A space-like determination of a_μ^{HLO} via μ-e scattering data

G. Venanzoni

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In collaboration with: G. Abbiendi, M. Alacevich, M. Bonomi, C.M.Carloni Calame, D. Galli, F.V. Ignatov, M. Incagli, U. Marconi, C. Matteuzzi, G. Montagna, O. Nicrosini, M. Passera, C. Patrignani, F. Piccinini, F. Pisani,A. Principe, M. Prest, R. Tenchini, L. Trentadue, E. Vallazza

Novosibirsk, 26 January 2018

Outline

- Muon g-2: present status
- “Traditional” calculation of HVP (timelike data)
- “Alternative” spacelike determination of HVP: MUonE proposal
- Status of MUonE
- Conclusions & Outlook

Muon g-2: summary of the present status

- E821 experiment at BNL has generated enormous interest:

$$a_\mu^{E821} = 11659208.9(6.3)\times 10^{-10} \quad \text{(0.54 ppm)}$$

- Tantalizing ~3σ deviation with SM (persistent since >10 years):

$$a_\mu^{SM} = 11659180.2(4.9)\times 10^{-10}(DHMZ)$$

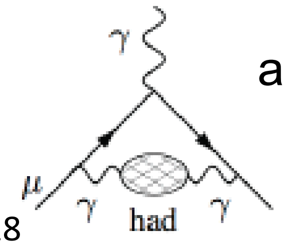
M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C71 (2011)

$$\boxed{a_\mu^{E821} - a_\mu^{SM} \sim (28\pm 8)\times 10^{-10}}$$

- Current discrepancy limited by:
  - Experimental uncertainty→ New experiments at FNAL and J-PARC **x4** accuracy
  - Theoretical uncertanty→ limited by hadronic effects

$$a_\mu^{SM} = a_\mu^{QED} + \boxed{a_\mu^{HAD}} + a_\mu^{Weak}$$

Hadronic Vacuum polarization (HLO)



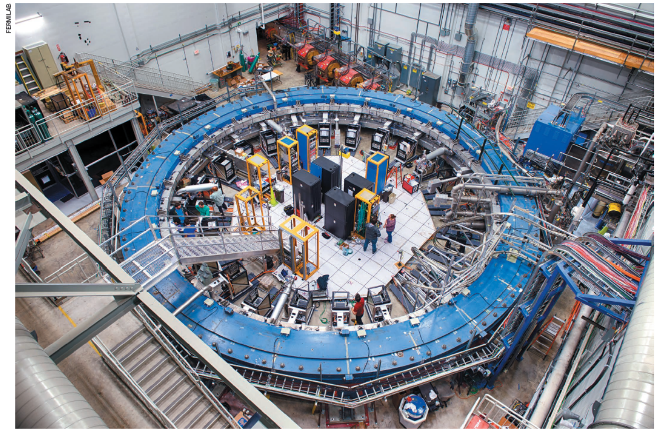
$$a_\mu^{HLO} = (692.3\pm 4.2)10^{-10}$$

$$\delta a_\mu^{HLO}/a_\mu^{HLO} \sim 0.6\%$$

$(g\text{-}2)_\mu$: a new experiment at FNAL (E989)

- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x stat**. w.r.t. E821. First result with BNL accuracy (0.54 ppm) expected in 2018-19.

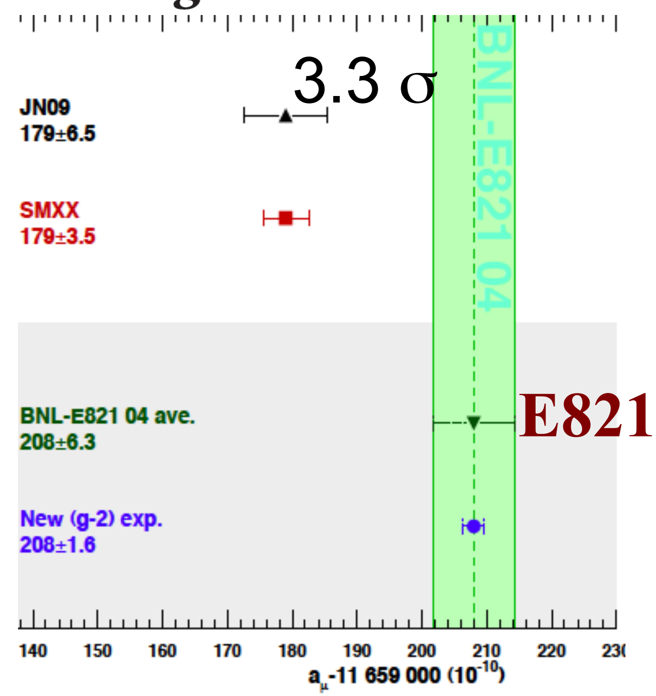
→ Ultimate precision: δa_μx4 improvement (0.14ppm)



The Muon g−2 experiment will look for deviations from the standard model by measuring how muons wobble in a magnetic field.

PARTICLE PHYSICS

Muons' big moment



$(g\text{-}2)_\mu$: a new experiment at FNAL (E989)

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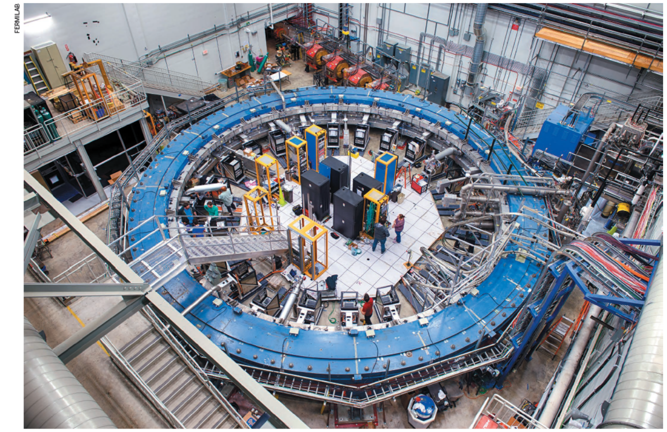
→ Ultimate precision: δa_μx4 improvement (0.14ppm)

If the central value remains the same ⇒ 5-8σ from SM* (enough to claim discovery of New Physics!)

***Depending on the progress on Theory**

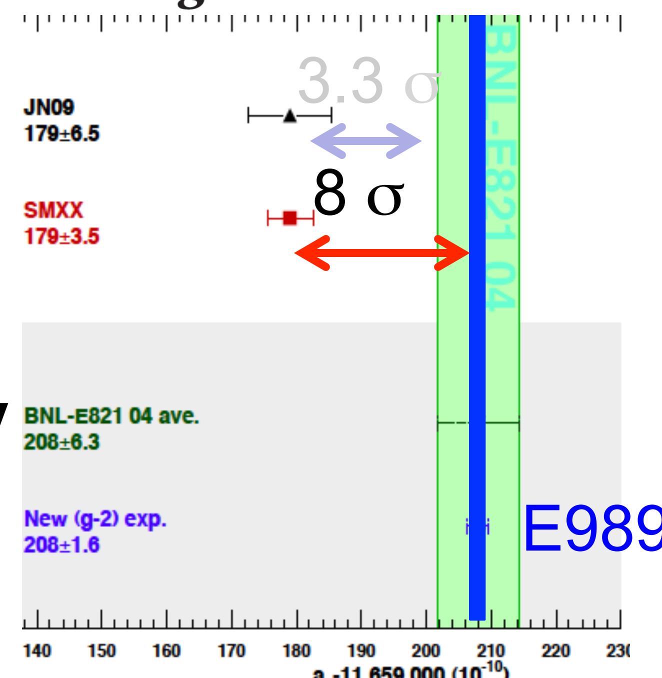
Thomas Blum; Achim Denig; Ivan Logashenko; Eduardo de Rafael; Lee
oberts, B.; Thomas Teubner; Graziano Venanzoni (2013). "The Muon (g-2)
heory Value: Present and Future". arXiv:1311.2198 [hep-ph].



The Muon g−2 experiment will look for deviations from the standard model by measuring how muons wobble in a magnetic field.

PARTICLE PHYSICS

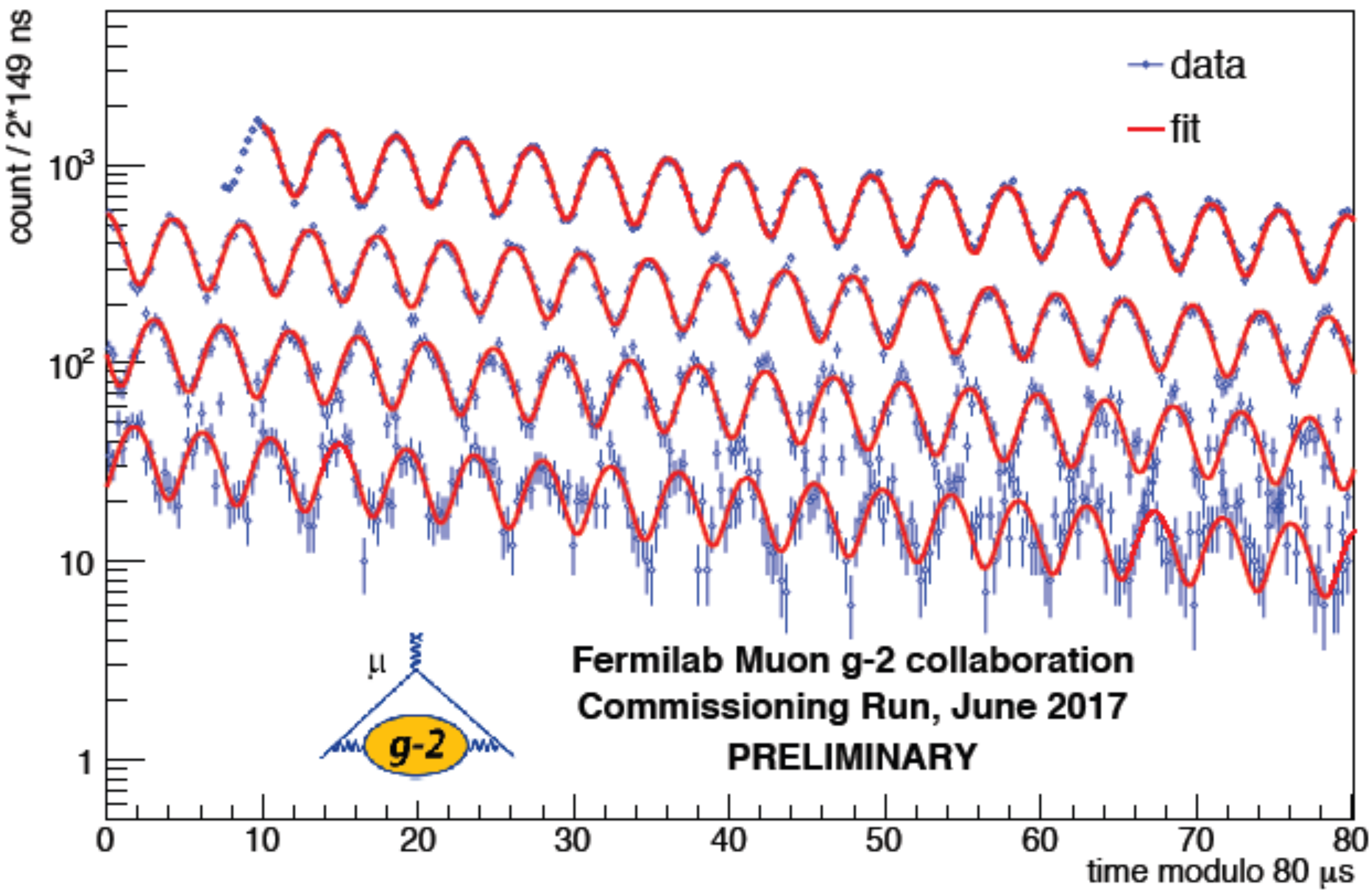
Muons' big moment



Complementary proposal at J-PARC in progress

$(g\text{-}2)_\mu$: First wiggle plot at FNAL (E989)

Number of high energy positrons as a function of time



- Complementary proposal at J-PARC in progress

Three Recent papers relevant for g-2!

20 years effort!

25 April 2017

High-precision calculation of the 4-loop contribution to the electron g-2 in QED

1100 digits!

Stefano Laporta*

Dipartimento di Fisica, Università di Bologna,
Istituto Nazionale Fisica Nucleare, Sezione di Bologna,
Via Irnerio 46, I-40126 Bologna, Italy

Abstract

I have evaluated up to 1100 digits of precision the contribution of the 891 4-loop Feynman diagrams contributing to the electron g-2 in QED. The total 4-loop contribution is

$$a_e = -1.912245764926445574152647167439830054060873390658725345\ldots\left(\frac{\alpha}{\pi}\right)^4 .$$

I have fit a semi-analytical expression to the numerical value. The expression contains harmonic polylogarithms of argument $e^{\frac{i\pi}{3}}$, $e^{\frac{2i\pi}{3}}$, $e^{\frac{i\pi}{2}}$, one-dimensional integrals of products of complete elliptic integrals and six finite parts of master integrals, evaluated up to 4800 digits.

Eur. Phys. J. C (2017) 77:139
DOI 10.1140/epjc/s10052-017-4633-z

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Experimental Physics

Measuring the leading hadronic contribution to the muon g-2 via μe scattering

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$\delta a_\mu^{HLO}/a_\mu^{HLO} \rightarrow 0.3\%_{stat}$

Received: 17 October 2016 / Accepted: 17 January 2017 / Published online: 1 March 2017

The hadronic vacuum polarization contribution to the muon $g-2$ from lattice QCD

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Abstract

We present a calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment, $a_\mu^{\rm hvp}$, in lattice QCD employing dynamical up and down quarks. We focus on controlling the infrared regime of the vacuum polarization function. To this end we employ several complementary approaches, including Padé fits, time moments and the time-momentum representation. We correct our results for finite-volume effects by combining the Gounaris-Sakurai parameterization of the timelike pion form factor with the Lüscher formalism. On a subset of our ensembles we have derived an upper bound on the magnitude of quark-disconnected diagrams and found that they decrease the estimate for $a_\mu^{\rm hvp}$ by at most 2%. Our final result is $a_\mu^{\rm hvp} = (654 \pm 32\,^{+21}_{-23}) \cdot 10^{-10}$, where the first error is statistical, and the second denotes the combined systematic uncertainty. Based on our findings we discuss the prospects for determining $a_\mu^{\rm hvp}$ with sub-percent precision.

$\delta a_\mu^{HLO}/a_\mu^{HLO} \sim 6\%$

a_μ^{HLO} calculation, traditional way: time-like data

[C. Bouchiat, L. Michel,'61; N. Cabibbo, R. Gatto 61; L. Durand '62-'63; M. Gourdin, E. De Rafael, '69; S. Eidelman F. Jegerlehner '95,. . . .]

