# Annual report second year of PhD course

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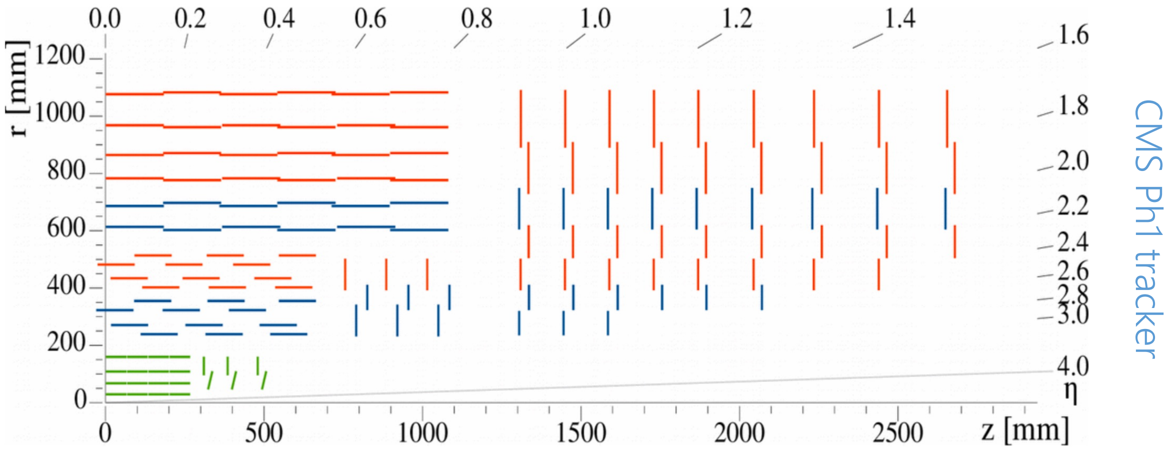
# Overview

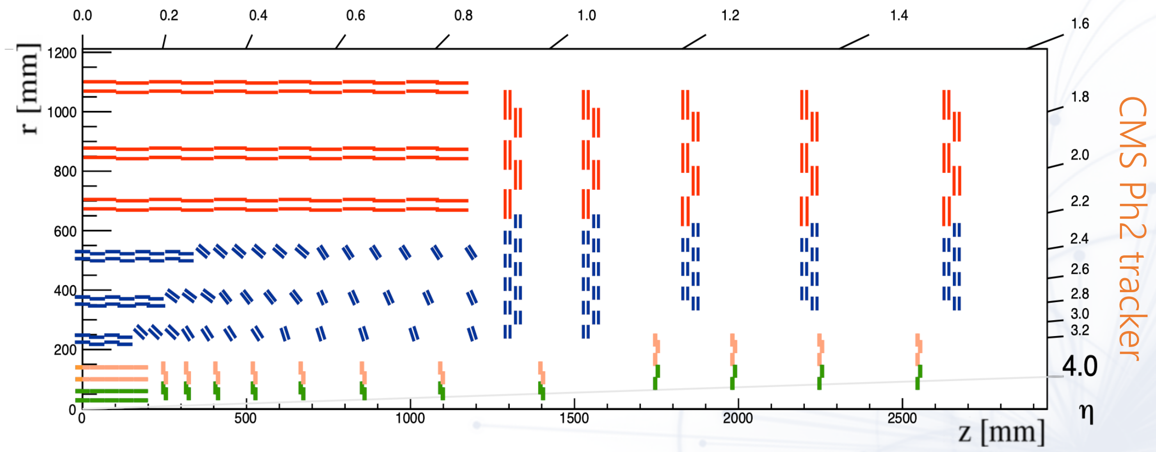
- CMS outer tracker upgrade for high luminosity
  - Anatomy of tracker modules for upgrade
  - DAQ for CMS HiLumi modules
- MUonE experiment test and deployment
  - Physics case
  - Measure
  - Detector
  - Data Acquisition
  - Test beam results

# CMS outer tracker upgrade for high luminosity

# CMS outer tracker

- Hi-Lumi upgrade of LHC after LS3 (~2026)
  - Peak Luminosity ~$7.5 \times 10^{34} cm^{-2}s^{-1}$
  - Expected Pile-up ~200
  - Higher rates and radiation dose wrt Run3
  - New Magnets (11T)
  - Etc..
- Necessary upgrade of current tracker:
  - leakage current or full depletion voltage limitations → big **part of current tracker will be inoperational**
  - Higher **radiation level** → upgraded tracker target: integrated luminosity of 3000 $fb^{-1}$
  - Efficient tracking + Higher pileup → **Increase of granularity needed**
  - Contribution to **level-1 trigger** → selection of interesting physics at the first trigger stage is extremely challenging at high luminosity



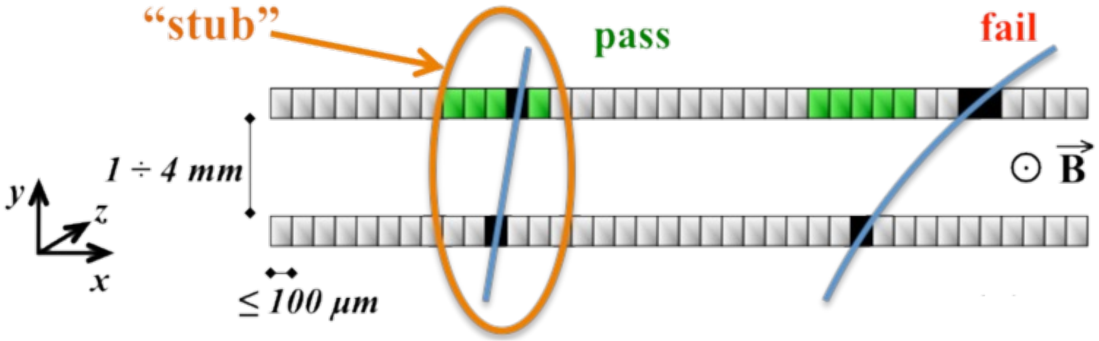



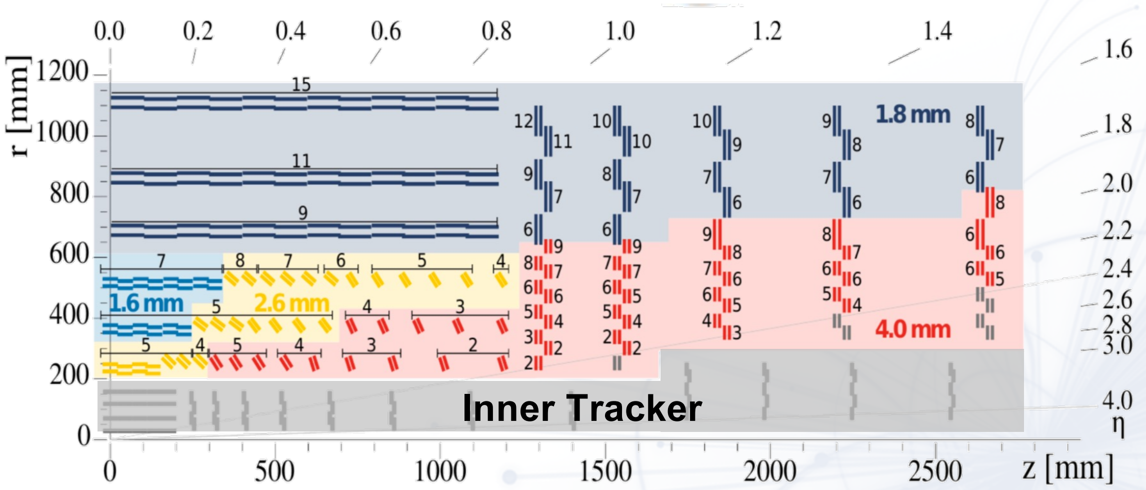
# CMS outer tracker

- HL-LHC → higher collision rate→ Most of charged particles have low $p_T$ → $p_T$ selection at readout level in order to reduce the L1 tracking input data size

