COMPASS experiment NA58 at CERN

GPD programme at CERN using the COMPASS spectrometer

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On behalf of the COMPASS Collaboration

COMPASS

Future Physics @ COMPASS

CERN, 26-27 September 2002

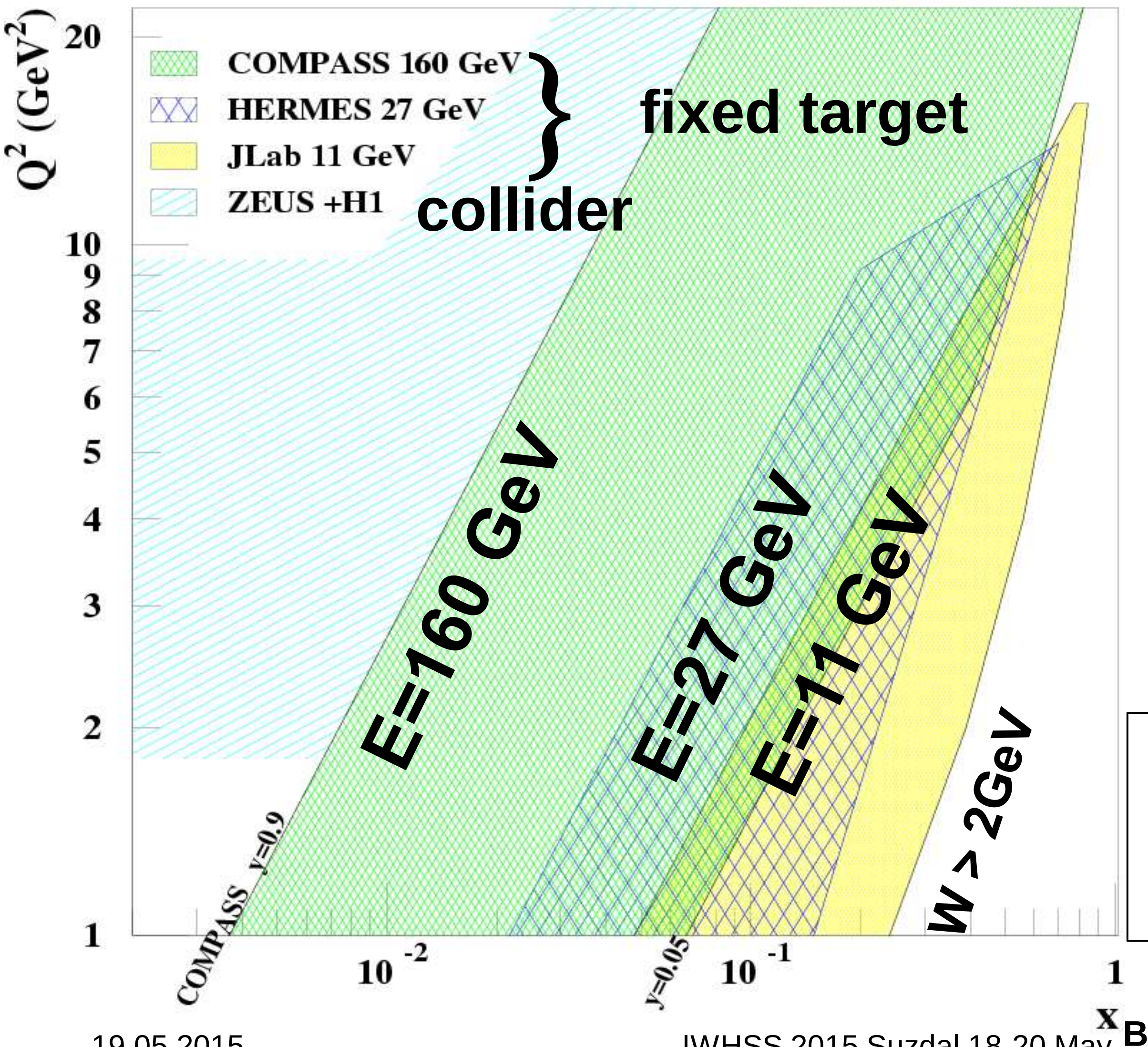
Long way towards GPD

In 2010 the COMPASS-II program has been approved by the CERN Research Board.
It consists of studies: DVCS, HEMP, SIDIS, Polarized Drell-Yan and Primakoff reactions.
(Finally in 2012, 2015-2017)

OMPASS
omb Field

M. Diehl	Introduction to Generalized Parton Distributions
N. d'Hose *et al.*	Possible Measurements of GPDs at COMPASS

COMPASS kinematical coverage (Q^2, x_{Bj}) for DVCS



CERN High energy muon - beam 100 - 190 GeV
μ+ and μ- available
80% polarisation
with opposite polarization

4.6 10^8 μ^+ /spill
Lumi= 10^{32} cm^{-2} s^{-1}
with 2.5m LH_2 target
$\sim 10^{-2} < x_{Bj} < \sim 10^{-1}$

$x_{Bj} \rightarrow$ 0.20 with extension of present calorimetry

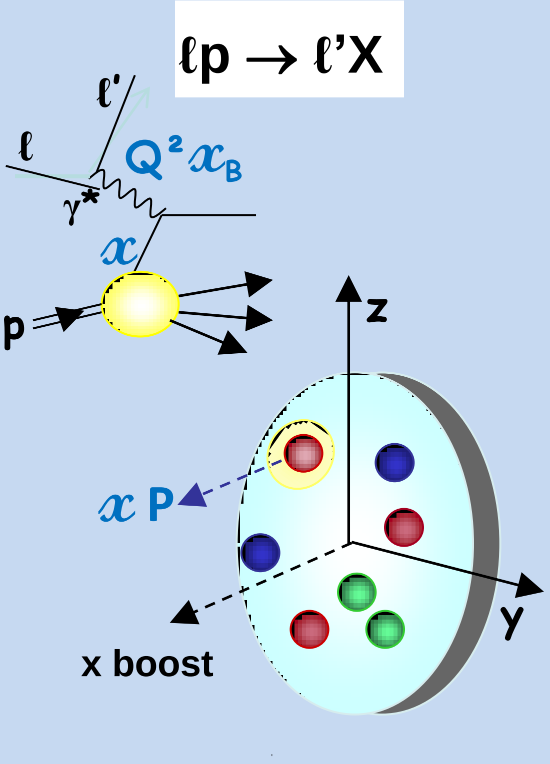
uncovered region between ZEUS+H1 & HERMES + Jlab before new colliders may be available

From PDFs to TMDs and GPDs

From Wigner distribution we can build ''mother distributions''
$\mathcal{W}(x, b_\perp, k_\perp)$ → 3-dimensional nucleon structure
in momentum and configuration space:

PDF (x)

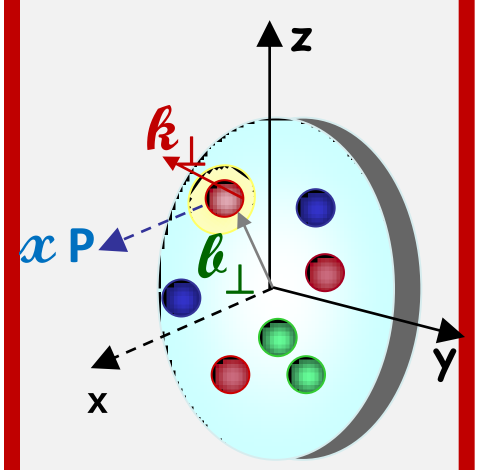
Deep Inelastic Scattering



Partons Distrib. q (x)

GPD $(x, b_\perp)$: Generalised Parton Distribution
(position in the transverse plane)

TMD $(x, k_\perp)$:Transverse Momentum Distribution
(momentum in the transv. plane)



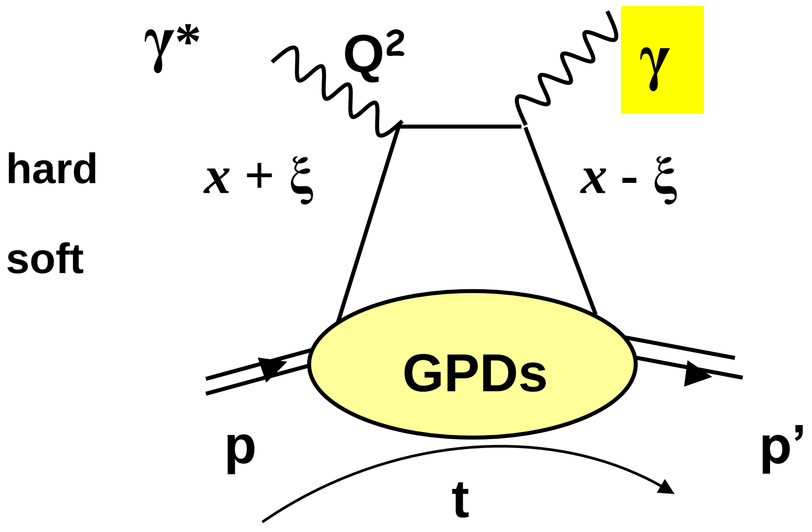
TMD accessible in SIDIS and DY

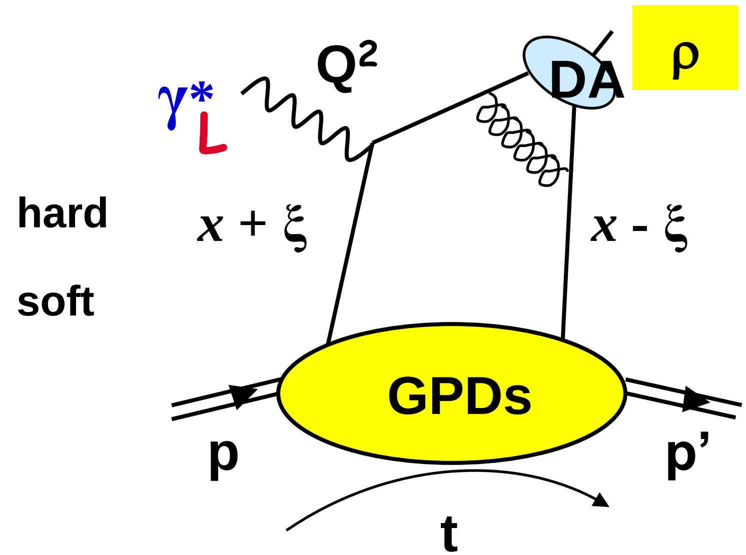
GPD in Exclusive reactions DVCS and HEMP

From inclusive reactions to the exclusive ones

Deeply Virtual Compton Scattering (DVCS): $\ell p \rightarrow \ell' p' \gamma$ **(golden channel)**

Hard Exclusive Meson Production (HEMP): $\ell p \rightarrow \ell' p' \rho / \phi / J/\psi / \omega$ …..

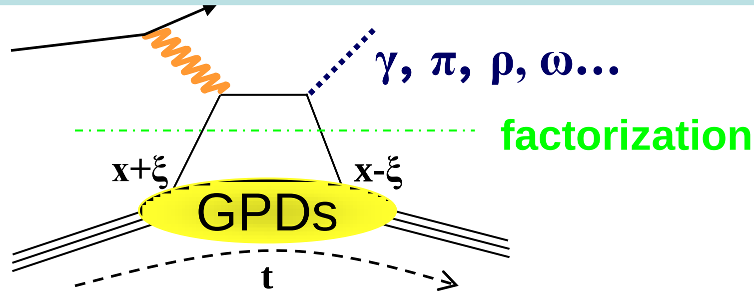




theoretically cleanest of the experimentaly accessible processes to measure GPDs

"Distribution Amplitude" should be taken in addition into account …. But gives possibility separate the flavors , access to GPDs gluons etc.

GPDs and relations to the physical observables



The observables are some integrals of GPDs over x

Fit of Parameters to the data

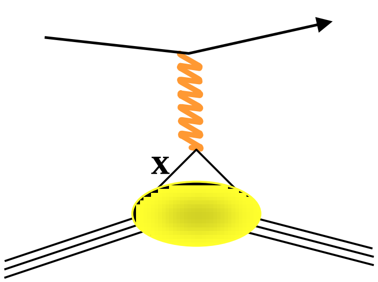
Dynamics of partons

in the Nucleon Models:

Parametrization

GPDs H, E, ...

