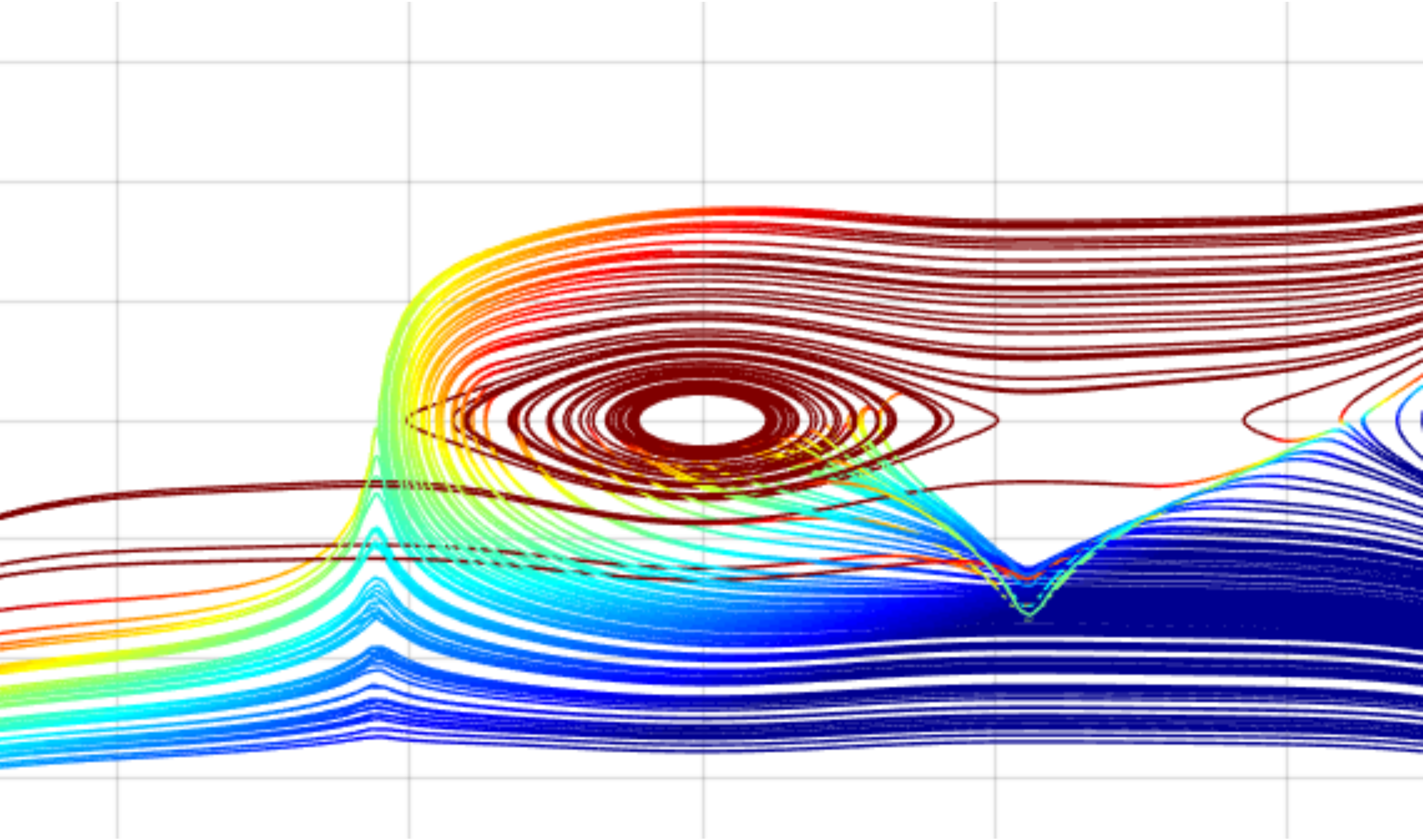


Search for a muon EDM with the frozen-spin technique

Francesco Renga
INFN Roma

Disclaimer

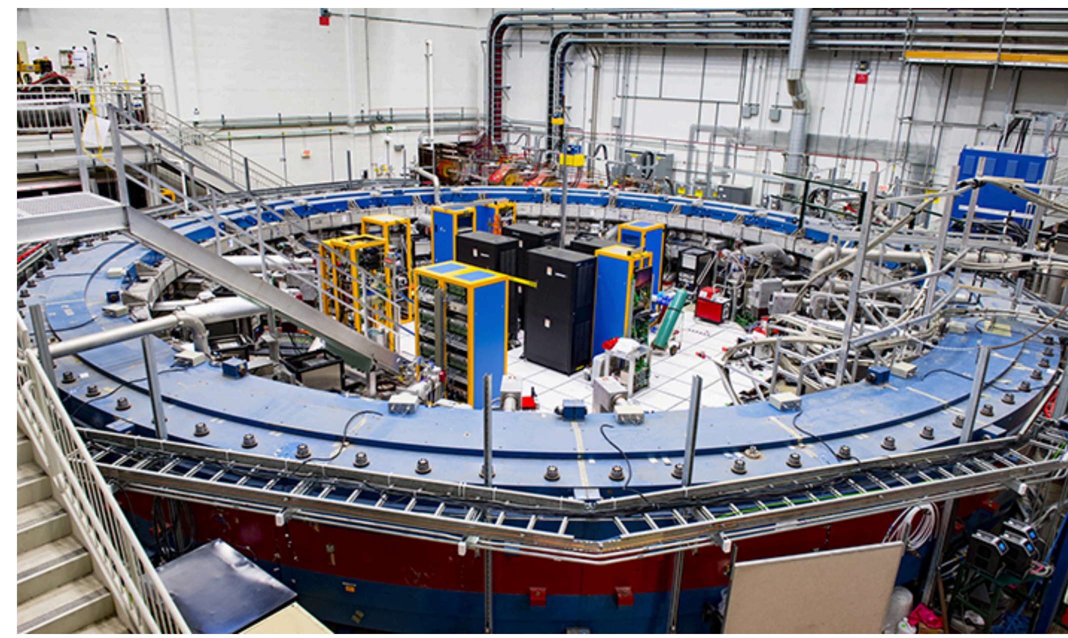
- Progetto non ancora presentato ufficialmente in CSN1:
  - non chiediamo l'apertura di una sigla per il 2023
  - presentazione introduttiva alla riunione di luglio, richiesta fondi per R&D e beam test per il prossimo anno
  - Sezioni attive: Roma, Pisa (+ manifestazione di interesse da Genova, Lecce, Pavia, Bologna e Padova)
- Progetto presentato al comitato scientifico del laboratorio di particelle del Paul Scherrer Institut (PSI), sotto forma di LoI, nel gennaio 2021:
  - feedback positivo dal comitato
  - si prevede di sottomettere un proposal formale alla prossima riunione nel gennaio 2023

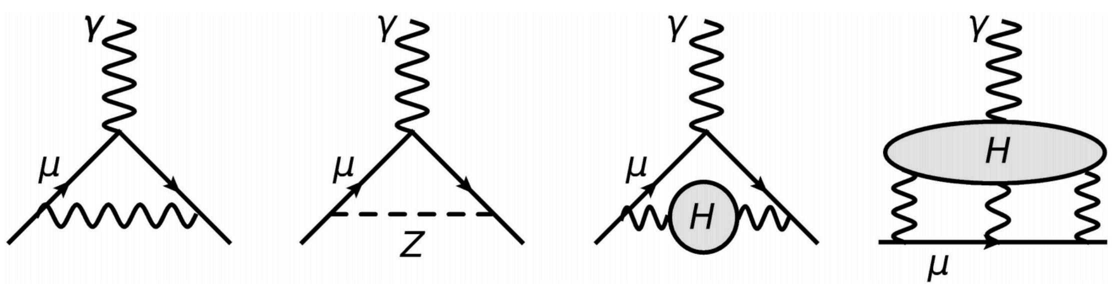
Physics Motivation

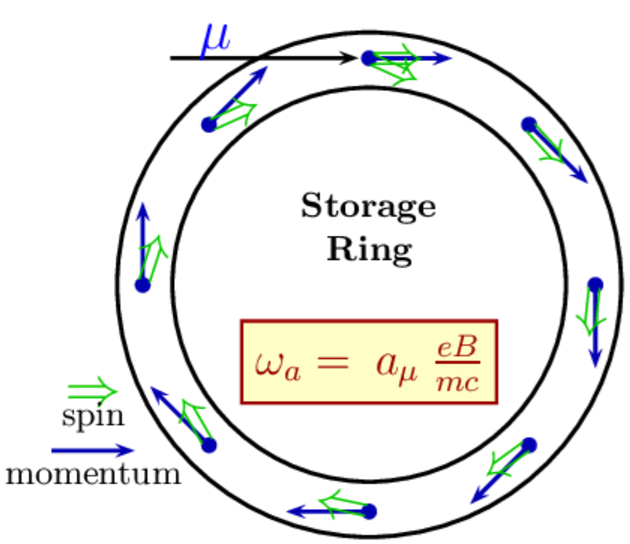
The g-2

- The long-standing deviation of the anomalous magnetic moment of the muon ($a_\mu = g_\mu - 2$) from SM predictions have been confirmed by the new FNAL experiment

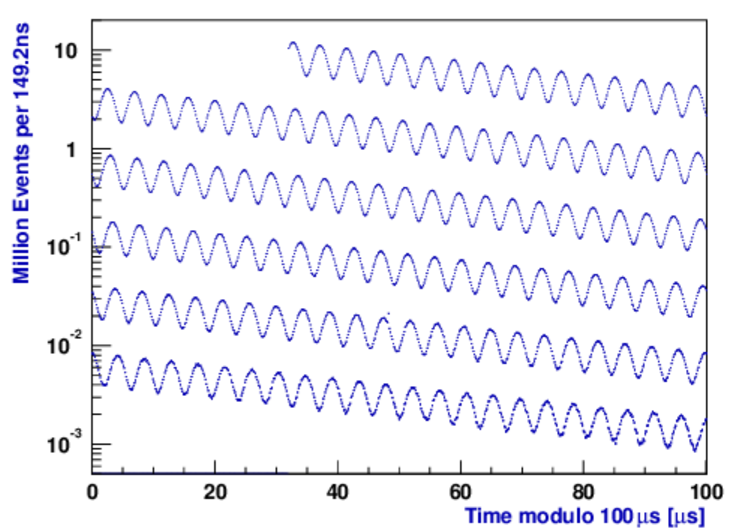
Phys. Rev. Lett. **126 (2021) 14, 141801**

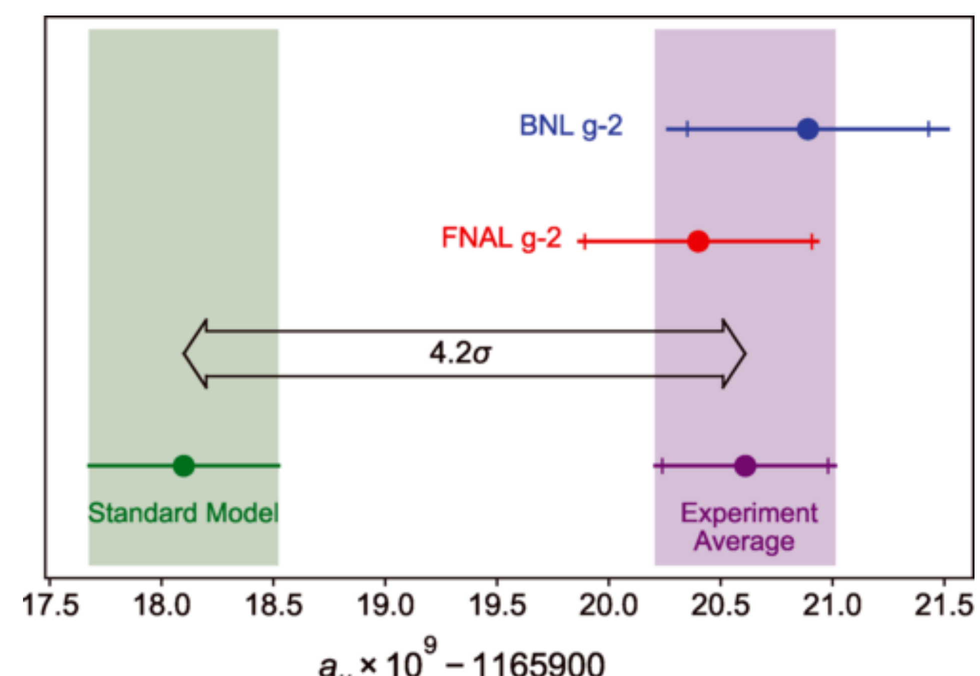




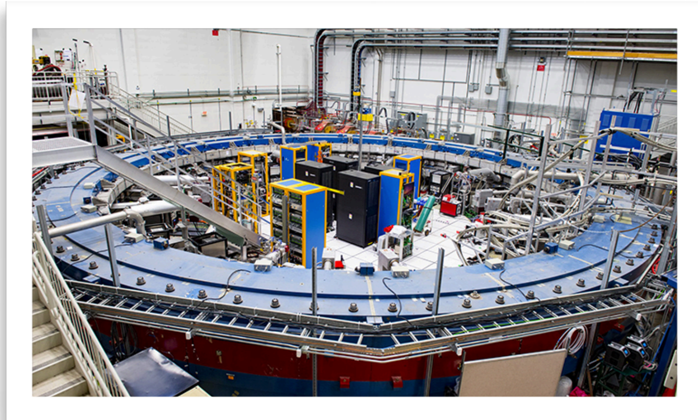


actual precession × 2





Dipole interactions in effective field theories



g-2 @ FNAL

ANOMALOUS MAGNETIC MOMENT

$$a_{\ell_i} = -\frac{4m_{\ell_i}}{e}\,\mathrm{Re}\,c_R^{\ell_i\ell_i}$$

Processes intrinsically connected

NP explanation for g-2 is likely to imply large LFV and muon EDM

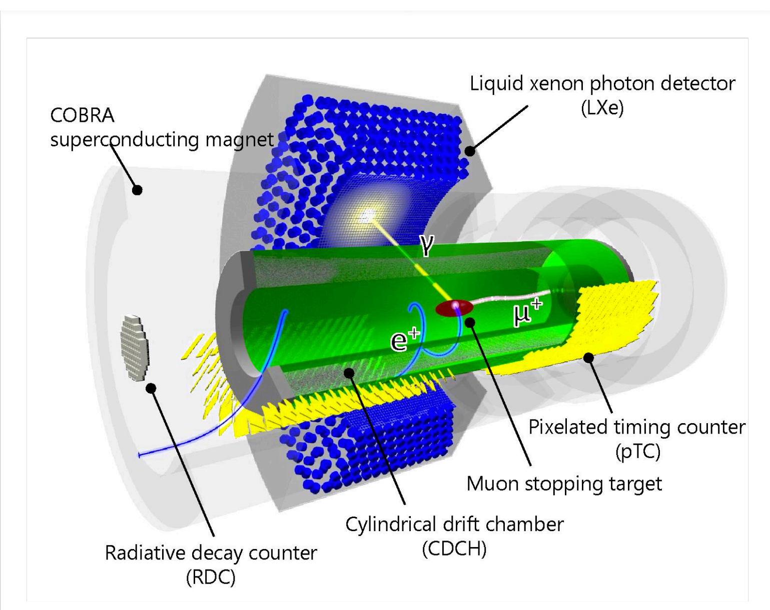
A. Crivellin and M. Hoferichter, arXiv:1905.03789
K. S. Babu, B. Dutta and R. N. Mohapatra, Phys. Rev. Lett. 85 (2000) 5064
E. O. Iltan, Eur. Phys. J. C 54 (2008) 583

$$\mathcal{H}_{\mathrm{eff}} = c_R^{\ell_f\ell_i}\,\bar{\ell}_f\sigma_{\mu\nu}P_R\ell_i F^{\mu\nu}$$

