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

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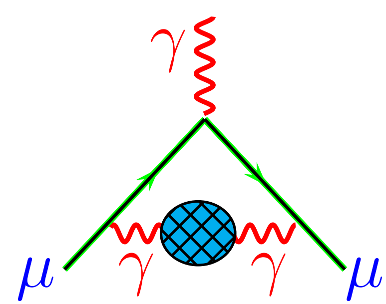
Physics Beyond Colliders



CERN, 7 September 2016

Outline

- Muon g-2: summary of the present status
- New approach to compute a_μ^{HLO} in the space-like region
- Proposal for a measurement a_μ^{HLO} with $\mu e \rightarrow \mu e$ at CERN
- Detector considerations
- Conclusions

Muon g-2: summary of the present status

- E821 experiment at BNL has generated enormous interest:

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

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

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

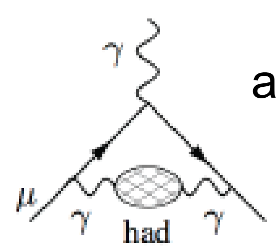
M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C71 (2011)

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

- 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)

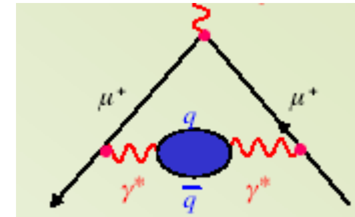


$a_\mu^{HLO} = (692.3\pm4.2)10^{-10}$

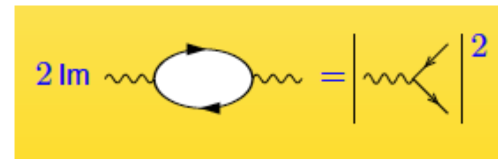
$\delta a_\mu/a_\mu \sim 0.6\%$

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

a_μ=(g-2)/2



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



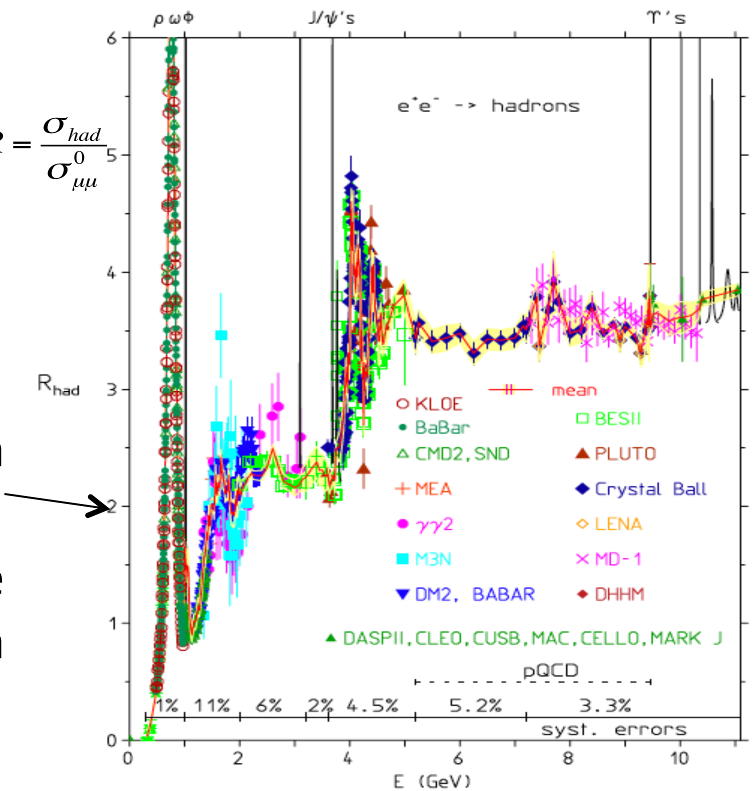
$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)(s/m^2)} \sim \frac{1}{s} \qquad \sigma_{e^+e^-\to hadr}(s) = \frac{4\pi}{s} \operatorname{Im}\Pi_{had}(s)$$

Traditional way: based on precise experimental (time-like) data:

a_μ^{HLO} = (692.3±4.2)10^{-10} (DHMZ)

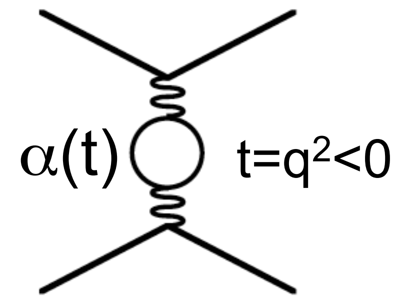
- Main contribution in the low energy region (**highly fluctuating!**)
- Current precision at 0.6% → needs to be reduced by a factor **~2** to be competitive with the new **g-2** experiments

$$R = \frac{\sigma_{had}}{\sigma^0_{\mu\mu}}$$



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

[C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni
Phys.Lett. B746 (2015) 325-32]

