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

Umberto Marconi
INFN Bologna (IT)

Rencontres de Moriond
QCD and High Energy Interactions
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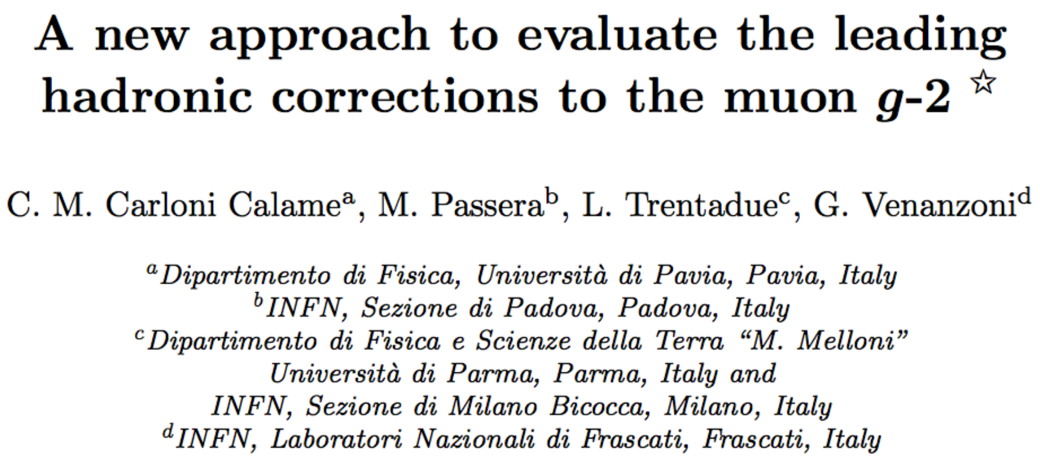
Reference papers

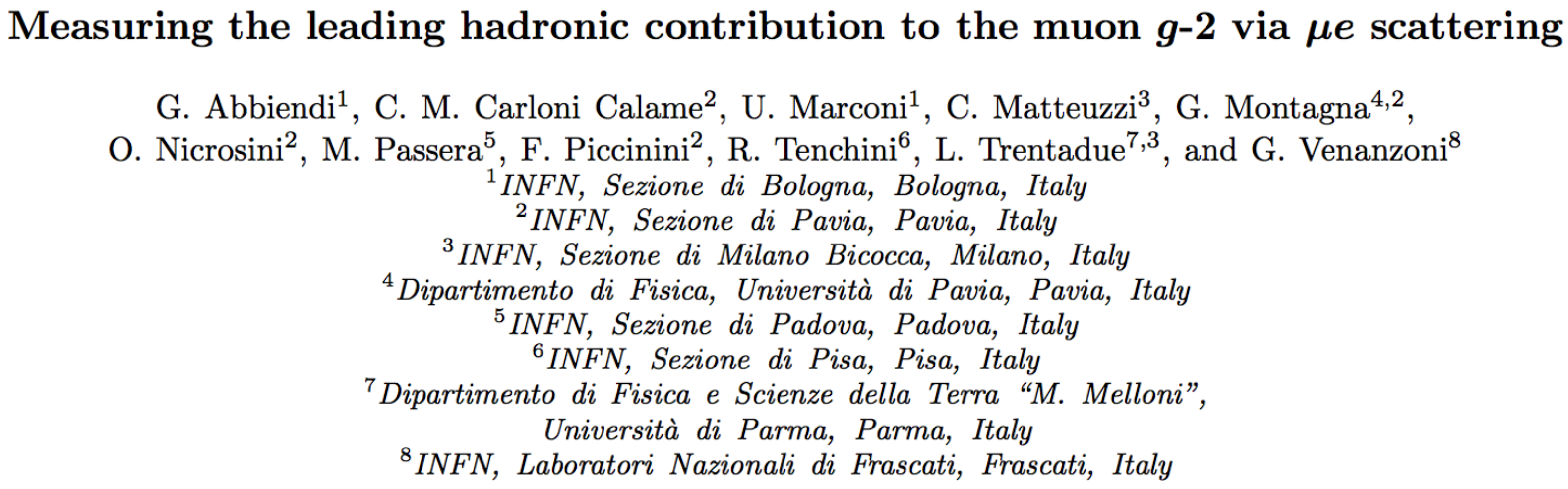


A new approach to evaluate the leading hadronic corrections to the muon g-2 ☆

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

[a] *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[b] *INFN, Sezione di Padova, Padova, Italy*
[c] *Dipartimento di Fisica e Scienze della Terra "M. Melloni"*
Università di Parma, Parma, Italy and
INFN, Sezione di Milano Bicocca, Milano, Italy
[d] *INFN, Laboratori Nazionali di Frascati, Frascati, Italy*

Phys. Lett. B 746 (2015) 325



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]
[1] *INFN, Sezione di Bologna, Bologna, Italy*
[2] *INFN, Sezione di Pavia, Pavia, Italy*
[3] *INFN, Sezione di Milano Bicocca, Milano, Italy*
[4] *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[5] *INFN, Sezione di Padova, Padova, Italy*
[6] *INFN, Sezione di Pisa, Pisa, Italy*
[7] *Dipartimento di Fisica e Scienze della Terra "M. Melloni",*
Università di Parma, Parma, Italy
[8] *INFN, Laboratori Nazionali di Frascati, Frascati, Italy*

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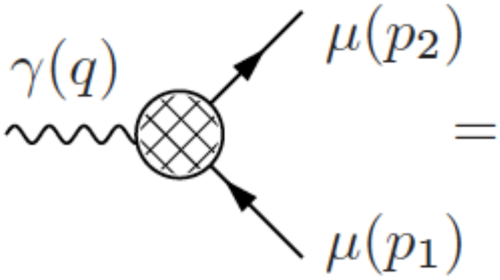
Muon g-2 anomaly

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

the muon anomaly

muon–γ vertex

Dirac form factor **Pauli form factor**



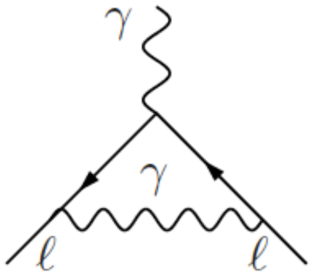
$$= (-\mathrm{i}e)\,\bar{u}(p_2)\left[\gamma^\mu F_\mathrm{E}(q^2) + \mathrm{i}\frac{\sigma^{\mu\nu}q_\nu}{2m_\mu}F_\mathrm{M}(q^2)\right]u(p_1)$$

