Status of MUonE experimental proposal

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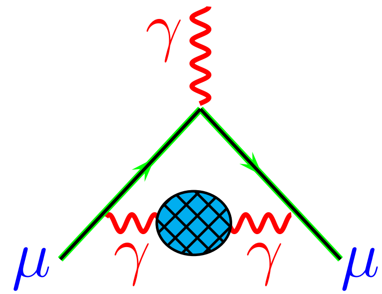

EPS-HEP2019 12 July 2019

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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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]

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

Muon g-2: summary of the present status

- E821 experiment at BNL has generated enormous interest:

$$a_\mu^{E821} = 11659208.9(6.3)\times 10^{-10} \quad (0.54\ \text{ppm})$$

- Tantalizing ~3σ deviation with SM (persistent since >10 years):

$$a_\mu^{SM} = 11659182.3(4.3)\times 10^{-10}$$

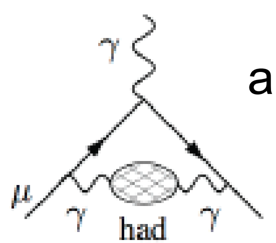
M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C77 (2017)

$$a_\mu^{E821} - a_\mu^{SM} \sim (26.8 \pm 7.6)\times 10^{-10} (3.5\sigma)$$

- Current discrepancy limited by:
  - Experimental uncertainty → New experiments at FNAL and J-PARC **x4** accuracy
  - Theoretical uncertanty → limited by hadronic effects

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

Hadronic Vacuum polarization (HLO)



$a_\mu^{HLO} = (693.1 \pm 3.4)10^{-10}$

$\delta a_\mu / a_\mu \sim 0.5\% \rightarrow 0.2\%$

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:

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

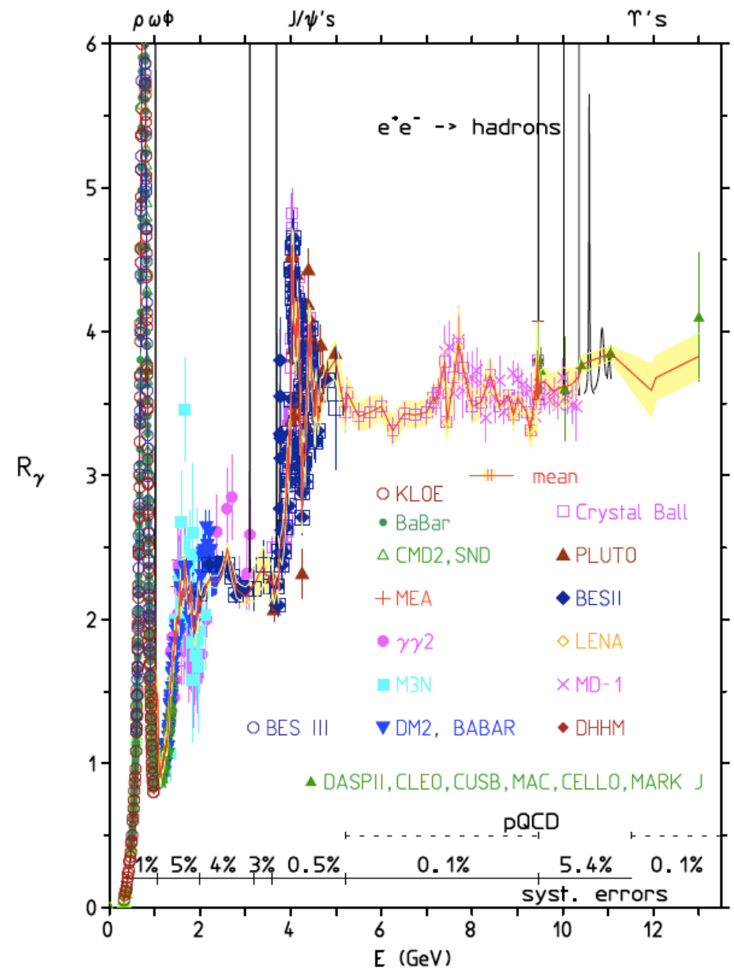
$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\cdot\sigma(s)_{(e^+e^-\to had)}$$

- The main contribution is in the highly fluctuating low energy

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

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



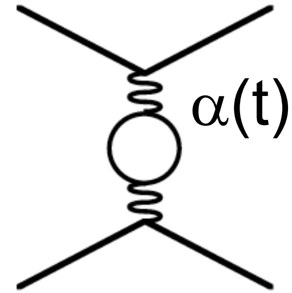
The high-energy tail of the integral is calculated using pQCD

Δ^{SM-BNL}~ 4% of a_μ^{HLO}

a_μ^{HLO} from space-like region

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

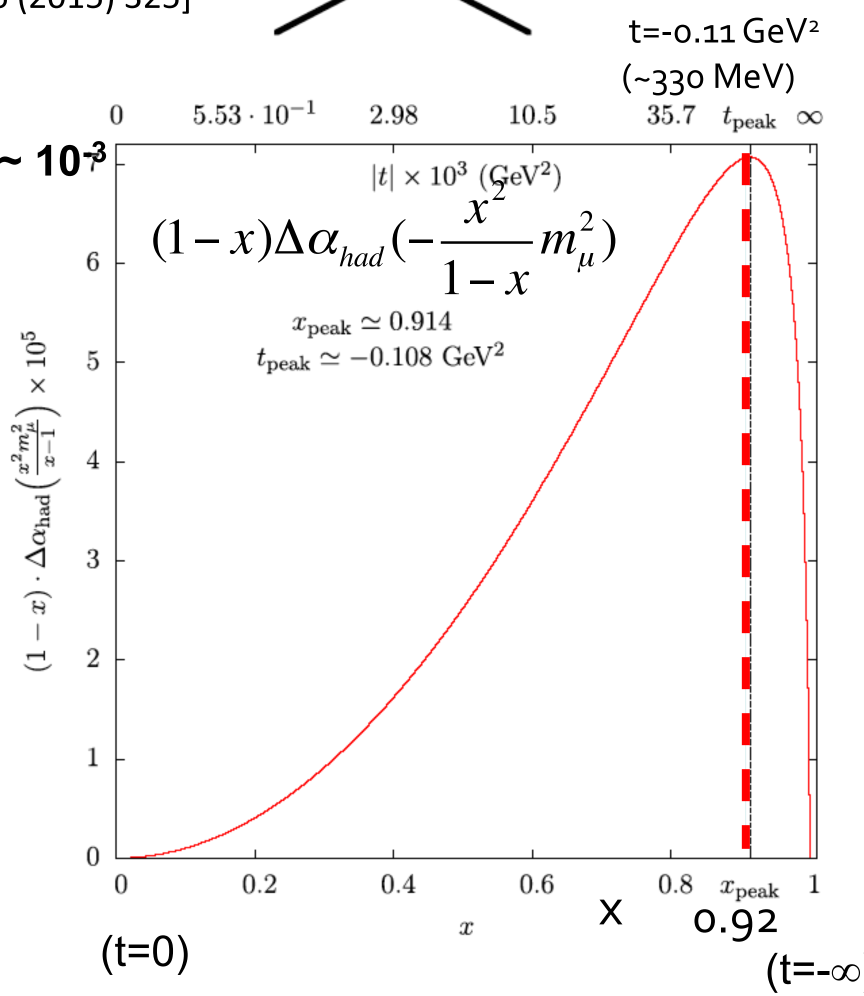
[C.M. C. Calame et al, Phys. Lett. B 746 (2015) 325]



