



Proposal for GPD studies at COMPASS

E. Burtin CEA-Saclay Irfu/SPhN

On behalf of the COMPASS Collaboration

MENU 2010 – College of William & Mary

Williamsburg - June 2nd, 2010

Proposal submitted to the SPS committee (May 17, 2010)

Physics topics:

- **Hard exclusive photon and meson production**
- **Unpolarized PDFs and TMD effects in SIDIS**
- **Pion induced Drell-Yan muon pair production (TMD)**
- **Experimental studies of chiral perturbation theory**

COMPASS II proposal available at : CERN-SPSC-2010-014 preprint

<http://cdsweb.cern.ch/record/1265628/files/SPSC-P-340.pdf>

Jura mountains

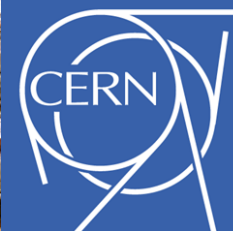
Lac Léman

COMPASS

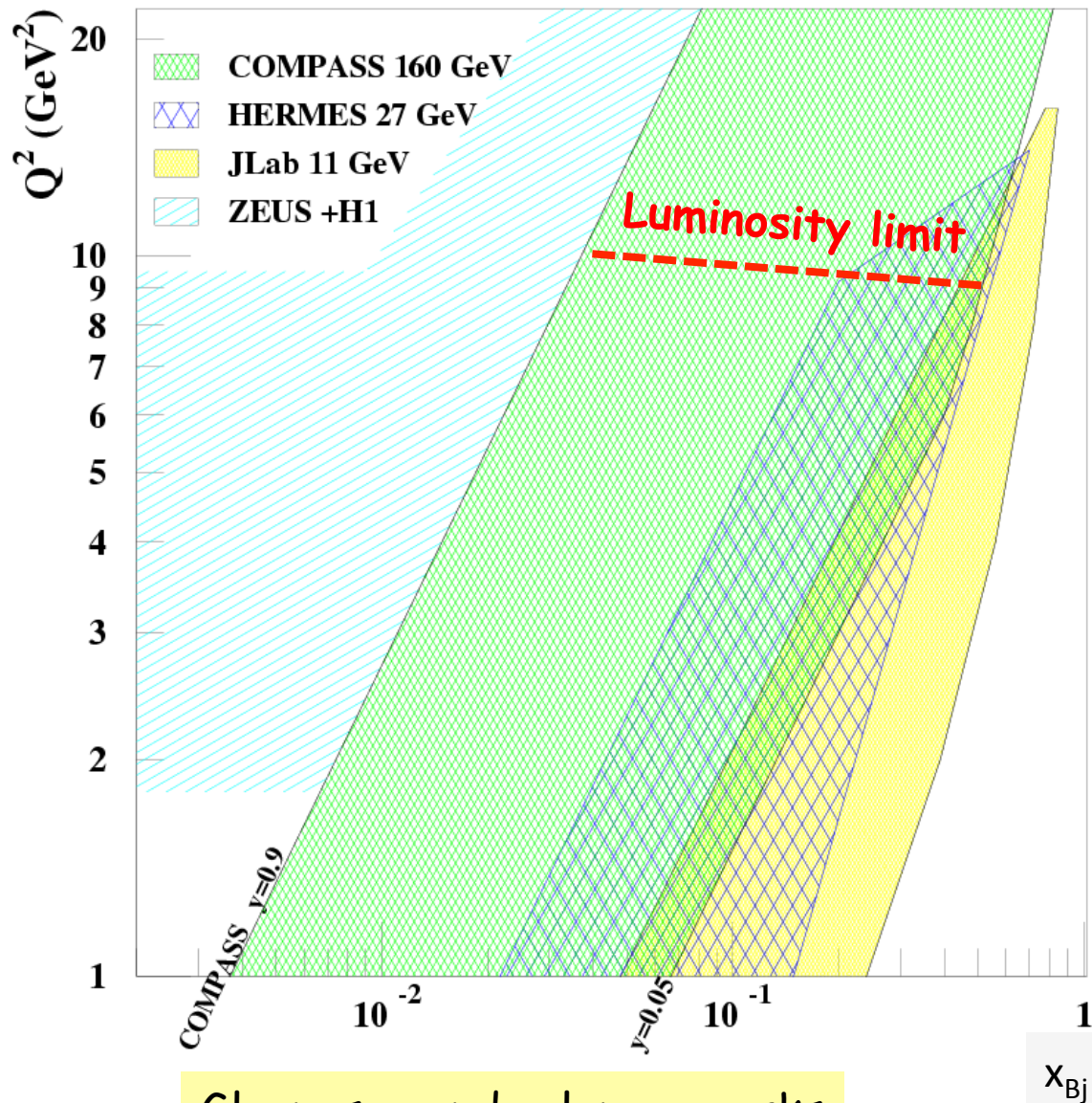


LHC

SPS



What makes Compass unique ?



Gluon, sea and valence quarks

CERN High energy muon beam

- 100 - 190 GeV
- 80% Polarisation
- μ^+ and μ^- available
 - ✓ Opposite polarization

Foreseen program :

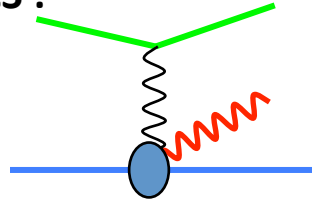
DVCS and meson production off a liquid H₂ target (unpolarized)

⇒ Will explore the intermediate x_{Bj} region

⇒ Uncovered region between ZEUS+H1 and HERMES+Jlab

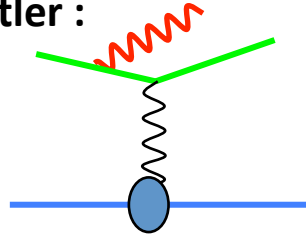
Comparison of BH and DVCS at 160 GeV

DVCS :

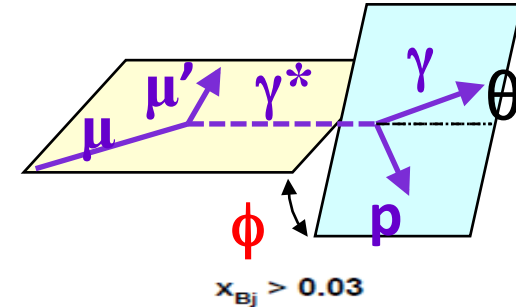


$$0.005 < x_{Bj} < 0.01$$

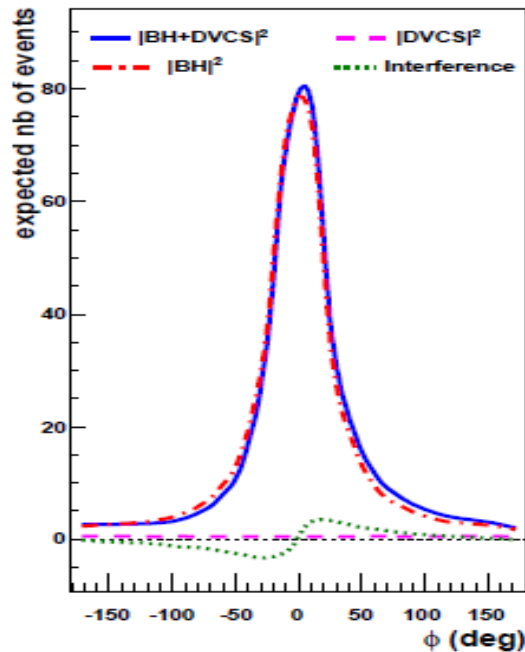
Bethe-Heitler :



$$0.01 < x_{Bj} < 0.03$$

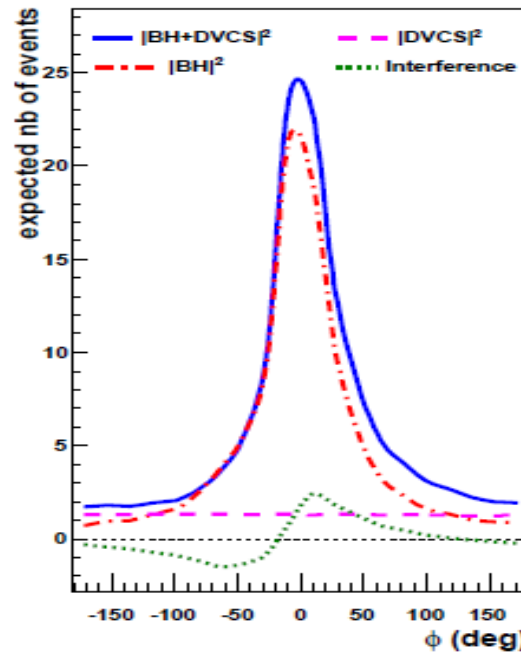


$$x_{Bj} > 0.03$$



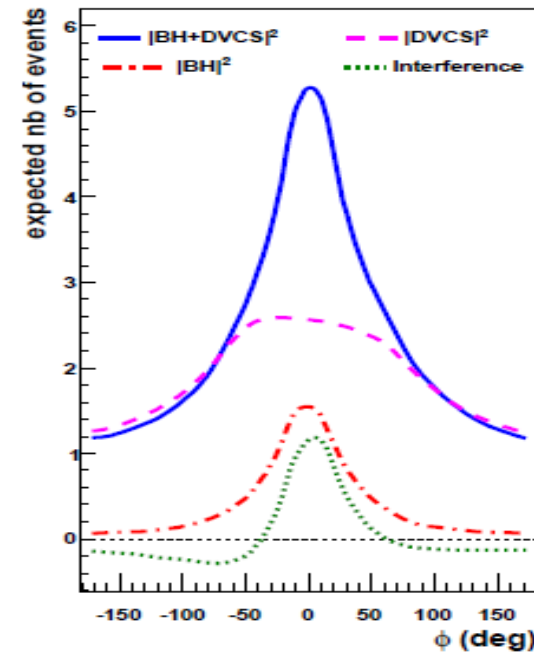
BH dominates

excellent
reference yield



BH and DVCS at the same level

access DVCS amplitude
through the interference

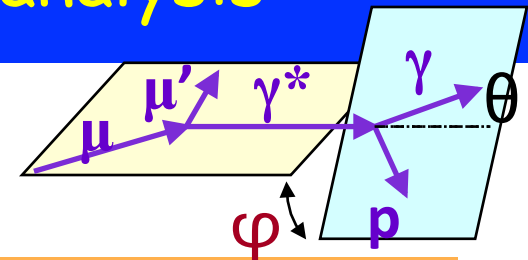


DVCS dominates

study of $d\sigma^{DVCS}/dt$

Azimuthal angular dependence analysis

from Belitsky, Kirchner, Müller :
polarized beam off unpolarized target



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

$$d\sigma^{BH} = \frac{\Gamma(x_B, Q^2, t)}{P_1(\varphi)P_2(\varphi)} (c_0^{BH} + c_1^{BH} \cos \varphi + c_2^{BH} \cos 2\varphi) \leftarrow \text{Known expression}$$

$$d\sigma^{DVCS}_{unpol} = \frac{e^6}{y^2 Q^2} (c_0^{DVCS} + c_1^{DVCS} \cos \varphi + c_2^{DVCS} \cos 2\varphi)$$

$$P_\mu \times d\sigma^{DVCS}_{pol} = \frac{e^6}{y^2 Q^2} (s_1^{DVCS} \sin \varphi)$$

$$e_\mu \times a^{BH} \Re A^{DVCS} = \frac{e^6}{xy^3 + P_1(\varphi)P_2(\varphi)} (c_0^{Int} + c_1^{Int} \cos \varphi + c_2^{Int} \cos 2\varphi + c_3^{Int} \cos 3\varphi)$$

$$e_\mu P_\mu \times a^{BH} \Im A^{DVCS} = \frac{e^6}{xy^3 + P_1(\varphi)P_2(\varphi)} (s_1^{Int} \sin \varphi + s_2^{Int} \sin 2\varphi)$$

