IPPP Seminar

MUonE

μ-e scattering at 10ppm

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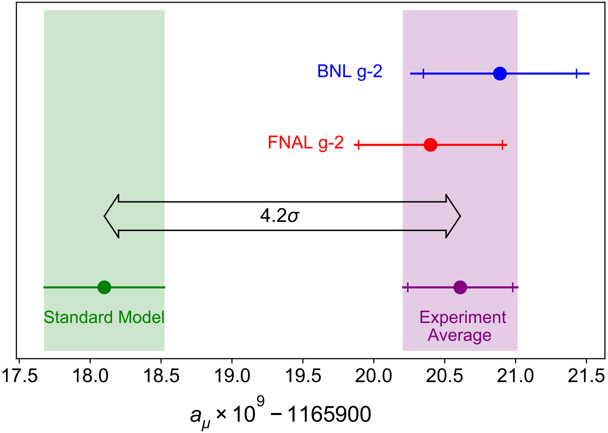
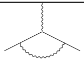
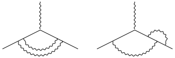
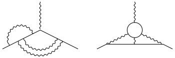
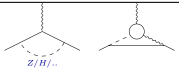
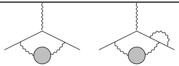
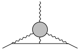
most precise measurement of $g-2$



$\Rightarrow$ needs precise theory

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

largest source of uncertainty & non-perturbative

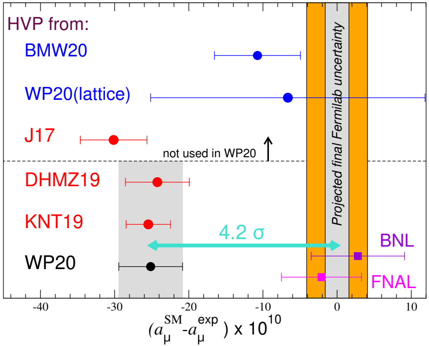
- historically: using dispersive data (see next slide)

$\Rightarrow$ 4.2σ BSM potential

- lattice only recently good enough
- BMW20 doesn't require BSM in $g-2$

$\Rightarrow$ this problem is bigger than $g-2$!

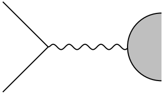
- more input is required



using optical theorem $s > 0$

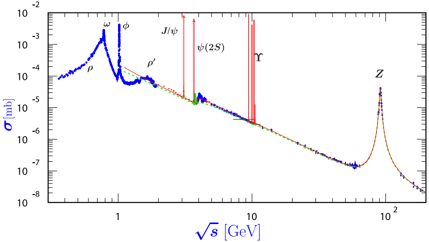
- measure $ee \to$ hadrons
- remove radiative corrections
- extrapolate to $s \to \infty$ using pQCD
- integrate over s

$$a_\mu \supset \int_{4m_\pi^2}^{\infty} \mathrm{d}s \Big(K(s)$$



$$\Big)$$

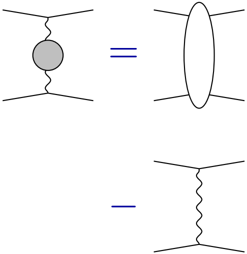
- most of the uncertainty comes from $s \lesssim 1\,\mathrm{GeV}$



measure low Q^2 regions

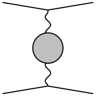
- instead measure in t-channel, i.e. space-like
- no resonances $\rightarrow$ much cleaner signal
- HVP is loop-induced $\rightarrow$ much smaller signal ($10^{-3} \times \mathrm{LO}$)
- competitive extraction @ 10^{-2}

