Measuring a_μ^{HLO} via μ-e scattering

G. Venanzoni

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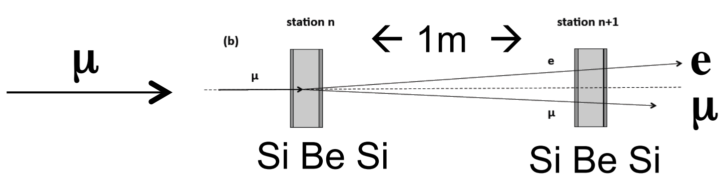
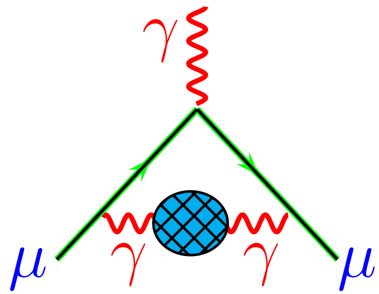
In collaboration with: G. Abbiendi, C.M.Carloni Calame, F.V. Ignatov, M. Incagli, U. Marconi, C. Matteuzzi, G. Montagna, O. Nicrosini, M. Passera, C. Patrignani, F. Piccinini, F. Pisani, R. Tenchini, L. Trentadue





First Workshop of the Muon g-2 Theory Initiative

Q Center, St. Charles IL, 5 June 2017

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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Phys. Lett. B 746 (2015) 325
Eur. Phys. J. C (2017) 77: 139.

Reference papers

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

- Optical theorem and analyticity:

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

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

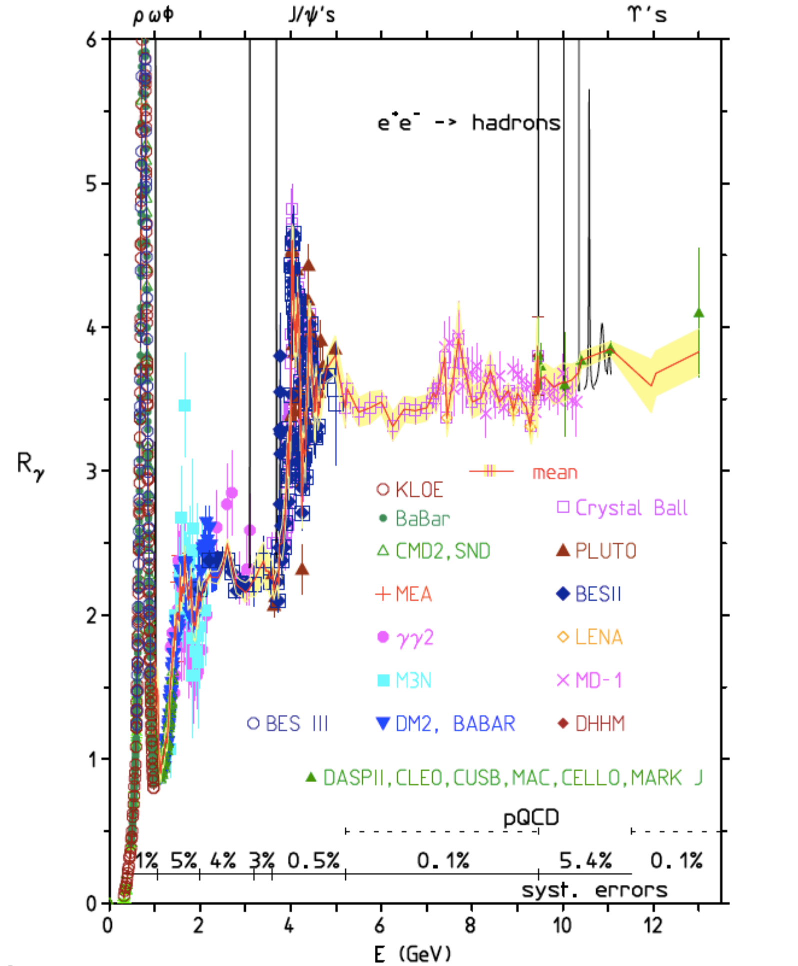
- The main contribution is in the highly fluctuating low energy region.

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

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**

F. Jegerlehner and A. Nyffeler, Phys. Rept. 477 (2009) 1

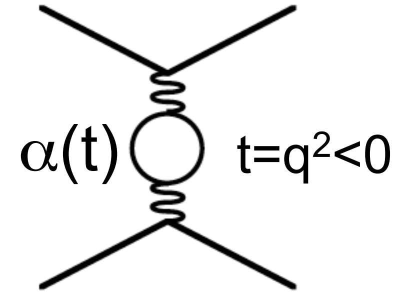
Collection of many experimental results



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

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

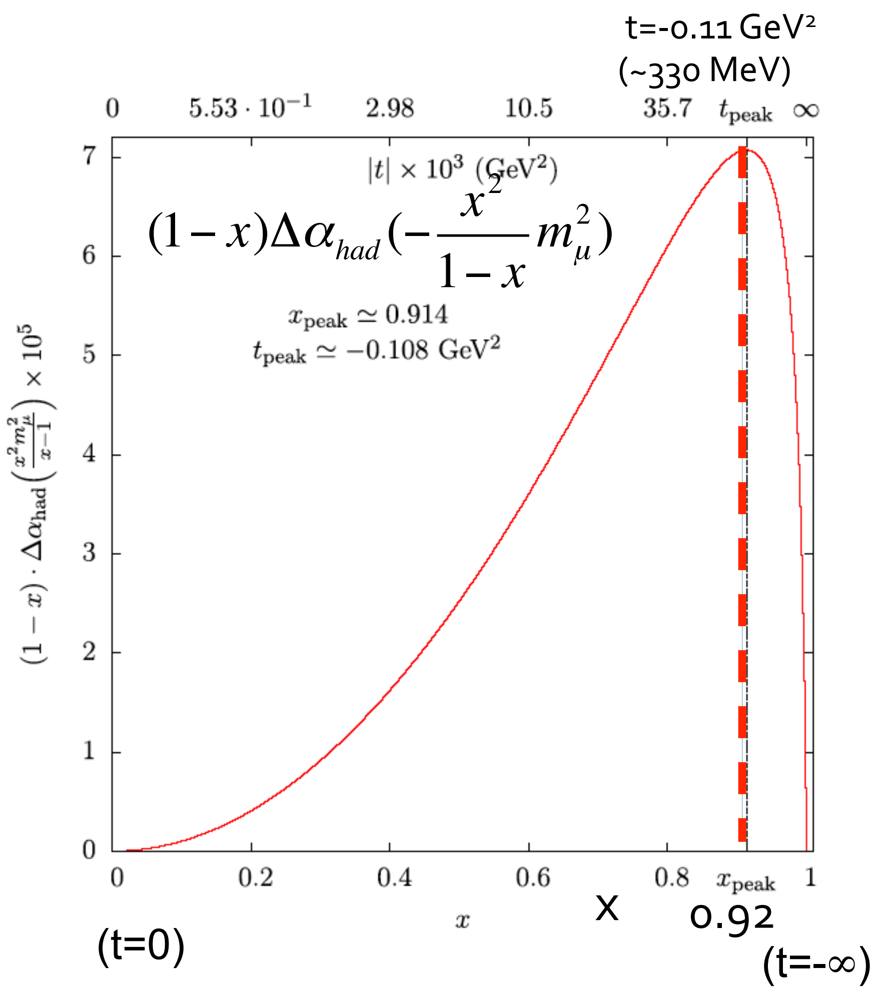
$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$



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

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

- 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

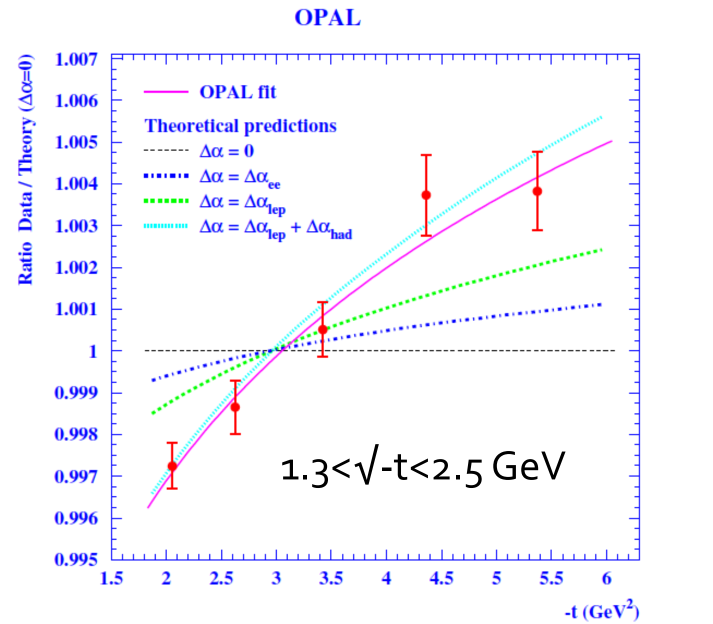


Measurement of $\Delta\alpha_{had}(t)$ spacelike at LEP

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

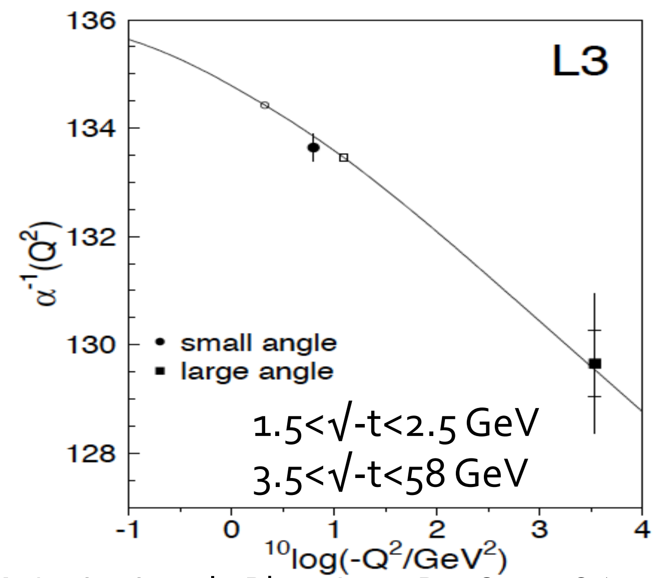
$$f(t) = \frac{N_{\rm data}(t)}{N^0_{\rm MC}(t)} \propto \left(\frac{1}{1-\Delta\alpha(t)}\right)^2 .$$

Accuracy at per mill level was achieved!



