Measuring Hadron Charge Radii with AMBER

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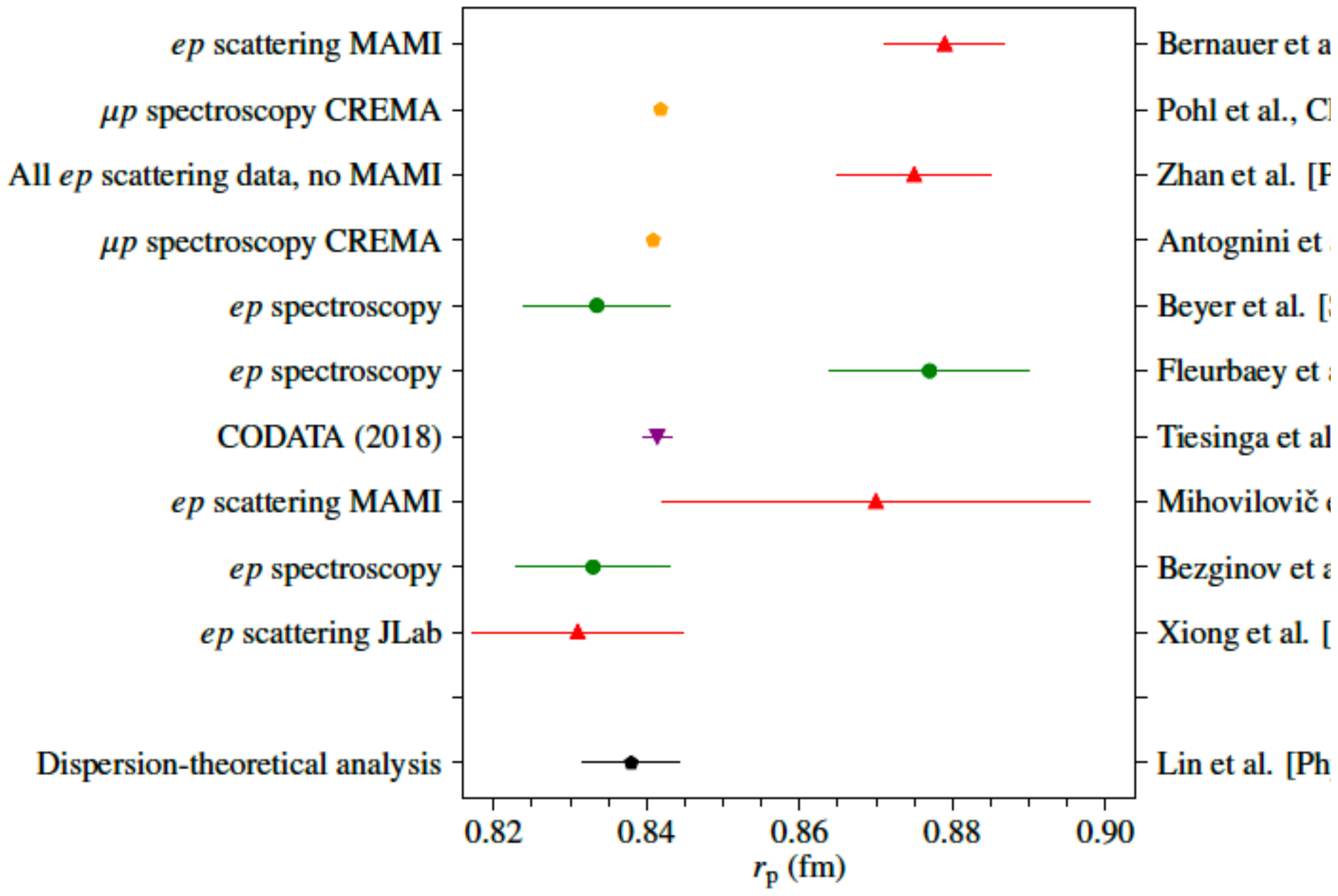
Paris

Proton Radius Measurements



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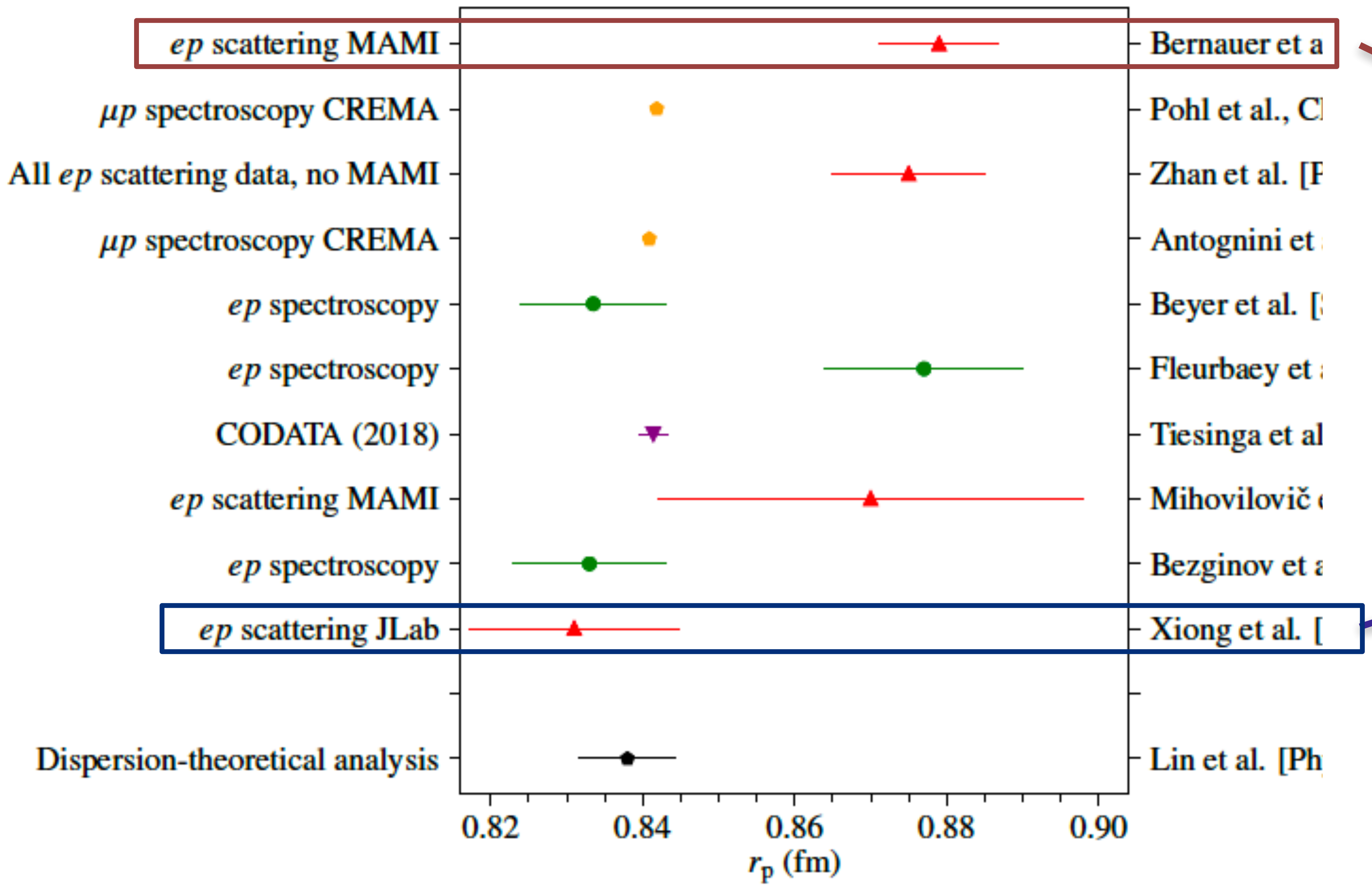
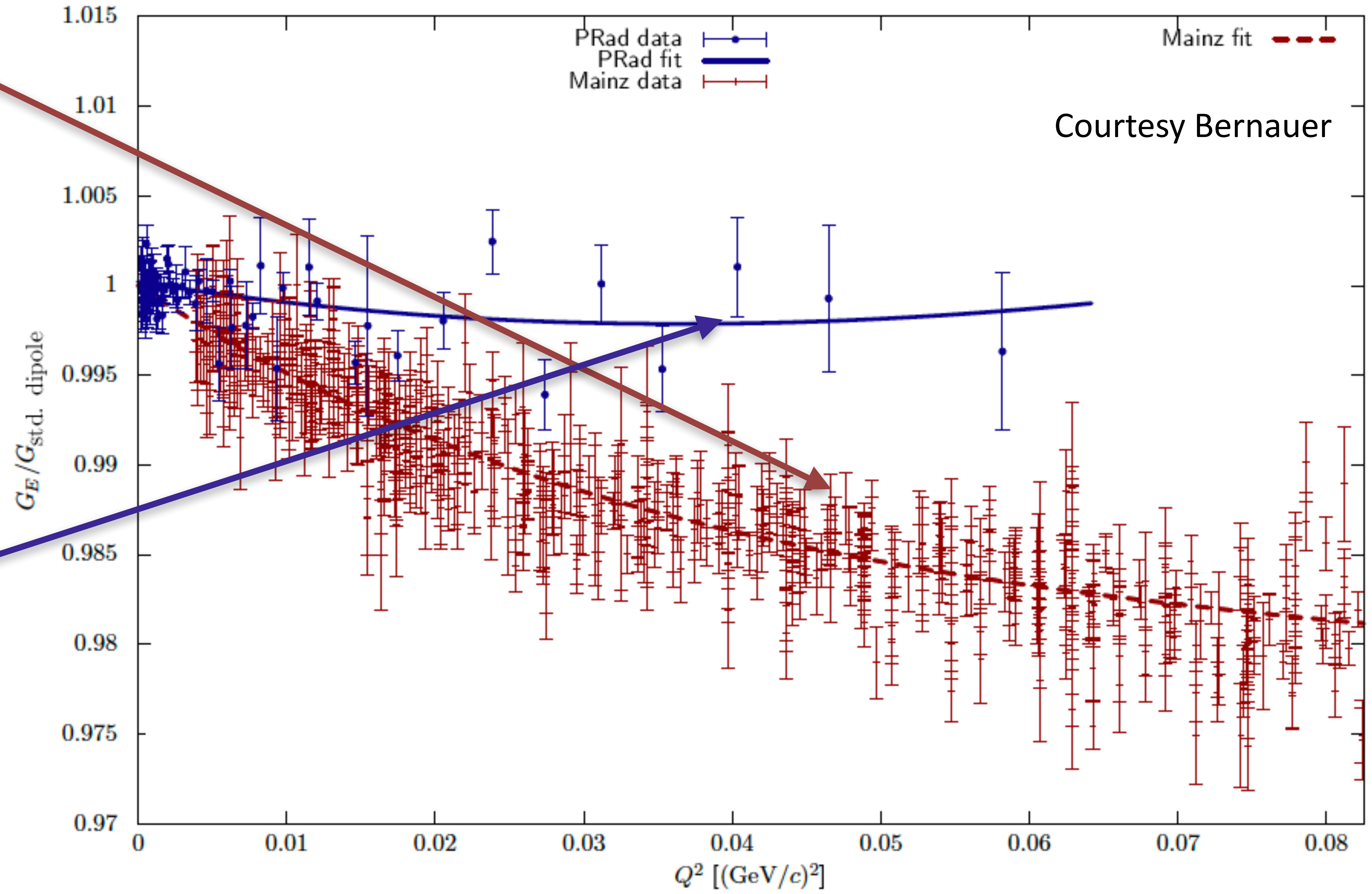




Alternative techniques

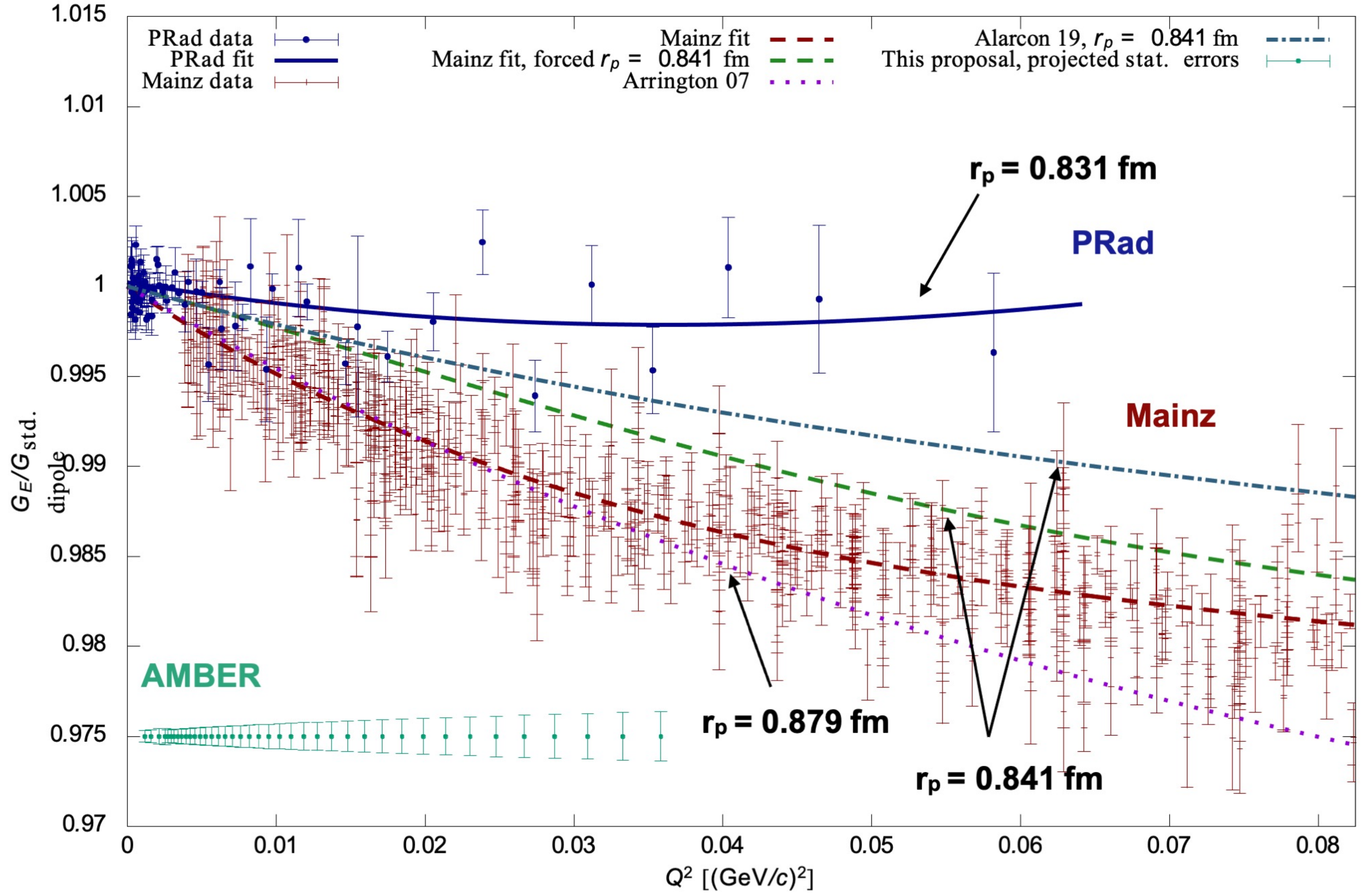
- MUSE: low energy μ and e beams of both polarities
- COMPASS: high energy μ beams of both polarities (x 500 beam energy of MUSE!!)
  - beam energy irrelevant.. Q^2 is important variable (see details later)
  - COMPASS has demonstrated excellent Q^2 resolution with Primakoff reactions
  - Coulomb peak from πA scattering $\pi + Z \rightarrow \pi + \gamma + Z_{recoil}$ - $\Delta Q^2 \approx 5 \times 10^{-4} (GeV/c)^2$
  - well performing spectrometer and well understood apparatus

....

Proposal of a New Measurement

$$< r_p^2 > = -6\hbar^2 \cdot \frac{dG_E(Q^2)}{dQ^2}\Bigg|_{Q^2\to 0} \qquad \frac{d\sigma^{\mu p\to\mu p}}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} R\left(\epsilon G_E^2 + \tau G_M^2\right)$$

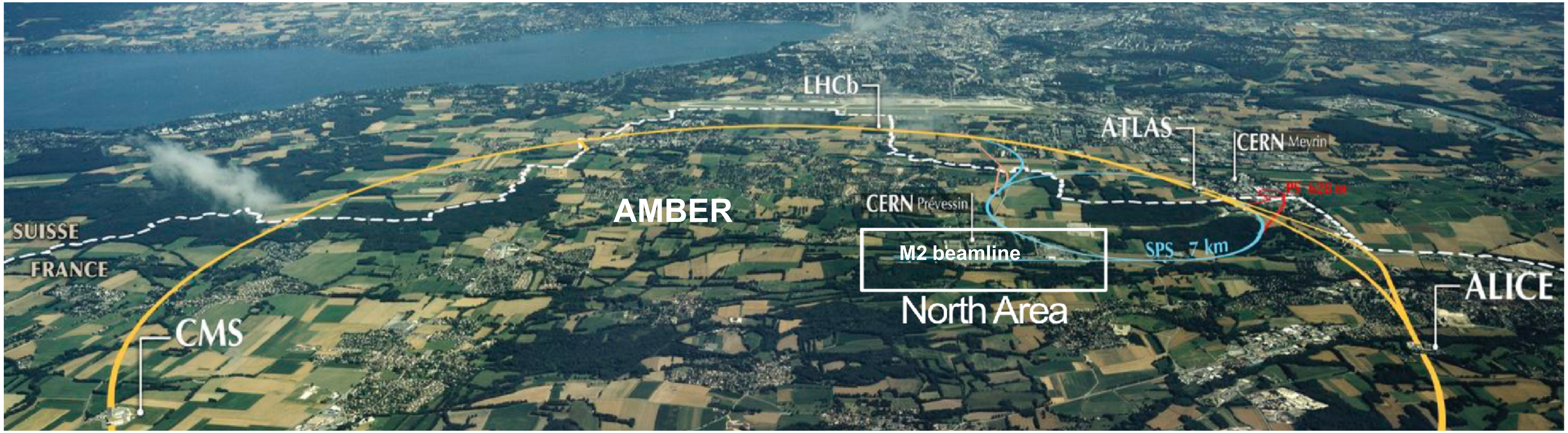
- Measure close to $Q^2 \to 0$
  $\to$ suppress influences from higher order terms (fit)
  $\to$ high-energy $\mathcal{O}$(10 - 100 GeV) — Cross-section $\propto (G_E^P(Q^2))$
- Sufficient Q^2 range to determine radius:
  $\to$ Aimed precision better 1 %
  $\to$ Aimed Q^2-range: 0.001 - 0.04 (GeV/c)^2
- Below $Q^2 = 0.001$ GeV^2/c^2:
  $\to$ Deviation from point-like proton level of $\mathcal{O}(10^{-3})$
  $\to$ systematic effects e.g. Q^2 resolution
- Above $Q^2 = 0.04$ (GeV/c)^2
  $\to$ Non-linearity of the cross section
  $\to$ Predominant source of uncertainty



Beamline for High-Energy Muon Beams

M2 beamline at *CERN's SPS*

North Area of *CERN* : M2 beamline provides a unique high-intensity muon beam



- Muon momenta up to 200 GeV/*c* - flux up to 10^7 μ/s
- PRM: beam momentum of 100 GeV/*c* and 2 MHz beam rate

- *AMBER* as successor at *COMPASS* location starting from 2021 with the first pilot run in October 2021

→ broad physics program: PRM, Drell-Yan, Anti-Proton Cross-Section, use RF separated beams

The AMBER µP measurement

Choose scattering of high energy muons o gaseous hydrogen

👍 high energy muons have little multiple scattering - good measurement of scattering angle

👍 high energy muons do not radiate (little)

👎 muon energy loss very small - basically no useable information from muon momentum

⇒ need to measure recoil proton

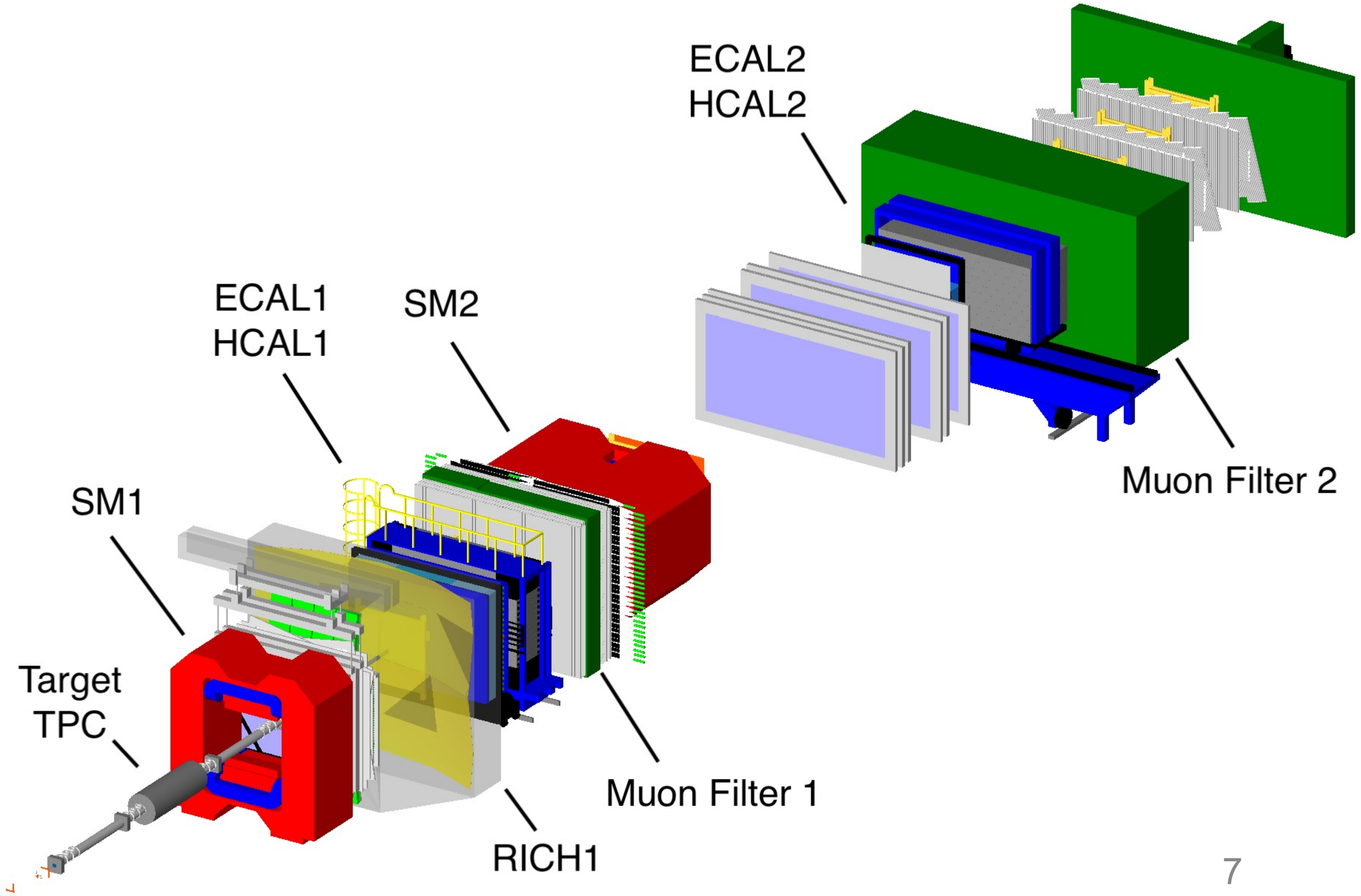
👎 low energy recoil protons carry information about Q^2

⇒ measure their energy via an active target

👍 keep the advantages and circumvent the disadvantage by excellent instrumentation

Proton Radius from Muon-Proton Elastic Scattering at High Energy

- 100 GeV muon beam
- Active-target TPC with high-pressure H_2
- goal: 70 million elastic scattering events in the range $10^{-3} < Q^2 < 4 \cdot 10^{-2}\ (GeV/c)^2$
- Precision on the proton radius ~0.01 fm



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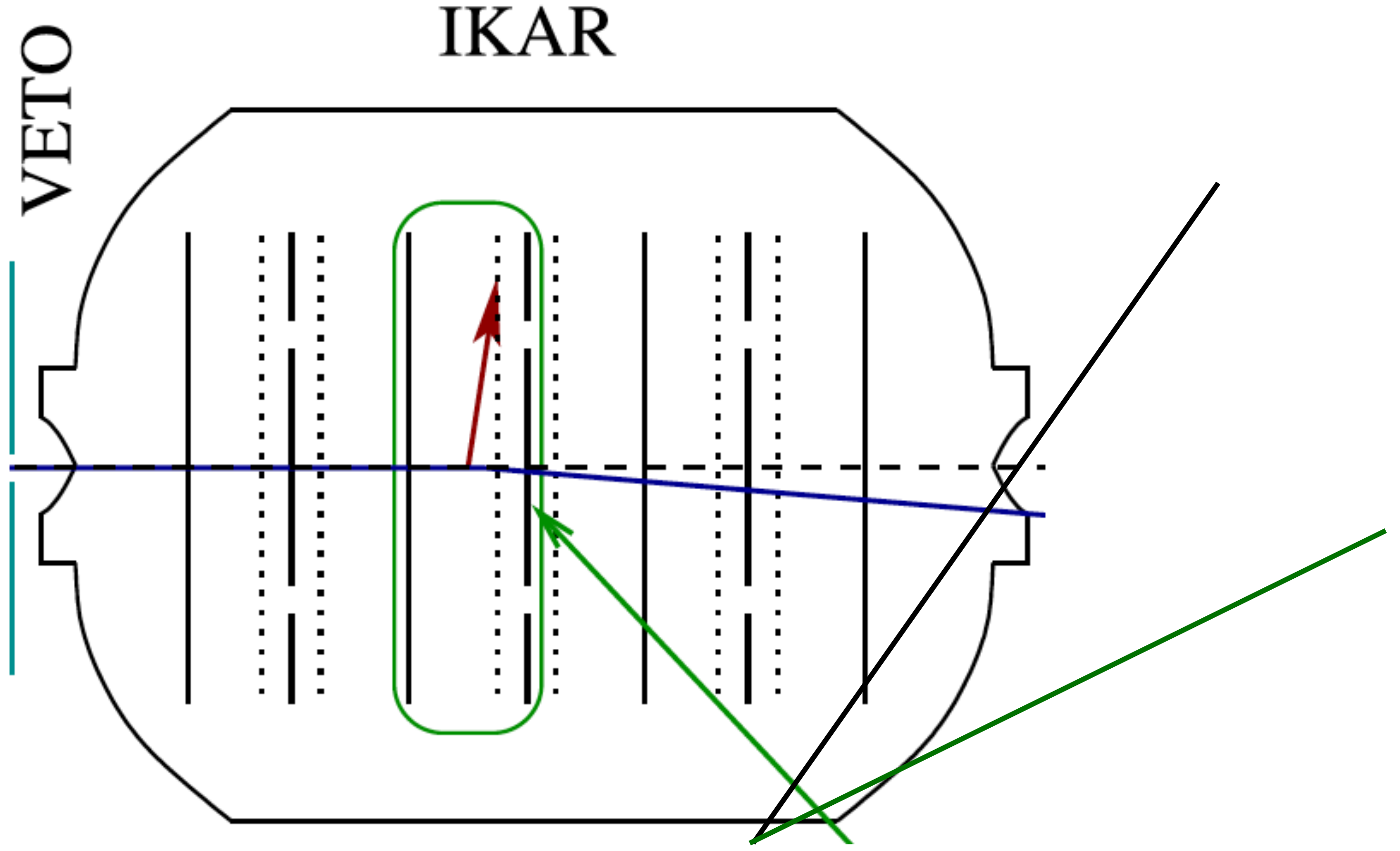
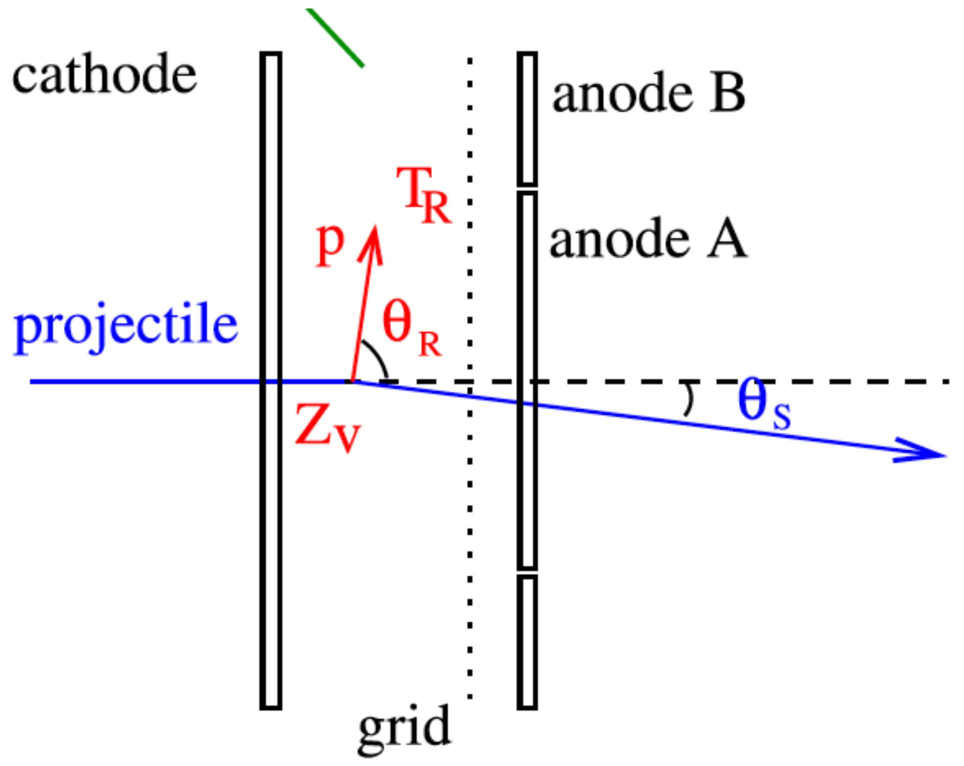
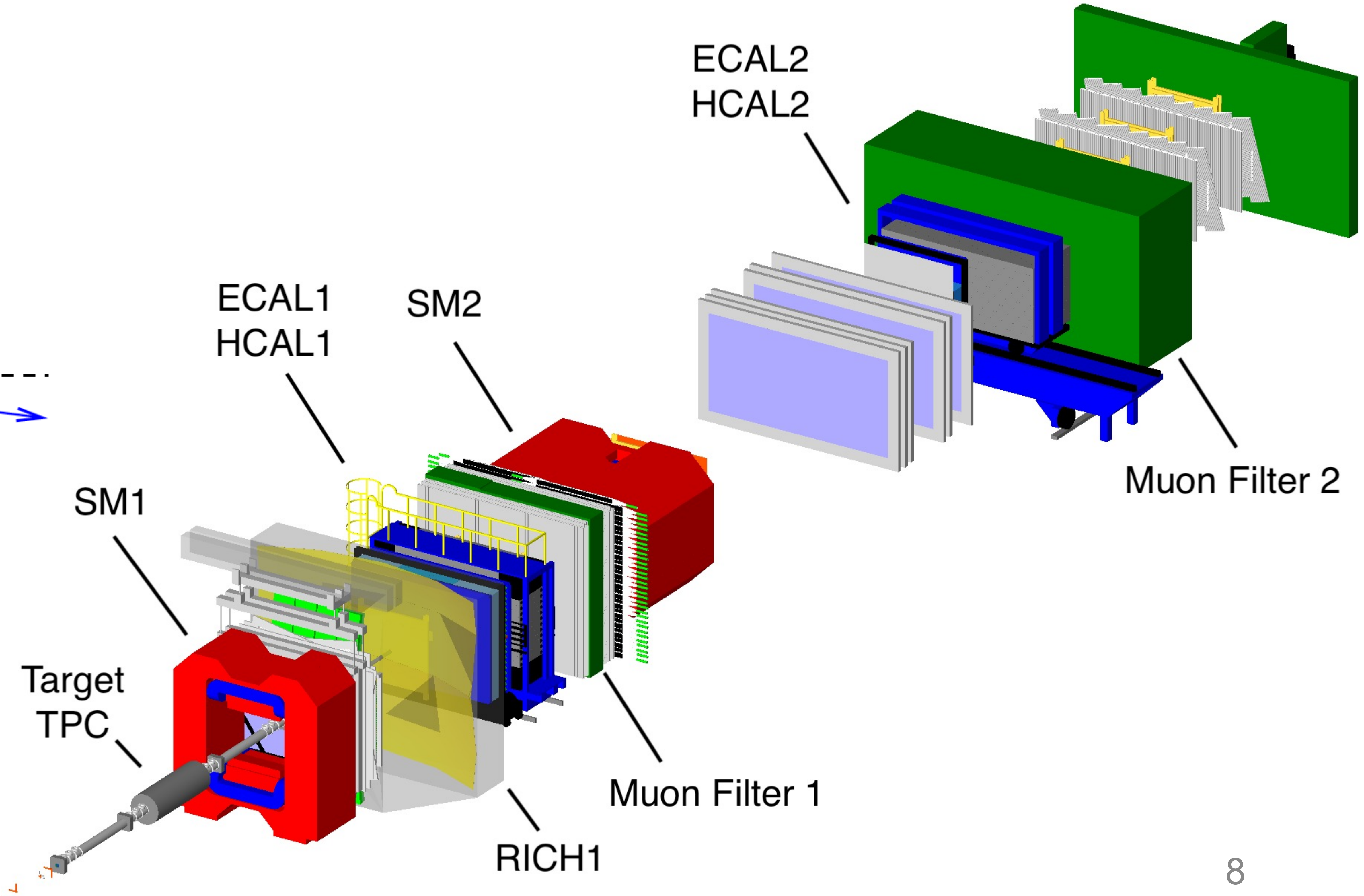


