Institute for Hadronic Structure and Fundamental Symmetries
Physics Department
Technical University of Munich

The AMBER Experiment at CERN
and
an Update on E18’s Scintillating Fiber Hodoscope

Karl Eichhorn and Christian Dreisbach

E18 Seminar
18.01.2024

AMBER/CERN

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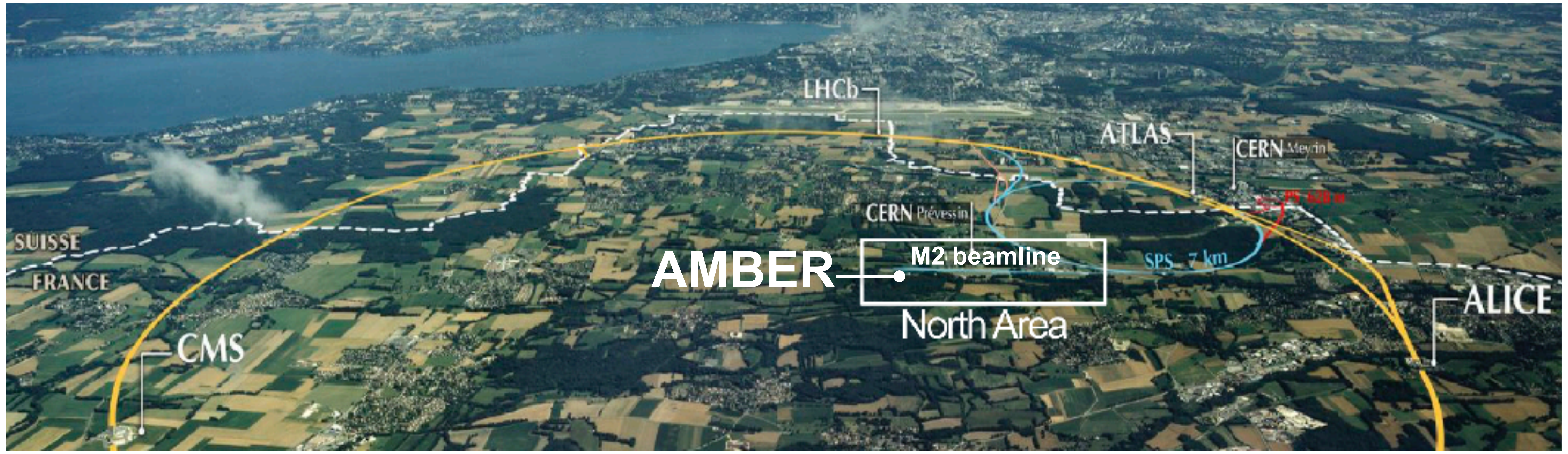
The **A**pparatus for **M**eson and **B**aryon **E**xperimental **R**esearch — AMBER

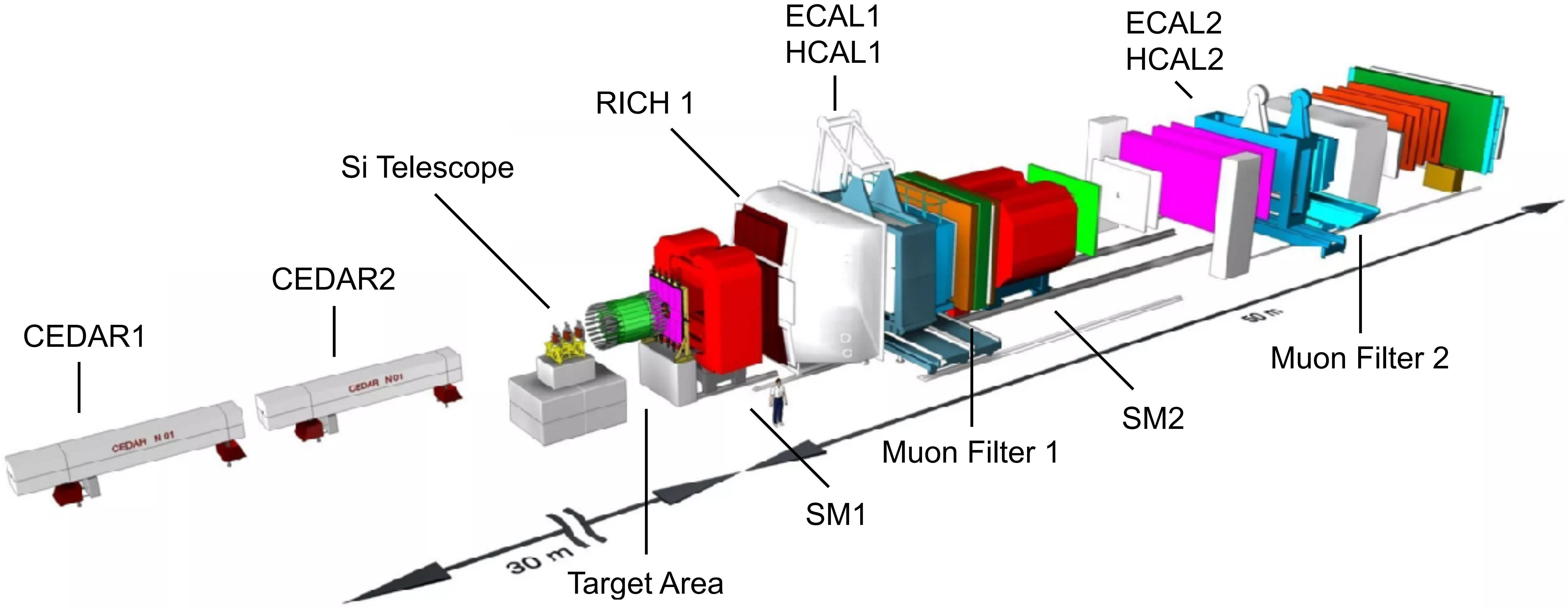
AMBER as successor of the COMPASS Experiment
Various new physics programs foreseen utilising the former COMPASS Spectrometer including upgrades and modernisations.

- Basic Facts:
  - → AMBER/NA66 has been approved in December 2020 as successor of COMPASS (20 years of running)
  - → New Collaboration with about 200 physicists from 34 institutes in 14 countries
  - → Located at M2 beamline at CERN's SPS: hadron and muon beams at momenta between 60-280 GeV

- Fixed-target two-stage magnetic spectrometer:
  - → Two stages along 50 meter long spectrometer: low (< 60 GeV) and high momenta
  - → Flexible target area for different physics programs
  - → Particle identification
  - → Momentum measurement and calorimetry
  - → Various kinds of tracking detectors



CERN



Physics Program

AMBER Physics program in the upcoming years

LHC Run 3
2021 - 2025

LHC Run 4
2029 - 2032

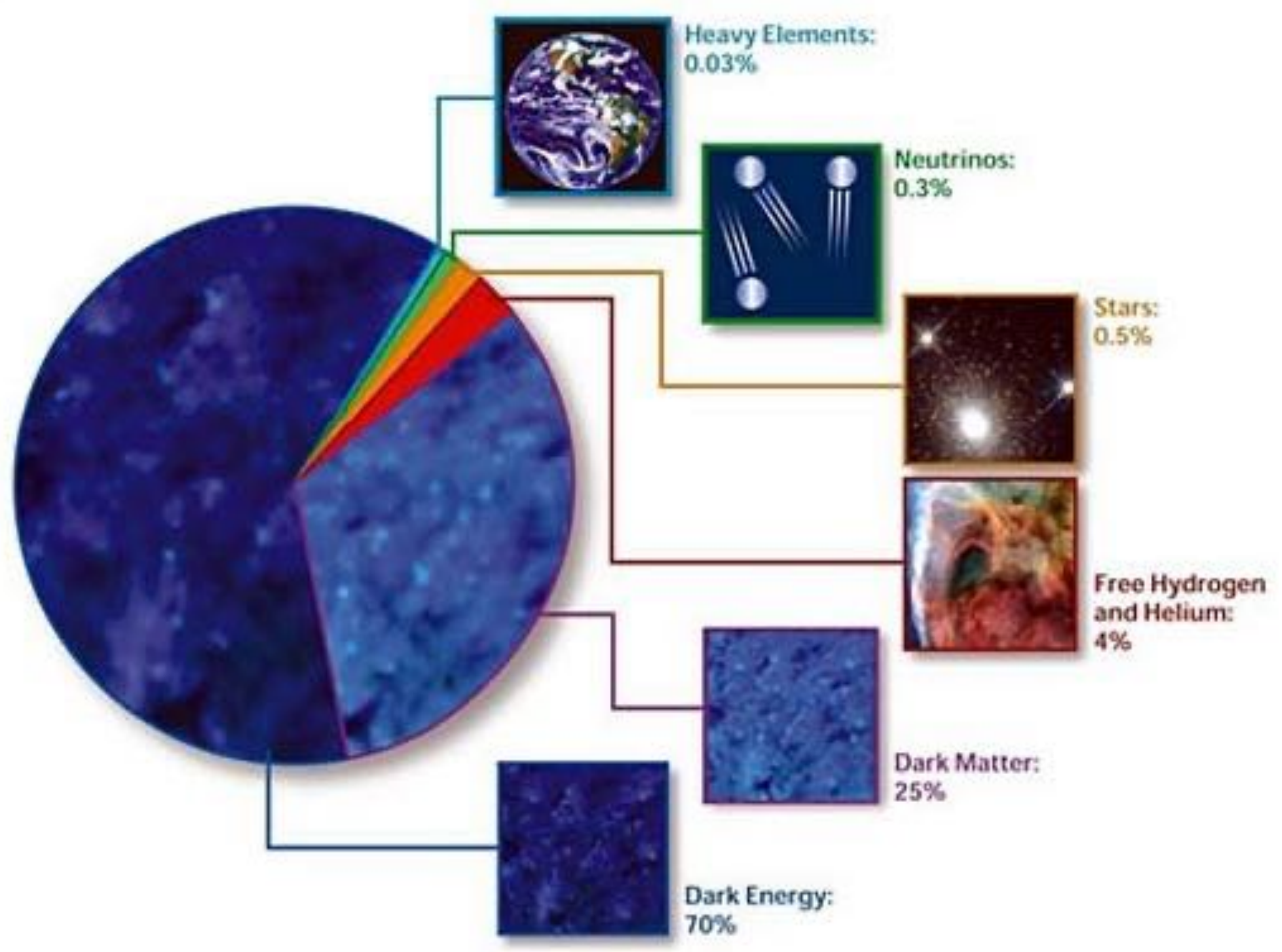
- Phase I (approved by CERN):
  → **Anti-proton production cross-section**
  → Proton charge radius
  → Pion and kaon structure functions

- Phase II (Proposal submission ongoing):
  → Strange-meson spectroscopy
  → Kaon polarisability
  → Prompt-photon production

Phase I - Antiproton Production Cross-Section Measurement

Study of the Antiproton Production
Contribution to indirect dark matter searches via improvements in antiproton production cross sections and its uncertainties.

- Facts about the Universe:
  - → Galaxies and stellar system motion cannot be explained taking into account the current knowledge of our universe
  - → Galaxies surrounded by a spherical halo of non-visible, non-baryonic material: dark matter (i.e. 90% of milky-way mass)
  - → So far, alternative approaches / theories have failed to describe exiting data
  - → The abundances and energy spectra of cosmic-ray particles are a probe to study processes in the galaxy like dark-matter annihilation
  - → Antiprotons are produced via cosmic rays interact with the interstellar medium (H, He,…) with main contribution: proton-proton, proton-He — or dark-matter annihilation?
  - → AMBER took first cross-section data on proton-He last year with 60-250 GeV — for 2024: proton-H + proton-D



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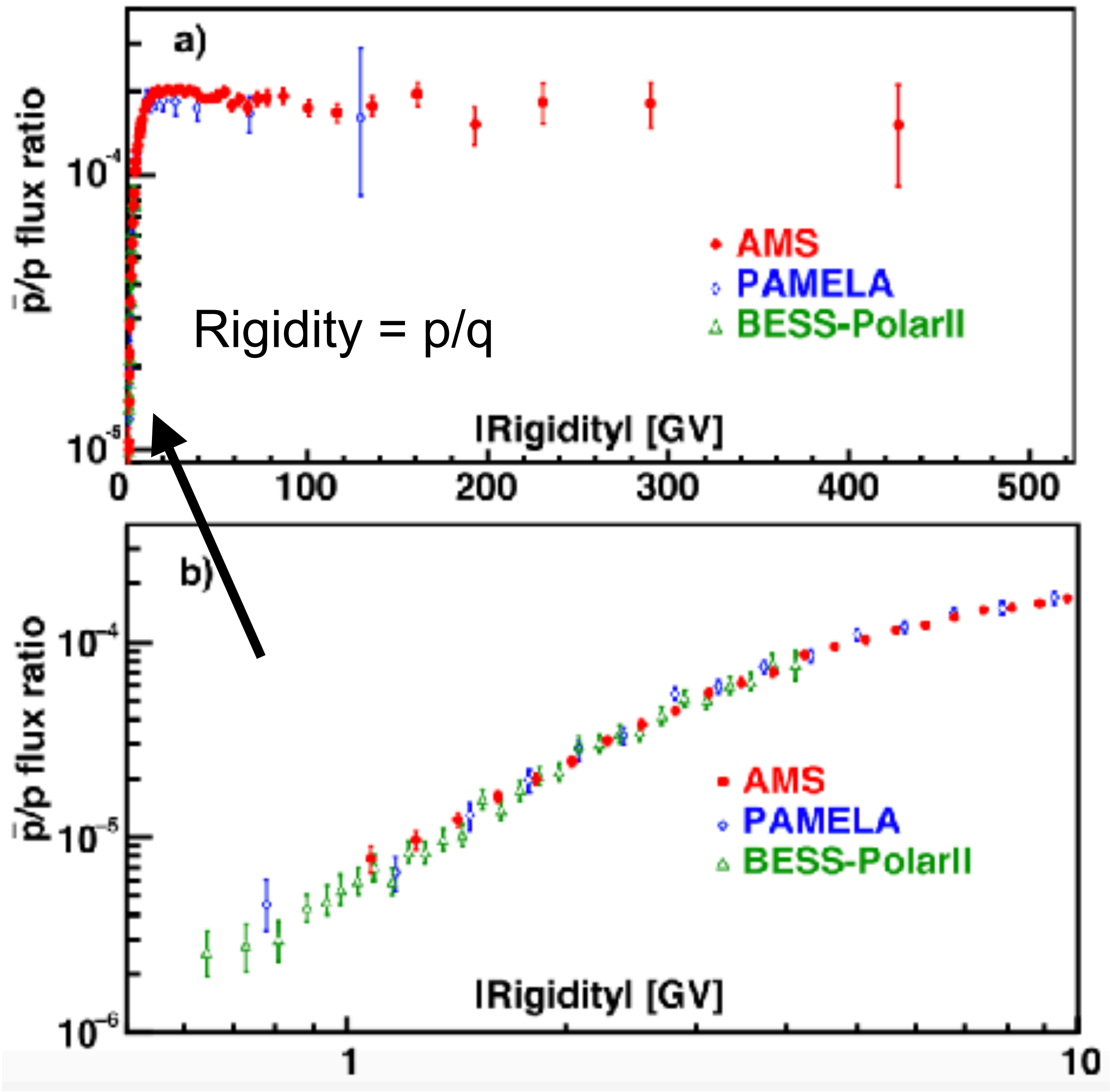
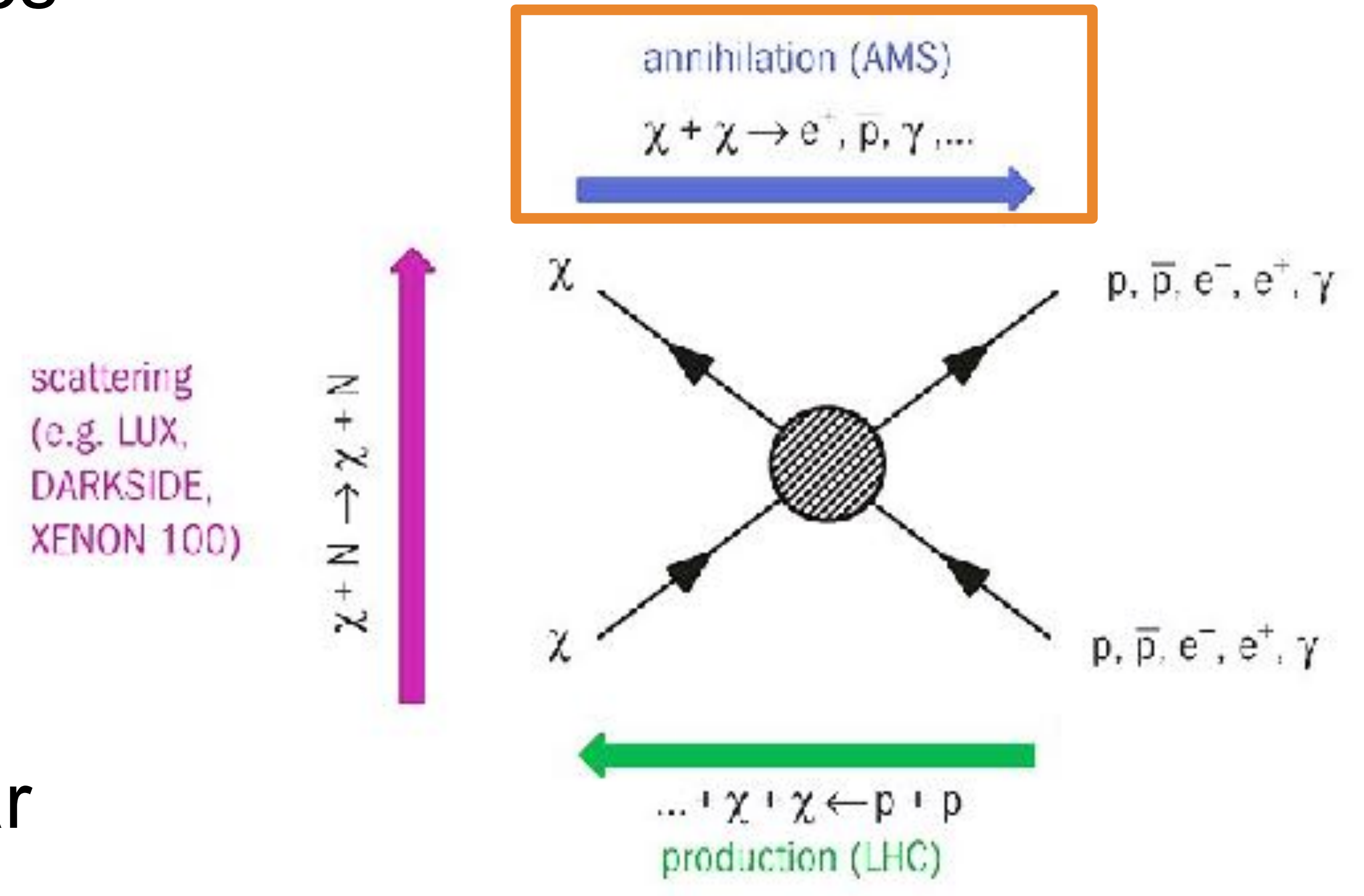


Physics Reports 894 (2021) 1–116

Dark Matter



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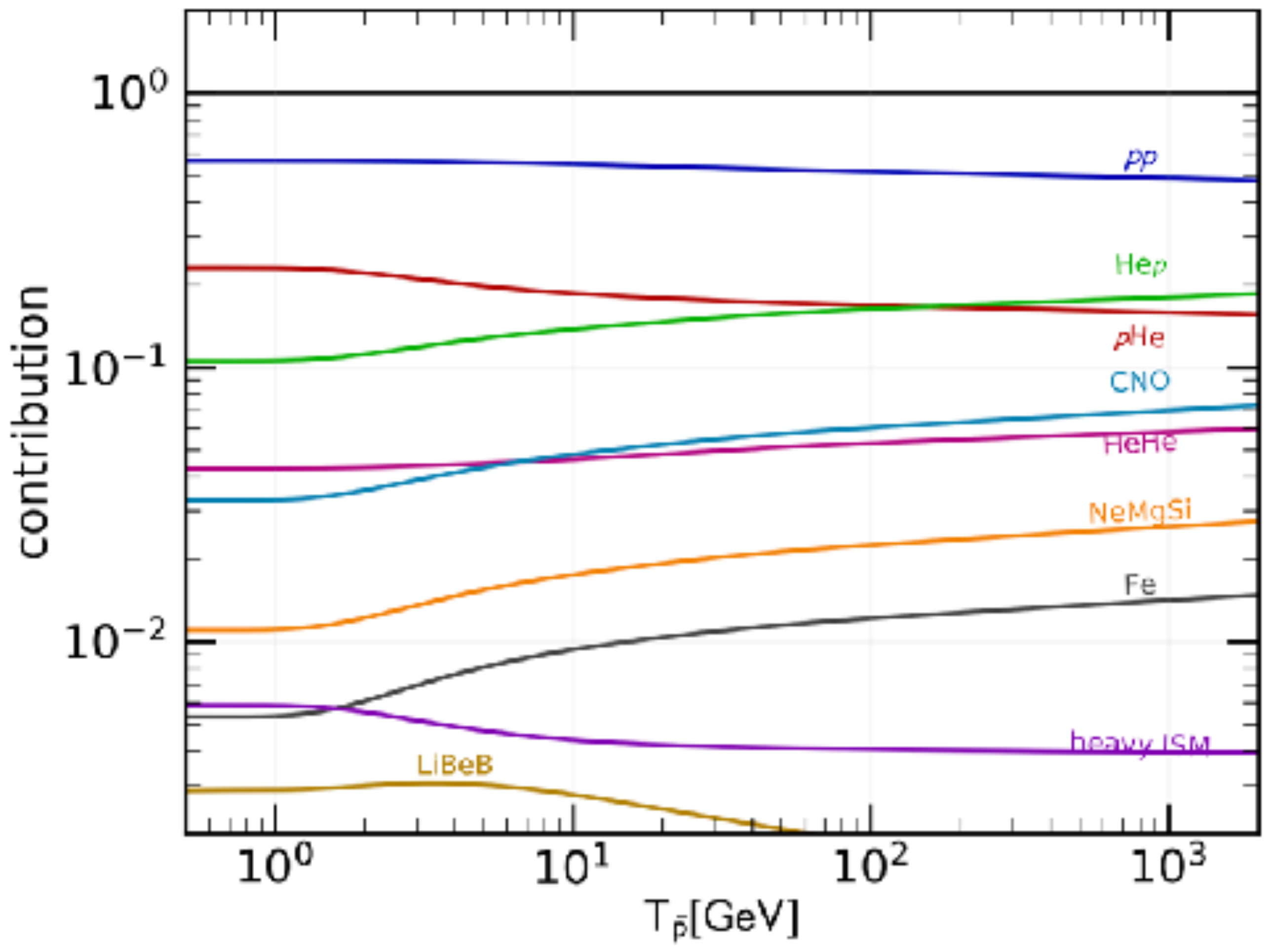

arXiv:1802.03030v2

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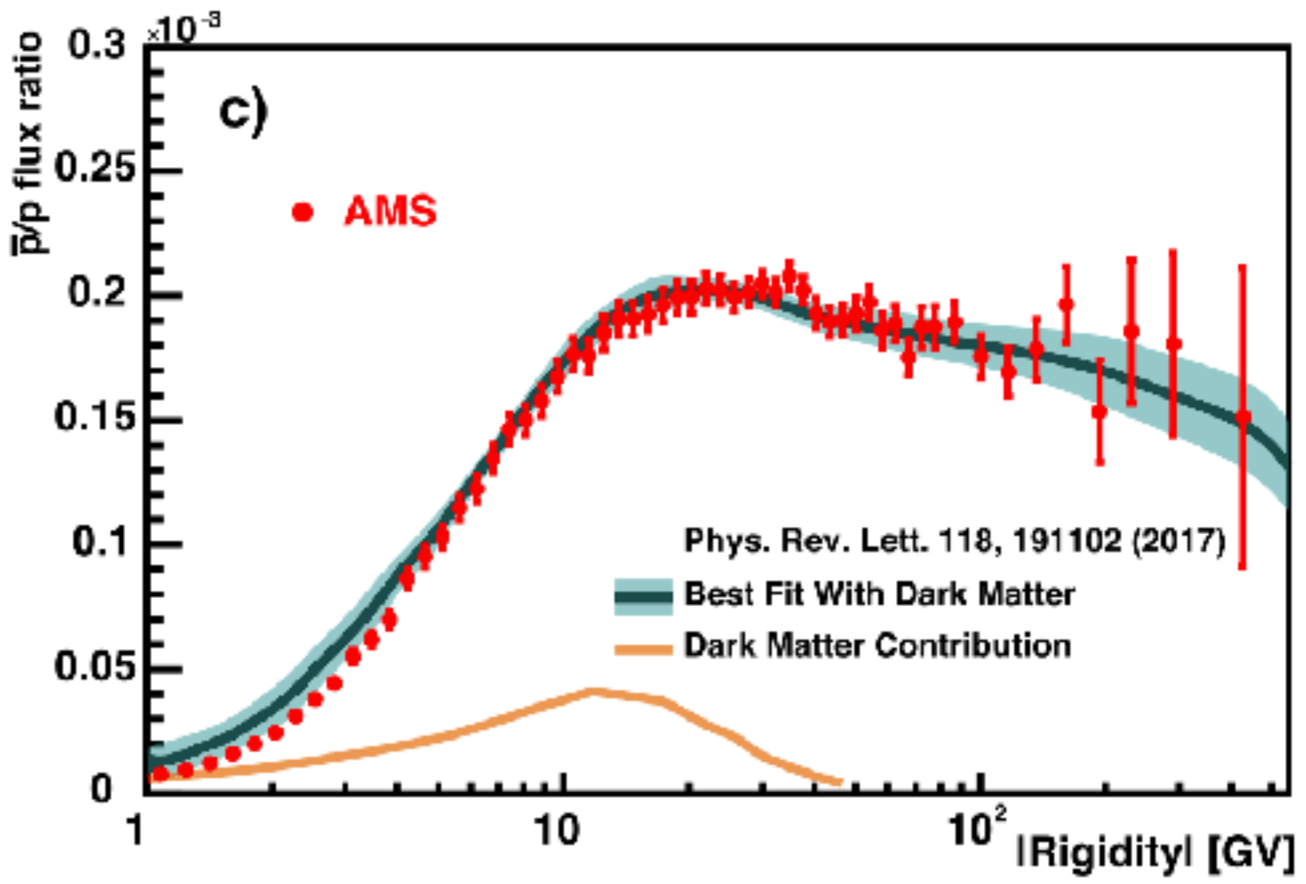