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

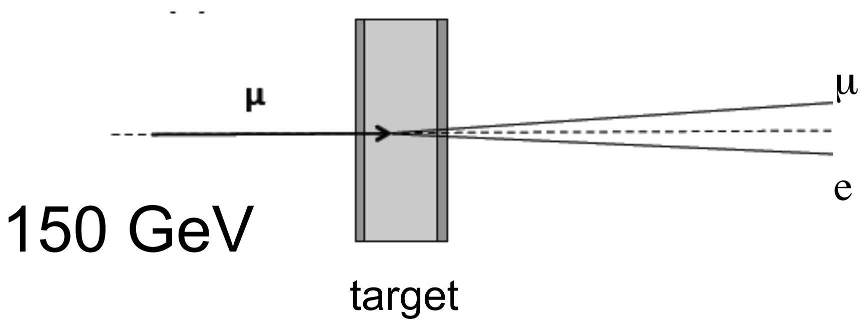
- For low t values (≤0.11 GeV^2) and higher precision (~10^{-5}) as in our case a different approach is needed!

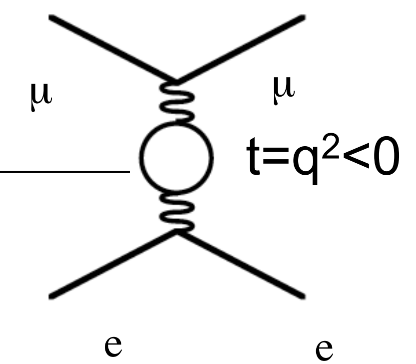


M. Acciarri et al., Phys. Lett. B476 40-48 (2000)

Experimental approach:

Use of a 150 GeV μ beam on Be target at CERN (elastic scattering μe →μ e)



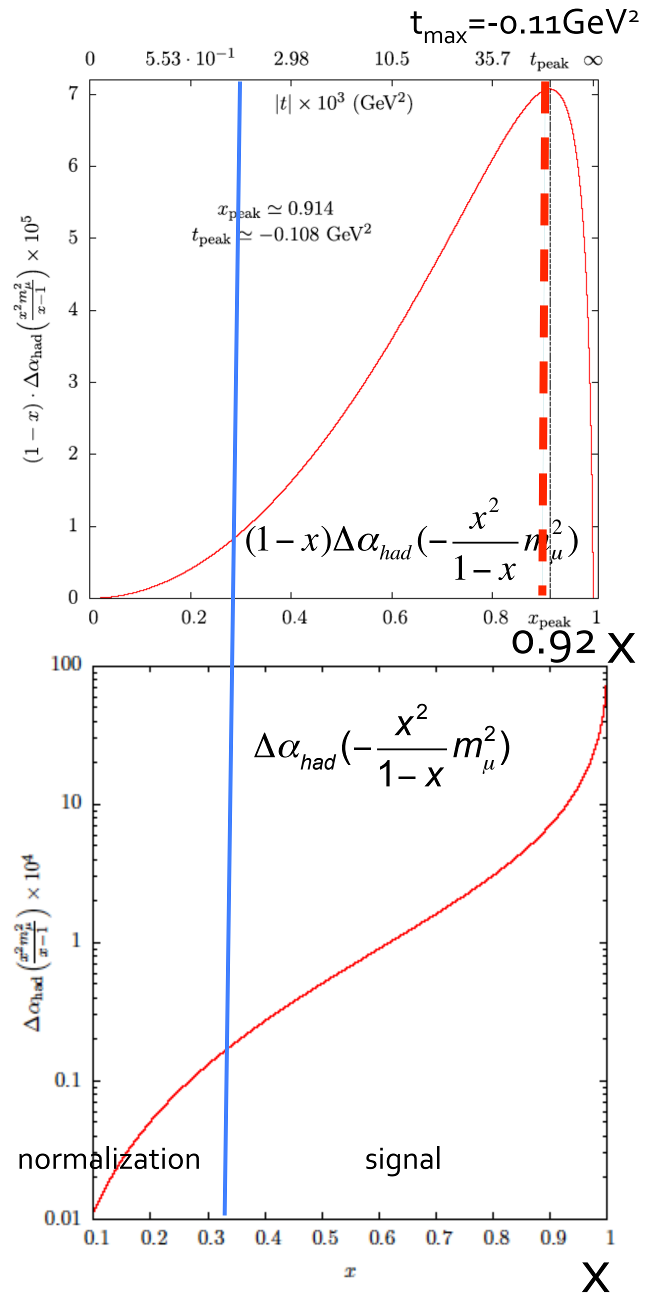


$$\left|\frac{\alpha(t)}{\alpha_0}\right|^2 = \left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

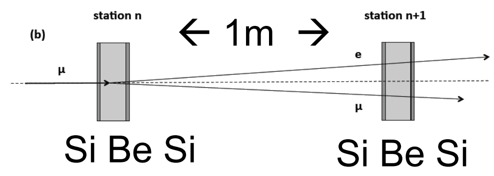
Why measuring $\Delta\alpha_{had}(t)$ with a 150 GeV μ beam on e^- target ?

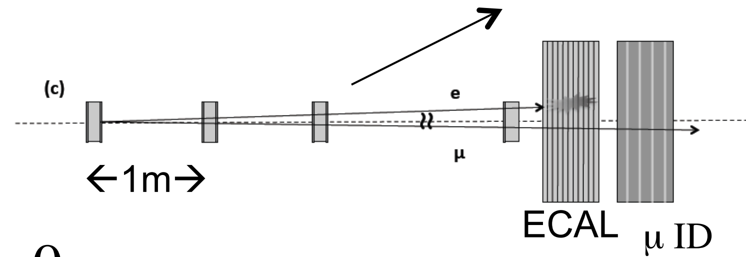
It looks an ideal process!

- $\mu e \rightarrow \mu e$ is pure t-channel (at LO)
- Simple kinematics (2 body process, $t=-2m_eE_e<0$) allows to span the region $0<-t<0.143$ GeV² ($0<x<0.93$); 87% of total a_μ^{HLO} (the rest can be computed by pQCD/time-like data)
- Angular measurement: 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 ($x<0.3$, $\Delta\alpha_{had}(t)<10^{-5}$) $\rightarrow$ cancellation of detector effects at first order



Detector considerations





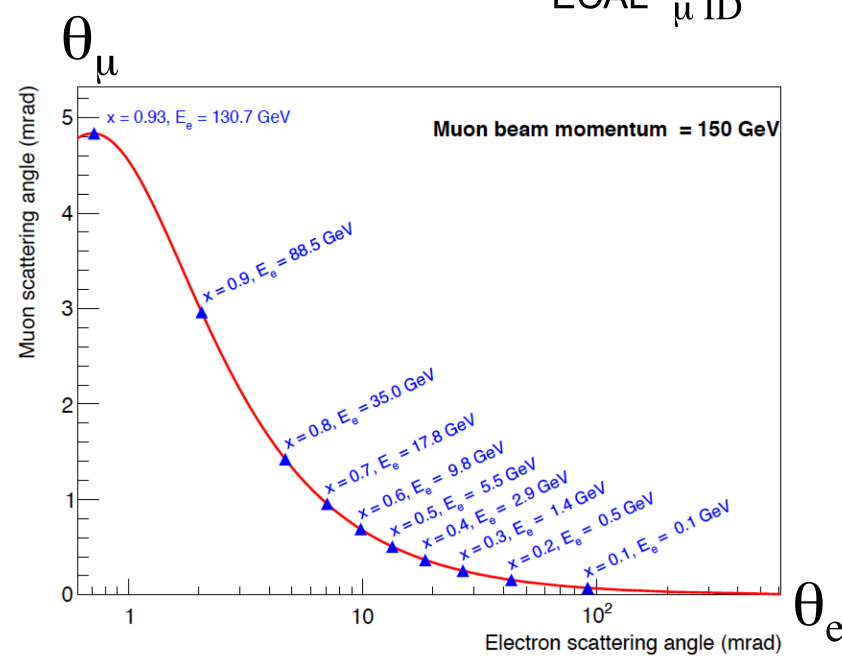
- Modular apparatus: 20 layers of 3 cm Be (target), each coupled to 1 m distant Si (0.3 mm) planes. It provides a 0.02 mrad resolution on the scattering angle

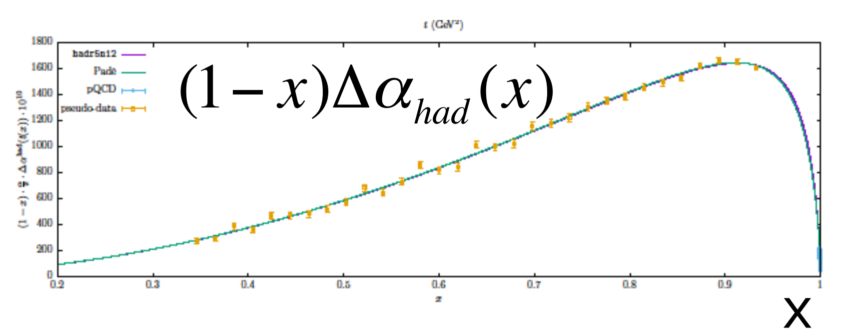
- The t=q² <0 of the interaction is determined by the electron (or muon) scattering angle (a` la NA7)

- 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}** (which is the accuracy needed to known the cross section at few per mille in the peak region)

- **Statistical** considerations show that a **0.3%** error can be achieved on a_μ^{HLO} in 2 years of data taking with 1.3×10^7 μ/s (available at CERN)





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".

