

IPPP Seminar

MUonE

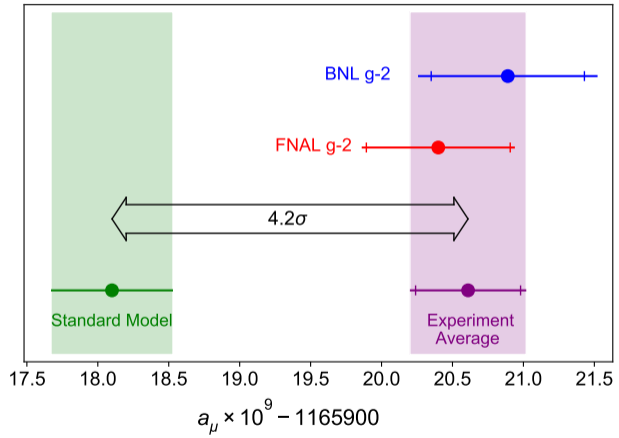
μ -e scattering at 10ppm

Yannick Ulrich











IPPP, University of Durham

10 MARCH 2023

most precise measurement of $g - 2$

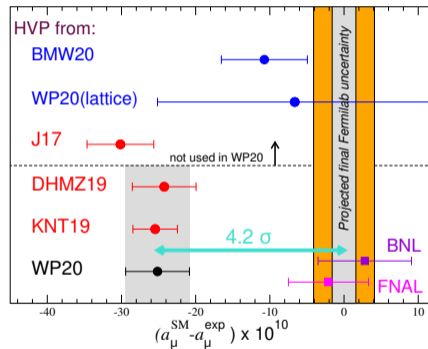


⇒ needs precise theory

	value	diagrams
QED 1-loop	$\alpha/2\pi = 116\,140\,973$	
QED 2-loop	-177 231	 
QED 3-loop	1 480	 
more QED	-5	+ 3 others + 1 conspiracy theory + 70 others
EW	153	 
HVP	6 845(40)	 
HLbL	92(17)	
total	116 591 810(43)	
FNAL+BNL	116 592 062(40)	

largest source of uncertainty & non-perturbative

- historically: using **dispersive** data (see next slide)
- \Rightarrow 4.2σ BSM potential
- lattice** only recently good enough
- BMW20** doesn't require BSM in $g - 2$
- \Rightarrow this problem is bigger than $g - 2$!
- more input is required

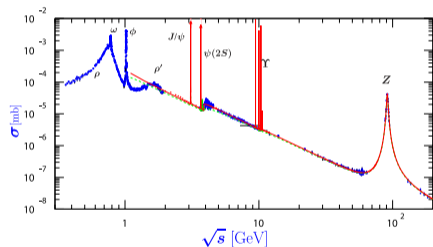


using optical theorem $s > 0$

- measure $ee \rightarrow \text{hadrons}$
- remove radiative corrections
- extrapolate to $s \rightarrow \infty$ using pQCD
- integrate over s

$$a_\mu \supset \int_{4m_\pi^2}^{\infty} ds \left(K(s) \right) \text{ [Diagram: a vertex with two lines, a wavy line, and a shaded semi-circle]$$

- most of the **uncertainty** comes from $s \lesssim 1 \text{ GeV}$

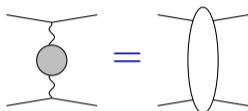


measure low Q^2 regions

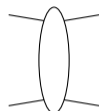
- instead measure in t -channel, i.e. space-like
- no resonances \rightarrow much cleaner signal
- HVP is loop-induced \rightarrow much smaller signal ($10^{-3} \times \text{LO}$)
- competitive extraction @ 10^{-2}

\Rightarrow goal for MUonE: measure $e\mu \rightarrow e\mu$ @ 10^{-5}

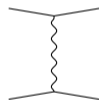
$$a_\mu \supset \int_0^1 dx \left(K' \left(t = \frac{m_\mu^2 x^2}{x-1} \right) \text{ [diagram] } \right)$$



