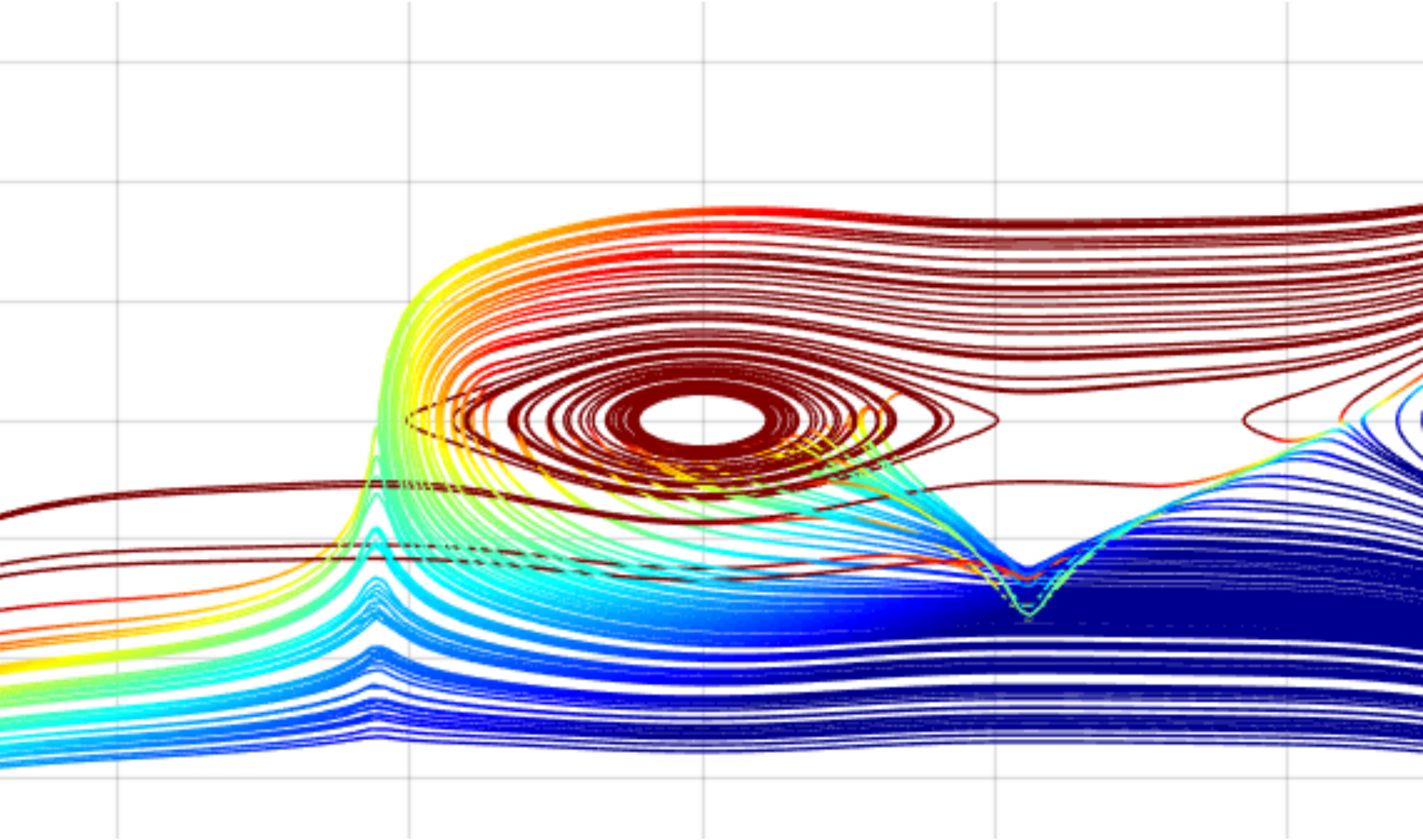


Search for a muon EDM with the frozen-spin technique

INFN
Istituto Nazionale di Fisica Nucleare

Francesco Renga
INFN Roma

Overview

- Physics motivation
- Experimental techniques for muon EDM searches
    - the frozen-spin technique
- A muon EDM search at PSI
    - Possible experimental concepts
    - Ongoing activities
    - Tentative schedule

Physics Motivation

Evidences of New Physics

- Despite its impressive experimental success, the Standard Model (SM) is clearly *not a complete theory — New Physics does exist*

- Beside cosmological and astrophysical evidences (dark matter, matter-antimatter asymmetry of the Universe), there is at least one purely particle-physics evidence:

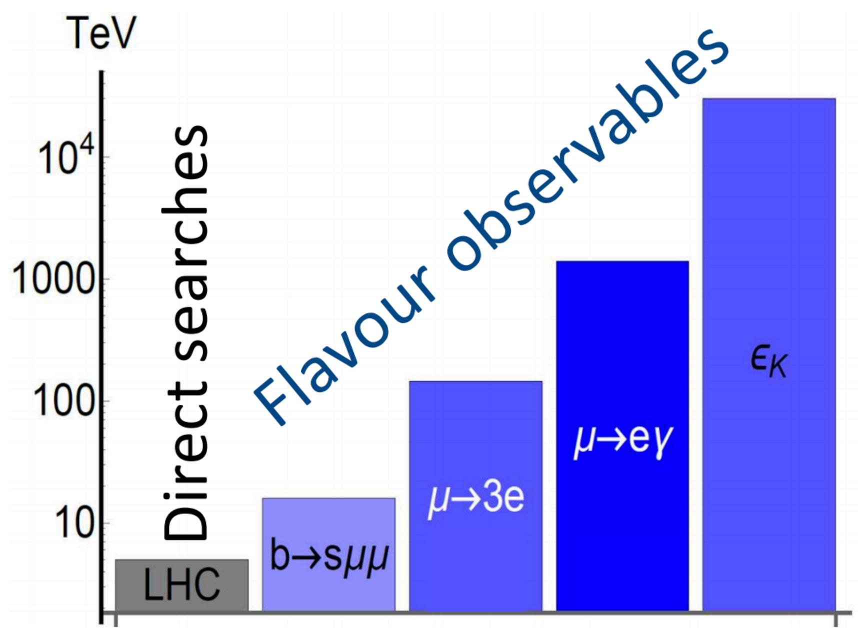
Where the neutrino mass comes from?

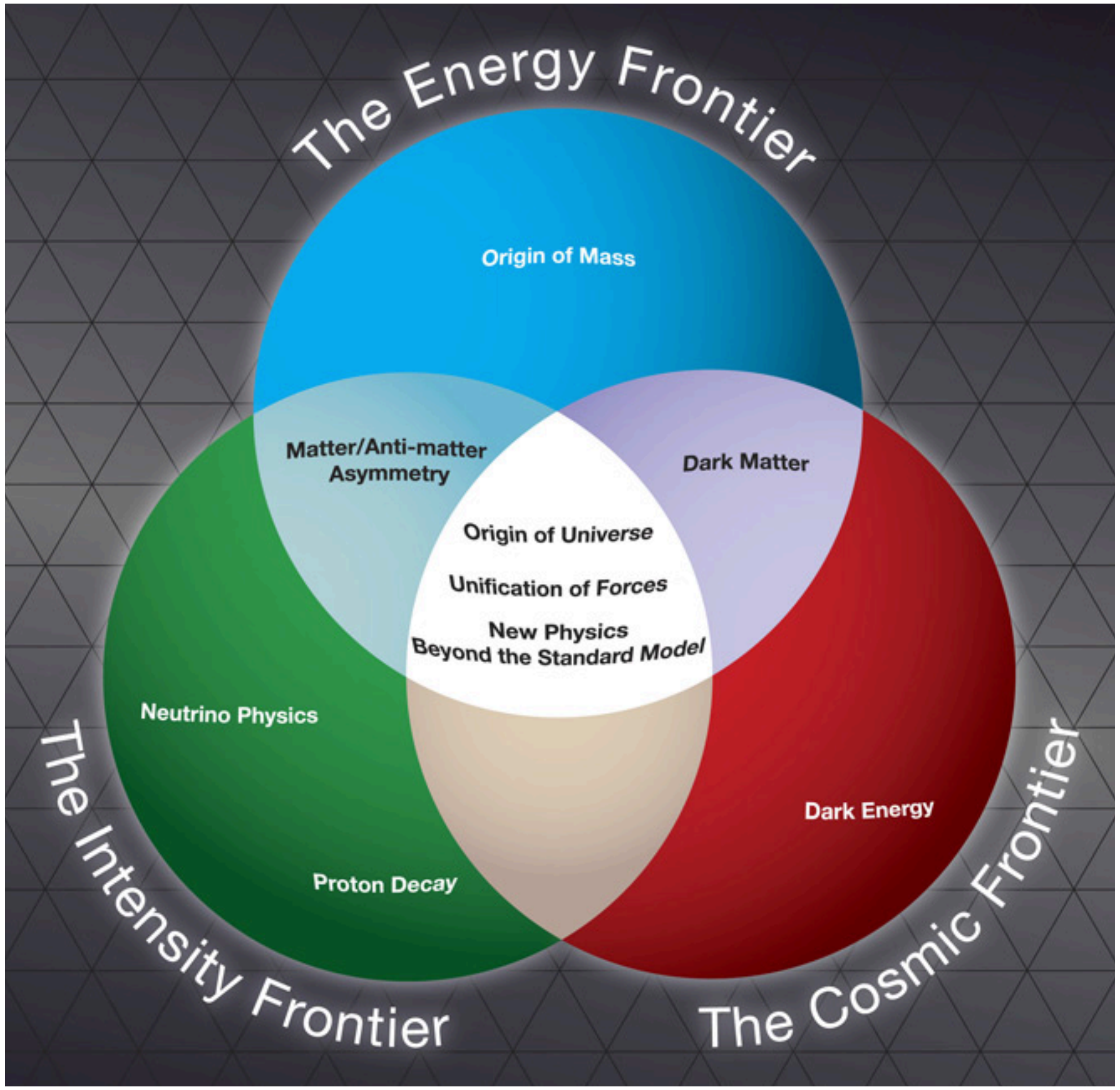
- This is indeed the most striking aspect of a more general problem:

Where the flavour structure of the SM comes from?
(namely, the hierarchy of masses and mixings)

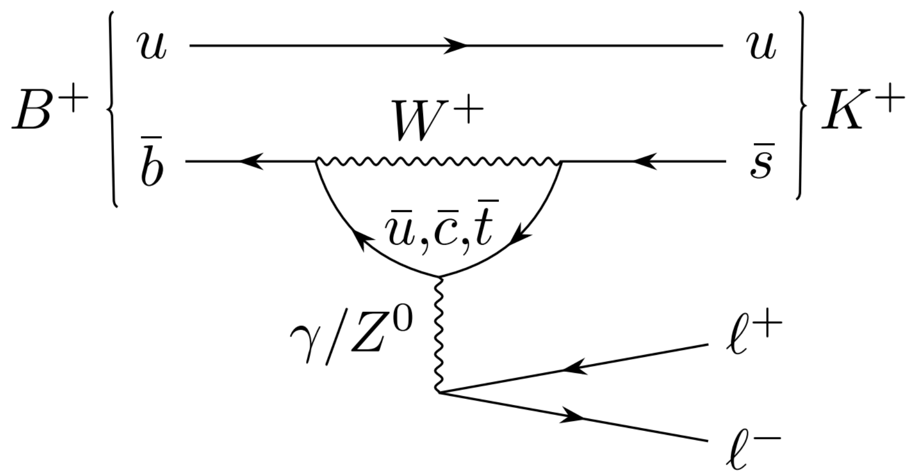
The quest for New Physics

- Exploring the intensity frontier appears crucial
  - direct look at the flavour problem from many different points of view
  - great sensitivity in a scenario where NP could be right above the energy of the next generation of accelerators





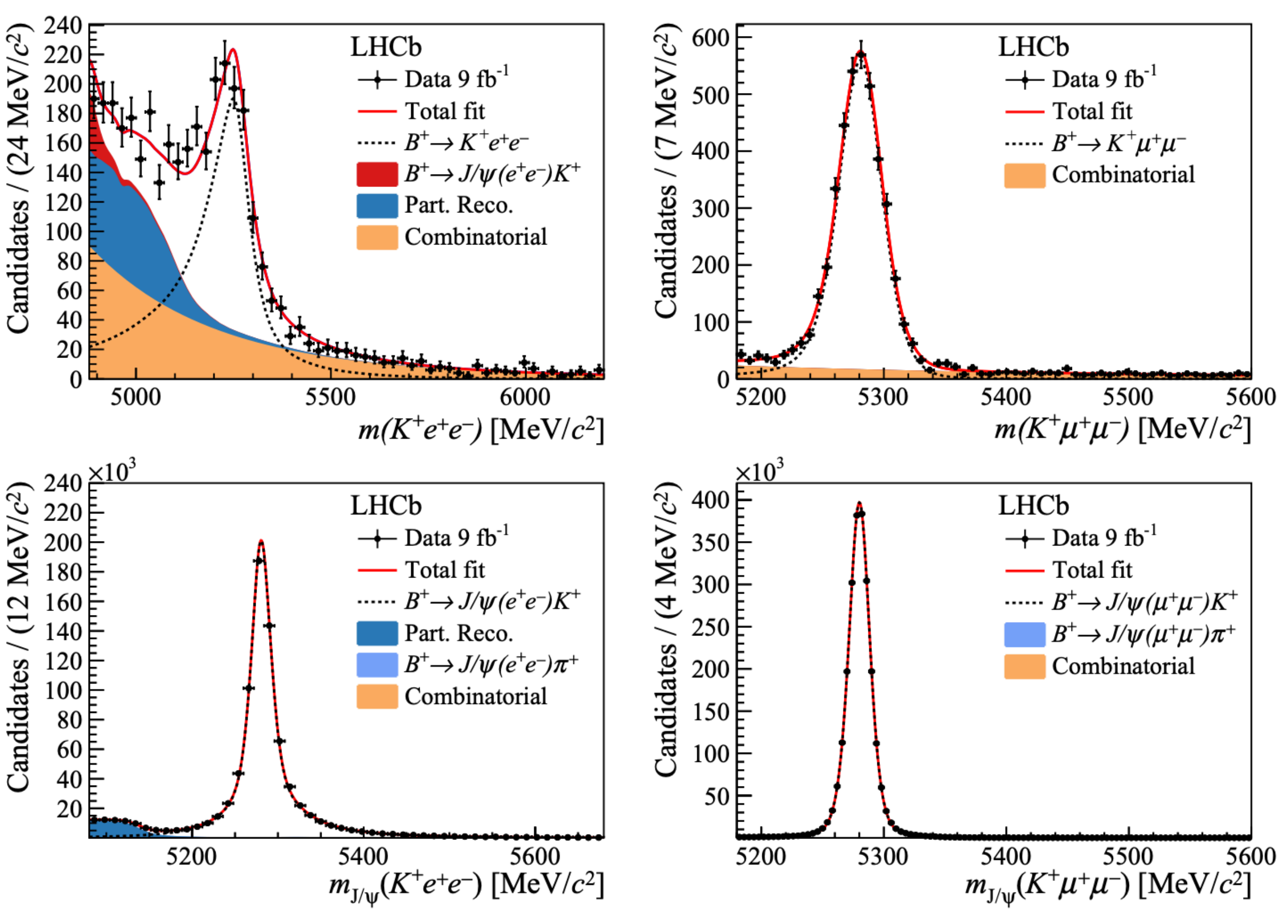
Recent news from the intensity frontier (I)

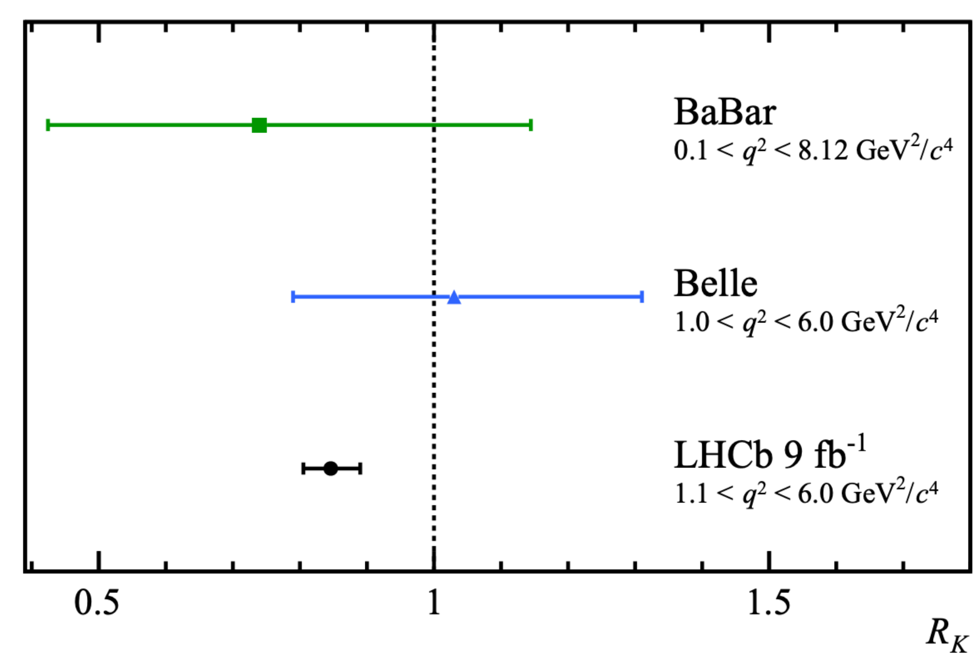


- Hint of Lepton-flavour universality violation (LFUV) in the theoretically and experimentally clean $B^+ \to K^+\ell^+\ell^-$ decays at LHCb

arXiv:2103.11769 [LHCb]

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to e^+e^-)K^+)}$$

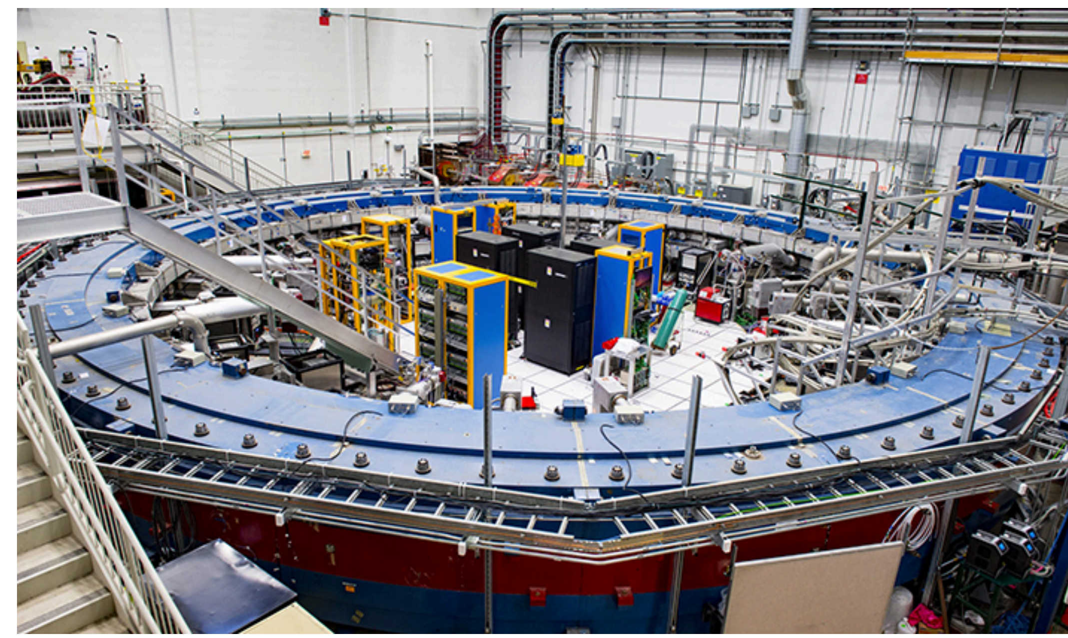


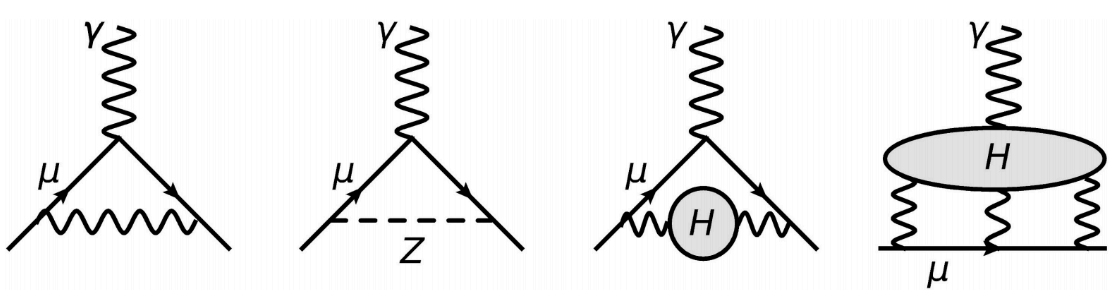


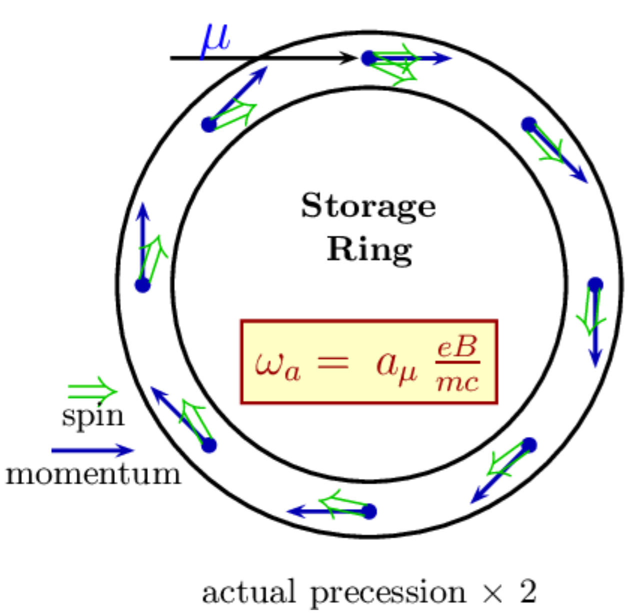
Recent news from the intensity frontier (II)

