GPD Measurements at COMPASS

Po-Ju Lin
IPN-Orsay CNRS/IN2P3 & DPhN, IRFU, CEA-Saclay

HADRON 2019
Guilin
August 20, 2019
• The COMPASS Experiment
• Deeply Virtual Compton Scattering
• Hard Exclusive Meson Production
• Summary
Versatile facility with hadron ($\pi^\pm$, $K^\pm$, $p$ ...) & lepton (polarized $\mu^\pm$) beams of energy $\sim 200$ GeV

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy
COMPASS Setup for GPD Measurements

- \( \mu^+ \) & \( \mu^- \) beams with opposite polarisation
- \( \text{About } \pm 80\% \text{ polarisation} \)
- Momentum: 160 GeV/c

Two-stage, large angle, and wide momentum range spectrometer. PID including hadron absorbers, RICH, HCALs, ECALs, and muon filters.

\[ \text{DVCS: } \mu + p \rightarrow \mu' + p + \gamma \]

\( \sim 60\text{m} \)
New equipements:

➢ 2.5m LH2 target
➢ 4m ToF Barrel CAMERA
➢ ECAL0

ECAL0: 2 × 2 m²

Shashlyk modules + MAPD readout
one module is made of 9 cells (4×4 cm²)
= 194 modules or 1746 cells

DVCS: \( \mu p \rightarrow \mu' p \gamma \)

2012 pilot run with 4-week data taking
2016-17 dedicated run. 2 x 6 months.

COMPASS Setup for GPD Measurement
CAMERA recoil proton detector surrounding the 2.5m long LH2 target

DVCS: $\mu^+ p \rightarrow \mu^- p \gamma$

+ SIDIS on unpolarized protons
COMPASS Coverage

- **Start 2001**
- **After 2016**
- **After 2030**

- Current DVCS data at colliders:
  - ZEUS- total xsec
  - ZEUS- dσ/dt
  - H1- total xsec
  - H1- dσ/dt
  - H1- ACU

- Current DVCS data at fixed targets:
  - HERMES- AUL, AUL, AUL
  - HERMES- ALT
  - HERMES- ALCU
  - CLAS- AUL
  - CLAS- total xsec, ALU

- Planned DVCS at fixed targets:
  - COMPASS- dσ/dt, ΣCSU, ΔCSU, ΔCSU
  - JLAB12- dσ/dt, ALU, AUL, AUL

- Future colliders: EIC...
Proton Picture

Wigner distributions

\[ \mathcal{W}(x, k_\perp, r_\perp) \]

- The complete partonic description of the nucleon

GPDs

- 8 in total
- Info. on transverse position
- Embody both PDFs and Form factors
- Accessible in exclusive processes
DVCS: $l + p \rightarrow l' + p' + \gamma$

DVCS: the golden channel to investigate the GPDs; Interference with the well-known BH process gives access to more info.

The variables measured in the experiment:

- $E_\ell$, $Q^2$, $x_{Bj} \sim 2 \xi/(1+\xi)$,
- $t$ (or $\theta_{\gamma*\gamma}$) and $\phi$ ($\ell\ell'$ plane/$\gamma\gamma*$ plane)
The GPDs depends on the following variables:

- $x$: average longitudinal momentum frac.
- $\xi$: longitudinal momentum diff.
- $t$: four momentum transfer
  (correlated to $b_{\perp}$ via Fourier transform)
- $Q^2$: virtuality of $\gamma^*$

Sensible to 4 GPDs, at COMPASS with small $x_B$ → focuses on $H$

$$\Re H(\xi, t) = P \int dx \frac{Im H(x, t)}{x - \xi} + d(t)$$
Transverse Imaging and Pressure Dist.

