MUonE: a novel approach to measure a_μ^{HLO}

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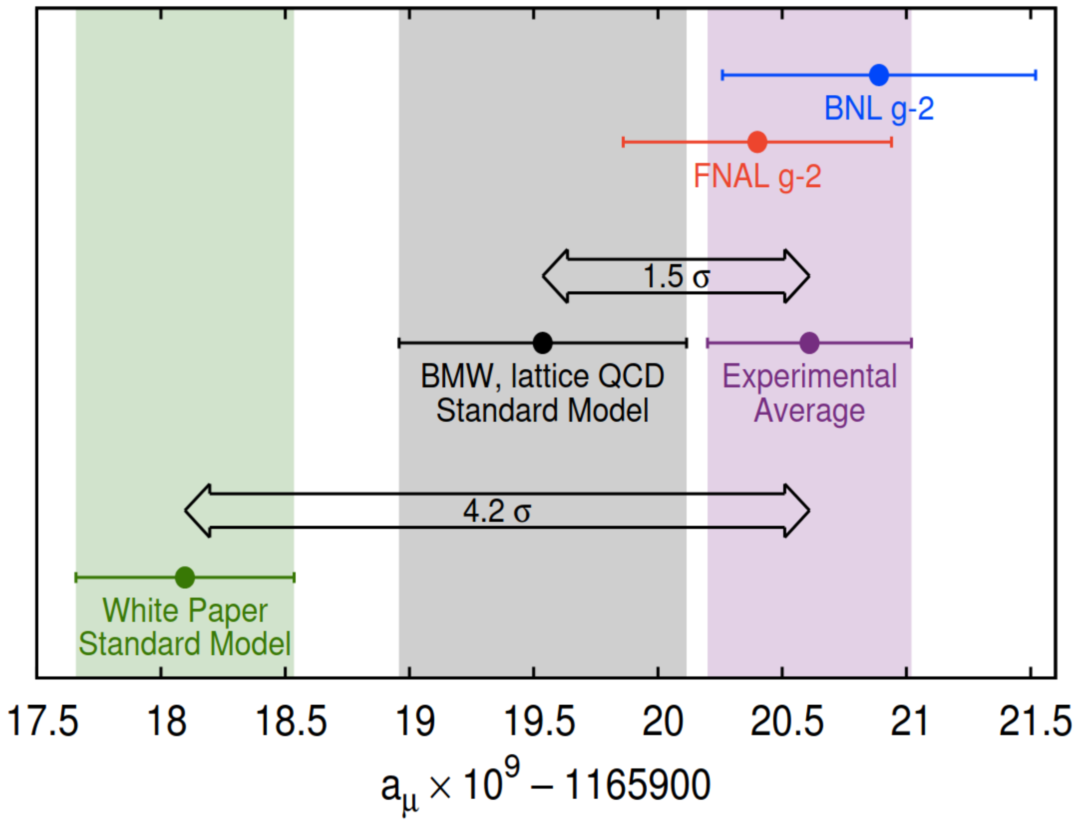
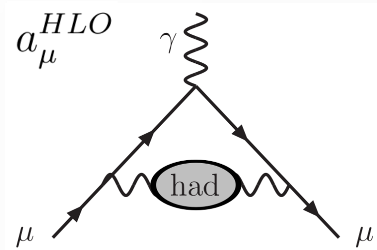
Potential Fermilab Muon Campus & Storage Ring Experiments Workshop
27th May 2021

The muon g-2: latest results



Main contribution
to the Standard Model uncertainty:
hadronic contribution a_μ^{HLO}



- Traditional time-like approach: relies on experimental data $e^+e^- \to hadrons$.

Precision currently achieved on a_μ^{HLO}:
0.6% (WP20) Phys. Rep. 887 (2020), 1

Discrepancy between BMW and time-like (WP20) results.

- Lattice QCD: BMW collaboration recently achieved a 0.8% precision.

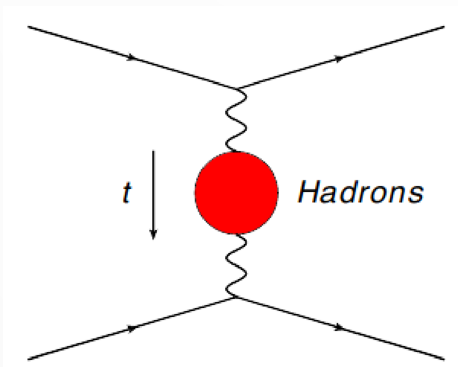
Nature 593, 51–55 (2021)

a_μ^{HLO} : space-like approach

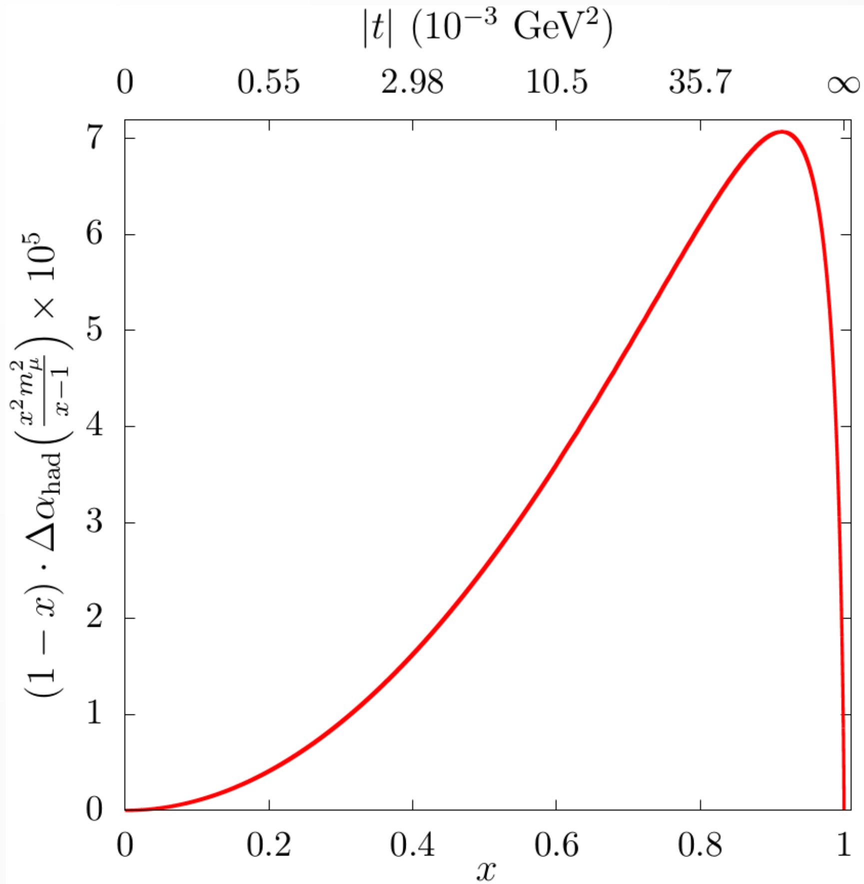
MUonE: a new independent evaluation of a_μ^{HLO}

$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$



Based on the measurement of $\Delta\alpha_{had}(t)$: hadronic contribution to the running of the electromagnetic coupling constant.

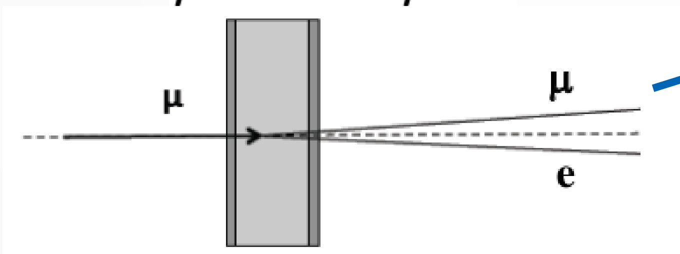


Phys. Lett. B 746 (2015), 325

The MUonE experiment

Extraction of $\Delta\alpha_{had}(t)$ from the differential cross section of the interaction

$$\mu\ e \rightarrow \mu\ e$$

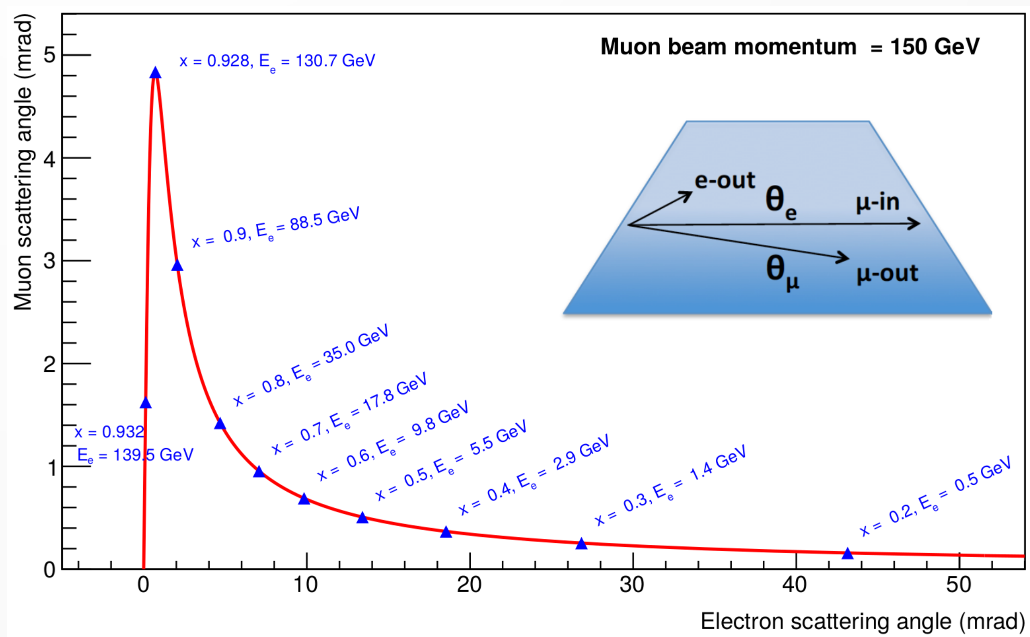


$$\frac{d\sigma_{data}/dt}{d\sigma_{MC}^{no\ VP}/dt} = \frac{1}{|1-\Delta\alpha_{lep}(t)-\Delta\alpha_{had}(t)|^2}$$

From theoretical calculation

To be measured

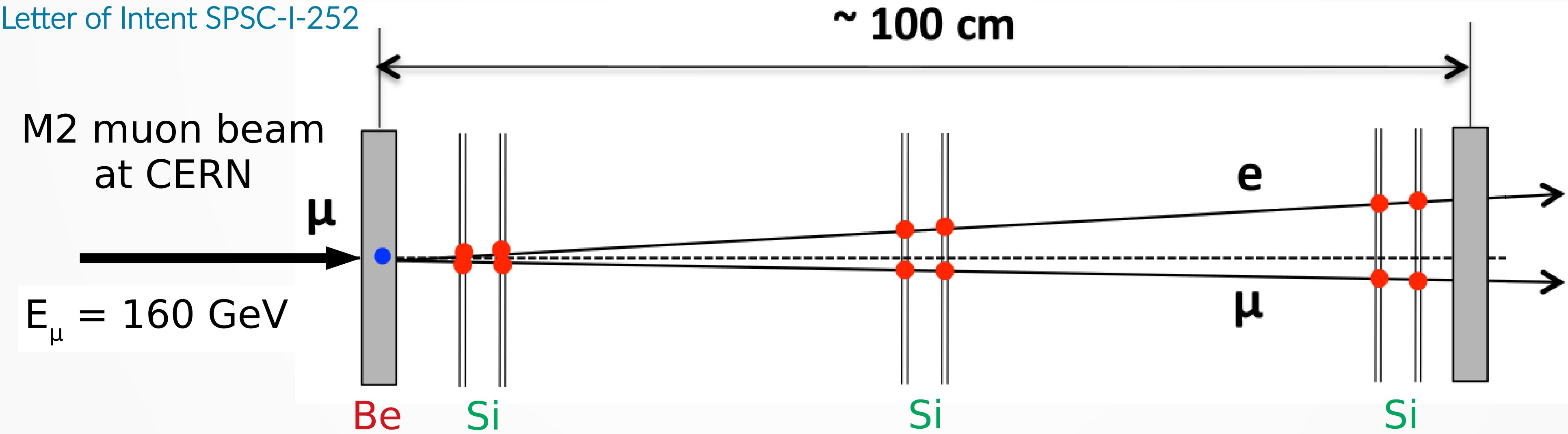
- A beam of 160 GeV muons allows to cover 87% of the a_μ^{HLO} integral.
- Correlation between muon and electron angles allows to select elastic events and reject background (e^+e^- pair production).
- Boosted kinematics: $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad.