High Pressure Hydrogen - 4bar



ionisation **TPC**



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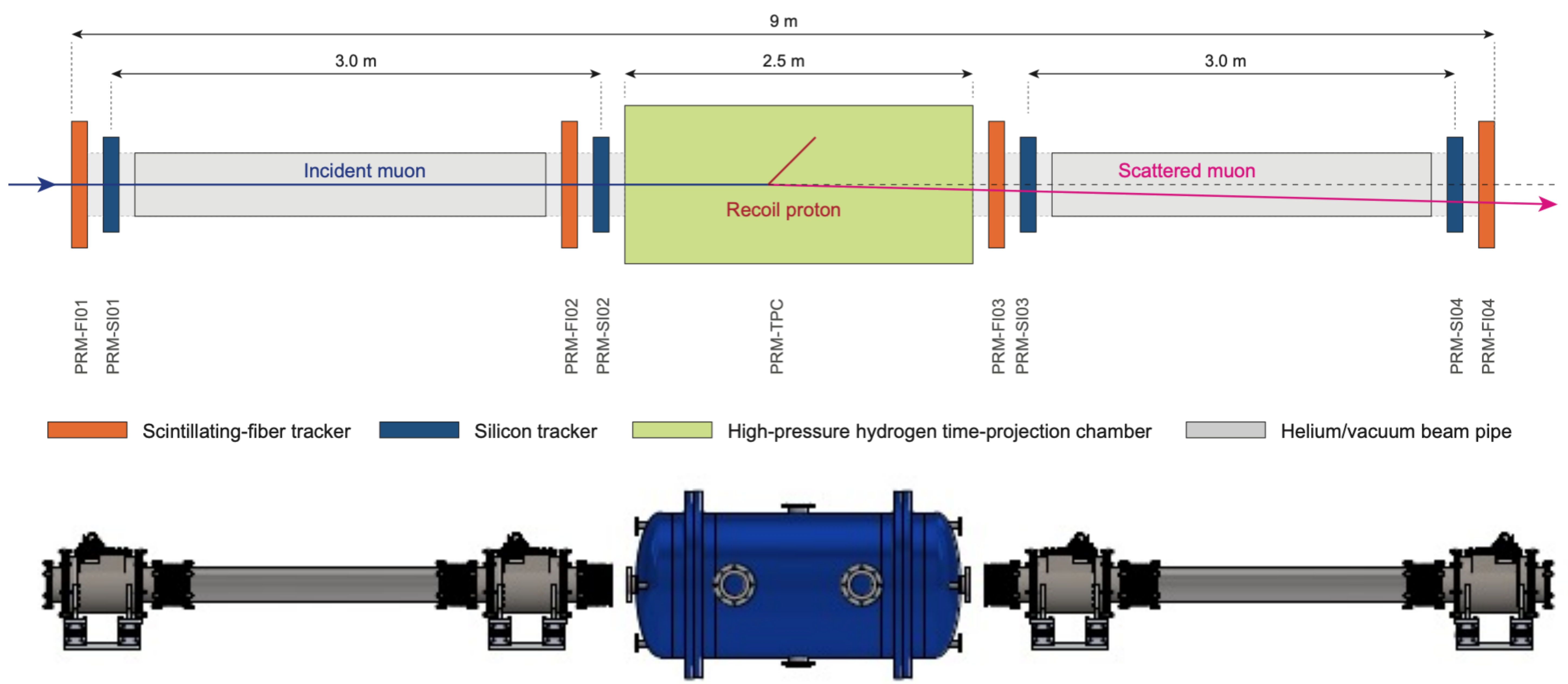
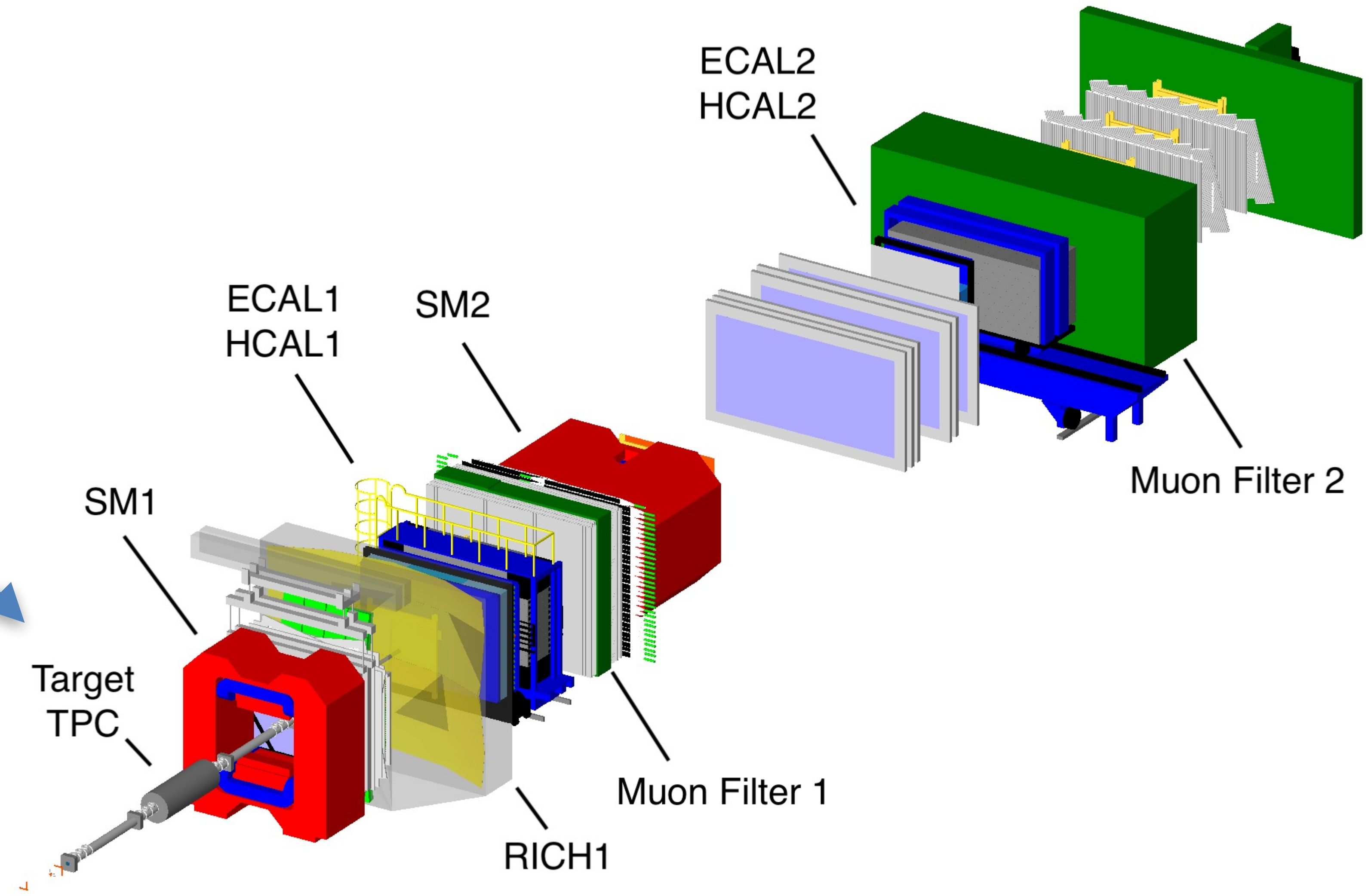
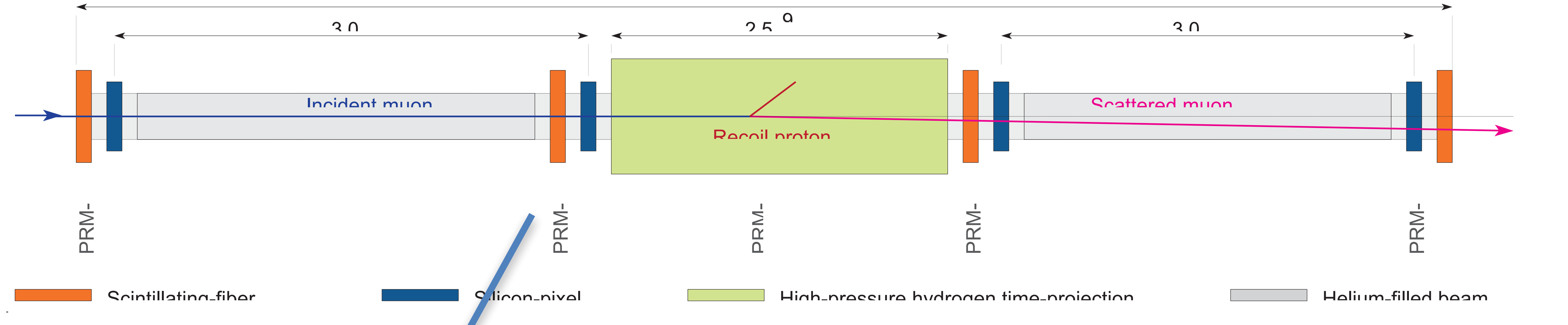




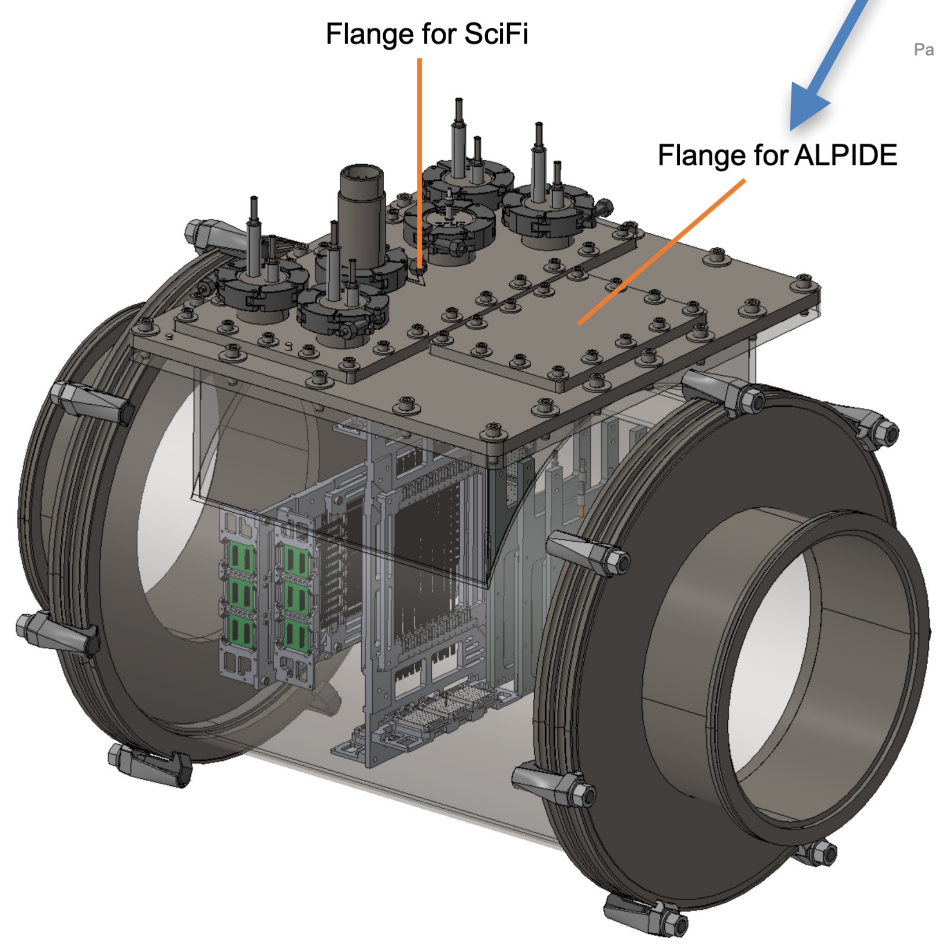
Layout of Proton-Radius Measurement in 2023

Measurement of low-Q^2 elastic-scattering coincidence of low-energy recoil-protons and scattered muons at small scattering-angles.



- TPC as an active target to measure recoil protons
- Silicon pixel detectors (ALPIDE) along long leaver-arm measure small scattering-angles
- Scintillating fibers for timing and tracking (10x10 cm^2)

→ Unified Tracking Station (UTS)



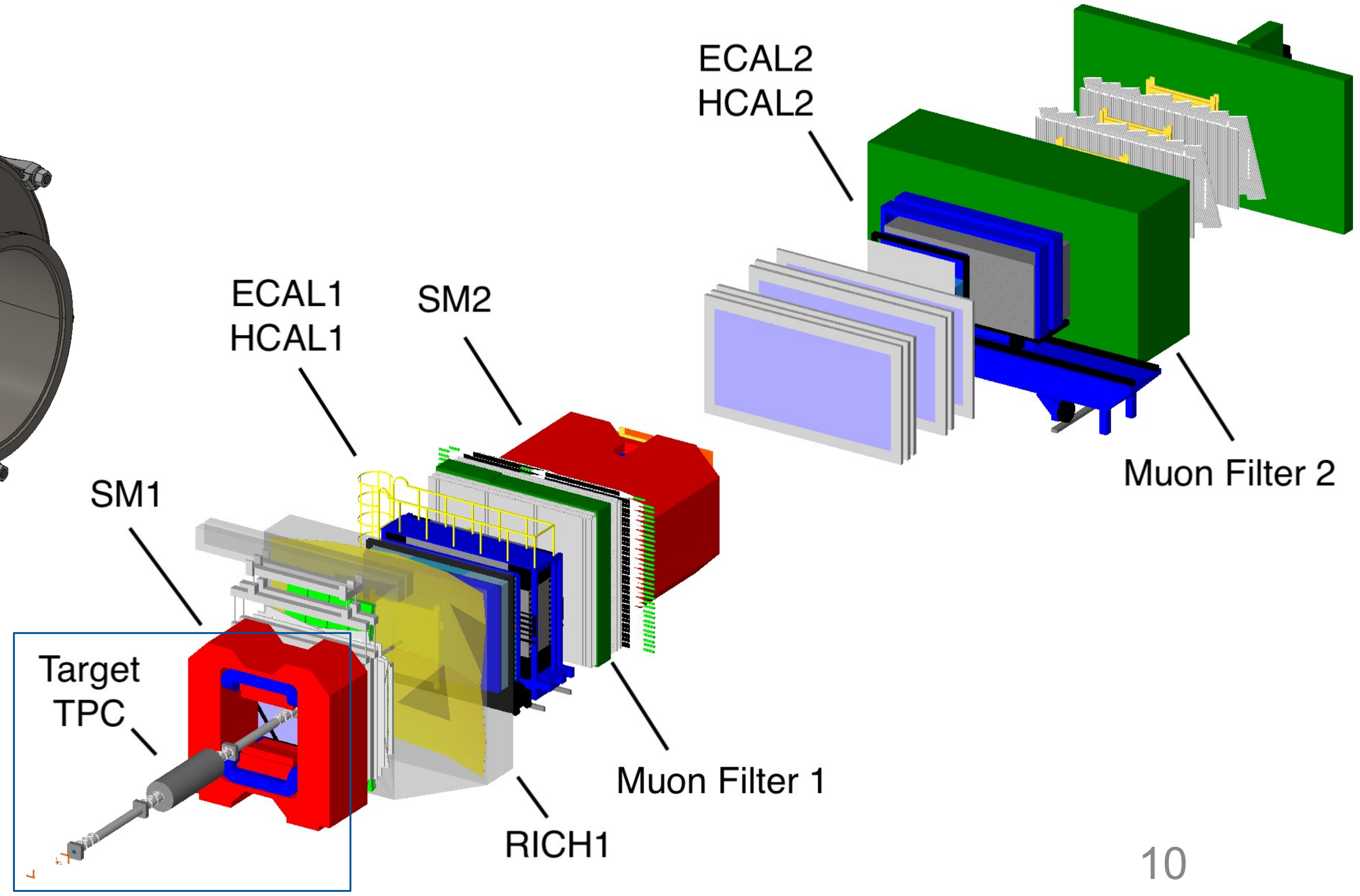
- New free-running DAQ and spectrometer upgrades

- *AMBER* spectrometer:

→ Momentum measurement of scattered muon

→ Radiative events using electromagnetic calorimeter

→ Muon identification with muon filter and hodoscope



Detection of Low-Q^2 Recoil-Protons

Pressurised hydrogen active-target TPC

Direct recoil-proton energy measurement with active target.

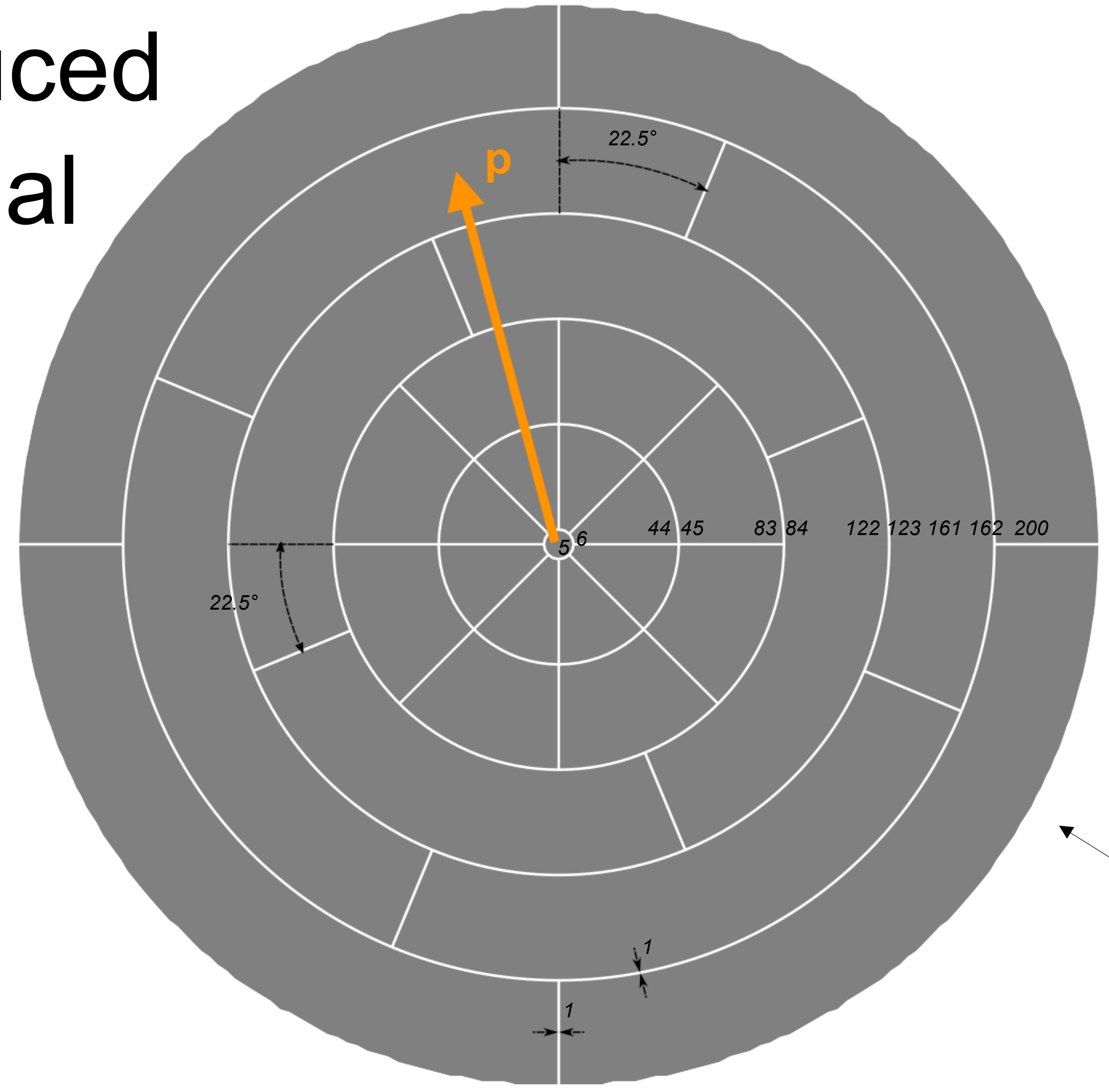
- 4 x 40 cm drift cells each with segmented readout
- Direct energy measurement without amplification (deposited energy through ionization of H_2)
- Segmented readout plane:

→ Spacial and angular resolution (both θ and φ)

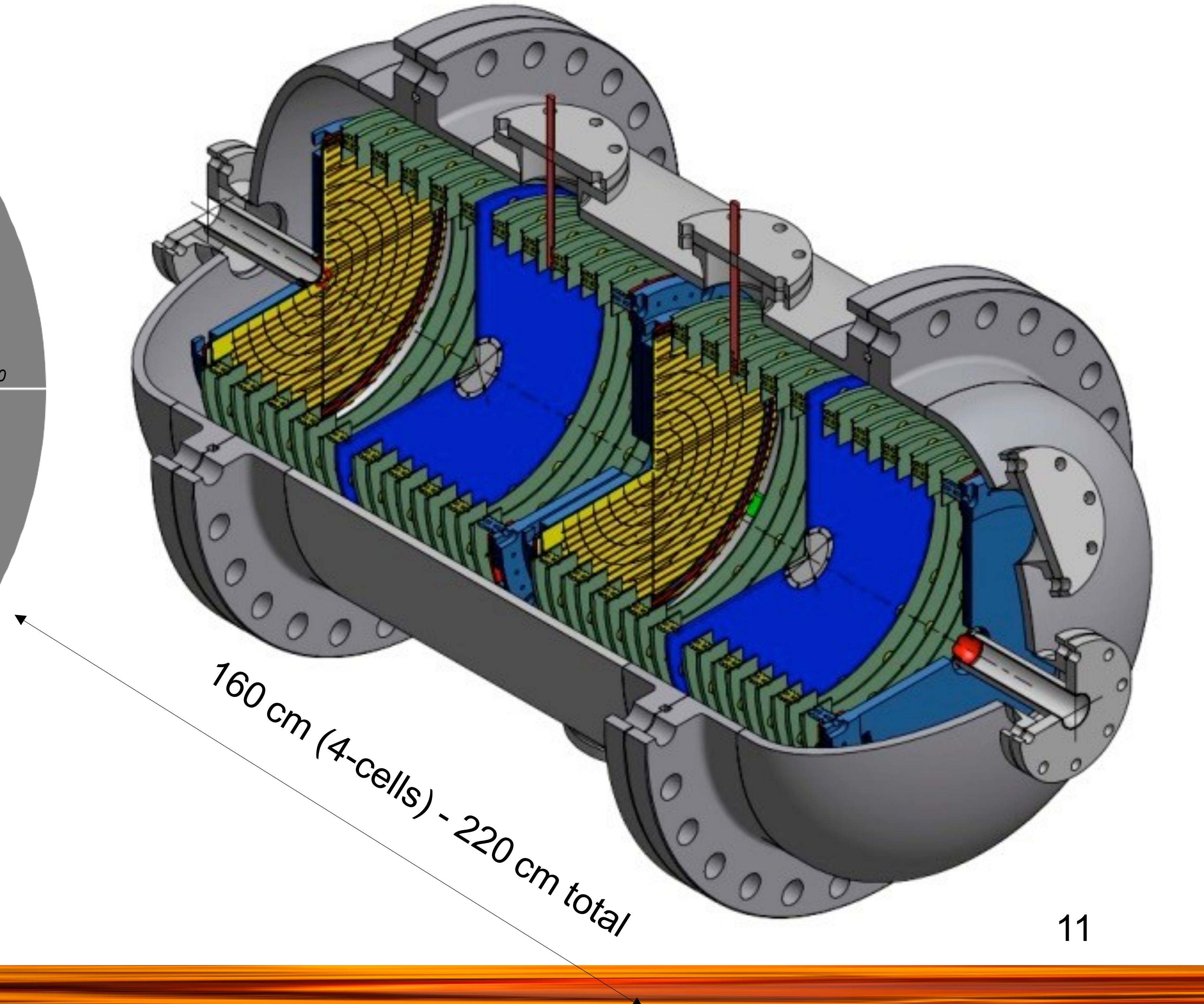
→ Beam induced ionisation noise reduced

- use low noise preamps to collect signal
- Integration (drift) time of TPC: 68 μs

