The analysis strategy of the MUonE experiment

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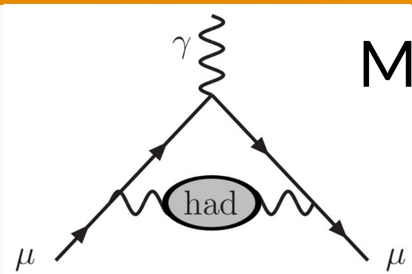
The MUonE experiment

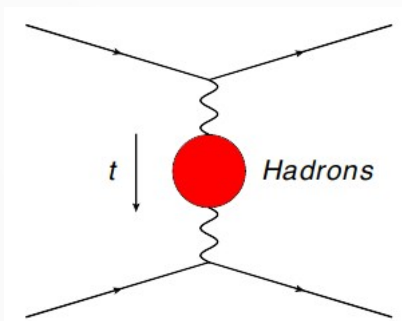


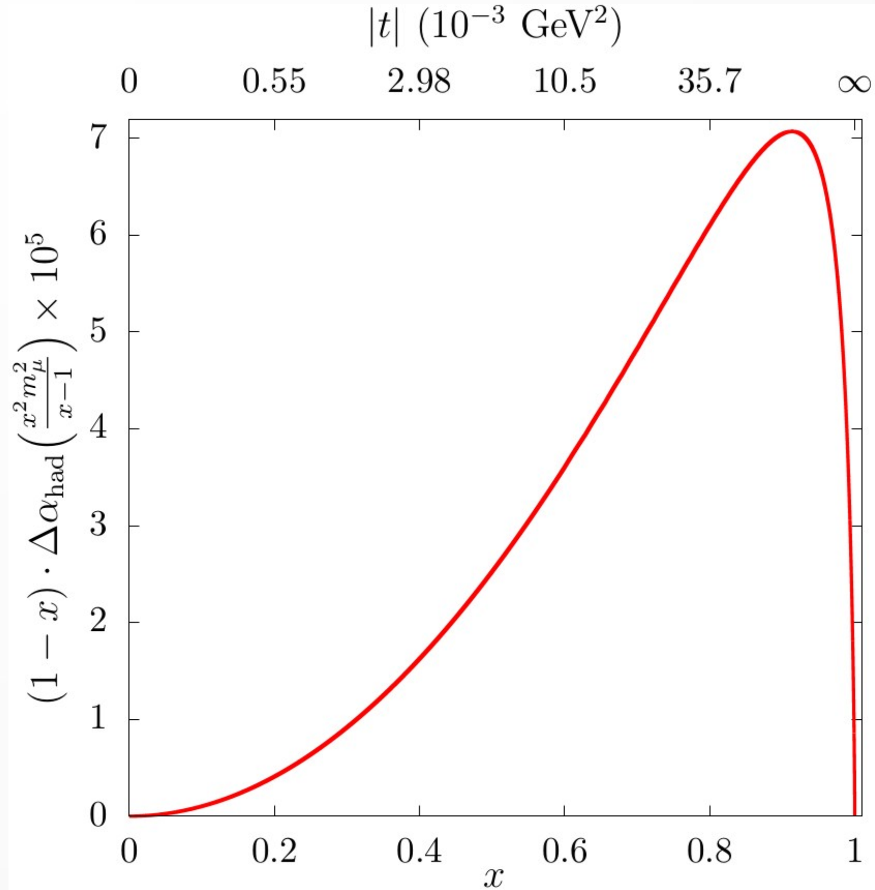
MUonE: a new independent evaluation of a_μ^{HLO}

Phys. Rep. C 3 (1972), 193

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

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





Phys. Lett. B 746 (2015), 325

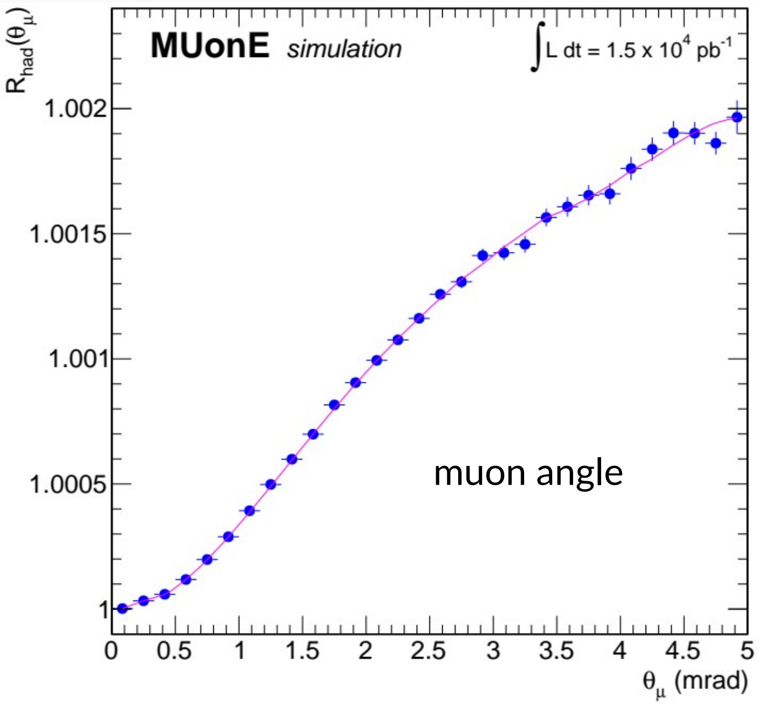
Based on the measurement of $\Delta\alpha_{\mathrm{had}}(t)$:
hadronic contribution to the running of the electromagnetic coupling constant.

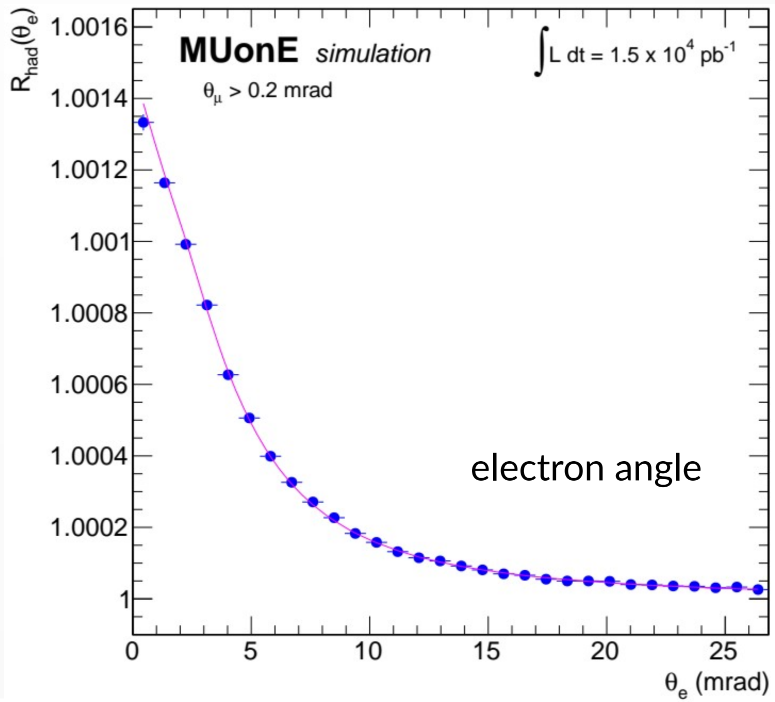
The MUonE experiment

Extraction of $\Delta\alpha_{had}(t)$ from the shape of the $\mu e \to \mu e$ differential cross section

$$R_{\text{had}} = \underbrace{\frac{d\sigma_{\text{data}}(\Delta\alpha_{\text{had}})}{d\sigma_{\text{MC}}(\Delta\alpha_{\text{had}} = 0)}}_{\text{From theoretical calculation}} \sim 1 + \underbrace{2\Delta\alpha_{\text{had}}(t)}_{\text{To be measured}}$$

$\Delta\alpha_{had}(t) < 10^{-3}$ in the MUonE kinematic region





$\Delta\alpha_{had}$ parameterization

Inspired from the 1 loop QED contribution of lepton pairs and top quark at $t < 0$

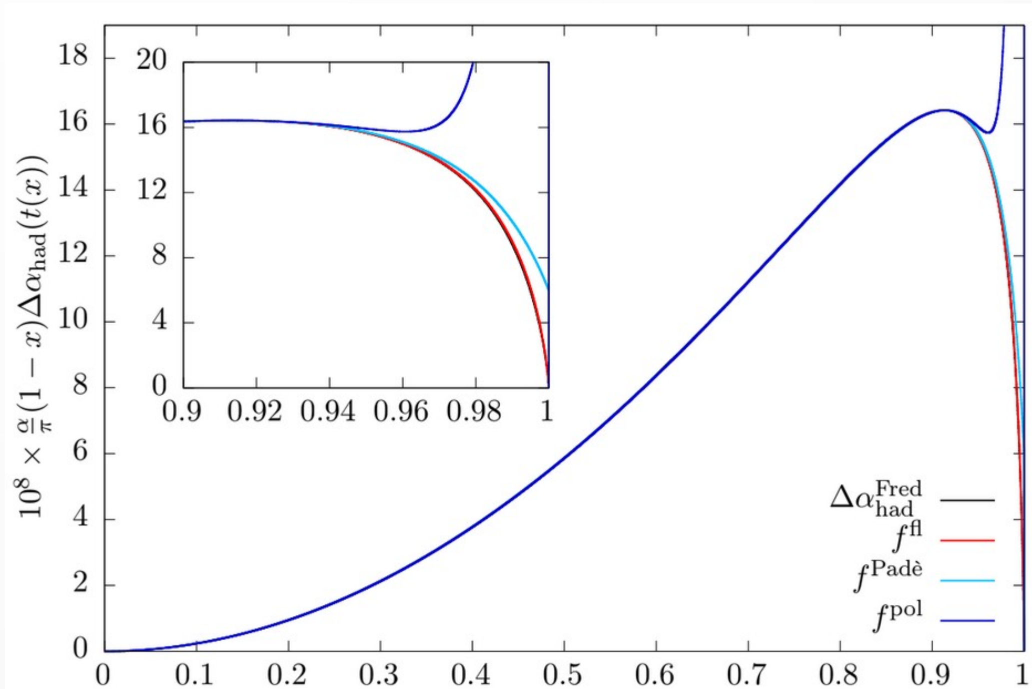
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2 parameters: K, M

