Access to Generalized Parton Distributions at COMPASS

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on behalf of the COMPASS collaboration

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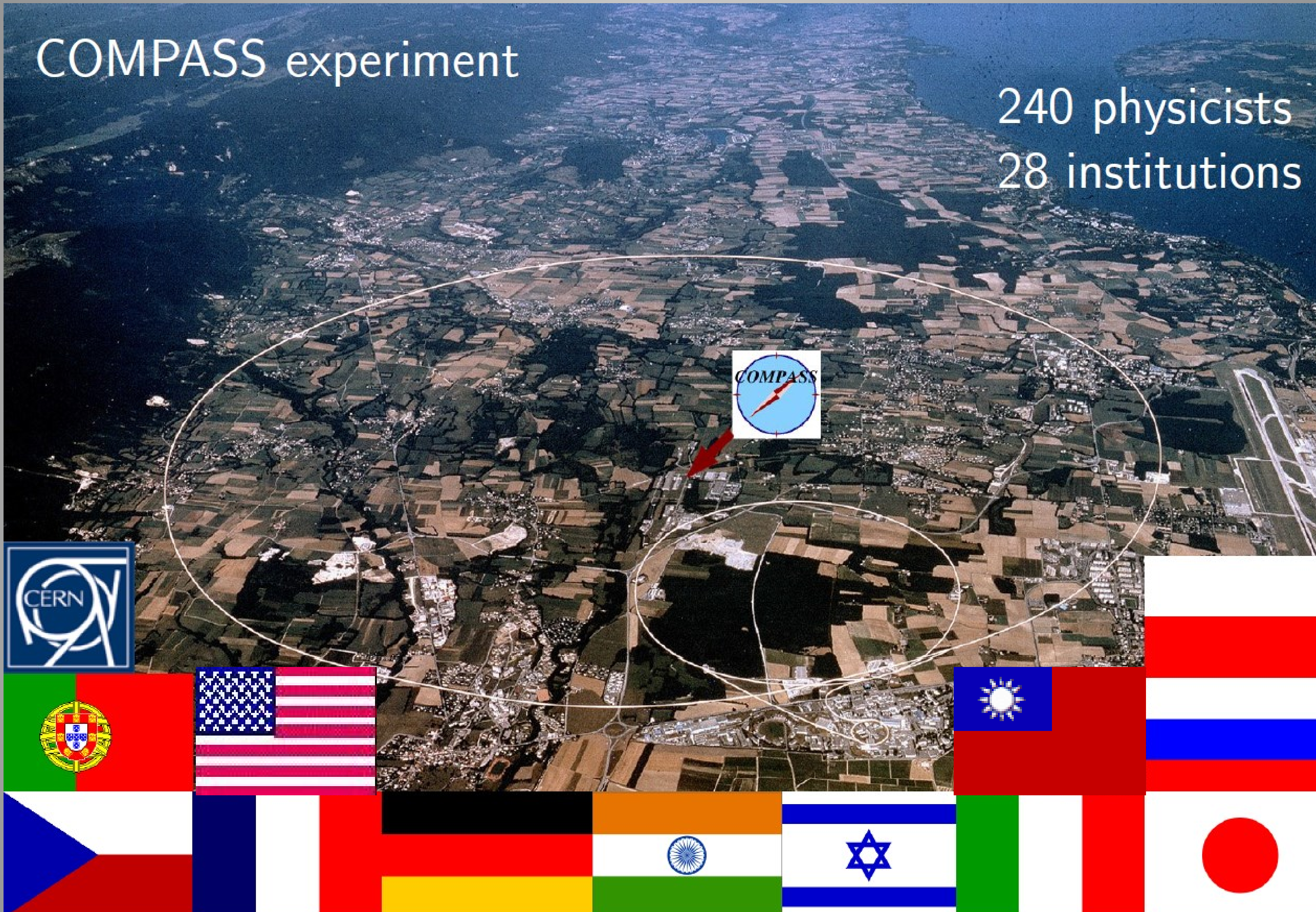
Outline

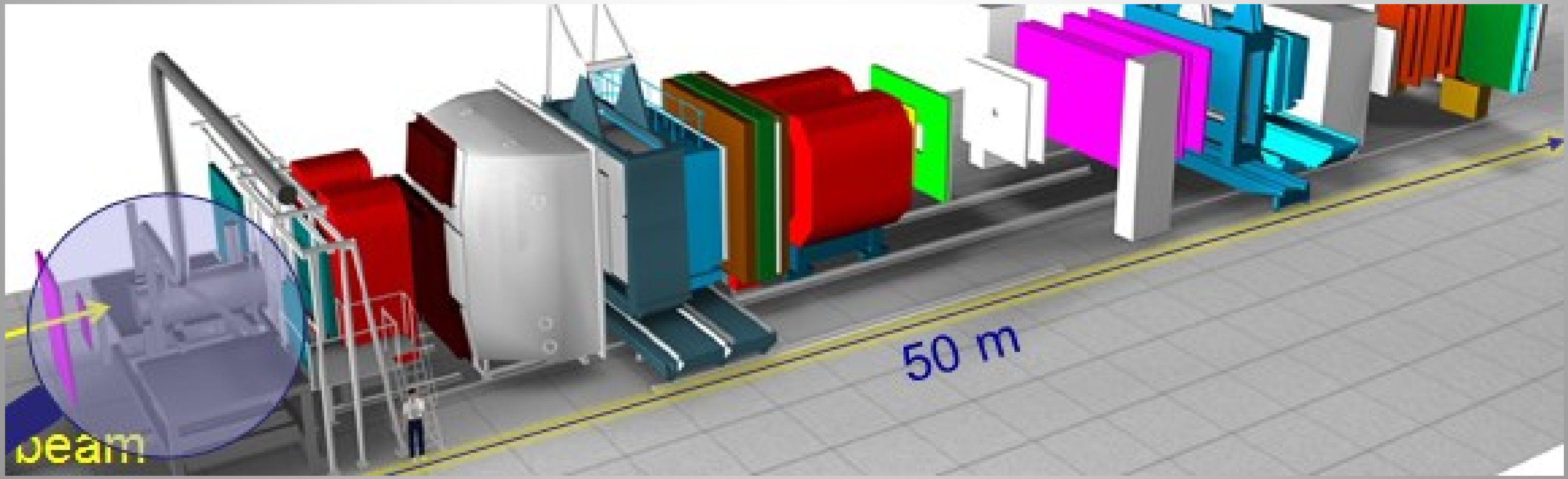
- The COMPASS experiment
- Deeply virtual Compton Scattering [DVCS]:
  * Cross section -> Transverse size of the nucleon
  * Asymmetries -> Generalized Parton Distributions [GPDs]
- Results: exclusive ρ^0 production: 2007 (^6LiD) /2010 (NH_3)
- Interpretation within phenomenological Goloskokov-Kroll model -> evidence for existence of transverse GPDs
- >2016/17: unpolarized *LH* target: DVCS and HEMP (hard exclusive meson production) -> constrain GPD *H*
- >2018: to constrain GPD *E*: need new transversely polarized target & recoil proton detection

COMPASS experiment

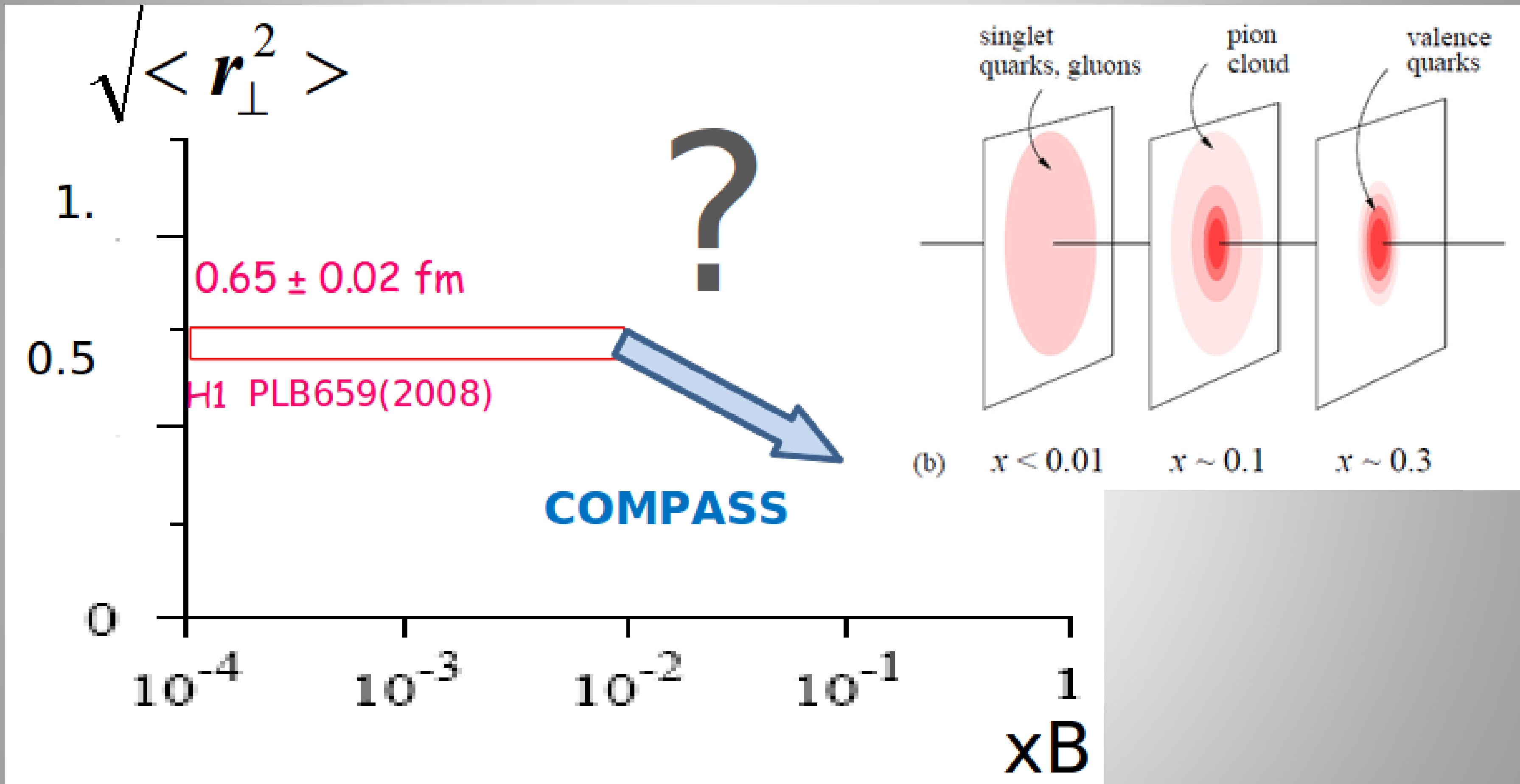


Unique Experimental Conditions at COMPASS

- High-energy 100-200 GeV/c (tertiary) muon beam (CERN)
- Natural high beam polarization: *O*(0.8); pos.[neg.] for mu-[+]
- 2007(^6LiD)& 2010(NH_3): transversely polarized *d* & *p* targets
- 2009 & 2012: DVCS test runs (*LH* target & small *RPD)*
- > 2015: unpolarized *liquid-hydrogen* (*LH*) target (no dilution)
- > 2015: large recoil-proton detector (*RPD*) around target
- Large acceptance; 2-stage tracking and calorimetry, PID

