Transverse extention of partons in the proton – Plans for a proton radius measurement with muons

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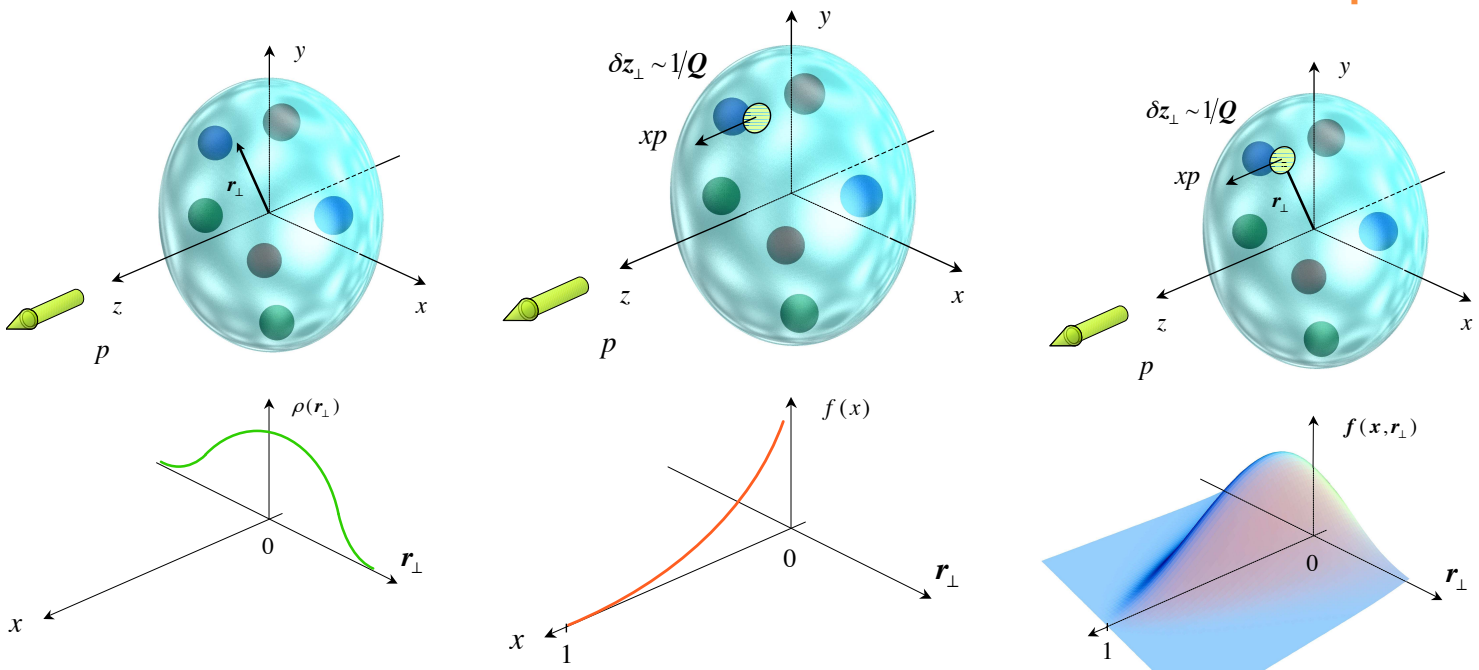
Motivation

Beyond the 1-dimensional picture of the nucleon

Elastic scattering

Deep inelastic scattering

Hard exclusive processes



Form factors

Parton distributions

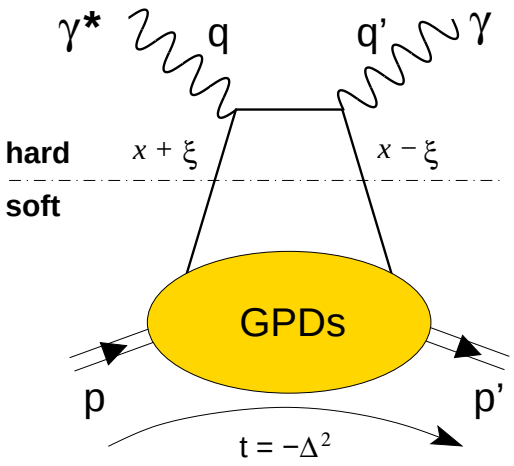
Generalized Parton Distributions (GPDs)

GPDs correlate transverse spatial size and longitudinal momentum

Outline

- **Transverse extention of proton**
  - GPDs at COMPASS
  - COMPASS experiment in 2016/17
  - Results from 2012 pilot run
- **Plans for Proton Radius measurement**
  - Experimental challenges
  - Proposed set-up
  - 2018 test measurement

Generalised parton distributions



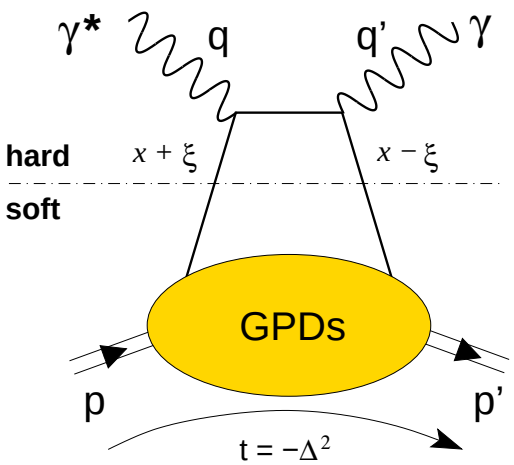
- accessible in exclusive reactions
- factorisation for Q^2 large, $|t| < 1$ GeV^2
- GPD for each quark flavour and for gluons
- depend on 3 variables: x, ξ, t
  with $\xi \approx \frac{x_{\mathrm{Bj}}}{2}$ at small x_{Bj}

- 8 GPDs: H, $\widetilde{\mathrm{H}}$, $\mathrm{H_T}$, $\widetilde{\mathrm{H}}_T$ conserve nucleon helicity
  E, $\widetilde{\mathrm{E}}$, $\mathrm{E_T}$, $\widetilde{\mathrm{E}}_T$ flip nucleon helicity, T: flip quark helicity

- **limits**: PDFs $q(x) = \mathrm{H}(x, 0, 0)$ and formfactors $F(t) = \int \mathrm{d}x\, \mathrm{H}(x, \xi, t)$

- sensitivity in deeply virtual Compton scattering (DVCS) and hard exclusive meson production (HEMP)

Deeply virtual Compton scattering

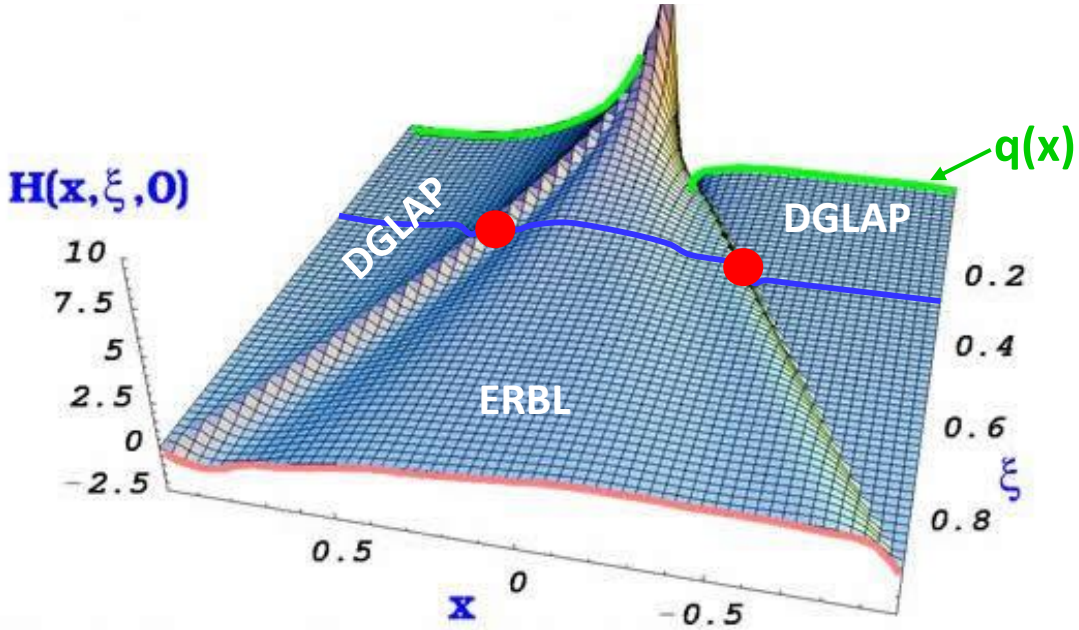


- mainly sensitive to GPD H for unpolarised target at COMPASS kinematics
- GPDs related to Compton form factors $\mathcal{H} = \Sigma e_f^2 \mathcal{H}^f$

$$\mathrm{Im}\,\mathcal{H}(\xi,t) \overset{\mathrm{LO}}{=} \mathrm{H}(\pm\xi,\xi,t)$$

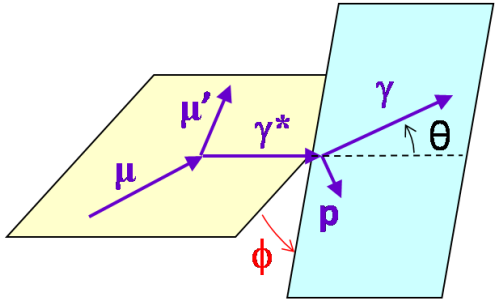
$$\mathrm{Re}\,\mathcal{H}(\xi,t) \overset{\mathrm{LO}}{=} \mathcal{P}\int_{-1}^{1} \mathrm{d}x\; \mathrm{H}(x,\xi,t)\frac{1}{x-\xi}$$

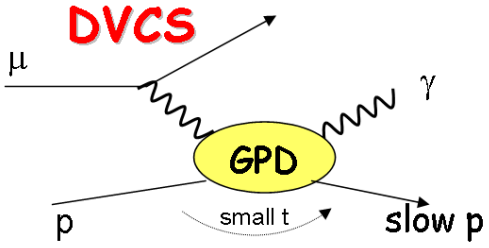
- Dependence on x cannot be measured $\rightarrow$ modelling very important

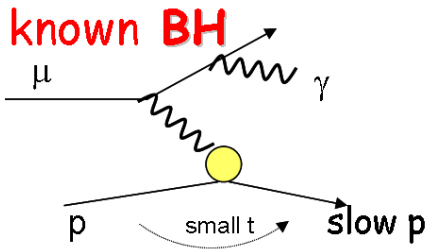


From Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)

