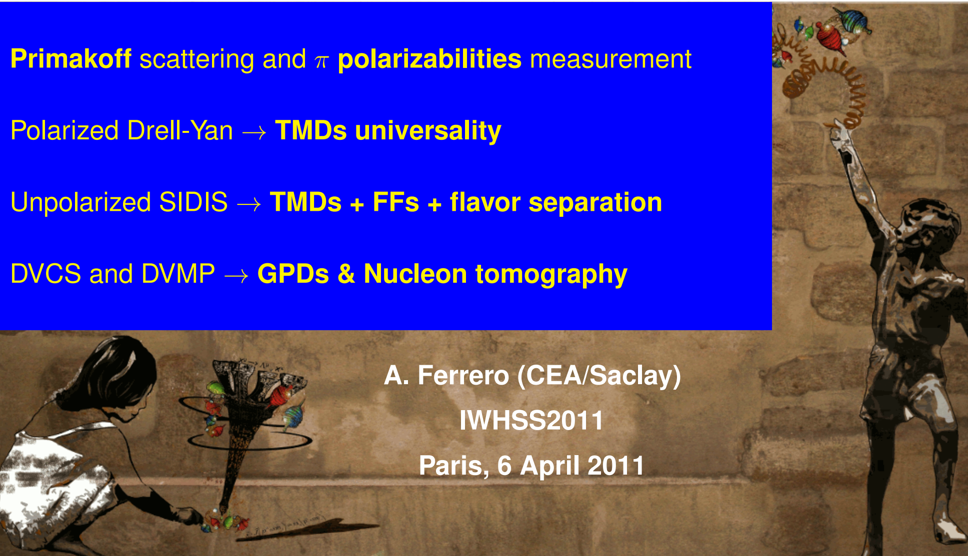
The COMPASS-II Program

Primakoff scattering and π **polarizabilities** measurement

Polarized Drell-Yan $\rightarrow$ **TMDs universality**

Unpolarized SIDIS $\rightarrow$ **TMDs + FFs + flavor separation**

DVCS and DVMP $\rightarrow$ **GPDs & Nucleon tomography**



A. Ferrero (CEA/Saclay)

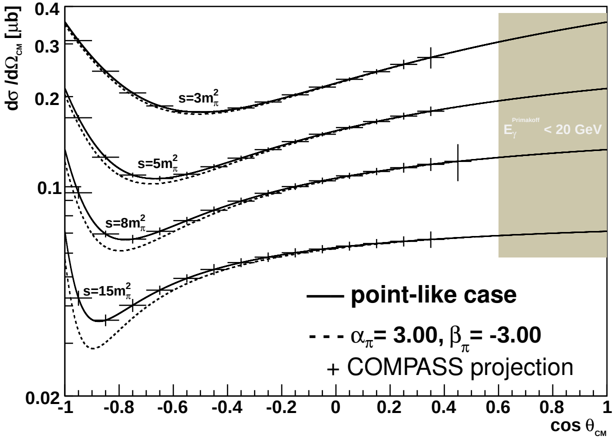
IWHSS2011

Paris, 6 April 2011

Projections for pion polarizabilities

Projections assuming 500k reconstructed Primakoff events

Polarizabilities increase with increasing s

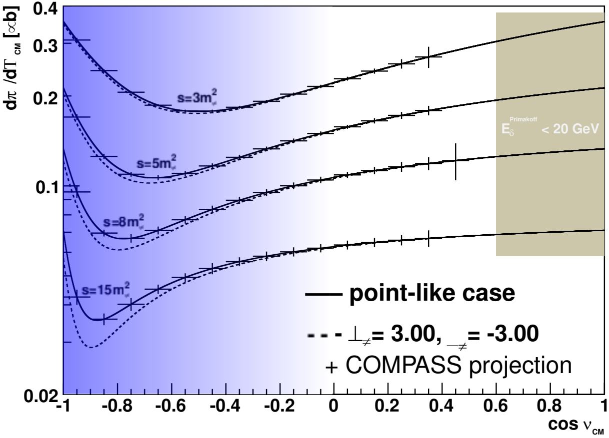


Projections for pion polarizabilities

Projections assuming 500k reconstructed Primakoff events

Backward angles:
$\alpha_\pi - \beta_\pi, \alpha_2 - \beta_2$

Polarizabilities increase with increasing s

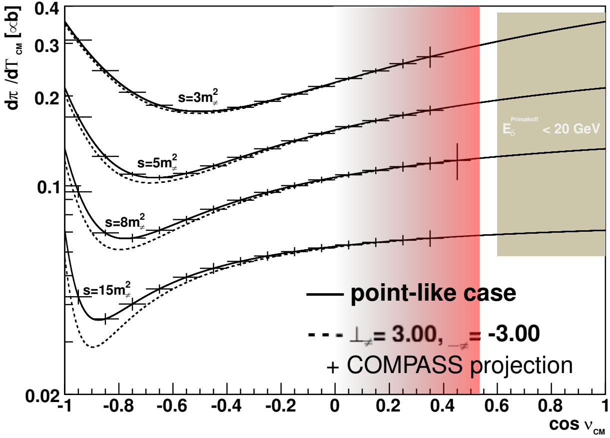


Projections for pion polarizabilities

Projections assuming 500k reconstructed Primakoff events

Forward angles:
$\alpha_\pi + \beta_\pi$

Polarizabilities increase with increasing s

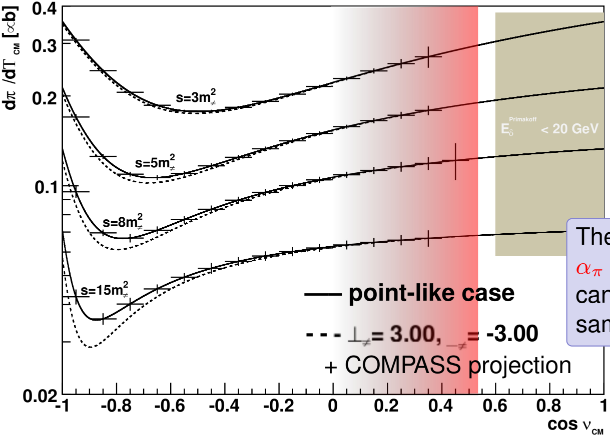


Projections for pion polarizabilities

Projections assuming 500k reconstructed Primakoff events

Forward angles: $\alpha_\pi + \beta_\pi$

Polarizabilities increase with increasing s



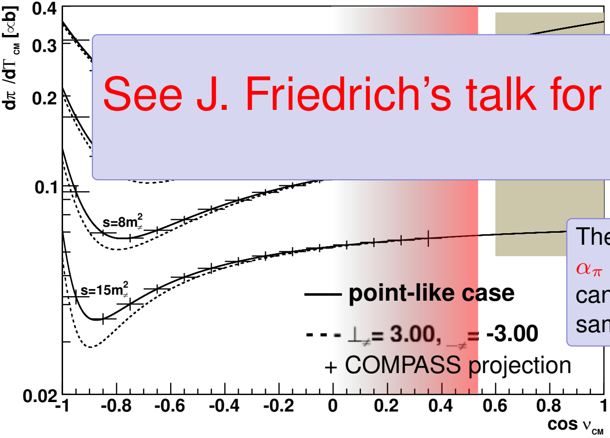
The 3 components $\alpha_\pi - \beta_\pi$, $\alpha_\pi + \beta_\pi$, $\alpha_2 - \beta_2$ can be measured in the same experiment