Elastic Form Factors



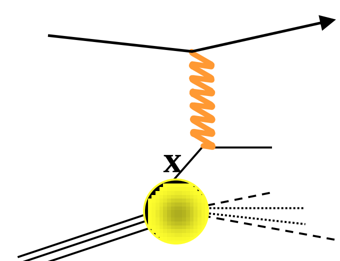
$\int H(x,\xi,t)dx = F(t)$

Ji's sum rule

$2J_q = \int x(H+E)(x,\xi,0)dx$

$1/2 = 1/2\ \Delta\Sigma + L_q + \Delta G + L_g$

"ordinary" parton density



$H(x,0,0) = q(x)$

$\tilde{H}(x,0,0) = \Delta q(x)$

The steps of the GPD Physics Program at COMPASS

2008: Very short test run & short (40 cm) LH_2 target
∘ First observation of exclusive photon production (mainly BH)

2009: 10 days, same LH_2 target (10 x statistics 2008)
∘ First a) hint of DVCS at large x_{Bj} b) observation « exclusive » π^0
c) background estimation for DVCS & « exclusive » π^0

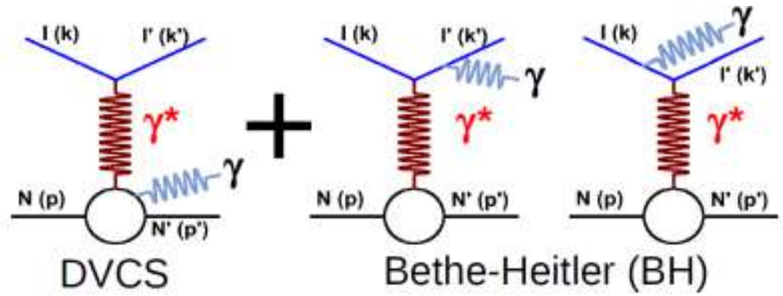
Detection efficiency :
$\varepsilon_{\mu+p\to\mu+p+\gamma} = 0.32 \pm 0.13$

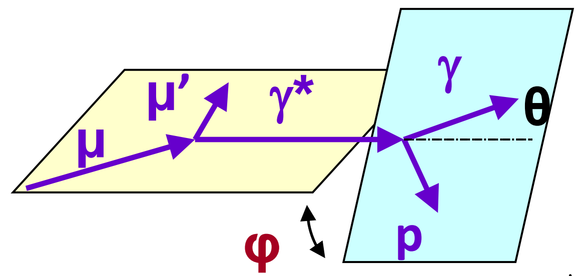
Global efficiency : $\varepsilon_{global} = 0.13 \pm 0.05$
- detection efficiency
- SPS & COMPASS availability
- Dead time & Trigger efficiency

2012: 4 weeks, full-scale LH_2 target, recoil detector and part of ECAL0
2016-2017: projections for 2 years of dedicated data taking (**GPD H**)
2007 and 2010: Exclusive vector meson production (no recoil detector)

>2018: DVCS with transversely polarized target and
recoil detector → **GPD E** Future addendum to COMPASS-II proposal

Exclusive single photon production $\ell p \rightarrow \ell' p' \gamma$



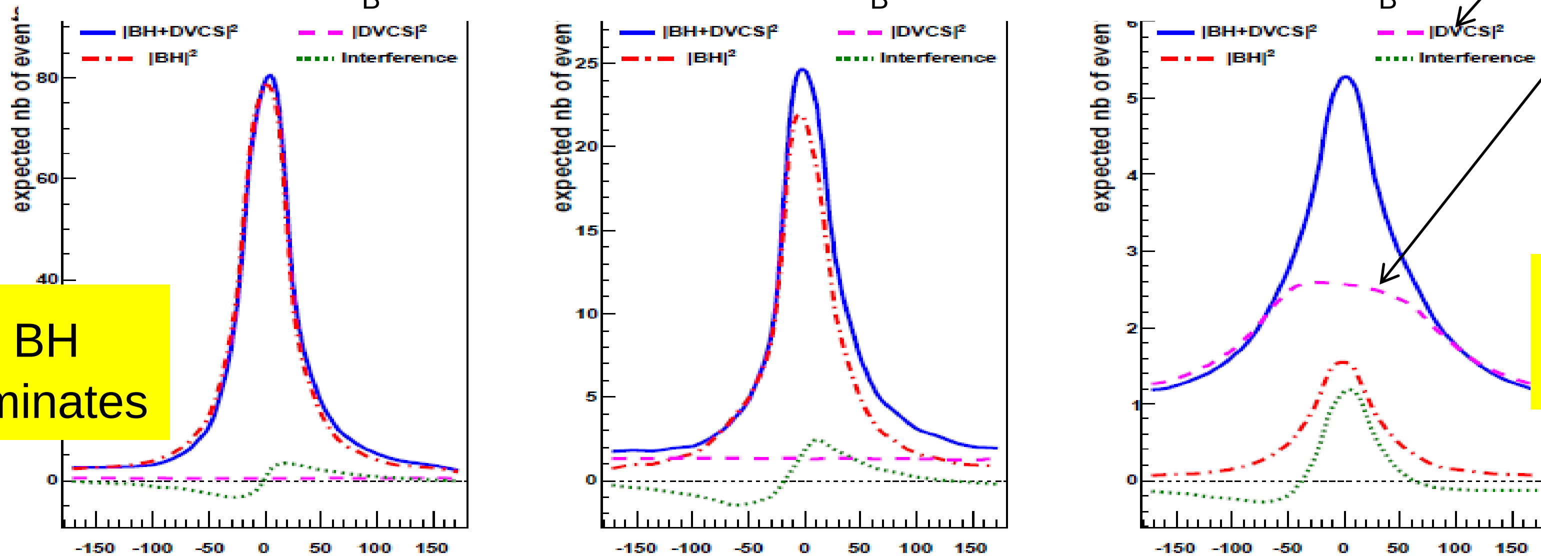


Known to 1 %

Monte-Carlo using set-up with ECAL1+ECAL2

$$d\sigma \;\alpha\; |T^{DVCS}|^2 \;+\; Im(T^{DVCS}) \cdot T^{BH} + Re(T^{DVCS}) \cdot T^{BH} \;+\; |T^{BH}|^2$$

$0.005 < x_B < 0.01$ $\quad$ $0.01 < x_B < 0.03$ $\quad$ $0.03 < x_B$



ECAL0 necessity

BH dominates

DVCS dominates

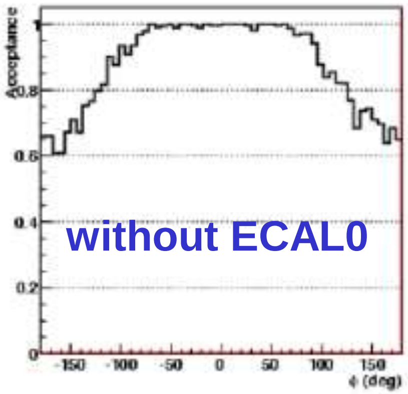
reference from almost pure Bethe-Heitler

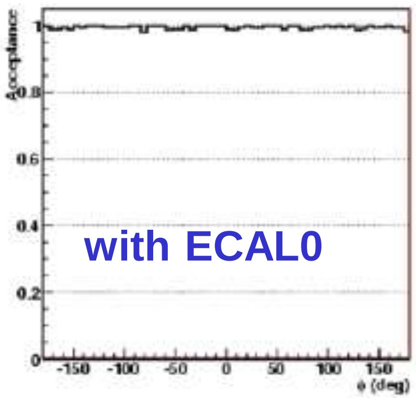
Study DVCS with:
$\Re(T^{DVCS})$ & $\Im(T^{DVCS})$
via $(d\sigma^{+\leftarrow} \pm d\sigma^{-\rightarrow})$

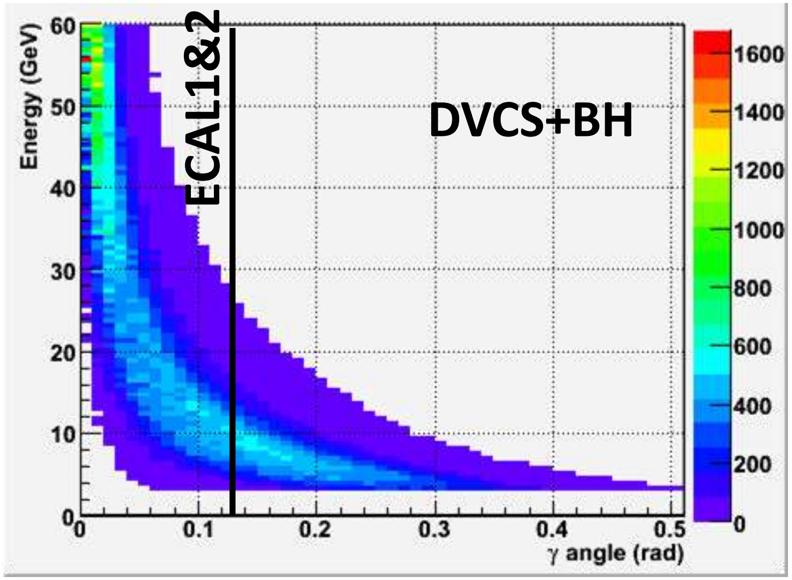
Transverse Imaging:
$d\sigma^{DVCS}/dt$
via $(d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$

Large-angle electromagnetic calorimeter ECAL0

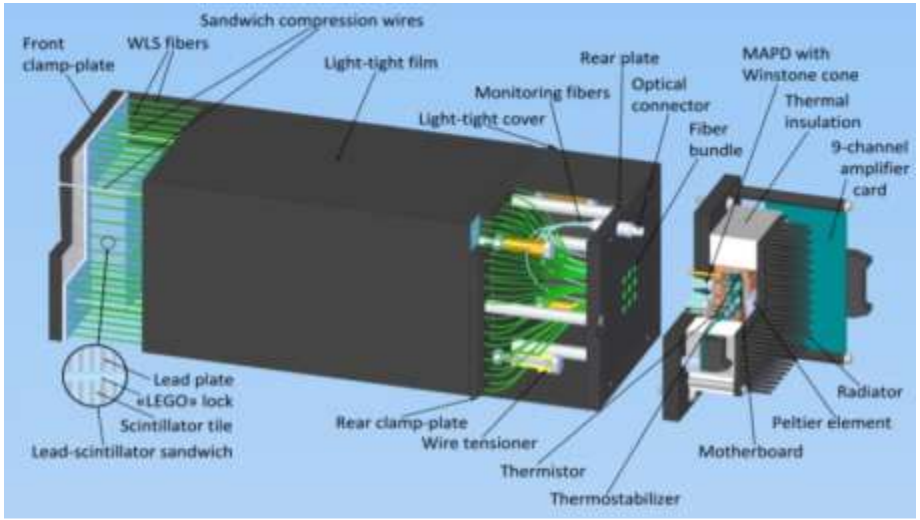
ϕ-dependence of acceptance



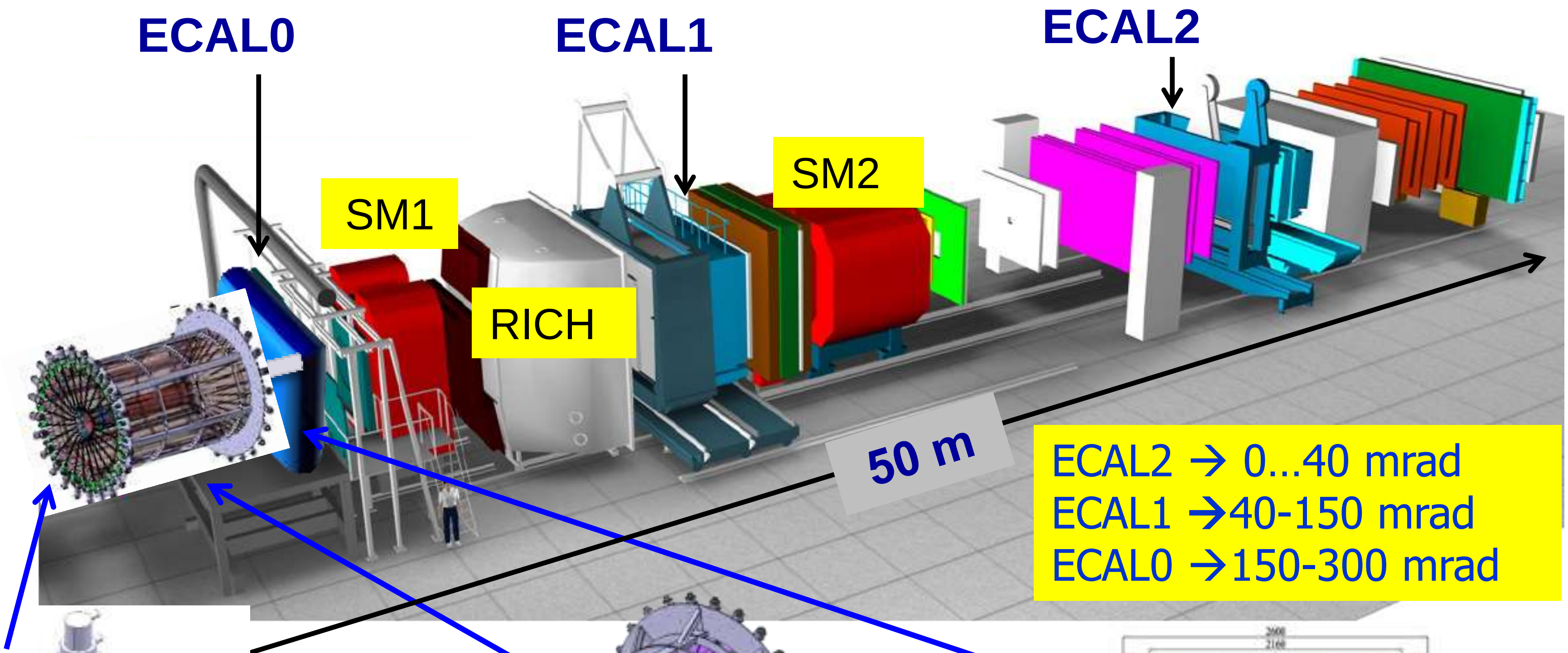




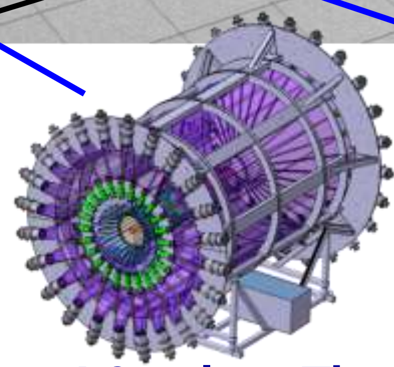
$Q^2 = 1.5 \pm 0.5\ (\mathrm{GeV}/c)^2$ and $x_{Bj} = 0.06 \pm 0.005$