t=q²<0

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

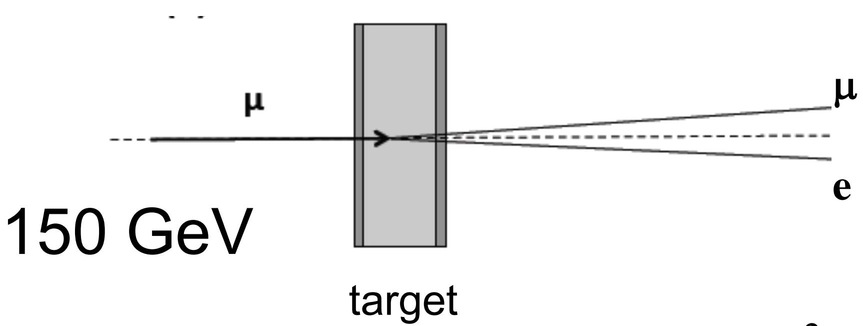
$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \qquad 0 \le x < 1;$$

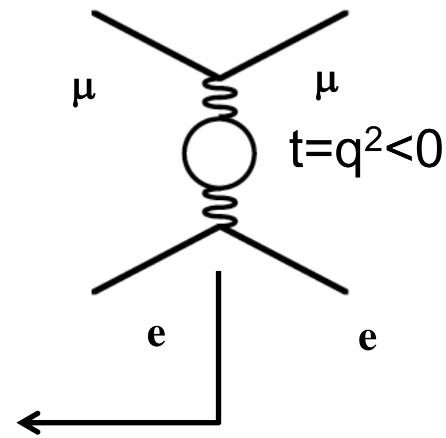


- **a_μ^{HLO} is given by the integral of the curve** (smooth behaviour)
- **It requires a measurement of** the hadronic contribution to the effective electromagnetic coupling in the space-like region **$\Delta\alpha_{had}$(t) (t=q²<0)**
- **It enhances** the contribution from **low** q² region (below 0.11 GeV²)
- **Its precision** is determined by the **uncertainty** on $\Delta\alpha_{had}$ (t) in this region

Experimental approach:

Extract $\Delta\alpha_{had}(t)$ from process $\mu e \rightarrow \mu e$ using 150 GeV μ on beryllium target. The measurement doesn't rely on the precise knowledge of the luminosity but on the shape of the distribution (relative measurement)





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

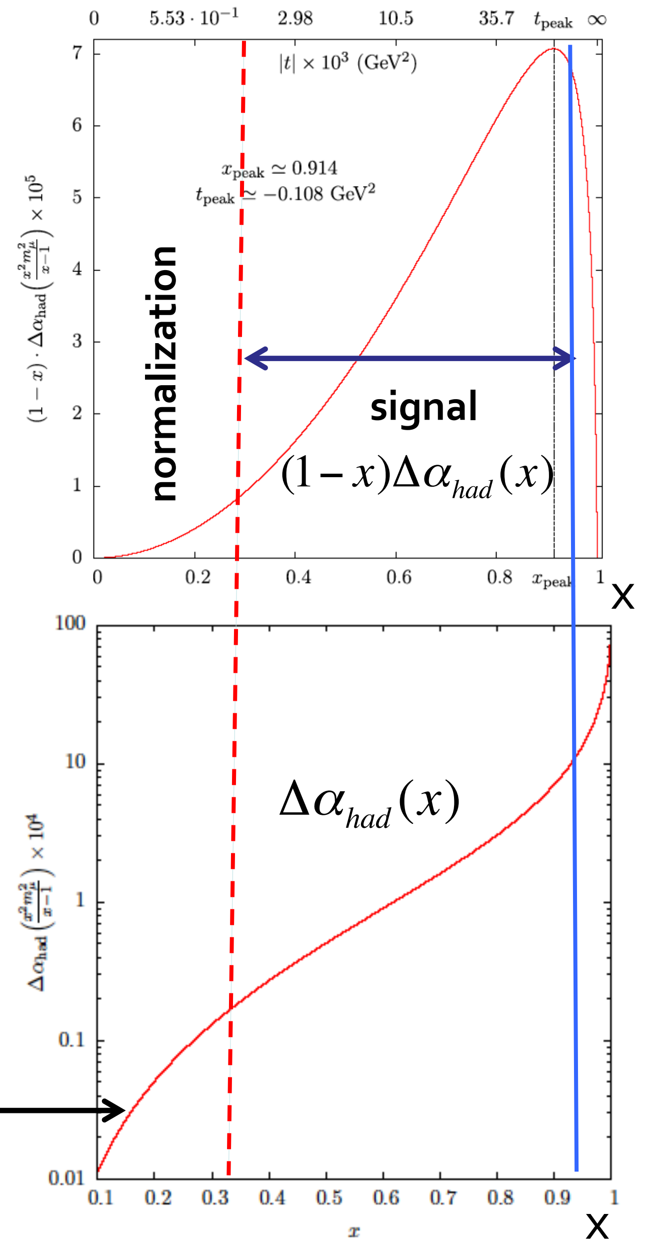
Why measuring $\Delta\alpha_{had}(t)$ with a 150 GeV μ beam on e^- target ?

$\mu\, e \rightarrow \mu\, e$ looks an ideal process!

- It is a pure t-channel (at LO)
- It allows to cover 83% of the integrand (**a_μ^{HLO}**). The missing part can computed with time-like data+pQCD
- The kinematics is very simple: $t=-2m_eE_e$
- High boosted system gives access to all angles (t) in the cms region