Allows to calculate the full value of a_μ^{HLO}

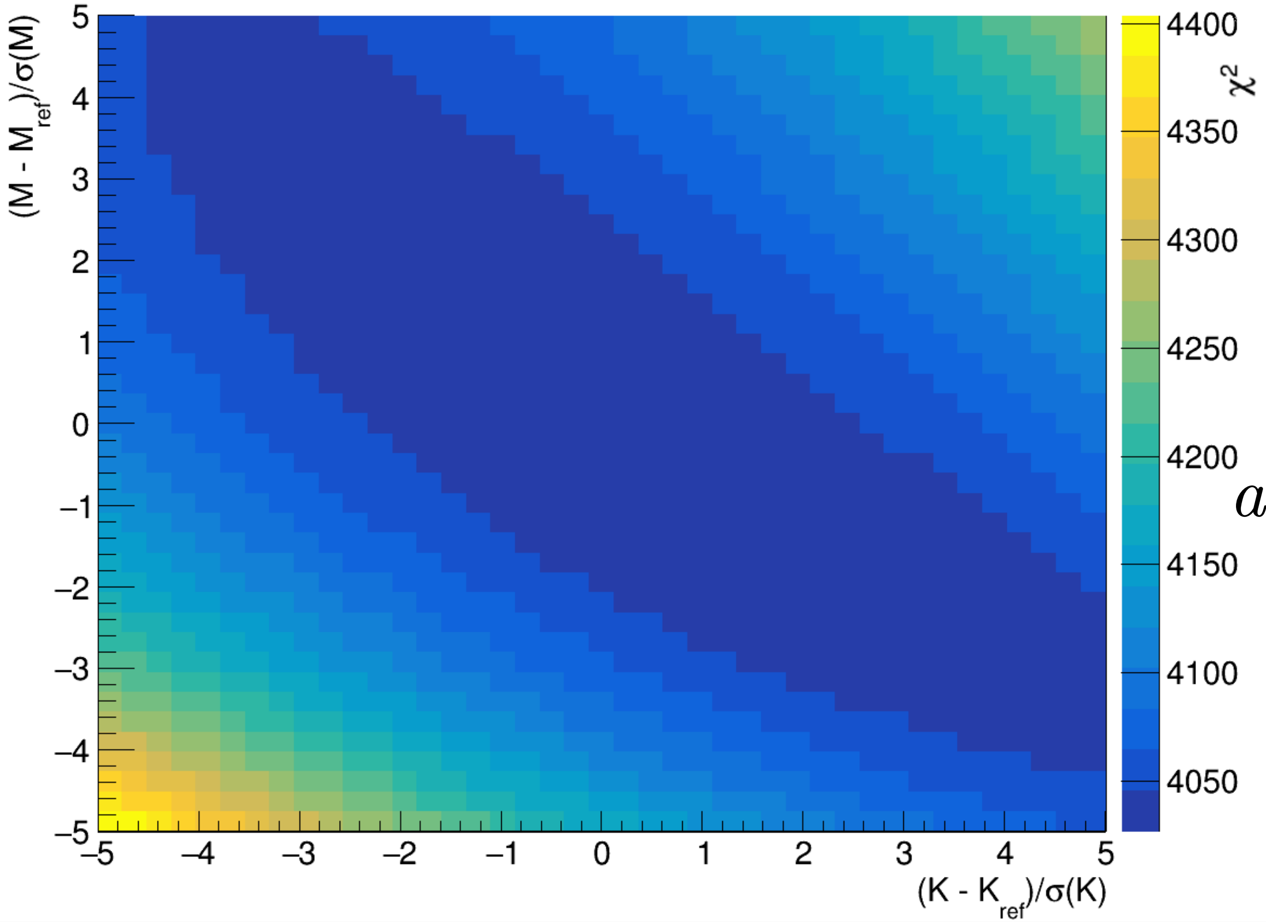
Dominant behaviour in the MUonE kinematic region:

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



Extraction of $a_\mu^{\rm HLO}$

Extraction of $\Delta\alpha_{\rm had}(t)$ through a template fit to the 2D (θ_e, θ_μ) distribution



Results from a simulation with the expected final statistics (4×10^{12} elastic events):

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

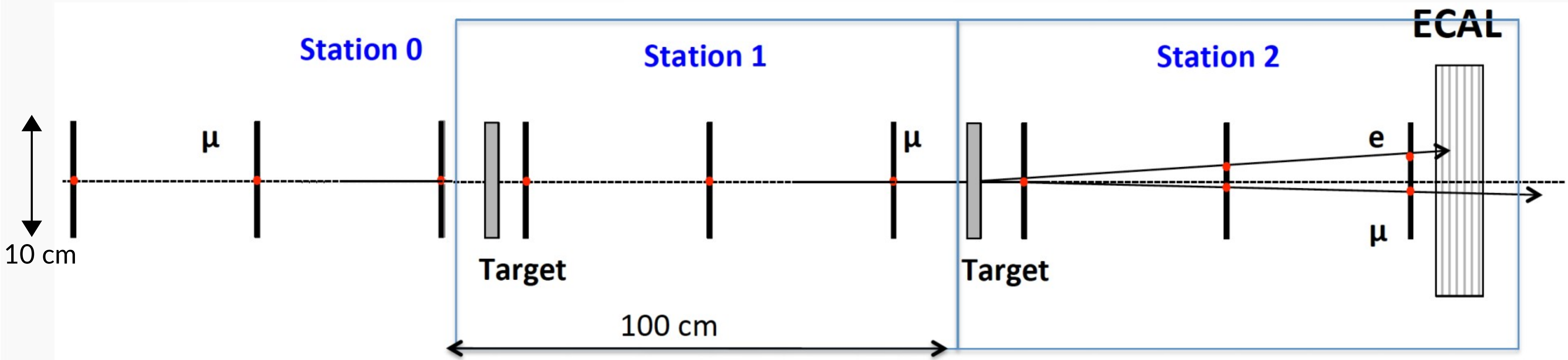
(0.35% accuracy)

Input value:

$$a_\mu^{\rm HLO} = 688.6 \times 10^{-10}$$

Test Run

A 3 weeks Test Run with a reduced detector
has been approved by SPSC, to validate our proposal.



Main goals:

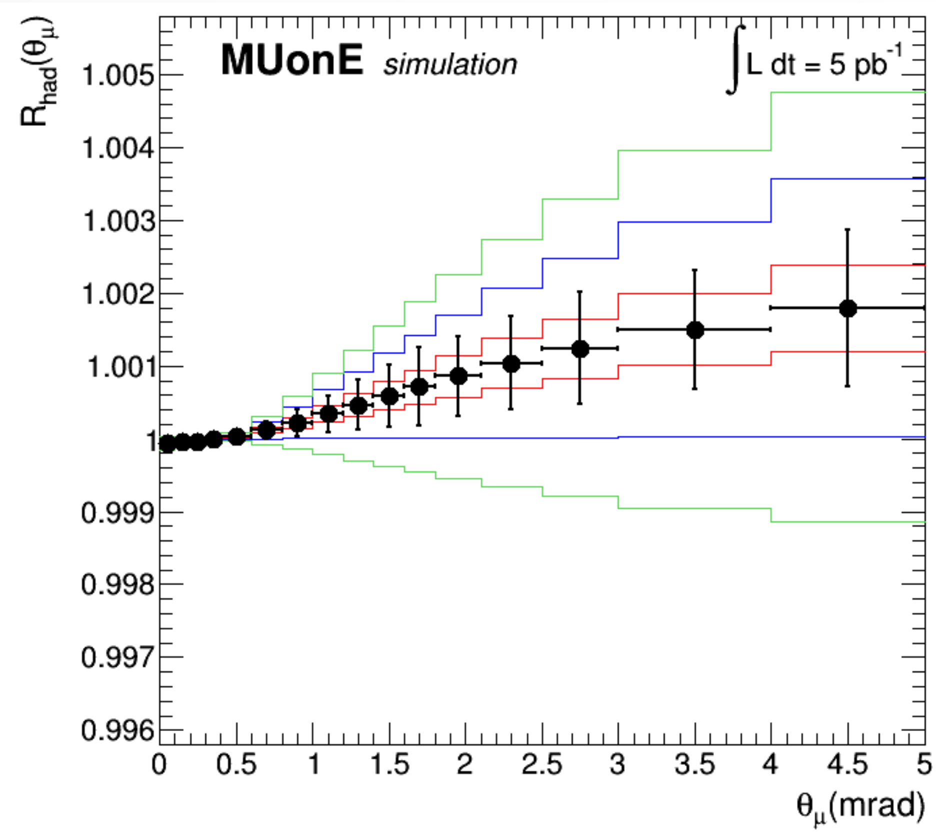
- Pretracker +
- 2 MUonE stations +
- ECAL

- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Assess the systematic errors.
- Initial sensitivity to $\Delta\alpha_{\mathrm{had}}(t)$.
- Possible measurement of $\Delta\alpha_{\mathrm{lep}}(t)$.

Test Run: expected sensitivity on $\Delta\alpha_{had}(t)$

Expected luminosity for the Test Run: $L_{TR} = 5\ pb^{-1}$ ⟷ ~10^9 events with $E_e > 1$ GeV ($\theta_e < 32$ mrad)

$$R_{\text{had}} = \frac{d\sigma_{\text{data}}(\Delta\alpha_{\text{had}})}{d\sigma_{\text{MC}}(\Delta\alpha_{\text{had}}=0)} \sim 1 + 2\Delta\alpha_{\text{had}}(t)$$



Low sensitivity to the hadronic running ($\Delta\alpha_{had}(t) < 10^{-3}$)

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

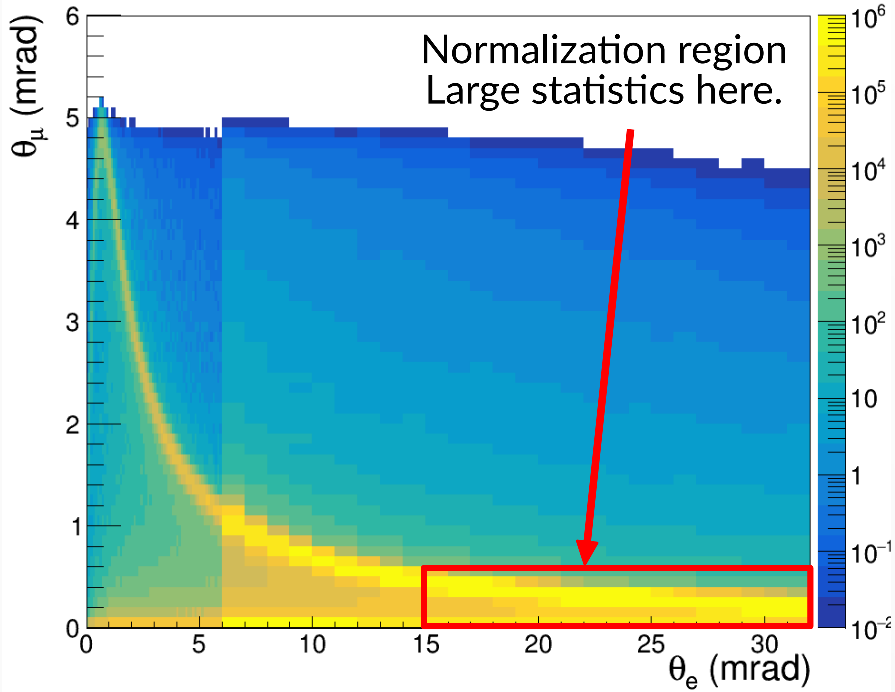
K = 0.136 ± 0.026
(20% stat error)

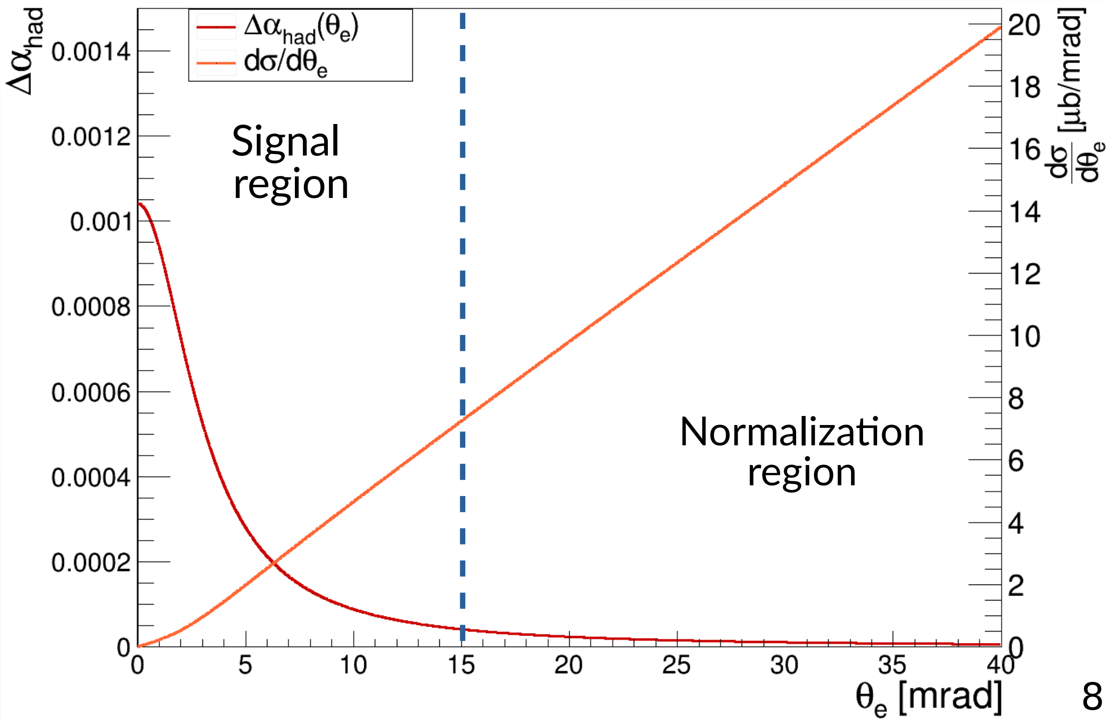
We will be sensitive to the leptonic running ($\Delta\alpha_{lep}(t) < 10^{-2}$)

Strategy for the systematic effects

Main systematics have large effects in the normalization region.
(no sensitivity to $\Delta\alpha_{\mathrm{had}}$ here)

- Angular intrinsic resolution.
- Knowledge of the beam energy.
- Multiple scattering.





