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

Massimo Passera
INFN Padova

LFC17
ECT* Trento
14 Sep 2017

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

- Uhlenbeck and Goudsmit in 1925 proposed:

$$\vec{\mu} = g\frac{e}{2mc}\vec{s}$$
$$g = 2 \quad \text{(not 1!)}$$

- Dirac 1928:

$$(i\partial_\mu - eA_\mu)\gamma^\mu\psi = m\psi$$

- A Pauli term in Dirac's eq would give a deviation…

$$a\frac{e}{2m}\sigma_{\mu\nu}F^{\mu\nu}\psi \quad \rightarrow \quad g = 2(1+a)$$

…but there was no need for it! g=2 stood for ~20 yrs.

$g \neq 2$

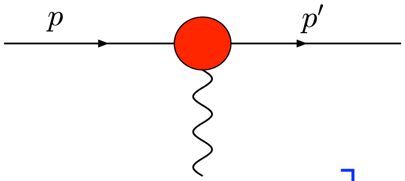
- **Kusch and Foley 1948:**

$$\mu_e^{\rm exp} = \frac{e\hbar}{2mc}\,(1.00119 \pm 0.00005)$$

- **Schwinger 1948 (triumph of QED!):**

$$\mu_e^{\rm th} = \frac{e\hbar}{2mc}\left(1 + \frac{\alpha}{2\pi}\right) = \frac{e\hbar}{2mc} \times 1.00116$$

- **Keep studying the lepton–γ vertex:**

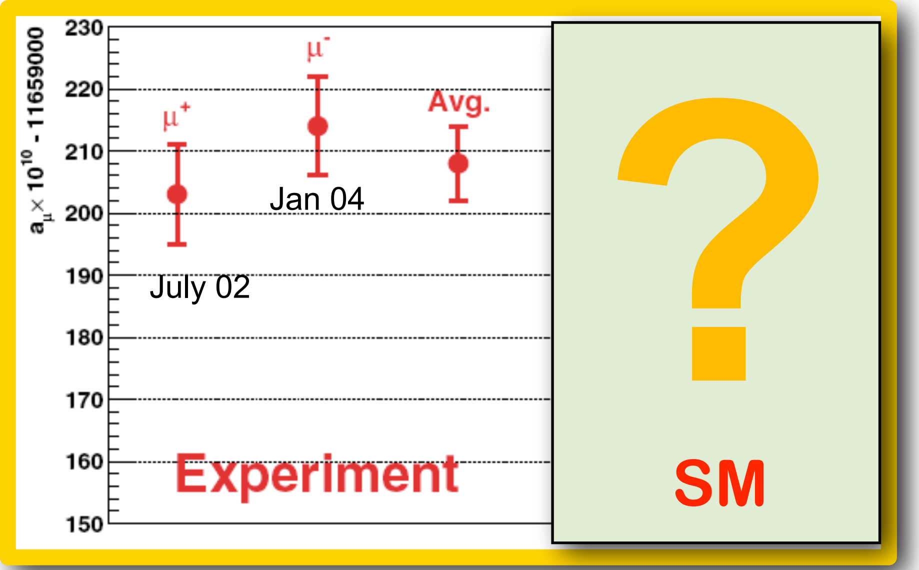


$$\bar{u}(p')\Gamma_\mu u(p) = \bar{u}(p')\left[\gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m}F_2(q^2) + \ldots\right]u(p)$$

$$F_1(0) = 1 \qquad F_2(0) = a_l$$

A pure "quantum correction" effect!

The muon g-2: experimental status



- **Today: $a_\mu^{EXP} = (116592089 \pm 54_{stat} \pm 33_{sys}) \times 10^{-11}$ [0.5ppm].**
- **Future: new muon g-2 experiments at:**
  - **Fermilab E989: aims at $\pm 16 \times 10^{-11}$, ie 0.14ppm.**
    Data taking starting in November. First result expected in 2018 with a precision comparable to that of BNL E821.
  - **J-PARC proposal: phase-1 start with 0.37ppm (TDR 2016).**
- **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

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

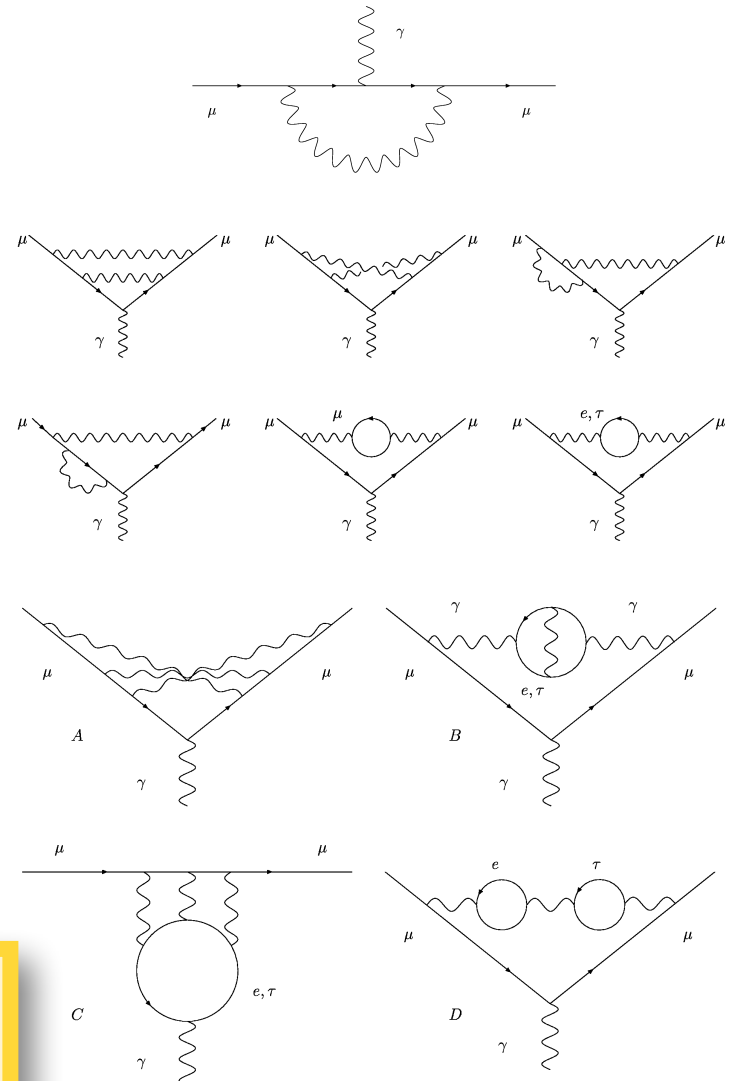
Remiddi, Laporta, Barbieri ... ; Czarnecki, Skrzypek; MP '04;
Friot, Greynat & de Rafael '05, Mohr, Taylor & Newell 2012

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

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). COMPLETED²!