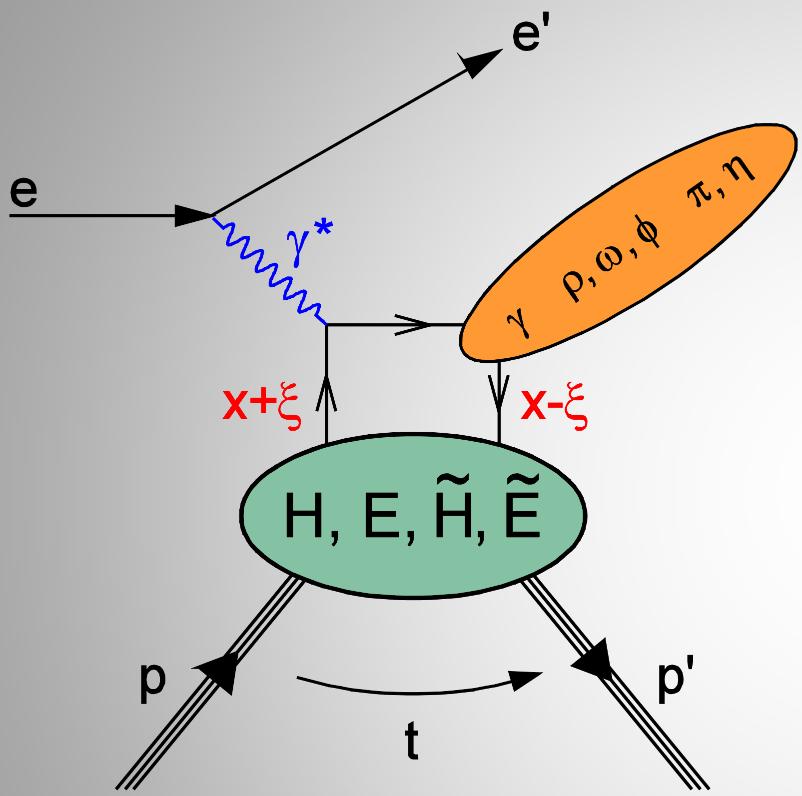


Transverse size of the nucleon vs. Bjorken-x



→ Compass covers low-x to medium-x region

Exclusive Processes: Access to GPDs



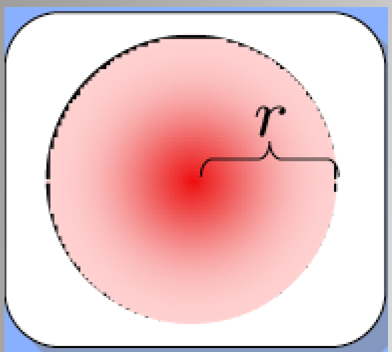
- For spin-1/2 target 4 chiral-even (= parton-helicity conserving) leading-twist parton GPDs: $H, E, \tilde{H}, \tilde{E}$
  - > $H, \tilde{H}$ conserve nucleon helicity,
  - > $E, \tilde{E}$ involve nucleon helicity flip
- Different final states are sensitive to different (combinations of) GPDs:
  - > DVCS (γ) → $H, E, \tilde{H}, \tilde{E}$
  - > Vector mesons (ρ, ω, ϕ) → H, E
  - > Pseudoscalar mesons (π, η) → $\tilde{H}, \tilde{E}$
- Also: chiral-odd (transverse‘) (= parton-helicity flip) GPDs:

  H_T $\qquad \bar{E}_T = 2\tilde{H}_T + E_T$

  > accessible e.g. in ρ production

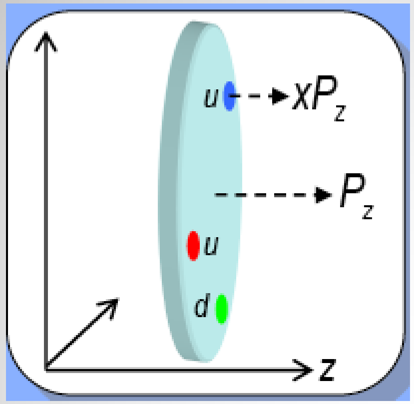
Interpretation of GPDs

Elastic Form Factors

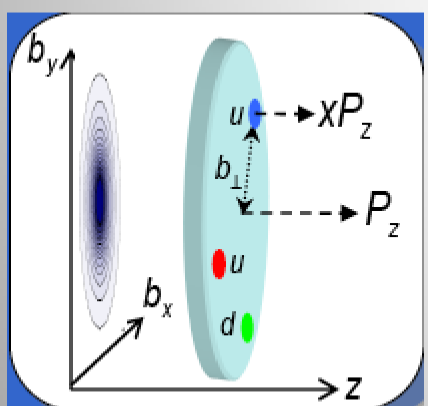


transverse position of partons

Parton Distribution Functions (PDFs)



longitudinal momentum of partons



Correlation between longitudinal momentum and transverse position

- GPDs include Form Factors and Parton Distribution Functions as moments and forward limits, resp.
- GPDs yield a multidimensional description of nucleon structure (longitudinal momentum vs. transverse position)

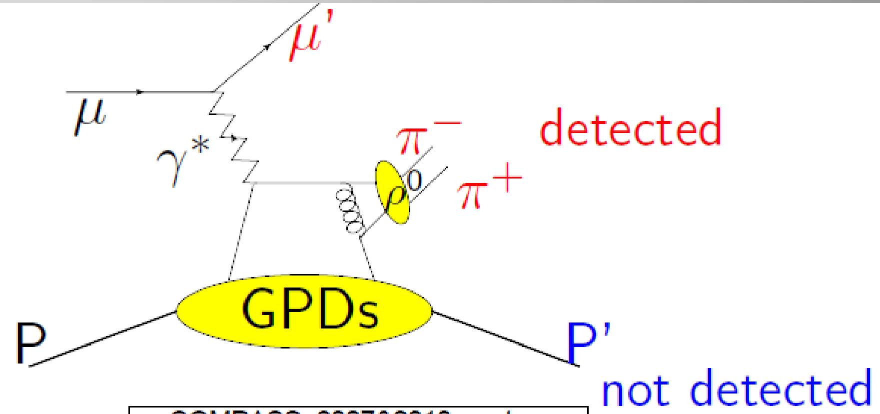
  → NUCLEON TOMOGRAPHY
- GPDs offer access to quark total angular momentum through the Ji relation (in principle also for gluons):

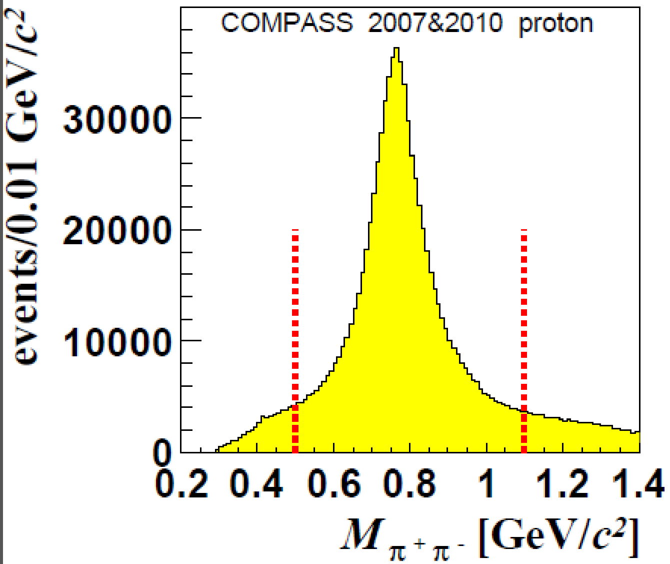
$$J_q = \lim_{t \to 0} \int_{-1}^{1} dx\, x \left[H_q(x,\xi,\xi) + E_q(x,\xi,\xi) \right]$$

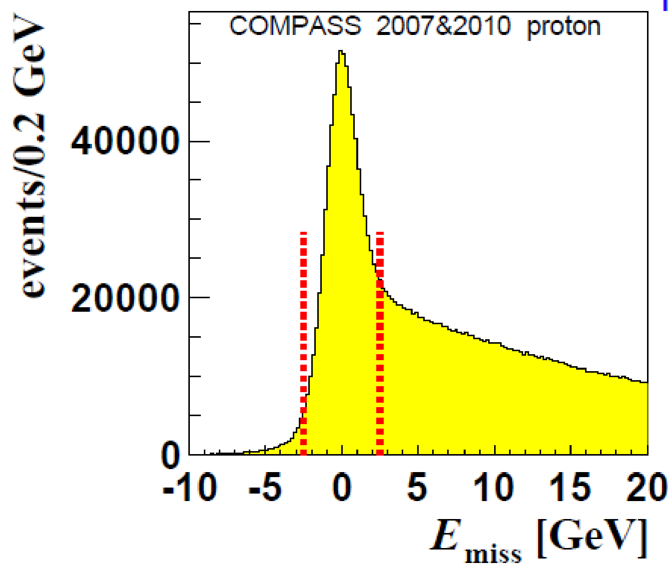
[X. Ji, Phys. Rev. Lett. 78 (1997) 610]

2010:Exclusive ρ^0 production: event selection

$$\mu + N^{\uparrow} \rightarrow \mu' + N' + \rho^0$$
$$\rho^0 \rightarrow \pi^+ + \pi^-$$





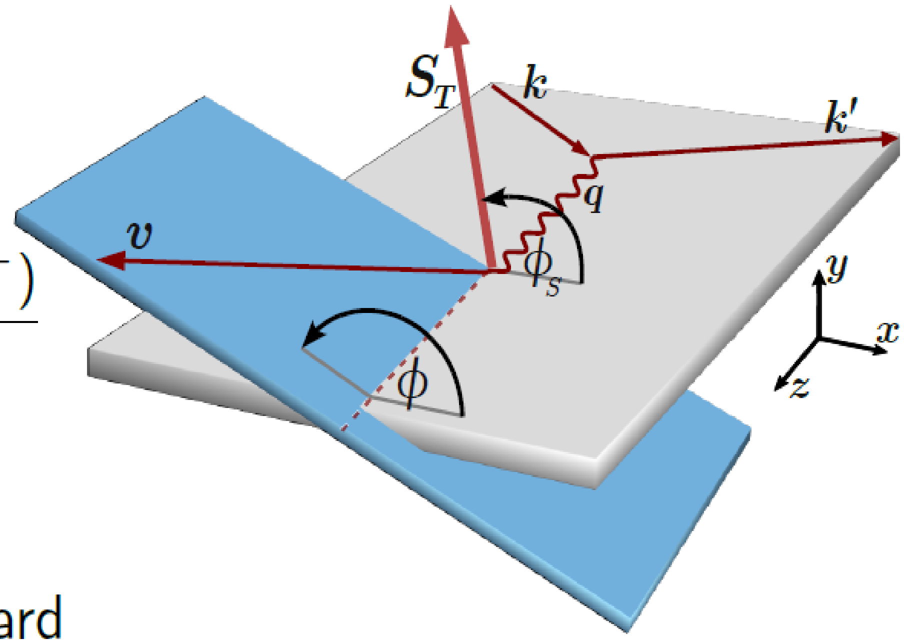


- Peak at ρ^0 mass ~ 0.775 GeV$/c^2$
- Signature for exclusivity $E_{miss} \sim 0$

$$E_{miss} = \frac{(p+q-\rho)^2 - p^2}{2 \cdot M_p} = \frac{M_X^2 - M_p^2}{2 \cdot M_p}$$

Hard exclusive ρ^0 production

- Factorisation valid for σ_L
- Leading twist term σ_{00}^{+-} sensitive to



$$A_{UT}^{\sin(\phi-\phi_s)} = -\frac{\mathrm{Im}\,(\sigma_{++}^{+-} + \varepsilon\, \sigma_{00}^{+-})}{\sigma_0}$$

$$\mathrm{Im}\,\frac{d\sigma_{00}^{+-}}{dt} \sim \mathrm{Im}\,(\mathcal{E}^{\star}\mathcal{H})$$

- $\mathcal{E}$ & $\mathcal{H}$ are convolution integrals of hard scattering kernels and the ρ^0 distribution amplitude with GPDs E & H where:

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

- Additional asymmetries contain higher twist terms

→ Constrain GPD E

Cross section of hard exclusive ρ^0 production

$$\left[\frac{\alpha_{\rm em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_B}{x_B}\,\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_B\,dQ^2\,d\phi\,d\psi} = \frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right) + \varepsilon\sigma_{00}^{++} - \varepsilon\cos(2\phi)\,\mathrm{Re}\,\sigma_{+-}^{++}$$

$$-\sqrt{\varepsilon(1+\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--}) \quad - P_\ell\sqrt{\varepsilon(1-\varepsilon)}\,\sin\phi\,\mathrm{Im}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--})$$

$$- S_L\left[\varepsilon\sin(2\phi)\,\mathrm{Im}\,\sigma_{+-}^{++} + \sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi\,\mathrm{Im}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

$$+ S_L P_\ell\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}-\sigma_{++}^{--}\right) - \sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

transversely polarized target

$$-S_T\left[\sin(\phi-\phi_S)\,\mathrm{Im}\,(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-}) + \frac{\varepsilon}{2}\sin(\phi+\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{+-} + \frac{\varepsilon}{2}\sin(3\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{-+}\right.$$

$$\left. + \sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi_S\,\mathrm{Im}\,\sigma_{+0}^{+-} + \sqrt{\varepsilon(1+\varepsilon)}\,\sin(2\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+0}^{-+}\right]$$