- Optical theorem and analyticity:

$$\boxed{\sigma(s)_{(e^+e^-\to had)} = \frac{4\pi}{s}\,\mathrm{Im}\,\Pi_{hadron}(s)}$$

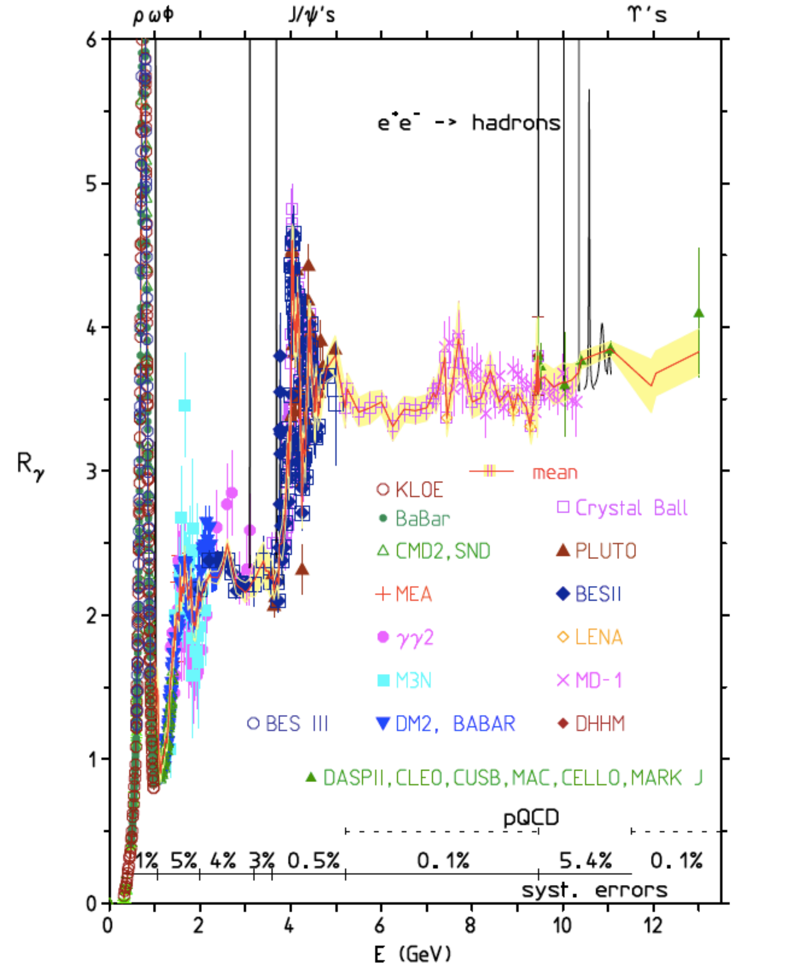
$$\boxed{a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\cdot\sigma(s)_{(e^+e^-\to had)}}$$

- The main contribution is in the highly fluctuating low energy region.

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

The enhancement at low energy implies that the $\rho \to \pi^+\pi^-$ resonance is dominating the dispersion integral (~ 75 %). Current precision at 0.6%→ need to be reduced by a factor **~2**

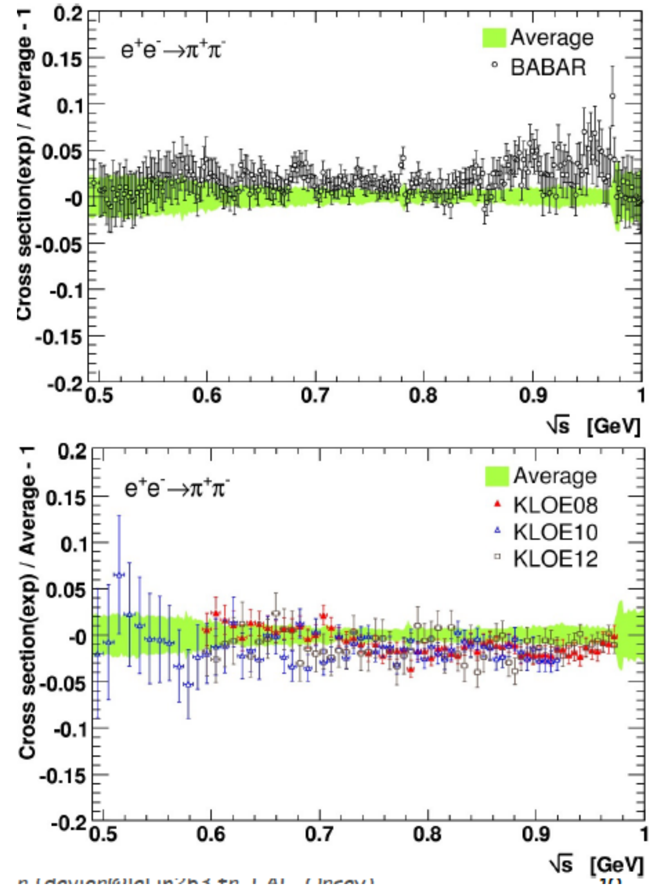
Collection of many experimental results



The high-energy tail of the integral is calculated using pQCD

Timelike data aiming at 0.2% on a_μ^{HLO}?

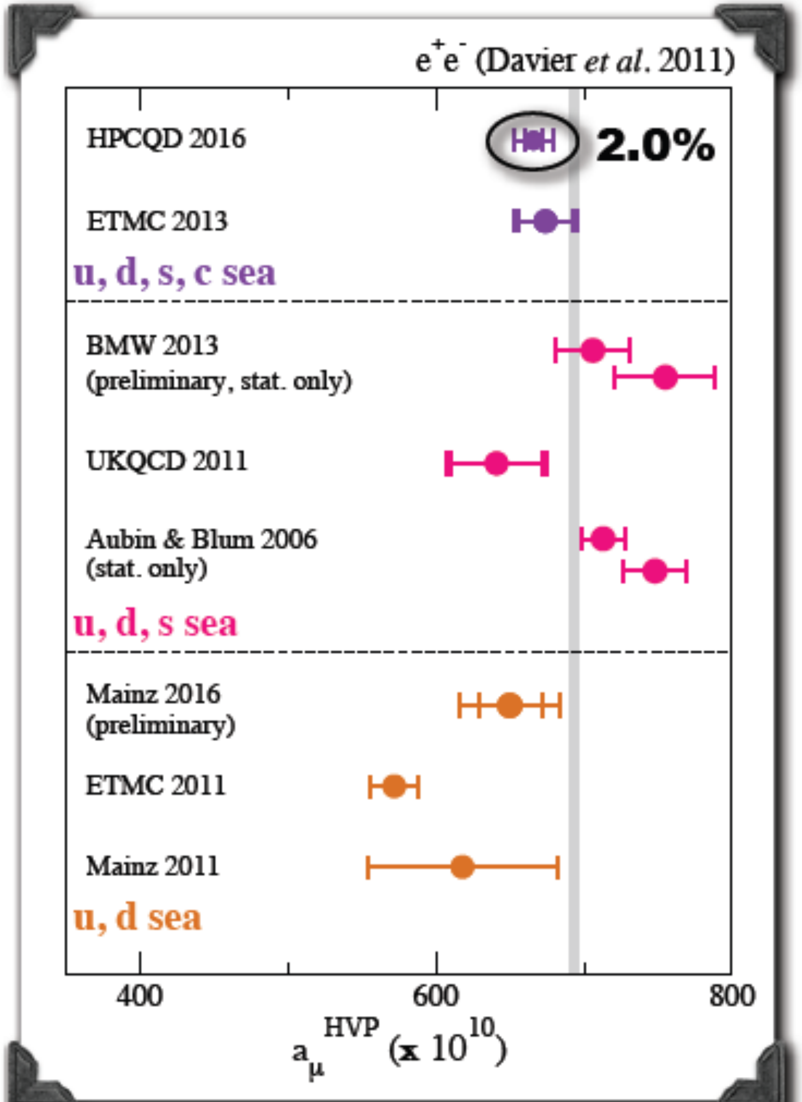
- Not an easy task!
  - >30 channels to keep under control (at (sub)percent level)
  - local discrepancies in main channels (2π (KLOE/Babar), K^+K^- CMD2/Babar)
  - Isospin corrections for not measured channels
  - Treatment of narrow resonances? (See F. Jegerlehner, ArXiv:1511.04473)
- New results expected by CMD3/SND



M. Davier, TAU16 WS

An independent/complementary approach is highly desirable!

Lattice-QCD progress on a_μ^{HVP}



- Can calculate nonperturbative vacuum polarization function $\Pi(Q^2)$ directly in lattice QCD from simple 2-point correlation function of EM quark current [Blum, PRL 91 (2003) 052001]
- Several ongoing lattice efforts yielding new results since ICHEP 2014 including:

(1) First calculation of quark-disconnected contribution [RBC/UKQCD, PRL116, 232002 (2016)]

(2) Second complete calculation of leading-order a_μ^{HVP} [HPQCD, arXiv:1601.03071]

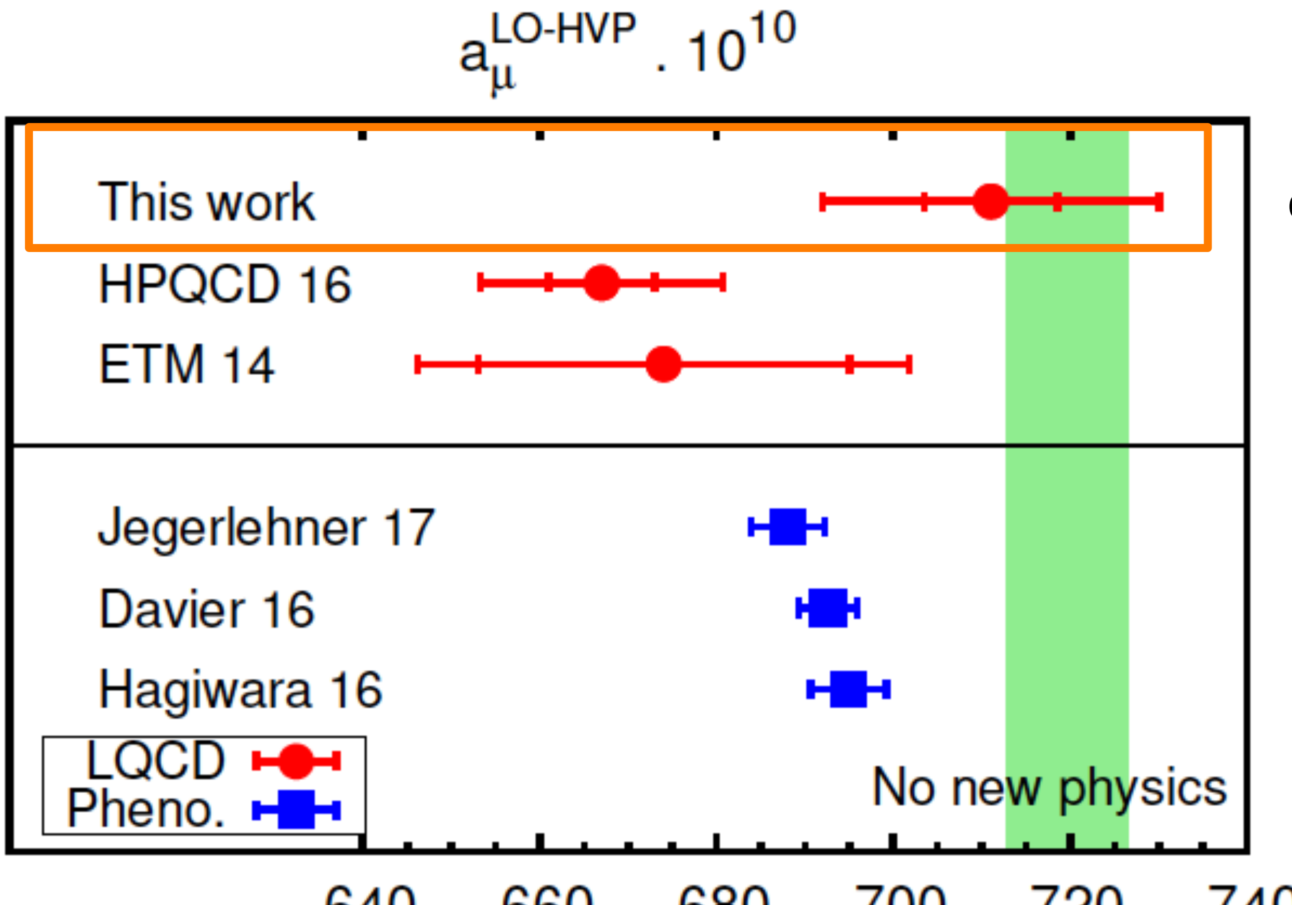
- First to reach precision needed to observe significant deviation from experiment

- ~1% total uncertainty by 2018 possible
- Sub-percent precision will require inclusion of isospin breaking & QED, and hence take longer

However: Recent Lattice evaluation

Hadronic vacuum polarization contribution to the anomalous magnetic moments of leptons from first principles

Sz. Borsanyi,[1] Z. Fodor,[1,2,3] C. Hoelbling,[1] T. Kawanai,[3] S. Krieg,[1,3]
L. Lellouch,[4] R. Malak,[4,5] K. Miura,[4] K.K. Szabo,[1,3] C. Torrero,[4] and B.C. Toth[1]
(Budapest-Marseille-Wuppertal collaboration)



error~2.7%

$$a_\mu^{\text{LO-HVP}} = 711.0(7.5)(17.3) \times 10^{-10}$$

stat syst

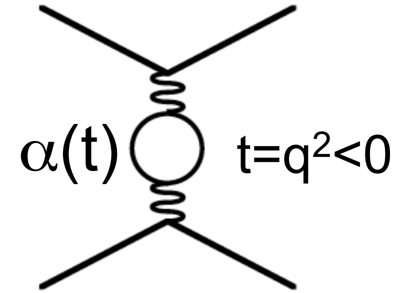
2.7%

arXiv:1711.04980v1 [hep-lat]
14 Nov

(NP). Using the SM contributions summarized in [8], we find $a_{\mu,\text{noNP}}^{\text{LO-HVP}} = (720.0 \pm 6.8) \times 10^{-10}$. The errors on the lattice results, which are in the range of 2.0 to 4.1% are substantially larger than those of the phenomenological approach. Our result for $a_\mu^{\text{LO-HVP}}$ is larger than those of the other lattice calculations and in slight tension with the one from HPQCD [33] which is 1.9 σ away. A more detailed flavor-by-flavor comparison is given in [45]. However, our result is consistent with those from phenomenology within about one standard deviation, as well as with $a_{\mu,\text{noNP}}^{\text{LO-HVP}}$. Thus, one will have to wait for the next generation of lattice QCD calculations to confirm or infirm the larger than 3 σ deviation between the measurement of a_μ and the prediction of the SM based on phenomenology.

Alternative approach: a_μ^{HLO} from space-like region

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

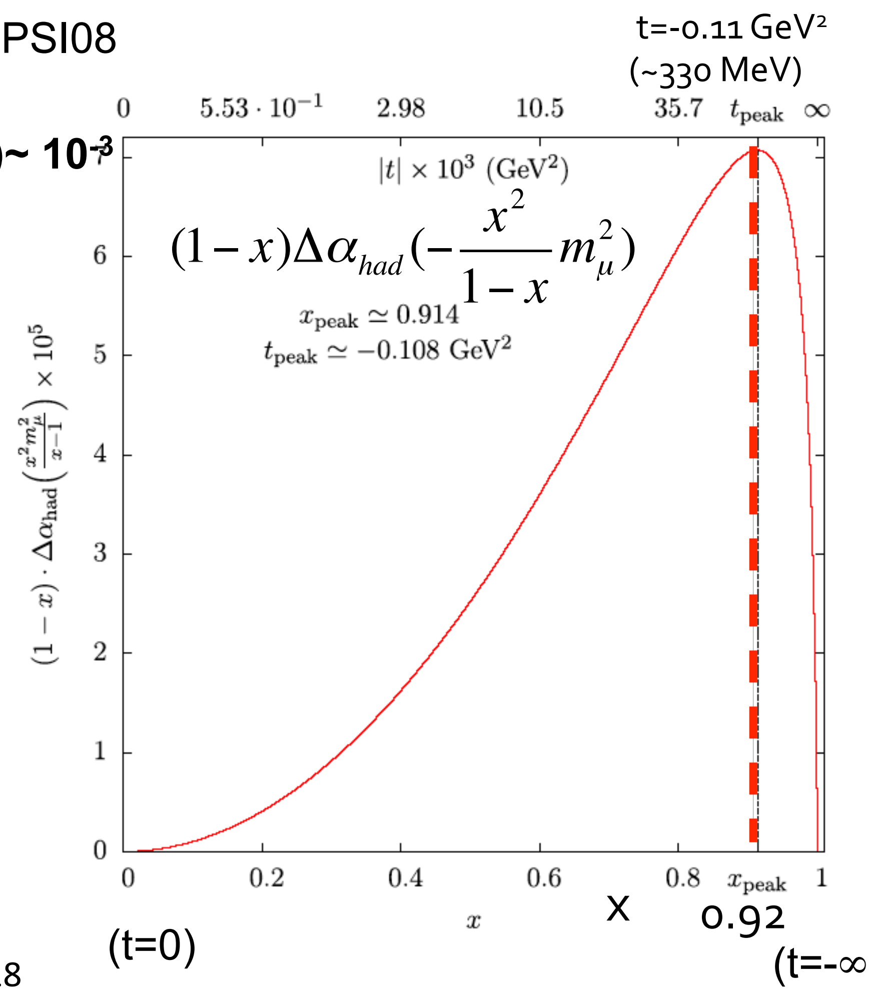


$$t = \frac{x^2 m_\mu^2}{x-1} \qquad 0 \le -t < +\infty$$

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

See G.Fedotovich, proceedings of PHIPSI08

$\Delta\alpha_{had}(0.92)\sim 10^{-3}$



- **a_μ^{HLO} is given by the integral of the curve** (smooth behaviour)
- **It requires a measurement of** the hadronic contribution to the effective electromagnetic coupling in the space-like region **$\Delta\alpha_{had}(t)$ ($t=q^2<0$)**
- **It enhances** the contribution from **low** q^2 region (below 0.11 GeV²)
- **Its precision** is determined by the **uncertainty** on $\Delta\alpha_{had}(t)$ in this region

Reference papers

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

C. M. Carloni Calame[a], M. Passera[b], L. Trentadue[c], G. Venanzoni[d]

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[d] *INFN, Laboratori Nazionali di Frascati, Frascati, Italy*

Measuring the leading hadronic contribution to the muon g-2 via μe scattering

G. Abbiendi[1], C. M. Carloni Calame[2], U. Marconi[1], C. Matteuzzi[3], G. Montagna[4,2], O. Nicrosini[2], M. Passera[5], F. Piccinini[2], R. Tenchini[6], L. Trentadue[7,3], and G. Venanzoni[8]
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[3] *INFN, Sezione di Milano Bicocca, Milano, Italy*
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[7] *Dipartimento di Fisica e Scienze della Terra "M. Melloni", Università di Parma, Parma, Italy*
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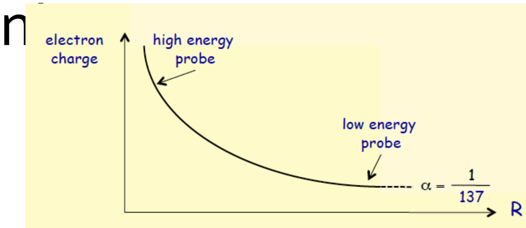
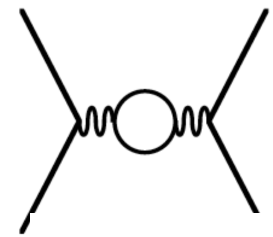
Phys. Lett. B 746 (2015) 325
Eur. Phys. J. C (2017) 77: 139.