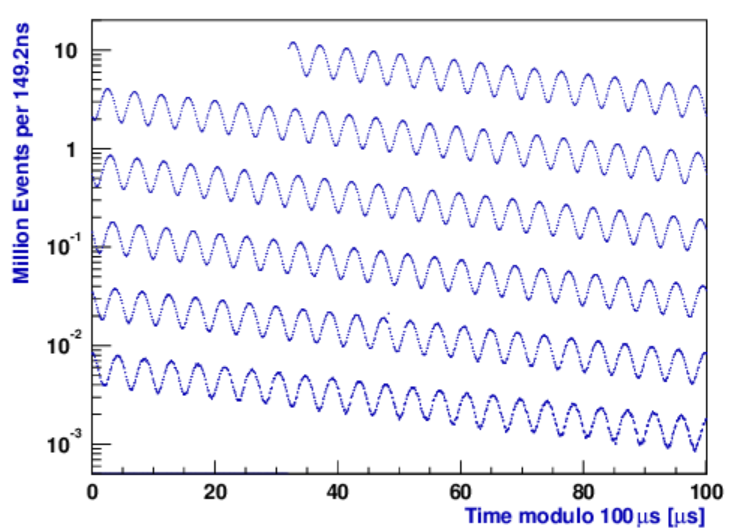
- The long-standing deviation of the anomalous magnetic moment of the muon ($a_\mu = g_\mu - 2$) from SM predictions have been confirmed by the new FNAL experiment

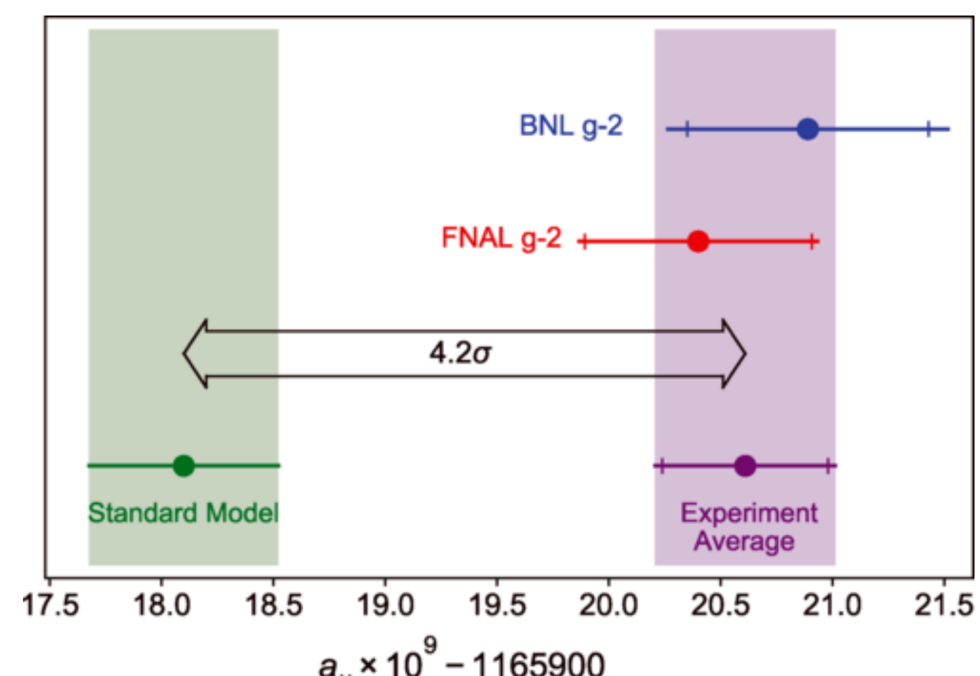
Phys. Rev. Lett. **126 (2021) 14, 141801**





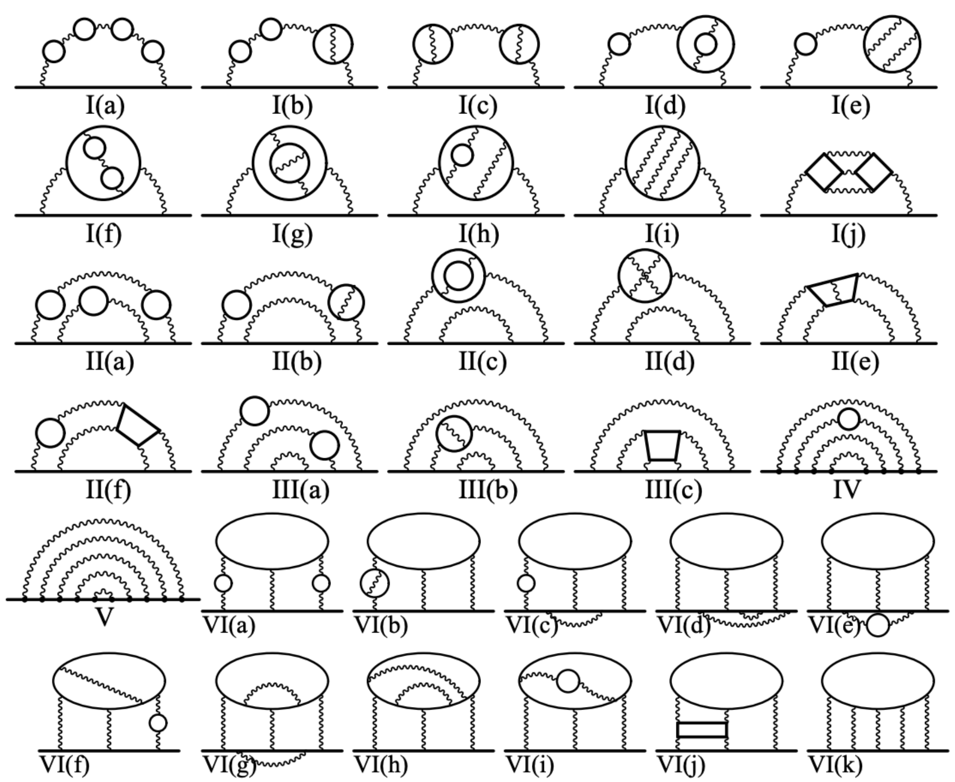






Recent news from the intensity frontier (III)

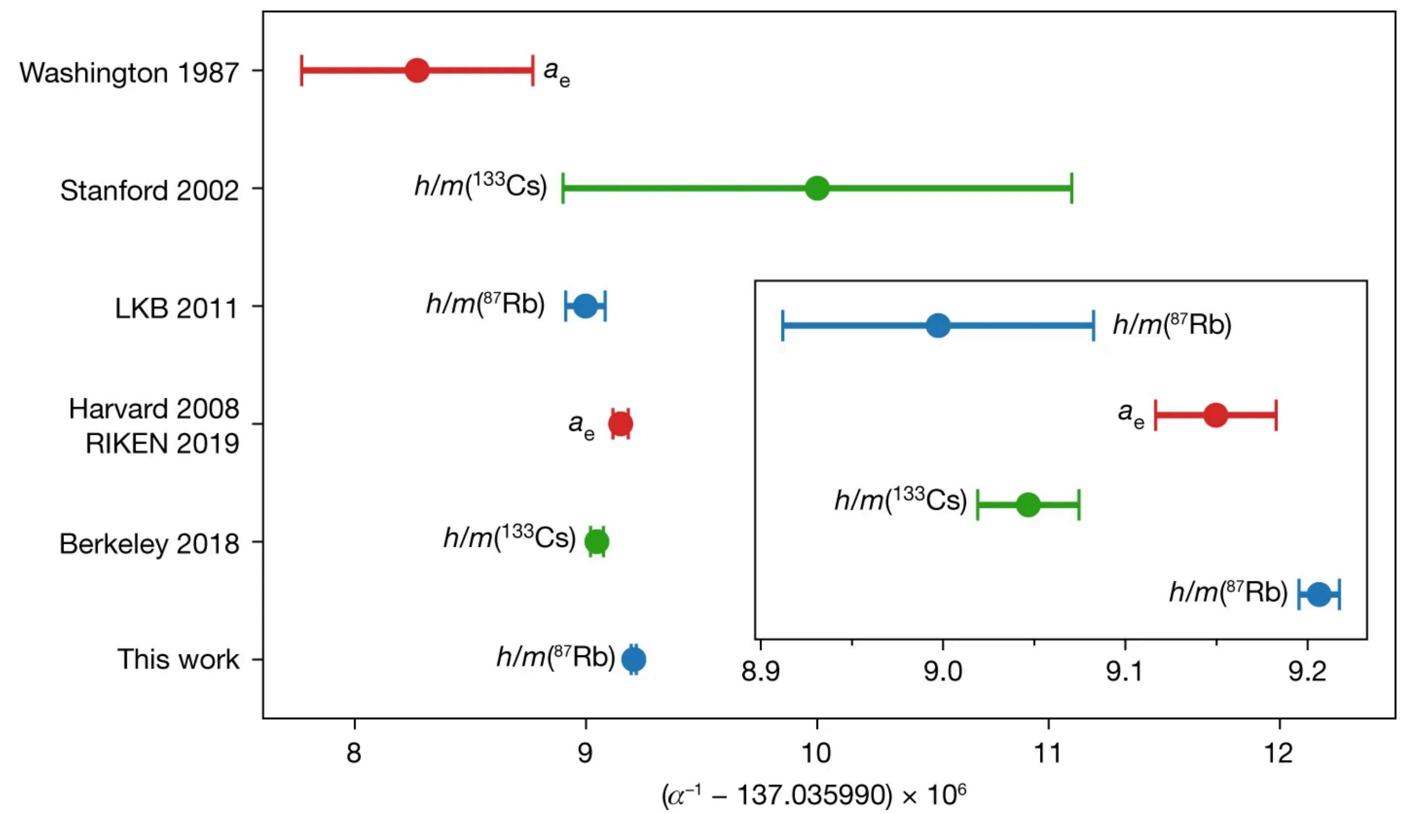
- Controversial measurements of α_{em} in ^{133}Cs (Berkeley, LBNL) and ^{87}Rb (Paris, LKB)
- If the LBNL measurement is taken as good and included in the $(g-2)_e$ SM calculation (at 10th order in QED!!!), there is a 2.4σ discrepancy with respect to the (0.1 ppb!!!) electron EDM measurement



… x 12672

$$\Delta a_e^{\rm LKB} = a_e^{\rm exp} - a_e^{\rm LKB} = (4.8 \pm 3.0) \times 10^{-13}$$
$$\Delta a_e^{\rm B} = a_e^{\rm exp} - a_e^{\rm B} = (-8.8 \pm 3.6) \times 10^{-13}$$

Science 360 (2018), 191
Phys. Rev. D 97 no. 3, (2018) 036001
Nature 588 (2020) 61



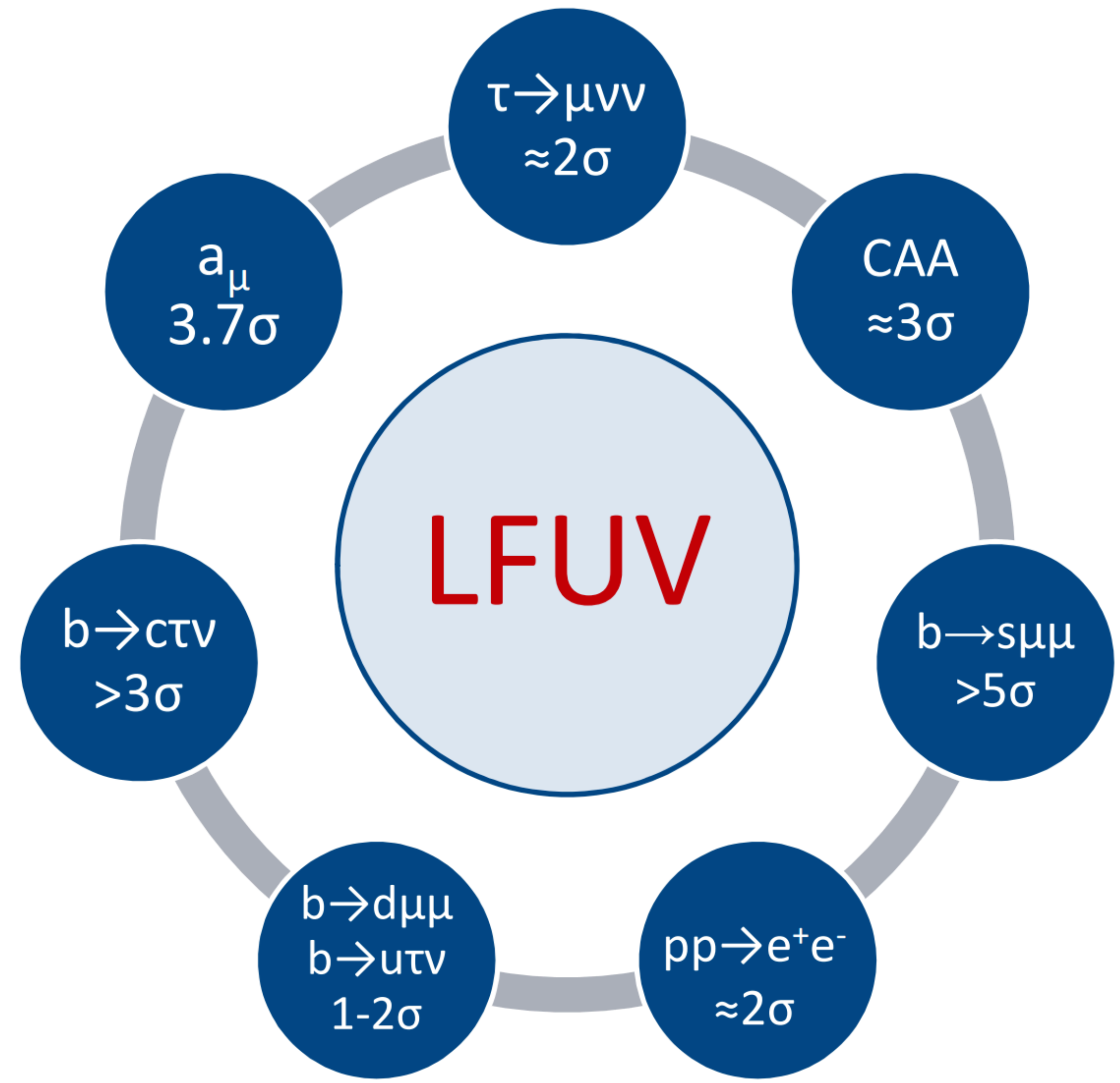
Muon g-2, electron g-2 and LFUV

A. Crivellin, HiMB Physics Case Workshop, PSI, Apr. 2021
A. Crivellin *et al., Phys.Rev.D* 103 (2021) 7, 073002

Taking the LBNL $\alpha_{\rm em}$ as good:

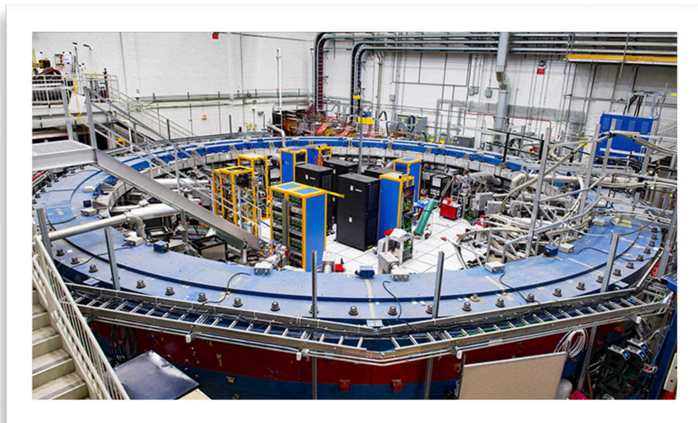
$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = (-87 \pm 36) \times 10^{-14}$$
$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (25.1 \pm 5.9) \times 10^{-10}$$

- The ***opposite sign*** in the experimental deviations of $(g-2)_{\mu,e}$ from the SM predictions could indicate an even worse tension and point toward **NP with LFUV**



e.g. Leptoquarks, gauged L_μ-L_τ symmetry…

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

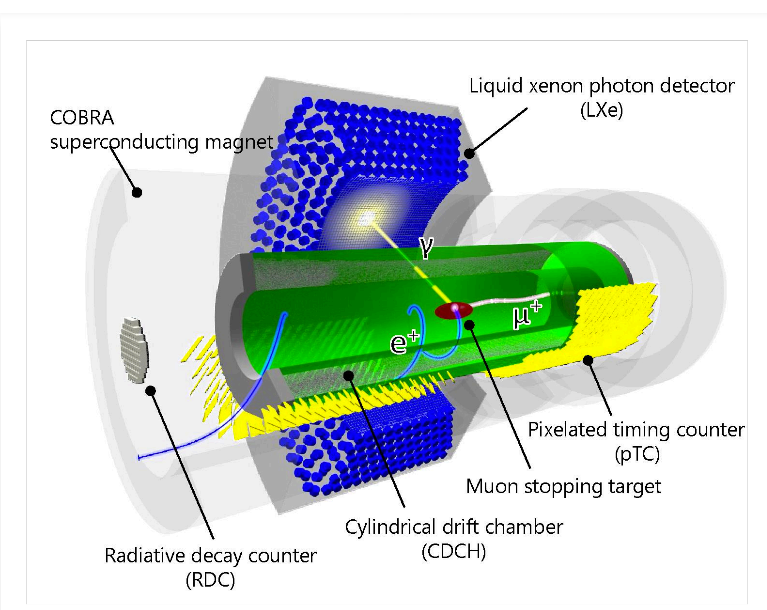
A. Crivellin and M. Hoferichter, arXiv:1905.03789
K. S. Babu, B. Dutta and R. N. Mohapatra, Phys. Rev. Lett. 85 (2000) 5064
E. O. Iltan, Eur. Phys. J. C 54 (2008) 583

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

This talk

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

ELECTRIC DIPOLE MOMENT (EDM)



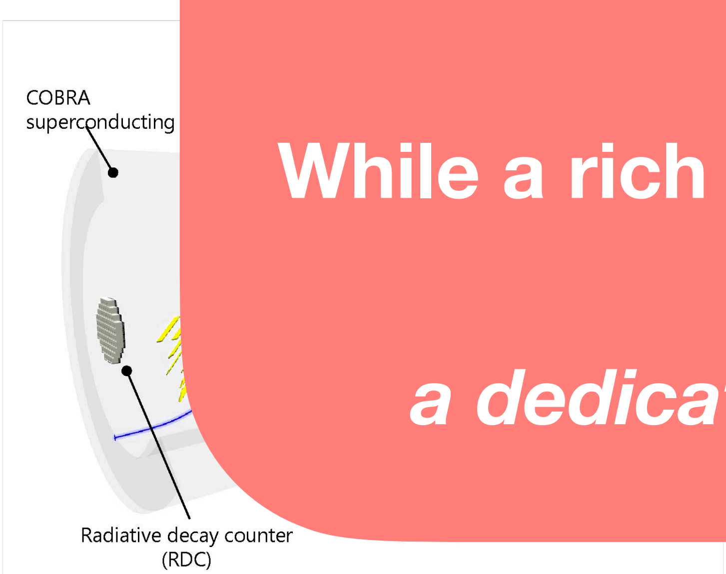
MEG II @ PSI

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

LEPTON FLAVOUR VIOLATION (LFV)

Dipole interactions in effective field theories

g-2 @



MEG II @ PSI

Experimental evidences tell us that flavour physics is still an extremely promising portal to NP

Several tensions between experiments and SM predictions point toward LFU-violating NP

In this scenario, dipole interactions play a central role

While a rich experimental program for the next decade exists for $(g-2)_\mu$ and LFV,

a dedicated effort for the muon EDM is missing

nnected

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EDM

905.03789
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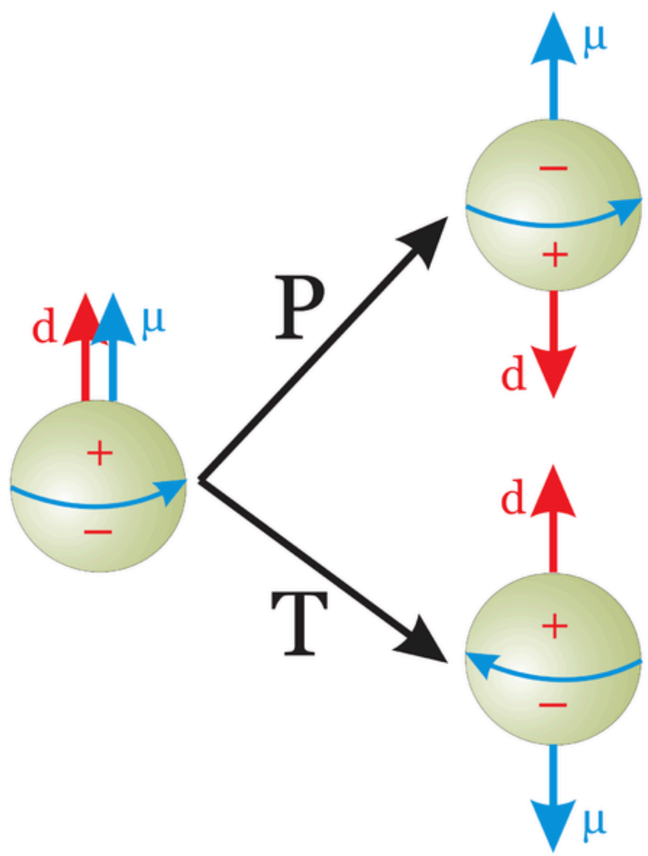
his talk

$c_R^{\ell_i \ell_i}$

ENT (EDM)

LEPTON FLAVOUR VIOLATION (LFV)