This talk

$$d_{\ell_i} = -2\,\mathrm{Im}\,c_R^{\ell_i\ell_i}$$

ELECTRIC DIPOLE MOMENT (EDM)

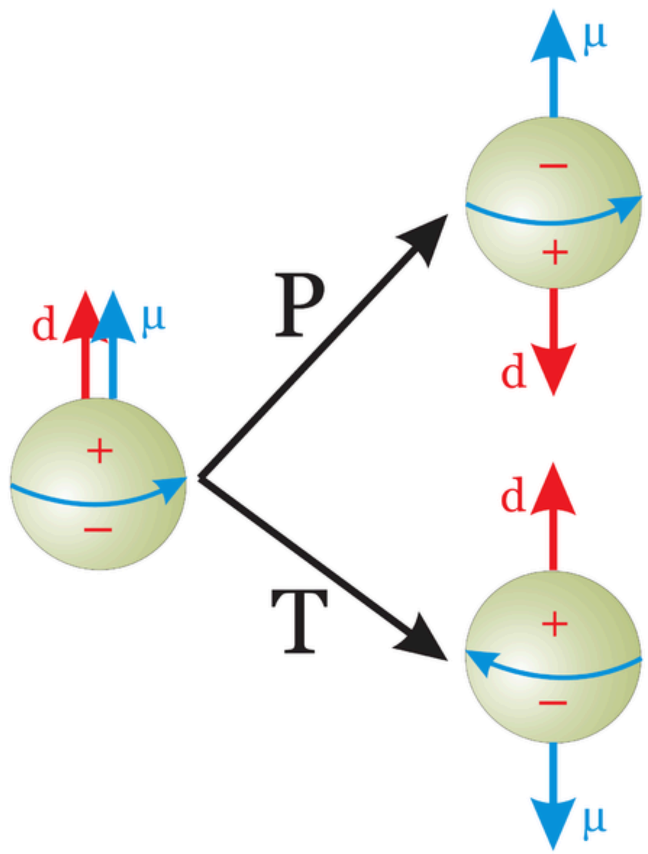


$$\mathrm{Br}[\mu\to e\gamma] = \frac{m_\mu^3}{4\pi\,\Gamma_\mu}\left(|c_R^{e\mu}|^2 + |c_R^{\mu e}|^2\right)$$

MEG II @ PSI

LEPTON FLAVOUR VIOLATION (LFV)

Electric dipole moments



$$\vec{\mu} = \frac{ge}{2mc}\vec{s}$$

$$\vec{d} = \frac{\eta e}{2mc}\vec{s}$$

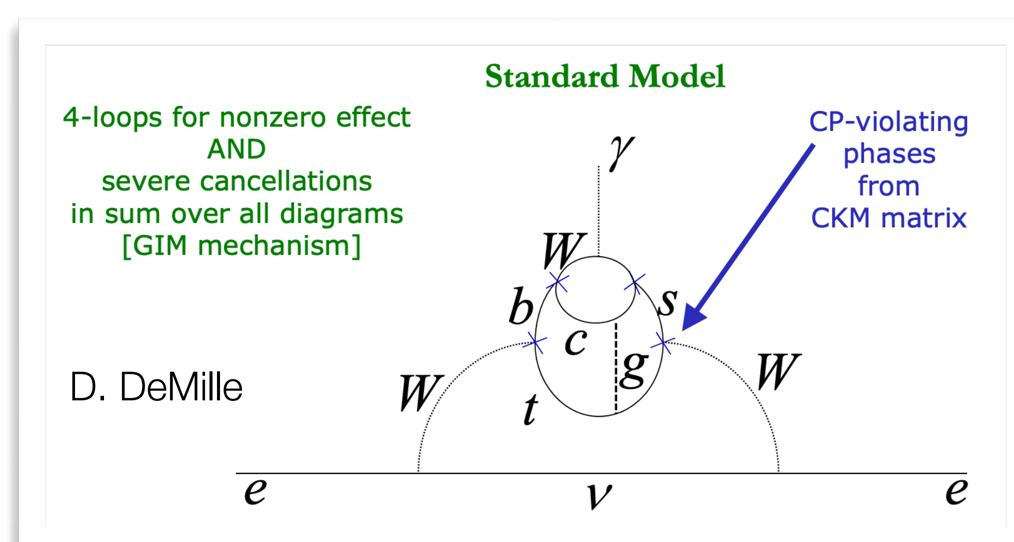
Magnetic dipole moment

$$U = -\,\vec{\mu}\cdot\vec{B}$$ **P- and T-even**

Electric dipole moment

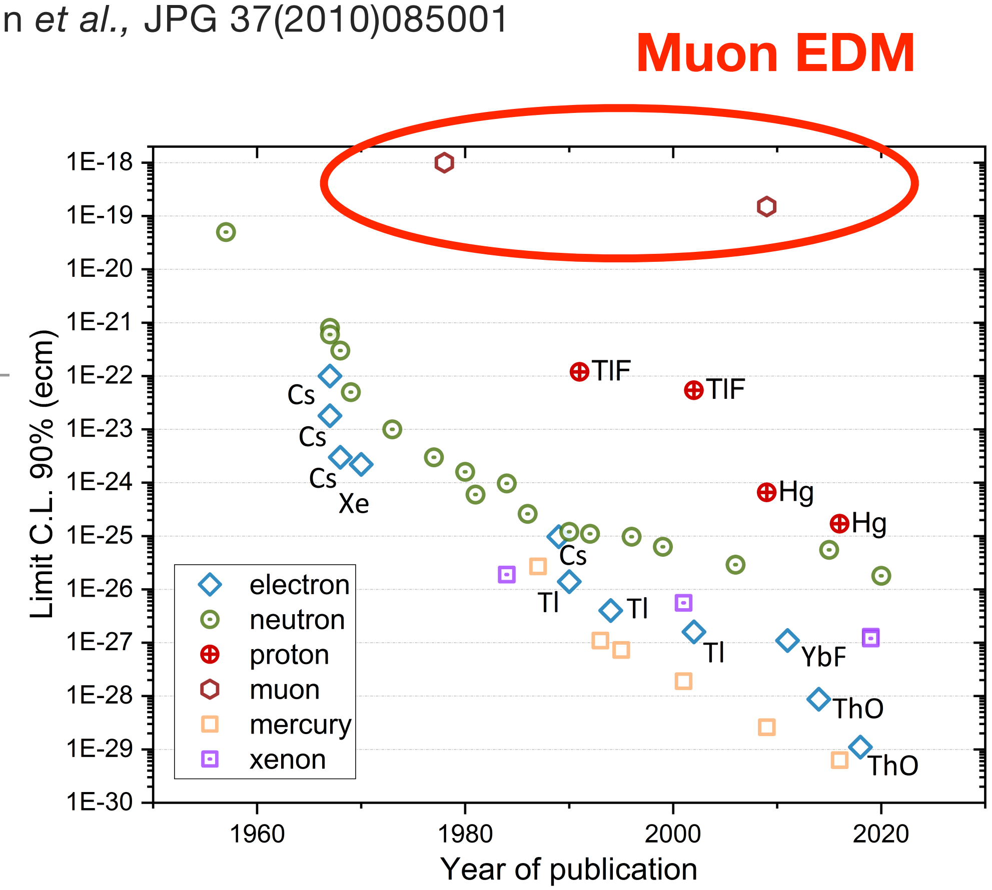
$$U = -\,\vec{d}\cdot\vec{E}$$ **P- and T-odd** **CPV!!!**

- EDMs of fundamental particles imply CP violation (CPV)
  - leptons EDM in the SM from CKM phases in loops involving quarks —> very small, not accessible



A. Adelmann *et al.*, JPG 37(2010)085001

Electron and muon EDM



- Muon EDM: strong link with g-2, would imply new sources of CPV (**matter-antimatter asymmetry of the universe**) and is negligible in the SM

- Strong constraints exist on the electron EDM (spin precession in molecular systems excited by lasers):
  - the muon EDM was somehow experimentally overlooked, due to the indirect constraint coming from the electron EDM under minimal flavour violation (MFV) assumptions

$$|d_e|_{\mathrm{exp}} \leq 8 \times 10^{-30}\, e\,\mathrm{cm}$$

MFV

$$|d_\mu|_{\mathrm{ind}} \leq 1.6 \times 10^{-27}\, e\,\mathrm{cm}$$

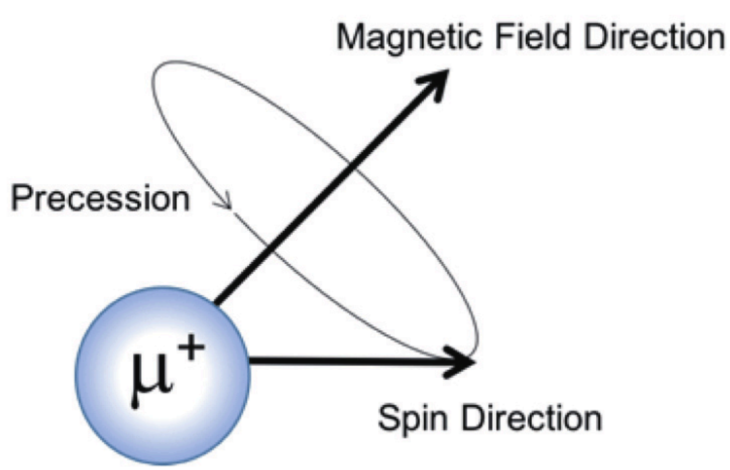
$$|d_\mu|_{\mathrm{exp}} \leq 1.5 \times 10^{-19}\, e\,\mathrm{cm}$$

- Current muon EDM limits produced as by-product of g-2 experiments

- **Indeed the new tensions in flavour physics, pointing toward Lepton Flavour Universality Violation (LUFV), challenge the MFV scenario and make a dedicated experiment to search for a muon EDM of great interest**

Experimental techniques for muon EDM searches

Dipole moments in electromagnetic fields



Magnetic spin precession in the particle rest frame

$$\overrightarrow{\omega}_L = 2\overrightarrow{\mu} \cdot \overrightarrow{B^*}/\hbar$$

$$\vec{\mu} = \frac{ge}{2mc}\vec{s}$$

Electric spin precession in the particle rest frame

$$\overrightarrow{\omega}_d = 2\vec{d} \cdot \overrightarrow{E^*}/\hbar$$

$$\vec{d} = \frac{\eta e}{2mc}\vec{s}$$

Electromagnetic spin precession in the laboratory rest frame

Cyclotron frequency

Thomas-Bargmann-Michel-Telegdi Equation (T-BMT)

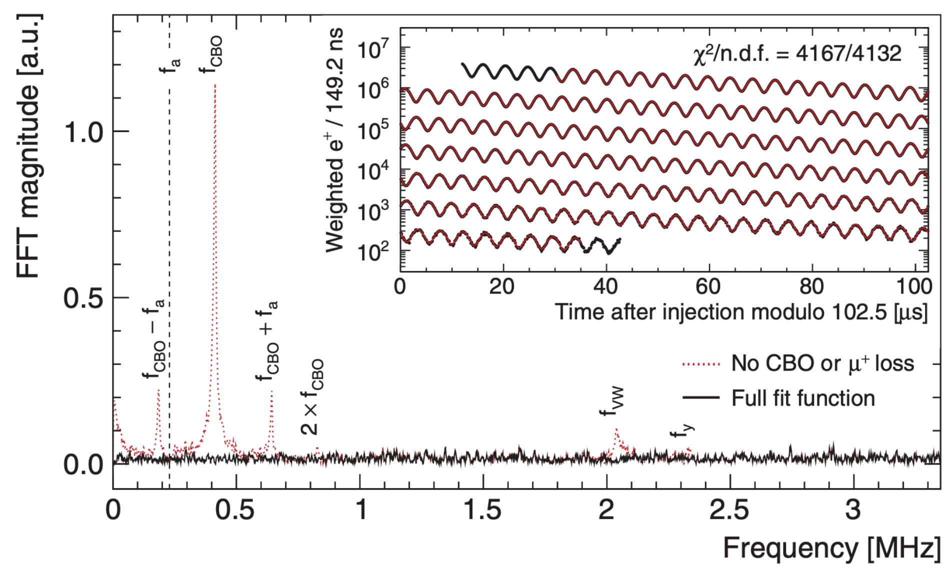
$$\vec{\Omega} = \vec{\Omega}_0 - \vec{\Omega}_c = \frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

