An alternative evaluation of the leading-order hadronic contribution to the muon g-2 with MUonE

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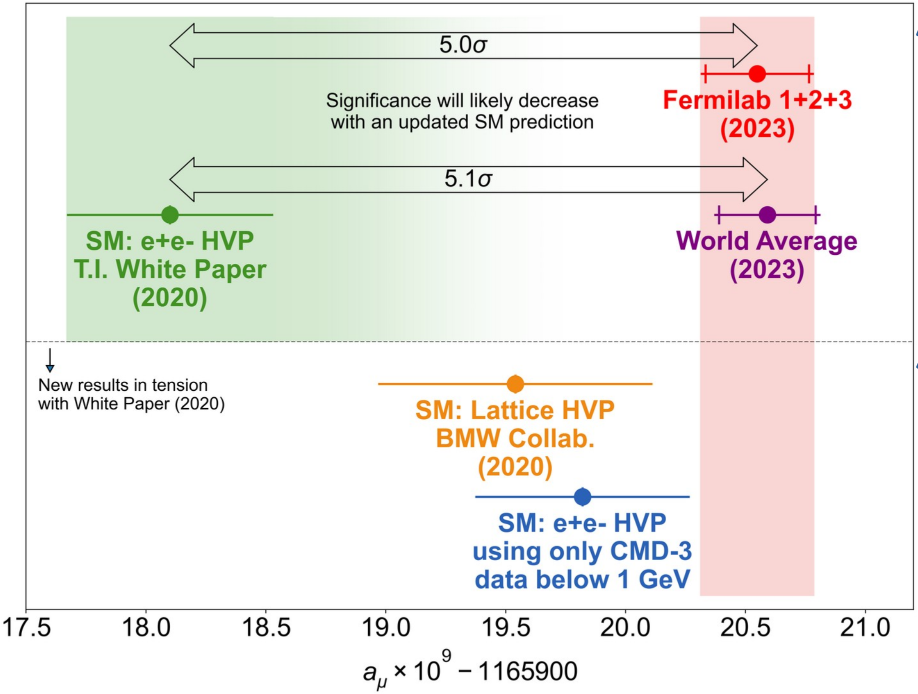
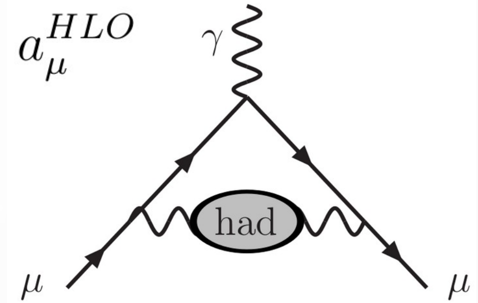
17th International Workshop on Tau Lepton Physics (TAU2023)
December 5th 2023

Muon g-2: current status

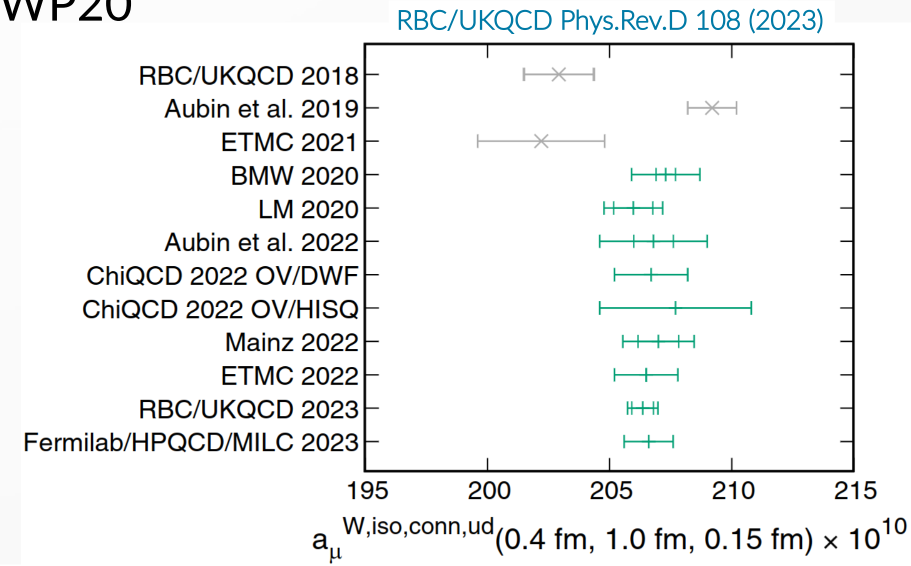


Comparison with WP20

New results after WP20



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



A clarification of the theoretical prediction is needed.

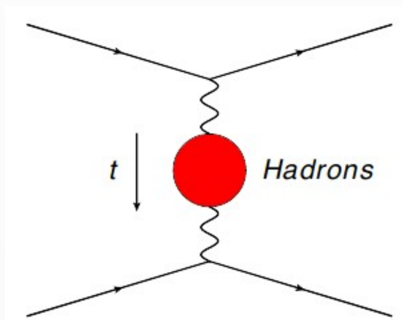
The MUonE experiment

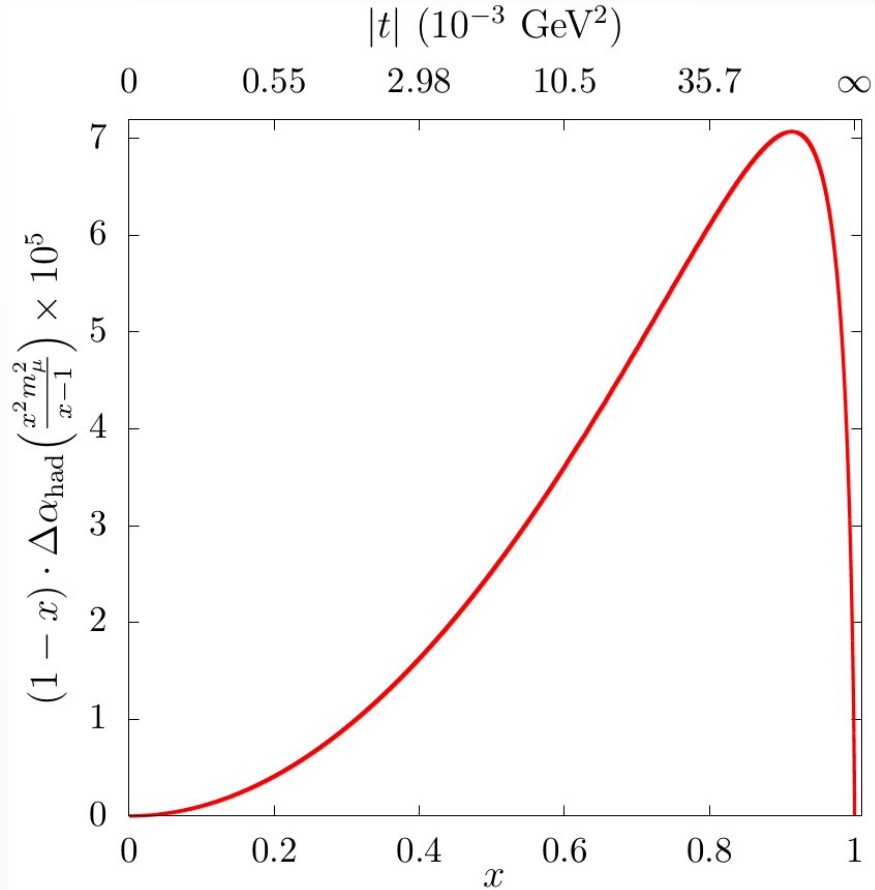
MUonE: a new independent evaluation of a_μ^{HLO}

Phys. Rep. C 3 (1972), 193

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

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



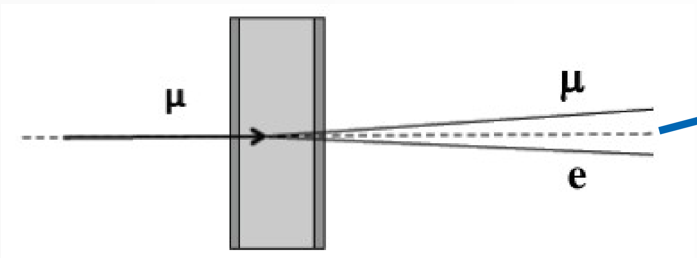


Phys. Lett. B 746 (2015), 325

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 $\mu e \rightarrow \mu e$ differential cross section

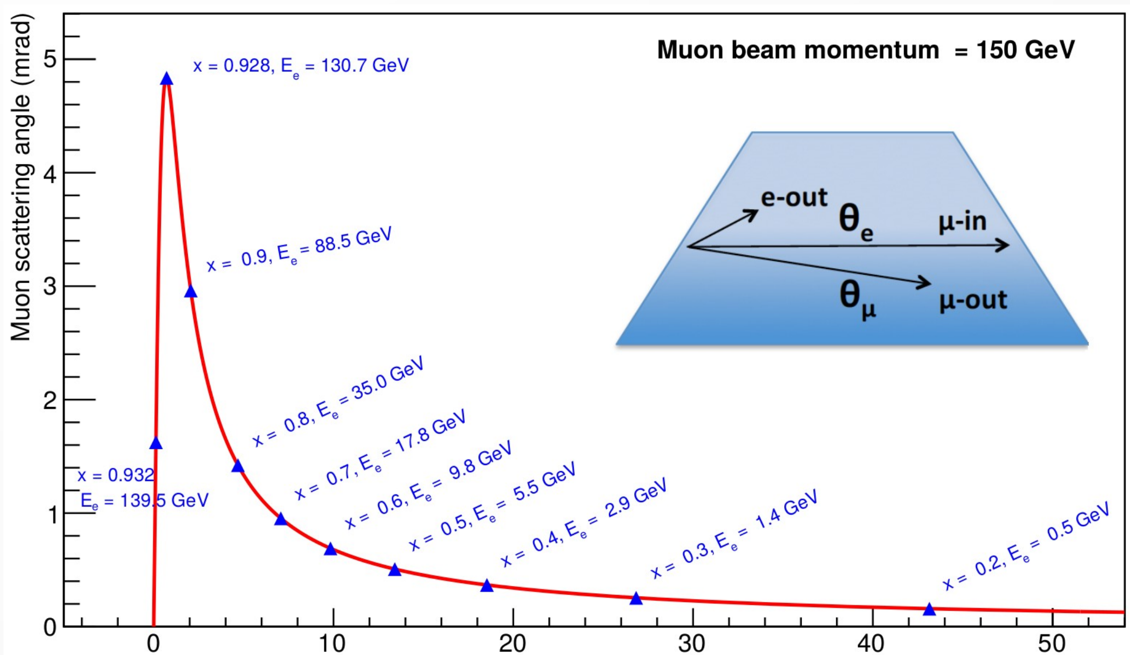


$$\frac{d\sigma_{\mathrm{data}}(\Delta\alpha_{\mathrm{had}})}{d\sigma_{\mathrm{MC}}(\Delta\alpha_{\mathrm{had}}=0)} \sim 1 + 2\Delta\alpha_{\mathrm{had}}(t)$$

From theoretical calculation

To be measured

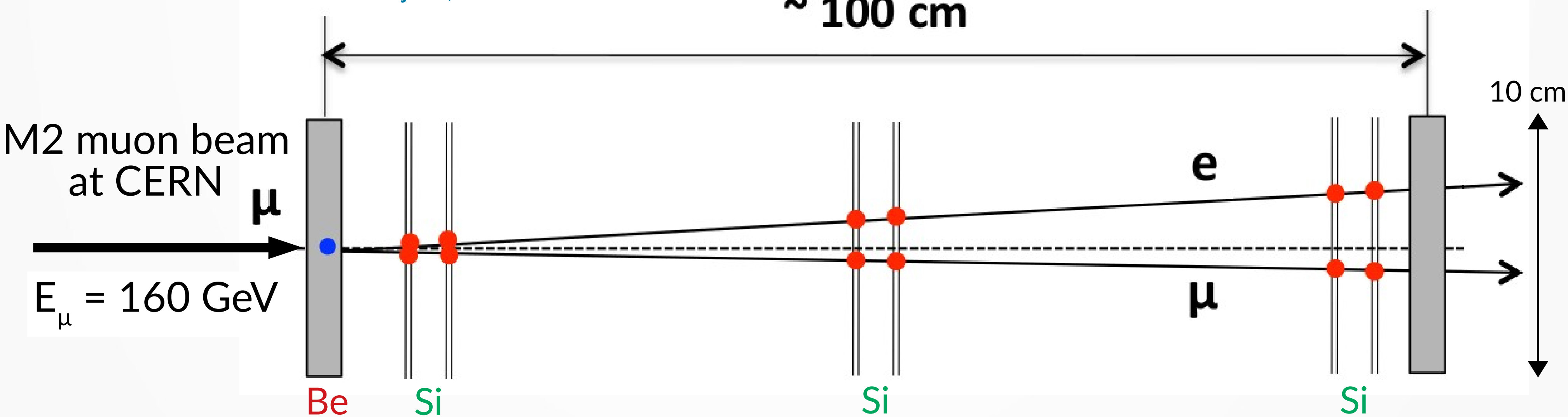
- Compute a_{μ}^{HLO} using data from one single experiment.
- Correlation between muon and electron angles allows to select elastic events and reject background (μ N $\rightarrow$ μ N $e^{+}e^{-}$).
- Boosted kinematics: $\theta_{\mu} < 5$ mrad, $\theta_{e} < 32$ mrad.



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

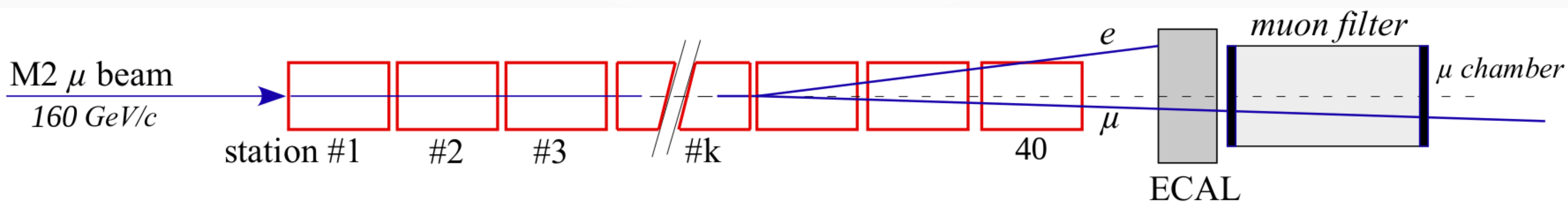
The experimental apparatus

Letter of Intent: The MUonE Project, SPSC-I-252



Be (or C) target
1.5 cm thickness

Tracking system:
3 pairs of silicon strip detectors (CMS 2S modules)



Achievable accuracy

40 stations (60 cm Be) + 3 years of data taking (~4x10^7 s) = $\boxed{\text{~0.3\% statistical accuracy on } a_\mu^{\mathrm{HLO}}}$

(I_μ ~ 10^7 μ^+/s)

~4x10^{12} events with E_e > 1 GeV

Competitive with the latest theoretical predictions.

$\Delta a_\mu^{\mathrm{HLO}}$(WP20) ~ 0.6%

$\Delta a_\mu^{\mathrm{HLO}}$(BMW) ~ 0.8%

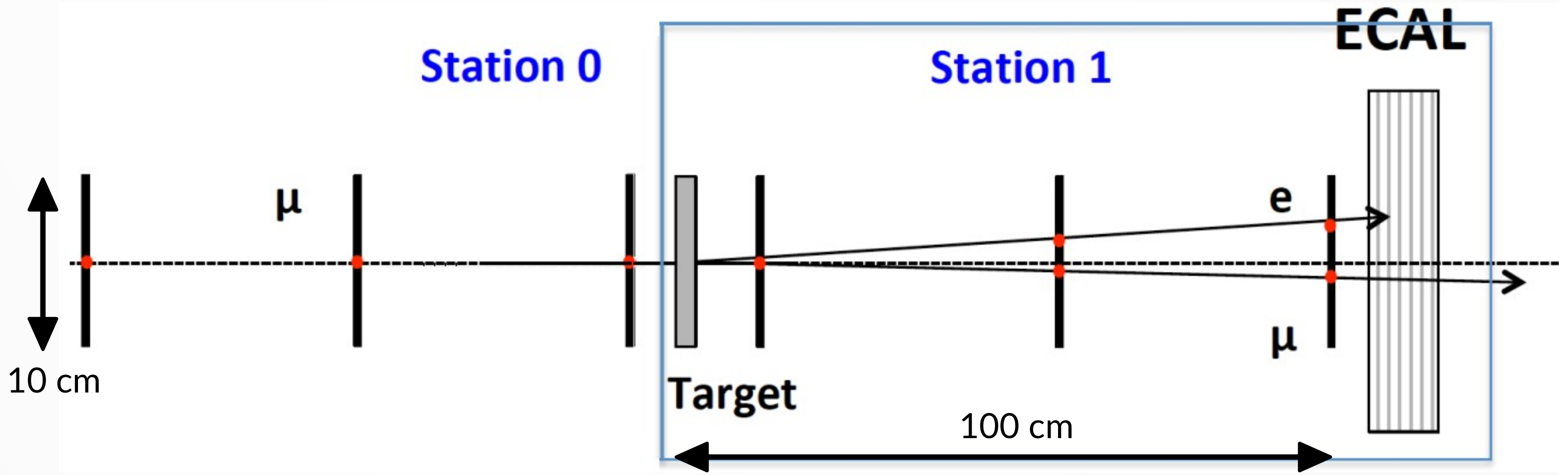
Main challenge:
keep systematic accuracy at the same level of the statistical one.

Systematic uncertainty of 10 ppm in the signal region (low θ_e, large θ_μ).