Electric dipole moments



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

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

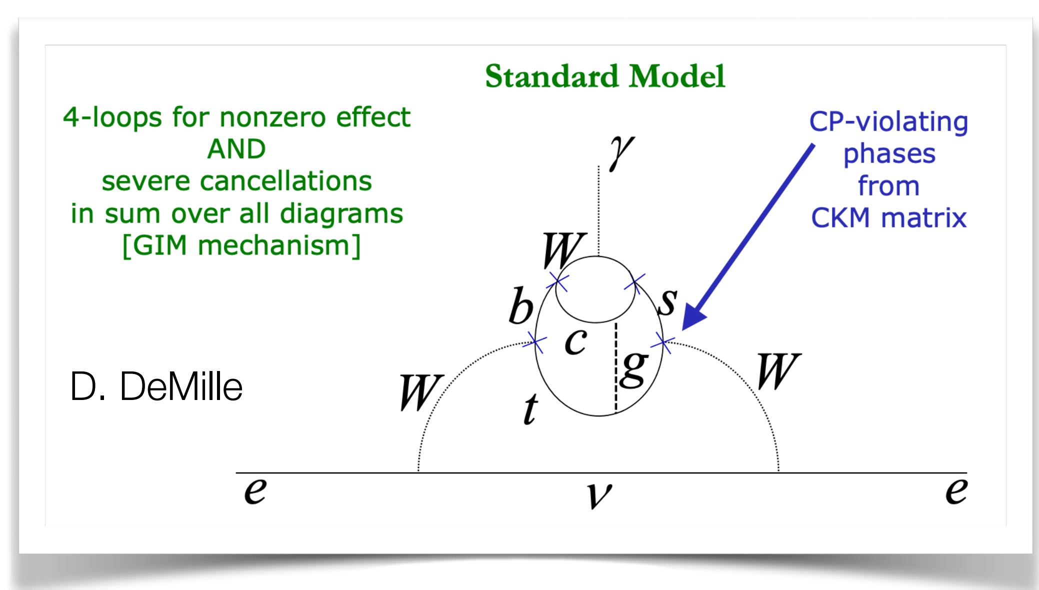
Magnetic dipole moment

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

Electric dipole moment

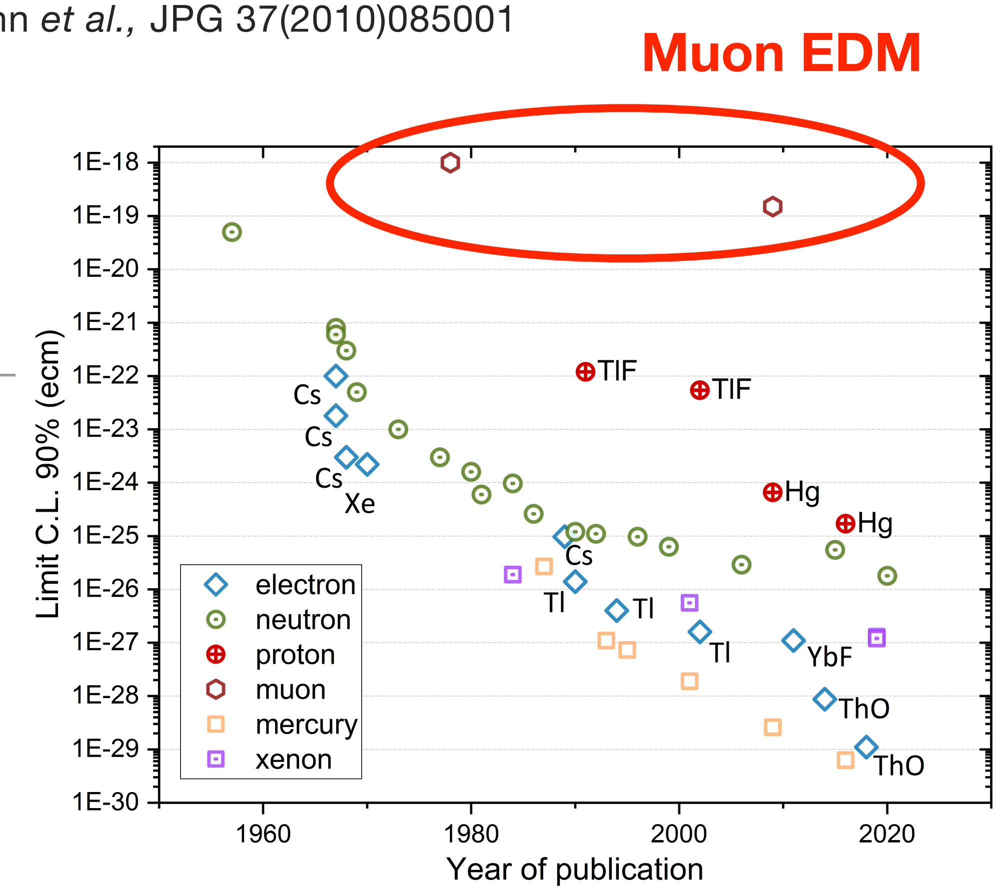
$$U = -\,\vec{d} \cdot \vec{E}$$ **P- and T-odd** **CPV!!!**

- 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



- The need of non-standard CPV sources to explain the **matter-antimatter asymmetry of the Universe** motivates many searches for EDMs

- 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

$$|d_e|_{\text{exp}} \leq 8 \times 10^{-30}\, e\,\text{cm} \quad \xrightarrow{\text{MFV}} \quad |d_\mu|_{\text{ind}} \leq 1.6 \times 10^{-27}\, e\,\text{cm}$$

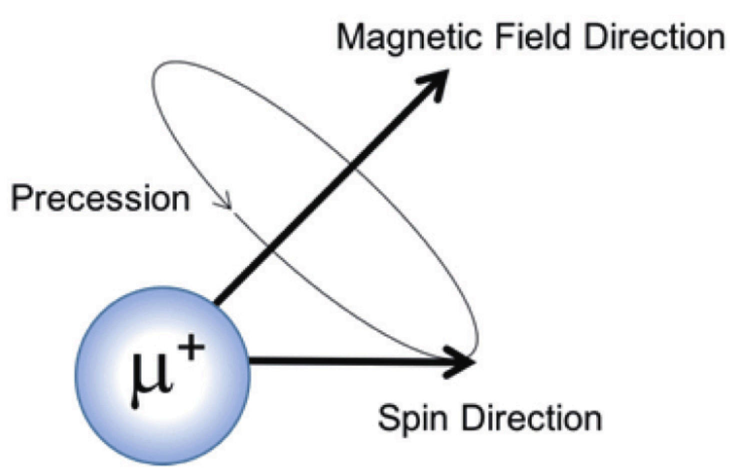
$$|d_\mu|_{\text{exp}} \leq 1.5 \times 10^{-19}\, e\,\text{cm}$$

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

- **Indeed the existing tensions, pointing toward LFUV, 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

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

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

Electric spin precession in the particle rest frame

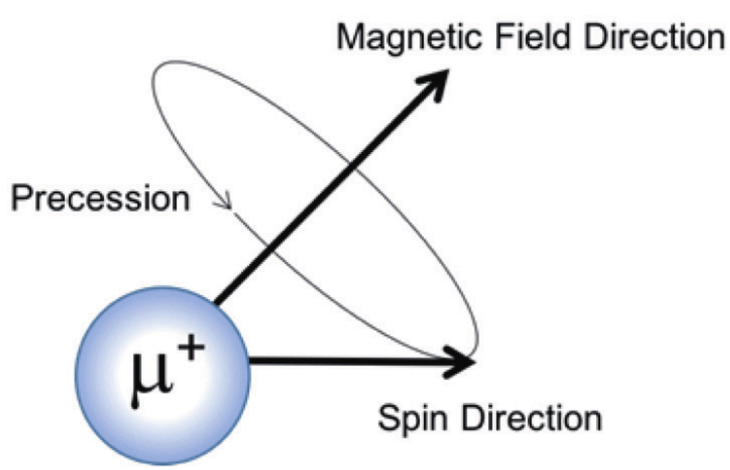
$$\overrightarrow{\omega}_d = 2\,\overrightarrow{d} \cdot \overrightarrow{E^*}/\hbar$$

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

Electromagnetic spin precession in the laboratory rest frame

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

Dipole moments in electromagnetic fields



Magnetic spin precession in the particle rest frame

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

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

Electric spin precession in the particle rest frame

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

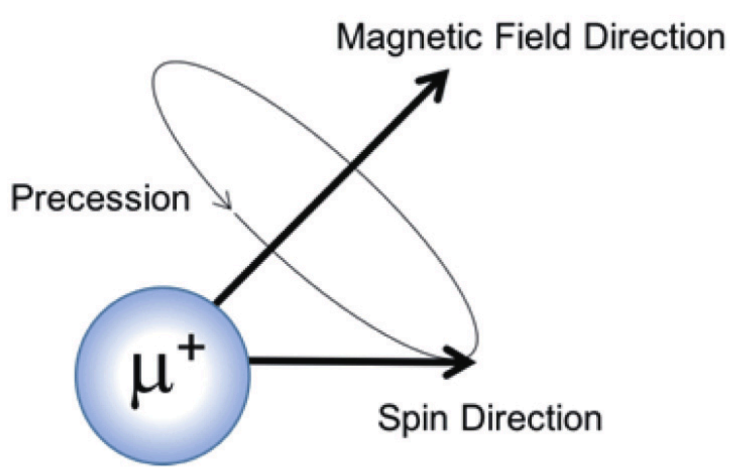
$$\boxed{\vec{d} = \frac{\eta e}{2mc}\vec{s}}$$

Electromagnetic spin precession in the laboratory rest frame

Cyclotron frequency

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

Dipole moments in electromagnetic fields



Magnetic spin precession in the particle rest frame

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

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

Electric spin precession in the particle rest frame

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

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

Electromagnetic spin precession in the laboratory rest frame

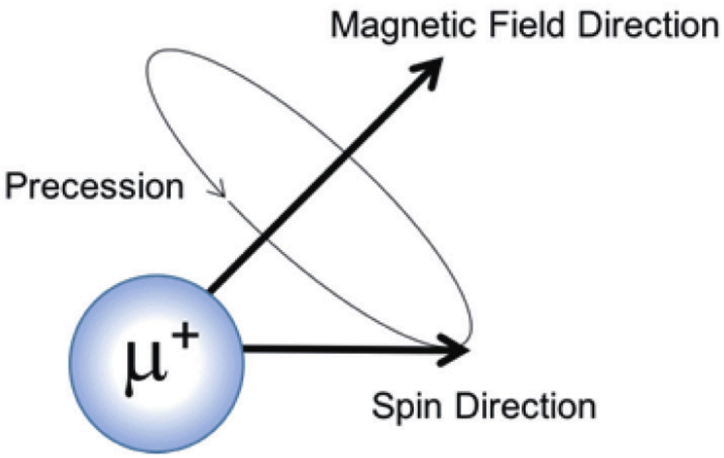
Cyclotron frequency

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

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

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

Dipole moments in electromagnetic fields



Magnetic spin precession in the particle rest frame

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

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

Electric spin precession in the particle rest frame

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

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

Electromagnetic spin precession in the laboratory rest frame

Cyclotron frequency

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

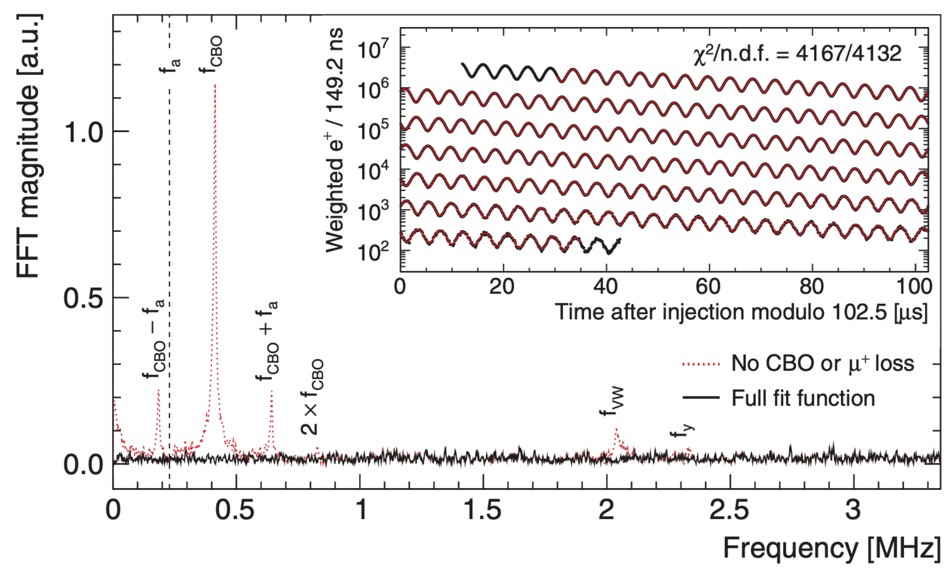
$$\vec{\Omega} = \vec{\Omega}_0 - \vec{\Omega}_c = \frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

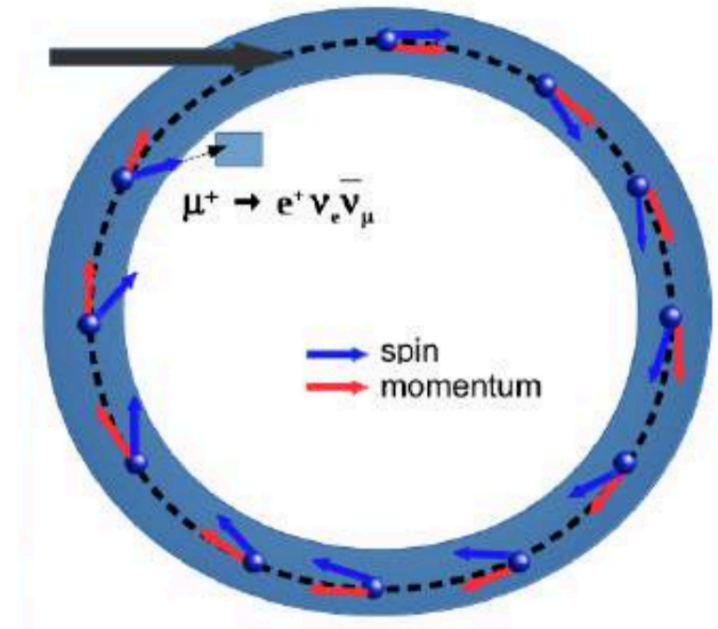
$$+\frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \frac{\gamma}{(\gamma+1)c}\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta}\right]$$

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 $\mathbf{\Omega}$





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

$p \simeq 3.09\ GeV/c$

("magic" momentum)

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

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

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

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**, $\overrightarrow{E^*} = \gamma c \vec{\beta} \times \vec{B} \sim 13.5 \text{ GV/m}$

- 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

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

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

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

$p \simeq 3.09\ GeV/c$

(“magic” momentum)

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

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

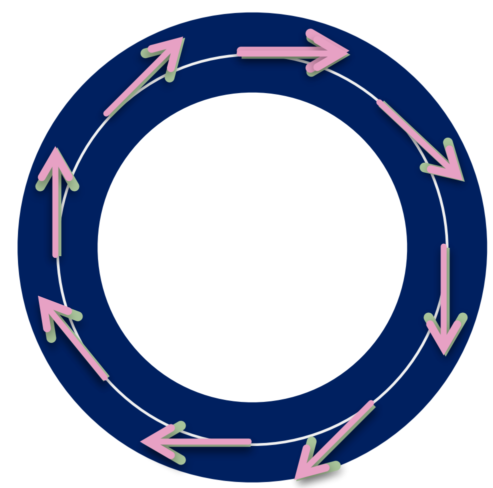
$$+ \frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \frac{\gamma}{(\gamma+1)c}\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta}\right].$$

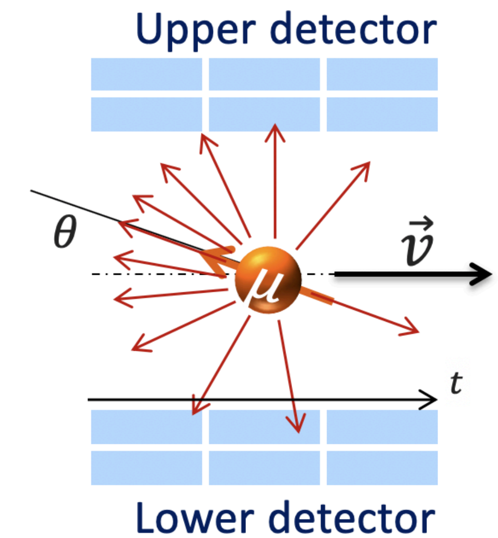
“Relativistic” electric field

Small

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

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

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

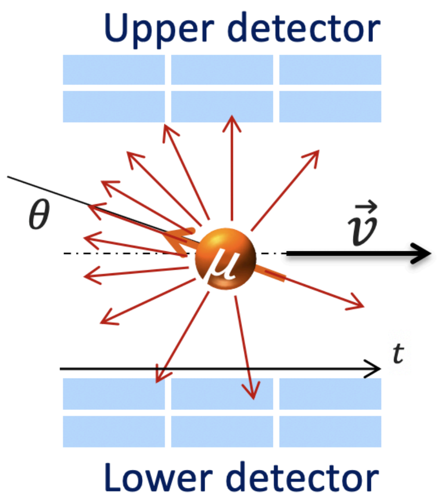
$$+ \frac{\eta q}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \frac{\gamma}{(\gamma+1)c}\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta}\right].$$

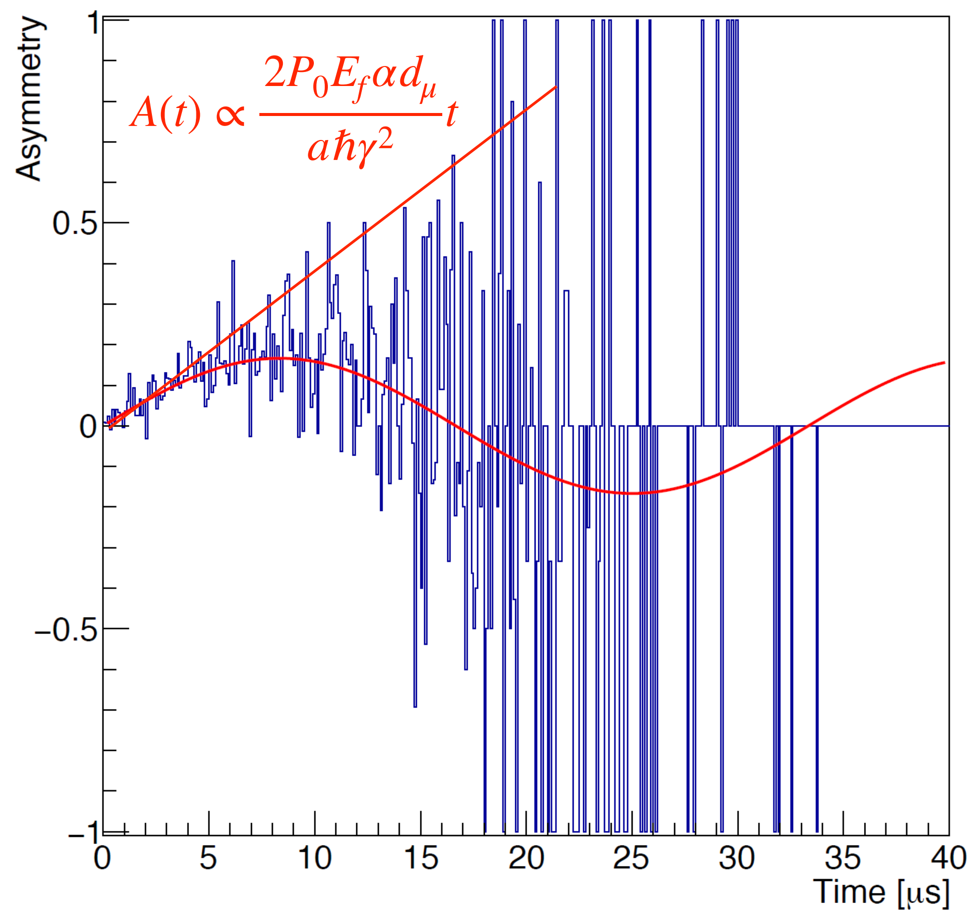
"Relativistic" electric field

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 a couple of muon lifetimes $\gamma\tau_\mu$

$$\sigma(|d_\mu|) = \frac{d|d_\mu|}{d\bar{A}}\sigma(\bar{A}) \sim \frac{a\hbar\gamma}{2P_0 E_f \sqrt{N}\tau_\mu \alpha}$$