transversely polarized target + longitudinally polarized beam

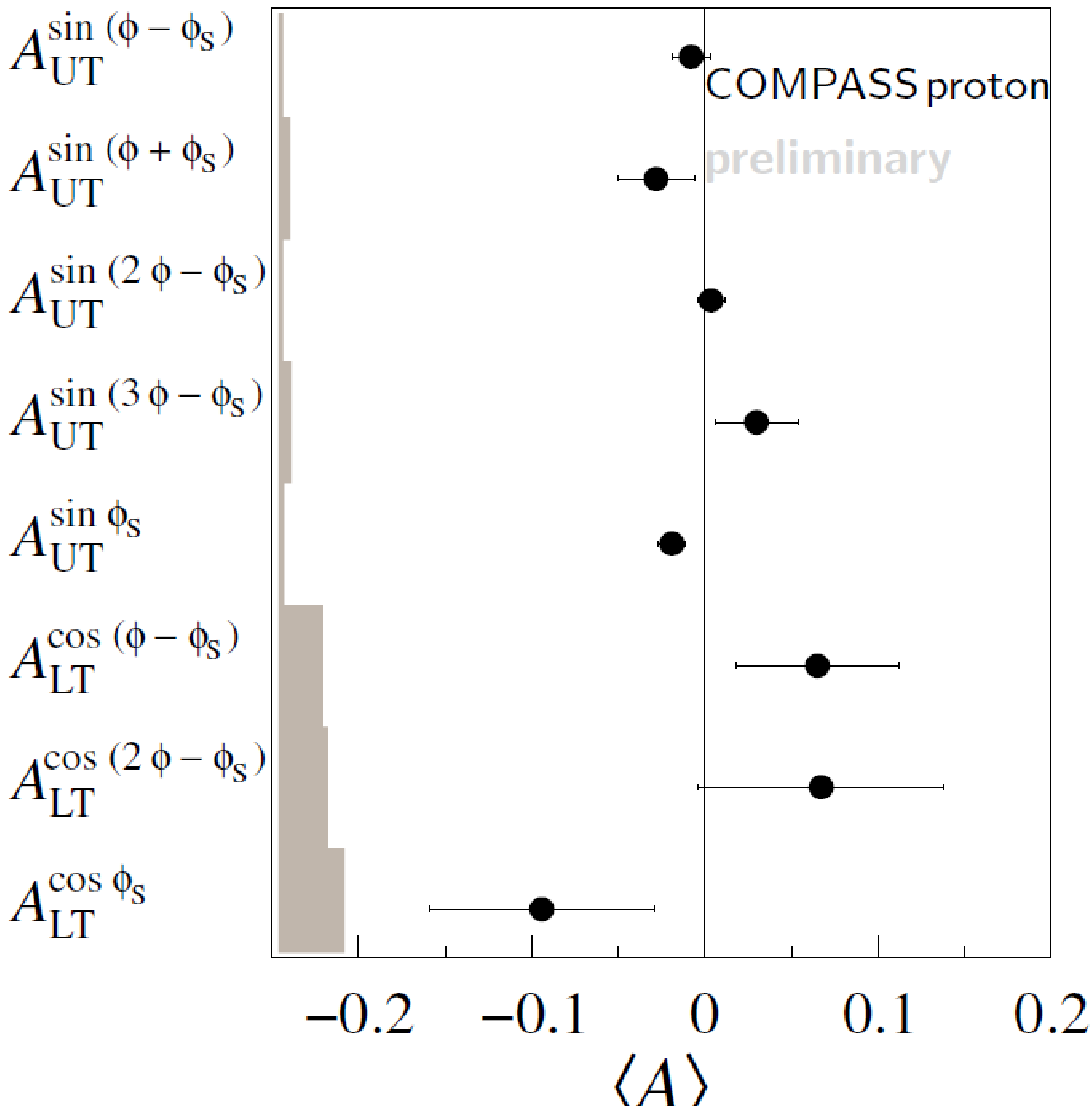
$$+ S_T P_\ell\left[\sqrt{1-\varepsilon^2}\,\cos(\phi-\phi_S)\,\mathrm{Re}\,\sigma_{++}^{+-} - \sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi_S\,\mathrm{Re}\,\sigma_{+0}^{+-}\right.$$

$$\left. - \sqrt{\varepsilon(1-\varepsilon)}\,\cos(2\phi-\phi_S)\,\mathrm{Re}\,\sigma_{+0}^{-+}\right]$$

ϵ = virtual photon polarization parameter
σ_{mn}^{ij} = spin dependent photoabsorption cross sections, interference terms
m,n = virtual-photon helicity
i,j = target nucleon helicity

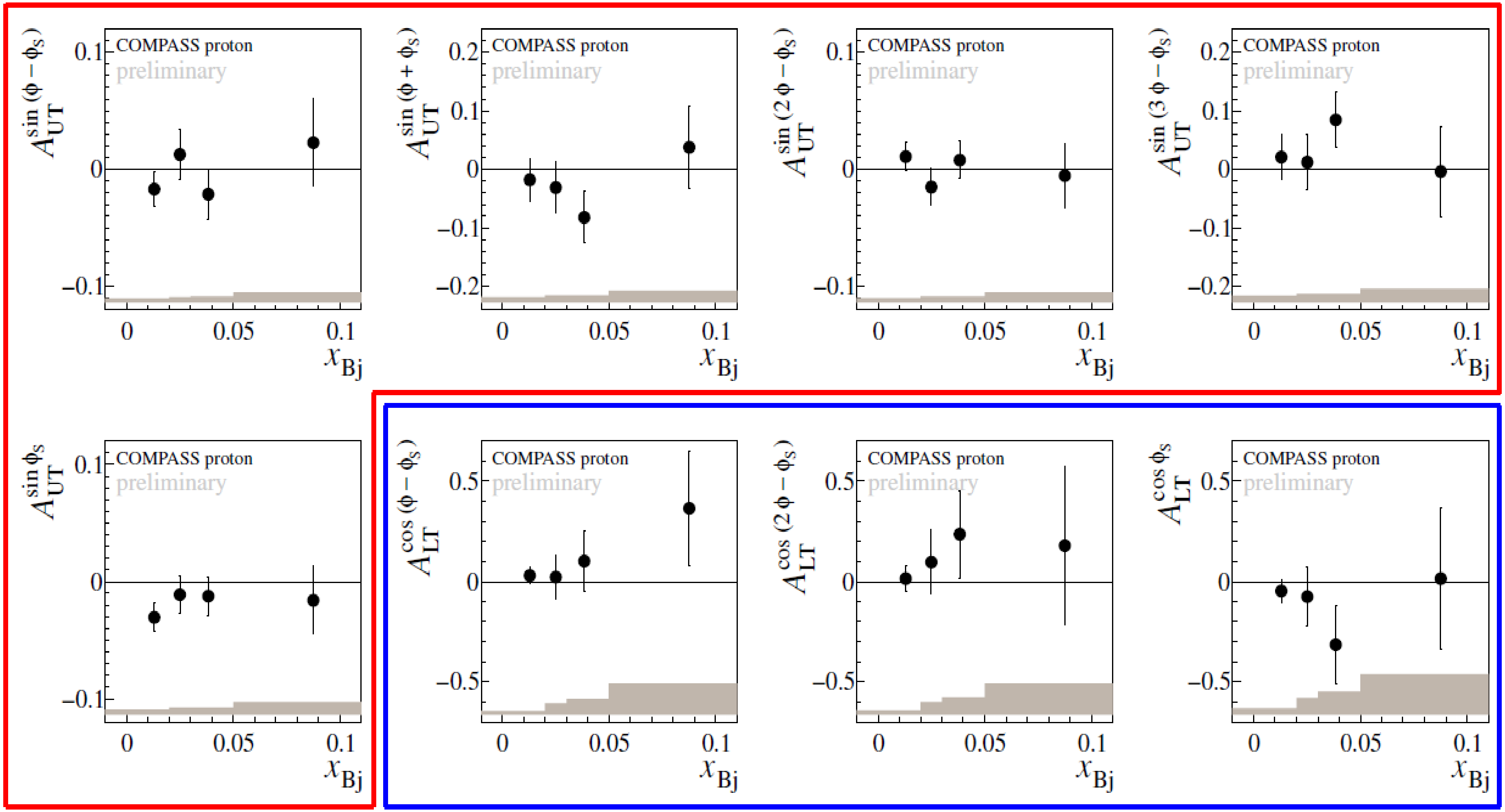
Diehl & Sapeta
Eur.Phys.J.C 41 (2005)

Mean asymmetries - NH_3 target (2007&2010)



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

as a function of x_{Bj}



- Asymmetry extraction using a 2D binned maximum likelihood fit after subtracting the SIDIS background

Comparison with a phenomenological GPD-based model

Goloskokov & Kroll

Eur.Phys.J.C 59 (2009)

- phenomenological 'handbag' approach
- based on $k_\perp$ factorisation
- includes twist-3 meson wave functions
- includes contributions from γ_L^* and γ_T^*

$$\sigma_{\mu\sigma}^{\nu\lambda} = \sum \mathcal{M}^*_{\mu'\nu',\mu\nu} \mathcal{M}_{\mu'\nu',\sigma\lambda}$$

$$A_{UT}^{\sin(\phi-\phi_s)}\sigma_0 = -2\mathrm{Im}\left[\epsilon \mathcal{M}^*_{0-,0+}\mathcal{M}_{0+,0+} + \mathcal{M}^*_{+-,++}\mathcal{M}_{++,++} + \frac{1}{2}\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,++}\right]$$

$$A_{UT}^{\sin(\phi_s)}\sigma_0 = -\mathrm{Im}\left[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,0+} - \mathcal{M}^*_{0+,++}\mathcal{M}_{0-,0+}\right]$$

$$A_{UT}^{\sin(2\phi-\phi_s)}\sigma_0 = -\mathrm{Im}\left[\mathcal{M}^*_{0+,++}\mathcal{M}_{0-,0+}\right]$$

$$A_{LT}^{\cos(\phi_s)}\sigma_0 = -\mathrm{Re}\left[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,0+} - \mathcal{M}^*_{0+,++}\mathcal{M}_{0-,0+}\right]$$

$\mathcal{M}_{\delta\gamma,\beta\alpha}$ = helicity amplitudes
α = initial-state proton helicity
β = virtual-photon helicity
γ = final-state proton helicity
δ = meson helicity

Comparison with a phenomenological GPD-based model

Up to now mainly used to describe DVCS and HEMP:
chiral-even GPDs

$\gamma^*_L \rightarrow \rho^0_L$	$\mathcal{M}_{0+,0+} \sim H$; $\mathcal{M}_{0-,0+} \sim E$	dominant
$\gamma^*_T \rightarrow \rho^0_T$	$\mathcal{M}_{++,++} \sim H$; $\mathcal{M}_{+-,++} \sim E$	suppressed

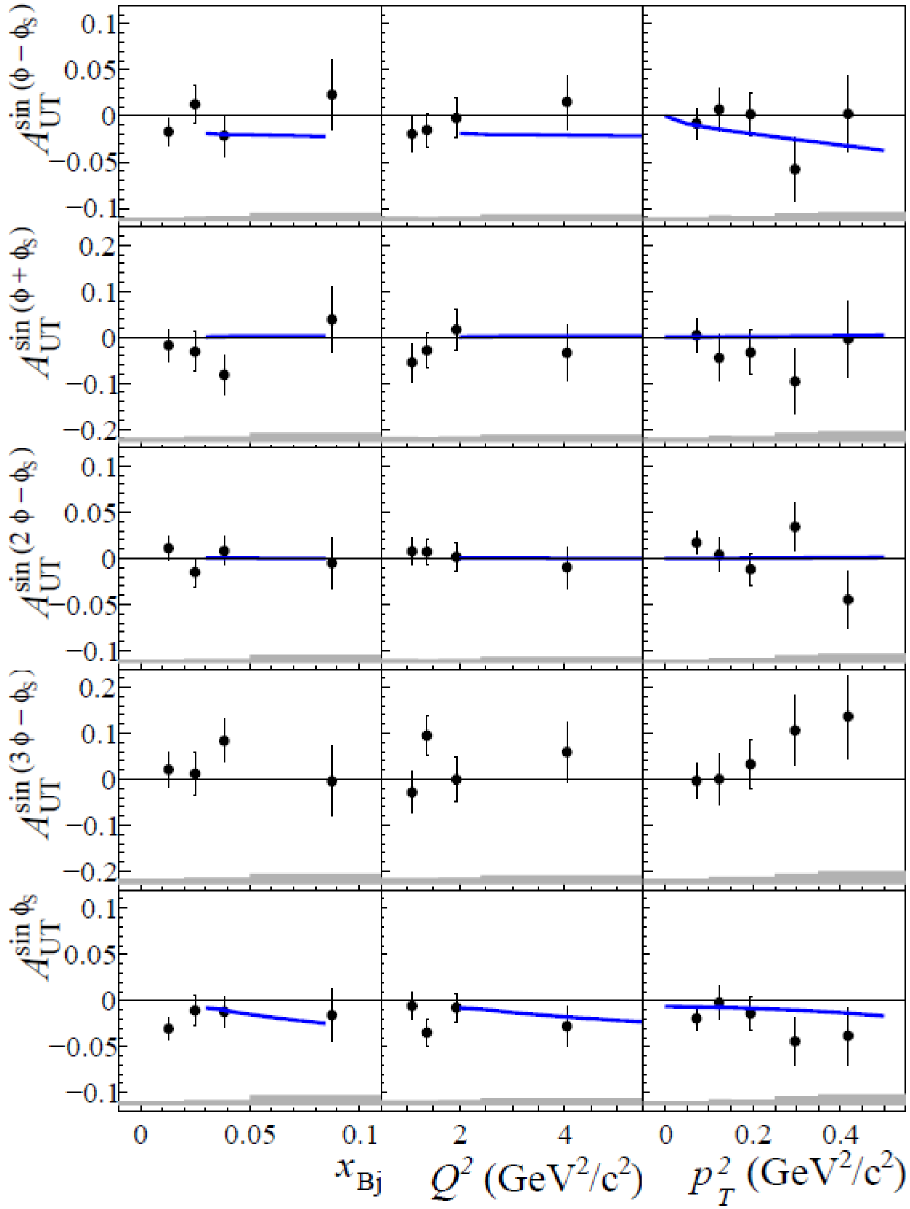
Recently introduced: chiral-odd (transverse) GPDs

$$\gamma^*_T \rightarrow \rho^0_L \qquad \mathcal{M}_{0-,++} \sim H_T; \ \mathcal{M}_{0+,++} \sim \bar{E}_T = 2\tilde{H}_T + E_T$$

