COMPASS II: Experiment and Physiscs Program

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on behalf of the COMPASScollaboration

IWHSS2013

Erlangen, 22-24 Juillet 2013

Outline:

Primakoff scattering and π **polarizabilities** measurement

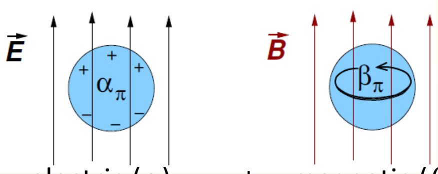
Polarized Drell-Yan → **TMDs universality**

Unpolarized SIDIS → **TMDs + FFs + flavor separation**

DVCS and DVMP → **GPDs & Nucleon tomography**

Measurement of Pion Polarizabilities @ COMPASS

Polarizabilities: deformation of the pion shape by an EM field



electric (α) and magnetic (β)

2-loop Ch PT predictions:

$\alpha_\pi + \beta_\pi = (0.2 \pm 0.1)10^{-4}\text{fm}^3$

$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0)10^{-4}\text{fm}^3$

Experiments:

$\alpha_\pi - \beta_\pi$ from 4 to 14 $\cdot 10^{-4}\text{fm}^3$

Inconclusive

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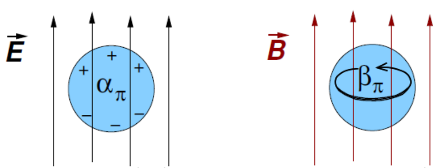

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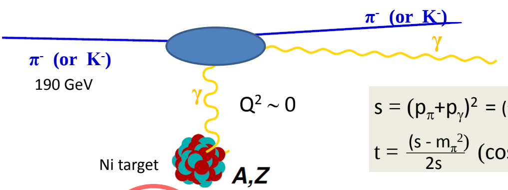
COMPASS: measurement via inverse Compton scattering



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

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

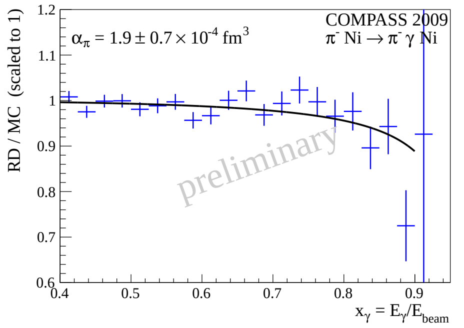
$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{CM}} = \left[\frac{d\sigma_{\pi\gamma}}{d\Omega_{CM}}\right]_{point-like} + C\frac{(s - m_\pi^2)}{s^2}\mathcal{P}(\alpha_\pi, \beta_\pi)$$

Deviation from point-like behaviour

Measured with muon beam

Polarizability results from 2009 data

$\pi^- \text{Ni} \to \pi^- \text{Ni}\, \gamma$



$\alpha_\pi - \beta_\pi$ extracted from the comparison with point-like MC

$$\boldsymbol{\alpha_\pi - \beta_\pi = (3.7 \pm 1.4_{stat} \pm 1.6_{syst}) \times 10^4\ \mathrm{fm}^3}$$

$\alpha_\pi = (1.9 \pm 0.7) \times 10^4\ \mathrm{fm}^3$

(assuming $\alpha_\pi + \beta_\pi = 0$)

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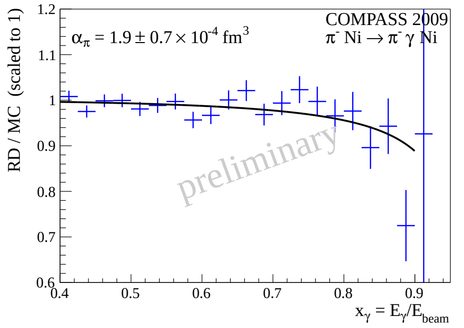
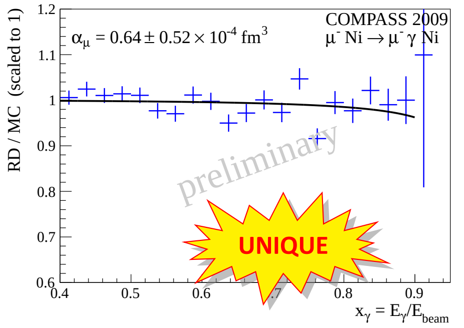


$\mu^- \mathrm{Ni} \rightarrow \mu^- \mathrm{Ni}\, \gamma$



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(assuming $\alpha_\pi + \beta_\pi = 0$)

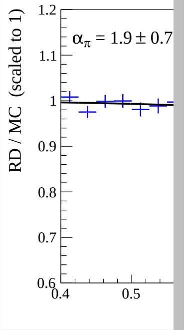
μ-beam control measurement with point-like beam particle

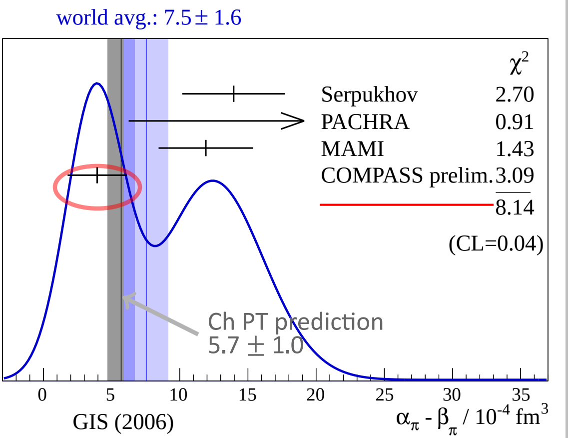
$\boldsymbol{\alpha_\mu = (0.64 \pm 0.52) \times 10^4\ \mathrm{fm}^3}$

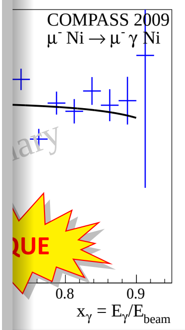
direct estimate of possible systematic uncertainties

Polarizability results from 2009 data

π^-N … Ni γ







$\alpha_\pi - \beta_\pi$ extract… …asurement
with point-like M… …n particle

$\boldsymbol{\alpha_\pi - \beta_\pi = (3.7}$ … $) \times \mathbf{10^4\ fm^3}$

$\alpha_\pi = (1.9 \pm 0.7$ … …ossible

(assuming α_π - … …nties

COMPASS result in agreement with ChPT prediction
Other dedicated measurements NOT CONFIRMED

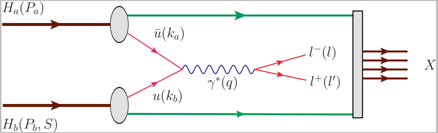
2012 data: 5-6 times larger statistics

access to $(\boldsymbol{\alpha_\pi + \beta_\pi})$ and $(\boldsymbol{\alpha_\pi - \beta_\pi})$

