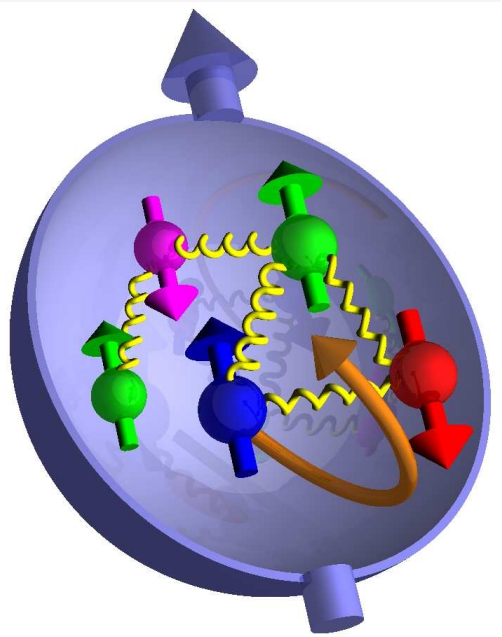
DVCS and Exclusive π^0 Production at COMPASS

A. Ferrero (CEA-Saclay/IRFU/DPhN)

for the COMPASS Collaboration

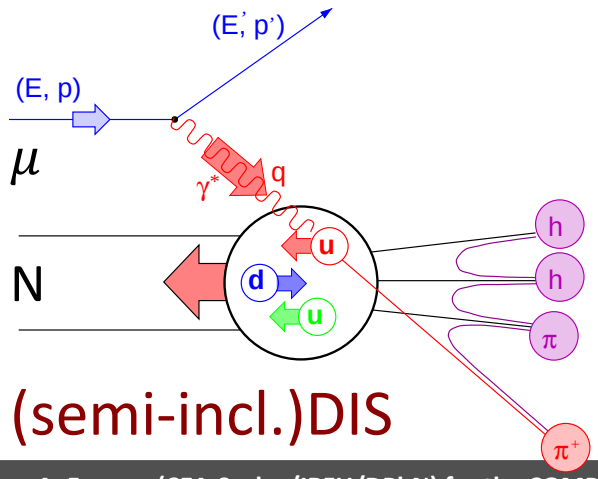
SPIN 2018 - Ferrara, 10-14/09/2018

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



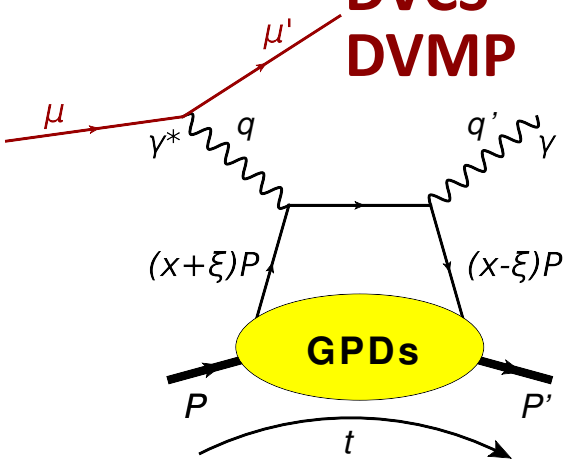
How the proton spin is decomposed in terms of parton's spins ($\Delta\Sigma$, ΔG) and orbital angular momentum (L_q, L_g) is still one of the big open questions in hadronic physics…

COMPASS experimental tools:

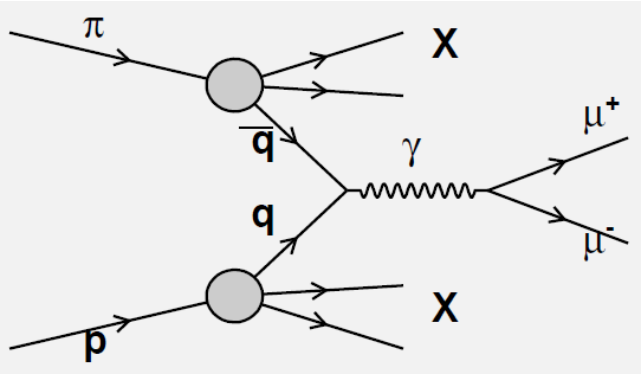


(semi-incl.)DIS

DVCS
DVMP



Drell-Yan process



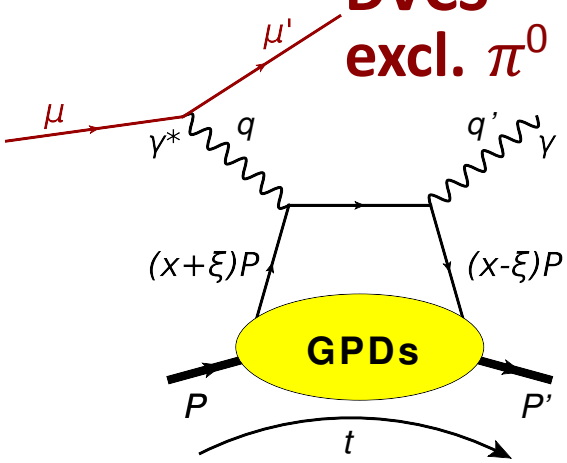
Proton spin sum rule: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$

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…

This talk:

COMPASS experimental tools:

DVCS excl. π^0



Drell-Yan process

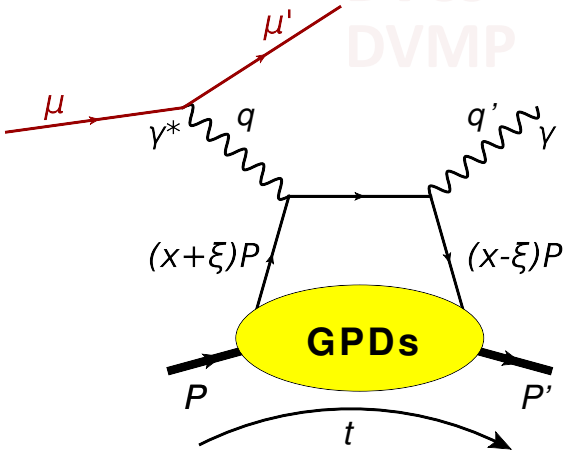
(semi-incl.)DIS

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

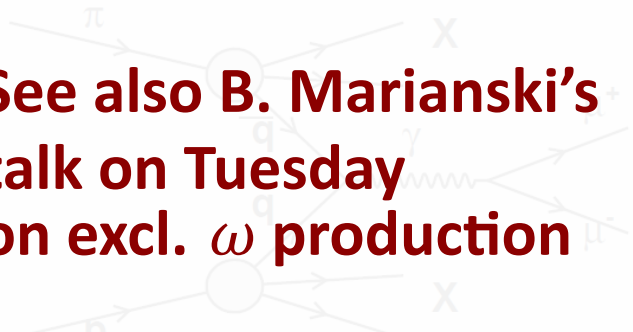
How the proton spin is decomposed in terms of parton's spins ($\Delta\Sigma$, ΔG) and orbital angular momentum (L_q, L_g) is still one of the big open questions in hadronic physics…

COMPASS experimental tools:

DVCS
DVMP



Drell-Yan process



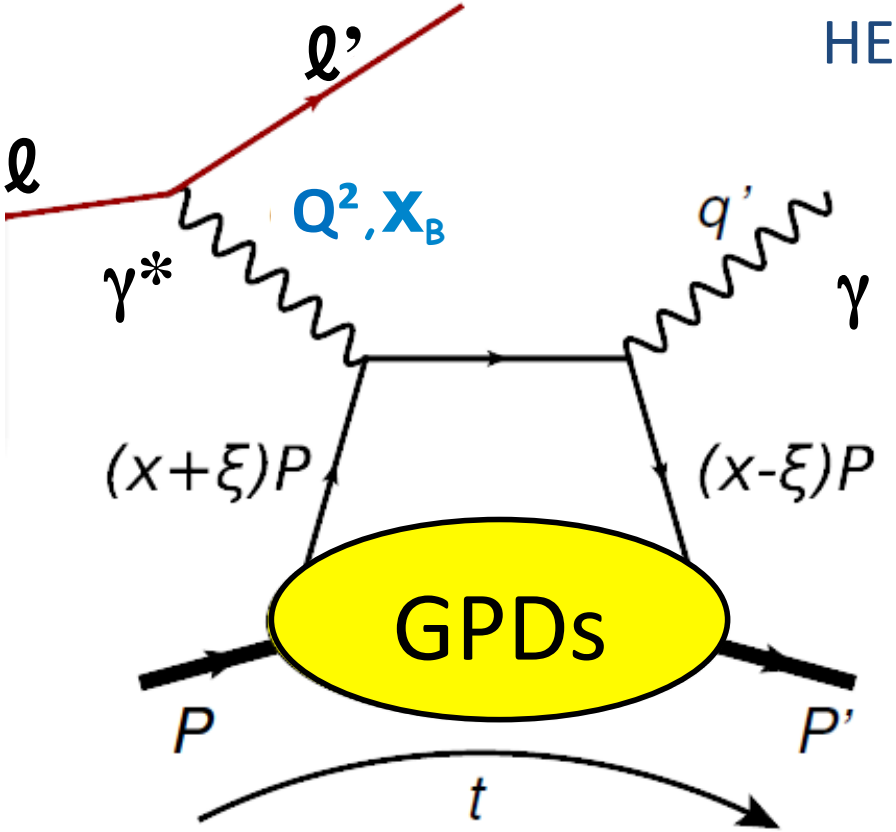
See also B. Marianski's talk on Tuesday on excl. ω production

(semi-incl.)DIS

Exclusive Reactions: DVCS and HEMP

DVCS: $\ell p \rightarrow \ell' p' \gamma$ (« golden » channel)

HEMP: $\ell p \rightarrow \ell' p' \rho$ or ϕ or J/ψ,…



γ or $\rho, \phi, J/\psi$,…

Definition of variables:

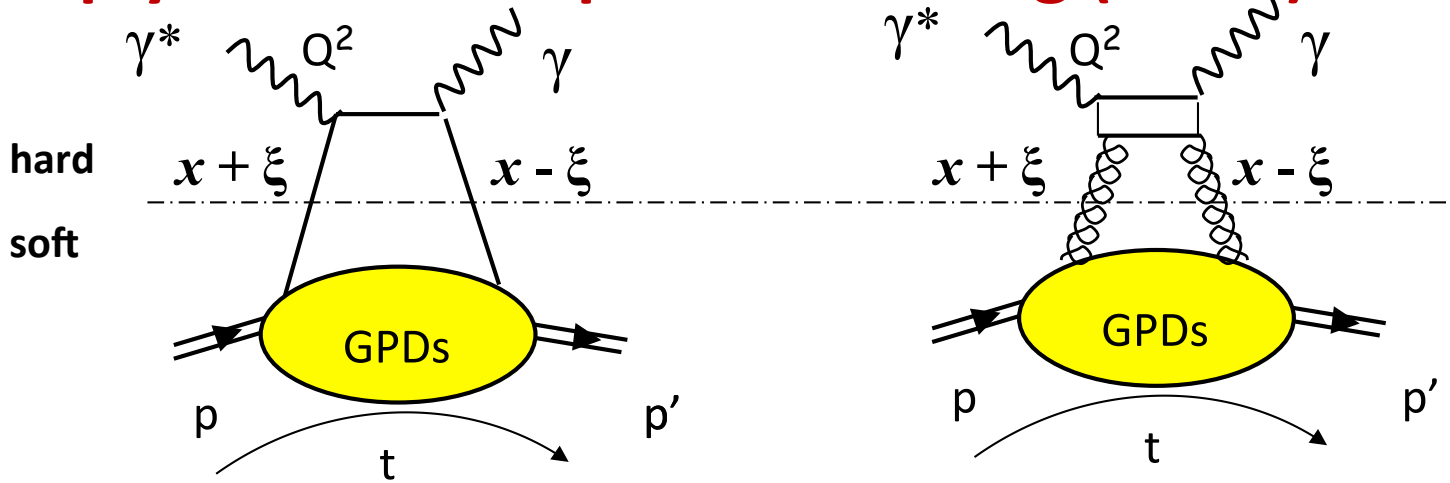
- x: average long. momentum - NOT ACCESSIBLE
- ξ: long. mom. difference $\simeq x_B/(2 - x_B)$
- t: four-momentum transfer related to $b_\perp$ via Fourier transform

D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

Exclusive Reactions: DVCS and HEMP

Deeply Virtual Compton Scattering (DVCS):

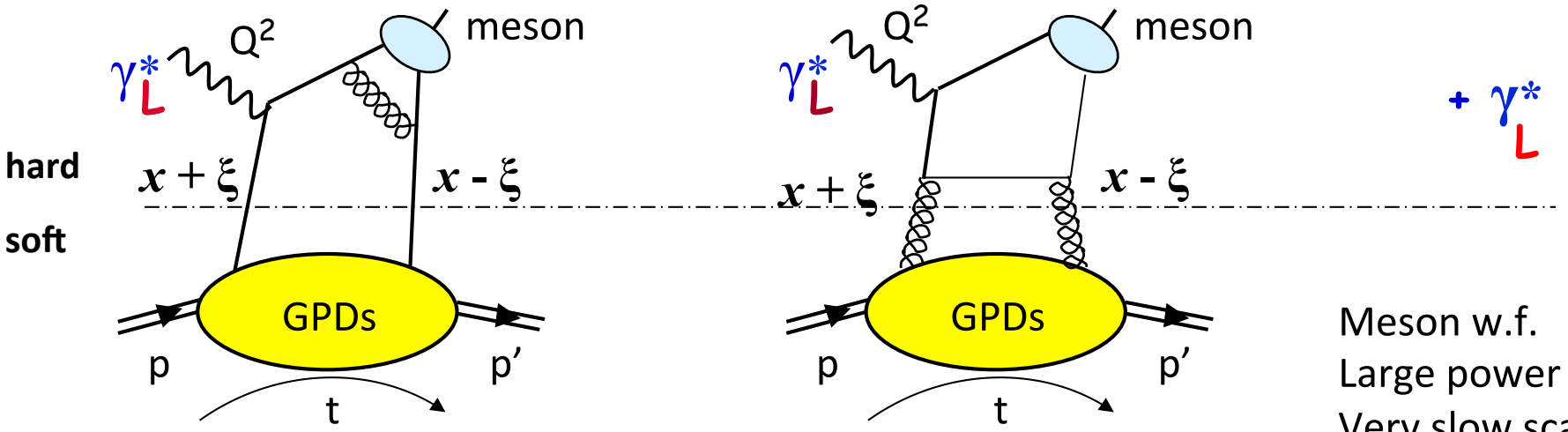
Factorisation:
Collins *et al.*



Q^2 large

$t << Q^2$

Hard Exclusive Meson Production (HEMP):



+ γ^*_L

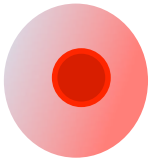
Meson w.f.
Large power & NLO
Very slow scaling

Quark contribution **Gluon contribution**

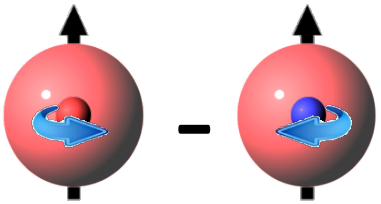
8 GPDs ↔ 8 TMDs

4 Chiral-even

$$H \longleftrightarrow q \text{ or } f_1$$

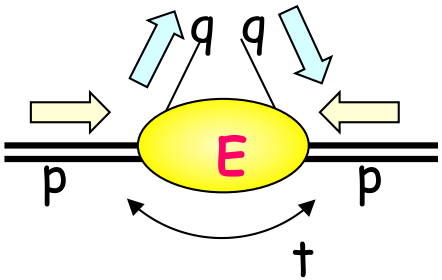


"Elusive" $E \sim f_{1T}^{\perp}$



Sivers: quark k_T & nucleon transv. Spin

Ji: $2J^q = \int x\,(H^q(x,\xi,0) + E^q(x,\xi,0))\,dx$



Relation to OAM

+ their partner for polarised quarks

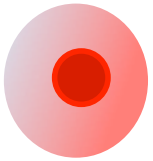
$$\tilde{H} \longleftrightarrow \Delta q \text{ or } g_{1L}$$

$$\tilde{E} \sim g_{1T}$$

8 GPDs ↔ 8 TMDs

2 of the 4 Chiral-even

$$H \longleftrightarrow q \text{ or } f_1$$



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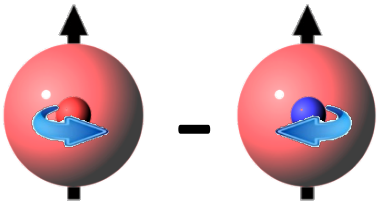
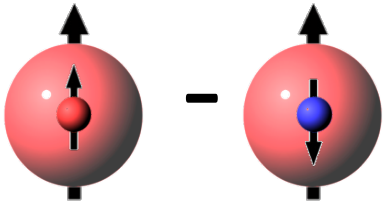


Sivers: quark k_T & nucleon transv. Spin

Ji: $2J^q = \int x \left(H^q(x,\xi,0) + E^q(x,\xi,0)\right) dx$

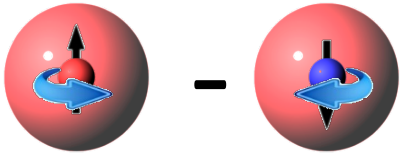
2 of the 4 Chiral-odd

$$H_T \longleftrightarrow h_1$$



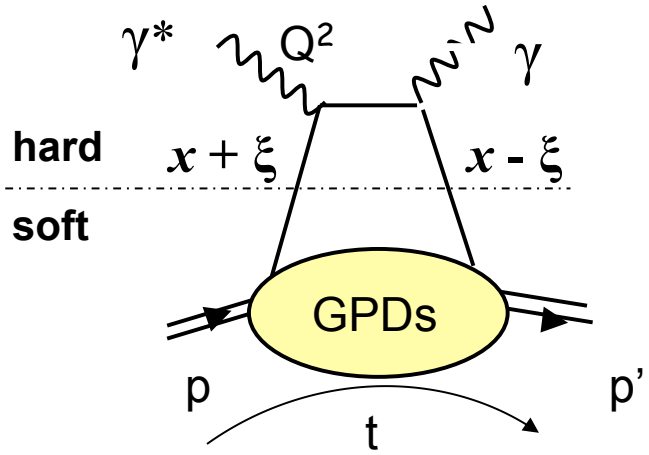
Transversity: quark spin & nucleon transv. spin

$$\bar{E}_T = 2\tilde{H}_T + E_T \sim h_1^{\perp}$$



Boer-Mulders: quark k_T & quark transverse spin

From DVCS to Compton Form Factors

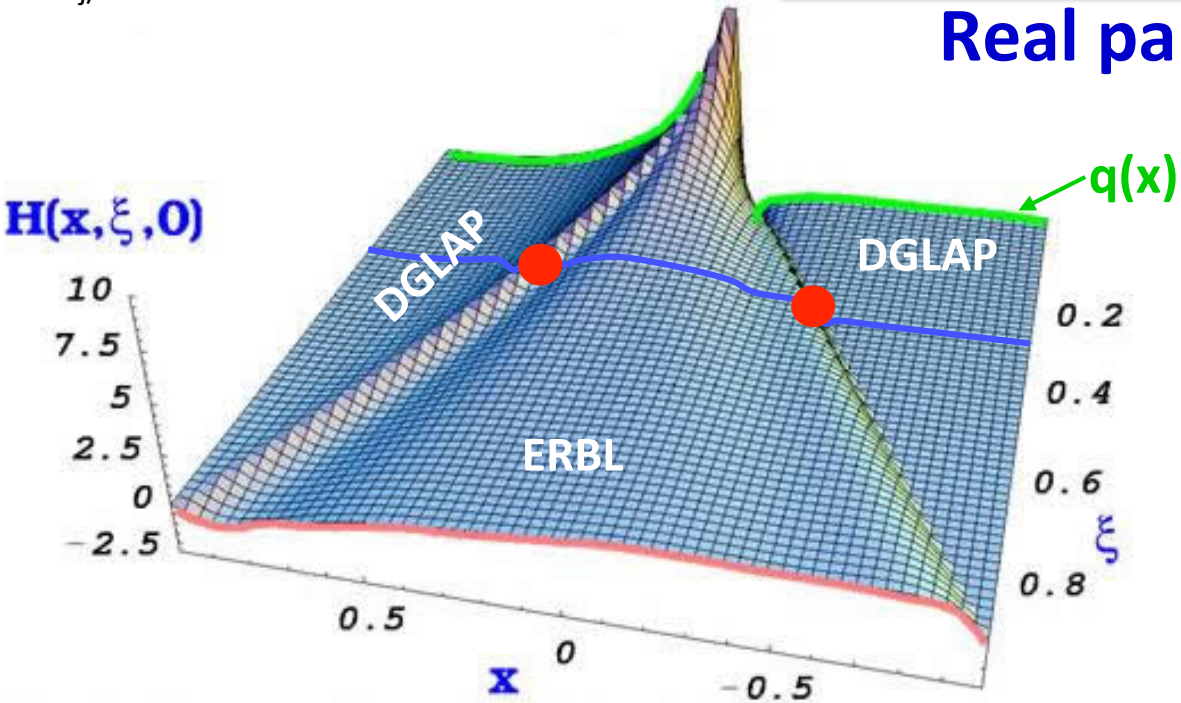


The DVCS amplitude at LT & LO in α_S:

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

t, $\xi \sim x_{Bj/2}$ fixed

Real part **Imaginary part**

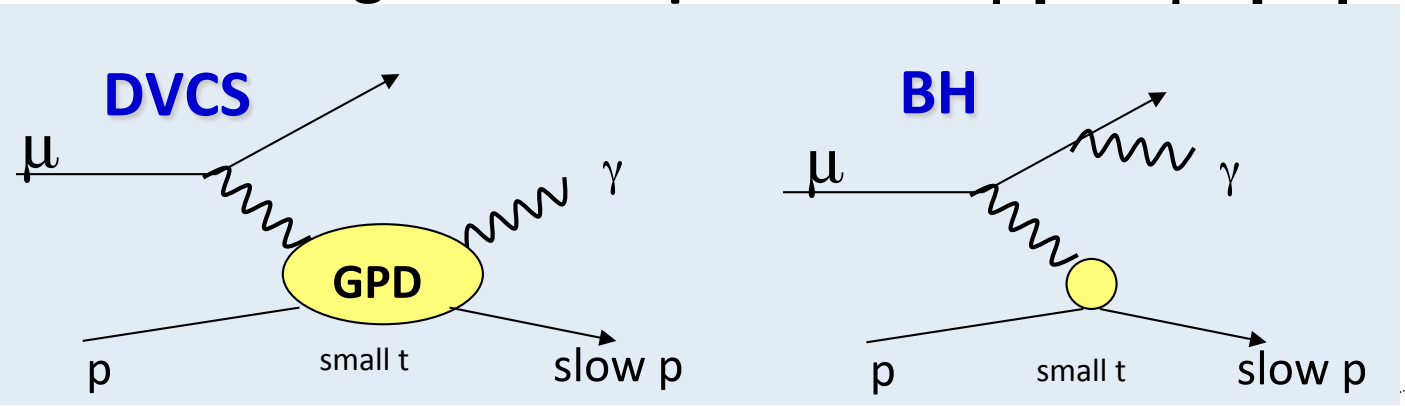


Im part measured in
Beam Spin
or **Target Spin** asymmetries

Real part measured in
Beam Charge asymmetry
or **cross section**

DVCS (Golden Channel) → CFF → GPD H (E)

Exclusive Single Photon production $\mu p \rightarrow \mu' p' \gamma$

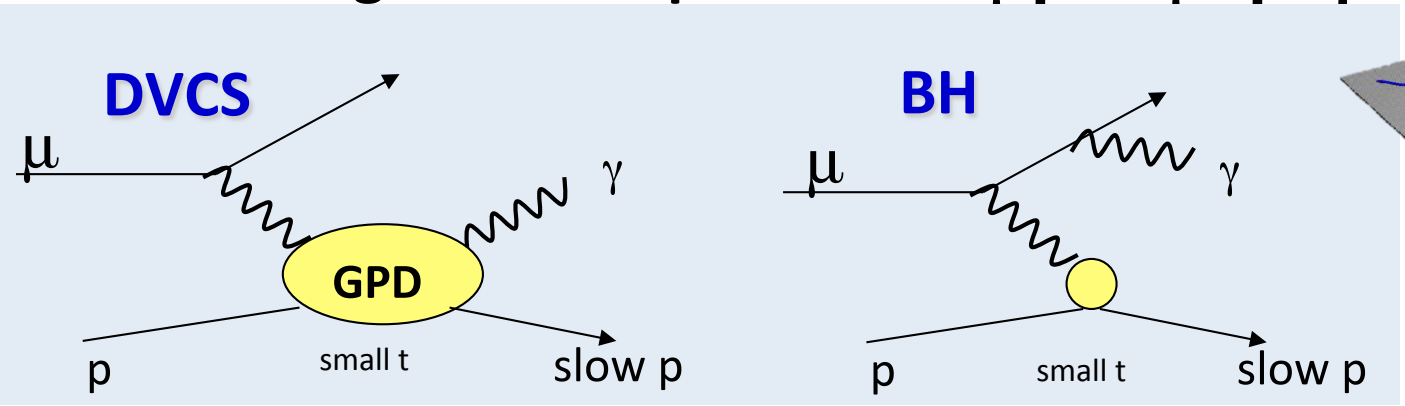


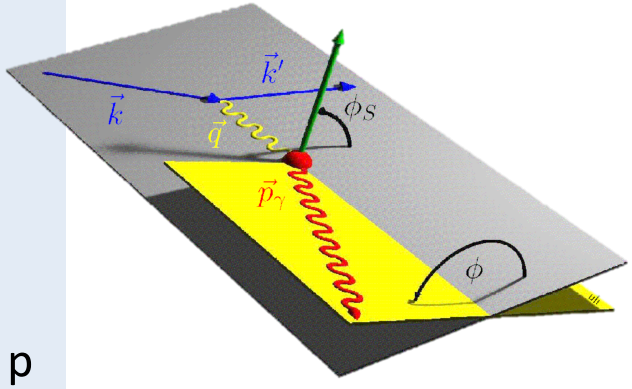
$$d\sigma \propto |T^{BH}|^2 + \mathrm{Im}(T^{DVCS}) \cdot T^{BH} + \mathrm{Re}(T^{DVCS}) \cdot T^{BH} + |T^{DVCS}|^2$$

Known to 1 % — Linear combination of GPDs — bilinear combination of GPDs

DVCS (Golden Channel) → CFF → GPD H (E)

Exclusive Single Photon production $\mu p \rightarrow \mu' p' \gamma$





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

Known to 1 % — Linear combination of GPDs — bilinear combination of GPDs

Beam Charge Difference on proton

small x_B

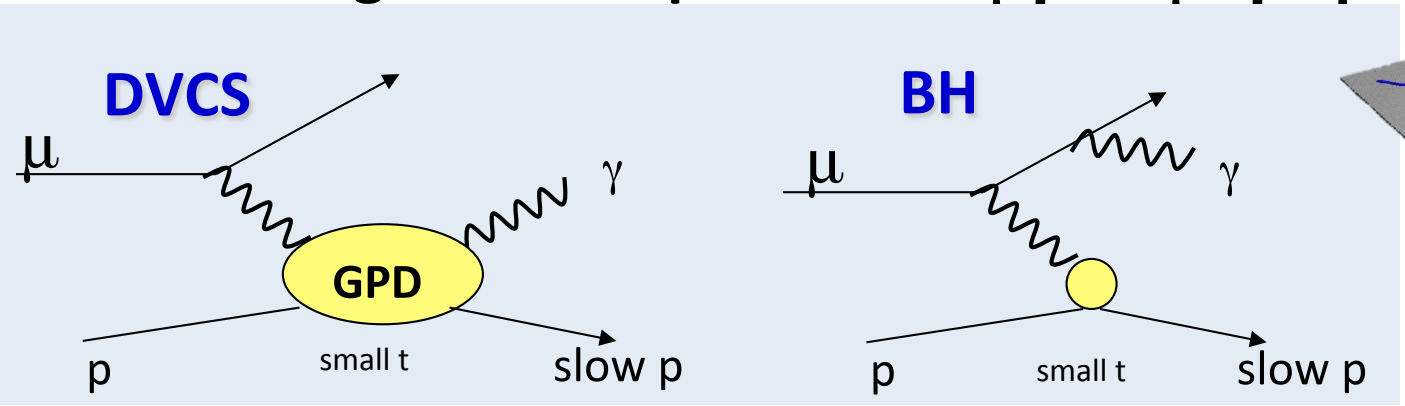
$$A_C^{\cos\phi} = Re\,(F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} - t/4m^2\, F_2\mathcal{E})) \rightarrow Re\,(F_1\mathcal{H})$$

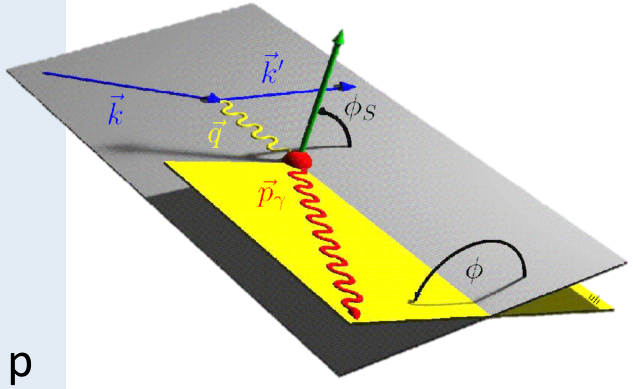
Beam Spin Difference on proton

$$A_{LU}^{\sin\phi} = Im\,(F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} - t/4m^2\, F_2\mathcal{E})) \rightarrow Im\,(F_1\mathcal{H})$$

DVCS (Golden Channel) → CFF → GPD H (E)

Exclusive Single Photon production $\mu p \rightarrow \mu' p' \gamma$





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

Known to 1 % — Linear combination of GPDs — bilinear combination of GPDs

Beam Spin Asym on **neutron**

$$A_{LU}^{\sin\phi} \rightarrow Im\,(F_{1n}\mathcal{H} - F_{2n}\mathcal{E})$$

$\mathcal{H}$ and $\mathcal{E}$

On the same footing

Transv. Target Spin Asym on proton

$$A_{UT}^{\sin(\phi - \phi_S)\cos\phi} \rightarrow Im\,(F_2\,\mathcal{H} - F_1\mathcal{E})$$

HEMP → $(MFF)^2$ → Filter for GPDs and Flavors

Hard Exclusive Meson Production (HEMP):

Vector meson production $(\rho,\omega,\phi, J/\psi\ldots)$ $\Rightarrow$ H & E

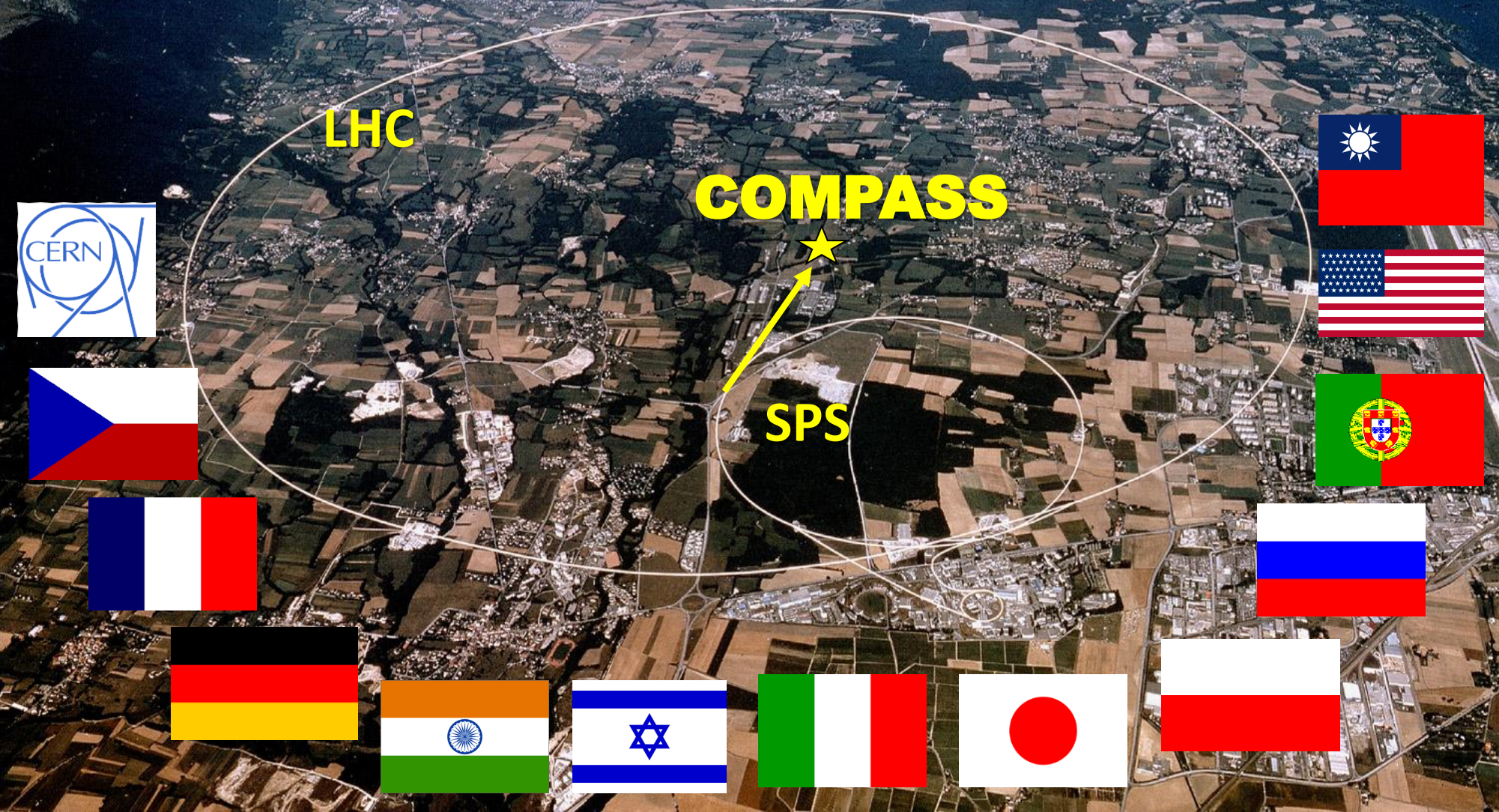
Pseudo-scalar production $(\pi,\eta\ldots)$ $\Rightarrow$ $\tilde{H}$ & $\tilde{E}$

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

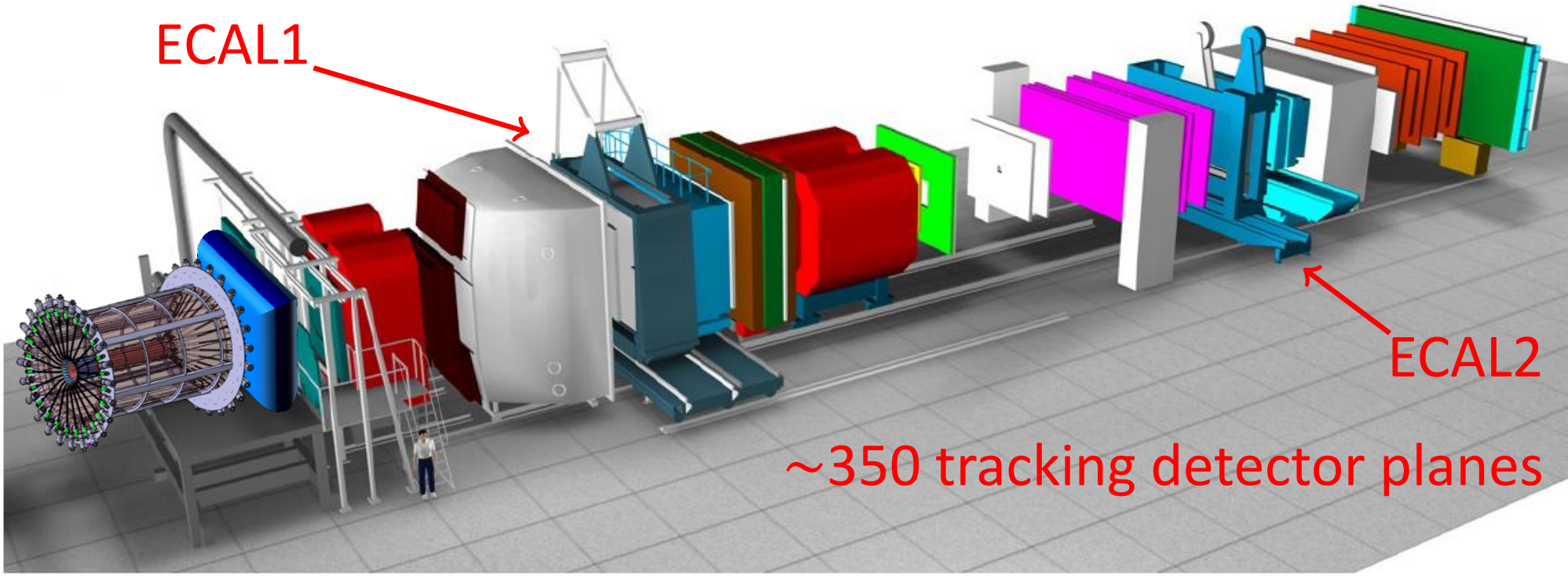
$$H\omega = 1/\sqrt{2}\,(2/3\, H^u - 1/3\, H^d + 1/8\, H^g)$$

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

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

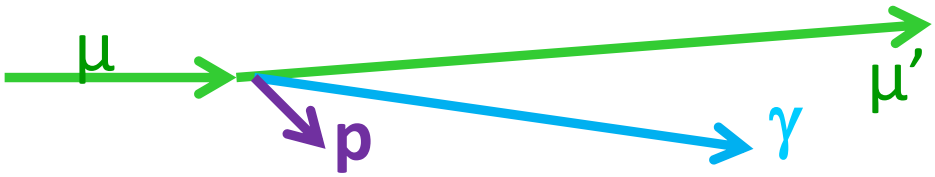


Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with:

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

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



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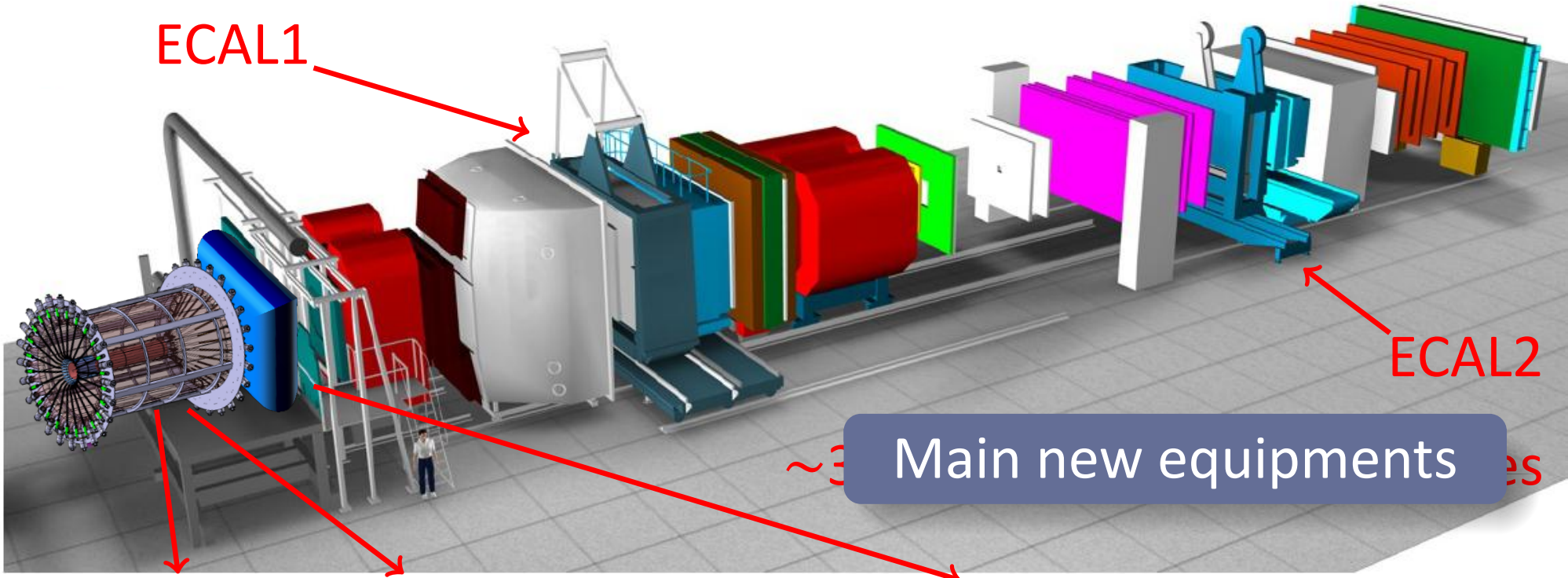
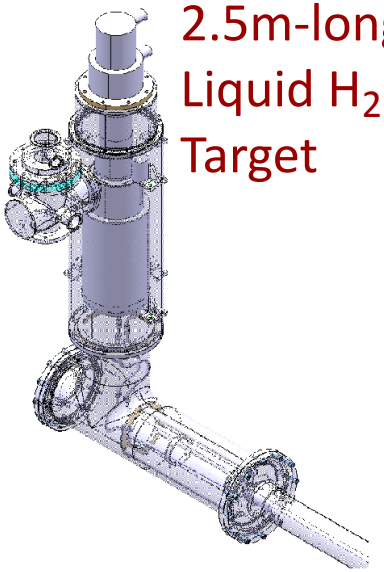
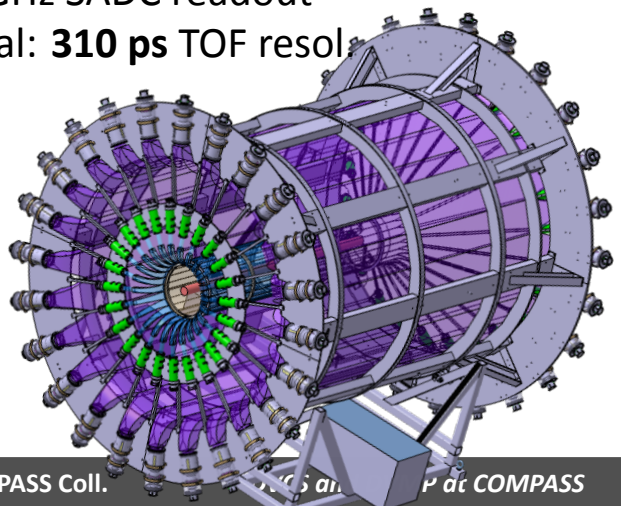




2.5m-long
Liquid H_2
Target

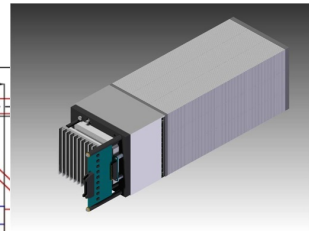
Target TOF System

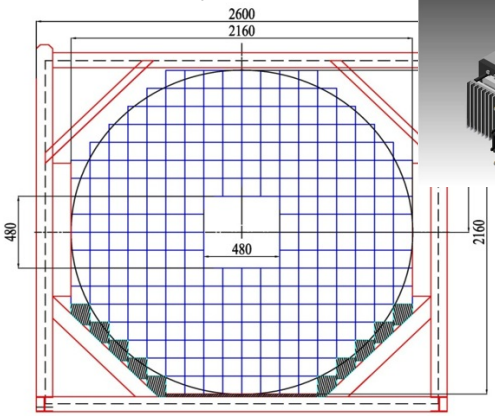
24 inner & outer scintillators
1 GHz SADC readout
goal: **310 ps** TOF resol.



