26-29 June 2017
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# Spacelike Measurement of the Hadronic Vacuum Polarization contribution to (g-2)μ


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and
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on behalf of the proponents


work done in collaboration with:

**G. Abbiendi, C. M. Carloni Calame, D. Galli, F. V. Ignatov, M. Incagli, V. Ivantchenko, U. Marconi, C. Matteuzzi, G. Montagna, O. Nicrosini, M. Passera, C. Patrignani, F. Piccinini, F. Pisani, L. Trentadue, R. Tenchini, G. Venanzoni**

based on:

C. M. Carloni Calame, M. Passera, L. Trentadue. and G. Venanzoni,
''A new approach to evaluate the leading hadronic corrections to the muon g-2'', Phys. Lett. B 746 (2015) 325

G. Abbiendi, C.M. Carloni Calame, U. Marconi, C. Matteuzzi, G. Montagna, O. Nicrosini M. Passera, F. Piccinini, R. Tenchini, L. Trentadue and G. Venanzoni,
"Measuring the leading hadronic contribution to the muon g-2 via mu-e scattering", Eur. Phys. J. C77 (2017) 3, 139. arXiv:1609.08987 [hep-ex].

# This talk is about **Vacuum**

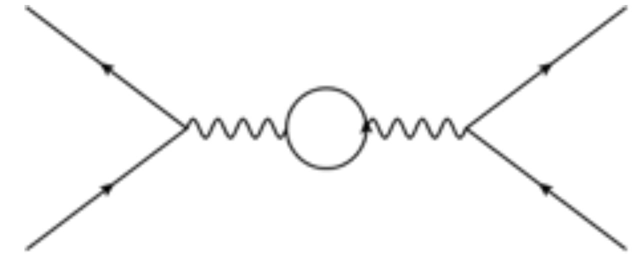
## Historical aside

Vacuum, since a long time ( 2500 years ), constitutes an always present issue in Physics or better in Natural Sciences Philosophy

Parmenides, Leucippos, Democritos, …...Torricelli, von Guericke…..
until nowadays

In Quantum Field Theory, in the perturbative phase,
the Vacuum is naturally represented by the vacuum polarization contribution

Vacuum Polarization makes $\alpha_{em}$ running assuming a well defined "effective" value at any scale



vacuum polarization and the "effective charge" are defined by:

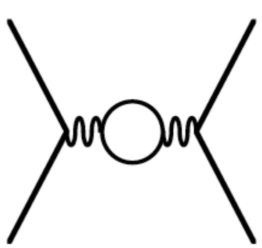
$$e^2 \to e^2(q^2) = \frac{e^2}{1+(\Pi(q^2)-\Pi(0))} \qquad \alpha(q^2) = \frac{\alpha(0)}{1-\Delta\alpha}; \quad \Delta\alpha = -\Re e\left(\Pi(q^2)-\Pi(0)\right)$$

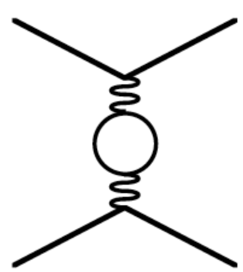
$\Delta\alpha$ takes contributions from leptonic and hadronic and gauge bosons elementary states

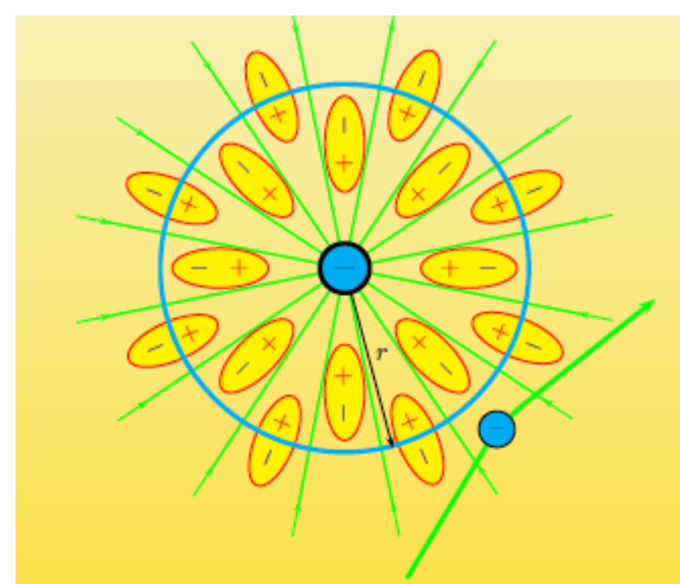
Among these the non-perturbative $\Delta\alpha_{had}$

$$\Delta\alpha = \Delta\alpha_{leptonic} + \Delta\alpha_{gb} + \Delta\alpha_{had} + \Delta\alpha_{top}$$

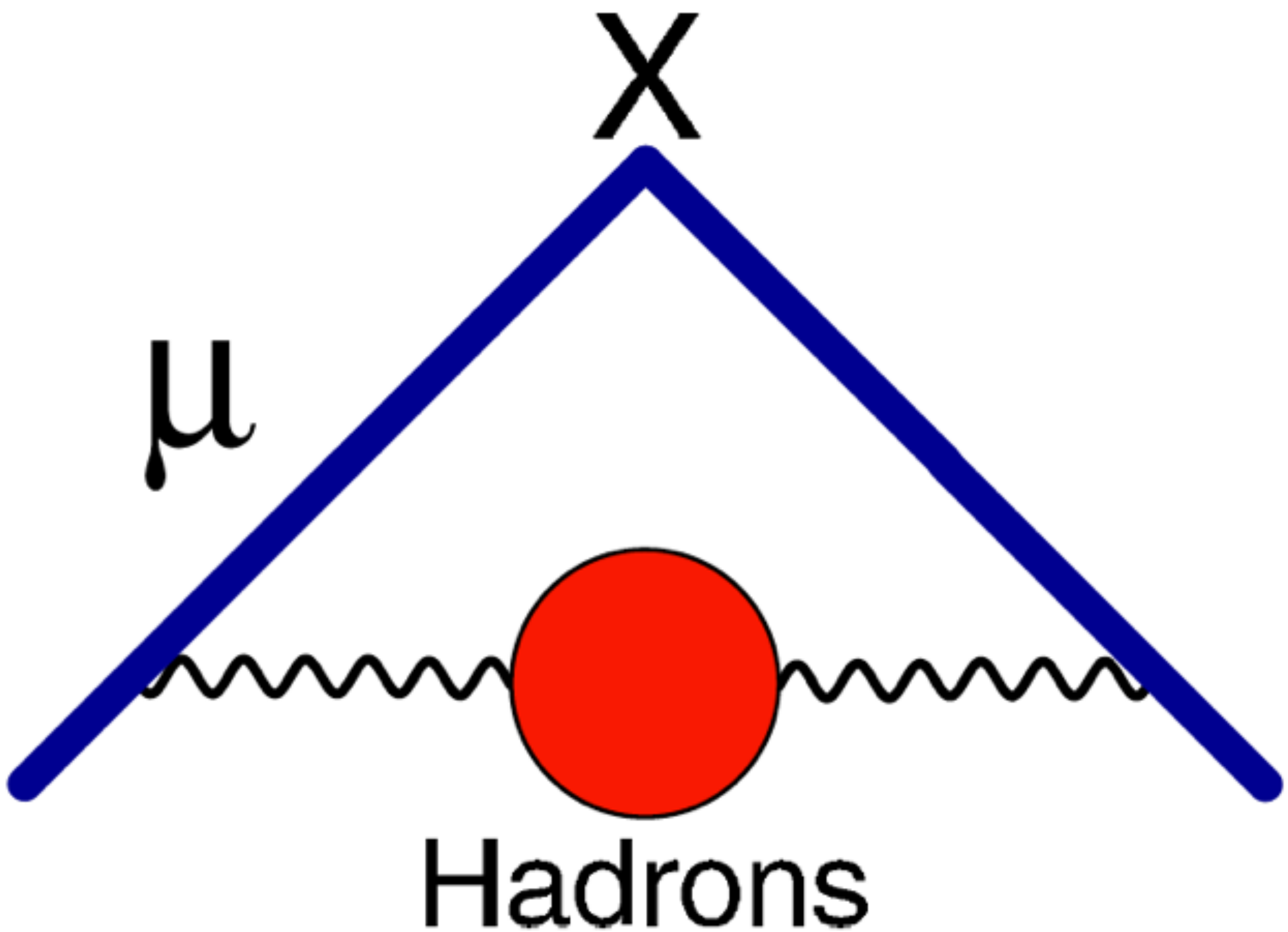
$\alpha$







Hadronic Leading Order (HLO) Contribution
to the Vacuum Polarization



The Standard Dispersive Approach
to the evaluation of the HLO contribution to
the muon anomalous magnetic moment goes
back to the ‘60

PHYSICAL REVIEW VOLUME 124, NUMBER 5 DECEMBER 1, 1961

# Electron-Positron Colliding Beam Experiments

N. Cabibbo and R. Gatto
*Istituti di Fisica delle Università di Roma e di Cagliari, Italy and Laboratori Nazionali di Frascati del C.N.E.N., Frascati, Roma, Italy*

(Received June 8, 1961)

Possible experiments with high-energy colliding beams of electrons and positrons are discussed. The role of the proposed two-pion resonance and of the three-pion resonance or bound state is investigated in connection with electron-positron annihilation into pions. The existence of a three-pion bound state would give rise to a very large cross section for annihilation into $\pi^0+\gamma$. A discussion of the possible resonances is given based on consideration of the relevant widths as compared to the experimental energy resolution. Annihilation into baryon-antibaryon pairs is investigated and polarization effects arising from the nonreal character of the form factors on the absorptive cut are examined. The density matrix for annihilation into pairs of vector mesons is calculated. A discussion of the limits from unitarity to the annihilation cross sections is given for processes going through the one-photon channel. The cross section for annihilation into pairs of spin-one mesons is rather large. The typical angular correlations at the vector-meson decay are discussed.

A neutral weakly interacting vector meson would give rise to a strong resonant peak if it is coupled with lepton pairs. Effects of the local weak interactions are also examined. The explicit relation between the $e^2$ corrections to the photon propagator due to strong interactions and the cross section for annihilation into strongly interacting particles is given.

of the local weak interactions are also examined. The explicit relation between the $e^2$ corrections to the photon propagator due to strong interactions and the cross section for annihilation into strongly interacting particles is given.

## 8. EXPRESSION FOR THE VACUUM POLARIZATION DUE TO STRONG INTERACTING PARTICLES

The quantity

$$\Pi(k^2) = -\frac{(2\pi)^3}{3k^2}\sum_{p^{(z)}=k}\langle 0|j_\nu(0)|z\rangle\langle z|j_\nu(0)|0\rangle \quad (105)$$

is known to be of fundamental importance in quantum electrodynamics.[29] In (105), $j_\nu$ is the current operator and the sum is extended over all the physical states

[29] G. Källén, Helv. Phys. Acta **25**, 417 (1952).



$^{(z)}=k$. The Fourier trans-

or

$(A_\mu(x')A_\nu(x))|0\rangle$,

l product and $A_\mu$ is the

e expressed in terms of

$$\times\frac{\bar{\Pi}(0)-\bar{\Pi}(k^2)-i\pi\Pi(k^2)}{k^2-i\epsilon}. \quad (106)$$

In (106) $\bar{\Pi}(k^2)$ is defined as

$$\bar{\Pi}(k^2)=P\int_0^\infty \frac{\Pi(-a)}{k^2+a}da. \quad (107)$$

We show in this section that the experimentally measured cross sections for processes $e^+ + e^- \to \gamma \to F$, where $F$ denotes a group of final states, is directly related to the contribution to (105) from the group of states $F$ in the summation over the intermediate states $z$. This result will permit, for instance, calculation of the modifications of the photon propagator due to virtual strong interacting particles, directly from the measured cross sections.

which gives the d
integrals of the type

must be convergent,
observable expressior
that for any group of

converges. Such a co
derived in Sec. 6 fr
the cross sections $\sigma_F$(

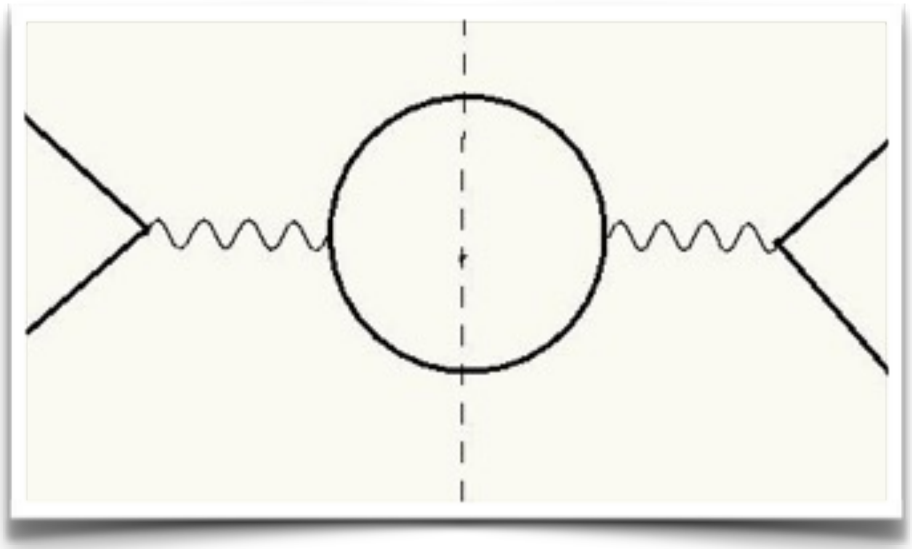
$\bar{\Pi}(0)$

is connected to charg
finite, $\int^\infty E\sigma_F(E)dE$
states $F$. If the cross
logarithmically diverg
ments about converg
channel and they are

9.