Eur. Phys. J. C 77.3 (2017), 139

The experimental apparatus

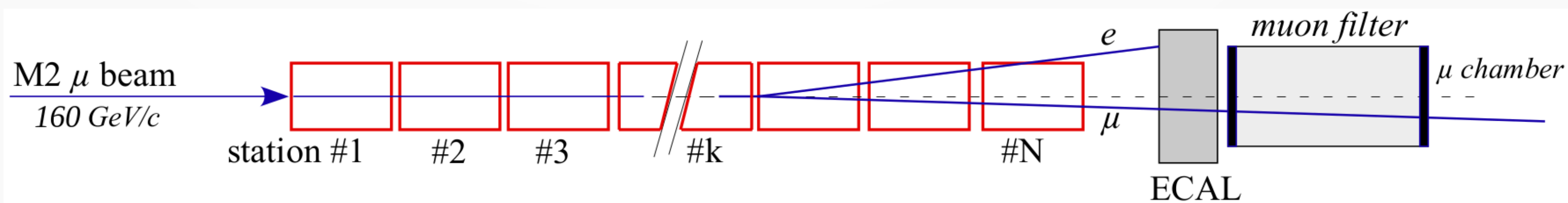
Letter of Intent SPSC-I-252



Beryllium target
1.5 cm thickness

Tracking system: 3 pairs of
silicon strip detectors

× 40



Achievable accuracy

40 stations + 2 years of data taking ($I_\mu \sim 10^7$ μ/s) = 0.3% statistical accuracy on a_μ^{HLO}

Competitive with the latest time-like accuracy.

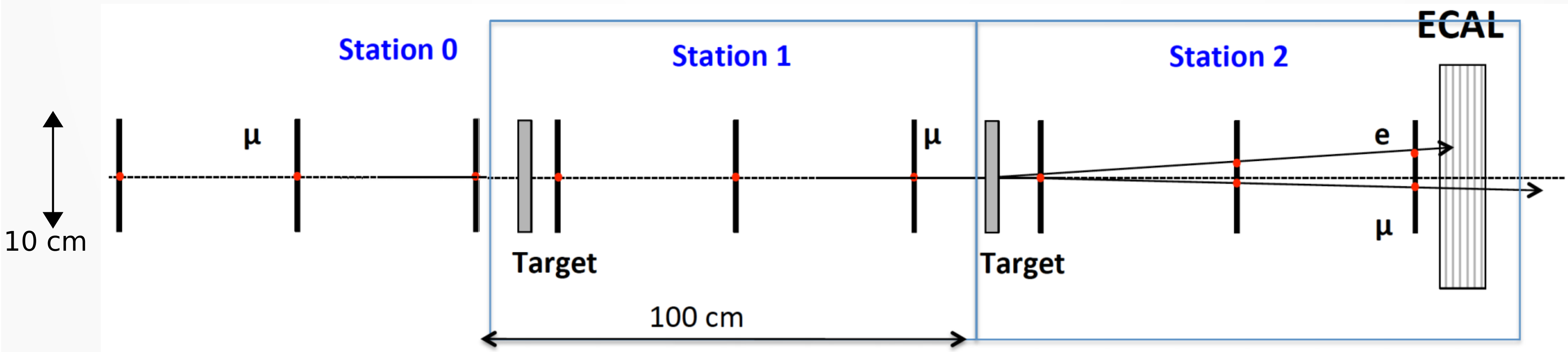
The big challenge of the experiment is to reach a comparable systematic accuracy

Systematic uncertainty of 10 ppm at the peak of the integrand function

- Longitudinal alignment (~10 μm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering (~1%)

Test Run setup

A Test Run with a reduced detector has been approved by SPSC, to validate our proposal.



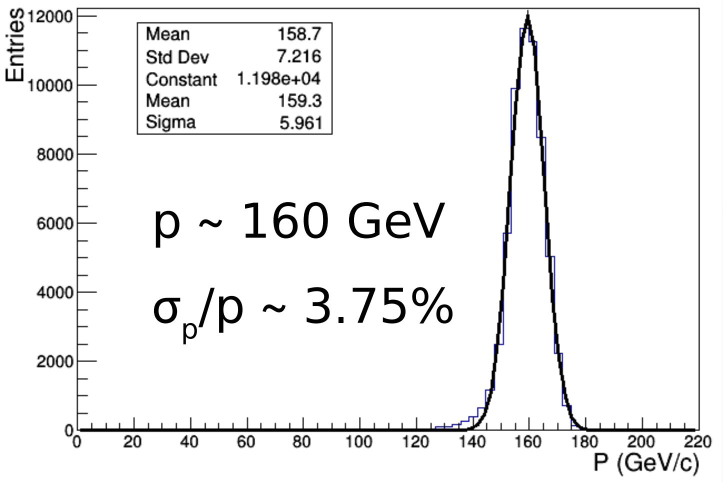
- Pretracker +
- 2 MUonE stations +
- ECAL

Main goals:

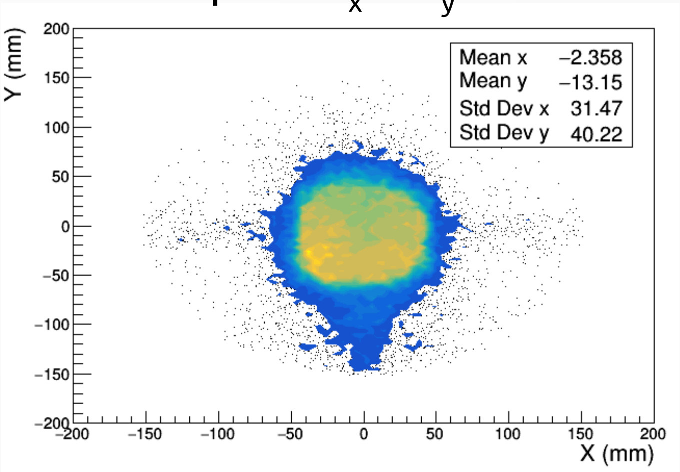
- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Check the DAQ system.
- Take data to extract $\Delta\alpha_{\mathrm{lep}}(t)$.

Location: M2 beam line at CERN

Beam momentum



Beam spot: $\sigma_x \sim \sigma_y \sim 2.7$ cm



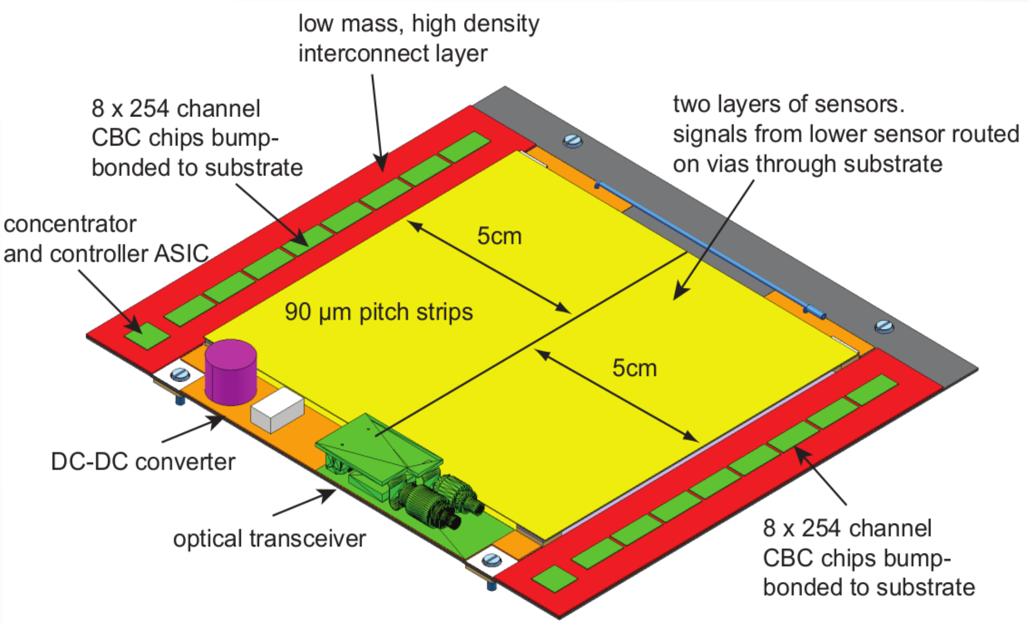
- Location: upstream the COMPASS detector (CERN North Area).
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} \sim 0.3$ mrad.
- Spill duration ~ 5 s. Duty cycle ~ 25%.
- Maximum rate: 50 MHz (~ $3\text{x}10^8$ μ^+/spill).

Tracker: CMS 2S modules

Silicon strip sensors currently in production for the CMS-Phase2 upgrade.

Two close-by strip sensors reading the same coordinate.

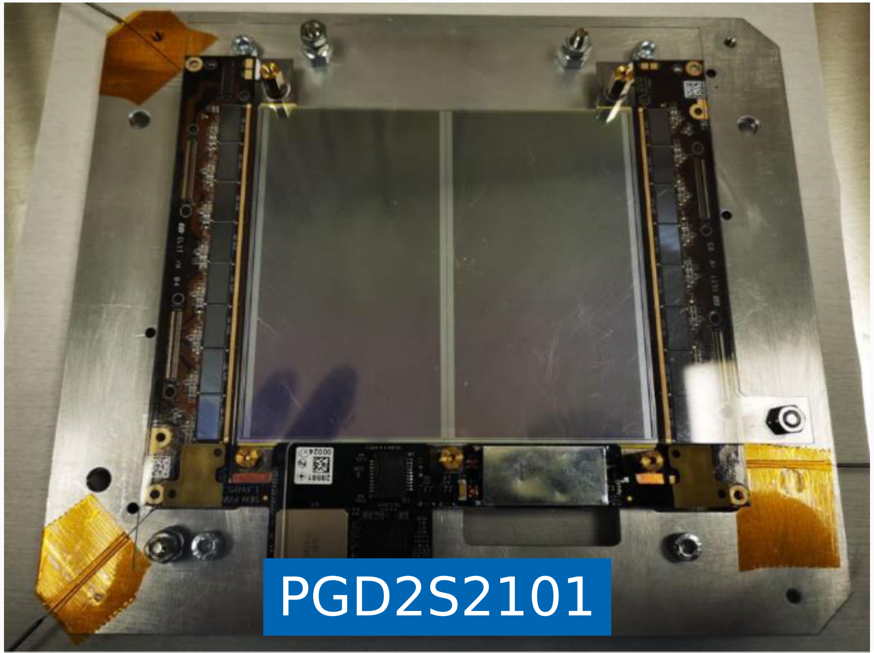
This provides background suppression from single-sensor hits and rejection of large angle tracks.



