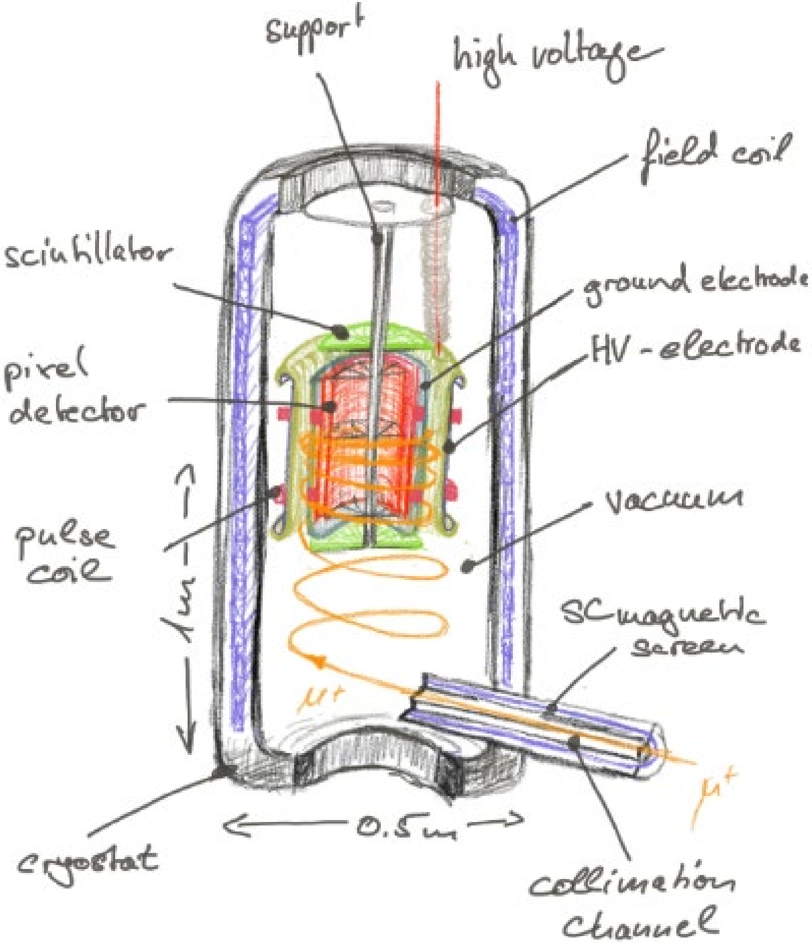
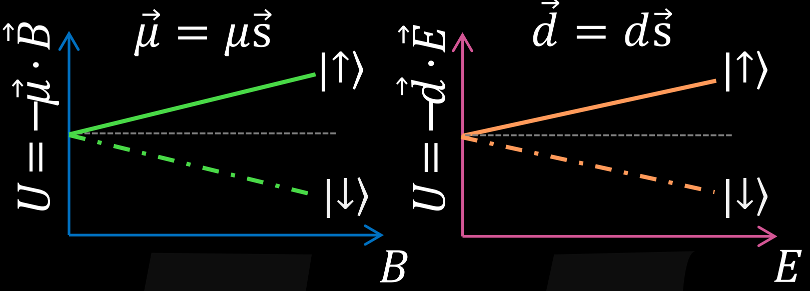
PAUL SCHERRER INSTITUT

