MUonE
Status and plans

U. Marconi
INFN, Bologna
On behalf of the proponents
Novosibirsk, 2019 February 25

Outlook

- **Plans**: the tight space-time constraints
- **Measurement technique**
- **Detector**
- **Analysis strategy**
  - Theory talks related to MUonE at this conference:
    - **C. Calame**, “Muon electron scattering at NLO”
    - **M. Passera**, “The MUonE project: theory progress”
- **Main systematics**

Measuring α(t) and a_μ^{HLO} with space-like data

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

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

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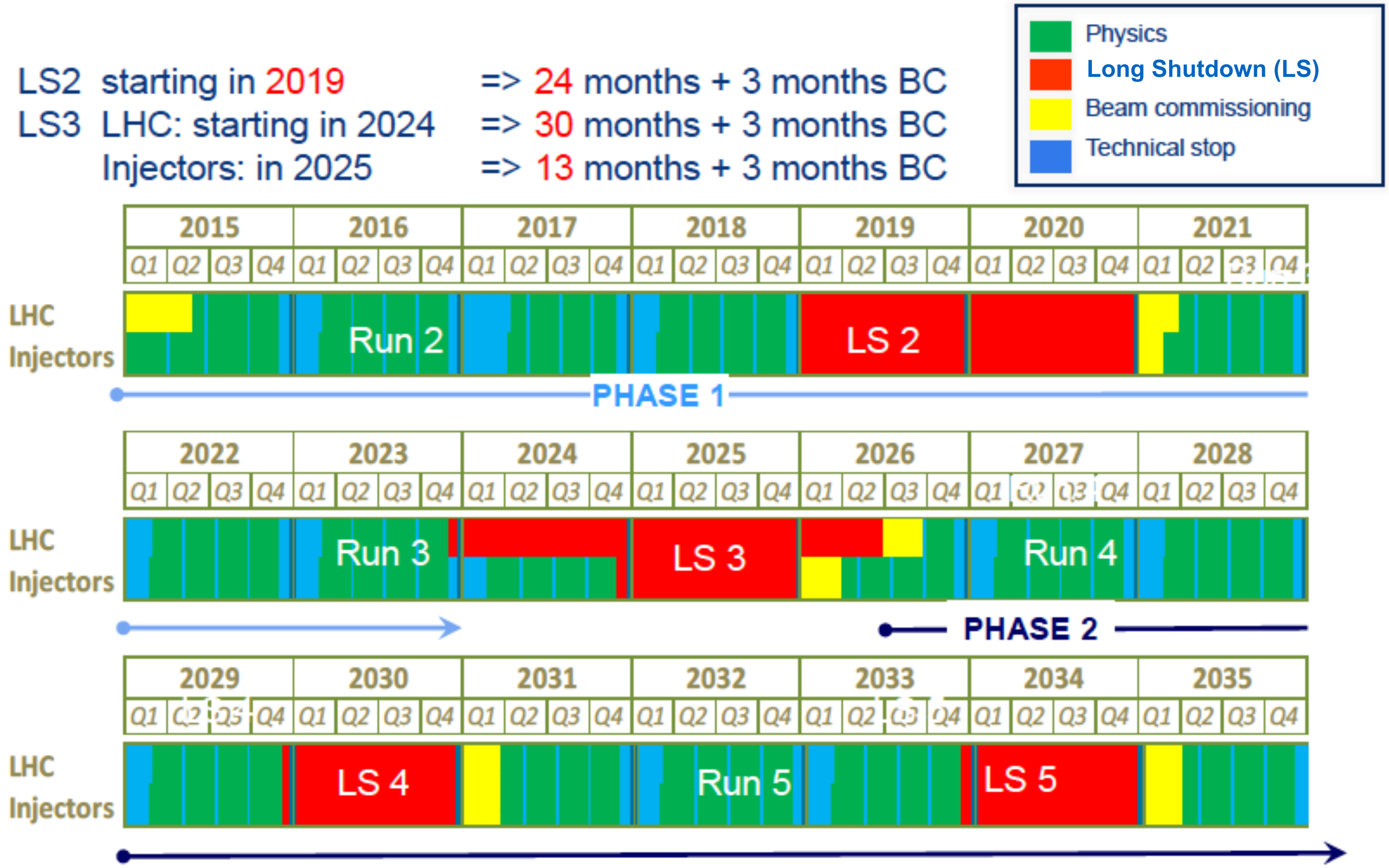
Eur. Phys. J. C (2017) 77: 139.

LHC roadmap, according to MTP 2016-2020*

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC



outline LHC schedule out to 2035 presented by Frederick Bordry to the SPC and FC June 2015

Possible location at CERN M2

- Between BSM and COMPASS

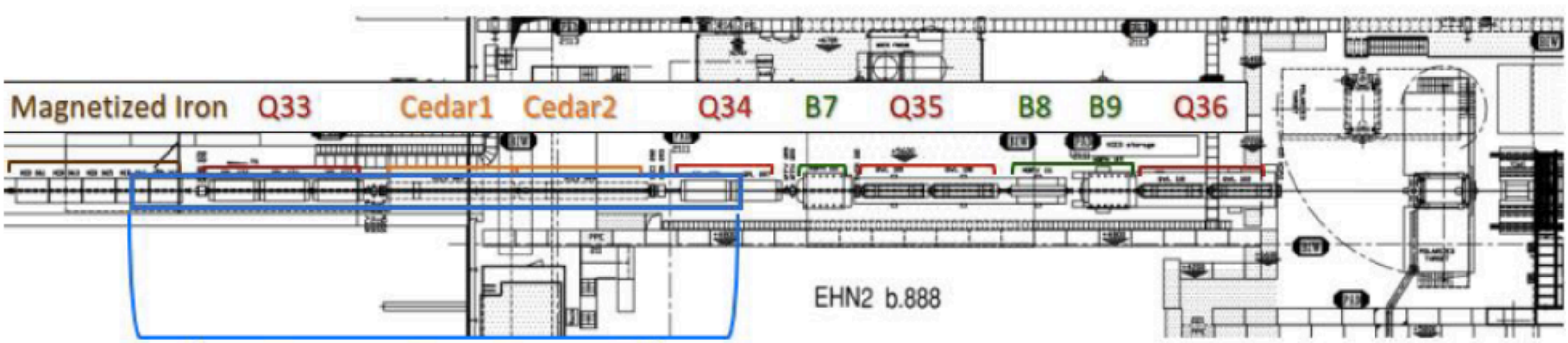
1/ μ-e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

- More upstream of Entrance Area of EHN2 (Proposed by Johannes B. & Dipanwita B.)

- Pro: Could allow running μ-e/μ-p_{Radius} in parallel.

- Questions: will require displacements (also removal) of some M2 components.

- Beam(s) compatibility for μ-e & μ-p_{Radius} : Optic's wise looks OK (see Add. Sl.14 from D.B.)



μ-e Upstream (under-study)
~ 30 m

⇦

Σ length required (updated): 35 m targets + trackers + 0.8 m Ecals + 3 m (μ-Filter) ~ 39 m

10

A. Magnon & C. Valle document

Plans

- **Proposal presented to CERN in the context of the PBC** http://arxiv.org/pdf/1811.11466.pdf
- **Test beam performed in 2017 and 2018**
- **2019**
  - **Finalize the LoI** by June this year.
  - Setting up the Collaboration.
  - Meeting scheduled at CERN, March 24-25
- **2020**
  - Detector design and analysis strategy optimization
- **2021**
  - Final feasibility studies with a detector prototype
- **2022 – 2023**
  - First measurement

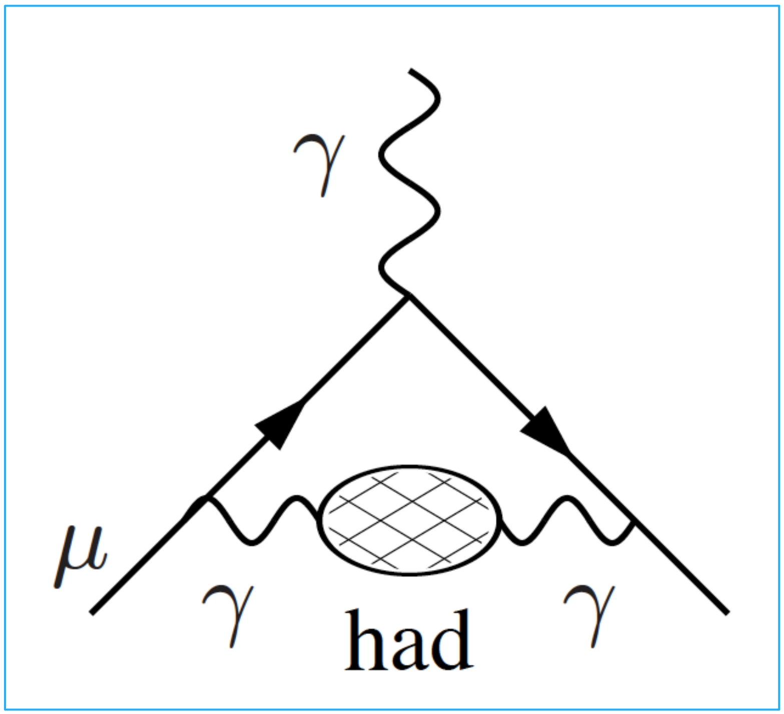
g-2 anomaly
Summary of the present status

- E821 experiment at BNL:
  $\mathbf{a_\mu^{E821} = (11659208.9 \pm 6.3)\times 10^{-10}}$ [0.54 ppm]
- The SM prediction:
  $\mathbf{a_\mu^{SM} = (11659180.2 \pm 4.9)\times 10^{-10}}$ [0.42 ppm]
- **3.5σ discrepancy**:

  $\mathbf{a_\mu^{E821} - a_\mu^{SM} = (28 \pm 8)\times 10^{-10}}$
- **Significance is limited by**:
  - **Experimental uncertainty**:
    New experiments ongoing at FNAL E989 and J-PARC, aiming to improve the precision x4.
  - **Theoretical uncertainty**:
    Theoretical precision is limited by low energy **hadronic effects**.

The Hadronic Leading Order Contribution

Main contribution to the muon g-2 anomaly due to non perturbative hadronic effects



The hadronic vacuum polarization

With time-like data

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

$$\delta a_\mu^{HLO} / a_\mu^{HLO} \sim 0.5\%$$

With with the new approach MUonE aims to a comparable precision

a_μ^{HLO} calculation with time-like data

- Optical theorem and analyticity:

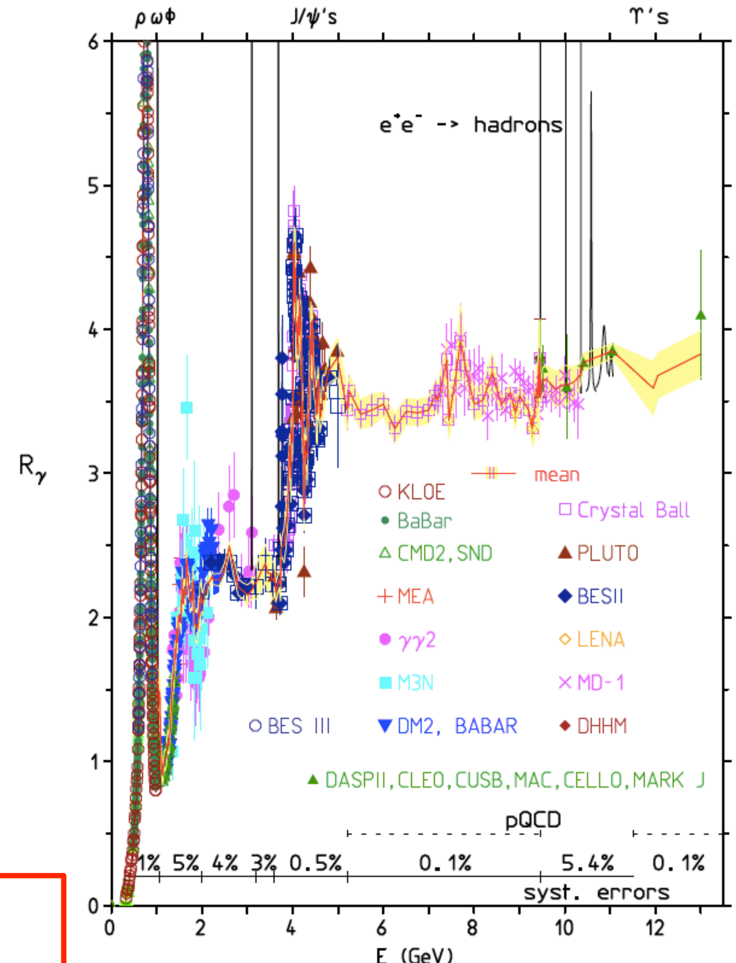
$$\sigma(s)_{(e^+e^-\to had)} = \frac{4\pi}{s}\,\mathrm{Im}\,\Pi_{hadron}(s)$$

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

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

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

Collection of many experimental results



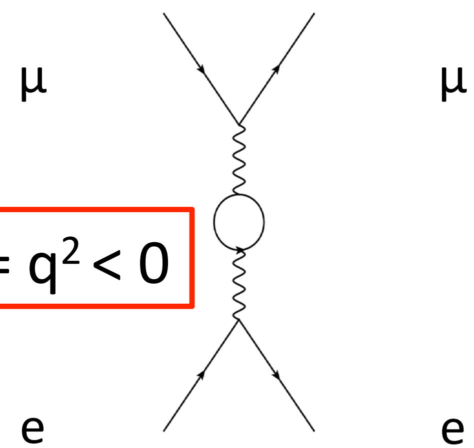
The high-energy tail of the integral is calculated using pQCD

α(t) through: μ + e → μ + e

t-channel: space-like four-momentum transfer

α(t) through:

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

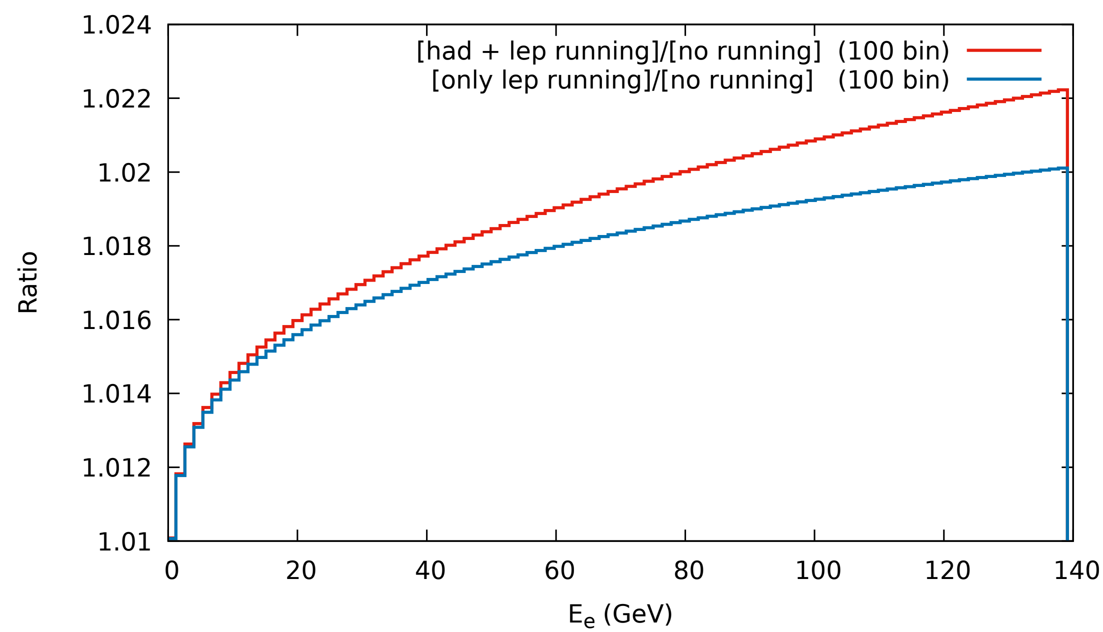


$t = q^2 < 0$

$$t = -2m_e E_e$$

Simulation of the LO differential cross-section μ + e → μ + e elastic scattering

Effect of the hadronic shift $\Delta\alpha_{had}$



Running of α(t) and $\Delta\alpha_{had}(t)$

$\Delta\alpha_{had}(t)$ through:

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

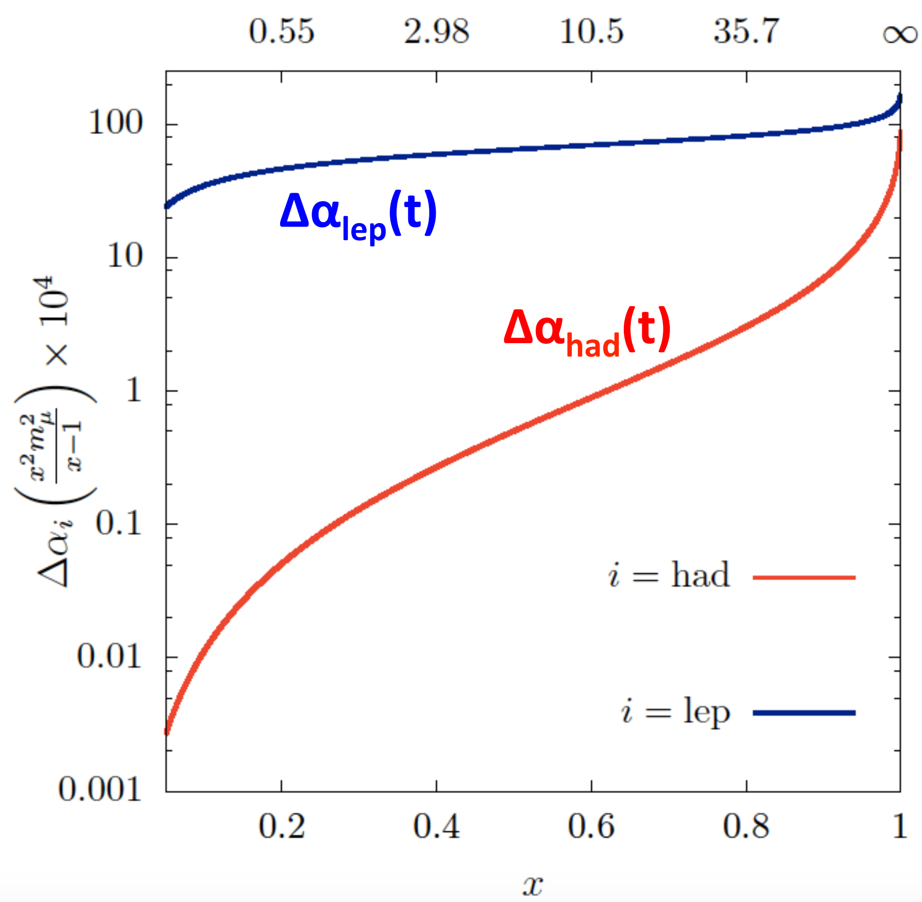
$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$

$\Delta\alpha_{lep}(t)$ can be calculated precisely

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

Expected shifts Δα(t)

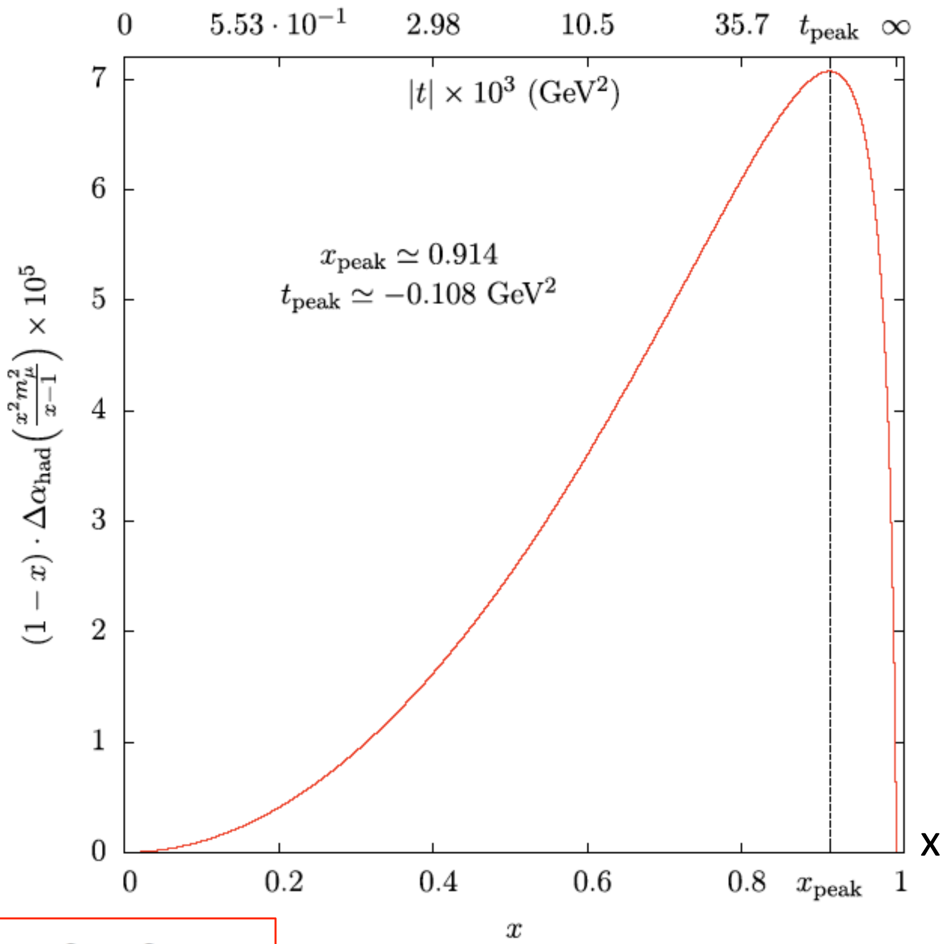
$$t = -m_\mu^2 \frac{x^2}{1-x} \; (10^{-3} GeV^2)$$



a_μ^{HLO} space-like

- Use high-intensity CERN's muon beam of **E_μ ~ 150 GeV** colliding on atomic electrons at rest to measure **$\Delta\alpha_h(t)$** with **$t = q^2 < 0$**.
- **Highly boosted final state**:
  $0 < -t < 0.161$ GeV^2
  $0 < x < 0.93$
- **87%** of the integral.
  Remaining **13%** using pQCD & time-like data, and/or lattice QCD results.

The expected shape of integral function



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

Muon beam M2 at CERN

~ 50 MHz

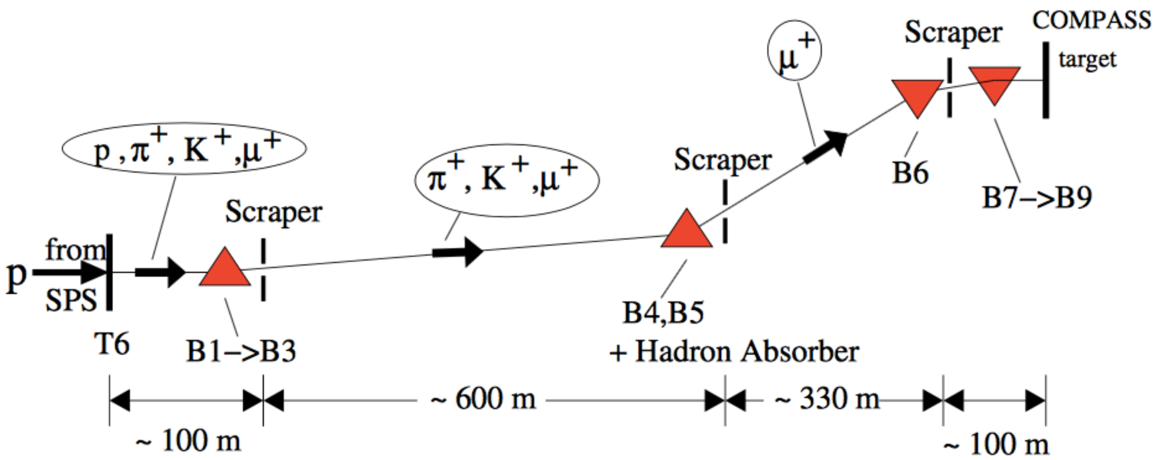


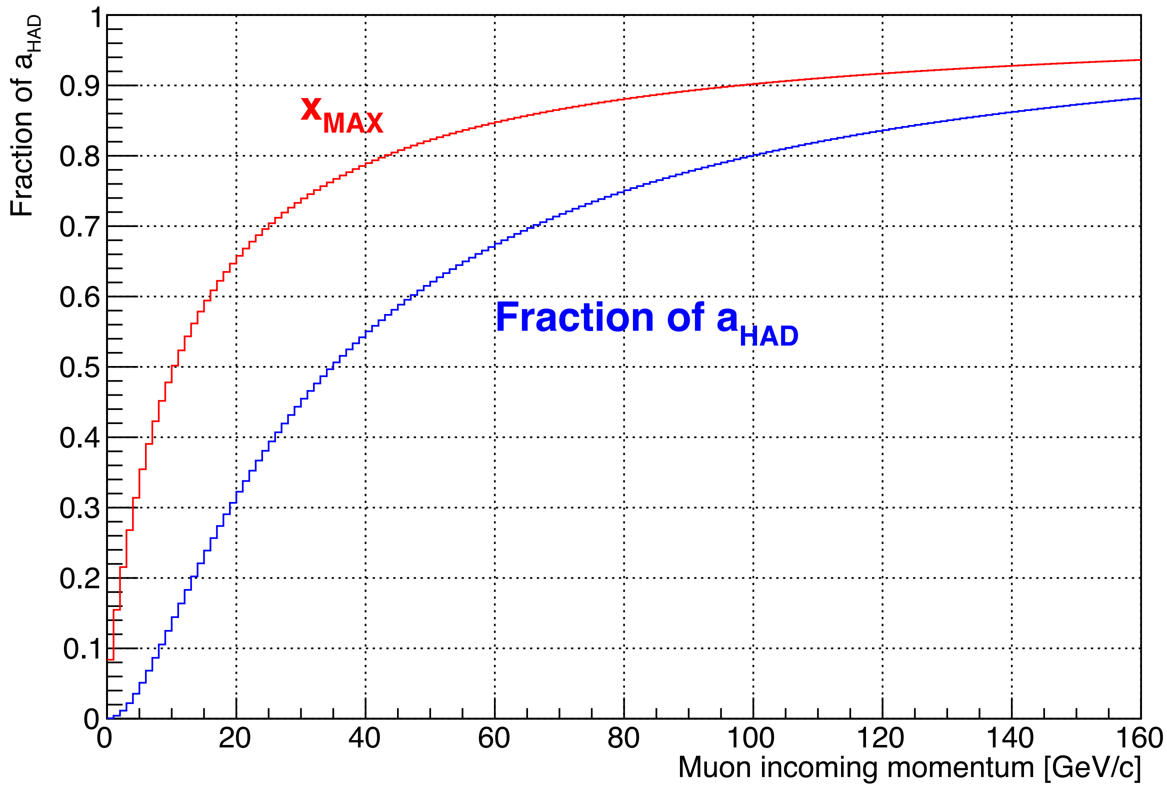
Table 3
Parameters and performance of the 160 GeV/c muon beam.

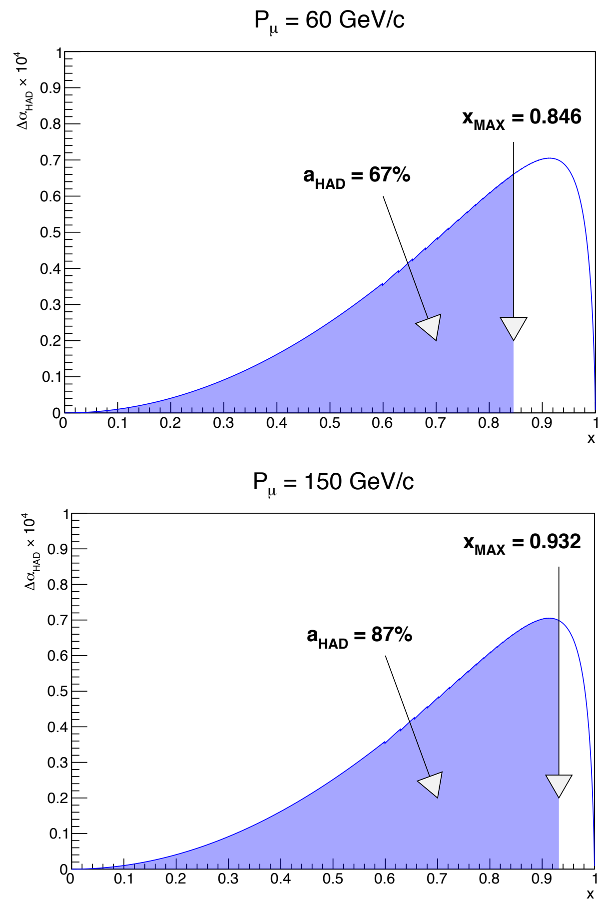
Beam parameters	Measured
Beam momentum $(p_\mu)/(p_\pi)$	$(160\,\mathrm{GeV}/c)/(172\,\mathrm{GeV}/c)$
Proton flux on T6 per SPS cycle	$1.2 \cdot 10^{13}$
Focussed muon flux per SPS cycle	$2 \cdot 10^{8}$
Beam polarisation	$(-80 \pm 4)\%$
Spot size at COMPASS target $(\sigma_x \times \sigma_y)$	$8 \times 8\,\mathrm{mm}^2$
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%

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

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 < 93).

