The MUonE Project: Theory Progress

Massimo Passera
INFN Padova

International Workshop on e^+e^- collisions from Phi to Psi
Budker Institute of Nuclear Physics & Novosibirsk State U.
Feb 28 2019

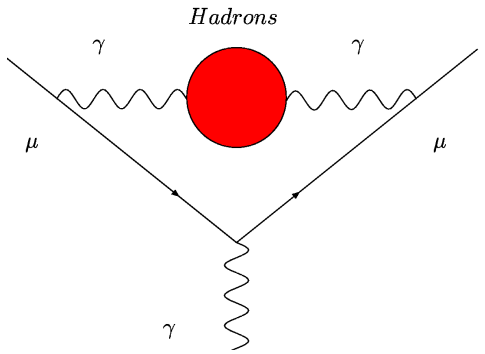
A new approach to a_μ^{HLO}

C. Carloni Calame, MP, L. Trentadue, G. Venanzoni

PLB 2015 - arXiv:1504.02228

Spacelike proposal for HLO

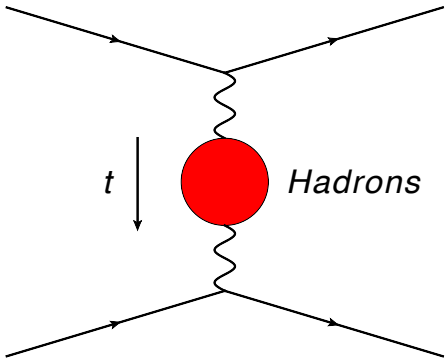
- At present, the leading hadronic contribution a_μ^{HLO} is computed via the timelike formula:



$$a_\mu^{\rm HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\,\sigma_{\rm had}^0(s)$$

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

- Alternatively, exchanging the x and s integrations in a_μ^{HLO}



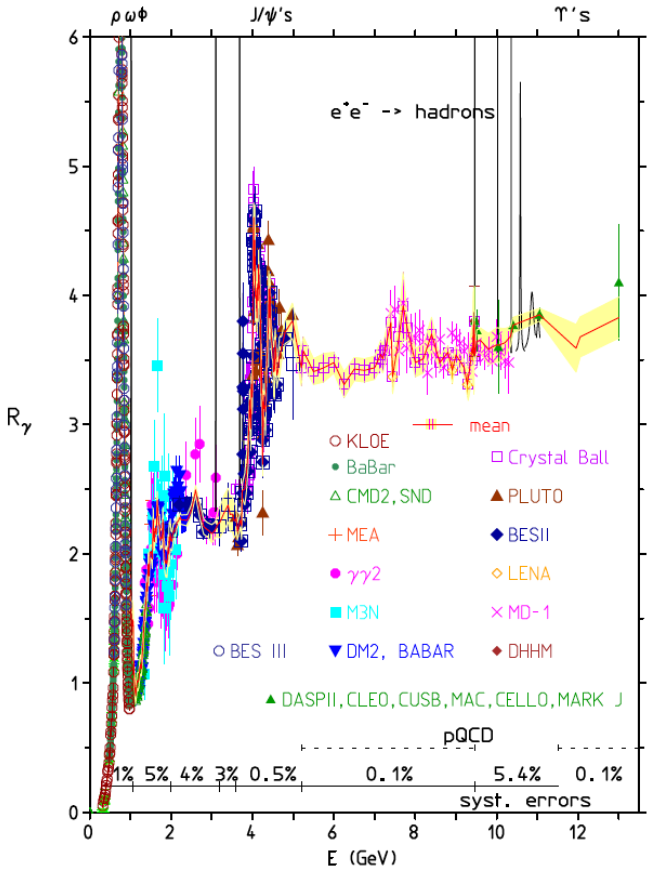
$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\rm had}[t(x)]$$

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

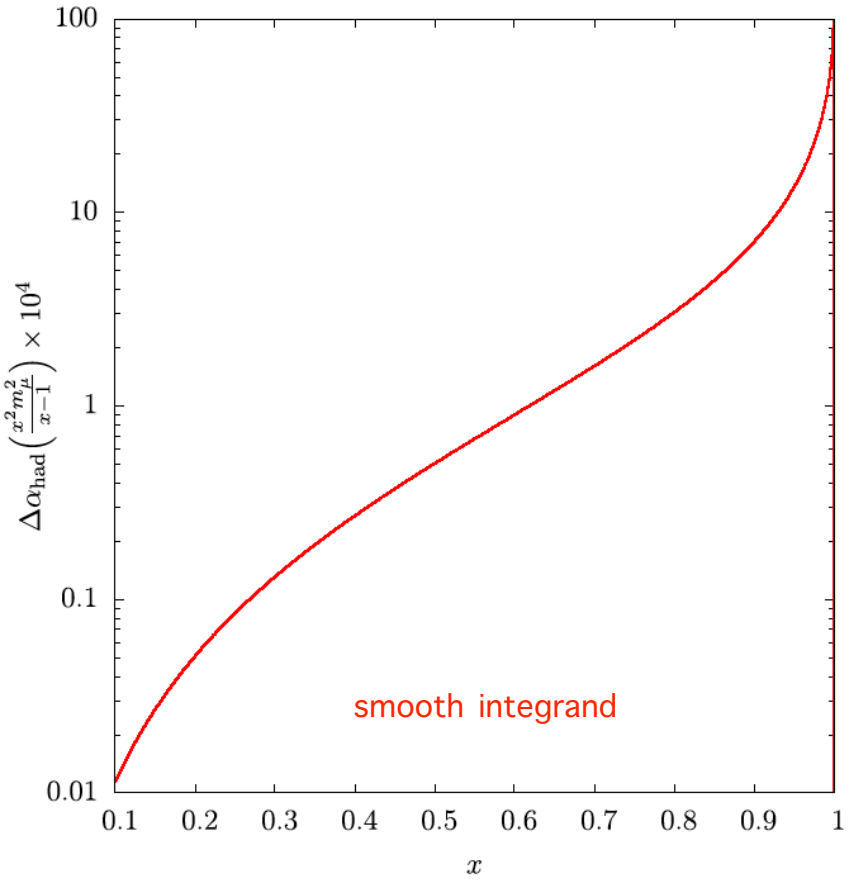
$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of α in the spacelike region. It can be extracted from scattering data!