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

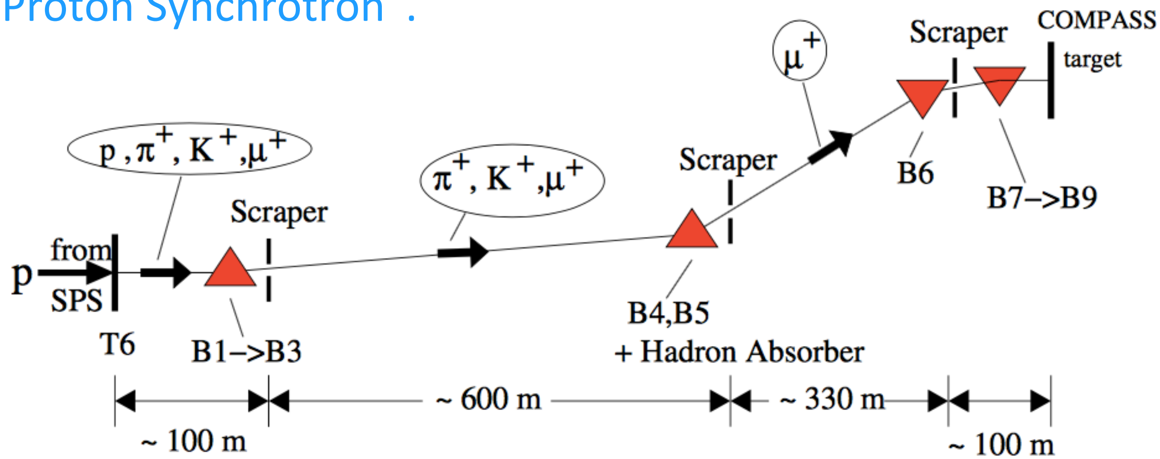


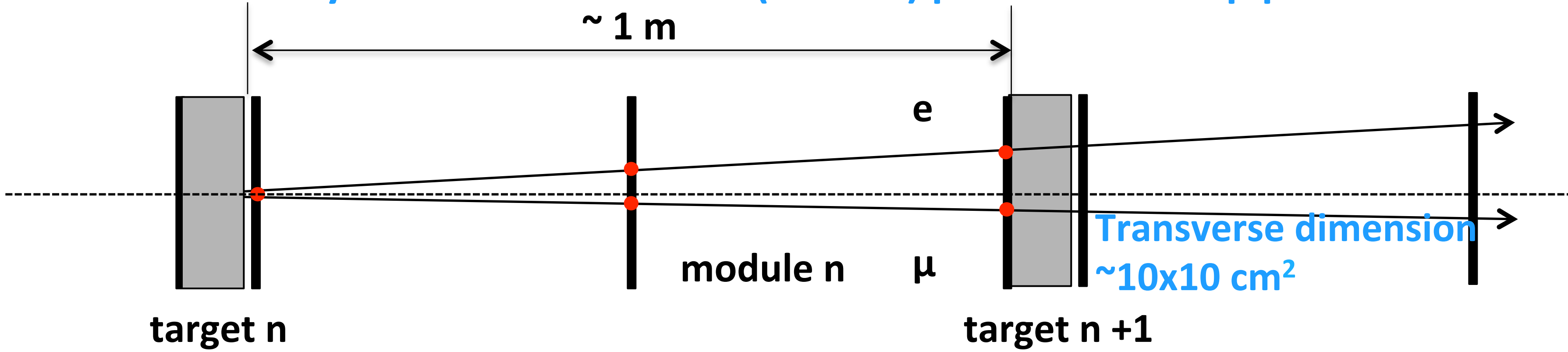
Table 3
Parameters and performance of the 160 GeV/c muon beam.

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%

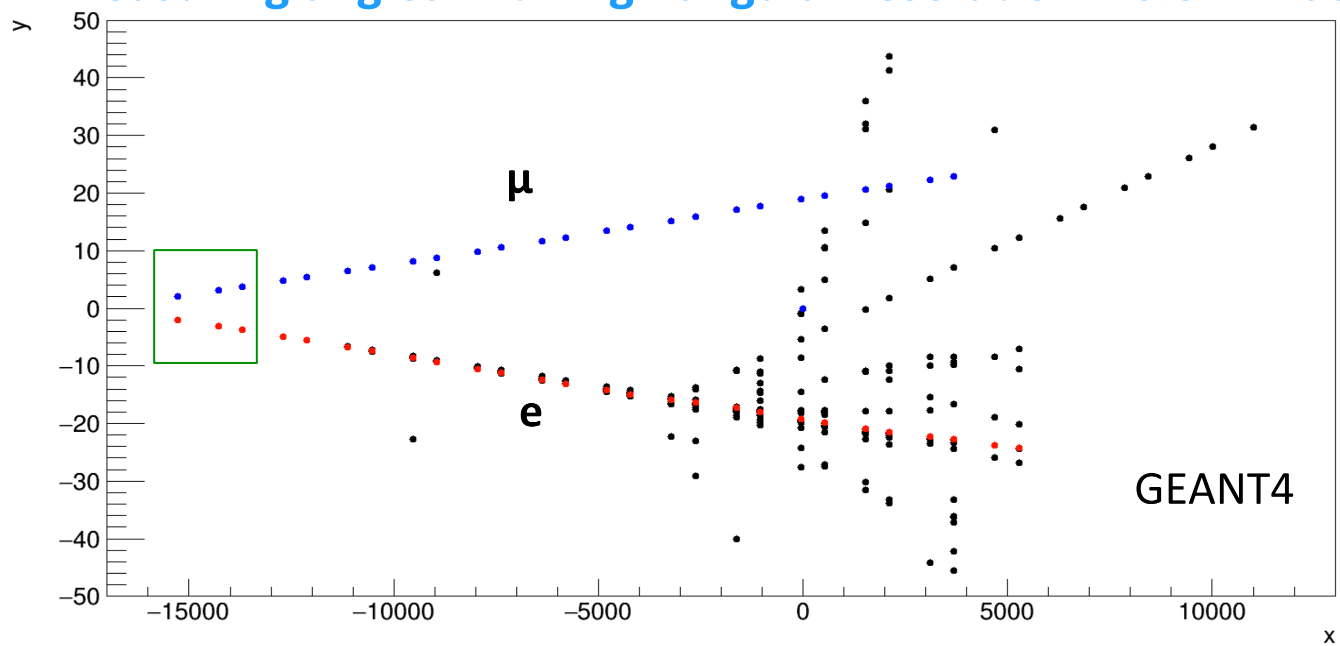
$I_{beam} > 10^7$ muon/s, $E_\mu = 150$ GeV

