Mu-e scattering: Measuring the leading hadronic contribution to $(g\text{-}2)_\mu$

Massimo Passera
INFN Padova

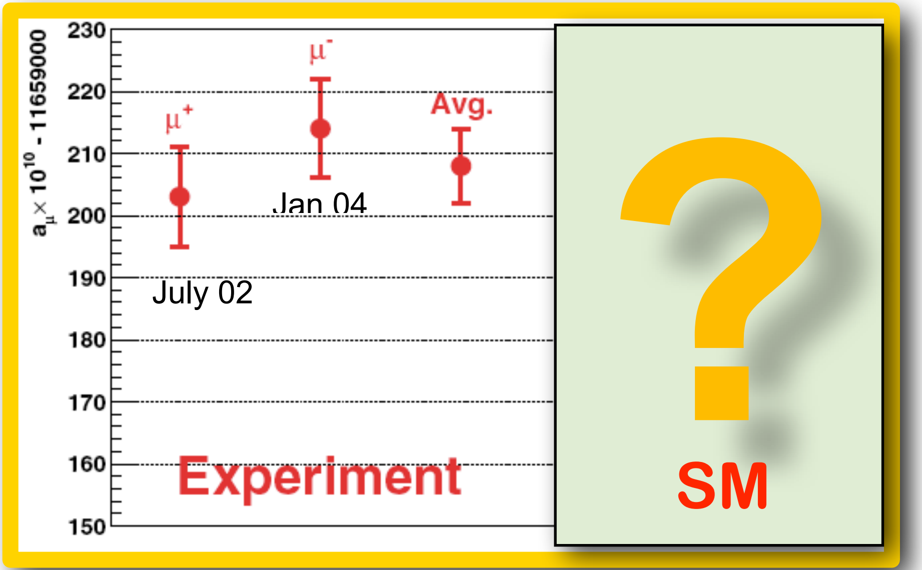
KEK
9 February 2018

Outline

- Status of the muon g-2
- Hadronic corrections to the muon g-2: a new approach
- Muon-electron scattering: proposal for a new experiment

Status of the muon g-2

The muon g-2: experimental status



- BNL E821: $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys}) \times 10^{-11}$ [0.5ppm].
- Future: new muon g-2 experiments at:
  - Fermilab E989: aims at $\pm 16 \times 10^{-11}$, ie 0.14ppm. Started taking data at the end of 2017. First result expected in late 2018 with a precision comparable to BNL E821.
  - J-PARC proposal: phase-1 start with 0.46ppm (TDR 2017).
- Are theorists ready for this (amazing) precision? Not yet!

The muon g-2: the QED contribution

$a_\mu^{QED} = (1/2)(\alpha/\pi)$ Schwinger 1948

$+ \ 0.765857426\ (16)\ (\alpha/\pi)^2$

Sommerfield; Petermann; Suura&Wichmann ’57; Elend ’66; MP ’04

$+ \ 24.05050988\ (28)\ (\alpha/\pi)^3$

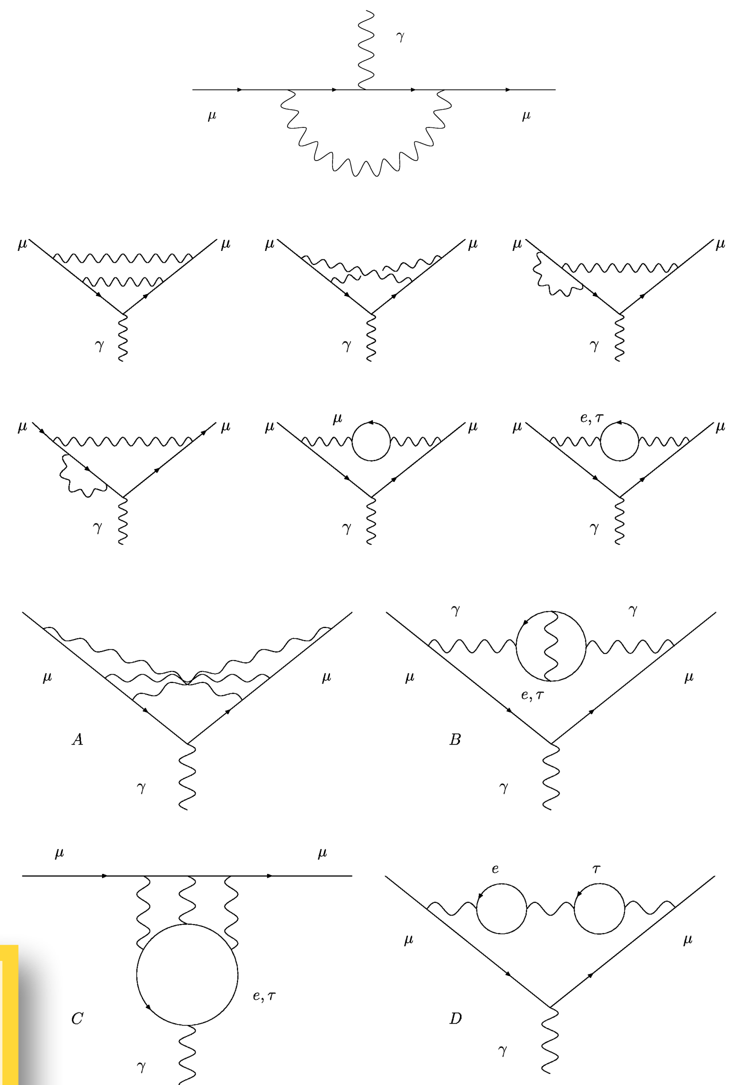
Remiddi, Laporta, Barbieri … ; Czarnecki, Skrzypek; MP ’04;
Friot, Greynat & de Rafael ’05, Mohr, Taylor & Newell 2012

$+ \ 130.8780\ (60)\ (\alpha/\pi)^4$

Kinoshita & Lindquist ’81, … , Kinoshita & Nio ’04, ’05;
Aoyama, Hayakawa,Kinoshita & Nio, 2007, Kinoshita et al. 2012 & 2015;
Steinhauser et al. 2013, 2015 & 2016 (all electron & τ loops, analytic);
S. Laporta, arXiv:1704.06996 (mass independent term). COMPLETED[2]!

$+ \ 750.80\ (89)\ (\alpha/\pi)^5$ **COMPLETED!**

Kinoshita et al. ‘90, Yelkhovsky, Milstein, Starshenko, Laporta,…
Aoyama, Hayakawa, Kinoshita, Nio 2012 & 2015 & 2017



Adding up, I get:

$a_\mu^{QED} = 116584718.976\ (20)(73) \times 10^{-11}$

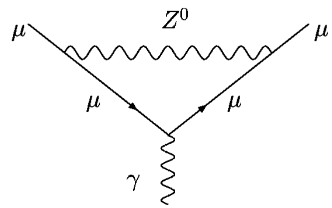
from coeffs, mainly from 4-loop unc   from δα(Rb)

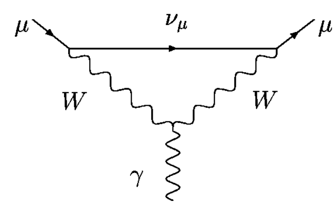
with $\alpha = 1/137.035998995(85)$ [0.62 ppb]

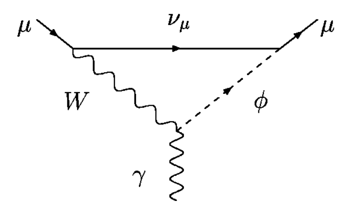
…

The muon g-2: the electroweak contribution

- **One-loop term:**







$$a_\mu^{\mathrm{EW}}(\text{1-loop}) = \frac{5 G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1+\frac{1}{5}\left(1-4\sin^2\theta_W\right)^2+O\left(\frac{m_\mu^2}{M^2_{Z,W,H}}\right)\right] \approx 195\times 10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda;