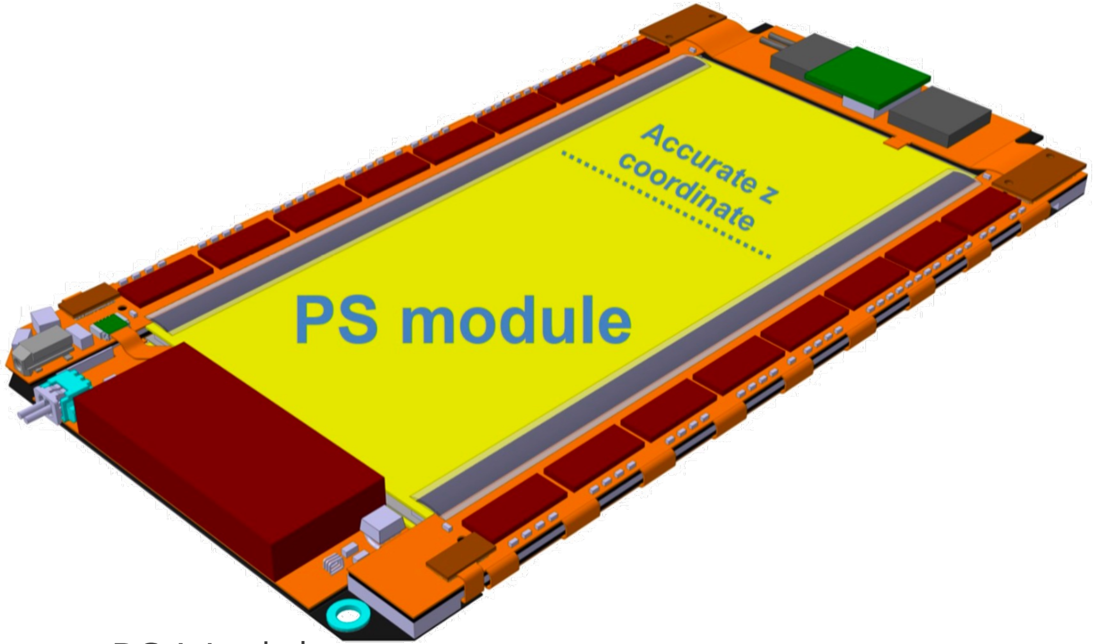
pT modules

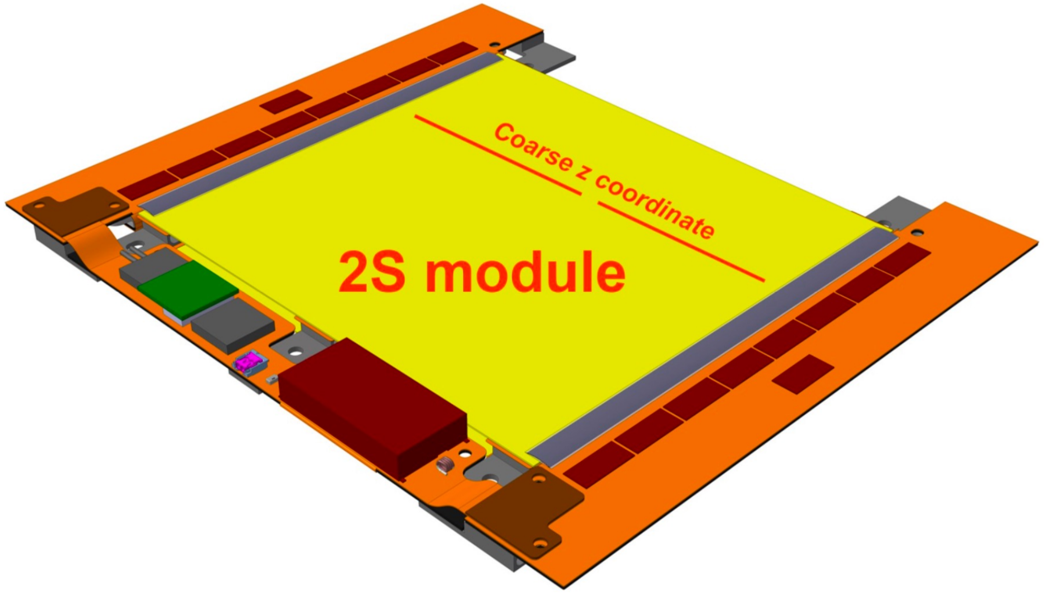
- Two silicon sensors with small spacing in a module
- Flex hybrid in order to get data from both sensors to one ASIC → Select track «stubs»
- Different sensor spacing for different detector region
- Tunable correlation windows



# CMS outer tracker

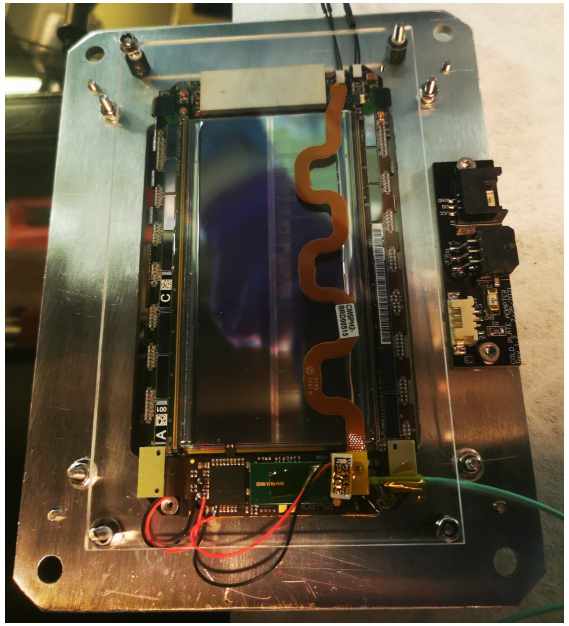



- PS Modules
  - 3 different spacing : 1.6mm & 2.6mm & 4mm
  - One strip sensor: 2.5cm x 100µm strips
  - One macro Pixel sensor : 1.5mm x 100µm pixels
  - Sensor dimension  5cm x 10 cm
    - two column of 960 strips
    - 32x960 pixels

- 2S Modules
  - 2 different spacing : 1.8mm & 4mm
  - 2 micro strip sensors with 5cm x 90µm strips
  - Sensor dimension are 10cm x 10cm
    - two column of 1016 strips

# CMS outer tracker



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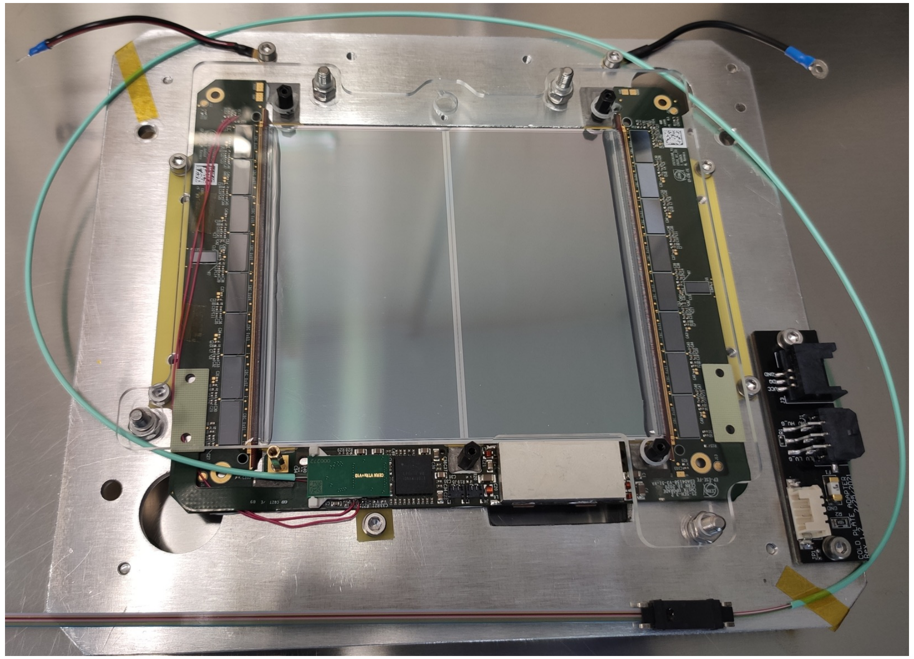

- 2S Modules
  - 2 different spacing : 1.8mm & 4mm
  - 2 micro strip sensors with 5cm x 90µm strips
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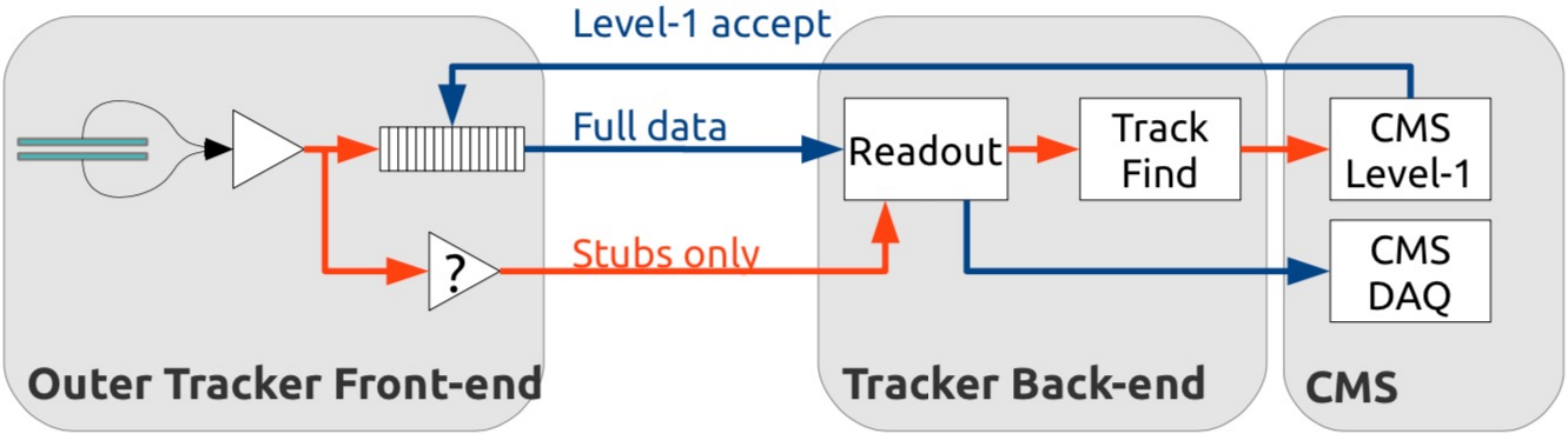
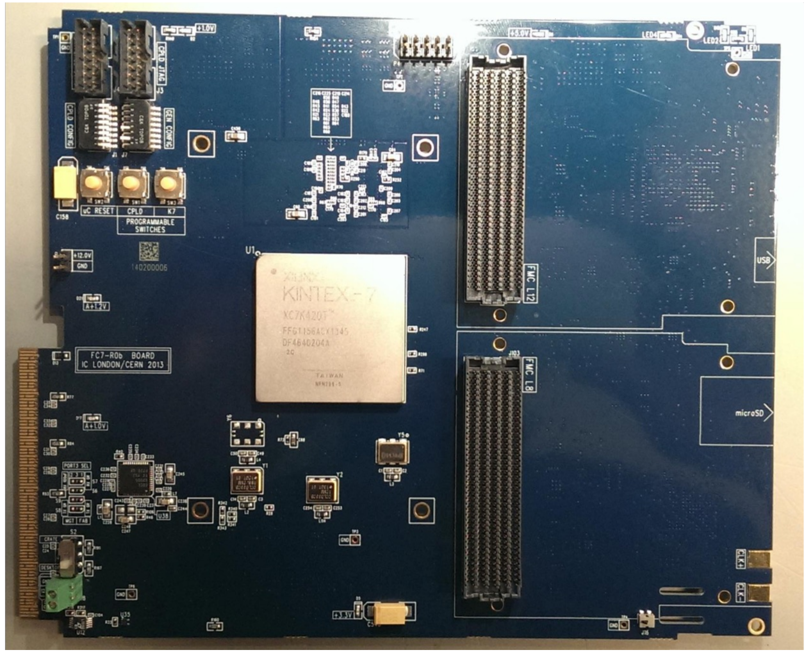
# DAQ for CMS modules

