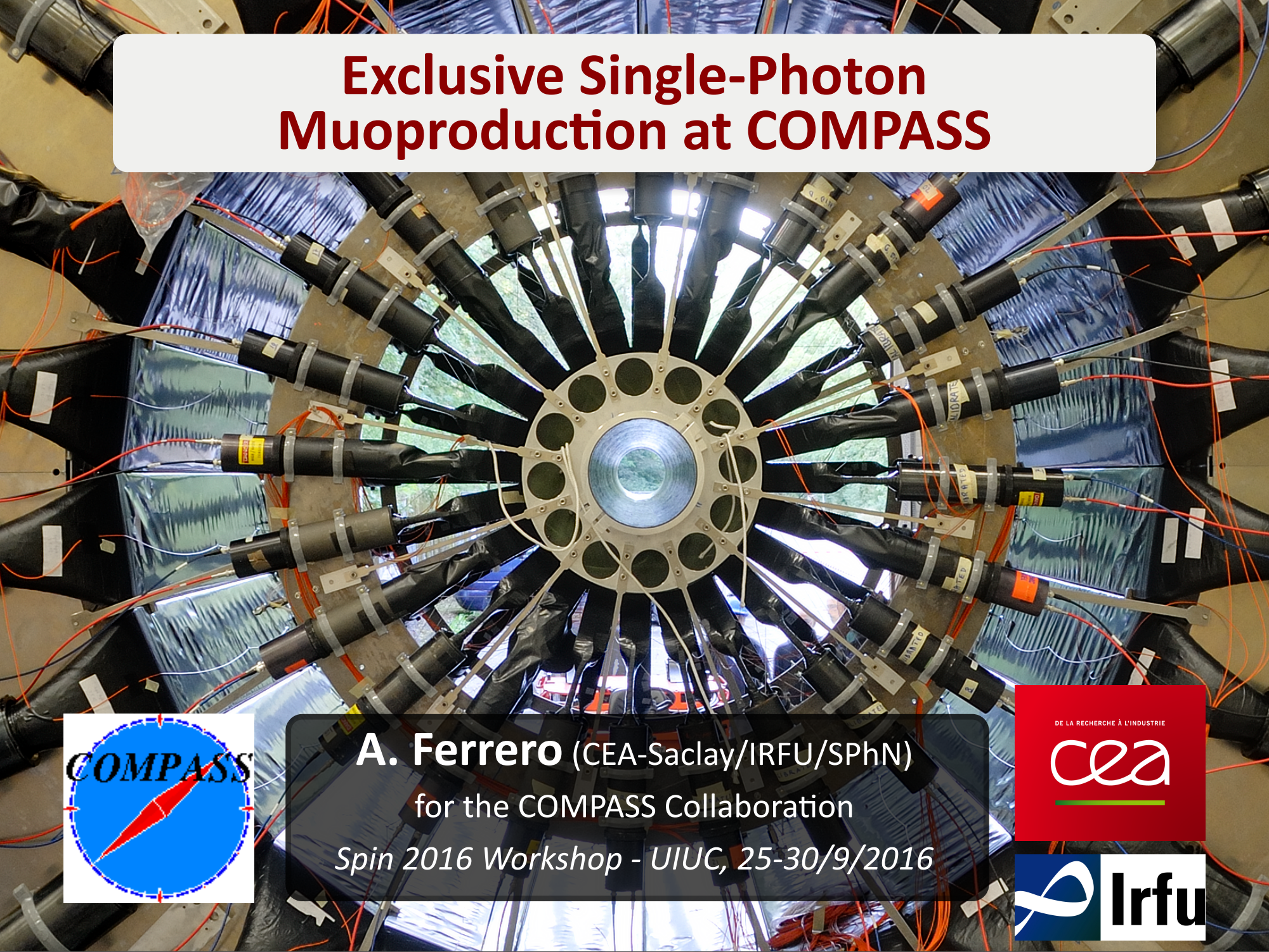
Exclusive Single-Photon Muoproduction at COMPASS



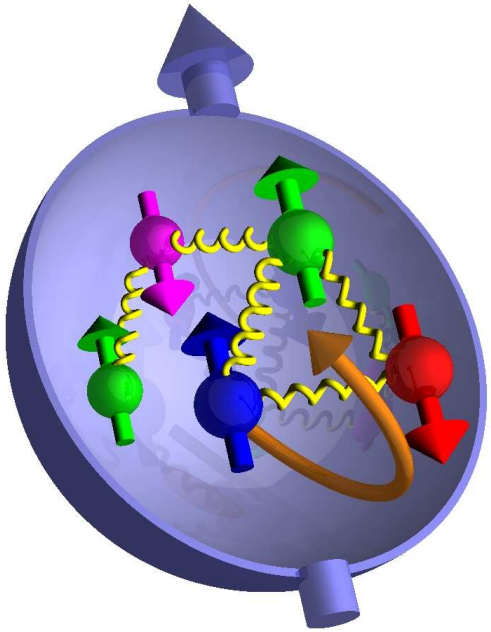
A. Ferrero (CEA-Saclay/IRFU/SPhN)

for the COMPASS Collaboration

Spin 2016 Workshop - UIUC, 25-30/9/2016

Where does the spin of the nucleons come from?

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

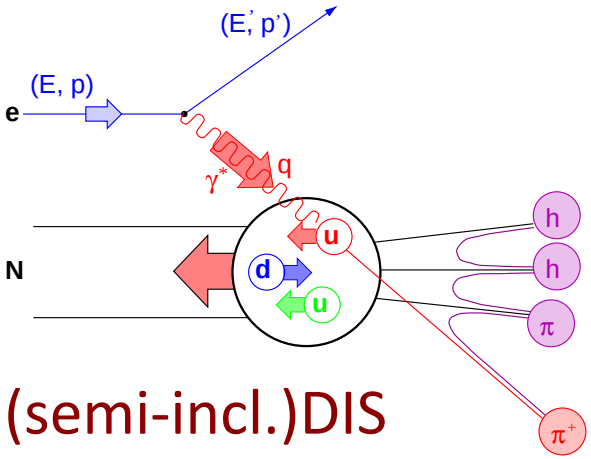


The "proton spin crisis" (EMC, 1988):

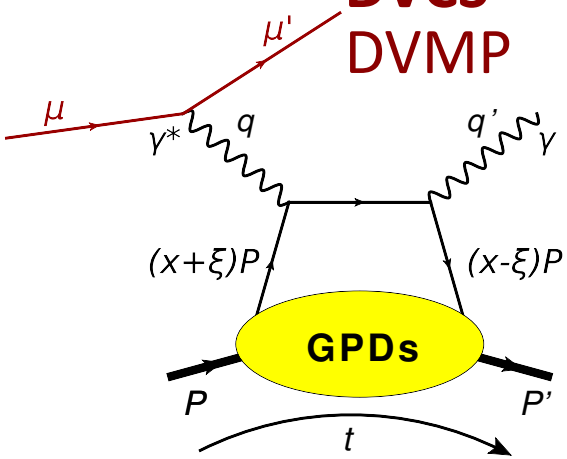
$$\Delta\Sigma \rightarrow \begin{cases} \text{Static quark model}: \Delta\Sigma = 1 \\ \text{Weak baryon decays}: \Delta\Sigma \simeq 0.58 \\ \text{Experiments}: \Delta\Sigma \simeq 0.3 \end{cases}$$

ΔG = ?? $L_{q,g}$ = ??

COMPASS experimental tools:

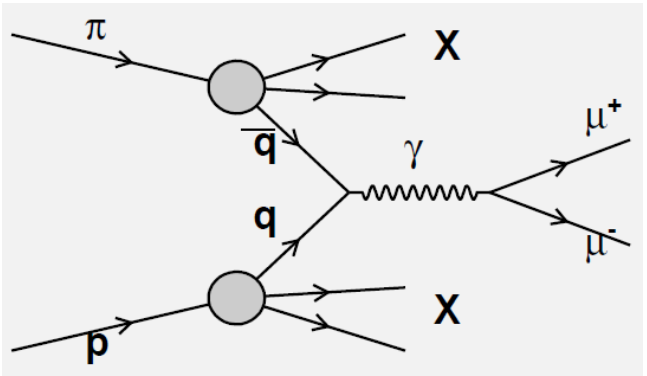


(semi-incl.)DIS



DVCS
DVMP

Drell-Yan process



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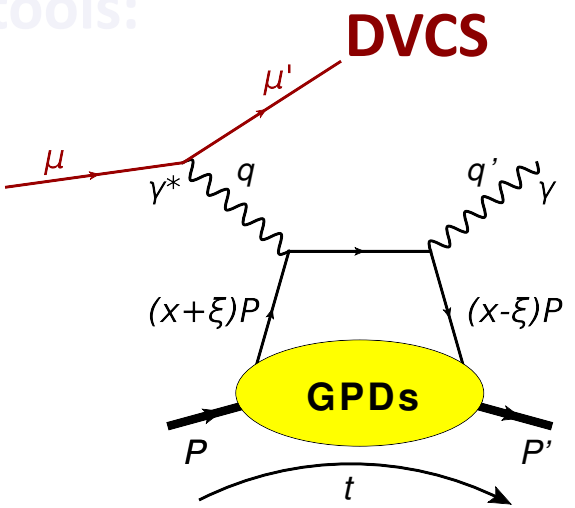
$\Delta G = ??$ $L_q + L_g = ??$

This talk:

COMPASS experimental tools:



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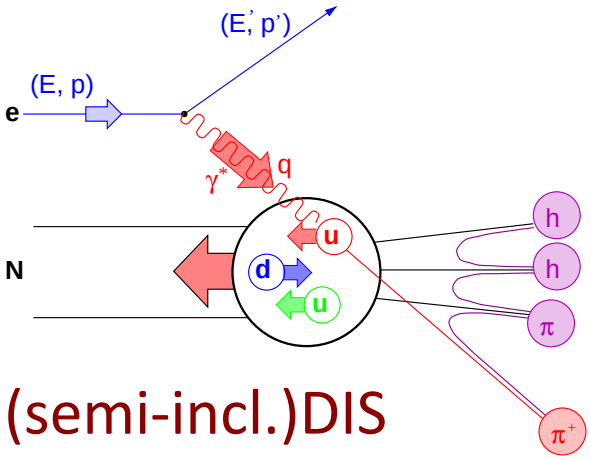
$\Delta G = ??$ $L_{q,g} = ??$

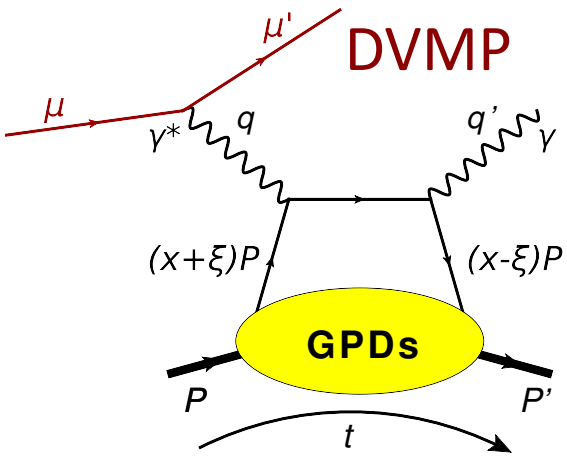
COMPASS experimental tools:

