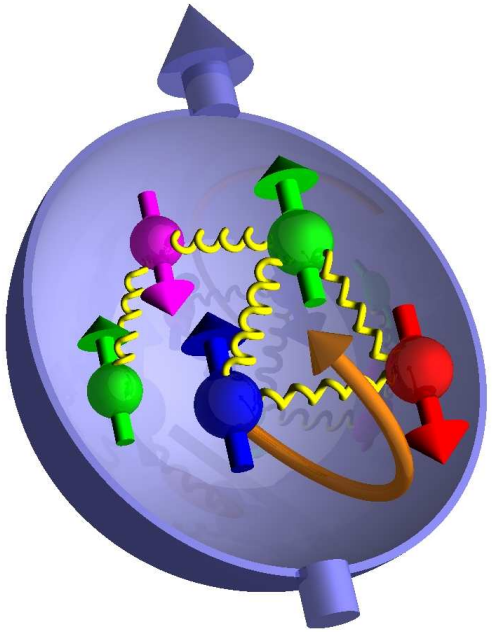
The GPD physics program at COMPASS: present results and future perspectives

A. Ferrero (CEA-Saclay/IRFU/SPhN)
on behalf of the COMPASS Collaboration

LightCone 2014 - Raleigh, May 26-30 2014

Where does the spin of the nucleons come from?

Proton spin sum rule: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$

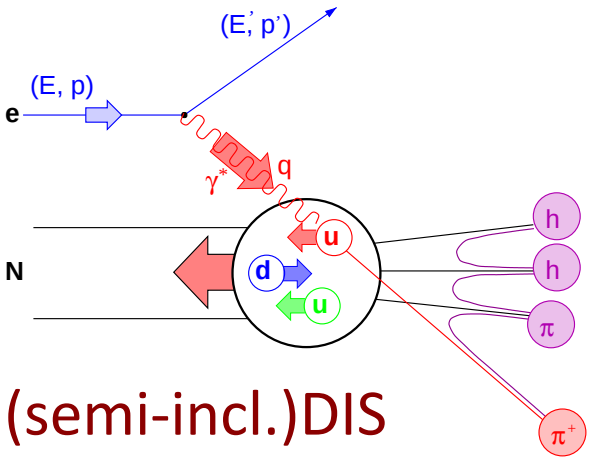


The ``proton spin crisis'':

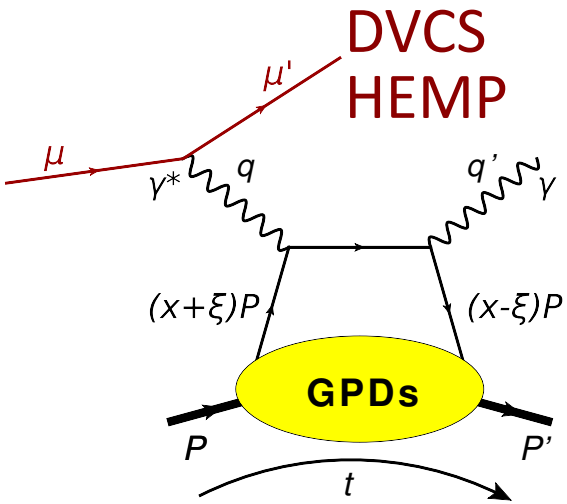
$$\Delta\Sigma \rightarrow \begin{cases} \text{Static quark model}: \Delta\Sigma = 1 \\ \text{Weak baryon decays}: \Delta\Sigma \simeq 0.58 \\ \text{Experiments}: \Delta\Sigma \simeq 0.3 \end{cases}$$

ΔG = ?? $L_{q,g}$ = ??

Our experimental tools:

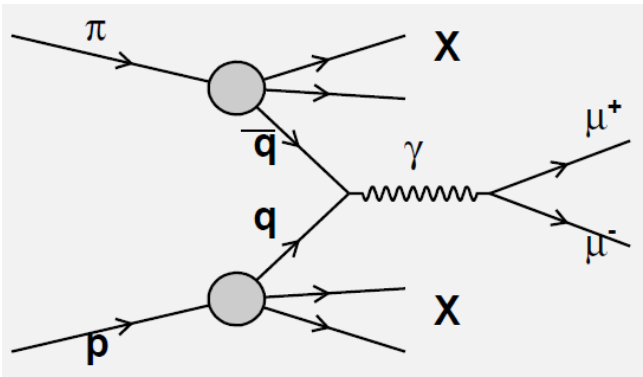


(semi-incl.)DIS



DVCS
HEMP

Pol. Drell-Yan



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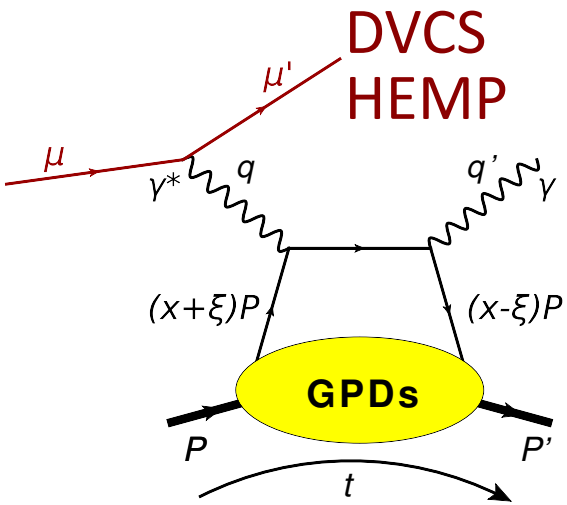
$\Delta G = ??$ $L_q + L_g = ??$

This talk:

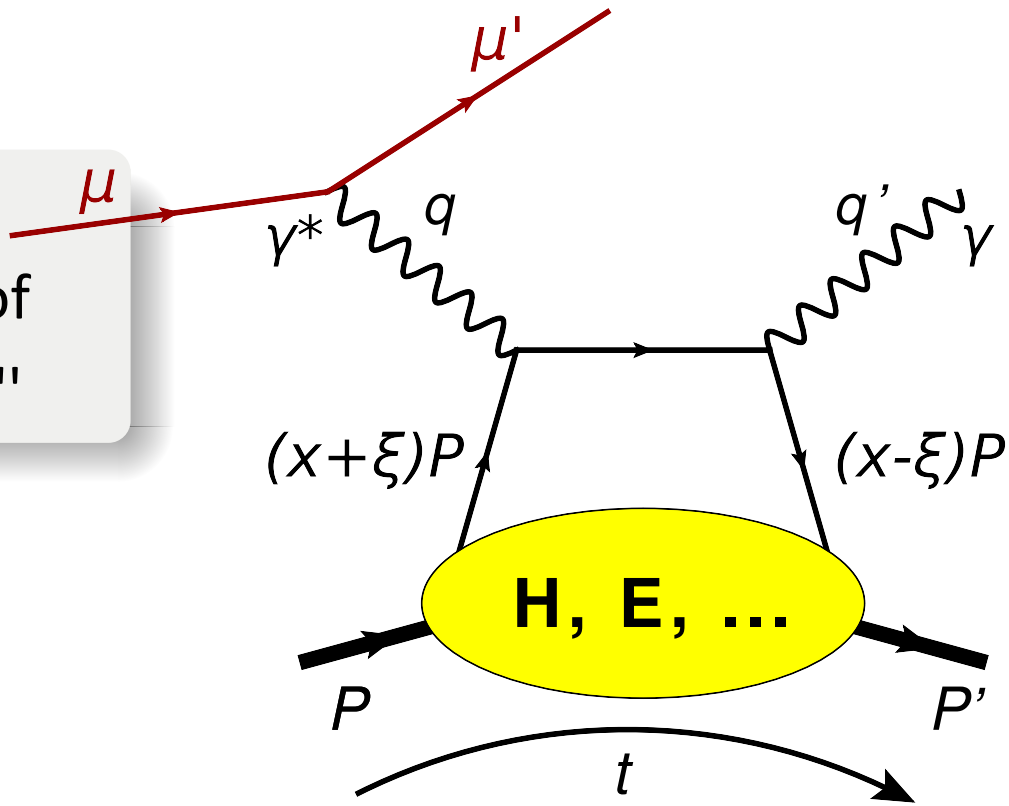
Our experimental tools:



Pol. Drell-Yan

Introduction to GPDs

``GPDs are **non-perturbative** objects entering the description of **hard exclusive** electroproduction''



Definition of variables:

- x: average long. momentum - NOT ACCESSIBLE
- ξ: long. mom. difference $\simeq x_B/(2 - x_B)$
- t: four-momentum transfer related to $b_\perp$ via Fourier transform

Introduction to GPDs

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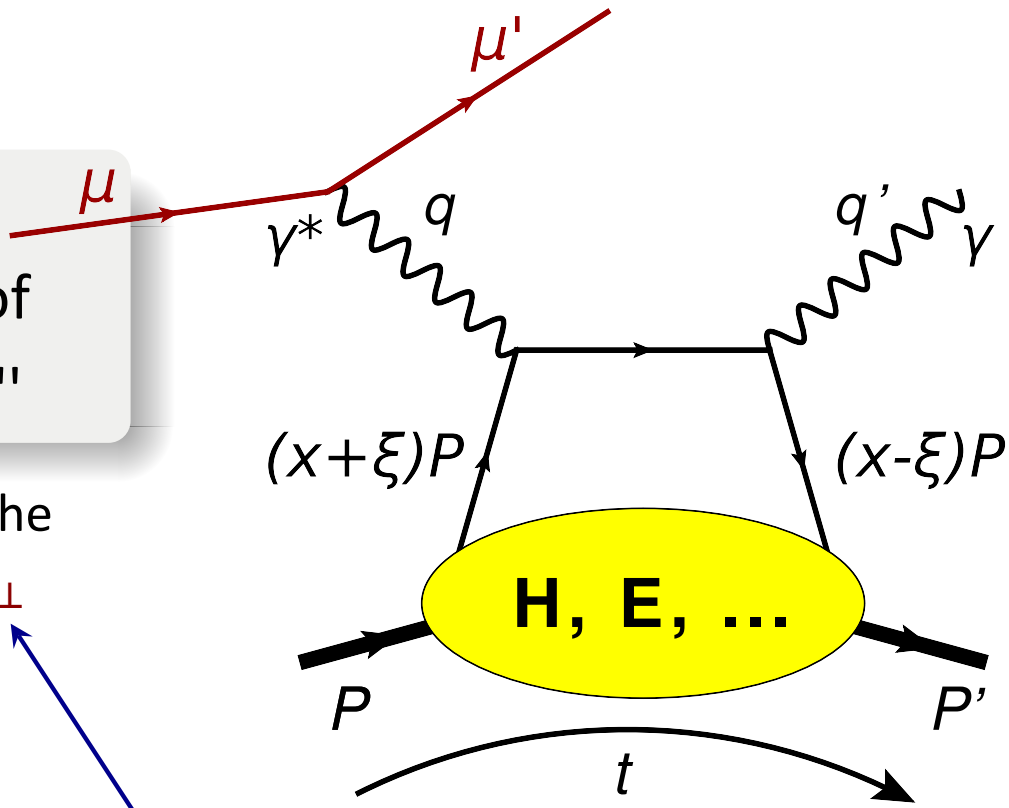
They encode **CORRELATIONS** between the long. mom. $\mathbf{x}$ and the transv. position $\mathbf{b}_\perp$ of partons



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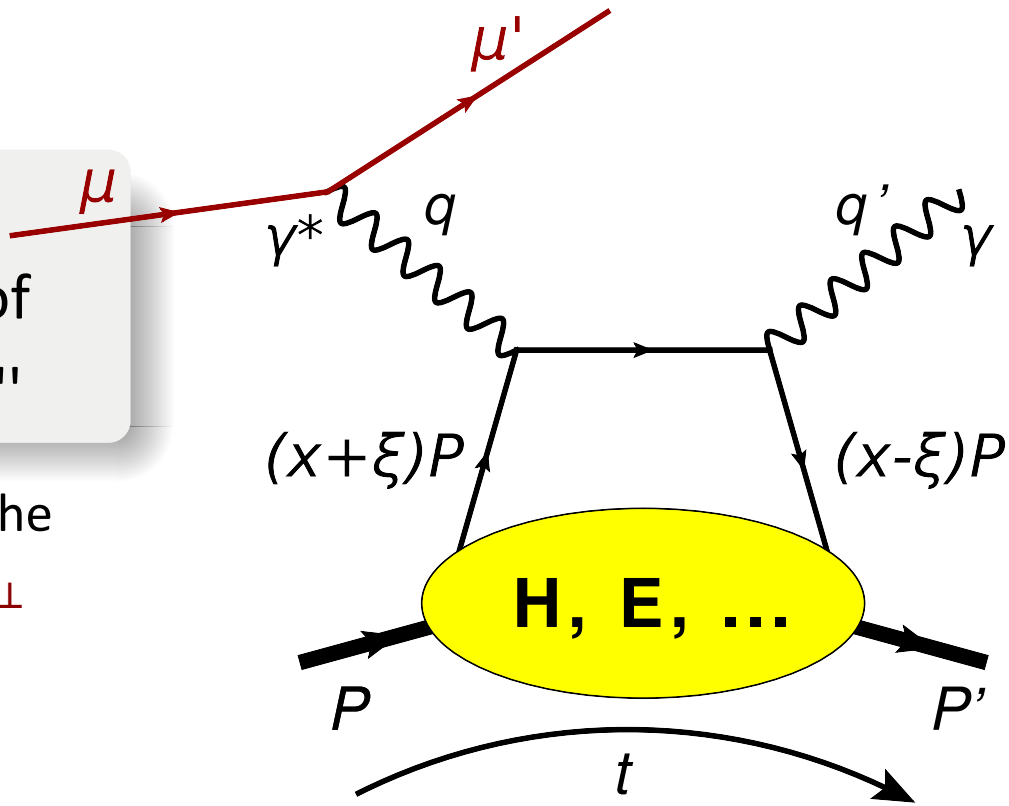

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Experimentally accessible through Compton Form Factors (CFFs):

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

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

Definition of variables:

- x: average long. momentum - NOT ACCESSIBLE
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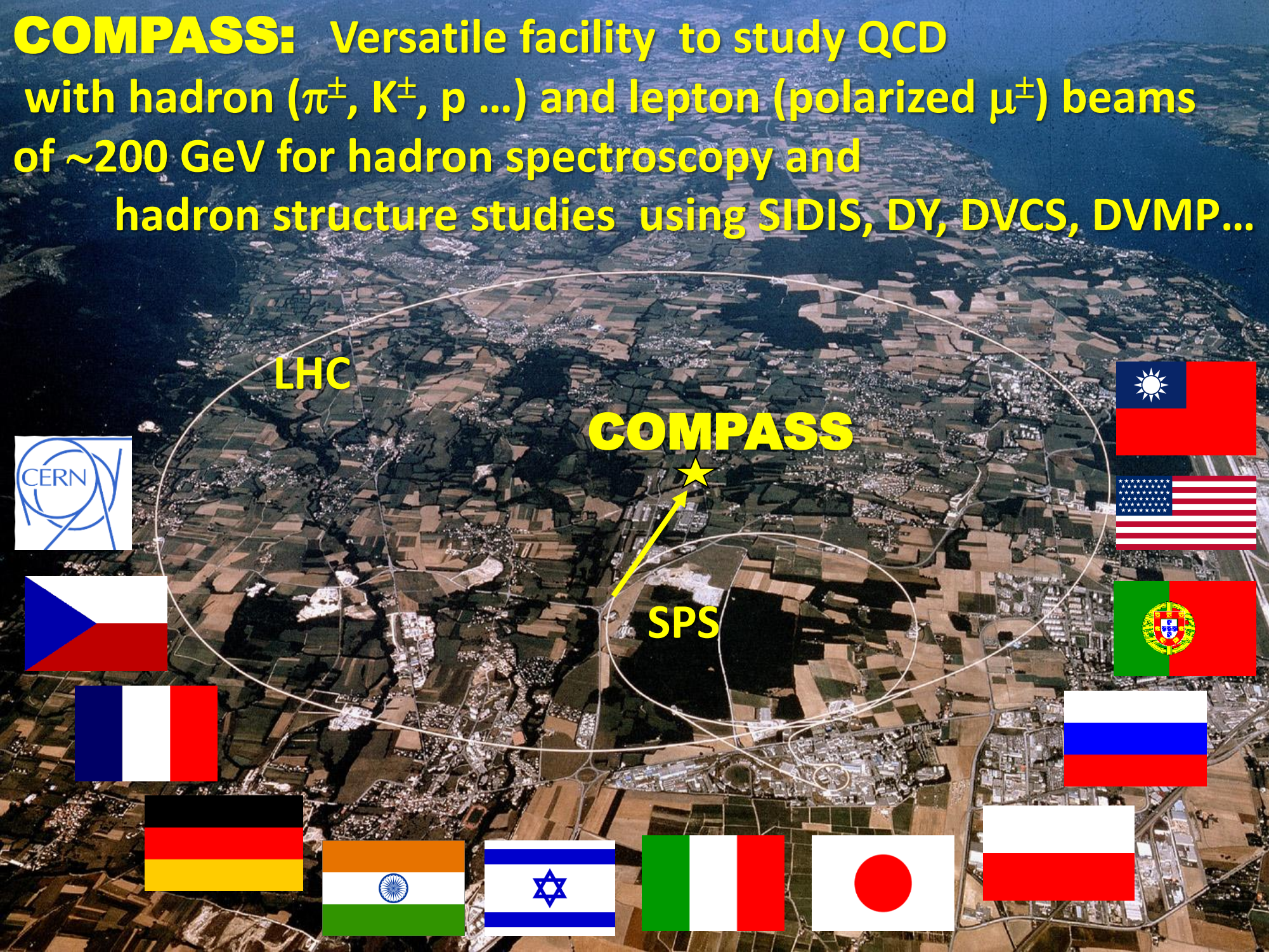
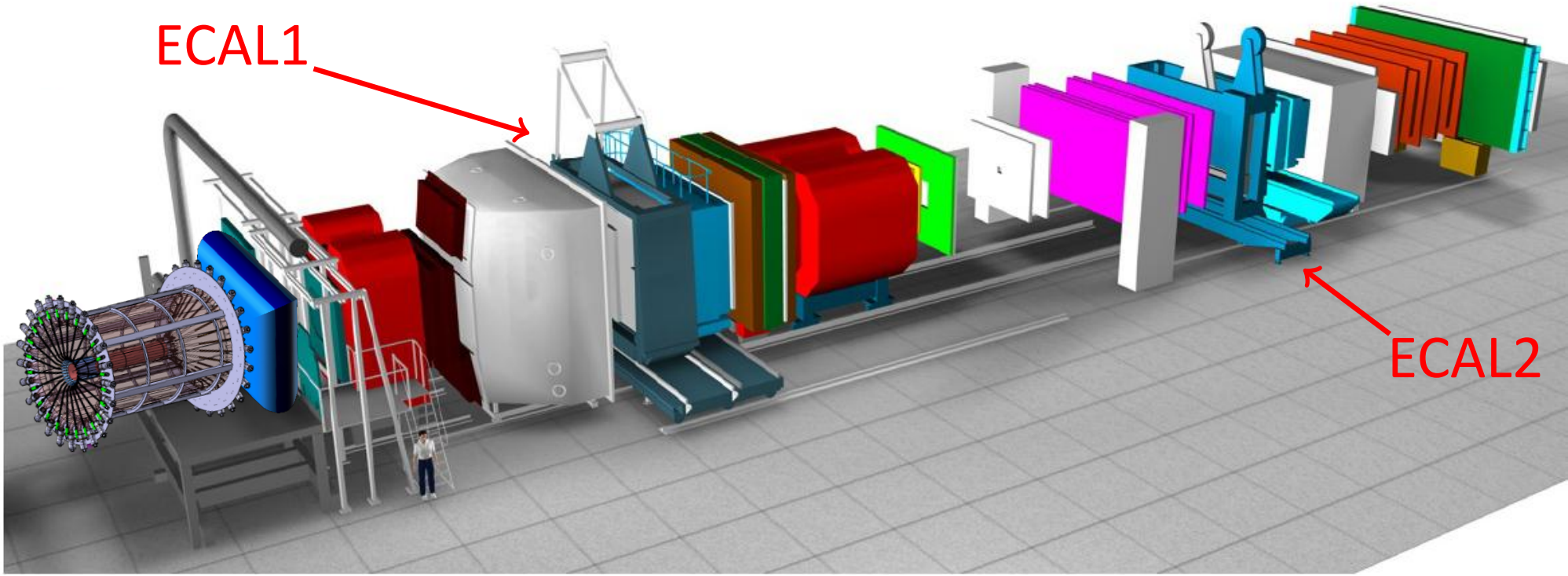

COMPASS: Versatile facility to study QCD
with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) and lepton (polarized $\mu^{\pm}$) beams
of ~200 GeV for hadron spectroscopy and
hadron structure studies using SIDIS, DY, DVCS, DVMP…
LHC
COMPASS
SPS
CERN

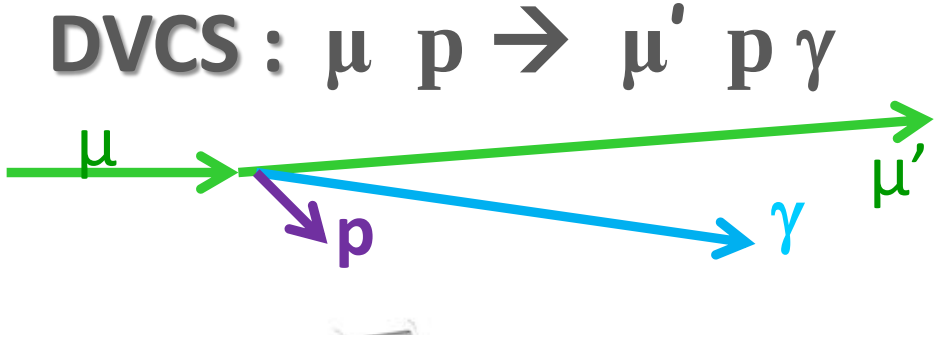
The COMPASS set-up for the GPD program



Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with:

- Ring Imaging Cerenkov Detector
- Electromagnetic calorimeters (**ECAL0**, **ECAL1** & **ECAL2**)
- Hadronic calorimeters
- Muon absorbers



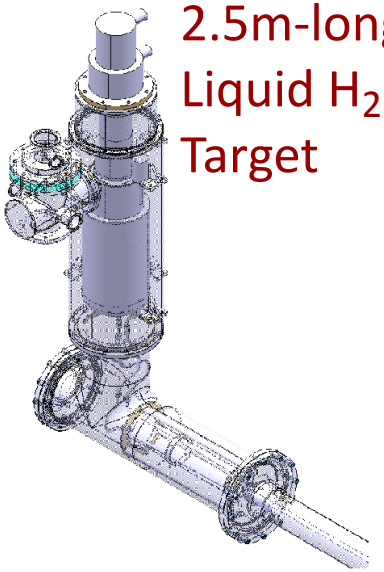
The COMPASS set-up for the GPD program

ECAL1

ECAL2

Main new equipments

2.5m-long
Liquid H_2
Target



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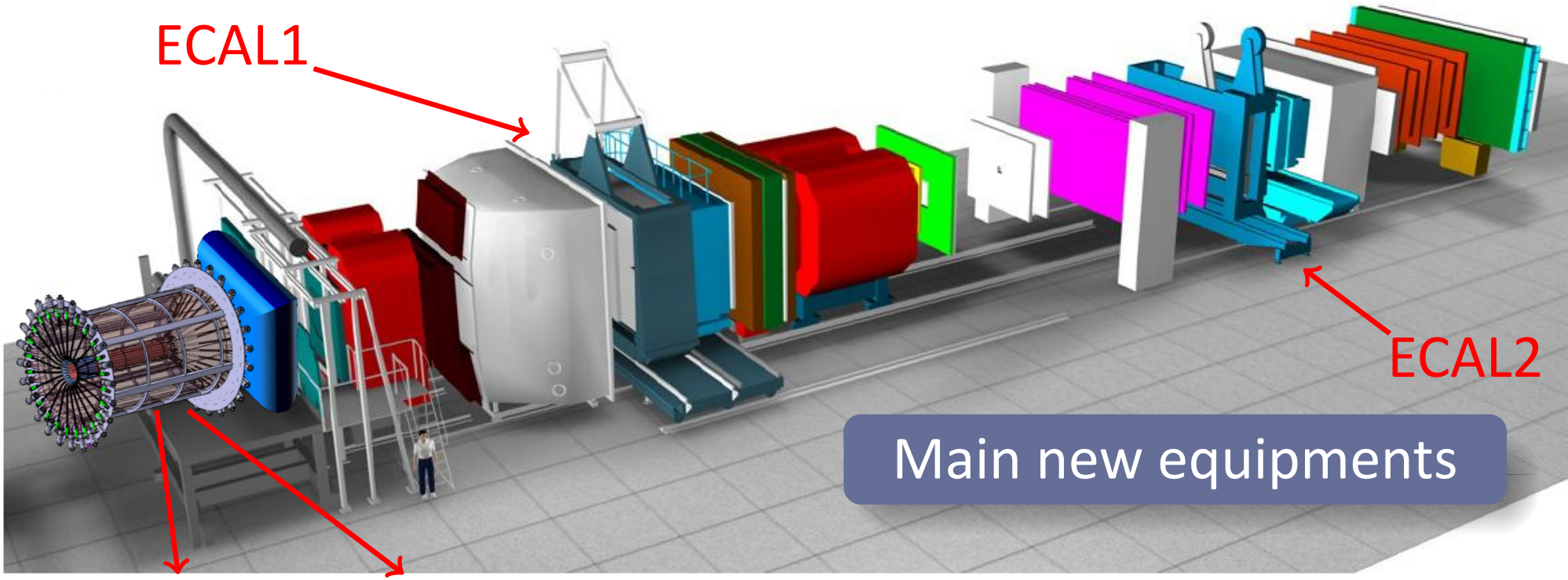
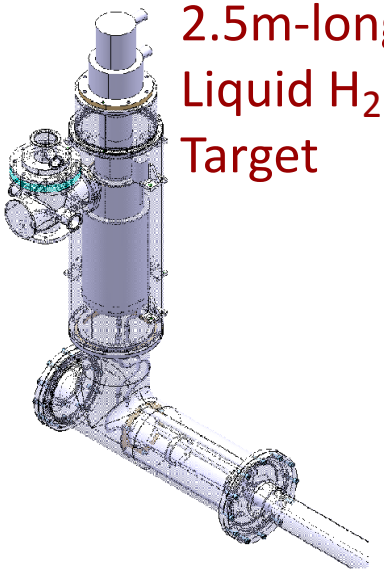




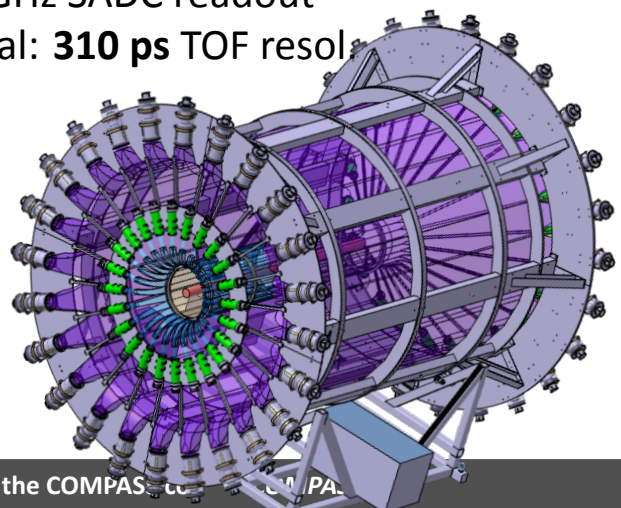
2.5m-long
Liquid H_2
Target

Target TOF System

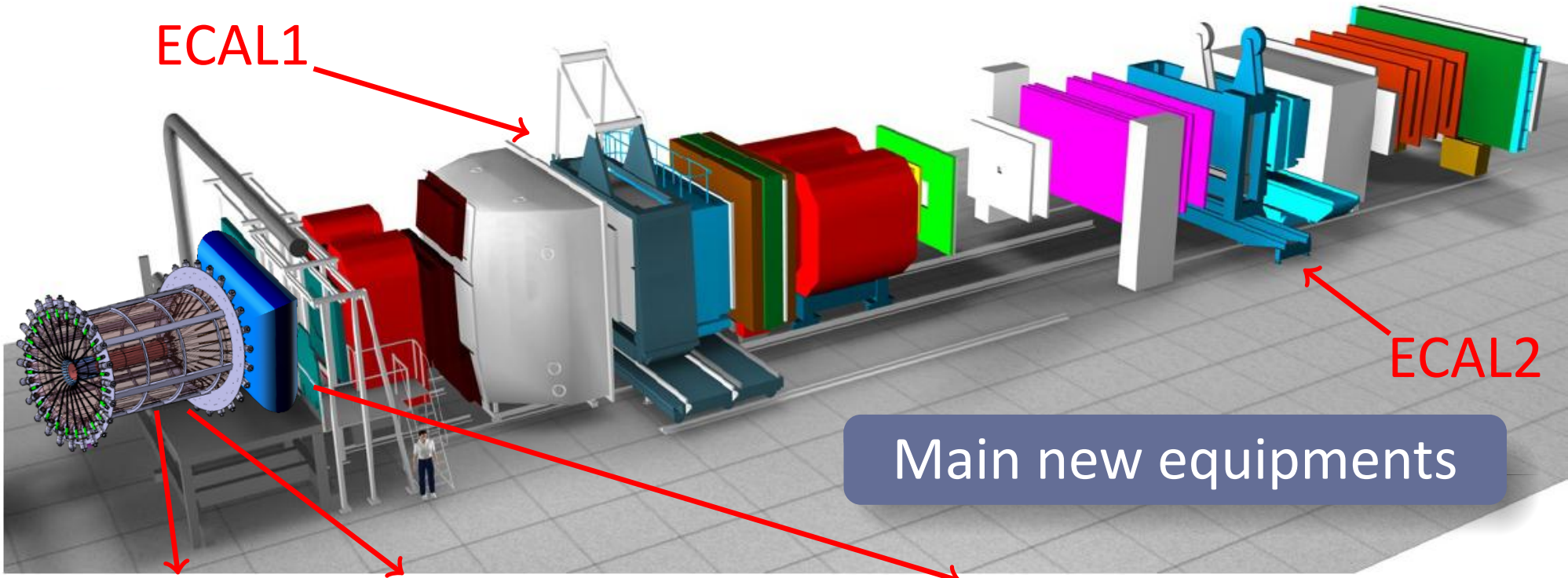
24 inner & outer scintillators

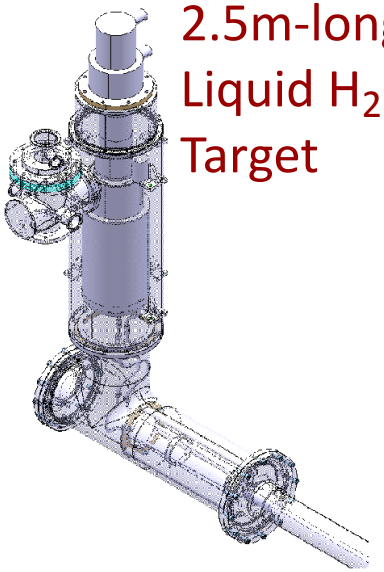
1 GHz SADC readout

goal: **310 ps** TOF resol.



