MuonE

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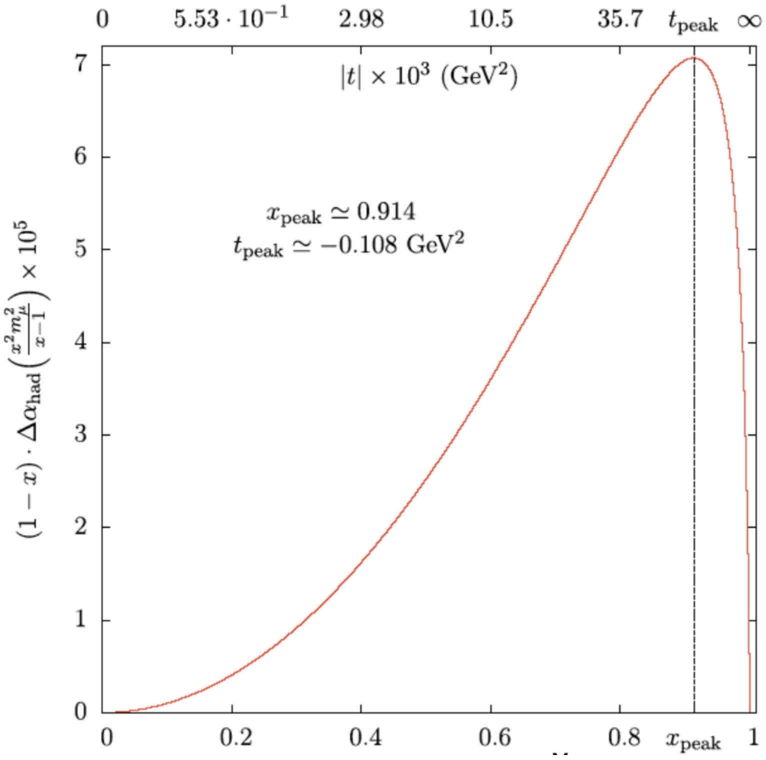
FCCP2021, 2021 September 16

The LO-HVP space-like

C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni, **Phys.Lett.B746(2015)325.**
Initially proposed for use with Bhabha scattering data from flavour factories

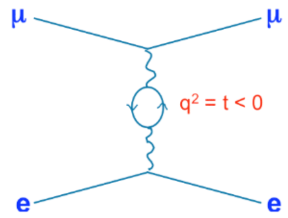
- $\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of $\alpha(t)$, to be measured in the space-like region $t = q^2 < 0$.
- The integrand function is a smoot function: there are no resonances.
- Low-energy enhancement: peak of the integrand at $x \cong 0.9$, $t = -0.11\ \mathrm{GeV}^2$, $\Delta\alpha had(t_{max}) \sim 10^{-3}$

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\cdot\Delta\alpha_{had}\left(-\frac{x^2 m_\mu^2}{1-x}\right)$$



MuonE experimental proposal

Eur. Phys. J. C77(2017)139



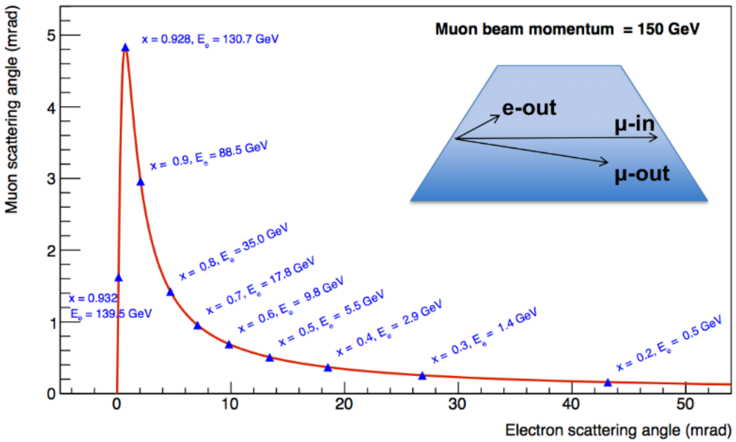
of α

$$\frac{d\sigma}{dt} \approx \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \approx \frac{d\sigma_0}{dt}\left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

$$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$$

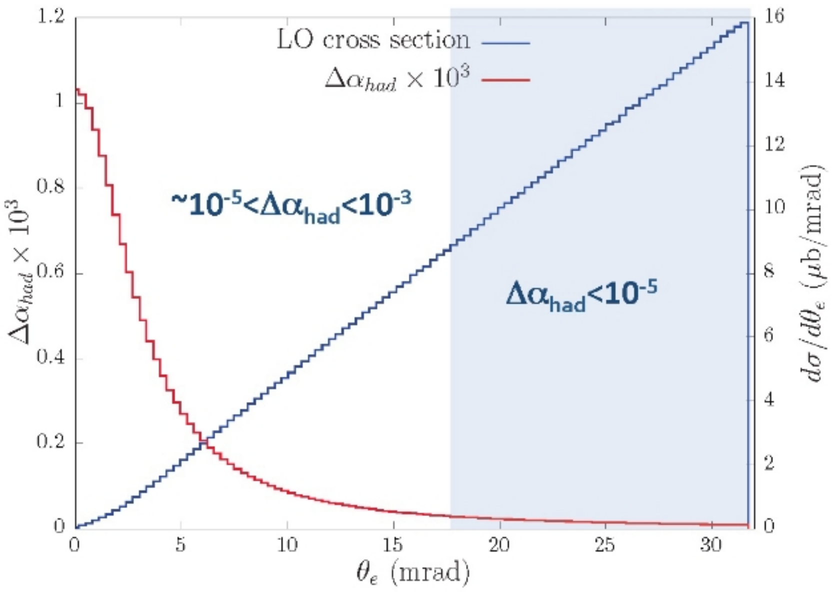
- Elastic scattering **μ + e → μ + e** with **E_μ = 160 GeV** colliding on atomic electrons of a fixed target with low Z.
- High intensity **CERN M2** muon beam: ~50MHz
- **The shape of the angular differential cross section** used to measure **$\Delta\alpha$(t)**.
  $\Delta\alpha_{had}$(t) requires subtracting **$\Delta\alpha_{lep}$(t)**
  We'll get a_μ^{HLO} with the space-like approach.
- **Higly boosted final states** produced in the collisions: 0 < -t < 0.161 GeV^2 , 0 < x < 0.93
  The **angular range** in the order of the mrad.
- For **E_μ = 160 GeV** the **phase space covers 87% of the integral**. Smooth extrapolation to the full integral with a proper fit model is possible.

Scattering angles



Main features of the elastic process

The hadronic contribution to the running as a function of the electron scattering angle: Effects are detectable for small electrons scattering angles



The differential cross section here is in blue

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{\lambda(s, m_e^2, m_\mu^2)}\left[\frac{(s - m_e^2 - m_\mu^2)^2}{t^2} + \frac{s}{t} + \frac{1}{2}\right]$$

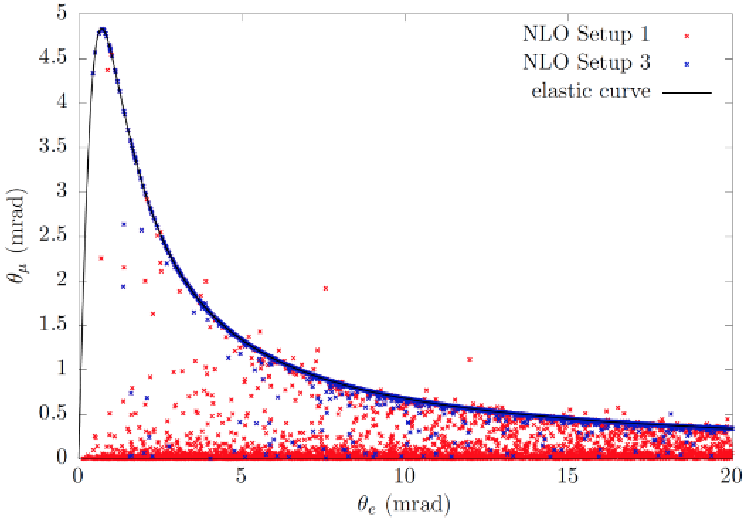
$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \qquad \alpha(t) = \frac{\alpha(0)}{1 - \Delta\alpha(t)}$$

$$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$$

Simple kinematics: $t \cong -2\, m_e E_e$

E_e can be determined from the scattering angle θ_e and the beam energy

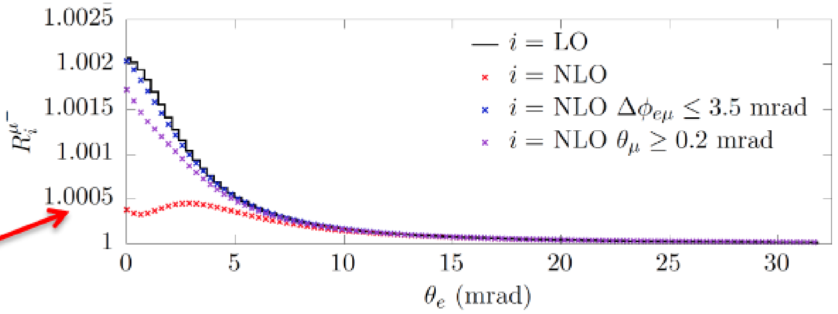
NLO and elastic selection



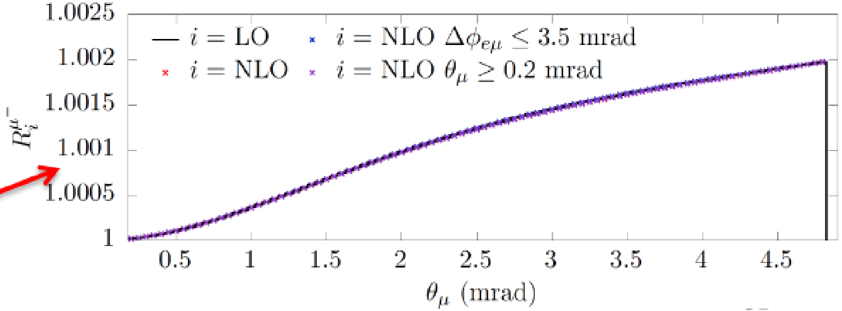
[M.Alacevich et al, JHEP02(2019)155](#)

NLO Setup 1 is the inclusive selection (no cuts)
Setup 3 has an acoplanarity cut $|\pi-(\phi_e-\phi_\mu)|<3.5$ mrad

Without any selection the signal sensitivity of the electron angle is destroyed -> necessary to implement an "elastic" selection

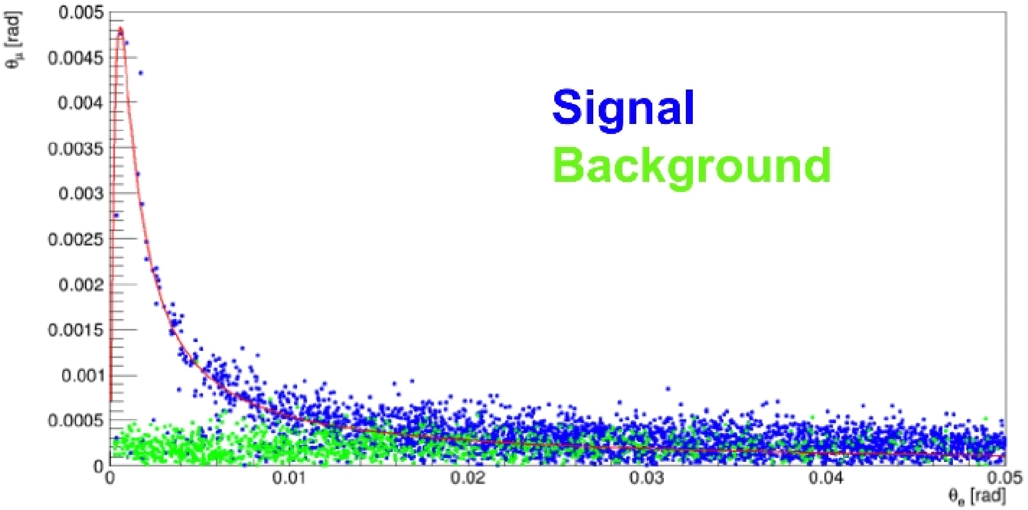


Instead the muon angle is a robust observable, stable w.r.t. radiative corrections -> it can be used with an inclusive selection (theoretically advantageous)