Test Run 2023 (21 Aug – 10 Sept)

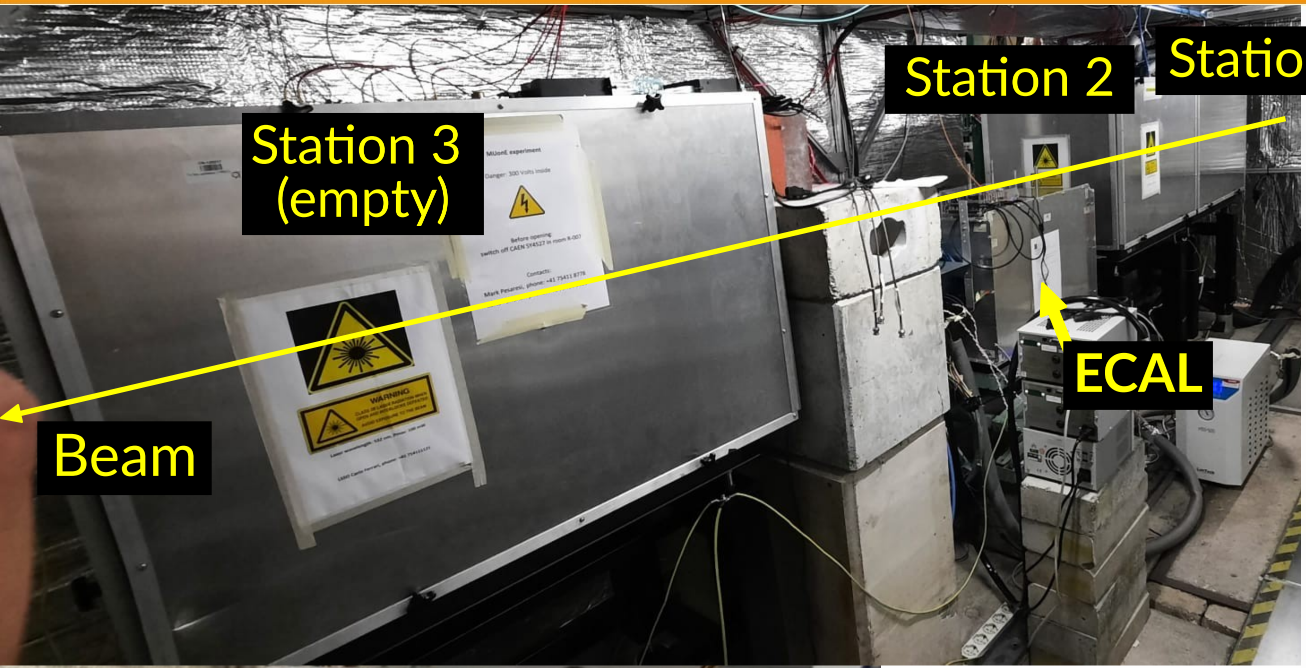
A 3 weeks Test Run with a reduced detector
has been approved by SPSC, to validate our proposal.

- Pretracker +
- 1 station +
- ECAL

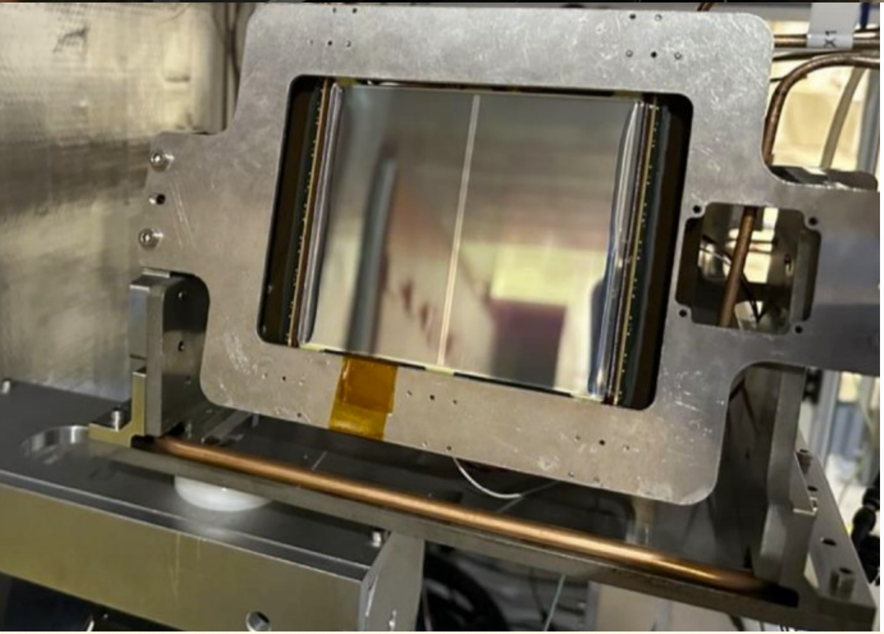


Main goals:

- Confirm the system engineering.
- Test the detector performance.
- Test the reconstruction algorithms and event selection.
- Study the background processes and the main sources of systematic error.
- Demonstration measurement: $\Delta\alpha_{\mathrm{lep}}(t)$ with O(5-10%) precision.



Test Run Analysis



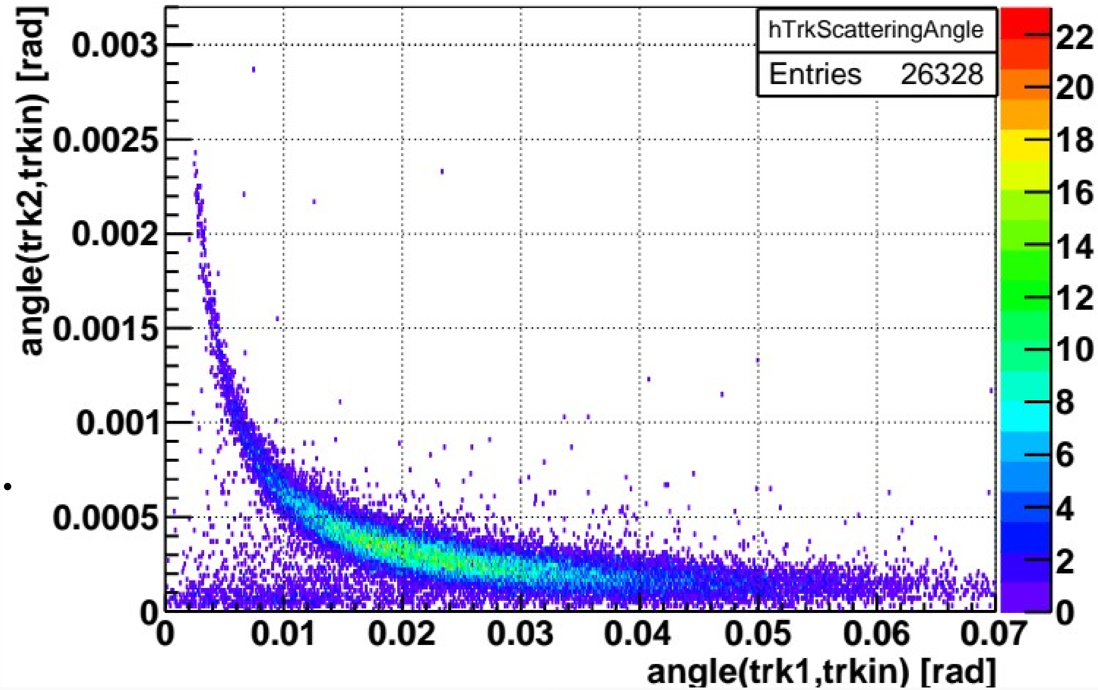
- Determine selection algorithms to be applied on FPGA.
- Beam rate measurements.
- Hardware metrology.
- Software alignment.
- Detector performance.

Test Run Analysis

Elastic events

Golden event selection:

- 1 hit/module in 1st station.
- 2 hits/module in 2nd station.
- 3 reconstructed tracks with good χ^2.
- Loose cut on z_{vertex} to select interactions in the target.



Ongoing work:

- Include a cut on the acoplanarity of the 3 tracks (elastic events are planar).
- Identify and study background events.

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

$\Delta\alpha_{had}(t)$ parameterization:
inspired from the 1 loop QED contribution of lepton pairs and t-quark at $q^2<0$

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

2 parameters:
K, M

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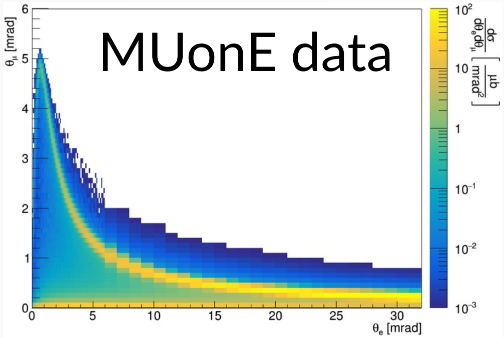
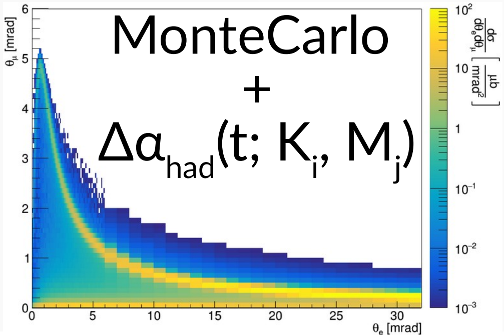
Extraction of $\Delta\alpha_{had}(t)$ through a template fit to the 2D (θ_e, θ_μ) distribution:





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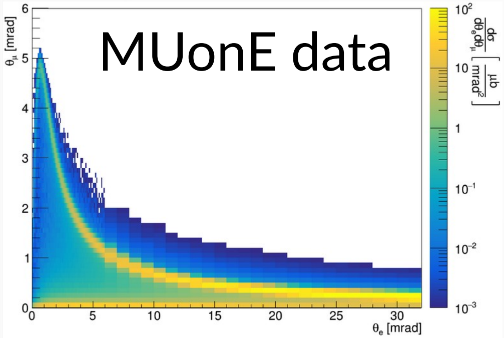
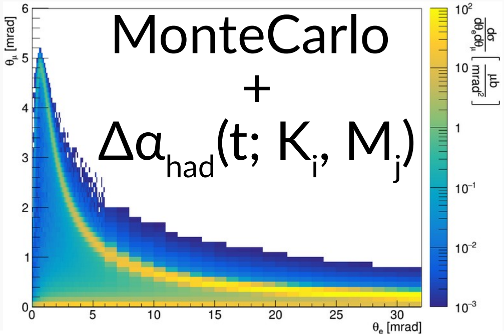
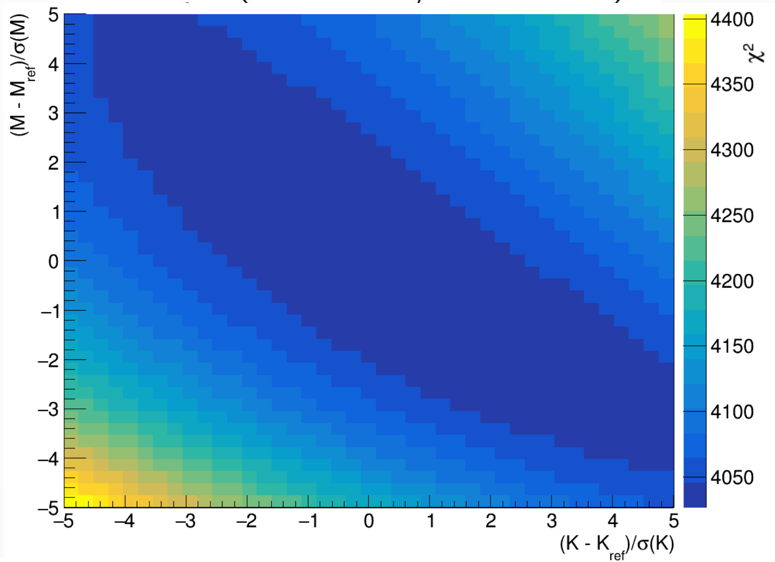


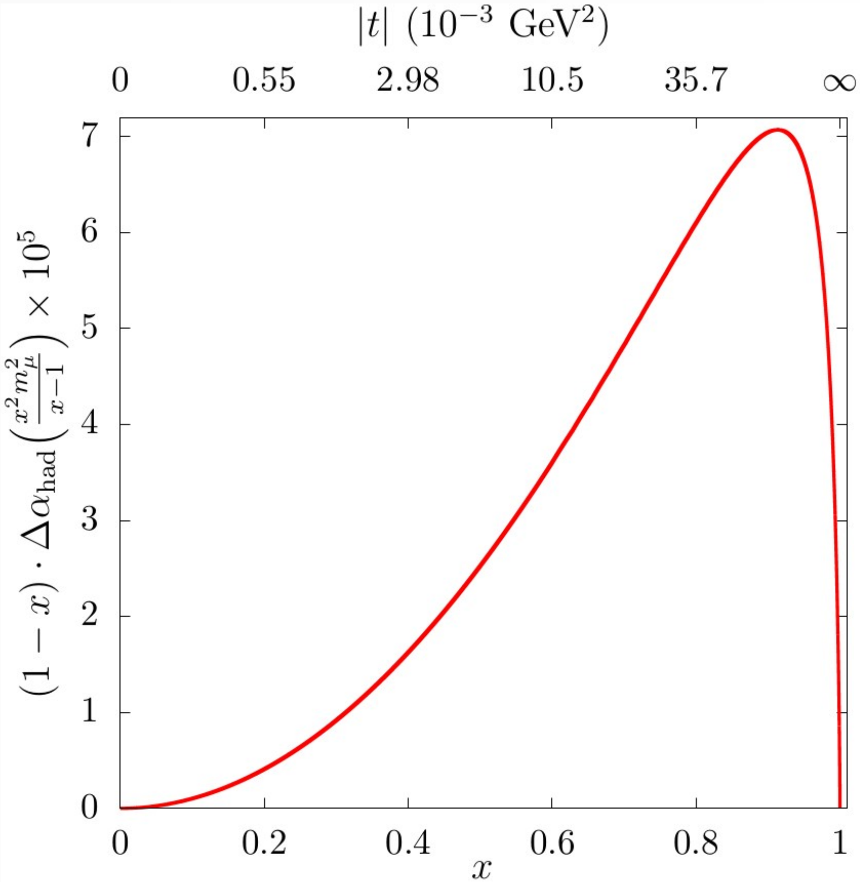


$$\chi^2 = \sum_i^{\text{bins}}\left(\frac{\text{data}_i - \text{templ}(K,M)_i}{\sigma_i^{\text{data}}}\right)^2$$



Compute a_μ^{HLO}

Input the best fit parameters in the MUonE master integral



(K_{best}, M_{best})

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

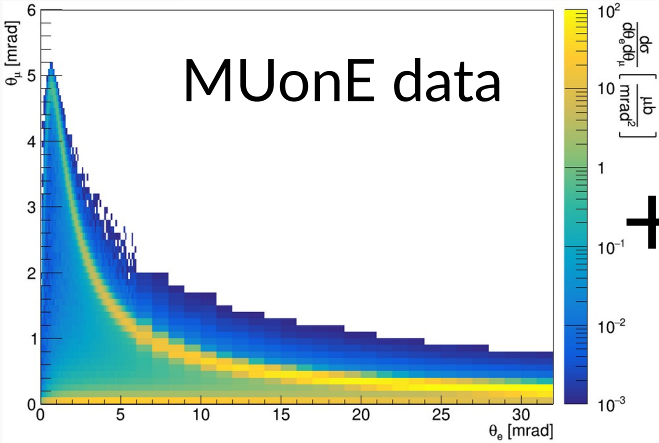
Results from a simulation with the expected final statistics (4×10^{12} elastic events):

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

(0.35% accuracy)

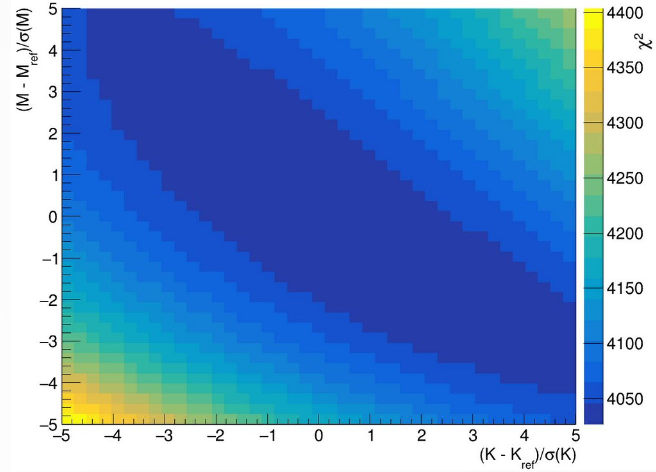
Input value

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



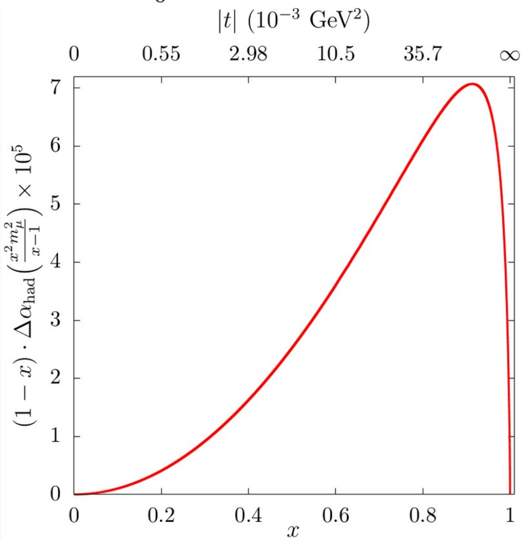
$+\ \Delta\alpha_{had}(t;\ K,\ M)$

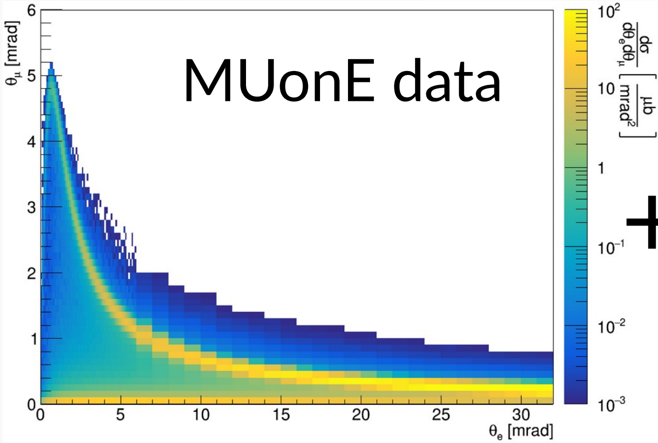
Template fit



$\Delta\alpha_{had}(t;\ K_{best},\ M_{best})$

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





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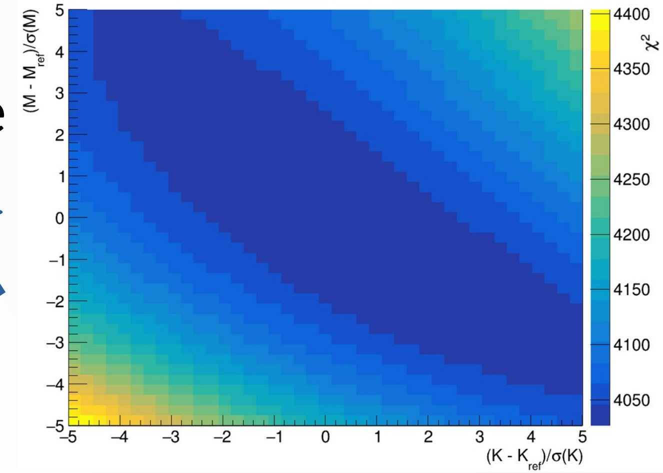
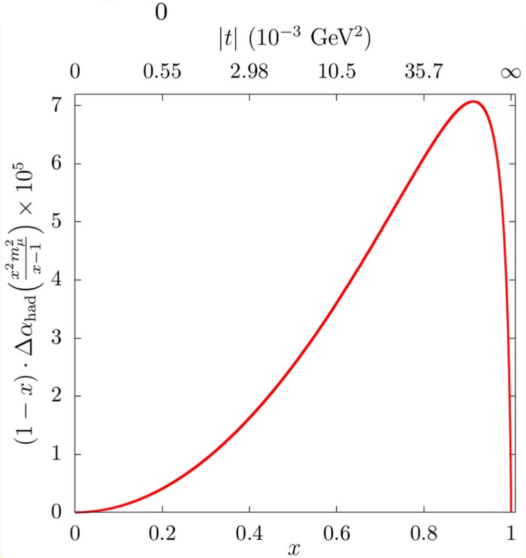


$\Delta\alpha_{had}(t;\, K_{best},\, M_{best})$

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



?

