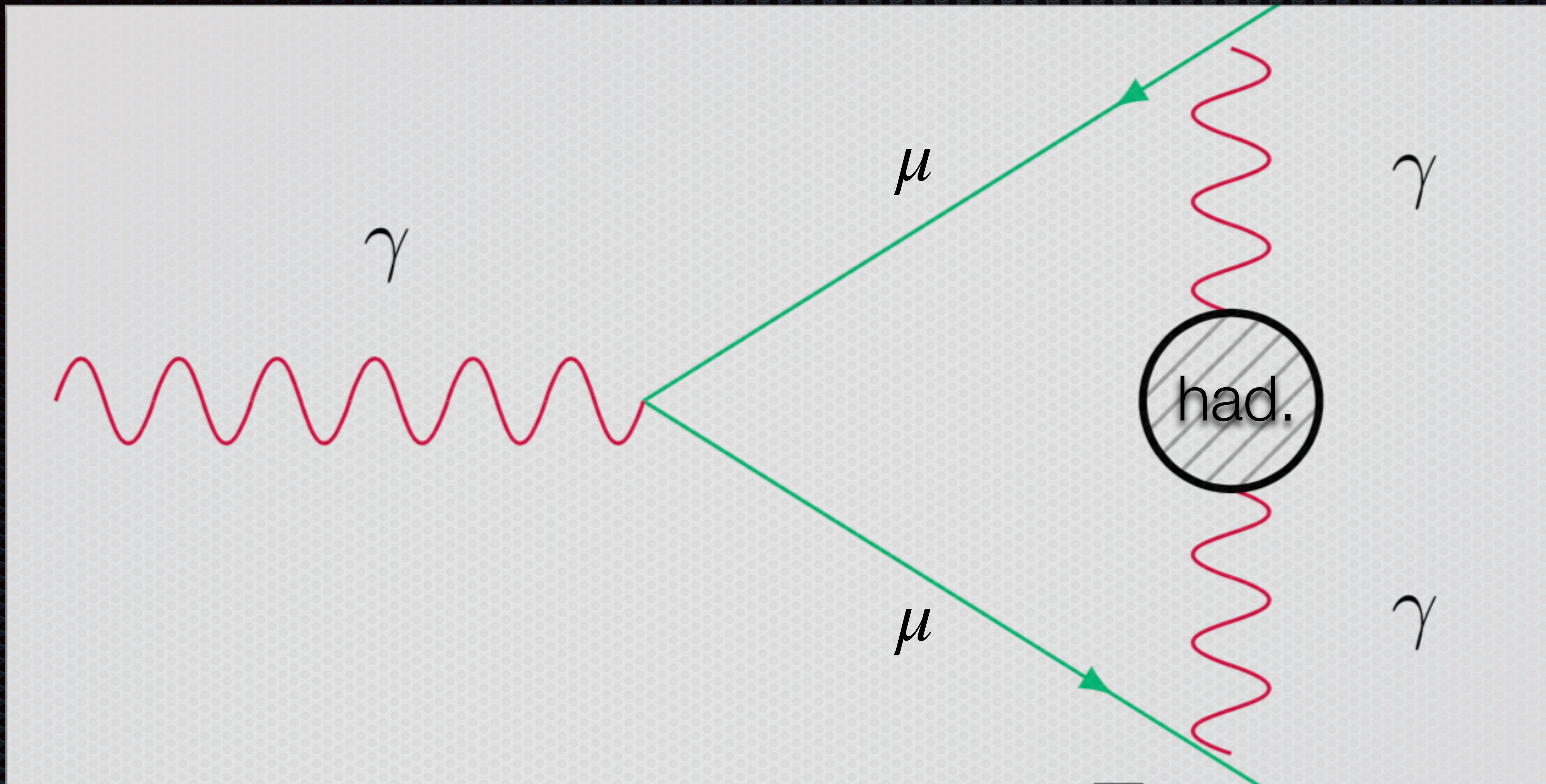

The MUonE experiment

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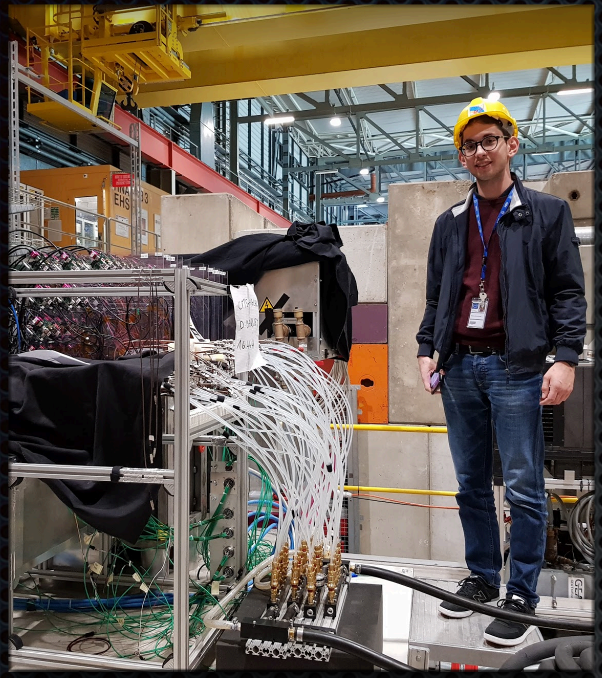
@mbonanom

LLR Student Seminar
LLR, Ecole Polytechnique
08/10/2019

"We are doing something unique here."

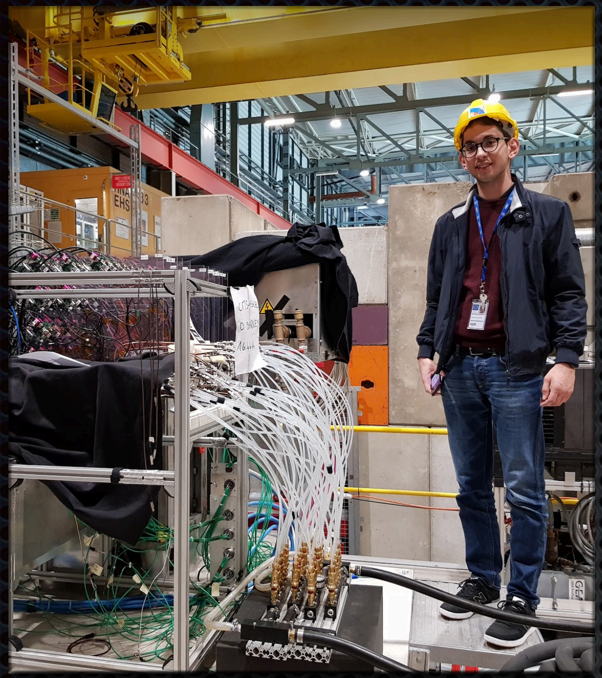
–Umberto Marconi

Who am I?



- Matteo Bonanomi, 24yo;
- MSc in Particle Physics at the University of Milano Bicocca on the **MUonE experiment**;
- Second year PhD student at École Polytechnique with the CMS esperiment;
- Working on the CMS High Granularity Calorimeter (HCGAL) beam tests analysis;
- ROOT User/addicted for my analyses …

Who am I?



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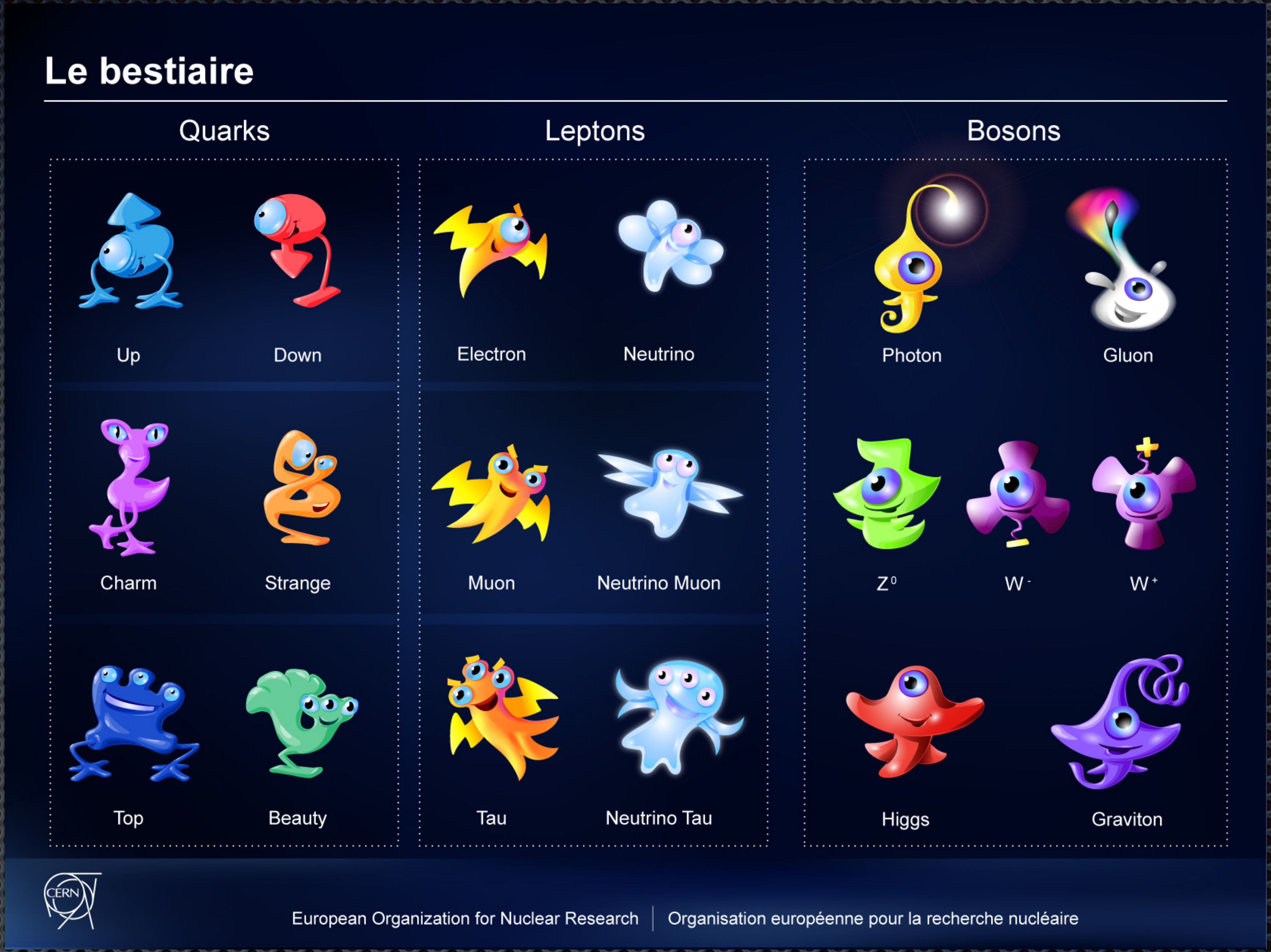
- ROOT User/addicted for my analyses … **before my PhD started (🐍😉)**

In this presentation

- The Standard Model in a nutshell;
- What is the **muon anomaly**: present and future;
- The **MUonE** experiment:
    - Theoretical framework;
    - Experimental overview and beam tests;
- Conclusions