TMDs Studies with Polarized DY

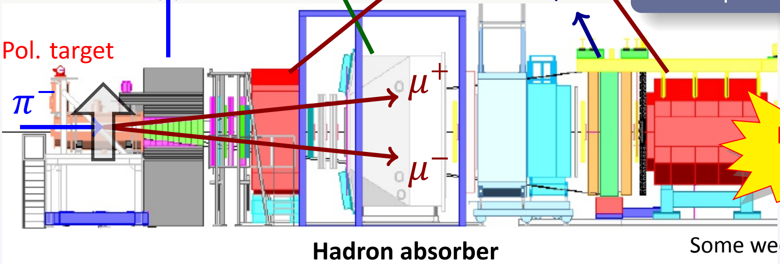
Drell-Yan with π^- beam and transversely polarized protons:

$$\pi^- p^\uparrow \rightarrow \mu^+\mu^- X$$



190 GeV π^-, 10^9 π/spill

Transv. polarized NH_3 target



Some weeks of pilot data to be collected end of 2014

New developments:

Hadron absorber

Scint. fiber vertex detector

Muon trigger in 1st spectrometer

TMDs Studies with Polarized DY

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

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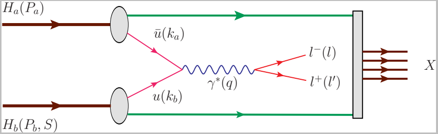
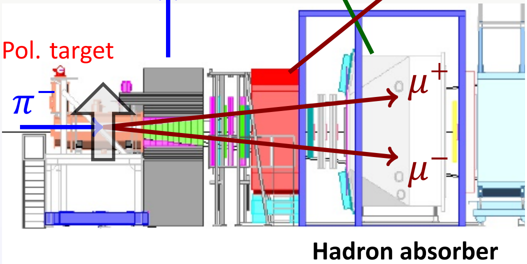
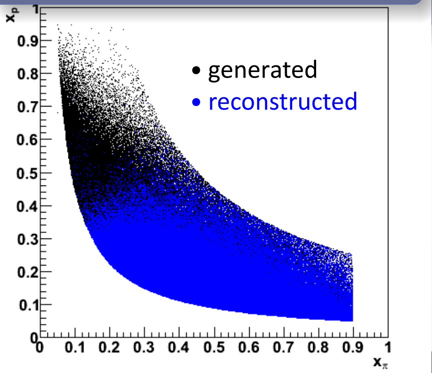




Large acceptance for valence region (where SSA are expected to be large)



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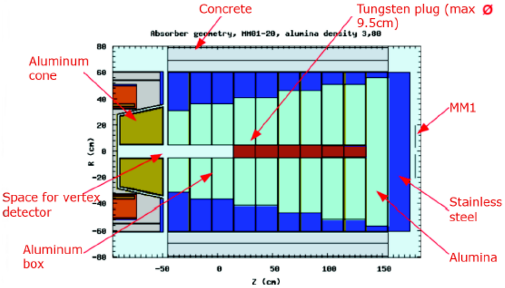
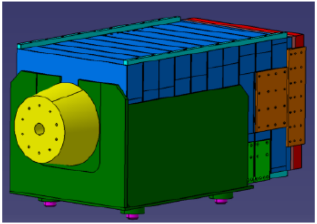
Hadron absorber

Scint. fiber vertex d

Muon trigger in 1st

The hadron absorber





Structure of the hadron absorber:

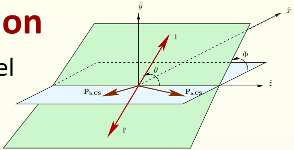
- 120cm tungsten beam plug
- aluminium conical part
- 200cm alumina (Al_2O_3)
- Stainless steel shielding sandwiches

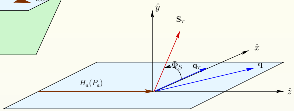
+ absorber surrounded by
2m of iron-free concrete on each side

Expansion of the DY cross-section

Expansion according to LO quark parton model

σ^{DY} dominated by $\bar{u}/u$ annihilation:





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

$$\begin{aligned} d\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) = 1 &+ \bar{h}_1^\perp \otimes h_1^\perp \cos 2\phi \\ &+ |S_T| \Big[\bar{f}_1 \otimes f_{1T}^\perp \sin\phi_S \\ &+ \bar{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi + \phi_S) \\ &+ \bar{h}_1^\perp \otimes h_1 \sin(2\phi - \phi_S) \Big] \end{aligned}$$

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

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

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

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

SIDIS → convolution of TMDs with FFs

DY → convolution of two TMDs

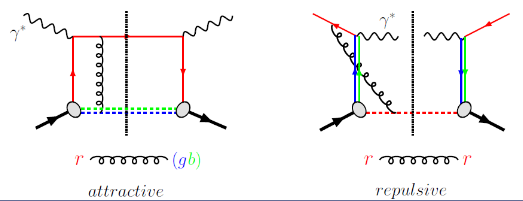
→ *Complementary information*

Universality test

TMDs: SIDIS ↔ DY

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:

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

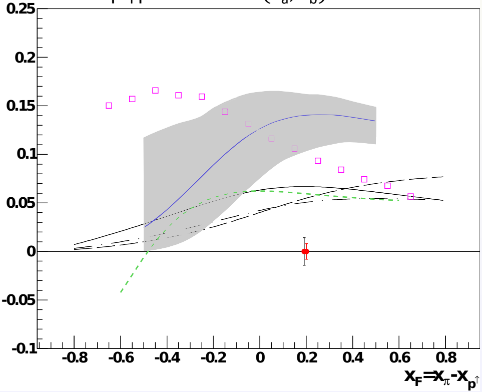
Crucial test of the consistency of the approach

Sivers asymmetry in polarized DY (I)

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

2 years data taking (1y = 140d)
$6 \cdot 10^8$ π/spill (9.6s/48s duty cycle)
1.1m transv pol. NH_3 target
Lumi=$1.2 \cdot 10^{32}$ $cm^{-2}s^{-1}$

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



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

Sivers asymmetry in polarized DY (II)

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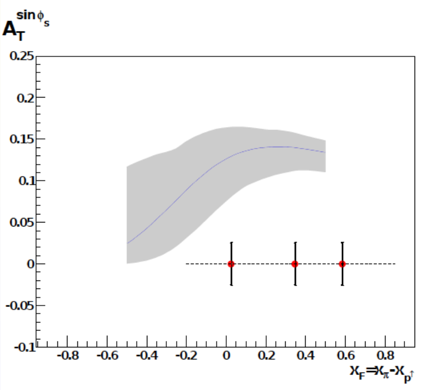
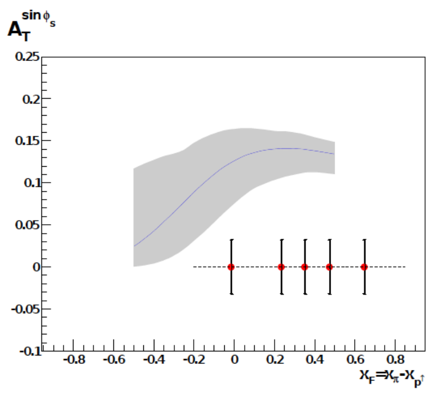
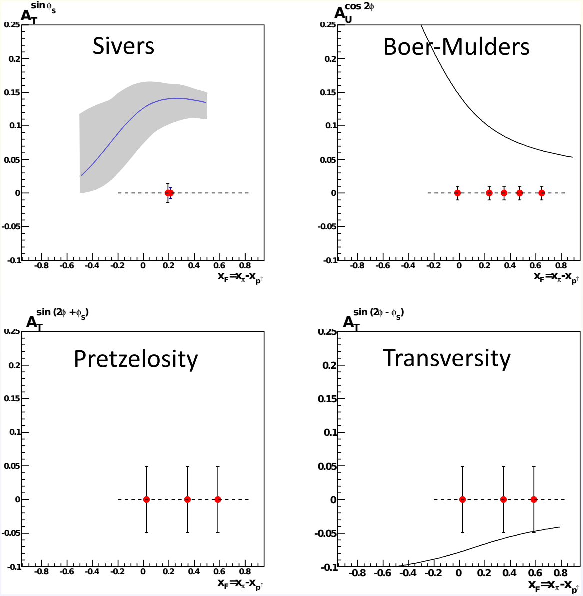