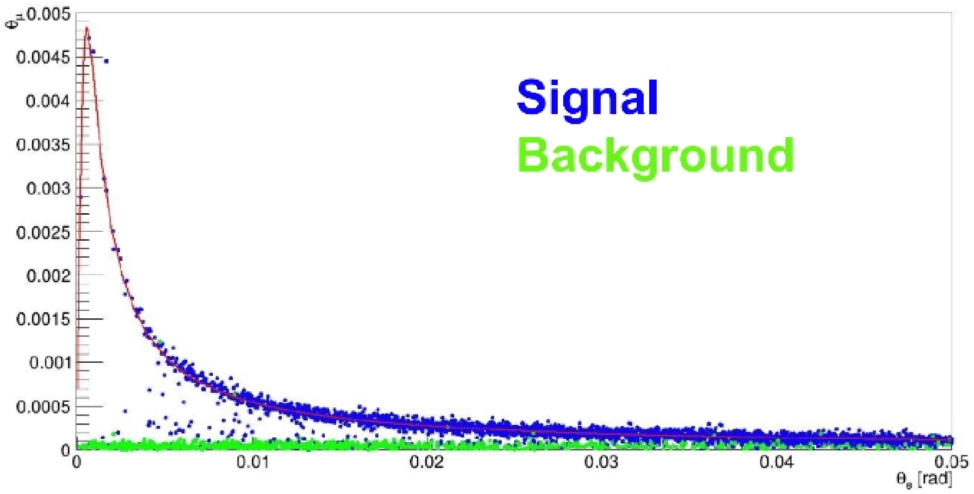


Crucial role of the silicon detector intrinsic resolution

Resolution 40μm



Resolution 10μm



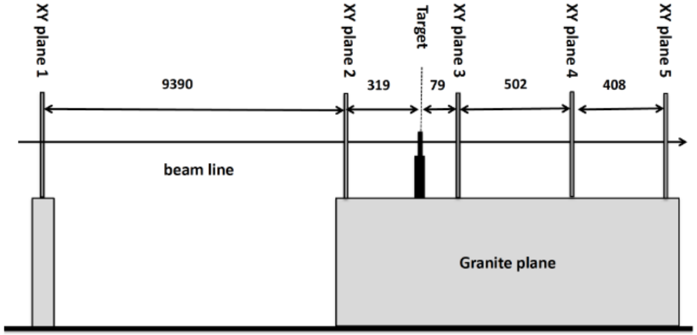
GEANT4 simulations

How the background's processes are described in GEANT4?

MCS studies: beam tests at CERN

JINST 15(2020) P01017

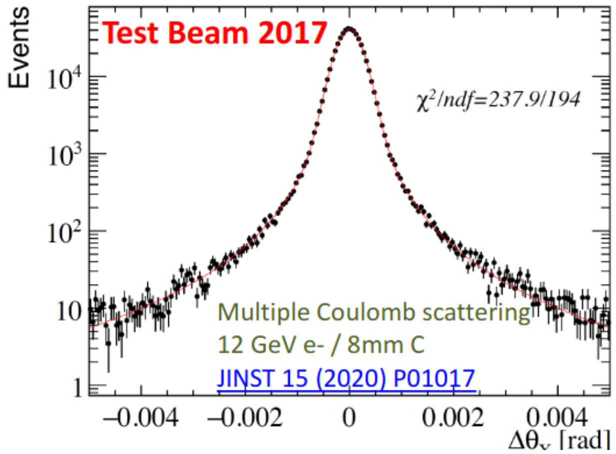
Adapted UA9 detector at CERN H8 Beam Line
Hit resolution 10 μm

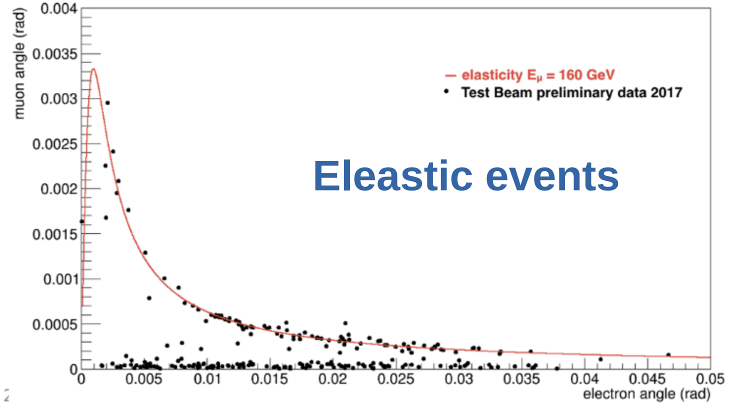


Evidence for μe elastic scattering with μ beam with E=160 GeV

Golden Selection: single track in, two tracks out

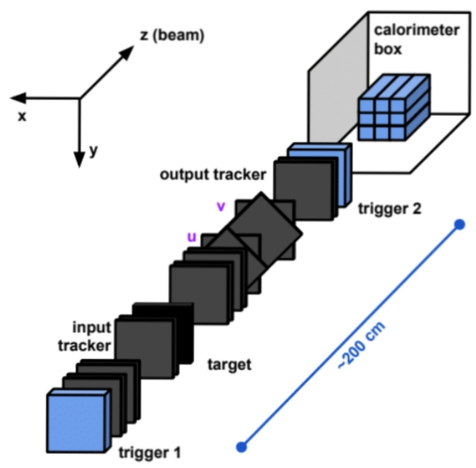
MSC effects: agreement to 1%

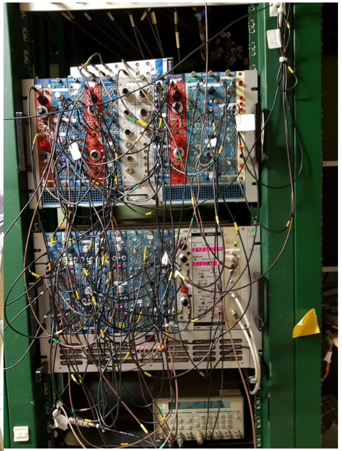




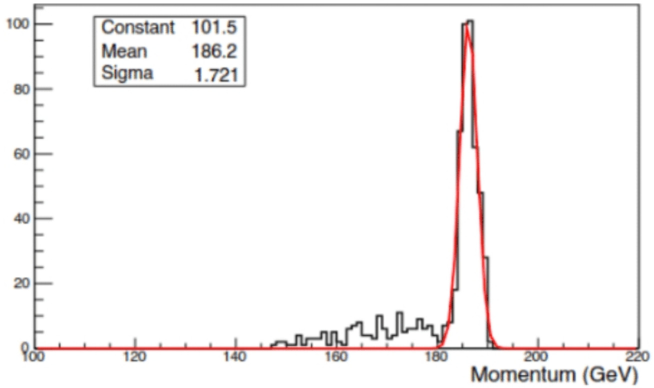
Eleastic events

TB2018: low counting rate





Muon momentum peaked at 187 GeV

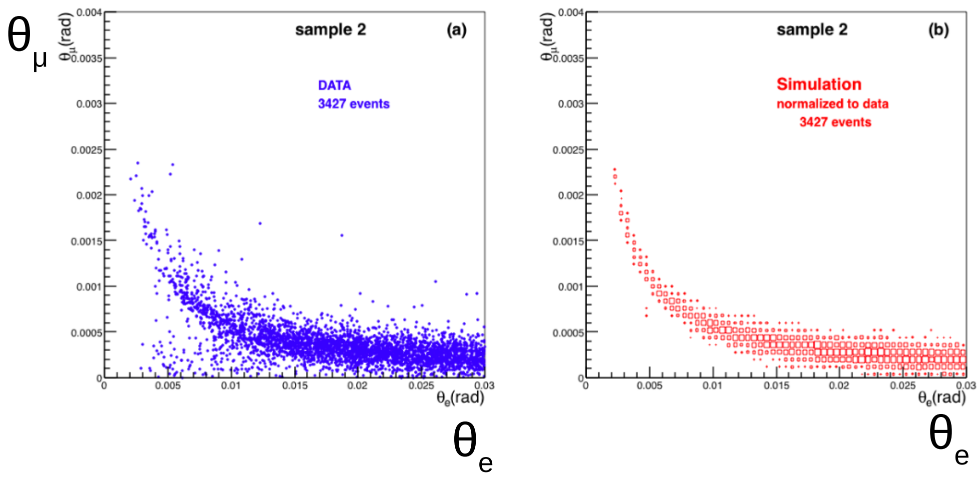


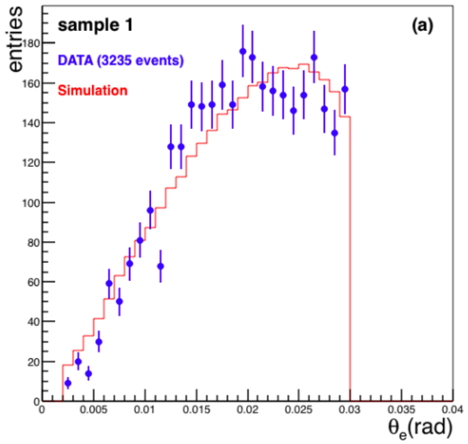
The Detector was located downstream COMPASS
Muons came from 190 GeV pions decaying in flight.
1m thick W filter installed to get rid of residual pions
Counting rate below **10 kHz**
Sensor hit resolution ~ **40 μm**

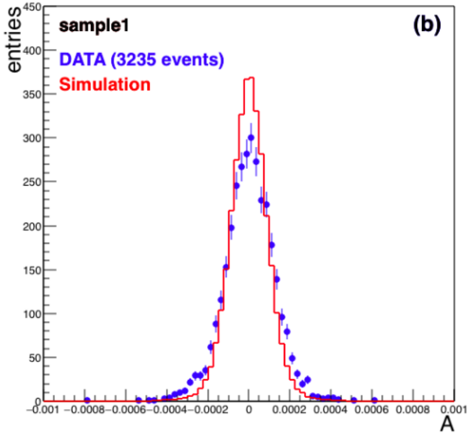
TB2018 data analysis

- **A study of muon-electron elastic scattering in a test beam. arXiv2021.11111, https://arxiv.org/pdf/2102.11111.pdf**
  Published by **JINST**