Standard Model in a nutshell

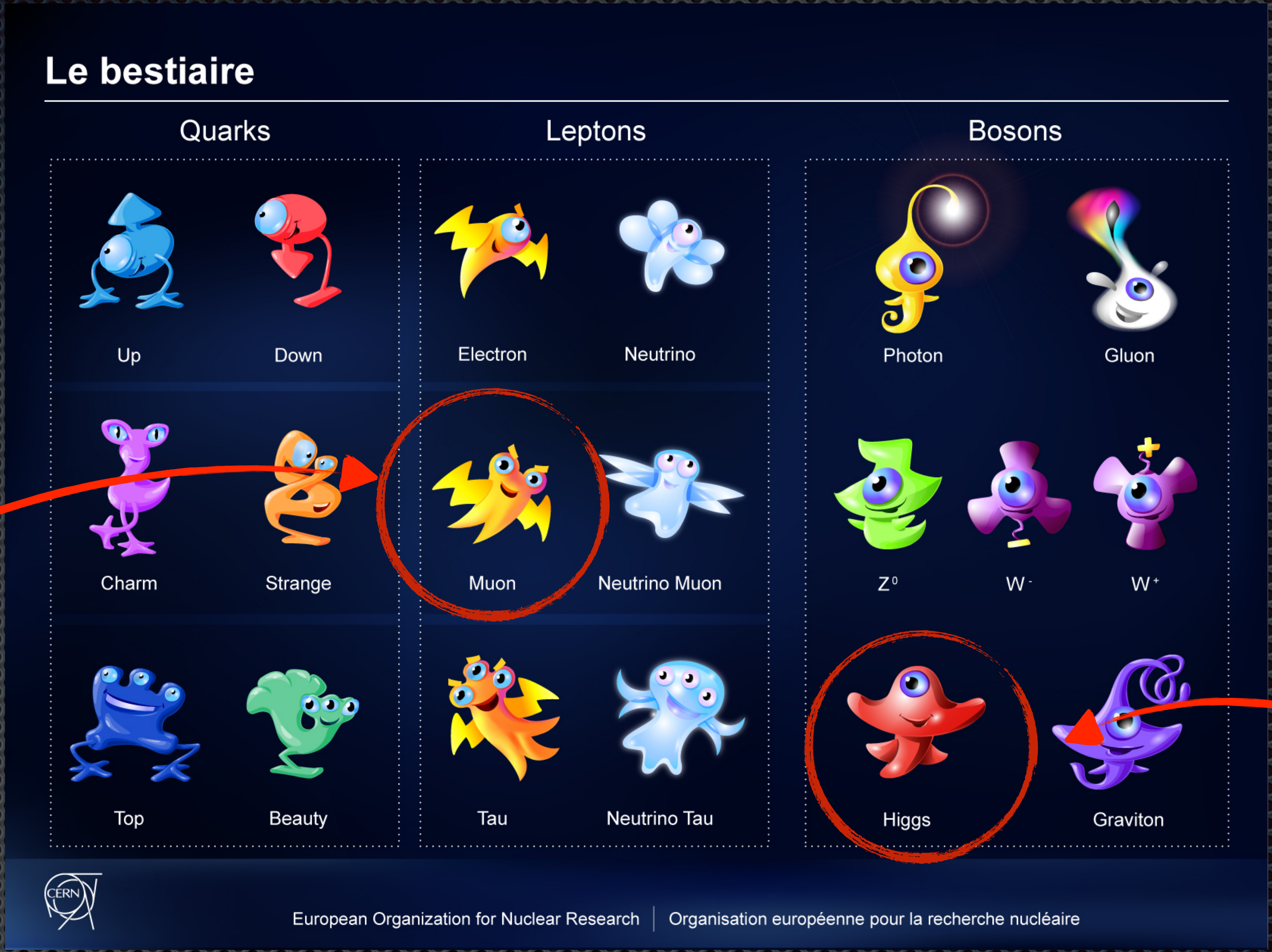


"A theory of fundamental interactions in which the electromagnetic, weak and strong interactions are described in terms of the exchange of virtual particles"

Standard Model in a nutshell

My PhD

Standard Model in a nutshell



My MSc thesis

My PhD

What do they have in common?

Matteo in the SM

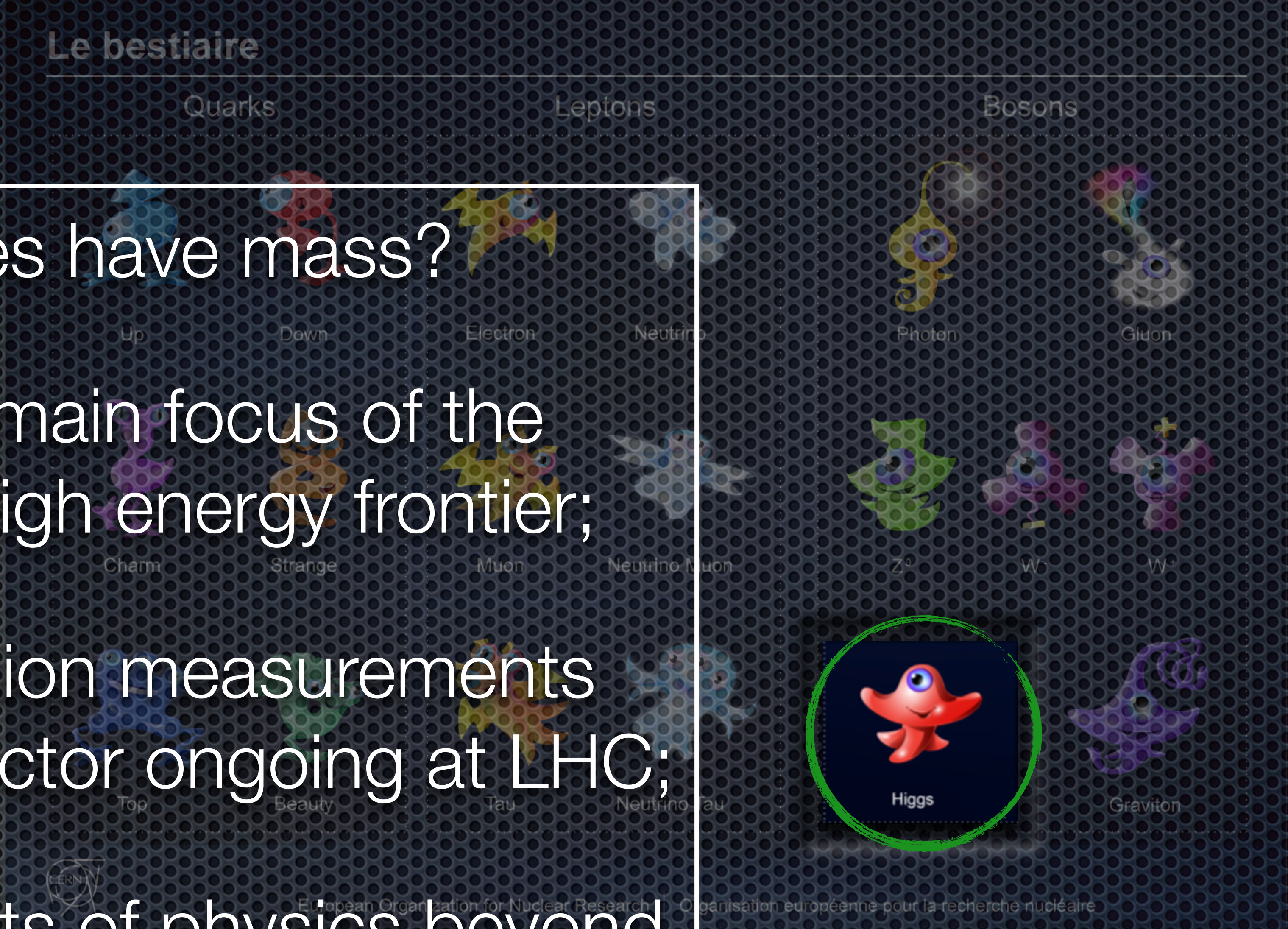
What do they have in common?

MUonE	CMS
Precision frontier;	High Energy frontier;
No collider;	At LHC;
Small collaboration O(1e2);	Large collaboration O(1e3);

- **Probe physics BSM;**

The high energy frontier

- Why particles have mass?
- From 2012 main focus of the physics at high energy frontier;
- Many precision measurements on Higgs sector ongoing at LHC;
- Possible hints of physics beyond the SM at accelerators;



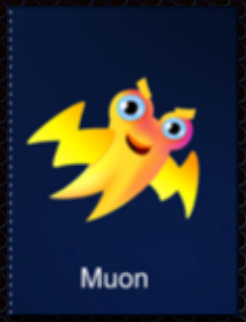
The precision frontier

- Indirect evidence of physics beyond the SM can come from the **precision frontier;**
- **BNL, Mainz;**
- **Flavour factories;**
- **g-2, M2e** @Fermilab;

“g-2: an uncomfortably lonely search for a crack in the SM”

–David W. Hertzog

The g-2 *anomaly* (I)



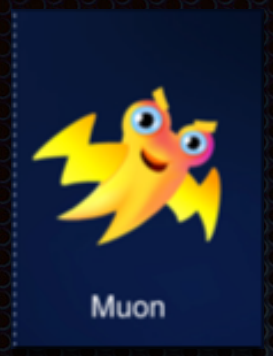
Magnetic dipole moment of a particle with spin:

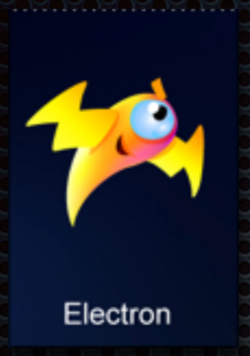
$$\vec{\mu} = g \frac{e}{2m} \vec{s}$$

- The constant *g* is known as **g-factor**;
- Dirac equation predicts $g = 2$;
- Due to QED and QCD effects we have

$$\vec{\mu} = 2(1+a) \frac{e}{2m} \vec{s}$$

The g-2 *anomaly* (II)





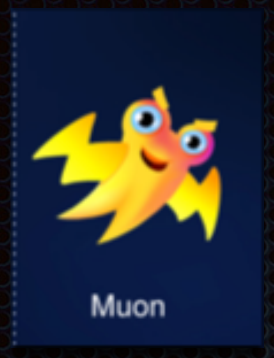
Having spin, they have

$$\vec{\mu} = 2(1+a)\frac{e}{2m}\vec{s}$$

$$a = \frac{g-2}{2}$$ is referred to as ***anomaly.***

Electron	Muon
$a_e^{exp} = 1159652180.73(28) \times 10^{-12}$ ± 0.24 ppb	$a_\mu^{exp} = 116592089(63) \times 10^{-11}$ ± 0.54 ppm
Less sensitive to heavier physics $\left(\frac{m_\mu}{m_e}\right)^2 \simeq 43000$	Strongly affected by hadronic contributions

The g-2 in the SM



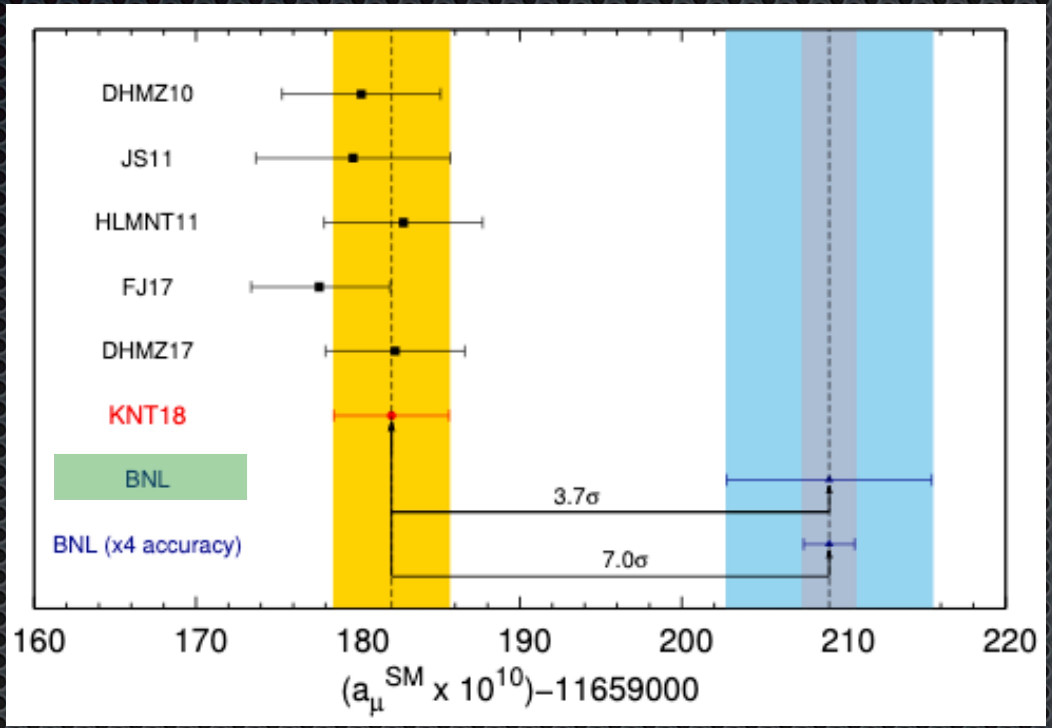
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{Had}$$

60 ppm on a_μ^{SM}

- a_μ^{QED}: Well known up to 5-loop diagrams;
- a_μ^{Weak} : well known at 1-loop, current work at 2-loops;
- $a_\mu^{Had} = a_\mu^{H-LO} + a_\mu^{H-HO} + a_\mu^{H-LbL}$;

Sensitive to mass scales in O(1e2) GeV region: W, Z bosons and possibly **BSM contributions**.