\[
\mathcal{H}(x, \xi, t) = \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\varepsilon}
\]

\[
\text{REAL part} = P \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} - i\pi H(x=\pm\xi, \xi, t)
\]

\[
\text{Imaginary part} \quad \text{Im} \mathcal{H}(x, t) = P \int dx \frac{\text{Im} \mathcal{H}(x, t)}{x - \xi} + d(t)
\]
Azimuthal Dependence

\[ D_{cs,u}(\phi) \equiv \frac{d\sigma(\mu^+ \rightarrow \mu^-)}{d\sigma(\mu^- \rightarrow \mu^+)} \]

\[ S_{cs,u}(\phi) \equiv \frac{d\sigma(\mu^+ \rightarrow \mu^-)}{d\sigma(\mu^- \rightarrow \mu^+)} + \frac{d\sigma(\mu^- \rightarrow \mu^+)}{d\sigma(\mu^+ \rightarrow \mu^-)} \]
Azimuthal Dependence

Beam Charge-spin difference & sum

$$D_{cs,u}(\phi) \equiv d\sigma(\mu^{+\rightarrow}) - d\sigma(\mu^{-\rightarrow})$$

$$S_{cs,u}(\phi) \equiv d\sigma(\mu^{+\rightarrow}) + d\sigma(\mu^{-\rightarrow})$$

$$\frac{d^4\sigma(\ell p \rightarrow \ell p\gamma)}{dx_BdQ^2dt|d\phi} = \left[ d\sigma^{\text{BH}} + \left( d\sigma^{\text{DVCS}_{\text{upol}}} + P_\ell d\sigma^{\text{DVCS}_{\text{pol}}} \right) \right] + \left( e_\ell \text{Re } I + e_\ell P_\ell \text{Im } I \right)$$

$D_{cs,u}(\phi)$

Twist-2 >> Twist-3, Twist-2 - double helicity flip for gluons (NLO)
Azimuthal Dependence

$$D_{cs,u}(\phi) \equiv d\sigma(\mu^{+\rightarrow}) - d\sigma(\mu^{-\rightarrow})$$

$$S_{cs,u}(\phi) \equiv d\sigma(\mu^{+\rightarrow}) + d\sigma(\mu^{-\rightarrow})$$
Azimuthal & $x_{Bj}$ Dependence

Increasing $x_{Bj}$

Low $x_{Bj}$: BH dominates

- $|BH|^2$
- $|DVCS|^2$
- $|BH+DVCS|^2$

Reference yield of almost pure Bethe-Heitler

$E_\mu=160\text{GeV}$ $Q^2=2\text{GeV}^2$ $t=-0.1\text{GeV}^2$

Study DVCS with:
\[ \text{Re}(T^{DVCS}) \& \text{Im}(T^{DVCS}) \]
via \( (d\sigma^{+-} \pm d\sigma^{-+}) \)

Large $x_{Bj}$: DVCS dominates

- $|BH|^2$
- $|DVCS|^2$
- $|BH+DVCS|^2$

Transverse Imaging:
\[ d\sigma^{DVCS}/dt \]
via \( (d\sigma^{+-} + d\sigma^{-+}) \)
Extraction of DVCS Events - 2012 data

Increasing $x_{Bj}$

$$S_{CS, u}(\phi) \equiv d\sigma(\mu^+ \leftrightarrow \mu^-) + d\sigma(\mu^- \leftrightarrow \mu^+) = 2[d\sigma^{BH} + d\sigma^{DVCS} + \text{Im } I]$$

$$= 2[d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos \phi + s_1^I \sin \phi + s_2^I \sin 2\phi]$$
Extraction of DVCS Events - 2012 data

\[ S_{CS,u}(\phi) \equiv d\sigma(\mu^+ \rightarrow ) + d\sigma(\mu^- \rightarrow ) = 2[ d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \text{Im } I ] \]

\[ = 2[ d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos \phi + s_1 I \sin \phi + s_2 I \sin 2\phi ] \]

\[ c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2} \mathcal{E}\mathcal{E}^* \rightarrow 4(\text{Im } \mathcal{H})^2 \]

