MUonE

Current status & future

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INFN
Istituto Nazionale di Fisica Nucleare

3rd Plenary Workshop of
the Muon g-2 Theory Initiative
INT-19-74W

Institute for Nuclear Theory, University of Washington, Seattle - September 9-13, 2019

Outline

- Introduction to the **MUonE project**
- Experimental status & Theory activity
- QED radiative corrections to $\mu e \to \mu e$ (NLO phenomenology)
- Plans for the future
- Fitting strategy
- Conclusions & Outlook

Relevant literature:

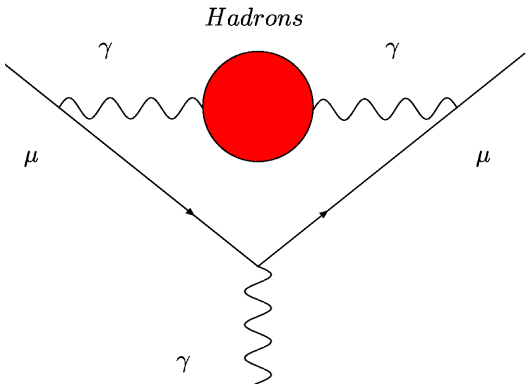
- **Letter of Intent**, June 2019, under review by the CERN SPSC
- G. Abbiendi *et al.*,
  Measuring the leading hadronic contribution to the muon g-2 via μe scattering
  Eur. Phys. J. C **77** (2017) no.3, 139 - `arXiv:1609.08987 [hep-ex]`
- C. M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni,
  A new approach to evaluate the leading hadronic corrections to the muon g-2
  Phys. Lett. B **746** (2015) 325 - `arXiv:1504.02228 [hep-ph]`

Master formula

- Standard approach

$$a_\mu^{\text{HLO}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^0_{e^+e^-\to\text{had}}(s)$$

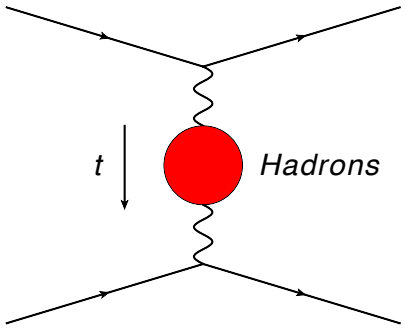
$$K(s) = \int_0^1 \frac{x^2(1-x)}{x^2+(1-x)\frac{s}{m_\mu^2}}$$



- Alternatively (exchanging s and x integrations in a_μ^{HLO})

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

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



Lautrup, Peterman, De Rafael, Phys. Rept. 3 (1972) 193

★ $\Delta\alpha_{\text{had}}(t)$ (and a_μ^{HLO}) can be directly measured in a (single) experiment involving a space-like scattering process

CC, Passera, Trentadue, Venanzoni PLB 746 (2015) 325

Arbuzov *et al.* EPJC 34 (2004) 267

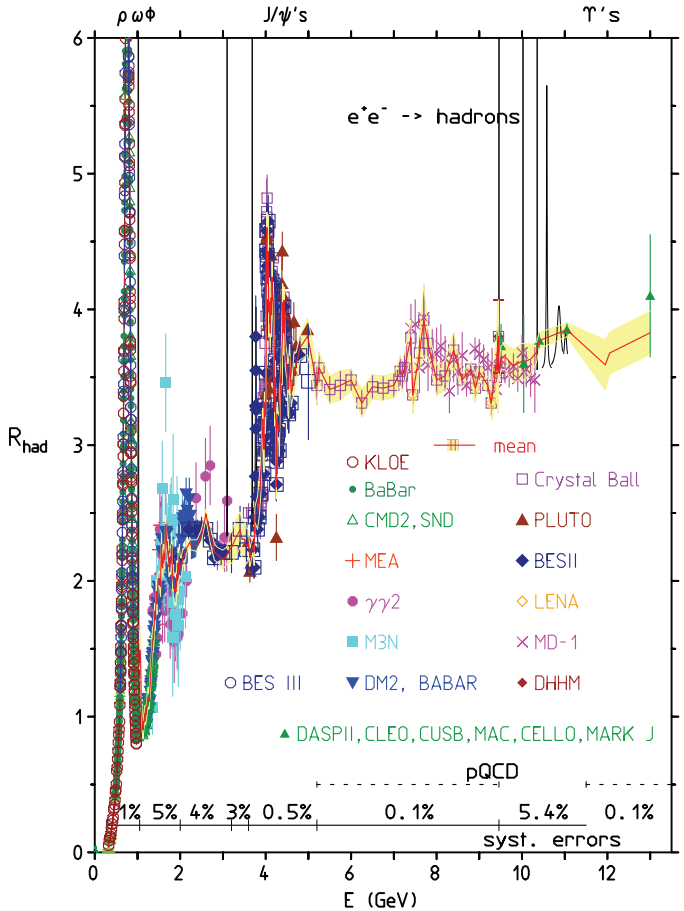
Abbiendi *et al.* (OPAL) EPJC 45 (2006) 1

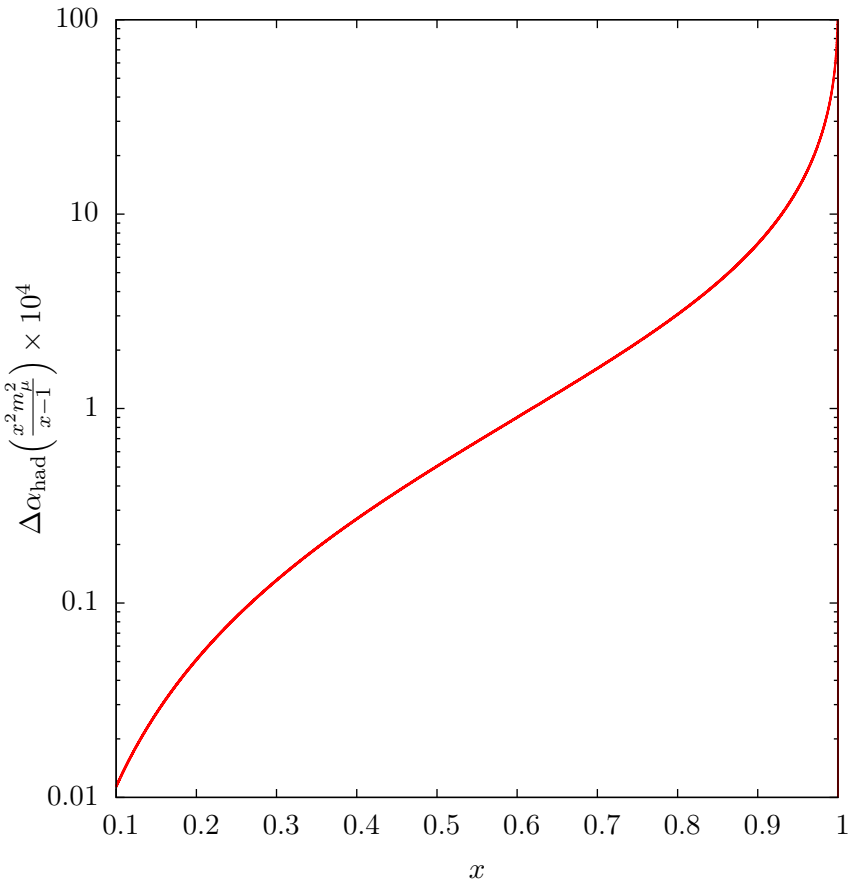
★ **Still a data-driven evaluation of a_μ^{HLO}, but with space-like data**

From time-like to space-like evaluation of $a_\mu^{\rm HLO}$

Time-like $\mapsto$ **Space-like**

F. Jegerlehner, EPJ Web Conf. 118





Smooth function

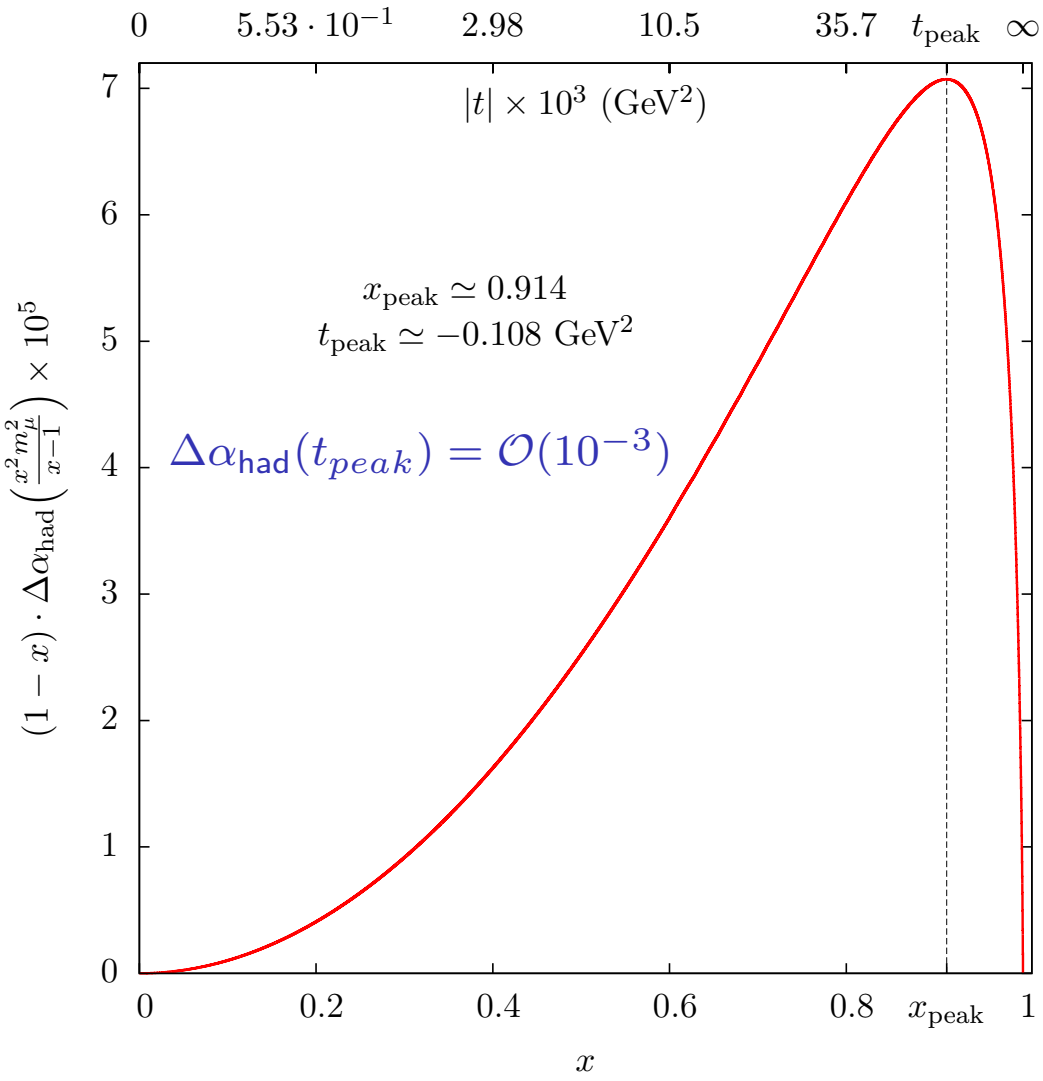
CC, Passera, Trentadue, Venanzoni PLB 746 (2015) 325

$\mapsto$ **Time-like:** combination of many experimental data sets,
control of RCs better than $\mathcal{O}(1\%)$ on hadronic channels required.

$\mapsto$ **Space-like:** in principle, one single experiment,
it's a one-loop effect, very high accuracy needed.

General considerations

$\rightsquigarrow$ Integrand function $(1-x)\Delta\alpha_{\text{had}}[t(x)]$



$x_{\text{peak}} \simeq 0.914 \qquad t_{\text{peak}} \simeq -0.108\ \text{GeV}^2 \simeq -(329\ \text{MeV})^2$

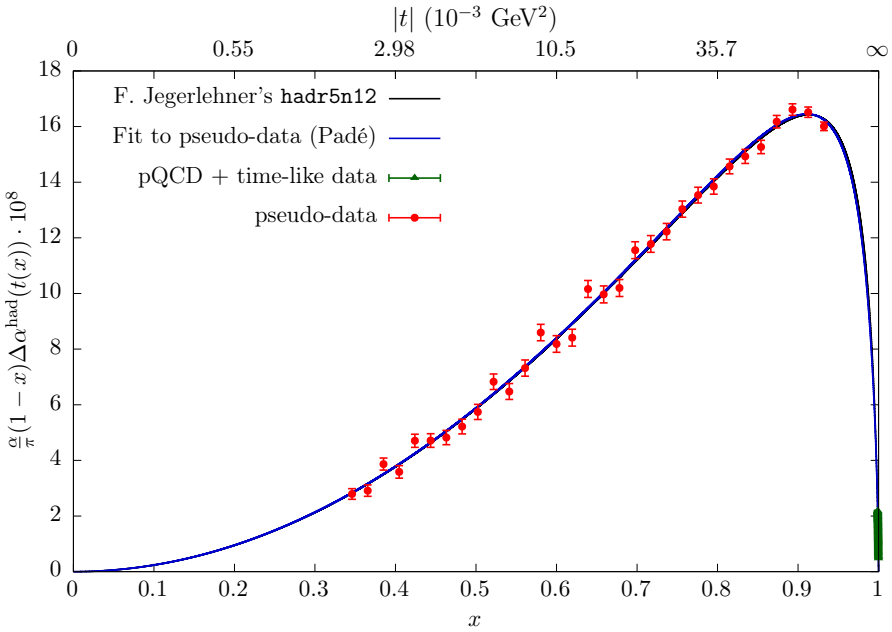
First idea: exploit Bhabha process

- To get $\Delta\alpha_{\rm had}(t)$, the goal is to measure the (absolute) running of $\alpha_{\rm QED}(t)$

$\rightarrow$ **The idea:** Bhabha events at e^+e^- (low-energy) colliders **[original proposal]**

CC, Passera, Trentadue, Venanzoni PLB 746 (2015) 325

$$\alpha(t) = \frac{\alpha}{1 - \Delta\alpha_{\rm other}(t) - \Delta\alpha_{\rm had}(t)} \qquad \Delta\alpha_{\rm had}(t) = 1 - \Delta\alpha_{\rm other}(t) - \frac{\alpha}{\alpha(t)}$$



Strategy:

- $\mapsto$ measure $\Delta\alpha_{\rm had}(t)$ within the exp. range
- $\mapsto$ if needed, get large $|t|$ values from elsewhere (time-like data, lattice) or extrapolate from measured region

  see also next talk by Marina
- $\mapsto$ fit $\Delta\alpha_{\rm had}(t)$
- $\mapsto$ integrate to get $a_\mu^{\rm HLO}$

Roughly, to be competitive with the current evaluations, $\Delta\alpha_{\rm had}(t)$ needs to be know at the sub-% level

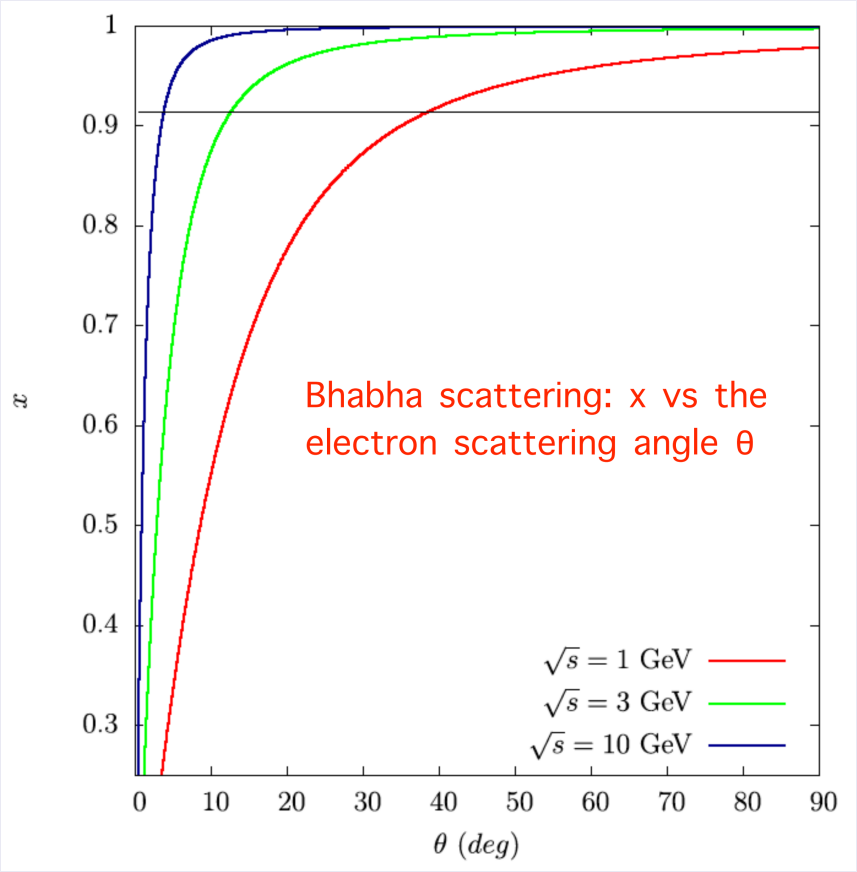
Original proposal: using Bhabha

CC, Passera, Trentadue, Venanzoni PLB 746 (2015) 325

$$\Delta\alpha_{\text{had}}(t_{peak}) = \mathcal{O}(10^{-3})$$

$$\frac{1}{2}\frac{\delta\sigma}{\sigma} \simeq \frac{\delta\alpha}{\alpha} \simeq \delta\Delta\alpha_{\text{had}}$$

$\rightsquigarrow$ in order to get $\Delta\alpha_{\text{had}}$ at $\%$, σ must be under control at 0.001%, *i.e.* 10^{-5}



Bhabha scattering promising, but

- "contamination" from s-channel (especially at large angles);
- higher energy colliders require covering lower angles $\rightarrow$ difficult.