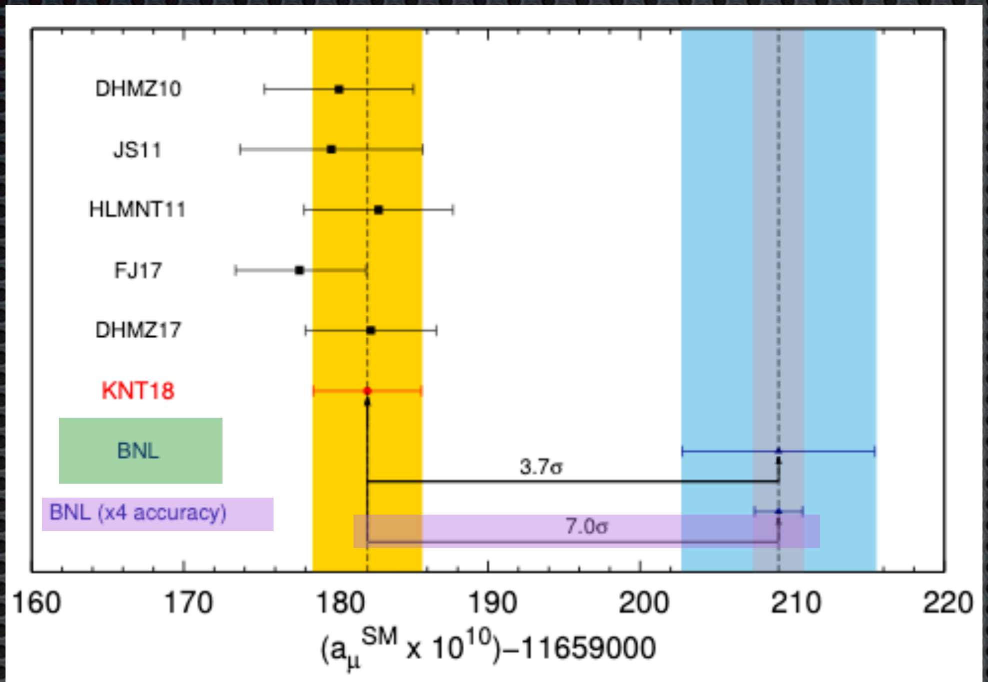
g-2 theory and experiment



E821 experiment @BNL and SM prediction have a long-standing $\sim 3.7\sigma$ discrepancy

$$\Delta a_\mu^{exp-SM} \simeq (261 \pm 78) \times 10^{-11}$$

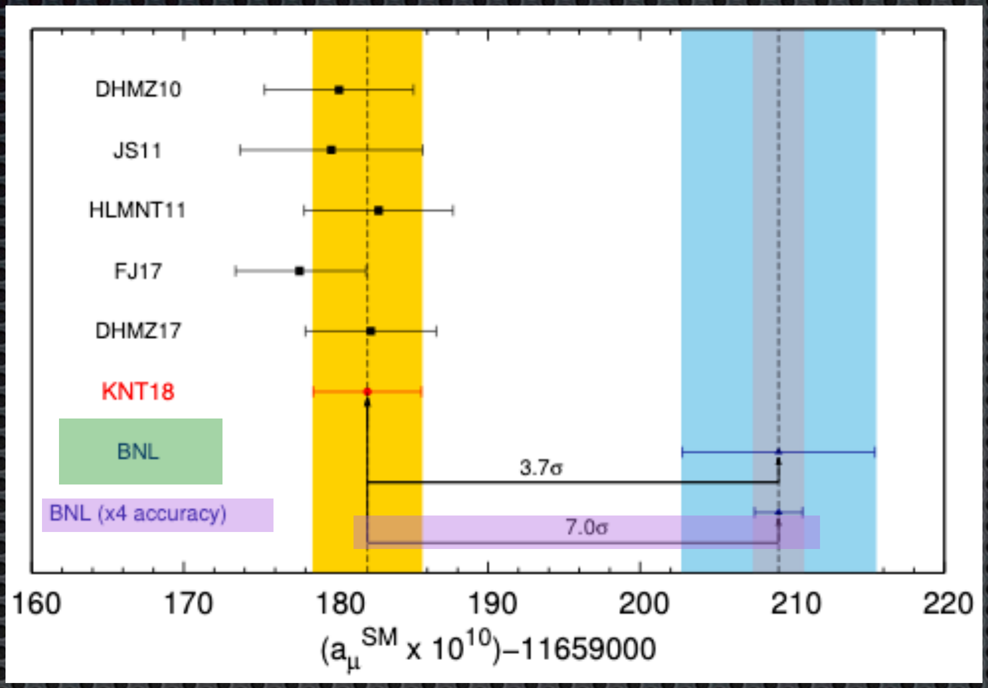
g-2 to nail down the 5σ



Theoretical uncertainty limits the SM prediction. Mostly dominated by **hadronic effects** (in particular **H-LO**)

Experimental uncertainty limited by available statistics. New experiments foreseen at **FNAL** and **J-PARC** (x4 BNL accuracy)

g-2 to nail down the 5σ



Theoretical uncertainty limits the SM prediction.

Mostly dominated by **hadronic effects** (in particular **H-LO**)

Requirement of **experimental data** as input to improve the computation.

How to measure a_μ^{H-LO} (I)

Dispersive approach : $a_\mu^{H-LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R_{had}(s)$

$$R_{had}(s) = \frac{\sigma_{tot}(e^+e^- \to had.)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

How to measure a_μ^{H-LO} (I)

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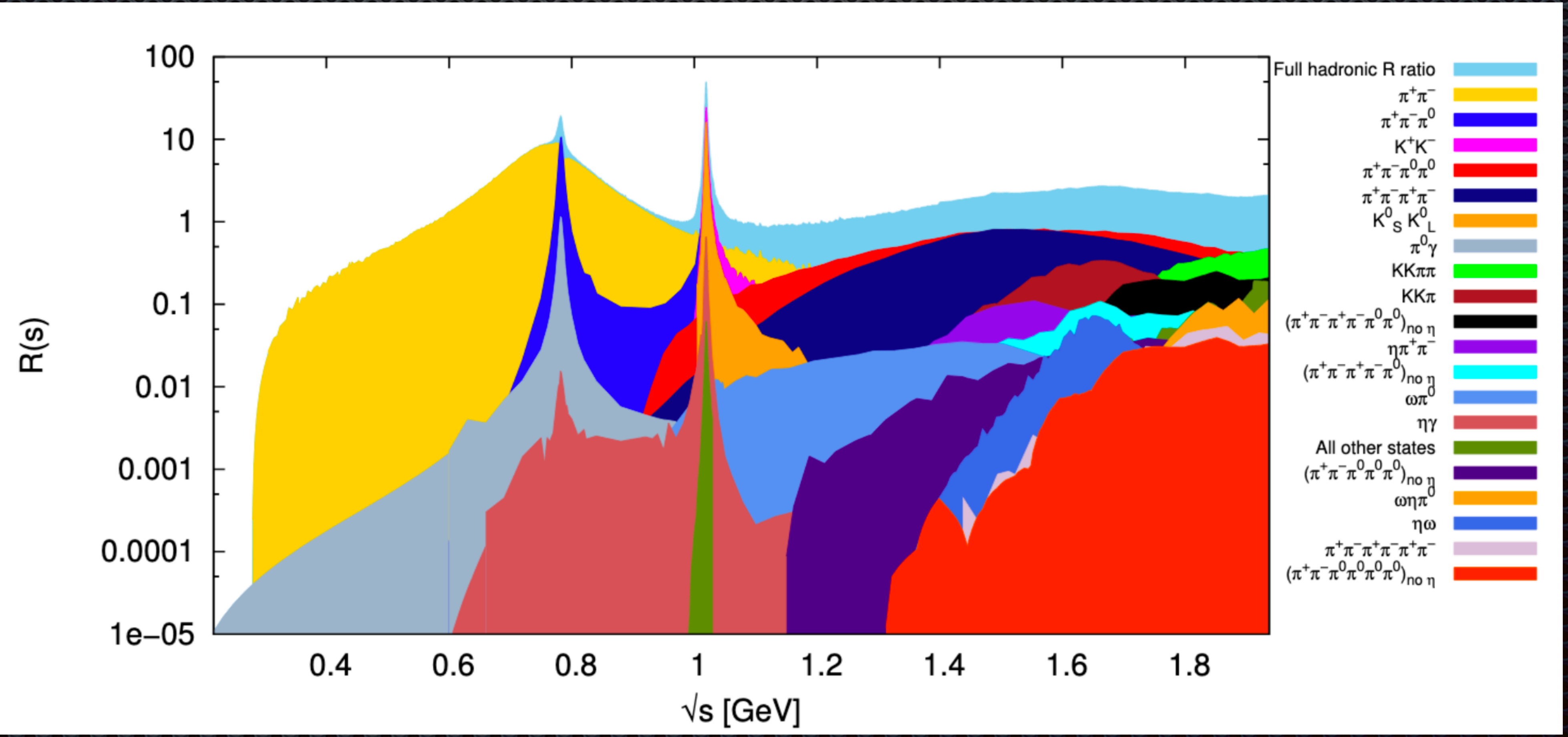
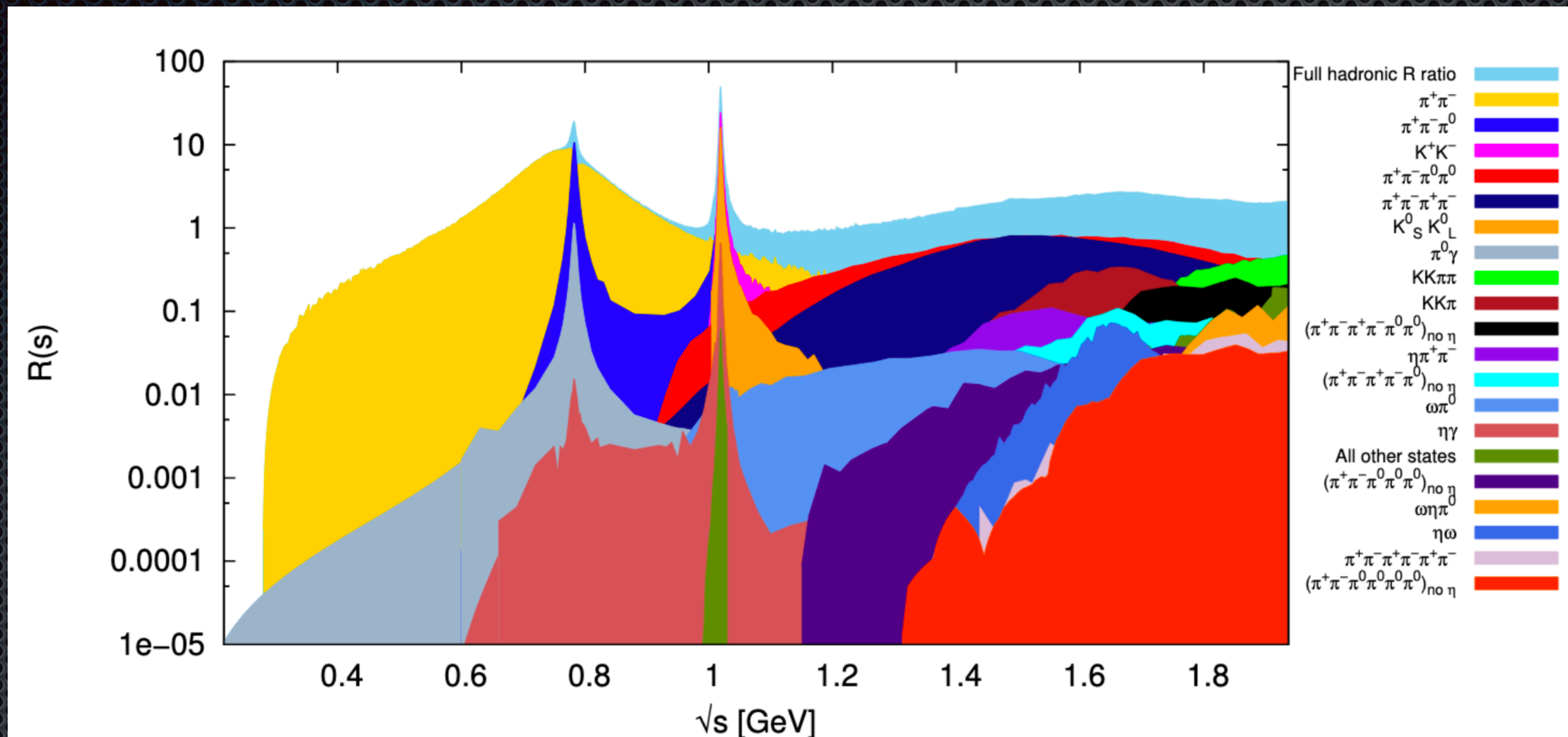


How to measure a_μ^{H-LO} (I)



- Sets the current precision at 3.7σ;
- Relies on many **experimental inputs**: BELLEII, BaBar, KLOE…
- **Hard to compute** in the low E region due to fluctuations.