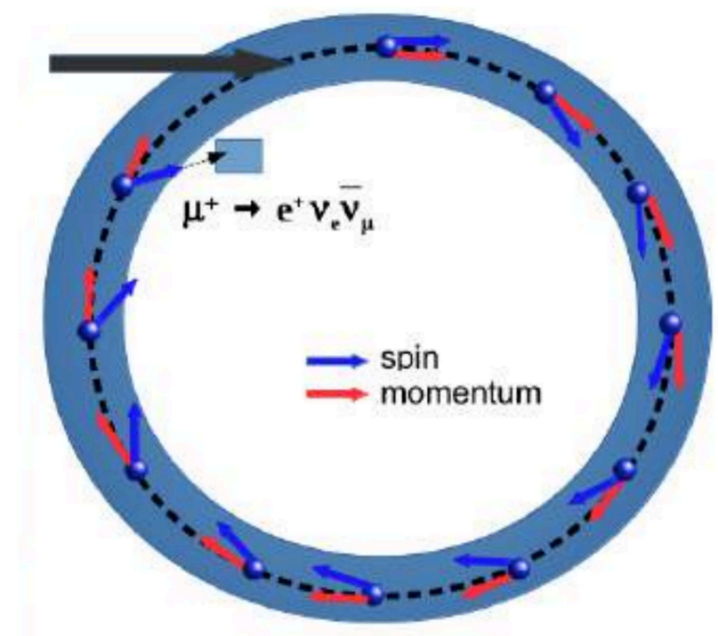
$$+ \frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \frac{\gamma}{(\gamma+1)c}\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta}\right]$$

EDM contribution

Muon g-2 measurements in storage rings

- Thanks to parity violation, the ***horizontally precessing*** spin is reflected into the angular distribution of electrons produced in muon decays
- Counts on detectors at a given angle oscillate with frequency Ω





$\gamma \simeq 1/\sqrt{a}$

$p \simeq 3.09\ GeV/c$

("magic" momentum)

$\vec{\beta} \perp \vec{B}$

$$\vec{\Omega} = \vec{\Omega}_0 - \vec{\Omega}_c = \frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$$+ \frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \frac{\gamma}{(\gamma+1)c}\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta}\right].$$

Neglected

Muon EDM from g-2 experiments

- Search for **vertical precession** due to the **"relativistic" electric field observed by the muon in its rest frame**, $\overrightarrow{E^*} = \gamma c \vec{\beta} \times \overrightarrow{B} \sim 13.5\ \mathrm{GV/m}$

- Although the experiments are not optimised for this measurement, the vertical granularity of the detectors combined with such a huge field still allows a precise measurement of the muon EDM

$$|d_\mu|_{\mathrm{exp}} \leq 1.5 \times 10^{-19}\, e\,\mathrm{cm}$$

***Phys.Rev.D* 80 (2009) 052008 [BNL Muon g-2]**

$\gamma \simeq 1/\sqrt{a}$

$p \simeq 3.09\ GeV/c$

("magic" momentum)

$\vec{\beta} \perp \overrightarrow{B}$

$$\vec{\Omega} = \vec{\Omega}_0 - \vec{\Omega}_c = \frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$$+ \frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \frac{\gamma}{(\gamma+1)c}\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta}\right].$$

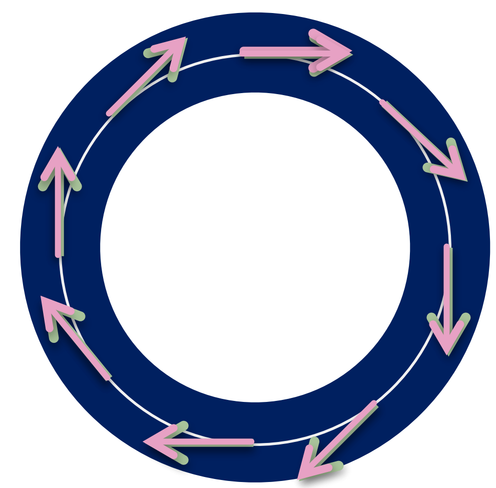
"Relativistic" electric field

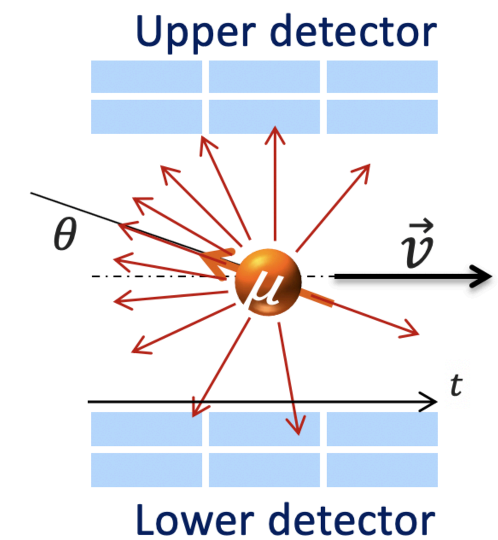
Small

Farley *at al.*, Phys. Rev. Lett. 93 (2004) 052001
Adelmann *et al.*, J. Phys. G 37 (2010), 085001

The frozen spin technique

- An electric field is applied to cancel the horizontal precession
- For $\eta = 0$, the spin is locked parallel to the momentum (as it has been produced in π decays)
- Search for a **vertical precession** due to a non-null EDM in the relativistic electric field





$\vec{\beta} \perp \vec{B}$ **+ apply an electric field** $E_f \simeq aBc\beta\gamma^2$ **so that**

$$a\vec{B} = \left(a - \frac{1}{\gamma^2 - 1}\frac{\vec{\beta} \times \vec{E}}{c}\right)$$

$$\vec{\Omega} = \vec{\Omega}_0 - \vec{\Omega}_c = \frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

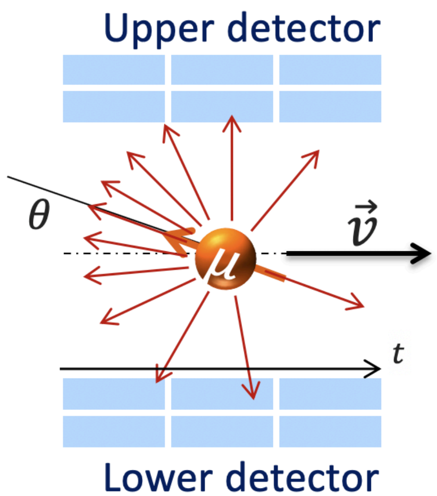
$$+ \frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \frac{\gamma}{(\gamma+1)c}\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta}\right].$$

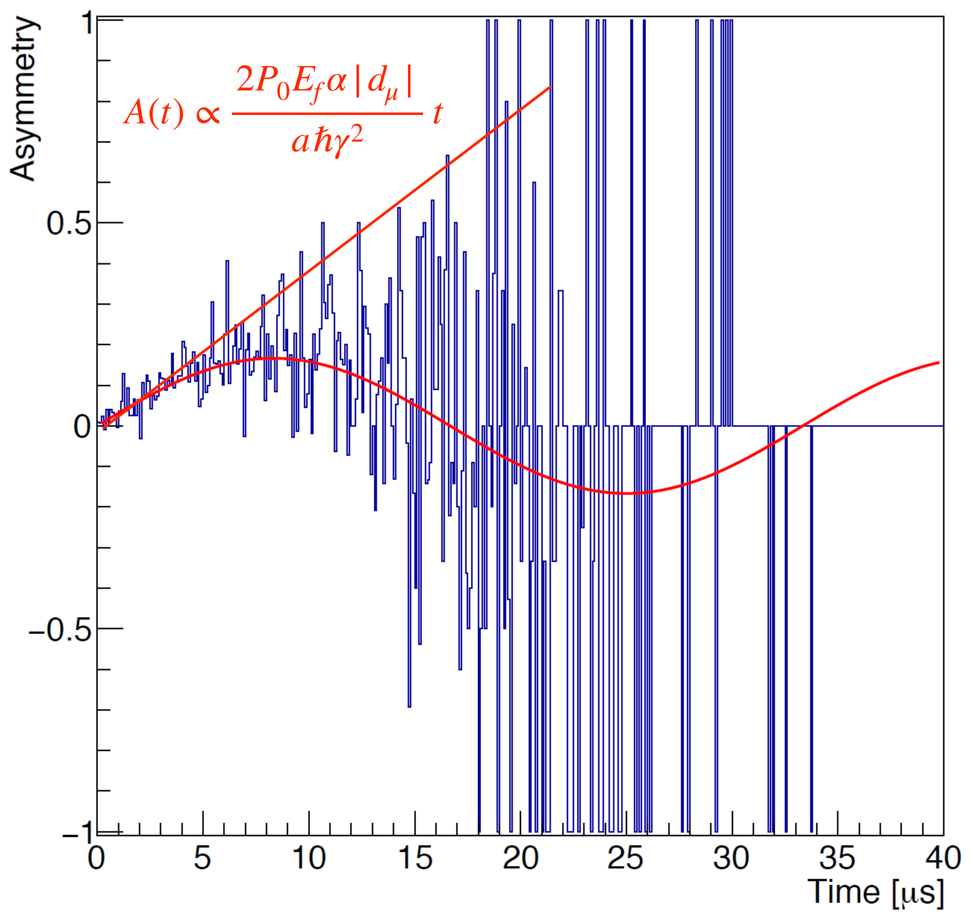
"Relativistic" electric field

Small

Experimental signal: up/down asymmetry

$$A(t) = \frac{N_{\uparrow}(t) - N_{\downarrow}(t)}{N_{\uparrow}(t) + N_{\downarrow}(t)}$$





Sensitivity from the asymmetry averaged over the muon decay time distribution (lifetime = $\gamma\tau_\mu$)

$$\sigma(|d_\mu|) = \frac{d|d_\mu|}{d\bar{A}}\sigma(\bar{A}) \sim \frac{a\hbar\gamma}{2P_0E_f\sqrt{N}\tau_\mu\alpha}$$

P_0 = initial polarisation degree
E = electric field in the lab frame
N = number of observed decays
τ_μ = muon lifetime
α = mean decay asymmetry (~ 0.3)

The "PENTA" formula

A muon EDM search at PSI

The muonEDM Proposal

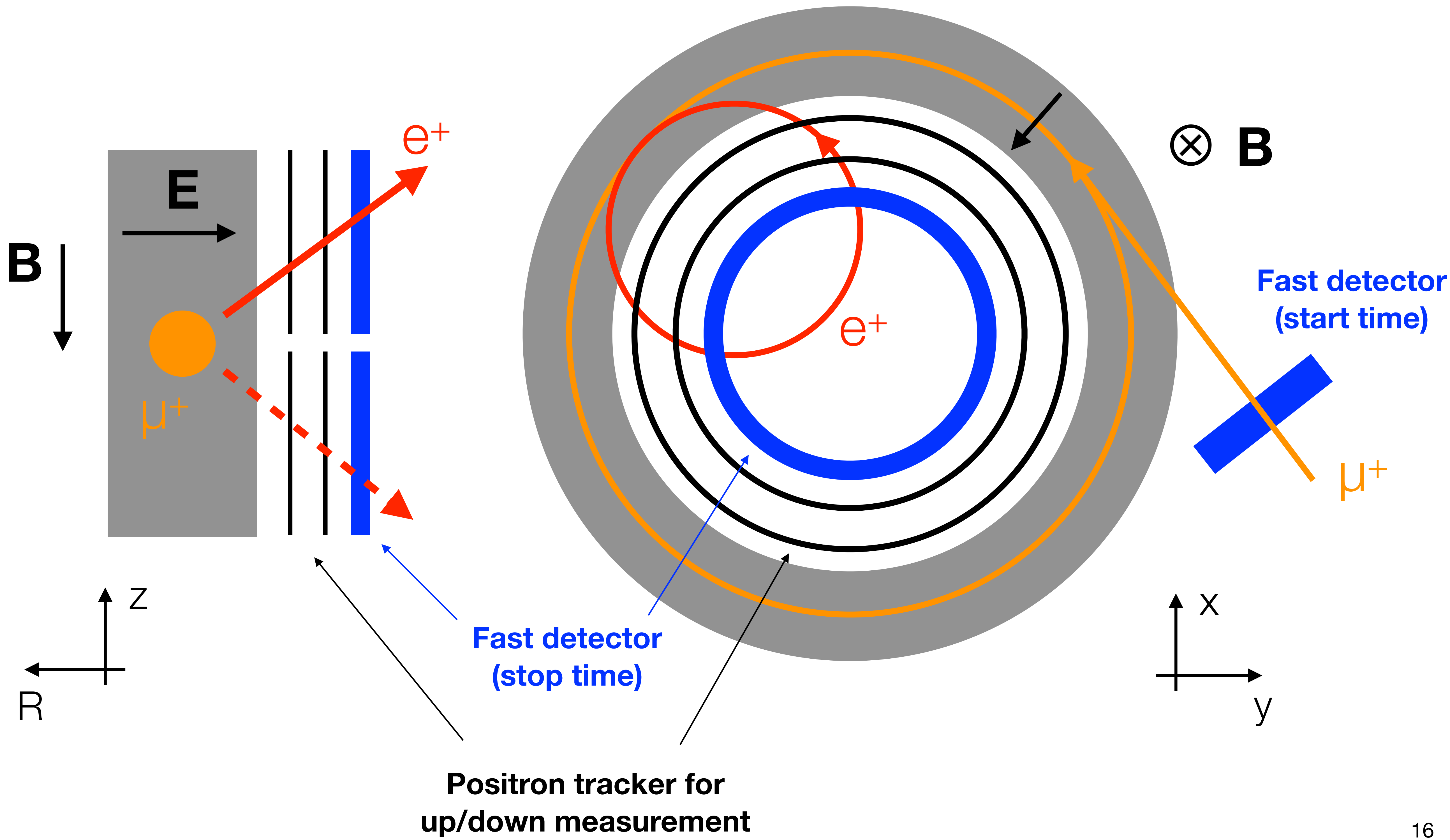
- A formal proposal for a Muon EDM experiment was presented in January 2023 to the PSI Research Committee for Particle Physics