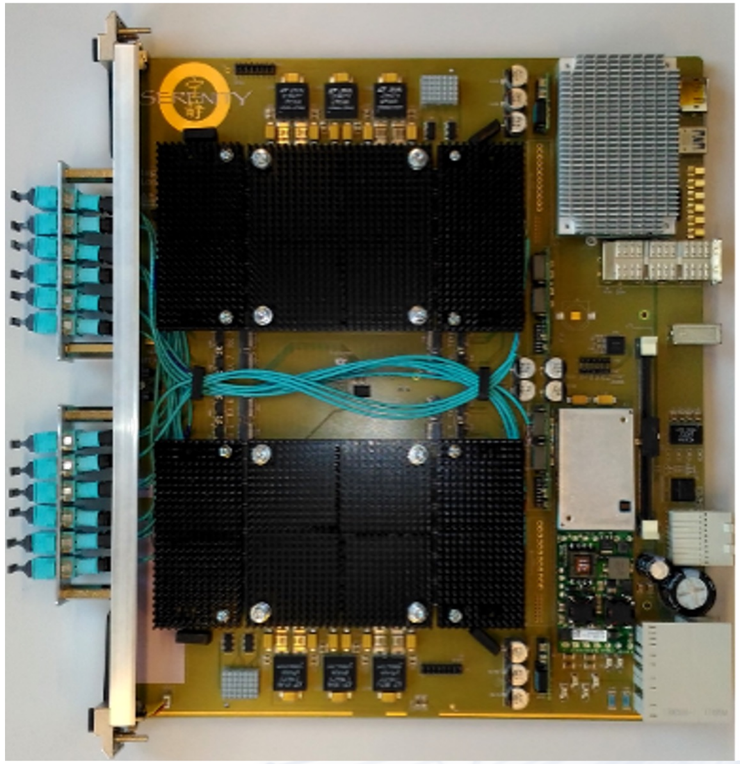



- Stubs: average position of the seed cluster + average position of the correlation cluster
  - L1 trigger
  - 40 MHz readout
- Hits: information on ALL the strips/pixel in a module (one bit per strip/pixel)
  - Final DAQ
  - 750 kHz readout

# Involvement for DAQ chain

- Passage from test system (uDTC) to final readout system (DTC)
  - From readout via optical + IPBus + computation in resident CPU → optical + computation in FPGAs in the board
  - Transition of the calibration software for 2S modules → calibration SW for PS has just been deployed on the test system, time to transition also that!



# MUonE

# MUonE Physics case - Introduction

- Anomalous magnetic moment of a lepton as precison test for SM
  - Can be (very) precisely calculated in SM framework
  - But… it's flavor dependent!

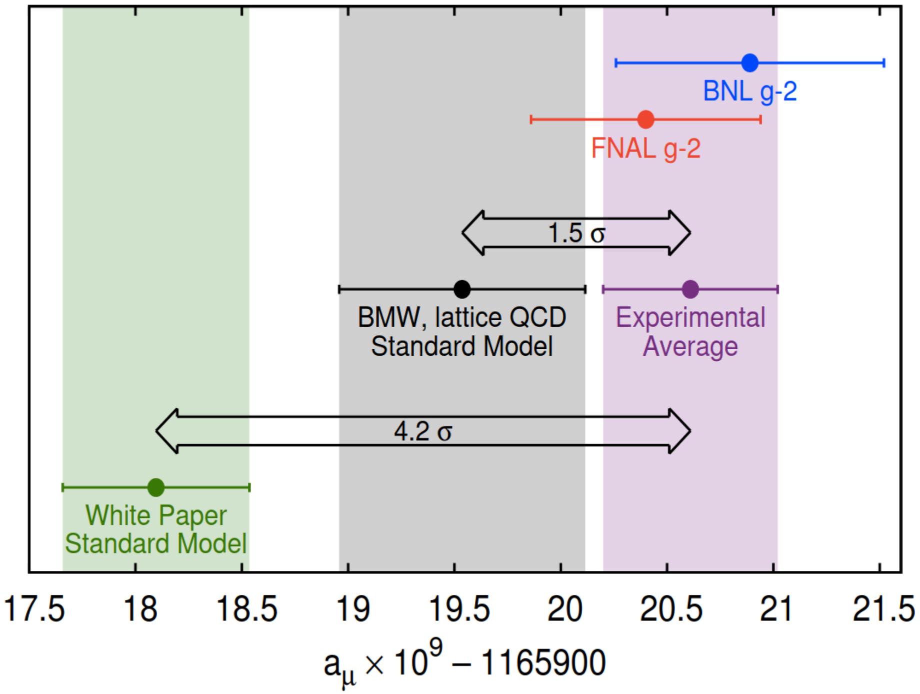
$$\vec{\mu} = g_\mu \frac{e\hbar}{2m_\mu c}\vec{s}$$

$$a_\mu = \frac{g_\mu - 2}{2}$$

- Electron
  - $g_e$-2 determined with high precision
  - Sensitivity to new particles limited by a ~$(m/M)^2$ factor
- Muon
  - Sensitivity to an higher mass region [GeV, TeV]
  - State of art: 4σ discrepancy from SM prediction

# State of the art

FNAL g-2 Run1 results:



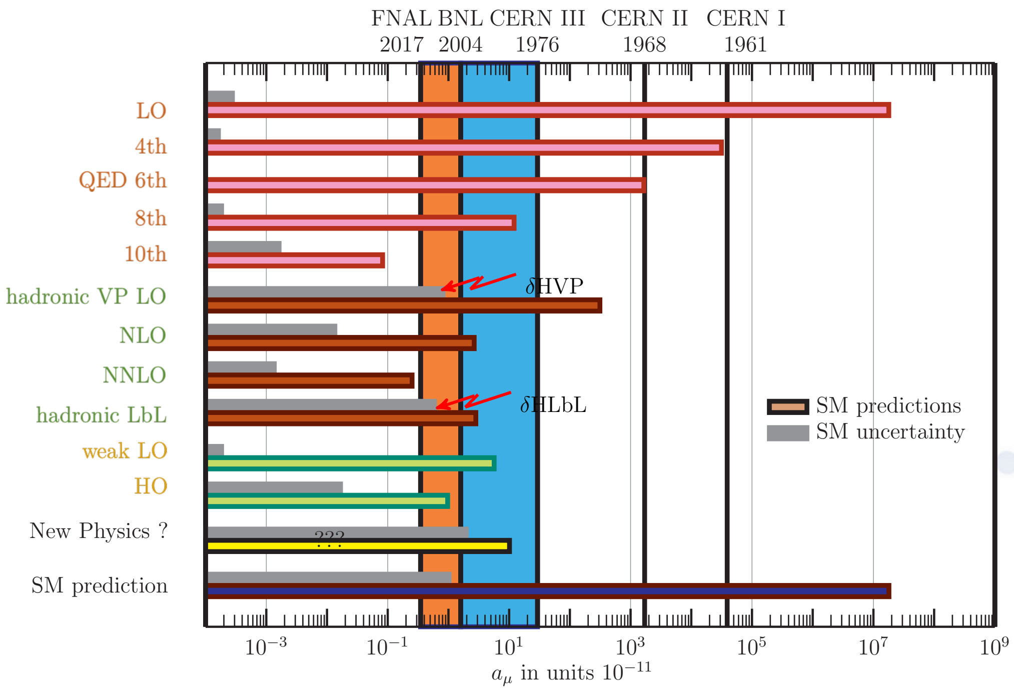

$a_\mu^{EXP} = (116592089 \pm 63) \times 10^{-11}$ [0.54ppm] BNL E821

$a_\mu^{EXP} = (116592040 \pm 54) \times 10^{-11}$ [0.46ppm] FNAL E989 Run 1

$a_\mu^{EXP} = (116592061 \pm 41) \times 10^{-11}$ [0.35ppm] WA

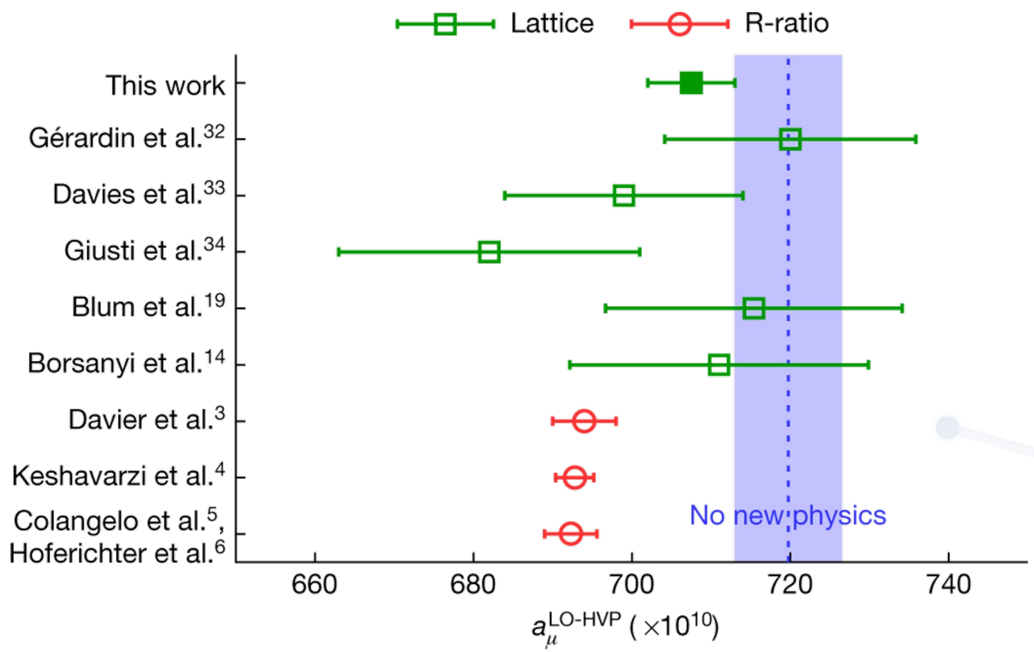
# Present theoretical uncertainties

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HAD}$$



# $a_\mu^{HLO}$: LO Hadronic contribution

- Traditionally computed via a dispersion integral using hadronic production cross sections in electron-positron annihilation at low energies
- QCD lactice calculation still not competitive
  - …at least up to the FNAL g-2 results…




Borsanyi, S., Fodor, Z., Guenther, J.N. et al.
*Leading hadronic contribution to the muon magnetic moment from lattice QCD* - Nature 593, 51–55 (2021).

# Measuring $a_\mu^{HLO}$ – how to

- MUonE: high precision measurement of $a_\mu^{HLO}$
  - 160 GeV μ beam on $e^-$ target at CERN
- Hadronic contribution to the effective electromagnetic coupling, $\Delta\alpha_{had}(q^2)$ for space-like squared four-momentum transfers $q^2 = t < 0$, via scattering data

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}(t(x))dx$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} \quad (0 \le -t \le +\infty)$$

t : momentum trasfered in the reaction

# Measuring $a_\mu^{HLO}$– how to

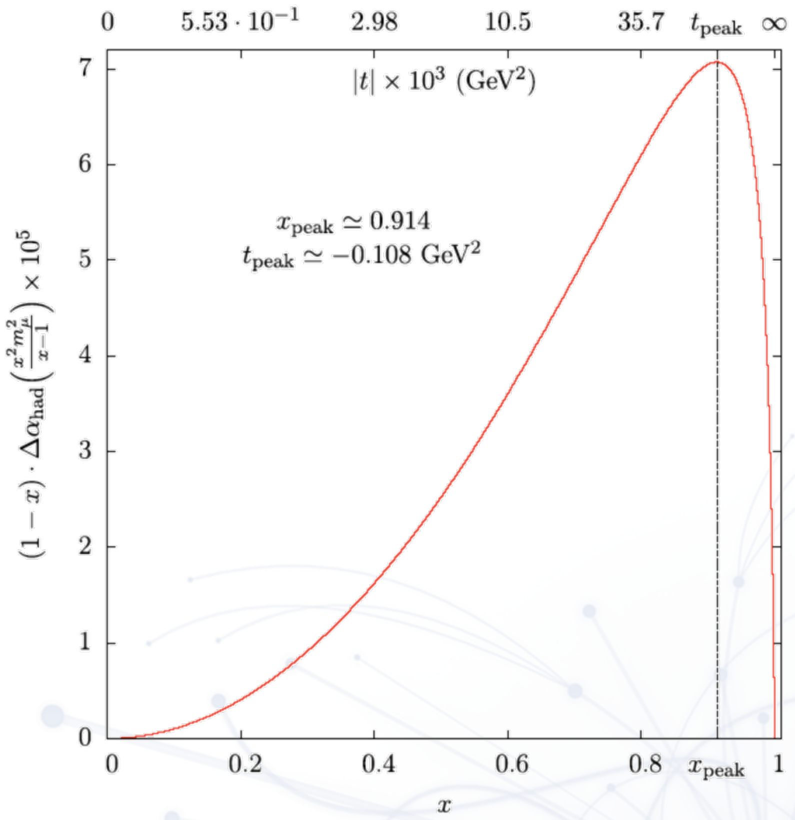
- Experimental kinematic limit:

  0 < -t < 0.161 GeV

  or

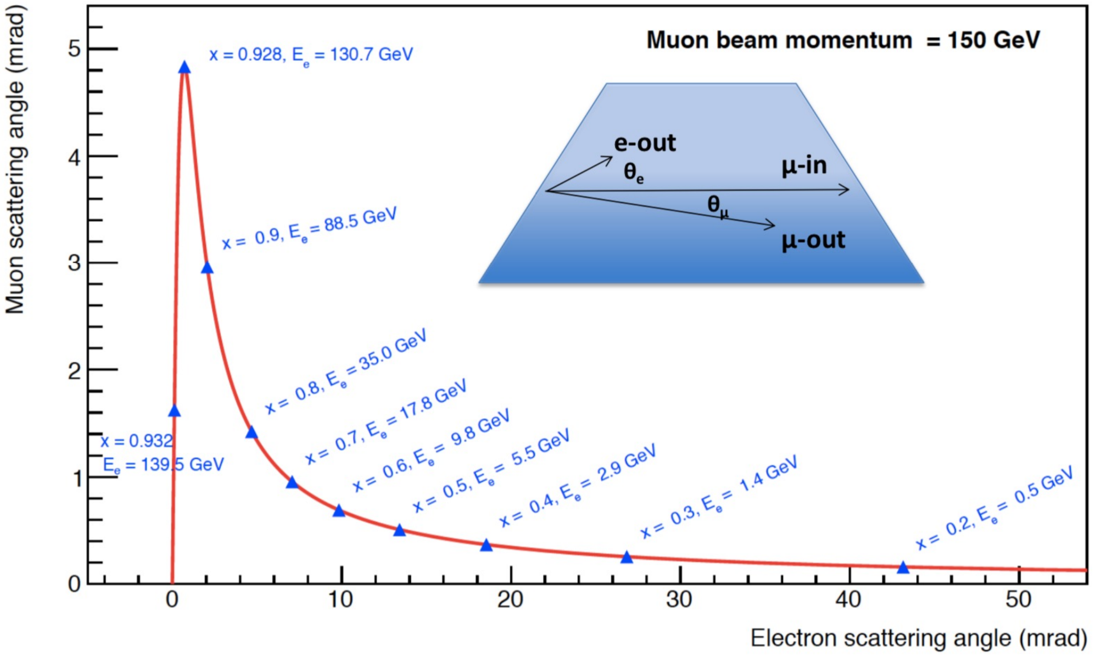
  0< x <0.93

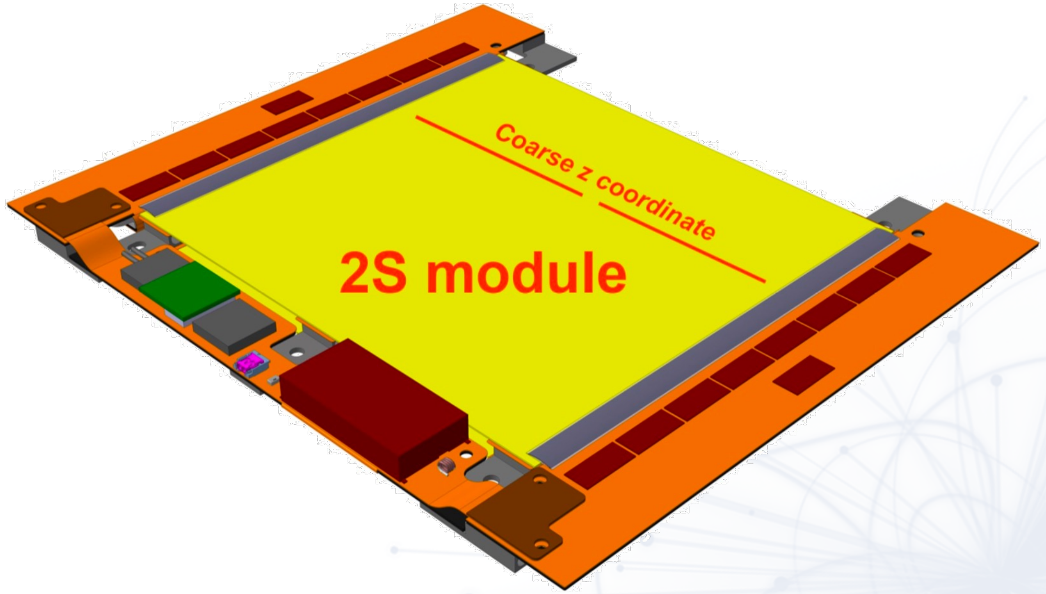
- ~87% of the area → extrapolated to 100% with functional model of $\Delta\alpha_{had}$ (t)



