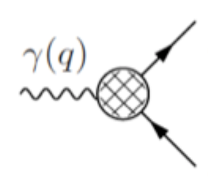
Measuring the leading hadronic contribution to the muon g-2 via μ-e scattering

G. Abbiendi, C. M. Carloni Calame, M. Incagli, U. Marconi, C. Matteuzzi, G. Montagna, O. Nicrosini, M. Passera, F. Piccinini, R. Tenchini, L. Trentadue, G. Venanzoni

1 Muon g-2 anomaly

$$\mu = g_\mu \frac{e\hbar}{2m_\mu c} s \qquad g_\mu = 2\,(1+a_\mu)$$ the muon anomaly

muon–γ vertex



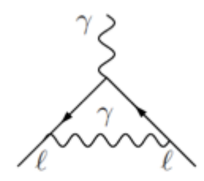
Dirac form factor — Pauli form factor

$$= (-\mathrm{i}e)\,\bar{u}(p_2)\left[\gamma^\mu F_{\mathrm{E}}(q^2) + \mathrm{i}\frac{\sigma^{\mu\nu}q_\nu}{2m_\mu}F_{\mathrm{M}}(q^2)\right]u(p_1)$$

Static (classical) limit

$$F_{\mathrm{E}}(0) = 1\ , \quad F_{\mathrm{M}}(0) = a_\mu$$

charge renormalization condition — the muon anomaly



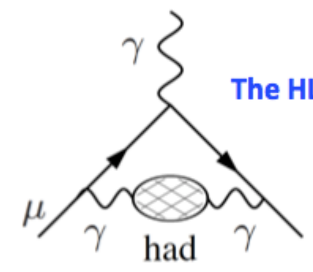
QED/SM
Largest contribution
J. Schwinger (1948)
α/2π

2 Summary of the present status

- E821 experiment at BNL:
  a_μ^{E821} = (11659208.9 ± 6.3)×10^{-10}
  [0.54 ppm]
- The SM prediction:
  a_μ^{SM} =(11659180.2 ± 4.9)×10^{-10}
  [0.42 ppm] (DHMZ)
- **3.5σ discrepancy**:
  $a_\mu^{E821} - a_\mu^{SM}$ = (28 ± 8)×10^{-10}
- **Significance is limited by**:
  - Experimental uncertainty:
    New experiments planned at FNAL E989 and J-PARC, aiming to improve the precision x4.
  - Theoretical uncertainty:
    Theoretical precision is limited by low energy hadronic effects.

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

Hadronic Vacuum Polarization



The HLO

a_μ^{HLO} = (692.3±4.2)×10^{-10}

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

We aim to
$\delta a_\mu^{HLO}/a_\mu^{HLO}$ ~ 0.3%
by means of the new approach

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

3 a_μ^{HLO} calculation with time-like data

- Optical theorem and analyticity:

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

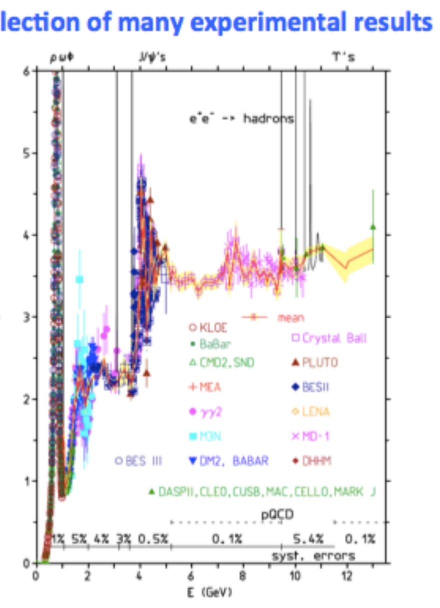
$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\cdot\sigma(s)_{(e^+e^-\to had)}$$

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

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

- Current precision at 0.6% needs to be reduced by a factor ~2 to be competitive with the planned g-2 experiments

