

Status and Future of COMPASS

Polarized Drell-Yan → TMDs universality

Unpolarized SIDIS → TMDs + FFs + flavor separation

DVCS and DVMP → GPDs & Nucleon tomography

Primakoff scattering and π **polarizabilities** measurement



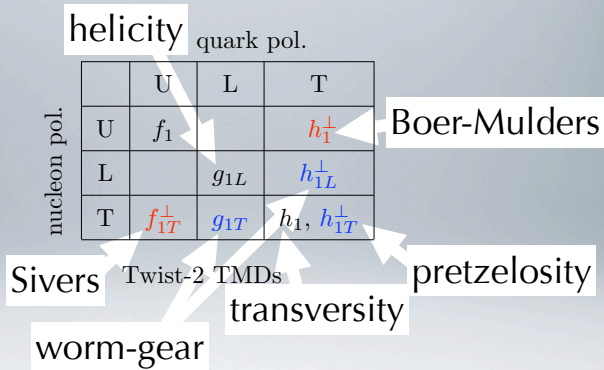
A. Ferrero (CEA/Saclay/SPhN)

Fall Meeting of the GDR PH-QCD

Orsay, 20 October 2011



The present picture of the nucleon

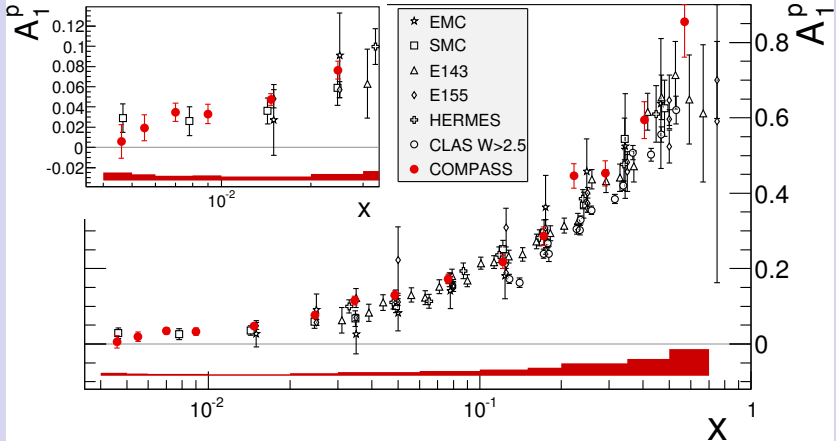


$f_1, g_{1L}, h_1, f_{1T}^\perp \rightarrow$ **need of high precision data + flavor separation**

$h_{1T}^\perp, g_{1T}, h_{1L}^\perp, h_1^\perp \rightarrow$ **unknown or poorly known**

COMPASS Results

A_1^p Asymmetry

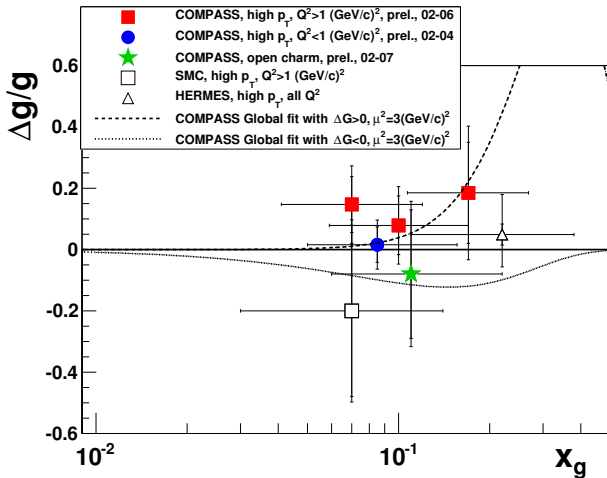


$f_1, g_{1L}, h_1, f_{1T}^\perp \rightarrow$ need of high precision data + flavor separation

$h_{1T}^\perp, g_{1T}, h_{1L}^\perp, h_1^\perp \rightarrow$ unknown or poorly known

COMPASS Results

$\Delta G/G$ from high- p_T and open charm



$f_1, g_{1L},$

$h_{1T}^\perp, g_{1T}, h_{1L}^\perp, h_1^\perp \rightarrow$ unknown or poorly known

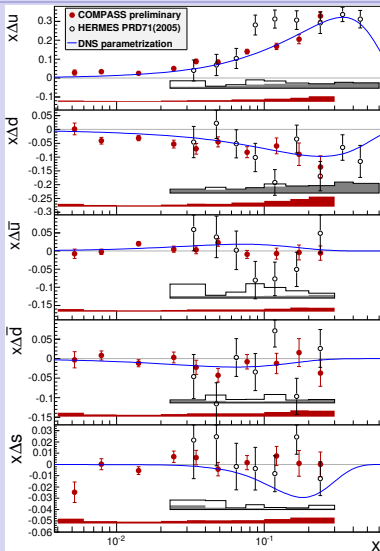
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COMPASS Results

Flavor Separation



$f_1, g_{1L},$

$h_{1T}^\perp, g_{1T}^\perp$

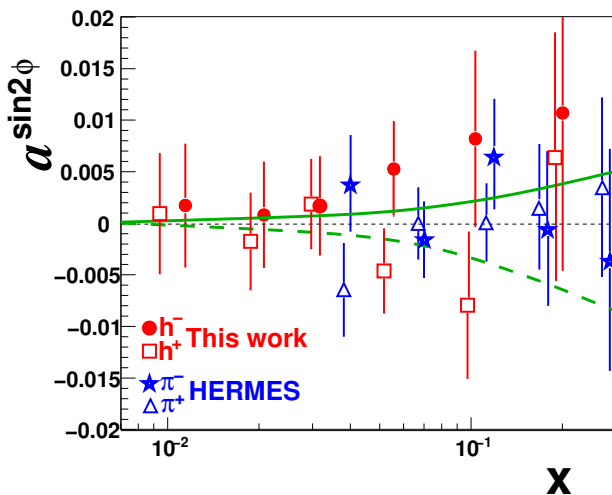
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COMPASS Results

$\sin(2\phi)$ modulation of h^\pm production



$f_1, g_{1L},$

$h_{1T}^\perp, g_{1T}, u_{1L}, u_1 \rightarrow$ unknown or poorly known

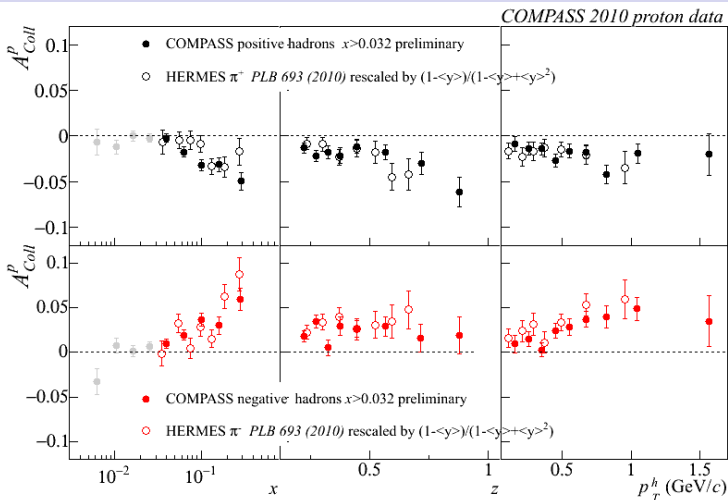
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COMPASS Results