- Binning in x_F feasible
- Access to larger x_F values compared to SIDIS

Projections on SSA Measurements (I)

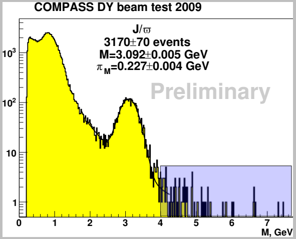


``Safe'' mass region

$4 < M_{\mu\mu} < 9$ GeV

Negligible background

low cross-section



2 years data taking (1y = 140d)

$6 \cdot 10^8$ π/spill (9.6s/48s)

1.1m transv pol. NH_3 target

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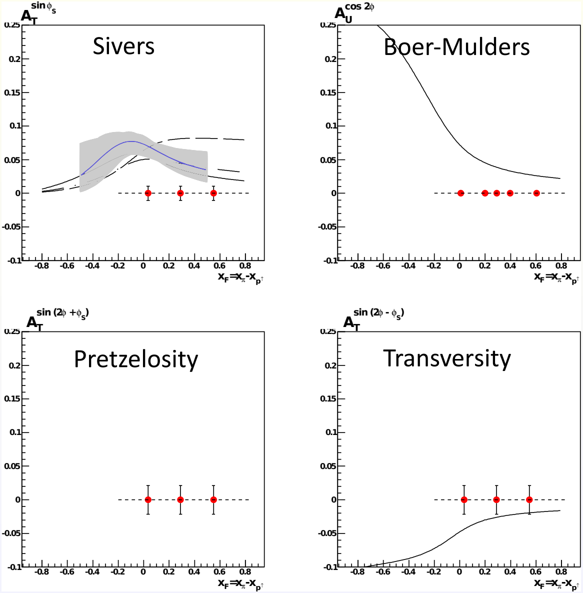
Projections on SSA Measurements (II)

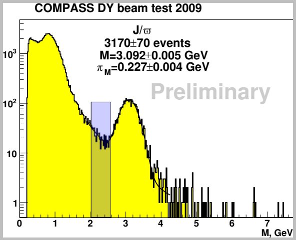


``Low'' mass region

$2 < M_{\mu\mu} < 2.5$ GeV

Larger background

High cross-section



2 years data taking (1y = 140d)

$6 \cdot 10^8$ π/spill (9.6s/48s)

1.1m transv pol. NH_3 target

Lumi=$1.2 \cdot 10^{32}$ cm^{-2}s^{-1}

Semi-Inclusive DIS (I)

Semi-inclusive DIS:
- with polarized targets (2002-2011)
- with unpolarized proton target (parallel to GPD program)

Goal: extensive measurement and fine binning in $(x,\ z,\ Q^2,\ p_T^h)$ to provide input for NLO global analysis of PDFs and FFs

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)

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

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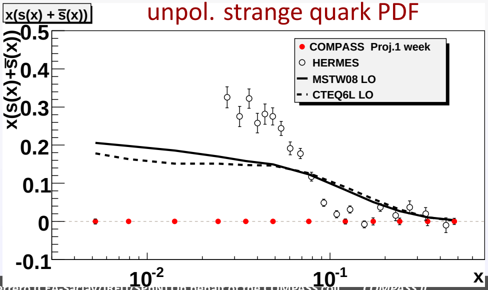
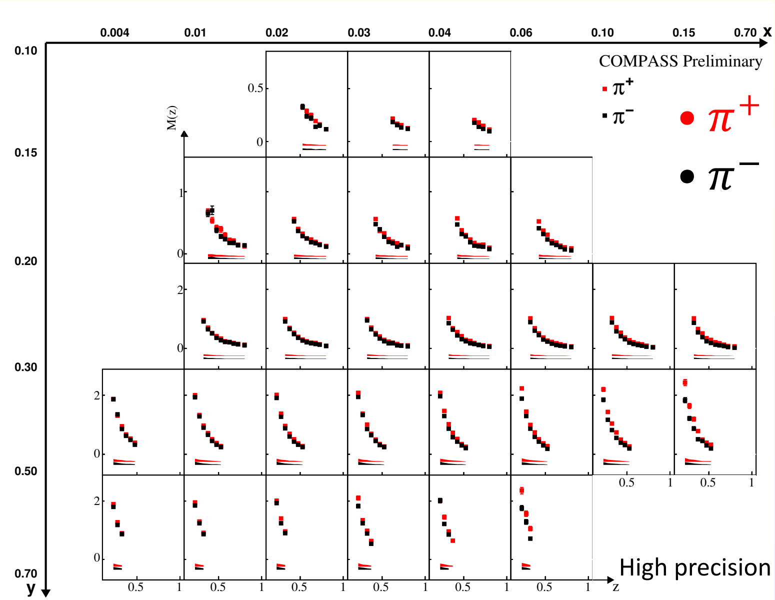
unpol. strange quark PDF



Projection for 1 week with 2.5m LH_2 target

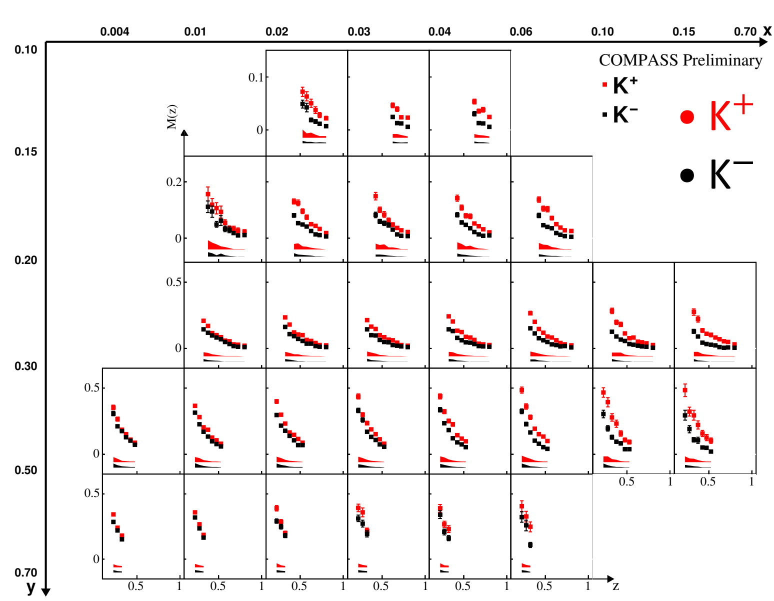
π^+ and π^- multiplicities vs. z in (x, y) bins