=



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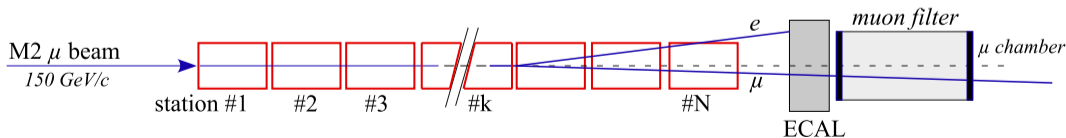
textbook QED

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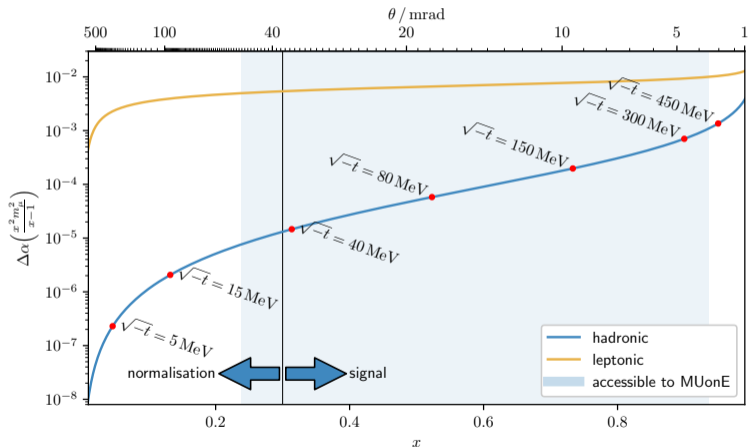
QED

5+ years,
4+ workshops,
34+ authors

- scattering μ of low- Z material (${}_4\text{Be}$)
 - pure t -channel $-s \simeq Q^2 \simeq 0$
- \Rightarrow high $s \leftrightarrow$ measure more of the curve
- beam energy needs to be quite high $E_\mu \simeq 160 \text{ GeV}$
- \Rightarrow M2 muon beam at CERN North Area
- main measurement: θ_e, θ_μ
 - + E_{beam} for calibration
 - + E_μ for particle ID



cancel systematic effects $\left(\frac{d\sigma}{d\theta}\right)_{\text{sig}} / \left(\frac{d\sigma}{d\theta}\right)_{\text{norm}}$



5 MUonE (adjacent) theory workshops over 5+ years



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	problem	solution	what?	doable up to?
①	lots of masses	massification	expand in m_e^2/Q^2	LP, two-loop
②	numerical issues in real corrections	NTS stabilisation	expand in $E_\gamma/\sqrt{Q^2}$	NLP, two-loop
③		jettification	expand in $\cos\theta \rightarrow 1$	LP, one-loop
	phase space	FKS ^ℓ	YFS-inspired subtraction scheme	all-orders

- NNLO double-boxes: ①
- NNLO real-virtual: ②
- N³LO real-virtual-virtual: ①, ②, ③

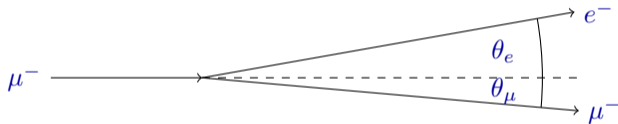


implemented in MCMULE v0.4.2

side note: new manual, let us know what you think!