Studenikin et al. ’80s

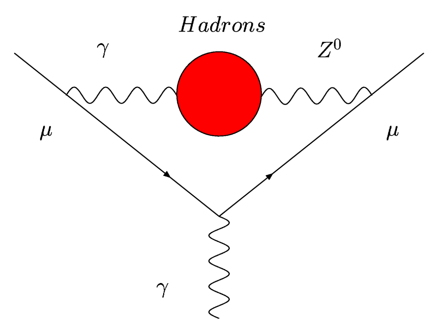
- **One-loop plus higher-order terms:**

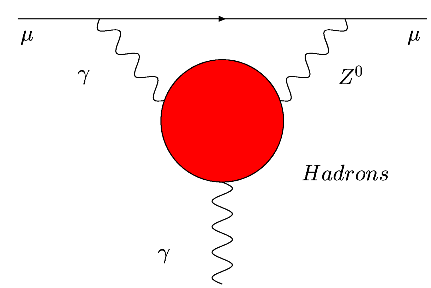
$$\boxed{a_\mu^{\mathrm{EW}} = 153.6\ (1) \times 10^{-11}}$$

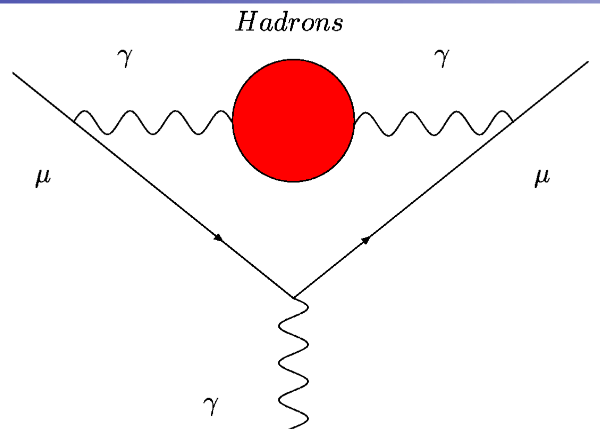
with M_{Higgs} = 125.6 (1.5) GeV

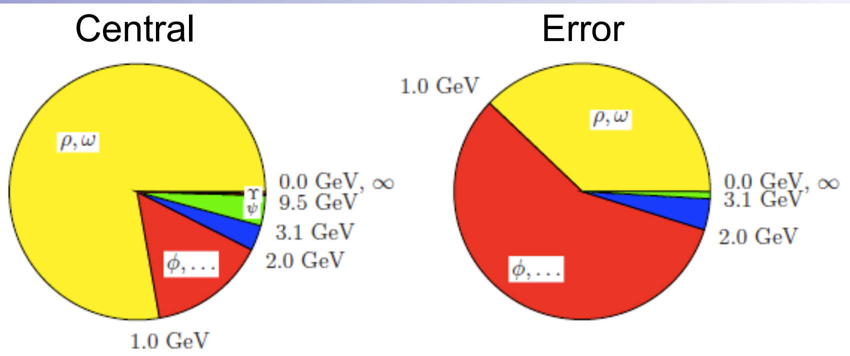
Hadronic loop uncertainties and 3-loop nonleading logs.

Kukhto et al. ’92; Czarnecki, Krause, Marciano ’95; Knecht, Peris, Perrottet, de Rafael ’02; Czarnecki, Marciano and Vainshtein ’02; Degrassi and Giudice ’98; Heinemeyer, Stockinger, Weiglein ’04; Gribouk and Czarnecki ’05; Vainshtein ’03; Gnendiger, Stockinger, Stockinger-Kim 2013.









F. Jegerlehner and A. Nyffeler, Phys. Rept. 477 (2009) 1

$$K(s) = \int_0^1 dx \, \frac{x^2(1-x)}{x^2 + (1-x)(s/m^2)} \qquad a_\mu^{\mathrm{HLO}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds \, K(s)\,\sigma^{(0)}(s) = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s) R(s)$$

$a_\mu^{\mathrm{HLO}} = 6894.6\ (32.5) \times 10^{-11}$ F. Jegerlehner, arXiv:1711.06089

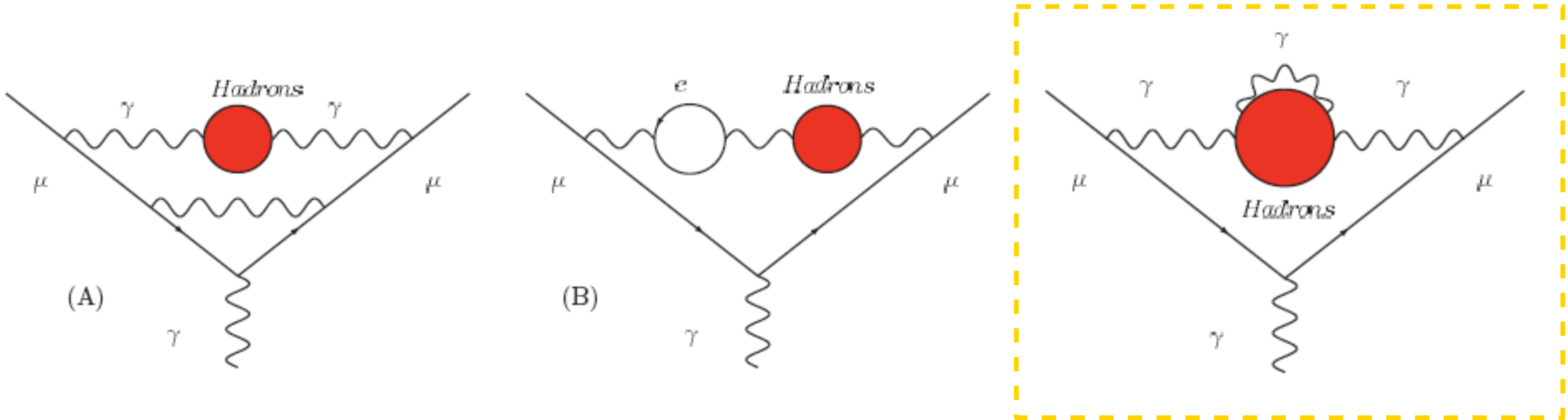
$= 6931\ (34) \times 10^{-11}$ Davier, Hoecker, Malaescu, Zhang, arXiv:1706.09436

$= 6932.7\ (24.6) \times 10^{-11}$ Keshavarzi, Nomura, Teubner, arXiv:1802.02995

- **Radiative Corrections are crucial.** S. Actis et al, Eur. Phys. J. C66 (2010) 585
- **Lots of progress in lattice calculations.** FNAL - Muon g-2 workshop - June 2017
  Capri - FCCP 2017 workshop - Sep 2017

HNLO: Vacuum Polarization

Already included in a_μ^{HLO}

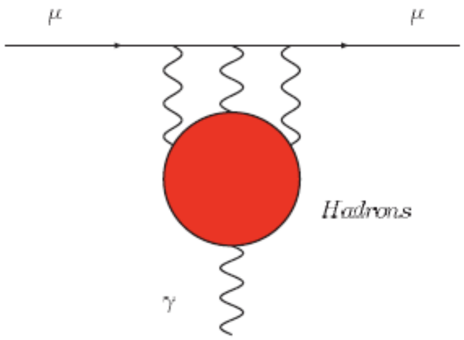


O(α^3) contributions of diagrams containing hadronic vacuum polarization insertions:

$$a_\mu^{HNLO}(vp) = -99.27\ (67) \times 10^{-11}$$

Krause '96, Alemany et al. '98, Hagiwara et al. 2011, Jegerlehner 2017

HNLO: Light-by-light contribution



- Unlike the HLO term, the hadronic l-b-l term relies at present on theoretical approaches.
- This term had a troubled life! Latest values:

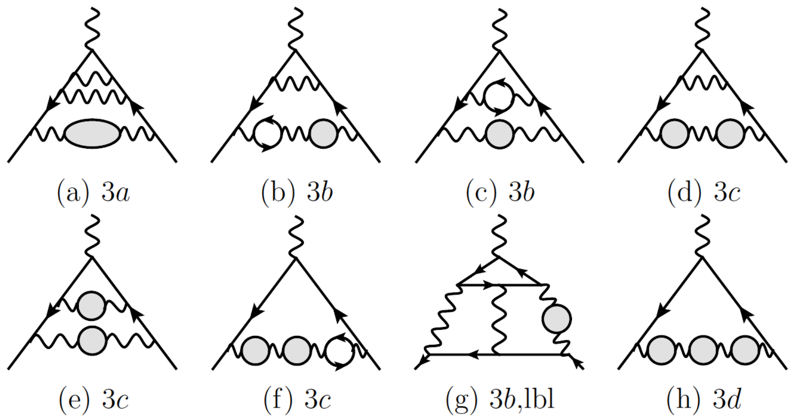
$a_\mu^{HNLO}(lbl) = +80\ (40) \times 10^{-11}$	Knecht & Nyffeler '02
$a_\mu^{HNLO}(lbl) = +136\ (25) \times 10^{-11}$	Melnikov & Vainshtein '03
$a_\mu^{HNLO}(lbl) = +105\ (26) \times 10^{-11}$	Prades, de Rafael, Vainshtein '09
$a_\mu^{HNLO}(lbl) = +100\ (29) \times 10^{-11}$	Jegerlehner, arXiv:1705.00263

Results based also on Hayakawa, Kinoshita '98 & '02; Bijnens, Pallante, Prades '96 & '02

- Improvements expected in the π^0 transition form factor A. Nyffeler 1602.03398
- The HLbL contribution can be expressed in terms of observables in a dispersive approach. Colangelo et al, 2014, 15 & 17; Pauk & Vanderhaeghen 2014.
- Progress on the lattice: $+53.5(13.5)\times 10^{-11}$. Statistical error only, finite-volume and finite lattice-spacing errors being studied. Omitted subleading disconnected graphs still need to be computed.

Blum, Christ, Hayakawa, Izubuchi, Jin, Jung, Lehner, arXiv:1610.04603

HNNLO: Vacuum Polarization



$O(\alpha^4)$ contributions of diagrams containing hadronic vacuum polarization insertions:

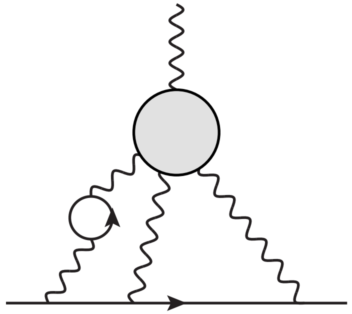
$$a_\mu^{HNNLO}(vp) = 12.4\ (1) \times 10^{-11}$$

Kurz, Liu, Marquard, Steinhauser 2014

HNNLO: Light-by-light

$$a_\mu^{HNNLO}(lbl)\ = 3\ (2) \times 10^{-11}$$

Colangelo, Hoferichter, Nyffeler, MP, Stoffer 2014



Comparisons of the SM predictions with the measured g-2 value:

$a_\mu^{EXP} = 116592091\ (63) \times 10^{-11}$

E821 – Final Report: PRD73 (2006) 072 with latest value of $\lambda=\mu_\mu/\mu_p$ from CODATA'10

$a_\mu^{SM} \times 10^{11}$	$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$	σ
116 591 783 (44)	$308\ (77) \times 10^{-11}$	4.0 [1]
116 591 820 (45)	$271\ (77) \times 10^{-11}$	3.5 [2]
116 591 821 (38)	$270\ (74) \times 10^{-11}$	3.7 [3]

with the hadronic light-by-light $a_\mu^{HNLO}(lbl) = 100\ (29) \times 10^{-11}$ of F. Jegerlehner arXiv:1705.00263, and the hadronic leading-order of:

[1] F. Jegerlehner, arXiv:1711.06089.
[2] Davier, Hoecker, Malaescu, Zhang, arXiv:1706.09436.
[3] Keshavarzi, Nomura, Teubner, arXiv:1802.02995.

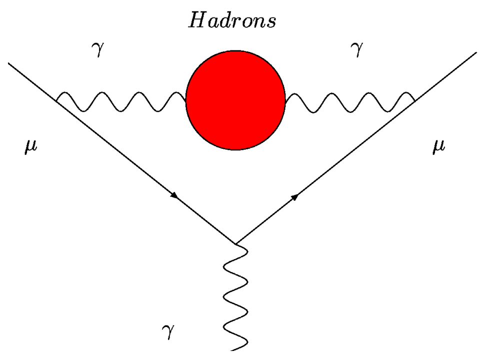
A new approach to a_μ^{HLO}

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

PLB 2015 - arXiv:1504.02228

New space-like proposal for HLO

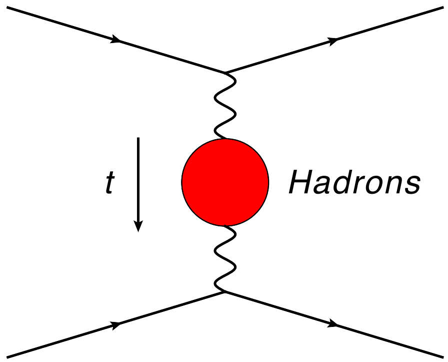
- At present, the leading hadronic contribution a_μ^{HLO} is computed via the time-like formula:



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

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

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



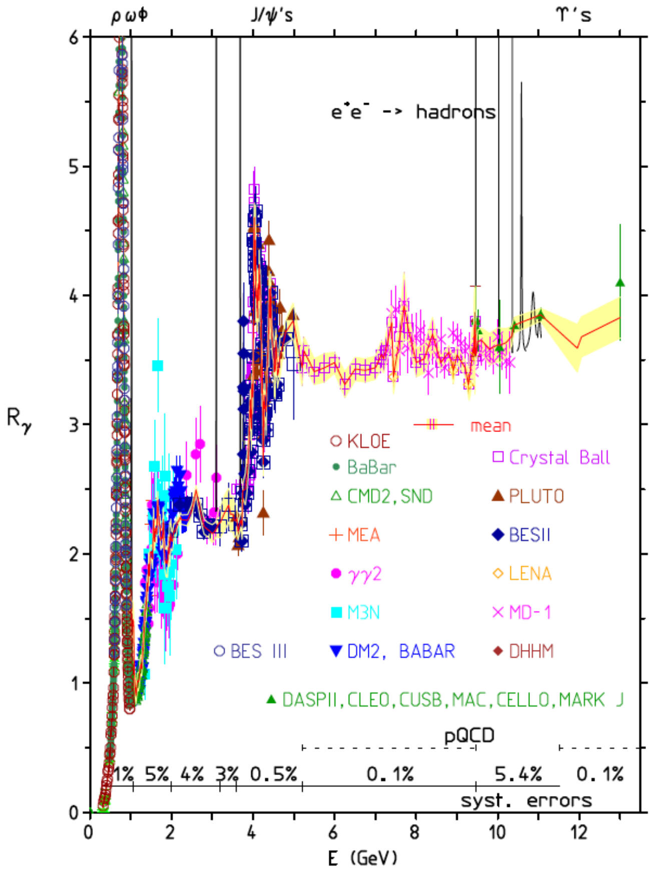
$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

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

which involves $\Delta\alpha_{had}(t)$, the hadronic contribution to the running of α in the space-like region. It can be extracted from scattering data!