High precision measurement

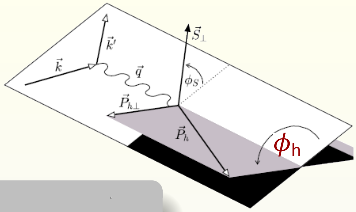
Analysis of p_T^h dependence ongoing

K^+ and K^- multiplicities vs. z in (x, y) bins



D_s^K is a key ingredient to extract $s(x)$ and $\Delta s(x)$

Semi-Inclusive DIS (II)



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

Unpolarized cross-section:

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

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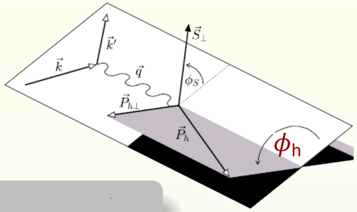

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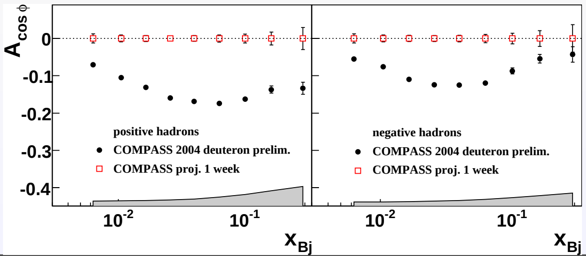
Cahn effect → info on k



☐ Compass projected: 1 week 2.5m LH_2 target

- 2004 Compass deuteron 4 weeks

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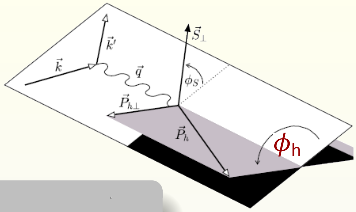

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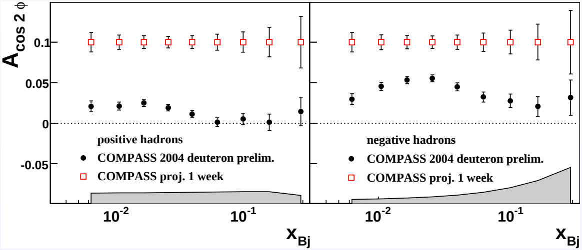
Boer-Mulders TMD ⊗ Collins FF + Cahn effect



□ Compass projected: 1 week 2.5m LH_2 target

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COMPASS-II SIDIS & DY - Conclusions

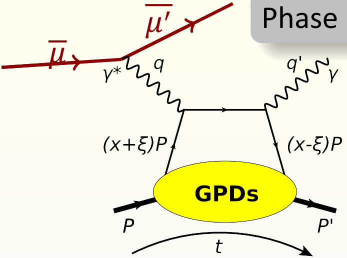
Polarized Drell-Yan experiment @ COMPASS:

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

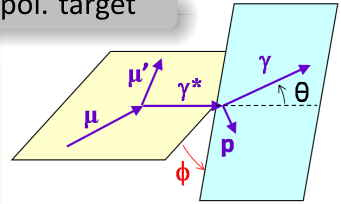
High statistics sample of unpol. μp scattering data

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

DVCS: What Can We Learn?



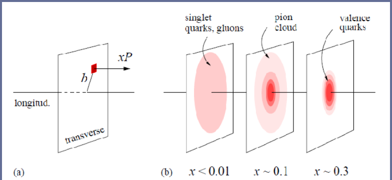
Phase 1: Polarized beam, unpol. target



DVCS dominance at large x_B

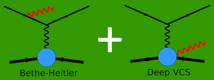
BH/DVCS interf. at intermediate x_B

x_B-dependent transv. size of nucleon



$\mathbf{r}_\perp$ parameter from slope of $d\sigma^{DVCS}/dt$

Interference between BH and DVCS



→ "Boost" of DVCS through int. term

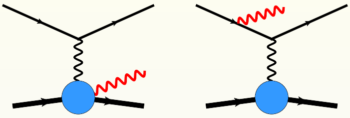
Measurement of $\mathrm{Re}\mathcal{H}(\xi,t)$ and $\mathrm{Im}\mathcal{H}(\xi,t)$ via ϕ-modulation of cross section

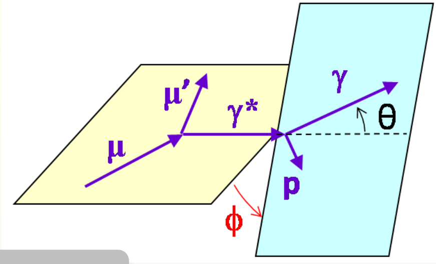
$$\mathrm{Re}\mathcal{H}(\xi,t) = P\int dx\, H(x,\xi,t)/(x-\xi)$$

$$\mathrm{Im}\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$$

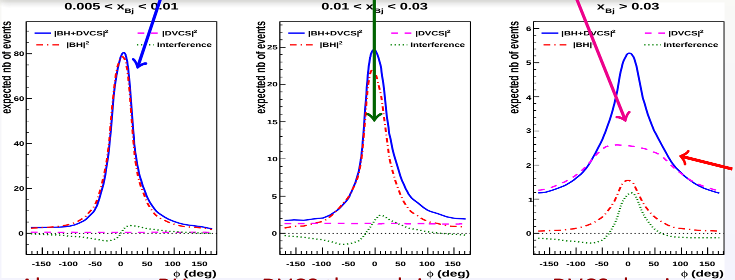
Exp. constrain to GPD H

BH and DVCS
at $E_\mu = 160$ GeV





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



MC simulation for COMPASS without ECAL0

Missing DVCS acceptance w/o ECAL0

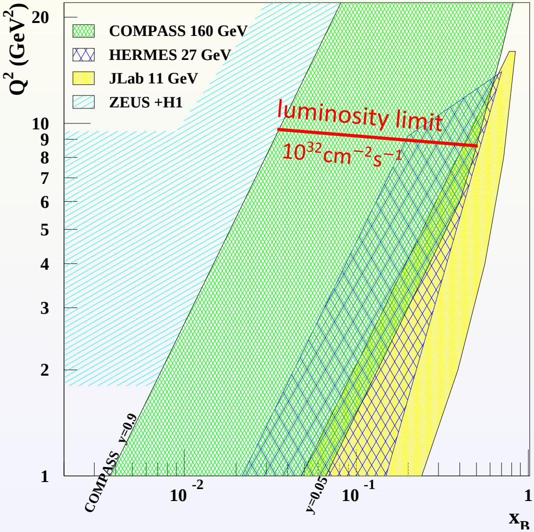
Almost pure BH
→ Ref. yield

DVCS through int. term
→ Re,Im(T^{DVCS})

DVCS dominates
→ $d\sigma^{DVCS}/dt$ (transv. imaging)

What Makes COMPASS Unique?