Static (classical) limit

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

charge renormalization condition

the muon anomaly



QED/SM

Largest contribution

J. Schwinger (1948)

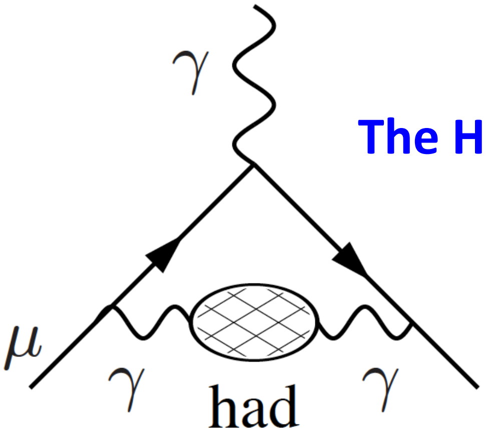
α/2π

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**:
  $a_\mu^{E821} - a_\mu^{SM} = (28 \pm 8)\times 10^{-10}$
- **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

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

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

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

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

a_μ^{HLO} calculation with time-like data

- Optical theorem and analyticity:

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

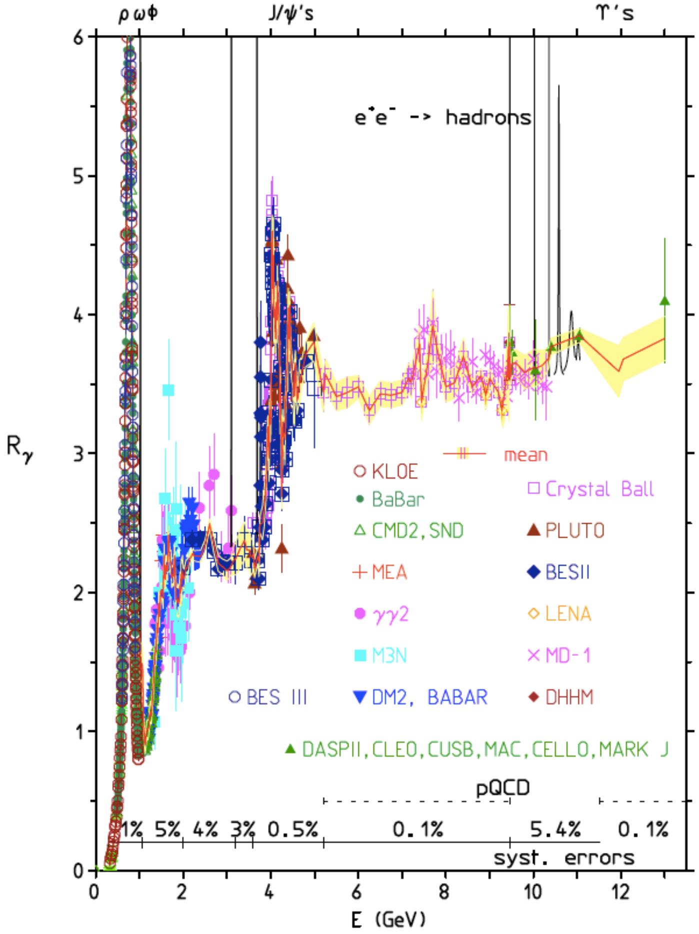
$$\boxed{a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\cdot\sigma(s)_{(e^+e^-\to had)}}$$

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

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

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

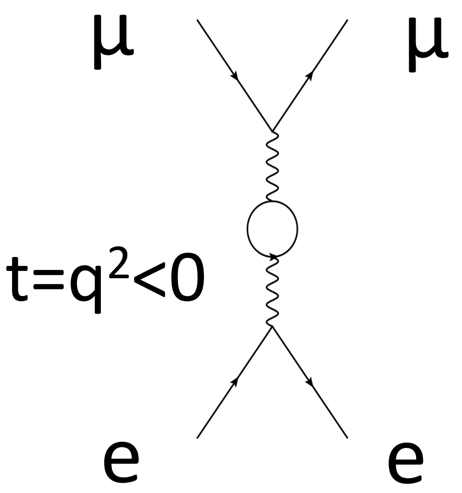
Collection of many experimental results



The elastic scattering μ + e → μ + e

$\alpha(t)$ through:

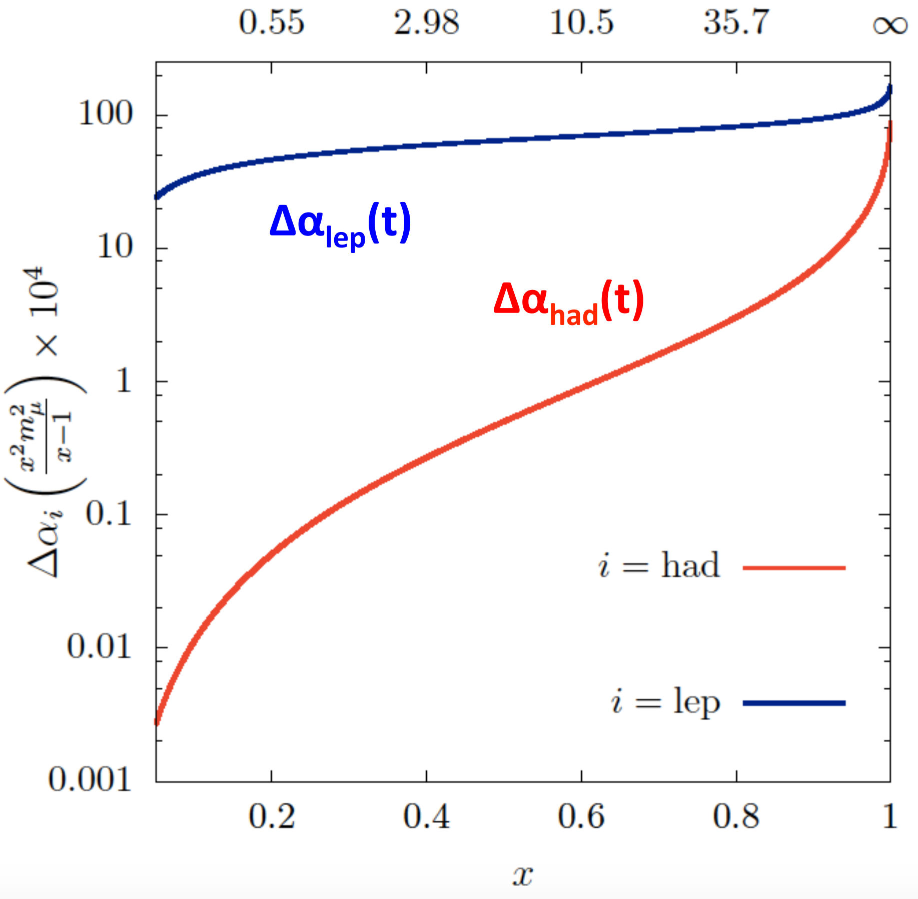
$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2$$