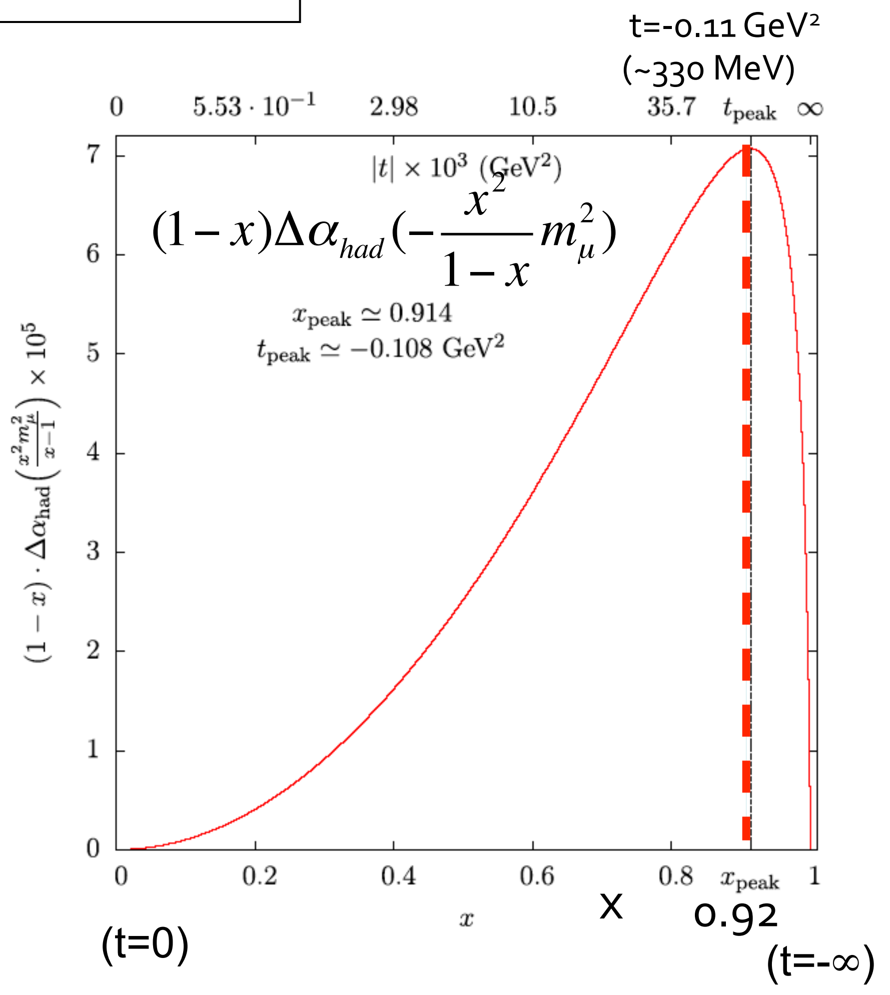


$$\boxed{a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx}$$

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

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

- **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

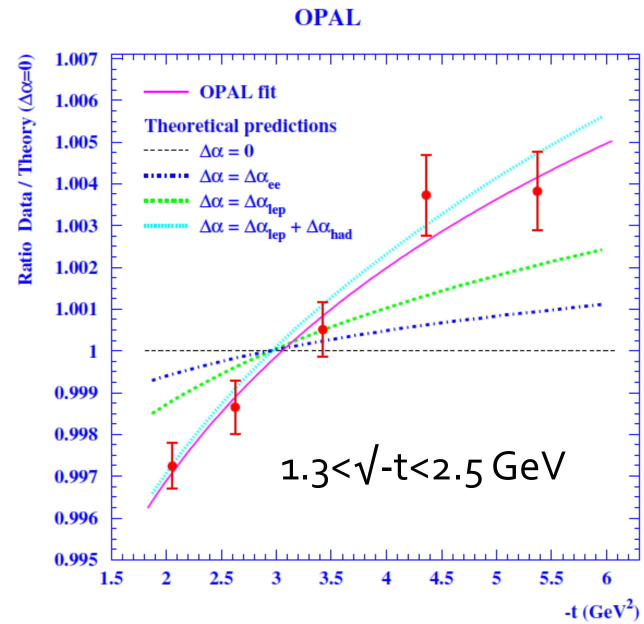


Measurement of $\Delta\alpha_{had}(t)$ spacelike at LEP

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

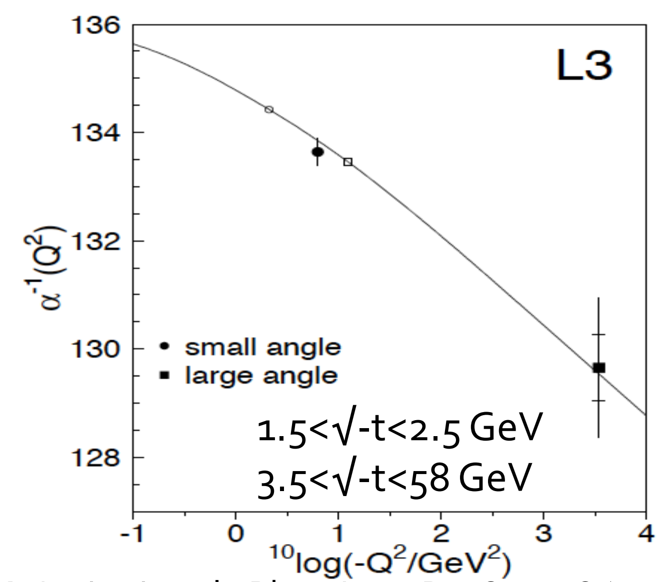
$$f(t) = \frac{N_{\rm data}(t)}{N^0_{\rm MC}(t)} \propto \left(\frac{1}{1 - \Delta\alpha(t)}\right)^2 .$$

Accuracy at per mill level was achieved!



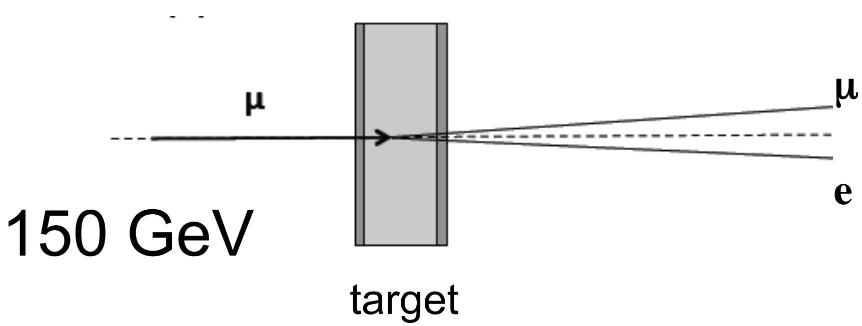
G. Abbiendi et al., Eur. Phys. J. C 45, 1–21 (2006)

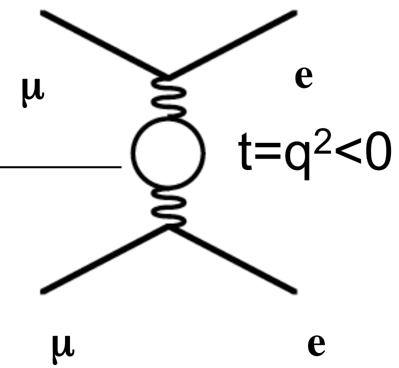
- For low t values (≤0.11 GeV²), like in our case flavour factories are needed!



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

$\Delta\alpha_{had}(t)$ can be measured with high energy muon beam (E~150 GeV) on electron low-Z target, through the elastic scattering $\mu e \rightarrow \mu e$