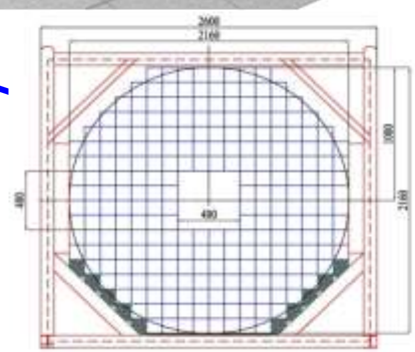
The DVCS experiment at COMPASS



2.5 m long LH target

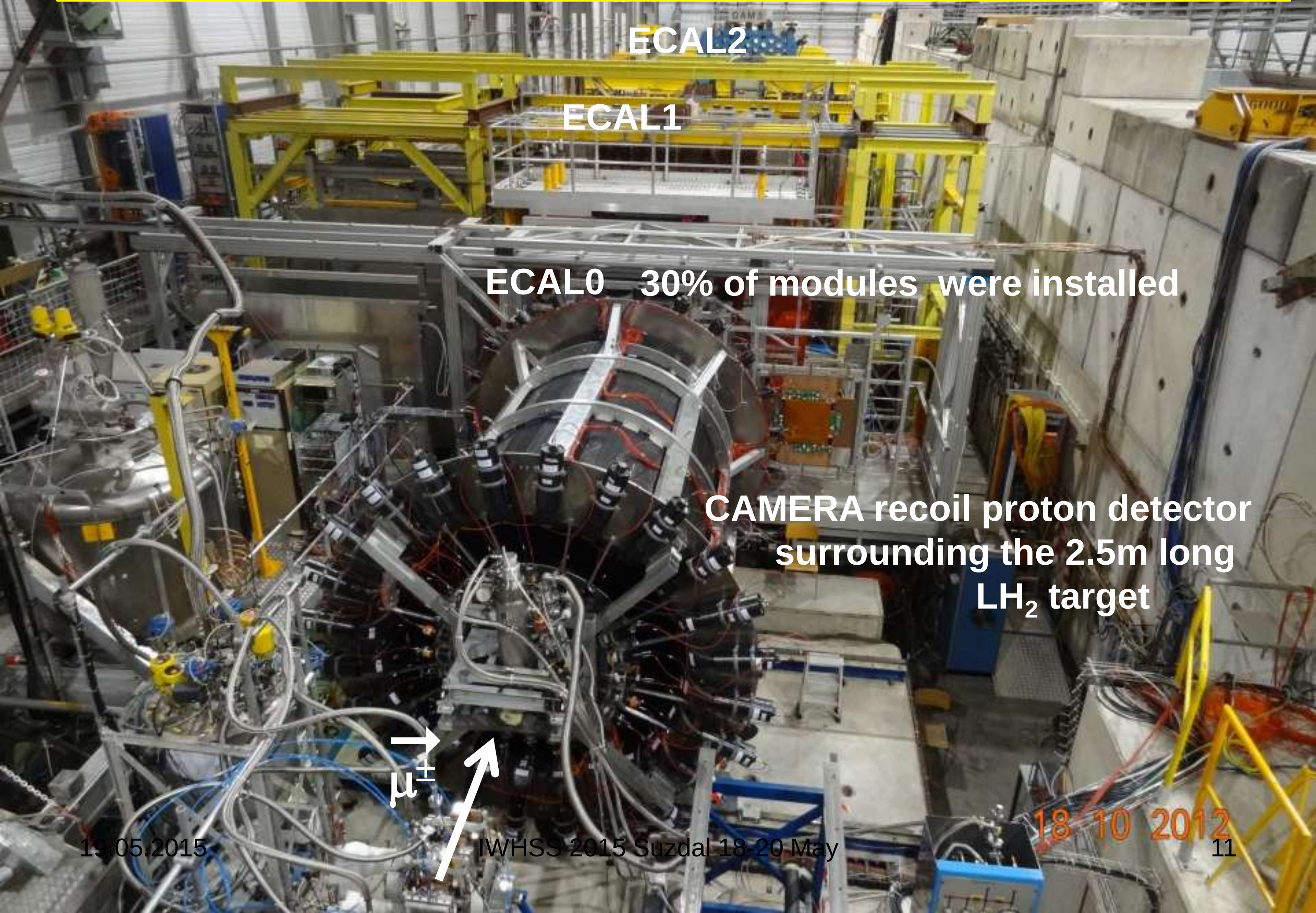


4.0 m longTime-Of-Flight detector: 24 inner and 24 outer slabs



2x2 m² electromagnetic calorimeter, ECAL0

DVCS data taking from 1-11 to 2-12-2012



Exclusive Photon Events Selection

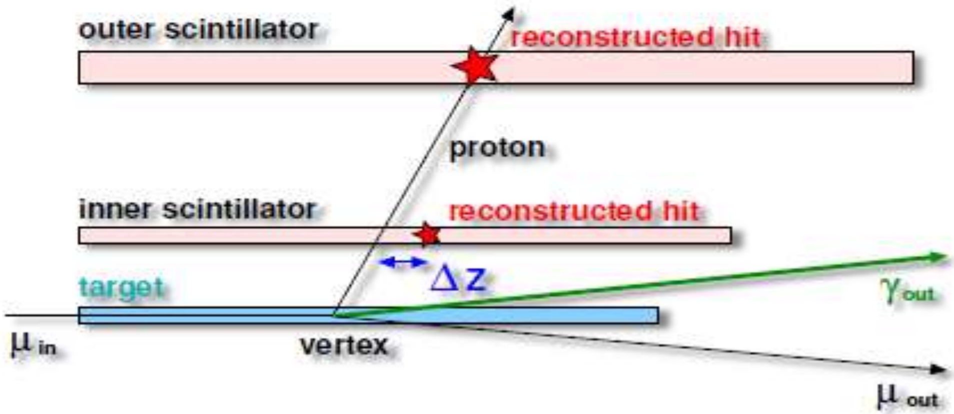
Reconstructed interaction vertex in **target volume**

One single photon above DVCS production threshold

$Q^2 > 1\ (\mathrm{GeV}/c)^2$, $0.05 < y < 0.9$, $0.06\ (\mathrm{GeV}/c)^2 < t < 0.64\ (\mathrm{GeV}/c)^2$

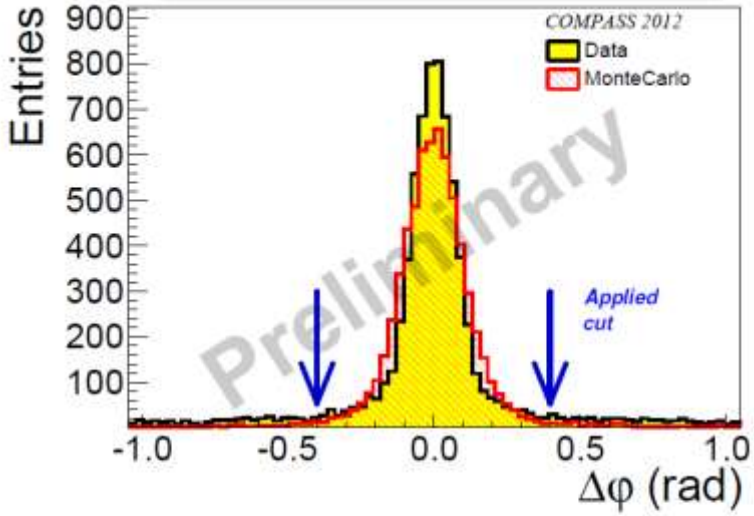
Exclusivity conditions:

- $\Delta\varphi = \varphi^{\mathrm{proton}}_{\mathrm{meas}} - \varphi^{\mathrm{proton}}_{\mathrm{reco}}$
- Vertex pointing (ΔZ)
- Transv. momentum balance: $\Delta p_{\perp} = p^{\mathrm{proton}}_{\perp,\mathrm{meas}} - p^{\mathrm{proton}}_{\perp,\mathrm{reco}}$
- Four-momentum balance: $M_X^2 = (p_{\mu_{\mathrm{in}}} + p_{p_{\mathrm{in}}} - p_{\mu_{\mathrm{out}}} - p_{p_{\mathrm{out}}} - p_{\gamma})^2$
- Missing energy: $((p_{\mu_{\mathrm{in}}} + p_{p_{\mathrm{in}}} - p_{\mu_{\mathrm{out}}} - p_{\gamma})^2 - M_p^2)/2M_p$