COMPASS covers the unexplored region between collider (H1+Zeus) and low-energy fixed target (Hermes+JLab) experiments



- μ^+ and μ^- beams
- momentum: 100 – 190 GeV/c
- beam polarization: 80 %

  opposite for μ^+ and μ^-

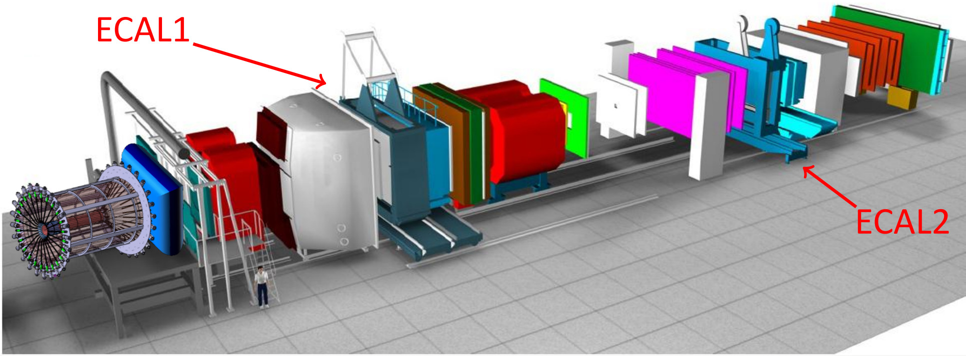
- coverage of intermediate x_B

  → low x_B: **pure BH**
  useful for normalization

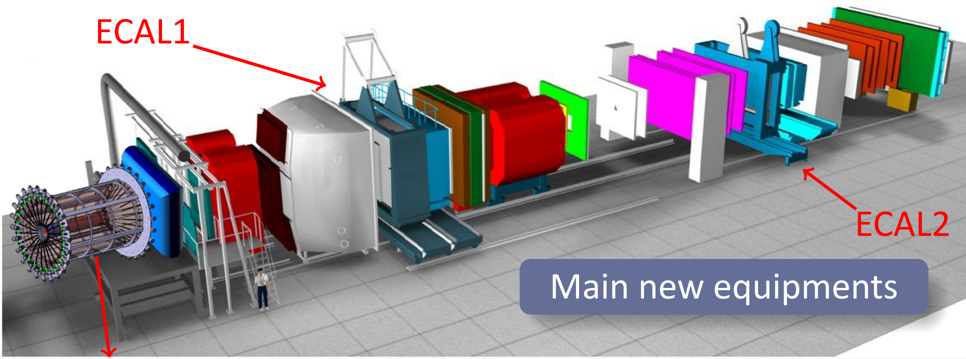
  → high x_B: **DVCS predominance**

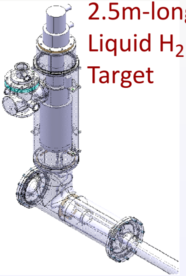
⇝ **unexplored region between ZEUS+H1 and HERMES+JLab**

The COMPASS set-up for the GPD program



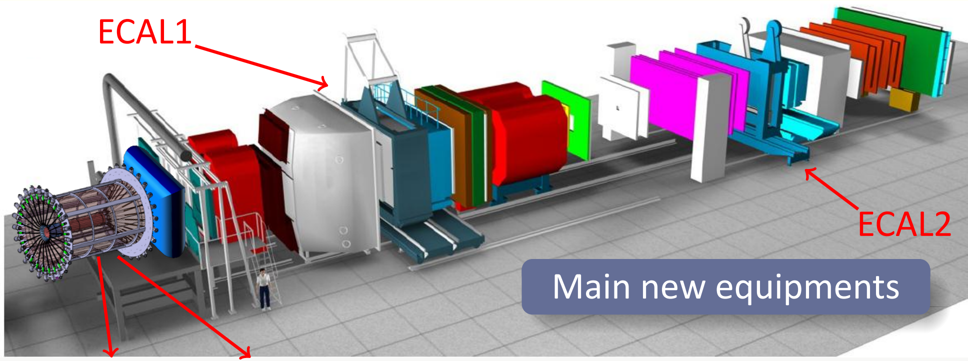
The COMPASS set-up for the GPD program

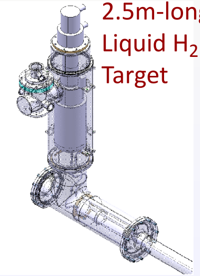




2.5m-long
Liquid H_2
Target

The COMPASS set-up for the GPD program

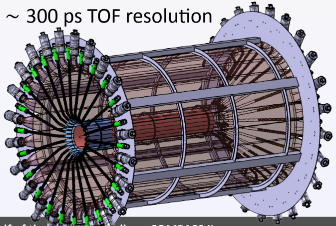




2.5m-long
Liquid H_2
Target

Target TOF System

24 inner & outer scintillators
1 GHz SADC readout
~ 300 ps TOF resolution



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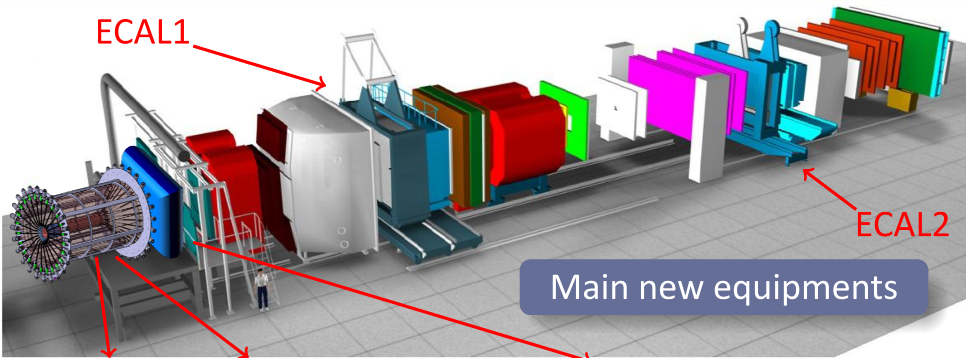
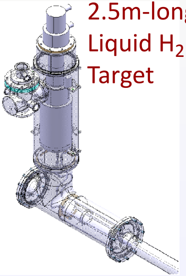
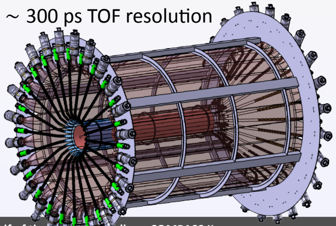




2.5m-long Liquid H_2 Target

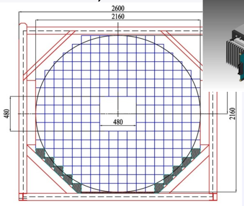
Target TOF System

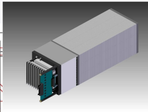
24 inner & outer scintillators
1 GHz SADC readout
~ 300 ps TOF resolution



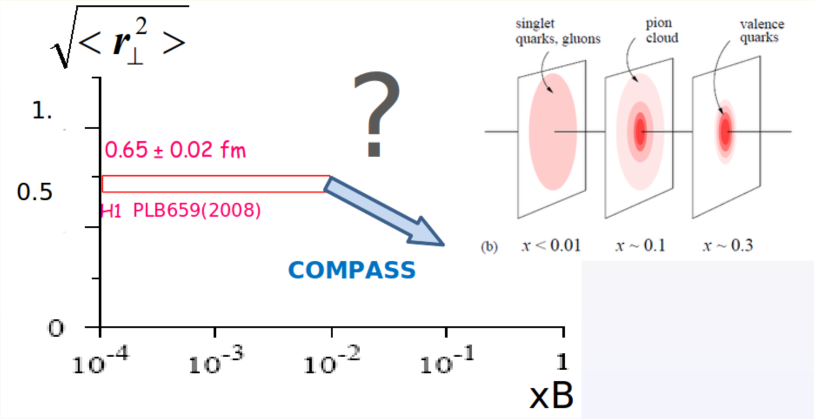
ECAL0 Calorimeter

Shashlyk modules + MAPD readout
~ 2×2 m^2, ~2200 ch.





