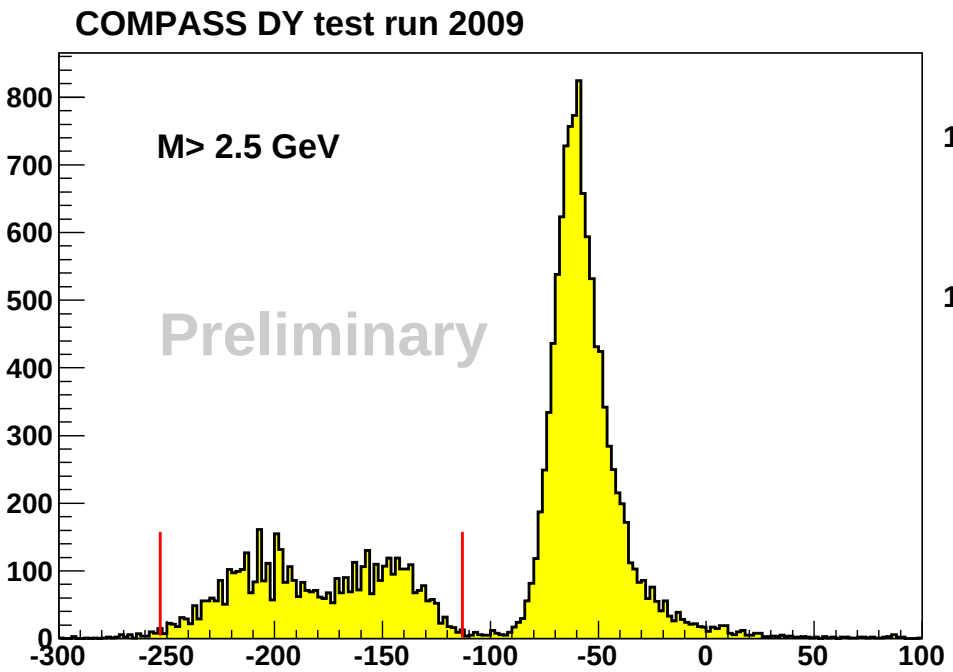


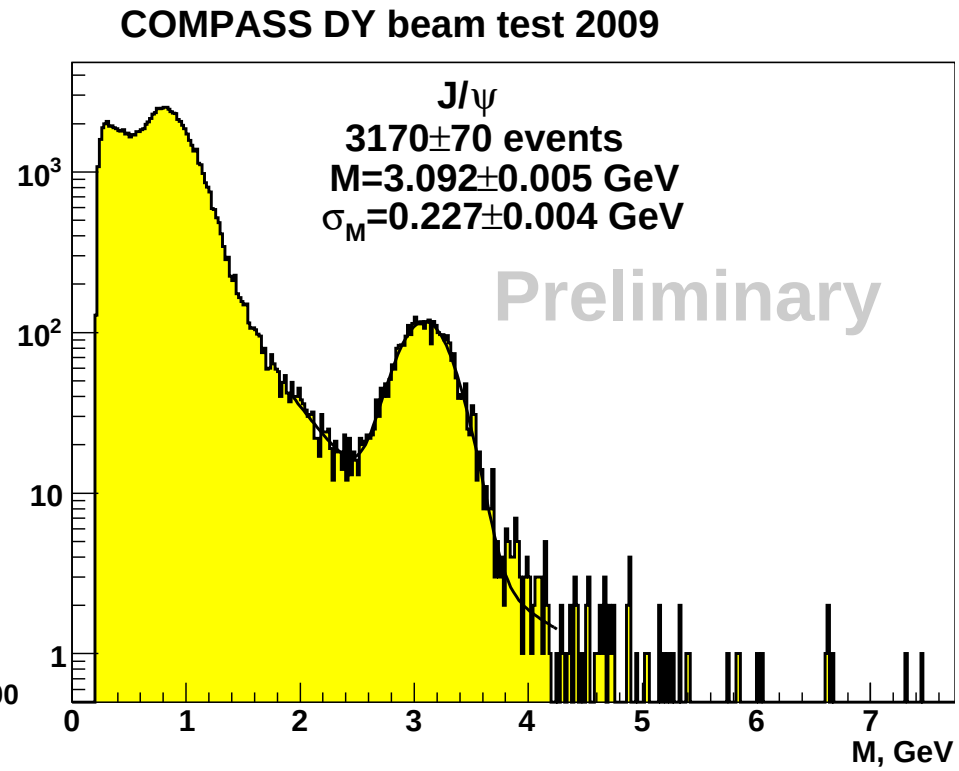
Drell–Yan @ COMPASS: experimental requirements