Model dependent
Tranverse extension of partons – 2012 data

\[ d\sigma^{DVCS}/d|t| \propto e^{-B|t|} \]

\[ \langle r_{\perp}^2(x_{Bj}) \rangle \approx 2B(x_{Bj}) \text{ at small } x_{Bj} \]

\[ \langle x_{Bj} \rangle = 0.056 \]
\[ \langle Q^2 \rangle = 1.8 \text{ (GeV/c)}^2 \]
\[ \langle W \rangle = 5.8 \text{ GeV/c} \]

\[ d\sigma(\gamma^* p \rightarrow \gamma p) \propto e^{-B|t|} \]

\[ B = 4.31 \pm 0.62^{+0.09}_{-0.25} \text{ (GeV/c)}^2 \]

1 (GeV/c)^2 < Q^2 < 5 (GeV/c)^2

10 GeV < \nu < 32 GeV

\[ \sqrt{\langle r_{\perp}^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} \pm 0.01_{\text{sys}} \pm 0.04_{\text{model}}) \text{ fm} \]

With \( \langle x_{Bj} \rangle = 0.056 \)
Tranverse extension of partons – 2012 data

- KM15 and GK parameterization shows the complete evolution of HERA and COMPASS data
- The transverse size evolution as a function of $x_{Bj}$
  - Expect at least 3 $x_{Bj}$ bins from 2016-17 data

\[ \langle r_{\perp}^2(x_{Bj}) \rangle \approx 2B(x_{Bj}) \text{ at small } x_{Bj} \]

\[
\sqrt{\langle r_{\perp}^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} \pm 0.01_{\text{sys}} \pm 0.04_{\text{model}}) \text{ fm}
\]

With $\langle x_{Bj} \rangle = 0.056$

- 10 times more stat in 2016-17
2016 – 2017 Data First Insight

**DVCS**: $\mu \, p \rightarrow \mu' \, p \, \gamma$

1) $\Delta p_T = p_T^{\text{cam}} - p_T^{\text{spec}}$
2) $\Delta \varphi = \varphi^{\text{cam}} - \varphi^{\text{spec}}$
3) $\Delta z_A = z_A^{\text{cam}} - z_A^{\text{Z6 and vertex}}$
4) $M_{X=0}^2 = (p_{\mu_\text{in}} + p_{p_\text{in}} - p_{p_\text{out}} - p_{p_\text{out}} - p_\gamma)^2$
All distributions obtained with $\mu^-$ are normalized to the same luminosity of the ones with $\mu^+$

- Very good agreement between $\mu^+$ and $\mu^-$ data observed.

\[
\mathcal{D}_{cs,u}(\phi) \equiv d\sigma(\mu^{+\to}) - d\sigma(\mu^{-\to})
\]

\[
S_{cs,u}(\phi) \equiv d\sigma(\mu^{+\to}) + d\sigma(\mu^{-\to})
\]
No $\pi^0$ subtraction.

DVCS contribution at high $x_{Bj}$ will allow to perform re-analysis

\[ d\sigma^{DVCS}/dt = e^{-B'|t|} \]

\[ = c_0^{DVCS} \]

This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications. This work is also part of the "Mapping Proton Quark Structure using Petabytes of COMPASS Data" PRAC allocation supported by the National Science Foundation (award number OCI 1713684).
Beam Charge-spin Difference

\[ D_{\text{CS, } U}(\phi) \equiv d\sigma(\mu^{+\rightarrow}) - d\sigma(\mu^{-\rightarrow}) \rightarrow c_0^I + c_1^I \cos \phi \]

\[ c_1^I = \Re F_1 \mathcal{H} \]

- KM10
- VGG

- With and \( \Re F_1 \mathcal{H} \) and \( \Im F_1 \mathcal{H} \)
  \( \rightarrow \) Extraction of D-term

\( \Re \mathcal{H} > 0 \) at H1
\( < 0 \) at HERMES

Value of \( x_{\text{Bj}} \) for the node?