Can we compute a_μ^{HLO} in a different way using MUonE data?

Phys. Lett. B 848 (2024) 138344

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Letter

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An alternative evaluation of the leading-order hadronic contribution to the muon $g-2$ with MUonE

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ARTICLE INFO

Editor: G.F. Giudice

ABSTRACT

We propose an alternative method to extract the leading-order hadronic contribution to the muon $g-2$, a_μ^{HLO}, with the MUonE experiment. In contrast to the traditional method based on the integral of the hadronic contribution to the running of the electromagnetic coupling, $\Delta\alpha_{had}$, in the space-like region, our approach relies on the computation of the derivatives of $\Delta\alpha_{had}(t)$ at zero squared momentum transfer t. We show that this approach allows to extract $\sim 99\%$ of the total value of a_μ^{HLO} from the MUonE data, while the remaining $\sim 1\%$ can be computed combining perturbative QCD and data on e^+e^- annihilation to hadrons. This leads to a competitive evaluation of a_μ^{HLO} which is robust against the parameterization used to model $\Delta\alpha_{had}(t)$ in the MUonE kinematic region, thanks to the analyticity properties of $\Delta\alpha_{had}(t)$, which can be expanded as a polynomial at $t \sim 0$.

An alternative method to compute $a_\mu^{\rm HLO}$ with MUonE

Based on:
S. Bodenstein et al, Phys. Rev. D 85 (2012)
C.A. Dominguez et al, Phys. Rev. D 96 (2017)

Start from traditional dispersive integral:

$$a_\mu^{\rm HLO} = \frac{\alpha^2}{3\pi^2}\int_{s_{\rm th}}^{\infty}\frac{ds}{s}K(s)R(s)$$

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)s/m_\mu^2}$$

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

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$$R(s) \propto \sigma(e^+e^- \to \mathrm{hadrons})$$

$$s_{\mathrm{th}} = m_{\pi^0}^2$$

$$s_0 \gtrsim (2\,\mathrm{GeV})^2$$

$$\frac{\alpha^2}{3\pi^2}\int_{s_{\mathrm{th}}}^{s_0}\frac{ds}{s}K(s)R(s) + \frac{\alpha^2}{3\pi^2}\int_{s_0}^{\infty}\frac{ds}{s}K(s)R(s)$$

pQCD

$$-\mathrm{Im}\Pi_{had}(s) = \frac{\alpha}{3}R(s)$$

Low energy integral

$$\int_{s_{\rm th}}^{s_0} \frac{ds}{s} K(s) \frac{{\rm Im}\Pi_{had}(s)}{\pi} =$$

$$\int_{s_{\rm th}}^{s_0} \frac{ds}{s} [K(s) - K_1(s)] \frac{{\rm Im}\Pi_{had}(s)}{\pi} + \int_{s_{\rm th}}^{s_0} \frac{ds}{s} K_1(s) \frac{{\rm Im}\Pi_{had}(s)}{\pi}$$

Low energy integral

$$\int_{s_{\rm th}}^{s_0} \frac{ds}{s} K(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} =$$

$$\int_{s_{\rm th}}^{s_0} \frac{ds}{s} [K(s) - K_1(s)] \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} + \boxed{\int_{s_{\rm th}}^{s_0} \frac{ds}{s} K_1(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi}}$$

$$K_1(s) = a_0 s + \sum_{n=1}^{3} \frac{a_n}{s^n}$$

$K_1(s)$ approximates $K(s)$ for $s < s_0$.
Meromorphic function:
no cuts, poles in $s = 0$.

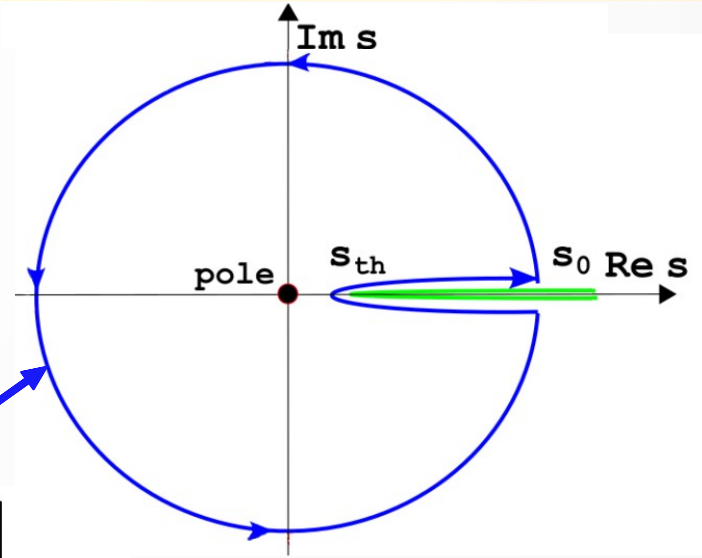
Two different techniques to get $K_1(s)$:

1) Least squares minimization

2) Minimize $\int_{s_{\rm th}}^{s_0} \frac{ds}{s} |K(s) - K_1(s)| R(s)$

Low energy integral

Use Cauchy's theorem



$$\int_{s_{\rm th}}^{s_0} \frac{ds}{s} K_1(s) \frac{{\rm Im}\Pi_{had}(s)}{\pi} =$$

$$\mathrm{Res}\left[\Pi_{had}(s)\frac{K_1(s)}{s}\right]_{s=0} - \frac{1}{2\pi i}\oint_{|s|=s_0} \frac{ds}{s} K_1(s)\Pi_{had}(s)\Big|_{\rm pQCD}$$

$$\mathrm{Res}\left[\Pi_{had}(s)\frac{K_1(s)}{s}\right]_{s=0} = \sum_{n=1}^{3}\frac{c_n}{n!}\frac{d^{(n)}}{ds^n}\Pi_{had}(s)\Big|_{s=0} = \sum_{n=1}^{3}\frac{c_n}{n!}\frac{d^{(n)}}{dt^n}\Delta\alpha_{had}(t)\Big|_{t=0}$$

From MUonE

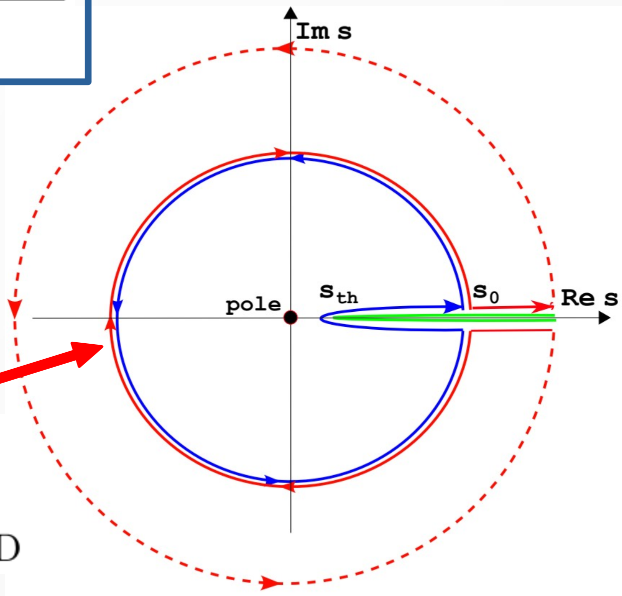
High energy integral

Similar strategy for the high energy part

$$\int_{s_0}^{\infty} \frac{ds}{s} K(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} =$$

$$\int_{s_0}^{\infty} \frac{ds}{s} [K(s) - \tilde{K}_1(s)] \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} + \boxed{\int_{s_0}^{\infty} \frac{ds}{s} \tilde{K}_1(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi}}$$

$$\tilde{K}_1(s) = K_1(s) - c_0 s$$



$$\int_{s_0}^{\infty} \frac{ds}{s} \tilde{K}_1(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} = \frac{1}{2\pi i} \oint_{|s|=s_0} \frac{ds}{s} \tilde{K}_1(s) \Pi_{had}(s) \Big|_{\mathrm{pQCD}}$$

Compute a_μ^{HLO}

Rearranging the previous equations...

$$a_\mu^{\mathrm{HLO}} = a_\mu^{\mathrm{HLO\ (I)}} + a_\mu^{\mathrm{HLO\ (II)}} + a_\mu^{\mathrm{HLO\ (III)}} + a_\mu^{\mathrm{HLO\ (IV)}}$$

$$a_\mu^{\mathrm{HLO\ (I)}} = -\frac{\alpha}{\pi} \sum_{n=1}^{3} \frac{c_n}{n!} \frac{d^{(n)}}{dt^n} \Delta\alpha_{had}(t)\Big|_{t=0}$$

$$a_\mu^{\mathrm{HLO\ (II)}} = \frac{\alpha}{\pi} \frac{1}{2\pi i} \oint_{|s|=s_0} \frac{ds}{s} c_0 s\ \Pi_{had}(s)\Big|_{\mathrm{pQCD}}$$

$$a_\mu^{\mathrm{HLO\ (III)}} = \frac{\alpha^2}{3\pi^2} \int_{s_{\mathrm{th}}}^{s_0} \frac{ds}{s} [K(s) - K_1(s)] R(s)$$

$$a_\mu^{\mathrm{HLO\ (IV)}} = \frac{\alpha^2}{3\pi^2} \int_{s_0}^{\infty} \frac{ds}{s} [K(s) - \tilde{K}_1(s)] R(s)$$

Compute a_μ^{HLO}

Rearranging the previous equations…

$$a_\mu^{\mathrm{HLO}} = a_\mu^{\mathrm{HLO\ (I)}} + a_\mu^{\mathrm{HLO\ (II)}} + a_\mu^{\mathrm{HLO\ (III)}} + a_\mu^{\mathrm{HLO\ (IV)}}$$

99%

$$\boxed{a_\mu^{\mathrm{HLO\ (I)}} = -\frac{\alpha}{\pi}\sum_{n=1}^{3}\frac{c_n}{n!}\frac{d^{(n)}}{dt^n}\Delta\alpha_{had}(t)\Big|_{t=0}}$$

MUonE

$$a_\mu^{\mathrm{HLO\ (II)}} = \frac{\alpha}{\pi}\frac{1}{2\pi i}\oint_{|s|=s_0}\frac{ds}{s}c_0 s\ \Pi_{had}(s)\Big|_{\mathrm{pQCD}}$$

$$a_\mu^{\mathrm{HLO\ (III)}} = \frac{\alpha^2}{3\pi^2}\int_{s_{\mathrm{th}}}^{s_0}\frac{ds}{s}[K(s) - K_1(s)]R(s)$$

$$a_\mu^{\mathrm{HLO\ (IV)}} = \frac{\alpha^2}{3\pi^2}\int_{s_0}^{\infty}\frac{ds}{s}[K(s) - \tilde{K}_1(s)]R(s)$$

Compute a_μ^{HLO}

Rearranging the previous equations...

$$a_\mu^{\mathrm{HLO}} = a_\mu^{\mathrm{HLO\ (I)}} + a_\mu^{\mathrm{HLO\ (II)}} + a_\mu^{\mathrm{HLO\ (III)}} + a_\mu^{\mathrm{HLO\ (IV)}}$$

99%

$$a_\mu^{\mathrm{HLO\ (I)}} = -\frac{\alpha}{\pi}\sum_{n=1}^{3}\frac{c_n}{n!}\frac{d^{(n)}}{dt^n}\Delta\alpha_{had}(t)\Big|_{t=0}$$

MUonE

1%

$$a_\mu^{\mathrm{HLO\ (II)}} = \frac{\alpha}{\pi}\frac{1}{2\pi i}\oint_{|s|=s_0}\frac{ds}{s}c_0 s\ \Pi_{had}(s)\Big|_{\mathrm{pQCD}}$$

$$a_\mu^{\mathrm{HLO\ (III)}} = \frac{\alpha^2}{3\pi^2}\int_{s_{\mathrm{th}}}^{s_0}\frac{ds}{s}[K(s) - K_1(s)]R(s)$$

$$a_\mu^{\mathrm{HLO\ (IV)}} = \frac{\alpha^2}{3\pi^2}\int_{s_0}^{\infty}\frac{ds}{s}[K(s) - \tilde{K}_1(s)]R(s)$$

Time-like data
+
pQCD

$a_\mu^{\mathrm{HLO\ (I)}}$ from MUonE data

$$a_\mu^{\mathrm{HLO\ (I)}} = -\frac{\alpha}{\pi}\sum_{n=1}^{3}\frac{c_n}{n!}\frac{d^{(n)}}{dt^n}\Delta\alpha_{had}(t)\Big|_{t=0}$$

The relevant quantities are the derivatives of $\Delta\alpha_{had}(t)$ at $t = 0$.

$a_\mu^{\mathrm{HLO\ (I)}}$ from MUonE data

$$a_\mu^{\mathrm{HLO\ (I)}} = -\frac{\alpha}{\pi}\sum_{n=1}^{3}\frac{c_n}{n!}\frac{d^{(n)}}{dt^n}\Delta\alpha_{had}(t)\Big|_{t=0}$$

The relevant quantities are the derivatives of $\Delta\alpha_{had}(t)$ at t = 0.

Try different parameterizations to fit MUonE data

(max 3 fit parameters, due to the statistics collected by MUonE)

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

Lepton-like

$$\Delta\alpha_{\mathrm{had}}(t) = P_1 t\frac{1+P_2 t}{1+P_3 t}$$

Padé approximant

$$\Delta\alpha_{\mathrm{had}}(t) = P_1 t + P_2 t^2 + P_3 t^3$$

3° polynomial

$a_\mu^{\mathrm{HLO}\ (\mathrm{I})}$ from MUonE data

Reconstruction approximants

D. Greynat, E. de Rafael, JHEP 2022 (5)

$$\Delta\alpha_{\mathrm{had}}(t) = \sum_{n=1}^{\mathrm{N}} \mathscr{A}(n,\mathrm{L}) \left(\frac{\sqrt{1-\frac{t}{t_0}}-1}{\sqrt{1-\frac{t}{t_0}}+1} \right)^n + \sum_{p=1}^{\lfloor \frac{\mathrm{L}+1}{2} \rfloor} \mathscr{B}(2p-1)\, \mathrm{Li}_{2p-1} \left(\frac{\sqrt{1-\frac{t}{t_0}}-1}{\sqrt{1-\frac{t}{t_0}}+1} \right)$$

$$\Delta\alpha_{\mathrm{had}}(t) = A_1 \mathscr{S}_1 + A_2 \mathscr{S}_2 + A_3 \mathscr{S}_3 + B_1 \mathscr{L}_1$$

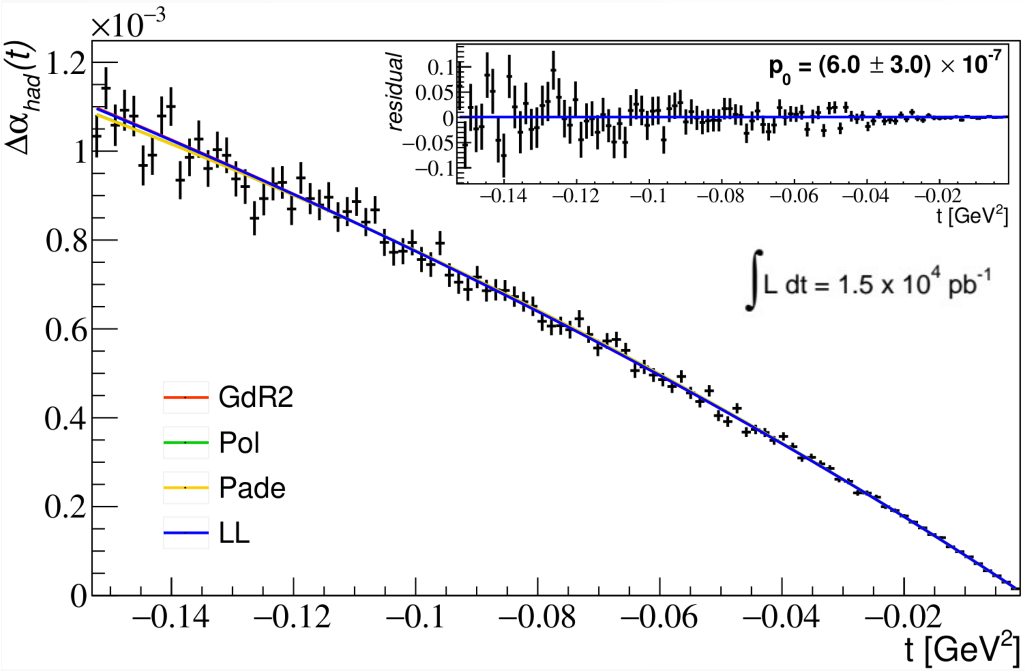
$$\mathscr{S}_i = \left(\frac{\sqrt{1-\frac{t}{t_0}}-1}{\sqrt{1-\frac{t}{t_0}}+1} \right); \qquad A_i = \mathscr{A}(i,1) \quad i = 1,\ 2,\ 3$$