A. Adelmann,[1,2] M. Backhaus,[1] C. Chavez Barajas,[3] N. Berger,[4] T. Bowcock,[3] C. Calzolaio,[2] G. Cavoto,[5,6] R. Chislett,[7] A. Crivellin,[2,8,9] M. Daum,[2] M. Fertl,[10] M. Giovannozzi,[8] G. Hesketh,[7] M. Hildebrandt,[2] I. Keshelashvili,[11] A. Keshavarzi,[12] K.S. Khaw,[13,14] K. Kirch,[1,2] A. Kozlinsky,[4] A. Knecht,[2] M. Lancaster,[12] B. Märkisch,[15] F. Meier Aeschbacher,[2] F. Méot,[16] A. Nass,[11] A. Papa,[2,17] J. Pretz,[11,18] J. Price,[3] F. Rathmann,[11] F. Renga,[6] M. Sakurai,[1] P. Schmidt-Wellenburg,[2] A. Schöning,[19] C. Voena,[6] J. Vossebeld,[3] F. Wauters,[4] and P. Winter[20]

1 ETH
2 PAUL SCHERRER INSTITUT PSI
3 UNIVERSITY OF LIVERPOOL
4 JG|U
5 SAPIENZA UNIVERSITÀ DI ROMA
6 INFN Istituto Nazionale di Fisica Nucleare
7 UCL
8 CERN
9 University of Zurich UZH
10 Cluster of Excellence PRISMA+
11 JÜLICH Forschungszentrum
12 MANCHESTER 1824 The University of Manchester
13 上海交通大學 SHANGHAI JIAO TONG UNIVERSITY
14 李政道研究所 Tsung-Dao Lee Institute
15 TUM
16 BROOKHAVEN NATIONAL LABORATORY "a passion for discovery"
17 UNIVERSITÀ DI PISA
18 RWTH AACHEN UNIVERSITY
19 UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
20 Argonne NATIONAL LABORATORY

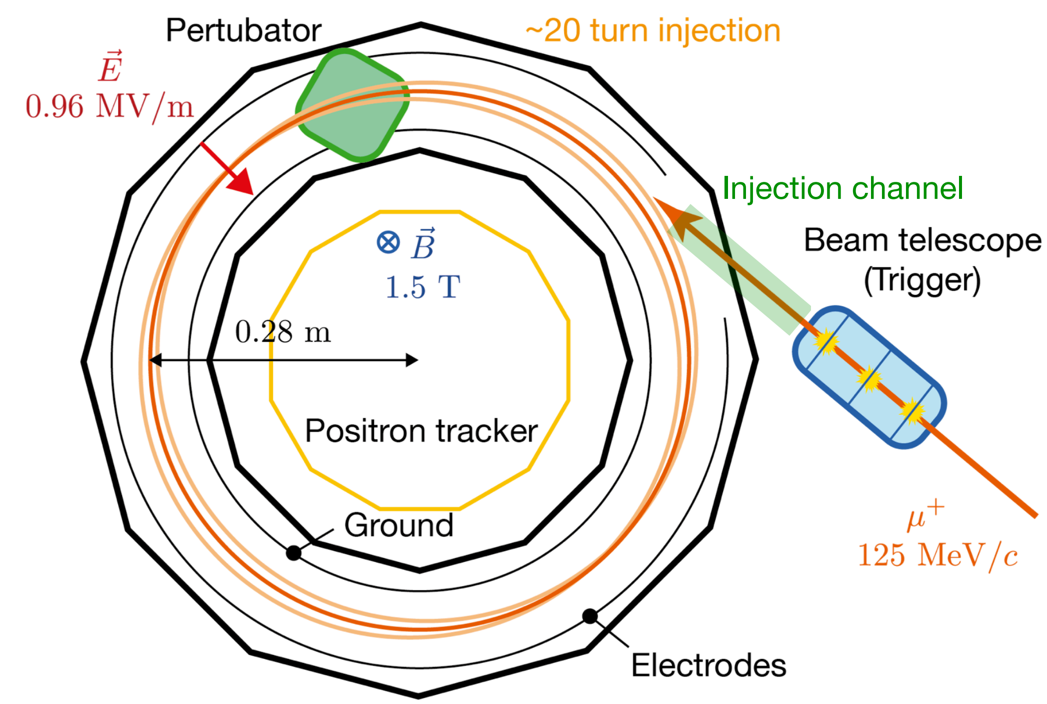
Experimental approach

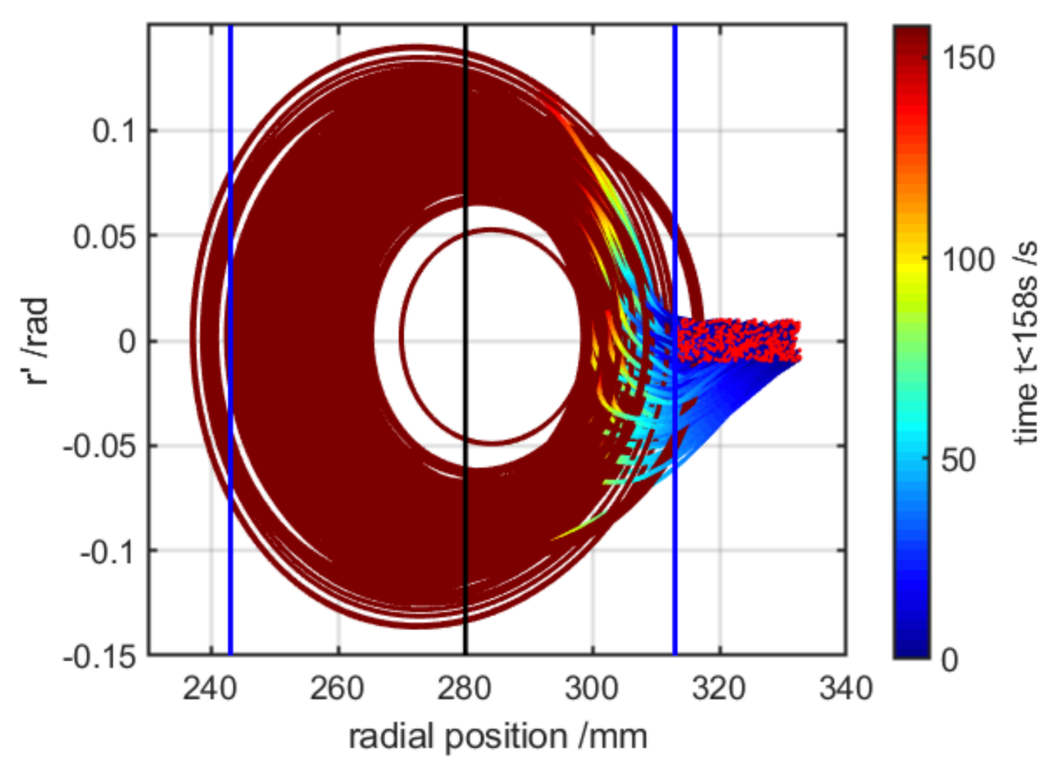
$$A(t) = \frac{N_{\uparrow}(t) - N_{\downarrow}(t)}{N_{\uparrow}(t) + N_{\downarrow}(t)}$$



Experimental concepts — Storage ring

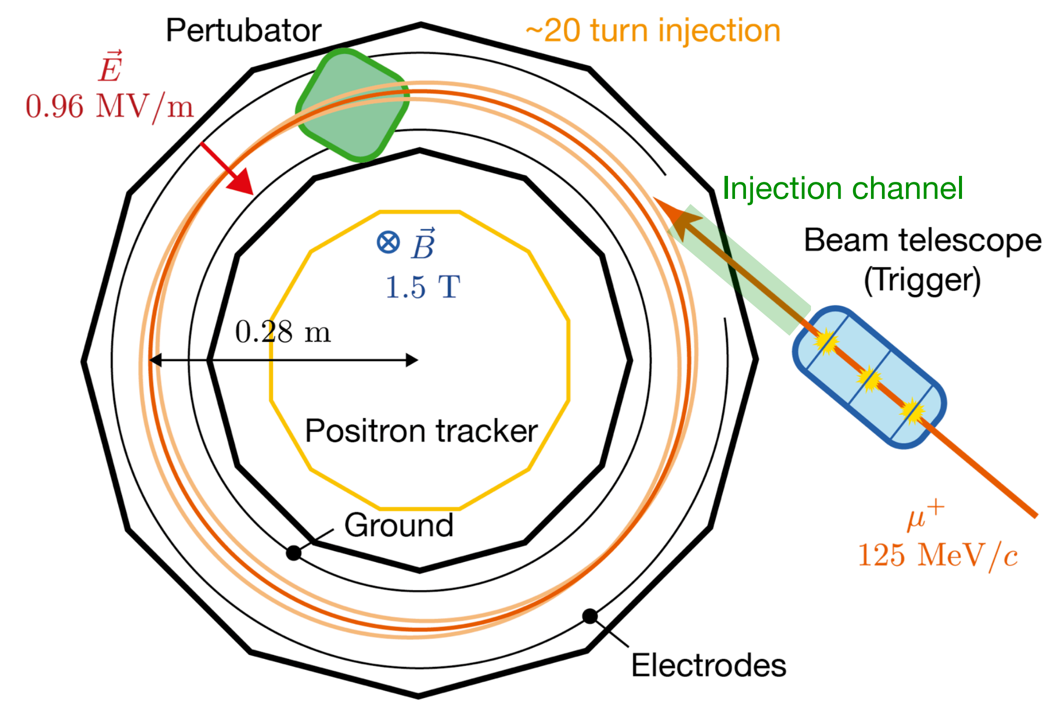
- Compact storage ring with lateral injection through a magnetic channel
- Need a **magnetic kick within 1 revolution (< 10 ns)** to avoid hitting the injection channel after 1 turn
- In principle, 0.14% injection efficiency is possible considering the emittance of the PSI beam lines

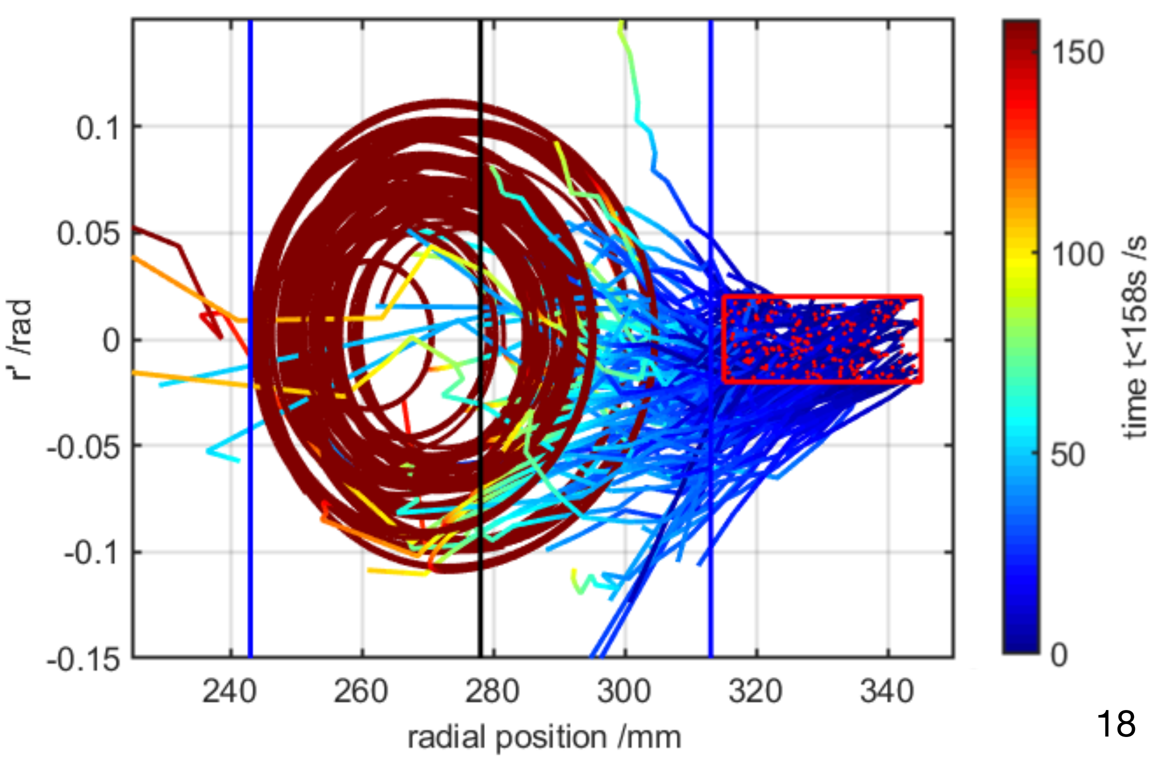




Experimental concepts — Storage ring

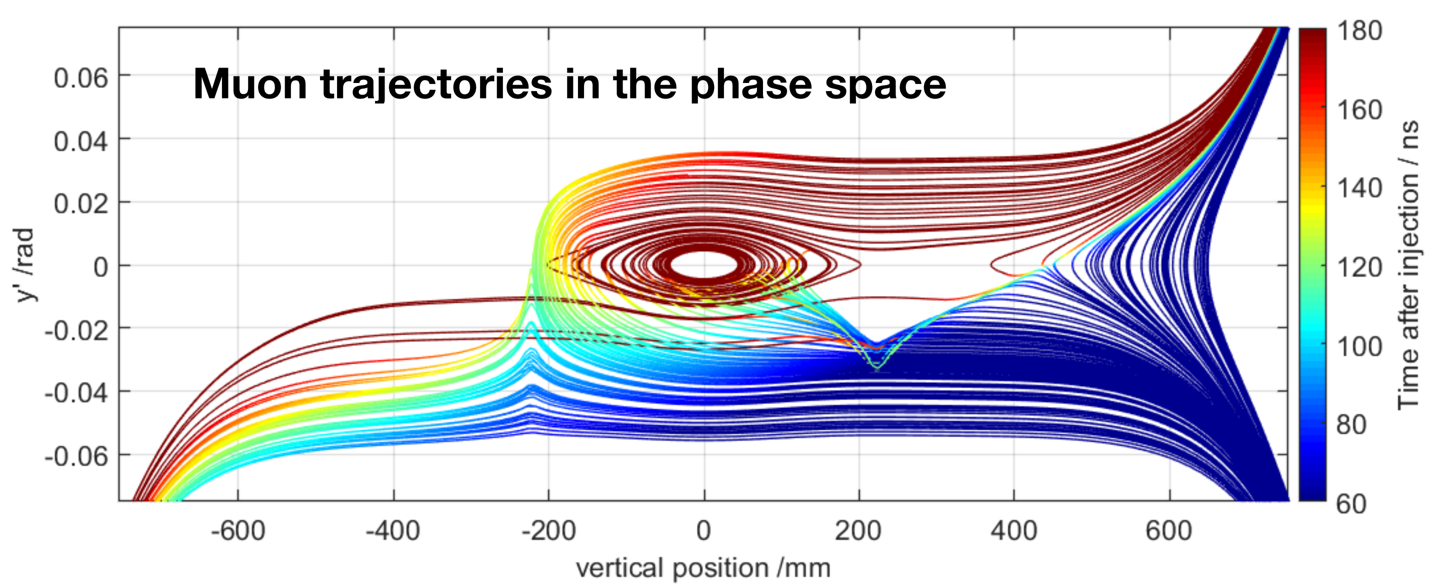
- Compact storage ring with lateral injection through a magnetic channel
- Need a **magnetic kick within 1 revolution (< 10 ns)** to avoid hitting the injection channel after 1 turn
- In principle, 0.14% injection efficiency is possible considering the emittance of the PSI beam lines
- In practice, before the orbit stabilises, muons are lost due to **MS through the E-field electrodes**
  - **efficiency ~ 10^{-4}**
  - positron detection rate ~ 10 kHz