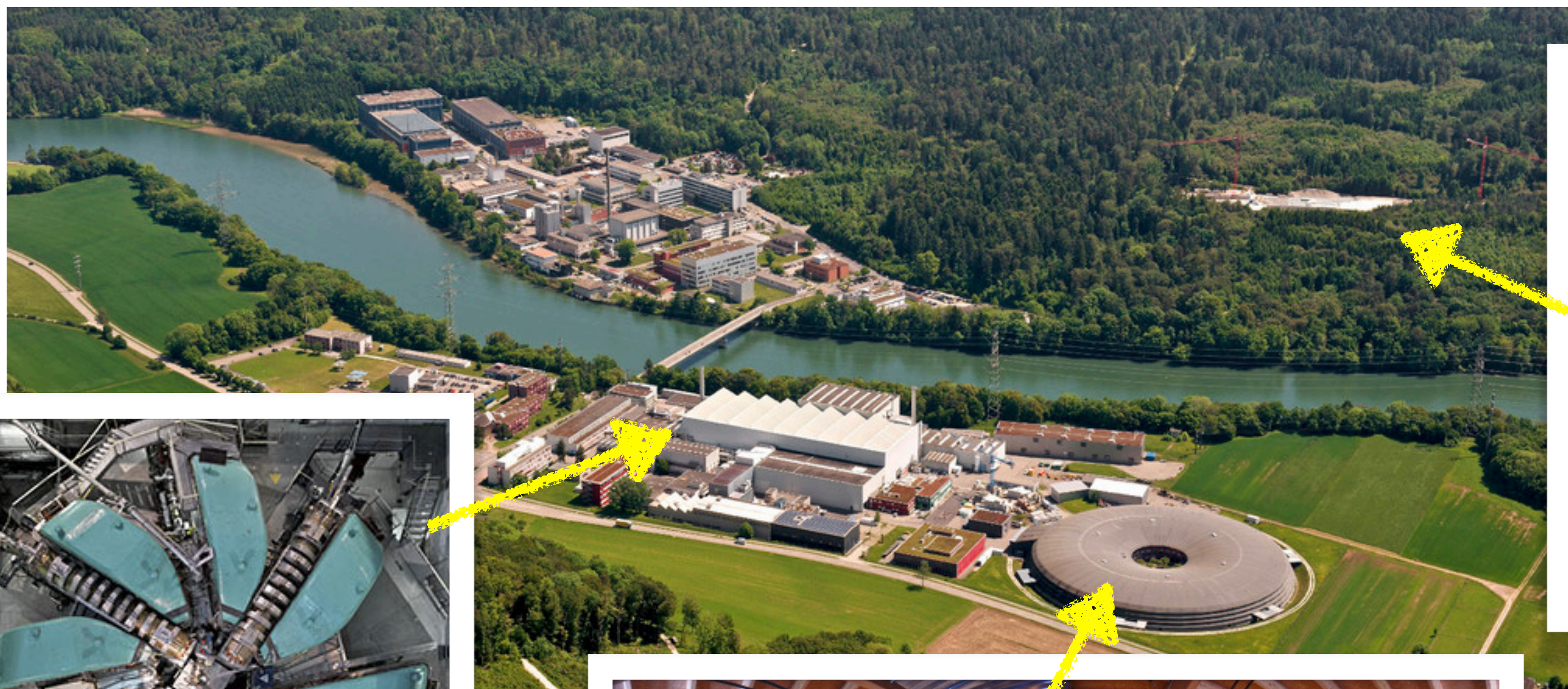
The "PENTA" formula

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)

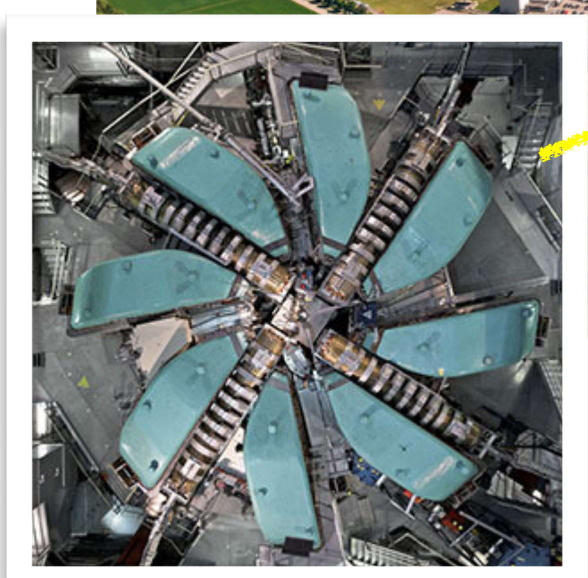
A muon EDM search at PSI

The Paul Scherrer Institute (PSI)

- The largest Swiss research institute for fundamental and applied science, with a strong multidisciplinary mission and operating large, world-leading user facilities



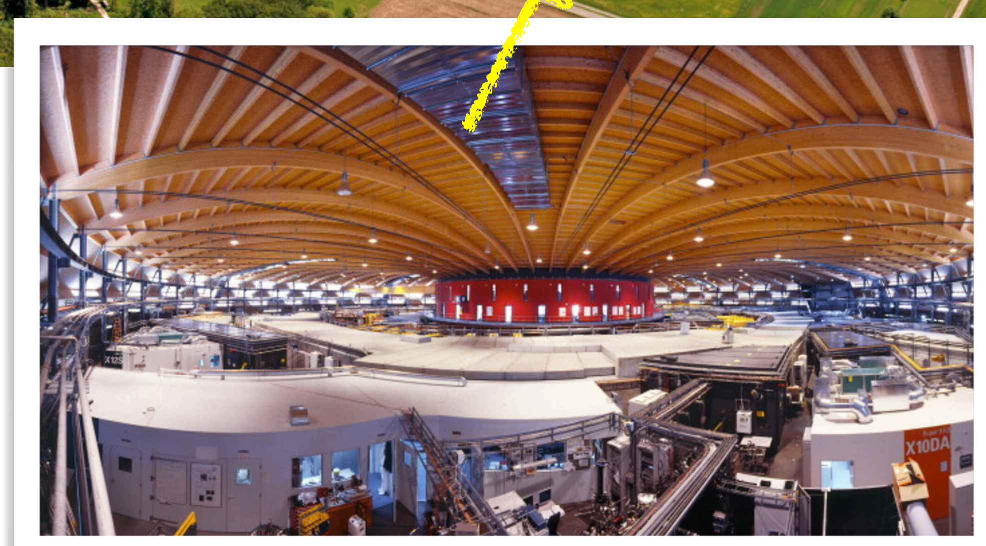
Swiss Free Electron Laser (SwissFEL)



High Intensity Proton Accelerator (HiPA)

also serving the

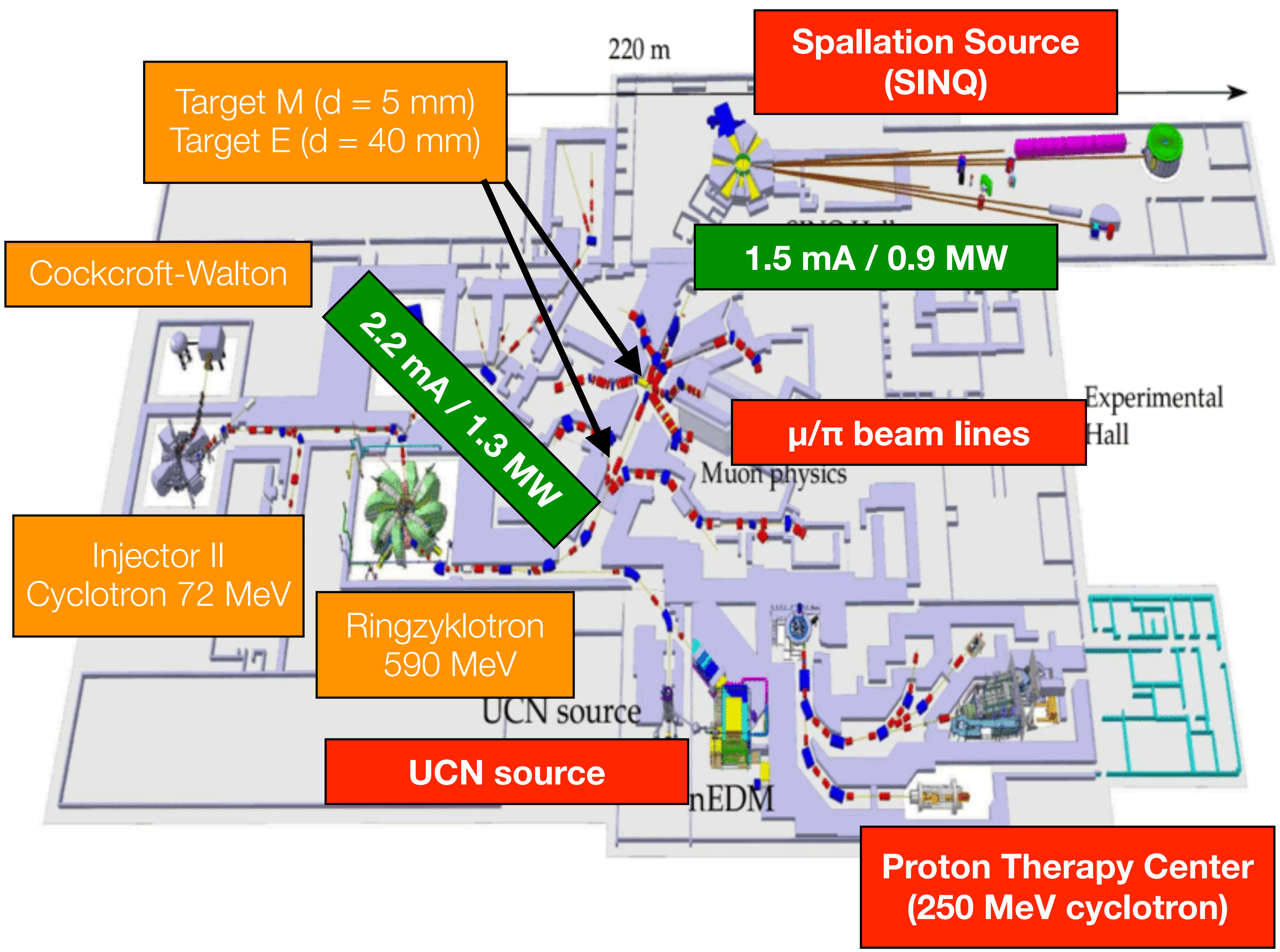
Swiss Spallation Neutron Source (SINQ)



Swiss Light Source (SLS)

Matter & Material
Human Health
Energy & Environment

The proton accelerator complex at PSI



- One of the most intense proton beams in the world (2.2 mA, 1.3 MW, 50 MHz RF)
- Producing the most intense continuous muon beams in the world (up to 10^8 μ/s)
  - μ from π decays (highly polarised & time distribution flattened by the π lifetime)
  - 15-500 MeV/c
- Several beam lines with different specs and applications (particle physics, muonic atoms, material science)

Muon beams at PSI (a few examples)

- The muonEDM sensitivity improves with **increasing muon intensity and $E_f/\gamma \propto \gamma$**
- **πE5**:
  - pions and muons, high intensity, **low energy**, e.g. surface muons (28.4 MeV/c muons produced by pions decaying at rest on the surface of the proton target) up to 10^8 μ/s
  - ideal for muon decay studies (e.g. LFV)
- **πE1**:
  - **medium intensity** pions, muons and electrons from 10 to 500 MeV/c
  - very good momentum resolution (down to 0.26%)
  - often used as a beam test facility
- **μE1**:
  - high intensity muon beam with very low pion and electron contamination
  - provides the **highest muon rates at high momentum** (typically 125 MeV/c)
  - mainly used for μSR experiments

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A good beam line for a muon EDM search

- **μE1**:
  - high intensity muon beam with very low pion and electron contamination
  - provides the **highest muon rates at high momentum** (typically 125 MeV/c)
  - mainly used for μSR experiments

The muonEDM LoI

- A LoI for a Muon EDM experiment was presented in January 2021 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]

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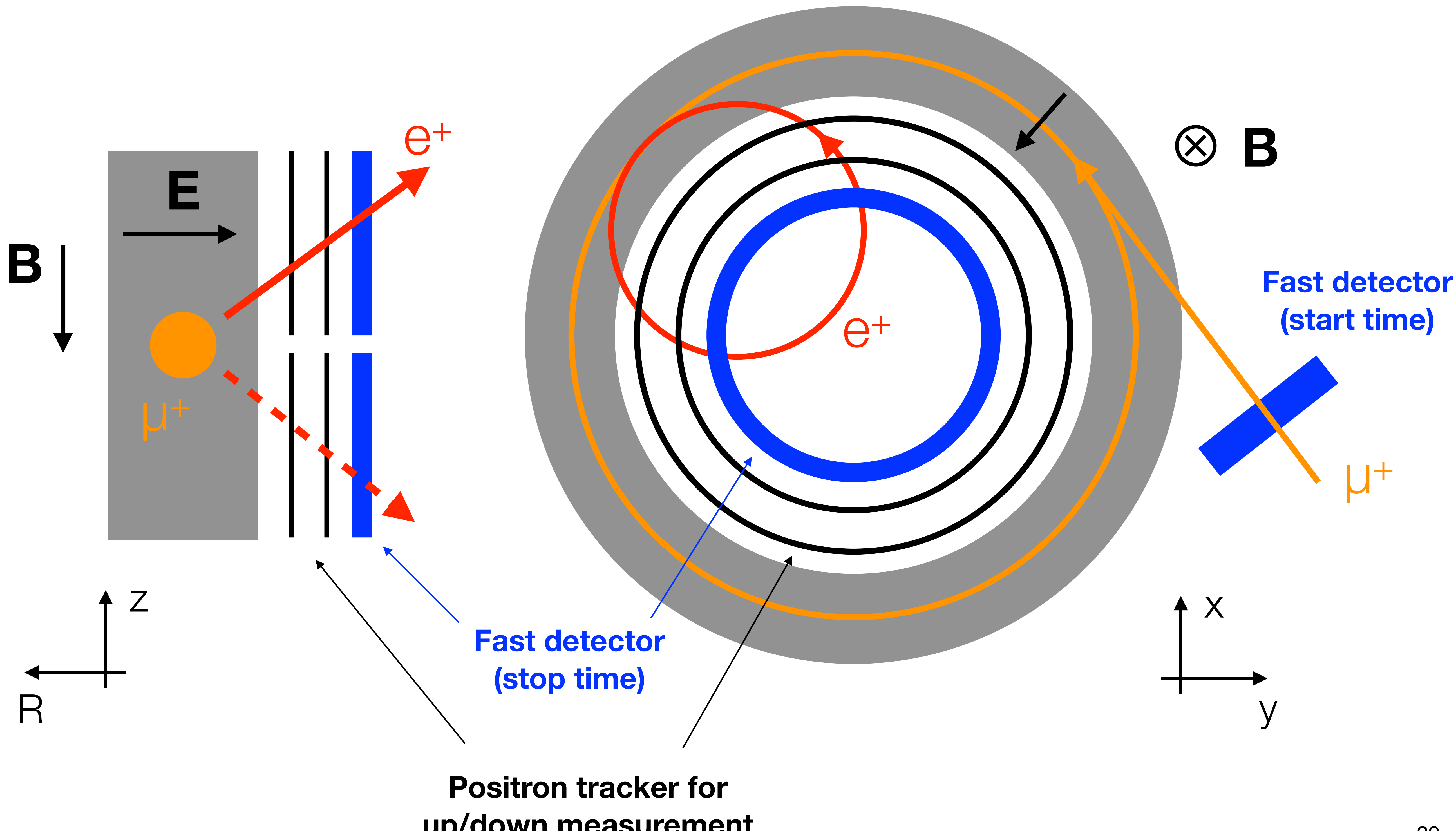
4 JG|U
5 SAPIENZA UNIVERSITÀ DI ROMA
6 INFN Istituto Nazionale di Fisica Nucleare
7 UCL
8 CERN
9 University of Zurich UZH
10 Cluster of Excellence PRISMA+
11 JÜLICH Forschungszentrum
12 MANCHESTER 1824 The University of Manchester
13 上海交通大學 SHANGHAI JIAO TONG UNIVERSITY
14 李政道研究所 Tsung-Dao Lee Institute
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

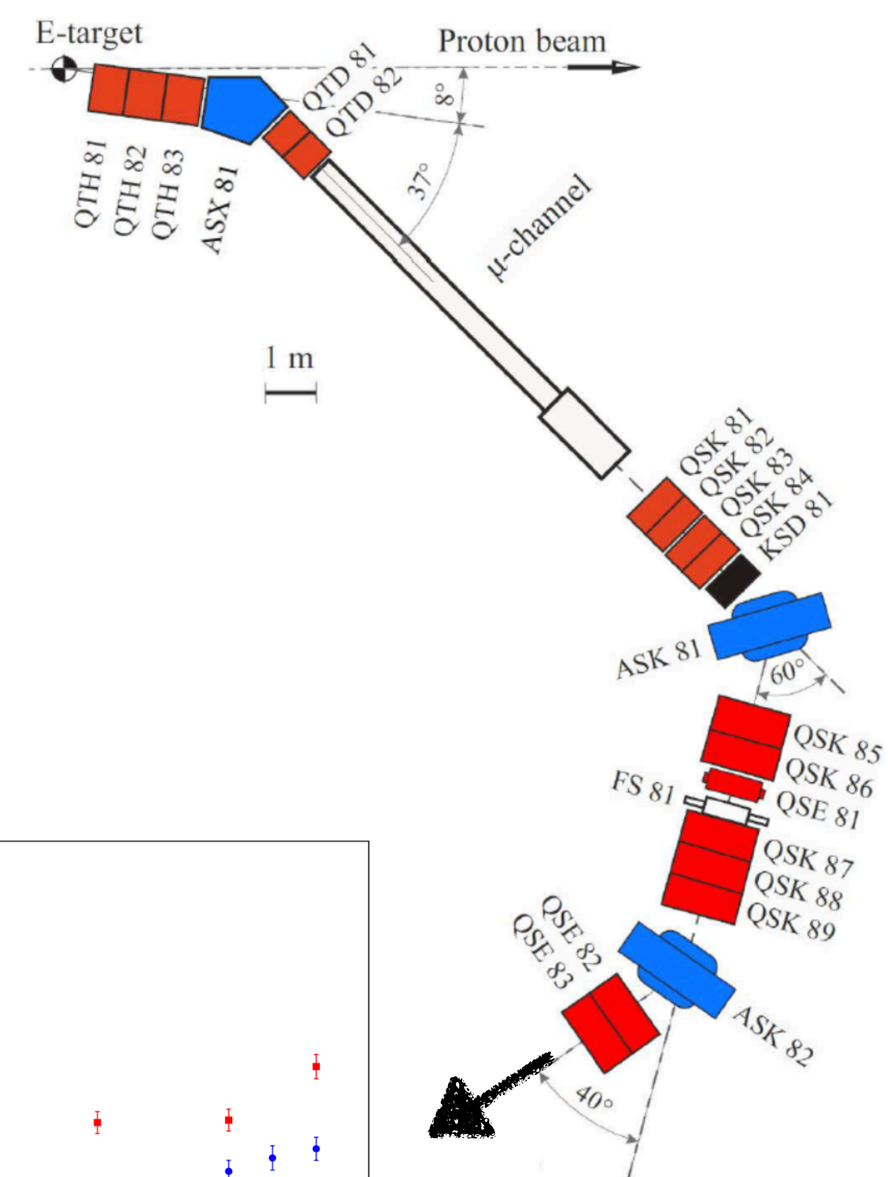
Experimental approach

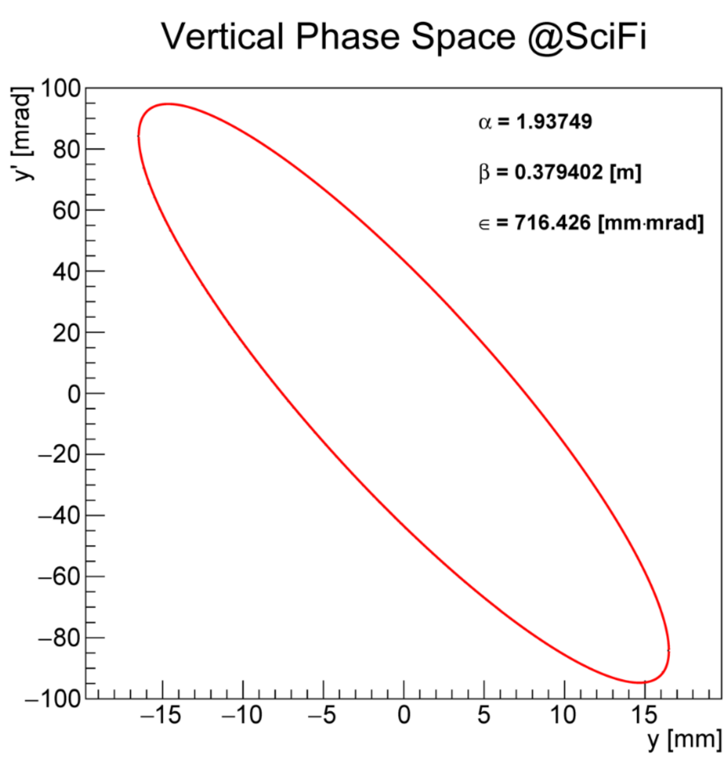
$$A(t) = \frac{N_{\uparrow}(t) - N_{\downarrow}(t)}{N_{\uparrow}(t) + N_{\downarrow}(t)}$$

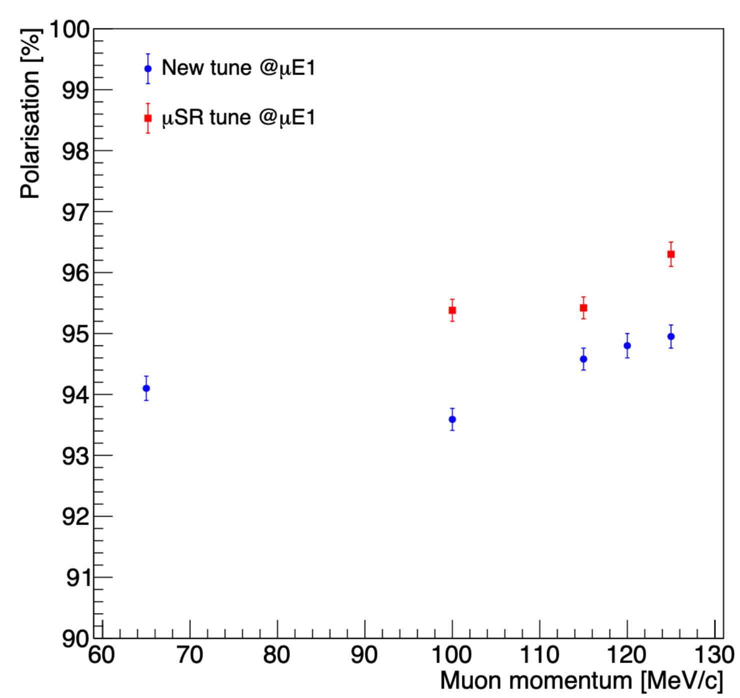


The μE1 beam line

- Up to 10^8 μ/s @ 125 MeV/c
- Emittance (1σ):
  - 945 mm·mrad horizontal
  - 716 mm·mrad vertical
- > 93% polarization