→ limits beam intensity to $2 \cdot 10^6/s$



Test layout - final: 300 mm



CERN-SPSC-2019-022; SPSC-P-360

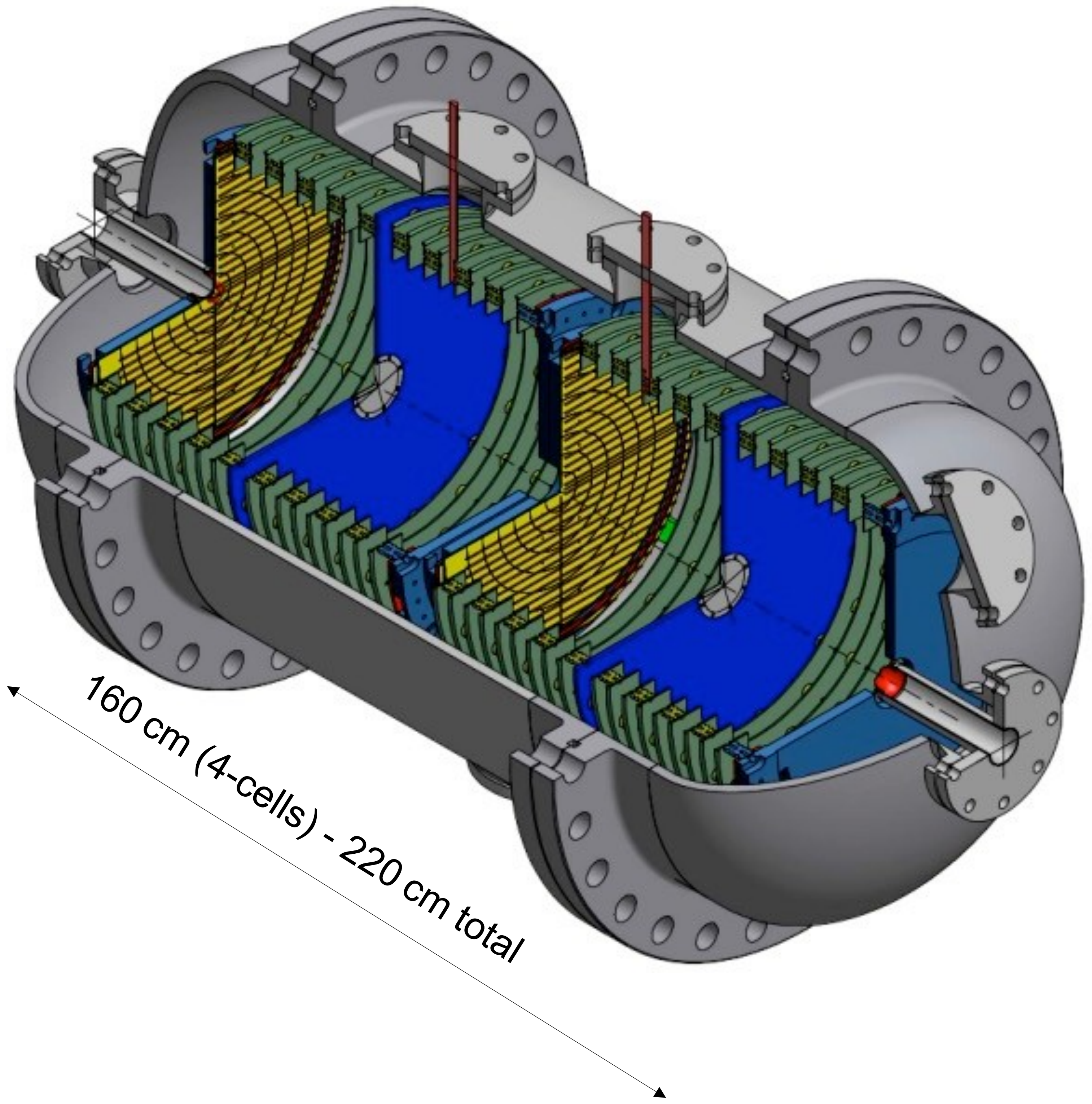
Detection of Low-Q^2 Recoil-Protons

Pressurised hydrogen active-target TPC

Direct recoil-proton momentum measurement with active target

- Requires proton to stop in target[1]

  - Q^2-range affects range of recoil proton:
    → Recoil-proton ranges of 2 - 300 mm (and more)
- large Q^2-range requires two pressure settings:



→ 20 bar ($0.0025\ \mathrm{GeV}^2/c^2 < Q^2 < 0.04\ \mathrm{GeV}^2/c^2$)
→ 4 bar ($Q^2 < 0.0025\ \mathrm{GeV}^2/c^2$)
→ Two overlapping datasets
→ Low-pressure region to correct noise at small Q^2-events
→ Relative energy resolution: $\sigma(E_{kin}) / E_{kin} < 0.06$ required for aimed precision < 1 %

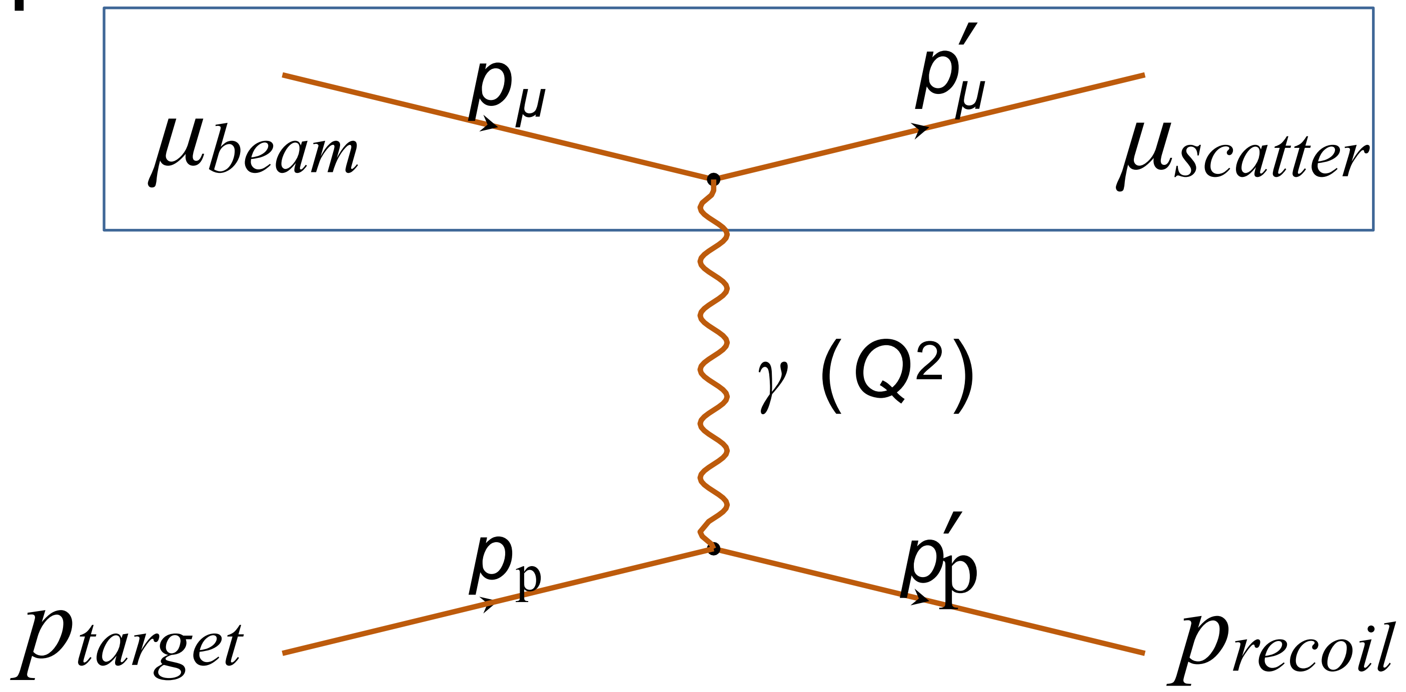
[1] stopping actually not quite necessary if set-in of Bragg curve in differential energy loss can be detected

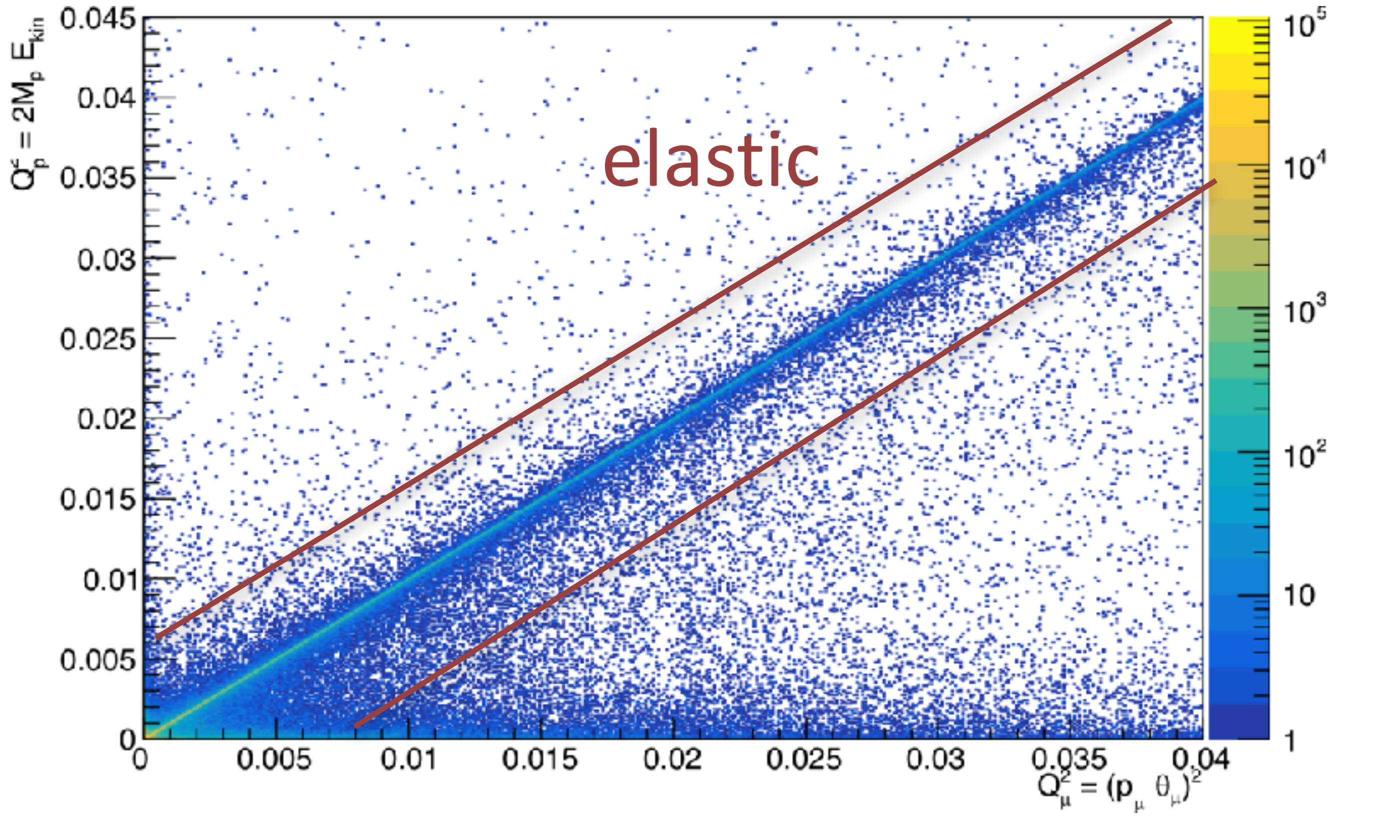
Control of Systematic Effects

Absolute calibration, inefficiencies, and background

Understanding of systematic effects is crucial for precision

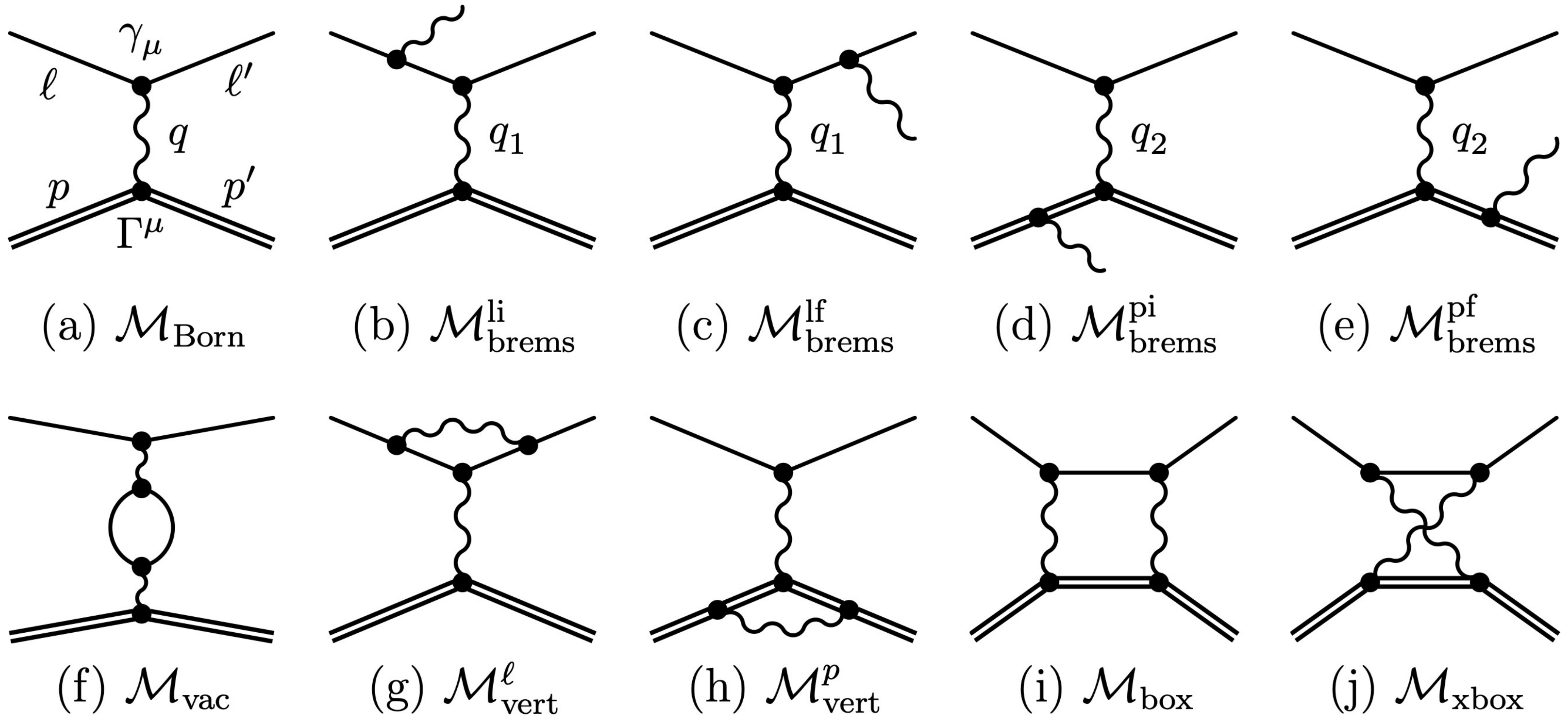
- Absolute calibration of the TPC recoil-proton energy-scale
- Inefficiencies in recoil-proton measurement
- Cross check of TPC measurement with (μ, μ')





Redundant measurement to control systematics
→ measurement of scattered muon kinematics

- Lepton-proton scattering accompanied by bremsstrahlung
  → NLO process on $\mathcal{O}(10^{-4})$ level for $E_\gamma > 500$ MeV
  → distortion of Q^2-spectrum
- $\varepsilon = 1$ → no contribution of 2γ



ESEPP arXiv:1401.2959

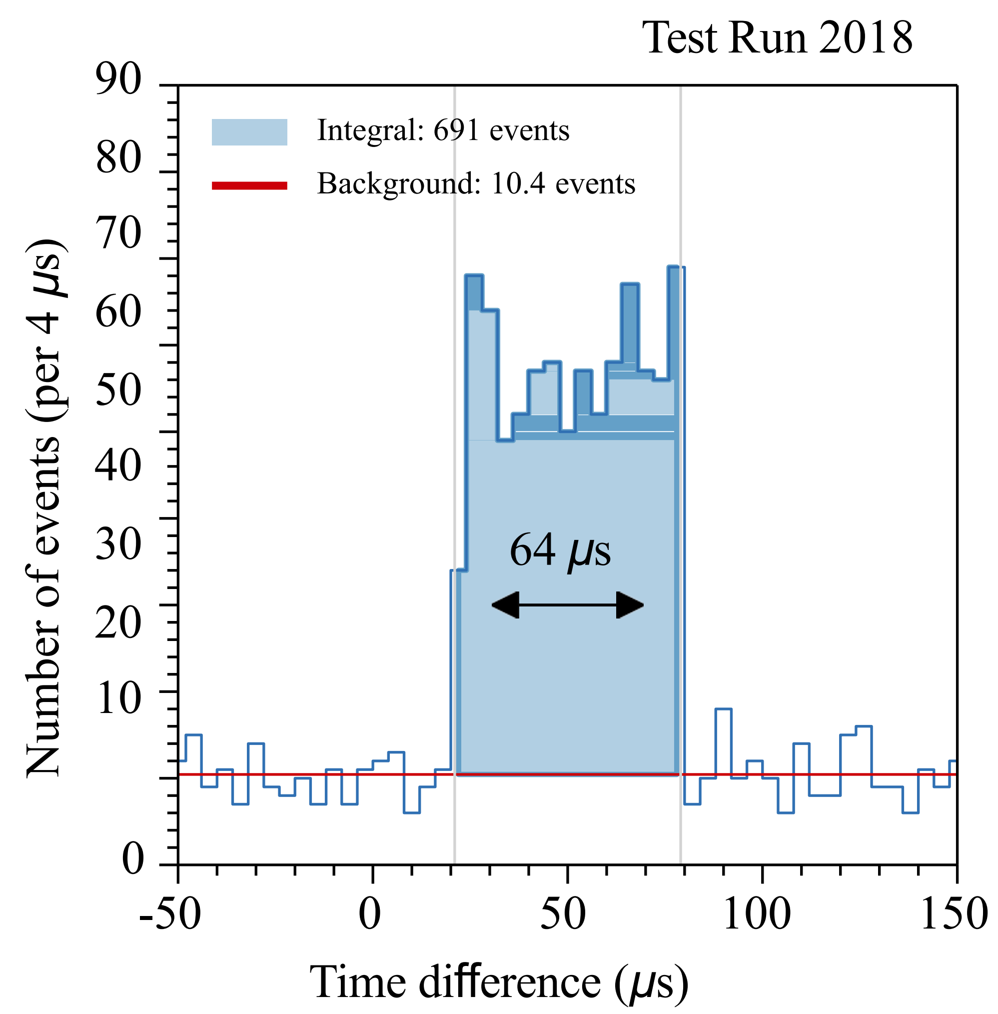
Use of *AMBER* spectrometer — tracking and calorimetry
→ understanding of background
→ muon momentum measurement

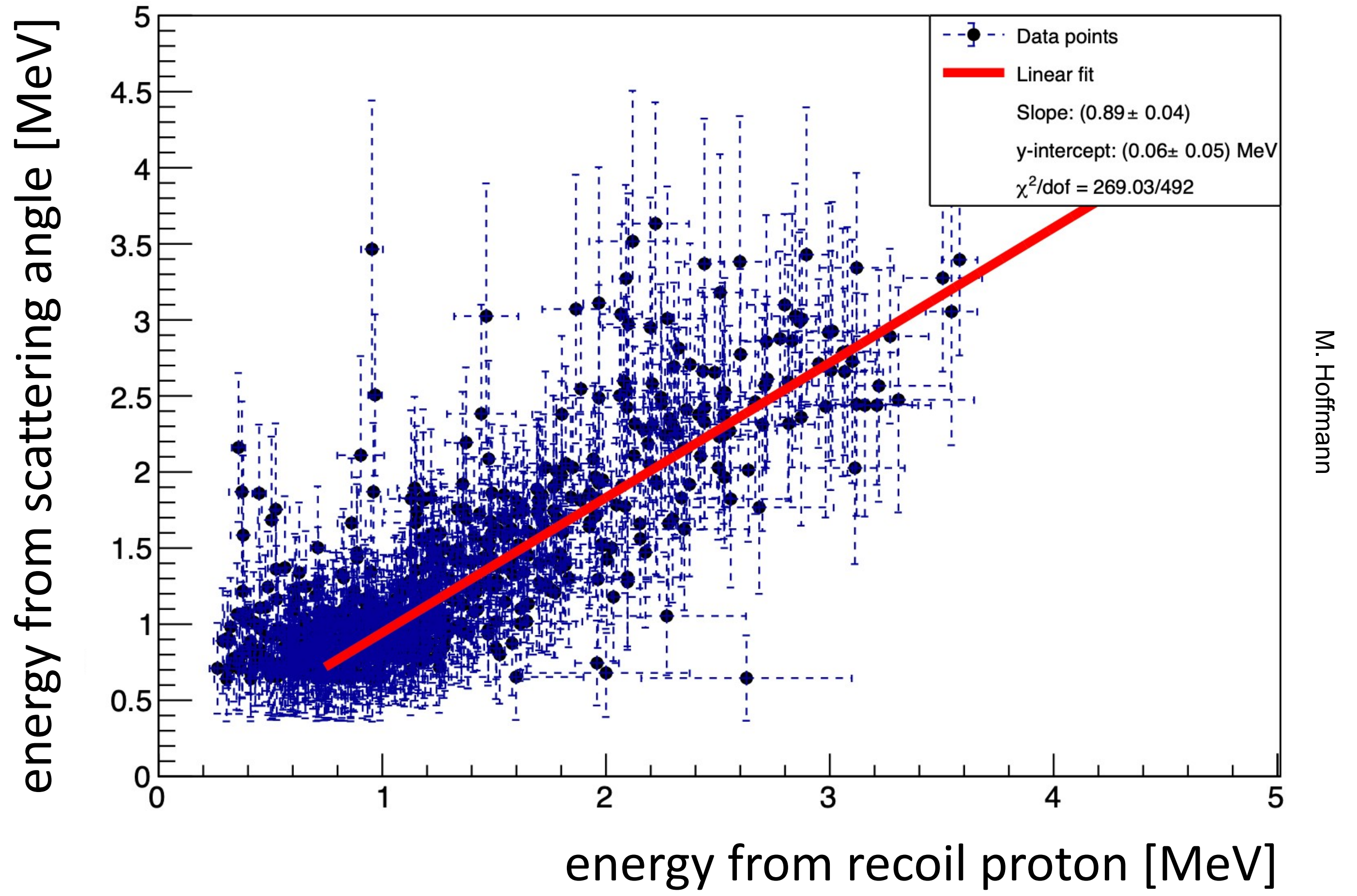
First Test Measurement performed in 2018 + 2021

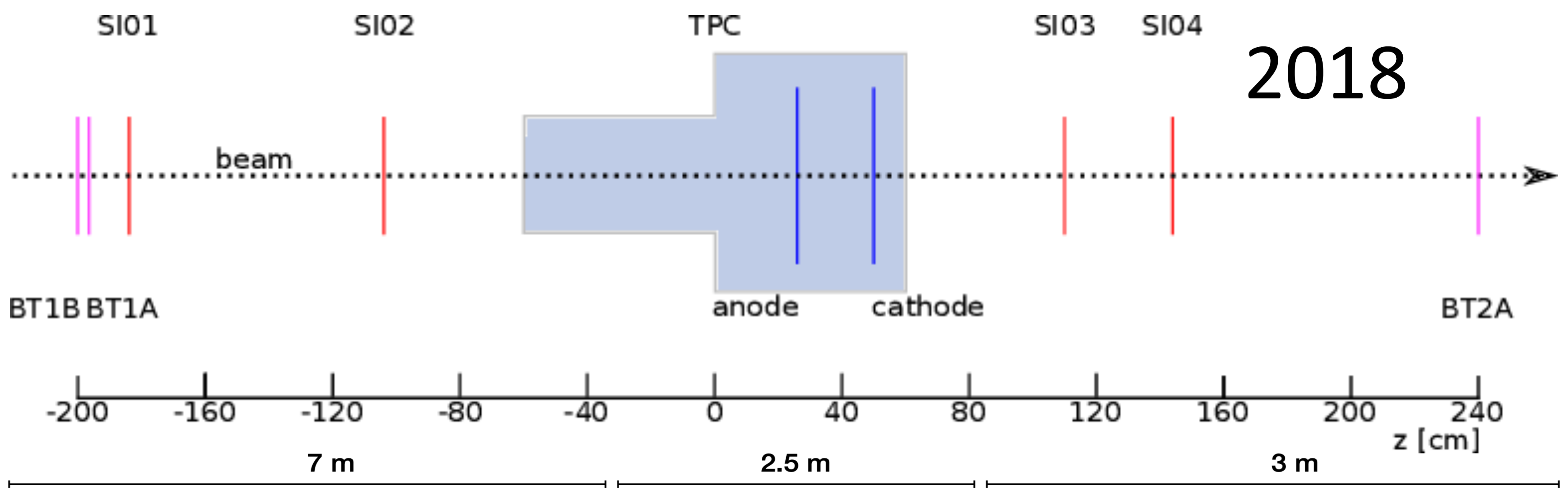
Feasibility test-measurement in 2018

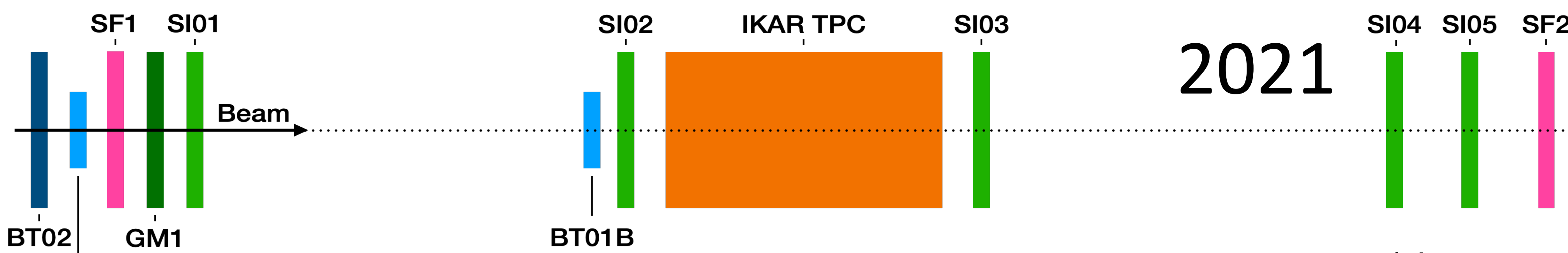
Using a simple setup with TPC, silicon tracking-detectors and beam trigger.

- General issue: combination of “slow” TPC with “fast” tracking detectors
- Goal: Proof-of-principle — working setup as in this “simple” manner
- Synchronisation of two dedicated DAQ systems based on common timestamp
- Association of muon tracks with recoil-proton events in the TPC



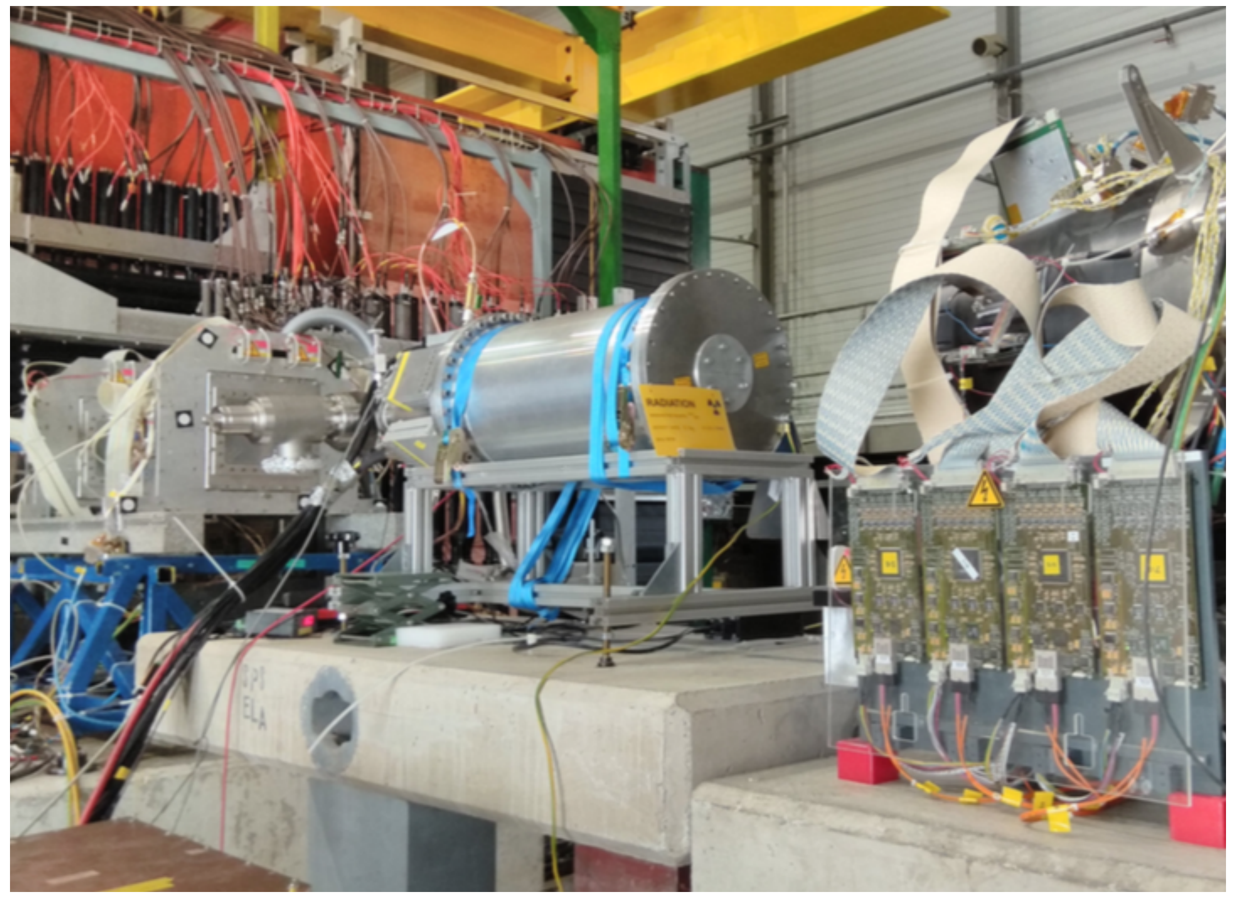




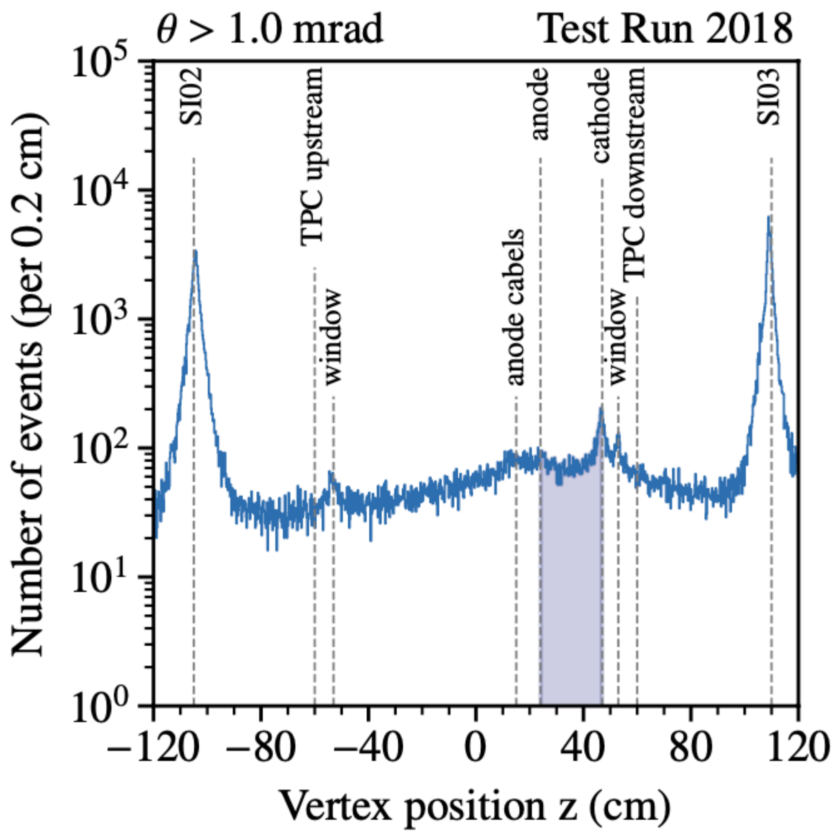


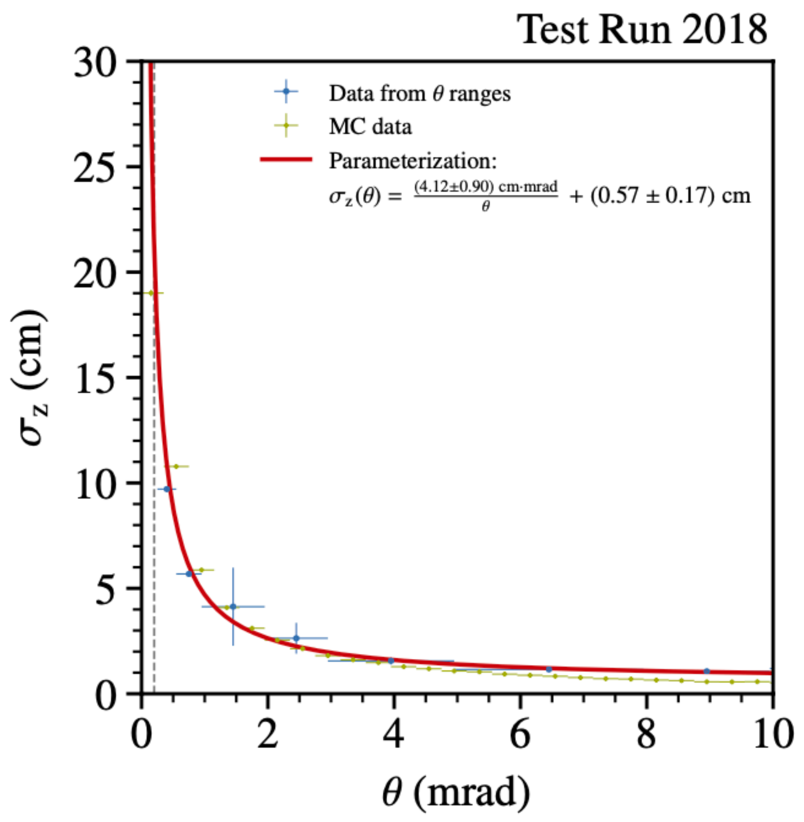
- Beam-noise studies in a high-rate muon beam with this active target
- Setup made use of parasitic *COMPASS* beam at a downstream test location