$\gamma^*_L \rightarrow \rho^0_T$, $\gamma^*_T \rightarrow \rho^0_{-T}$ known to be suppressed, neglected in the model

$A_{UT,p}^{\sin(\phi_S)}$ = -0.019 $\pm$ 0.008 $\pm$ 0.003 evidence for existence of chiral-odd GPD H_T

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



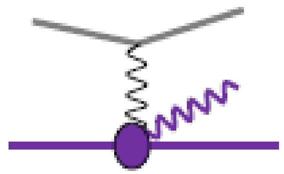
COMPASS proton

Phys.Lett. B731 (2014) 96

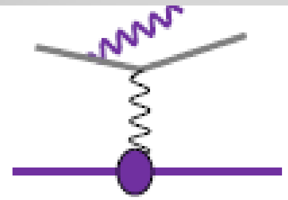
arXiv:1310.1454

- 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$/c)^2$

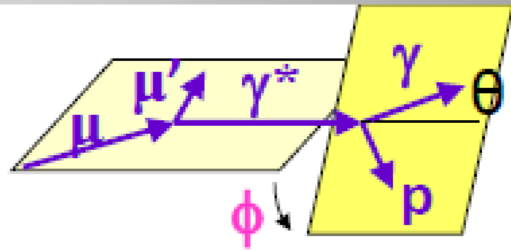
DVCS at COMPASS: Monte Carlo Simulation



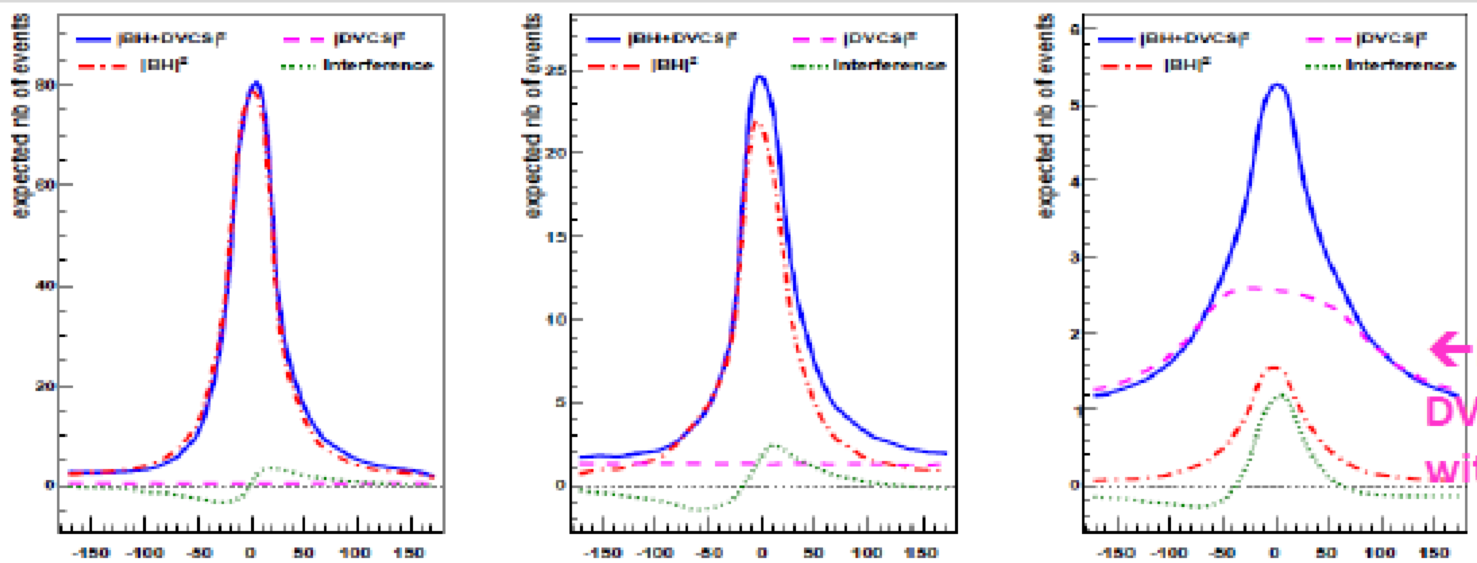
Deep VCS



Bethe-Heitler



$d\sigma \propto |T^{BH}|^2$ + 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

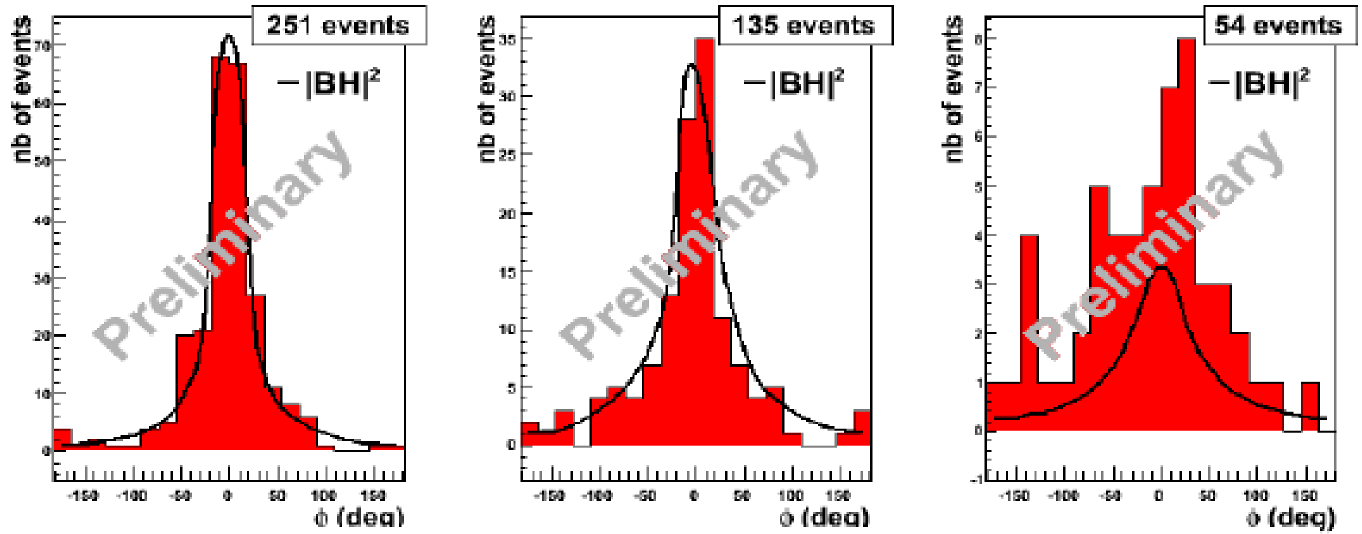
study of $d\sigma^{DVCS}/dt$

→ Transverse Imaging

DVCS at COMPASS: 2009 test run data

Test runs in 2009 & 2012 with 40 cm long target & small recoil detector:

3 x-Bjorken regions -> indication for DVCS signal



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

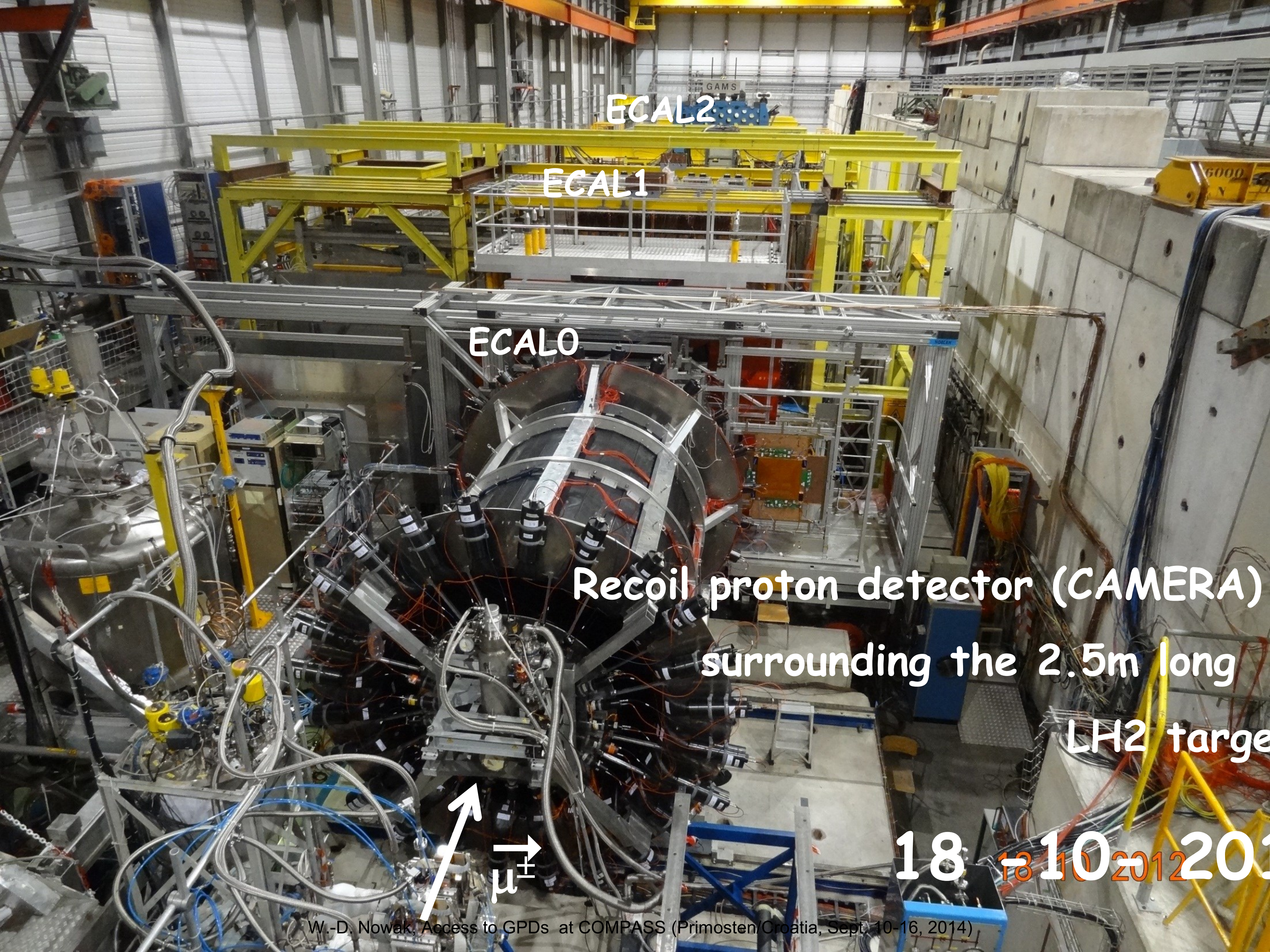
$\varepsilon_{\mu p \rightarrow \mu' \gamma p} \approx 35\%$

$\times (0.8)^4$ for SPS + COMPASS avail. + trigger eff + dead time

$\varepsilon_{global} \approx 0.14$ confirmed $\varepsilon_{global} = 0.1$ as assumed for COMPASS II predictions

54 evts = 20 BH

\+ a significant DVCS contri. which can be polluted by γ from π^0 decay


GAMS
ECAL2
ECAL1
ECAL0
Recoil proton detector (CAMERA)
surrounding the 2.5m long
LH2 targe
$\vec{\mu}^{\pm}$
18 -10- 201
18 10 2012

DVCS at COMPASS: How to constrain GPDs ?