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

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

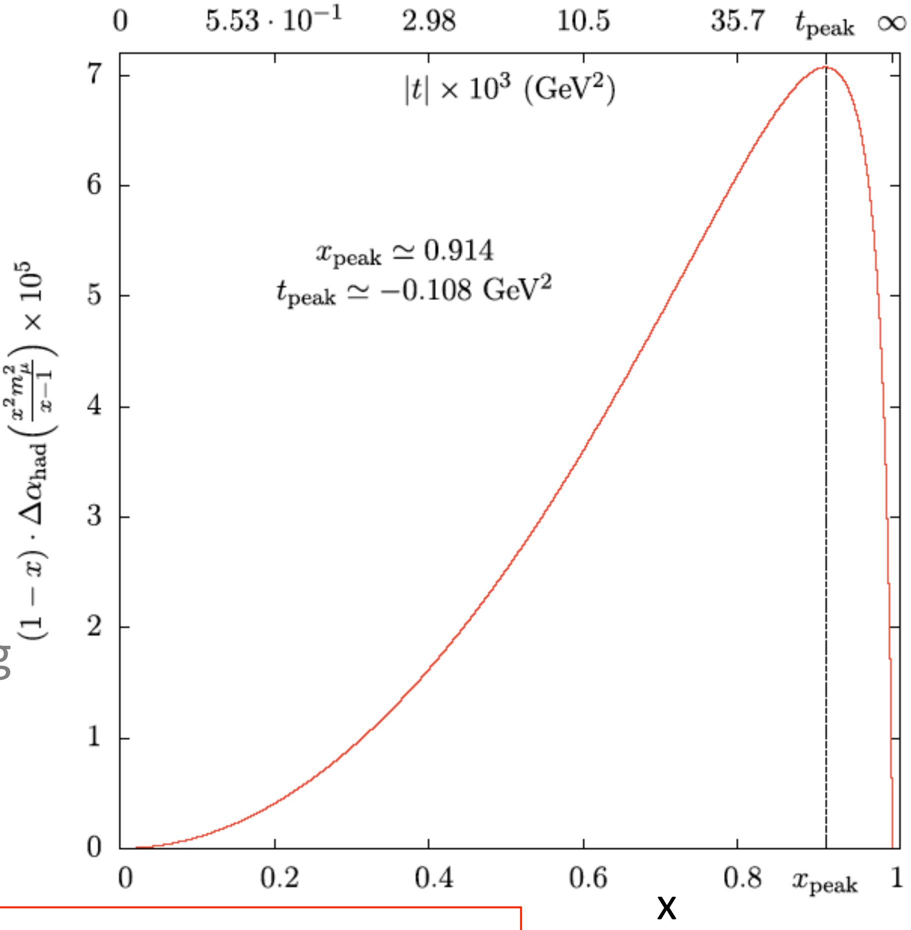
$$t = -m_\mu^2 \frac{x^2}{1-x}\ (10^{-3}GeV^2)$$



a_μ^{HLO} space-like approach

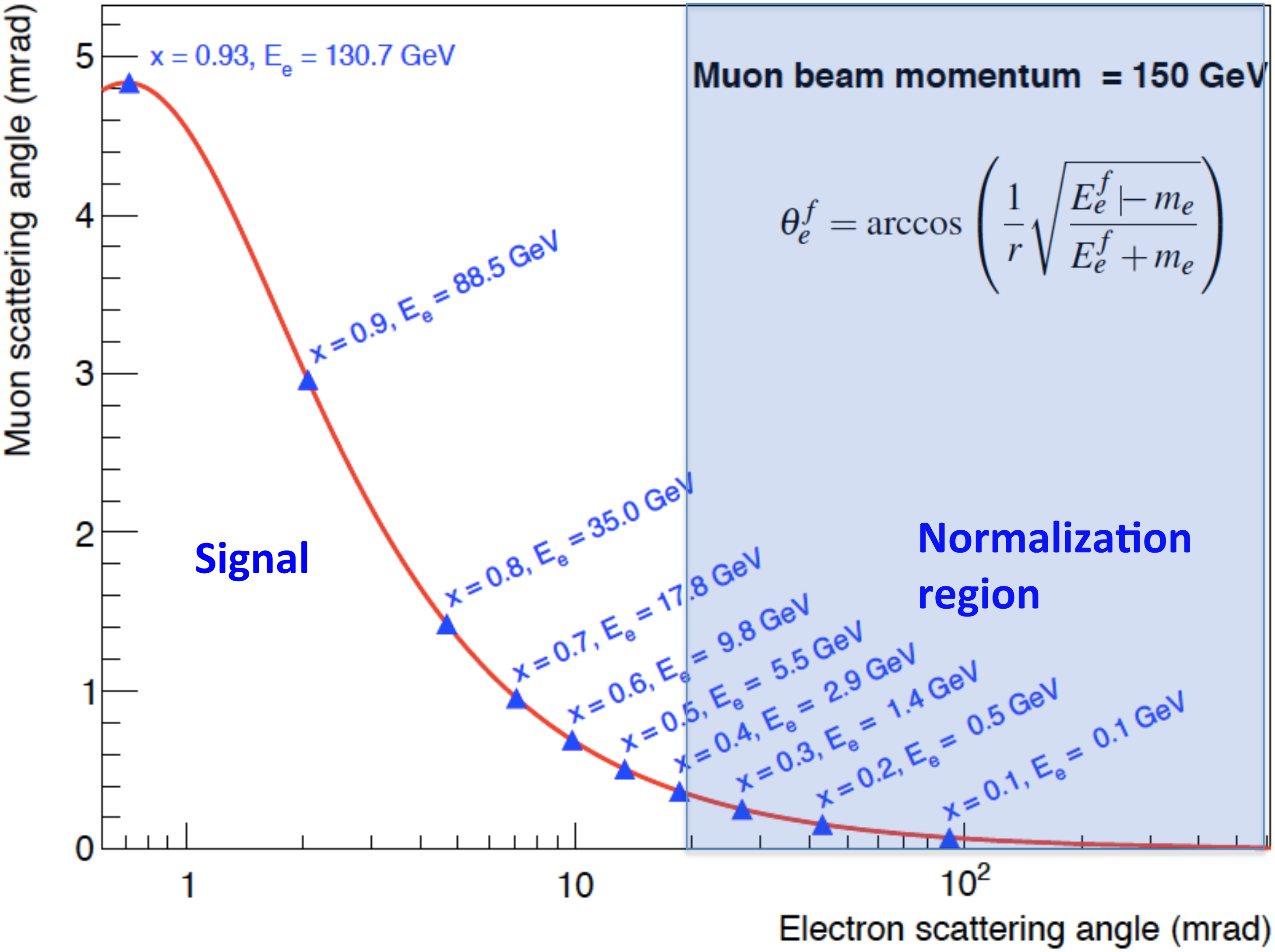
- **It requires just the single process $\mu + e \rightarrow \mu + e$ elastic**
  High intensity CERN muon beam of **E_μ ~ 150 GeV** colliding on atomic electrons at rest.
- **Highly boosted final state**:
  $0 < -t < 0.161$ GeV^2
  $0 < x < 0.93$ (peak is at $x = 0.914$)
  The range covers **87%** of 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