Strategy for the systematic effects

Promising strategy: 2 steps workflow

1. Use normalization region to calibrate the larger systematic effects (beam energy, angular intrinsic resolution).

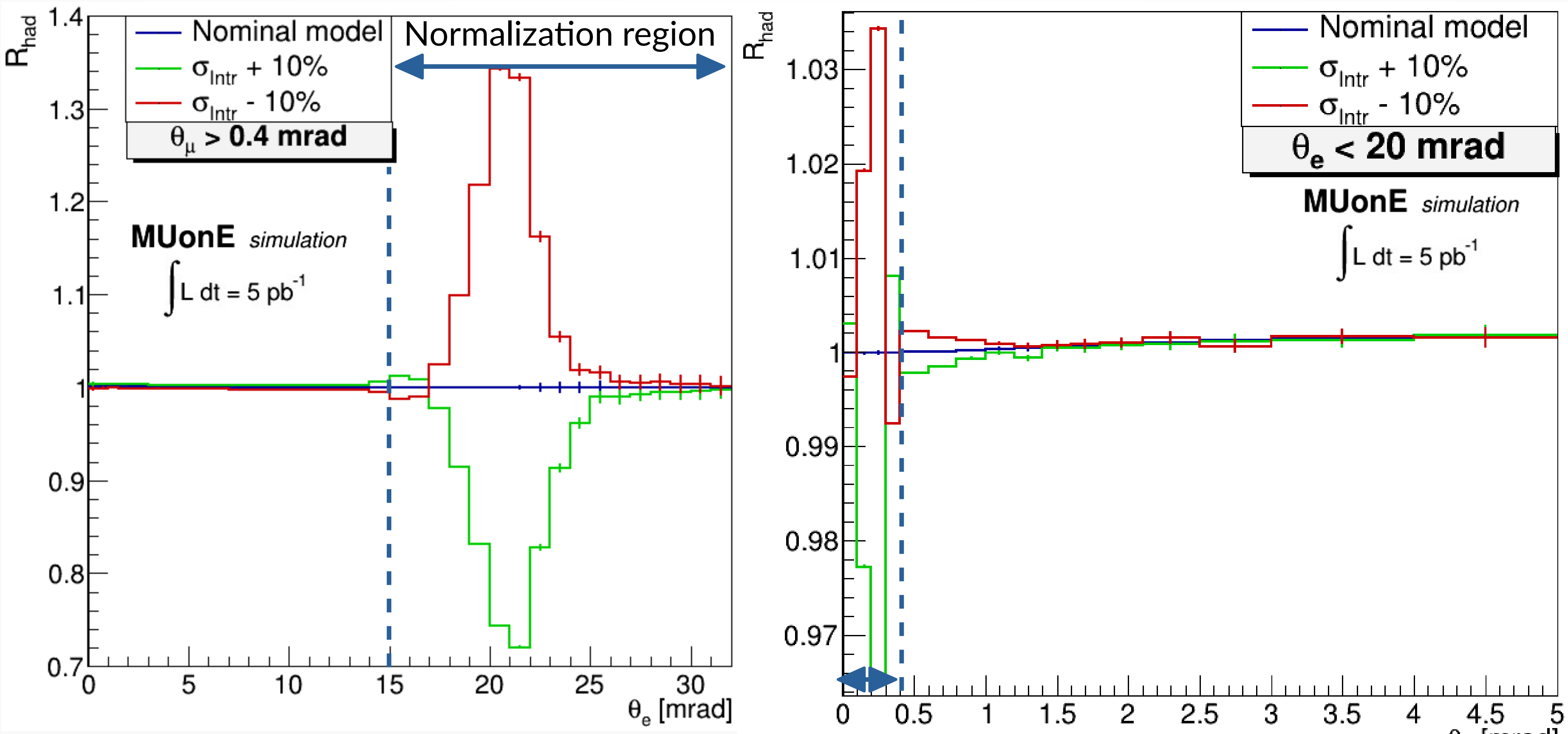
2. Include residual systematics as nuisance parameters in a combined fit with signal.

- MESMER MC + fast detector simulation to generate template distributions.
- Combine analysis tool to perform the combined likelihood fit to the signal + systematics.

  https://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/

Systematic error on the angular intrinsic resolution

±10% error on the angular intrinsic resolution: huge effect.

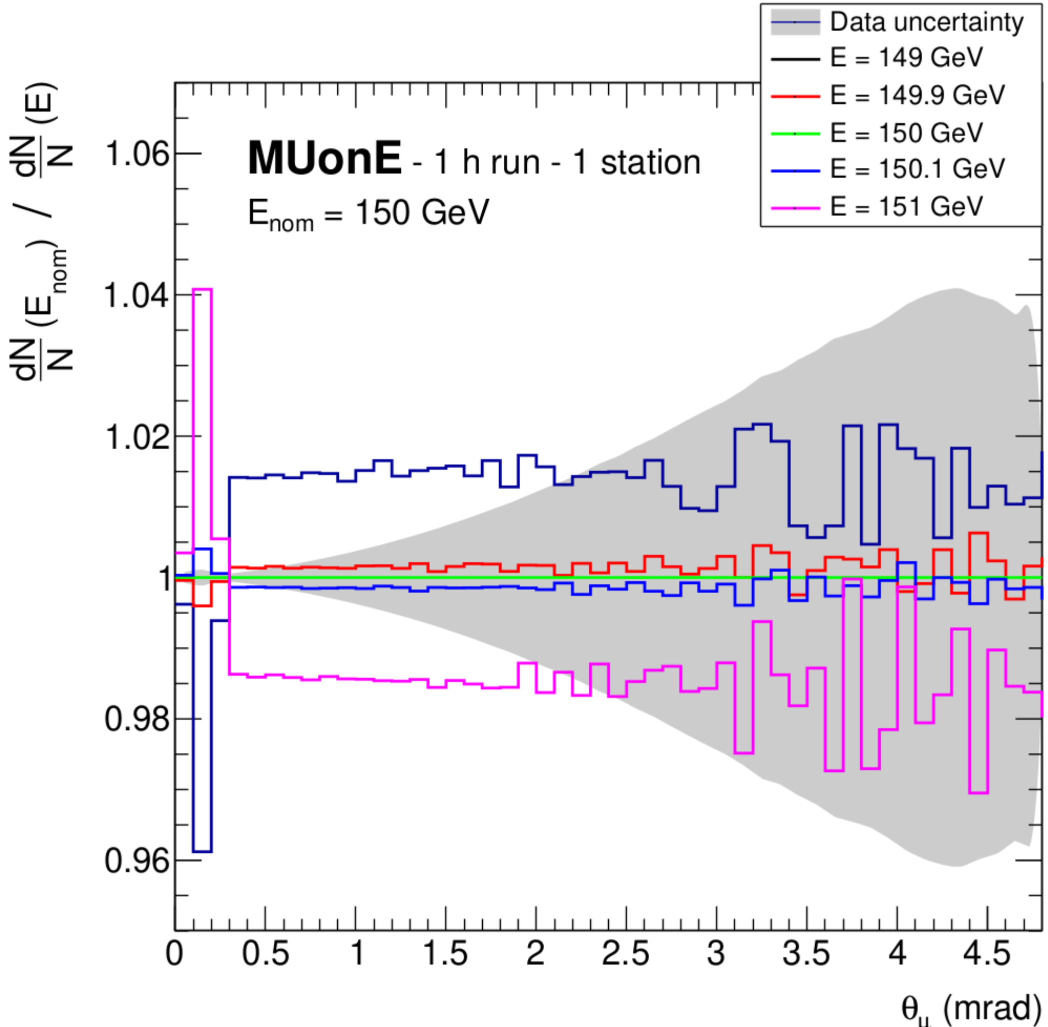


Normalization region

Systematic error on the muon beam energy

Accelerator division provides E_{beam} with O(1%) precision (~ 1 GeV).
It must be controlled by a physical process.

Effects of such shift on E_{beam} can be seen in our data in 1h of data taking per station.

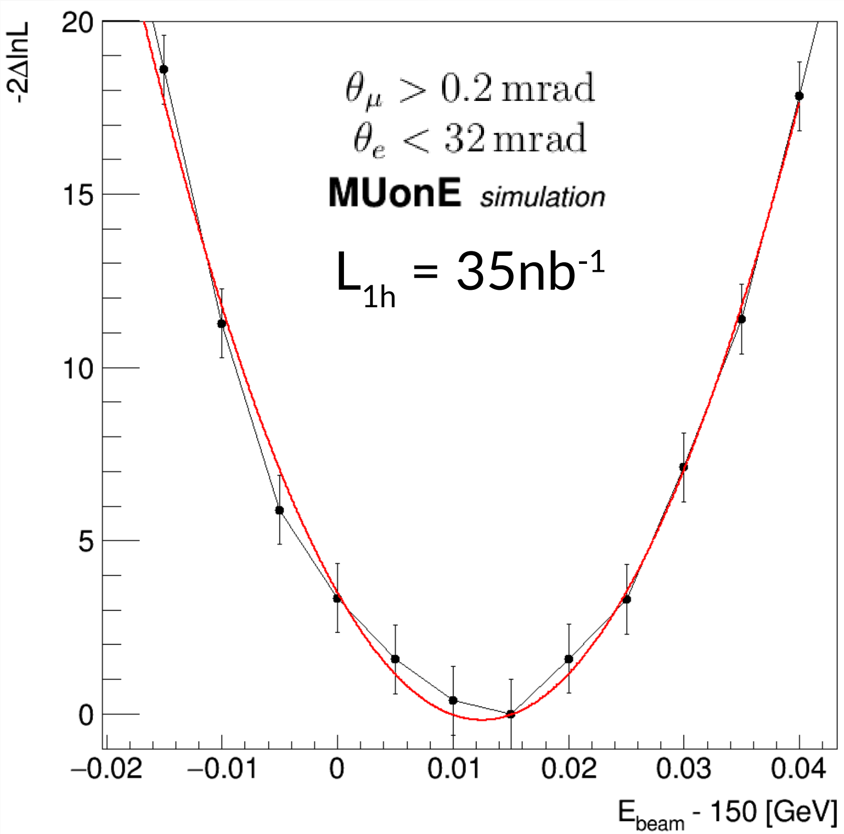


G Abbiendi Phys. Scr. (2022) 97 054007

Step 1: tuning larger systematic effects

Pseudo-data sample:

- E_{beam} = 150.012 GeV
- $\sigma_{Intr} \rightarrow +5\%$



1h data taking per station to tune the main systematics

(assuming a fixed model for $\Delta\alpha_{had}$)