In high energy

$$a_\mu^{HLO} = (\frac{\alpha}{\pi^2}) \int_0^\infty \frac{ds}{s} K(s)\ Im\Pi_{had}(s+i\epsilon) \qquad \hat{K}(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)\frac{s}{m_\mu^2}}$$



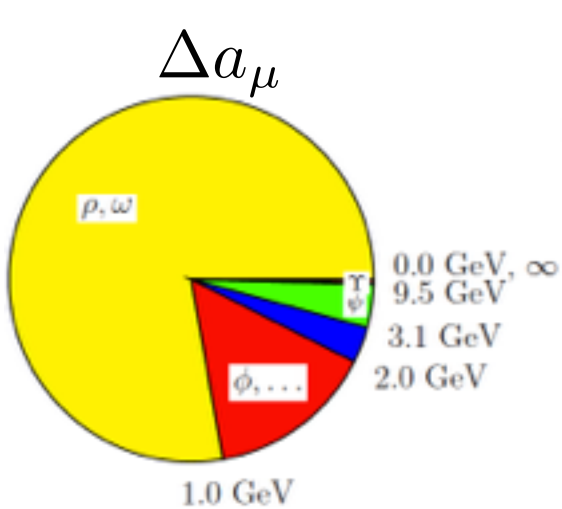
Optical Theorem

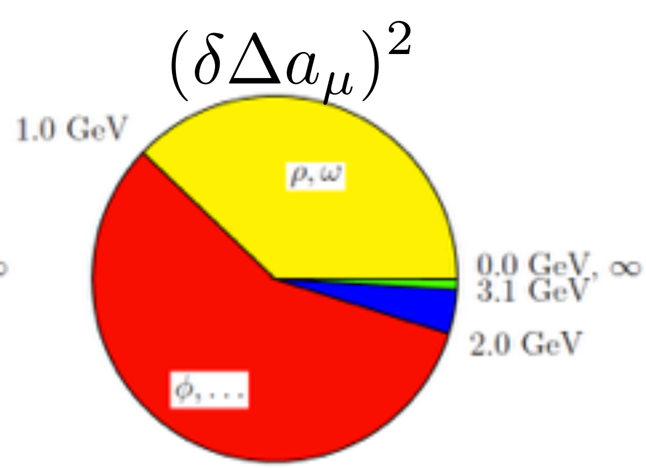
$$Im\ \hat{\Pi}_{had}(s) \to \sigma_{tot}^{had}(s)$$

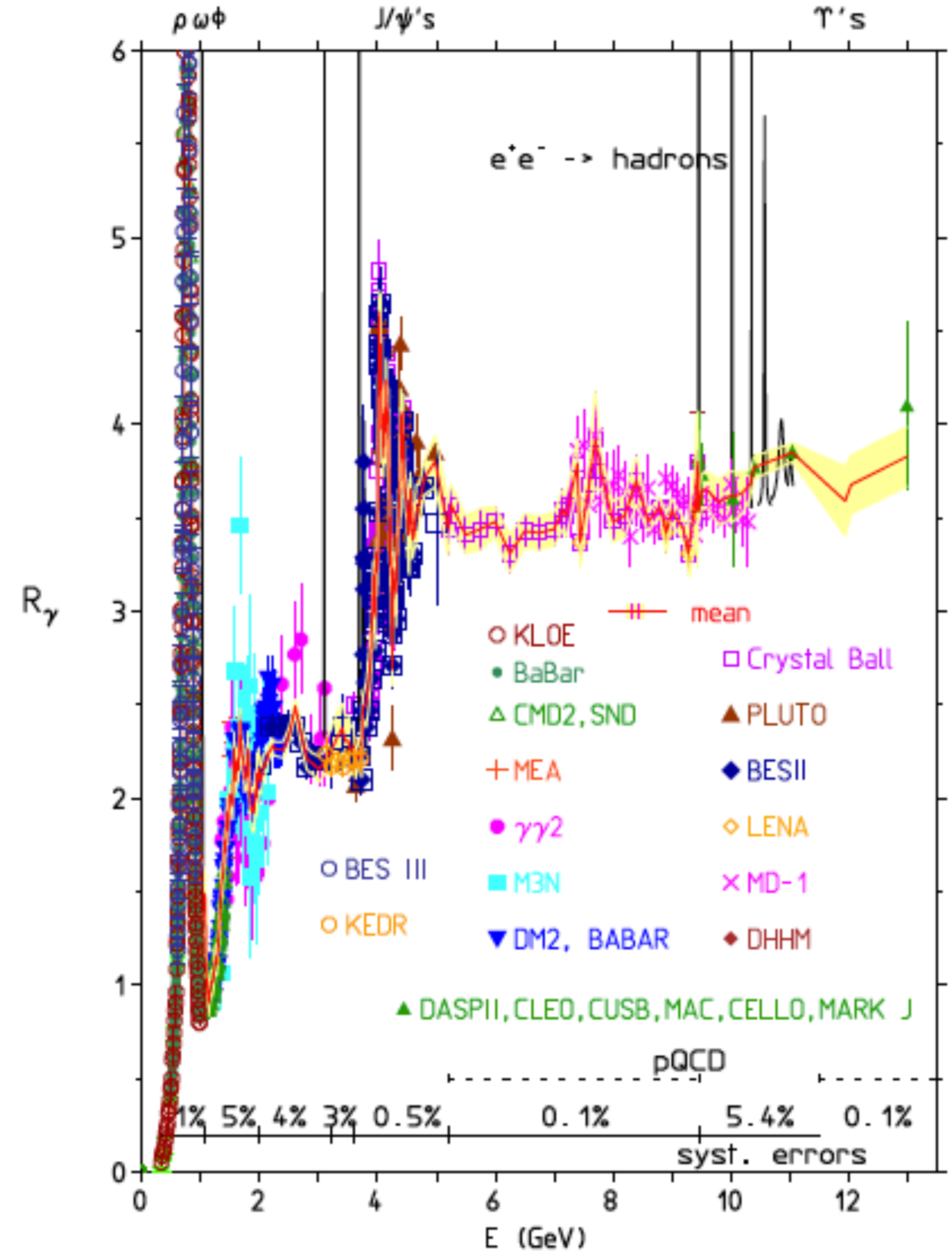
$$a_\mu^{HLO} = (\frac{\alpha m_\mu}{3\pi})^2 \int_{4m_\pi^2}^\infty ds \frac{\hat{K}(s) R_{had}(s)}{s^2}$$

$$R_{had}(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

from F. Jegerlehner talk in Frascati March 23, 2016




from F. Jegerlehner talk in Frascati March 23, 2016

# Measurement of the running of $\alpha_{em}$

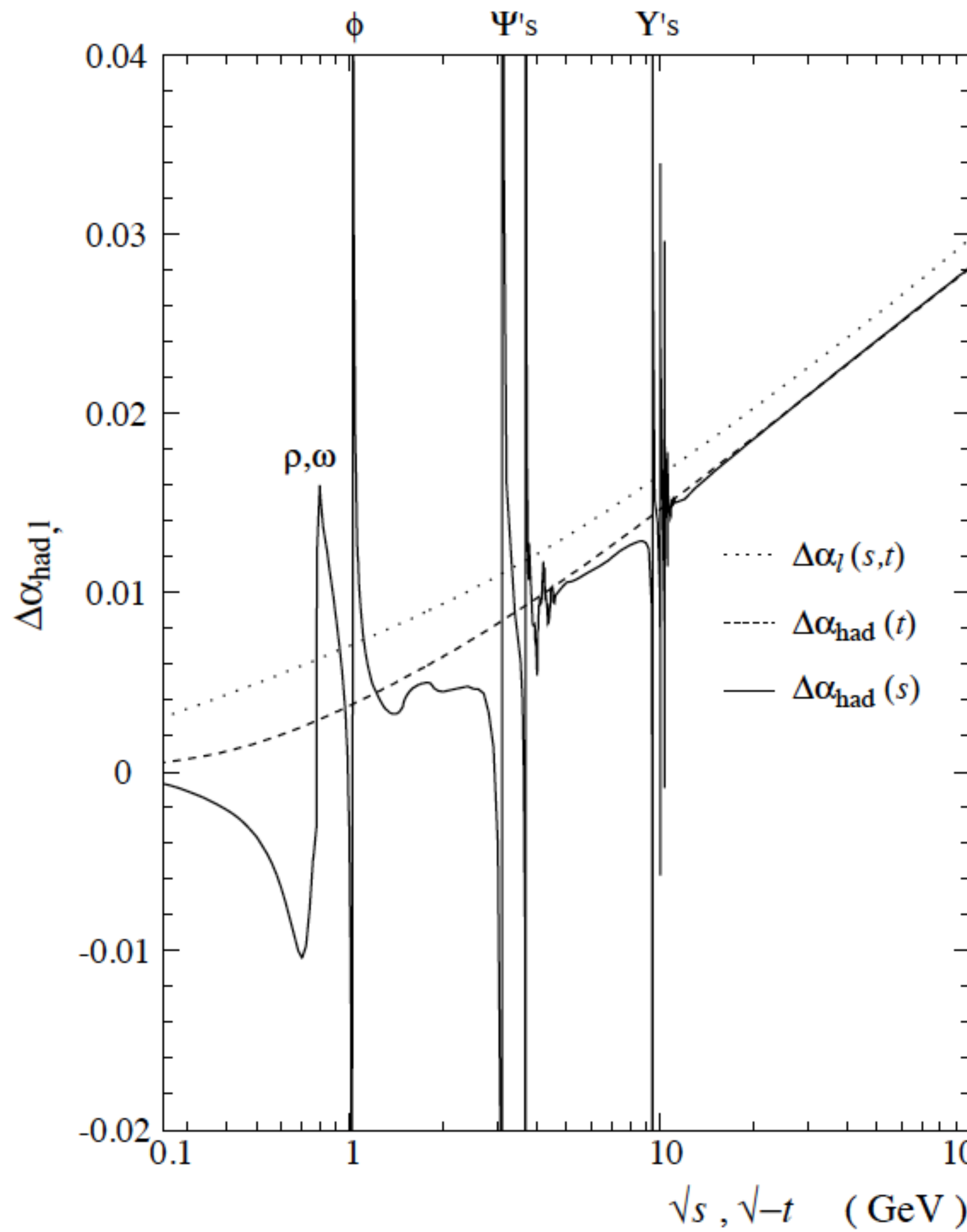
A direct measurement of $\alpha_{em}(s/t)$ in space/ time-like regions can show the running of $\alpha_{em}(s/t)$

It can provide a test of "duality" (far away from resonances)

It has been done in past by few experiments at $e^+e^-$ colliders by comparing a "well-known" QED process with some reference (obtained from data or MC)

$$\left(\frac{\alpha(q^2)}{\alpha(q_0^2)}\right)^2 \sim \frac{N_{signal}(q^2)}{N_{norm}(q_0^2)}$$

$N_{signal}$ can be any QED process, muon pairs, etc…
$N_{norm}$ can be Bhabha process, pure QED as γγ pair production, a well as theory, or any other reference process.



