GPD Program at COMPASS

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for the COMPASS Collaboration

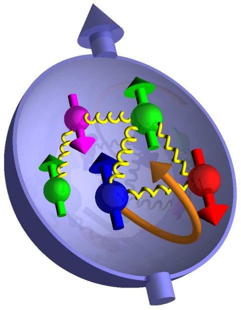
IPN Orsay - 29/5/2017

COMPASS

DE LA RECHERCHE À L'INDUSTRIE
cea

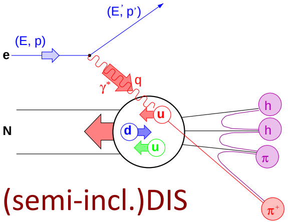
Irfu

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



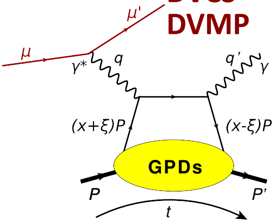
How the proton spin is decomposed in terms of parton's spins ($\Delta\Sigma$, ΔG) and orbital angular momentum (L_q, L_g) is still one of the big open questions in hadronic physics…

COMPASS experimental tools:

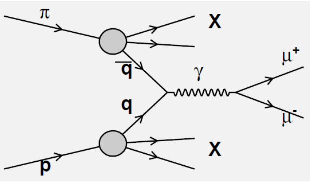


(semi-incl.)DIS

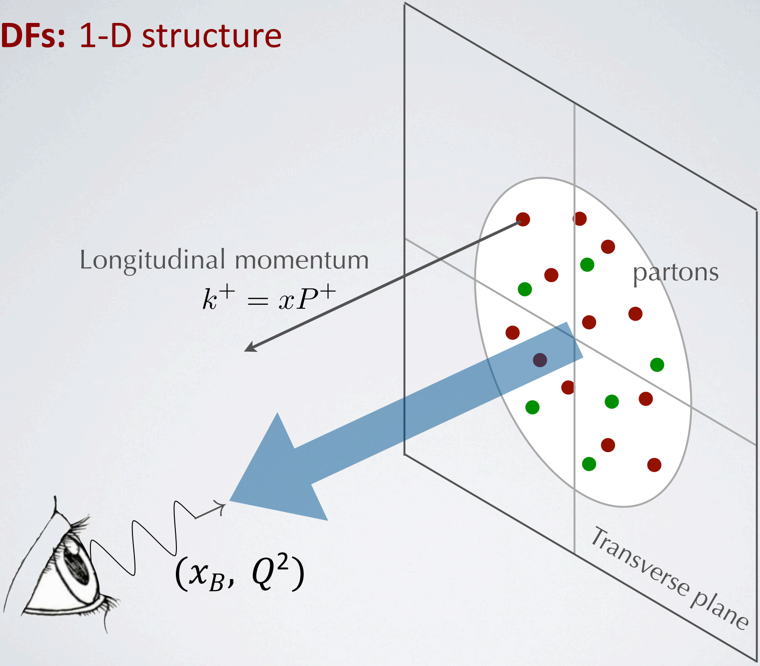
DVCS
DVMP



Drell-Yan process



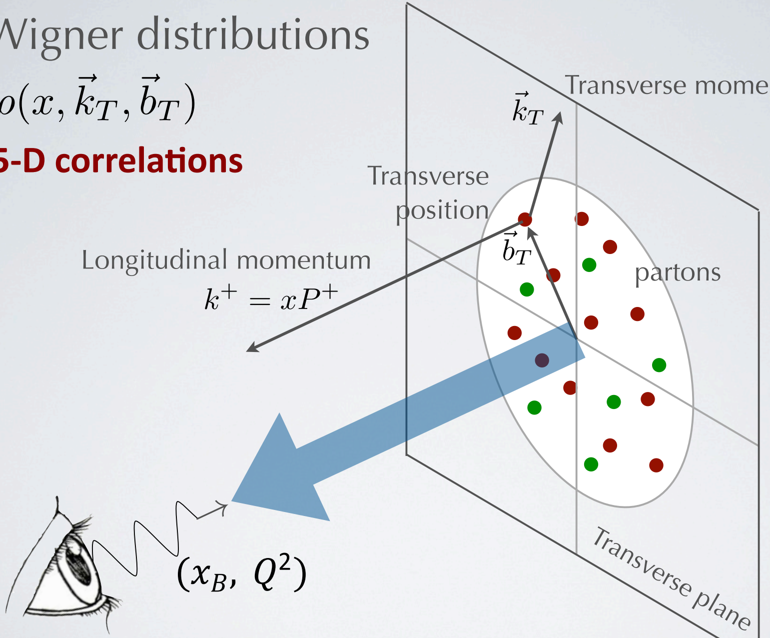
PDFs: 1-D structure



Wigner distributions

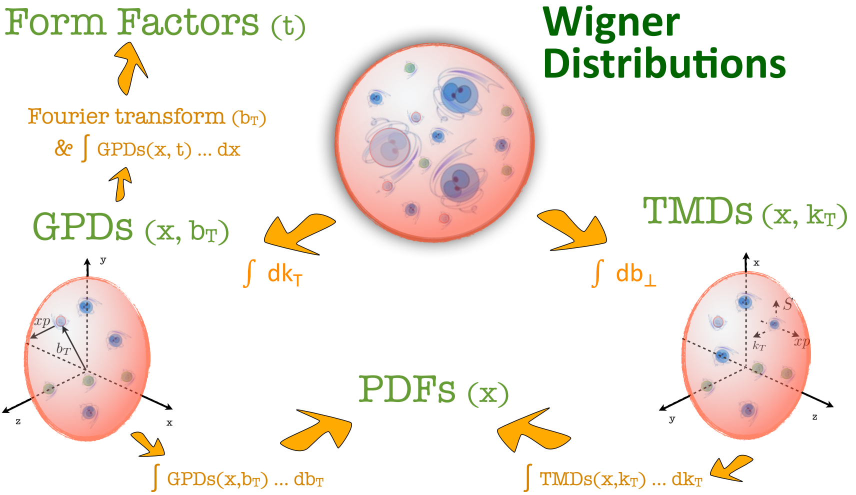
$\rho(x, \vec{k}_T, \vec{b}_T)$

5-D correlations



see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

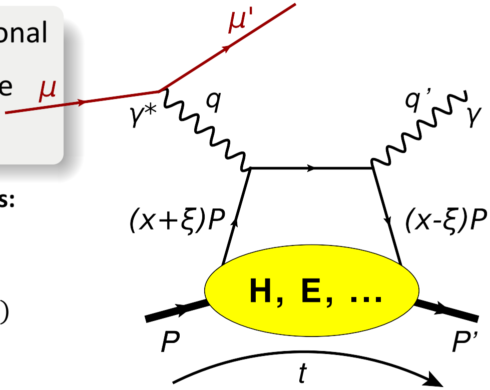
Towards a 3D Picture of the Nucleon...



PDFs $\rightarrow \Delta\Sigma, \Delta G$

TMDs, GPDs $\rightarrow \begin{cases} \text{nucleon"tomography"} \\ L_{q,g} \end{cases}$

GPDs: correlation between fractional long. momentum x and transverse position $b_\perp$ of partons



GPDs depend on the following variables:

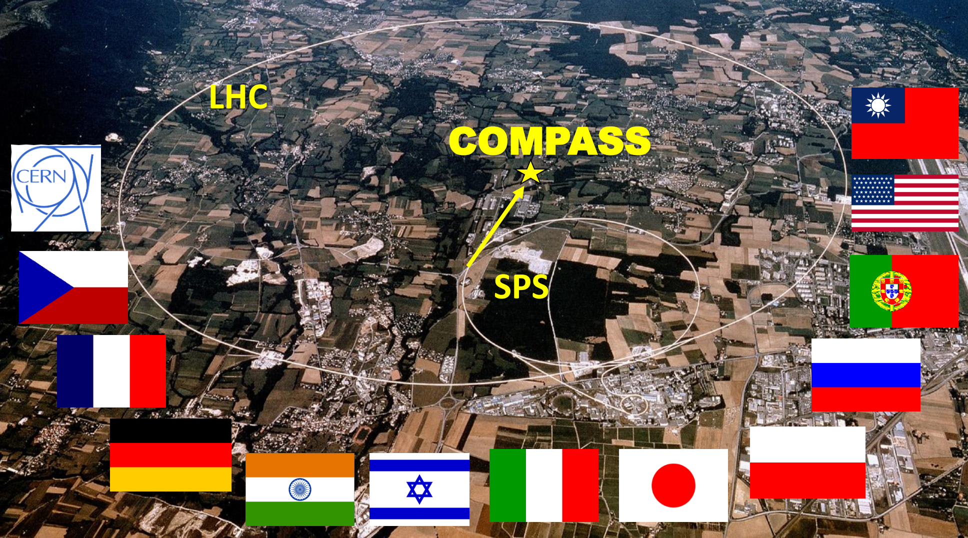
- $\mathbf{x}$: average long. momentum (NOT MEASURABLE)
- ξ: long. mom. difference $\simeq x_B/(2 - x_B)$
- $\mathbf{t}$: four-momentum transfer related to $b_\perp$ via Fourier transform