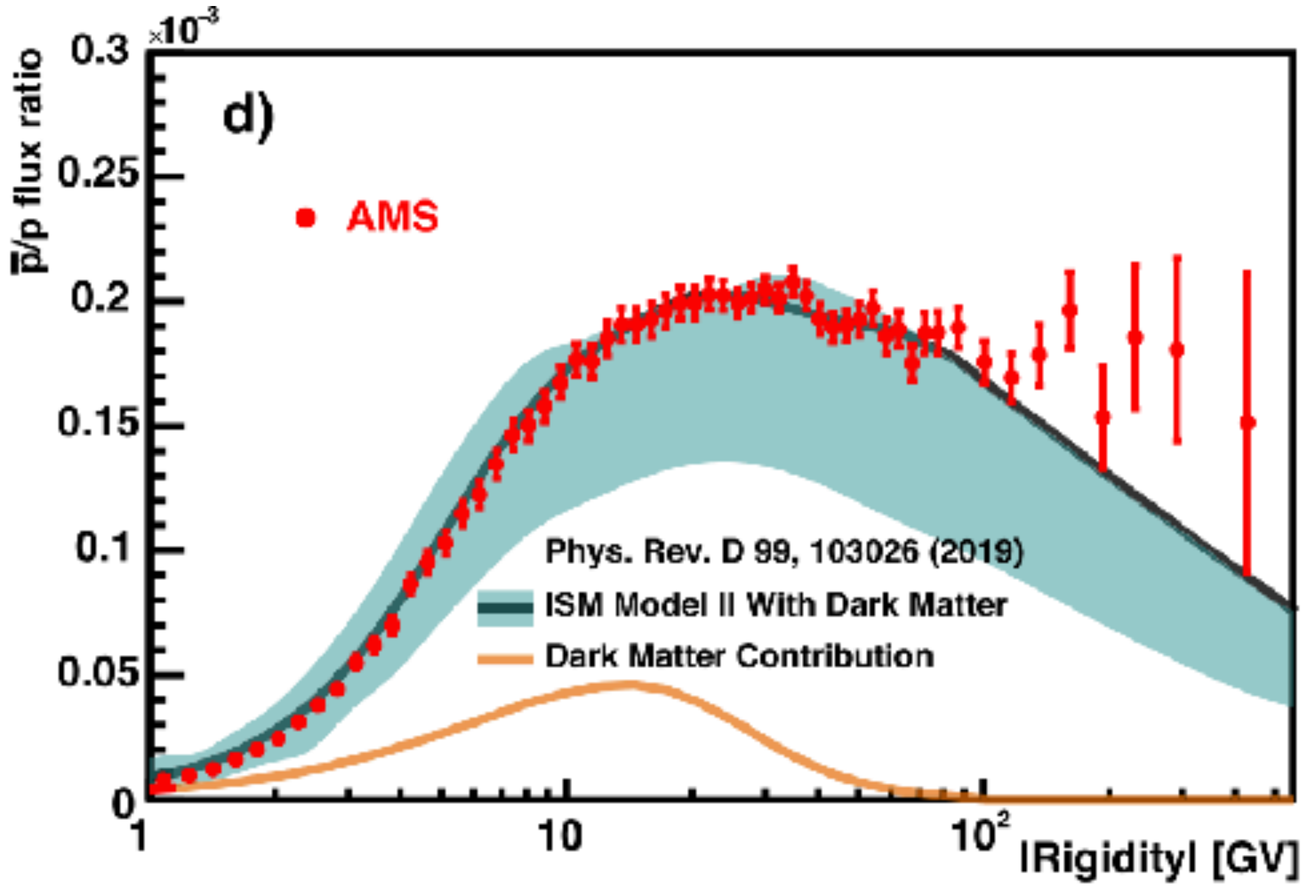

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**Rigidity @ AMBER: 10 - 60 GV
(Limited by RICH)**

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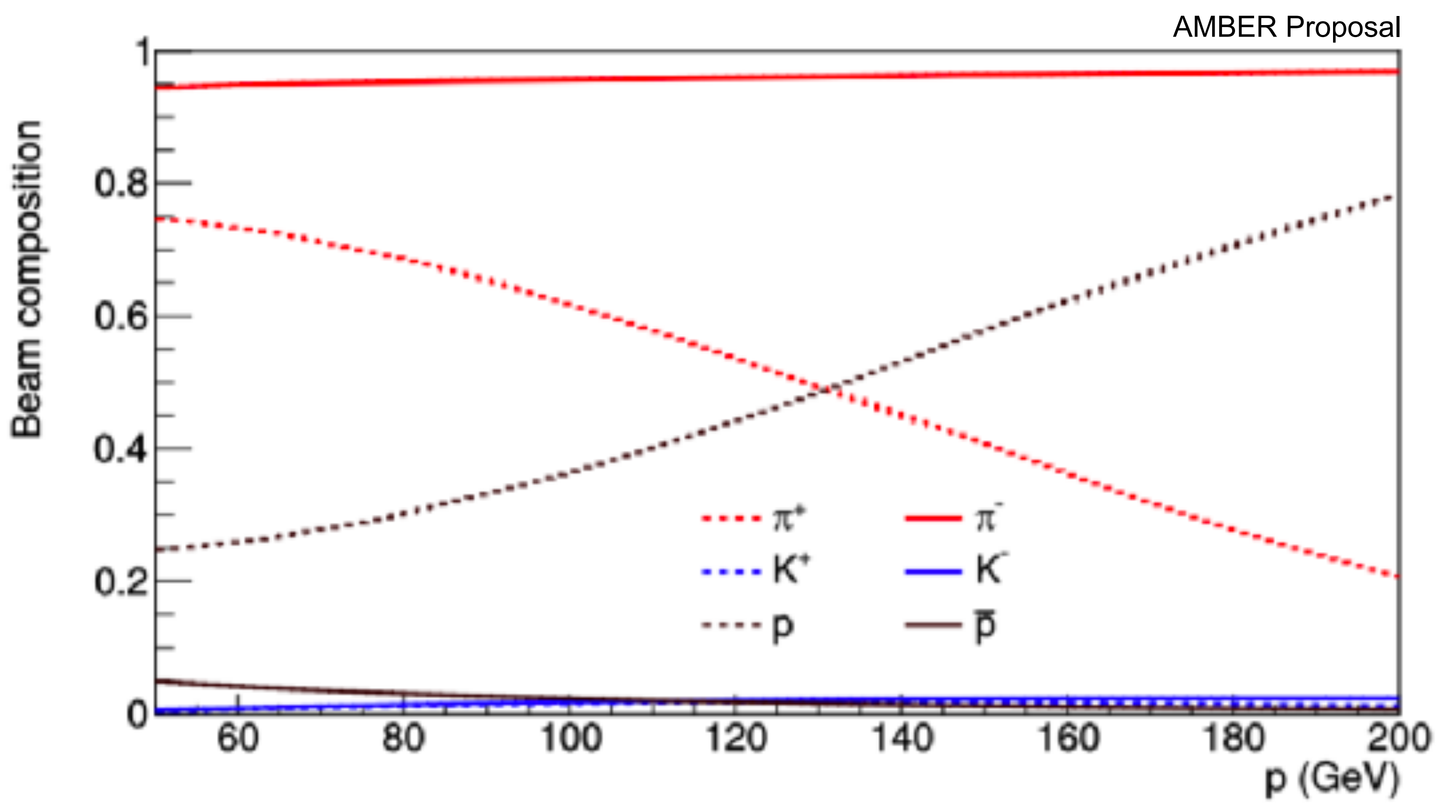
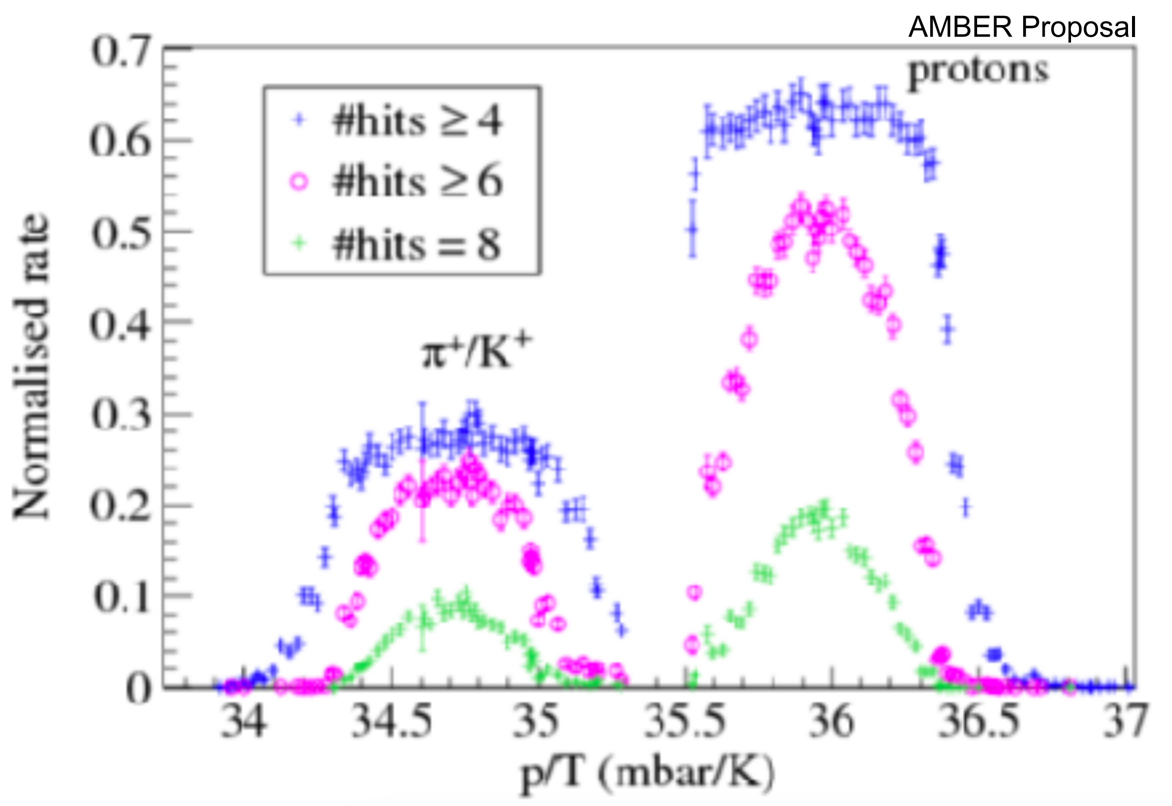
Experiment Requirements and (very) First Results

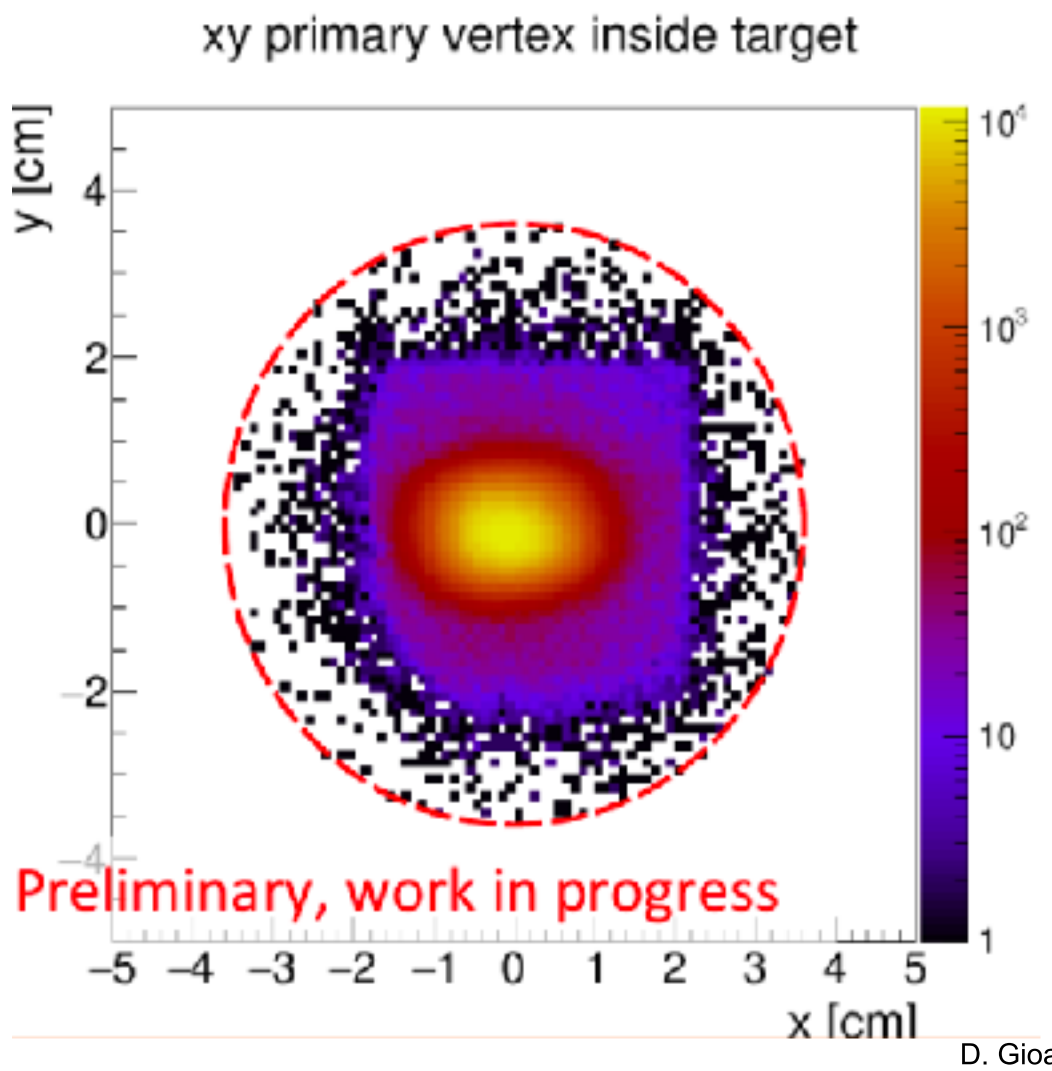
Beamline and Target

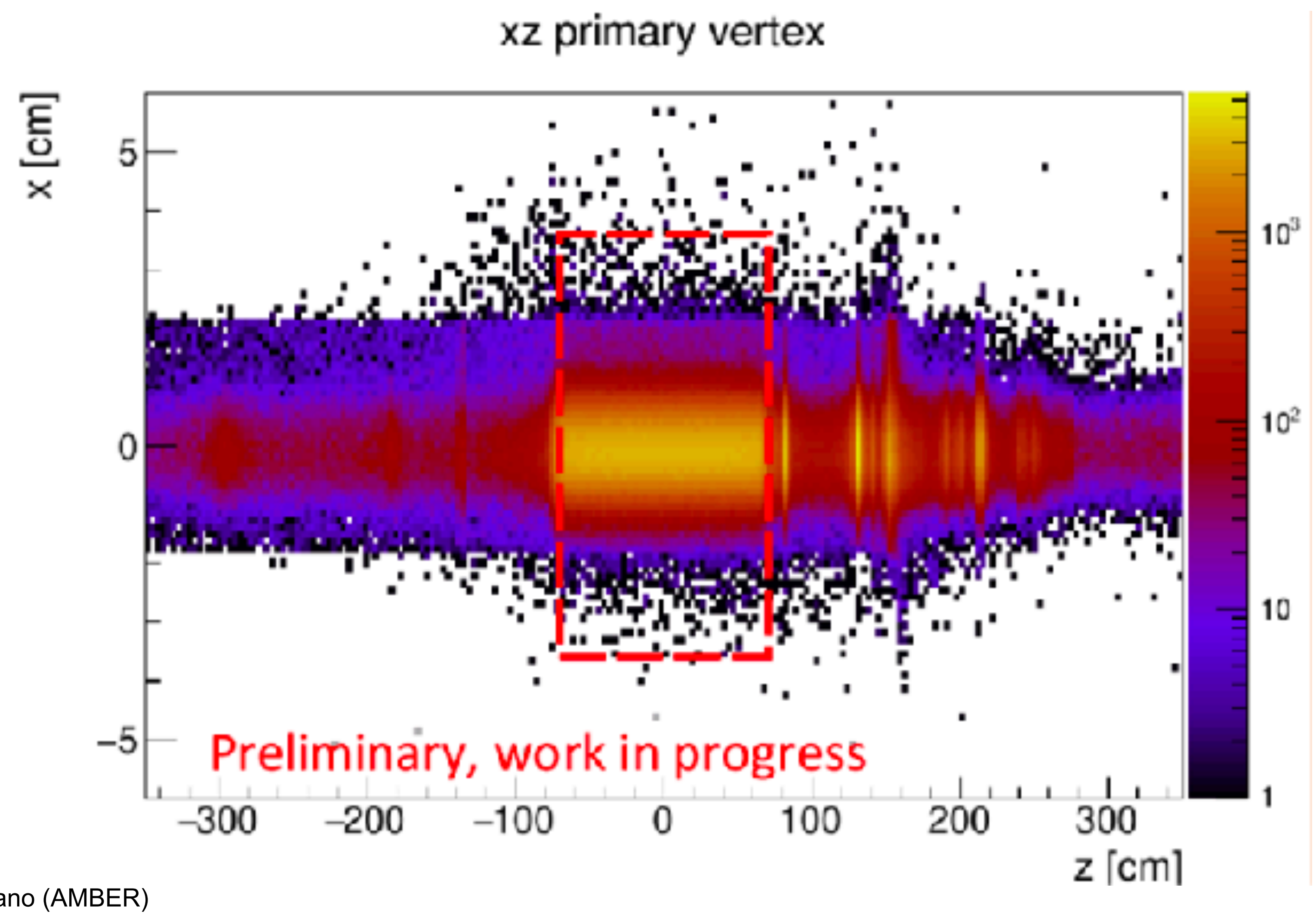
- AMBER at M2 beamline:
  - → 400 GeV proton beam impinging on 500 mm thick primary production Be-target
  - → Result: secondary hadron (p,K,pi) beam 60-280 GeV
  - → Important: beam PID via two CEDAR detectors installed 30 m upstream of the target region
  - → Proton PID efficiency > 90%, purity > 95%
  - → Avoid trigger prescaling: reduced beam intensity 5x10^5 p/s ("simple" beam trigger + beam killer was used)

- Target:
  - → Re-use of existing cryogenic target (of prev. measurement)
  - → 140 cm filled with liquid helium: p-He scattering
  - → For upcoming p-H and p-D a different target cell is foreseen (this year: start mid of April)









D. Gioardano (AMBER)

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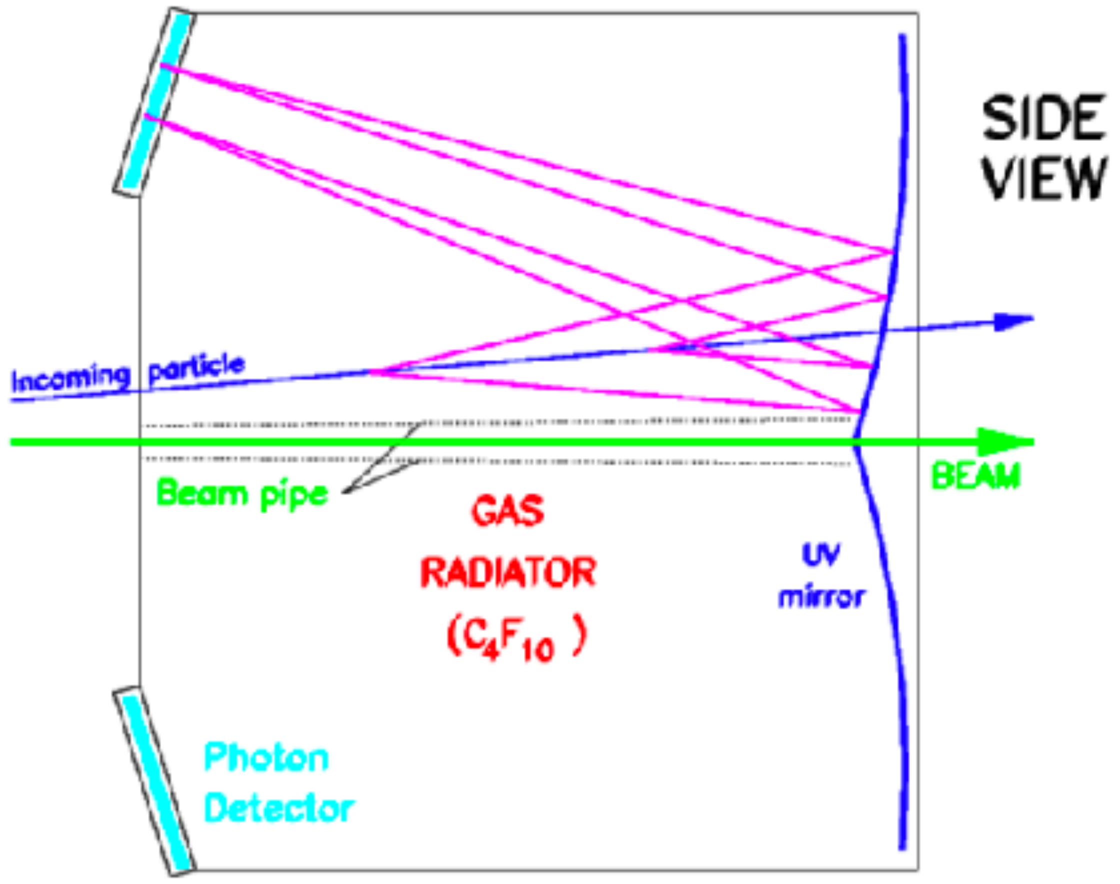
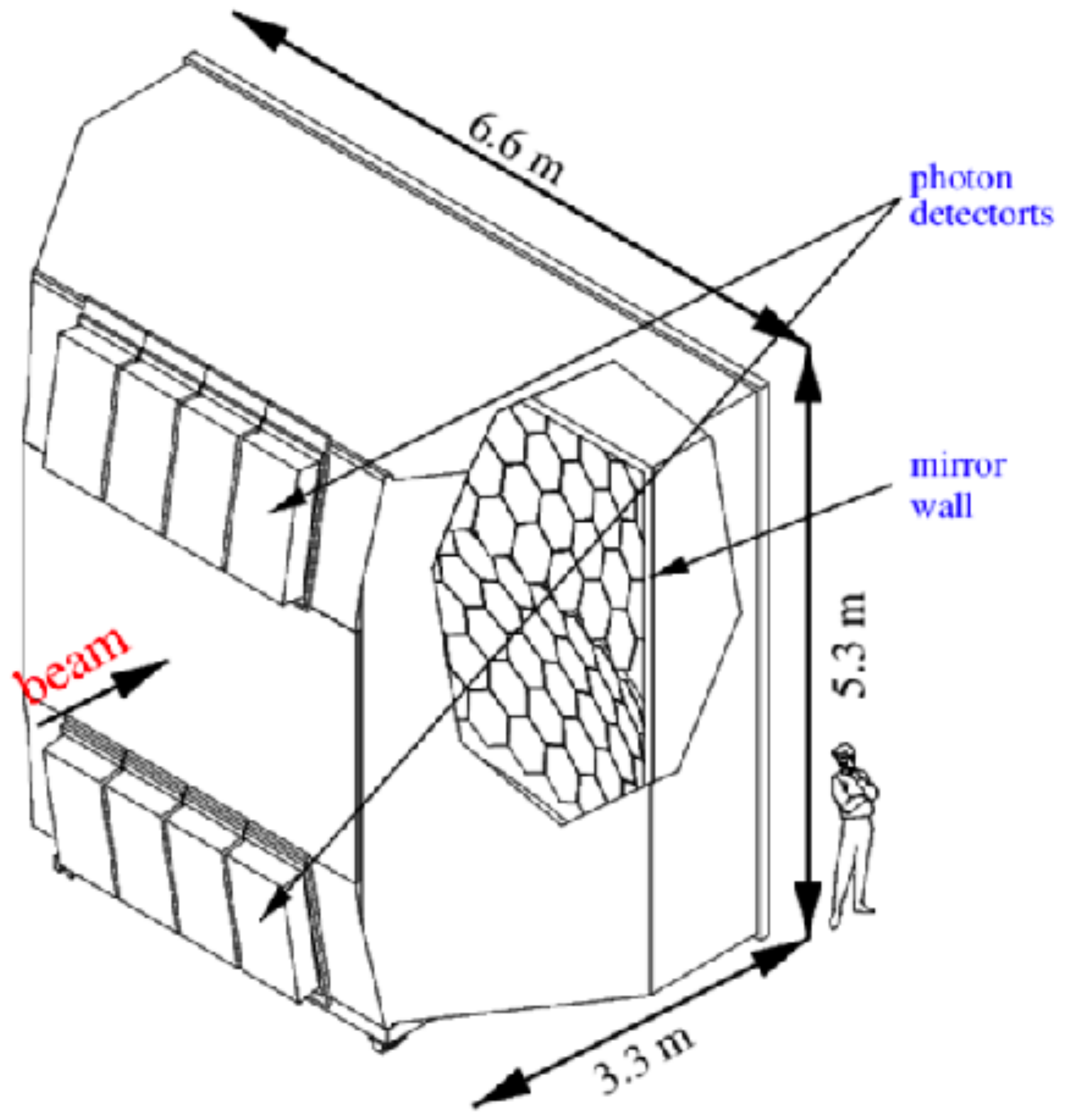
Experiment Requirements and (very) First Results