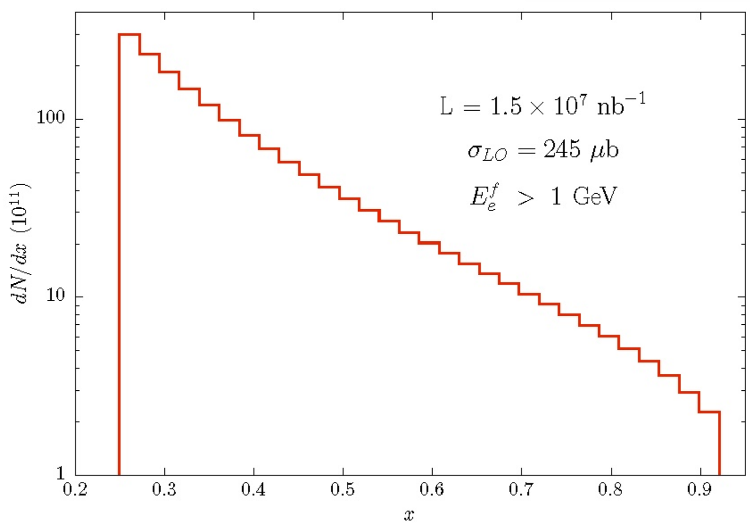


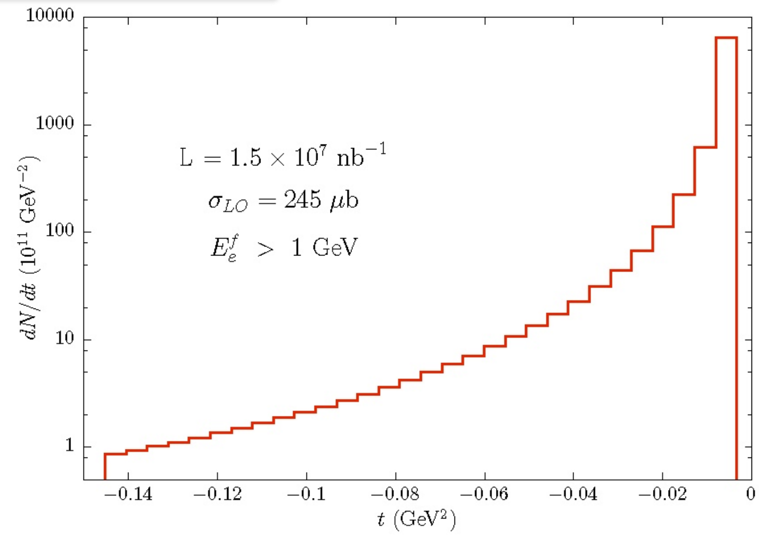


Luminosity

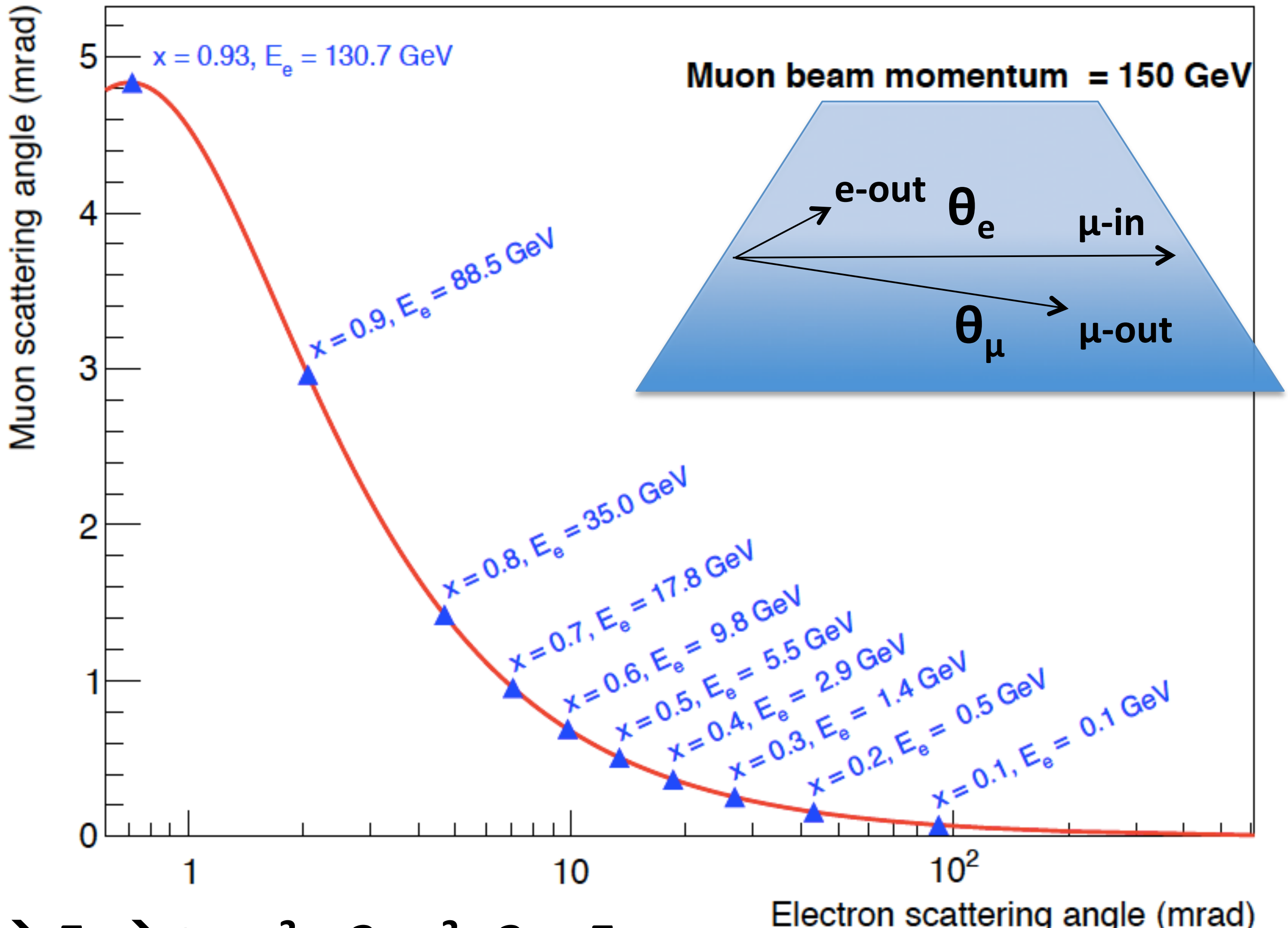
- LO cross-section: $\sigma_{LO}(E_e > 1\ \text{GeV}) = 245\ \mu b$
- **Low Z material**, Beryllium or Carbon, $\rho \approx 2\ g/cm^3$, $Z/A \approx 2$, **$n_e \approx 6 \times 10^{23}\ cm^{-3}$**
- **Rate = $\mathcal{L} \times \sigma = (I_\mu\, n_e\, d)\, \sigma$**
- With the CERN 150 GeV muon beam, which has an average intensity of ~ **$1.3 \times 10^7\ \mu/s$**, incident on **d = 60 cm of Be**, and 2 years of data taking with a running time of 2×10^7 s/yr, one can reach an integrated luminosity of

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





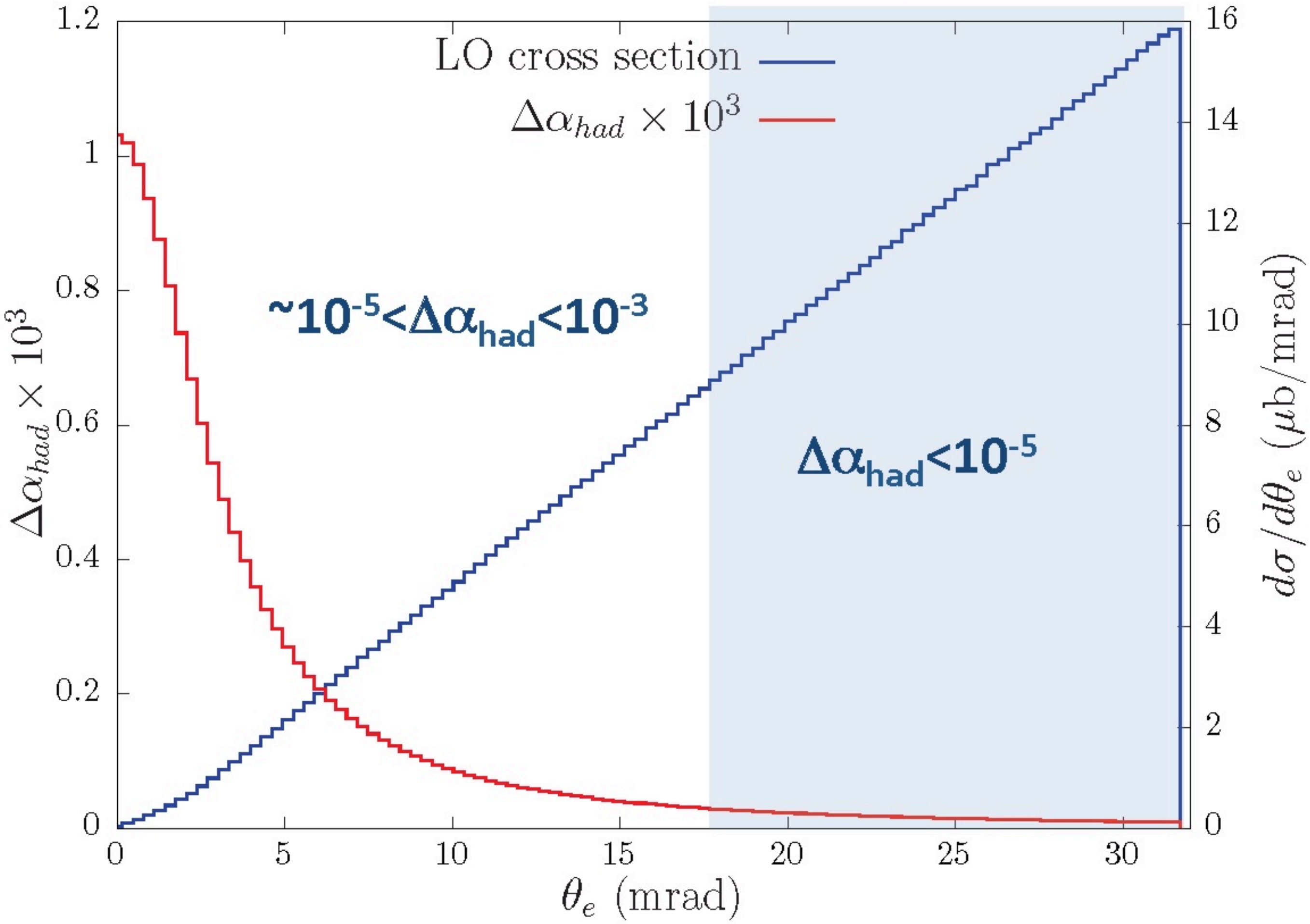
Signature: elastic scattering in the (θ_e , θ_μ) plane



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

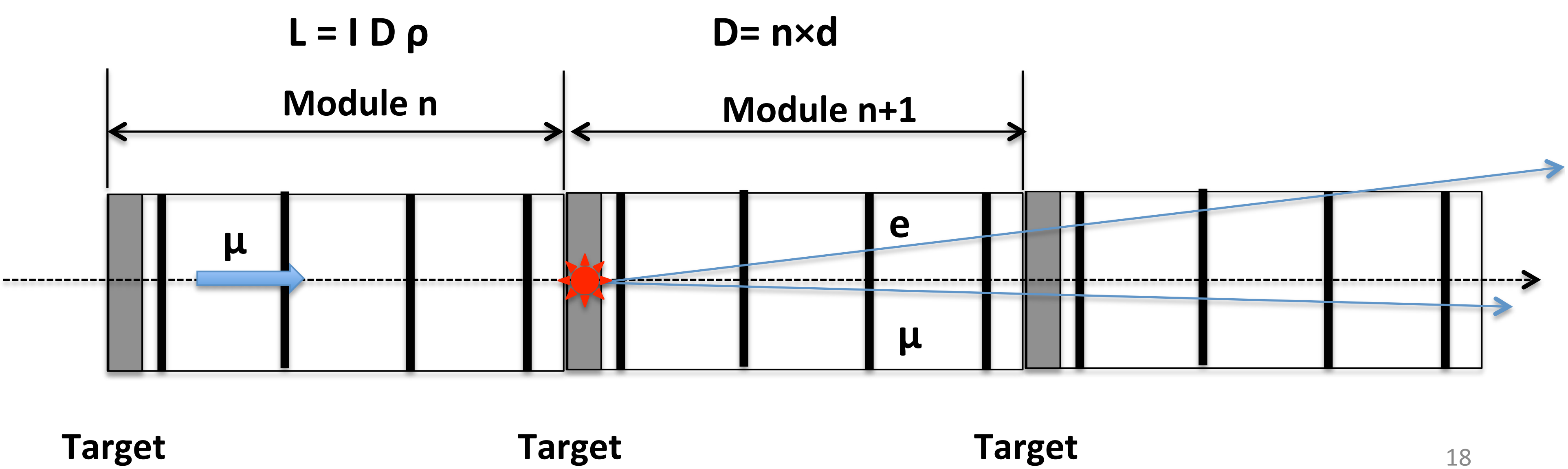
Cross section and the signal

To reach a precision on a_μ^{HLO} as with time-like data (4×10^{-10}):
2 years of data taking, with a muon beam of intensity of $1.3 \times 10^7\ s^{-1}$
60 cm of low Z material segmented in thin layers, each of 10mm



The detector

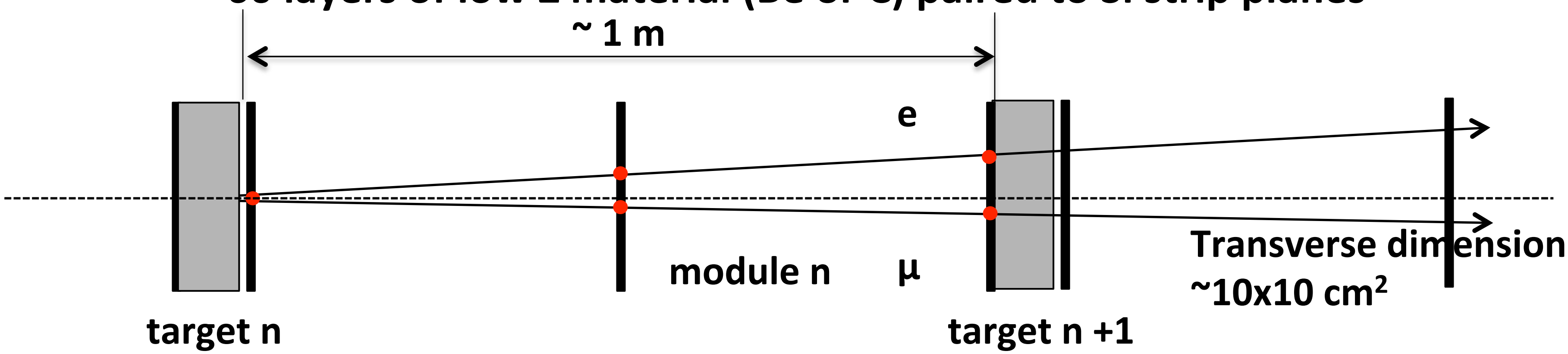
- **Use state of the art silicon detectors**
- A module must be transparent to non interacting muons. Each module tracks muons passing through: to measure the incoming direction right before the next stage.
- The module, where the interaction will take place, acts as a standalone detector.



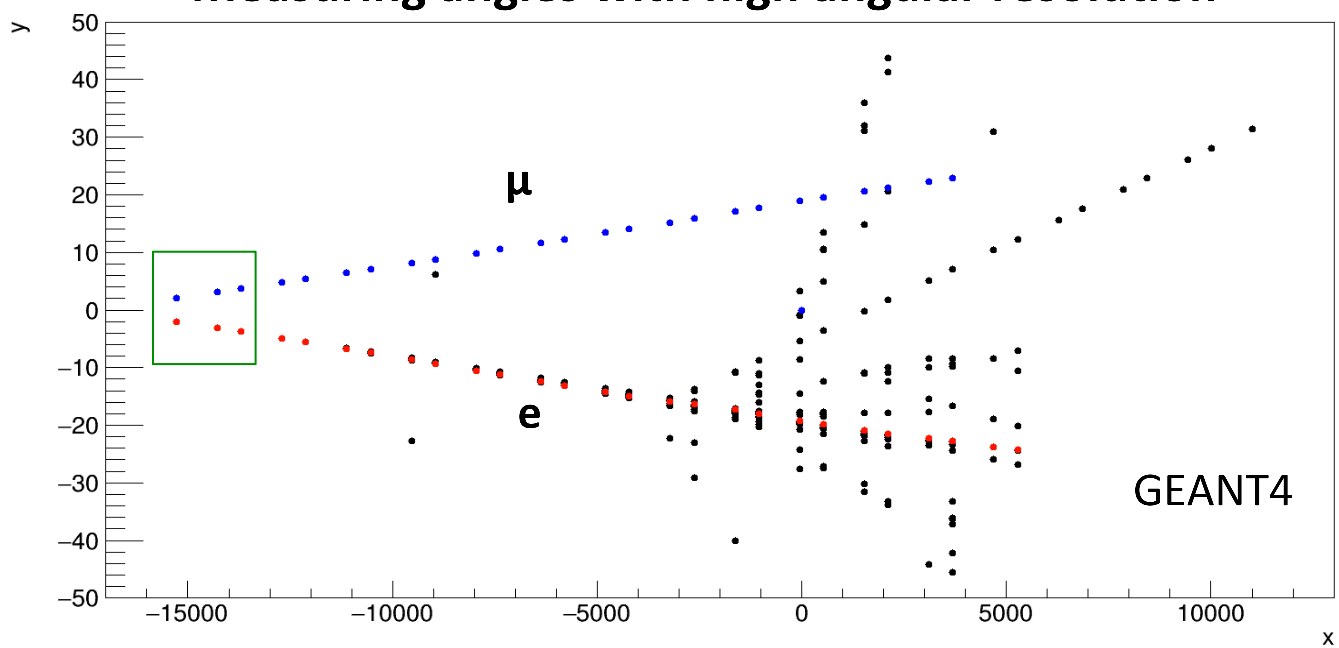
The detector (2)

Modular apparatus covering the full angular acceptance with high uniformity.