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



textbook QED

$$a_\mu \supset \int_0^1 \mathrm{d}x \Bigg(K'\Big(t = \frac{m_\mu^2 x^2}{x-1}\Big)$$



$$\Bigg) \quad - \ \mathrm{QED}$$

5+ years,
4+ workshops,
34+ authors

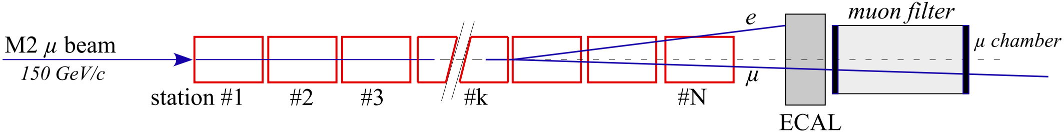
- scattering μ of low-Z material (${}_4\mathrm{Be}$)
- pure t-channel $-s \simeq Q^2 \simeq 0$

$\Rightarrow$ high $s \leftrightarrow$ measure more of the curve

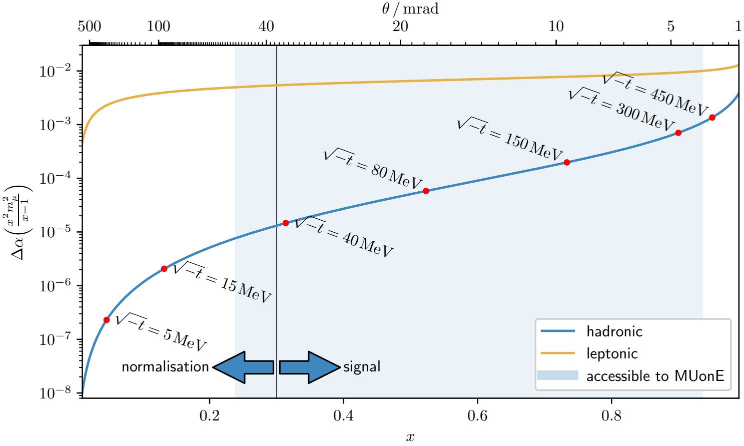
- beam energy needs to be quite high $E_\mu \simeq 160\,\mathrm{GeV}$

$\Rightarrow$ M2 muon beam at CERN North Area

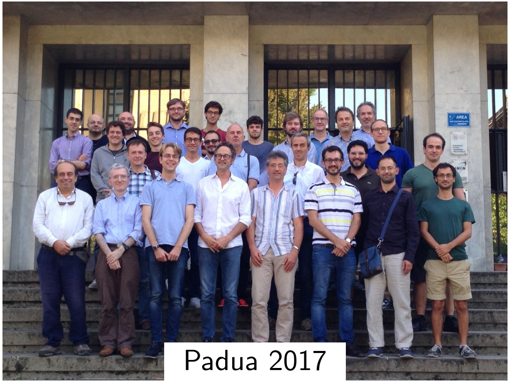
- main measurement: θ_e, θ_μ
  - $+$ E_{beam} for calibration
  - $+$ E_μ for particle ID



cancel systematic effects $\Big(\mathrm{d}\sigma/\mathrm{d}\theta\Big)_{\text{sig}}\Big/\Big(\mathrm{d}\sigma/\mathrm{d}\theta\Big)_{\text{norm}}$