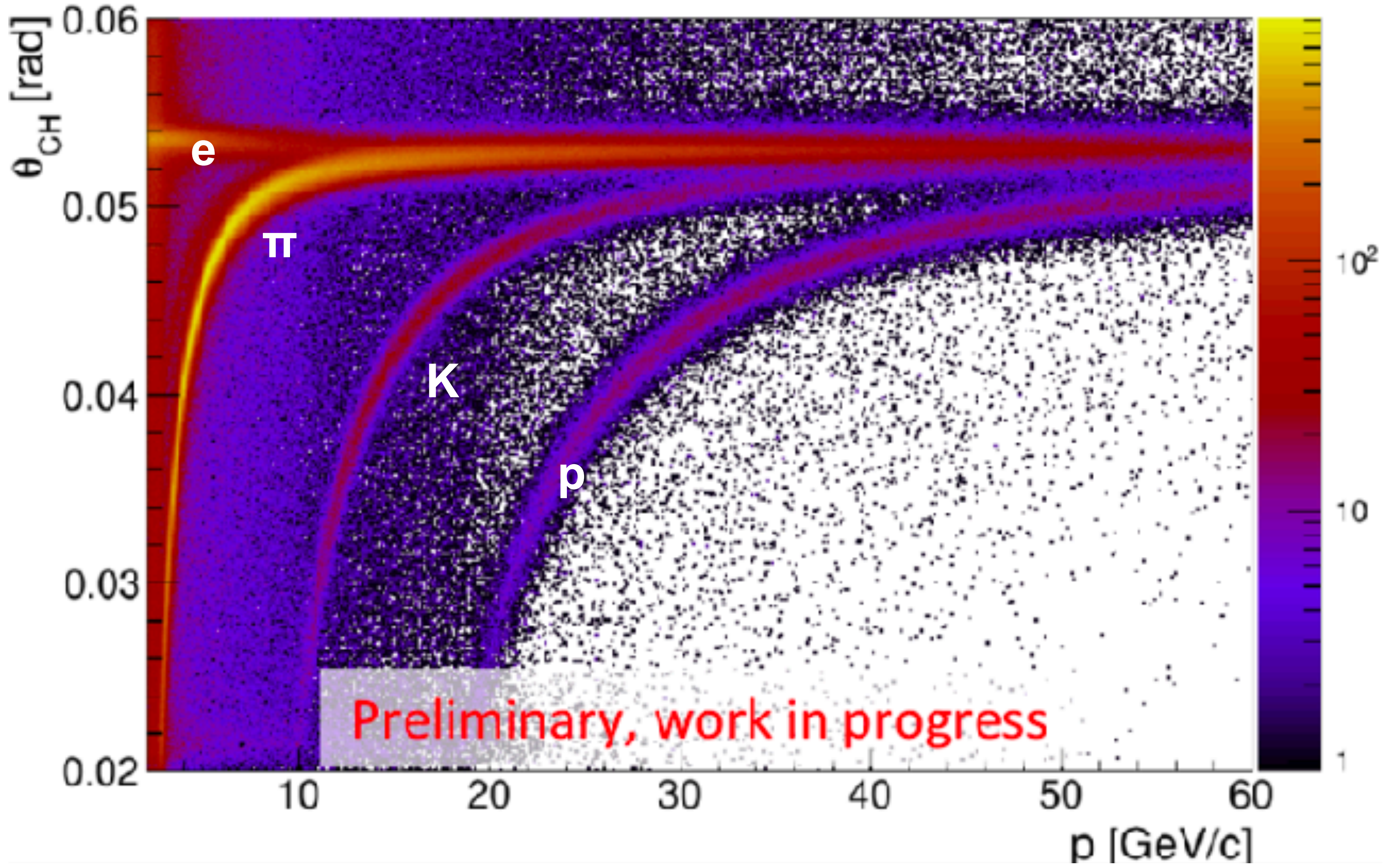
Particle Identification in Spectrometer

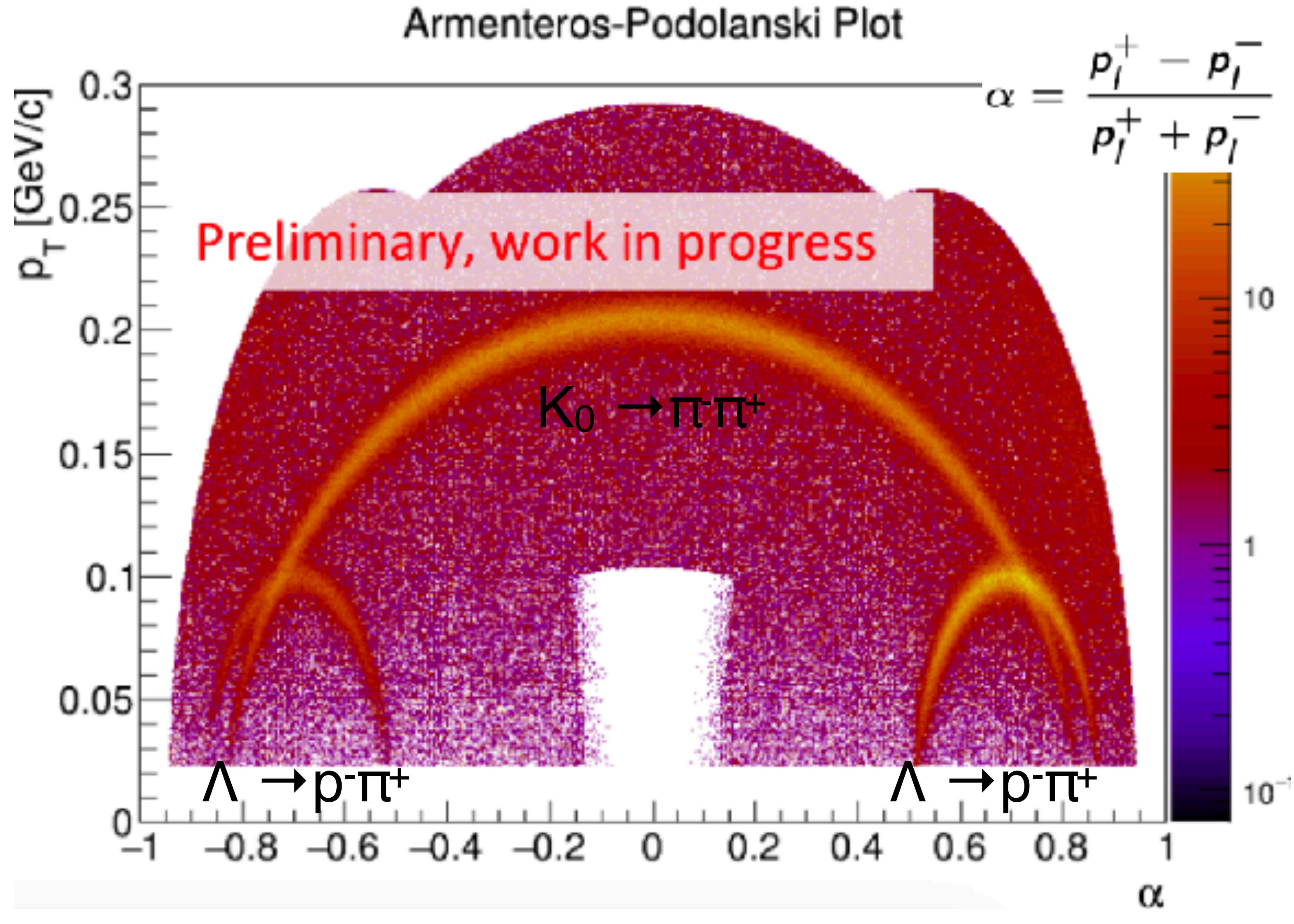
- Particle Identification:
  - → RICH1 detector: separation of π, K, p from 10 up to 60 GeV
  - → Ongoing: usage of so-called V0's to extract PID efficiencies

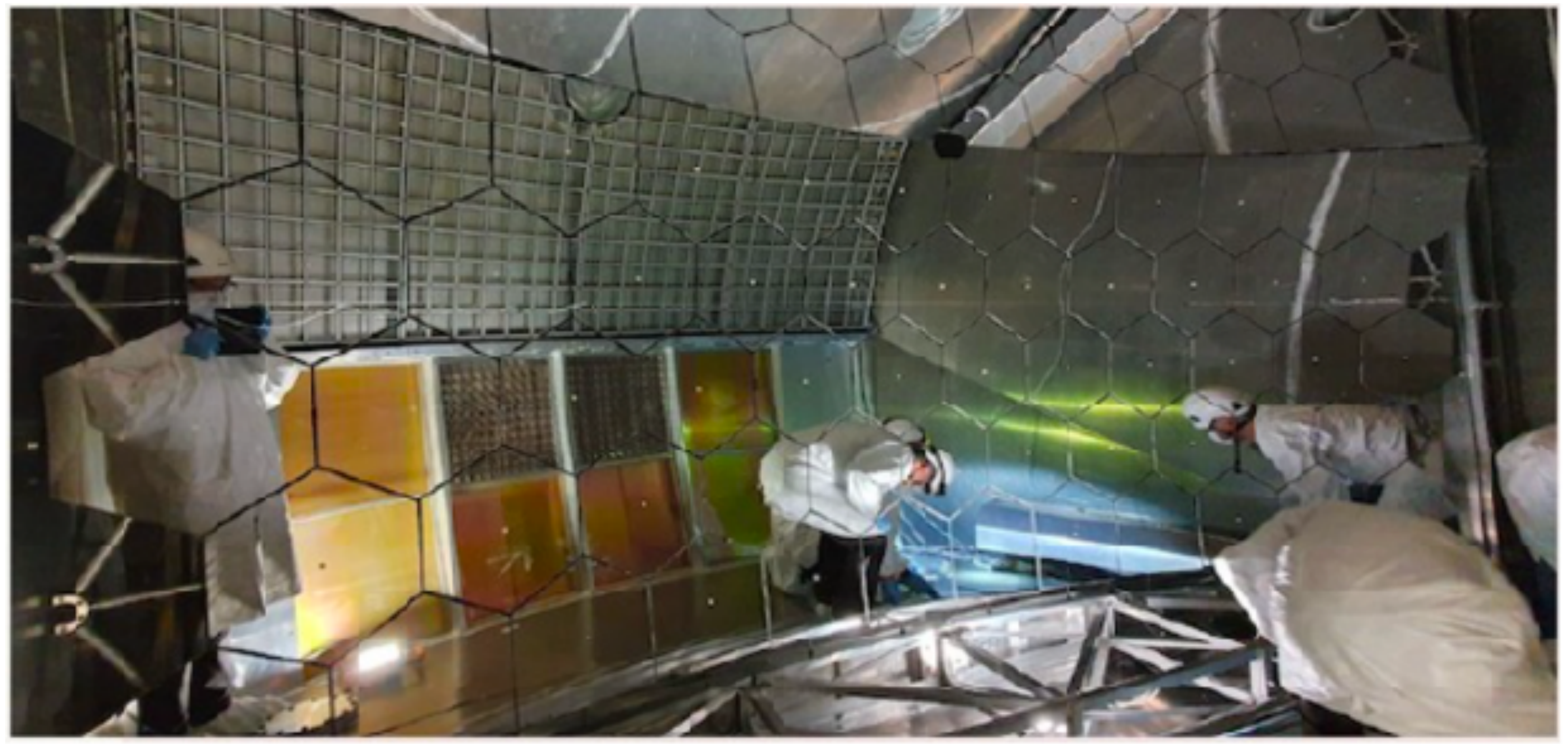
Hadrons	Decays	
	Channel	BR (%)
K_S	$\pi^+\pi^-$	(69.20 ± 0.05)
ϕ	K^+K^-	(48.9 ± 0.5)
$\Lambda(\bar{\Lambda})$	$p\pi^-\ \left(\bar{p}\pi^+\right)$	(63.9 ± 0.5)











Data collected so far and Future Steps

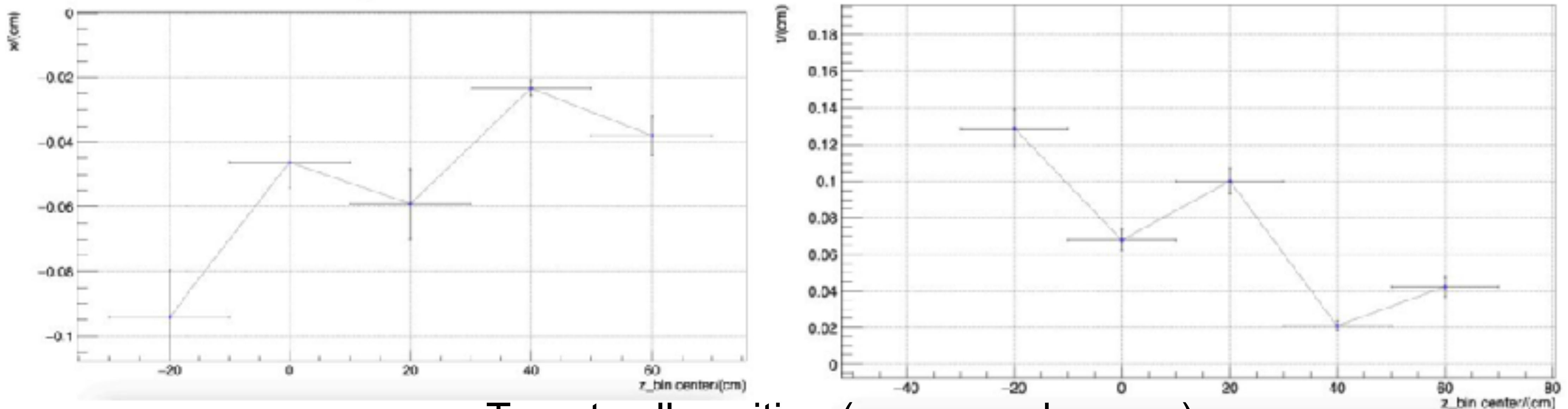
- Promising amount of various data in the momentum range of 60-250 GeV

- Still — ongoing work:
  - → Detector alignment in spectrometer: first version finished
  - → RICH efficiencies + refractive index extraction: almost finished
  - → Bad spill analysis (avoid problematic runs and spills): 10% rejection rate
  - → For cross-section: Trigger and DAQ Dead Time required
  - → Target position verification
  - → Monte Carlo — still some work to do:
    - → Beam parametrisation / beam file extraction: ready
    - → Detector efficiency description: ready
    - → Update of geometry description done: mainly RICH + target

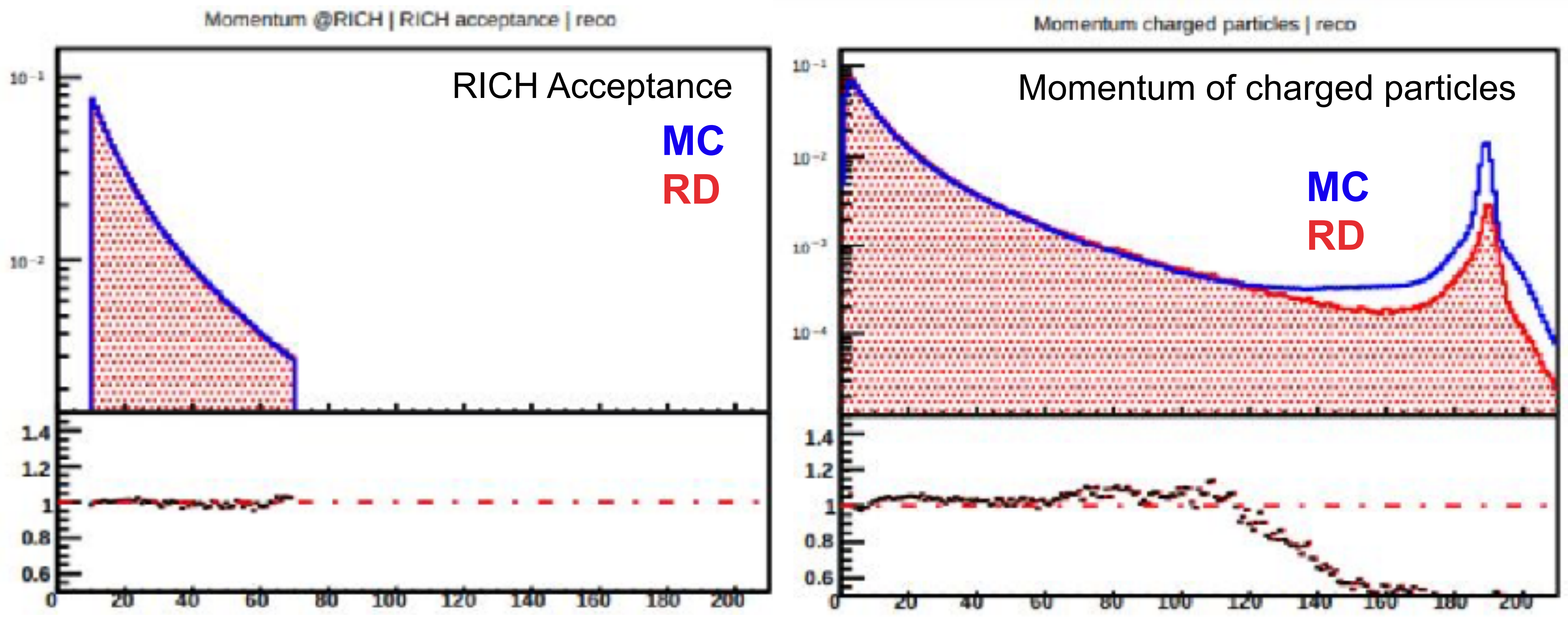
- Similar work steps required for 2024 data

- Preparations for targets (H,D) ongoing: Beam time starts mid of April 2024

Beam momentum (GeV/c)	Collision energy ($\sqrt{s_{NN}}$) (GeV)	Start Date	End Date	Number of spills
60	10.7	24.05	30.05	37000
80	12.3	17.06	25.06	13400
100	13.8	01.06	11.06	13700
160	17.3	14.06	17.06	8500
190	18.9	19.05	24.05	11000
250	21.7	11.06	14.06	7300



Target cell position (x vs. z and y vs. z)



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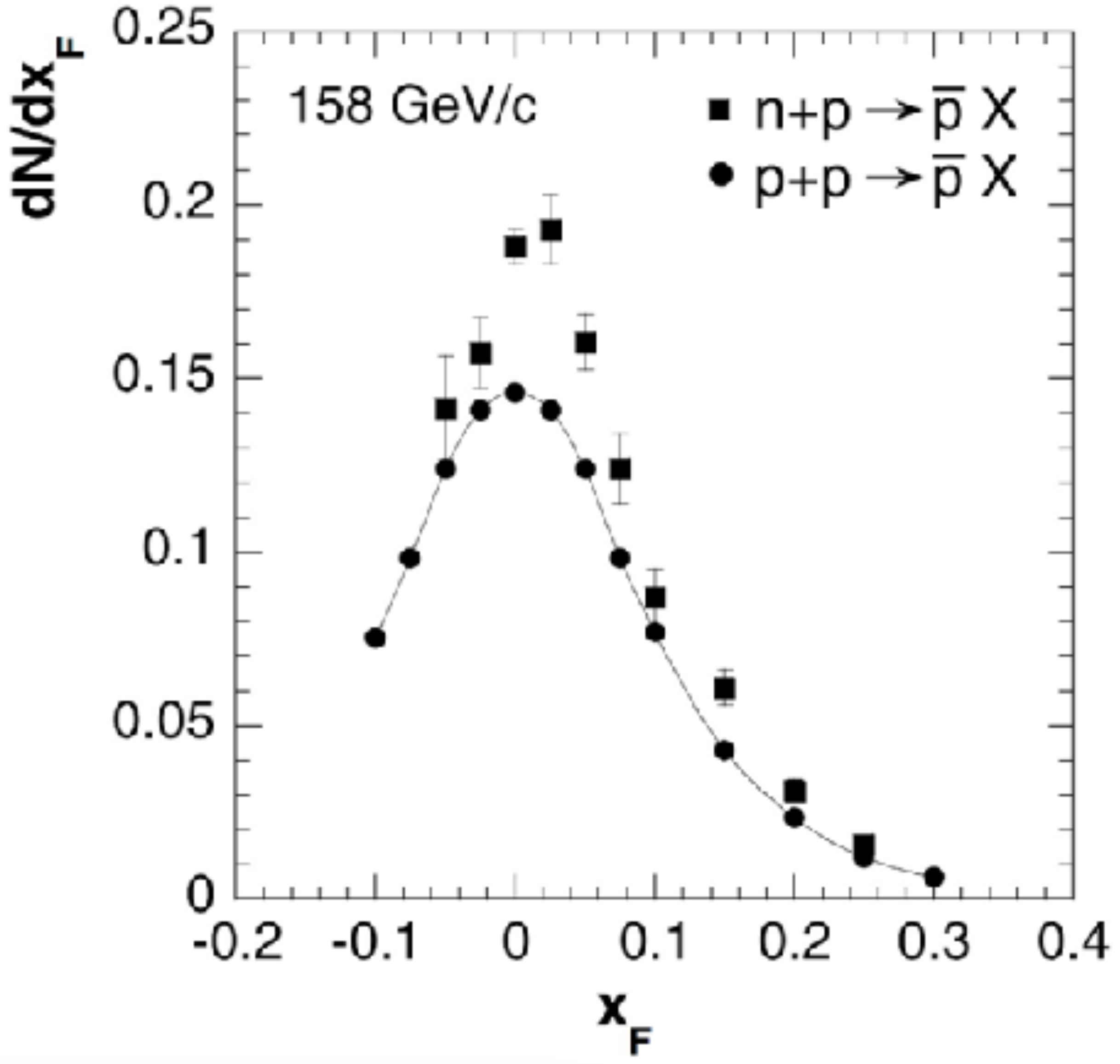
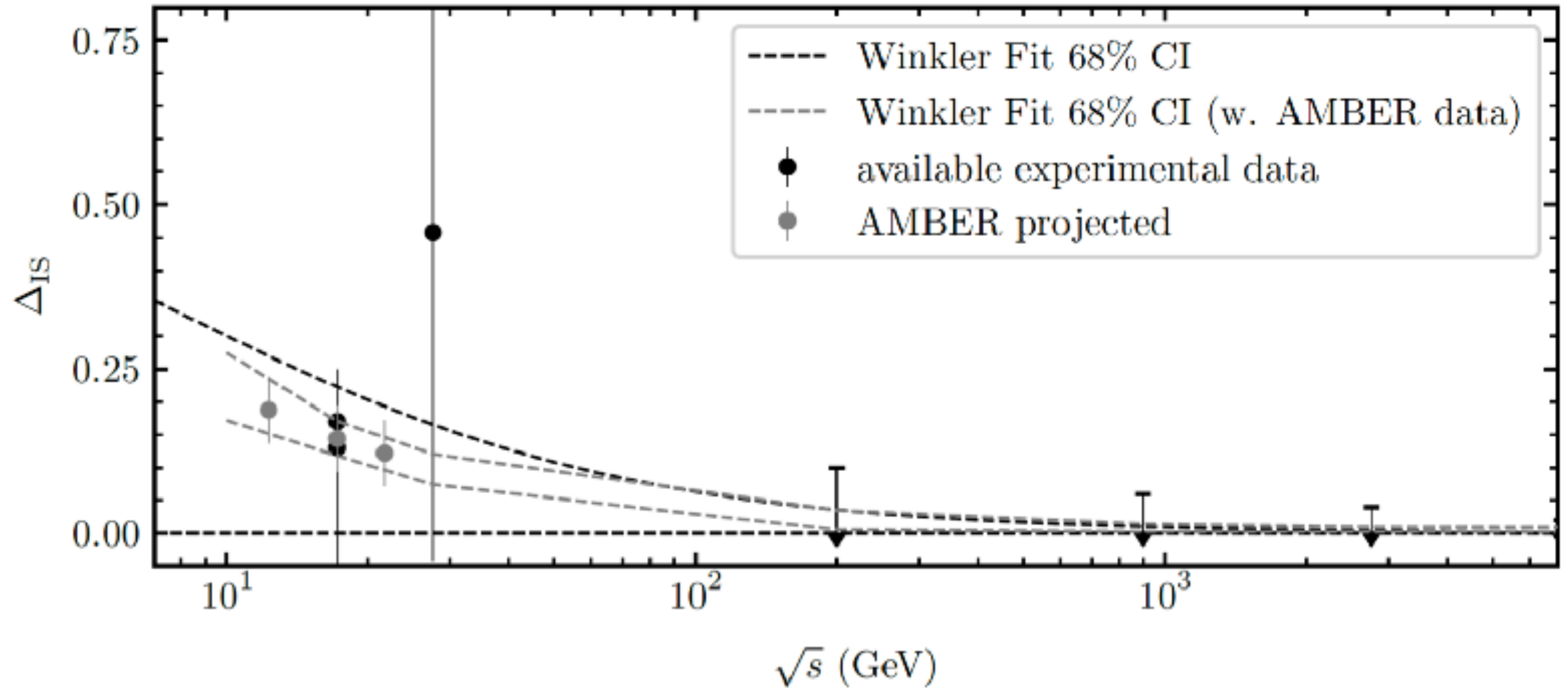
Perspective: Measurement of the Isospin Asymmetry

- Comparison of antiproton vs antineutron: $p + p \rightarrow \bar{p}$ + X to $p + p \rightarrow \bar{n}$ + X:
  $\rightarrow$ Alternative via flipped reaction: $p + n \rightarrow \bar{p} + X$

- First comparison done by NA49 using a deuteron beam and hydrogen target
  $\rightarrow$ tagging the spectator proton: distinguish *np* and *pp* reactions
  $\rightarrow$ larger $\bar{p}$ production in *np* compared to *pp* reactions
  $\rightarrow$ Difference in $x_F = p_L/p_{L,max}$ observed



- AMBER: repeat measurement! (It will be simply included in the data)
  $\rightarrow$ Use proton beam instead of deuterium and use different targets, i.e. Hydrogen and Deuterium
    $\rightarrow$ Extract contribution from *pn* collisions via $f^{pn}_{\bar{p}} = f^{pD}_{\bar{p}} - f^{pp}_{\bar{p}}$
    $\rightarrow$ Advantage: only change in target and not spectrometer
    $\rightarrow$ Lack of data around $\sqrt{s} \approx 10$ GeV — add AMBER data!
    $\rightarrow$ Constrain possible isospin asym. to 10 % a precision of 3%-5% required



Physics Program… and a bit of History

AMBER Physics program in the upcoming years

Run 3
2021 - 2025

Run 4
2029 - 2032

- <u>Phase I (approved):</u>
  → Anti-proton production cross-section
  → **Proton charge radius**
  → Pion and kaon structure functions

- <u>Phase II (Proposal submission ongoing):</u>
  → Strange-meson spectroscopy
  → Kaon polarisability
  → Prompt-photon production

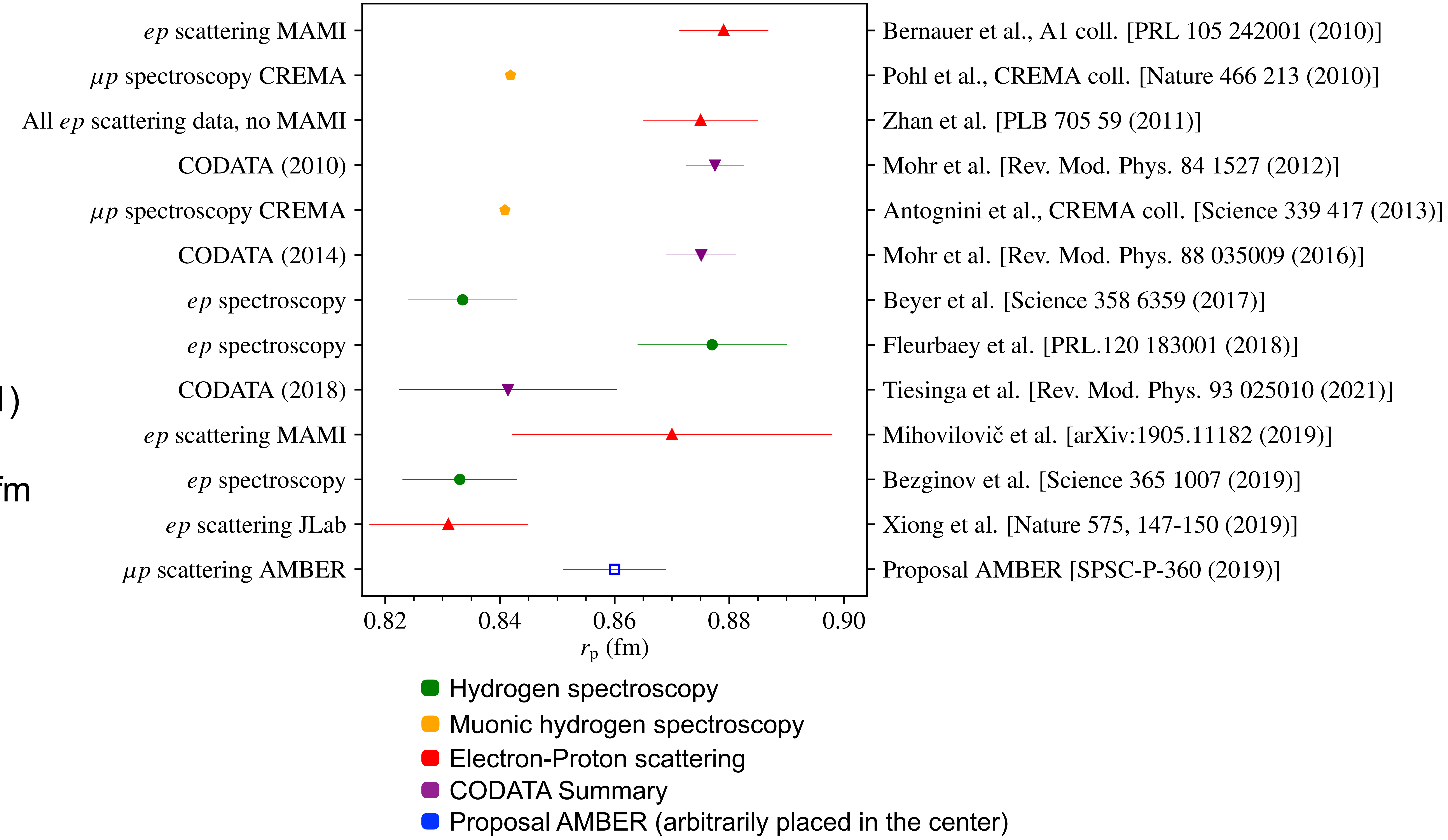
2017 Initial proposal by German groups → **2018** Proton Charge Radius: Feasibility Test → **2018** AMBER: Letter of Intent → **2019** AMBER: Proposal → **2021** Proton Charge Radius: Pilot Run (TPC)

Phase I - The Proton Charge Radius

Data from spectroscopy and electron-proton scattering

Several experiments with different approaches measured the proton radius with contradicting results.