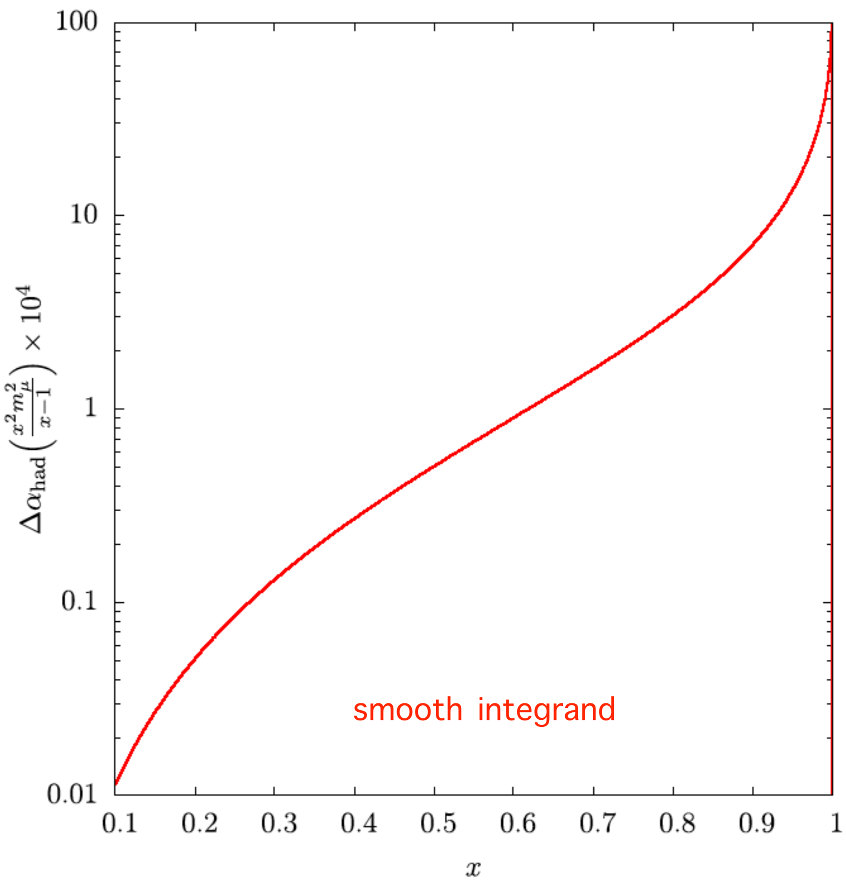
New space-like proposal for HLO (2)

Time-like



F. Jegerlehner, arXiv:1511.04473

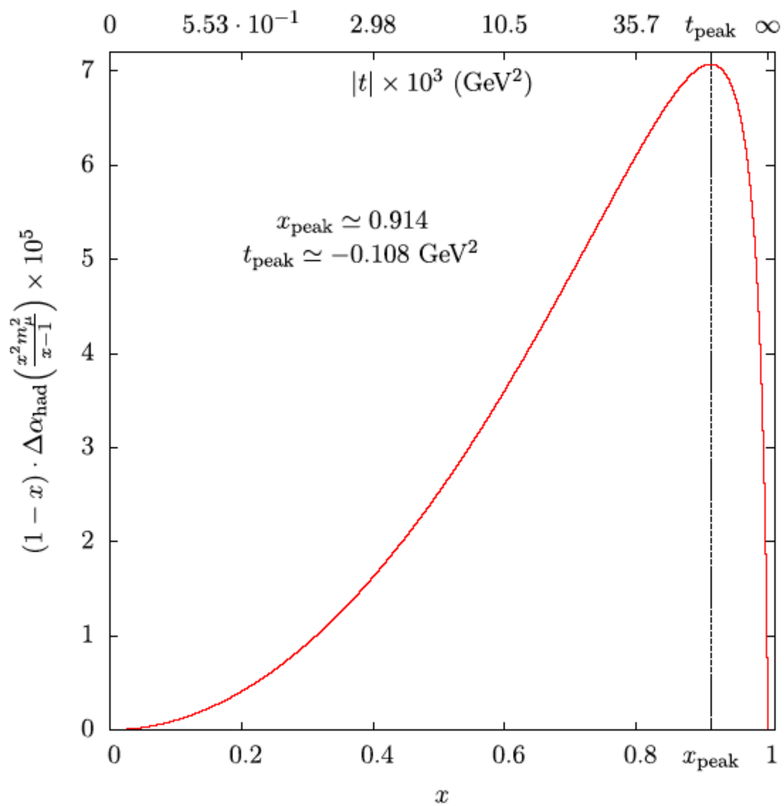
Space-like

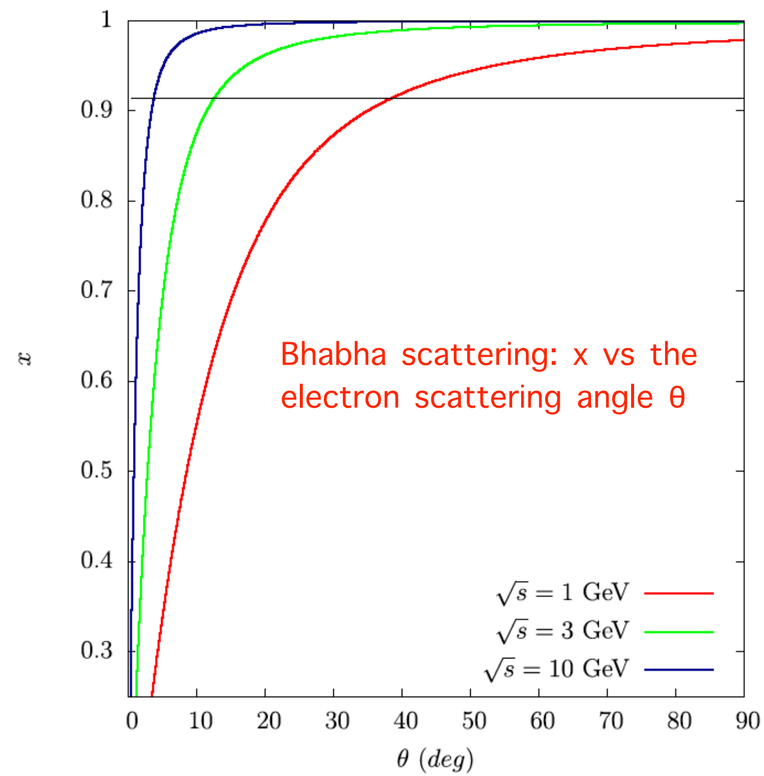


Carloni Calame, MP, Trentadue, Venanzoni, PLB 2015

New space-like proposal for HLO: which experiment?

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





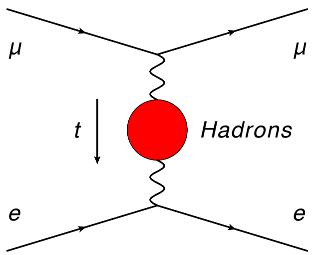
- The peak occurs at $x_{peak} = 0.914$, $t_{peak} = -0.108$ GeV^2 $\simeq -(330$ MeV$)^2$

Carloni Calame, MP, Trentadue, Venanzoni, PLB 2015

Muon-electron scattering

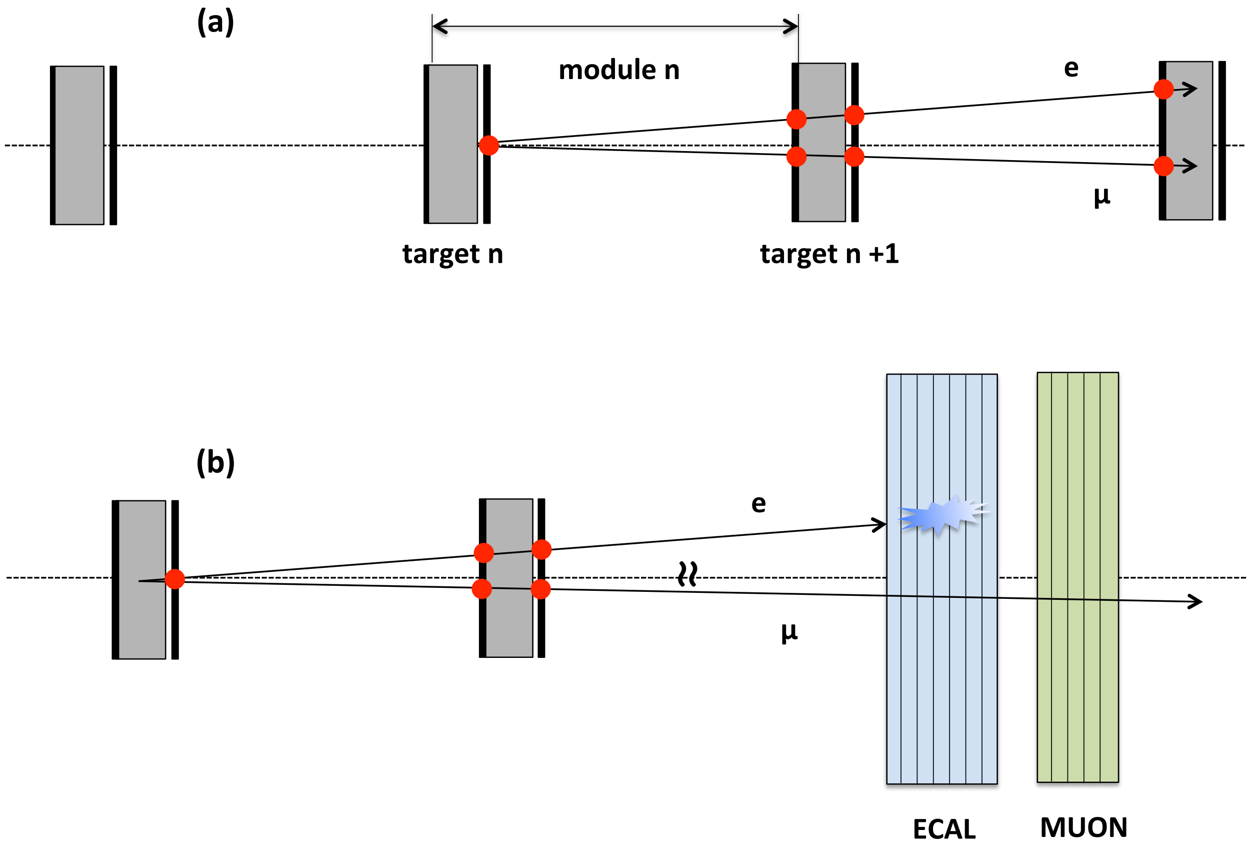
Abbiendi, Carloni Calame, Marconi, Matteuzzi, Montagna, Nicrosini, MP, Piccinini, Tenchini, Trentadue, Venanzoni