How to measure a_μ^{H-LO} (II)

Alternative approach based on ***space-like*** phase space integration:

$$a_\mu^{H-LO} = \left(\frac{\alpha}{\pi}\right)\int_0^1 dx(1-x)\Delta\alpha_{had}(t(x))$$

- Allows to compute the H-LO contributions in an independent way;
- Space-like phase space only, no channels interference!
- Depends on **the running of α_{em} …**

… yes, α_{em} is not constant 1/137 😉

How to measure a_μ^{H-LO} (II)

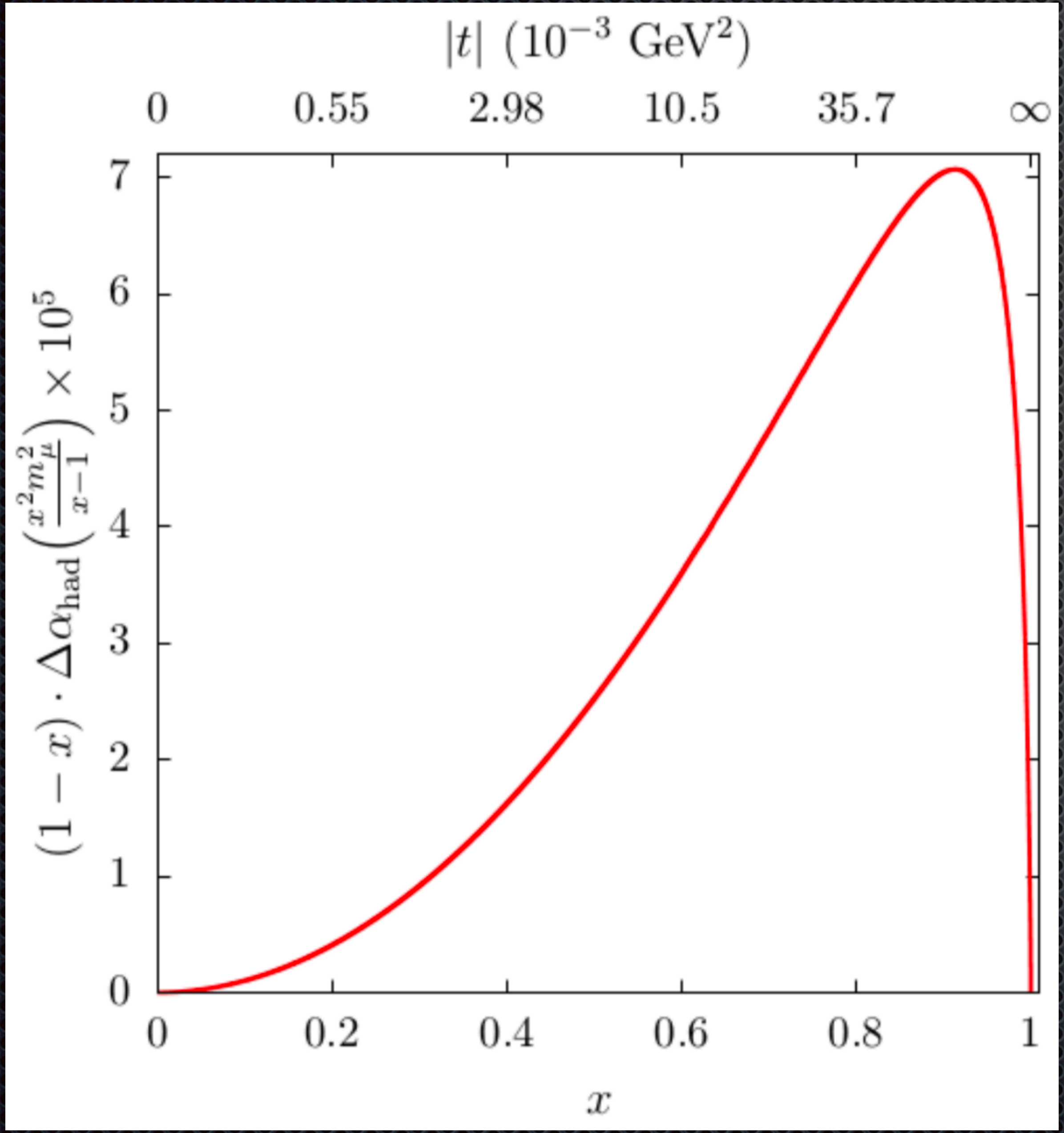
Alternative approach based on ***space-like*** phase space integration:

$$a_\mu^{H-LO} = \left(\frac{\alpha}{\pi}\right) \int_0^1 dx (1-x) \Delta\alpha_{had}(t(x))$$

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

How to measure a_μ^{H-LO} (II)

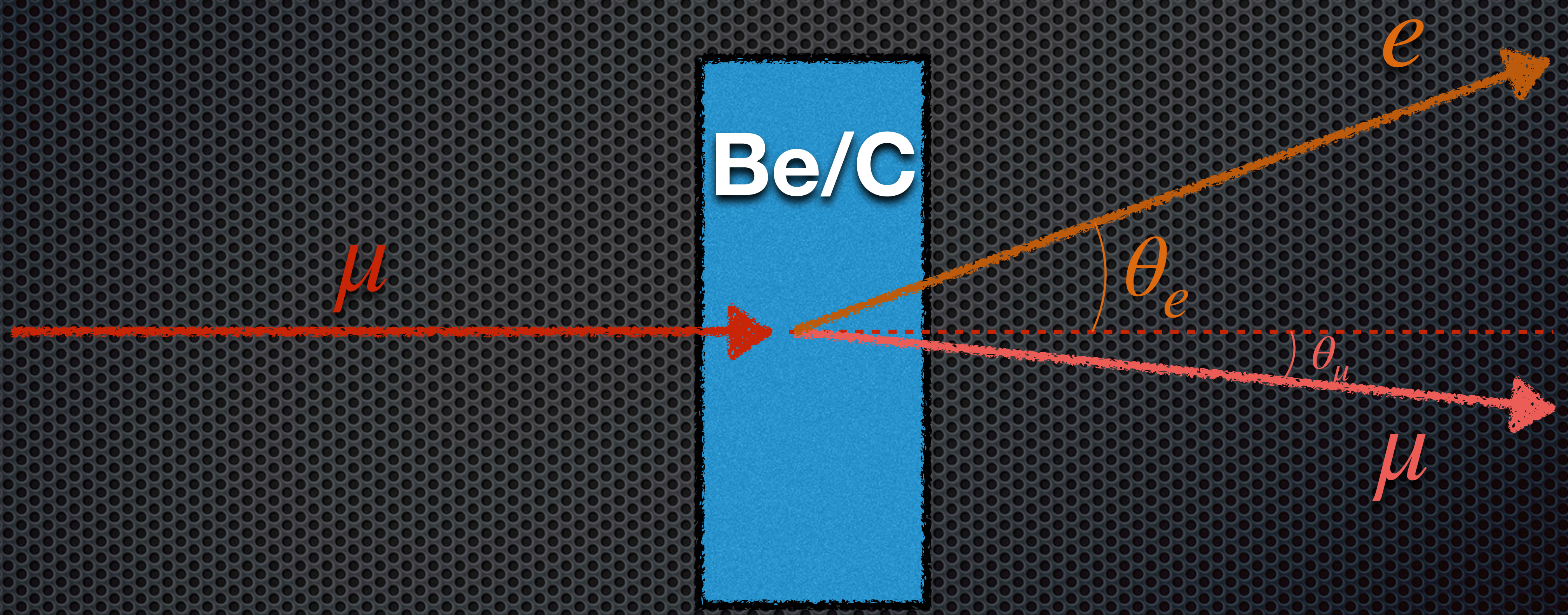
$$a_\mu^{H-LO} = \left(\frac{\alpha}{\pi}\right)\int_0^1 dx(1-x)\Delta\alpha_{had}(t(x))$$



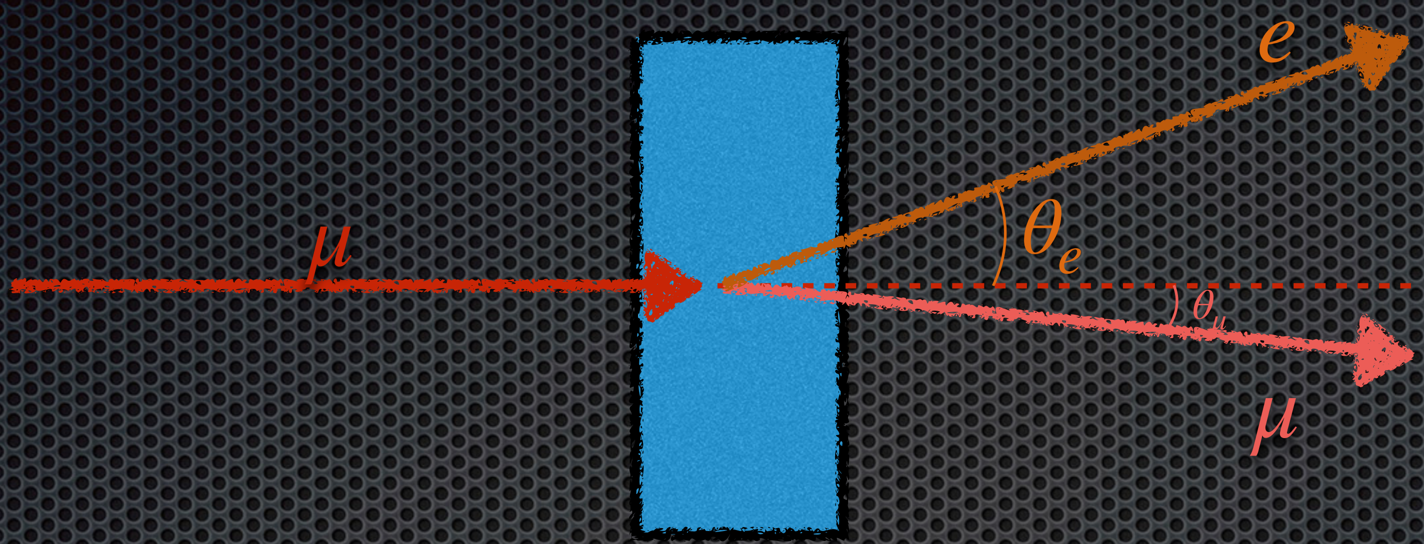
- Smooth integral, free from resonances: can be fully **extracted from data;**
- Pure *t-like* approach, allows to select channels w/o interference;
- 🤔 … but how do we measure $\Delta\alpha_{had}(t(x))$?;

The μONe experiment

Scattering of **high energy muons** ($E_\mu \simeq 150$GeV) on **atomic electrons** of **low Z target**



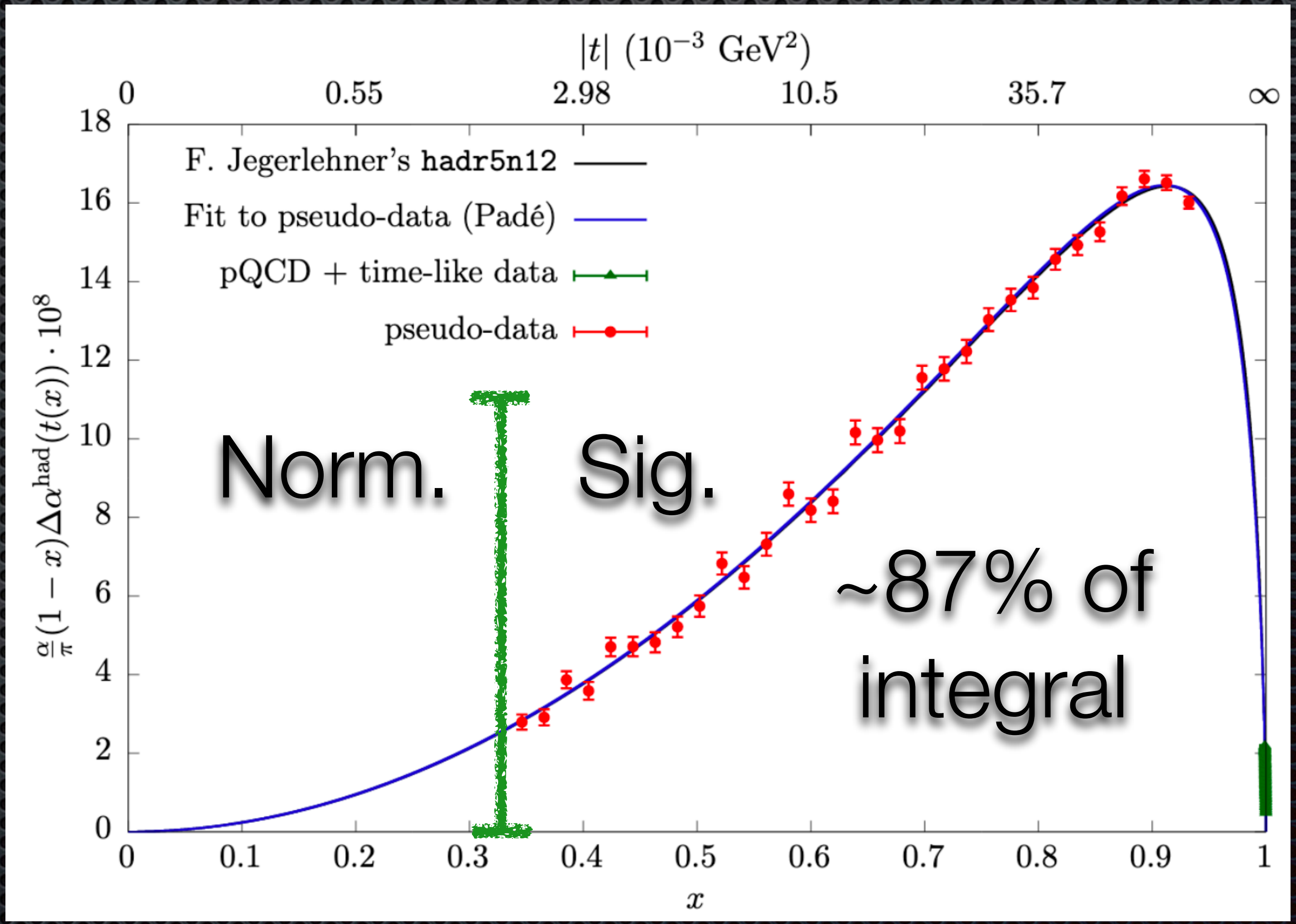
The μONe experiment



- Pure *t-channel* process with $\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2$
- Two body scattering with closed kinematics $E^e_f = m_e \frac{1 + r^2\cos^2\theta_e}{1 - r^2\cos^2\theta_e}$
- Boosted kin. allows to keep systematics under control