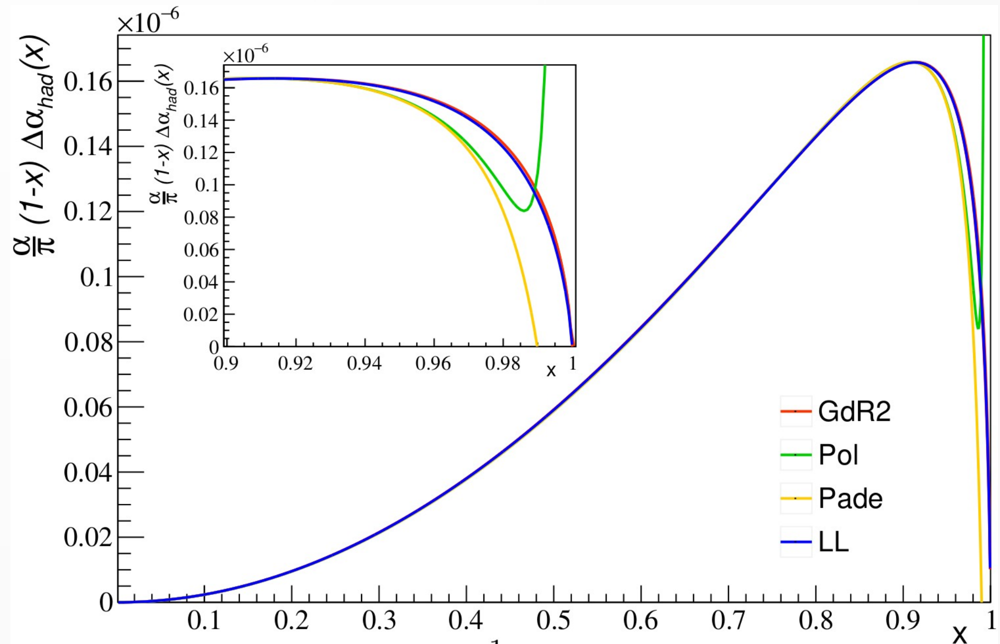
$$\mathscr{L}_1 = \mathrm{Li}_1 \left(\frac{\sqrt{1-\frac{t}{t_0}}-1}{\sqrt{1-\frac{t}{t_0}}+1} \right); \qquad B_1 = \mathscr{B}(1)$$

Tested L = 1, N = 3
Several variants with different number of free parameters

Fit the MUonE data

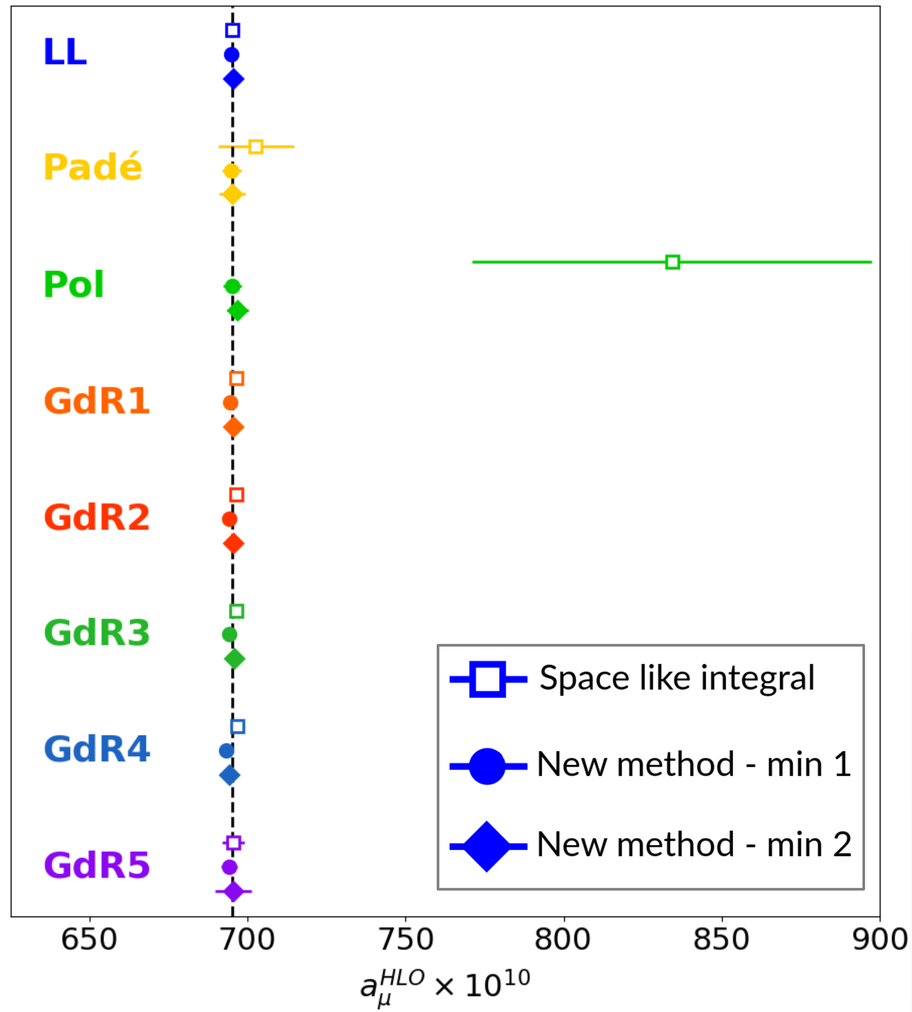
Simplified fit: simulate the MUonE signal using time-like compilations of $\Delta\alpha_{had}$. Error bars according to the MUonE final statistics.



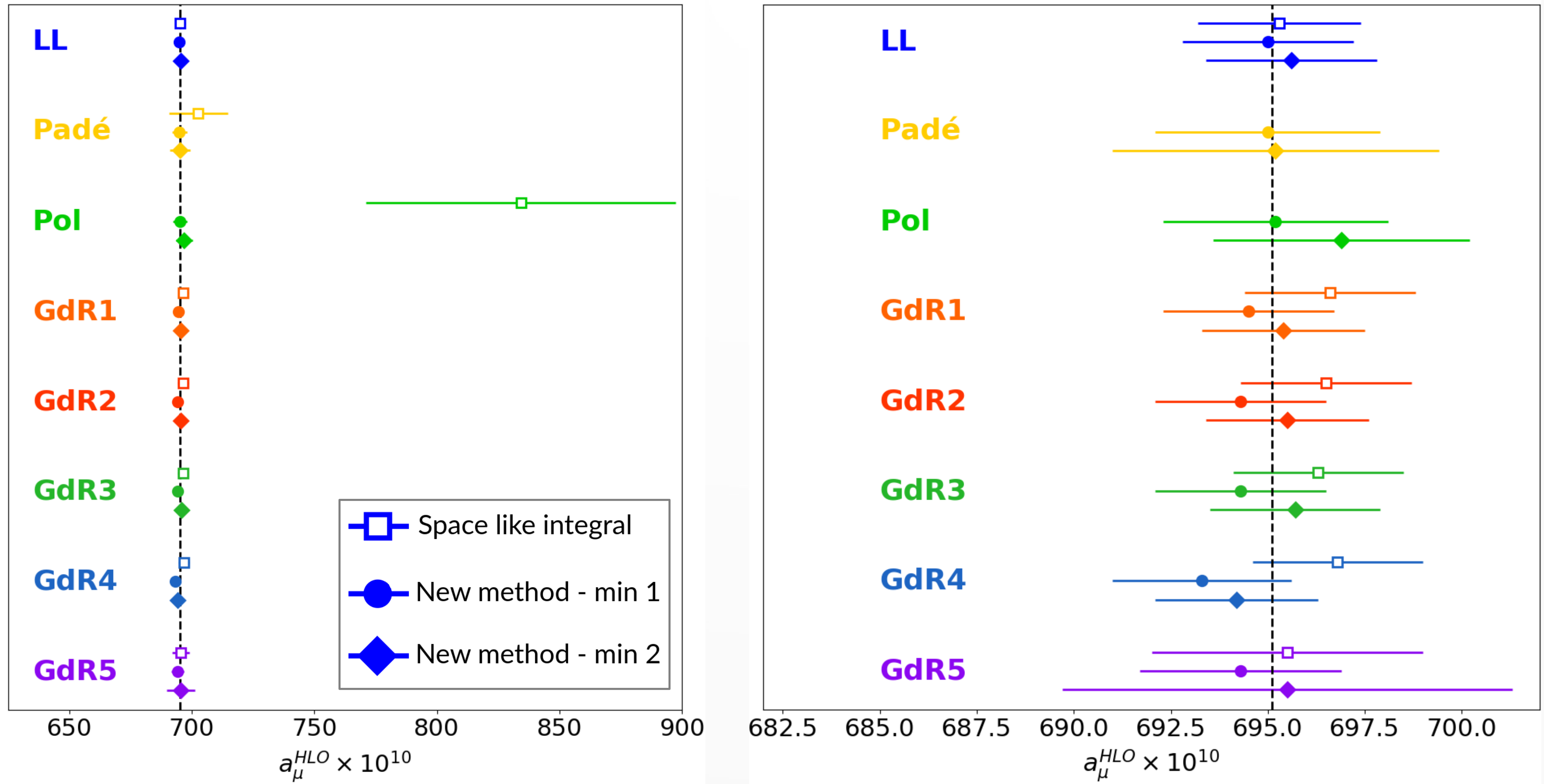


$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

Results: a_μ^{HLO}



Results: a_μ^{HLO}



Conclusions

MUonE web site

- MUonE will provide an independent calculation of a_μ^{HLO}, competitive with the latest evaluations.

- 3 weeks Test Run 2023: proof of concept of the experimental proposal. Data analysis ongoing.
  Request for a longer commissioning run in 2025 instrumenting more tracking stations.

- Full apparatus (40 stations) after CERN Long Shutdown 3 (2026-28) to achieve the target precision (~0.3% stat and similar syst).

- Alternative method to calculate a_μ^{HLO} with MUonE data:
  less sensitive to the parameterization chosen to model $\Delta\alpha_{\mathrm{had}}(t)$ in the MUonE kinematic range.
  Comparable uncertainty to the space-like integral method.

New collaborators are welcome!

CERN
Exp-Th

INFN +Univ. (Bologna, Milano-Bicocca, Padova, Pavia, Perugia, Pisa, Trieste)
Exp-Th

Imperial College (London), Liverpool U. Durham U.
Exp-Th

Krakow IFJ Pan
Exp

The MUonE Collaboration

Cornell U., Northwestern U., Regis U., Virginia U.
Exp

Budker Inst. (Novosibirsk)
Exp

Demokritos INPP (Athens) ***Exp-Th***

Shanghai Jiao Tong U.
Exp

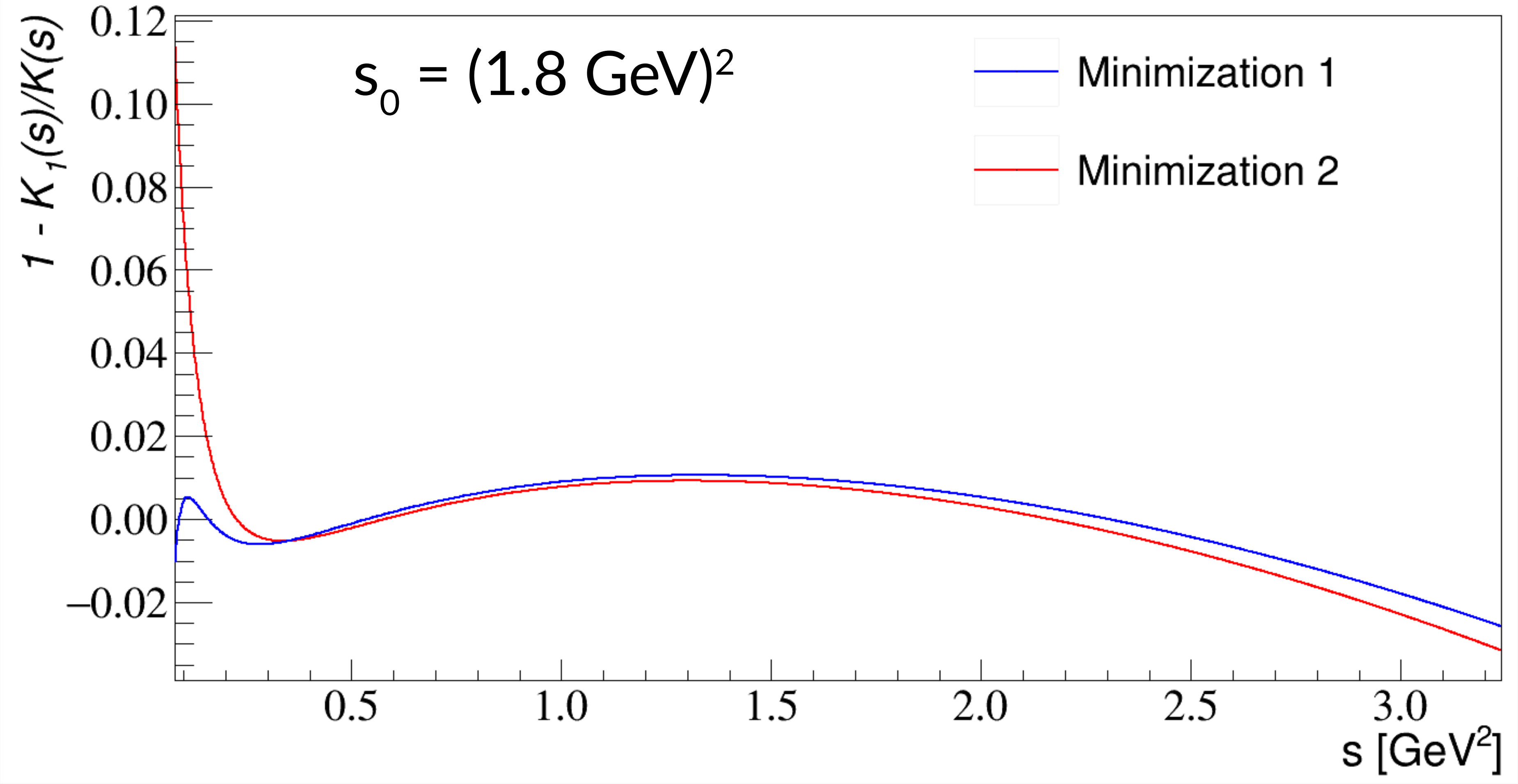
PSI (Villigen), U.Zürich, ETH Zürich
Th

Mainz U., Max-Planck Inst.
Exp-Th

+ other involved theorists from: New York City Tech (USA), Vienna U. (A)

BACKUP

Difference $K_1(s)$ - $K(s)$



Results: $a_\mu^{\mathrm{HLO\ (I)}}$

$$a_\mu^{\mathrm{HLO\ (I)}} = -\frac{\alpha}{\pi}\sum_{n=1}^{3}\frac{c_n}{n!}\frac{d^{(n)}}{dt^n}\Delta\alpha_{had}(t)\Big|_{t=0}$$

Minimization I	$a_\mu^{\mathrm{HLO\ (I)}}$ (10^{-10})							
s_0 values	LL	Padé	Pol	GdR1	GdR2	GdR3	GdR4	GdR5
$(1.8\ \mathrm{GeV})^2$	688.7±2.2	688.7±2.9	688.9±2.9	688.2±2.2	688.0±2.2	688.0±2.2	687.0±2.3	688.0±2.6
$(2.5\ \mathrm{GeV})^2$	691.7±2.2	691.6±3.0	691.8±3.0	691.0±2.2	690.8±2.2	690.8±2.2	689.8±2.3	690.9±2.9
$(12\ \mathrm{GeV})^2$	696.3±2.2	696.3±3.0	696.3±3.2	695.4±2.2	695.3±2.2	695.2±2.2	694.1±2.3	695.3±3.7
Minimization II	$a_\mu^{\mathrm{HLO\ (I)}}$ (10^{-10})							
s_0 values	LL	Padé	Pol	GdR1	GdR2	GdR3	GdR4	GdR5
$(1.8\ \mathrm{GeV})^2$	688.5±2.2	688.1±4.2	689.8±3.3	688.3±2.1	688.4±2.1	688.6±2.2	687.1±2.1	688.4±5.8
$(2.5\ \mathrm{GeV})^2$	689.5±2.2	689.1±4.2	690.8±3.3	689.3±2.1	689.4±2.1	689.6±2.2	688.1±2.1	689.4±5.7
$(12\ \mathrm{GeV})^2$	690.3±2.1	689.9±4.6	691.6±3.6	689.8±2.1	690.1±2.2	690.2±2.2	688.6±2.1	690.0±5.9

$a_\mu^{\mathrm{HLO\ (I)}}$ ~ 99% of the total value.

($a_\mu^{\mathrm{HLO}} = 695.1\times10^{-10}$ input from time-like data).