- *U*npolarized beam: 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

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

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

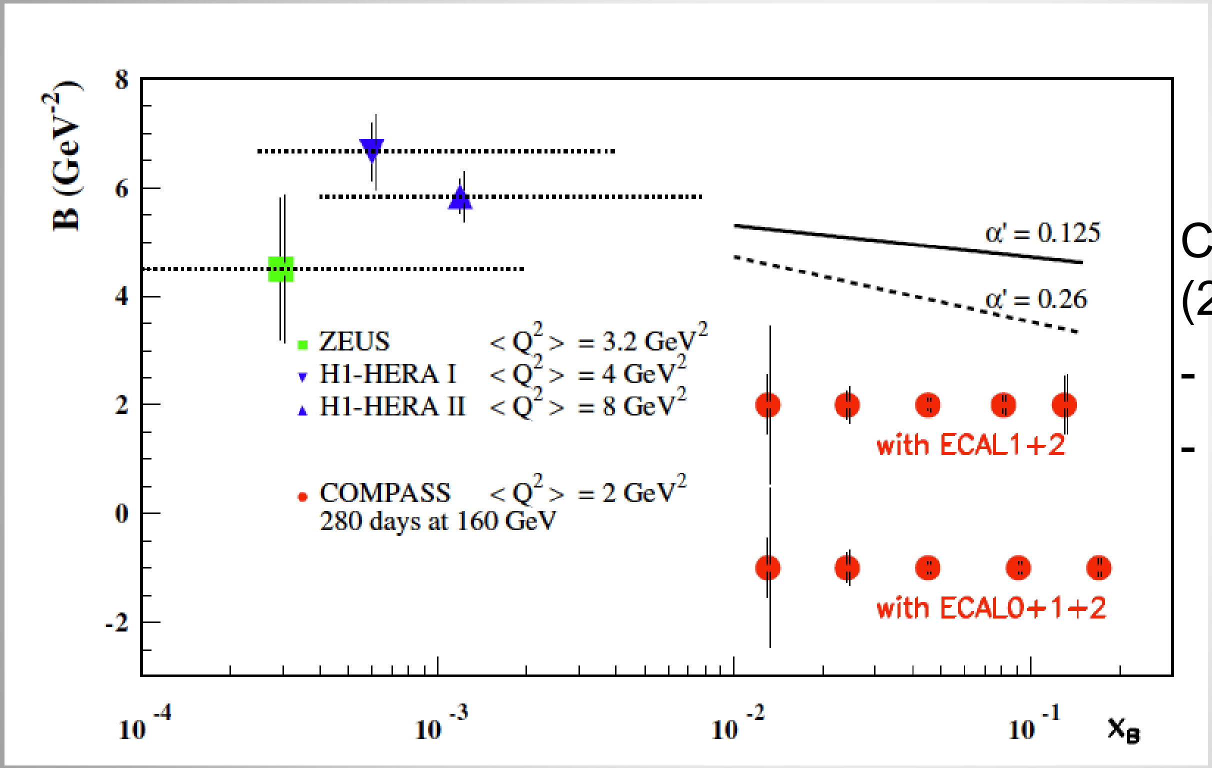
- *T*ransversely polarized target: Access GPD E (> 2018)

(addendum to proposal required)

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

DVCS cross section: transverse size of nucleon

$$\mathcal{S}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\, I),$$



$$\frac{d\sigma^{DVCS}_{unpol}}{dt} \propto \exp(-B|t|)$$

COMPASS expected results (2016+2017):

- 40 weeks of data,
- 2.5 m LH target

→ Transverse size of the nucleon as a function of Bjorken-x

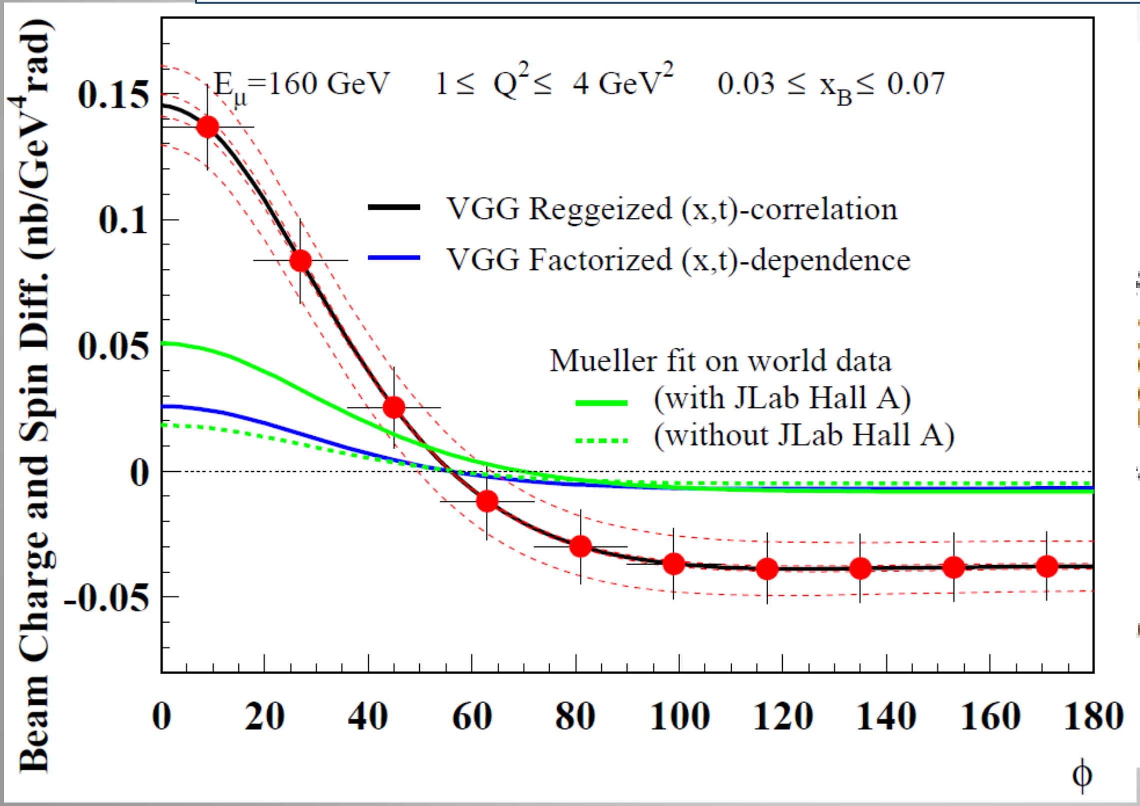
Measure difference of DVCS cross sections

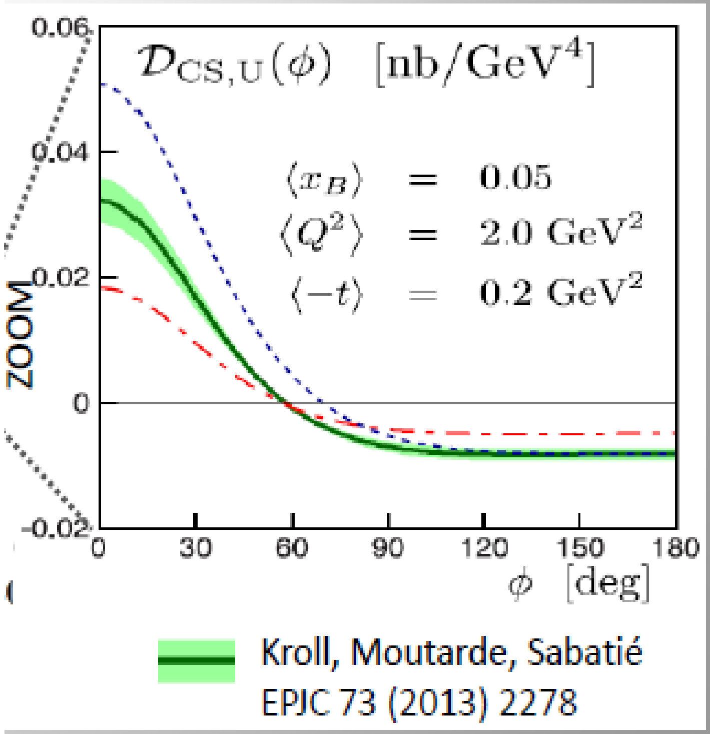
$$D_{CS,U} = d\sigma(\mu^{+\rightarrow}) - d\sigma(\mu^{-\leftarrow}) \propto P_\mu d\sigma_{pol}^{DVCS} + e_\mu \mathrm{Re}(I) \propto c_0^{Int} + c_1^{Int} \cos\phi$$

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

COMPASS expected results (2016+2017):

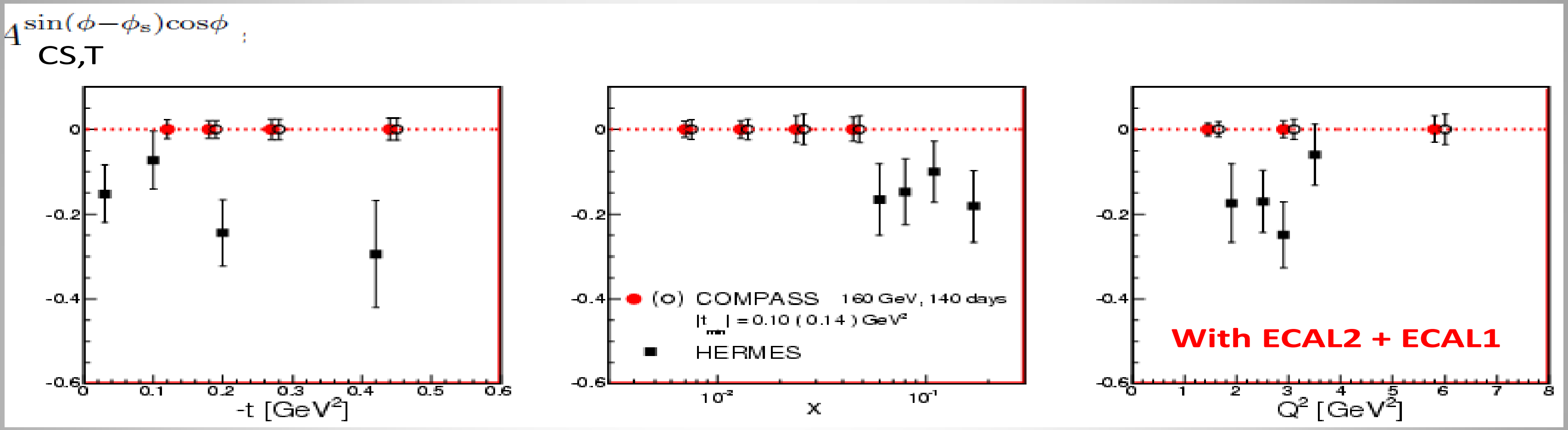
40 weeks of data, 2.5 m LH target, 10% global efficiency

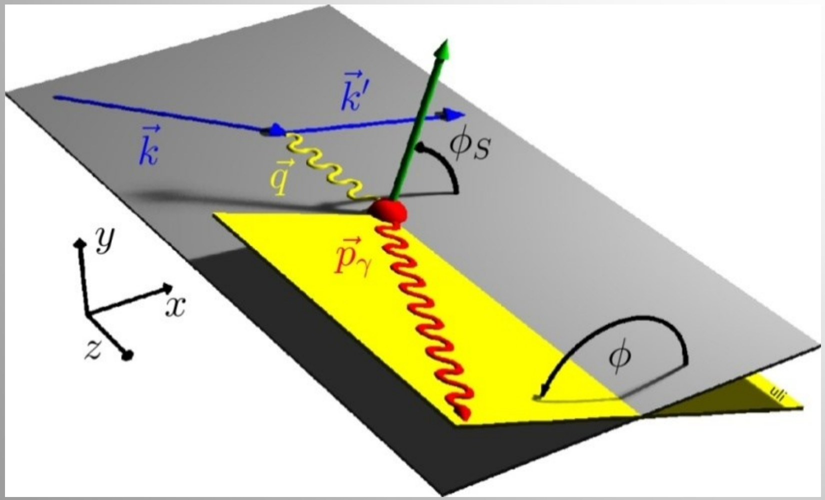




DVCS with a transversely polarized Target

> 2018: 2 "years" data taking; E=160 GeV/c;10% efficiency;
(new transversely polarized target & recoil proton detection)