The COMPASS set-up for the GPD program





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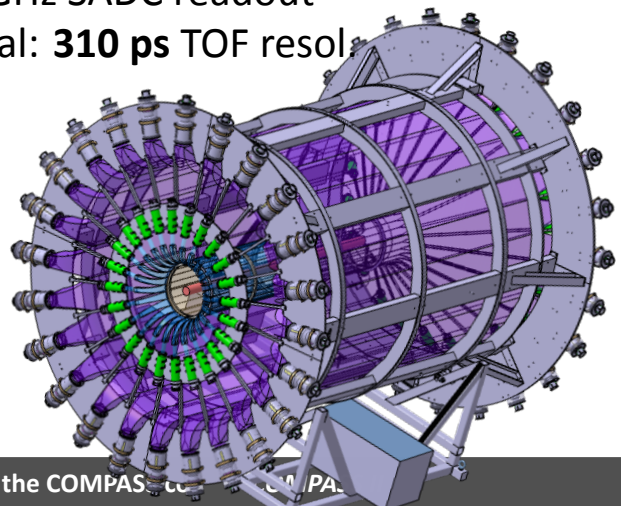
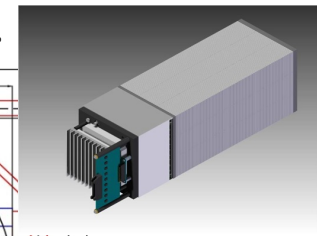
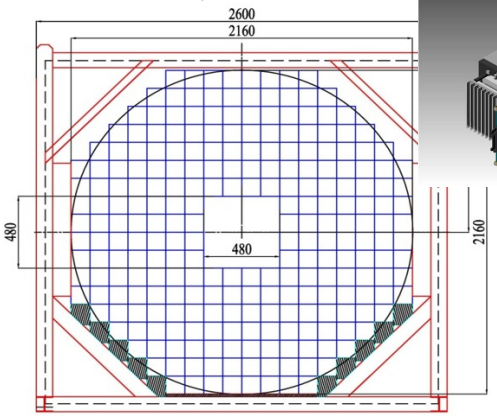


ECAL0 Calorimeter

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





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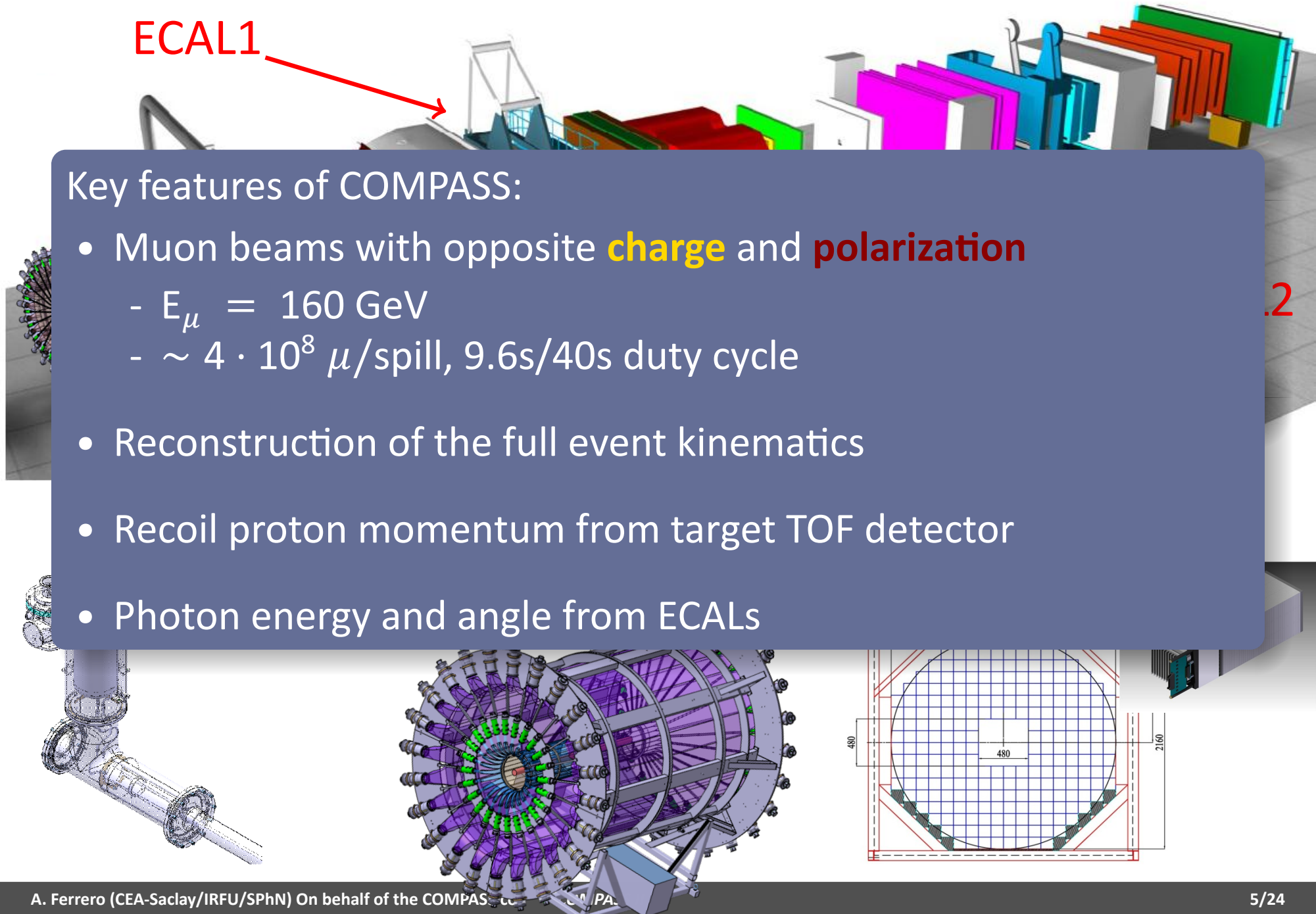


Key features of COMPASS:

- Muon beams with opposite **charge** and **polarization**
  - $E_\mu = 160$ GeV
  - $\sim 4 \cdot 10^8$ μ/spill, 9.6s/40s duty cycle
- Reconstruction of the full event kinematics
- Recoil proton momentum from target TOF detector
- Photon energy and angle from ECALs

The GPD Physics Program at COMPASS

2008: Very short test run, short LH_2 target

Observation of exclusive photon production

Estimation of global efficiency: $\epsilon_{\text{global}} \simeq 10\%$

2009: **10 days**, short LH_2 target

Coarse binning in x_B

First hint of DVCS at large x_B

2004-10: Exclusive vector meson production on a **transv. pol. target** and **no recoil detector**

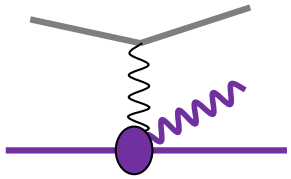
2012: **4 weeks**, full-scale LH_2 target and recoil detector

2016-7: **2 years** of dedicated data taking

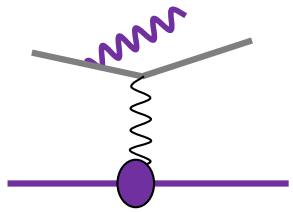
>2018: DVCS with **transv. pol. target** and **recoil detector** → **GPD E**

Future addendum to COMPASS-II proposal

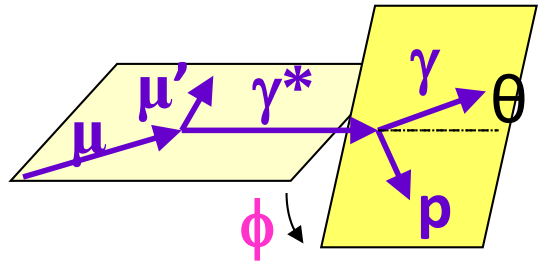
The DVCS Process at COMPASS Kinematics



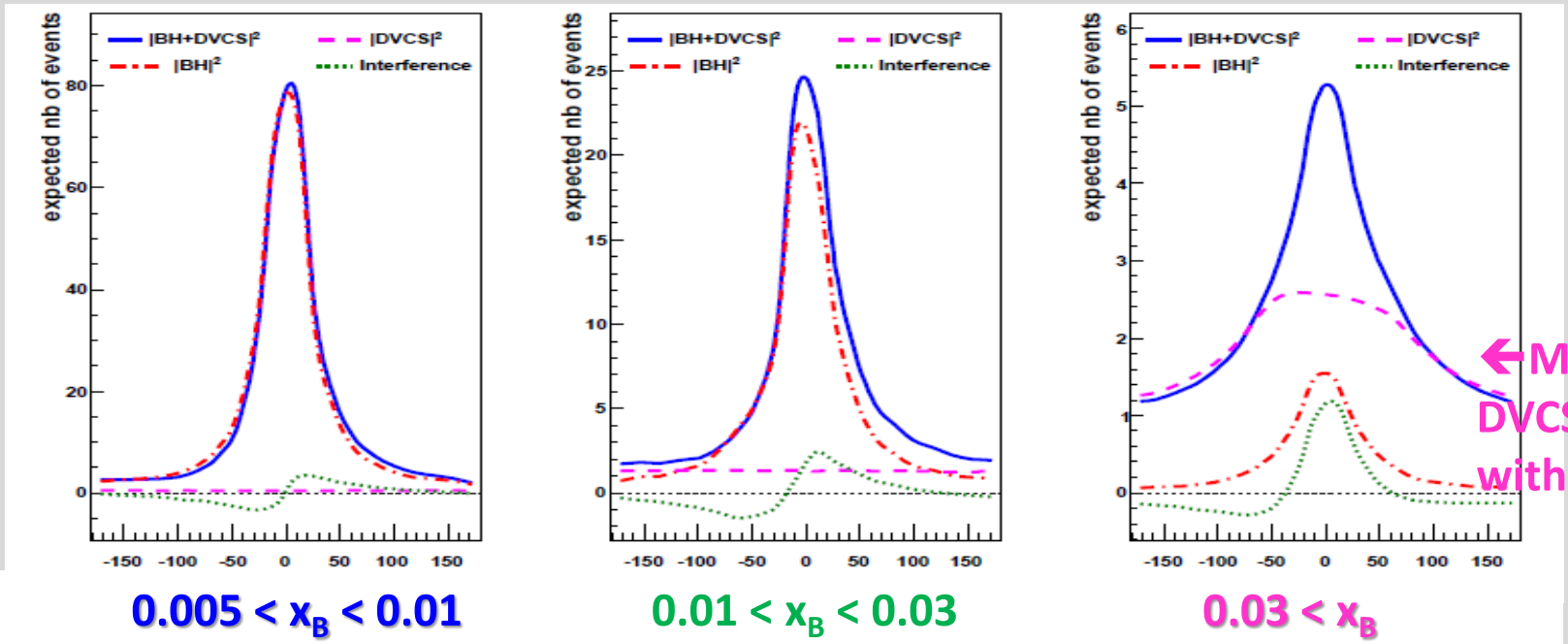
Deep VCS



Bethe-Heitler



$d\sigma \alpha |T^{BH}|^2 + \text{Interference Term} + |T^{DVCS}|^2$



$0.005 < x_B < 0.01$ | $0.01 < x_B < 0.03$ | $0.03 < x_B$

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

←Missing DVCS acceptance without ECAL0

BH dominates

excellent

reference yield

study of Interference

→ Re T^{DVCS}

or Im T^{DVCS}

DVCS dominates

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

→ Transverse Imaging

Measurements of DVCS and BH Cross-sections

cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

$$d\sigma_{(\mu p \to \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol} + e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} + e_\mu P_\mu\, a^{BH}\, \mathcal{I}m\, A^{DVCS}$$

Charge & Spin Difference and Sum:

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto C_0^{Int} + C_1^{Int}\cos\phi \quad \text{and} \quad c_{0,1}^{Int} \sim F_1\, \mathcal{R}e\, \mathcal{H}$$

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int}\sin\phi \quad \text{and} \quad s_1^{Int} \sim F_1\, \mathcal{I}m\, \mathcal{H}$$

$$C_1^{Int} \propto \mathcal{R}e\left(F_1\,\mathcal{H} + \xi(F_1+F_2)\,\tilde{\mathcal{H}} - t/4m^2\, F_2\,\mathcal{E}\right)$$