Correlation plots **Emission angle** **Acoplanarity**

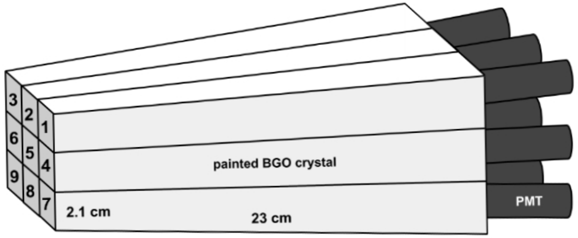


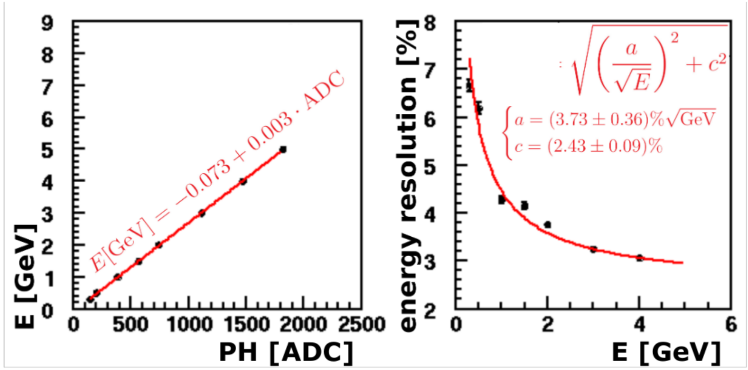


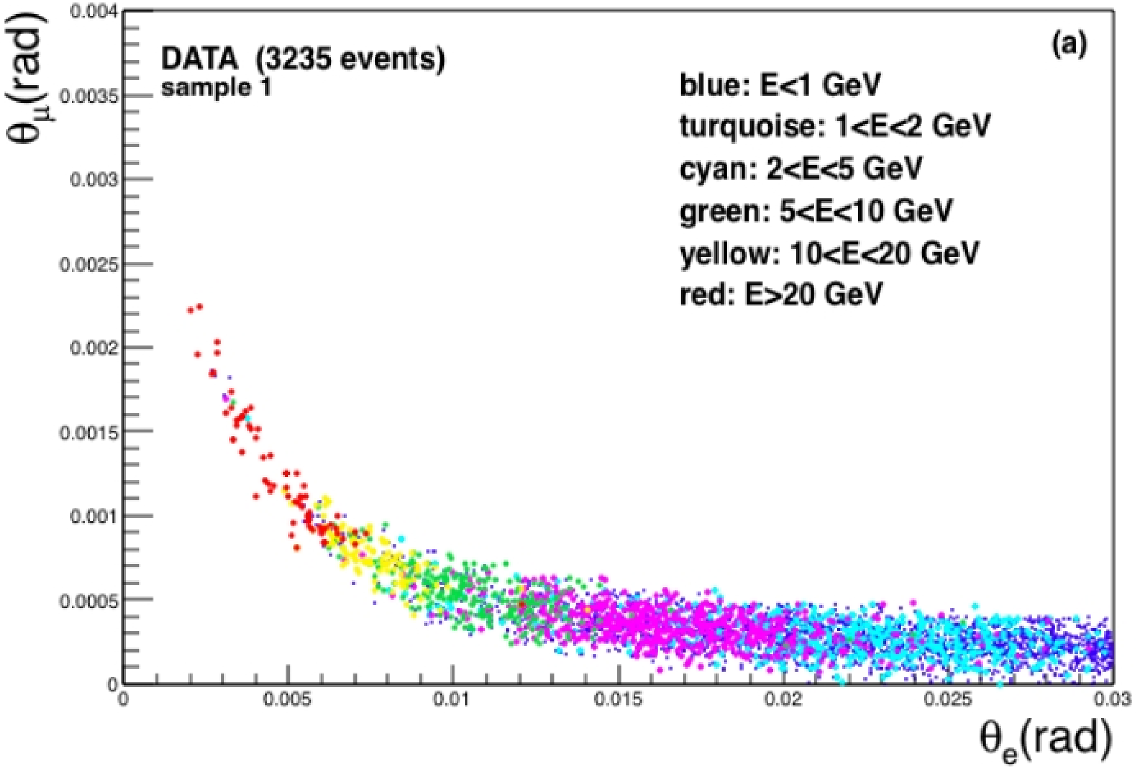


- **Conclusions**: We were able to select a clean sample of elastic events. Background description deserve a dedicated study.

TB2018 data analysis





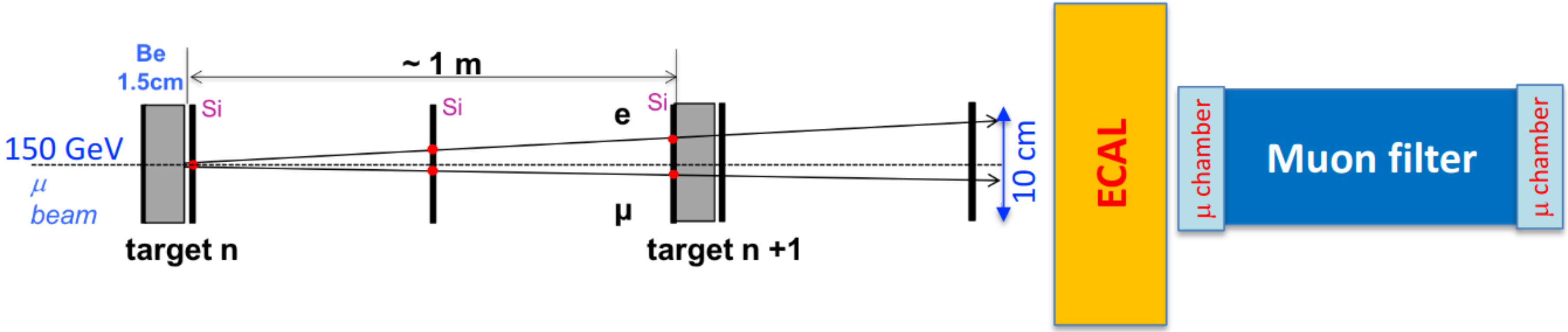


BGO tapered crystals, obtained by machining bigger spare blocks of the L3 endcap calorimeter

Detector layout

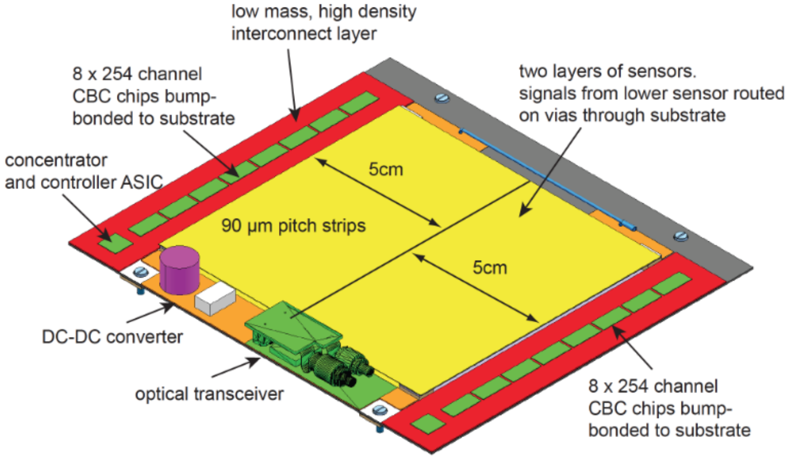
Letter of Intent SPSC-I-252

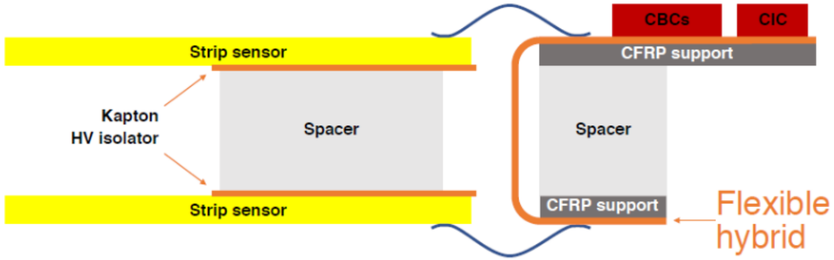
- Boosted kinematics: θ_e <32mrad (for E_e>1 GeV), θ_μ<5mrad
  The whole acceptance can be covered with a 10x10cm² silicon sensor at 1m distance from the target, reducing many systematic errors
- Minimal distortions of the outgoing e/μ trajectories within the target material and small rate of radiative events
- Modular structure of ~40 independent and precise tracking stations, with split thin light targets equivalent to 60cm Be
- ECAL and Muon filter after the last station, for PID and background rejection.



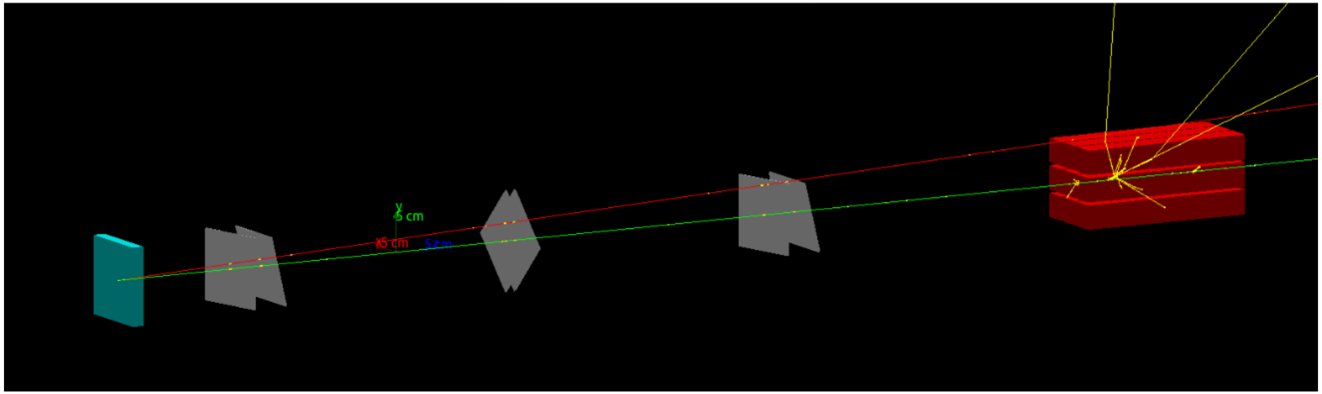
The silicon strip detector

- 2S modules, designed for the planned CMS upgrade exist: their surface is wide and they run fast.
- A modules consists of paired sensors to provide **stubs** at 40MHz
- Sensor’s pitch is 90µm, thickness is 320µm. A moules is twice as thick.
- Distance bewteen sensors 1.8mm
- 16 CBC chips, each reading 254 strips: 127 of the top and 127 of bottom sensor Binary readout.





Rotating the 2S sensors



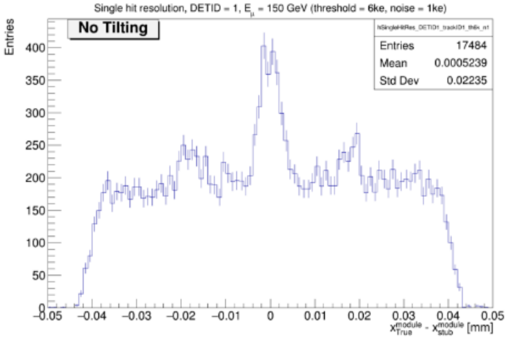
With a pitch of 90μm and the strip digital readout the expected resolution of a single sensor layer for single-strip cluster is **90/sqrt(12) ≅ 26μm**

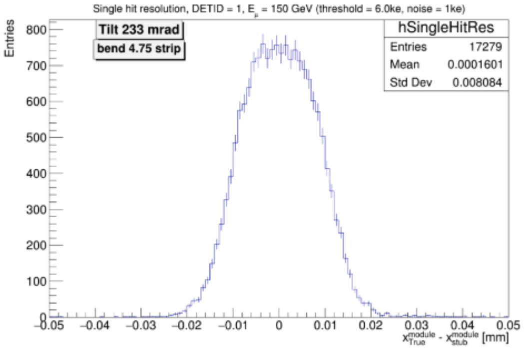
Rotating a sensor around an axis parallel to the strips direction improves the hit resolution.