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

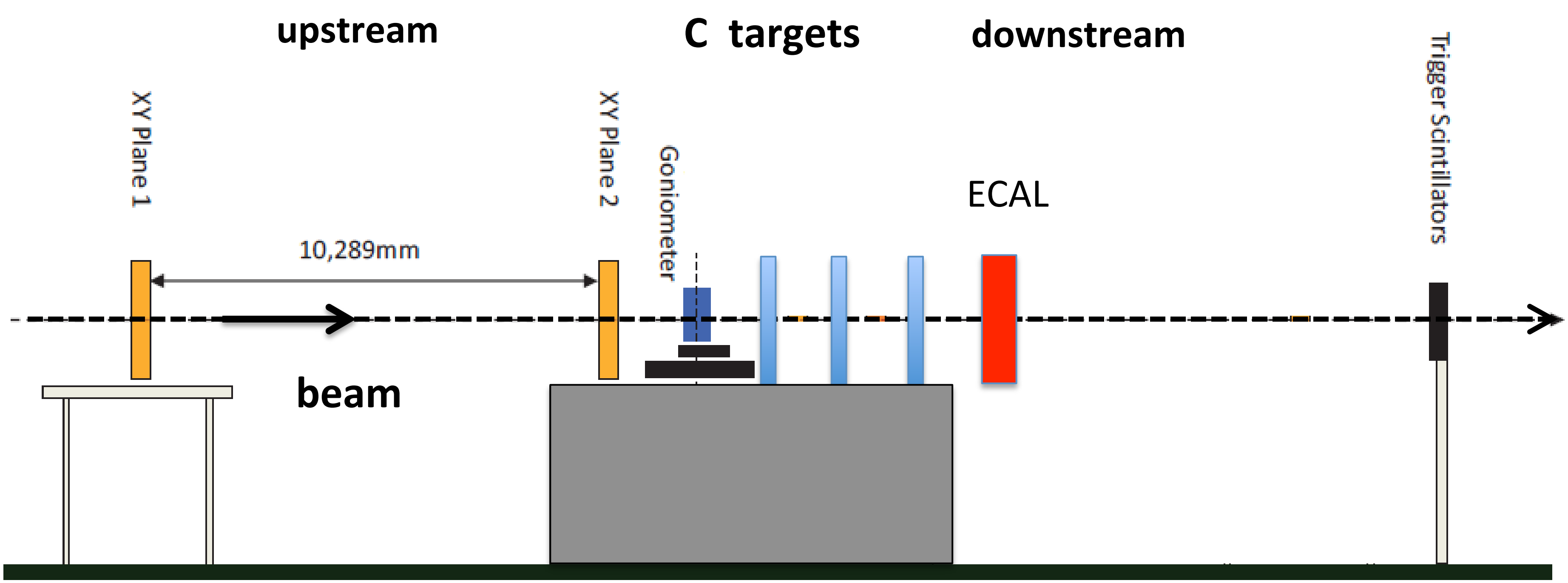


Measuring angles with high angular resolution



Test Beam 2017: the setup

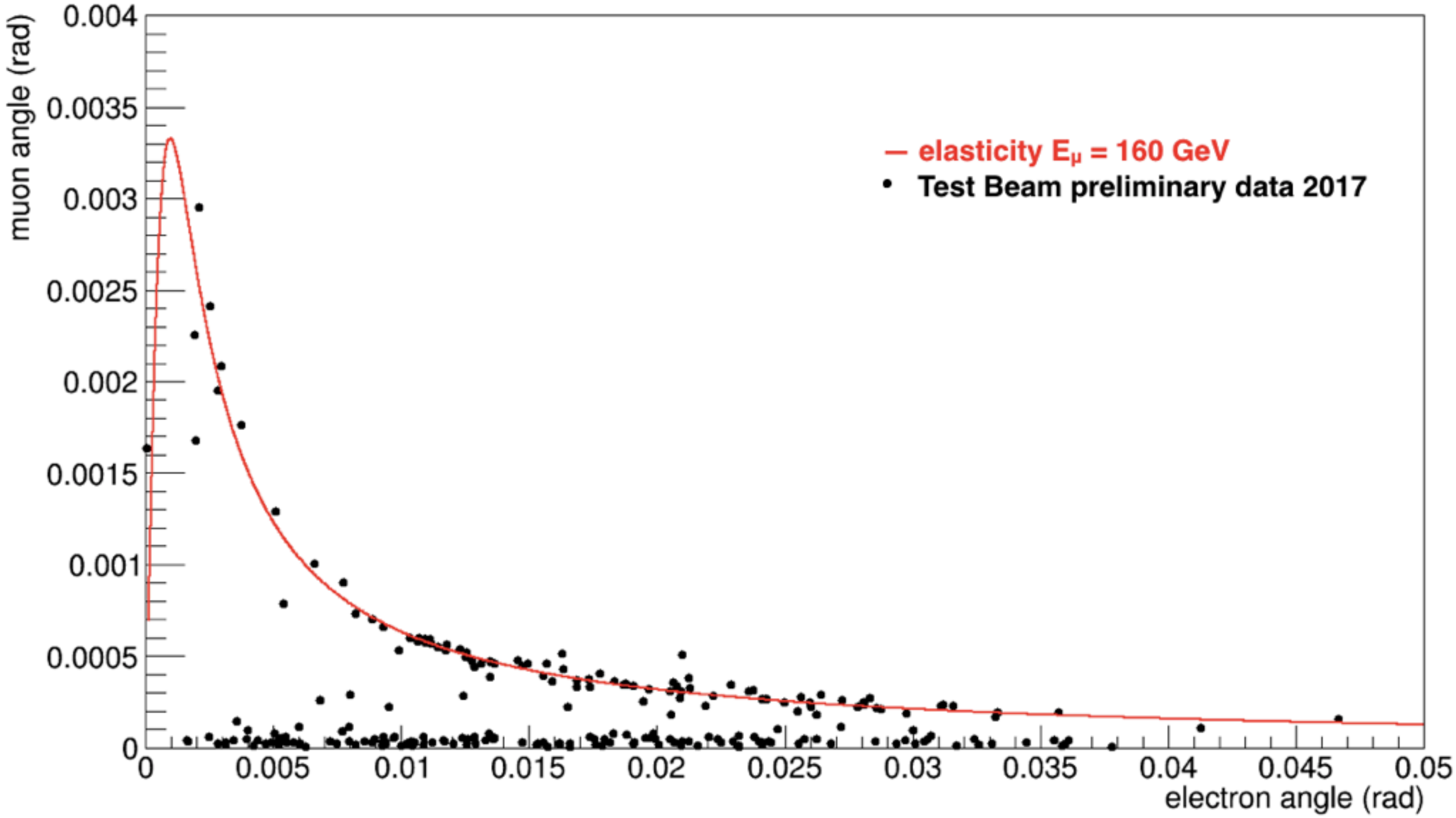
- We used the UA9 tracking system to record scattering data
- Alignment, tracking, pattern recognition done by ourselves starting from scratch as well as for the Geant4 simulations.
- **The goal**: reach **~1%** in the **core** of the MSC distributions and **few per cent on the tales**



UA9 detector

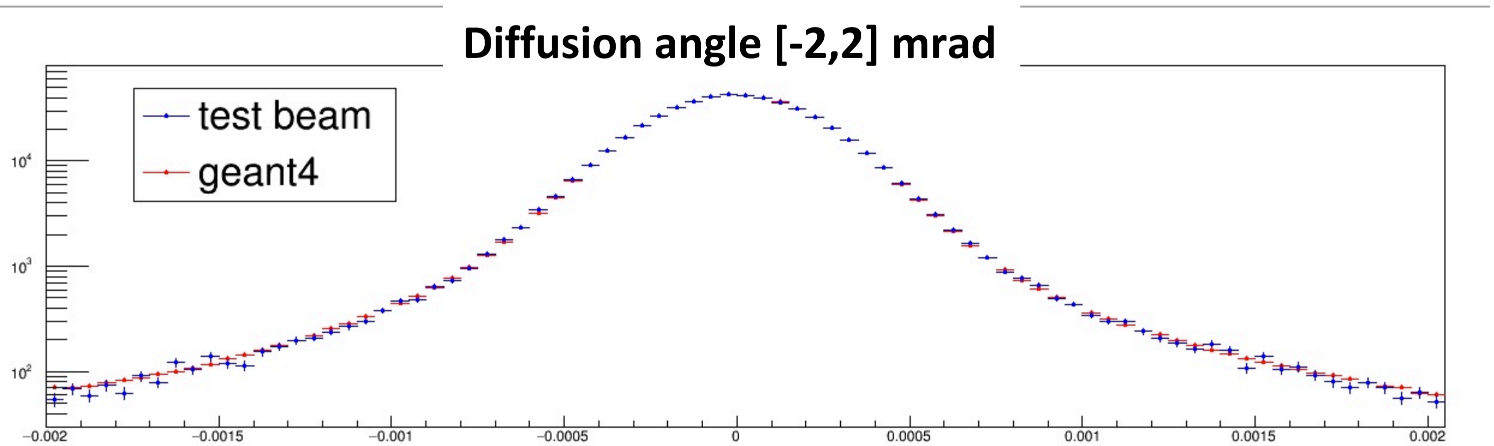
2017 Test Beam Result

Evidence of the elastic scattering

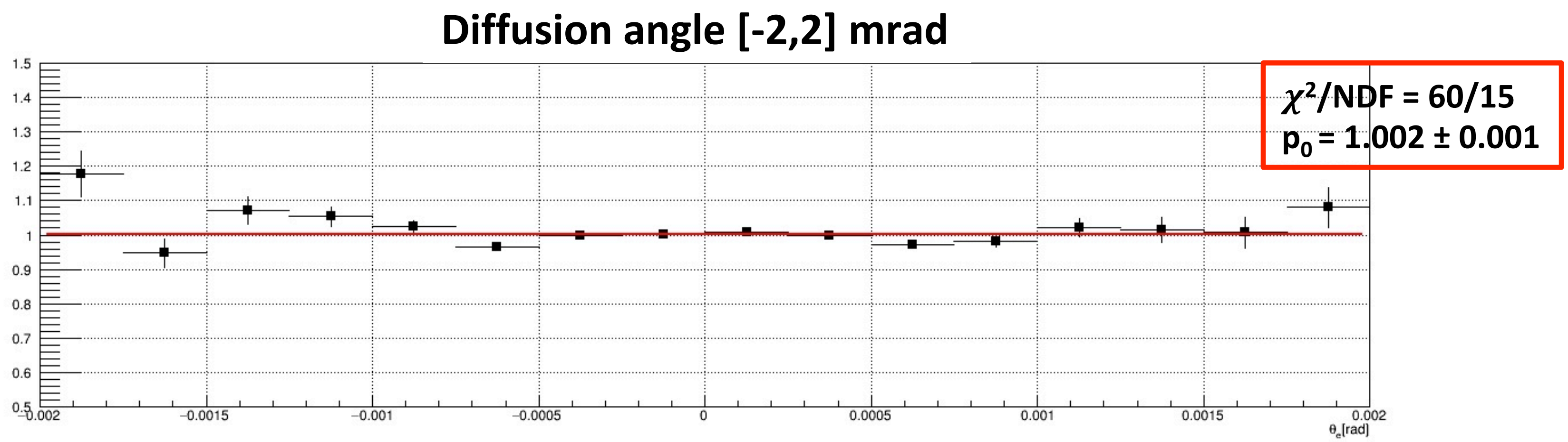


160 GeV muon beam, 8 mm C target
Golden selection: single track in, and two tracks out

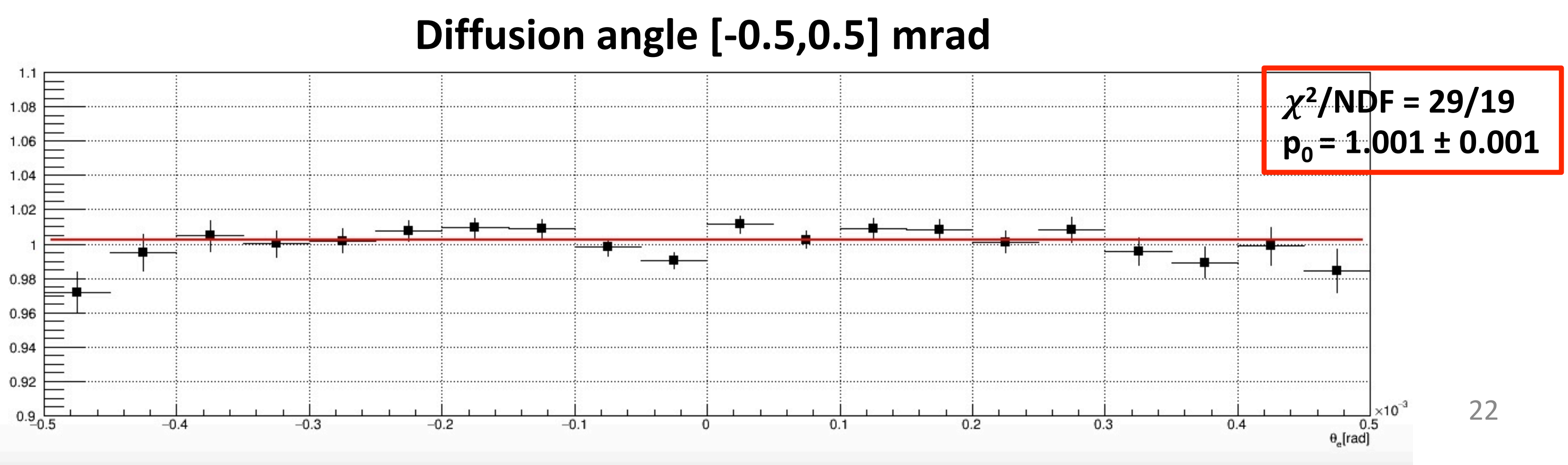
8mm, 12 GeV



Diffusion angle [-2,2] mrad
test beam
geant4



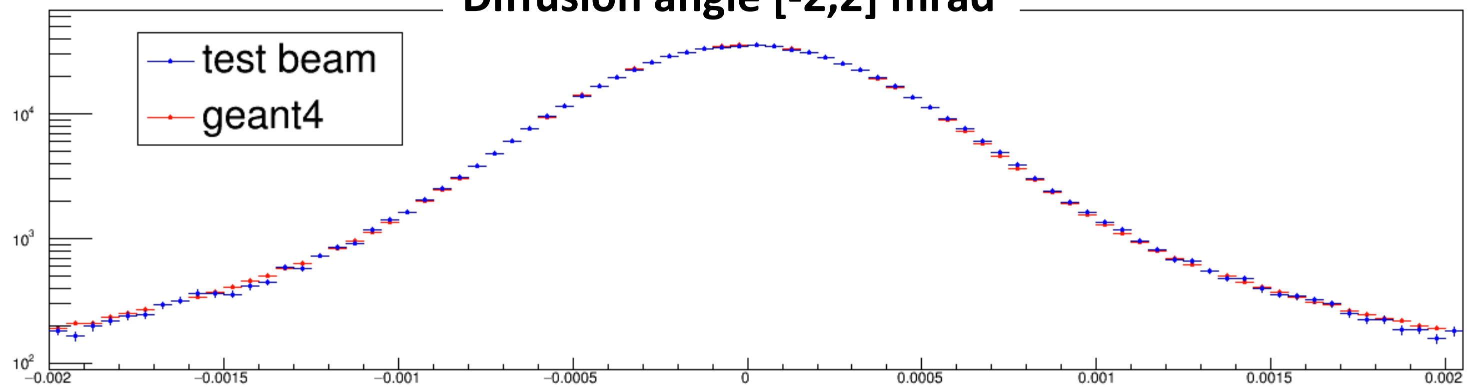
Diffusion angle [-2,2] mrad
χ^2/NDF = 60/15
p_0 = 1.002 ± 0.001
θ_e[rad]



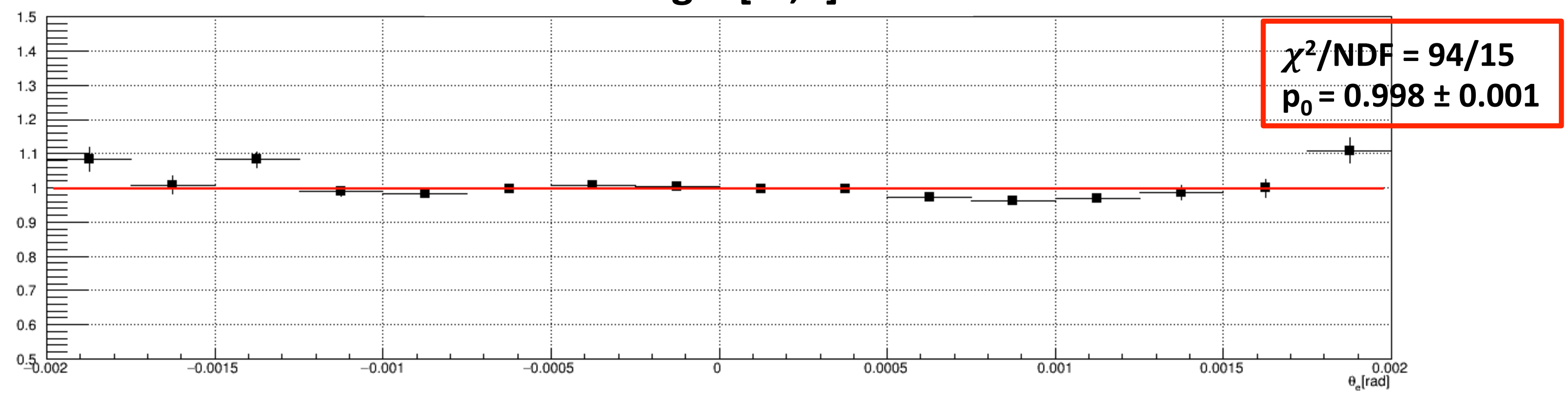
Diffusion angle [-0.5,0.5] mrad
χ^2/NDF = 29/19
p_0 = 1.001 ± 0.001
×10⁻³
θ_e[rad]