E_{beam}: template fit parameter

μ_{Intr}: nuisance parameter for intrinsic resolution systematics

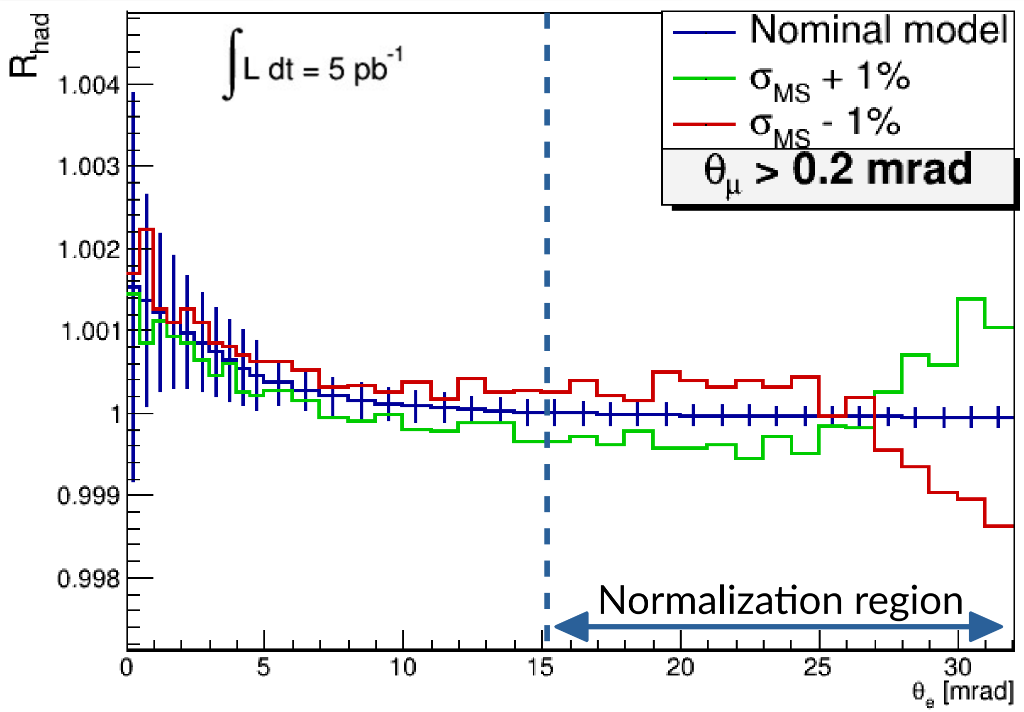
Selection cuts	Fit results
$\theta_\mu > 0.2\,\mathrm{mrad}$ $\theta_e < 32\,\mathrm{mrad}$	$E_{Beam} = (150.012 \pm 0.007)$ GeV $\mu_{Intr} = (5.2 \pm 0.1)\%$

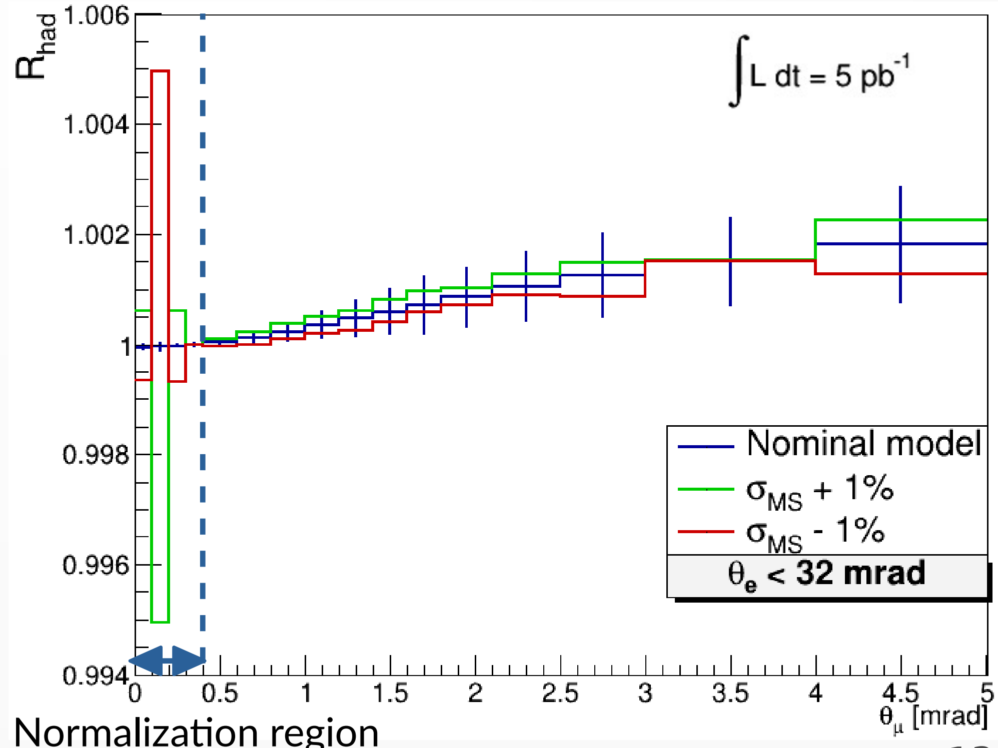
Similar results also for distributions with no PID.

Systematic error on the multiple scattering

Expected precision on the multiple scattering model: ± 1%

G. Abbiendi et al JINST (2020) 15 P01017





Step 2: combined fit signal + systematics

Pseudo-data sample:

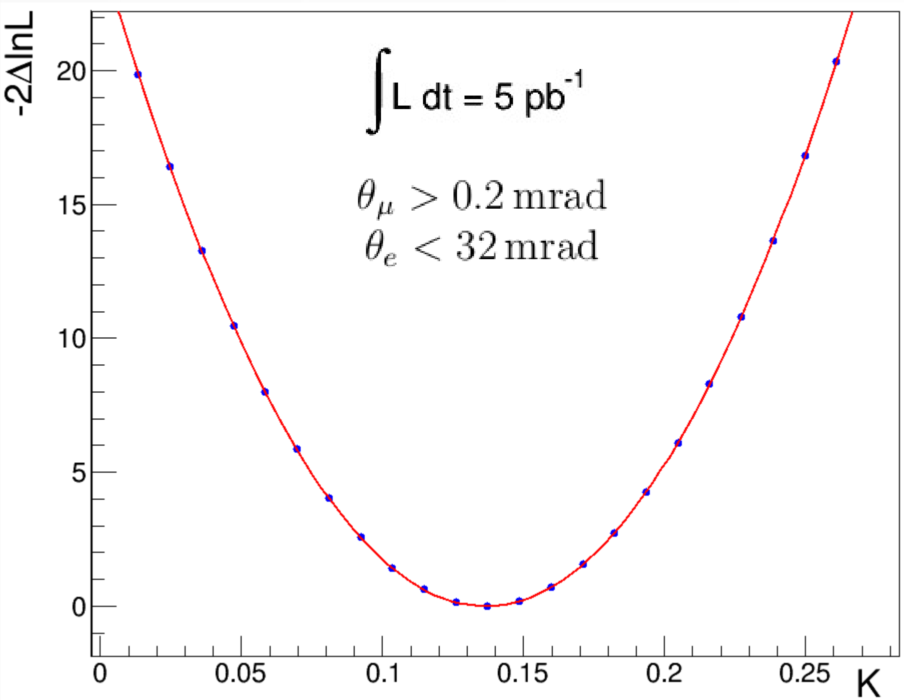
- $E_{beam} \rightarrow + 6$ MeV
- $\sigma_{Intr} \rightarrow + 5\%$
- $\sigma_{MS} \rightarrow + 0.5\%$

K : signal parameter

μ_{Ebeam} : nuisance parameter for beam energy

μ_{Intr} : nuisance parameter for intrinsic resolution

μ_{MS} : nuisance parameter for multiple scattering



Selection cuts	Fit results
$\theta_\mu > 0.2\,\mathrm{mrad}$ $\theta_e < 32\,\mathrm{mrad}$	$K = 0.135 \pm 0.026$ $\mu_{E_{Beam}} = (5.9 \pm 0.5)$ MeV $\mu_{Intr} = (4.99 \pm 0.02)\%$ $\mu_{MS} = (0.51 \pm 0.03)\%$

Systematic effects identified with good precision.
No degradation on the signal parameter.

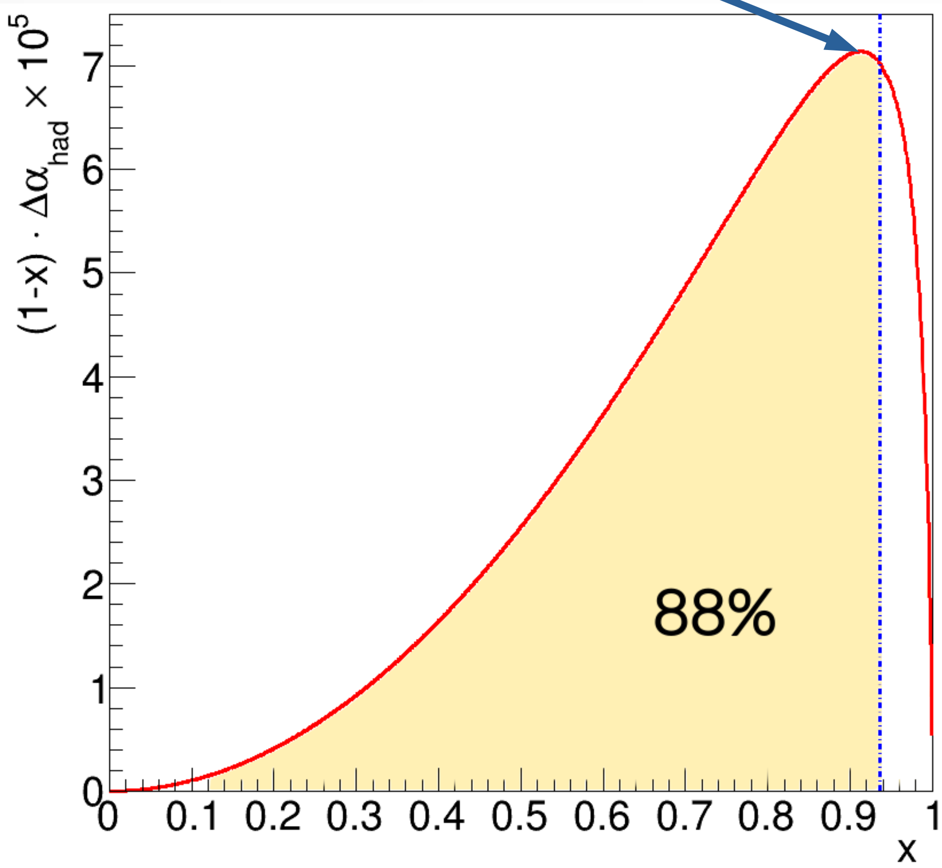
Conclusions

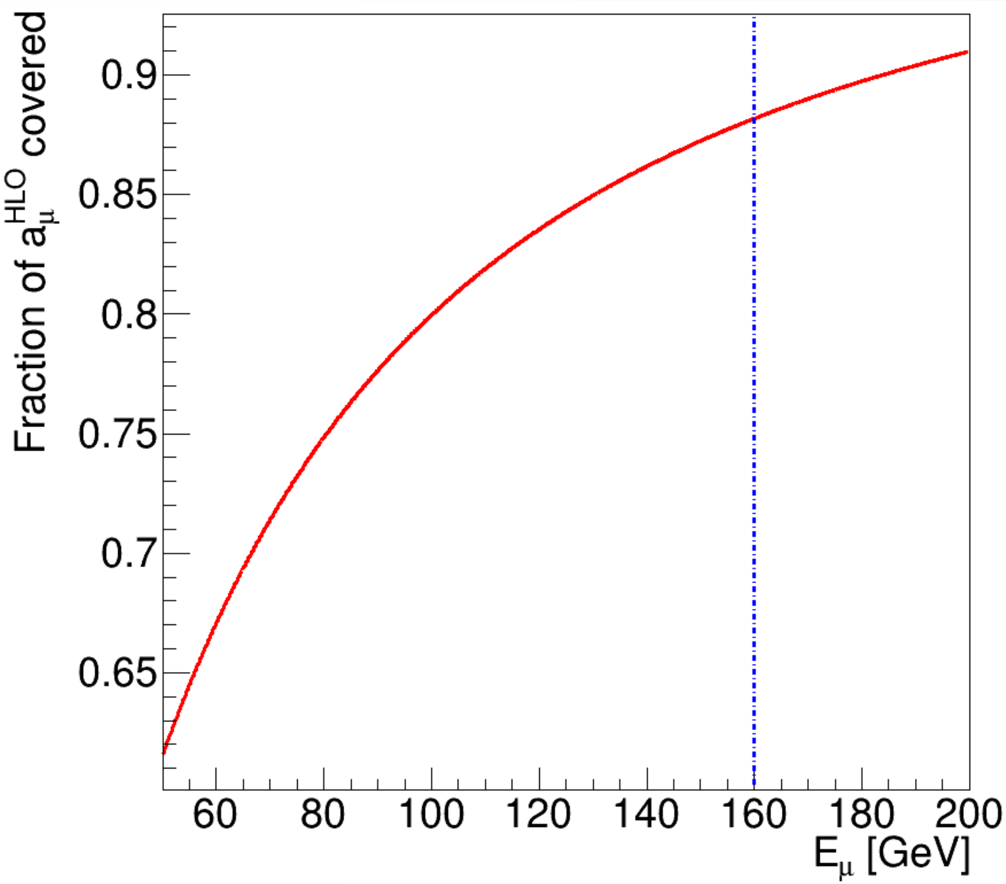
- The new method proposed by MUonE to calculate a_μ^{HLO} is independent and competitive with the latest evaluations.
- Promising strategy to control the systematic effects: use the elastic scattering events to tune the main systematics, then perform a combined fit of signal and residual effects.
- Simulation studies for the Test Run case show that the proposed procedure is capable of identifying precisely the main systematic effects, without worsening the results on the signal parameter.
- Next steps: optimize the procedure, add further systematic effects, verify the procedure with the final experiment statistics (two signal parameters).