EPJC 2017 - arXiv:1609.08987

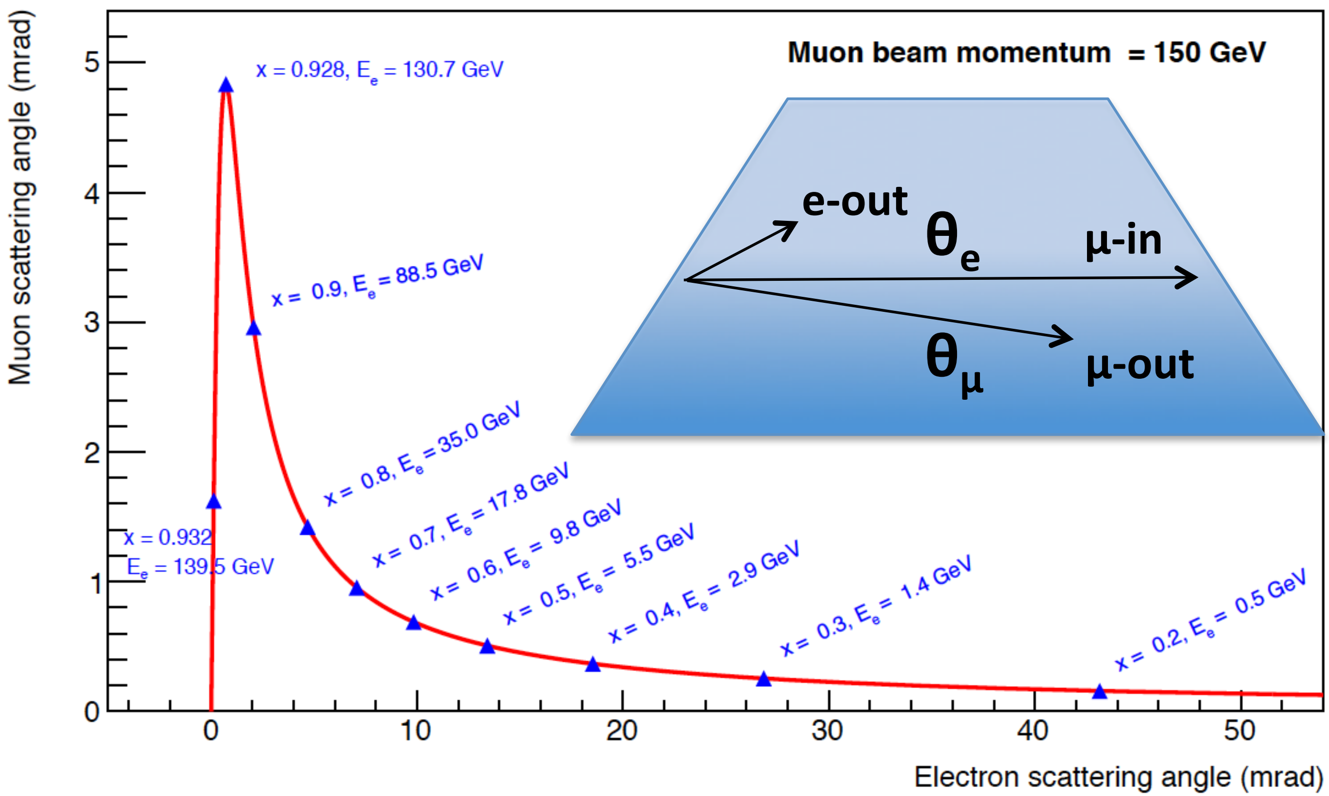


Muon-electron scattering

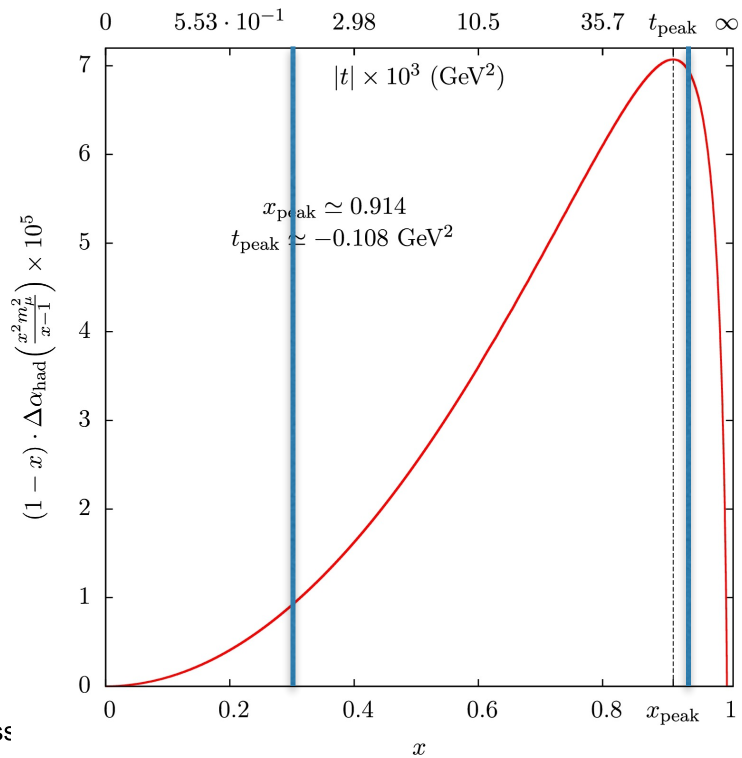
- $\Delta\alpha_{had}(t)$ can also be measured via the elastic scattering $\mu\, e \rightarrow \mu\, e$.
- We propose to scatter a 150 GeV muon beam, available at CERN's North Area, on a fixed electron target. Modular apparatus, several layers of low Z material (Be) paired to Si strip planes.