HERMES
JLab

COMPASS
2 years of data
\( E_{\mu} = 160 \text{ GeV} \)
\( 1 < Q^2 < 8 \text{ GeV}^2 \)
GPDs in Hard Exclusive Meson Production

4 chiral-even GPDs: helicity of parton unchanged

\[
\begin{align*}
\mathbf{H}^q(x, \xi, t) & \quad \mathbf{E}^q(x, \xi, t) & \text{For Vector Meson} \\
\tilde{\mathbf{H}}^q(x, \xi, t) & \quad \tilde{\mathbf{E}}^q(x, \xi, t) & \text{For Pseudo-Scalar Meson}
\end{align*}
\]

+ 4 chiral-odd or transversity GPDs: helicity of parton changed

(not possible in DVCS)

\[
\begin{align*}
\mathbf{H}_T^q(x, \xi, t) & \quad \mathbf{E}_T^q(x, \xi, t) \\
\tilde{\mathbf{H}}_T^q(x, \xi, t) & \quad \tilde{\mathbf{E}}_T^q(x, \xi, t) \\
\tilde{\mathbf{E}}_T^- & = 2 \ 	ilde{\mathbf{H}}_T^q + \mathbf{E}_T^q
\end{align*}
\]

➢ Universality of GPDs, quark flavor filter
➢ Ability to probe the chiral-odd GPDs.
➢ Additional non-perturbative term from meson wave function
➢ In addition to nuclear structure, provide insights into reaction mechanism
Exclusive $\pi^0$ Production on Unpolarized Proton

$$e+p \rightarrow e\pi^0 p$$

$$\frac{d^2\sigma}{dt d\phi_\pi} = \frac{1}{2\pi} \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right] + \epsilon \cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_\pi \frac{d\sigma_{LT}}{dt}$$

Leading twist expected to be dominant
But measured as $\approx$ only a few % of $\frac{d\sigma_T}{dt}$

The other contributions arise from coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k' t' Q^6} \left\{ (1 - \xi^2) \left| \langle \hat{H} \rangle \right|^2 - 2\xi^2 \text{Re} \left[ \langle \hat{H} \rangle^* \langle \hat{E} \rangle \right] - \frac{t'}{4mv^2} \xi^2 \left| \langle \hat{E} \rangle \right|^2 \right\}$$

A large impact of $\vec{E}_T$ can be identified:

- $\sigma_{TT}$ contribution
- The dip at small $|t|$ of $\sigma_T$
2012 Exclusive $\pi^0$ Prod. on Unpolarized Proton

$$\frac{d^2\sigma}{dt d\phi_{\pi^0}} = \frac{1}{2\pi} \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right] + \epsilon \cos 2\phi_{\pi^0} \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_{\pi^0} \frac{d\sigma_{LT}}{dt}$$

A dip at small $t$ would indicate a large impact of $E_T$

$e^+ p \rightarrow e^+ \pi^0 p$

$\sigma_{TT}$ large (impact of $E_T$)
$\sigma_{LT}$ smaller but significantly positive

hep-ex/1903.12030, subm. to PLB
SCHC \( (\lambda^\gamma = \lambda^\chi) \)
(S-Channel Helicity Conservation)

SCHC implies:

- \( r^1_{1-1} + \text{Im} r^2_{1-1} = 0 \)
  
  \[ = -0.010 \pm 0.032 \pm 0.047 \quad \text{OK} \]

- \( \text{Re} r^5_{10} + \text{Im} r^6_{10} = 0 \)
  
  \[ = 0.014 \pm 0.011 \pm 0.013 \quad \text{OK} \]

- \( \text{Im} r^7_{10} - \text{Re} r^8_{10} = 0 \)
  
  \[ = -0.088 \pm 0.110 \pm 0.196 \quad \text{OK} \]

- all elements of classes C, D, E should be 0
  for \( \gamma^* L \rightarrow \chi^* T \) and \( \gamma^* T \rightarrow \chi^* T \) OK within errors

not obeyed for transitions \( \gamma^* T \rightarrow \chi^* L \)