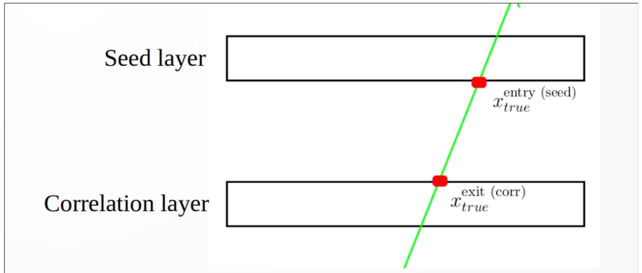
Optimal performance is obtained when **<cluster width> ~ 1.5** (same number of clusters made of 1 or 2 strips) for a **tilt angle ~14 degrees**

Further improvement by a small tilt of 25mrad, which is equivalent to an half-strip staggering of the two sensor layers of a 2S module

Sensors' tilted geometry







$$x_{stub} = \frac{x_{seed} + x_{corr}}{2}$$

$$\text{bend} = x_{corr} - x_{seed}$$

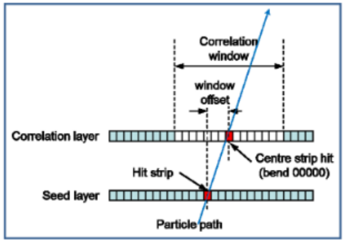
$$x_{stub} = x_{seed} + \frac{\text{bend}}{2}$$

Final resolution:

22 µm → 8-11 µm

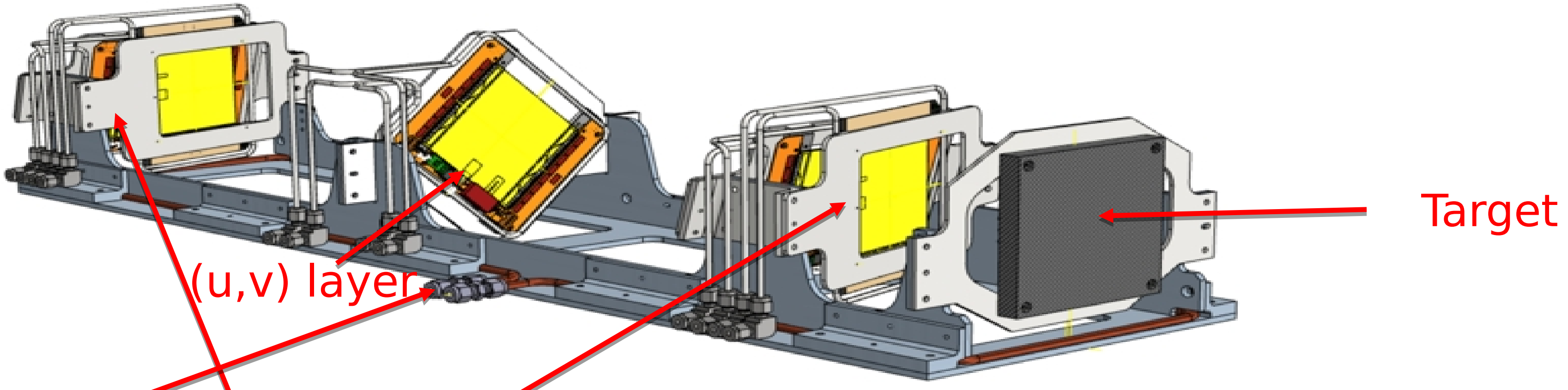
2S stubs at 40 MHz

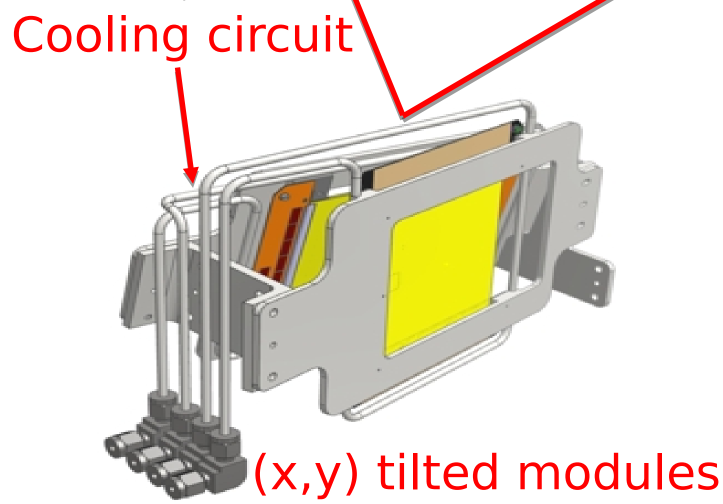
measured coordinate (x) determined by hit position on one layer and direction of the track stub



Tilt angle [mrad]	<bend> [strips]	threshold [σ]	resolution [µm]	<cluster width> [strips]
210	4.25	5	7.8	1.51
221	4.5	5.5	11.5	1.51
233	4.75	6	8.0	1.50
245	5	6.5	11.2	1.51
257	5.25	7	8.7	1.50
268	5.5	7.5	11.0	1.49

Tracker station

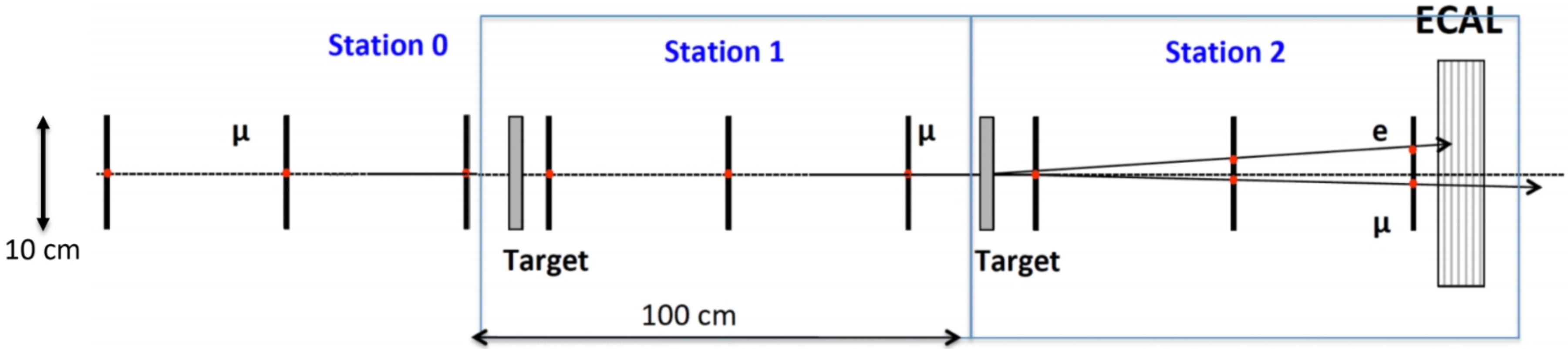




- (x,y) modules tilted with respect to the strip axis
- (u,v) central modules rotated to resolve ambiguities

- High mounting precision and mechanical stability required
- Low thermal expansion coefficient material: Invar, CTE = 1.2 x 10^{-6} K^{-1}
- Cooling circuit foreseen to control temperature

The final detector prototype



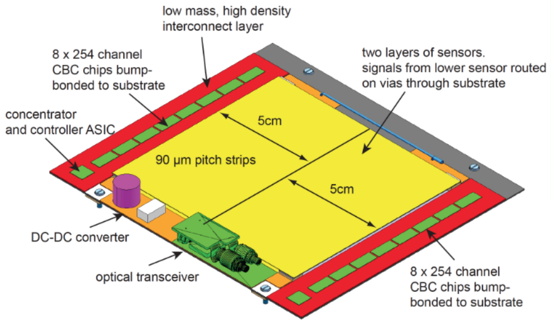
At the M2 beamline, upstream of the COMPASS detector, after its BMS

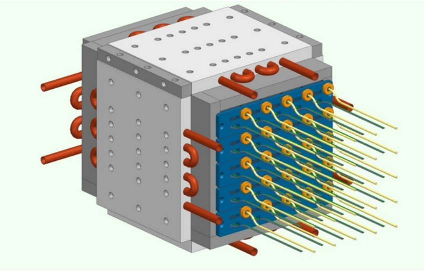
Check the FEE and the DAQ system.

Confirm system engineering:
check mechanical and thermal stability.

Test alignment procedures.

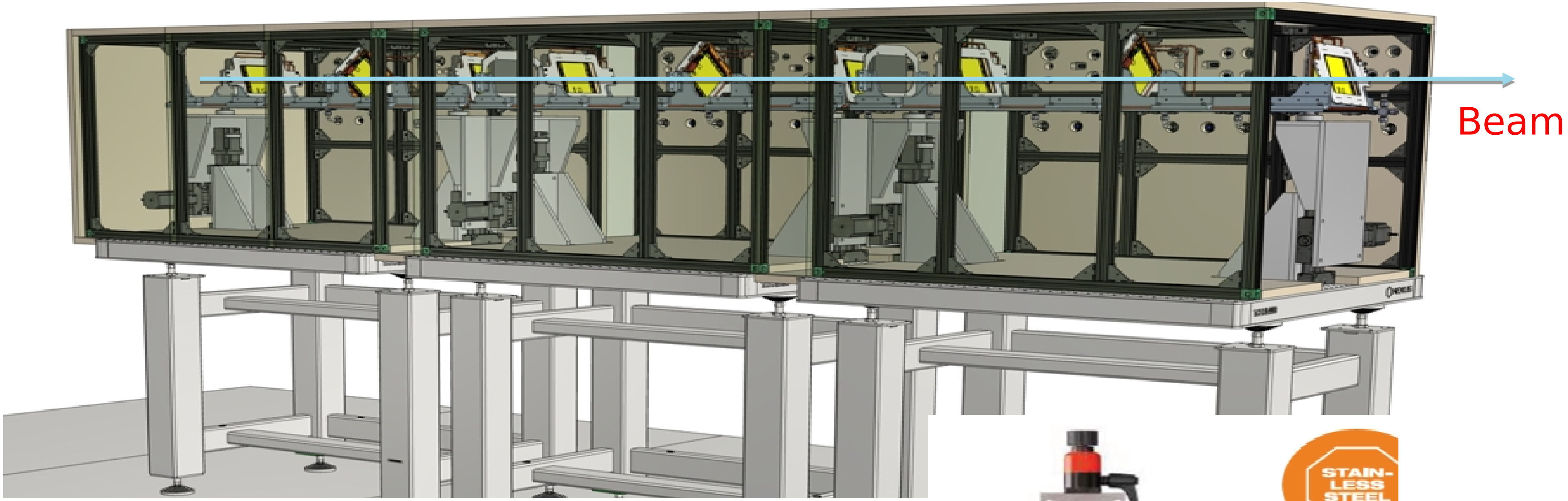
Detection efficiency, background, etc.





The tracking system details

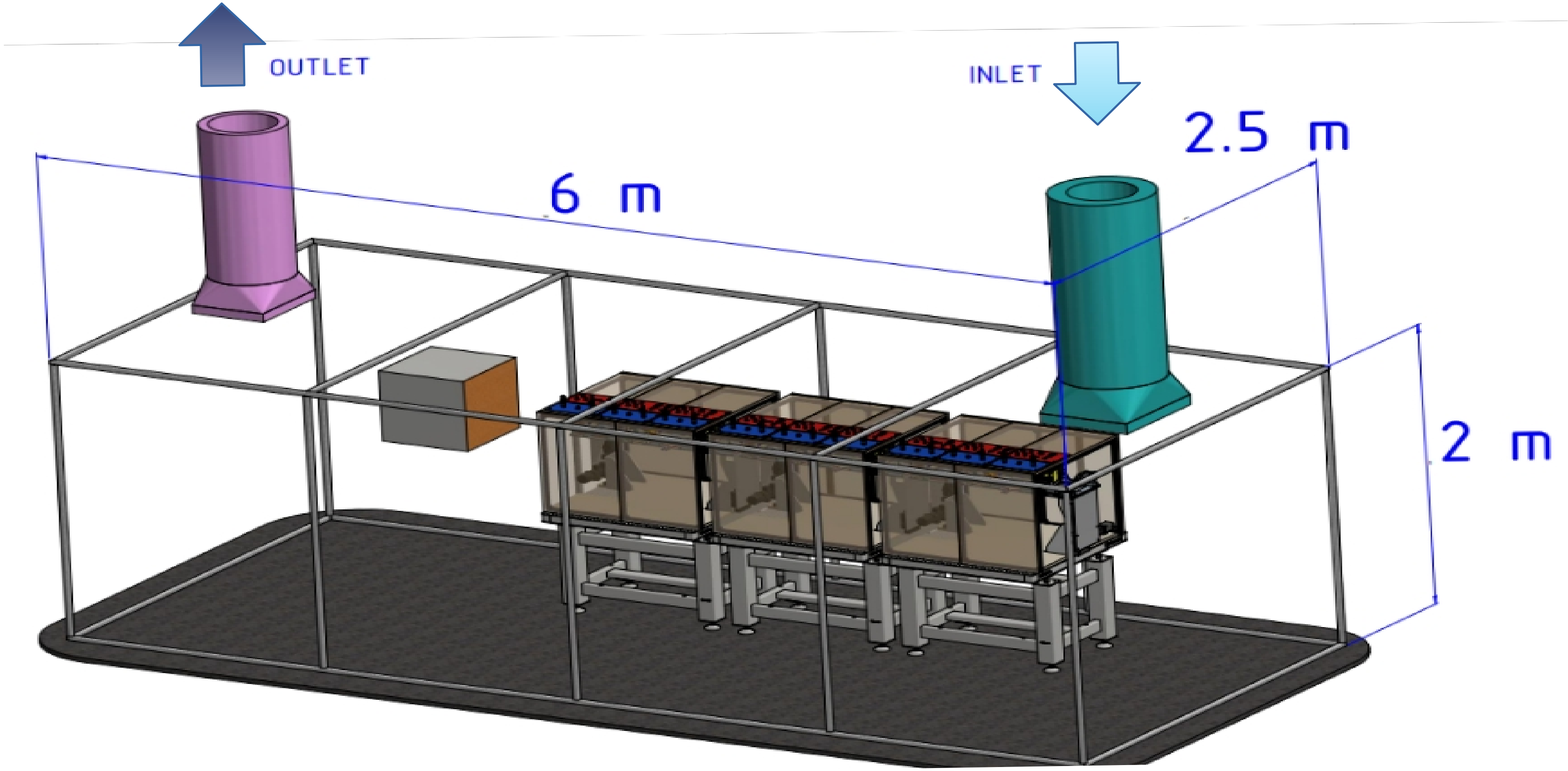
- Each tracker station is mounted on a breadboard through actuators to center the beam and allow for the precise positioning.