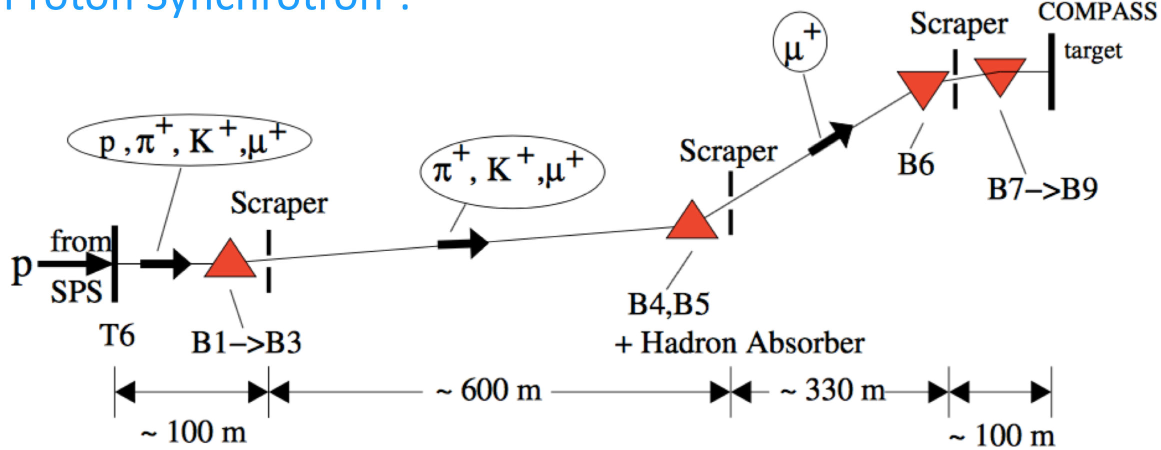
θ_e^{LAB}<32 mrad (E_e>1 GeV)
θ_μ^{LAB}<5 mrad

- It allows using the same detector for signal and normalization. Events at $x \lesssim 0.3$ ($t \sim -10^{-3}$ GeV²) can be used for normalization ($\Delta\alpha_{had}(t) \lesssim 10^{-5}$)



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”.



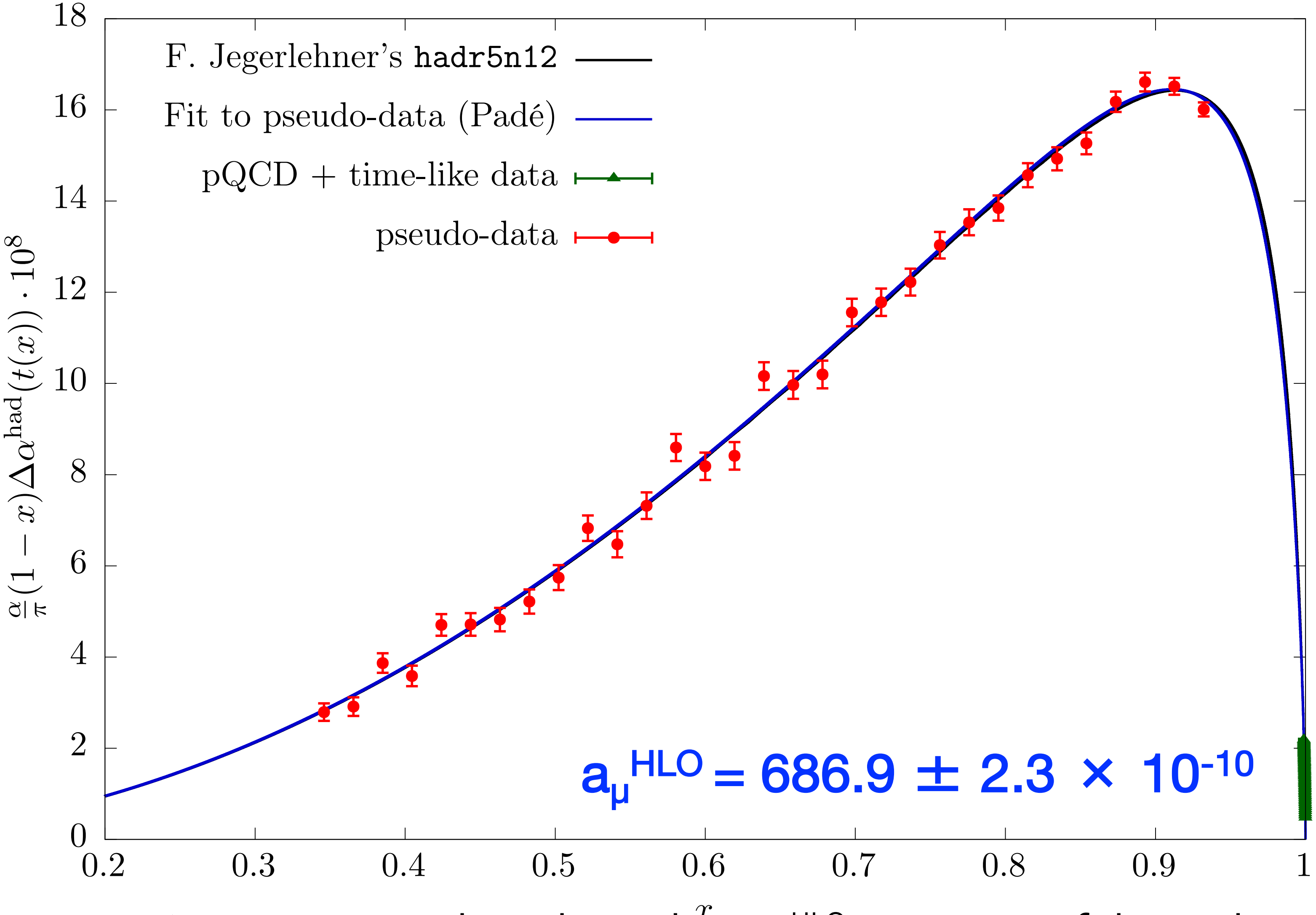
https://arxiv.org/pdf/hep-ex/0703049.pdf