20mm, 12 GeV

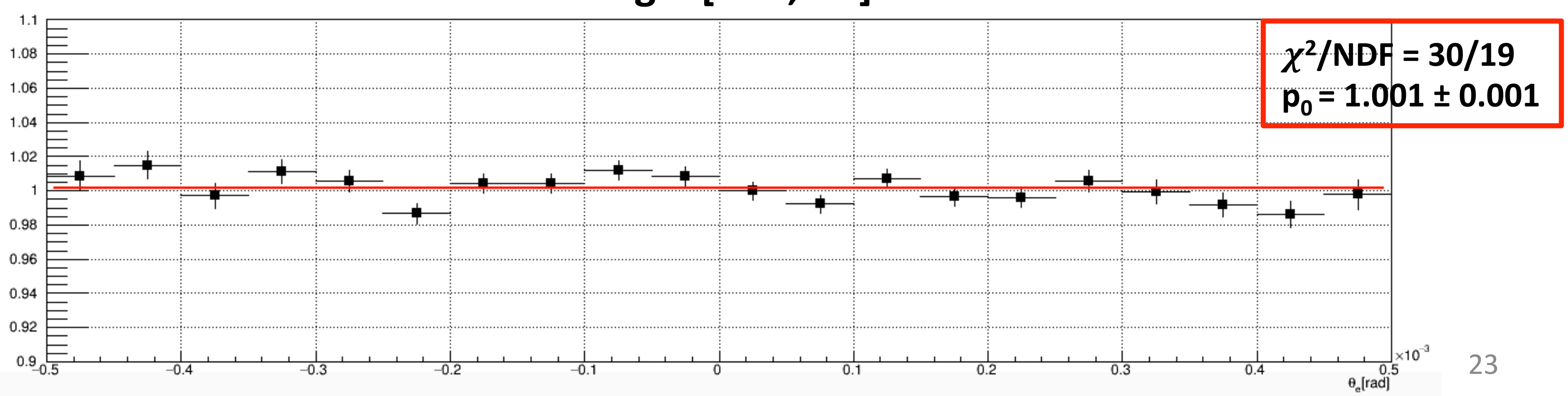
Diffusion angle [-2,2] mrad



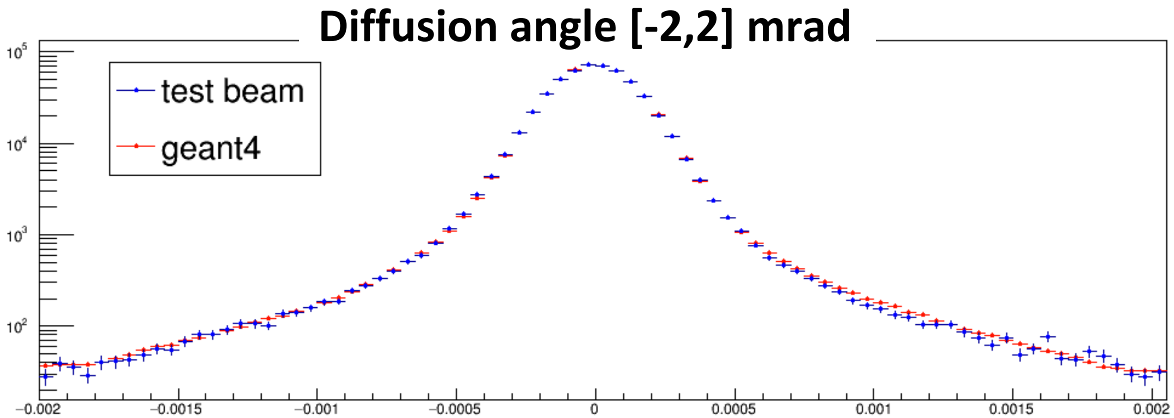
Diffusion angle [-2,2] mrad

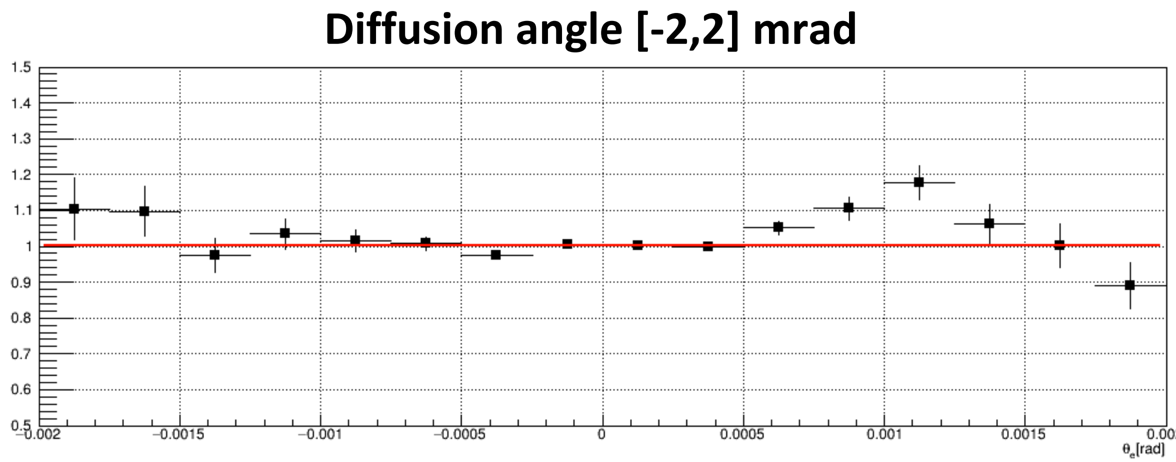


Diffusion angle [-0.5,0.5] mrad

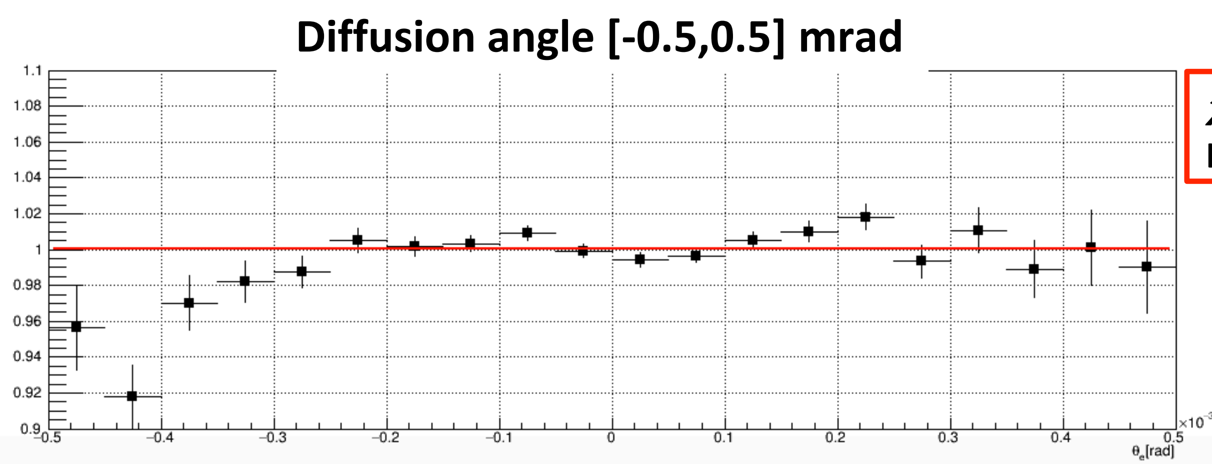


8mm, 20 GeV





χ^2/NDF = 62/15
p_0 = 1.001 ± 0.001

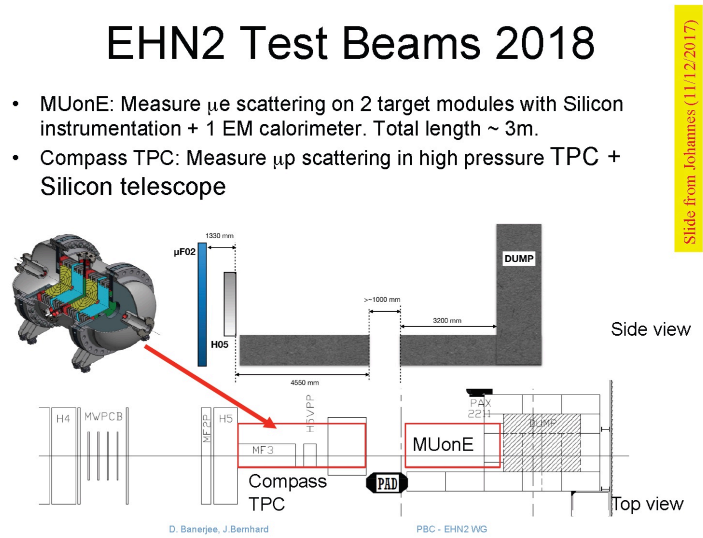


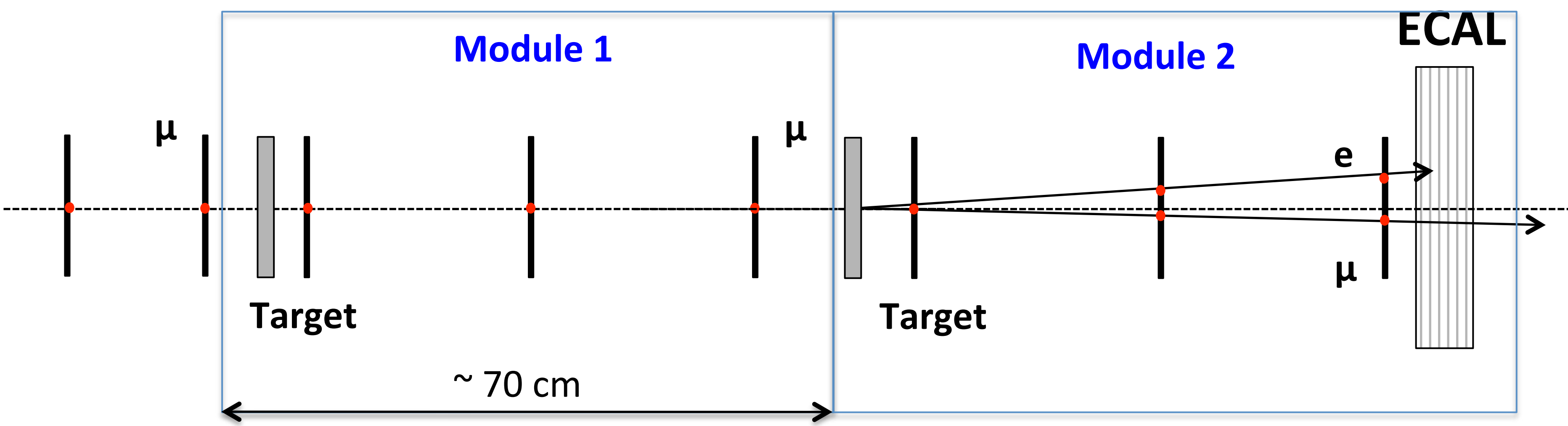
χ^2/NDF = 55/19
p_0 = 1.001 ± 0.001

Test beam 2018

- The setup has been located downstream COMPASS, behind the Tungsten hadrons filter.
- Aim of the measurement campaign: muon – electron elastic scattering with high statistics
  - Using muons from pions decays (hadron beam) with an estimated beam momentum p = (187±7) GeV
  - To measure the correlation between the scattering angles: muon angle vs the electron angle;
  - Electron energy vs the electron angle correlation and PID.
- The detector consists of:
  - Tracking system: stations equipped with the AGILE silicon strip sensors: 400 micron thick, single sided,
    about 40 micron intrinsic hit resolution.
  - Electromagnetic calorimeter: 3x3 cell matrix.