- Three points of support - Linear stages motorized:
  - XY upstream
  - XY and X downstream

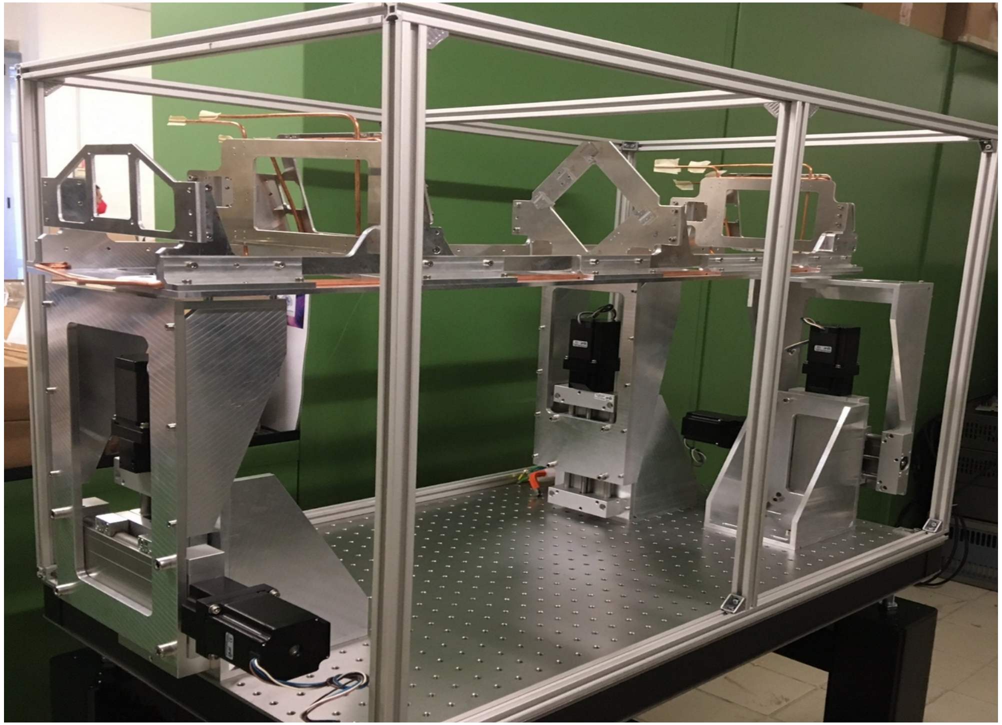
Insulation to get $\Delta T < \pm 1^{\circ}C$

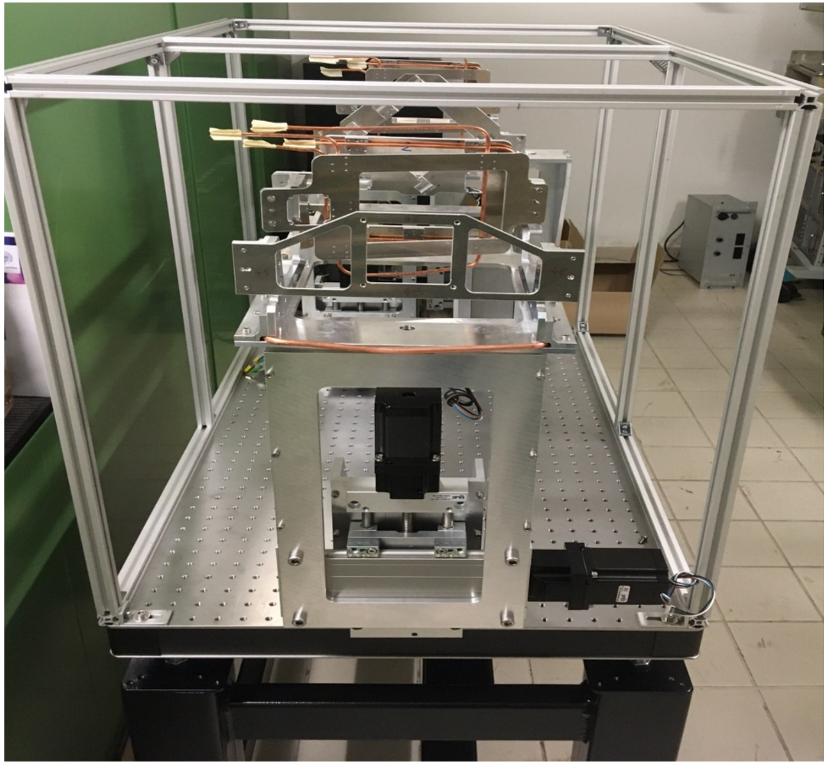
Panels: polyurethane foam (l=0.022 W/mK), 40 mm



The Aluminium prototype

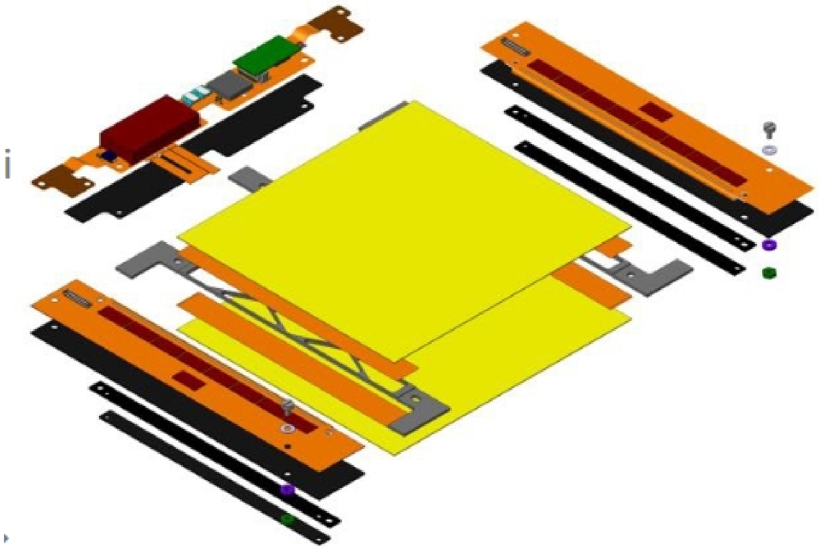
Stepper motors installed and tested:
200 steps/revolution, 2 mm lead screw, 10 um steps,
± 26 mm stroke

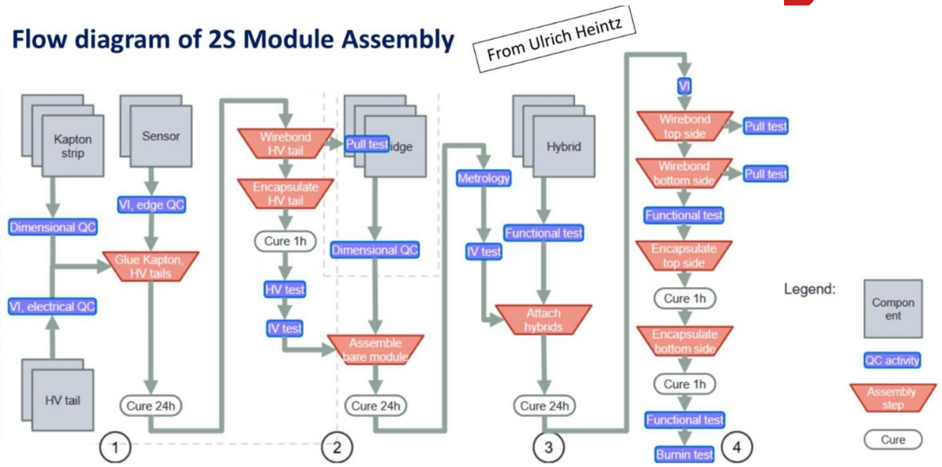


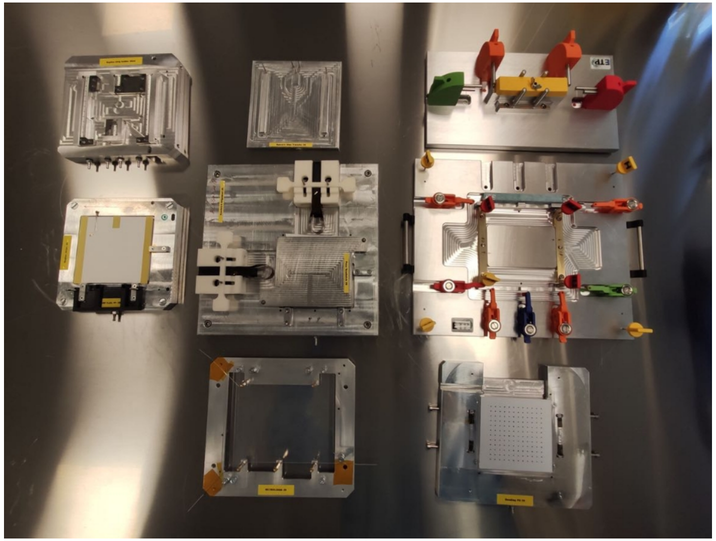


Enclosure almost done, patch panels milled
Cooling tubes manifacturing is ongoing

2S Modules Assembly

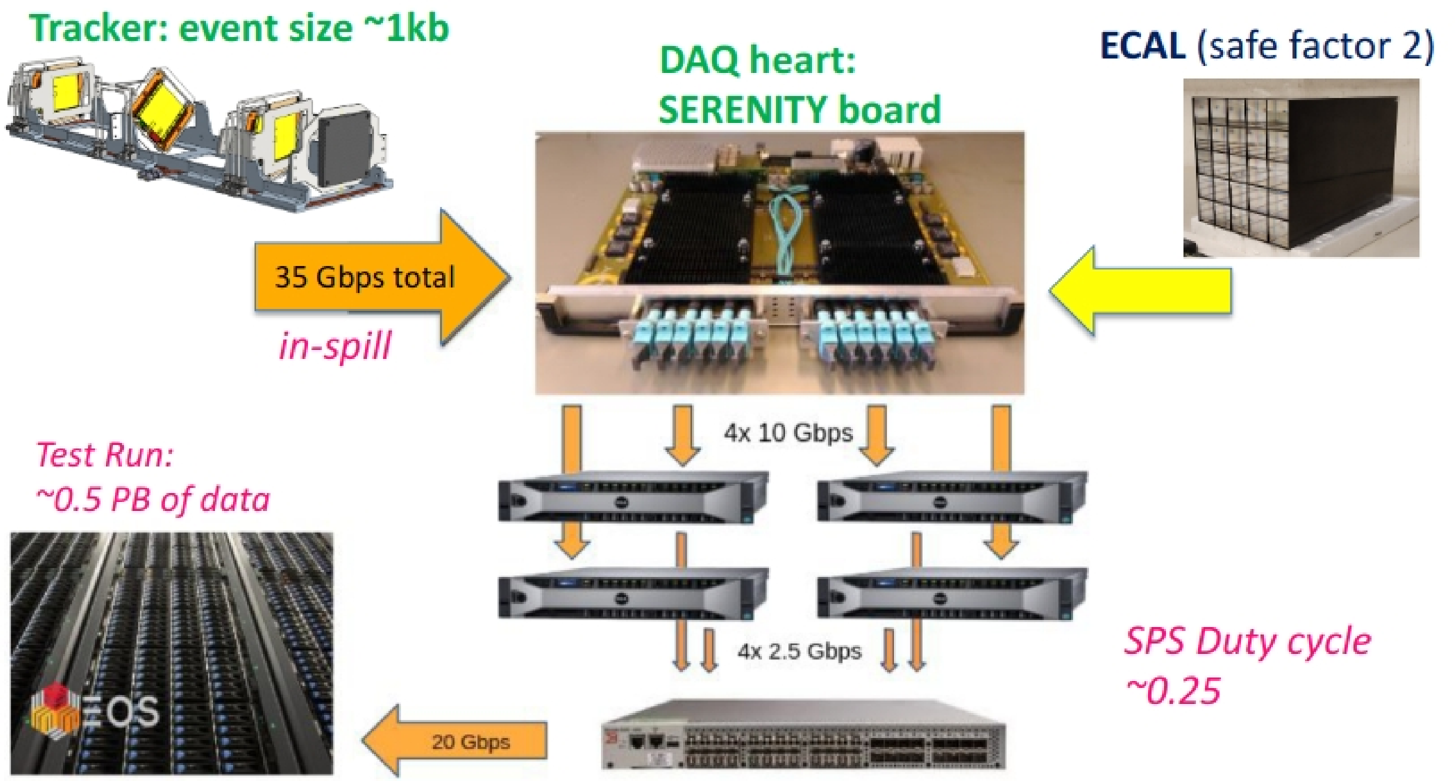






The most serious issue we are facing at the moment, because of the shortage of electronics components, namely of working service hybrids.