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

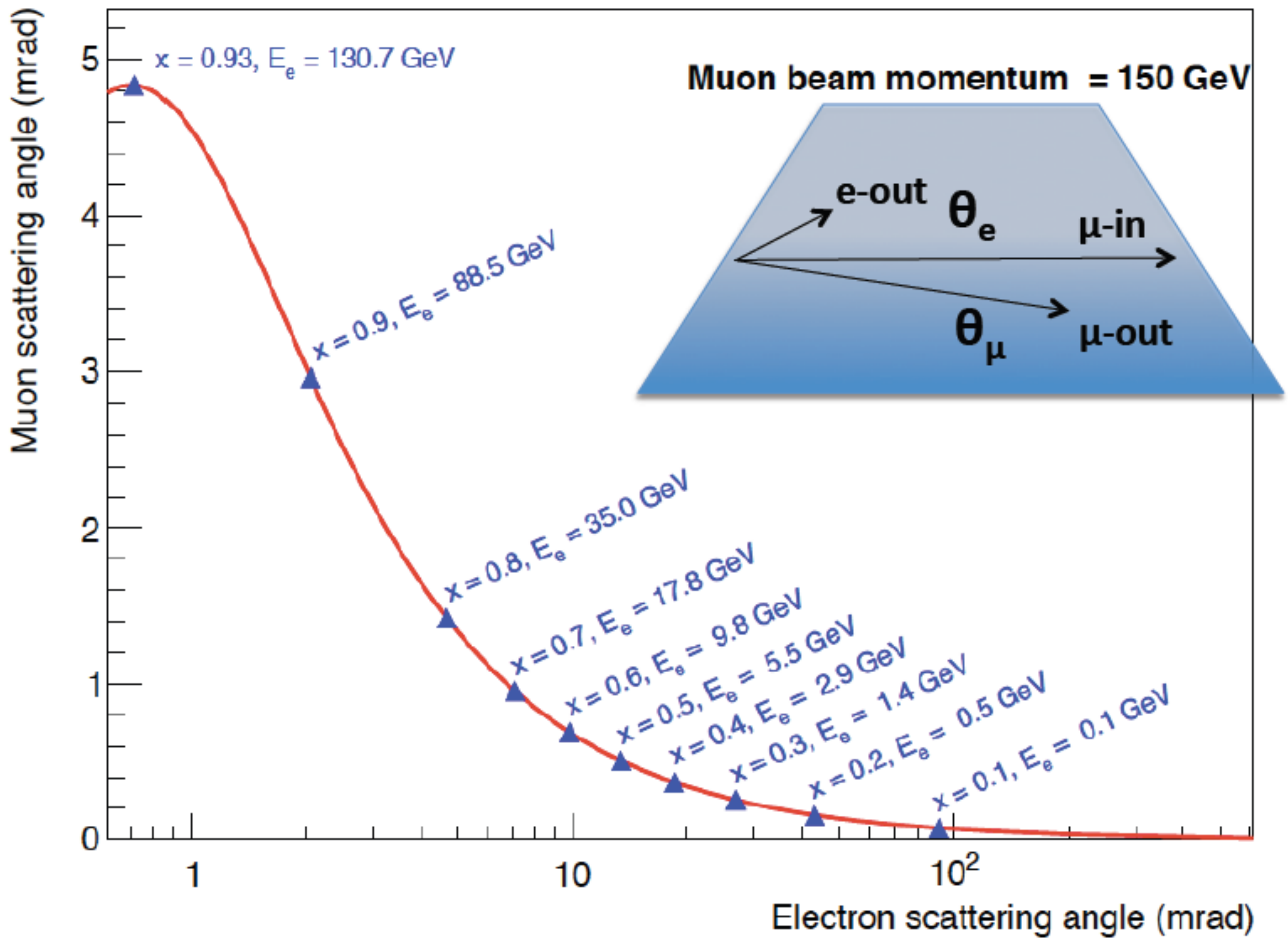
Statistical reach of MUonE on a_μ^{HLO}
(2 years of data taking at $1.3 \times 10^7 \mu/s$)



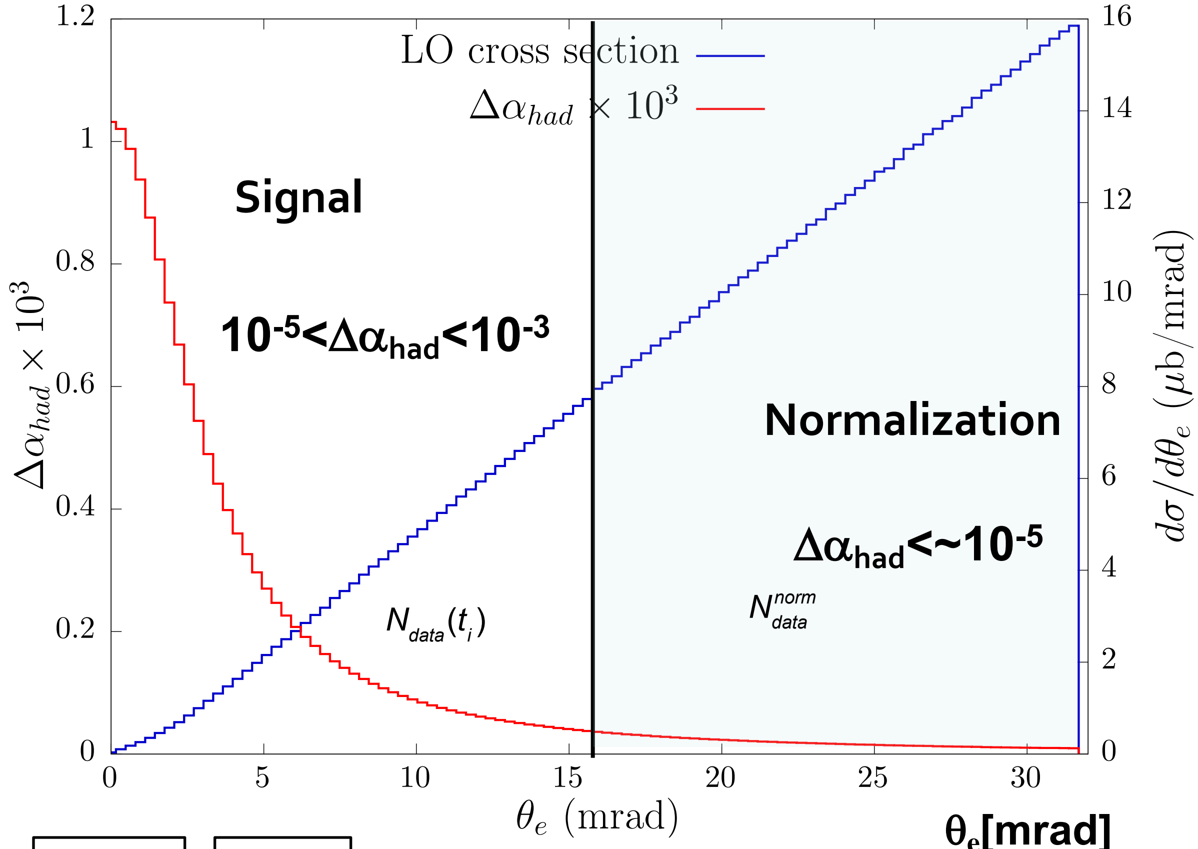
A **0.3%** stat error can be achieved on a_μ^{HLO} in 2 years of data taking with $\sim 10^7\ \mu/s$ ($4 \times 10^{14} \mu$ total)

Elastic scattering in the (θ_e , θ_μ) plane

Coplanarity of the momentum vectors and angular kinematical constraint



MUonE : signal/normalization region



$$\frac{N_{data}(t_i)}{N^0_{MC}(t_i)} = \boxed{\frac{N_{data}(t_i)}{N^{norm}_{data}}} \times \boxed{\frac{\sigma^{0,norm}_{MC}}{\sigma^0_{MC}(t_i)}} \sim 1 - 2(\Delta\alpha_{lep}(t_i) + \Delta\alpha_{had}(t_i))$$

Ratio of the theoretical cross section (with no VP)

