The MUonE experiment

E Conti

Presentazione in CdS 25/6/2019

Muon g-2

- measurement of the anomalous magnetic moment is one of the most stringent test of QED and a way to unvail discrepancies in the Standard Model and possible new physics
- for the muon $a_\mu = (g-2)/2$
- E821 experiment at BNL

  $a_\mu^{exp} = (\ 11659209.1 \pm 6.3)\ 10^{-10}$ (0.54 ppm)
- vs theoretical SM prediction:

  $a_\mu^{SM} = (\ 11659182.0 \pm 3.6)\ 10^{-10}$

$$a_\mu^{exp} - a_\mu^{SM} \approx (27 \pm 7)\ 10^{-10}$$

- **it is a 3.7σ difference**

Experiment

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

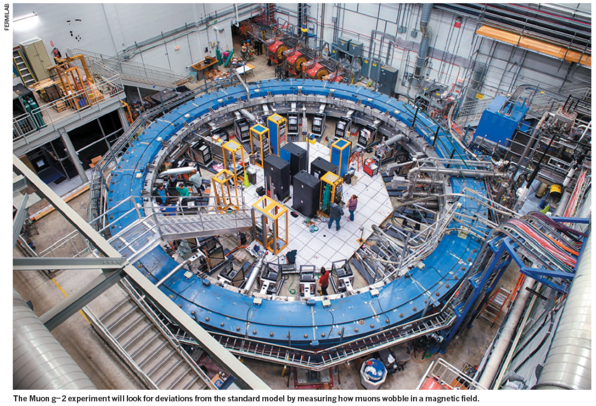
- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x stat**. w.r.t. E821. First result with BNL accuracy (0.54 ppm) expected in 2018-19.

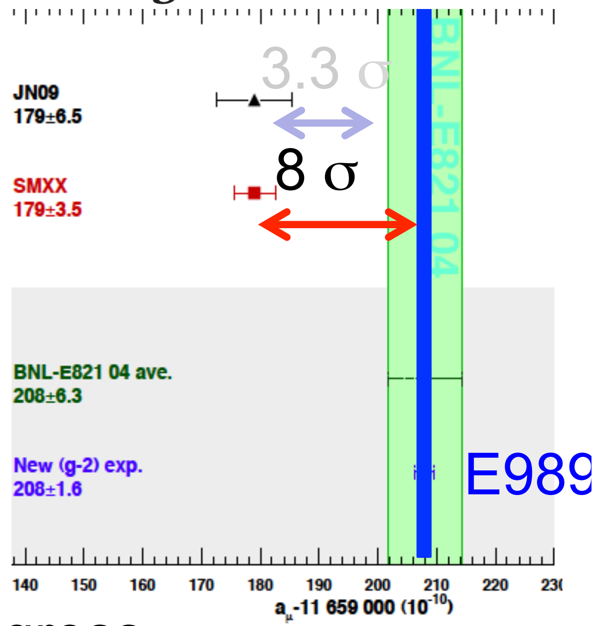
→ Ultimate precision: δa_μx4 improvement (0.14ppm)

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].





Complementary proposal at J-PARC in progress

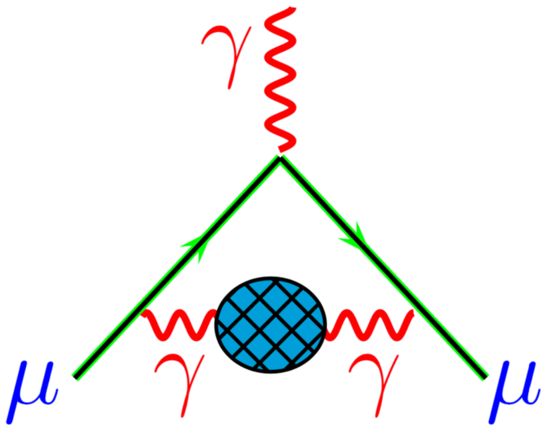
Theory

- Theoretical uncertainties limited by hadronic effects

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

$$a_\mu^{QED} = 116584718.95(0.08)\times10^{-11}$$
$$a_\mu^{Weak} = 153.6(1.0)\times10^{-11}$$

$$a_\mu^{HAD} = 693.1(3.3)\times10^{-10}$$



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:

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

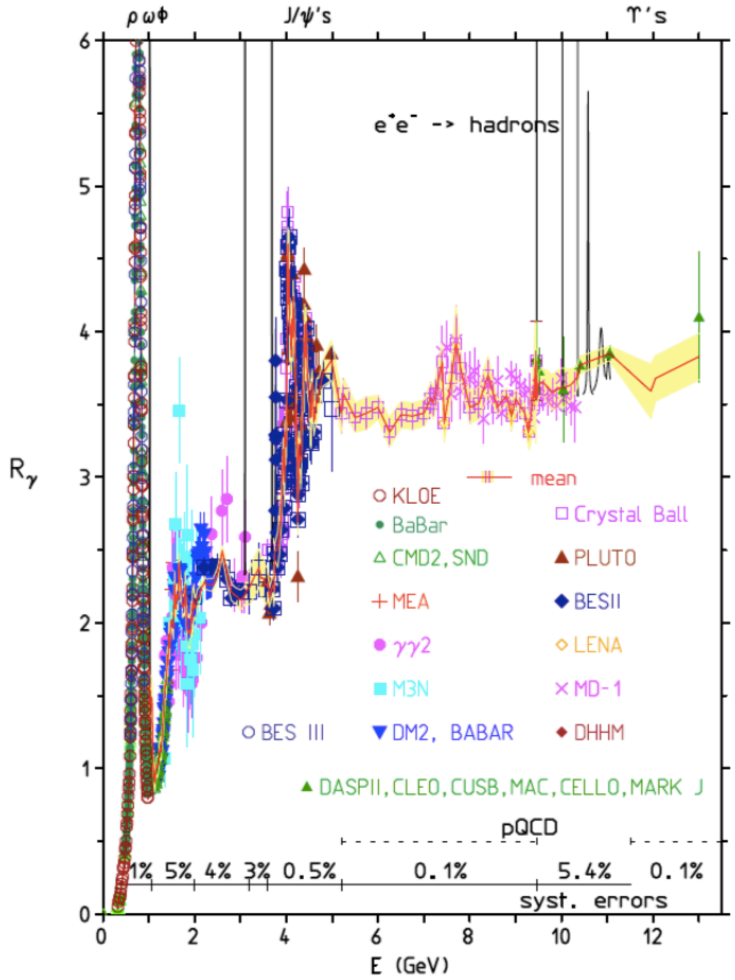
$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\cdot\sigma(s)_{(e^+e^-\to had)}$$

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

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

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

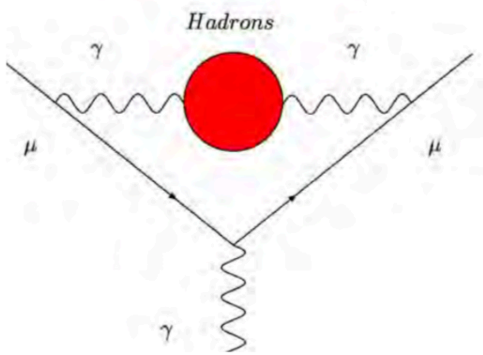


The high-energy tail of the integral is calculated using pQCD

- for timelike approach difficult to reach a 0.2% precision on a_μ^{HLO} :
    - > 30 channels to keep under control
    - local discrepancies in many channels
    - etc.
- Alternative approach is Lattice QCD, which is in progress but at the moment far from the requested precision

A new idea: from timelike to spacelike

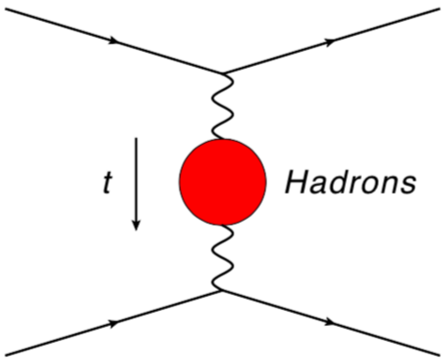
- **At present, the leading hadronic contribution a_μ^{HLO} is computed via the timelike formula:**



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

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

- **Alternatively, exchanging the x and s integrations in a_μ^{HLO}**



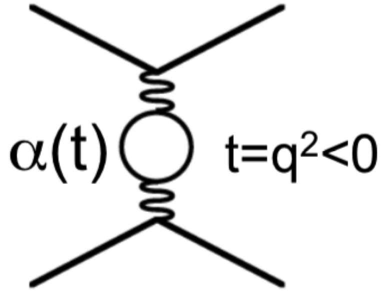
$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\rm had}[t(x)]$$

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

$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of α in the spacelike region. It can be extracted from scattering data!

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

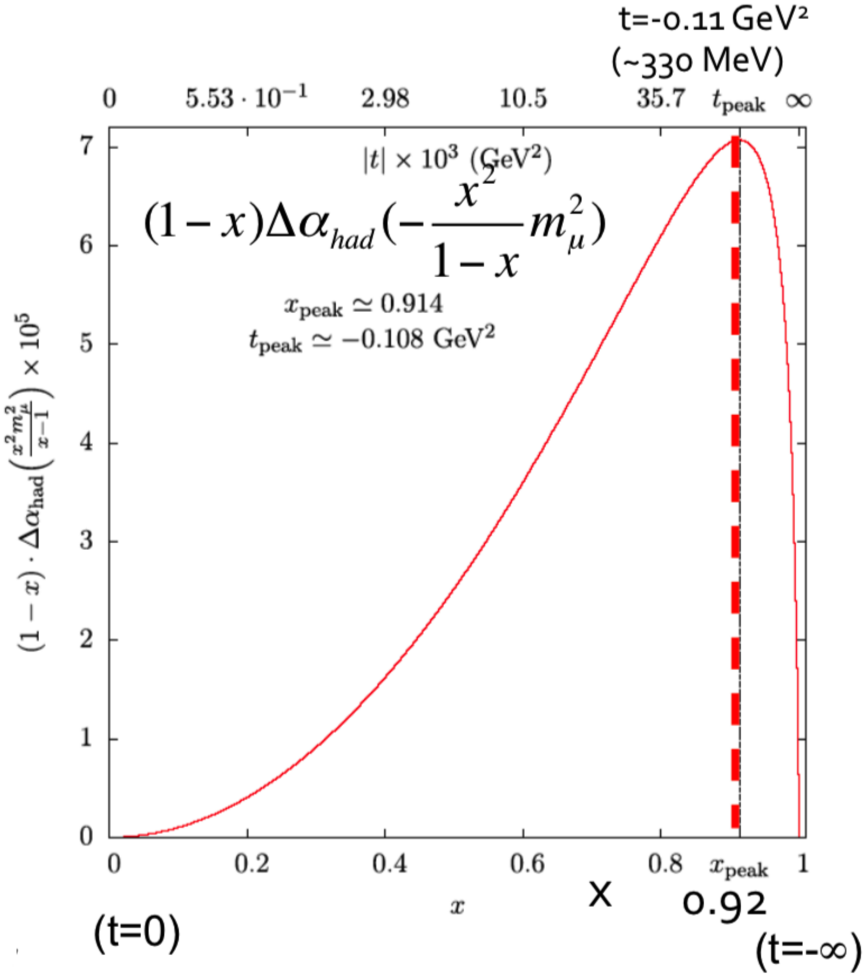
$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$