DVCS ($\mathbf{l\ p \rightarrow l'\ \gamma\ p'}$): "golden" channel for GPD studies

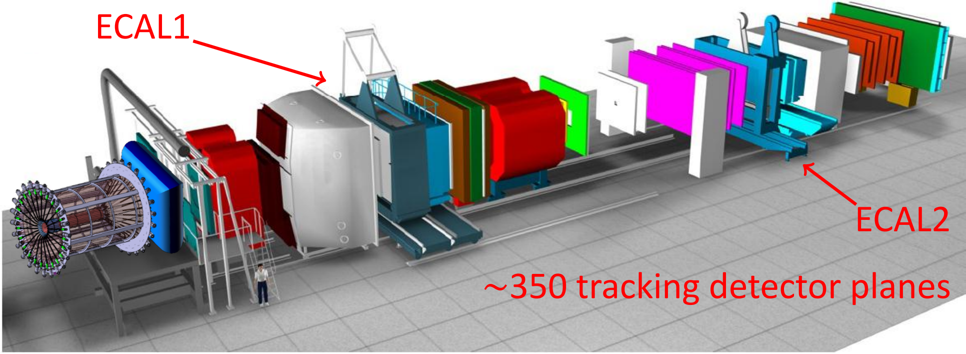
GPDs enter in the DVCS amplitude through Compton Form Factors (CFF):

$$\mathcal{H}(\xi,t) = \int_{-1}^{1} dx \frac{H^q(x,\xi,t)}{x-\xi+i\epsilon} = \mathcal{P}\int_{-1}^{1} dx \frac{H(x,\xi,t)}{x-\xi} + i\pi H(x=\pm\xi,\xi,t)$$

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…



The COMPASS set-up for the GPD programme

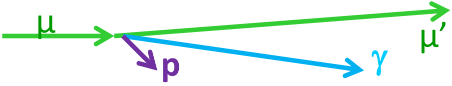


Two stage magnetic spectrometer for **large angular & momentum acceptance**

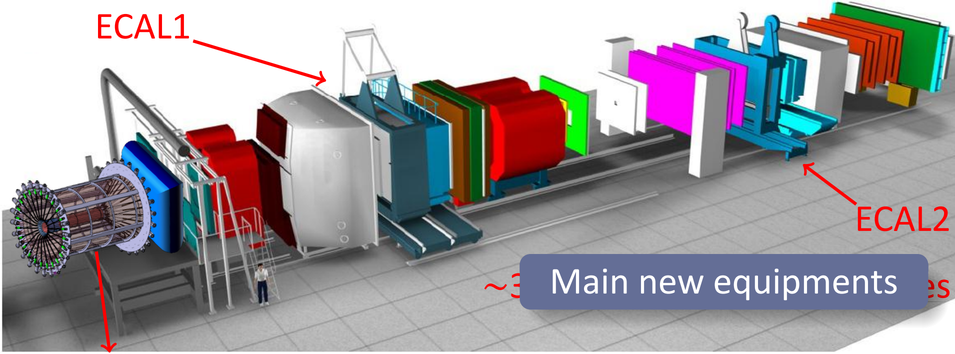
Particle identification with:

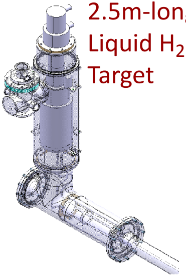
- Ring Imaging Cerenkov Detector
- Electromagnetic calorimeters (**ECAL0**, **ECAL1** & **ECAL2**)
- Hadronic calorimeters
- Muon absorbers

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



The COMPASS set-up for the GPD programme





2.5m-long
Liquid H_2
Target

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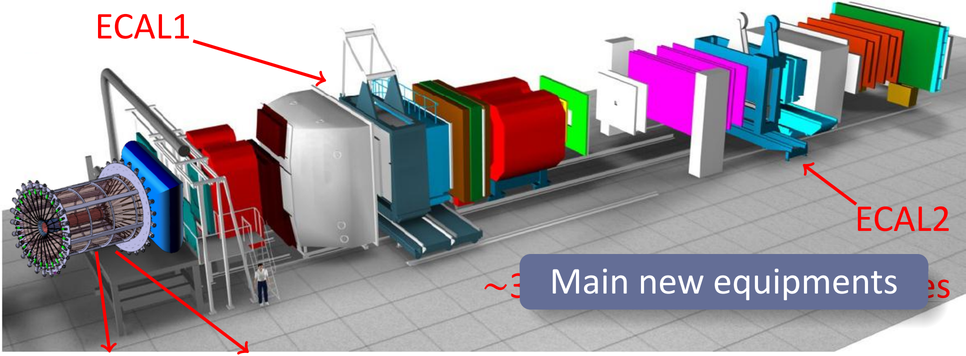
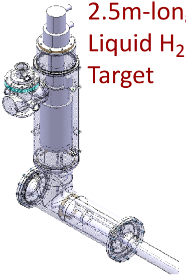
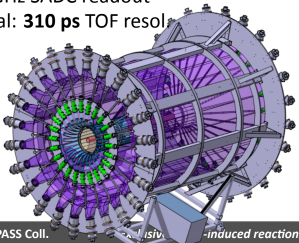




2.5m-long
Liquid H_2
Target

Target TOF System
24 inner & outer scintillators
1 GHz SADC readout
goal: **310 ps** TOF resol.



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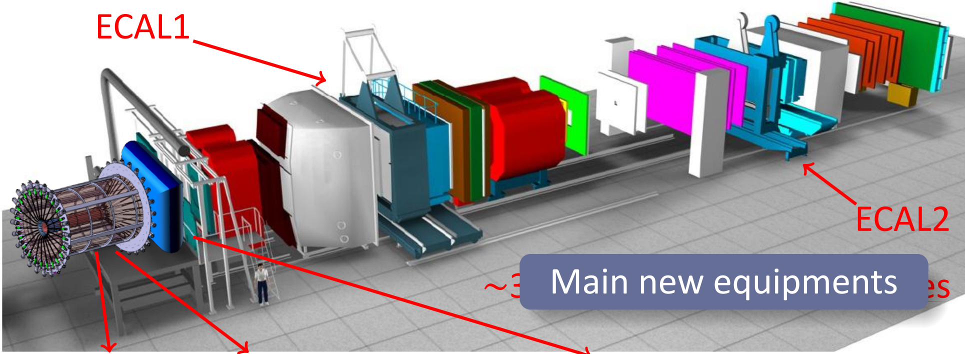

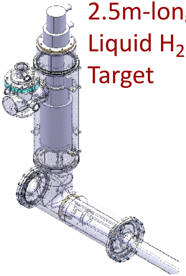

2.5m-long Liquid H_2 Target

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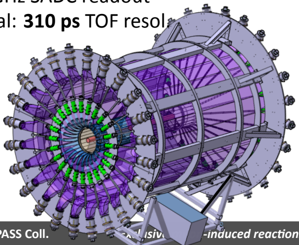
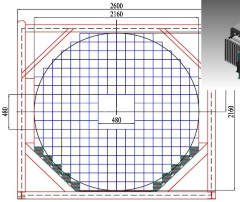
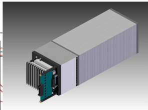


ECAL0 Calorimeter

Shashlyk modules + MAPD readout
$\sim 2 \times 2$ m^2, ~2200 ch.