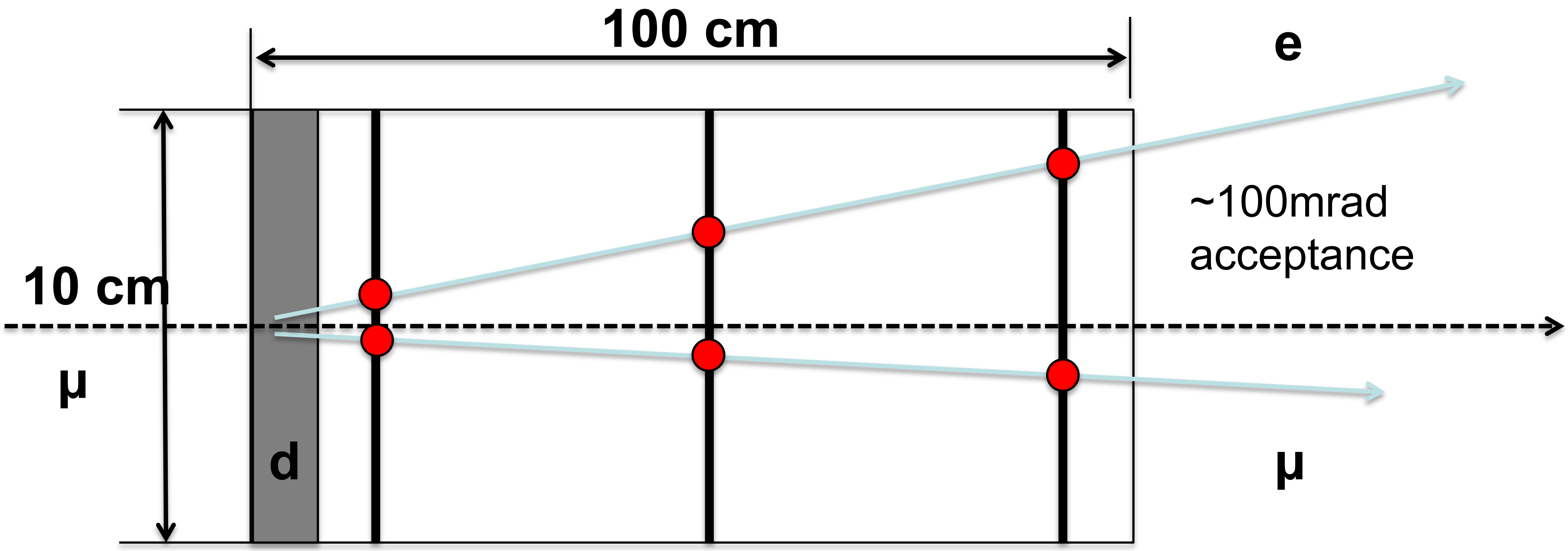
Ratio of data $N_{signal}(t)/N_{normalization}$

a_μ^{HLO} at 0.3% → These two ratios should be known at 10^{-5}

Detector concept

Repetition (x40) of this single module

(~ 40 m total length)



1.5cm Be Target

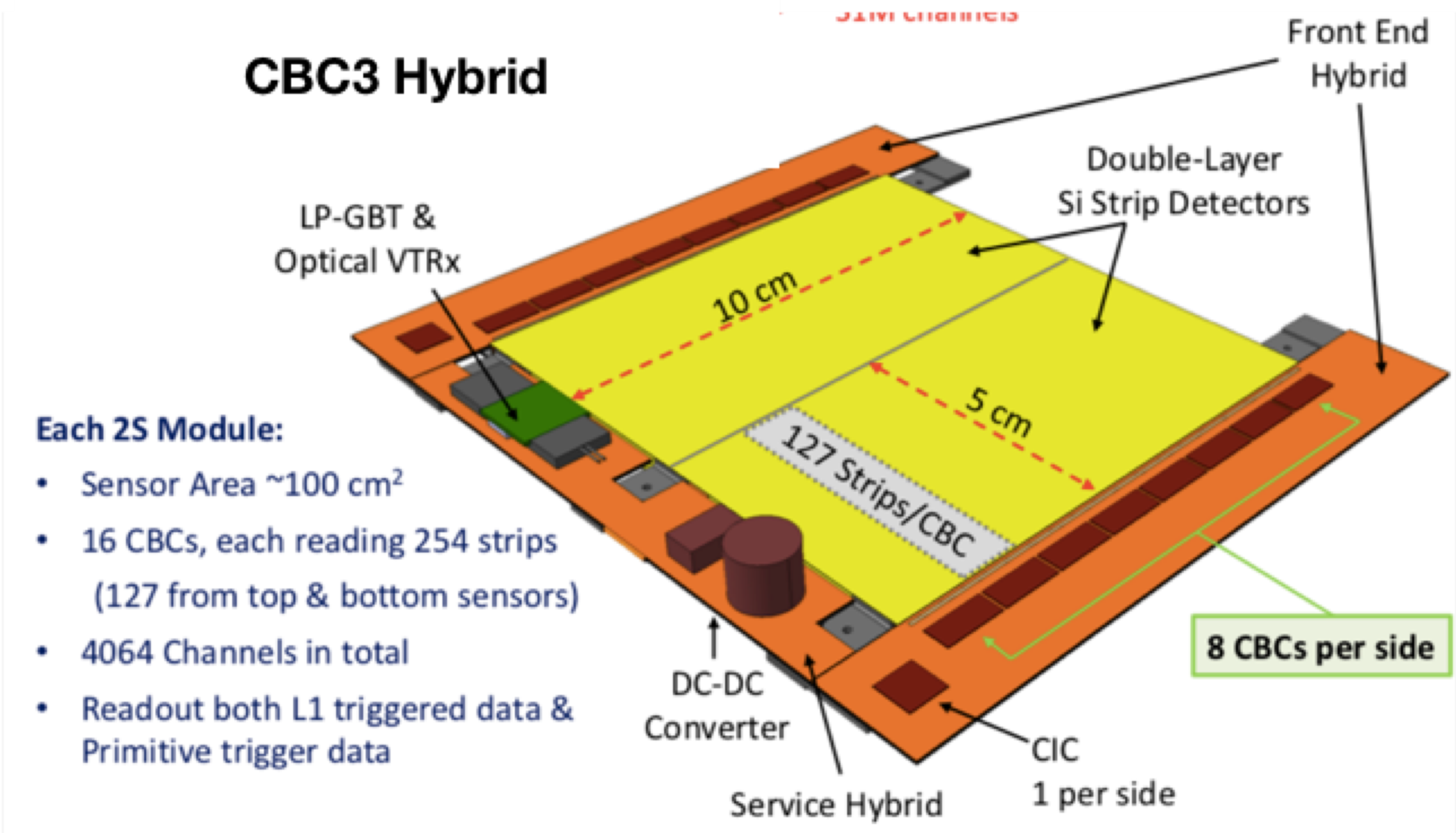
State-of-art Silicon strip detectors hit resolution ~20 μm

Expected angular resolution ~ 20 μm / 1m = 0.02 μrad$_2$

At the end ECAL and Muon Filter for PID

Baseline design

2S module of CMS detector



Hit resolution ~ 18 μm

Systematics

1. Multiple scattering
2. Tracking (alignment & misreconstruction)
3. PID
4. Knowledge of muon momentum distribution
5. Background
6. Theoretical uncertainty on the mu-e cross section (see later)
7. …