P. Schmidt-Wellenburg

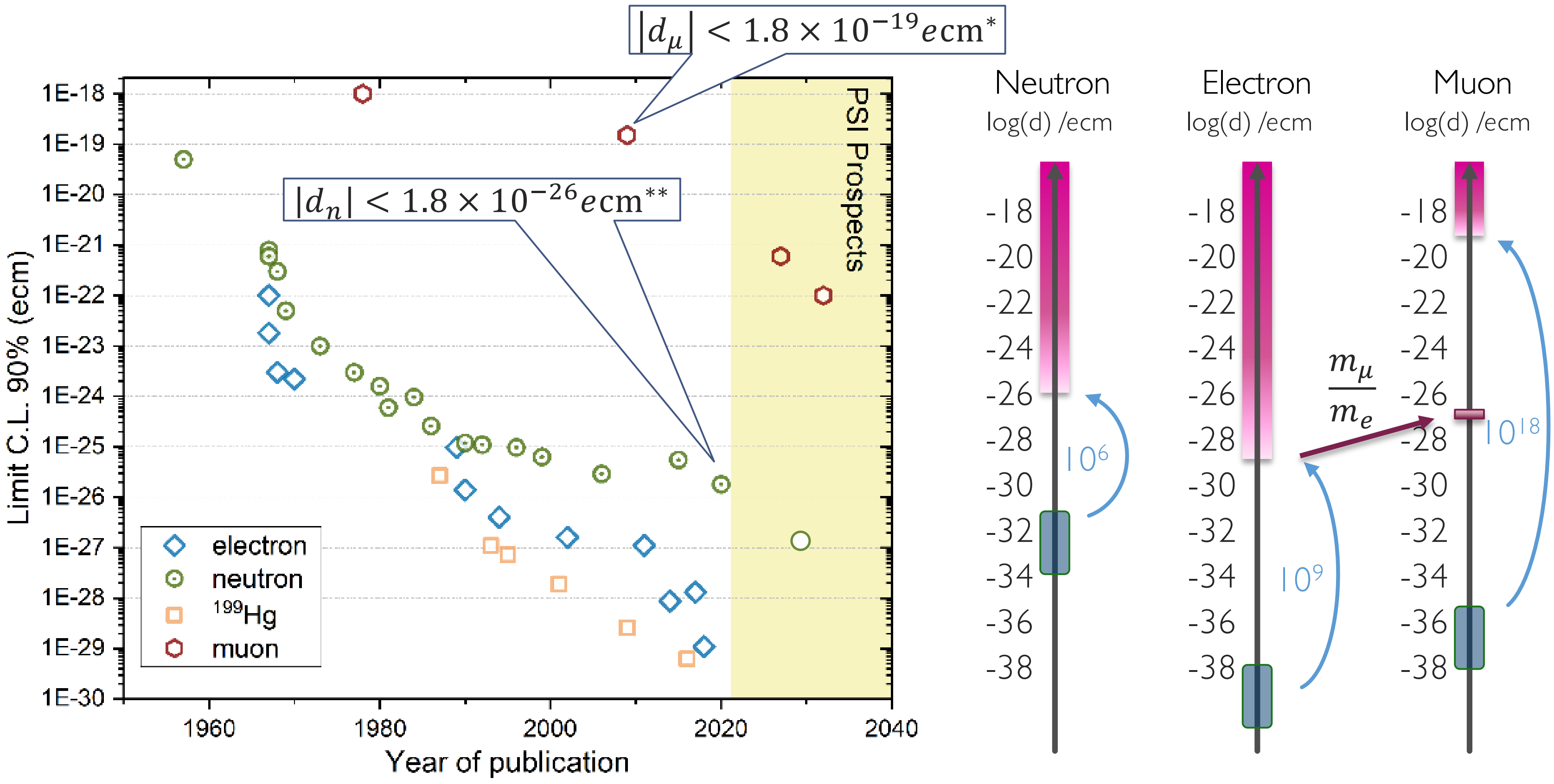
Search for the muon EDM at PSI



CP violation & edm



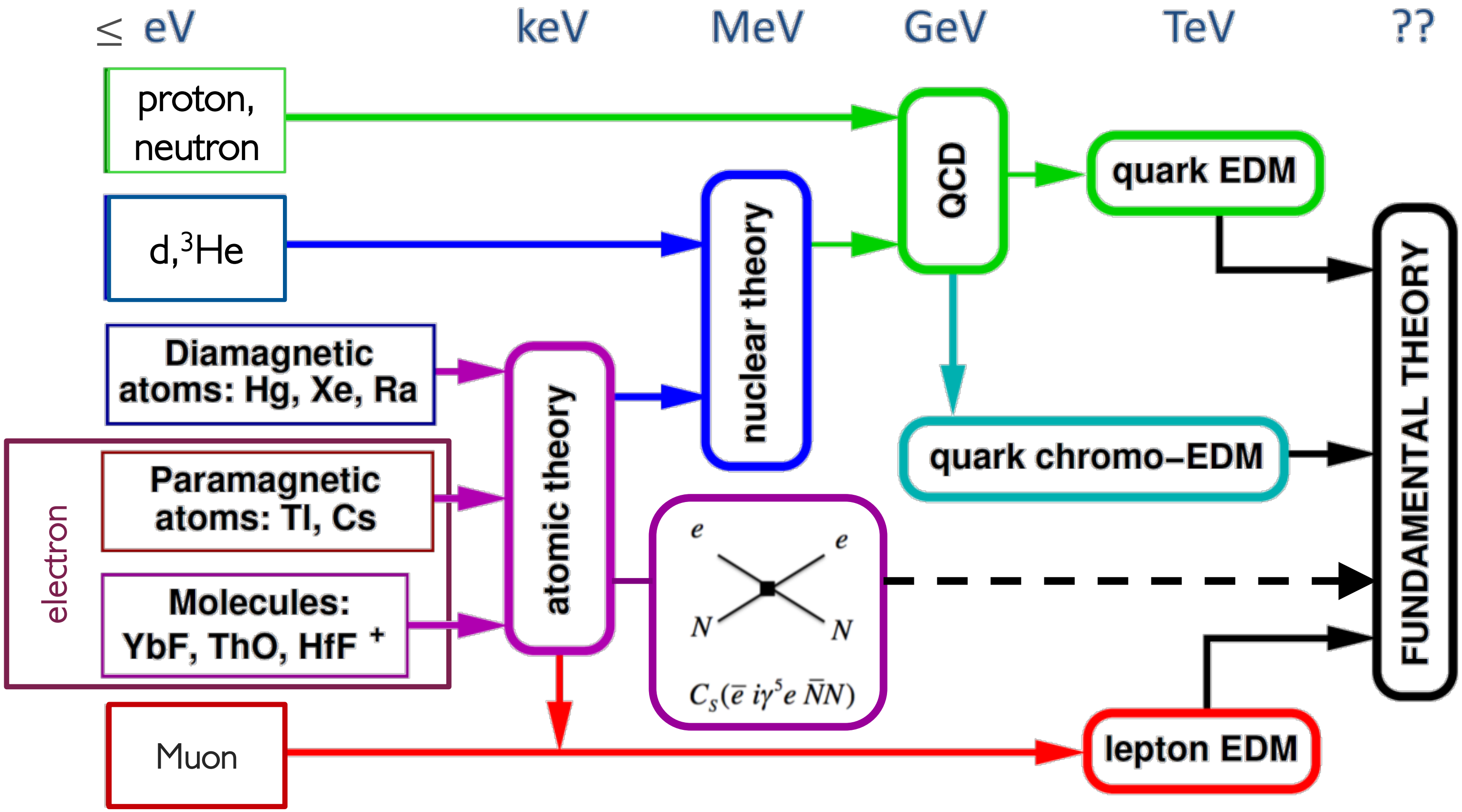
A brief history of EDM searches



*Bennett et al., PRD80(2009)052008

** Abel et al., PRL124(2020)081803

Complementarity of EDM searches

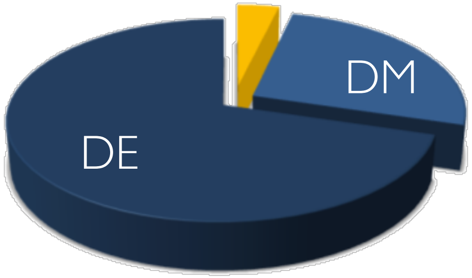


Scheme: adapted from Rob G. E. Timmermans

CP violation and hints for new physics

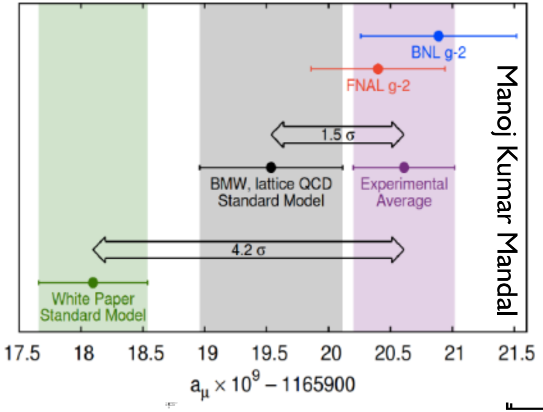
CP violation

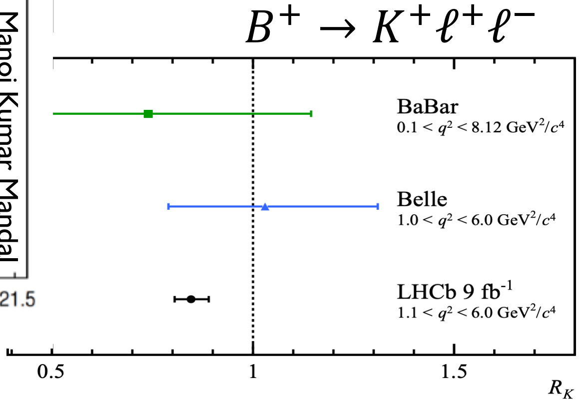
- Matter/Antimatter imbalance (BAU)
- Constituencies of dark matter (axions)
- Natural in many BSM theories



Laboratory hints for NP

- Muon g-2 $4.2\,\sigma$?
- LFUV in B decays
  - Individual channels up to $3.1\,\sigma$
  - Semileptonic decays combined: $> 5\,\sigma$





Corroborating evidence for NP
in muons

EFT analysis of contributions to F2 and F3

magnetic-dipole

Anapole - moment

$$\langle p'|J_\mu^{\mathrm{EM}}|p\rangle = \bar{\Psi}(p')\left[F_1\gamma_\mu + \boxed{\frac{iF_2}{2M}\sigma_{\mu\nu}q^\nu} + \boxed{\frac{iF_3}{2M}\sigma_{\mu\nu}\gamma_5 q^\nu} + \frac{F_4}{M^2}(q^2\gamma_\mu - \gamma^\mu q_\mu q_\mu)\right]\Psi(p)$$

charge

electric-dipole

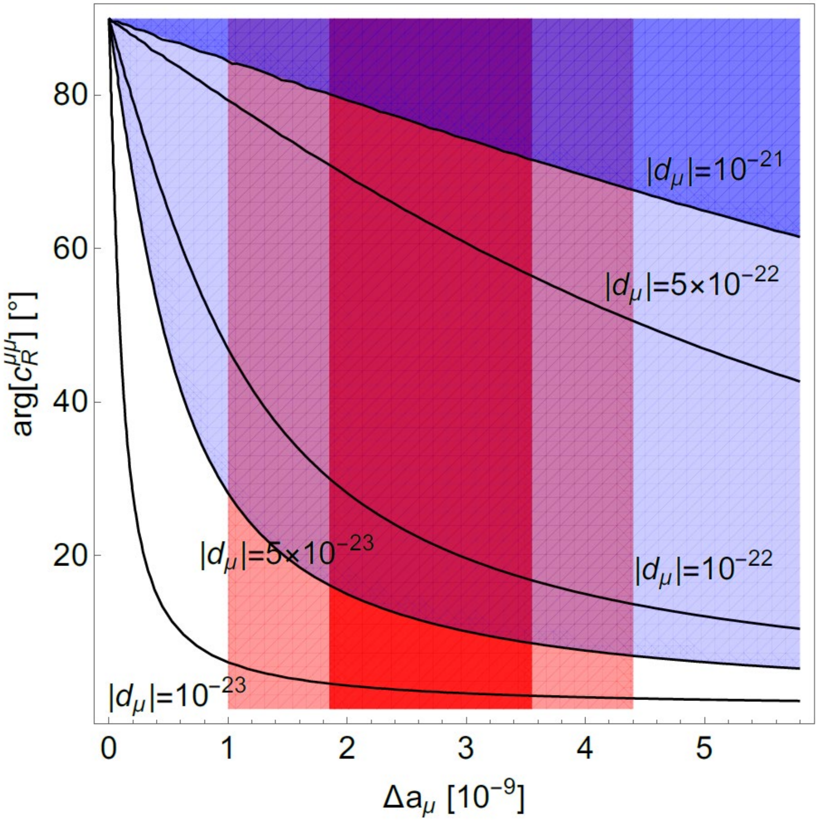
Effective Hamiltonian:

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

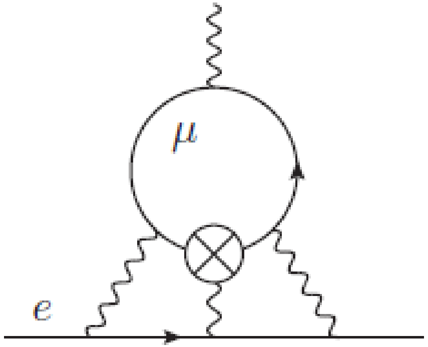
$$\delta F_2 = a_{\ell_i} = -\frac{2m_{\ell_i}}{e}\left(c_R^{\ell_i\ell_i} + c_R^{\ell_i\ell_i*}\right) = -\frac{4m_{\ell_i}}{e}\,\mathrm{Re}\,c_R^{\ell_i\ell_i}$$

$$F_3 = d_{\ell_i} = i\left(c_R^{\ell_i\ell_i} - c_R^{\ell_i\ell_i*}\right) = -2\,\mathrm{Im}\,c_R^{\ell_i\ell_i},$$

General limits on μEDM in flavor violating models



- EFT phase of Wilson parameter $c_R^{\mu\mu}$ hardly constraint

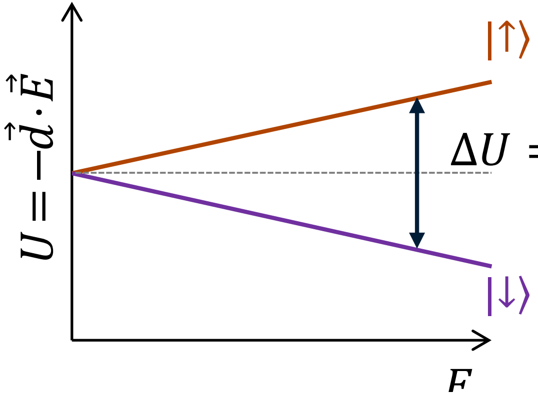


- μEDM contribution in electron EDM allows for large value: $d_\mu \leq 7.5 \times 10^{-19}\ e\mathrm{cm}$

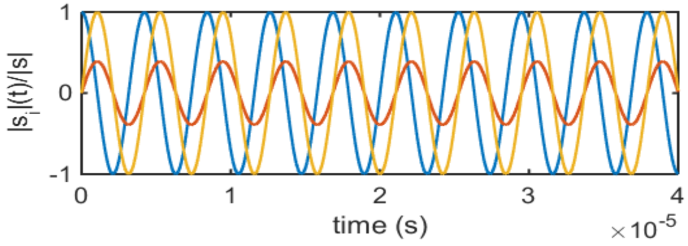
A.Crivellin, M. Hoferichter, PSW PRD 98(2018) 113002

Frequencies, state of the art, and the frozen spin

$$\vec{\omega} = \vec{\omega}_L - \vec{\omega}_c = -\frac{q}{m}\underbrace{\left[a\vec{B} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]}_{\text{g-2 term } \omega_a}$$

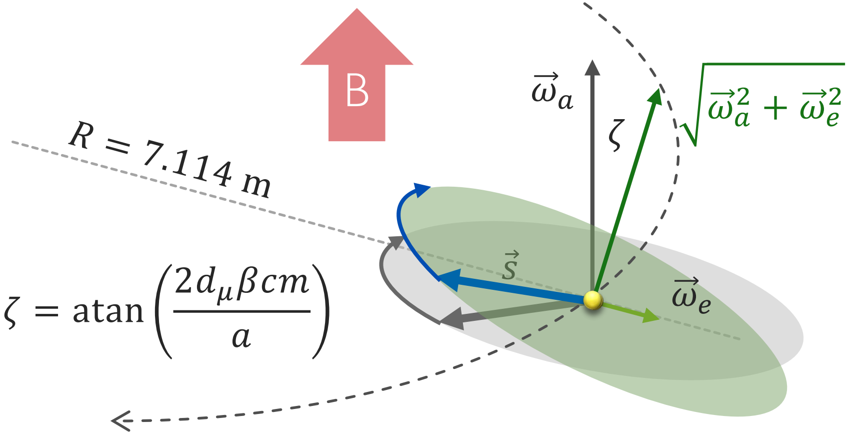


$$\Delta U = \hbar\omega_e = 2dE$$



$$\sigma(d_\mu) \approx 10^{-21} e\mathrm{cm}$$

FNAL* & JPARC**



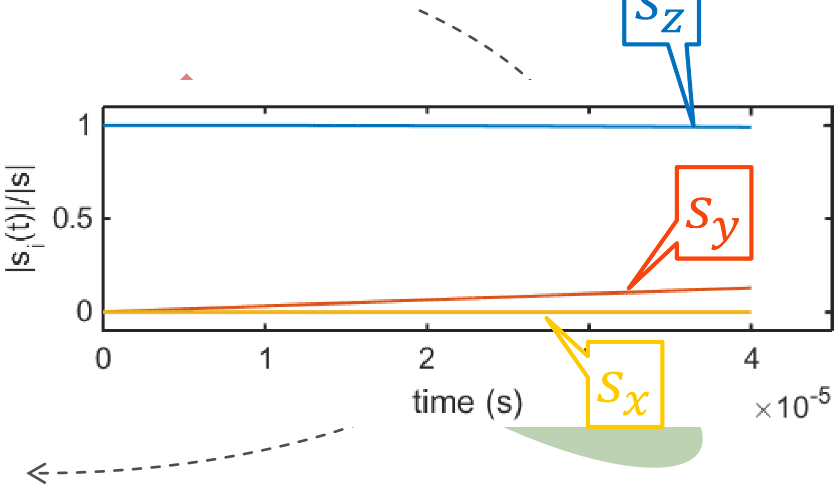
$$\zeta = \mathrm{atan}\left(\frac{2d_\mu\beta cm}{a}\right)$$

[*Chislett et al., EPJConf. 118 01005(2016), **Abe et al., PTEP053C02 (2019)]

State of the art and the frozen spin*

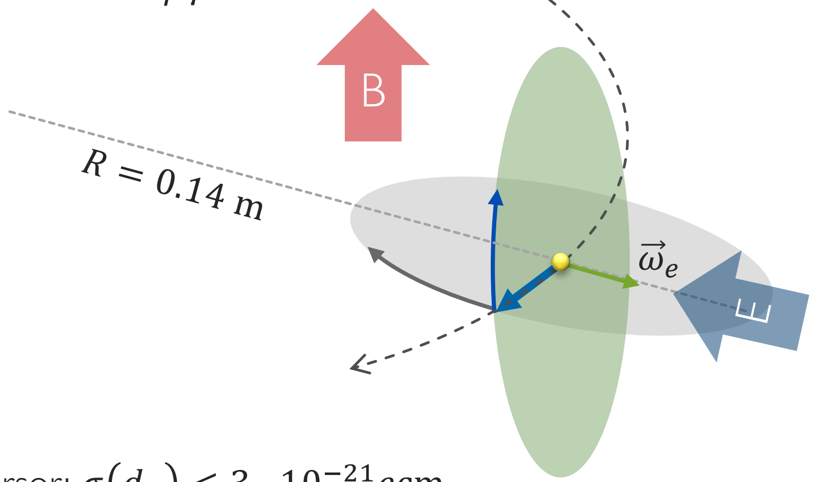
$$\vec{\omega} = -\frac{q}{m}\left[\underbrace{\cancel{a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}}_{\text{g-2 term } \omega_a} + \underbrace{\frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\text{EDM term } \omega_e}\right]$$