$\mu e \to \mu e$ scattering in fixed target experiment

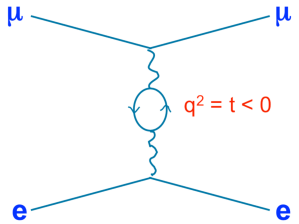
Abbiendi *et al.* EPJC 77 (2017) no.3, 139

Part of the CERN *Physics Beyond Colliders* program, **LoI under review by the SPSC**

Muon-electron scattering ($\mu e \to \mu e$) on a low-Z target (Be or C) looks an ideal process

⋆ it is a "pure" t-channel process →

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha}\right|^2$$



↦ A 150 GeV high-intensity ($\sim 10^7$ μ's/s) μ beam is available at CERN NA (M2 line)

$s \simeq 0.164\ \mathrm{GeV}^2$ $\quad -0.143 \lesssim t < 0\ \mathrm{GeV}^2$ $\quad 0 < x \lesssim 0.93$ **it spans the integrand peak!**

it can cover with data 87% of the a_μ^{HLO} integral!

Pros:

⋆ highly boosted kinematics

⋆ the same detector and process can be exploited for signal and normalization

⋆ with **2 yrs** of data taking in our proposed setup, **statistically competitive a_μ^{HLO}**

$$\left[\delta a_\mu^{\mathrm{HLO}}/a_\mu^{\mathrm{HLO}}\right]_{\mathrm{stat}} \simeq 0.3\%$$

Cons:

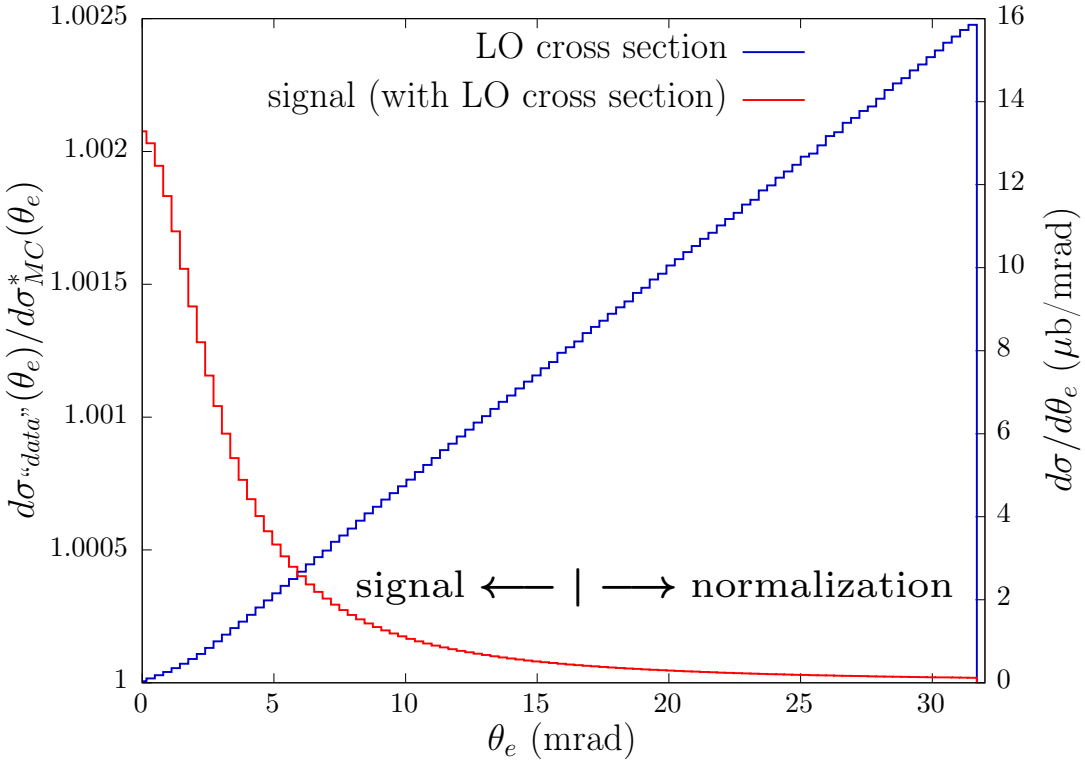
⋆ high accuracy needed: control of systematics at the 10^{-5} level

Our "signal"

$$\text{Our signal} \equiv \frac{dN_{data}(O_i)}{dN_{MC}(O_i)|_{\Delta\alpha_{\text{had}}(t)=0}} \equiv \frac{dN_{data}(O_i)}{dN^*_{MC}(O_i)} =$$

$$= \frac{d\sigma_{data}(O_i)}{d\sigma^*_{MC}(O_i)} = \frac{dN_{data}(O_i)}{N^{norm}_{data}} \times \frac{\sigma^{norm}_{MC}}{d\sigma^*_{MC}(O_i)} \simeq$$

$$\simeq 1 + 2\left[\Delta\alpha_{\text{lep}}(O_i) + \Delta\alpha_{\text{had}}(O_i)\right] \qquad \text{(at LO)}$$



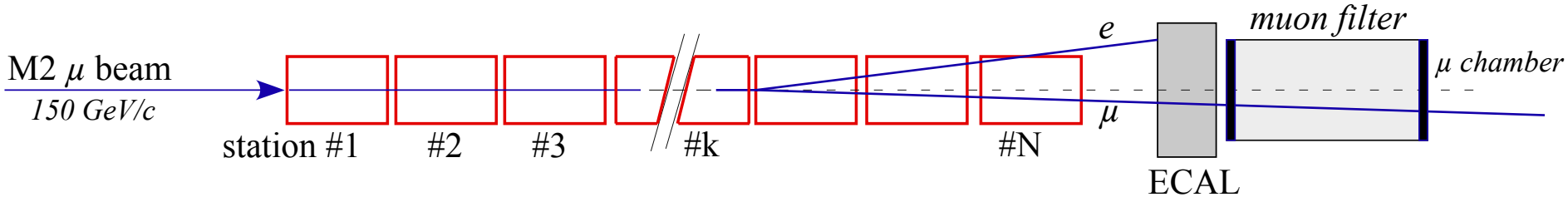
★ **Beyond LO & with apparatus effects, a template fitting procedure must be used**

MUonE proposed apparatus

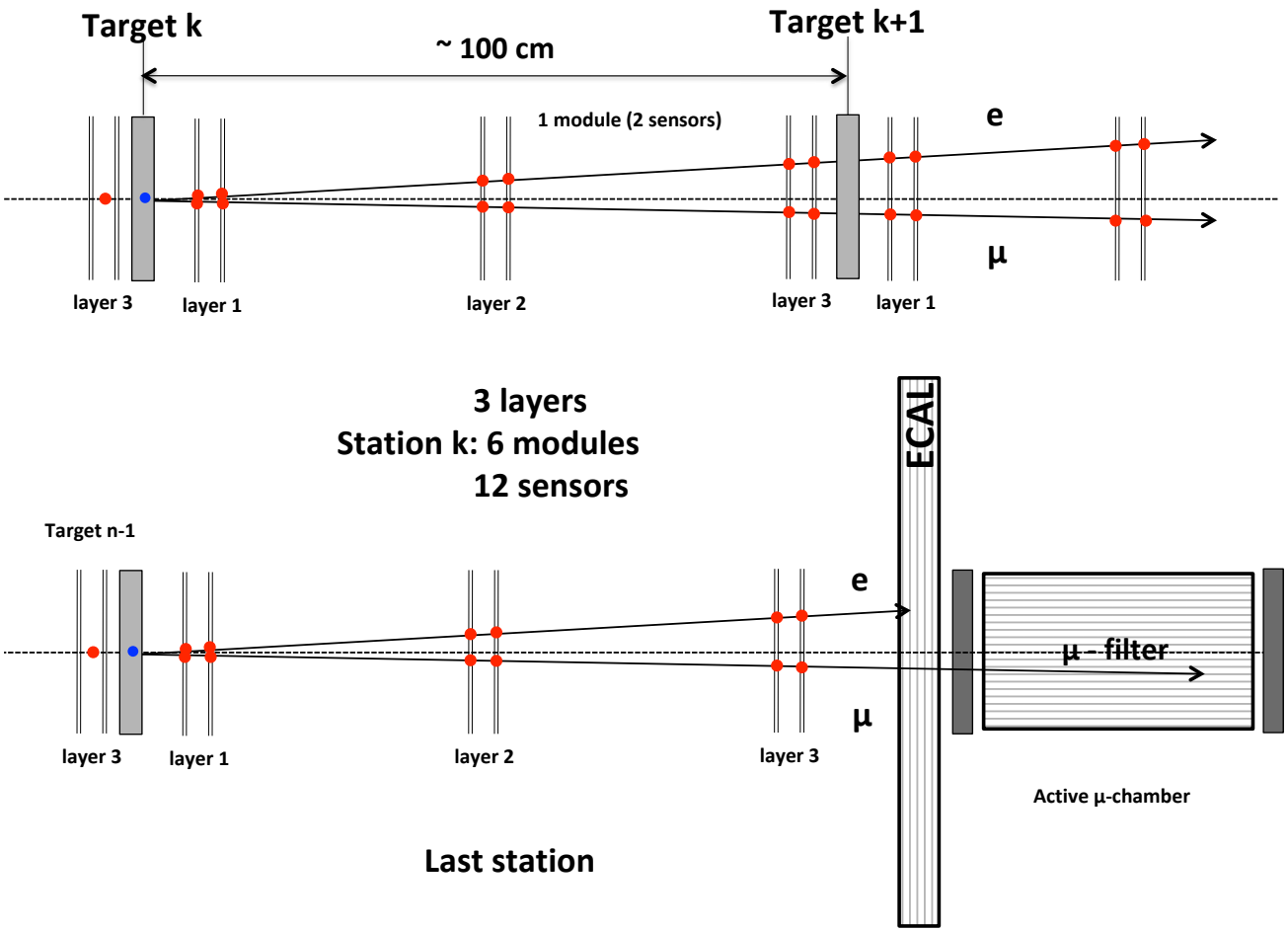
- ⋆ The setup is designed to measure e and μ angles with the highest accuracy
- ⋆ Modular apparatus:

⇝ 60 cm Be target distributed over ~ 40 tracking stations (each 1m-long), in ~ 1.5 cm slices

⇝ ECAL (and eventually μ filter with μ chambers) positioned downstream

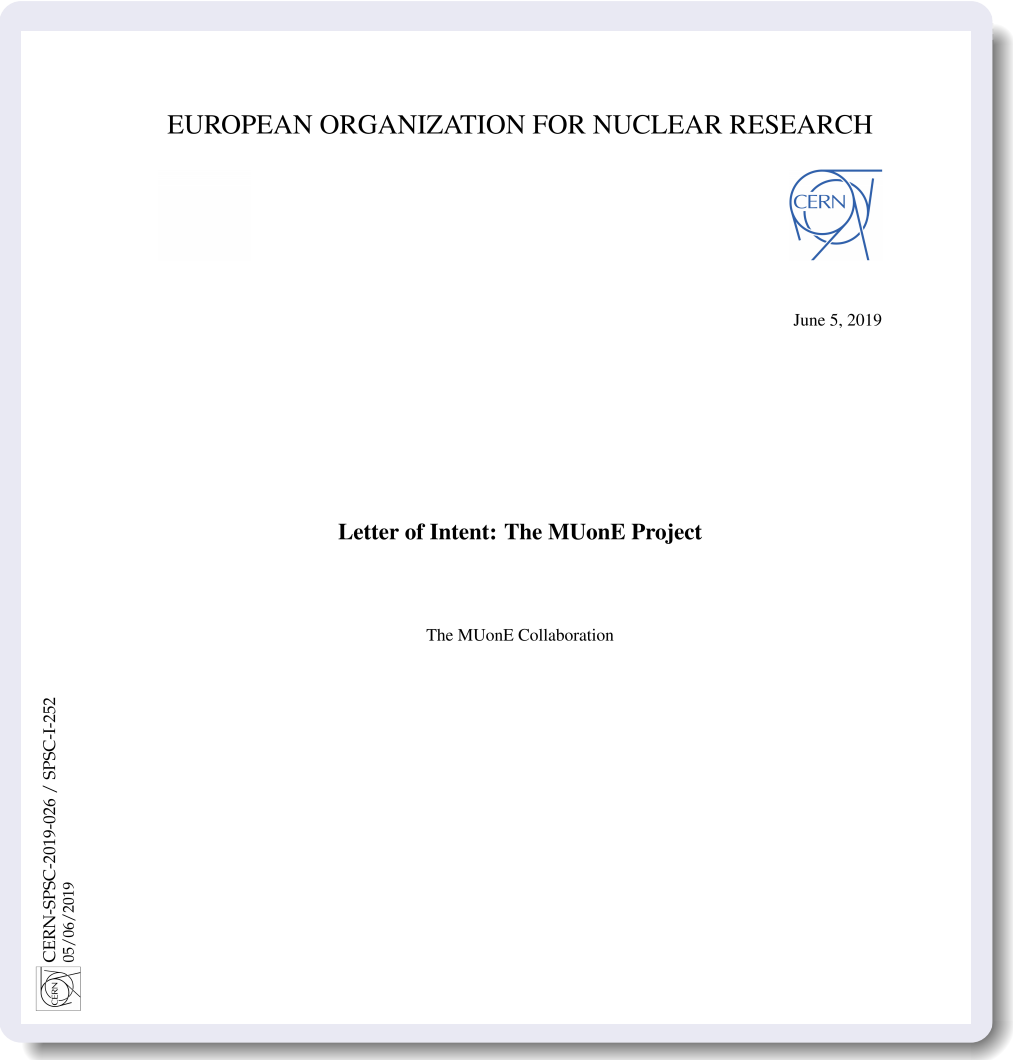


MUonE proposed apparatus (detail)



- Silicon-detector tracking system based on 10cm×10cm strip sensors produced for the CMS Tracker for the HL-LHC upgrade (CMS 2S);
- They have the adequate spacial resolution, can sustain high readout rate (40 MHz) with frontend electronics, not too thick.
  The CMS production schedule is in line with MUonE timescale.

MUonE Letter of Intent



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

June 5, 2019

Letter of Intent: The MUonE Project

The MUonE Collaboration

CERN-SPSC-2019-026 / SPSC-I-252
05/06/2019

Members from
CERN, BINP, Dublin U., IFJ Krakow, Imperial College London, INFN (Bologna, Florence, Milan, Padua, Pavia, Pisa, Trieste), Liverpool U., PSI, Shangai Jiao Teng U., Virginia U.