NOTE: ✓ dominance of $\mathcal{H}$ with a proton target at COMPASS kinematics

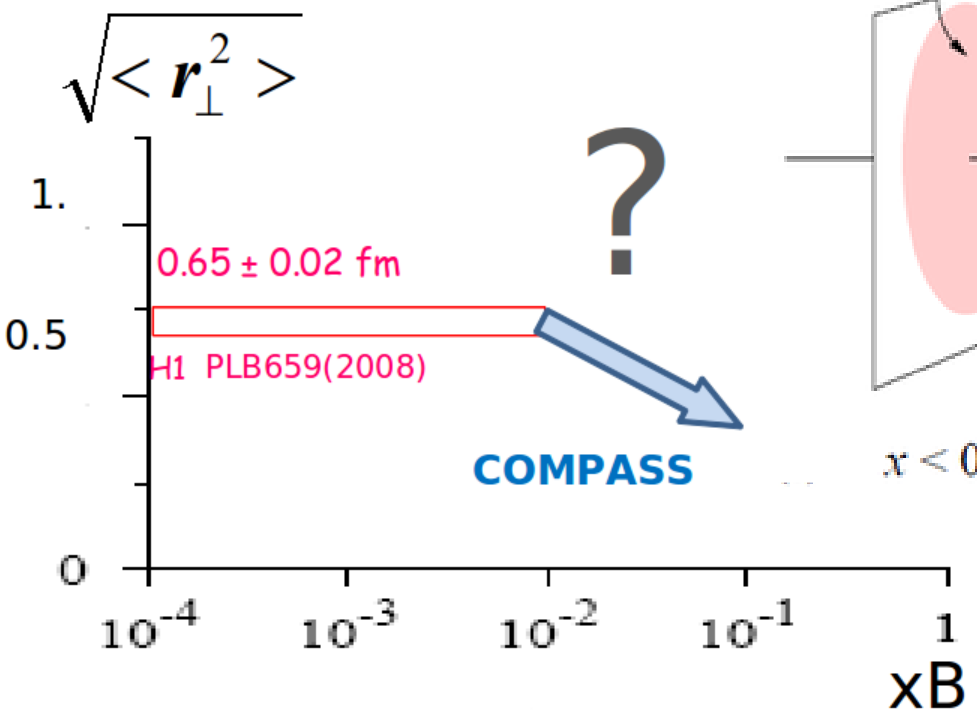
✓ only leading twist and LO

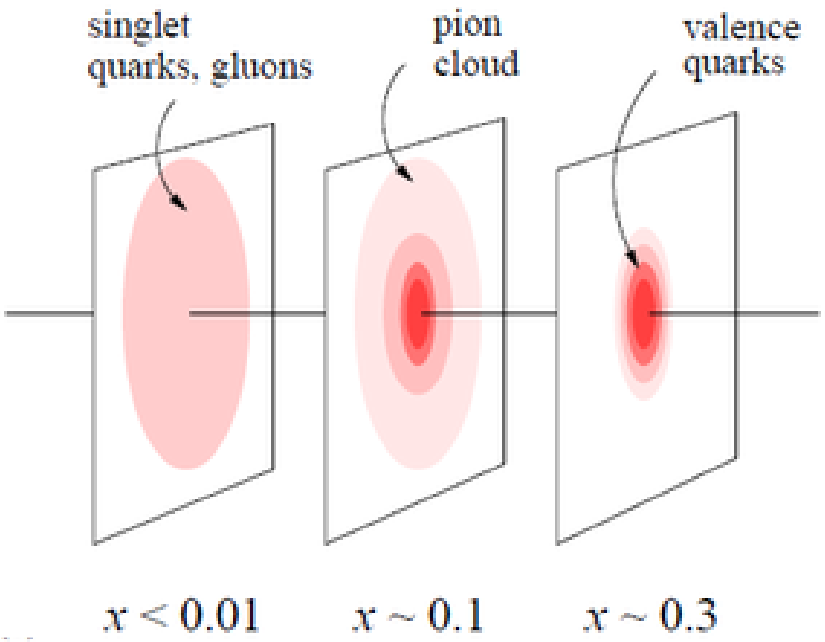
Transverse Nucleon Imaging at COMPASS

Beam Charge and Spin **SUM**:

$$\mathbf{S_{CS,U}} \equiv \mathbf{d\sigma}(\boldsymbol{\mu}^{+\leftarrow}) + \mathbf{d\sigma}(\boldsymbol{\mu}^{-\rightarrow}) \propto \mathbf{d\sigma^{BH}} + \mathbf{d\sigma^{DVCS}_{unpol}} + \mathbf{Ks_1^{Int}} \sin\boldsymbol{\phi}$$

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





$$< r_\perp^2(x_B) > \approx 2B(x_B)$$

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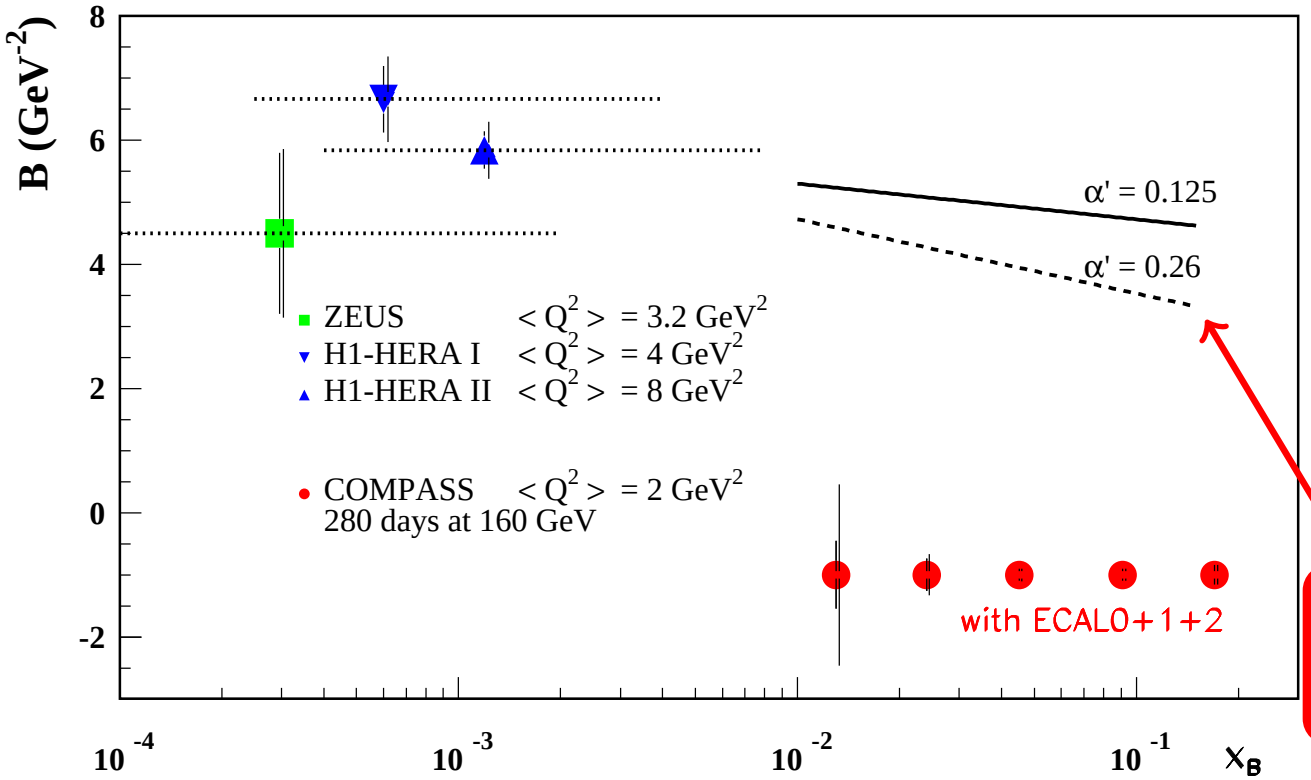


2 years of data

2.5 m LH_2 target

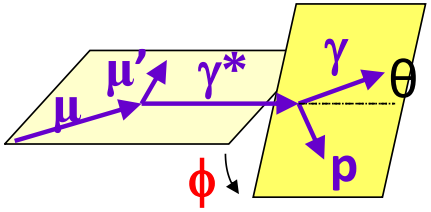
ε_{global} = 10%

Ansatz at small $\mathbf{x_B}$:

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

expected statistical and systematic uncertainties are shown

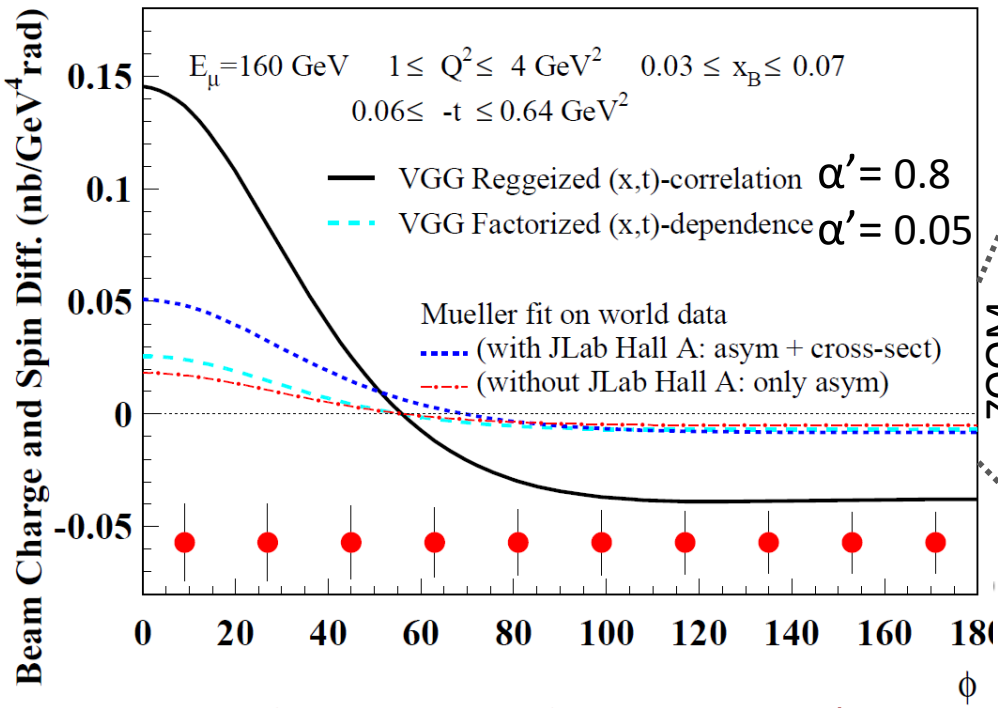
Beam Charge and Spin DIFFERENCE

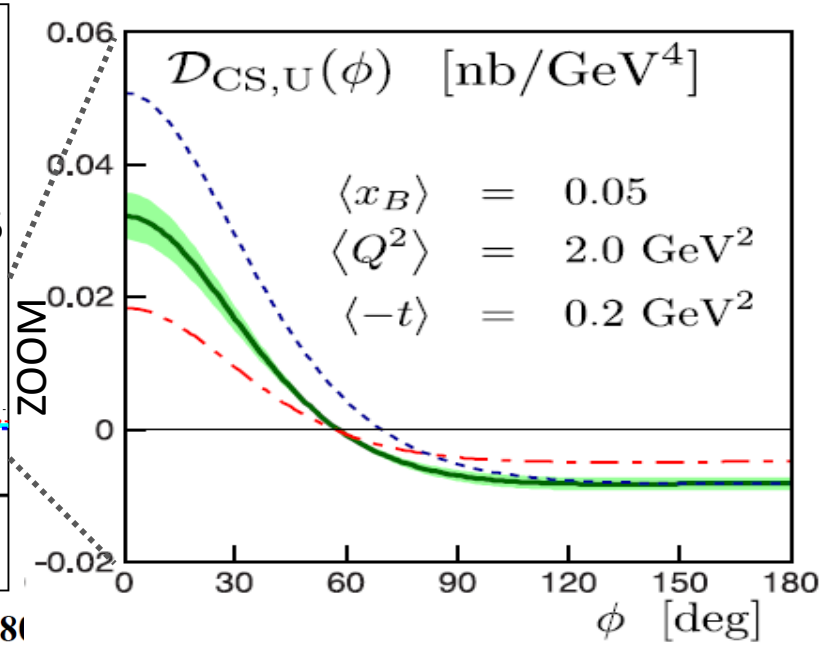


$$D_{CS,U} \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow}) \propto c_0^{Int} + c_1^{Int}\cos(\phi)$$

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

CFFs $\mathcal{H}$ accessed through ϕ modulation of $D_{CS,U}$

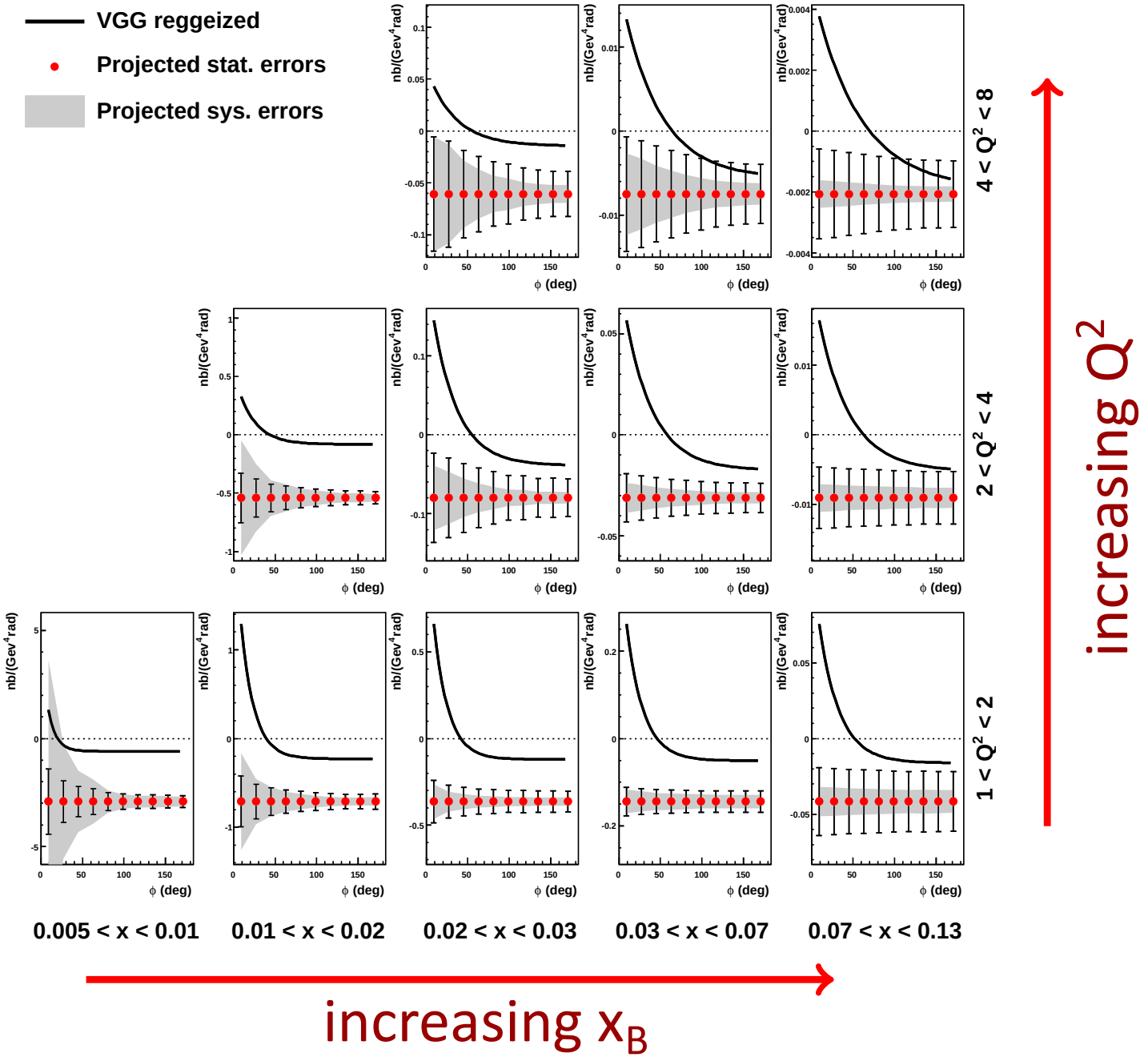




Predictions for 2 years of data taking (2016-17)