Collins Asymmetry - 2010 proton data

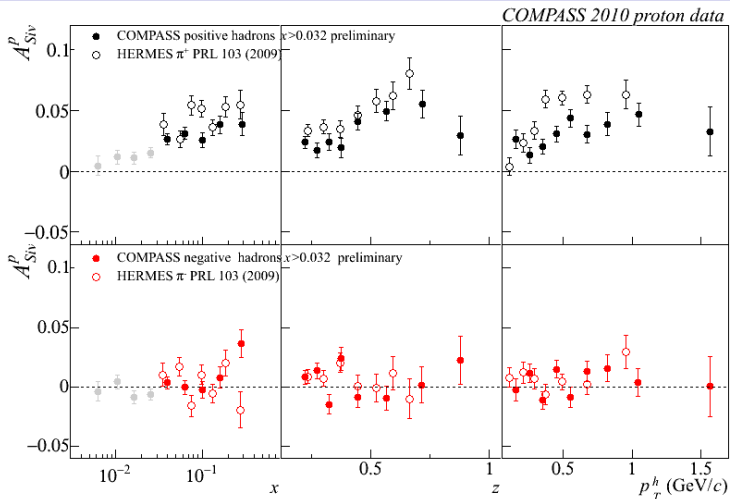


f_1, g

h_{1T}^\perp

COMPASS Results

Sivers Asymmetry - 2010 proton data

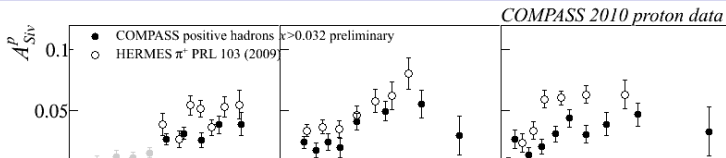


f_1, g

h_{1T}^\perp

COMPASS Results

Sivers Asymmetry - 2010 proton data



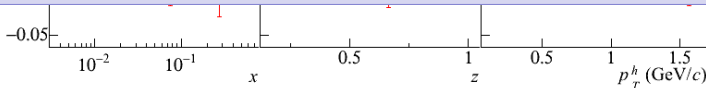
Next phase: 2D partonic structure



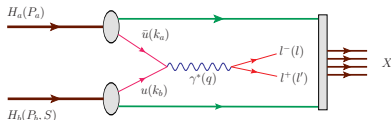
TMDs & GPDs

f_1, g

$h_{1T}^\perp,$



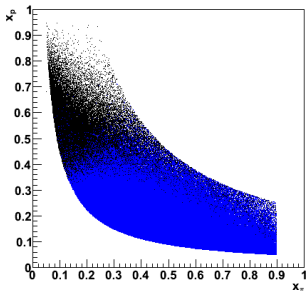
Drell-Yan with π^- beam and transversely polarized protons:



COMPASS: 190 GeV π^- beam (up to $6 \cdot 10^8$ π /spill)
Transversely polarized NH_3 target

- Large acceptance for valence region (where SSA are expected to be large)
- σ^{DY} dominated by \bar{u}/u annihilation

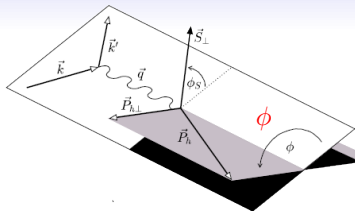
$$\sigma^{DY} \propto f_{\bar{u}|\pi} \otimes f_{u|p}$$



SIDIS \rightarrow convolution of TMDs with FFs
DY \rightarrow convolution of two TMDs

\rightarrow Complementary information
Universality test

- Expansion according to LO quark parton model
- 4 TMDs giving rise to azimuthal modulations:
 - Transversity, Sivers, Boer-Mulders, Pretzelosity
- Convolved with f_1 or Boer-Mulders distributions of the beam pion



$$d\sigma(\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X) = 1 + \bar{h}_1^\perp \otimes h_1^\perp \cos 2\phi$$

$$+ |S_T| \left[\bar{f}_1 \otimes f_{1T}^\perp \sin \phi_S \right.$$

$$+ \bar{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi + \phi_S)$$

$$\left. + \bar{h}_1^\perp \otimes h_1 \sin(2\phi - \phi_S) \right]$$

$$\rightarrow (\text{B.-M.})_\pi \otimes (\text{B.-M.})_p$$

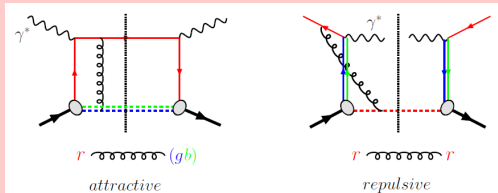
$$\rightarrow (f_1)_\pi \otimes (\text{Sivers})_p$$

$$\rightarrow (\text{B.-M.})_\pi \otimes (\text{Pretz.})_p$$

$$\rightarrow (\text{B.-M.})_\pi \otimes (\text{Transv.})_p$$

The T-odd character of the Sivers and Boer-Mulders functions implies that their characteristics are process-dependent

In order not to vanish by time-reversal invariance the SSAs require an initial (DY) or final (SIDIS) state interaction of the struck parton



We expect an **opposite sign** in SIDIS and DY:

Sivers:

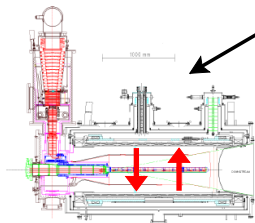
$$f_{1T}^\perp(\text{SIDIS}) = -f_{1T}^\perp(\text{DY})$$

Boer-Mulders:

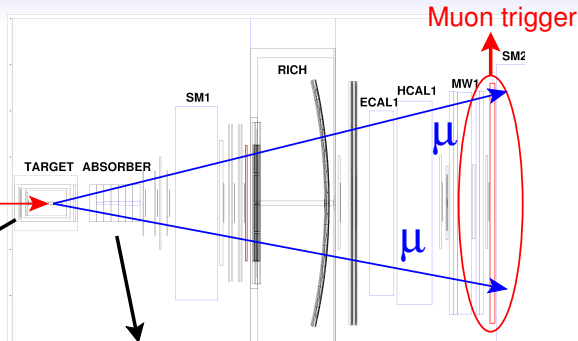
$$h_1^\perp(\text{SIDIS}) = -h_1^\perp(\text{DY})$$