# Measuring $a_\mu^{HLO}$– key element

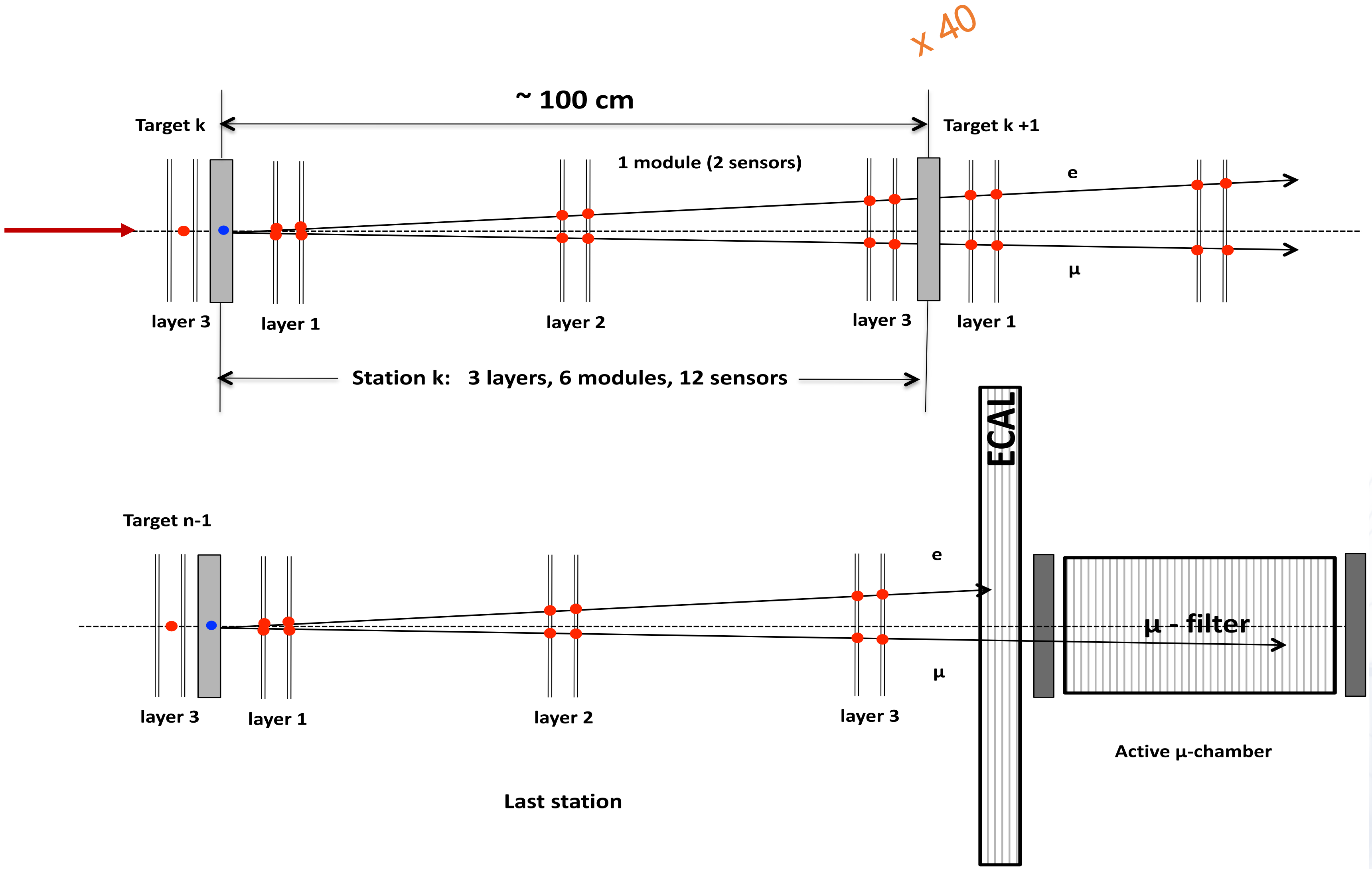
- Measure of the scattering angles precise tracking and at high rate
- Best solution: 2S modules from CMS



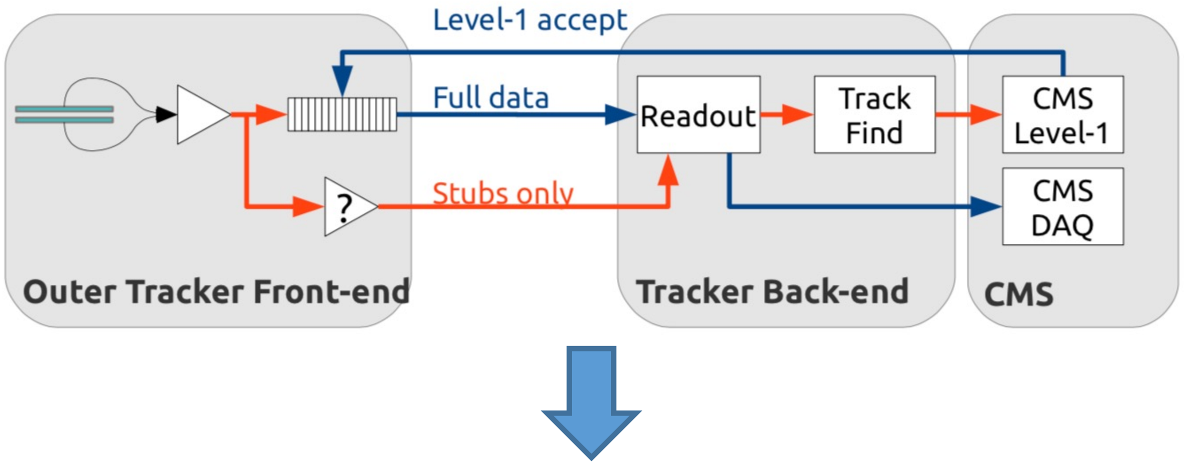
# MUonE Detector

High Intensity μ beam (160GeV)