$+ \; 752.85\,(93)\,(\alpha/\pi)^5$ **COMPLETED!**

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



...

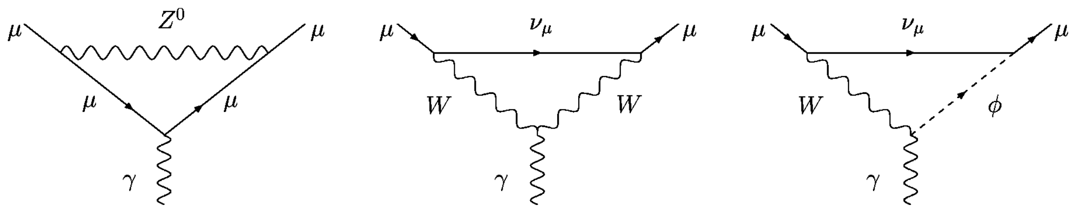
Adding up, I get:

$a_\mu^{QED} = 116584718.944\,(21)(77) \times 10^{-11}$

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

with $\alpha = 1/137.035999049(90)$ [0.66 ppb]

- **One-loop term:**



$$a_\mu^{\rm EW}(\text{1-loop}) = \frac{5G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1+\frac{1}{5}\left(1-4\sin^2\theta_W\right)^2+O\left(\frac{m_\mu^2}{M_{Z,W,H}^2}\right)\right] \approx 195\times10^{-11}$$

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

Studenikin et al. '80s

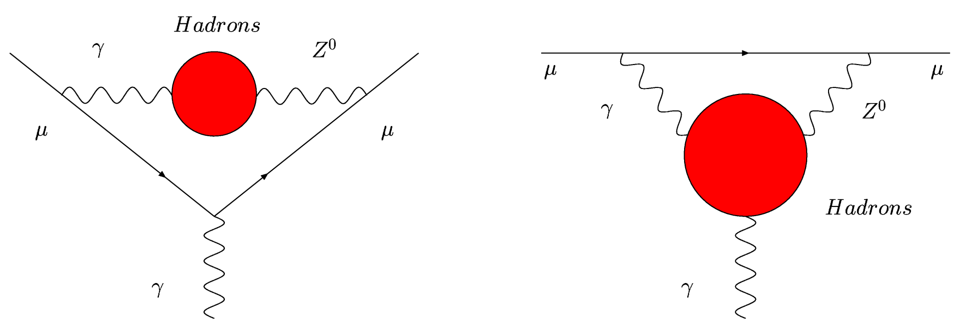
- **One-loop plus higher-order terms:**

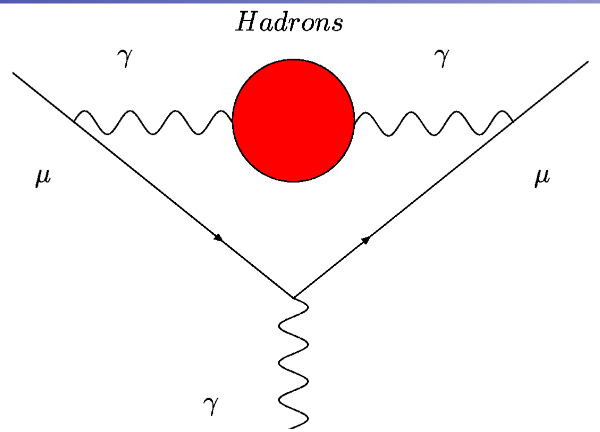
$a_\mu^{\rm EW} = 153.6\ (1) \times 10^{-11}$

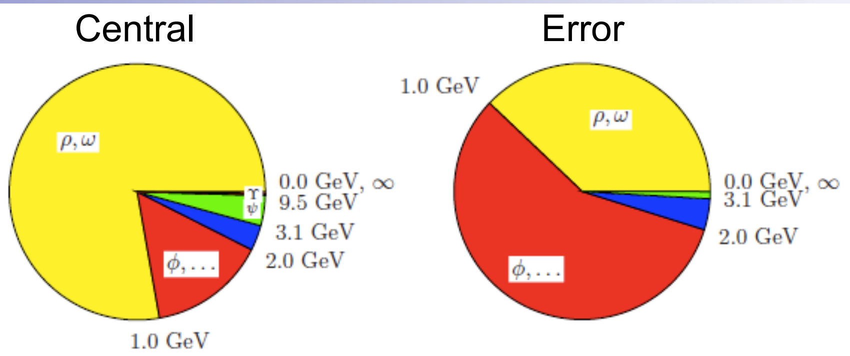
with M_{Higgs} = 125.6 (1.5) GeV

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

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

$a_\mu^{\rm HLO}$ = 6870 (42)$_{\rm tot}$ x 10^{-11} — F. Jegerlehner, arXiv:1511.04473 (includes BESIII 2π)

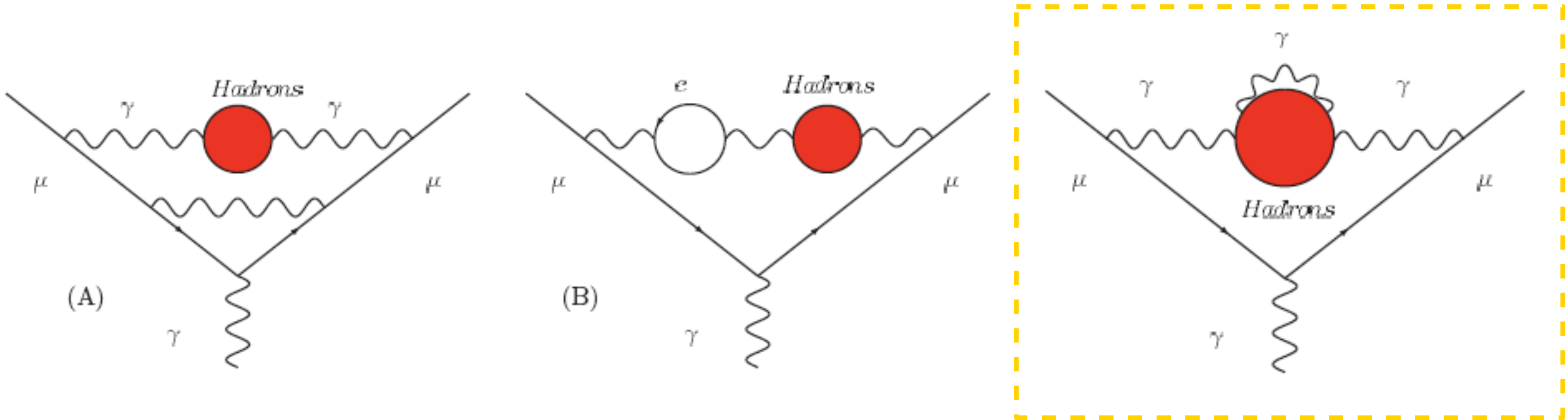
= 6926 (33)$_{\rm tot}$ x 10^{-11} — M. Davier, arXiv:1612.02743