ϕ - angle between the lepton scattering and hadron production planes

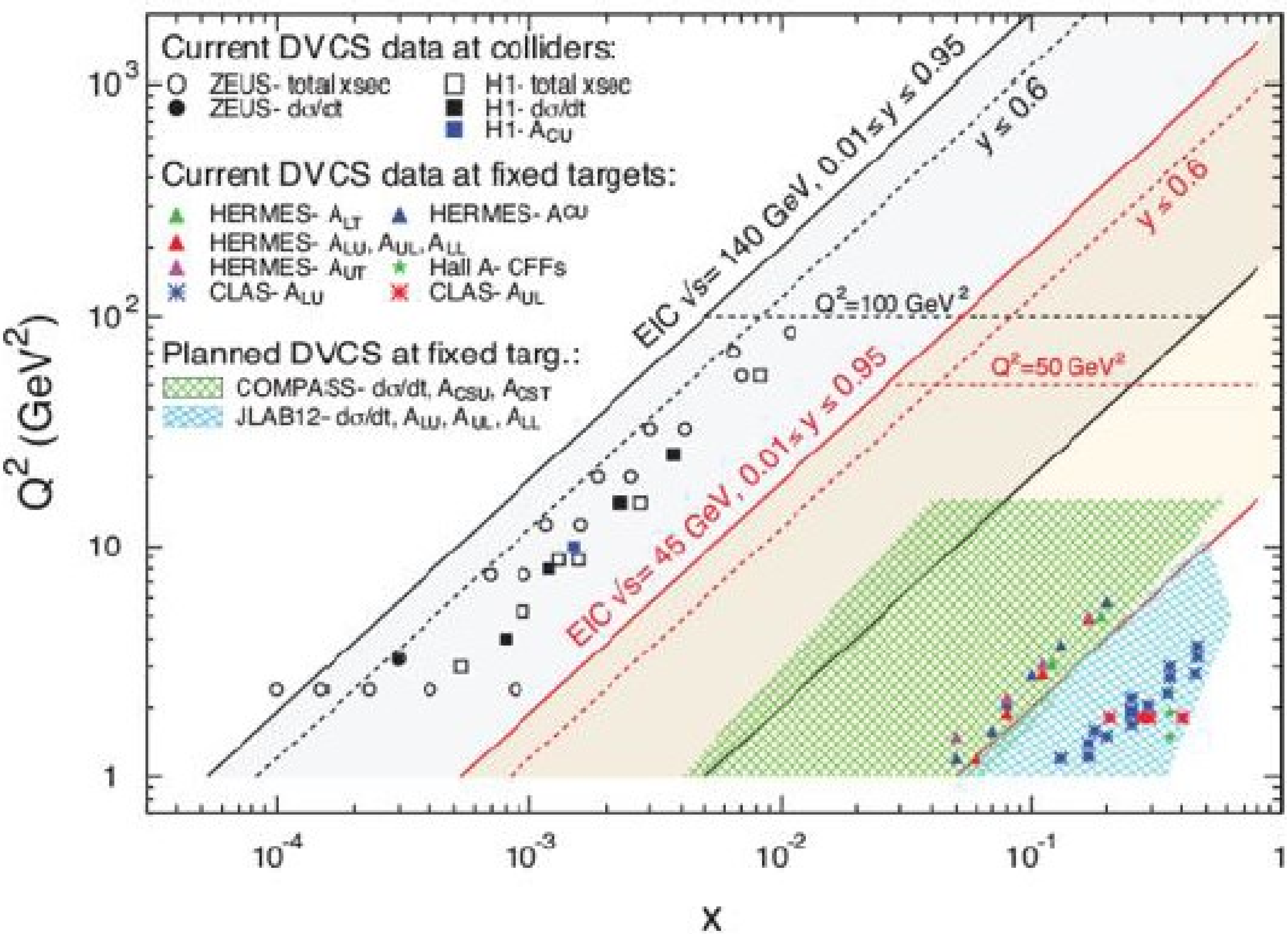
ϕ_S -angle between the target spin direction and the lepton scattering plane

Conclusions and Outlook

- Generalized Parton Distributions are a well-suited tool to explore the structure of the nucleon (nucleon tomography)
- COMPASS is a unique place to study DVCS and HEMP in the medium-x region
- COMPASS results on 2010 exclusive ρ^0 production show indications for transverse GPDs, when interpreted in terms of phenomenological Goloskokov-Kroll model
- 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

For a detailed discussion of 2009/2012 DVCS test run results: **see talk by O. Kouznetsov)**

SPARE SLIDES



Current DVCS data at colliders:
ZEUS- total xsec
ZEUS- dσ/dt
H1- total xsec
H1- dσ/dt
H1- A_CU
Current DVCS data at fixed targets:
HERMES- A_LT
HERMES- A^CU
HERMES- A_LU, A_UL, A_LL
HERMES- A_UT
Hall A- CFFs
CLAS- A_LU
CLAS- A_UL
Planned DVCS at fixed targ.:
COMPASS- dσ/dt, A_CSU, A_CST
JLAB12- dσ/dt, A_LU, A_UL, A_LL
EIC √s= 140 GeV, 0.01≤y≤0.95
y≤0.6
EIC √s= 45 GeV, 0.01≤y≤0.95
y≤0.6
Q²=100 GeV²
Q²=50 GeV²
Q² (GeV²)
x

Semi-inclusive background estimation

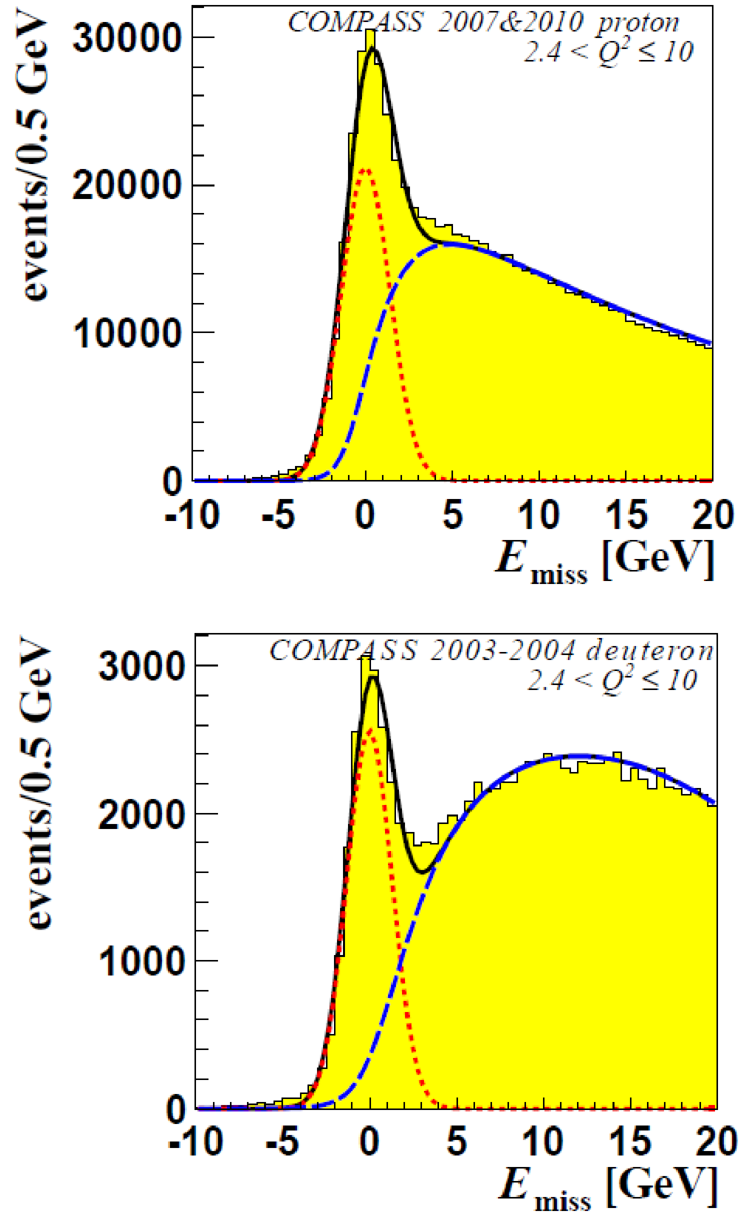
- LEPTO MC (COMPASS tuning)

1.) Parameterization of MC:

- MC weighted with the like sign sample

$$w = \frac{N_{\text{data}}^{h^+h^+}(E_{\text{miss}}) + N_{\text{data}}^{h^-h^-}(E_{\text{miss}})}{N_{\text{MC}}^{h^+h^+}(E_{\text{miss}}) + N_{\text{MC}}^{h^-h^-}(E_{\text{miss}})}$$

- Parameterize the E_{miss} shape of weighted MC
- Binning appropriate for asymmetry extraction (x_{Bj}, Q^2 or p_T^2, target cell)



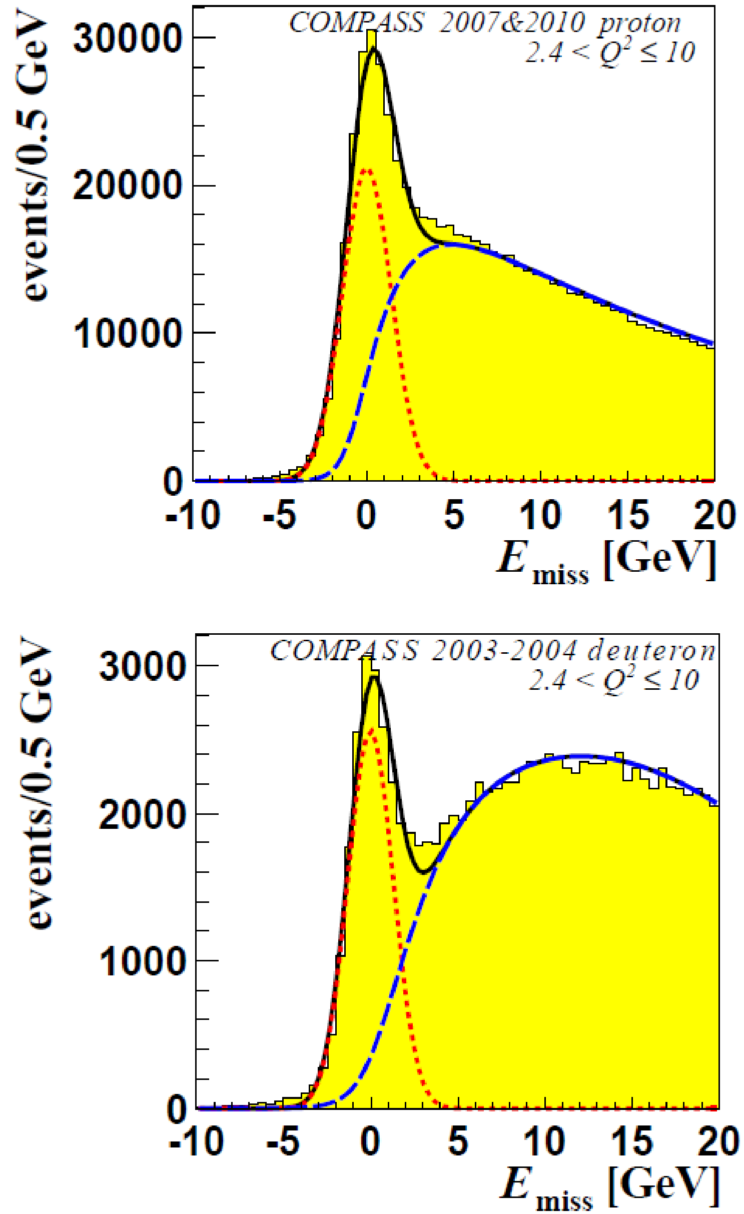
Semi-inclusive background estimation

- LEPTO MC (COMPASS tuning)

2.) Fit to data:

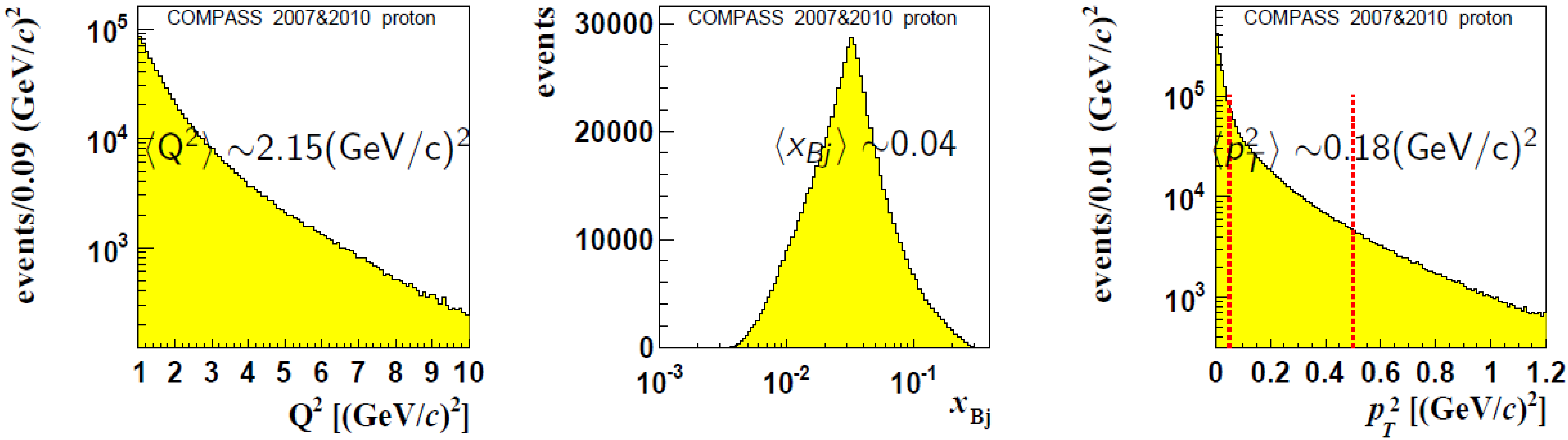
- Normalize MC E_{miss} shape to data by performing a two component signal (gauss) + background fit
- ϕ, ϕ_S distribution for $7 < E_{\text{miss}} < 20$ GeV scaled with the number of background events and subtracted from ϕ, ϕ_S distribution in signal range $-2.5 < E_{\text{miss}} < 2.5$ GeV
- Asymmetry extraction with corrected ϕ, ϕ_S distribution