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

Elastic scattering in the (θ_e , θ_μ) plane

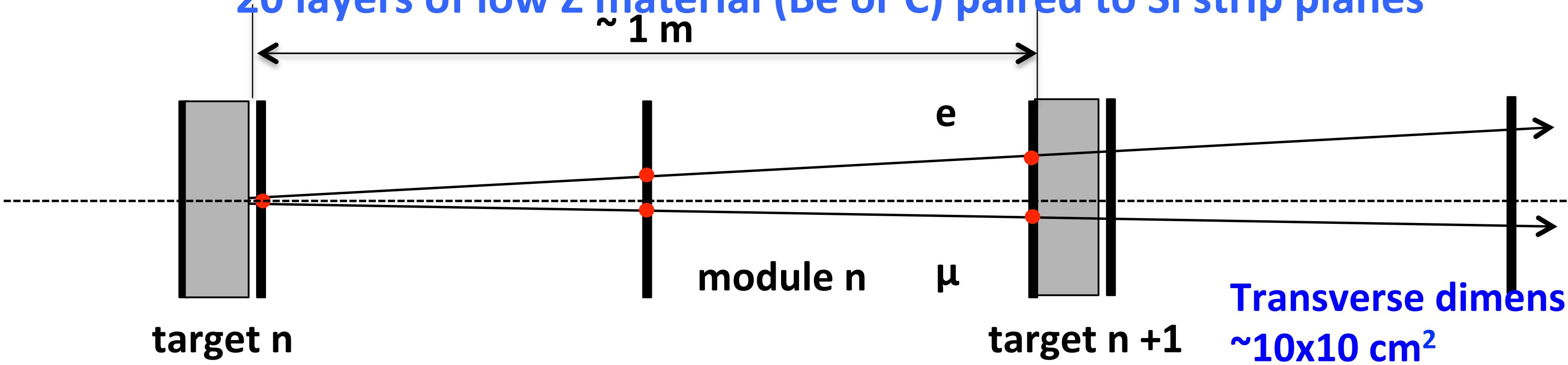


$$\theta_e^f = \arccos\left(\frac{1}{r}\sqrt{\frac{E_e^f - m_e}{E_e^f + m_e}}\right)$$

Detection technique

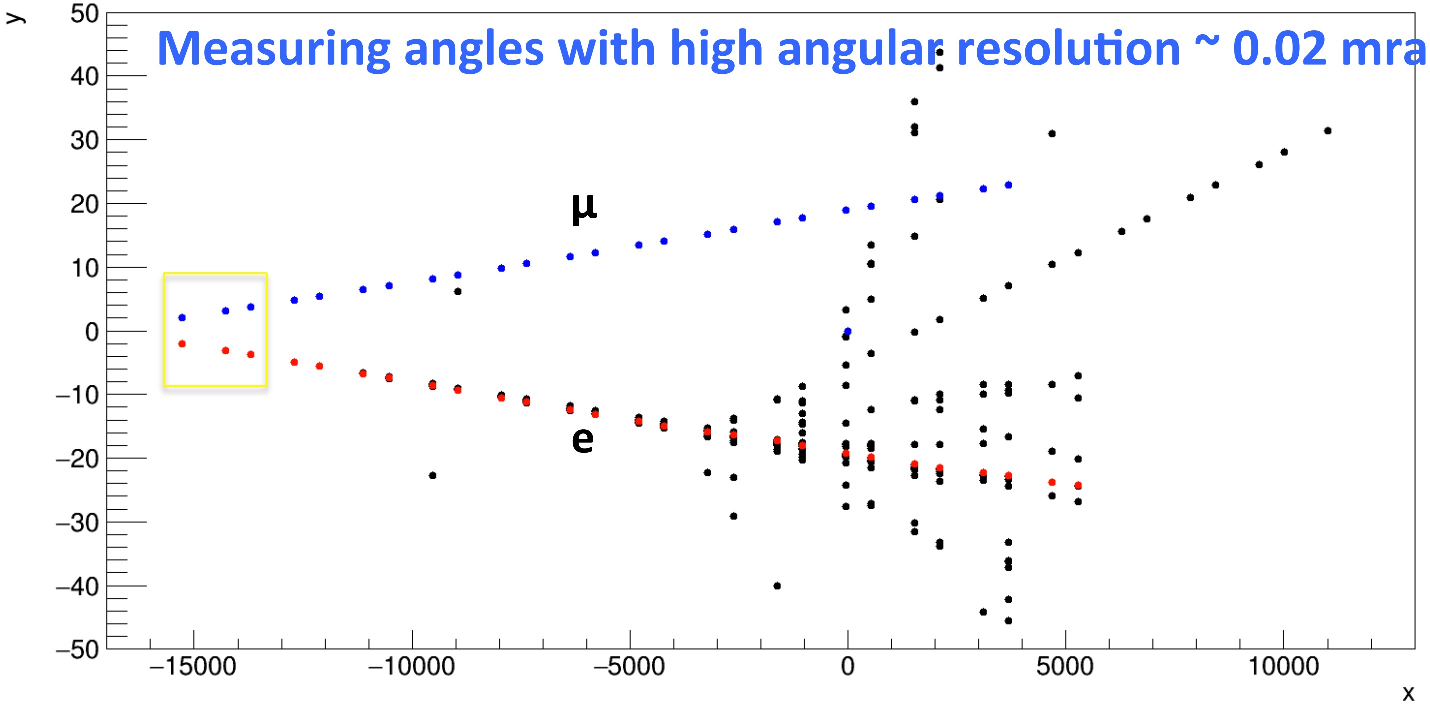
Modular apparatus covering the full angular acceptance with high uniformity.