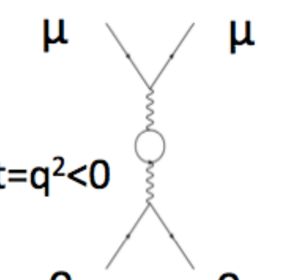
Collection of many experimental results



4 The elastic scattering μ + e → μ + e

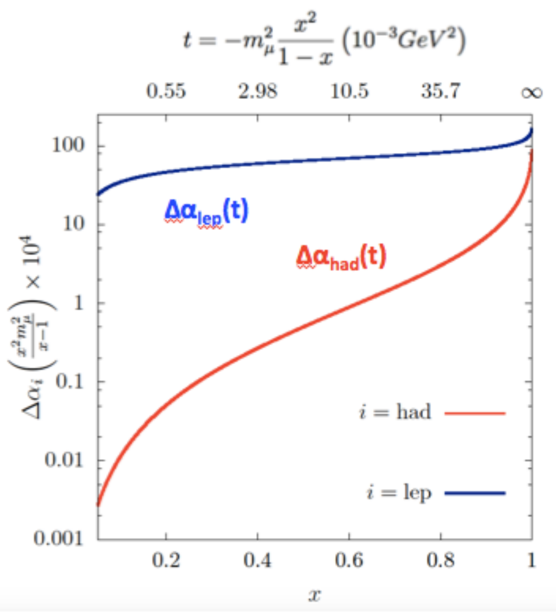
α(t) through:

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



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

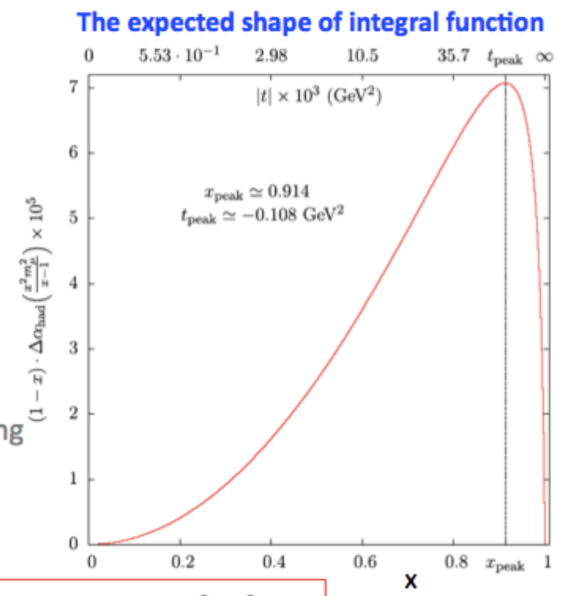
$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$



5 a_μ^{HLO} space-like approach

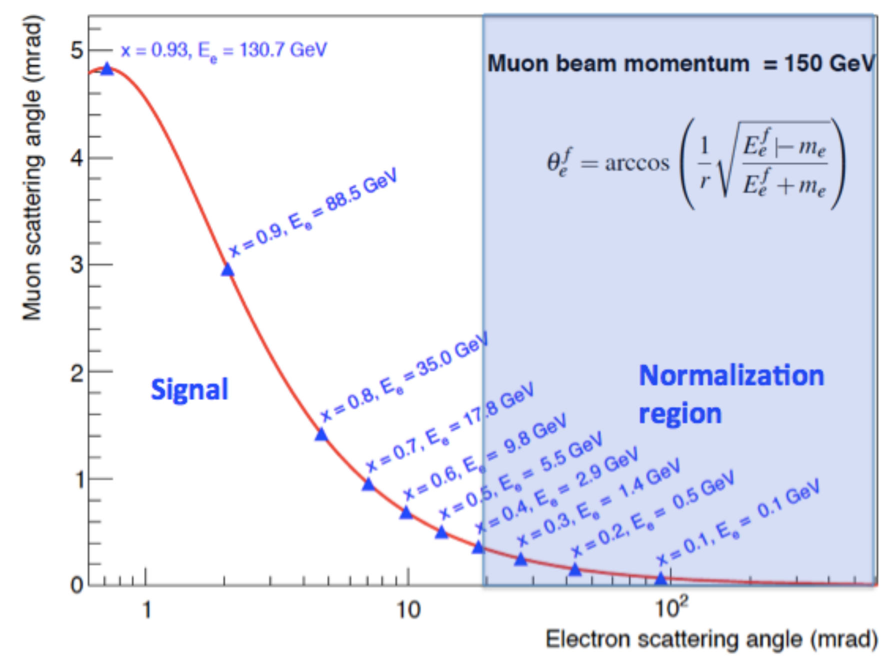
- **It requires just the single process μ + e → μ + e elastic**
  High intensity CERN muon beam of E_μ ~ **150 GeV** colliding on atomic electrons at rest.
- **Highly boosted final state:**
  0 < - t < 0.161 GeV^2
  0 < x < 0.93 (peak is at x = 0.914)
  The range covers **87%** of the integral.
- Beyond the kinematics limit the integral (13%) can be determined using pQCD & time-like data, and/or lattice QCD results.