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

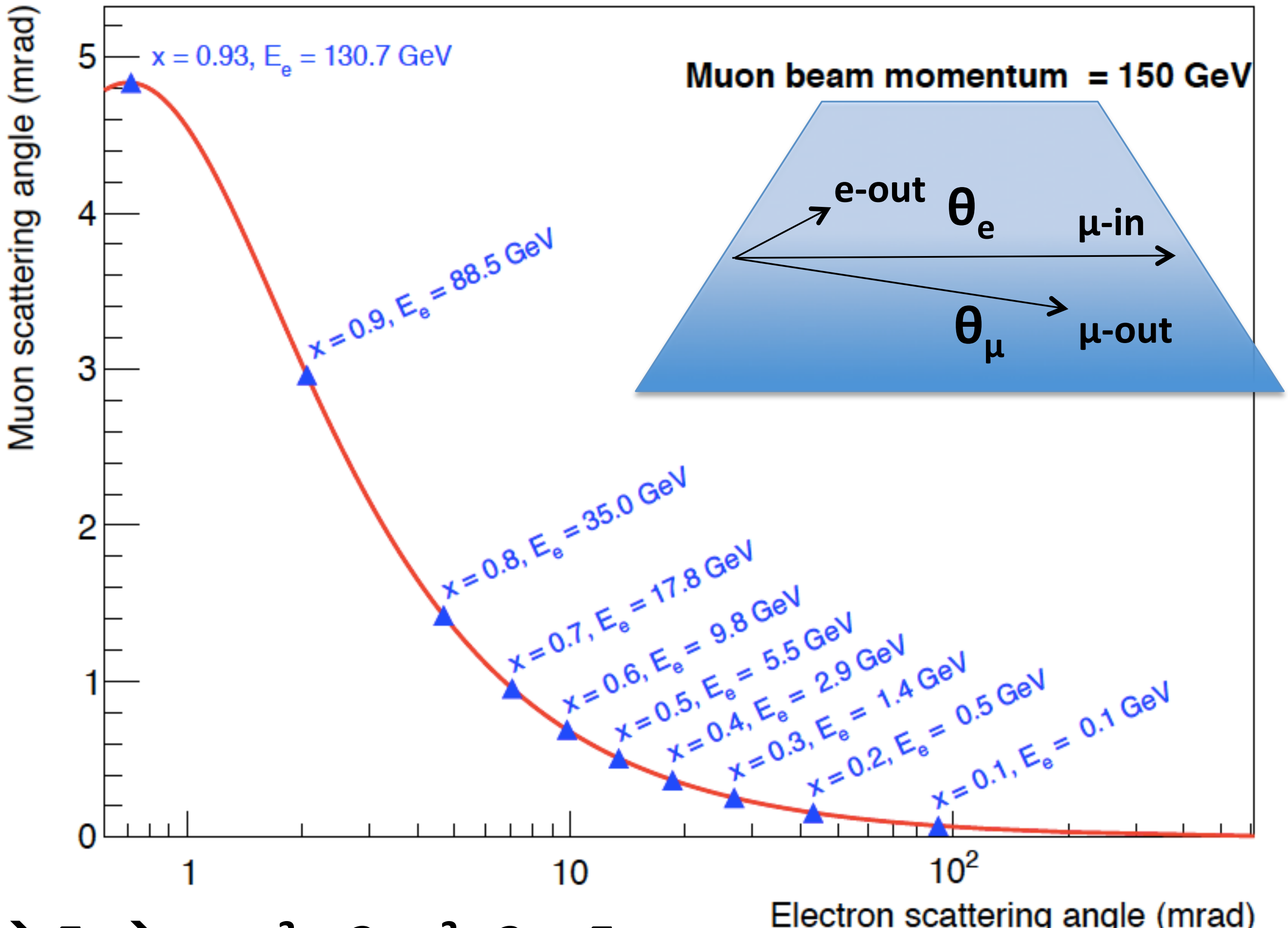


Measuring angles with high angular resolution ~ 0.02 mrad



Elastic scattering in the (θ_e , θ_μ) plane

Coplanarity of the momentum vectors and angular kinematical constraint

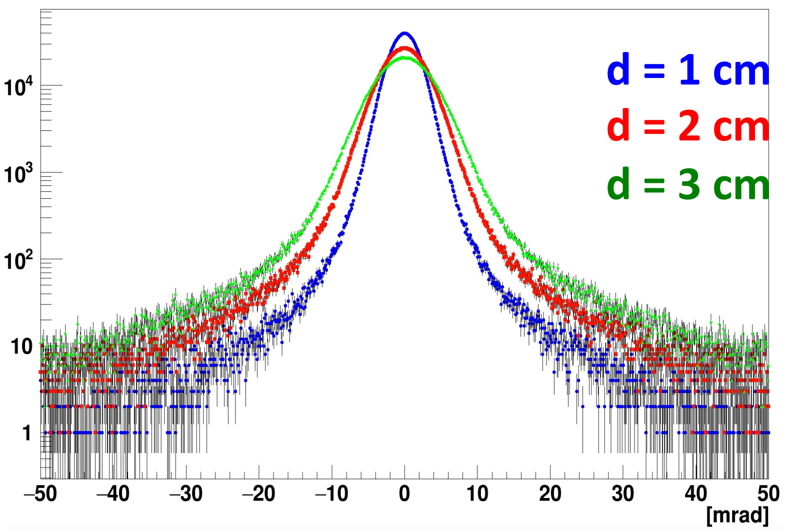


$\theta_e \rightarrow E_e \rightarrow t = q^2 = 2m_e^2 - 2m_eE_e$

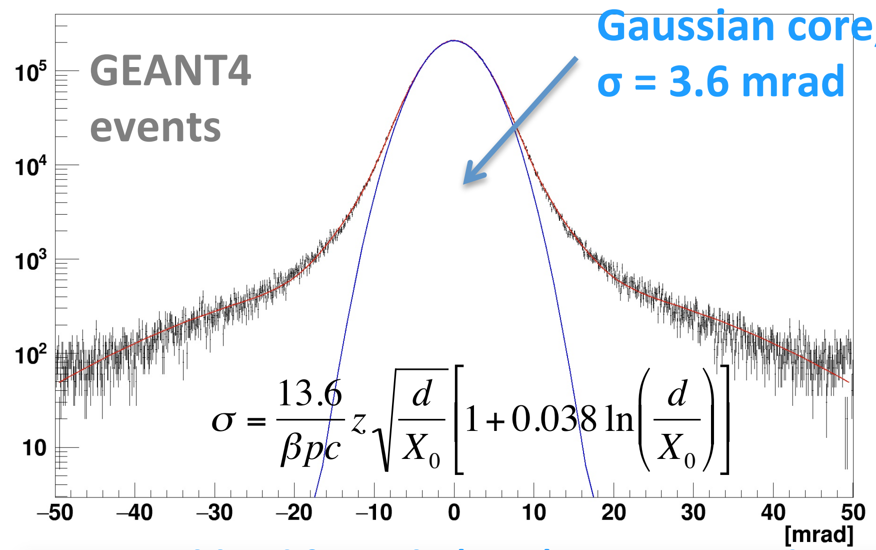
The role of Multiple Scattering:

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.

GEANT4, 1 GeV electrons, Be target



1 GeV, d = 3 cm



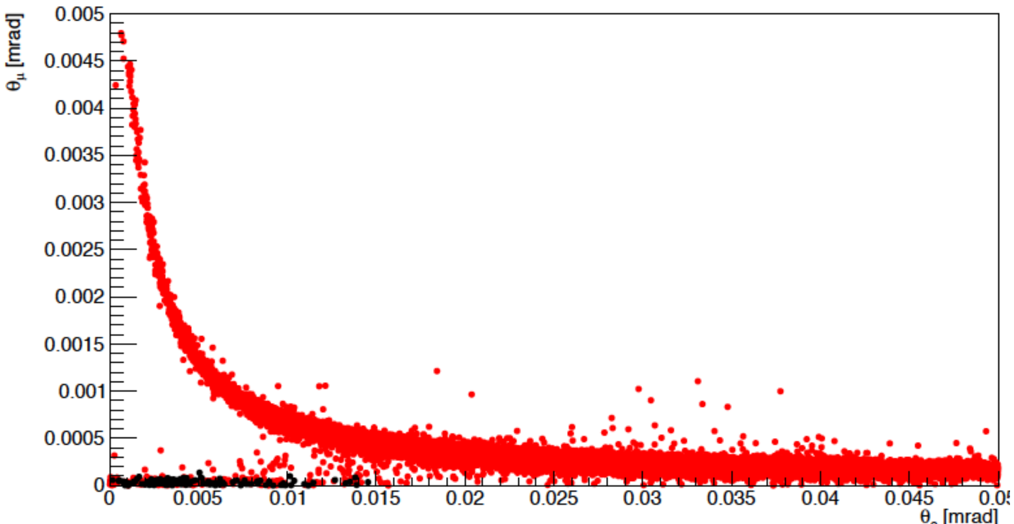
Highland formula (PDG) = 3.593 mrad

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.

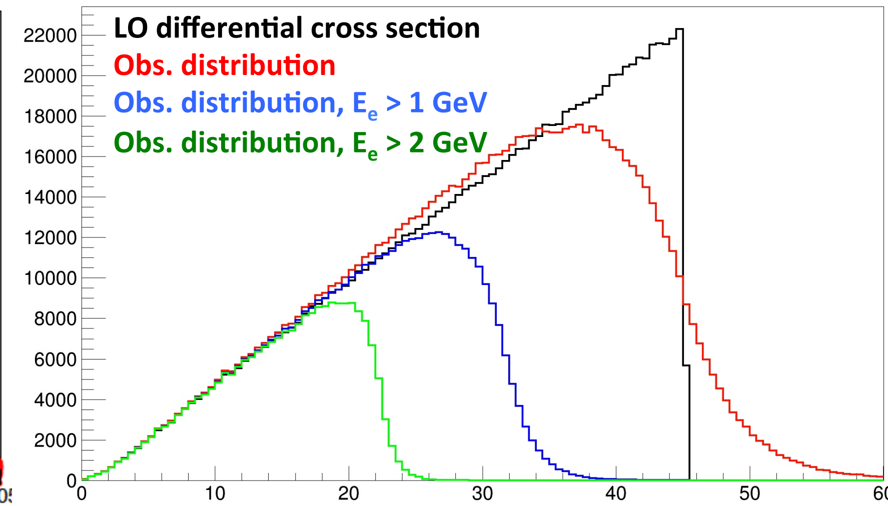
Analytical considerations (confirmed by fast simulation) shows that 1% uncertainty on MSC model → <10ppm on the cross section

13

Events in the (θ_e , θ_μ) plane: 10^8 Geant-4 events



electron angle [mrad]

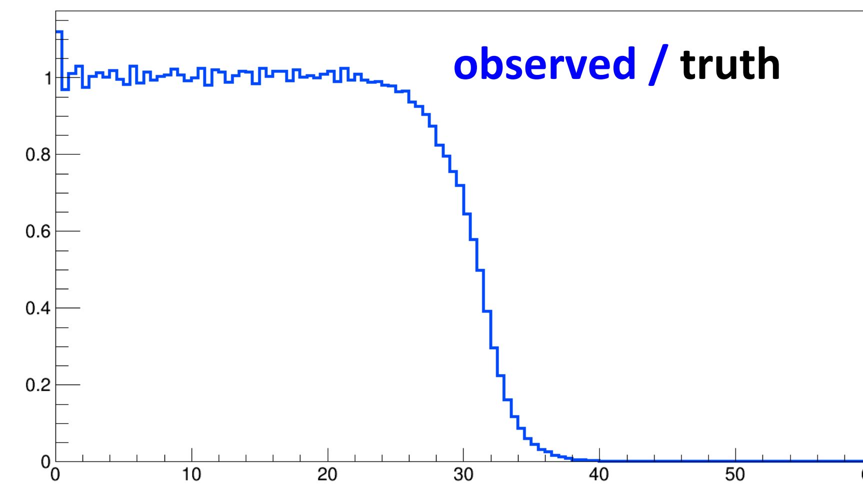


electron angle [mrad]