α running and the Vacuum Polarization

- Due to Vacuum Polarization effects $\alpha(q^2)$ is a runn parameter depending on the 4-momentum transfer q^2

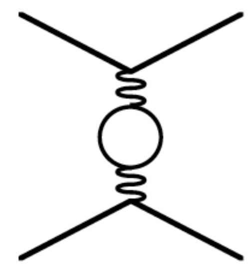


- The "Vacuum Polarization" function $\Pi(q^2)$ can be "absorbed" in a redefinition of an effective charge:



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

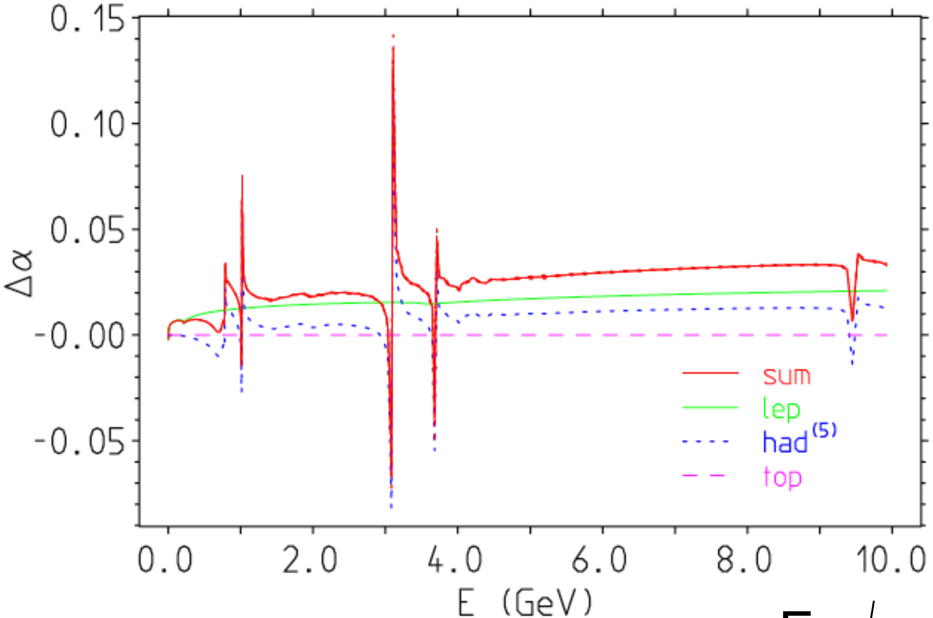
$$\Delta\alpha = \Delta\alpha_l + \Delta\alpha^{(5)}_{had} + \Delta\alpha_{top}$$

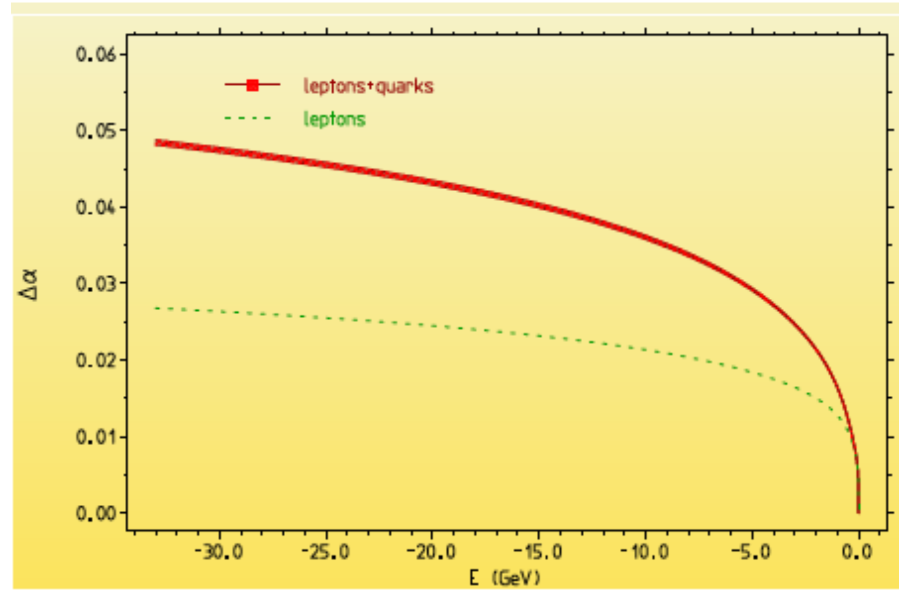


- Δa takes a contribution by non perturbative hadronic effects ($\Delta a^{(5)}_{had}$) which exibits a different behaviour in time-like and space-like region

- $\Delta\alpha^{(5)}_{had}$ at limits precision physics (EW fit) at M_Z!

Running of $\alpha(q^2)$



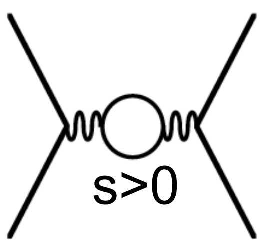


E=√s

E=-√-t

Time-like

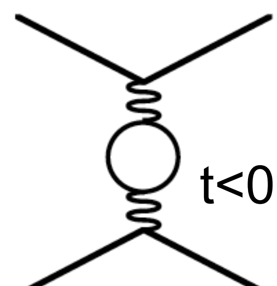
Behaviour characterized by the opening of resonances



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

Space-like

Very smooth behaviour



$$\Delta\alpha_{had}^{(5)}(-q_0^2) = -\frac{\alpha M_Z^2}{3\pi}\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s+q_0^2)}$$

Measurement of the running of $\alpha(s)$ time-like at KLOE ($e^+e^- \rightarrow \mu^+\mu^-\gamma$)

Phys. Lett. B 767 (2017) 485-492

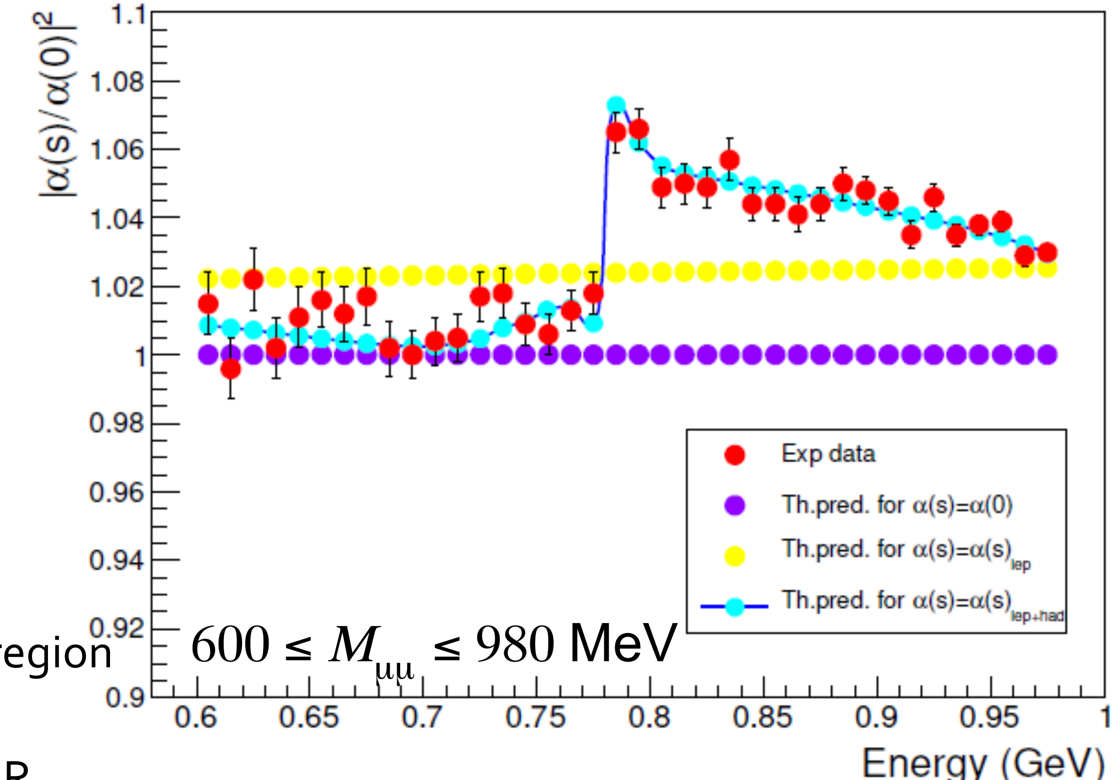
$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{\frac{d\sigma^{ISR}}{dM_{\mu\mu}}}{\frac{d\sigma^{MC}}{dM_{\mu\mu}}}$$

MC with $\alpha=\alpha(0)$

$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{1}{|1-\Delta\alpha(s)|^2}$$

$$\Delta\alpha(s) = \Delta\alpha_{lep} + \Delta\alpha_{had}$$

(we neglect the top contribution)



– Δa_{had} obtained by dispersive approach using data in time-like region provided by F. Jegerlehner

- Excellent agreement with other R compilation (Teubner / Ignatov)

Systematic error at ~1% level

$$\Delta\alpha_{had}(s) = -\left(\frac{\alpha(0)s}{3\pi}\right) Re \int_{m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\epsilon)}$$

$$R(s) = \frac{\sigma_{tot}(e^+e^- \to \gamma* \to hadrons)}{\sigma_{tot}(e^+e^- \to \gamma* \to \mu^+\mu^-)}$$

Measurement of $\Delta\alpha_{had}(t)$ spacelike at LEP

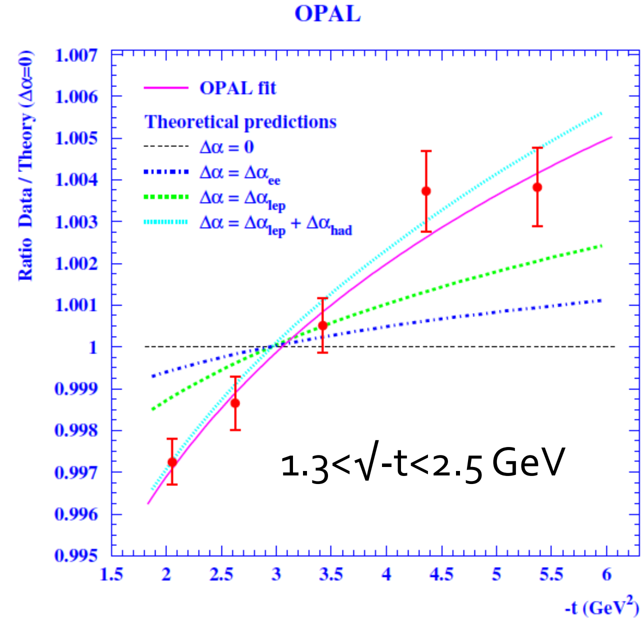
- $\Delta\alpha_{had}$ (t) (t<o) has been measured at LEP using small angle Bhabha scattering

$$f(t) = \frac{N_{\mathrm{data}}(t)}{N^0_{\mathrm{MC}}(t)} \propto \left(\frac{1}{1-\Delta\alpha(t)}\right)^2 .$$

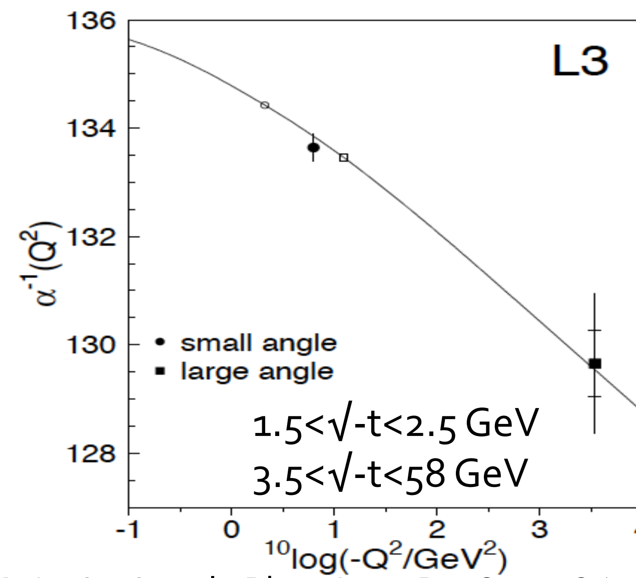
Accuracy at per mill level was achieved!

[see also A. Arbuzov et al. **Eur.Phys.J. C34 (2004) 267-275]**

- For low t values (≤0.11 GeV²) and higher precision (~10⁻⁵) as in our case a different approach is needed!



G. Abbiendi et al., Eur. Phys. J. C 45, 1–21 (2006)



M. Acciarri et al., Phys. Lett. B476 40-48 (2000)

Proposal to measure a_μ^{HLO} in the spacelike region

From last talk in 2016!

G. Venanzoni
LNF-INFN
(in collaboration with G. Abbiendi, C.M.C. Calame, U. Marconi, C. Matteuzzi, G. Montagna, O. Nicrosini, M. Passera, F. Piccinini, L. Trentadue)

[*based on* Phys.Lett. B746 (2015) 325-32]

Novosibirsk, 5 February 2016

Experimental considerations

From last talk in 2016!

Using Bhabha at small angle (to emphasize t-channel contribution) to extract $\Delta\alpha$:

$$\left(\frac{\alpha(t)}{\alpha(0)}\right)^2 \sim \frac{d\sigma_{ee\to ee}(t)}{d\sigma^0_{MC}(t)}$$

Where $d\sigma^0_{MC}$ is the MC prediction for Bhabha process with α(t)=α(0), and there are corrections due to RC…

$$\Delta\alpha_{had}(t) = 1 - \left(\frac{\alpha(t)}{\alpha(0)}\right)^{-1} - \Delta\alpha_{lept}(t)$$

$\Delta\alpha_{lep}(t)$ theoretically well known!

Which experimental accuracy we are aiming at?
$\delta\Delta\alpha_{had}$~1/2 fractional accuracy on $d\sigma(t)/d\sigma^0_{MC}(t)$.