✓ Letter of Intent submitted in June 2019 to the CERN SPSC.
Available at

`https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf`

Location at CERN M2

- **Between BSM and COMPASS**

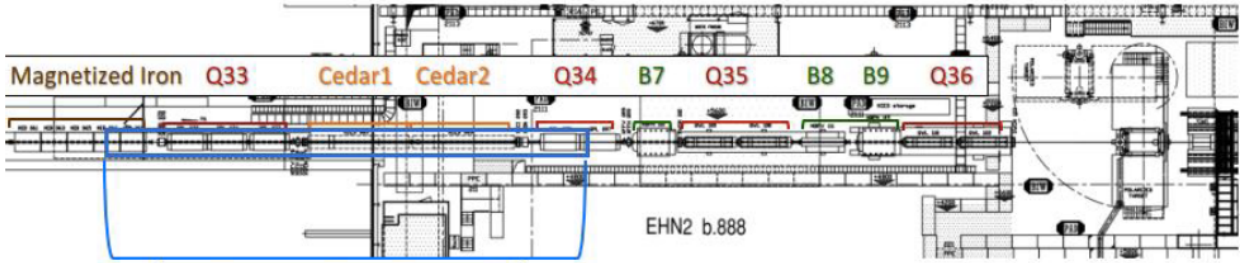
1/ μ-e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

- More upstream of Entrance Area of EHN2 (Proposed by Johannes B. & Dipanwita B.)

- Pro: Could allow running μ-e/μ-p_{Radius} in parallel.

- Questions: will require displacements (also removal) of some M2 components.

- Beam(s) compatibility for μ-e & μ-p_{Radius} : Optic's wise looks OK (see Add. Sl.14 from D.B.)



μ-e Upstream (under-study) ~ 30 m

Σ length required (updated): 35 m targets + trackers + 0.8 m Ecals + 3 m (μ-Filter) ~ 39 m

10

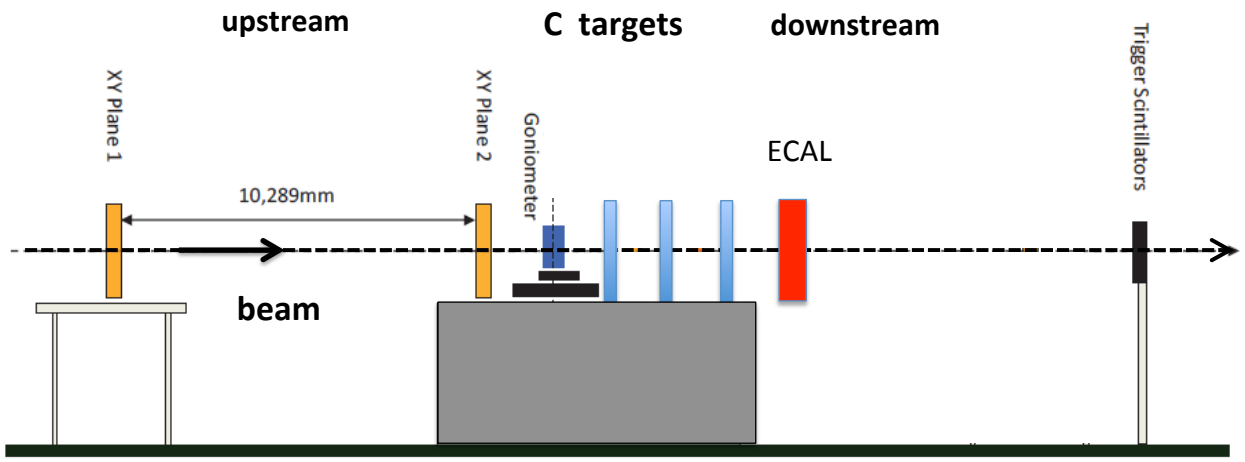
Space available : 40 m upstream COMPASS

30

U. Marconi, talk at FCCP2019

Test Beam 2017: the setup

- We used the UA9 tracking system to record scattering data
- Alignment, tracking, pattern recognition done by ourselves starting from scratch as well as for the Geant4 simulations.
- **The goal**: reach **~1%** in the **core** of the MSC distributions and **few per cent on the tales**



UA9 detector

13

U. Marconi, talk at FCCP2019

- Need to control multiple-scattering effect, studied in 2017 with a test beam
- Results reported in `arXiv:1905.11677`, submitted to JINST

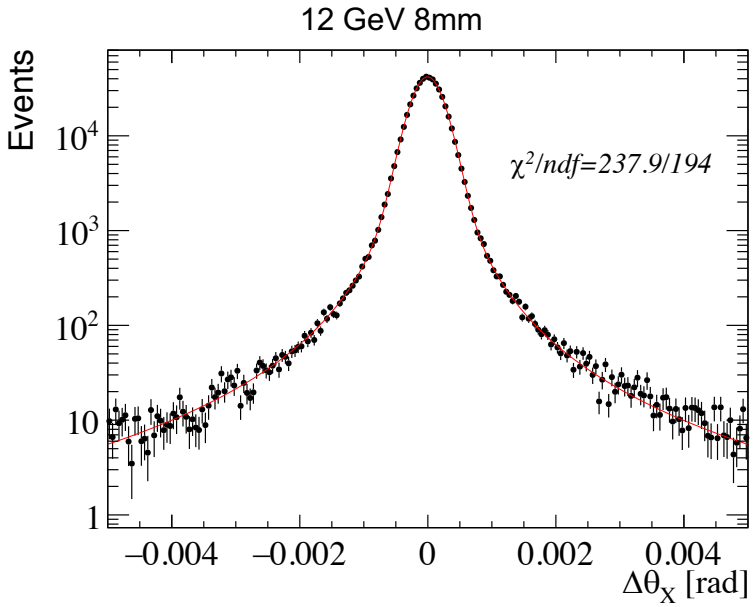
Test beam 2017 (& 2018)

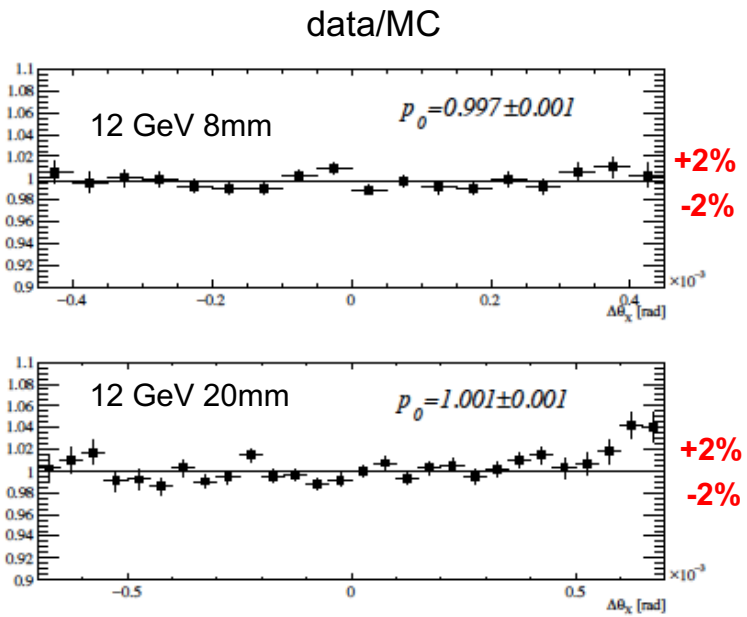
arXiv:1905.11677

Results on Multiple Coulomb Scattering from 12 and 20 GeV electrons on Carbon targets (8, 20 mm)

Submitted to JINST

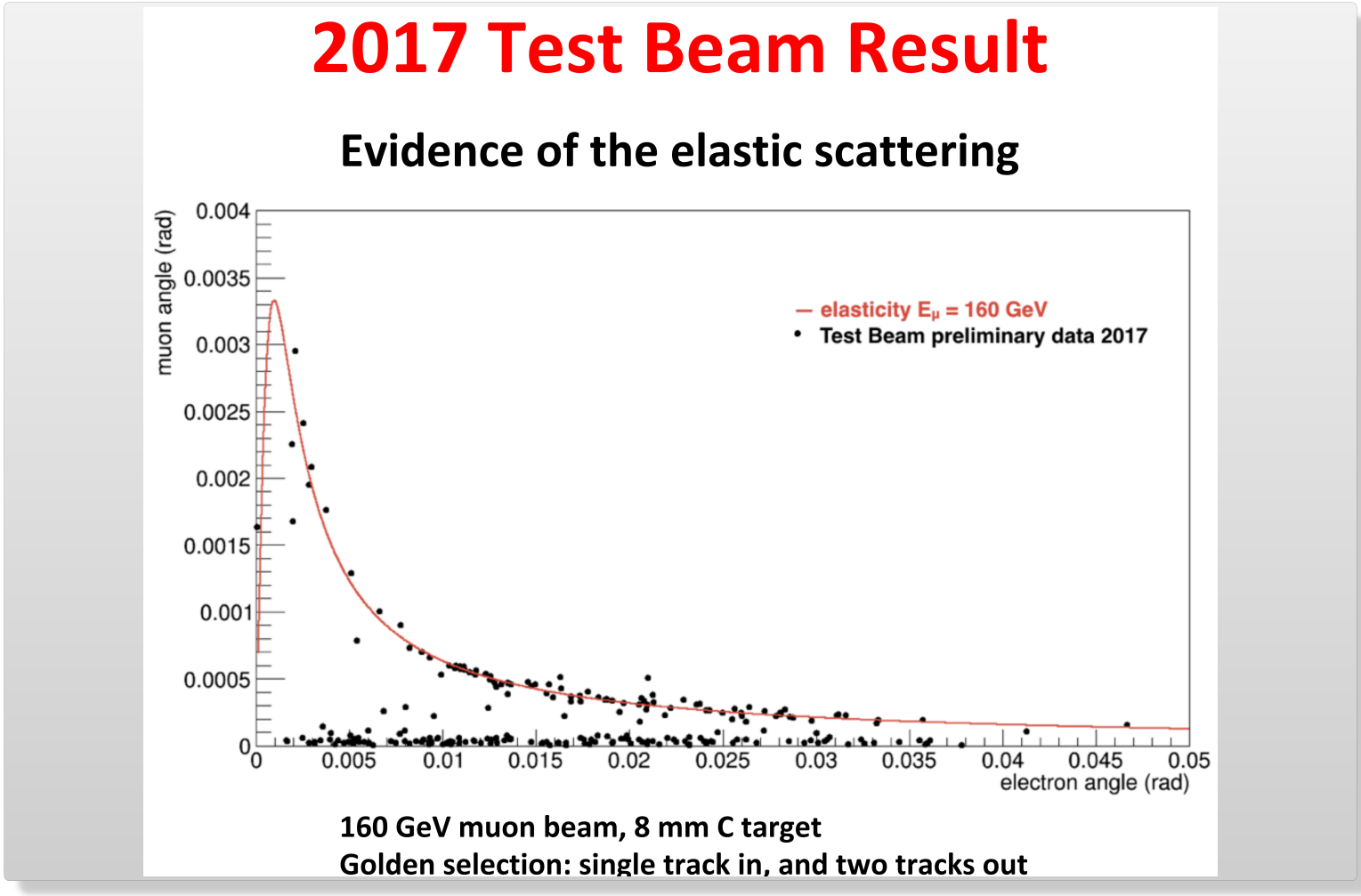
G. Abbiendi[a], J. Bernhard[b], F. Betti[a,c], M. Bonanomi[d], C. M. Carloni Calame[e], M. Garattini[b,g], Y. Gavrikov[f], G. Hall[g], F. Iacoangeli[h], F. Ignatov[i], M. Incagli[j], V. Ivanchenko[b,k], F. Ligabue[j,l], T. O. James[g], U. Marconi[a], C. Matteuzzi[d], M. Passera[m], M. Pesaresi[g], F. Piccinini[e], R. N. Pilato[j,n], F. Pisani[a,b,c], A. Principe[a,c], W. Scandale[b], R. Tenchini[j], and G. Venanzoni[j,1]





G. Venanzoni, EPS 2019 Ghent, 12 July 2019

G. Venanzoni, talk at EPS 2019



U. Marconi, talk at FCCP2019

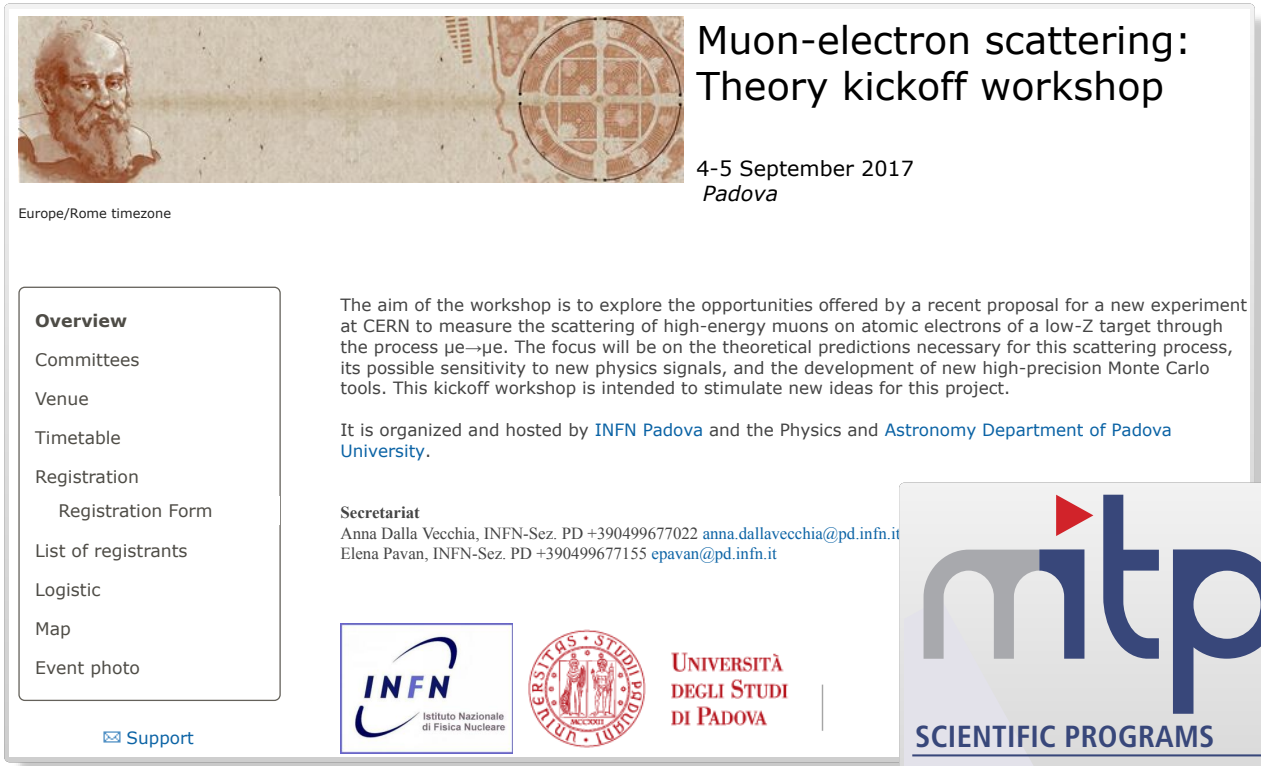
- A further TB performed in 2018, with 2 modules & silicon tracker. Poorer resolution.

Planned activities and MUonE timescale

We expect a first feedback from SPSC in the next months, and hopefully have a pilot run approved for 2021.

- **2019-2020:**
  - prepare for a pilot run in 2021 (2 working modules)
  - theory development, systematics studies (beam momentum scale, detector resolution, MS), design optimization, data analysis development, establish an "official" collaboration.
- **2021:** pilot run.
- **2022:** add stations in sync with CMS production plan (50% by spring, 50% by end of the year).
- **2023-2024:** data taking with full apparatus.

Theory activity



Muon-electron scattering: Theory kickoff workshop

4-5 September 2017
Padova

Europe/Rome timezone

Overview
Committees
Venue
Timetable
Registration
Registration Form
List of registrants
Logistic
Map
Event photo

✉ Support

The aim of the workshop is to explore the opportunities offered by a recent proposal for a new experiment at CERN to measure the scattering of high-energy muons on atomic electrons of a low-Z target through the process μe→μe. The focus will be on the theoretical predictions necessary for this scattering process, its possible sensitivity to new physics signals, and the development of new high-precision Monte Carlo tools. This kickoff workshop is intended to stimulate new ideas for this project.

It is organized and hosted by INFN Padova and the Physics and Astronomy Department of Padova University.