= 6949 (37)$_{\rm exp}$ (21)$_{\rm rad}$ x 10^{-11} — Hagiwara et al, JPG 38 (2011) 085003

- **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}

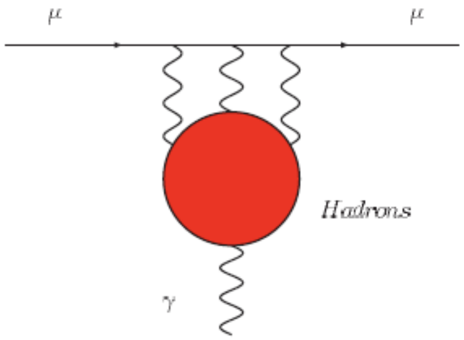


O(α^3) contributions of diagrams containing hadronic vacuum polarization insertions:

$$a_\mu^{HNLO}(vp) = -98\ (1) \times 10^{-11}$$

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

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
$a_\mu^{HNLO}(lbl) = +102\ (39) \times 10^{-11}$	Jegerlehner, arXiv:1511.04473

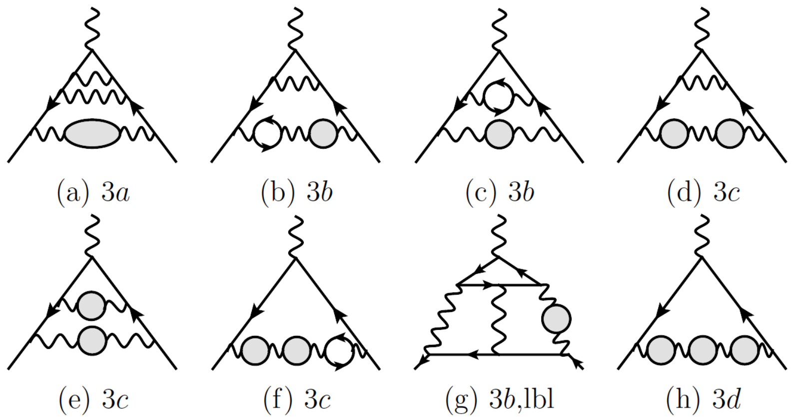
Results based also on Hayakawa, Kinoshita ’98 & ’02; Bijnens, Pallante, Prades ’96 & ’02

- 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: $+53.5(13.5)\times10^{-11}$. 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

The muon g-2: the Hadronic NNLO contributions (HNNLO)

HNNLO: Vacuum Polarization



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

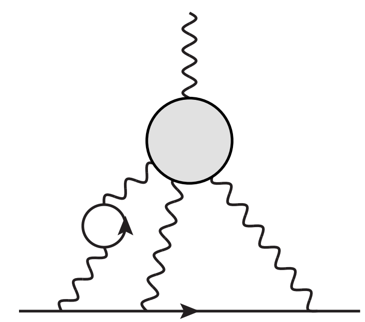
$a_\mu^{HNNLO}(vp) = 12.4\ (1) \times 10^{-11}$

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
116 591 761 (57)	$330\ (85) \times 10^{-11}$	3.9 [1]
116 591 818 (51)	$273\ (81) \times 10^{-11}$	3.4 [2]
116 591 841 (58)	$250\ (86) \times 10^{-11}$	2.9 [3]

with the recent "conservative" hadronic light-by-light $a_\mu^{HNLO}(lbl) = 102\ (39) \times 10^{-11}$ of F. Jegerlehner arXiv:1511.04473, and the hadronic leading-order of:

[1] Jegerlehner, arXiv:1511.04473.
[2] Davier, arXiv:1612:02743.
[3] Hagiwara et al, JPG38 (2011) 085003.

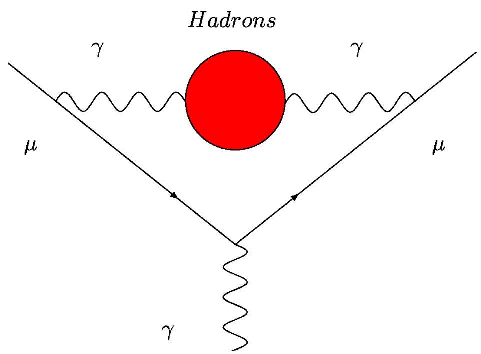
A new approach to a_μ^{HLO}

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

PLB 2015 - arXiv:1504.02228

New space-like proposal for HLO

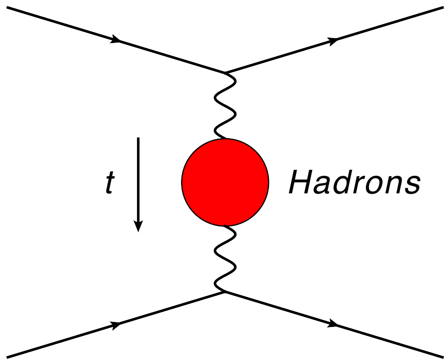
- At present, the leading hadronic contribution a_μ^{HLO} is computed via the time-like formula:



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

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

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



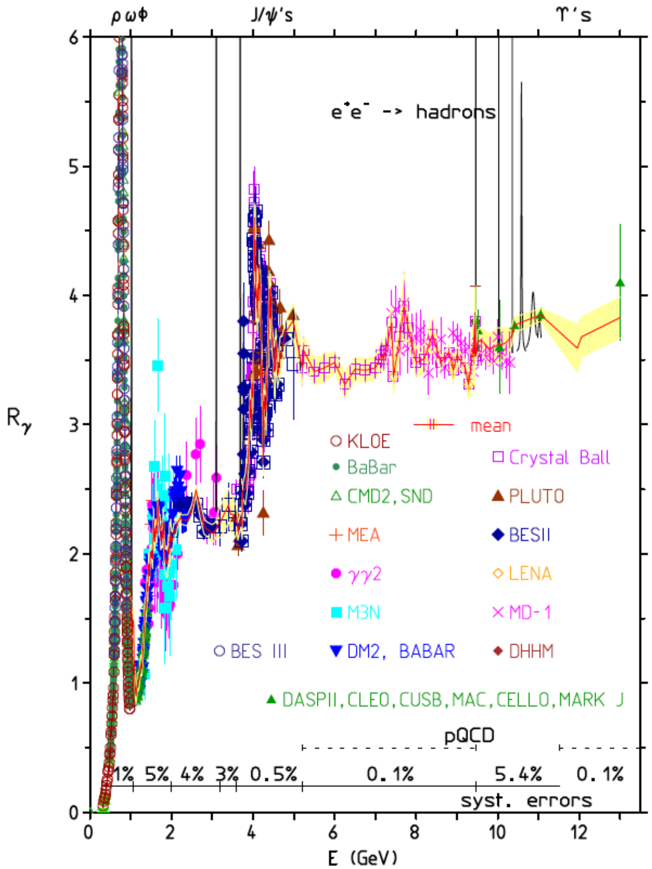
$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi} \int_0^1 dx\,(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