- Hydrogen spectroscopy:
  - → Muonic or ordinary hydrogen
  - → Highest precision using laser spectroscopy
  - → Favoured value of (0.841±0.001) fm
- Elastic electron-proton scattering:
  - → Measurement using momentum transfer
  - → Recent data: MAMI A1 (2010) or JLab (2011)
  - → Favoured value of (0.879±0.008) fm
  - → New in 2019: PRad value of (0.831±0.014) fm
- Two significantly different values obtained
  - → The proton-radius puzzle



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Upcoming Experiments Addressing the Puzzle

New data from lepton-proton scattering
Several proposed and preparing experiments to solve the puzzle in the next years.

- **PRad**: electron-proton with E_e = 1.1/2.2 GeV
  → Recent publication of results: smaller value
  → PRad2: detector upgrade planned (run in 2025?)
- **MAMI**: electron-proton with E_e < 750 MeV
  → Two new experiments in preparation
- **MAGIX-MESA**: electron-proton with E_e < 150 MeV
  → Electric and magnetic form factor
  → New accelerator - start in 2024
- **MUSE**: muon/electron-proton with $E_{e,\mu}$ < 140 MeV
  → Comparison of electron and muon scattering
  → Data production ongoing, more data to come
- **ULQ2/Tokuha:** electron-proton E_e = 20 – 60 MeV
- **ProRad@PRAE:** electron-protons E_e = 30 – 70 MeV

Proton Radius Experiment at Jefferson Lab

PRoton Radius

ULQ² collaboration
(Ultra-Low Q²)

- **Missing**: muon-proton with E_μ of $\mathcal{O}$(10 - 100 GeV)

→ Data for high-energy elastic muon-proton scattering
→ Test of lepton universality
→ Different systematics compared to others
→ **Proton Radius Measurement @ AMBER**

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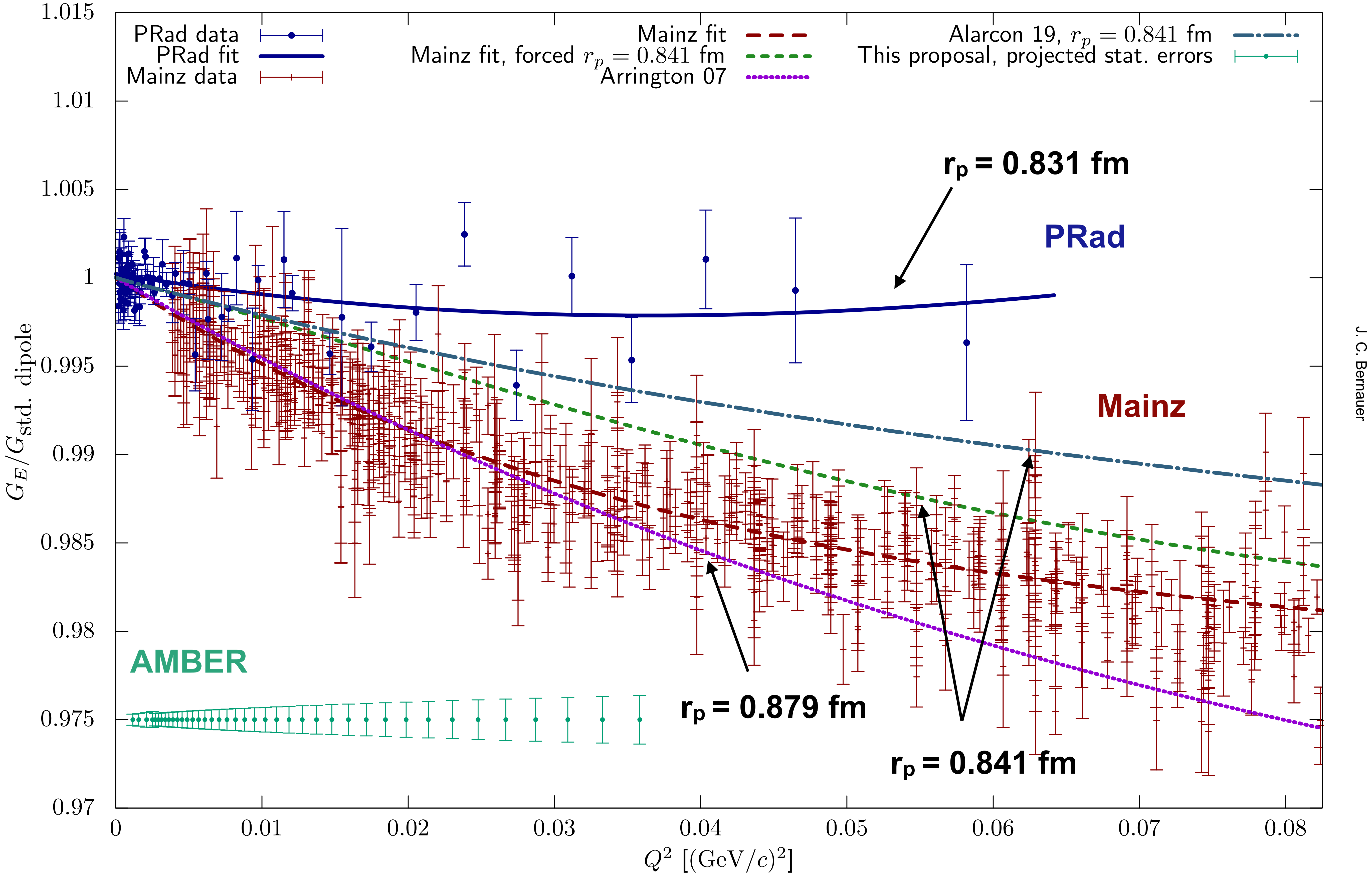
Proposal of a New Measurement

High-energy elastic muon-proton scattering

Measurement of the cross-section of elastic muon-proton scattering using the *CERN M2* beamline. (SPSC-P-360)

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

- Measure as close as possible to $Q^2 \to 0$
  → suppress influences from higher order form-factor terms
  → high-energy $\mathcal{O}$(10 - 100 GeV) — Cross-section ∝ G_E^2
- Disagreement on experimental data: PRad and MAMI
- Sufficient range to determine radius:
  → Aimed precision of below 1 %
  → Aimed Q^2-range: 0.001 - 0.04 GeV^2/c^2
- Below Q^2 = 0.001 GeV^2/c^2:
  → Deviation from point-like proton level of $\mathcal{O}(10^{-3})$
  → Smaller than unavoidable systematic effects
- Above Q^2 = 0.04 GeV^2/c^2:
  → Non-linearity of the cross section
  → Predominant source of uncertainty



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Layout of Proton-Radius Measurement

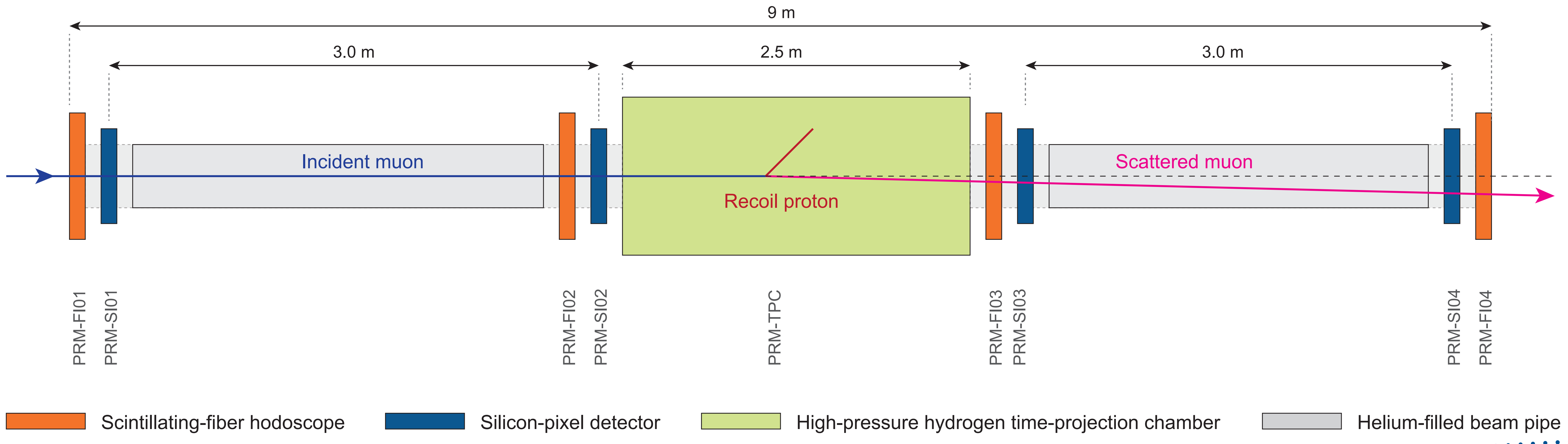
Measurement of low-Q^2 elastic-scattering events
New approach: Combined measurement of low-energetic recoil-protons and scattered muons at small scattering-angles.

- Time-Projection-Chamber (TPC) as an active target to measure recoil protons (beam rate: 2 MHz)
- Silicon trackers along long leaver-arm to measure small scattering-angles
- Scintillating fibers for timing and tracking

→ Combined in an Unified Tracking Station (UTS)

- New continuously-running DAQ required (slow + fast detectors)

- *AMBER* spectrometer:
  → Momentum measurement of scattered muon
  → Radiative background using electromagnetic calorimeter
  → Muon identification with muon filter and hodoscope



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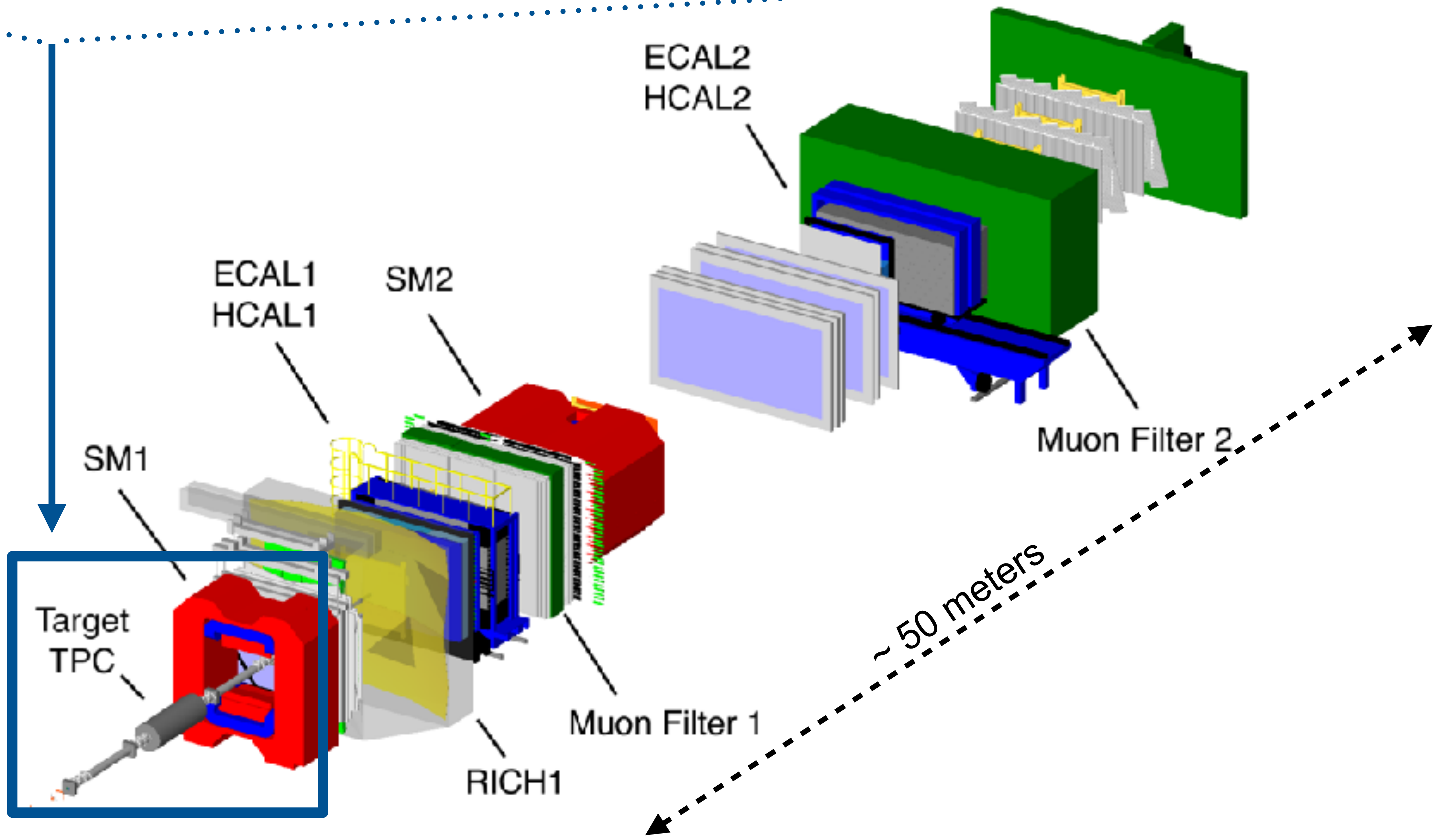

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Control of Systematic Effects

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

> Redundant measurement to control systematics
> → Measurement of scattered muon kinematics

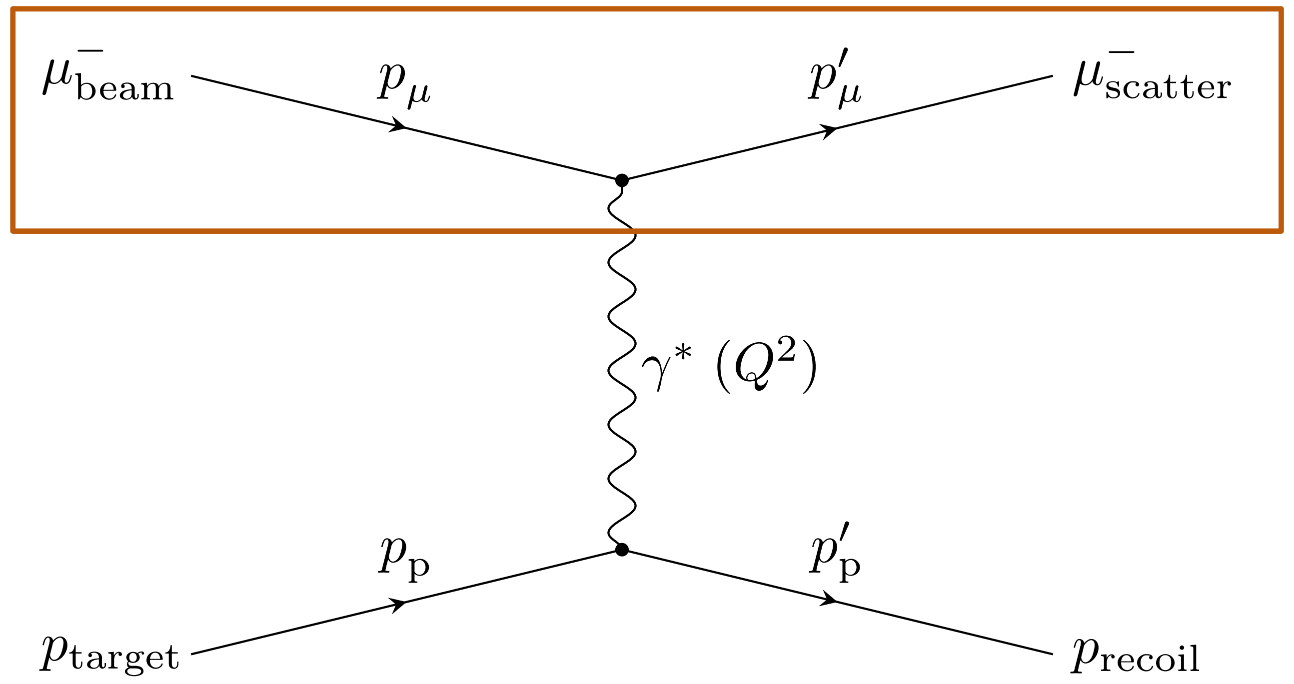
- Lepton-proton scattering accompanied by bremsstrahlung

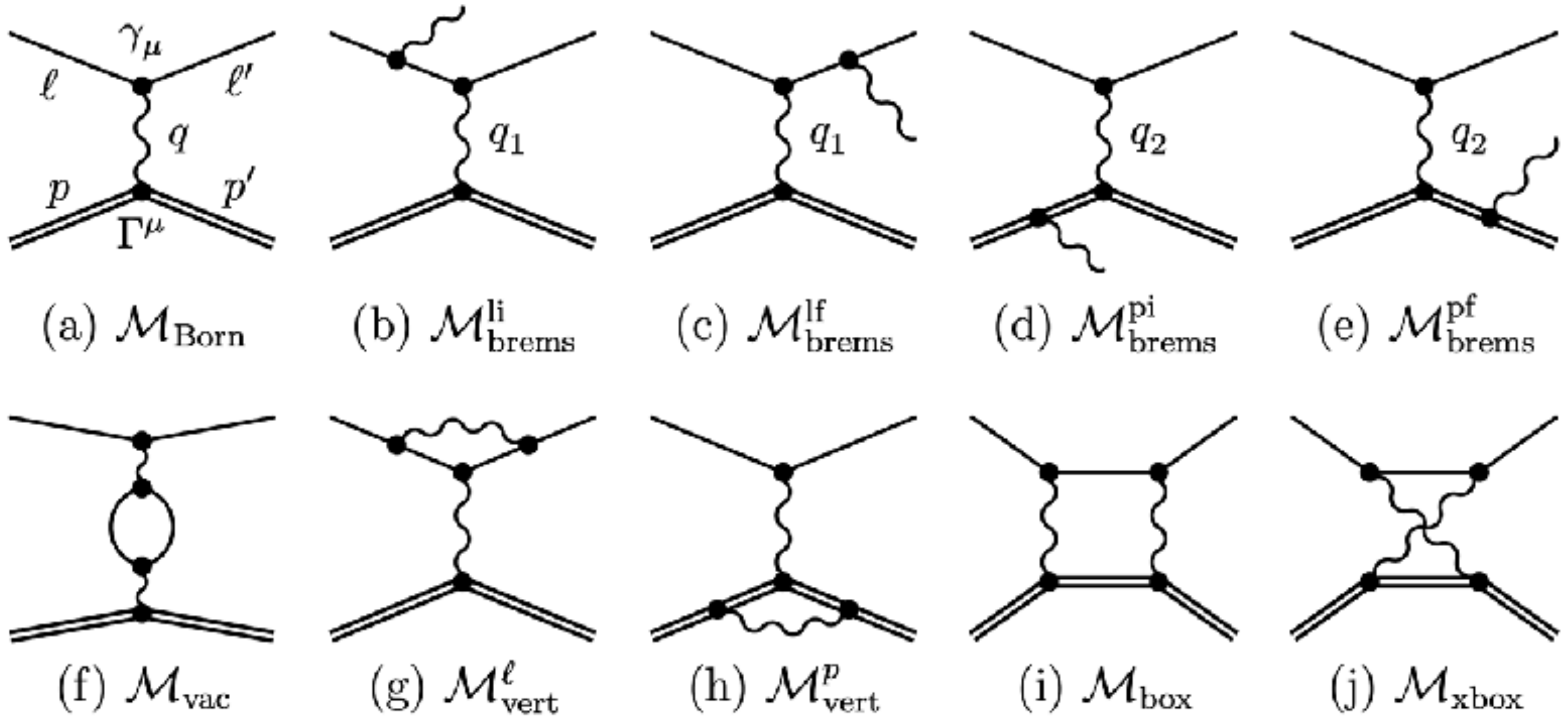
→ NLO process on $\mathcal{O}(10^{-4})$ level for $E_\gamma > 500$ MeV

→ Distortion of Q^2-spectrum

→ For muons: lower radiative corrections compared to electrons

> Usage of *AMBER* spectrometer — tracking and calorimetry
> → Understanding of background
> → Muon momentum measurement





ESEPP arXiv:1401.2959

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Detection of Low-Q² Recoil-Protons

Pressurised hydrogen active-target TPC
Direct recoil-proton momentum measurement with active target.

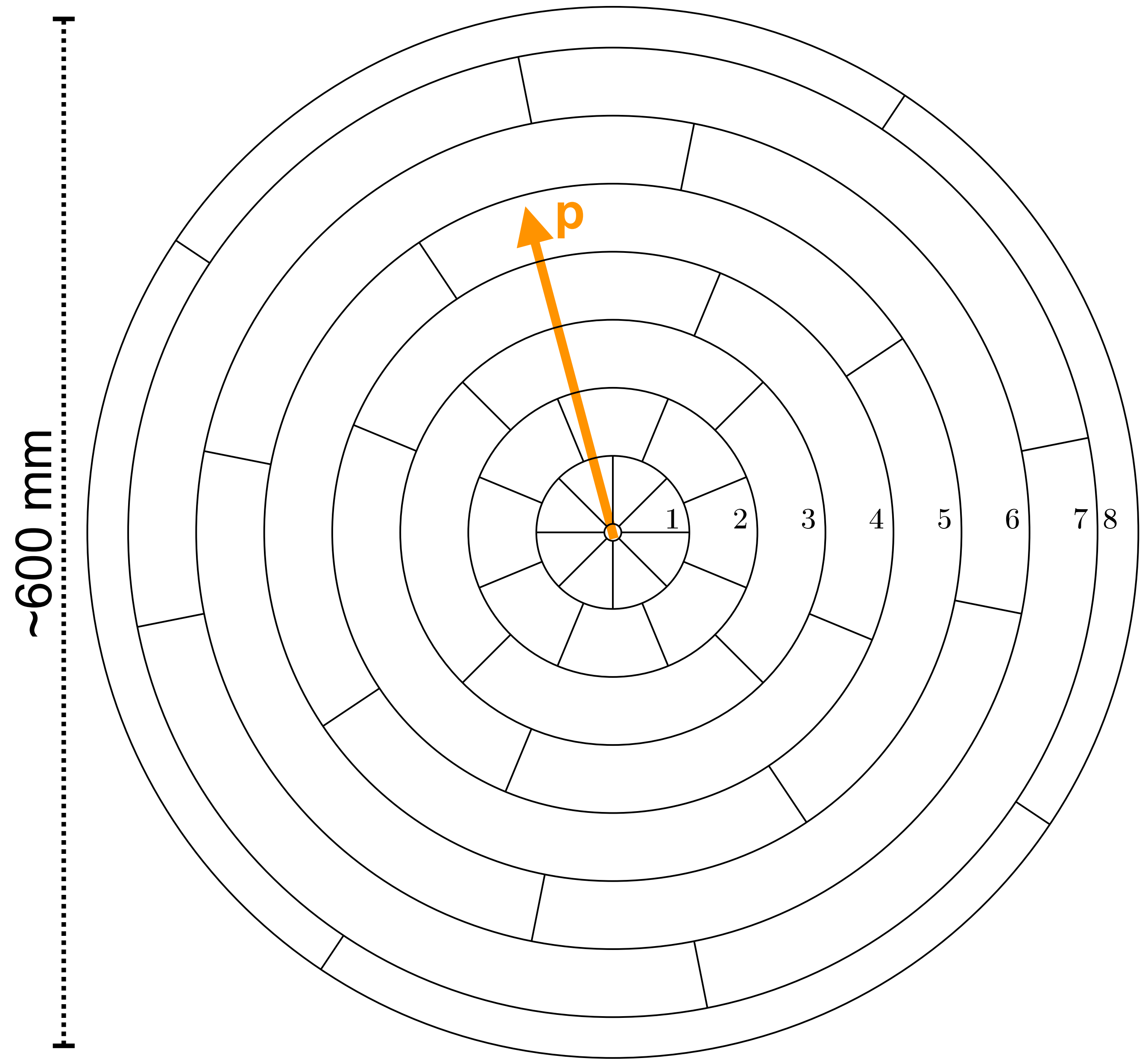
- 4x 40 cm long drift cells — Preliminary: start with a 2-cell type
  → Hydrogen pressure up to 20 bar
  → Direct energy measurement without amplification