Spacelike proposal for HLO (2)

Timelike



Spacelike

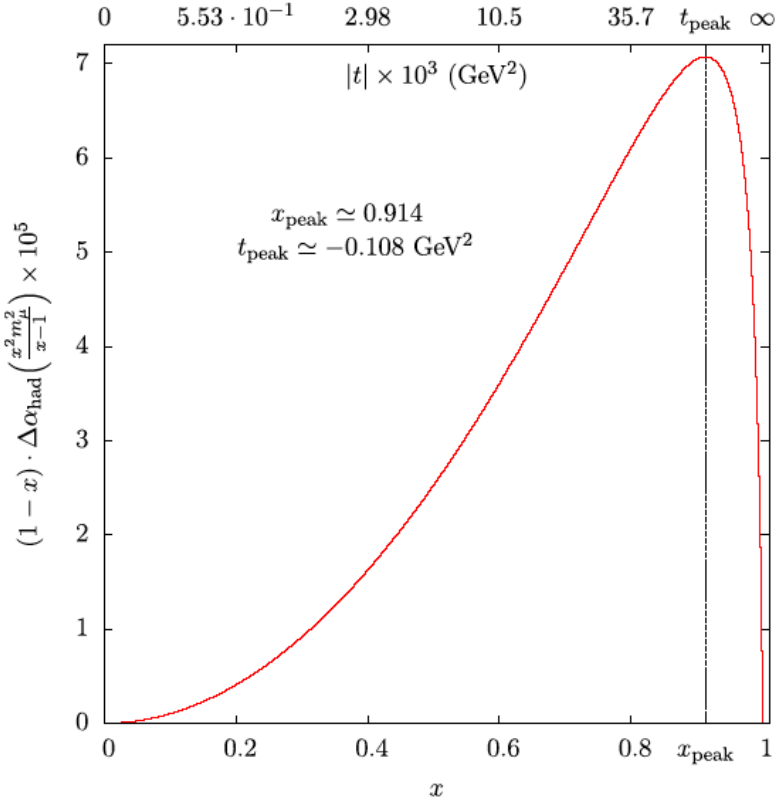


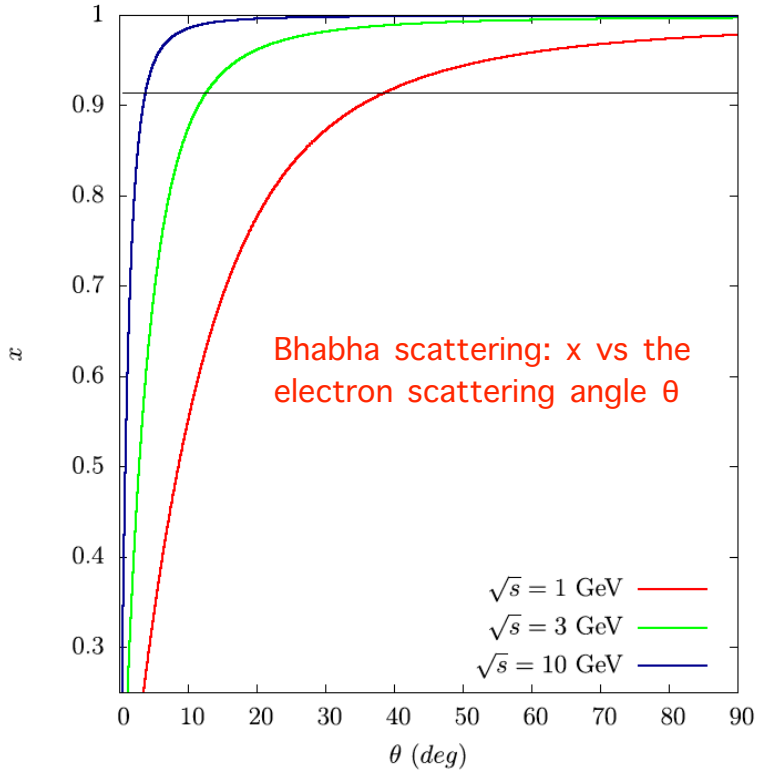
F. Jegerlehner, arXiv:1511.04473

Carloni Calame, MP, Trentadue, Venanzoni, PLB 2015

Spacelike proposal for HLO: which experiment?

- $\Delta\alpha_{had}(t)$ can be measured via Bhabha scattering:





- The peak occurs at $x_{peak} = 0.914$, $t_{peak} = -0.108$ GeV$^2 \simeq -(330$ MeV$)^2$

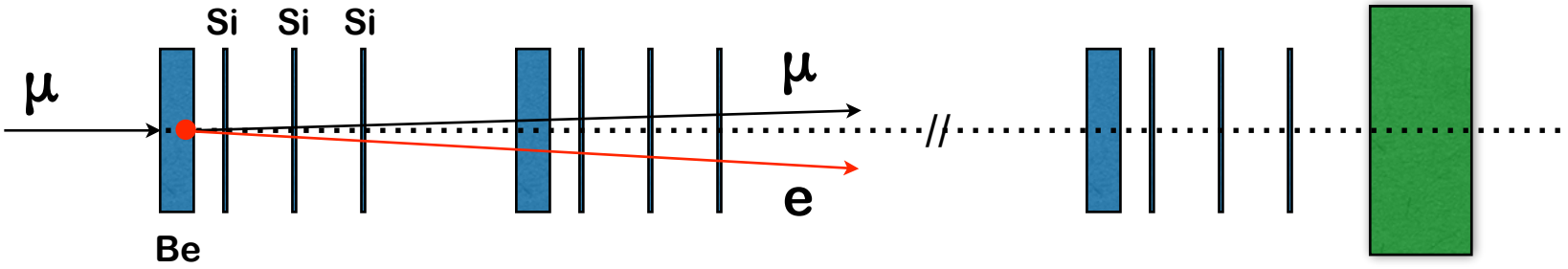
Muon-electron scattering: The MUonE Project