Twist-2 M^{11}

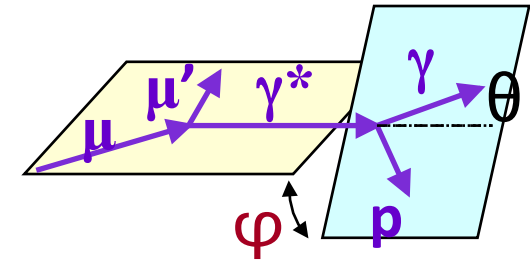
>>

Twist-3 M^{01}

Twist-2 gluon M^{-11}

Angular dependence analysis

Case of COMPASS : $\mu+(P=-0.8)$ and $\mu-(P=+0.8)$
unpolarized H_2 target



$$S_{U,CS} : d\sigma_{\mu+} + d\sigma_{\mu-} = 2(d\sigma^{BH} + d\sigma^{DVCS}_{unpol}) + 2 e_{\mu} P_{\mu} a^{BH} Im A^{DVCS}$$

$$c_0^{DVCS+BH} + c_1^{DVCS+BH} \cos \varphi + c_2^{DVCS+BH} \cos 2\varphi$$

=> $d\sigma/dt$

$$s_1^{Int} \sin \varphi + s_2^{Int} \sin 2\varphi$$

=> $Im(F_1 \mathcal{H})$

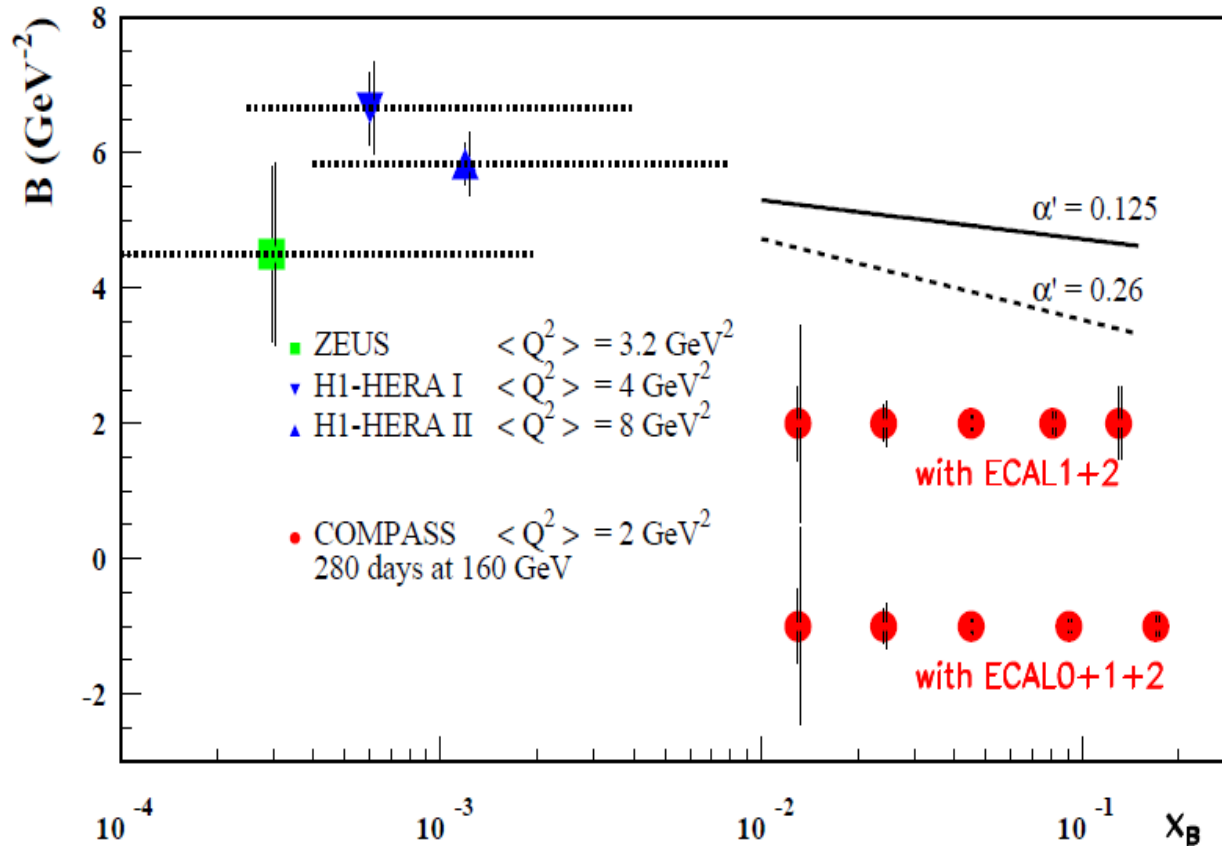
$$D_{U,CS} : d\sigma_{\mu+} - d\sigma_{\mu-} = 2 P_{\mu} d\sigma^{DVCS}_{pol} + e_{\mu} a^{BH} Re A^{DVCS}$$

$$s_1^{DVCS} \sin \varphi$$

$$c_0^{Int} + c_1^{Int} \cos \varphi + c_2^{Int} \cos 2\varphi + c_3^{Int} \cos 3\varphi$$

=> $Re(F_1 \mathcal{H})$

From $S_{U,CS}$: transverse imaging



Using $S_{U,CS}$:

$$d\sigma_{DVCS} / dt \sim \exp(-Bt)$$

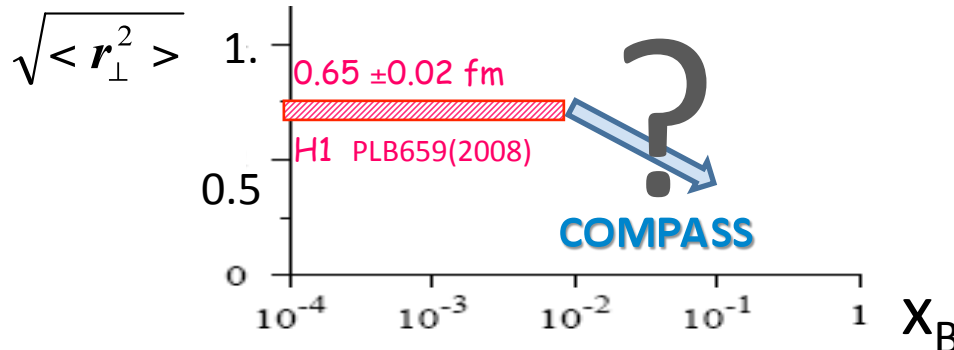
$$B \sim \frac{1}{2} \langle r^2 \rangle$$

Ansatz at small x :

$$B(x) = b_0 + 2 \alpha' \ln(x_0/x)$$

$$\alpha' = 0.125 \text{ GeV}^{-2} \text{ (FFS)}$$

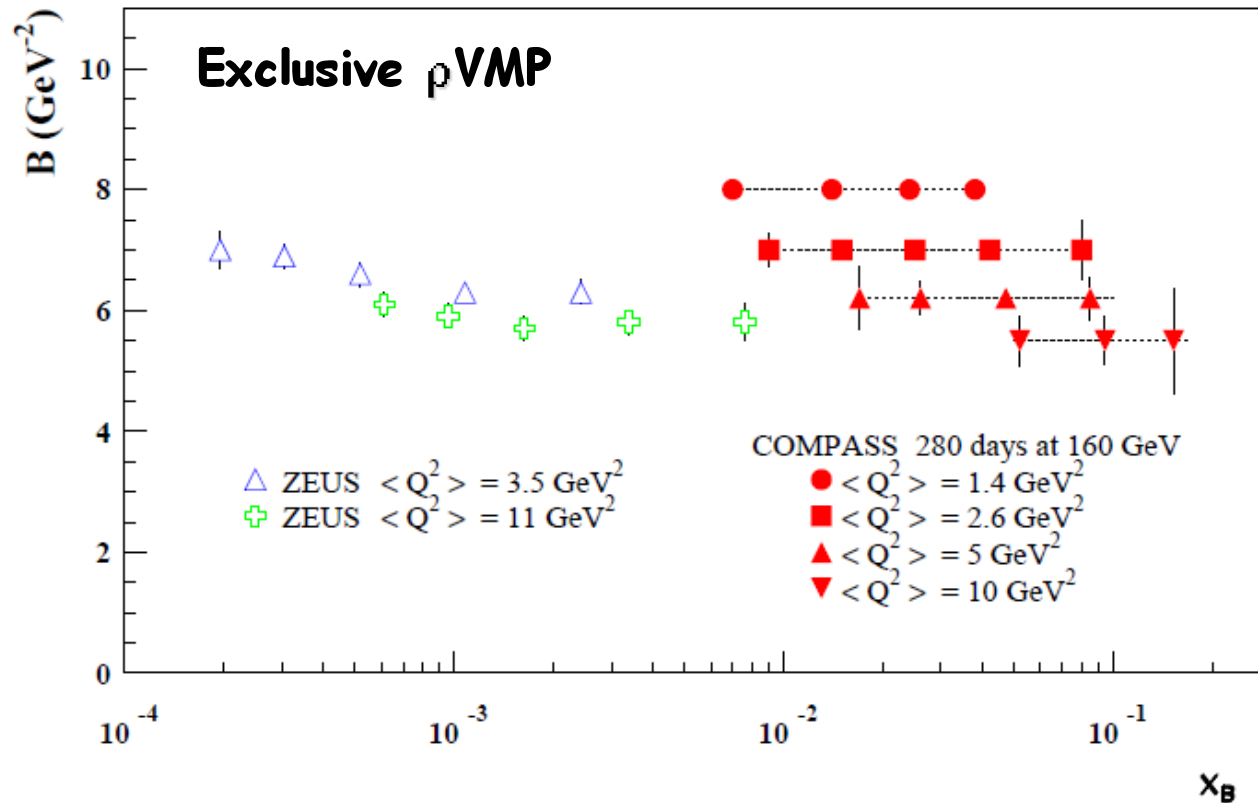
160 GeV muon beam
 2.5m LH₂ target
 2 years
 $L = 1222 \text{ pb}^{-1}$
 $\epsilon_{\text{global}} = 10 \%$



Assuming 3% syst. error on BH subtraction

2.5 σ slope meas. for:
 $\alpha' > 0.26$ (ECAL 1+2)
 $\alpha' > 0.125$ (ECAL 0+1+2)

Exclusive production of rho mesons



$$d\sigma_{\rho\text{VMP}} / dt \sim \exp(-Bt)$$

ρ VMP model developed
by Sandacz
Normalised according
Goloskokov and Kroll

160 GeV muon beam
2.5m LH₂ target
2 years
L = 1222 pb⁻¹
 $\epsilon_{\text{global}} = 10 \%$

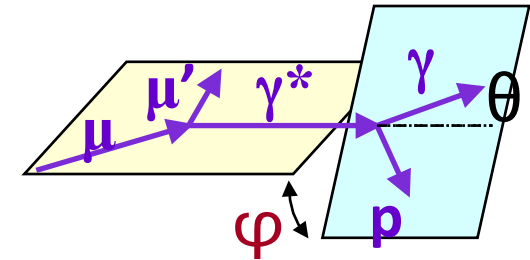
Sensitive to the nucleon size
+ the transverse size of the meson

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

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

Angular dependence analysis

Case of COMPASS : $\mu+(P=-0.8)$ and $\mu-(P=+0.8)$
unpolarized H_2 target



$$\mathcal{S}_{U,CS} : d\sigma_{\mu+} + d\sigma_{\mu-} = 2(d\sigma^{BH} + d\sigma^{DVCS}_{unpol}) + 2 e_{\mu} P_{\mu} a^{BH} \text{Im} A^{DVCS}$$

$$c_0^{DVCS+BH} + c_1^{DVCS+BH} \cos \varphi + c_2^{DVCS+BH} \cos 2\varphi$$

=> $d\sigma/dt$

$$s_1^{Int} \sin \varphi + s_2^{Int} \sin 2\varphi$$

=> $\text{Im}(\mathbf{F}_1 \mathcal{H})$

$$\mathcal{D}_{U,CS} : d\sigma_{\mu+} - d\sigma_{\mu-} = 2 P_{\mu} d\sigma^{DVCS}_{pol} + e_{\mu} a^{BH} \text{Re} A^{DVCS}$$

$$s_1^{DVCS} \sin \varphi$$

$$c_0^{Int} + c_1^{Int} \cos \varphi + c_2^{Int} \cos 2\varphi + c_3^{Int} \cos 3\varphi$$