Crucial test of the factorization approach

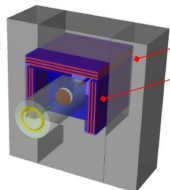
π^- beam:
190 GeV
up to $6 \cdot 10^8 \pi^-$ /spill



NH_3 , 2 oppositely polarized cells
 $\sim 90\%$ polarization
 $\sim 15\%$ dilution factor



RICH1, Calorimetry: PID & background reduction



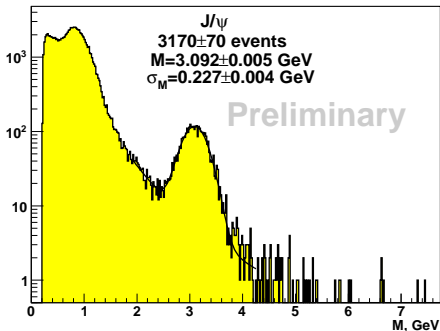
Hadron absorber



Prototype hadron absorber
Solid CH₂ target

π^- beam up to $1.5 \cdot 10^8 \pi/\text{spill}$

COMPASS DY beam test 2009

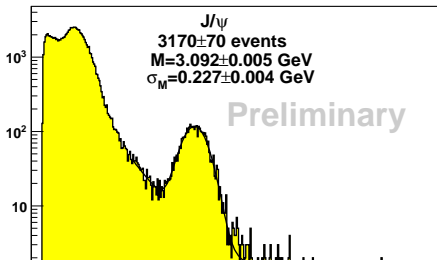




Prototype hadron absorber
Solid CH₂ target

π^- beam up to $1.5 \cdot 10^8 \pi/\text{spill}$

COMPASS DY beam test 2009



expected: 3600 \pm 600 J/ψ and 110 \pm 22 DY

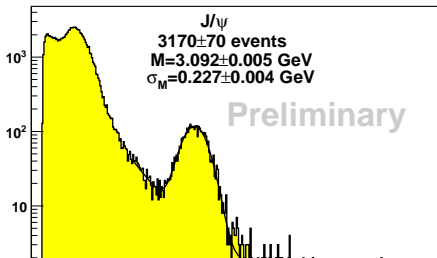
measured: 3170 \pm 70 J/ψ and 84 \pm 10 DY



Prototype hadron absorber
Solid CH₂ target

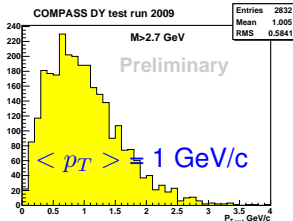
π^- beam up to $1.5 \cdot 10^8 \pi/\text{spill}$

COMPASS DY beam test 2009



expected: 3600±600 J/ψ and 110±22 DY

measured: 3170±70 J/ψ and 84±10 DY

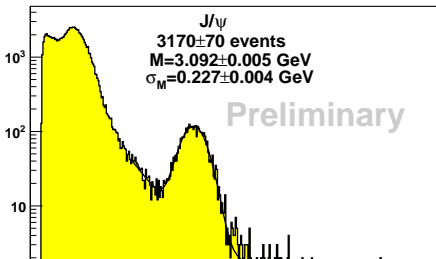




Prototype hadron absorber
Solid CH₂ target

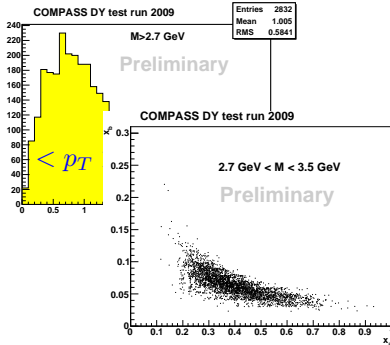
π^- beam up to $1.5 \cdot 10^8 \pi/\text{spill}$

COMPASS DY beam test 2009



expected: 3600 ± 600 J/ ψ and 110 ± 22 DY

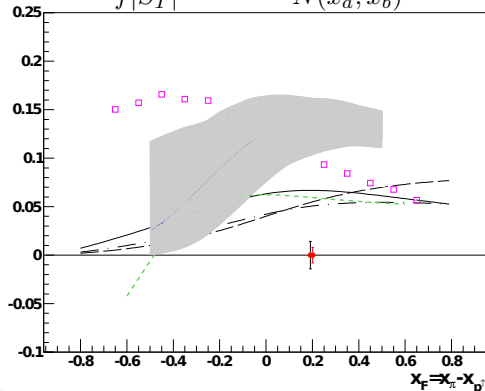
measured: 3170 ± 70 J/ ψ and 84 ± 10 DY



$A_T^{\sin \phi_S}$ (Sivers) SSA in the safe dimuon mass region $4 < M_{\mu\mu} < 9$ GeV

2 years data taking
 $6 \cdot 10^8$ π /spill (of 9.6s)
 1.1m transv pol. NH_3 target
Lumi=1.2 · 10³² cm⁻²s⁻¹

$$A_T^{\sin \phi_S} = \frac{2}{f|S_T|} \frac{\int d\phi_S d\phi \frac{dN(x_a, x_b, \phi, \phi_S)}{d\phi d\phi_S} \sin \phi_S}{N(x_a, x_b)}$$



blue line with grey band:

Anselmino et al., PRD79 (2009)

Black solid and dashed:

Efremov et al., PLB612 (2005)

Black dot-dashed:

Collins et al., PRD73 (2006)

Squares:

Bianconi et al., PRD73 (2006)

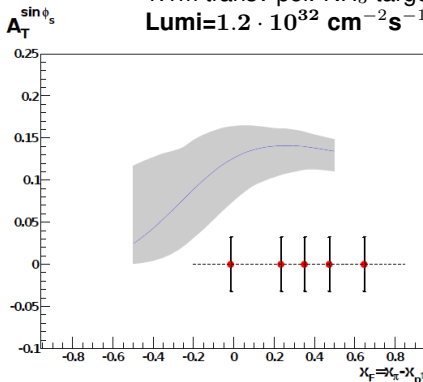
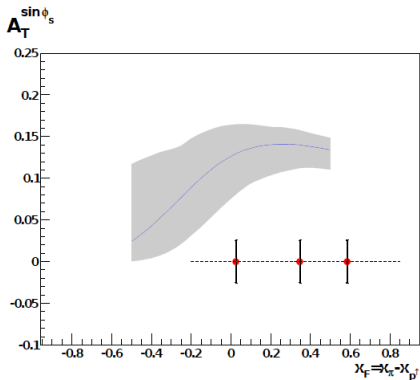
Green short-dashed:

Bacchetta et al., PRD78 (2008)

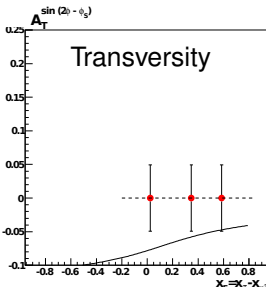
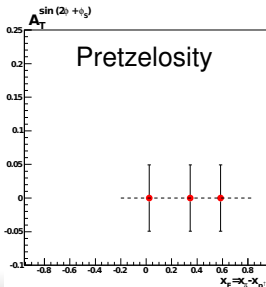
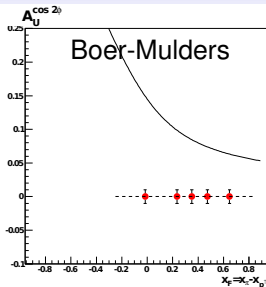
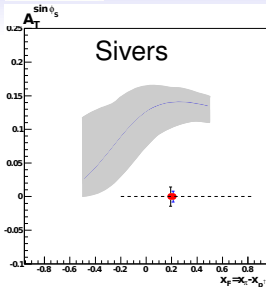
**CHECK OF SIDIS ↔ DY
SIGN CHANGE**

$A_T^{\sin \phi_S}$ (Sivers) SSA in the safe dimuon mass region $4 < M_{\mu\mu} < 9$ GeV

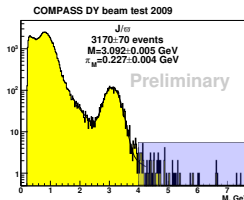
2 years data taking
 $6 \cdot 10^8$ π /spill (of 9.6s)
 1.1m transv pol. NH₃ target
Lumi= $1.2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$



- Binning in x_F feasible
- Access to larger x_F values compared to SIDIS

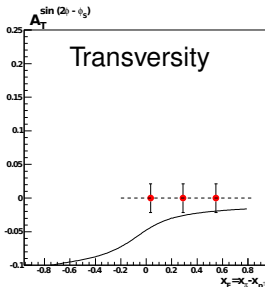
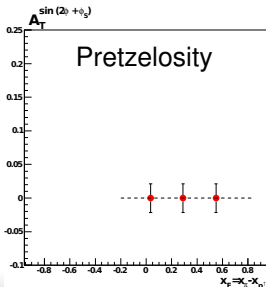
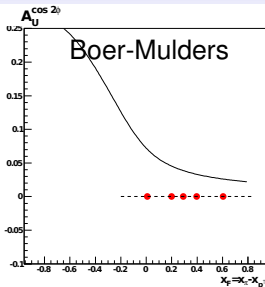
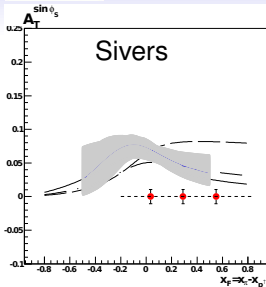


“Safe” mass region
 $4 < M_{\mu\mu} < 9 \text{ GeV}$

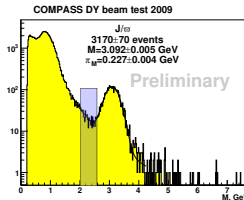


Negligible background
 low cross-section

2 years data taking
 $6 \cdot 10^8 \pi/\text{spill}$ (of 9.6s)
 1.1m transv pol. NH_3 target
 $\text{Lumi} = 1.2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$



Low mass region
 $2 < M_{\mu\mu} < 2.5 \text{ GeV}$



High statistics

large combinatorial
 background (S/B ~ 1)

2 years data taking
 $6 \cdot 10^8 \pi/\text{spill}$ (of 9.6s)
 1.1m transv pol. NH_3 target
Lumi = $1.2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

160 GeV muon beam and unpolarized proton target

Goal: significant progress in the extraction of **unpolarized PDFs and FFs**

$$\text{Hadron multiplicities at LO: } \frac{dN^{\mathbf{h}}(x, z, Q^2)}{dN^{DIS}} = \frac{\sum_q e_q^2 q(x, Q^2) D_q^{\mathbf{h}}(z, Q^2)}{\sum_q e_q^2 q(x, Q^2)}$$

COMPASS: proton target and high-perf. PID (RICH + calorimeters)

$\mathbf{h} = K^+, K^-, K^0, \pi^+, \pi^-, \pi^0, \Lambda, \dots \rightarrow$ flavor separation

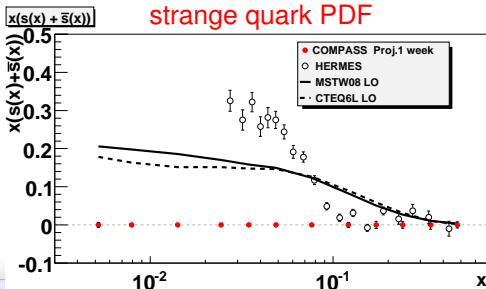
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Projection for 1 week
with 2.5m LH₂ target

160 GeV muon beam and unpolarized proton target

Goal: significant progress in the extraction of **unpolarized PDFs and FFs**

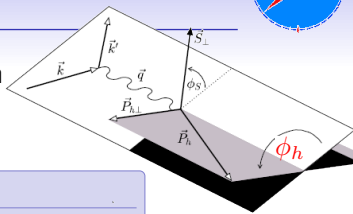
Hadron multiplicities at LO:
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COMPASS: proton target and high-perf. PID (RICH + calorimeters)

$\mathbf{h} = K^+, K^-, K^0, \pi^+, \pi^-, \pi^0, \Lambda, \dots \rightarrow$ flavor separation

Final goal: extensive measurement and fine binning in (x, Q^2, z, p_T, \dots) to provide input to NLO global analysis for PDFs and FFs

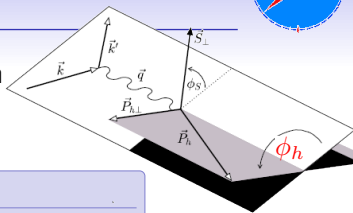
Azimuthal asymmetries in unpolarized SIDIS can reveal quark transverse momentum (k_{\perp}) effects beyond the collinear approximation



Unpolarized cross-section:

$$\frac{d\sigma}{dx dy d\phi} \propto F_{UU} + \epsilon_1 \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon_2 \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + \lambda_\mu \epsilon_3 \sin \phi_h F_{LU}^{\sin \phi_h}$$

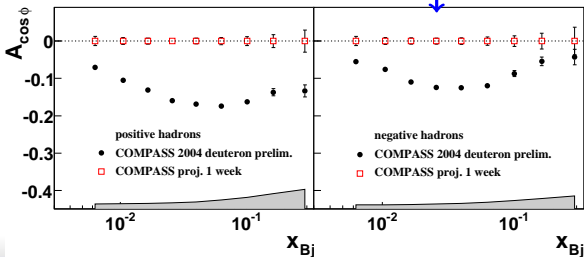
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Unpolarized cross-section:

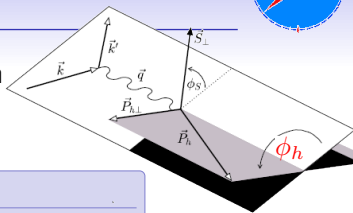
$$\frac{d\sigma}{dx dy d\phi} \propto F_{UU} + \epsilon_1 \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon_2 \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + \lambda_{\mu} \epsilon_3 \sin \phi_h F_{LU}^{\sin \phi_h}$$

Cahn effect \rightarrow info on k_{\perp}



- Compass projected: 1 week 2.5m LH₂ target
- 2004 Compass deuteron 4 weeks

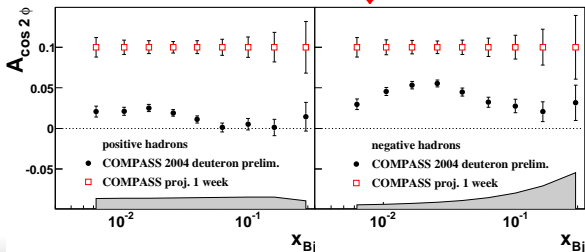
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↓ Boer-Mulders TMD ⊗ Collins FF + Cahn effect



- Compass projected:
1 week 2.5m LH₂ target
- 2004 Compass deuteron
4 weeks



Polarized Drell-Yan experiment @ COMPASS:

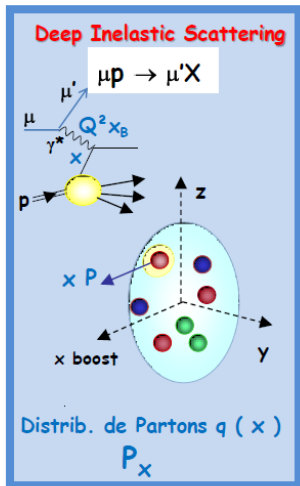
- TMDs universality SIDIS \leftrightarrow DY
- Sivers and Boer-Mulders sign in DY
- Study of J/Ψ production mechanism

DY experiment feasibility proven by 2009 test data

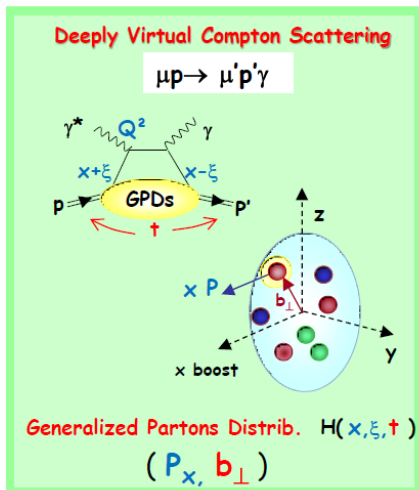
- J/Ψ and DY yields as expected
- Radioprotection scheme validity proven

High statistics sample of unpol. μp scattering data

- Identified hadron multiplicities \rightarrow light and strange quark PDFs and FFs
- Azimuthal asymmetries \rightarrow TMDs
- Data collected in parallel to GPDs program



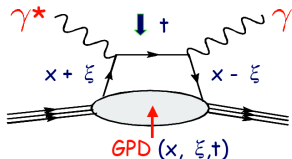
**Observation of the Nucleon Structure
in 1 dimension**



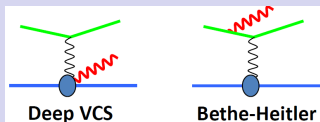
in 1+2 dimensions

GPDs can be probed in hard exclusive reactions,
like **Deeply Virtual Compton Scattering (DVCS)**

$$Q^2 \gg 1 \text{ GeV}^2 \quad -t < 1 \text{ GeV}^2$$

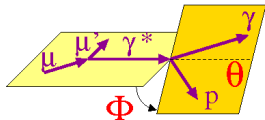


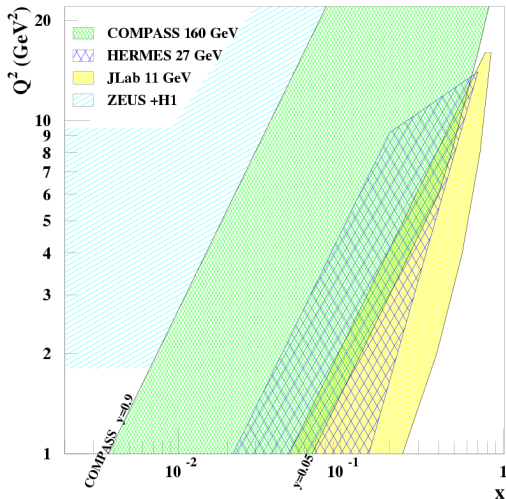
The total cross-section is the coherent sum of DVCS and BH



For polarized beam and unpolarized target:

$$d\sigma_{\mu p \rightarrow \mu p \gamma} = d\sigma^{\text{BH}} + d\sigma_{\text{unpol}}^{\text{DVCS}} + \mathbf{P}_\mu d\sigma_{\text{pol}}^{\text{DVCS}} + e_\mu \text{Re}(\mathbf{I}) + e_\mu \mathbf{P}_\mu \text{Im}(\mathbf{I})$$





CERN high energy muon beam

- 100 - 190 GeV
- 80% polarization
- μ^+ and μ^- beams with opposite polarization

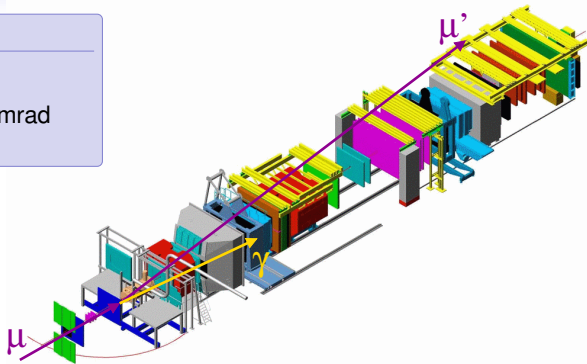
- Uncovered region between ZEUS+H1 and HERMES+Jlab before new colliders may be available