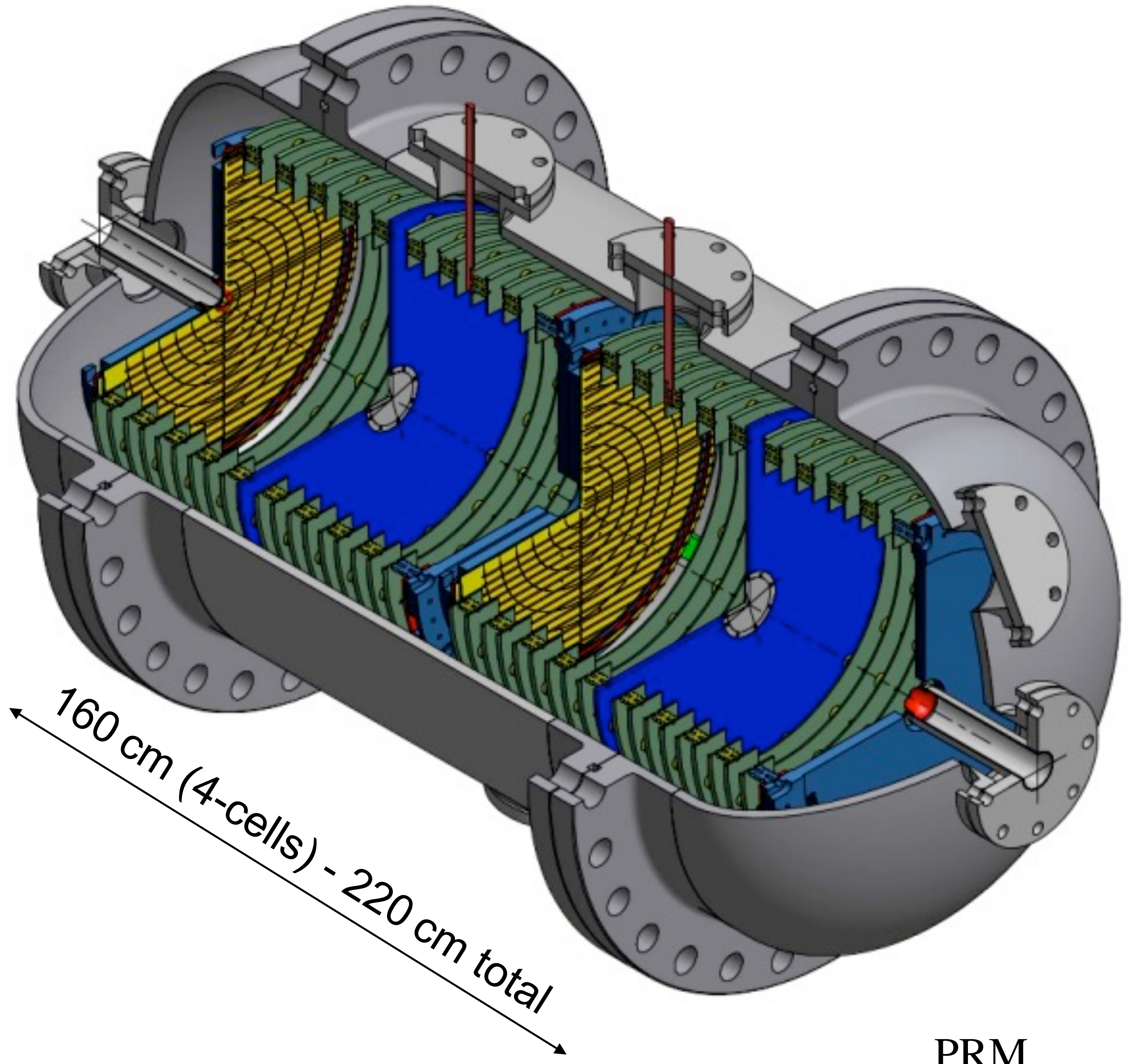
- Segmented readout plane for each cell:
  → Spatial and angular resolution (both θ and φ)

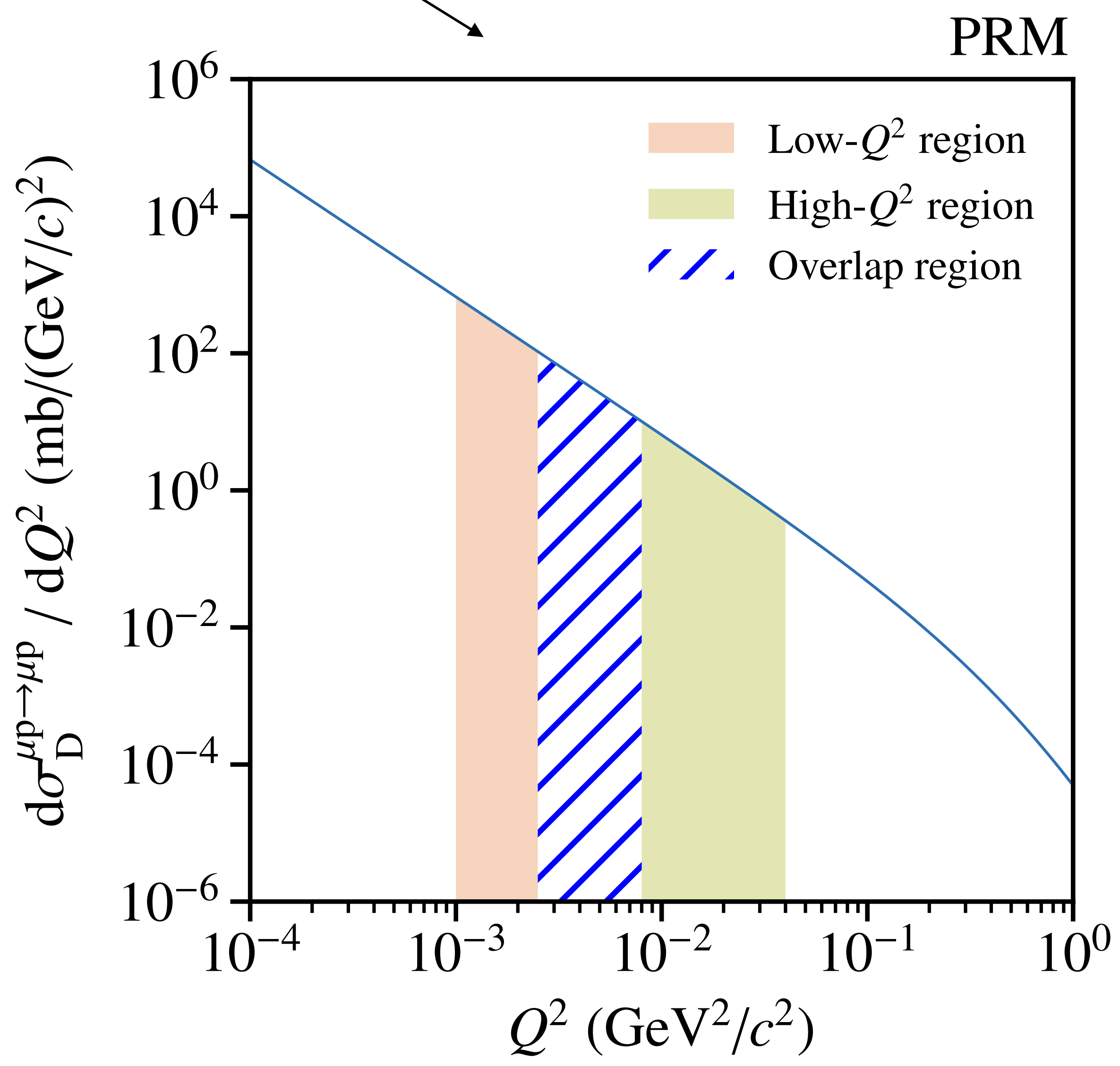
- Transmitted Q^2 affects range of recoil proton:
  → Recoil-proton ranges of 2 - 300 mm (and more)

- Active target: beam induced ionisation noise
  → Central beam region mostly affected

- Measurement at two pressure settings required:
  → 4 bar ($Q^2 < 0.0025$ GeV$^2/c^2$)
  → 20 bar (0.001 GeV$^2/c^2 < Q^2 < 0.04$ GeV$^2/c^2$)
  → Low-pressure region to correct noise at small-Q^2 events
  → Two overlapping datasets (estimate: 6 + 27 million events)
  → Energy resolution < 6 % required for aimed precision < 1 %







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Small Scattering-Angle Tracking

Unified Tracking Station — UTS

Dedicated station with high-resolution silicon pixel-detectors and scintillating fibers for muon tracking in the target area.

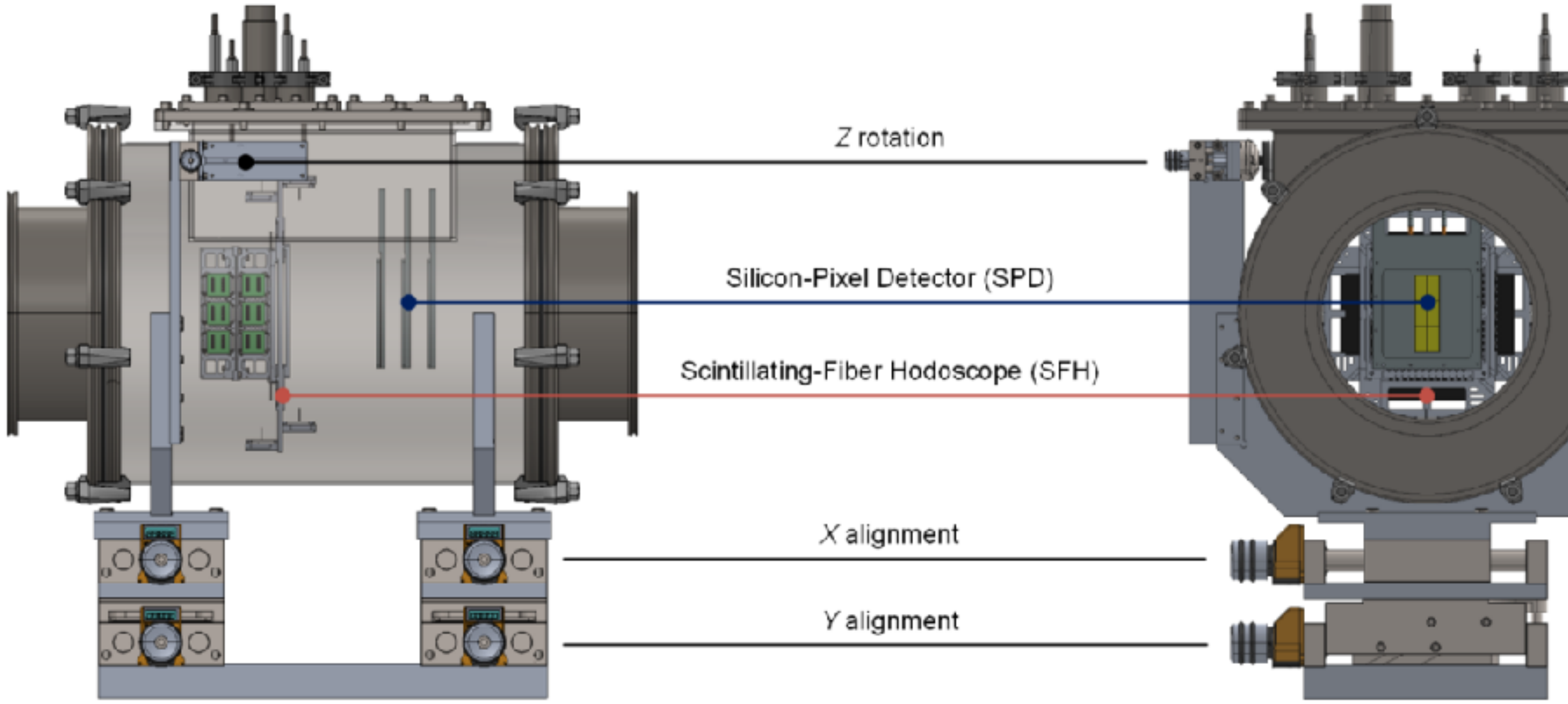
- Four stations in total planned
  → Two upstream and two downstream surrounding the TPC

- Three Silicon Pixel-Detector (SPD) planes:
  → Based on ALPIDE chips in covering an area of 9 x 9 cm²
  → Spatial resolution of about 8 μm with 5-10 μs integration time
  → Problem of pile-up at larger beam rates

- Four Scintillating-Fiber Hodoscope (SFH) planes: Karl
  → Based on 500 μm thick fibers with SiPM readout (9.6 x 9.6 cm²)
  → Provide hit-time information for the SPD to disentangle pile-up

- Simplistic hit-time association between SFH and SPD shows promising efficiencies of > 99 % up to 10 MHz — further improved with full tracking

- Optimised material budget per station of about $X/X_0 = 1.3$ %



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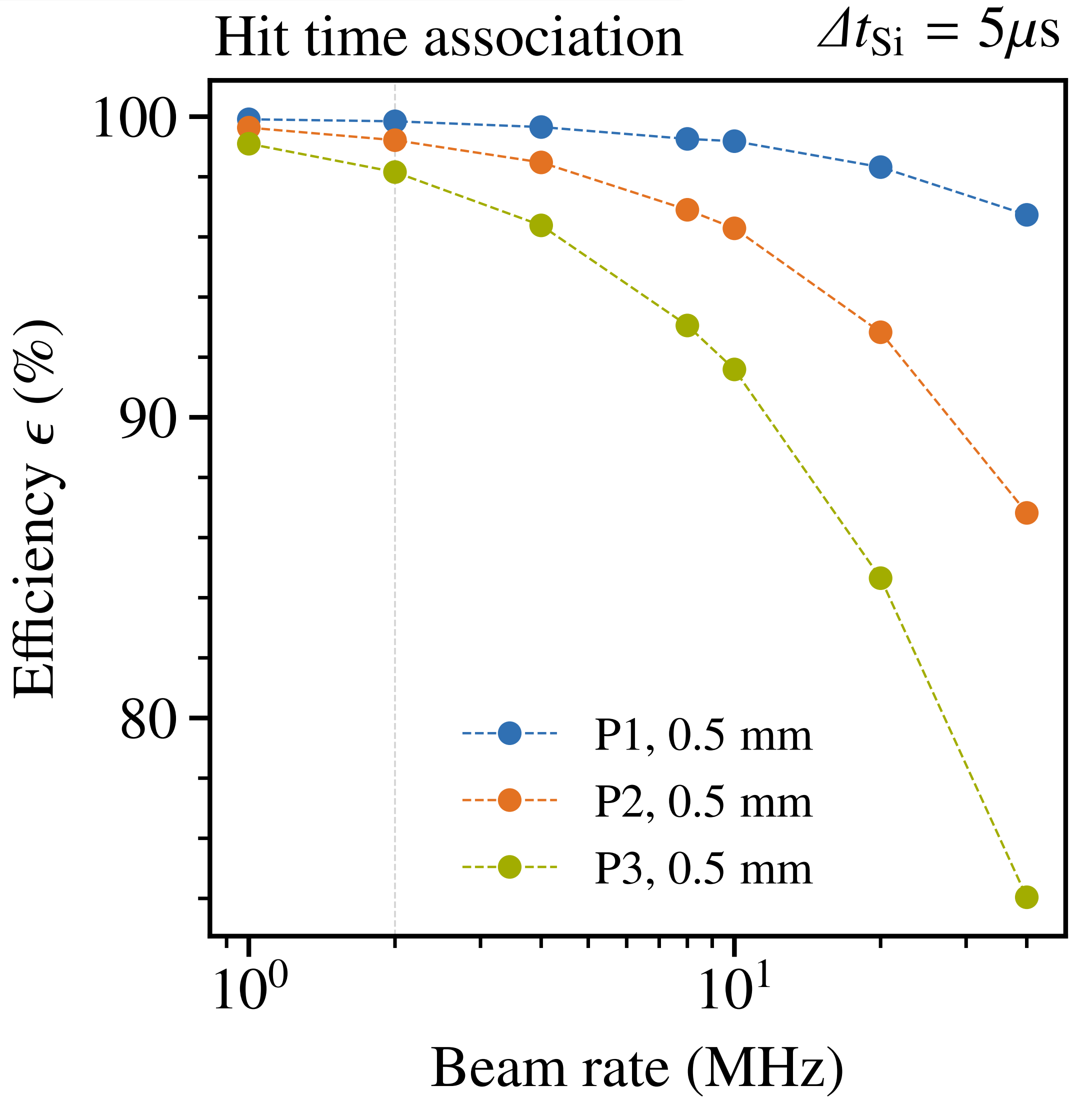

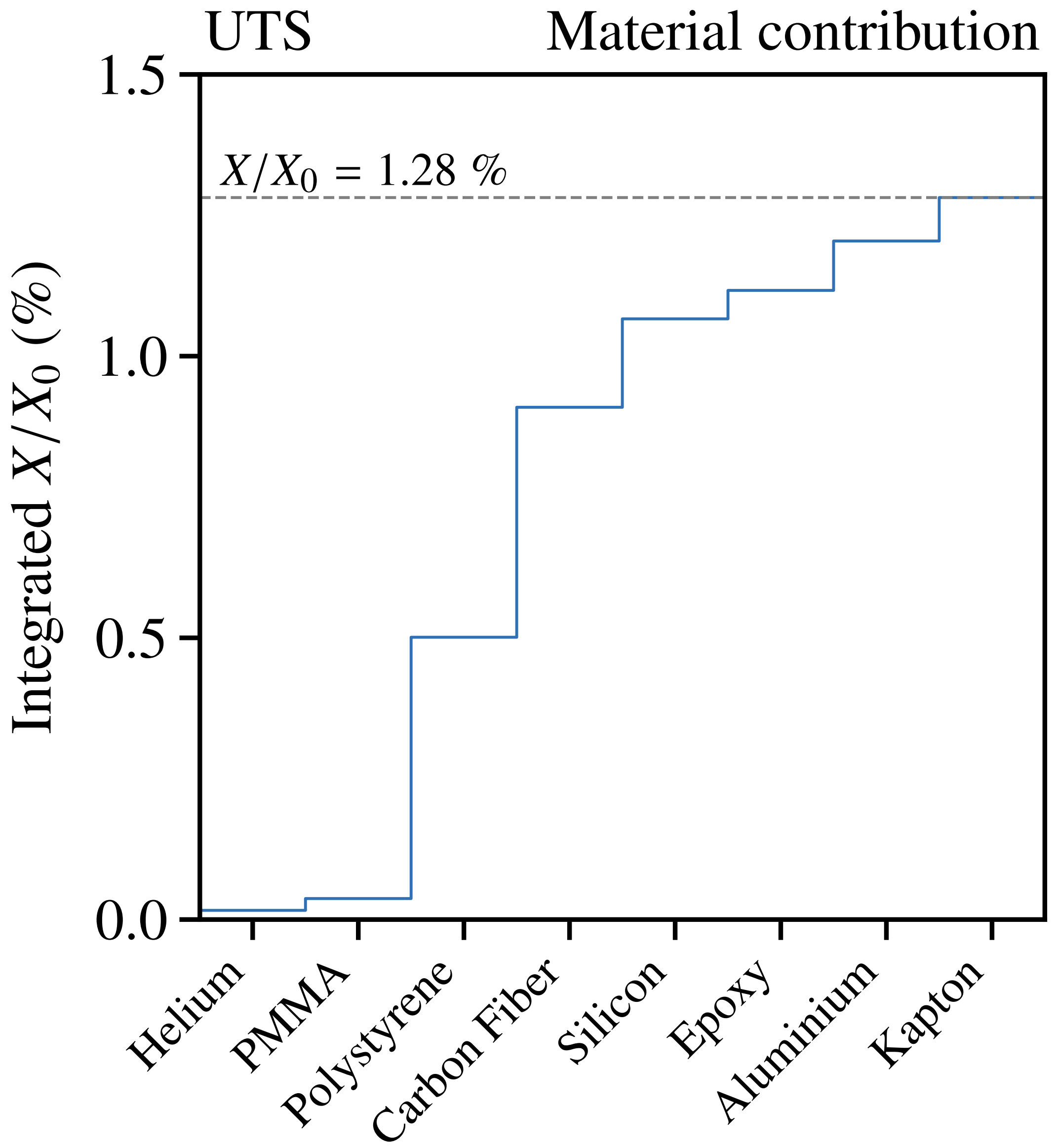

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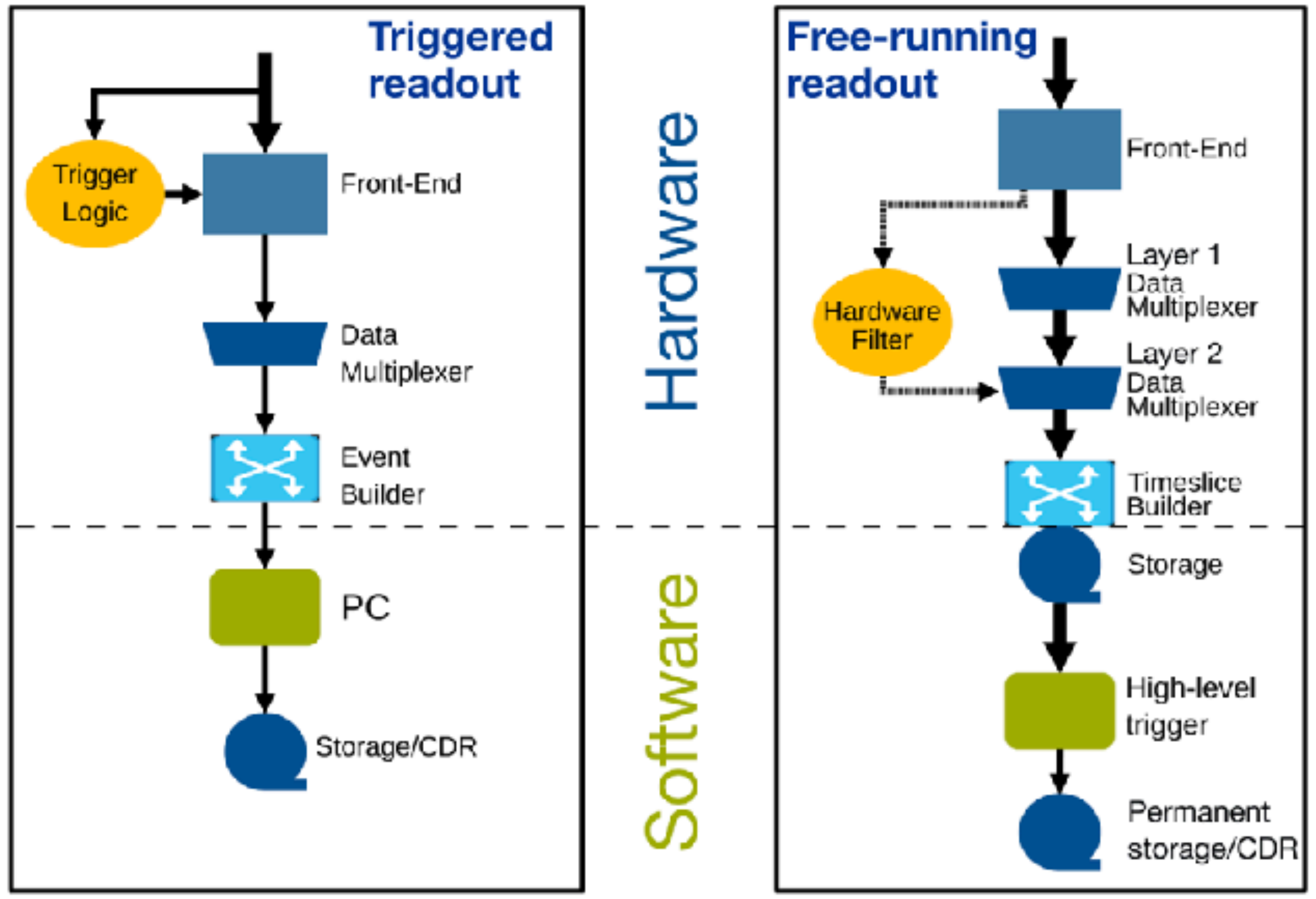
New Streaming DAQ with High-Level Trigger

New DAQ development for *AMBER* and PRM
Combination of slow and fast detectors with a continuous readout and software trigger logic for data reduction.

- Initially: Hardware trigger logic
  → Storage of data in front-end electronics up to $\mathcal{O}$(μs)
  → Example PRM: TPC drift time ~100 μs
- Transition: Trigger-less front-end electronics
  → Data stream sorted in time slices
  → Detector data ordered in time images based on to resolution
- Hardware event builder stores data
  → Online high-level trigger selects time slices + images
  → Example PRM trigger: TPC recoil proton event
- New DAQ hardware installed; tests are ongoing
- Conversion required from the new streaming format into an event definition



DOI: 10.1109/TNS.2021.3093701

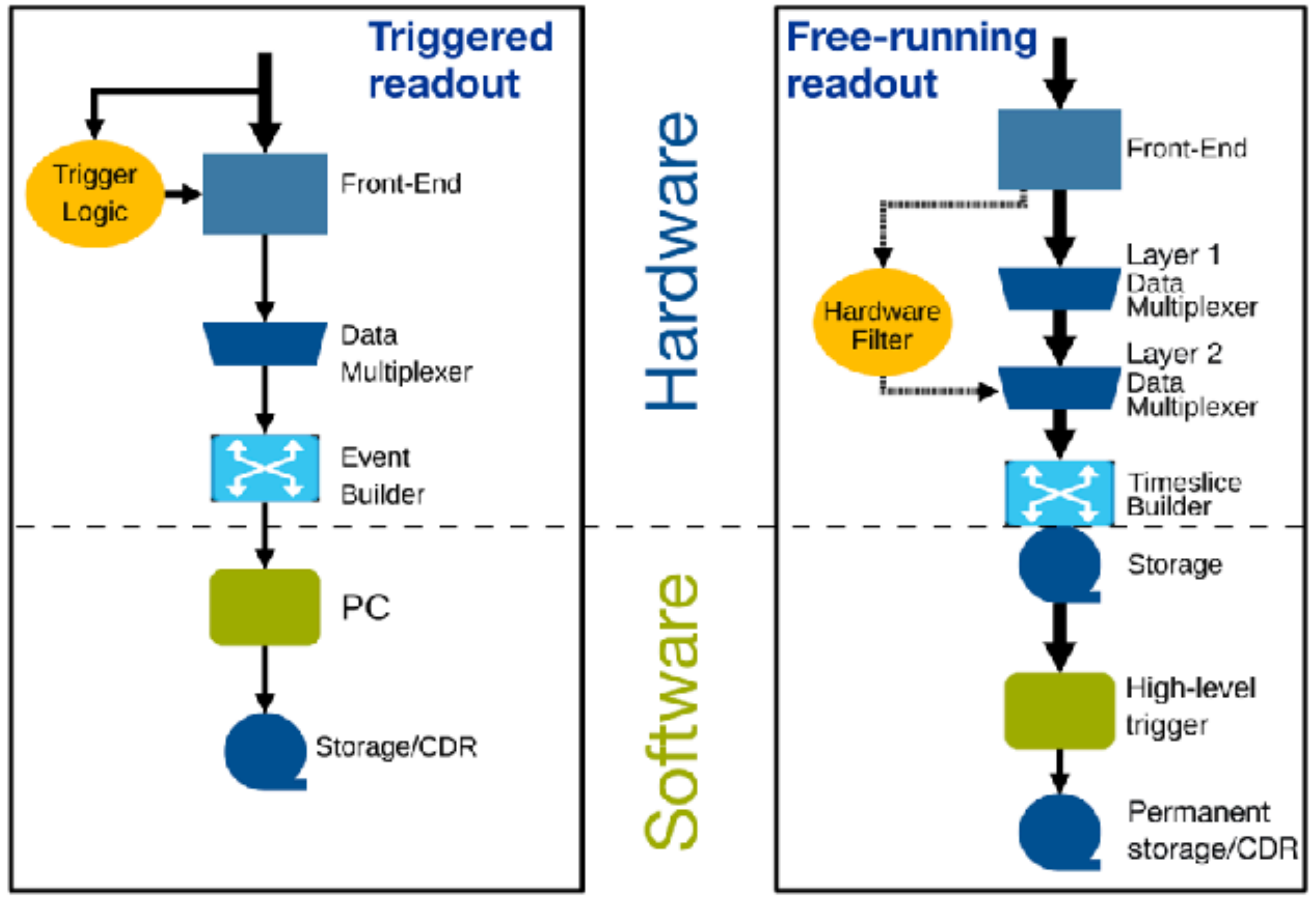
CERN-SPSC-2019-022; SPSC-P-360

Institute for Hadronic Structure and Fundamental Symmetries
Physics Department
Technical University of Munich

New Streaming DAQ with High-Level Trigger

New DAQ development for *AMBER* and PRM
Combination of slow and fast detectors with a continuous readout and software trigger logic for data reduction.