FNAL & JPARC $\sigma(d_\mu) \approx 10^{-21}$ m



Frozen spin at PSI: $\sigma(d_\mu) < 6 \cdot 10^{-23} ecm$

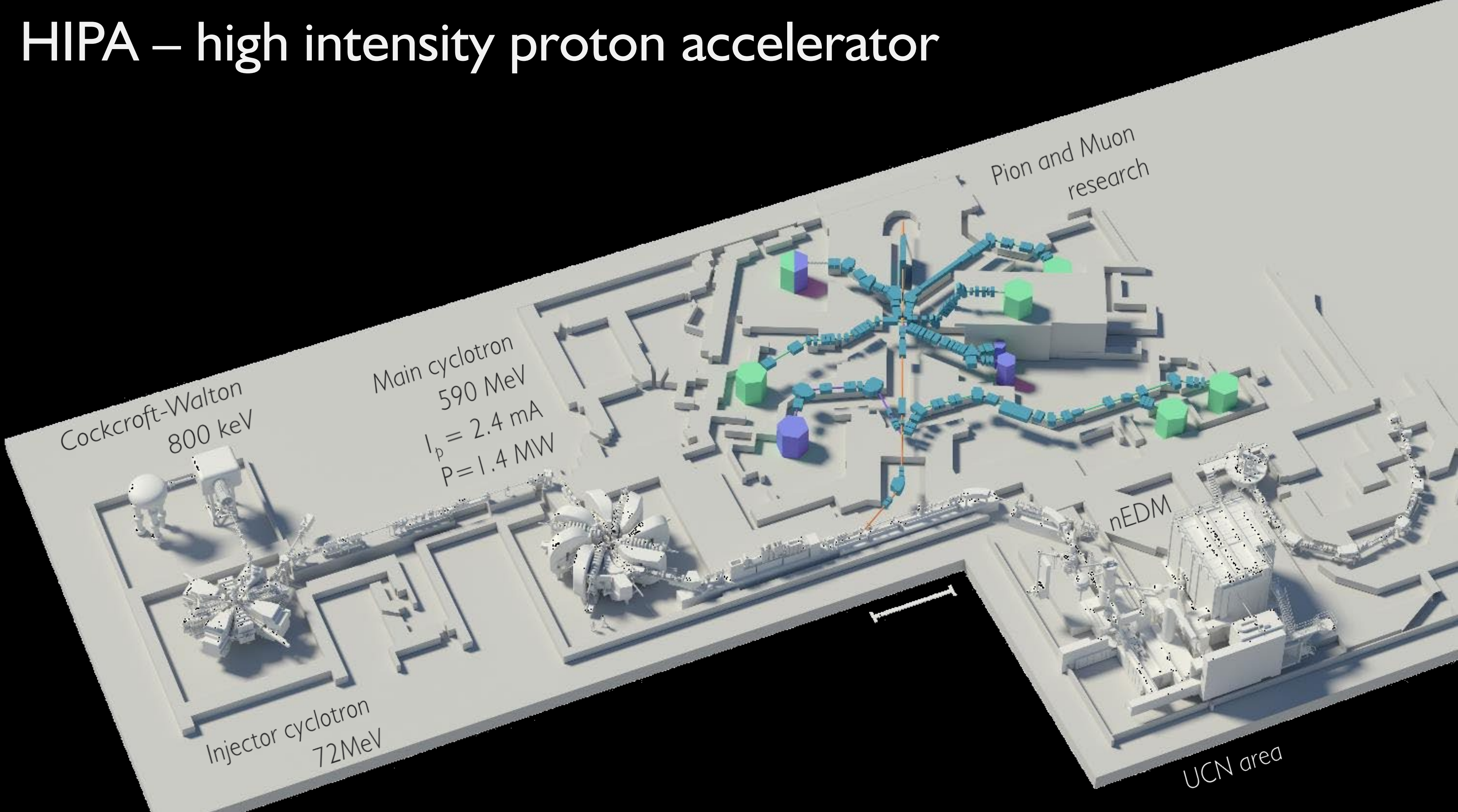
set $E \cong aBc\beta\gamma^2$



Prescursor: $\sigma(d_\mu) < 3 \cdot 10^{-21} ecm$

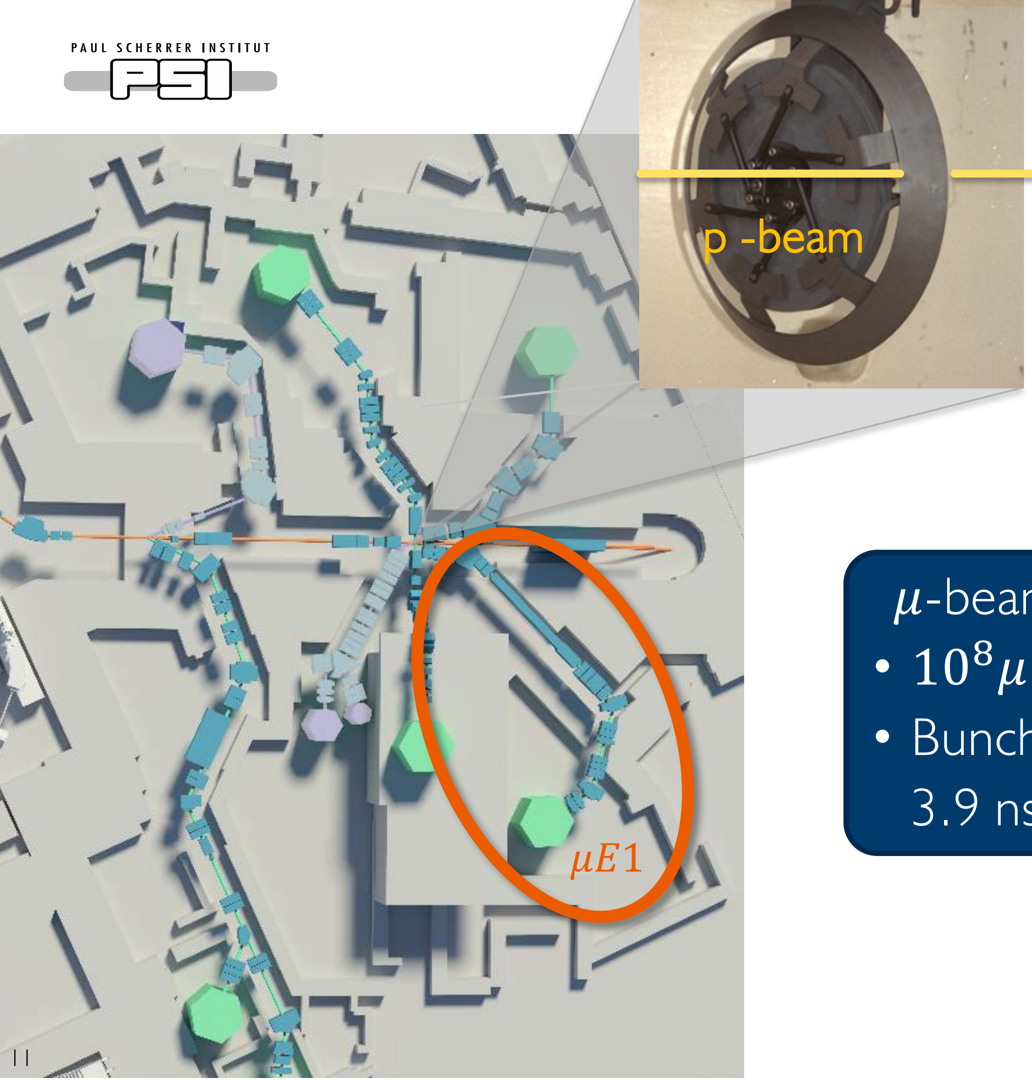
[*Farley et al,, PRL93 042001 (2004)] ,

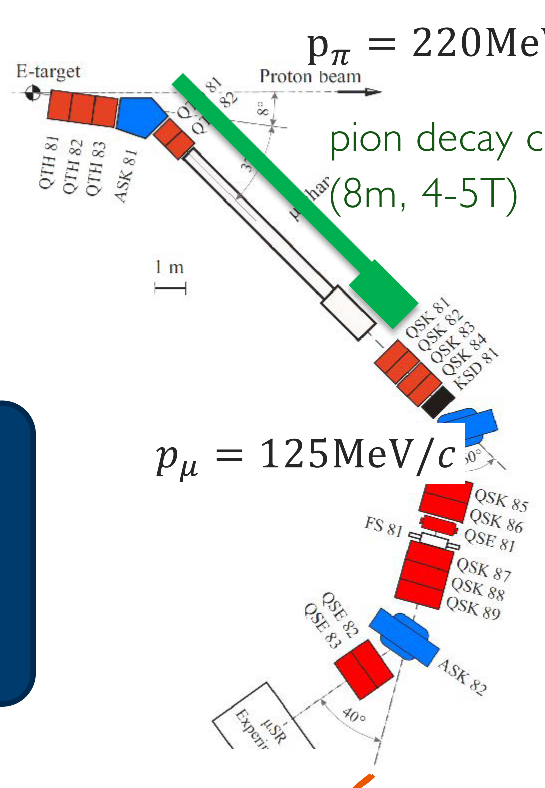
HIPA – high intensity proton accelerator



PAUL SCHERRER INSTITUT PSI

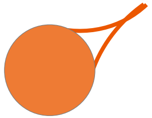
A search for a μEDM at PSI





μ-beam:

- $10^8 \mu^+/s$
- Bunch width 3.9 ns



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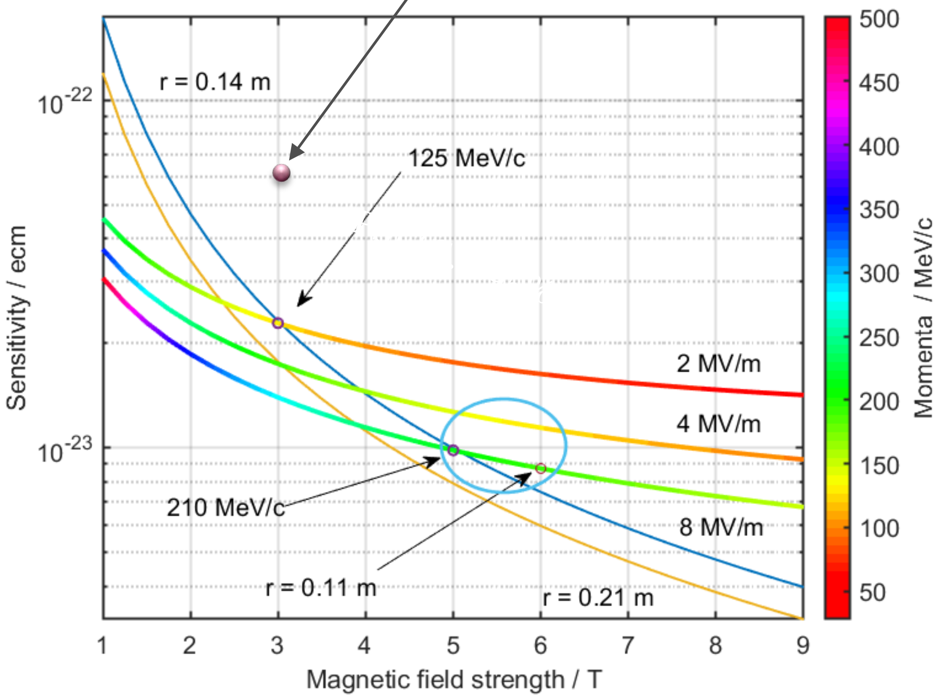
Sensitivity of muon EDM

$$\hbar\gamma a_\mu / (2PE_f\sqrt{N}\tau_\mu\alpha)$$

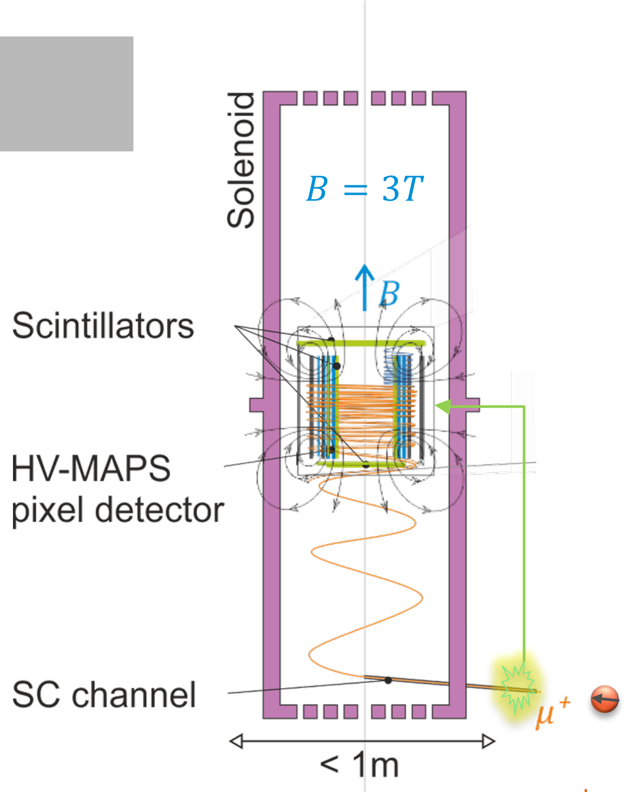
$$\boxed{E \cong aBc\beta\gamma^2}$$

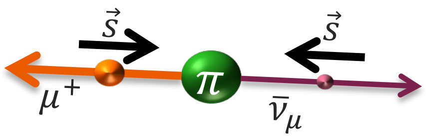