Projections for pion polarizabilities

Projections assuming 500k reconstructed Primakoff events

Forward angles:
$\alpha_\pi + \beta_\pi$

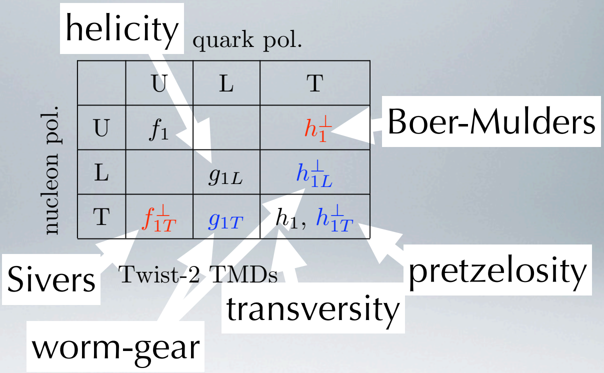
Polarizabilities increase with increasing s



See J. Friedrich’s talk for the details!

The 3 components
$\alpha_\pi - \beta_\pi,\ \alpha_\pi + \beta_\pi,\ \alpha_2 - \beta_2$
can be measured in the same experiment

The present picture of the nucleon

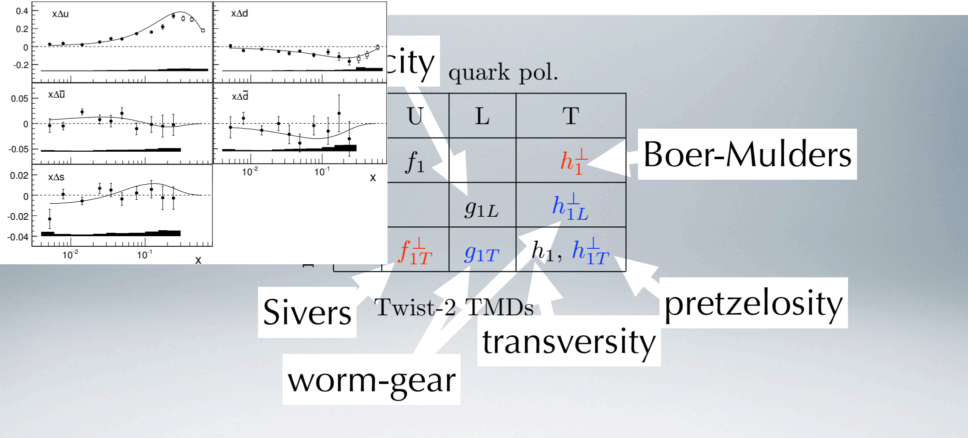


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

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

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

The present picture of the nucleon



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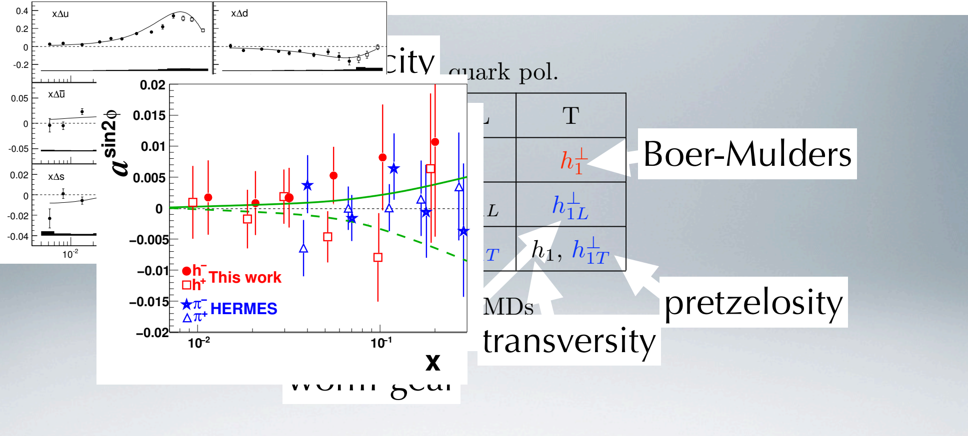

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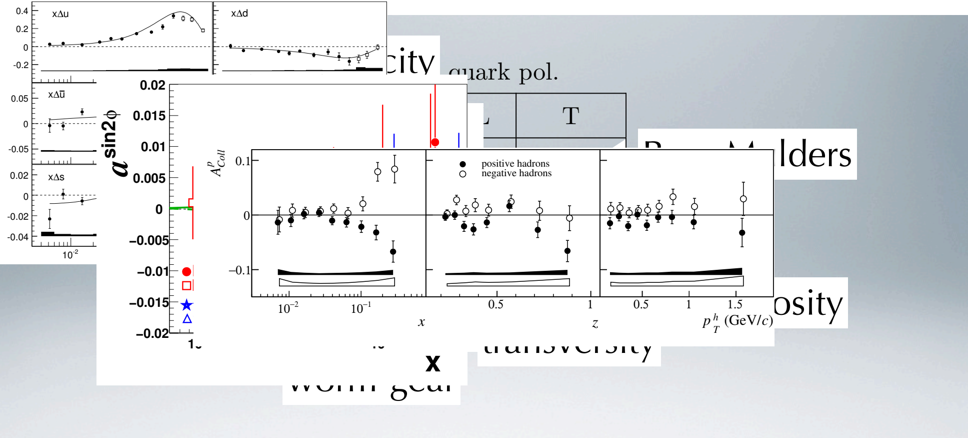