If we assume to measure $\delta\Delta\alpha_{had}$ at 5% at the peak of the integrand ($\Delta\alpha_{had}$ ~10^{-3} at x=0.92) → fractional accuracy on $d\sigma(t)/d\sigma^0_{MC}(t)$ ~ 10^{-4} !

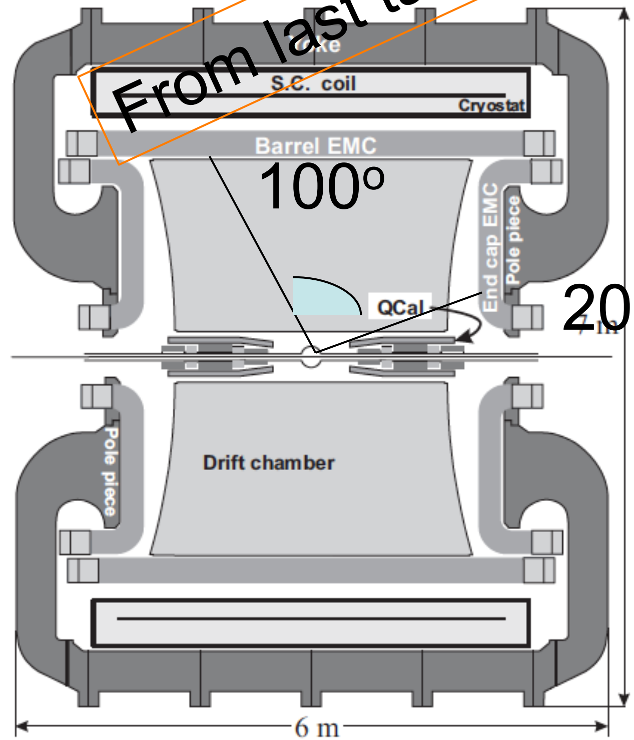
Very challenging measurement (one order of magnitude improvement respect to date) for systematic error

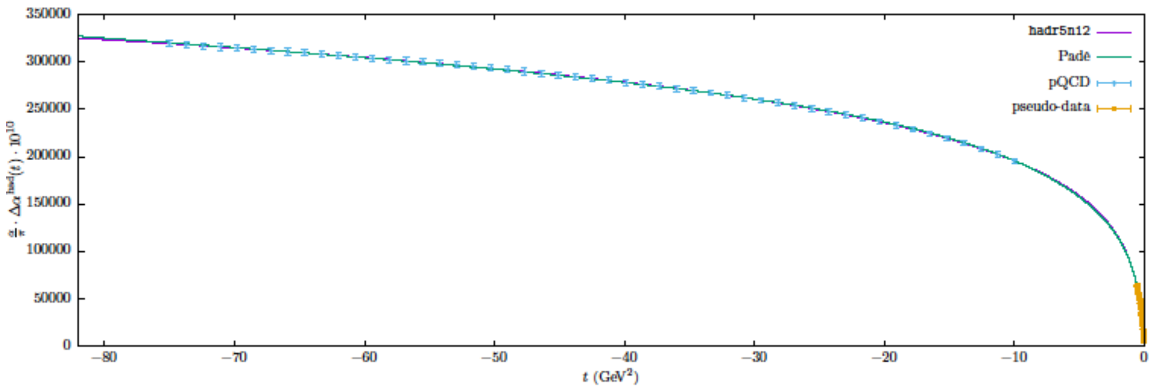
What can be done a KLOE/KLOE2?

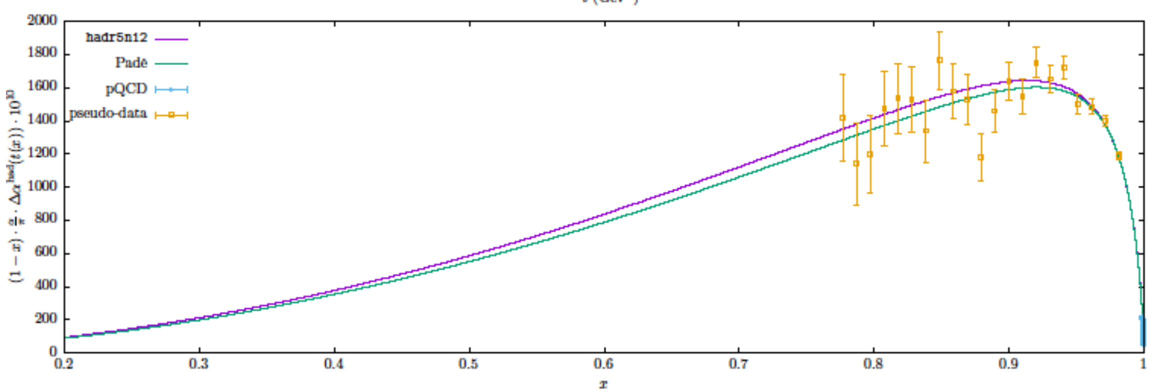
From last talk in 2016!

We did the following simulation:

- 20 points between $20^o < \theta < 100^o$ ($0.03 < -t < 0.59$ GeV^2; $0.78 < x < 0.98$) @ $\sqrt{s}=1$ GeV
- For each point $\delta\sigma_{e+e-}/\sigma_{e+e-} \sim 10^{-4}$ (stat and syst)
- We fit $\Delta\alpha_{had}(t)$ using our points+ pQCD for $-t>10$ GeV^2 with a polinomial function (like lattice)





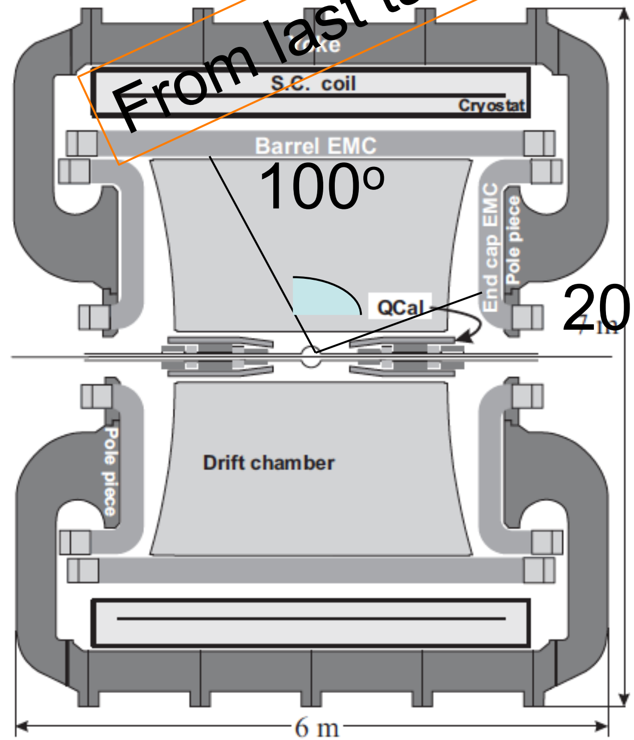


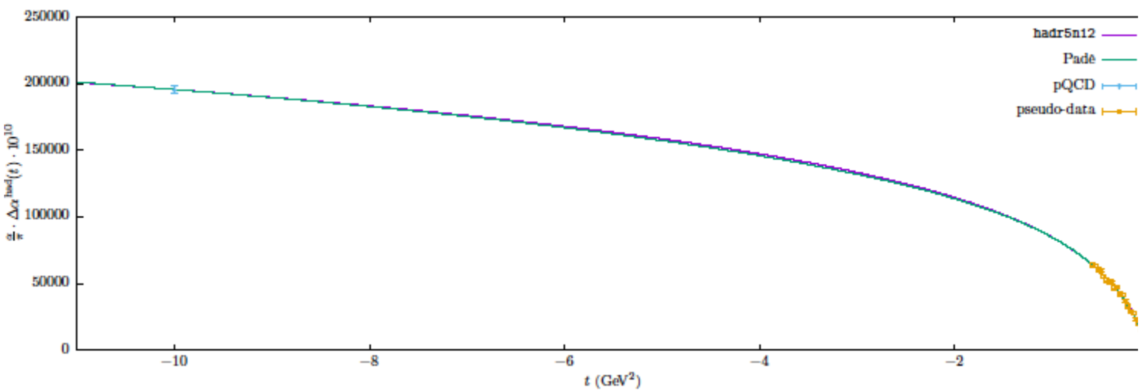
What can be done a KLOE/KLOE2?

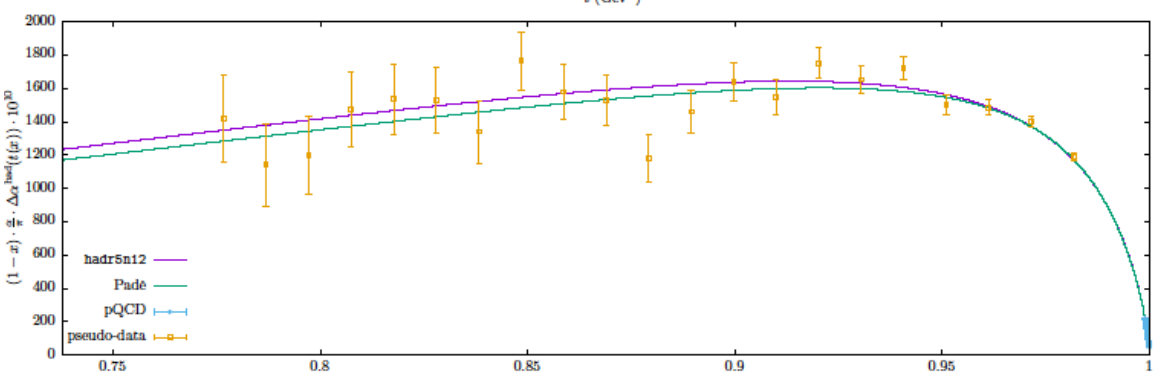
From last talk in 2016!

We did the following simulation:

- 20 points between $20^o < \theta < 100^o$ ($0.03 < -t < 0.59$ GeV^2; $0.78 < x < 0.98$) @ $\sqrt{s} = 1$ GeV
- For each point $\delta\sigma_{e+e-}/\sigma_{e+e-} \sim 10^{-4}$ (stat and syst)
- We fit $\Delta\alpha_{had}(t)$ using our points+ pQCD for $-t > 10$ GeV^2 with a polinomial function (like lattice)







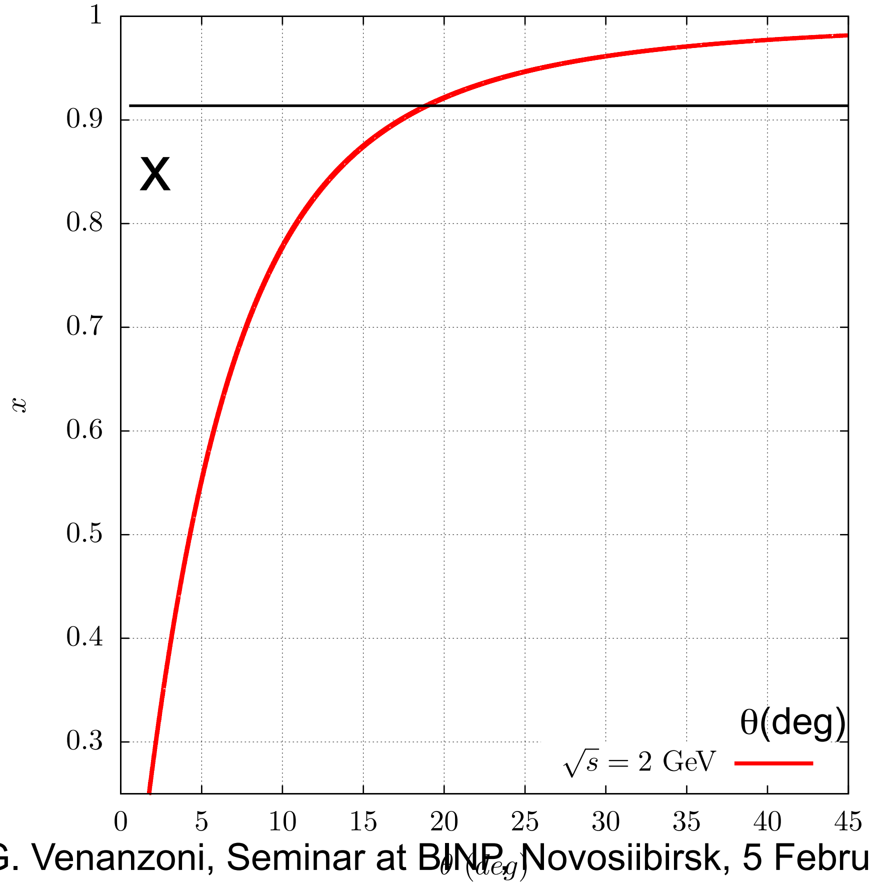
$\delta a_\mu^{HLO} \sim 3\%_{stat} \oplus 7\%_{syst}$

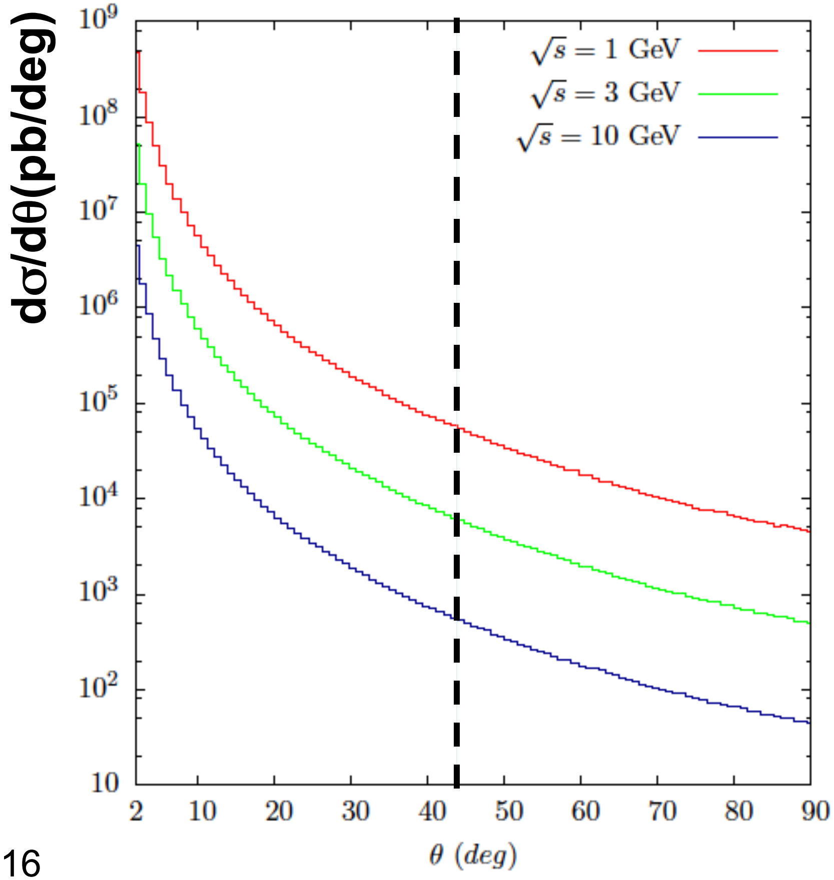
(preliminary)

Measurement at Novosibirsk ($\sqrt{s}$=2 GeV)?

From last talk in 2016!