The MUonE experiment

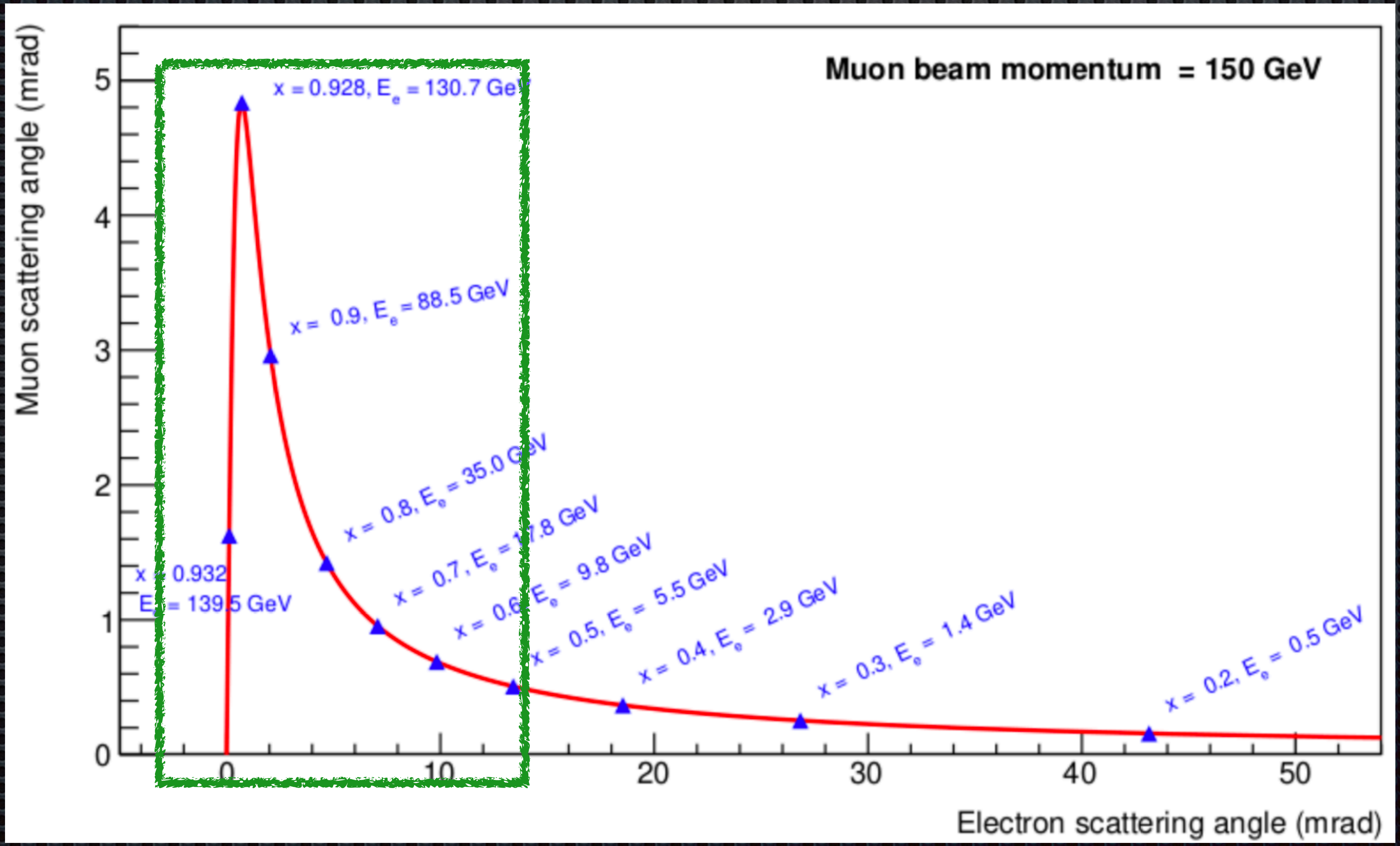
- Systematics under control: same process for both signal and normalisation region;
- Simulating 2y data taking: 0.3% stat uncertainty on a_μ^{H-LO}



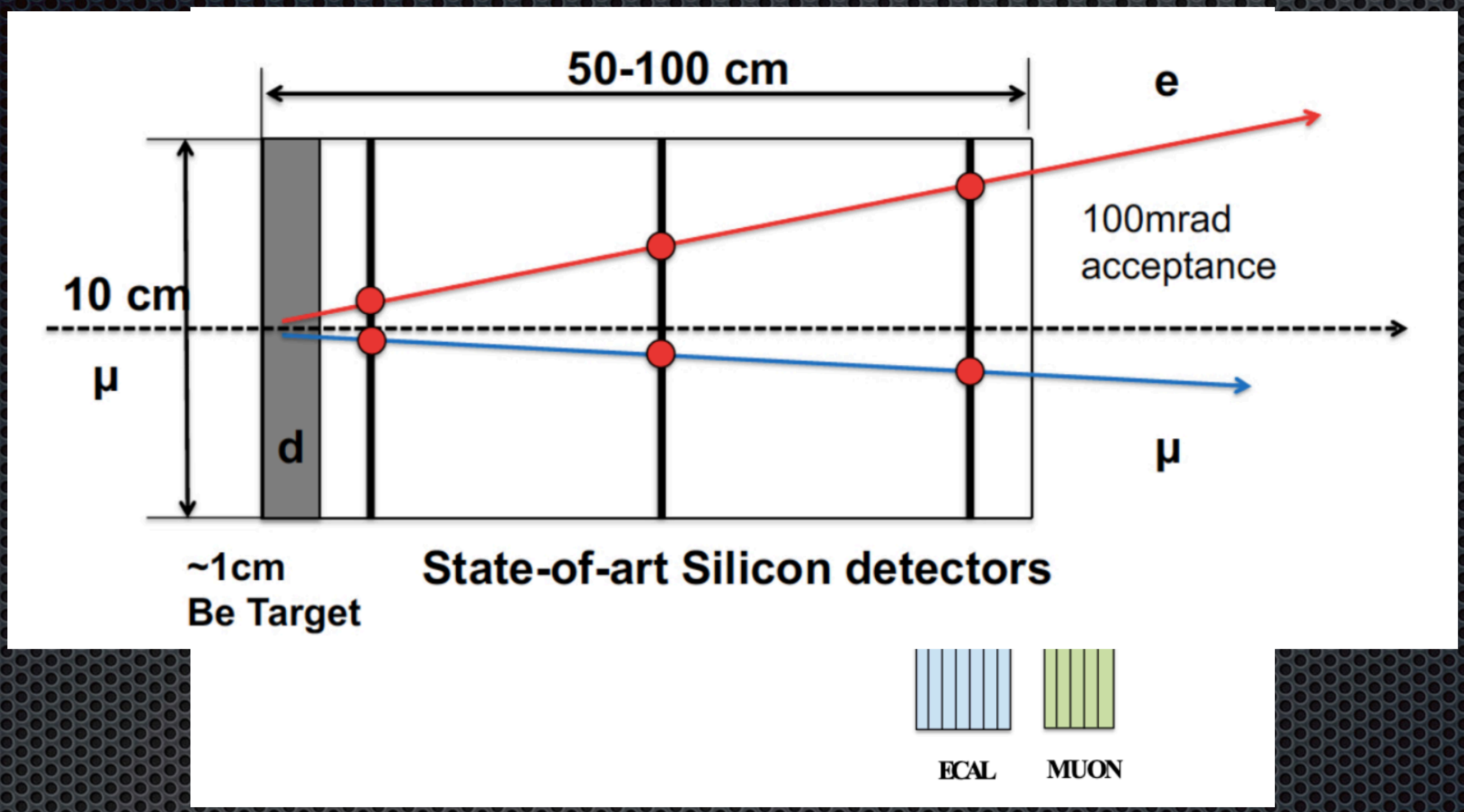
The μONe experiment

Correlation between electron and muon angles can be exploited to retrieve elastic scattering events.

Signal region for $\theta_e < 10$mrad and $E_e > 10$GeV

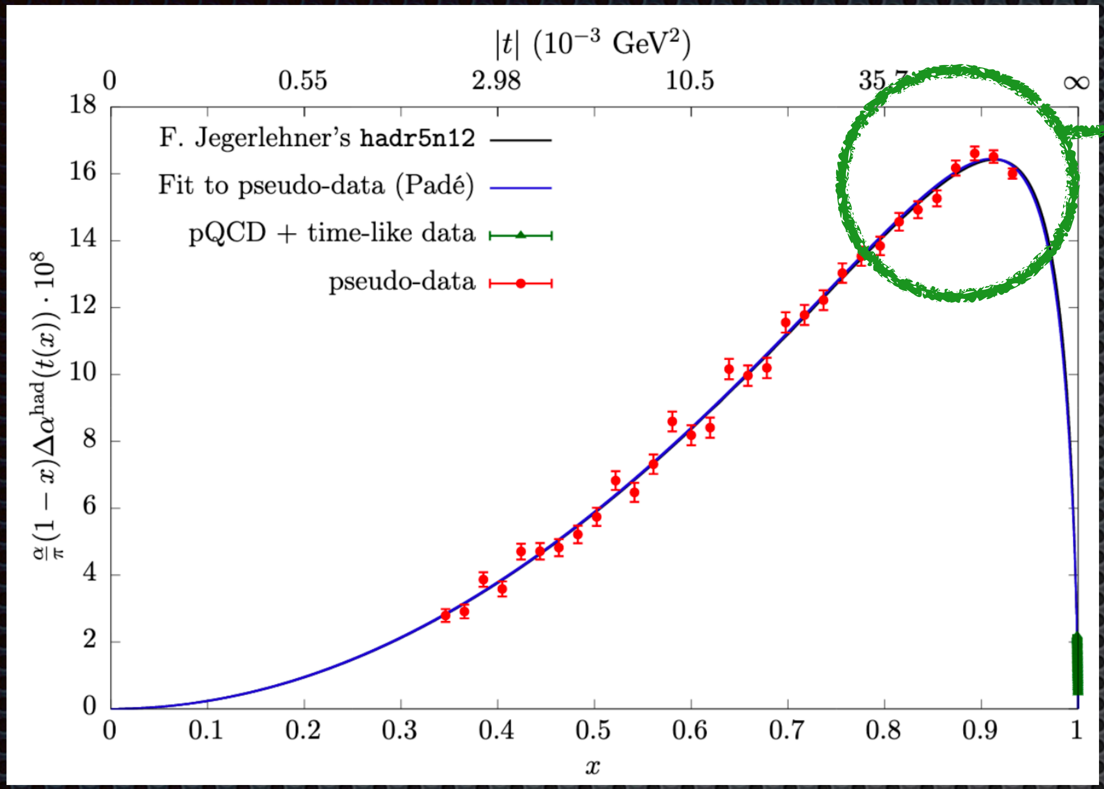


μONe : the detector



- 60 modules: 1 cm Be target + 3 Si trackers;
- State of art Si detectors to achieve ~20um resolution;
- ECAL and muon chamber for particle ID.

μONe : facing systematics

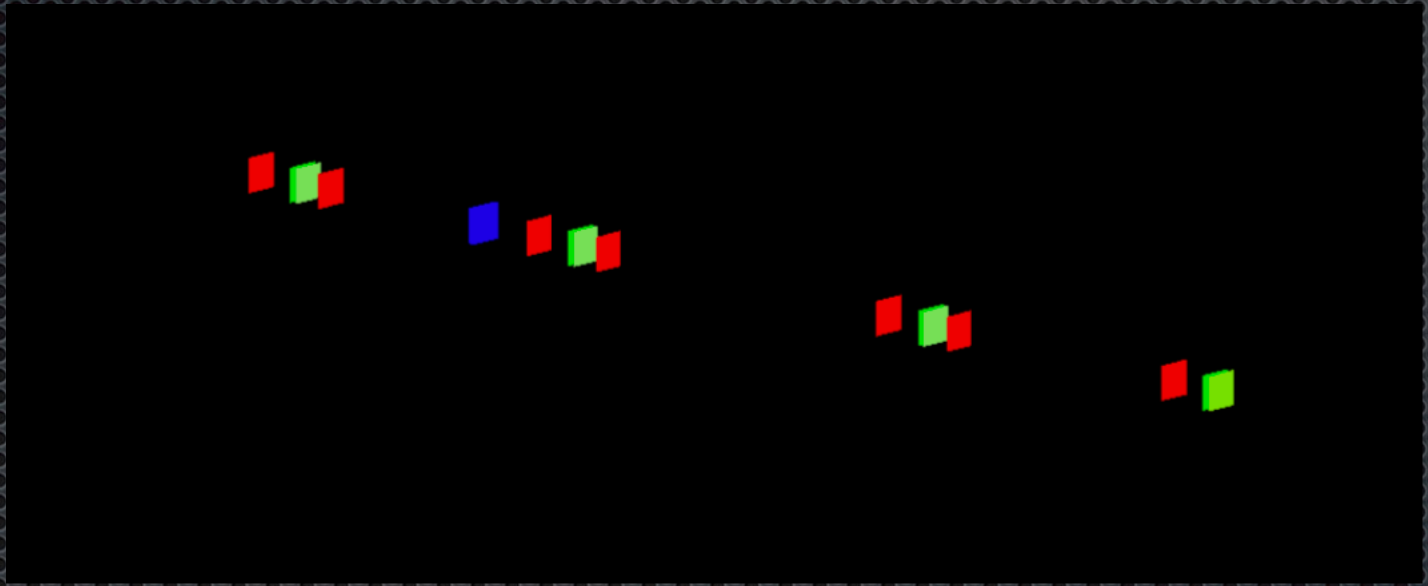


Precise measurement of a_μ^{H-LO} requires knowledge of signal/norm ratio with **10ppm systematic uncertainty**