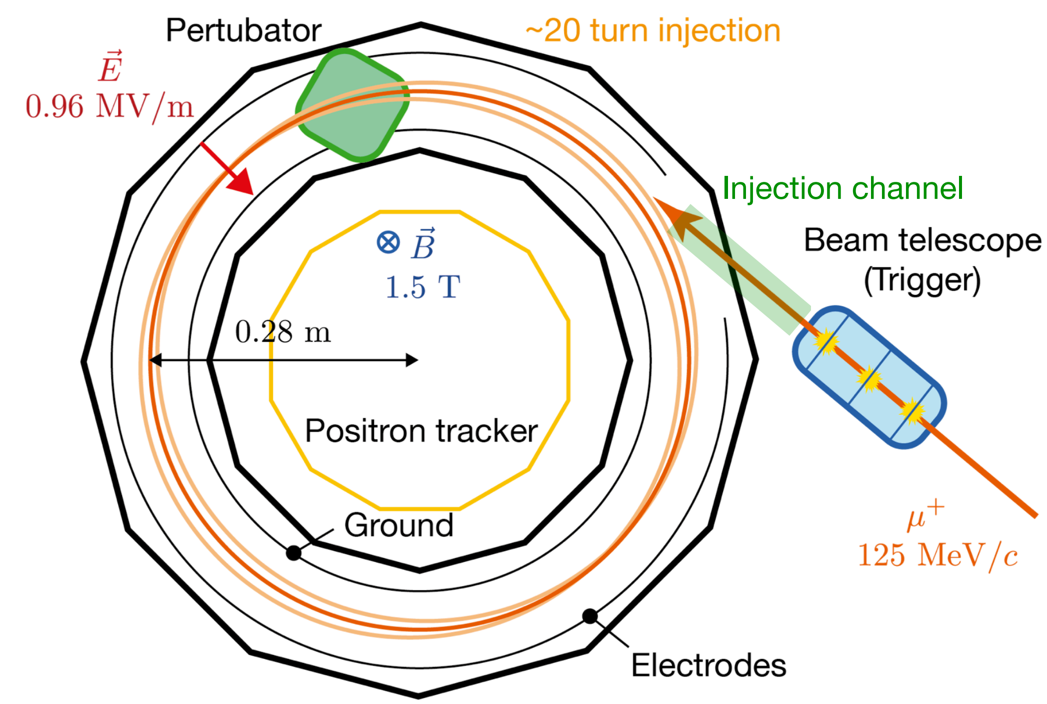


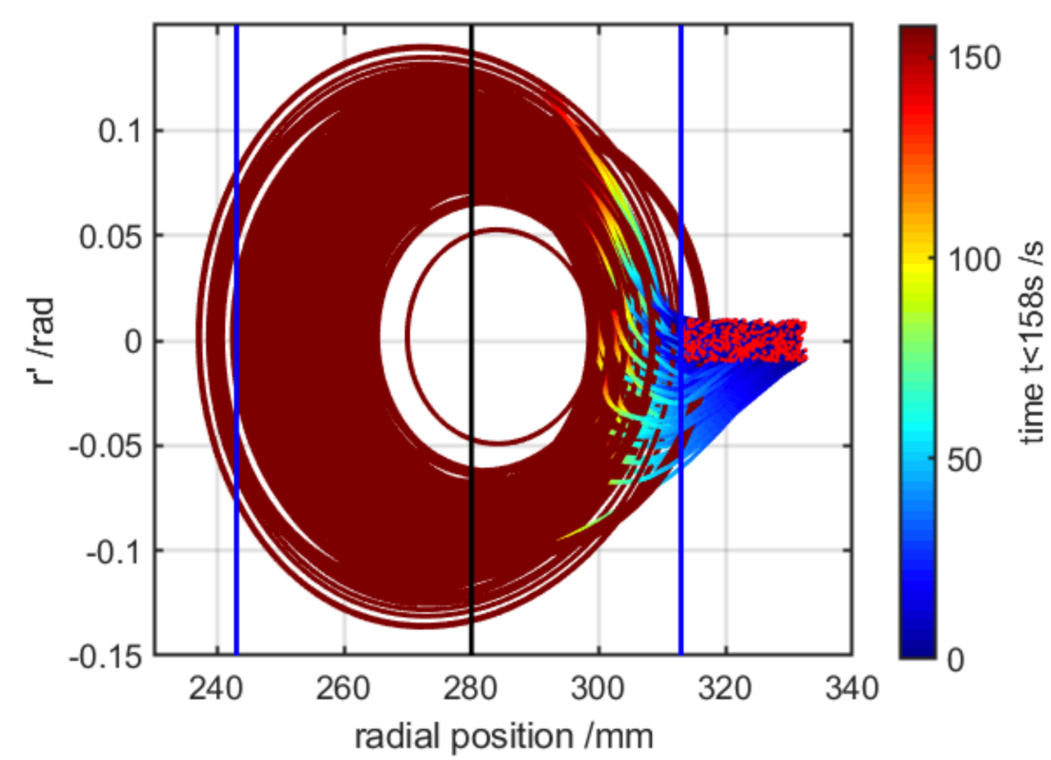




Experimental concepts — Storage ring

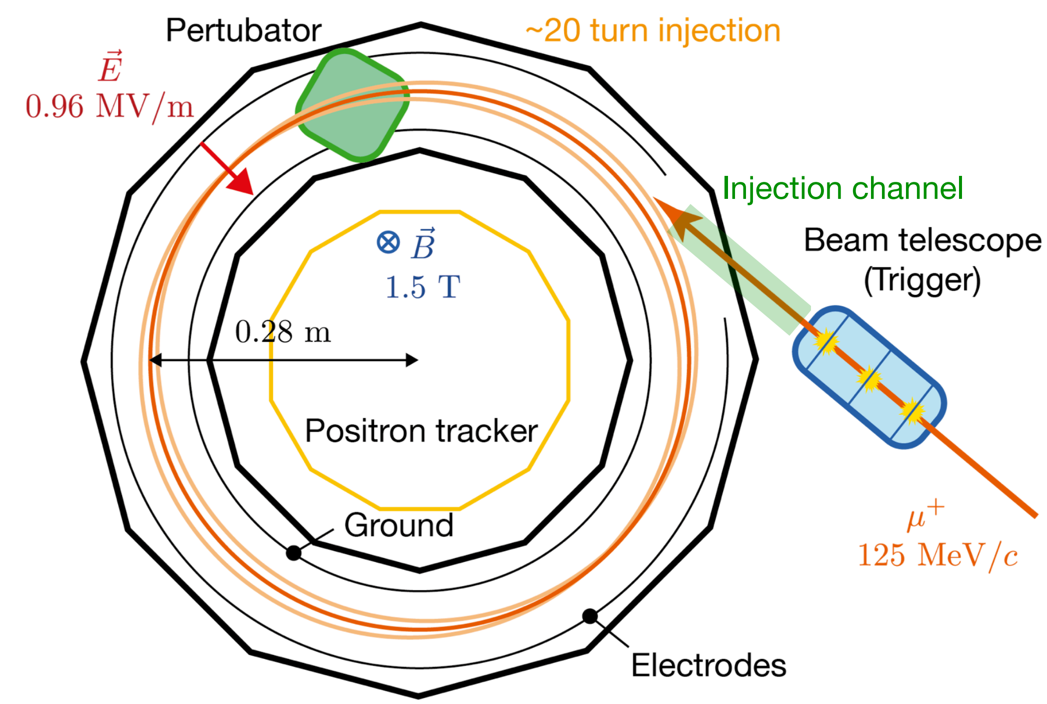
- Compact storage ring with lateral injection through a magnetic channel
- Need a **kick within 1 revolution (10 ns)** to avoid hitting the injection channel after 1 turn
- In principle, 0.14% injection efficiency is possible

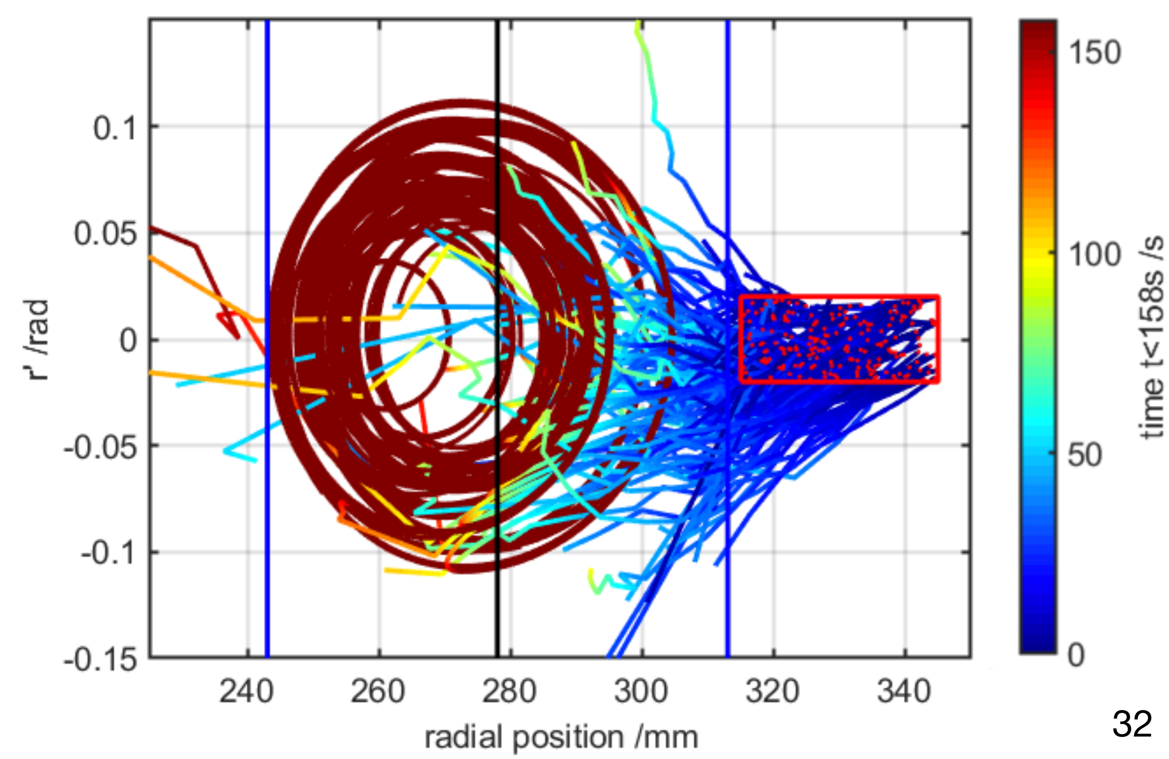




Experimental concepts — Storage ring

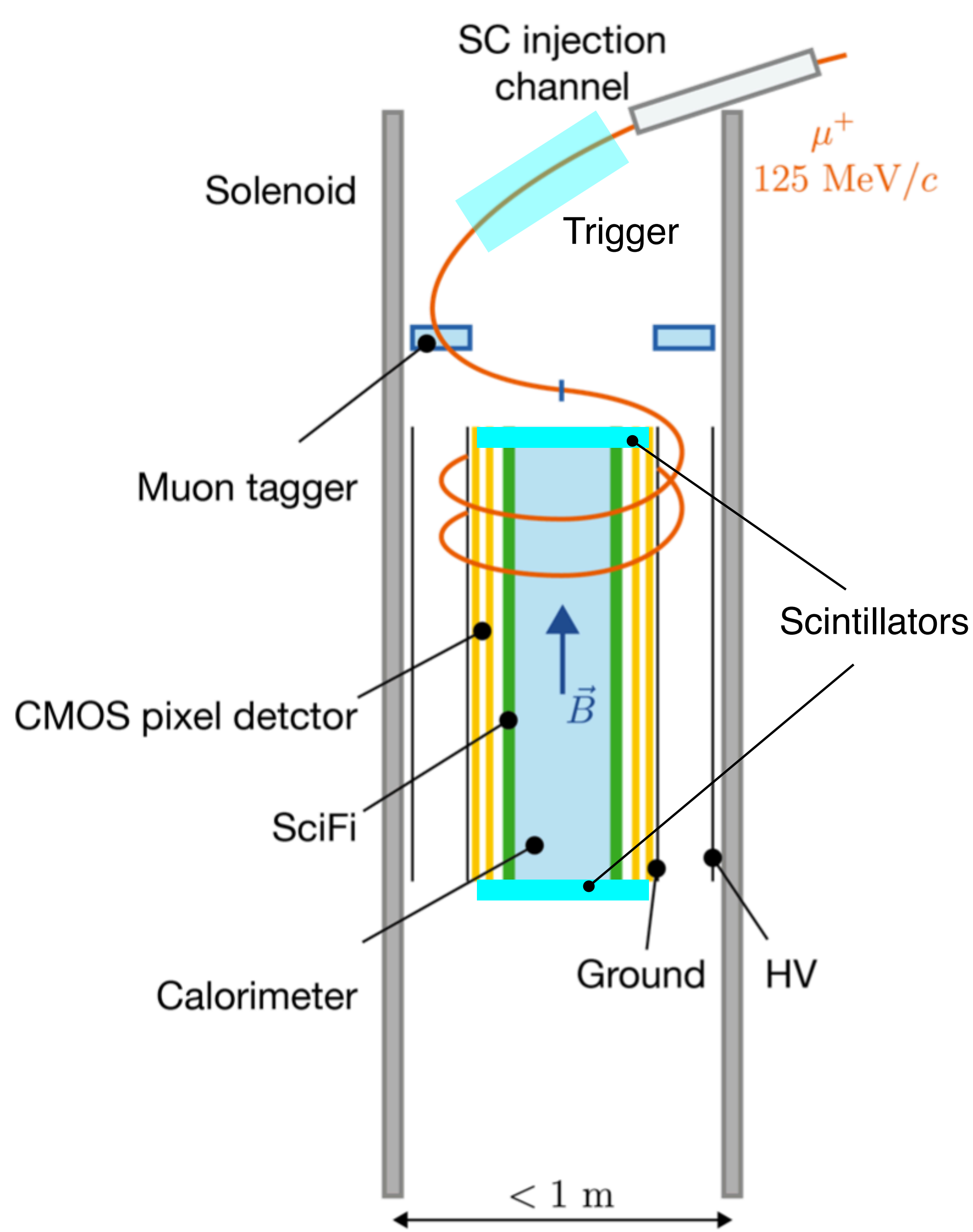
- Compact storage ring with lateral injection through a magnetic channel
- Need a **kick within 1 revolution (10 ns)** to avoid hitting the injection channel after 1 turn
- In principle, 0.14% injection efficiency is possible
- In practice, before the orbit stabilises, muons are lost due to **MS through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



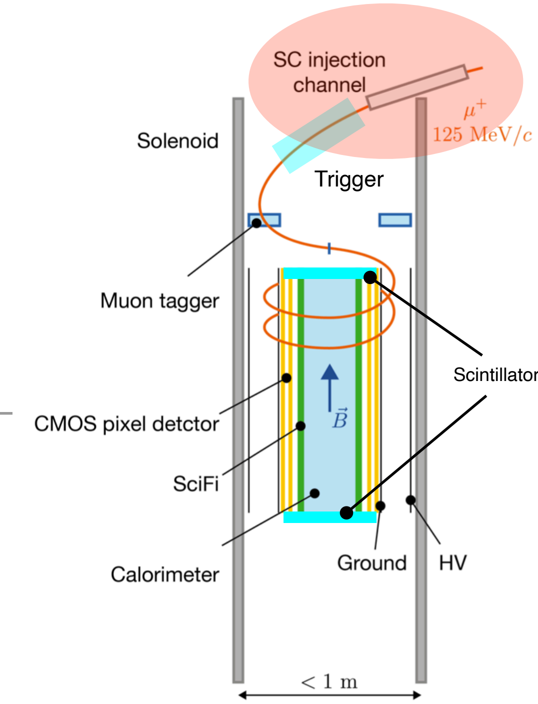


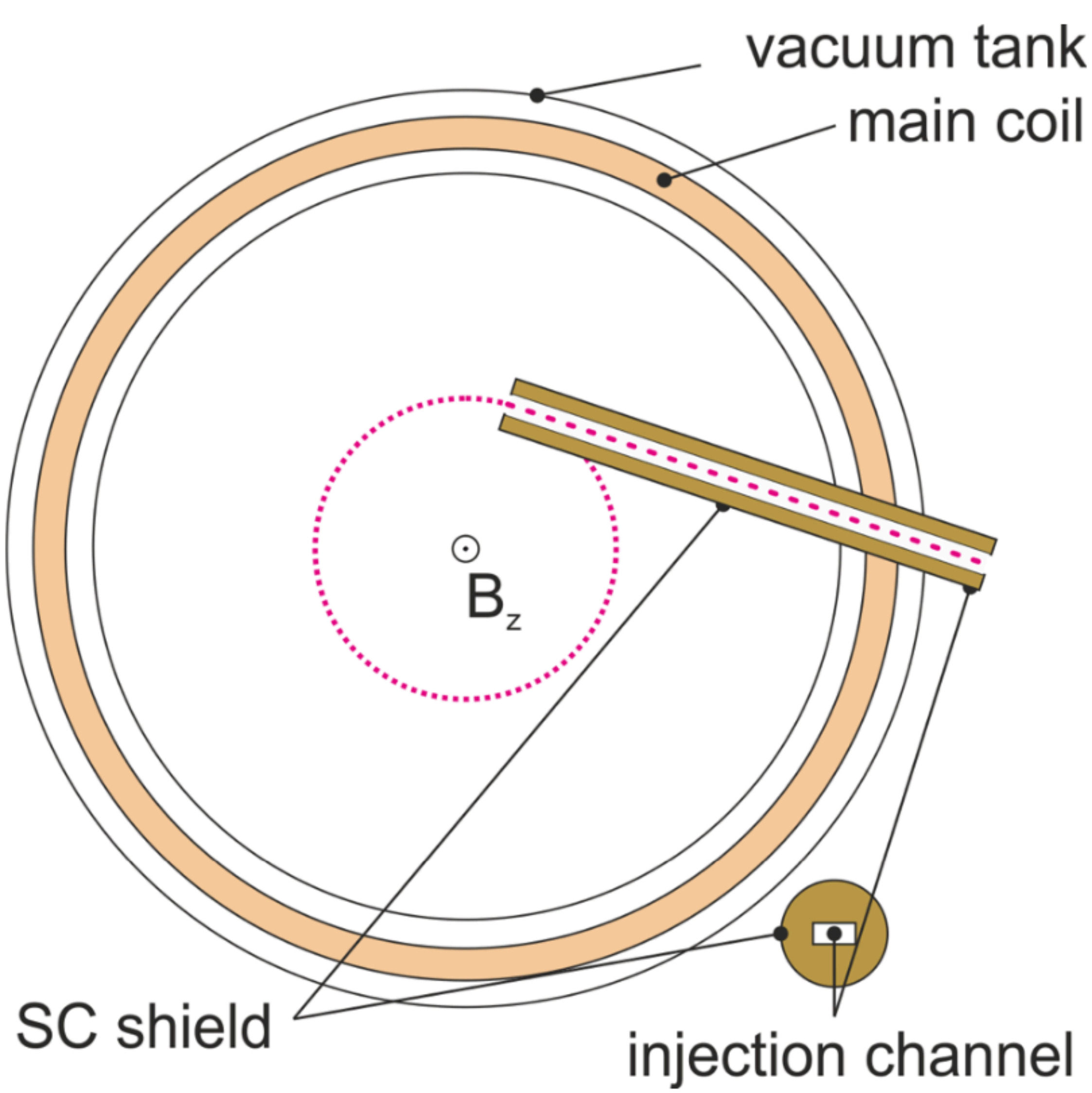
Experimental concepts — Helix muonEDM

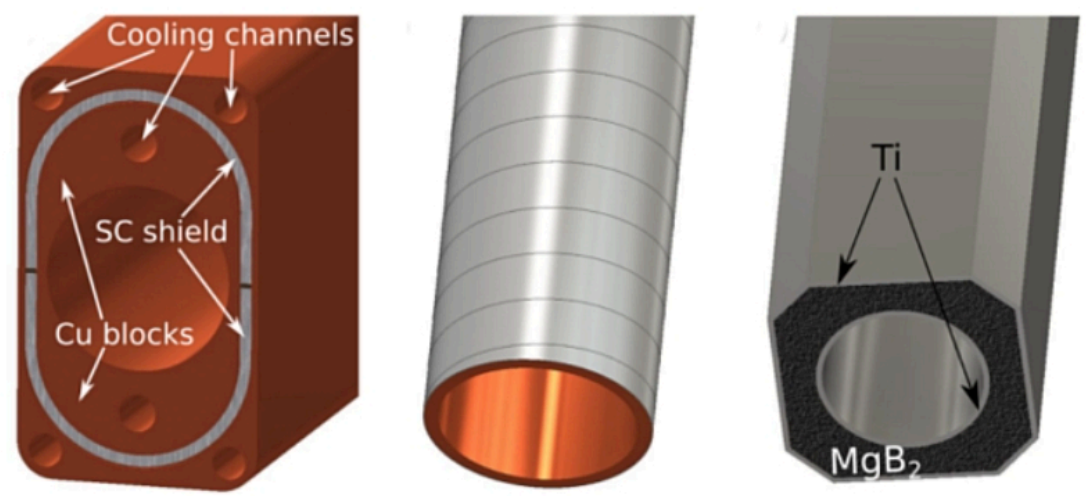
- Vertical injection into a 3T solenoid
- Also need a **kick** to stabilise the orbit in the central region, but **within > 50 ns**
- **No material along the muon trajectories**