M. Wilfert
V. Andrieux
F. Bradamante
L. Silva
B. Parsamyan
S. Sirtl
N. Makke



(semi-incl.)DIS

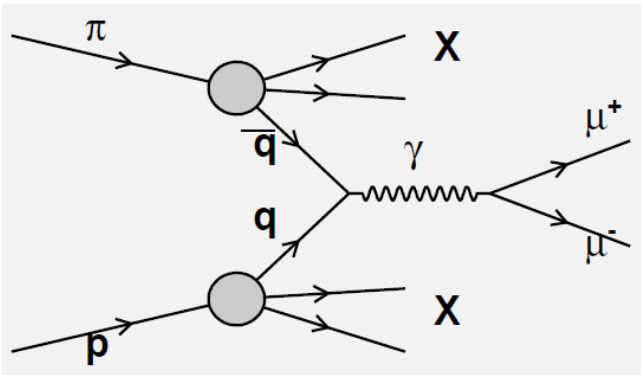
M. Gorzellik



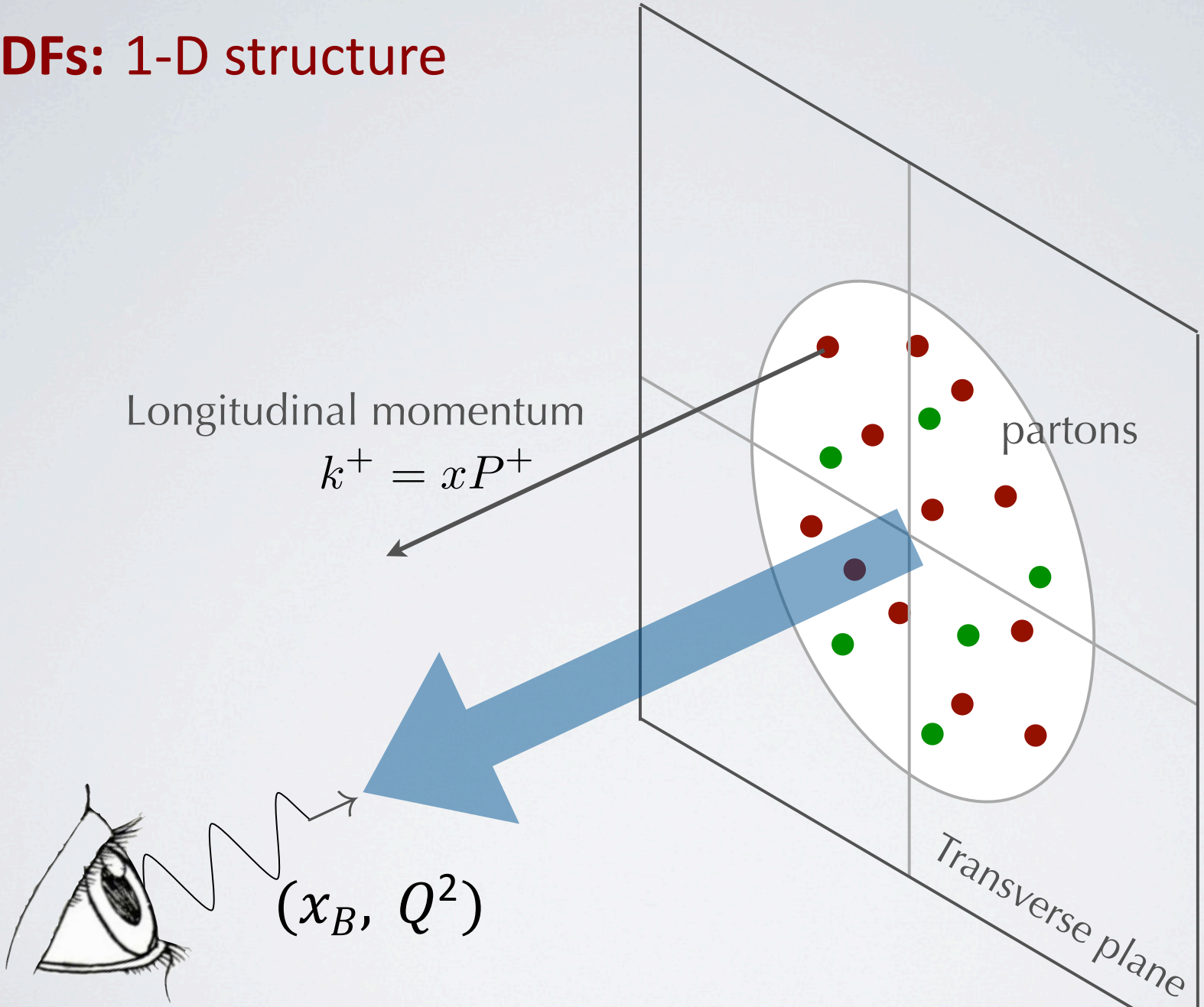
DVMP

J. Matousek
G. Nukazuka
M. Quaresima
B. Parsamyan

Drell-Yan process



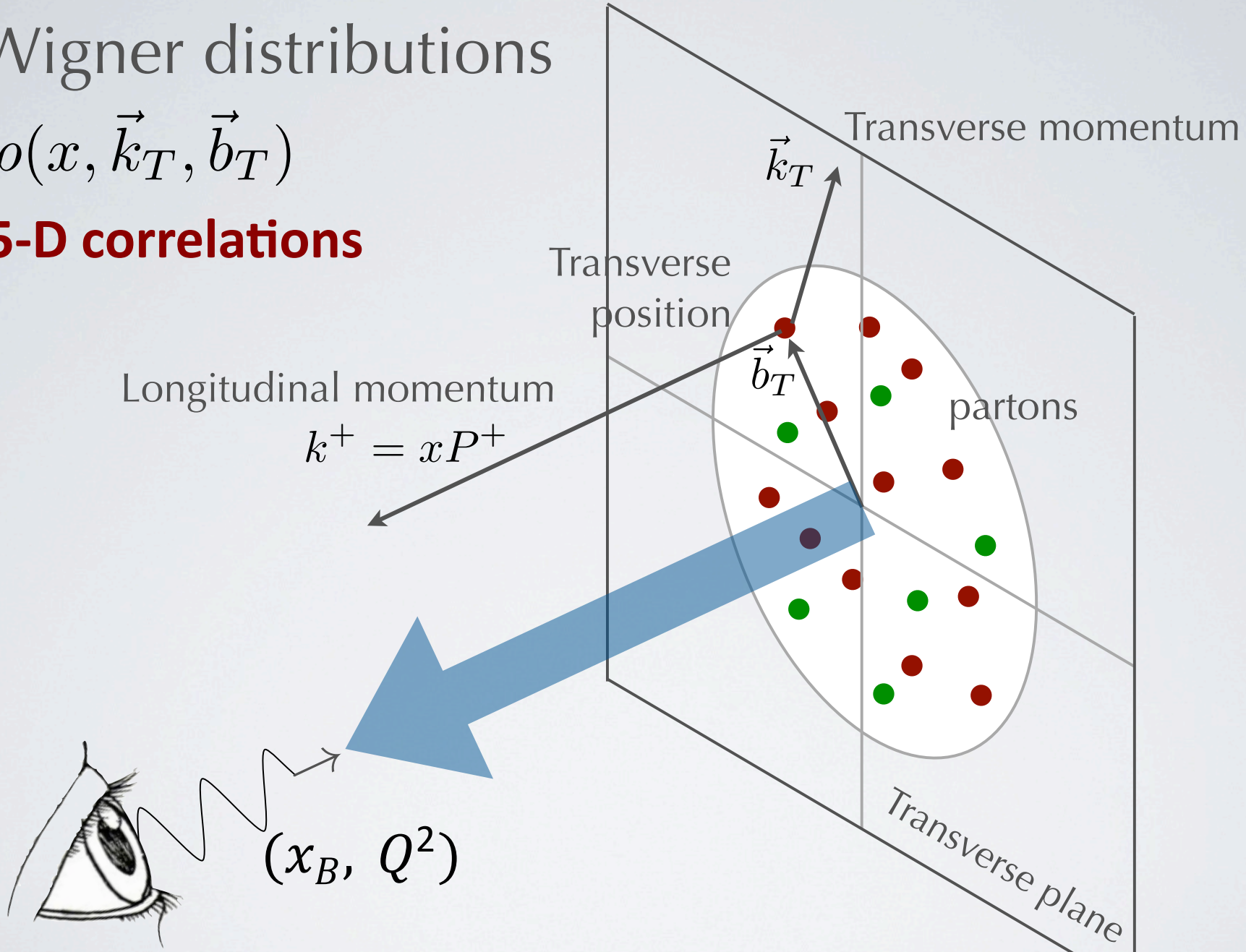
PDFs: 1-D structure



Wigner distributions

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

5-D correlations



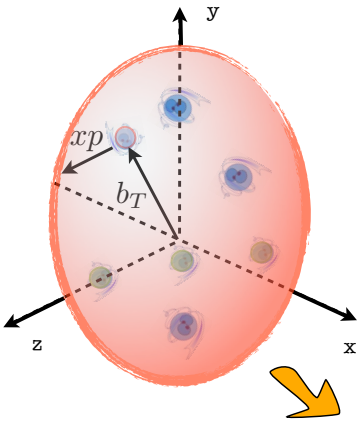
see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Towards a 3D Picture of the Nucleon…

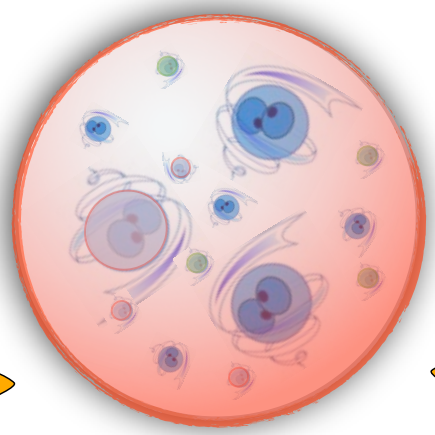
Form Factors (t)

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

GPDs (x, b_T)



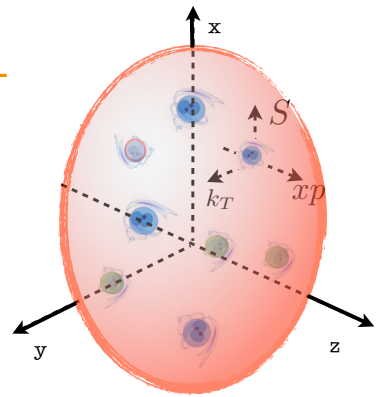
$\int dk_T$



Wigner Distributions

$\int db_\perp$

TMDs (x, k_T)



PDFs (x)

$\int$ GPDs(x,b_T) … db_T

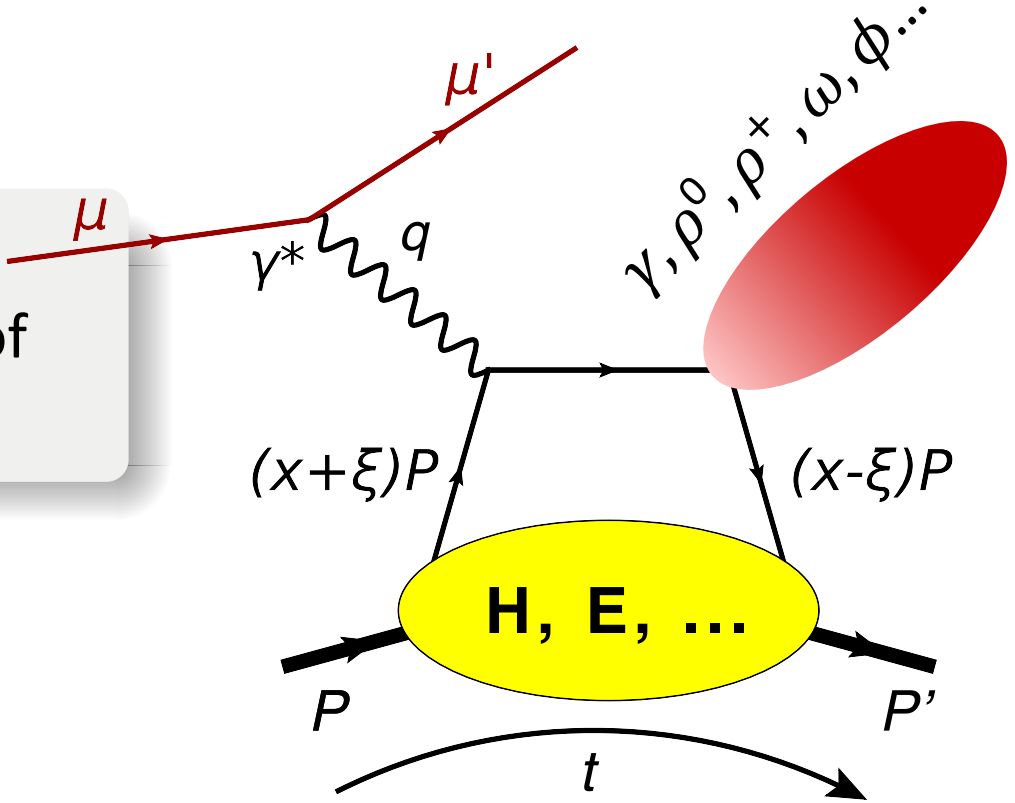
$\int$ TMDs(x,k_T) … dk_T

PDFs → ΔΣ, ΔG

TMDs, GPDs → { nucleon″tomography″ ; $L_{q,g}$

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

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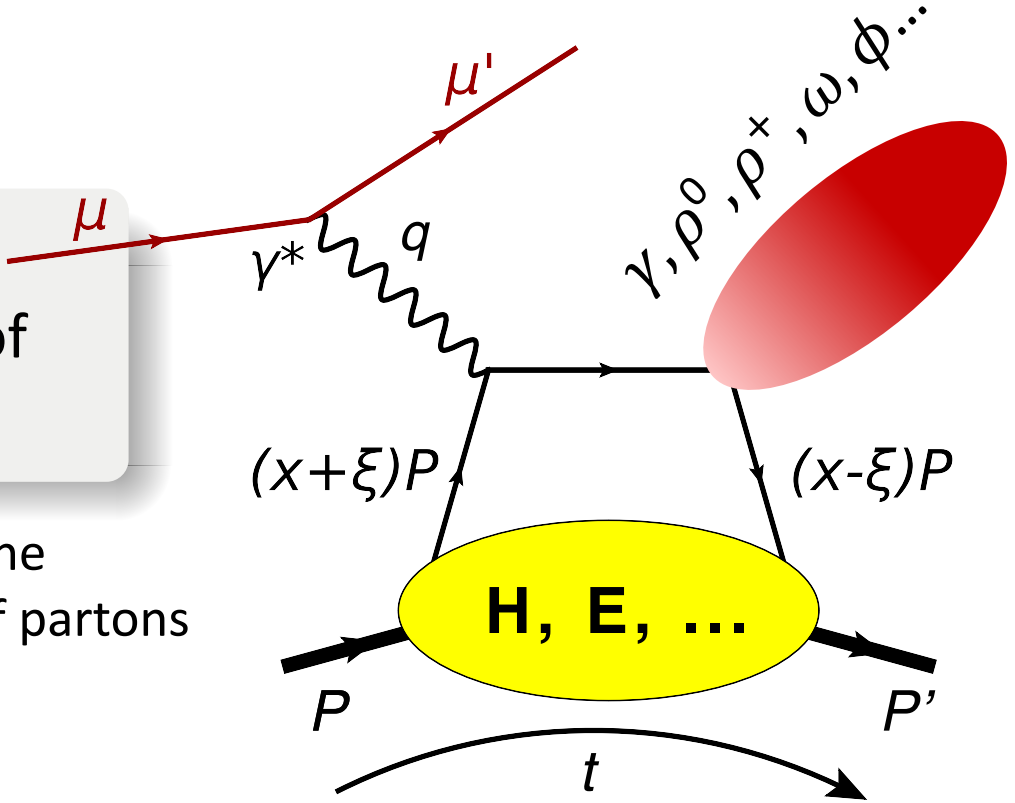

They encode **CORRELATIONS** between the long. mom. **x** and the transv. position of partons

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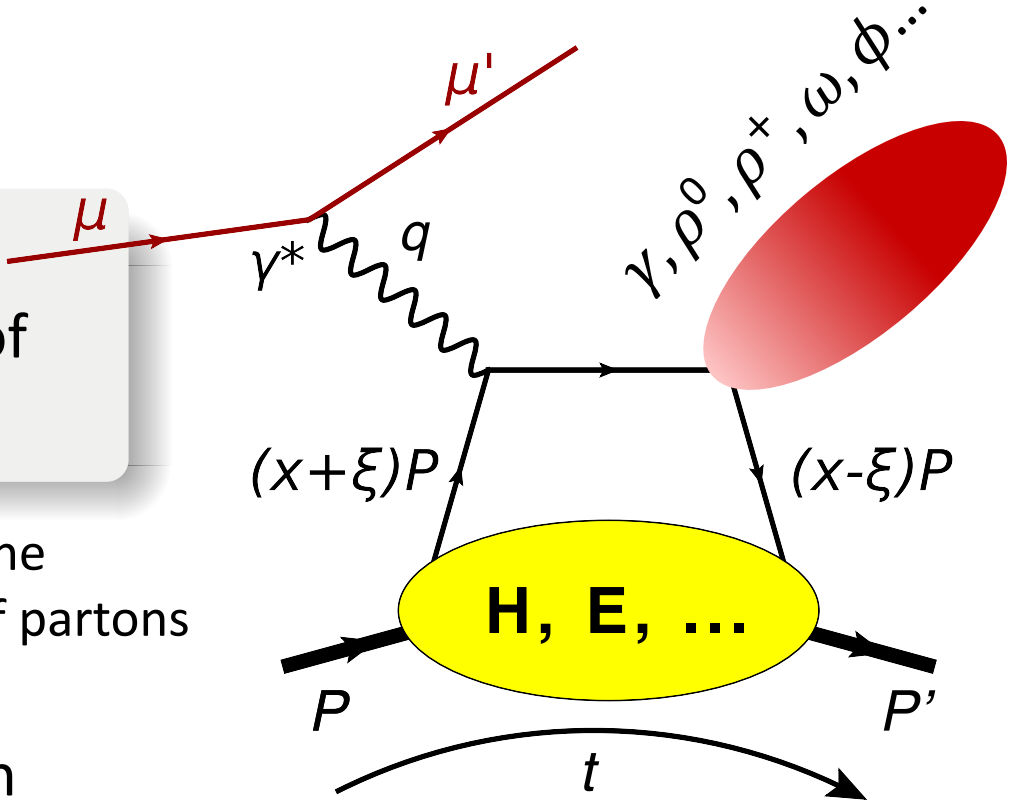

They encode **CORRELATIONS** between the long. mom. **x** and the transv. position of partons

Experimentally accessible through Compton Form Factors (CFFs):

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

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

Definition of variables:

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

Introduction to GPDs

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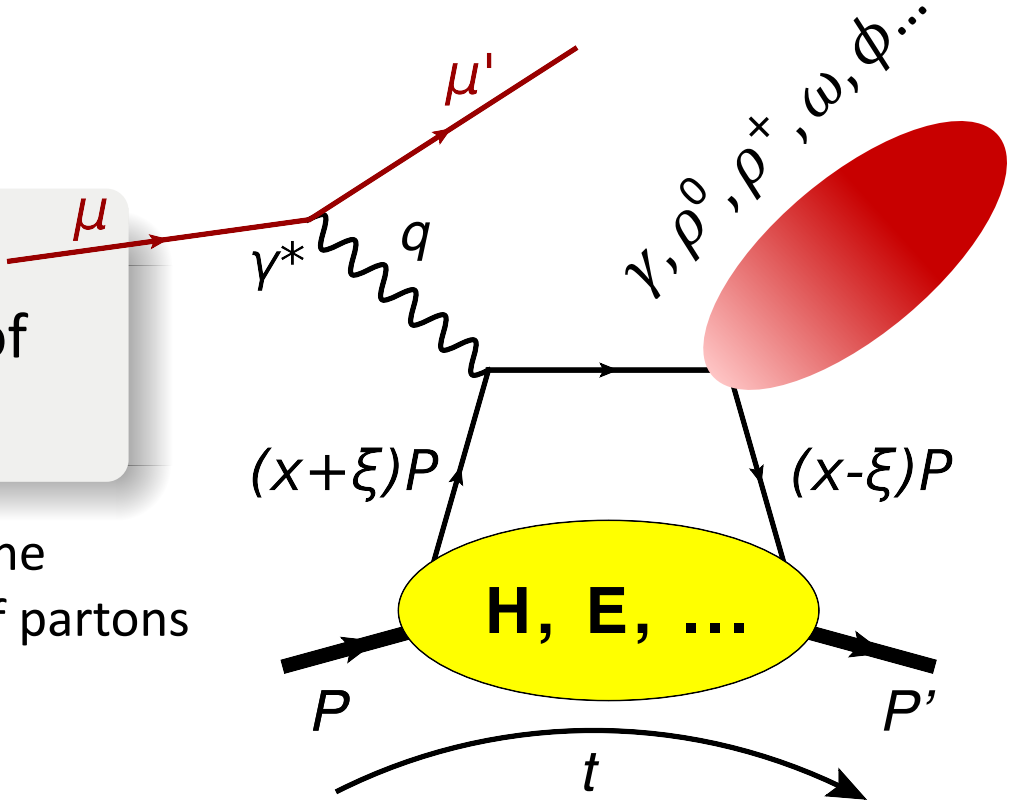