Abbiendi, Carloni Calame, Marconi, Matteuzzi, Montagna, Nicrosini, MP, Piccinini, Tenchini, Trentadue, Venanzoni

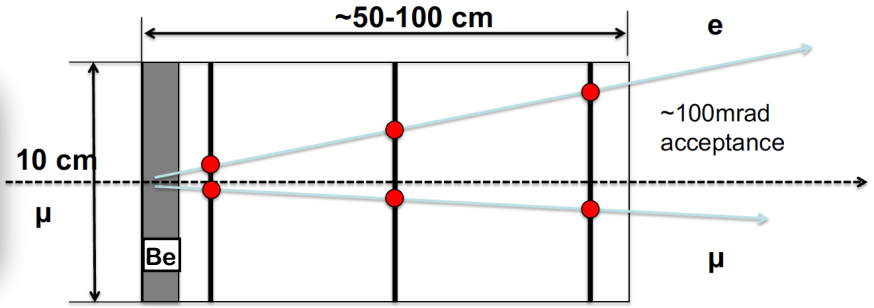
EPJC 2017 - arXiv:1609.08987

Muon-electron scattering @ CERN

- $\Delta\alpha_{had}(t)$ can also be measured via the elastic scattering $\mu\, e \rightarrow \mu\, e$.
- We propose to scatter a 150 GeV muon beam, available at CERN's North Area, on a fixed electron target (Beryllium). Modular apparatus: each module has one layer of Beryllium (target) followed by several thin Silicon strip detectors.



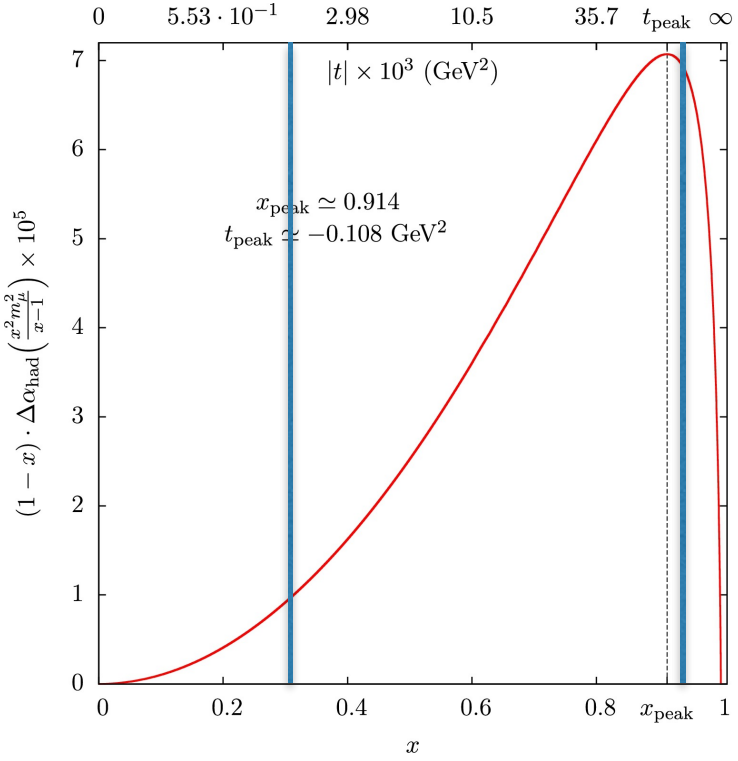
See Marconi's talk

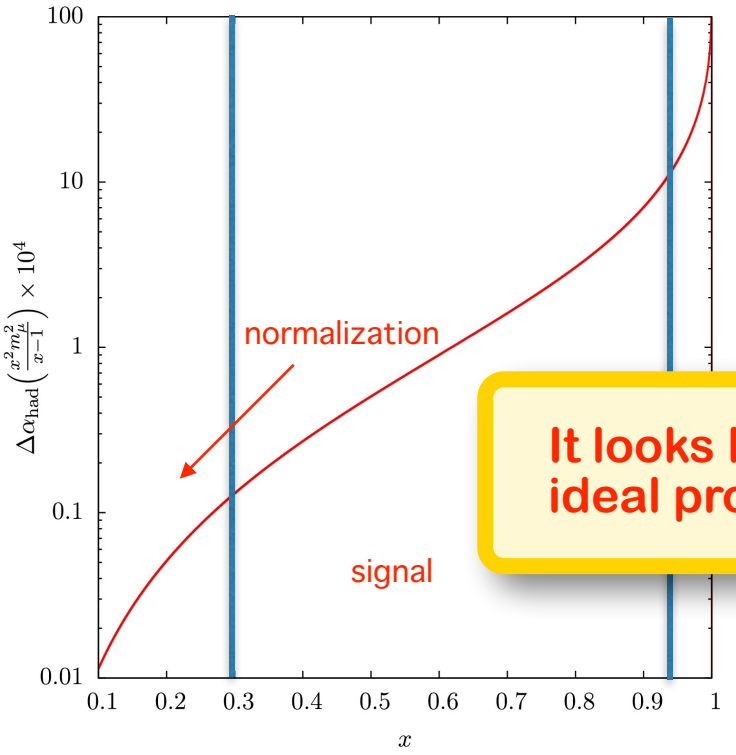


- State-of-the-art Si detectors: ~20μm hit resolution → ~0.02mrad expected angular resolution. ECAL and μ filter at the end for PID.

a_μ^{HLO} via muon-electron scattering

- For a 150 GeV muon beam, the scan region extends up to x=0.932, ie beyond the peak! (the peak is at x=0.914)
- The integrand in the remaining region x ∈ [0.932,1] accounts for ~13% of the a_μ^{HLO} integral. It cannot be reached by our experiment but it can be determined using time-like data & pQCD, and/or lattice QCD results.