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

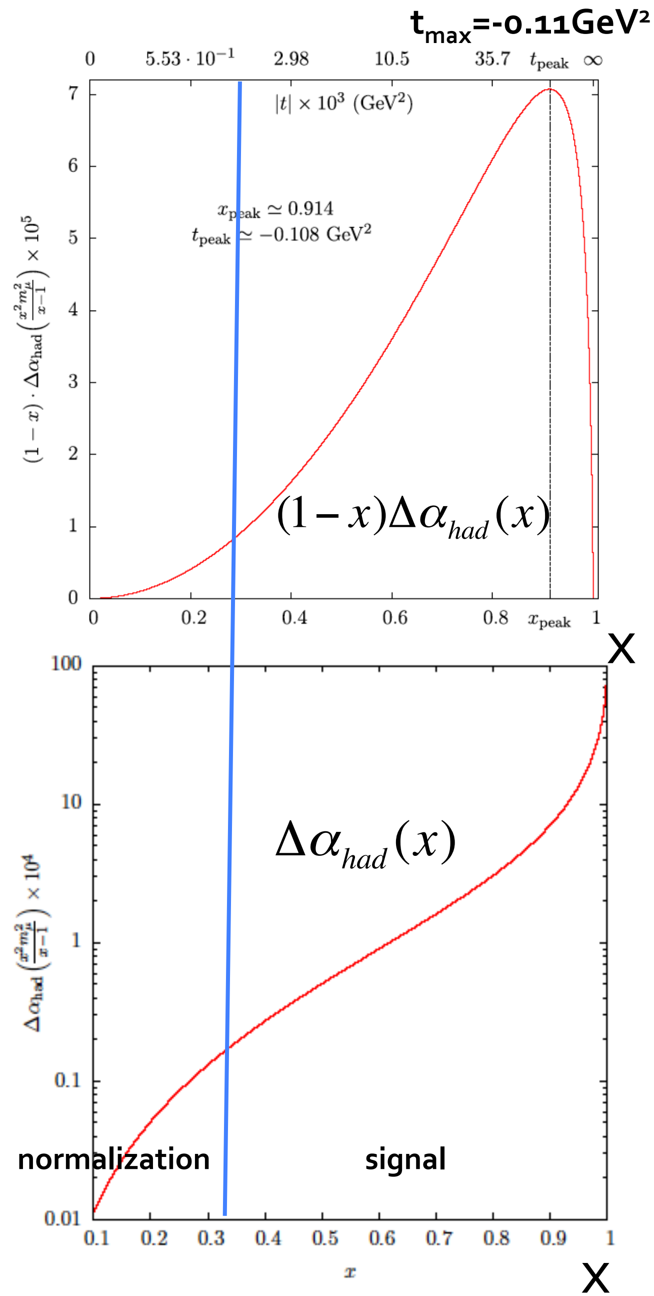
Why measuring $\Delta\alpha_{had}(t)$ with a 150 GeV μ beam on e^- target ?

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: $t=-2m_eE_e$
- 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 ($\Delta\alpha_{had}(t)<10^{-5}$)



Detector considerations I

- In order to be competitive with a_μ^{HLO} from time-like data (0.6% error) a subpercent uncertainty on a_μ^{HLO} is required

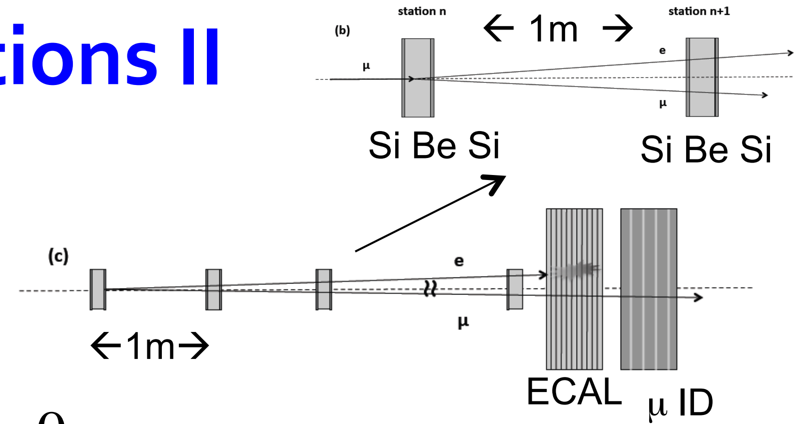
$$R^{MC} = \frac{d\sigma_0^{MC}(t)}{d\sigma_0^{MC}(t_0)}$$

$$\delta\Delta\alpha_{had}(t) \sim 0.5\sqrt{\left(\frac{\delta N^{data}(t)}{N^{data}(t)}\right)^2 + \left(\frac{\delta N^{norm}(t_0)}{N^{norm}(t_0)}\right)^2 + \left(\frac{\delta R^{MC}}{R^{MC}}\right)^2} + corr.\,terms$$

- $\delta\Delta\alpha_{had}/\Delta\alpha_{had}$ at 0.5% at peak region (x=0.92, Δa_{had}~10^{-3})→
  $\delta N(t)/N(t)$~10^{-5}

- Such an accuracy demands high **statistics** keeping **low systematic** errors!
- Dense (active) target would provide the required statistics at a price of an unavoidable large multiple scattering and background process (pair production, bremsstrahlung, nuclear interaction)
- Our **choice** goes to light Z (Be) target with a modular apparatus which minimizes systematic errors

Detector considerations II



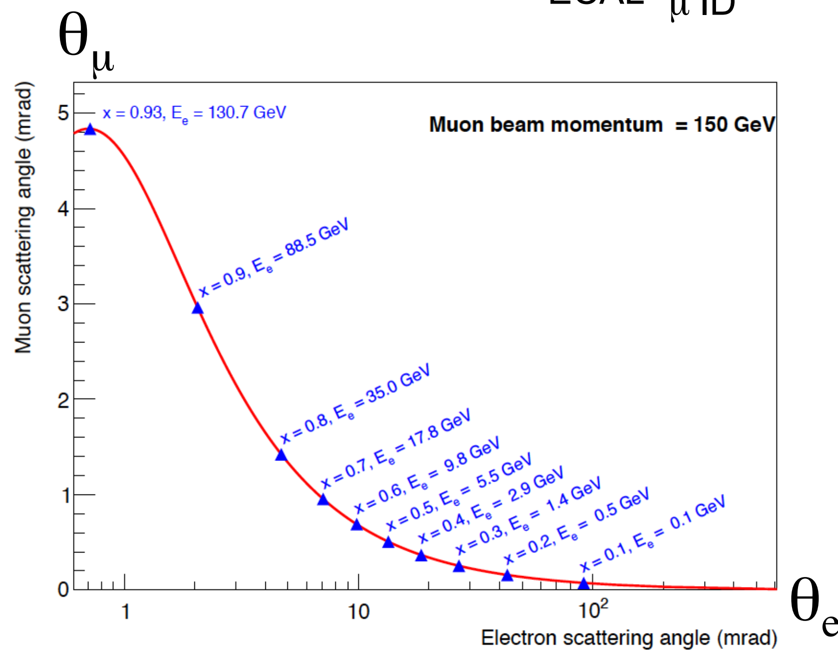
- Modular apparatus: 20 layers of 3 cm Be (target), each coupled to 1 m distant Si (0.3 mm) planes. It provides a 0.02 mrad resolution on the scattering angle