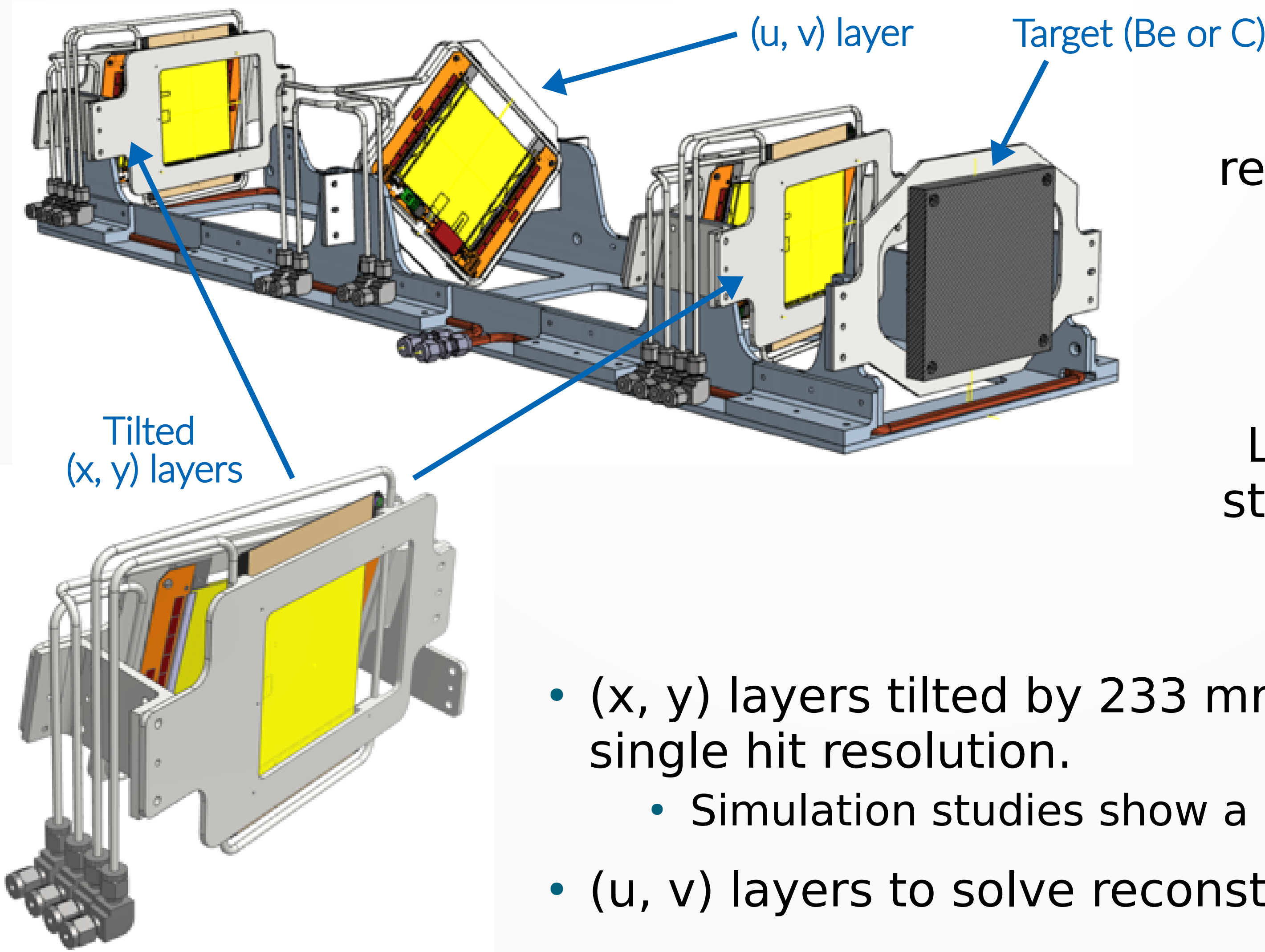
- Thickness: $2 \times 320\ \mu\mathrm{m}$
- Pitch: $90\ \mu\mathrm{m} \rightarrow \sigma_x \sim 26\ \mu\mathrm{m}$
- Readout rate: $40\ \mathrm{MHz}$
- Area: $10\ \mathrm{cm} \times 10\ \mathrm{cm}$ → Complete and uniform angular acceptance with one module.

Tracker: CMS 2S modules

- Two dummy 2S modules have been assembled in Perugia.
- Assembly procedure is well defined, metrology measurements meet the CMS quality requirements.
- Ready to build functional 2S modules, as soon as components will be made available by CMS.



Tracking station



Stringent request: relative position within a station must be stable at 10 μm.

↓

Low CTE mechanical structure: INVAR (alloy of 65%Fe, 35%Ni).

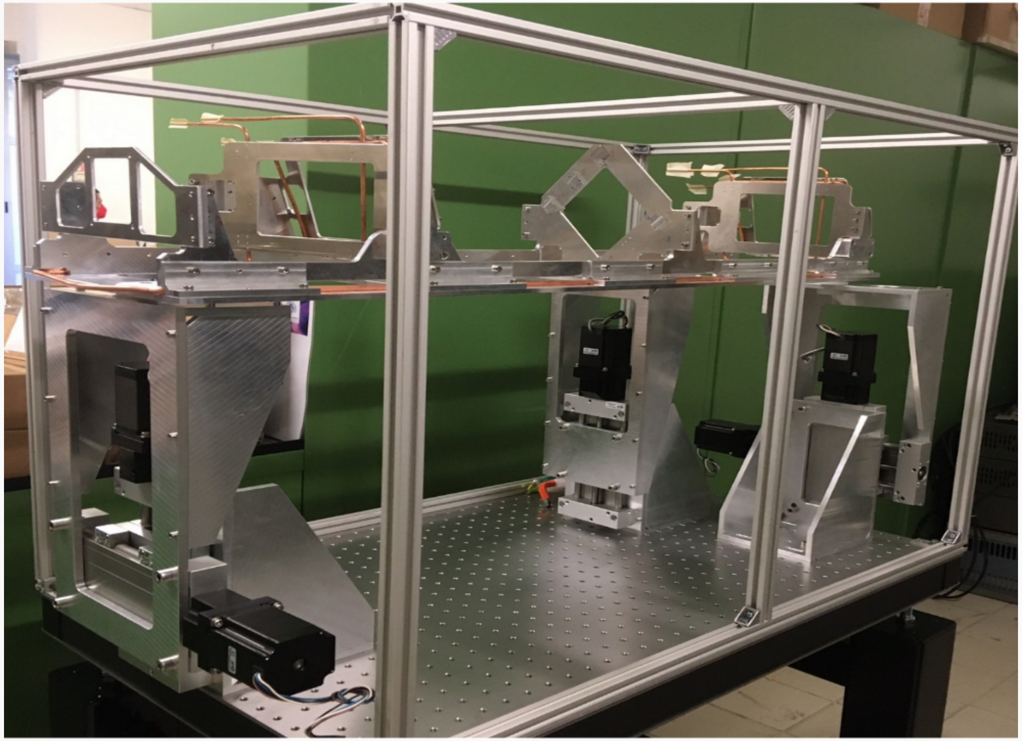
- (x, y) layers tilted by 233 mrad, to improve single hit resolution.
  - Simulation studies show a resolution of ~10 μm.
- (u, v) layers to solve reconstruction ambiguities.

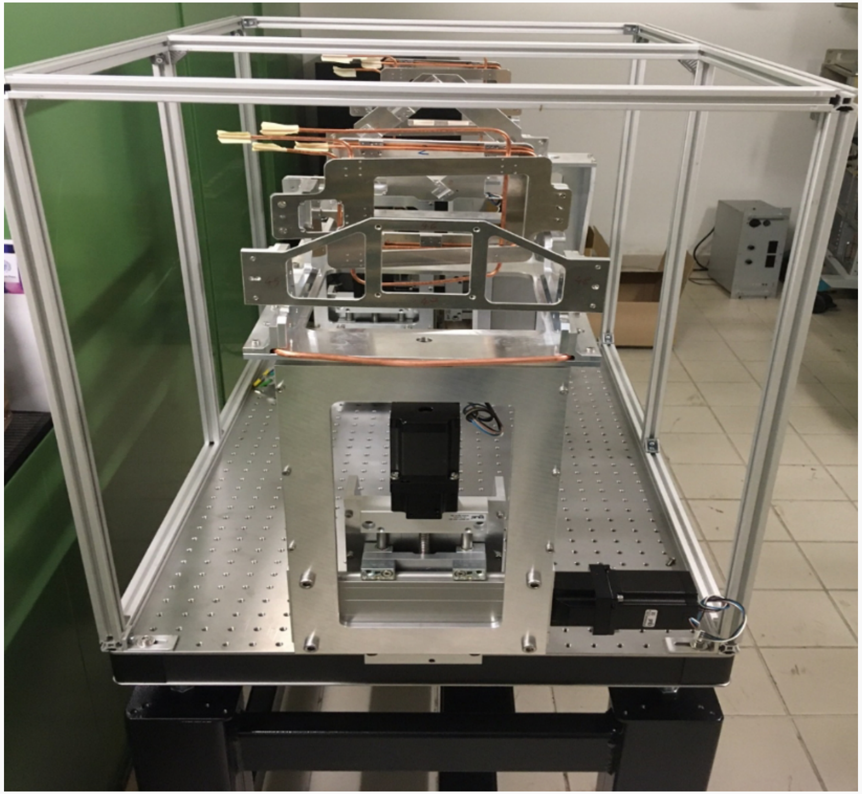
Tracking station

Aluminum mockup ready.

Stepper motors will be used to align the station to the beam.

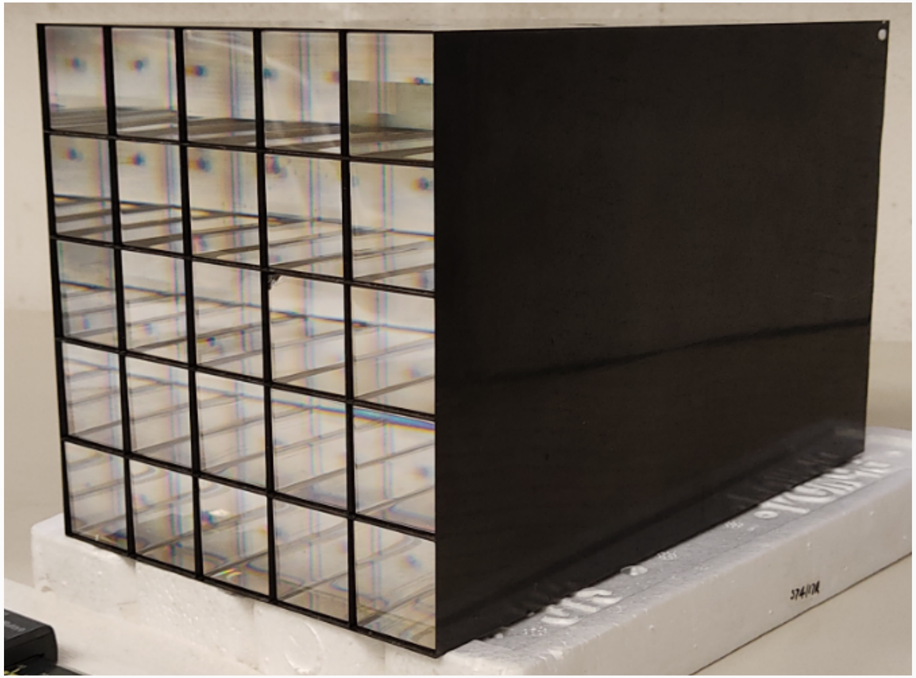
They have been installed and successfully tested in Pisa.





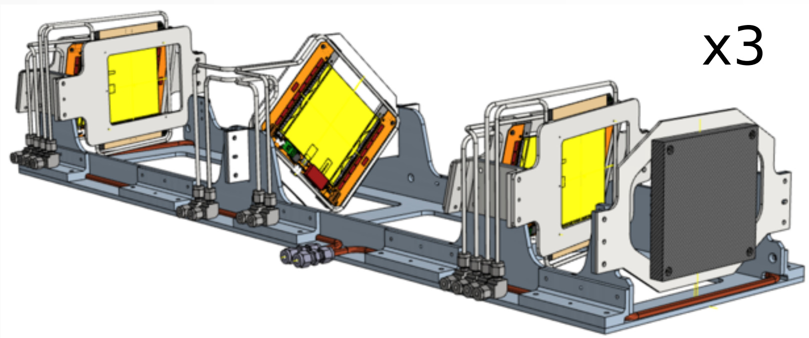
ECAL

- 5x5 $PbWO_4$ crystals (CMS ECAL).
  - 2.85x2.85 cm^2.
  - Length: 22cm (~25 X_0).
- Total area: ~14x14 cm^2.
- Readout: APD sensors, 10x10mm^2 photosensitive area.