- The region 0.2<x<0.98 can be explored at $\sqrt{s}$=2 GeV with $2^o<\theta<45^o$ (for x>0.98 pQCD could be used)
- Normalization can be provided by Bhabha at very small angle ($2^o<\theta<5^o$) where $\Delta\alpha^{had}<10^{-5}$ (1% of the $\Delta\alpha^{had}$(x=0.92))
- $L=10^{32}$ would allow to do a measurement of a_μ^{HLO}<1% within 1 year (statistically)

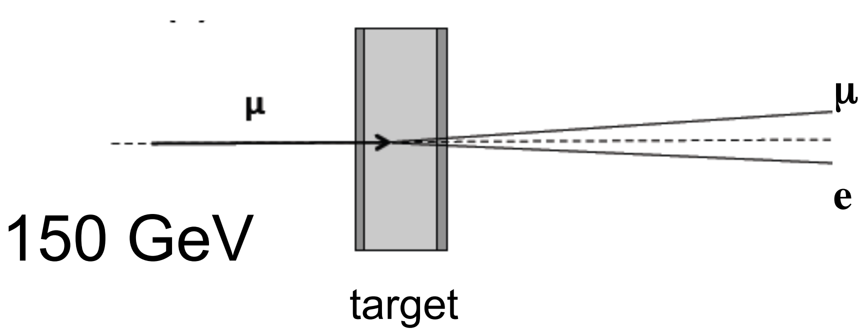


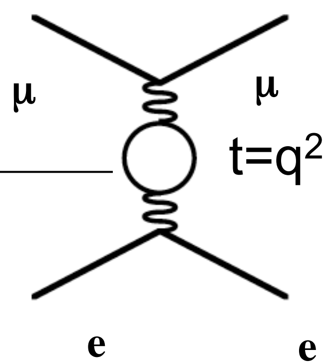


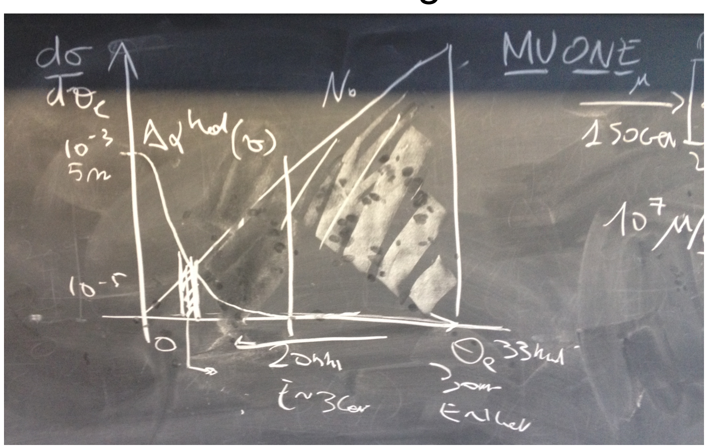
New(!) Experimental approach: MUonE

High precision measurement of a_μ^{HLO} with a 150 GeV μ beam on Be target at CERN

(through the elastic scattering $\mu e \rightarrow \mu e$)







$$\left|\frac{\alpha(t)}{\alpha_0}\right|^2 = \left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

Statistical accuracy on a_μ^{HLO}: 0.3%!

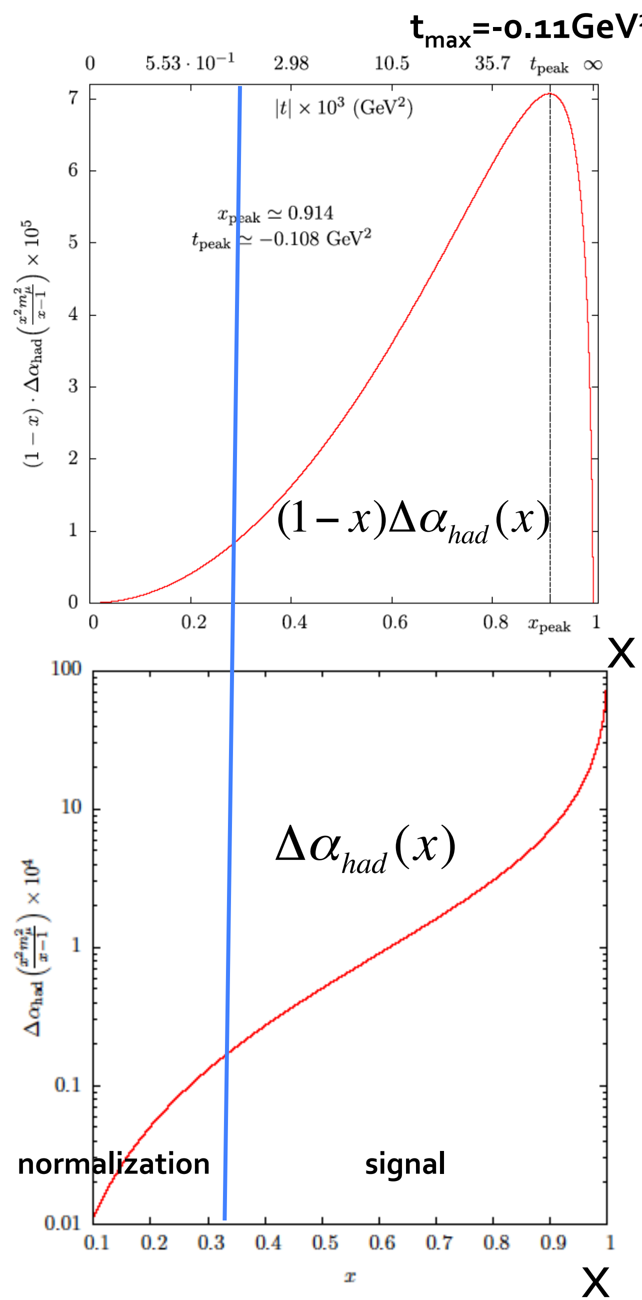
G. Venanzoni, Seminar at CERN, 5 October 2017

Why measuring $\Delta\alpha_{had}(t)$ with a 150 GeV μ beam on e^- target ?

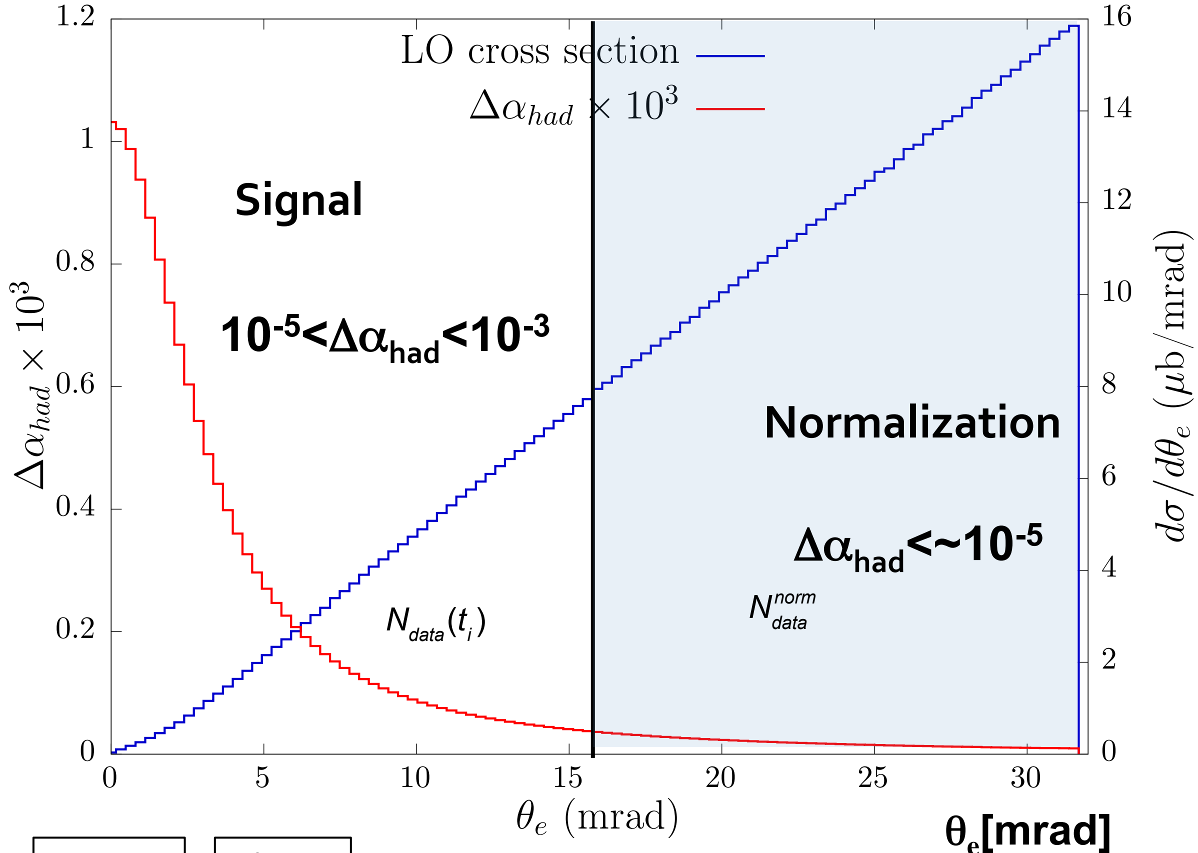
It looks an ideal process!

- $\mu\, e \rightarrow \mu\, e$ is pure t-channel (at LO)
- It gives $0<-t<0.161$ GeV^2 ($0<x<0.93$)
- The kinematics is very simple: $t=-2m_e E_e$
- High boosted system gives access to all angles (t) in the cms region

  $\theta_e^{LAB}<32$ mrad ($E_e>1$ GeV)
  $\theta_\mu^{LAB}<5$ mrad
- It allows using the same detector for signal and normalization
- Events at $x\sim0.3$ ($t\sim-10^{-3}$ GeV^2) can be used as normalization ($\Delta\alpha_{had}(t) < 10^{-5}$)



MUonE : signal/normalization region



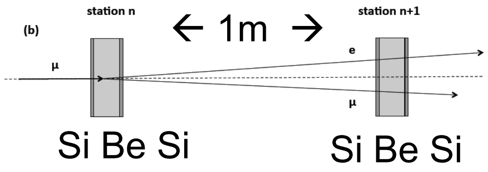
$$\frac{N_{data}(t_i)}{N^0_{MC}(t_i)} = \boxed{\frac{N_{data}(t_i)}{N^{norm}_{data}}} \times \boxed{\frac{\sigma^{0,norm}_{MC}}{\sigma^0_{MC}(t_i)}} \sim 1-2(\Delta\alpha_{lep}(t_i)+\Delta\alpha_{had}(t_i))$$

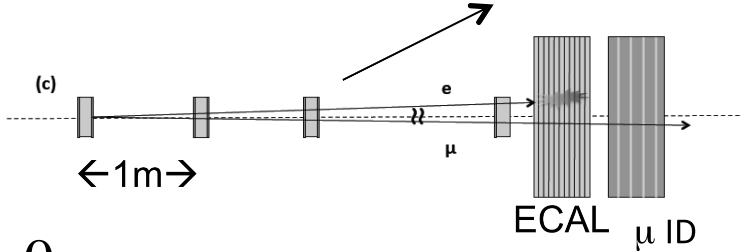
Ratio of the theoretical cross section (with no VP)

Ratio of data $N_{signal}(t)/N_{normalization}$

a_μ^{HLO} at 0.3% → These two ratios should be known at 10^{-5}

Detector considerations





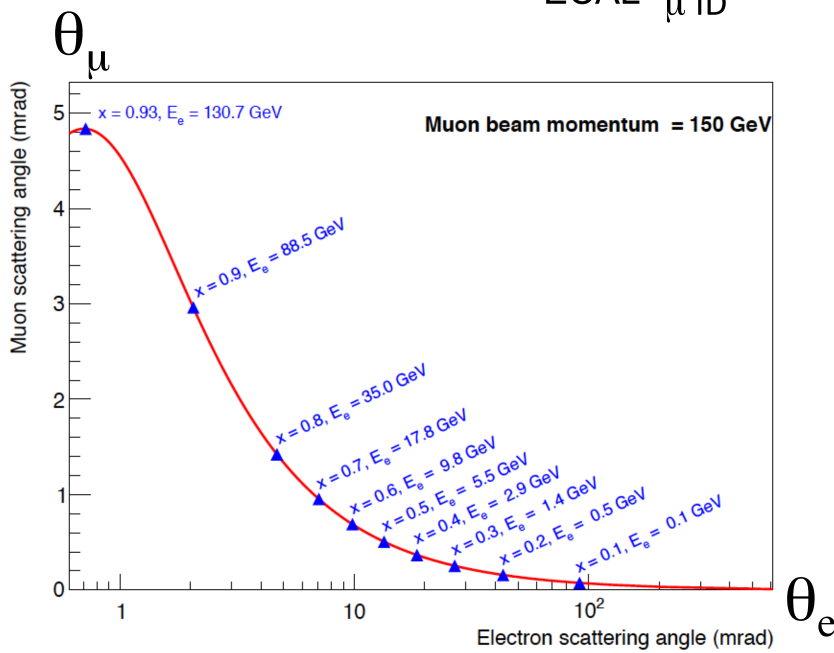
- Modular apparatus: 20 layers of ~1 cm Be (target), each coupled to 1(0.5) m distant Si (0.3 mm) planes. It provides a 0.02 mrad resolution on the scattering angle

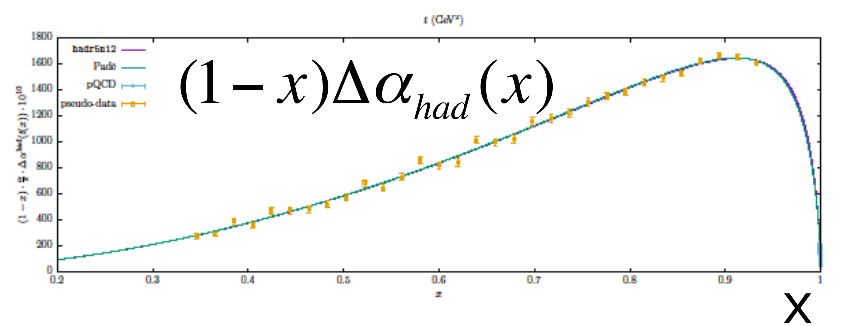
- The $t=q^2<0$ of the interaction is determined by the electron (or muon) scattering angle (a\` la NA7)

- ECAL and μ Detector located downstream to solve PID ambiguity below 5 mrad. Above that, angular measurement gives correct PID

- It provides uniform full acceptance, with the potential to keep the systematic errors at 10^{-5} (main effect is the multiple scattering for normalization which can be studied by data)

- Statistical considerations show that a **0.3%** error can be achieved on a_μ^{HLO} in 2 years of data taking with 2×10^7 μ/s





Muon beam M2 at CERN

"Forty years ago, on 7 May 1977, CERN inaugurated the world's largest accelerator at the time – the Super Proton Synchrotron".

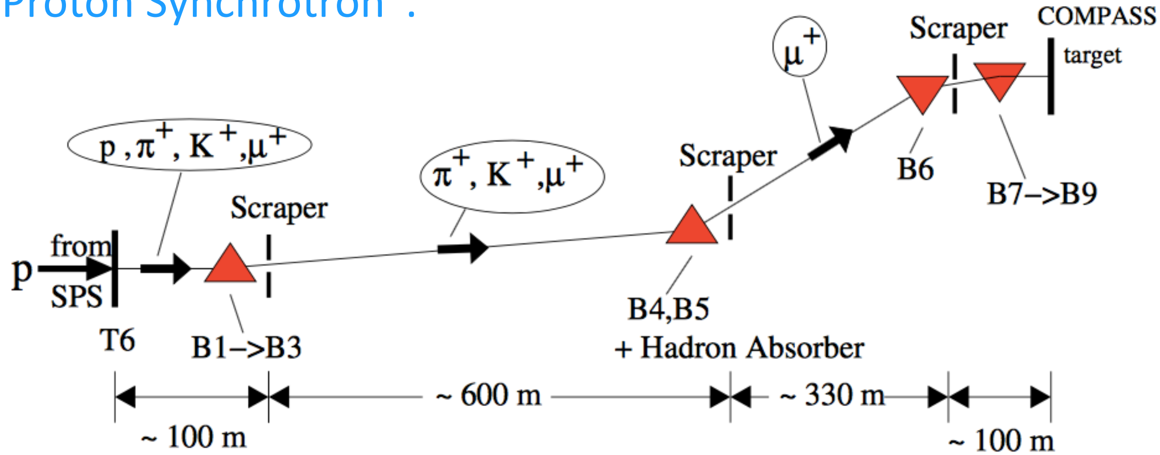


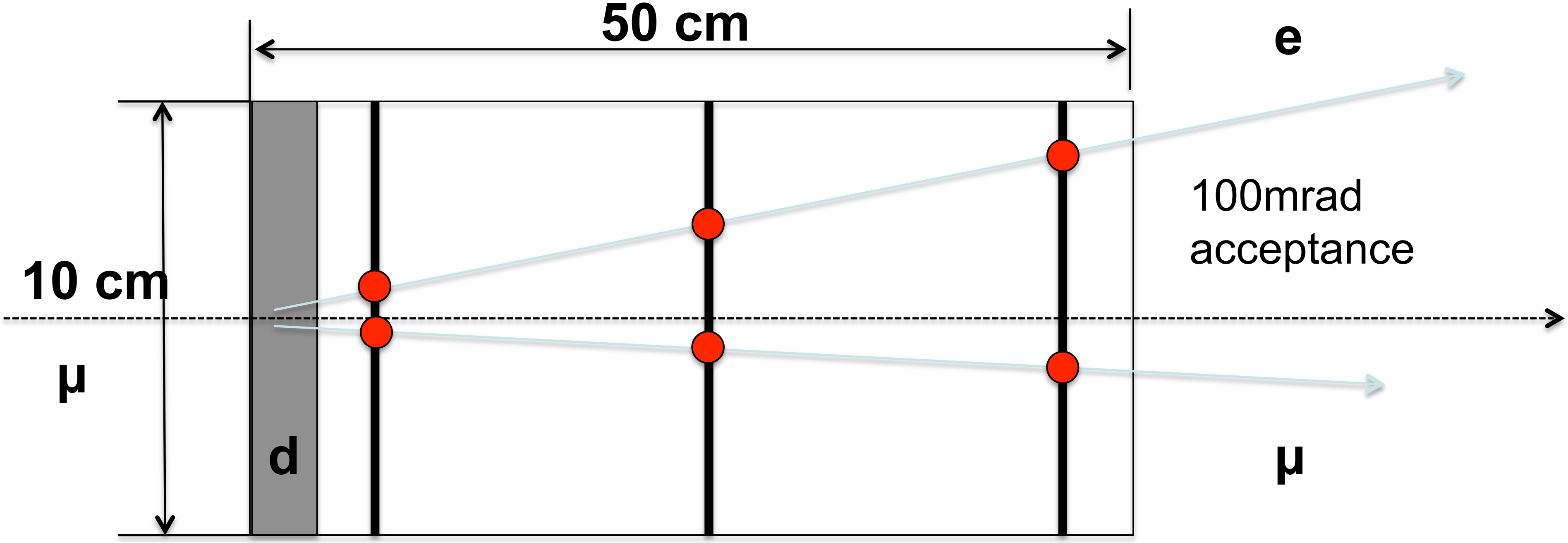
Table 3
Parameters and performance of the 160 GeV/c muon beam.