- low x_B : pure BH (useful for normalization)

high x_B : DVCS predominance

ECAL2

- 3000 channels
- ~ 0 mrad to ~ 40 mrad acceptance



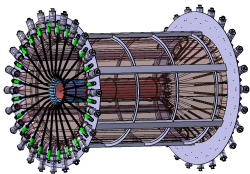
Beam

- 100-190 GeV
- 80% polarization
- μ^+ and μ^- with opposite polarization

ECAL1

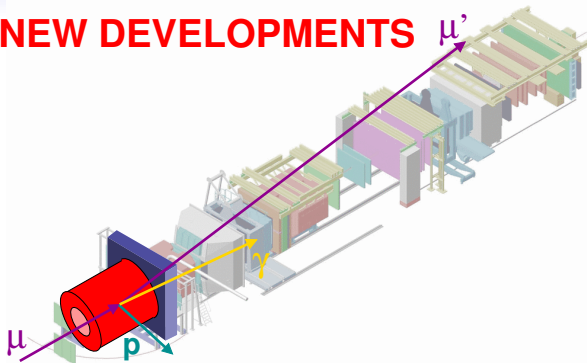
- 1500 channels
- ~ 40 mrad to ~ 150 mrad acceptance

Future Target & RPD

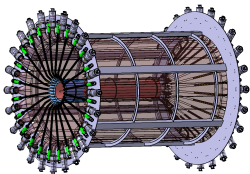


- **2.5m** long **LH2** target
- **4m** long TOF barrel
- recoil proton ID by **TOF** and **dE/dx**
- GANDALF boards:
1 GHz digitization
ENOB: **12bit**

NEW DEVELOPMENTS

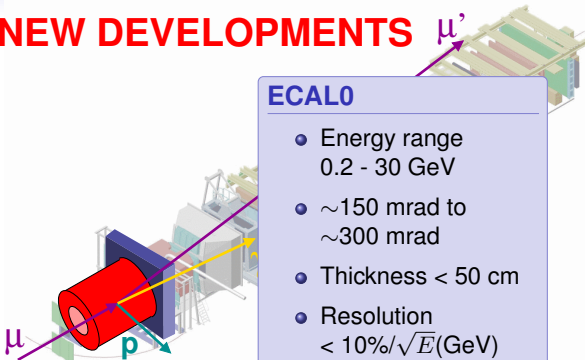


Future Target & RPD



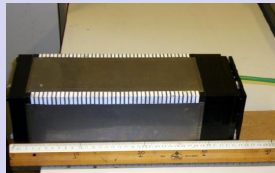
- 2.5m long LH2 target
- 4m long TOF barrel
- recoil proton ID by TOF and dE/dx
- GANDALF boards:
1 GHz digitization
ENOB: 12bit

NEW DEVELOPMENTS

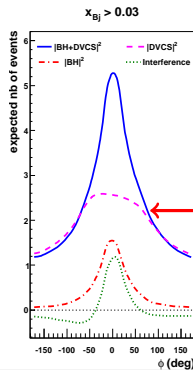
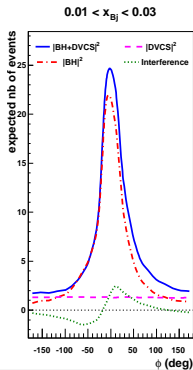
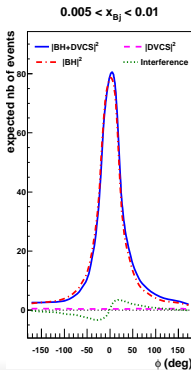


ECAL0

- Energy range
0.2 - 30 GeV
- ~ 150 mrad to
 ~ 300 mrad
- Thickness < 50 cm
- Resolution
< $10\%/\sqrt{E}(\text{GeV})$



$$d\sigma \propto |T^{BH}|^2 + \text{Int. Term} + |T^{DVCS}|^2$$



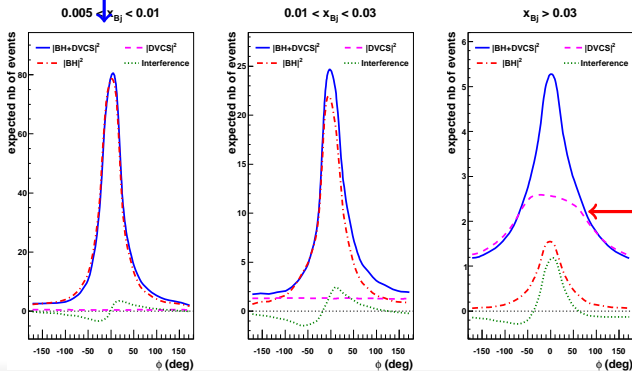
Monte-Carlo simulation for COMPASS set-up with only ECAL1+2

Missing DVCS acceptance without ECAL0

$$d\sigma \propto |T^{BH}|^2 + \text{Int. Term} + |T^{DVCS}|^2$$

BH dominance at low- x_B

Excellent reference yield and control signal



Monte-Carlo simulation for COMPASS set-up with only ECAL1+2

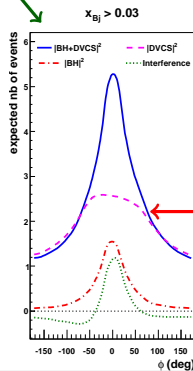
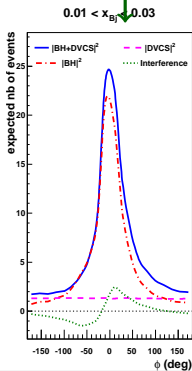
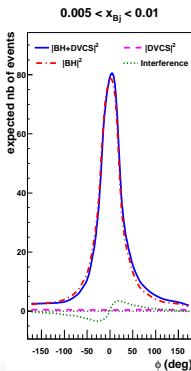
Missing DVCS acceptance without ECAL0

$$d\sigma \propto |T^{BH}|^2 + \text{Int. Term} + |T^{DVCS}|^2$$

Int. term \rightarrow access to $\text{Re}(T^{DVCS})$ and $\text{Im}(T^{DVCS})$

$\text{Re}(T^{DVCS}) \rightarrow P \int dx H(x, \xi, t)/(x - \xi)$

$\text{Im}(T^{DVCS}) \rightarrow H(x = \xi, \xi, t)$



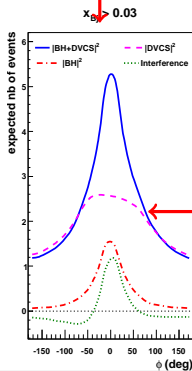
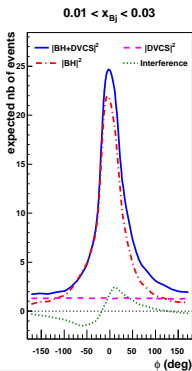
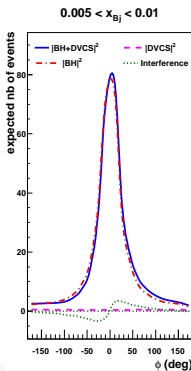
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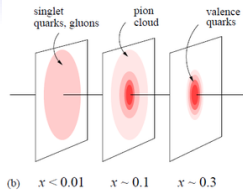
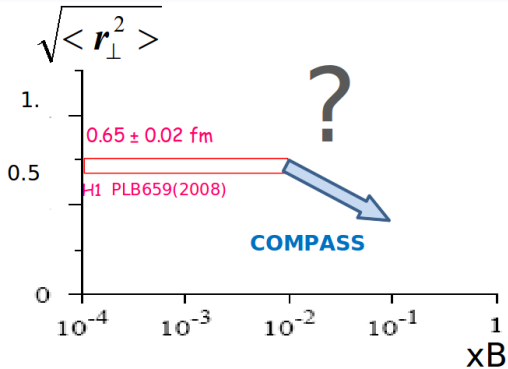
DVCS dominance at large- x_B