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

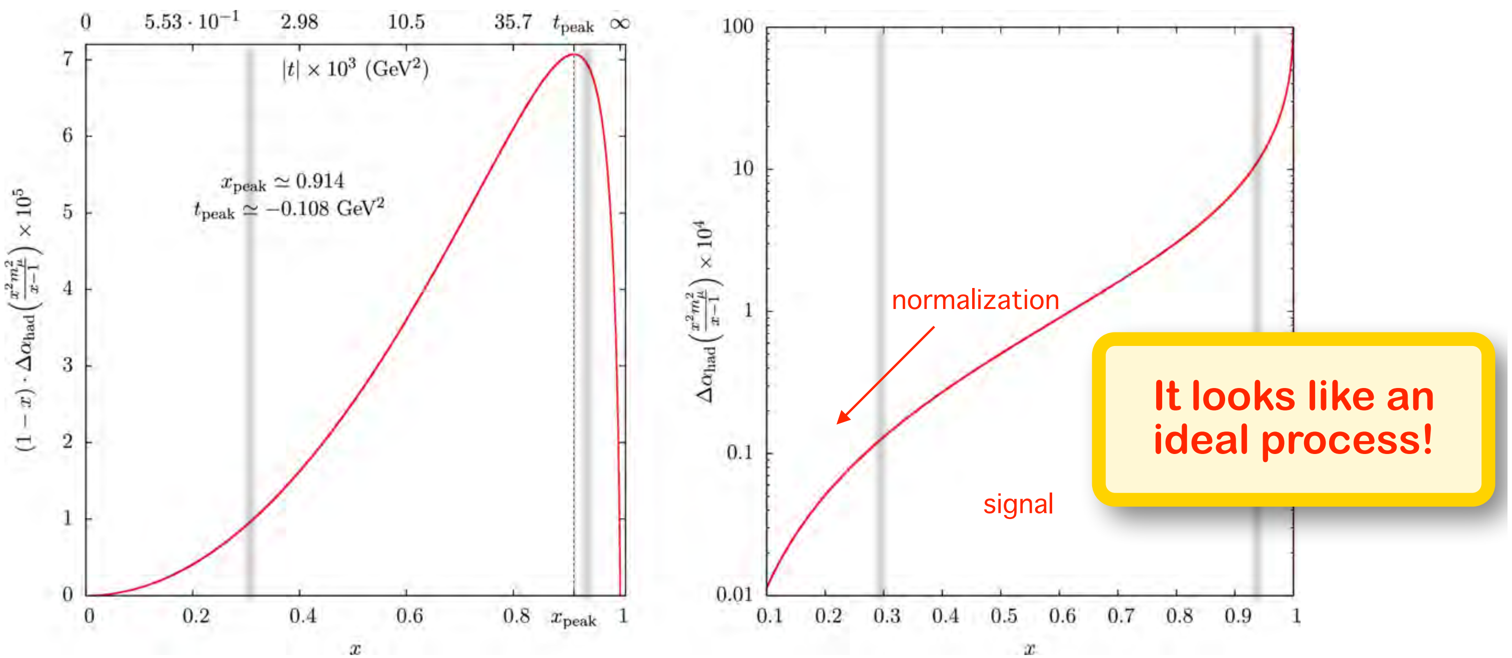
$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \quad 0 \le x < 1;$$