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

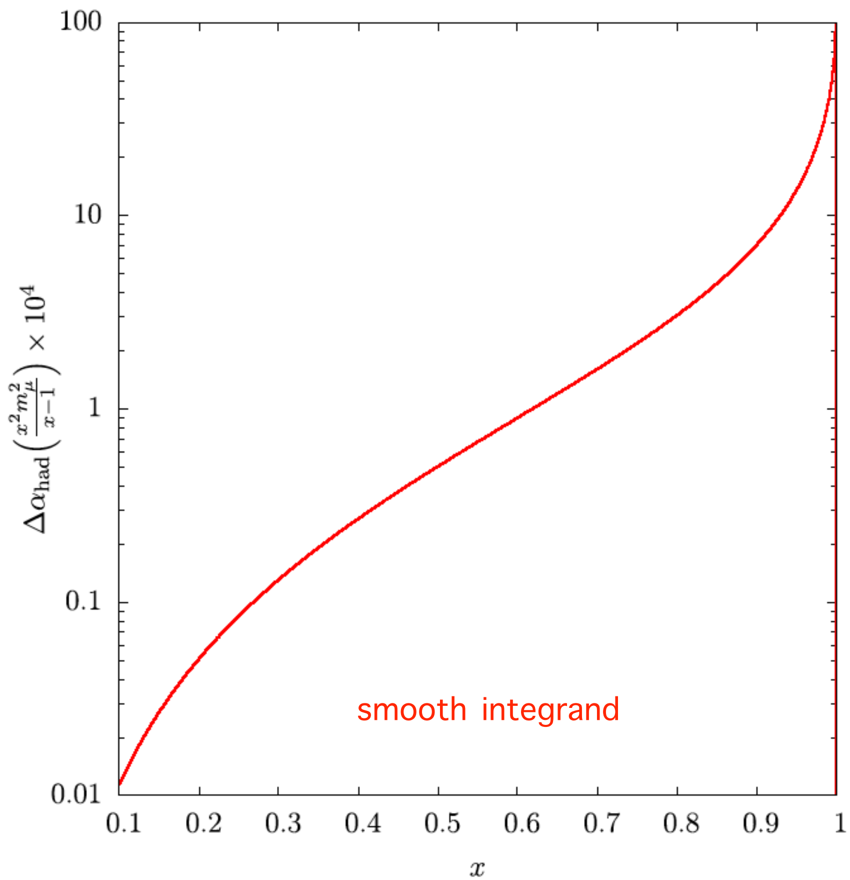
which involves $\Delta\alpha_{had}(t)$, the hadronic contribution to the running of α in the space-like region. It can be extracted from scattering data!

New space-like proposal for HLO (2)

Time-like



Space-like

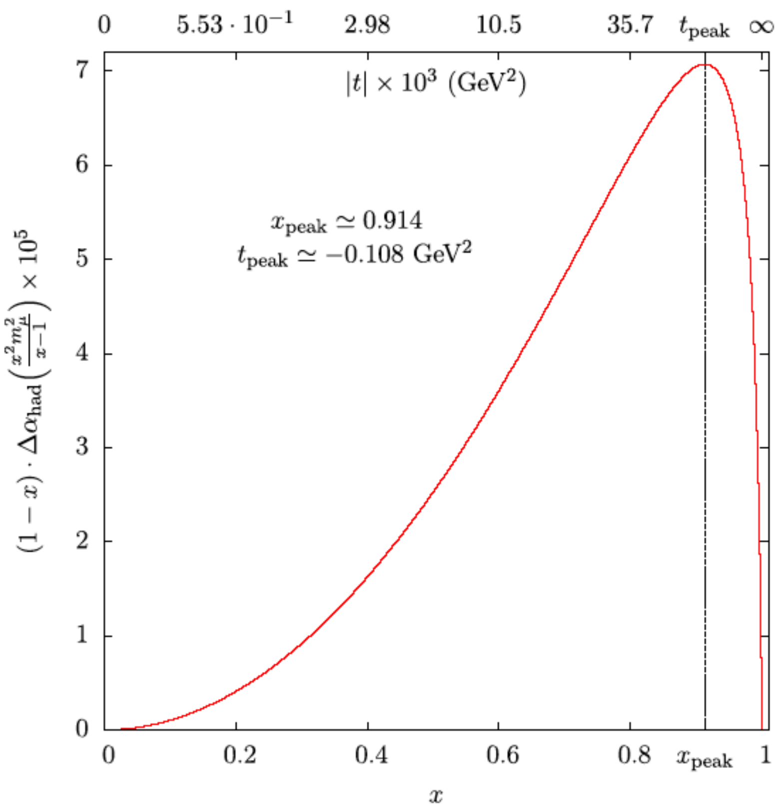


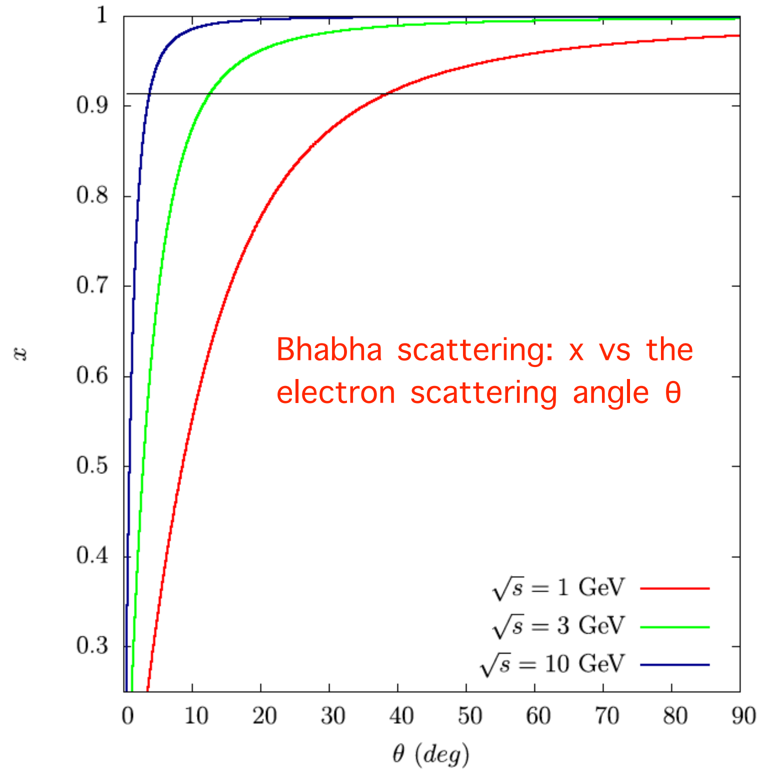
F. Jegerlehner, arXiv:1511.04473

Carloni Calame, MP, Trentadue, Venanzoni, PLB 2015

New space-like proposal for HLO (3)