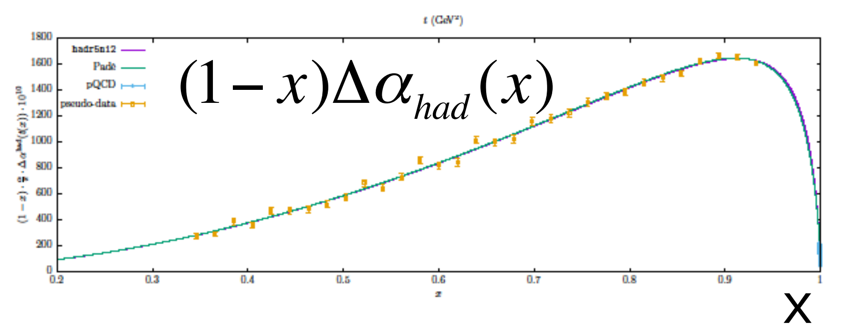
- The $t=q^2<0$ of the interaction is determined by the electron (or muon) scattering angle (a\` la NA7)

- 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)

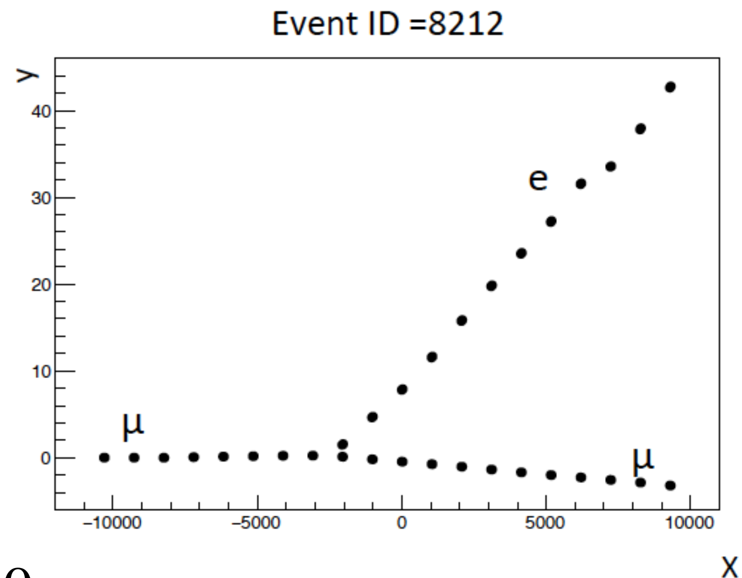
- **Statistical considerations show that a 0.3% error can be achieved on a_μ^{HLO} in 2 years of data taking with 2×10^7 μ/s**

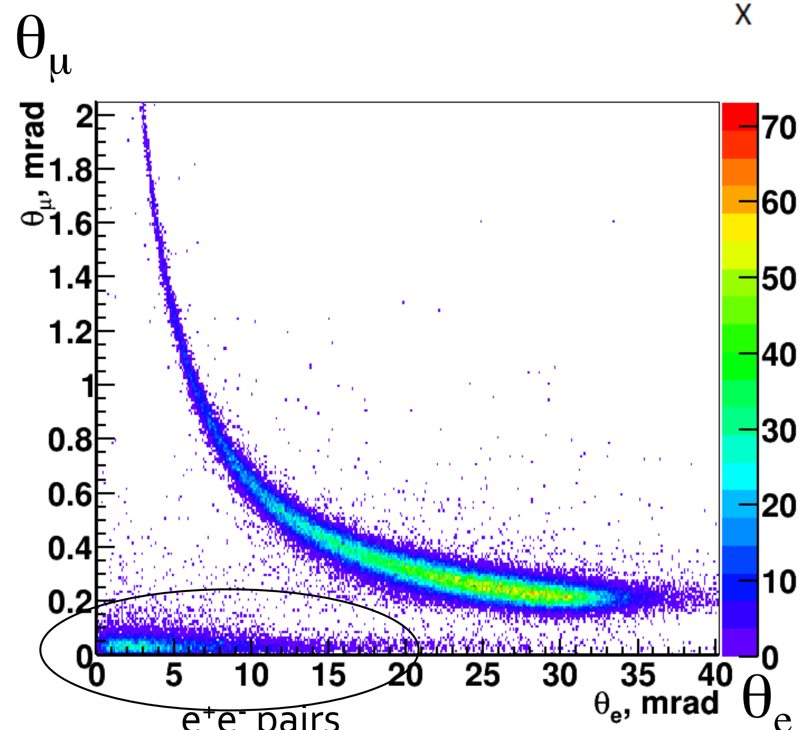




First simulation

- A simulation of the detector based on GEANT-4 has started
- μ-e elastic scattering events have a clear topology
- Background events can be easily identified and rejected in the θ_μ vs θ_e plane
- Multiple scattering can be studied by data as it **breaks** the μ-e two-body angular correlation, moving events out of the kinematic constraint. It also causes **acoplanarity**, while two-body events are planar.
- Simulation will help to optimize the detector (i.e. additional thin layer(s) can be placed for luminosity)





Conclusion I

- We present an alternative method to determine the full contribution to $\mathbf{a_\mu^{HLO}}$ based on the measurement of $\boldsymbol{\Delta\alpha_{had}(t)}$ in **space-like region**. It consists in measuring the scattering $\mu\ e \rightarrow \mu\ e$ using a high energy muon beam (E~150 GeV) available in the North Area at CERN on electron target

- A detector concept based on a modular structure of light Z (Be) target and Silicon planes allows to reach a statistical uncertainty of **~0.3%** on a_μ^{HLO} in ~2 years of data taking and an angular precision of ~ 0.02 mrad on the scattering angle

- The $t=q^2<0$ of the events can be obtained by a precise measurement of *e* and μ scattering angles

- Such a simple and robust technique has the potential to keep systematic effects under control

Conclusion II

- Theory side: high precision MC must be developed to control the systematics. The present knowledge of QED Radiative Corrections is at a few 10^{-4} level; work is in progress to extend MC used at flavour factories (BabaYaga) to μe scattering with expected accuracy at (better than) 10^{-5} on cross section ratios

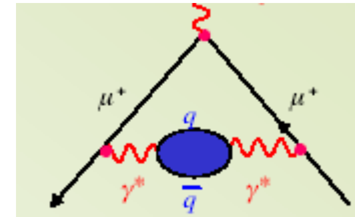
- In experiments dedicated to high-precision measurements, several systematic effects can be explored within the experiment itself. In this respect the proposed modularity of the apparatus will help. **A test with a single module could provide a proof-of-concept of the proposed method.**

Thanks!