20 layers of low Z material (Be or C) paired to Si strip planes



Transverse dimension ~10x10 cm^2

Measuring angles with high angular resolution ~ 0.02 mrad

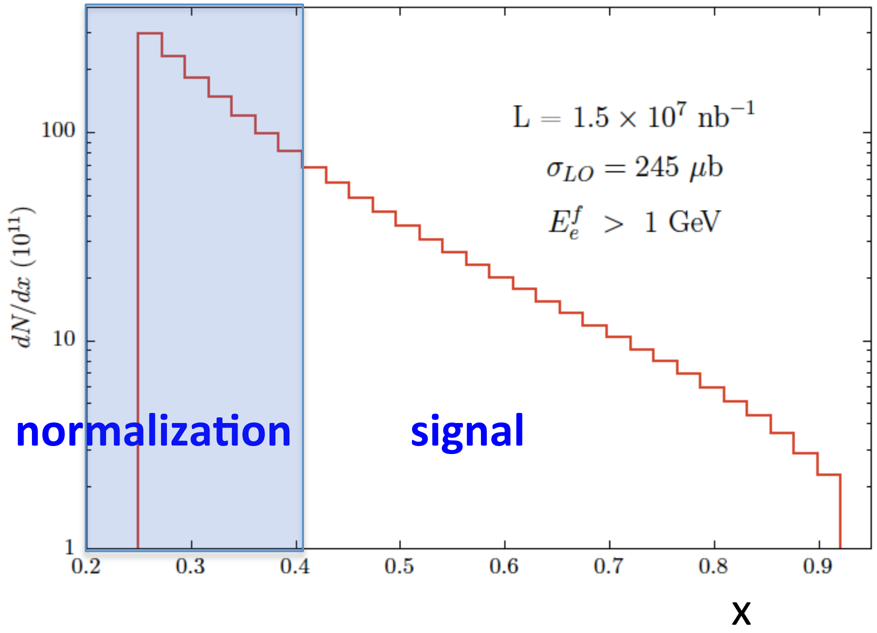


Luminosity and statistical error

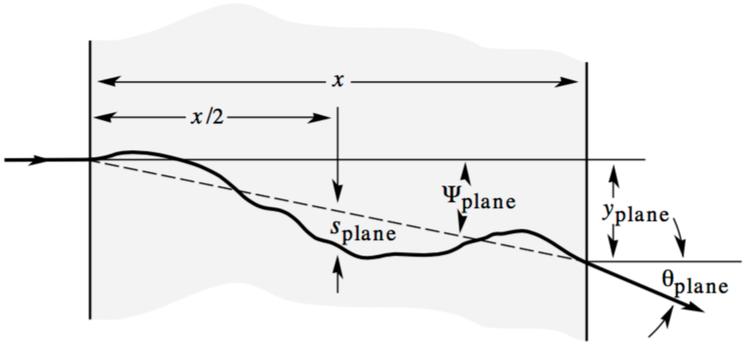
- With the CERN 150 GeV muon beam, which has an average intensity of ~ 1.3×10^{7} μ/s, incident on 20 Be layers, each 3 cm thick, and 2 years of data taking with a running time of 2 ×107 s/yr, one can reach an integrated luminosity of

$\mathcal{L}_{\text{int}} \sim 1.5 \times 10^{7}\ \text{nb}^{-1}$

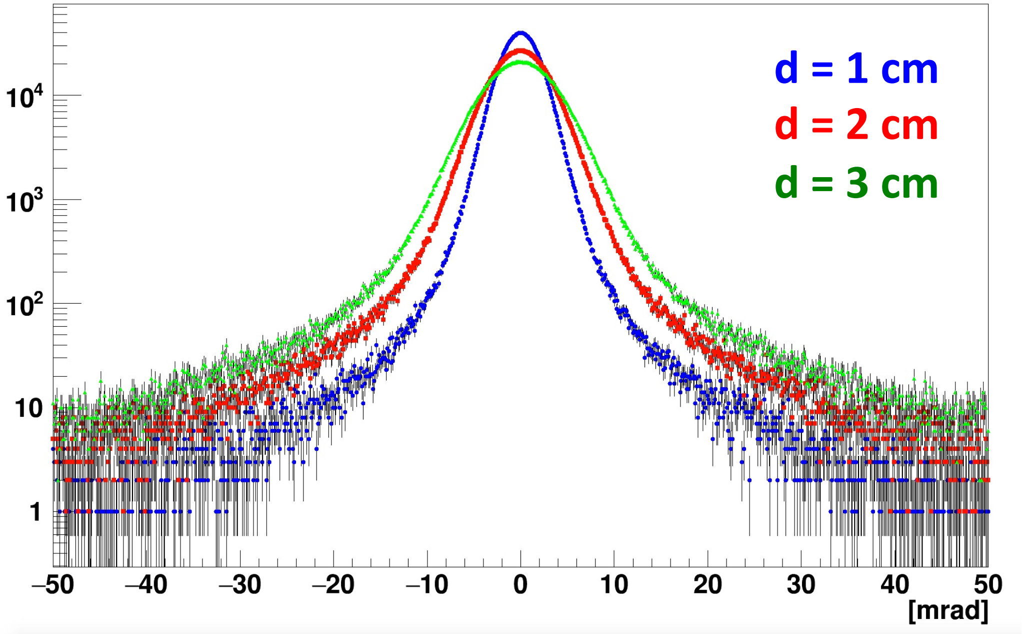
- $\mathcal{L}_{\text{int}}$ implies a statistical sensitivity of ~ 0.3% on a_μ^{HLO} ($\delta a_\mu^{\text{HLO}} \sim 2 \times 10^{-10}$)
- $\sigma_{\text{LO}}(E_e > 1\ \text{GeV}) = 245\ \mu\text{b}$



The role of Multiple Scattering (MSC)