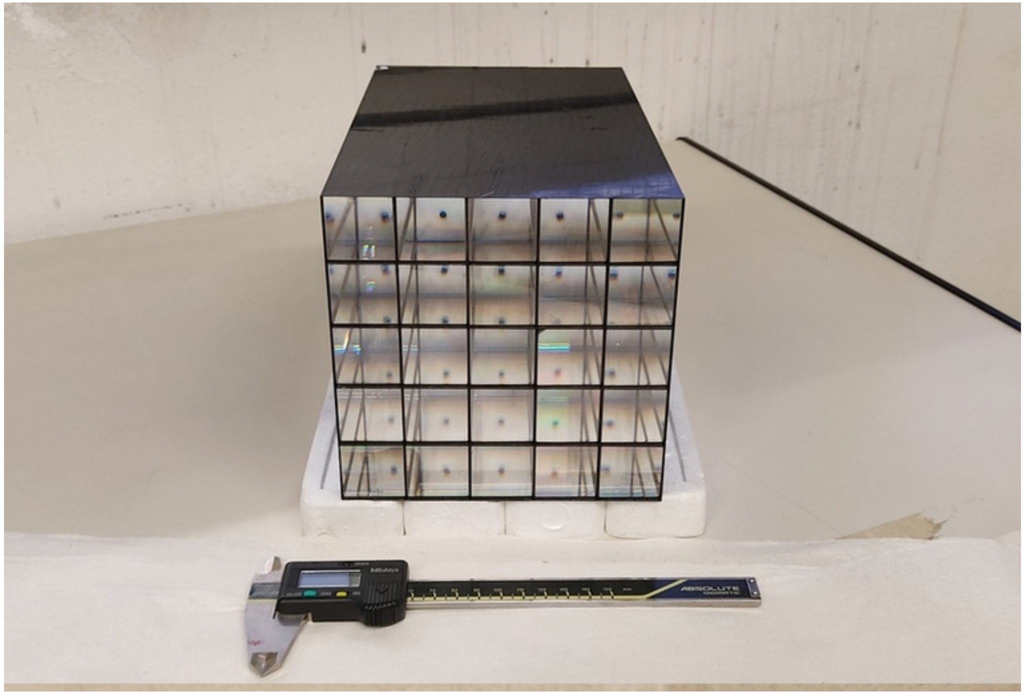
DAQ



Tracker: event size ~1kb
DAQ heart:
SERENITY board
ECAL (safe factor 2)
35 Gbps total
in-spill
4x 10 Gbps
Test Run:
~0.5 PB of data
EOS
4x 2.5 Gbps
SPS Duty cycle
~0.25
20 Gbps

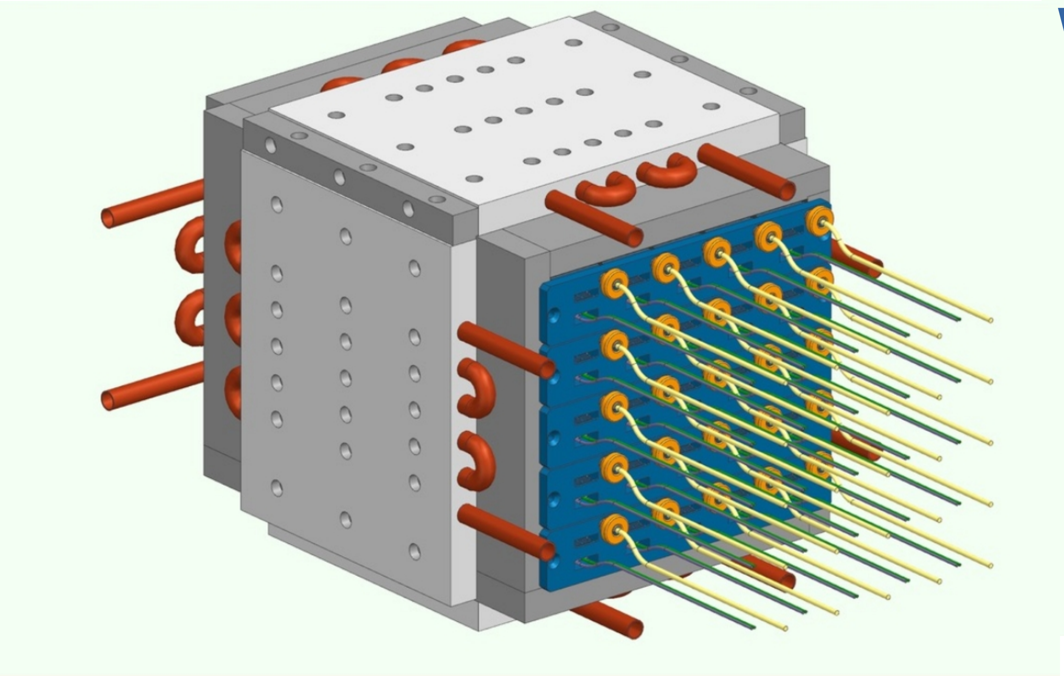
ECAL

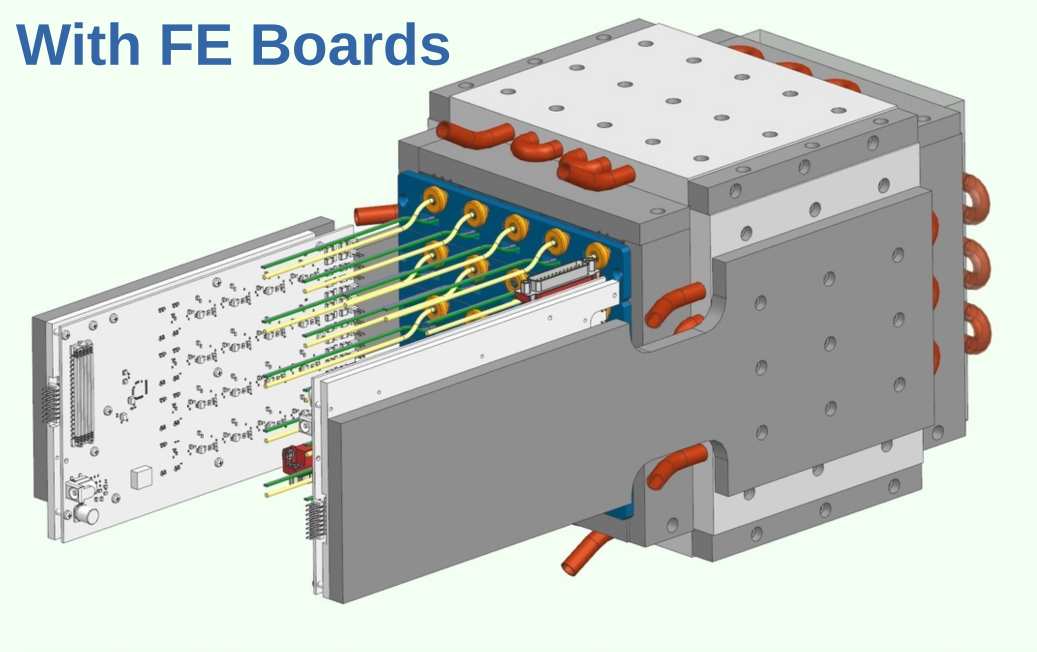
- **Mechanics and crystal tests**
  Padova
- **APDs purchase and test**
  University of Virginia
- **Front End Board**
  Imperial College
- **Laser system**
  Pisa, Trieste
- **HV and LV**
  Krakow



The matrix of 25 PbWO crystals borrowed from CMS

Mechanics layout

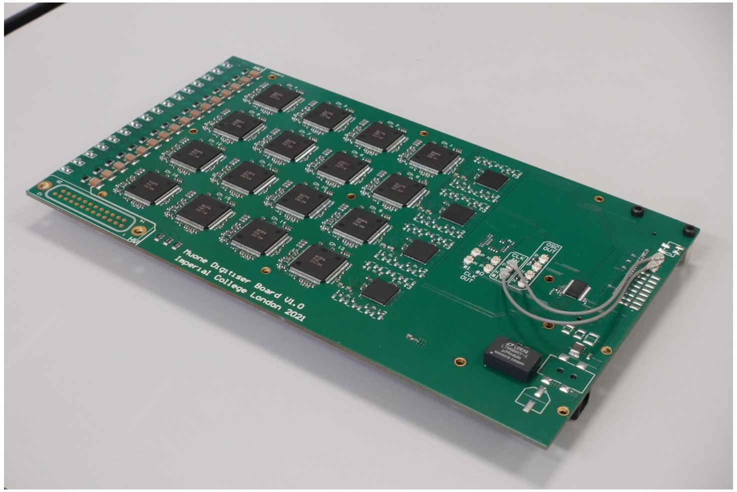


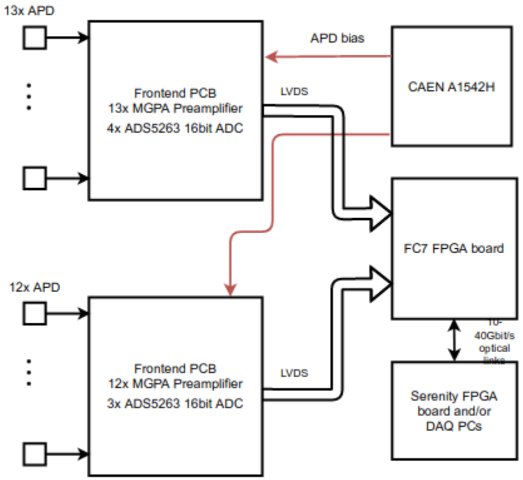


Housing structure for the PbWO crystal matrix. Temperature control through Al plates in contact with the carbon-fiber structure, with pipes for chiller water.

ECAL FEB

- FEB is based on the **MGPA(v2)** preamplifier originally developed for the CMS ECAL (the 16 chips in a 4x4 array). However, in contrast to the CMS ECAL system this board uses only one gain-range for simplicity and reduced power consumption,
- **Commercial 16-bit ADC** (TI ADS5263, the 4 chips in one line). The board contains circuitry for generating the supply voltages for MGPAs and ADCs.
- **Passive networks for biasing the APDs** from an external high-voltage power supply (e.g. the big capacitors along left-hand edge). The small parts between the ADCs and the FMC connector are clock distribution (QFN) and an I2C multiplexer (SO).
- **The data from the ADCs is streamed over the FMC connector** to an **FC7 FPGA** board which collect data streams from 2 frontend boards and in turn stream the data over optical fibers using the **lpGBT protocol to the backend**.