They encode **CORRELATIONS** between the long. mom. **x** and the transv. position of partons

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

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

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

Definition of variables:

- q: exchanged photon four-momentum
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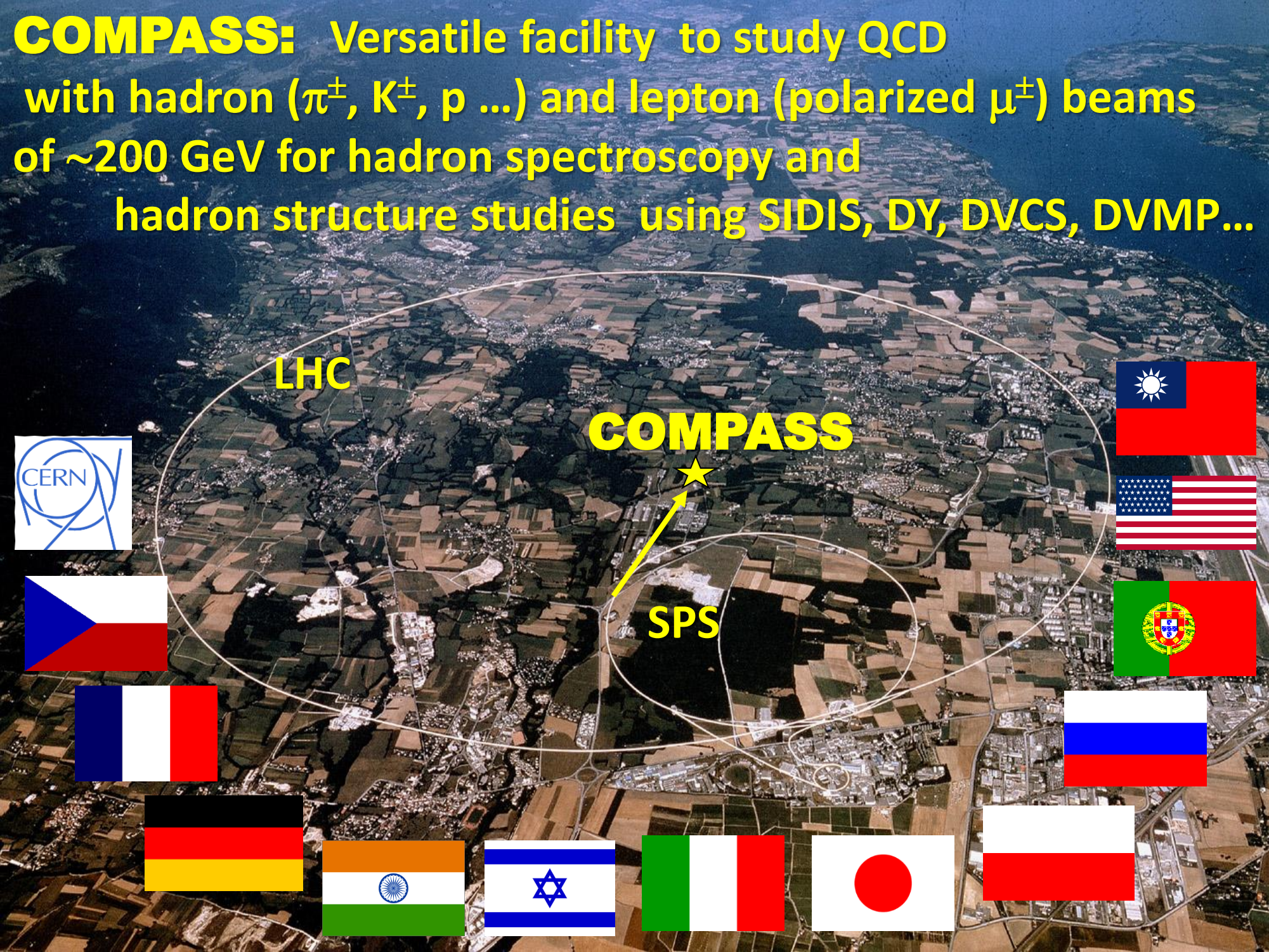
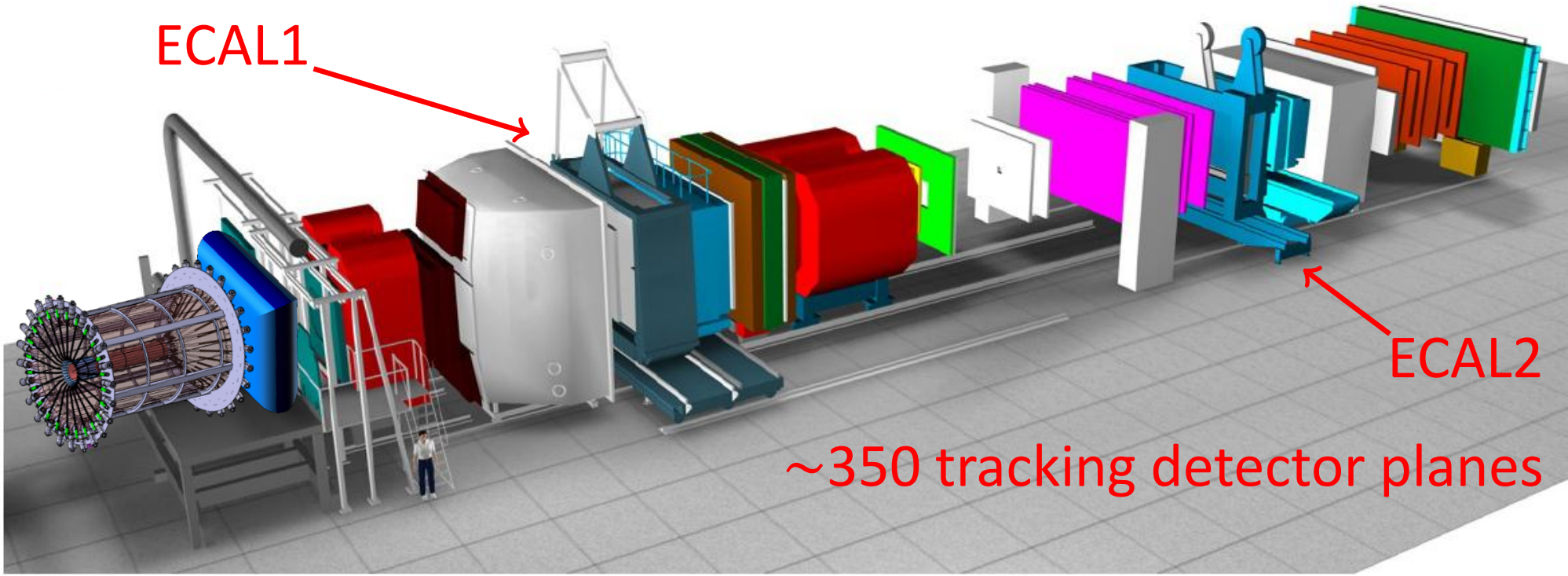
- t: four-momentum transfer

$r_\perp$: distance between the struck parton and the spectators


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…
LHC
COMPASS
SPS
CERN

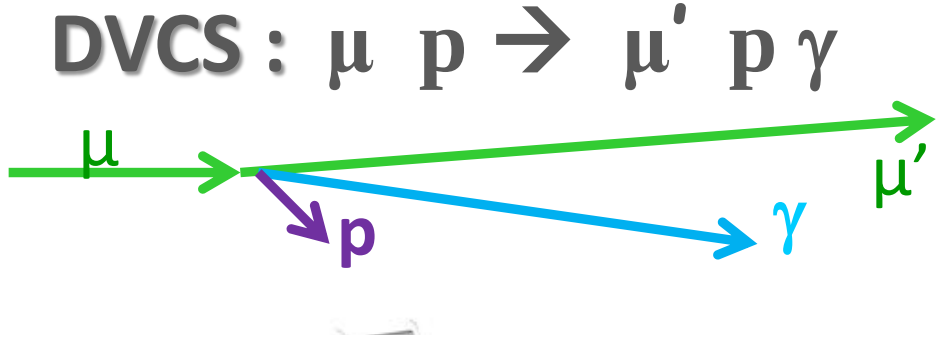
The COMPASS set-up for the GPD programme



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



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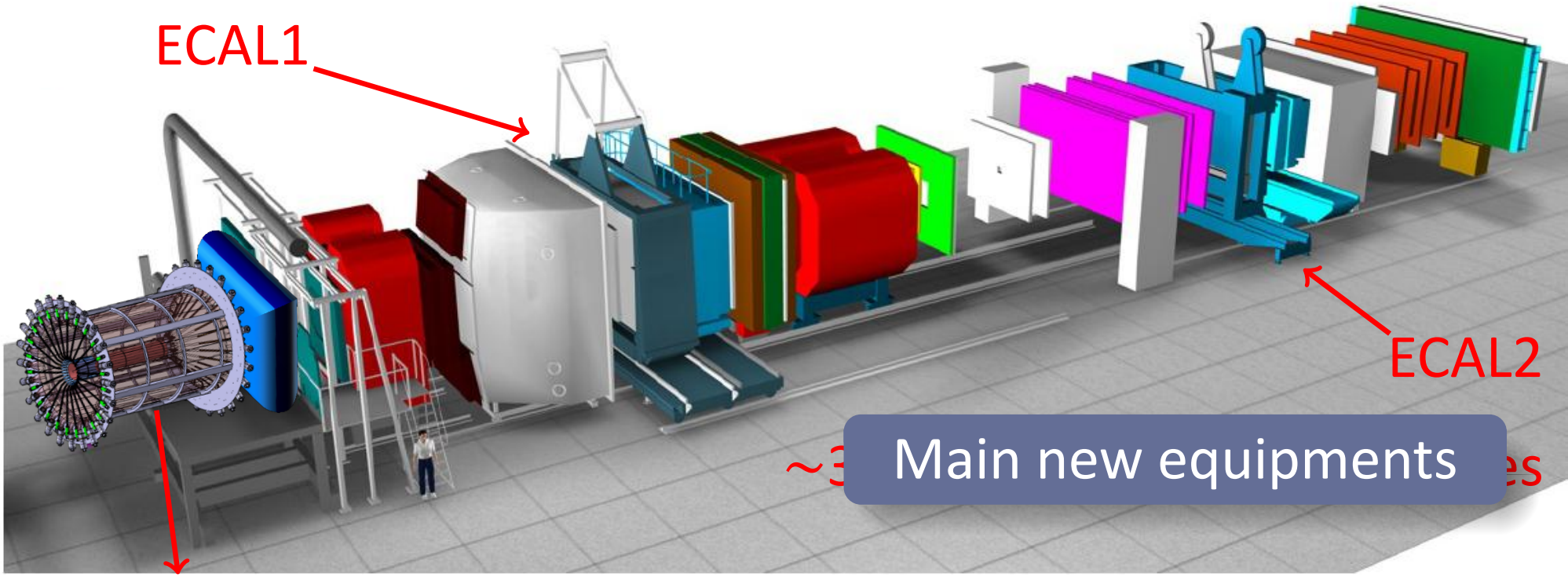
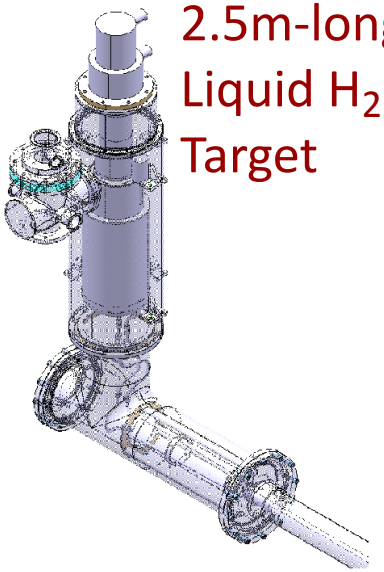




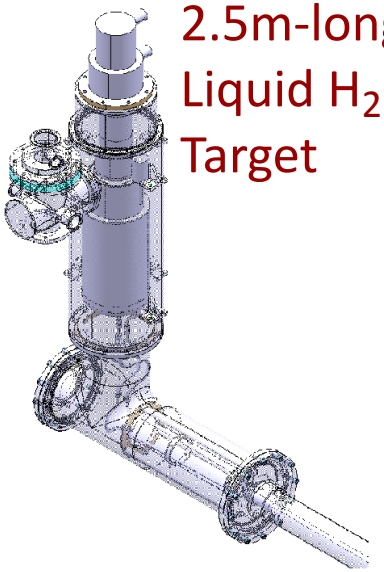
The COMPASS set-up for the GPD programme

ECAL1

ECAL2

Main new equipments

2.5m-long
Liquid H_2
Target

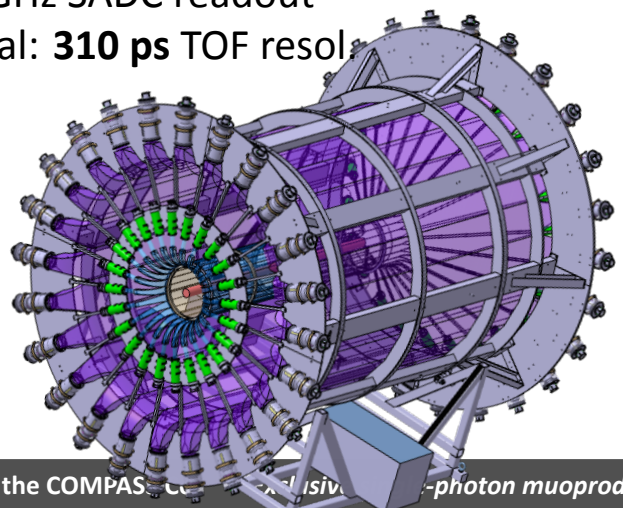


Target TOF System

24 inner & outer scintillators

1 GHz SADC readout

goal: **310 ps** TOF resol



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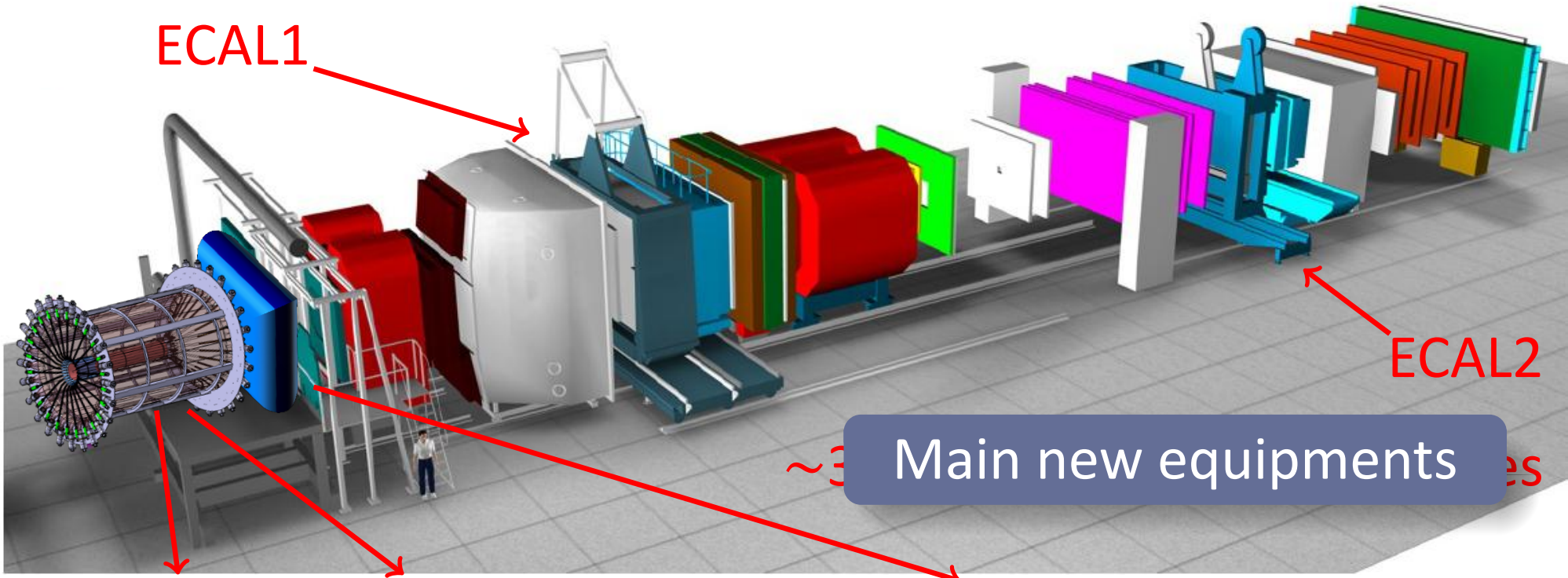