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





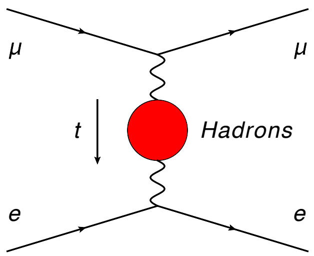
- **The peak occurs at $x_{peak} = 0.914$, $t_{peak} = -0.108\ \text{GeV}^2 \simeq -(330\ \text{MeV})^2$**

Carloni Calame, MP, Trentadue, Venanzoni, PLB 2015

Muon-electron scattering

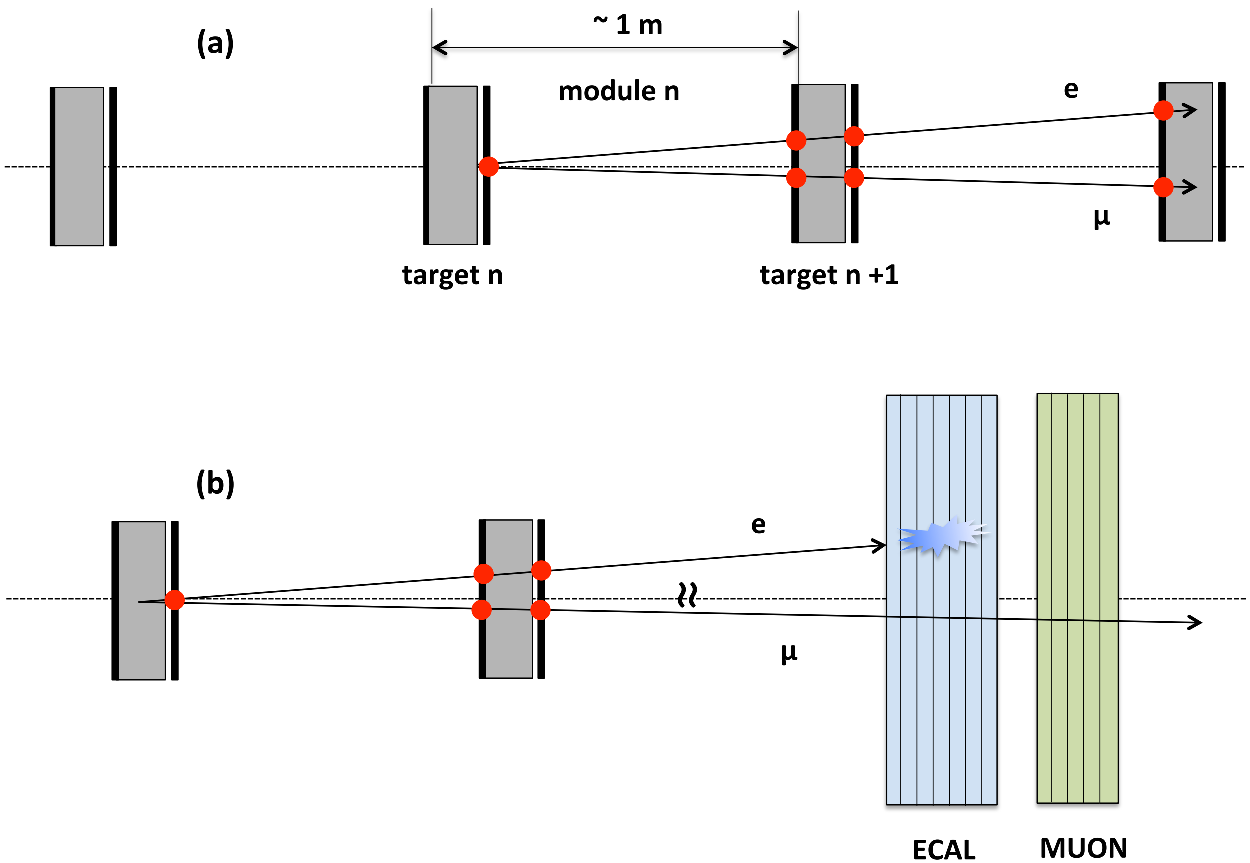
Abbiendi, Carloni Calame, Marconi, Matteuzzi, Montagna, Nicrosini, MP, Piccinini, Tenchini, Trentadue, Venanzoni