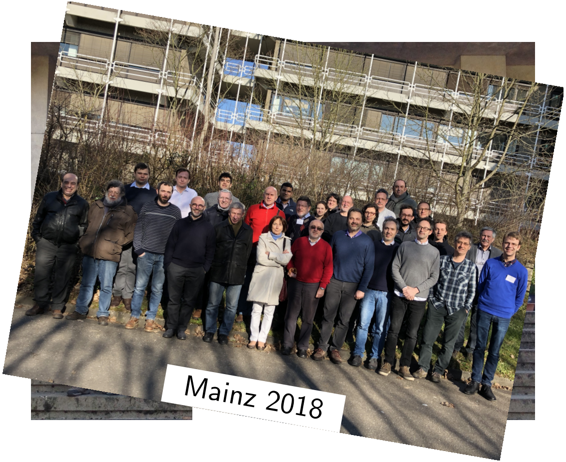


5 MUonE (adjacent) theory workshops over 5+ years



Padua 2017

5 MUonE (adjacent) theory workshops over 5+ years



5 MUonE (adjacent) theory workshops over 5+ years

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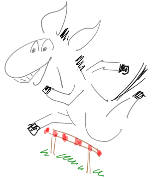
	problem	solution	what?	doable up to?
①	lots of masses	massification	expand in m_e^2/Q^2	LP, two-loop
②	numerical issues in real corrections	NTS stabilisation	expand in $E_\gamma/\sqrt{Q^2}$	NLP, two-loop
③		jettification	expand in $\cos\theta \to 1$	LP, one-loop
	phase space	FKS$^\ell$	YFS-inspired subtraction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

- NNLO double-boxes: ①
- NNLO real-virtual: ②
- N^{3}LO real-virtual-virtual: ①, ②, ③

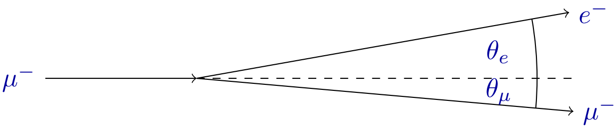


implemented in McMule v0.4.2

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

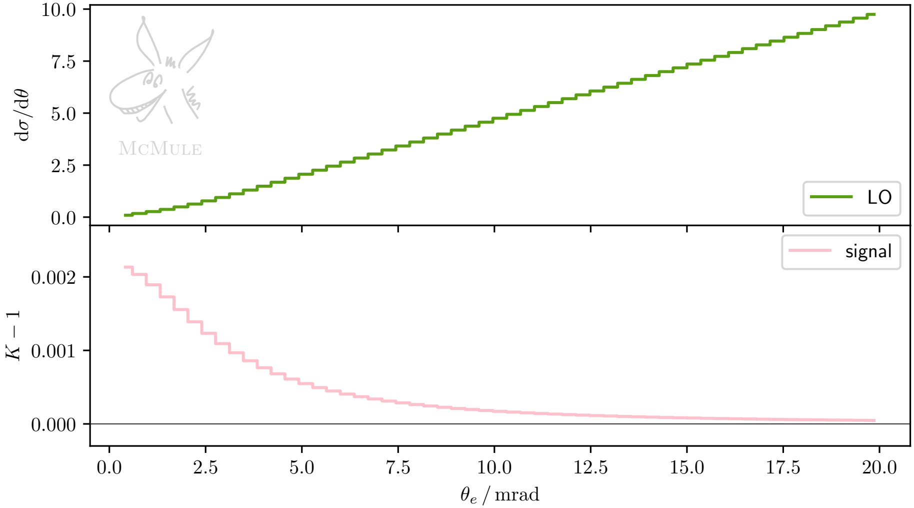
`https://mule-tools.gitlab.io/manual/`

- $\mu^- e^- \to \mu^- e^-$



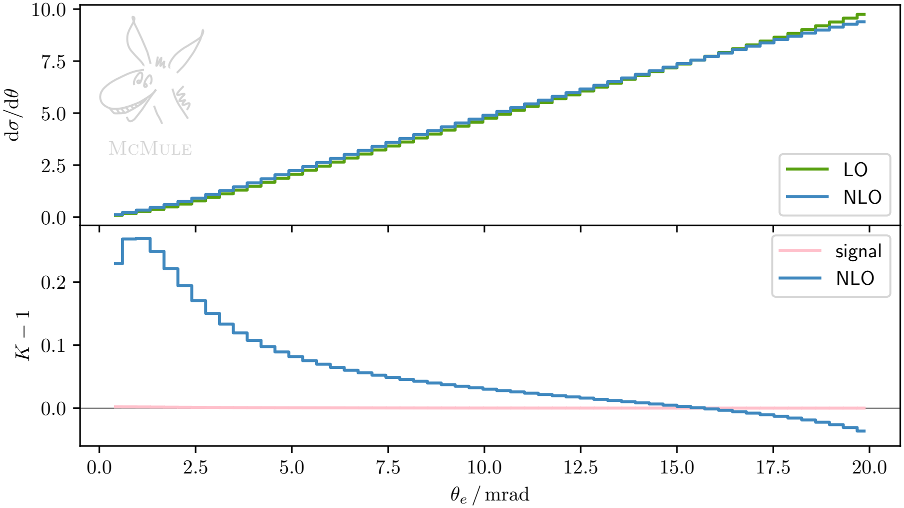
- `S1`: $E_e > 1\,\mathrm{GeV}$, $\theta_\mu > 0.3\,\mathrm{mrad}$
- run for 2.5 CPU yr
  (290 kWh energy / 3.5 kgCO2e)