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

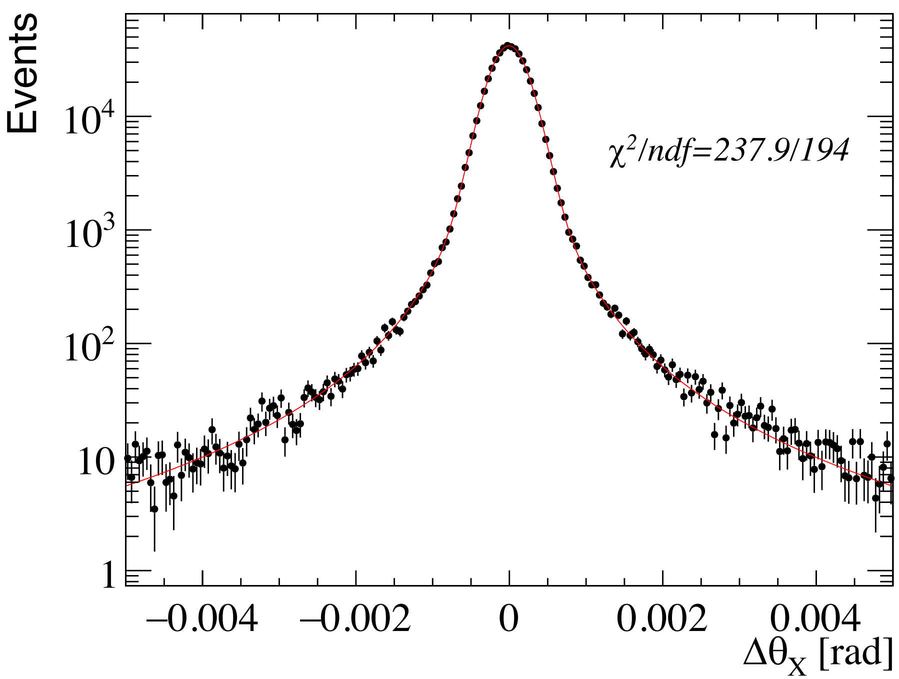
arXiv:1905.11677

Results on Multiple Coulomb Scattering from 12 and 20 GeV electrons on Carbon targets (8, 20 mm)

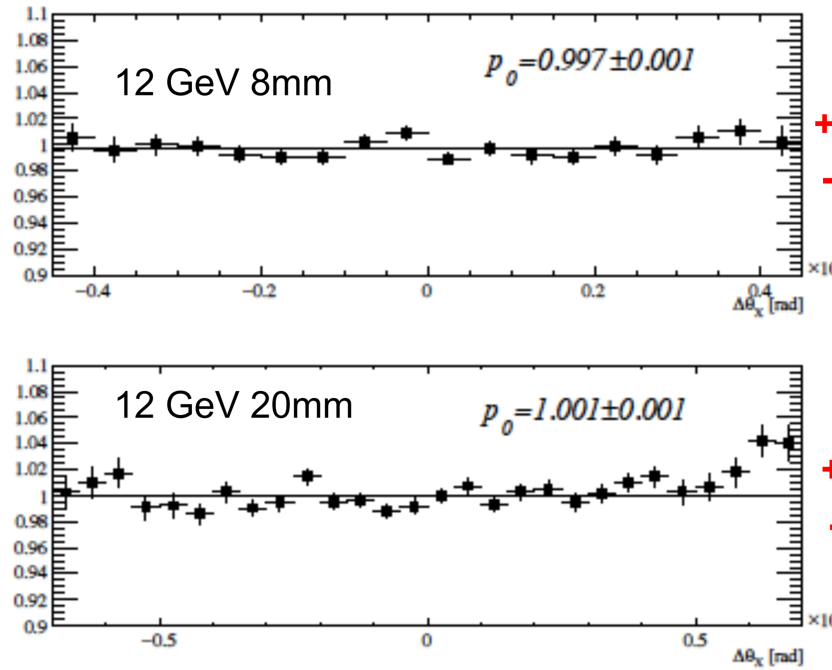
Submitted to JINST

G. Abbiendi[a], J. Bernhard[b], F. Betti[a,c], M. Bonanomi[d], C. M. Carloni Calame[e], M. Garattini[b,g], Y. Gavrikov[f], G. Hall[g], F. Iacoangeli[h], F. Ignatov[i], M. Incagli[j], V. Ivanchenko[b,k], F. Ligabue[j,l], T. O. James[g], U. Marconi[a], C. Matteuzzi[d], M. Passera[m], M. Pesaresi[g], F. Piccinini[e], R. N. Pilato[j,n], F. Pisani[a,b,c], A. Principe[a,c], W. Scandale[b], R. Tenchini[j], and G. Venanzoni[j,1]

12 GeV 8mm



data/MC



Theory

- QED NLO MC generator with full mass dependence has been developed and is currently under use (Pavia group) : M. Alacevich, *et al* **arXiv:1811.06743**.

- First results obtained for the NNLO box diagrams contributing to μ-e scattering in QED (Padova group): P. Mastrolia, *et al*, **JHEP 1711 (2017) 198**; S. Di Vita, *et al.* **JHEP 1809 (2018) 016**; M. Fael, **arXiv:1808.08233**; M. Fael , M. Passera **arXiv:1901.03106;** **r**esummation (effects beyond fixed-order perturbation theory) and "massification" (massless matrix elements → differential cross section) (A. Signer, Y. Ulrich, PSI Group)

An unprecedented precision challenge for theory: a full NNLO MC generator for μ-e scattering (10^{-5} accuracy)
→ **International** efforts!

Status of the Collaboration and plans

- Collaboration is growing and interest from International groups from CERN, China (Shangai), Poland (Krakov), Russia (Novosibirsk), UK (Liverpool London), USA (Virginia) has been expressed.

- Results so far encouraging; we are part of "Physics Beyond Collider" process at CERN (http://pbc.web.cern.ch/).