- Initially: Hardware trigger logic
  → Storage of data in front-end electronics up to $\mathcal{O}$(µs)
  → Example PRM: TPC drift time ~100 µs
- Transition: Trigger-less front-end electronics
  → Data stream sorted in time slices
  → Detector data ordered in time images based on to resolution
- Hardware event builder stores data
  → Online high-level trigger selects time slices + images
  → Example PRM trigger: TPC recoil proton event
- New DAQ hardware installed; tests are ongoing
- Conversion required from the new streaming format into an event definition



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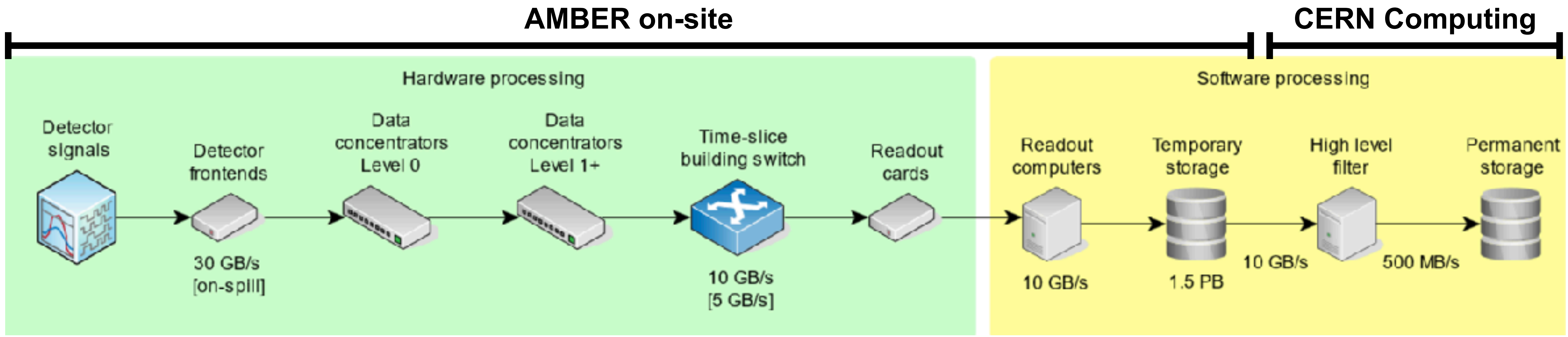
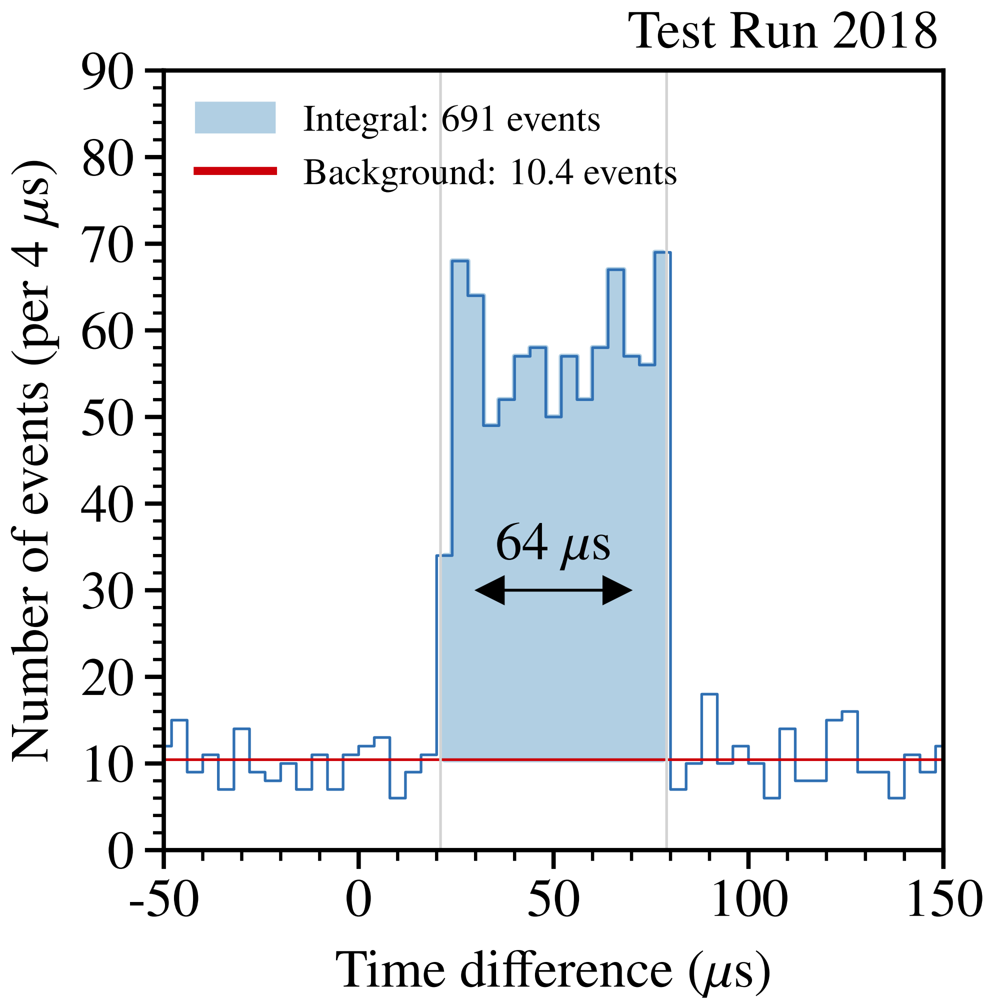


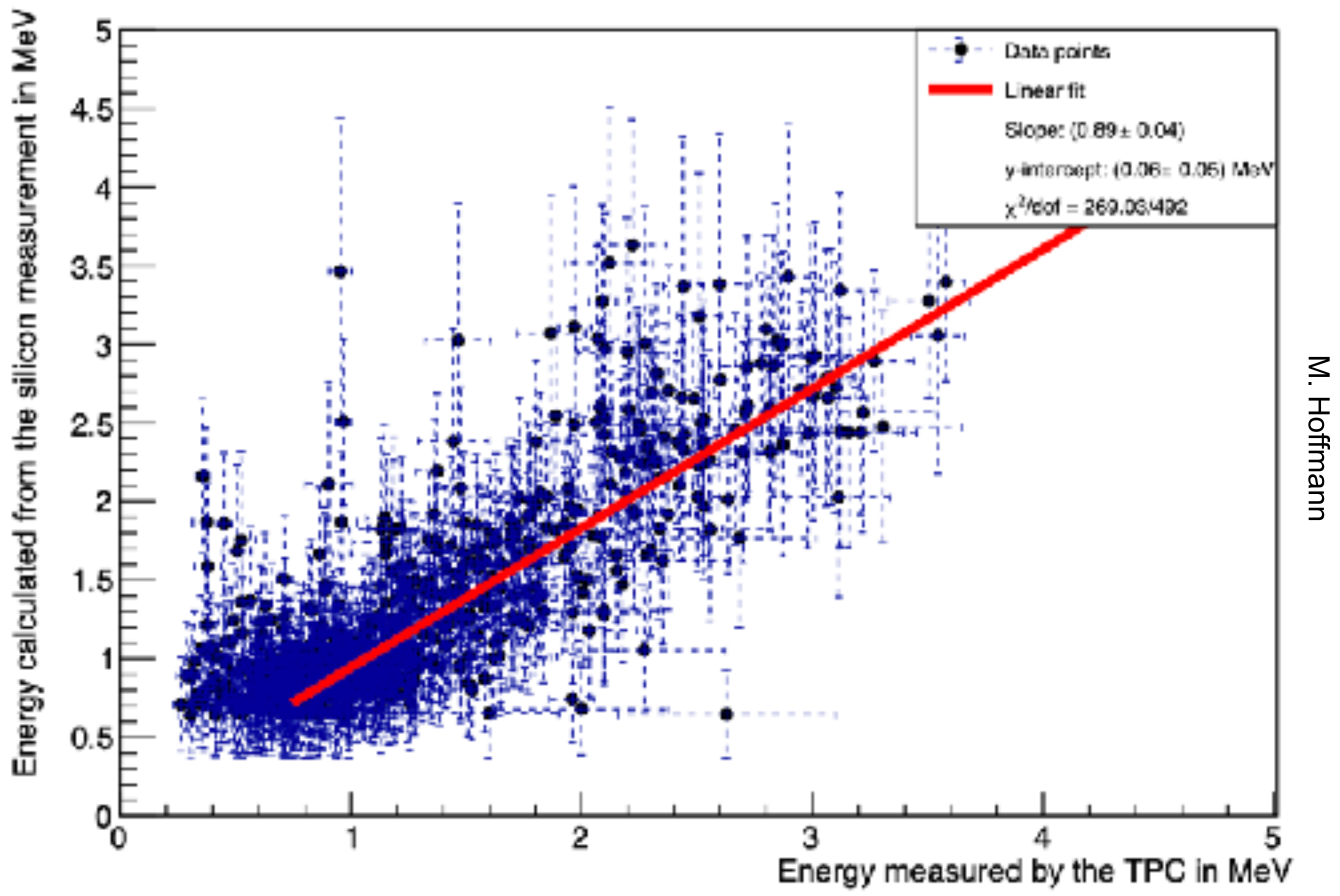
First Test Measurement performed in 2018

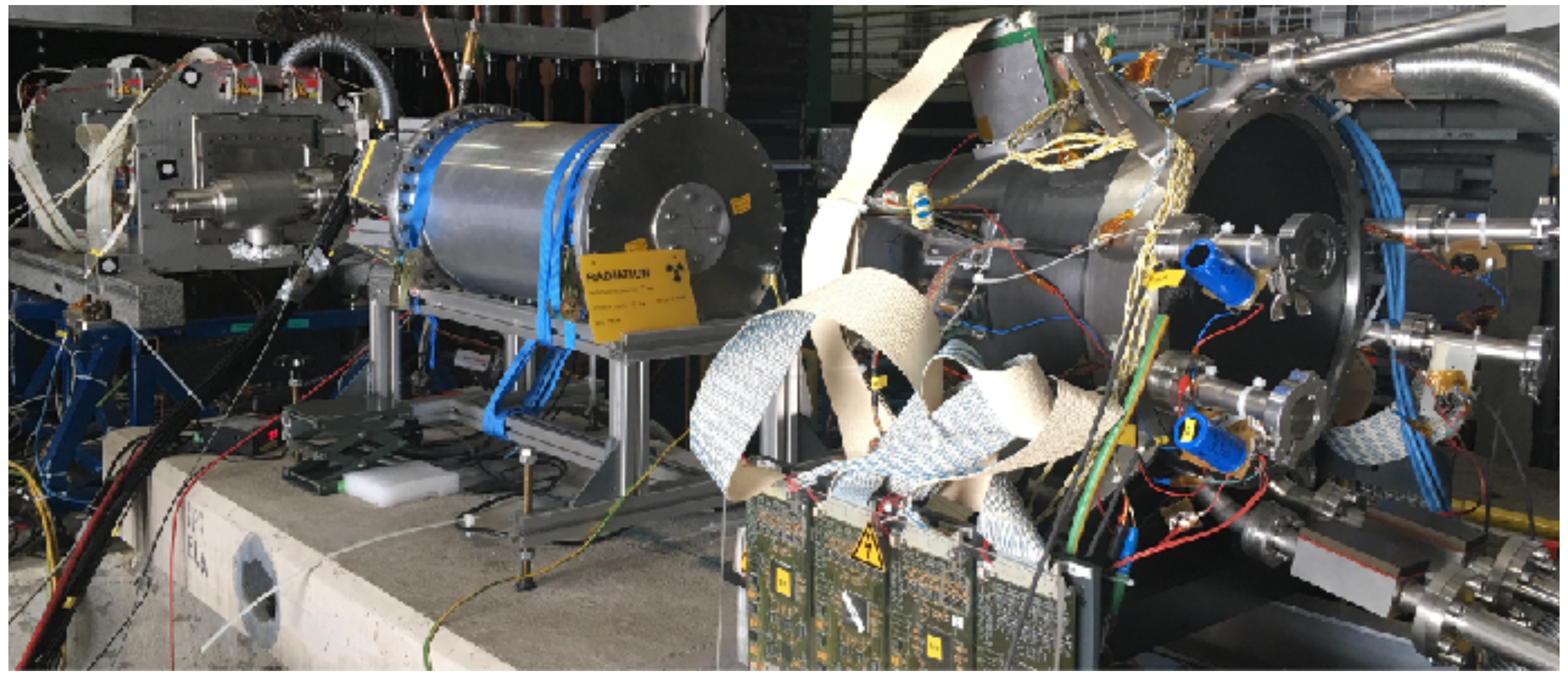
Feasibility test-measurement in 2018

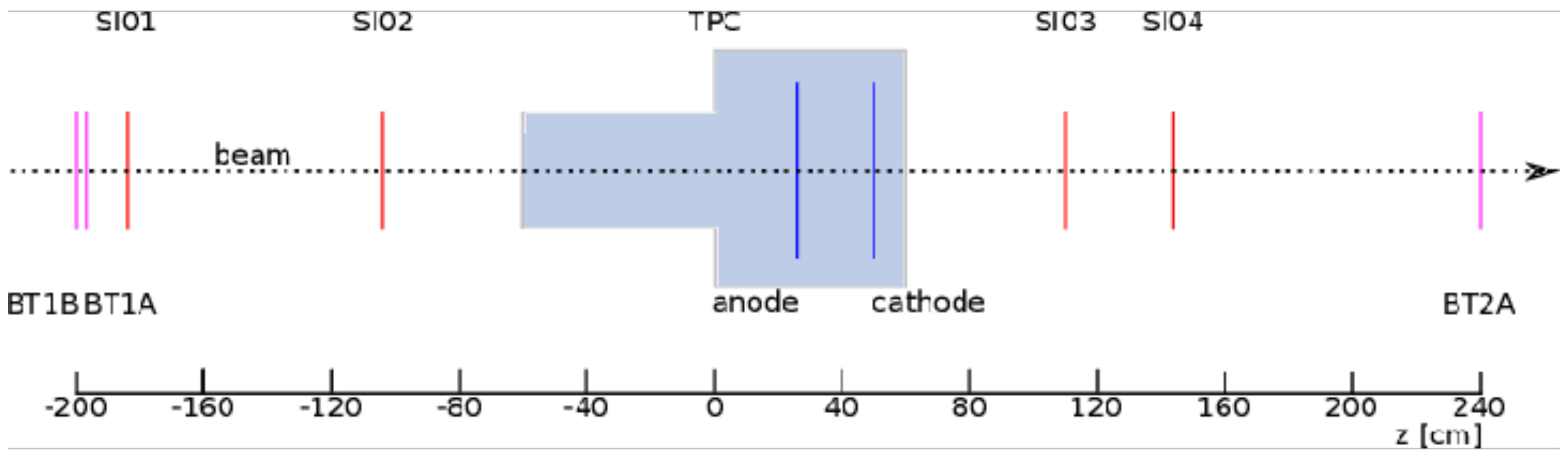
Using a simple setup with TPC (ACTAF2), silicon tracking-detectors and beam trigger.

- Goal: Proof-of-principle — working setup as in this “simple” manner
- Setup made use of parasitic *COMPASS* beam at a downstream test location
- General issue: combination of “slow” TPC with “fast” tracking detectors
- Synchronisation of two dedicated DAQ systems based on common timestamp
- First insigne on the beam-noise studies in a high-rate muon beam
- Association of muon tracks with recoil-proton events in the TPC matches expectation









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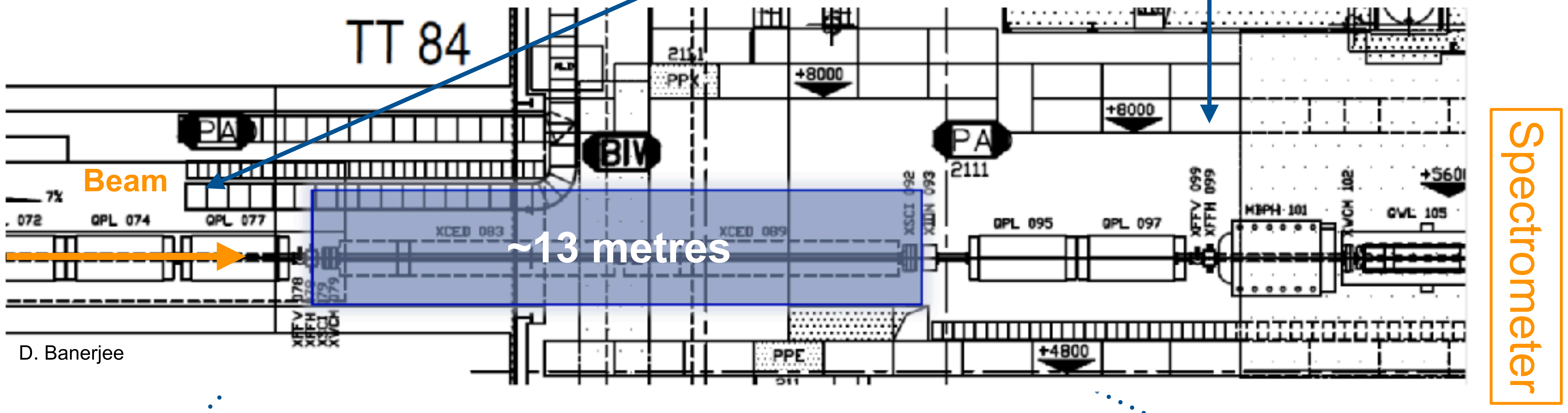
AMBER PRM - Pilot Run in October 2021

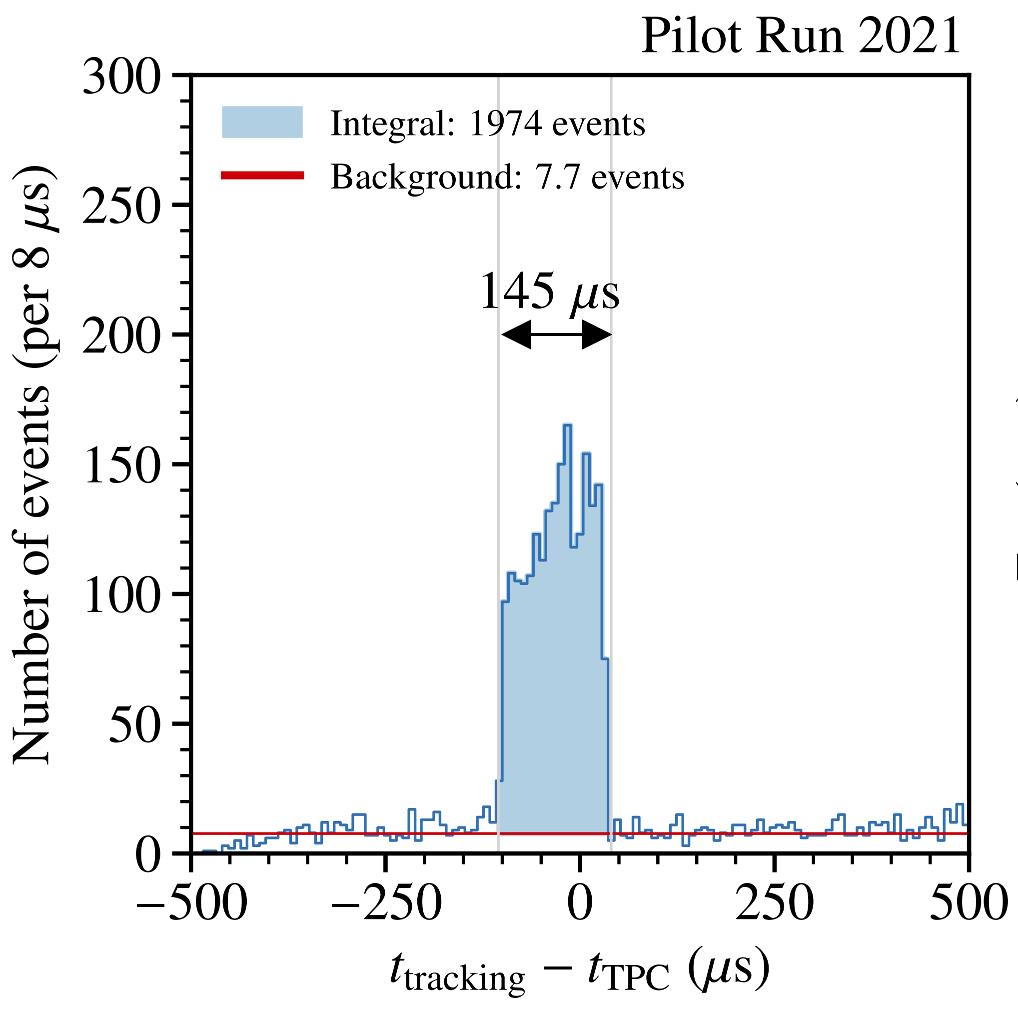
Pilot run required prior to a possible main run
Setup with close-to-final layout of the measurement to study overall properties of the setup in the test beam location in the M2 beam line.

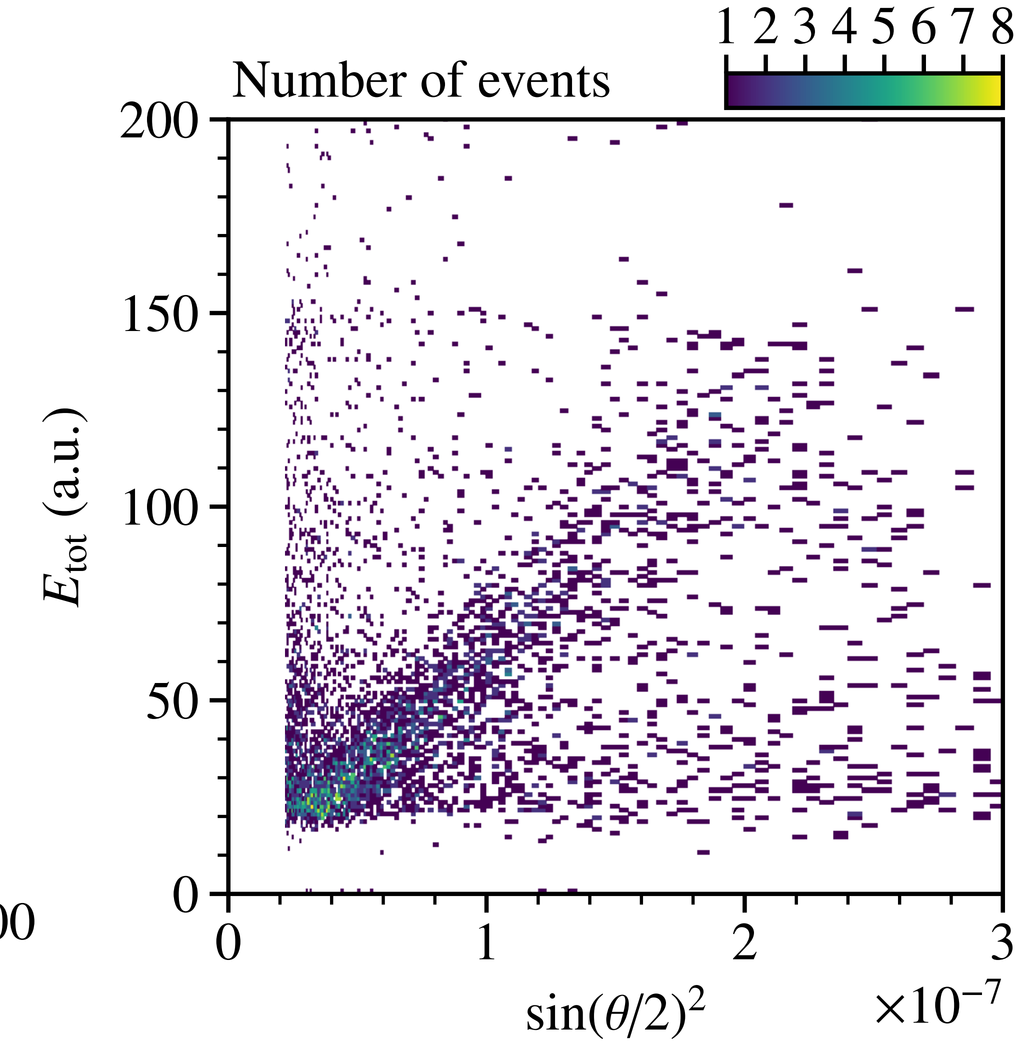
- 21 days dedicated data taking (06.10. — 27.10.)
- Comparable geometry and beam settings

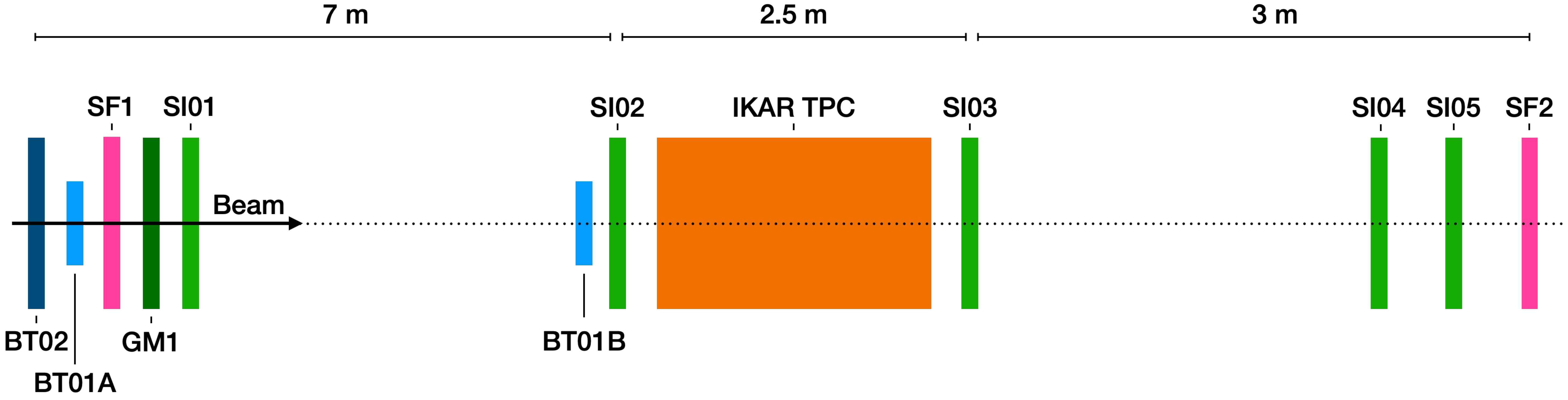
- TPC — downscaled: 2 chambers, p_{max} = 8 bar (IKAR):
- Tracking — existing sci-fis, silicons and spectrometer

Challenge:
- Inclined beam by 3.6 mrad
- Bending and focusing towards spectrometer required!