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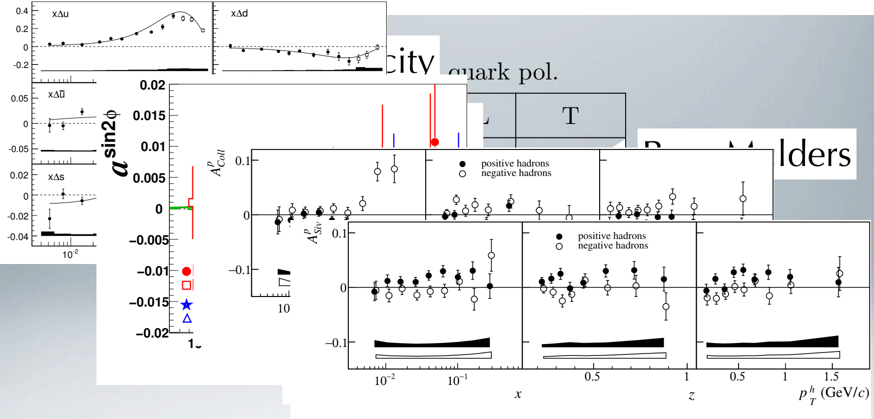

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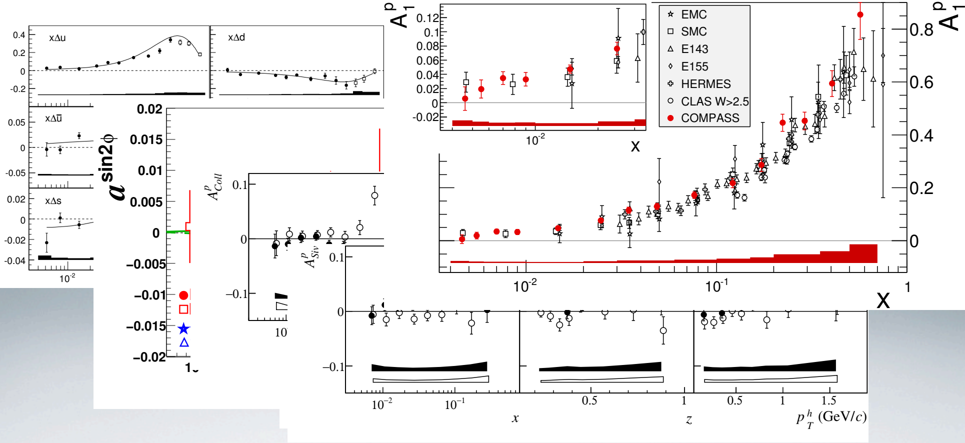

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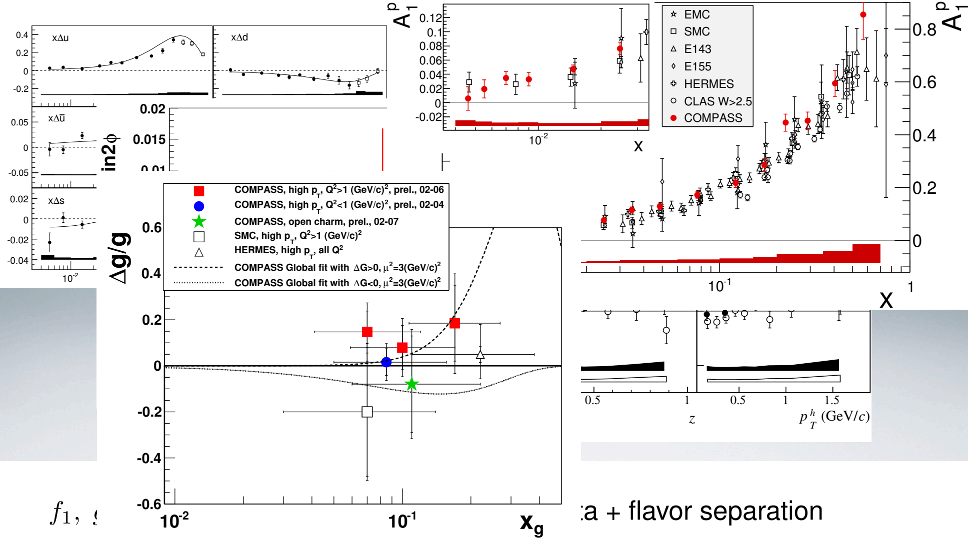
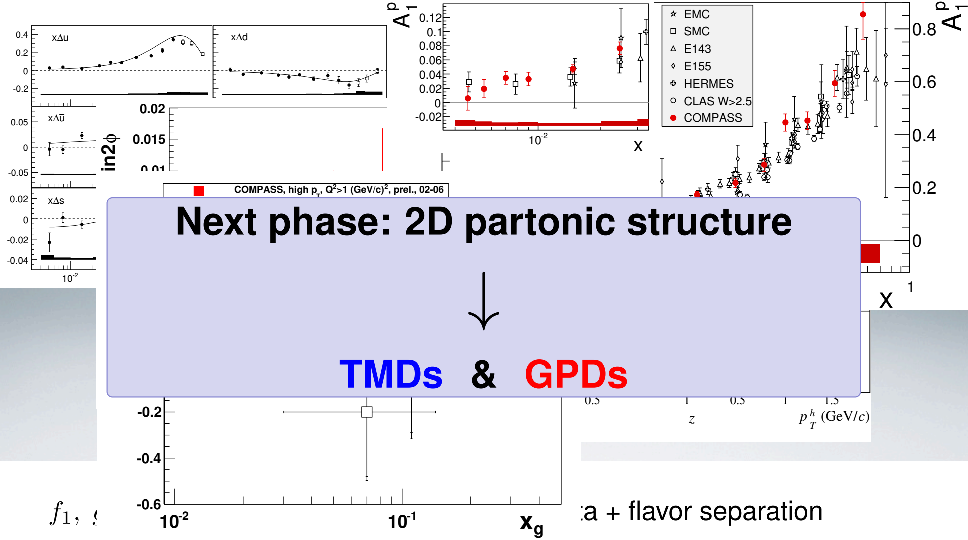


f_1, g … a + flavor separation

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

The present picture of the nucleon



Next phase: 2D partonic structure

↓

TMDs & GPDs

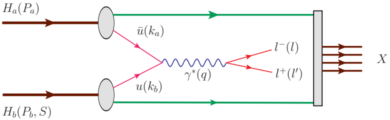
f_1, g … a + flavor separation

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

TMDs Studies with Polarized DY

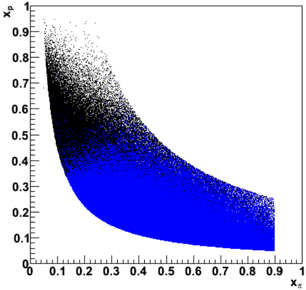
Drell-Yan with π^- beam and transversely polarized protons:

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



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 $\overline{u}/u$ annihilation