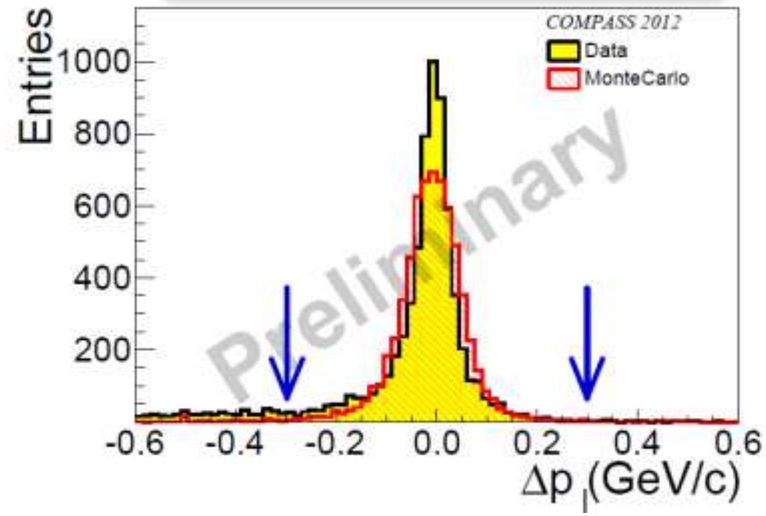
Exclusivity Variables: $\Delta\varphi$

$$\Delta\varphi = \varphi^{proton}_{meas} - \varphi^{proton}_{reco}$$



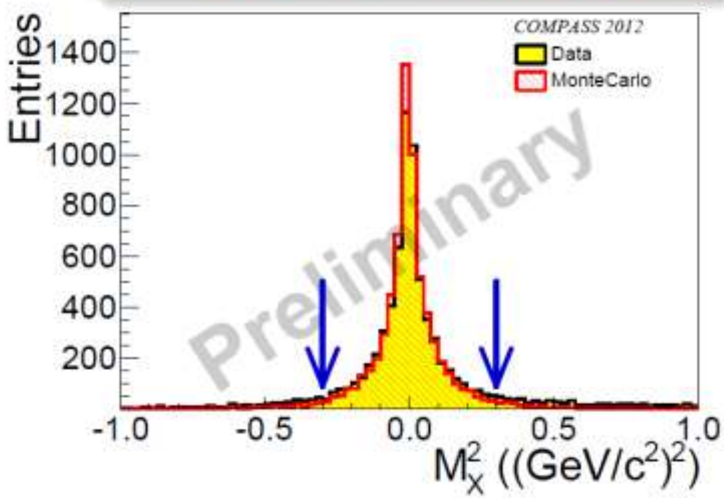
Exclusivity Variables: $\Delta p_\perp$

$$\Delta p_\perp = p^{proton}_{\perp,meas} - p^{proton}_{\perp,reco}$$

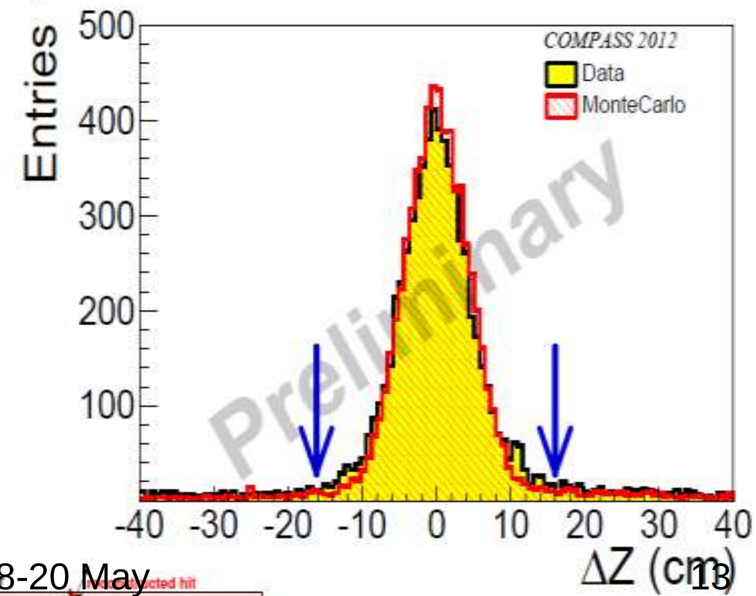


Exclusivity Variables: M_X^2

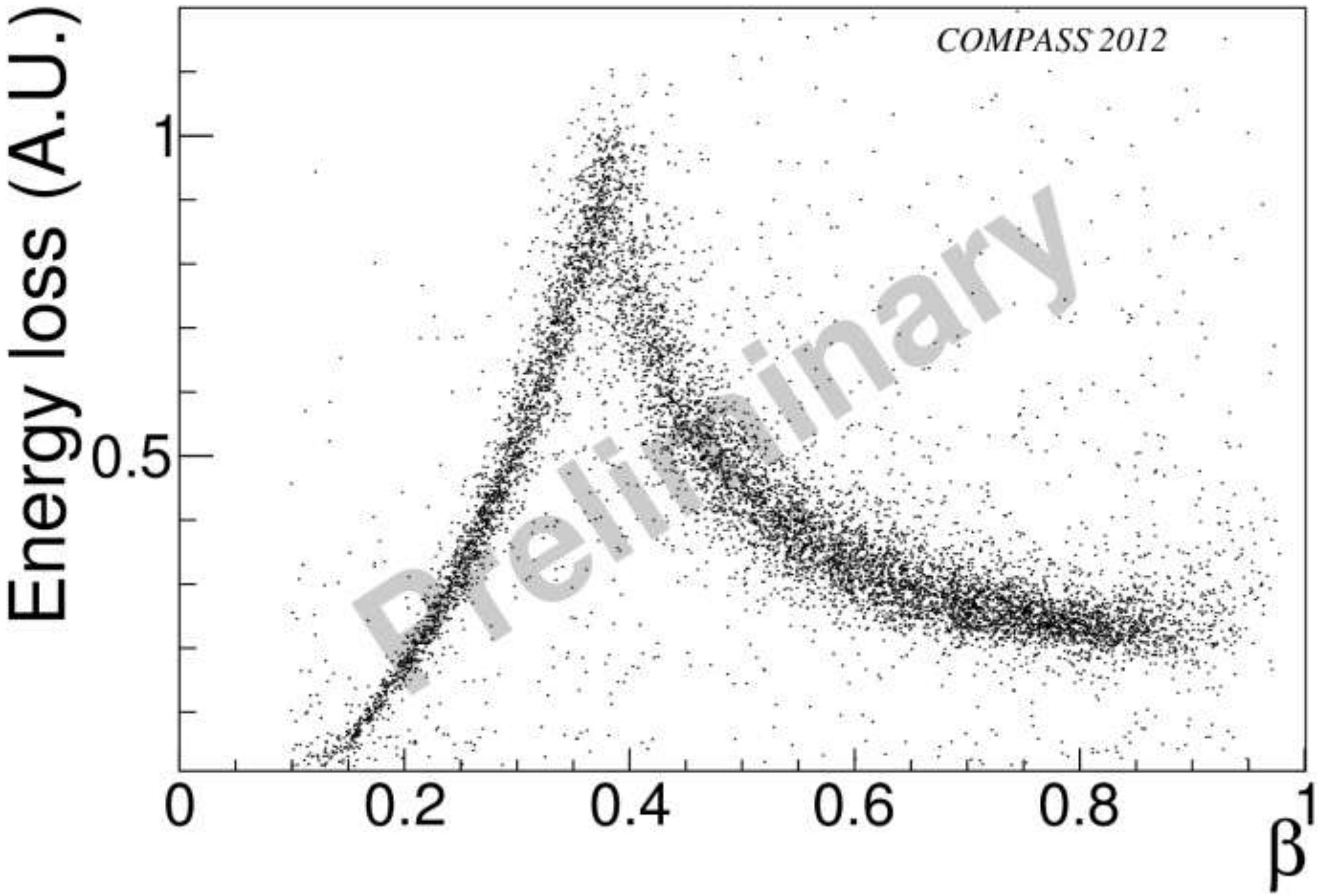
$$M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_\gamma)^2$$



Exclusivity Variables: ΔZ



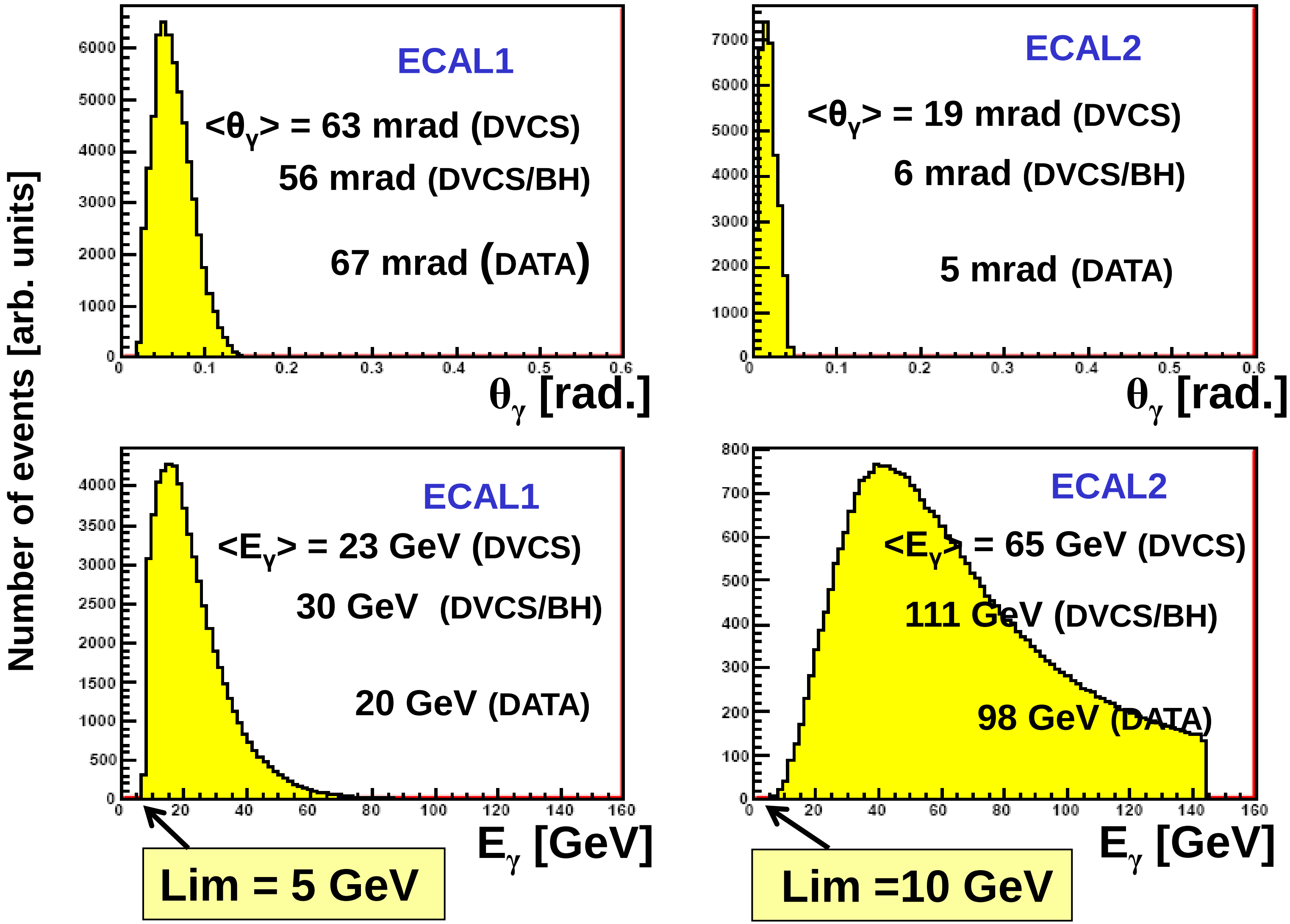
The proton “signature” in the Recoil Detector after all exclusivity cuts



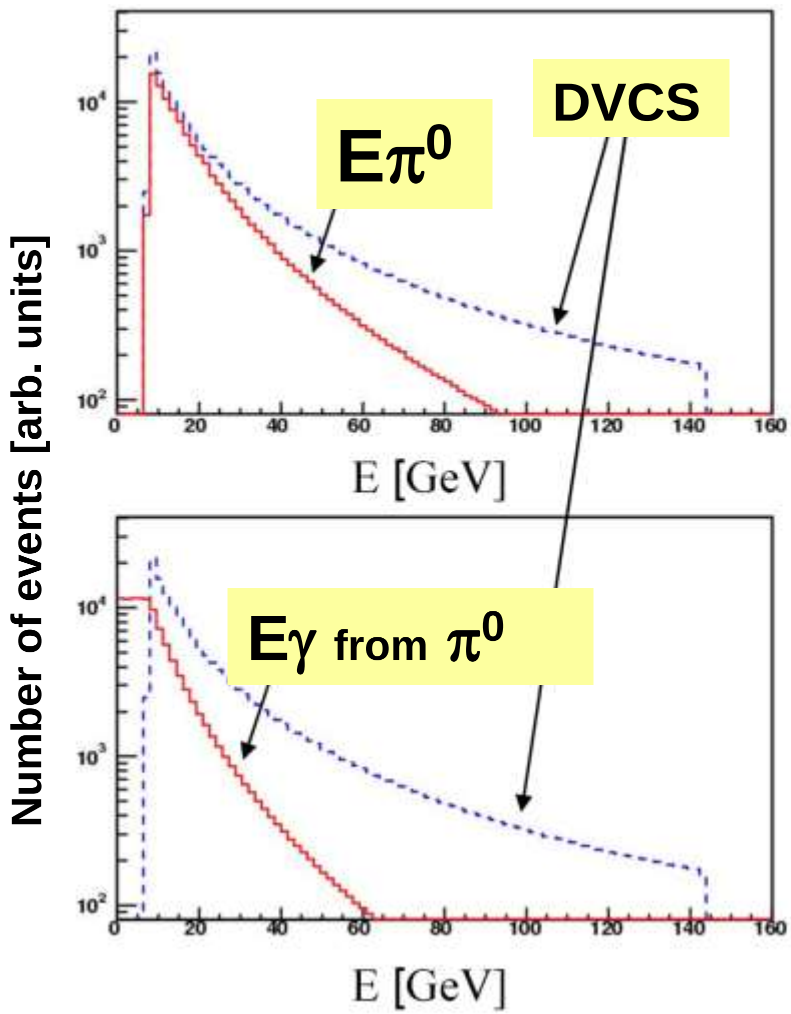
Signal amplitude in outer scintillators vs. beta of recoiling particle