Spare

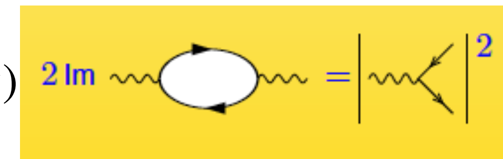
a_μ^{HLO} calculation, traditional way: time-like data

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



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

$$a_\mu^{HLO.} = \frac{\alpha}{\pi^2}\int_0^\infty \frac{ds}{s}K(s)\,\mathrm{Im}\,\Pi_{had}(s) \qquad \sigma_{e^+e^-\to hadr}(s) = \frac{4\pi}{s}\mathrm{Im}\,\Pi_{had}(s)$$

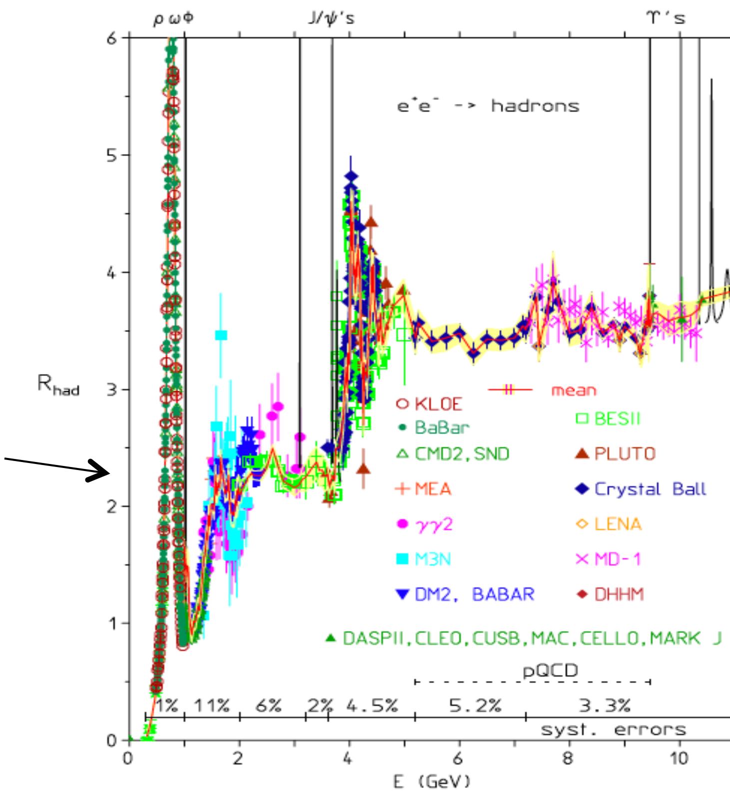


$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)(s/m^2)} \sim \frac{1}{s}$$

Traditional way: based on precise experimental (time-like) data:

a_μ^{HLO} = (692.3±4.2)10^{-10} (DHMZ)

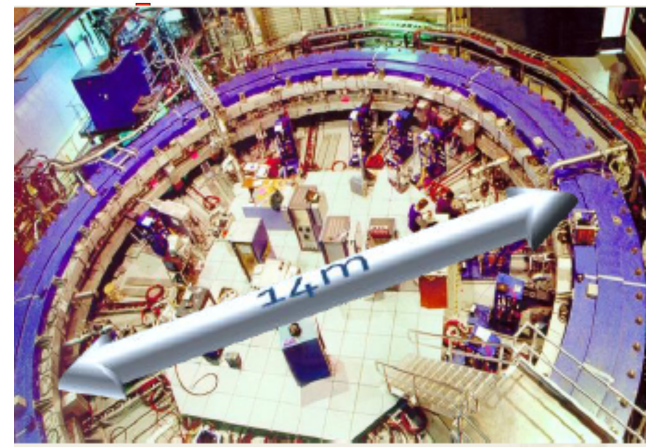
- Main contribution in the low energy region (**highly fluctuating!**)
- Current precision at 0.6% → needs to be reduced by a factor **~2** to be competitive with the new **E989** experiment

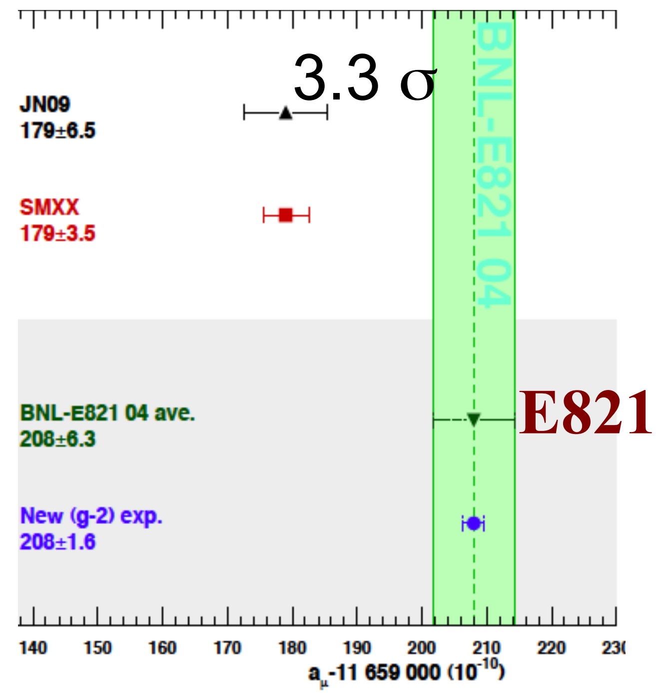


(g-2)$_\mu$: a new experiment at FNAL (E989)

- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x stat**. w.r.t. E821. Relocate the BNL storage ring to FNAL.

$\rightarrow$ δa_μx4 improvement (0.14ppm)





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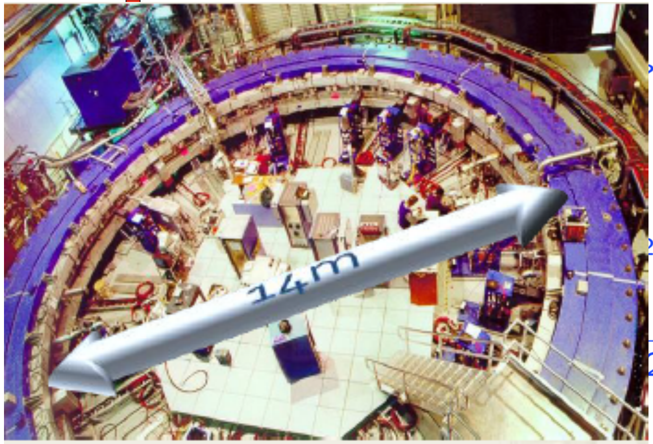
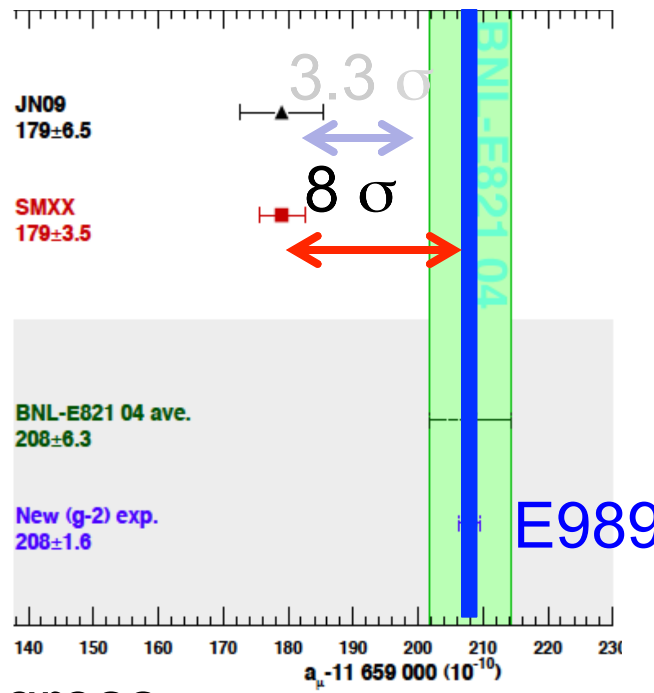


$\rightarrow \delta a_\mu$x4 improvement (0.14ppm)

If the central value remains the same $\Rightarrow$ 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].