- **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



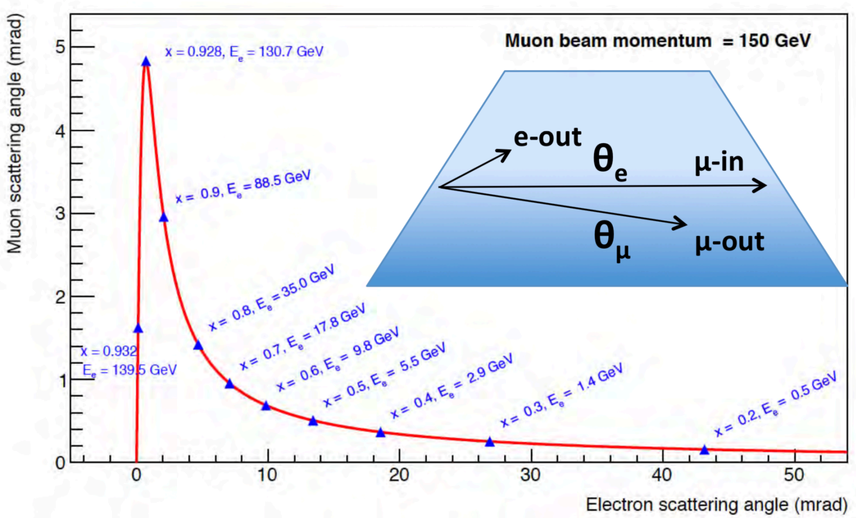
$\mu\, e \rightarrow \mu\, e$ elastic scattering

- Muon beam at 150 GeV/c
  - For a 150 GeV muon beam, the scan region extends up to x=0.932, ie beyond the peak! (the peak is at x=0.914)
  - The integrand in the remaining region x ∈ [0.932,1] accounts for ~13% of the a_μ^{HLO} integral. It cannot be reached by our experiment but it can be determined using time-like data and/or lattice QCD results.



150 GeV/c muon beam

- electron at rest, simple kinematics, only angular measurements (θ_e & θ_μ w.r.t. incident μ direction)
- kinematic boosted forward in Lab system:
  - $\theta_e \leq 30$ mrad for threshold = 1 GeV
  - $\theta_\mu < 5$ mrad
  - electron endpoint @139 GeV
- allows using the same detector for signal and for normalization ($x < 0.3$, $\Delta\alpha_{had}(t) < 10^{-5}$)
  ⇒ cancellation of detector effects at first order
- high beam intensity at CERN SPS (M2)



Errors

- goal: measure a_μ^{HLO} at < 1% level
- statistical error at 0.3% level in 2 years of data taking at :
  1.3×10^7 μ/s (SPS M2 beam)
  with a 60 cm thick Be target
  ⇒ luminosity $1.5 \; 10^7 \; nb^{-1}$
- all systematic errors must be kept within 10^{-5}
- main enemy: multiple coulombian scattering
  ⇒ target is divided in many slices, each instrumented with its tracking system

Experimental setup

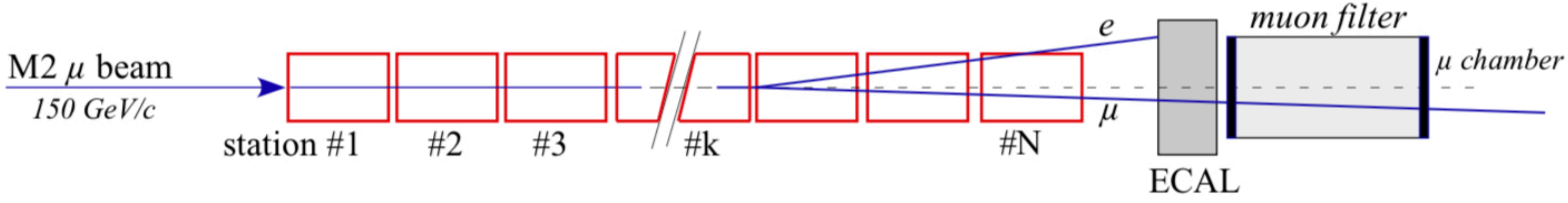


Fig. 3: Schematic view of the MUonE experimental apparatus (not to scale).

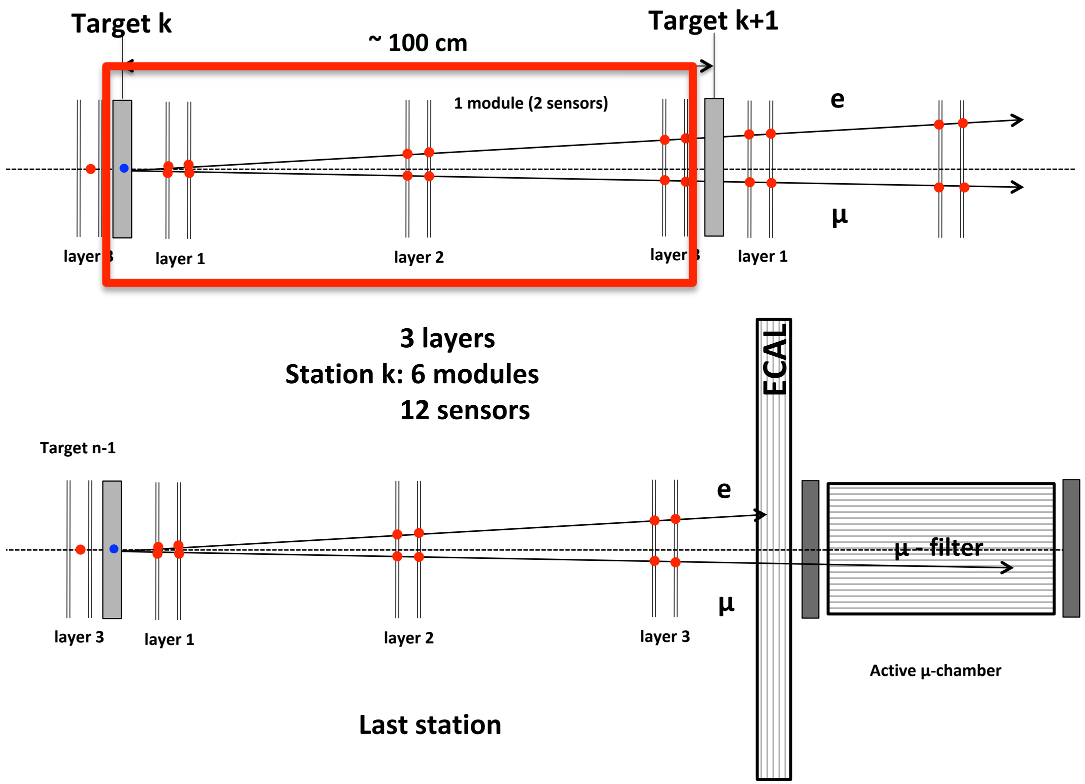
Each module composed by:
- 1.5 cm thick Be target
- 3 x-y Si tracking system (10x10 cm^2 area)
- level arm = 1m