→ Total amout of SIDIS background: 18% (^{6}LiD), 22% (NH_3)

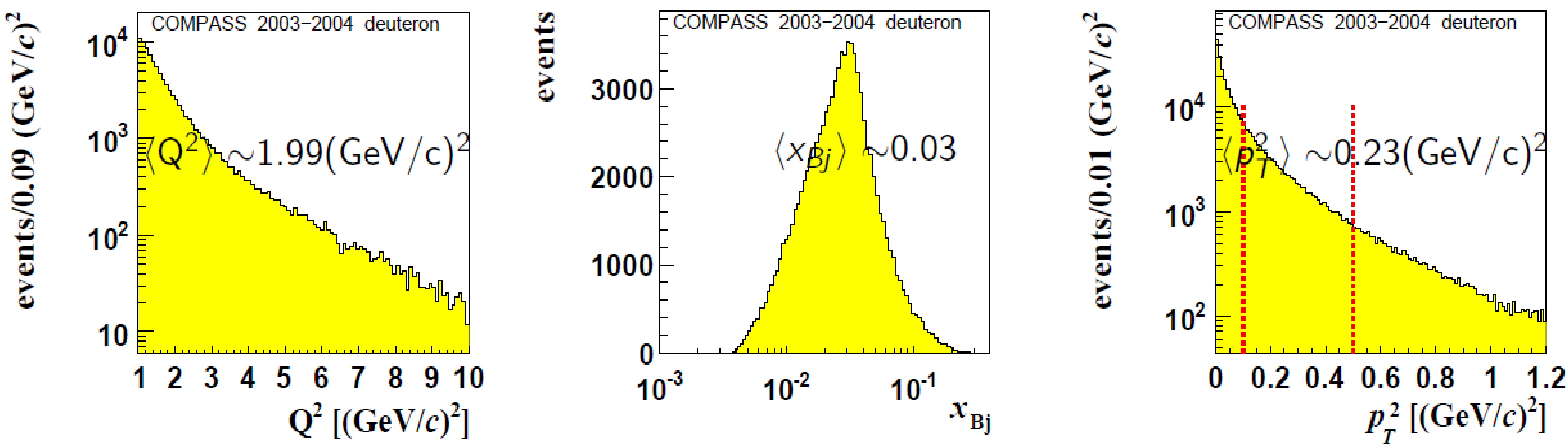


Exclusive ρ^0 production - kinematical distributions

protons

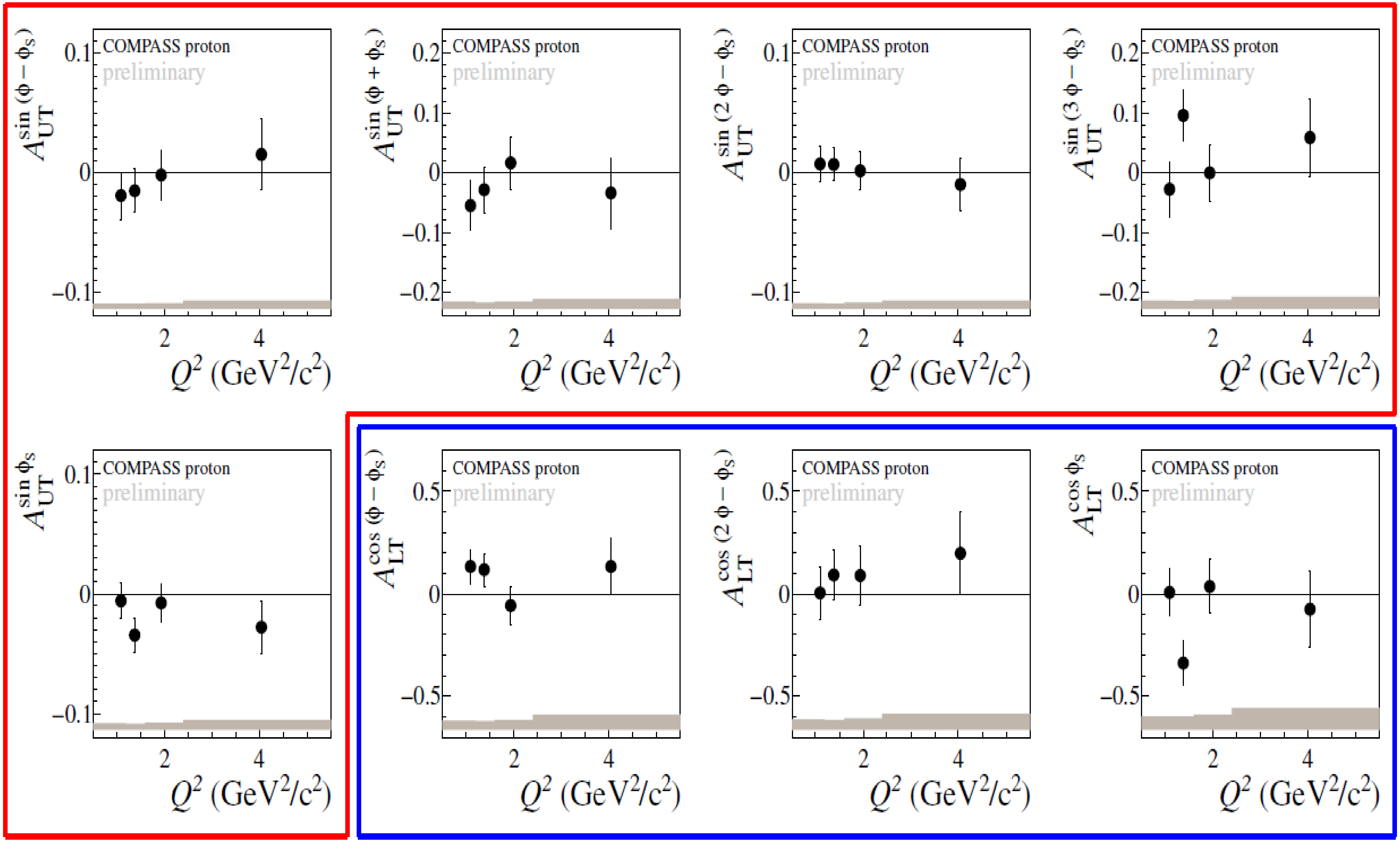


deuterons



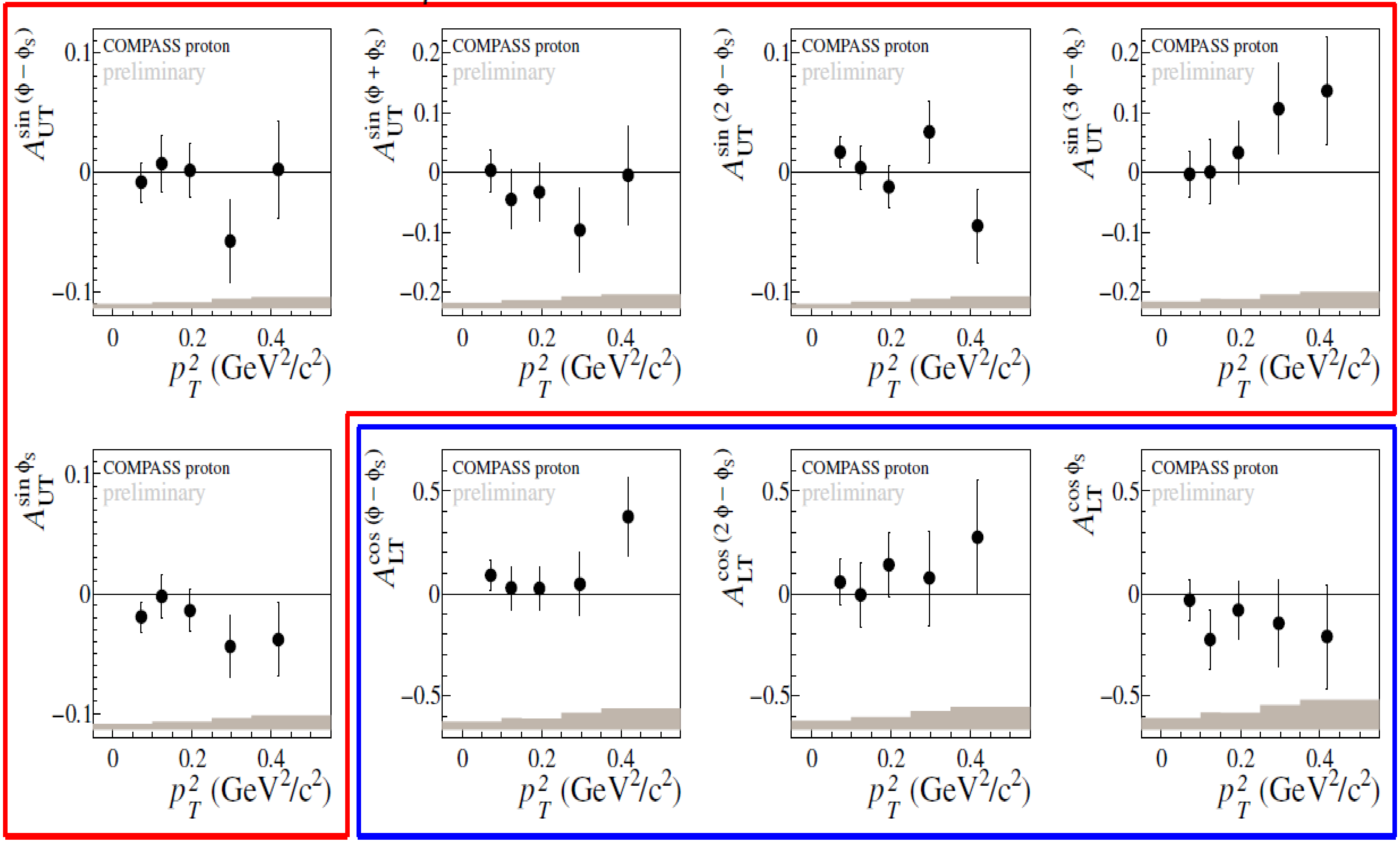
Asymmetry $A_{UT,LT}$ - NH_3 target (2007&2010)