Muon on request (single muon at-a-time)

Gamma factor ($p_\mu = 125\mathrm{MeV}/c$)	γ	1.57
Initial polarization	P	0.95
Electric field ($B = 3T$)	E_f	2MV/m
Detection rate		45kHz
Mean decay asymmetry	α	0.3
Detections (200days)	N	5×10^{11}
$\sigma = \hbar\gamma a_\mu/(2PE_f\sqrt{N}\tau_\mu\alpha)$	$<$	6×10^{-23} ecm

Search for a muEDM using the frozen spin with longitudinal injection





μ^+ @ $125\mathrm{MeV}/c$

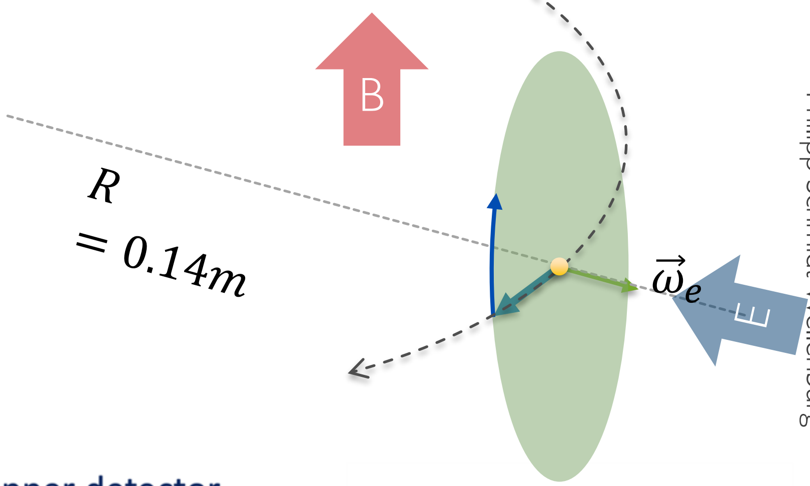
- μ^+ from **Pion-decay** → high polarization $p \approx 95\%$
- Injection through **superconducting channel**
- **Fast** scintillator **triggers** pulse
- Magnetic **pulse stops** longitudinal motion of μ^+
- Weakly focusing field for **storage**
- **Thin electrodes** provide electric field for **frozen spin**
- Pixelated detectors for e^+- **tracking**