Exclusive \( \omega \) production on unpolarized proton

\[ r_{00}^5 \propto \text{Re} \left[ \langle E_T \rangle^*_L \langle H \rangle^*_{LL} + \frac{1}{2} \langle H_T \rangle^*_L \langle E \rangle^*_{LL} \right] \]

Goloskokov and Kroll, EPJC 74 (2014) 2725

Exclusive \( \rho^0 \), \( \omega \) production with trans. pol. target

COMPASS, NPB865 (2012) 1-20
COMPASS, PLB731 (2014) 19
COMPASS, NPB915 (2017) 454-475
Summary

- GPD by DVCS and HEMP in COMPASS

Sum and difference of DVCS $x$-sections with polarized $\mu^+$ and $\mu^-$:

- Transverse extension of partons as a function of $x_{Bj}$
- $\text{Im} \mathcal{H}(\xi,t)$ and $\text{Re} \mathcal{H}(\xi,t)$ for D-term and pressure distribution

HEMP of $\pi^0$, $\rho$, $\omega$, $\phi$, $J/\psi$

- Universality of GPDs - Transverse GPDs - Flavor Decomposition

Results on 2016-17 data are coming!
Expected to start at 2022

- Unique beam line with polarised $\mu^\pm$ and high-intensity Pion beam
- Possible high-intensity antiproton and Kaon beams, provided by RF-separation technique
- With upgraded apparatus

Proposed physics goals

- Proton Radius
- Meson PDF – gluon PDF
- Proton spin structure
- 3D imaging (TMDs and GPDs)
- Hadron spectroscopy
- Anti-matter cross section
Possible RPD for COMPASS++/AMBER

A recoil proton detector (RPD) is mandatory to ensure the exclusivity. A Silicon detector is included *between* the target surrounded by the modified MW cavity *and* the polarizing magnet.

No possibility for ToF ➞ PID of p/π with dE/dx
Momentum and trajectory measurements

$|t|_{\text{min}} \sim 0.1 \text{ GeV}$
π^0 Background

π^0 are one of the main background sources for excl. photon events.

Two possible case:

- **Visible** (both γ detected ➔ subtracted)
  
  the DVCS photon after all exclusivity cuts is combined with all detected photons below the DVCS threshold: 4,5,10 GeV in ECAL0, 1, 2

- **Invisible** (one γ lost ➔ estimated by MC)

  - Semi-inclusive LEPTO 6.1
  - Exclusive HEPGEN π^0 (Goloskokov-Kroll model)

Comparing the two components to the data allows the determination of their relative normalisation. The sum of the 2 components is normalized to the visible π^0 contamination in the M_{γγ} peak.
**GPD H Global Analysis**

**Im $H$** is better understood

**Re $H$** linked to the $d$ term is still poorly constrained


**GK** S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011)
GPD E Global Analysis

Figure made by D. Mueller and K. Kumericki

$Q^2 = 2 \text{GeV}^2$

$t = -0.3 \text{GeV}^2$

$\text{Im } \mathcal{E}$ is rather unknown

$\text{Re } \mathcal{E}$ is rather unknown

KM15 K Kumericki and D Mueller  arXiv:1512.09014v1
\( \frac{d^4\sigma(\ell p \rightarrow \ell p\gamma)}{dx_B dQ^2 d|\ell| d\phi} = \sigma^{BH} + \left( \sigma^{DVCS\,unpol}_{\text{NLO}} + P_\ell \sigma^{DVCS\,pol}_{\text{NLO}} \right) + (e_\ell \text{Re } I + e_\ell P_\ell \text{Im } I) \)

\[ 
\sigma^{BH} \propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi \\
\sigma^{DVCS\,unpol} \propto c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi \\
\sigma^{DVCS\,pol} \propto s_1^{DVCS} \sin \phi \\
\text{Re } I \propto c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi \\
\text{Im } I \propto s_1^I \sin \phi + s_2^I \sin 2\phi 
\]

\[ 
\phi\text{ Dep. of BH+DVCS with Unpol Target} \\
\]

\[ 
4(\mathcal{H}\mathcal{H}^* + \mathcal{H}\mathcal{H}^*) + \frac{t}{M^2} \mathcal{E}\mathcal{E}^* \rightarrow 4 \left( \text{Im } \mathcal{H} \right)^2
\]
Experimental angular distributions

\[ \mathcal{W}^U + L (\Phi, \phi, \cos \Theta) = \mathcal{W}^U (\Phi, \phi, \cos \Theta) + P_\theta \mathcal{W}^L (\Phi, \phi, \cos \Theta) \]