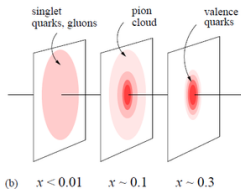
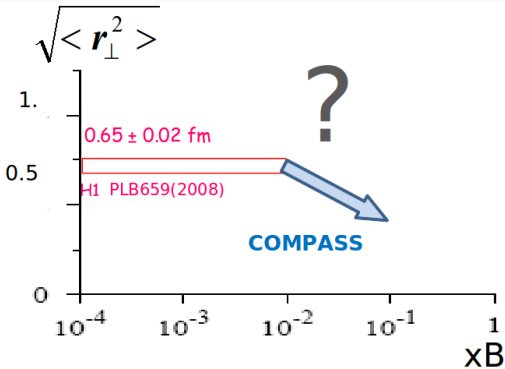
Transverse nucleon imaging ($d\sigma^{DVCS}/dt \sim \exp(-B|t|)$)



Monte-Carlo simulation for COMPASS set-up with only ECAL1+2

Missing DVCS acceptance without ECAL0

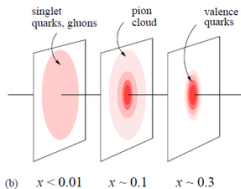
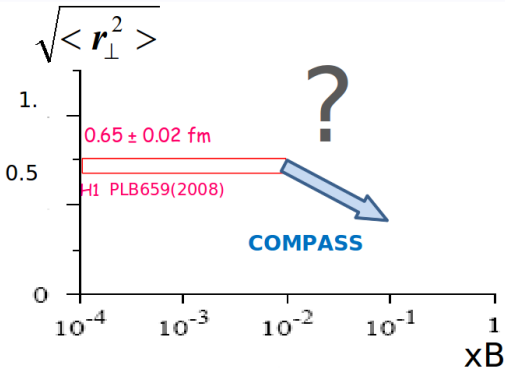




$$d\sigma^{\text{DVCS}}/dt \sim \exp(-B|t|)$$

$$B(x_B) = 1/2 \langle r_{\perp}^2(x_B) \rangle$$

$r_{\perp} \rightarrow$ **Transverse size
of the Nucleon**



$$d\sigma^{\text{DVCS}}/dt \sim \exp(-B|t|)$$

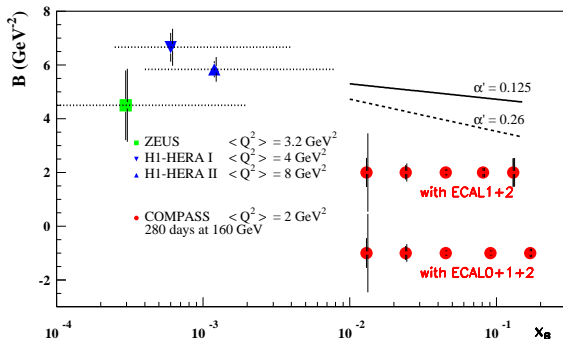
$$B(x_B) = 1/2 \langle r_{\perp}^2(x_B) \rangle$$

$r_{\perp} \rightarrow$ **Transverse size of the Nucleon**

The transverse size r_{\perp} as function of x_B can be extracted in a model-independent way from the **t-slope** of the measured DVCS cross-section \rightarrow **"Nucleon Tomography"**

$$S_{CS,U} \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \propto d\sigma^{BH} + d\sigma_{unpol}^{DVCS} + e_{\mu} P_{\mu} \text{Im}(I)$$

Integrating $S_{CS,U}$ over ϕ and after subtraction of the BH contribution one obtains $d\sigma^{DVCS}/dt \sim \exp(-B|t|)$



COMPASS Projected:

- 2 years of data
- eff = 10%
- lumi = $\sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

Ansatz at small x_B :

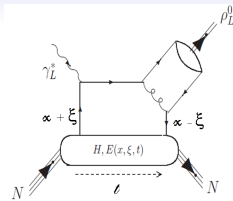
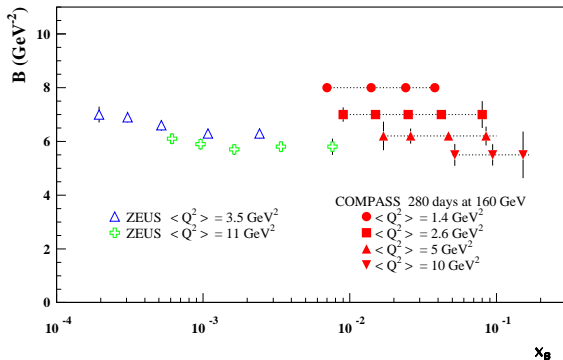
$$B(x_B) = B_0 + 2\alpha' \ln(x_0/x_B)$$

α' slope of Regge traject

Accuracy $\geq 2.5\sigma$ if
 $\alpha' > 0.125$ and full ECALs

Systematic errors dominated by **BH subtraction** at low x_B

$$d\sigma^{\text{DVMP}}/dt \sim \exp(-B|t|)$$



Red points:

COMPASS ρ^0 projected

- 2 years of data
- eff = 10%
- lumi = $\sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

We are sensitive to the Nucleon size + the transv. meson size

$$Q^2 = 1 \text{ GeV}^2 \quad B \sim 8 \text{ GeV}^{-2}$$

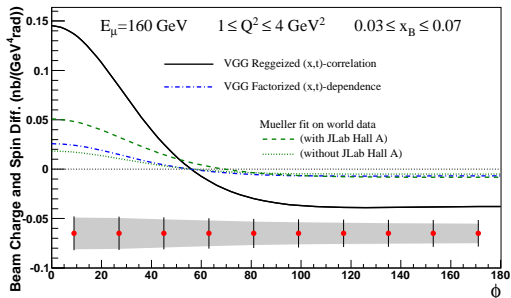
$$Q^2 = 10 \text{ GeV}^2 \quad B \sim 5.5 \text{ GeV}^{-2}$$



$$d\sigma_{\mu p \rightarrow \mu p \gamma} = d\sigma^{\text{BH}} + d\sigma_{\text{unpol}}^{\text{DVCS}} + P_{\mu} d\sigma_{\text{pol}}^{\text{DVCS}} + e_{\mu} \text{Re}(\mathbf{I}) + e_{\mu} P_{\mu} \text{Im}(\mathbf{I})$$

$$d\sigma_{\mu p \rightarrow \mu p \gamma} = d\sigma^{\text{BH}} + d\sigma_{\text{unpol}}^{\text{DVCS}} + P_{\mu} d\sigma_{\text{pol}}^{\text{DVCS}} + e_{\mu} \text{Re}(\mathbf{I}) + e_{\mu} P_{\mu} \text{Im}(\mathbf{I})$$