Results: $a_\mu^{\mathrm{HLO\ (II,\ III,\ IV)}}$

$$a_\mu^{\mathrm{HLO\ (II)}} = \frac{\alpha}{\pi}\frac{1}{2\pi i}\oint_{|s|=s_0}\frac{ds}{s}c_0 s\ \Pi_{had}(s)\Big|_{\mathrm{pQCD}} \qquad a_\mu^{\mathrm{HLO\ (III)}} = \frac{\alpha^2}{3\pi^2}\int_{s_{\mathrm{th}}}^{s_0}\frac{ds}{s}[K(s)-K_1(s)]R(s)$$

$$a_\mu^{\mathrm{HLO\ (IV)}} = \frac{\alpha^2}{3\pi^2}\int_{s_0}^{\infty}\frac{ds}{s}[K(s)-\tilde{K}_1(s)]R(s)$$

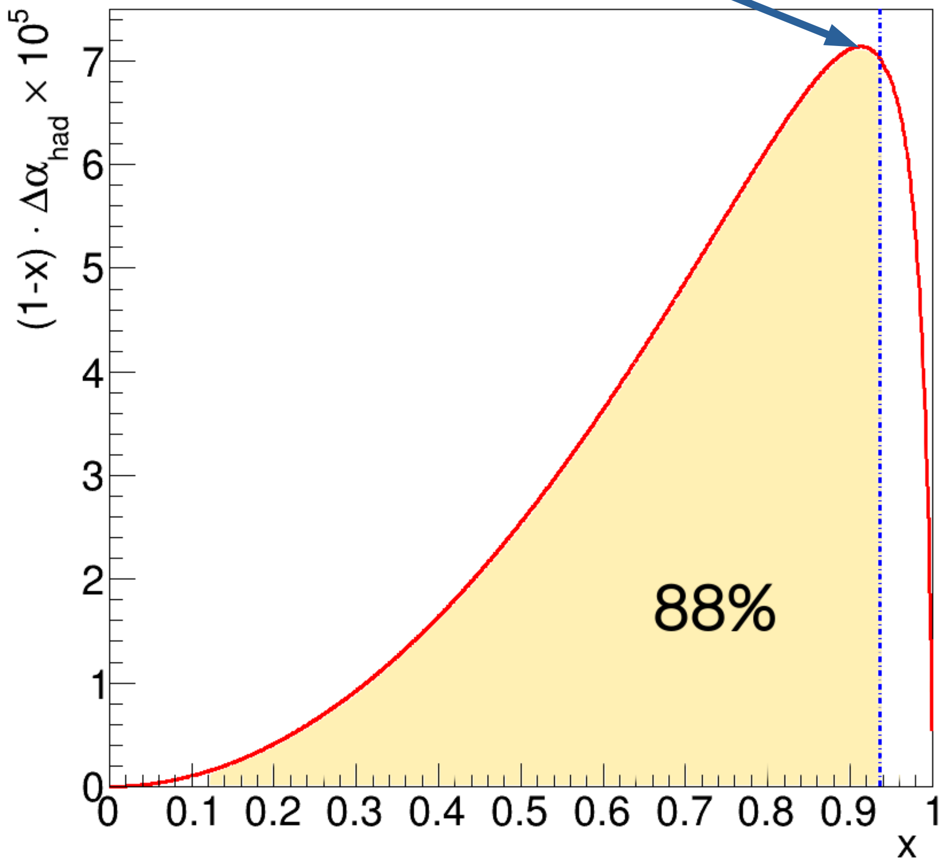
Minimization I			
s_0 values	$a_\mu^{\mathrm{HLO\ (II)}}$ (10^{-10})	$a_\mu^{\mathrm{HLO\ (III)}}$ (10^{-10})	$a_\mu^{\mathrm{HLO\ (IV)}}$ (10^{-10})
$(1.8\ \mathrm{GeV})^2$	2.94 ± 0.04	0.43 ± 0.01	2.95 ± 0.05
$(2.5\ \mathrm{GeV})^2$	1.84 ± 0.01	-0.34 ± 0.01	1.79 ± 0.02
$(12\ \mathrm{GeV})^2$	0.208 ± 0.001	-1.695 ± 0.035	0.079 ± 0.001
Minimization II			
s_0 values	$a_\mu^{\mathrm{HLO\ (II)}}$ (10^{-10})	$a_\mu^{\mathrm{HLO\ (III)}}$ (10^{-10})	$a_\mu^{\mathrm{HLO\ (IV)}}$ (10^{-10})
$(1.8\ \mathrm{GeV})^2$	3.23 ± 0.04	0.91 ± 0.02	3.00 ± 0.05
$(2.5\ \mathrm{GeV})^2$	2.54 ± 0.01	1.52 ± 0.02	1.96 ± 0.02
$(12\ \mathrm{GeV})^2$	0.360 ± 0.001	4.85 ± 0.05	0.096 ± 0.001

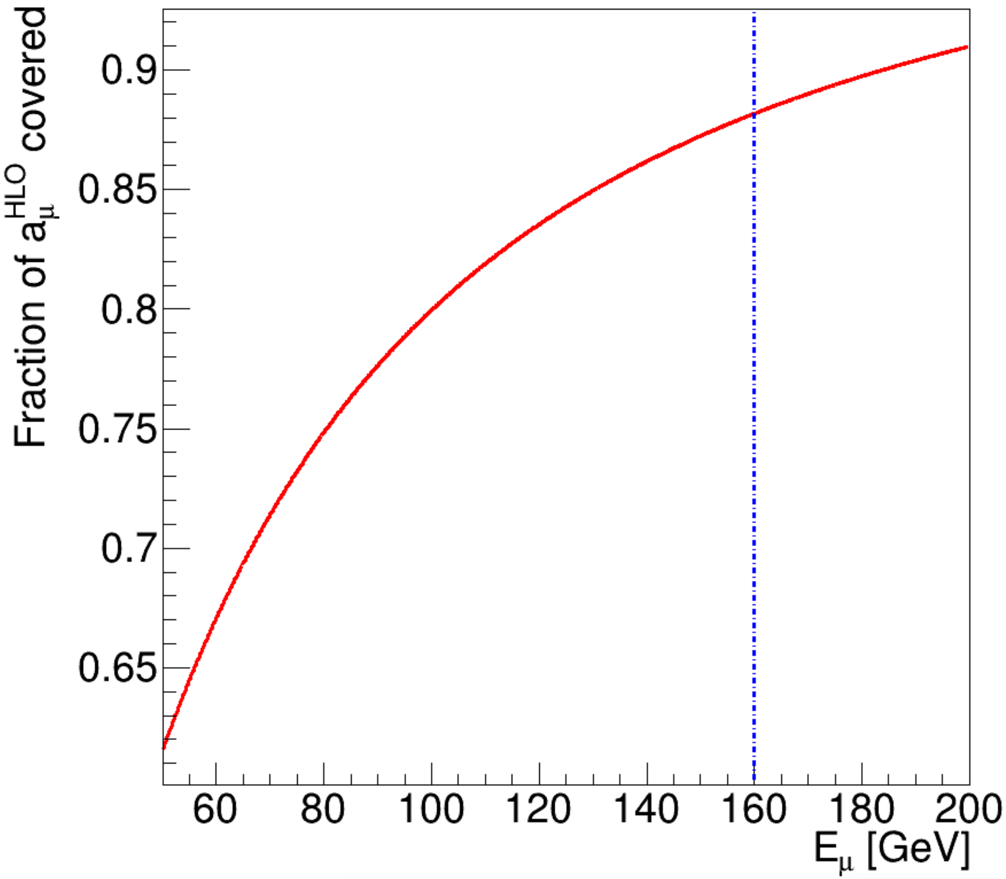
$a_\mu^{\mathrm{HLO\ (II+III+IV)}}$ ~ 1% of the total value.

($a_\mu^{\mathrm{HLO}} = 695.1\times10^{-10}$ input from time-like data).

$x < 0.936$

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



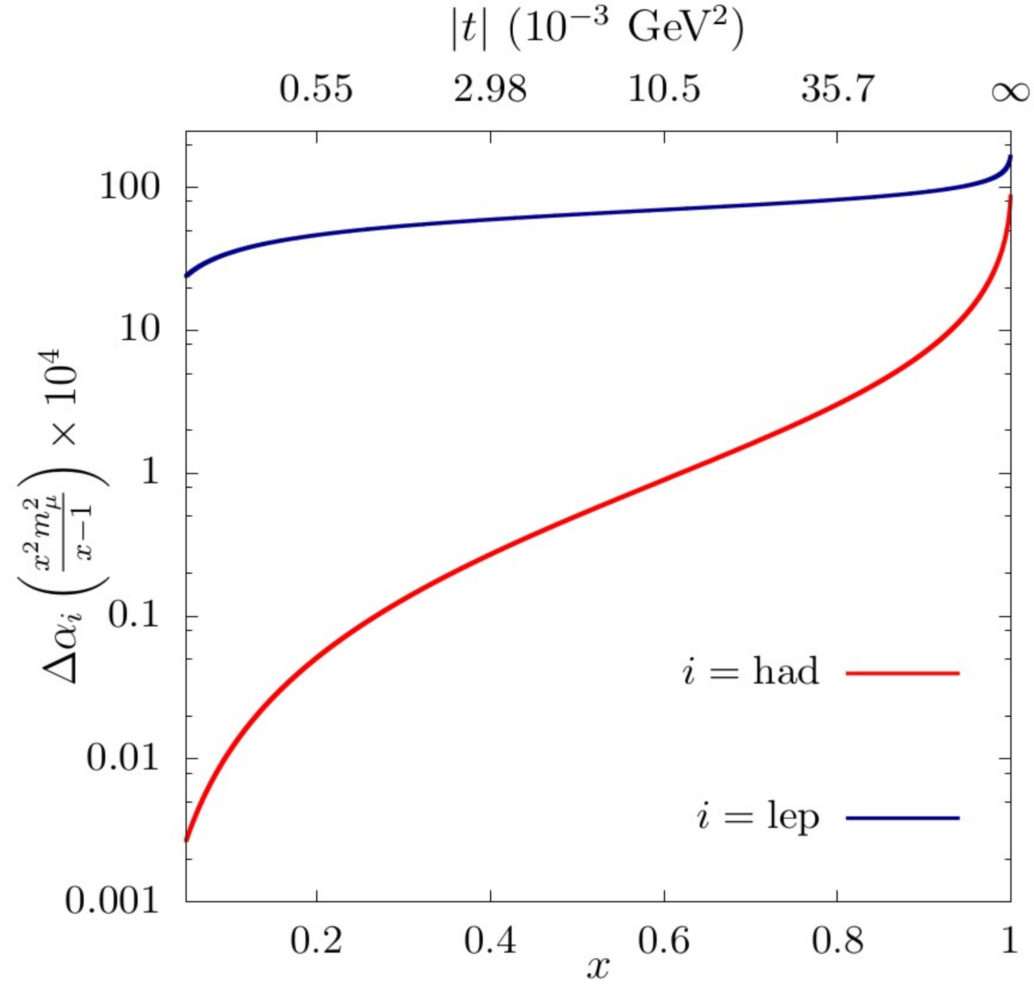


- 160 GeV muon beam on atomic electrons.

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

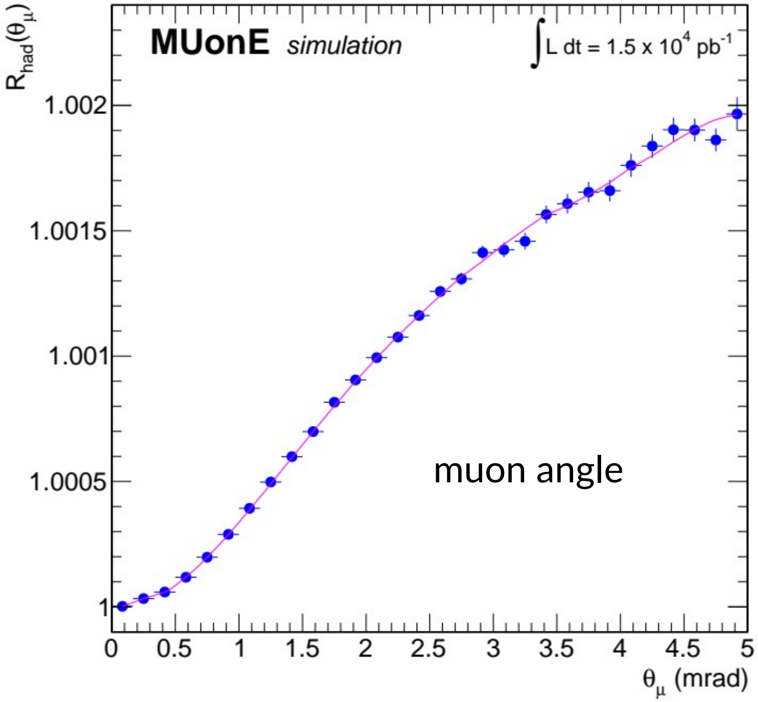
$$-0.153\,\mathrm{GeV}^2 < t < 0\,\mathrm{GeV}^2$$

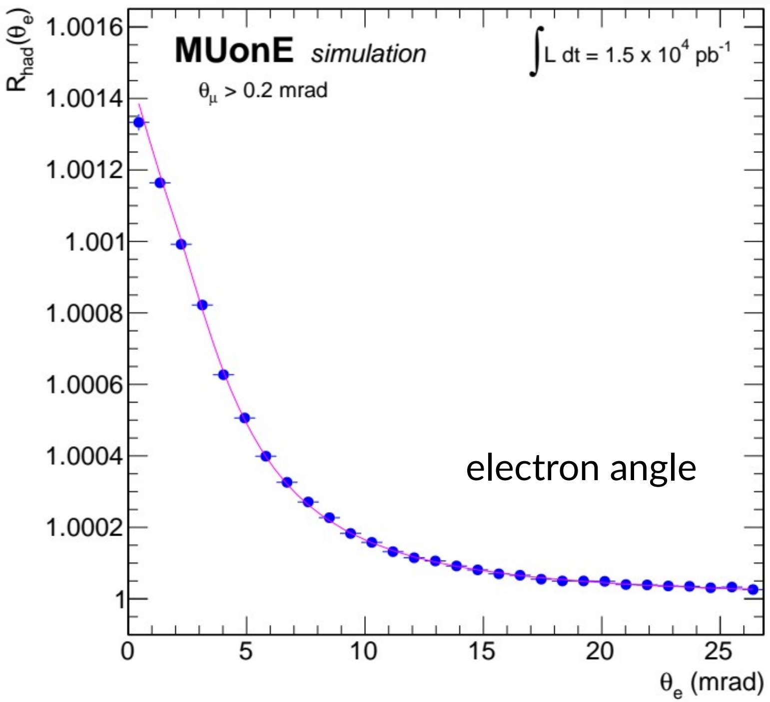
$$\Delta\alpha_{had}(t) \lesssim 10^{-3}$$



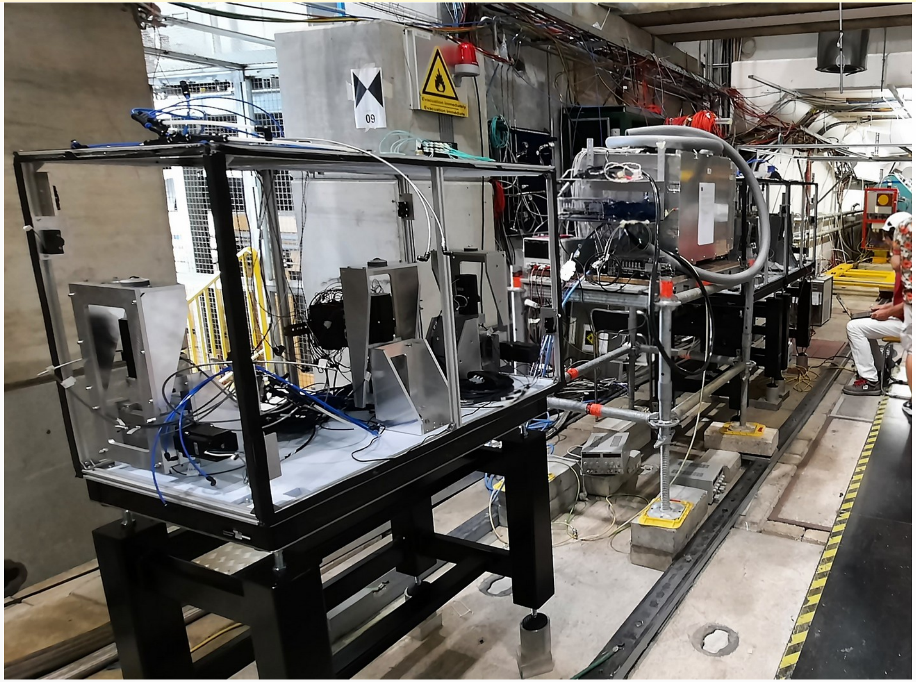
$$R_{\text{had}} = \underbrace{\frac{d\sigma_{\text{data}}(\Delta\alpha_{\text{had}})}{d\sigma_{\text{MC}}(\Delta\alpha_{\text{had}} = 0)}}_{\text{From theoretical calculation}} \sim 1 + \underbrace{2\Delta\alpha_{\text{had}}(t)}_{\text{To be measured}}$$