The expected shape of integral function



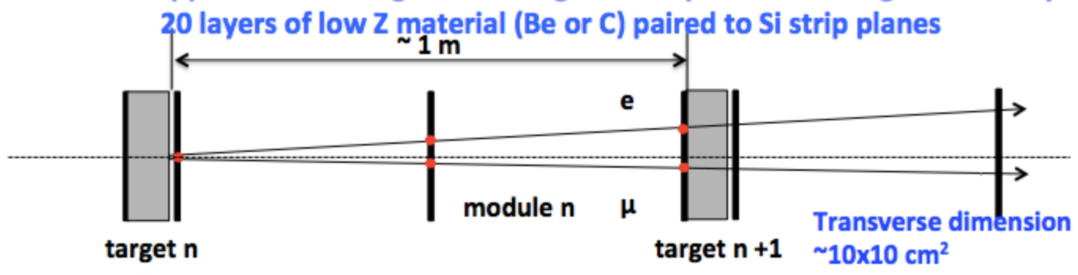
$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\cdot\Delta\alpha_{had}\left(-\frac{x^2 m_\mu^2}{1-x}\right)$$

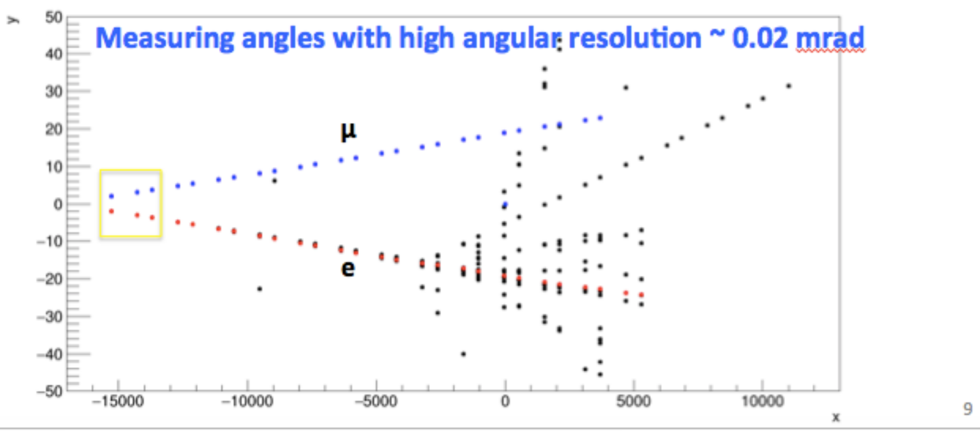
6 Elastic scattering in the (θ_e, θ_μ) plane



7 Detection technique

Modular apparatus covering the full angular acceptance with high uniformity.
20 layers of low Z material (Be or C) paired to Si strip planes