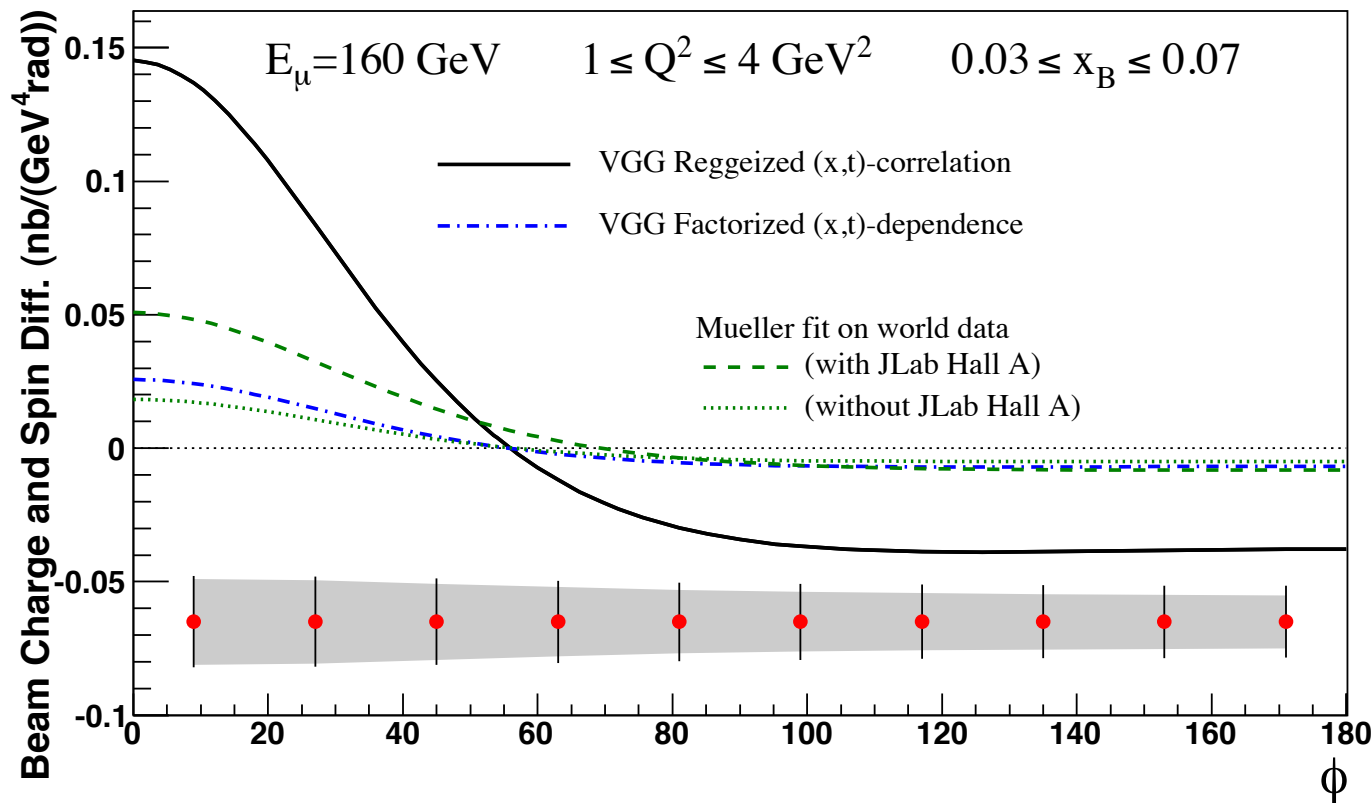
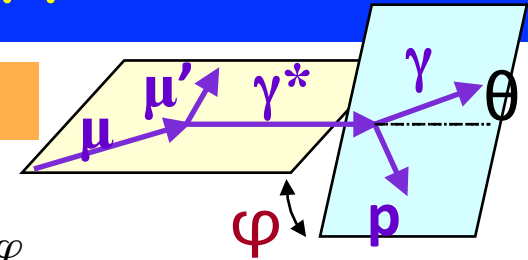
=> $\text{Re}(\mathbf{F}_1 \mathcal{H})$

$\mathcal{D}_{U,CS}$: Beam Charge & Spin Difference

$$\mathcal{D}_{U,CS} : d\sigma_{\mu^+} - d\sigma_{\mu^-} = 2 P_{\mu} d\sigma_{pol}^{DVCS} + e_{\mu} a^{BH} \mathcal{R}e A^{DVCS}$$

$$s_1^{DVCS} \sin \varphi$$

$$c_0^{Int} + c_1^{Int} \cos \varphi + c_2^{Int} \cos 2\varphi + c_3^{Int} \cos 3\varphi$$



160 GeV muon beam
2.5m LH₂ target
2 years
L = 1222 pb⁻¹
ε_{global} = 10 %

$$\dots + c_1^{Int} \cos \varphi + \dots$$

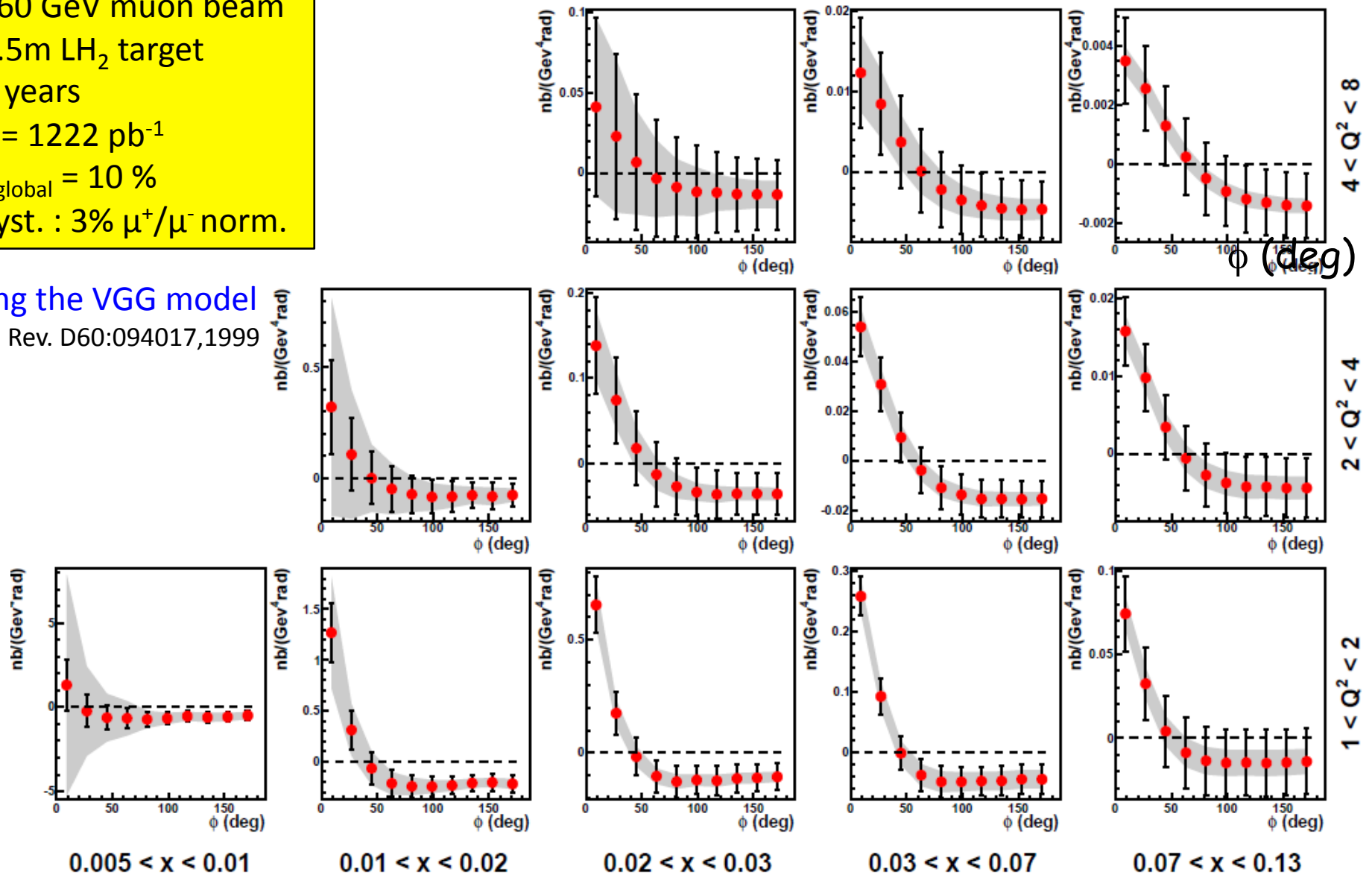
$$\Rightarrow \mathcal{R}e(F_1 \mathcal{H})$$

Systematic errors : 3% charge-dependent effect between μ^+ and μ^-

$\mathcal{D}_{U,CS}(\phi)$ over the kinematical domain

160 GeV muon beam
 2.5m LH₂ target
 2 years
 $L = 1222 \text{ pb}^{-1}$
 $\epsilon_{\text{global}} = 10 \%$
 Syst. : 3% μ^+/μ^- norm.

using the VGG model
 Phys. Rev. D60:094017,1999



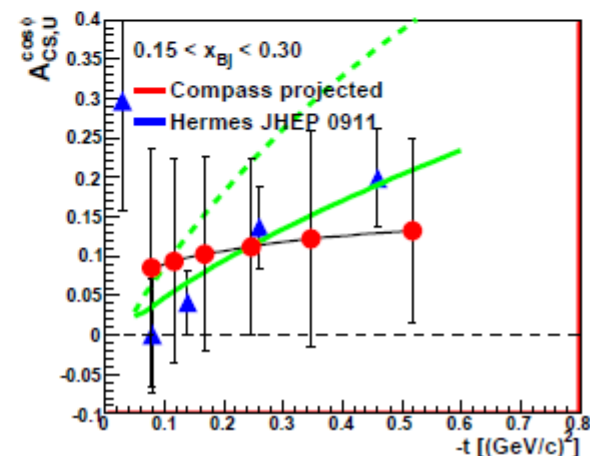
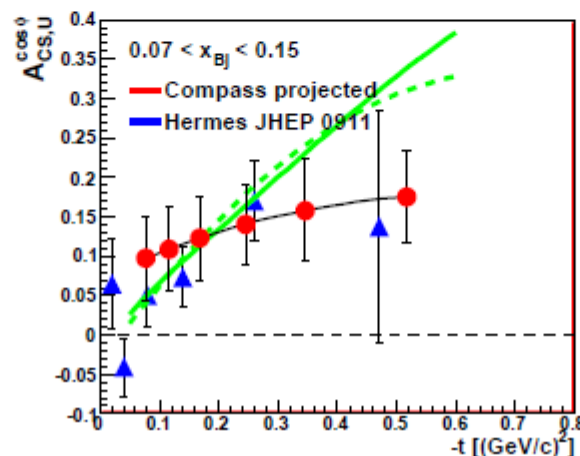
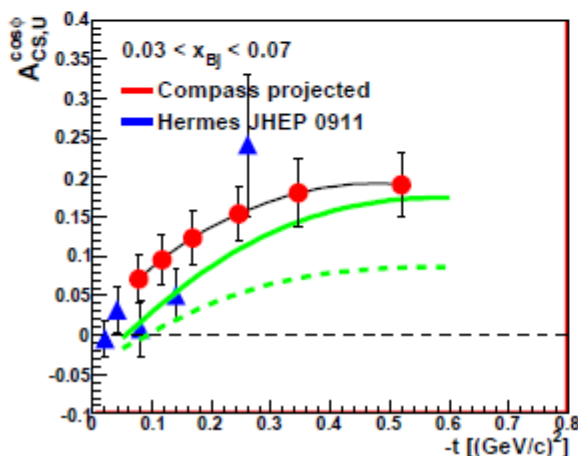
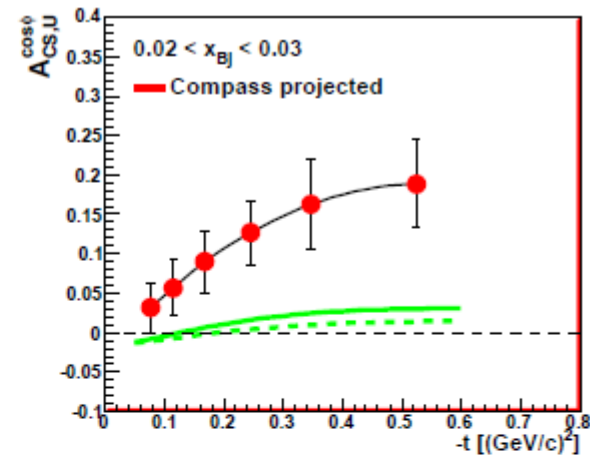
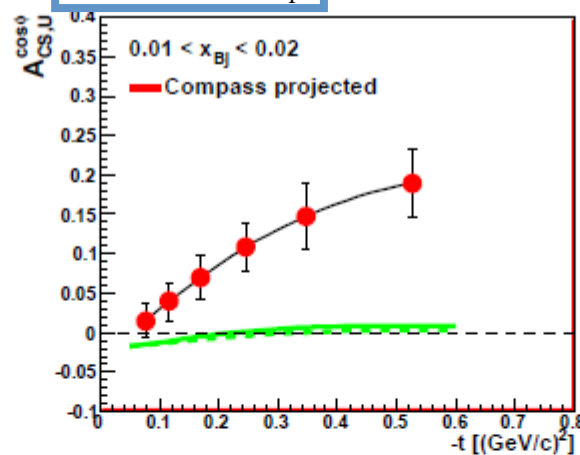
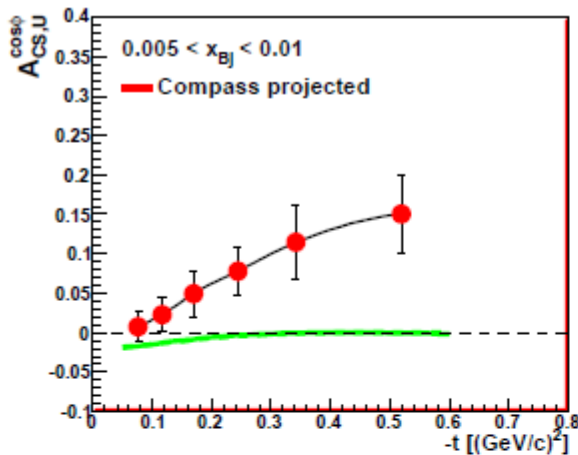
Sensitivity of COMPASS: $\cos\phi$ modulation

$$BCSA = \mathcal{D}_{U,CS} / S_{U,CS} = A_0 + A_{CS,U} \cos\phi + A_2 \cos 2\phi$$

\Rightarrow related to c_1^{Int}

Mueller's fit on world data'

- (with JLab Hall A)
- - - (without JLab Hall A)