Beam parameters	**Measured**
Beam momentum $(p_\mu)/(p_\pi)$	$(160\,\mathrm{GeV}/c)/(172\,\mathrm{GeV}/c)$
Proton flux on T6 per SPS cycle	$1.2 \cdot 10^{13}$
Focussed muon flux per SPS cycle	$2 \cdot 10^{8}$
Beam polarisation	$(-80 \pm 4)\%$
Spot size at COMPASS target $(\sigma_x \times \sigma_y)$	$8 \times 8\,\mathrm{mm}^2$
Divergence at COMPASS target $(\sigma_x \times \sigma_y)$	$0.4 \times 0.8\,\mathrm{mrad}$
Muon halo within 15 cm from beam axis	16%
Halo in experiment $(3.2 \times 2.5\,\mathrm{m}^2)$ at $\lvert x, y\rvert > 15\,\mathrm{cm}$	7%

https://arxiv.org/pdf/hep-ex/0703049.pdf

$I_{beam} > 10^7$ muon/s, $E_\mu = 150$ GeV

Measuring e- and muon angle:
Repetition (x50) of this single module



Target State-of-art Silicon strip detectors

hit resolution ~10 μm

expected angular resolution ~ 10 μm / 0.5 m = 0.02 mrad

Systematics

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

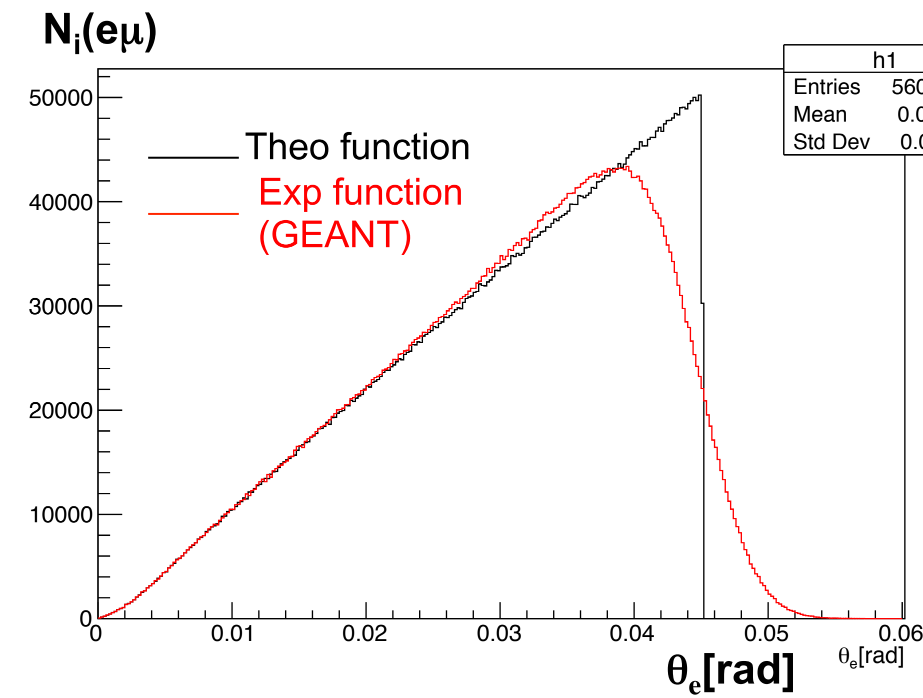
Full simulation needed

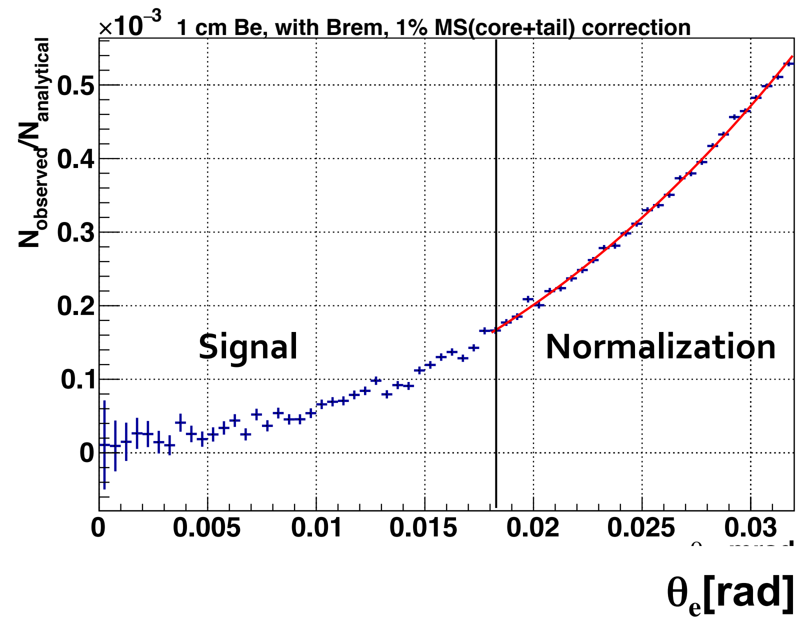
All the systematic effects must be known to ensure an error on the cross section < 10ppm

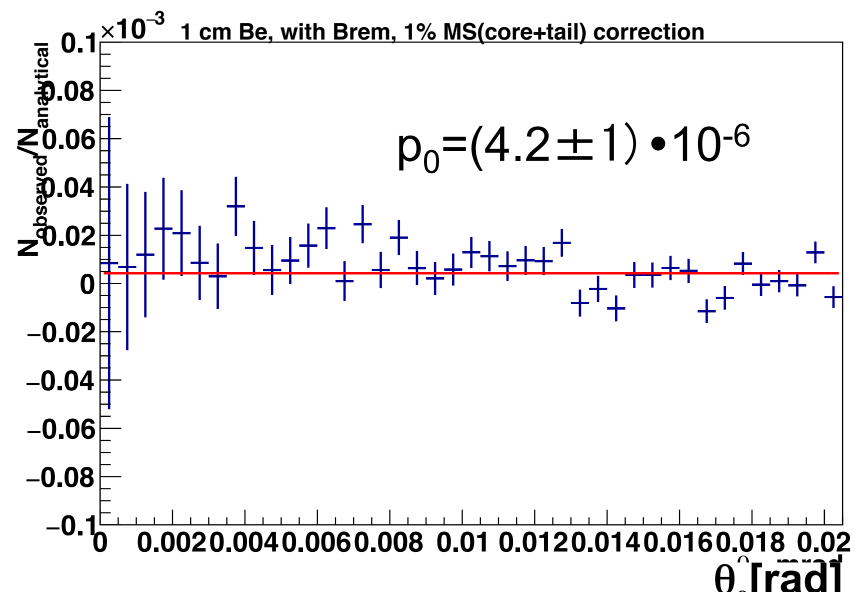
Multiple Scattering resolution:

a worst-case scenario

(thanks to F. Ignatov!)





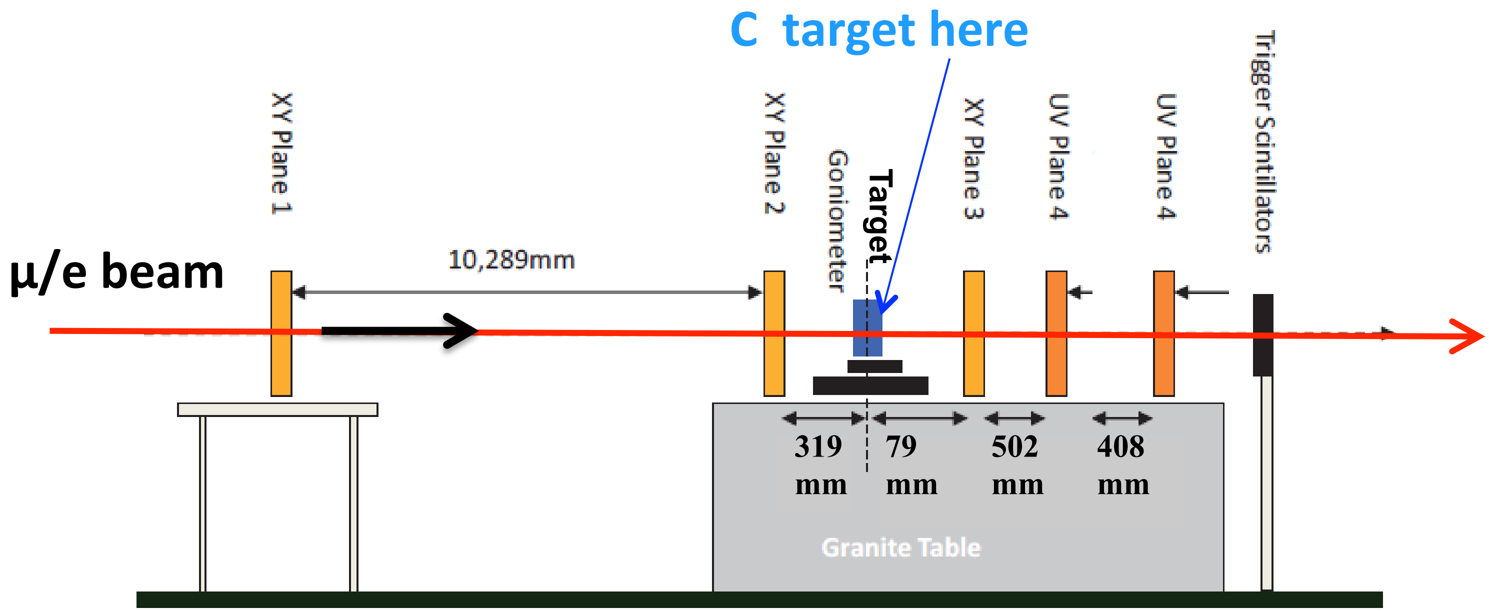


- The detector effects (mostly MS in the target) modify the theoretical spectrum ($N(\theta_e)$)
- We assume a 1% miscalibration on the GEANT model for $\sigma_{\theta e}$ MS (N_{mis})
- N_{mis} quadratically in θ_e respect to NO bias (N_i)
- By correcting N_{mis}/N_i in the normalization region → residual effects $<10^{-5}$ in the signal region

Results from Test Beam

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)