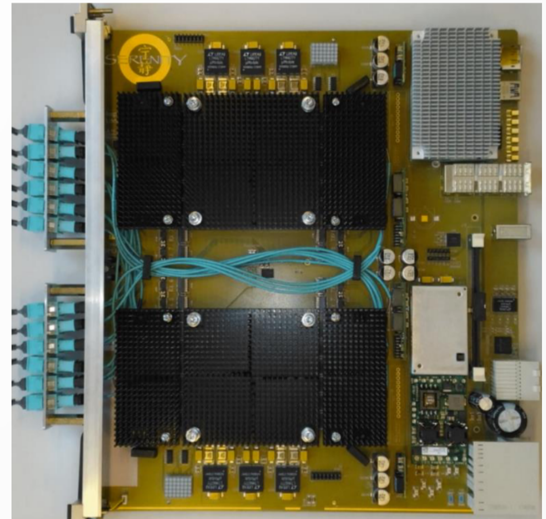
Mechanics and crystal tests currently ongoing in Padova.

DAQ system



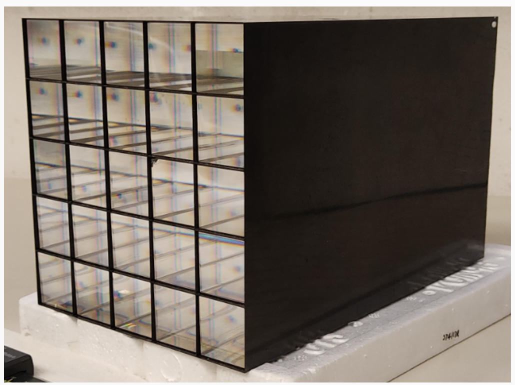
x3

CMS Serenity board



~ 35Gbps in spill

ECAL

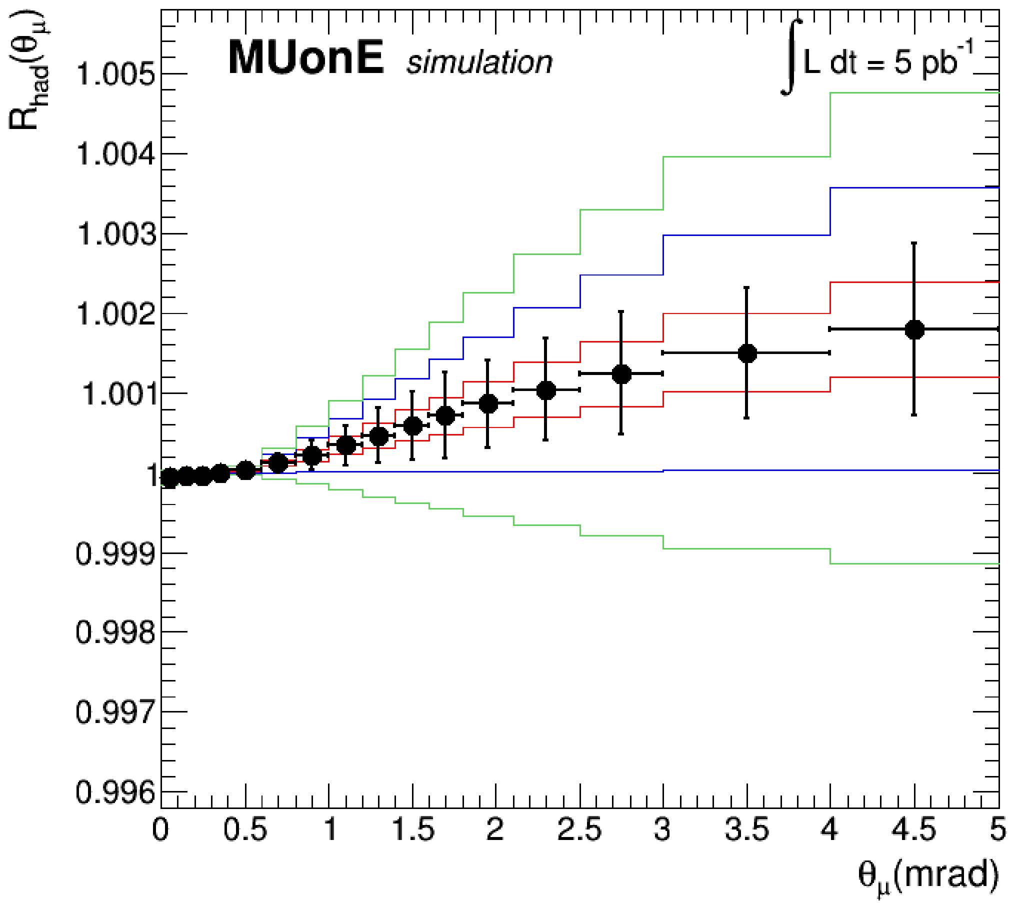


STORAGE

- Test Run: read all data with no event selection.
- Information will be used to determine online selection algorithms to be used in the Full Run.

Sensitivity to $\Delta\alpha_{had}(t)$

Expected luminosity for the Test Run: L = 5 pb^{-1} ⟷ ~10^9 events with E_e > 1 GeV (θ_e < 30 mrad)



We will be able to extract the leptonic running ($\Delta\alpha_{lep} \sim 10^{-2}$)

Initial sensitivity also to the hadronic running ($\Delta\alpha_{had} \sim 10^{-3}$)

$$K = 0.137 \pm 0.027$$

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

Conclusions

- The new method proposed by MUonE to determine a_μ^{HLO} is independent and competitive with the latest evaluations.

- A Test Run of 3 weeks is foreseen at CERN in Fall 2021-early 2022. The aim of the Test Run will be to verify the detector design and evaluate the analysis strategy.

- If the Test Run will confirm the goodness of our proposal, a Run with the full detector is envisaged in 2022-24.

- If you are interested to contribute to MUonE you are welcome!

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Thanks for your attention!

BACKUP

a_μ^{HLO} : time-like approach

a_μ^{HLO} cannot be calculated using perturbative QCD.

↓

Data-driven approach.

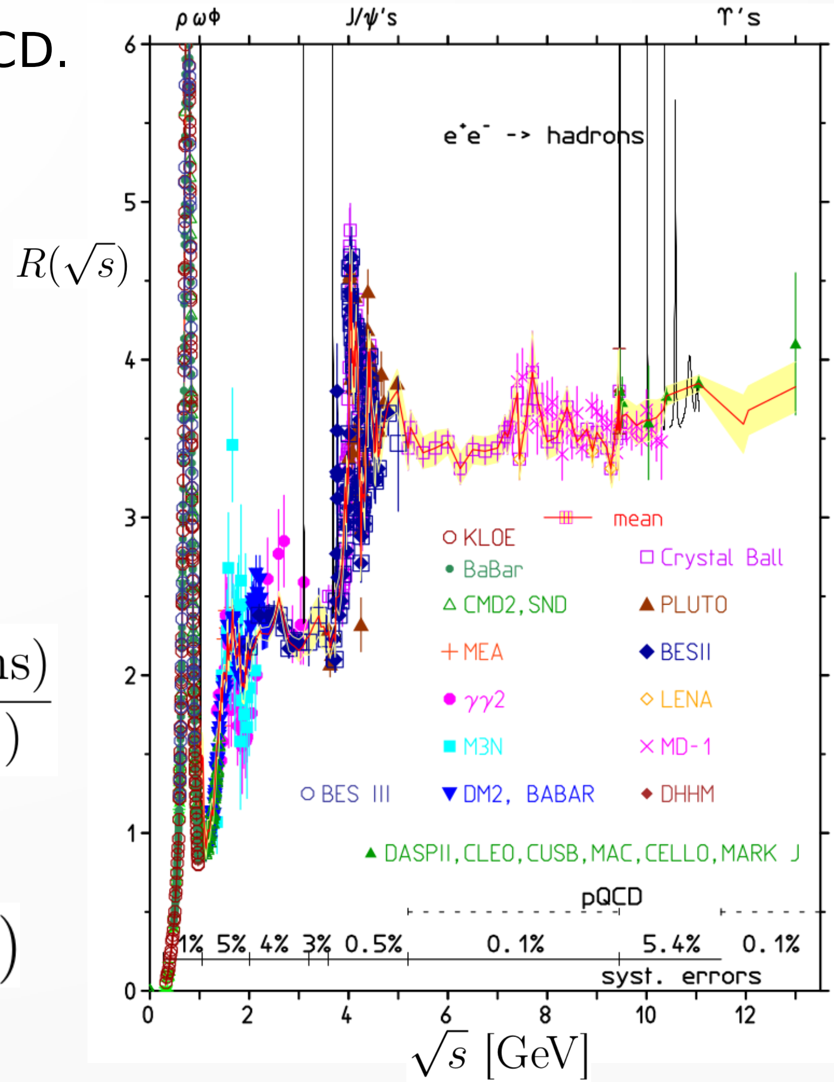
$$a_\mu^{HLO} = \frac{\alpha_0^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$K(s) \sim 1/s$
smooth function

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$a_\mu^{HLO} = (693.1 \pm 4.0) \times 10^{-10} \quad (0.6\%)$$