BACKUP

$x < 0.936$

$t_{peak} \sim -0.108\ \mathrm{GeV}^2$ $\quad$ $x_{peak} \sim 0.92$



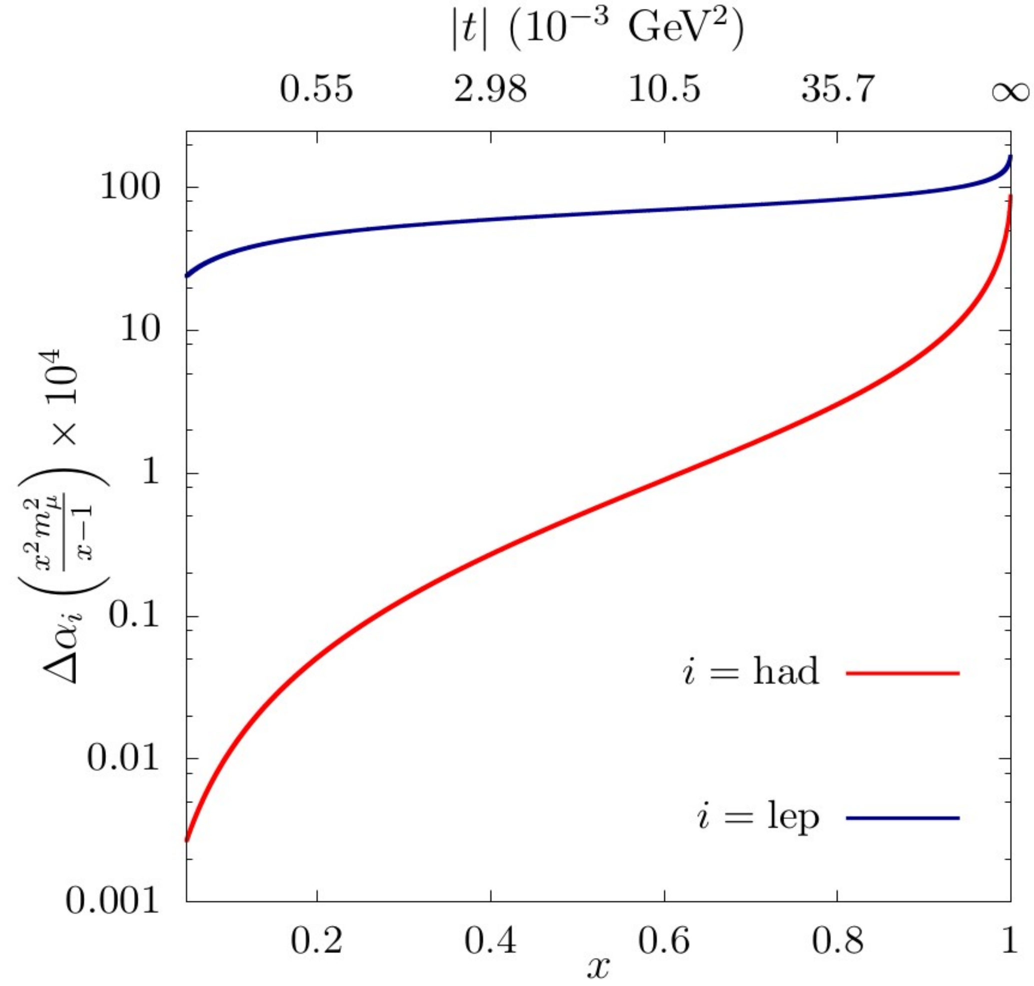


- 160 GeV muon beam on atomic electrons.

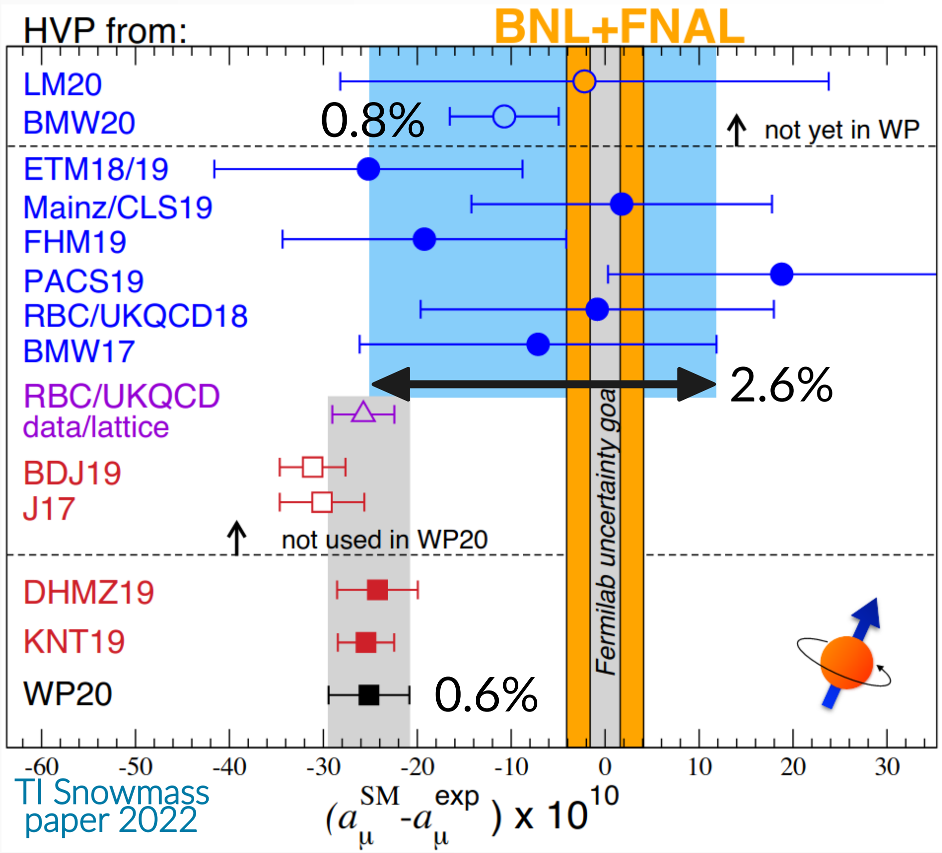
$$\sqrt{s} \sim 420\,\mathrm{MeV}$$

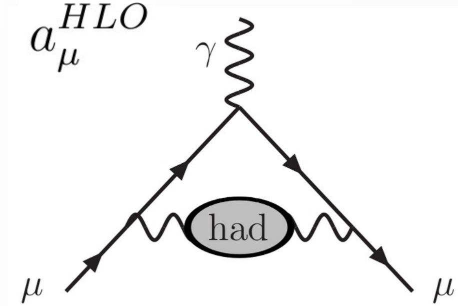
$$-0.153\,\mathrm{GeV}^2 < t < 0\,\mathrm{GeV}^2$$

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

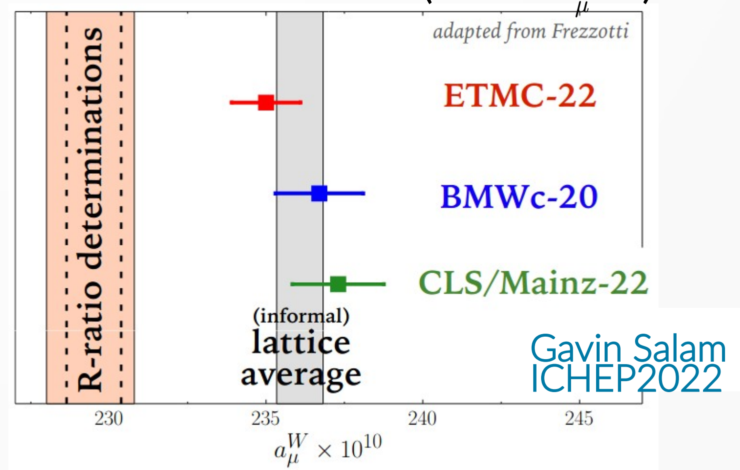


a_μ^{HLO} : present status





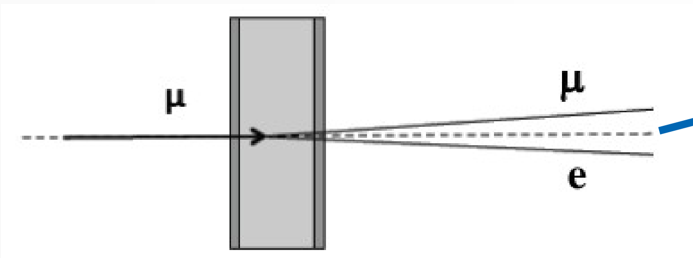
New lattice results in the intermediate window (~30% a_μ^{HLO}):



“Further insights into these connections will be provided by another complementary method for HVP, which is expected to become available over the next years at the MUonE experiment”. (TI Snowmass paper 2022)

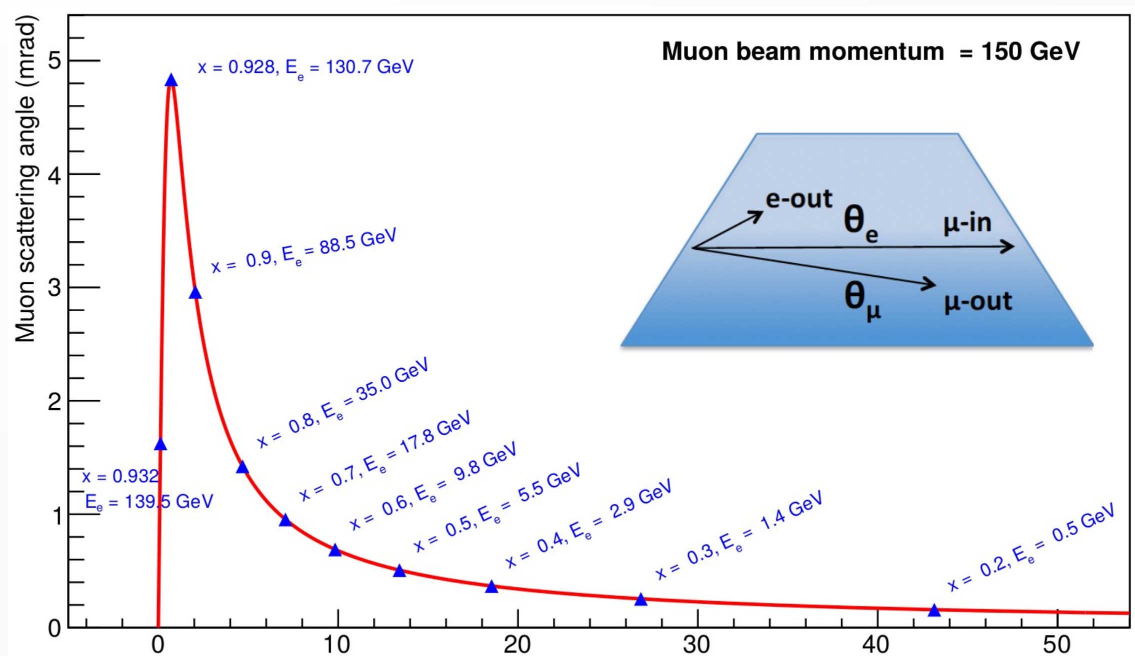
The MUonE experiment

Extraction of $\Delta\alpha_{had}(t)$ from the shape of the $\mu e \to \mu e$ differential cross section



$$\underbrace{\frac{d\sigma_{\mathrm{data}}(\Delta\alpha_{\mathrm{had}})}{d\sigma_{\mathrm{MC}}(\Delta\alpha_{\mathrm{had}}=0)}}_{\text{From theoretical calculation}} \sim 1 + \underbrace{2\Delta\alpha_{\mathrm{had}}(t)}_{\text{To be measured}}$$

- A beam of 160 GeV muons allows to get the whole a_μ^{HVP} (88% directly measured + 12% extrapolated).
- 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.



Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139

Achievable accuracy

40 stations (60 cm Be) + 3 years of data taking ($\sim 4\text{x}10^7$ s) ($I_\mu \sim 10^7\ \mu^+/\text{s}$) $\sim 4\text{x}10^{12}$ events with $E_e > 1$ GeV = $\boxed{\sim 0.3\%\text{ statistical accuracy on } a_\mu^{\mathrm{HLO}}}$

Competitive with the latest theoretical predictions.

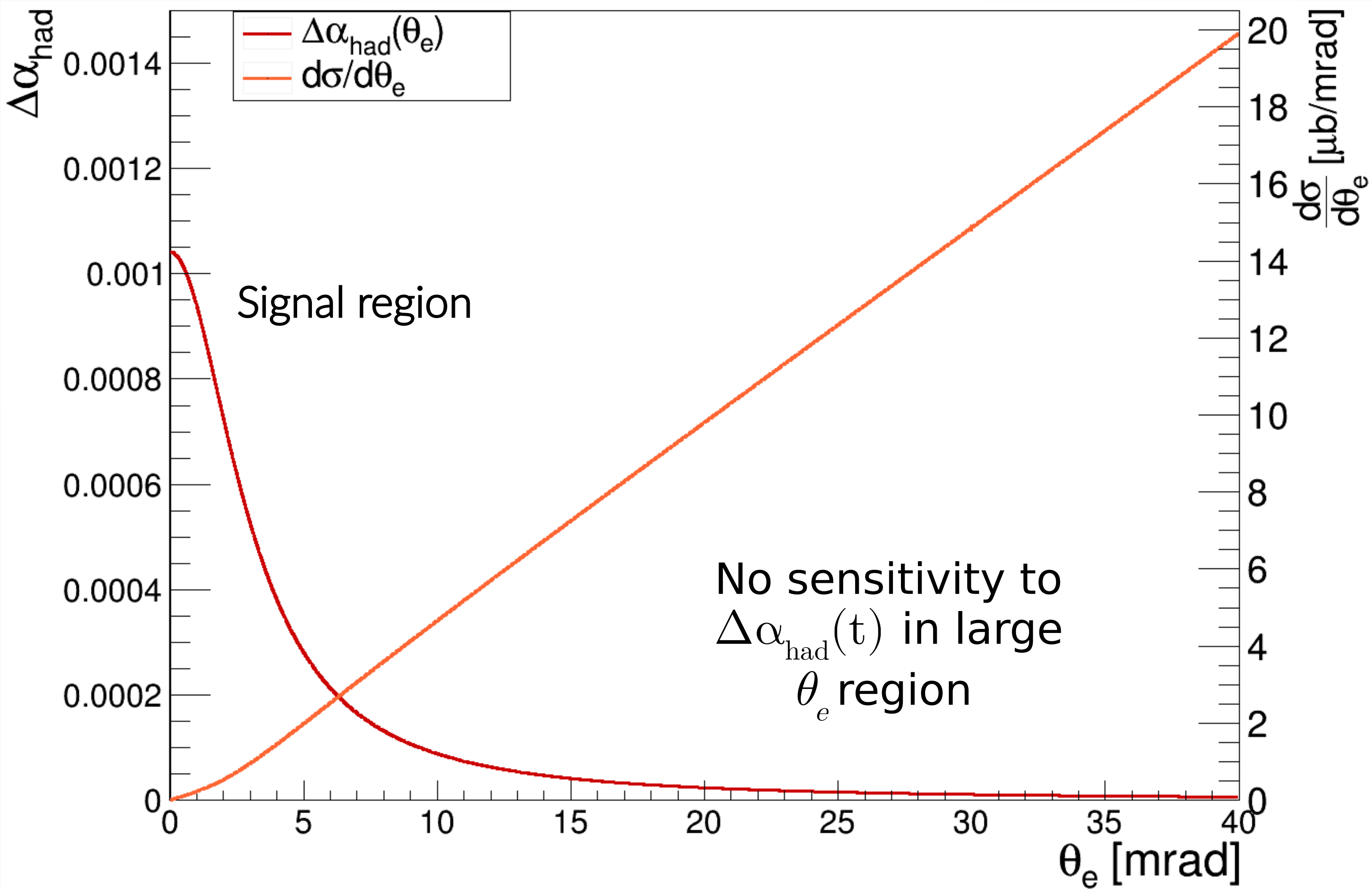
Main challenge:
keep systematic accuracy at the same level of the statistical one

Systematic uncertainty of 10 ppm at the peak of the integrand function (low θ_e, large θ_μ)

Main systematic effects:

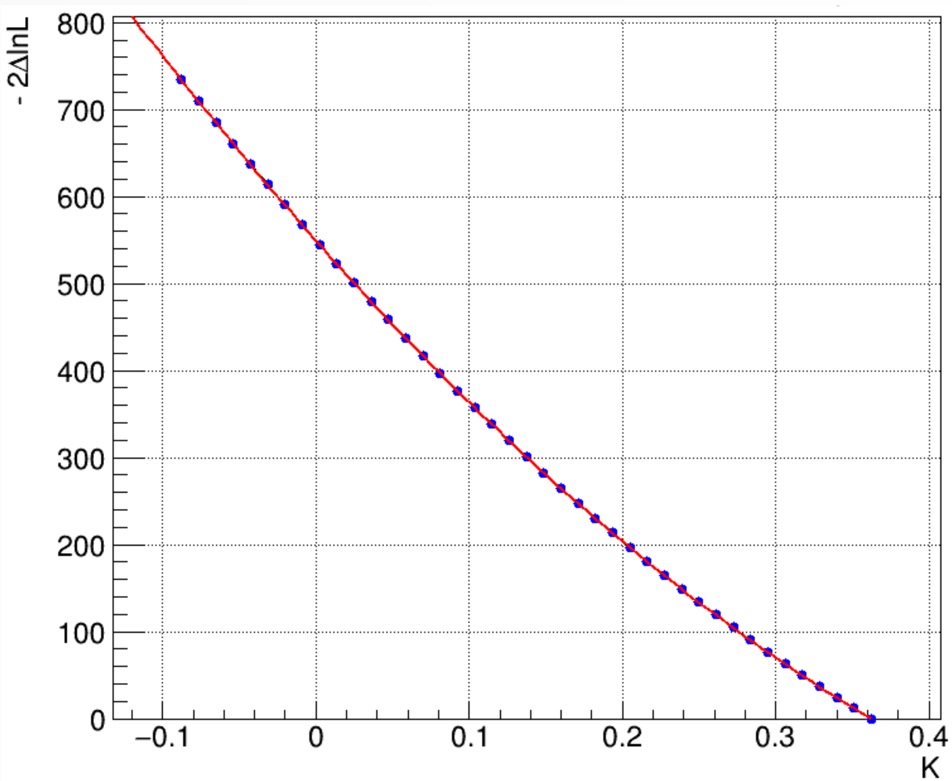
- Longitudinal alignment (~10 µm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering (~1%)
- Angular intrinsic resolution (few %)