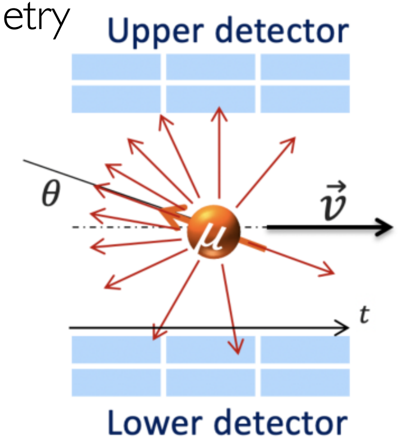
The general experimental idea

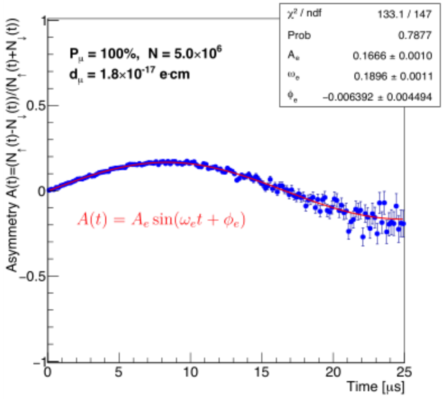
- If the EDM $\neq 0$, then there will be a vertical precession out of the plane of the orbit
  - An asymmetry increasing with time will be observed recording decay positrons

- If the EDM $= 0$, then the spin should always be parallel to the momentum – asymmetry should be zero

- Some asymmetry could still be observed due to systematic effects

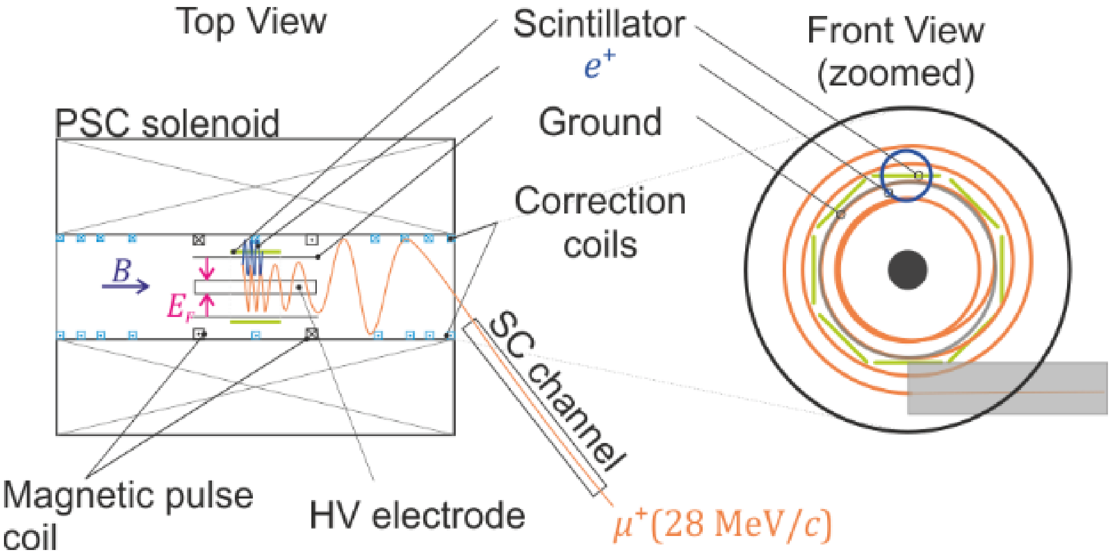






The muEDM precursor

Test bed and frozen spin demonstrator



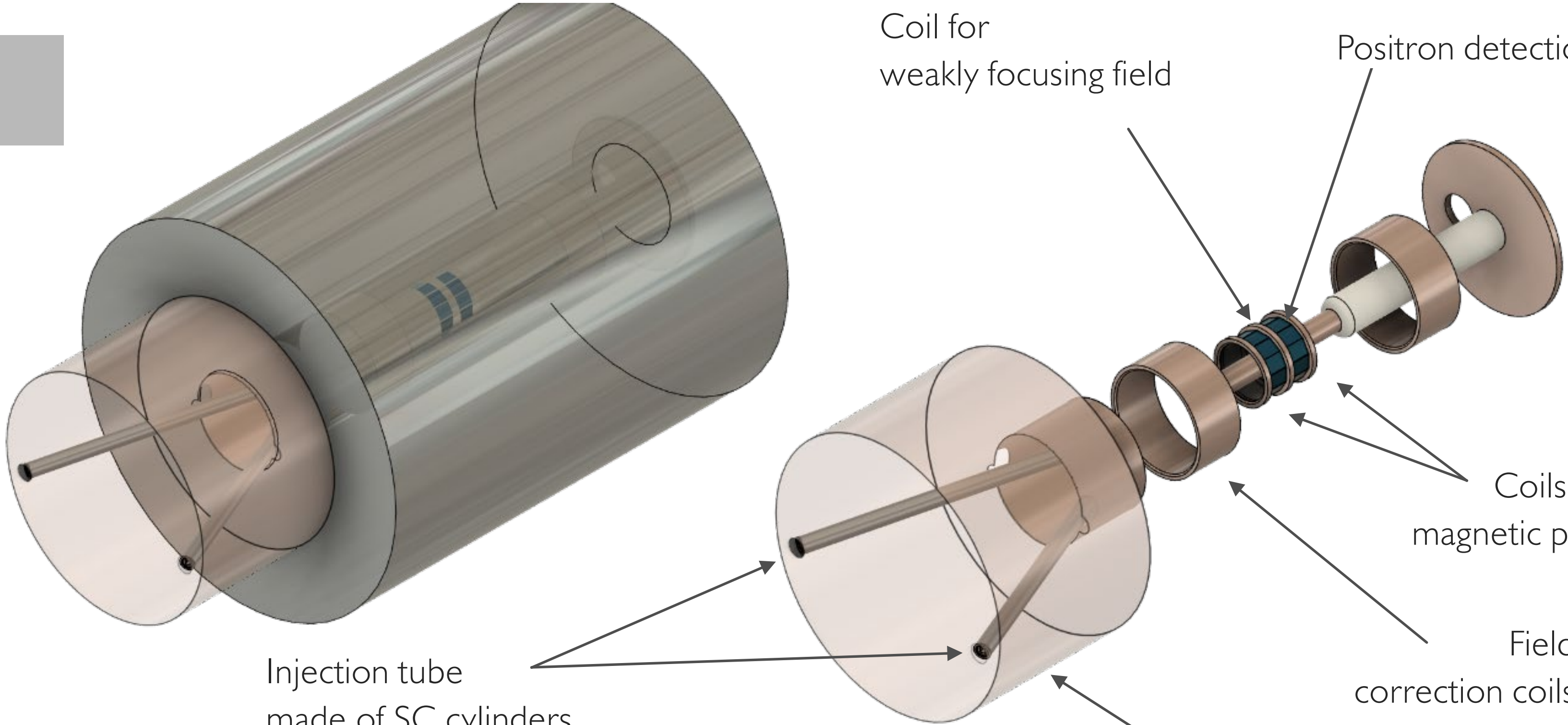
- muEDM measurement $< 3 \cdot 10^{-21} e\mathrm{cm}$

Sensitivity at PSI $\sigma(d_\mu) = \frac{\hbar \gamma a_\mu}{2 p E_\mathrm{f} \sqrt{N}\, \tau_\mu\, \alpha}$