**Within the framework of low-energy high precision measurements the long-standing (3-4) $\sigma$ discrepancy between the experimental value of the muon anomalous magnetic moment and the Standard Model prediction**

$$a_\mu = \frac{g-2}{2}$$

$$\Delta a_\mu(Exp - SM) \simeq 28 \pm 8 \cdot 10^{-10}$$

The accuracy of the SM prediction $5 \cdot 10^{-10}$

is limited by **strong interactions** effects

The present error on the leading order hadronic contribution to muon $g-2$

$$\delta a_\mu^{HLO} \simeq 4 \cdot 10^{-10}$$

**It constitutes the main uncertainty of the SM predictions**

## 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

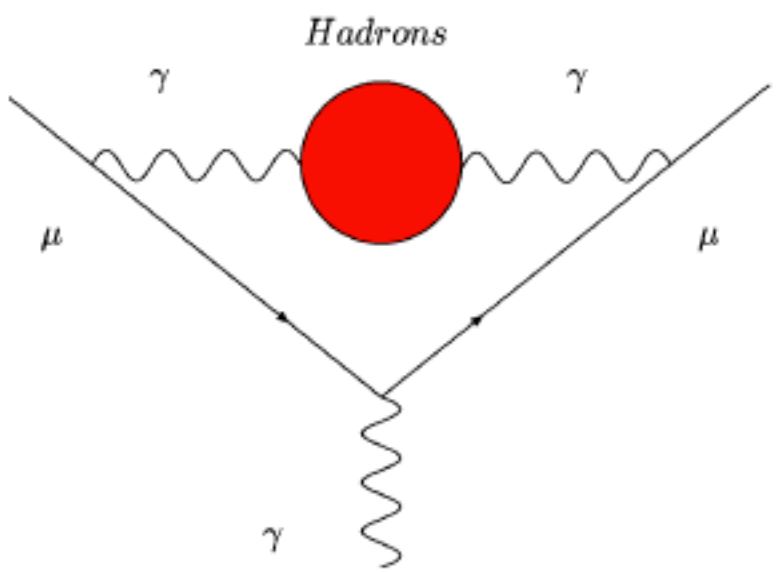
| $a_\mu^{SM} \times 10^{11}$ | $\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$ | $\sigma$ |
|---|---|---|
| 116 591 761 (57) | $330\ (85) \times 10^{-11}$ | 3.9 [1] |
| 116 591 818 (51) | $273\ (81) \times 10^{-11}$ | 3.4 [2] |
| 116 591 841 (58) | $250\ (86) \times 10^{-11}$ | 2.9 [3] |

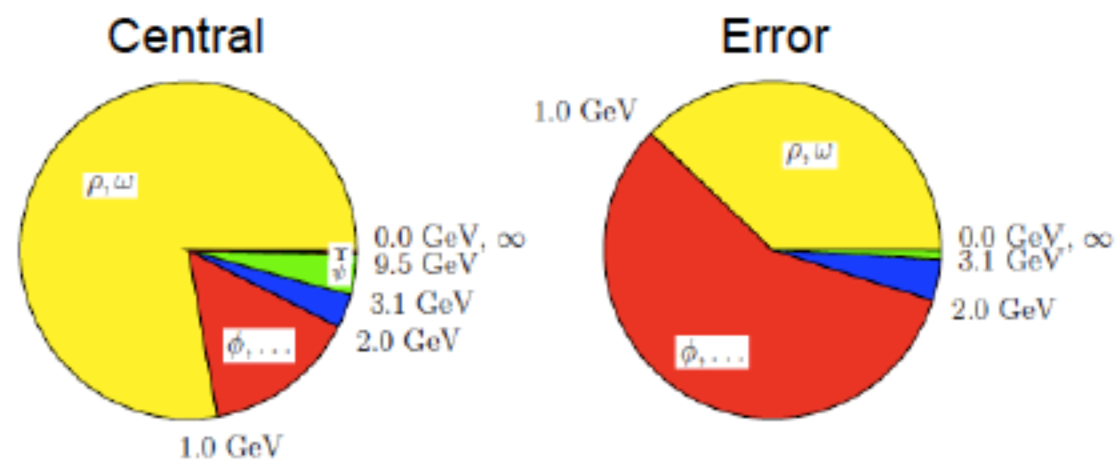
with the recent "conservative" hadronic light-by-light $a_\mu^{HNLO}(lbl) = 102\ (39) \times 10^{-11}$ of F. Jegerlehner arXiv:1511.04473, and the hadronic leading-order of:


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


from M. Passera

# The muon g-2 - The Hadronic contribution




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

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

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

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

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

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

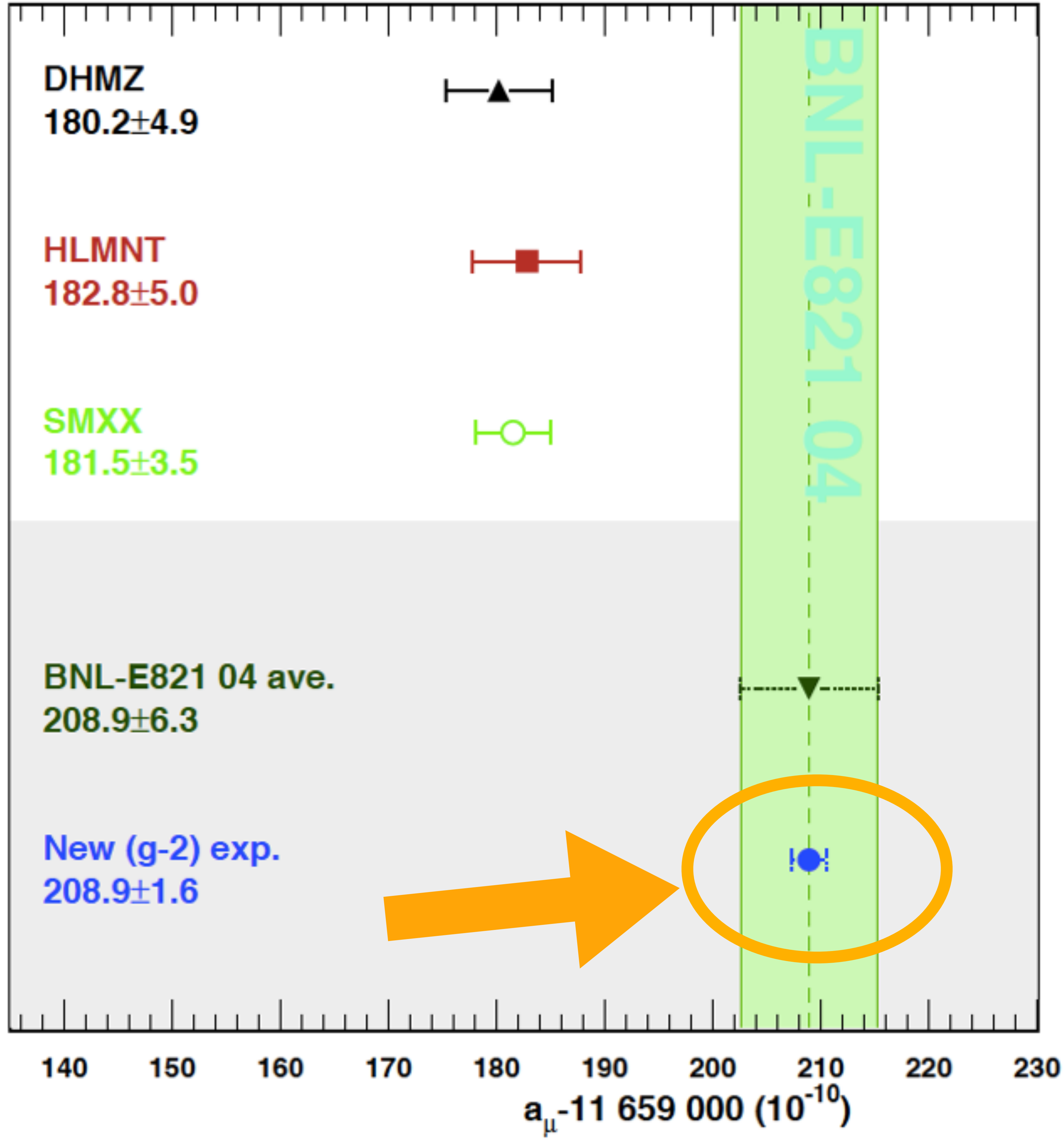
from M. Passera

Comparison between the SM predictions and the experimental determinations

Theory parametrizations DHMZ ( M.Davier et al. ) , HLMNT ( K. Hagiwara et al. ) SMXX is the average of the two previous values

BNL-E821 04 average is the current experimental value of aμ

New (g-2) exp. is the same central value with a fourfold improved precision of future g-2 experiments at Fermilab and J-PARC.




.From T. Blum et. al., “The Muon g-2 Theory Value: Present and Future” arXiv:1311.2198 [hep-ph] will this possibly change in the next few years ?

a fourfold gain

The present experimental error as from the **BNL E821** is

$$\delta a_\mu^{Exp} \simeq 6.3 \cdot 10^{-10} [0.54\ ppm]$$

The new experiments in preparation at **Fermilab** and **J-PARC** are aiming to a precision of *

$$\delta a_\mu^{Exp-FL/J-PARC} \simeq 1.6 \cdot 10^{-10} [0.14\ ppm]$$

(*assuming the same central value as today's one)

The question is how to cope with such an improvement from the theory side

We propose an alternative approach

# The alternative approach of using a space-like formula for the vacuum polarization

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx\ (1-x)\bar{\Pi}_{had}(t(x)) = \frac{\alpha}{\pi}\int_0^1 dx\ (1-x)\ \Delta\alpha_{had}(t(x))$$

$$a_\mu^{HLO} = (\frac{\alpha}{\pi})\int_{-\infty}^0 \frac{dt}{\beta t}(\frac{1-\beta}{1+\beta})^2\bar{\Pi}_{had}(t) = -(\frac{\alpha}{\pi})\int_{-\infty}^0 \frac{dt}{\beta t}(\frac{1-\beta}{1+\beta})^2\Delta\alpha_{had}(t(x))$$