$$\boxed{\Delta\alpha_{\text{had}}(t) < 10^{-3}}$$

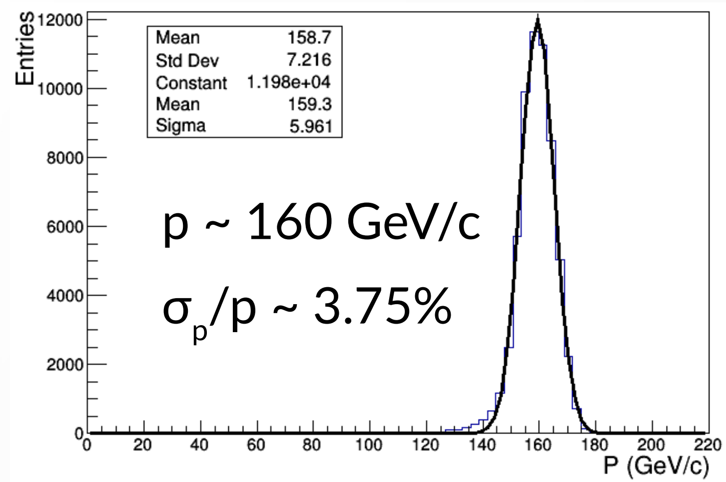




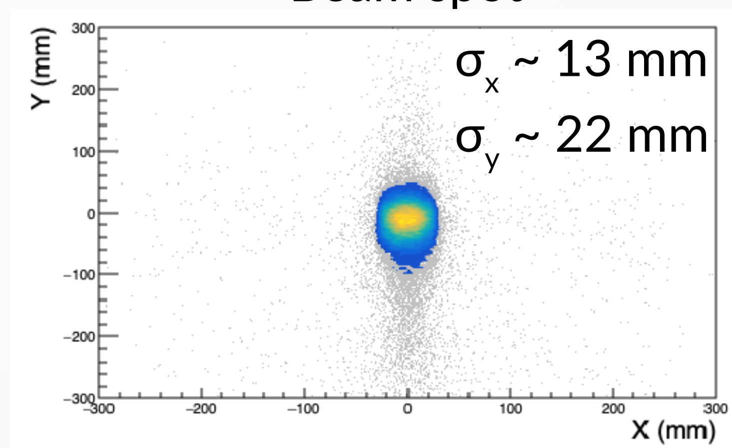
Location: M2 beamline at CERN



Beam momentum

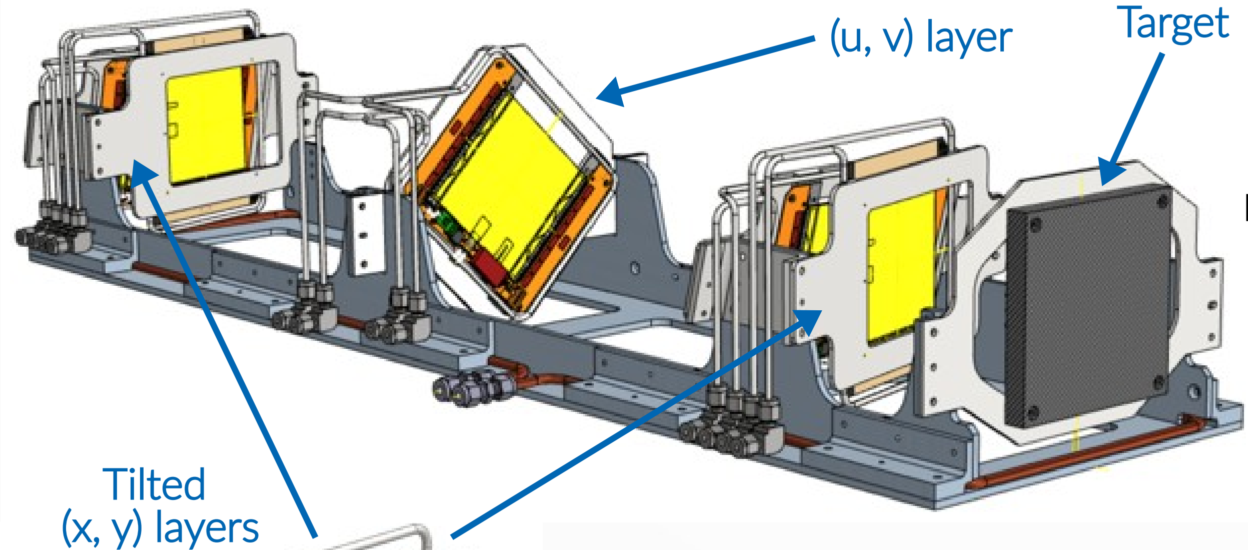


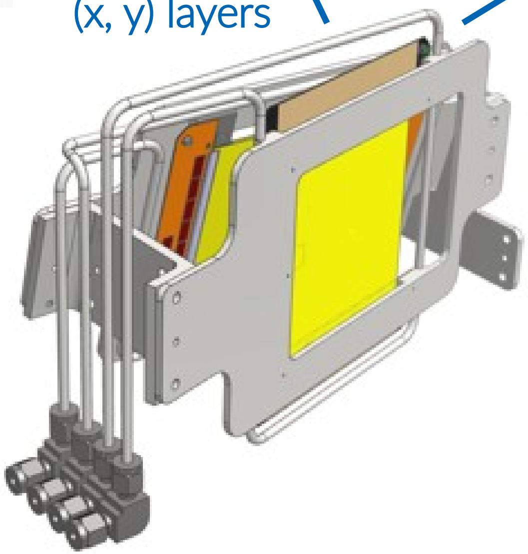
Beam spot



- Location: upstream the COMPASS detector (CERN North Area).
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} \sim 0.2$ mrad.
- Spill duration ~ 5 s. Duty cycle ~ 25%.
- Maximum rate: 50 MHz (~ 2-3x10^8 μ^+/spill).

Tracking station





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

Low CTE material:
INVAR (CTE ~ 1.2×10^{-6} K^{-1})

Laser holographic system to monitor stability.

- (x, y) layers tilted by 233 mrad:
  reduce the effective pitch and improve spatial resolution.
  - Simulations: ~22µm → ~10 µm.
- (u, v) layers to solve reconstruction ambiguities.

Tracker: CMS 2S modules

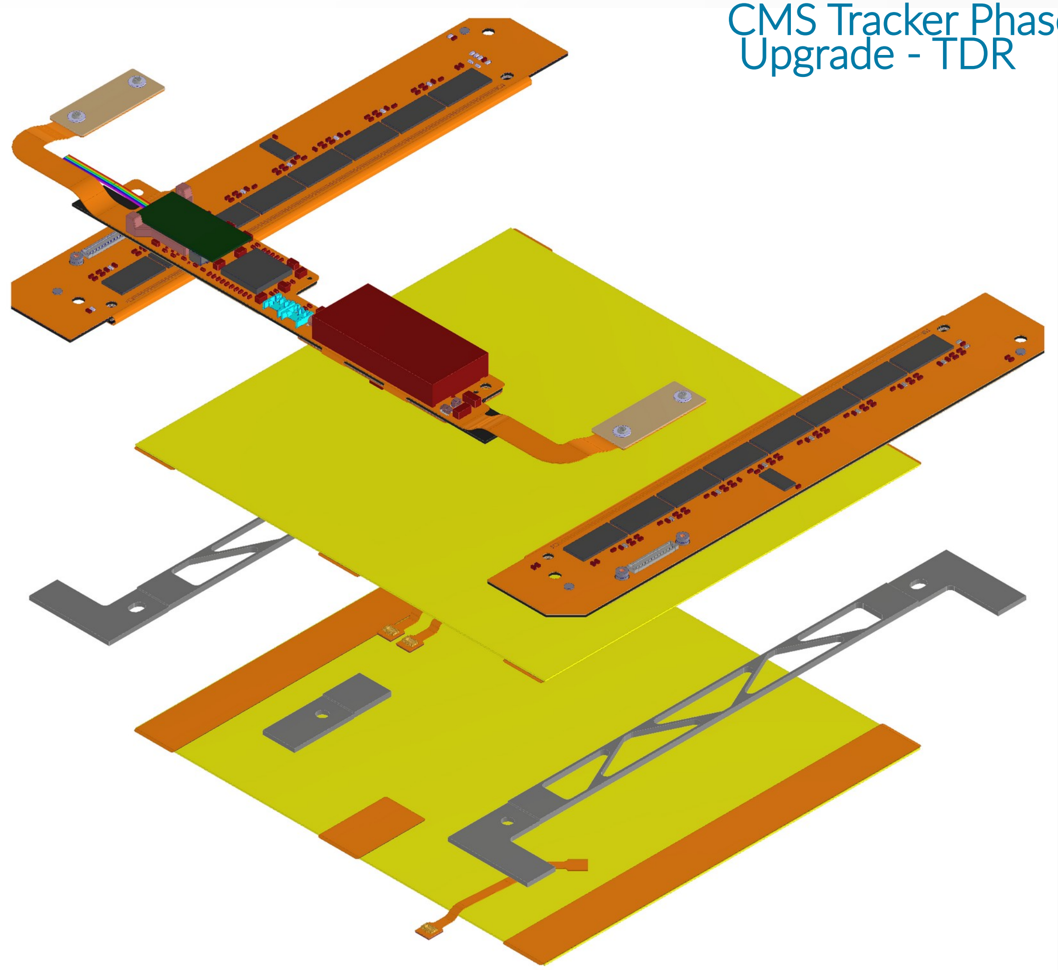
Silicon strip sensors currently in production for the CMS-Phase2 upgrade.

Two close-by strip sensors reading the same coordinate:

- Suppress background of single sensor hits.
- Reject large angle tracks.

- Pitch: 90 µm
- Digital readout
- Readout rate: 40 MHz
- Area: 10×10 cm^2 (~90 cm^2 active)
- Thickness: 2 × 320 µm

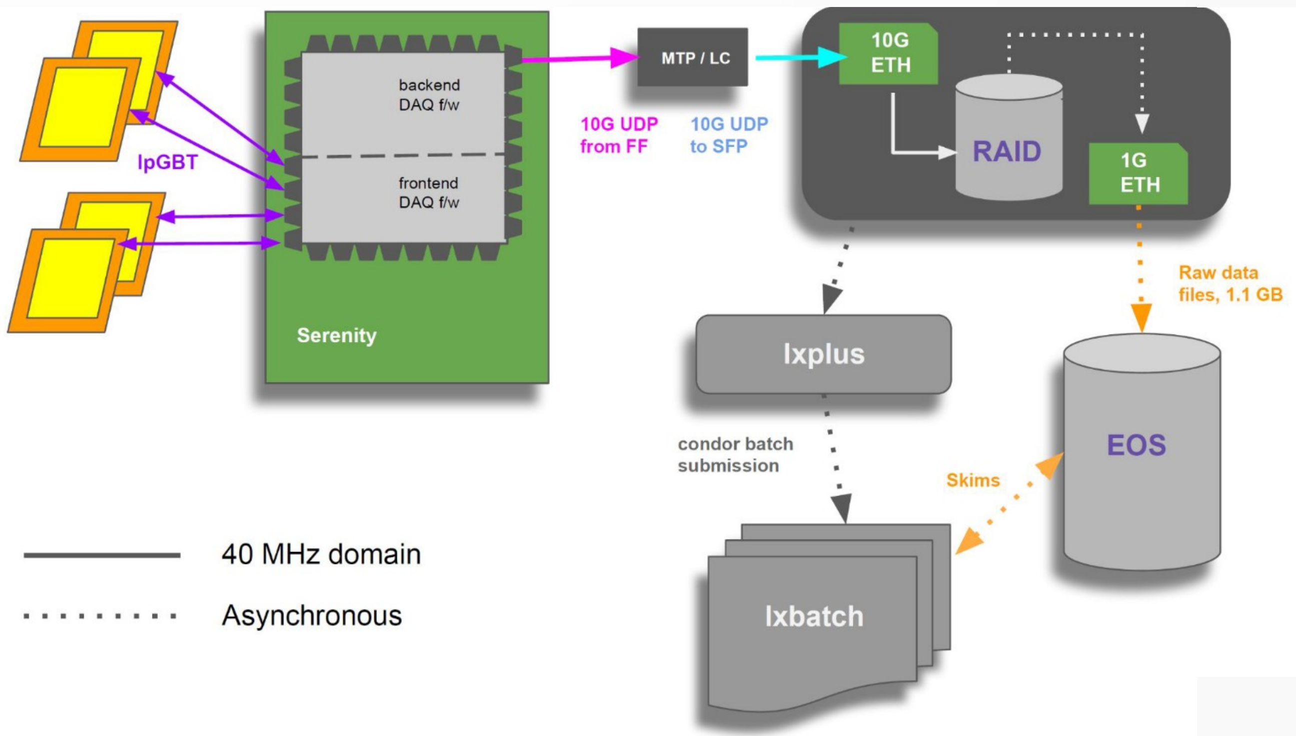
CMS Tracker Phase2 Upgrade - TDR



DAQ system

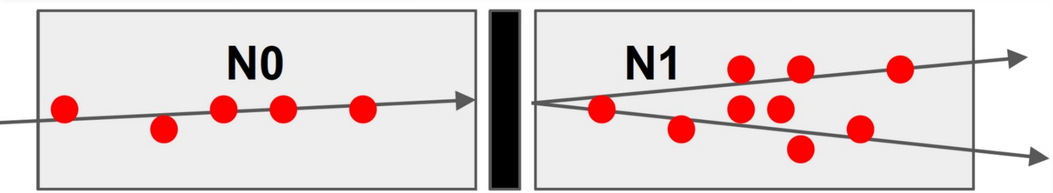
Frontend control and readout via Serenity board
(to be used in the CMS-Phase2 upgrade).

- Asynchronous beam: triggerless readout of the 2S modules @40MHz.
- Event aggregator on FPGA.
- Further data aggregation on the PC.
- Transmission to EOS into ~1GB files.



Test Run Analysis

Online event selection



Select potential elastic events by looking at the number of hits in two consecutive stations:

- $N_{hits}^{0} \geq 5$ &&
- $N_{hits}^{1} \geq 5$ &&
- $N_{hits}^{1} - N_{hits}^{0} \geq 3\text{-}5$

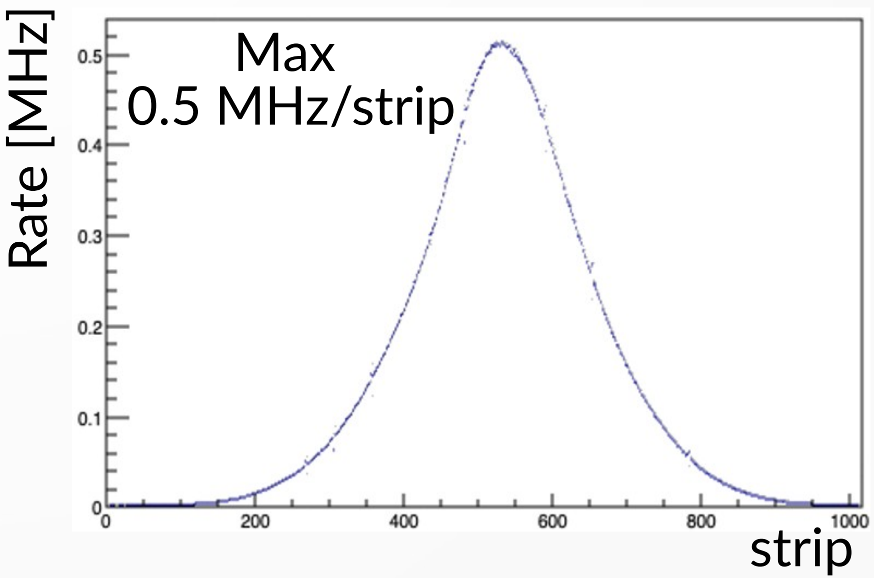
Reduce the data flow to 1%-2%

Can be easily implemented on FPGA.

Beam rate

$1\text{-}2 \times 10^{8}$ μ/spill

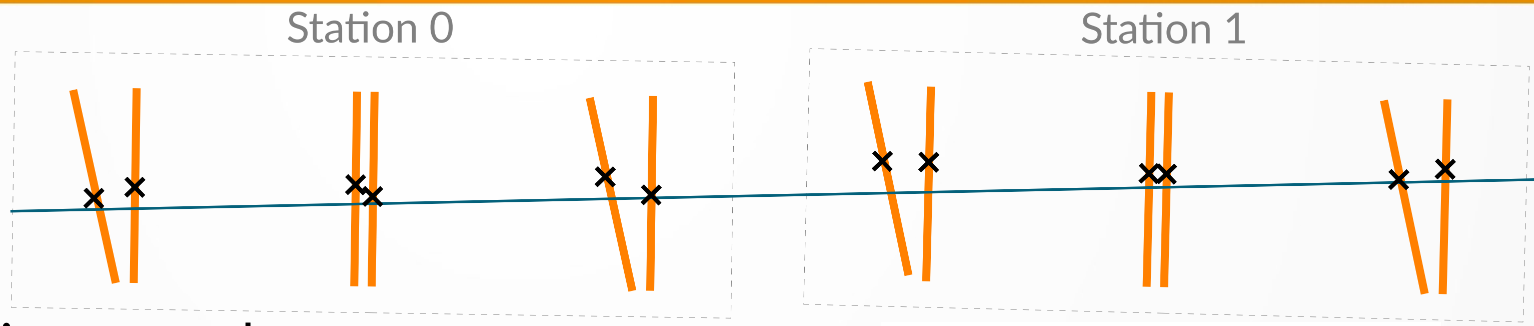
(1 spill = 5s)



Goal:

count the total number of muons per run (input for expected luminosity)

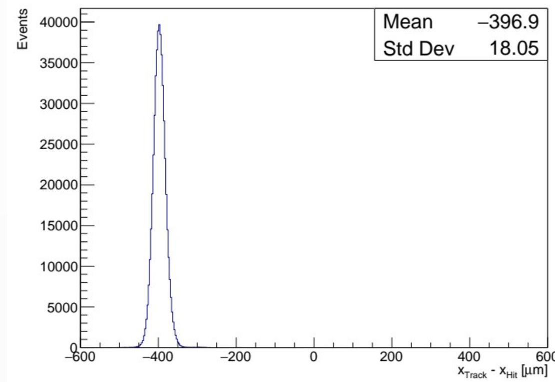
Test Run Analysis



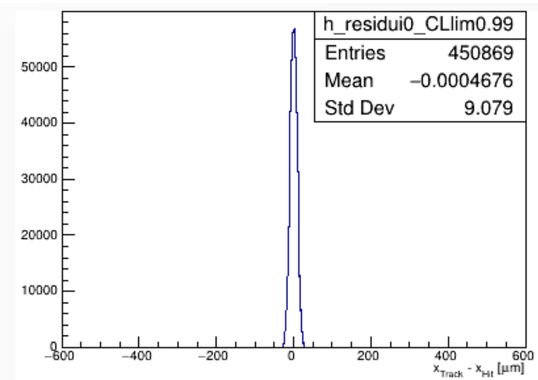
Alignment

Currently:

- Track based iterative procedure:
  2 alignment parameters per module
  (offset in the measured direction
  and rotation angle around the beam axis).



- Align the coordinate orthogonal to the measurement direction by measuring the image of module's middle line.

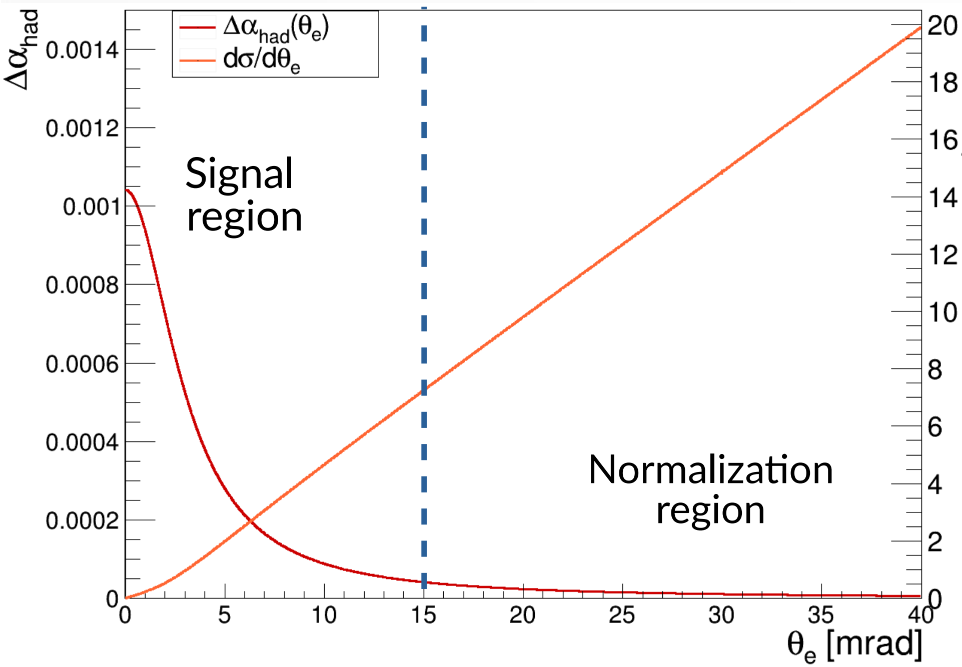


Ongoing work:

- Include the hardware metrology measurements as starting point of the track based alignment.
- Global alignment.