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



Drell–Yan @ COMPASS: Results from 2009 beam test

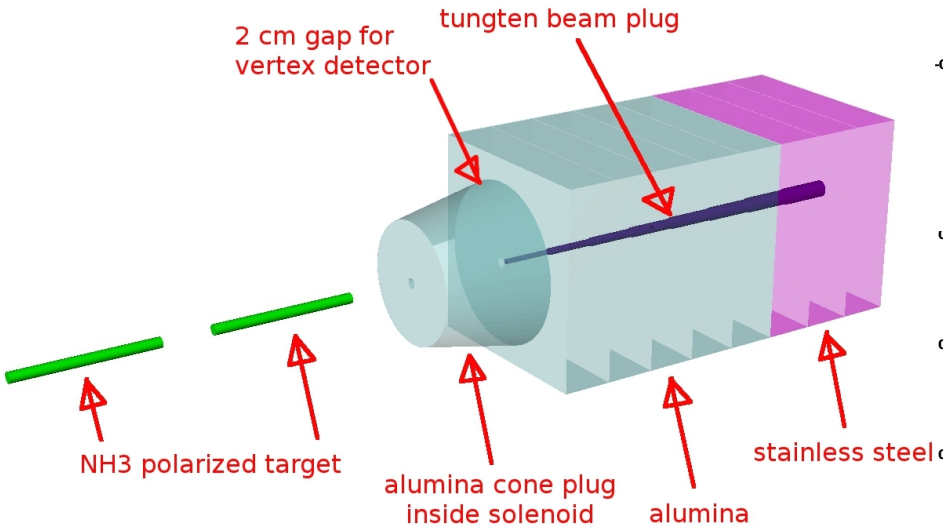


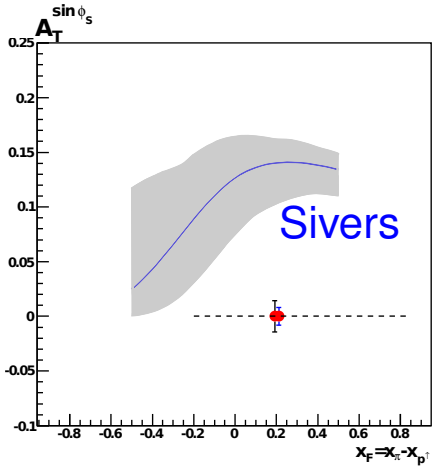


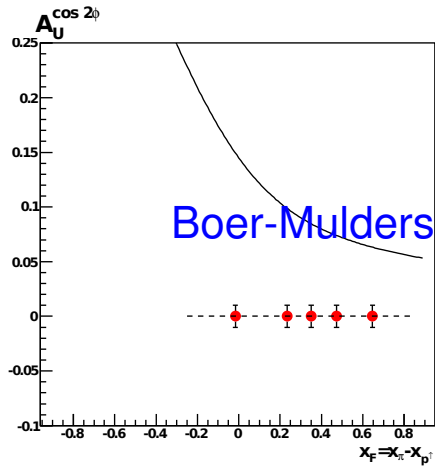
– 3 days of data taking
– $8 \cdot 10^7 \pi^-$/9.6 s spill
– 2 cells of CH_2 of 40-20-40 cm
– temporary absorber
– simple trigger

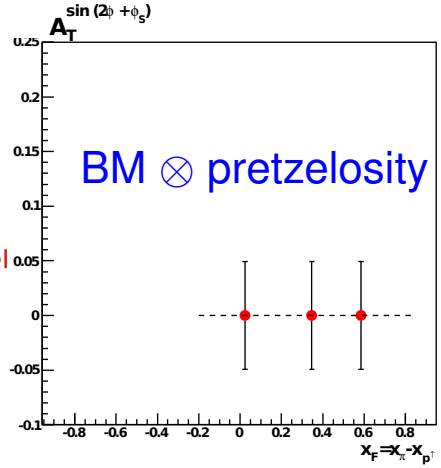
Drell–Yan @ COMPASS: Projections for azimuthal asymmetries

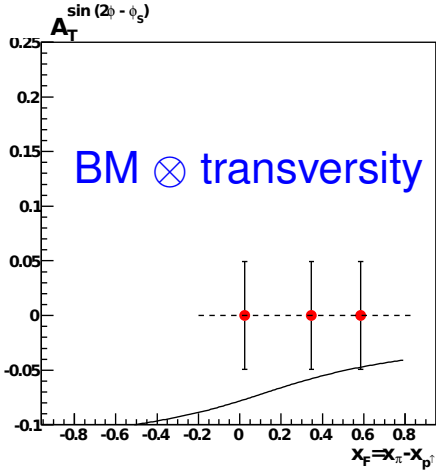
- projections for 4 GeV/$c^2 < M_{\mu\mu} <$ 9 GeV/c^2
- 2 years of data taking
- $6{\cdot}10^8$ pions /9.6 s spill
- 1.1 m long, polarised NH_3 target











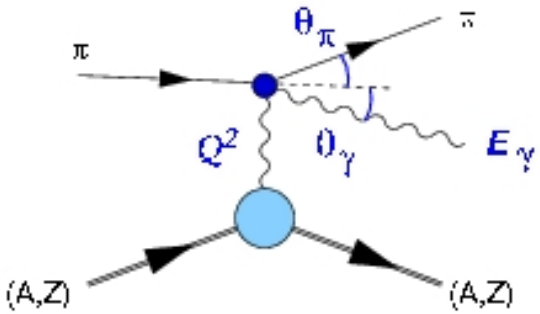
Goals: change of sign between DIS and SIDIS in $h_1^\perp$,
J/Ψ production mechanism,...