40 modules, total apparatus length ~ 45 m, in CERN North Area (COMPASS)

Downstream: ECAL (1x1 m^2 area) for
- measurement of electron energy
- PID

If pion contamination not low enough:
- muon filter with muon chambers

Modules



State-of-art Silicon strip detector:
10x10 cm^2 area
hit resolution 10-20μm, expected angular resolution ~ 20μrad

Tracker could be made with the sensors for the CMS upgrade:
strips in 1 direction, double layer ⇒ 3x(2x2) planes = 12 Si planes

ECAL

- tasks:
  - particle identification, especially when $\theta_e \approx \theta_\mu$
  - measure electron energy (+gammas) for redundancy, countercheck tracker for systematics, background
  - event selection (for example, 2 showers: $e + \gamma$)
- proposal of a 1x1 m^2 $PbWO_4$ similar to CMS
  - not cover full acceptance for all kinematics and all targets but enough for $\theta_e \leq 5$ mrad where it is relevant for PID
  - 2.5x2.5x23 cm^3 ($26X_0$)
  - final dimension/geometry to be optimized

performance from MC simulation

- *Angular resolution*
  for E ≥ 40 GeV: $\sigma(\theta_e) \approx$ 0.1-0.3 mrad
  except last target $\sigma(\theta_e) \approx$ 0.4 mrad

  We evaluate the centroid of the shower and use the target-ECAL distance

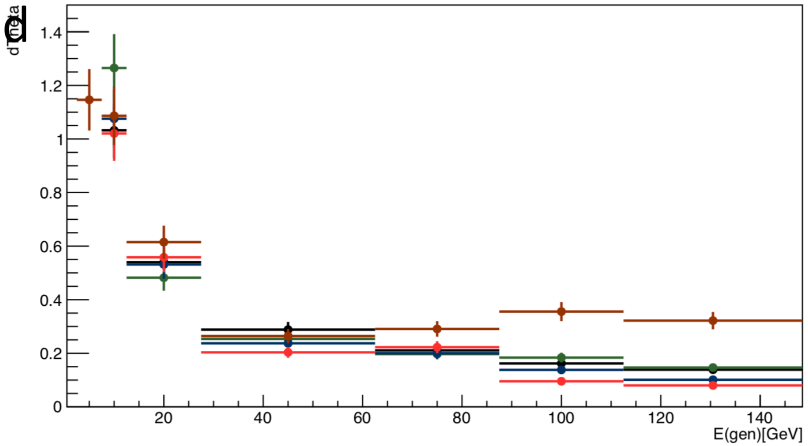


Fig. 8: Angular resolution (mrad) of the reconstructed electron direction, as a function of the electron energy, produced in the 1st (black), 5th (green), 10th (blue), 15th (red), and 20th (last) (maroon) target. In the final apparatus, these stations correspond to 21st, 25th, 30th, 35th and 40th.

- *Energy resolution* is affected by the material before entering the detector
  for E > 20 GeV, $\sigma(E)/E \leq 5\%$