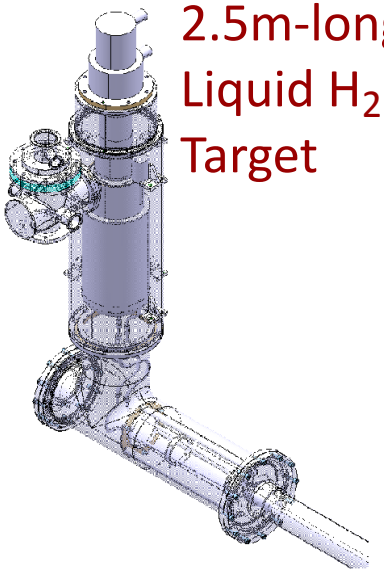

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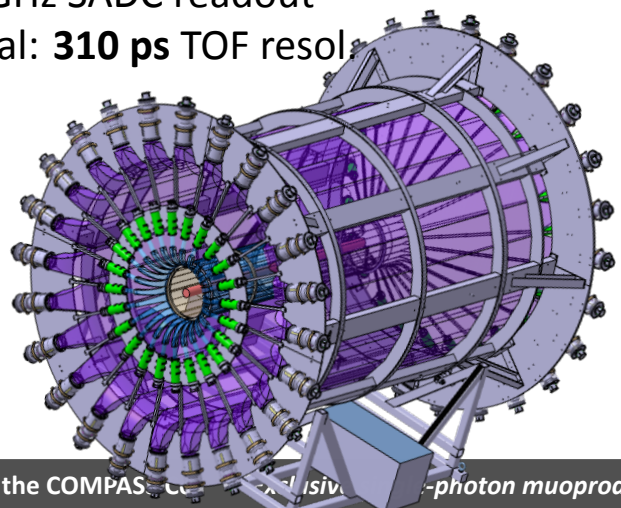
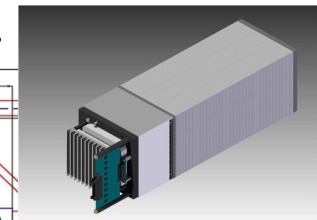
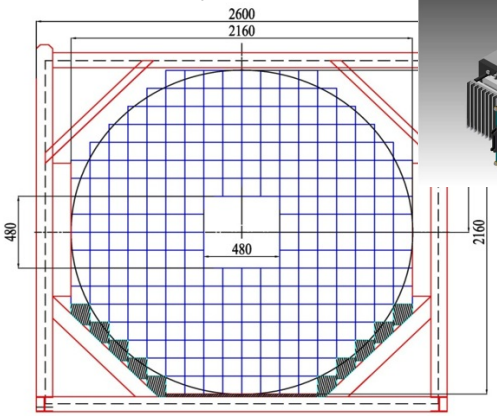


ECAL0 Calorimeter

Shashlyk modules + MAPD readout
~ 2 × 2 m^2, ~2200 ch.



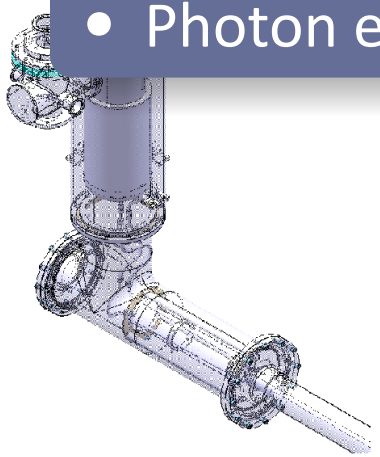


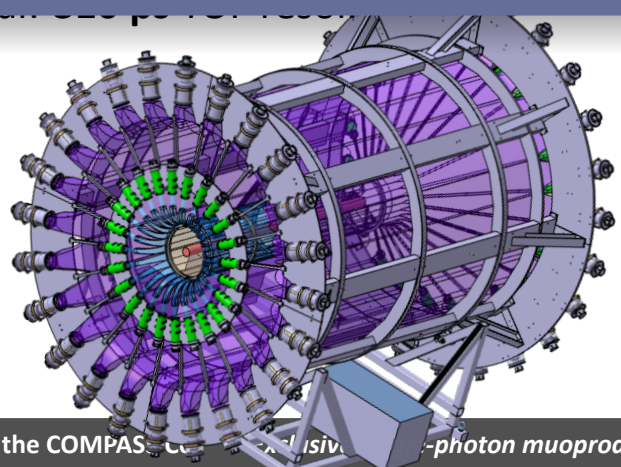
The COMPASS set-up for the GPD programme

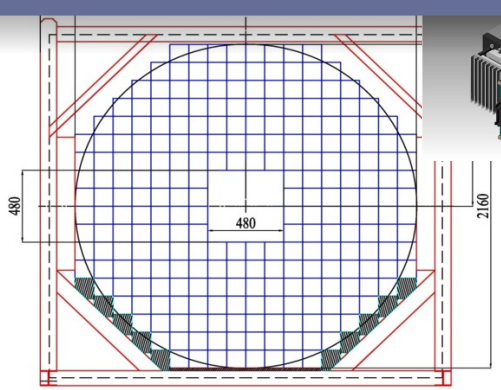
ECAL1

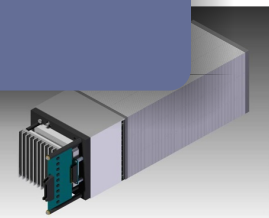
Key features of COMPASS:

- 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

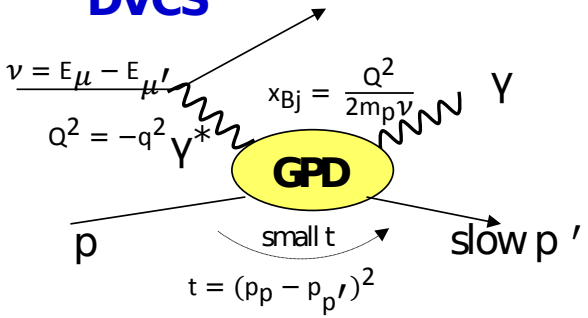




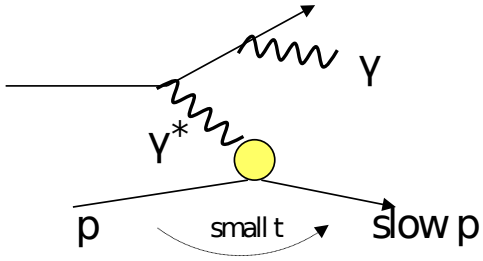


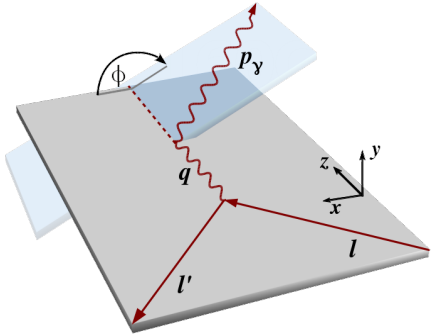


DVCS

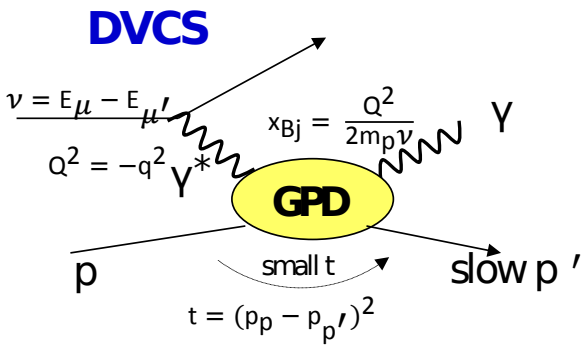


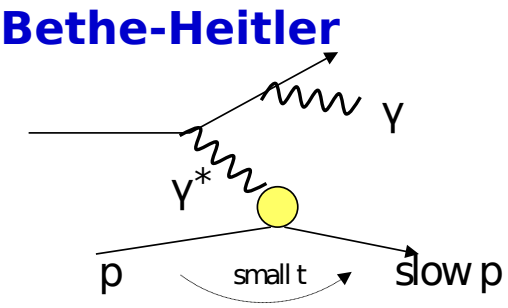
Bethe-Heitler

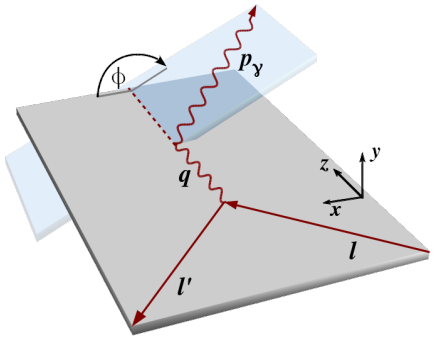




$$d\sigma \propto \underbrace{|T_{DVCS}|^2}_{\text{bilinear combination of GPDs}} + \underbrace{|T_{BH}|^2}_{\text{known to 1 \%}} + \underbrace{\text{interference term}}_{\text{linear combination of GPDs}}$$







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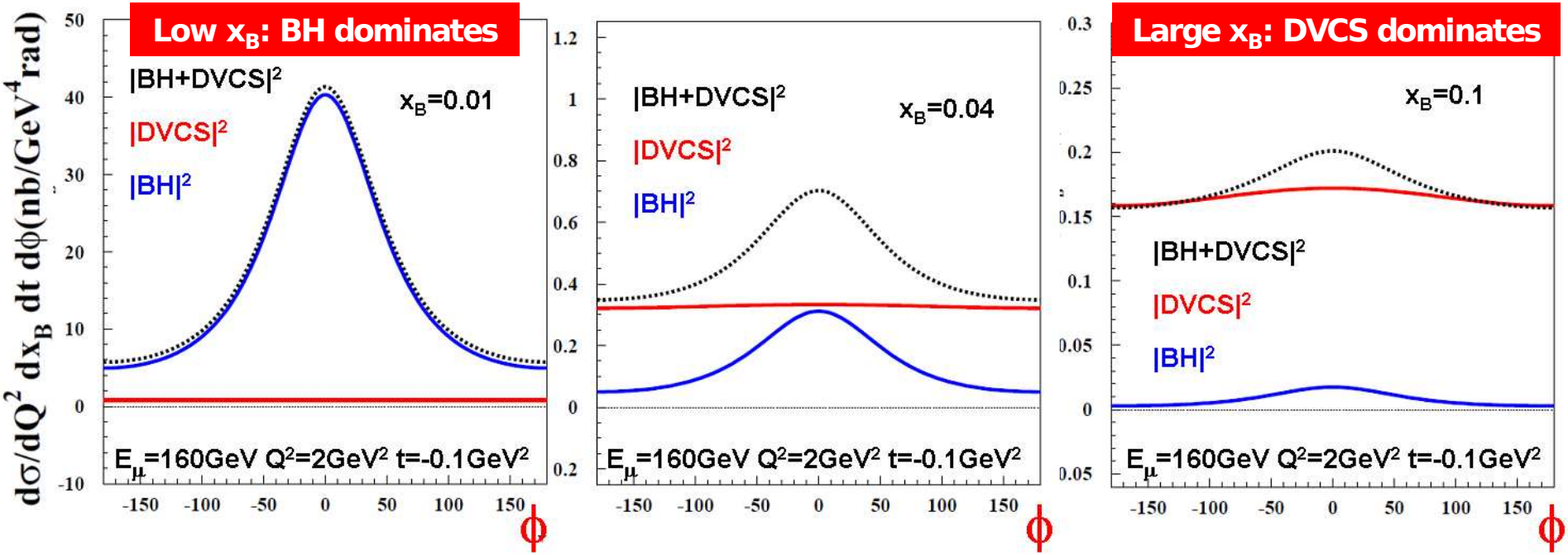


reference yield of almost pure Bethe-Heitler

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

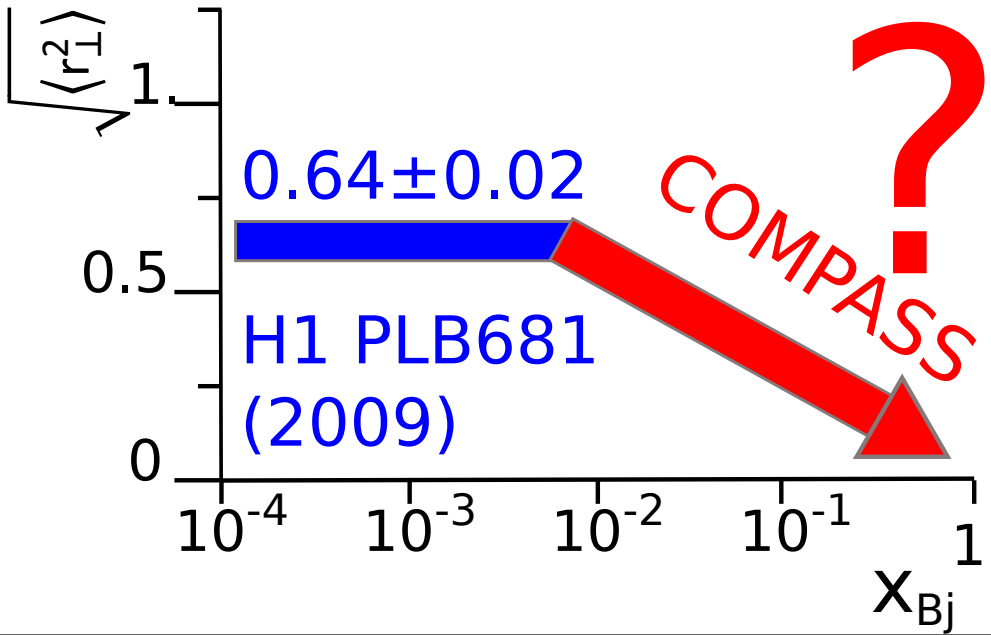
Beam Charge and Spin **SUM**:

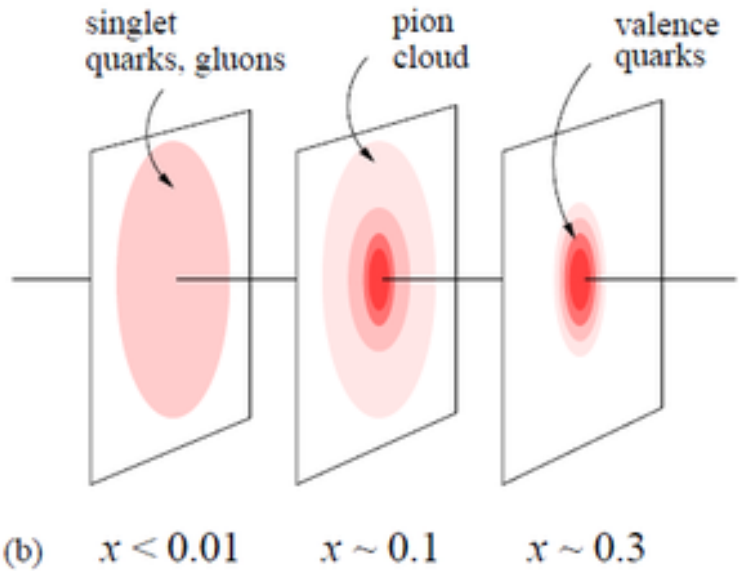
$$\mathbf{S_{CS,U}} \equiv \mathbf{d\sigma}(\boldsymbol{\mu}^{+\leftarrow}) + \mathbf{d\sigma}(\boldsymbol{\mu}^{-\rightarrow}) \propto \mathbf{d\sigma^{BH}} + \mathbf{d\sigma^{DVCS}_{unpol}} + \mathbf{Ks_1^{Int}} \sin\boldsymbol{\phi}$$

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

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

$r_\perp$ → distance between struck and spectator partons





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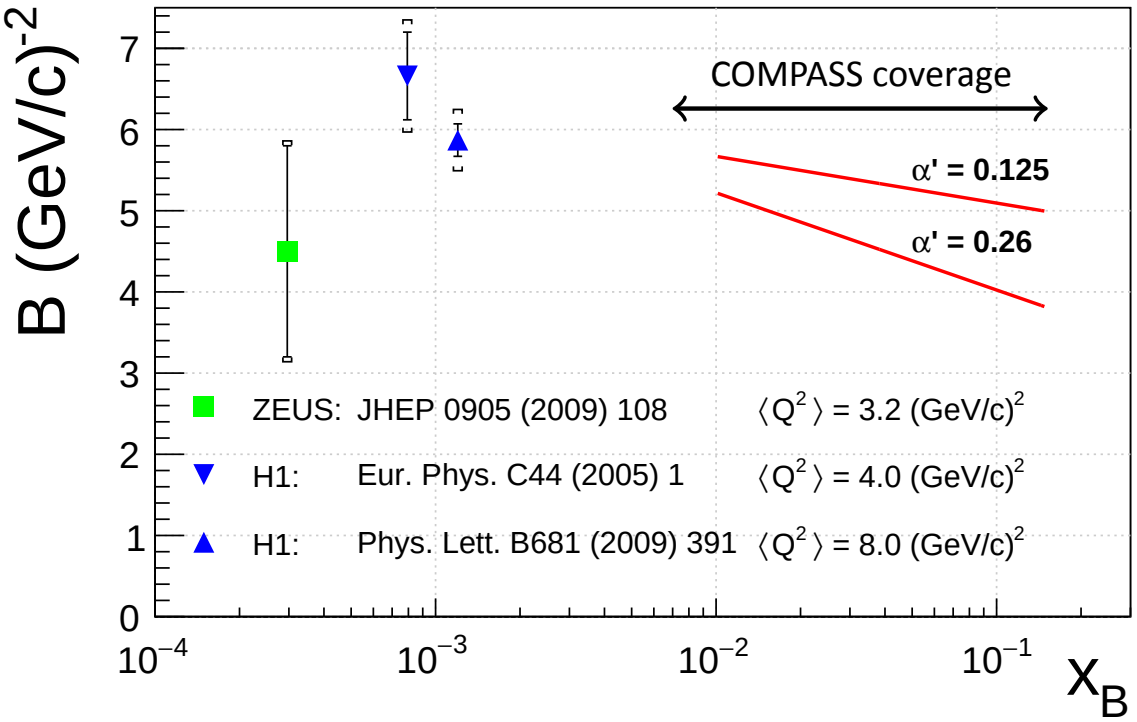
Integration over ϕ and BH subtraction → $\mathbf{d\sigma^{DVCS}/d|t| \sim exp(-B|t|)}$

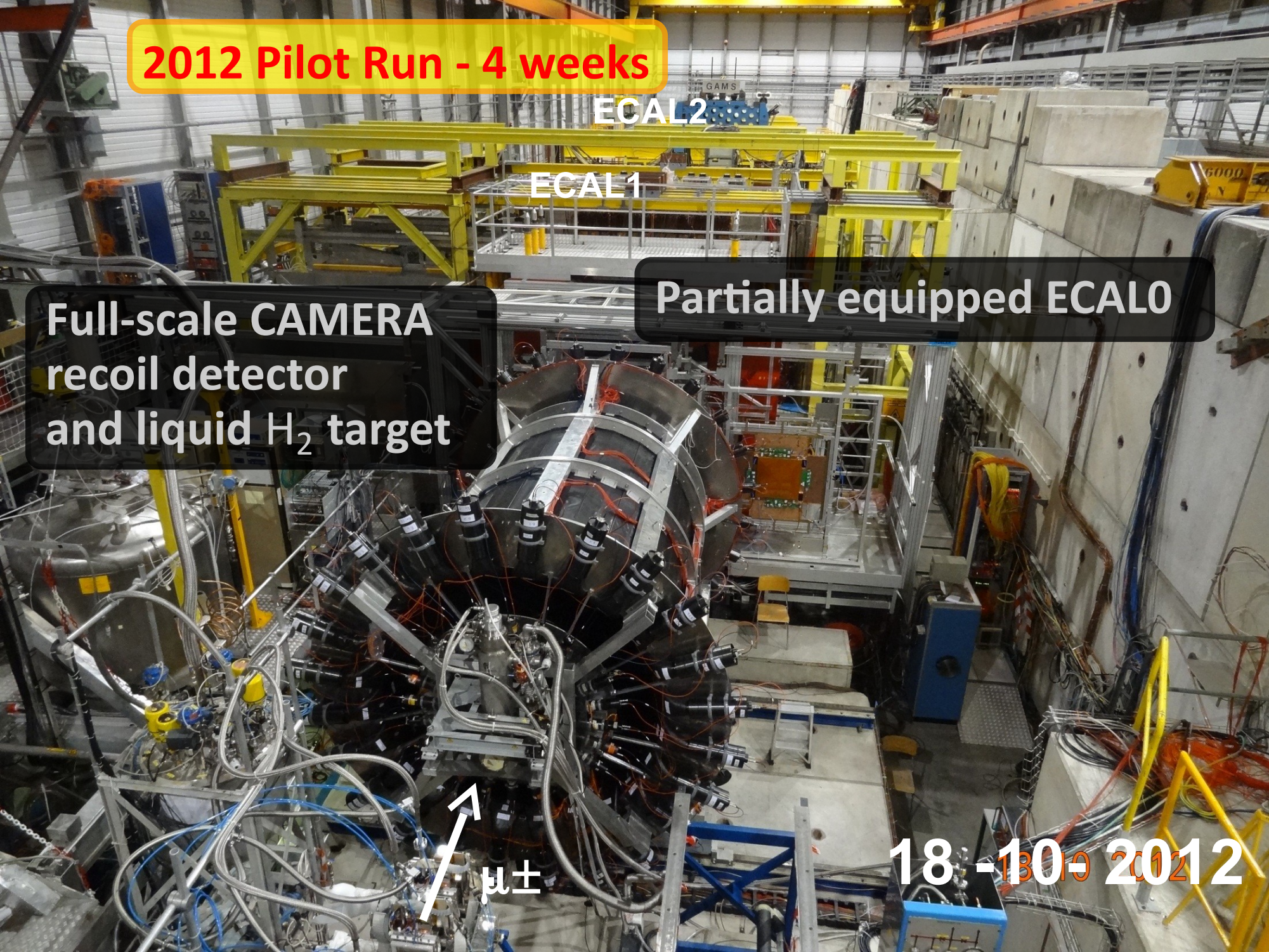
Currently available HERA measurements:



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
GAMS
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

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

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

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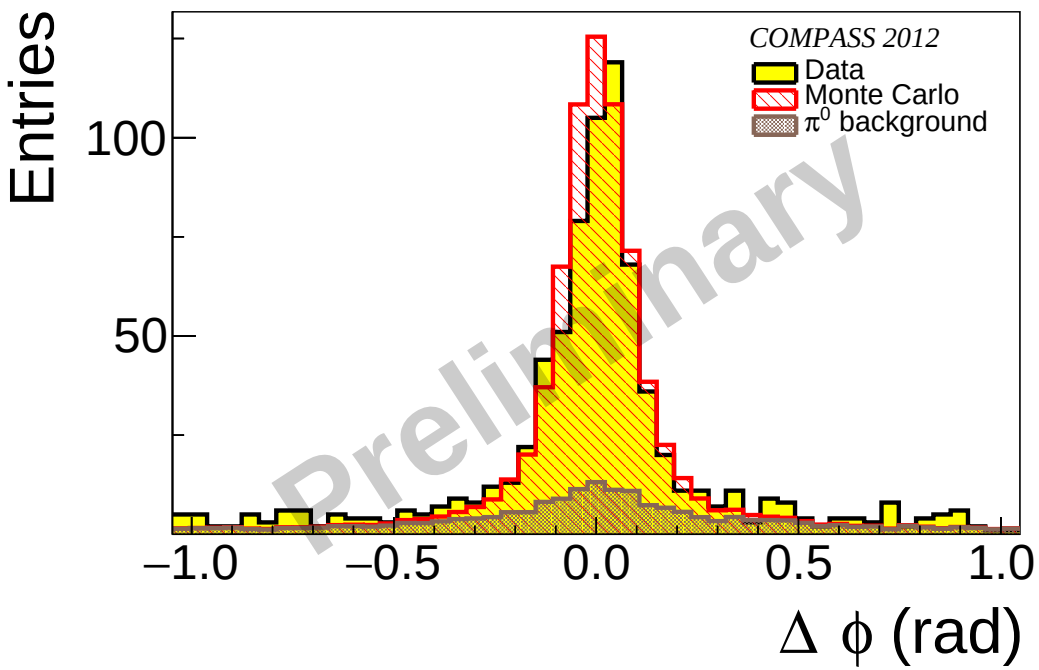
Exclusivity conditions:

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



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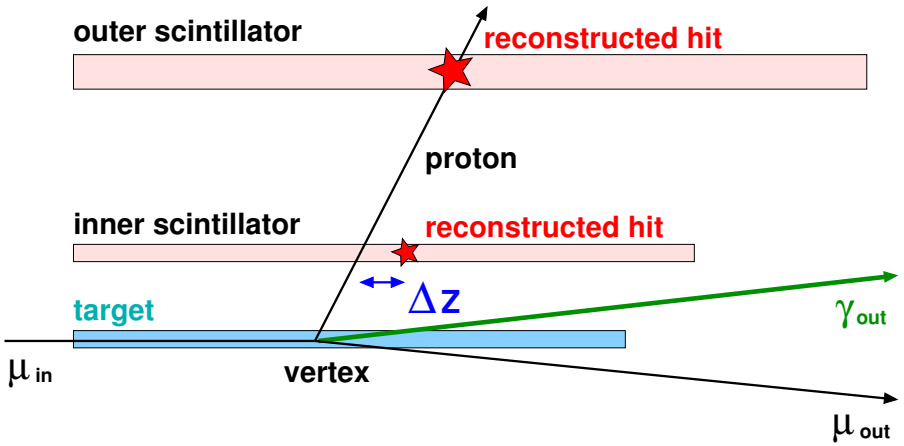
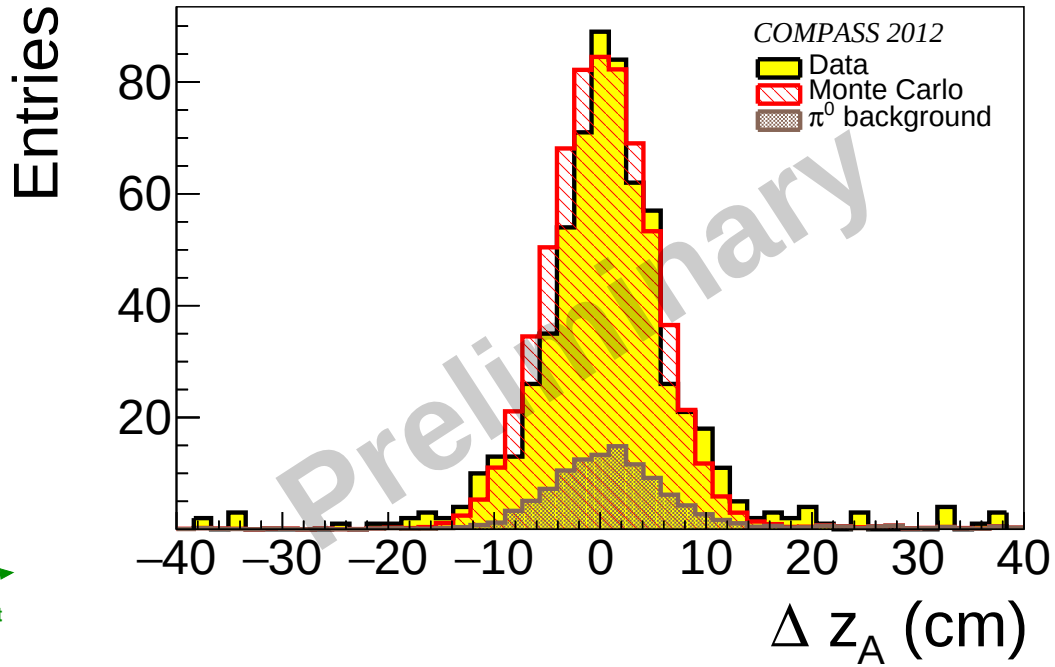
- $\Delta\varphi = \varphi^{\mathrm{proton}}_{\mathrm{meas}} - \varphi^{\mathrm{proton}}_{\mathrm{reco}}$
- Vertex pointing (ΔZ_A)





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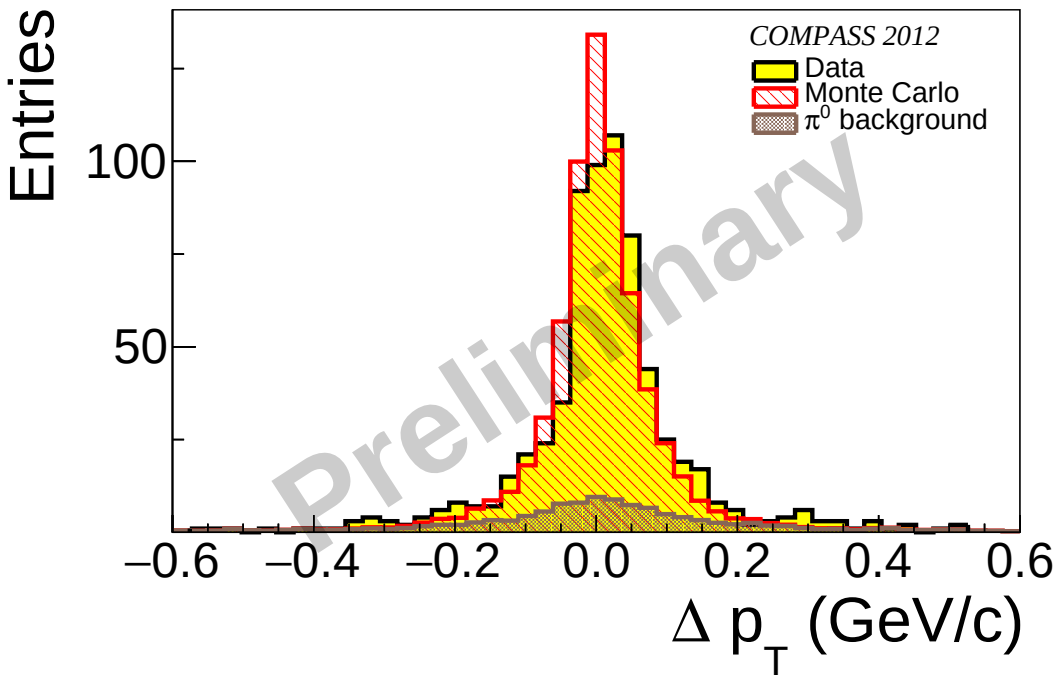
Exclusivity conditions:

- $\Delta\varphi = \varphi^{proton}_{meas} - \varphi^{proton}_{reco}$
- Vertex pointing (ΔZ_A)
- Transv. mom. balance:
  $\Delta p_T = p^{proton}_{T,meas} - p^{proton}_{T,reco}$



Exclusive Photon Events Selection

Reconstructed interaction vertex in **target volume**

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Exclusivity conditions:

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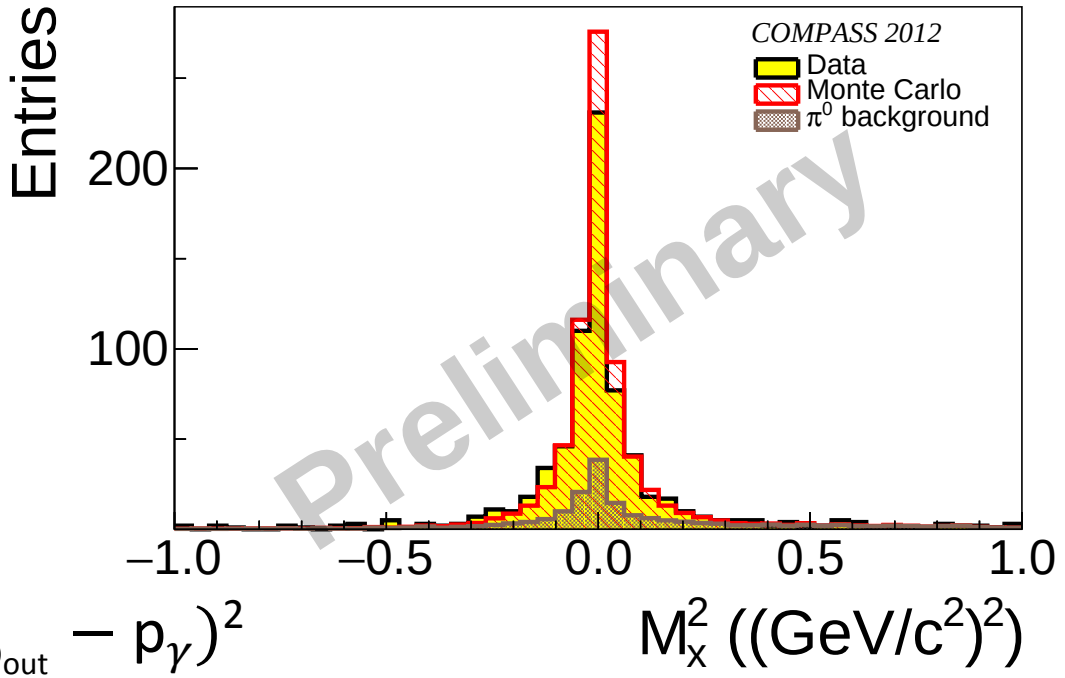
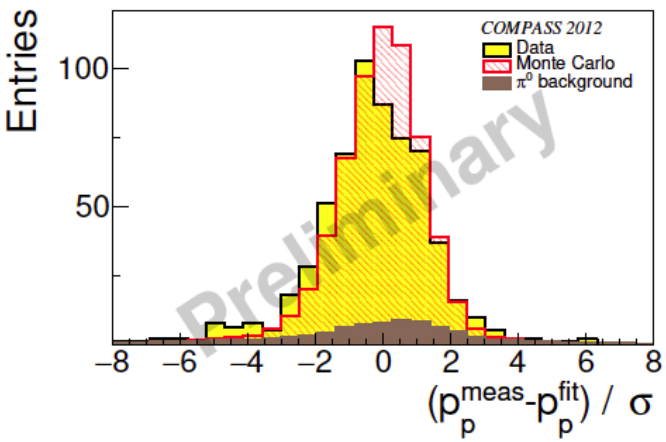
- Vertex pointing (ΔZ_A)
- Transv. mom. balance:
  $\Delta p_T = p^{proton}_{T,meas} - p^{proton}_{T,reco}$
- Four-momentum balance:
  $M_x^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_\gamma)^2$



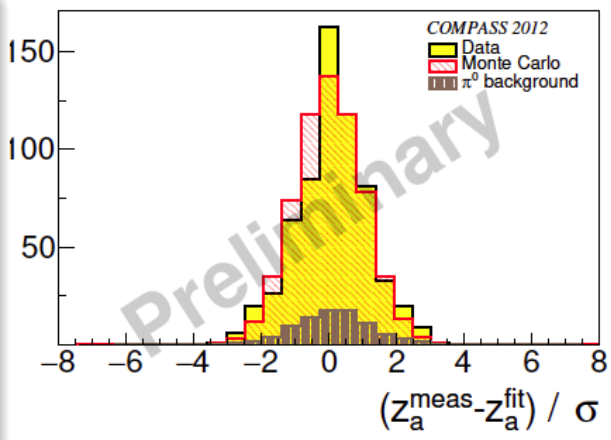
Kinematically constrained fit

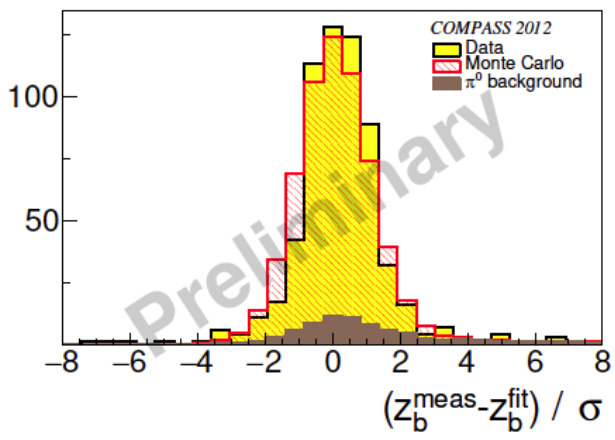
- constrained χ^2 minimisation with NDF=9
- full 4-momentum conservation of the reaction $\mu p \rightarrow \mu p \gamma$
- vertex constraints for μ, μ' and p' included in the fit

$\Rightarrow$ most accurate determination of t

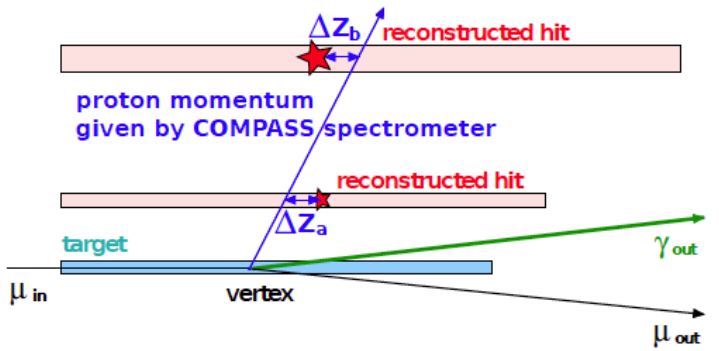


recoil proton momentum



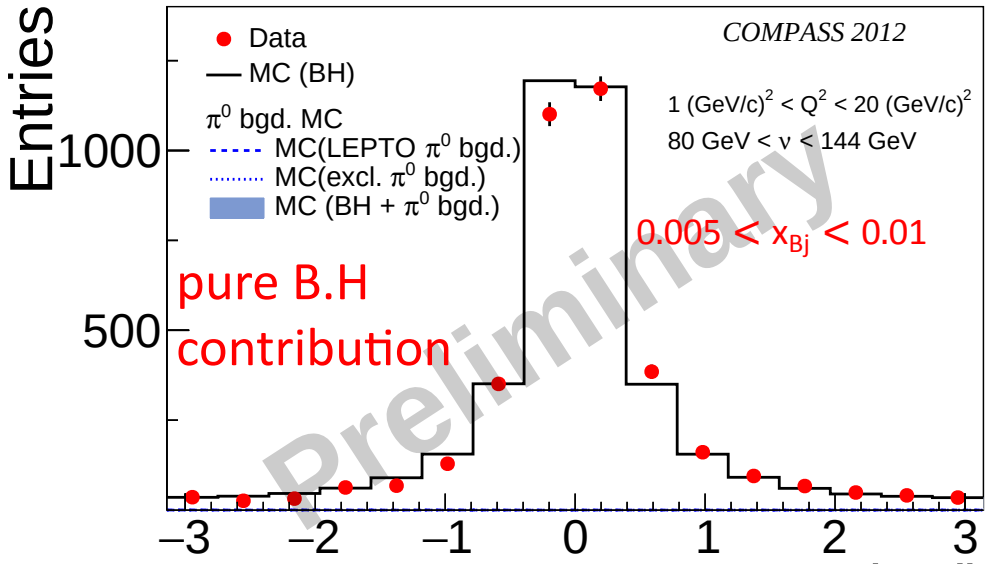


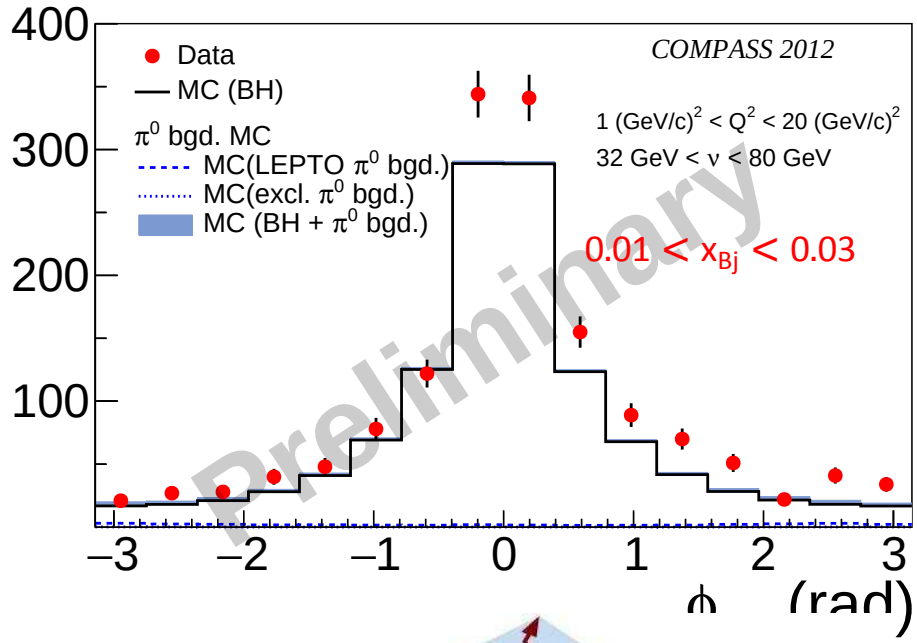
recoil proton direction

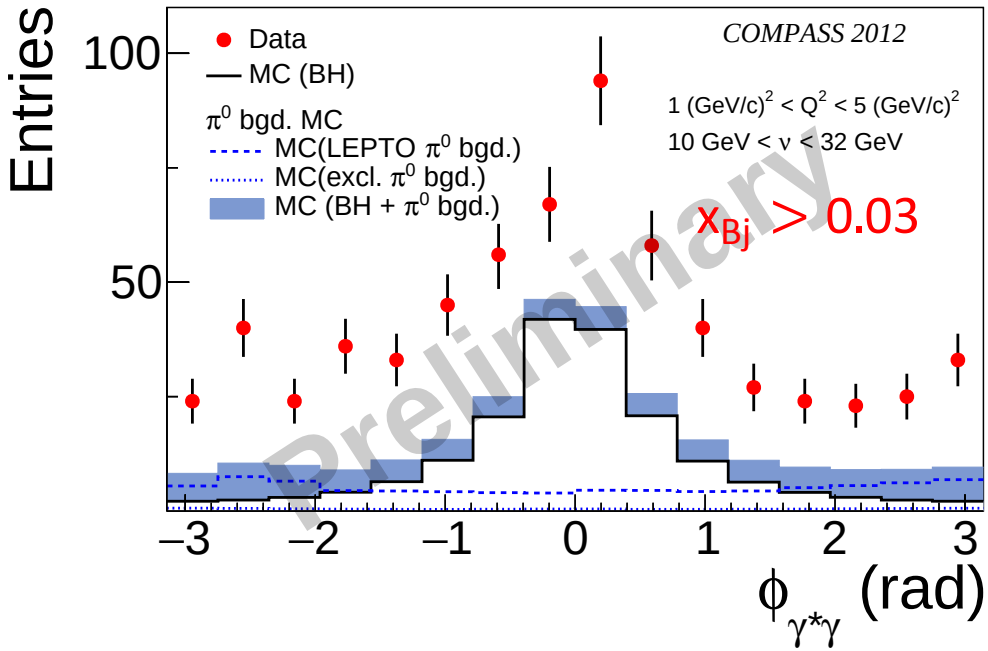


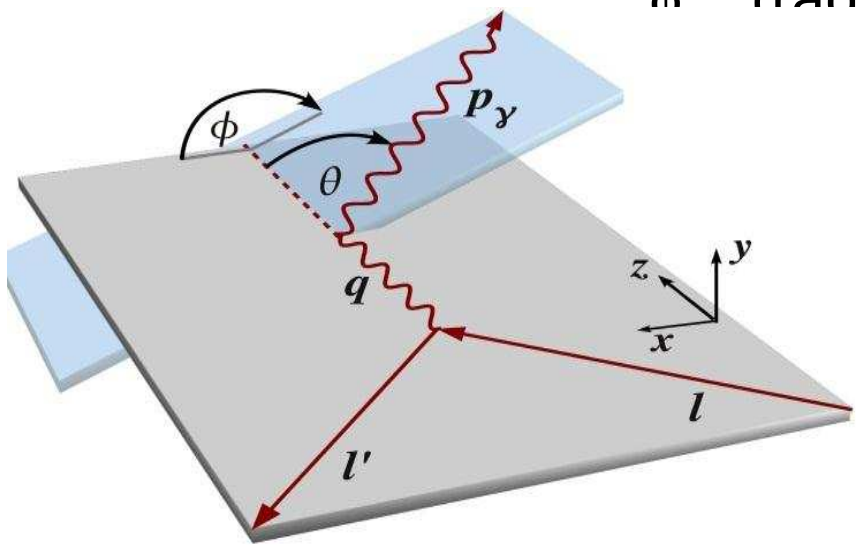
Exclusive γ Azimuthal Distributions for DVCS