ECAL0 Calorimeter

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





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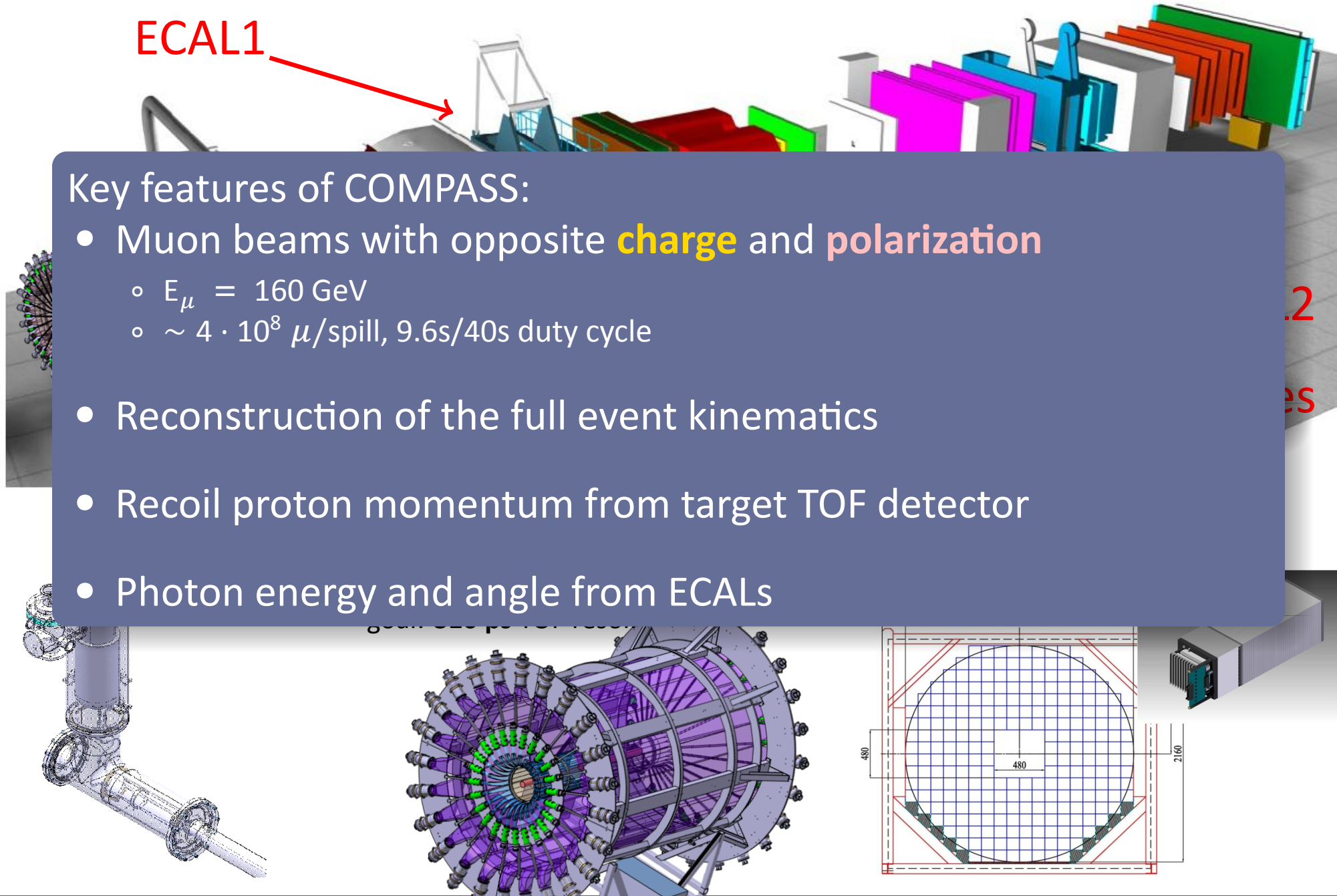
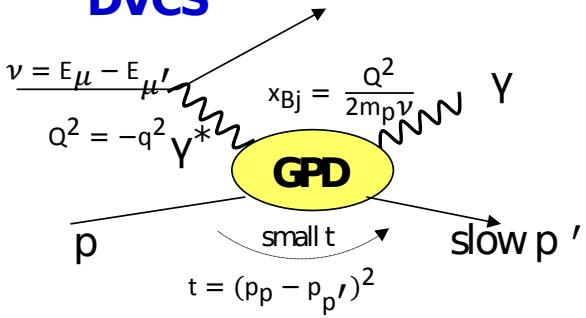


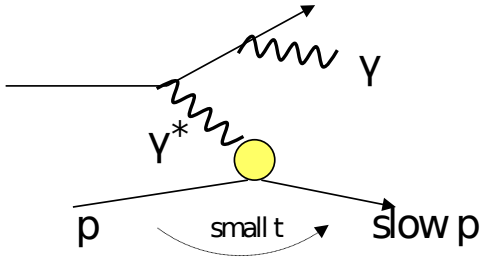
Key features of COMPASS:

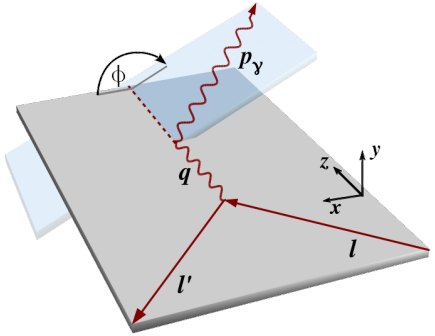
- Muon beams with opposite **charge** and **polarization**
  - $E_\mu = 160$ GeV
  - $\sim 4 \cdot 10^8$ μ/spill, 9.6s/40s duty cycle
- Reconstruction of the full event kinematics
- Recoil proton momentum from target TOF detector
- Photon energy and angle from ECALs

DVCS

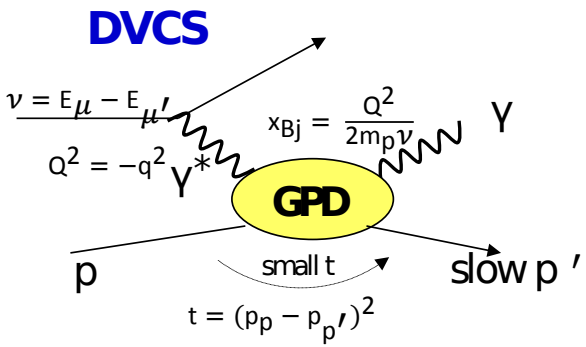


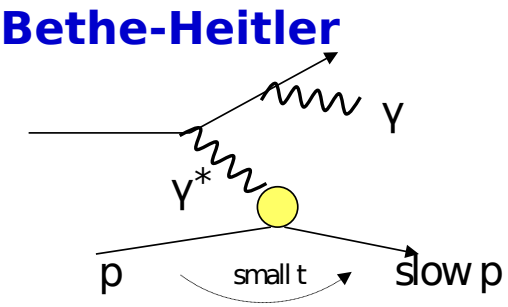
Bethe-Heitler

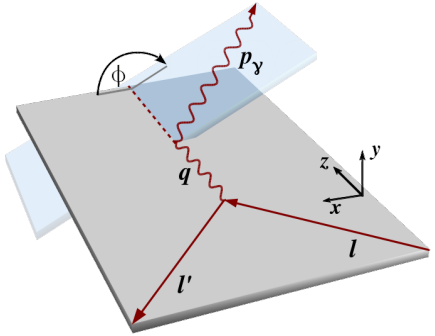




$$d\sigma \propto \underbrace{|T_{DVCS}|^2}_{\text{bilinear combination of GPDs}} + \underbrace{|T_{BH}|^2}_{\text{known to 1 \%}} + \underbrace{\text{interference term}}_{\text{linear combination of GPDs}}$$







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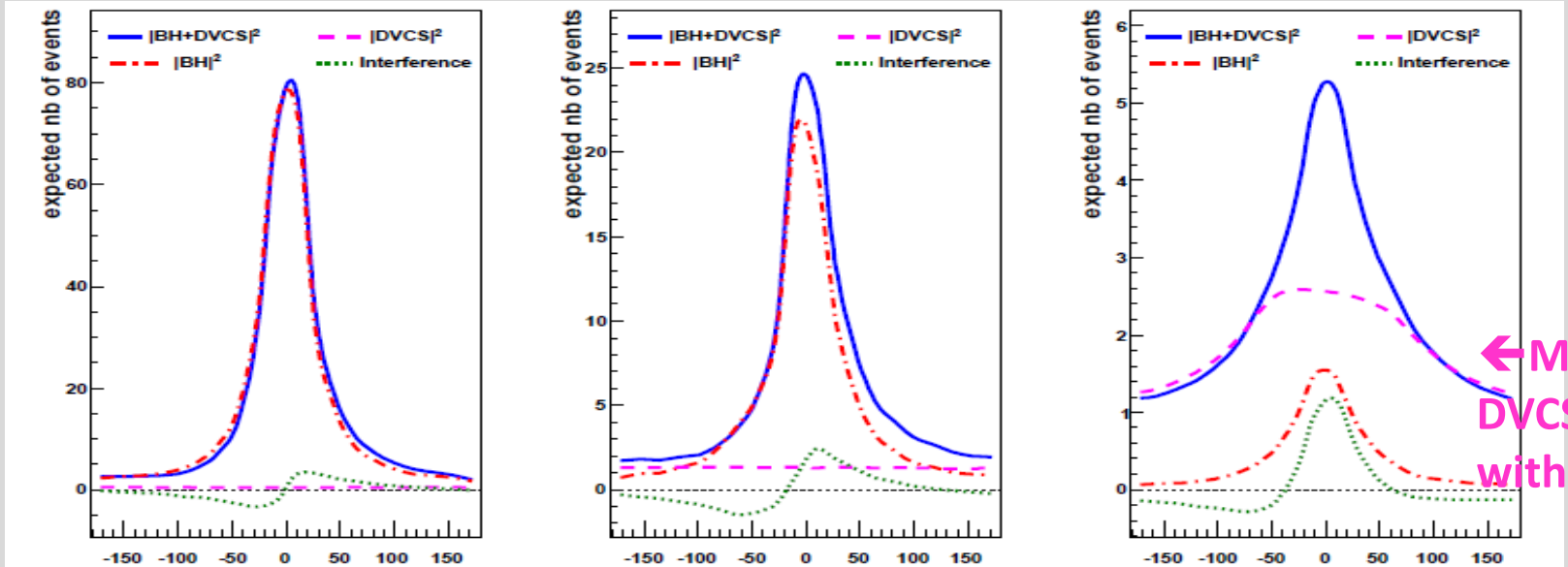


Monte-Carlo Simulation for COMPASS set-up with only ECAL1+2

← Missing DVCS acceptance without ECAL0

$0.005 < x_B < 0.01$ — **BH dominates**

excellent reference yield

$0.01 < x_B < 0.03$ — **study of Interference**

→ Re T^{DVCS} or Im T^{DVCS}

$0.03 < x_B$ — **DVCS dominates**

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

→ Transverse Imaging

Transverse Nucleon Imaging at COMPASS

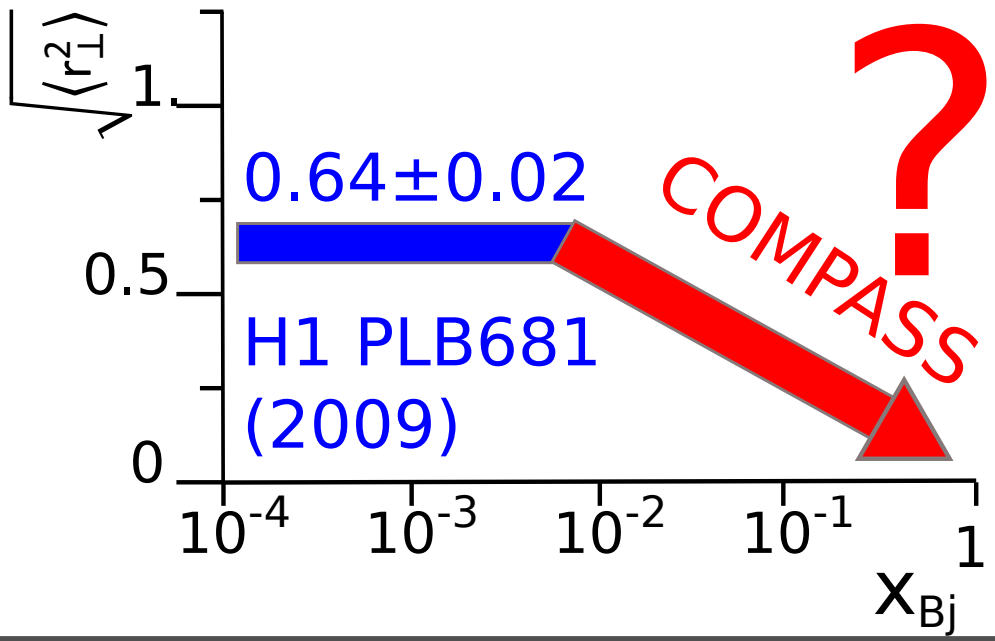
Beam Charge and Spin **SUM**:

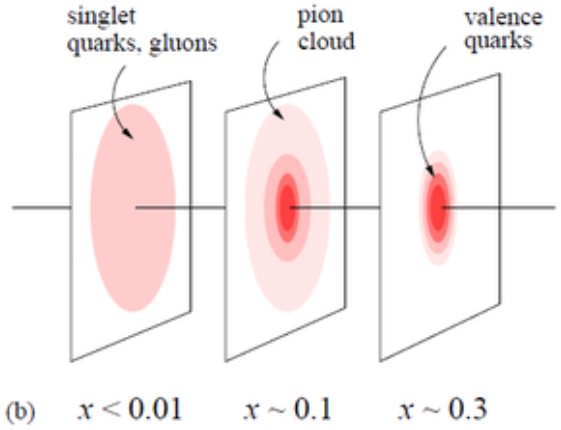
$$\mathbf{S_{CS,U} \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K s_1^{Int} \sin\phi}$$

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

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

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

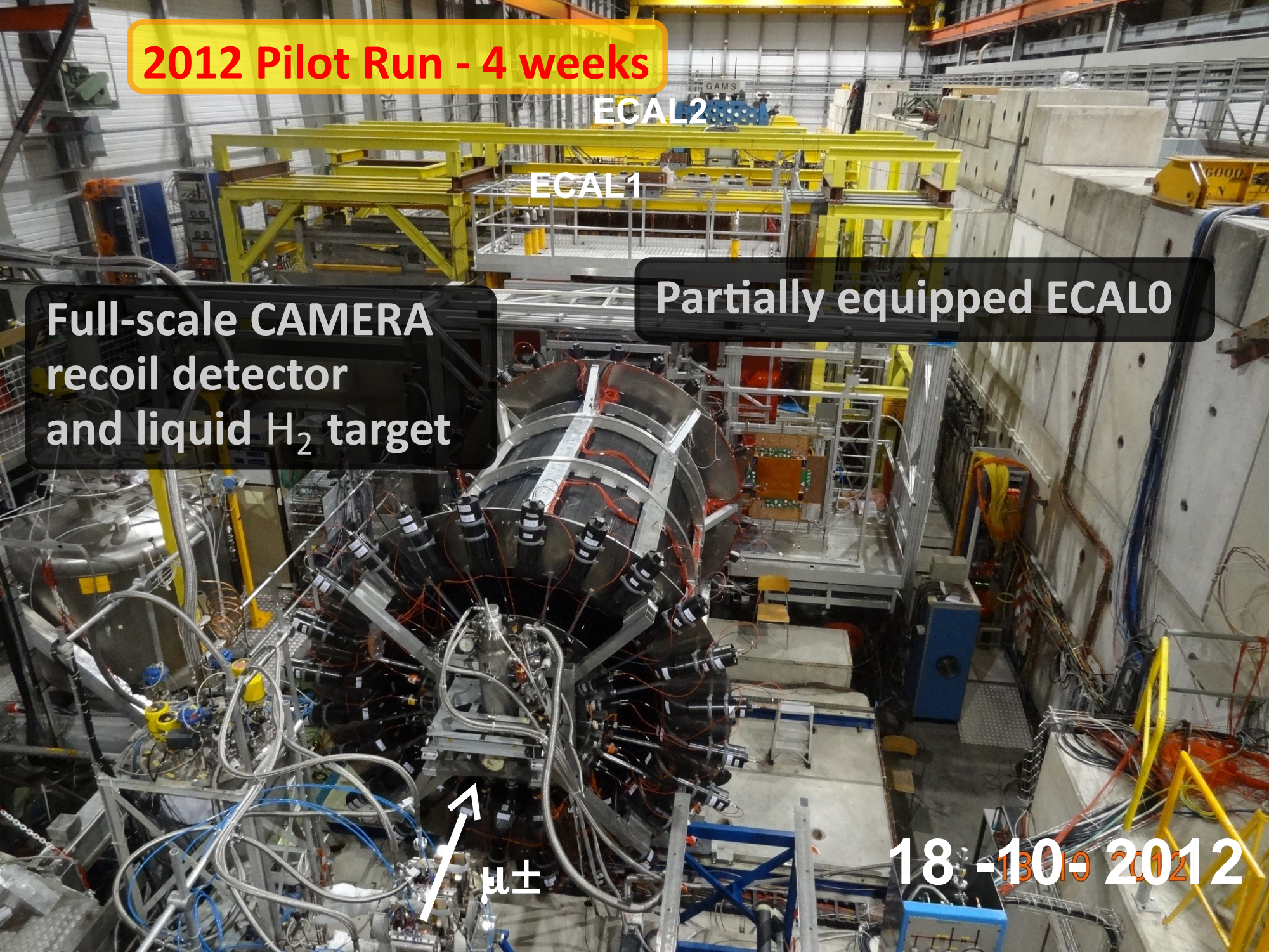




Ansatz at small x_B:

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

(inspired by Regge phenomenology)


2012 Pilot Run - 4 weeks
ECAL2
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

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

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

Exclusive Photon Events Selection

Reconstructed interaction vertex in **target volume**

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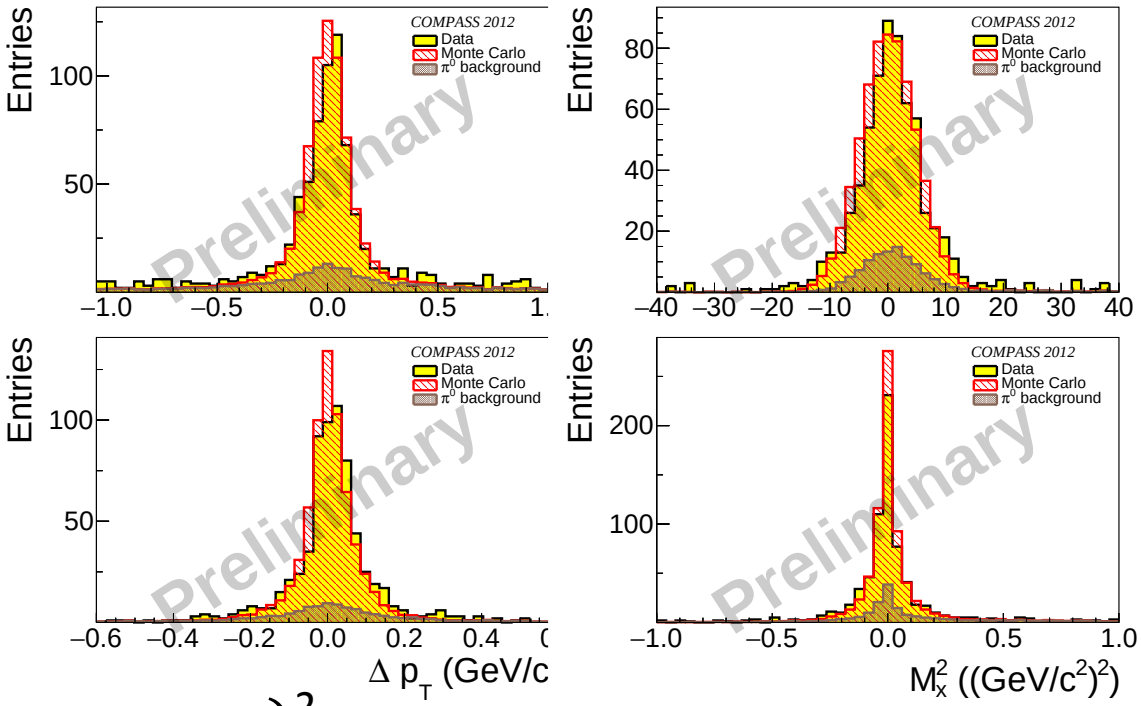
$0.08\ (\mathrm{GeV/c})^2 < t < 0.64\ (\mathrm{GeV/c})^2$