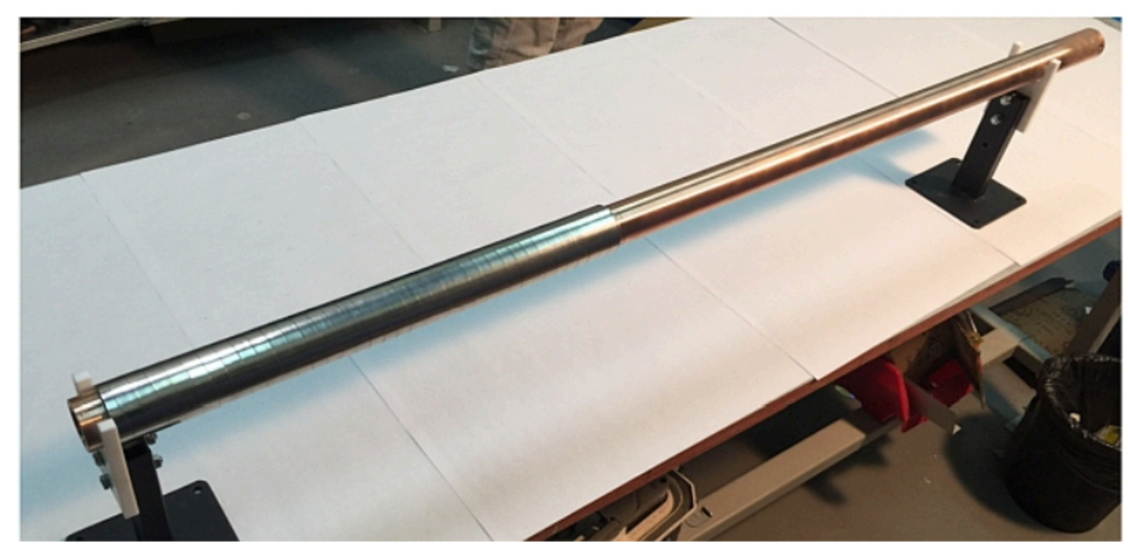


Injection channel

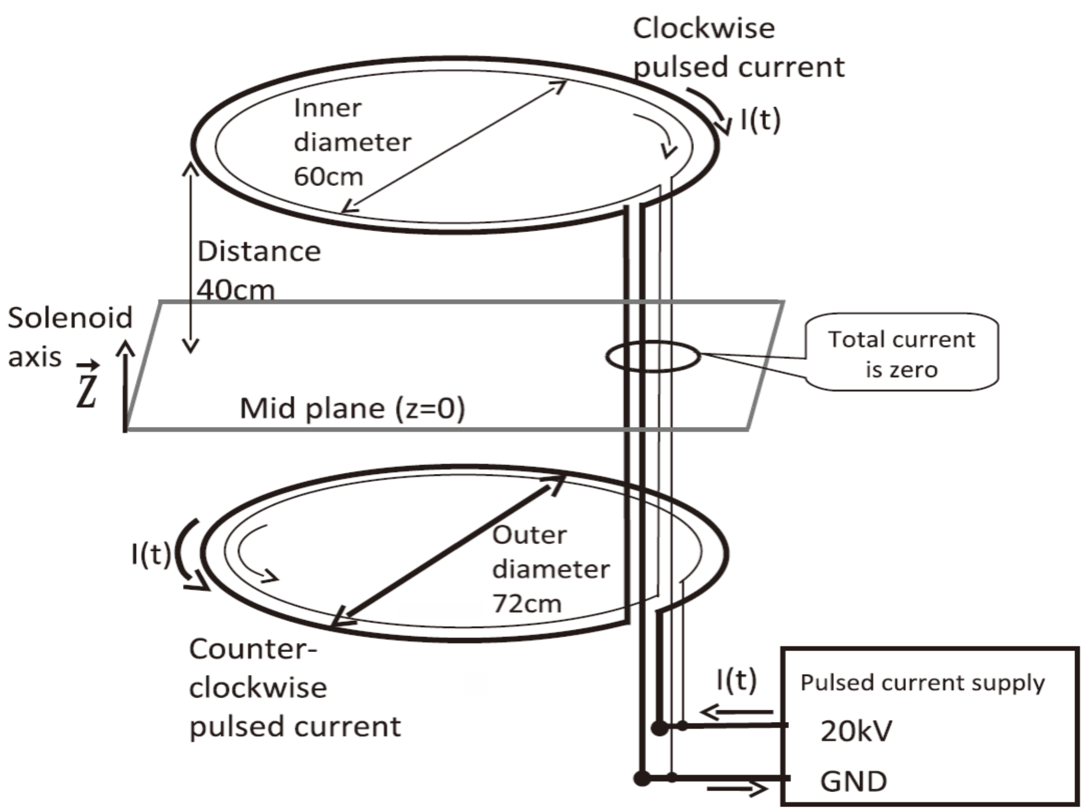


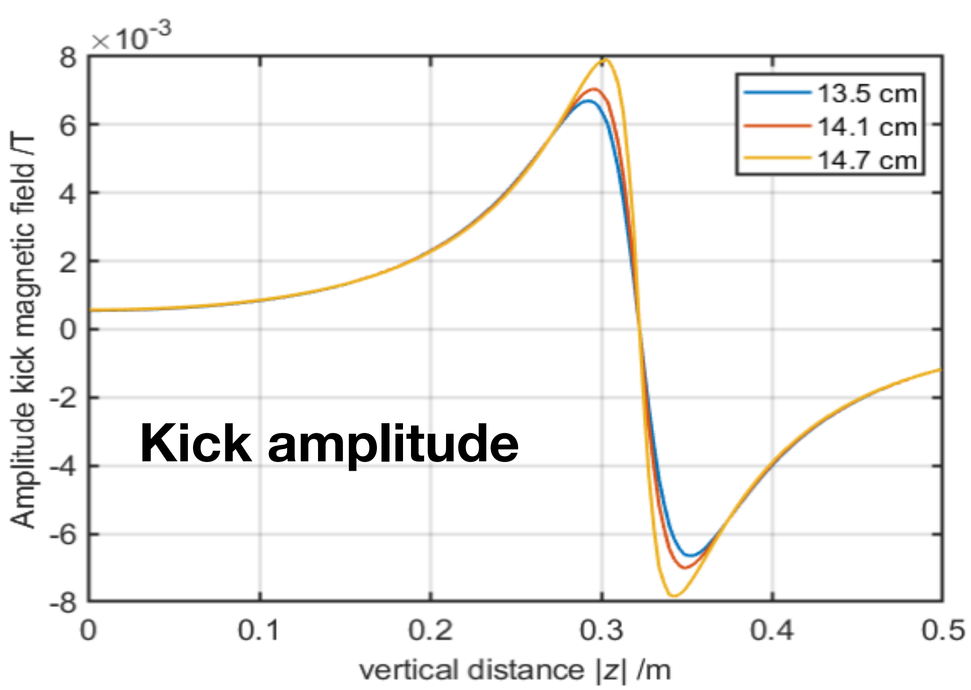




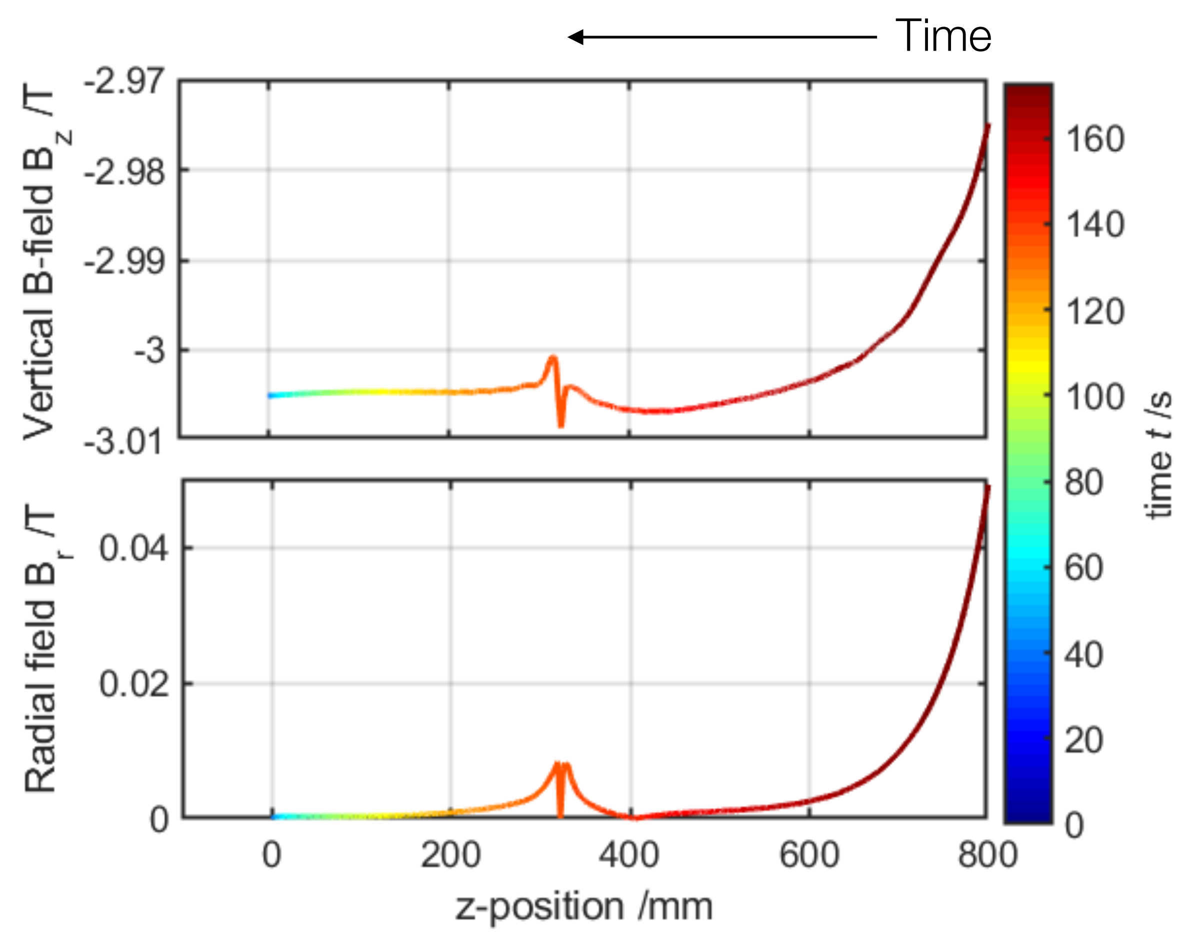


Magnetic field kicker



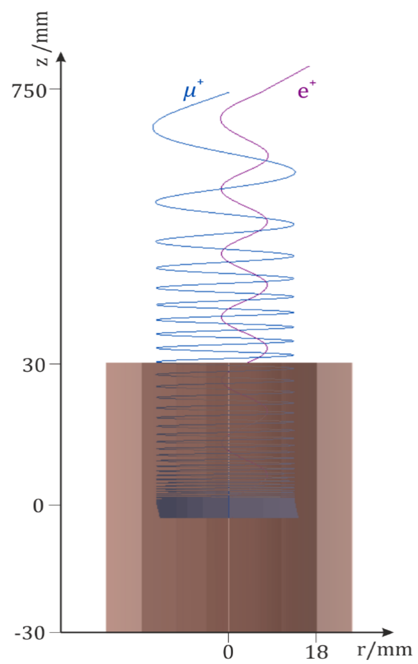


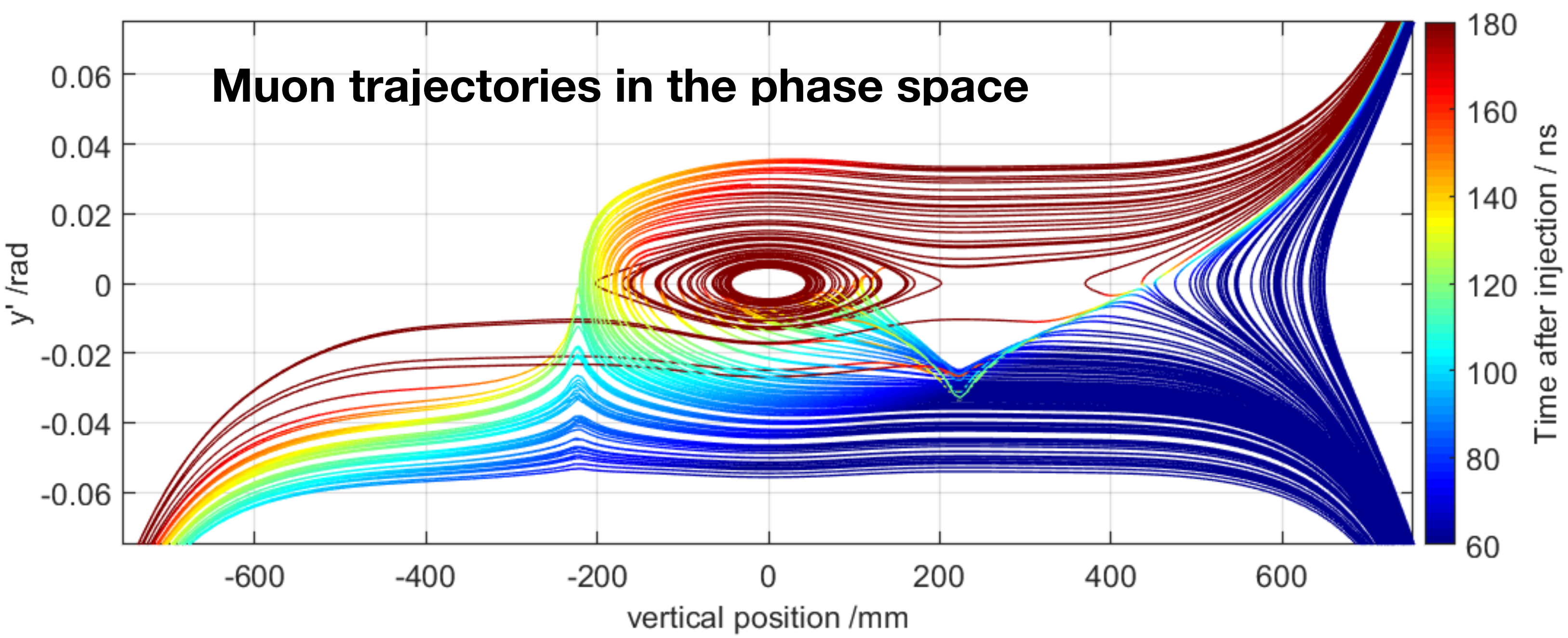
Magnetic field along the nominal trajectory



N.B. due to the necessity of a kick and the continuous structure of the beam, **only one muon at a time can be stored**

Expected injection performances





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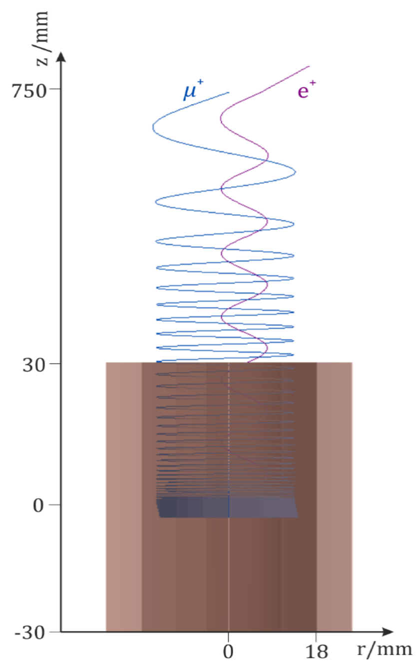

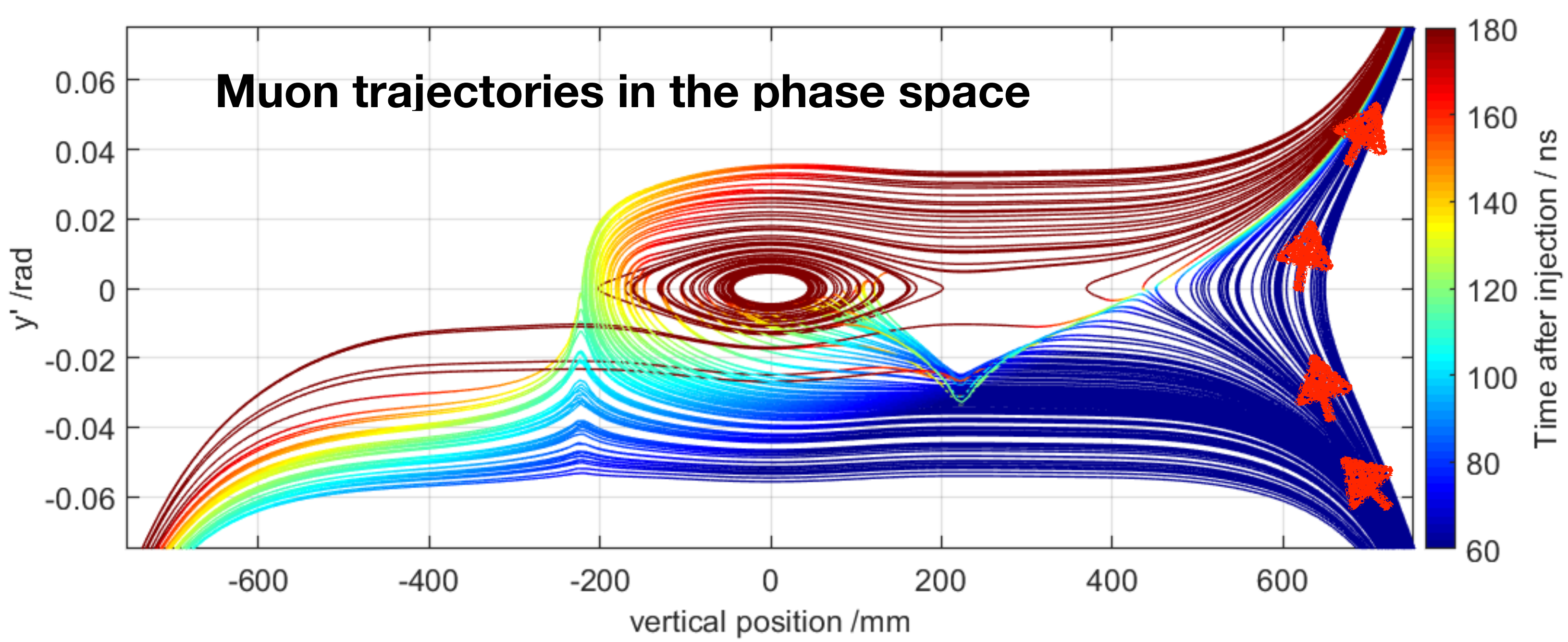

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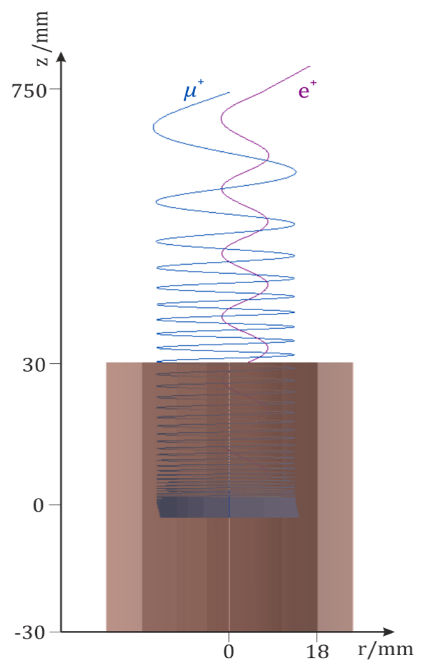