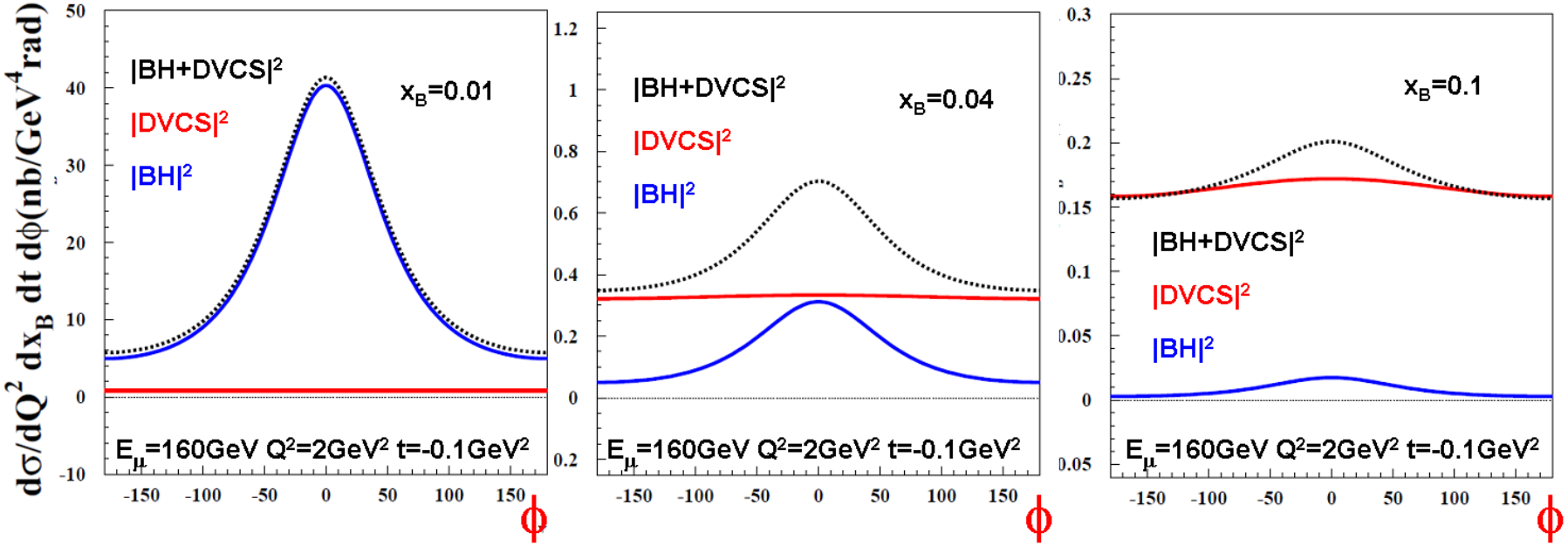
DVCS and Bethe-Heitler







$E = 160\,\text{GeV}$ $\quad \mathbf{d\sigma \sim |T^{BH}|^2 + Interference\ Term + |T^{DVCS}|^2}$

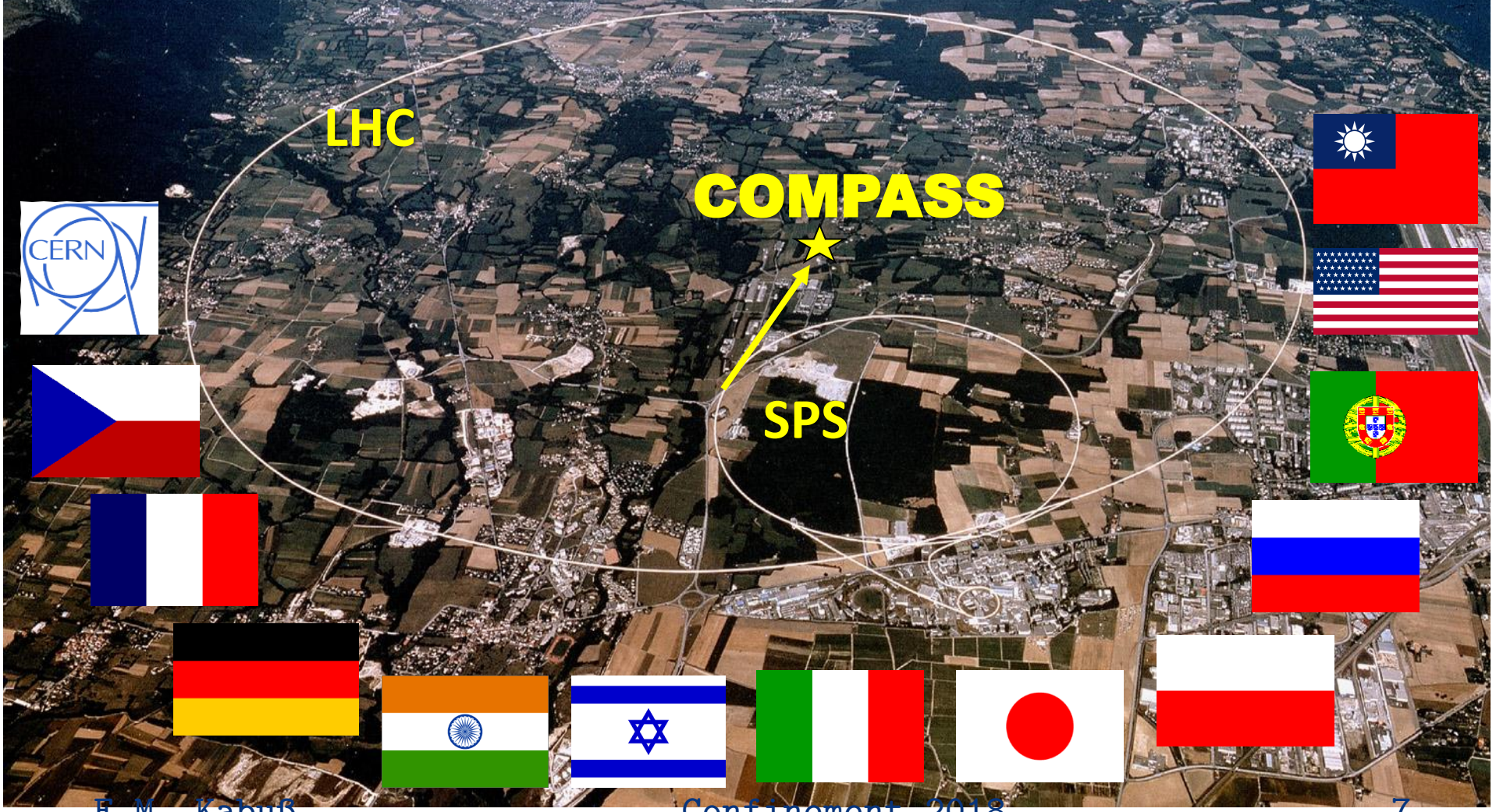


BH dominates, reference yield

access to DVCS amplitude via interference

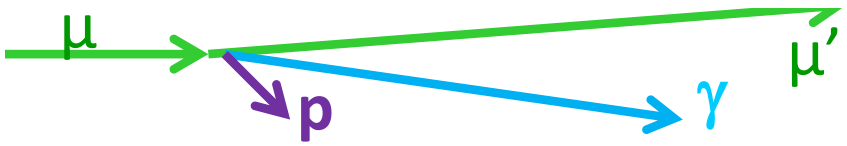
DVCS dominates, study of $\mathrm{d}\sigma/\mathrm{d}|t|$,

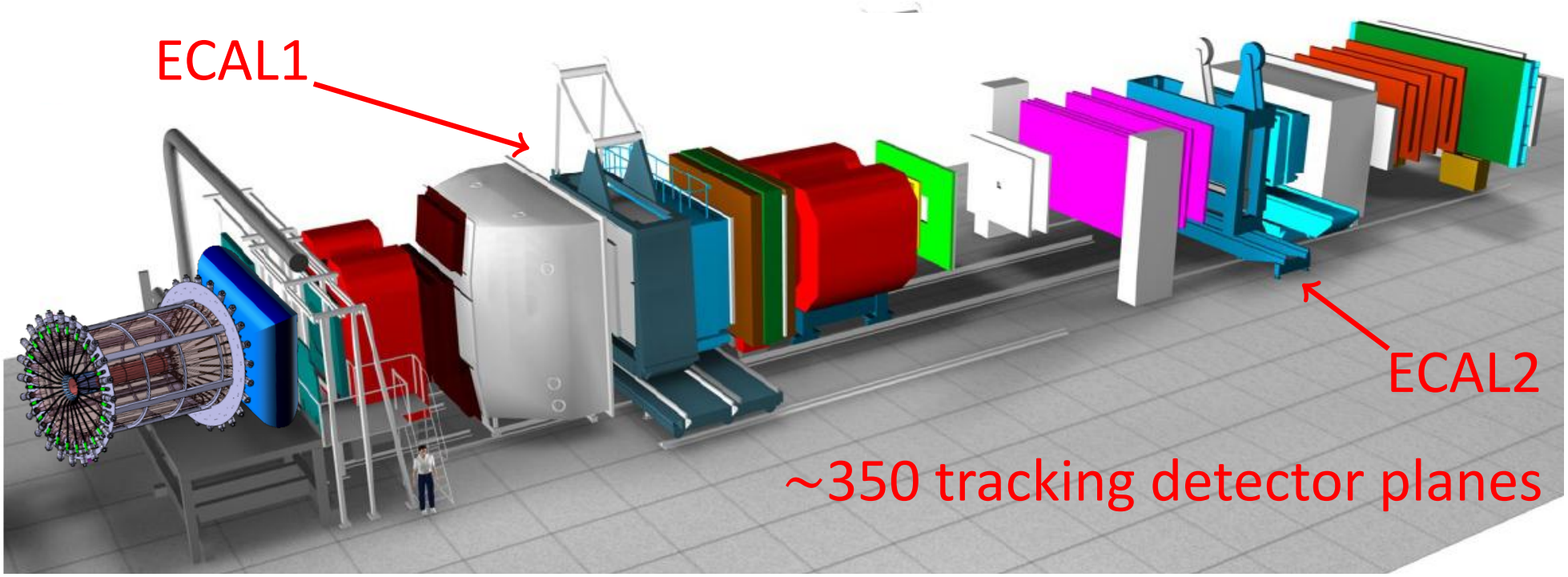
COMPASS: Versatile facility to study QCD with hadron ($\pi^{\pm}$, $K^{\pm}$, p ...) and lepton (polarized $\mu^{\pm}$) beams of ~200 GeV for hadron spectroscopy and hadron structure studies using SIDIS, DY, DVCS, DVMP...