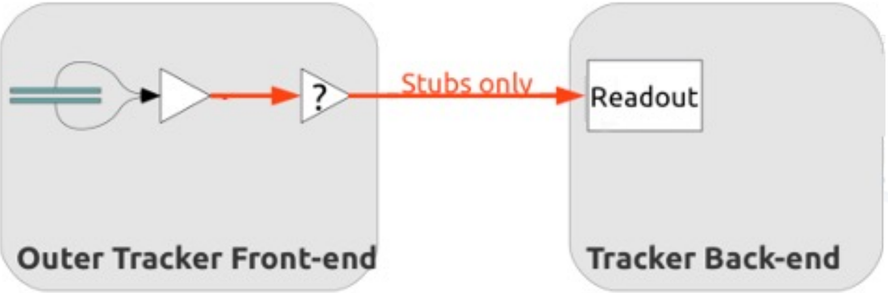


# MUonE DAQ chain

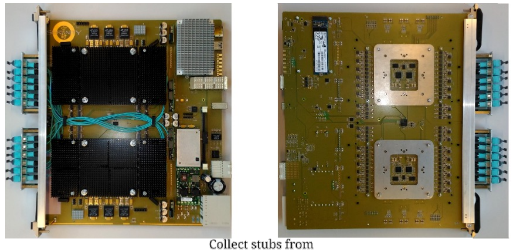
CMS

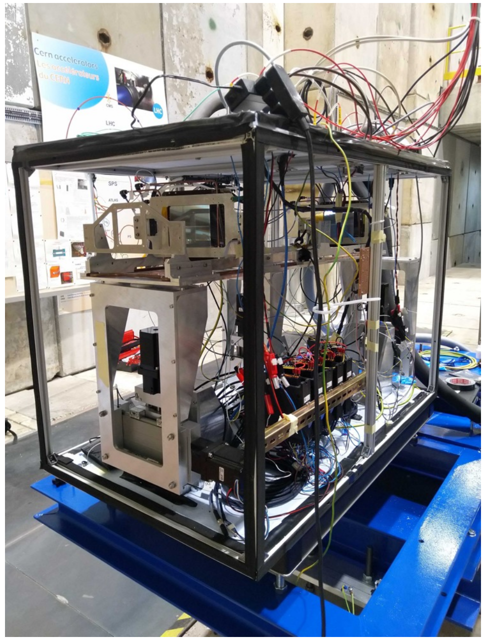


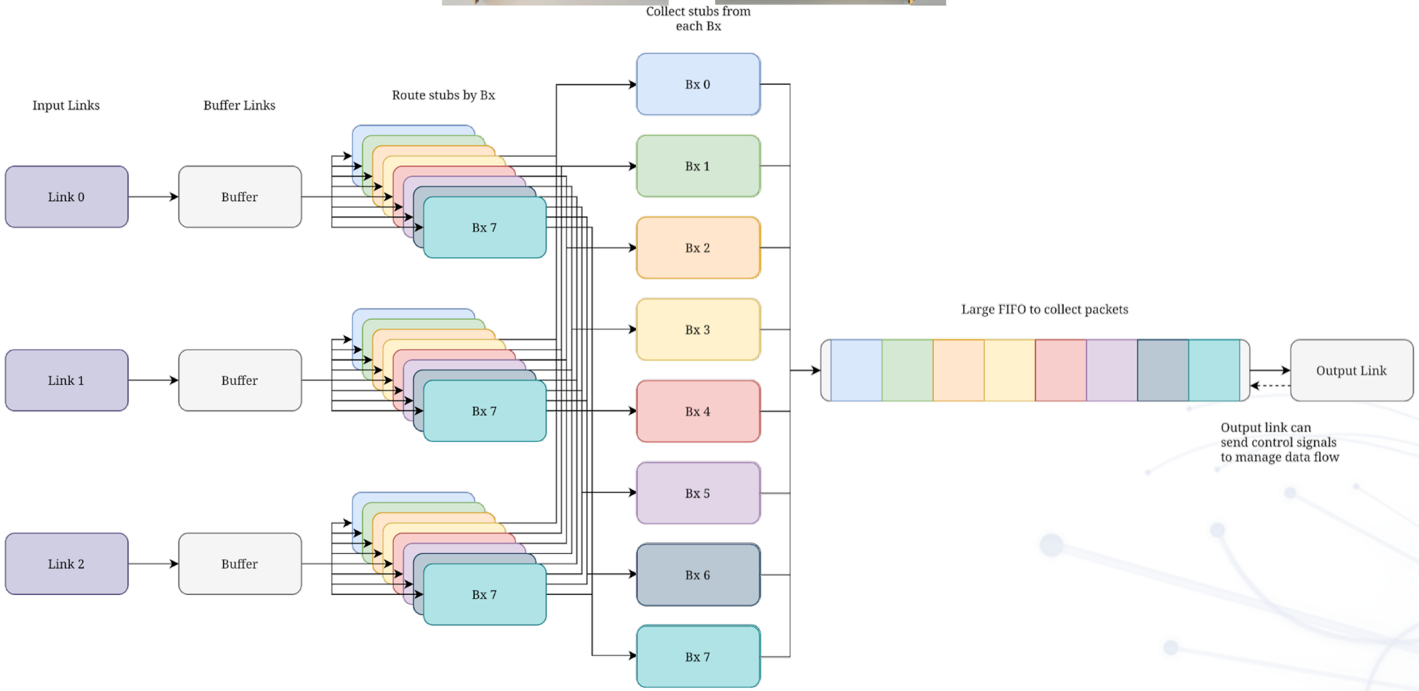

MUonE



# MUonE DAQ chain

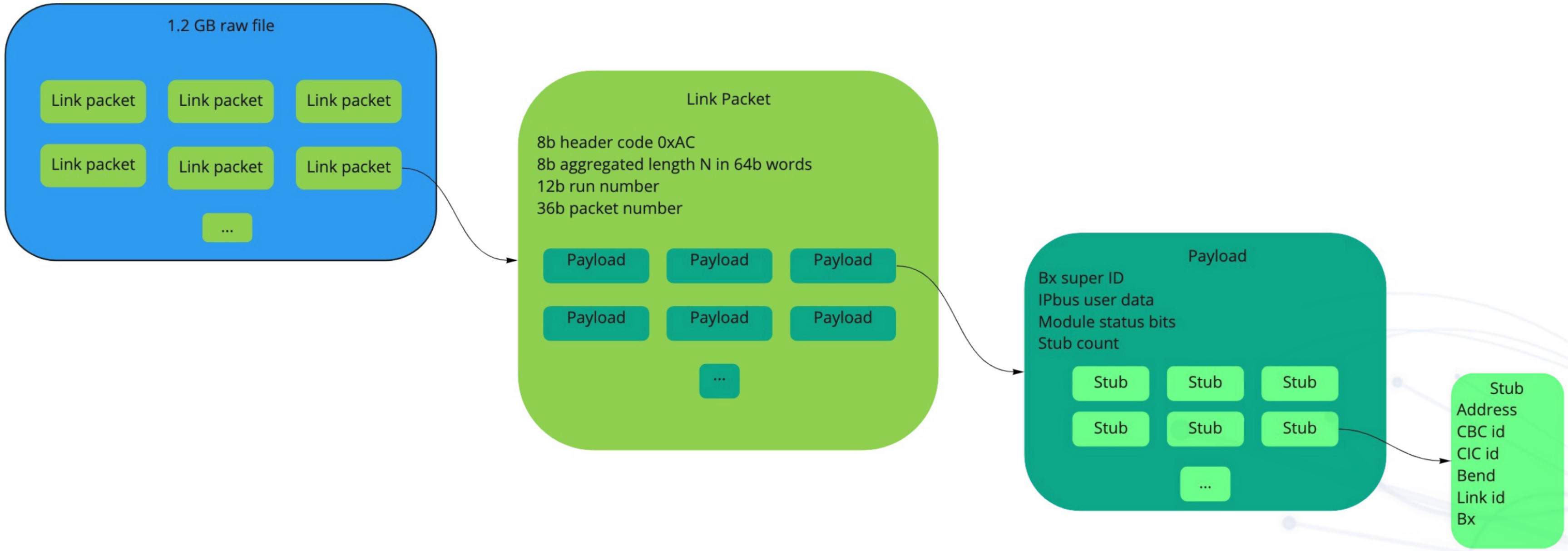






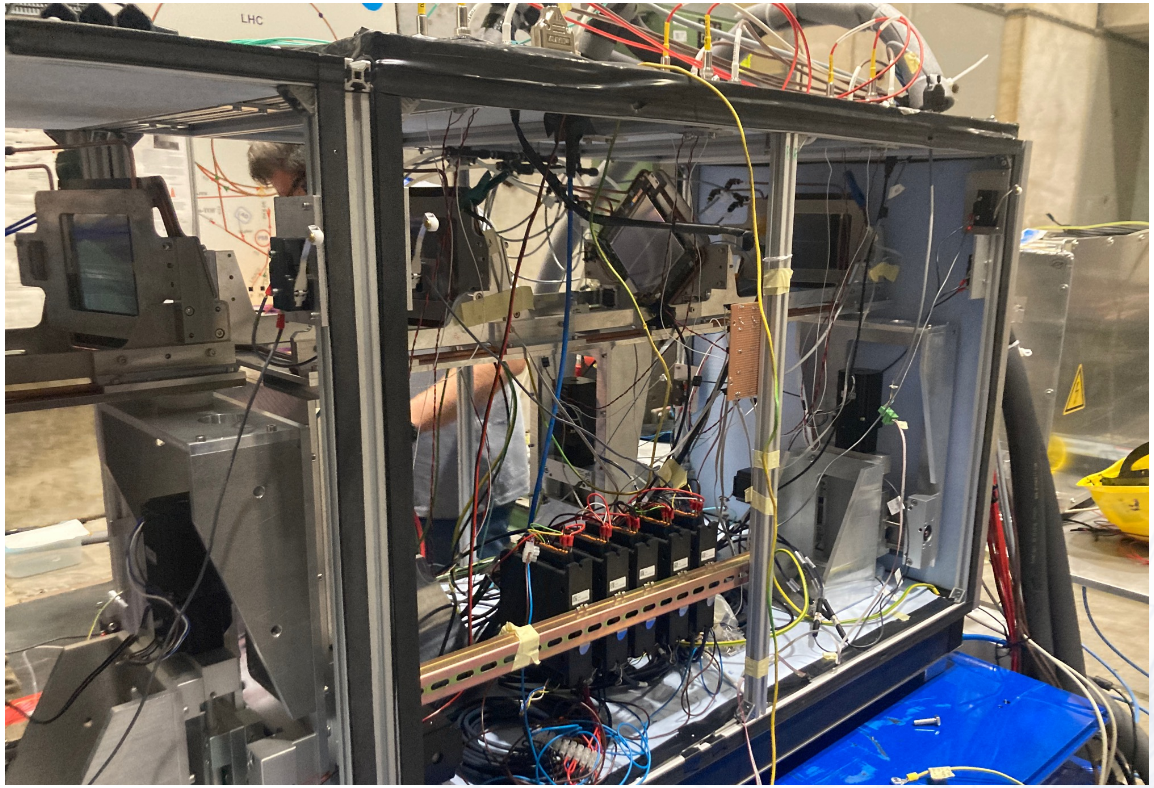

# Data Structure from the 10 GB link

- On the sink PC 1.2 GB raw files are saved
- Raw files structure:
- Decoding of raw data → different readable formats for analysers