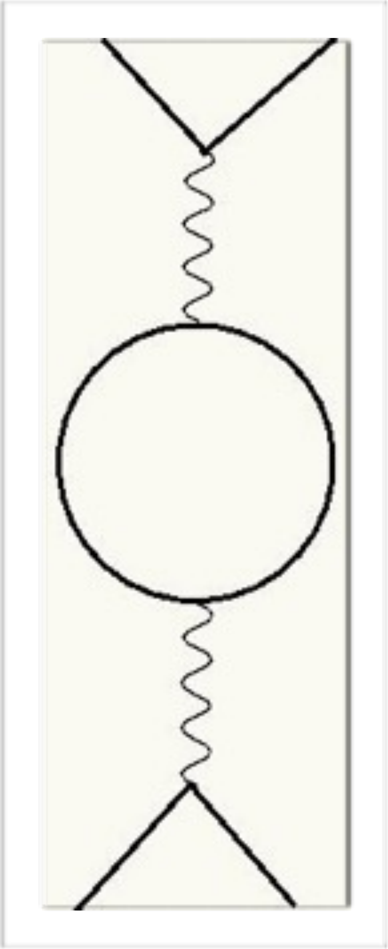
$$\beta = \sqrt{1-\frac{4m_\mu^2}{t}}$$

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

$$\alpha(t) = \frac{\alpha(0)}{1-\Delta\alpha(t)}$$

$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of $\alpha$

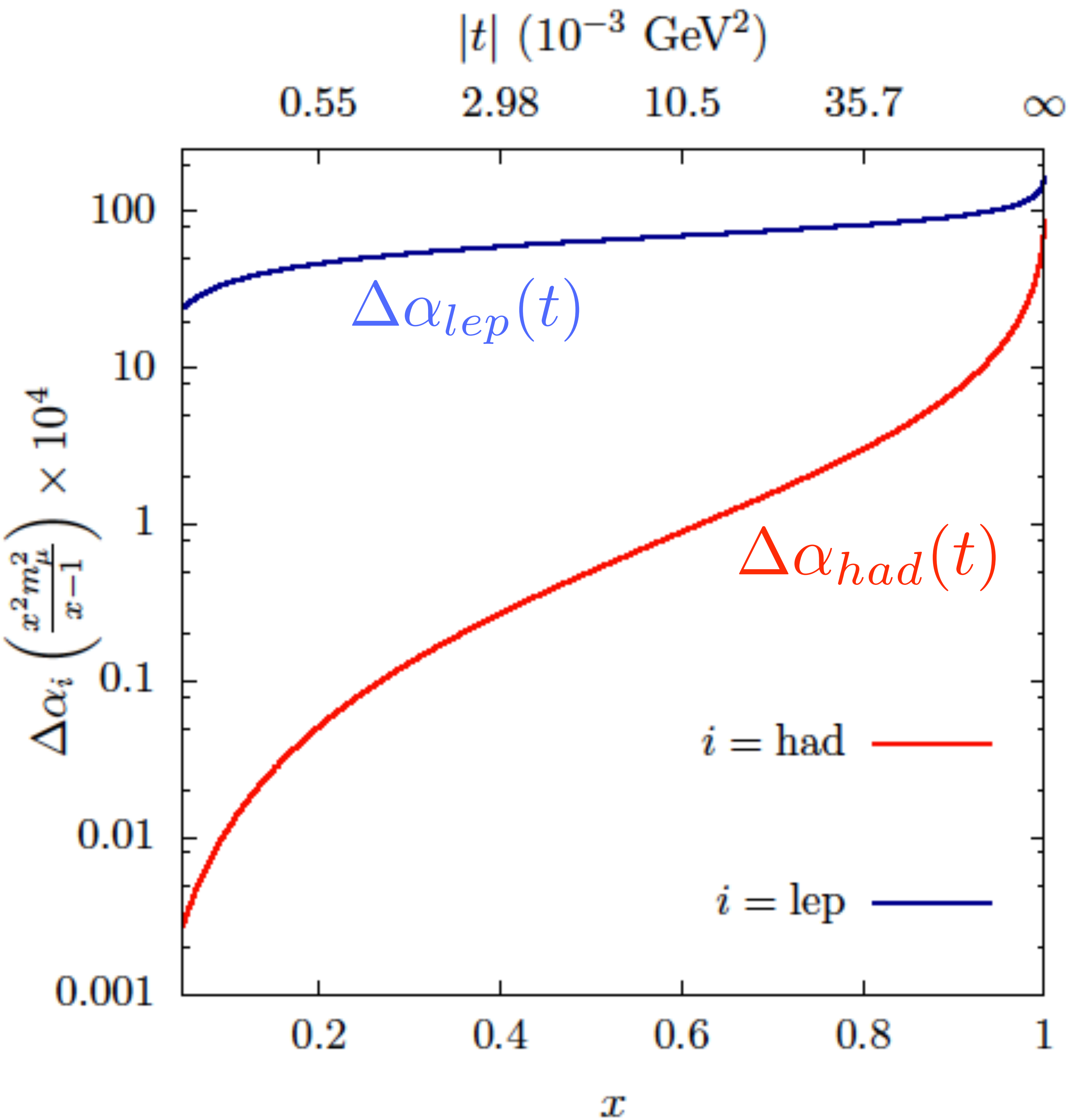
$$t = -|q|^2$$



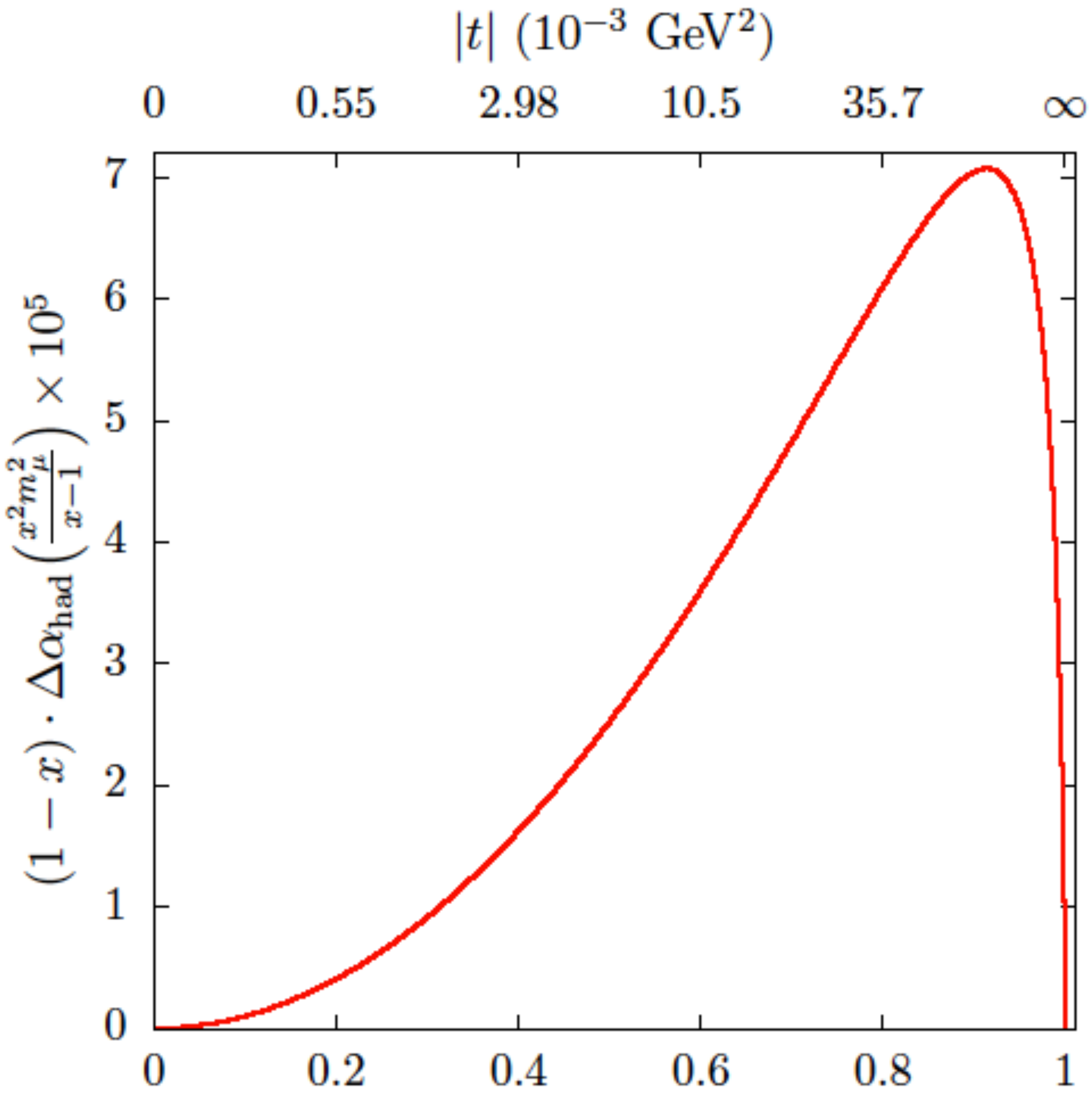
$$\Delta\alpha_{had}(t) = \Delta\alpha(t) - \Delta\alpha_{lep}(t)$$

This may be obtained by using Bhabha scattering

$\Delta\alpha_i(t(x))$



The integrand function




$$x_{peak} = 0.914 \quad t_{peak} = -0.108\ GeV^2$$

## 2. Theoretical framework

The leading-order hadronic contribution to the muon $g$-2 is given by the well-known formula [4,15]

$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi^2} \int_0^\infty \frac{ds}{s} \, K(s) \, {\rm Im}\Pi_{\rm had}(s + i\epsilon), \tag{1}$$

where $\Pi_{\rm had}(s)$ is the hadronic part of the photon vacuum polarization, $\epsilon > 0$,

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

is a positive kernel function, and $m_\mu$ is the muon mass. As the total cross section for hadron production in low-energy $e^+e^-$ annihilations is related to the imaginary part of $\Pi_{\rm had}(s)$ via the optical theorem, the dispersion integral in Eq. (1) is computed integrating experimental time-like ($s > 0$) data up to a certain value of $s$ [2,18,19]. The high-energy tail of the integral is calculated using perturbative QCD [20].

Alternatively, if we exchange the $x$ and $s$ integrations in Eq. (1) we obtain [21]

$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi} \int_0^1 dx \, (x-1) \, \overline{\Pi}_{\rm had}[t(x)] \, , \tag{3}$$

where $\overline{\Pi}_{\rm had}(t) = \Pi_{\rm had}(t) - \Pi_{\rm had}(0)$ and

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

The space-like kinematics allows a direct comparison with the lattice evaluations

is a space-like squared four-momentum. If we invert Eq. (4), we get $x = (1-\beta)(t/2m_\mu^2)$, with $\beta = (1-4m_\mu^2/t)^{1/2}$, and from Eq. (3) we obtain

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi} \int_{-\infty}^{0} \overline{\Pi}_{\mathrm{had}}(t) \left(\frac{\beta-1}{\beta+1}\right)^2 \frac{dt}{t\beta}. \quad (5)$$

Eq. (5) has been used for lattice QCD calculations of $a_\mu^{\mathrm{HLO}}$ [22]; while the results are not yet competitive with those obtained with the dispersive approach via time-like data, their errors are expected to decrease significantly in the next few years [23].


[22] C. Aubin, T. Blum, Phys. Rev. D 75 (2007) 114502;
P. Boyle et al., Phys. Rev. D 85 (2012) 074504;
X. Feng et al.,Phys. Rev. Lett. 107 (2011) 081802;
M. Della Morte et al. ,J. High Energy Phys. 1203 (2012) 055.

[23] T. Blum et al., PoS LATTICE 2012 (2012) 022.

To summarize

$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Pi_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$

$$t = \frac{x^2 m_\mu^2}{x-1} \qquad 0 \le -t < +\infty$$

$a_\mu=(g-2)/2$

$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \qquad 0 \le x < 1;$$

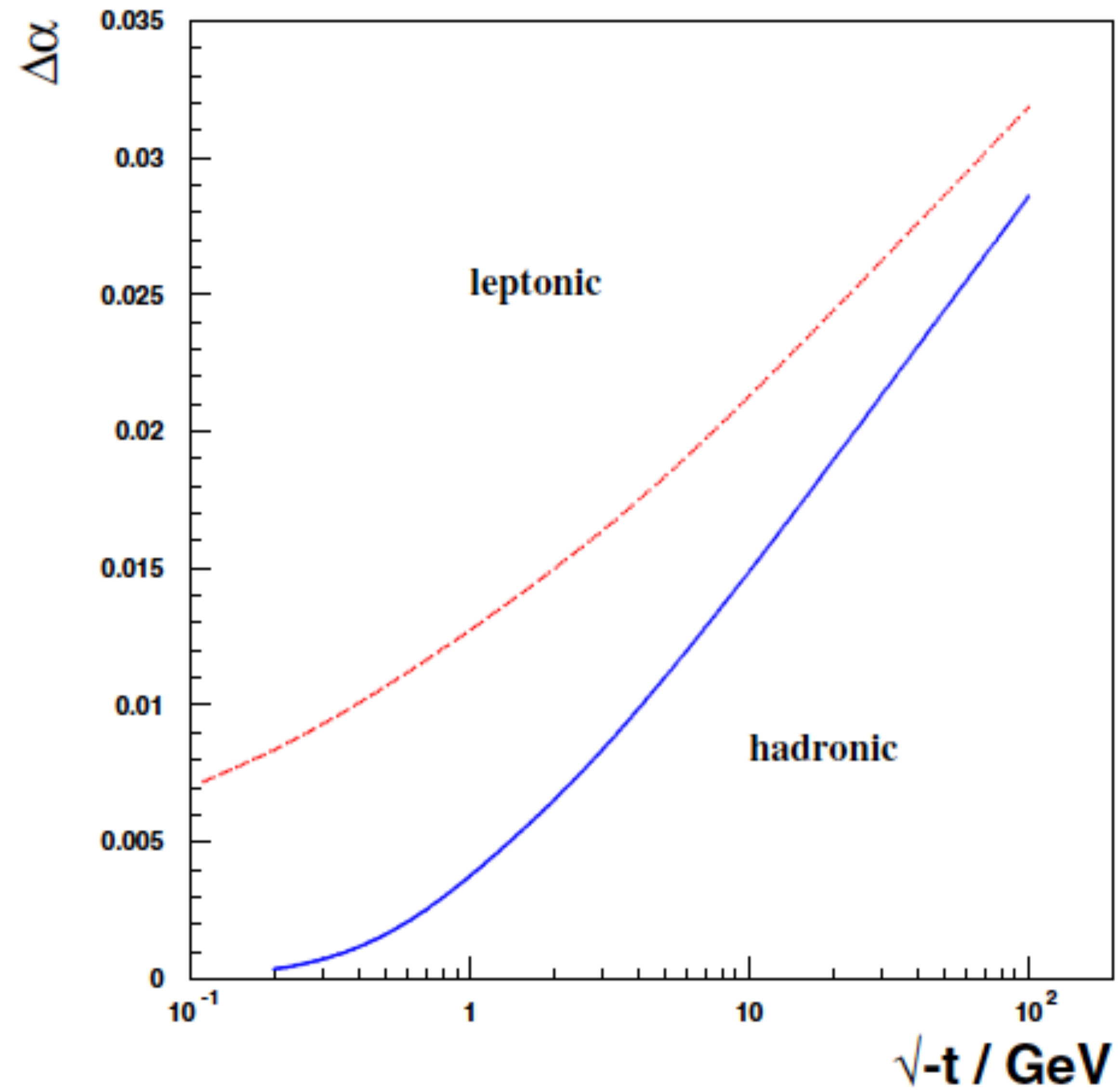
$$t = -s\sin^2\left(\frac{\vartheta}{2}\right)$$