Self analysis... with phi and cosTheta

15 'unpolarized' and 8 'polarized' SDMEs

\[
\mathcal{W}^U (\Phi, \phi, \cos \Theta) = \frac{3}{8\pi^2} \left[ \frac{1}{2} (1 + r_{00}^{04}) + \frac{1}{2} (3r_{00}^{04} + 1) \cos^2 \Theta - \sqrt{2} \text{Re} \{ r_{10}^{04} \} \sin 2\Theta \cos \phi - r_{1-1}^{04} \sin^2 \Theta \cos 2\phi \right. \\
\left. - \varepsilon \cos 2\Phi \left( r_{11}^{1} \sin^2 \Theta - r_{00}^{1} \cos^2 \Theta - \sqrt{2} \text{Re} \{ r_{10}^{1} \} \sin 2\Theta \cos \phi - r_{1-1}^{1} \sin^2 \Theta \cos 2\phi \right) \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \cos \Phi \left( r_{11}^{5} \sin^2 \Theta + r_{00}^{5} \cos^2 \Theta - \sqrt{2} \text{Re} \{ r_{10}^{5} \} \sin 2\Theta \cos \phi - r_{1-1}^{5} \sin^2 \Theta \cos 2\phi \right) \right]

\[
\mathcal{W}^L (\Phi, \phi, \cos \Theta) = \frac{3}{8\pi^2} \left[ \frac{1}{2} (1 - r_{00}^{04}) + \frac{1}{2} (3r_{00}^{04} - 1) \cos^2 \Theta - \sqrt{2} \text{Re} \{ r_{10}^{04} \} \sin 2\Theta \cos \phi + r_{1-1}^{04} \sin^2 \Theta \cos 2\phi \right. \\
\left. + \sqrt{2\varepsilon(1+\varepsilon)} \cos \Phi \left( r_{11}^{1} \sin^2 \Theta + r_{00}^{1} \cos^2 \Theta - \sqrt{2} \text{Re} \{ r_{10}^{1} \} \sin 2\Theta \cos \phi + r_{1-1}^{1} \sin^2 \Theta \cos 2\phi \right) \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin \Phi \left( \sqrt{2} \text{Im} \{ r_{10}^{1} \} \sin 2\Theta \sin \phi + \text{Im} \{ r_{1-1}^{1} \} \sin^2 \Theta \sin 2\phi \right) \right]
\]
COMPASS Acceptance of $\phi$ for DVCS

\[ \frac{d^3\sigma_{TP}^{\mu P}}{dQ^2 dv dt} = \int_{-\pi}^{\pi} d\phi \left( d\sigma - d\sigma^{BH} \right) \propto c_0^{DVCS} \]

Flux of transverse virtual photons

\[ \frac{d\sigma^{*P}}{dt} = \frac{1}{\Gamma(Q^2, \nu, E_\mu)} \frac{d^3\sigma_{TP}^{\mu P}}{dQ^2 dv dt} \]

Acceptance

- $\mu^-$ beam
- $\mu^+$ beam

$|t| (GeV/c)^2$

$Q^2 (GeV/c)^2$
Results of 2012 Data

- **Global Fit – MSW (grey band):** fit of CFF in the PARTON framework at LO and LT, using a GPD parametrization that only involves valence and sea quarks.
- **VGG Model:** with valence and sea quarks only.
- **GK Model:** includes also gluons.

Nice manifestation of gluons or NLO effect
Dominance of $\text{Im} H$ (with respect of $\text{Re} H$ and other CFF) at small $x_B$