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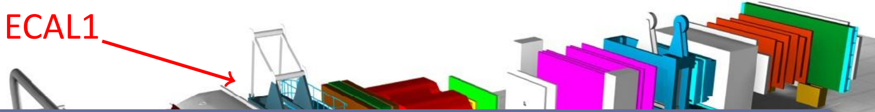
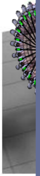
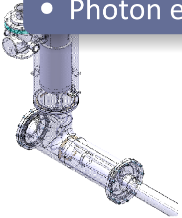
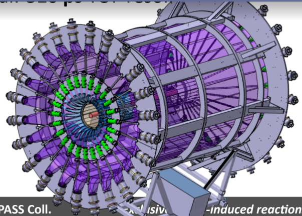


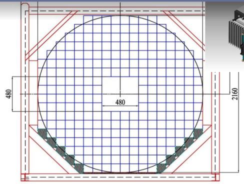
Key features of COMPASS:

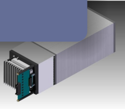
- Muon beams with opposite **charge** and **polarization**
  - $E_\mu = 160$ GeV
  - $\sim 4 \cdot 10^8$ μ/spill, 9.6s/40s duty cycle
- Reconstruction of the full event kinematics
- Recoil proton momentum from target TOF detector
- Photon energy and angle from ECALs



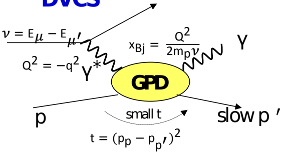




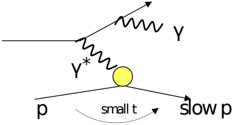


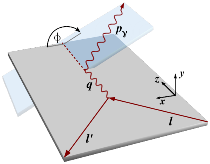


DVCS



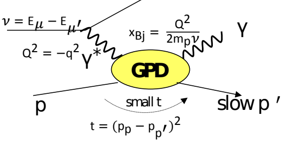
Bethe-Heitler





$$d\sigma \propto \underbrace{|T_{DVCS}|^2}_{\text{bilinear combination of GPDs}} + \underbrace{|T_{BH}|^2}_{\text{known to 1 \%}} + \underbrace{\text{interference term}}_{\text{linear combination of GPDs}}$$

DVCS



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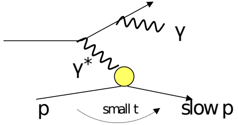

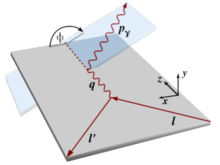

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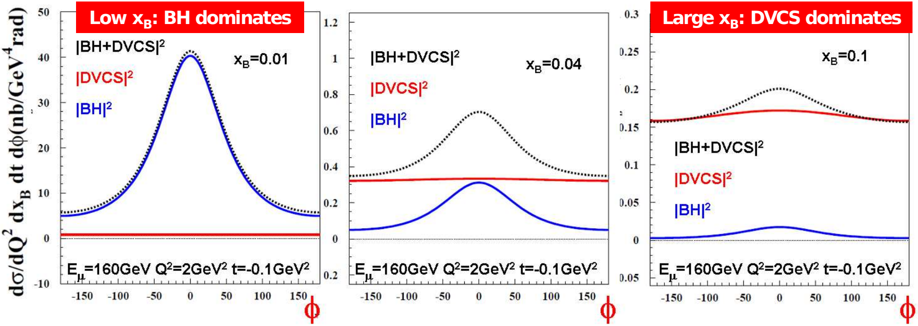


reference yield of almost pure Bethe-Heitler	Study DVCS with: $\mathrm{Re}(T^{DVCS})$ & $\mathrm{Im}(T^{DVCS})$ via $(d\sigma^{+\leftarrow} \pm d\sigma^{-\rightarrow})$	Transverse Imaging: $d\sigma^{DVCS}/d\|t\|$ via $(d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$

Transverse Nucleon Imaging at COMPASS

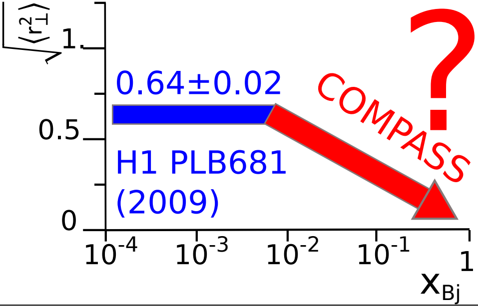
Beam Charge and Spin **SUM**:

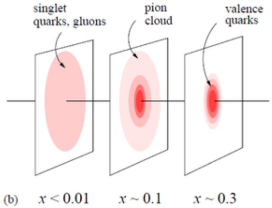
$$\mathbf{S_{CS,U} \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + Ks^{Int}_{1} \sin\phi}$$

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

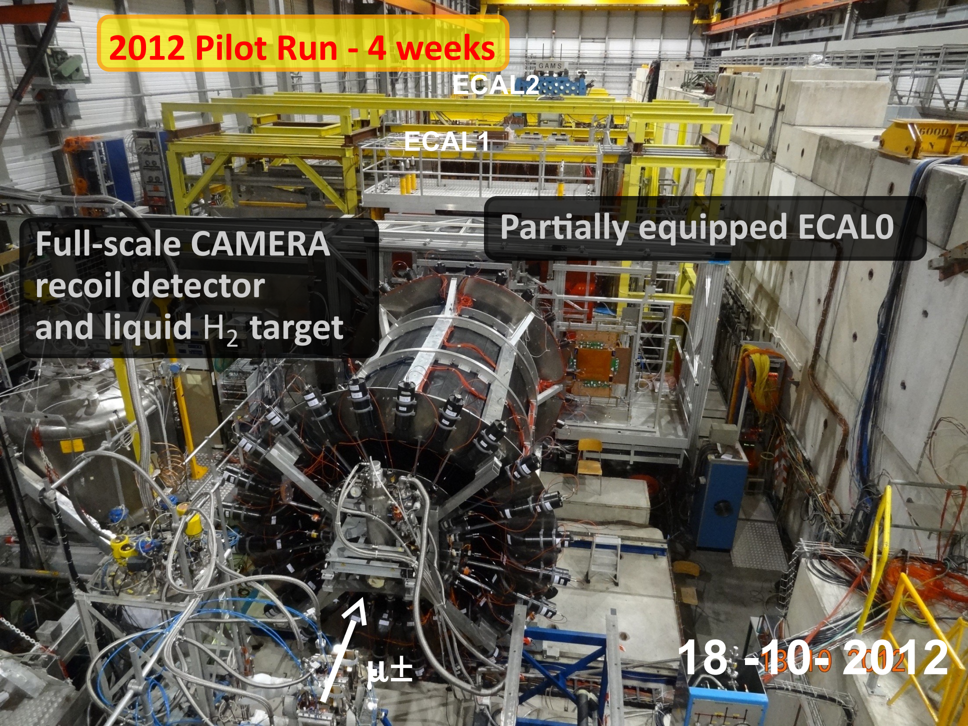
$$< b_{\perp}^{2}(x_B) > \approx 2\mathbf{B(x_B)}$$

$b_{\perp}$ → distance between struck parton and baricenter of momentum





Ansatz at small $\mathbf{x_B}$:
$\mathbf{B(x_B) \simeq B_0 + 2\alpha' \ln(x_0/x_B)}$
(inspired by Regge phenomenology)


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

Exclusive Photon Events Selection

Reconstructed interaction vertex in **target volume**

One single photon above DVCS production threshold

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

$0.08\ (\mathrm{GeV}/c)^2 < t < 0.64\ (\mathrm{GeV}/c)^2$

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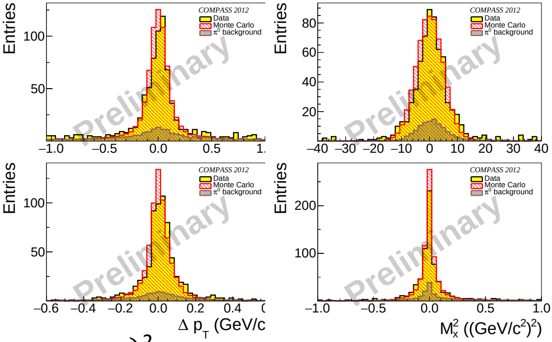
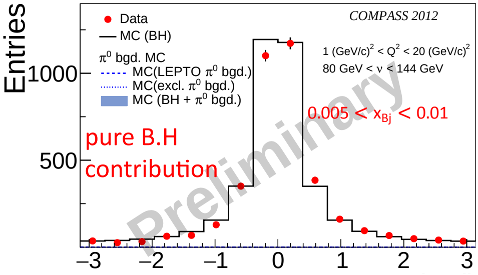
Exclusivity conditions:

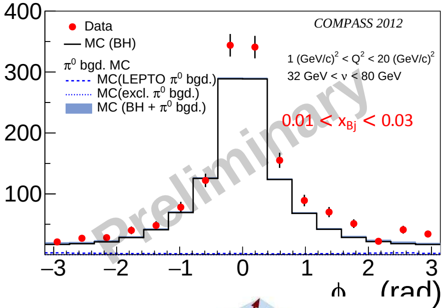
- $\Delta\varphi = \varphi^{\mathrm{proton}}_{\mathrm{meas}} - \varphi^{\mathrm{proton}}_{\mathrm{reco}}$
- Vertex pointing (ΔZ_A)
- Transv. mom. balance: $\Delta p_T = p^{\mathrm{proton}}_{T,\mathrm{meas}} - p^{\mathrm{proton}}_{T,\mathrm{reco}}$
- Four-momentum balance: $M_x^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\gamma})^2$