Proton Radius Measurement
Key results from first feasibility study 2018

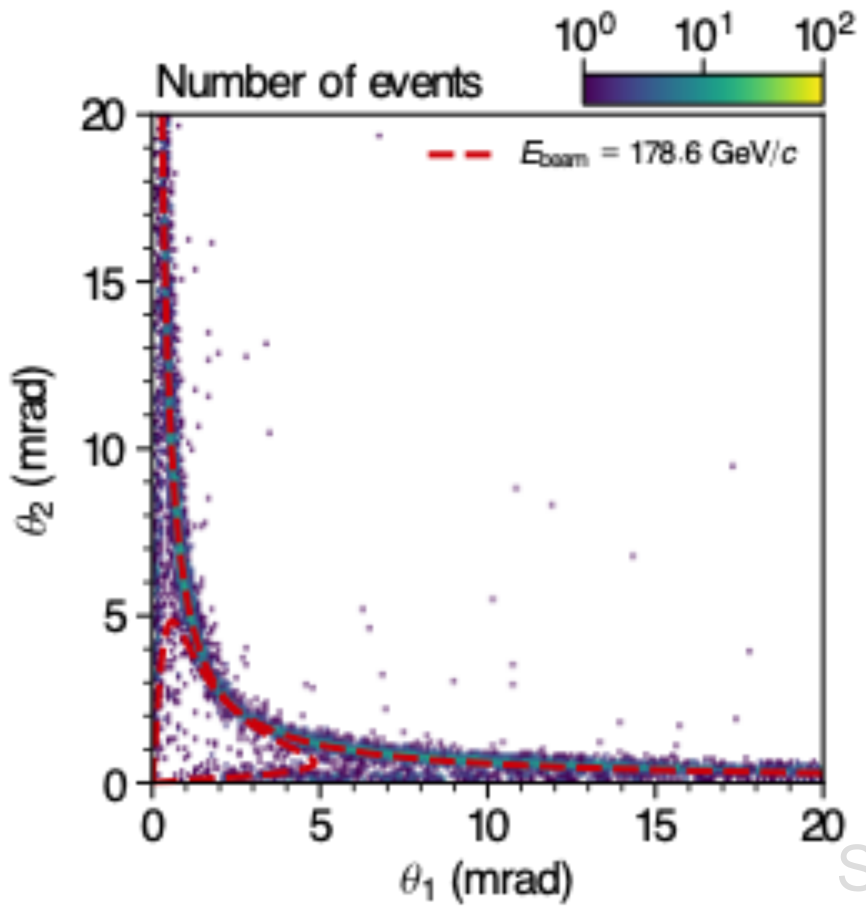


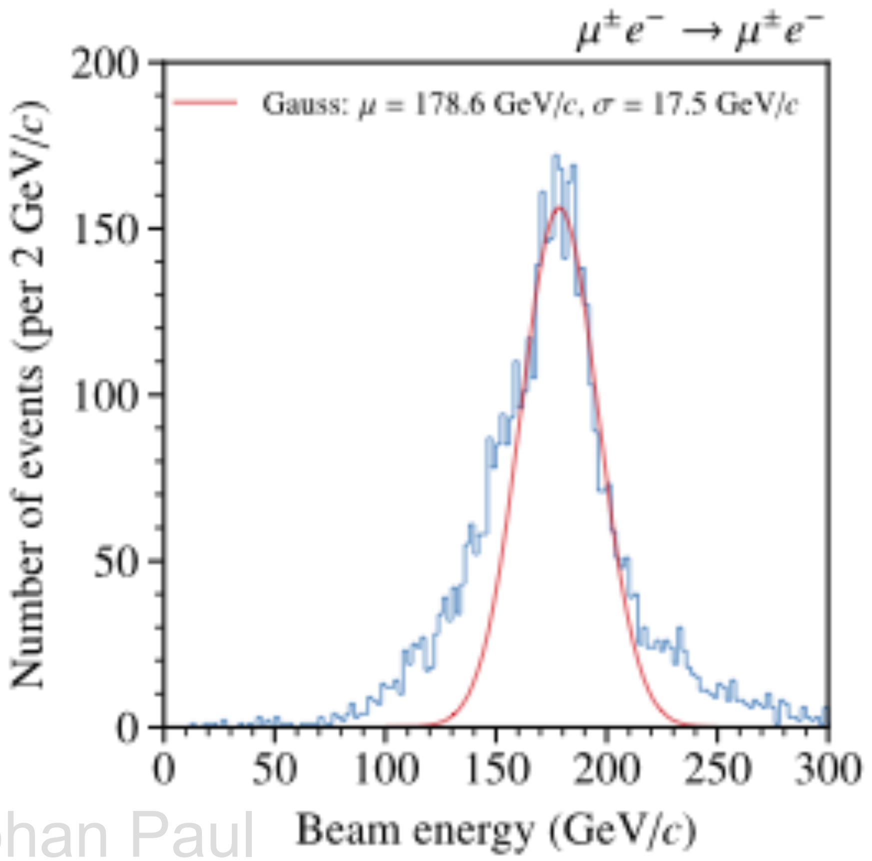
- Resolution along beam of muon scattering in hydrogen (without using TPC information)



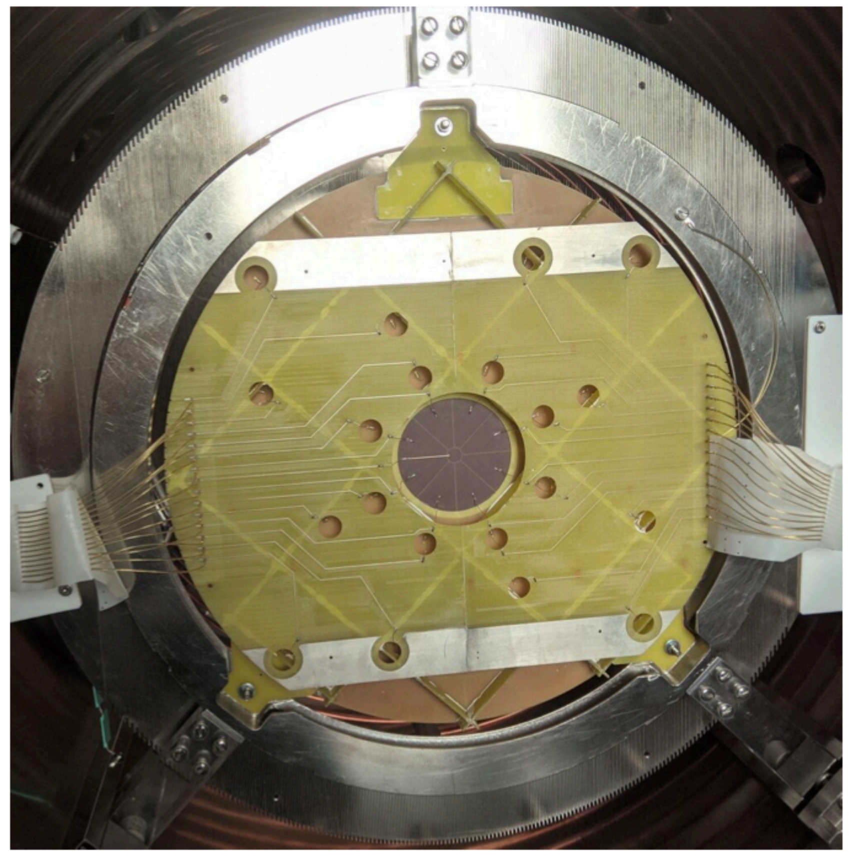


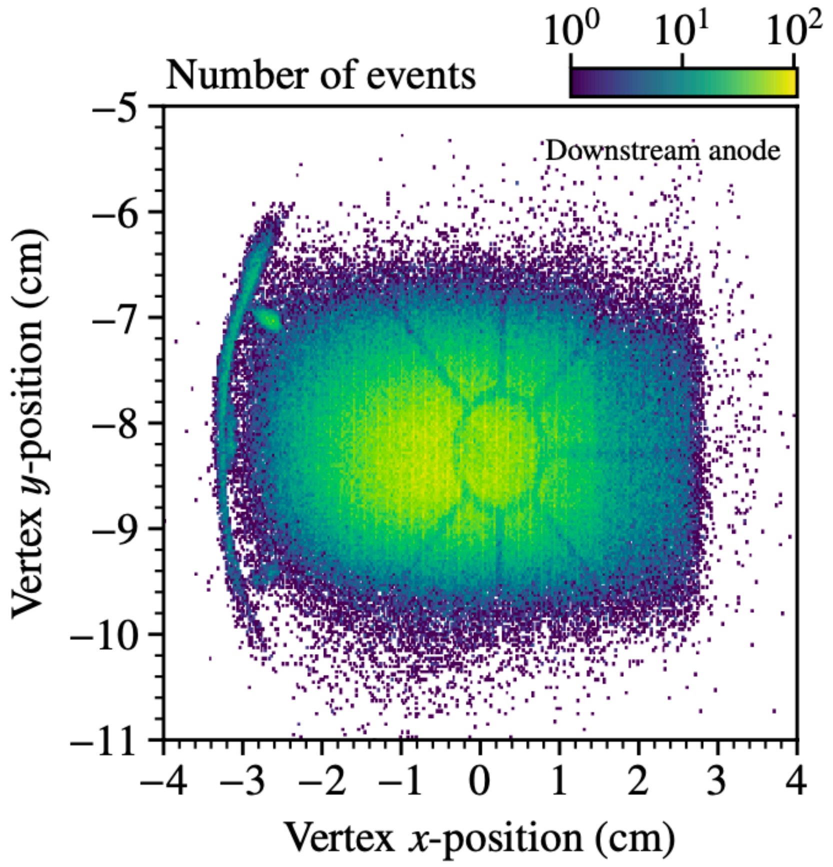
- Reconstruction of elastic muon-electron scattering and beam energy from angles alone

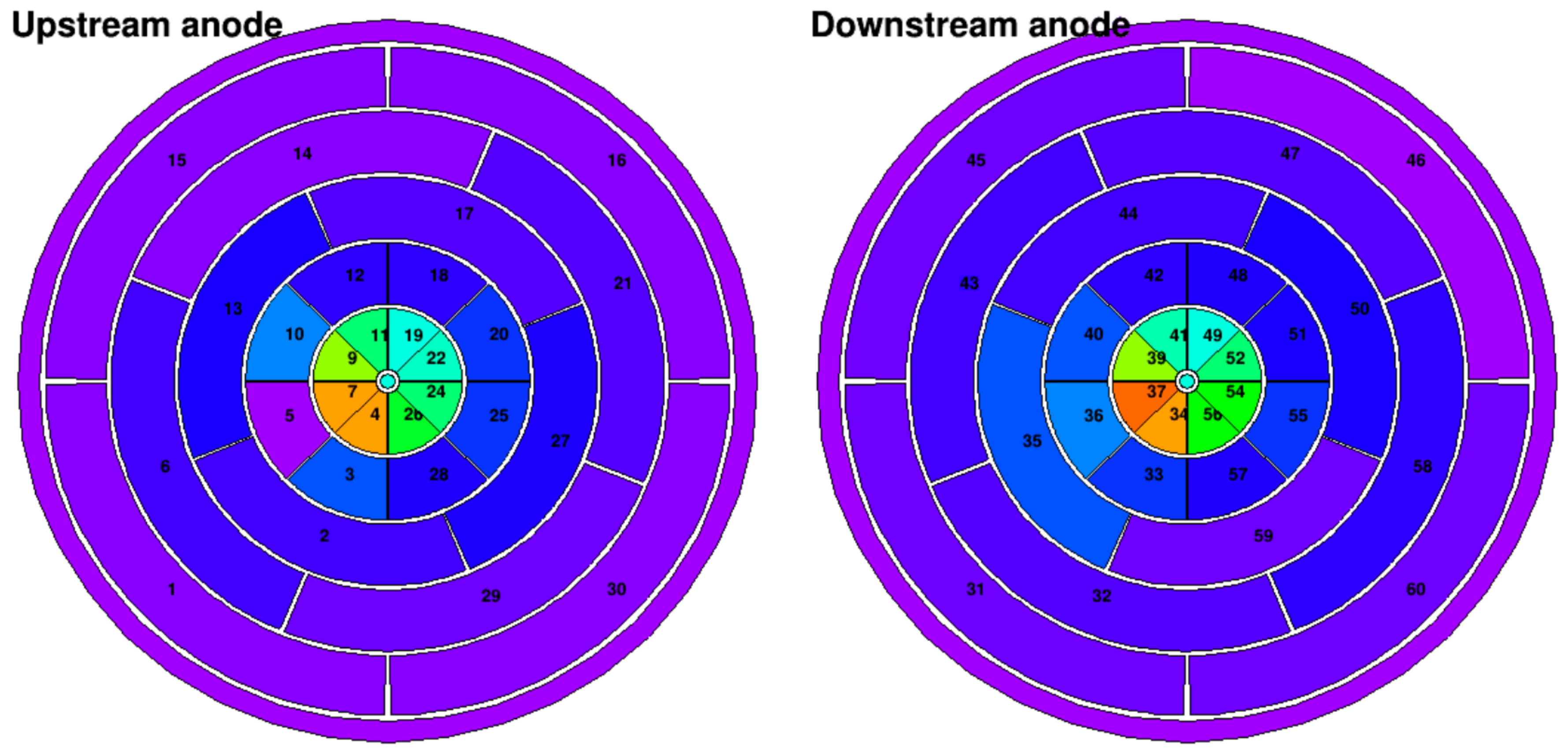


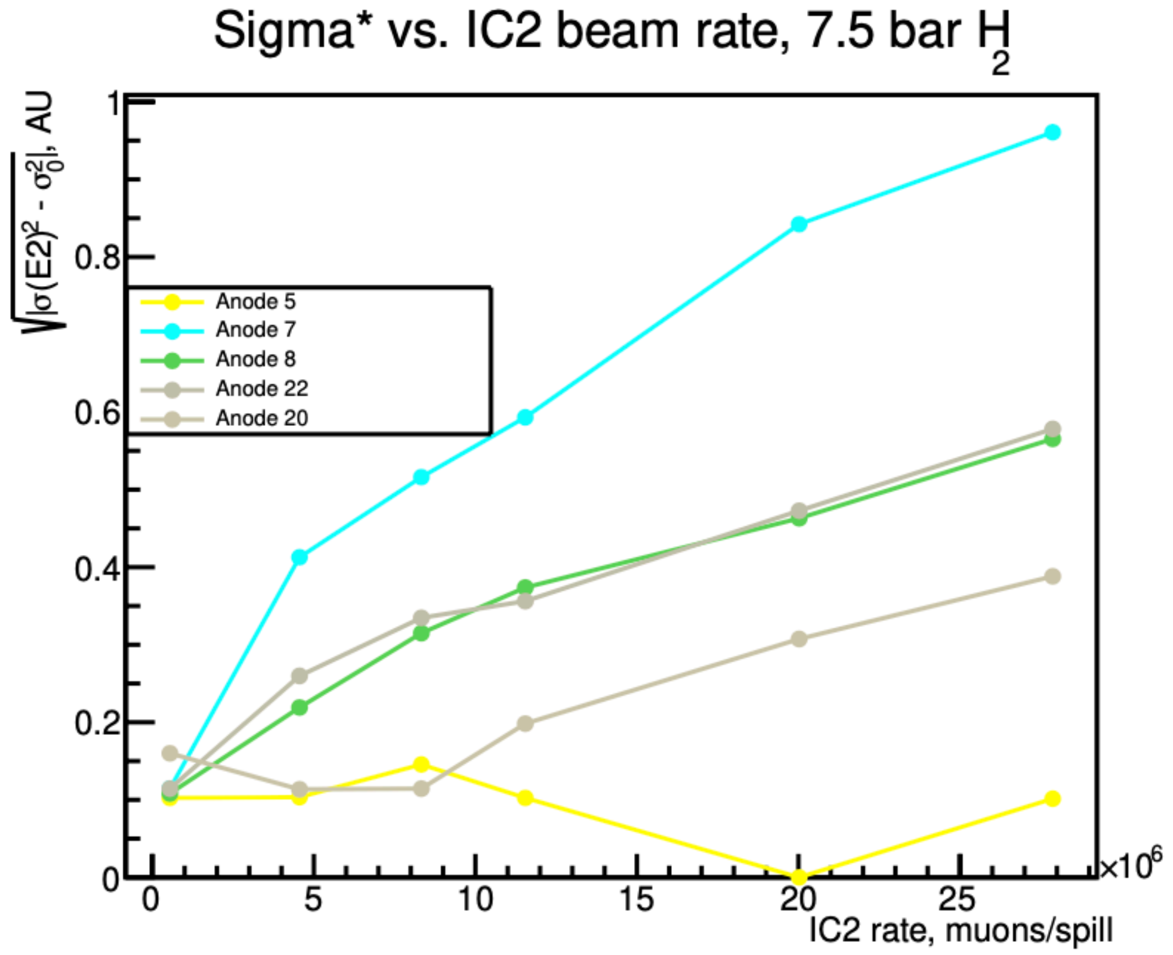


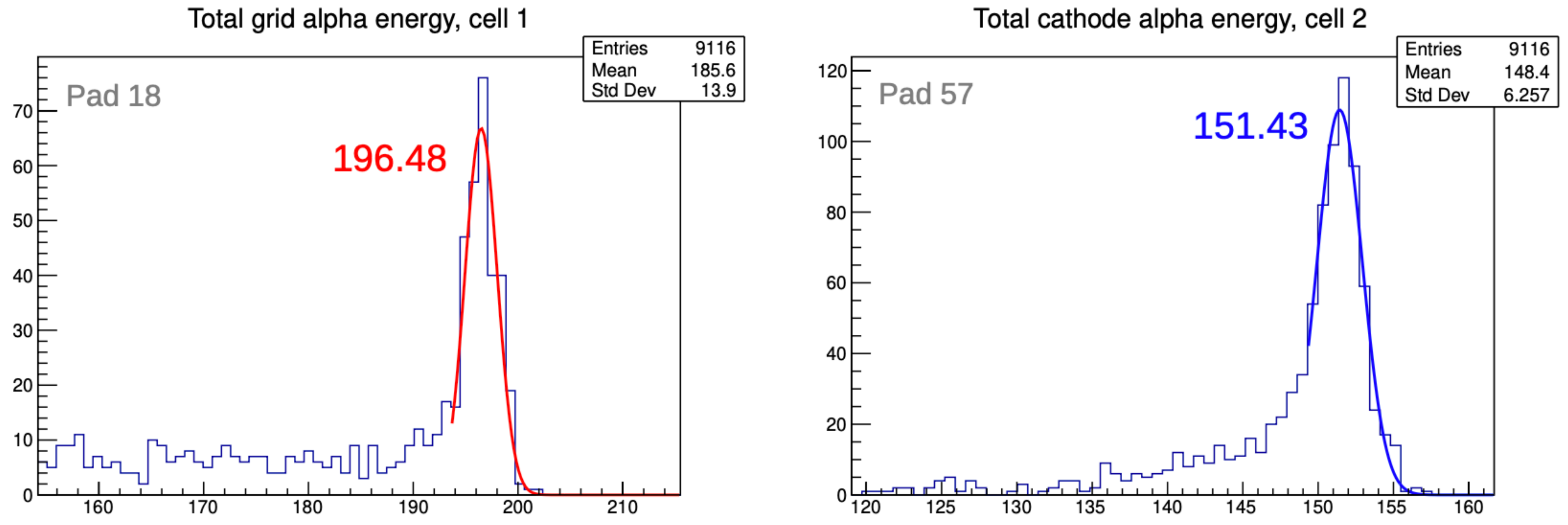
2021 IKAR TPC performance







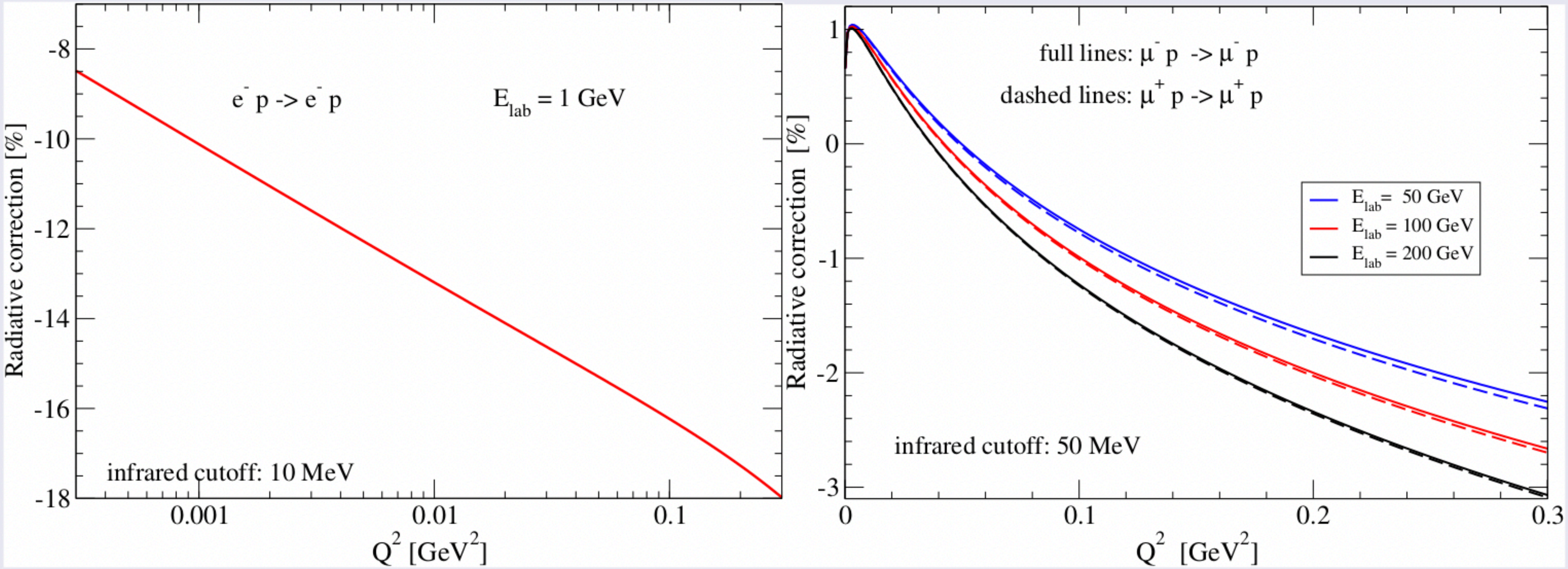




- Linear increase of noise with beam intensity
- Ongoing: alpha calibration (~40 keV energy resolution)

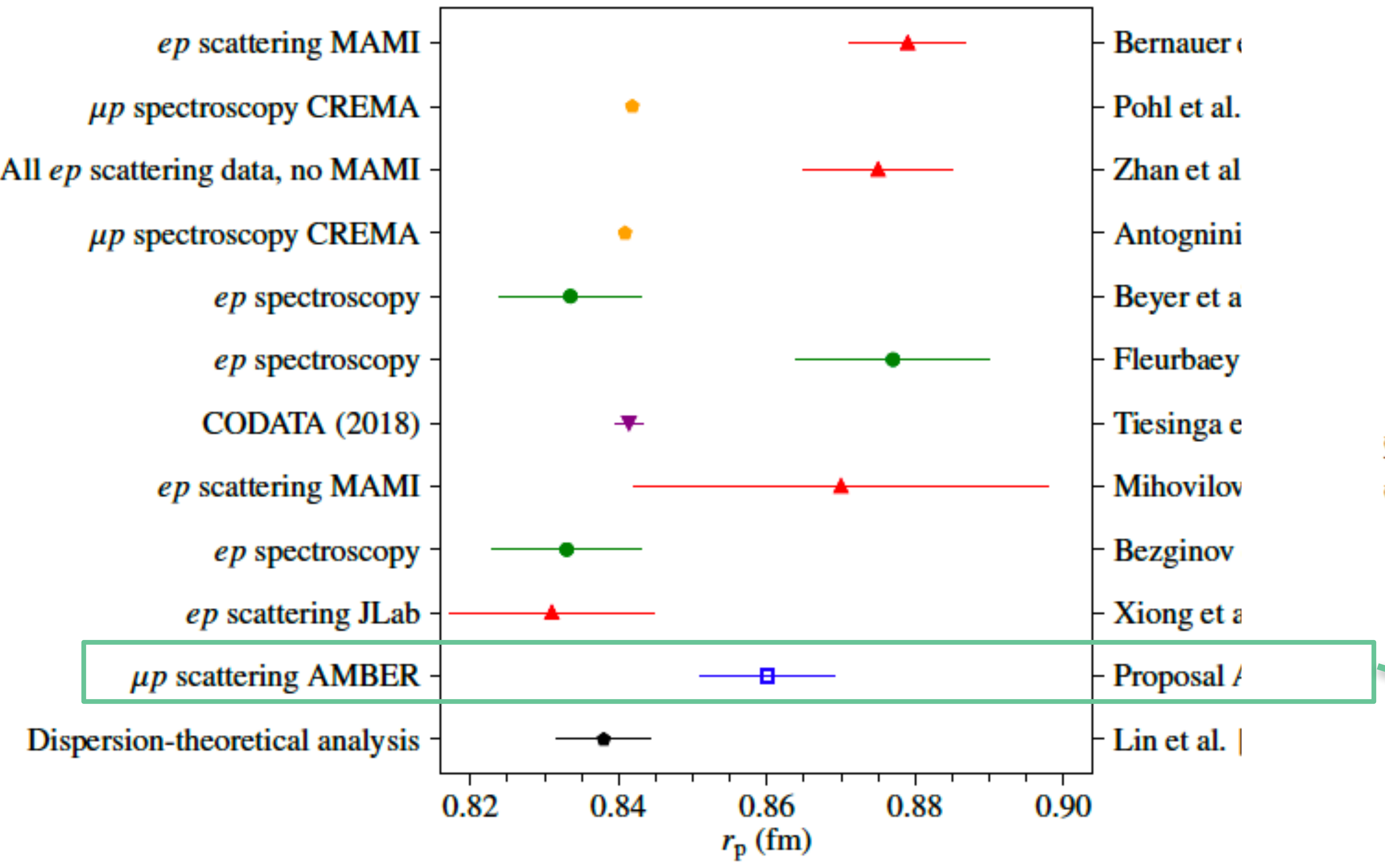
Radiative corrections for electron and muon scattering