Precusor $\pi E1$ ($p_\mu = 28$ MeV/c)		
muon beam rate		$2 \times 10^6\ \mathrm{s}^{-1}$
Collimation channel 50%		$1 \times 10^6\ \mathrm{s}^{-1}$
Injection **efficiency** 0.3%		3kHz
Gamma factor	γ	1.03
Initial polarization	P	0.95
Electric **field** ($B = 3T$)	E_f	0.3MV/m
e^+ **detection rate**		0.5kHz
Mean decay asymmetry	α	0.3
Detections **(200days)**	N	4×10^{11}
Sensitivity	$<$	$3\times10^{-21}\ e\mathrm{cm}$

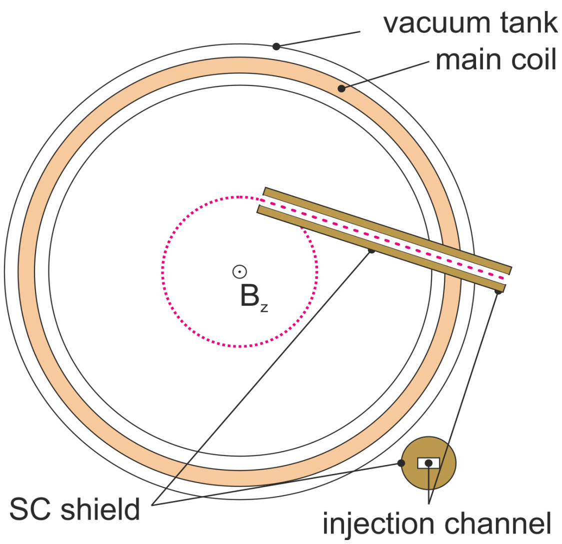
Final $\mu E1$ (125MeV/	
	$1.2 \times 10^8\ \mathrm{s}^{-1}$
0.5%	$0.6 \times 10^6\ \mathrm{s}^{-1}$
60%	480kHz
γ	1.77
P	0.95
E_f	2MV/m
	80kHz
α	0.3
N	10^{12}
$<$	$6\times10^{-23}\ e\mathrm{cm}$

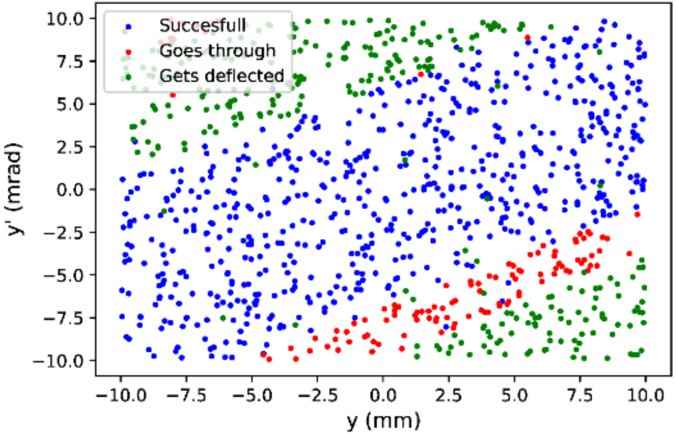
CAD view injection channel and



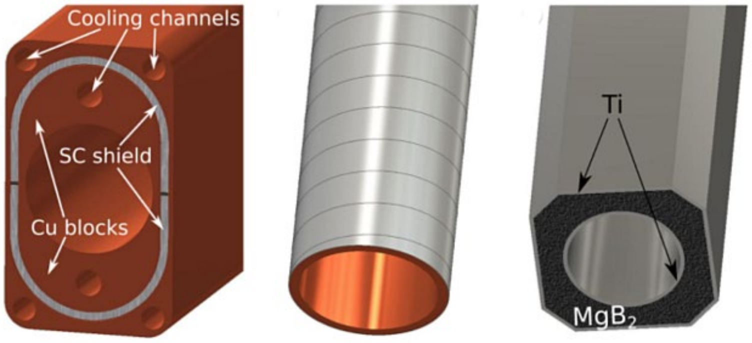
Injection channel

- Injection channel with SC magnetic shield
- Defines vertical and horizontal divergence

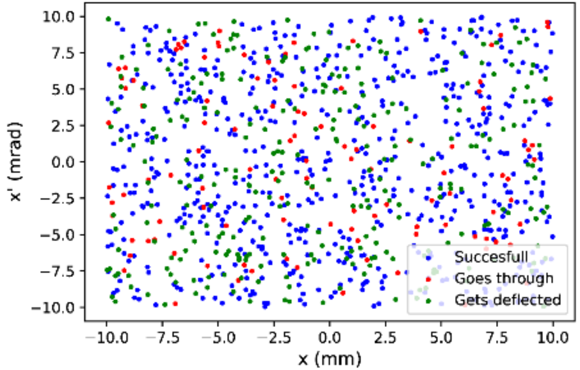




vertical



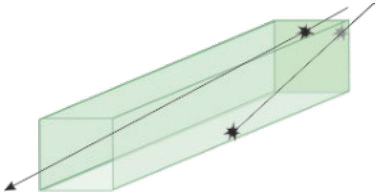
horizontal



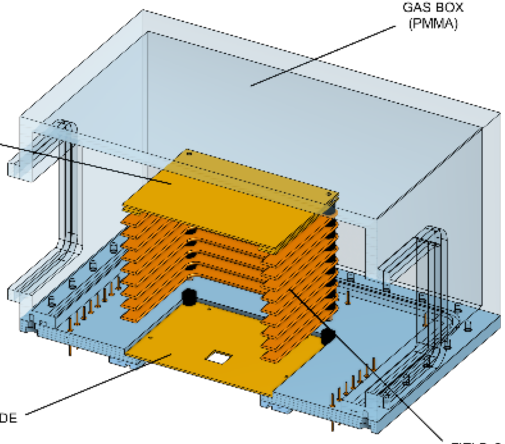
D. Barna et al., PR Acc. B 20 (2017) 041002
D. Barna et al., IEEE Trans. Appl. Supercond. 29 (2018) 4900108.
D. Barna et al., IEEE Trans. Appl. Supercond. 29 (2018) 4101310.

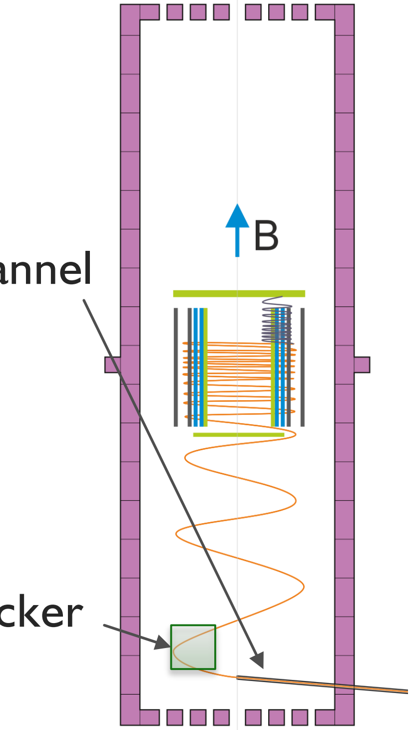
Open questions:

- Collimation efficiency using scintillating channel for anti-coincidence trigger
  - Specular reflections on scintillator