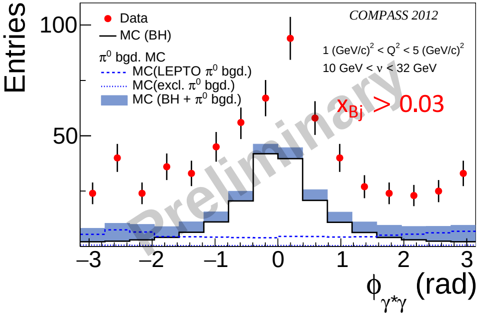


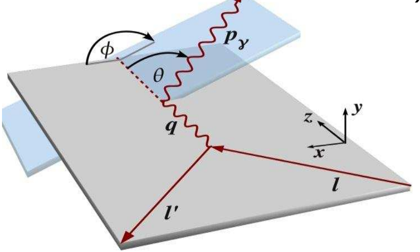
Exclusive γ Azimuthal Distributions for DVCS

Kinematically constrained vertex fit applied









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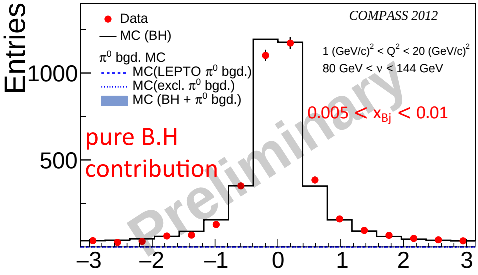
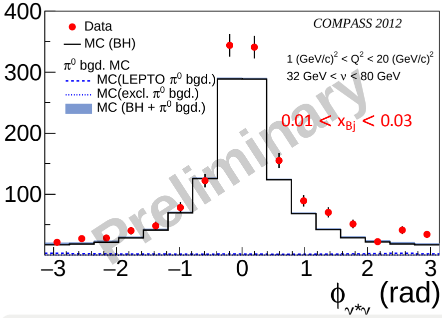
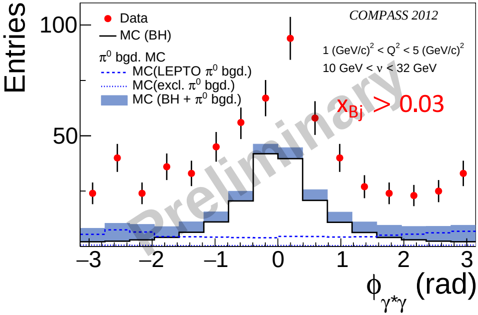






- BH Monte Carlo normalization based on integrated luminosity
- BH process dominant at small x_{Bj}
- π^0 background contributing at large x_{Bj}
- **clear excess of DVCS at large x_{Bj}**

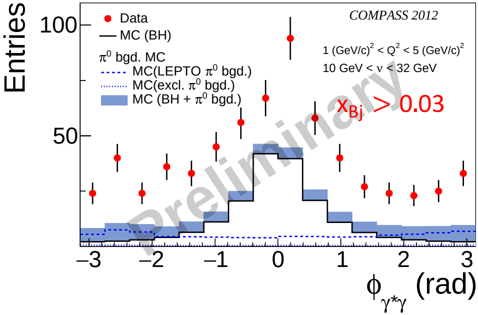
Exclusive γ Azimuthal Distributions for DVCS

Kinematically constrained vertex fit applied

t-dependence of DVCS cross-section for $x_{Bj} > 0.03$:

- Subract BH contribution
- Subtract π^0 background
- Experimental acceptance correction & luminosuty normalization

$\Rightarrow$ **DVCS cross-section in 4 bins of $|t|$**



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π^0 Background Estimation

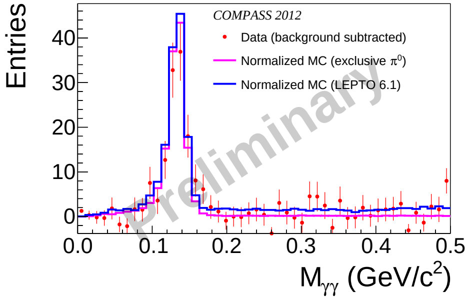
π^0s are one of the main **background sources** for excl. photon events

Two possible cases:

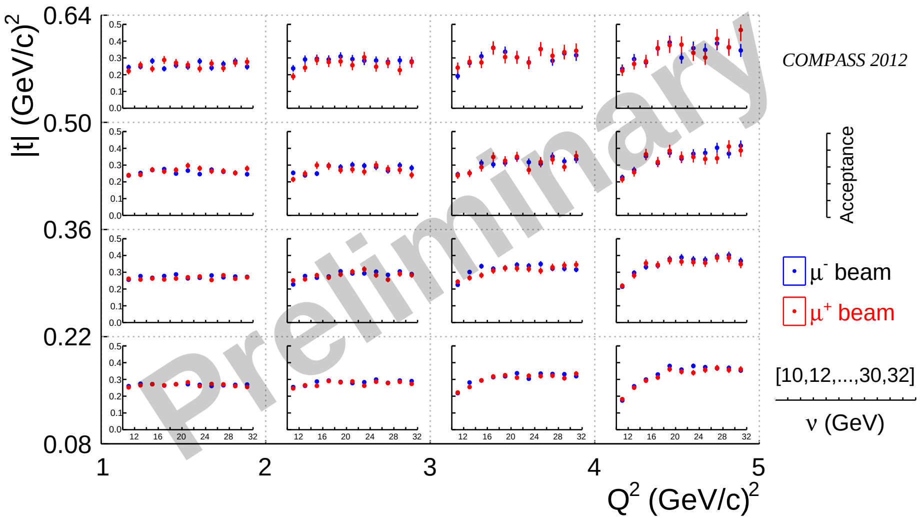
- **visible** (both γ detected, **subtracted**)
- **invisible** (one γ "lost", **estimated with MC**)
  - **Semi-inclusive** → LEPTO
  - **Exclusive** → HEPGEN/π^0 (Goloskokov-Kroll model)

MC samples normalized to $M_{\gamma\gamma}$ peak in real data

$M_{\gamma\gamma}$ distribution ("visible" π^0)