<https://mule-tools.gitlab.io/manual/>

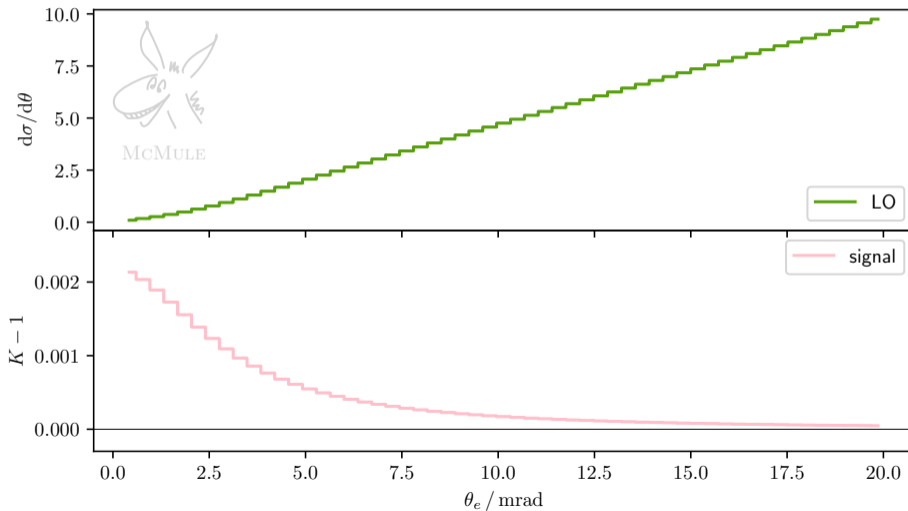
- $\mu^- e^- \rightarrow \mu^- e^-$

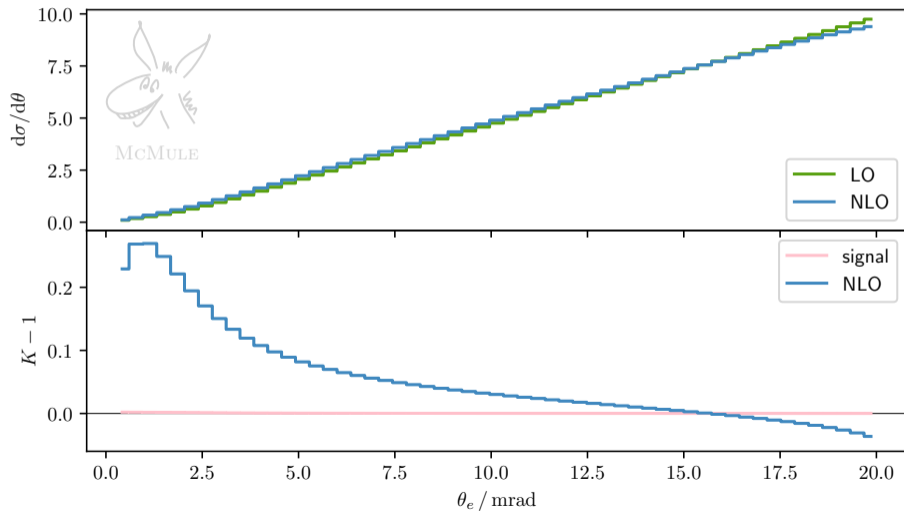


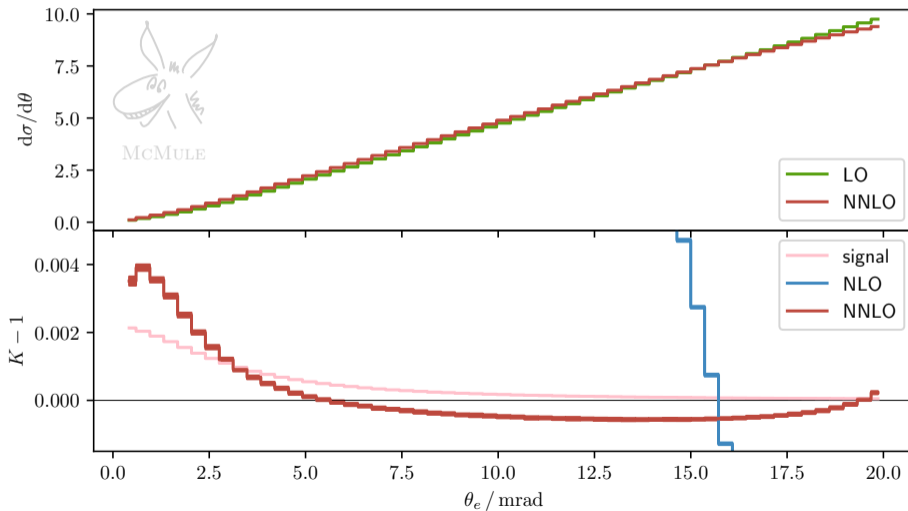
- S1: $E_e > 1 \text{ GeV}$, $\theta_\mu > 0.3 \text{ mrad}$
- run for 2.5 CPU yr
(290 kWh energy / 3.5 kgCO₂e)