Combine μ^{+} and μ^{-} data with opposite beam polarizations



Example: $d\sigma_{\mu^{+\downarrow}} - d\sigma_{\mu^{-\uparrow}}$

$$D_{\text{CS,U}} \equiv d\sigma_{\mu^{+\downarrow}} - d\sigma_{\mu^{-\uparrow}} \propto c_0^{\text{Int}} + c_1^{\text{Int}} \cos(\phi)$$

$$c_{0,1}^{\text{Int}} \propto \text{Re}(\mathbf{F}_1 \mathcal{H})$$

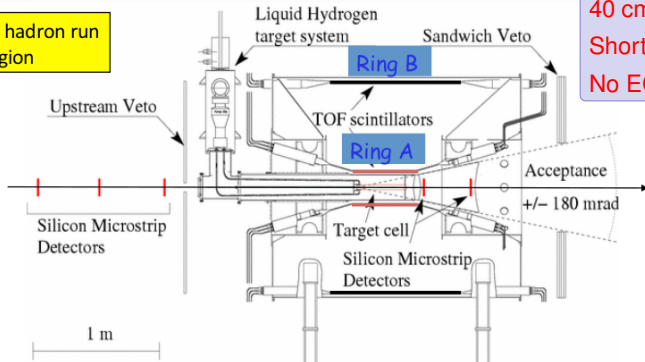
Red points: **COMPASS Projected**

- 2 years of data
- eff = 10%
- lumi = $\sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

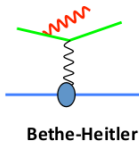
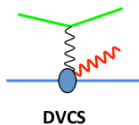
$\text{Re}\mathcal{H}(\xi, t)$ and $\text{Im}\mathcal{H}(\xi, t) \rightarrow$ **Exp. constrain to GPD \mathcal{H} !**

Syst. error: 3% charge-dependent effect between μ^{+} and μ^{-}

Compass hadron run
Target region



40 cm LH2 target
Short RPD
No ECAL0



Selection of events :

- one vertex with μ and μ'
- no other charged tracks
- only 1 high energy photon ($\Delta t < 5\text{ns}$)
- 1 proton in RPD with $p < 1. \text{GeV}/c$

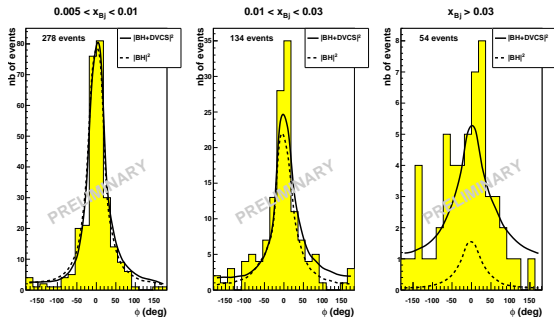
2008: observation of exclusive single photon production

confirmed $\epsilon_{global} \simeq 10\%$ assumed in simulations

2009: observation of BH and DVCS events

Comparison of MC simulation (solid & dashed lines) with data

MC yield normalized to low- x_B bin (where BH dominates)



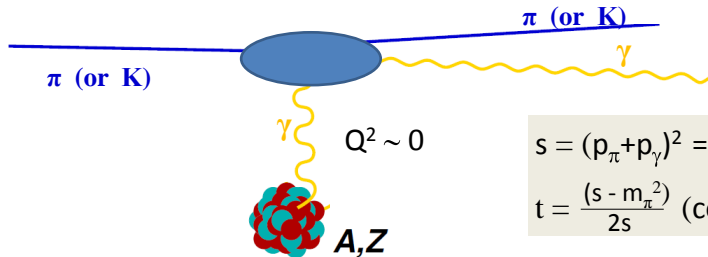
Excess of data
at $x_B > 0.03$
is a sign for DVCS

- COMPASS-II will investigate quark GPDs through DVCS
 - **Intermediate x_B regime** not accessible to present or planned facilities in the near future
 - Two beam charges available with opposite polarizations
access to real and imaginary parts of DVCS amplitude

Constrain **GPD H** through ϕ dependence of $D_{CS,U}$ and $S_{CS,U}$

- Nucleon **transversal dimension** as function of x_B
("Nucleon Tomography")
- Complementary information from exclusive meson production
- In a second phase, constrain of **GPD E** by using a transversely polarized target

Primakoff experiments with π , K or inverse Compton Scattering on π , K



$$s = (p_\pi + p_\gamma)^2 = (\pi\gamma \text{ CM energy})^2$$

$$t = \frac{(s - m_\pi^2)}{2s} (\cos \vartheta_{\text{cm}} - 1)$$

The chiral perturbation theory (ChPT) predicts the low-energy behavior of the cross section with s varying from threshold (m_π^2) to a few m_π^2

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

Deviation due to π polarisabilities

the point-like cross section is measured with the muon beam

Summary for Primakoff @ COMPASS

6

$\alpha_\pi, \beta_\pi, \alpha_2 - \beta_2$ polarisabilities measured for the first time in $\gamma + \pi \rightarrow \pi + \gamma$

in 120 days 90 days for π beam 30 days for μ beam	$\alpha_\pi - \beta_\pi$ in 10^{-4} fm^3	$\alpha_\pi + \beta_\pi$ in 10^{-4} fm^3	$\alpha_2 - \beta_2$ in 10^{-4} fm^5
2-loop ChPT prediction	5.70 ± 1.0	0.16 ± 0.10	16
experimental accuracy	± 0.66	± 0.025	± 1.94

→ clear sensitivity to ChPT parameters in COMPASS kinematics

in parallel: chiral anomaly F_3 in $\gamma + \pi \rightarrow \pi + \pi^0$

+ similar reactions induced by kaons



COMPASS-II Physics Topics:

- Chiral perturbation theory - soft QCD
- TMDs with Drell-Yan and SIDIS
- GPDs with DVCS and DVMP
- Precise unpolarized PDFs and FFs measurement



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**COMPASS-II Proposal approved by CERN
Research Board on 1st December 2010**



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COMPASS-II timelines as in proposal:

- 2012: Pion and kaon polarizabilities
- 2013: long SPS shutdown
- 2014-2016: GPDs + DY