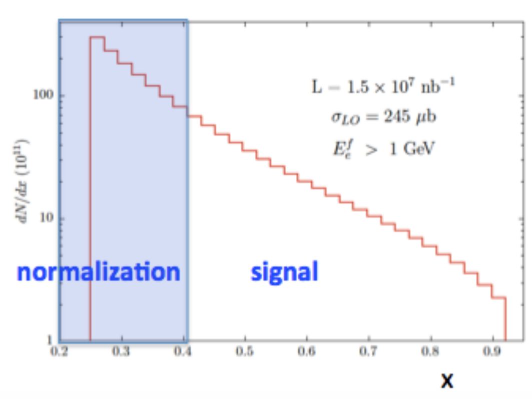


8 Luminosity and statistical error

- With the CERN 150 GeV muon beam, which has an average intensity of ~ 1.3×10^7 μ/s, incident on 20 Be layers, each 3 cm thick, and 2 years of data taking with a running time of 2 ×107 s/yr, one can reach an integrated luminosity of

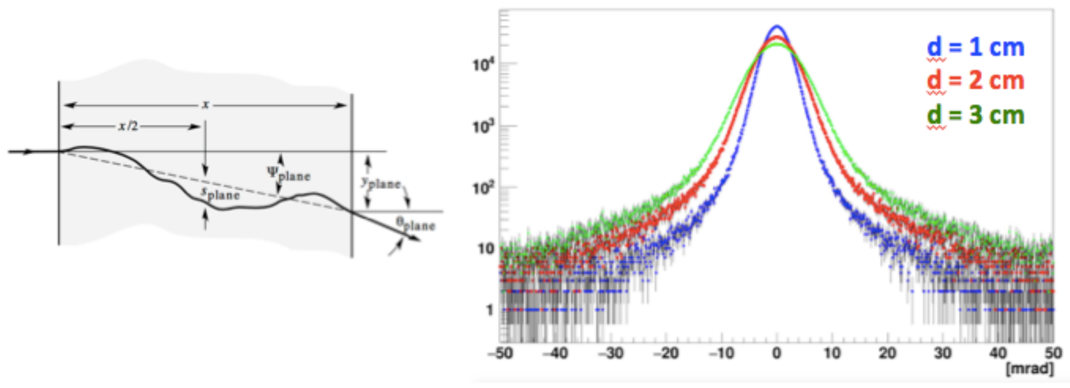
$\mathcal{L}_{int}$ ~ 1.5 × 10^7 nb^{-1}

- $\mathcal{L}_{int}$ implies a statistical sensitivity of ~ 0.3% on a_μ^{HLO} (δa_μ^{HLO} ~ 2 × 10^{-10})
- $\sigma_{LO}(E_e > 1\ \mathrm{GeV})$ = 245 μb



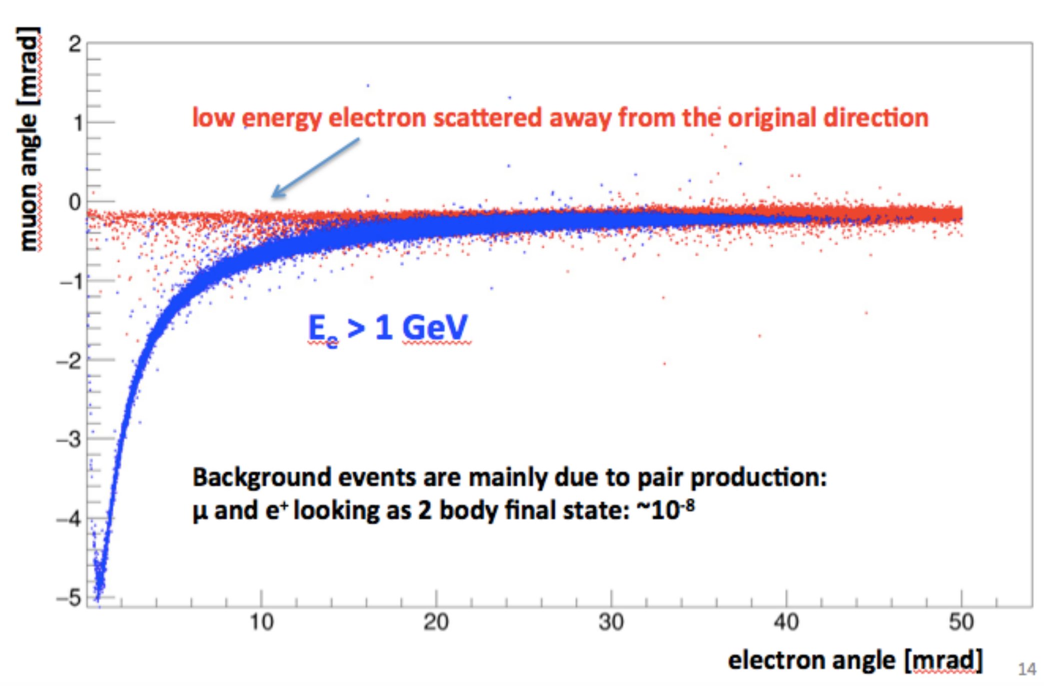
9 The role of Multiple Scattering (MSC)