Exclusivity conditions:

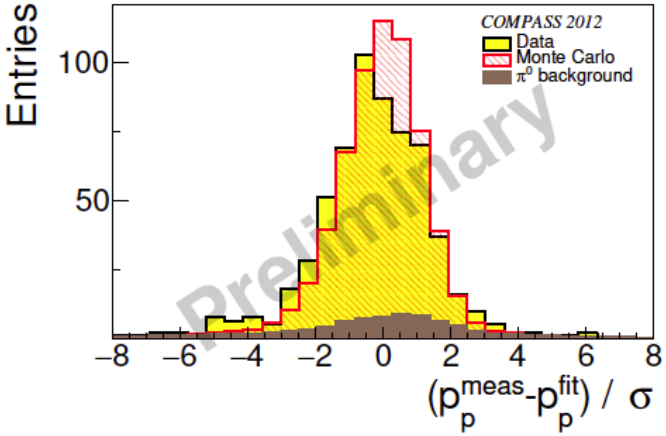
- $\Delta\varphi = \varphi^{\mathrm{proton}}_{\mathrm{meas}} - \varphi^{\mathrm{proton}}_{\mathrm{reco}}$
- Vertex pointing (ΔZ_A)
- Transv. mom. balance: $\Delta p_T = p^{\mathrm{proton}}_{T,\mathrm{meas}} - p^{\mathrm{proton}}_{T,\mathrm{reco}}$
- Four-momentum balance: $M_x^2 = (p_{\mu_{\mathrm{in}}}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



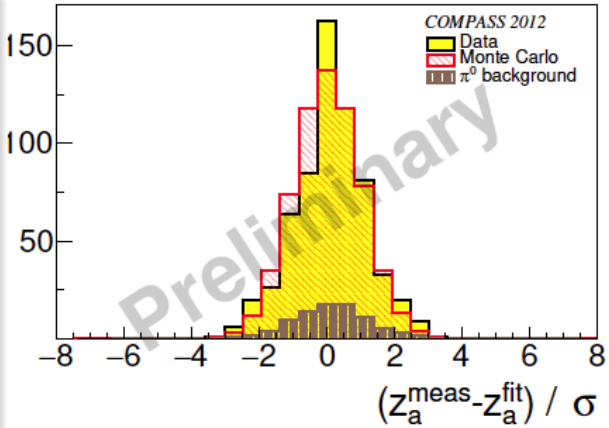
Kinematically constrained fit

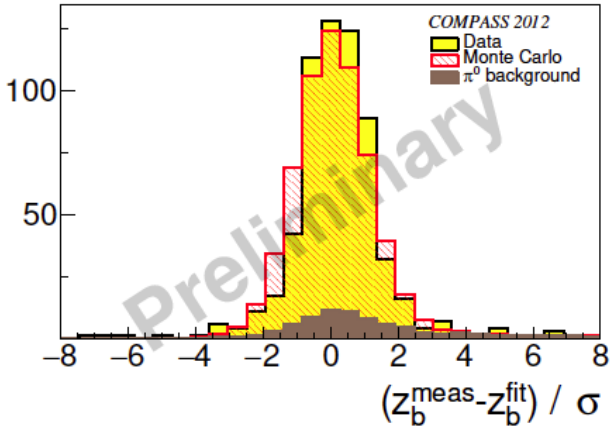
- constrained χ^2 minimisation with NDF=9
- full 4-momentum conservation of the reaction $\mu p \to \mu p \gamma$
- vertex constraints for μ,μ' and p' included in the fit

$\Rightarrow$ most accurate determination of t

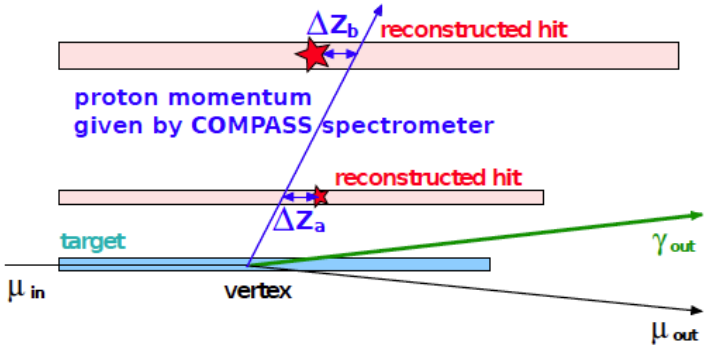


recoil proton momentum





recoil proton direction



π^0 Background Estimation

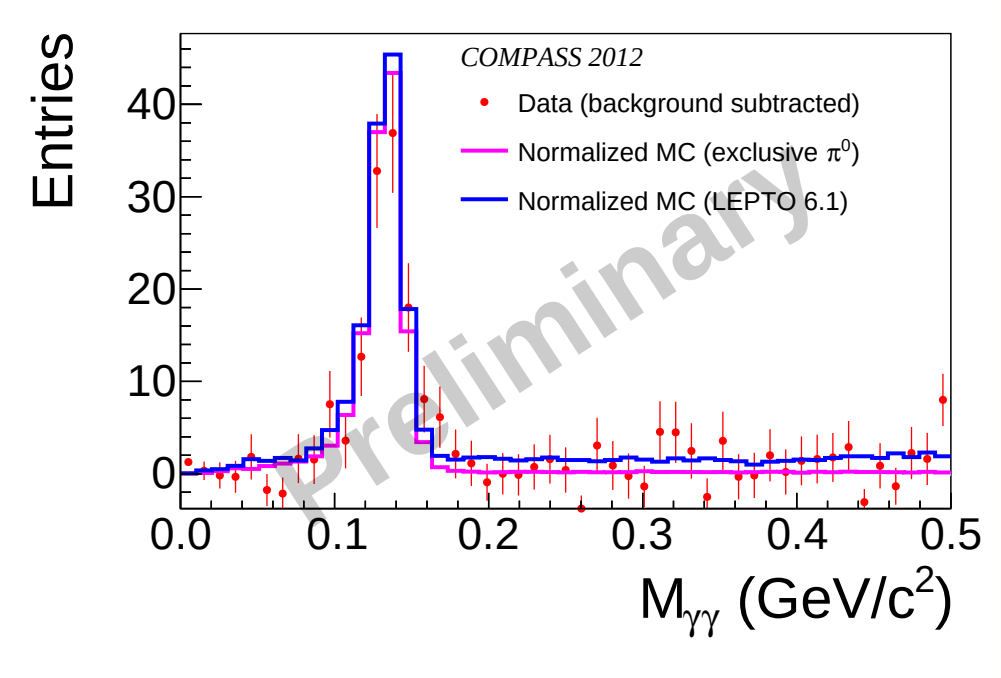
π^0s are one of the main **background sources** for excl. photon events

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)

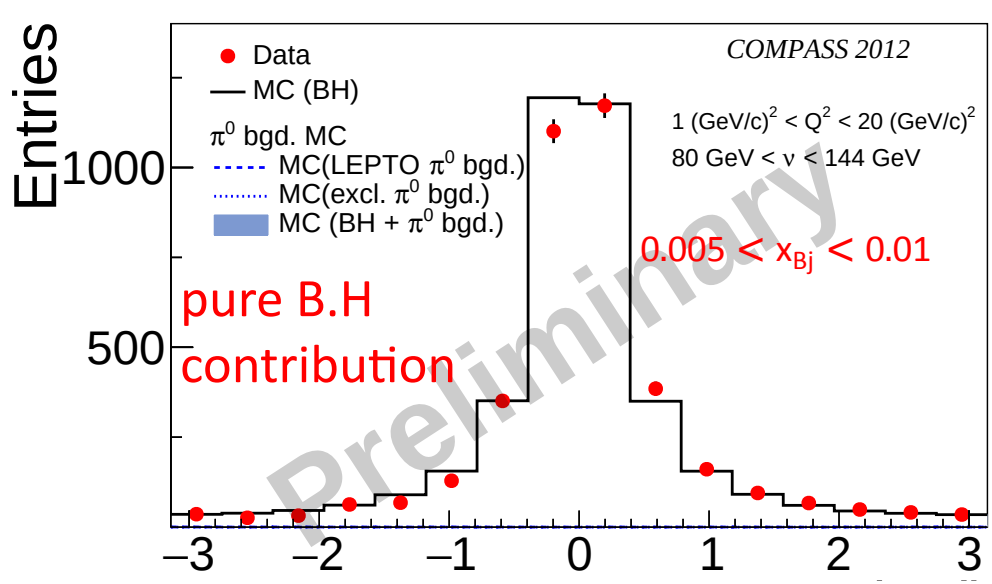
MC samples normalized to $M_{\gamma\gamma}$ peak in real data

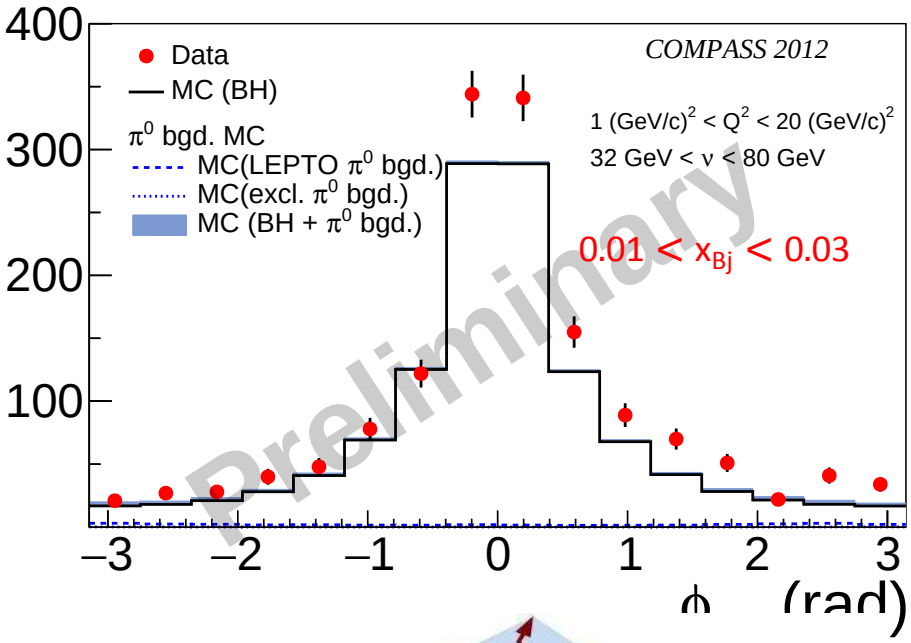
$M_{\gamma\gamma}$ distribution ("visible" π^0)

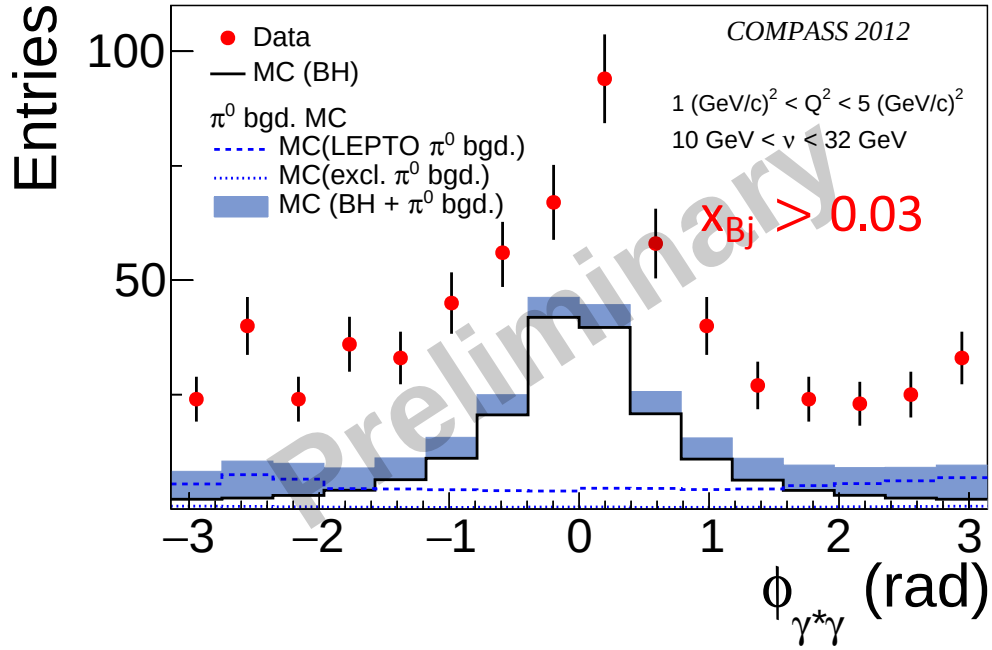


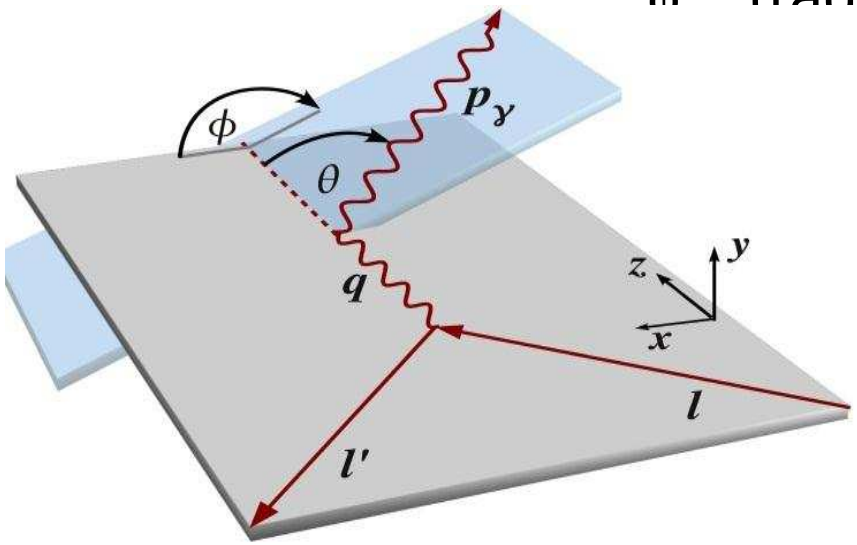
Exclusive γ Azimuthal Distributions for DVCS

Kinematically constrained vertex fit applied



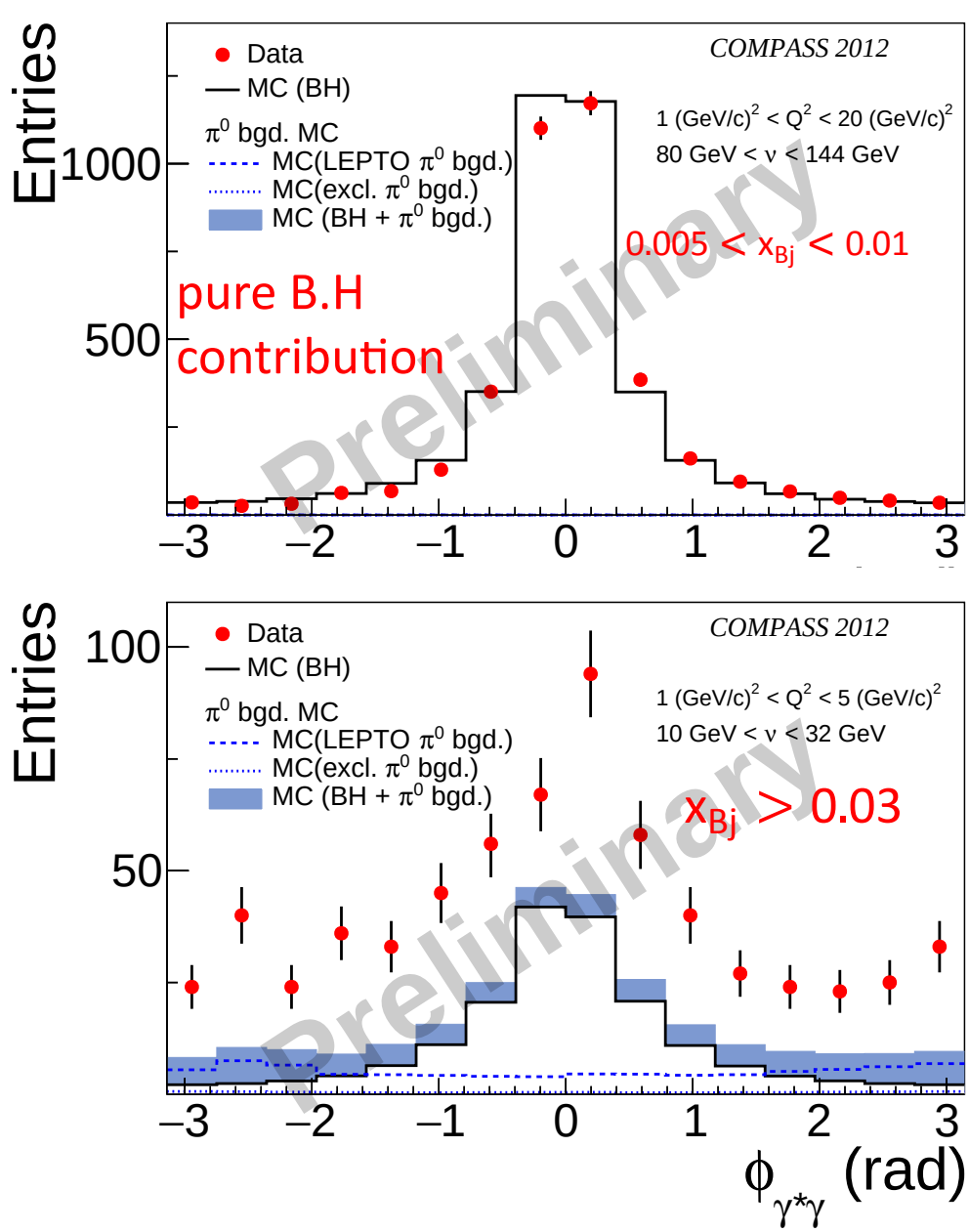


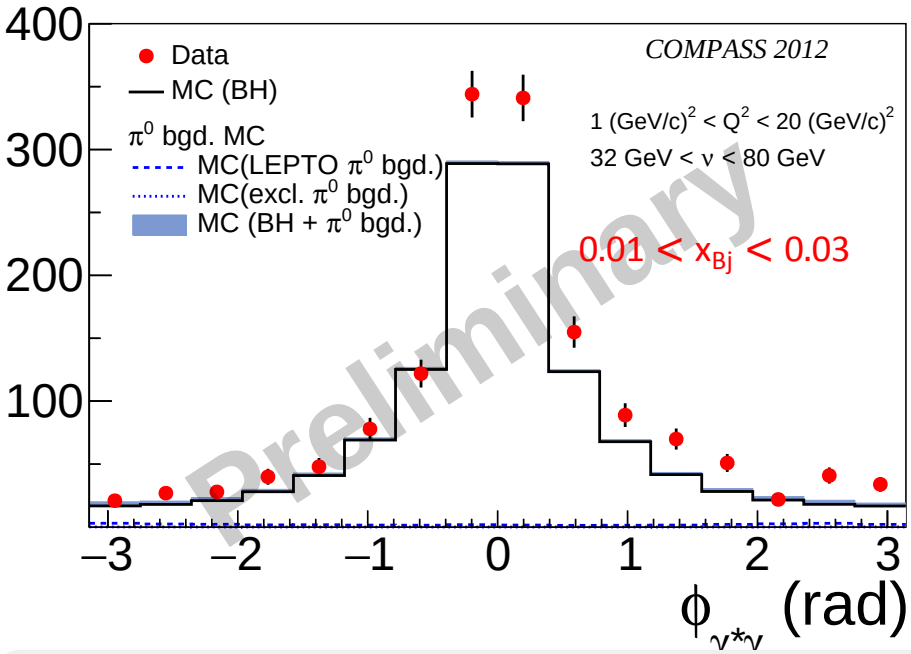




Exclusive γ Azimuthal Distributions for DVCS

Kinematically constrained vertex fit applied





- 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}**

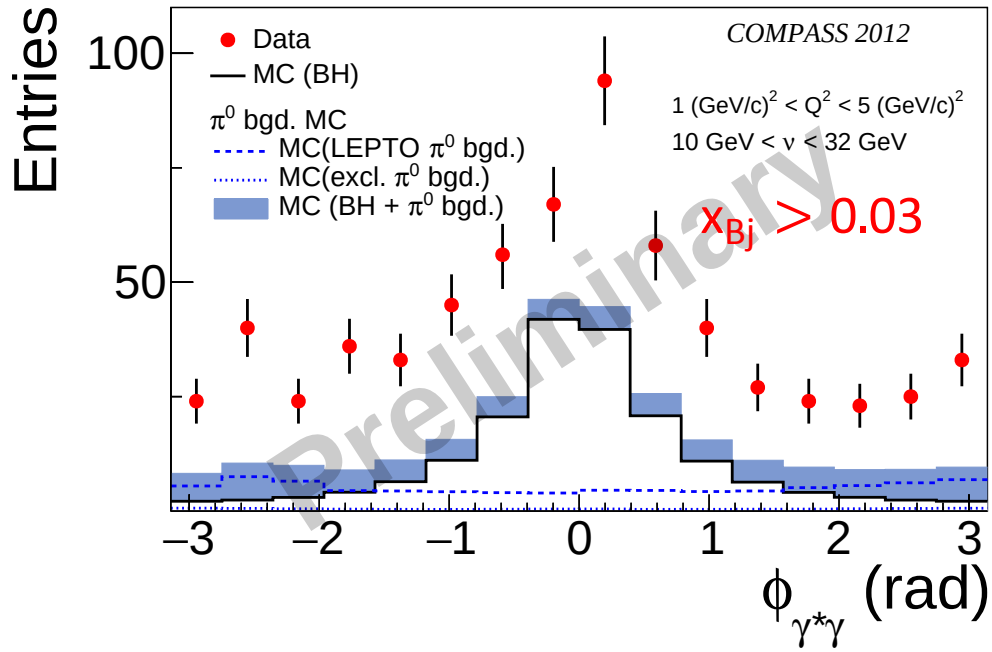
Exclusive γ Azimuthal Distributions for DVCS