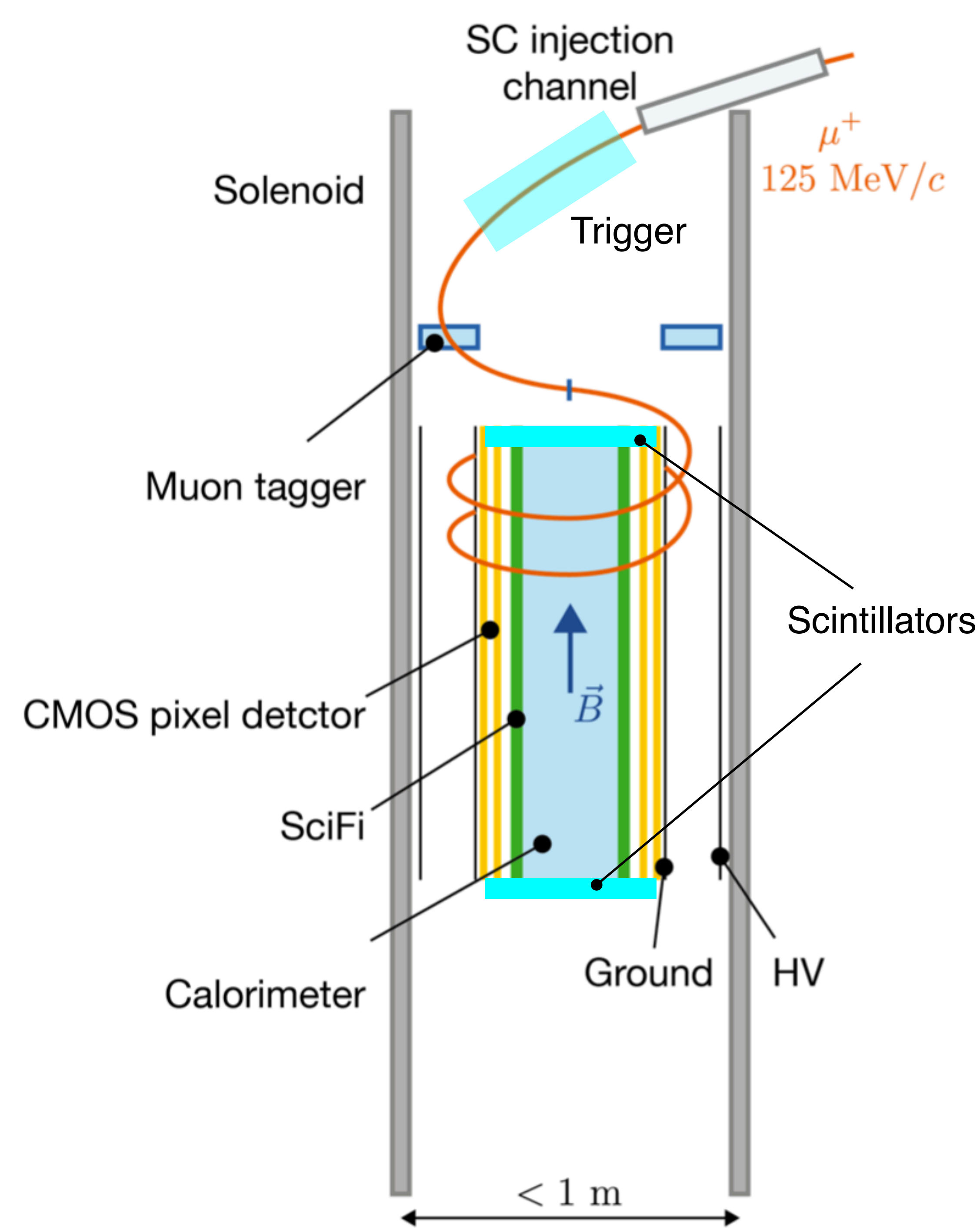




Experimental concepts — Helix muonEDM

- Vertical injection into a 3T solenoid
- Also need a **kick** to stabilise the orbit in the central region, but **within > 50 ns**
- **Minimal material budget** along the muon trajectories
- **5 x 10^{-4} capture efficiency**
  - 50 kHz detection rate



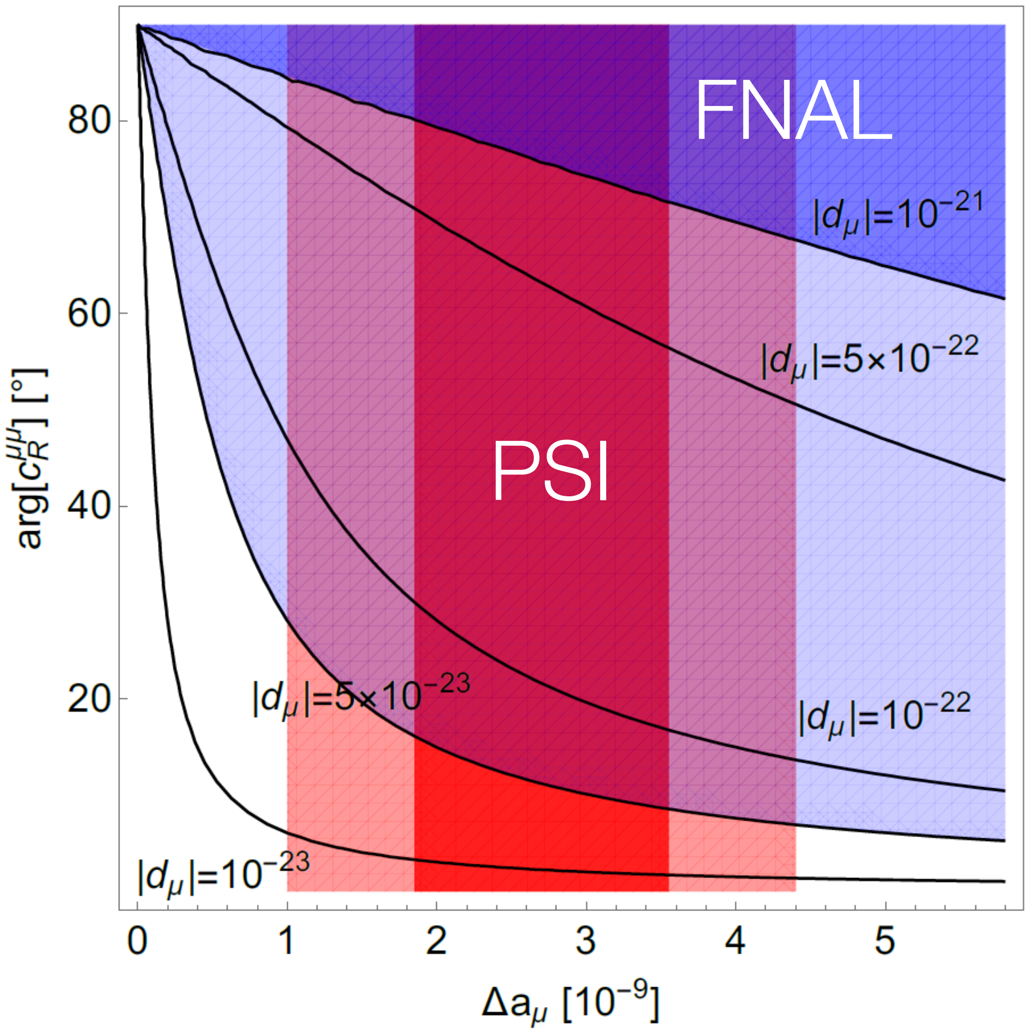


Sensitivity and Physics reach (1 year run)

- $a = 1.12 \times 10^{-3}$
- $\gamma = 1.55$
- $P_0 = 0.93$
- E = 20 kV/cm
- N = 50 MHz x 200 days = 7×10^{11}
- $\tau = 2.2 \times 10^{-6}$ s
- $\alpha = 0.3$

$$\sigma(|d_\mu|) = \sim \frac{a\hbar\gamma}{2P_0E_f\sqrt{N}\tau_\mu\alpha}$$

$$\sigma(|d_\mu|) \leq 6 \times 10^{-23} e \cdot \text{cm}$$

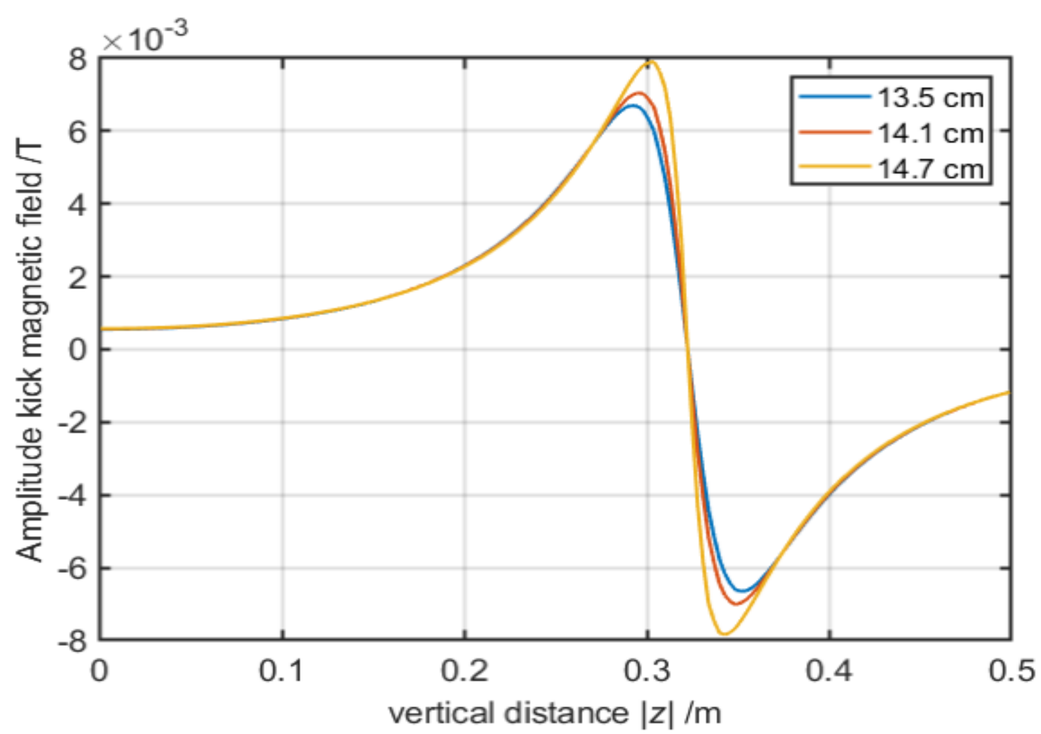


A staged approach

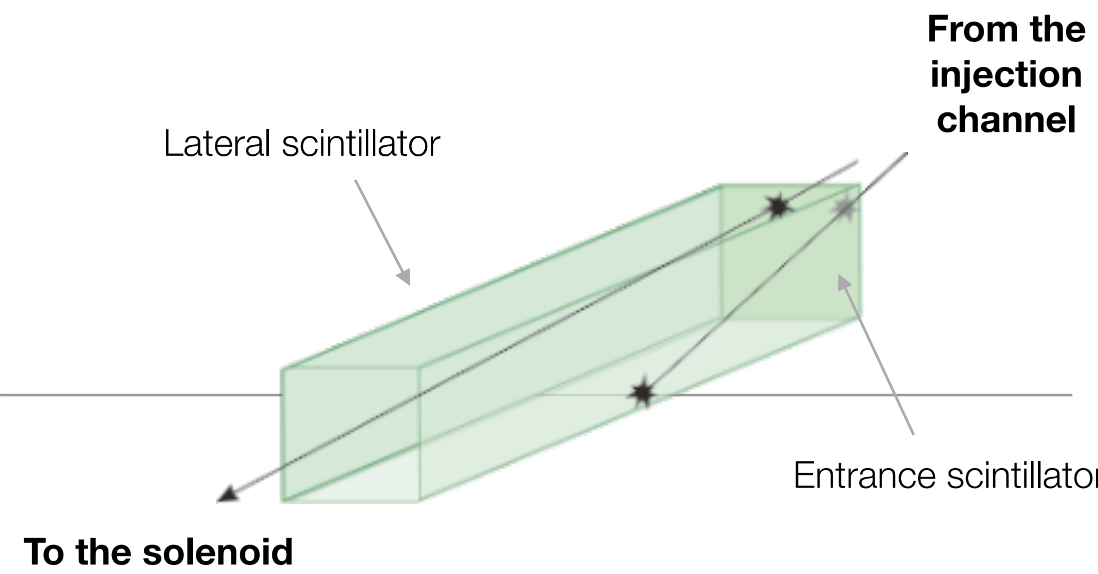
- Phase-1 (precursor experiment):
  - **goals: demonstrate the feasibility of injection principle and frozen spin technique + improve the current limit by x50** (competitive with final results from ongoing g-2 experiments)
  - existing magnet (3 T, 10 cm bore)
  - non-optimal beam line (28 MeV/c) to match the magnet strength and size and to avoid conflicts with other activities
  - E ~ 3 kV/cm
  - simplest detector solutions
  - partially covered by an ERC CoG at PSI
- Phase-2
  - **goal: improve the current limit by x2000**
  - dedicated magnet (3T)
  - best suited beam line (125 MeV/c)
  - E ~ 20 kV/cm
  - optimal detector solutions