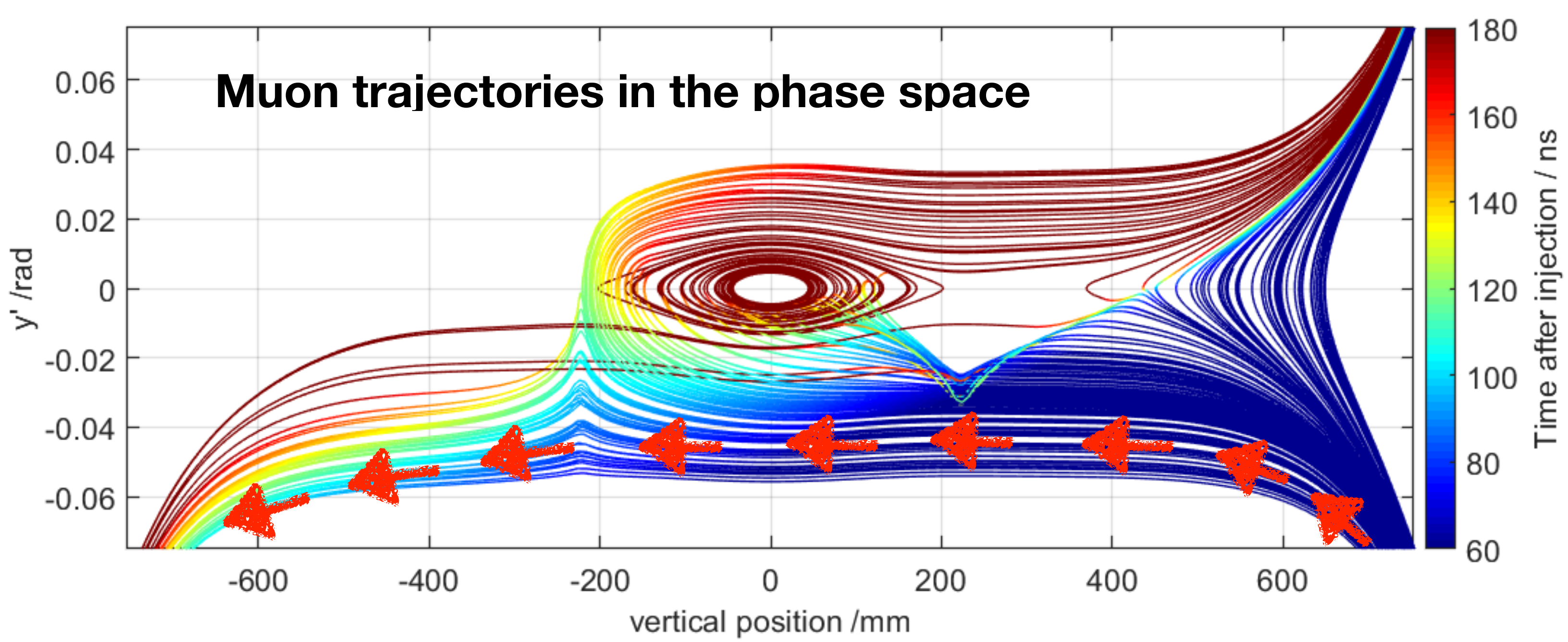

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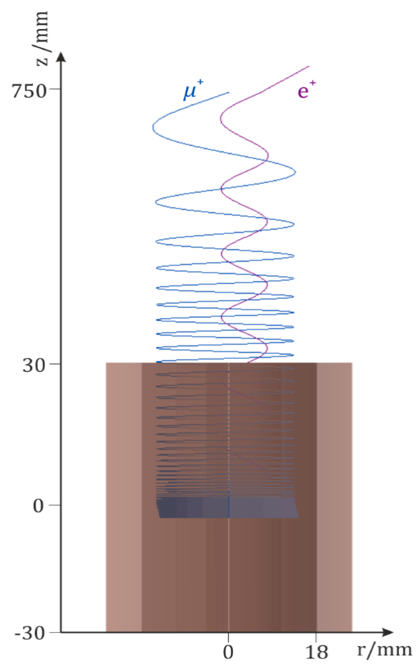
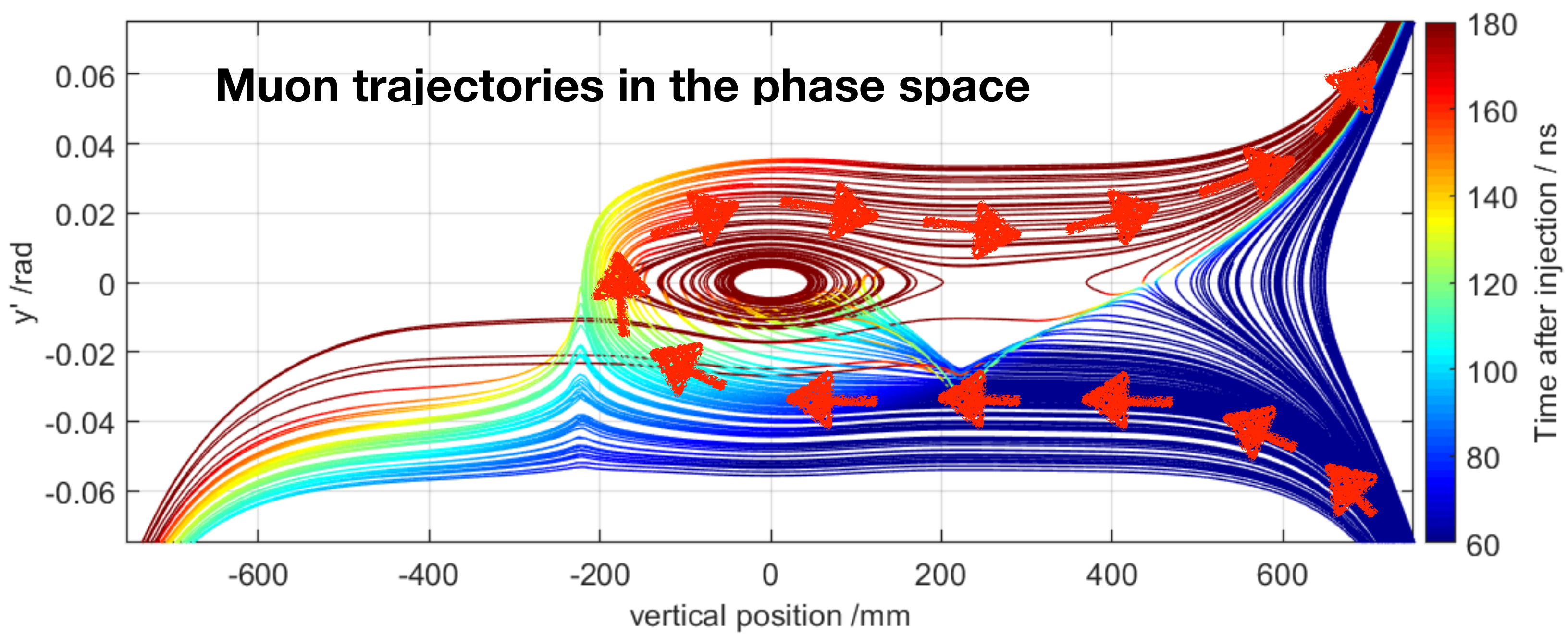
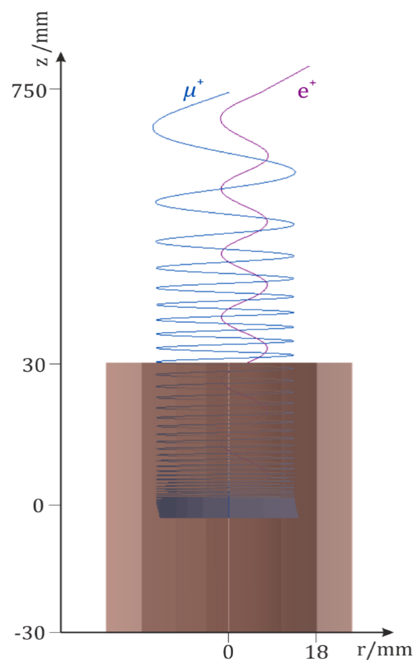
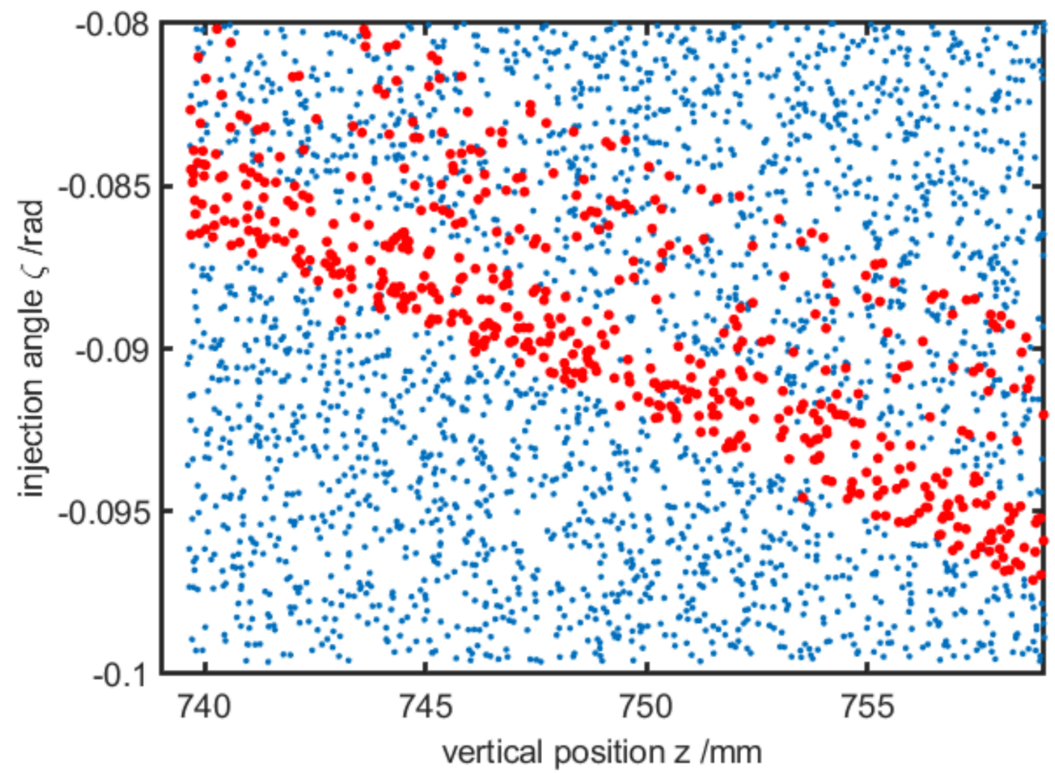




Expected injection performances

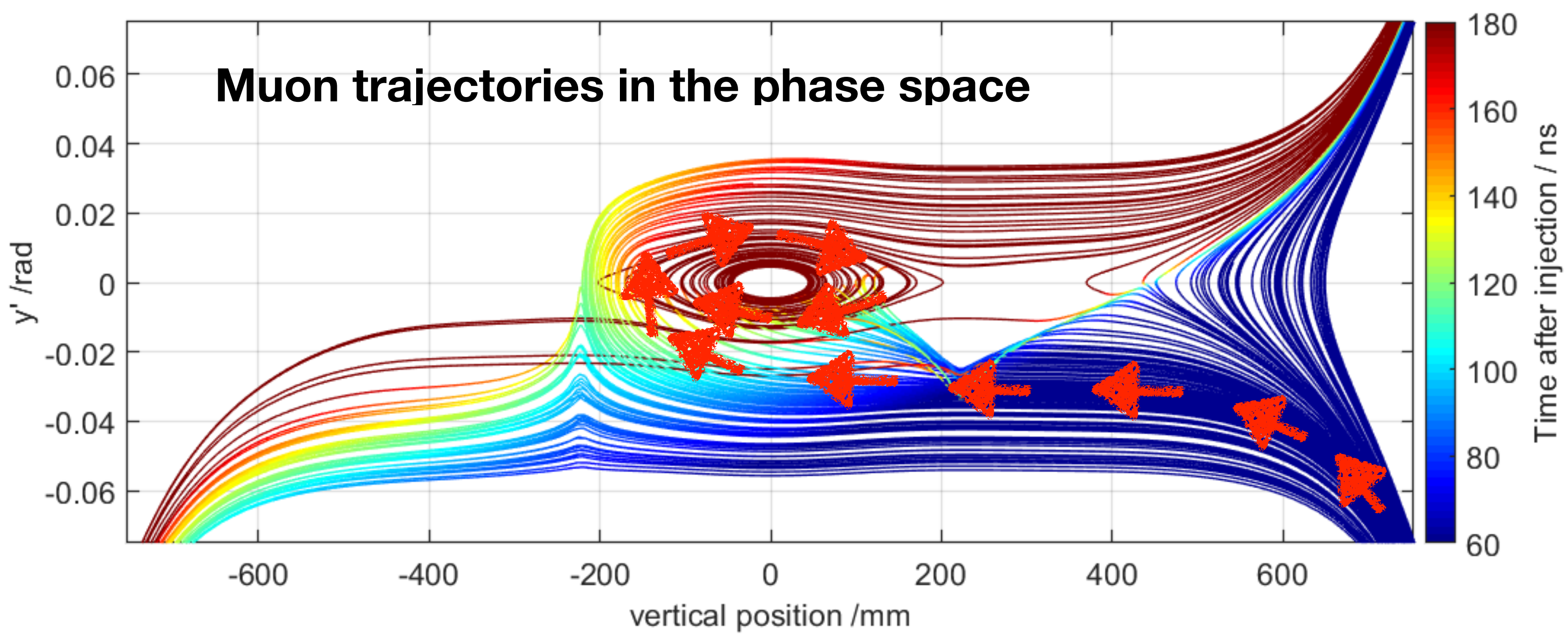




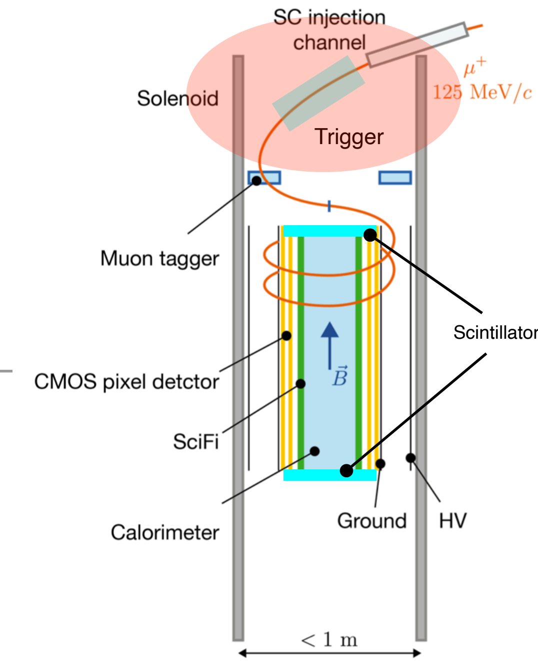
Generated initial phase space points

Initial phase space points of muons decaying in the central region

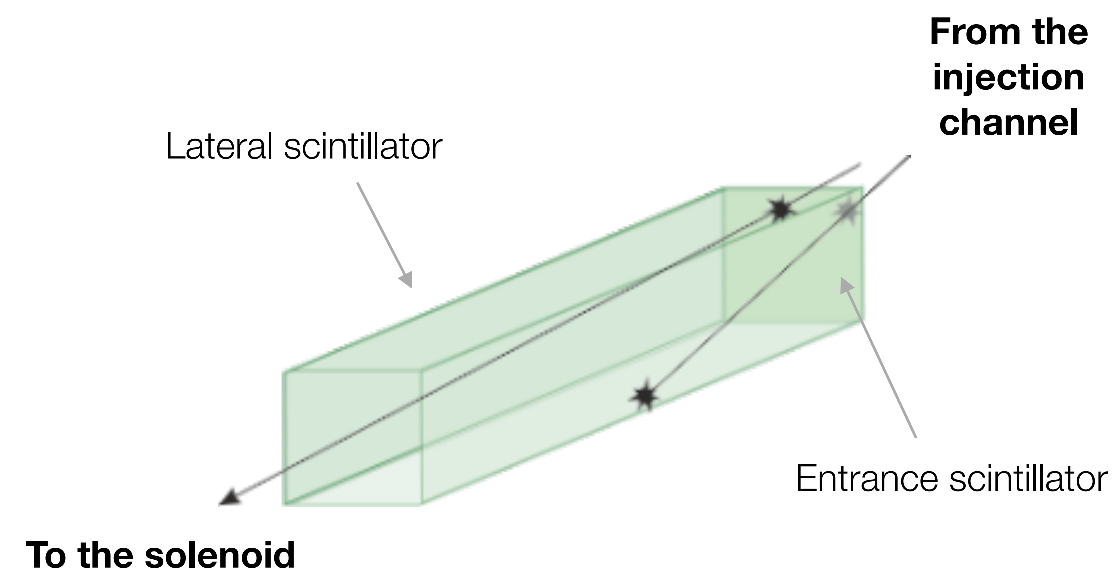
- **Efficiency ~ 5 x 10^{-4}**
- Detection rate ~ 50 kHz
- Looks promising, but still a lot of room for improvements.
- Contributions and new ideas are welcome!



The Detector — Entrance trigger



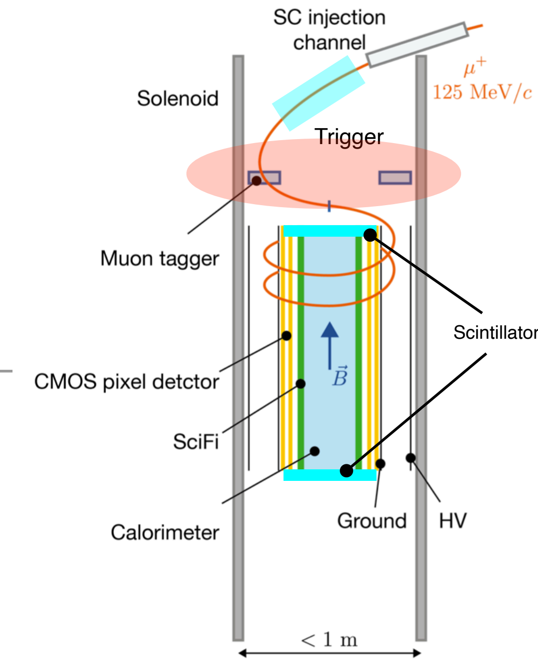
- A muon detector with reasonable timing performances (~ ns) is needed at the entrance to:
  - set the T_0 for the precession measurement
  - trigger the magnetic kick
  - start the measurement cycle
- O(10 MHz) muons pass the injection channel, only O(60 kHz) are in a phase space region that allows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



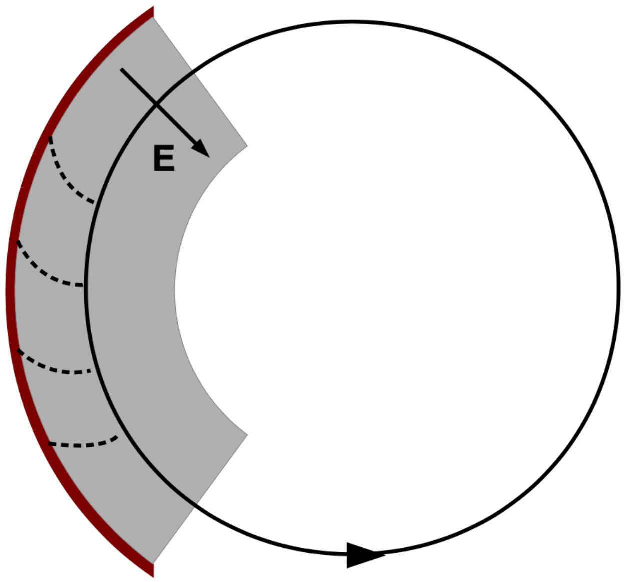
Anti-coincidence between entrance and lateral scintillators

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

The Detector — Muon tagger

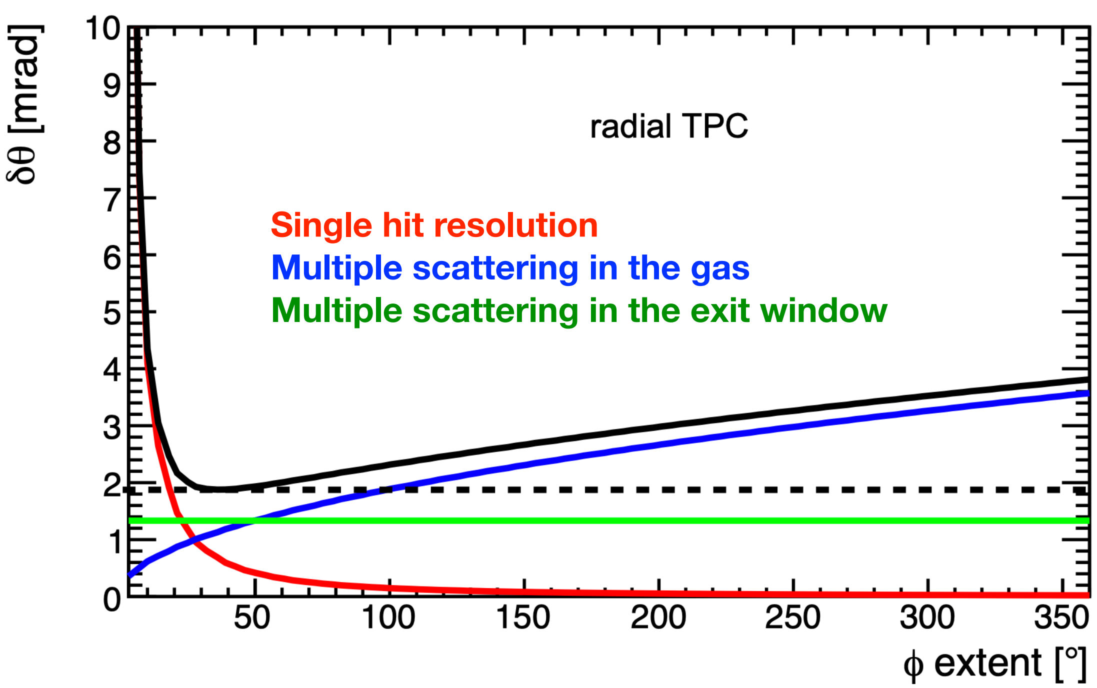


- Among triggered muons, there will be still some with a relatively large vertical angle in the measurement region
  - the measurement of the decay angle can be biased

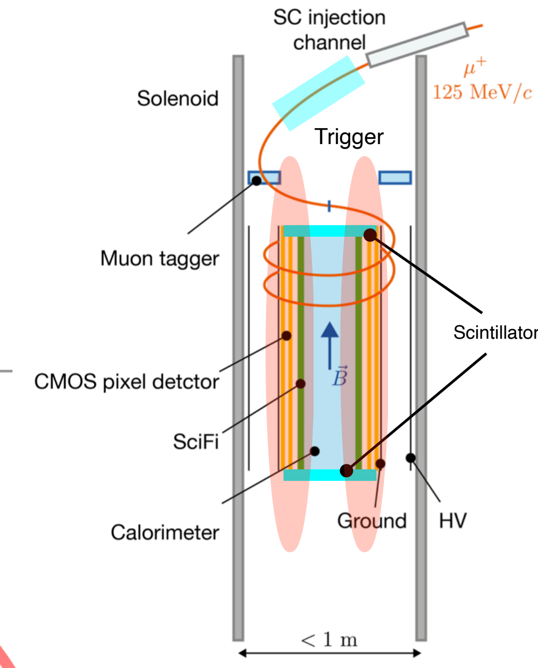


MPGD-based radial TPC

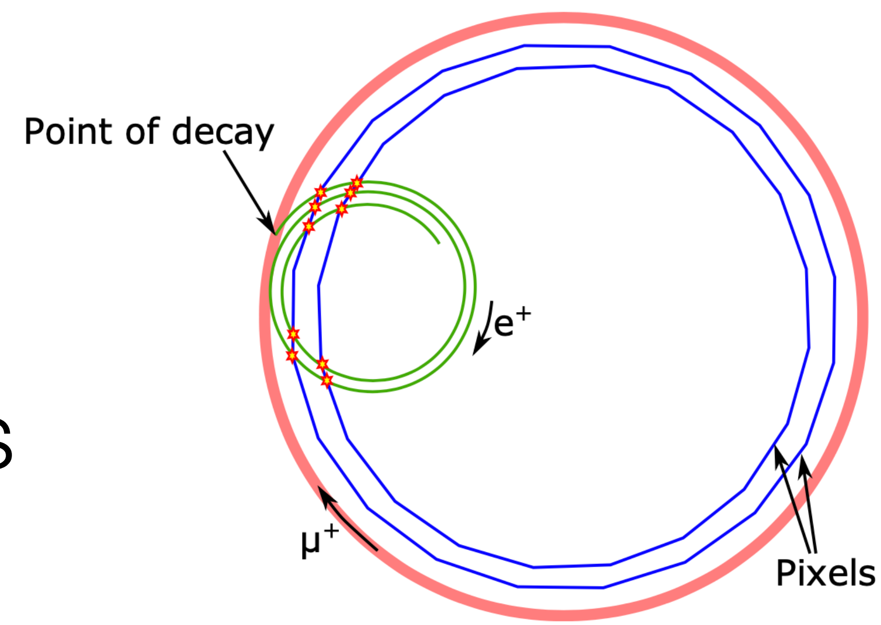
- A muon tracker/tagger can identify such events for a proper treatment
  - needs σ(θ) ~ 1 mrad —> very precise and very light