# MUonE – 2022 test beam setup

- *First time*: 6 modules readout at high intensity
- One completely equipped station + target → first possibility to reconstruct tracks and study MUonE capabilities and resolution
- Stress test for DAQ final system → 20 MHz muon beam ~ half of the expected rate in CMS for HiLumi

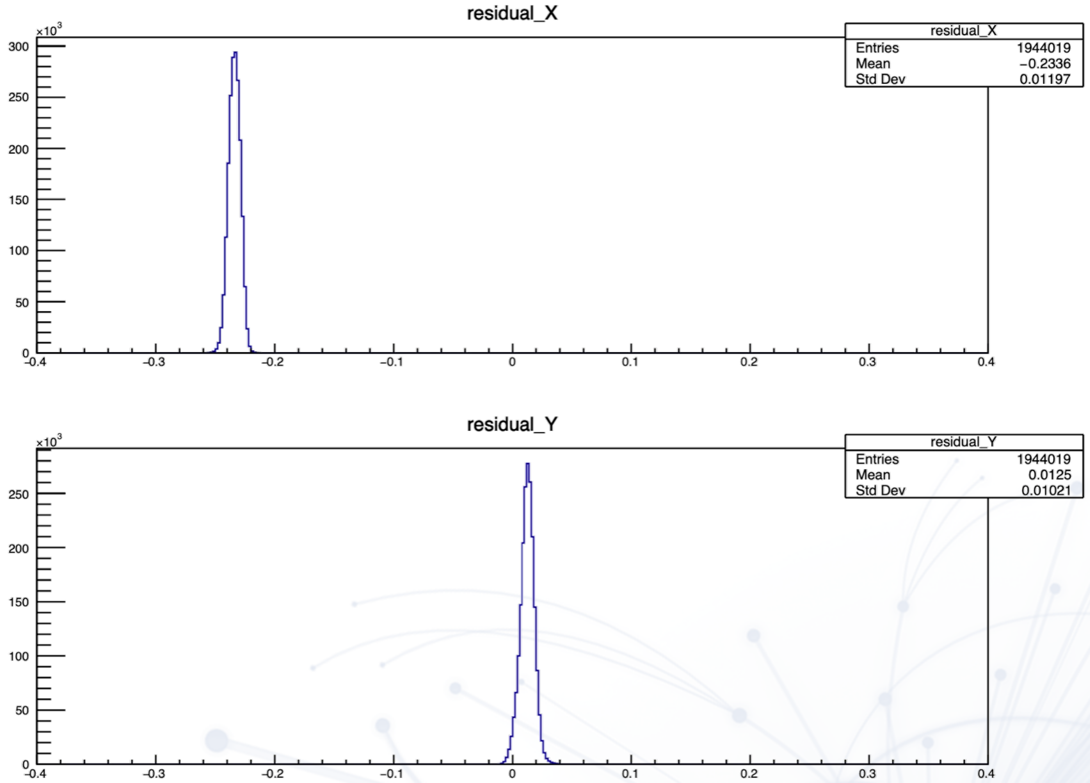


# Data Quality Monitoring

- Deployment of DQM tools:
  - Fast
  - Interactive
  - Keeping track of both firmware errors and hardware conditions
  - With an eye on scalability for the future
  - In progress: adding fast reconstruction of tracks

# Offline analysis

- Firsts results from tracking of this year TB – ended yesterday
- First simple tracking with just a single particle passing through the detector → estimate of residuals
- Results around what expected ~ 100 um resolution → preliminar! Alignment still to be done



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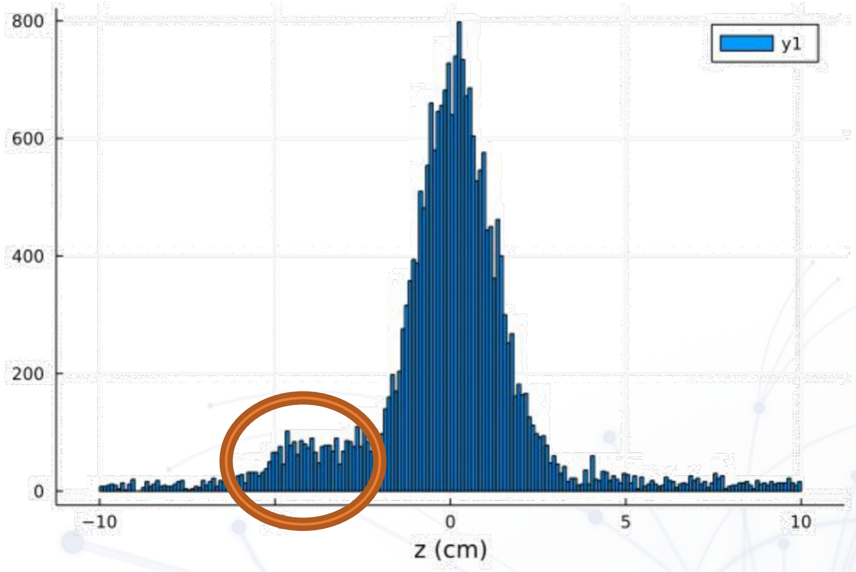
- First track reconstruction in 2D performed

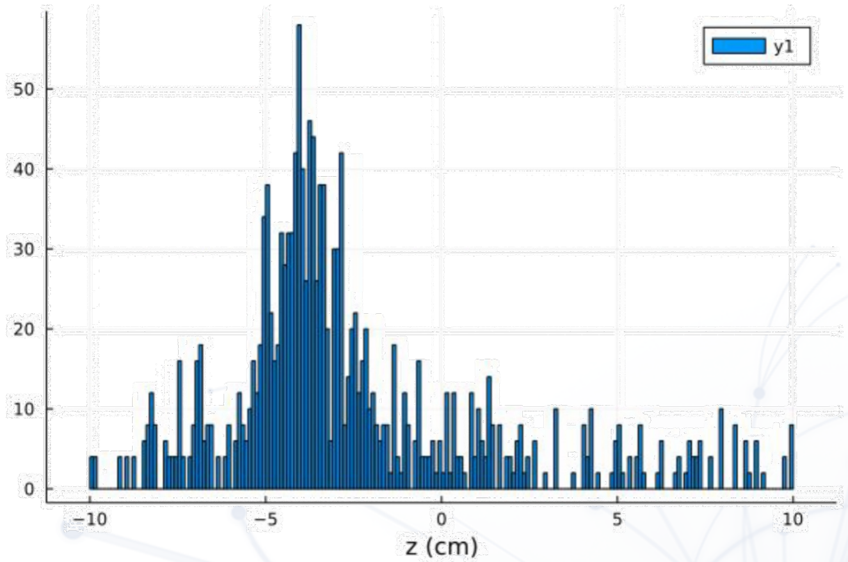
Position of the interaction vertex with target



# Offline analysis

- Firsts results from tracking of this year TB – ended yesterday
- First simple tracking with just a single particle passing through the detector → estimate of residuals
- Results around what expected ~ 100 um resolution → preliminar! Alignment still to be done
- First track reconstruction in 2D performed
- You can recognize budget material

Position of the interaction vertex **without** target



# Plans for the next year

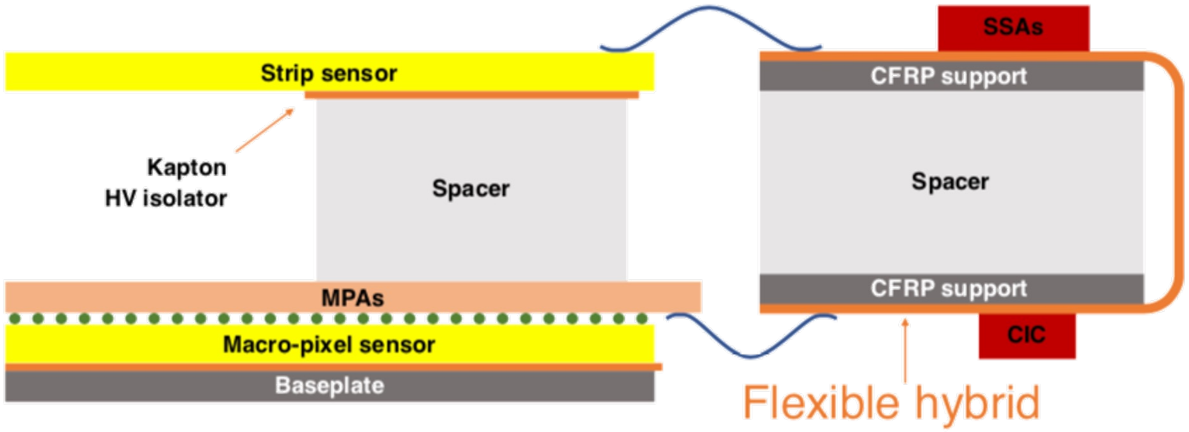
- Continuous work on passage from test DAQ system → final DAQ system. First step: transition of the whole calibration code for PS modules
- Analysis on test beam dataset:
  - Alignment of the modules – never done still with stubs data stream
  - Studies on track reconstruction algorithms
  - Estimate of MUonE capability, resolution and extrapolation to sensitivity of the whole experiment
  - Characterization of CMS 2S modules
  - Characterization of failures in high intensity for DAQ firmware