Challenges

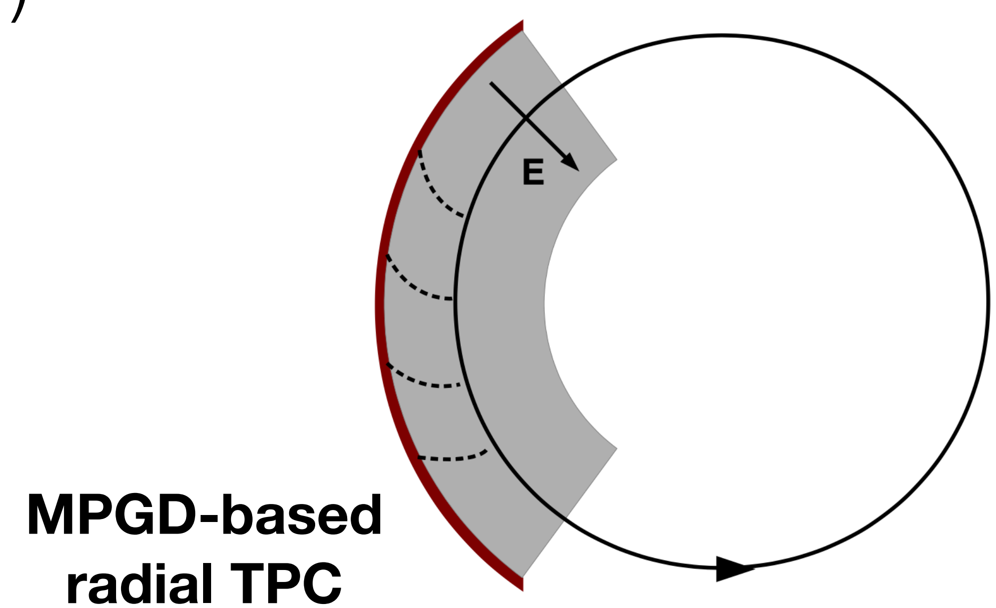
- Fast and very thin detectors in the injection channel to trigger the magnetic kick
- Fast ramping of kick magnets
- Detectors with minimal material budget, operating in vacuum
- Accurate rotation of the full apparatus to invert the injection direction and suppress systematics from disuniformities of the fields
- Large eddy currents from the magnetic kick



Detector developments



- Fast kick trigger from muons:
  - extremely thin scintillator to preserve the muon emittance (critical to keep a high capture efficiency)
- Very light muon tracker to characterise the beam and the trigger before the EDM measurement **— high granularity TPC**
- Positron tracking and timing in a harsh environment (vacuum, limited space, eddy currents…) **— scintillating fibers/ silicon detectors**



Straw tubes

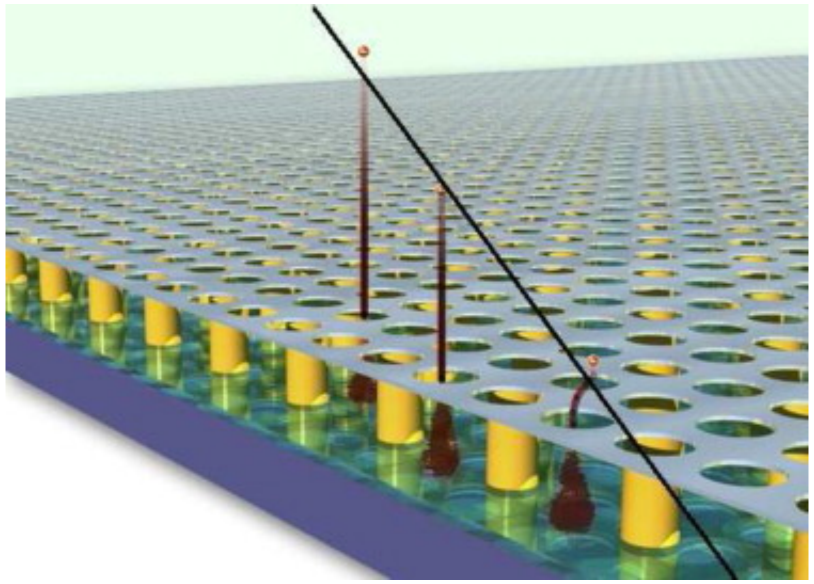
INFN Roma: interests and opportunities

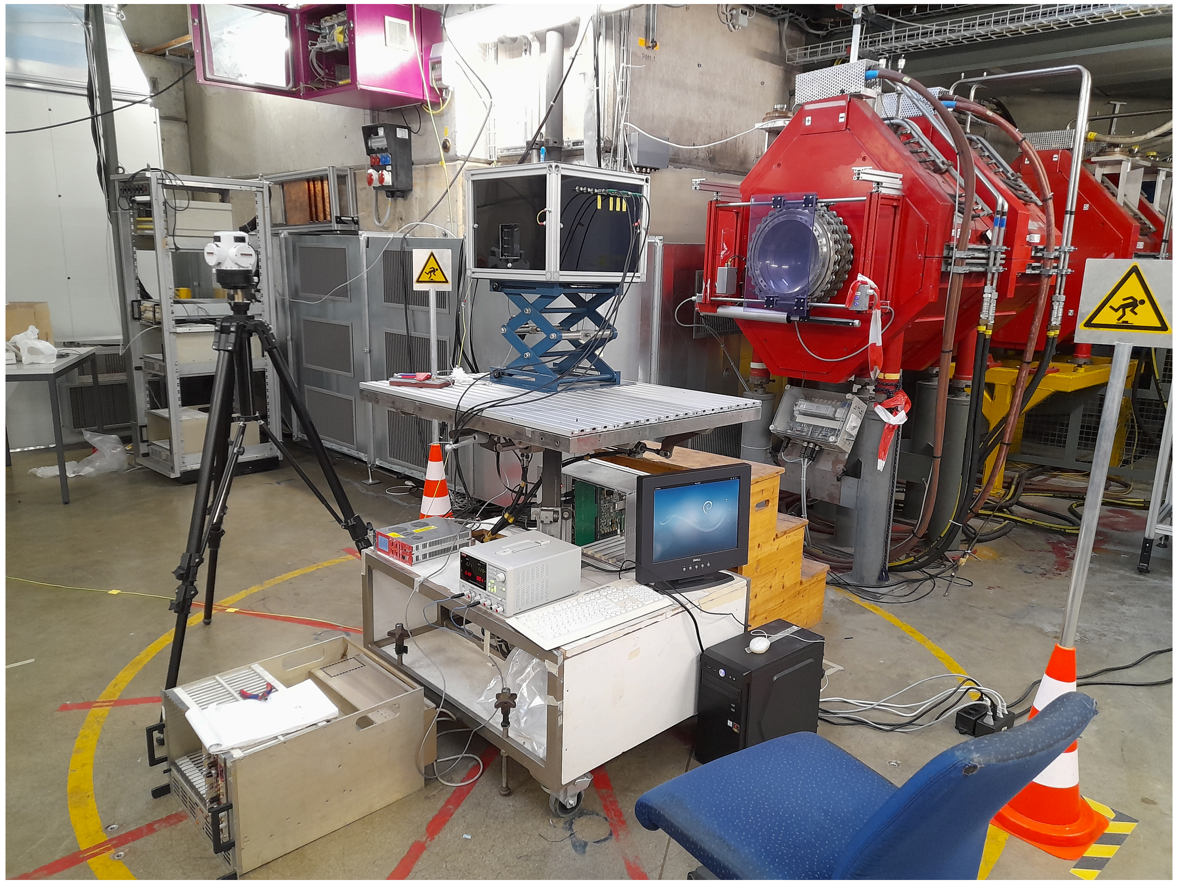
- Muon tracker:
  - R&D for a TPC with high granularity readout
- Mechanical integration
  - Criticalities in engineering manpower availability at PSI
  - Concrete possibility of taking a leading role
- Many other opportunities if there are people interested to join:
  - beam injection
  - fast trigger electronics
  - analysis and simulation
  - …

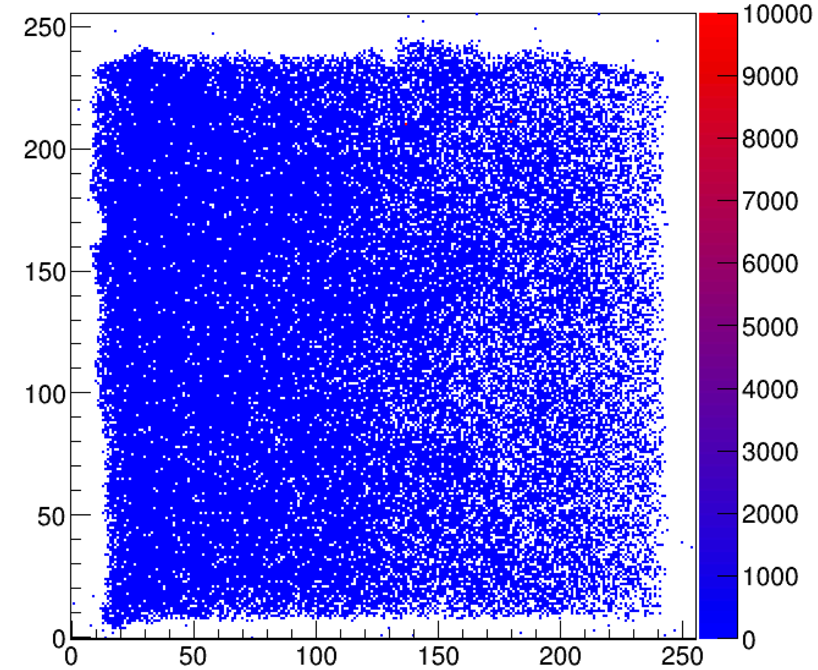
Muon tracker R&D (INFN Roma & Sapienza)

- TPC with high granularity readout (GridPix)
  - two test beams in 2022 @ PSI
  - one paper submitted to JINST, second paper in preparation

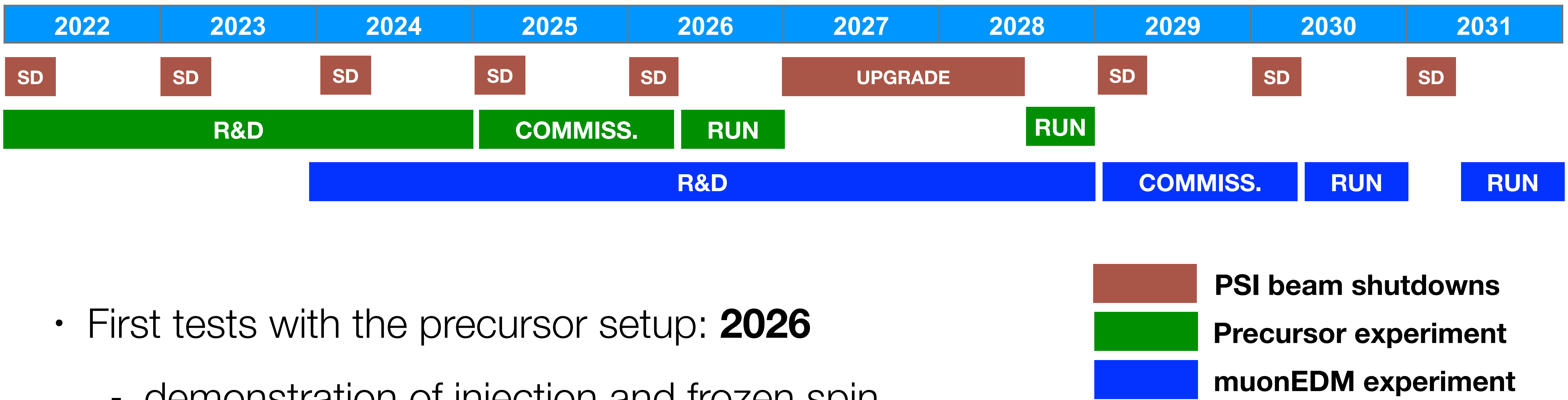
50 μm pixel readout







Tentative Schedule



- First tests with the precursor setup: **2026**
  - demonstration of injection and frozen spin
- PSI long shutdown: **2027**
  - upgrade of the muon beam lines
- Precursor experiment: **2028**
- Final experiment: **2030 - 2031**
  - in combination with innovative beam-cooling approaches (muCool) could yield a much higher injection probability

Conclusions

- A dedicated experiment to search for a muon EDM is highly desirable to complete the experimental coverage on dipole interactions and new sources of CP violation
- Excellent prospects for a ground-breaking muon EDM experiment at PSI within this decade
  - improving the limit by 3 orders of magnitudes, down to 6×10^{-23} $e \cdot$ cm per year
  - improving the expected limit from FNAL g-2/EDM by a factor 20
- Still in a conceptual design phase, many challenges to face, a lot of room for new ideas and new contributions
- Close synergies with other activities at INFN Roma: MEG (physics, logistic), RD51-DRD1 (detectors, electronics), aMUSE (physics, beam studies)