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

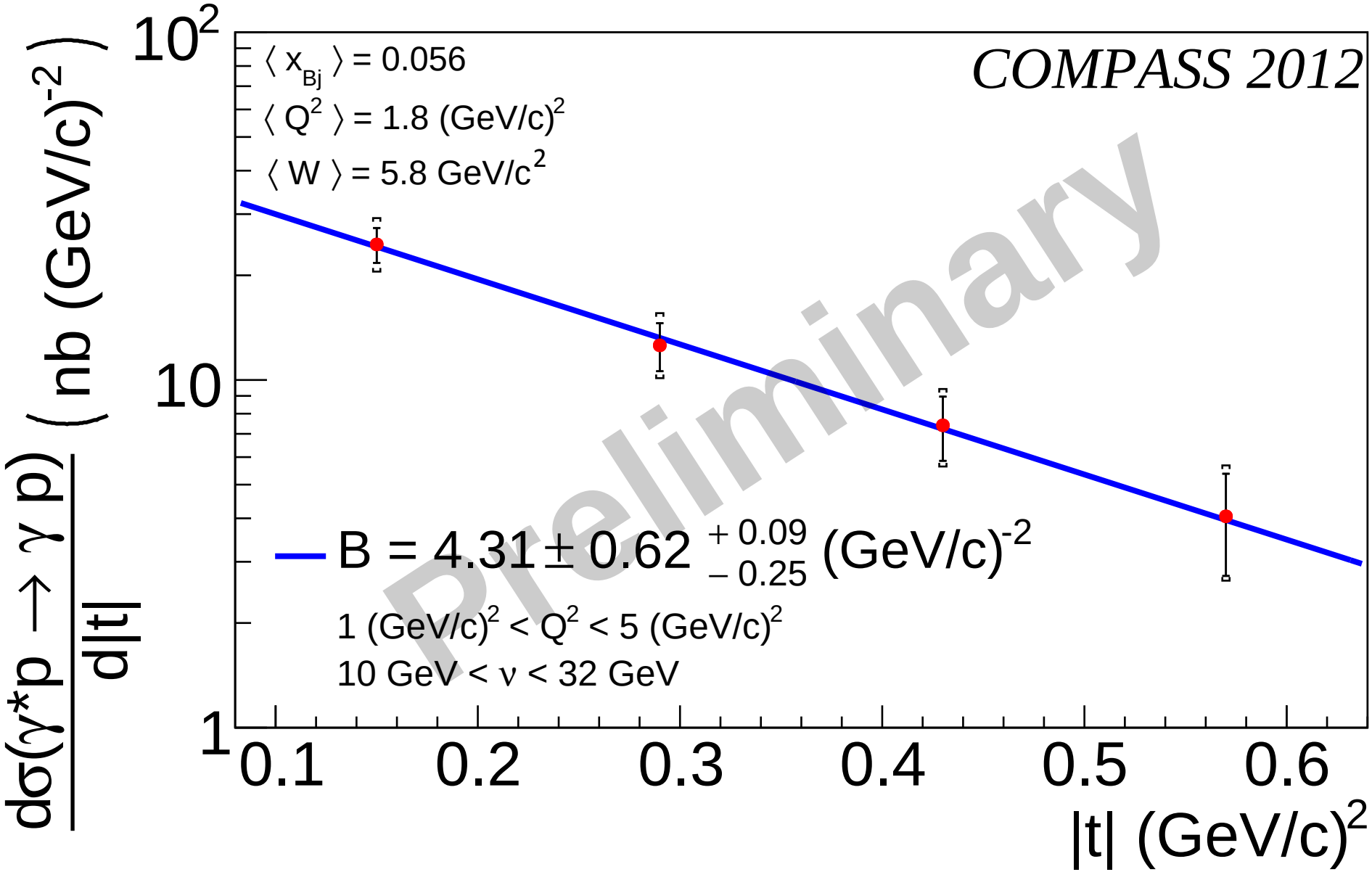
⇒ **DVCS cross-section in 4 bins of |t|**



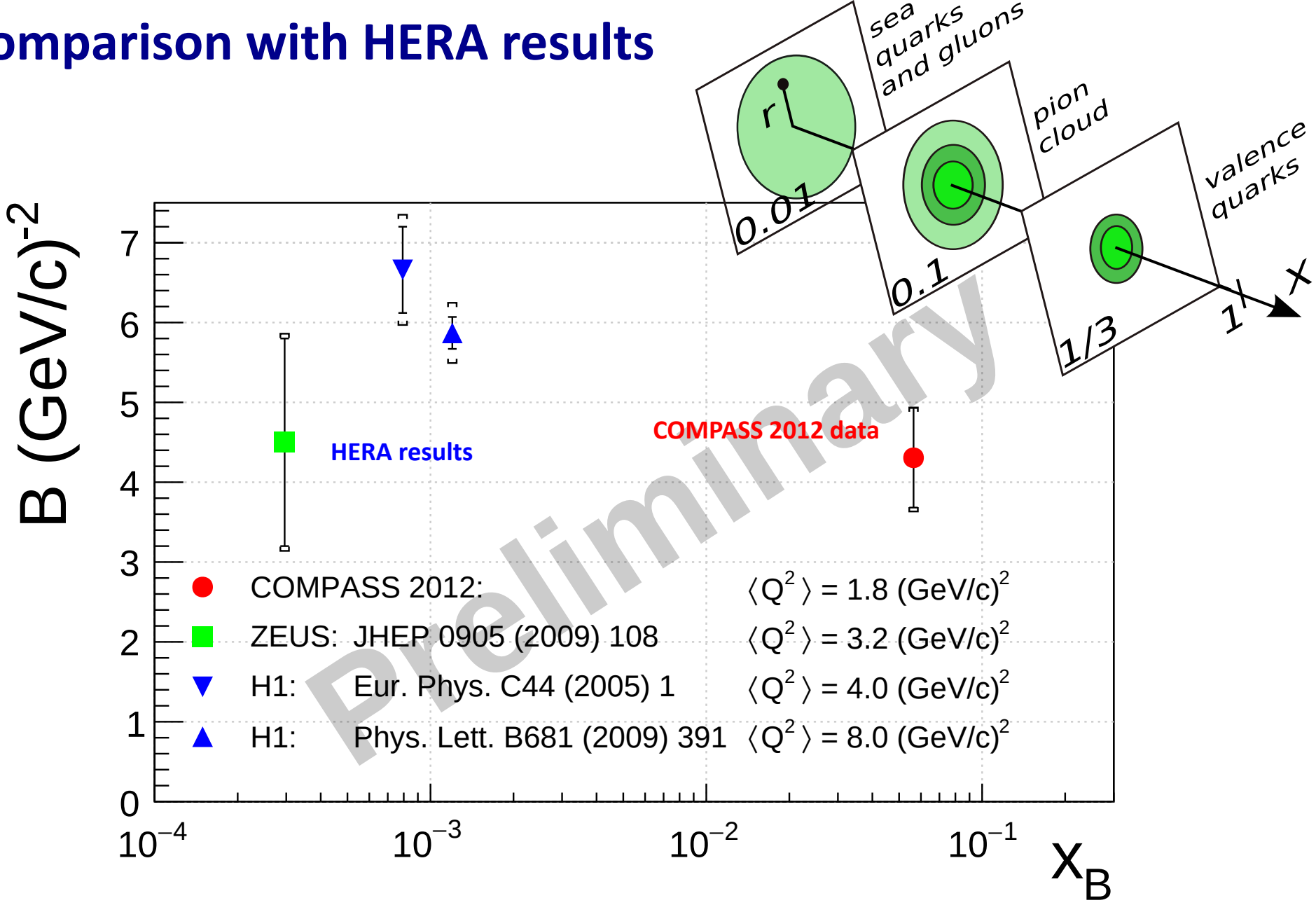
- BH Monte Carlo normalization based on integrated luminosity
- BH process dominant at small x_{Bj}
- π^0 background contributing at large x_{Bj}
- **clear excess of DVCS at large x_{Bj}**

DVCS x-section and t-slope extraction

Kinematically constrained vertex fit applied



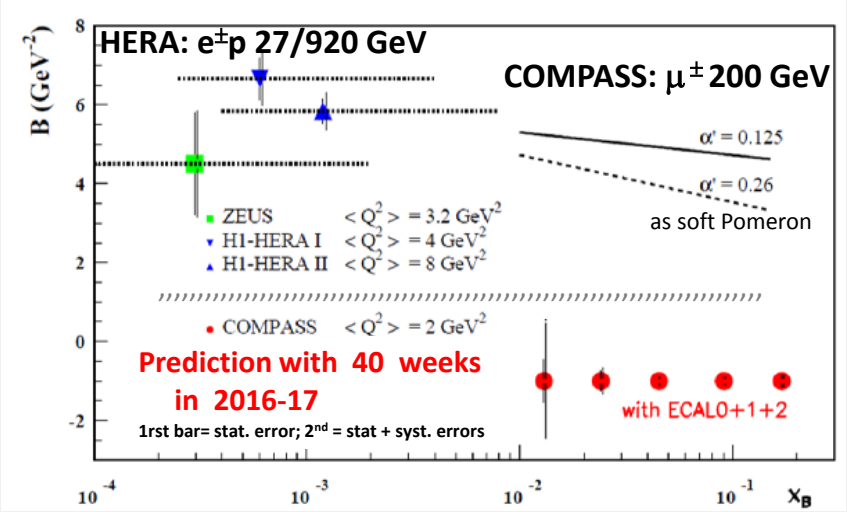
Comparison with HERA results



Comparison with HERA results

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:

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

Exclusive π^0 production on unpolarized protons

e p → e π^0 p

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

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

Leading twist should be dominant

but ≈ 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

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

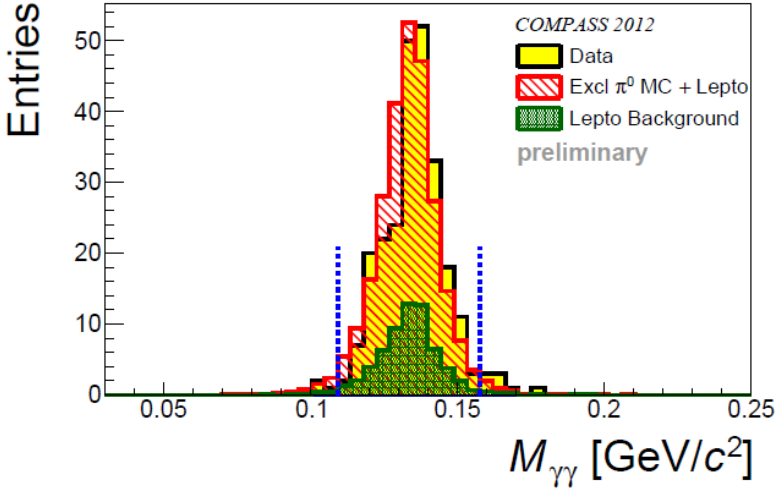
$$\bar{E}_T = 2\tilde{H}_T - E_T$$

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

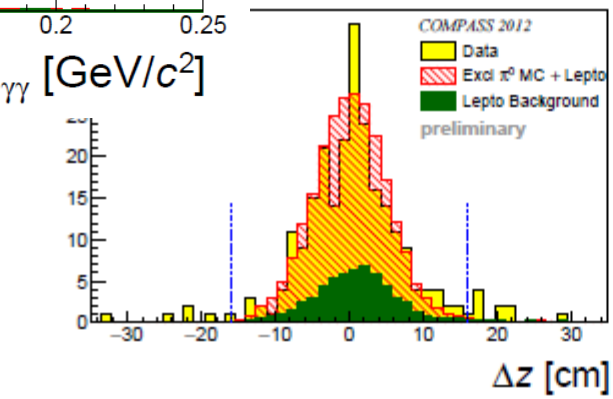
A large impact of $\bar{E}_T$ should be clearly visible in σ_{TT} and in the dip at small t of σ_T

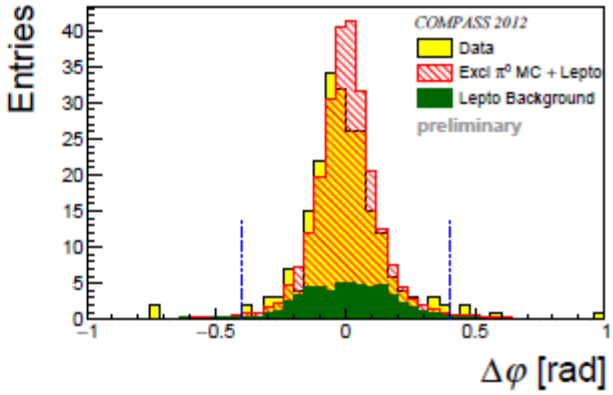
Exclusive Events Selection

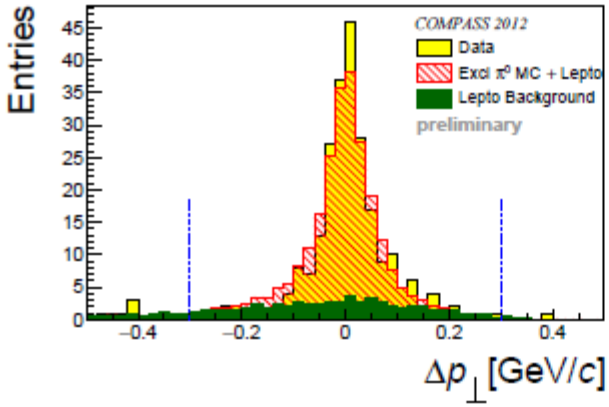


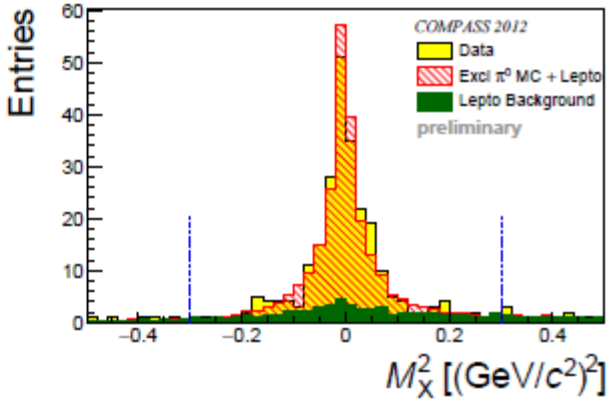
Selection of exclusive events
Background of semi-inclusive LEPTO
+ Kinematic fit

all the cuts
are applied except
on the variable
which is shown
in each plot









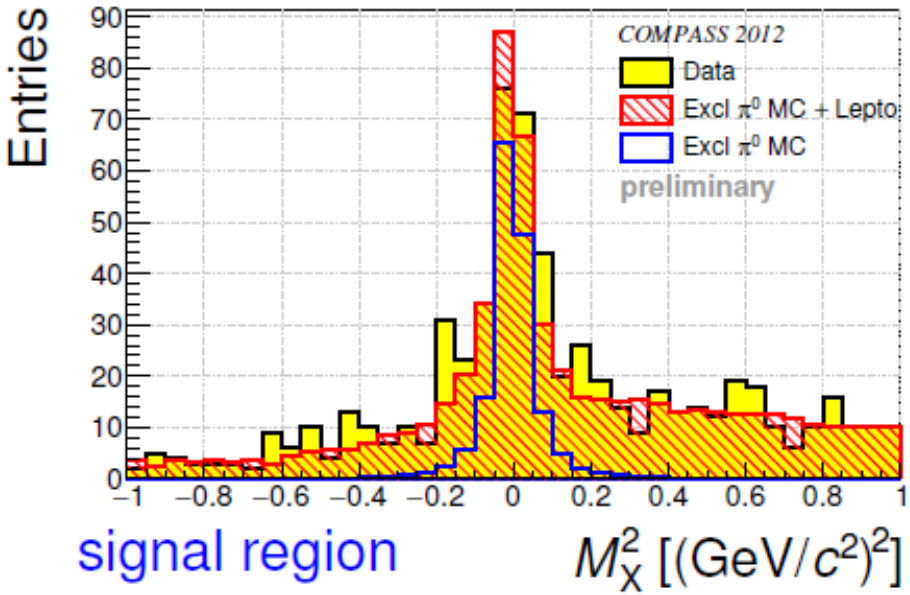
SIDIS Background Estimation

SIDIS background estimation

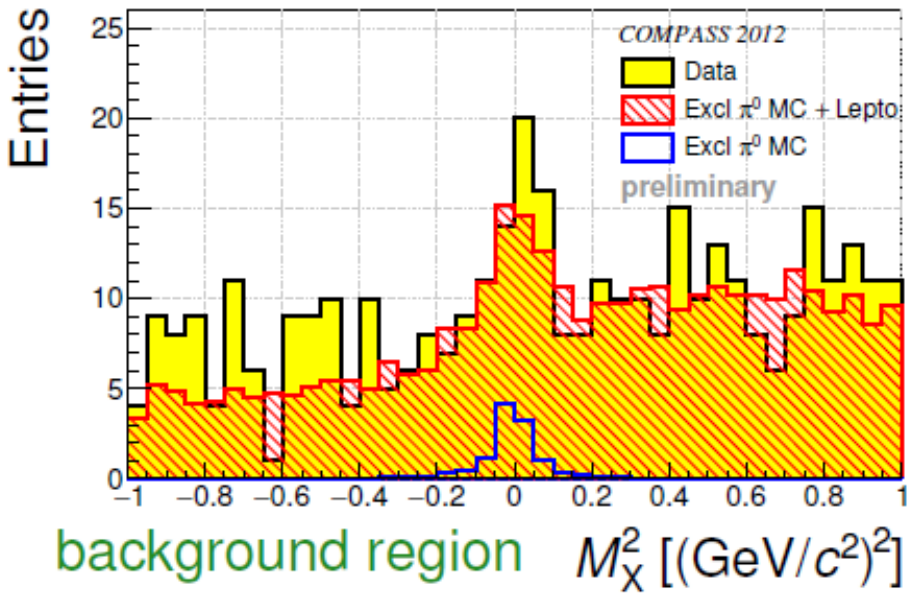
- use LEPTO MC to describe non exclusive background
- use exclusive π^0 MC to describe signal contribution
- find best description of data
  - in signal region (only two photon clusters)
  - in background region (more photon clusters)