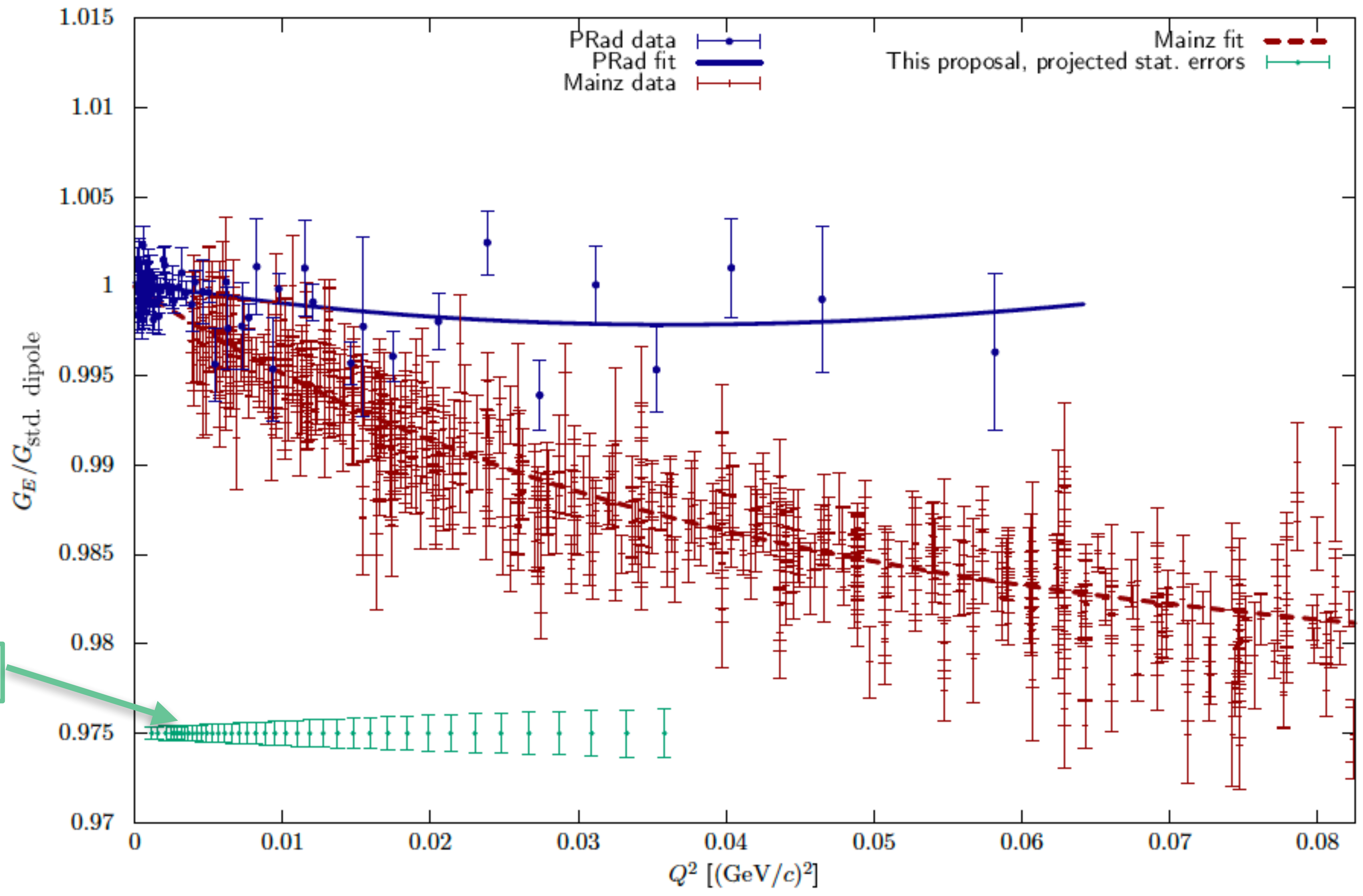
QED radiative corrections



- for soft bremsstrahlung photon energies ($E_\gamma / E_{beam} \sim 0.01$), QED radiative corrections amount to $\sim$ 15-20% for electrons, and to $\sim$ 1.5% for muons
- important contribution to the uncertainty of elastic scattering intensities: *change* of this correction over the kinematic range of interest

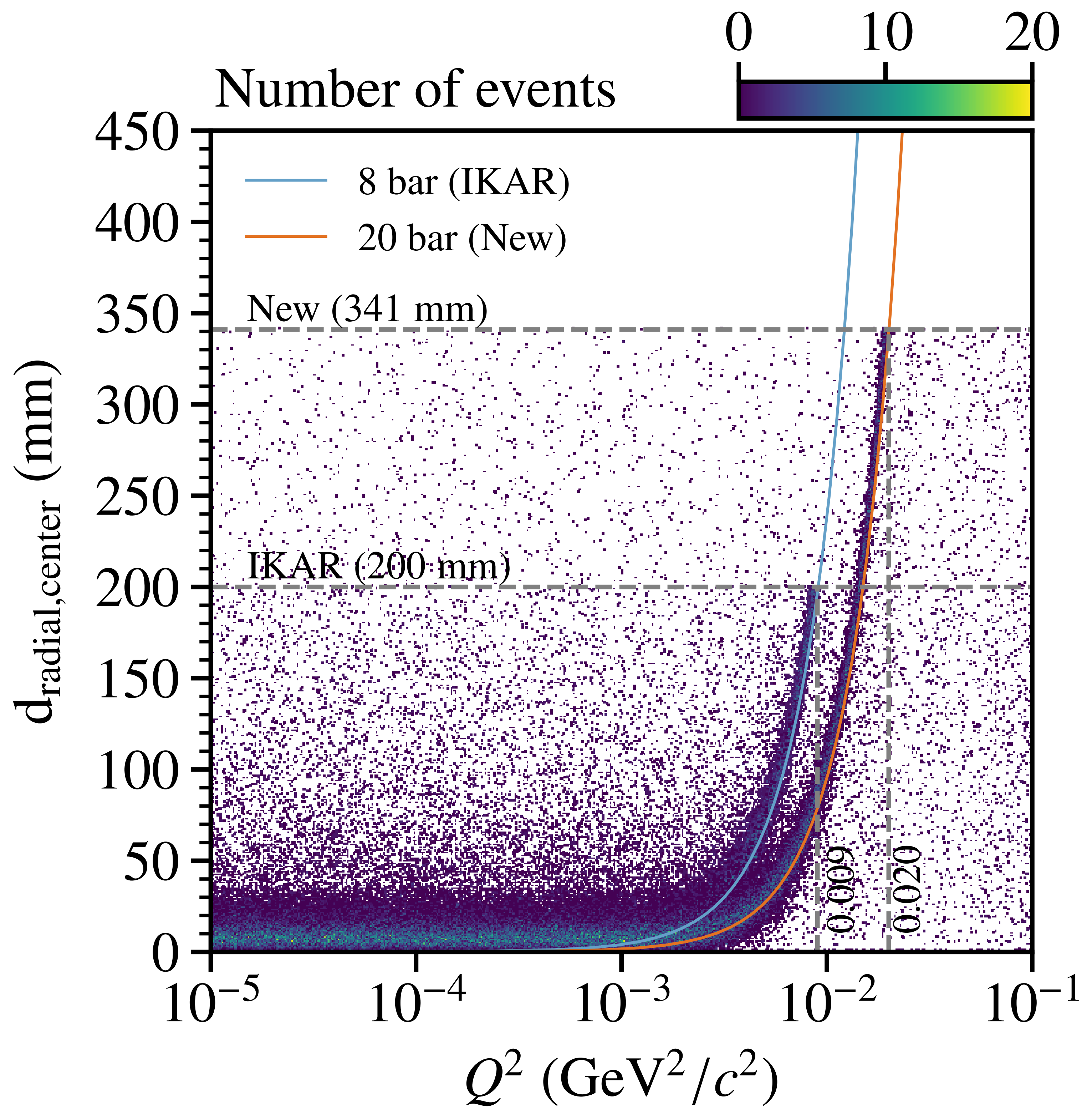
Proton Radius Measurements





What About the Target TPC ?

- New target TPC being developed together with GSI/PNPI St. Petersburg
- owing to political and financial issues - foresee usage of old IKAR TPC in 2022 (2023 ?)
- consequences:
  - Count rates
    - reduced target pressure (20bar max ➪ 8bar max)
    - reduced target thickness: 4x40cm ➪ 2x40cm
  - kinematic range
    - reduced radius 34cm ➪ 20 cm ➪ reduced proton range : $Q^2_{max} = 4 \cdot 10^{-2}\ (GeV/c)^2 \rightarrow 8 \cdot 10^{-3}\ (GeV/c)^2$



Start data taking for low Q²

Summary and Outlook

High-energy elastic muon-proton scattering — PRM@*AMBER*

Preparations are ongoing with promising developments so far.

- New approach based on elastic muon-protons scattering at E_μ = 100 GeV

→ Redundant measurement to control systematic effects

→ Radiative corrections smaller compared to electron-proton scattering

→ Additional dataset to contribute to a solution of the puzzle

- Test runs in agreement with expectations

Challenging time schedule

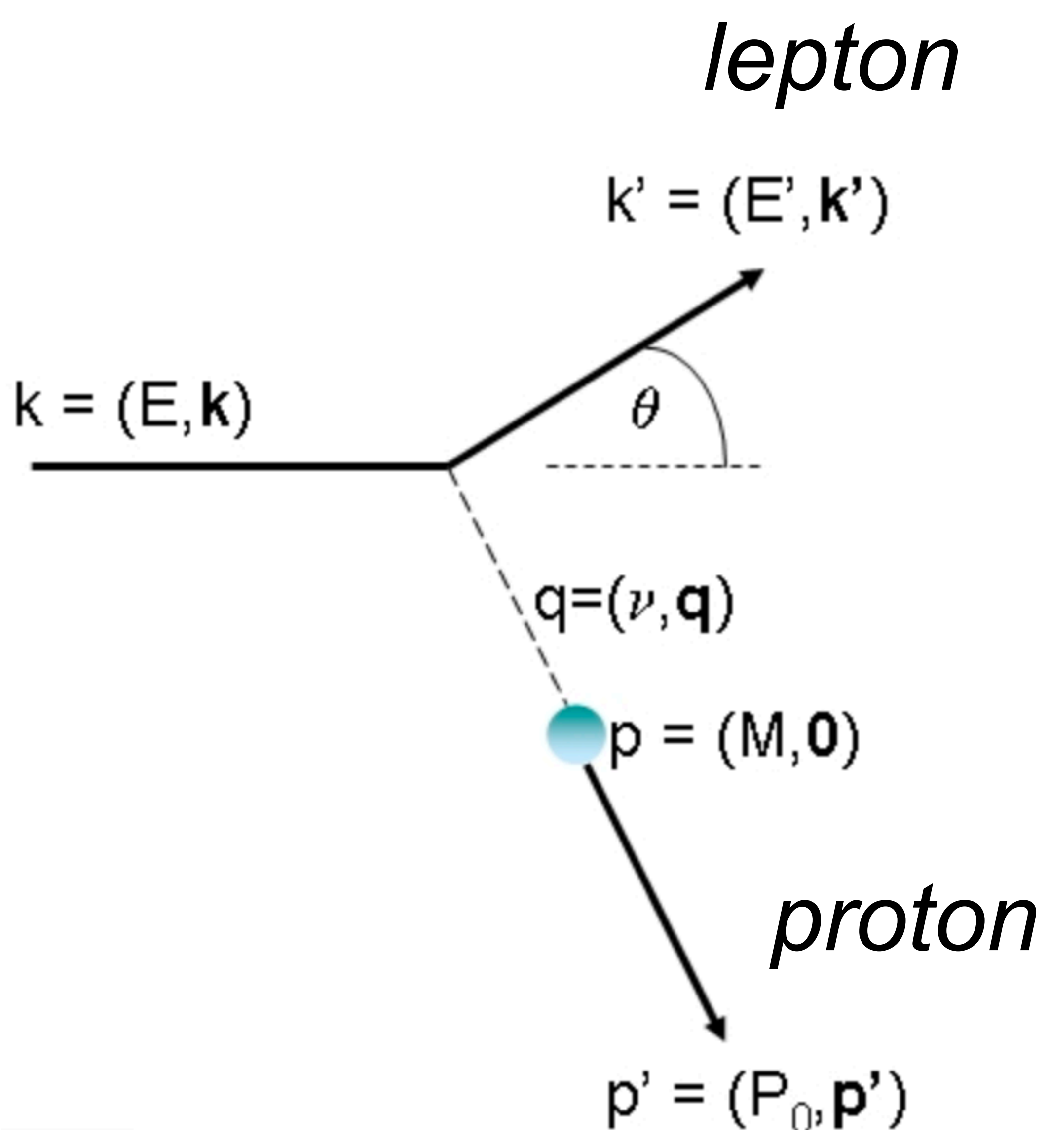
→ New detector systems with novel triggerless DAQ — beam tests this year

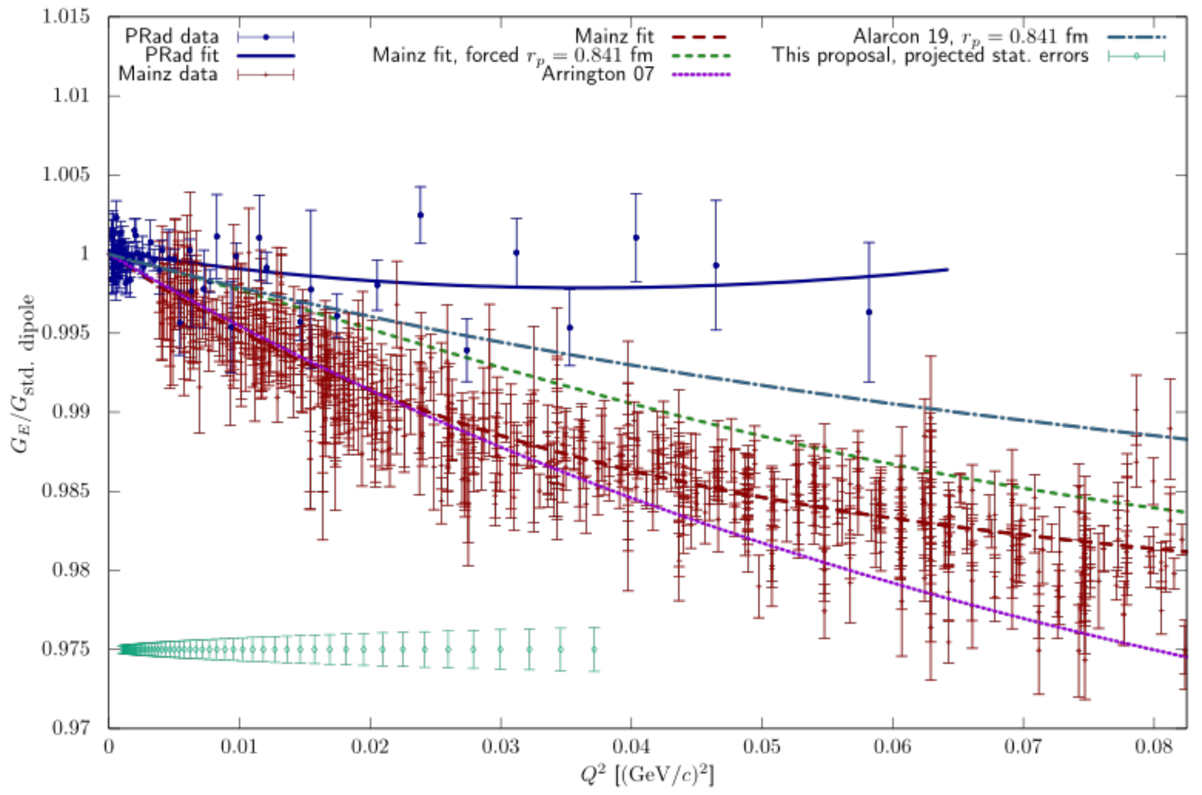
→ Main physics run foreseen in 2023 ? (2024)

Hadron Charge Radii
Through Elastic Lepton Scattering at low Q²

Protons in hydrogen target (or other stable nuclei):
Measurement via elastic electron or muon scattering
Cross section:

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} R \left(\varepsilon G_E^2 + \tau G_M^2\right)$$

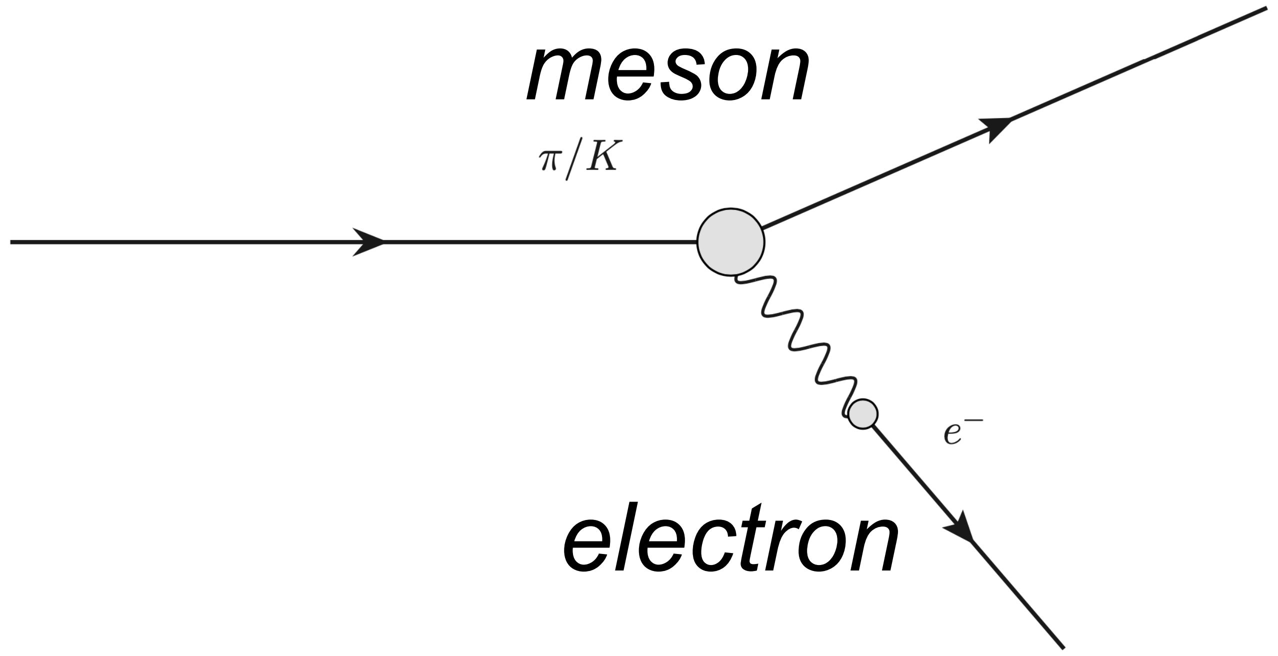




Charge radius from the slope of G_E

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

For unstable particles, electron scattering can only be realised in *inverse kinematics*



Hadron Radius Measurements

From: EPJC 8 (**1999**) 59, The WA89 Collaboration (measurement of Σ^- charge radius)   updated 21.6.2022

Measured $\langle r^2_{ch} \rangle$ in fm^2 of various hadrons

	Experiment	Soliton [7]	Skyrme [8]	non-relat. quark [12]	Skyrme [9]	Cloudy Bag [11]	experiment year
p	$\approx 0.84 - 0.87$	0.78	1.20	0.67	0.775	0.714	2020
n	-0.1101 ± 0.0086	-0.09	-0.15		-0.308	-0.121	2021
Σ^-	$0.61 \pm 0.12 \pm 0.09$	0.75	1.21	0.55	0.751	0.582	2001
π^-	0.439 ± 0.008 [5]	S. R. Amendolia, et al. , Nucl. Phys. B **277**, 168 (1986)					1986
K^-	0.34 ± 0.02 [6]	S. R. Amendolia, et al. , Phys. Lett. B **178**, 435 (1986)					1986
K_L^0	$-0.077 \pm 0.007 \pm 0.011$		$K_L^0 \to \pi^-\pi^+e^+e^-$				1998

comparatively good accuracies (pion radius ~1%) stem from assuming a theoretical shape of the form factor

Pion and Kaon Form Factor Measurements by NA7

S.R. Amendolia et al. / Pion electromagnetic form factor 193

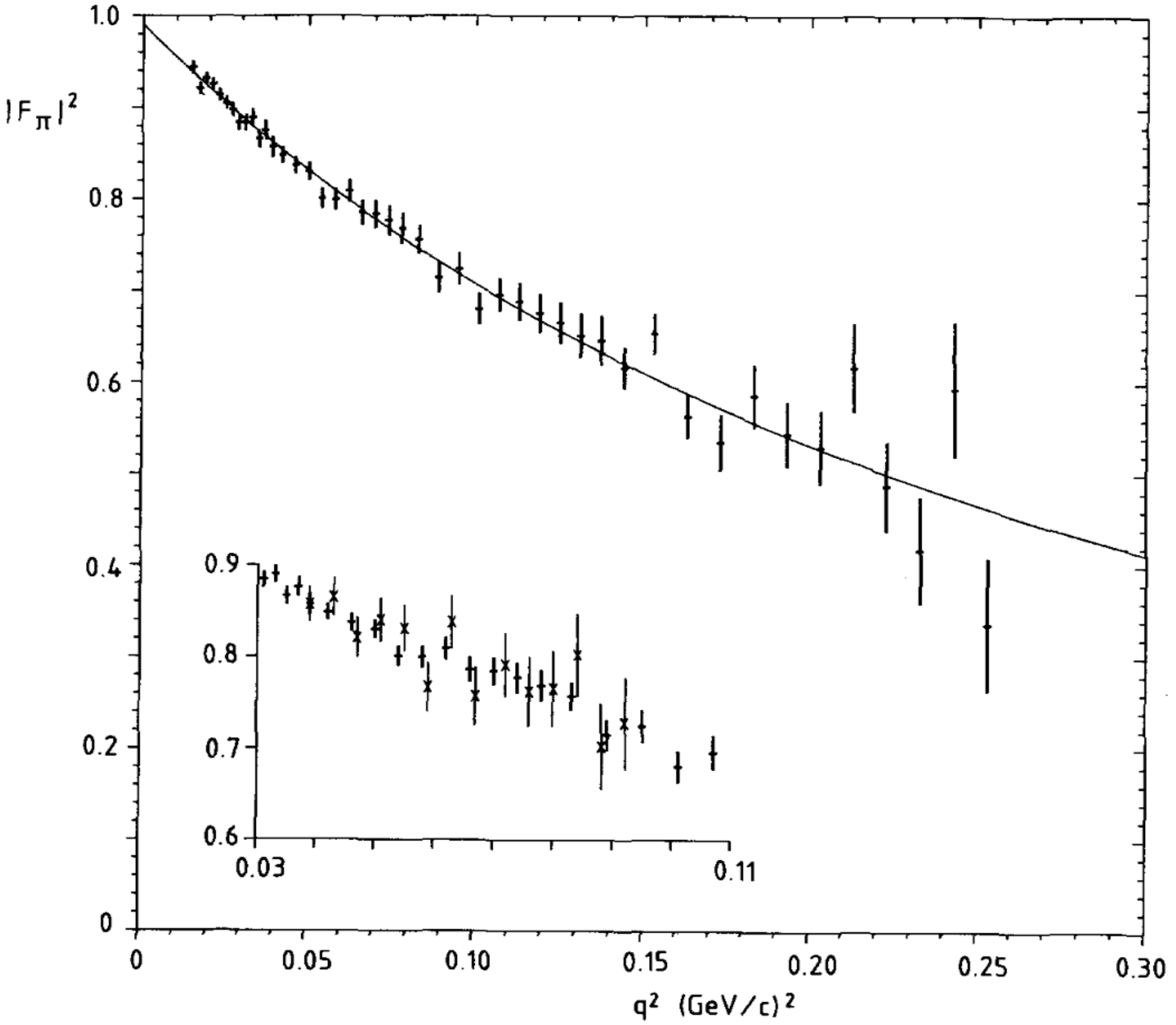


Fig. 17. The square of the pion form factor, $|F_\pi|^2$ versus q^2, with statistical error bars only. The line

S. R. Amendolia, et al. , Phys. Lett. B **178**, 435 (1986)

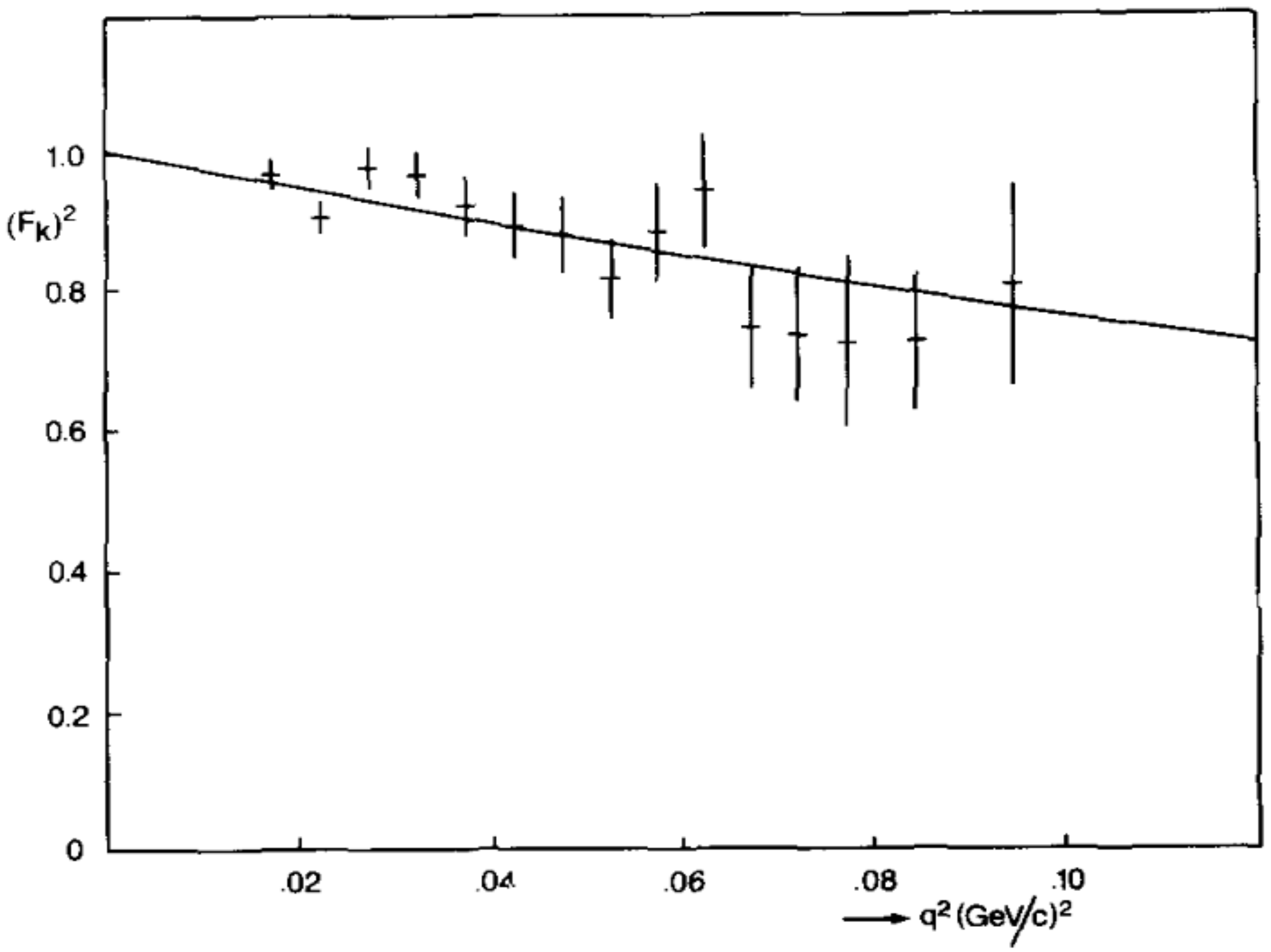


Fig. 3. The measured kaon form factor squared. The line corresponds to the pole fit with $\langle r^2 \rangle = 0.34$ fm^2.

~380,000 pion-electron scattering events

~400,000 kaon triggers (~30,000 kaon-electron scatterings)

Measuring Hadron Charge Radii in Inverse Kinematics

Why using inverse kinematics ?