Transverse Size of the Nucleon

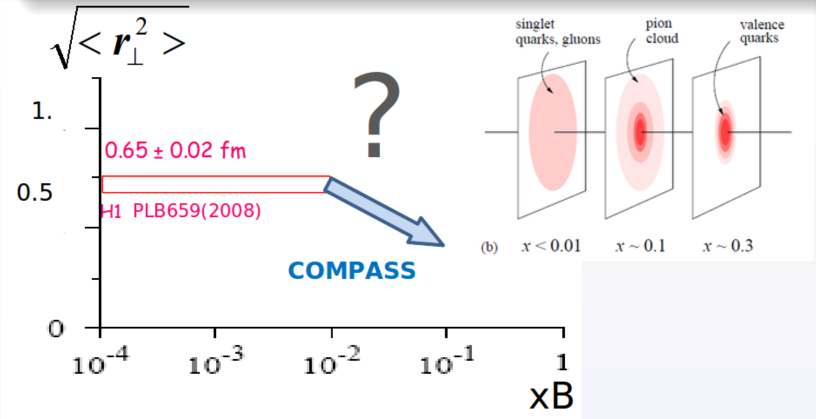


Transverse Size of the Nucleon

Beam Charge and Spin **SUM**:

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

Integration over ϕ and BH subtraction → $\mathbf{d\sigma^{DVCS}/dt \sim exp(-B|t|)}$



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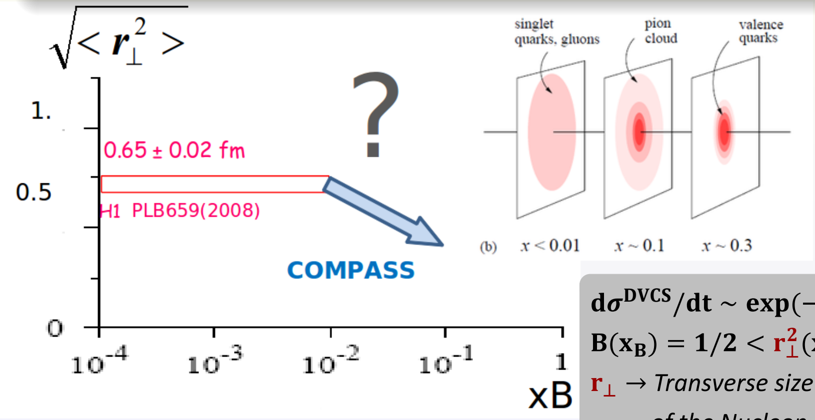

$\mathbf{d\sigma^{DVCS}/dt \sim exp(-B|t|)}$

$\mathbf{B(x_B) = 1/2 < r_\perp^2(x_B) >}$

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

Transverse Size of the Nucleon

Beam Charge and Spin **SUM**:

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

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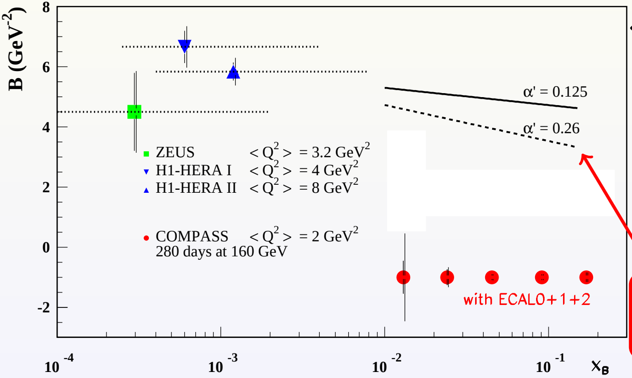

← 40 weeks of data

2.5 m LH_2 target

$\epsilon_{global} = 10\%$

$L = 1222\,\mathbf{pb^{-1}}$

Ansatz at small $\mathbf{x_B}$:

$\mathbf{B(x_B) \simeq B_0 + 2\alpha' ln(x_0/x_B)}$

Transverse Size of the Nucleon

Beam Charge and Spin **SUM**:

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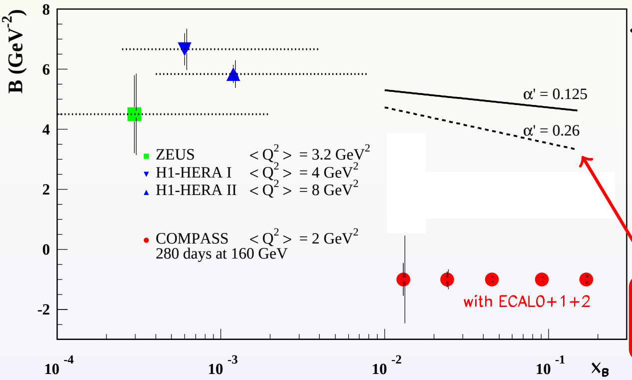
Integration over ϕ and BH subtraction → $\mathbf{d\sigma^{DVCS}/dt \sim exp(-B|t|)}$



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Ansatz at small $\mathbf{x_B}$:
$\mathbf{B(x_B) \simeq B_0 + 2\alpha' ln(x_0/x_B)}$

if $\alpha' > 0.125$ → **accuracy** $> 2.5\sigma$

Cross-section Difference

Beam Charge and Spin **DIFFERENCE**:

$$\mathbf{D_{CS,U} \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow}) \propto P_\mu d\sigma^{DVCS}_{pol} + e_\mu Re(I) \propto c_0^{Int} + c_1^{Int}\cos(\phi)}$$

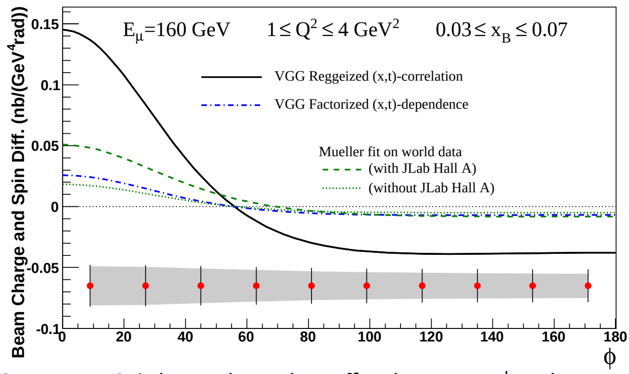
$$\mathbf{c_{0,1}^{Int} \propto Re(F_1\mathcal{H}); \quad Re\mathcal{H}(\xi, t) = P\int dx\, H(x,\xi,t)/(x-\xi)}$$