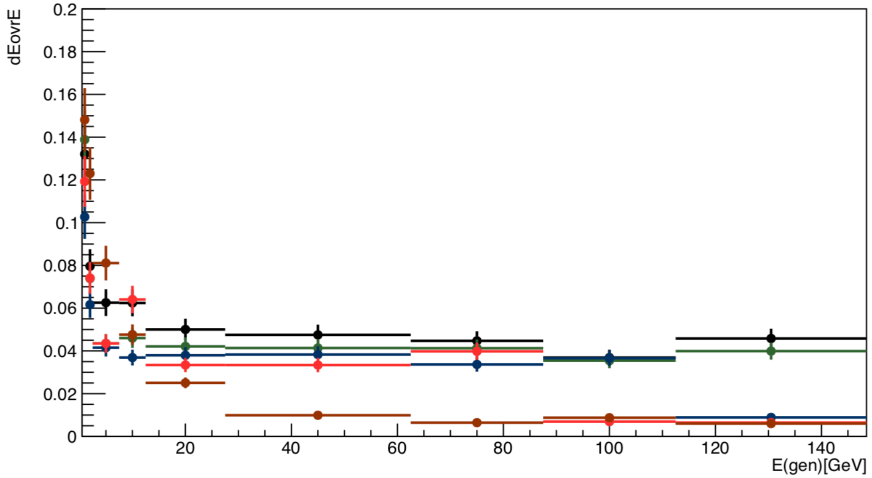
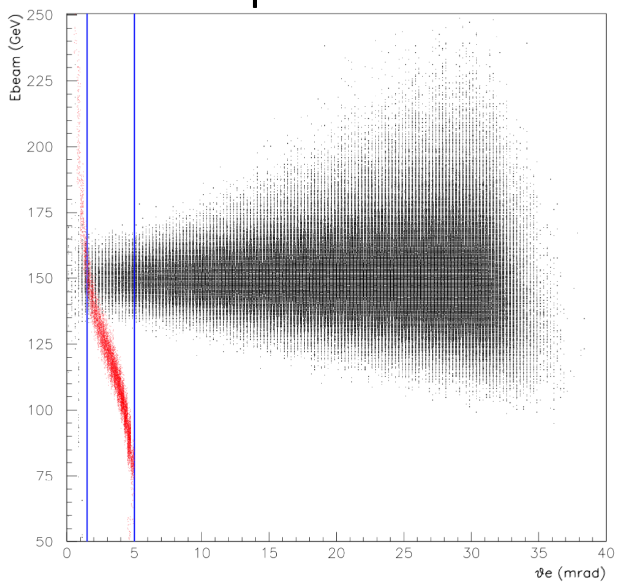
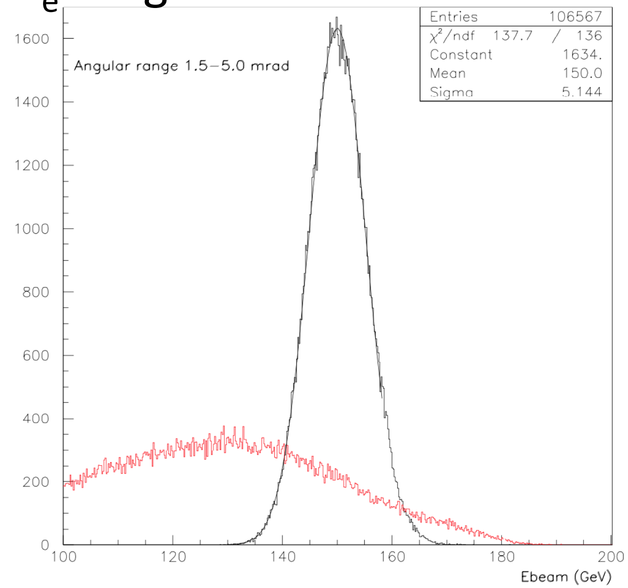


Fig. 10: Rms width of the δ_E distributions as a function of the electron energy, for electrons produced in the 1st (black), 5th (green), 10th (blue), 15th (red), and 20th (maroon) target. In the final apparatus, these stations correspond to 21st, 25th ,30th, 35th, and 40th.

Particle IDentification

– use of the inverse kinematics method
– knowledge of scattering angles is enough to close the kinematics on electron at rest
– generate events at LO and simulate multiple scattering (E=150 GeV, σ(E)/E = 3.75%)
– get back the muon momentum
– same with particle identity swapped (red points/histo)
– PID works except in the 1-5 mrad θ_e range. ECAL needed.





Extraction of a_μ from exp. data

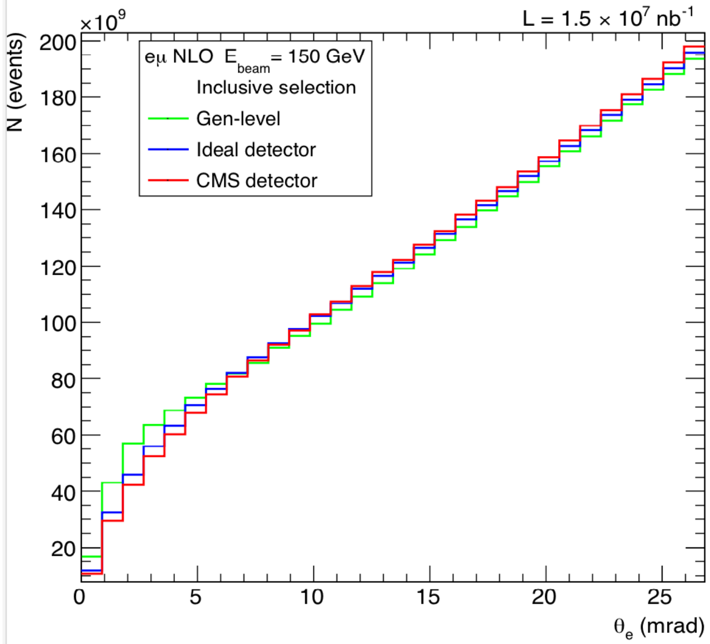
- Master formula: $$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}[t(x)]\,dx$$