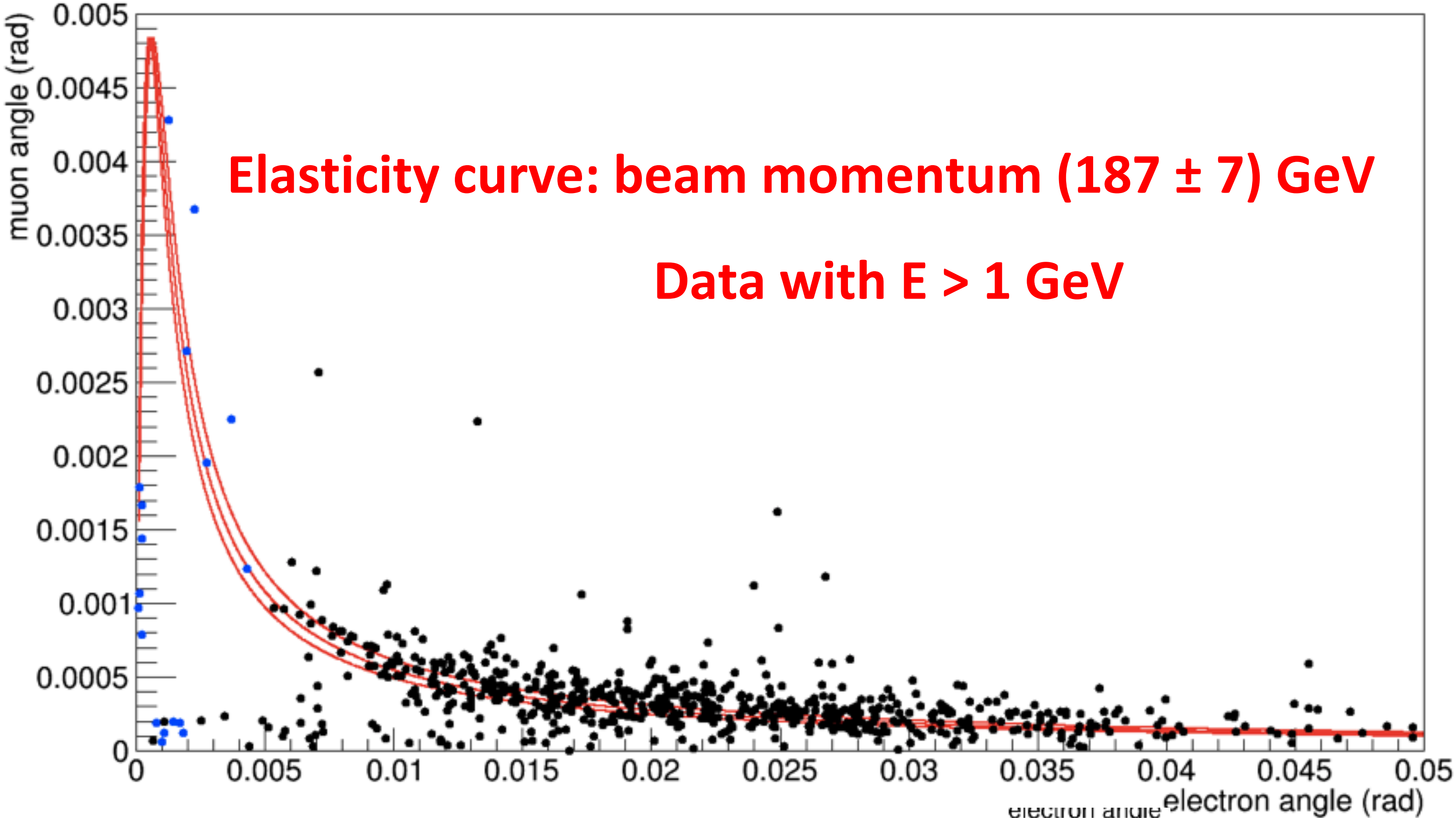
Test Beam 2018

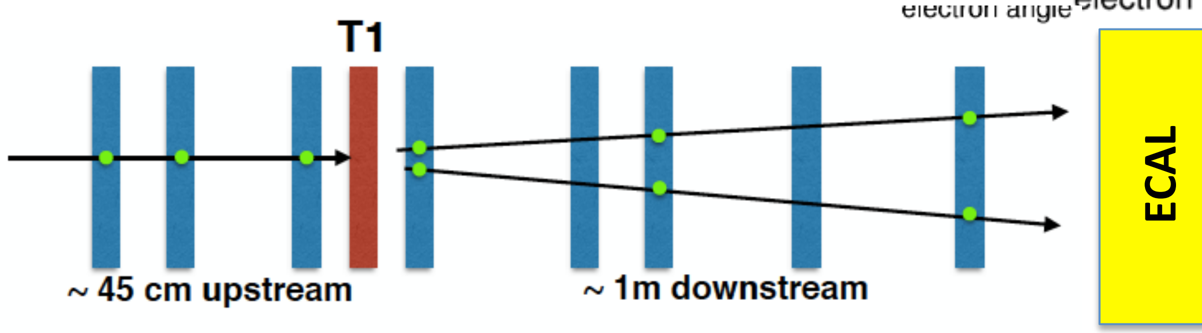





Test beam 2018
With remote control
beam

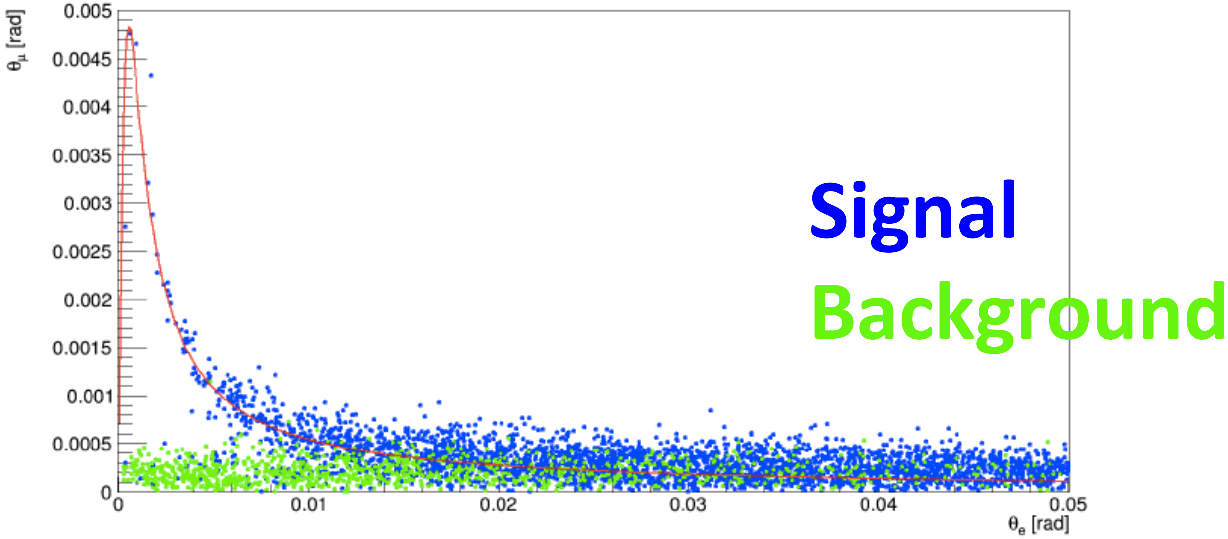
Data: using the Calorimeter

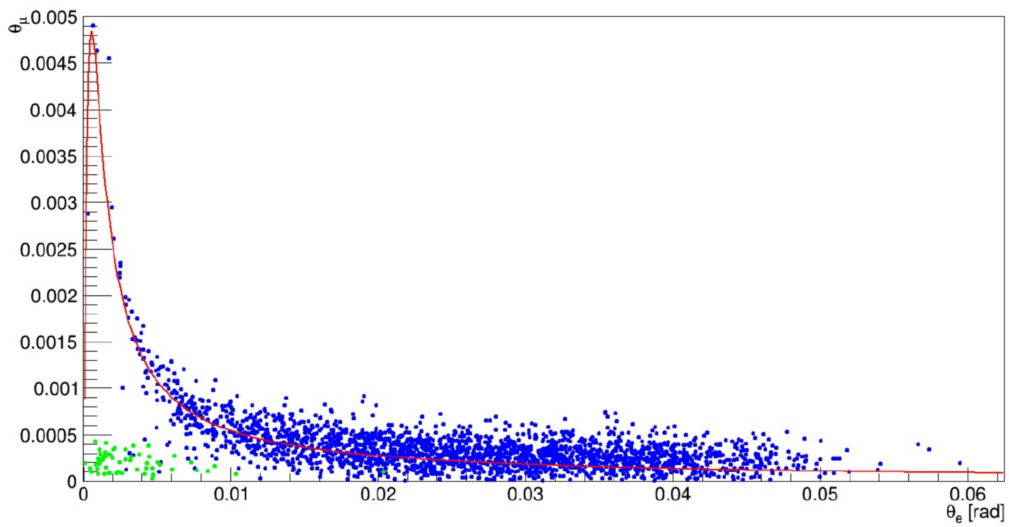




Simulation: Test beam 2018, GEANT4

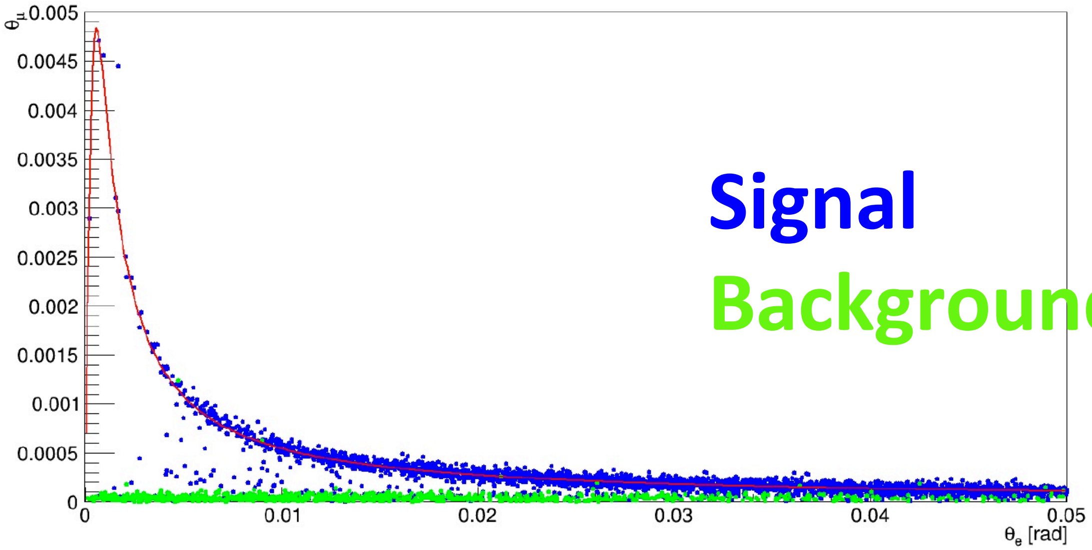
angle_μ vs angle_e





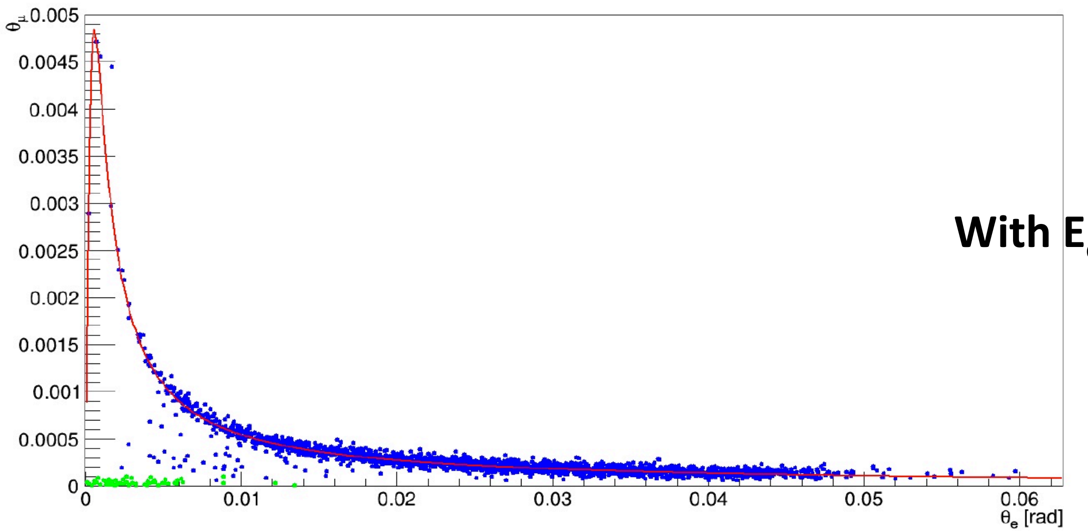
With E_e > 1 GeV energy cut

Effect of the resolution: GEANT4
UA9 resolution 7µm



Signal

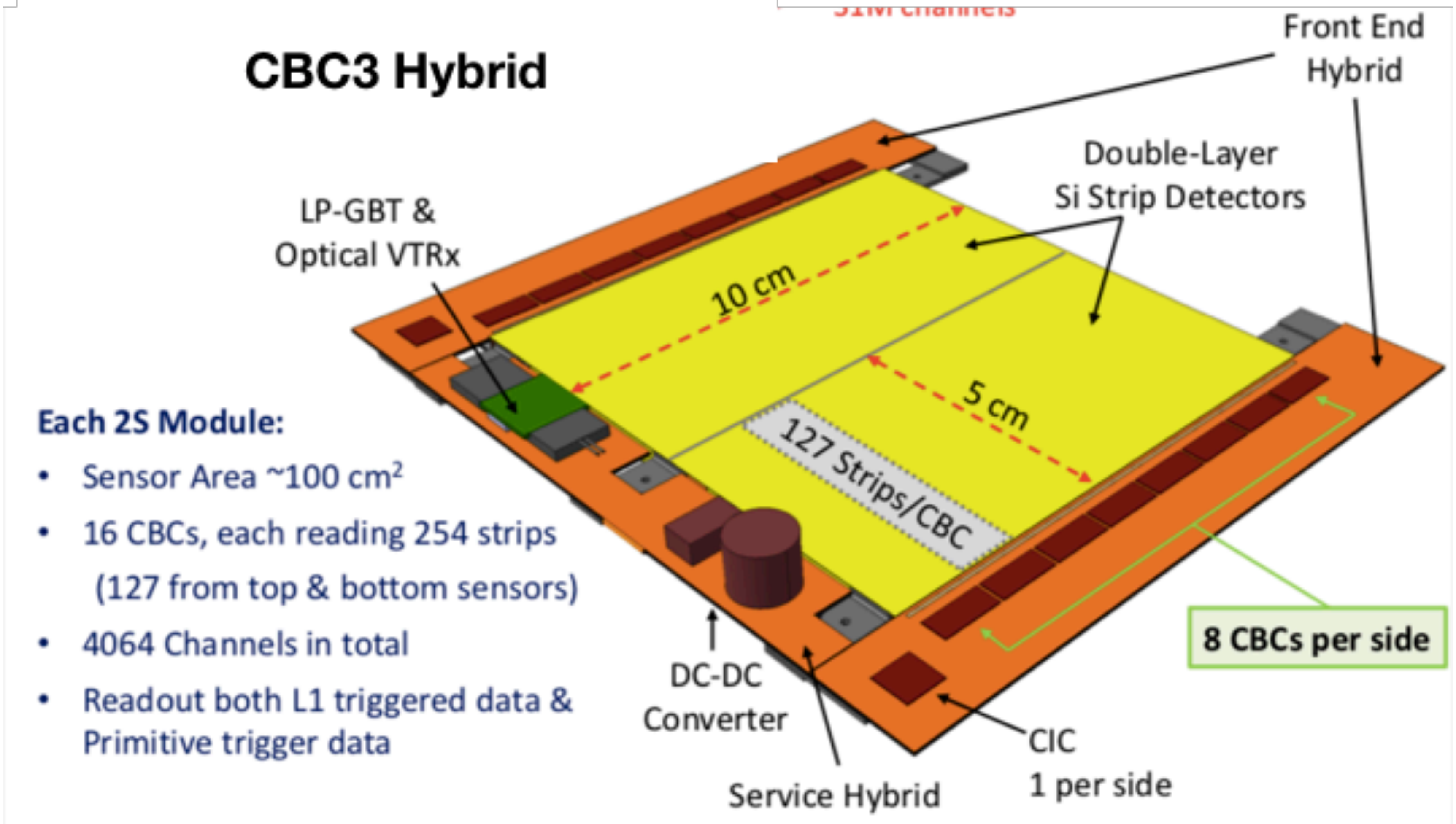
Background



With E_e > 1 GeV energy cut

CBC3 based CMS detector

Intrinsic hit resolution 18 micron

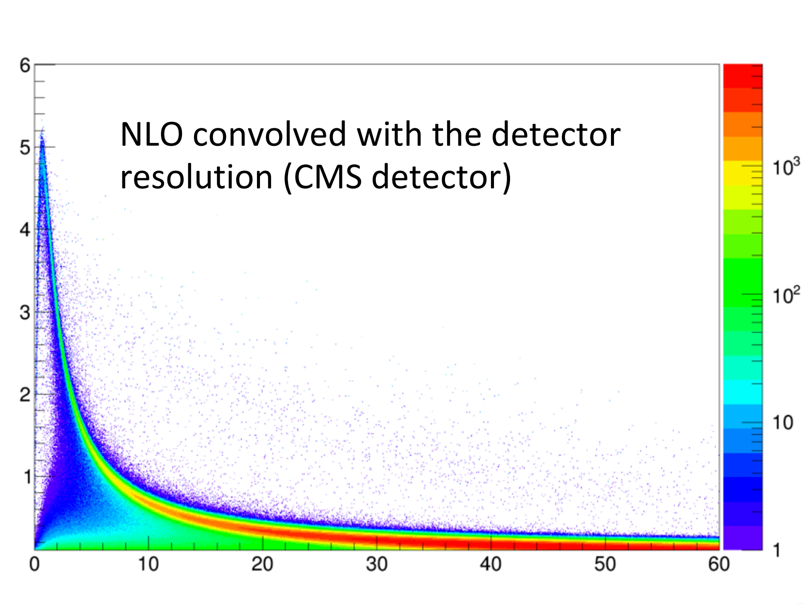


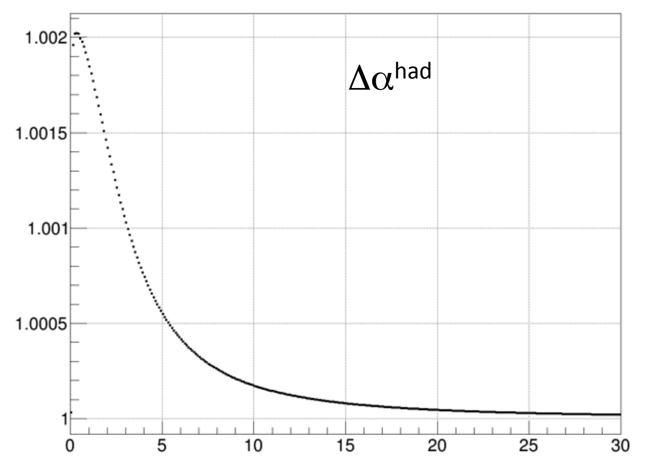
$\alpha(t)$ LO studies

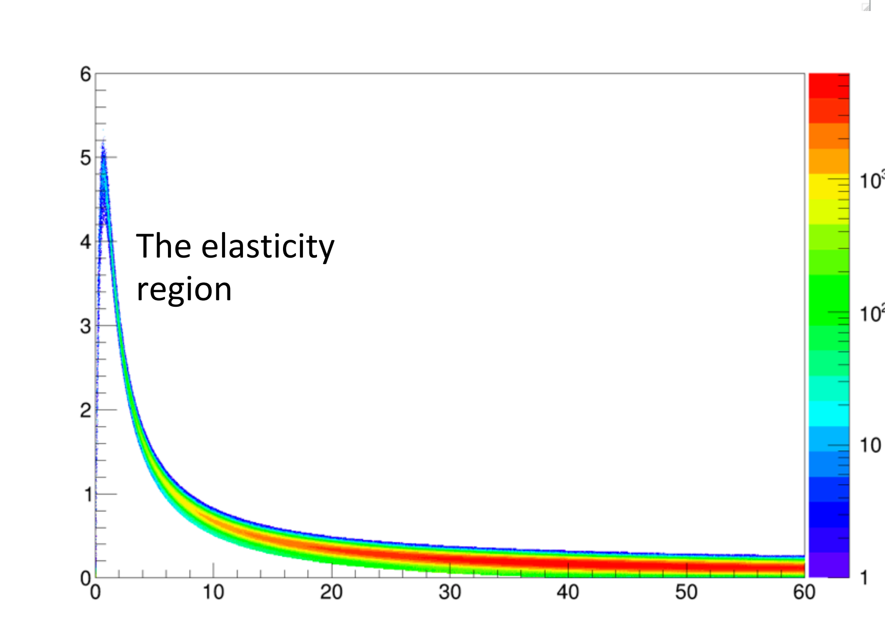
- We studied the feasibility of the measurement in all the details in the leading order approximation.
- Fitting of the pseudo experiment data samples returns the expected values of the leading order hadronic contribution to the muon g-2 anomaly, within the expect precision of 0.5%
- Systematic effects, due to MSC turns out to be controllable, to the required precision.