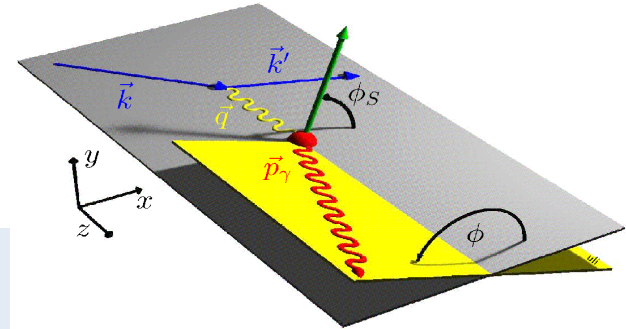


Continuation of the GPD program : constrain the GPD E

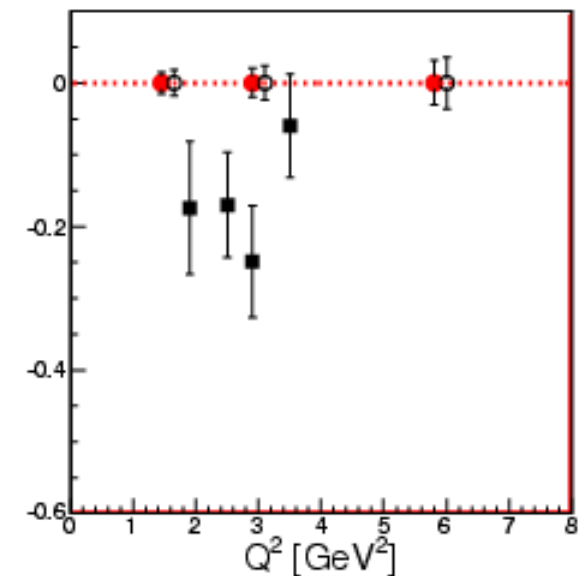
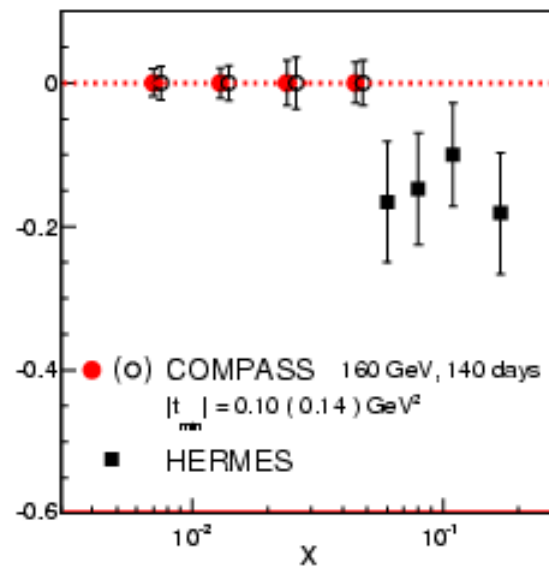
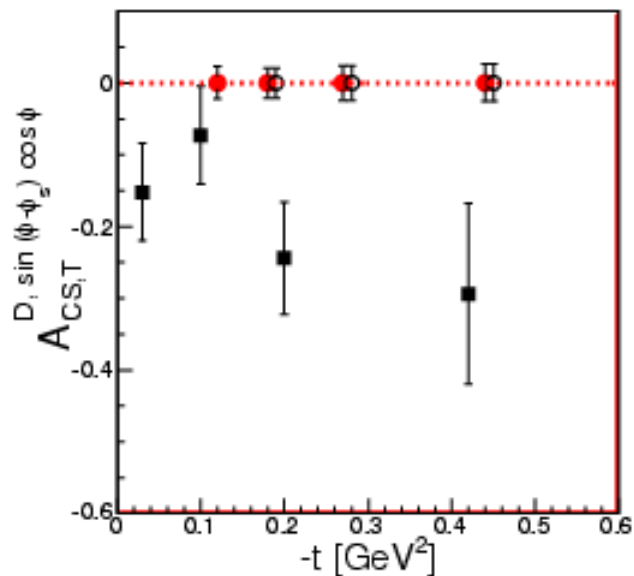
with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam and transversely polarized NH3 (proton) target

$$D_{T,CS} \equiv d\sigma_T (\mu^{+\downarrow}) - d\sigma_T (\mu^{-\uparrow})$$

$$\propto \text{Im}(\mathbf{F}_2 \mathcal{H} - \mathbf{F}_1 \mathcal{E}) \sin(\phi - \phi_S) \cos \phi$$



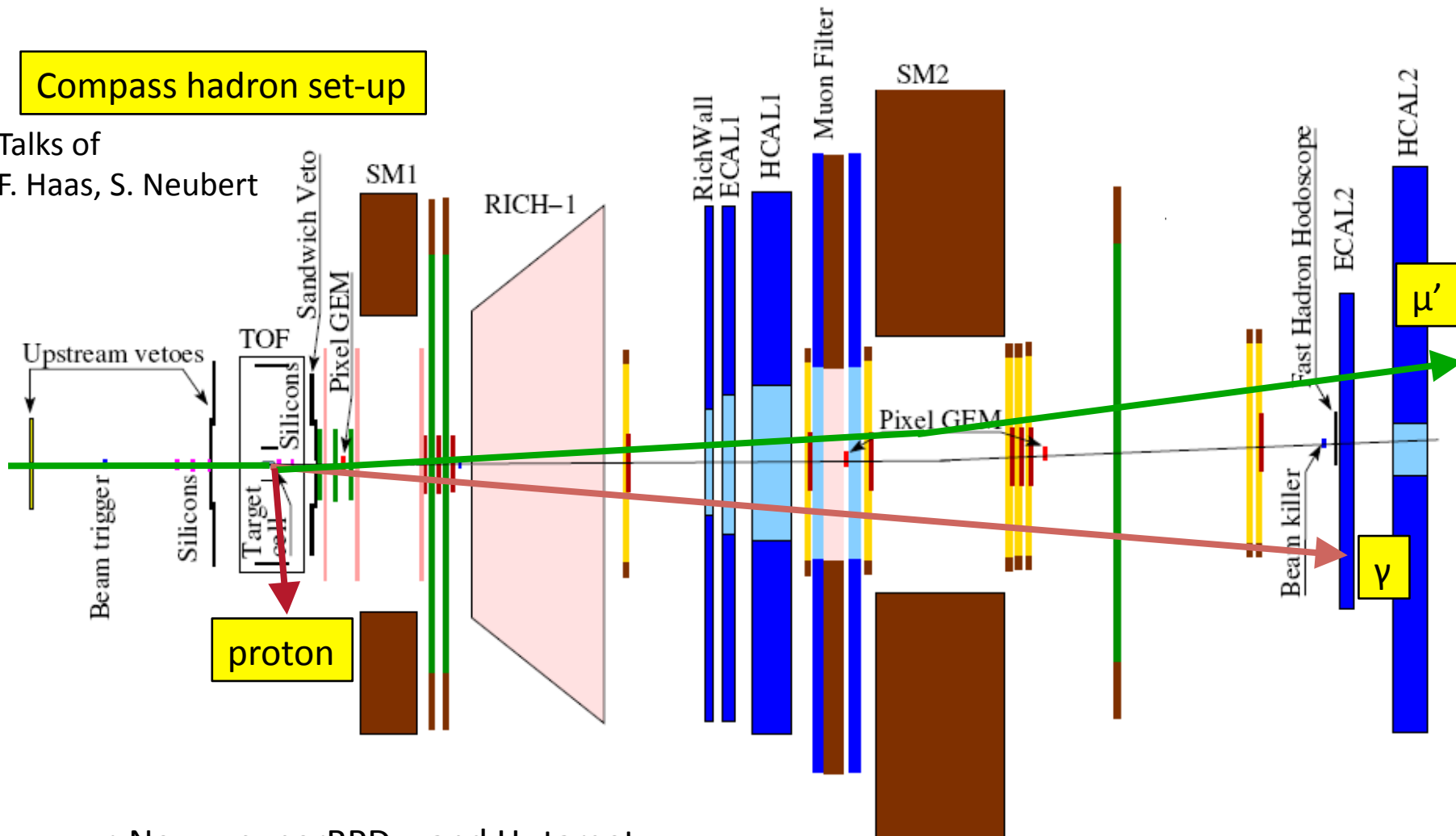
160 GeV muon beam
1.2 m polarized NH3 target (f=0.26)
2 years - $\epsilon_{\text{global}} = 10\%$



Experimental realisation

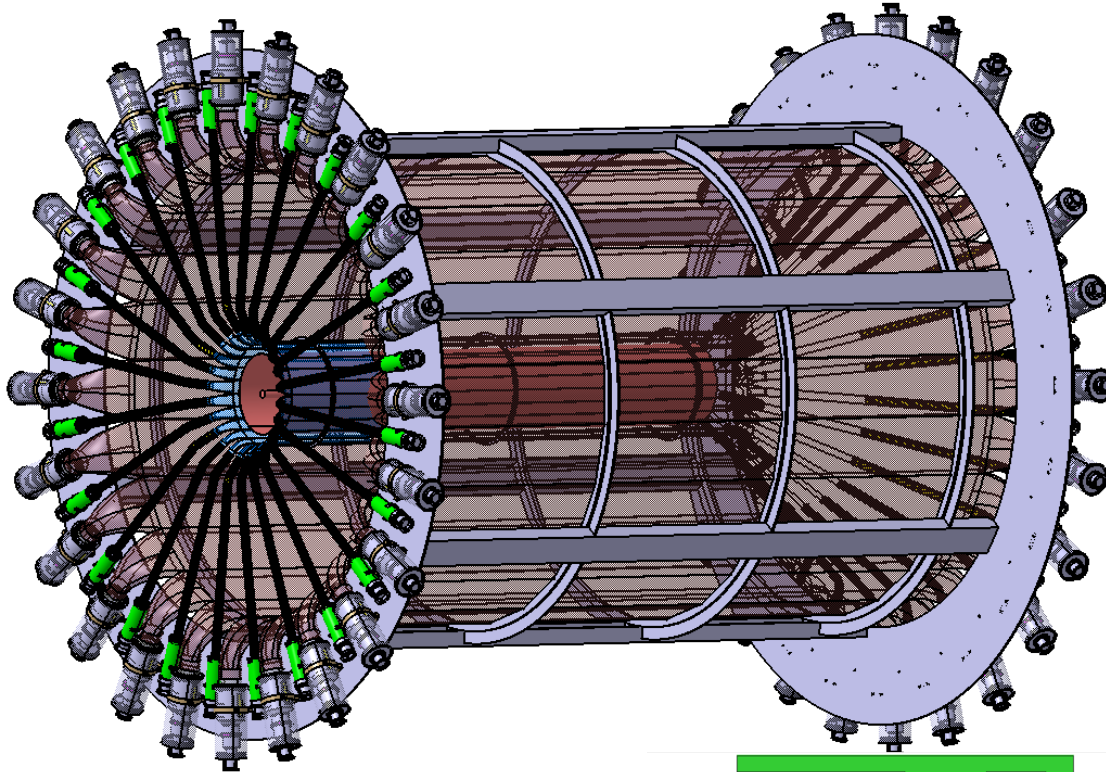
Compass hadron set-up

Talks of
F. Haas, S. Neubert



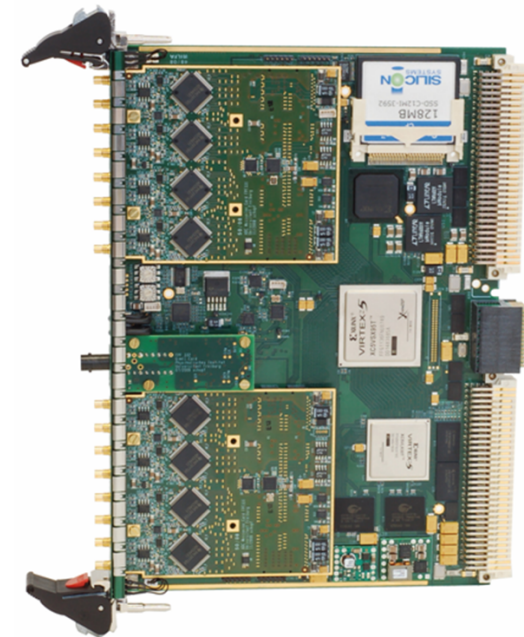
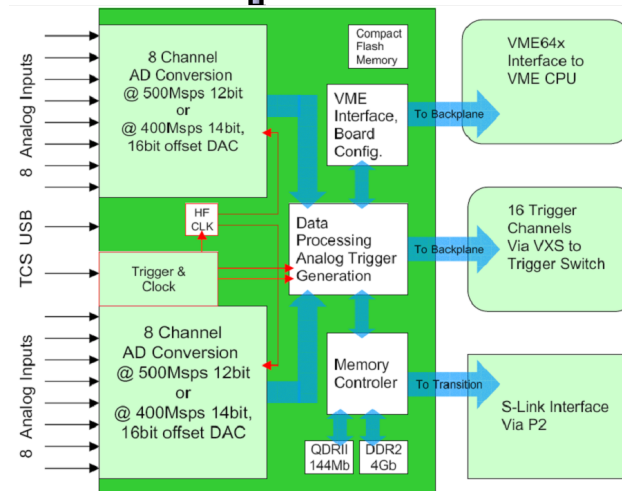
- New « superRPD » and H₂ target
- Hermetic calorimetry : Move ECALs upstream and/or complete ECAL2
- New ECAL0 upstream of SM1