- **Multiple scattering** in thin absorber: need to be known at ~1% (in core region);
- Beam energy knowledge at 0.8% using BMS spectrometer;
- Tracking uniformity, alignment and angles reconstruction

μONe: beam tests

Beam tests in October 2017 and April 2018 to understand Multiple Scattering effects and to have a first proof-of-concept of the detector



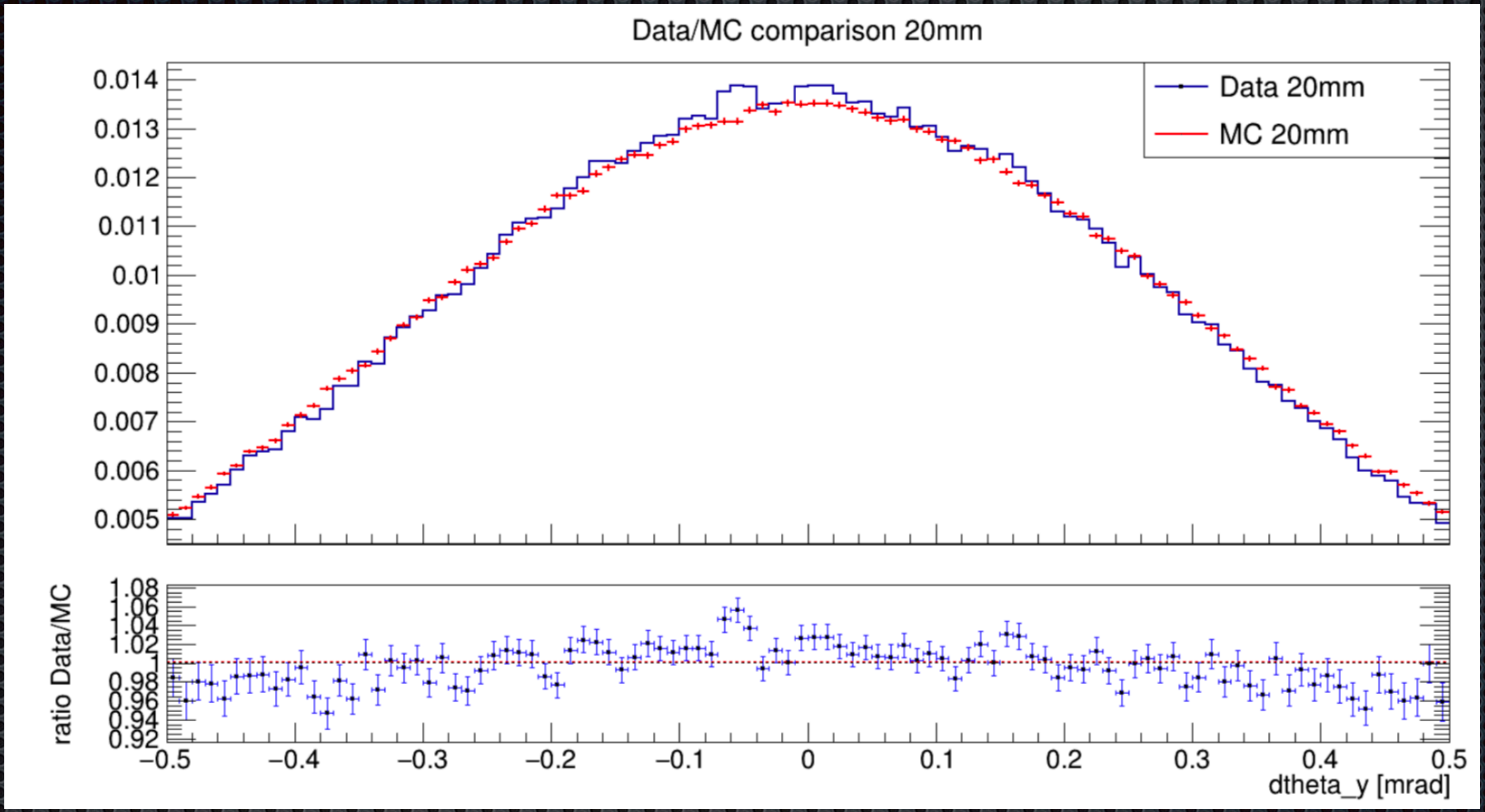
October 2017 beam test @CERN, using UA9 telescope:

1 module tested: 2 upstream + 3 downstream planes

C, Be targets for 2, 4, 8, 20 mm

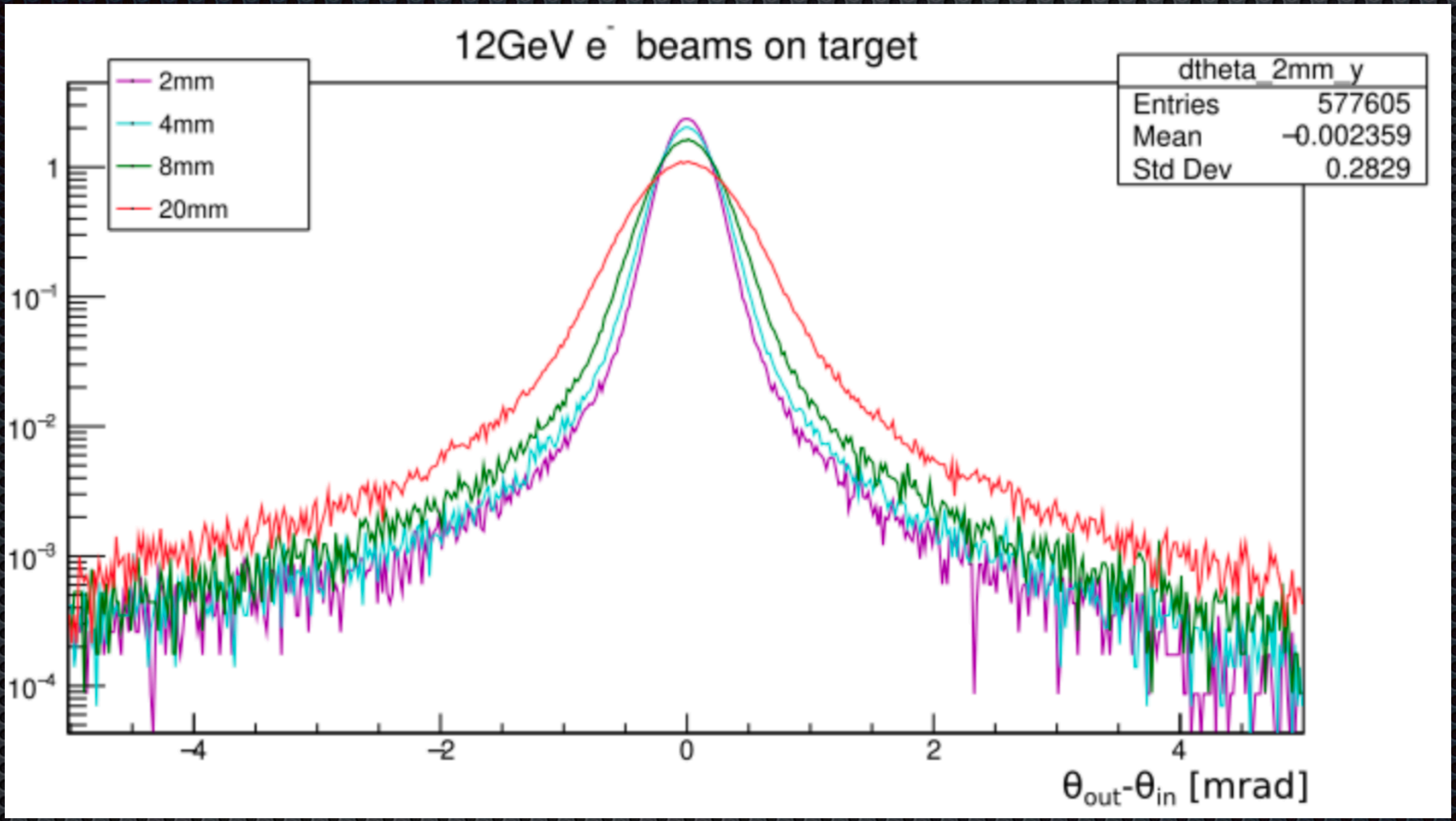
$12,20$GeV e^- beams

μONe: Multiple Scattering



- Multiple Scattering increases with target thickness;
- Dedicated Geant4 simulation of the apparatus describes at ~1% data;

μONE : Multiple Scattering



🙂 : MSC core is gaussian, we can deal with it

🙁 : What do we do with the tails? MSC events end there!

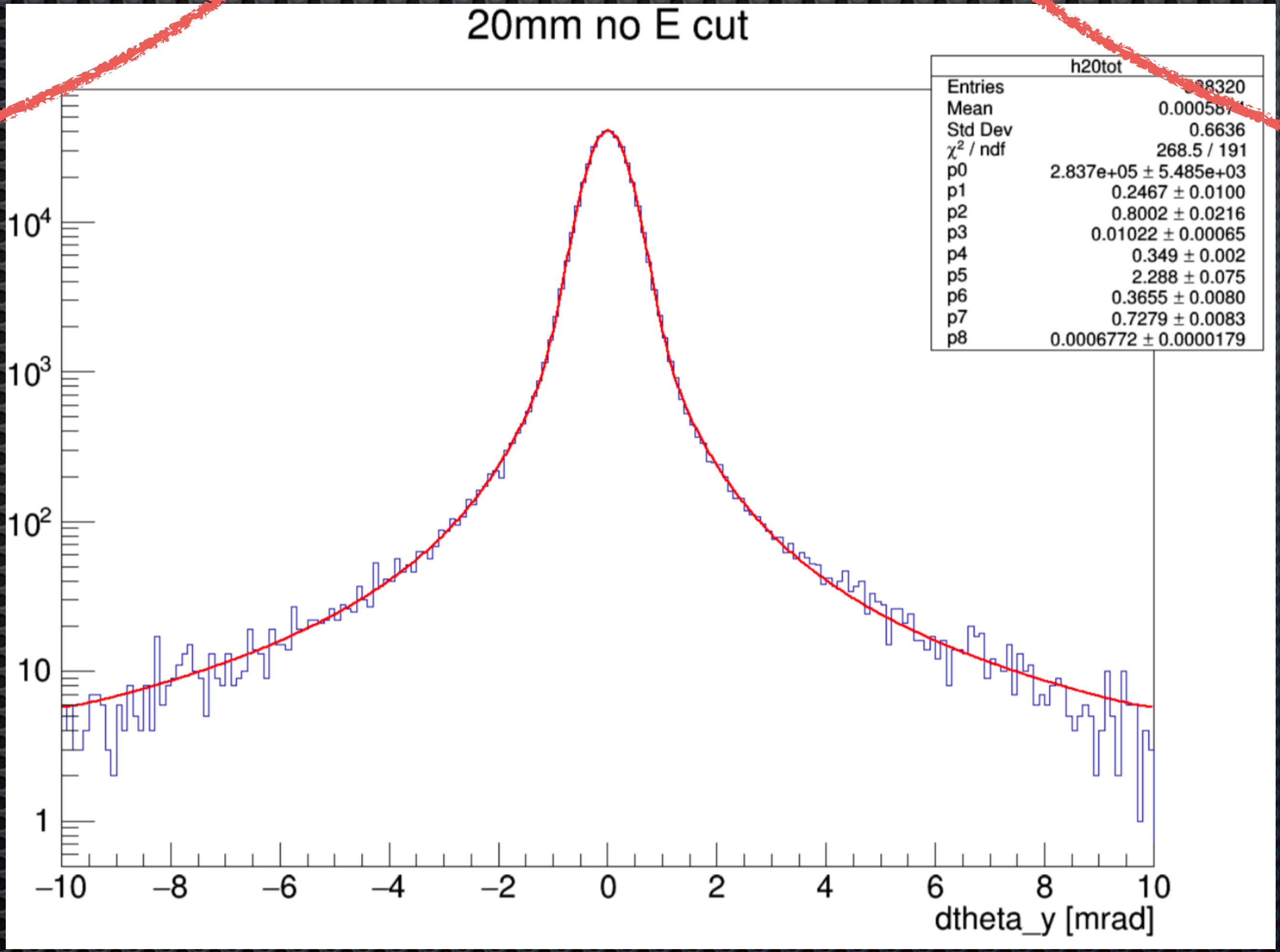
μONe : Describing Multiple Scattering

📈 : What do we do with the tails? We fit them!