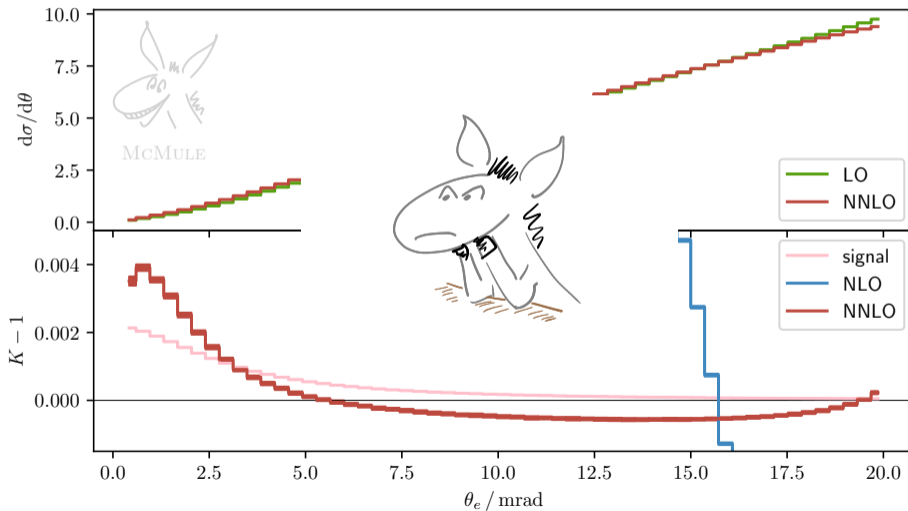


all results and data: <https://mule-tools.gitlab.io/user-library//mu-e-scattering/muone-full-legacy/>