Recoil Proton Detector



- 4 m long scintillator slabs
- ~ 300ps timing resolution
- Full scale prototype tested successfully

Gandalf Project:
1 GHz digitalisation
of the PMT signal to
cope for high rate



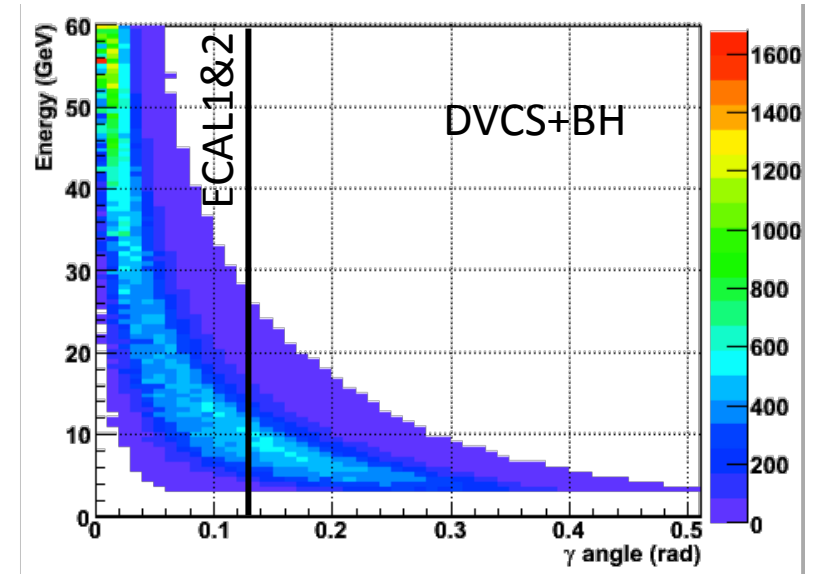
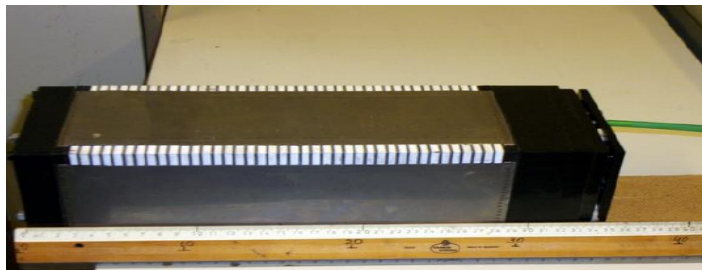
ECAL 0

Requirements

- Photon energy range 0.2- 30 GeV
- Size: 320cm x 320cm ;
- Granularity 4x4 - 6x6 cm²
- Energy resolution $< 10.0\%/\sqrt{E}$ (GeV)
- Thickness < 50 cm,
- Insensitive to the magnetic field.

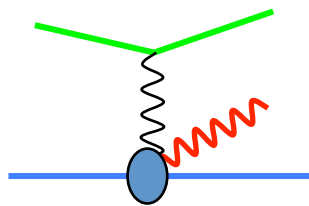
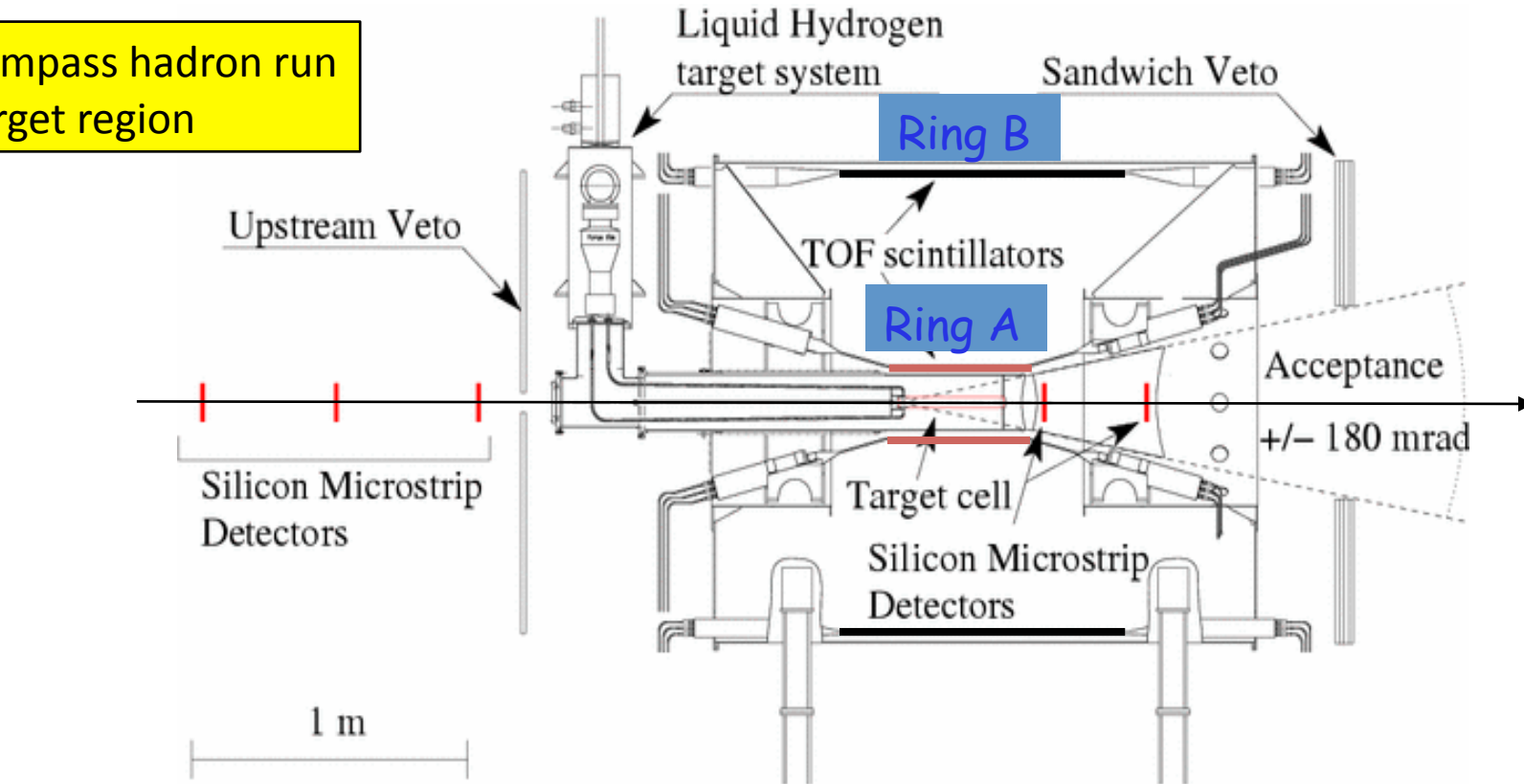
Prototype under studies

- Shaschlyk module with AMPD readout
- Tested

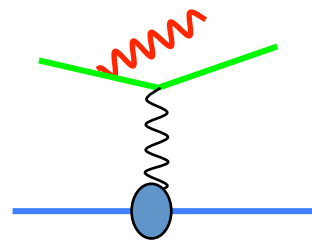


2008-2009 DVCS tests

Compass hadron run
Target region



DVCS

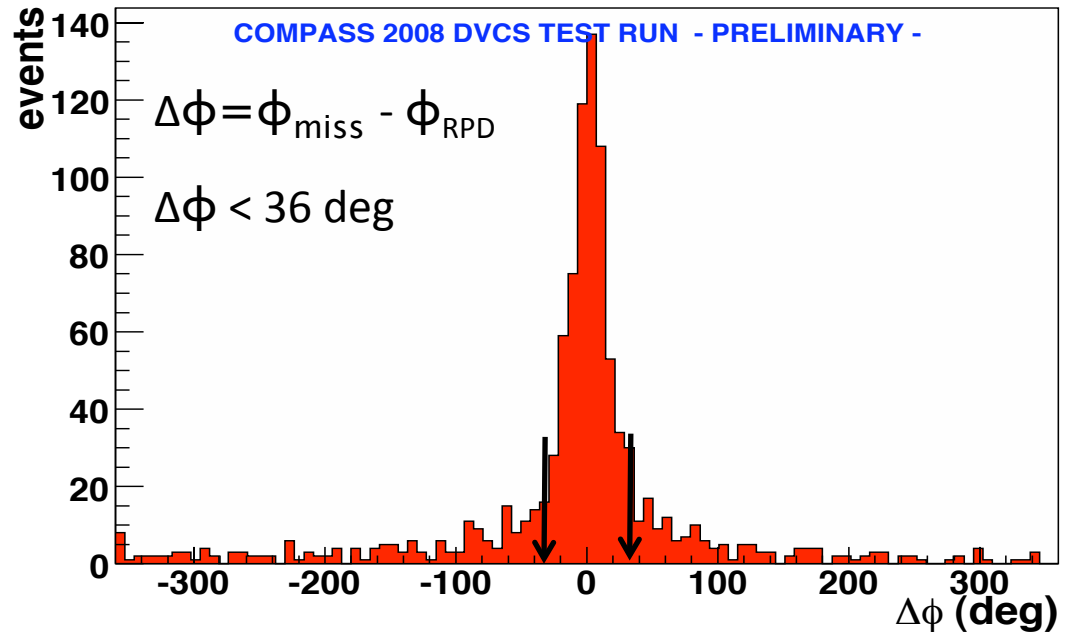
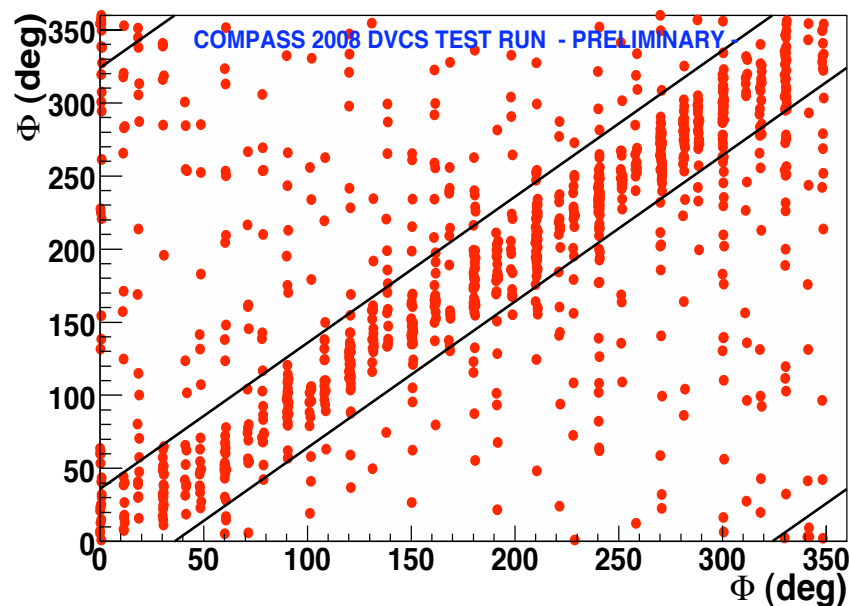
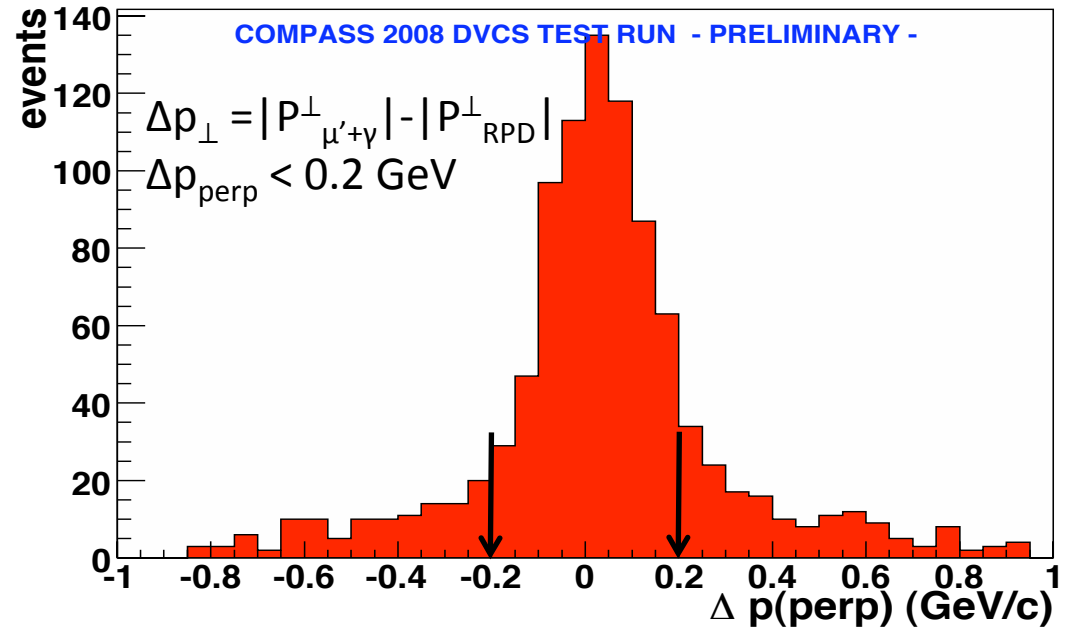
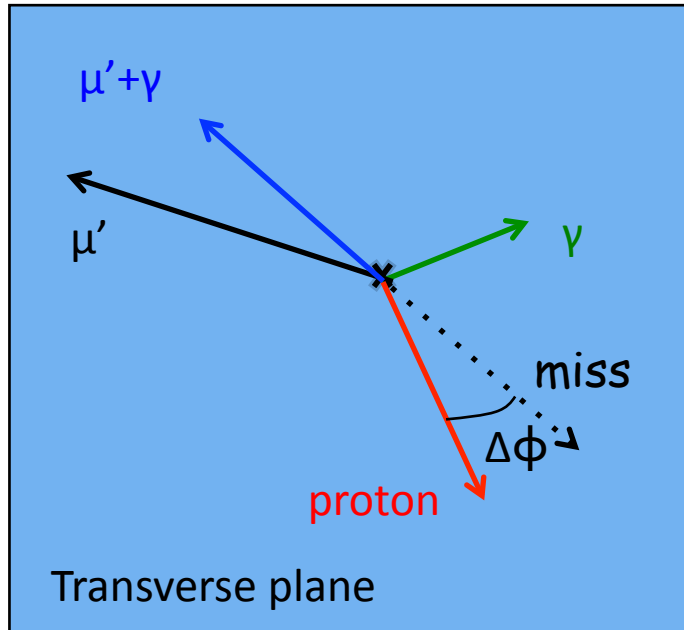