It looks like an ideal process!

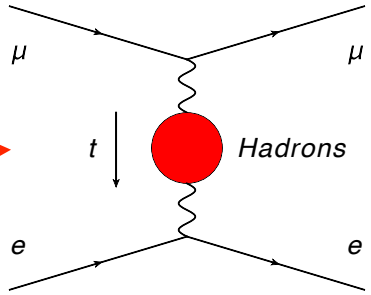
a_μ^{HLO} via muon-electron scattering (2)

- **Statistics**: With CERN's 150 GeV muon beam M2 (1.3×10^7 μ/s), incident on Be layers (total thickness 60cm), 2 years of data taking (2×10^7 s/yr) → integrated luminosity $\mathcal{L}_{int} \sim 1.5 \times 10^7$ nb^{-1}.

- With this $\mathcal{L}_{int}$ we estimate that we can reach a statistical sensitivity of ~ 0.3% on a_μ^{HLO}, ie ~ 20×10^{-11}.

- **Systematics:** Systematic effects must be known at ≲ 10ppm.

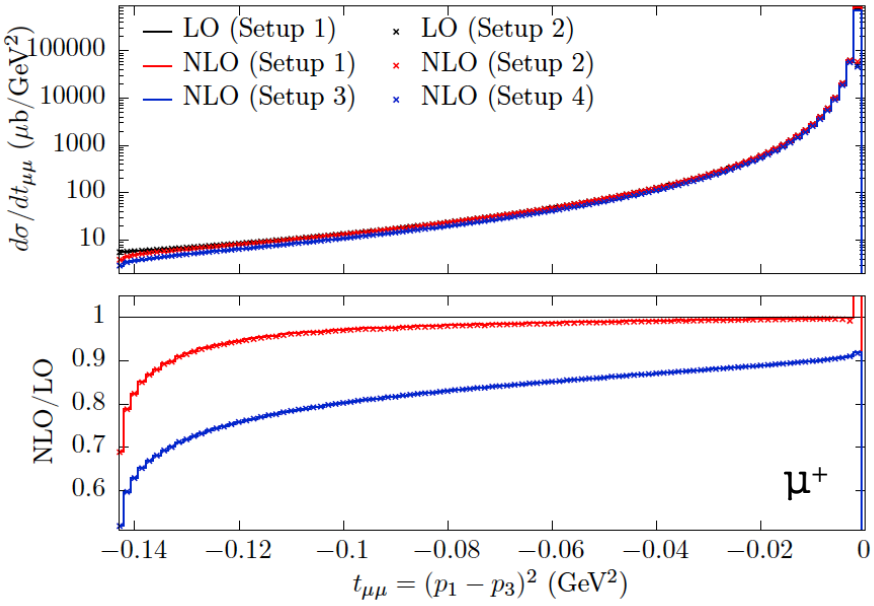
- **Theory:** To extract $\Delta\alpha_{had}(t)$ from this measurement, the ratio of the SM cross sections in the signal and normalisation regions must be known at ≲ 10ppm!

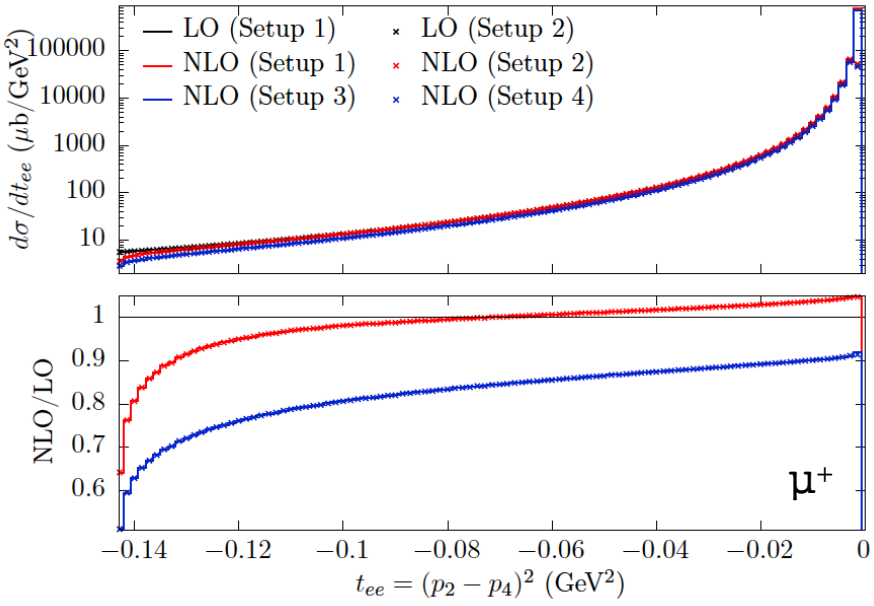


Theory of μe scattering: NLO

- **Full set of NLO QED + EW corrections computed & checked.**

Pavia Group





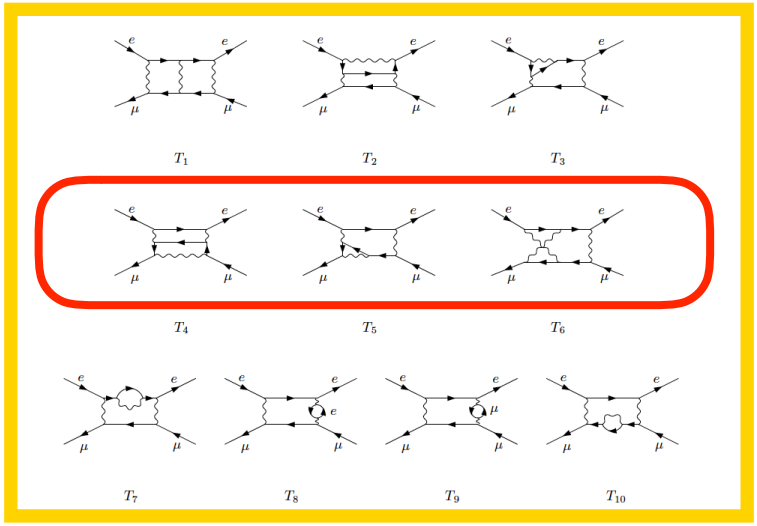
Alacevich, Chiesa, Montagna, Nicrosini, Piccinini, Carloni Calame, arXiv:1811.06743.