COMPASS spectrometer for GPD programm

$$\mu^{\pm} p \longrightarrow \mu^{\pm} \gamma p$$

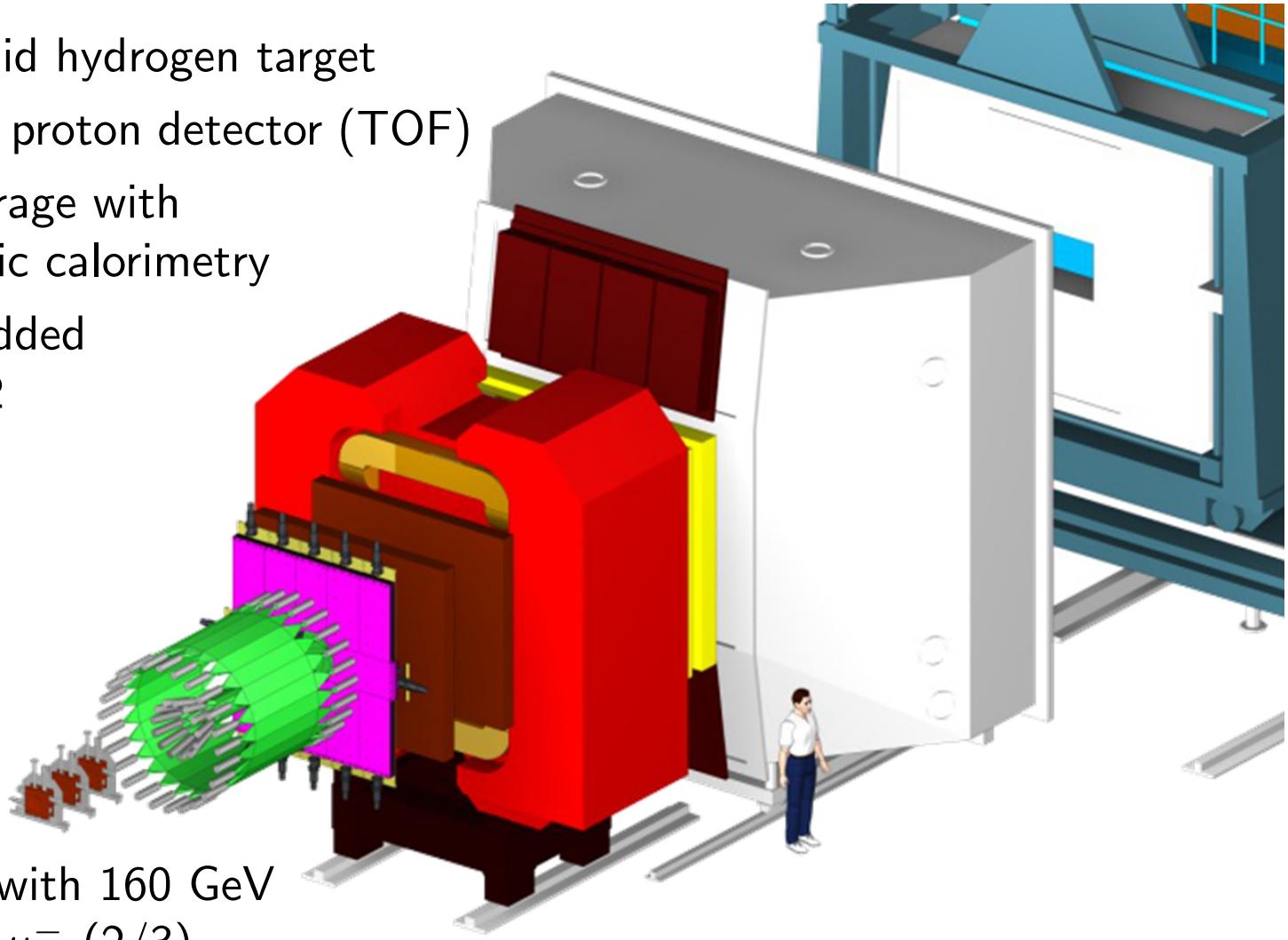




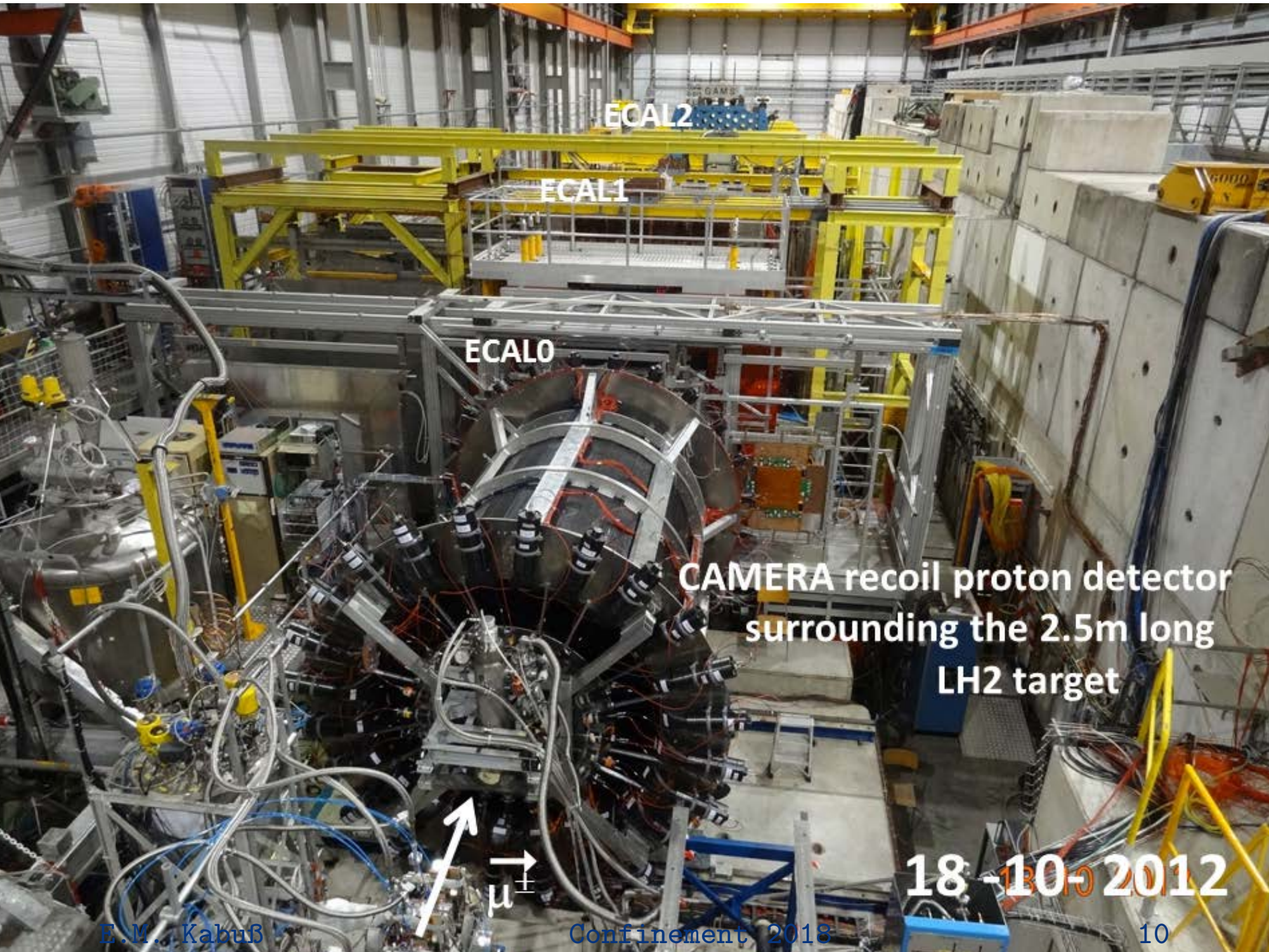
- two stage magnetic spectrometer
- electromagnetic calorimeters (ECAL1/2) for photon dectection
- absorbers for muon identification
- PID with ring imaging Cherenkov detector

New target region for DVCS

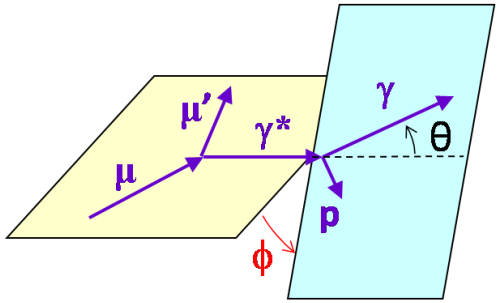
- 2.5m long liquid hydrogen target
- 4m long recoil proton detector (TOF)
- hermetic coverage with electromagnetic calorimetry
- new ECAL0 added partial in 2012



- measurement with 160 GeV μ^+ (1/3) and μ^- (2/3)
- pilot run 2012


ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
$\vec{\mu}^{\pm}$
18 -10- 2012

Selection of exclusive events

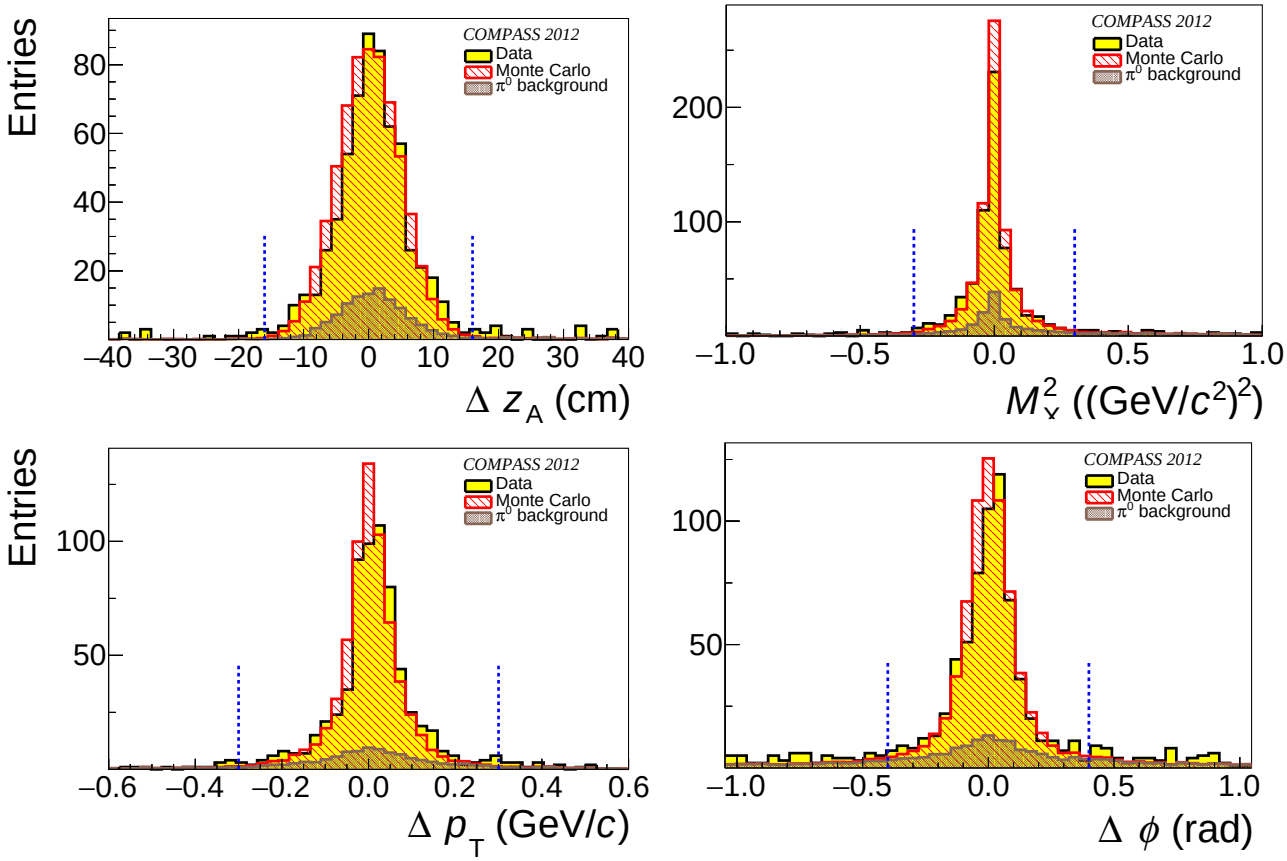


vertex with μ,μ', no other charged track
one high energy γ, proton in RPD

difference between spectrometer prediction and measurement with recoil detector

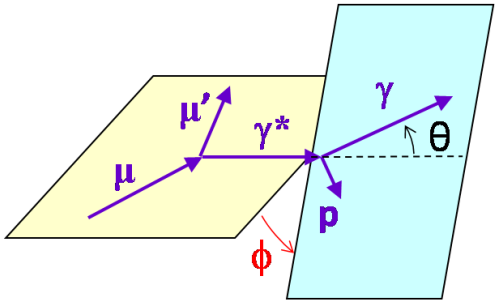
exclusivity requirements

- vertex pointing
- four-momentum balance
- transverse momentum balance
- azimuthal angle