- with no stable meson target existing - use stable lepton target
  - hadron is beam particle —> reaction in inverse kinematics

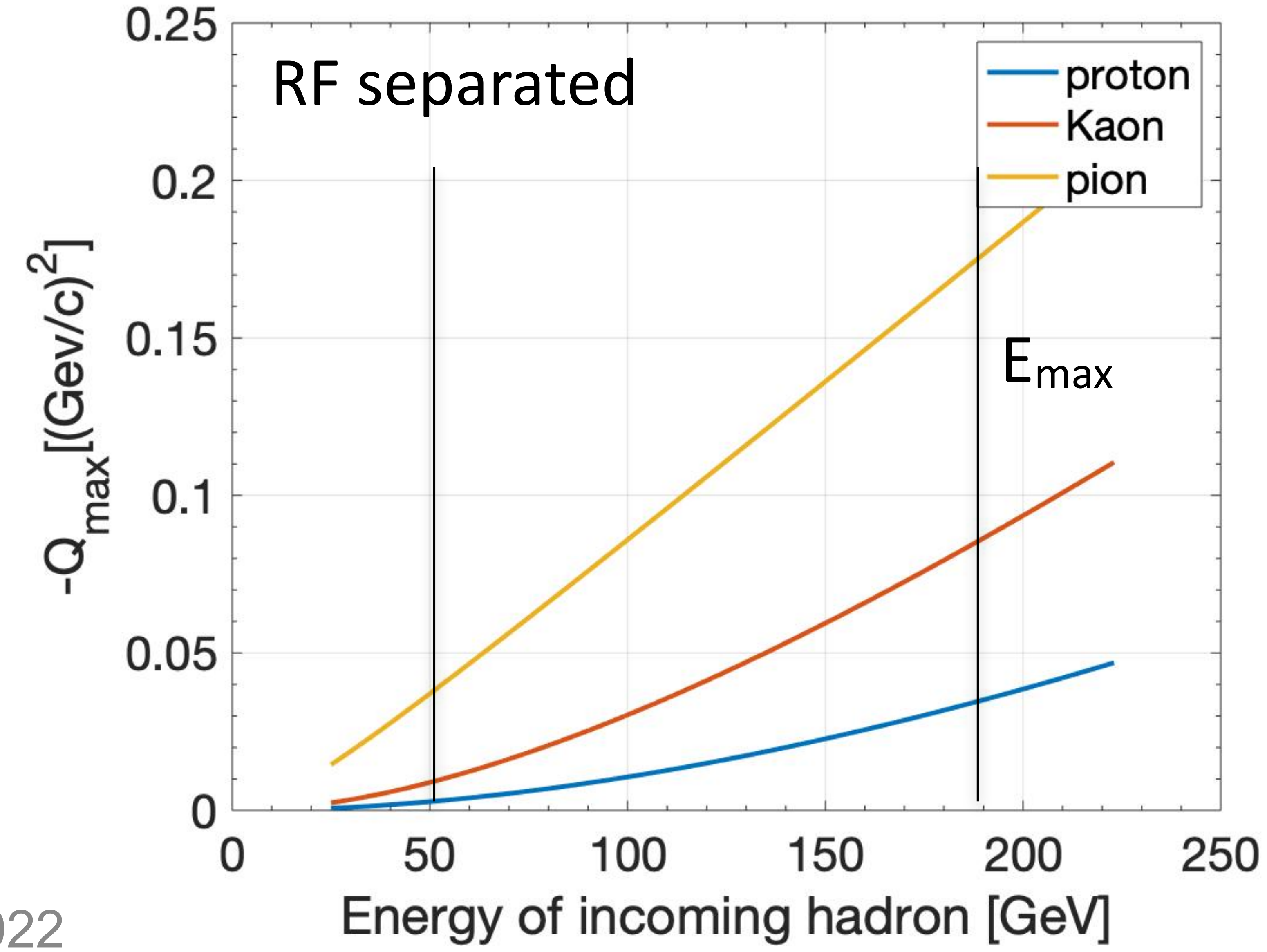
- kinematic range experimentally „unreachable“
  - make use of „easily“ measurable quantities to address „difficult regime“ (mostly low Q^2)
- electron initially at rest —> no initial external Bremsstrahlung
- final electron is accelerated —> external Bremsstrahlung for outgoing electron
  - impact on particle momentum
  - Impact on particle trajectory
- internal Bremsstrahlung effects independent of reference system (vertex corrections)

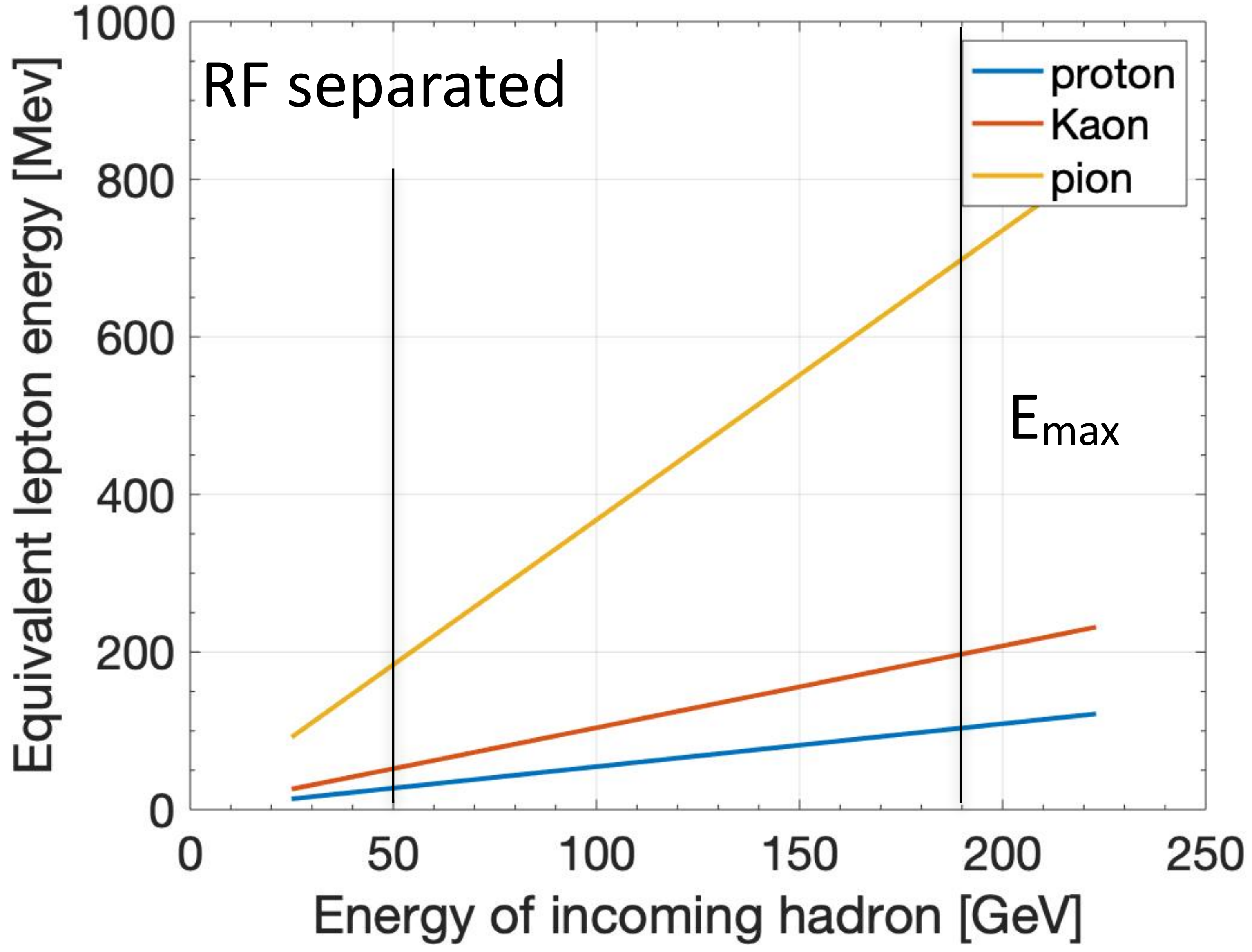
Getting Familiar with Kinematic Regimes

- Which beam energies do we need for which hadron ?
- Which momentum transfer can we get ?
- What are the equivalent electron energies in „conventional“ kinematics ?

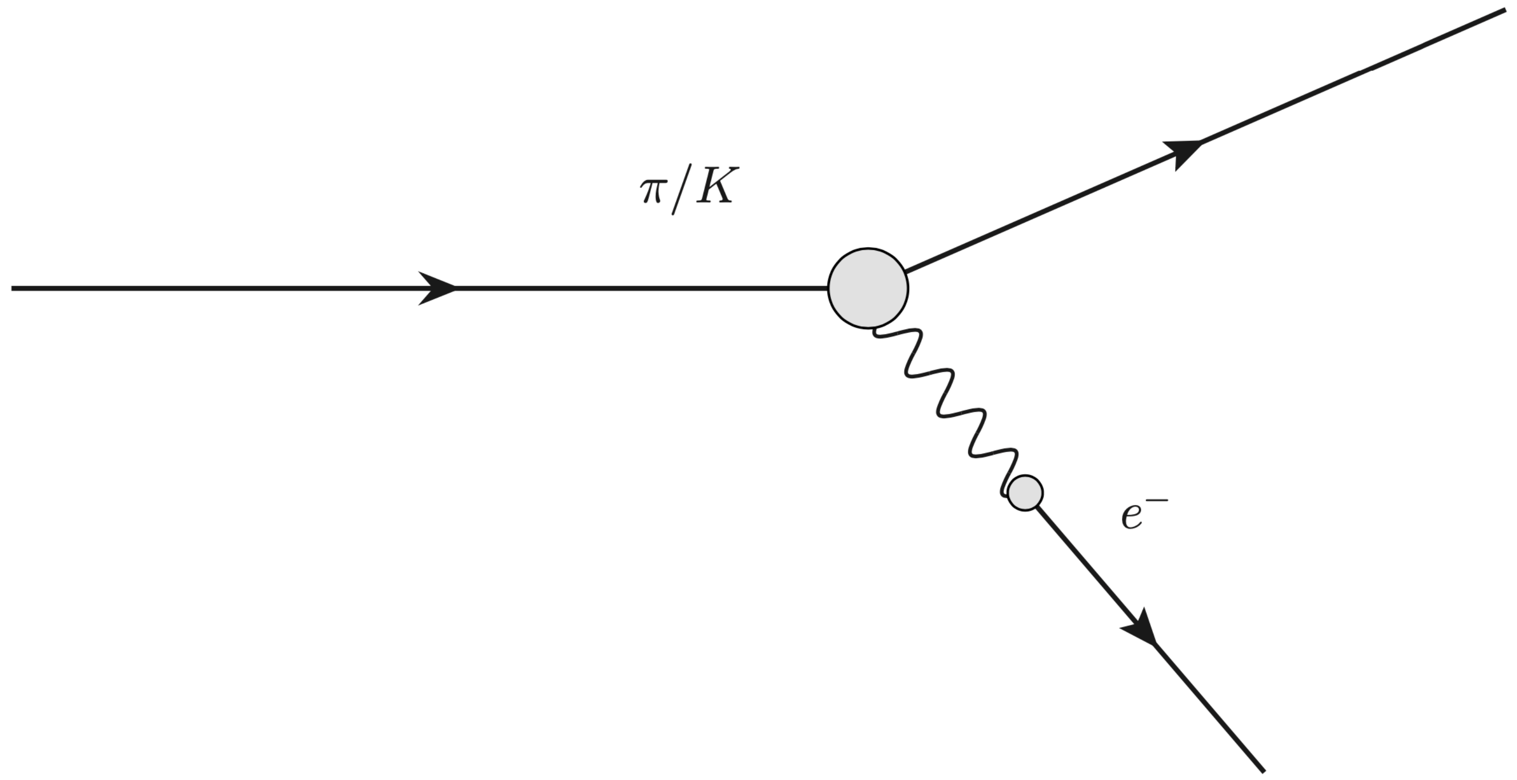
Remember: $m_\pi \approx 275 \times m_{electron}$ —> hit a ping pong ball with a bowling sphere

—> inefficient in terms of cm energy $\sqrt{s}$ and momentum transfer $-Q^2$





Kinematics



$$K^- \, e^-_{target} \rightarrow \; K^- \, e^-$$

$$Q^2 \approx 2m_e \cdot E_e$$

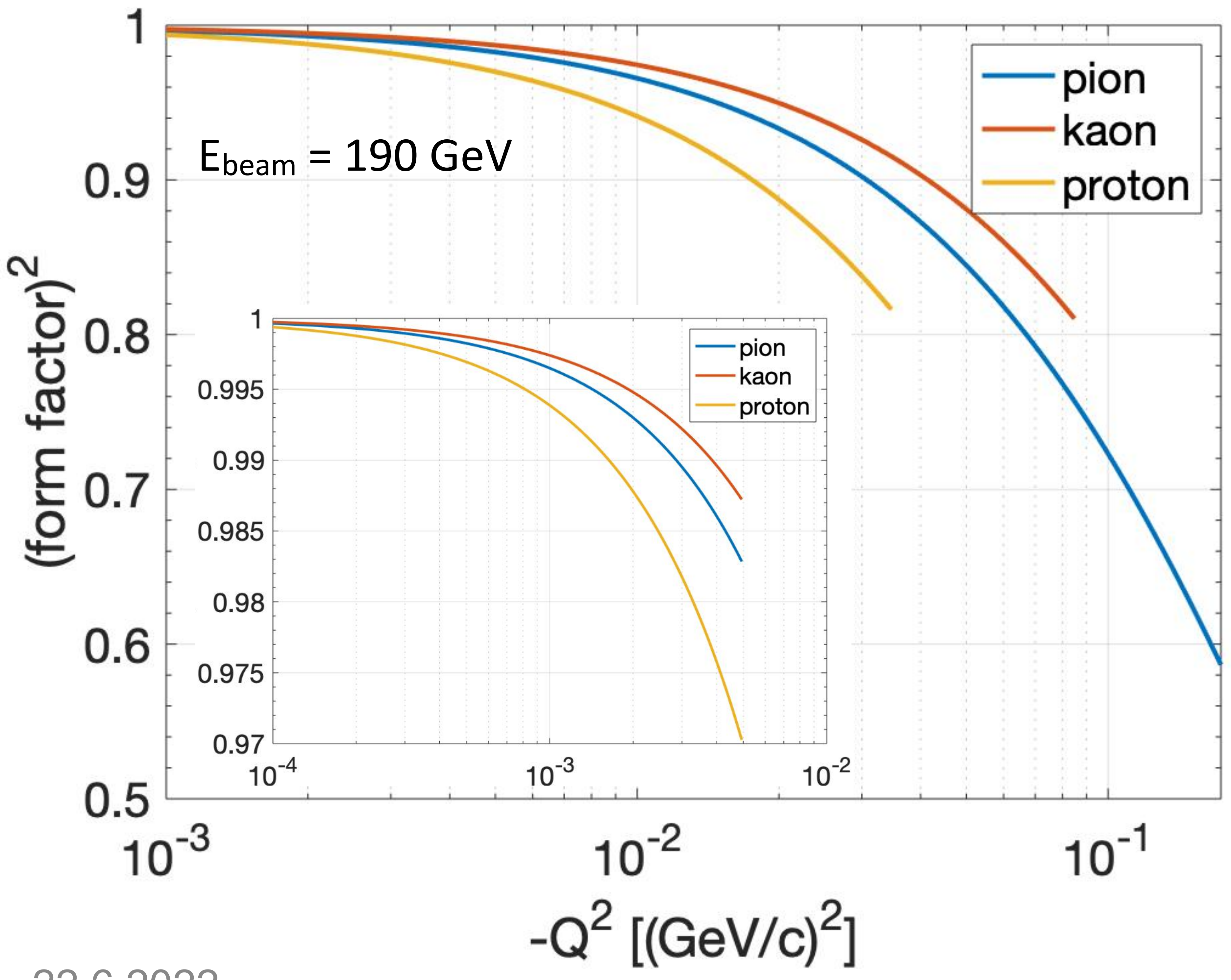
$$s = 2E_b m_e + m_b^2 + m_e^2$$

$$Q^2_{max} = \frac{4 \cdot m_e^2 \cdot p_b^2}{s} = 4 \cdot p_{cm}^2$$

Beam	Ebeam [GeV]	Q^2_{max} [GeV²]	$E^{min}_{scatter}$ [GeV]	$E^{electron}_{max}$ Q^2_{max} [GeV]	CM momenta [GeV]
π	190	0,176	17.2	173	0,210
K	190	0,086	105.2	84.7	0,147
K	80	0,021	59.7	20.2	0,072
K	50	0,009	41.3	8.7	0,047
p	190	0,035	155.3	34.3	0,094

What is the role of Q^2_{max}

- large values of Q²: higher sensitivity to charge distribution —> $< r_E^2 >$
- small values of Q²: smaller extrapolation uncertainties to Q² = 0 and $\frac{dF(Q^2)}{dQ^2}|_{Q^2=0}$

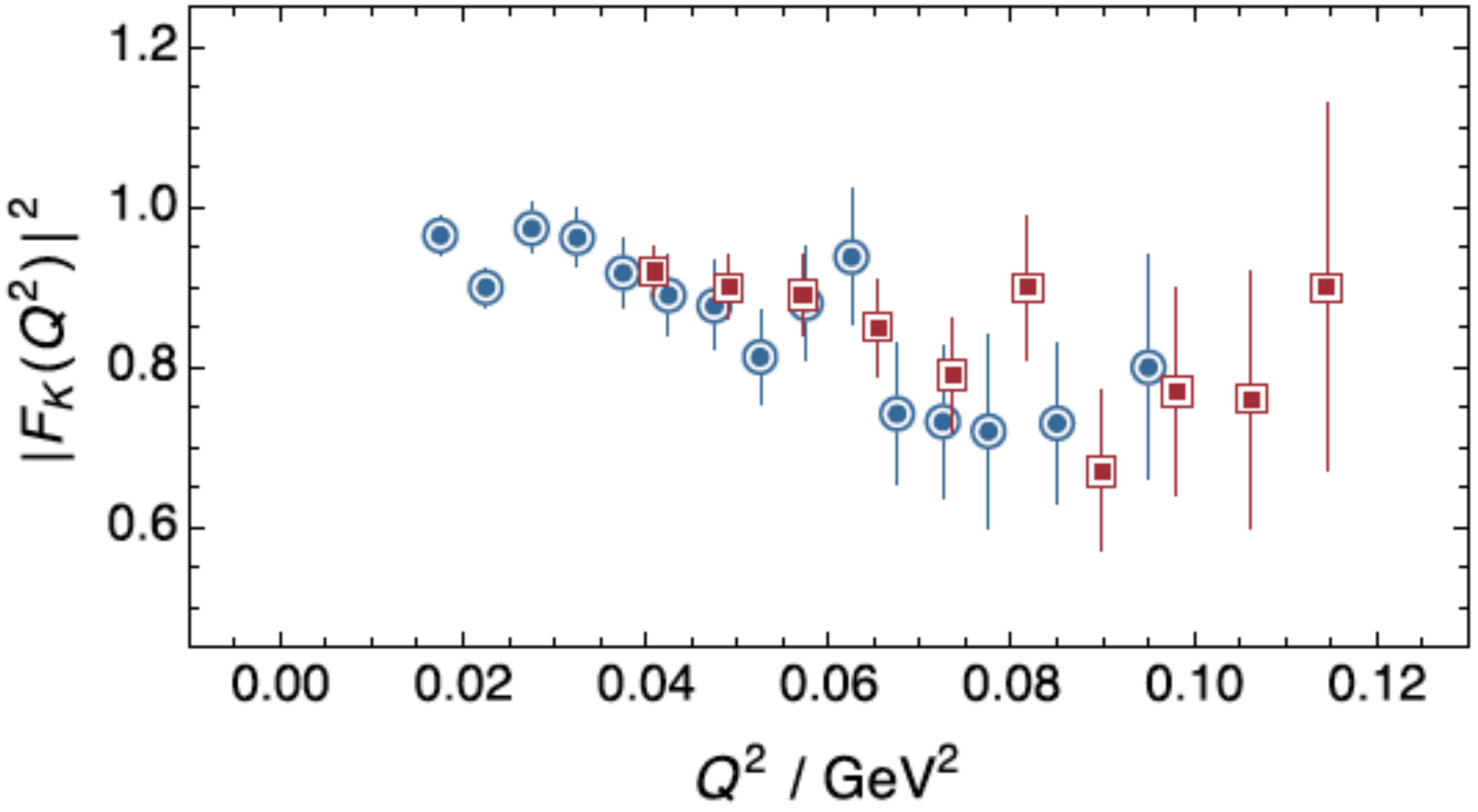


Beam	E_{beam} [GeV]	Q^2_{max} [GeV²]	Relative charge-radius effect on σ(Q²)
π	190	0,176	~40%
K	190	0,086	~20%
K	80	0,021	~5%
K	50	0,009	~2-3%
p	190	0,035	~18%

The Kaon Case

- Only scattering data: NA 7
- 250 GeV beam
- 23 cm LH_2 target
- Beam intensity: 4.5 x 10^4/s

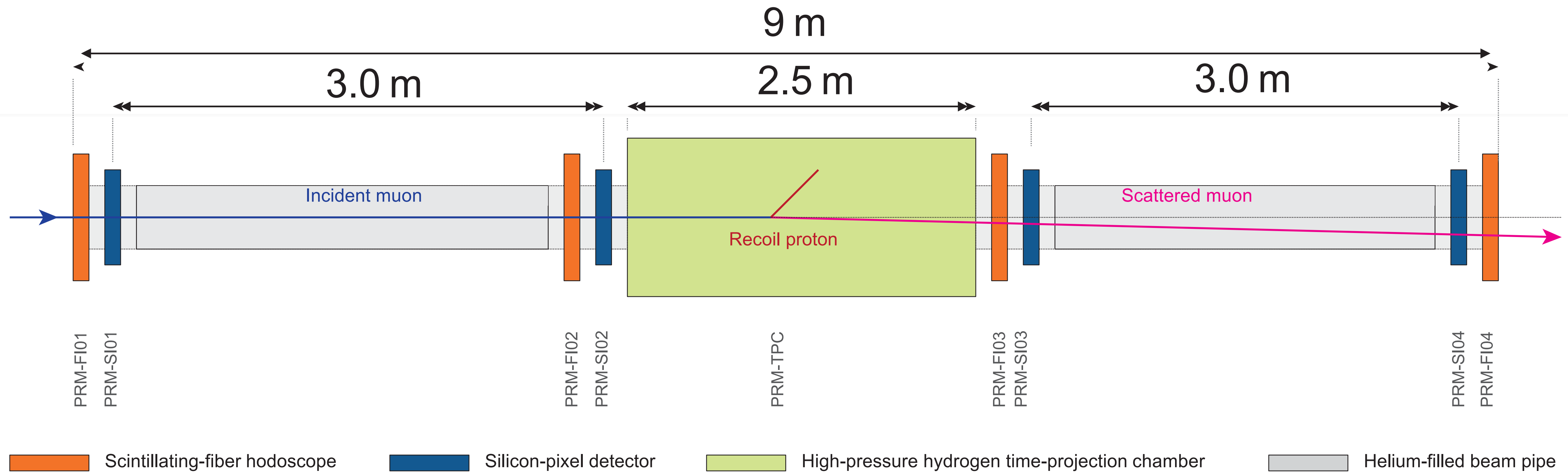
from Physics Letters B 822 (2021) 136631

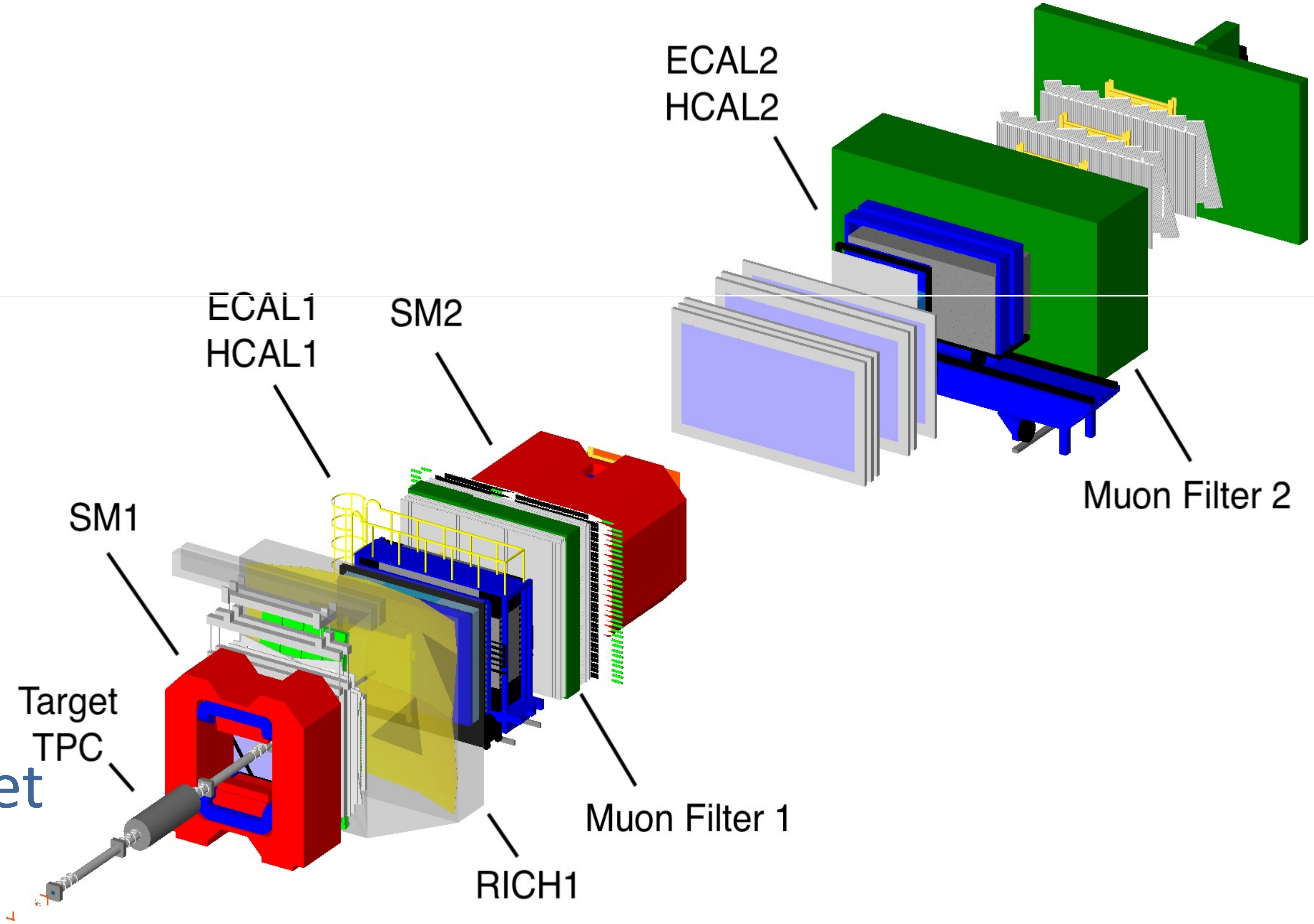


$[(GeV/c)^2]$

Measurements with AMBER

- Forward Spectrometer with 2 EM calorimeters

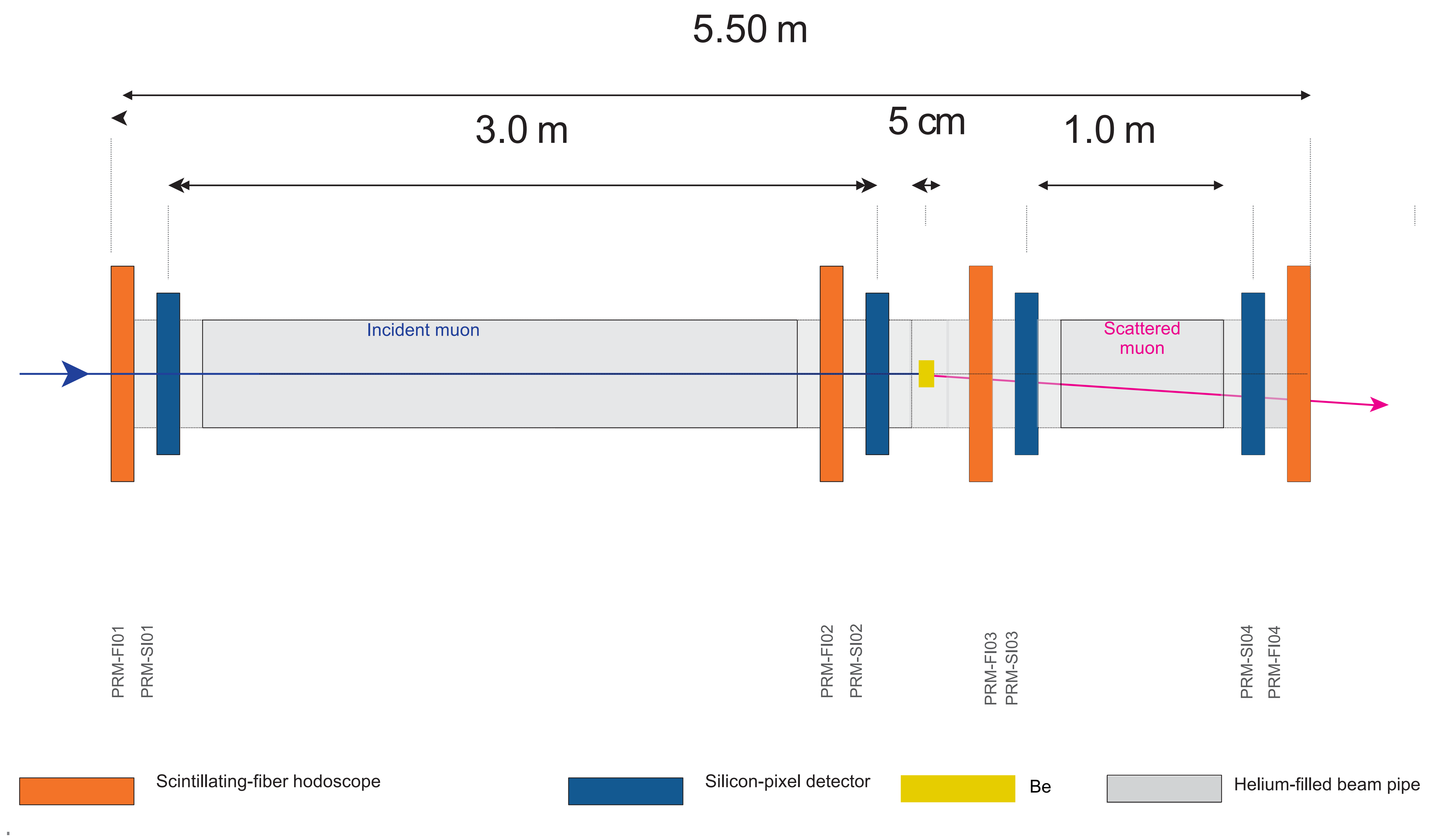




- Dedicated target station
- 4 x 40cm target cells (20 bar) or 40cm LH_2 target
- beam rates: $4 \cdot 10^6/s$ (duty cycle $\approx 1/7$)
- SciFi (fibre tracker): 10cm x 10cm ($\pm$ 10mrad)
- assume for now: passive target cells

Setup for solid target

- solid target (e.g. 1mm Be) offers large acceptance for outgoing electron
- reduce lever arm of downstream telescope