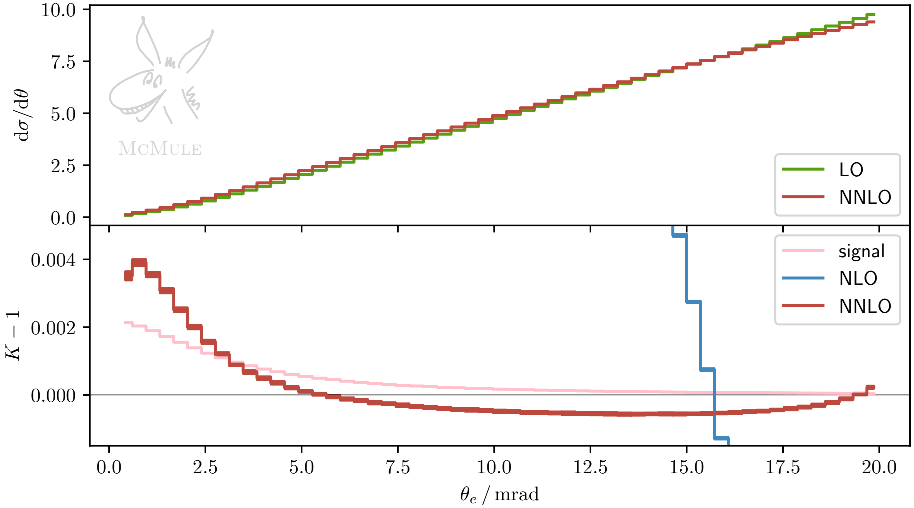
all results and data: `https://mule-tools.gitlab.io/user-library//mu-e-scattering/muone-full-legacy/`

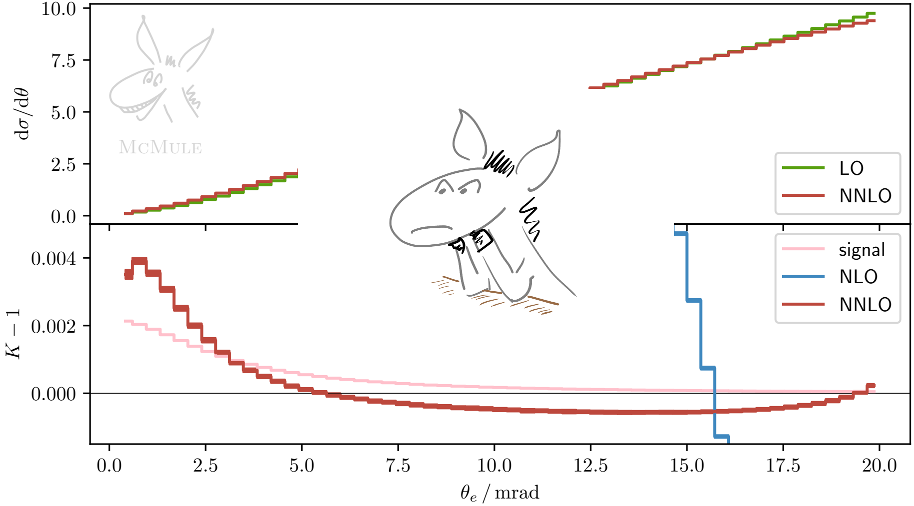


10.0
7.5
5.0
2.5
0.0
$d\sigma/d\theta$
McMule
LO
signal
0.002
0.001
0.000
$K-1$
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
θ_e / mrad