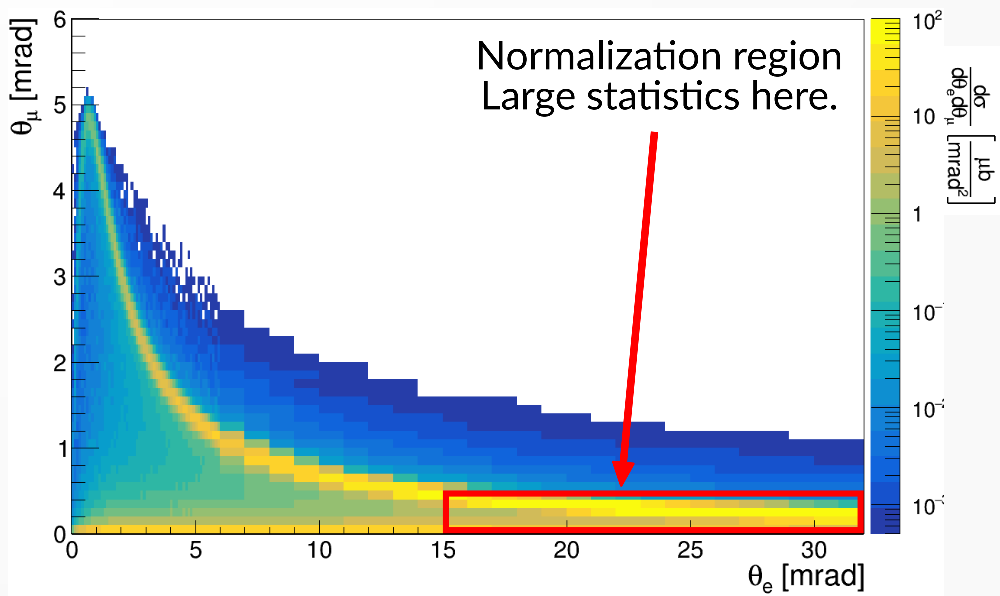
Strategy for the systematic effects

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



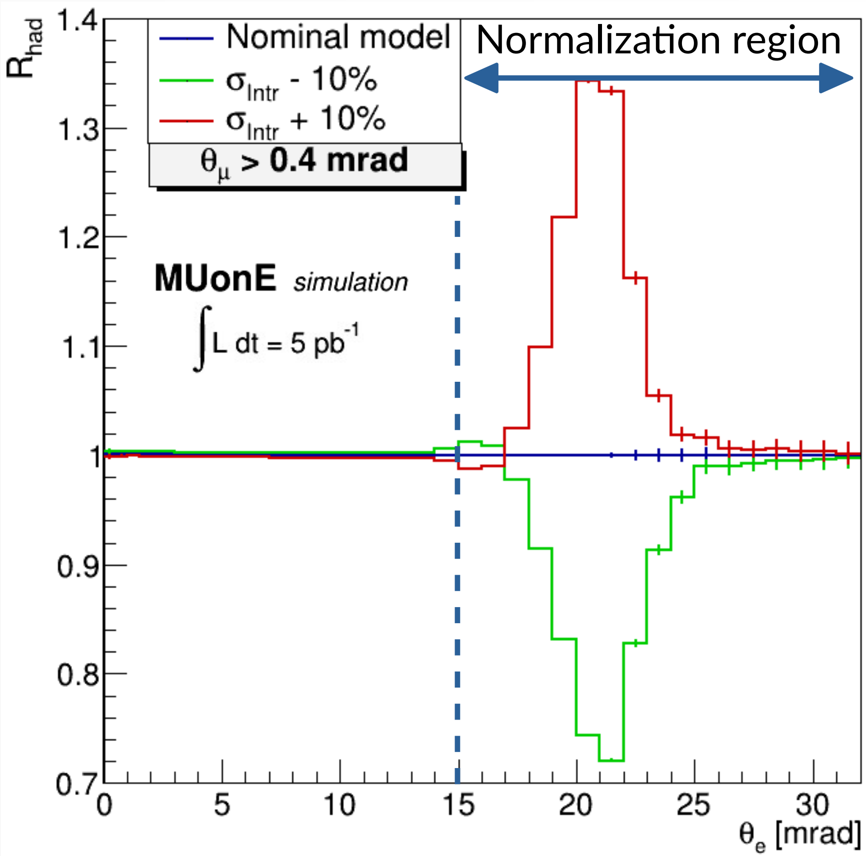
Promising strategy:

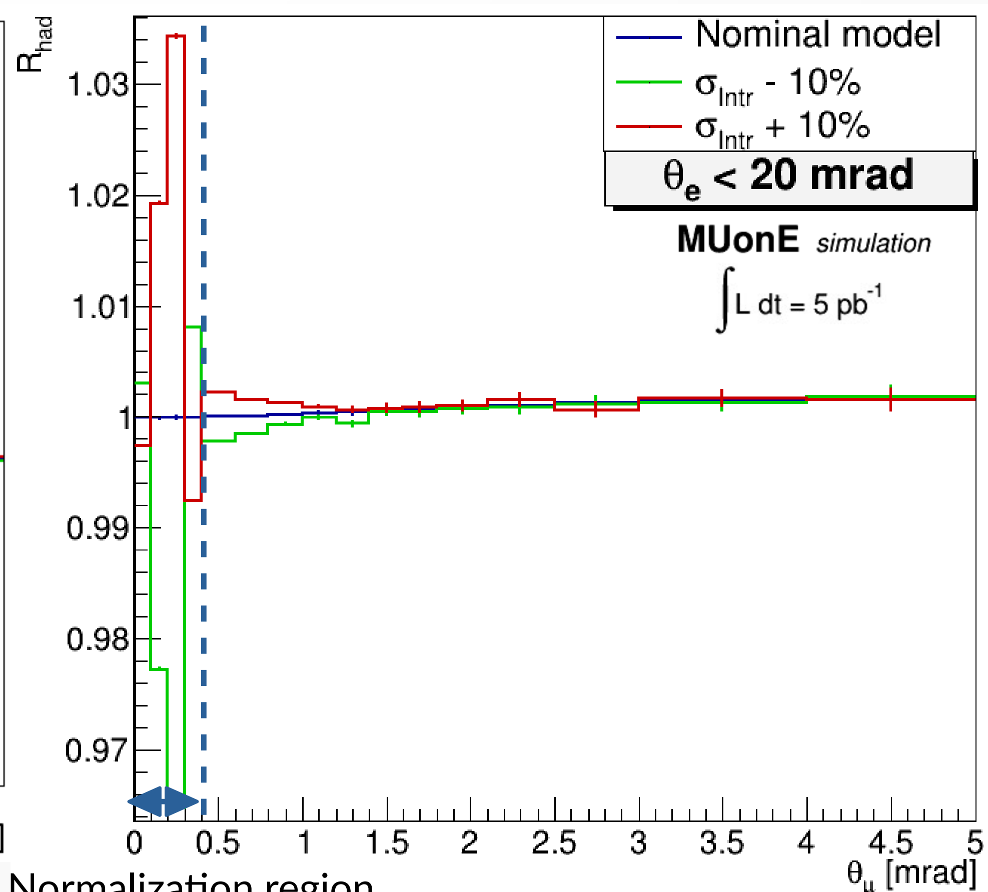
- Study the main systematics in the normalization region.
- Include residual systematics as nuisance parameters in a combined fit with signal.



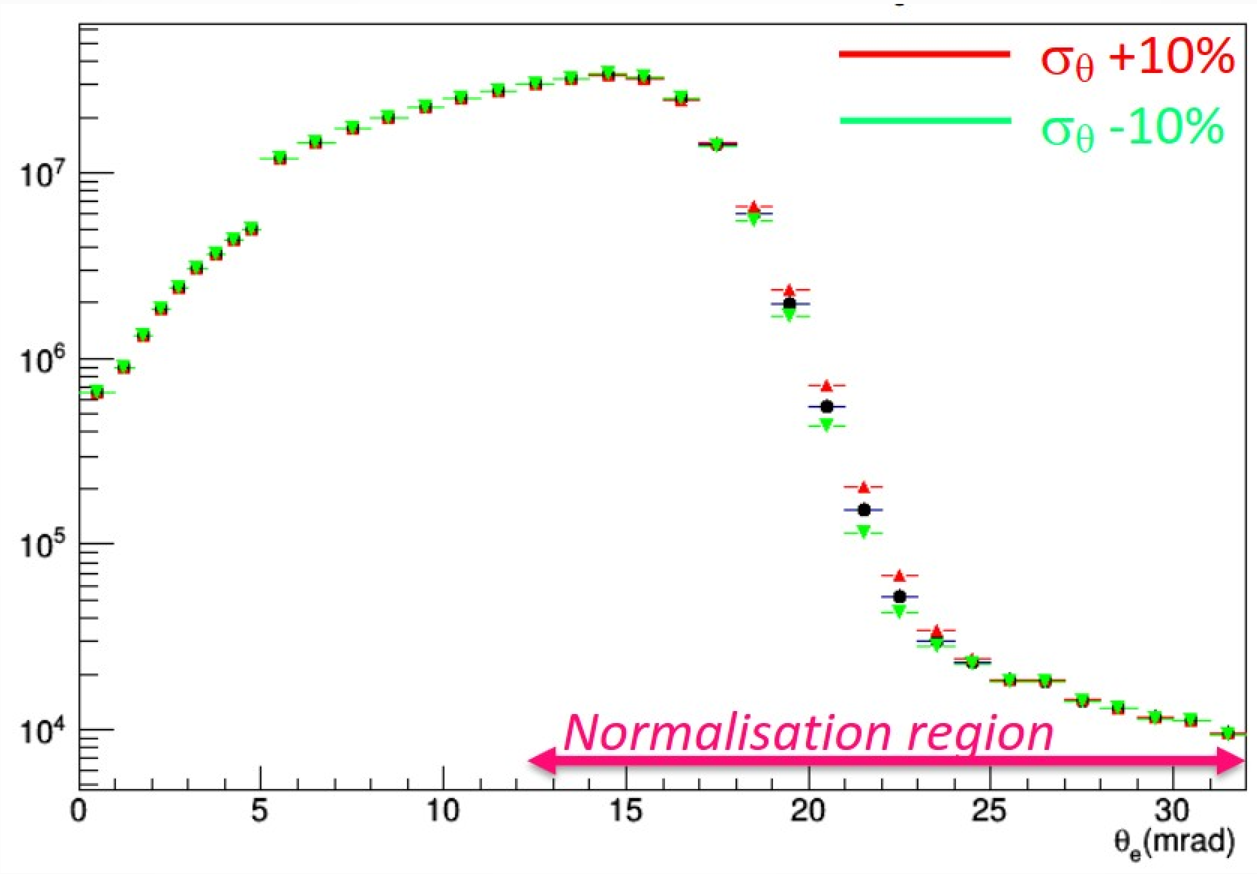
Systematic error on the angular intrinsic resolution

±10% error on the
angular intrinsic resolution.





Normalization region



σθ +10%
σθ -10%
10^7
10^6
10^5
10^4
Normalisation region
0
5
10
15
20
25
30
θe(mrad)

The need of including systematic effects in the analysis

What if systematic effects are not included in the template fit?

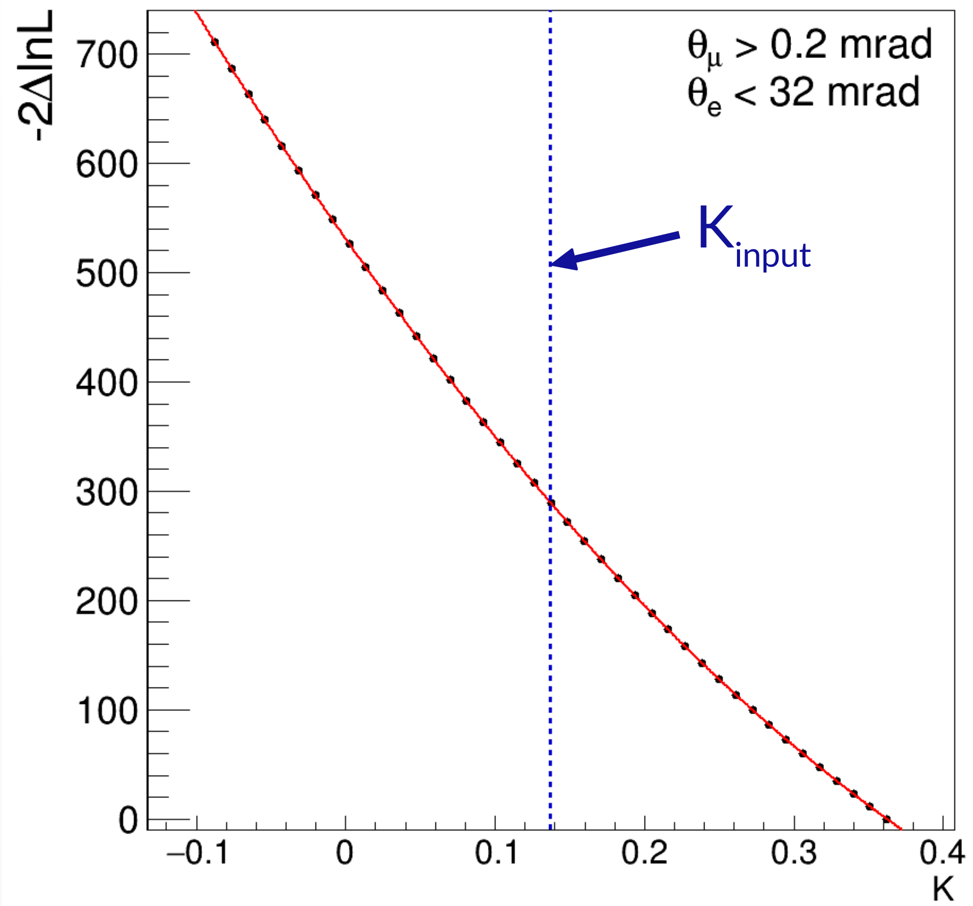
Simplified situation:

- 1 fit parameter (K).

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

- L = 5 pb^{-1}.
  ~10^9 elastic events
  (~4000 times less than the final statistics)

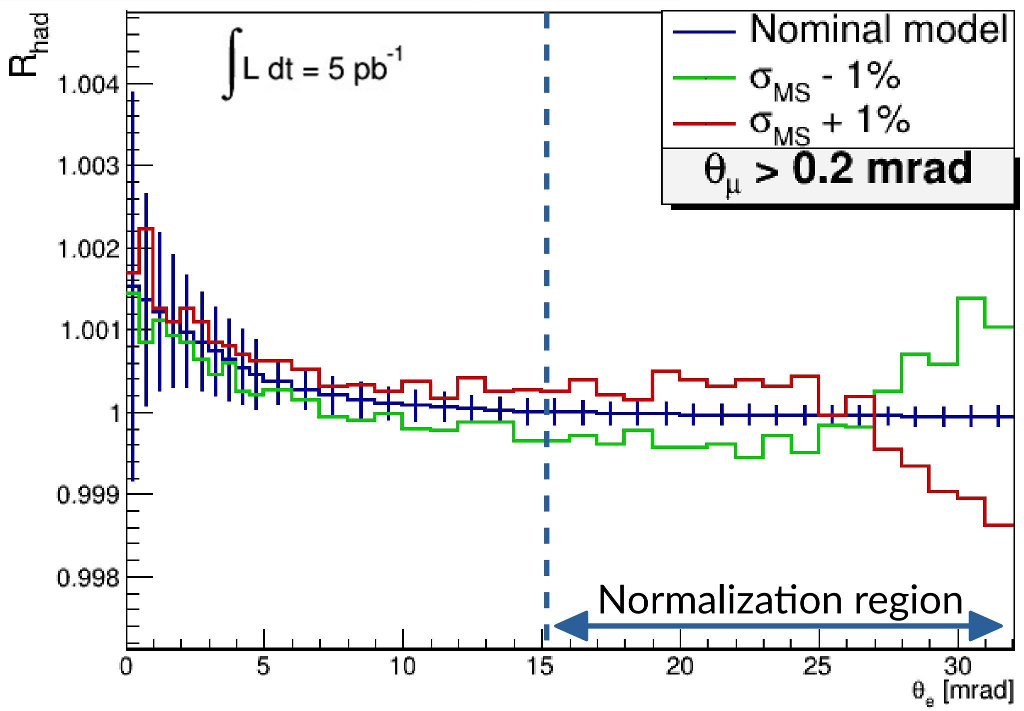
- Shift in the pseudo-data sample:
  $\sigma_{Intr} \rightarrow \sigma_{Intr} + 5\%$.