$$f(\theta) = f_{telescope}(\theta) * f_{target}(\theta)$$

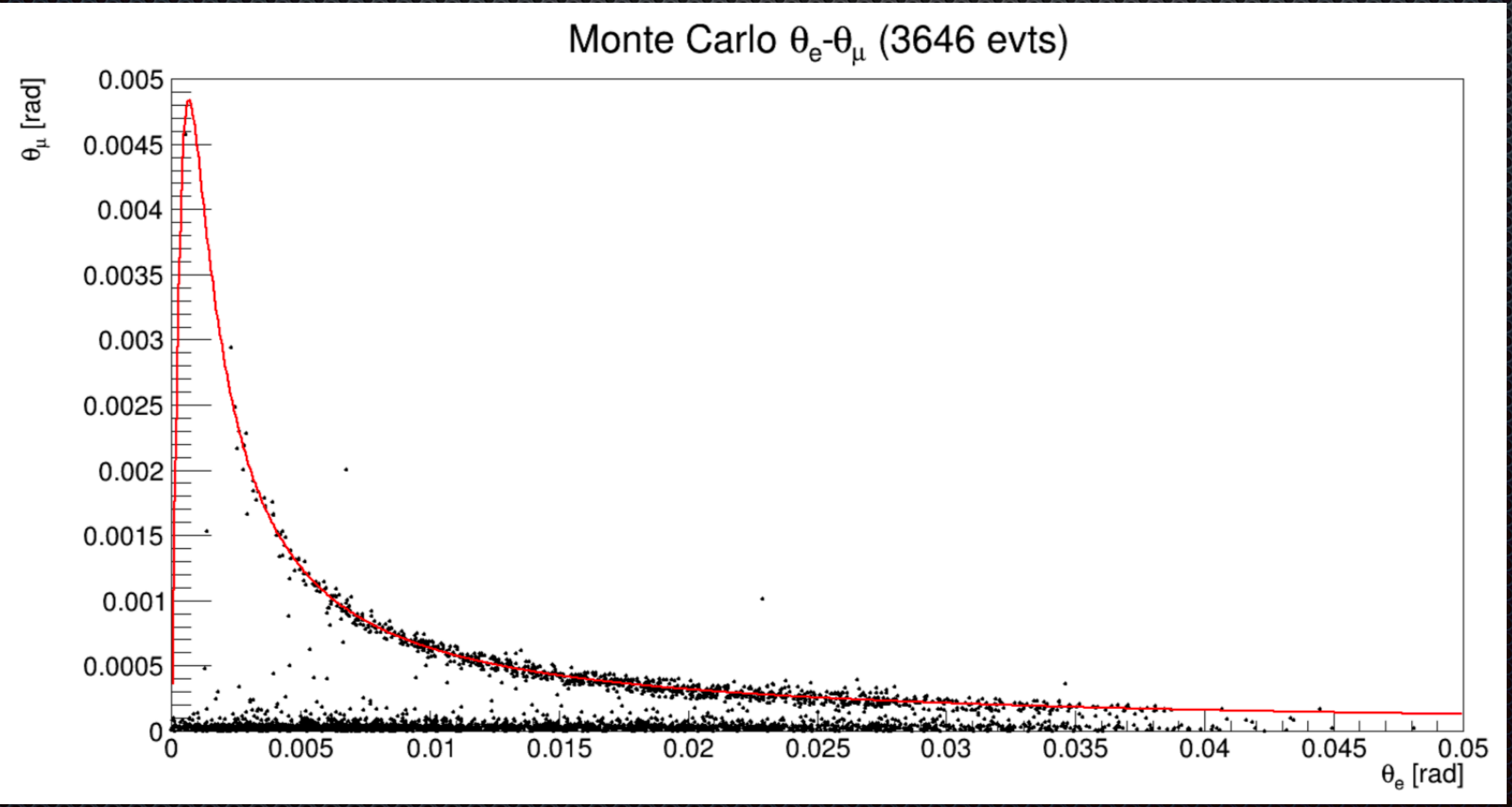
Gauss + t-Student

t-Student



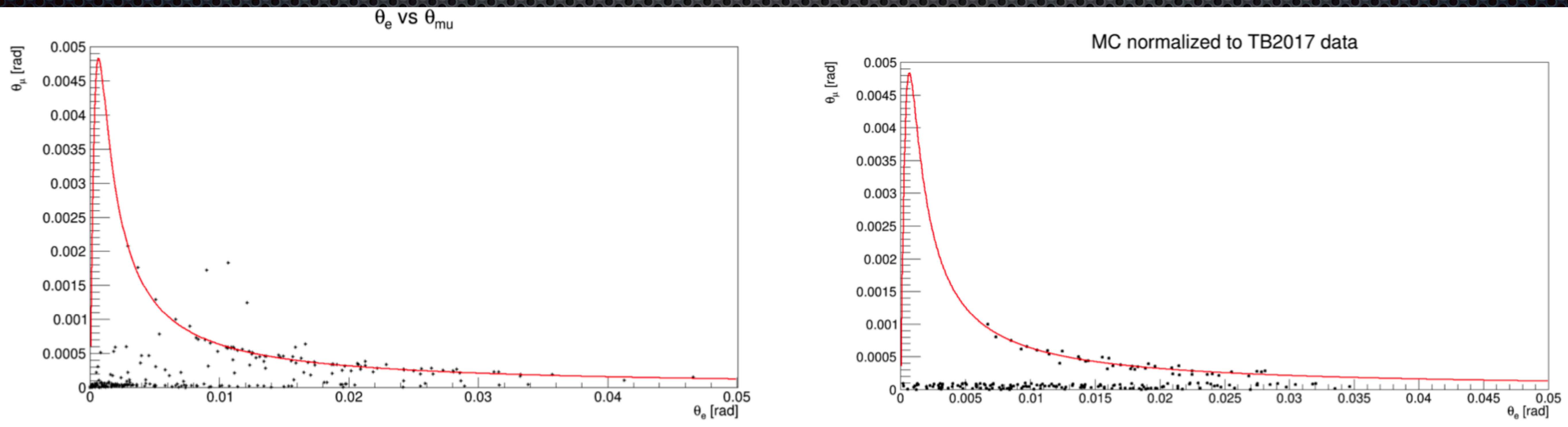
μONE : Tracking

- Scattered electron and mu from χ^2 minimisation on downstream planes;
- Delicate to take into account MSC errors.



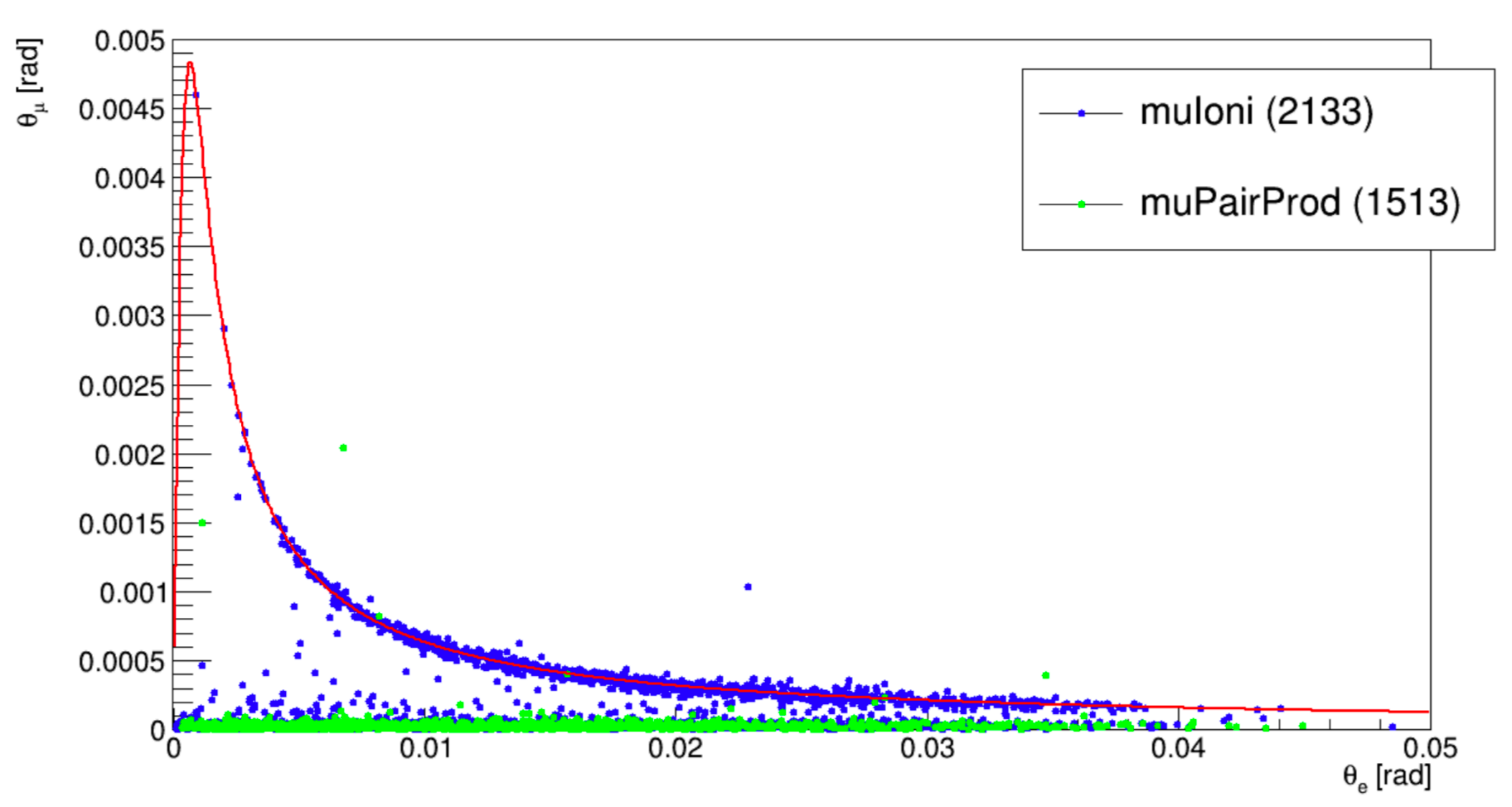
μONe : Tracking

Qualitative good agreement between data and simulation for the reconstruction of elastic scattering events!



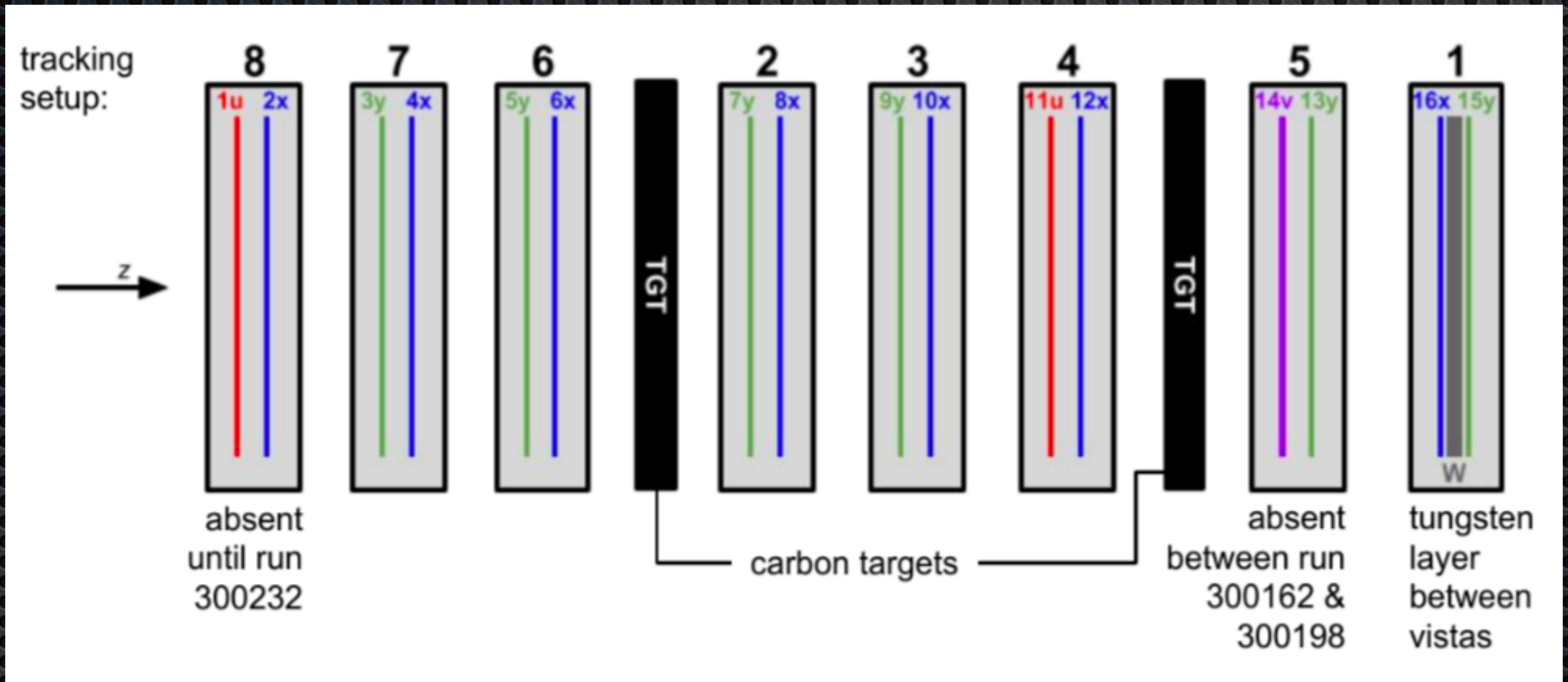
μONe : What is the background?