- **Fully differential fixed order MC @ NLO ready!**

See C. Carloni Calame's talk

Theory of μe scattering: NNLO QED

- **NNLO: Missing MI for both planar and non-planar 2-loop box diagrams computed!** Padova Group
- **Method of differential equations and Magnus exponential series adopted. Massless electron, full muon mass dependence.**



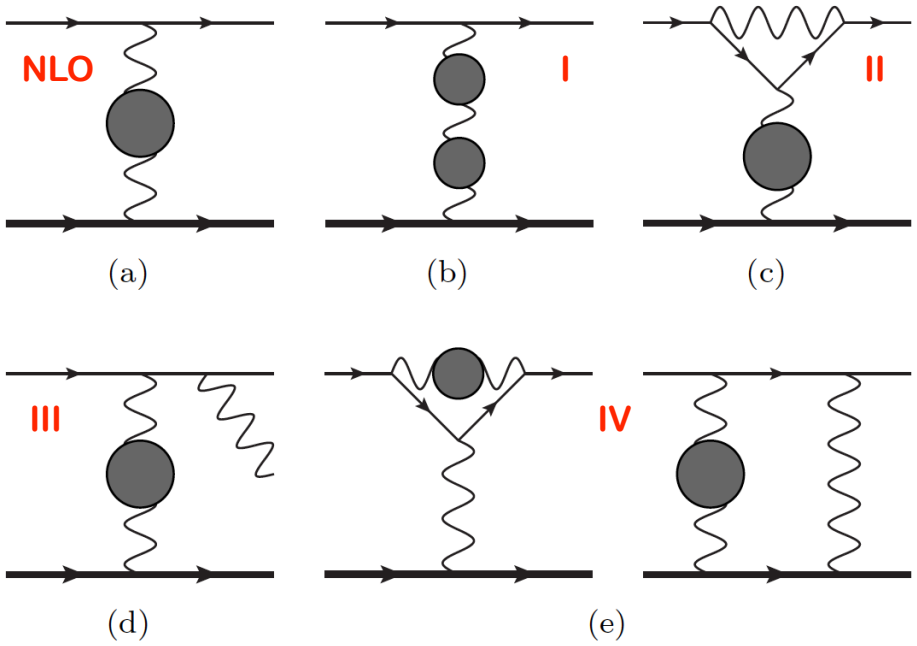
Mastrolia, MP, Primo, Schubert, arXiv:1709.07435 (planar)
Di Vita, Laporta, Mastrolia, Primo, Schubert, arXiv:1806.08241 (non-planar)

- **Interplay with Dimuon & ttbar production calculations**

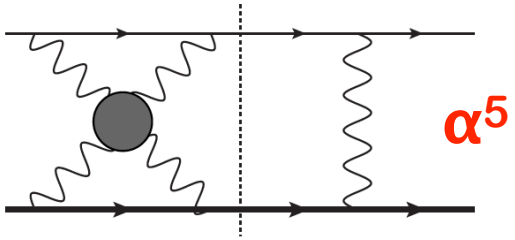
Bern, Dixon, Ghinculov, hep-ph/0010075
Bonciani, Ferroglia, Gehrmann, Maitre, Studerus, 0806.2301
Bonciani, Ferroglia, Gehrmann, von Manteuffel, Studerus,1309.445
Lee, Mingulov, 1901.04441

Theory of μe scattering: NNLO hadronic

- **Muon-electron scattering at NNLO: the hadronic corrections**



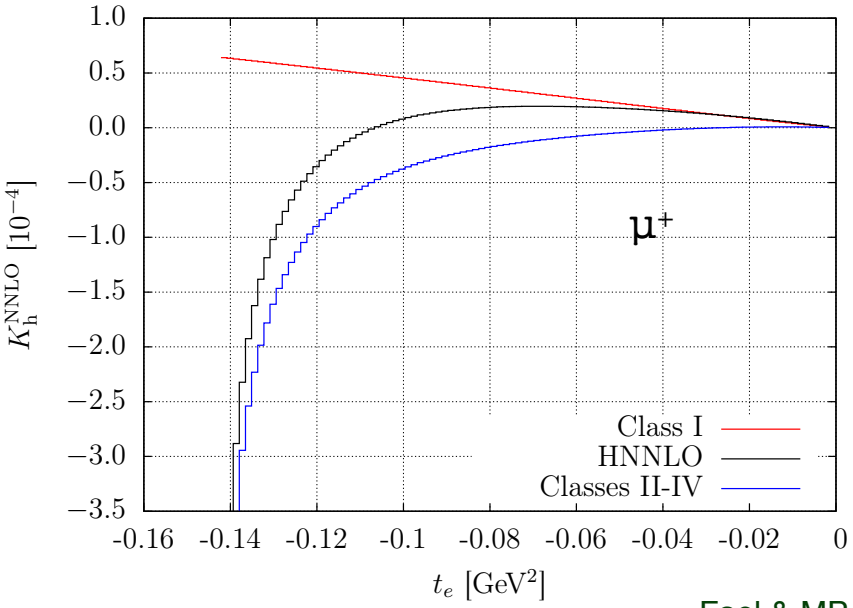
NB: There are no LbL corrections @ NNLO!