$$\Delta\alpha_{had}(t) = -\Pi_{had}(t) \qquad for\ t<0$$

with the "t" kernel

$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$

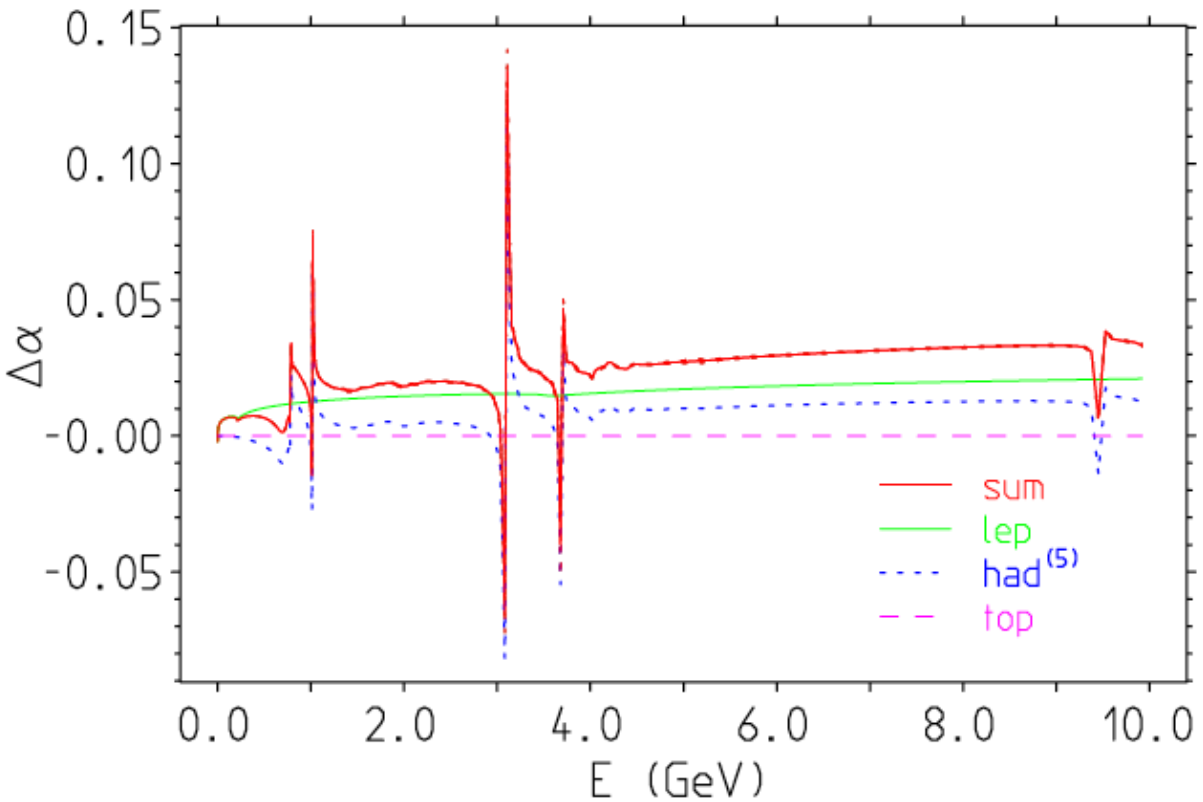
# functional form of the kernel

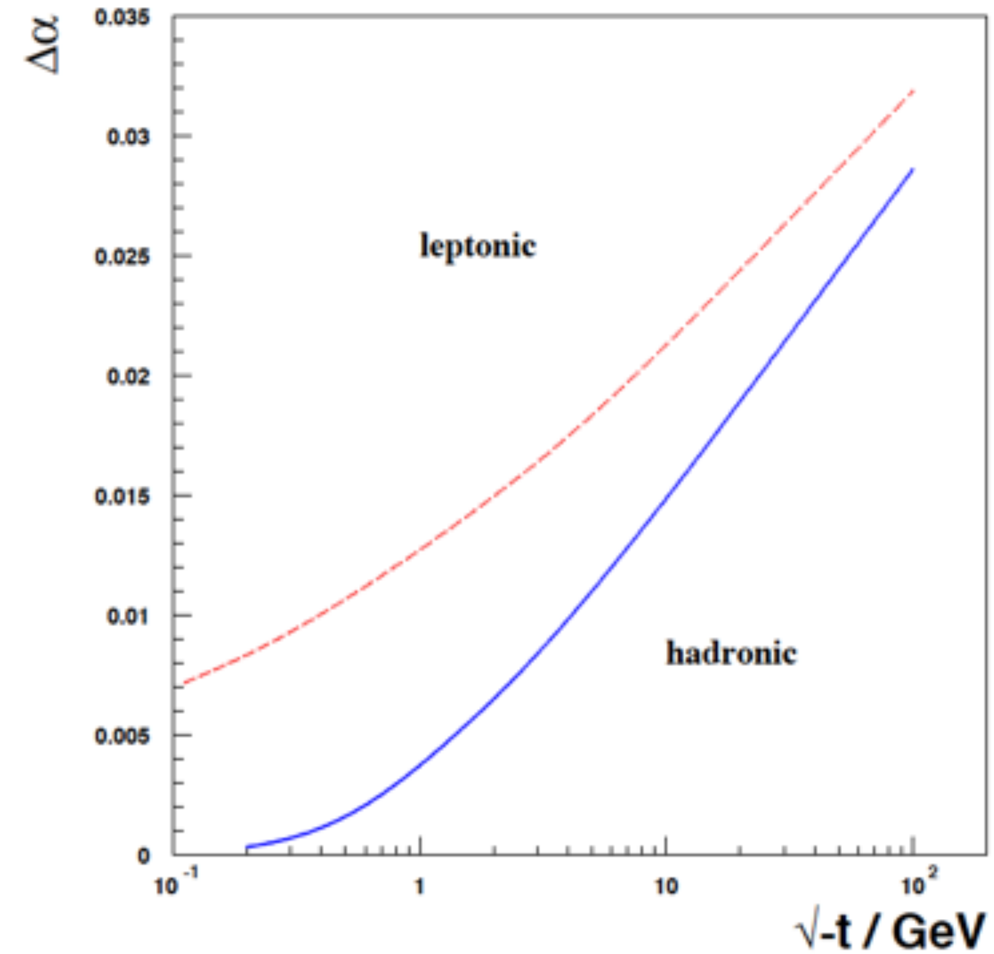



$\Delta\alpha$ is dominated at low t by leptonic contributions

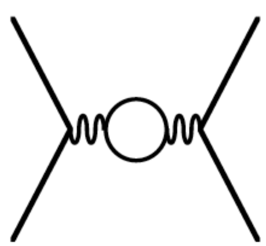
A. Arbuzov, D.Haidt, C.Matteuzzi,M.Paganoni, L.T. Eur. Phys. J. C 34 (2004) 267

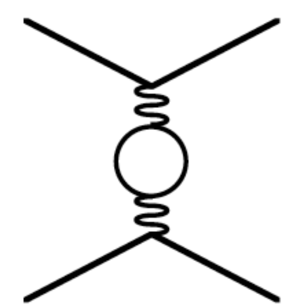
# Running of $\alpha_{em}$




time-like





space-like

$$\Delta\alpha_{had}^{(5)}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi} \mathrm{Re} \int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s - M_Z^2 - i\varepsilon)}$$

# A new possibility
# via
# $$\mu e \to \mu e$$
# scattering

G. Abbiendi, C.M. Carloni Calame, U. Marconi, C. Matteuzzi, G. Montagna,
O. Nicrosini M. Passera, F. Piccinini, R. Tenchini, L.T. and G. Venanzoni,
arXiv:1609.08987 [hep-ex], Eur. Phys. J. C77 (2017) 3, 139

# $\mu e \to \mu e$

- High intensity muon beam available in the CERN North Area E =150 GeV
- pure t-channel process

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt} \left| \frac{\alpha(t)}{\alpha(0)} \right|^2$$

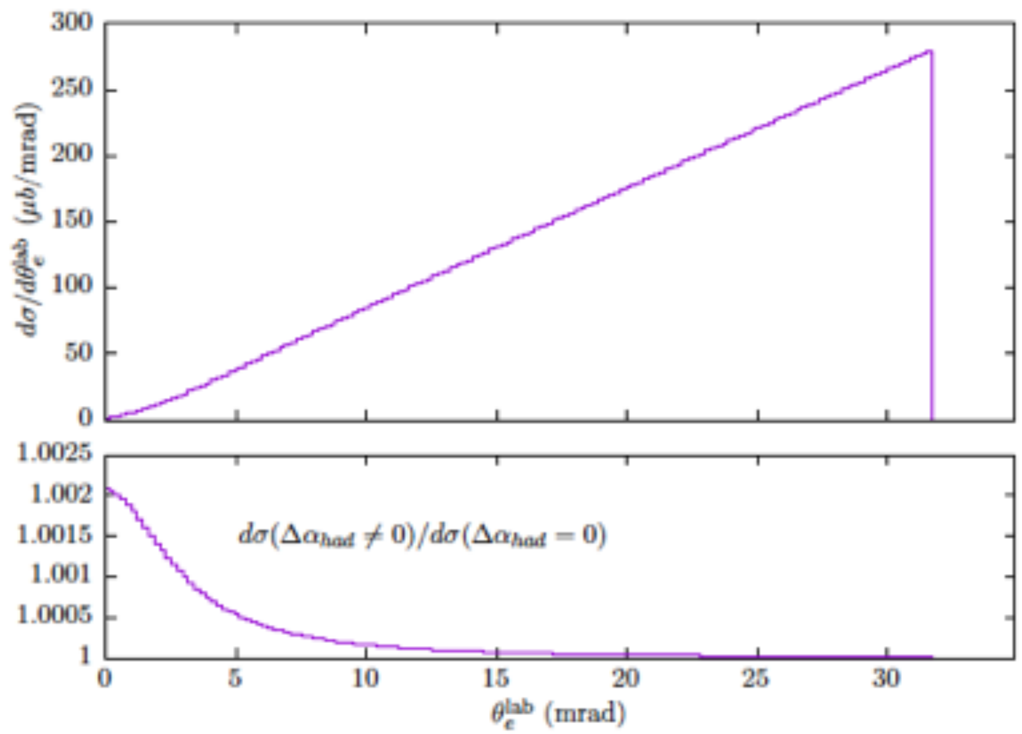
$$s \simeq 0.16\ GeV^2 \quad -0.14 \le t \le 0\ GeV^2 \quad 0 \le x \le 0.93$$

- the $2 \to 2$ kinematics reads

$$t = 2m_e^2 - 2m_e E_e, \qquad s = m_\mu^2 + m_e^2 + 2m_e E_\mu^i \qquad r \equiv \frac{\sqrt{(E_\mu^i)^2 - m_\mu^2}}{E_\mu^i + m_e}$$

$$E_e = m_e \frac{1 + r^2 c_e^2}{1 - r^2 c_e^2}, \qquad \theta_e = \arccos\left(\frac{1}{r}\sqrt{\frac{E_e - m_e}{E_e + m_e}}\right) \qquad c_e \equiv \cos\theta_e$$

- $0 < \theta_e < 31.85$ mrad $\longleftrightarrow 139.8 > E_e > 1$ GeV $\longleftrightarrow -0.143 < t < -10^{-3}$ GeV$^2$




→ differential cross-section at LO (including vacuum polarization) as a function of $\theta_e$

→ effect due to $\Delta\alpha_{\text{had}}(t)$

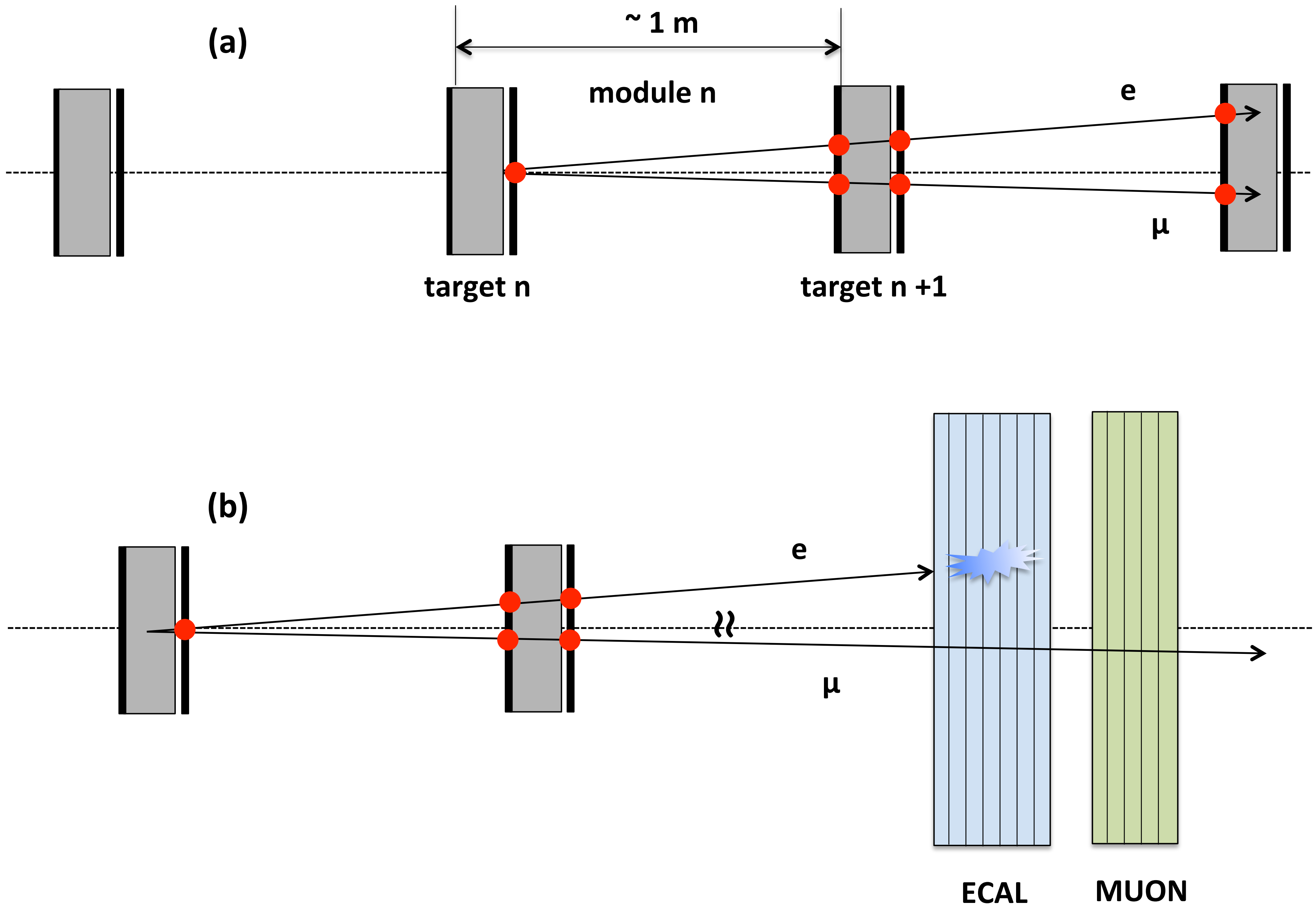
→ for instance the region $\theta_e > 20 \div 25$ mrad can be used as normalization