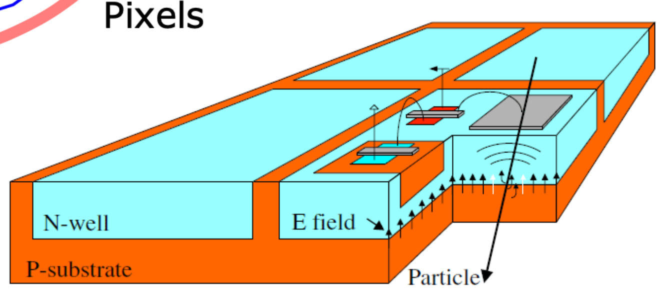


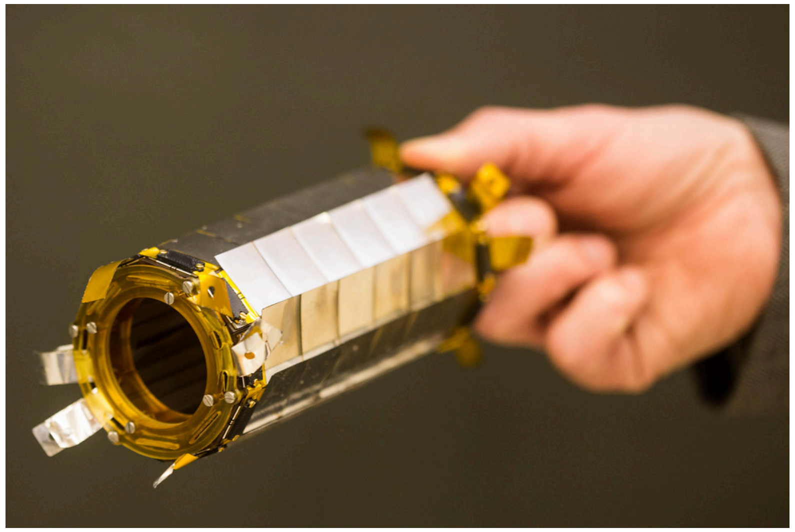
The Detector — Positron tracker



- 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 ($\mu^+ \to e^+e^+e^-$ @ PSI)

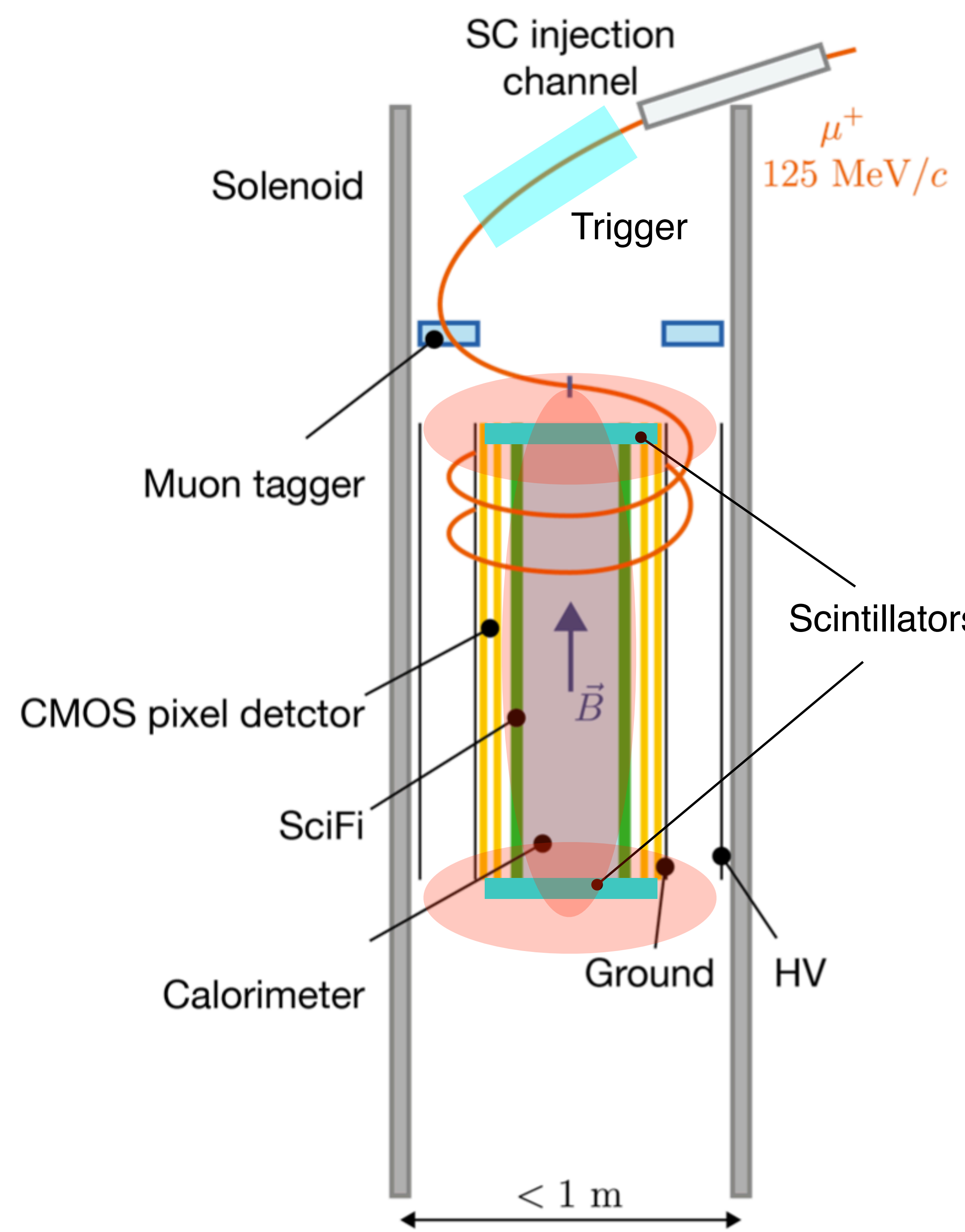






The Detector — End signals

- 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

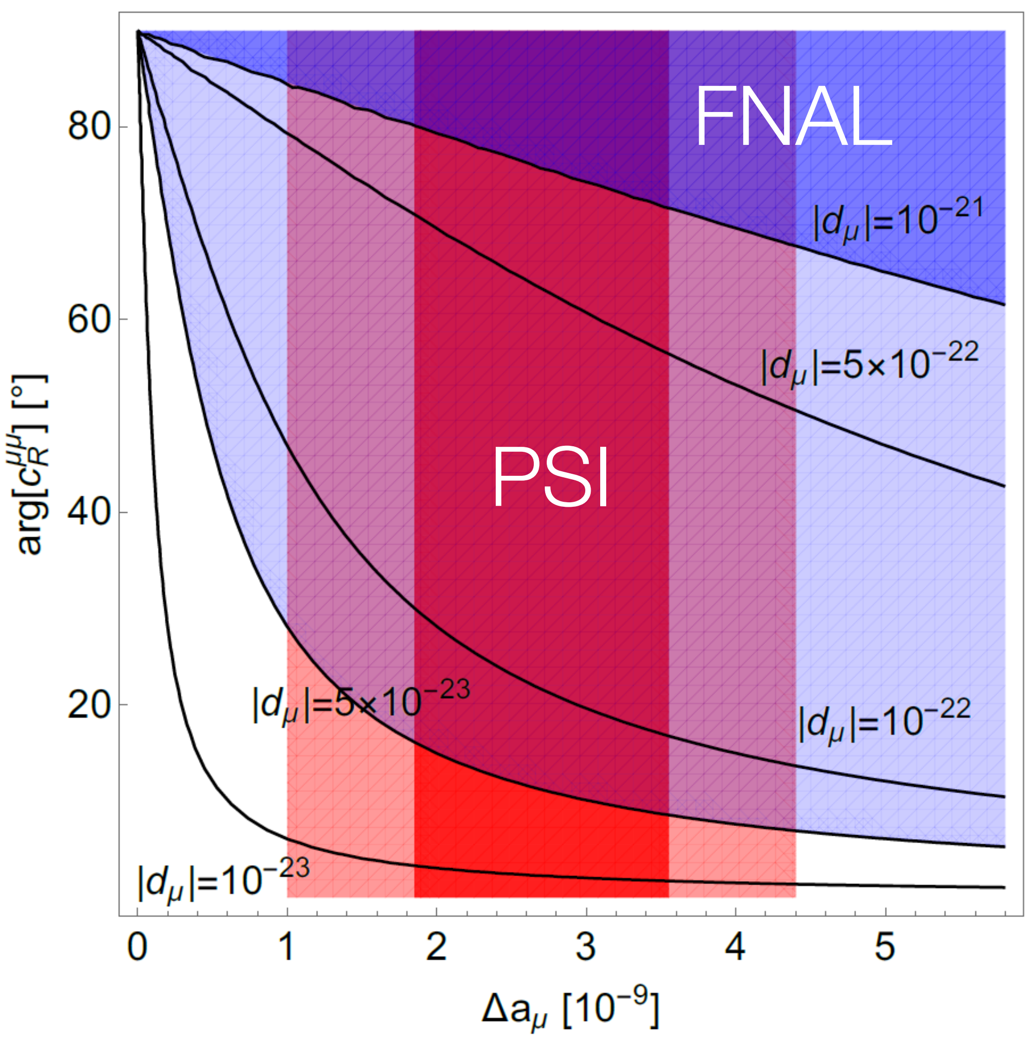
+

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
- $\alpha = 0.3$

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

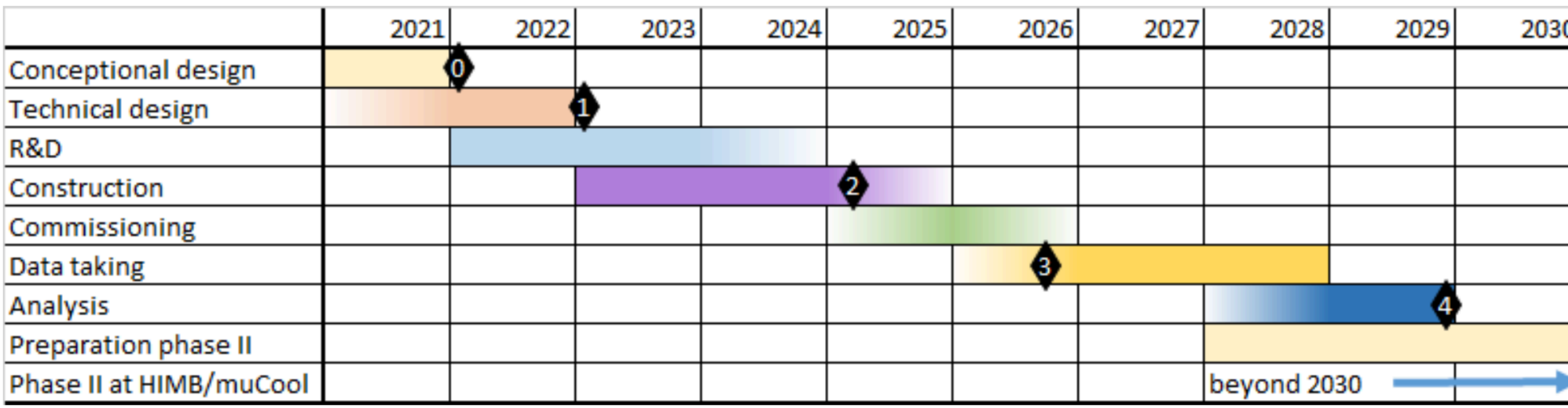


$$\sigma(|d_\mu|) \leq 6 \times 10^{-23} e \cdot \mathrm{cm}$$

Challenges

- Fast injection & injection trigger
- Field uniformity and characterisation
- Detectors in high E & B fields
- Minimal material budget
- …

Tentative Schedule



- An intermediate phase with a demonstrator to be installed on a medium-intensity beam line is being considered
  - the present limit could be challenged in a very short time scale
- PSI is considering an upgrade of the muon beam lines (HiMB, 10^{10} μ/s)
  - combined with innovative beam-cooling approaches (muCool), a much higher injection probability could be reached

Conclusions

- In a scenario where several hints of NP with LFUV are arising, a dedicated experiment to search for a muon EDM is highly desirable

- Excellent prospects for a ground-breaking muon EDM experiment at PSI within this decade

    - improving the present limit by 3 orders of magnitudes, down to 6×10^{-23} $e \cdot$ cm per year

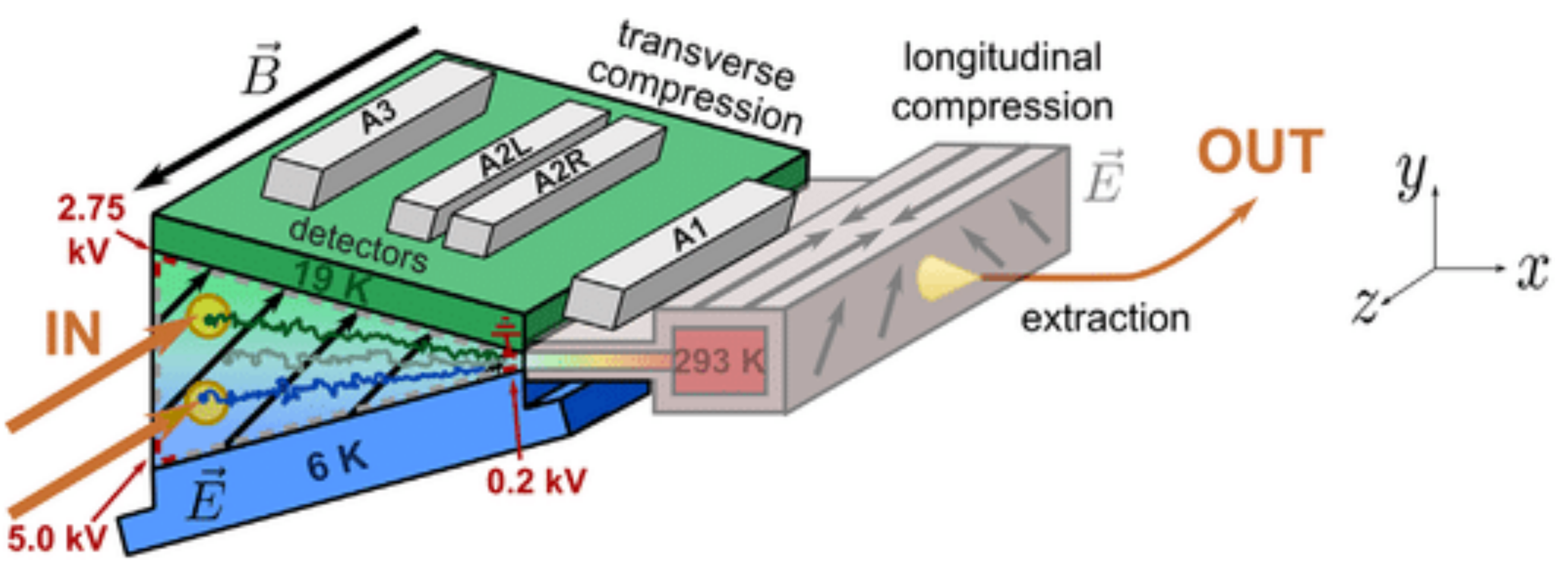
    - improving the expected limit from FNAL g-2/EDM by a factor 20

- Excellent long term prospects with the upgrade of the PSI beam lines

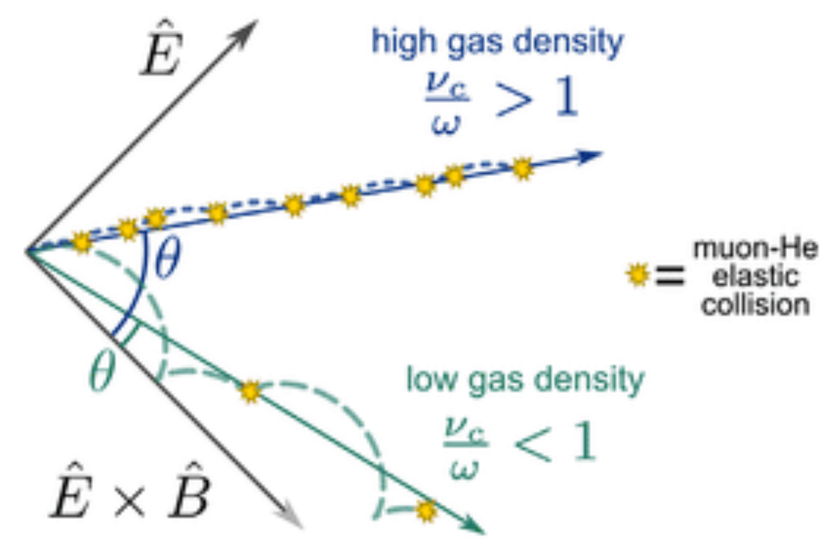
- Still in a conceptual design phase, many challenges to face, a lot of room for new ideas and new contributions

Backup

muCool



$\vec{B}$
transverse compression
longitudinal compression
A3
A2L
A2R
A1
detectors
19 K
2.75 kV
IN
6 K
$\vec{E}$
5.0 kV
0.2 kV
293 K
$\vec{E}$
OUT
extraction
y
x
z



$\hat{E}$
high gas density
$\frac{\nu_c}{\omega} > 1$
θ
θ
= muon-He elastic collision
low gas density
$\frac{\nu_c}{\omega} < 1$
$\hat{E} \times \hat{B}$

The HiMB Project @ PSI

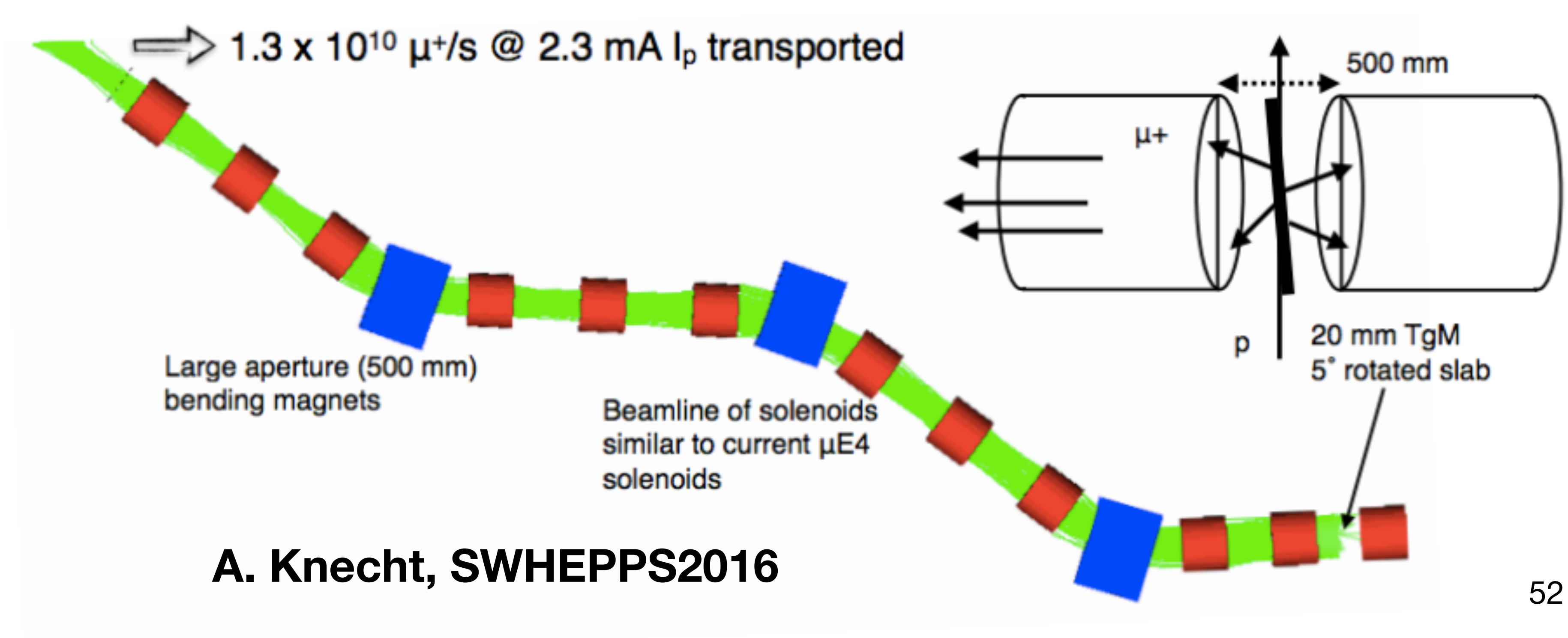
- PSI is designing a high intensity muon beam line (HiMB) with a goal of ~ 10^{10} μ/sec (x100 the MEG-II beam)
- Optimization of the beam optics:
  - improved muon capture efficiency at the production target
  - improved transport efficiency to the experimental area

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