EPJC 2017 - arXiv:1609.08987

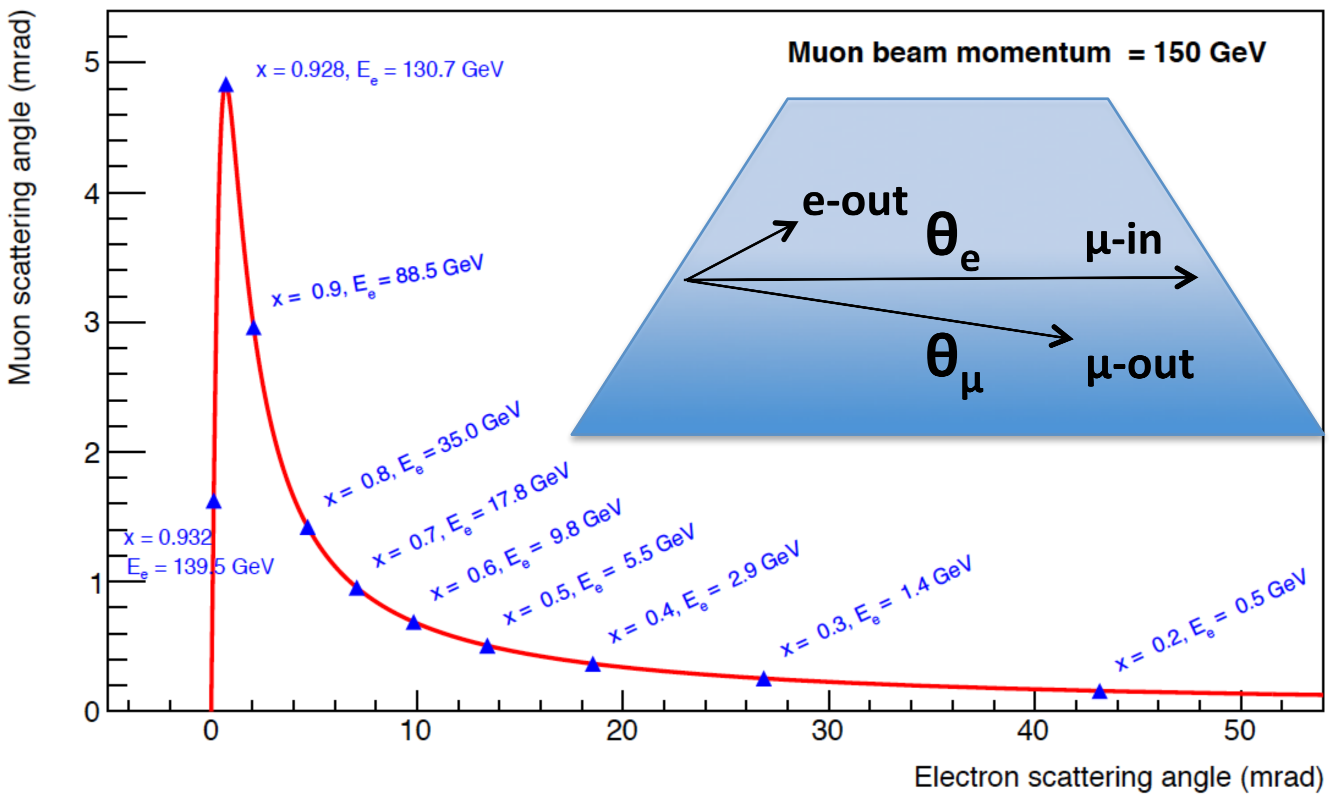


Muon-electron scattering

- $\Delta\alpha_{had}(t)$ can also be measured via the elastic scattering $\mu\, e \to \mu\, e$.
- We propose to scatter a 150 GeV muon beam, available at CERN's North Area, on a fixed electron target. Modular apparatus, 20 layers of low Z material (Be or C) paired to Si strip planes.



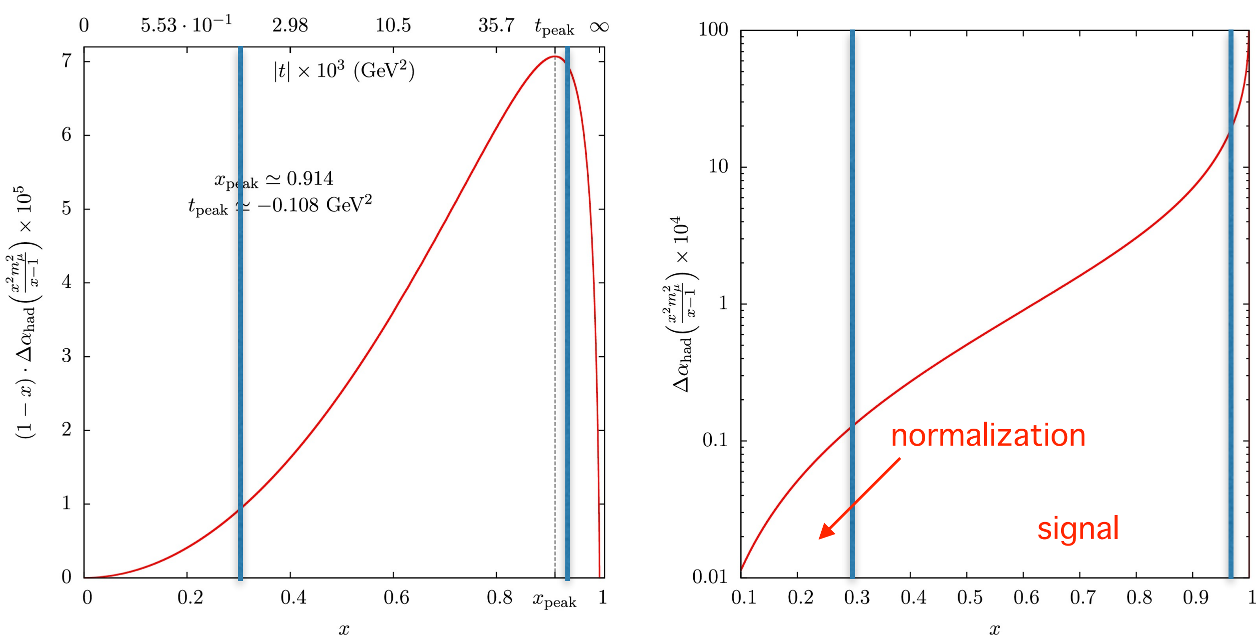
- With CERN's 150 GeV muon beam M2, which has an average of ~ 1.3×10^7 μ/s, incident on 20 Be layers, each 3 cm thick, and 2 years of data taking with a running time of 2×10^7 s/yr, one can reach an int. luminosity of $\mathcal{L}_{int} \sim 1.5 \times 10^7$ nb^{-1} (σ_{LO}~245μb)



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 $x \in [0.932,1]$ 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.
- 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}!

It looks like an ideal process!



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

- 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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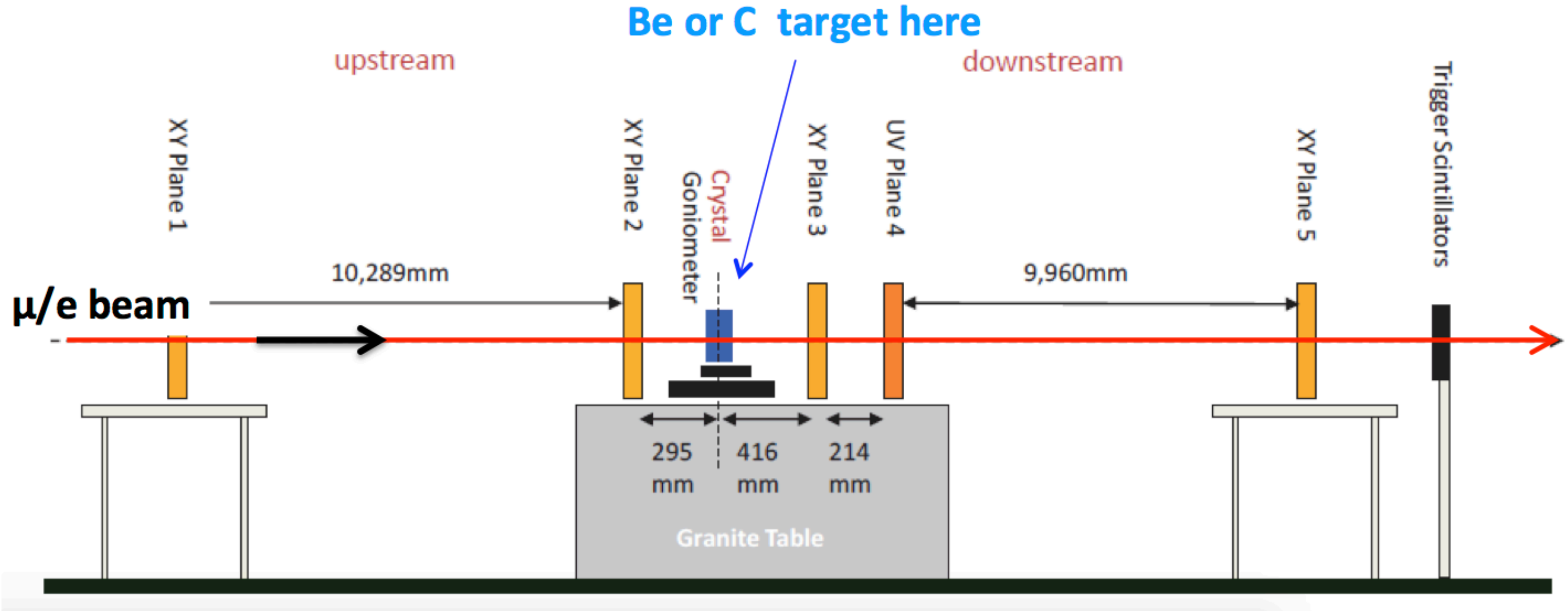
G. Venanzoni, Fermilab, June 5th 2017