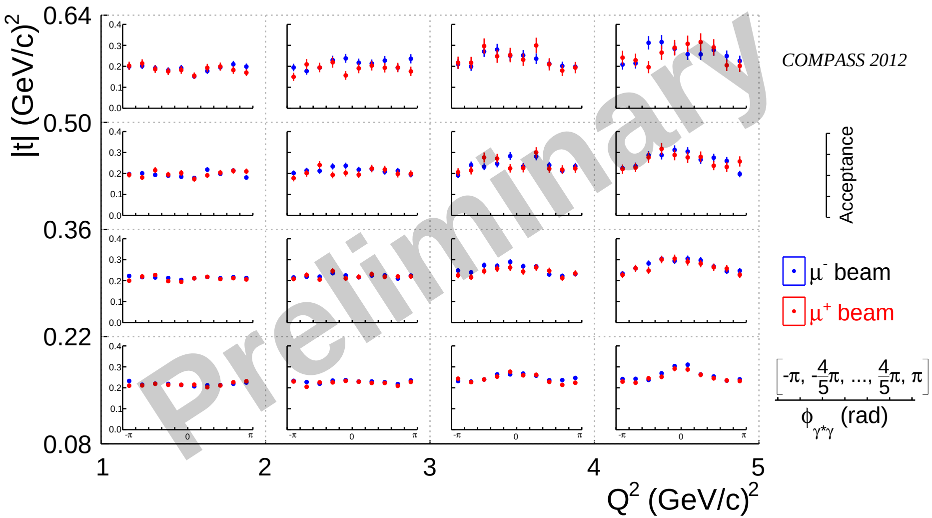


Experimental acceptance for DVCS events



Acceptance binning in Q^2, ν and $|t|$

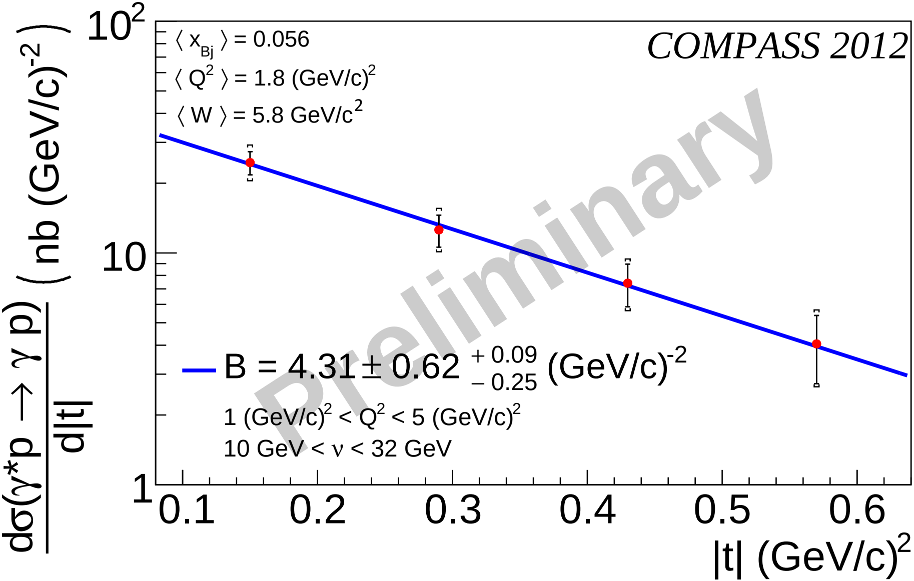
Experimental acceptance for DVCS events



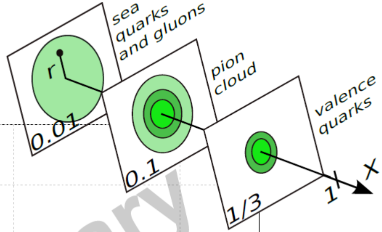
Symmetric acceptance around $\phi = 0$

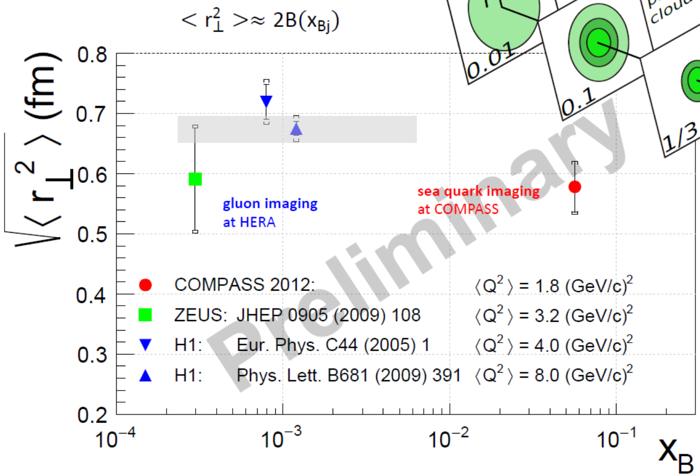
DVCS x-section and t-slope extraction

Kinematically constrained vertex fit applied



Comparison with HERA results



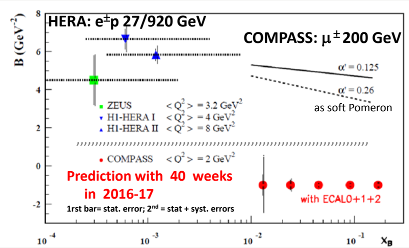


$\sqrt{< r_\perp^2 >}$ to be compared to $\sqrt{4\frac{d}{dt}F_1^p}\Big|_{t=0} = 0.66 \pm 0.01$ fm $\neq \sqrt{4\frac{d}{dt}G_E^p + \sqrt{\kappa / m_p^2}}\Big|_{t=0} = 0.72 \pm 0.01$ fm

$r_p = 0.88$ fm

COMPASS OUTLOOK:

- Dedicated beam time for GPD studies in 2016-17
- x_{Bj}-dependence of t-slope parameter in sea-quarks domain



- Real and imaginary parts of CFF $\mathcal{H}$ from interference term
- Complementary measurements with exclusive mesons:

$$\pi^0, \rho^0, \phi, \omega ...$$

What kind of "proton transverse size" are we measuring?

$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$

$B(x_B) = ½ < r_\perp^2(x_B) >$

distance between the active quark
and the center of momentum of spectators

Transverse size of the nucleon

mainly dominated by $H(x=\xi, \xi, t)$

$A^{DVCS \text{ linked to ImH}} \sim \exp(-B'|t|)$

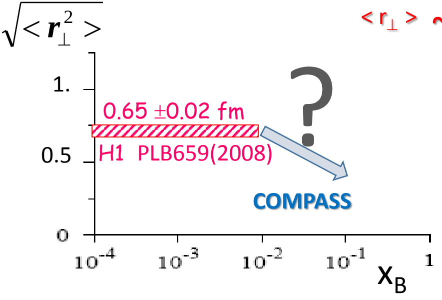
$B'(x_B) = 1/4 < b_\perp^2(x_B) >$

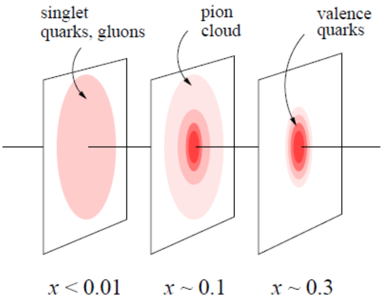
distance between the active quark
and the center of momentum of the nucleon

Impact Parameter Representation

$q(x, b_\perp) <-> H(x, \xi=0, t)$

$< r_\perp > \sim <b_\perp>/ (1-x)$





Note 0.65 fm $= \sqrt{2/3} \times 0.8$ fm

Constraining the GPD H @ COMPASS

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

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

Charge & Spin Difference and Sum:

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

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

$$c_1^{Int} \propto \mathcal{Re}\left(F_1\, \mathcal{H} + \xi(F_1 + F_2)\, \tilde{\mathcal{H}} - t/4m^2\, F_2\, \mathcal{E}\right)$$

NOTE:
- ✓ dominance of $\mathcal{H}$ with a proton target at COMPASS kinematics
- ✓ only leading twist and LO

Constraining the GPD H @ COMPASS

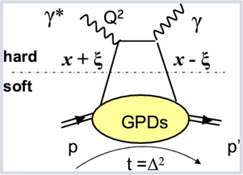
cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

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

Charge & Spin Difference and Sum:

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

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



$\xi \sim x_B / (2-x_B)$

$$\mathcal{I}m \, \mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$$

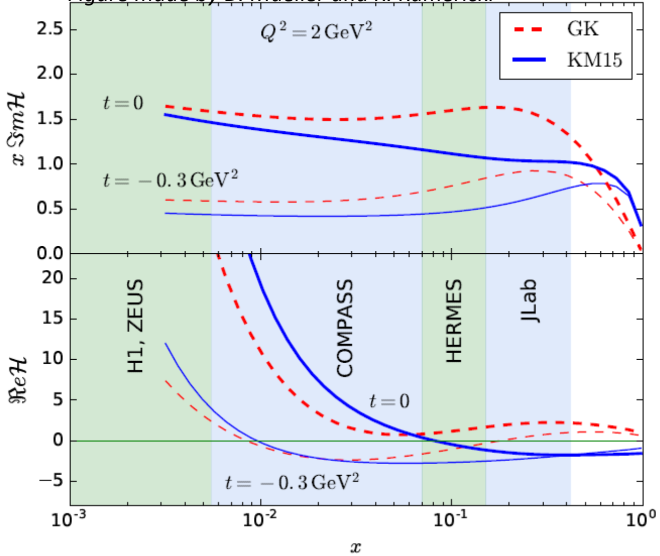
$$\mathcal{R}e \, \mathcal{H}(\xi,t) = \mathcal{P}\int dx \, \frac{H(x,\xi,t)}{x-\xi} = \mathcal{P}\int dx \, \frac{H(x,x,t)}{x-\xi} + \mathcal{D}(t)$$

$\mathcal{R}e$ part of the *Compton Form Factors* linked to the $\mathcal{D}$ *term*