COMPARISON to NA7 - Kaons

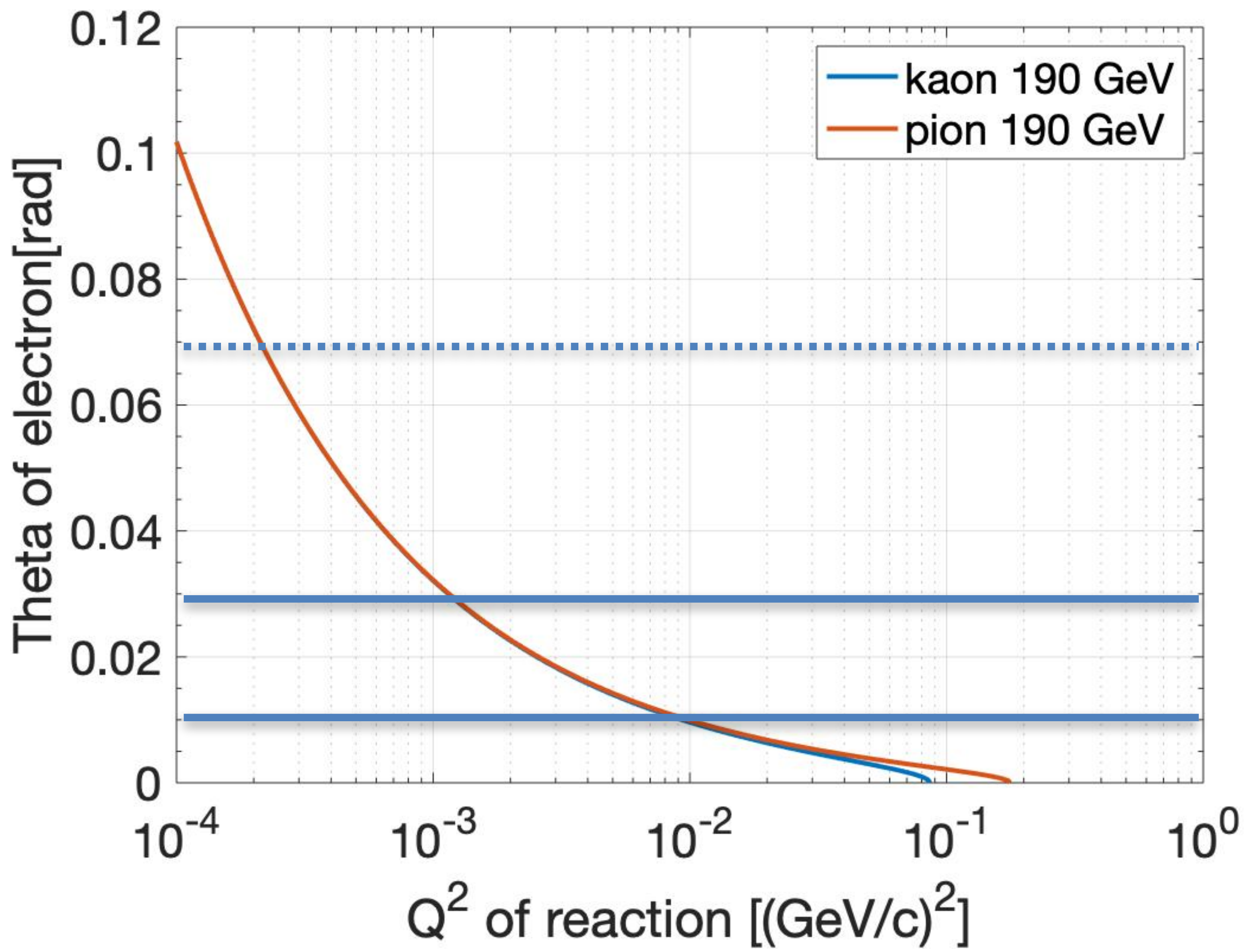
- Technology has advanced !!
- use 40cm length LH_2 target/1mm Beryllium
- resolution (scattered hadron): $\Delta p/p \approx 3 \cdot 10^{-3}(flat\ldots), \delta\theta \approx 30\mu rad$
- NA7: $\Delta p/p \approx 10^{-2}$
- separation from hadronic interaction is important: $\sigma(Ke^-) \approx 10^{-3}\sigma(hadronic)$

item	NA7	AMBER	Ratio	
target	23 cm LH_2	40 cm LH_2 or 1mm Be	> 2	
π beam [Hz] K beam [Hz]	$5 \cdot 10^5/s$ $4.5 \cdot 10^4/s$	$4 \cdot 10^6/s$ $8 \cdot 10^4/s$	4 2	in spill
trigger rate [Hz]	350	10^5	> 30	
Q^2 acceptance	> 0,014	> 10^{-4}		
beam energy π K	300 GeV 250 GeV	50-190 GeV		

Full Event Reconstruction

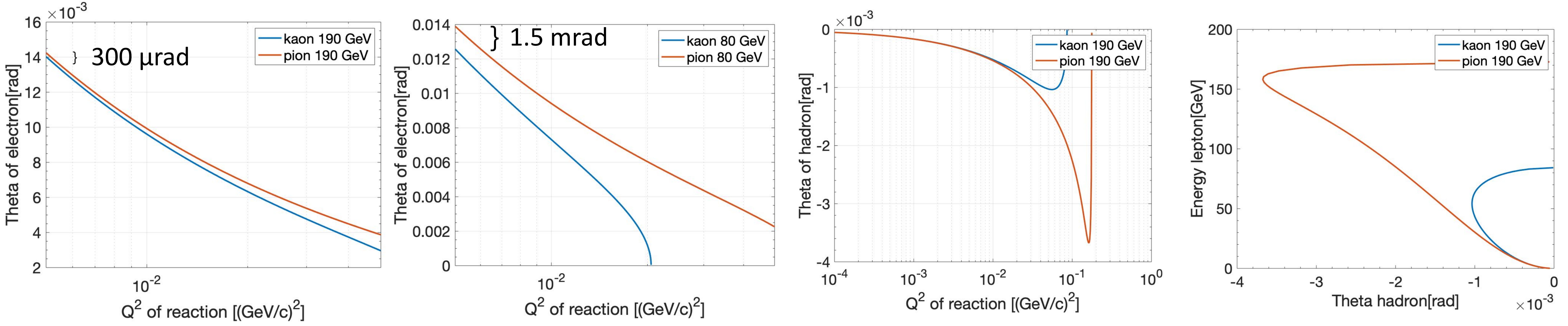
If angle of scattered hadron and outgoing lepton are measured

- geometrical acceptance cuts into Q^2 range (any cryogenic or pressurized target)
- two scenarios: $\theta_e < 30mr$ and $\theta_e < 10mr$



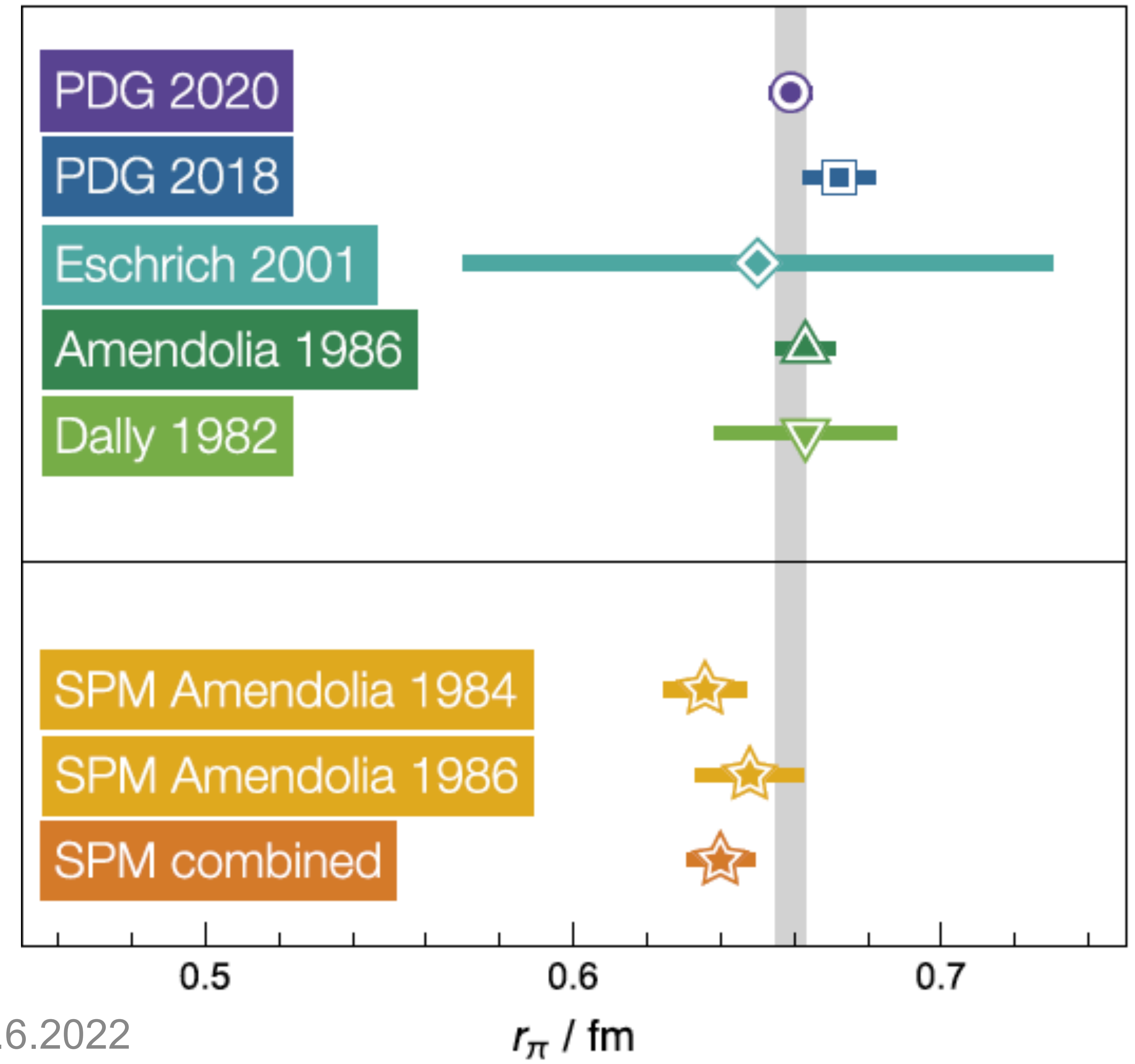
Separation of Kaon and Pion Induced Reactions

- CEDAR leaves Kaon beam with large pion contamination (about 3%)
- Can we separate kaon and pion induced reactions through kinematics ?
- yes.. but only for $Q^2 > \approx 5 - 10 \cdot 10^{-3}$ (may jeopardize radiative tail detection)

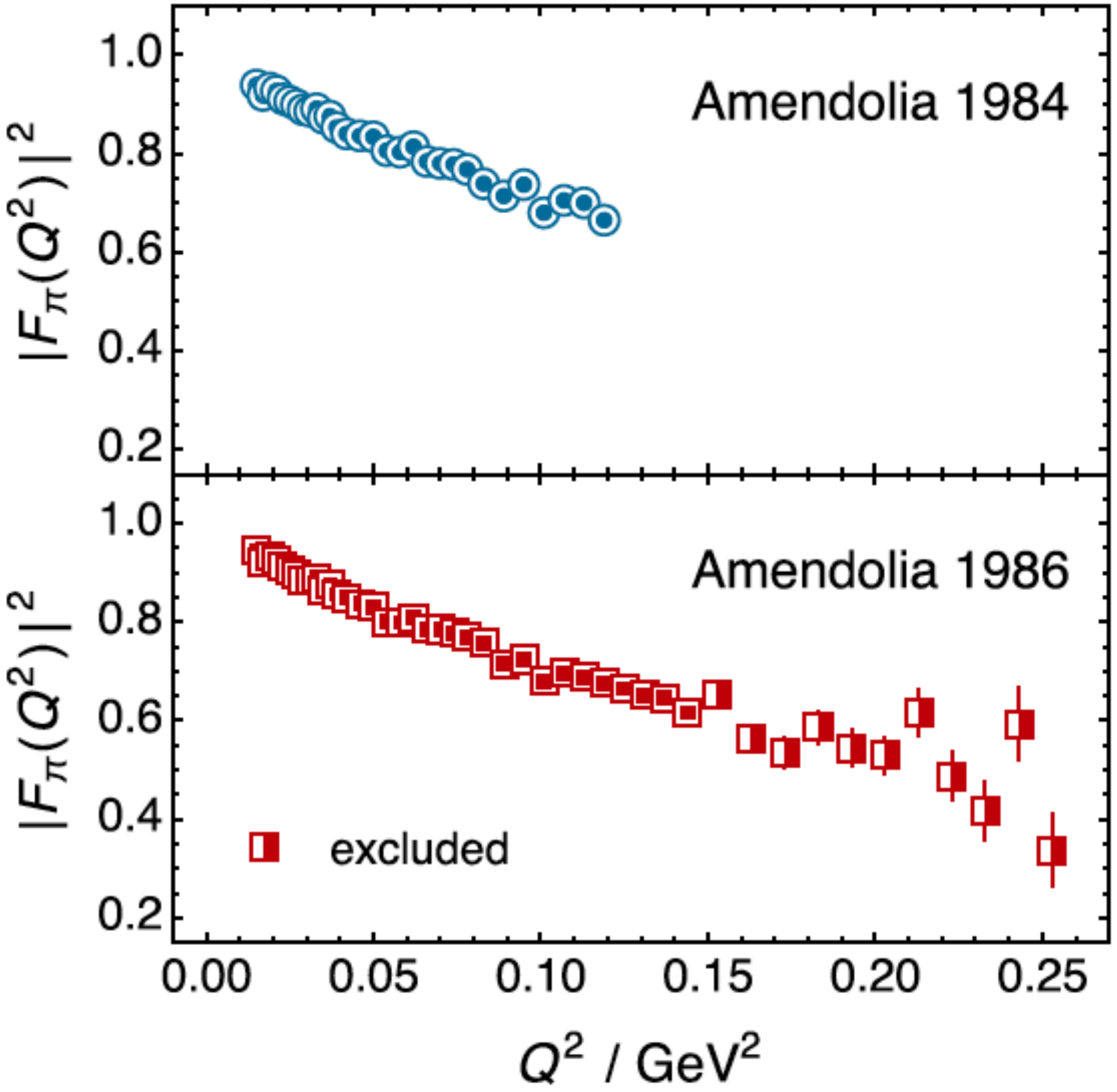


Pion-Electron scattering

from Physics Letters B 822 (2021) 136631



from Physics Letters B 822 (2021) 136631



Proton-Electron scattering

Why p-e^- scattering ?

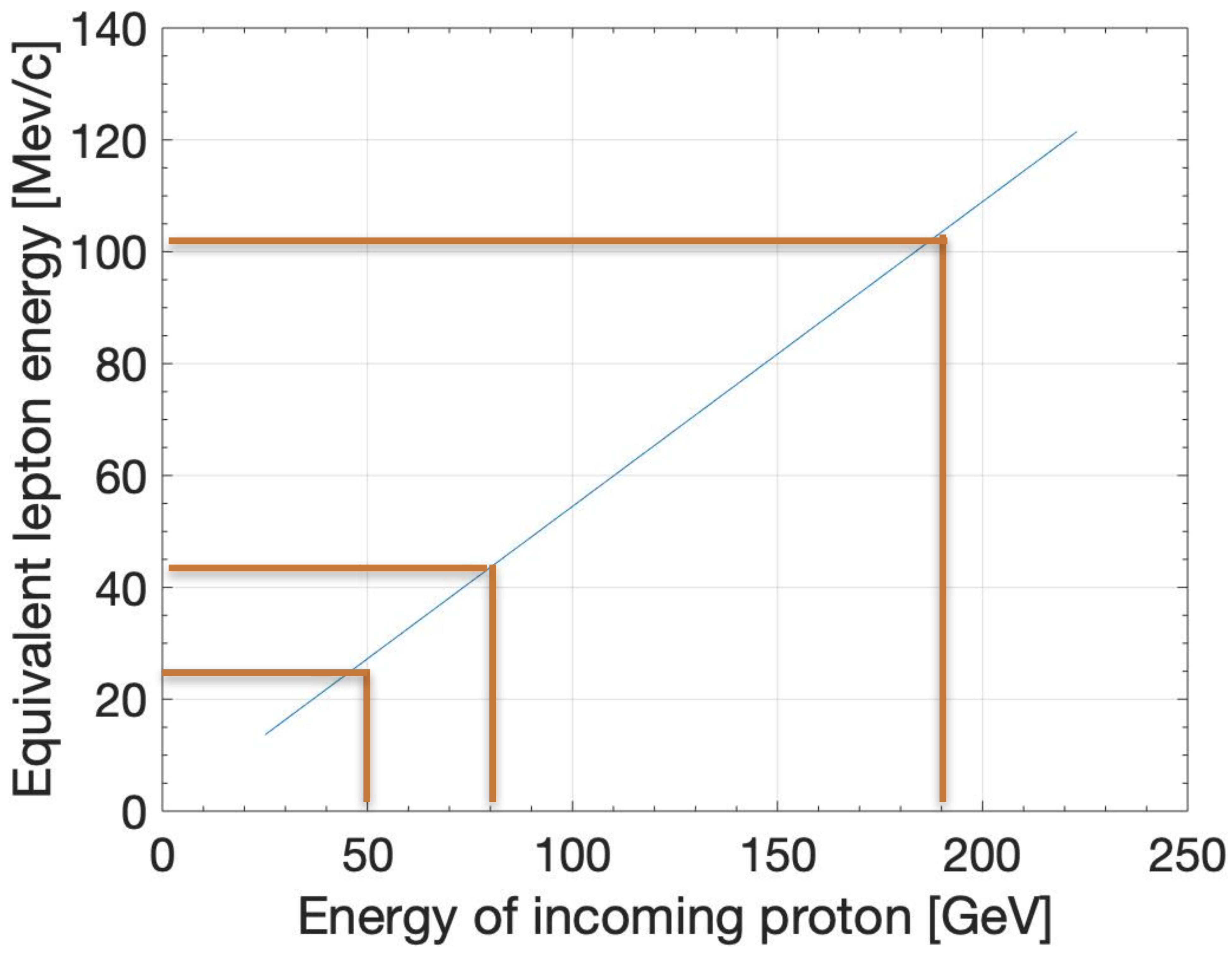
- complementary measurement to Mainz, JLAB and PSI
- very different kinematics and twofold reconstruction of Q^2
  - scattered proton (multiple scattering of little issue)
  - outgoing electron (Bremsstrahlung corrections and multiple scattering of low energy electron)
  - high beam quality (small divergence, small beam spot size)

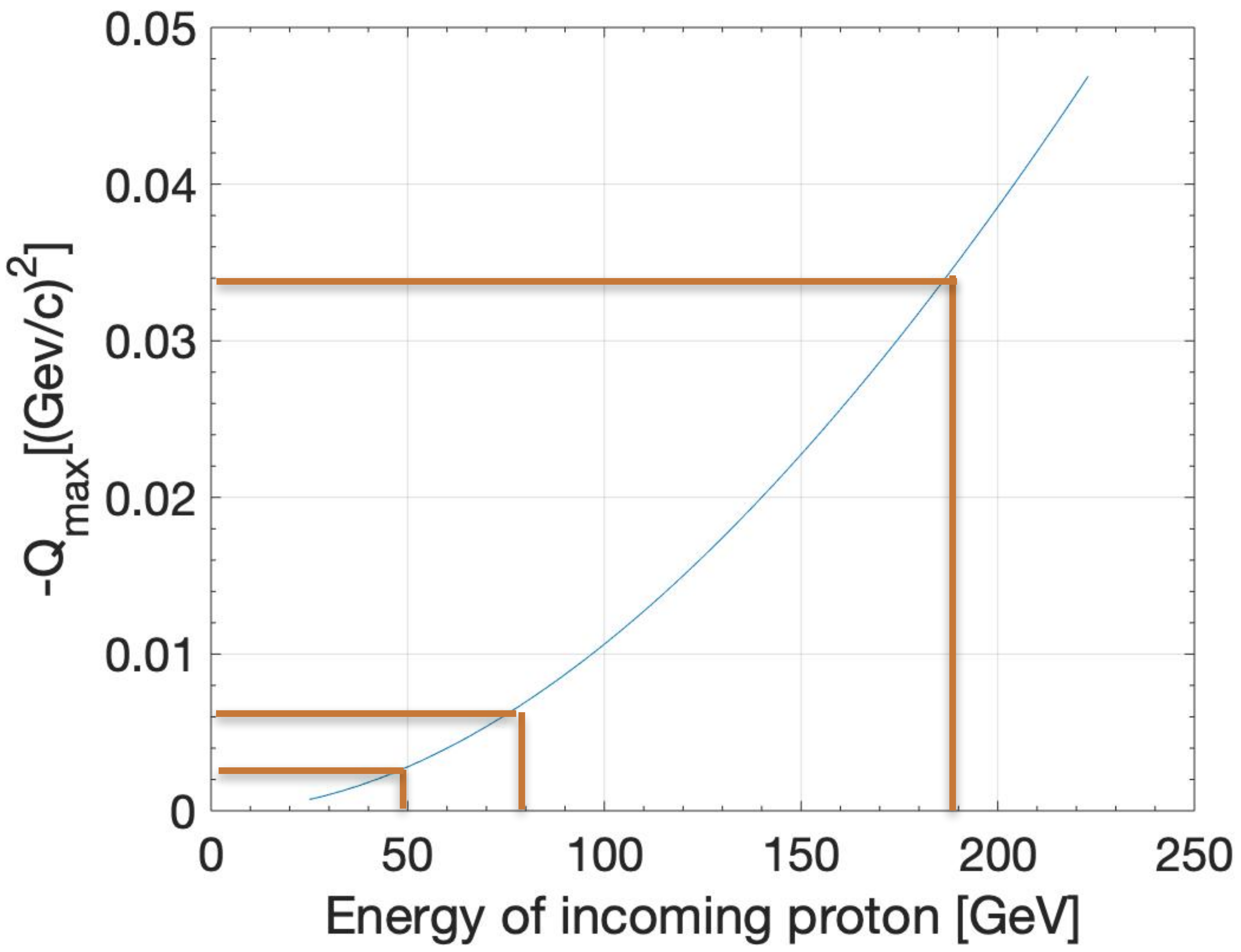
What is the equivalent for electron-proton scattering ?

- assume p^{proton}=190 GeV/c
- equivalent normal kinematics using proton at rest: $p^{electron}$=103.5 MeV/c
- calculate internal Bremsstrahlung for the equivalent kinematics
- variation of beam energy easy

Reaction Kinematics for Protons

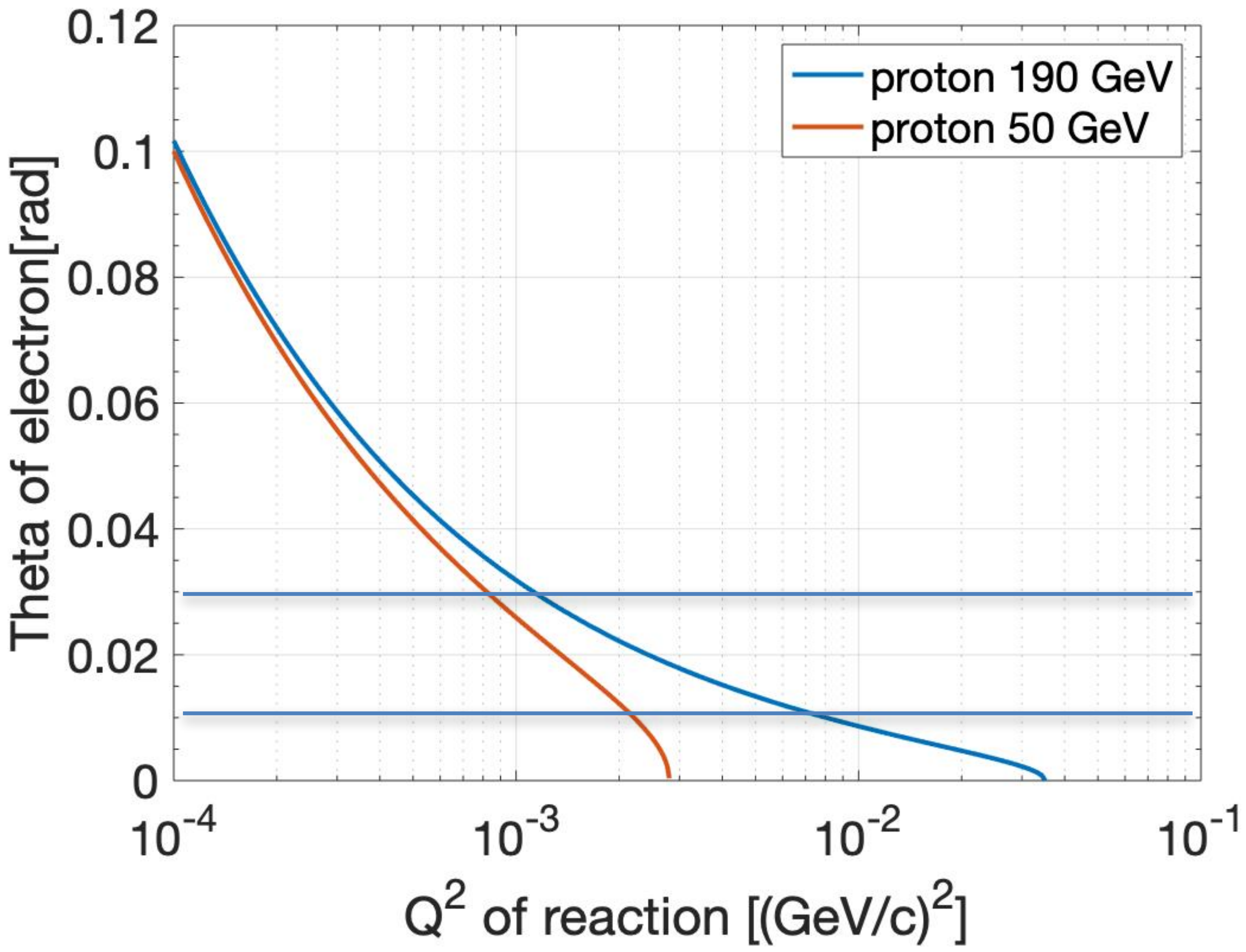
- complementary to stable proton target - use stable lepton target
- reaction in inverse kinematics





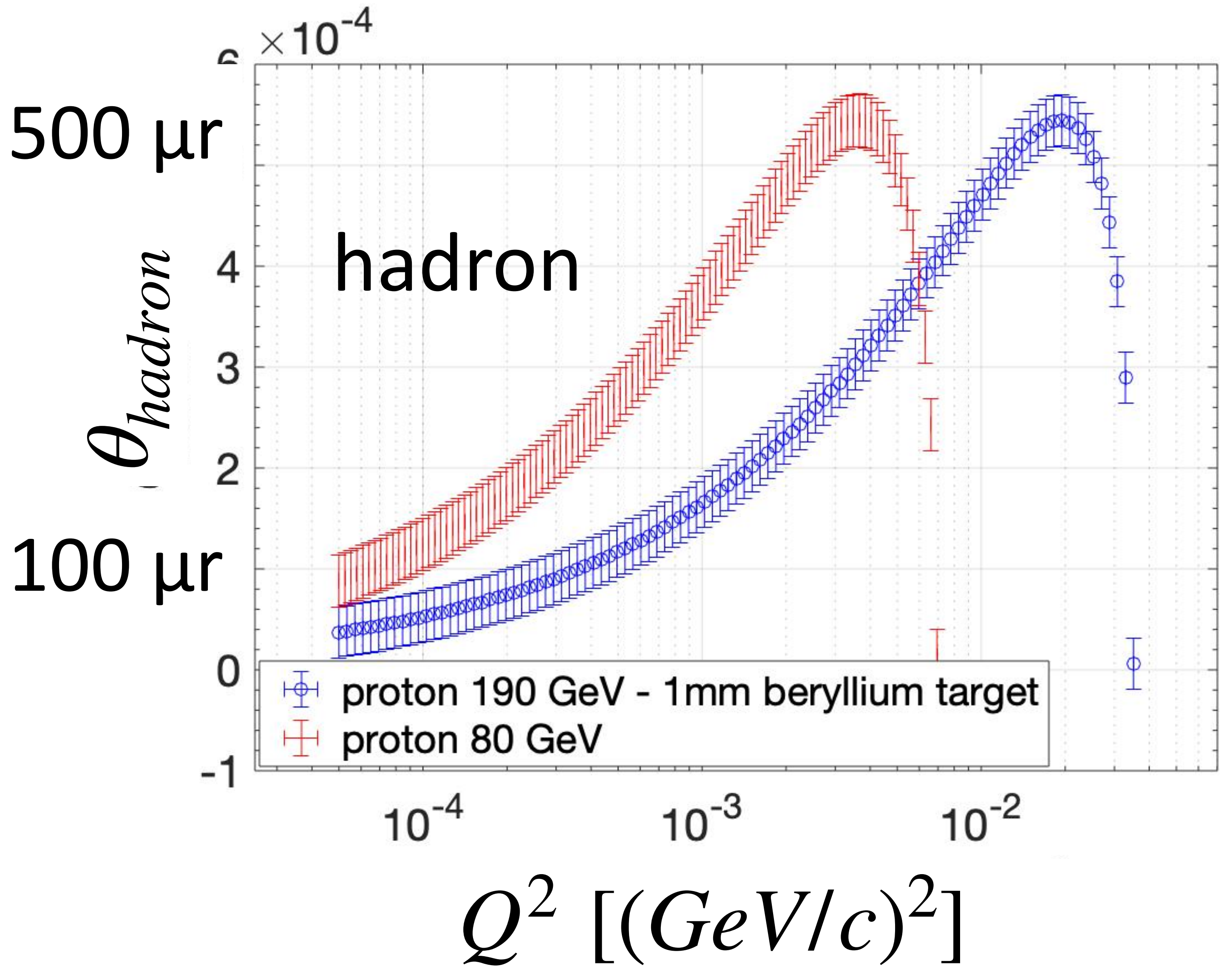
Acceptance Impact

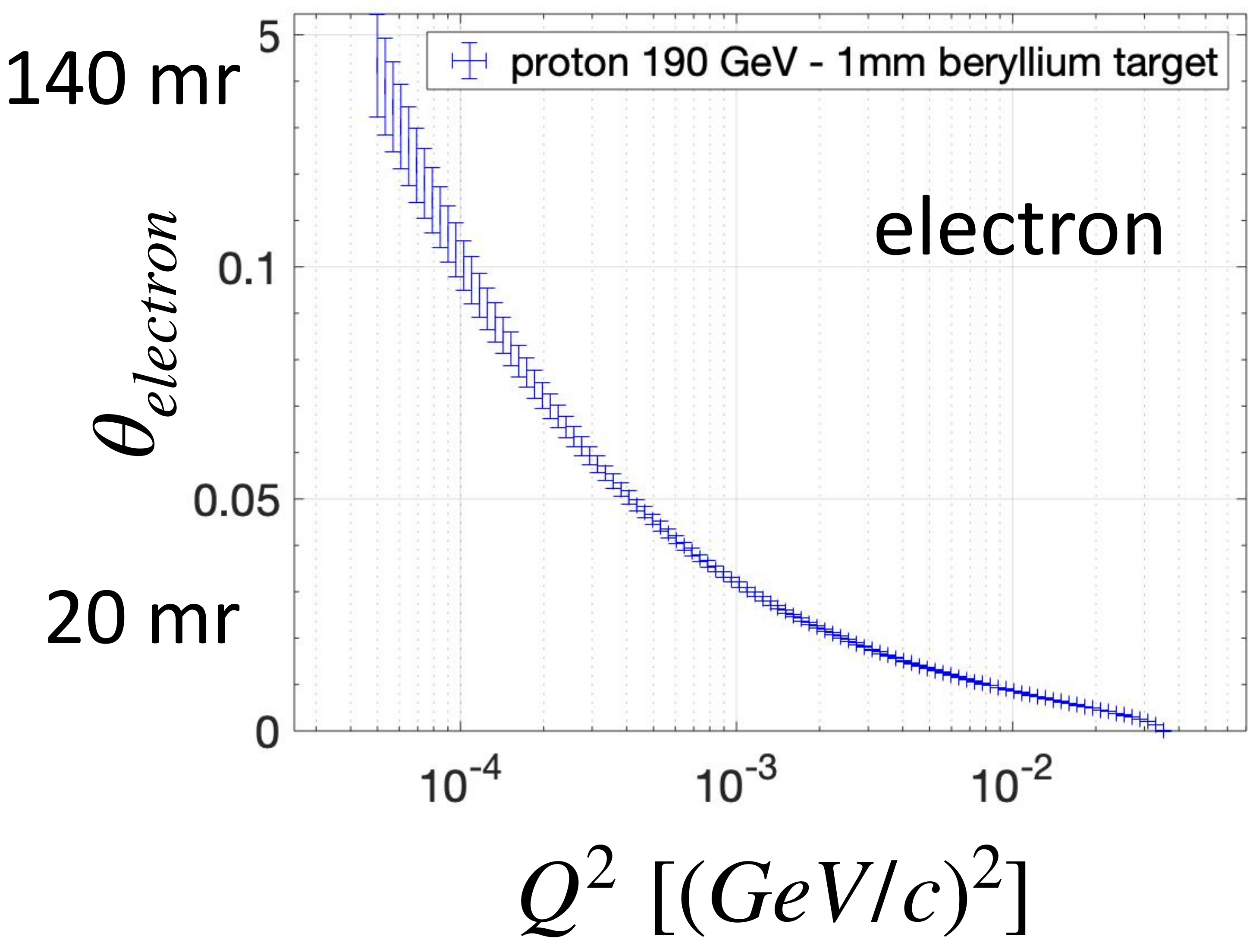
- large impact on Q^2 range due to acceptance cut for electron
  - Long LH_2 target - narrow pressure window strongly limit acceptance for scattered electron
  - required to cleanly identify elastic scattering
- regain physics if larger angular range can be covered