arXiv:1802.02739

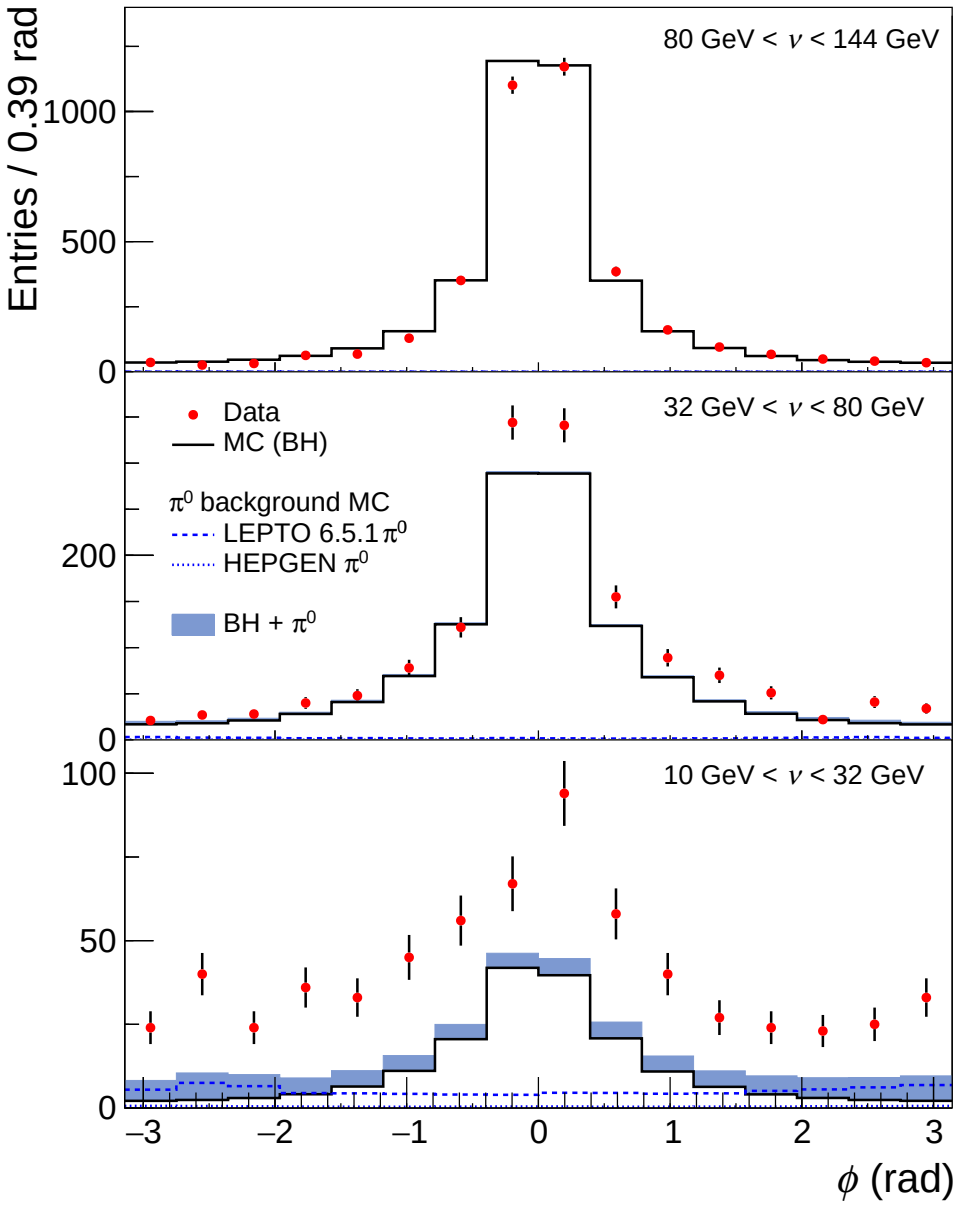
Signal in 2012



kinematic variables measured using μ,μ'

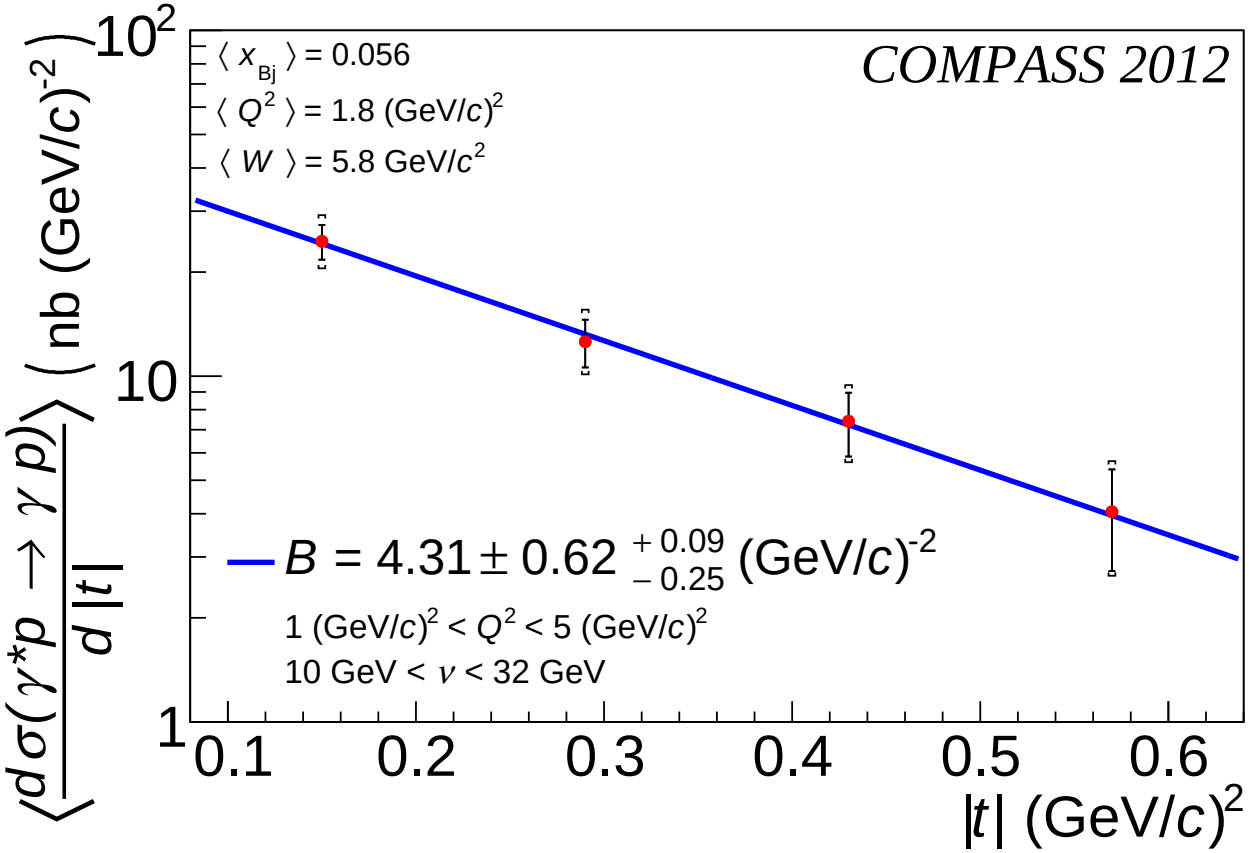
Q^2	γ^* momentum transfer squared
ν	γ^* energy
$x_{\mathrm{Bj}} = Q^2/2M\nu$	Bjorken variable

- Φ distribution for 3 bins in ν
- normalised to integrated luminosity
- compared to prediction for pure BH
- π^0 background estimate using HEPGEN and LEPTO



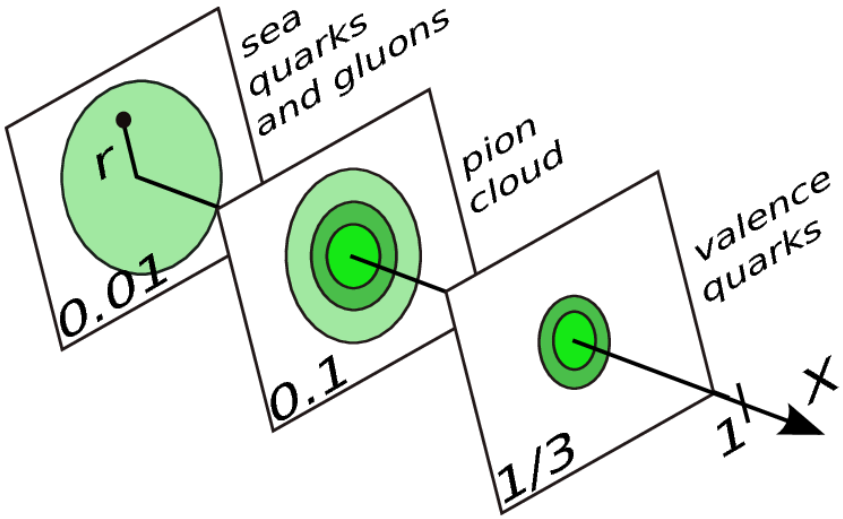
Result for DVCS cross section

- cross section determined in four bins of t
- corrected for BH contribution and π^0 background
- using photon flux according to Hand convention $\mathrm{d}\sigma^{\gamma^* p \to \gamma p}$ extracted



statistical errors (inner bars) added in quadrature to systematic errors (outer bars)

Transverse imaging



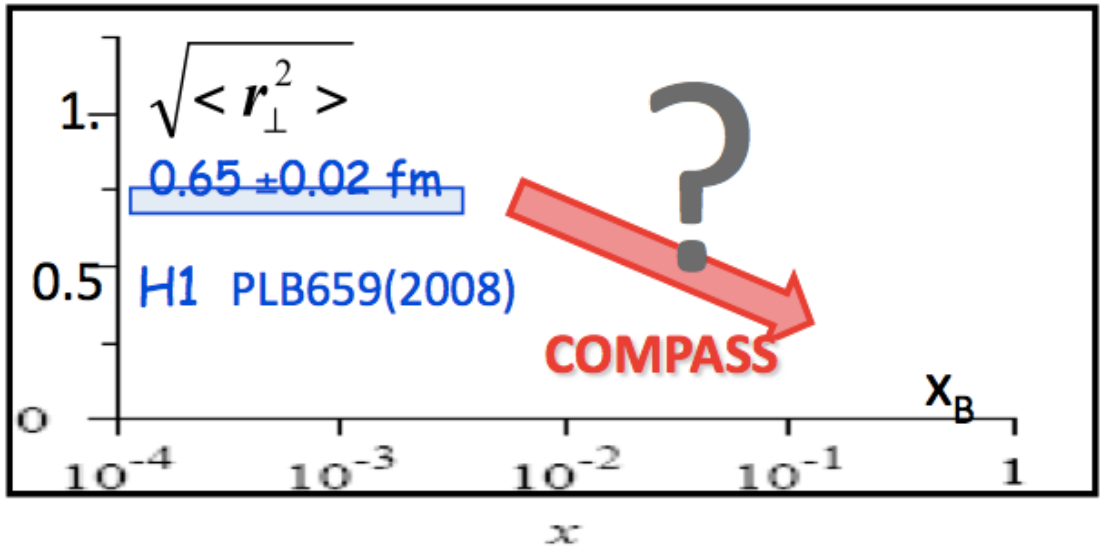
- t-slope of DVCS cross section $B(x_{\mathrm{Bj}})$