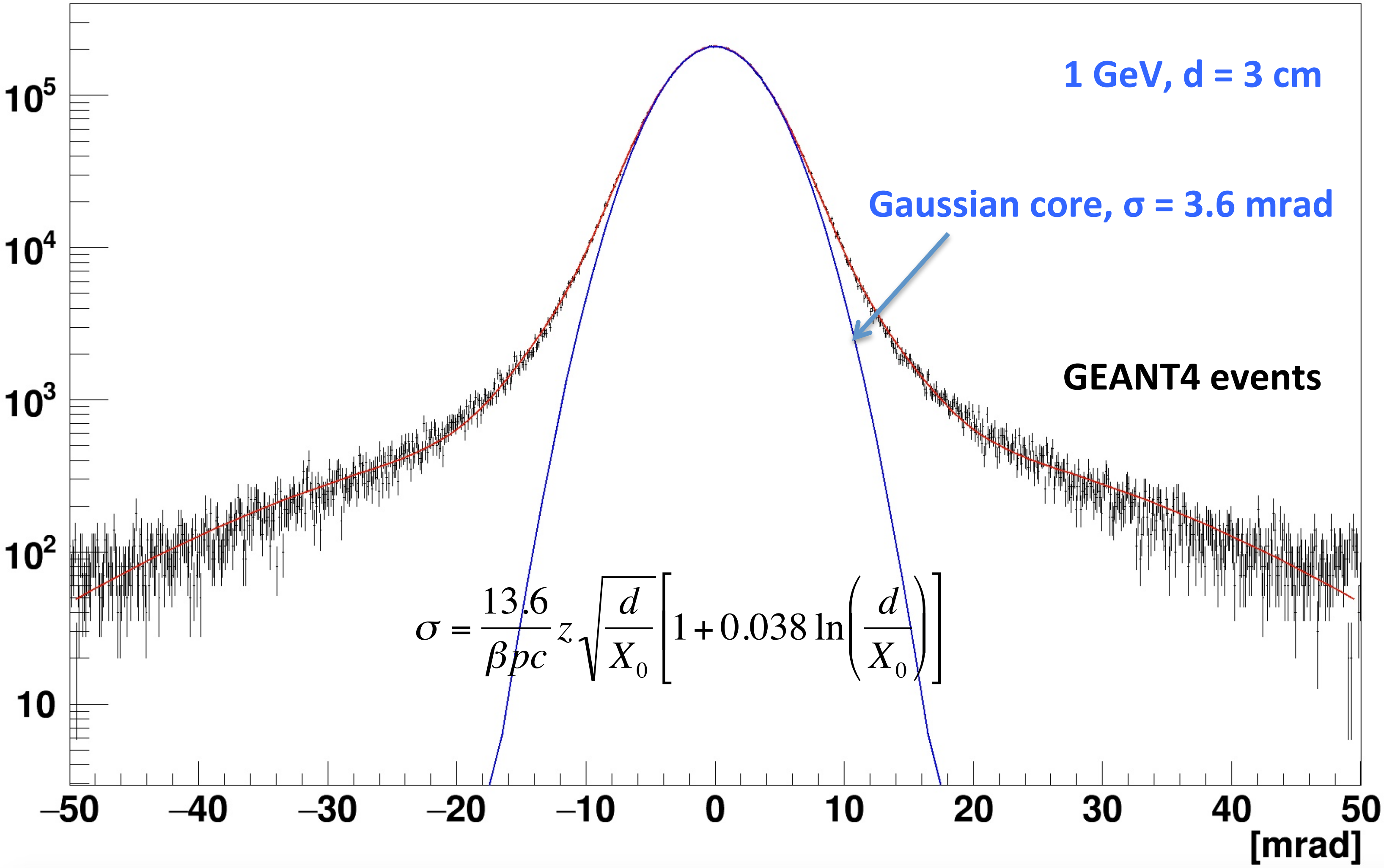


GEANT4, 1 GeV electrons, Be target



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.