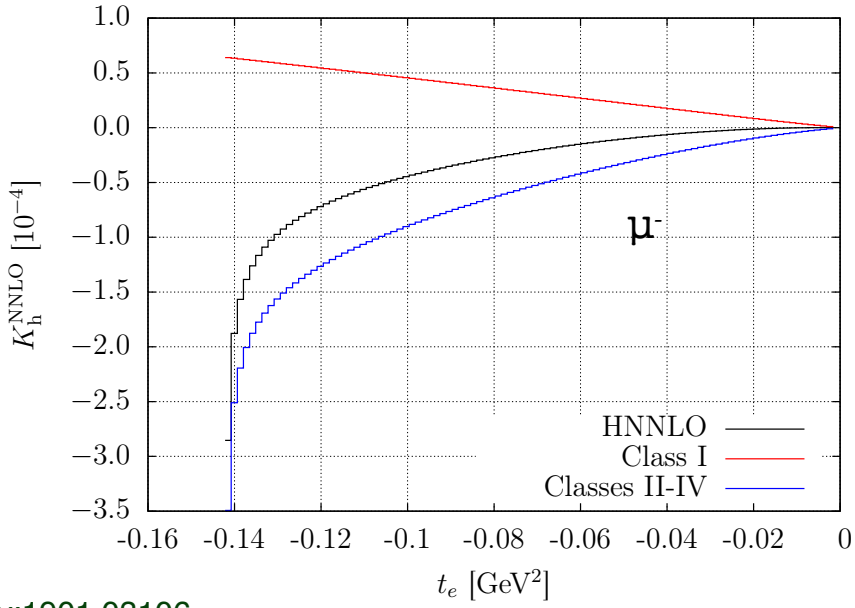


Fael & MP, arXiv:1901.03106

Theory of μe scattering: NNLO hadronic (2)

- Full m_e & m_μ dependence. Two independent implementations:
  1. FeynArts + FormCalc + Collier (Fortran). FKS for IR.
  2. FeynCalc + Package-X (Mathematica). Slicing for IR.
- $\Pi_{had}(t)$ & $R_{had}(z)$ from Jegerlehner's alphaQEDc17 and Keshavarzi, Nomura, Teubner's VP_KNT_v3_0.





Fael & MP, arXiv:1901.03106

- These corrections are 10^{-4} – 10^{-5} → crucial for MUonE!

Theory of μe scattering: NNLO hadronic (spacelike)

- **Hadronic corrections at NNLO with spacelike data (MUonE data!) via the hyperspherical integration method**

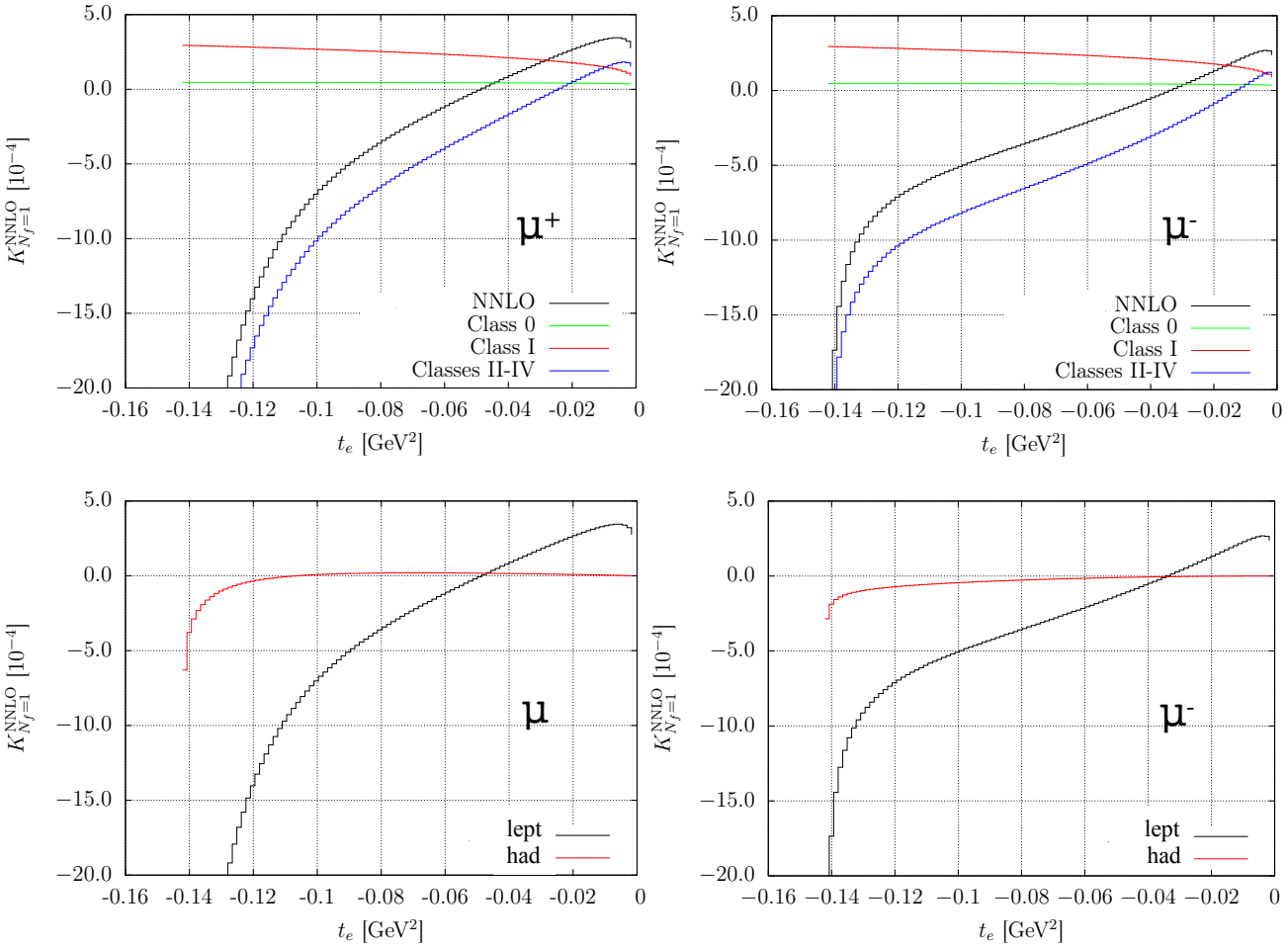
Fael, arXiv:1808.08233

	To $R(s)$	Not to $R(s)$
Based on	$\Pi_{\rm had}(t<0)$ & $\mathrm{Im}\Pi_{\rm had}(s>0)$	$\Pi_{\rm had}(t<0)$
Data input	timelike $R(s)$	MUonE
	$\sqrt{s}\in[2m_\pi, 11.5\mathrm{GeV}]$	$t\in[-0.143,0]\ \mathrm{GeV}^2+\ldots$
Th. Assumptions	$\Pi^{(NLO)}_{\rm had}(t)\neq\Pi^{(NNLO)}_{\rm had}(t)$	$\Pi^{(NLO)}_{\rm had}(t)=\Pi^{(NNLO)}_{\rm had}(t)$
Class IV integrands	Oscillatory	Smooth
IR "safe"	⚠	✓
Fortran code	✓	✗