$$\mathrm{d}\sigma^{DVCS}/\mathrm{d}|t| \propto \exp(-B(x_{\mathrm{Bj}})|t|)$$

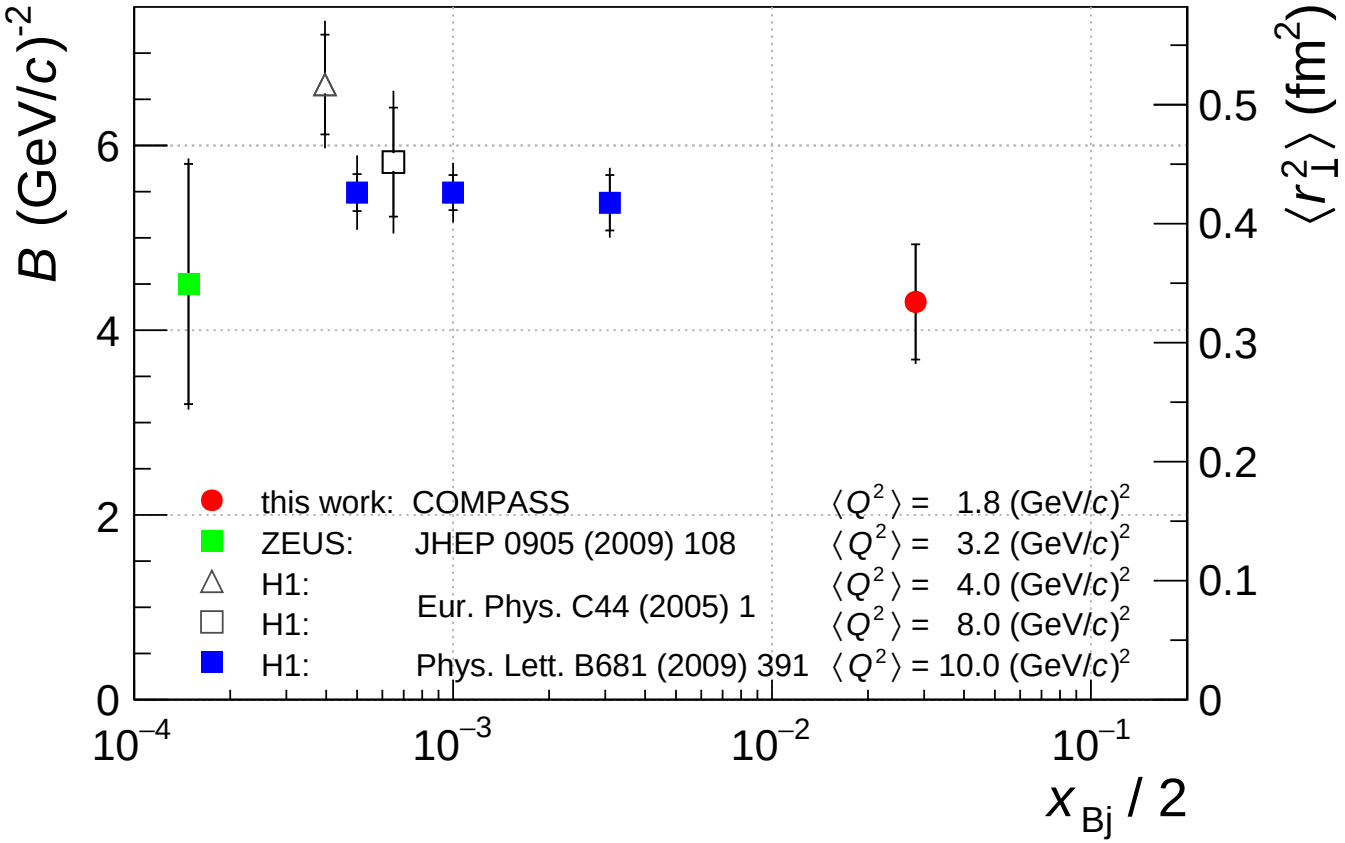
- related to distance $\langle r_\perp^2(x)\rangle$ between struck quark and spectator c.m.

$$B(x_{\mathrm{Bj}}) \sim 1/2\,\langle r_\perp^2(x_{\mathrm{Bj}})\rangle$$

- model independent



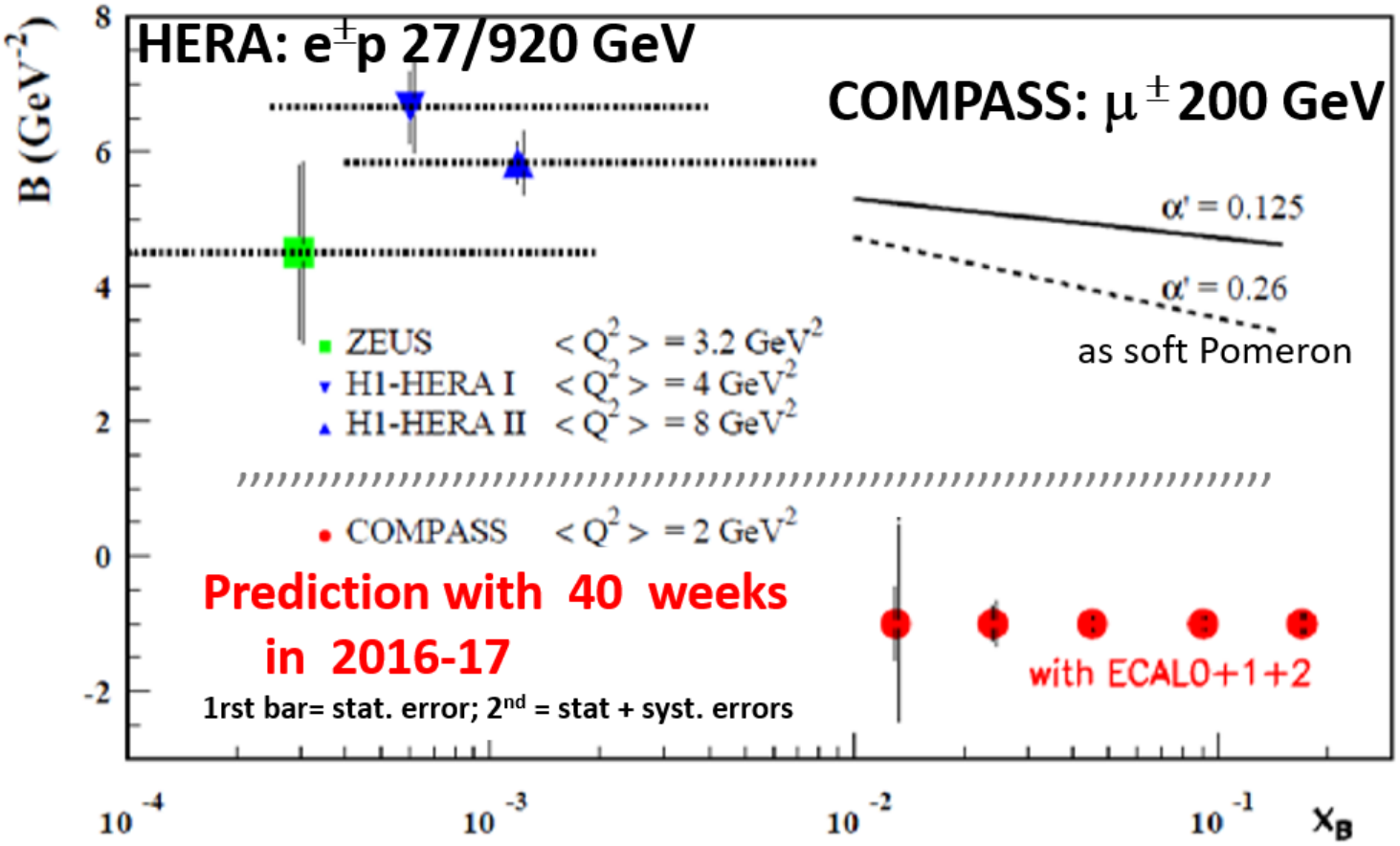
Results for transverse size



$$\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04(\mathrm{stat}))^{+0.02}_{-0.02}(\mathrm{syst})\,\mathrm{fm}$$

- COMPASS result at $\langle x_{\mathrm{Bj}} \rangle = 0.056$ and $\langle W \rangle = 5.8$ GeV$/c^2$
- comparison with HERA data at smaller x_{Bj}: indication of shrinkage??
  $\rightarrow$ more data needed

Outlook



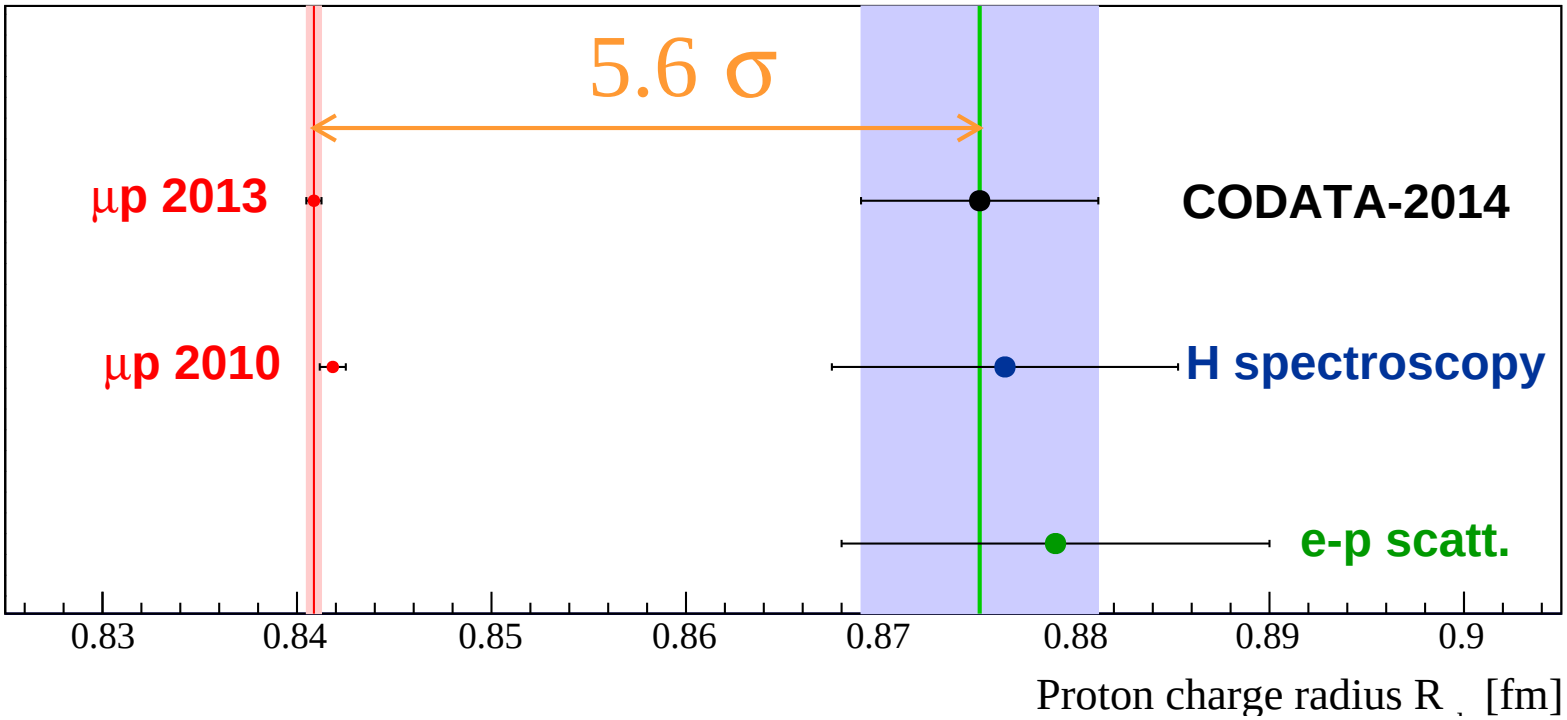
- Ansatz at small x_{Bj}: $B(x_{\mathrm{Bj}}) = B_0 + 2\alpha' \ln \frac{x_0}{x_{\mathrm{Bj}}}$
- with 2016/2017 DVCS data about factor 10 more data available