Modeling the MSC



1 GeV, d = 3 cm

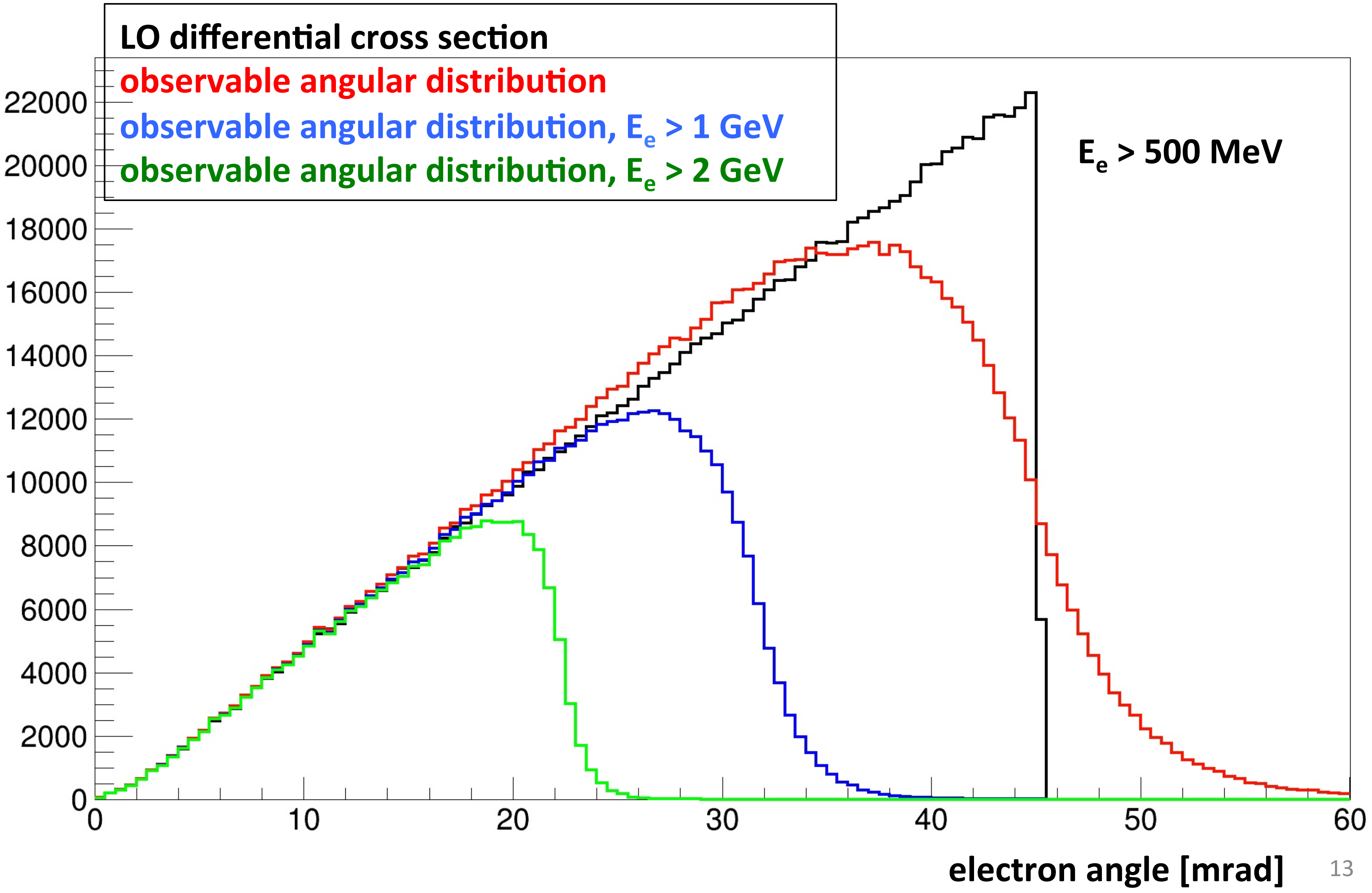
Gaussian core, σ = 3.6 mrad

GEANT4 events

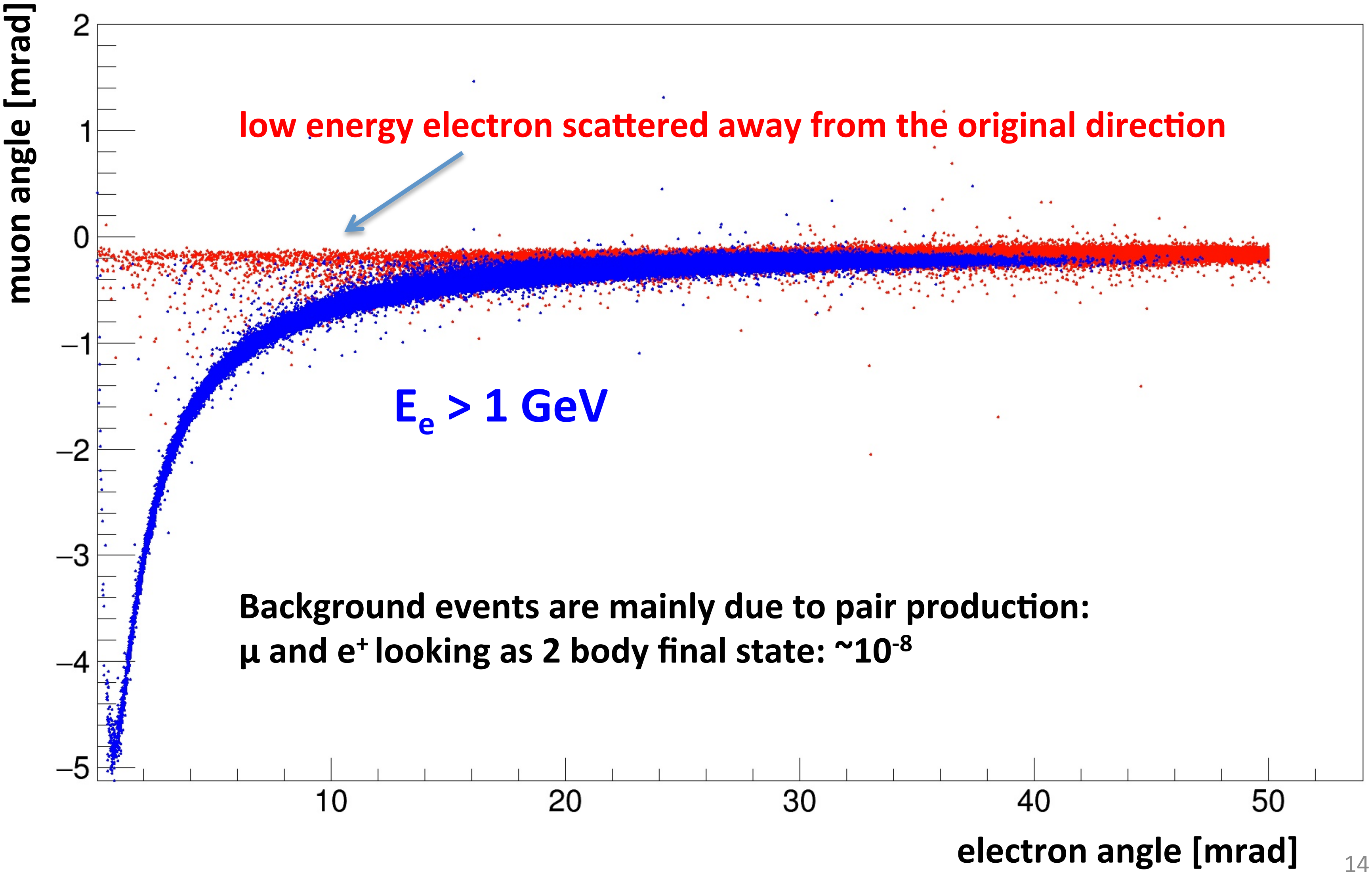
$$\sigma = \frac{13.6}{\beta pc} z \sqrt{\frac{d}{X_0}} \left[1 + 0.038 \ln\left(\frac{d}{X_0} \right) \right]$$

Highland formula (PDG) = 3.593 mrad

Resolution models



Events in the (θ_e , θ_μ) plane



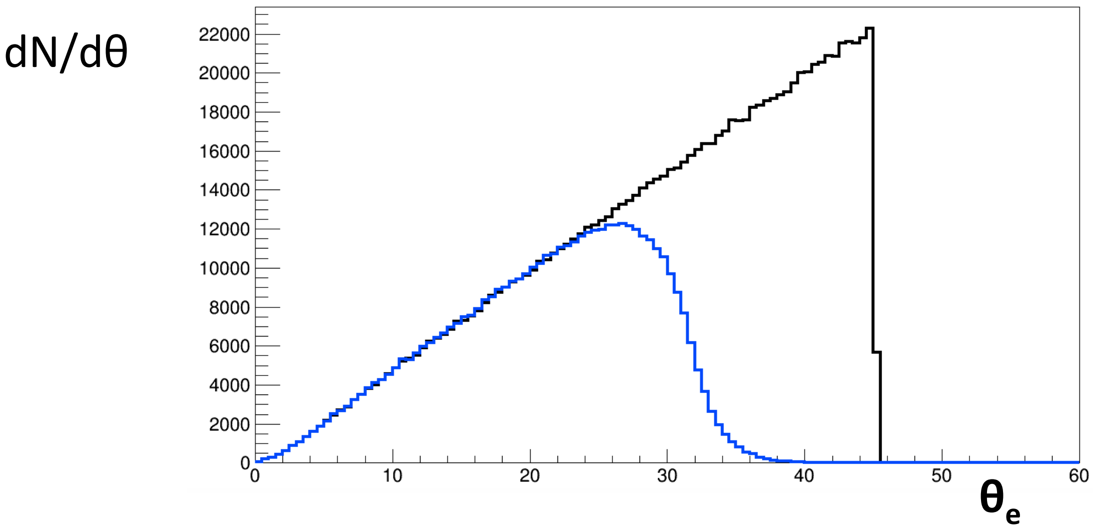
low energy electron scattered away from the original direction