We can use Geant4 - 😩 - to better understand how the $\theta_e - \theta_\mu$ plot gets populated… most of the background comes from e^+e^- pair production!



μONe : The importance of tracking

In April 2018: new beam test!



u, v planes for discrimination; x,y for tracking

Two targets to measure independently mu-e events;

Si trackers with **40um** (20um in 2017TB);

Larger detector arm, up to **15mrad** full acceptance;

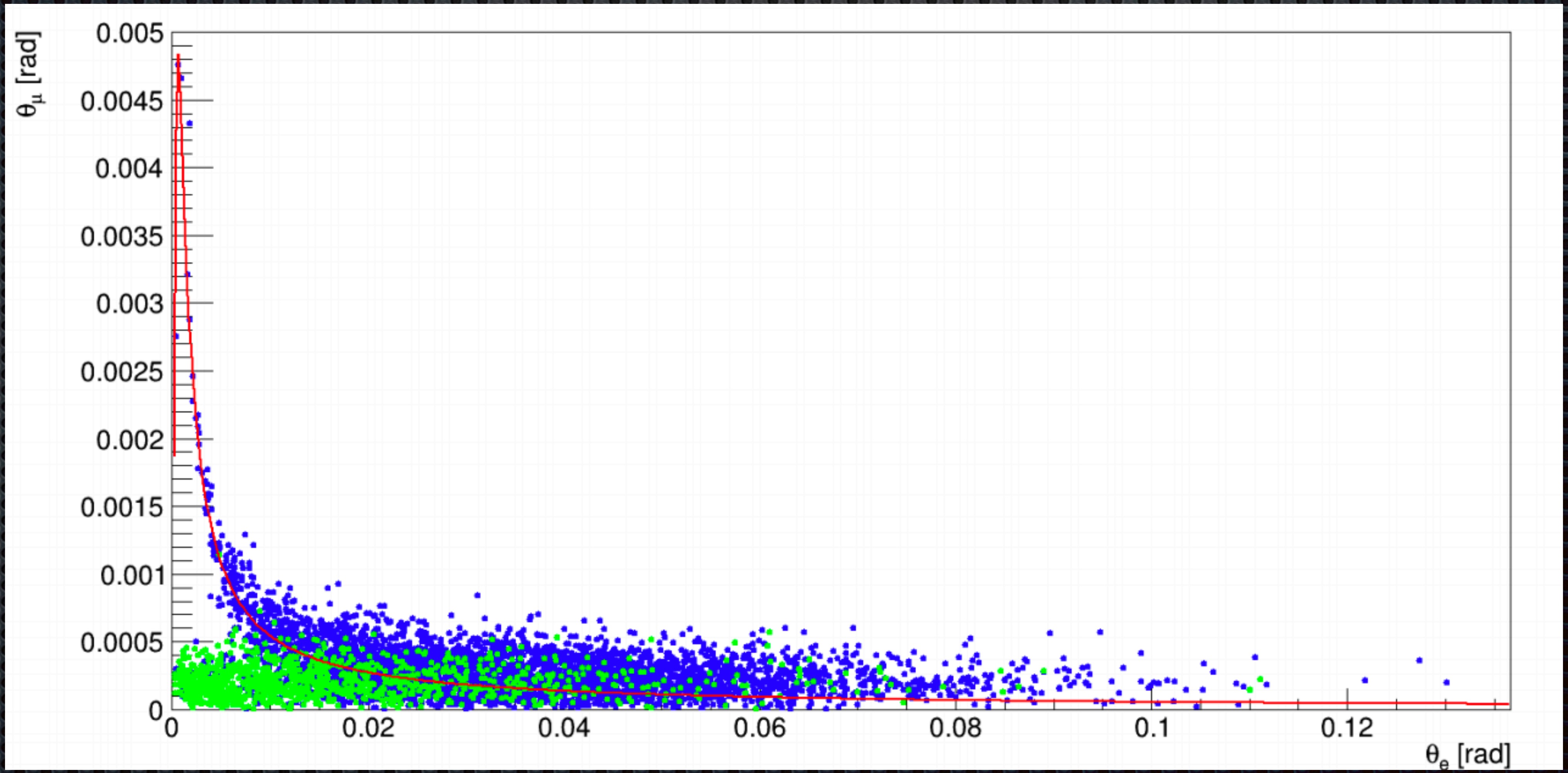
Upstream **BGO-PMT calorimeter** for PID.

μONe : The importance of tracking

In April 2018: new beam test!

Two stations

Worse Si trackers (40um res), **larger** acceptance (12mrad)



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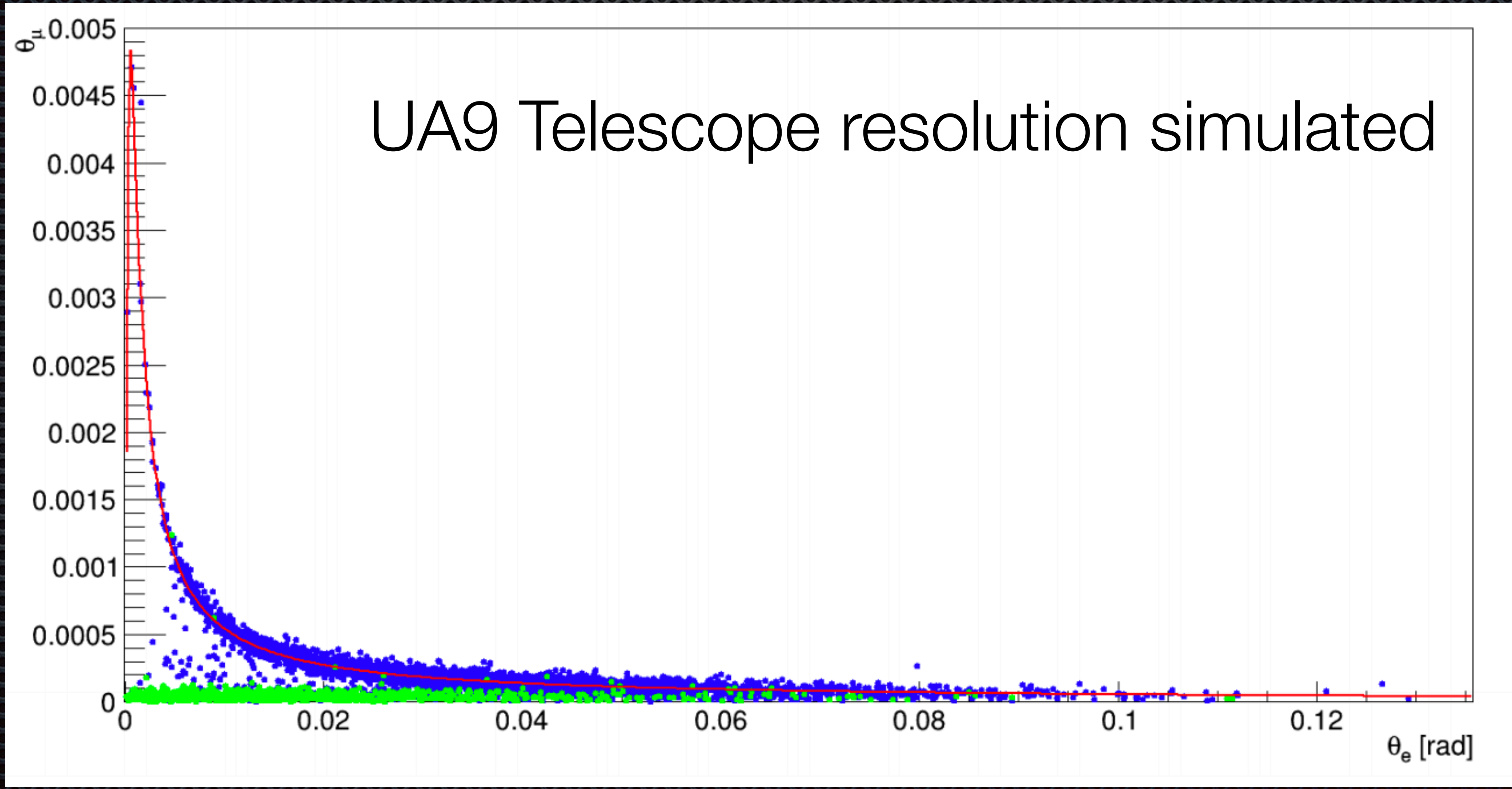

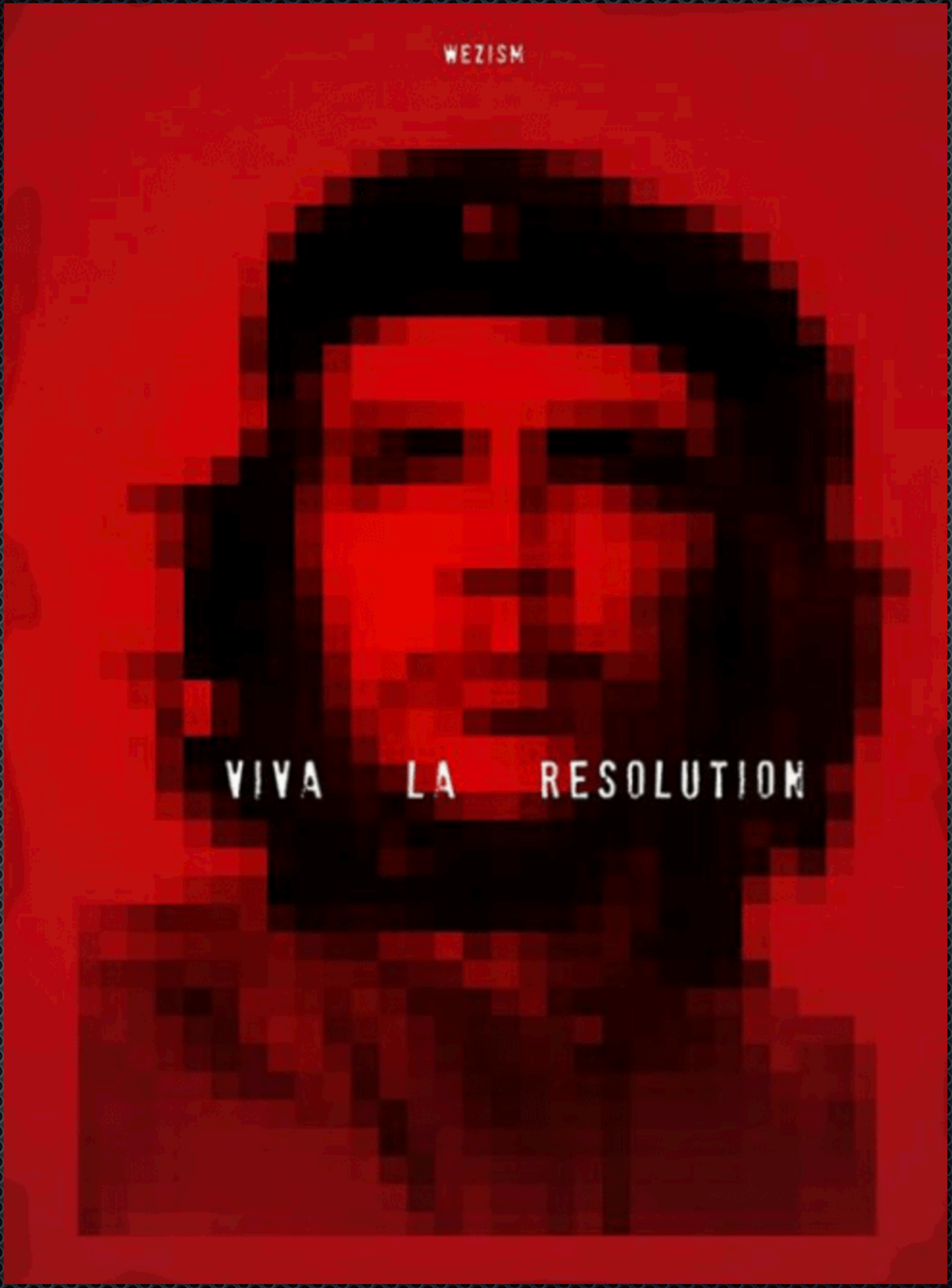
WEZISM
VIVA LA RESOLUTION

Conclusions

- $(g-2)_\mu$ discrepancy between E821 and SM at $\sim 4\sigma$
  - Extremely interesting portal to BSM physics
- H-LO contribution is the dominant source of theoretical uncertainty: MUonE aims to nail it down;
  - LOI submitted in 2019; First pilot run 2021;
  - Possible start of physics run in 2023.
- Delicate experiment aiming to reach **ppm** precision: very challenging but very stimulating!

Feedback form

https://forms.gle/bjQu4JBBQtVmEaAw9