Complementary proposal at J-PARC in progress

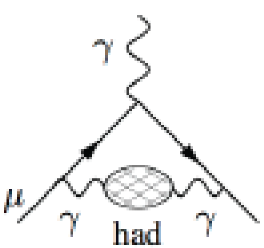
Muon G-2:summary of the present status

- E821 experiment at BNL has generated enormous interest
- Tantalizing ~3σ deviation with SM (persistent since >10 years)
- Current discrepancy limited by:
  - experimental uncertainty (BNL) → New experiments at FNAL and J-PARC
  - Theoretical uncertanty limited by Hadronic Vacuum polarization

$$a_\mu^{EXP} - a_\mu^{TH} \sim (28 \pm 8) \bullet 10^{-10}$$

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

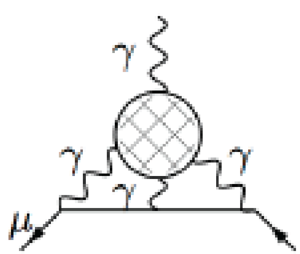
HLO VP



$a_\mu^{HLO} = (695 \pm 4.3) 10^{-10}$

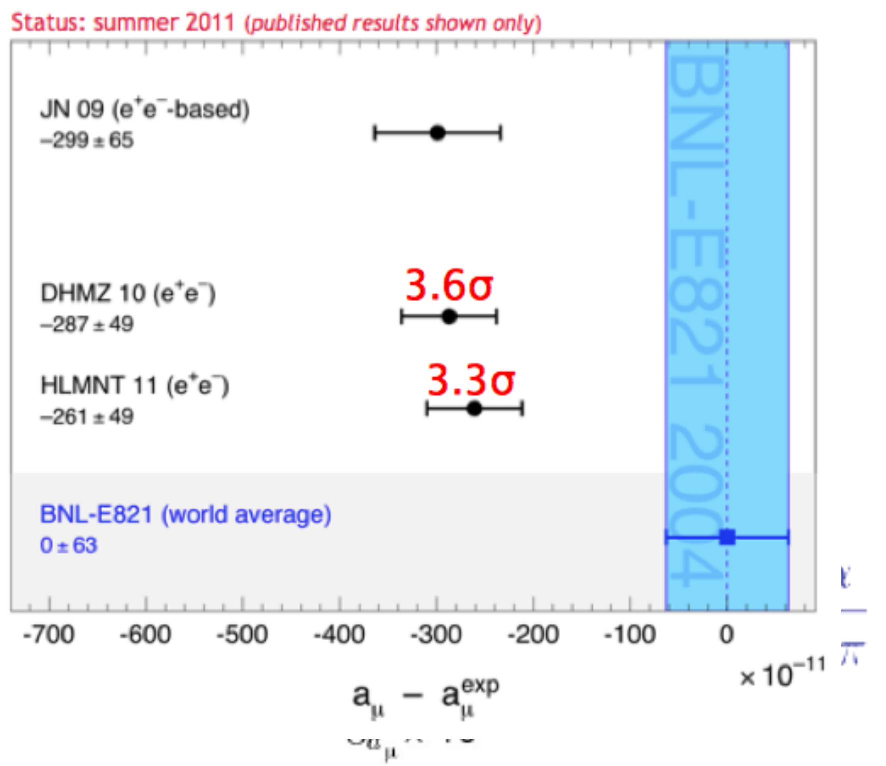
$\delta a_\mu^{HLO} \sim 0.7\%$

H LbL



$a_\mu^{HLbL} = (10.5 \pm 2.6) 10^{-10}$

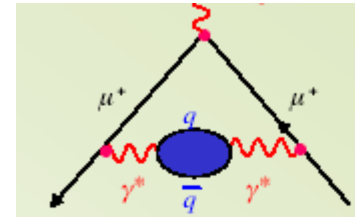
$\delta a_\mu^{HLbL} \sim 25\%$



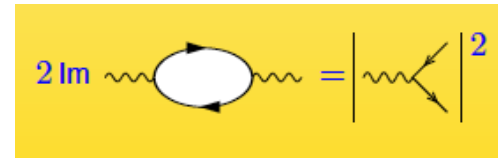
a_μ^{HLO} calculation, traditional way: time-like data

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

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



$$a_\mu^{HLO.} = \frac{\alpha}{\pi^2}\int_0^\infty \frac{ds}{s}K(s)\,\mathrm{Im}\,\Pi_{had}(s) \qquad \sigma_{e^+e^-\to hadr}(s) = \frac{4\pi}{s}\mathrm{Im}\,\Pi_{had}(s)$$

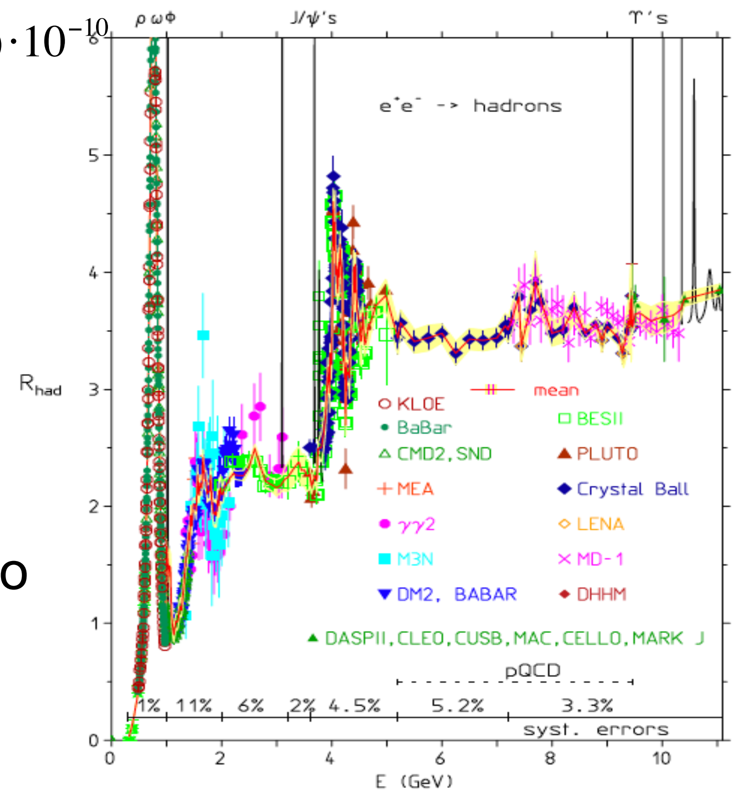


$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)(s/m^2)} \sim \frac{1}{s} \qquad a_\mu^{had} = (689.7\pm 4.4)\cdot 10^{-10}$$