Same process can be used for signal and normalization

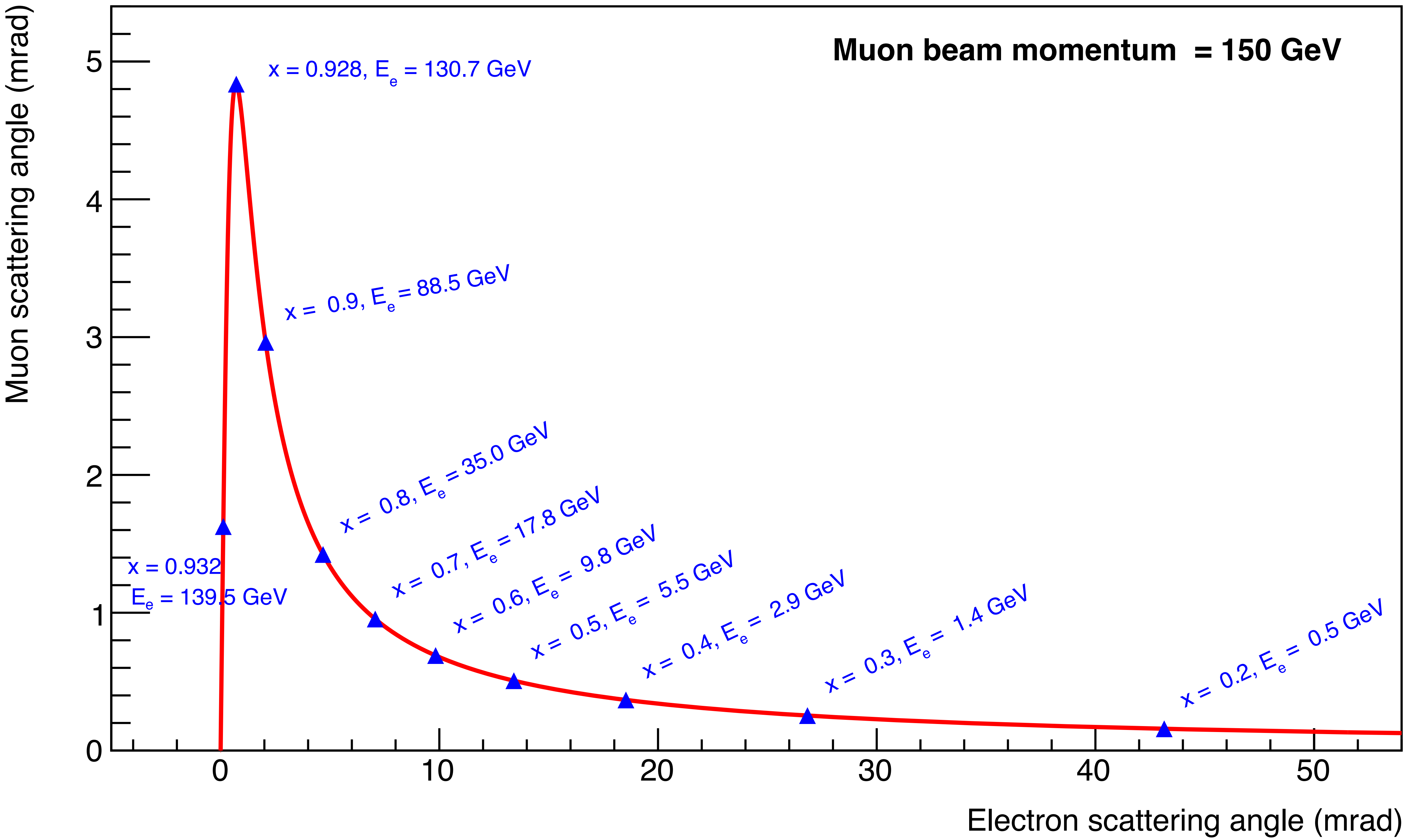
# The Detector

i) Initial muons have to be tagged with their direction and momentum
ii) 20 Be (C) layers interfaced with Si planes spaced by 1m air gap modularly spaced
iii) The use of a low Z material in order to reduce multiple scattering and background
iv) A final EM calorimeter to discriminate e/mu at small angles ( 2-3 mrad )



Muon and electron scattering angles are correlated

This very important constraint may be used to select elastic events, reject background from radiative events and minimize systematics



# This experiment has been proposed to CERN

- The idea has been presented on the 3 and 4 September 2016 to the "Physics Beyond Collider Study Group"

- C. Matteuzzi and G. Venanzoni are members of the board as the experiment representatives.

- Physics Beyond Collider Study Group will select experiments aiming to:

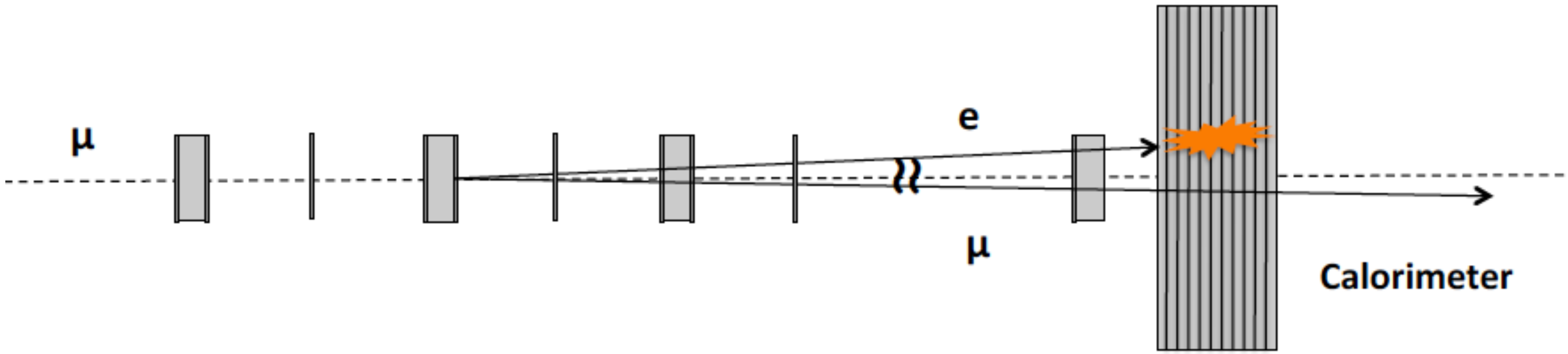
- Enrich and diversify the CERN scientific program
  Exploit the unique opportunities offered by CERN's accelerator complex and scientific infrastructure
  Complement the laboratory's collider programme (LHC, HL-LHC and possible future colliders).
  The scientific findings will be collected in a report to be delivered by the end of 2018.

This document will also serve as input to the next update of  the European Strategy for Particle Physics.

# and to the INFN NSCI on May 2017

U. Marconi at the CSN1 May 2017

# Detector design/optimization




- Electromagnetic calorimeter needed to:
  - Perform the PID: muon/electron discrimination.
    - PID capabilities also reconstructing the electromagnetic shower in the tracking system.
  - Triggering : (muon in) AND (ECAL $E > E_{th}$)
    - There is an alternative trigger condition: (muon in) AND (2 prongs into a given module)
- Establish how to measure $E_e$ in order to get rid of events with electron energy below 1 GeV

U. Marconi at the CSN1 May 2017

# 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 targets to resolve vertex position
8. Uncertainty in the muon beam momentum:
   decay kinematics constraints
9. Effects of Multiple Scattering:
   Require dedicated ancillary measurements

(Items 1–5:) Affordable by means of GEANT4 based simulations

U. Marconi at the CSN1 May 2017

# Plans

- 2018 - 2019
  - Detector optimization
  - Test beam
  - Theoretical studies
  - Letter of Intent
  - Set up a collaboration
- 2020
  - Detector construction and installation
- Start the data taking after LS2 by 2021
- 2021 – 2023
  Reach a relative precision on $a_\mu^{HLO}$ of 1%

U. Marconi at the CSN1 May 2017

# On the Theory side

Resummaton of dominant corrections up to all orders, matched with NLO corrections. Mass effects should be included.

NNLO corrections: some classes of NNLO re-usable from existing Bhabha calculations, some new ones due to the presence of different mass scales $m_\mu$ and $m_e$. In any case, NNLO contributions must be obtained.

See "Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data"
Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies
S. Actis et al. Eur. Phys. J. C 66 (2010) 585 and references therein.

Development of dedicated MC tools including all the above ingredients.

Detailed study of all the mentioned corrections, comparison among independent calculations, estimate of higher-order corrections.

A planned theory workshop this year in Padova 4-5 September and in 2018 here in Mainz a topical Workshop:
"The Evaluation of the Leading Hadronic Contribution to the muon anomalous magnetic moment"
February 19-23

# Muon-electron scattering: Theory kickoff workshop

4-5 September 2017

*Padova*

Europe/Rome timezone

- **Overview**
- Venue
- Timetable
- Logistic
- Map

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 $\mu e \to \mu e$. 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.

**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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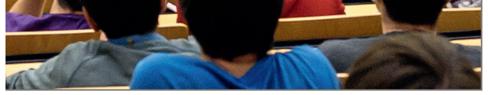

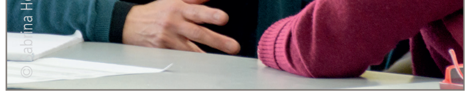

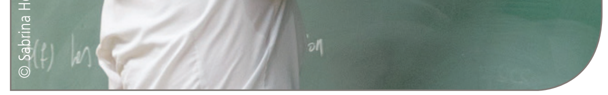

# Mainz Institute for Theoretical Physics

# ACTIVITIES 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**, Salvatore Vitale **MIT**, Luis Lehner **Perimeter Inst.**
**June 4-15, 2018**

**The Future of BSM Physics**
Giulia Ricciardi **U Naples Federico II**, Gian Giudice **CERN** Tobias Hurth, Joachim Kopp, Matthias Neubert **JGU**
**June 4-15, 2018, Capri, Italy**

**Probing Baryogenesis via LHC and Gravitational Wave Signatures**
Germano Nardini **U. Bern**, Carlos E.M. Wagner **U Chicago / Argonne NatLab.**, Pedro Schwaller **JGU**
**June 18-29, 2018**

**From Amplitudes to Phenomenology**
Fabrizio Caola **IPPP Durham**, Bernhard Mistlberger, Giulia Zanderighi **CERN**
**August 13-24, 2018**

**String Theory, Geometry and String Model Building**
Philip Candelas, Xenia de la Ossa, Andre Lukas **U Oxford**, Daniel Waldram **Imperial College London**, Gabriele Honecker, Duco van Straten **JGU**
**September 10-21, 2018**

## 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**

**The Proton Radius Puzzle and Beyond**
Gil Paz **Wayne State U**, Richard Hill **Perimeter Inst.**, Randolf Pohl **JGU**
**July 23-27, 2018**

**Scattering Amplitudes and Resonance Properties from Lattice QCD**
Maxwell T. Hansen **CERN**, Sasa Prelovsek **U Ljubljana**, Steve Sharpe **U Washington**, Georg von Hippel, Hartmut Wittig **JGU**
**August 27-31, 2018**

**Quantum Fields – From Fundamental Concepts to Phenomenological Questions**
Astrid Eichhorn **U Heidelberg**, Roberto Percacci **SISSA Trieste**, Frank Saueressig **U Nijmegen**
**September 26-28, 2018**

## MITP SUMMER SCHOOL 2018

Johannes Henn, Matthias Neubert, Stefan Weinzierl, Felix Yu **JGU**
**Juli 2018**

**For more details: http://www.mitp.uni-mainz.de**

Mainz Institute for Theoretical Physics

Cluster of Excellence PRISMA

You are all welcome!

# Conclusions and Outlook

This new approach for a direct measurement of the hadronic contribution to the anomalous muon magnetic moment represents a path within an unexplored region of field theoretical dynamics

It constitutes an independent determination, alternative and potentially competitive with respect to the time-like dispersive approach

The (crossed) t-channel dynamics, as complementary and independent with respect to the s-channel one, will permit a direct comparison with the lattice evaluations

It will consolidate the theoretical prediction for the muon g-2 in the Standard Model and allow a firmer interpretation of the measurements of the future muon g-2 experiments at Fermilab and J-PARC

This work is dedicated to the memory of our colleague and friend

**Eduard Alekseevich Kuraev**

Physics Letters B 746 (2015) 325–329

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www.elsevier.com/locate/physletb

ELSEVIER

## A new approach to evaluate the leading hadronic corrections to the muon g-2

CrossMark

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ARTICLE INFO

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Editor: A. Ringwald

This work is dedicated to the memory of our friend and colleague Eduard A. Kuraev

ABSTRACT

We propose a novel approach to determine the leading hadronic corrections to the muon g-2. It consists in a measurement of the effective electromagnetic coupling in the space-like region extracted from Bhabha scattering data. We argue that this new method may become feasible at flavor factories, resulting in an alternative determination potentially competitive with the accuracy of the present results obtained with the dispersive approach via time-like data.