π^0 background to DVCS: kinematic ranges for photons in ECAL1 and ECAL2

MC by Andrzej Sandacz



π^0 and γ energies from MC by Andrzej Sandacz



dist = distance between cluster's centers

- **2γ separation dist>2 cm**
- **100% efficiency dist~4-5 cm**
- **$E\pi^0$ =100 GeV dist ~8 cm**
- **$E\pi^0$ <100 GeV from MC**
- **no bkg from 2γ non separated**

$$\mu p \rightarrow \mu' p' \pi^0 \rightarrow \mu' p' \gamma\gamma$$

- **only bkg if 1γ is non detected**

$$\mu p \rightarrow \mu' p' \pi^0 \rightarrow \mu' p' \gamma$$

- **The photons from π^0 should be mainly registered in ECAL0 & ECAL1**

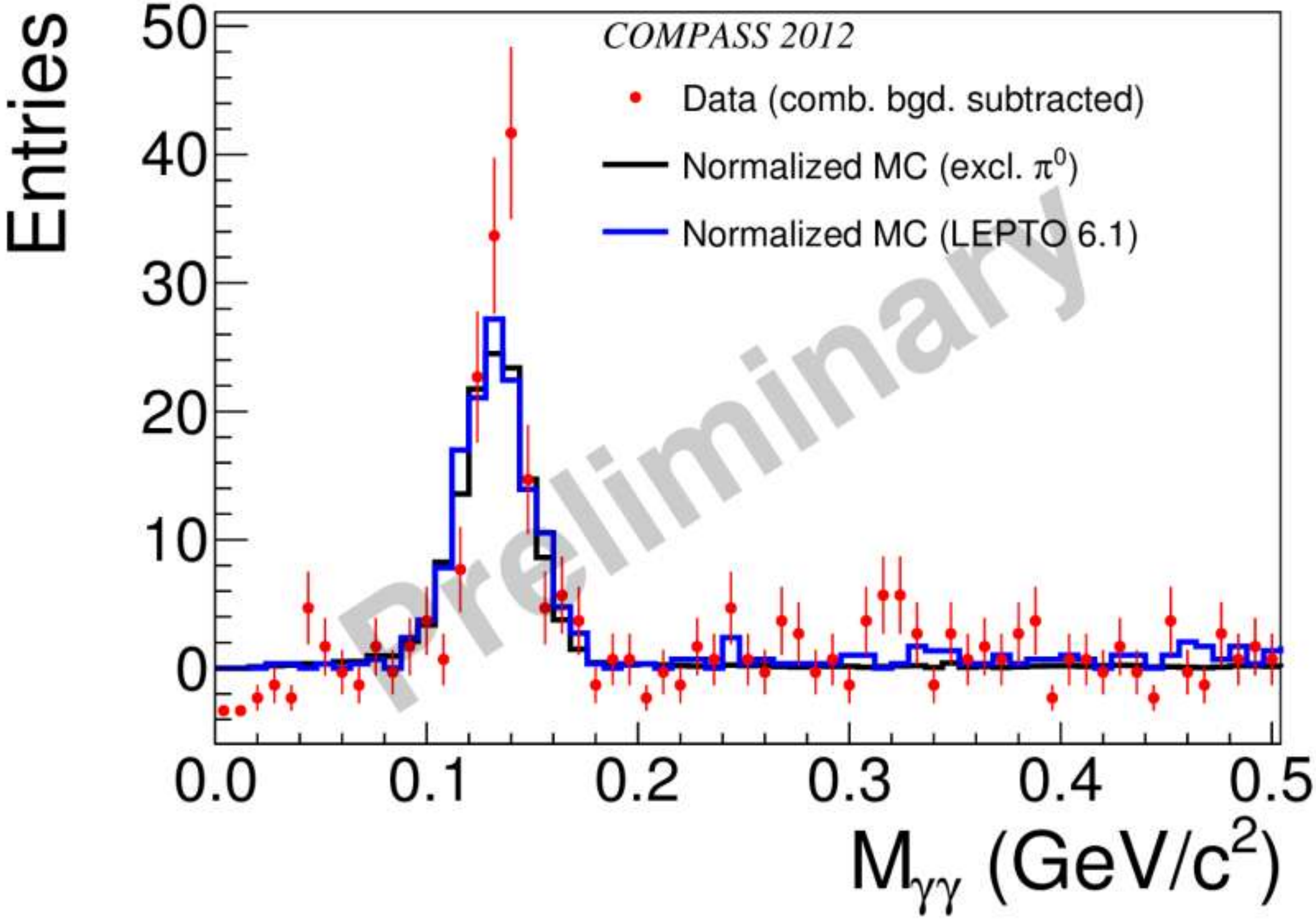
π^0 background to DVCS: complementarities of HEPGEN and LEPTO generators

HEPGEN predicts the possible background to exclusive single-γ events from exclusive π^0. However, in Real Data the semi-inclusive reactions enter in the game as the exclusive ones due to the imperfect overall energy resolution of the spectrometer.

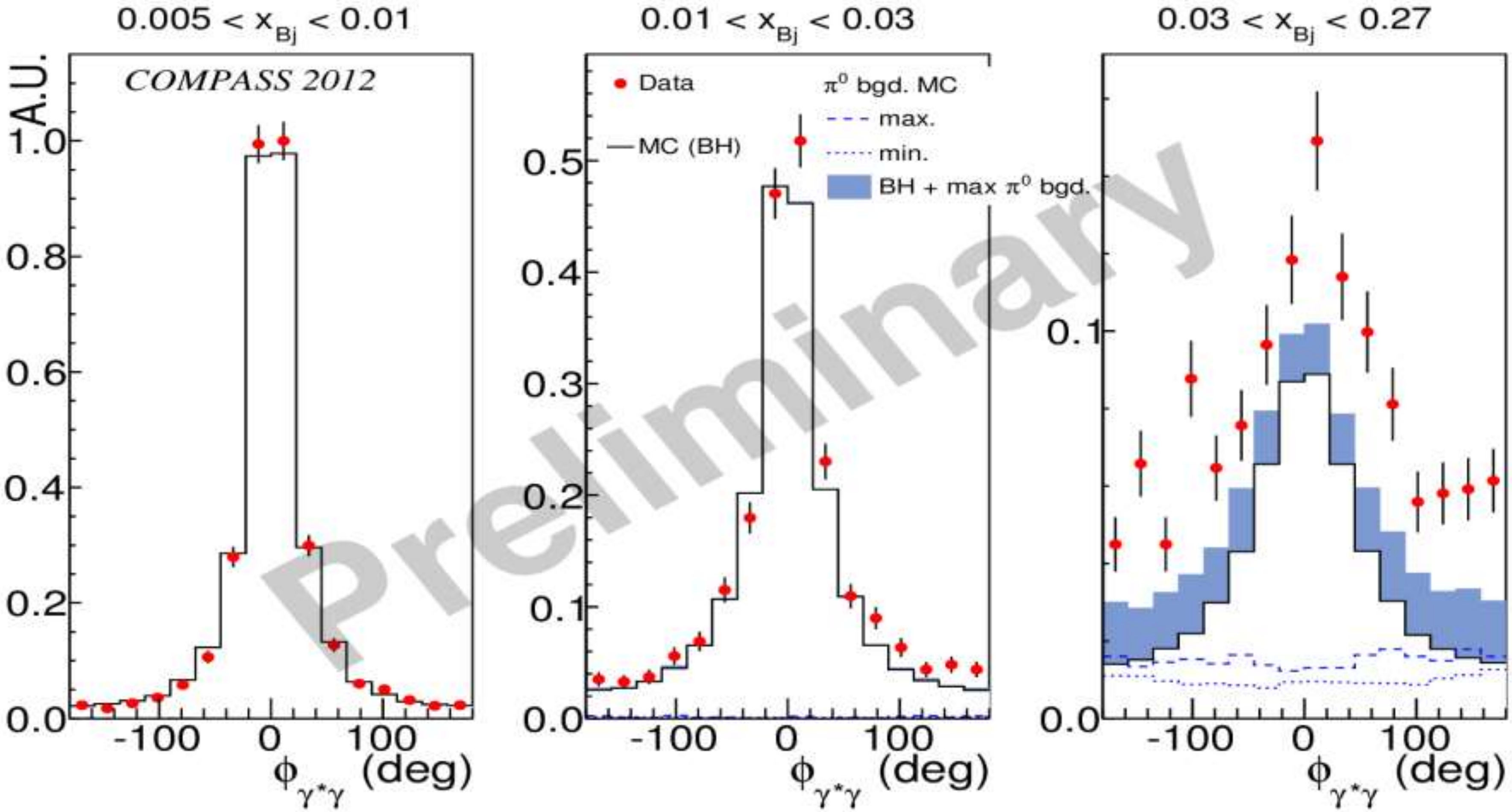
LEPTO doesn't generate exclusive events but semi-inclusive ones. It is a general and flexible Monte Carlo generator to simulate complete lepton-nucleon scattering events and integrate cross sections. In contrast with HEPGEN Monte Carlo, LEPTO allows us to perform a more realistic comparison with Real Data. Moreover, it also permits to make predictions for the background for both the exclusive single-γ and the π^0 reactions

- "visible" π^0 (both γ detected, useful for MC normalization)
- "invisible" π^0 (one γ ``lost'', only estimated with MC)

π^0 background estimation



Azimuthal distributions for exclusive γ events in 3 x_{Bj} bins



BH good agreement Data/MC

Excess of events (DVCS) after bkg subtraction

DVCS measurements with polarized μ^+ and μ^- beams

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

Unpolarized target: Constrain GPD H (2016-2017)

- **S**um of cross sections: **imaginary part** of Compton Form Factor
- **D**ifference of cross sections: **real part** of Compton Form Factor

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

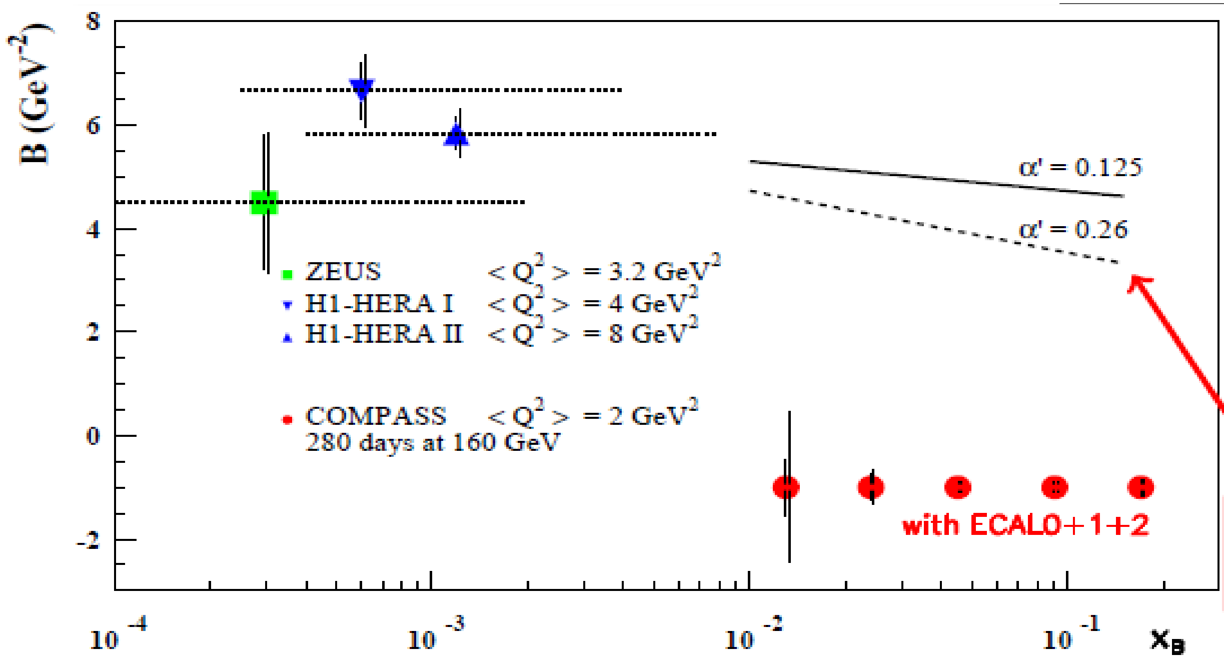
Integration over ϕ and BH subtraction $\rightarrow$ $d\sigma^{DVCS}/dt \sim \exp(-B|t|)$

t-slope extraction $\rightarrow$ nucleon tomography $< r_\perp^2 (x_B) > \approx 2 B(x_B)$

First result will come from DVCS 2012 data soon

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int} \cos\phi$$ and $c_{0,1}^{Int} \sim F_1 \, \mathcal{Re}\, \mathcal{H}$