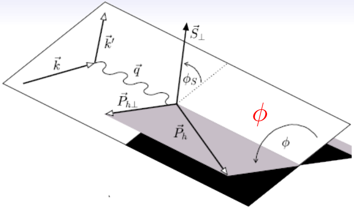
$$\sigma^{DY} \propto f_{\overline{u}|\pi} \otimes f_{u|p}$$

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

$\rightarrow$ Complementary information
Universality test

Expansion of the DY cross-section

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

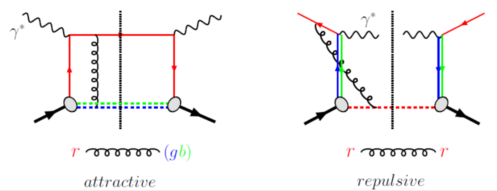


$$\begin{aligned}
\mathrm{d}\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) \;=\; & 1 \;+\; \overline{h}_1^\perp \otimes h_1^\perp \cos 2\phi && \to (\text{B.-M.})_\pi \otimes (\text{B.-M.})_p \\
& + \; |S_T| \Big[\; \overline{f}_1 \otimes f_{1T}^\perp \sin\phi_S && \to (f_1)_\pi \otimes (\text{Sivers})_p \\
& + \qquad \overline{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi+\phi_S) && \to (\text{B.-M.})_\pi \otimes (\text{Pretz.})_p \\
& + \qquad \overline{h}_1^\perp \otimes h_1 \sin(2\phi-\phi_S) \Big] && \to (\text{B.-M.})_\pi \otimes (\text{Transv.})_p
\end{aligned}$$

TMDs: SIDIS $\longleftrightarrow$ 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:

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

Boer-Mulders:

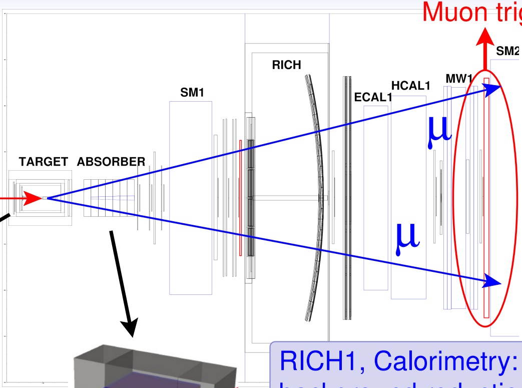
$$h_1^{\perp}(SIDIS) = -h_1^{\perp}(DY)$$

Crucial test of the factorization approach

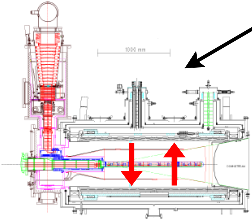
Drell-Yan @ COMPASS

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

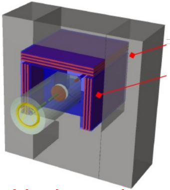
Muon trigger



RICH1, Calorimetry: PID & background reduction



NH$_3$, 2 oppositely polarized cells
$\sim$90% polarization
$\sim$15% dilution factor

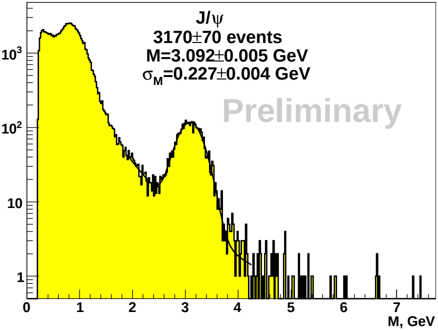


Hadron absorber

2009 DY Test Run

Prototype hadron absorber
Solid CH_2 target
π^- beam up to $1.5 \cdot 10^8$ π/spill

COMPASS DY beam test 2009



2009 DY Test Run

Prototype hadron absorber

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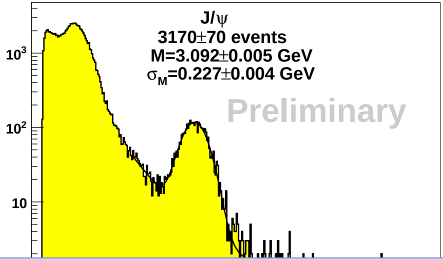
COMPASS DY beam test 2009



expected: 3600±600 J/ψ and 110±22 DY

measured: 3170±70 J/ψ and 84±10 DY

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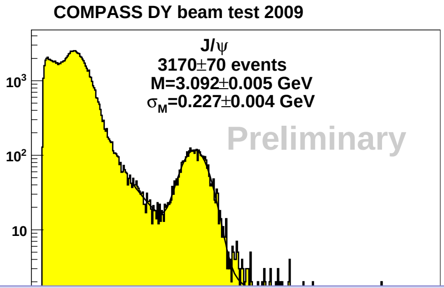

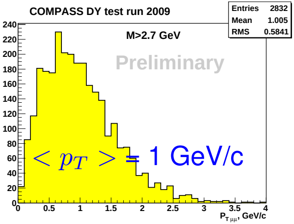

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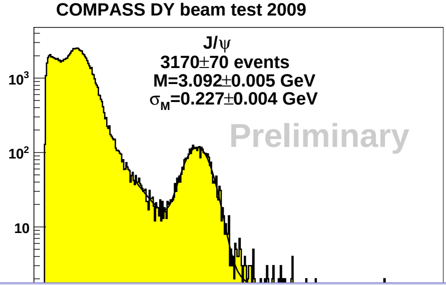

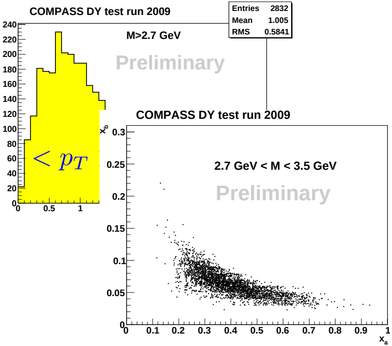

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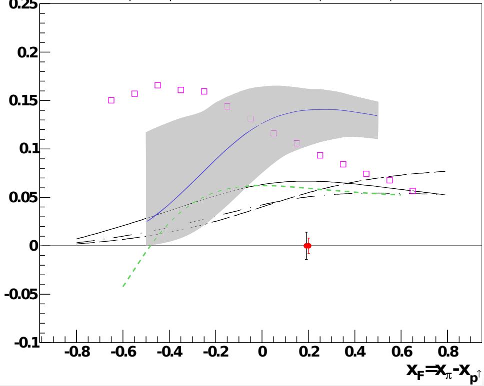
Projections on SSA Measurements (I)

$A_T^{\sin\phi_S}$ (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=$1.2 \cdot 10^{32}$ 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 $\leftrightarrow$ DY
SIGN CHANGE