Cross-section Difference

Beam Charge and Spin **DIFFERENCE**:

$$\mathbf{D_{CS,U}} \equiv \mathbf{d}\boldsymbol{\sigma}(\boldsymbol{\mu}^{+\leftarrow}) - \mathbf{d}\boldsymbol{\sigma}(\boldsymbol{\mu}^{-\rightarrow}) \propto \mathbf{P}_{\boldsymbol{\mu}}\mathbf{d}\boldsymbol{\sigma}_{\mathbf{pol}}^{\mathbf{DVCS}} + \mathbf{e}_{\boldsymbol{\mu}}\mathbf{Re(I)} \propto \mathbf{c}_0^{\mathbf{Int}} + \mathbf{c}_1^{\mathbf{Int}}\mathbf{cos}(\boldsymbol{\phi})$$

$$\mathbf{c}_{\mathbf{0,1}}^{\mathbf{Int}} \propto \mathbf{Re}(\mathbf{F_1}\mathcal{H}); \quad \mathbf{Re}\mathcal{H}(\boldsymbol{\xi},\mathbf{t}) = \mathbf{P}\int \mathbf{dx}\,\mathbf{H}(\mathbf{x},\boldsymbol{\xi},\mathbf{t})/(\mathbf{x}-\boldsymbol{\xi})$$



← 40 weeks of data

2.5 m LH_2 target

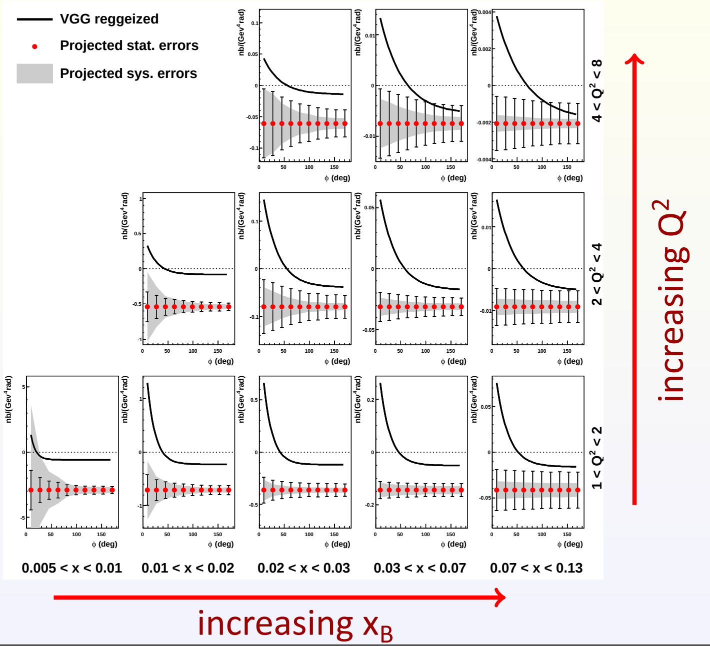
ϵ_{global} = 10%

L = 1222$\mathbf{pb}^{-1}$

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

Exp. constrain to GPD **H**

Cross-section Difference - All Bins



Real and imaginary parts of $\mathcal{H}(\xi, t)$ CFF

The use of both μ^+ and μ^- beams will provide a direct access to the **Re** and **Im** parts of the *Compton From Factors*

$$\mathbf{D_{CS,U} \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow}) \propto c_0^{Int} + c_1^{Int}\cos(\phi)}, \qquad \mathbf{c_{0,1}^{Int} \propto Re(F_1\mathcal{H})}$$

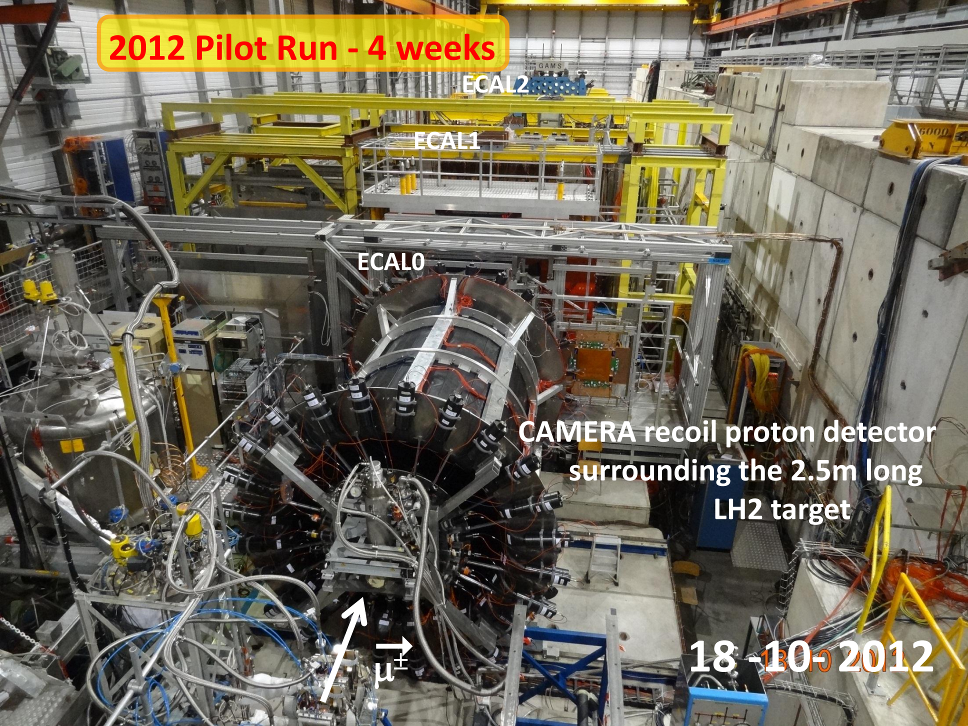
$$\mathbf{S_{CS,U} \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K \cdot s_1^{Int}\sin(\phi)}, \quad \mathbf{s_1^{Int} \propto Im(F_1\mathcal{H})}$$

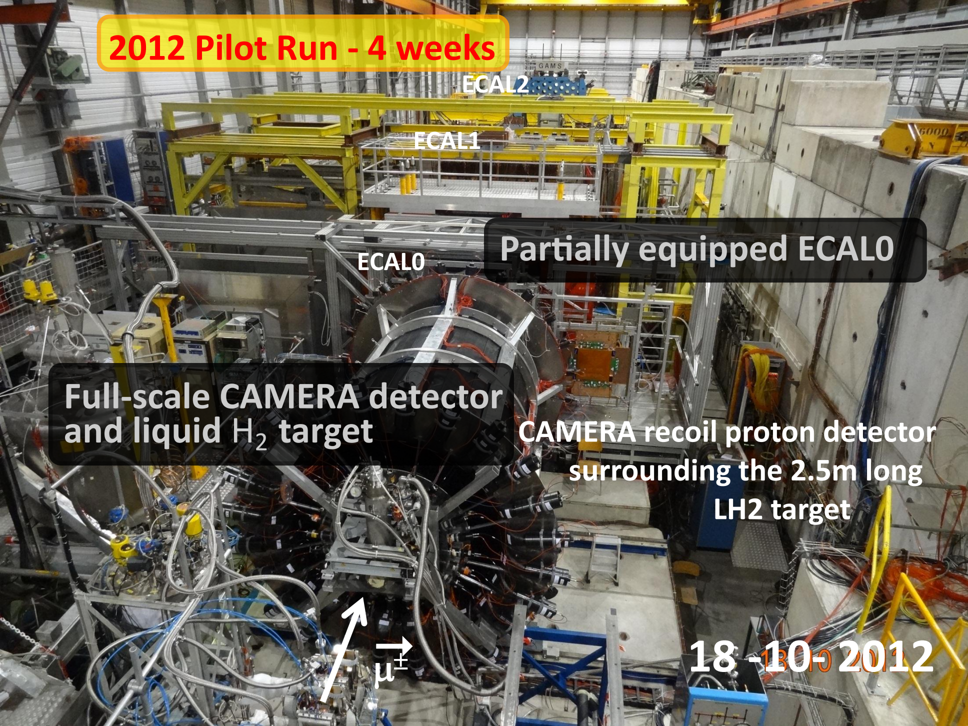
and

$$\mathbf{Im\mathcal{H}(\xi, t) = H(x = \xi, \xi, t)}$$

$$\mathbf{Re\mathcal{H}(\xi, t) = \frac{\int dx\, H(x, \xi, t)}{(x - \xi)} = \frac{\int dx\, H(x, x, t)}{(x - \xi)} + Dterm}$$