M. Fael, 3rd MUonE Theory Workshop, U. Zurich, 6 Feb 2019

Theory of μe scattering: NNLO leptonic

- **Muon-electron scattering at NNLO: the "leptonic" corrections**



Fael & MP 2019

- **Partial cancelations with e^+e^- production corrections.**

Theory of μe scattering: to do & open issues

- **NNLO: QED double-virtual matrix elements**
  Di Vita, Fael, Glaus, Laporta, Mastrolia, MP, Peraro, Primo, Schubert, Spira, Torres-Bobadilla, …
- **NNLO: QED double real radiation & real-virtual corrections**
  Fael, Mastrolia, Ossola, MP, Signer, Ulrich, Torres-Bobadilla, …
- **NNLO: leptonic and hadronic pair production** Pavia group, Czyż, …
- **NNLO: hadronic corrections with spacelike data** Fael, MP, …
- **NNLO: "Massification", ie how to obtain the leading electron mass terms from the corresponding massless amplitude and virtual soft contribution?** Banerjee, Becher, Broggio, Engel, Signer, Ulrich, …
- **Extend the MC to fixed order NNLO** Pavia group, Czyż, …
- **Match the NNLO calculations with resummation of the log contributions**
- **Resummation & experimental cuts: Log(of what?)? How can we assess the higher-order uncertainties?**

Still lots of work needed towards our final TH goal!

1st MUonE theory workshop: Padova 2017

Muon-electron scattering: Theory kickoff workshop

4-5 September 2017

https://agenda.infn.it/internalPage.py?pageId=0&confId=13774

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 t
tools. This kickoff workshop is intended to stimulate

It is organized and hosted by INFN Padova and the
University.

Organizing Committee
Carlo Carloni Calame - INFN Pavia
Pierpaolo Mastrolia - U. Padova
Guido Montagna - U. Pavia
Oreste Nicrosini - INFN Pavia
Paride Paradisi - U. Padova
Massimo Passera - INFN Padova (Chair)
Fulvio Piccinini - INFN Pavia
Luca Trentadue - U. Parma

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INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI PADOVA

2nd MUonE theory workshop: Mainz 2018

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

2018

3rd MUonE theory workshop: Zurich 2019

2^{nd} Workstop / Thinkstart: 4^{th} – 7^{th} Feb 2019

Theory for muon-electron scattering @ 10ppm

Y36 K08, Physik-Institut, University of Zurich

Organized by
A. Signer & Y. Ulrich

4th MUonE theory workshop in 2020

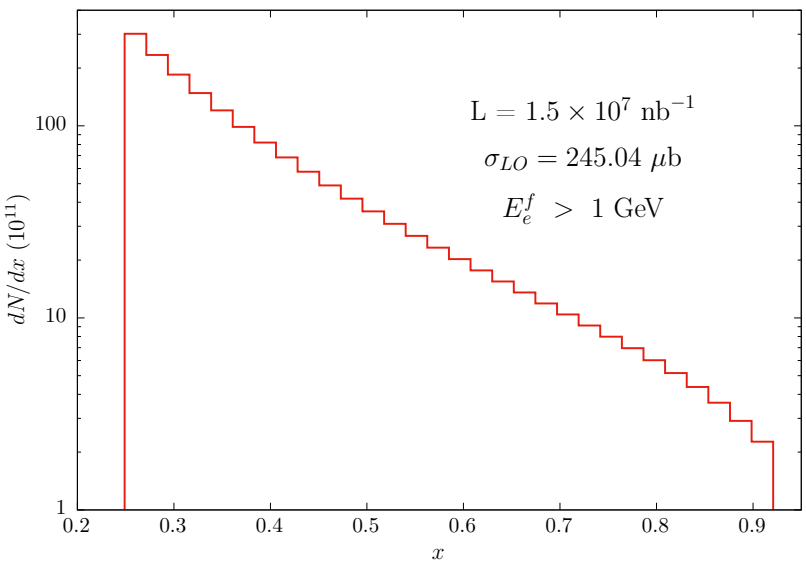
Conclusions

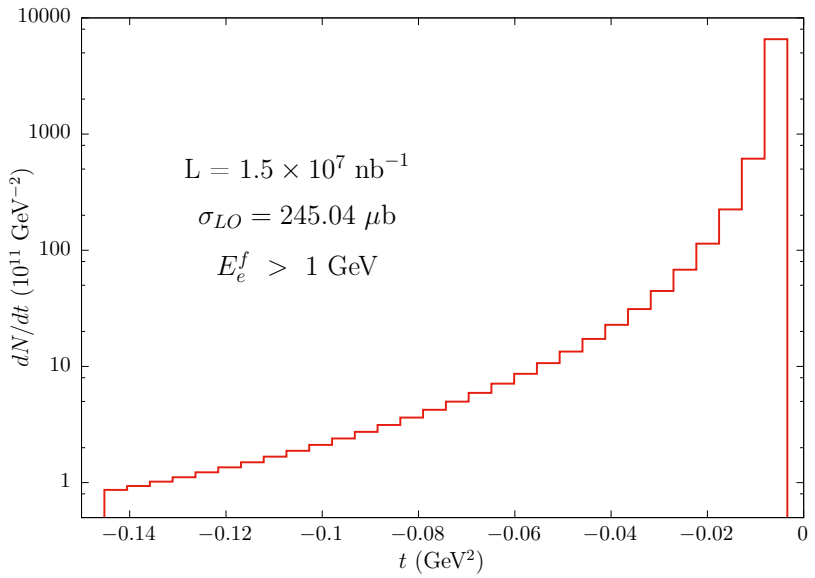
- MUonE: a proposal for a new experiment at CERN to measure the leading hadronic contribution to the muon g-2 via μe scattering. It is a very challenging experiment!
- Positive report from CERN's "Physics Beyond Colliders" Working Group. LoI to CERN's SPSC planned by 2019.
- Great theory progress: Fully differential fixed order MC @ NLO ready. NNLO: All missing MI for 2-loop box diagrams computed. NNLO: hadronic & leptonic corrections computed.
- Lots of theory work still needed towards our final theory goal: a running MC code for the ratio of the SM cross sections in the signal and normalisation regions at $\lesssim$ 10ppm!