Backup

The HiMB Project @ PSI

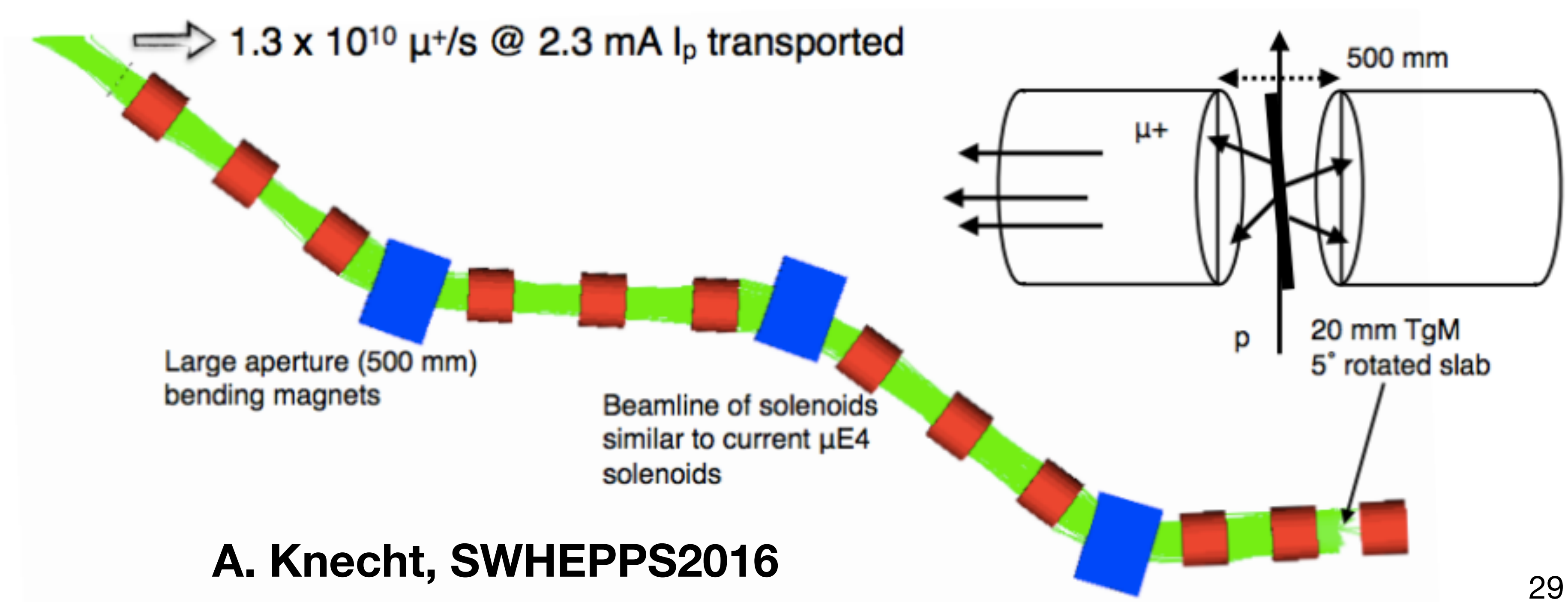
- PSI is designing a high intensity muon beam line (HiMB) with a goal of ~ 10^{10} μ/sec (x100 the MEG-II beam)
- Optimization of the beam optics:
    - improved muon capture efficiency at the production target
    - improved transport efficiency to the experimental area

x4 μ capture eff.

x6 μ transport eff.

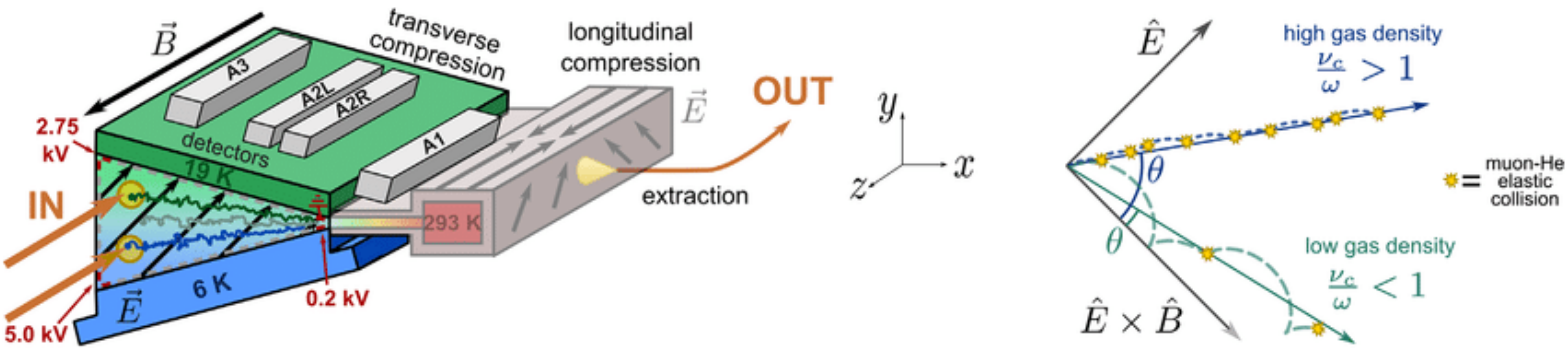
1.3 x 10^{10} μ/s

in the experimental area with 1400 kW beam power



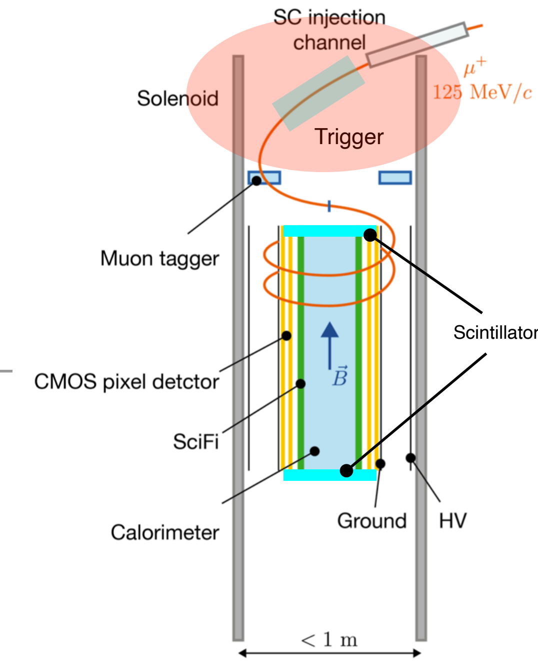
A. Knecht, SWHEPPS2016

muCool

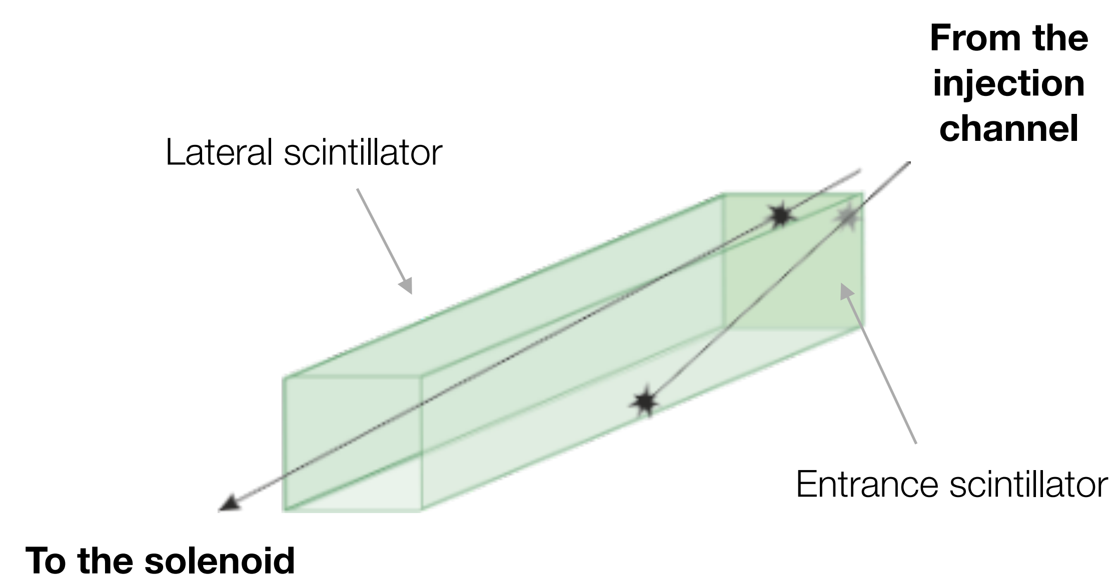


B
transverse compression
longitudinal compression
A3
A2L
A2R
A1
detectors
19 K
2.75 kV
IN
OUT
E
293 K
extraction
6 K
0.2 kV
5.0 kV
y
x
z
Ê
high gas density
$\frac{\nu_c}{\omega} > 1$
θ
= muon-He elastic collision
low gas density
$\frac{\nu_c}{\omega} < 1$
Ê × B̂

The Detector — Entrance trigger



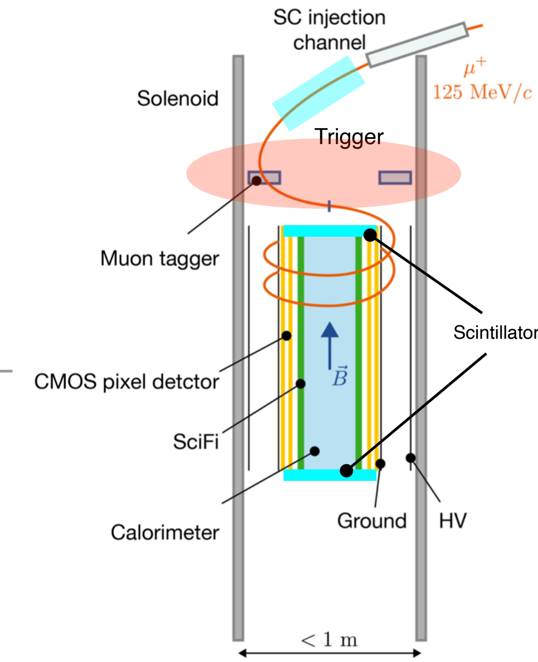
- A muon detector with reasonable timing performances (~ ns) is needed at the entrance to:
  - set the T_0 for the precession measurement
  - trigger the magnetic kick
  - start the measurement cycle
- O(10 MHz) muons pass the injection channel, only O(60 kHz) are in a phase space region that allows the capture:
  - to avoid a large dead time, need to trigger only muons that can be captured



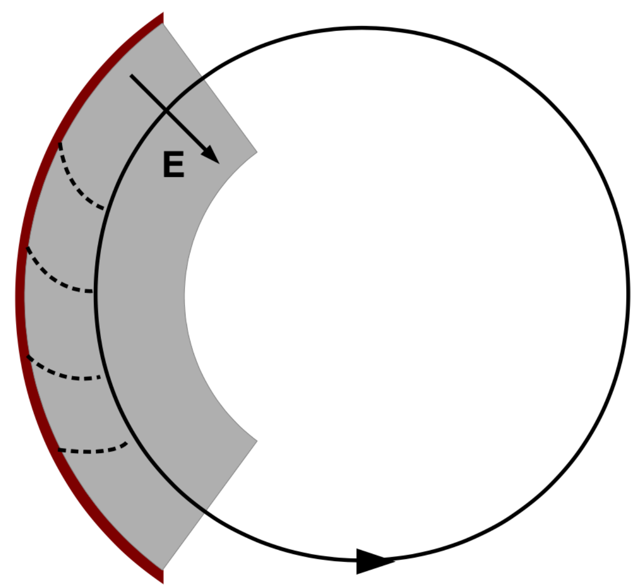
Anti-coincidence between entrance and lateral scintillators

Only muons on a trajectory close to the nominal one will be triggered

The Detector — Muon tagger

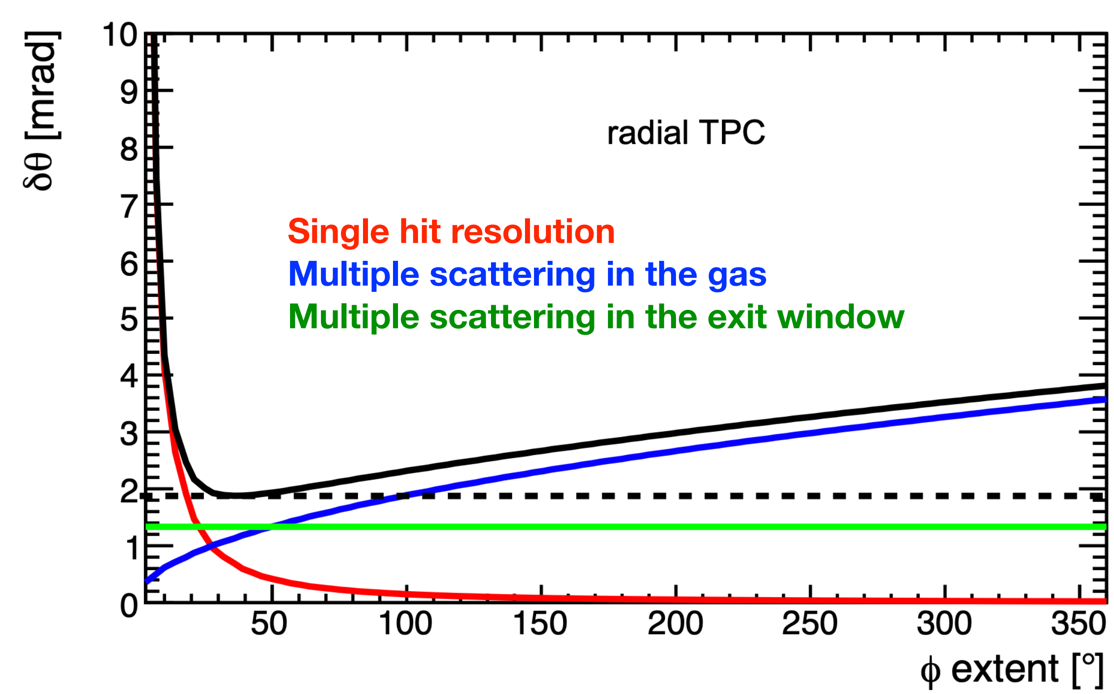


- Among triggered muons, there will be still some with a relatively large vertical angle in the measurement region
  - the measurement of the decay angle can be biased