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

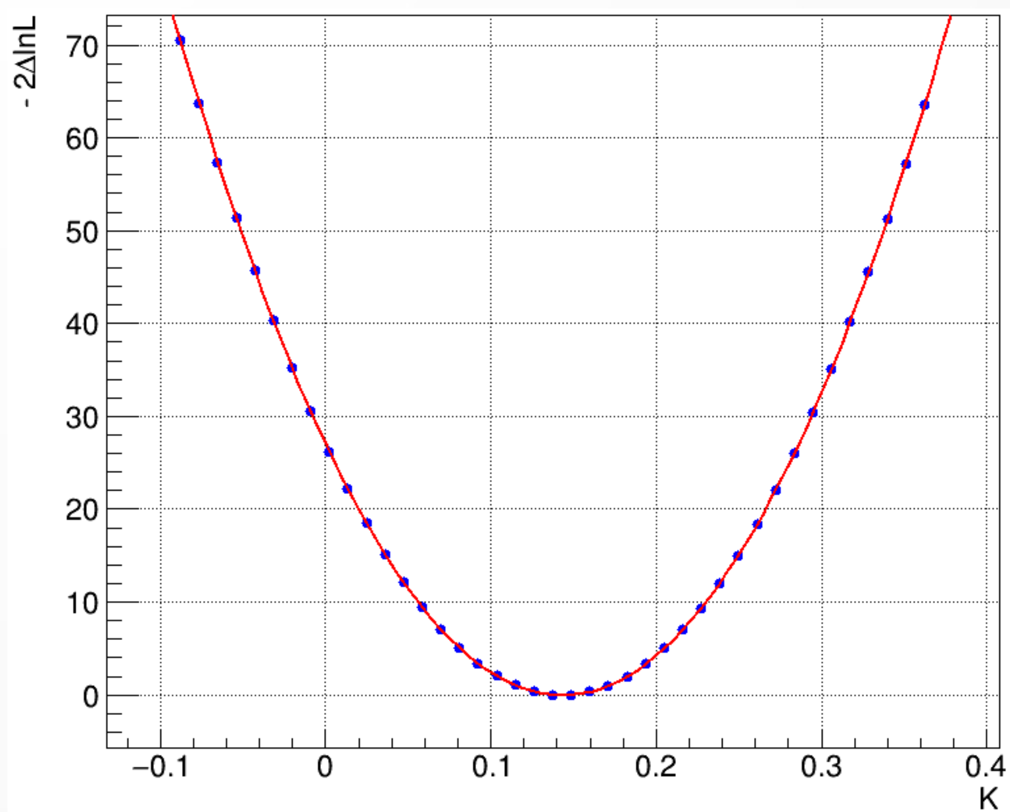


Simultaneous fit signal + nuisance parameters @L_{TR}

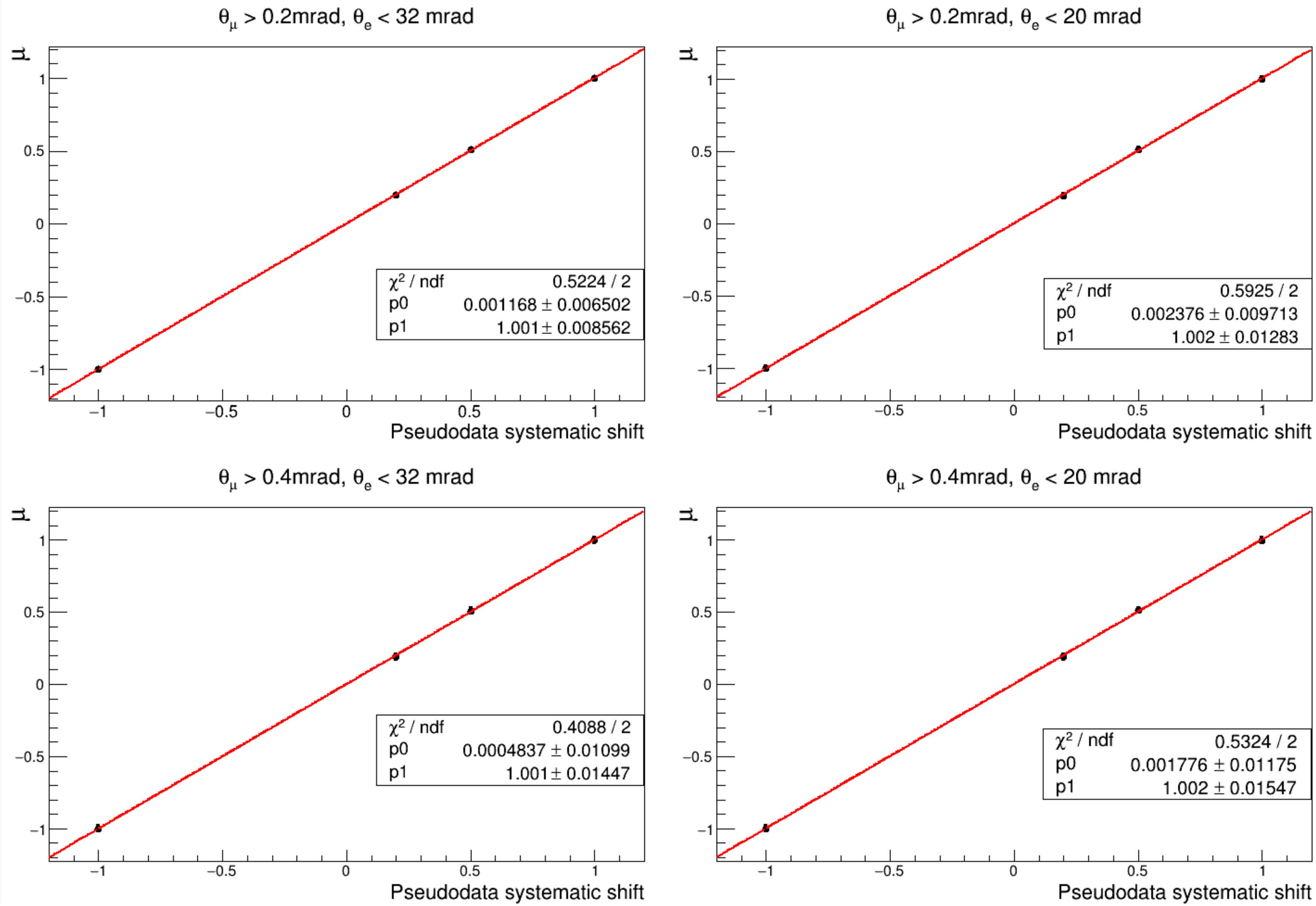
If the systematics are not taken into account in the fit...



If the nuisance parameters are introduced in the fit procedure...



Fit of MS nuisance using different pseudodata shifts



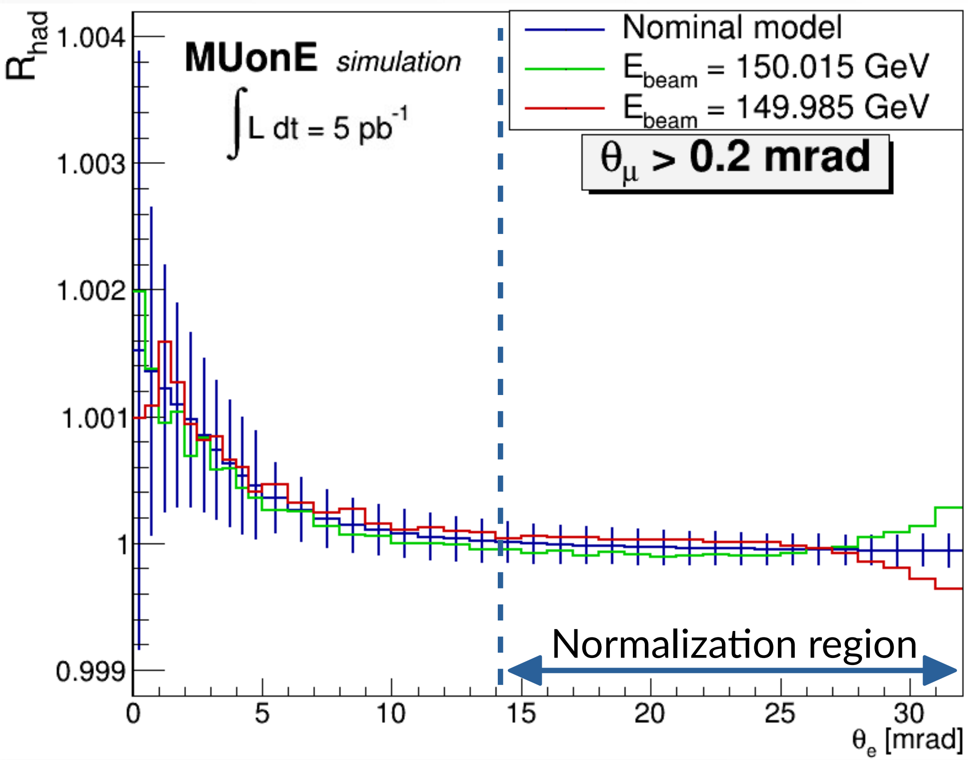
μ = {-1%, 0.2%, 0.5%, 1%}

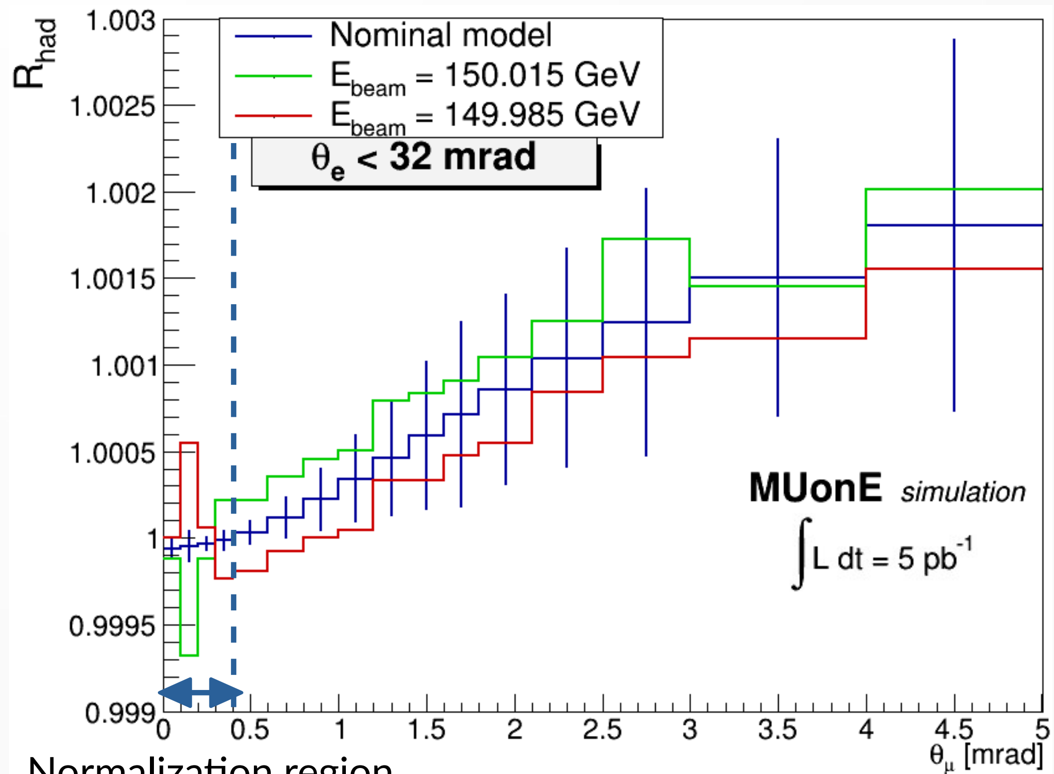
Linear relation between fitted value of μ and pseudodata shift

OK!