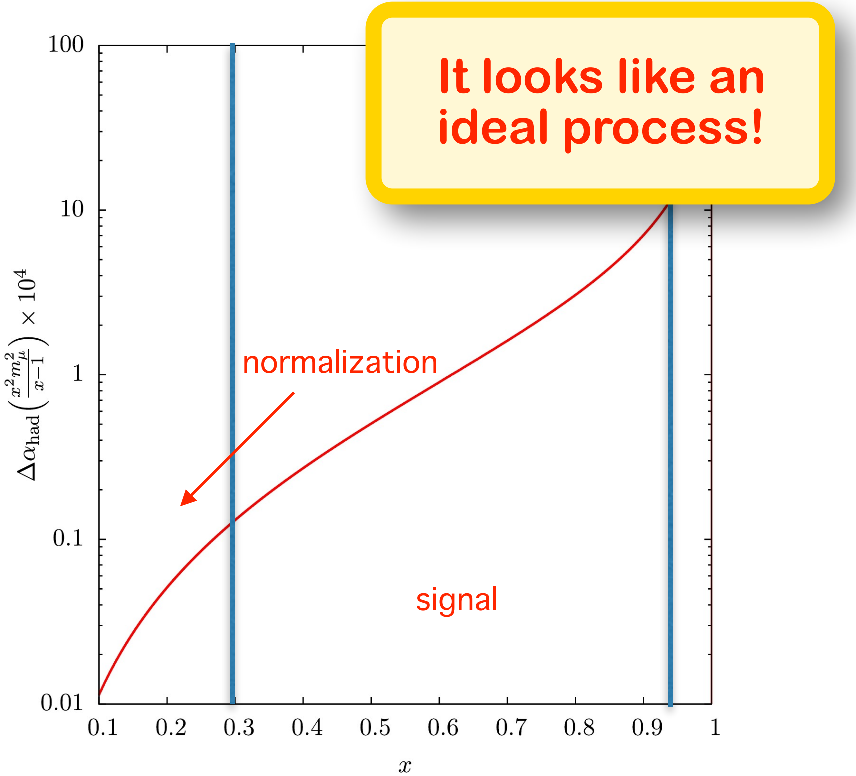


- With CERN's 150 GeV muon beam M2, which has an average of ~ 1.3×10^7 μ/s, incident on Be layers for a total thickness of 60cm, and 2 years of data taking with a running time of 2×10^7 s/yr, one can reach an int. luminosity of $\mathcal{L}_{int} \sim 1.5 \times 10^7$ nb^{-1}.

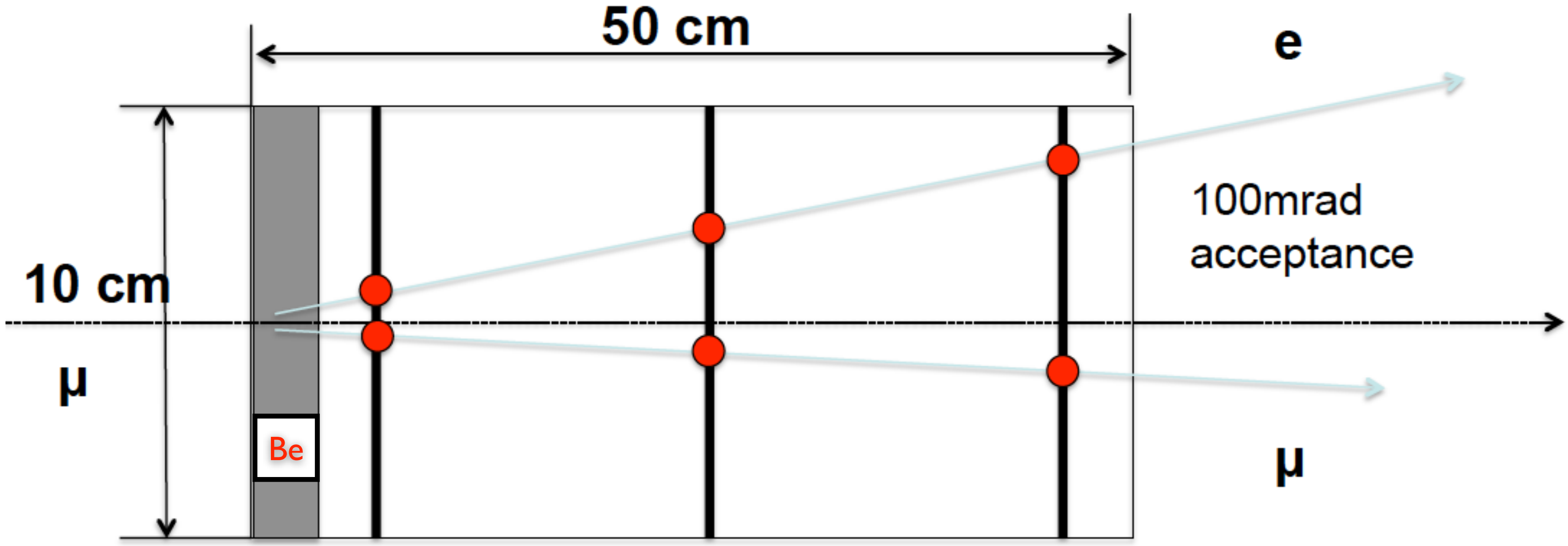


- For a 150 GeV muon beam, the scan region extends up to x=0.932, ie beyond the peak! (the peak is at x=0.914)
- The integrand in the remaining region $x \in [0.932,1]$ accounts for ~13% of the a_μ^{HLO} integral. It cannot be reached by our experiment but it can be determined using pQCD & time-like data, and/or lattice QCD results.
- Same detector for signal and normalization ($x \lesssim 0.3$, $\Delta\alpha_{had}(t) \lesssim 10^{-5}$) leads to cancellation of detector effects at first order.





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



- Modular apparatus: one Beryllium target (~1cm thick) coupled to three Silicon planes (thickness: 300μm).
- State-of-the-art Silicon strip detectors with hit resolution ~10 μm will provide an expected angular resolution of ~10 μm / 0.5 m = 0.02 mrad
- ECAL and μ detector located downstream will solve PID ambiguity below 5 mrad (above that, the angular measurements provide PID).
- With $\mathcal{L}_{int} \sim 1.5 \times 10^7$ nb^{-1} we estimate that we can reach a statistical sensitivity of ~ 0.3% on a_μ^{HLO}, ie ~ 20×10^{-11}!

a_μ^{HLO} via muon-electron scattering (3)

- **Systematic effects must be known at the level of $\lesssim$ 10ppm!**

Systematics

1. Acceptance
2. Tracking
3. Trigger
4. PID
5. Effects of E_e energy cut
6. Signal/Background:
   It requires a dedicated event generator.
7. Uncertainty in the location of interaction vertices: Segmented/active target to resolve the vertex position
8. Uncertainty in the muon beam momentum:
   Scattering kinematics to determine the beam momentum
9. Effects of Multiple Scattering (must be known at ~1%):
   It requires dedicated work on simulation and measurements (test beam).
10. Theoretical uncertainty on the mu-e cross section (see later)

Items 1–6: Affordable by means of GEANT4 based simulations

All the systematic effects must be known to ensure an errror on the cross section < 10ppm