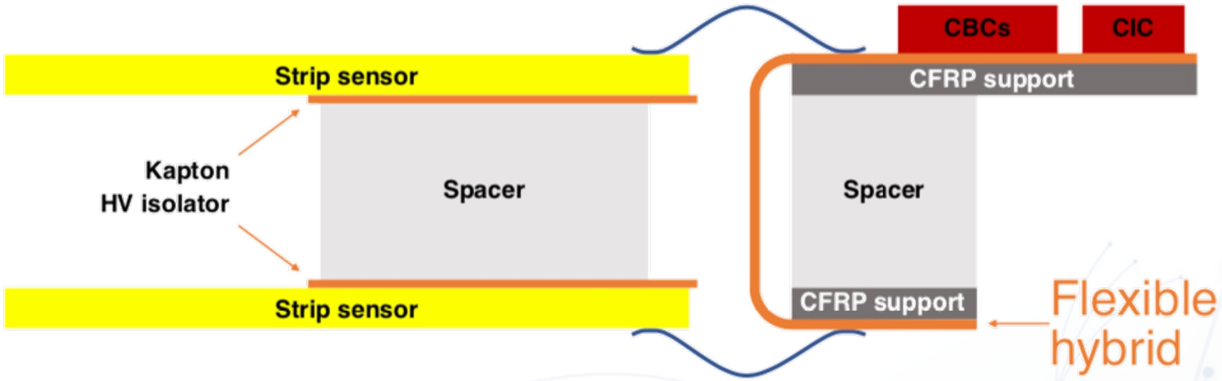
# Backup

# Educational activities

- INFN School of Statistics 2022 [1]
- Standard Model at the LHC 2022 [2]

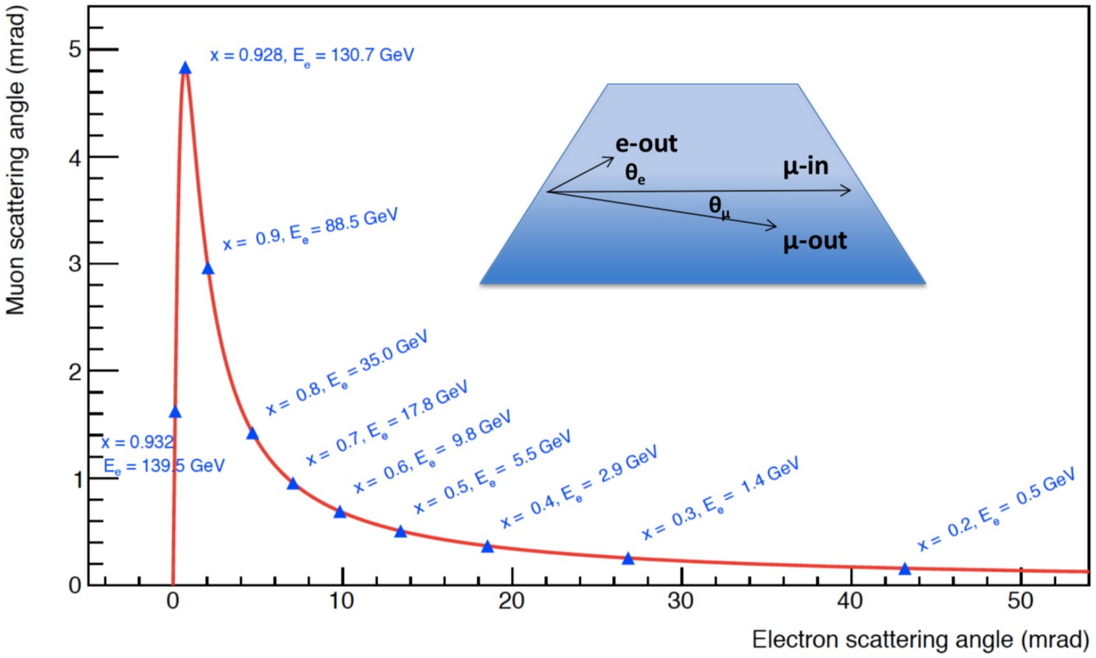
# DAQ for CMS modules



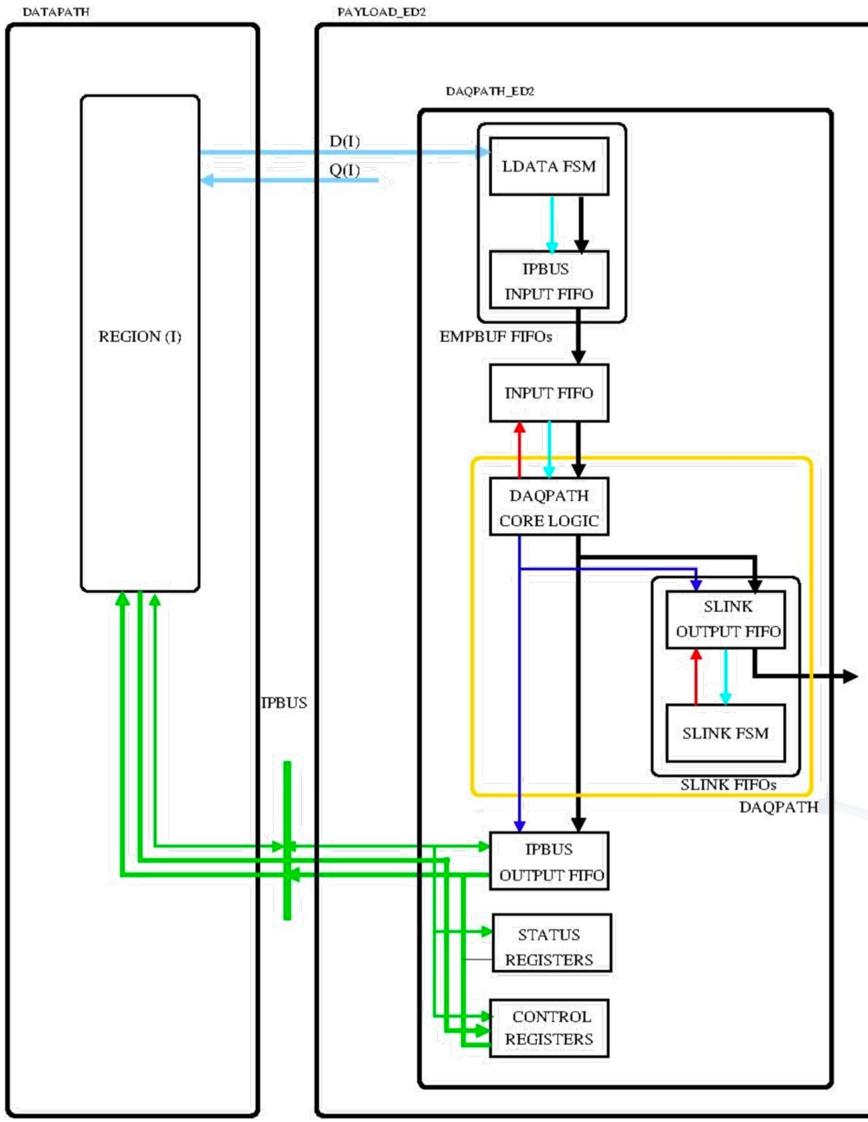
# Key element

- The key elemet to achieve the precision required is the measure of the scattering angles




- Experimental needs:
  - PID to separate electron and muon → ECAL + μ-filter
  - Precise tracking for angles → Tracker
  - Electron energy measurement to add redoundancy and reduce systematics→ECAL

# DAQPath inclusion and testing



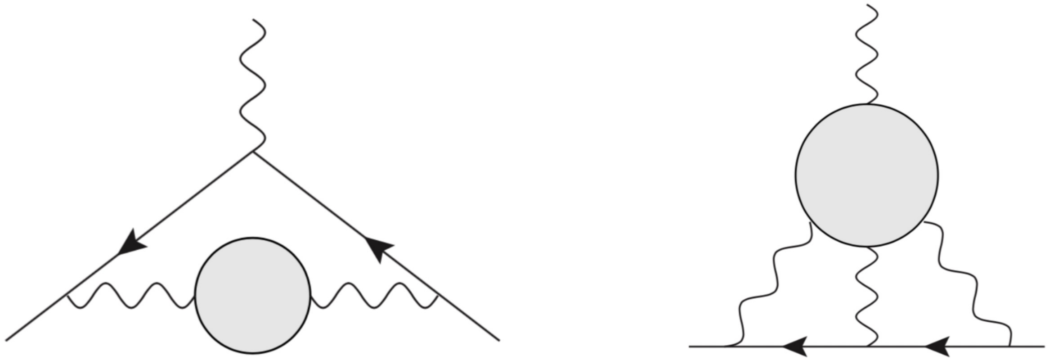


Figure 1: The hadronic contributions to $(g-2)_\mu$ dominating the theory uncertainty budget. Left: the hadronic vacuum polarisation contribution. Right: the hadronic light-by-light scattering contribution. A solid line represents the muon propagator, the wavy lines represent photon propagators. The external magnetic field is represented by a photon line coming in from the top.

https://arxiv.org/pdf/1911.08123.pdf