Transverse size of the nucleon vs. Bjorken-x



2 years of data

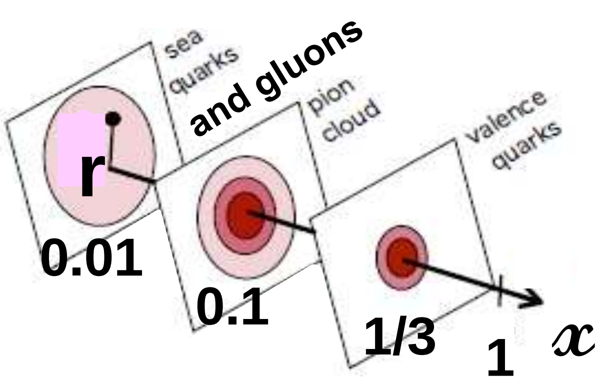
2.5 m LH_2 target

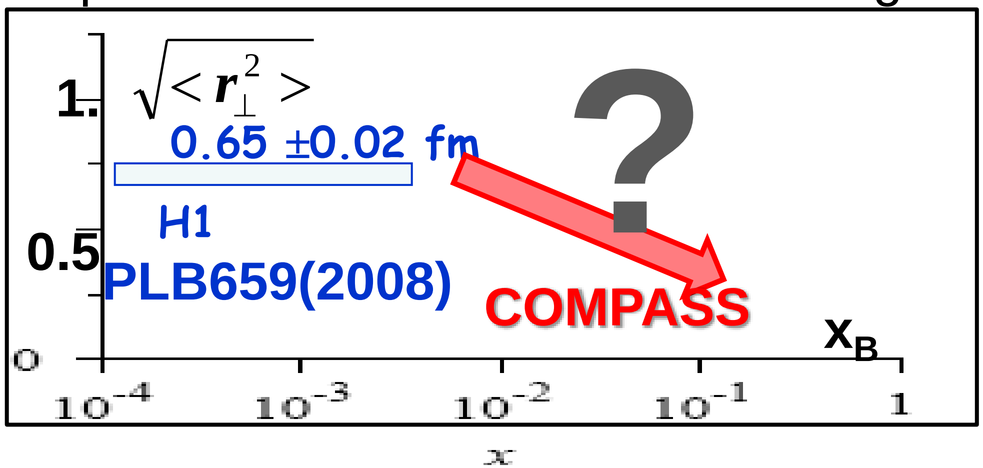
ε_{global} = 10%

2.5 σ slope meas. for :
α' > 0.26 (ECAL1+2)
α' > 0.125 (ECAL0+1+2

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

Compass covers low-x to medium-x region



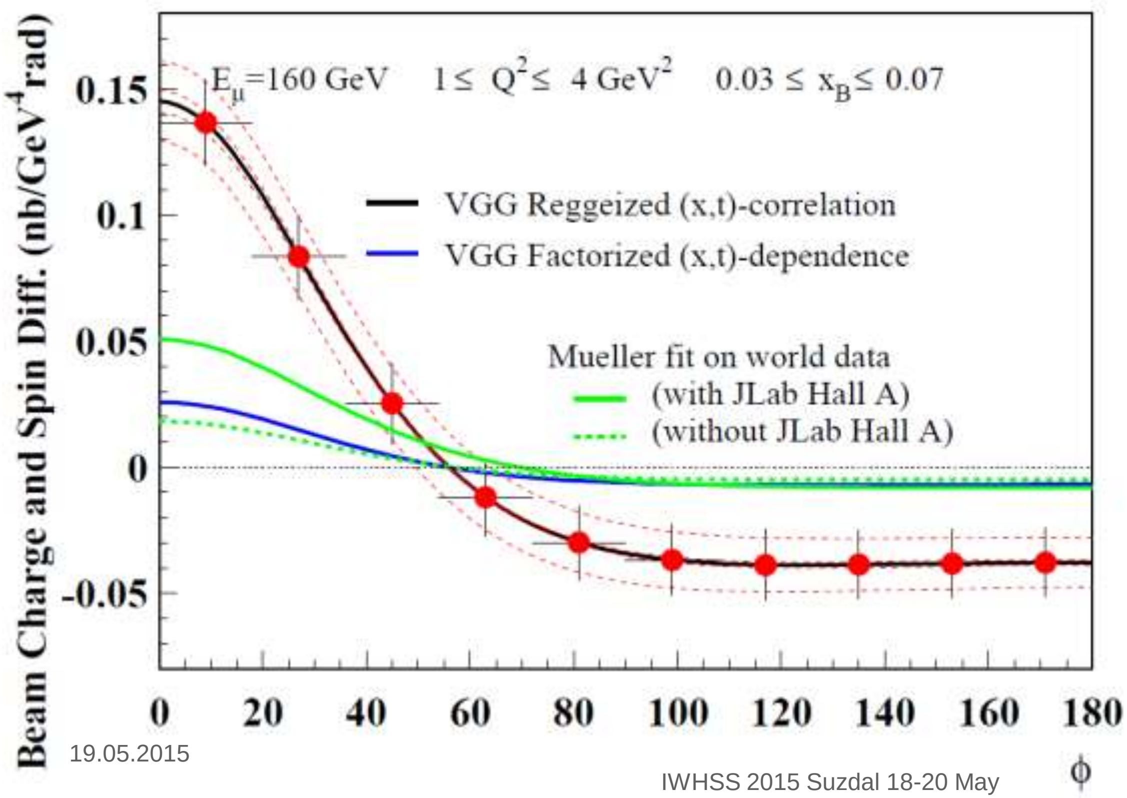


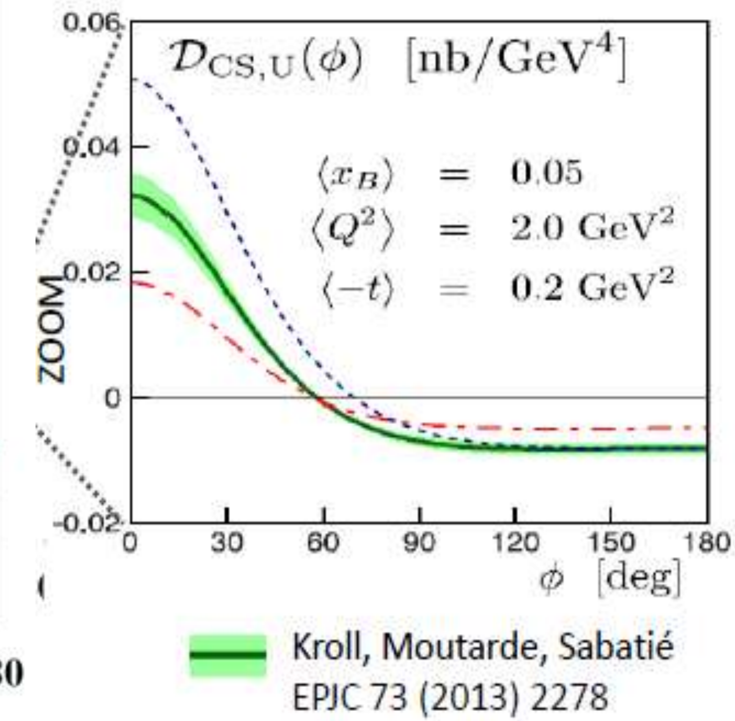
Measure difference of DVCS cross sections

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

$$c_{0,1} \propto \mathrm{Re}(F_1 H(x,t))$$

COMPASS expected results in comparison with different models



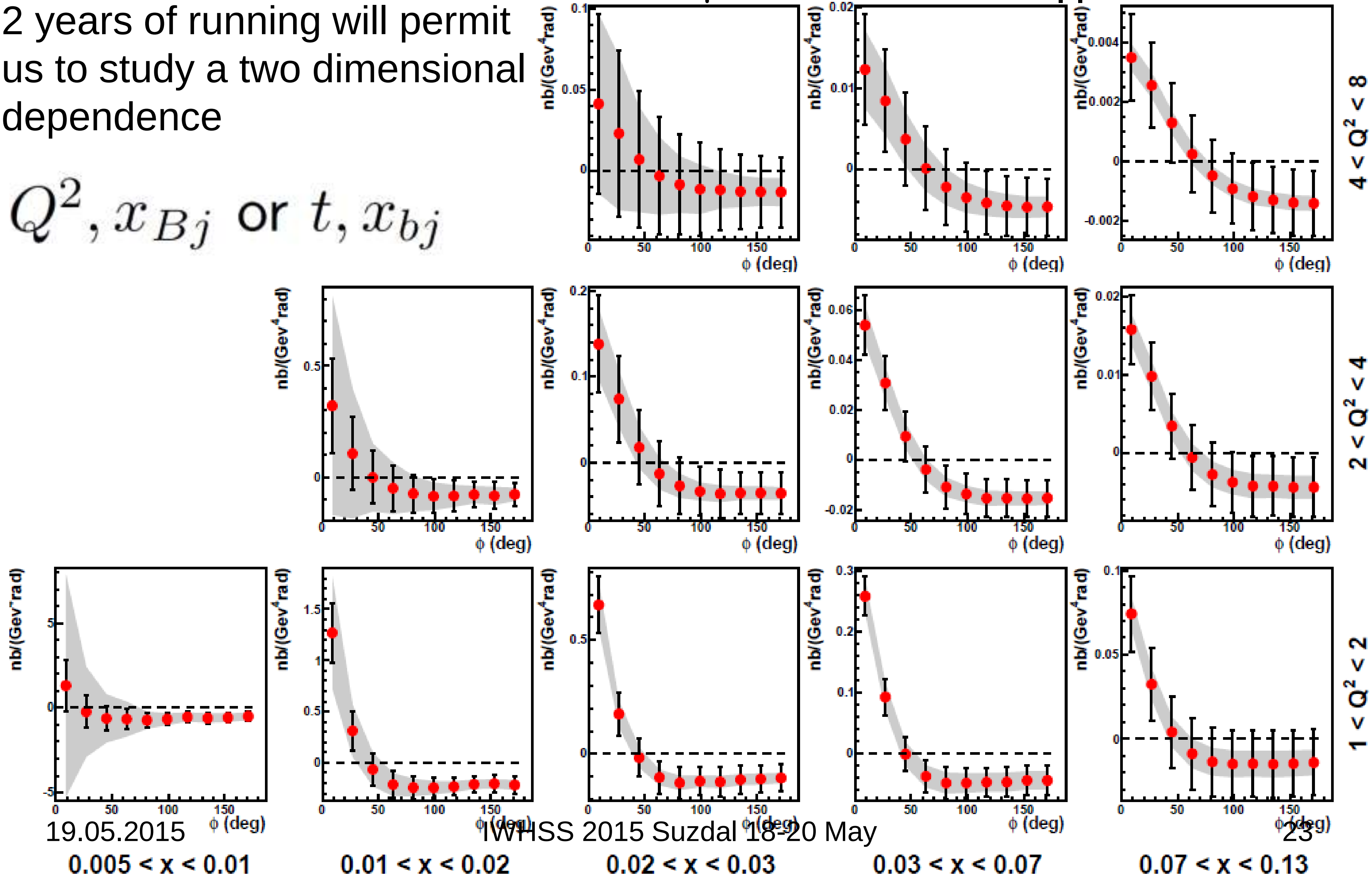


Difference of DVCS cross sections in (Q^2, X_{BJ})

$E\mu$ = 160 GeV $0.06 < |t| < 0.64$ GeV^2

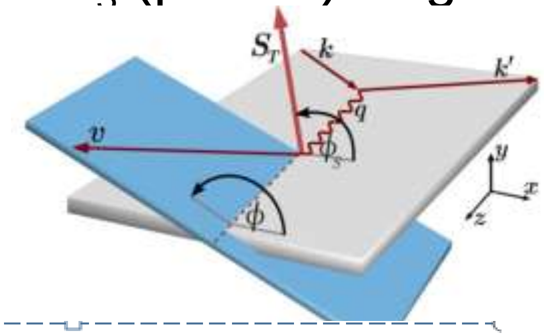
2 years of running will permit us to study a two dimensional dependence

$$Q^2, x_{Bj} \text{ or } t, x_{bj}$$



DVCS on transversely polarized target: access GPD E (> 2018)

with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam and transversely polarized NH_3 (proton) target



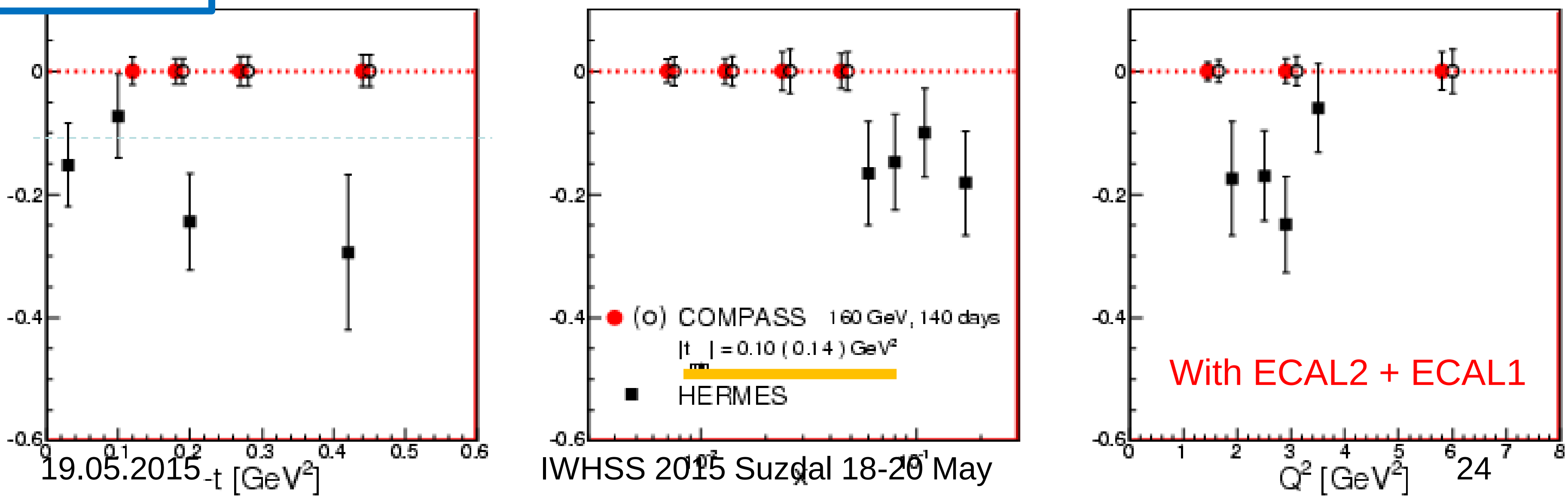
$$\mathcal{D}_{CS,T} \equiv d\sigma_T(\mu^{+\downarrow}) - d\sigma_T(\mu^{-\uparrow})$$
$$\propto Im(F_2\mathcal{H} - F_1\mathcal{E})\,\sin(\phi-\phi_S)\cos\phi$$