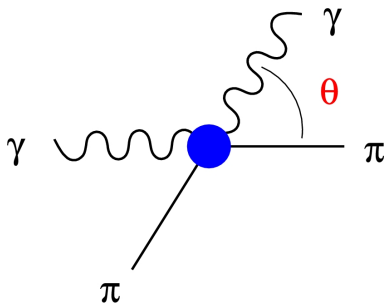
Future Drell–Yan experiments

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	*cancelled*
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

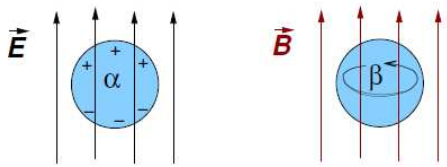
Primakoff ($\pi^- Z \to \pi^- Z\gamma$) and Compton ($\pi\gamma \to \pi\gamma$) processes





- 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

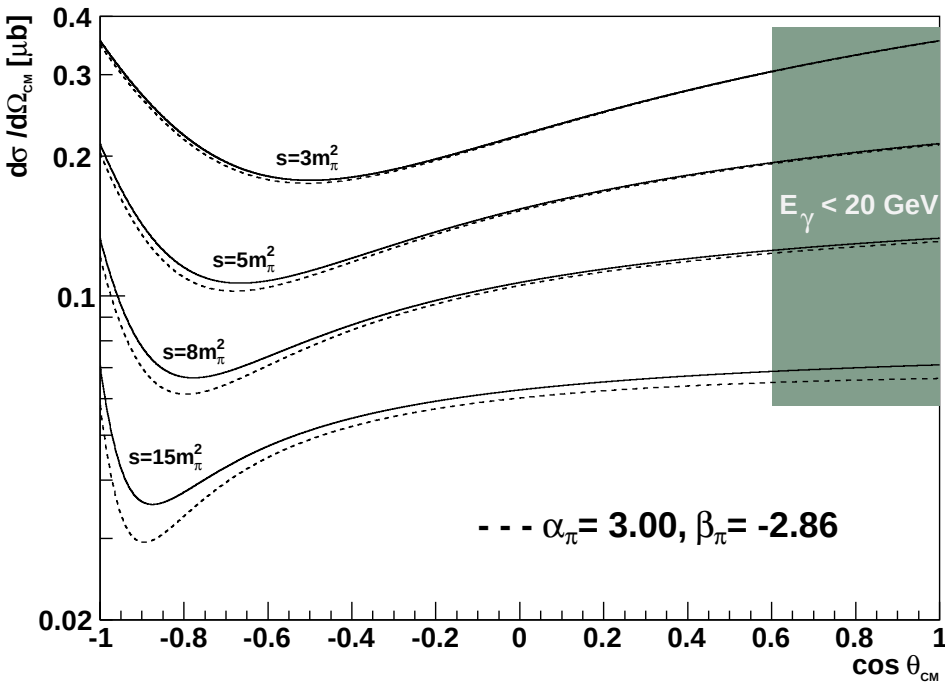
$$\frac{\mathrm{d}\sigma_{\pi\gamma}}{\mathrm{d}\Omega_{\mathrm{cm}}} = \left[\frac{\mathrm{d}\sigma_{\pi\gamma}}{\mathrm{d}\Omega_{\mathrm{cm}}}\right]_{\mathrm{point-like}} + C\frac{s - m_\pi^2}{s^2} P\left(\alpha_\pi, \beta_\pi\right)$$



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

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 for COMPASS II

Proposal: CERN–SPSC–2010–014 (SPSC–P–340) of May 17, 2010
Approved in December 2010, initially 3 years data taking, 2014-16 (Phase 1)
wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf

- 2012 setup and tests: Primakoff with π, K beams, 8 weeks
  $\Longrightarrow$ test of χPT;
  DVCS with μ^+, μ^- beams on unpolarised protons, 4 weeks;
- 2013 SPS shutdown; polarised target installation;
- 2014 Drell-Yan with π beam $\Longrightarrow$ TMD;
- 2015 DVCS with μ^+, μ^- beams on unpolarised protons,
  – 2016 $\Longrightarrow$ constrain GPD H and t-slope parameter B.
  Parallely SIDIS $\Longrightarrow$ PDF, TMD, FF (especially for s-quark).
- $\geq$2017 Addendeum ??? DVCS with μ^+, μ^- beams on $\perp$ polarised protons
  $\Longrightarrow$ constrain GPD E (Phase 2).

First we were thirsty...

...then we were curious...

...and started investigating nature...

...which brought us wings...

...and we became happy...

...and we became happy...

...and we became happy...

Thanks to Cyprus...

...and to Christophe!