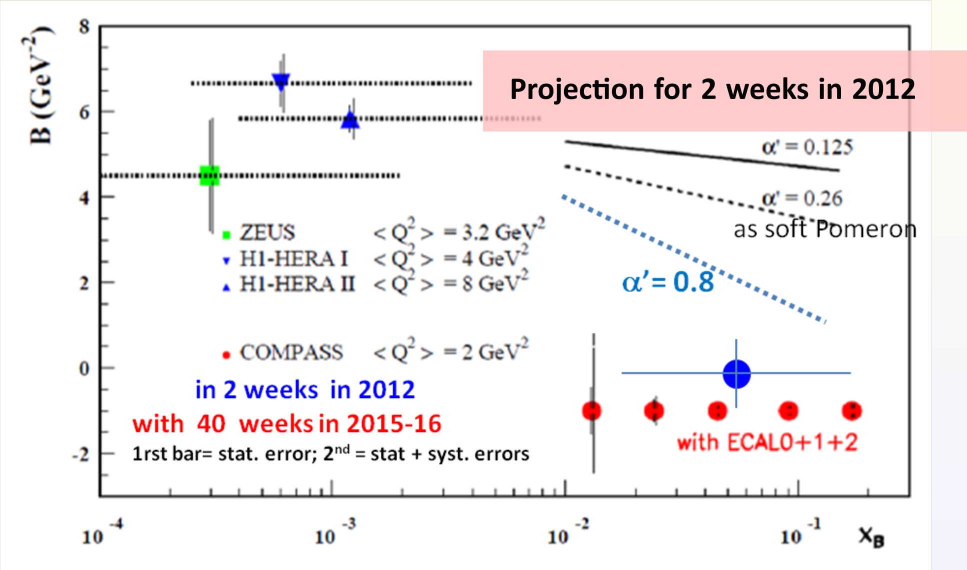
Really new information from D-term


2012 Pilot Run - 4 weeks
GAMS
ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
$\vec{\mu}^{\pm}$
18 -10- 2012



2012 Pilot Run - 4 weeks
GAMS
ECAL2
ECAL1
ECAL0
Partially equipped ECAL0
Full-scale CAMERA detector and liquid H_2 target
CAMERA recoil proton detector surrounding the 2.5m long LH2 target
$\vec{\mu}^{\pm}$
18 -10- 2012

Projection for 2012 Pilot Run

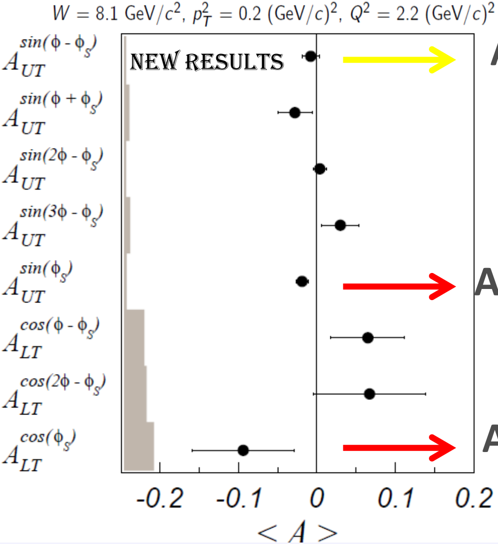


Exclusive ρ^0 production with transv. pol. target

$\mu \; p \rightarrow \mu' + \rho^0 + p_{\text{non détecté}}$

$\hookrightarrow \pi^+\pi^-$

COMPASS 2007-2010,without recoil detector



$A_{UT}^{\sin(\phi-\phi_S)} \propto Im(\mathcal{E}^* \mathcal{H})$

$E\rho^0 \propto 2/3\, E^u + 1/3\, E^d + 3/8\, E^g$
Cancellation between gluon and sea contributions and $E^{u\,val} \sim -E^{d\,val}$

$A_{UT}^{\sin(\phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T - \mathcal{H}^* \mathcal{H}_T)$

$A_{LT}^{\cos(\phi_S)} \propto Re(\mathcal{E}^* \bar{\mathcal{E}}_T - \mathcal{H}^* \mathcal{H}_T)$

H_T could be not small

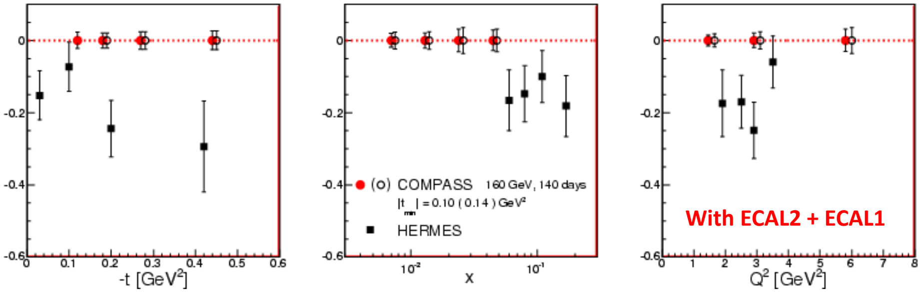
DVCS with a transversely polarized target

COMPASS-II (future addendum) **: with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam** and **transversely** polarized NH3 (proton)

$$\mathcal{D}_{CS,T} \equiv d\sigma_T(\mu^{+\downarrow}) - d\sigma_T(\mu^{-\uparrow})$$
$$\propto Im(F_2\mathcal{H} - F_1\mathcal{E})\ \sin(\phi - \phi_S)\cos\phi$$

2 years of data
160 GeV muon beam
1.2 m polarised NH_3 target
$\varepsilon_{global} = 10\%$

$A^{\sin(\phi-\phi_s)\cos\phi}_{CS,T}$



COMPASS II GPDs - Conclusions

→ COMPASS-II will investigate quark GPDs through DVCS

- *Intermediate* $\mathbf{x_B}$ *regime* not accessible to present or planned facilities in the near future
- Two beam charges available with opposite polarizations

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

- Nucleon *transversal dimension* as function of $\mathbf{x_B}$ (``Nucleon Tomography'')

→ Complementary information from exclusive meson production

→ New pilot data collected at end of 2012 - more than 2 weeks

→ In a second phase, constrain of *GPD E* by using a transversely polarized target