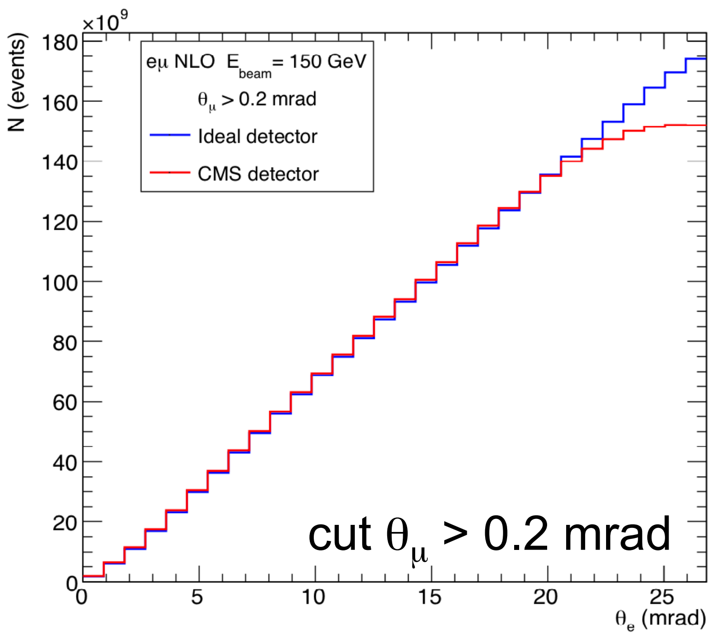
  $\Delta\alpha_{had}$ is the hadronic contribution to the running of α

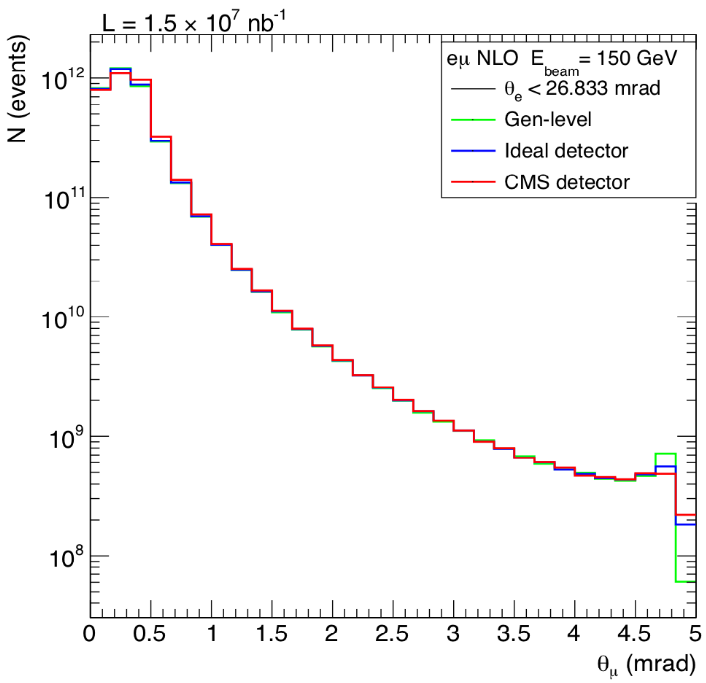
  $$t = \frac{x^2 M^2}{x-1} < 0$$

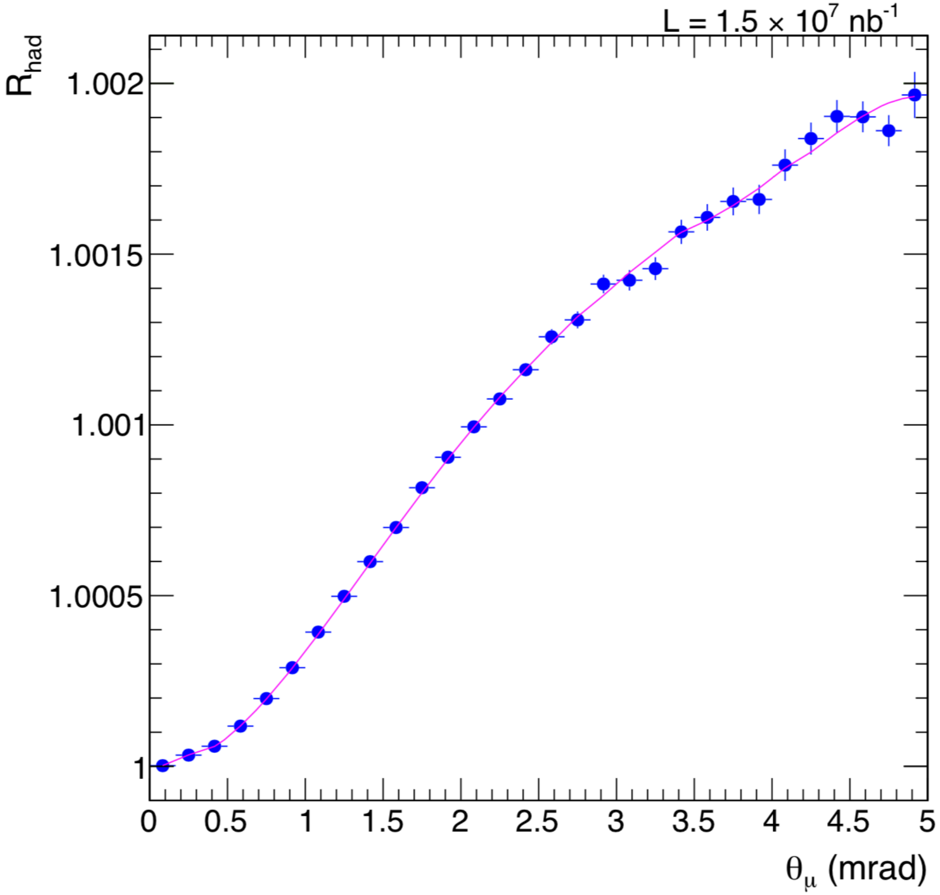
  $$R_{had}^{LO} = \frac{\left(d\sigma/d\theta\right)_{\exp}}{\left(d\sigma/d\theta\right)_{LEPT}^{theor}} = \left(1 - \frac{\Delta\alpha_{had}(t)}{1-\Delta\alpha_{LEPT}(t)}\right)^2 \approx 1 + 2\frac{\Delta\alpha_{had}(t)}{1-\Delta\alpha_{LEPT}(t)}$$