Secretariat
Anna Dalla Vecchia, INFN-Sez. PD +390499677022 anna.dallavecchia@pd.infn.it
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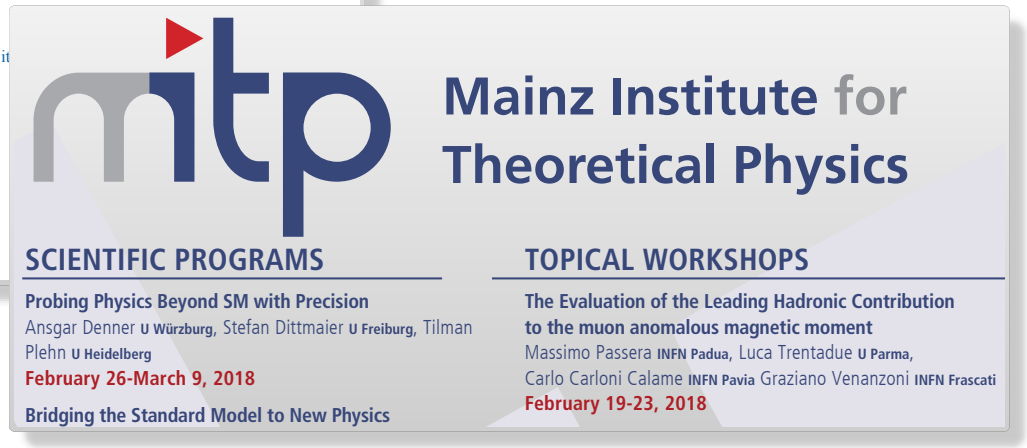
INFN Istituto Nazionale di Fisica Nucleare
Università degli Studi di Padova



mitp Mainz Institute for Theoretical Physics

SCIENTIFIC PROGRAMS

Probing Physics Beyond SM with Precision
Ansgar Denner U Würzburg, Stefan Dittmaier U Freiburg, Tilman Plehn U Heidelberg
February 26-March 9, 2018

Bridging the Standard Model to New Physics

TOPICAL WORKSHOPS

The Evaluation of the Leading Hadronic Contribution to the muon anomalous magnetic moment
Massimo Passera INFN Padua, Luca Trentadue U Parma, Carlo Carloni Calame INFN Pavia Graziano Venanzoni INFN Frascati
February 19-23, 2018

- growing community!

↦ link to the **Padova Theory Kickoff Workshop**, September 2017

↦ link to the **MITP Topical Workshop**, February 2018

Theory activity

- 2nd ThinkStart/WorkStop: Theory of μ-e scattering @ 10ppm, Zurich, Feb. 2019.
  Common paper/document in preparation

- Next meeting: MITP Topical Workshop, end of March 2020.
  Registration opening soon

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Mainz Institute for Theoretical Physics

The Evaluation of the Leading Hadronic Contribution to the Muon g-2: Toward the MUonE Experiment

30 March 2020 to 3 April 2020
Mainz Institute for Theoretical Physics, Johannes Gutenberg University
Europe/Berlin timezone

Theory: status (NLO) & quick deliverables at NNLO

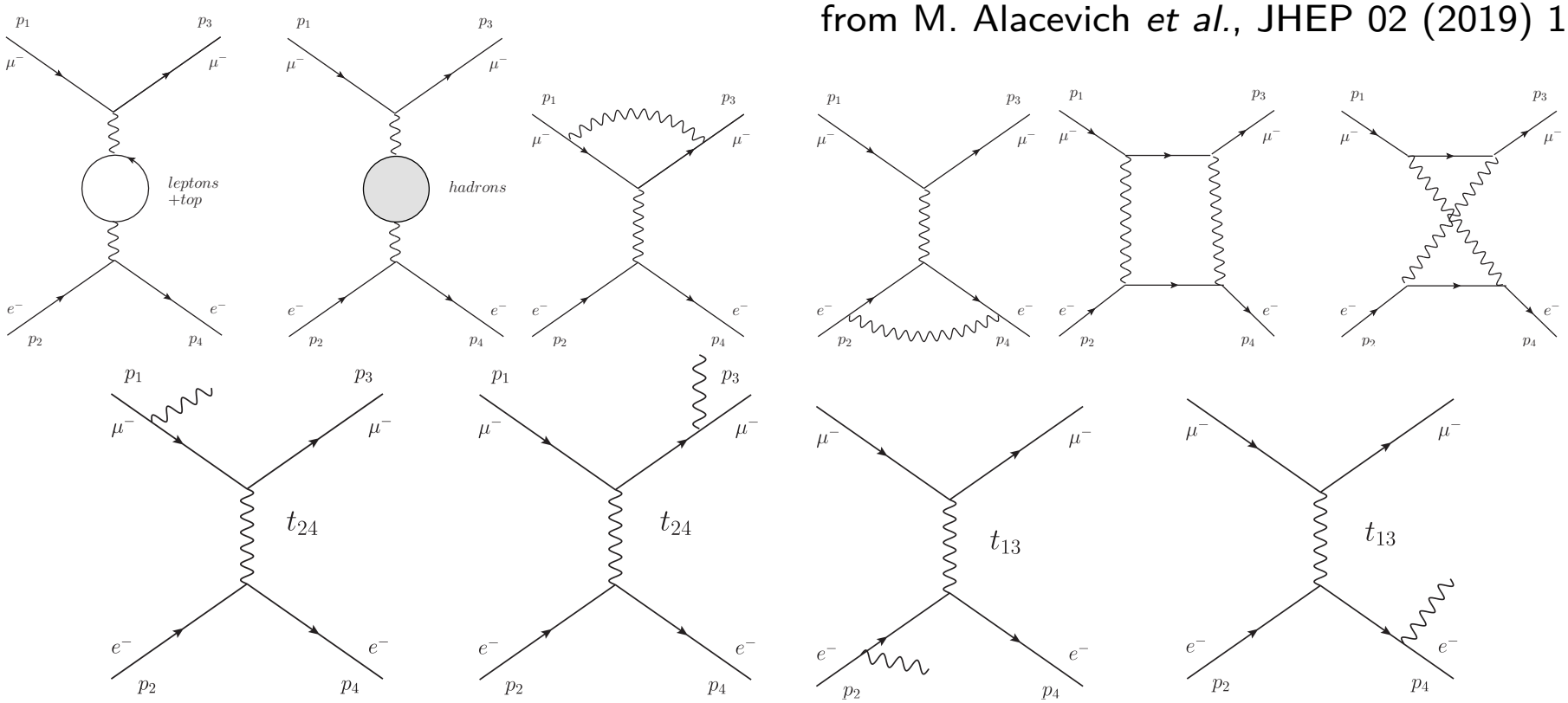
- Theory must predict differential cross sections with the highest accuracy
- QED Radiative Corrections are mandatory
- Full NNLO QED + resummation of higher orders are mandatory
- Calculations must be implemented into a fully differential Monte Carlo event generator, the only way to account for complex experimental selection criteria

Relevant literature

- NLO (QED + EW) into a MC EG: **M. Alacevich** *et al.*, **JHEP 02 (2019) 155**
- NNLO: **M. Fael and M. Passera, PRL 122 (2019) 19, 192001**
  M. Fael, JHEP 1902 (2019) 027
  S. Di Vita *et al.*, **JHEP 1809 (2018) 016**
  P. Mastrolia *et al.*, **JHEP 1711 (2017) 198**

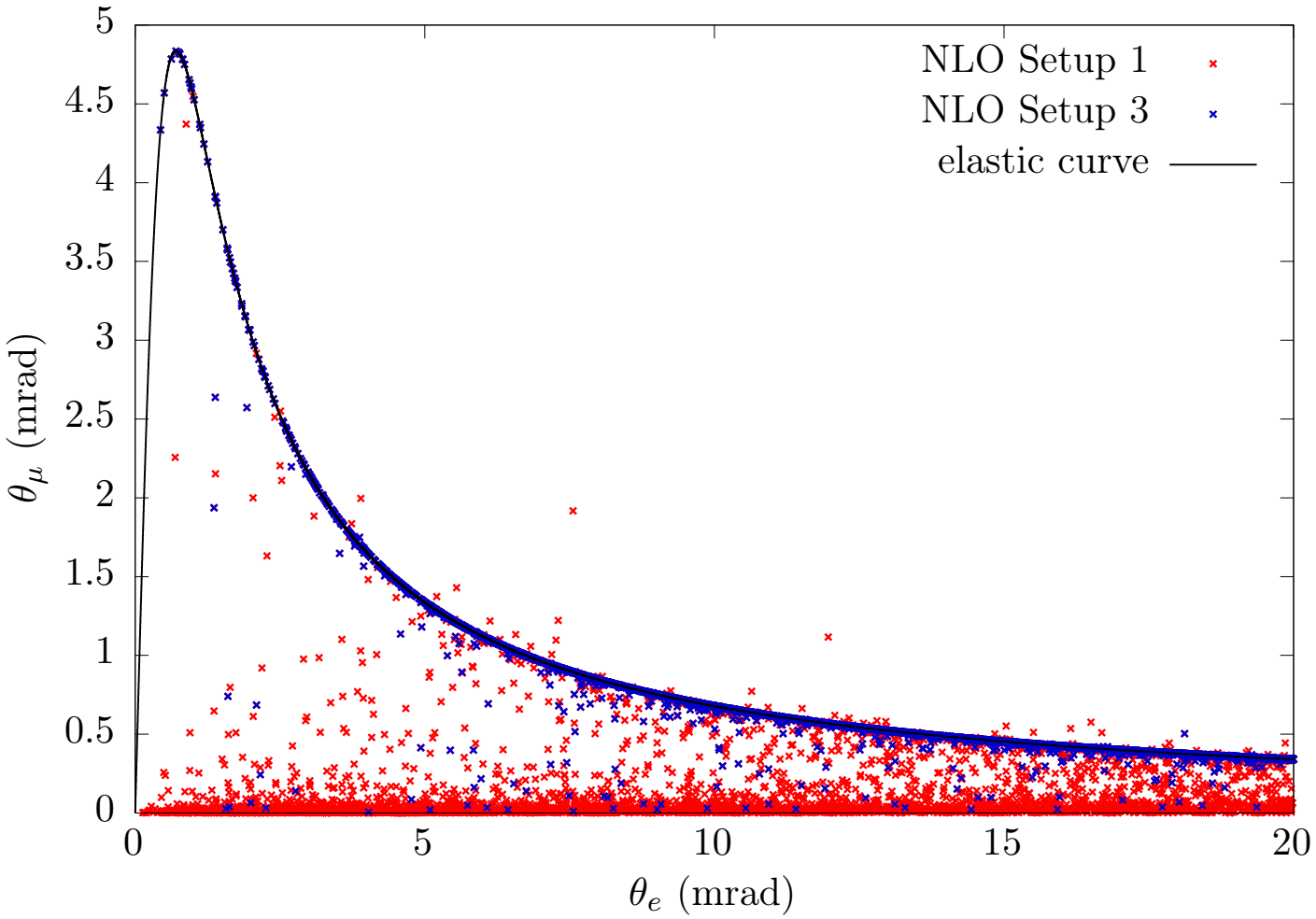
NLO phenomenology (selected results)

from M. Alacevich *et al.*, JHEP 02 (2019) 155



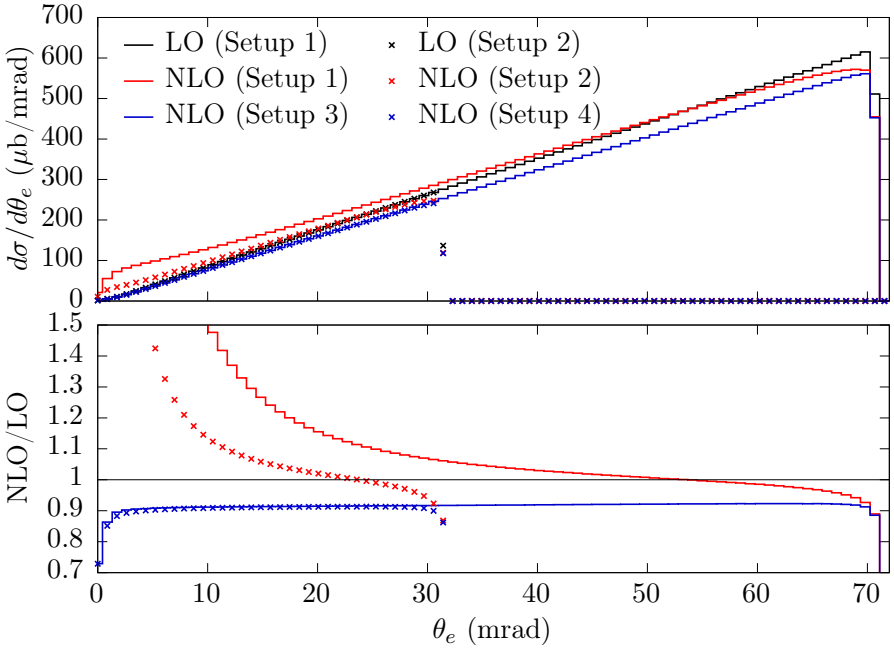
- The bunch of QED diagrams calculated with standard techniques (`FORM`, `LoopTools/Collier`, phase-space slicing,...).
- Full m_μ & m_e dependency kept.
- Also NLO weak RC studied, with the help of `RECOLA`.
- Impact of RC studied within realistic experimental setups.
- The calculation is implemented into an exclusive NLO Monte Carlo, used in current simulations.

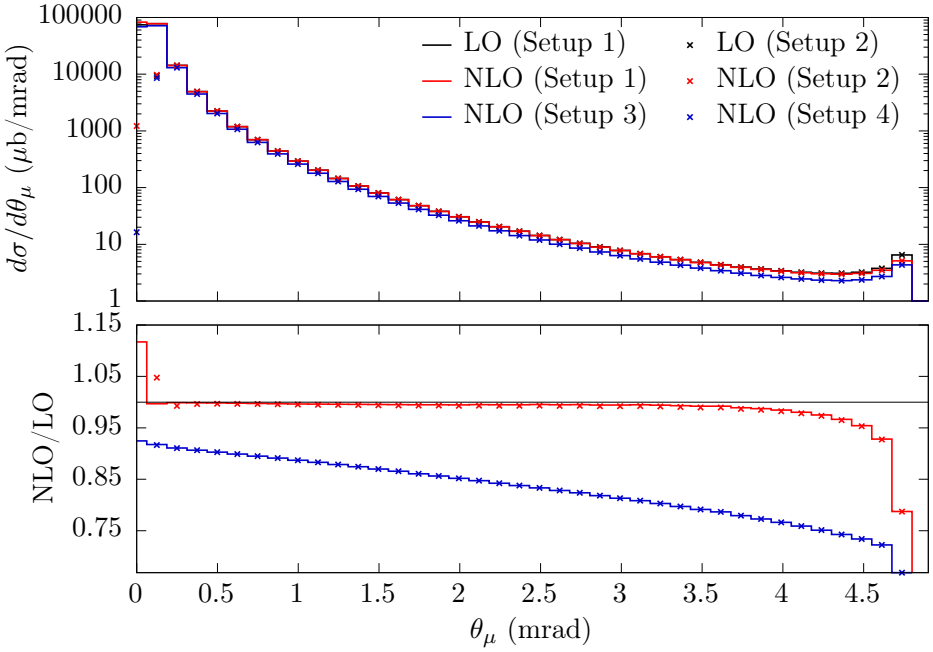
θ_e-θ_μ correlation **(in the lab. frame)**



- ↦ **Setup 1 [2]**: $\boldsymbol{E_e^{\text{lab}} \geq 0.2}$ **[1.] GeV**
- ↦ **Setup 3 [4]**: Setup 1 [2] + acoplanarity $\phi_{e\mu} \leq 3.5$ mrad (simple elasticity cut)
- ↦ In Setup 3/4 the extra elasticity cut is applied