Kroll, Moutarde, Sabatié
EPJC 73 (2013) 2278

Cross-section Difference - All Bins

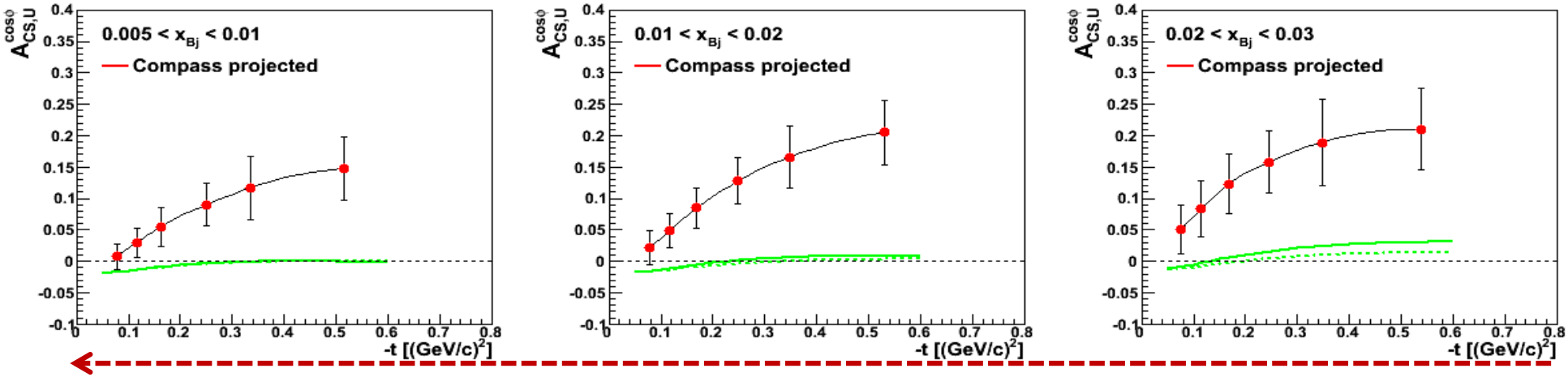


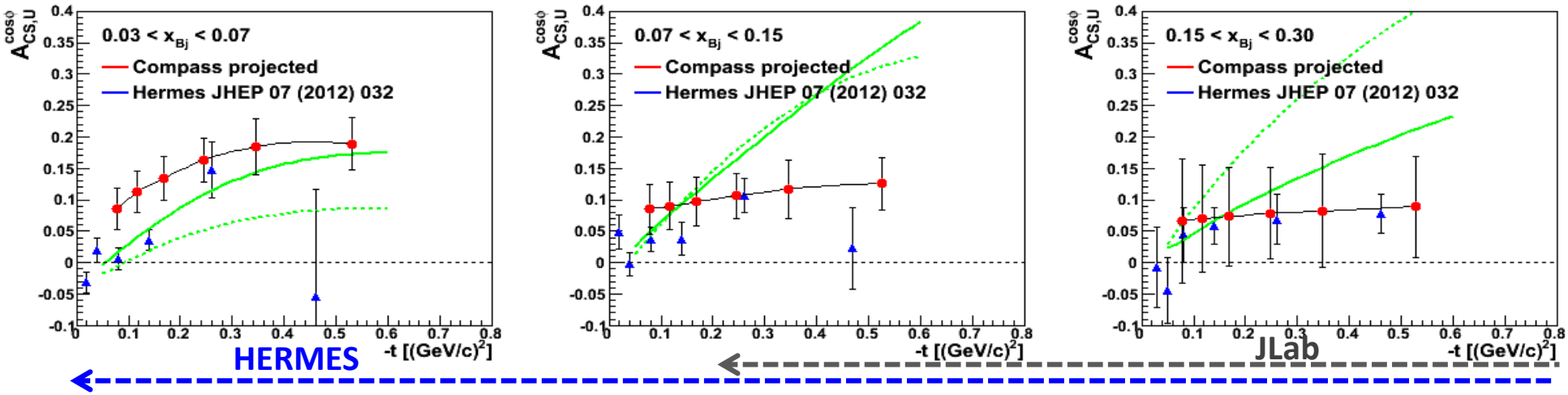
Cross-section Asymmetry

$A_{CS,U}^{\cos\phi}$ related to c_1^{Int}

Predictions with
VGG and **D.Mueller**

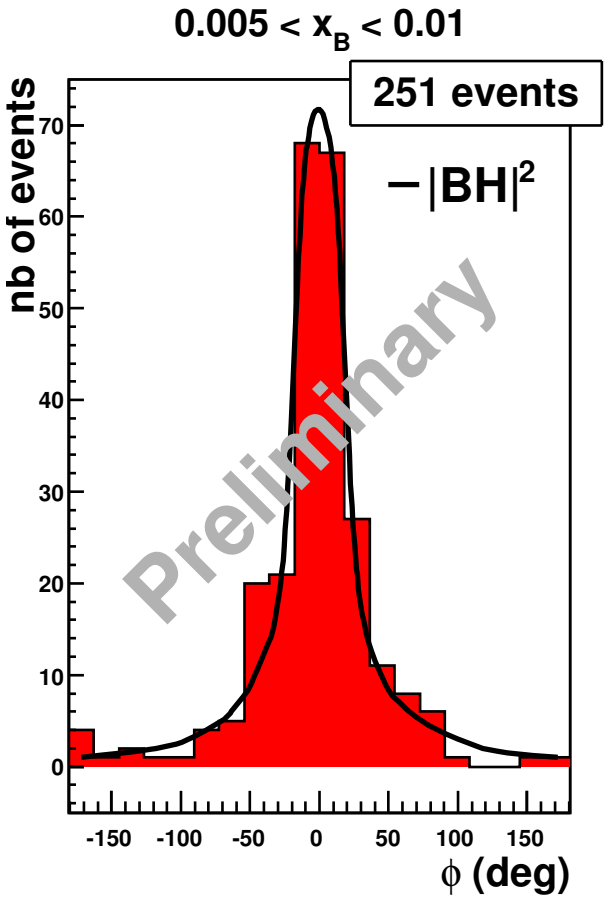
$\mathcal{Re}\,\mathcal{H}$ **> 0 at H1**
< 0 at HERMES/JLab
Value of x_B for the node?

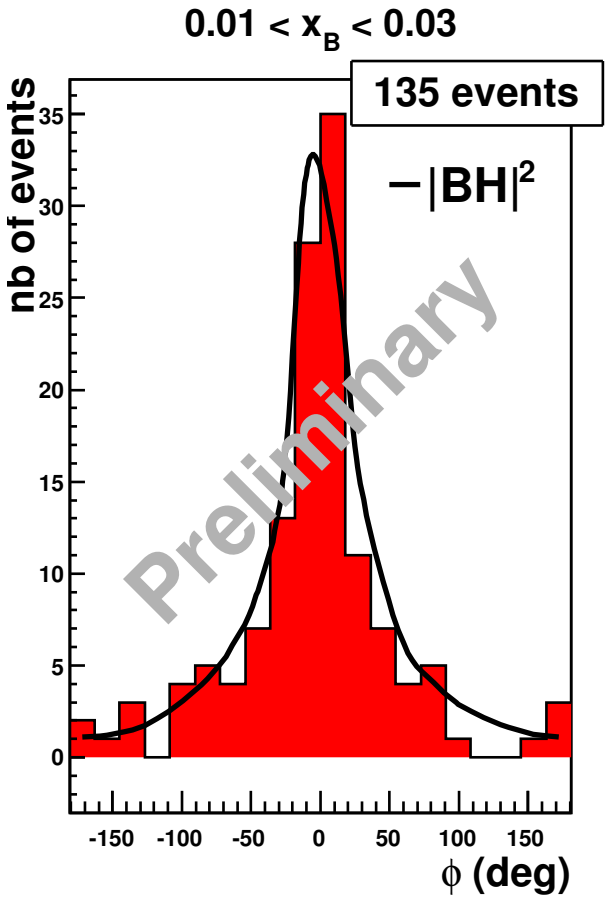


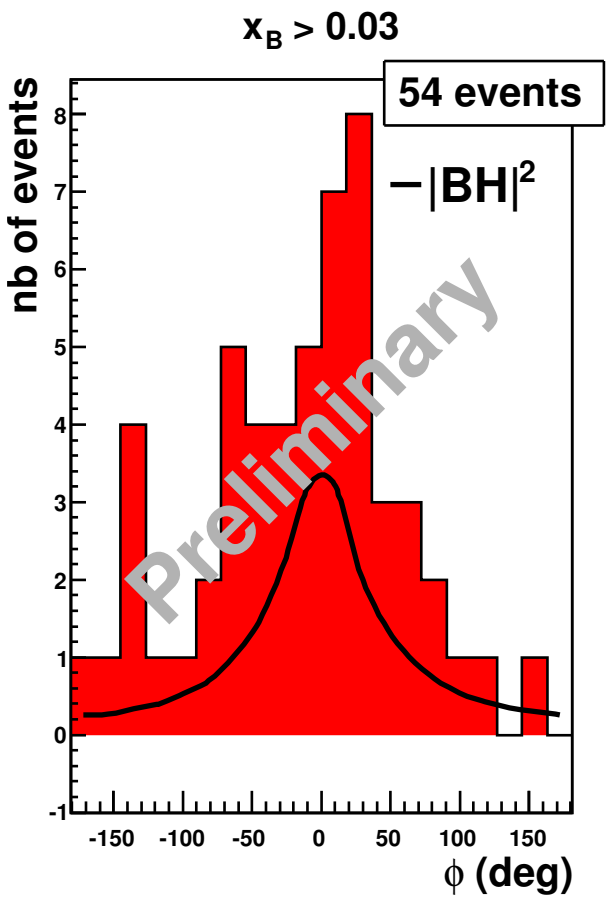


COMPASS **2 years of data** **Eμ= 160 GeV** **$1 < Q^2 < 8$ GeV^2**

2008-9 Test Measurements







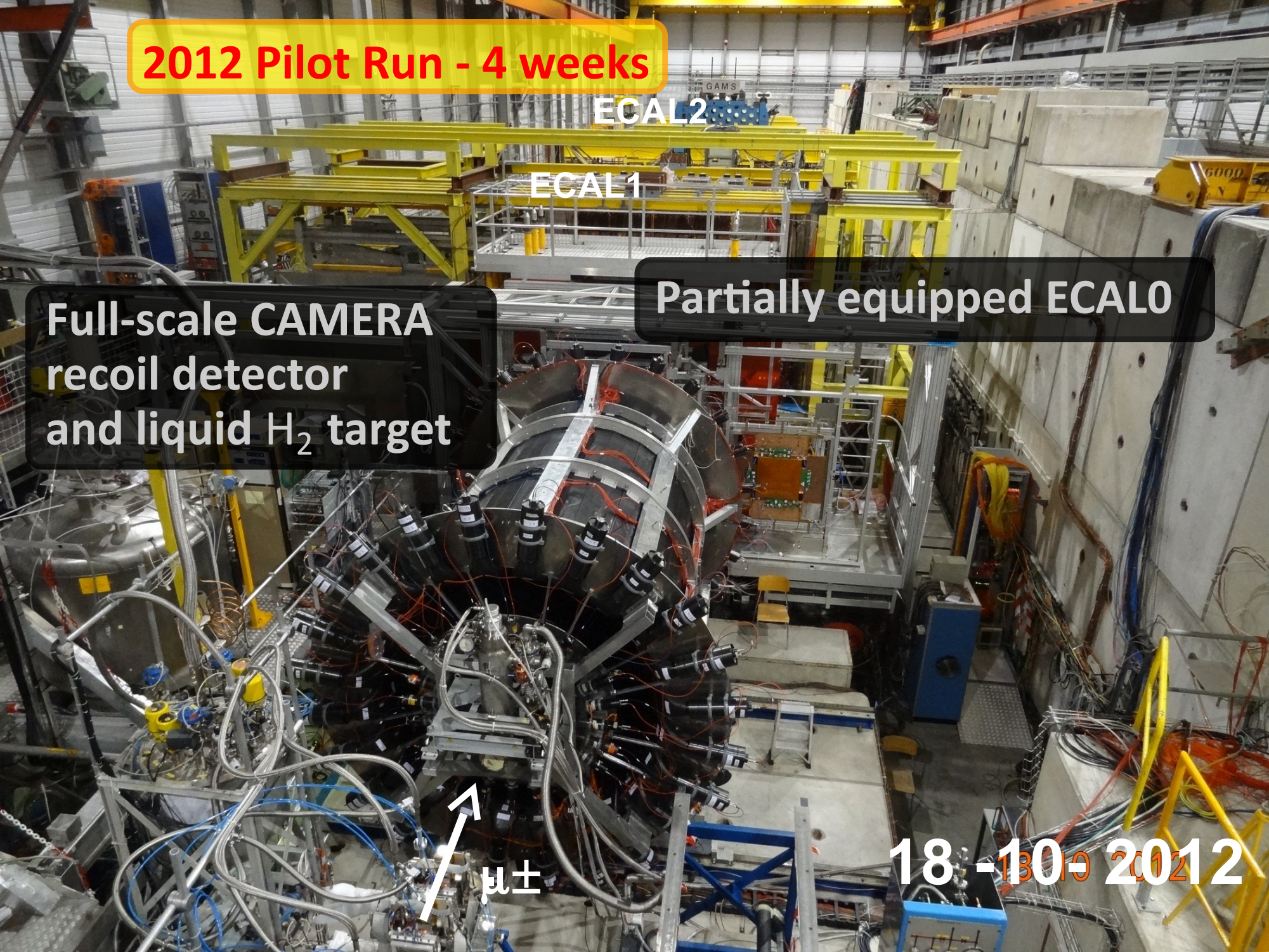
Detector efficiency:

$\varepsilon_{det} \approx 30\%$

Global efficiency:

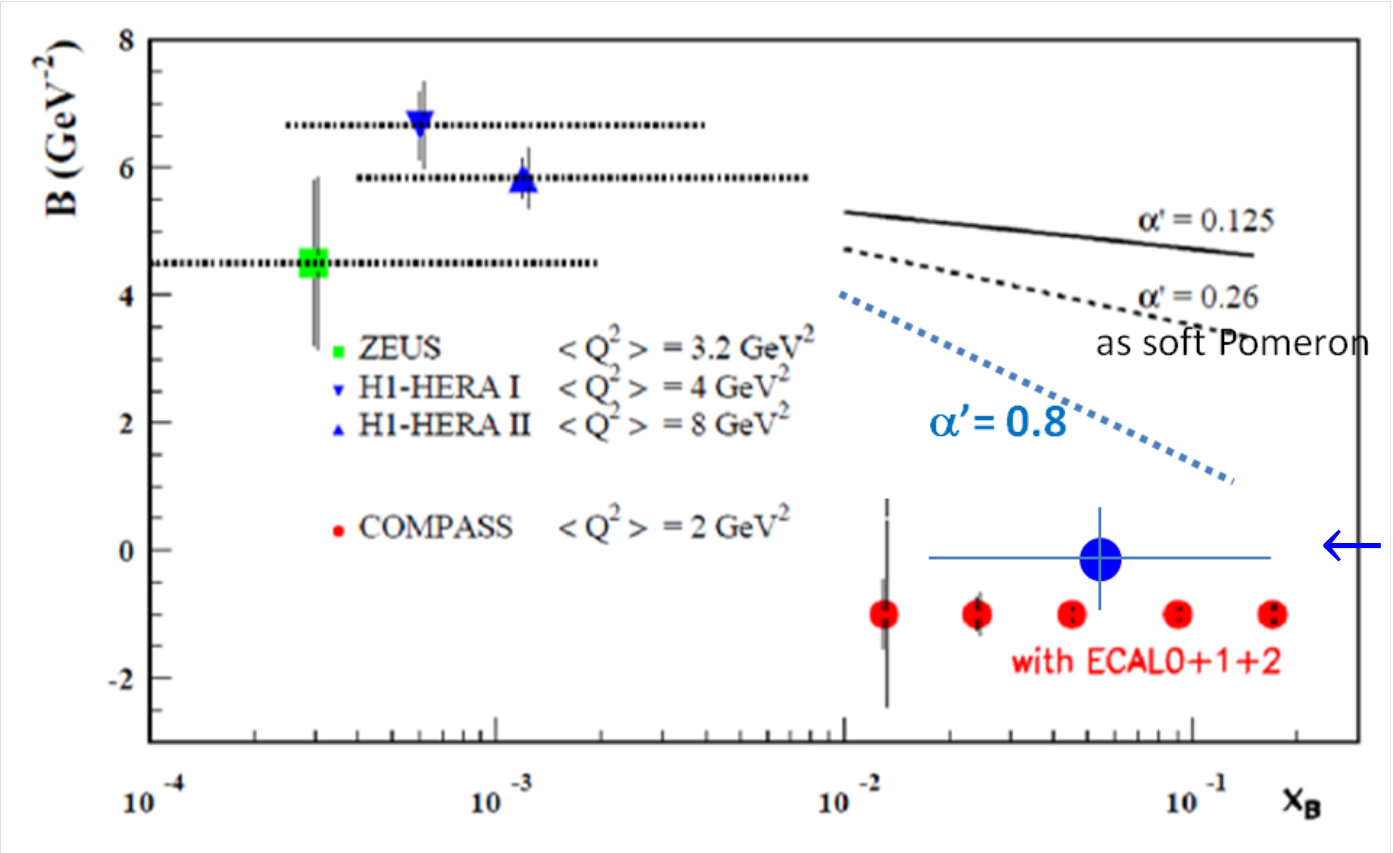
$\varepsilon_{global} \approx 10\%$

- Detector efficiency
- SPS and COMPASS availability
- Dead times + trigger efficiency