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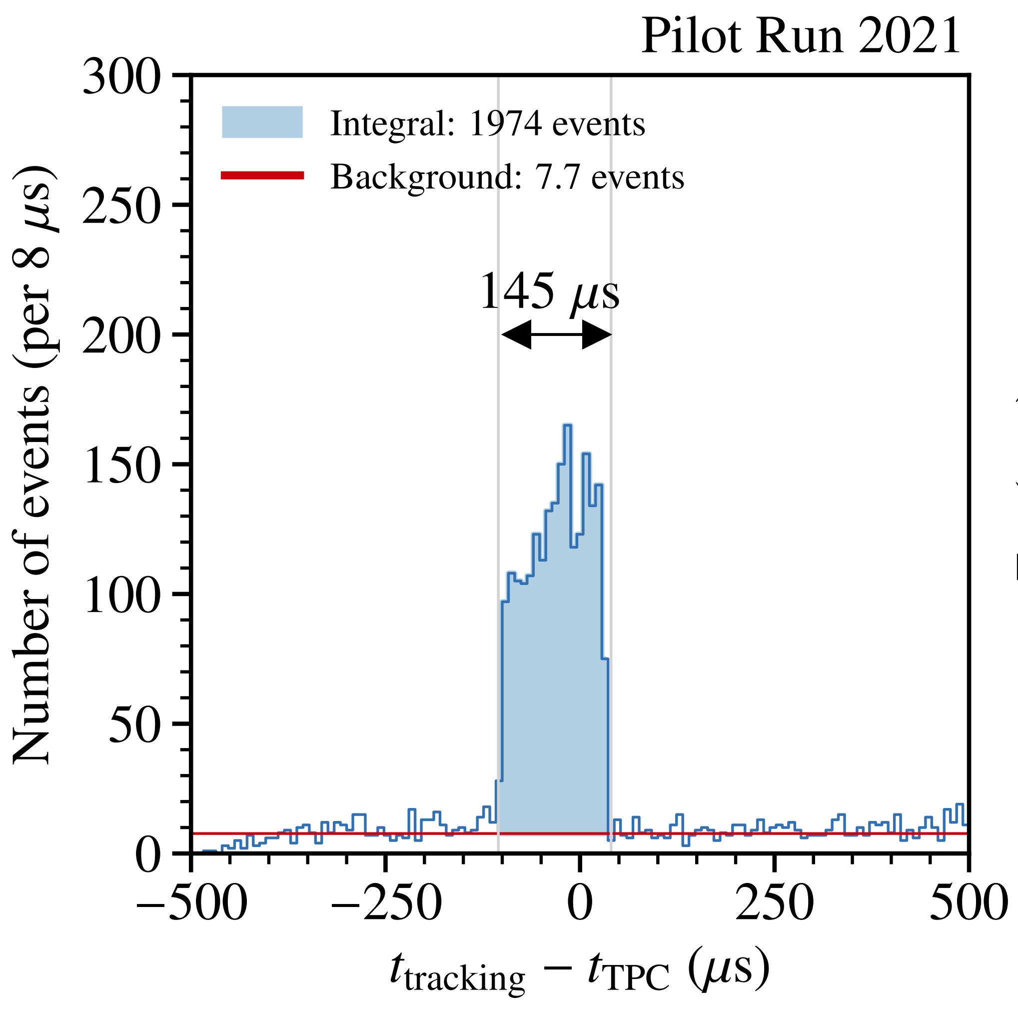

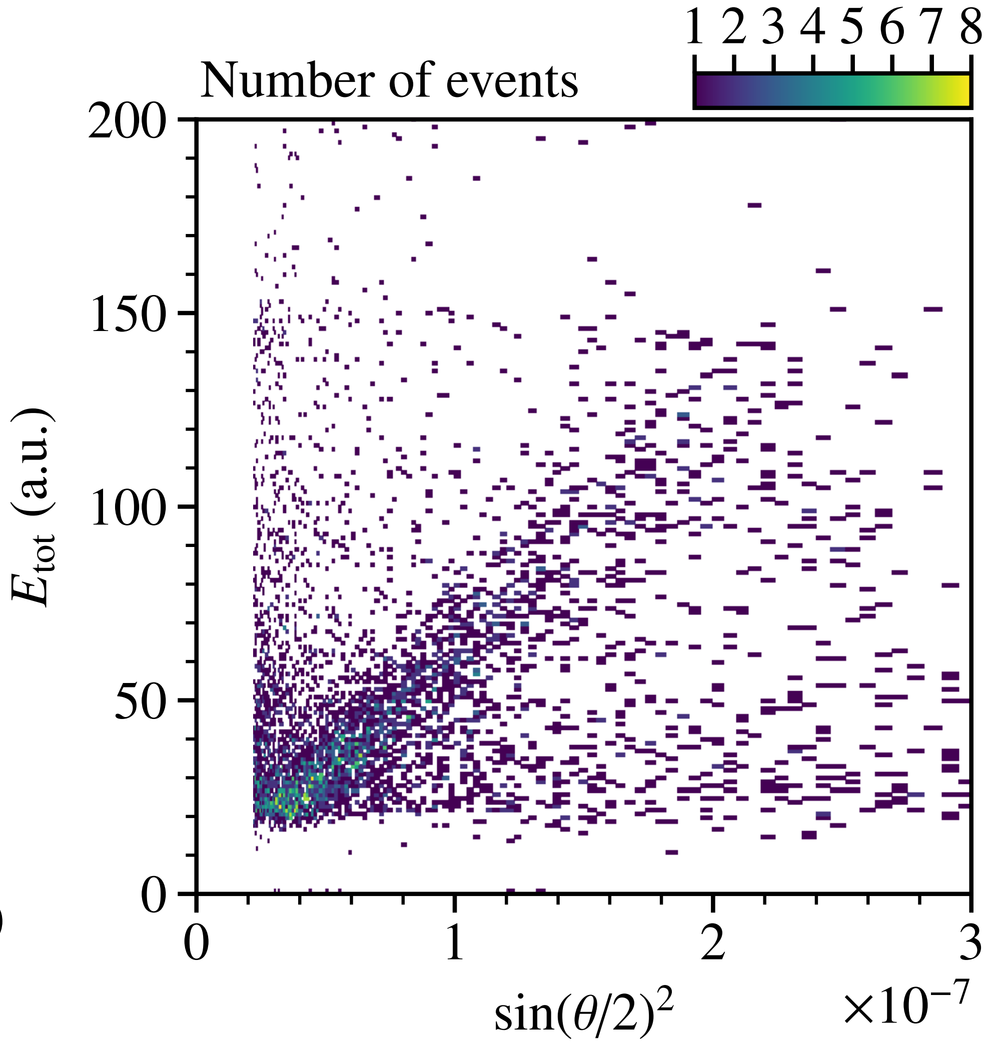

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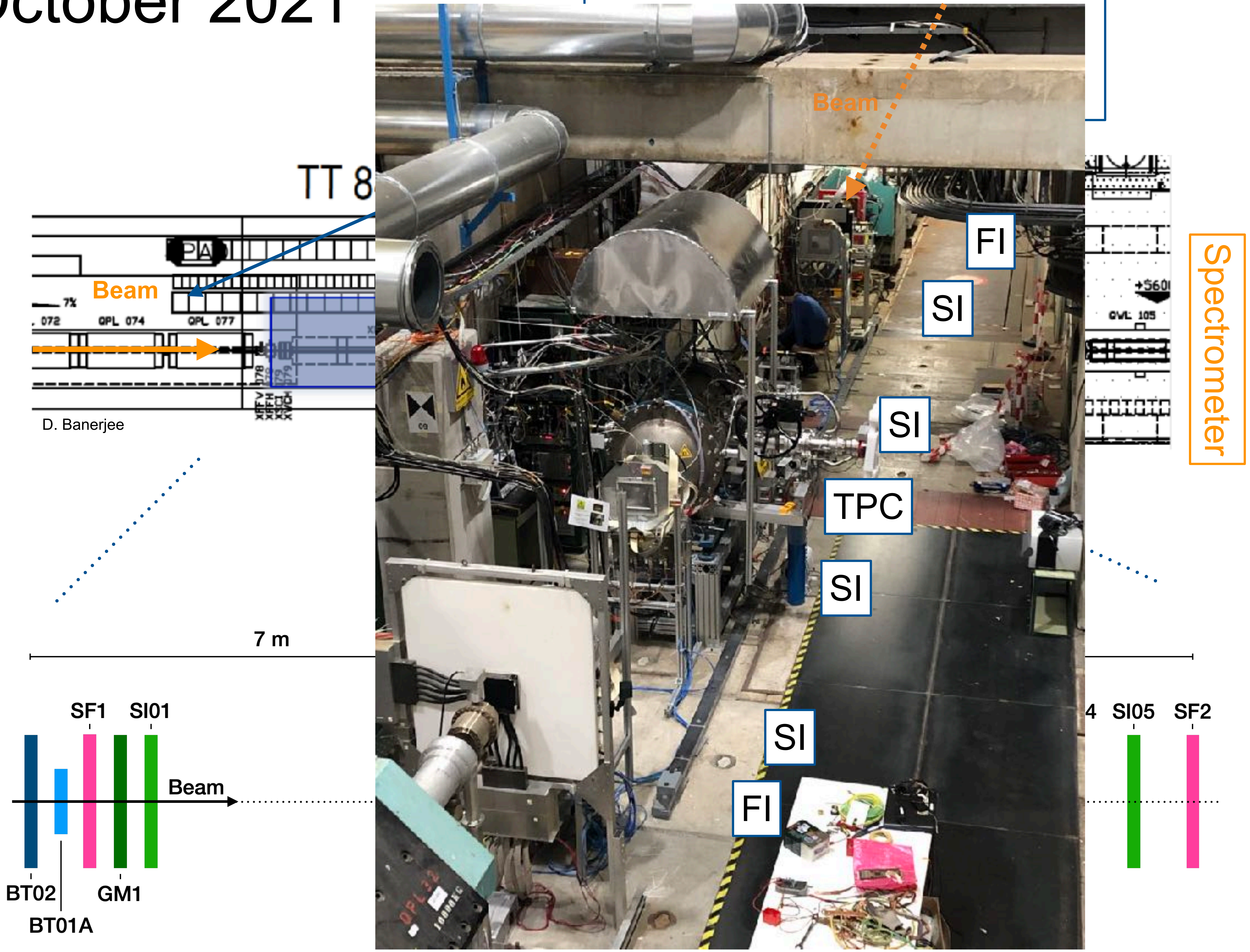


AMBER PRM - Test Run in September 2023

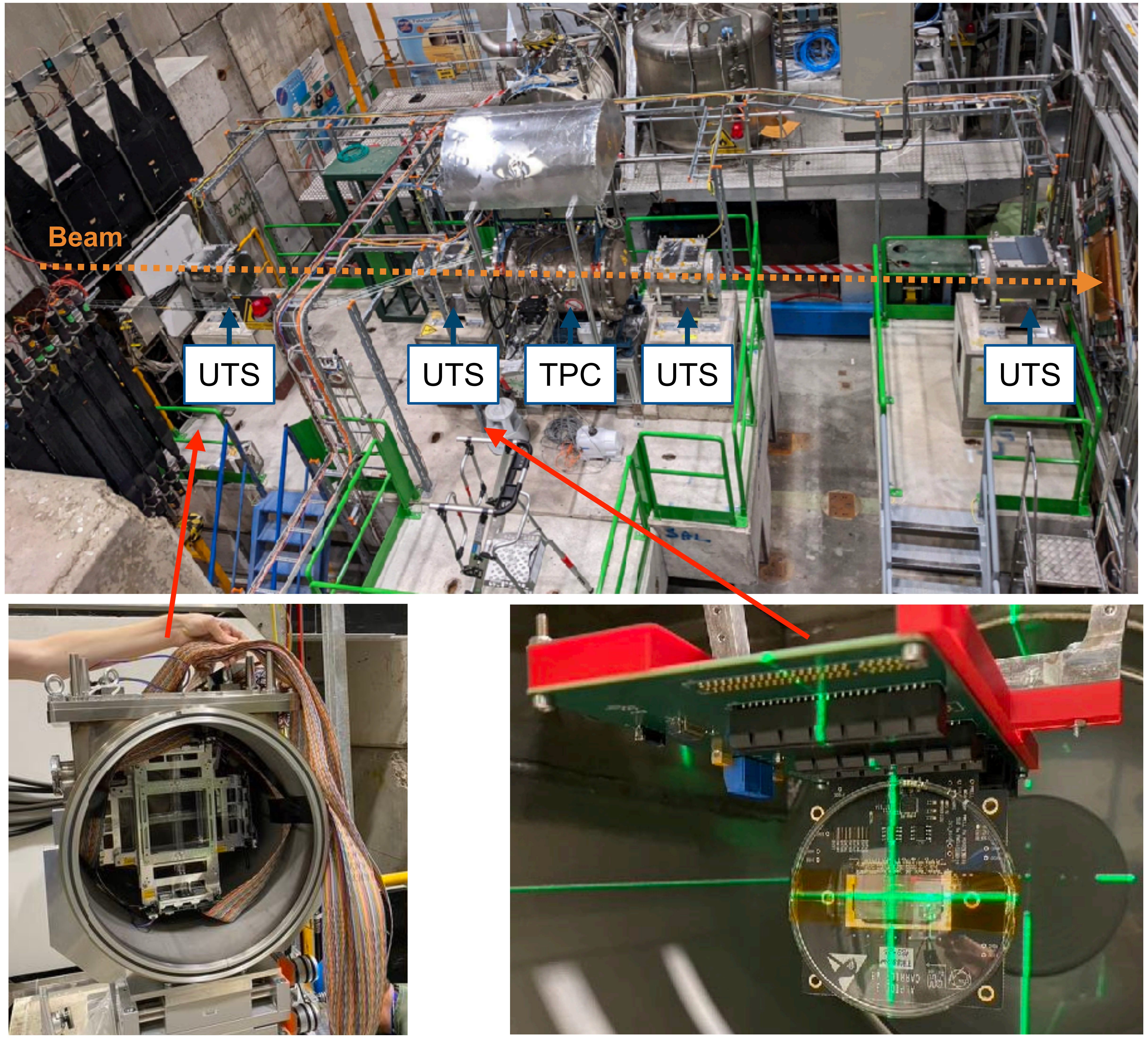
- Detector and DAQ tests during dedicated beam time
  → Setup at final location and with final beam properties

- Operate IKAR TPC with hydrogen (major success!)
  → Safety was a huge effort
  → Gas infrastructure newly installed
  → Studies at final beam optics and rates

- Muon tracking with partially equipped UTS
  → Idea: 1 SFH + 2-4 SPDs
    → But: 1 SFH + 0 SPDs
  → Studies with different Fiber to SiPM couplings

- Add-on idea: TPC synchronisation with tracking
  (but did not work out)

- New GEM with new VMM readout and for streaming DAQ
- New MWPC readout for streaming DAQ



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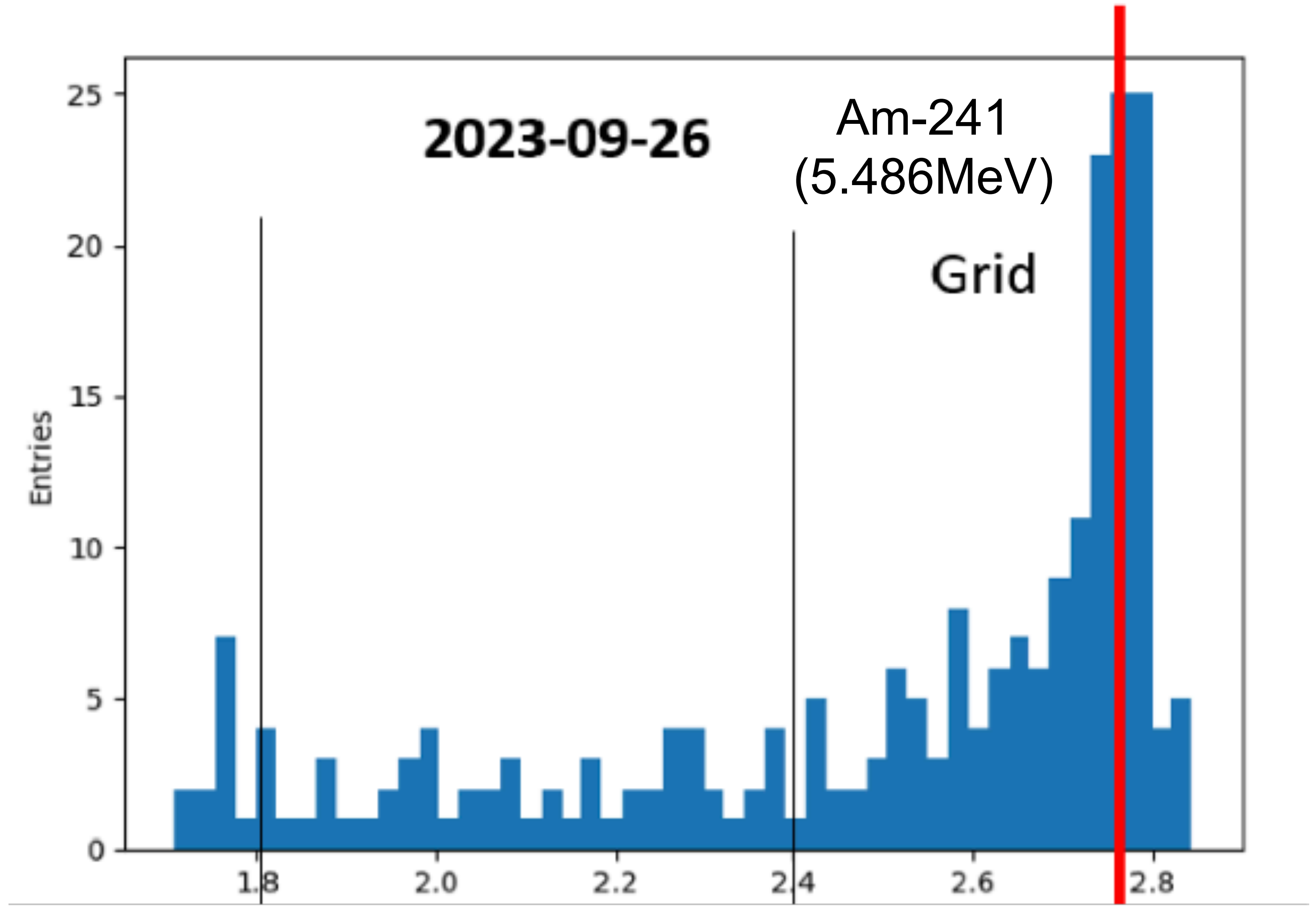
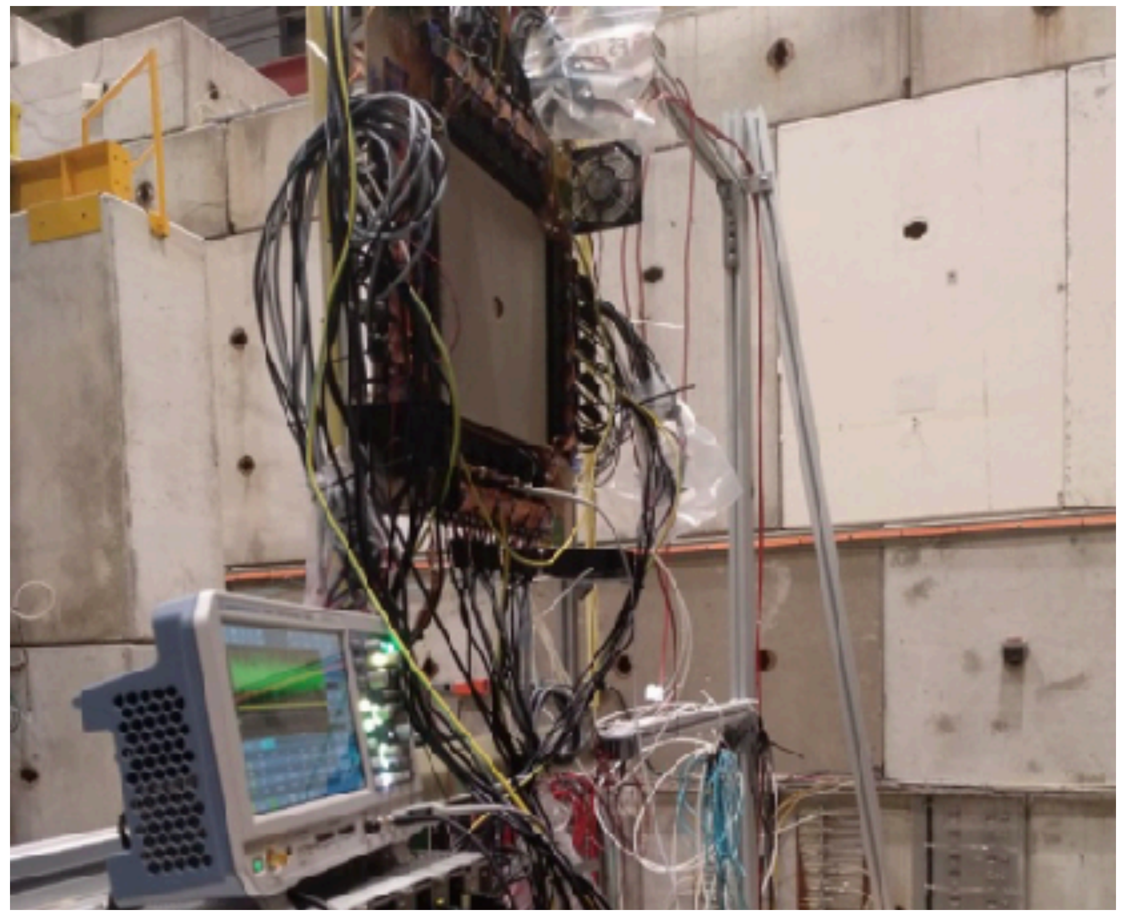
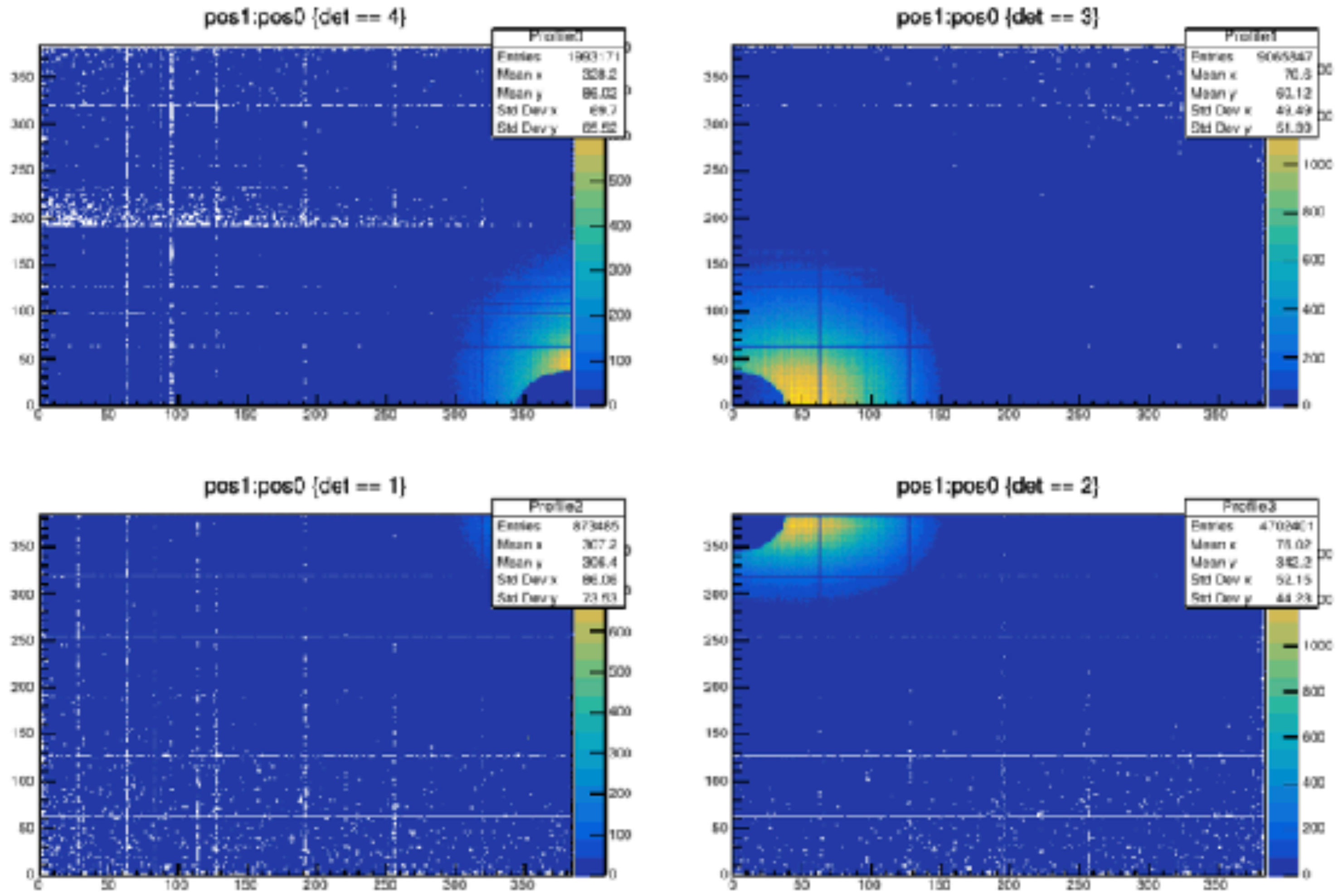