Kinematically constrained vertex fit applied



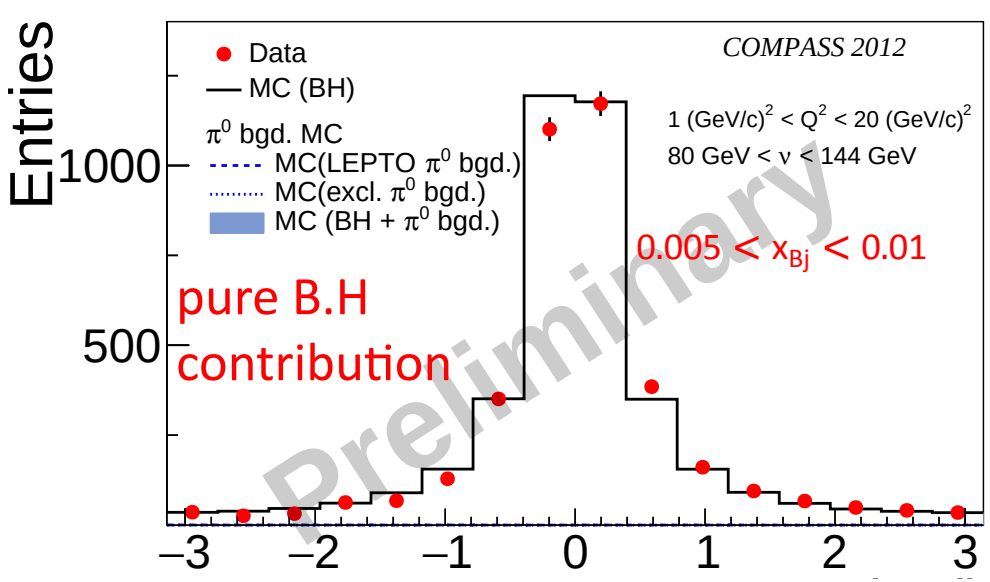


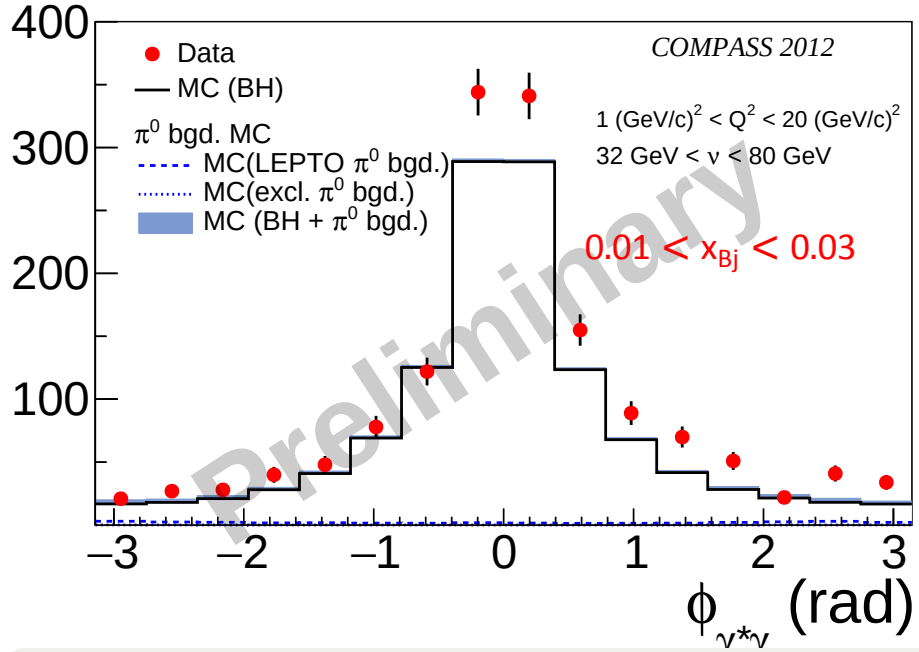


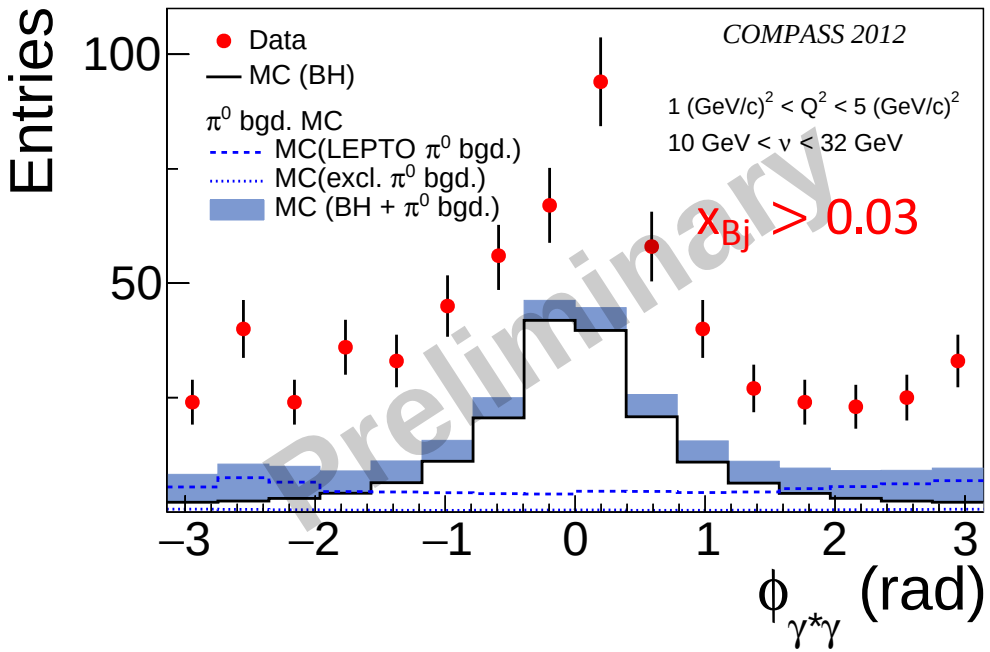


Exclusive γ Azimuthal Distributions for DVCS

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}**

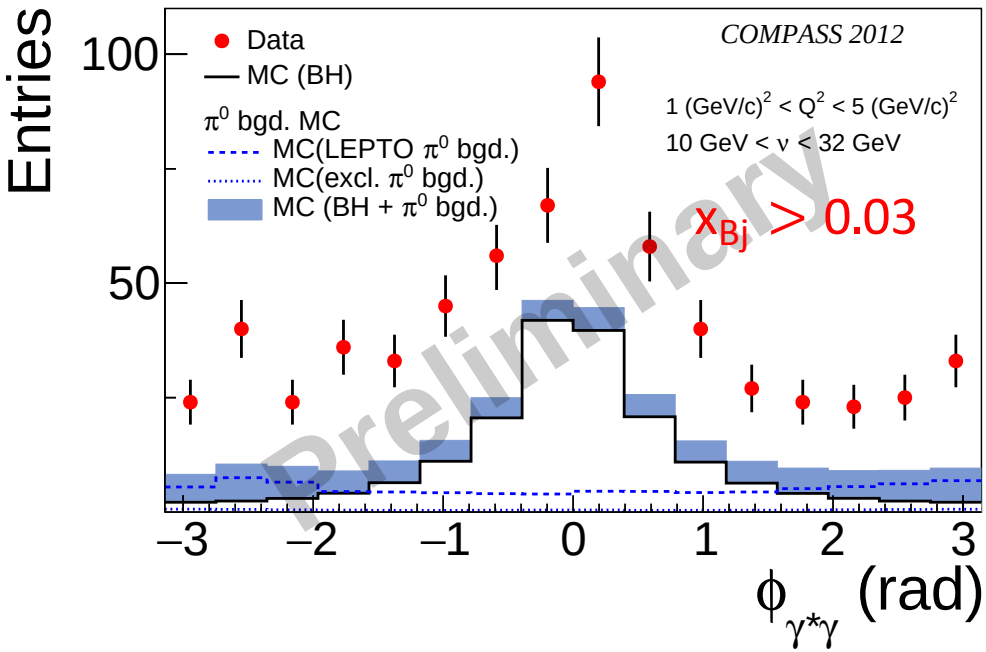
Exclusive γ Azimuthal Distributions for DVCS

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

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



- BH Monte Carlo normalization based on integrated luminosity
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- **clear excess of DVCS at large x_{Bj}**

π^0 Background Estimation

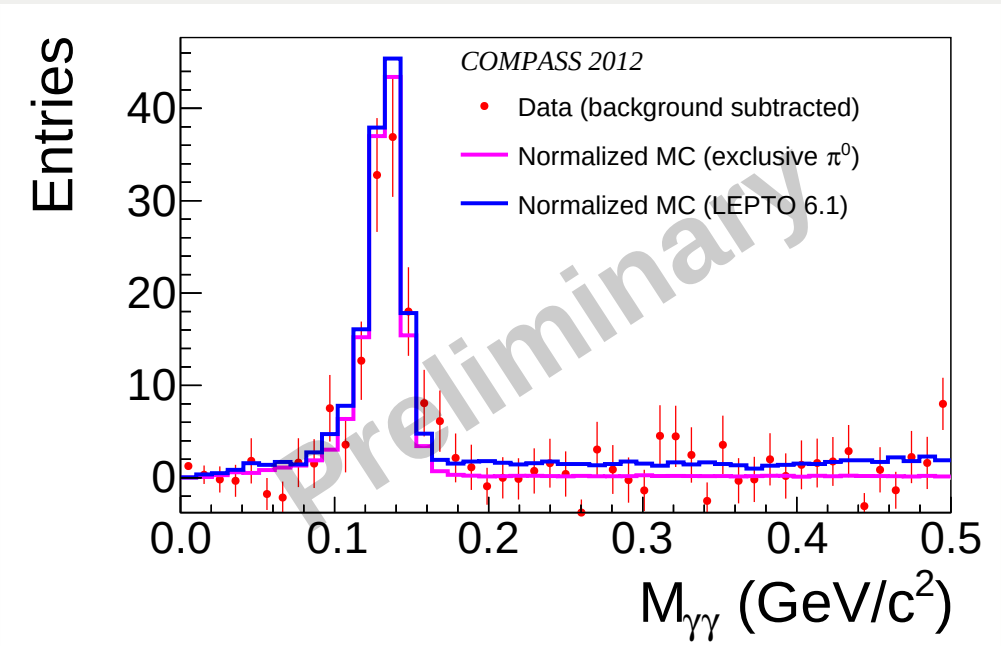
π^0s are one of the main **background sources** for excl. photon events

Two possible cases:

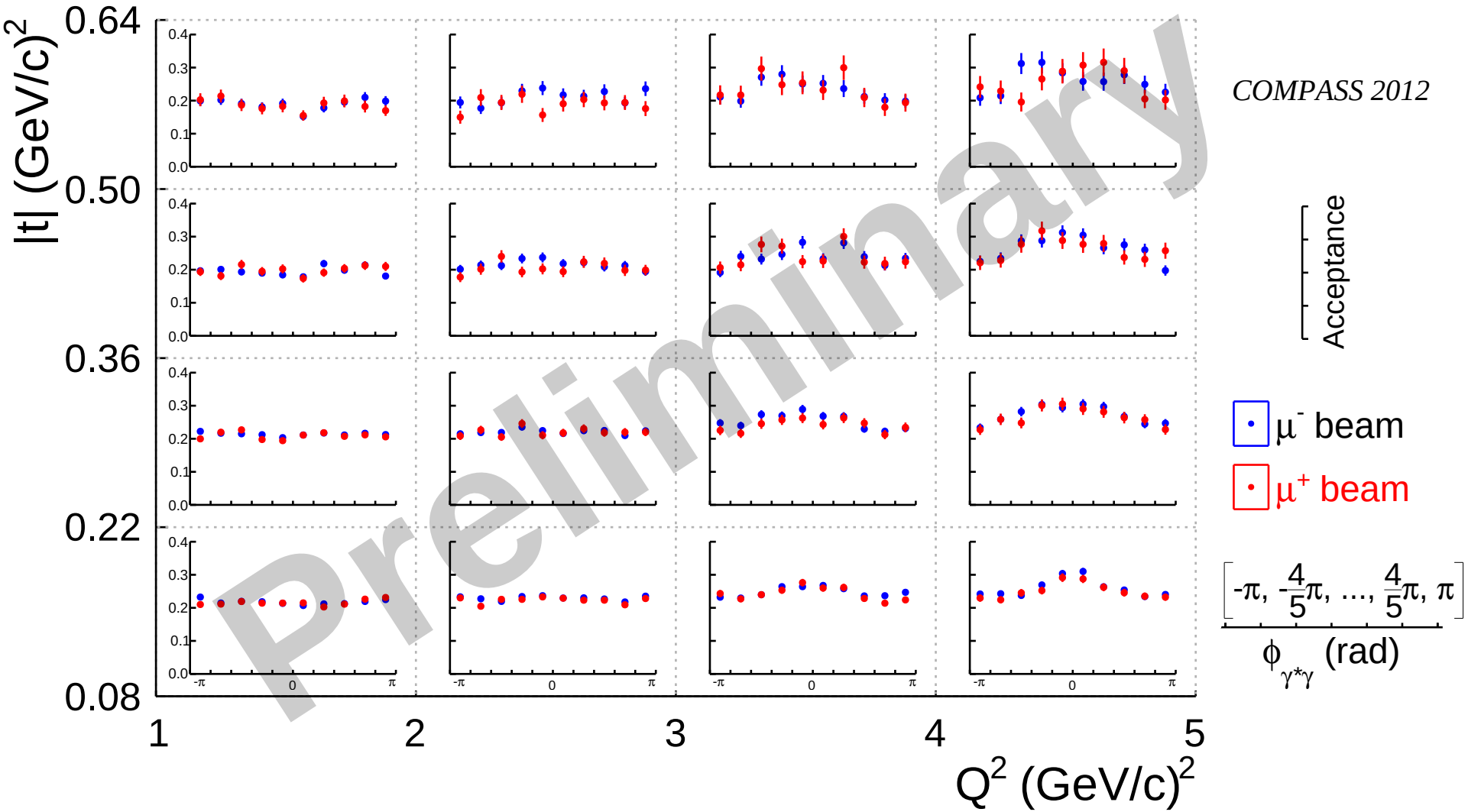
- **visible** (both γ detected, **subtracted**)
- **invisible** (one γ "lost", **estimated with MC**)
  - **Semi-inclusive** → LEPTO
  - **Exclusive** → HEPGEN/π^0 (Goloskokov-Kroll model)