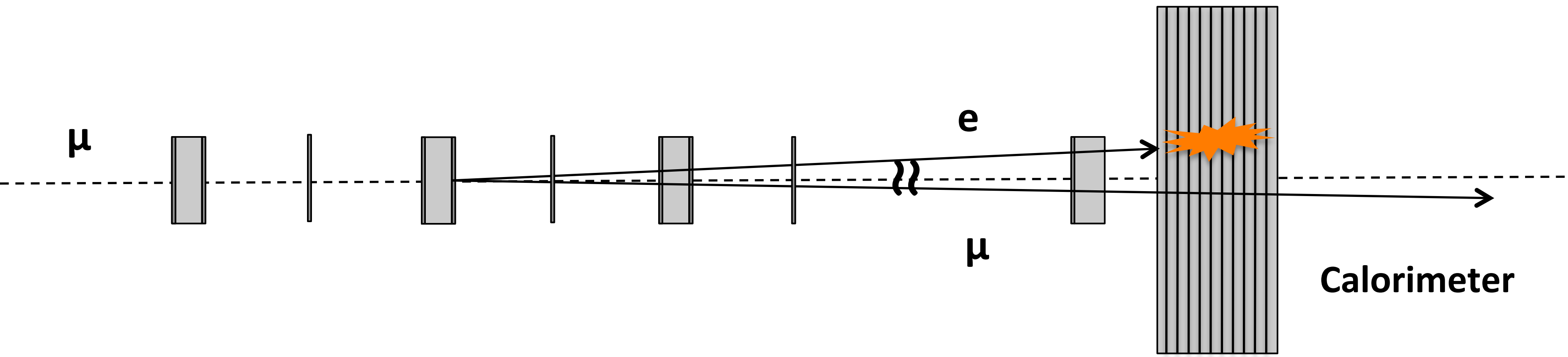
Background events are mainly due to pair production:
μ and e^+ looking as 2 body final state: ~10^{-8}

Cut at E>1GeV (x=0.1) reduces much of the MSC effects from **low energy electron scattered away from the original direction**

ratio= observed / truth turns out to be 1. within few parts per mille (without any correction)



Detector design/optimization



- Electromagnetic calorimeter needed to:
  - Perform the PID: muon/electron discrimination.
    - PID capabilities also reconstructing the electromagnetic shower in the tracking system.
  - Triggering : (muon in) AND (ECAL E > E_{th})
    - There is an alternative trigger condition: (muon in) AND (2 prongs into a given module)
- Measure E_e to get rid of events with E_e< 1 GeV

Systematics

1. Acceptance
2. Tracking
3. Trigger
4. PID
5. Effects of E_e energy cut
6. Signal/Background:
   It requires a dedicated event generator.

Affordable by means of GEANT4 based simulations

7. Uncertainty in the location of interaction vertices: Segmented/active target to resolve the vertex position
8. Uncertainty in the muon beam momentum:
   Scattering kinematics to determine the beam momentum
9. Effects of Multiple Scattering (must be known at ~1%):
   It requires dedicated work on simulation and measurements (test beam).
10. Theoretical uncertainty on the mu-e cross section (see later)

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

Activity on the theory side

1. QED NLO corrections. Easy.

2. Resummation of dominant corrections up to all orders, matched with NLO corrections. Non-trivial issue: mass effects in this case are important

3. NNLO corrections: some classes of NNLO re-usable from existing Bhabha calculations, some new due to different mass scales ($\mathbf{m}_\mu$ and $\mathbf{m}_e$). In any case, NNLO must be matched with 1. and 2. [references: Eur. Phys. J. C 66 (2010) 585 and references therein]

4. Development of dedicated MC tools including all the above ingredients

5. Detailed study of all the mentioned corrections, comparison among independent calculations, estimate of further-missing higher-order corrections

6. Theory workshop this year in Padova (5-5 September 2017), and one next year in Mainz (19-24 February 2018). You are all invited!

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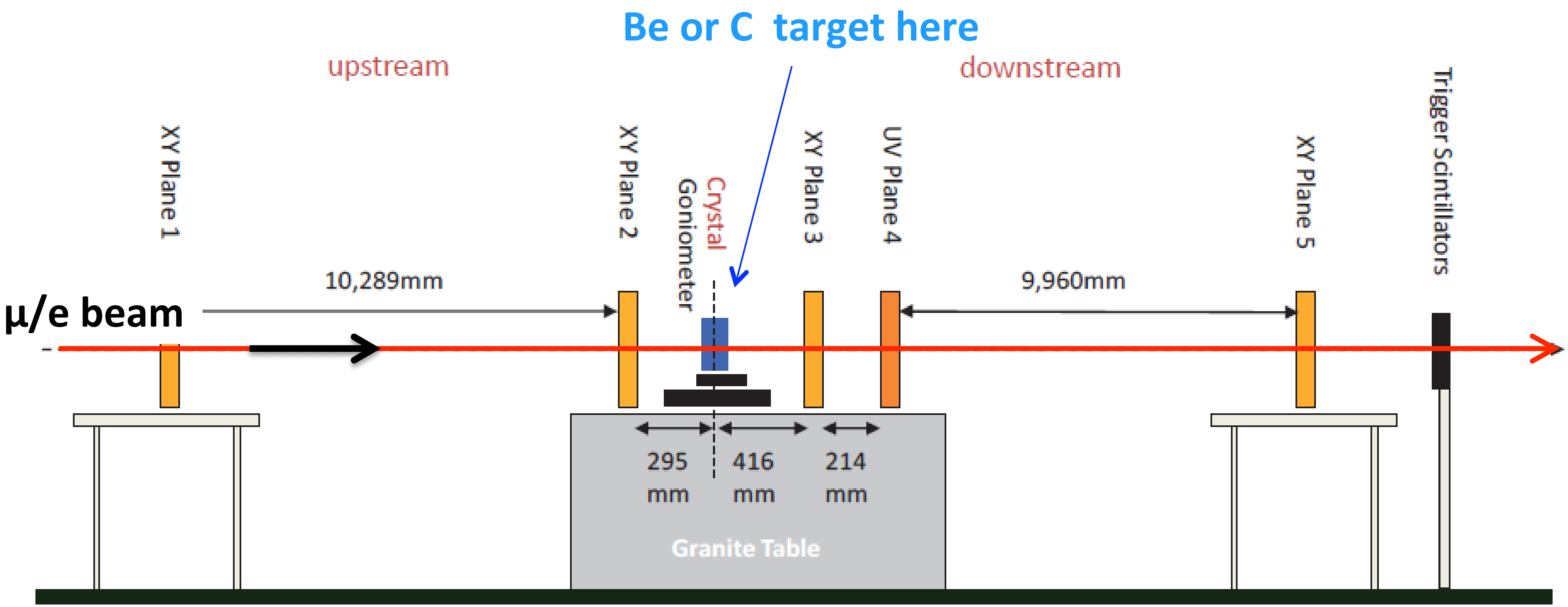
Test Beam

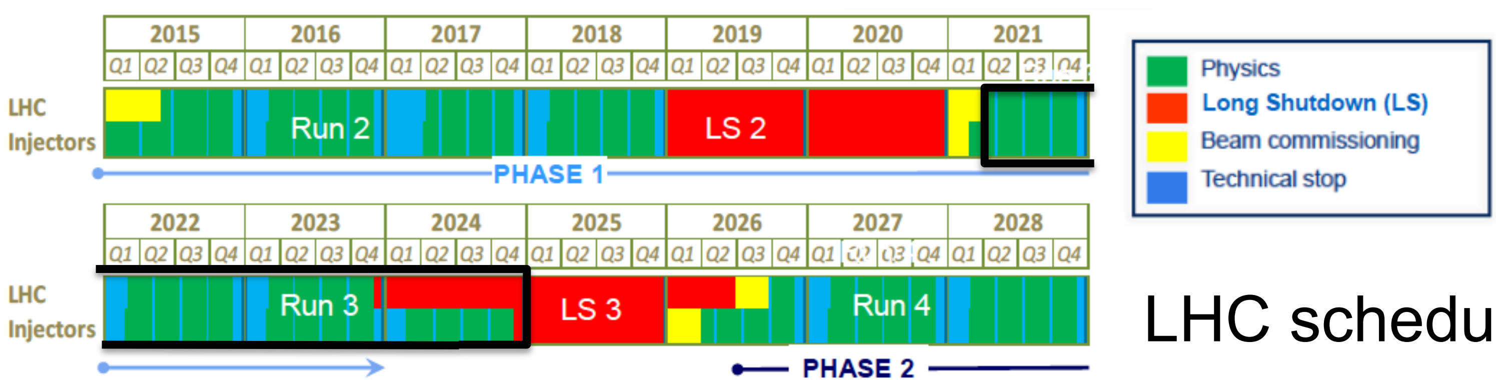
Check Geant4 MSC prediction and populate the 2D (θ_e , θ_μ) scattering plane

- 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



Plans

- **2017 - 2019**
  - Detector optimization studies
  - Test beams (first on 27 Sep-3 October 2017 at CERN)
  - Set up a collaboration
  - Theoretical studies
  - Letter of Intent to the SPSC
- **2020**
  - Detector construction and installation
    (a staged version of the detector may be)
- **2021 – 2024**
  - Start the data taking after LS2 to measure $\mathbf{a_\mu^{HLO}}$
    (not necessarily the ultimate precision)



LHC schedule

Conclusion

- Proposal part of the CERN "Physics Beyond Collider Study Group" at CERN
  (http://pbc.web.cern.ch/)
- If approved (by CERN SPSC) first results in the same period of the g-2 measurements at Fermilab and J-Parc