Four-momentum balance:

$$M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\pi^0})^2$$



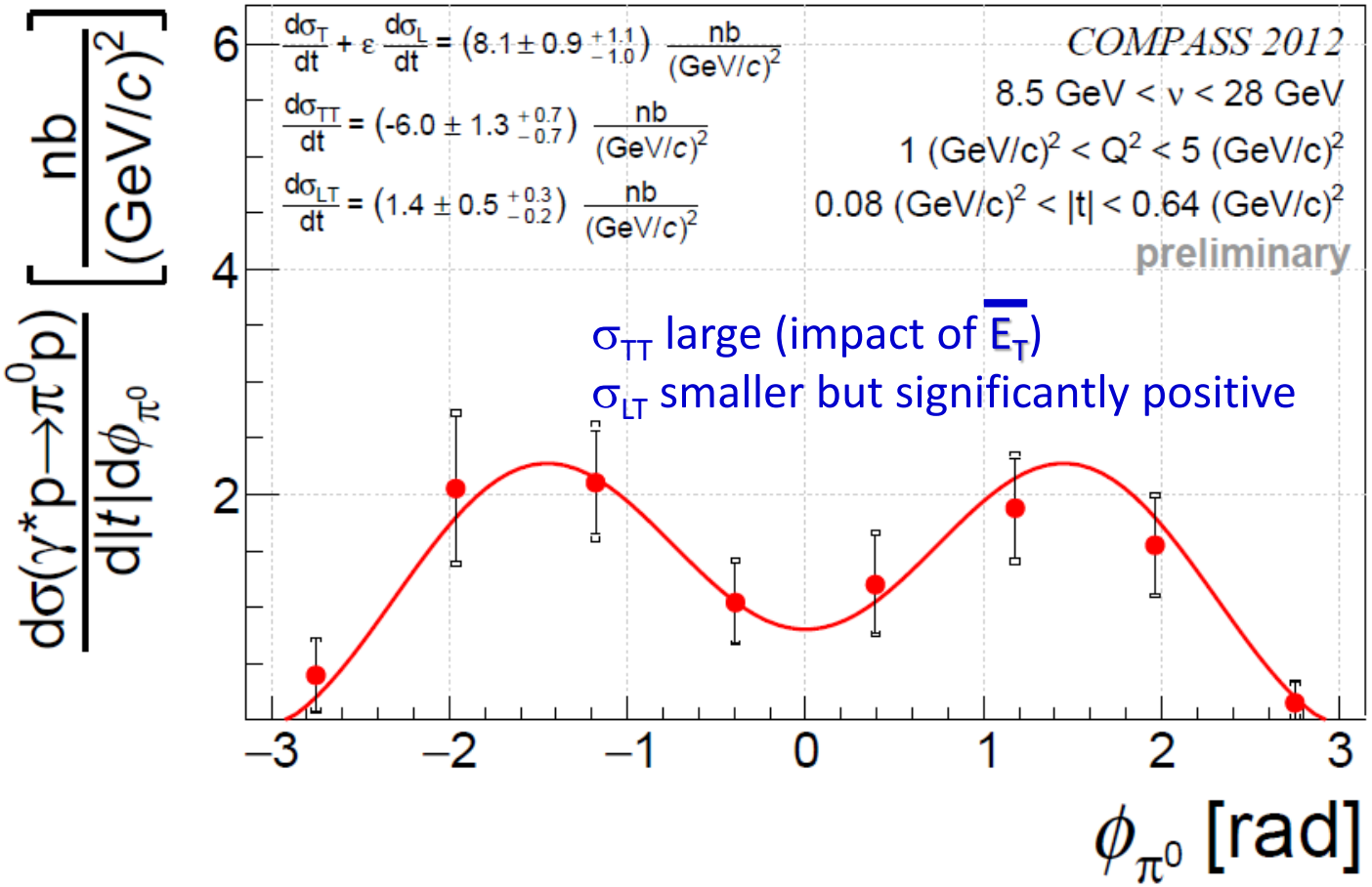
signal region



background region

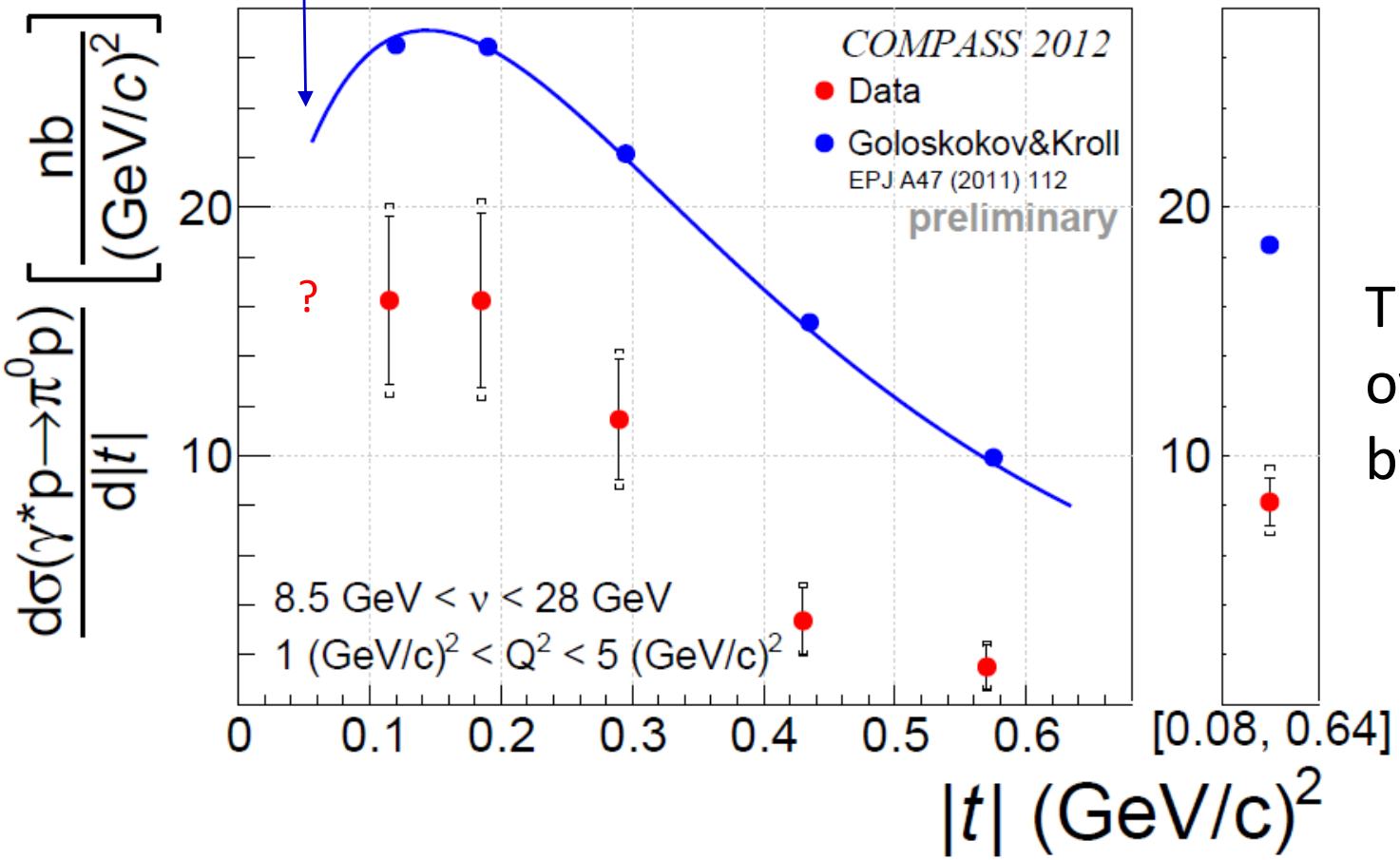
ϕ Modulation of the π^0 production cross-section

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



t-dependence of the π^0 production cross-section

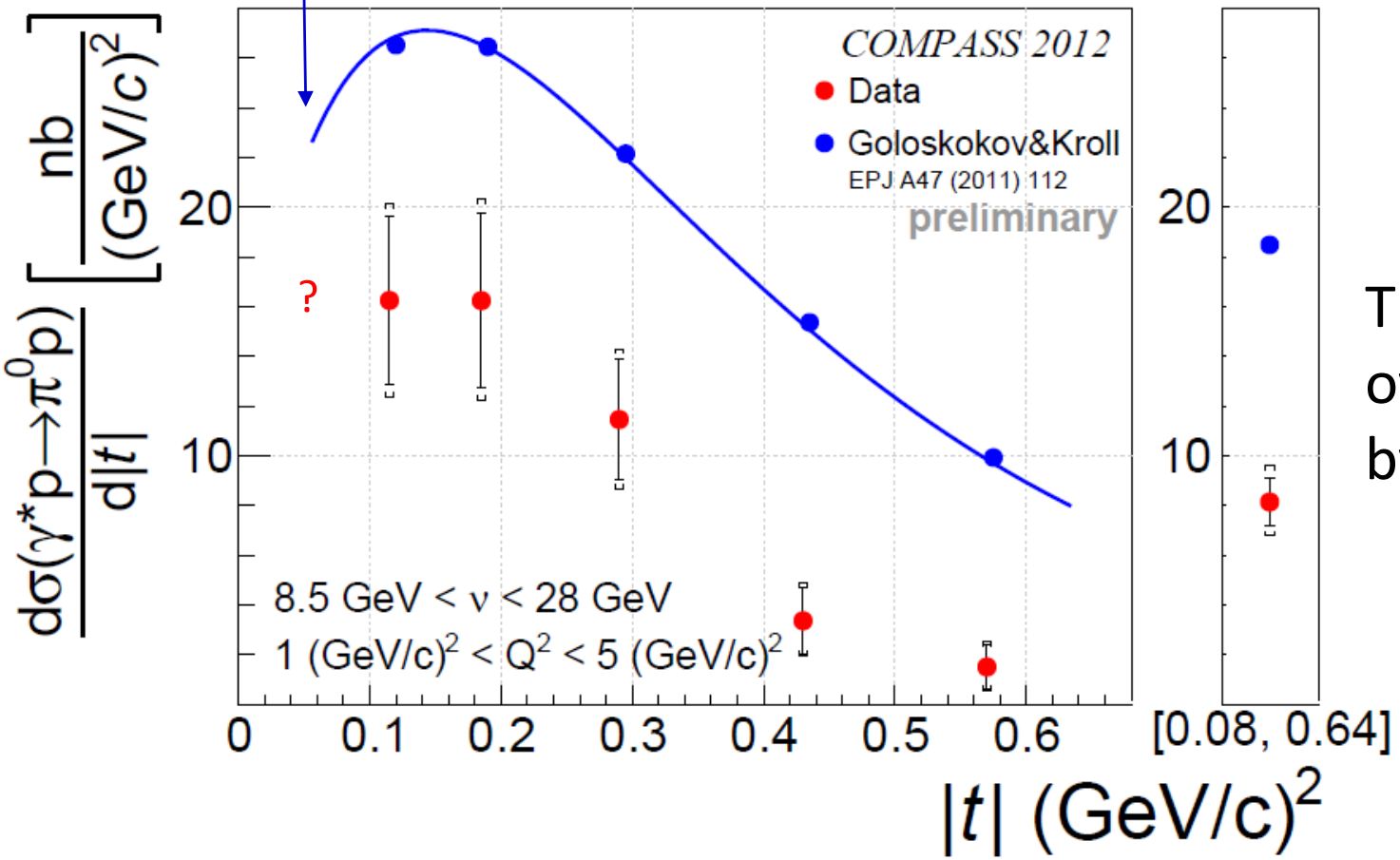
The dip at small t
indicates the large impact of ETbar



The GK model overestimates by a factor 2

t-dependence of the π^0 production cross-section

The dip at small t
indicates the large impact of ETbar



The GK model overestimates by a factor 2

S.V. Goloskokov and P. Kroll are currently improving their model to better fit our data

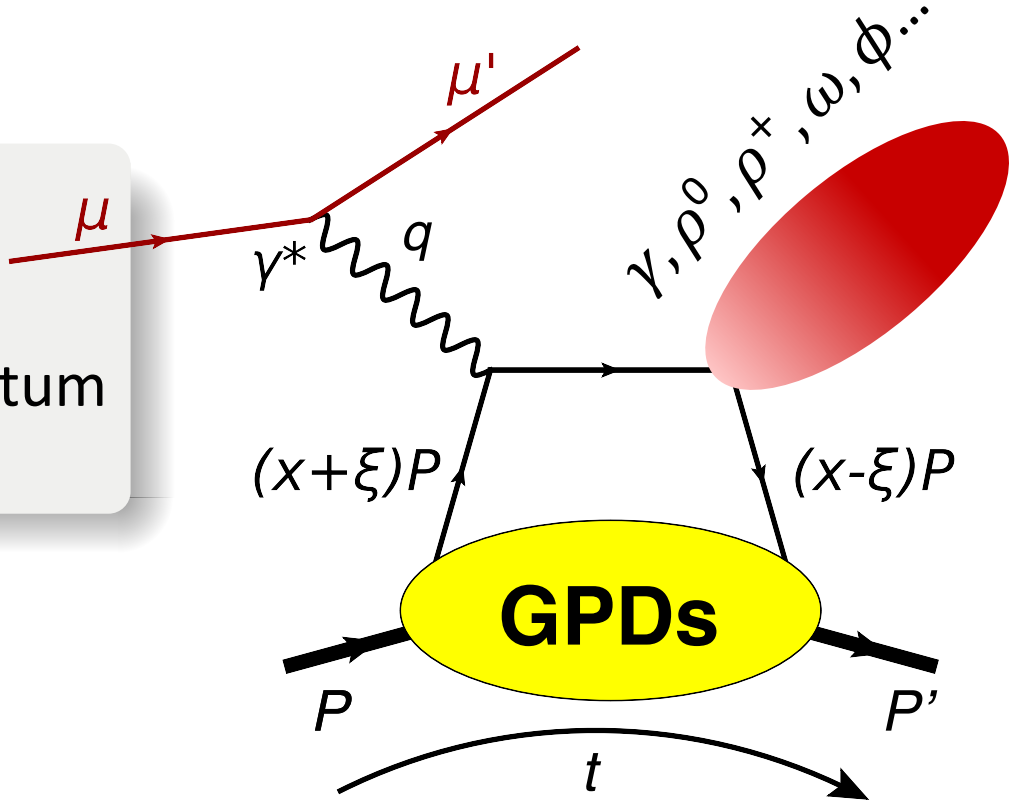
Conclusions and Outlook

- **COMPASS is measuring muon-induced exclusive reactions** in several channels
  - Simultaneously opposite charge and long. polarization of the beam
  - Access to exclusive γ (DVCS), π^0 and vector mesons
- **Pilot data taking in 2012**
  - → t-dependence of DVCS cross-section
  - → t and ϕ dependence of excl. π^0 cross-section
  - analysis of vector meson production in progress
- **Dedicated beam time in 2016 and 2017**
  - Expected about 10× more statistics than 2012
  - → t-slope of DVCS xsec in several x_{Bj} bins
  - → Real and imaginary parts of CFF $\mathcal{H}$
  - Analysis of Deeply Virtual Meson Production from the same data
- The DVCS measurement on a **transversely polarized proton target** is under study for a **future extension** of the COMPASS physics program

Backup Slides

Introduction to GPDs

GPDs provide a **"3D"** description of the nucleon by encoding **CORRELATIONS** between momentum and position of partons

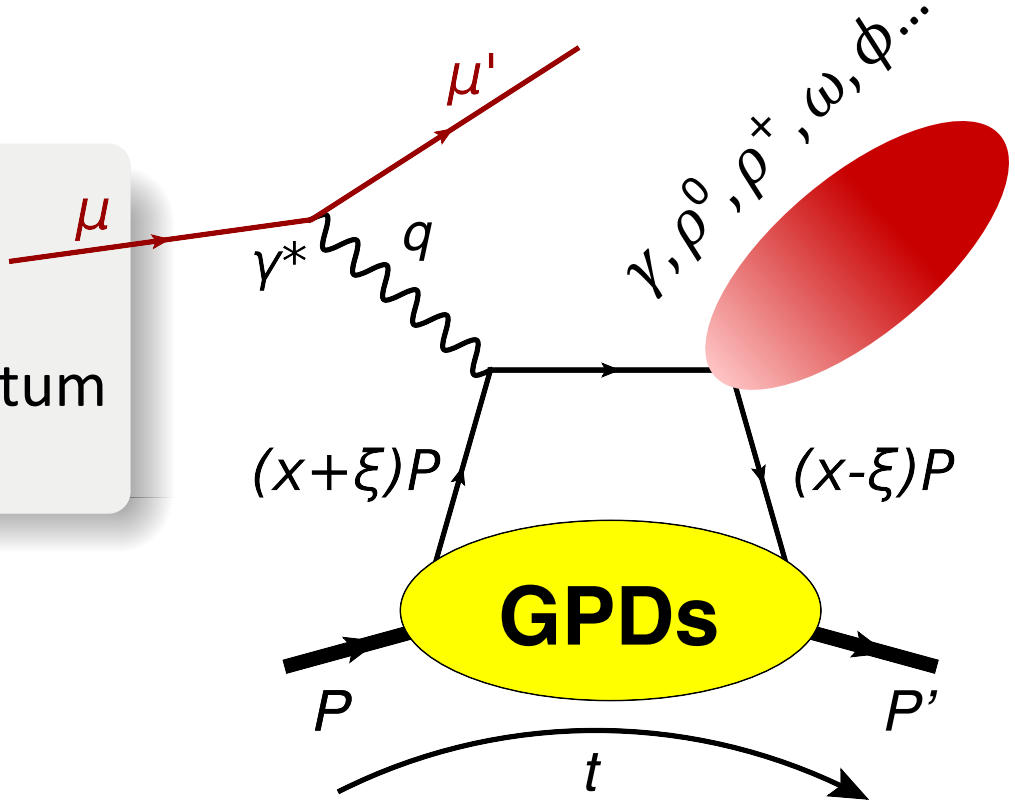


Definition of variables:

- 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 provide a **"3D"** description of the nucleon by encoding **CORRELATIONS** between momentum and position of partons



Definition of variables:

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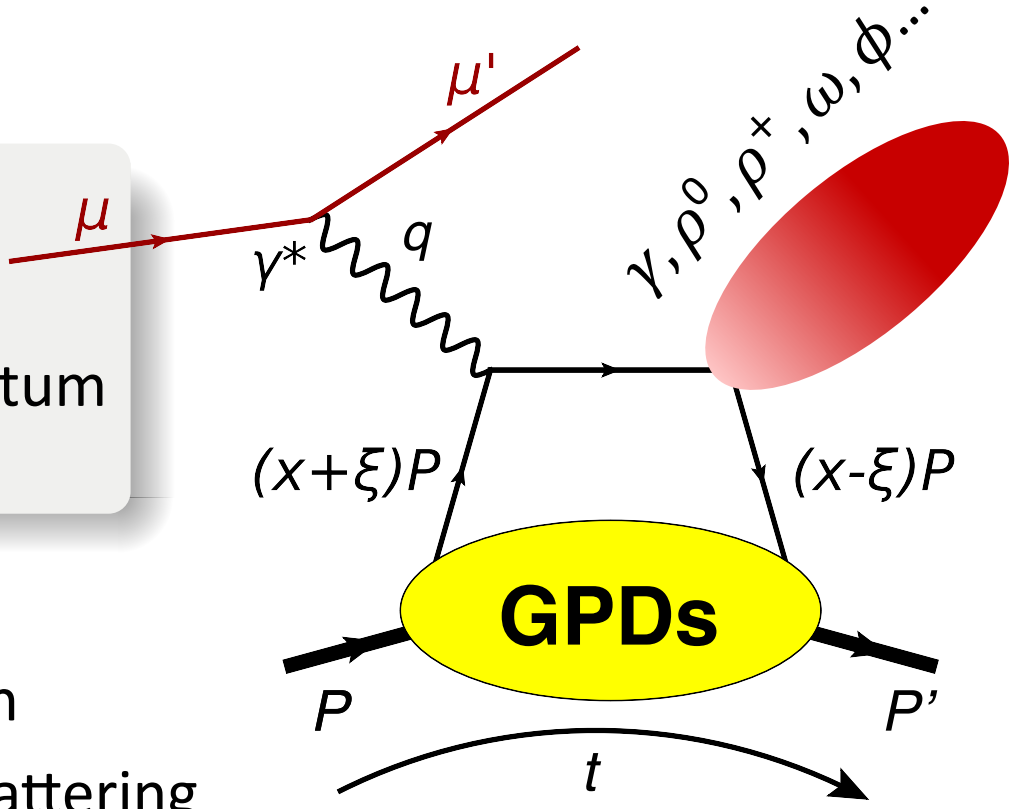
- t: four-momentum transfer

For proton target:

- 4 chiral-even GPDs:
  $\mathbf{H} \quad \widetilde{\mathbf{H}} \quad \mathbf{E} \quad \widetilde{\mathbf{E}}$
- 4 chiral-odd ("transversity") GPDs:
  $\mathbf{H_T} \quad \widetilde{\mathbf{H}}_\mathbf{T} \quad \mathbf{E_T} \quad \widetilde{\mathbf{E}}_\mathbf{T}$

Introduction to GPDs

GPDs provide a **"3D"** description of the nucleon by encoding **CORRELATIONS** between momentum and position of partons