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

ϕ - angle between the lepton scattering and hadron production planes

ϕ_S -angle between the target spin direction and the lepton scattering plane

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



HEMP: access GPD E (< 2018)

- Hard Exclusive Meson Production (HEMP)
- Vector meson production (ρ, ω, ϕ, J/ψ…) $\Rightarrow$ H & E

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

2007 & 2010 data with transversely polarized target but without proton recoil detector

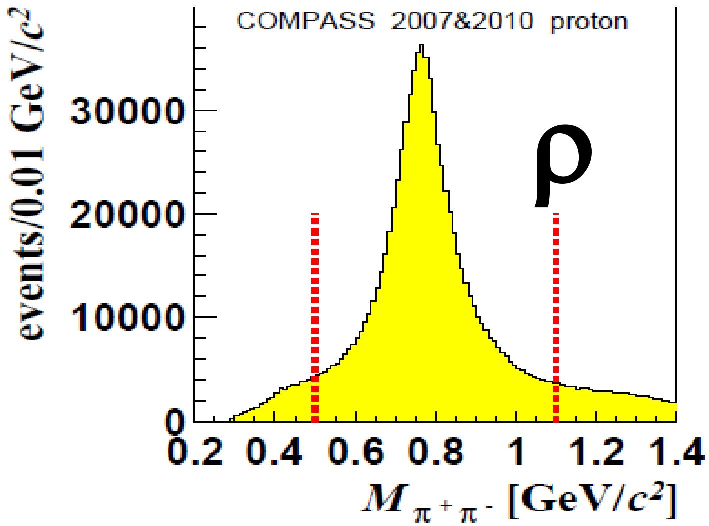
$$\mu N \rightarrow \mu N \rho^0, \quad \rho^0 \rightarrow \pi^+ + \pi^-$$

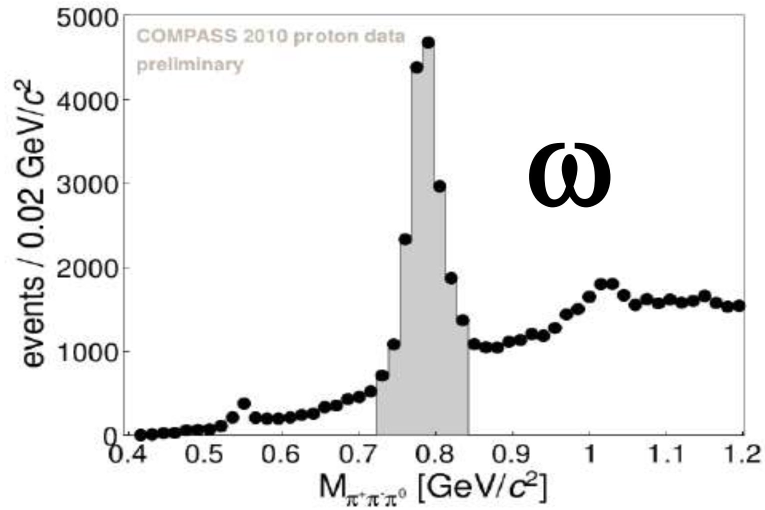
Both 2007&2010 data

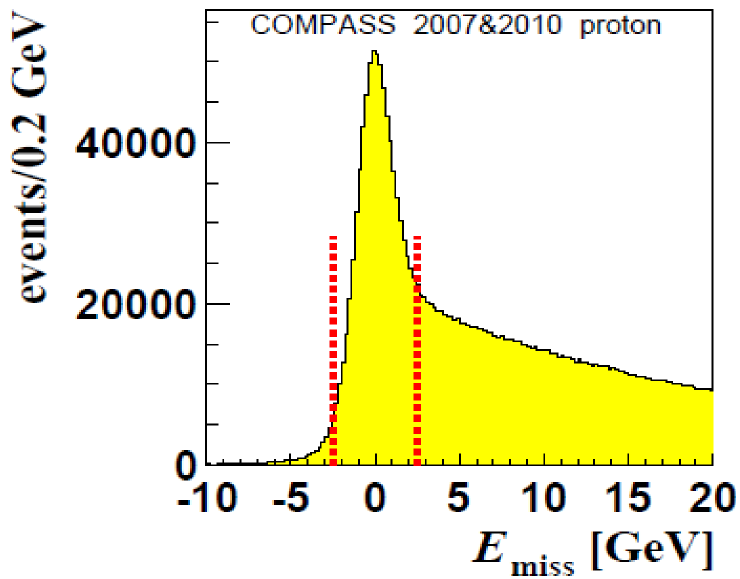
$$\mu N \rightarrow \mu N \omega, \quad \omega \rightarrow \pi^+ + \pi^- + \pi^0, \quad \pi^0 \rightarrow \gamma + \gamma$$

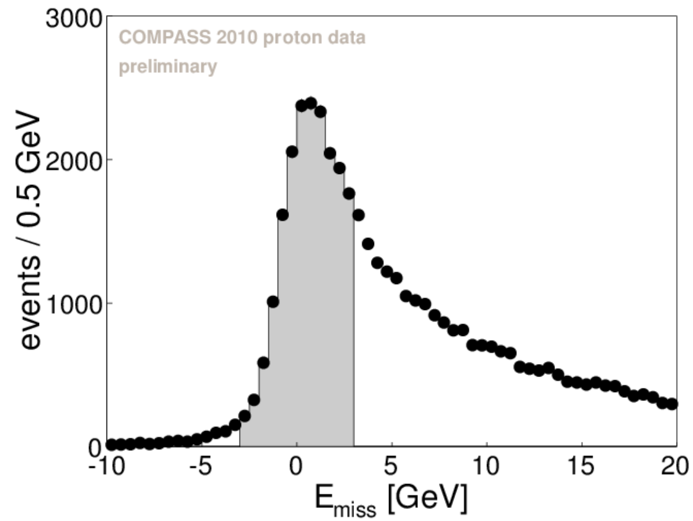
Only 2010 data

Reconstructed mass of ρ and ω mesons and the corresponding E_{miss} distributions

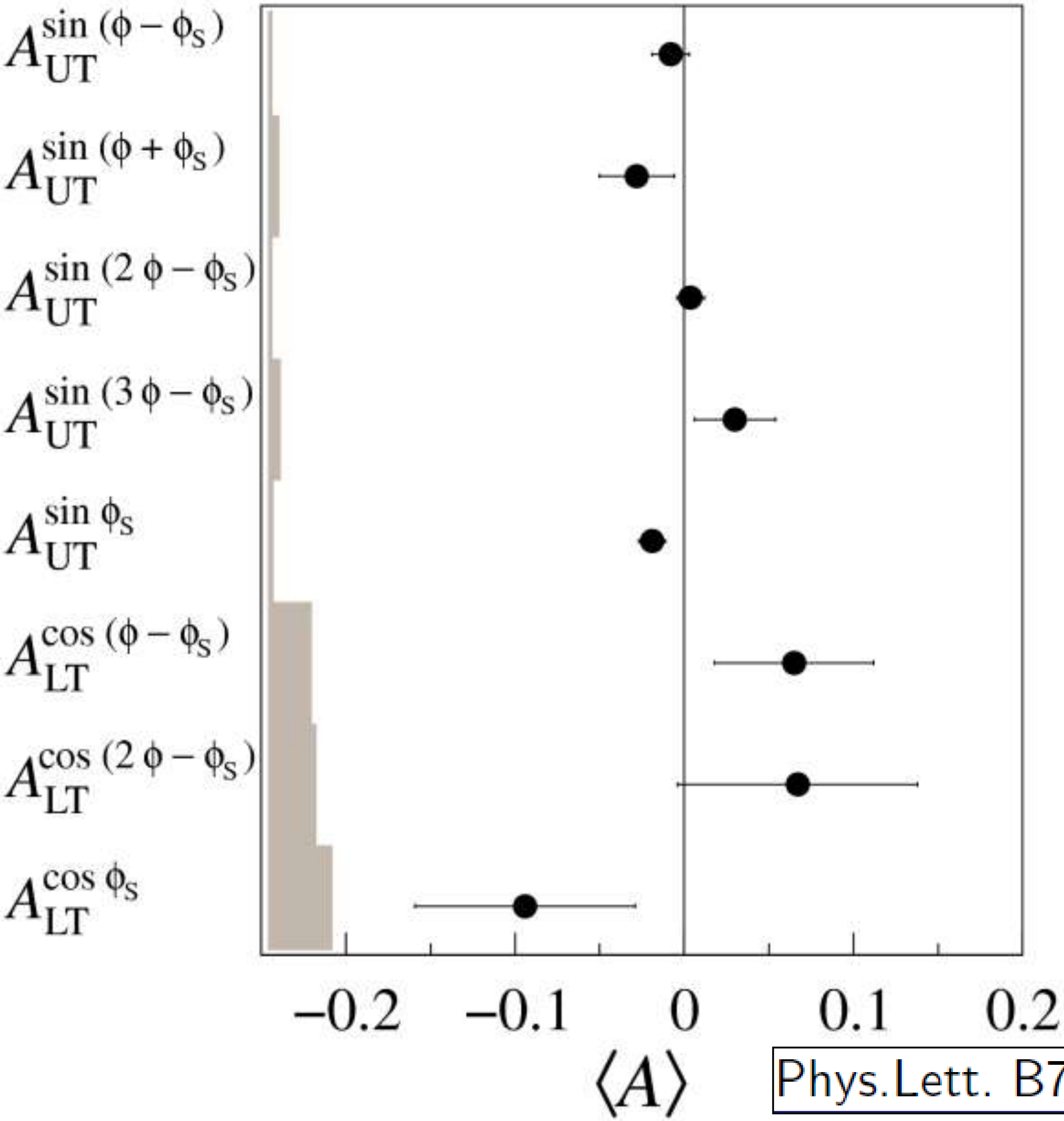








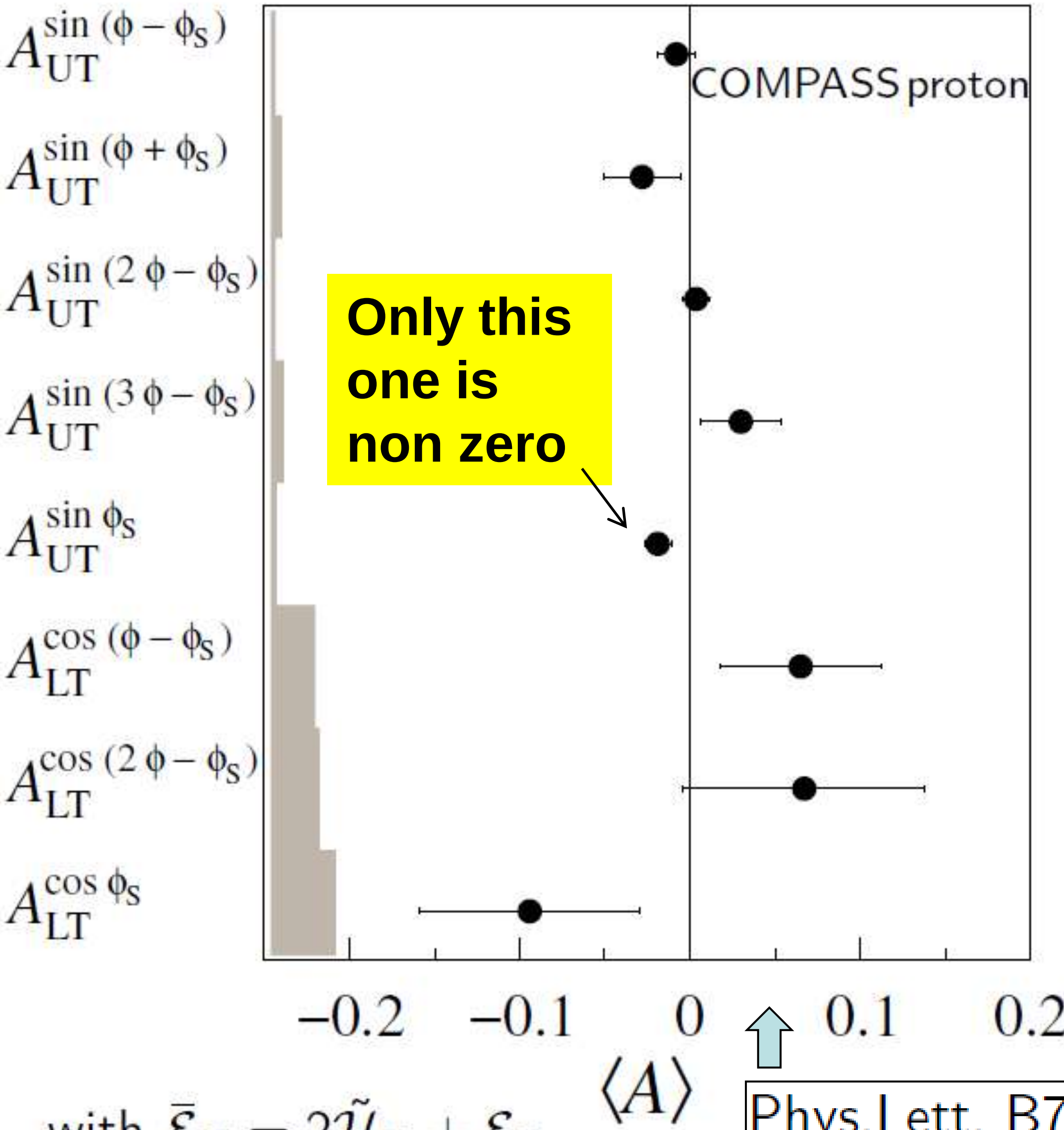
Mean asymmetries - NH_3 target



Phys.Lett. B731 (2014) 19-26

Mean asymmetries - NH_3 target

Goloskokov & Kroll
Eur.Phys.J. C74 (2014)