Test Beam

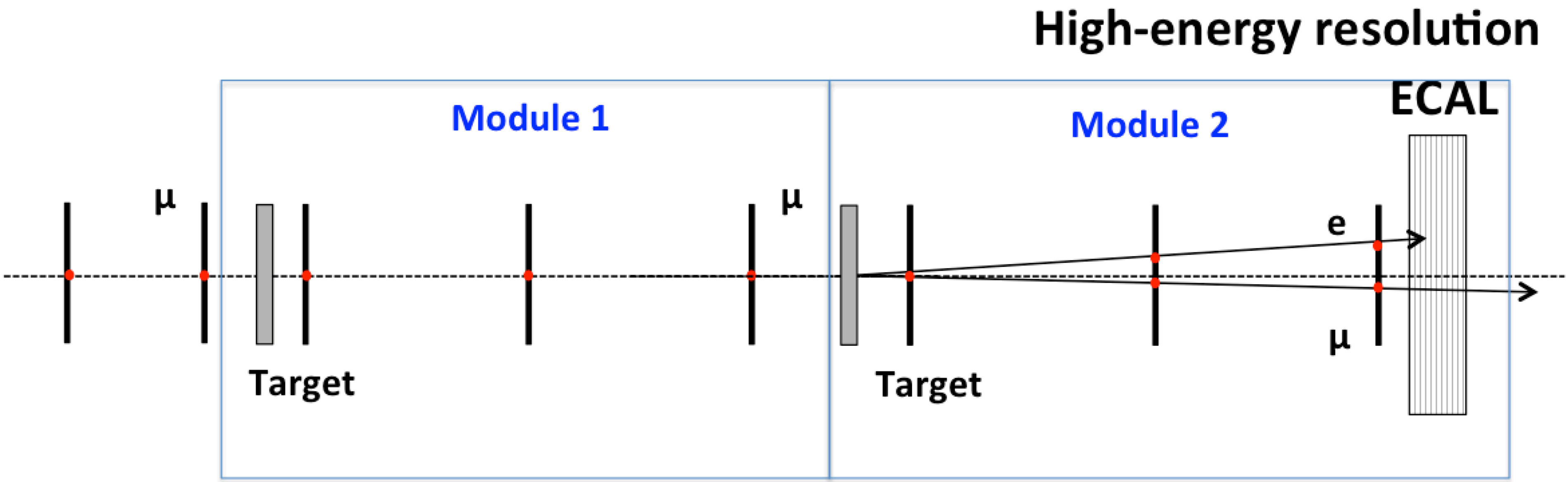
Check Geant4 MSC prediction and populate the 2D (θ_e, θ_μ) scattering plane

- 27 Sep-3 October 2017 allocated at CERN in "H8 Beam Line"
- 5 Si strips planes: 2 before (upstream) and 3 after the target
- Max rate 10 kHz
- Beam energy in the range 90 - 190 GeV