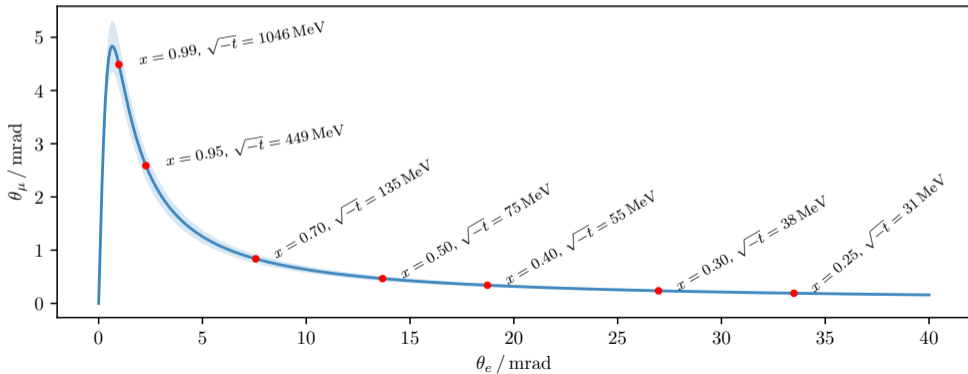


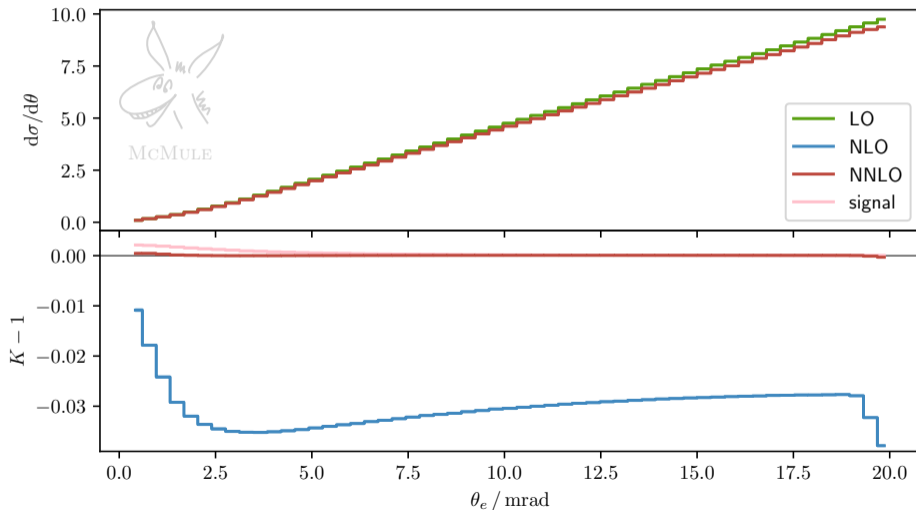


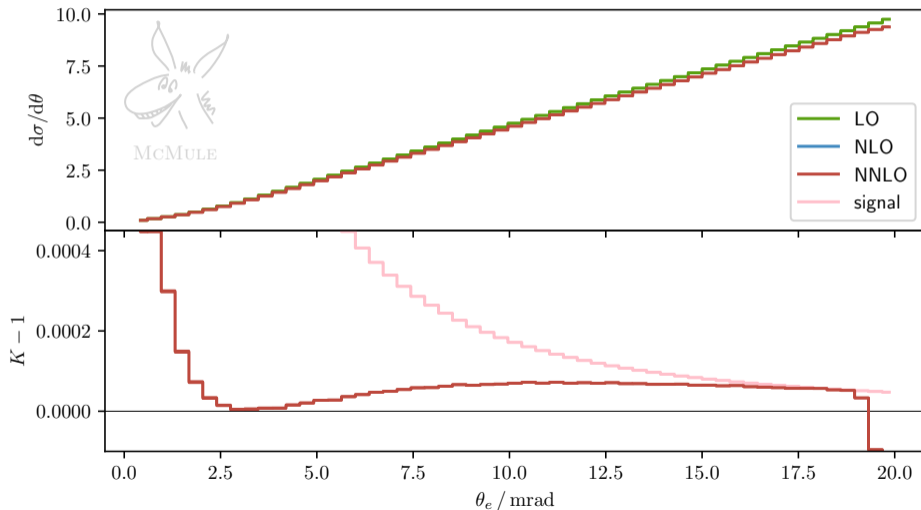


this clearly isn't working

- at this rate ($\sim 10\%$ NLO, $\sim 0.1\%$ NNLO), we would need N⁴LO to reach 10^{-5}
- most of this is due to hard radiation
- S2: same as S1 + needs to be in the band