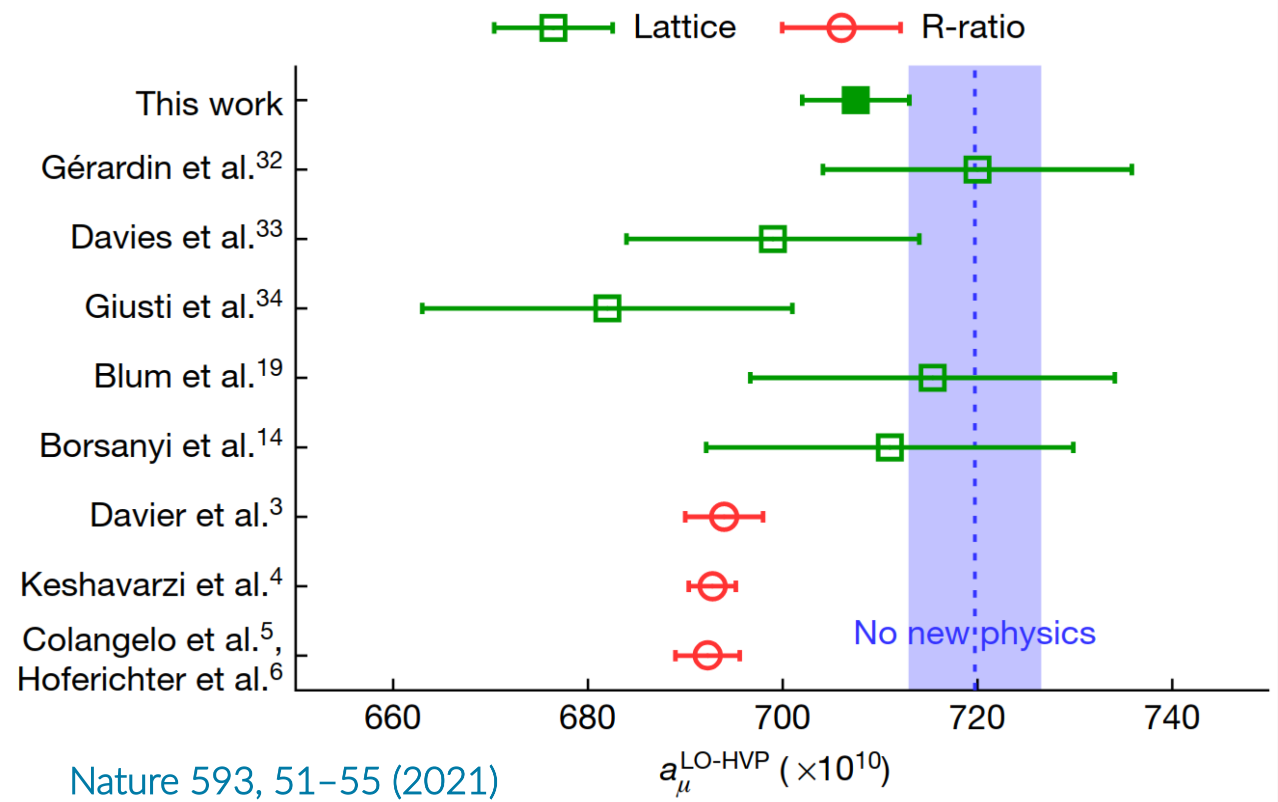
Phys. Rep. 887 (2020), 1



a_μ^{HLO} : lattice QCD

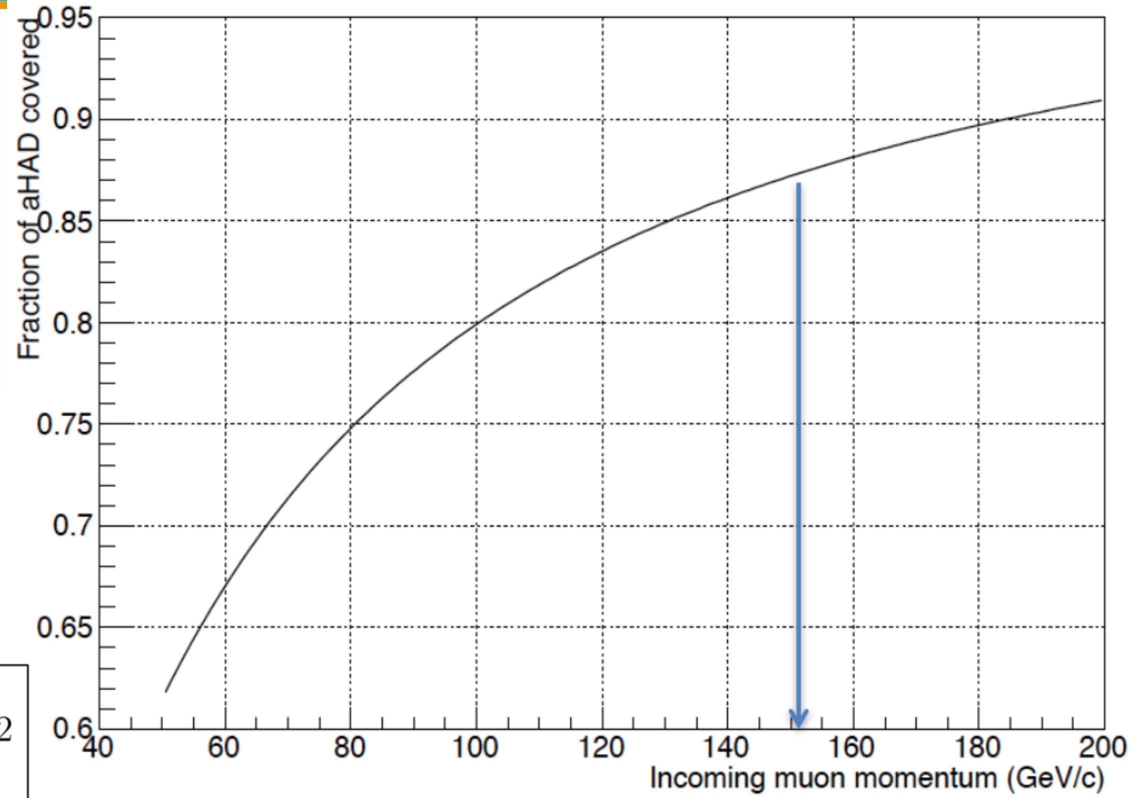
Great improvement in lattice QCD calculations during last years.

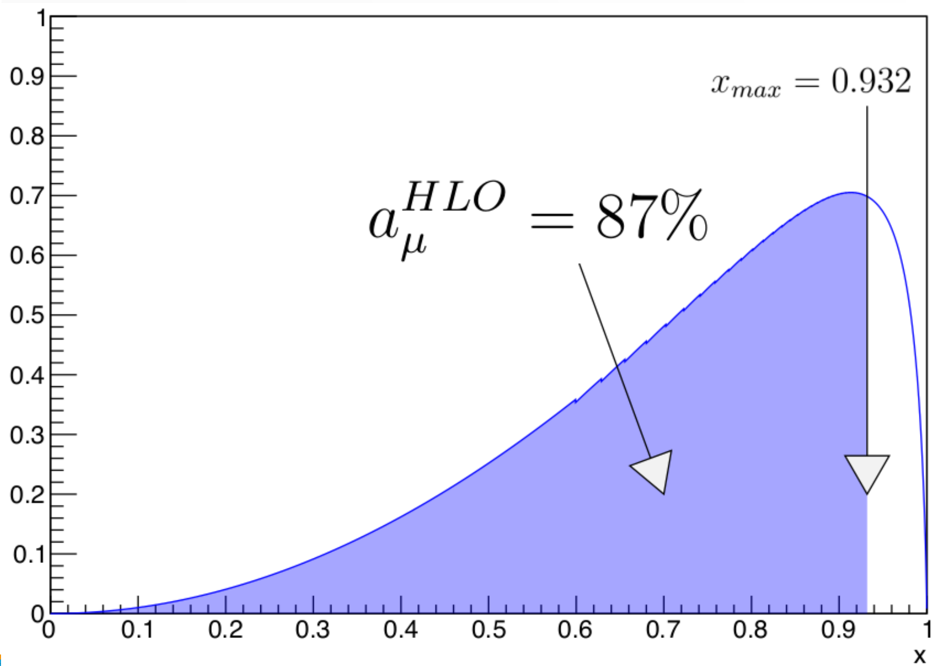
BMW collaboration recently achieved 0.8% precision.



Nature 593, 51–55 (2021)

$$x \lesssim 0.93$$



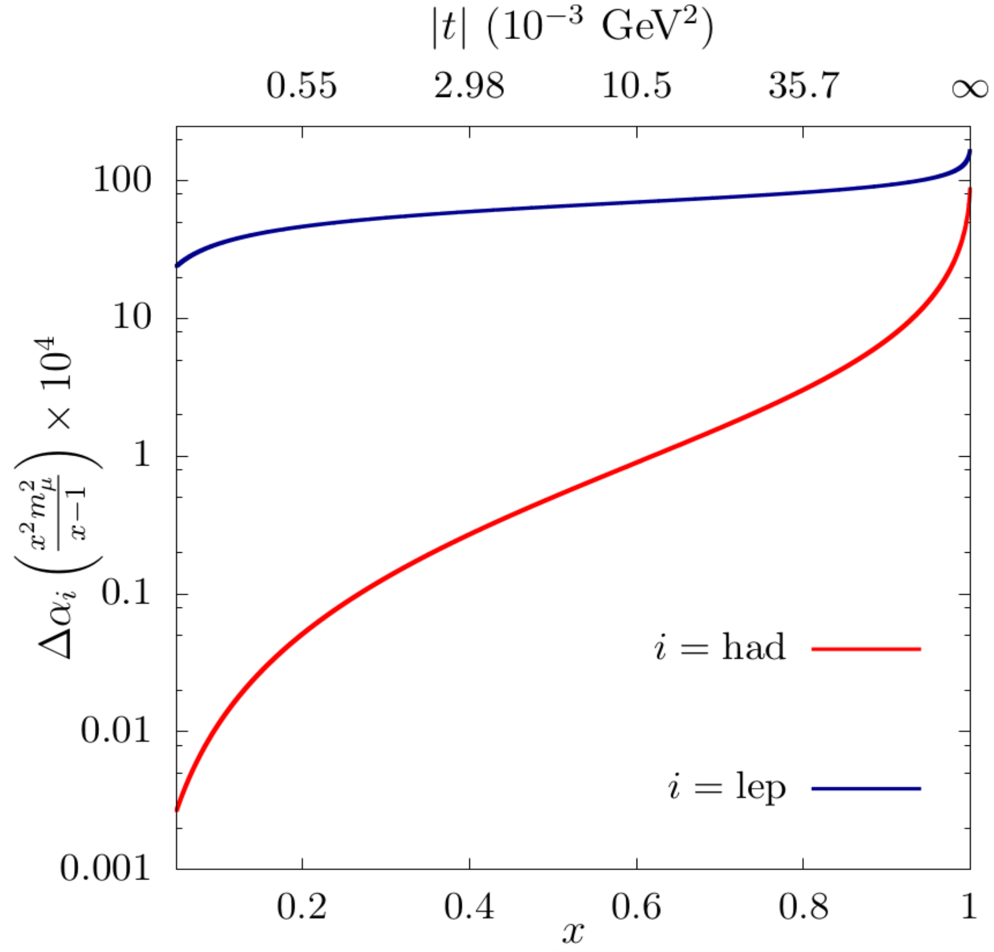


- 160 GeV muon beam on atomic electrons.