Fast ECAL simulation

5 input parameters

SHOWER PARAMETRIZATION

"GFLASH" By Grindhammer and Peters [arXiv:hep-ex/0001020]

ENERGY DISTRIBUTION: $dE(\vec{r}) = E f(t)dt\, f(r)dr\, f(\phi)d\phi$

Longitudinal profile as a function of t (shower depth in unit of X_0)

Radial profile as a function of r (transversal distance in units of R_M)

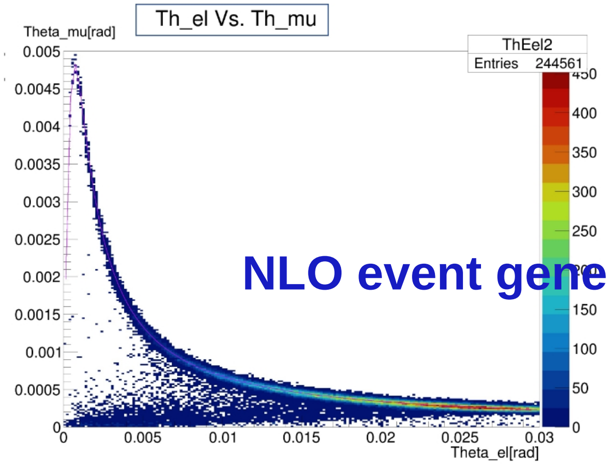
Function of azimuthal angle assumed uniform

AVERAGE:

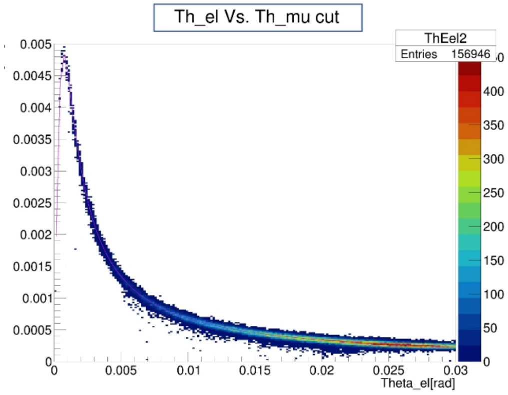
$$f(t) = \frac{(\beta t)^{\alpha-1}\beta\exp(-\beta t)}{\Gamma(\alpha)}$$

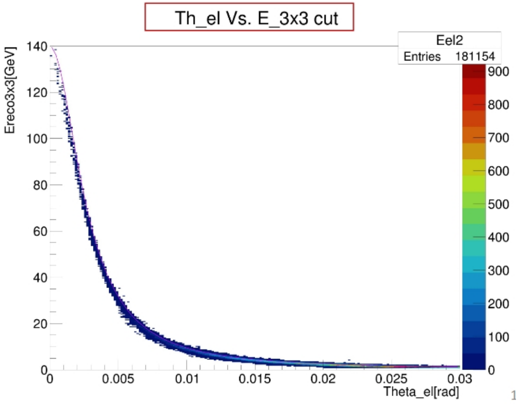
$$f(r) = p\frac{2rR_C^2}{(r^2+R_C^2)^2} + (1-p)\frac{2rR_T^2}{(r^2+R_T^2)^2}$$

https://amslaurea.unibo.it/23207/



NLO event generator





Applying elasticity selection cuts

$\Delta\alpha_{had}(t)$ parametrization

Physics-inspired from the calculable contribution of lepton-pairs and top quarks at t<0

$$\Delta\alpha_{had}(t) = k\left\{-\frac{5}{9} - \frac{4M}{3t} + \left(\frac{4M^2}{3t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\log\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

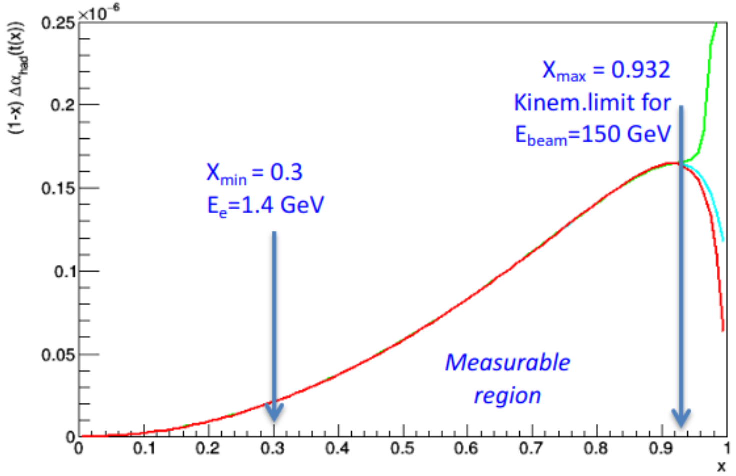
M with dimension of mass squared, related to the mass of the fermion in the vacuum polarization loop
k depending on the coupling $\alpha(0)$, the electric charge and the colour charge of the fermion

Low-|t| behavior dominant in the MUonE kinematical range:

$$\Delta\alpha_{had}(t) \simeq -\frac{1}{15}\frac{k}{M}t$$

a_μ^{HLO} calculable from the master integral in the FULL phase space with this parameterization.

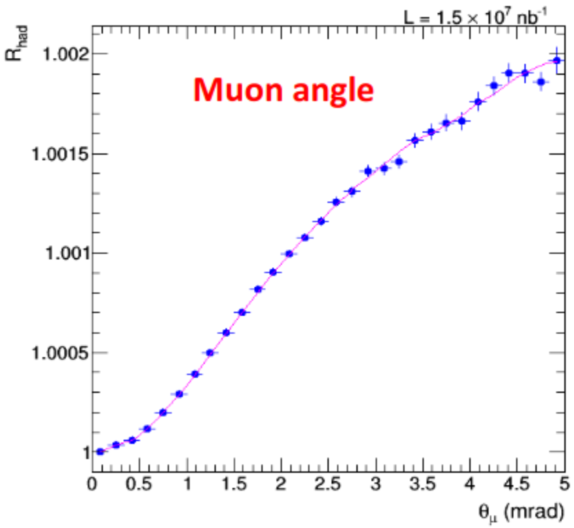
Instead simple polinomials diverge for x->1 (green is a cubic polinomial in t)

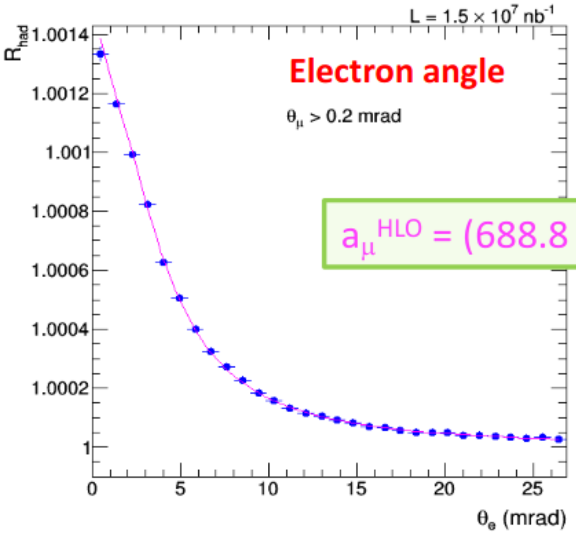


Measuring the hadronic running

Most easily displayed by taking ratios of the observed angular distributions and the theory predictions evaluated for $\alpha(t)$ corresponding to only the leptonic running.
Observable effect ~ 10^{-3} / wanted precision ~10^{-2} → required precision ~10^{-5}

Example toy experiment shown with statistics corresponding to the nominal integrated Luminosity L = 1.5 x 10^7 nb^{-1} (corresponding to 3-year run)





$a_\mu^{HLO} = (688.8 \pm 2.4) \times 10^{-10}$

Template fit to the 2D angular distribution from NLO MC generator with parameterised detector resolution.
$\Delta\alpha_{had}(t)$ parameterised according to the "Lepton-Like" form. Shape-only χ^2 fit.

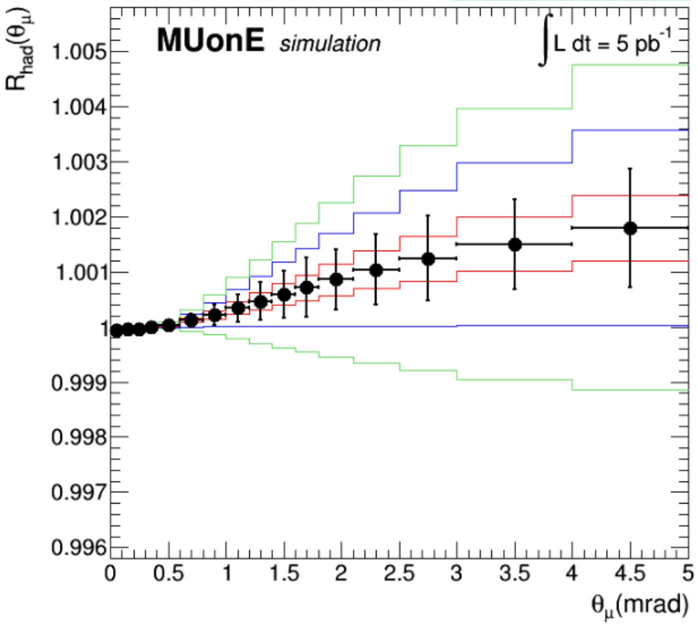
Sensitivity in a first physics run

2 stations

Expected integrated Luminosity with the Test Run setup with full beam intensity & detector efficiency ~ 1pb^{-1}/day

In one week ~5pb^{-1} → ~10^9 μe scattering events with $E_e > 1$ GeV ($\theta_e < 30$ mrad)

arXiv:2012.07016



$$R_{had}(\theta_\mu) = \frac{d\sigma_{data}(\Delta\alpha_{had})}{d\sigma_{MC}(\Delta\alpha_{had}=0)}$$

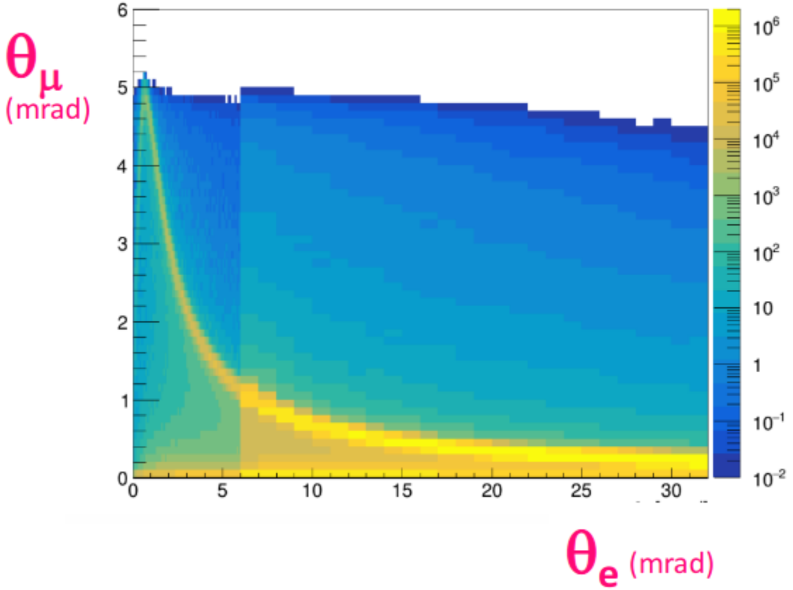
Initial sensitivity to the hadronic running of α.