- LoI submitted to SPSC in June 2019: a few- weeks pilot run expected in 2021 for the validation of the detector design and performances; 2-years data taking in 2022-2024 for final (per mille) accuracy on a_{μ}^{HLO}

Letter of Intent

(submitted to SPSC in June)

70 authors; 16 Institutions

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

To be specified

Letter of Intent: The MUonE Project

MUonE Collaboration

Contents

POSSIBLE LOCATION AT EHN2

Conclusion

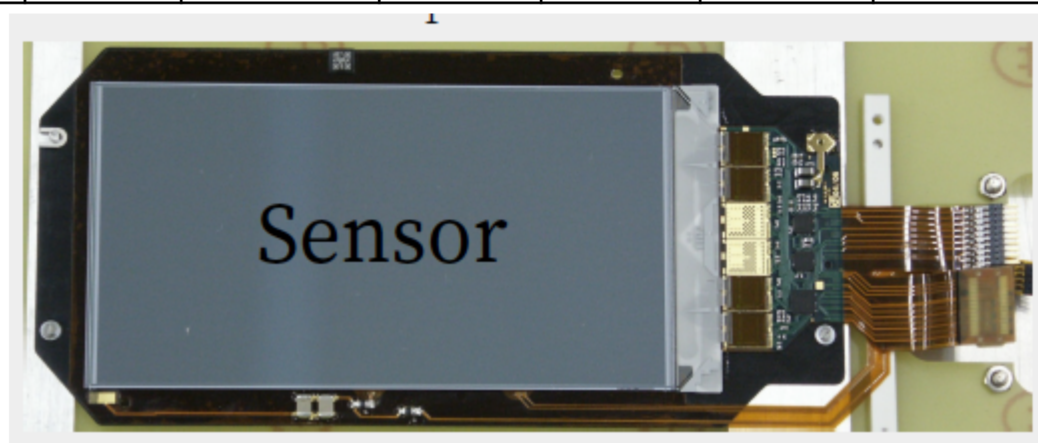
- Exciting times for the muon g-2!
- Alternative/competitive determinations of a_μ^{HLO} are essential.
- MUonE: a novel way (space-like region) to measure a_μ^{HLO} at per mille accuracy
- Many progress in the last years
- Growing interest from both experiment and theory community
- LoI submitted to SPSC in 2019; if approved a few-weeks pilot run in 2021 to assess the detector performance and validate the design; then 2 years run (2022-2024) for ultimate precision

THE END

Spare

Silicon detectors survey

	ALICE Upg Inner	**ALICE** Upg Outer	**CMS** Upg 2S	2 × **CMS** Upg 2S	**CMS** Upg PS	**CMS** Upg Pixel	2 × **CMS** Current	**Mimosa26**	**LHCb** VELO-pix
Technology	MAPS	MAPS	Hybrid strip	Hybrid strip	Hybrid strip/px	Hybrid pixel	Hybrid strip	MAPS	Hybrid pixel
active x [cm]	27	21	10	10	10	33	10	1.06	4.246
active y [cm]	1.5	3	10	10	5	44.2	10	2.12	1.408
pixel size x [μm]	30	30	90	90	100	50	90	18.4	55
pixel size y [μm]	30	30	50000	90	1400	50	50000	18.4	55
σx [μm]	2	2	26	26	29	7	18	3.2	12
σy [μm]	2	2	14434	26	404	7	18	3.2	12
Material [x/X_0]	0.3%	0.8%	2.3%	4.5%	3.8%	2.0%	4.5%	0.10%	0.94%
Sensor mat. [x/X_0]	0.3%	0.8%	0.3%	0.6%	3.8%	2.0%	0.6%	0.10%	0.94%



Possible location at CERN M2

- Between BSM and COMPASS

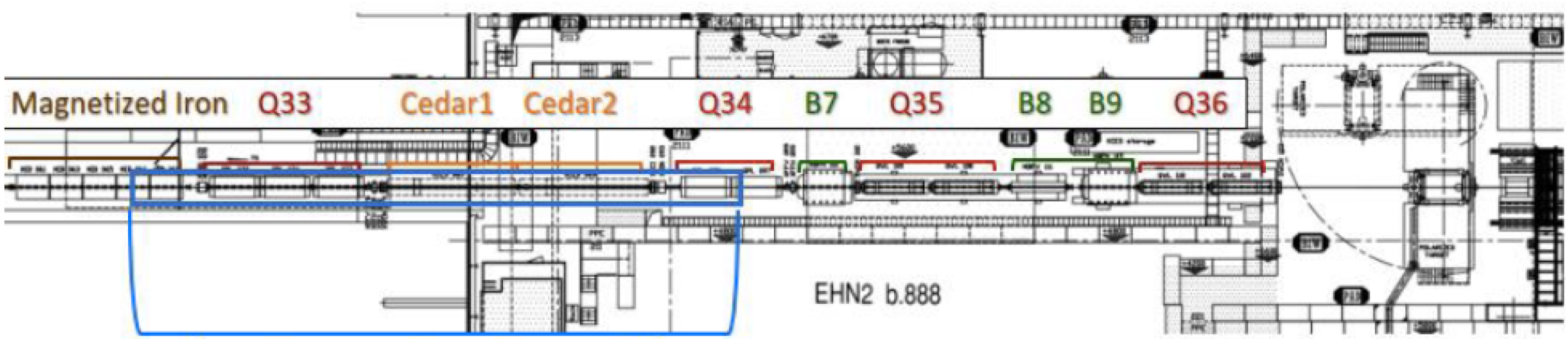
1/ μ-e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