Proton radius puzzle

The proton rms charge radius measured with

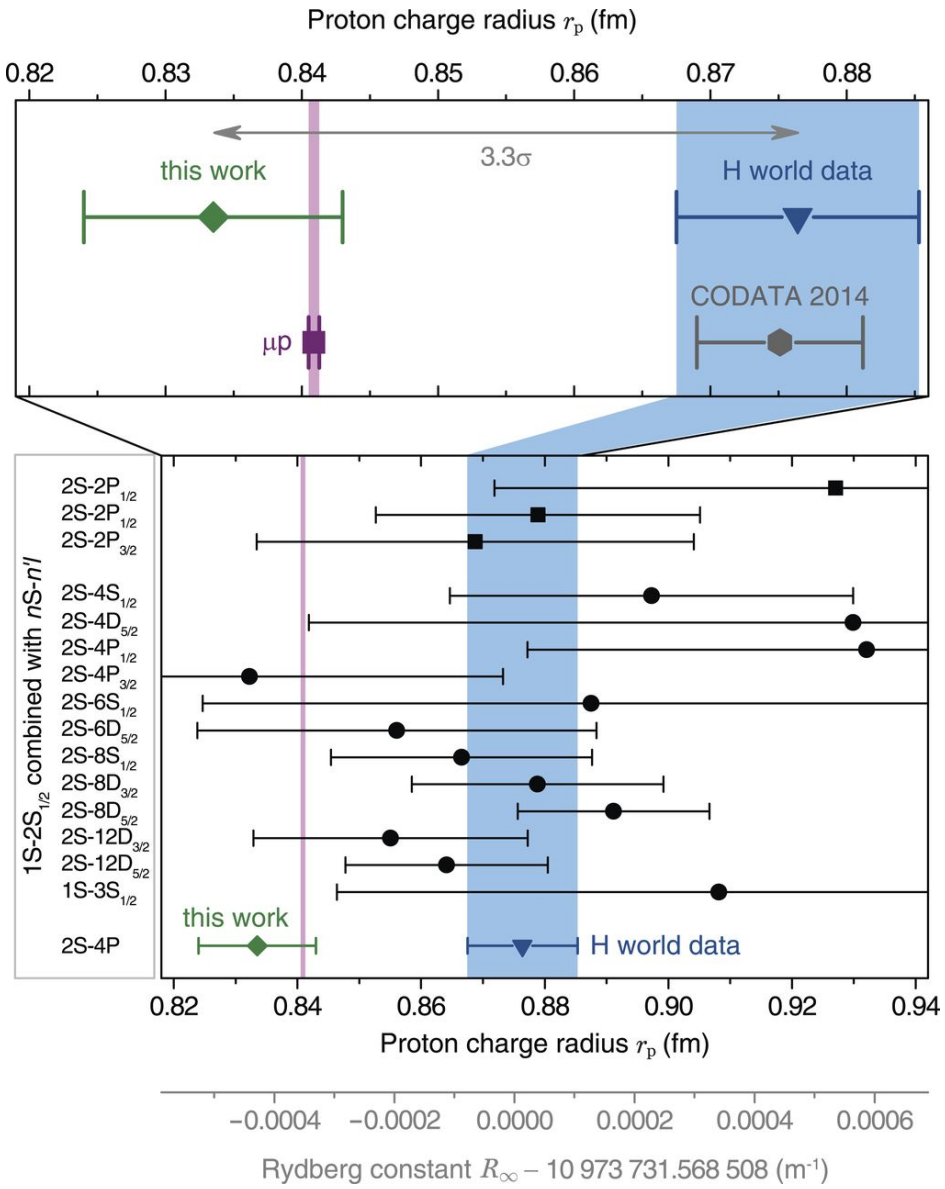
electrons: 0.8751 ± 0.0061 fm

muons: 0.8409 ± 0.0004 fm



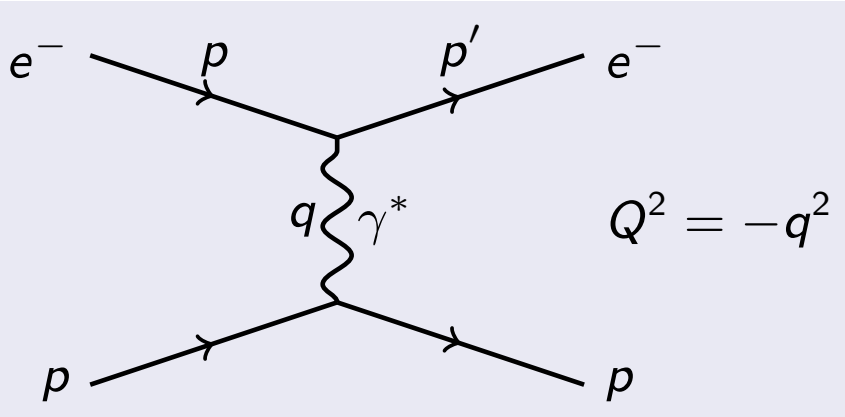
arXiv:1706.00696

More data



Science 358(2017)79

Elastic electron/muon-proton scattering



$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} = \frac{\pi\alpha^2}{Q^4 M^2 \vec{p}^2}\left[\left(G_E^2 + \tau G_M^2\right)\frac{4E^2M^2 - Q^2(s-m^2)}{1+\tau} - G_M^2\frac{2m^2Q^2 - Q^4}{2}\right]$$

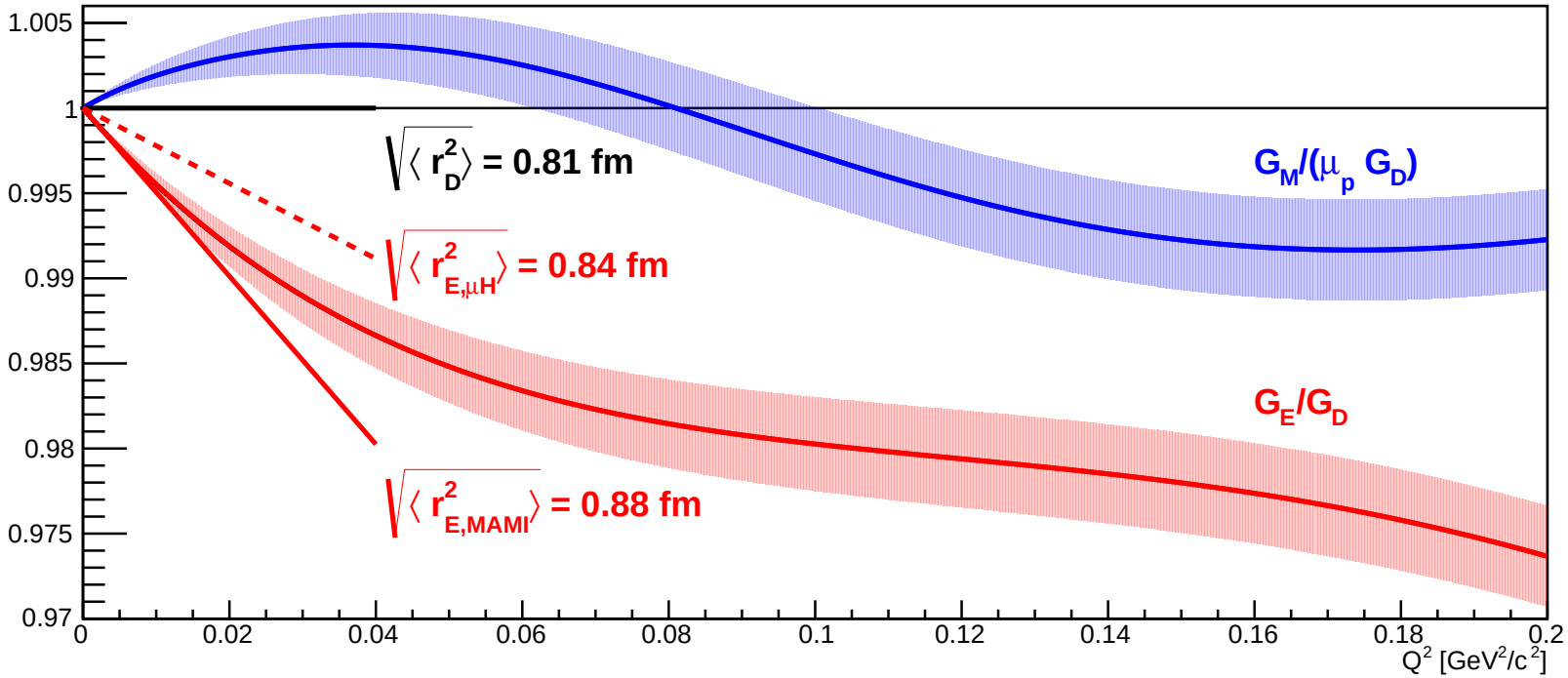
$$\text{with } \tau = Q^2/(4M^2)$$

mean square charge radius

$$\boxed{\langle r_E^2\rangle = -6\hbar^2 \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2}\Big|_{Q^2\to 0}}$$

Experimental method

- precise measurement of $G_E(Q^2)$ in large Q^2 range down to as small value as possible
- extrapolation towards zero, introduces some model dependence $\rightarrow$ slope at $Q^2 = 0$



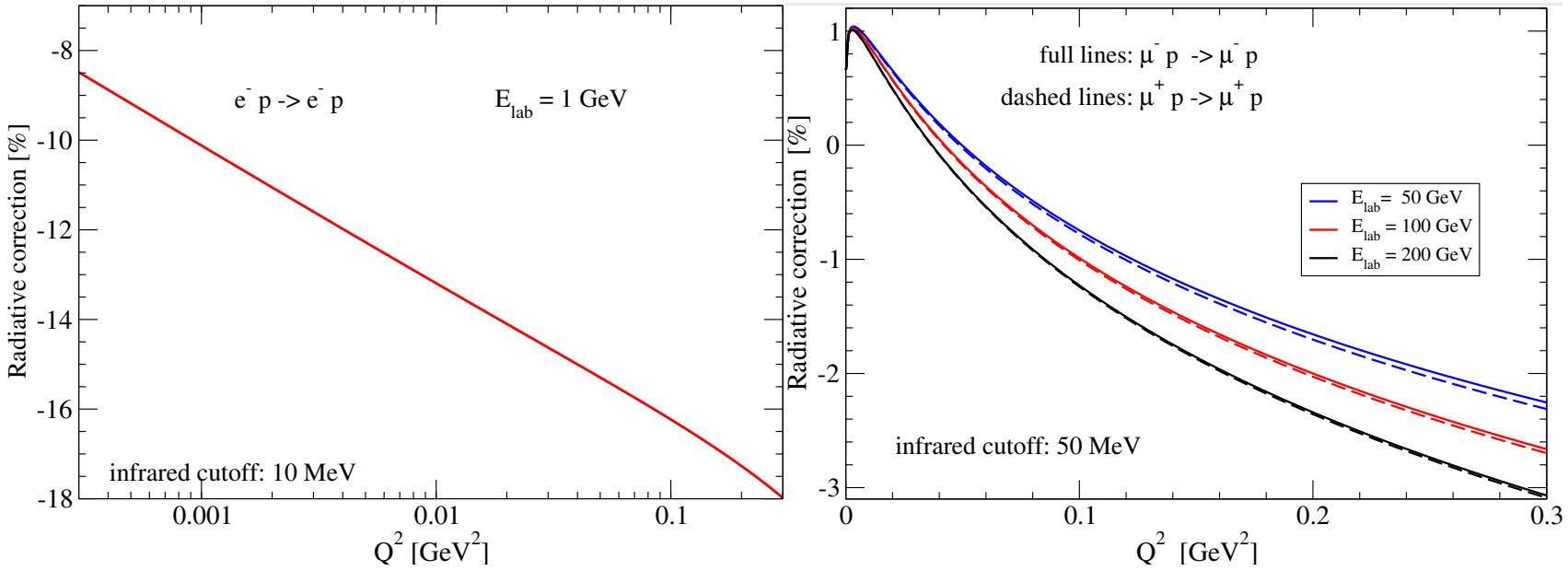
results from most recent MAMI measurement used