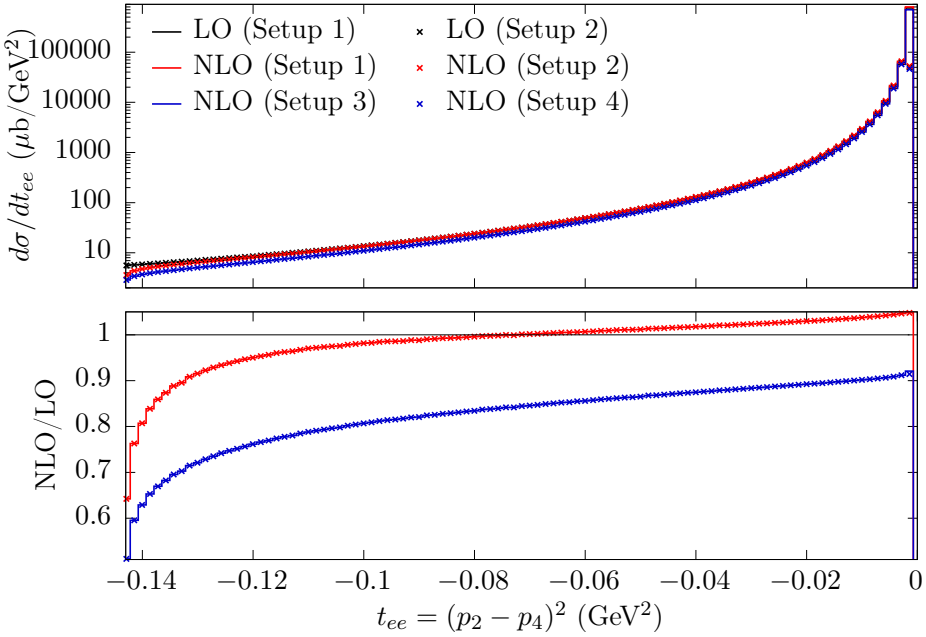
QED RCs on θ_e & θ_μ (incoming μ^+)

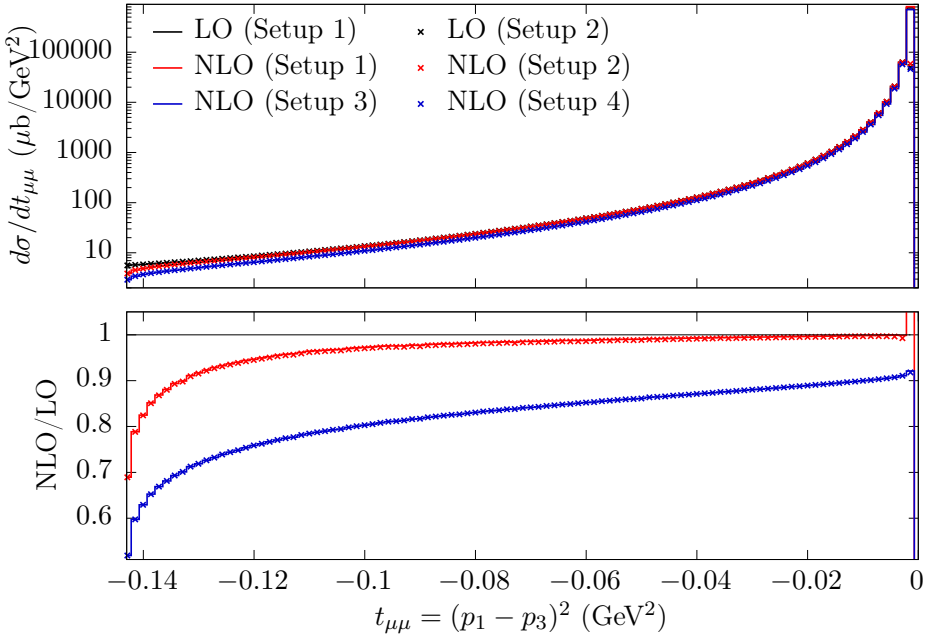




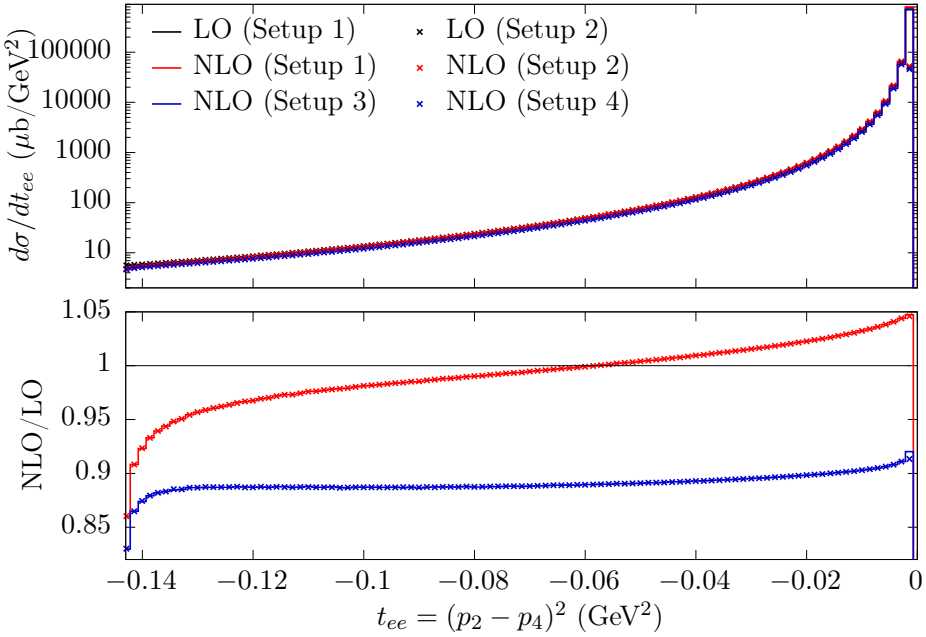
- Large RCs <u>on θ_e</u> in Setup 1 & 3 induced by hard bremsstrahlung

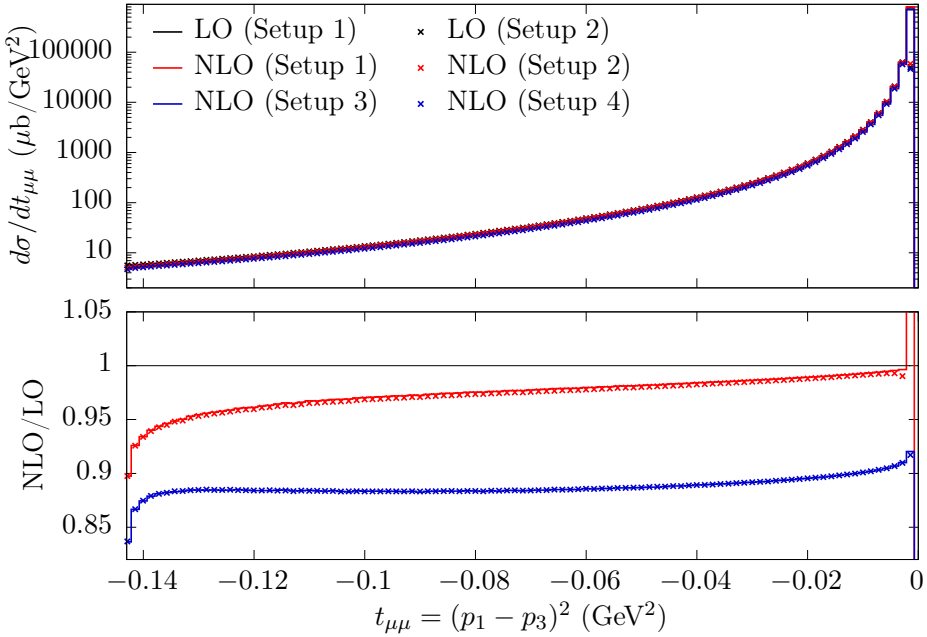
QED RCs on t_{ee} & $t_{\mu\mu}$ (incoming μ^+)





QED RCs on t_{ee} & $t_{\mu\mu}$ (incoming μ^-)



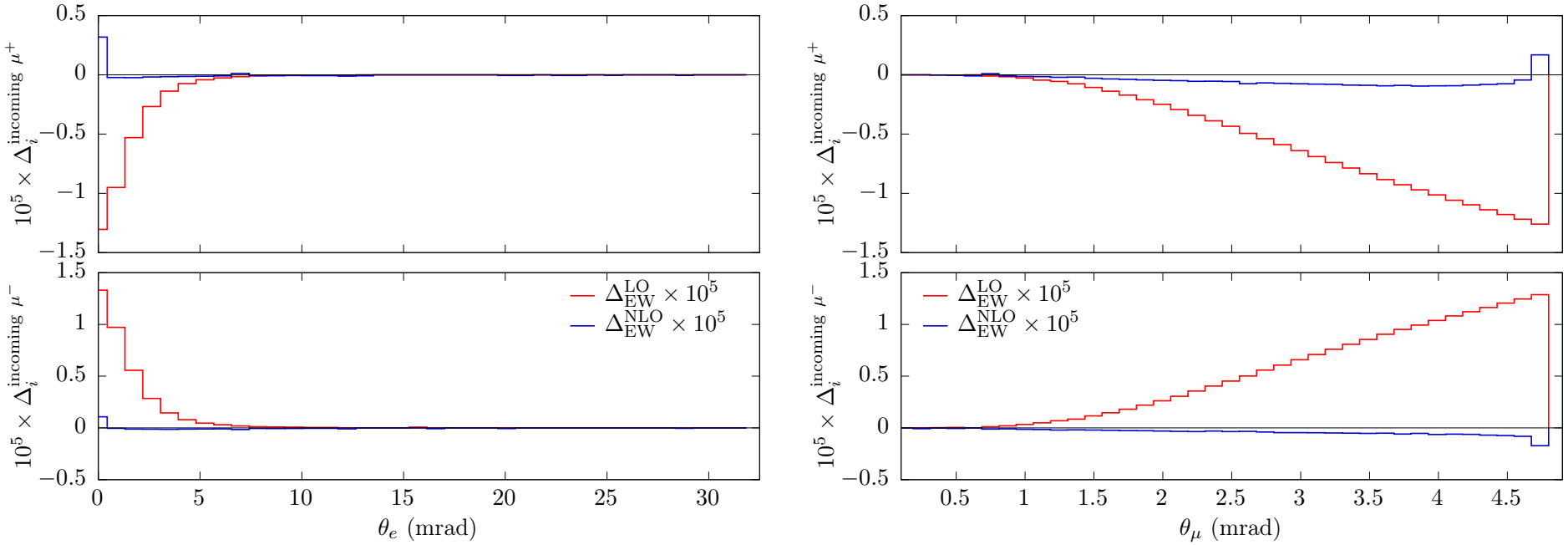


EWKology on θ_e & θ_μ

↦ Full EWK RCs calculated in the on-shell (complex mass) scheme with **RECOLA**

S. Actis *et al.*, JHEP 04:037, 2013

S. Actis *et al.*, CPC 214:140–173, 2017



$$\Delta_{\text{EW}}^{\text{LO}} = \frac{d\sigma_{\text{EW}}^{\text{LO}} - d\sigma_{\text{QED}}^{\text{LO}}}{d\sigma_{\text{QED}}^{\text{LO}}} \qquad \Delta_{\text{EW}}^{\text{NLO}} = \frac{\left(d\sigma_{\text{EW}}^{\text{NLO}} - d\sigma_{\text{EW}}^{\text{LO}}\right) - \left(d\sigma_{\text{QED}}^{\text{NLO}} - d\sigma_{\text{QED}}^{\text{LO}}\right)}{d\sigma_{\text{QED}}^{\text{NLO}}}$$

- $\Delta_{\text{EW}}^{\text{NLO}}$ measures the (gauge-invariant) purely weak RC, in QED NLO units

Further NLO studies

- Gauge invariant QED subsets: RC to e-current, μ-current, [up-down] interference

  $\hookrightarrow$ dominated by e-current RCs, as expected

- Finite size m_e effects, 'cause at NNLO keeping full m_e dependence is extremely difficult

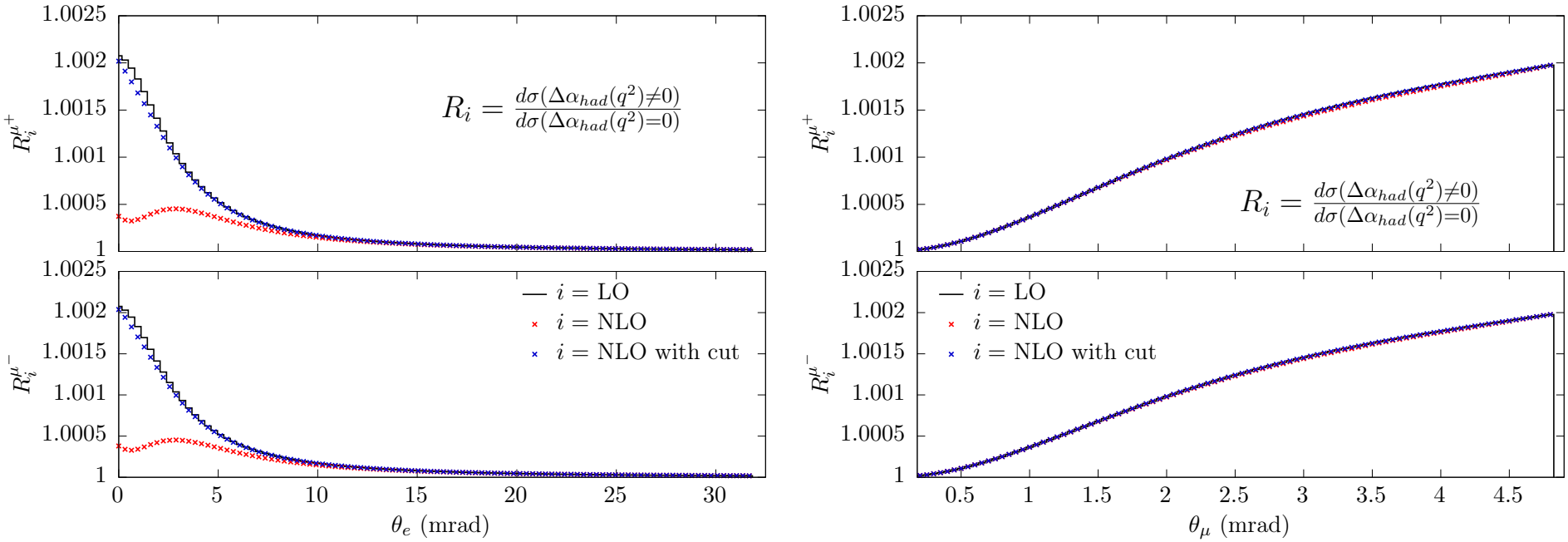
  $\hookrightarrow$ *Educated guess* from NLO results:

  at NNLO the limit $m_e \to 0$ seems phenomenologically safe, *i.e.* it's likely finite m_e contributions are negligible at NNLO

Signal sensitivity to RCs

$$\text{Our "signal" on observable } O \equiv \frac{d\sigma^{\text{best}}(O, \Delta\alpha_{\text{had}}(q^2) \neq 0)}{d\sigma^{\text{best}}(O, \Delta\alpha_{\text{had}}(q^2) = 0)}$$

- Does it survive radiative corrections?



- Elasticity cuts mandatory to keep signal sensitivity on θ_e
- θ_μ is more "robust" under RCs (in particular "hard" photon radiation)

"Quick" deliverables at NNLO (from Monte Carlo point of view)

$\rightsquigarrow$ An impressive amount of work is currently put in NNLO/resummation calculations

M. Fael and M. Passera, PRL 122 (2019) 19, 192001

M. Fael, JHEP 1902 (2019) 027

S. Di Vita *et al.*, JHEP 1809 (2018) 016

P. Mastrolia *et al.*, JHEP 1711 (2017) 198

2nd ThinkStart/WorkStop: Theory of μ-e scattering @ 10ppm, Zurich, February 4-7 '19

see talk by Matteo

$\mapsto$ QED NLO to $\mu^\pm e^- \to \mu^\pm e^- \gamma$

- ✓ (almost) straightforward

$\mapsto$ $\mu^\pm e^- \to \mu^\pm e^- e^+ e^-, \to \mu^\pm e^- \mu^+ \mu^-$ (NNLO leptonic real pair corrections)

- ✓ partially cancelled by NNLO virtual leptonic RCs
- ✗ how the experiment will deal with these final states?

$\mapsto$ $\mu^\pm e^- \to \mu^\pm e^- \pi^0 (\to \gamma\gamma), \to \mu^\pm e^- \pi^+ \pi^-$

- ✓ collaboration with Henryk Czyż

$\mapsto$ Consider first full NNLO QED RCs to e and μ currents separately (already known)?