S1 θ_e spectrum



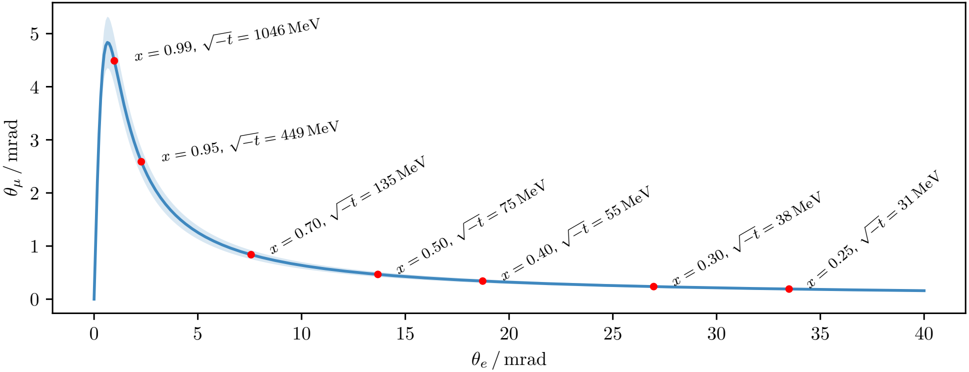

10.0
7.5
5.0
2.5
0.0
$d\sigma/d\theta$
McMule
LO
NNLO
0.004
0.002
0.000
$K-1$
signal
NLO
NNLO
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
θ_e / mrad



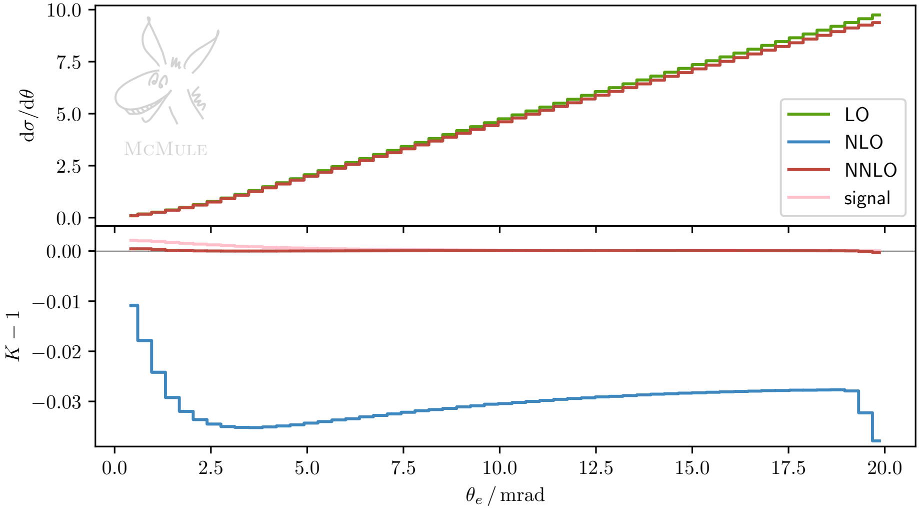
MCMULE
LO
NNLO
signal
NLO
NNLO
dσ/dθ
K − 1
θe / mrad
10.0
7.5
5.0
2.5
0.0
0.004
0.002
0.000
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