Projections on SSA Measurements (I)

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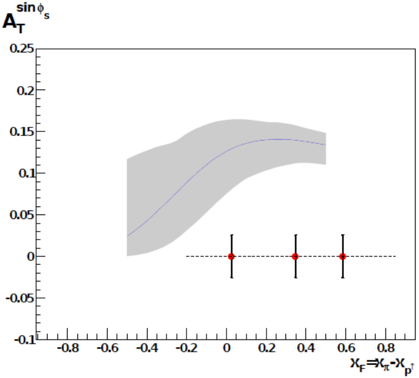
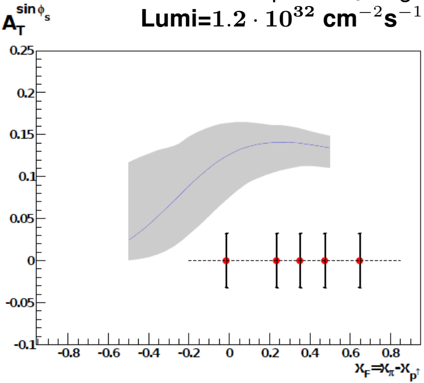
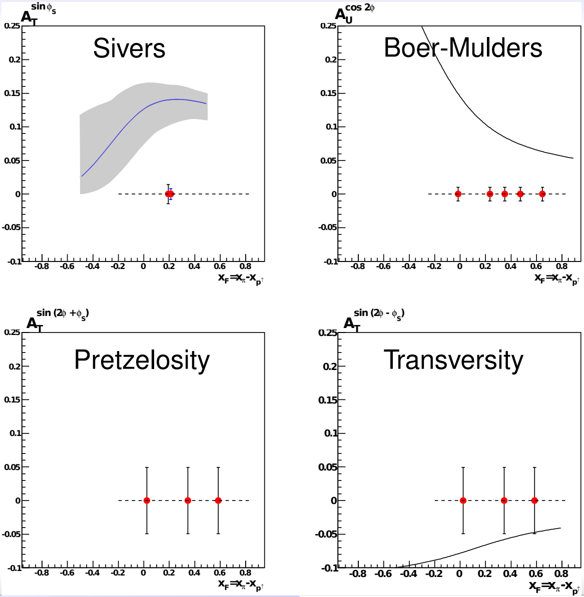




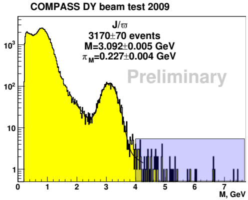
- Binning in x_F feasible
- Access to larger x_F values compared to SIDIS

Projections on SSA Measurements (II)



"Safe" mass region

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



Negligible background

low cross-section

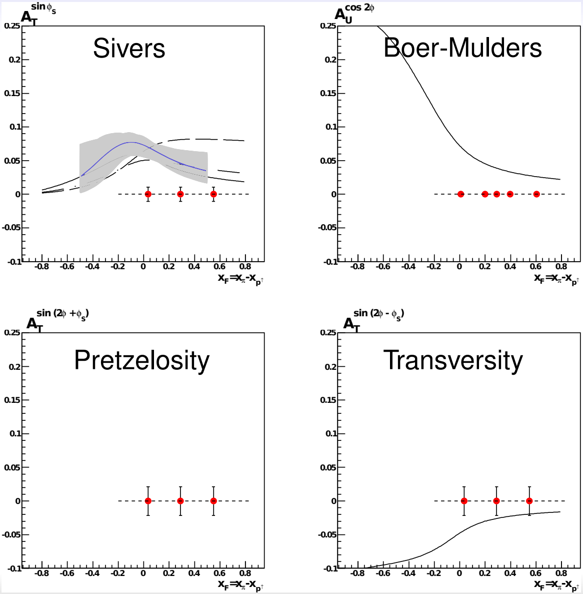
2 years data taking

$6 \cdot 10^8$ π/spill (of 9.6s)

1.1m transv pol. NH_3 target

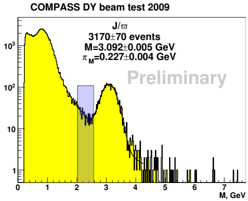
Lumi=$1.2 \cdot 10^{32}$ cm^{-2}s^{-1}

Projections on SSA Measurements (II)



Low mass region

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



High statistics

large combinatorial background (S/B $\sim$ 1)

2 years data taking

$6 \cdot 10^8$ π/spill (of 9.6s)

1.1m transv pol. NH_3 target

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

Semi-Inclusive DIS (I)

160 GeV muon beam and unpolarized proton target

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

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

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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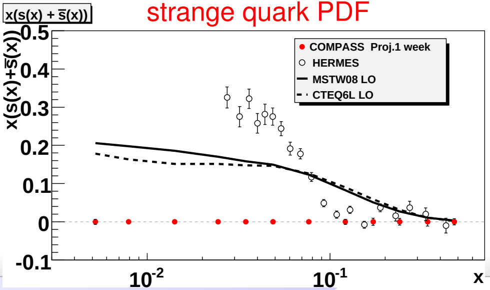
strange quark PDF



Projection for 1 week with 2.5m LH_2 target

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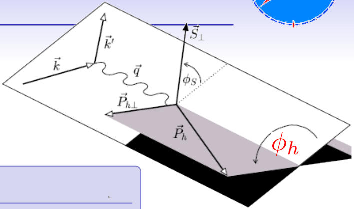
COMPASS: proton target and high-perf. PID (RICH + calorimeters)
$\mathbf{h} = K^+, K^-, K^0, \pi^+, \pi^-, \pi^0, \Lambda, \ldots$ → flavor separation

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

Semi-Inclusive DIS (II)

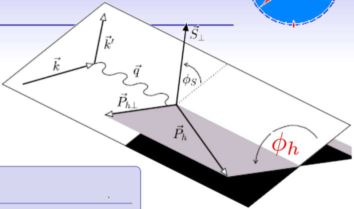


Azimuthal asymmetries in unpolarized SIDIS can reveal quark transverse momentum ($k_\perp$) effects beyond the collinear approximation

Unpolarized cross-section:

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

Semi-Inclusive DIS (II)



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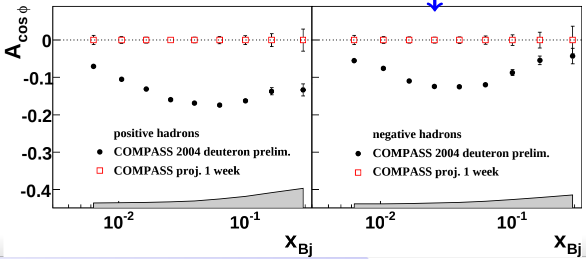
Cahn effect $\rightarrow$ info on $k_\perp$