- 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

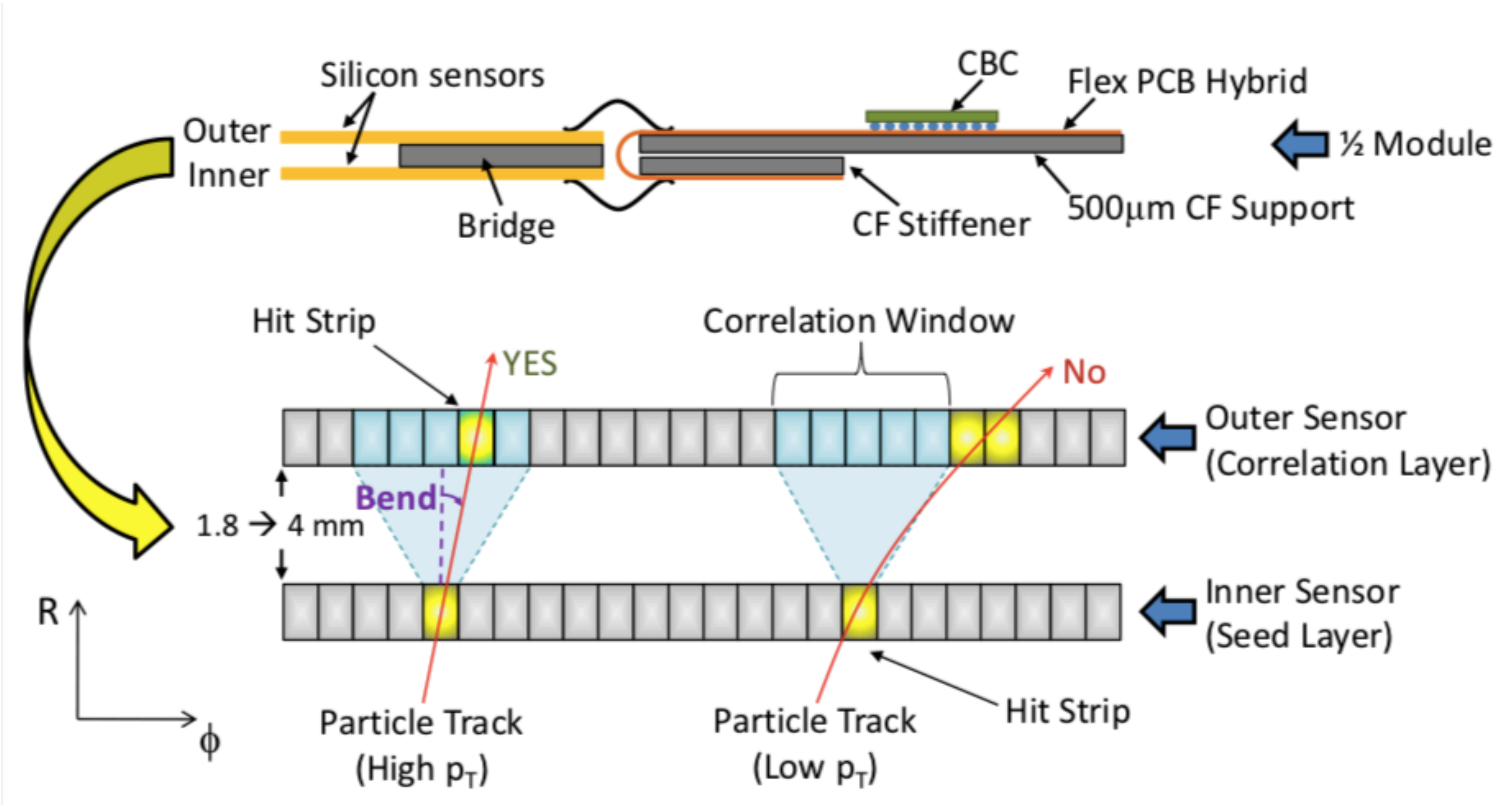
⇦

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

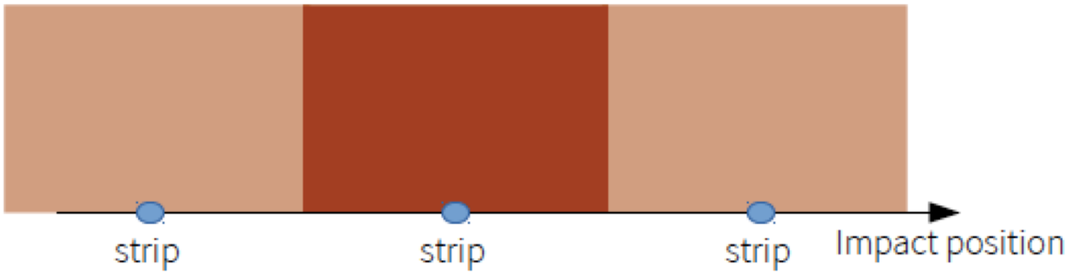
10

Beam Synergy/sharing at M2 under study (thanks to A. Magnon)

The concept of stub

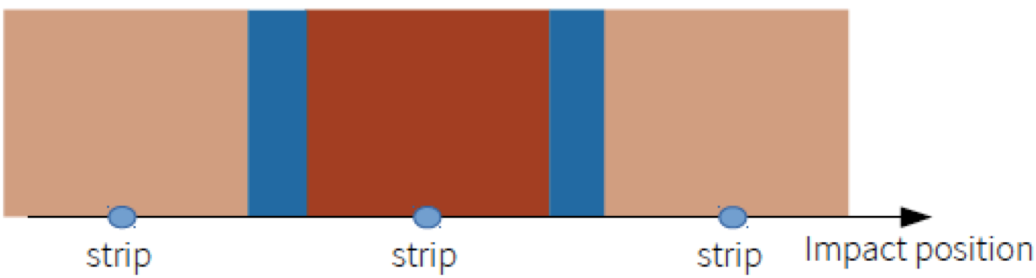


Cluster size & resolution



100% 1-strip clusters

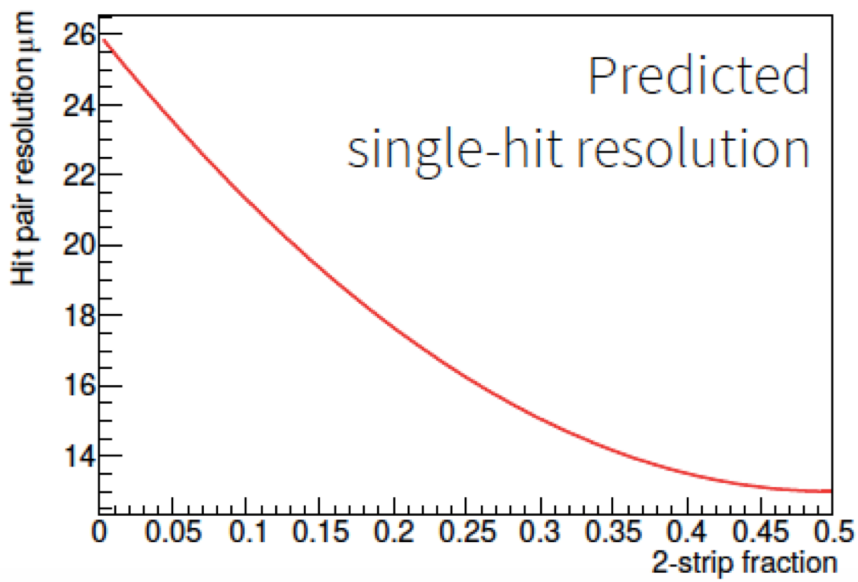
$$\sigma_S = \frac{p}{\sqrt{12}} \simeq 26\,\mu\text{m}$$



80% 1-strip clusters

20% 2-strip clusters

$$\begin{aligned}\sigma_S &= 0.8 \times \frac{0.8p}{\sqrt{12}} + 0.2 \times \frac{0.2p}{\sqrt{12}} \\ &\simeq 18\,\mu\text{m}\end{aligned}$$



In general (back of the envelope)

α 2-strip cluster fraction

$$\sigma_S = \frac{p}{\sqrt{12}}(2\alpha^2 - 2\alpha + 1)$$

Hit pair resolution

$\sigma_P = \sigma_S/\sqrt{2} \approx 10\,\mu\text{m}$

achievable limit **ideally!**

Some numbers:

- 60 cm total Be target ($2X_0$) segmented in 40 stations with 1.5 cm target ($0.03\ X_0$)
- ~40 m total detector length
- 10x10 cm^2 silicon detectors
- Resolve each μ,e track with uniform efficiency
- Best possible resolution on $\theta\mu$ (<5mrad),θe (<50 mrad)
- μ rate: ~60 MHz (peak) → 15 MHz (averaged)
- μ separation: 17 ns (peak) → 68 ns (averaged)
- Collect 4×10^{12} events with E_e>1GeV in ~2 years
- Scattering probability (E_e>1GeV): 1.7×10^{-4}/cm
- Scattering event rate (E_e>1GeV): ~10 kHz per station (peak); 2.5 (avg)
- Scattering separation (E_e>1GeV): 100 μs per station