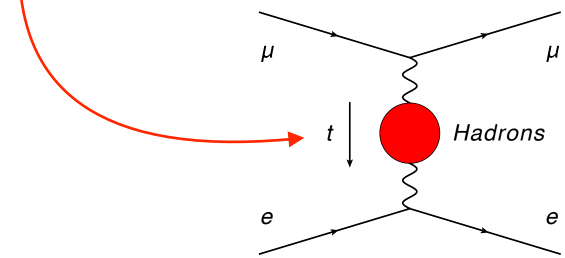
U. Marconi, CSN1, Roma, May 12 2017

- **Build up and test a full scale prototype.**



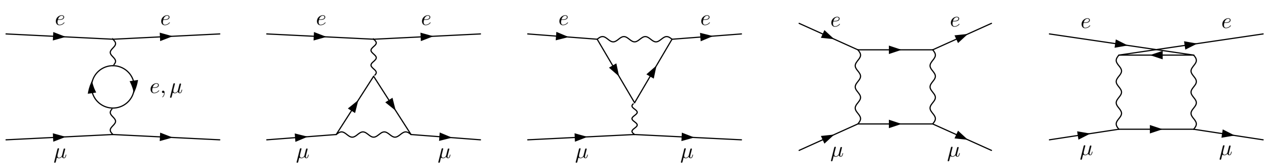
U. Marconi, CSN1, Torino, Sep 12 2017

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



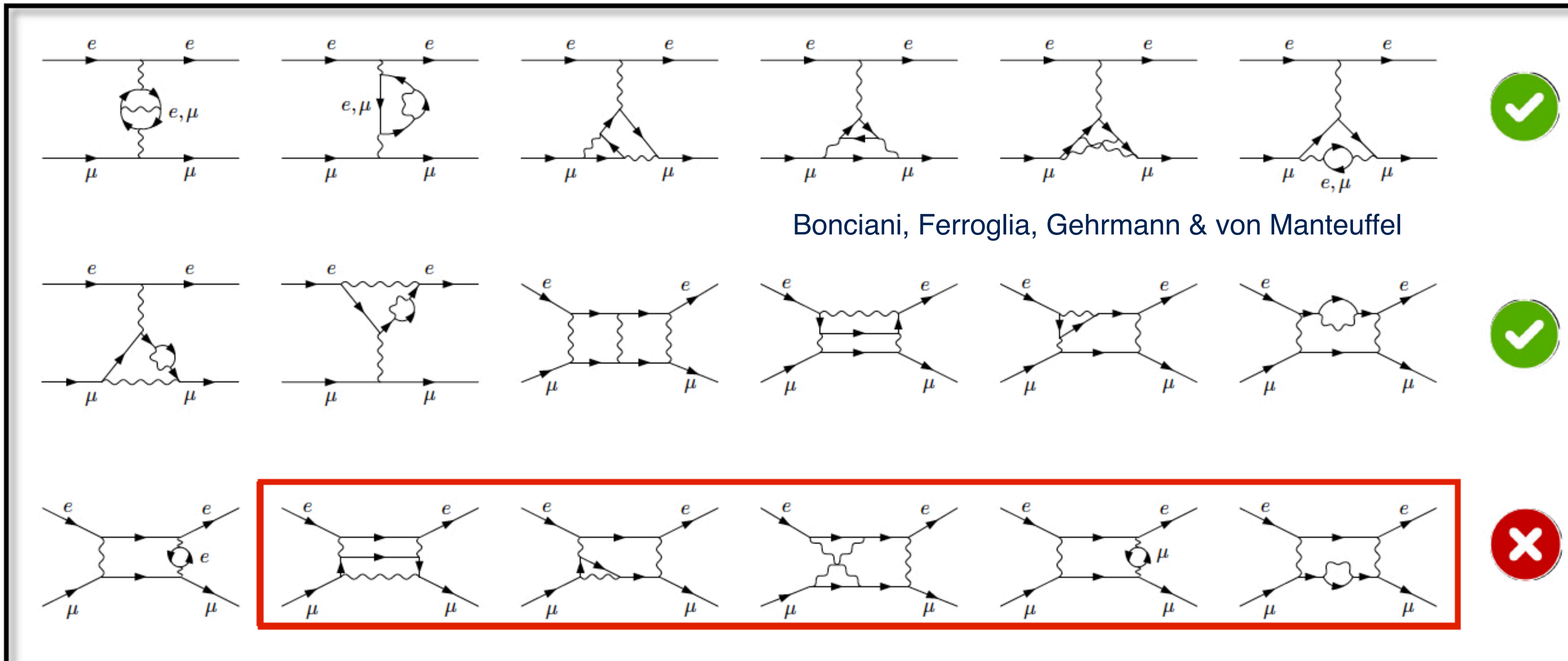
- NLO QED corrections known & checked. Pavia group: MC ready!

Carloni Calame, Padova μe theory kick-off workshop, Sep 4-5 2017



- NNLO QED corrections unknown.
- NLO hadronic contributions unknown.
- Dedicated high-precision MC tools needed.
- Possible interplay with lattice calculations.

- **State-of-the-art methods required to calculate the 2-loop diagrams.**
- **Examples of 2-loop diagrams:**



Mastrolia, MP, Primo & Schubert, work in progress.

Theory workshop in Padova

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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INFN Istituto Nazionale di Fisica Nucleare

Università degli Studi di Padova

MITP 2018 workshop in Mainz

μe


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

Conclusions

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

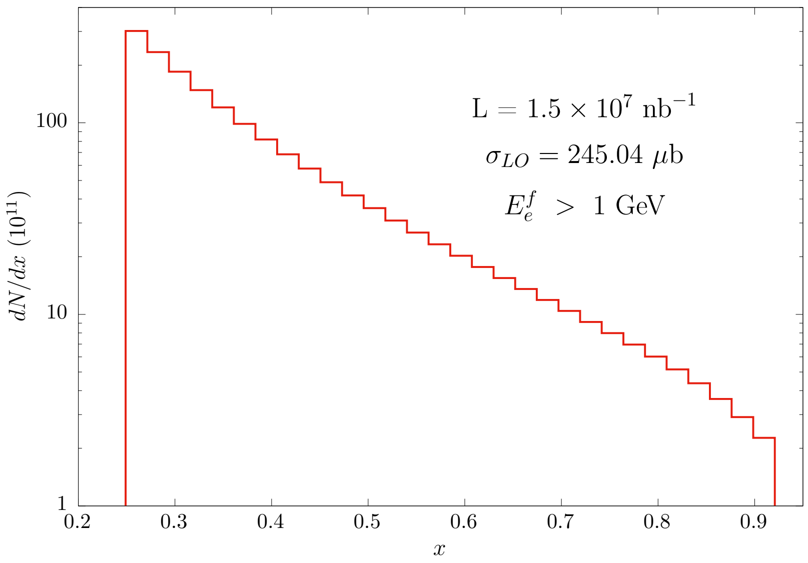
- New proposal for an experiment at CERN to measure the leading hadronic contribution to the muon g-2 via μ-e elastic scattering.

- In collaboration with:

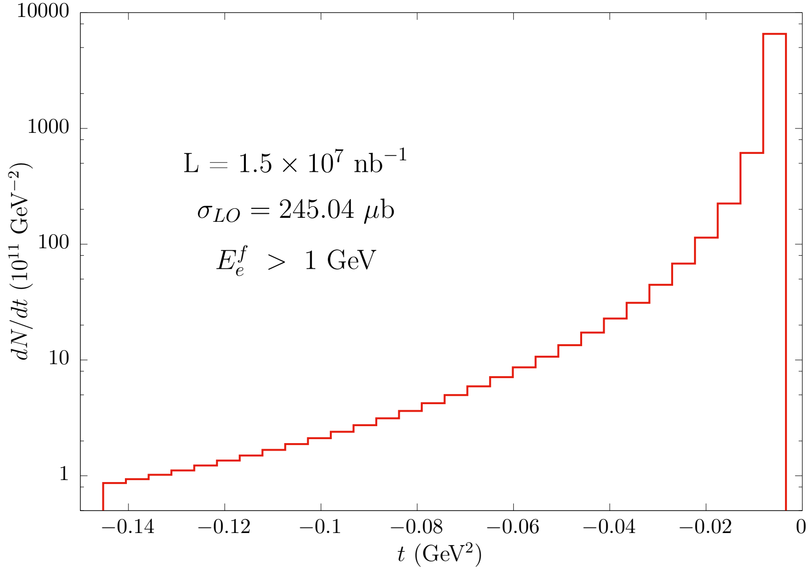
  G. Abbiendi, M. Alacevich, G. Ballerini, M. Bonanomi, C. Brizzolari, A. Broggio, R. Calabrese, C. Carloni Calame, E. Conti, E. Del Nobile, M. Fael, A. Ferroglia, D. Galli, F.V. Ignatov, M. Incagli, E. Luppi, U. Marconi, V. Mascagna, P. Mastrolia, C. Matteuzzi, G. Montagna, O. Nicrosini, G. Ossola, L.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

JOIN US!

The End



$L = 1.5 \times 10^7\ \mathrm{nb}^{-1}$
$\sigma_{LO} = 245.04\ \mu\mathrm{b}$
$E_e^f\ >\ 1$ 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



$L = 1.5 \times 10^7\ \mathrm{nb}^{-1}$
$\sigma_{LO} = 245.04\ \mu\mathrm{b}$
$E_e^f\ >\ 1$ GeV
$dN/dt\ (10^{11}\ \mathrm{GeV}^{-2})$
$t\ (\mathrm{GeV}^2)$
10000
1000
100
10
1
−0.14
−0.12
−0.1
−0.08
−0.06
−0.04
−0.02
0