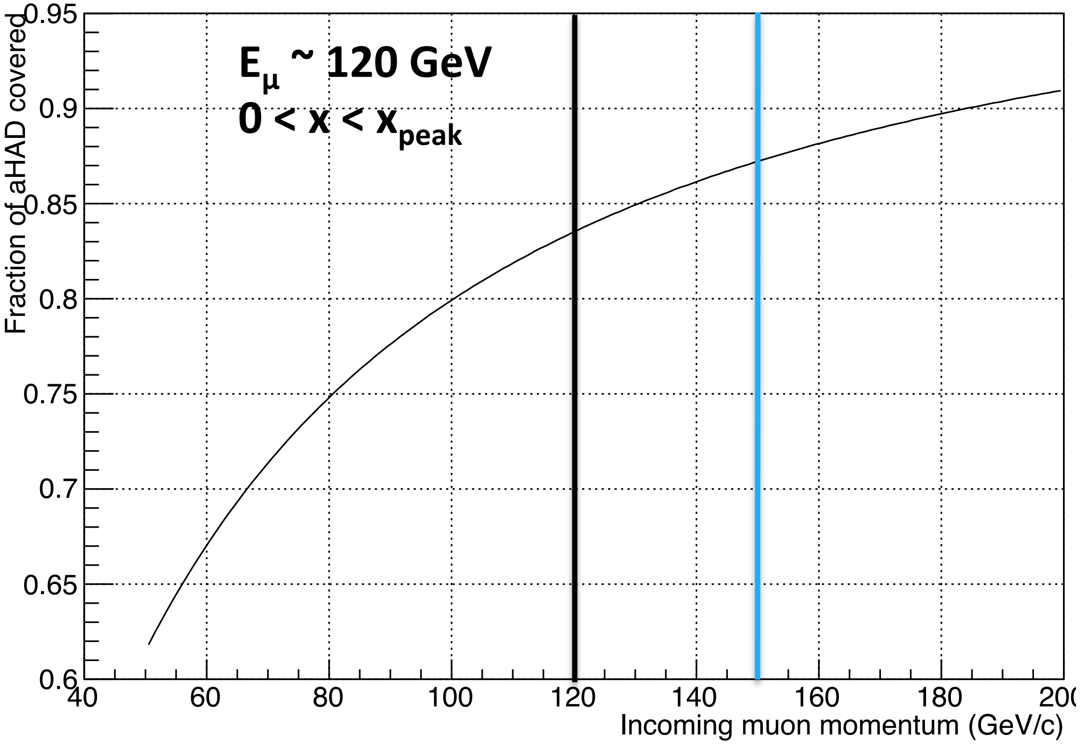
We are setting up the collaboration: if you are interested you are welcome!
(send an email to graziano.venanzoni(at)pi.infn.it)

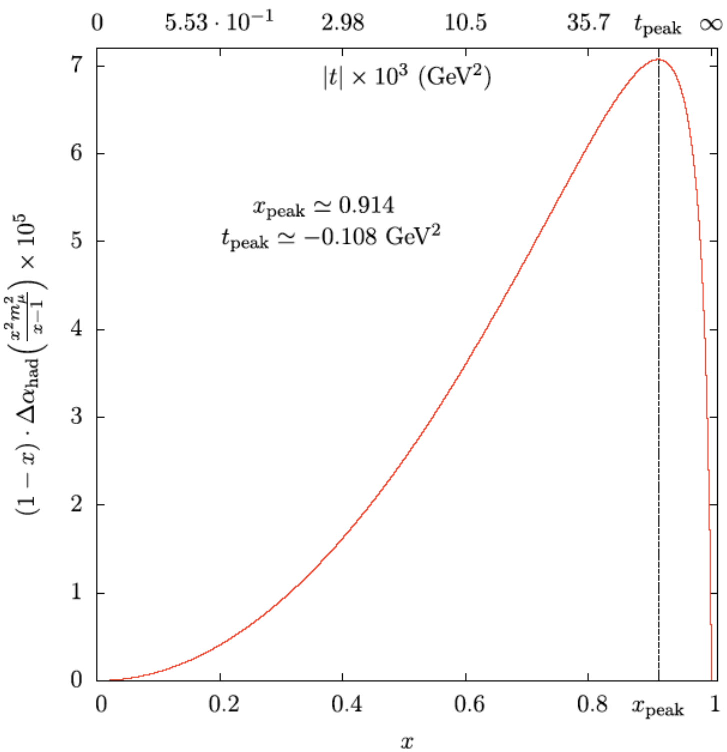
Thanks!

Spare

Optimal Muon Beam Momentum

Fraction of the a_μ^{HLO} integral as a function of the muon beam momentum: p_μ = 150 GeV → 87% of the integral (0 < x <0.93).





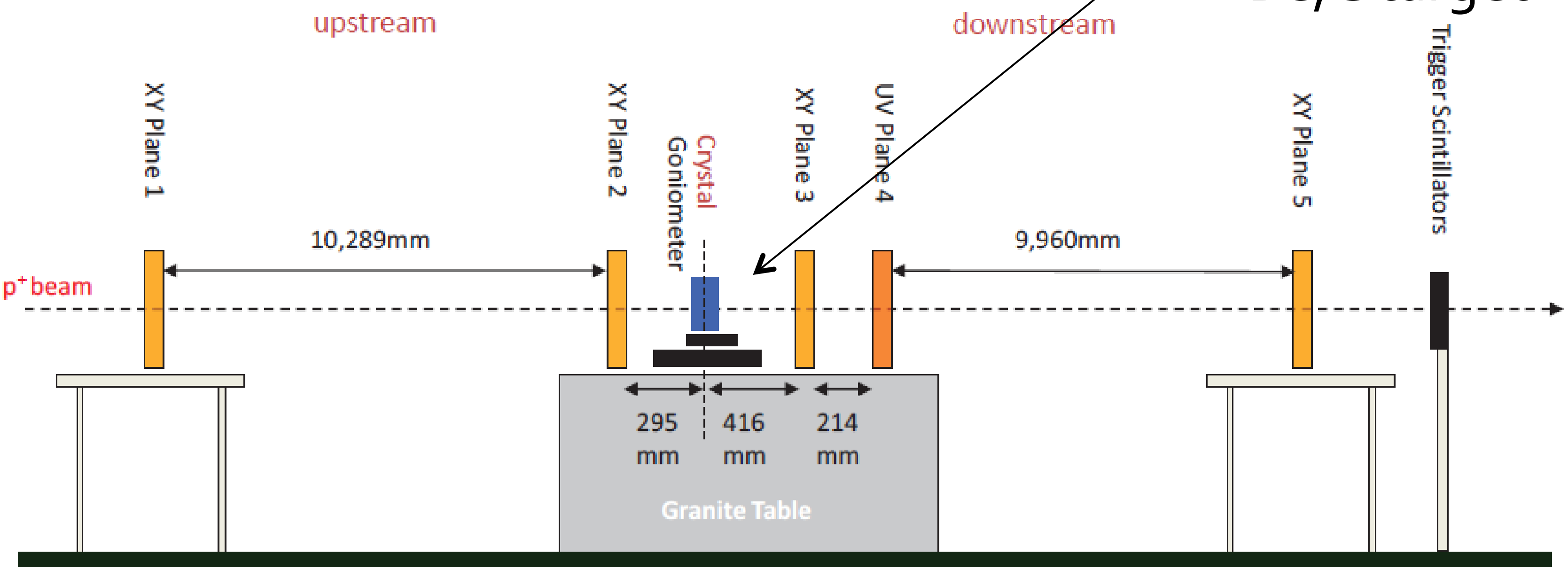
Beyond the kinematic limit the integral can be determined using pQCD & time-like data, and/or lattice QCD results.

Test Beam

27 Sep-3 October 2017
Plan to use existing UA9 setup in H8

max rate ≈ 10 kHz
p beam ≈ 57%-100% of 180 GeV

Replacing crystal with thin Be,C target



Basic setup from IC :

5 Si planes, 2 before and 3 after the target, 3.8x3.8 cm2
as is it the setup achieves 5.2 μrad, limited by the MS in the Si

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

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

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

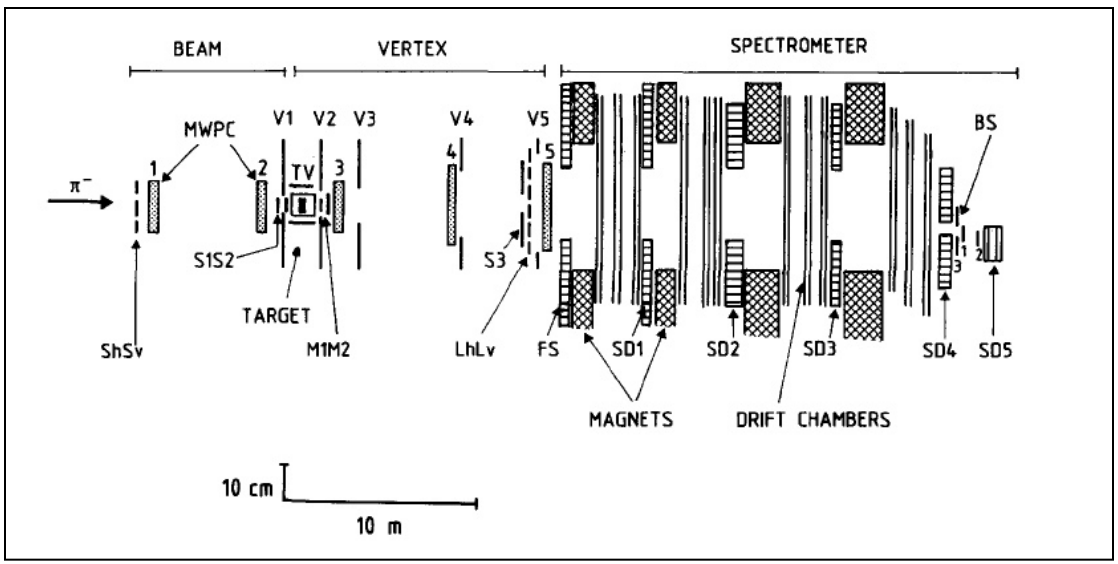
- $\delta\Delta\alpha_{had}/\Delta\alpha_{had}$ at 0.5% at peak region (x=0.92, Δa_{had}~10^{-3})→
  $\delta N(t)/N(t)$~10^{-5}

- 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

NA7 experiment

A MEASUREMENT OF THE SPACE-LIKE PION ELECTROMAGNETIC FORM FACTOR,

"The pion form factor has been measured in the space-like q^2 region 0.014 to 0.26 $(GeV/c)^2$ by **scattering 300 GeV pions from the electrons of a liquid hydrogen target**".