□ Compass projected:
1 week 2.5m LH_2 target

- 2004 Compass deuteron 4 weeks

Semi-Inclusive DIS (II)

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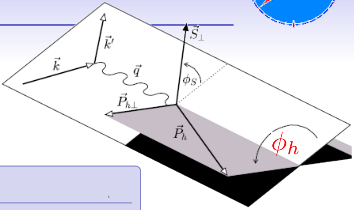

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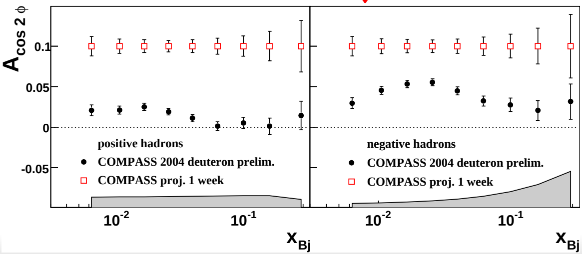
Boer-Mulders TMD ⊗ Collins FF + Cahn effect



- □ Compass projected: 1 week 2.5m LH_2 target
- ● 2004 Compass deuteron 4 weeks

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

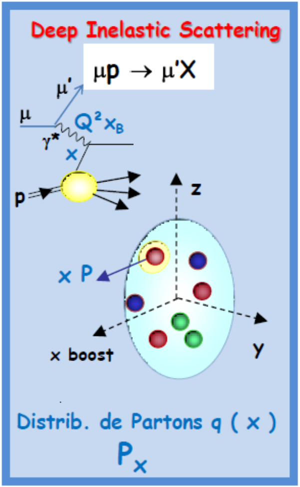
DY experiment feasibility proven by 2009 test data

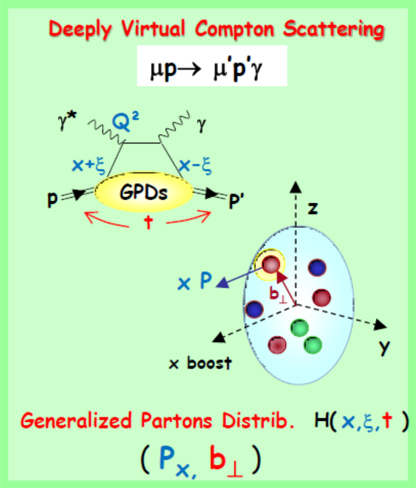
- J/Ψ and DY yields as expected
- Radioprotection scheme validity proven

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

From PDFs to GPDs





Observation of the Nucleon Structure

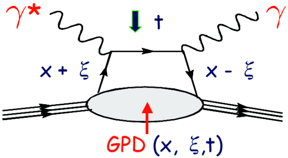
in 1 dimension

in 1+2 dimensions

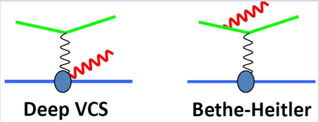
Deeply Virtual Compton Scattering

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

$Q^2 >> 1\ \mathrm{GeV}^2$ $-t < 1\ \mathrm{GeV}^2$

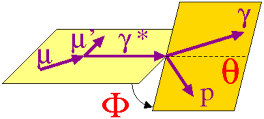


The total cross-section is the coherent sum of DVCS and BH

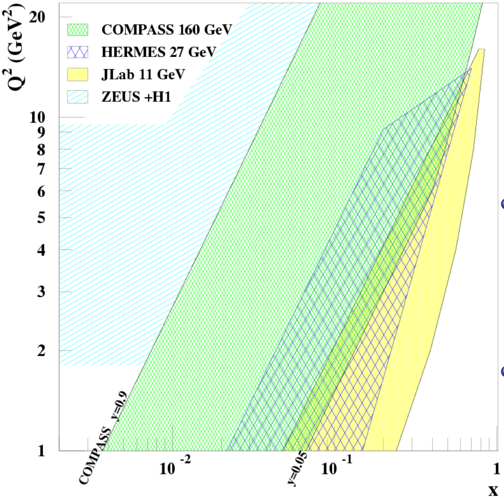


For polarized beam and unpolarized target:

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



What Makes COMPASS Unique?



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

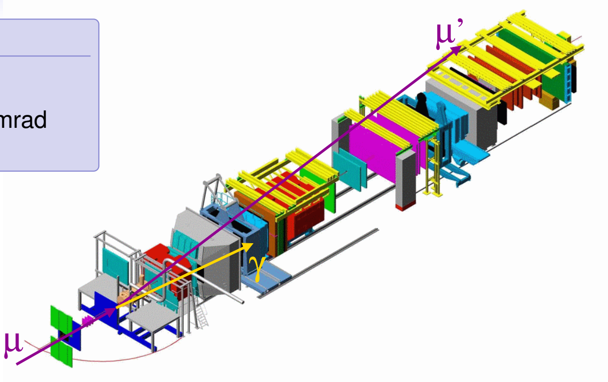
- low x_B: pure BH (useful for normalization)

high x_B: DVCS predominance

The COMPASS Apparatus for DVCS

ECAL2

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



Beam

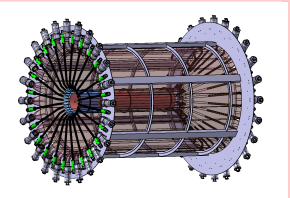
- 100-190 GeV
- 80% polarization
- μ^+ and μ^- with opposite polarization

ECAL1

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

The COMPASS Apparatus for DVCS

Future Target & RPD

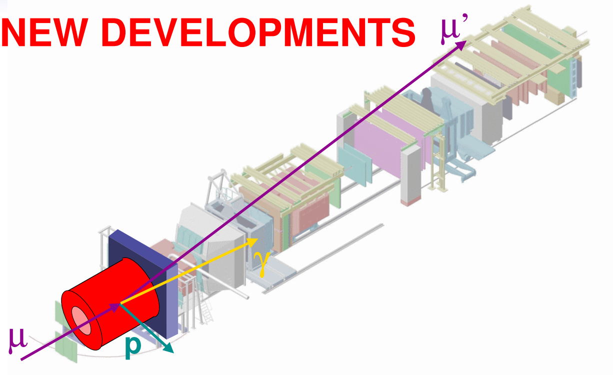


- **2.5m** long **LH2** target
- **4m** long TOF barrel
- recoil proton ID by **TOF** and **dE/dx**
- GANDALF boards:

  1 GHz digitization

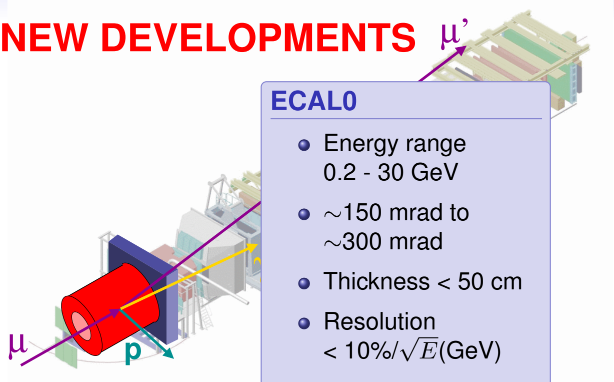
  ENOB: **12bit**

NEW DEVELOPMENTS

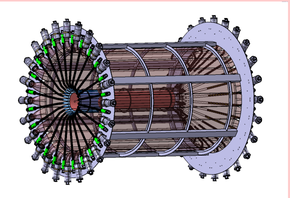


The COMPASS Apparatus for DVCS

NEW DEVELOPMENTS



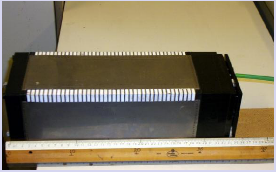
Future Target & RPD



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

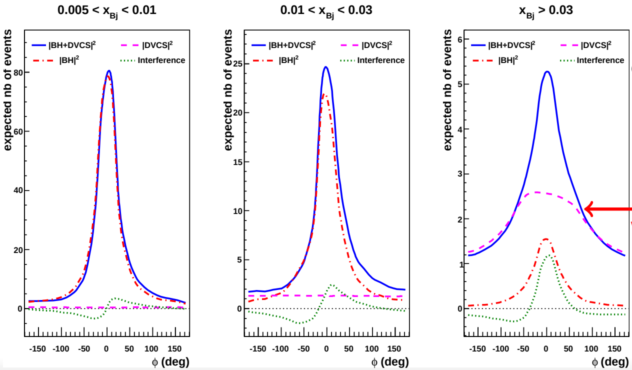
ECAL0

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



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

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



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

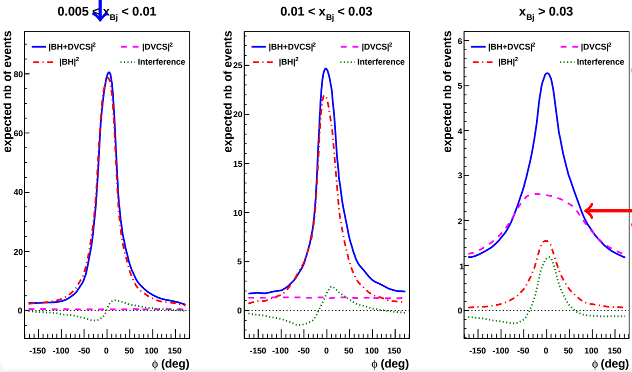
Missing DVCS acceptance without ECAL0

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

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

BH dominance at low-x_B

Excellent reference yield and control signal



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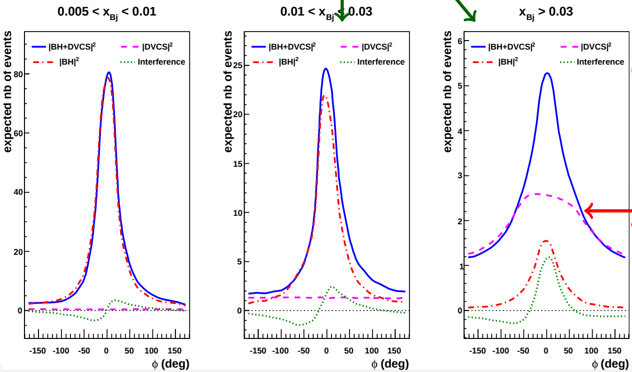
Missing DVCS acceptance without ECAL0

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

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

Int. term $\rightarrow$ real and imaginary parts of DVCS amplitude

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



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

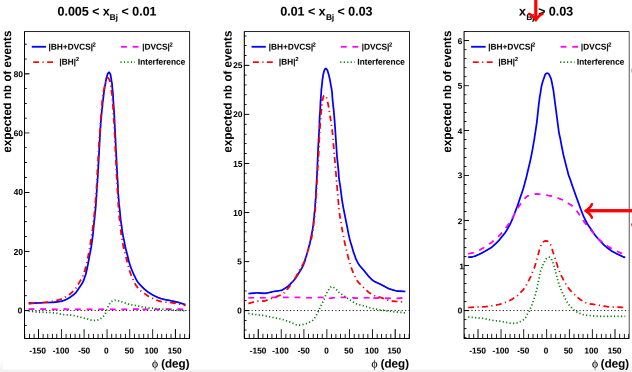
Missing DVCS acceptance without ECAL0

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

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

DVCS dominance at large-x_B

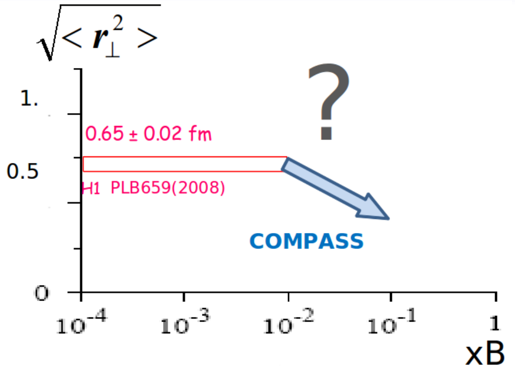
Transverse nucleon imaging ($d\sigma^{DVCS}/dt \sim \exp(-B|t|)$)

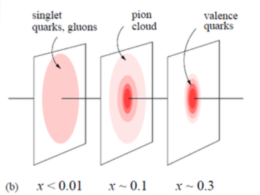


Monte-Carlo simulation for COMPASS set-up with only ECAL1+2

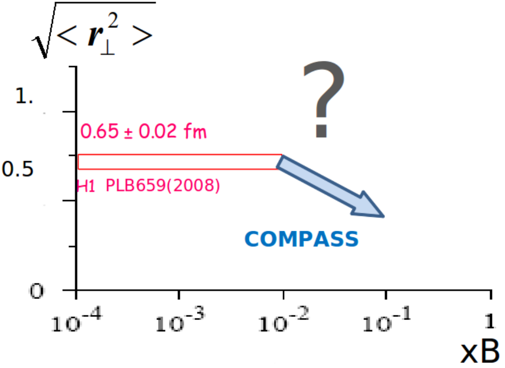
Missing DVCS acceptance without ECAL0

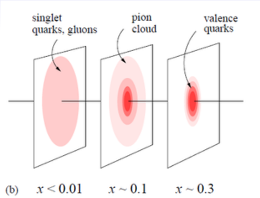
Transverse Size of the Nucleon (I)