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

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

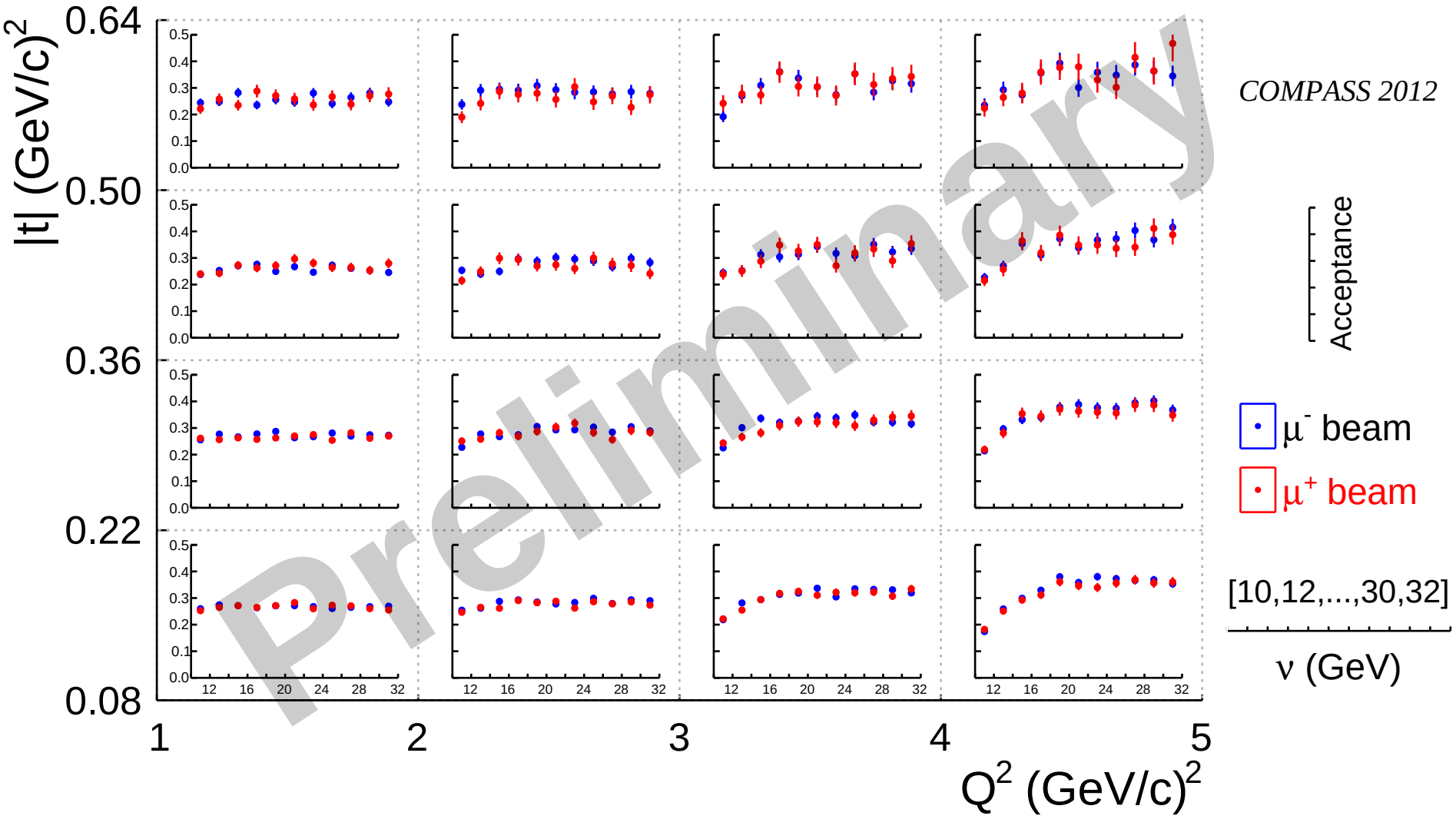


Experimental acceptance for DVCS events



Symmetric acceptance around $\phi = 0$

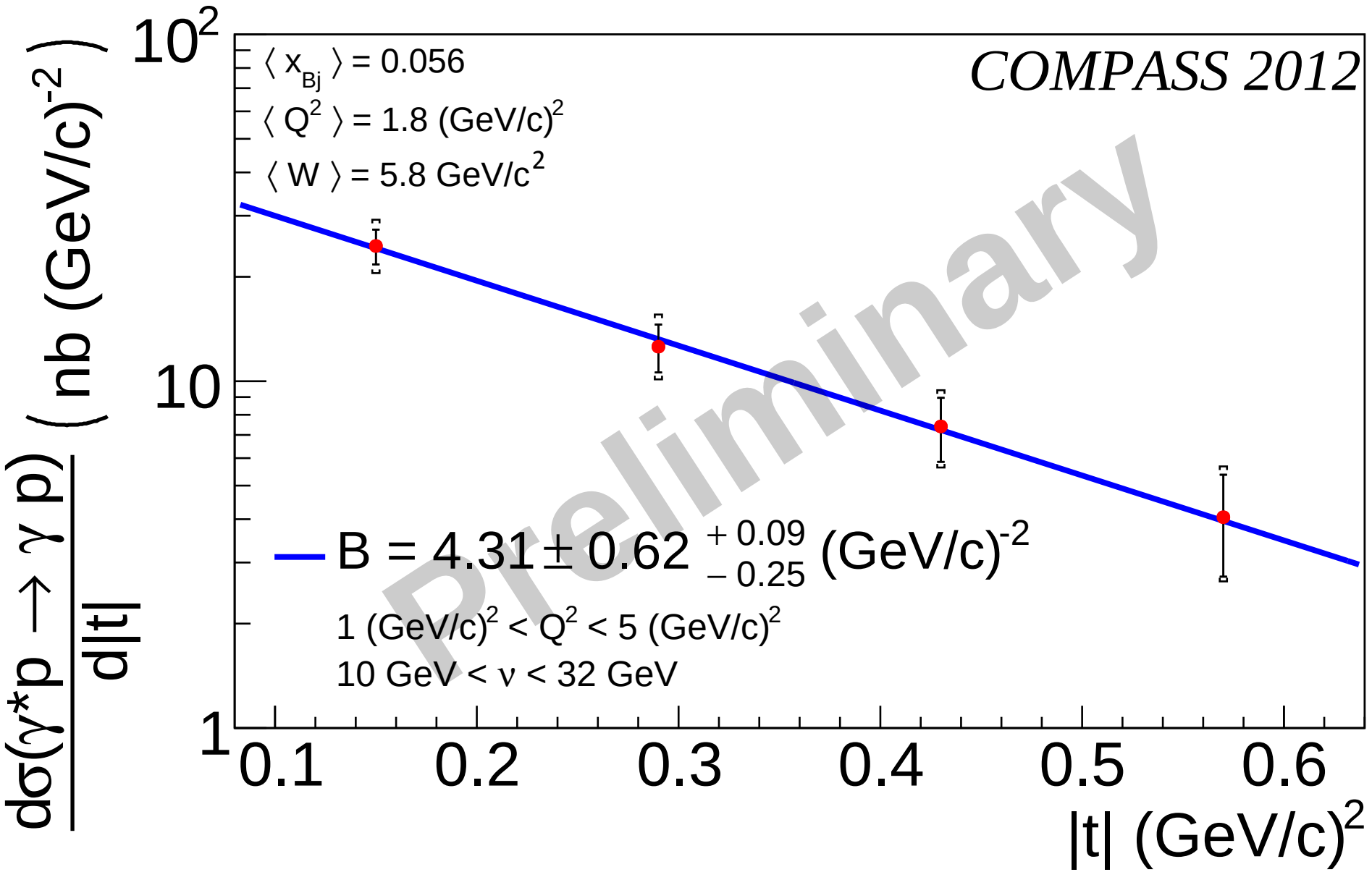
Experimental acceptance for DVCS events



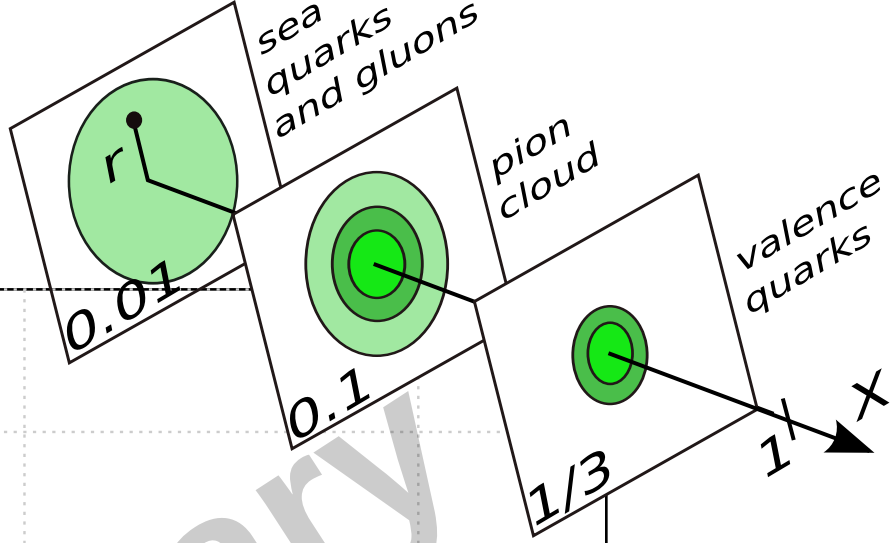
Acceptance binning in Q^2, ν and |t|

DVCS x-section and t-slope extraction

Kinematically constrained vertex fit applied



Comparison with HERA results



$< r_\perp^2 > \approx 2B(x_{Bj})$

$\sqrt{< r_\perp^2 >}$ (fm)

0.8
0.7
0.6
0.5
0.4
0.3
0.2

10^{-4} 10^{-3} 10^{-2} 10^{-1} X_B

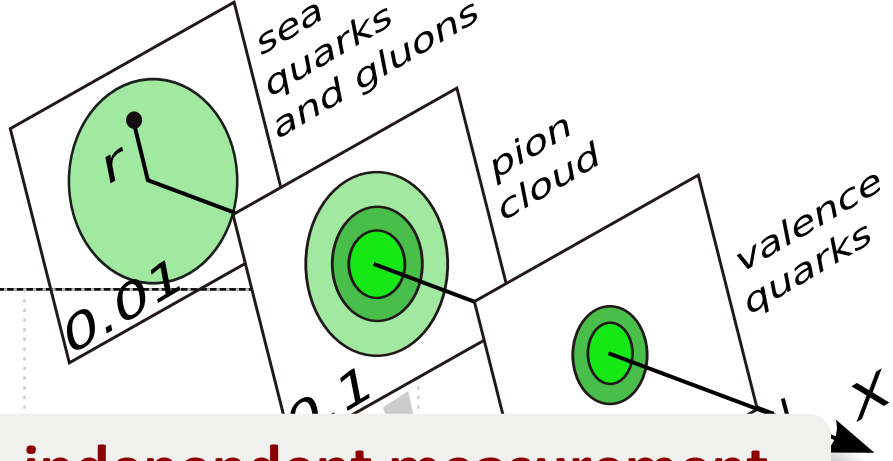
gluon imaging
at HERA

sea quark imaging
at COMPASS

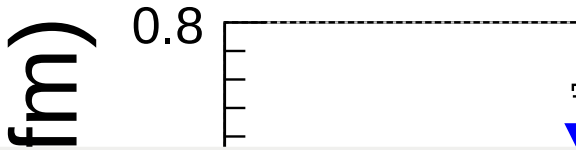
Preliminary

●	COMPASS 2012:	$\langle Q^2 \rangle = 1.8$ (GeV/c)^2
■	ZEUS: JHEP 0905 (2009) 108	$\langle Q^2 \rangle = 3.2$ (GeV/c)^2
▼	H1: Eur. Phys. C44 (2005) 1	$\langle Q^2 \rangle = 4.0$ (GeV/c)^2
▲	H1: Phys. Lett. B681 (2009) 391	$\langle Q^2 \rangle = 8.0$ (GeV/c)^2

Comparison with HERA results



$< r_\perp^2 > \approx 2B(x_{Bj})$



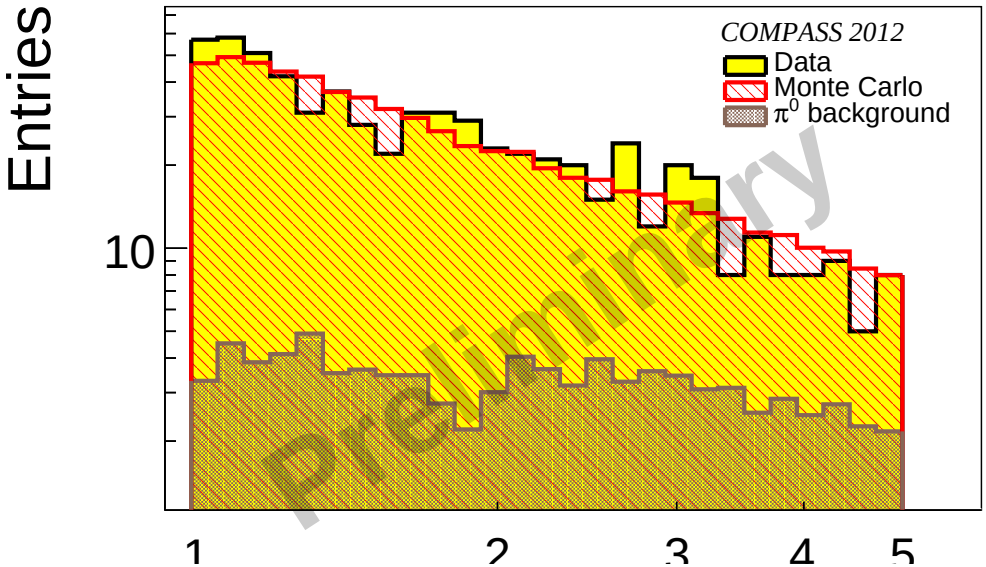
COMPASS performed the first model-independent measurement of $r_\perp$ in the sea-quarks domain using the pilot 2012 data set

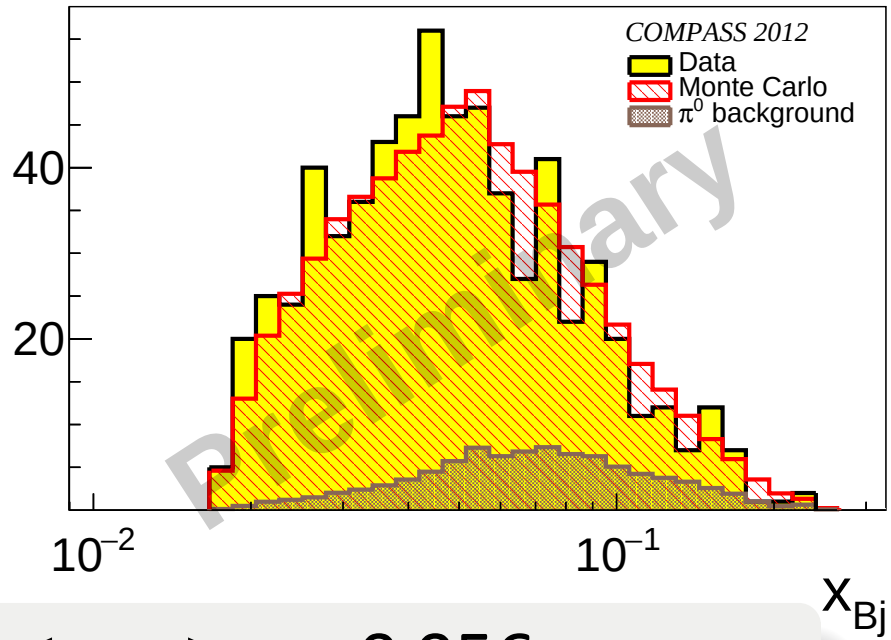
OUTLOOK:

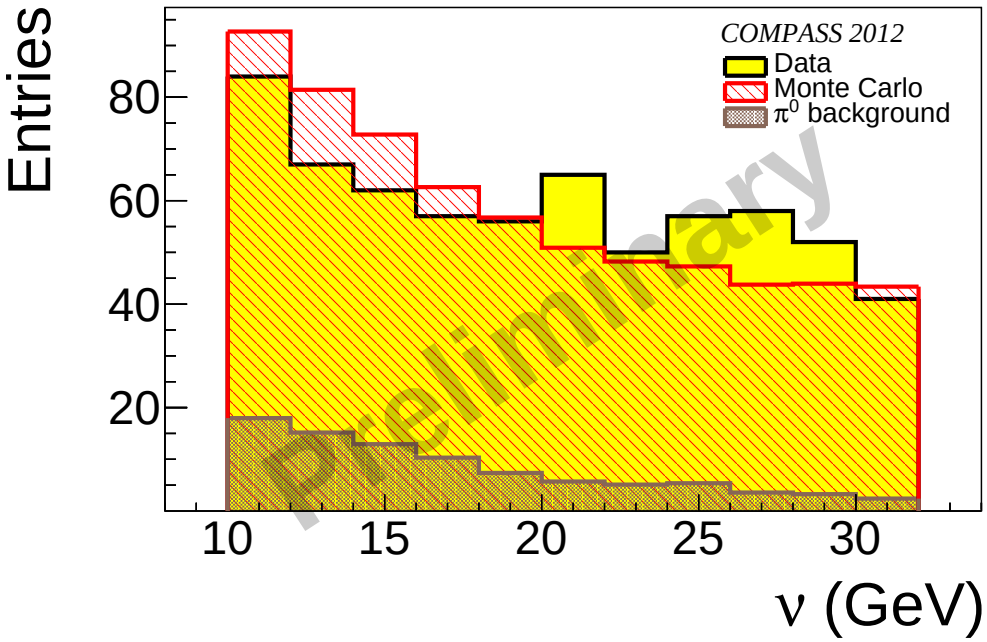
- Dedicated beam time for GPD studies in 2016-17
- x_{Bj}-dependence of t-slope parameter in sea-quarks domain
- Real and imaginary parts of CFF $\mathcal{H}$ from interference term
- Complementary measurements with exclusive mesons:
  $\pi^0, \rho^0, \phi, \omega \ldots$

Backup Slides

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