Systematic error on the beam energy scale

Effect of a ± 15 MeV shift

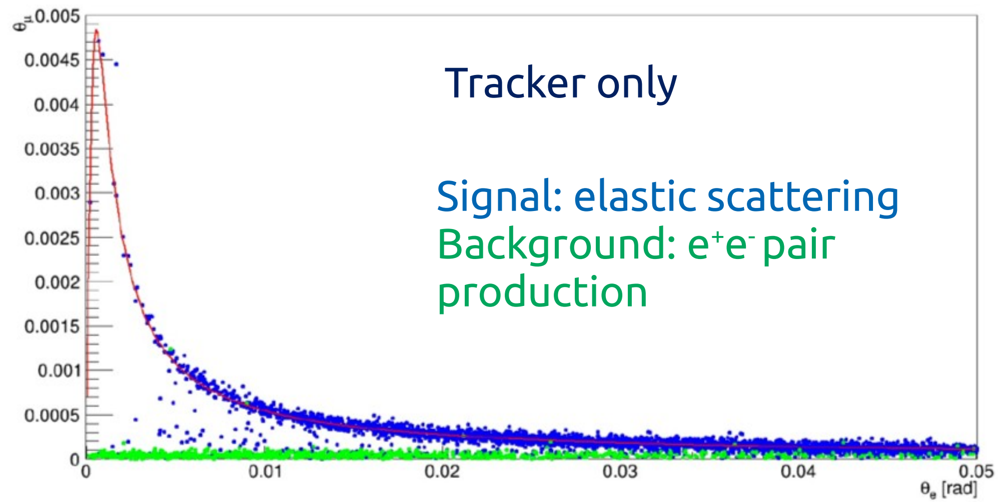


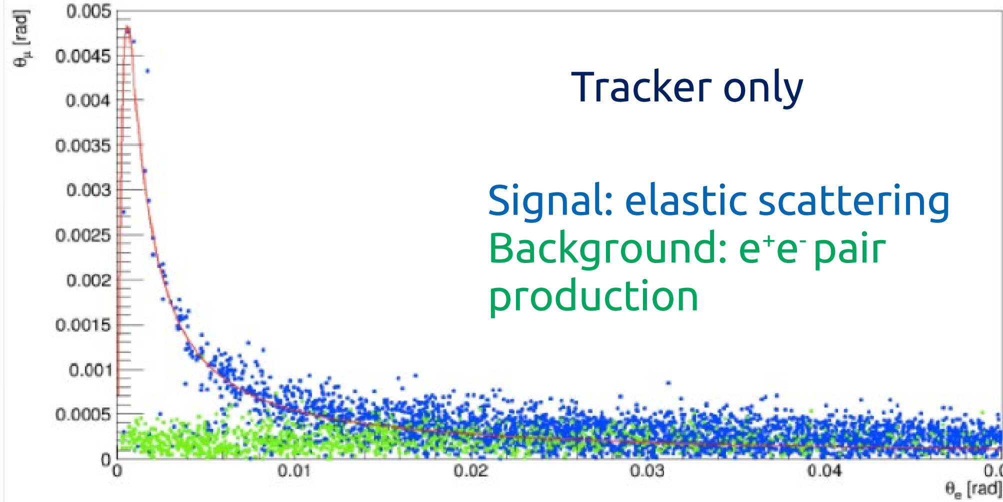


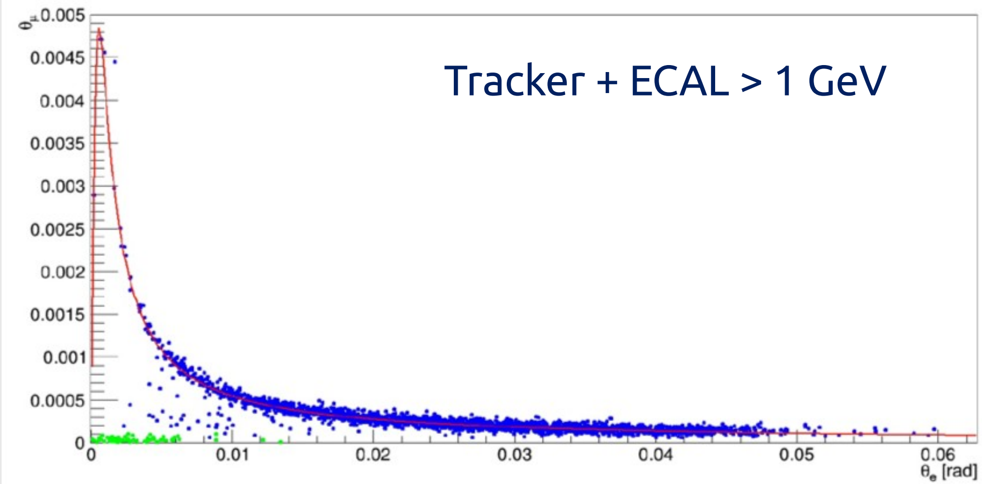
Normalization region

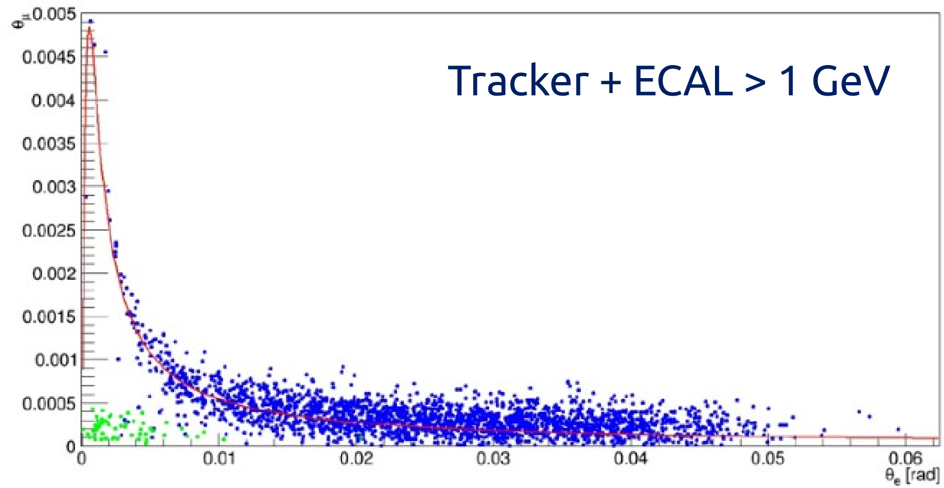
GEANT4 simulations

TB2017 (resolution ~7μm) | TB2018 (resolution ~40μm)

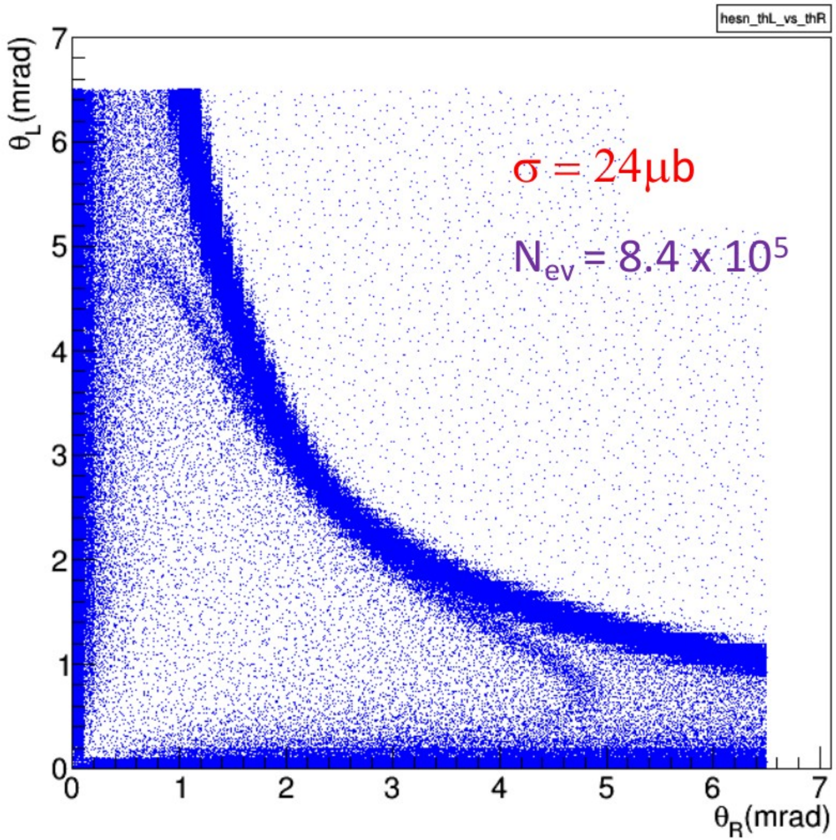


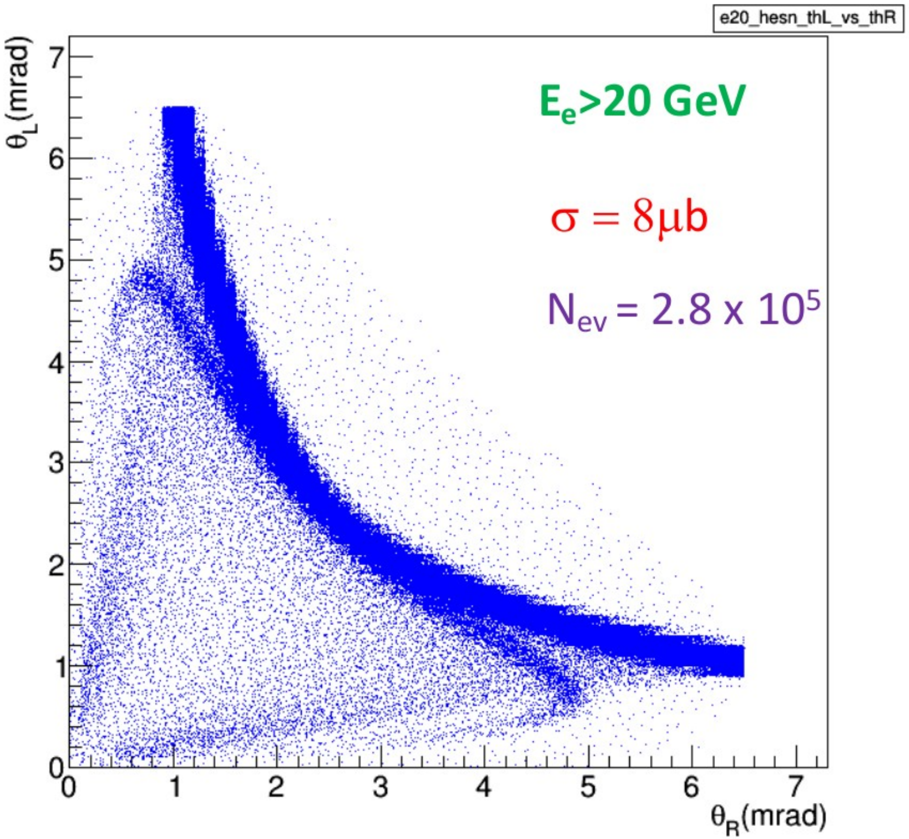






Effect of energy selection using the calorimeter



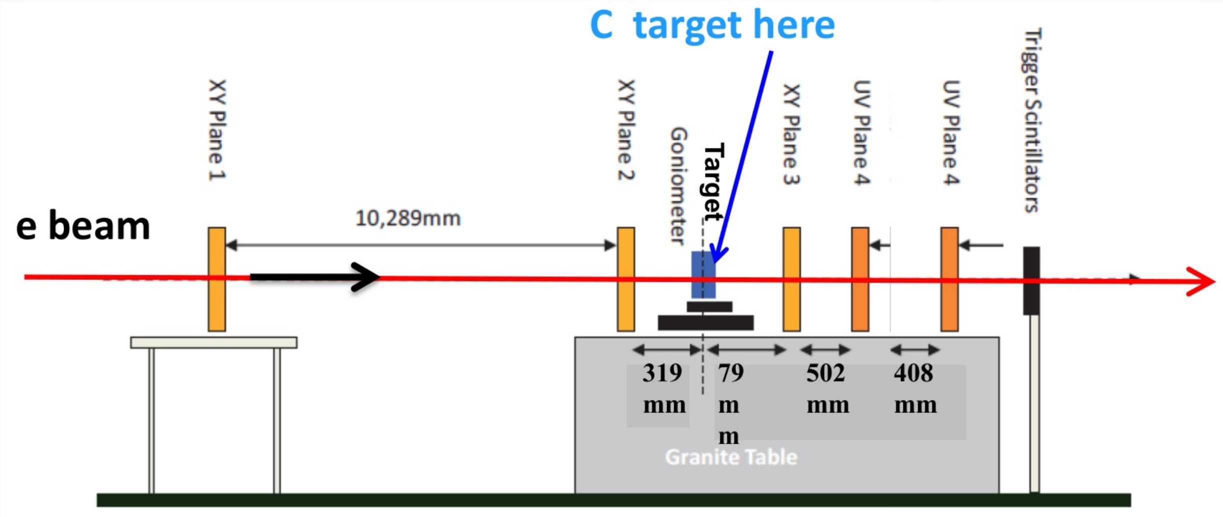


Multiple scattering: results from TB2017

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

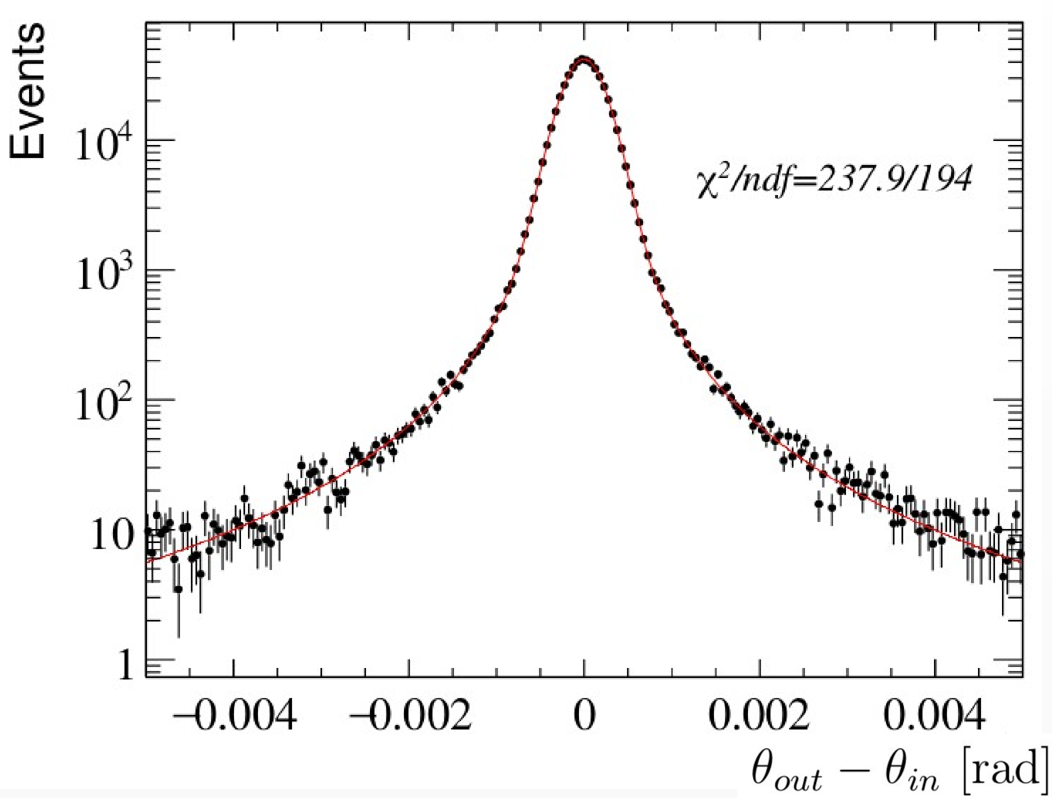
Main goals:

- 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