New round of scattering experiments

- electrons ($\mathcal{O}$(GeV), single arm): MAMI, Jlab
- electrons ($\mathcal{O}$(GeV), proton recoil): MAMI/GSI/PNPI using active target
- low energy muons (100-200 MeV): MUSE

new idea (about 1 year old): **high energy muons (50-200 GeV)**

$\rightarrow$ much smaller Coulomb corrections compared to low energy muons
$\rightarrow$ much reduced radiative corrections compared to electrons



Elastic muon-proton scattering

- scattering of high energy muons off proton target
- measurement of Q^2 dependence of elastic cross section
- no G_E-G_M separation possible at high energies $\rightarrow G_E^2 + \tau G_M^2$ measured

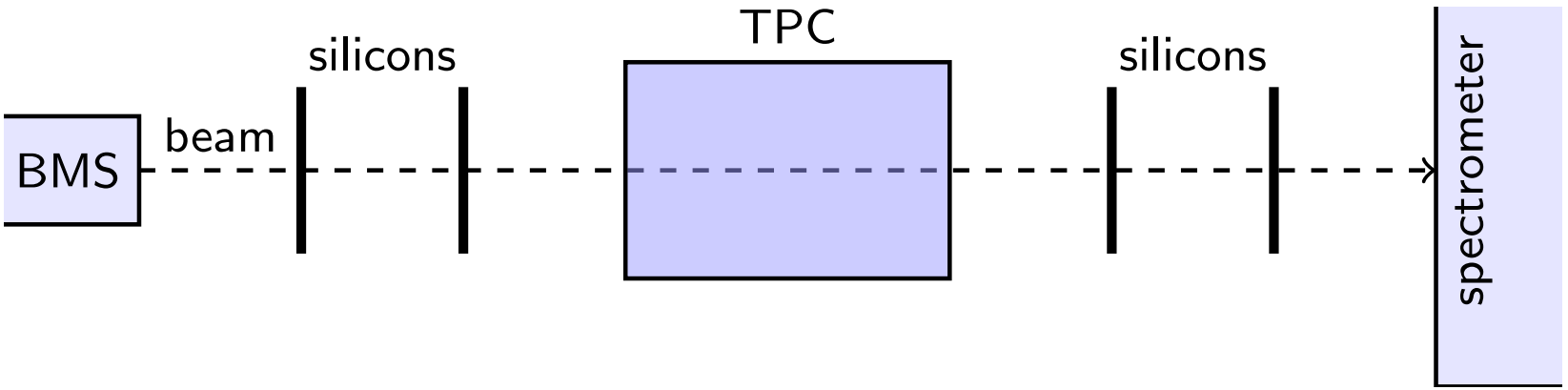
experimental challenge: identify elastic reaction

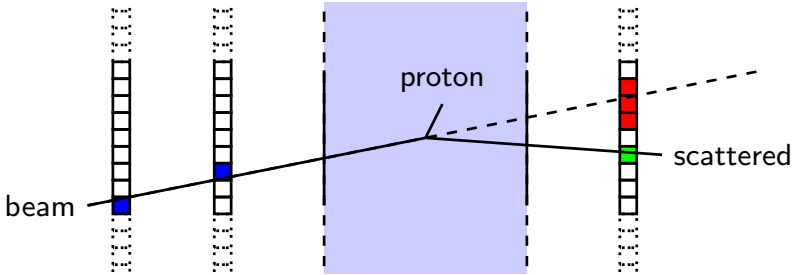
- low energy recoil proton with angles of about 90 degree
- very small muon scattering angles ($> 300\,\mu$rad) and energy same as incoming energy

experimental requirements

- measurement of proton energy and muon scattering angle
- active proton target mandatory at low $Q^2 < 0.02\ (\mathrm{GeV}/c)^2$
- fast, high resolution tracking detectors

Proposed set-up

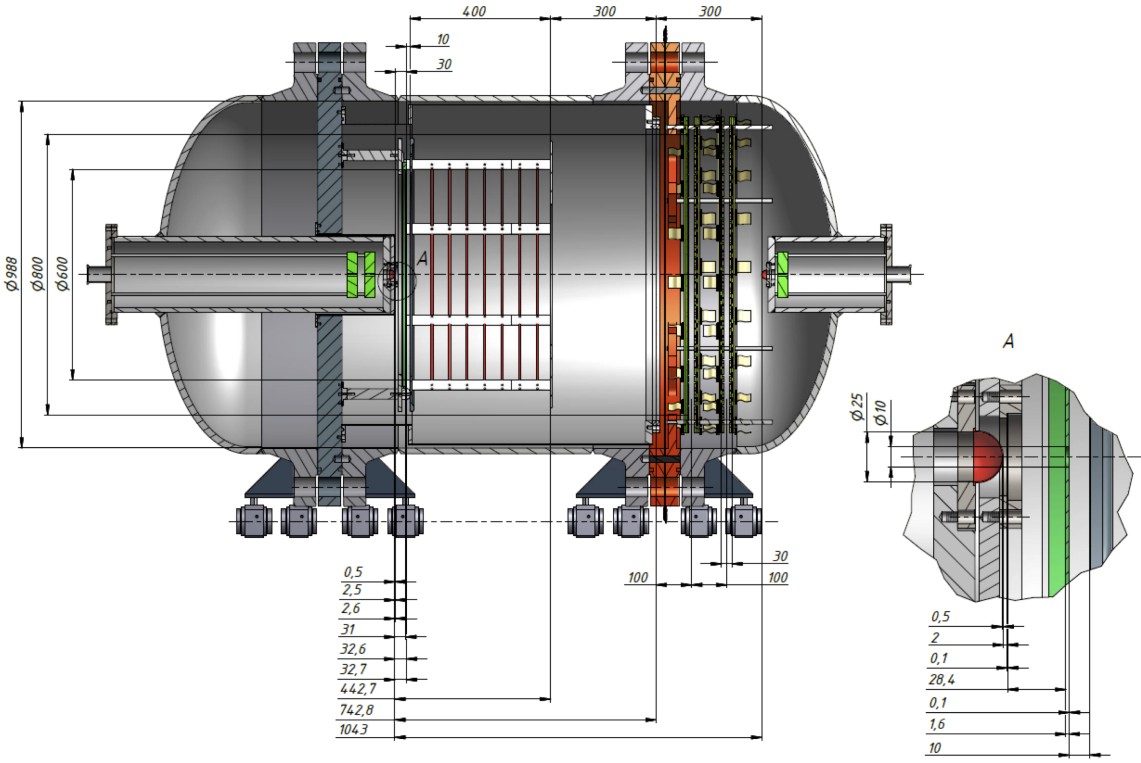




- hydrogen TPC as active target
- required energy resolution $\mathcal{O}(50\ \text{keV})$
- silicon telescopes up- and downstream of target
- required spatial resolution $\mathcal{O}(75\ \mu\text{m})$
- trigger on recoil proton and kink in muon track
- muon ID provided by spectrometer

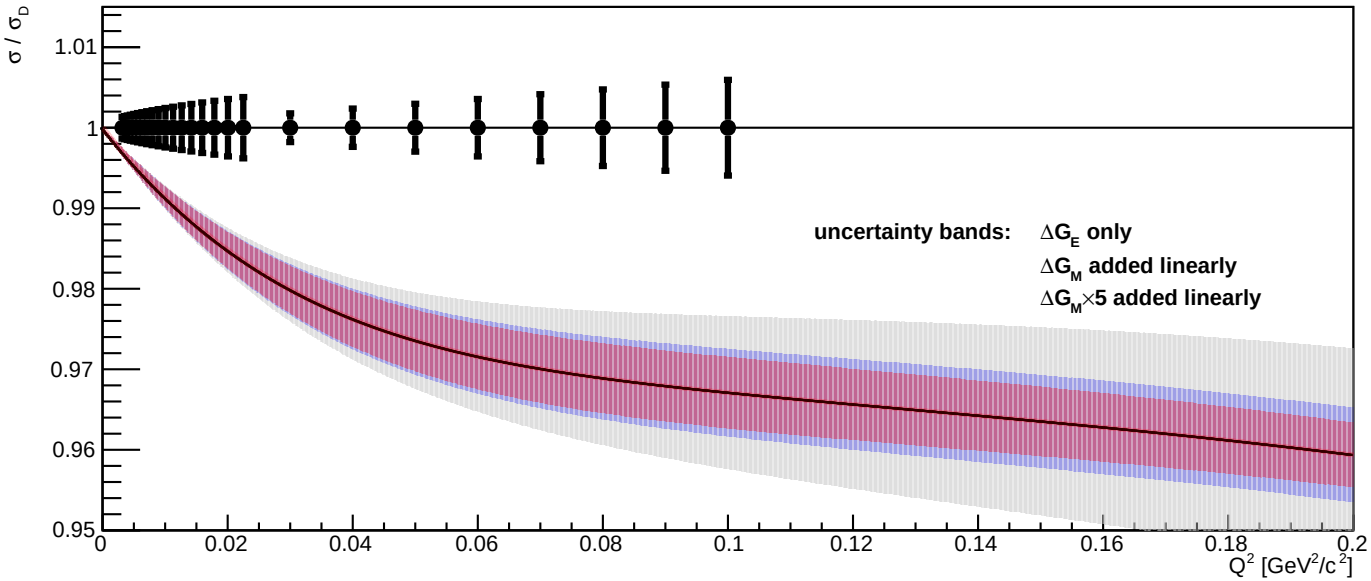
Active target

- high pressure hydrogen TPC developed by PNPI
  in use e.g. for nuclear physics experiments
- measurement of recoil proton energy
- necessary range from 0.5 MeV to 100 MeV
- use different pressures from 4 to 20 bar
- covering overlapping Q^2 ranges