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

Experimentally accessible through correlation with lepton-parton scattering

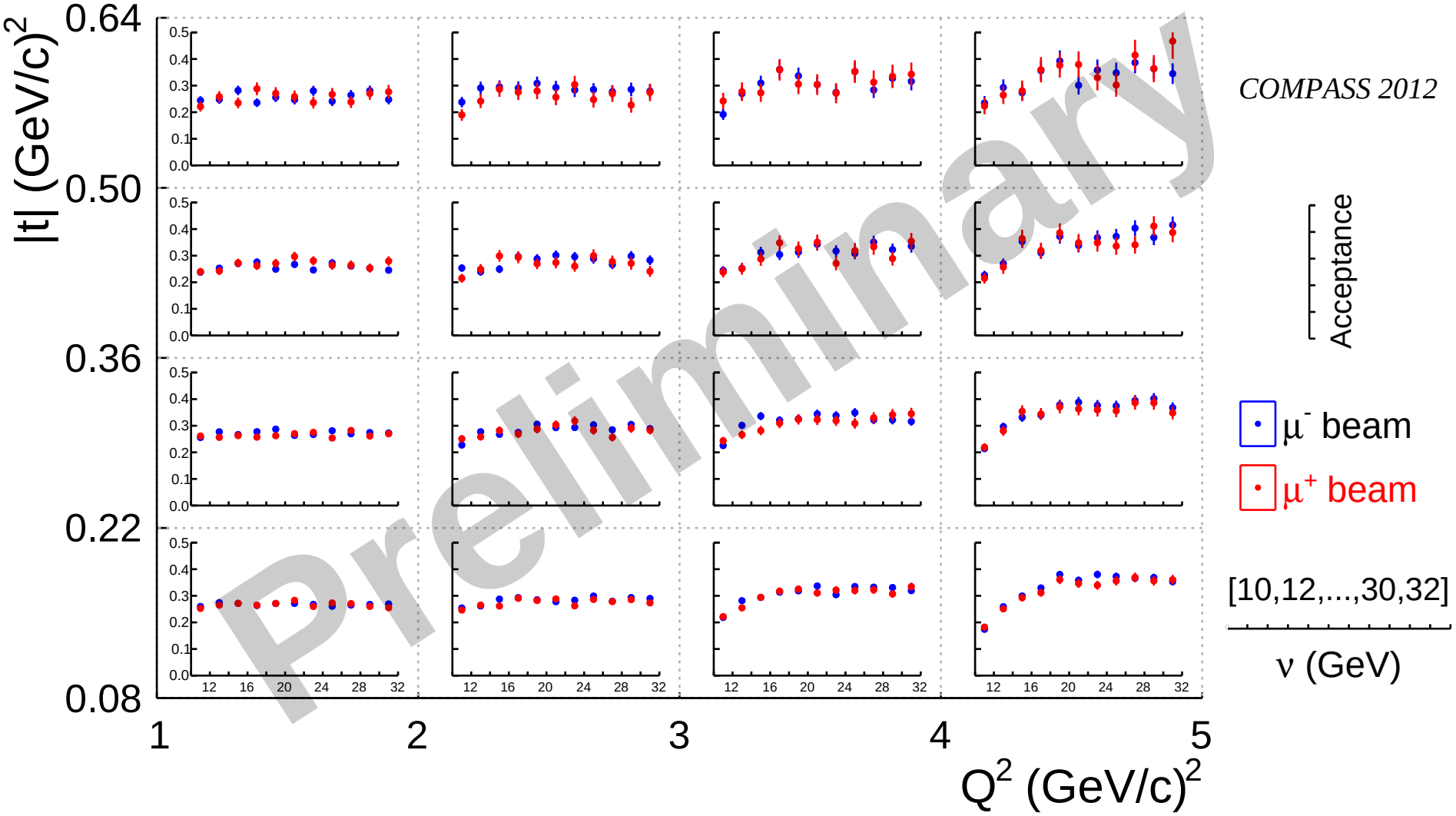
→ **Compton Form Factors (CFFs)**:

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

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

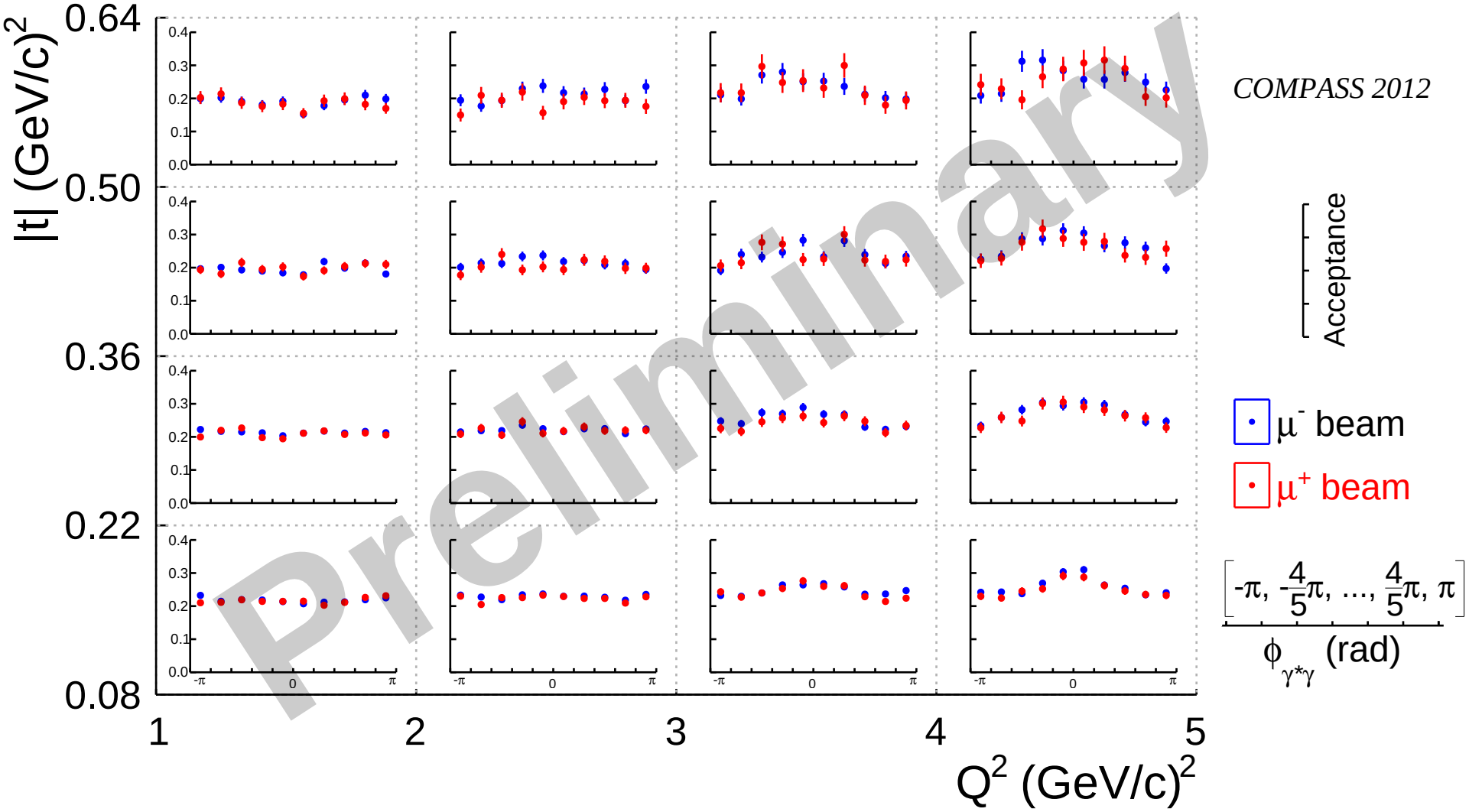
$\mathcal{D}(t)$ connected to **energy-momentum tensor** (Polyakov, PLB 555 (2003) 57-62)

Experimental acceptance for DVCS events



Acceptance binning in Q^2, ν and |t|

Experimental acceptance for DVCS events



Symmetric acceptance around $\phi = 0$

Proton « radius » measured at JLab

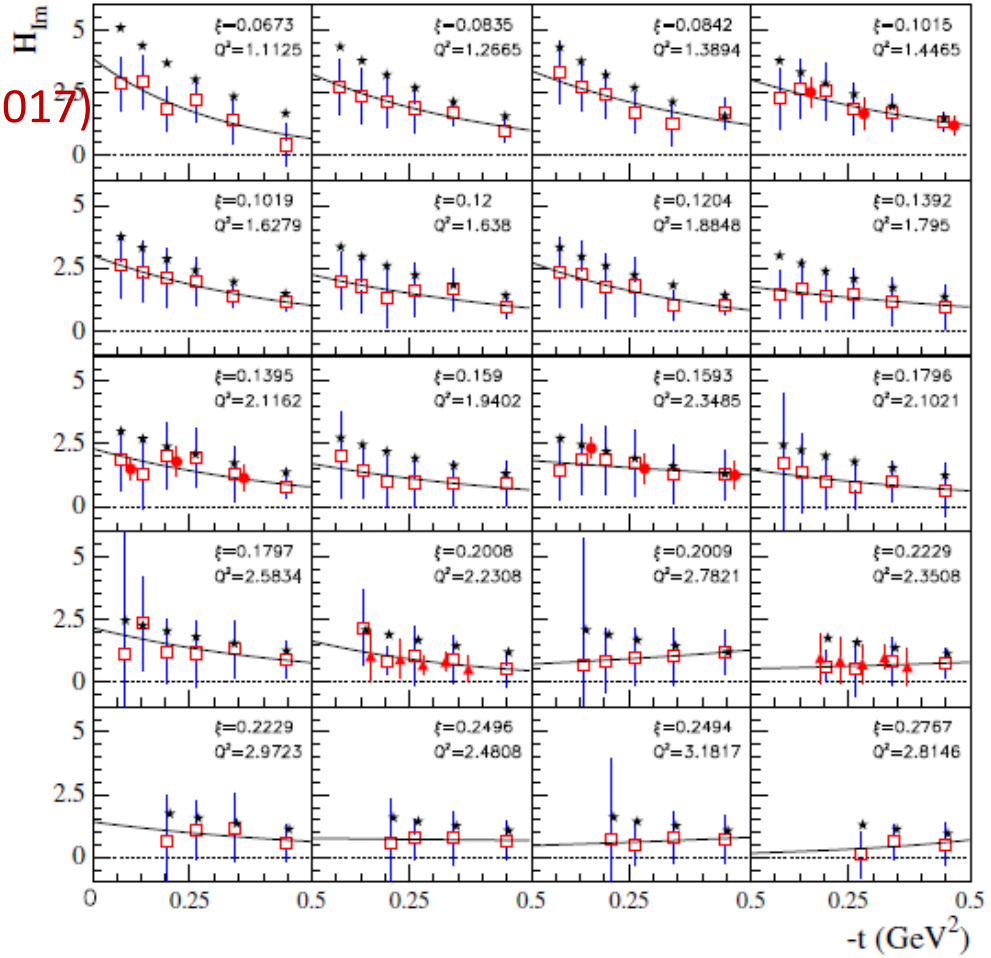
Fit of 8 CFFs at L.O and L.T.

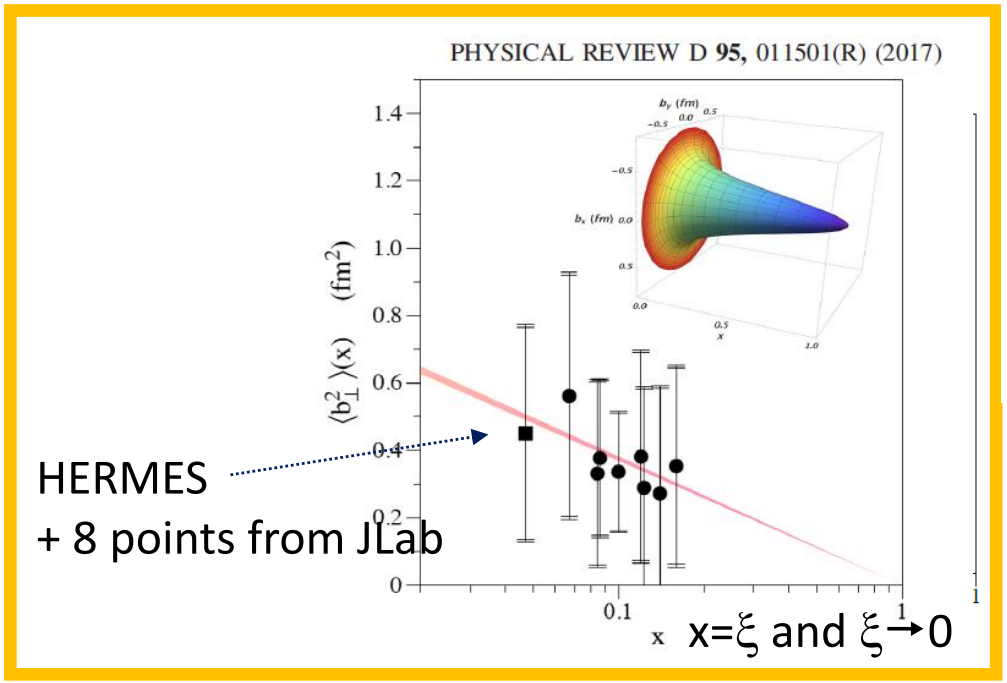
Dupré, Guidal, Vanderhaeghen, PRD95, 011501(R)(2017)

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

- □ CLAS σ and Δσ
- ▲ HallA σ and Δσ
- ● CLAS A_{UL} and A_{LL}
- ★ VGG model
- — Fit $A\, e^{-B'|t|}$

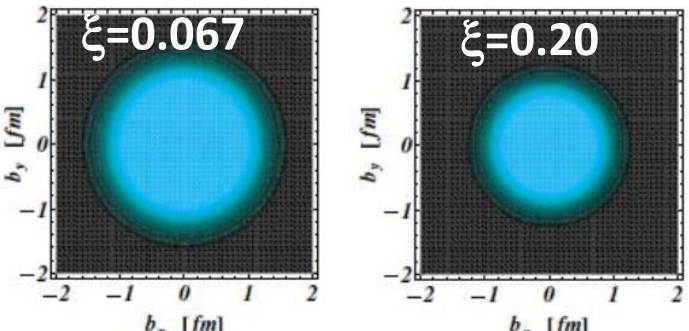
$$\langle b_\perp^2 \rangle \approx 4\, B'$$





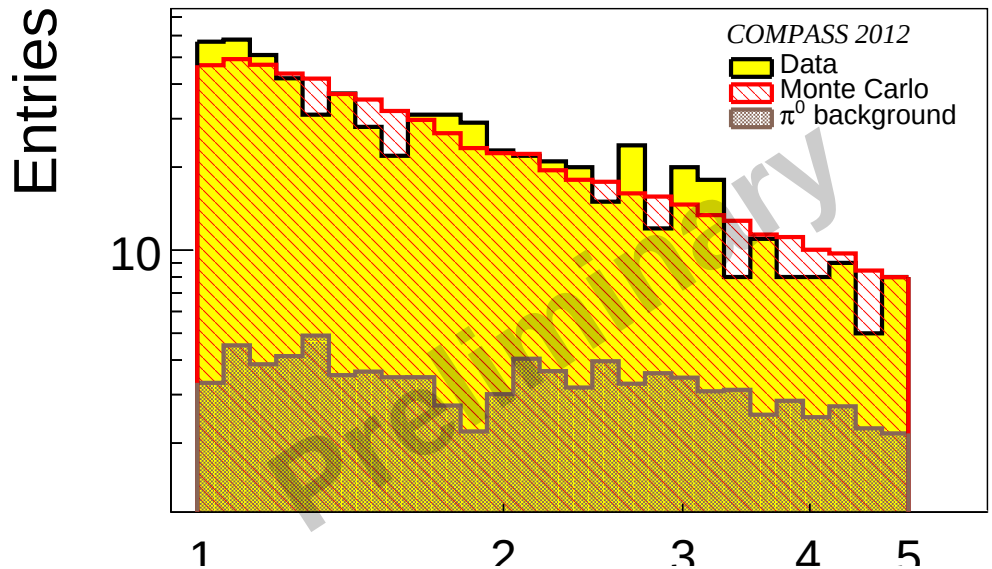
HERMES
+ 8 points from JLab

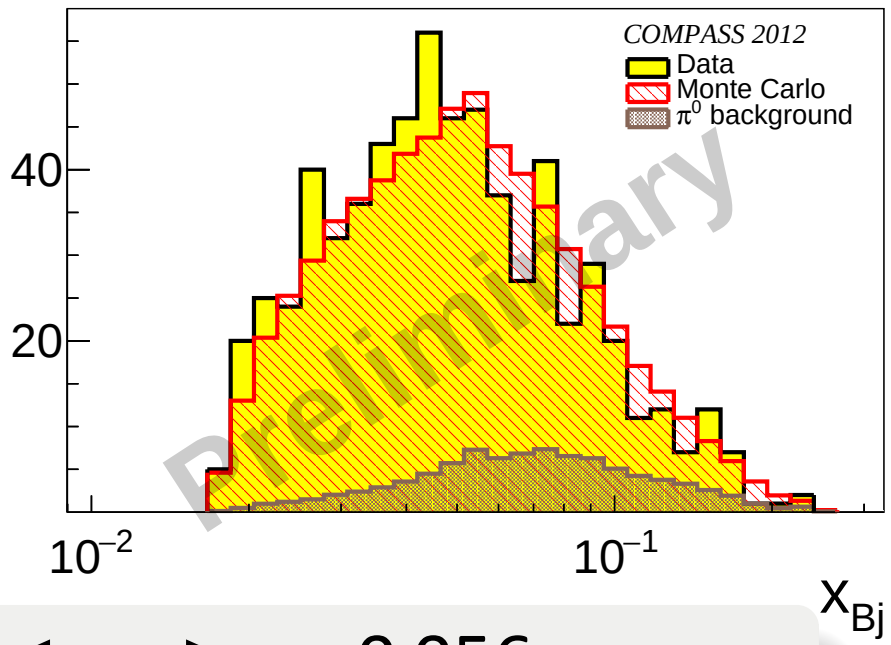
x=ξ and ξ→0

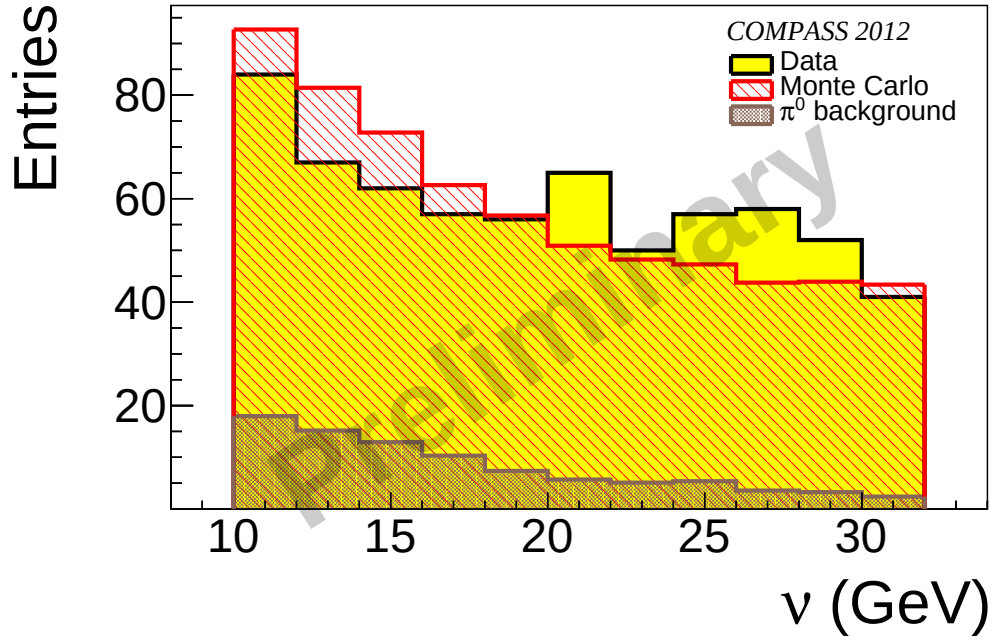


Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013)

Kinematic Distributions for DVCS







$< x_{Bj} > = 0.056$

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

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

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

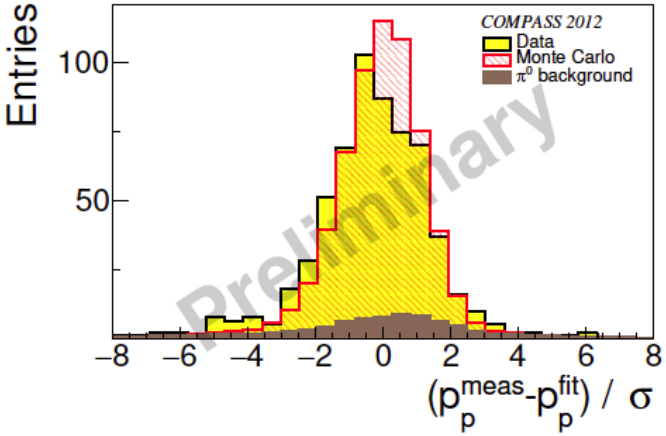
2016-7: **2 x 6 months** with LH_2 target and recoil det. → **GPD H**

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

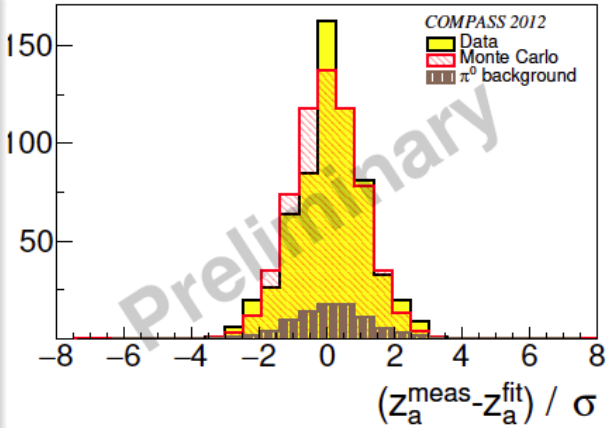
Kinematically constrained fit

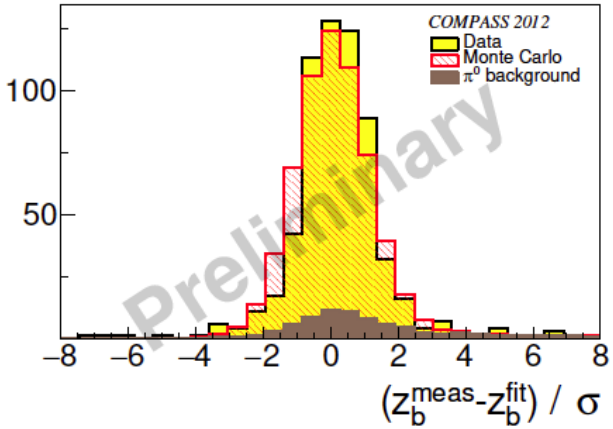
- constrained χ^2 minimisation with NDF=9
- full 4-momentum conservation of the reaction $\mu p \to \mu p \gamma$
- vertex constraints for μ,μ' and p' included in the fit