GEANT4, 1 GeV electrons, Be target

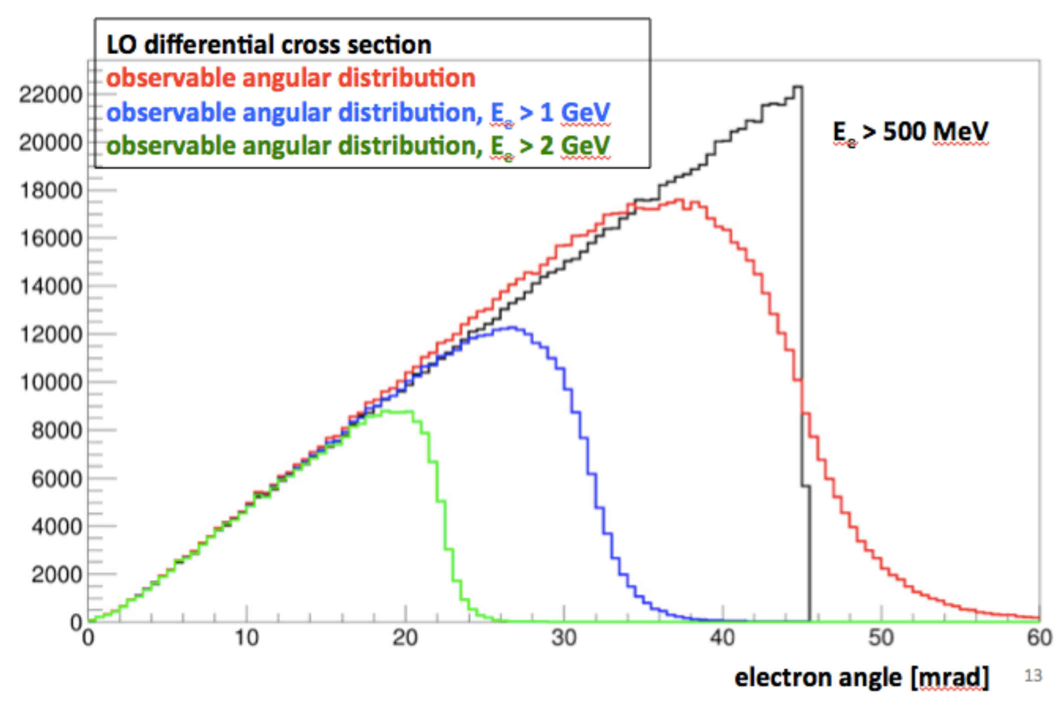


Vertices of the μ + e → μ + e collisions will be uniformly distributed inside the target along the direction of the beam axis.
The observable angles (electron and muon angles) depend therefore on the particles' path length inside the material and on their energies.
We need a MSC model to relate the observed angles to the scattering ones.

10 Events in the (θ_e, θ_μ) plane



11 Resolution models



12 Conclusions

- The proposed experiment can reach the required statistical precision of 0.3%
- We need to estimate systematics errors related to MSC.
  - In collaboration with Geant4 developers.
  - Planned test beam at CERN this year.
- From the theoretical side: NNLO MC event generation and fit for HLO.
- A proto-experiment at CERN M2 will require one module station only.
- The plan for the next year is of starting a Collaboration to write a TDR.

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

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