this clearly isn't working

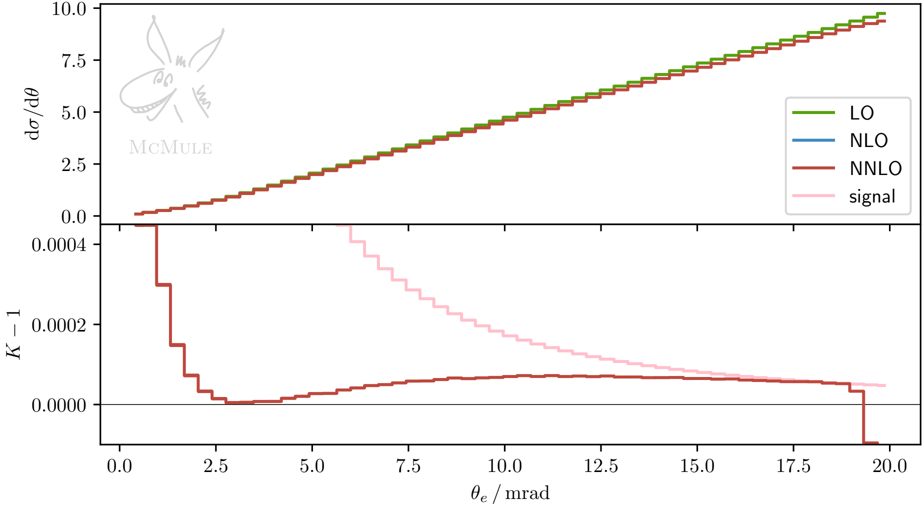
- at this rate ($\sim 10\%$ NLO, $\sim 0.1\%$ NNLO), we would need N^{4}LO to reach 10^{-5}
- most of this is due to hard radition
- S2: same as S1 + needs to be in the band