- ✓ it can be the first step towards full fixed-order NNLO MC
- ✓ it can be the testing playground to implement matching with exponentiation at NNLO
  (*e.g.* along the lines of NLO matching with QED Parton Shower in `BabaYaga@NLO`)

Fitting $\Delta\alpha_{\text{had}}(t)$: strategy

$$\text{to be fitted} = \frac{d\sigma^{\text{best}}(O, \Delta\alpha_{\text{had}}^{\text{fit}}(q^2, \{P_1, \cdots, P_n\}))}{dO}$$

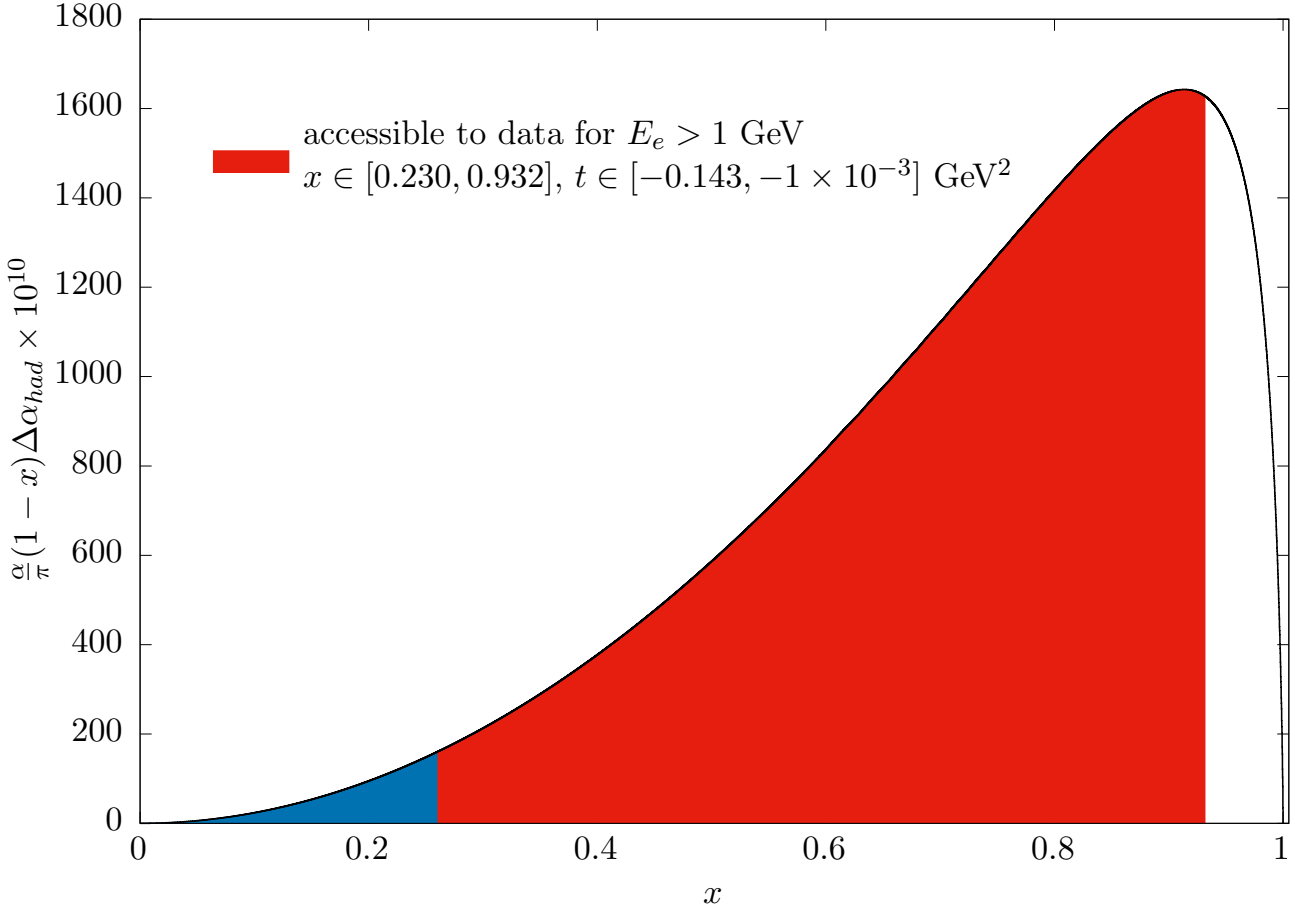
- ⇝ **"best"** means including best theoretical prediction & all experimental (detector) effects
- ⇝ $d\sigma^{\text{best}}/dO$ (parametric in $P_1, P_2, \cdots$) must be compared to data through a template fitting

↪ **Which functional form to choose for $\Delta\alpha_{\text{had}}^{\text{fit}}(q^2, \{P_1, \cdots, P_n\})$?**

- → Studied also in the LoI, using NLO MC & including simulation of detector effects with `GEANT4`
- → MUonE statistical reach confirmed with more realistic simulation
- → The procedure is robust to evaluate the impact on a_μ^{HLO} from MUonE of any systematic effect (MS, μ energy scale,. . .)

Fitting $\Delta\alpha_{\text{had}}(t)$: strategy

✓ For pseudo-data, we use here old Fred's `hadr5n12.f` routine, any other would do the job



$$10^{10} \times a_\mu^{\text{HLO}} = 10^{10} \times \frac{\alpha}{\pi} \int_0^1 dx\,(1-x)\Delta\alpha_{\text{had}}^{\text{Fred}}\,(t\,(x)) = 688.57^{\pm 5.03}$$

$$\int_0^{x_{max}} = \int_0^{x_{min}} + \int_{x_{min}}^{x_{max}} = 13.92^{\pm 0.10} + 586.84^{\pm 4.18} = 600.75^{\pm 4.28} \simeq 87\% \times \int_0^1$$

Choosing $\Delta\alpha_{\rm had}^{\rm fit}(t)$

explored in L. Pagani's master degree thesis, Bologna U., Sept. '17 (sup. Marconi, Passera, CC)

$$f^{\rm pol}(t, P_{1\ldots3}) = P_1 t + P_2 t^2 + P_3 t^3 \qquad f^{\rm Padè}(t, P_{1\ldots3}) = P_1 t \cdot \frac{1+P_2 t}{1+P_3 t}$$

$$\underbrace{f^{\rm f.l.}(t, P_1, P_2)}_{\text{"fermion-like"}} = \frac{P_1}{3}\left(-\frac{5}{3} - \frac{4P_2}{t} + \frac{\frac{8P_2^2}{t^2} + \frac{2P_2}{t} - 1}{\sqrt{1-\frac{4P_2}{t}}} \log\left|\frac{1-\sqrt{1-\frac{4P_2}{t}}}{1+\sqrt{1-\frac{4P_2}{t}}}\right|\right)$$

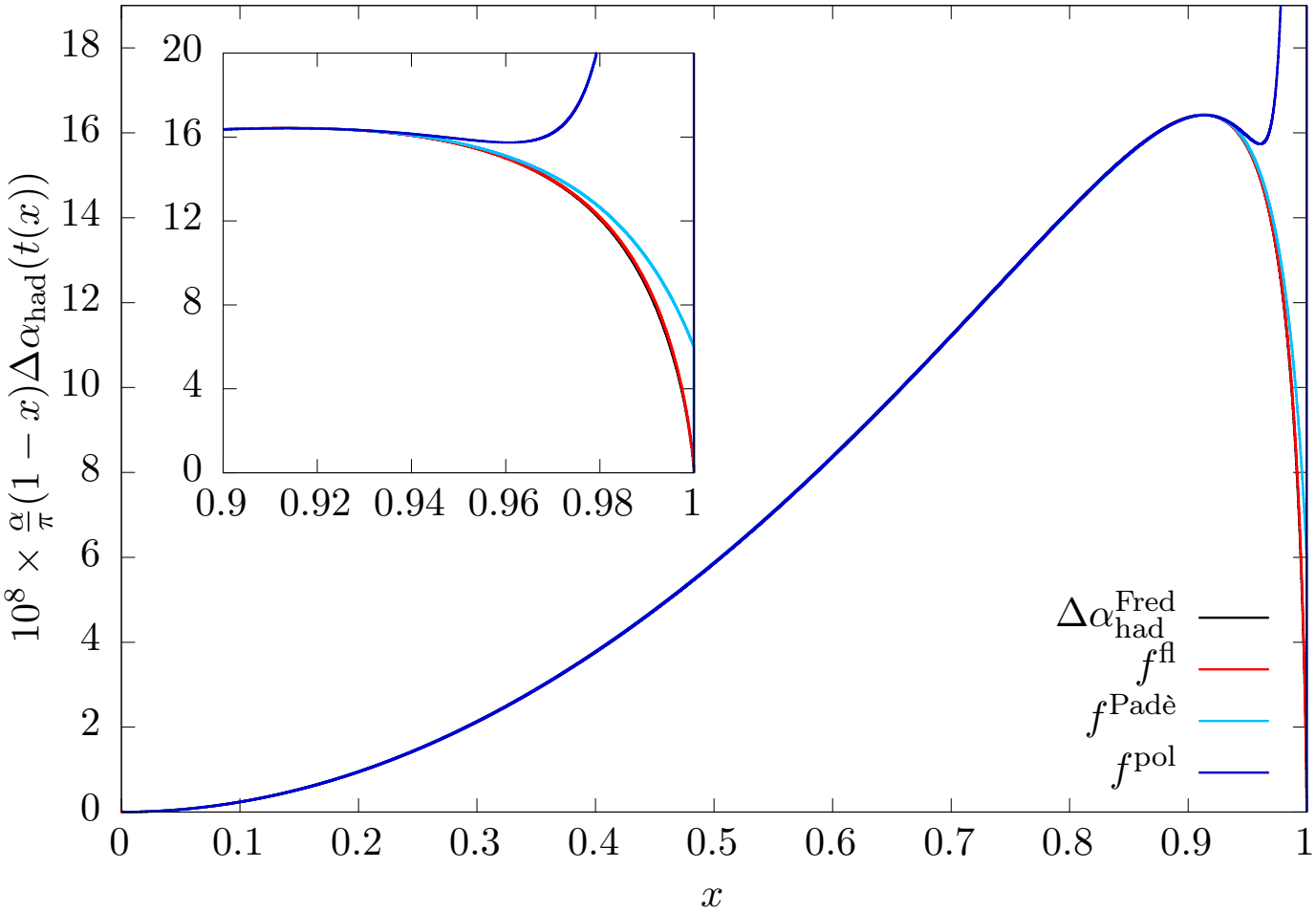
- $f^{\rm f.l.}(t, \{P_i\})$ inspired (why not?) by subtracted LO fermionic contribution to VP, with "coupling" $\propto \sqrt{P_1}$ and "mass" $\sqrt{P_2}$
  - ✓ easy (?) to plug-in into HNNLO
  - ✓ it has polinomial limit as $t \to -0$ and a nice log behaviour as $t \to -\infty$

$$f^{\rm f.l.}(t, P_1, P_2) = \begin{cases} \frac{P_1}{3}\left(\log\frac{-t}{P_2} - \frac{5}{3}\right) & t \to -\infty \\ -\frac{P_1}{15}\frac{t}{P_2} + \mathcal{O}(t^2) & t \to -0 \end{cases}$$

- by fitting $\Delta\alpha_{\rm had}^{\rm Fred}(t)$ from (old) `hadr5n12.f` **in the MUonE accessible range**

	P_1	P_2	P_3
$f^{\rm pol}$	$-9.13776 \cdot 10^{-3}$	-0.0176392	-0.0300122
$f^{\rm Padè}$	$-9.15347 \cdot 10^{-3}$	-0.693855	-2.74919
$f^{\rm f.l.}$	$2.39479 \cdot 10^{-3}$	0.0523448	
		[→ "mass" 0.23 **GeV]**	

Extrapolating the fits



$$10^{10} \times \frac{\alpha}{\pi}\int_0^{x_{max}} dx\ (1-x)[f^{\rm pol}, f^{\rm Padè}, f^{\rm f.l.}, \Delta\alpha_{\rm had}^{\rm Fred}](t(x)) = [600.6, 601.0, 600.9, \underline{600.8}]$$

$$10^{10} \times \frac{\alpha}{\pi}\int_0^{1} dx\ (1-x)[\boldsymbol{f}^{\rm pol}, f^{\rm Padè}, \boldsymbol{f}^{\rm f.l.}, \boldsymbol{\Delta\alpha}_{\rm had}^{\rm Fred}](t(x)) = [\infty, 692.8, \mathbf{688.9}, \underline{\mathbf{688.6}}]$$

Conclusions & Outlook

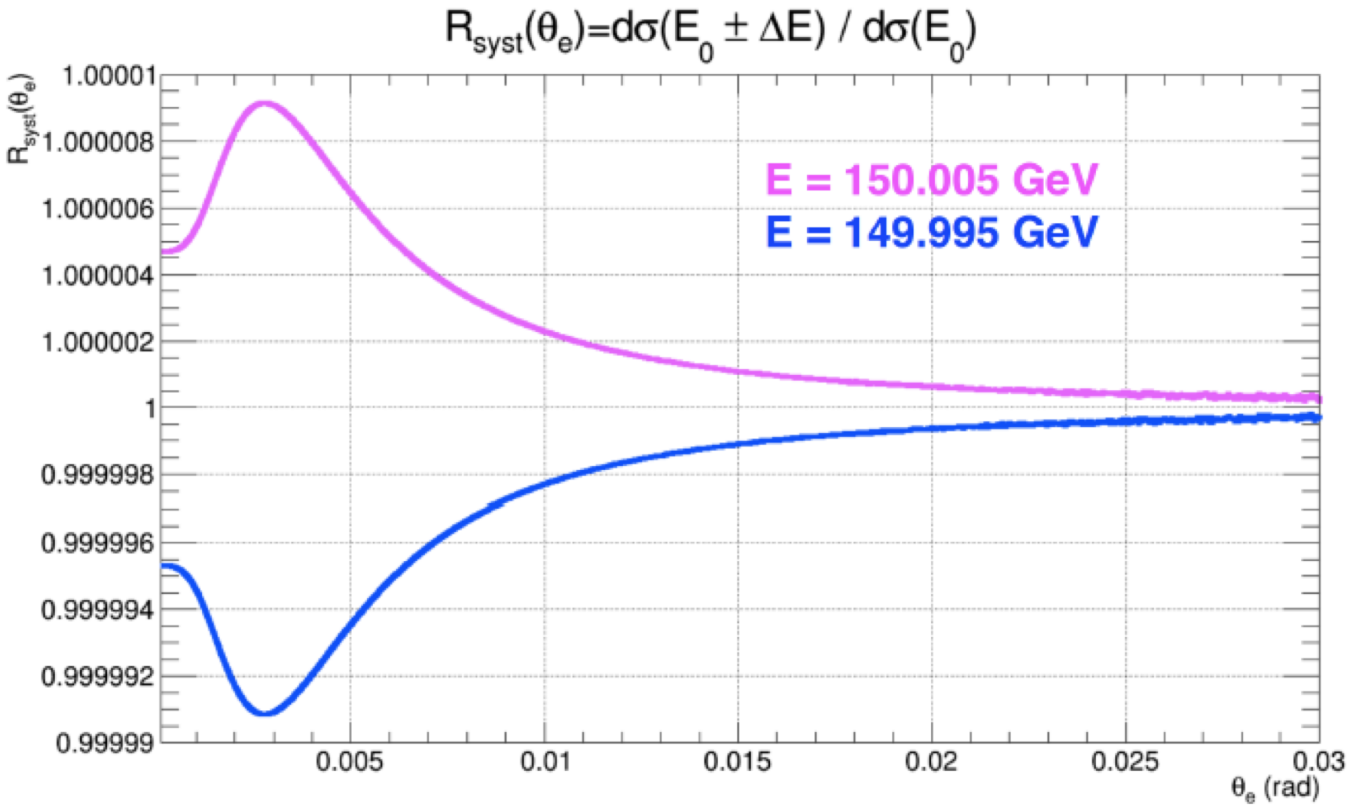
- ⋆ MUonE is on track, and waiting for a (positive) response from CERN SPSC.
- ⋆ The collaboration is growing. New collaborators always welcome!
- ⋆ A lot of work is going on, both on the experiment and theory side, to tackle the demanding challenges of MUonE.
- ⋆ If approved, a pilot run will start in 2021. In the following 3 years, full deployment and data taking are planned.