Bethe-Heitler

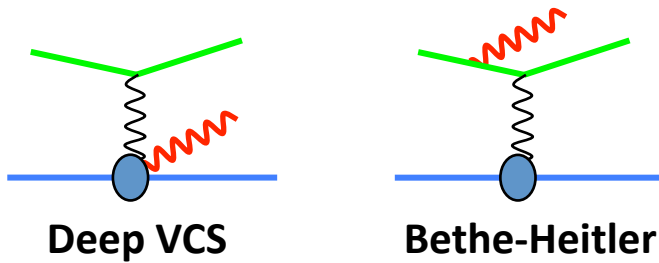
Selection of events :

- 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 beam test : exclusivity cuts

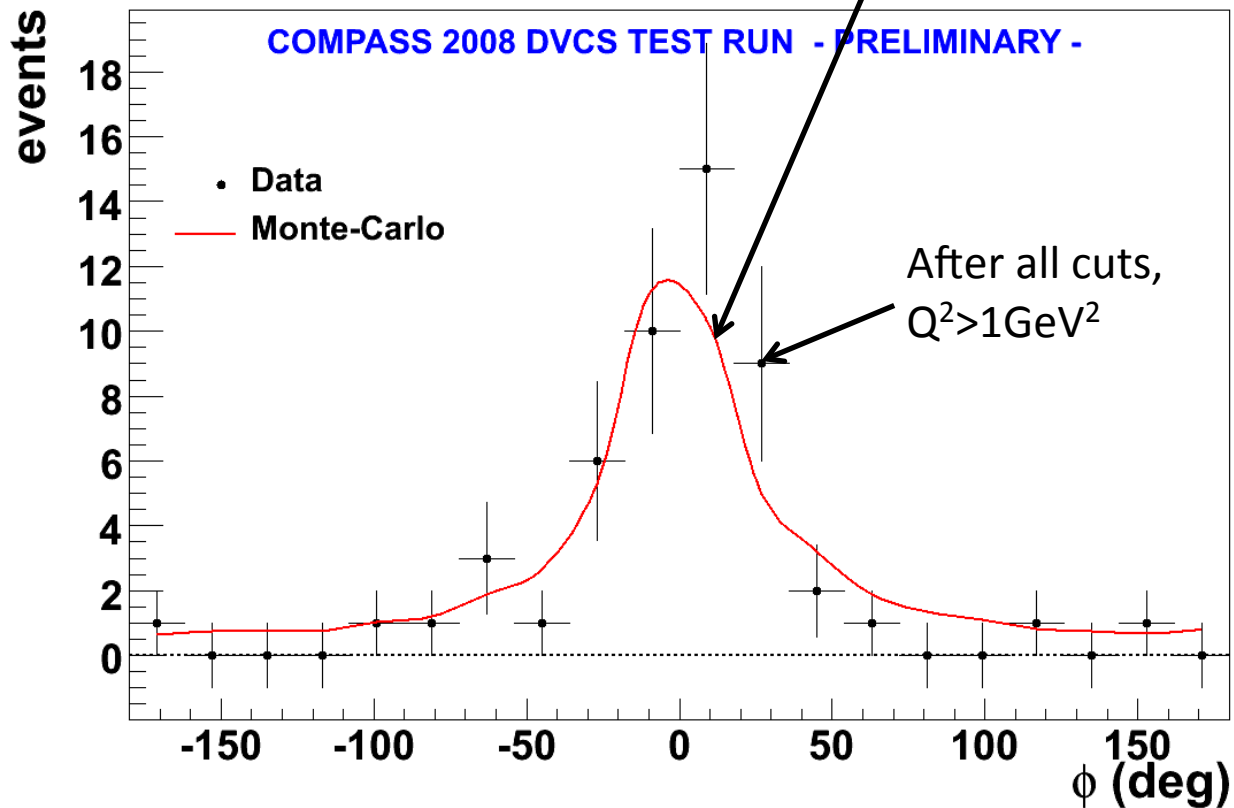


2008 beam test : Bethe-Heitler signal



Monte-Carlo simulation
of BH (dominant) and DVCS

=> Bethe-Heitler observed



~ 10 times more data taken in 2009

Detection efficiency :

$$\epsilon_{\mu+p \rightarrow \mu+p+\gamma} = 0.32 \pm 0.13$$

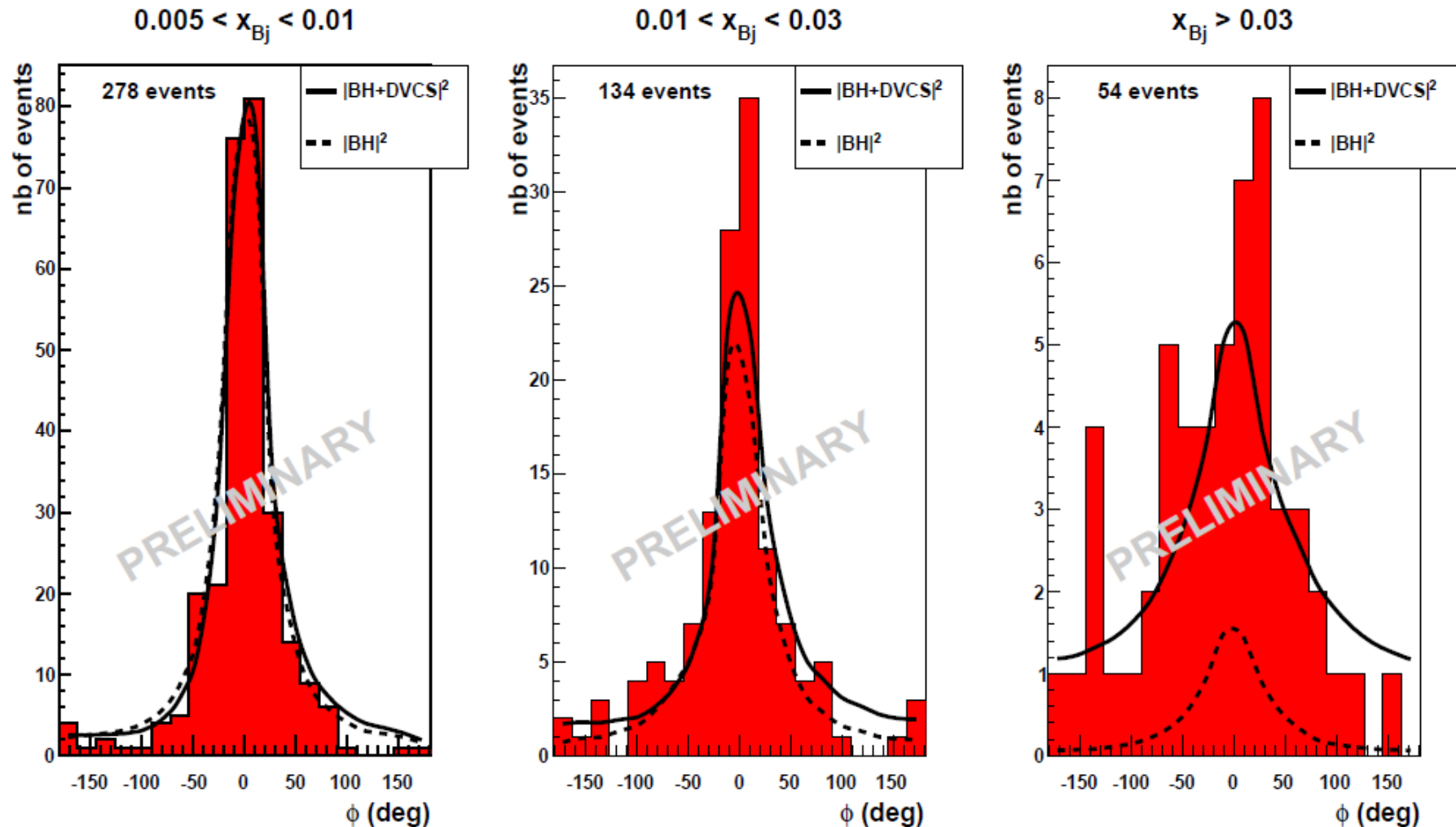
Global efficiency :

- $\mu+p \rightarrow \mu+p+\gamma$ efficiency
- SPS & COMPASS availability
- Dead time
- trigger efficiency

$$\Rightarrow \epsilon_{\text{global}} = 0.13 \pm 0.05$$

**Projections of errors
are realistic**

2009 beam test : DVCS signal



~ 10 times more data taken than in 2008

⇒ Excess of events for $x_{bj} > 0.03$
is a sign for DVCS

Conclusions & perspectives

the COMPASS-II proposal has been submitted

- Wide physics case proposed :
GPDs, TMDs, Chiral perturbation theory, unpolarized PDFs
- SPS Committee meets at the end June

COMPASS has a great potential in GPDs physics

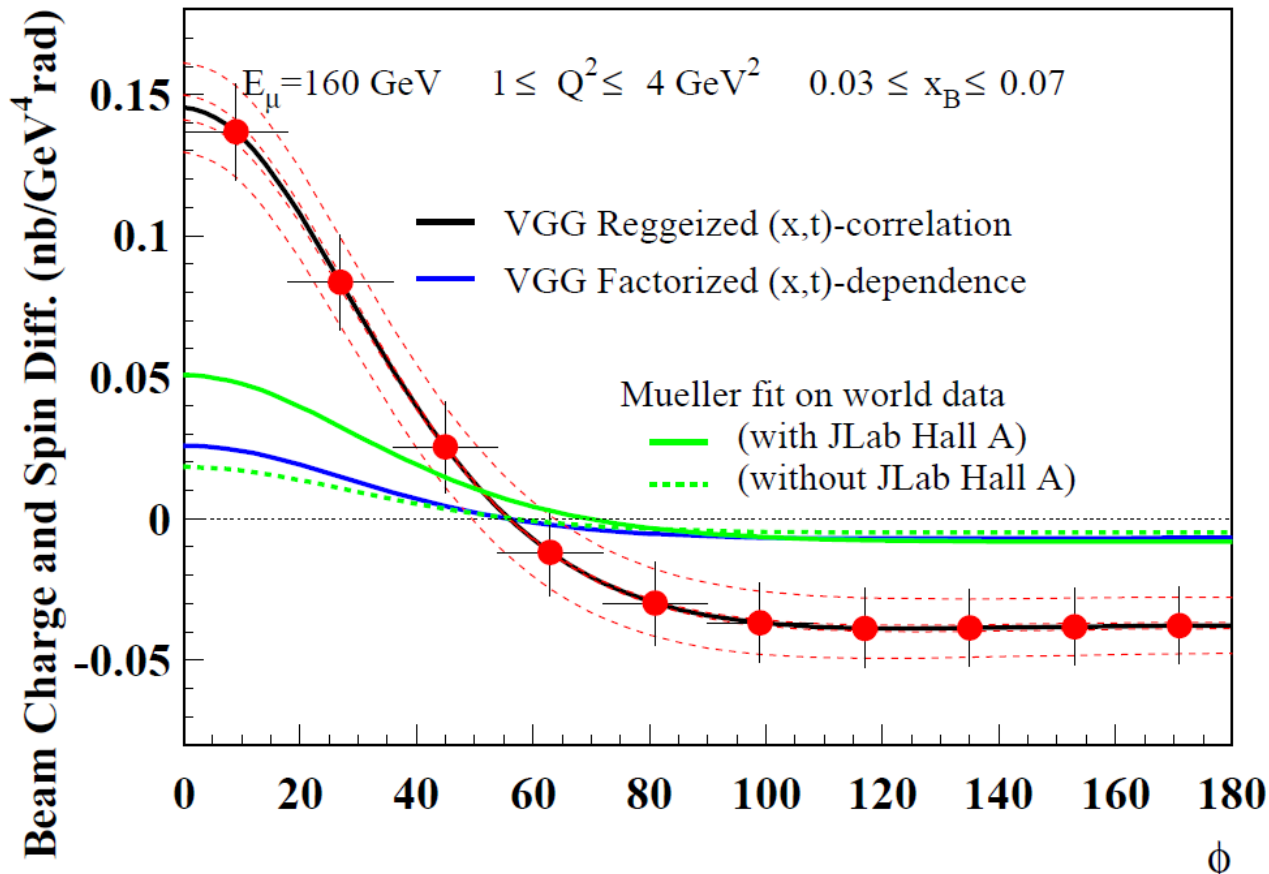
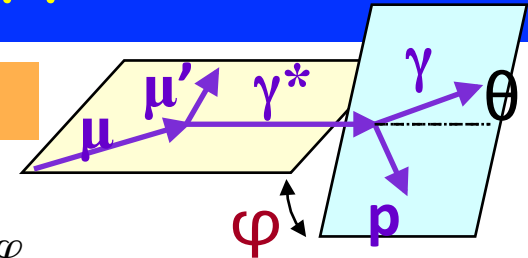
- Study of the GPD H with a LH2 target: 2013-
measurement of t-slopes - transverse partonic structure of the nucleon
measurement of Beam Charge and Spin differences & asymmetries
- Equipments needed :
4m long RPD, 2.5m LH2 target, Extended & improved calorimetry
- at a later stage :
study of the GPD E with a transversely polarized target