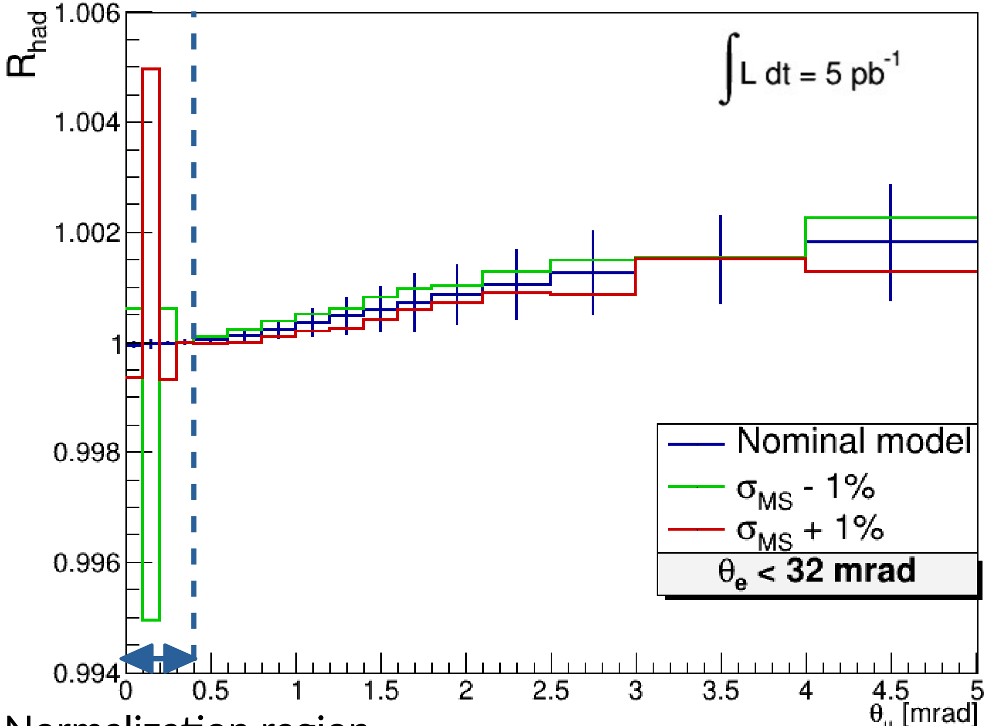


Systematic error on the multiple scattering

Expected precision on the multiple scattering model: ± 1%

G. Abbiendi et al JINST (2020) 15 P01017

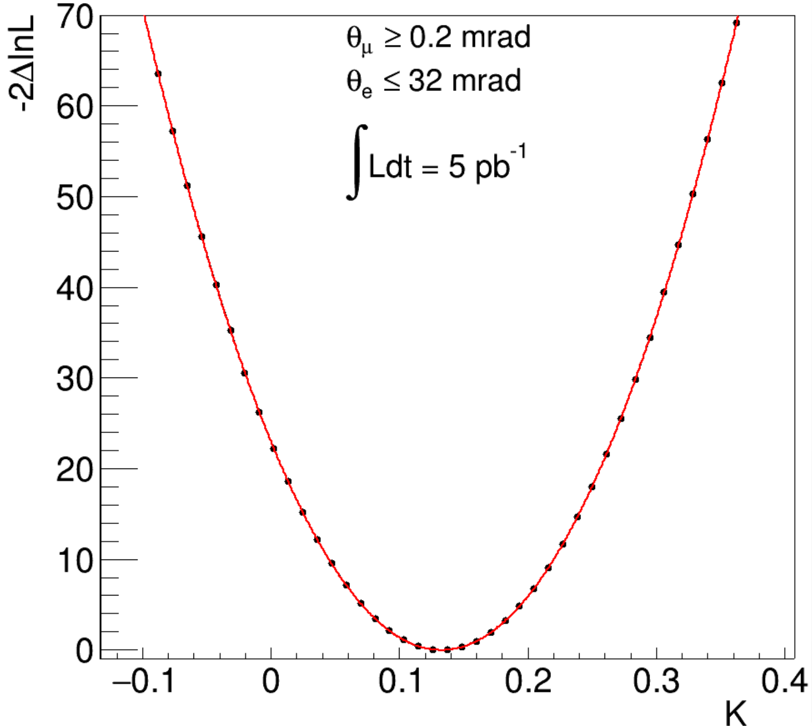




Normalization region

Combined fit
signal + systematics

- Include residual systematics as nuisance parameters in the fit.
- Simultaneous likelihood fit to K and systematics using the Combine tool.



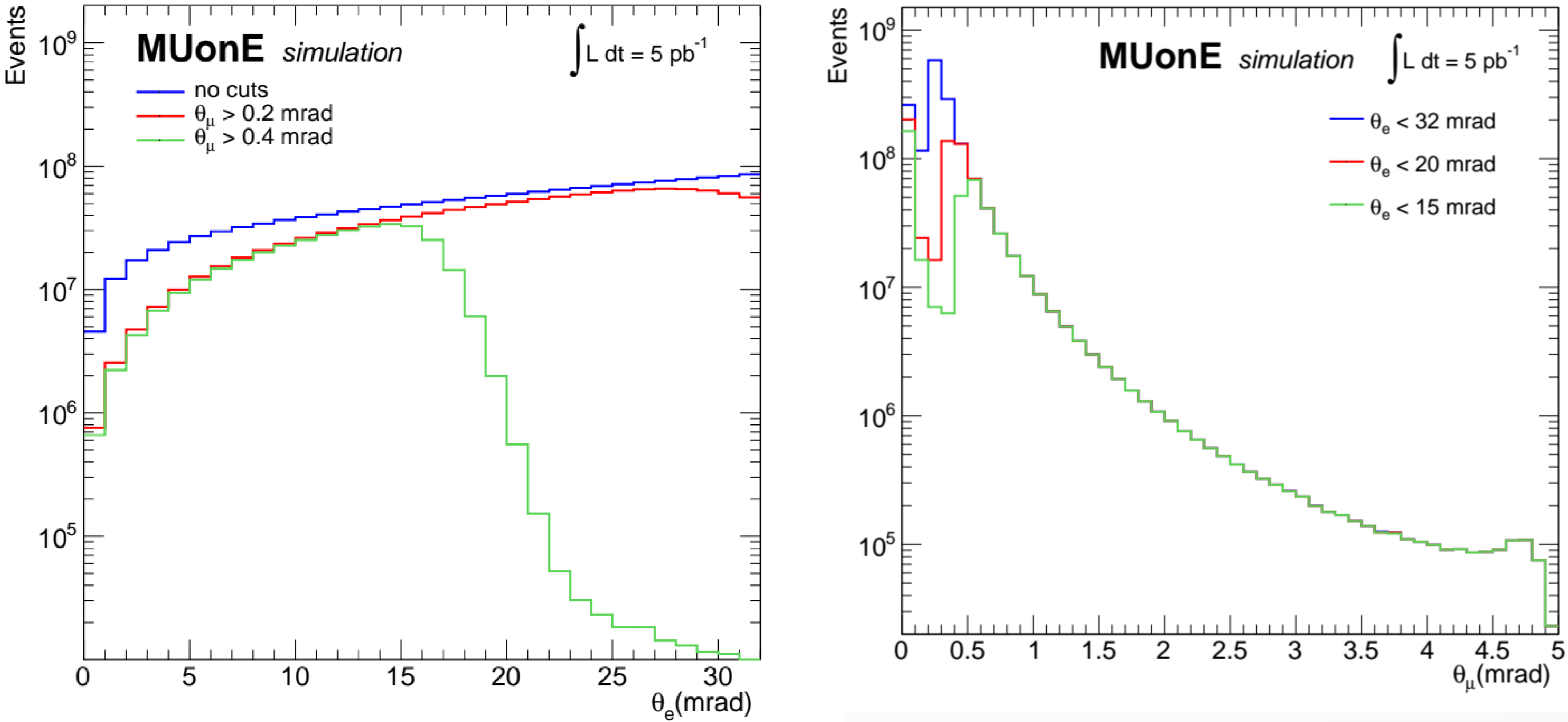
- K_{ref} = 0.137
- shift MS: +0.5%
- shift intr. res: +5%
- shift E_{beam}: +6 MeV

Selection cuts	Fit results
$\theta_e \leq 32\,\mathrm{mrad}$ $\theta_\mu \geq 0.2\,\mathrm{mrad}$	$K = 0.133 \pm 0.028$ $\mu_{\mathrm{MS}} = (0.47 \pm 0.03)\%$ $\mu_{\mathrm{Intr}} = (5.02 \pm 0.02)\%$ $\mu_{\mathrm{E_{Beam}}} = (6.5 \pm 0.5)\ \mathrm{MeV}$ $\nu = -0.001 \pm 0.003$

Similar results also for different selection cuts.

Next steps:

- Test the procedure for the MuonE design statistics.
- Improve the modelization of systematic effects.

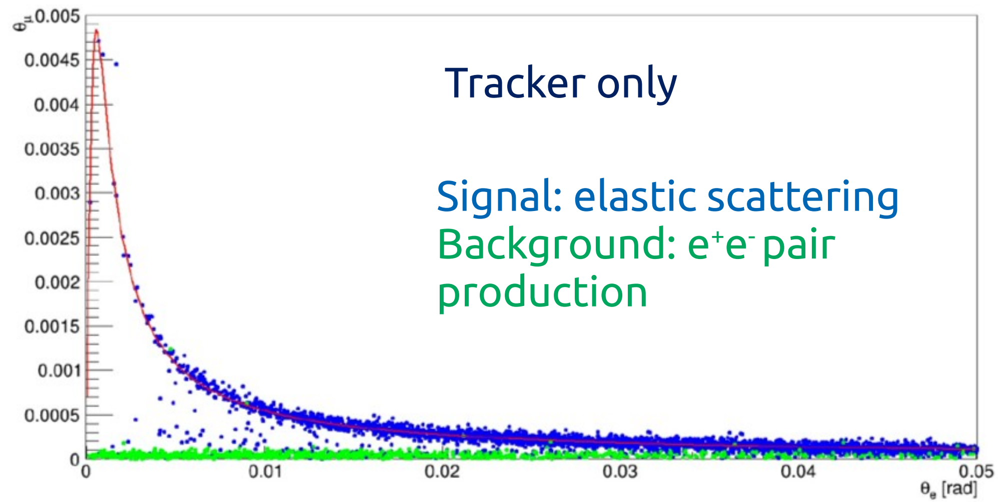


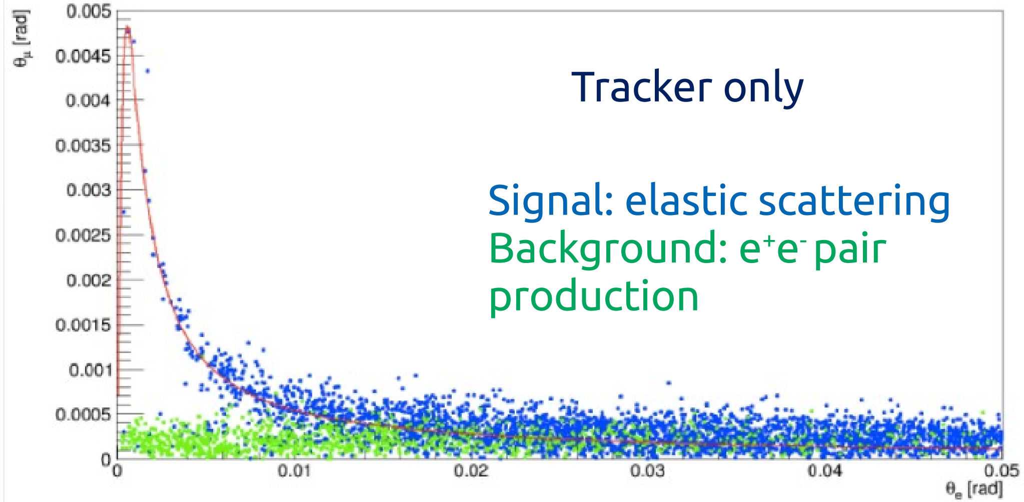
MUonE simulation
$\int L\,dt = 5\ pb^{-1}$
no cuts
$\theta_\mu > 0.2$ mrad
$\theta_\mu > 0.4$ mrad
Events
θ_e(mrad)
$\theta_e < 32$ mrad
$\theta_e < 20$ mrad
$\theta_e < 15$ mrad
θ_μ(mrad)

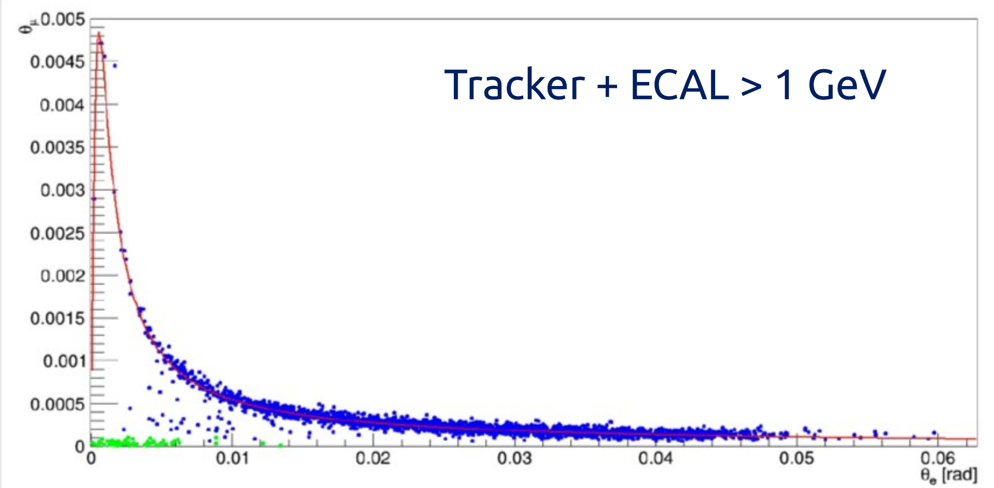
GEANT4 simulations

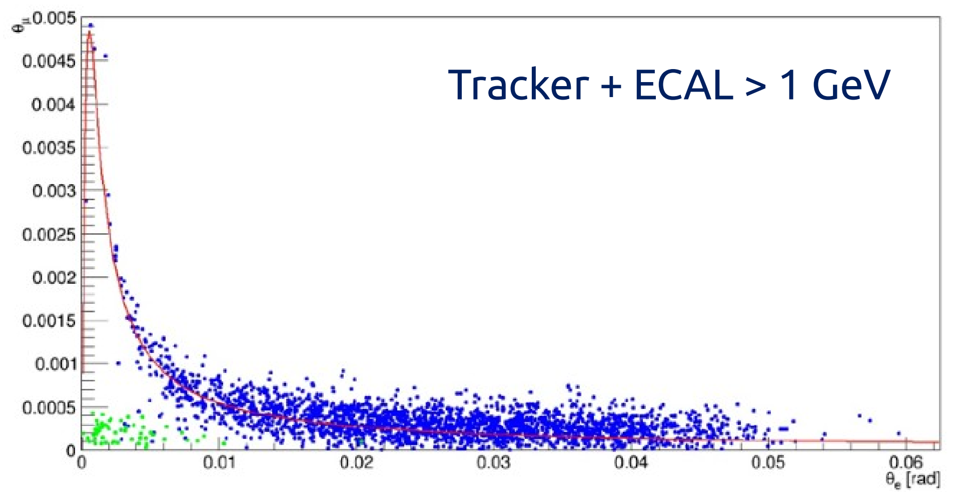
TB2017 (resolution ~7μm)

TB2018 (resolution ~40μm)

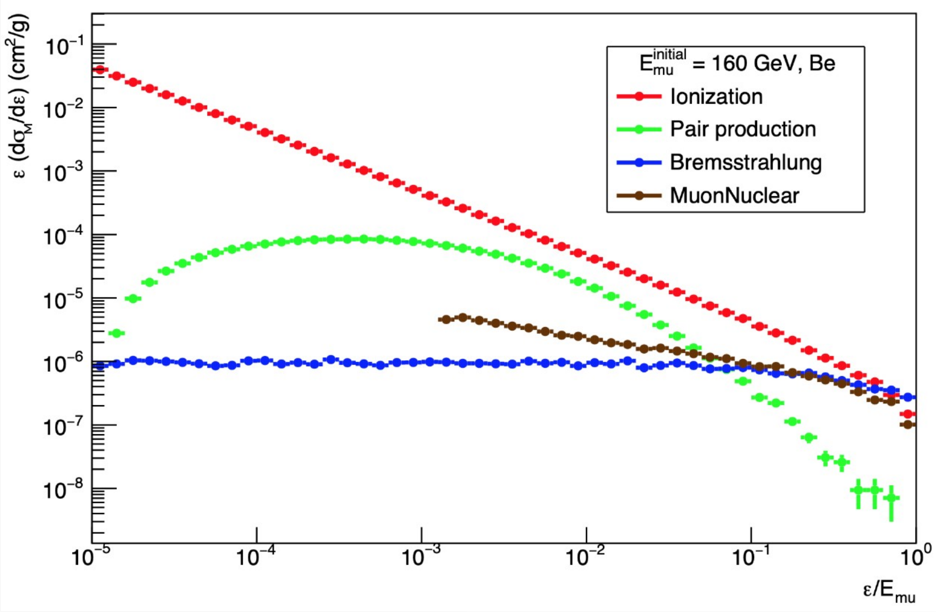


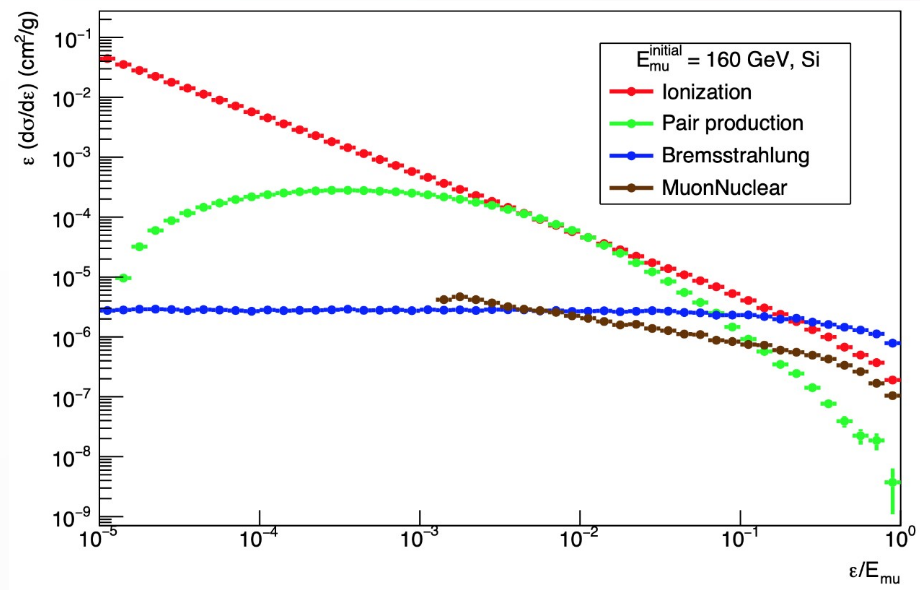






Backgrounds





MESMER

- $\mu e^- \to \mu e^- \gamma$
- $\mu e^- \to \mu e^- e^+ e^-$
- $\mu N \to \mu N e^+ e^-$

GEANT4

- $\mu N \to \mu N \gamma$
- $\mu N \to \mu X$