Some acknowledgements:
Many friends and colleagues have been supporting and encouraging with us.
In particular we would like to thank Carlo Broggini, Lau Gatignon, Fred Jegerlehner, Marina Marinkovic and Thomas Teubner for fruitful discussions, and
Fedor Ignatov for fruitful discussions and help in the simulations.

Last but not least we are extremely grateful to Fred Jegerlehner for his continuous advice, support and encouragement.

FINIS

# Spare Transparencies

# AN EXAMPLE OF A SPACE-LIKE APPROACH

arXiv:hep-ph/0402211v1 19 Feb 2004

# The running of the electromagnetic coupling $\alpha$ in small-angle Bhabha scattering

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DESY, Notkestrasse 85, D-22603 Hamburg, Germany

C. Matteuzzi M. Paganoni
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Department of Physics, CERN Theory Division, 1211 Geneva 23, Switzerland

**Abstract**

A method to determine the running of $\alpha$ from a measurement of small-angle Bhabha scattering is proposed and worked out. The method is suited to high statistics experiments at $e^+e^-$ colliders, which are equipped with luminometers in the appropriate angular region. A new simulation code predicting small-angle Bhabha scattering is also presented.

A. Arbuzov, D. Haidt, C. Matteuzzi, M. Paganoni and L.T., Eur. Phys. J. C 34 (2004) 267

The method to measure the running of $\alpha$ exploits the fact that the cross section for the process $e^+e^- \to e^+e^-$ can be conveniently decomposed into three factors :

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{\mathrm{d}\sigma^0}{\mathrm{d}t}\left(\frac{\alpha(t)}{\alpha(0)}\right)^2 (1 + \Delta r(t)) \qquad (3)$$

each one of them known with an accuracy of at least 0.1%

1st factor

$$\frac{\mathrm{d}\sigma^0}{\mathrm{d}t} = \frac{\mathrm{d}\sigma^B}{\mathrm{d}t}\left(\frac{\alpha(0)}{\alpha(t)}\right)^2.$$

$$\frac{\mathrm{d}\sigma^B}{\mathrm{d}t} = \frac{\pi\alpha_0^2}{2s^2}\mathrm{Re}\{B_t + B_s + B_i\},$$

$$\begin{aligned}
B_t &= \left(\frac{s}{t}\right)^2\left\{\frac{5+2c+c^2}{(1-\Pi(t))^2} + \xi\frac{2(g_v^2+g_a^2)(5+2c+c^2)}{(1-\Pi(t))}\right. \\
&+ \left.\xi^2\left(4(g_v^2+g_a^2)^2 + (1+c)^2(g_v^4+g_a^4+6g_v^2g_a^2)\right)\right\} \\
B_s &= \frac{2(1+c^2)}{|1-\Pi(s)|^2} + 2\chi\frac{(1-c)^2(g_v^2-g_a^2)+(1+c)^2(g_v^2+g_a^2)}{1-\Pi(s)} \\
&+ \chi^2[(1-c)^2(g_v^2-g_a^2)^2 + (1+c)^2(g_v^4+g_a^4+6g_v^2g_a^2)] \\
B_i &= 2\frac{s}{t}(1+c)^2\left\{\frac{1}{(1-\Pi(t))(1-\Pi(s))}\right. \\
&+ (g_v^2+g_a^2)\left(\frac{\xi}{1-\Pi(s)} + \frac{\chi}{1-\Pi(t)}\right) \\
&+ \left.(g_v^4+6g_v^2g_a^2+g_a^4)\xi\chi\right\}
\end{aligned}$$

The Born cross section contains all the soft and virtual corrections

Bhabha is a pure QED process
Quarks enter only in loops

2nd factor

$$\left(\frac{\alpha(t)}{\alpha(0)}\right)^2$$

Vacuum polarization effects

gives the running of alpha

3rd factor

$$(1+\Delta r(t))$$

with all the real and virtual effects not incorporated in the running of alpha

$$\alpha(q^2) = \frac{\alpha(0)}{1 - \Delta\alpha(q^2)},$$

$\alpha(0)$ is the Sommerfeld fine structure constant measured with a precision of $O(10^{-9})$

$\Delta\alpha(q^2)$ from loop contributions to the photon propagator

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN-PH-EP/2005-014
21 February 2005
Revised 28 June 2005

# Measurement of the running of the QED coupling in small-angle Bhabha scattering at LEP

OPAL Collaboration

## Abstract

Using the OPAL detector at LEP, the running of the effective QED coupling $\alpha(t)$ is measured for space-like momentum transfer from the angular distribution of small-angle Bhabha scattering. In an almost ideal QED framework, with very favourable experimental conditions, we obtain:

$$\Delta\alpha(-6.07\,\mathrm{GeV}^2) - \Delta\alpha(-1.81\,\mathrm{GeV}^2) = (440 \pm 58 \pm 43 \pm 30) \times 10^{-5}\,,$$

where the first error is statistical, the second is the experimental systematic and the third is the theoretical uncertainty. This agrees with current evaluations of $\alpha(t)$. The null hypothesis that $\alpha$ remains constant within the above interval of $-t$ is excluded with a significance above $5\,\sigma$. Similarly, our results are inconsistent at the level of $3\,\sigma$ with the hypothesis that only leptonic loops contribute to the running. This is currently the most significant direct measurement where the running $\alpha(t)$ is probed differentially within the measured $t$ range.

This has been made possible by a very accurate determination of the Luminosity by the OPAL collaboration

# A measurement of the Luminosity at $10^{-4}$ at LEP

Giovanni Abbiendi

INFN - Bologna

Eur. Phys. J. C 45, 1–21 (2006)
Digital Object Identifier (DOI) 10.1140/epjc/s2005-02389-3

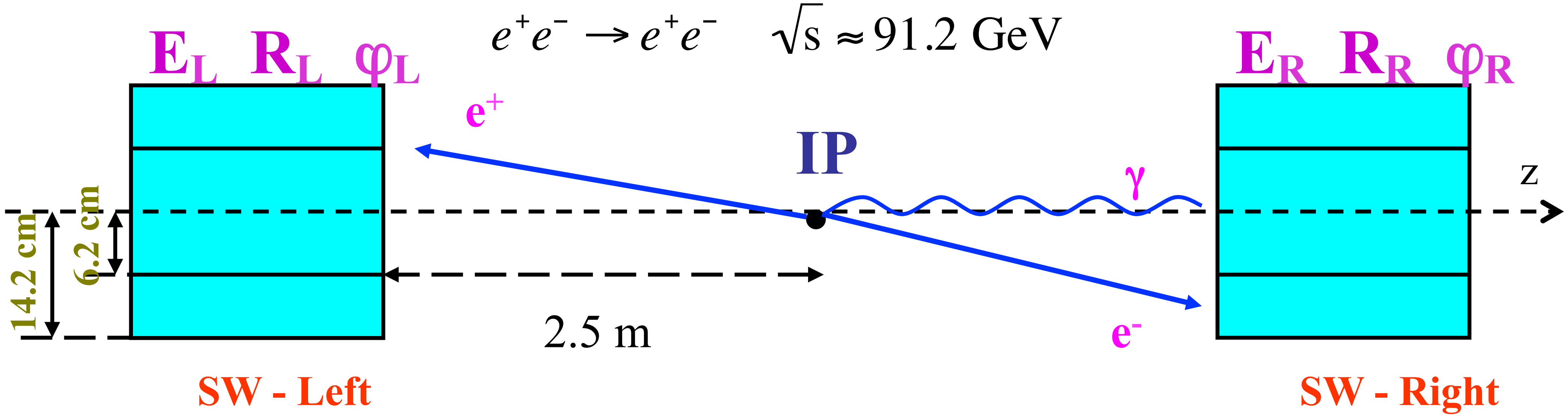
THE EUROPEAN PHYSICAL JOURNAL C

## Measurement of the running of the QED coupling in small-angle Bhabha scattering at LEP

The OPAL Collaboration

G. Abbiendi[2], C. Ainsley[5], P.F. Åkesson[3,y], G. Alexander[22], G. Anagnostou[1], K.J. Anderson[9], S. Asai[23], D. Axen[27], I. Bailey[26], E. Barberio[8,p], T. Barillari[32], R.J. Barlow[16], R.J. Batley[5], P. Bechtle[25], T. Behnke[25], K.W. Bell[20], P.J. Bell[1], G. Bella[22], A. Bellerive[6], G. Benelli[4], S. Bethke[32], O. Biebel[31], O. Boeriu[10], P. Bock[11], M. Boutemeur[31], S. Braibant[2], R.M. Brown[20], H.J. Burckhart[8], S. Campana[4], P. Capiluppi[2], R.K. Carnegie[6], A.A. Carter[13], J.R. Carter[5], C.Y. Chang[17], D.G. Charlton[1], C. Ciocca[2], A. Csilling[29], M. Cuffiani[2], S. Dado[21], G.M. Dallavalle[2], A. De Roeck[8], E.A. De Wolf[8,s], K. Desch[25], B. Dienes[30], J. Dubbert[31], E. Duchovni[24], G. Duckeck[31], I.P. Duerdoth[16], E. Etzion[22], F. Fabbri[2], P. Ferrari[8], F. Fiedler[31], I. Fleck[10], M. Ford[16], A. Frey[8], P. Gagnon[12], J.W. Gary[4], C. Geich-Gimbel[3], G. Giacomelli[2], P. Giacomelli[2], R. Giacomelli[2], M. Giunta[4], J. Goldberg[21], E. Gross[24], J. Grunhaus[22], M. Gruwé[8], P.O. Günther[3], A. Gupta[9], C. Hajdu[29], M. Hamann[25], G.G. Hanson[4], A. Harel[21], M. Hauschild[8], C.M. Hawkes[1], R. Hawkings[8], R.J. Hemingway[6], G. Herten[10], R.D. Heuer[25], J.C. Hill[5], D. Horváth[29,c], P. Igo-Kemenes[11], K. Ishii[23], H. Jeremie[18], P. Jovanovic[1], T.R. Junk[6,i], J. Kanzaki[23,u], D. Karlen[26], K. Kawagoe[23], T. Kawamoto[23], R.K. Keeler[26], R.G. Kellogg[17], B.W. Kennedy[20], S. Kluth[32], T. Kobayashi[23], M. Kobel[3], S. Komamiya[23], T. Krämer[25], P. Krieger[6,l], J. von Krogh[11], T. Kuhl[25], M. Kupper[24], G.D. Lafferty[16], H. Landsman[21], D. Lanske[14], D. Lellouch[24], J. Letts[o], L. Levinson[24], J. Lillich[10], S.L. Lloyd[13], F.K. Loebinger[16], J. Lu[27,w], A. Ludwig[3], J. Ludwig[10], W. Mader[3,b], S. Marcellini[2], A.J. Martin[13], T. Mashimo[23], P. Mättig[m], J. McKenna[27], R.A. McPherson[26], F. Meijers[8], W. Menges[25], F.S. Merritt[9], H. Mes[6,a], N. Meyer[25], A. Michelini[2], S. Mihara[23], G. Mikenberg[24], D.J. Miller[15], W. Mohr[10], T. Mori[23], A. Mutter[10], K. Nagai[13], I. Nakamura[23,v], H. Nanjo[23], H.A. Neal[33], R. Nisius[32], S.W. O'Neale[1,*], A. Oh[8], M.J. Oreglia[9], S. Orito[23,*], C. Pahl[32], G. Pásztor[4,g], J.R. Pater[16], J.E. Pilcher[9], J. Pinfold[28], D.E. Plane[8], O. Pooth[14], M. Przybycień[8,n], A. Quadt[3], K. Rabbertz[8,r], C. Rembser[8], P. Renkel[24], J.M. Roney[26], A.M. Rossi[2], Y. Rozen[21], K. Runge[10], K. Sachs[6], T. Saeki[23], E.K.G. Sarkisyan[8,j], A.D. Schaile[31], O. Schaile[31], P. Scharff-Hansen[8], J. Schieck[32], T. Schörner-Sadenius[8,z], M. Schröder[8], M. Schumacher[3], R. Seuster[14,f], T.G. Shears[8,h], B.C. Shen[4], P. Sherwood[15], A. Skuja[17], A.M. Smith[8], R. Sobie[26], S. Söldner-Rembold[16], F. Spano[9], A. Stahl[3,x], D. Strom[19], R. Ströhmer[31], S. Tarem[21], M. Tasevsky[8,s], R. Teuscher[9], M.A. Thomson[5], E. Torrence[19], D. Toya[23], P. Tran[4], I. Trigger[8], Z. Trócsányi[30,e], E. Tsur[22], M.F. Turner-Watson[1], I. Ueda[23], B. Ujvári[30,e], C.F. Vollmer[31], P. Vannerem[10], R. Vértesi[30,e], M. Verzocchi[17], H. Voss[8,q], J. Vossebeld[8,h], C.P. Ward[5], D.R. Ward[5], P.M. Watkins[1], A.T. Watson[1], N.K. Watson[1], P.S. Wells[8], T. Wengler[8], N. Wermes[3], G.W. Wilson[16,k], J.A. Wilson[1], G. Wolf[24], T.R. Wyatt[16], S. Yamashita[23], D. Zer-Zion[4], L. Zivkovic[24]