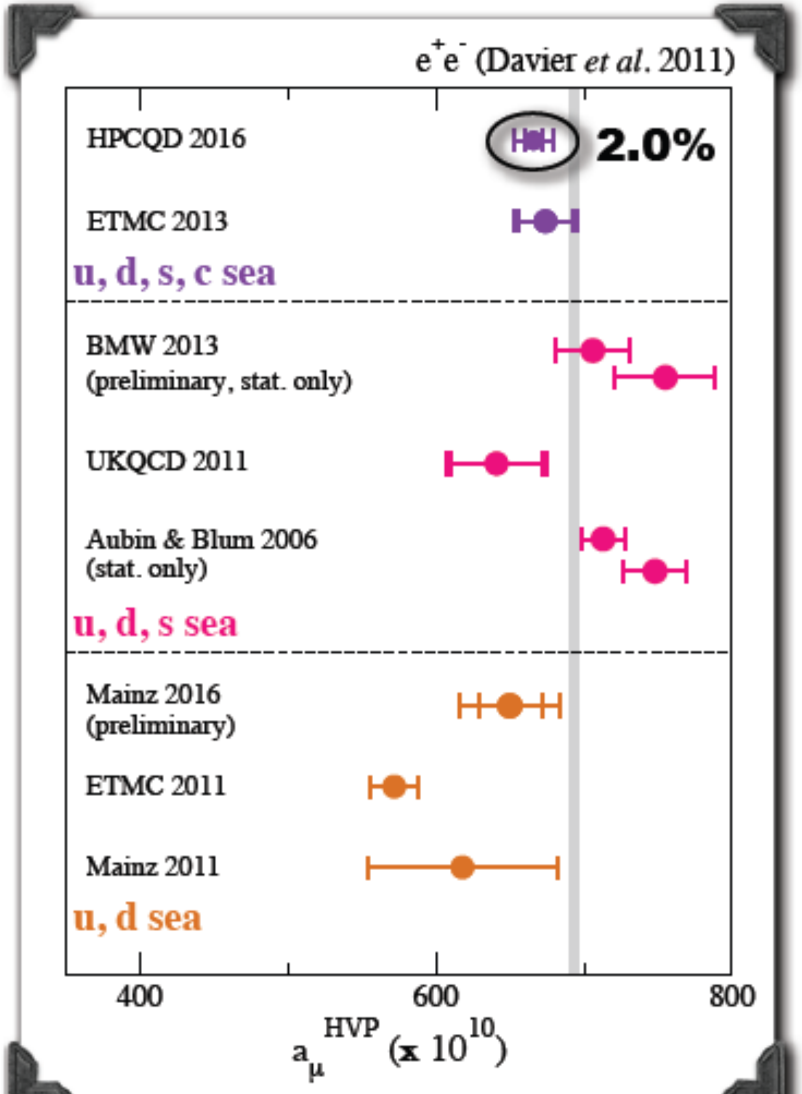
Traditional way: based on precise experimental (time-like) data:

Main contribution in the low energy region (**highly fluctuacting!**)

Current precision at 0.7% → needs to be reduced by a factor ~2 to be competitive with the new E989 experiment: not easy task due to local experimental discrepancies and uncertainties on theoretical ingredients (FSR, Isospin corrections, etc..)



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)]

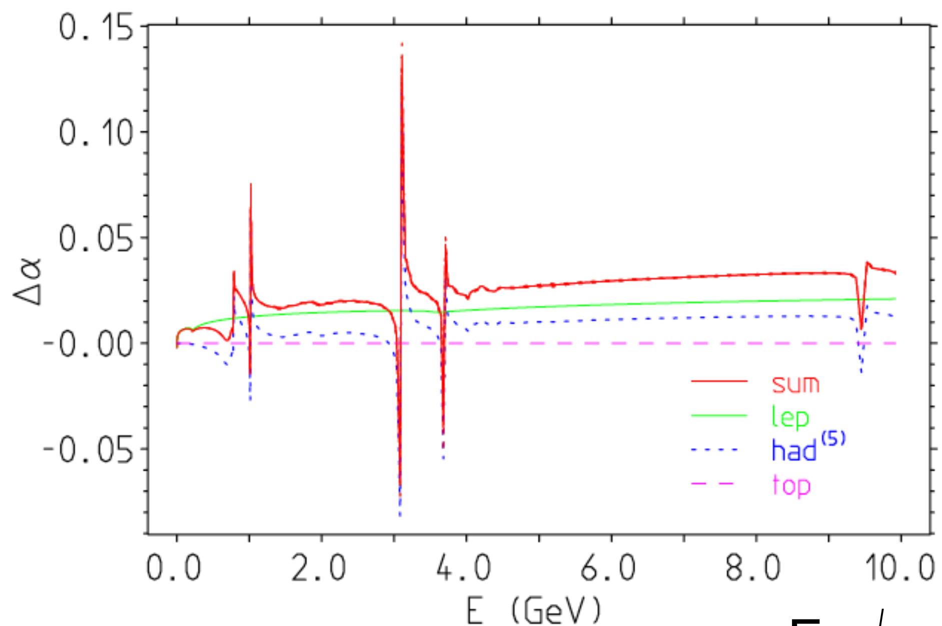
(2) Second complete calculation of leading-order a_μ^{HVP} [HPQCD, arXiv:1601.03071]