Target: 28 cm liquid Hydrogen

X_0 (liquid H_2) = 890.5 cm

S.R. Amendolia et al. / Pion electromagnetic form factor 173

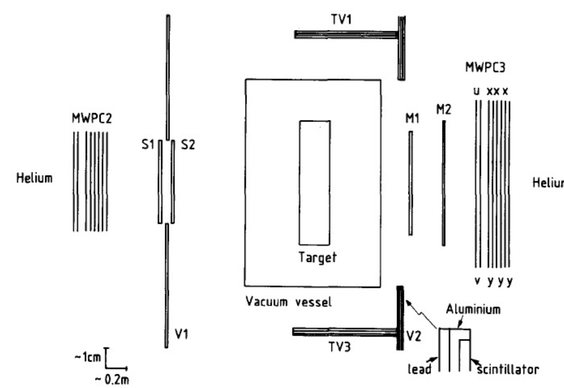


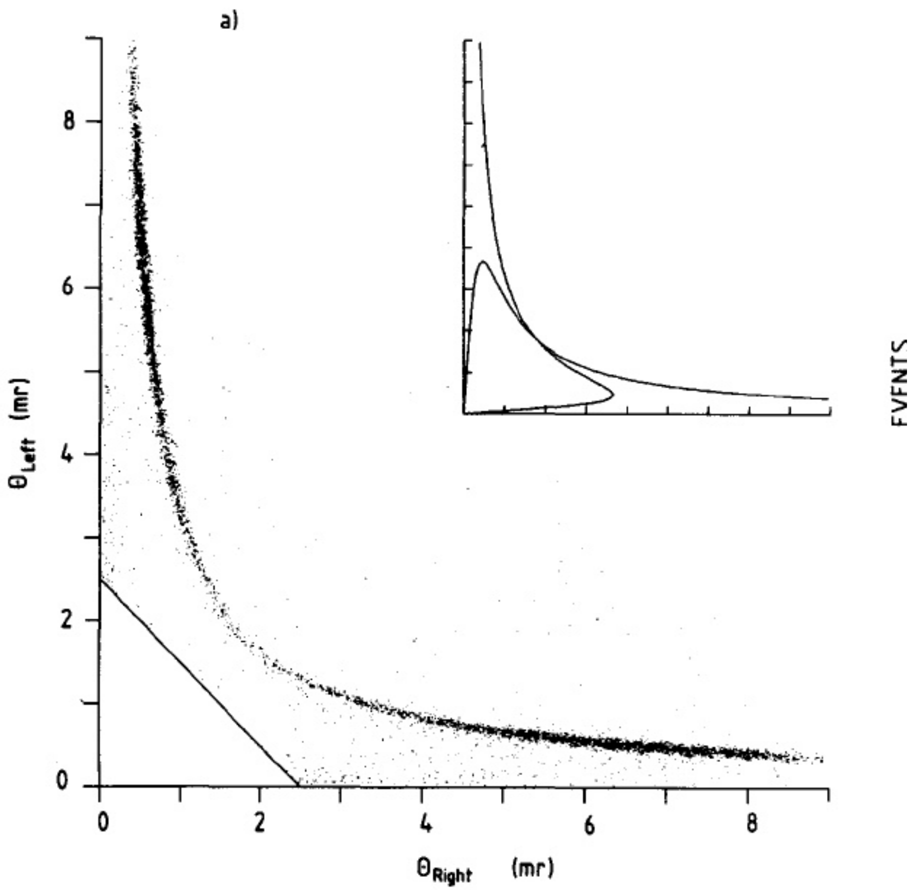
Fig. 4. Apparatus surrounding the target.

"**The q^2 variable for the final sample was determined from the angles alone**, up to the kinematic ambiguity which was resolved using the shower detectors. In this procedure the only rejection criterion involving the momenta was a cut against electrons of less than 1 GeV/c".

Nuclear Physics B277 (1986) 168-196

NA7 experiment

Elastic scattering in the (θ_R,θ_L) plane



"The scatter distribution of the measured polar angles of the right and left-going particles (θ_R,θ_L). Our estimate of q^2 was made from the point on the theoretical kinematic curve nearest to these angle coordinates".

Coplanarity

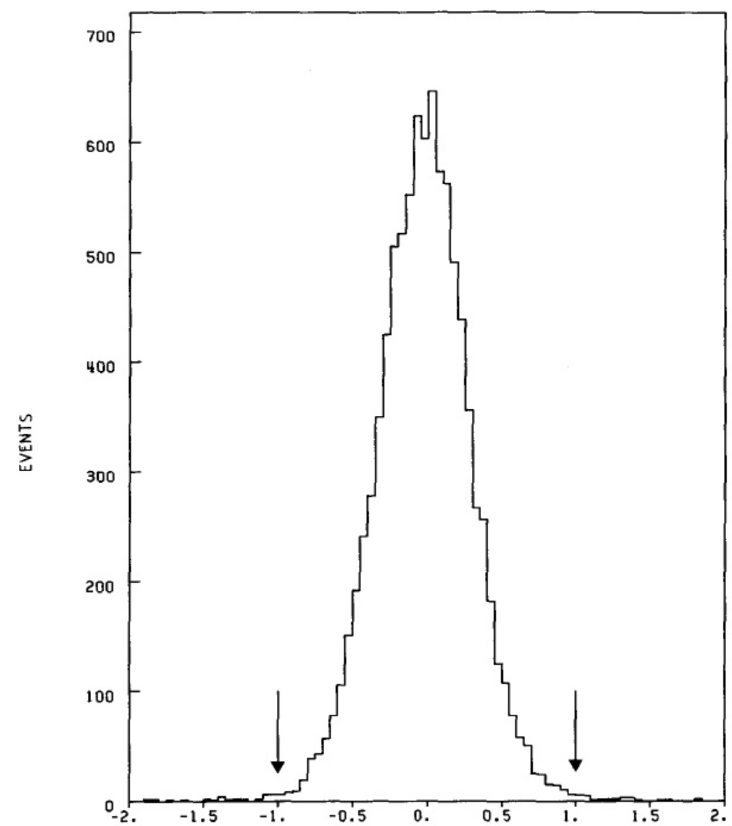


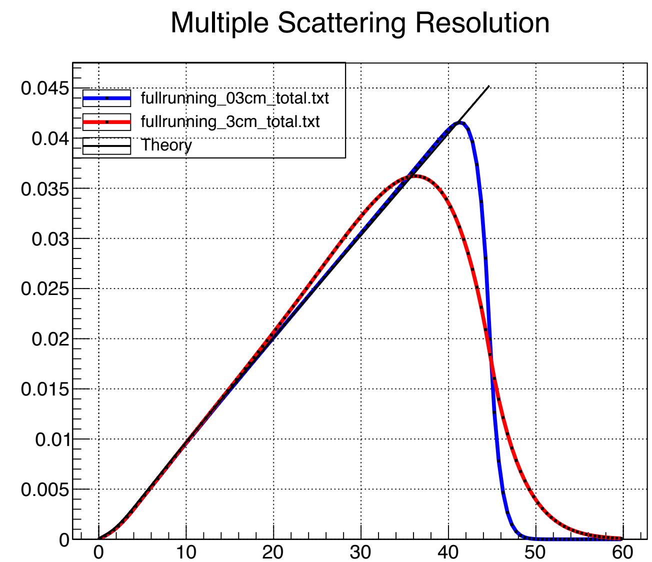
Fig. 8. The distribution of the triple scalar product of unit vectors along the incident and scattered tracks, in units of the applied cut. This varied smoothly with decreasing opening angle from 1.1×10^{-6} to 0.6×10^{-6}.

"A fraction of the hadronic background was rejected by requiring coplanarity of the incident and scattered tracks"

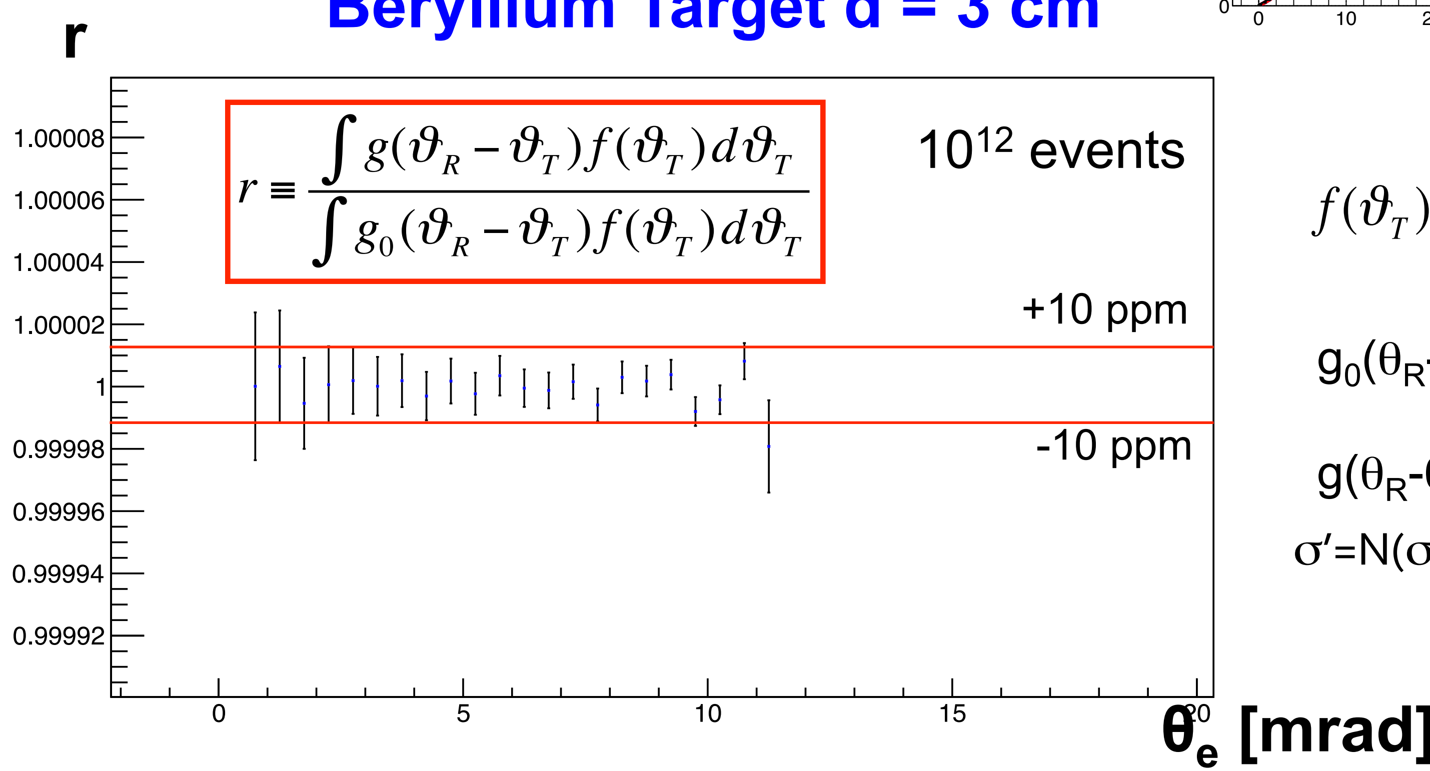
MSC studies: Gaussian model with 1% uncertainty