The μONE collaboration is growing…

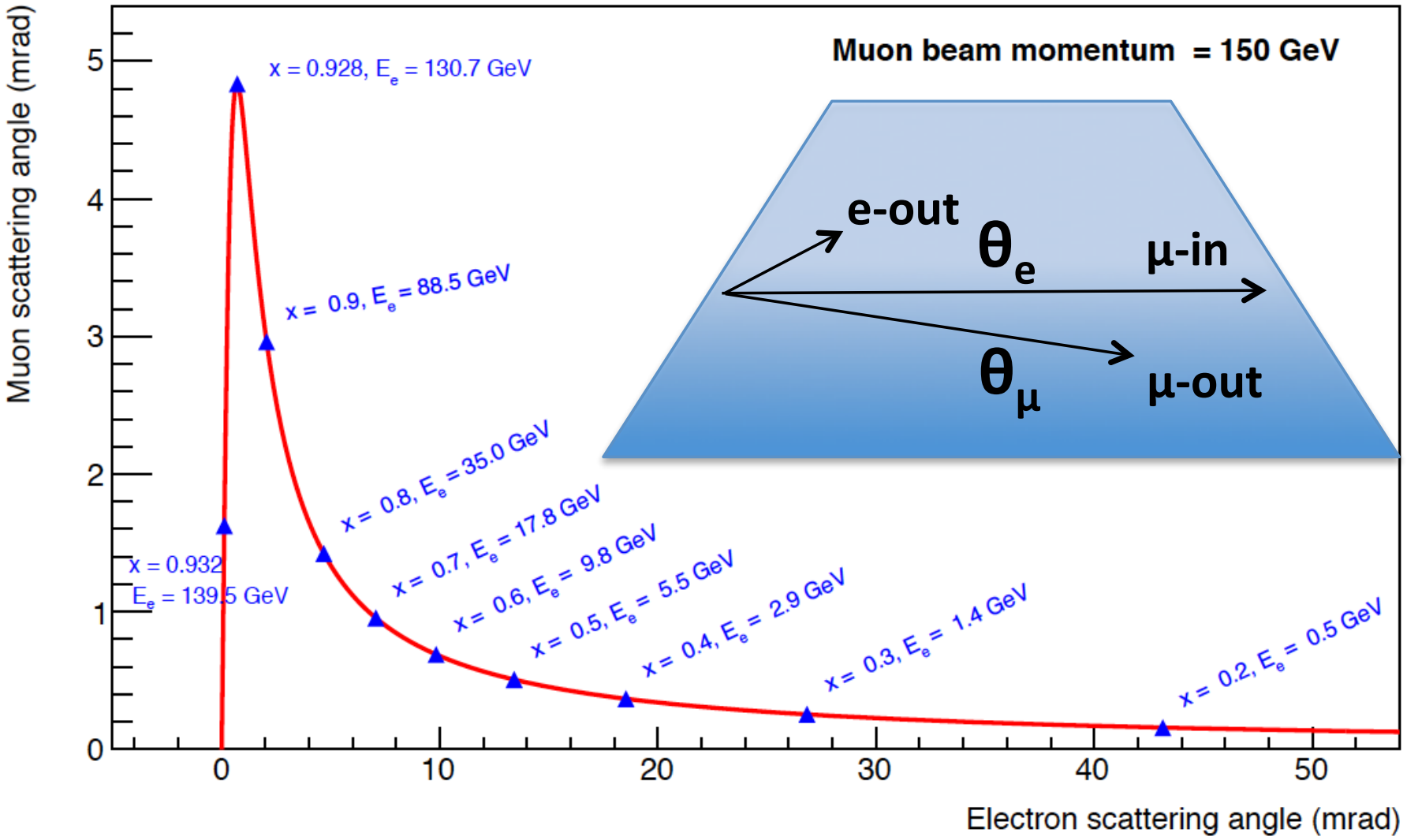
The End

Backup


L = 1.5 × 10^7 nb^−1
σ_LO = 245.04 μb
E_e^f > 1 GeV
dN/dx (10^11)
x
100
10
1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


L = 1.5 × 10^7 nb^−1
σ_LO = 245.04 μb
E_e^f > 1 GeV
dN/dt (10^11 GeV^−2)
t (GeV^2)
10000
1000
100
10
1
−0.14
−0.12
−0.1
−0.08
−0.06
−0.04
−0.02
0

Muon-electron scattering — kinematics



Future plans

- CERN's Physics Beyond Colliders Working Group Report:
  "The aim of the MUonE proposal… would be an extremely valuable independent determination for the value of $(g-2)_\mu$"

  A. Dainese et al., CERN-PBC-REPORT-2018-008, arXiv:1901.04482

- 2019
  - March 24-25: 1st collaboration meeting @ Cern
  - Letter of Intent planned to CERN's SPSC

- 2020-21
  - Detector design, construction & installation
  - Final feasibility studies with a detector prototype

- 2022-24
  - 1st run: scaled detector and reduced accuracy

See Marconi's talk