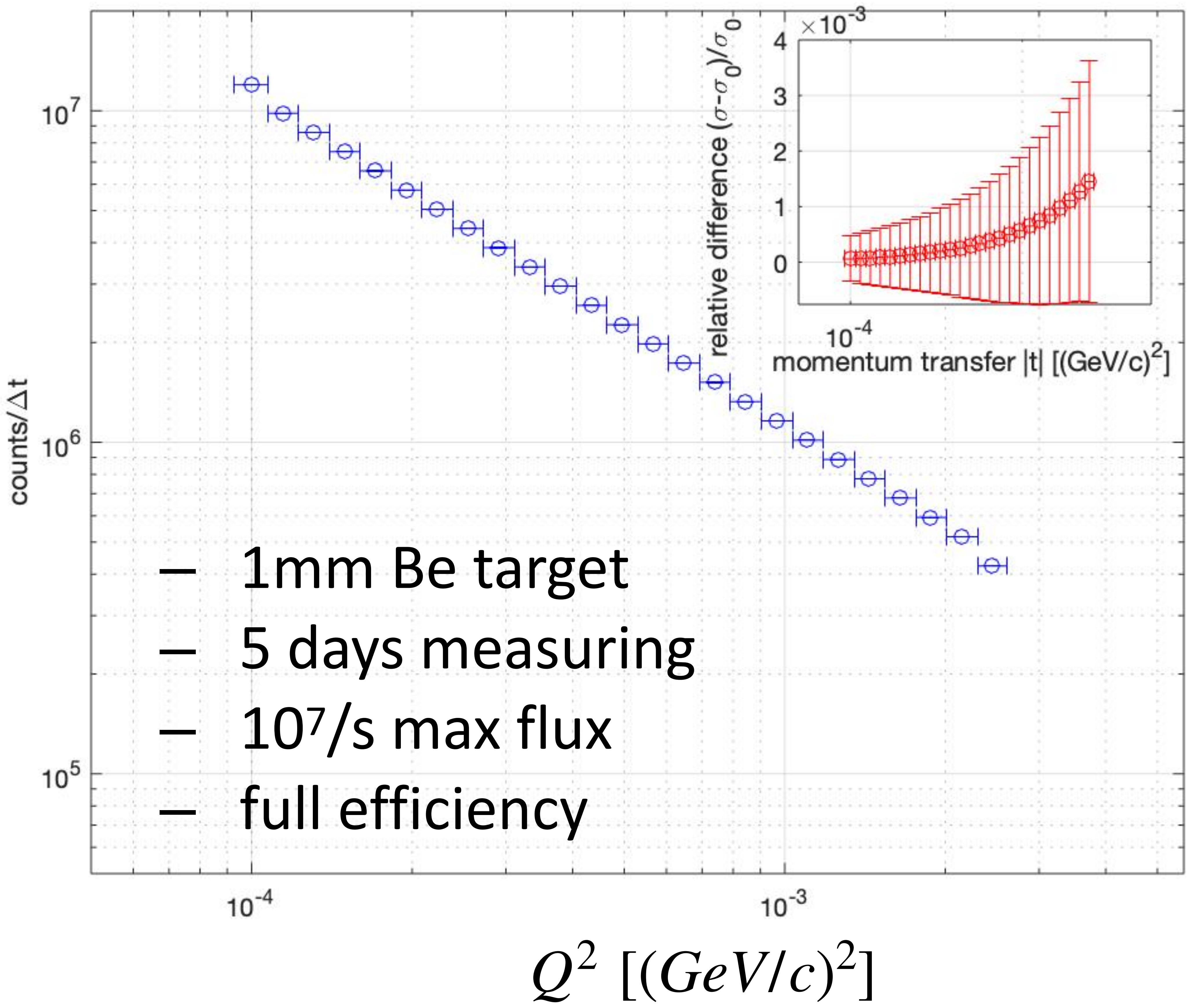
Acceptance Impact II

- for small Q^2: use thin solid target
  - determination of Q^2 through hadron scattering angle
  - use 50 GeV for higher resolution
  - keep multiple scattering low - 1mm Be target
    Q^2 resolution 1-2 10^{-4} $(GeV/c)^2$





rates in 5 days

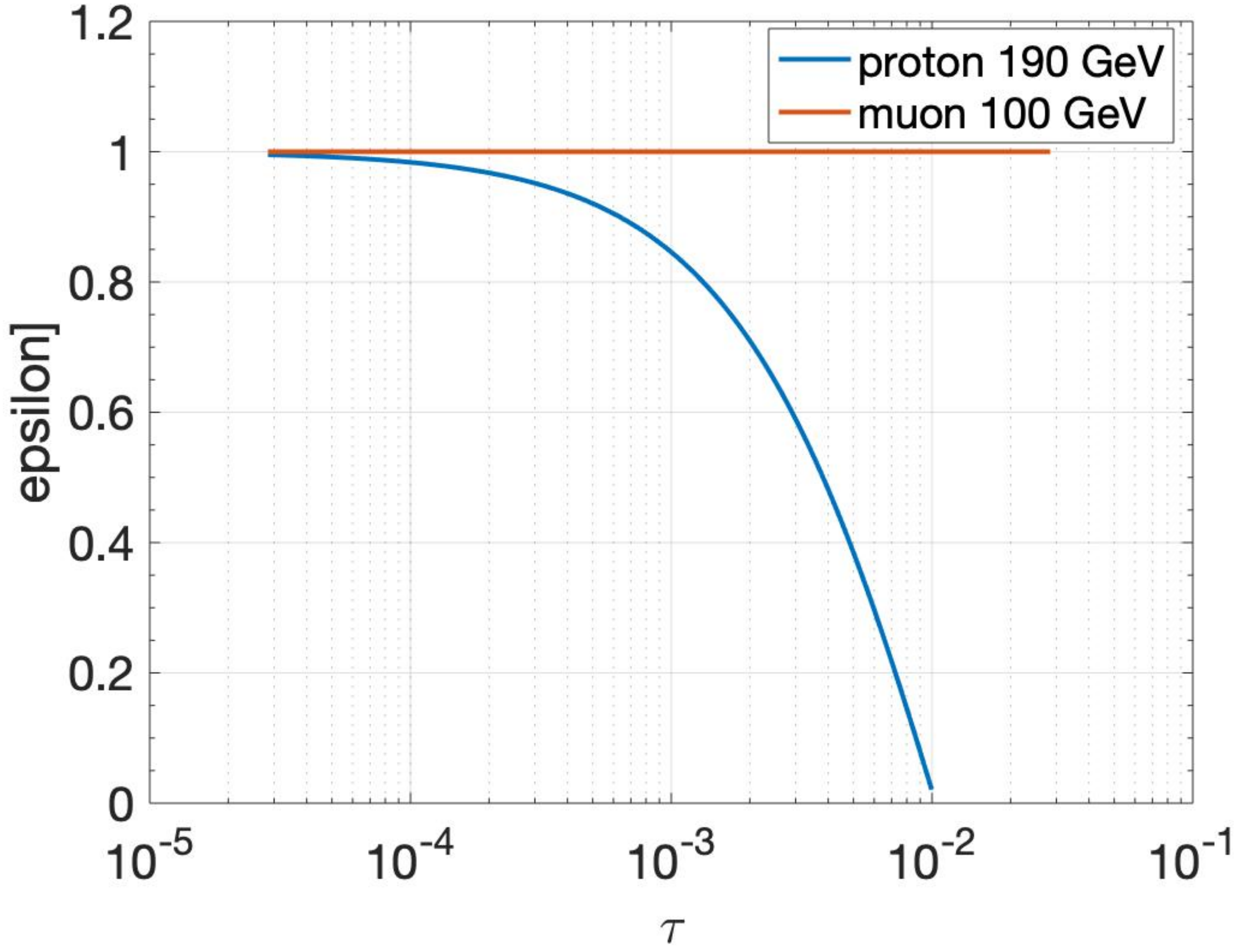


  - assume 1m lever arm and 6µm spatial resolution ($\delta\theta_{hadron} \approx 20 - 30\mu r$)

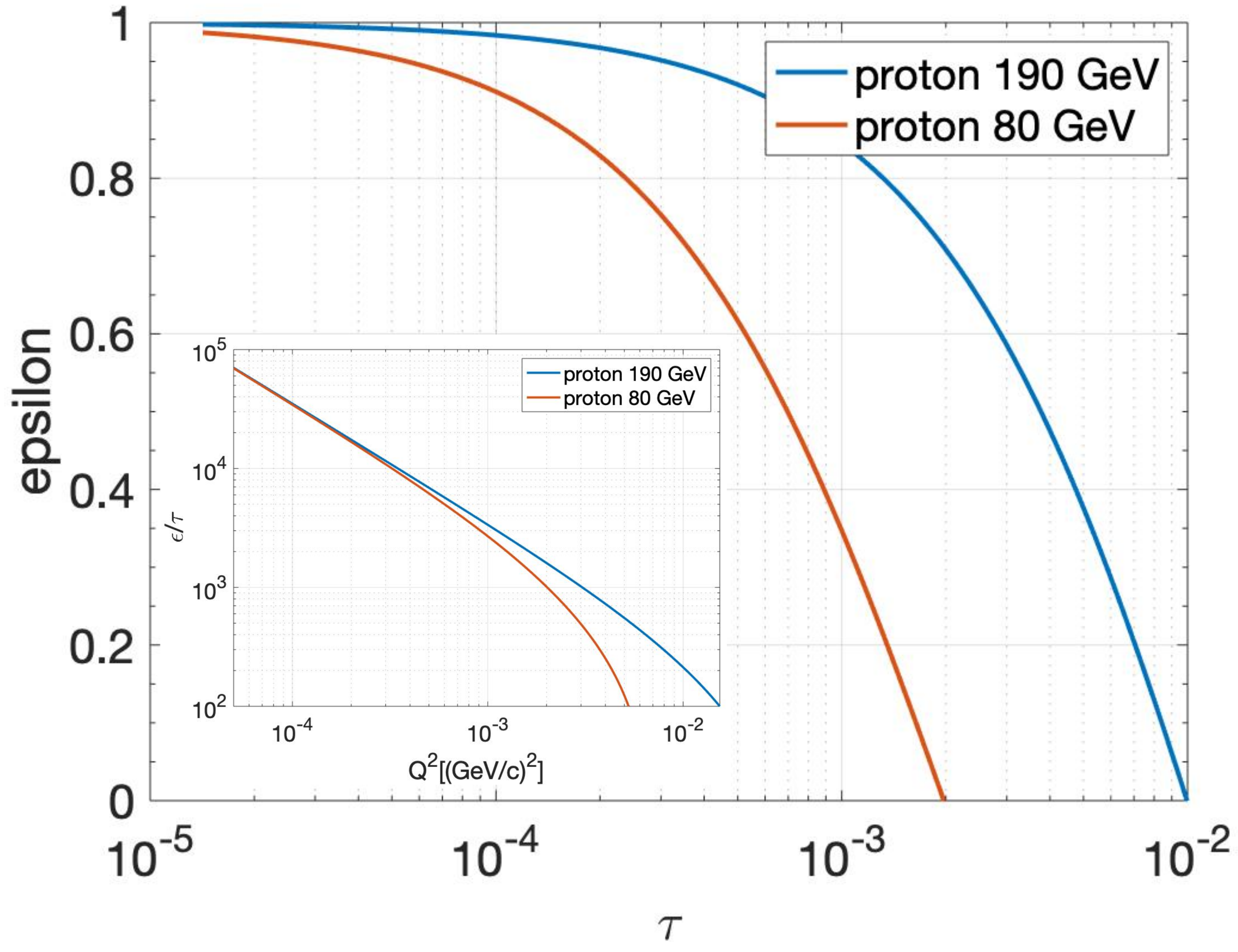
Other Physics with Inverse Kinematics

Inverse kinematics allows easy way to access difficult *ep* kinematics

- kinematic variables R, ε, τ $\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4} R\left(\epsilon \cdot G_E^2 + \tau \cdot G_M^2\right)$
- access Rosenbluth technique through variation of p_{beam} $\sigma_R = \left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_M \frac{\epsilon(1+\tau)}{\tau} = \frac{\epsilon}{\tau} G_E^2 + G_M^2$



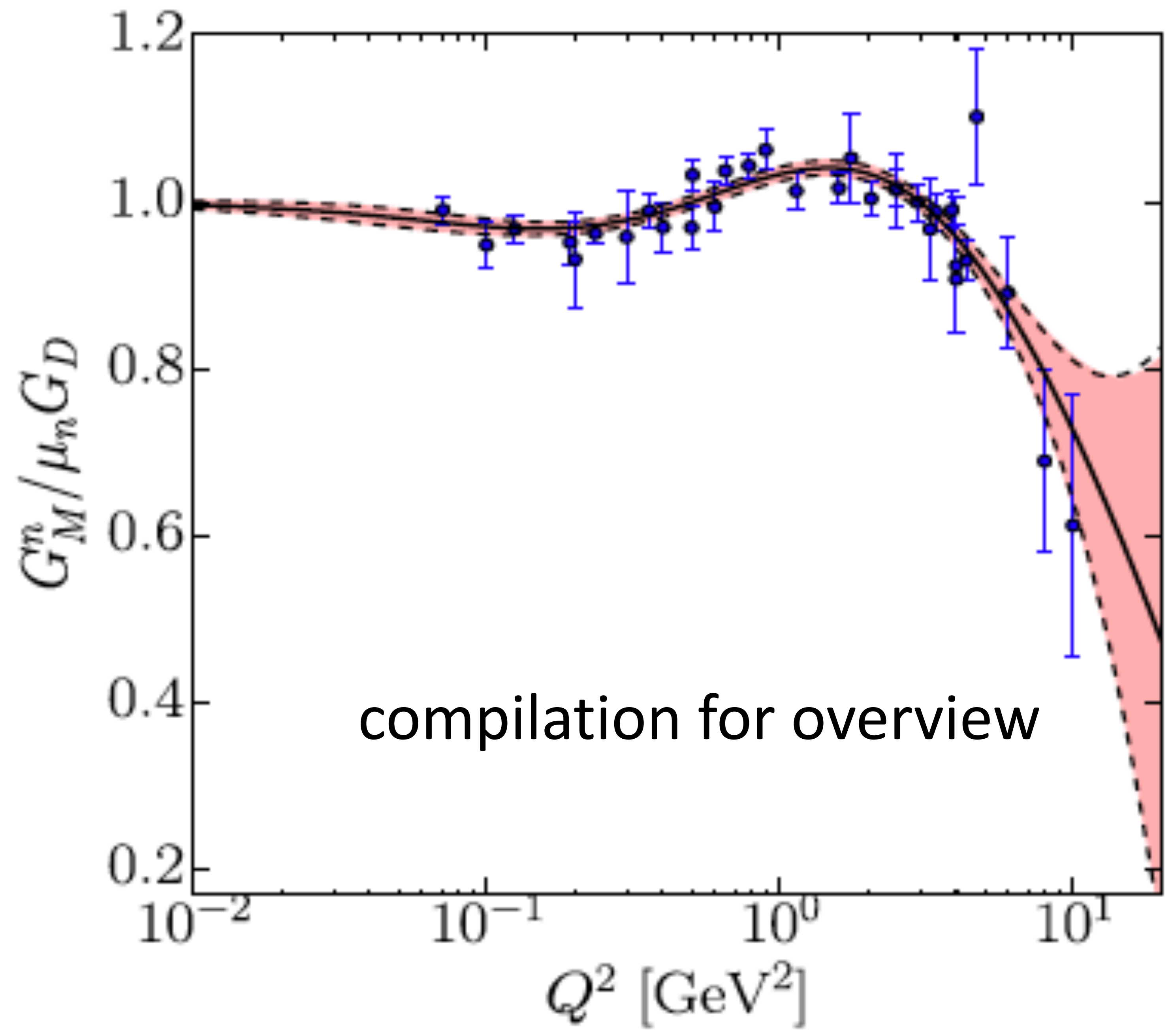
high energy muon scattering:
little sensitivity to $G_M^2(Q^2)$



use different beam momenta to access $G_M^2(Q^2)$

$G_M^p(Q^2)$

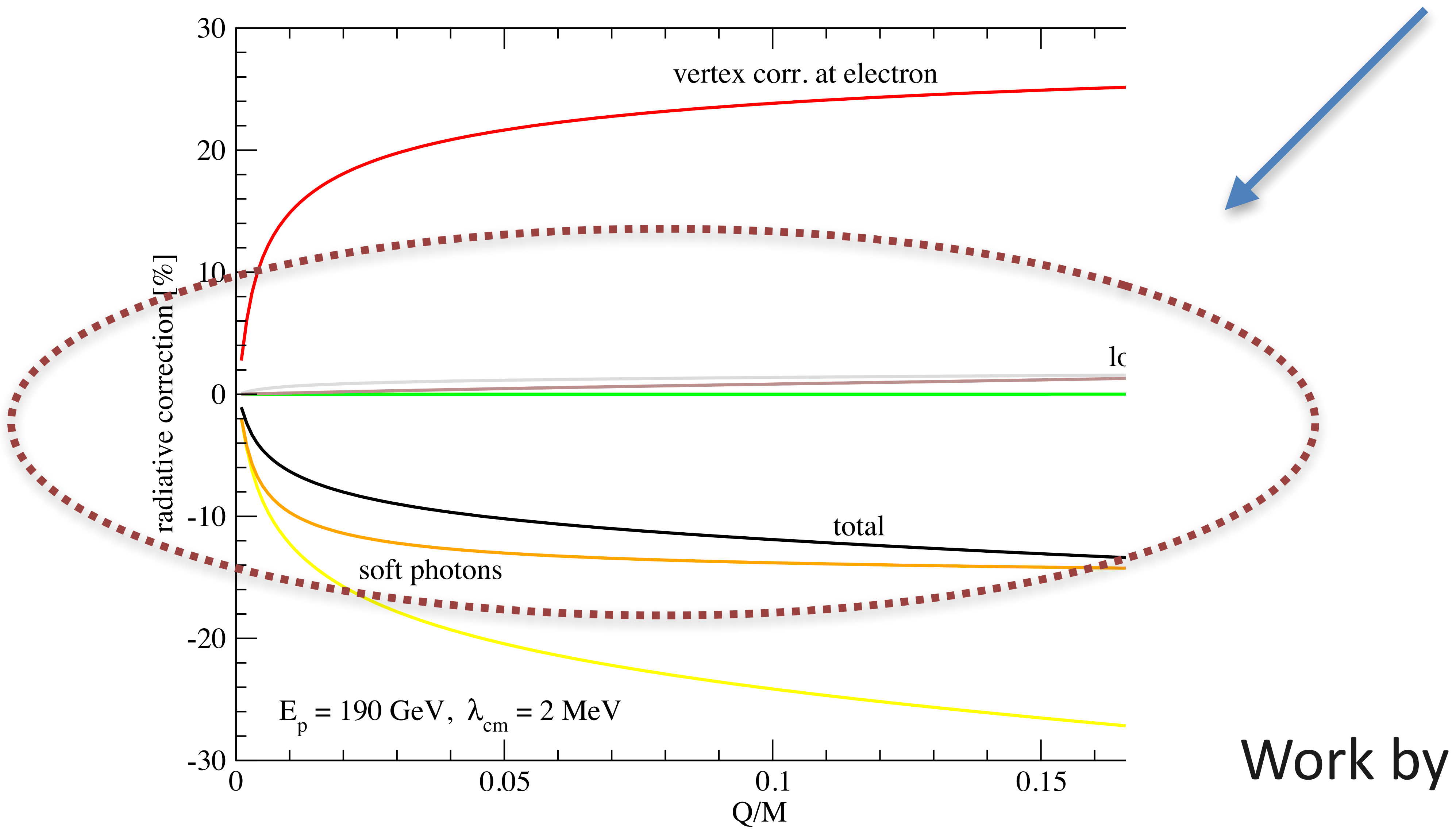
- Rosenbluth separation allows for extract $G_M^p(Q^2)$ at low Q2 !
- presently - knowledge data only for $Q^2 > 0.08(GeV/c)^2$ (Mz)
- Inverse kinematics could add kinematically $0.0004 > Q^2 > 0.04(GeV/c)^2$
- first measurement in this kinematic range for this quantity !
- equivalent incoming electron energies: 30-105 MeV



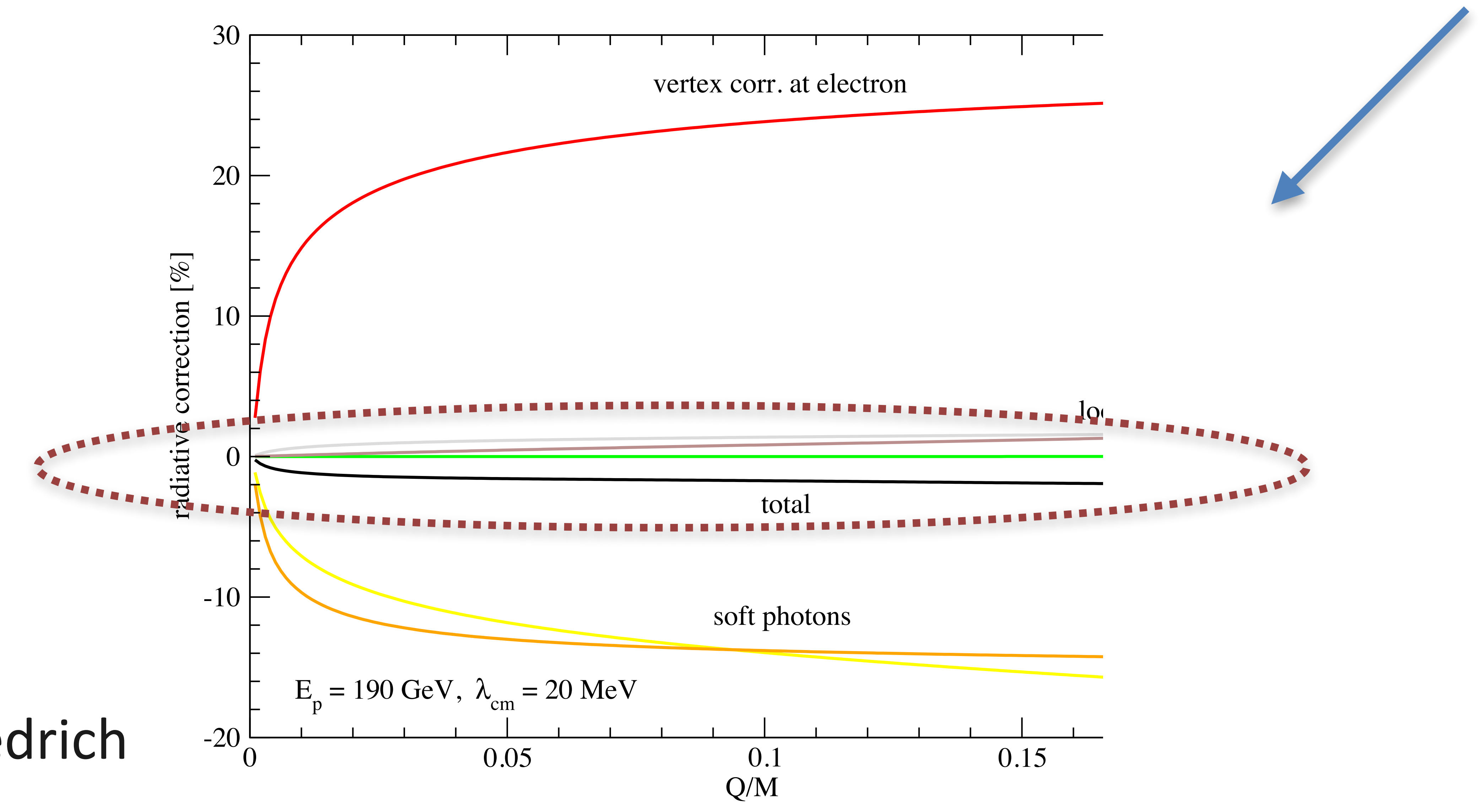
Radiative Corrections

- with 190 GeV protons, we have to consider the case of incoming e^- of 105 MeV beam energy
- Vertex correction and internal Bremsstrahlung enter with opposite sign
- Issue: identification of p-e^- scattering - kinematic correlation of outgoing particles
  - cut in cm on 2% momentum correlation (2 MeV) - cut in cm on 20% momentum correlation (20 MeV)

12%



2%



Work by Kaiser/Friedrich

Conclusions p-e⁻ Scattering

- inverse kinematics allows to access v very low Q^2 region without relying on very low energy electrons
- comparison to high energy muon scattering: equivalent incoming lepton energy low

$$\frac{d\sigma}{dQ^2} = \frac{\pi\alpha^2}{Q^4\, m_p^2\, \vec{p}_\mu^{\,2}} \left[\left(G_E^2 + \tau\, G_M^2\right) \frac{4E_\mu^2 m_p^2 - Q^2(s - m_\mu^2)}{1+\tau} - G_M^2 \frac{2m_\mu^2 Q^2 - Q^4}{2} \right]$$

- small $\overline{p}_\mu^2$ (inverse kinematics) : stronger contribution of G_M^2
- high $\overline{p}_\mu^2$ (AMBER proposal) : G_M^2 contribution negligible
- cross section w.r.t. G_E^2 almost independent on beam momenta (counting rates see AMBER proposal)
- radiative corrections: work with N. Kaiser ongoing

And Now ?

- Disclaimer: Many ideas arisen within the last weeks
- As with all new ideas..
  - x-check analytic calculations
  - GEANT simulations must back analytical calculations
- …. and if things work out fine.. make a proposal to CERN

Conclusions - Elastic hadron-e^- Scattering with Inverse Kinematics

- very interesting alternative to classical electron scattering
- Challenges:
  - high values of Q^2 (requires high beam momentum)
  - very low values of Q^2
    - angular acceptance for electrons
    - determination of Q^2
    - separation of K vs. π induced reactions (only important for kaons)
- AMBER advantages
  - high density LH_2 target (without TPC insert)
  - high beam intensity
  - high resolutions for hadron kinematics

Summary

- Meson radii are of key interest in understanding their inner structure and the emergence of hadron mass
- For pions, some deeper investigations would be needed to see whether and how the data of previous experiments can be challenged (statistics !!)
- For kaons, a significant increase of the form factor knowledge in the range $0.001 < Q^2 < 0.086$ appears in reach (factor 10)
- large Q^2 range possible (in particular down to very small Q^2)
  accessible Q^2 range determined by detection requirements for outgoing electron
- Proton inverse kinematics allows low Q^2 kinematics and Rosenbluth separation $G_M^p(Q^2)$

BACKUP

TPC numbers

- TPC windows:
  - 35mm diameter
  - 1mm thickness Be on each side
  - 1.4% X_0

  - total thickness tracking + TPX: 4.2% X_0

Variables for Inverse Kinematics

- Compare muon-proton and proton-electron scattering