2012 Pilot Run - 4 weeks
GAMS
ECAL2
ECAL1
Partially equipped ECAL0
Full-scale CAMERA
recoil detector
and liquid H_2 target
μ±
18 -10- 2012

DVCS 2012 Test Run

$$S_{CS,U} \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \rightarrow d\sigma^{DVCS}/dt \sim \exp(-B|t|)$$

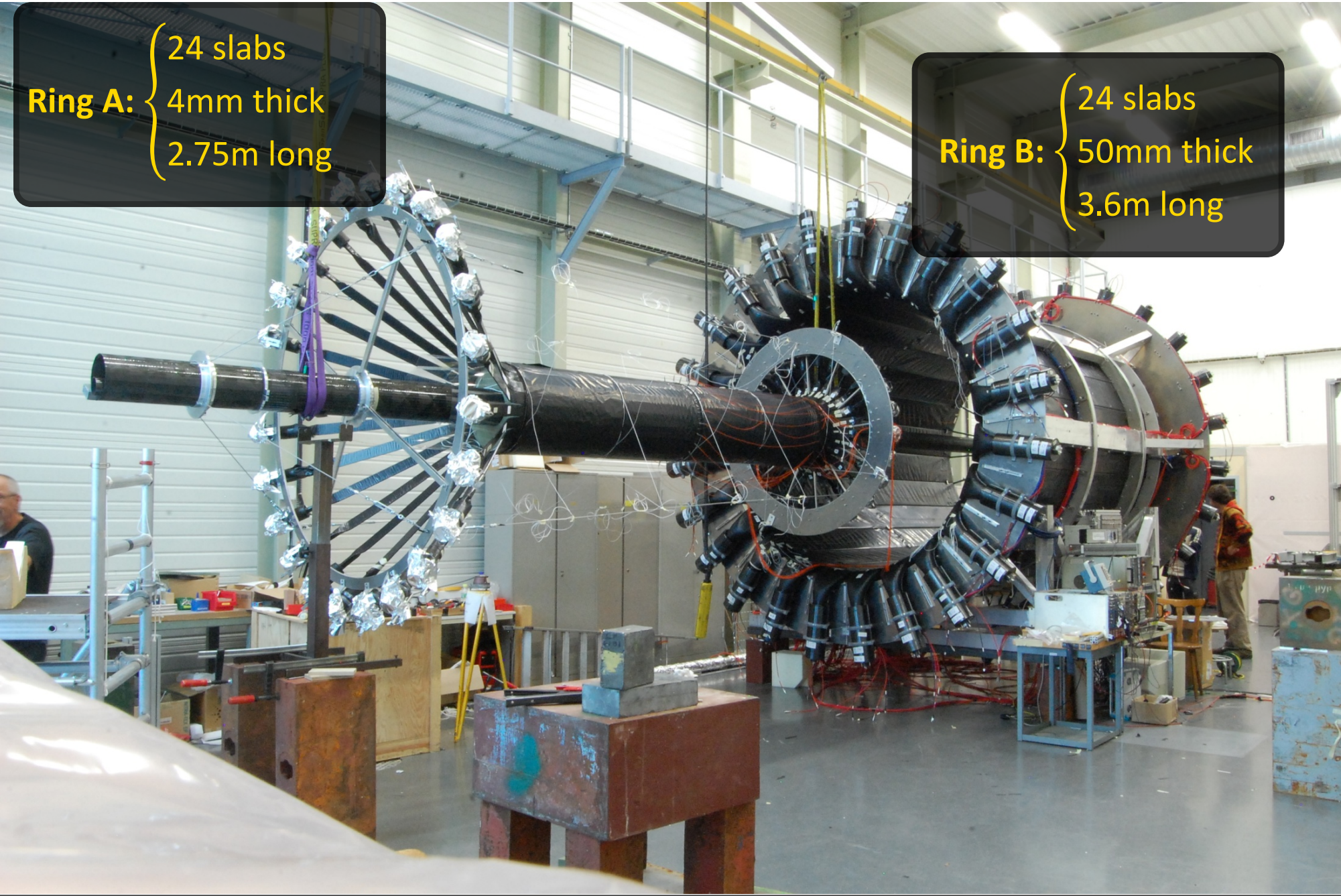


$$< r_\perp^2(x_B) > \approx 2B(x_B)$$

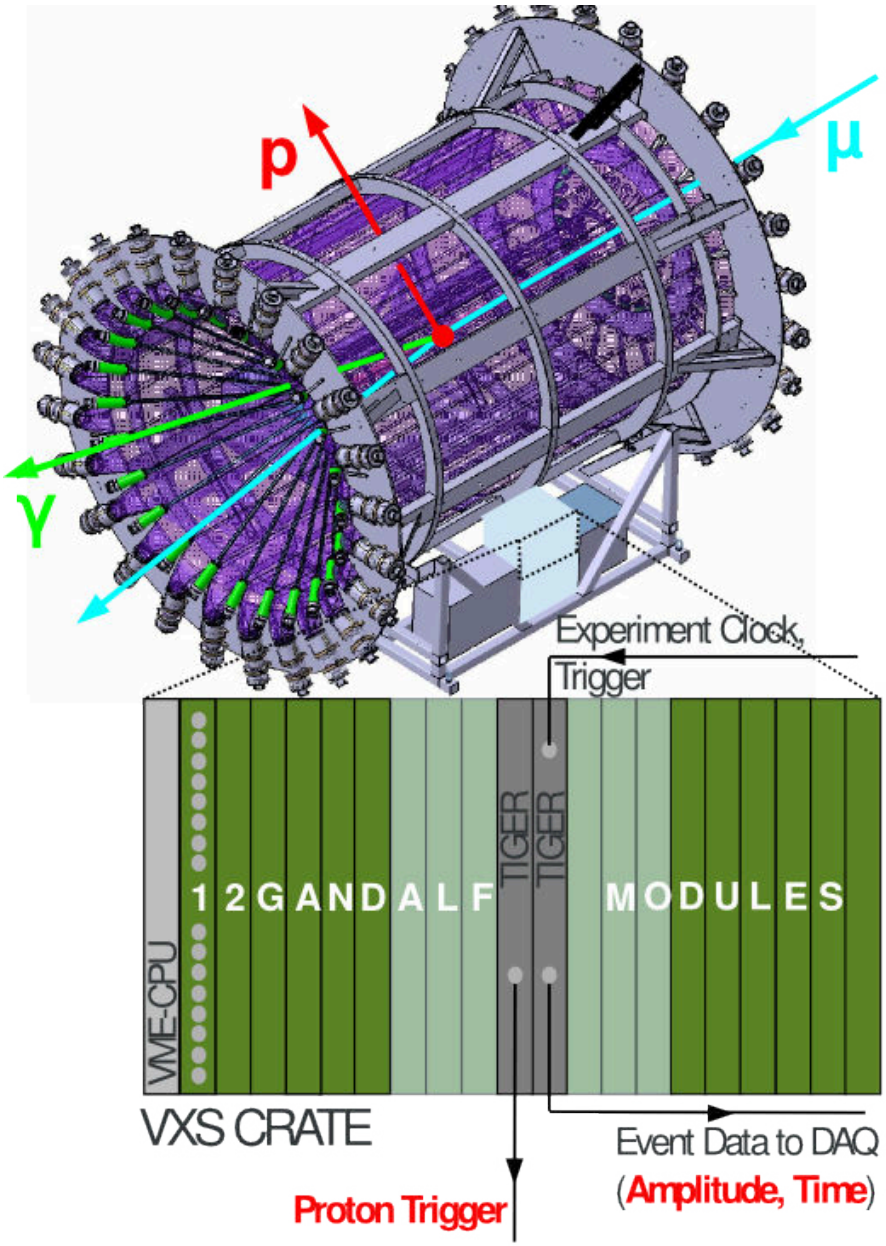
← 4 weeks in 2012

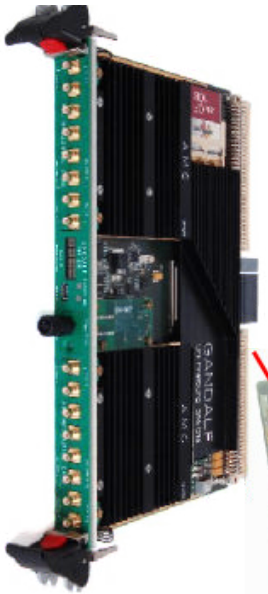
2012: we can expect one mean value of B in the COMPASS kinematic range

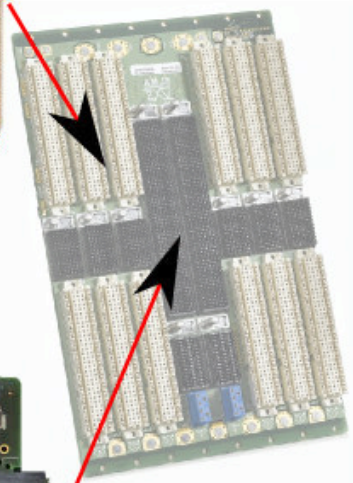
The Recoil TOF Detector CAMERA



CAMERA Readout







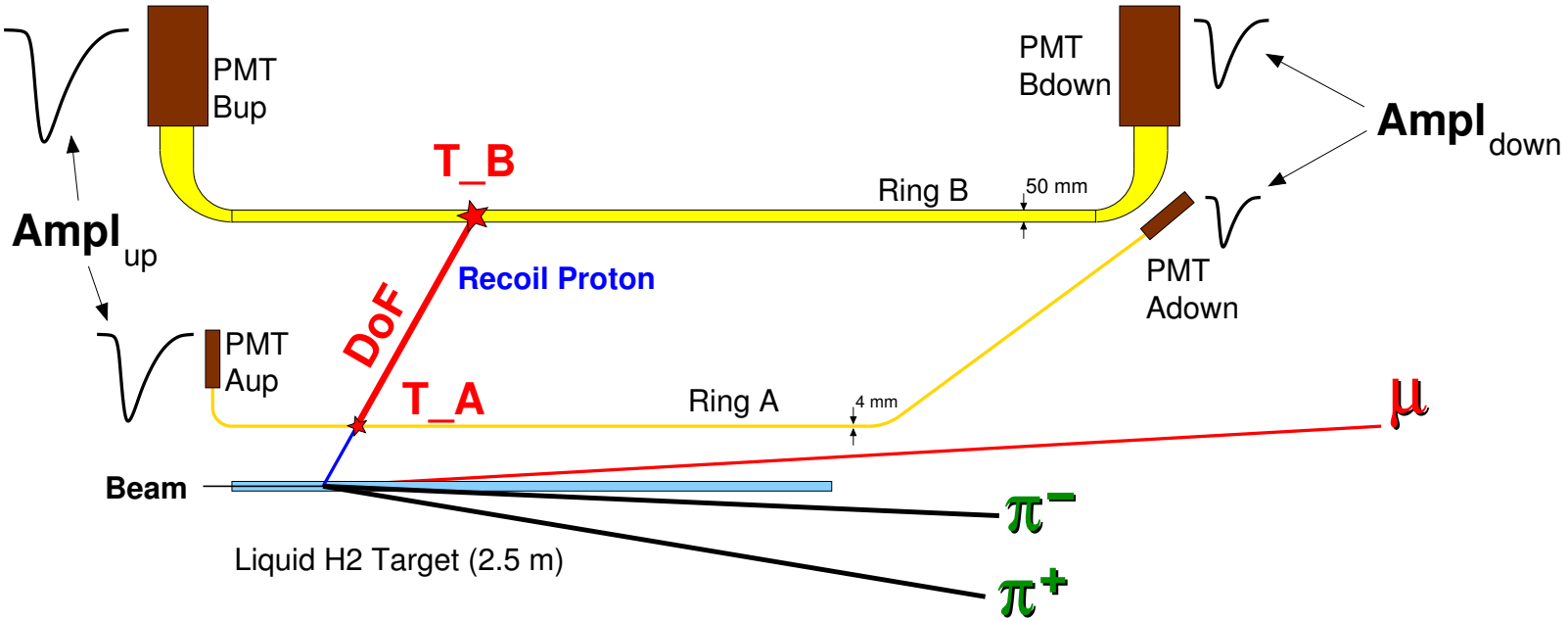
GANDALF

Virtex-5 VSX95
8 channels
1 GS/s
12 bit resolution

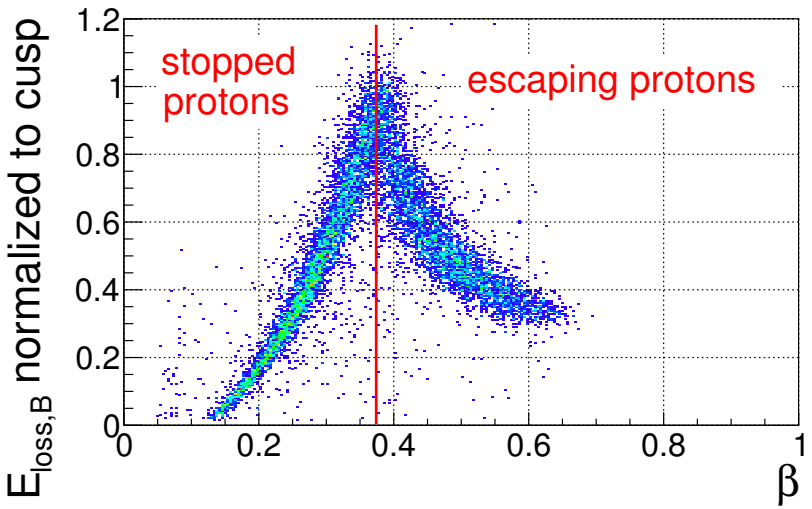
TIGER

Virtex-6 VLX365
onBoard GPU
2x SFP+
COM Express

Recoil particle Measurement in CAMERA



Eloss vs. beta – RING B



$$E_{loss} \sim \sqrt{Ampl_{up} * Ampl_{down}}$$

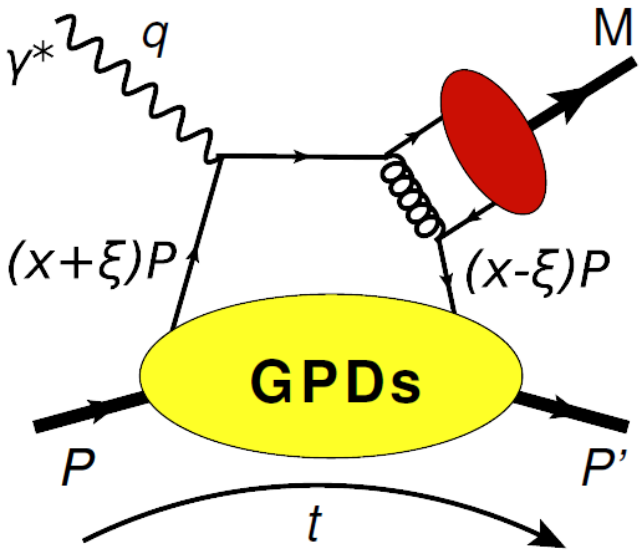
$$\textbf{TOF} \rightarrow (t_{up} + t_{down})_{A,B}$$

$$\textbf{z} \rightarrow t_{up} - t_{down}$$

Count rates: > 5 MHz in ring A

~1 MHz in ring B

Hard Exclusive Meson Production (HEMP)