# Small-angle Bhabha scattering in OPAL




**2 cylindrical calorimeters** encircling the beam pipe at ± 2.5 m from the Interaction Point

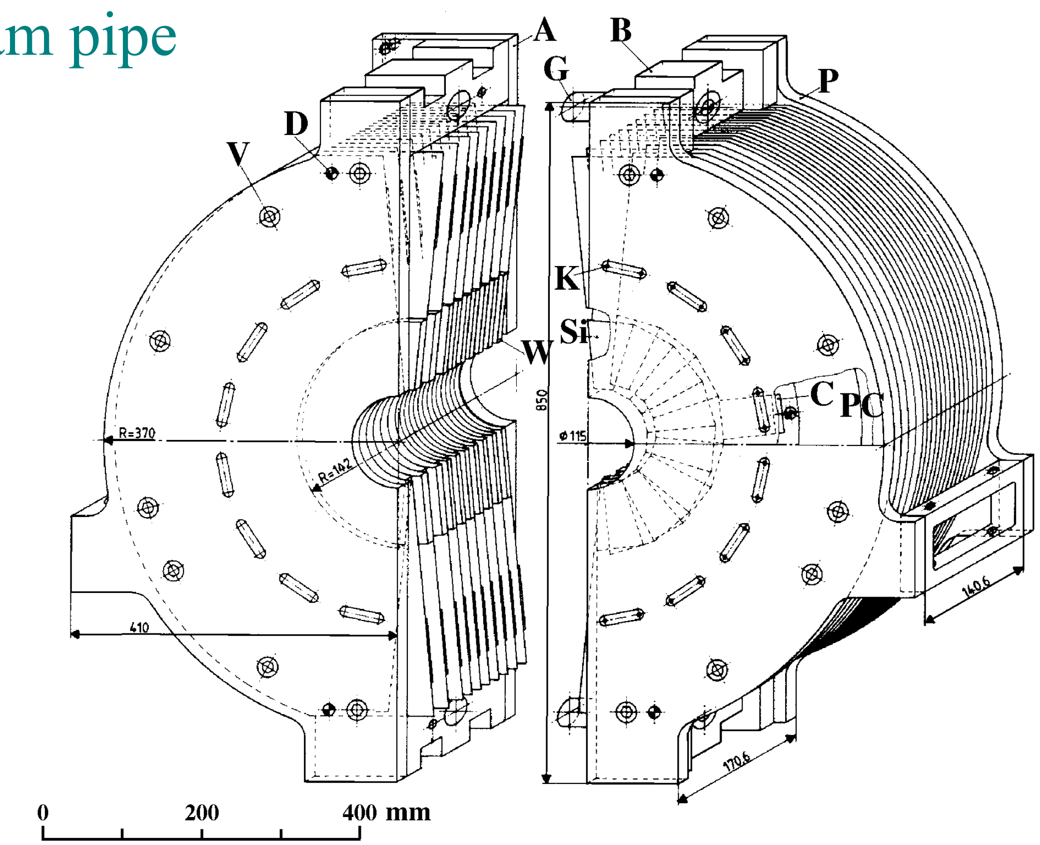
**19 Silicon layers**

**18 Tungsten layers**

Total Depth 22 $X_0$
(14 cm)

Each detector layer divided into 16 overlapping wedges

**Sensitive radius**: **6.2 – 14.2 cm**, corresponding to **scattering angle** of **25 – 58 mrad** from the beam line



# Final Error on Luminosity

After all the effort on Radial reconstruction the dominant systematic error is related to Energy (mostly tail in the E response and nonlinearity) Quantitatively: (OPAL Collaboration, Eur.Phys.J. C14 (2000) 373)

| | Systematic Error ($\times 10^{-4}$) |
|---|---|
| Energy | 1.8 |
| Inner Anchor | 1.4 |
| Radial Metrology | 1.4 |

**Total Experimental Systematic Error : $3.4 \times 10^{-4}$**

**Theoretical Error on Bhabha cross section: $5.4 \times 10^{-4}$**

The Method used follows the above parametrization/factorization of the Bhabha cross-section

$$\frac{d\sigma}{dt} = \frac{d\sigma^{(0)}}{dt}\left(\frac{\alpha(t)}{\alpha_0}\right)^2 (1+\epsilon)\,(1+\delta_\gamma) + \delta_Z$$

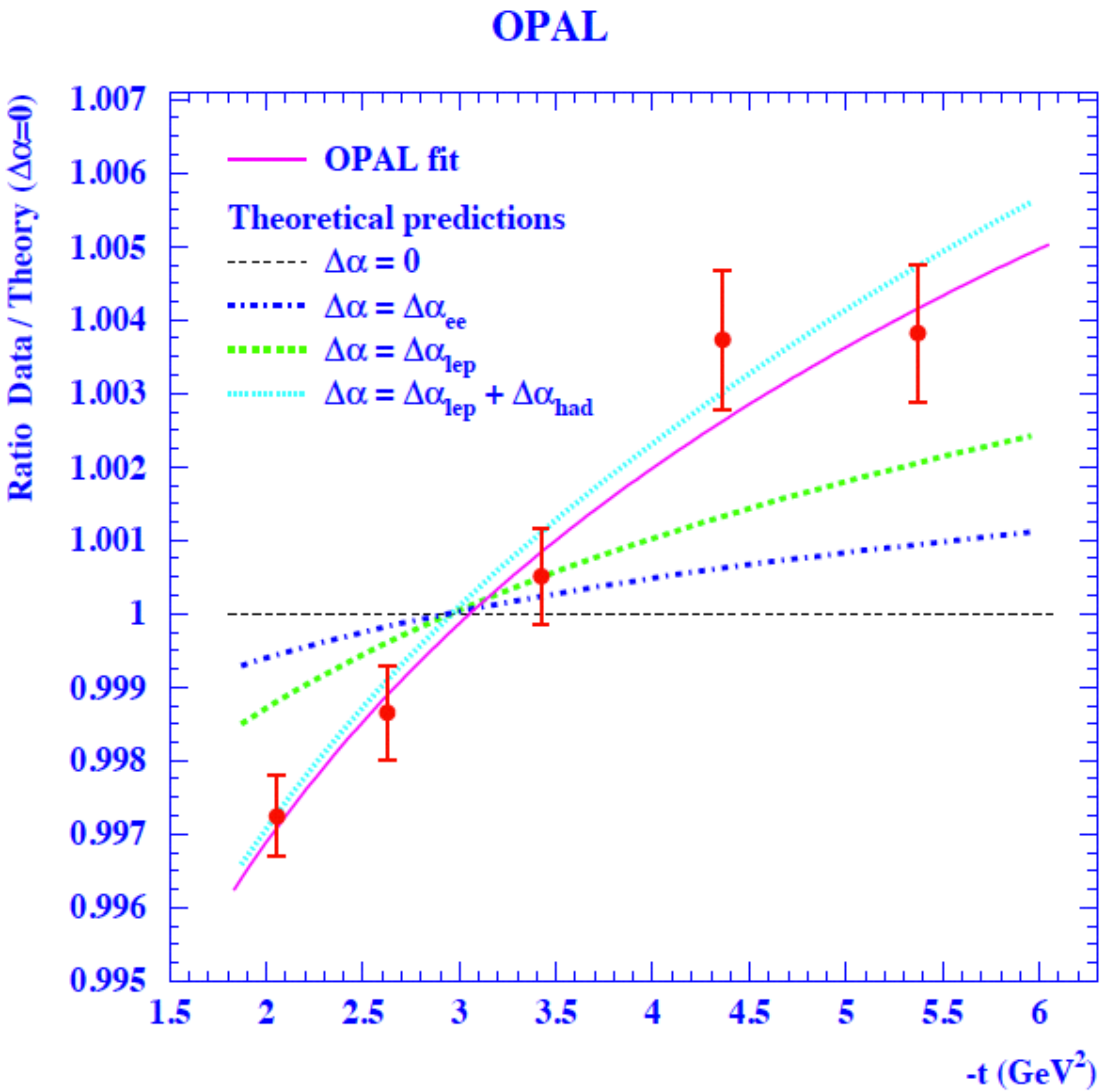
$$\frac{d\sigma^{(0)}}{dt} = \frac{4\pi\alpha_0^2}{t^2}$$

We determined the effective slope of the Bhabha momentum transfer distribution which is simply related to the average derivative of $\Delta\alpha$ as a function of $\ln t$ in the range $2\ \mathrm{GeV}^2 \leq -t \leq 6\ \mathrm{GeV}^2$. The observed $t$-spectrum is in good agreement with Standard Model predictions. We find:

$$\Delta\alpha(-6.07\,\mathrm{GeV}^2) - \Delta\alpha(-1.81\,\mathrm{GeV}^2) = (440 \pm 58 \pm 43 \pm 30) \times 10^{-5}\,,$$

where the first error is statistical, the second is the experimental systematic and the third is the theoretical uncertainty.

This measurement is one of only a very few experimental tests of the running of $\alpha(t)$ in the space-like region, where $\Delta\alpha$ has a smooth behaviour. We obtain the strongest direct evidence for the running of the QED coupling ever achieved differentially in a single experiment, with a significance above $5\,\sigma$. Moreover we report clear experimental evidence for the hadronic contribution to the running in the space-like region, with a significance of $3\,\sigma$.


OPAL
Ratio Data / Theory (Δα=0)
OPAL fit
Theoretical predictions
$\Delta\alpha = 0$
$\Delta\alpha = \Delta\alpha_{ee}$
$\Delta\alpha = \Delta\alpha_{lep}$
$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{had}$
1.007
1.006
1.005
1.004
1.003
1.002
1.001
1
0.999
0.998
0.997
0.996
0.995
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
-t ($GeV^2$)

PHYSICAL REVIEW VOLUME 124, NUMBER 5 DECEMBER 1, 1961

# Electron-Positron Colliding Beam Experiments

N. Cabibbo and R. Gatto
*Istituti di Fisica delle Università di Roma e di Cagliari, Italy and Laboratori Nazionali di Frascati del C.N.E.N., Frascati, Roma, Italy*

(Received June 8, 1961)

Possible experiments with high-energy colliding beams of electrons and positrons are discussed. The role of the proposed two-pion resonance and of the three-pion resonance or bound state is investigated in connection with electron-positron annihilation into pions. The existence of a three-pion bound state would give rise to a very large cross section for annihilation into $\pi^0+\gamma$. A discussion of the possible resonances is given based on consideration of the relevant widths as compared to the experimental energy resolution. Annihilation into baryon-antibaryon pairs is investigated and polarization effects arising from the nonreal character of the form factors on the absorptive cut are examined. The density matrix for annihilation into pairs of vector mesons is calculated. A discussion of the limits from unitarity to the annihilation cross sections is given for processes going through the one-photon channel. The cross section for annihilation into pairs of spin-one mesons is rather large. The typical angular correlations at the vector-meson decay are discussed.

A neutral weakly interacting vector meson would give rise to a strong resonant peak if it is coupled with lepton pairs. Effects of the local weak interactions are also examined. The explicit relation between the $e^2$ corrections to the photon propagator due to strong interactions and the cross section for annihilation into strongly interacting particles is given.

of the local weak interactions are also examined. The explicit relation between the $e^2$ corrections to the photon propagator due to strong interactions and the cross section for annihilation into strongly interacting particles is given.

“La Bibbia” ( “The Bible“) - June 1961

## 8. EXPRESSION FOR THE VACUUM POLARIZATION DUE TO STRONG INTERACTING PARTICLES

The quantity

$$\Pi(k^2) = -\frac{(2\pi)^3}{3k^2} \sum_{p^{(z)}=k} \langle 0 | j_\nu(0) | z \rangle \langle z | j_\nu(0) | 0 \rangle \quad (105)$$

is known to be of fundamental importance in quantum electrodynamics.[29] In (105), $j_\nu$ is the current operator and the sum is extended over all the physical states

[29] G. Källén, Helv. Phys. Acta **25**, 417 (1952).

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106)

In (106) $\bar{\Pi}(k^2)$ is defined as

$$\bar{\Pi}(k^2) = P \int_0^\infty \frac{\Pi(-a)}{k^2+a} da. \quad (107)$$

We show in this section that the experimentally measured cross sections for processes $e^+ + e^- \rightarrow \gamma \rightarrow F$, where $F$ denotes a group of final states, is directly related to the contribution to (105) from the group of states $F$ in the summation over the intermediate states $z$. This result will permit, for instance, calculation of the modifications of the photon propagator due to virtual strong interacting particles, directly from the measured cross sections.

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In high energy