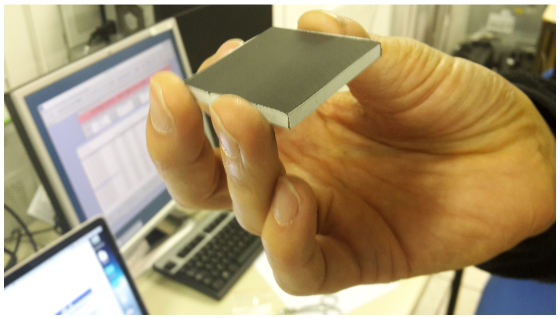


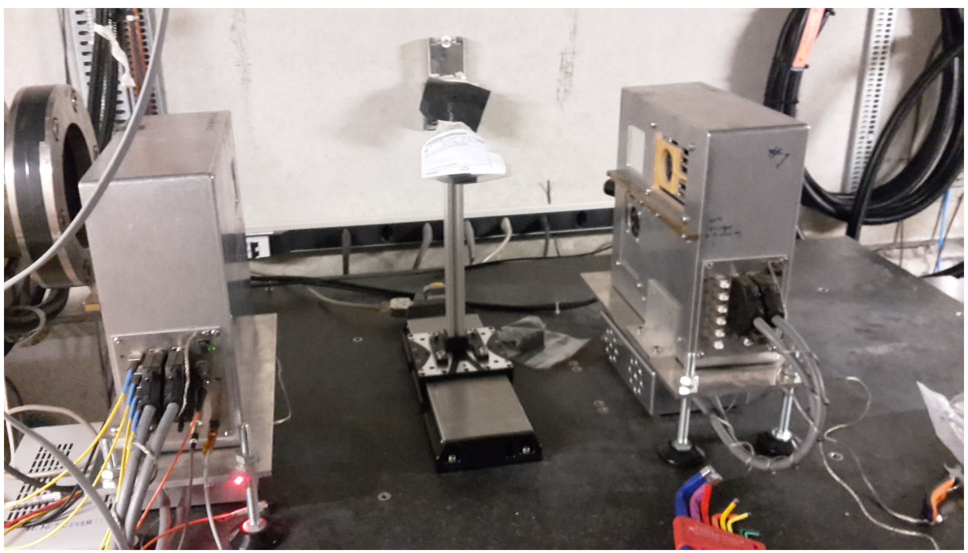
Adapted UA9 apparatus

5 Si planes: 2 before and 3 after the target, 3.8x3.8 cm2 intrinsic resolution ~**100**μrad (with preliminary alignment)

Test Beam setup and target

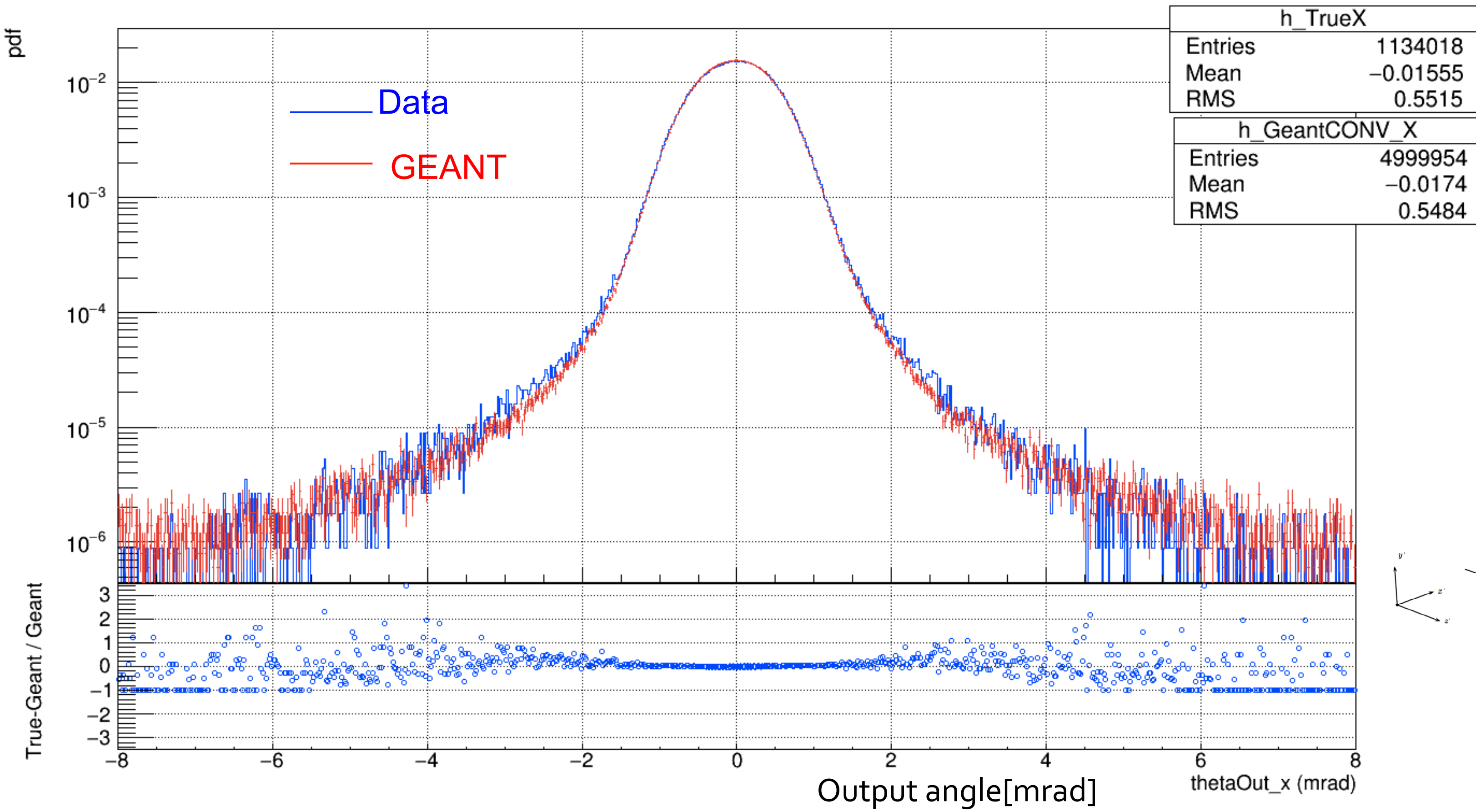
Thanks to the UA9 Collaboration (particularly M. Garattini, R. Iaconageli, M. Pesaresi), J. Bernhard

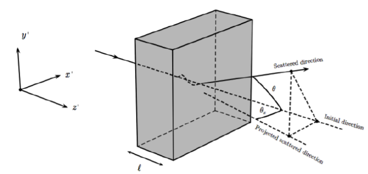




(Preliminary) Analysis of Test Beam data

12 GeV e$^-$ 8mm C

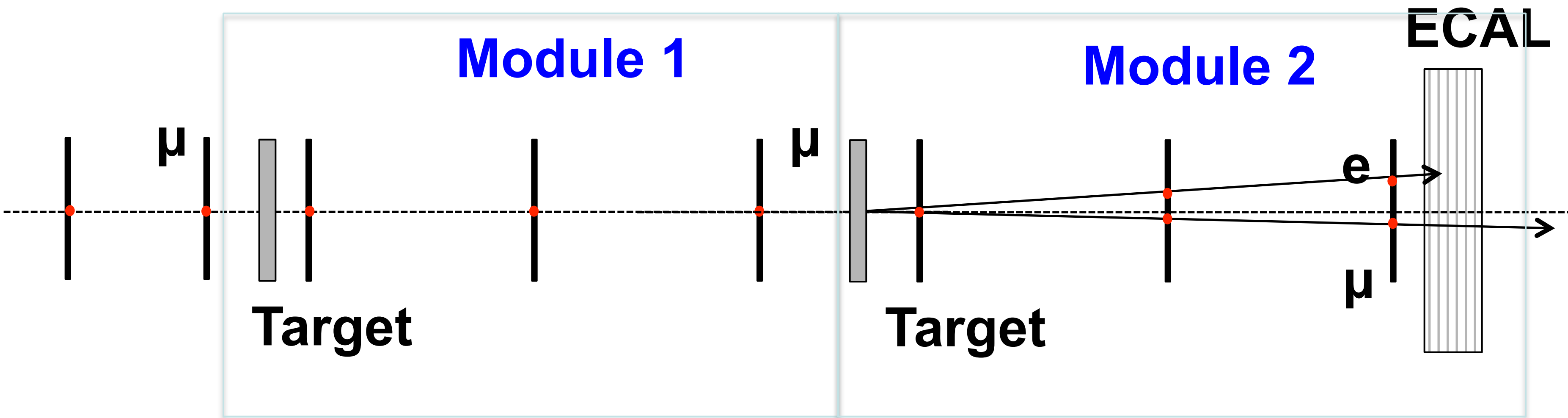




- With a preliminary analysis: data-MC agree on σ(core) at 2%
- Improvement expected due to better alignment and track fit
- Analysis of tails in progress

Plans for 2018

Build up and test a full scale prototype (2 modules).



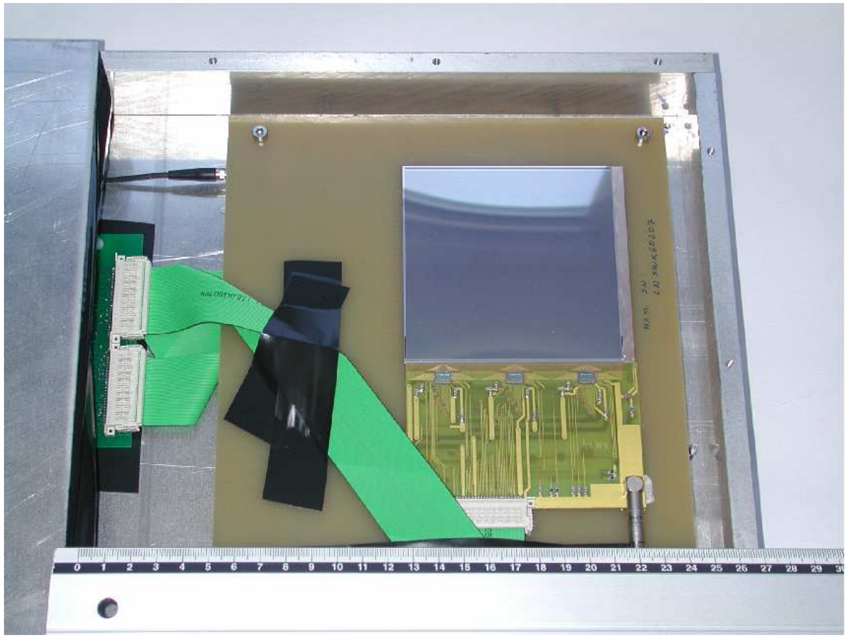
- Run of a 2 full scale modules on a muon beam in North area or on M2 (behind COMPASS)
- Study of the detector performance: signal/background; trigger; understand the systematics
- Try a first measurement (at 10-20% error) of a_μ^{HLO}

The silicon detectors

Sensors developed for AGILE, being used by LEMMA

Table 1
Main features of the AGILE silicon detector

Item	Value
Dimension (cm^2)	9.5×9.5
Thickness (μm)	410
Readout strips	384
Readout pitch (μm)	242
Physical pitch (μm)	121
Bias resistor (MΩ)	40
AC coupling Al resistance (Ω/cm)	4.5
Coupling capacitance (pF)	527
Leakage current (nA/cm^2)	1.5



M. Prest et al., NIM A, 501:280–287, 2003

Daniela Lietti, PhD thesis. VISION: a Versatile and Innovative SIlicON tracking system

http://insulab.dfm.uninsubria.it/images/download_files/thesis_phd_lietti.pdf

Theory

- QED NLO MC generator with full mass dependence has been developed (Pavia group)

- First results obtained for the NNLO box diagrams contributing to mu-e scattering in QED (Padova group)

1709.07435

Master integrals for the NNLO virtual corrections to μe scattering in QED: the planar graphs

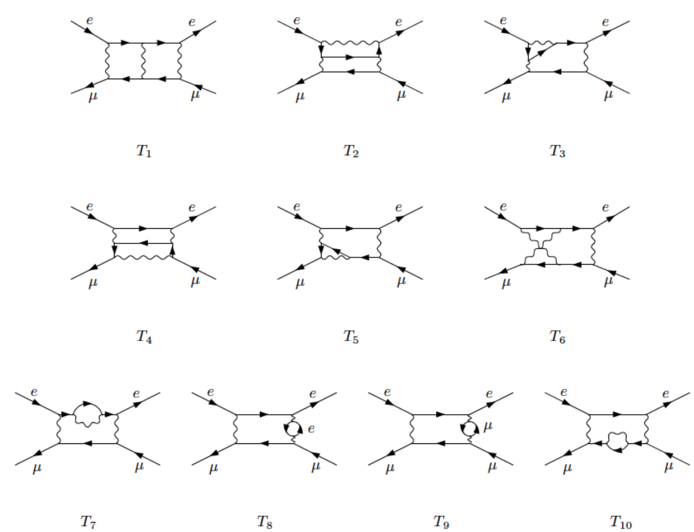
Pierpaolo Mastrolia,[a,b] Massimo Passera,[b] Amedeo Primo,[a,b] Ulrich Schubert[c]

[a] *Dipartimento di Fisica ed Astronomia, Università di Padova, Via Marzolo 8, 35131 Padova, It*

[b] *INFN, Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy*

[c] *High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*

E-mail: pierpaolo.mastrolia@pd.infn.it, massimo.passera@pd.infn.it, amedeo.primo@pd.infn.it, schubertmielnik@anl.gov



- An unprecedented precision challenge for theory: a full NNLO MC generator for μ-e scattering (10^{-5} accuracy)

Theory

- A kick-off theory meeting has been held in Padova last September: https://agenda.infn.it/internalPage.py?pageId=0&confId=13774 .

Muon-electron scattering: Theory kickoff workshop

4-5 September 2017
Padova

Europe/Rome timezone

- A Topical workshop on the theoretical aspects of mu-e scattering will take place next February at MITP, Mainz https://indico.mitp.uni-mainz.de/event/128/ with many experts

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

mitp Mainz Institute for Theoretical Physics

The Evaluation of the Leading Hadronic Contribution to the Muon Anomalous Magnetic Moment

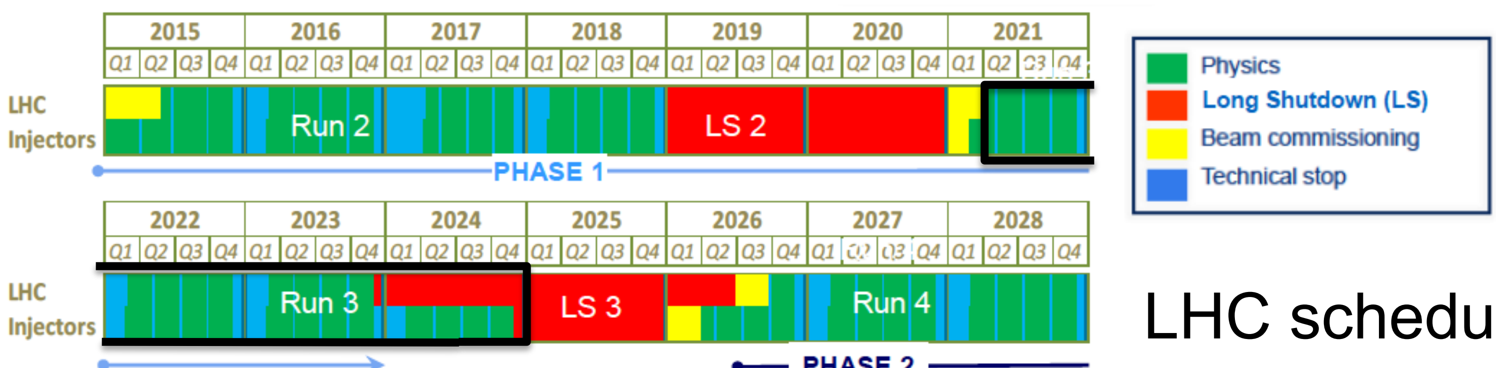
19-23 February 2018
Mainz Institute for Theoretical Physics, Johannes Gutenberg University
Europe/Berlin timezone

Status of the Collaboration and plans

- The proposal has been presented in September at the National Scientific Committee 1 (CSN1) of INFN. Funds have been allocated to contribute effectively to a full-scale test of detector prototype in 2018.
- Collaboration is growing and interest from International groups from CERN, Poland, Russia (Novosibirsk), UK has been expressed.
- Results so far encouraging; we are working hard toward a formal LoI.

Plans

- **2018-2019**
  - Detector optimization studies: Simulation and Test Beam
  - Theoretical studies
  - Set up a collaboration
  - Letter of Intent to the SPSC
- **2020-2021**
  - Detector construction and installation
    (a staged version of the detector may be)
- **2022–2024**
  - Start the data taking after LS2 to measure $\mathbf{a}_\mu^{\mathrm{HLO}}$
    (not necessarily the ultimate precision)



LHC schedule

Conclusion

- Exciting times for the muon g-2: new experiments at FNAL and J-Park
- Important results on hadronic cross sections expected by VEPP2000 and flavour factories (ISR)
- Alternative/competitive determinations of a_μ^{HLO} are essential
- MUonE proposal to measure a_μ^{HLO} in the space-like region with 0.3% (stat) . Part of the CERN "Physics Beyond Collider Study Group" (http://pbc.web.cern.ch/)
- Collaboration is growing: already more than 30 persons with International groups (strong collaboration with Novosibirsk!)
- If approved (by CERN SPSC) first results in the same period of the g-2 measurements at Fermilab and J-Parc (first results around 2021-2024)
- Many experimental and theoretical challenges: very exciting!!

Thanks!