as a function of Q^2

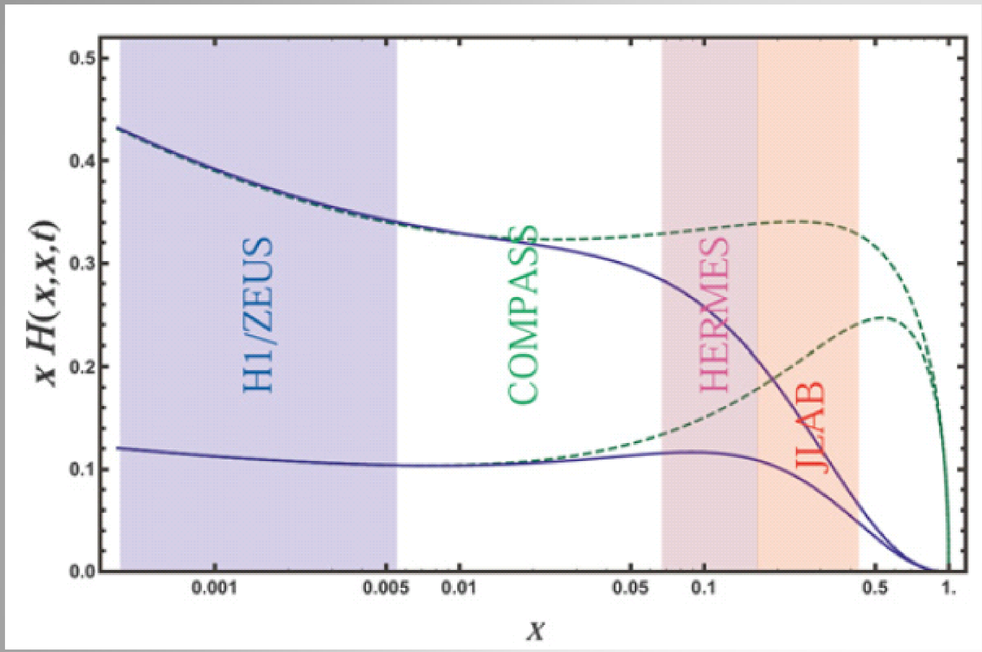


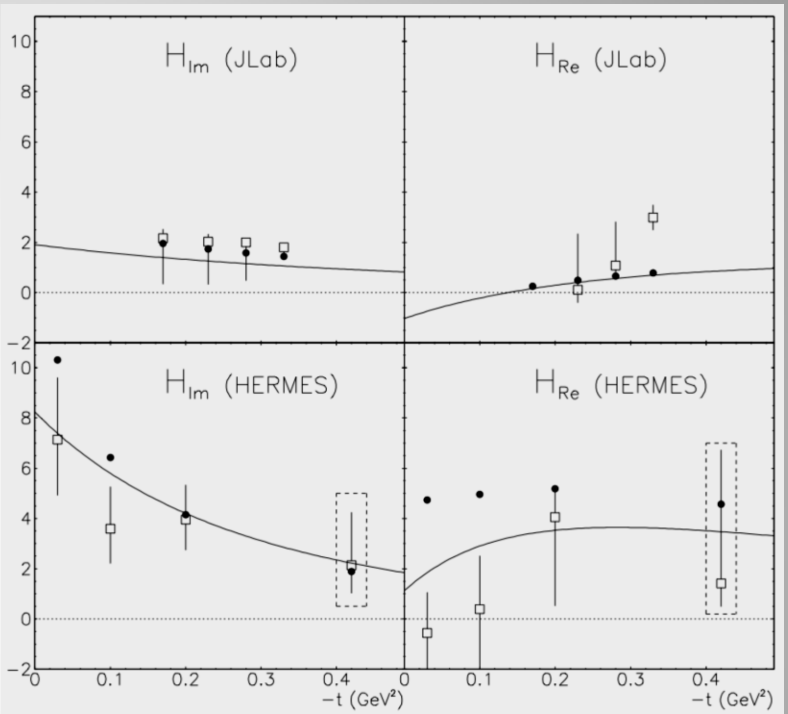
Asymmetry $A_{UT,LT}$ - NH_3 target (2007&2010)

as a function of p_T^2



Extraction of GPDs





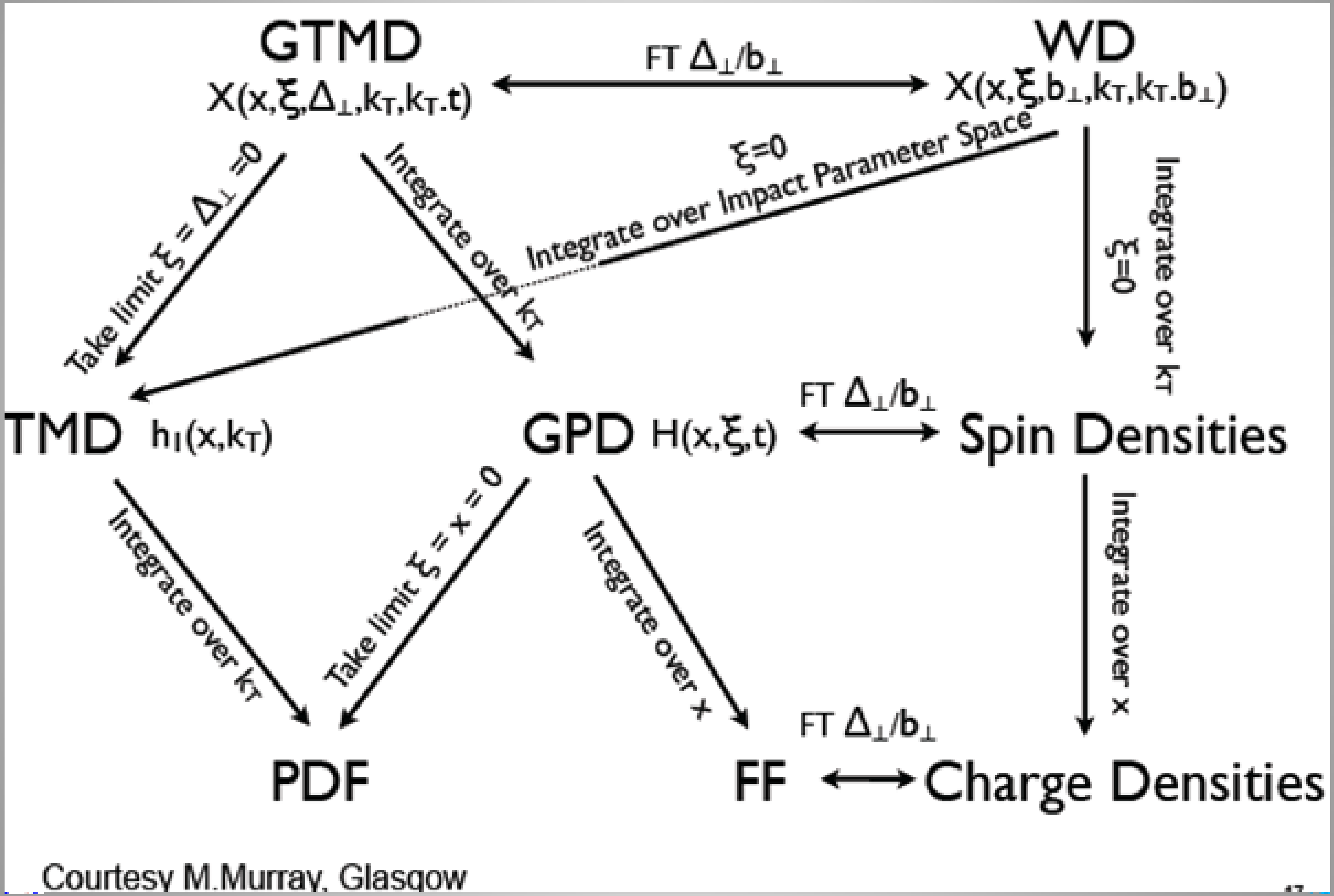
- Postulate GPDs from first principle models

  K. Kumerički and D. Müller, Nucl. Phys. B 841, (2010) 1

- Fit Compton form factors to asymmetry data

  M. Guidal and H. Moutarde, Eur.Phys.J. A 42 (2009) 71

Contempory hierarchy of parton distributions



Fourier Amplitudes

$$\left|\tau_{BH}\right|^2 = \frac{K_{BH}}{P_1(\phi)P_2(\phi)}\left\{\sum_{n=0}^{2} c_n^{BH}\cos(n\phi) + s_1^{BH}\sin(\phi)\right\}$$

$$\left|\tau_{DVCS}\right|^2 = K_{DVCS}\left\{\sum_{n=0}^{2} c_n^{DVCS}\cos(n\phi) + \sum_{n=1}^{2} s_n^{DVCS}\sin(n\phi)\right\}$$

$$I = -\frac{K_I e_l}{P_1(\phi)P_2(\phi)} K_{DVCS}\left\{\sum_{n=0}^{3} c_n^{I}\cos(n\phi) + \sum_{n=1}^{3} s_n^{I}\sin(n\phi)\right\}$$

Azimuthal asymmetries in DVCS

- Cross section

$$\sigma_{LU}(\phi; P_B, C_B) = \sigma_{UU}[1 + \boxed{P_B} A_{LU}^{DVCS} + \boxed{C_B P_B} A_{LU}^{I} + \boxed{C_B} A_C]$$

- Beam-charge asymmetry

$$A_C(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) - (\sigma^{-\leftarrow} + \sigma^{-\rightarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\leftarrow} + \sigma^{-\rightarrow})} = -\frac{1}{D(\phi)} \frac{x_B}{y} \sum_{n=0}^{3} \boxed{c_n^I} \cos(n\phi)$$

- Charge-difference beam-helicity asymmetry

$$A_{LU}^{I}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})} = -\frac{1}{D(\phi)} \frac{x_B}{y} \sum_{n=1}^{2} \boxed{s_n^I} \sin(n\phi)$$

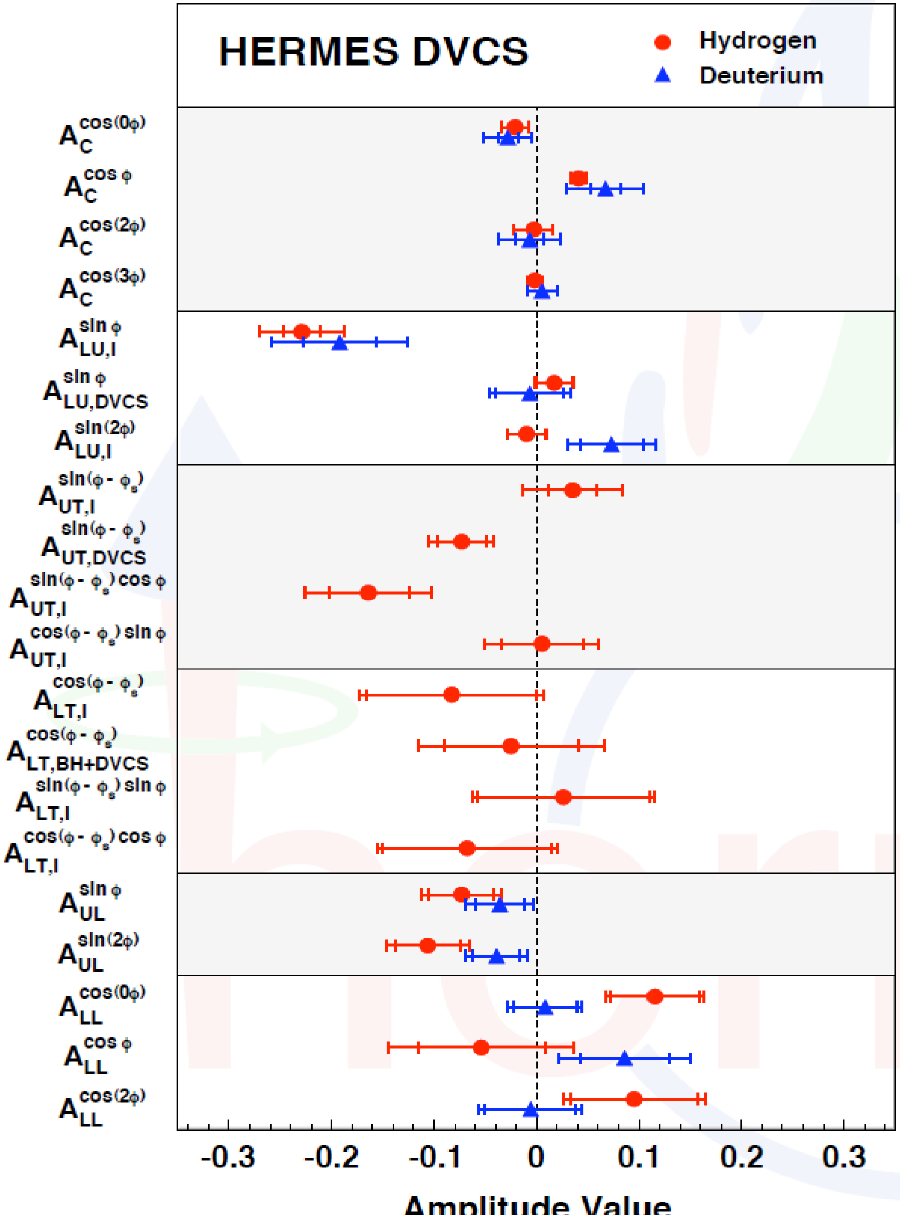
- Charge-averaged beam-helicity asymmetry

$$A_{LU}^{DVCS}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\leftarrow} + \sigma^{-\rightarrow})} = \frac{1}{D(\phi)} \cdot \frac{x_B^2 t \mathcal{P}_1(\phi) \mathcal{P}_2(\phi)}{Q^2} \boxed{s_1^{DVCS}} \sin(\phi)$$

- Separation of contributions from DVCS and interference term
- Impossible in case of single-charge beam-helicity asymmetry

$$A_{LU}(\phi) = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$$

HERMES measured a wealth of azimuthal amplitudes



Beam-charge asymmetry:
GPD H

PRD 75 (2007) 011103
NPB 829 (2010) 1
JHEP 11 (2009) 083
PRC 81 (2010) 035202
PRL 87 (2001) 182001
JHEP 07 (2012) 032

Beam-helicity asymmetry:
GPD H

Transverse target spin asymmetries:
GPD E from proton target

JHEP 06 (2008) 066
PLB 704 (2011) 15

Longitudinal target spin asymmetry:
GPD $\tilde{H}$

JHEP 06 (2010) 019
NPB 842 (2011) 265

Double-spin asymmetry:
GPD $\tilde{H}$