Transverse Size of the Nucleon (I)



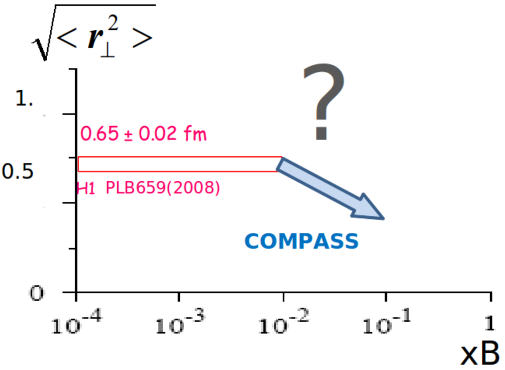


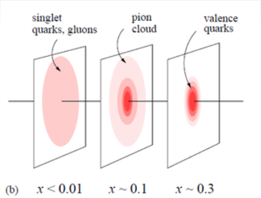
$$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$$

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

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

Transverse Size of the Nucleon (I)





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

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

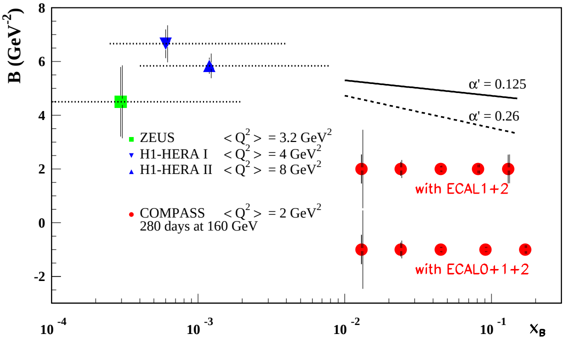
$r_\perp \rightarrow$ **Transverse size of the Nucleon**

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"**

Transverse Size of the Nucleon (II)

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

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



COMPASS Projected:

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

Ansatz at small $\mathbf{x_B}$:

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

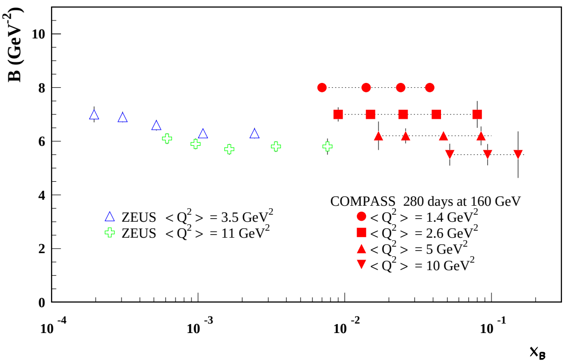
α' slope of Regge traject

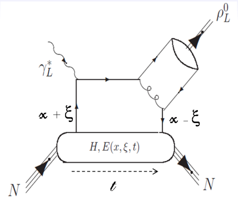
Accuracy $\geq 2.5\sigma$ if $\alpha' > 0.125$ and full ECALs

Systematic errors dominated by **BH subtraction** at low $\mathbf{x_B}$

Tranverse Imaging with Vector Mesons

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





Red points:

COMPASS ρ^0 projected

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

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

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

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

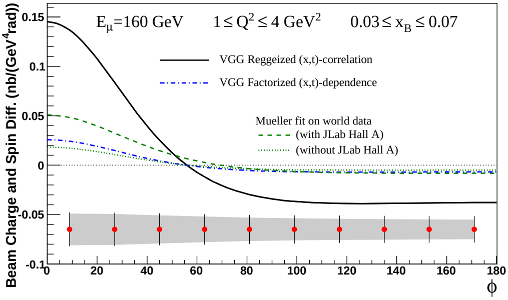
Angular Dependence of $\mathrm{d}\sigma$

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

Angular Dependence of $d\sigma$

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

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



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

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

$$c_{0,1}^{Int} \propto Re(F_1\mathcal{H})$$

Red points: COMPASS Projected

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

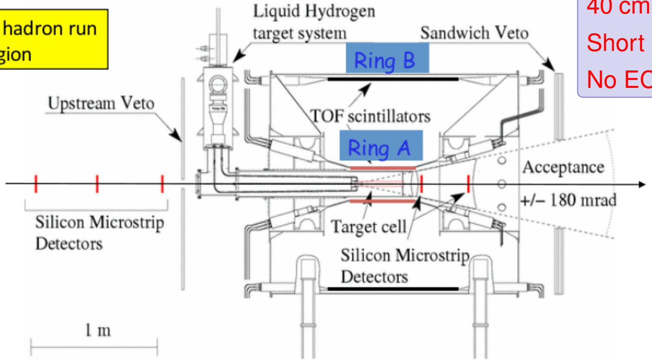
$Re\mathcal{H}(\xi,t)$ and $Im\mathcal{H}(\xi,t)$ $\rightarrow$ **Exp. constrain to GPD H!**

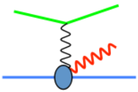
Syst. error: 3% charge-dependent effect between μ^+ and μ^-

2008-9 DVCS Test

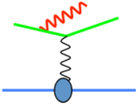
Compass hadron run
Target region

40 cm LH2 target
Short RPD
No ECAL0





DVCS



Bethe-Heitler

Selection of events :

- one vertex with μ and μ'
- no other charged tracks
- only 1 high energy photon (Δt<5ns)
- 1 proton in RPD with p < 1. GeV/c

2008-9 DVCS Test - Results

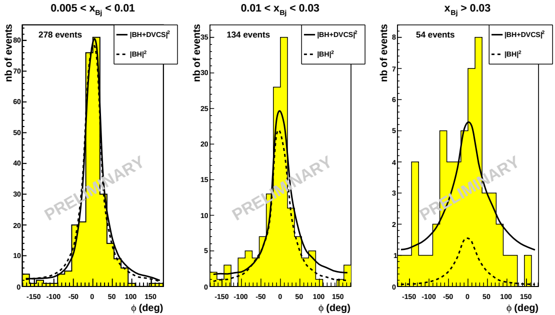
2008: observation of exclusive single photon production

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

DVCS and DVMP - Conclusions

- 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

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 1$^{\mathrm{st}}$ December 2010

COMPASS-II Conclusions & Outlook

COMPASS-II Physics Topics:

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- GPDs with DVCS and DVMP
- Precise unpolarized PDFs and FFs measurement

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COMPASS-II timelines as in proposal:

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