Spare

μ-e proposal: plans (next 2 years)

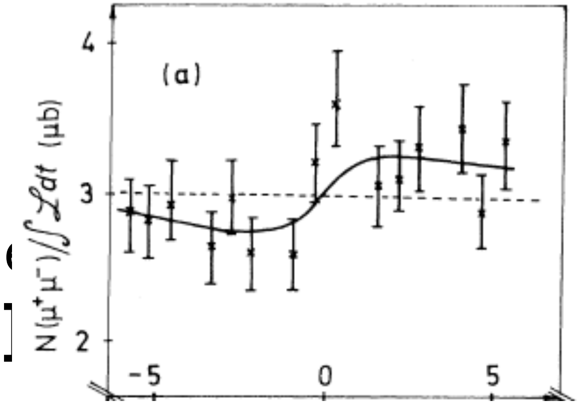
- Focus on Multiple Scattering (MSC) effects:
  - How non gaussian tails affects our measurement and can be monitored/ controlled (2D plots and acoplanarity)
- Background subtraction and modeling in GEANT
- Optimization of target/detector and full detail simulation
- Test beam(s) and proto-experiment with a realistic module
- NNLO MC generation of μe process
- Design possible implementation in M2
- Consolidate the collaboration and write a CDR

Proposal part of the Physics Beyond Collider Working Group

http://pbc.web.cern.ch/

Previous tests of the hadronic contribution to VP

1) '73: $\phi(1020)$ contribution to VP at ACO (Orsay e+e-) in the $e^+e^- \rightarrow \mu^+\mu^-$ process: evidence at 3σ in the region ±5 MeV around the ϕ peak [**Phys.Rev.Lett. 30 (1973) 462-464)]**



-5 MeV m_ϕ 5 MeV

2) 70's: g-2 experiment at CERN: evidence for hadronic contribution to g-2 at 6σ **[Phys. Lett. 67B (1977) 225; Phys. Lett. 68B (1977) 191]**

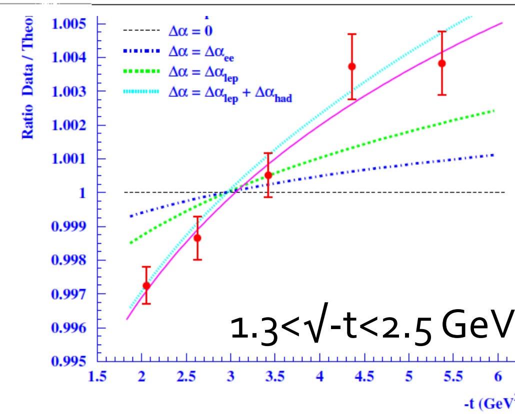
exp

$$a_\mu = 1\ 165\ 924\ (8.5) \times 10^{-9}\ (7\ \text{ppm}).$$

theo

QED terms	Muon	Numerical values ($\times 10^9$)	
2nd order: A	0.5	Total QED:	1 165 852 (1.9)
4th order: B	0.765 782 23	Strong interactions:	66.7 (8.1)
6th order: C	24.452 (26)	Weak interactions:	2.1 (0.2)
8th order: D	135 (63)	Total theory:	1 165 921 (8.3)
10th order: E	420 (30)		

3) 2006: OPAL at LEP: evidence for hadronic contributon Δa_{had} (t) (t<0) at 3σ in Bhabha scattering at small angle **[Eur.Phys.J. C45 (2006) 1-21]**



Recent Lattice evaluation

Hadronic vacuum polarization contribution to the anomalous magnetic moments of leptons from first principles

Sz. Borsanyi,[1] Z. Fodor,[1,2,3] C. Hoelbling,[1] T. Kawanai,[3] S. Krieg,[1,3] L. Lellouch,[4] R. Malak,[4,5] K. Miura,[4] K.K. Szabo,[1,3] C. Torrero,[4] and B.C. Toth[1]
(Budapest-Marseille-Wuppertal collaboration)

$$a_\mu^{\text{LO-HVP}} = 711.0(7.5)(17.3) \times 10^{-10}$$

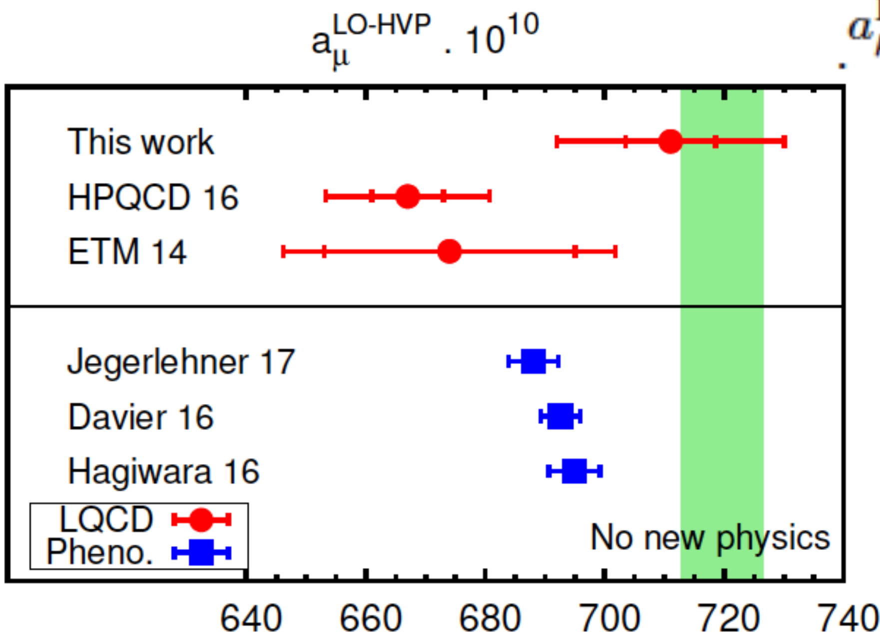
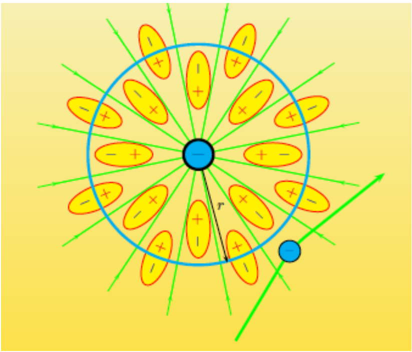


FIG. 1. Comparison of our result for $a_\mu^{\text{LO-HVP}}$ with the only other two $N_f = 2+1+1$ lattice QCD calculations [24, 33] and with recent ones obtained from phenomenology [8, 17, 19]. For the lattice results, the first error is statistical and the second is the total error, including systematics. The shaded region is the value that $a_\mu^{\text{LO-HVP}}$ would have to have to explain the experimental measurement of a_μ, assuming no new physics.

arXiv:1711.04980v1 [hep-lat]

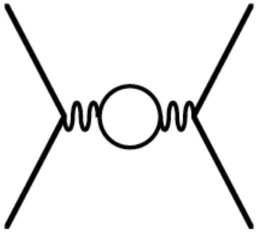
α_{em} running and the Vacuum Polarization



- Due to Vacuum Polarization effects $\alpha_{em}(q^2)$ is a running parameter from its value at vanishing momentum transfer to the effective q^2.

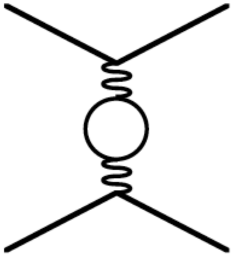
- The "Vacuum Polarization" function $\Pi(q^2)$ can be "absorbed" in a redefinition of an effective charge:

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



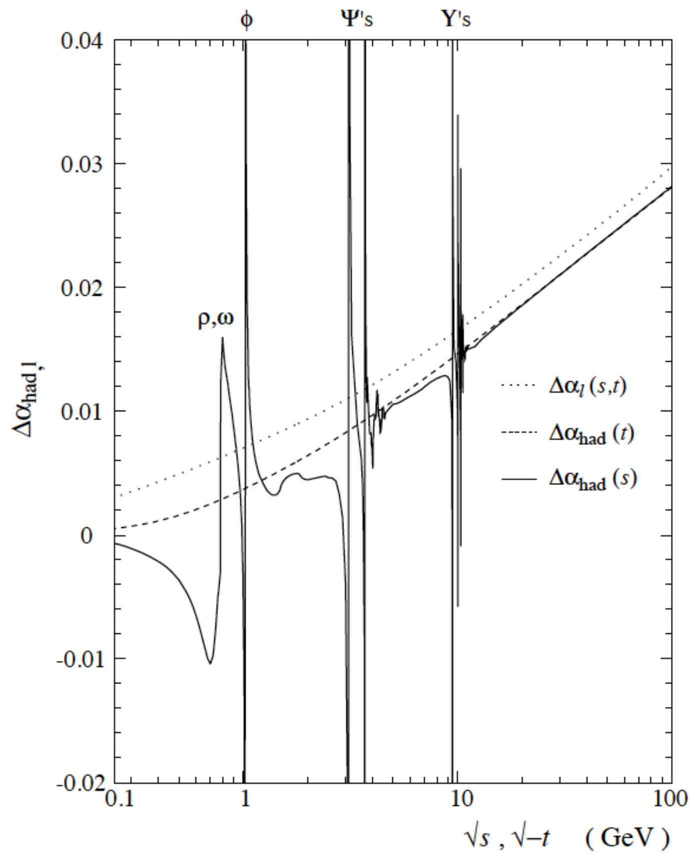
$$\Delta\alpha = \Delta\alpha_l + \Delta\alpha^{(5)}_{had} + \Delta\alpha_{top}$$

- Δa takes a contribution by non perturbative hadronic effects ($\Delta a^{(5)}_{had}$) which exibits a different behaviour in time-like and space-like region



Measurement of α running

- Measurements of $\alpha(q^2)$ in space/time like region can prove the running of α
- It can provide a test of "duality" (fare way 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)

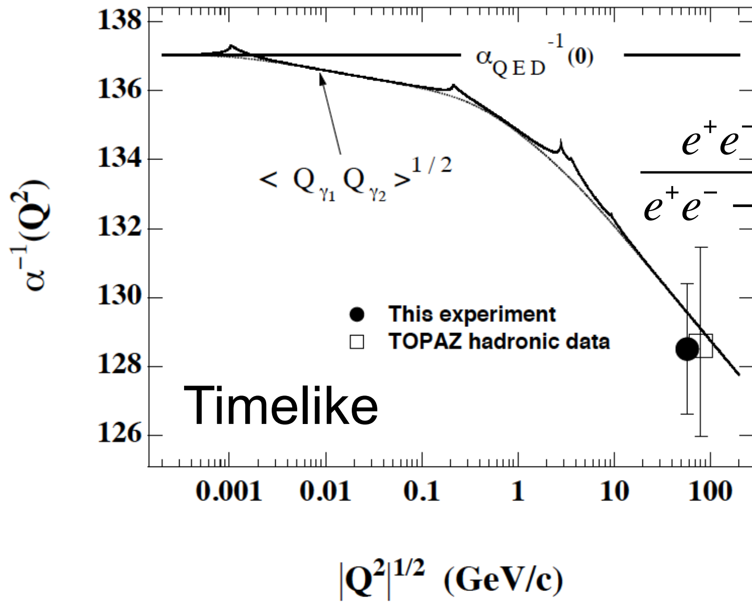


$$\left(\frac{\alpha(q^2)}{\alpha(q_0^2)}\right)^2 \sim \frac{N_{signal}(q^2)}{N_{norm}(q_0^2)}$$

N_{signal} can be Bhabha process, muon pairs, etc…
N_{signal} can be Bhabha process, $\gamma\gamma$ pairs, Theory, etc…

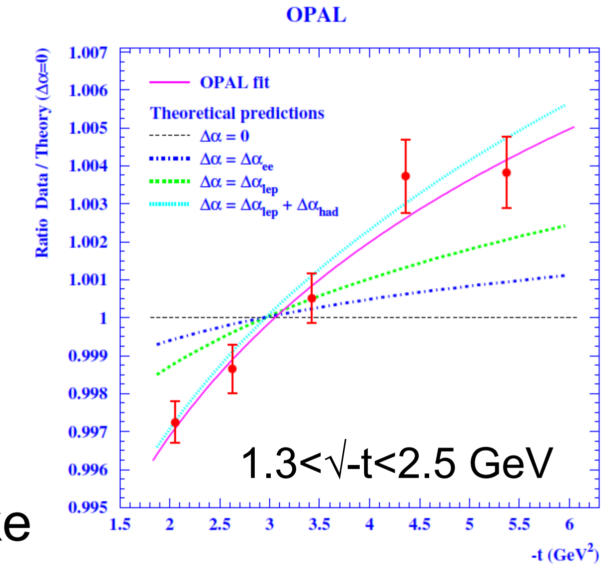
Direct measurement of α running

e+e- collider TRISTAN at √s=57.8 GeV,

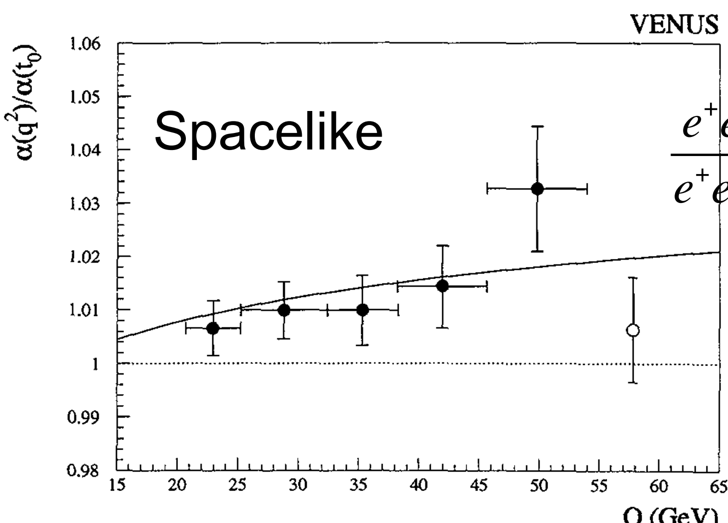


$$\frac{e^+e^- \to \mu^+\mu^-}{e^+e^- \to e^+e^-\mu^+\mu^-}$$

e+e- collider LEP at √s=189 GeV, using **Bhabha** events

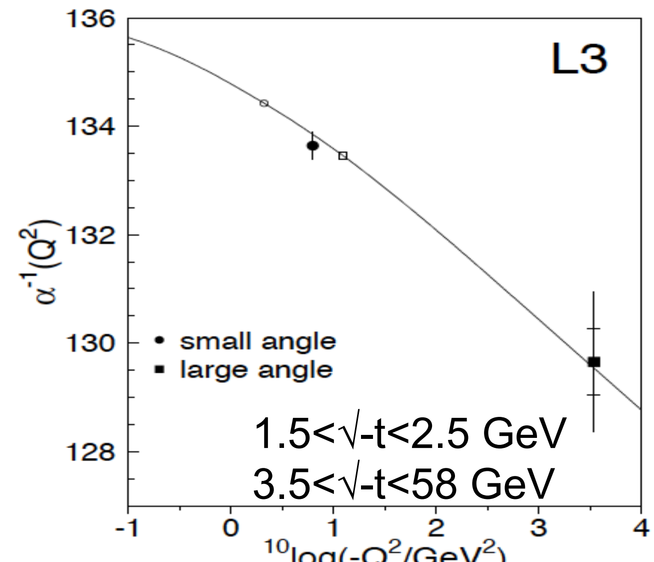


Spacelike



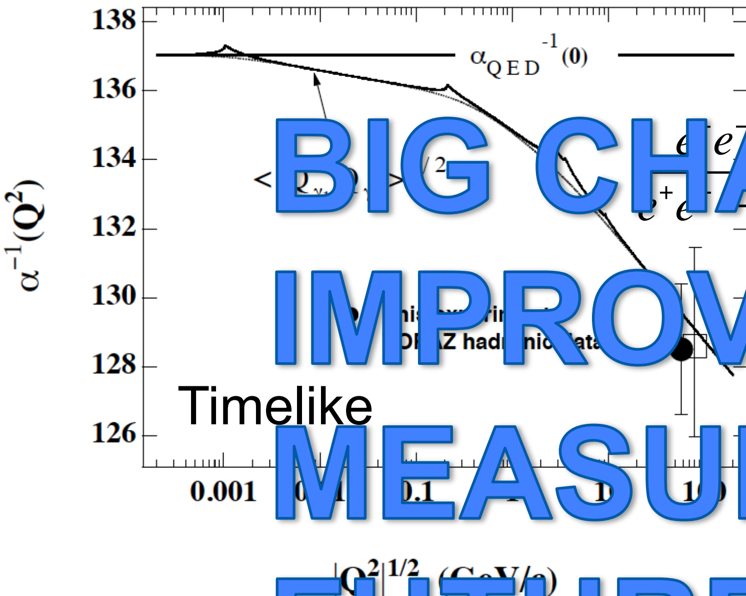
$$\frac{e^+e^- \to e^+e^-}{e^+e^- \to \mu^+\mu^-}$$

10<√-t<54 GeV

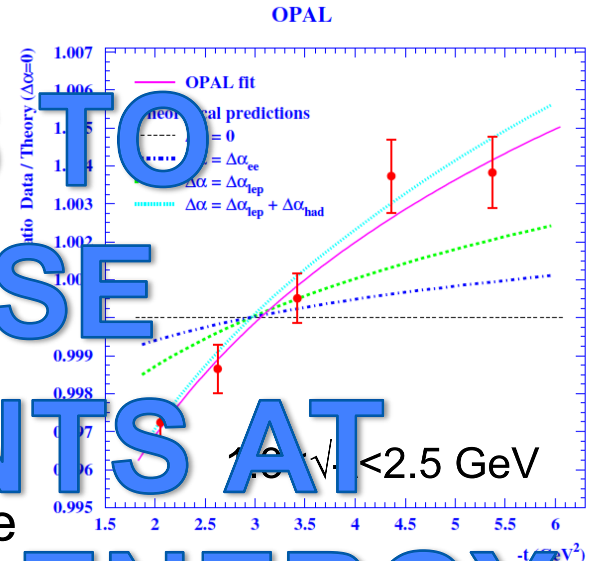


Direct measurement of α running

e+e- collider TRISTAN at $\sqrt{s}$=57.8 GeV,



e+e- collider LEP at $\sqrt{s}$=189 GeV, using **Bhabha** events



BIG CHANCES TO IMPROVE THESE MEASUREMENTS AT FUTURE HIGH ENERGY COLLIDER (ILC/FCCee)