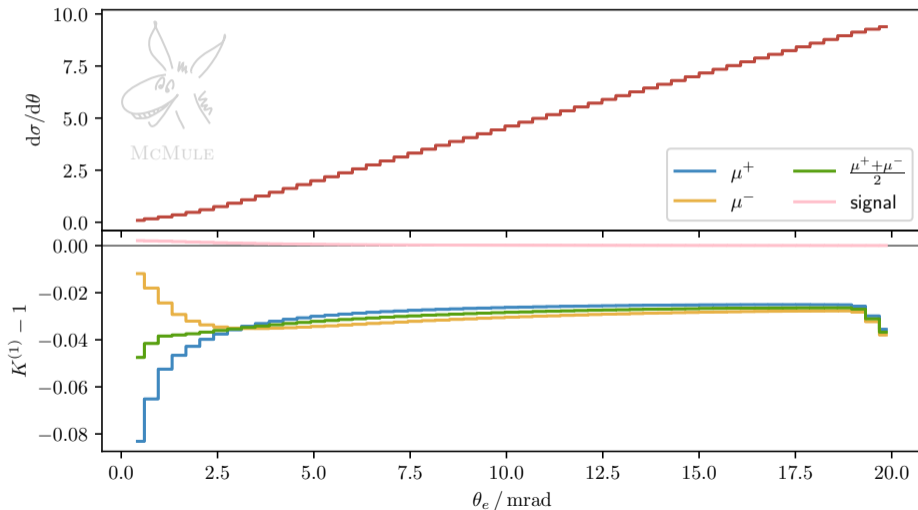
the beam can do both μ^+ and μ^-

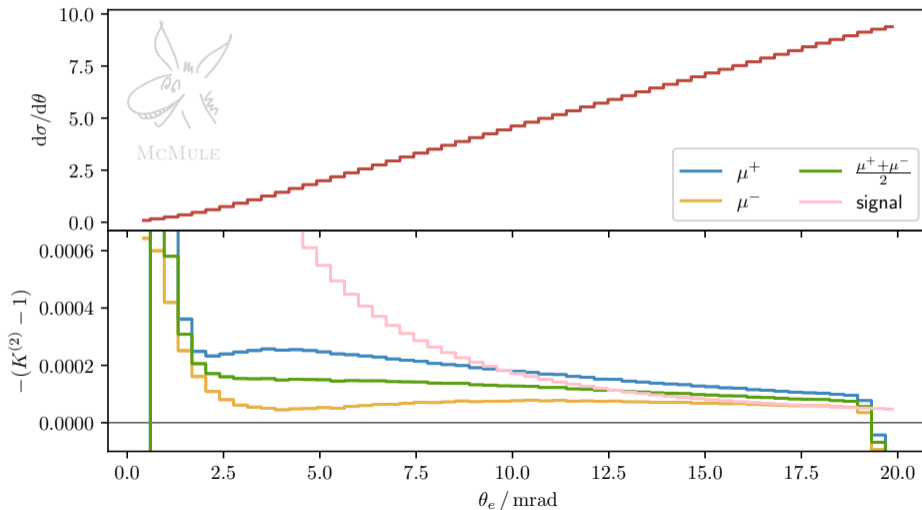
$$\sigma \sim Q_e Q_\mu \left(Q_e^2 Q_\mu^1 \times \text{[diagram]} \right.$$

$$+ \underbrace{Q_e^3 Q_\mu^1 \times \text{[diagram]}}_{\text{easy}} + \underbrace{Q_e^2 Q_\mu^2 \times \text{[diagram]}}_{\text{okay}} + \underbrace{Q_e^1 Q_\mu^3 \times \text{[diagram]}}_{\text{easy}}$$

$$+ \underbrace{Q_e^5 Q_\mu^1 \times \text{[diagram]}}_{\text{easy}} + \underbrace{Q_e^4 Q_\mu^2 \times \text{[diagram]}}_{\text{really difficult}} + \underbrace{Q_e^3 Q_\mu^3 \times \text{[diagram]}}_{\text{really difficult}} + \underbrace{Q_e^2 Q_\mu^4 \times \text{[diagram]}}_{\text{really difficult}} + \underbrace{Q_e^1 Q_\mu^5 \times \text{[diagram]}}_{\text{easy}} \left. \right)$$

- proposal $\sigma(\mu^+) + \sigma(\mu^-)$
- ⇒ some of the difficult stuff cancels





- ✓ first NNLO with multiple external masses
- ✓ event generation (not in MCMULE)
- ✓ iterative HVP extraction procedure
- ✓ precision now: $\mathcal{O}(10^{\{-3,-4\}})$, goal: $\mathcal{O}(10^{-5})$
 - lots of optimisation still possible (observable, beam, polarisation etc)
 - resummation (analytic & parton shower)
 - partial N³LO ($Q_e^8 Q_\mu^2$)





McMULE

mule-tools.gitlab.io

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