Allows for flavor separation:

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

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

$E\phi = -1/3\,E^s - 1/8\,E^g$

Cross section measurements:

- Pseudo-scalar: π, η, ... $\Rightarrow \tilde{H}$ & $\tilde{E}$
- Vector meson: ρ, ω, ϕ... $\Rightarrow$ **H** & **E**

$\rho : \omega : \phi \sim 9 : 1 : 2$ (at large Q^2)

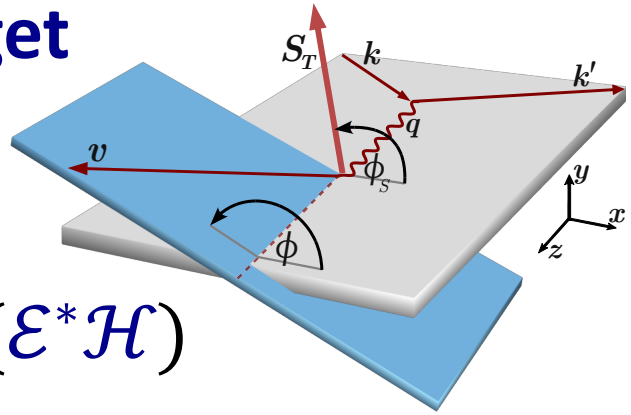
- Vector meson production from transversely polarized target asymmetry $\Rightarrow$ **E/H**

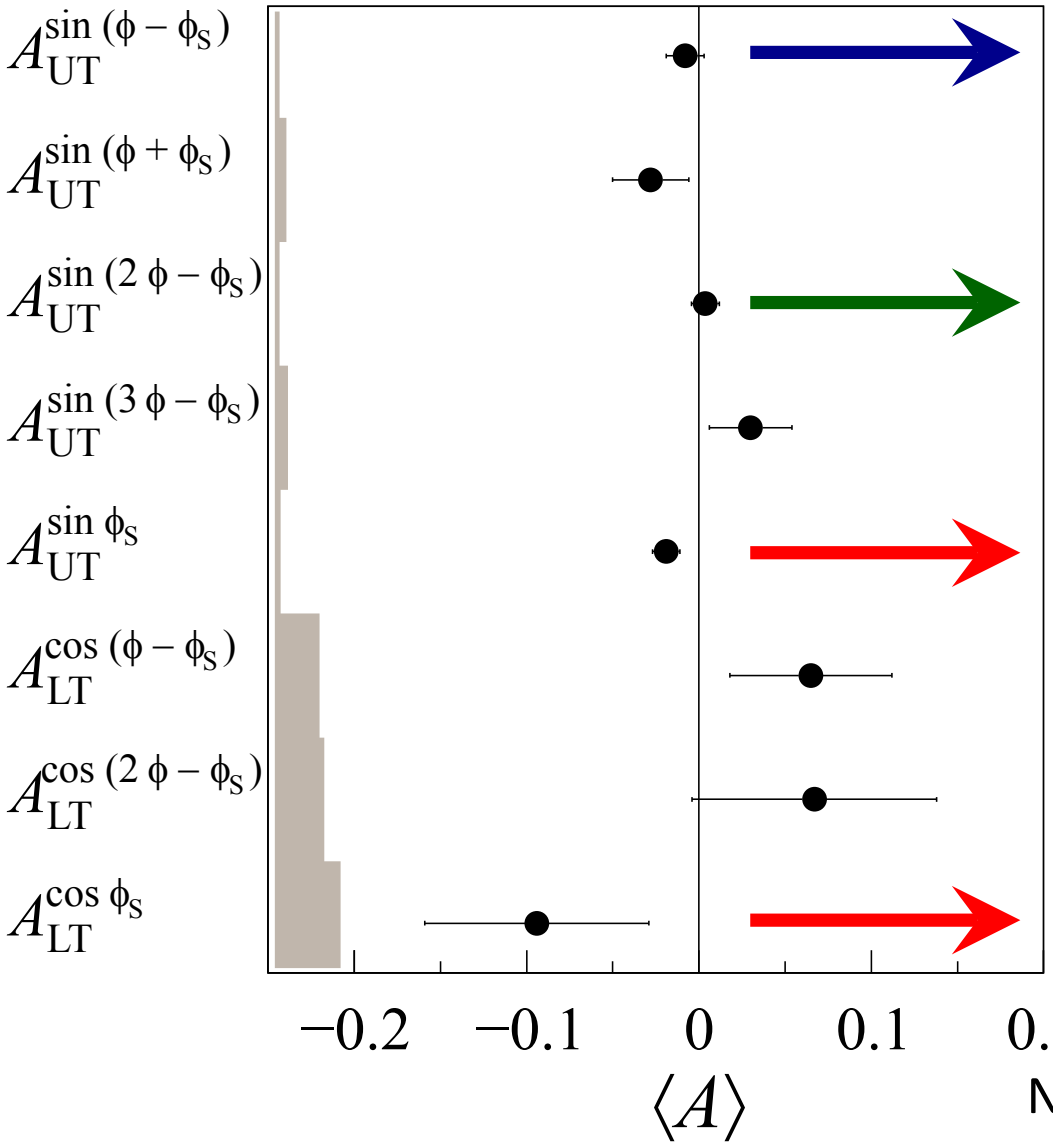
Presently studied at COMPASS without RPD

Exclusive ρ^0 Prod. on a Transv. Pol. Target

$$\mu\, p \rightarrow \mu' + \rho^0\,(+\,p)_{\text{undetected}}$$

COMPASS 2007-2010 data **without recoil detector**





$\propto \mathrm{Im}(\mathcal{E}^*\mathcal{H})$

$\propto \mathrm{Im}(\mathcal{E}^*\overline{\mathcal{E}}_{\mathcal{T}})$

$\propto \mathrm{Im}(\mathcal{E}^*\overline{\mathcal{E}}_{\mathcal{T}} - \mathcal{H}^*\mathcal{H}_{\mathcal{T}})$

Possible evidence of non-vanishing $\mathbf{H_T}$

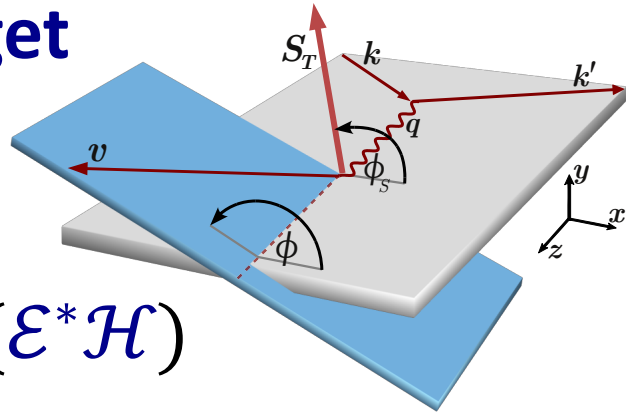
$\propto \mathrm{Re}(\mathcal{E}^*\overline{\mathcal{E}}_{\mathcal{T}} - \mathcal{H}^*\mathcal{H}_{\mathcal{T}})$

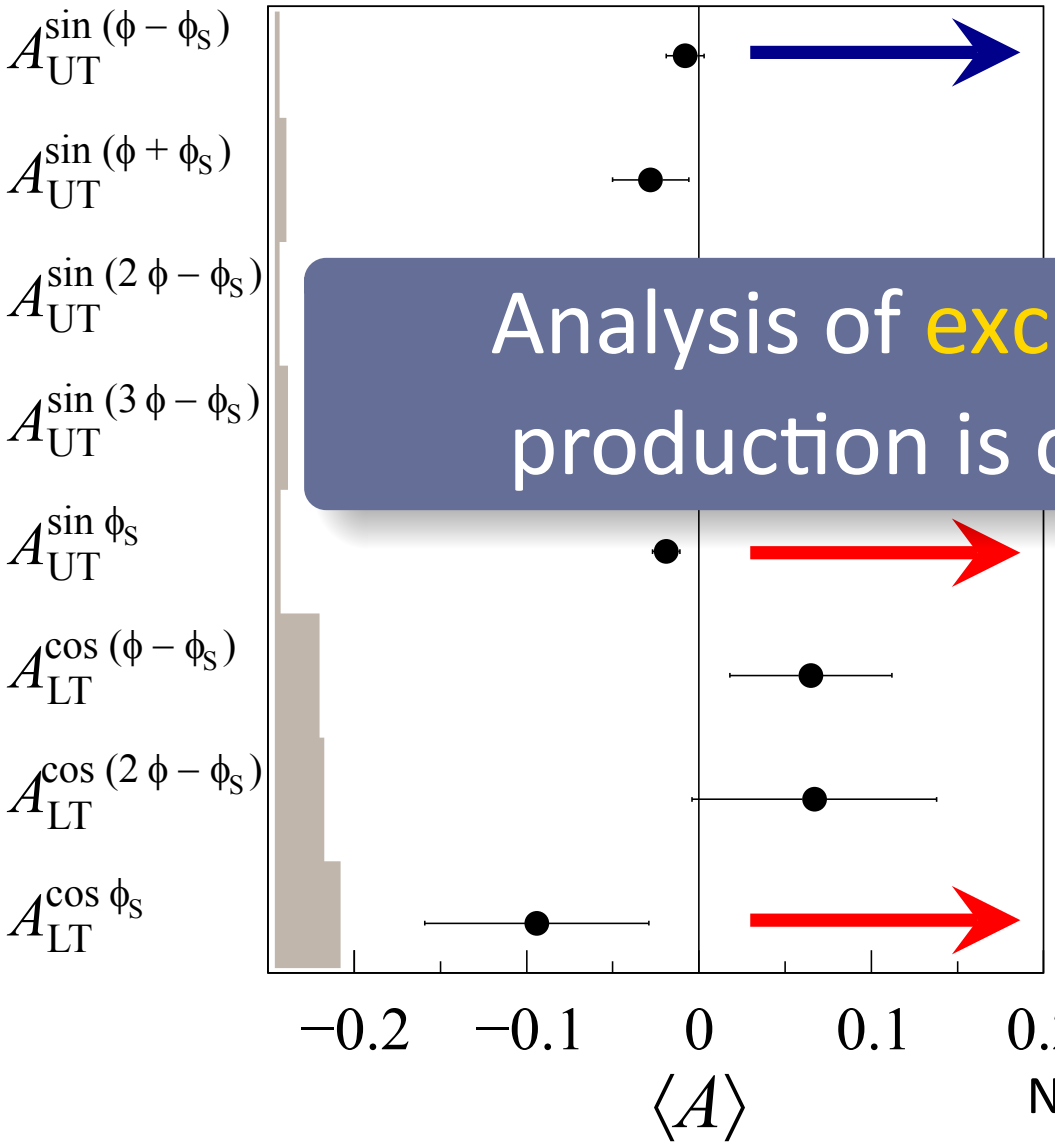
NPB 865 (2012) 1, PLB 731 (2014) 19

Exclusive ρ^0 Prod. on a Transv. Pol. Target

$$\mu\, p \rightarrow \mu' + \rho^0\,(+\,p)_{\text{undetected}}$$

COMPASS 2007-2010 data **without recoil detector**





$\propto \mathrm{Im}(\mathcal{E}^*\mathcal{H})$

Analysis of exclusive ω production is ongoing

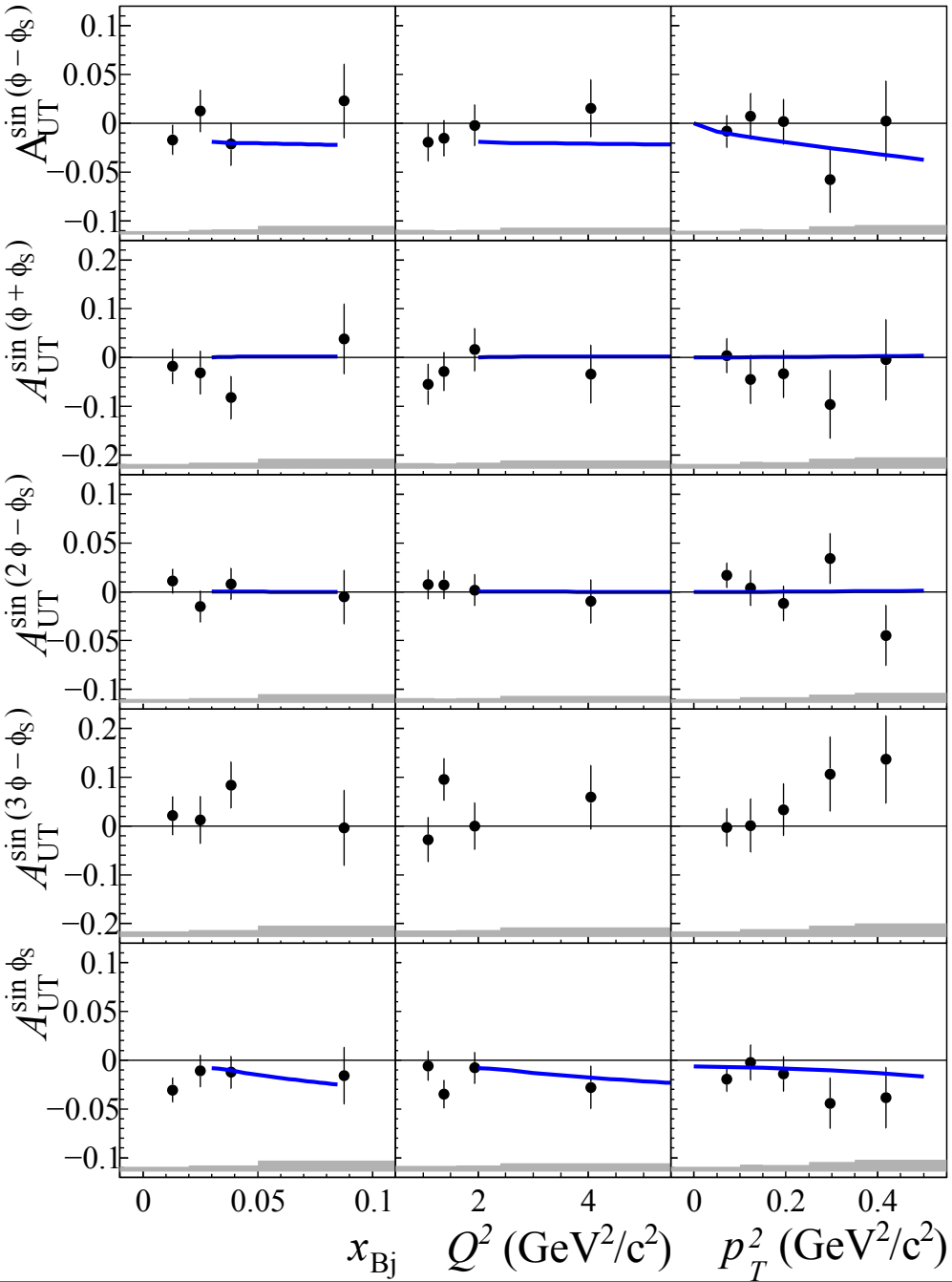
$\propto \mathrm{Im}(\mathcal{E}^*\mathcal{E}_{\mathcal{T}} - \mathcal{H}^*\mathcal{H}_{\mathcal{T}})$