NLO Studies

- MC NLO available (Pavia Theory group)
- An elasticity region can be defined (containing 95% of the events).
- Sensitivity to the hadronic contribution to the running of α(t) is the expected one.
- The total selection efficiency will depends on additional cuts (coplanarity, energy threshold, etc) needed







Experimental systematics

- Tracking efficiency (homogeneity, angular isotropy)
- Longitudinal position of the sensors.
- Beam momentum energy scale.
- Residual corrections tothe target MSC effects.
- Fitting model

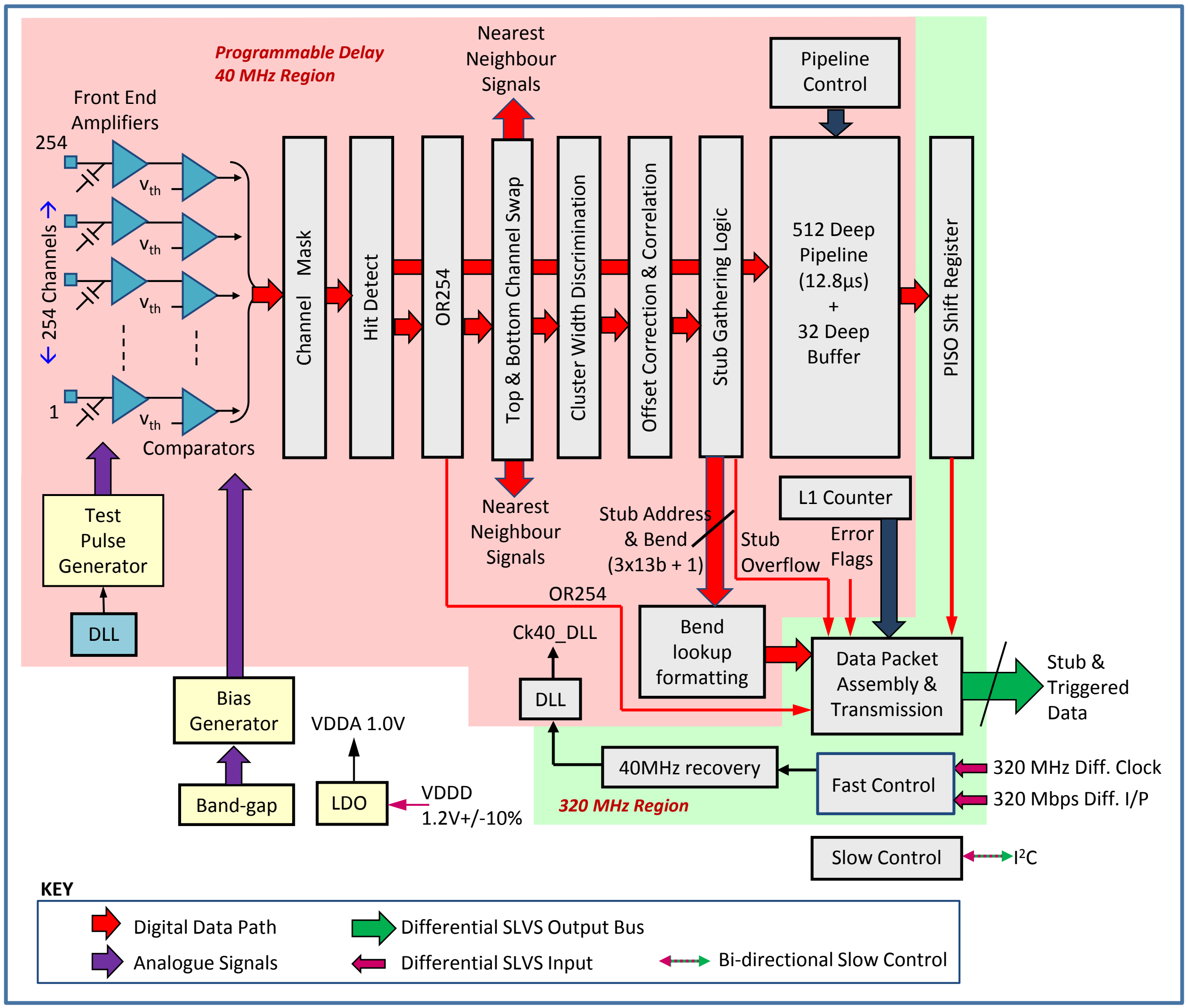
Conclusions

- We are in the phase of writing the Letter of Intent to be submitted by June to the CERN's SPSC
- Still a lot of work ahead of us
  - Workflow in the NLO conditions
  - Evaluate main systematics, in this context
- Valuable solutions for the tracker exist
- Hopefully we will manage to fit within the space and time constraints.

F. Jegelrlehner, April 2018:
https://arxiv.org/pdf/1804.07409.pdf
"Therefore, the very different Euclidean approaches, lattice QCD and **the proposed alternative direct measurements of the hadronic shift Δα (q^2)**[79], in the long term will be indispensable as complementary cross-checks"

The End

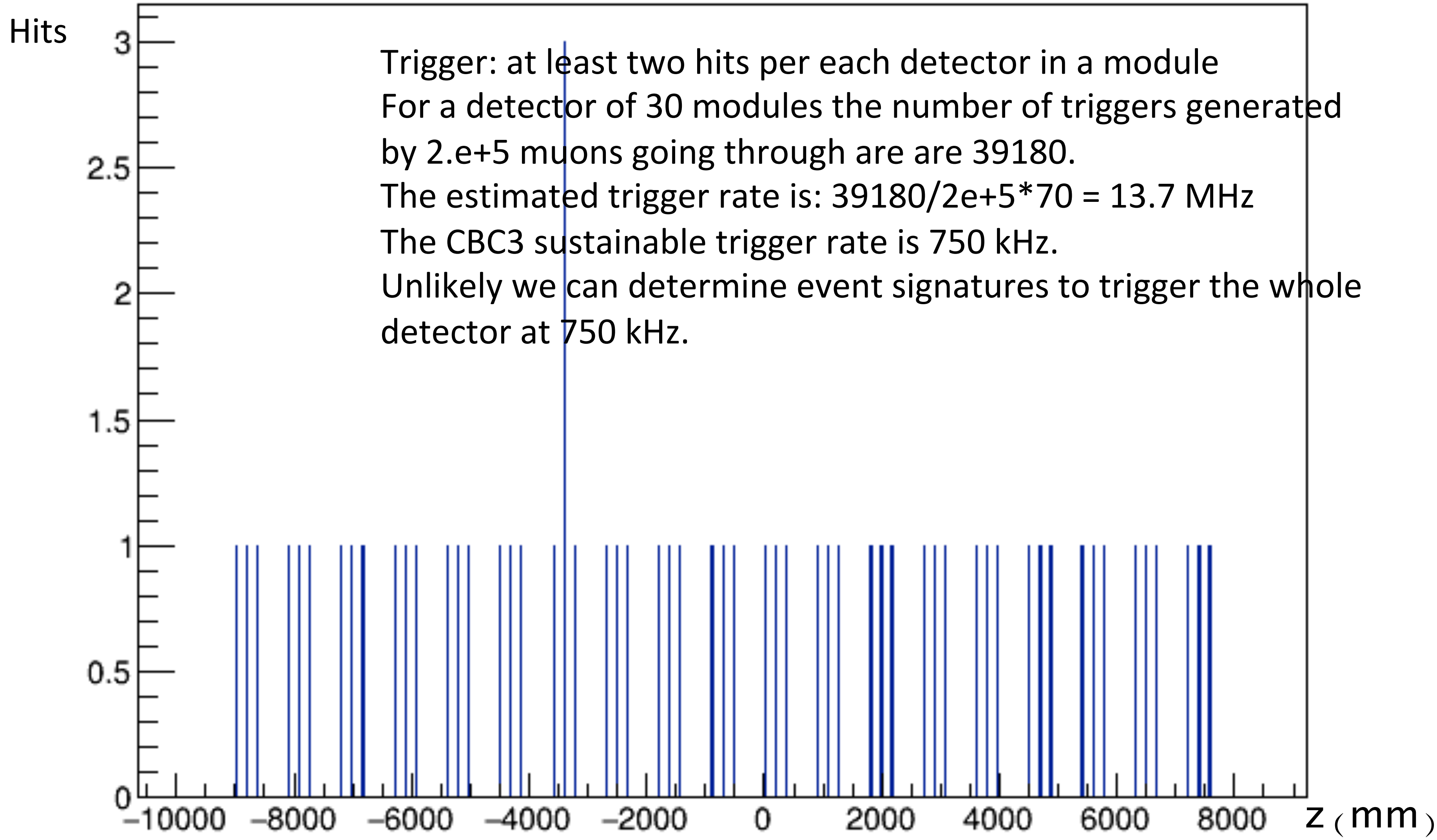
CMS CBC ASIC



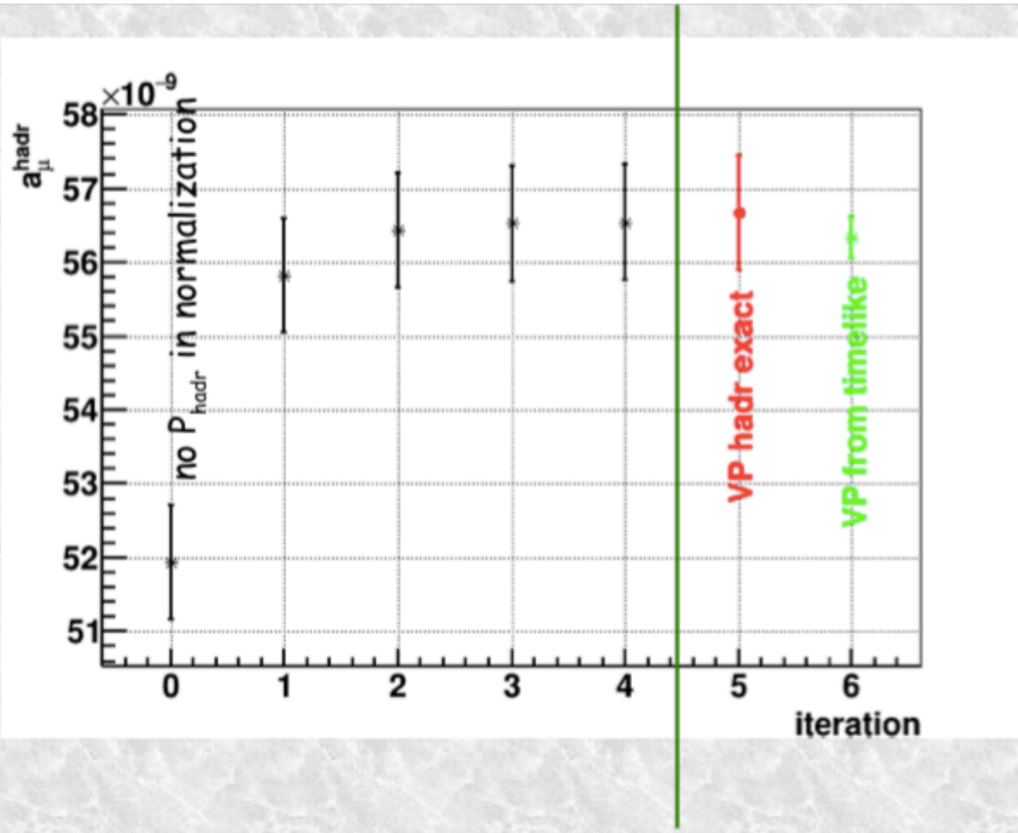
Programmable Delay
40 MHz Region
Nearest Neighbour Signals
Front End Amplifiers
254
254 Channels
1
Vth
Comparators
Channel Mask
Hit Detect
OR254
Top & Bottom Channel Swap
Cluster Width Discrimination
Offset Correction & Correlation
Stub Gathering Logic
Pipeline Control
512 Deep Pipeline (12.8µs) + 32 Deep Buffer
PISO Shift Register
Test Pulse Generator
DLL
Bias Generator
Band-gap
VDDA 1.0V
LDO
VDDD 1.2V+/-10%
Nearest Neighbour Signals
Stub Address & Bend (3x13b + 1)
Stub Overflow
Error Flags
L1 Counter
OR254
Ck40_DLL
DLL
Bend lookup formatting
Data Packet Assembly & Transmission
Stub & Triggered Data
40MHz recovery
Fast Control
320 MHz Diff. Clock
320 Mbps Diff. I/P
320 MHz Region
Slow Control
I2C
KEY
Digital Data Path
Analogue Signals
Differential SLVS Output Bus
Differential SLVS Input
Bi-directional Slow Control

Trigger

Trigger: at least two hits per each detector in a module
For a detector of 30 modules the number of triggers generated by 2.e+5 muons going through are are 39180.
The estimated trigger rate is: 39180/2e+5*70 = 13.7 MHz
The CBC3 sustainable trigger rate is 750 kHz.
Unlikely we can determine event signatures to trigger the whole detector at 750 kHz.



Fitting for $\alpha = \alpha(t)$ cross-section LO



X= 0.377952 - 0.931984

From timelike data:
Δa_μ^{LO} = 563.4 +- 2.8 x 10^{-10}

Integral After last iteration:
565.5 +- 7.8 x 10^{-10}

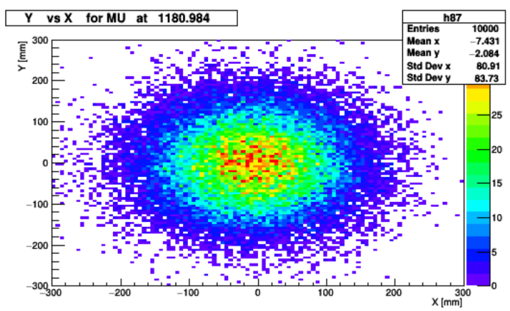
Precision 1.37%
Compatible with 0.4%

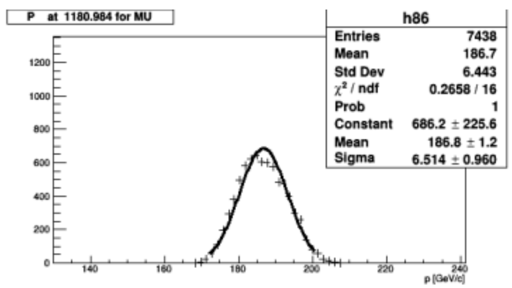
Test Beam 2018

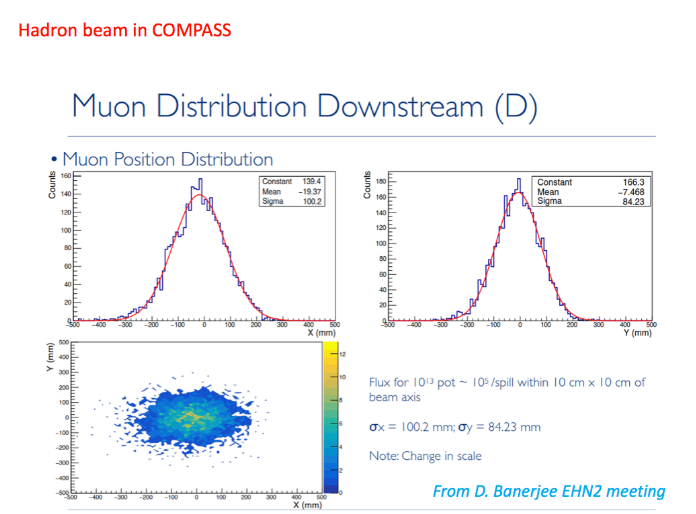
190 GeV/c μ-beam at the MuonE test-setup position : Y vs X and Pμ

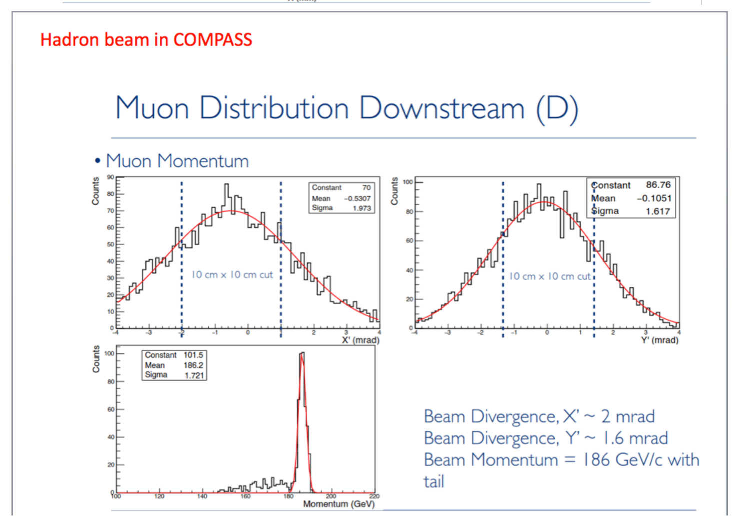
σ_X = 80.9 mm
σ_Y = 83.7 mm

<Pμ> = 186.8 GeV
$\sigma_{P\mu}$ = 6.5 GeV





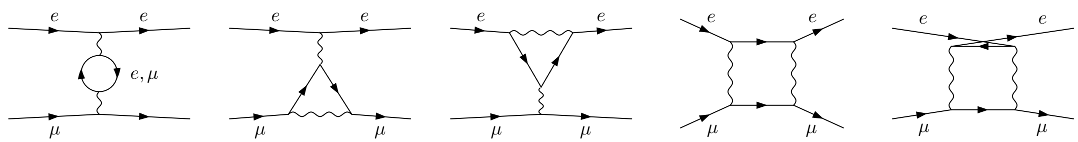




Beam momentum 186 GeV/c

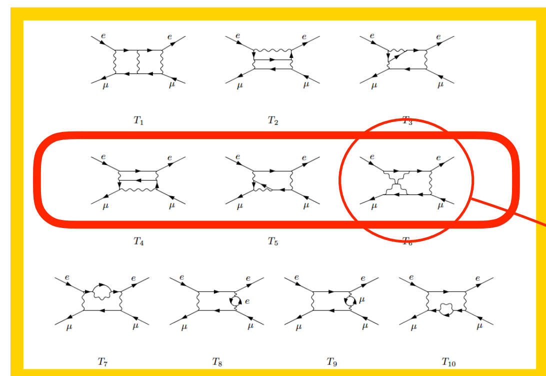
Muon-electron scattering: theory progress

- NLO QED corrections known & checked. MC @ NLO ready and tailored to the fixed target kinematics.