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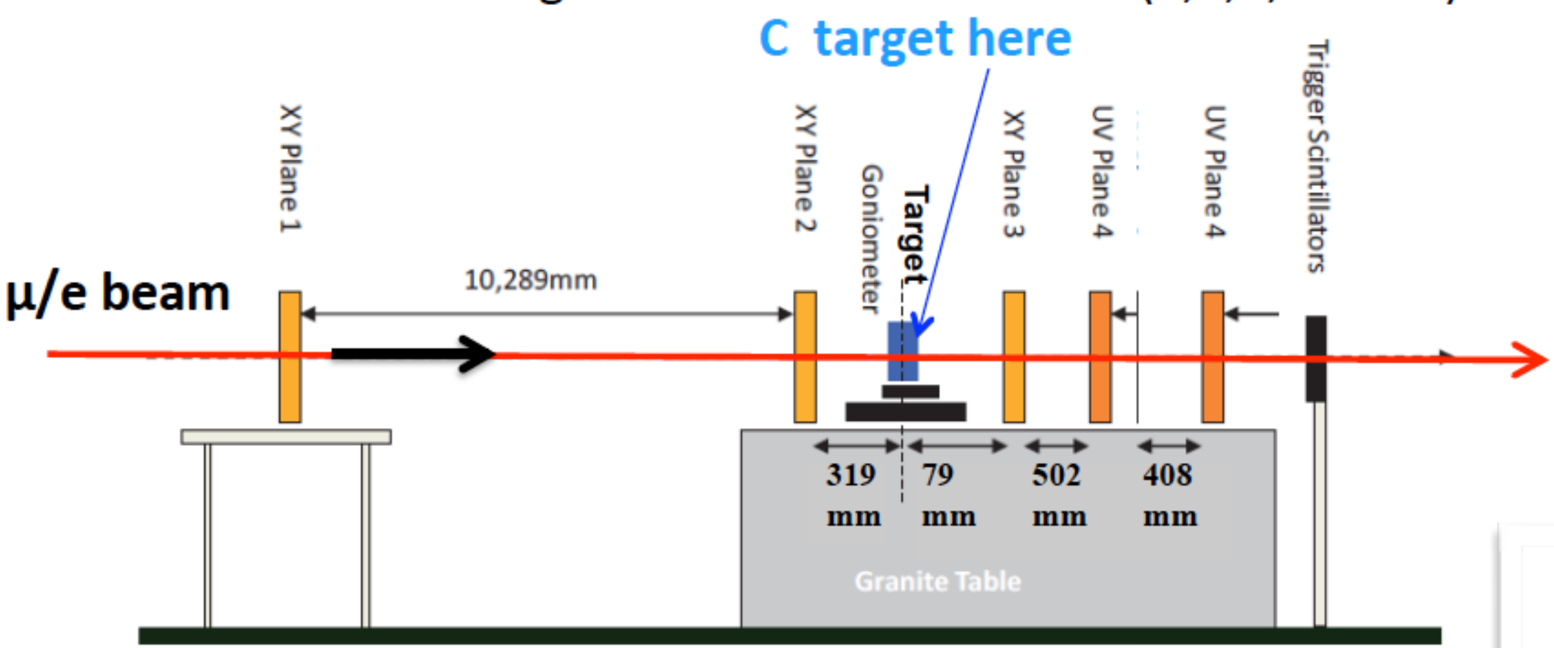
G. Venanzoni, Fermilab, June 5th 2017

Test Beam at CERN — Sep 2017

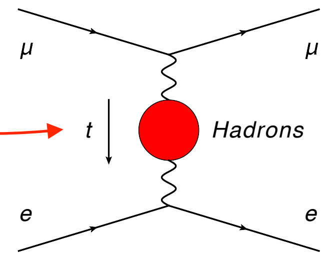
Check GEANT MSC prediction and populate the 2D (θ_e , θ_μ) scattering plane

- 27 Sep-3 October 2017 at CERN "H8 Beam Line"
- Adapted UA9 Apparatus
- Beam energy: e- of 12/20 GeV; μ of 160 GeV
- 10^7 events with C targets of different thickness (2,4,8,-20mm)

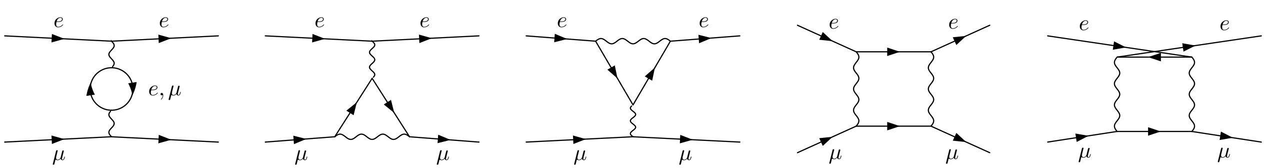


- **Data analysis under way.**

- To extract $\Delta\alpha_{had}(t)$ from the measured cross section, the SM prediction must be known at NNLO!

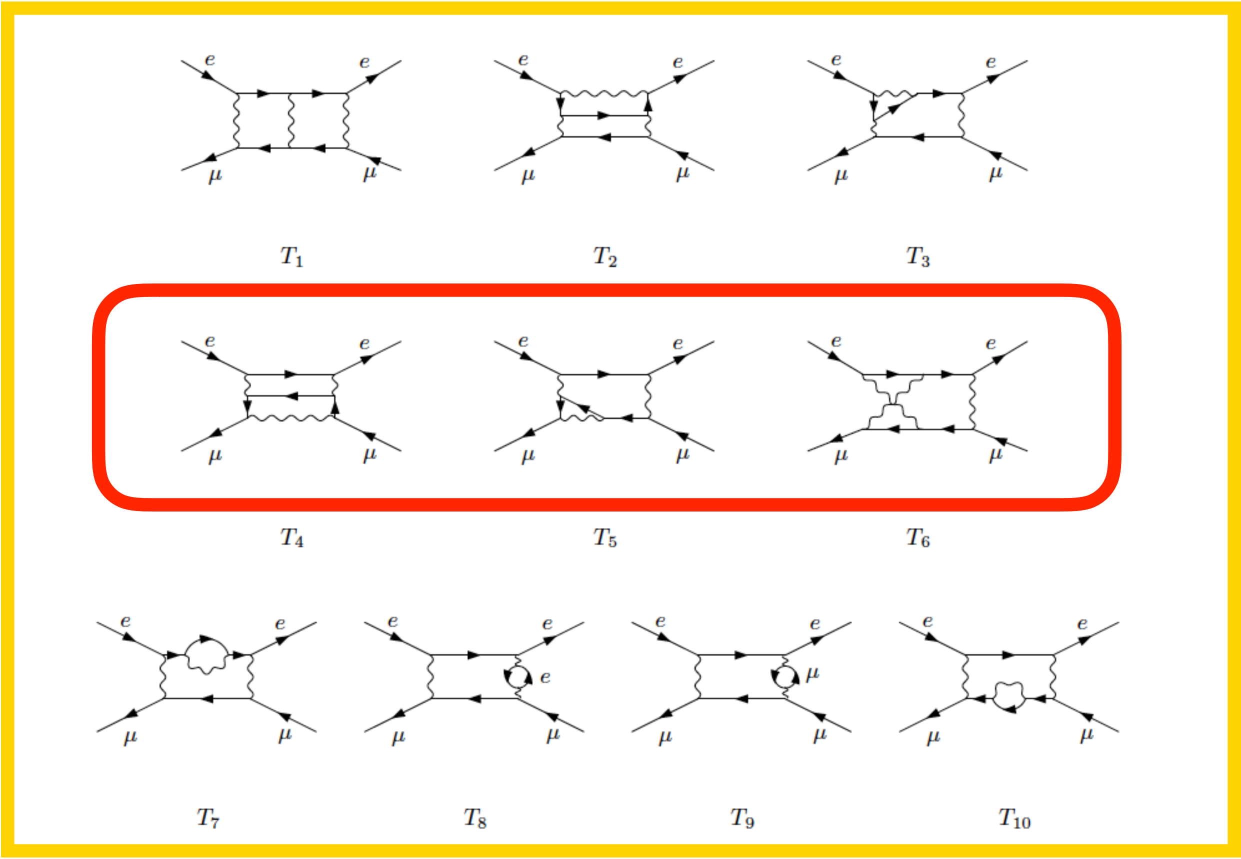


- NLO QED corrections known & checked. Pavia group: MC ready!



- NNLO QED corrections unknown.
- NLO hadronic contributions unknown. NB: the hadronic light-by-light contributions are of higher order!! 😀
- Dedicated high-precision MC tools needed.
- Possible interplay with lattice calculations.
- Explore the new physics sensitivity of this experiment!

- State-of-the-art methods required to calculate the 2-loop diagrams.
- Two-loop box diagrams:



- Missing Master Integrals for the planar 2-loop box diagrams computed.

Mastrolia, MP, Primo & Schubert, arXiv:1709.07435.