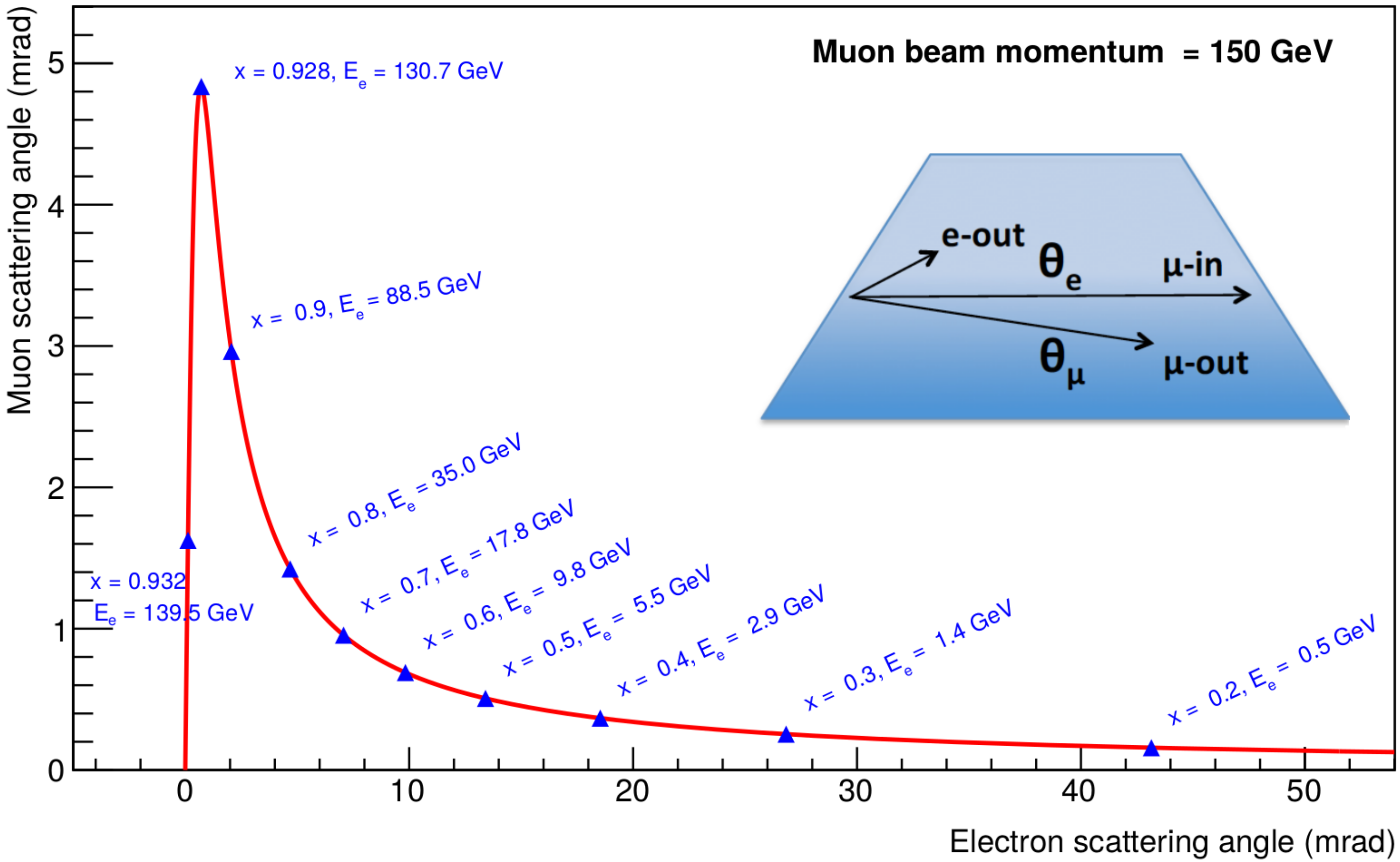
$$\sqrt{s} \sim 420\,\mathrm{MeV}$$

$$-0.153\,\mathrm{GeV}^2 < t < 0\,\mathrm{GeV}^2$$

$$\Delta\alpha_{had}(t) \lesssim 10^{-3}$$



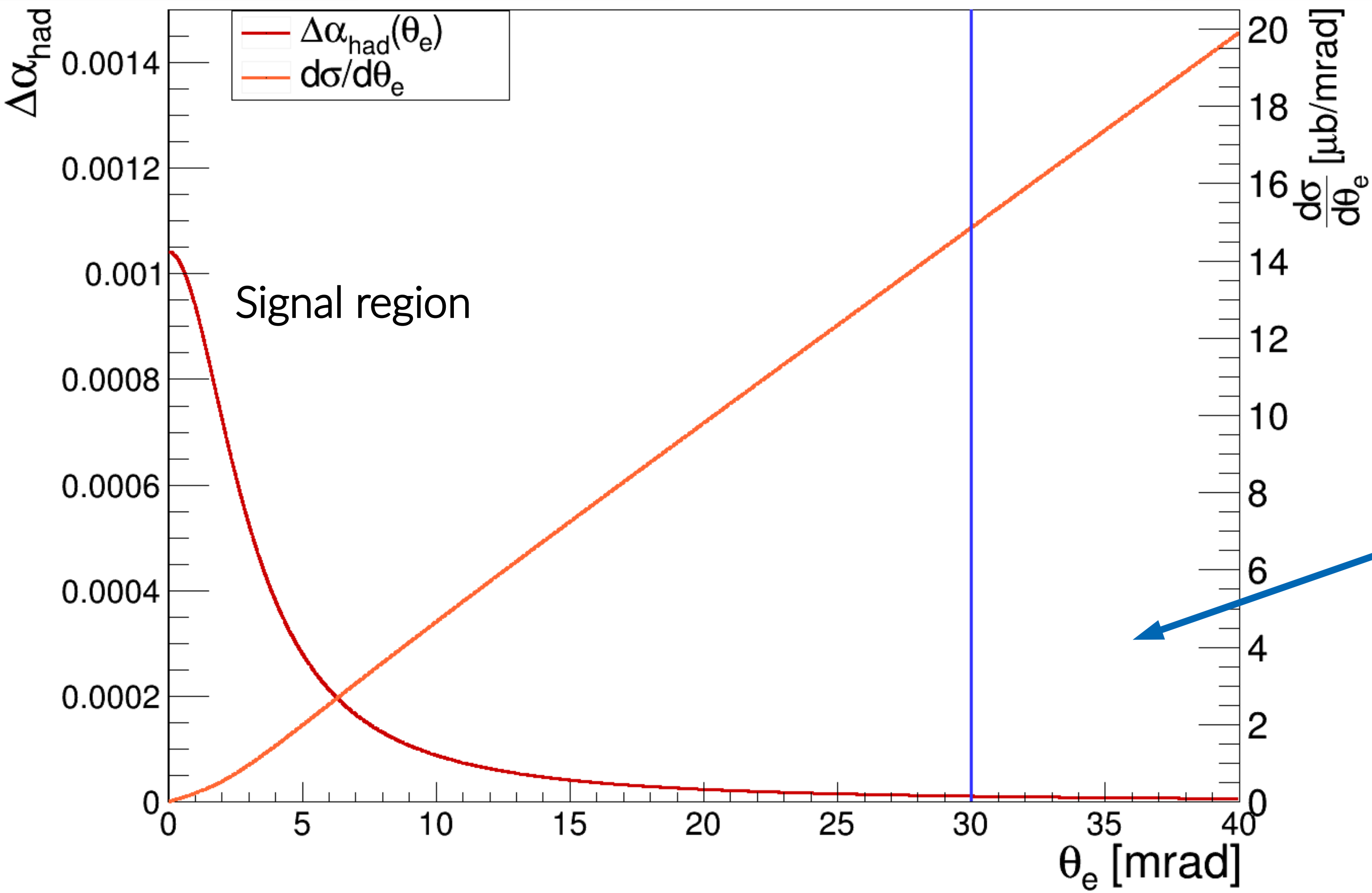
Correlation curve (θ_e, θ_μ)



It allows to select signal events and reject the background

$$\sin\theta_\mu = \frac{p'_e \sin\theta_e}{p'_\mu} = \sin\theta_e \sqrt{\frac{E_e^2(\theta_e) - m_e^2}{[E_\mu + m_e - E_e(\theta_e)]^2 - m_\mu^2}}$$

Extraction of $\Delta\alpha_{had}(t)$



No sensitivity to $\Delta\alpha_{had}(t)$ in this region:

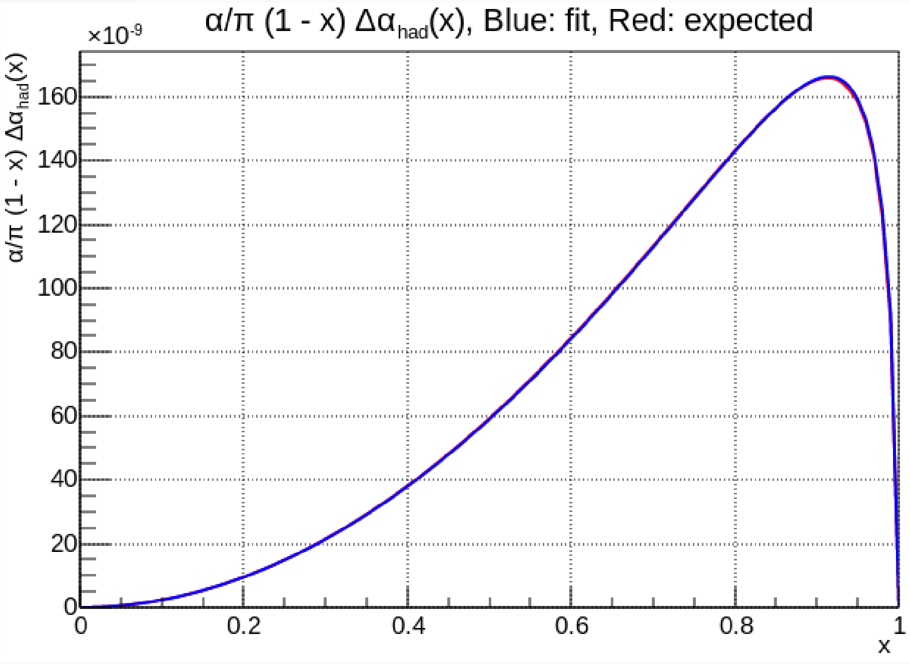
$$\Delta\alpha_{had}(t) \lesssim 10^{-5}$$

$$\theta_e \gtrsim 30 \text{ mrad}$$

“Lepton-like” parameterization

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

Inspired from the analytical function of the leading order leptonic running

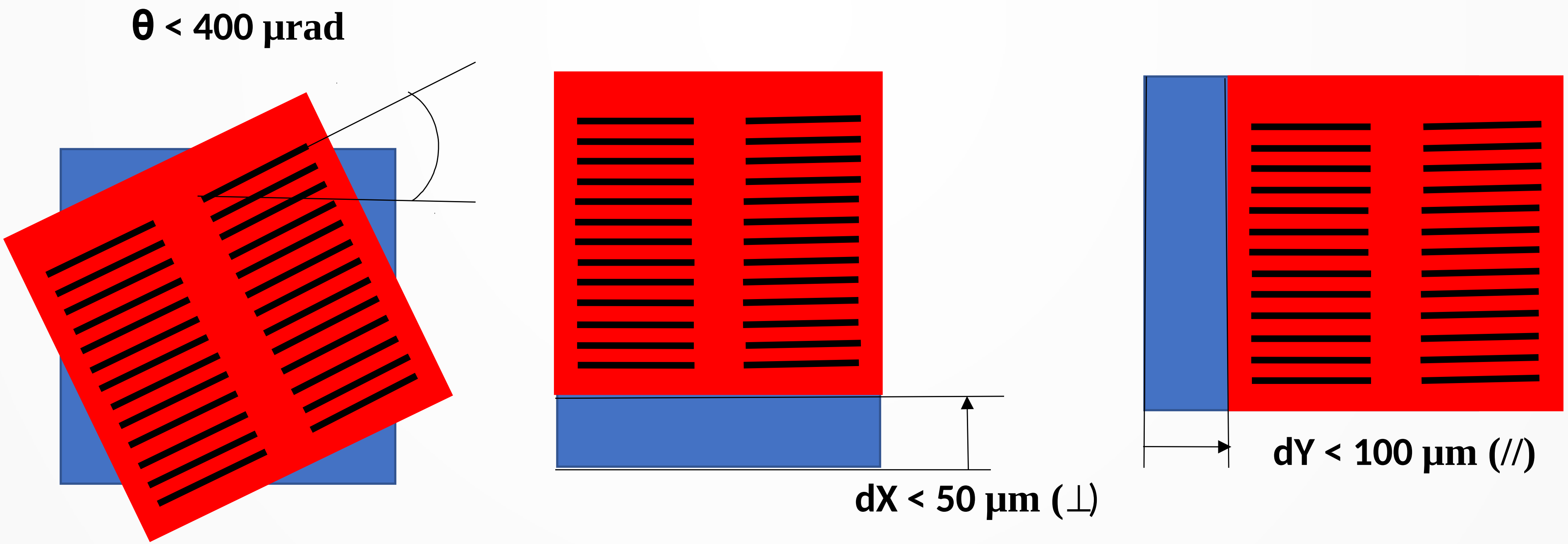


K = related to α_0 and the electric charge of the lepton in the loop (and also colour charge for quarks)

M = related to the squared mass of the particle in the loop

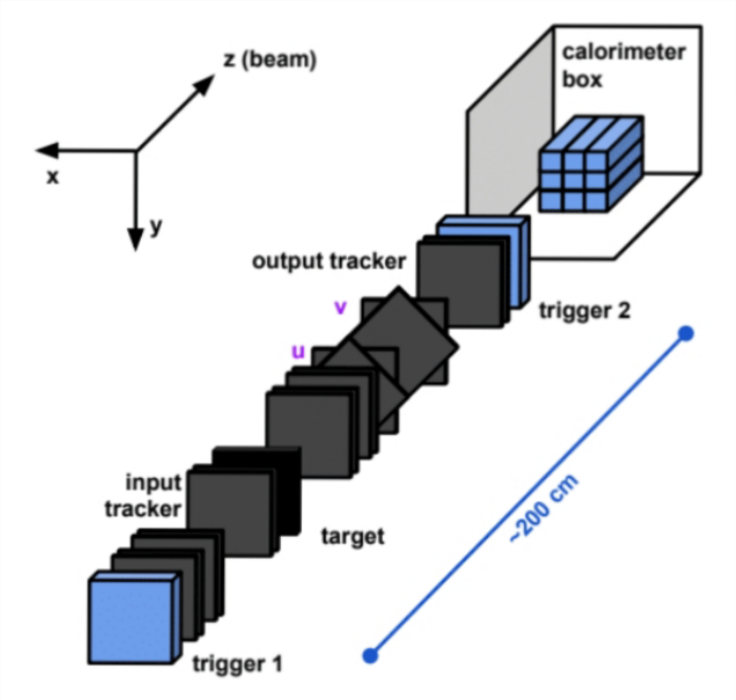
It allows to extrapolate $\Delta\alpha_{had}(t)$ also in the region which is not accessible by kinematics (x > 0.93).