SPARES

POSSIBLE LOCATION AT EHN2

G. Venanzoni, g-2 Physics Week, La Biodola, 27 May 2019

Beam scale



To achieve 10ppm error → It needs to control the energy scale to ~ 6 MeV (4×10^{-5}) ! How to measure the beam scale at such an accuracy?

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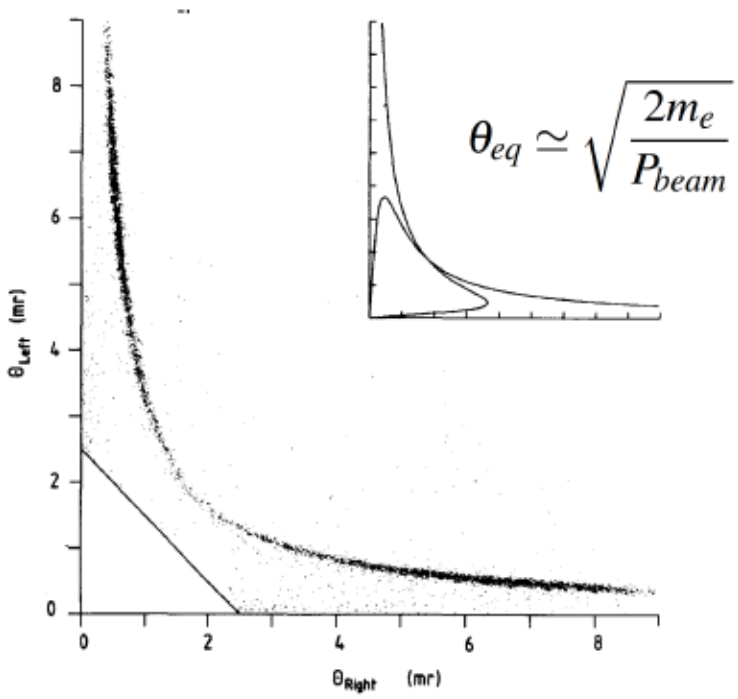
Beam scale

S.R.Amendolia et al, Phys.Lett.B146(1984)116 / Nucl.Phys.B277(1986)168

πe Elastic scattering in the (θ_R, θ_L) plane



- Beam energy determined by kinematics by measuring the angles of the two outgoing particles. Method previously used by NA7
- Selection of events ~ 2.7 mrad (E~75 GeV) Distribution of the angles sum (or the average angle) for the selected events.
- This technique is robust against transverse misalignments (null effect to the first order).
- Longitudinal misalignments should be limited to O(10) microns.

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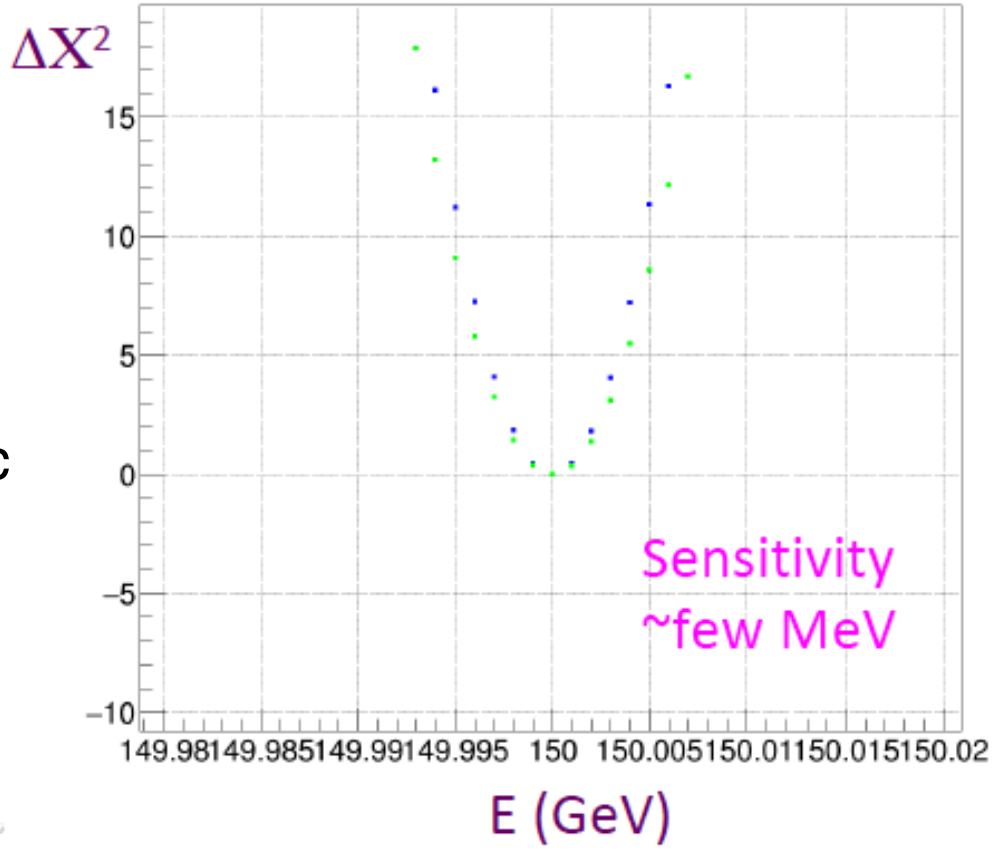
G. Venanzoni, g-2 Physics Week, La Biodola, 27 May 2019

Beam scale

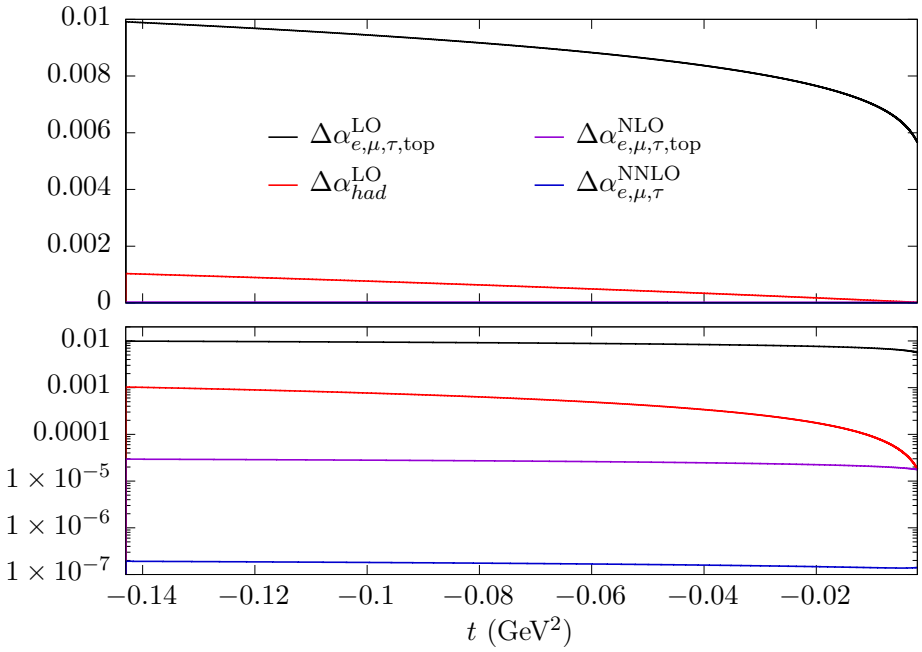
Template method: χ^2 comparison of pseudodata with distributions for the average angle obtained with variable Ebeam.

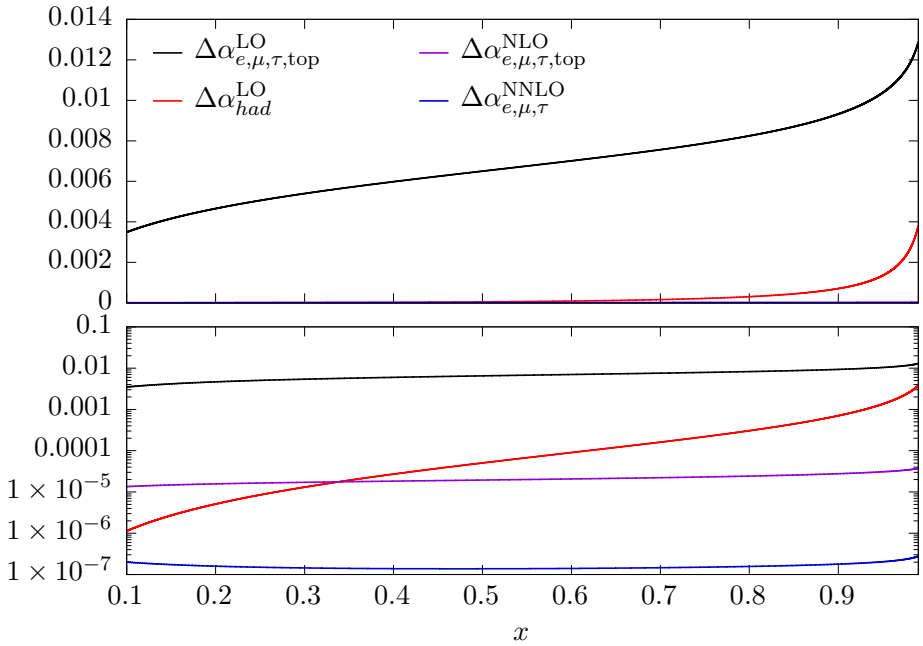
- Ebeam = 150 GeV with 1% spread (spectrometer)
- Generation of 10^7 events selecting an angular region around θ~2.5 mrad and realistic angular spread
- Accuracy ~ 1 MeV
- Systematic error ~MeV



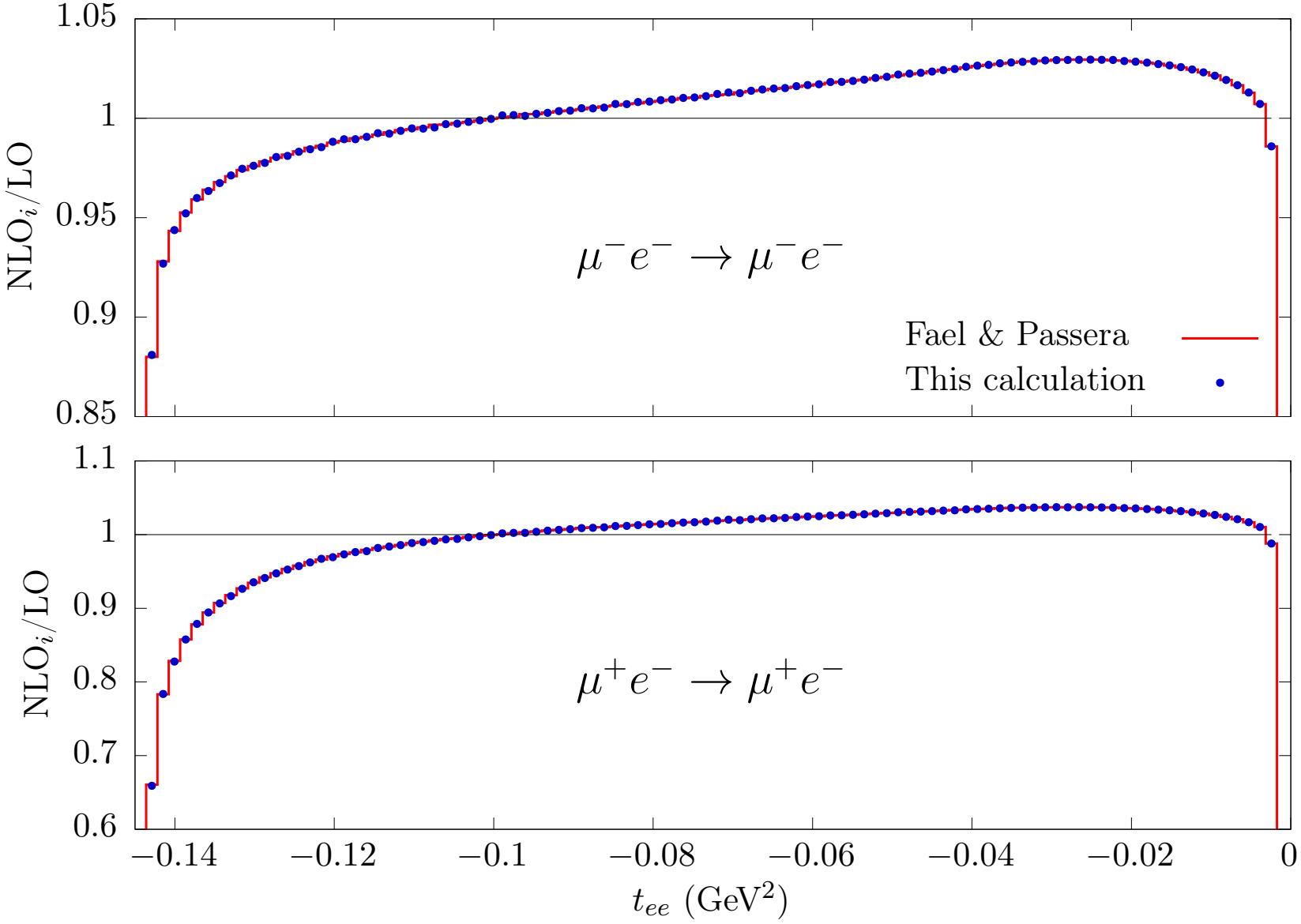
G. Venanzoni, g-2 Physics Week, La Biodola, 27 May 2019

$\Delta\alpha_{\rm lep}(t)$ at higher orders





Tuned comparison with Fael & Passera



Matching NLO and PS (in BabaYaga@NLO)

As originally developed for $e^+e^- \to e^+e^-, \to \mu^+\mu^-, \to \gamma\gamma$ at flavour factories

Balossini *et al.*, Nucl. Phys. **B758** (2006) 227, CMCC *et al.*, Nucl. Phys. Proc. Suppl. **131** (2004) 48

Exact $\mathcal{O}(\alpha)$ (NLO) soft+virtual (SV) corrections and hard-bremsstrahlung (H) matrix elements can be combined with QED PS *via* a matching procedure

- $d\sigma^{\infty}_{PS} = \Pi(Q^2,\varepsilon)\ \sum_{n=0}^{\infty} \frac{1}{n!}\ |\mathcal{M}_{n,PS}|^2\ d\Phi_n$
- $d\sigma^{\alpha}_{PS} = [1 + C_{\alpha,PS}]\,|\mathcal{M}_0|^2 d\Phi_2 + |\mathcal{M}_{1,PS}|^2 d\Phi_3 \equiv d\sigma^{SV}_{PS}(\varepsilon) + d\sigma^{H}_{PS}(\varepsilon)$
- $d\sigma^{\alpha}_{\rm NLO} = [1 + C_{\alpha}]\,|\mathcal{M}_0|^2 d\Phi_2 + |\mathcal{M}_1|^2 d\Phi_3 \equiv d\sigma^{SV}_{\rm NLO}(\varepsilon) + d\sigma^{H}_{\rm NLO}(\varepsilon)$
- $F_{SV} = 1 + (C_\alpha - C_{\alpha,PS})$ $\qquad F_H = 1 + \frac{|\mathcal{M}_1|^2 - |\mathcal{M}_{1,PS}|^2}{|\mathcal{M}_{1,PS}|^2}$

$$d\sigma^{\infty}_{\rm matched} = F_{SV}\ \Pi(Q^2,\varepsilon)\ \sum_{n=0}^{\infty} \frac{1}{n!}\ \left(\prod_{i=0}^{n} F_{H,i}\right)\ |\mathcal{M}_{n,PS}|^2\ d\Phi_n$$

$d\Phi_n$ is the exact phase space for n final-state particles

(2 fermions + an arbitrary number of photons)

Any approximation is confined into matrix elements

$\rightsquigarrow$ The same QED PS & NLO matching framework successfully applied also to Drell-Yan processes (`HORACE`) and $H \to 4\ell$ (`Hto4l`)

CMCC *et al.*, JHEP 0710 (2007) 109; CMCC *et al.*, JHEP 0612 (2006) 016; S. Boselli *et al.*, JHEP 1506 (2015)

Matching NLO and PS (in BabaYaga@NLO)

- F_{SV} and $F_{H,i}$ are infrared/collinear safe and account for missing $\mathcal{O}(\alpha)$ non-logs, avoiding double counting of leading-logs
- $\left[\sigma^{\infty}_{matched}\right]_{\mathcal{O}(\alpha)} = \sigma^{\alpha}_{\rm NLO}$
- Exponentiation of higher orders LL (PS) contributions is preserved
- The cross section is still fully differential in the momenta of the final state particles (F's correction factors are applied on an event-by-event basis)
- as a by-product, part of photonic $\alpha^2 L$ included by means of terms of the type $F_{SV\ |\ H,i} \otimes$ [leading-logs]

  G. Montagna et al., **PLB** 385 (1996)
- The theoretical error is shifted to $\mathcal{O}(\alpha^2)$ (NNLO) *not infrared*, singly collinear terms: naively and roughly (for photonic corrections)

$$\frac{1}{2!}\alpha^2 L \equiv \frac{1}{2!}\alpha^2 \log\frac{s}{m_e^2} \sim 3.5 \times 10^{-4}$$

- **Need to generalize to NNLO matching!**
  Then, the error will be at the level of

$$\frac{1}{3!}\alpha^3 L^2 \sim 1.1 \times 10^{-5}$$

- Can we further improve with analytic resummation?