Theory workshop in Padova — Sep 2017

μe

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 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 Physi
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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Università degli Studi di Padova

MITP 2018 workshop in Mainz

Mainz Institute for Theoretical Physics

VITIES 2018

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 with the Parity Violation Program at MESA
Jens Erler **UNAM**, Mikhail Gorshteyn, Hubert Spiesberger **JGU**
April 23-May 4, 2018

Modern Techniques for CFT and AdS
Bartlomiej Czech **IAS Princeton**, Michal P. Heller **MPI for Gravitational Physics**, Alessandro Vichi **EPFL**
May 28-June 8, 2018

The Dawn of Gravitational Wave Science
Rafael A. Porto **ICTP-SAIFR**, Riccardo Sturani **IIP Natal**,

TOPICAL WORKSHOPS

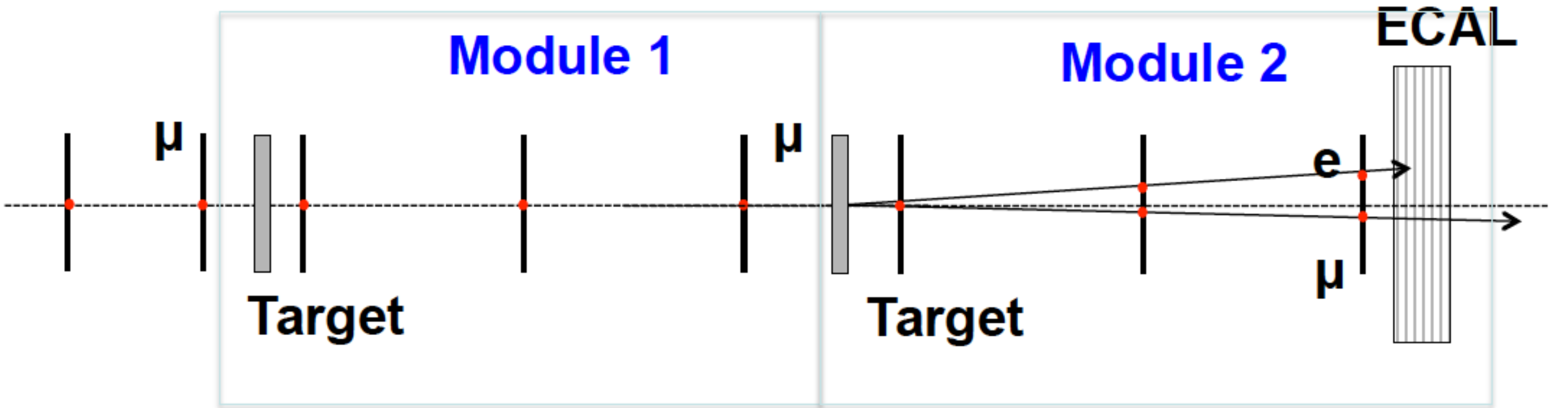
The Evaluation of the Leading Hadronic Contribution to the muon anomalous magnetic moment
Massimo Passera **INFN Padua**, Luca Trentadue **U Parma**, Carlo Carloni Calame **INFN Pavia** Graziano Venanzoni **INFN Frascati**
February 19-23, 2018

Challenges in Semileptonic B Decays
Paolo Gambino **U Turin**, Andreas Kronfeld **Fermilab**, Marcello Rotondo **INFN-LNF Frascati**, Christof Schwanda **OEWA Vienna**
April 16-20, 2018

Tension in LCDM Paradigm
Cora Dvorkin **U Harvard**, Silvia Galli **IAP Paris**, Fabio Iocco **ICTP-SAIFR**, Federico Marinacci **MIT**
May 14-18, 2018

Experimental plans for 2018

- Build & test a full-scale prototype (2 modules) on a muon beam at Cern:



- We have been allocated 1 week (22-29 August 2018) of high-energy muon beam (160 GeV) in H8 (A138).
- We will also run on the M2 line behind COMPASS (start-up in April).
- This proposal is part of the Physics Beyond Colliders activities @ Cern
- Proposal presented in 2017 to INFN's Committee 1. Funds have been allocated for a full-scale test of a detector prototype in 2018. Letter of Intent planned for 2018-19.

Conclusions

- Muon g-2: $\Delta a_\mu \sim 3.5 - 4\ \sigma$. New upcoming measurement: QED & EW ready. Lots of progress in the hadronic sector, but not yet ready!

- New proposal for an experiment at CERN to measure the leading hadronic contribution to the muon g-2 via μ-e elastic scattering.

- μ-e exp: first μ-e testbeam completed at CERN in October. Data analysis under way. One more week of testbeam allocated next August. Test run planned also on CERN's M2 line in April. INFN funds allocated for a test of a detector prototype in 2018.

- μ-e th: NLO MC generator ready. Lots of theoretical work needed! NNLO QED & NLO hadronic corrections unknown. First results obtained for the NNLO planar box diagrams contributing to μ-e scattering in QED. Dedicated high-precision MC tools needed. The new physics sensitivity of this experiment must be explored!

G. Abbiendi, M. Alacevich, M. Bonomi, A. Broggio, C. Carloni Calame, E. Conti, D. Galli, M. Fael, A. Ferroglia, F.V. Ignatov, M. Incagli, U. Marconi, M.K. Marinković, P. Mastrolia, C. Matteuzzi, G. Montagna, O. Nicrosini, G.Ossola, L.Pagani, M. Passera, P. Paradisi, C. Patrignani, F. Piccinini, F. Pisani, M. Prest, A. Primo, A. Principe, M. Pruna, M. Rocco, U. Schubert, L. Tancredi, R. Tenchini, L. Trentadue, E. Vallazza, G. Venanzoni, A. Vicini, E. Del Nobile…

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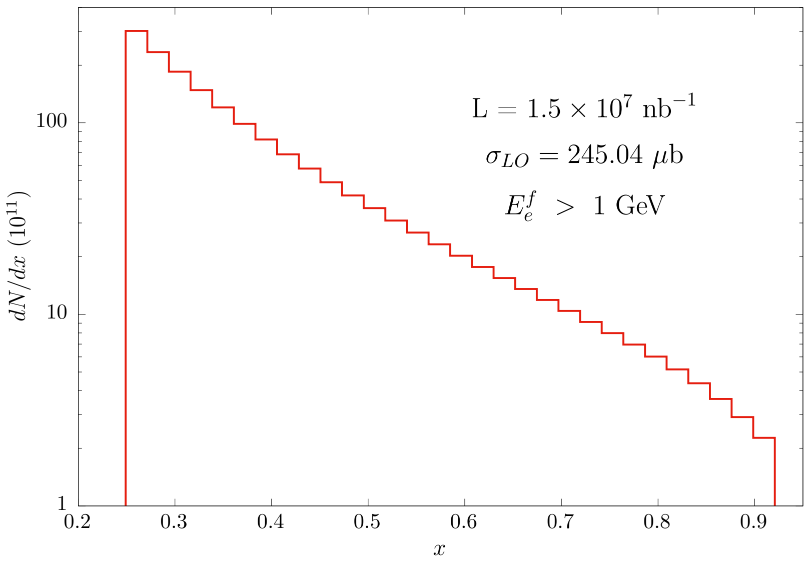
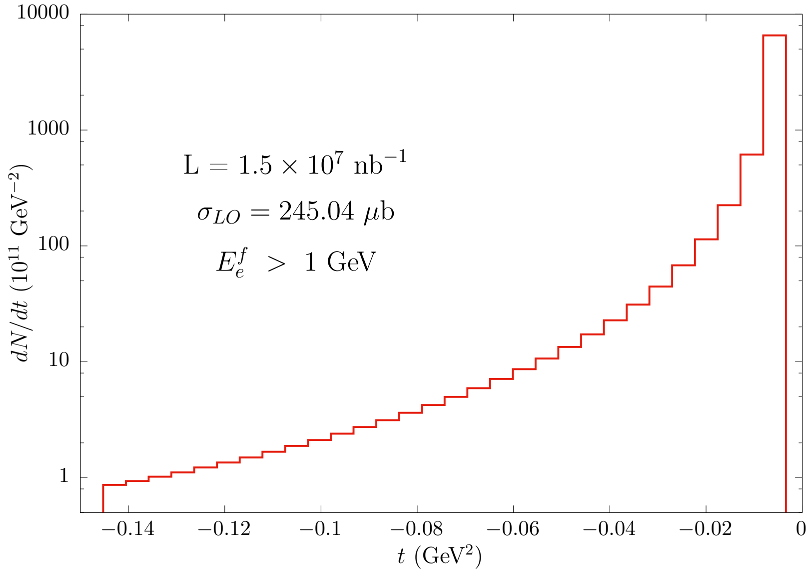
The End



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