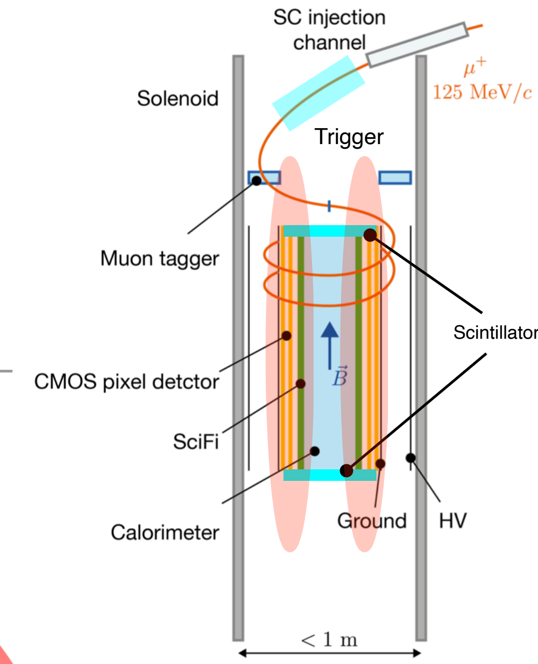


MPGD-based radial TPC

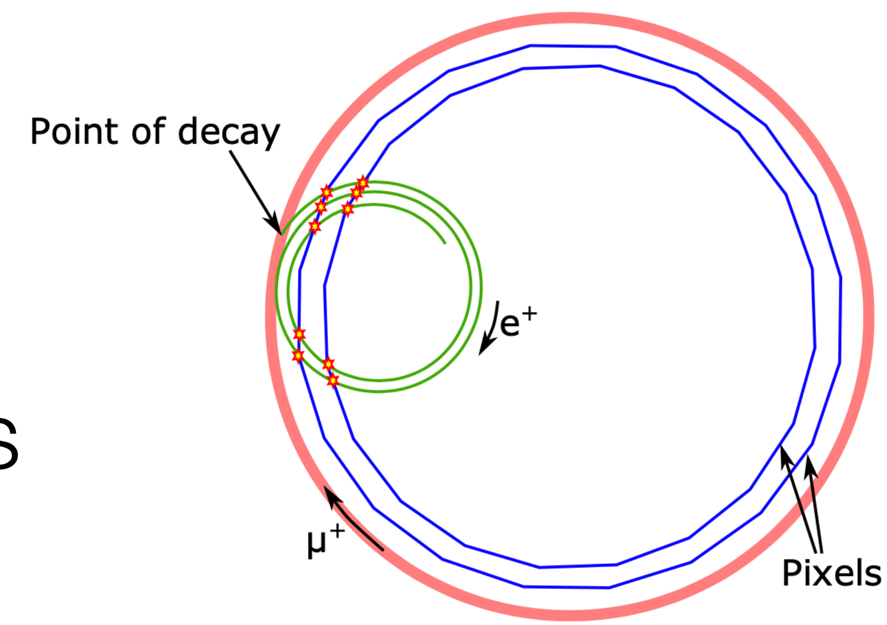
- A muon tracker/tagger can identify such events for a proper treatment
  - needs $\sigma(\theta)$ ~ 1 mrad —> very precise and very light



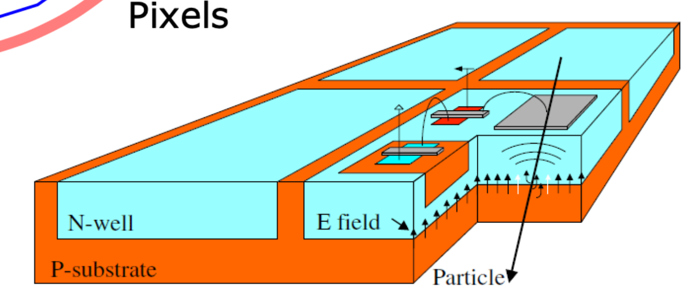
The Detector — Positron tracker



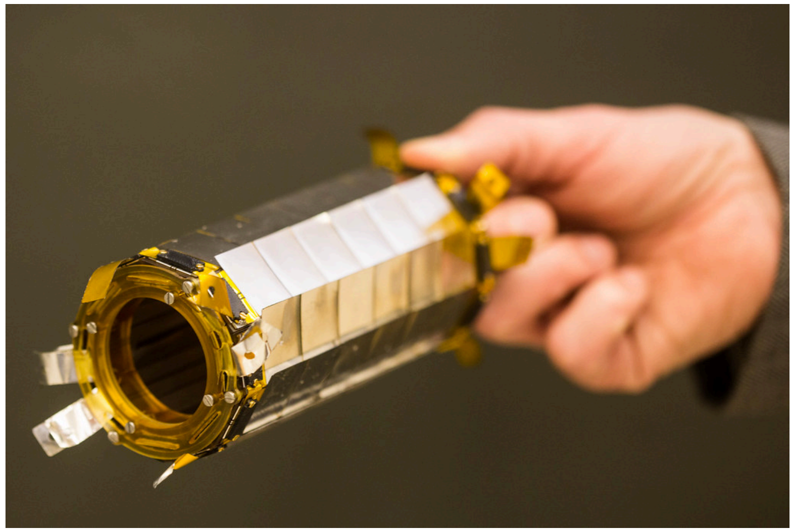
- Silicon pixels (50 μm DMAPS)



  - very good solution for low-momentum positrons
  - precise determination of the trajectory to determine the up/down asymmetry

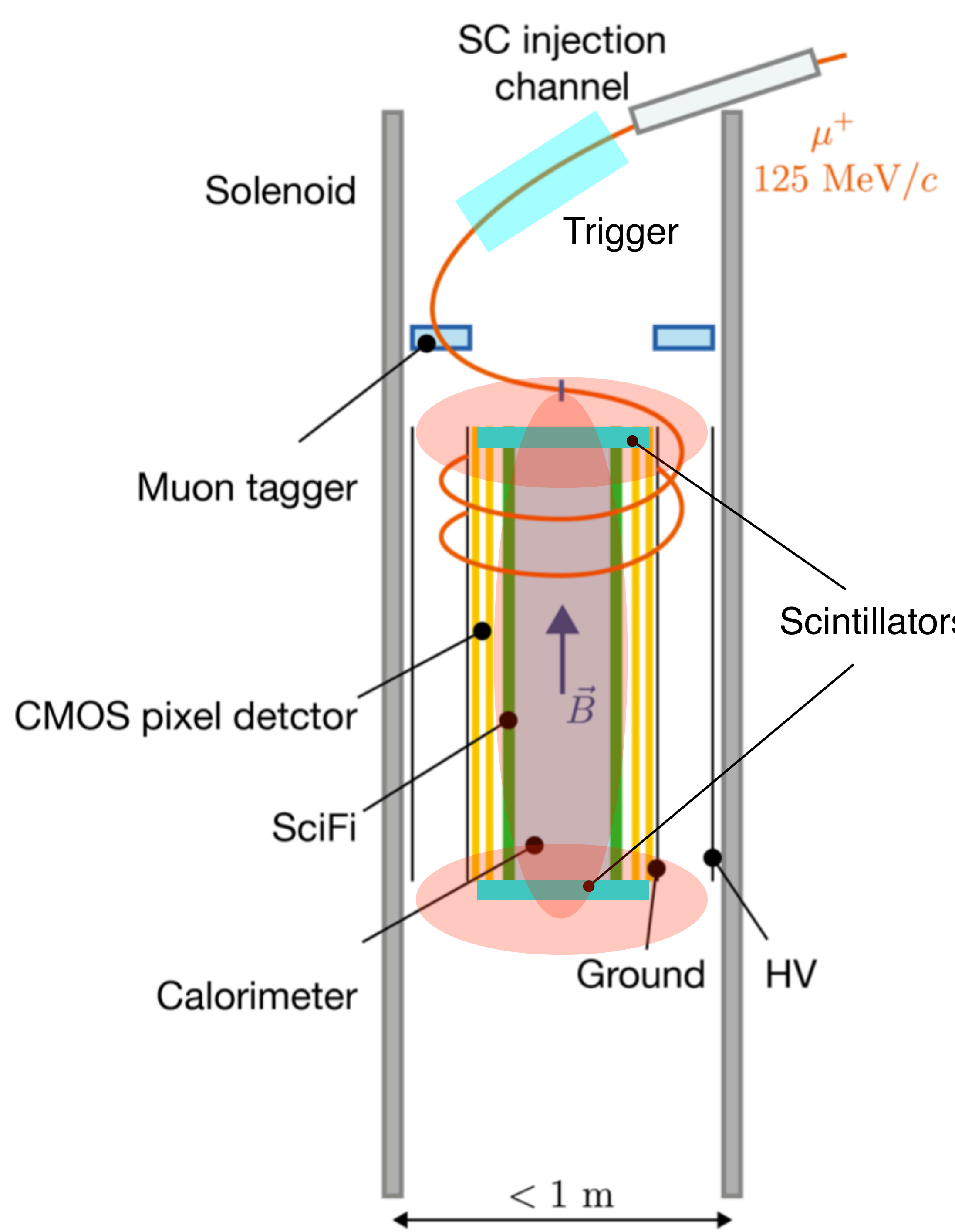


  - Design derived from Mu3e ($\mu^+ \rightarrow e^+e^+e^-$ @ PSI)



The Detector — End signals

- The measurement has to be stopped as early as possible to allow a new entrance trigger and avoid dead time
- Stop signal should arrive when:
  - a positron from the muon decay is detected
  - the muon exits the measurement region
- Fast scintillators to:
  - measure the decay time
  - lift the veto for a subsequent entrance trigger
  - identify muons exiting the measurement region before decaying



Systematic uncertainties

- The main sources of systematic uncertainties were discussed in the paper by Farley *et al.*

  1. $B_r \neq 0$
  2. Misalignment of B and E planes
  3. Electric field not on a plane —> magnetic precession in the rest frame —> vertical precession in the lab frame
  4. Residual (g-2) precession + locally non-horizontal orbit = vertical precession
  5. $B_\theta \neq 0$
  6. Early-to-late detector effects

Vertical orbit oscillations!
Average to 0, but can deteriorate the quality of the asymmetry fit

Can be canceled by comparing ***clockwise (CW)*** *and* ***counter-clockwise (CCW)*** *injection*

CW vs. CCW

+

Single muon storage avoids high detector rates changing with time

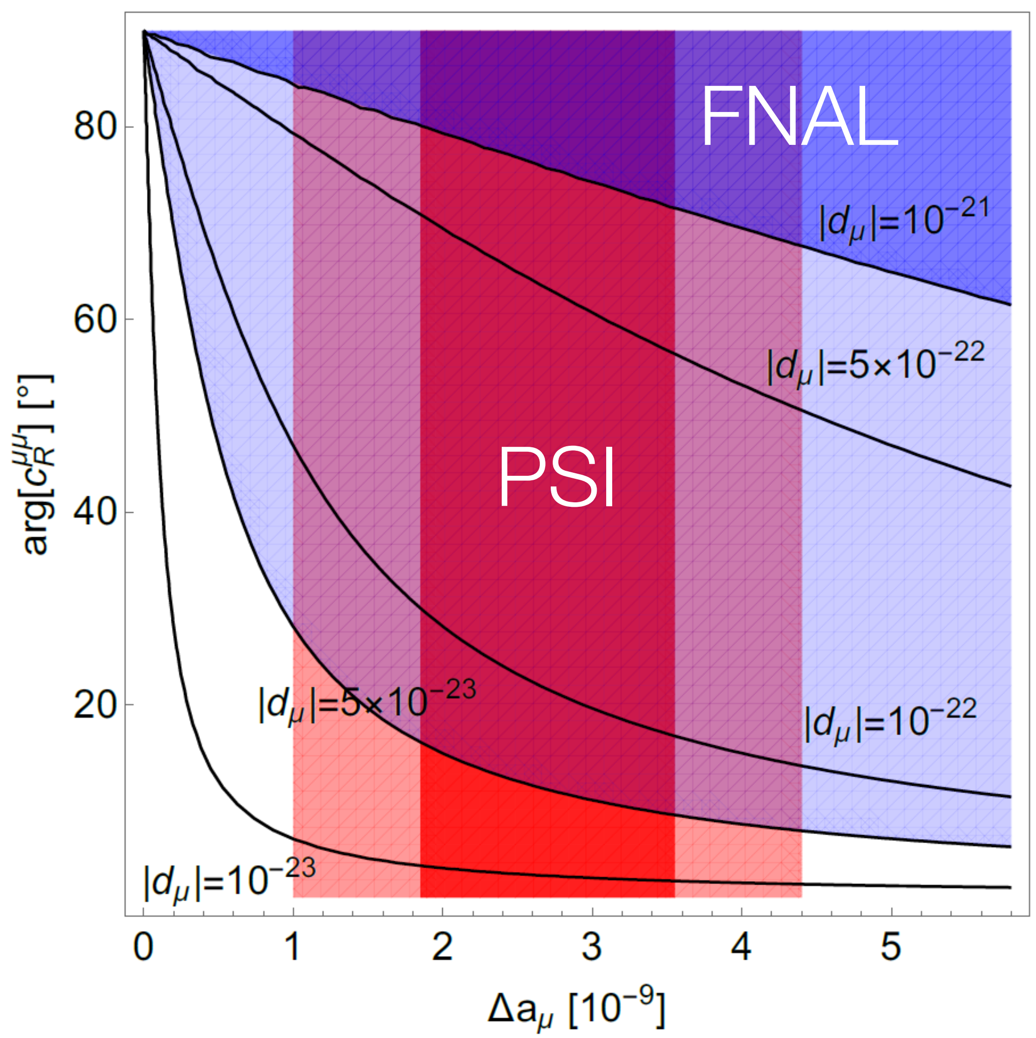
+

injection effects measured without muons

Sensitivity and Physics reach (1 year run)

- $a = 1.12 \times 10^{-3}$
- $\gamma = 1.55$
- $P_0 = 0.93$
- $E = 2$ MV/m
- $N = 50$ MHz x 200 days $= 7 \times 10^{11}$
- $\tau = 2.2 \times 10^{-6}$ s
- $\alpha = 0.3$

$$\sigma(|d_\mu|) = \sim \frac{a\hbar\gamma}{2P_0E_f\sqrt{N}\tau_\mu\alpha}$$



$$\sigma(|d_\mu|) \leq 6 \times 10^{-23} e \cdot \mathrm{cm}$$