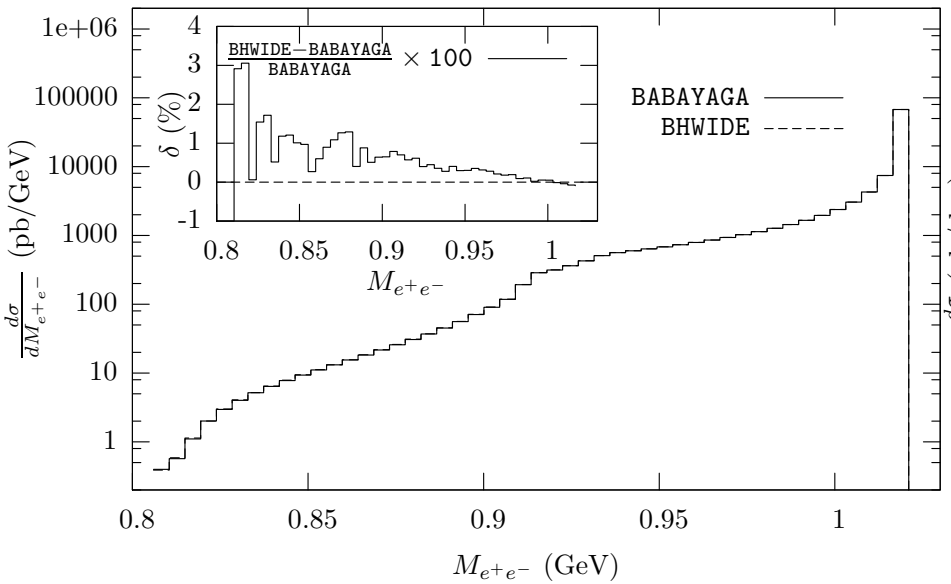
Estimating the theoretical accuracy

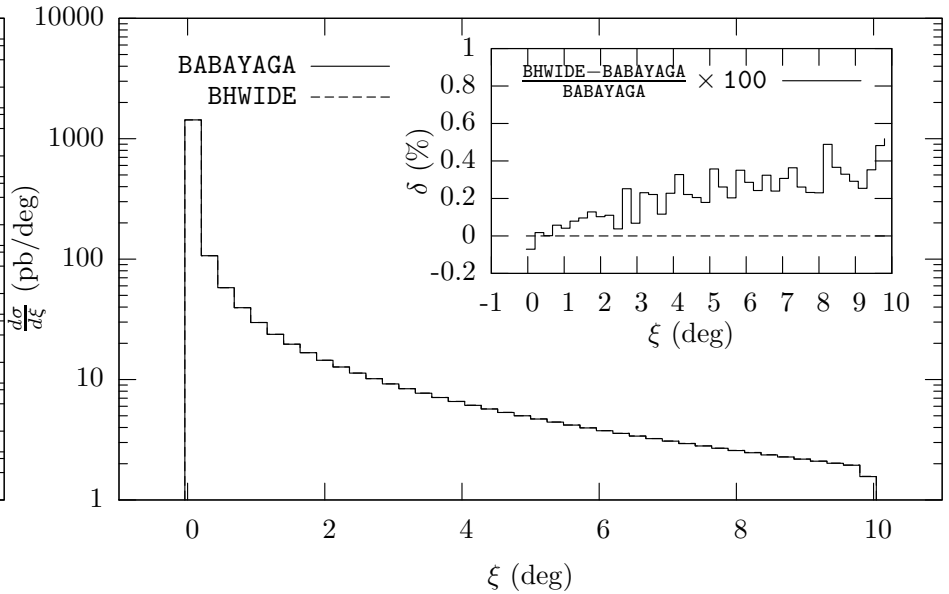
S. Actis et al. Eur. Phys. J. C **66** (2010) 585

"Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data"

- It is extremely important to compare independent calculations/implementations/codes, in order to
  - ↦ asses the technical precision, spot bugs (with the same th. ingredients)
  - ↦ estimate the theoretical error when including partial/incomplete higher-order corrections
- E.g. comparison `BabaYaga@NLO` vs. `Bhwide` at KLOE

S. Jadach *et al.* PLB 390 (1997) 298

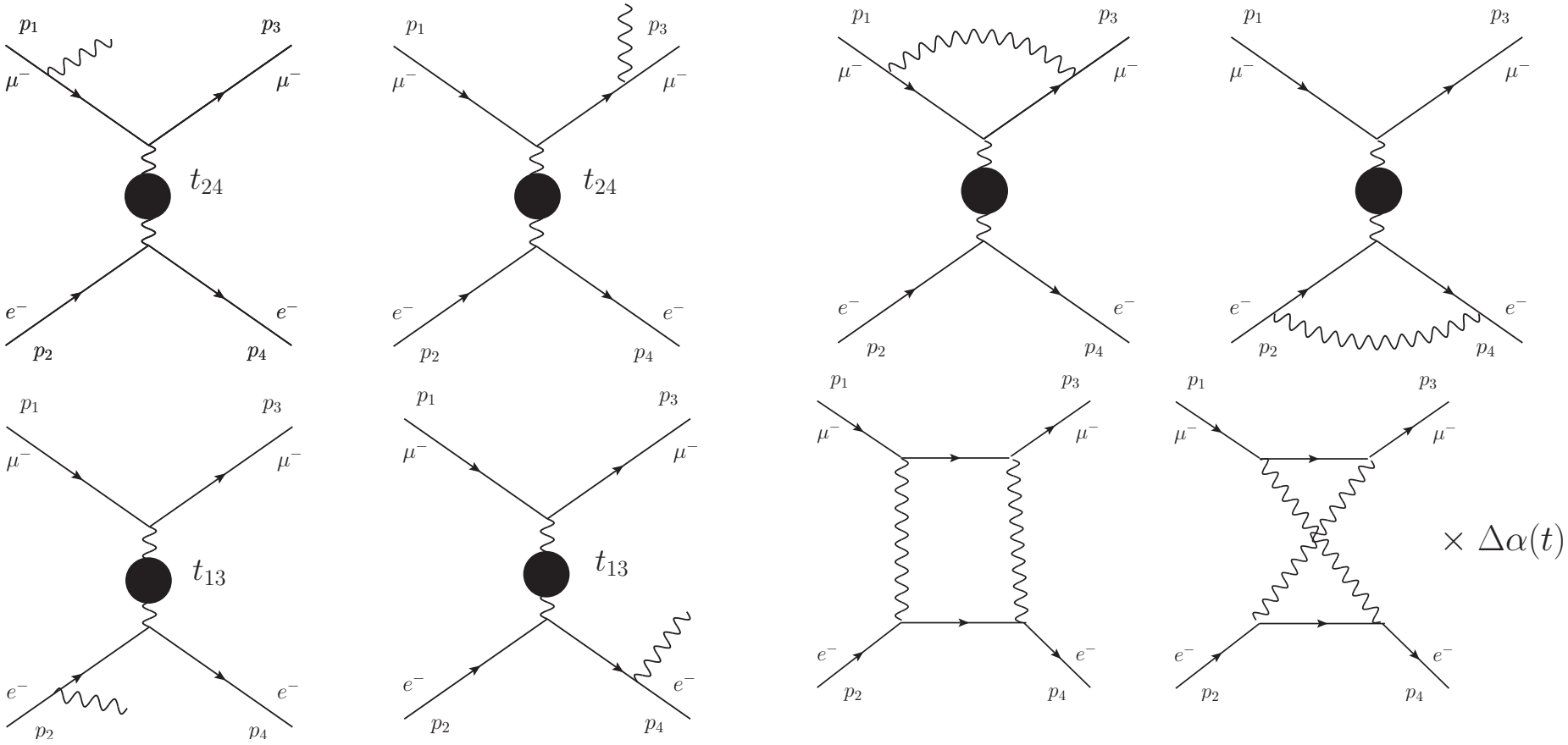




Approximating NNLO fermionic & hadronic corrections

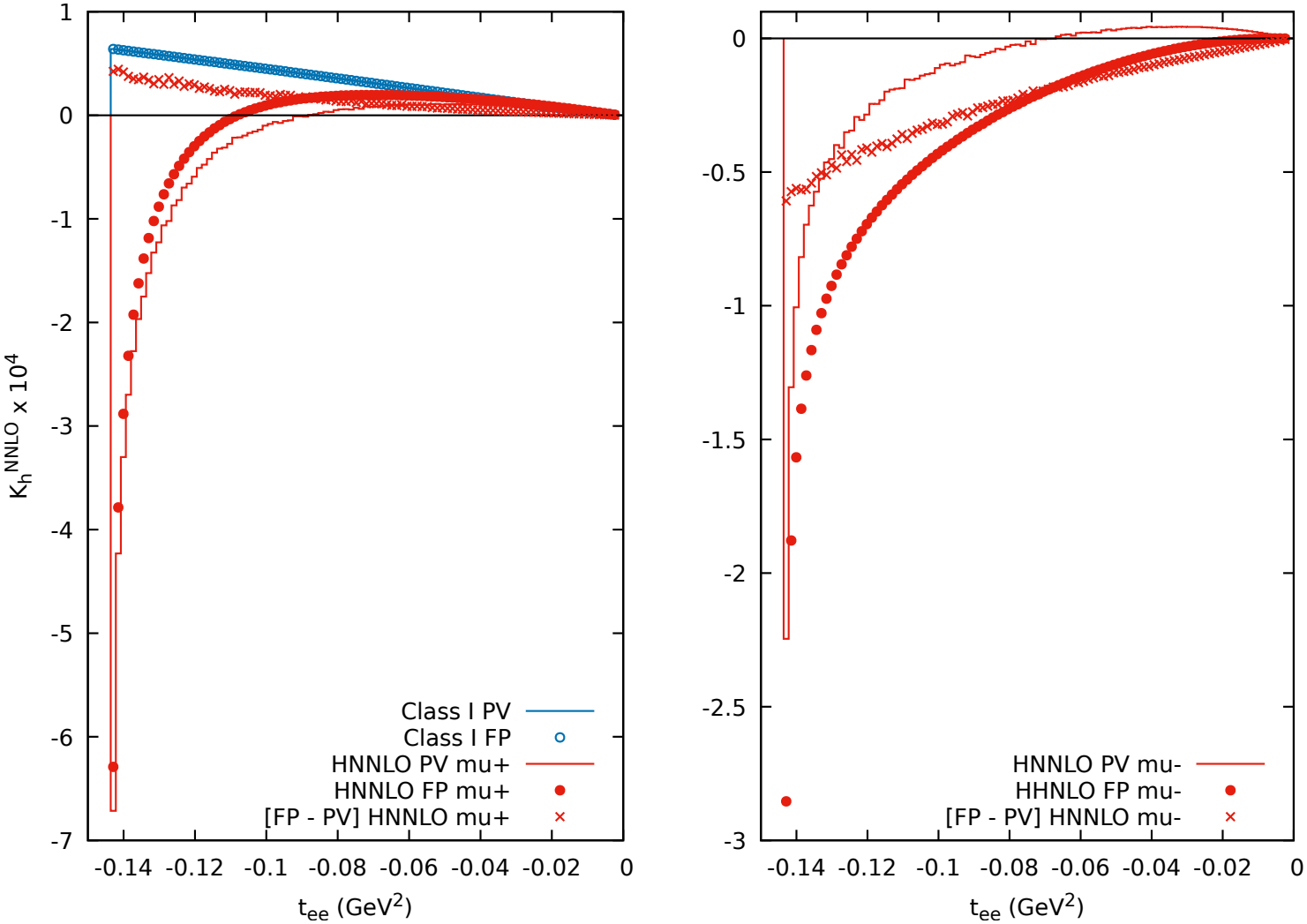
see also CMCC *et al.*, JHEP **1107** (2011) 126

- VP ($\Delta\alpha(q^2)$) can be inserted into QED NLO to approximate fermionic NNLO
  - $\rightsquigarrow$ exactly into $\mu^\pm e^- \to \mu^\pm e^- \gamma$ and into "non-loop γ" of vertex corrections
  - $\rightsquigarrow$ insertion into box diagrams can be approximated as $\mathcal{A}^{\text{box}} \cdot \mathcal{A}^0 \to \mathcal{A}^{\text{box}} \cdot \mathcal{A}^0 \times \Delta\alpha(t)$
  - $\rightsquigarrow$ VP insertion into "loop γ" at the vertex is missed



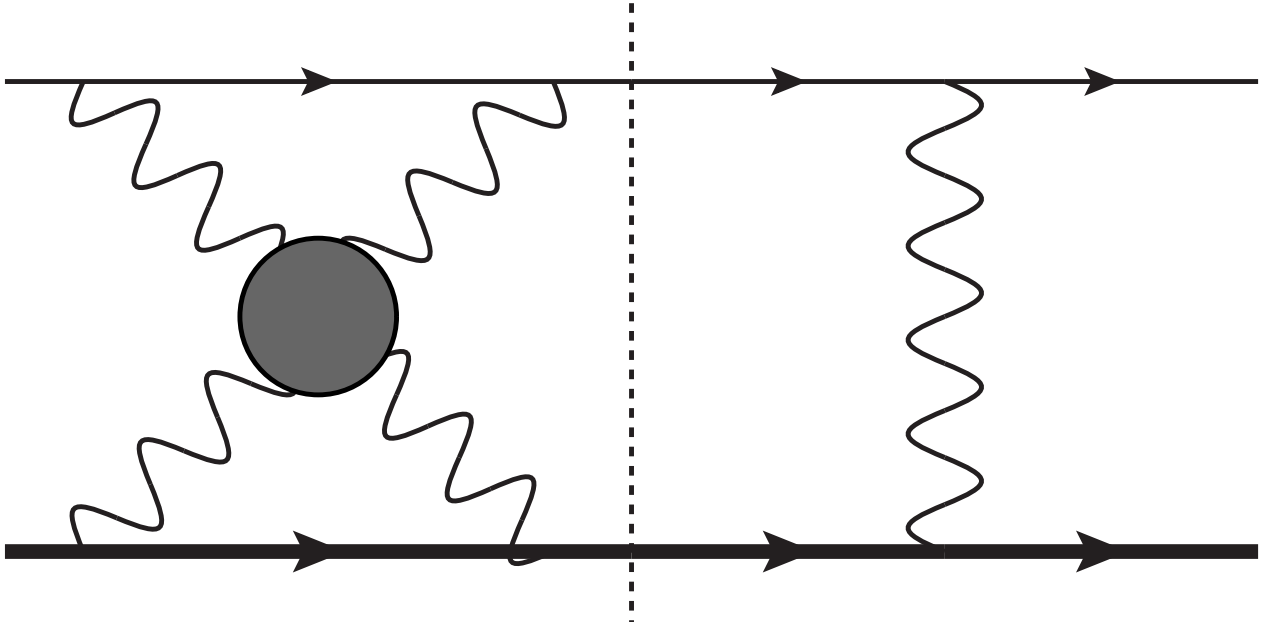
Approximate NNLO hadronic corrections

- E.g., isolating only corrections $\propto \Delta\alpha_{\rm had}$ and comparing with Fig. 2 of M. Fael and M. Passera, PRL 122 (2019) 19, 192001



- The bulk of HNNLO corrections is catched (better for μ^+ than μ^-)

No LbL up to N^{3}LO in μe scattering



is of $O(\alpha^5)$.

[i.e. $\mathcal{O}(\alpha^3)$ w.r.t. LO]

M. Fael, talk at MITP Topical Workshop, February 2018