Possible evidence of non-vanishing $\mathbf{H_T}$

$\propto \mathrm{Re}(\mathcal{E}^*\overline{\mathcal{E}}_{\mathcal{T}} - \mathcal{H}^*\mathcal{H}_{\mathcal{T}})$

NPB 865 (2012) 1, PLB 731 (2014) 19

Exclusive ρ^0 Prod. on a Transv. Pol. Target



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

COMPASS 2007-2010 data without recoil detector

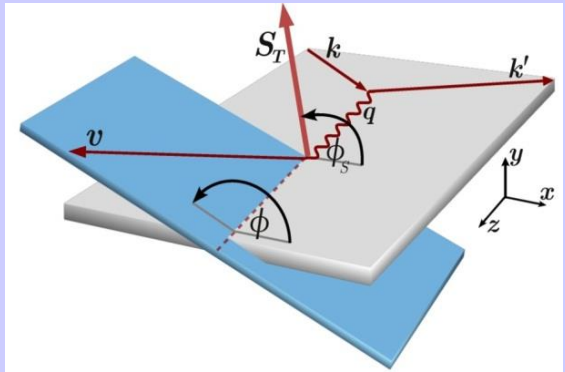
Curves from:
Goloskokov and Kroll,
EPJ C74 (2014) 2725

$$A_{UT}^{\sin(\phi_S)} \propto \mathrm{Im}(\mathcal{E}^*\overline{\mathcal{E}}_{\mathcal{T}} - \mathcal{H}^*\mathcal{H}_{\mathcal{T}})$$

Beyond 2018: DVCS on a Transversely Polarized Target

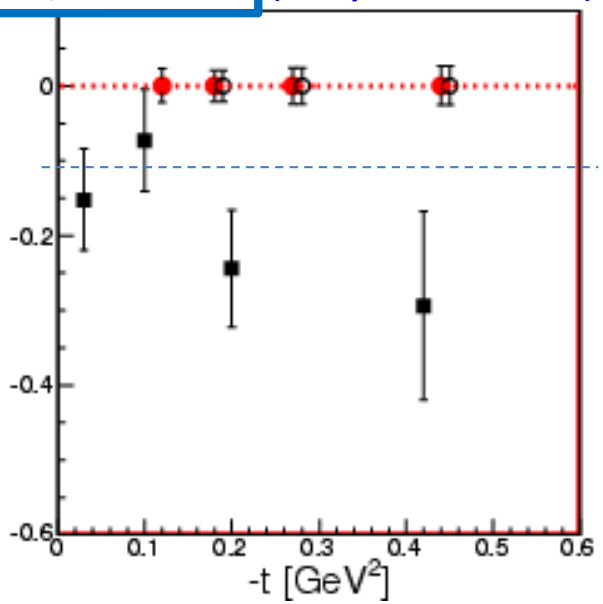
with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam and **transversely** polarized NH3 (proton) target

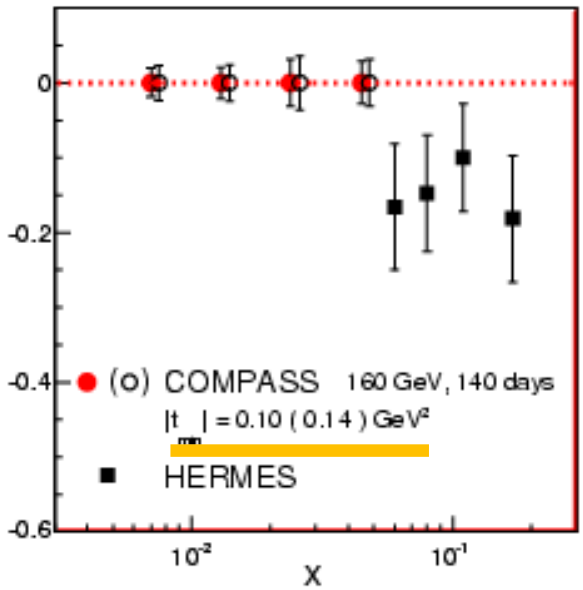
$$D_{CS,T} \equiv d\sigma_T(\mu^{+\downarrow}) - d\sigma_T(\mu^{-\uparrow}) \propto Im(F_2\mathcal{H} - F_1\mathcal{E})\sin(\phi - \phi_S)\cos\phi$$

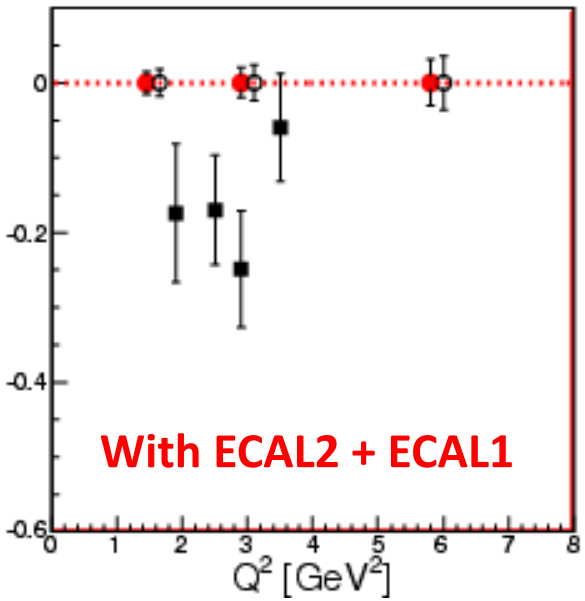


$A^{\sin(\phi-\phi_s)\cos\phi}_{CS,T}$ **related to H and E** (only stat .error)

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



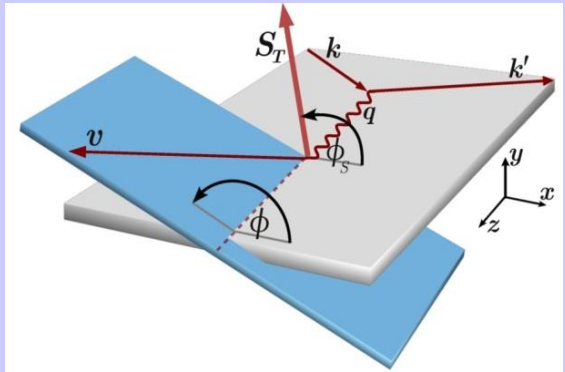




Beyond 2018: DVCS on a Transversely Polarized Target

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

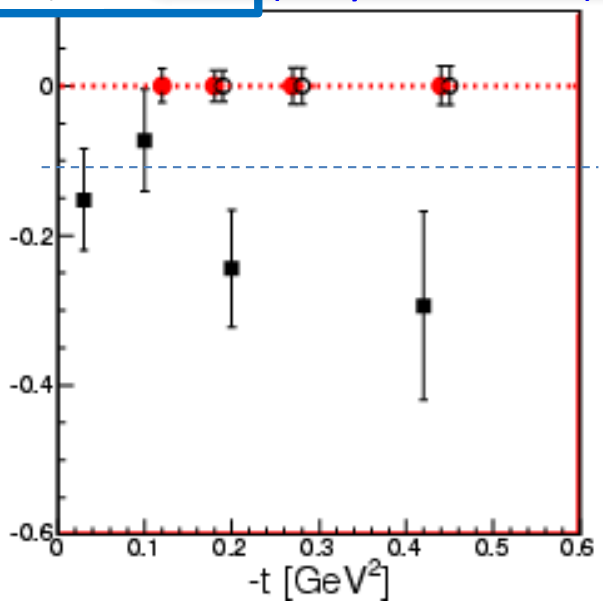
$$\mathcal{D}_{CS,T} \equiv d\sigma_T(\mu^{+\downarrow}) - d\sigma_T(\mu^{-\uparrow}) \propto Im(F_2\mathcal{H} - F_1\mathcal{E})\sin(\phi - \phi_S)\cos\phi$$

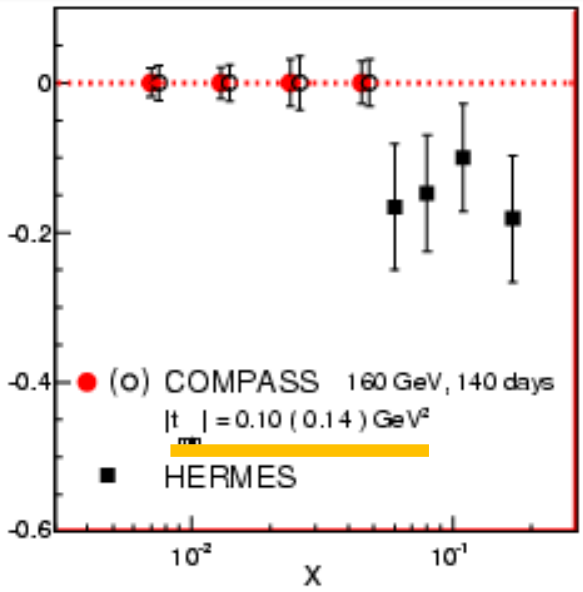


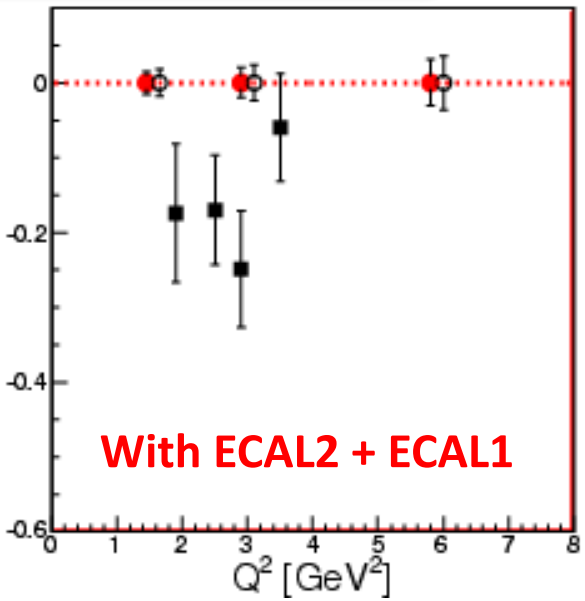
Possible addendum to the COMPASS-II Program

$A^{\sin(\phi-\phi_S)\cos\phi}_{CS,T}$ (only stat .error)

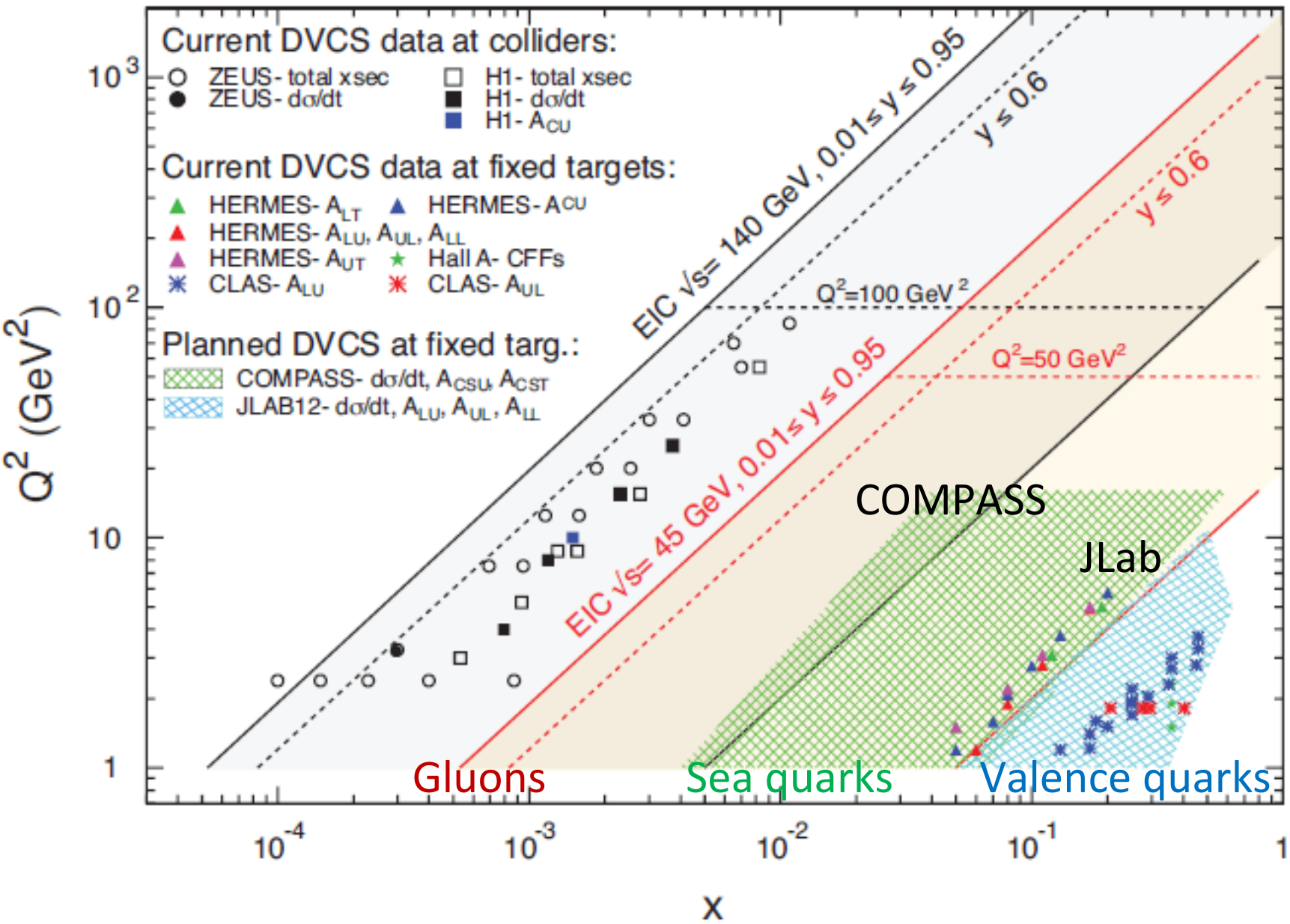
1.2 m polarised NH_3 target $\delta_{global} \sim 10\%$







Past, Present and Future GPD Experiments



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