- Rotation: ~ 123 μrad (I), ~ 30 μrad (II)
- Shift parallel: ~ 25 μm (I), ~ 9 μm (II)
- Shift perpendicular: ~ 14 μm (I), ~ 29 μm (II)

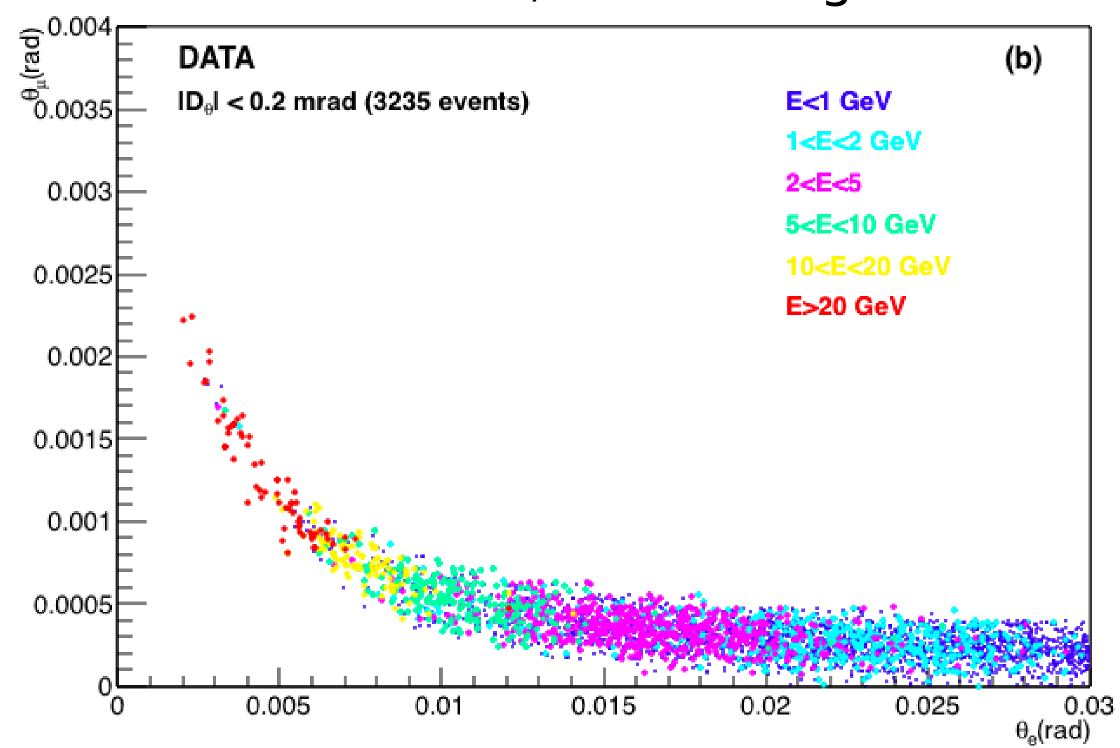


Test Beam 2018

arxiv:2102.11111



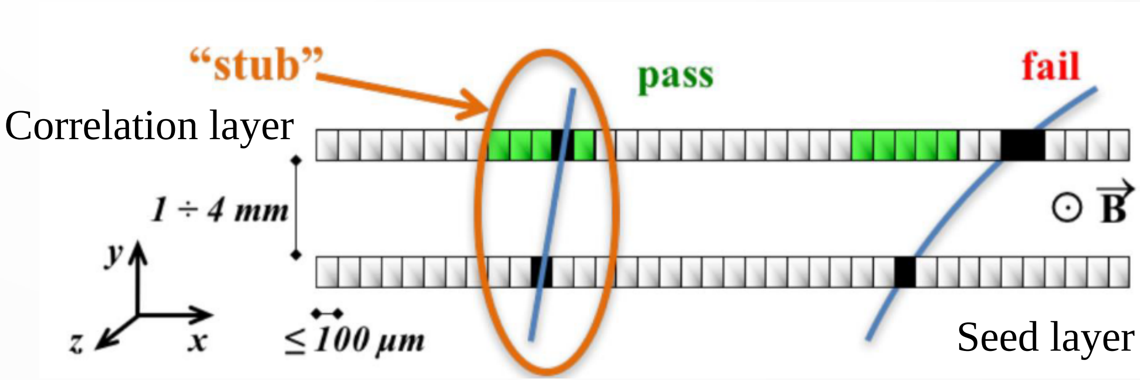
- Detector located downstream Compass.
  - 8 mm C target
  - Si strip sensors (AGILE) ~40μm intrinsic resolution
  - 3x3 BGO ECAL. $2.1\text{x}2.1\text{cm}^2$, 23 cm length



First evidence of elastic scattering.

2S modules

Select only particles above a certain transverse momentum p_t for the 40 MHz readout.



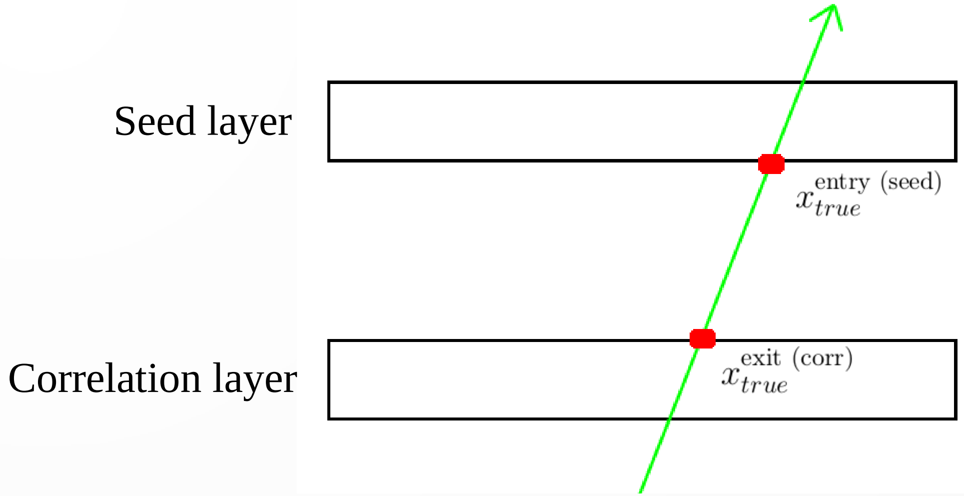
Correlation window: ±7 strips.
Window offset = 0.
Max cluster width = 4 strips.

Stub information: position of the cluster in the seed layer + distance between position of correlation cluster and seed cluster (bend)

Single hit resolution – some definitions

The single hit resolution is defined as the st.dev. of the distribution

$$x_{true} - x_{stub}$$



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

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

$$x_{true} = \frac{x_{true}^{\text{exit (corr)}} + x_{true}^{\text{entry (seed)}}}{2}$$

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

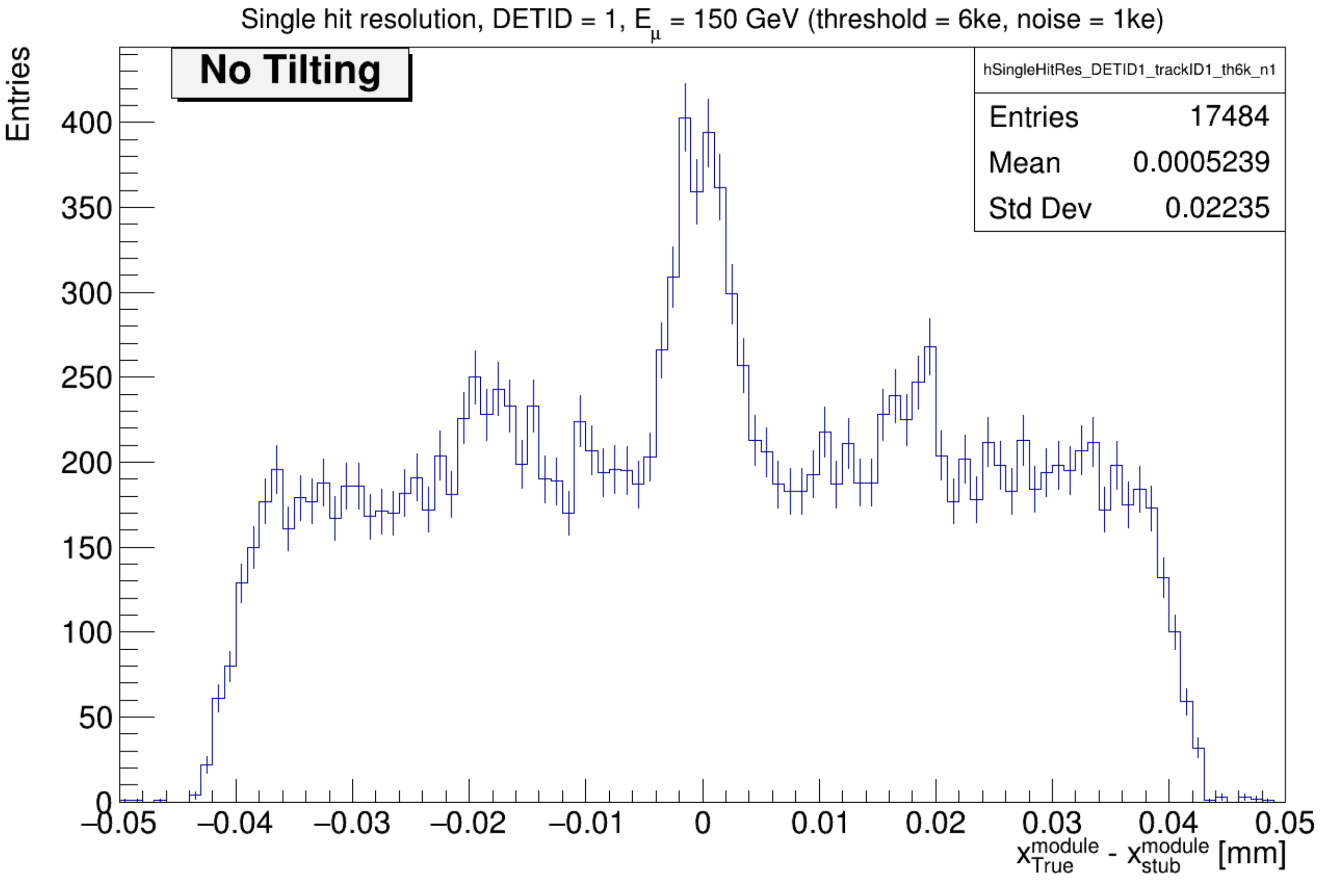
x_{true} = μ position in the middle of the 2S module

$x_{true}^{\text{exit (corr)}}$ and $x_{true}^{\text{entry (seed)}}$ taken from Geant4

x_{stub} = μ position retrieved from the stub information

Single hit resolution – non tilted geometry

$$\sigma_{1hit} = 22.4\,\mu m$$



Single hit resolution – tilted geometry

Tilted geometry: improvement in resolution due to two different effects:

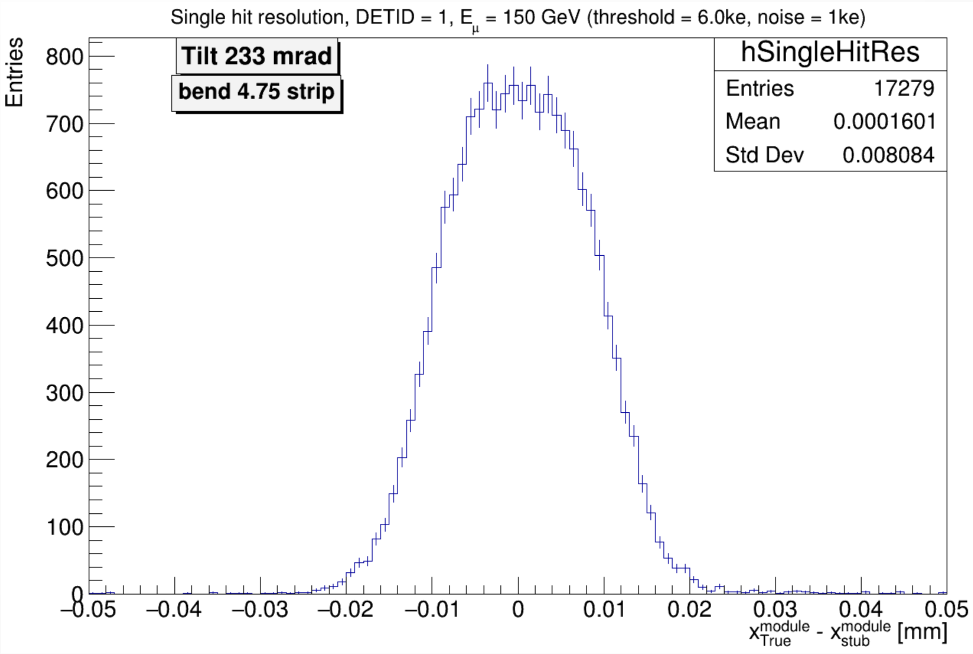
1) charge sharing: energy deposition of particles in the Si is shared among neighbouring strips

2) effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½pitch

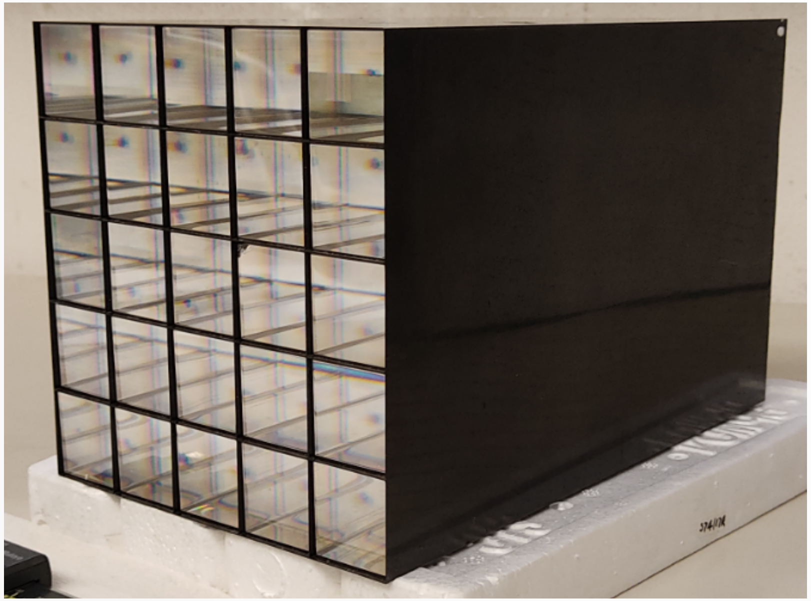
optimal point:
tilt angle: 233 mrad
threshold: 6σ

Resolution for
150 GeV muons:

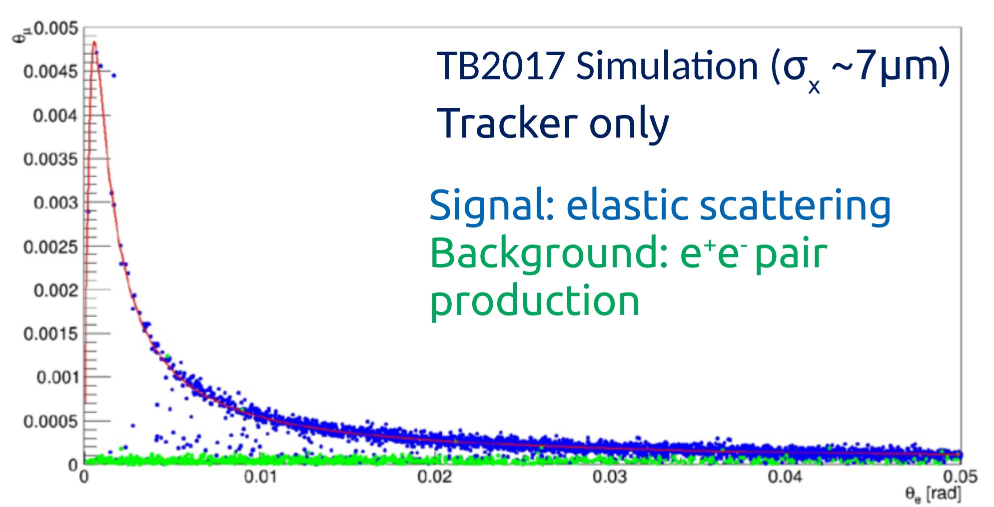
$$\sigma_{1hit} = 8.0\,\mu\text{m}$$

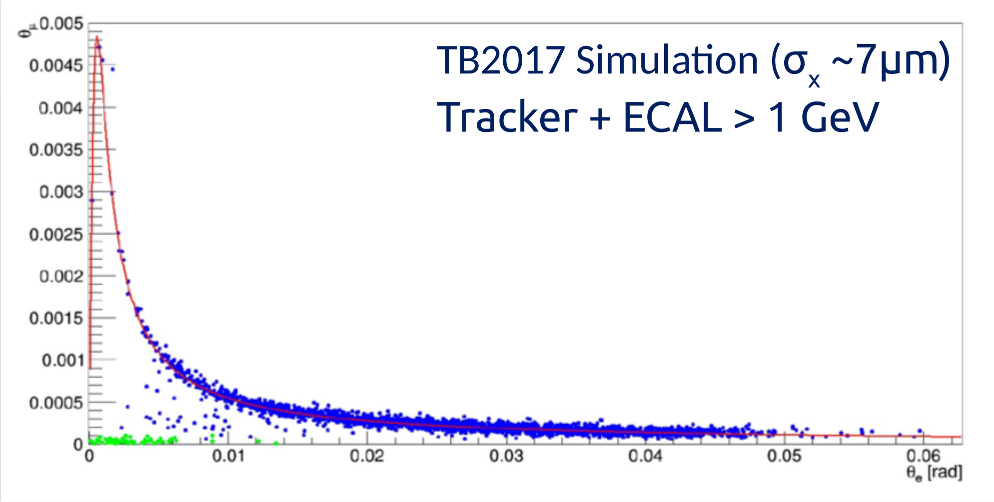


ECAL



- 5x5 $PbWO_4$ crystals (CMS ECAL).
- $2.85 \times 2.85\ cm^2$
- Total area: $\sim 14 \times 14\ cm^2$
- Readout: APD sensors.



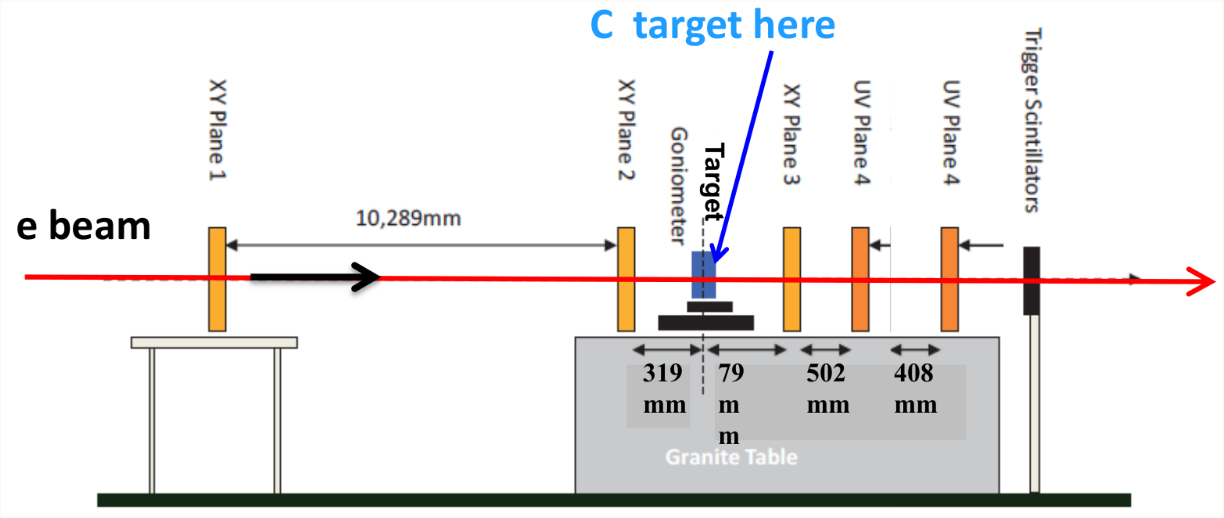


Multiple scattering: results from TB2017

Multiple scattering effects of electrons with 12 and 20 GeV on Carbon targets (8 and 20 mm)

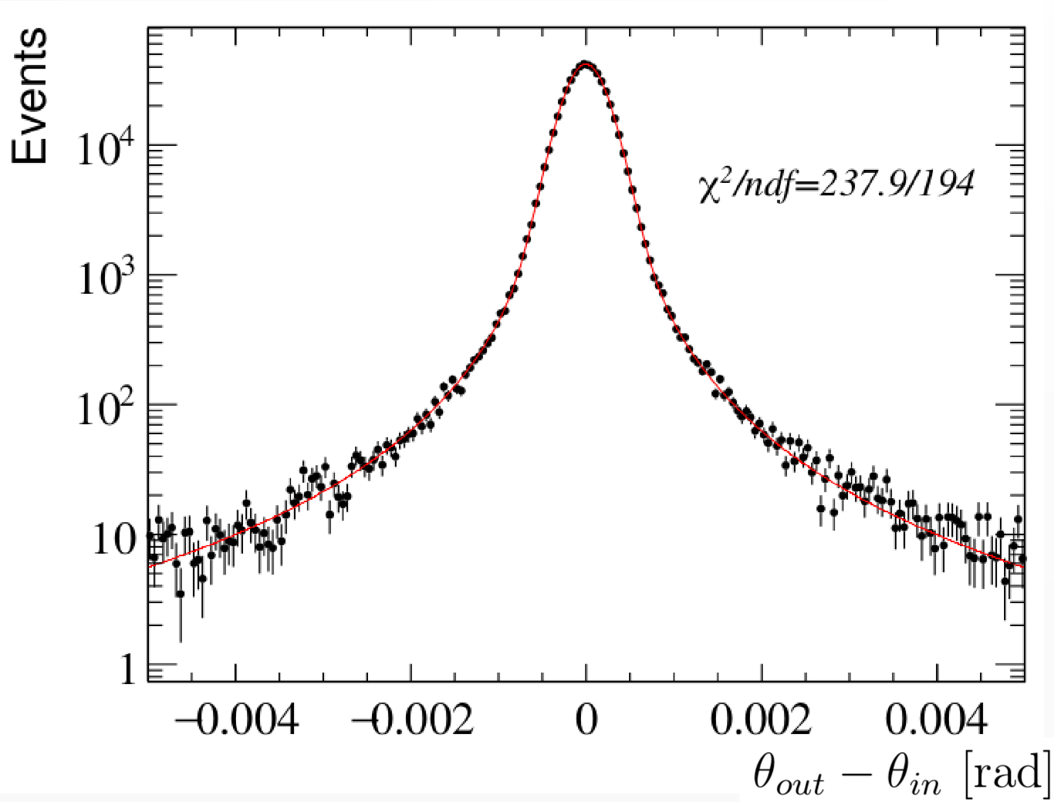
Main goals:

- to determine a parameterization able to describe also non Gaussian tails
- to compare data with a GEANT4 simulation of the apparatus



Multiple scattering: results from TB2017

$$f_e(\delta\theta_e^x) = N\left[(1-a)\frac{1}{\sqrt{2\pi}\sigma_G}e^{-\frac{(\delta\theta_e^x-\mu)^2}{2\sigma_G^2}} + a\frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\nu\pi}\sigma_T\Gamma(\frac{\nu}{2})}\left(1+\frac{(\delta\theta_e^x-\mu)^2}{\nu\sigma_T^2}\right)^{-\frac{\nu+1}{2}}\right]$$



$$\vec{p} = [N,\ a,\ \mu,\ \sigma_G,\ \nu,\ \sigma_T]$$

Results show a ~1% agreement between data and MC for the Gaussian core