- At NLO this ratio is a complicated expression, evaluated with MC simulation:
  - at NLO level
  - ideal detector but real beam, gaussian energy spread $\sigma(E)/E = 3.75\%$
  - real detector


L = 1.5 × 10^7 nb^-1
eμ NLO E_beam = 150 GeV
Inclusive selection
Gen-level
Ideal detector
CMS detector
N (events)
θe (mrad)


eμ NLO E_beam = 150 GeV
θμ > 0.2 mrad
Ideal detector
CMS detector
cut θμ > 0.2 mrad
N (events)
θe (mrad)


L = 1.5 × 10^7 nb^-1
eμ NLO E_beam = 150 GeV
θe < 26.833 mrad
Gen-level
Ideal detector
CMS detector
N (events)
θμ (mrad)



statistics of 2 years
data taking

Effect of hadronic running ≤ 0.2%

Fit with chi2 minimization: good quality, we found the same parameters used for NLO generator

Systematic errors

- Possible systematic errors:
  - fit model and extrapolation
  - average beam energy scale
  - beam energy spread
  - tracker efficiency and reconstruction uniformity
  - tracker alignment and longitudinal positioning
  - e-μ identification
  - multiple scattering
  - normalization
  - ....

Present status and plans

- We have recently submitted a Letter of Intent to the CERN SPSC https://cds.cern.ch/record/2677471
  We are in competition for the beam with COMPASS
- We asked for beam time in 2021 for a Pilot Run (2 modules + small ECAL)
- expected time delivery of Si tracker:
  - 50% by spring 2022
  - 50% by end 2022
- Start data taking with half apparatus in 2022, with complete apparatus in 2023-24.

LoI

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The collaboration

Table 1: Current manpower for the experiment

Group	Researchers	Activity
Bologna	6	Calorimeter, simulation, systematics
Firenze	1	Tracker
Imperial College	5	Electronics, DAQ
Krakow	5	DAQ, tracking algorithms, analysis
Milano-Bicocca	3	Mechanics, simulation, analysis
Budker Institute	3	Simulation, systematics, analysis
Padova	7	Calorimeter, simulation, analysis
Pisa	9	Tracker, mechanics, analysis
Trieste	2	Mechanics
Shangai Jiao Teng U.	2	Simulation, analysis
University of Liverpool	2	Mechanics, alignment, simulation
University of Virginia	3	Calorimeter, simulation, systematics
CERN	see text	Survey, alignment, thermalization, beam

manpower: experiment

Table 2: Current manpower for the theory

Group	Researchers	Activity
Padova	11	NNLO QED, hadronic calculations
Parma	1	NNLO calculations, resummation
Pavia	5	Higher order calculations, theory MC development
PSI	2	NNLO calculations, resummation
Dublin	1	Lattice QCD

manpower: theory

Costs

- Crude estimate

Table 3: Preliminary cost estimates

Item	Cost estimate (kEuro)
Si sensors and electronics	750 (+ 15 pilot run)
DAQ	140
Mechanics (without survey system)	120
Calorimeter ($PbWO_4$)	See text
Muon-filter and active chambers	Recycling existent material
Computing	150 – 500
Targets	40
Service and infrastructure	350 – 450

Total: 1.5-2 M€

+ *Calorimeter*: expensive, we want to keep budget low. Asked for CMS spare or extra PWO but not available.
Trying to recover crystal from old experiments (BGO from L3?)
We are investigating possible alternatives.

Padova

- Experimental + theory group
- Exp:

A. Bragagnolo (PhD)	0.2	
E. Conti	0.5	
M. Presilla (PhD)	0.2	
P. Ronchese	0.1	
G. Simi	0.0	
F. Simonetto	0.15	
R. Stroili	0.1	TOT: 1.25

- Theory:

S. Laporta	
P. Mastrolia	
P. Paradisi	
M. Passera	
+ PhD, postdoc	TOT ~ 1-1.5

Activity

- Simulations
- Hardware: we would like to develop the ECAL

- Theory group: NNLO QED corrections