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

$A_{UT}^{sin(\phi+\phi_S)} \propto \mathrm{Im}\,(\bar{\mathcal{E}}_T^*\mathcal{H}_T)$

$A_{UT}^{(2\phi-\phi_S)} \propto \mathrm{Im}\,(\bar{\mathcal{E}}_T^*\mathcal{E})$

Evidence for existance of H_T

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

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

$A_{LT}^{cos(2\phi-\phi_S)} \propto \mathrm{Re}\,(\bar{\mathcal{E}}_T^*\mathcal{E})$

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

with $\bar{\mathcal{E}}_T = 2\tilde{\mathcal{H}}_T + \mathcal{E}_T$

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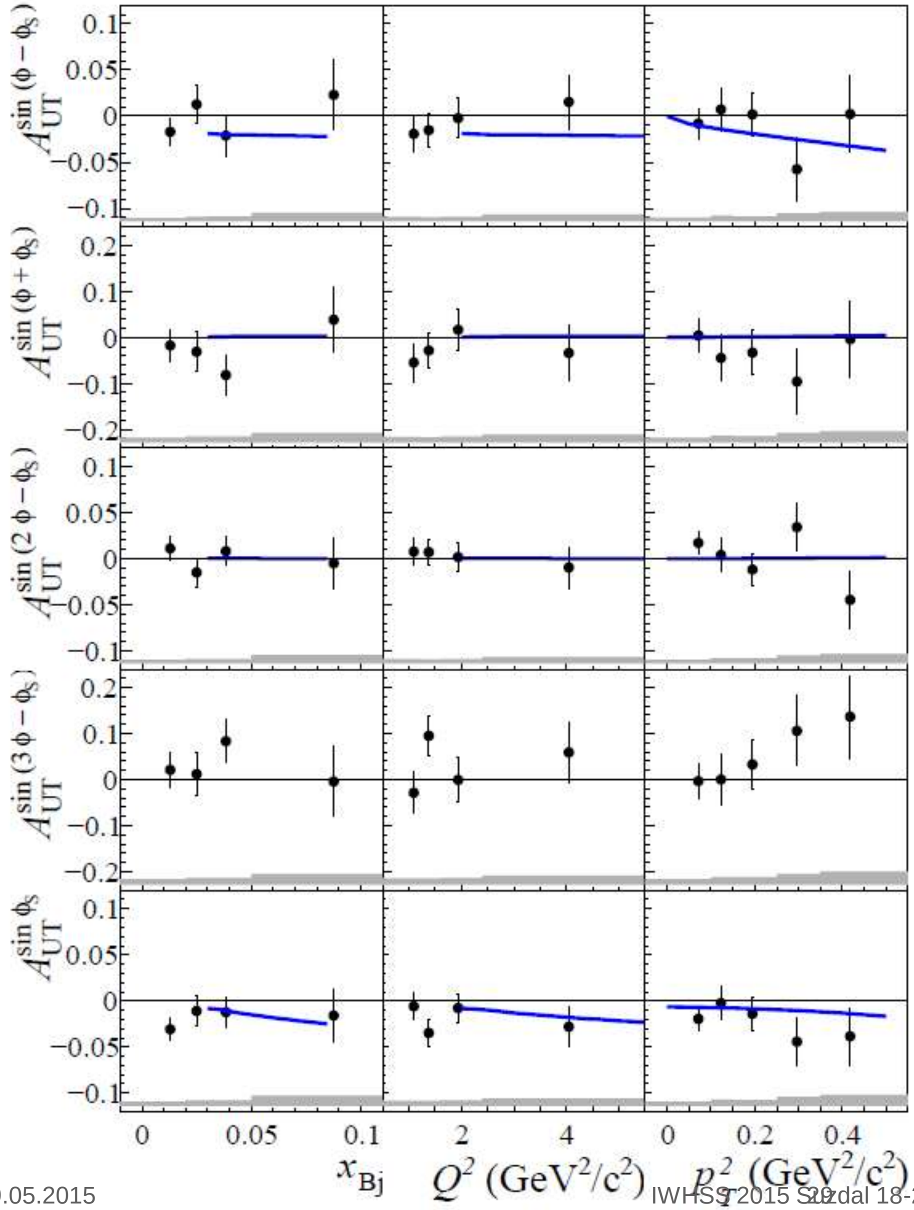
Asymmetry $A_{UT,p}$ - NH_3 target (2007&2010)



COMPASS proton

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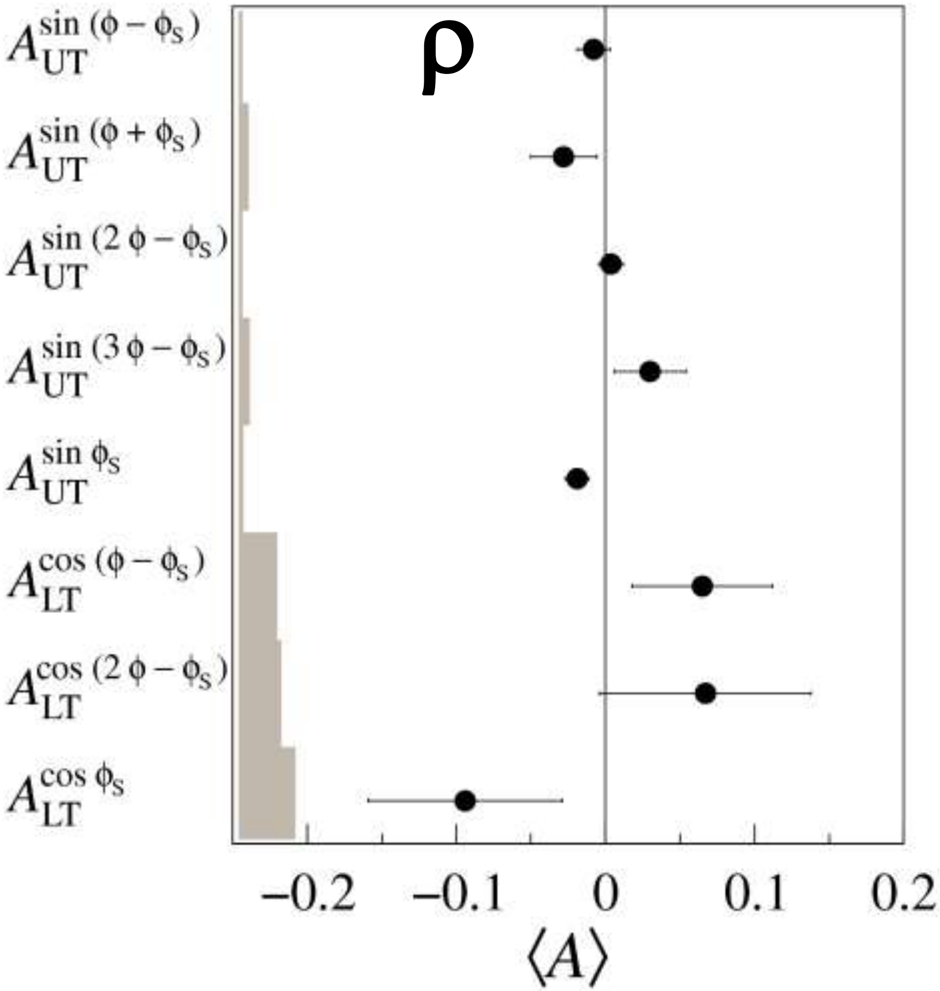
- Blue line: Model from Goloskokov and Kroll
- Predictions for COMPASS kinematic
  $W = 8.1$ GeV$/c^2$,
  $p_T^2 = 0.2$ (GeV$/c)^2$,
  $Q^2 = 2.2$ (GeV$/c)^2$

← Only this asymmetry was measured to be non zero

Mean ρ and ω asymmetries - NH_3 target



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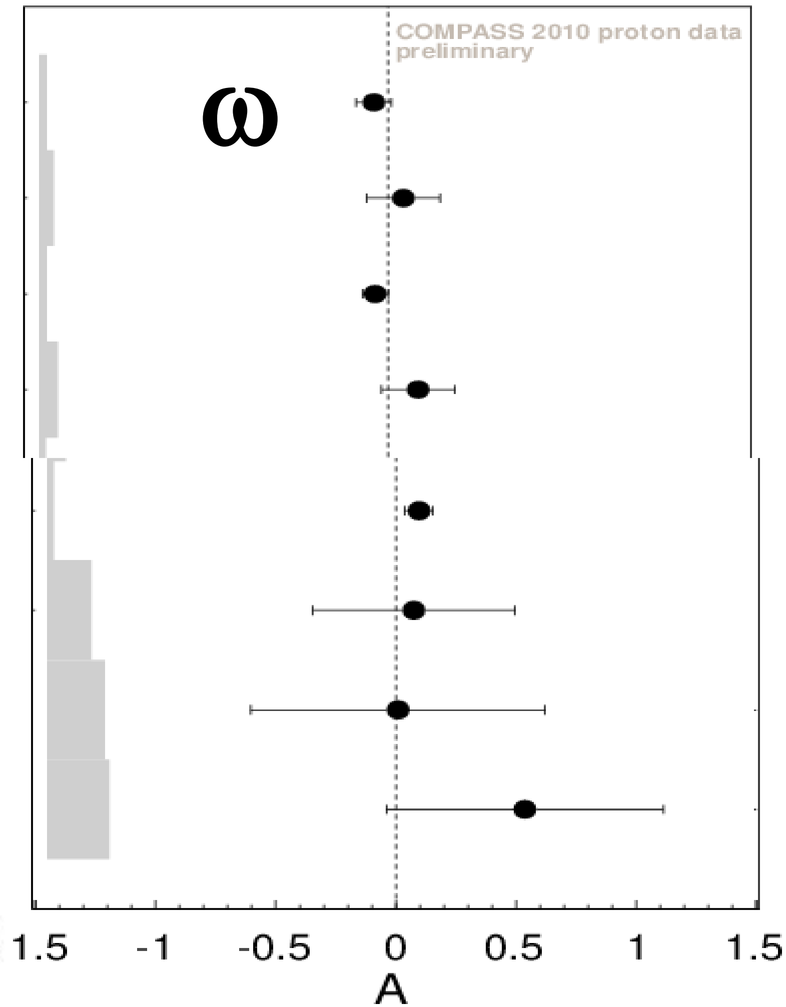

preliminary

Conclusions and Outlook

- GPDs are a well-suited tool to explore the structure of the nucleon
- COMPASS is a unique place to study DVCS and HEMP in the medium-X_{BJ} region
- The results of the 2012 DVCS test run are promising
- Exclusive meson production provides with complementary measurements to DVCS, flavour separation for GPDs, sensitivity to chiral-odd GPDs

- COMPASS results on exclusive ρ production show indications for GPD H_T, (results interpretation in terms of phenomenological Goloskokov-Kroll model)
- Transverse target spin asymmetries sensitive to

GPD E ($\rightarrow$ orbital angular momentum) & GPD H_T ($\rightarrow$ transversity)

- 2016/17 data will deliver COMPASS DVCS results to help constraining GPD H and to better understand the transverse size of the nucleon
- Further ideas exist for >2018 to constrain GPD E

Input for Projections

Naturally polarized μ Beam with 160 GeV/c momentum → P_{Beam}=80%

48 s SPS cycle with 9.6 s spill duration

beam intensity 4.6 x 10^8 μ^+/spill = 9.6 x 10^6 μ^+/s (DC)

3 times smaller intensity for μ^-

data taking: 280 days → 70 days μ^+, 210 days μ^-

Target: a) 2.5m liquid Hydrogen → $\mathcal{L}$ = 1 x 10^{32} $cm^{-2}s^{-1}$

b) 1.2m NH_3 (polarized) → $\mathcal{L}$ = 3.4 x 10^{32} $cm^{-2}s^{-1}$

P_{target}=90%, dilution factor f=0.17

New recoil-proton detector

ECAL1 (40…150mrad), ECAL2 (0…40mrad) + new ECAL0 (150…300mrad)

Global efficiency ε=0.1 (SPS, COMPASS, tracking, photon)