PRM — Summary and next Steps

- So far:
  → 2-cell TPC vessel produced: inner part t.b.d.
  → UTS-SPD: Single chips tested + work on assembly procedure ongoing
  → UTS-SFH: Prototype tested with beam
  → DAQ-HTL: Full chain tested
  → New GEM prototype with VMM readout tested

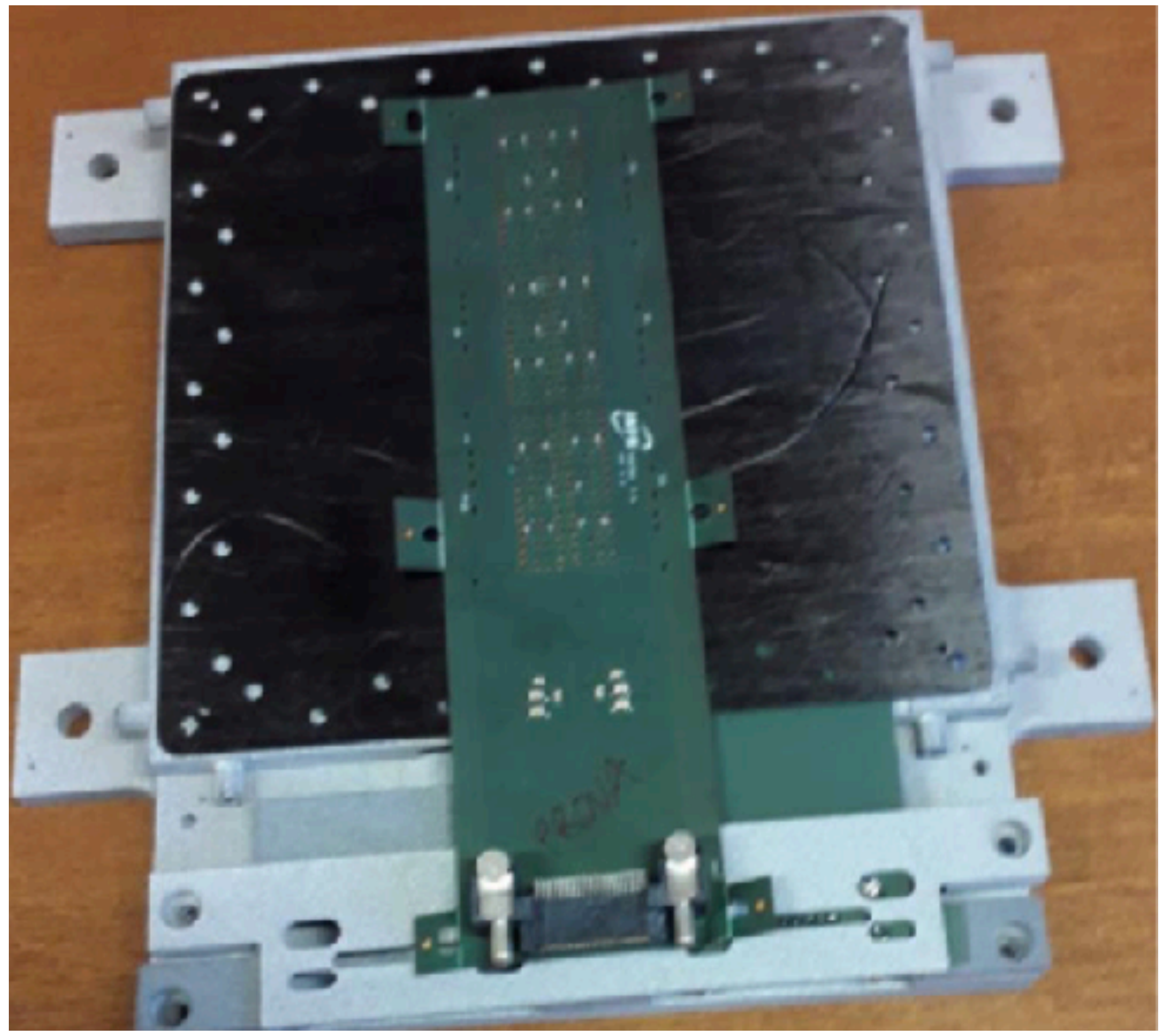
- Todo:
  → TPC inner part and gas system
  → UTS-SPD: First prototype+readout to be assembled and tested in 2024
  → UTS-SFH: New readout + … KARL!
  → DAQ-HLT: Decoding + Framework + Reconstruction
  → …

- “Rough” schedule
  → PRM Pilot Run: Mid/End of 2024 (until end of September)
  → PRM Data Taking in 2025 (before long shutdown)

New TPC vessel!
(“Big Science Tank”)

2x3 Single ALPIDE Chips
($15x30mm^2$)

SPD:
9x9 ALPIDE Chips

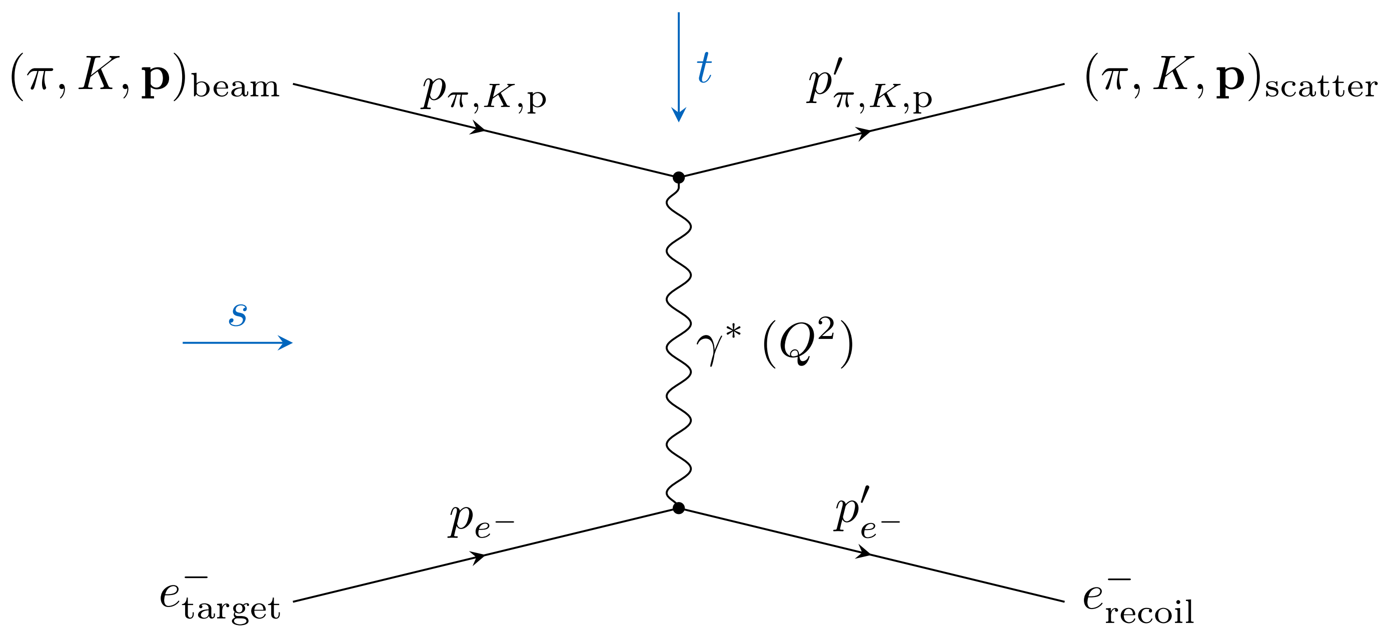


Perspective: Inverse Kinematics — Elastic Hadron-Electron Scattering

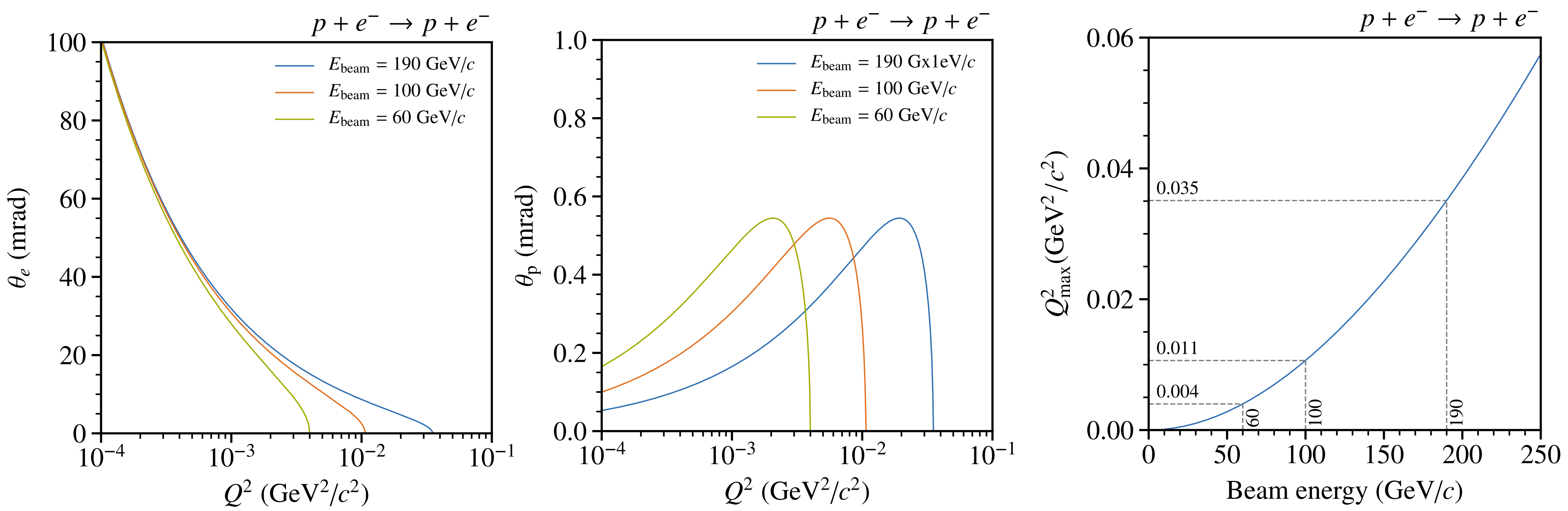
Elastic Hadron-Electron Scattering

As example, usage of a solid thin target (Be) and measurement of outgoing hadron and electron angle to determine momentum transfer — extract radii of hadrons.

- Can be applied for instance: proton, pions and kaons
- Also possible: access to G_M with different beam momenta
- Similar setup can be used as the currently planned PRM

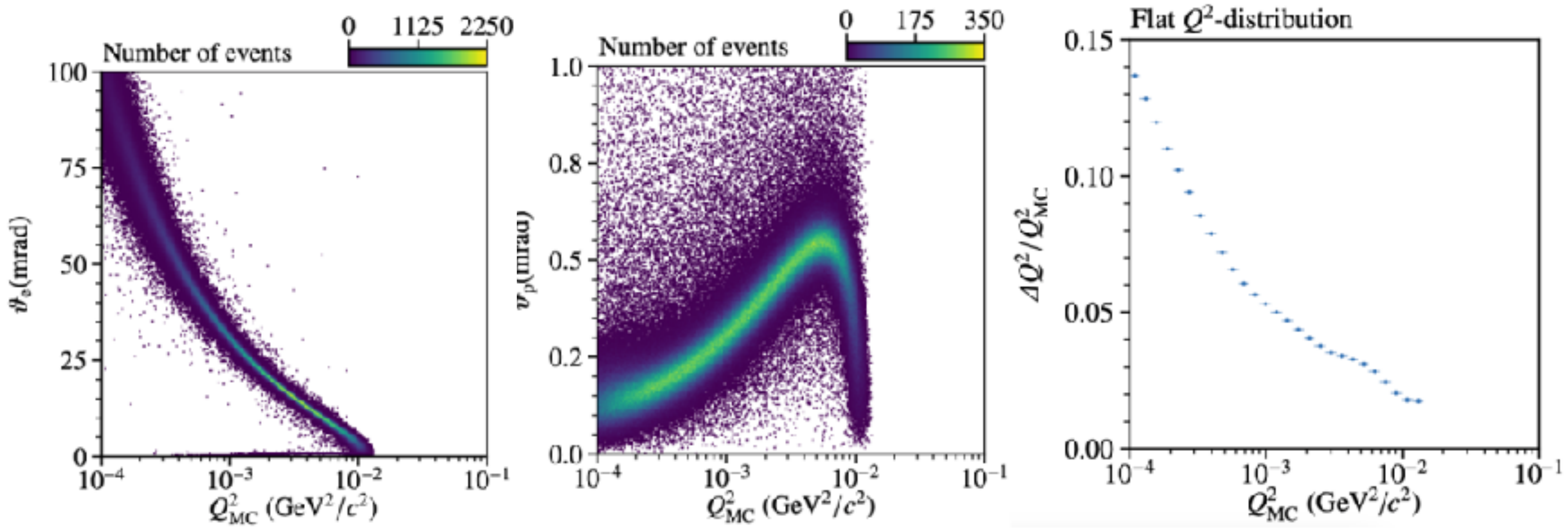


- In the proton case — elastic proton-electron scattering:
  → For G_E complementary measurement to Mainz, PRad, PSI
  → G_M possible first measurement for $Q^2 < 0.08\ \text{GeV}^2/c^2$
  (MAMI, Phys. Rev. C 90, 015206 (2014))



- Maximal Q^2 depends on beam momentum
- But: challenging kinematic region
  → Electrons: scattering angles up to 30 mrad ($Q^2 = 10^{-3}\ \text{GeV}^2/c^2$)
  → Protons: scattering angles between 50 to 500 µrad
  → Beneficial: variation of beam momenta

p = 100 GeV (proton)



Physics Program

AMBER Physics program in the upcoming years

LHC Run 3
2021 - 2025

LHC Run 4
2029 - 2032

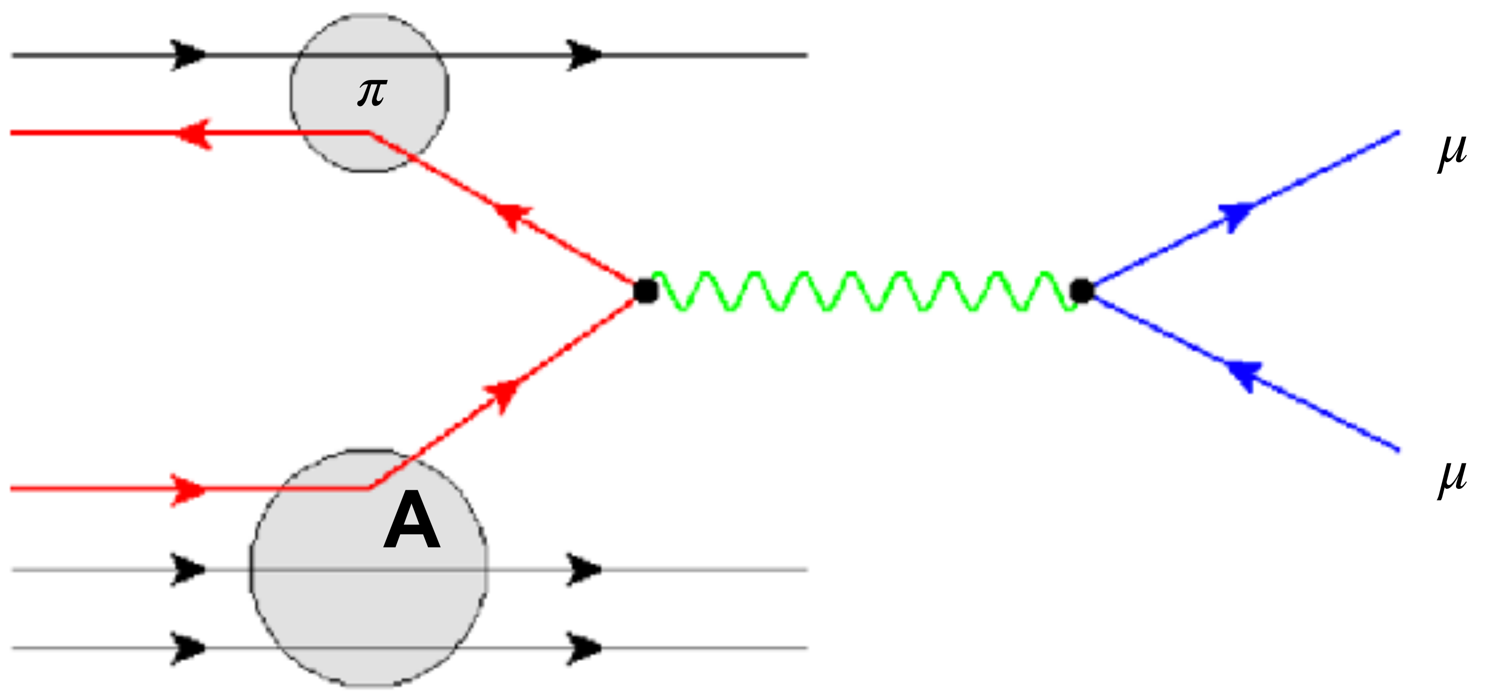
- Phase I (approved by CERN):
  → Anti-proton production cross-section
  → Proton charge radius
  → **Pion and kaon structure functions**

- **Phase II (Proposal submission ongoing):**
  → **Strange-meson spectroscopy**
  → **Kaon polarisability**
  → **Prompt-photon production**

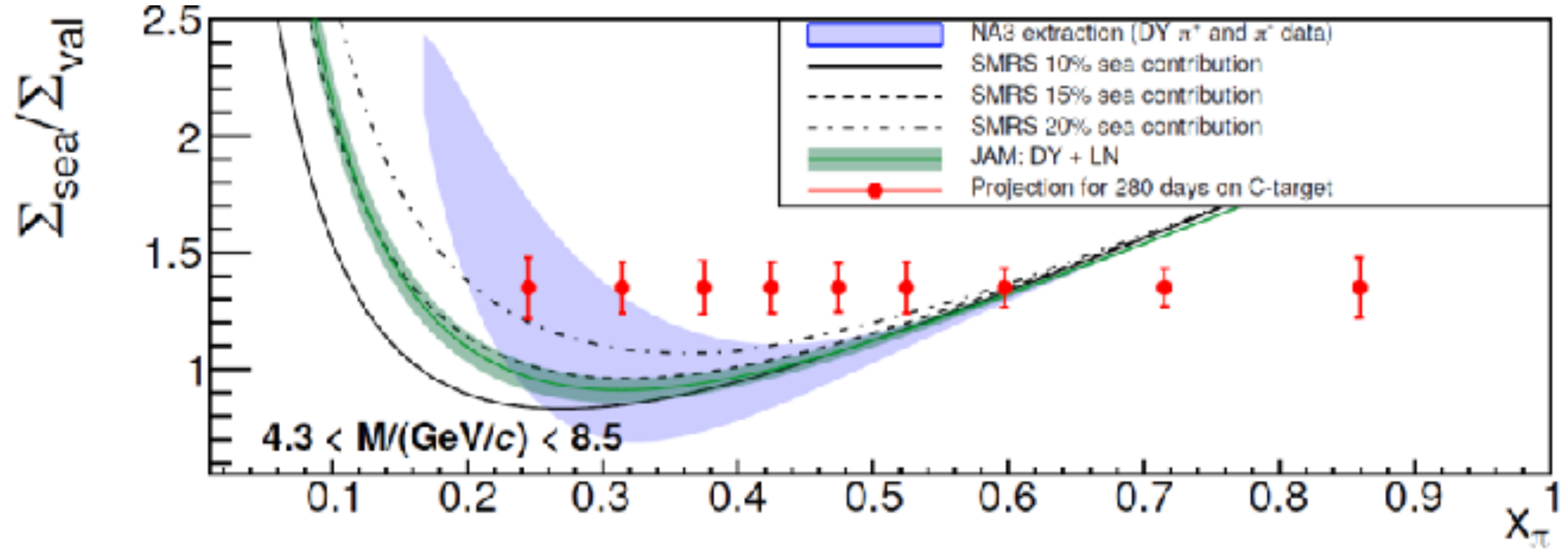
AMBER — Future and Phase II

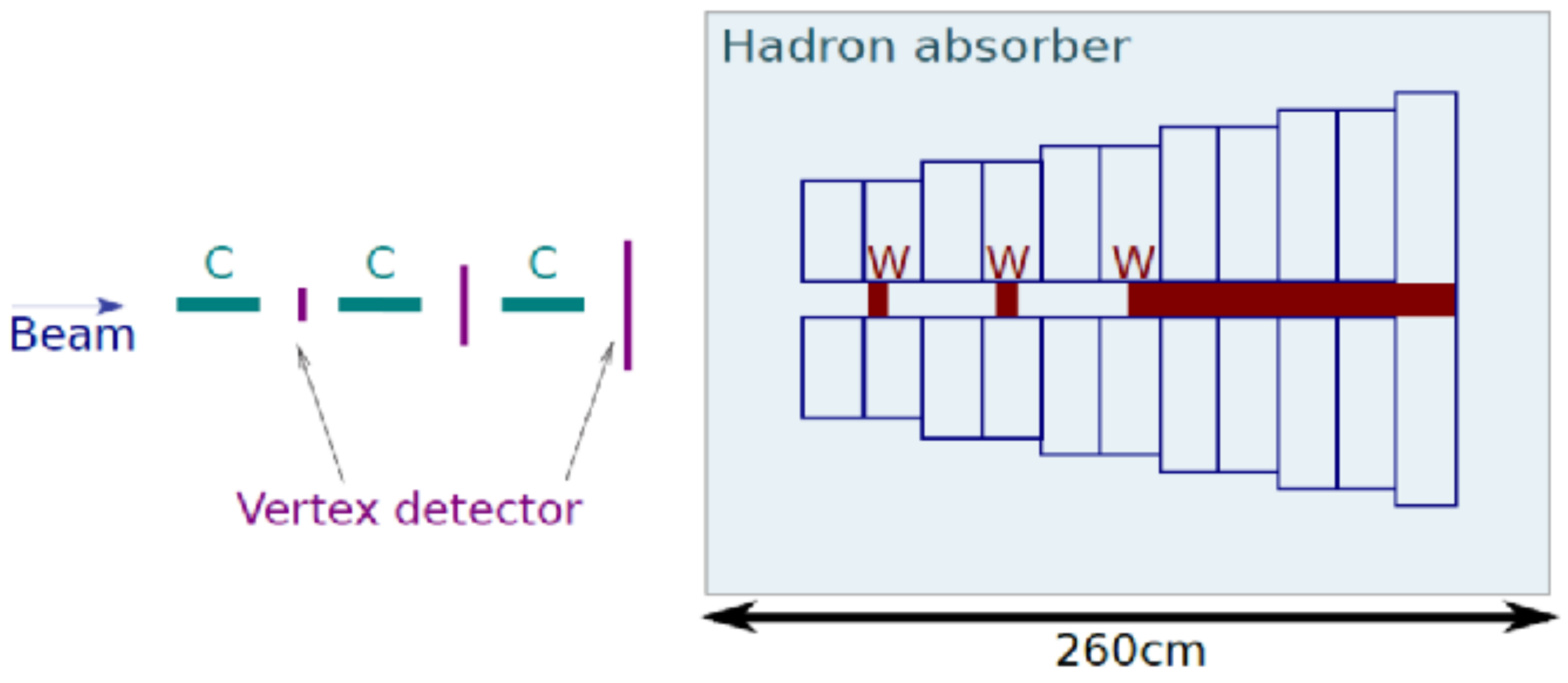
QCD Initiatives beyond LHC Run 4

Usage of conventional and RF-separated beams studied in the framework of PBC at CERN.

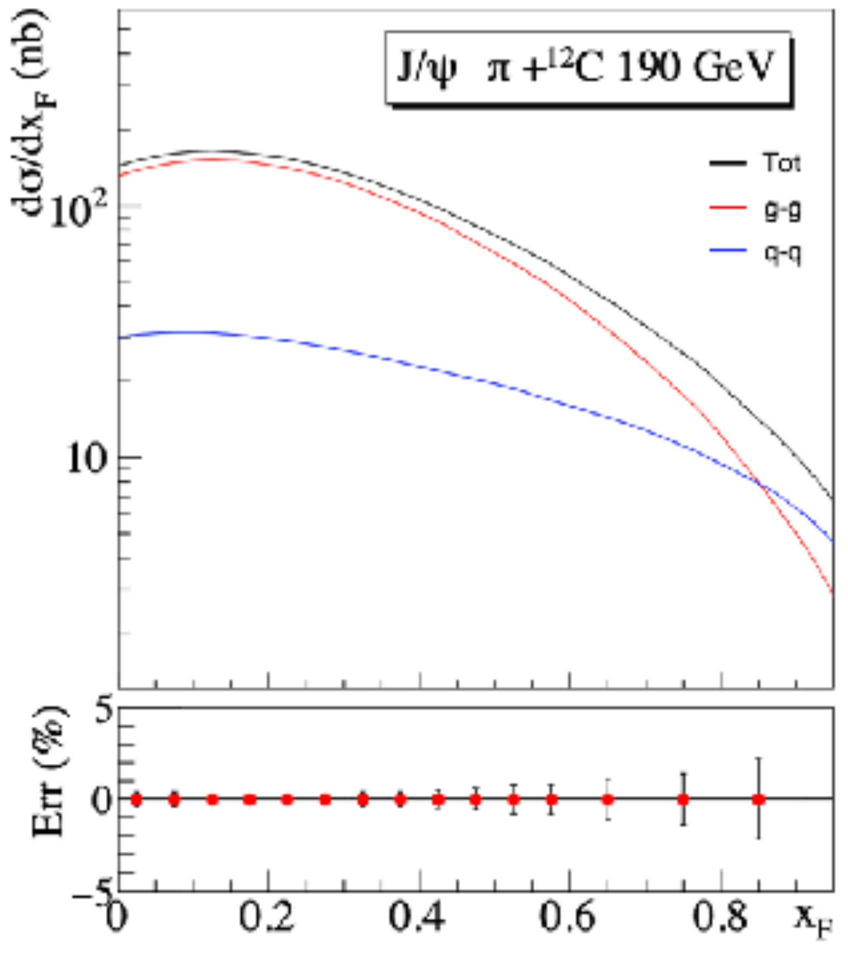


- Pion-induced Drell-Yan dimuon production
  → Precise measurement of sea-quark distribution of pion (goal: 10x more data!)
  → Requires new target + vertex detectors and hadron absorbers





- In parallel: J/Psi-production: $\pi + A \rightarrow J/\Psi + X$
  → Dominated by $q\bar{q}, gg \rightarrow J/\Psi$ at low p_T < M(J/Ψ): Access to gluon PDF of pion



- **<u>Phase 2 (>2025):</u>** kaon PDFs + polarisability (Primakoff), strange spectroscopy, etc.

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Next:

UTS and Scintillating Fiber Hodoscope — Karl