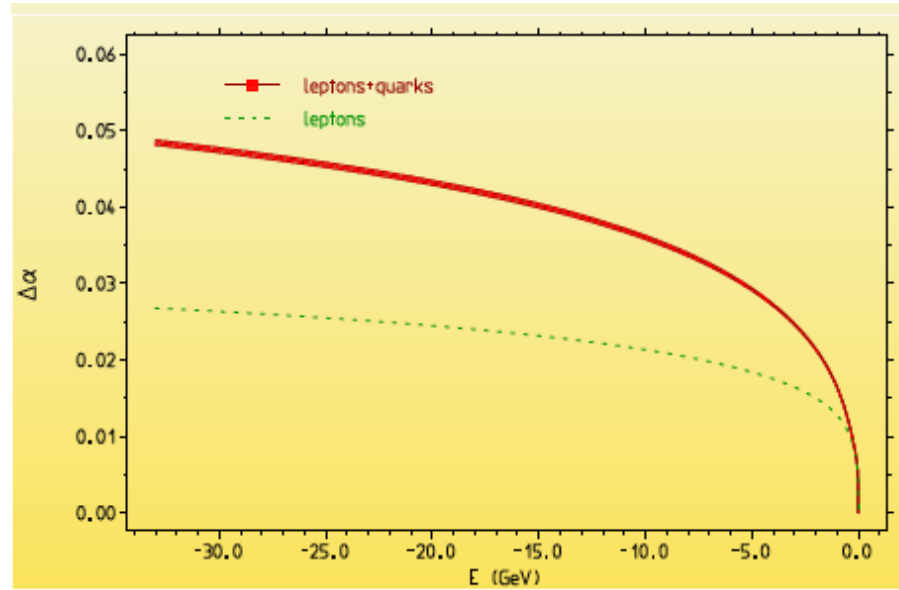
  - *First to reach precision needed to observe significant deviation from experiment*

- ~1% total uncertainty by 2018 possible

- Sub-percent precision will require inclusion of isospin breaking & QED, and hence take longer

Running of α_{em}

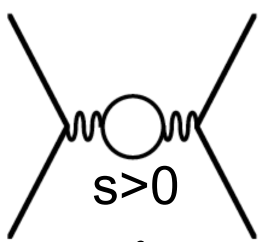




$E=\sqrt{s}$

Time-like

Behaviour characterized by the opening of resonances

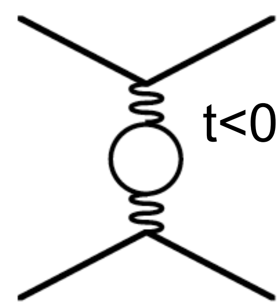


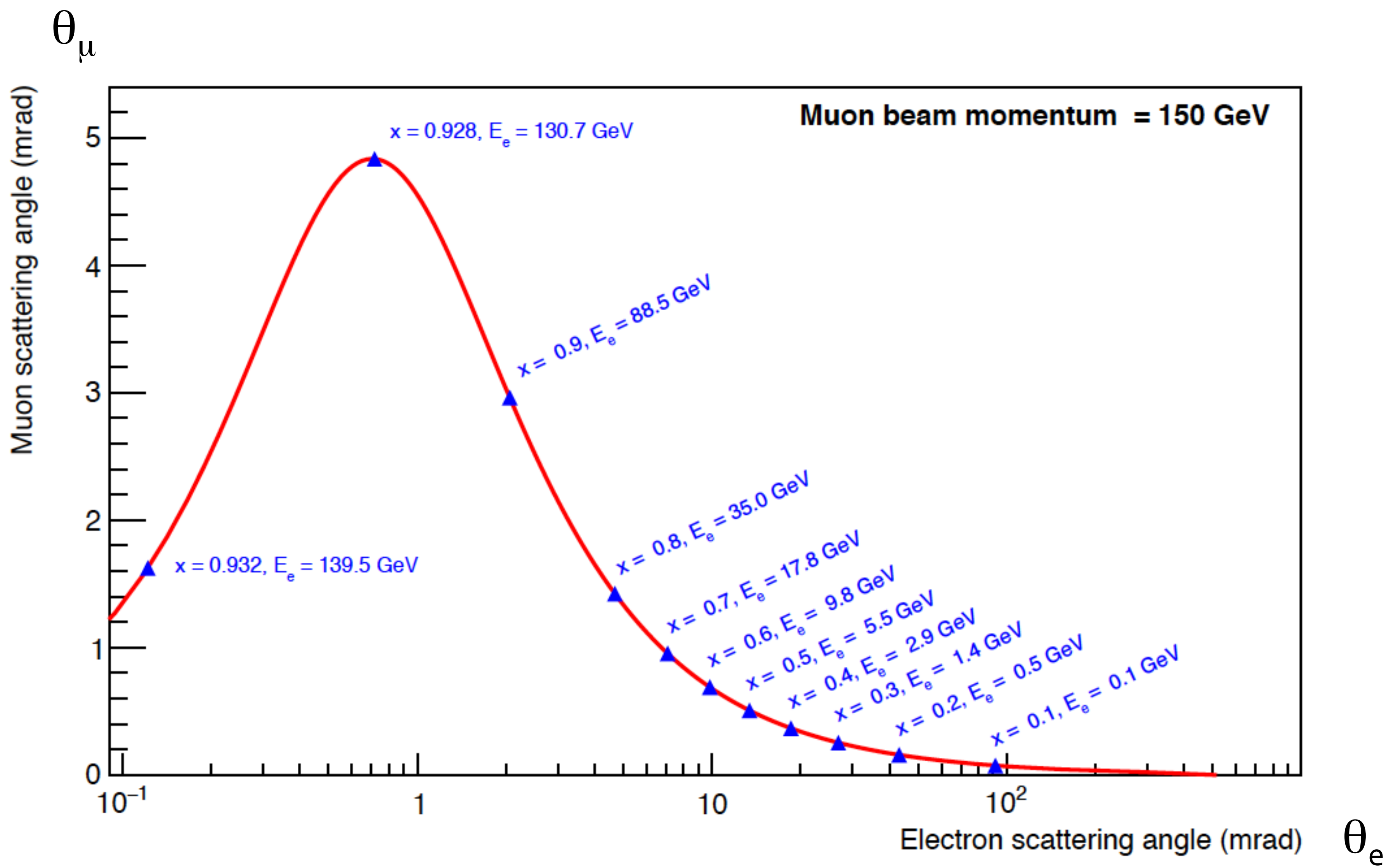
$$\Delta\alpha^{(5)}_{had}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s-M_Z^2-i\varepsilon)}$$

$E=-\sqrt{-t}$

Space-like

Very smooth behaviour





θ_μ
Muon scattering angle (mrad)
Muon beam momentum = 150 GeV
x = 0.928, E_e = 130.7 GeV
x = 0.932, E_e = 139.5 GeV
x = 0.9, E_e = 88.5 GeV
x = 0.8, E_e = 35.0 GeV
x = 0.7, E_e = 17.8 GeV
x = 0.6, E_e = 9.8 GeV
x = 0.5, E_e = 5.5 GeV
x = 0.4, E_e = 2.9 GeV
x = 0.3, E_e = 1.4 GeV
x = 0.2, E_e = 0.5 GeV
x = 0.1, E_e = 0.1 GeV
0
1
2
3
4
5
10^{-1}
1
10
10^2
Electron scattering angle (mrad)
θ_e