$$g_0(\theta_R - \theta_T) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(\theta_R - \theta_T)^2}{2\sigma^2} \right]$$

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



Beryllium Target d = 3 cm



$$f(\vartheta_T) = \frac{dN(e\mu \to e\mu)}{d\vartheta_T}$$

$g_0(\theta_R - \theta_T) \sim N(\theta_T, \sigma)$

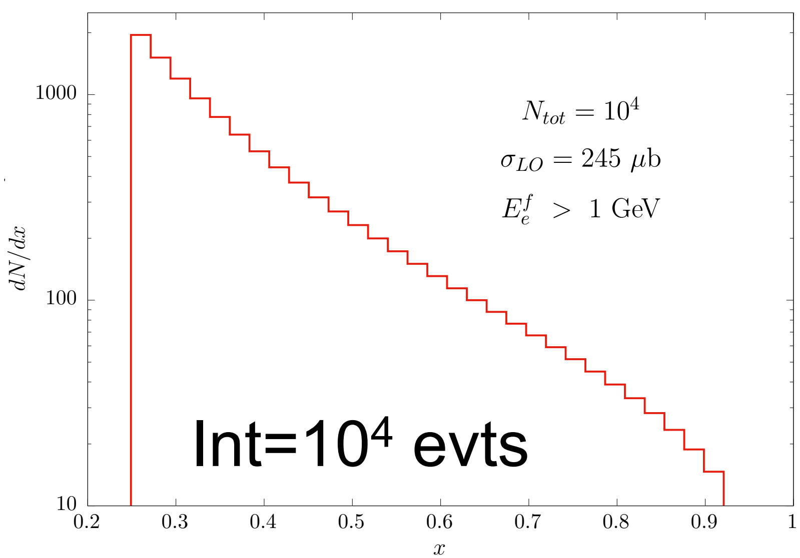
$g(\theta_R - \theta_T) \sim N(\theta_T, \sigma')$

$\sigma' = N(\sigma, 0.01\sigma)$

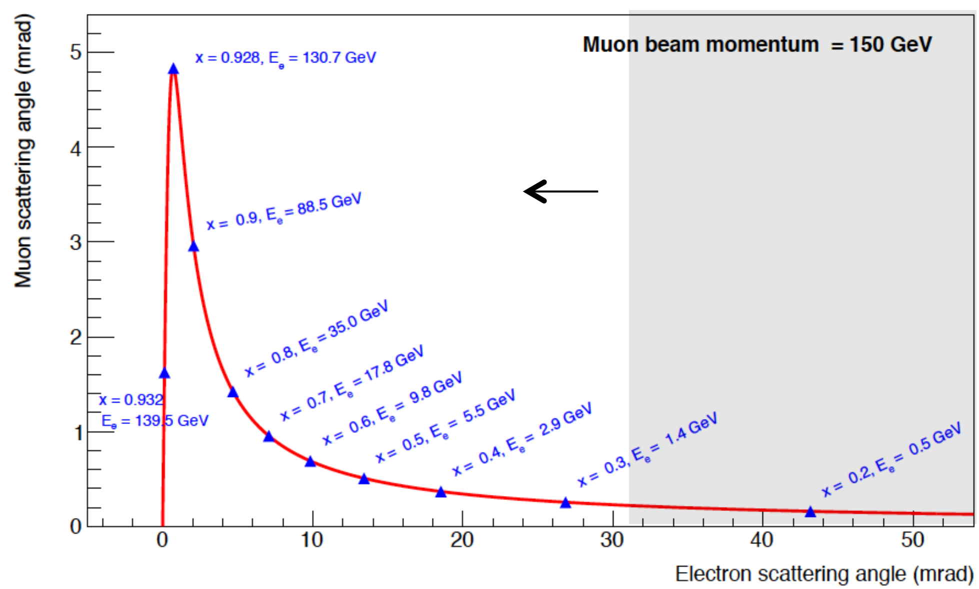
Goal of the TB

- Measure the angle of e- and muons
- Isolate the signal (elastic scattering) events
- plot 2D θ_μ vs θ_e (in the allowed region)
- Compare with simulation

Preliminary: $O(10^4)$ μe evts expected within $\theta<30$ mrad assuming 10kHz μ



30mrad 1mrad



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/

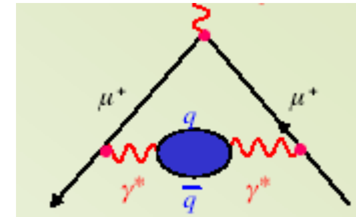
Systematics

Source	Effect	Notes
Multiple scattering	Must be known at ~% level;	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. Different target Test Beams
Acceptance	To be studied	
Tracking	To be studied	High uniformity; three layers system
Trigger		
PID		
Uncertainty on Muon momentum		
Theory	$O(10^{-5})$	See later

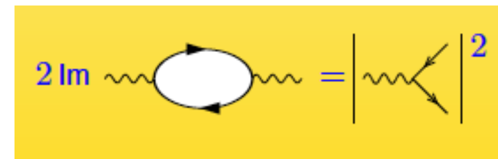
The cross section must be known at level of O(10ppm)

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

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



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

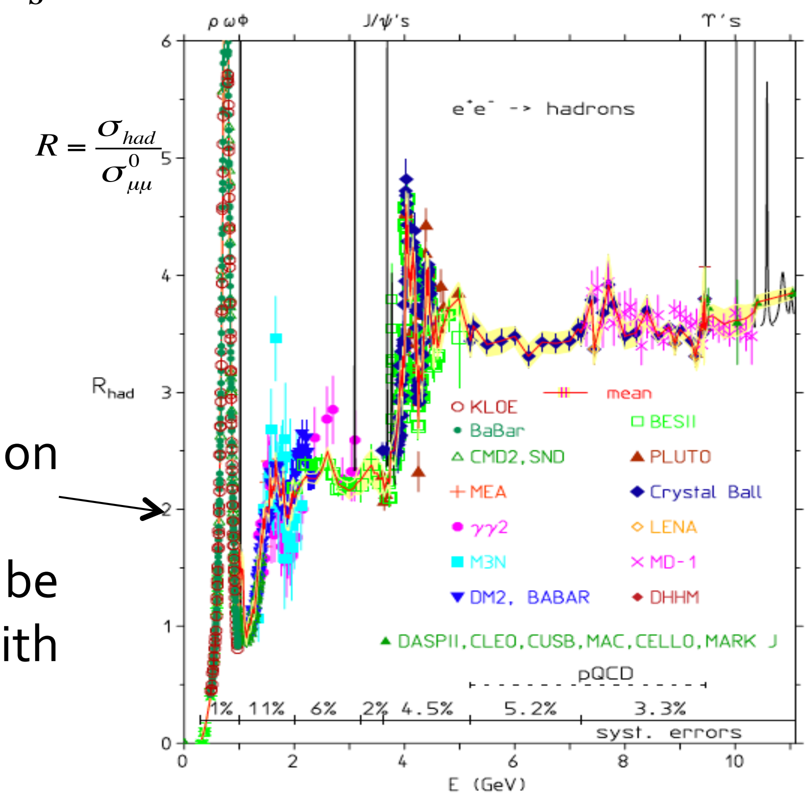


$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)(s/m^2)} \sim \frac{1}{s} \qquad \sigma_{e^+e^-\to hadr}(s) = \frac{4\pi}{s}\operatorname{Im}\Pi_{had}(s)$$

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

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



Plans (next 2 years) and Conclusion

- 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 TDR

Experiment proposed to CERN

- Idea presented to the "Physics Beyond Collider Study Group"
- C. Matteuzzi and G. Venanzoni experiment representatives.
- Physics Beyond Collider Study Group will select experiments aiming to:
  - Enrich and diversify the CERN scientific program
  - Exploit the unique opportunities offered by CERN's accelerator complex and scientific infrastructure
  - Complement the laboratory's collider programme (LHC, HL-LHC and possible future colliders).
  - The scientific findings will be collected in a report to be delivered by the end of 2018. This document will also serve as input to the next update of the European Strategy for Particle Physics.