Energy-Momentum Tensor : Polyakov, PLB 555 (2003) 57-62

$\mathrm{Re}\mathcal{H}$ and $\mathrm{Im}\mathcal{H}$ from Recent Models

Figure made by D. Mueller and K. Kumericki



***Im* $\mathcal{H}$**
Is it rather well known ?

Re* $\mathcal{H}$** linked to the ***D term is still poorly constrained

KM15 K Kumericki and D Mueller arXiv:1512.09014v1

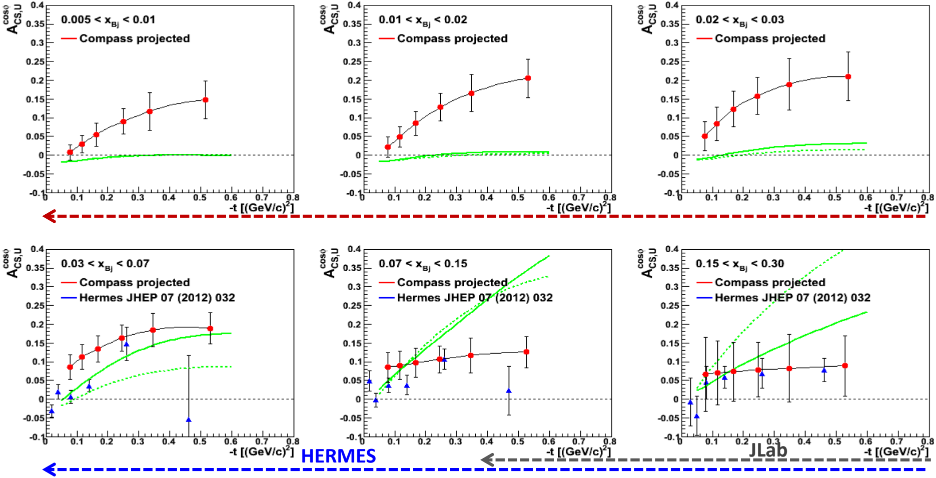
GK S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011)

Beam Charge & Spin Difference

$c_1^I = Re\, F_1 \mathcal{H}$

Predictions with
VGG and D.Mueller KM10

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



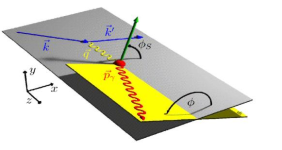
COMPASS 2 years of data $E\mu$= 160 GeV 1 < Q^2 < 8 GeV^2

Deeply Virtual Meson Production @ COMPASS

This talk: ρ^0 and ω

M. Gorzellik this afternoon: π^0

Exclusive ρ^0 production



$$\left[\frac{\alpha_{em}}{8\pi^3}\frac{y^2}{1-\varepsilon}\frac{1-x_B}{x_B}\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_{Bj}\,dQ^2\,dt\,d\phi\,d\phi_s}$$

$$= \frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\sigma_{00}^{++}-\varepsilon\cos(2\phi)\,\mathrm{Re}\,\sigma_{+-}^{++}-\sqrt{\varepsilon(1+\varepsilon)}\cos\phi\,\mathrm{Re}\left(\sigma_{+0}^{++}+\sigma_{+0}^{--}\right)$$

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

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

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

transsv. polar. target

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

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

transv. polar. target + long. polar. beam

σ^{ij}_{mn}: ij for nucleon helicity, mn for photon helicity

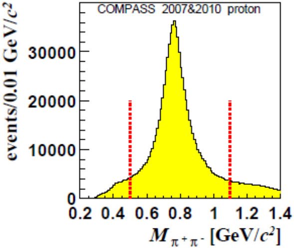
Dominant interference terms:

LL $\gamma^*_L \to \rho^0_L$

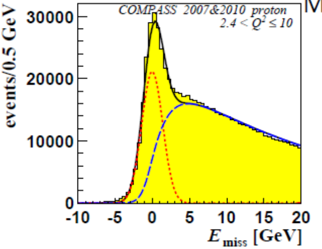
then LT $\gamma^*_T \to \rho^0_L$

Selection of $\mu\, p \rightarrow \mu'\, V\, p_{undet.}$ Events

V= $\rho^0 \rightarrow \pi^+\pi^-$



$E_{miss}=(M^2_X-M_p^2)\,/2M_p$



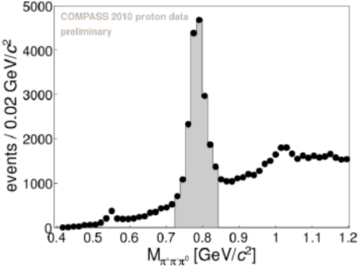
$$M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_V)^2$$

$-2.5 < E_{miss} < 2.5$ GeV

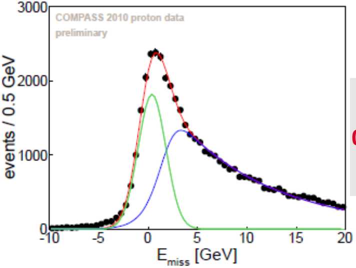
$0.1 < p_T^2 < 0.5$ GeV²

Background ~22%

V= $\omega \rightarrow \pi^+\pi^-\pi^0$ BR=89%



$E_{miss}=(M^2_X-M_p^2)\,/2M_p$



$-3 < E_{miss} < 3$ GeV

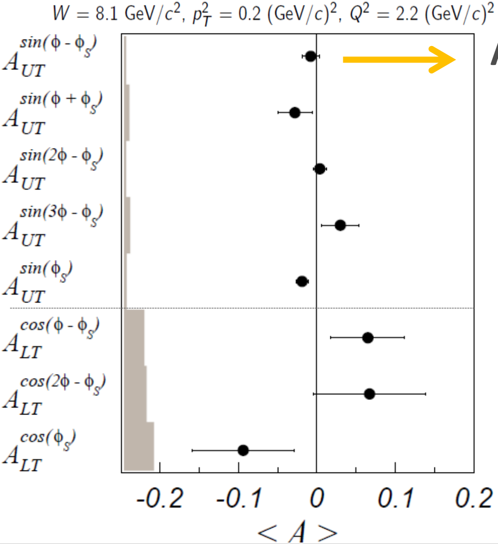
$0.05 < p_T^2 < 0.5$ GeV²

Background ~34%

Excl. ρ^0 Production with Transv. Pol. Target

$\mu\ p \rightarrow \mu' + \rho^0 + p_{\text{non detected}}$
$\hookrightarrow \pi^+\pi^-$

COMPASS 2007-2010,without recoil detector



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

$E\rho^0 \propto 2/3\ E^u + 1/3\ E^d + 3/8\ E^g$

- ✓ Cancellation between gluon and sea contributions
- ✓ $E^{u\ val} \sim -E^{d\ val}$

COMPASS, NPB 865 (2012) 1-20

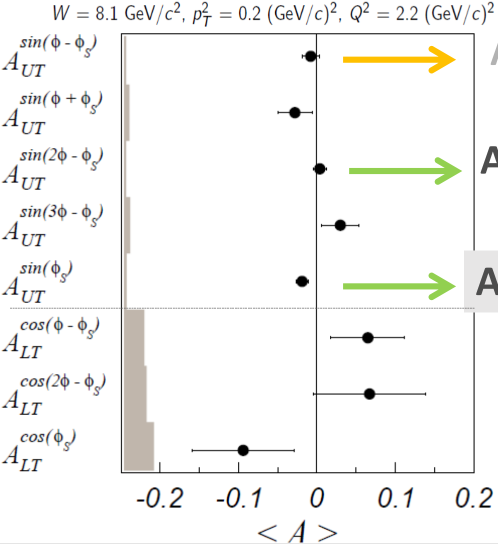
ω production should be powerful

$E\omega \propto 2/3\ E^u - 1/3\ E^d + 3/8\ E^g$

Excl. ρ^0 Production with Transv. Pol. Target

$\mu\ p \rightarrow \mu' + \rho^0 + p_{\text{non detected}}$, $\rho^0 \hookrightarrow \pi^+\pi^-$

COMPASS 2007-2010,without recoil detector



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

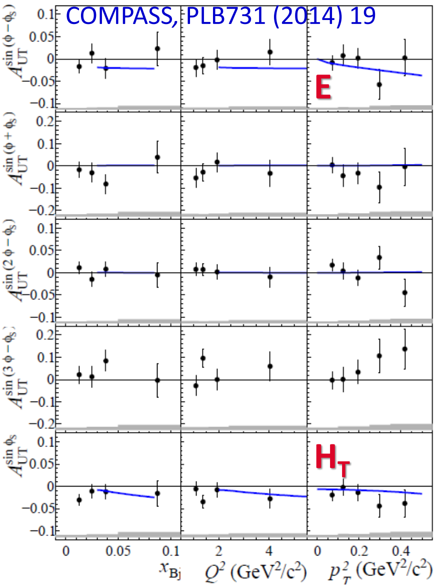
$A_{UT}^{\sin(2\phi-\phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T)$