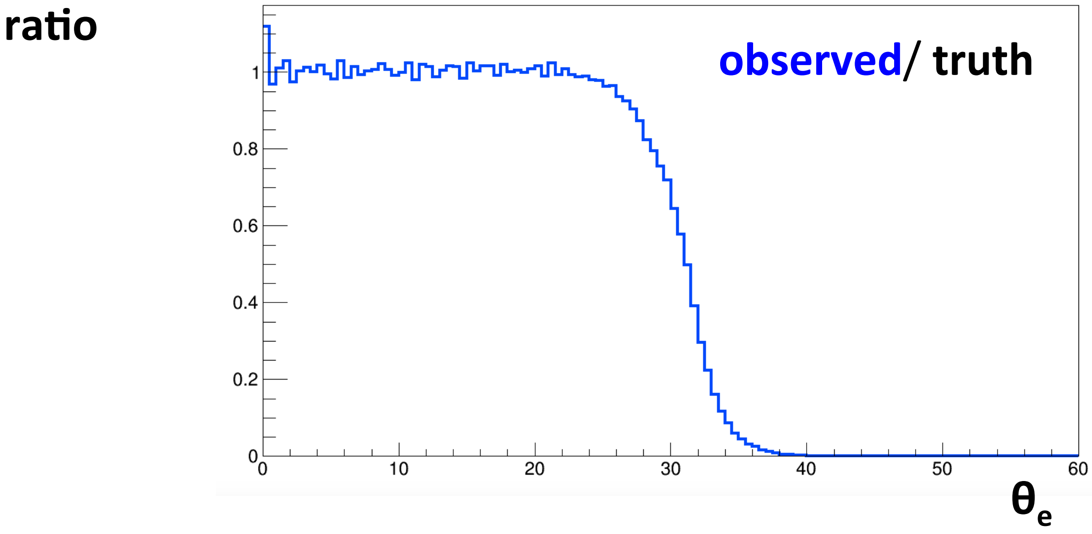
$E_e > 1$ GeV

Background events are mainly due to pair production:
μ and e^+ looking as 2 body final state: ~10^{-8}

Convolution coefficients

10^8 Geant-4 events





Values of the coefficients
ratio= observed / truth
turn out to be 1. within few
parts per mille

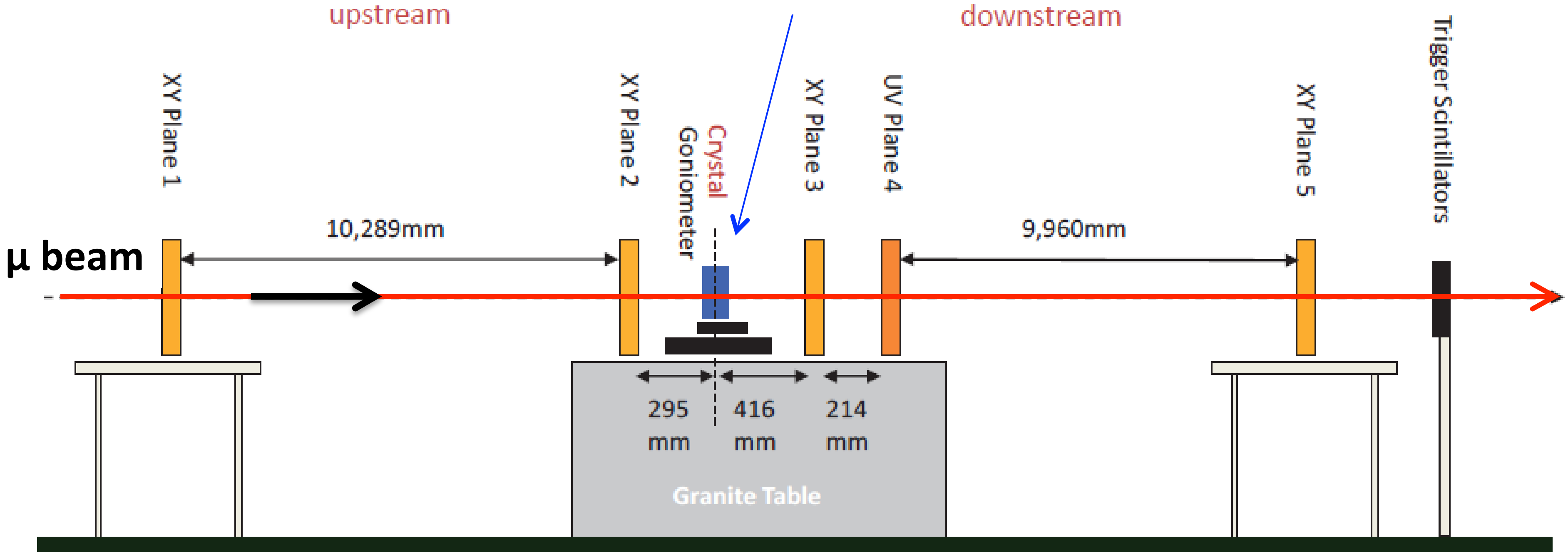
Detector optimization

- Modeling MSC effects.
  - Geant4 is the the tool: likely to be tuned on data.
- Target material and geometry.
  - Best low Z material and geometry.
  - Active target to determine vertex positions.
- Define the calorimeter layout: to measure electron energy (energy cut) and for particle ID
- Test beam at CERN M2 beam line by September 2017
  - Identify elastic scattering events: ~10^4 events expected.
  - Measure MSC effects, variable beam energy and targets' thickness

Test Beam

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

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



Be or C target here

Theory

1. Resummation of dominant corrections up to all orders, matched with NLO corrections.
   - Non-trivial issue: mass effects in this case are important.
2. NNLO corrections: some classes of NNLO re-usable from existing Bhabha calculations, some new due to different mass scales ($\mathbf{m}_m$ and $\mathbf{m}_e$). In any case, NNLO must be matched with 1. and 2. Reference: Eur. Phys. J. C 66 (2010) 585 and references therein.
3. Development of dedicated MC tools including all the above ingredients.
4. Detailed study of all the mentioned corrections, comparison among independent calculations, estimate of further-missing higher-order corrections.
5. Planned theory workshop this year in:
   Padova.
   Zurich.
   Mainz.

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.