$\Rightarrow$ most accurate determination of t

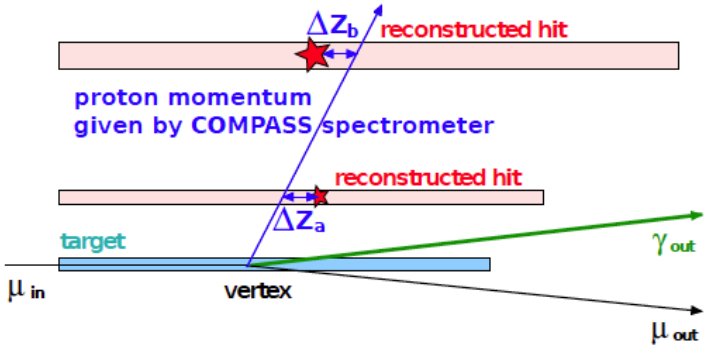


recoil proton momentum



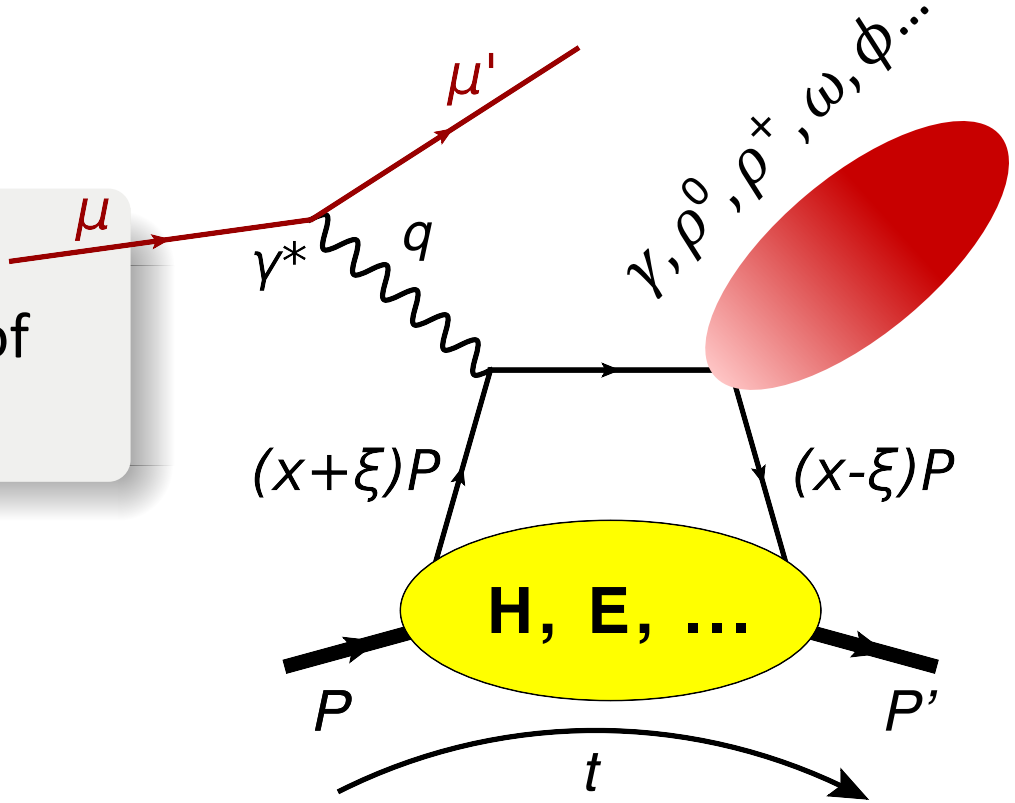


recoil proton direction



Introduction to GPDs

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



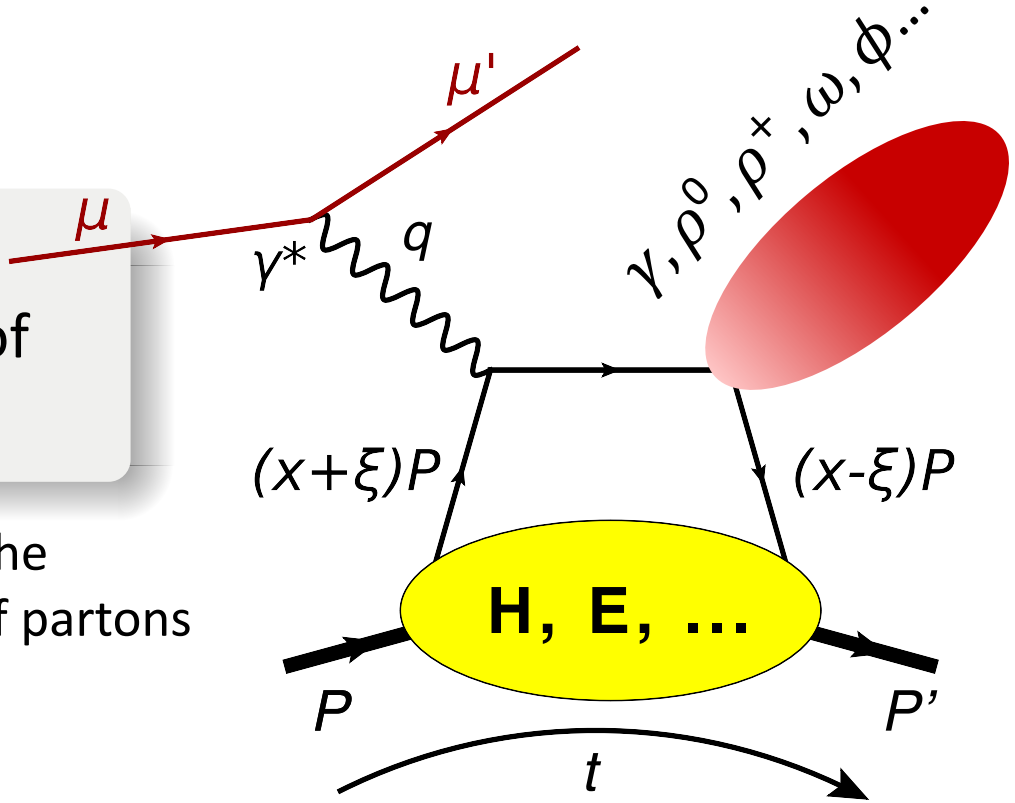
Definition of variables:

- 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



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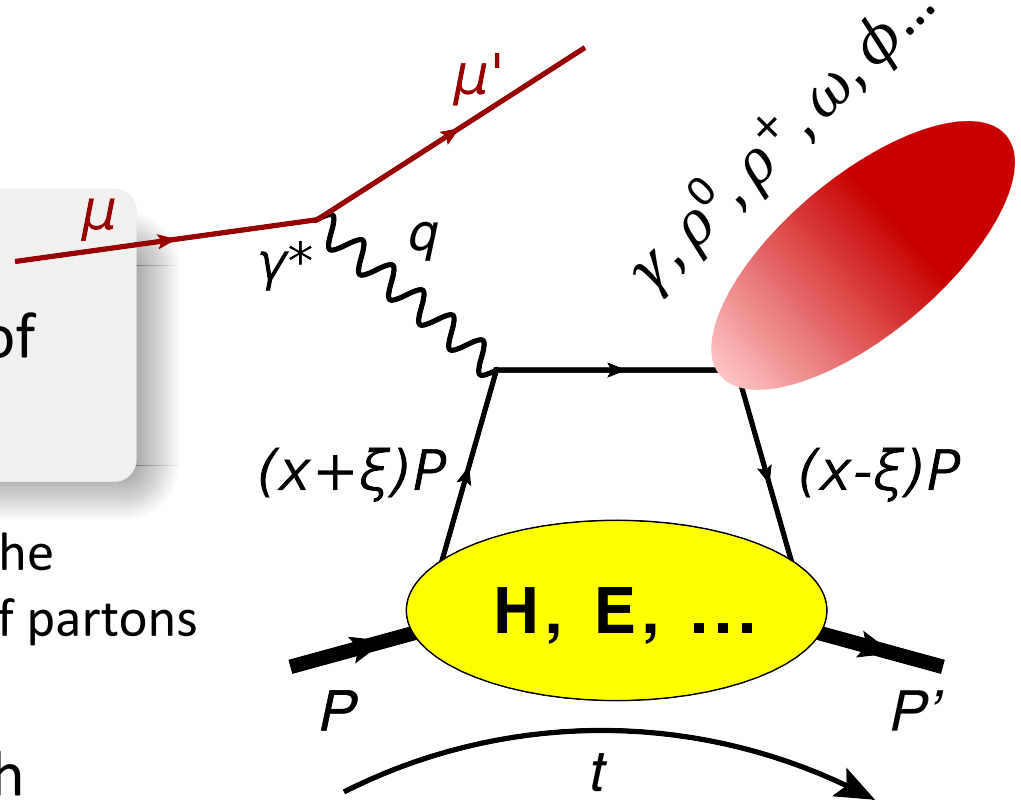


They encode **CORRELATIONS** between the long. mom. **x** and the transv. position of partons

Experimentally accessible through Compton Form Factors (CFFs):

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

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

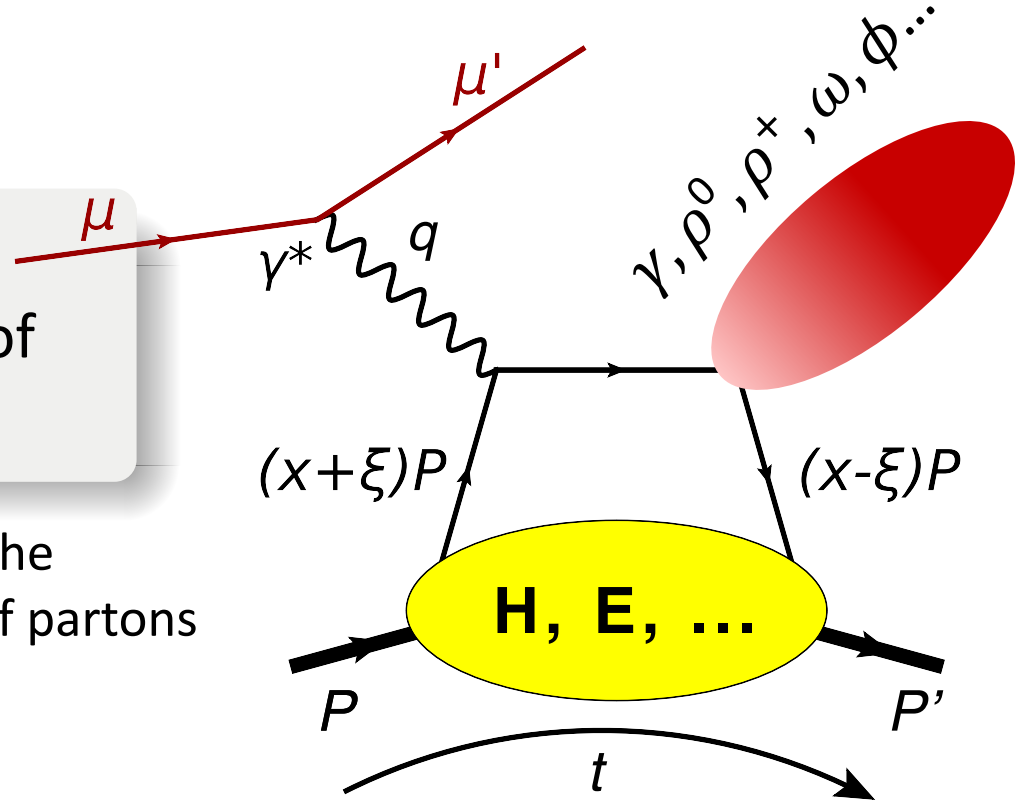
Definition of variables:

- 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

$\mathcal{D}(\mathrm{t})$ 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"**:

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

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

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

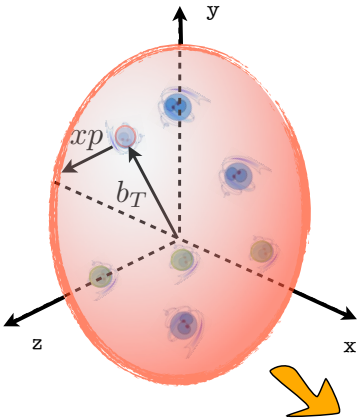
$b_\perp$: distance between the struck parton and center of momentum

Towards a 3D Picture of the Nucleon…

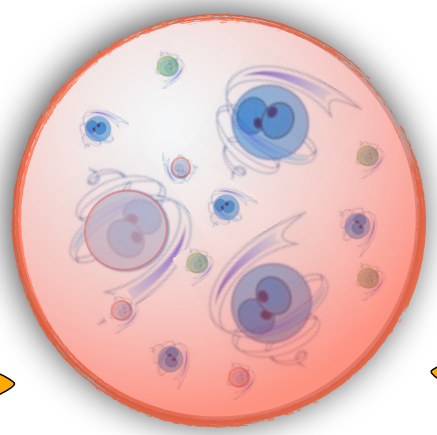
Form Factors (t)

Fourier transform (b_T)
& $\int$ GPDs(x, t) … dx

GPDs (x, b_T)



$\int$ GPDs(x,b_T) … db_T

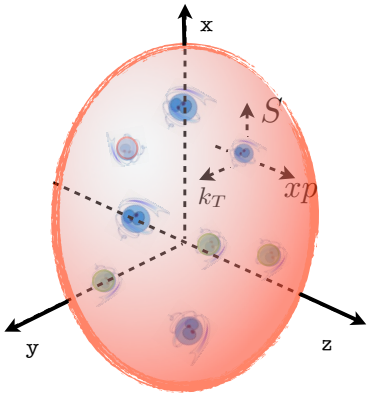


Wigner Distributions

$\int$ dk_T

$\int$ d$b_\perp$

TMDs (x, k_T)



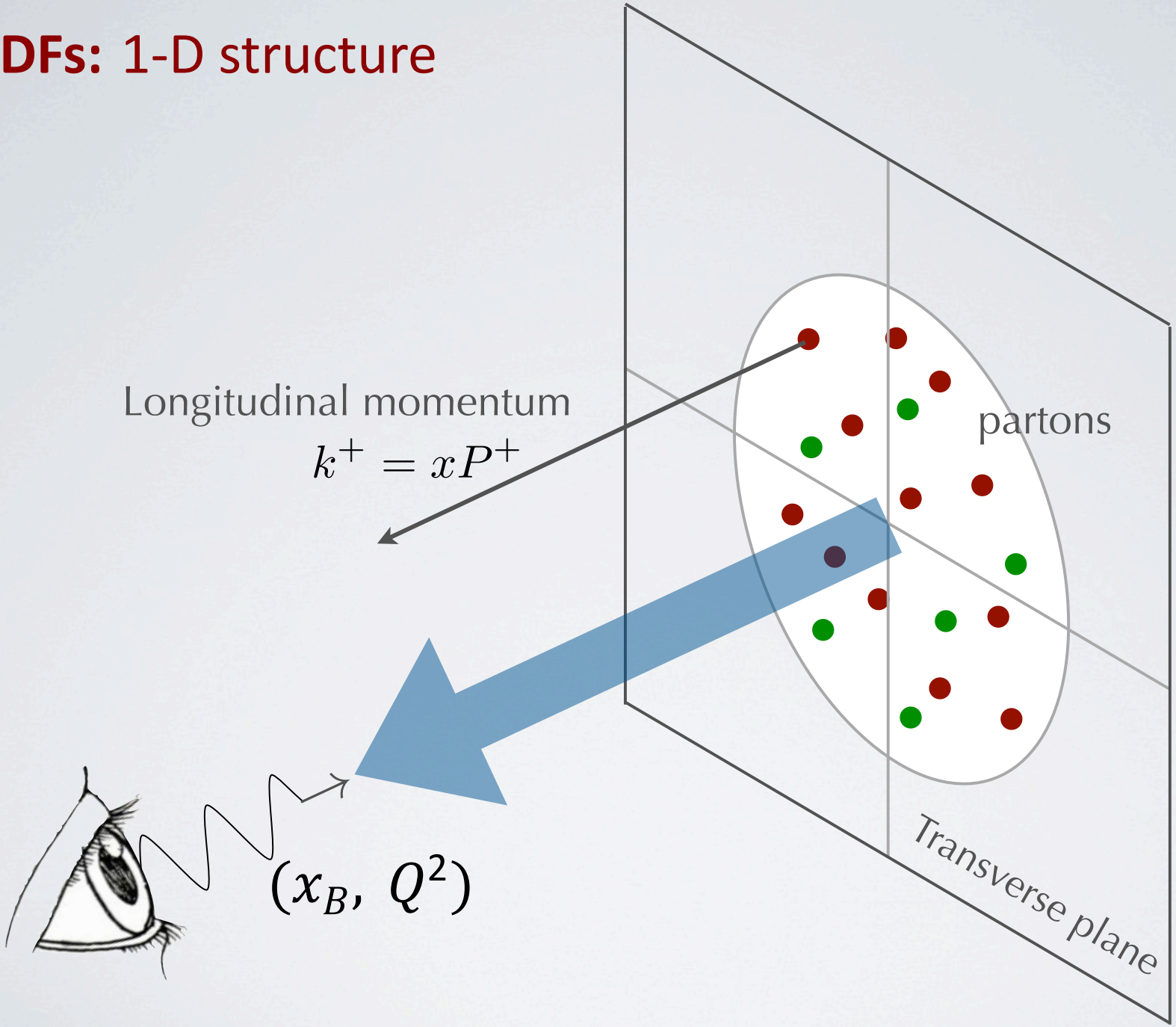
$\int$ TMDs(x,k_T) … dk_T

PDFs (x)

PDFs → $\Delta\Sigma$, ΔG

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

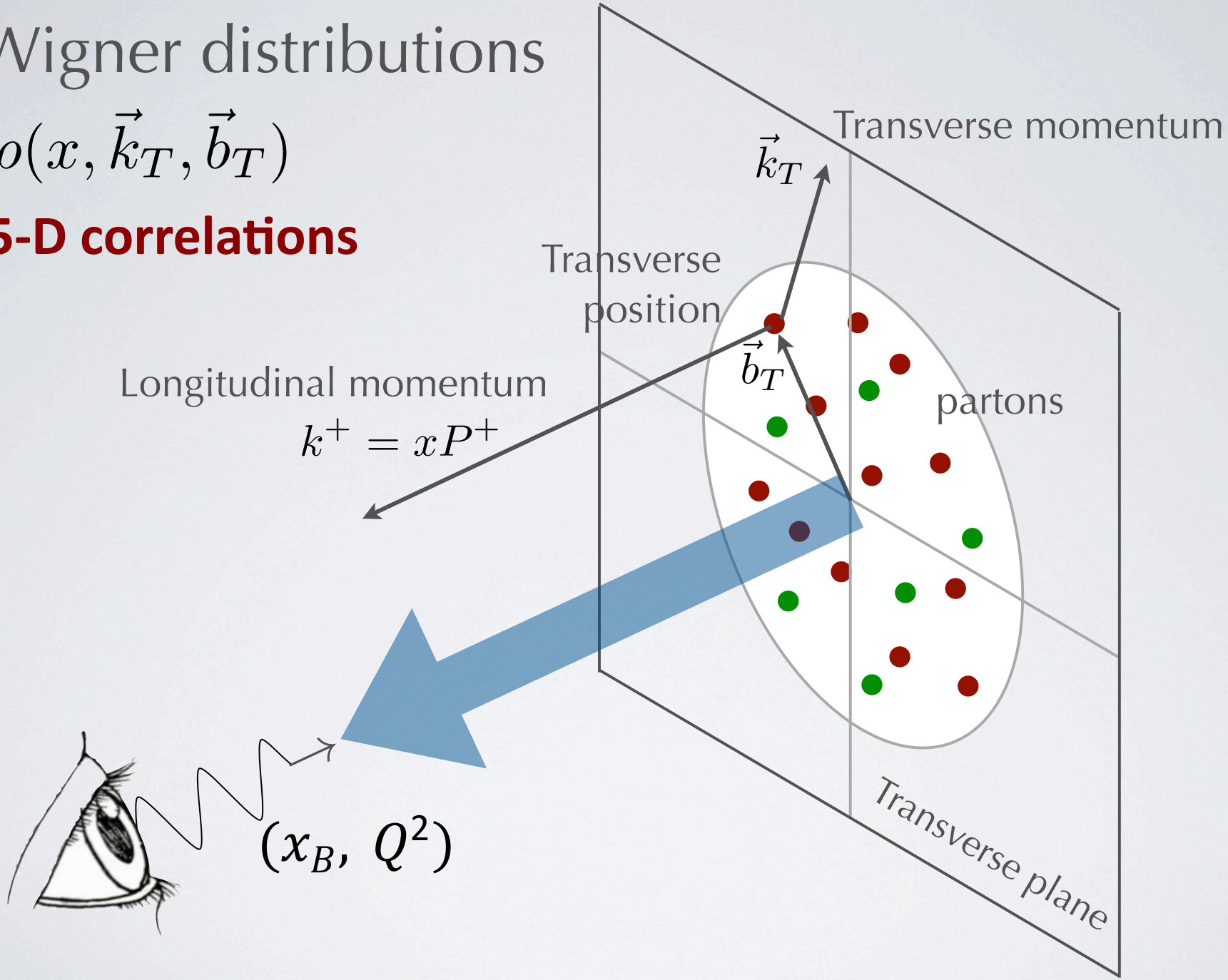
PDFs: 1-D structure



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)