$\mathcal{D}_{U,CS}$: Beam Charge & Spin Difference

$$\mathcal{D}_{U,CS} : d\sigma_{\mu^+} - d\sigma_{\mu^-} = 2 P_{\mu} d\sigma_{pol}^{DVCS} + e_{\mu} a^{BH} \mathcal{R}e A^{DVCS}$$

$$s_1^{DVCS} \sin \varphi$$

$$c_0^{Int} + c_1^{Int} \cos \varphi + c_2^{Int} \cos 2\varphi + c_3^{Int} \cos 3\varphi$$



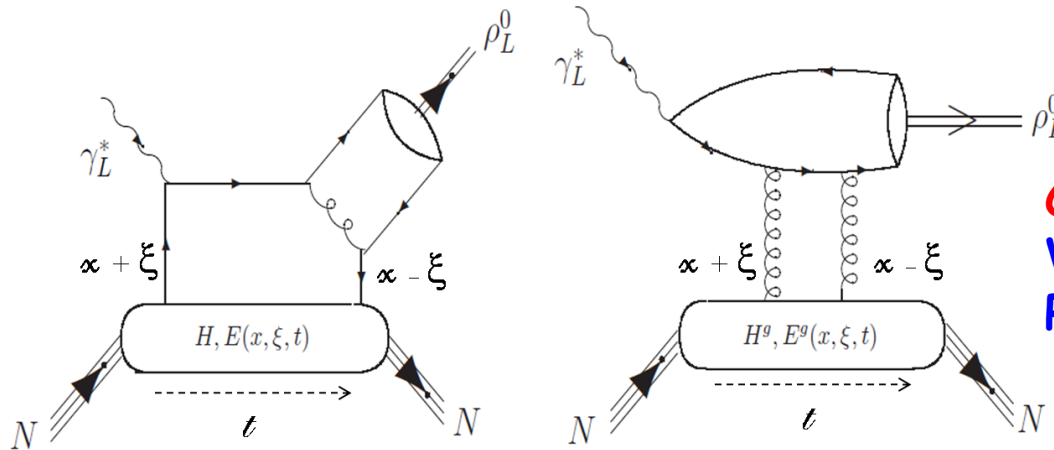
160 GeV muon beam
 2.5m LH₂ target
 2 years
 $L = 1222 \text{ pb}^{-1}$
 $\epsilon_{\text{global}} = 10 \%$

$$\dots + c_1^{Int} \cos \varphi + \dots$$

$$\Rightarrow \mathcal{R}e(F_1 \mathcal{H})$$

Systematic errors : 3% charge-dependent effect between μ^+ and μ^-

Meson production : filter of GPDs



Cross section measurement :

Vector meson : $\rho, \omega, \phi \dots \Rightarrow H \text{ \& \ } E$

Pseudo-scalar : $\pi, \eta \dots \Rightarrow \tilde{H} \text{ \& \ } \tilde{E}$

Would allow for flavor separation :

$$H_{\rho^0} = 1/\sqrt{2} (2/3 H^u + 1/3 H^d + 3/8 H^g)$$

$$H_{\omega} = 1/\sqrt{2} (2/3 H^u - 1/3 H^d + 1/8 H^g)$$

$$H_{\phi} = -1/3 H^s - 1/8 H^g$$

$$\Rightarrow \rho : \omega : \phi \sim 9 : 1 : 2 \text{ at large } Q^2$$

Transversely polarized target asymmetry on vector meson :

$\Rightarrow E/H$ (studied at COMPASS without RPD)

GPD program : new equipments

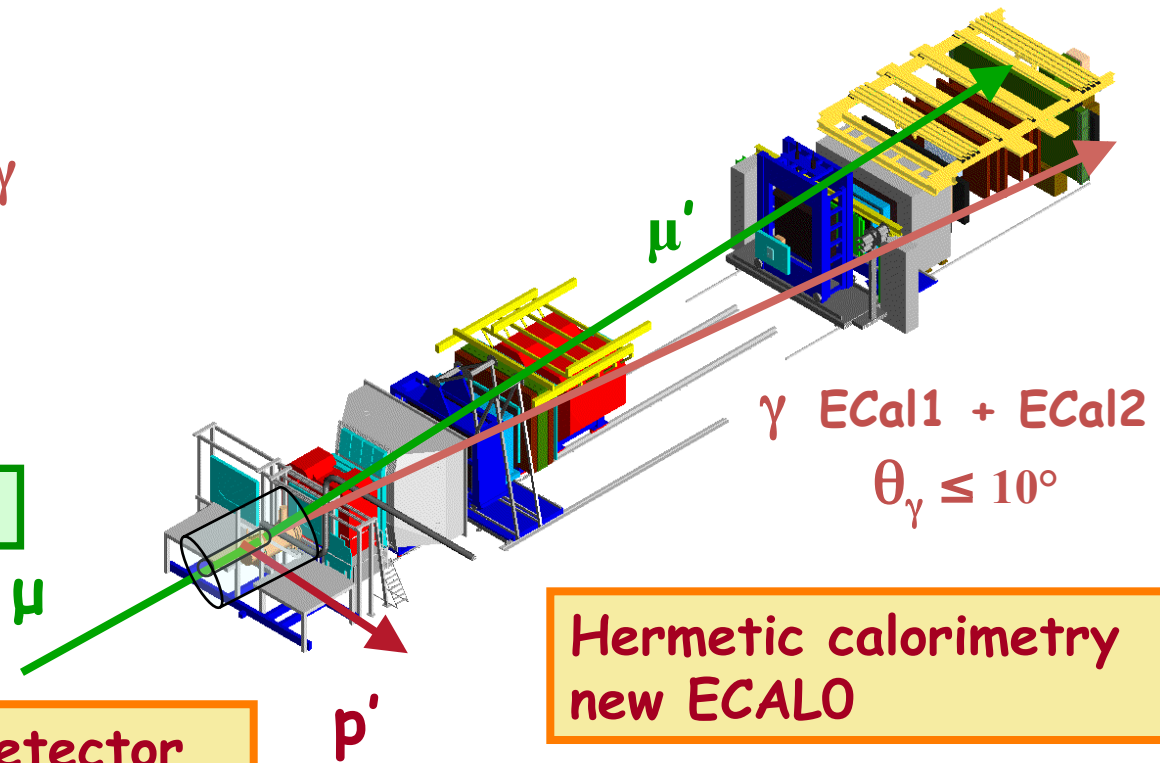
DVCS $\mu p \rightarrow \mu' p' \gamma$

2.5 m liquid H₂ target

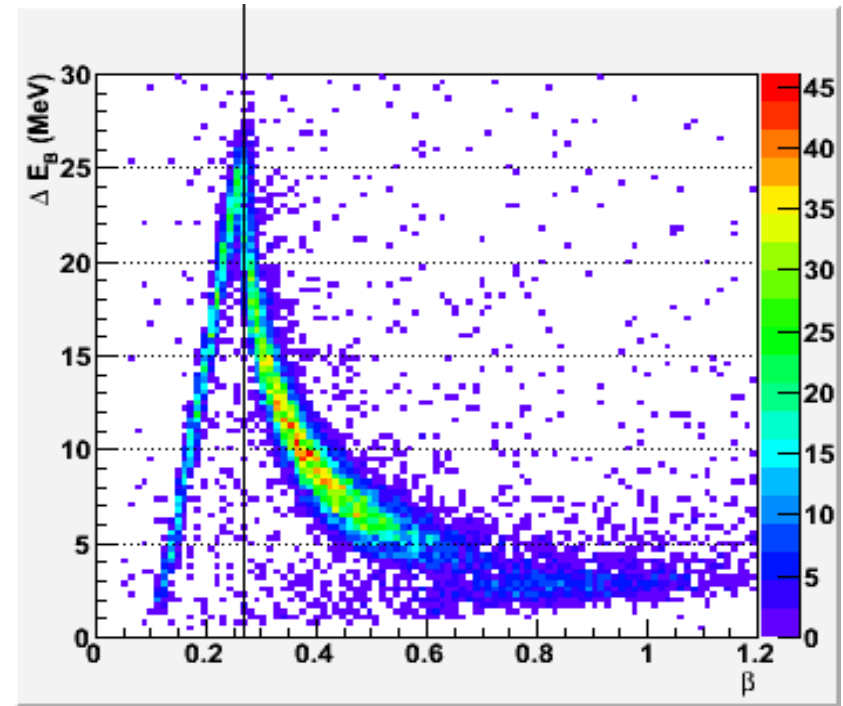
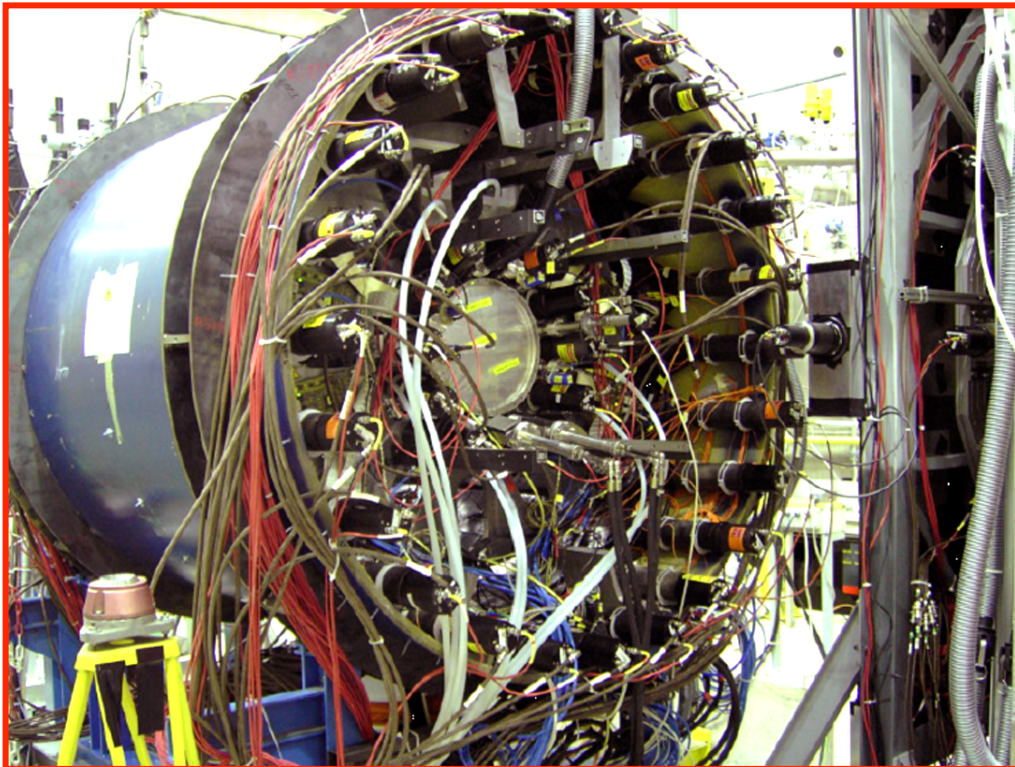
4m long Recoil Proton Detector