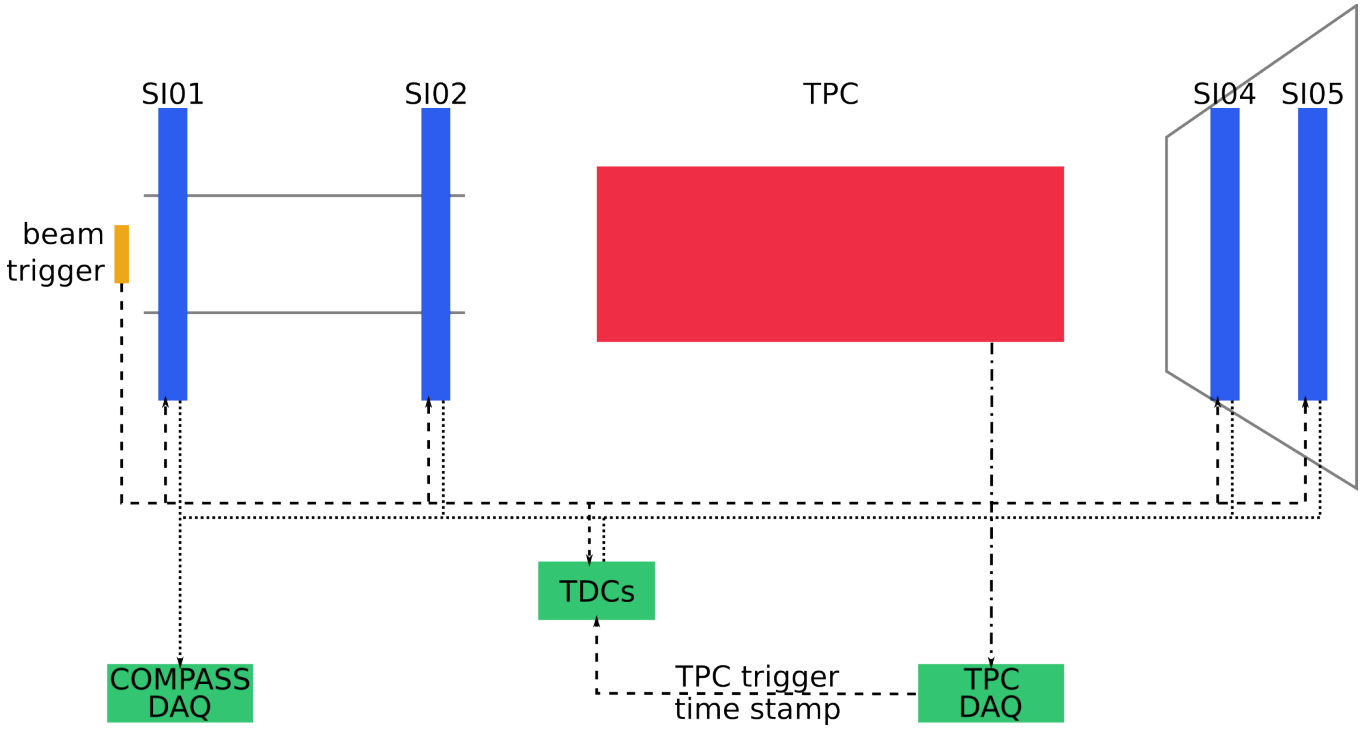
- long target required for high luminosity (long drift times)
- not all protons stopped in TPC for higher Q^2

Goal of measurement

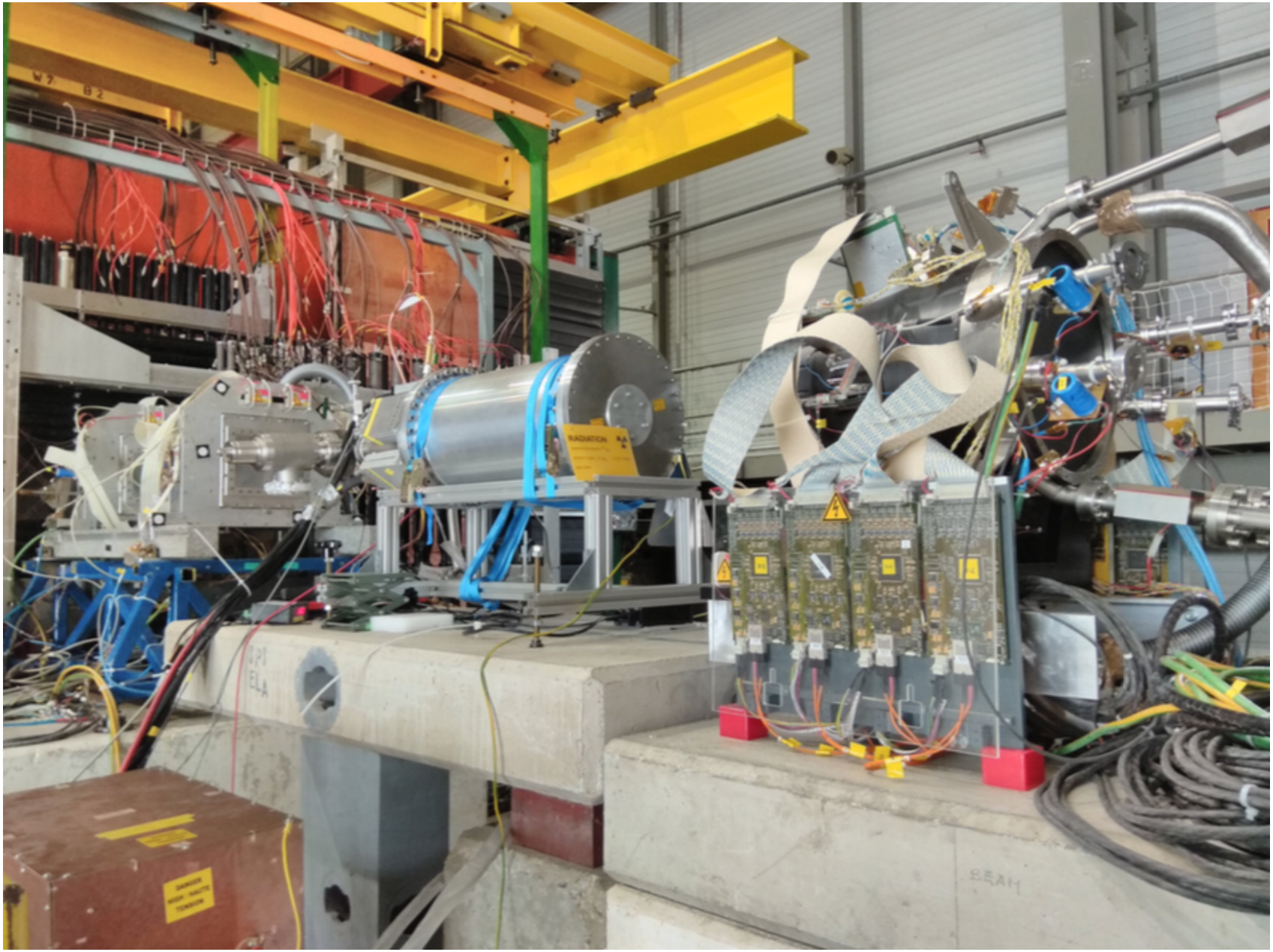


- measurement between $10^{-3}\,(\mathrm{GeV}/c)^2 < Q^2 < 0.1\,(\mathrm{GeV}/c)^2$
- lower limit: precision of Q^2, upper limit: uncertainty on G_M
- **goal:** uncertainty of $\sqrt{\langle r_E^2 \rangle} \approx 0.01$ fm

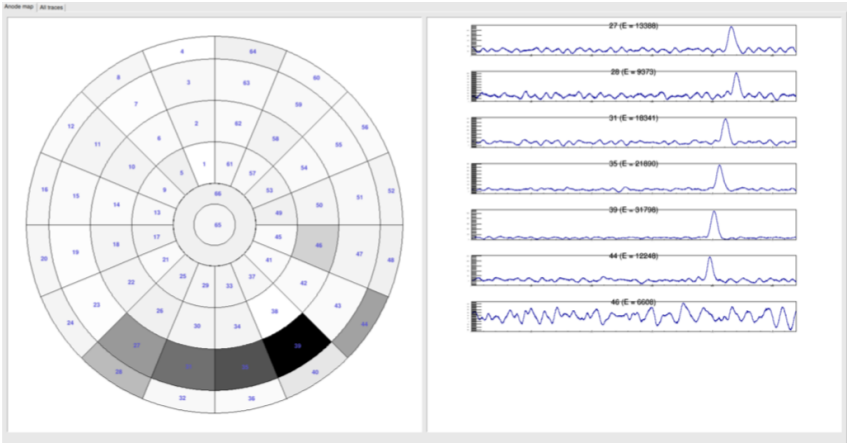
Test setup 2018



- two silicon telescopes plus TPC (from MAMI) installed downstream COMPASS spectrometer
- in addition beam trigger elements
- study performance of TPC in muon beam, study granularity of readout plane
- correlate TPC signals with events in silicon detectors

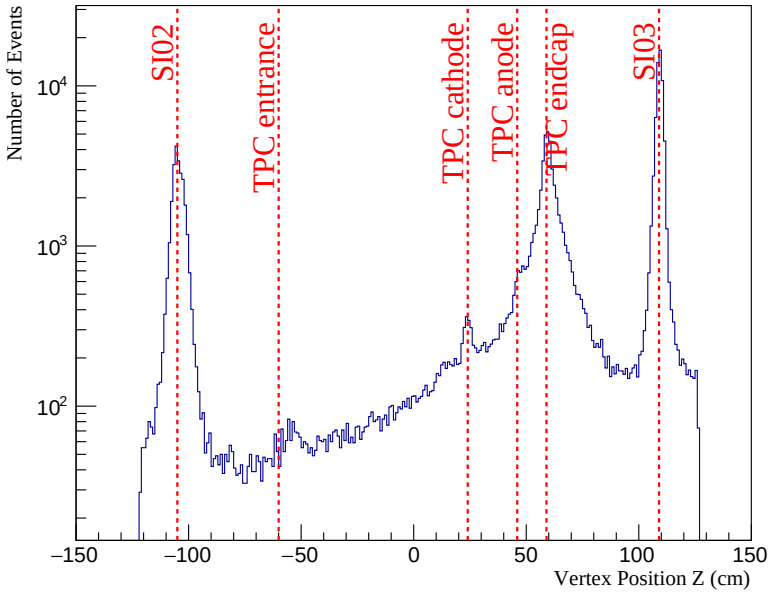


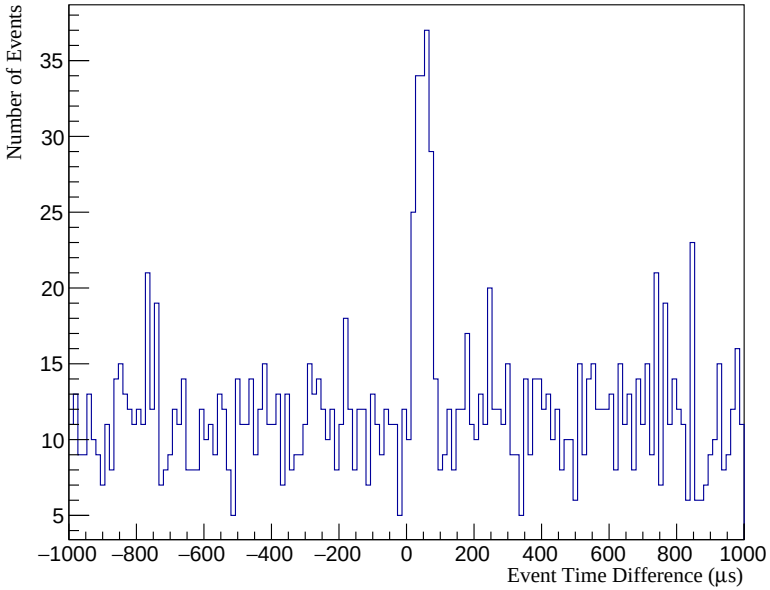
Signals in 2018



recoil protons observed with μ beam

reconstructed vertices from silicon telescope tracks
reliable alignment
vertices at expected positions





correlation of TPC signals with events with a vertex inside TPC volume

Summary

- DVCS measurement performed by COMPASS in 2016/17
  - study generalised parton distributions
  - pilot run in 2012 with nearly complete set-up
  - result for t-dependence of DVCS cross section
  - sensitivity to transverse extension of parton distributions
  - first measurement in sea quark region
- Proposal to measure elastic muon-proton scattering
  - proton radius puzzle
  - plan to use CERN high energy muon beam
  - challenging experimental set-up
  - first tests of equipment performed this year
  - experiment could be done in 2022