Pavia Group

- NNLO: Missing MI for the planar 2-loop box diagrams computed.



Mastrolia, MP, Primo & Schubert, arXiv:1709.07435.

Non-planar: not yet!

- NNLO amplitudes: virtual 2-loop, real-virtual, double real, automation, subtractions… — Mastrolia, Ossola, MP, Primo, Schubert, Torres
- NNLO hadronic contributions — Fael, MP
- Fixed-order NNLO + Resummation — Broggio, Signer, Ulrich
- Towards a MC at NNLO — Pavia group, Czyz
- Interplay with lattice calculations — Marinković

Our final TH goal: a running MC for the ratio of the SM cross sections in the signal and normalization regions below, at the level, of 10ppm

Theory (2)

1st MUonE theory workshop: Padova - Sep 2017

μe

Muon-electron scattering:
Theory kickoff workshop

4-5 September 2017

https://agenda.infn.it/internalPage.py?pageId=0&confId=13774

The aim of the workshop is to explore the opportunities offered by a recent proposal for a new experiment at CERN to measure the scattering of high-energy muons on atomic electrons of a low-Z target through the process $\mu e \to \mu e$. The focus will be on the theoretical predictions necessary for this scattering process, its possible sensitivity to new physics signals, and the development of new high-precision Monte Carlo tools. This kickoff workshop is intended to stimulate new ideas for this project.

It is organized and hosted by INFN Padova and the Physi
University.

Organizing Committee
Carlo Carloni Calame - INFN Pavia
Pierpaolo Mastrolia - U. Padova
Guido Montagna - U. Pavia
Oreste Nicrosini - INFN Pavia
Paride Paradisi - U. Padova
Massimo Passera - INFN Padova (Chair)
Fulvio Piccinini - INFN Pavia
Luca Trentadue - U. Parma

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Anna Dalla Vecchia, INFN-Sez. PD +390499677022 anna.da
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INFN Istituto Nazionale di Fisica Nucleare

Università degli Studi di Padova

2nd MUonE theory workshop: Mainz - Feb 2018

μe

Mainz Institute for Theoretical Physics

2018

SCIENTIFIC PROGRAMS

Probing Physics Beyond SM with Precision
Ansgar Denner U Würzburg, Stefan Dittmaier U Freiburg, Tilman Plehn U Heidelberg
February 26-March 9, 2018

Bridging the Standard Model to New Physics

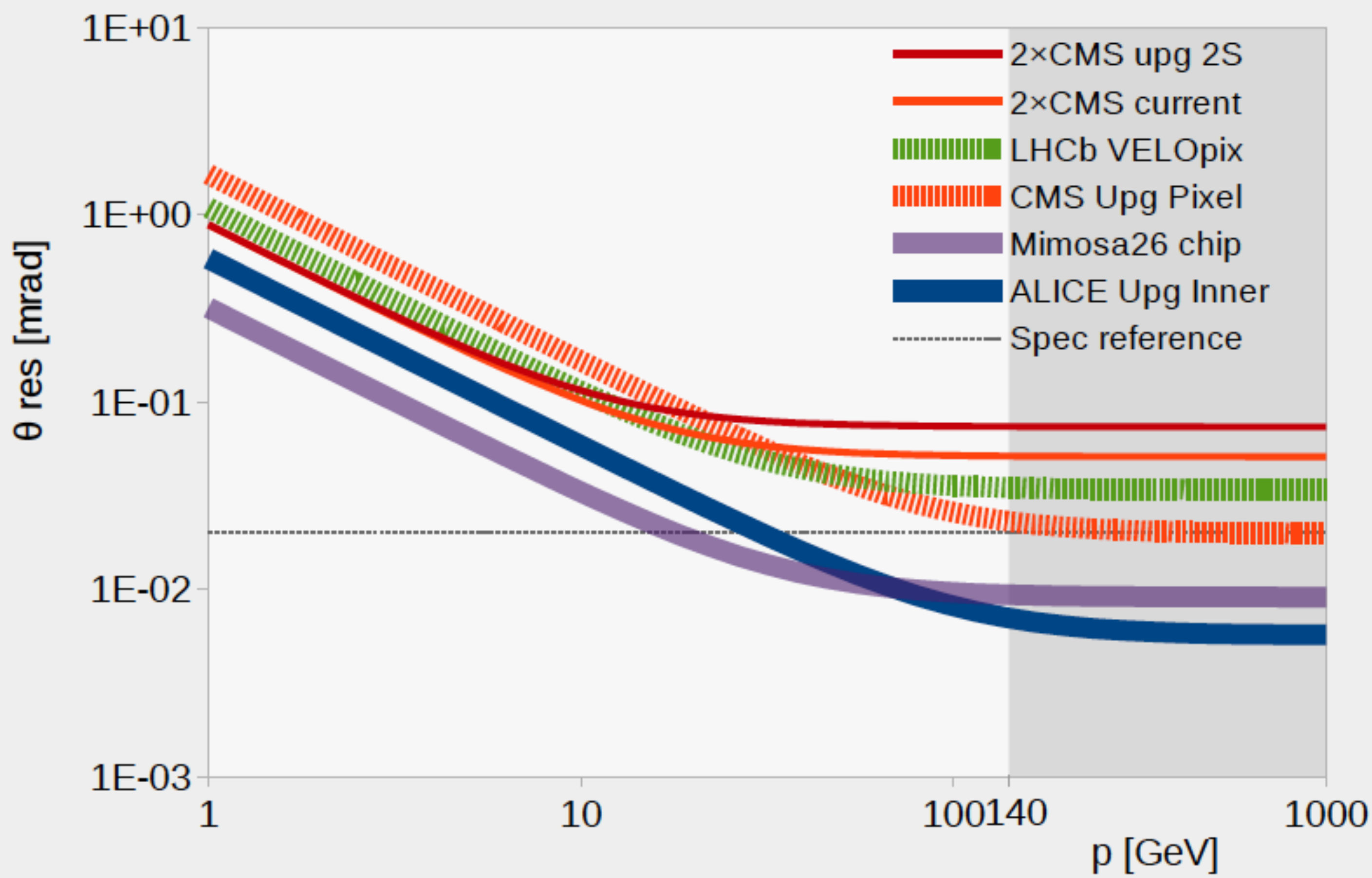
TOPICAL WORKSHOPS

The Evaluation of the Leading Hadronic Contribution to the muon anomalous magnetic moment
Massimo Passera INFN Padua, Luca Trentadue U Parma, Carlo Carloni Calame INFN Pavia Graziano Venanzoni INFN Frascati
February 19-23, 2018

M. Passera CERN PBC Mar 11

Next theory workshop in Zurich - Feb 2019

Resolution dominated by MS up to 100 GeV/c



Angle resolution:

$$\Delta\theta^2 = \Delta\theta_I^2 + \Delta\theta_{MS}^2$$

Angle intrinsic resolution:

$$\Delta\theta_I = \frac{\Delta x\sqrt{2}}{0.5\,\mathrm{m}}$$

MS angle:

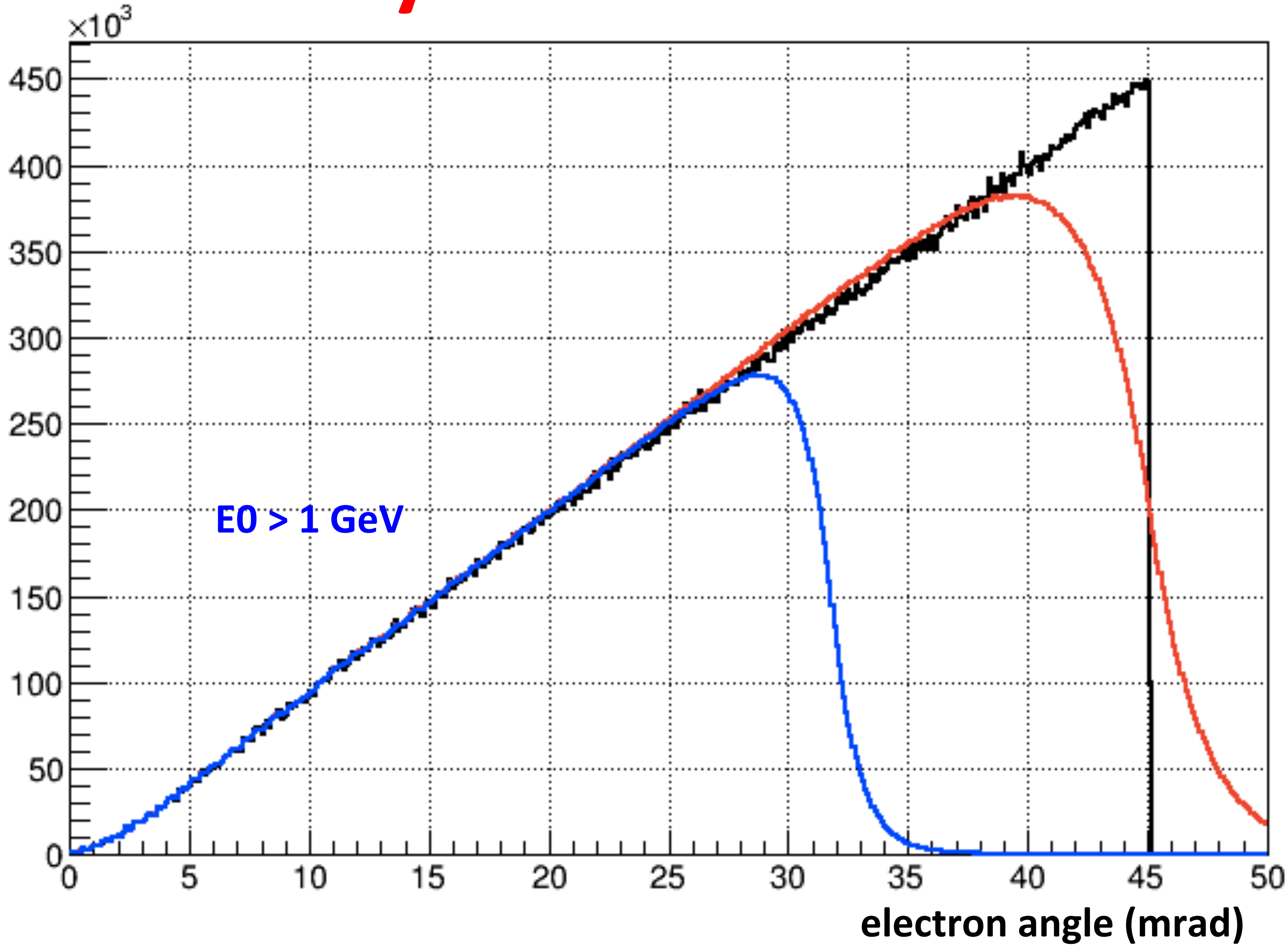
$$\Delta\theta_{MS} = \frac{13.6}{p/\mathrm{MeV}}\sqrt{m}\times(1+0.038\ln m)$$

Scattering material: first layer only

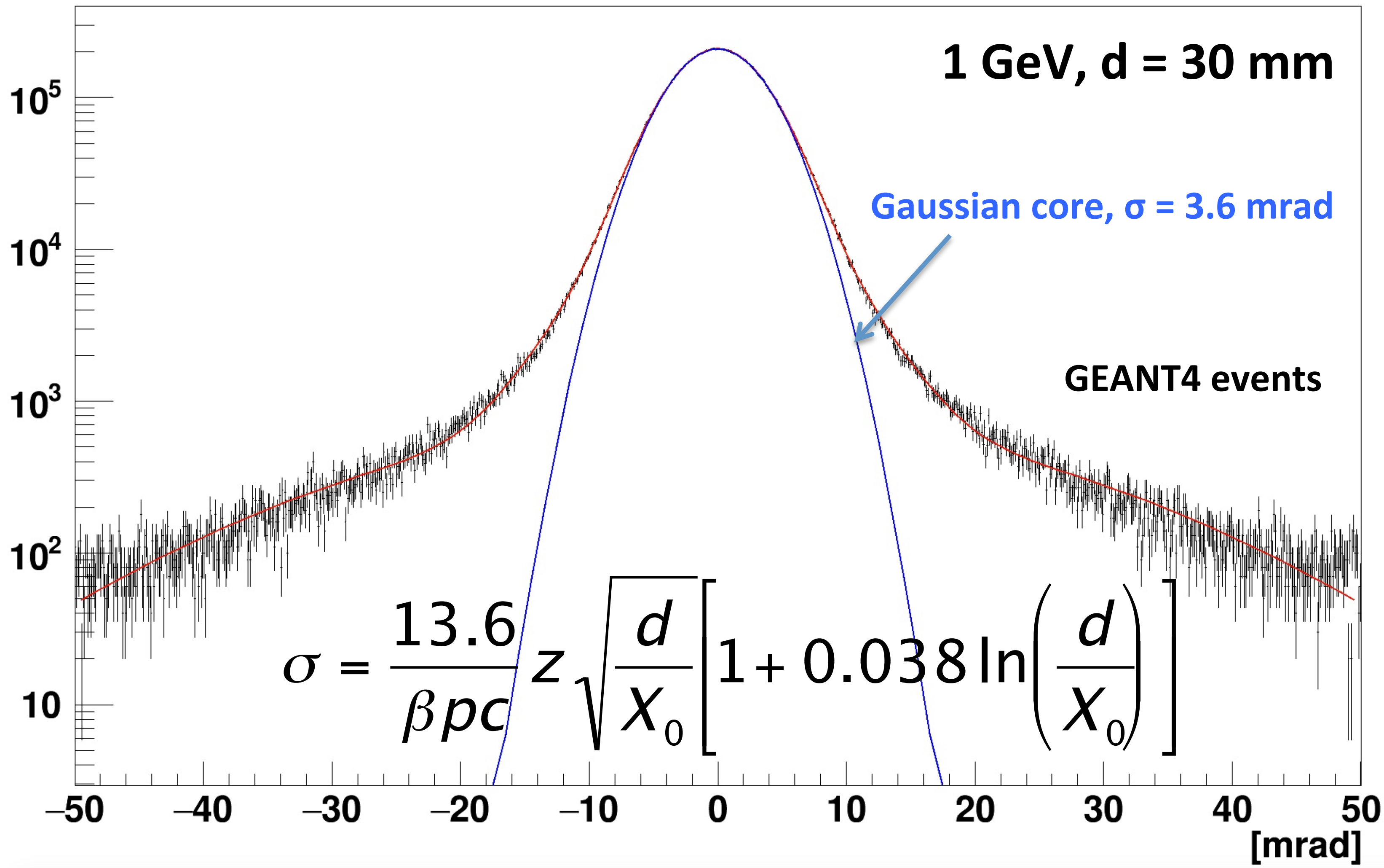
$$m = \left(\frac{x}{X_0}\right)_{\mathrm{det}}$$

- Resolution on scattering angle assumptions:
- 2 measurement plane 0.5 m apart
- Scattering on:
  - No plane (ideal resolution)
  - First detector plane (pure tracker resolution)
  - First plane + ½ Be target (includes “average” MS in target)
- Core of MS only considered (no tails)

Beryllium d = 10 mm



Effect of the target (Geant)



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

Highland formula (PDG) = 3.593 mrad