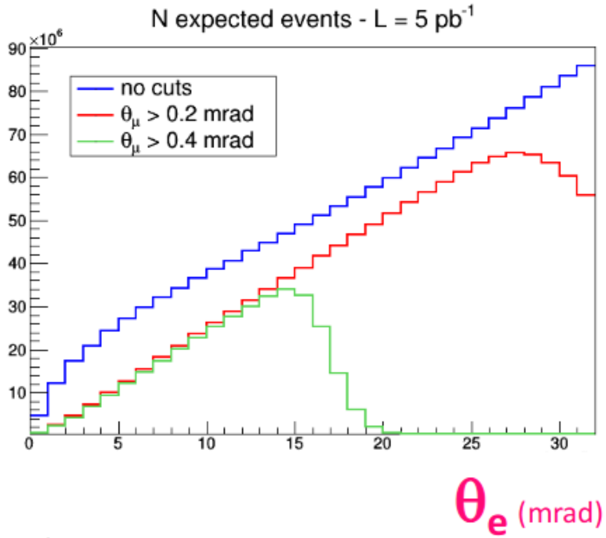
Pure statistical level: 5.2σ
2D (θ_μ,θ_e) K=0.136 ± 0.026

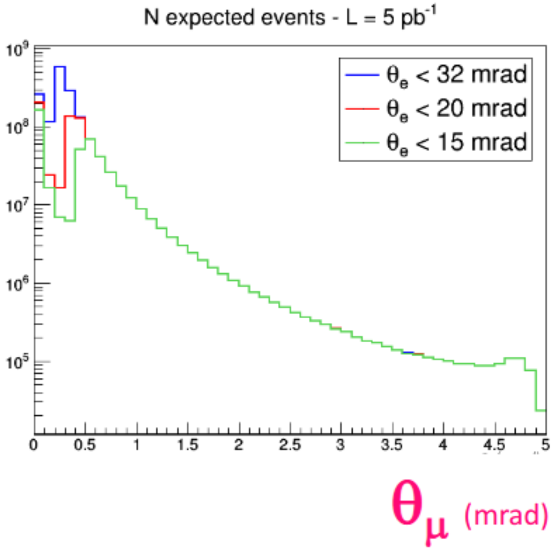
Definitely we will have sensitivity to the leptonic running (ten times larger)

Template fit with just one fit parameter K= k/M in the $\Delta\alpha_{had}$ parameterization.
The other parameter fixed at its expected value: M = 0.0525 GeV^2

Event kinematics





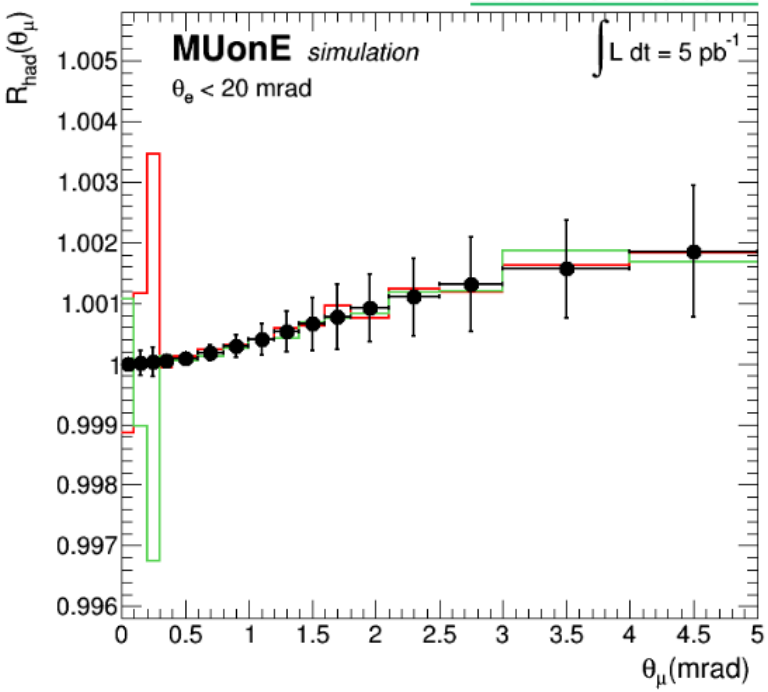


Systematics: MCS

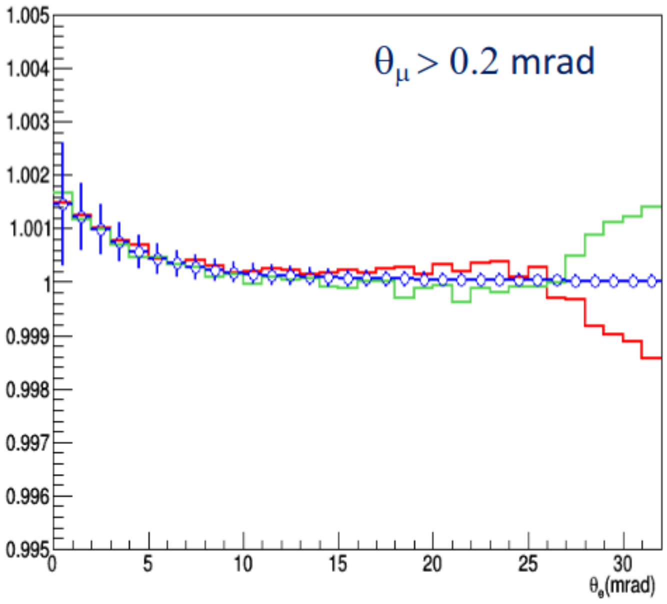
Effect of a flat error of ±1% on the core width of multiple scattering

on the θ_μ distribution

arXiv:2012.07016



on the θ_e distribution



Fitting systematics effect

$\sigma_{MCS} = \sigma_{MCS}(1+\mu)$ Pseudodata generated with μ=0.5%

Cuts	Fit results using (θ_e, θ_μ) distribution		
$\theta_\mu \geq 0.4\,\mathrm{mrad}$ $\theta_e \leq 32\,\mathrm{mrad}$	$K = (0.137 \pm 0.032)$	$\nu = 0.046 \pm 0.054$	$\boxed{\mu = 0.510 \pm 0.020}$
$\theta_\mu \geq 0.4\,\mathrm{mrad}$ $\theta_e \leq 20\,\mathrm{mrad}$	$K = (0.137 \pm 0.032)$	$\nu = 0.028 \pm 0.054$	$\boxed{\mu = 0.515 \pm 0.022}$
$\theta_\mu \geq 0.2\,\mathrm{mrad}$ $\theta_e \leq 32\,\mathrm{mrad}$	$K = (0.136 \pm 0.028)$	$\nu = -0.075 \pm 0.029$	$\boxed{\mu = 0.509 \pm 0.012}$
$\theta_\mu \geq 0.2\,\mathrm{mrad}$ $\theta_e \leq 20\,\mathrm{mrad}$	$K = (0.137 \pm 0.031)$	$\nu = 0.060 \pm 0.045$	$\boxed{\mu = 0.514 \pm 0.018}$

- Combine fit successfully determining the MCS nuisance to better than 5%
- No degradation on the signal parameter K
  - K and μ affects different kinematical regions

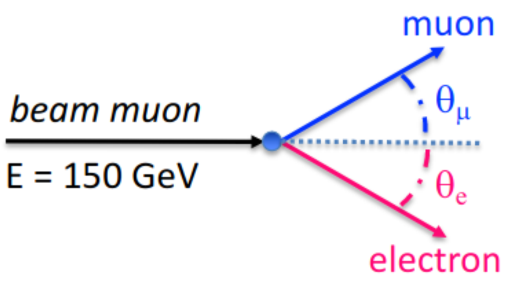
The beam energy scale

Time dependency of the beam energy profile has to be continuously monitored during the run:

- SPS monitor
- COMPASS BMS

} needed external infos

However, the absolute beam energy scale has to be calibrated by a physics process: kinematical method on elastic μe events

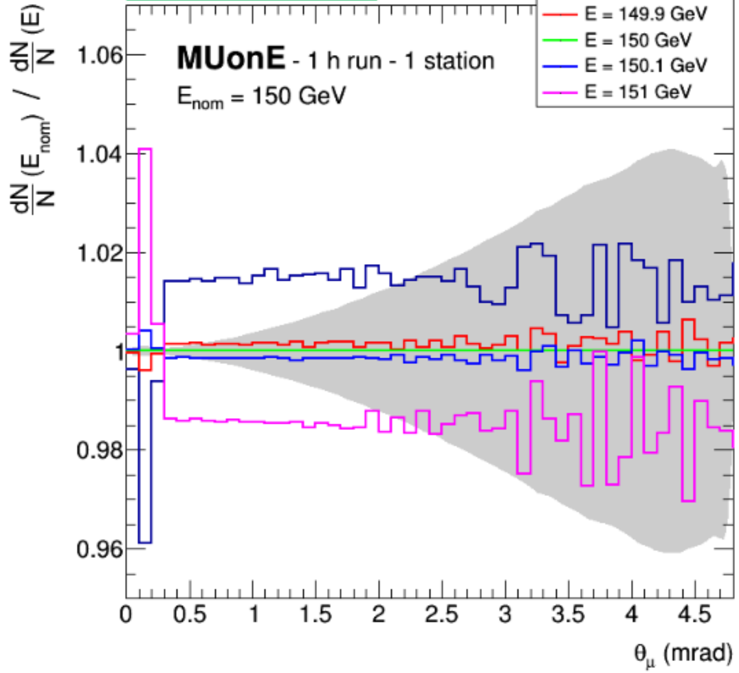


For equal angles:
$\theta_\mu = \theta_e \equiv \theta$

$$\theta \simeq \sqrt{\frac{2m_e}{E}}$$

Can reach <3 MeV uncertainty in a single station in less than one week
From SPS E scale ~1% : 1.5 GeV

arXiv:2012.07016



Effect of a syst shift of the average beam energy on the θ_μ distribution: 1h run / 1 station

Simulation and analysis tools

- In the context of the **TB2018** analysis
  - Detector response modeled in the **FairRoot** framework using **GEANT4**
    https://github.com/FairRootGroup/FairRoot
    https://github.com/FairRootGroup/FairSoft
  - The tracking algorithm had been tested thoroughly
- In the perspective of the **Test Run**
- **Stub** (double hits) generation/modeling is under development
  - Tracking efficiency as a function of the scattering angle
- **New GEANT releases** being tested focusing on the background for rejection and cuts optimization studies
- A **parametric fast detector simulation tool**, a la CMS, for ECAL studies with NLO events has been developed to define ECAL cells' occupancy and the range of the energy scale.

Theory progresses

- **P. Mastrolia, M. Passera, A. Primo and U. Schubert, JHEP 1711 (2017) 198**
- **S. Di Vita, S. Laporta, P. Mastrolia, A. Primo, U. Schubert, JHEP 1809 (2018) 016**
- **M. Alacevich et al, JHEP 02 (2019) 155**
- **M. Fael, JHEP 1902 (2019) 027**
- **M. Fael and M. Passera, PRL 122 (2019) 192001**
- **A. Masiero, P. Paradisi, and M. Passera, PRD102 (2020) 075013**
- **C. M. Carloni Calame, et al, JHEP 11 (2020) 028**
- **P. Banerjee, T. Engel, A. Signer, and Y. Ulrich, SciPost Phys. 9 (2020) 027**
- **Theory for muon-electron scattering @ 10 ppm: A report of the MUonE theory initiative**
  https://inspirehep.net/literature/1793261

https://web.infn.it/MUonE/

The MuonE WEB site

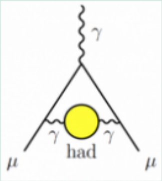
HOME Collaboration Activities Documents MUonE internal pages

https://web.infn.it/MUonE

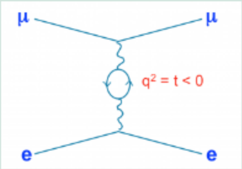
The MUonE project

(MUon ON Electron elastic scattering)

The MUonE experiment aims at an independent and precise determination of the leading hadronic contribution to the muon anomalous magnetic moment $a_\mu=(g_\mu-2)/2$, based on a novel method, as proposed in Eur.Phys.J. C77 (2017) 139, complementary to the existing ones.



The method needs the measurement of the effective electromagnetic coupling in the space-like region at low momentum transfer. This can be achieved by measuring with unprecedented precision the shape of the differential cross section of μ-e elastic scattering, using the intense muon beam available at CERN, with energy of 160 GeV, off



Conclusions

- First tests of the 2S modules using the DAQ board are ongoing.
- Parasit tests with muon beam shall teach a lot.
- Test of the final prototype planned in 2022
- We’re planning the future, beyond the 2022:
  Be ready with the experiment proposal in the end of 2022
  Make a first measurement in 2023-2024
  By adding 10 tracking stations to the existing prototype we estimated a 2% statistical precision could be achieved, running 4 months.