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

→ H_T **should not be small**

COMPASS, PLB731 (2014) 19

Excl. ρ^0 Production with Transv. Pol. Target



$\langle x_{Bj} \rangle \approx 0.039$, $\langle Q^2 \rangle \approx 2.0$ GeV^2, $\langle p_T^2 \rangle \approx 0.18$ GeV^2

$\mu\ p \rightarrow \mu' + \rho^0 + p_{\text{non detected}}$, $\rho^0 \hookrightarrow \pi^+\pi^-$

Comparison with a phenomeno-logical GPD-based model

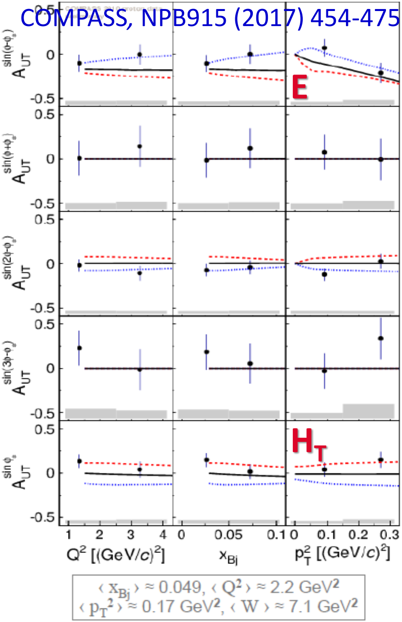
Goloskokov and Kroll (EPJ C74 (2014))

- Phenomenological 'handbag' approach
- Includes twist-3 ρ^0 meson wave functions
- Includes contributions from γ_L^* and γ_T^*

Large contribution of the GPDs E and H_T

Excl. ω Production with Transv. Pol. Target

COMPASS, NPB915 (2017) 454-475

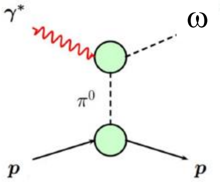


$\mu \; p \rightarrow \mu' + \omega + p_{\text{non détecté}}$

$\hookrightarrow \pi^+\pi^-\pi^0$

GK model predictions (EPJ A50 (2014)) including all the GPDs and transverse GPDs

+ the pion pole exchange which is large for ω production



- positive $\pi\omega$ form factor
- no pion pole
- negative $\pi\omega$ form factor

no unambigous determination of the sign

Backup Slides

Proton « radius » measured at JLab

Fit of 8 CFFs at L.O and L.T.

Dupré, Guidal, Vanderhaeghen, PRD95, 011501(R)(2017)

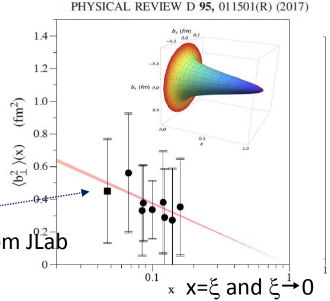
$s_1^I = Im\ F_1 \mathcal{H}$

- □ CLAS σ and Δσ
- ▲ HallA σ and Δσ
- ● CLAS A_{UL} and A_{LL}

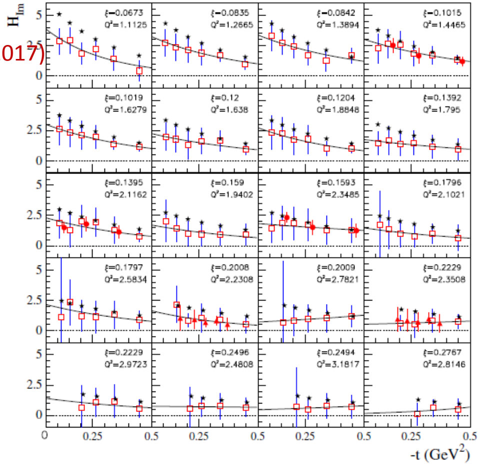
★ VGG model

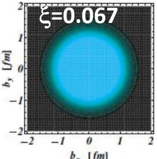
— Fit $A\, e^{-B'|t|}$

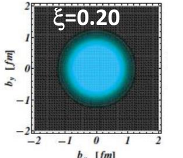
$< b_\perp^2 > \approx 4 B'$



x=ξ and ξ→0

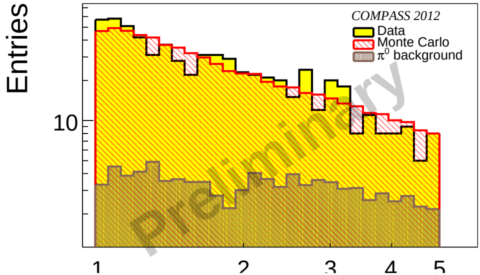


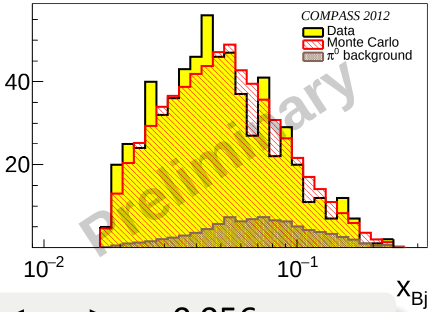


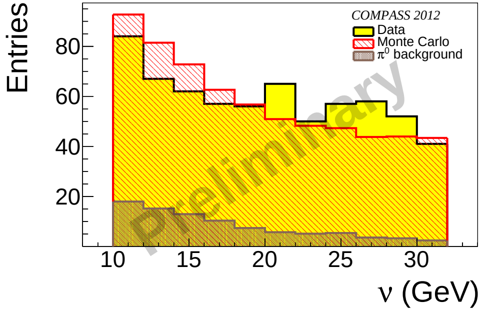


Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013)

Kinematic Distributions for DVCS







$< x_{Bj} > = 0.056$

$< Q^2_{Bj} > = 1.8\ (GeV/c)^2$

$< W > = 5.8\ GeV/c^2$

The GPD Physics Programme at COMPASS

2008: Very short test run, short LH_2 target

- Observation of exclusive photon production
- Confirmed the global efficiency $\simeq$ 10% used for projections

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

- Coarse binning in x_B
- First hint of DVCS at large x_B

2003-10: Exclusive ρ^0 and ω^0 meson production on a **transv. pol. target** and **no recoil detector**

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

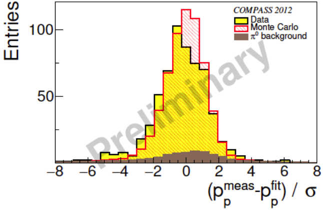
2016-7: **2 x 6 months** with LH_2 target and recoil det. → **GPD H**

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

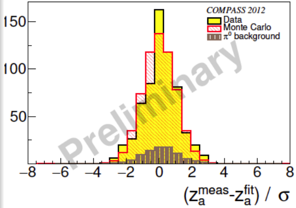
Kinematically constrained fit

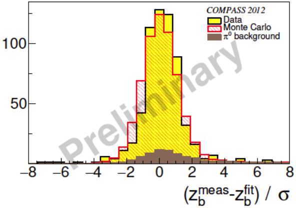
- constrained χ^2 minimisation with NDF=9
- full 4-momentum conservation of the reaction $\mu p \to \mu p \gamma$
- vertex constraints for μ, μ' and p' included in the fit

$\Rightarrow$ most accurate determination of t

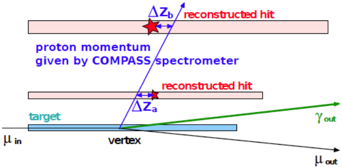


recoil proton momentum



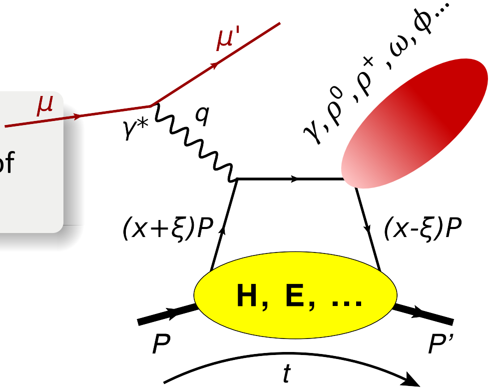


recoil proton direction



Introduction to GPDs

"GPDs are **non-perturbative** objects entering the description of **hard exclusive** leptoproduction"

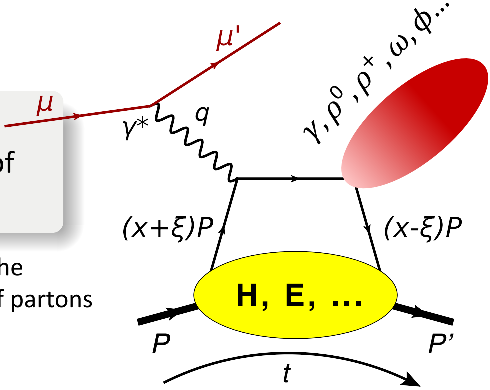


Definition of variables:

- q: exchanged photon four-momentum
- x: average long. momentum - NOT ACCESSIBLE
- ξ: long. mom. difference $\simeq x_B/(2 - x_B)$
- t: four-momentum transfer

Introduction to GPDs

"GPDs are **non-perturbative** objects entering the description of **hard exclusive** leptoproduction"



They encode **CORRELATIONS** between the long. mom. **x** and the transv. position of partons

Definition of variables:

- q: exchanged photon four-momentum
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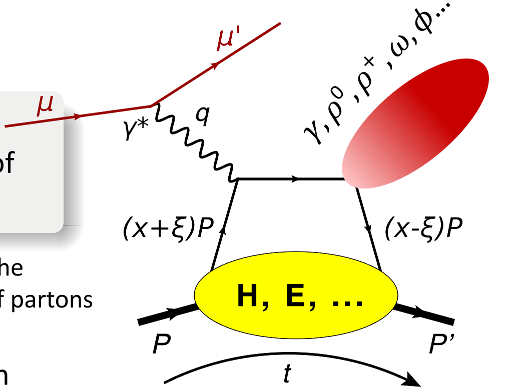
Introduction to GPDs

"GPDs are **non-perturbative** objects entering the description of **hard exclusive** leptoproduction"

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



Experimentally accessible through Compton Form Factors (CFFs):

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

$$\mathrm{Re}\mathcal{H}(\xi, t) = \mathcal{P}\int \frac{dx\, H(x, x = \xi, t)}{(x - \xi)} + \mathcal{D}(t)$$

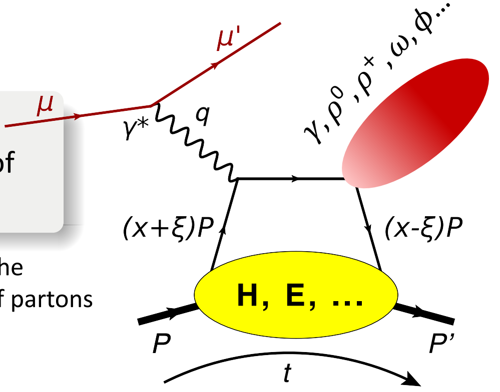
Definition of variables:

- q: exchanged photon four-momentum
- x: average long. momentum - NOT ACCESSIBLE
- ξ: long. mom. difference $\simeq x_B/(2 - x_B)$
- t: four-momentum transfer

$\mathcal{D}(t)$ connected to **energy-momentum tensor** (Polyakov, PLB 555 (2003) 57-62)

Introduction to GPDs

"GPDs are **non-perturbative** objects entering the description of **hard exclusive** leptoproduction"



They encode **CORRELATIONS** between the long. mom. **x** and the transv. position of partons

They allow to perform so-called **"nucleon tomography"**:

$$d\sigma^{DVCS}/d|t| \sim \exp(-B|t|)$$

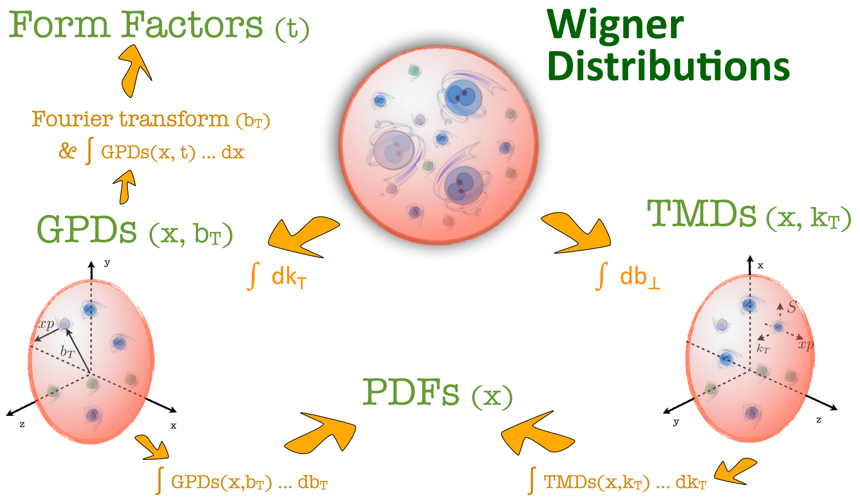
$$< b_\perp^2(x_B) > \approx 2B(x_B)$$

Definition of variables:

- q: exchanged photon four-momentum
- x: average long. momentum - NOT ACCESSIBLE
- ξ: long. mom. difference $\simeq x_B/(2 - x_B)$
- t: four-momentum transfer

$b_\perp$: distance between the struck parton and center of momentum

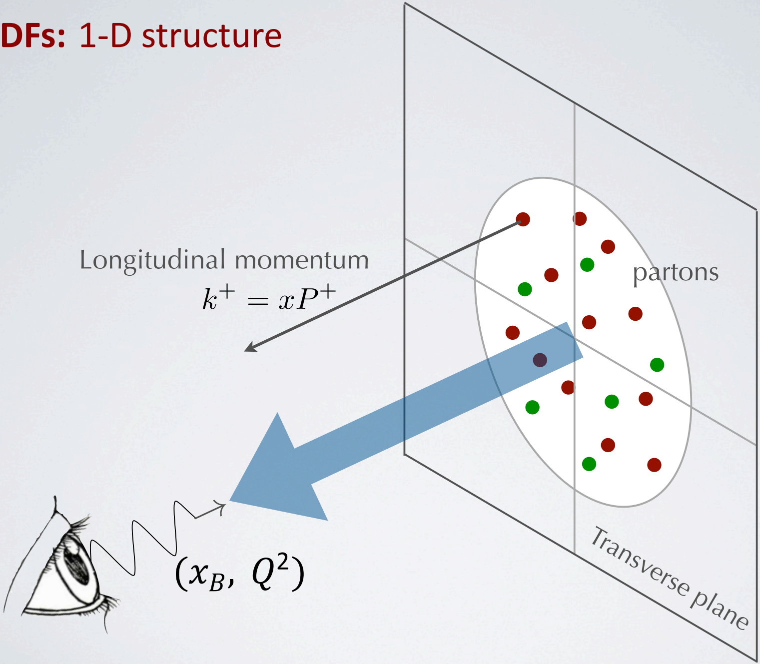
Towards a 3D Picture of the Nucleon…



PDFs → ΔΣ, ΔG

TMDs, GPDs → $\begin{cases} \text{nucleon"tomography"} \\ L_{q,g} \end{cases}$

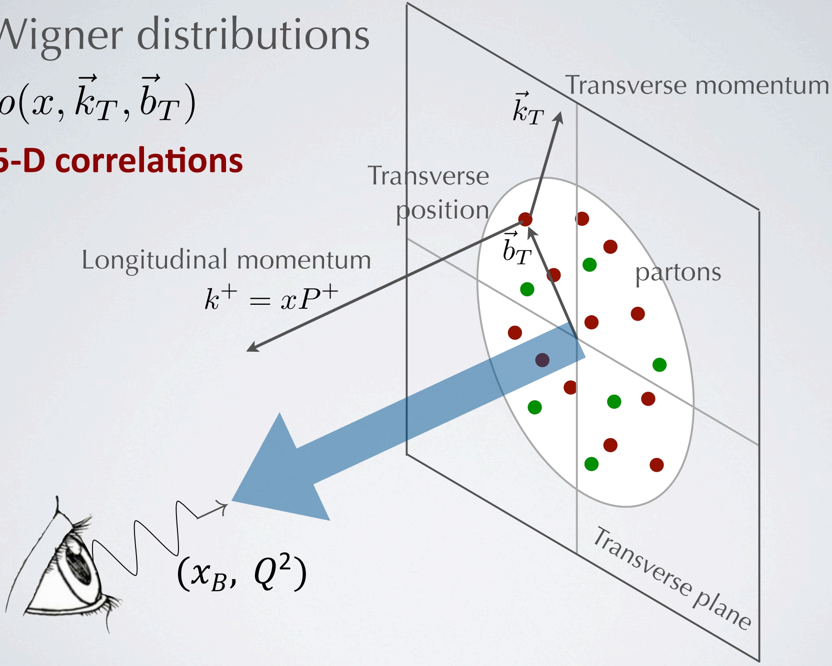
PDFs: 1-D structure



Wigner distributions

$\rho(x, \vec{k}_T, \vec{b}_T)$

5-D correlations



 see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)