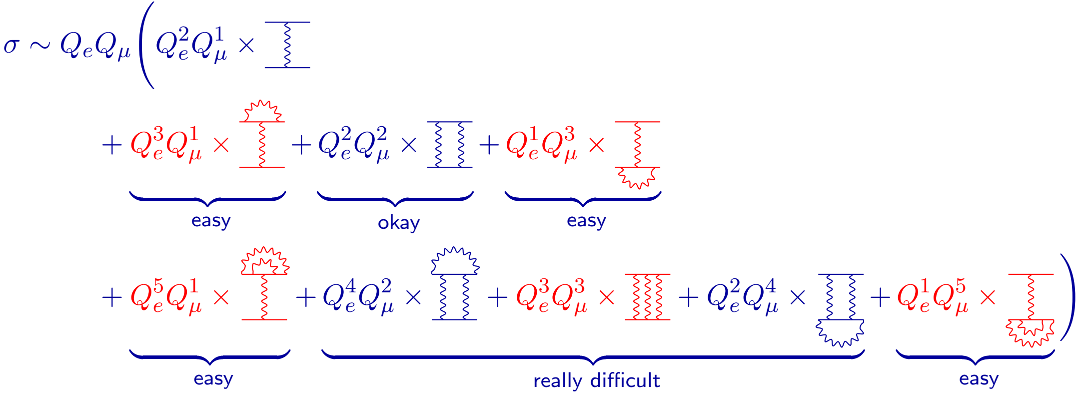
S2 θ_e spectrum



S2 θ_e spectrum

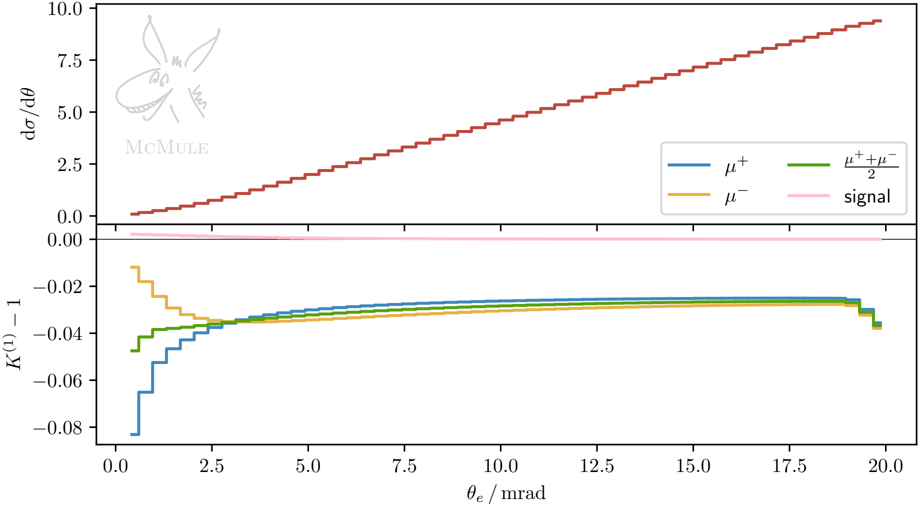


the beam can do both μ^+ and μ^-



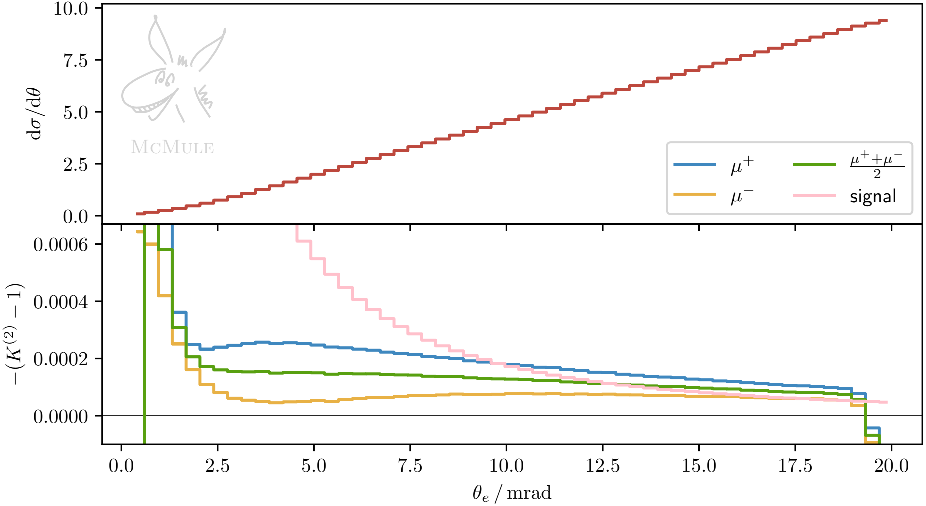
- proposal $\sigma(\mu^+) + \sigma(\mu^-)$

$\Rightarrow$ some of the difficult stuff cancels



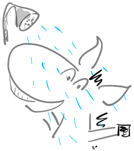
MCMULE
10.0
7.5
5.0
2.5
0.0
$d\sigma/d\theta$
μ^+
μ^-
$\frac{\mu^+ + \mu^-}{2}$
signal
0.00
−0.02
−0.04
−0.06
−0.08
$K^{(1)} - 1$
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
θ_e / mrad

playing with the beam



NNLO done, much left to do

- ✓ 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 N^{3}LO ($Q_e^8 Q_\mu^2$)



f.l.t.r.: F.Hagelstein (Mainz), A.Coutinho (IFIC), N.Schalch (Bern), L.Naterop (Zurich & PSI), S.Kollatzsch (Zurich & PSI), A.Signer (Zurich & PSI), M.Rocco (PSI), T.Engel (Freiburg), V.Sharkovska (Zurich & PSI), Y.Ulrich (Durham), A.Gurgone (Pavia)
not pictured: P.Banerjee (IIT Guwahati), D.Moreno (PSI), D.Radic (Tubingen)

McMule

mule-tools.gitlab.io