Hermetic calorimetry
new ECALO

Later stage...
Transversely polarized target
Associated RPD

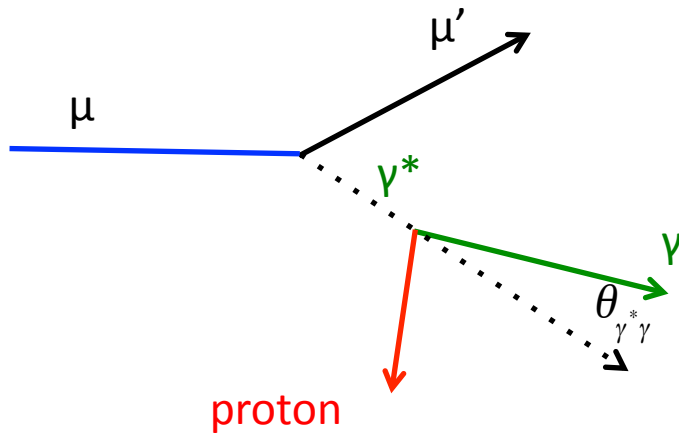


Hadron program RPD



Proton identification in RPD
Elastic scattering (hadron beam)

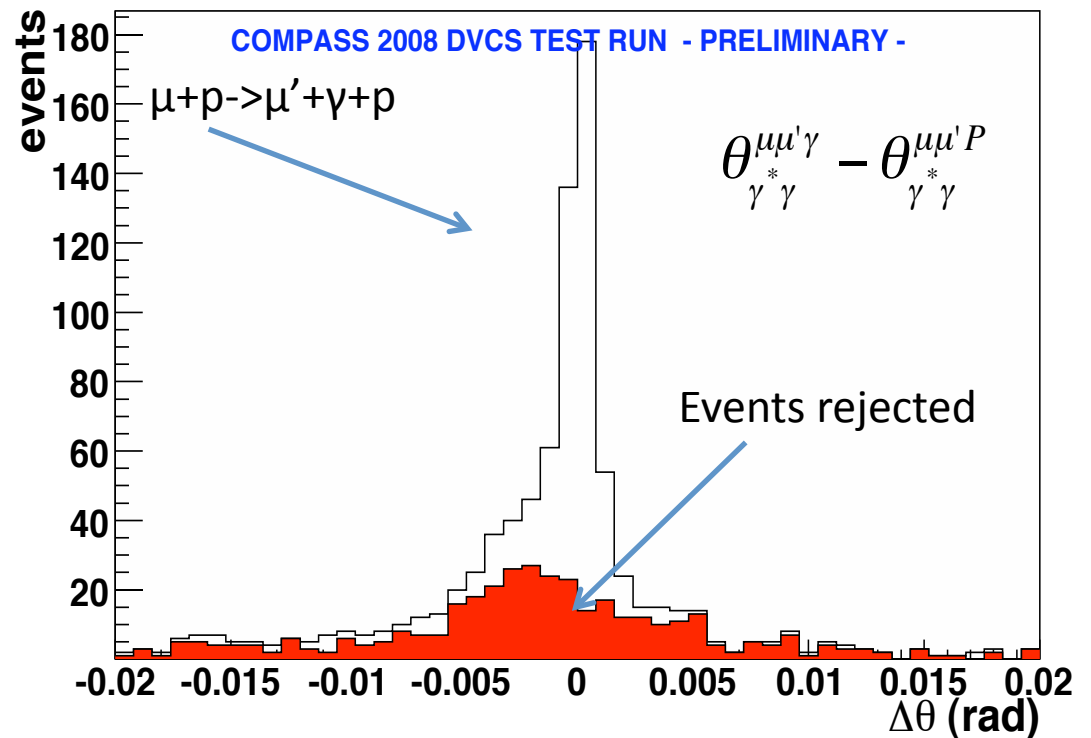
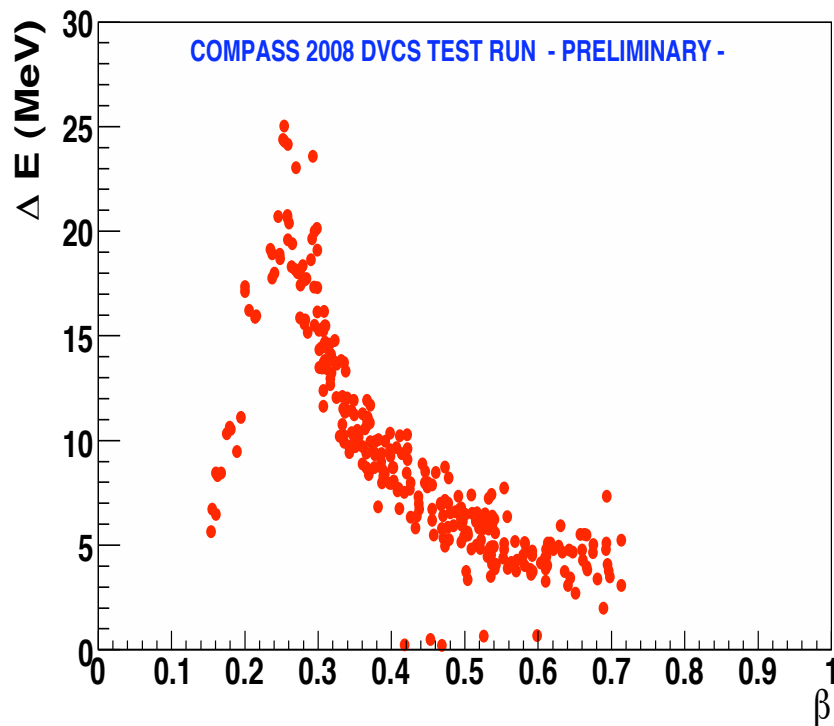
Kinematical consistency : $\theta_{\gamma^*\gamma}$



With μ , μ' and γ : $\theta_{\gamma^*\gamma}^{\mu\mu'\gamma}$

With μ , μ' and proton :

$$\cos\theta_{\gamma^*\gamma}^{\mu\mu'P} = \frac{1}{\sqrt{1 + 4M_P^2 x^2 / Q^2}} \left(1 + \frac{2M_P^2 x}{Q^2} \frac{t + Q^2}{t + Q^2 / x} \right)$$



Measurements and Estimations for resolution

$$\frac{\Delta P}{P} \approx \frac{1}{1-\beta^2} \frac{\sin^2 \vartheta}{R_B - R_A} \sqrt{\cos^2 \vartheta (v_A^2 \sigma_A^2 + v_B^2 \sigma_B^2) + \beta^2 c^2 \sigma_{ToF}^2}$$

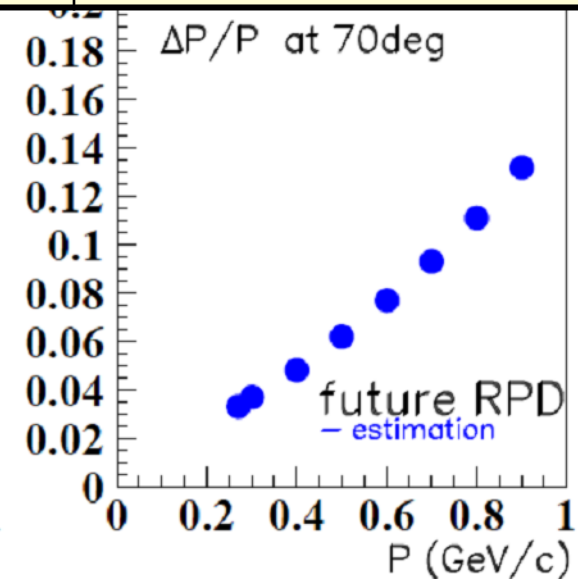
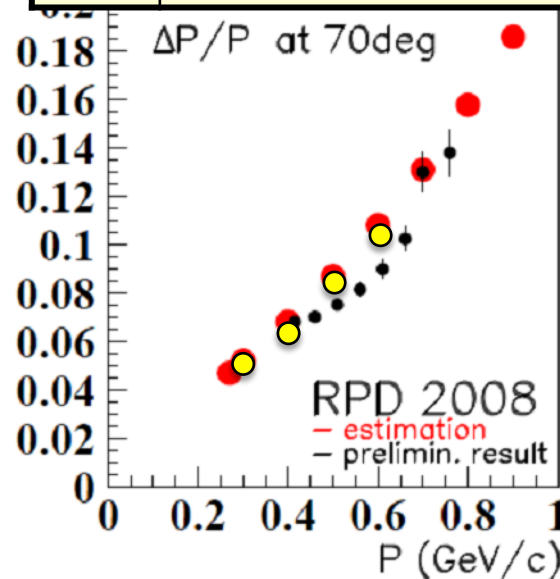
$$\frac{\Delta t}{t} \approx 2 \frac{\Delta P}{P}$$

$$t_{min} = -0.06 \text{ GeV}^2$$

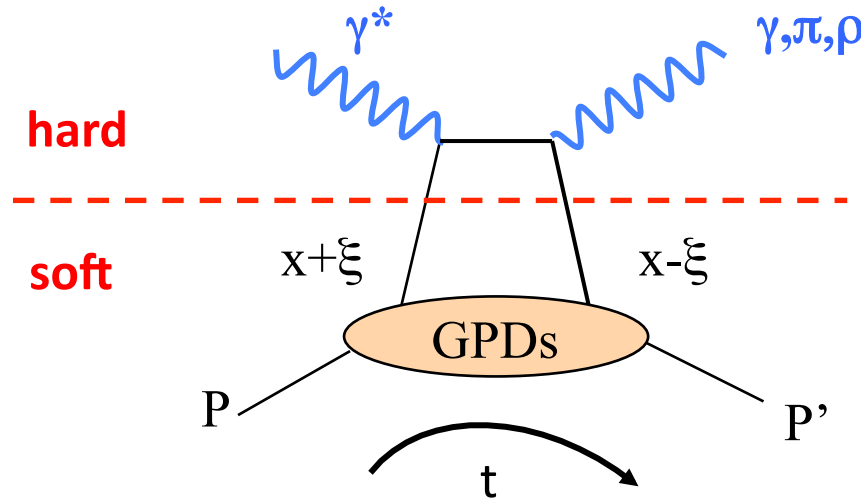
Good resolution in t

Importance for the
the transverse imaging

	RPD(2008)	MuRex (2006)
B	L=1m; th=1cm Atten length = 0.7m $\sigma_B = 300 \text{ ps}$	L=4m; th=5cm Atten length = 4m $\sigma_B = 200 \text{ ps}$
A	L=50cm; th=5mm $\sigma_A = 180 \text{ ps}$	L=2.83m; th=4mm $\sigma_A = 270 \text{ ps}$
ToF	$\sigma_{ToF} = 350 \text{ ps}$ $R_B - R_A = 85 - 12 = 63 \text{ cm}$	$\sigma_{ToF} = 310 \text{ ps}$ $R_B - R_A = 110 - 25 = 85 \text{ cm}$



Generalized Parton Distributions



Factorisation:
 Q^2 large, $-t < 1 \text{ GeV}^2$

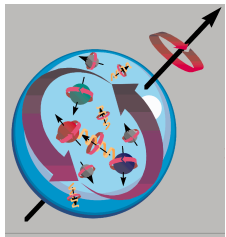
Generalized Parton Distributions

for quarks :

4 functions $H, E, \tilde{H}, \tilde{E}(x, \xi, t)$

contains pdf
 $H(x, 0, 0) = q(x)$
measured in DIS

contains form factors
 $F(t) = \int dx H(x, \xi, t)$
measured in elastic scattering

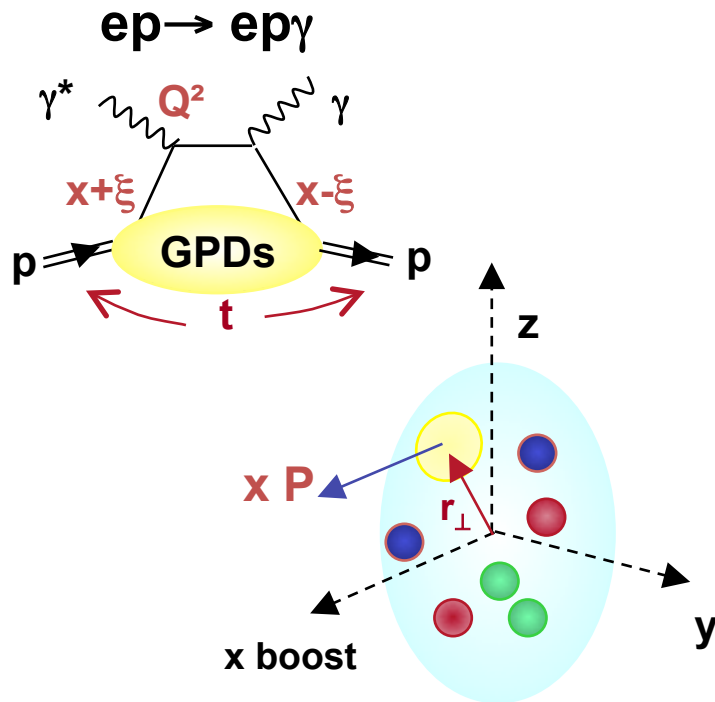


contains information on the nucleon spin :

Ji's sum rule :
$$\int x(H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0))dx = J^q$$

3-D partonic structure of the nucleon ($P_z, r_{y,z}$)

Hard Exclusive Scattering
Deeply Virtual Compton Scattering



GPDs : $H(x, \xi, t)$

access to correlations :
($P_x, r_{y,z}$)
Fourier ($\xi=0$)

Burkardt, Belitsky, Müller, Ralston, Pire