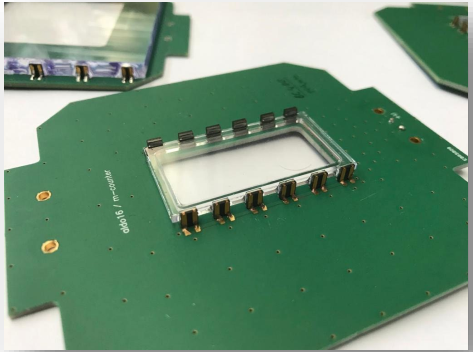


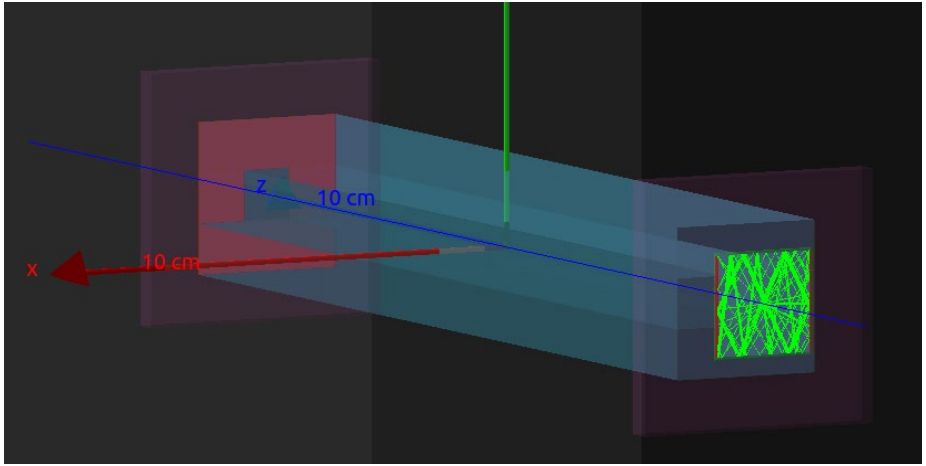
- Efficiency of muon tagger/tracker
  - Track resolution
  - Multiple scattering on gas and windows

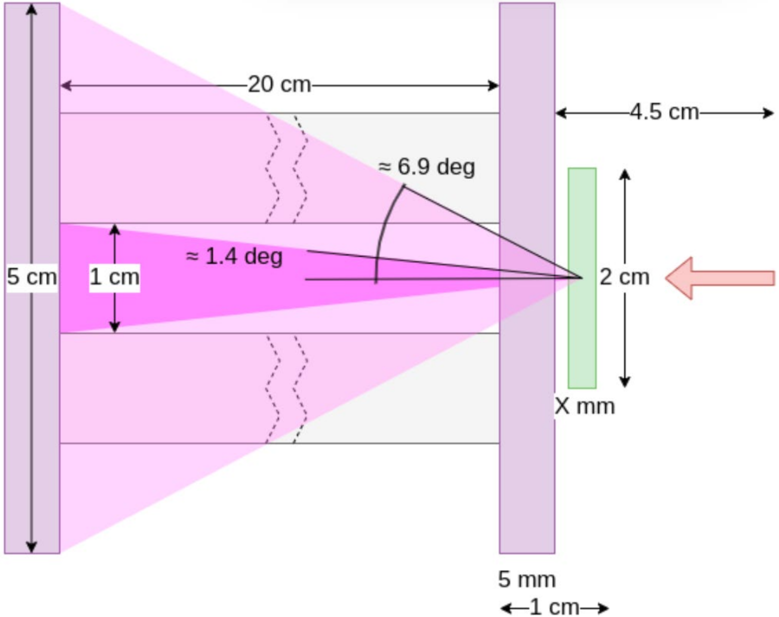




Test of entrance trigger Nov. 22

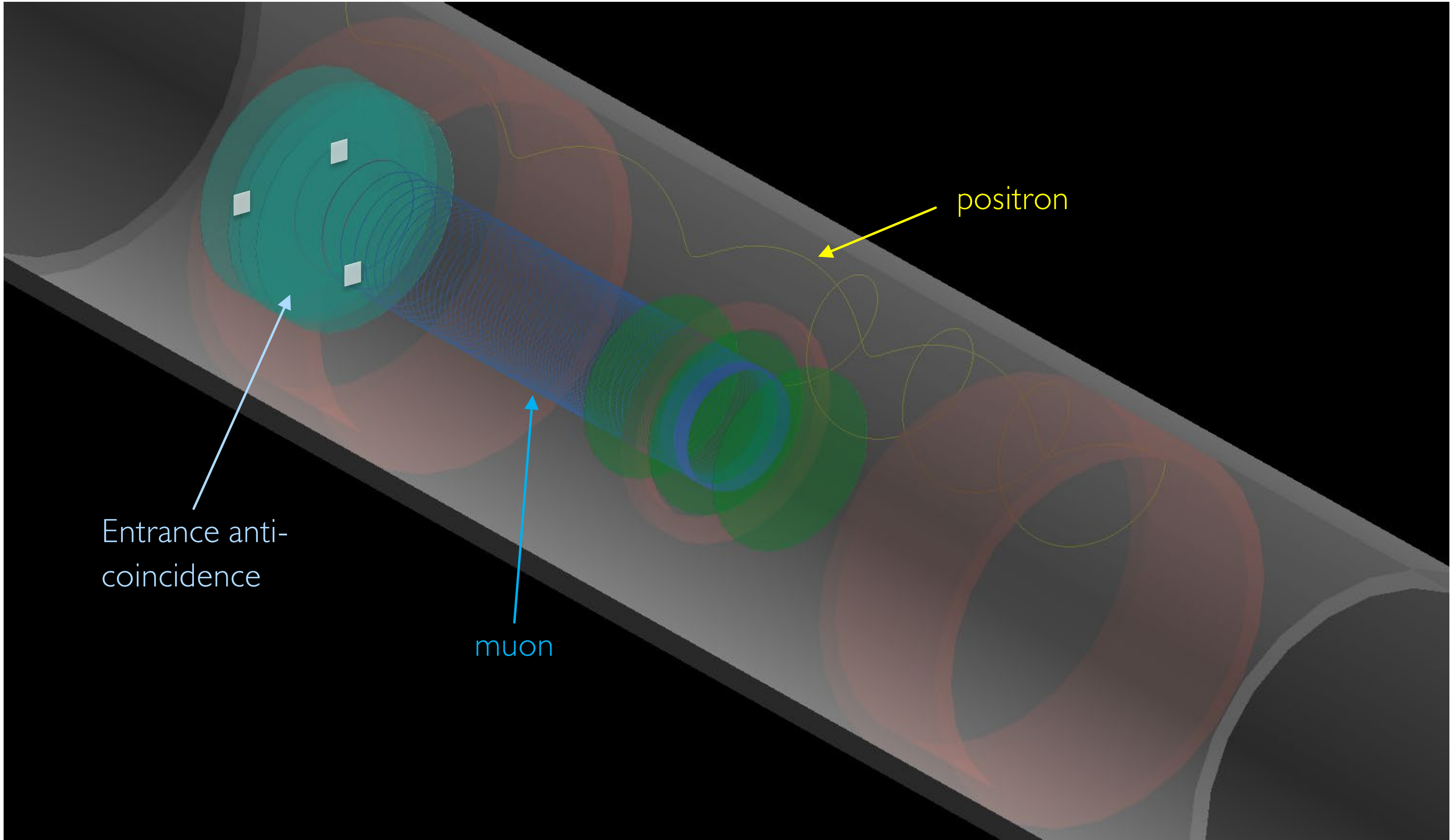




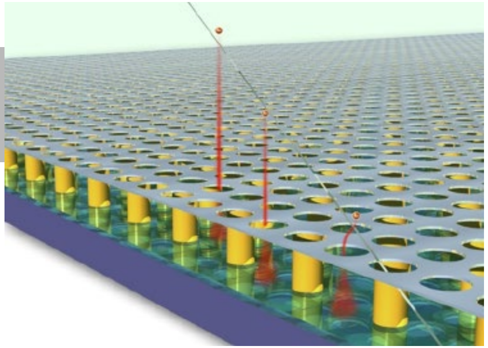


- Entrance scintillating window $20 \times 20\ \mathrm{mm}^2$
- Collimation channel $10 \times 10\ \mathrm{mm}^2$
- Anticoincidence side walls of channel
- Window test with different thickness $(20, 30, 50;\ 300, 600, 1000 \mu\mathrm{m})$

Spiral entrance veto and storage simulation



Muon tracker prototype (TPC)

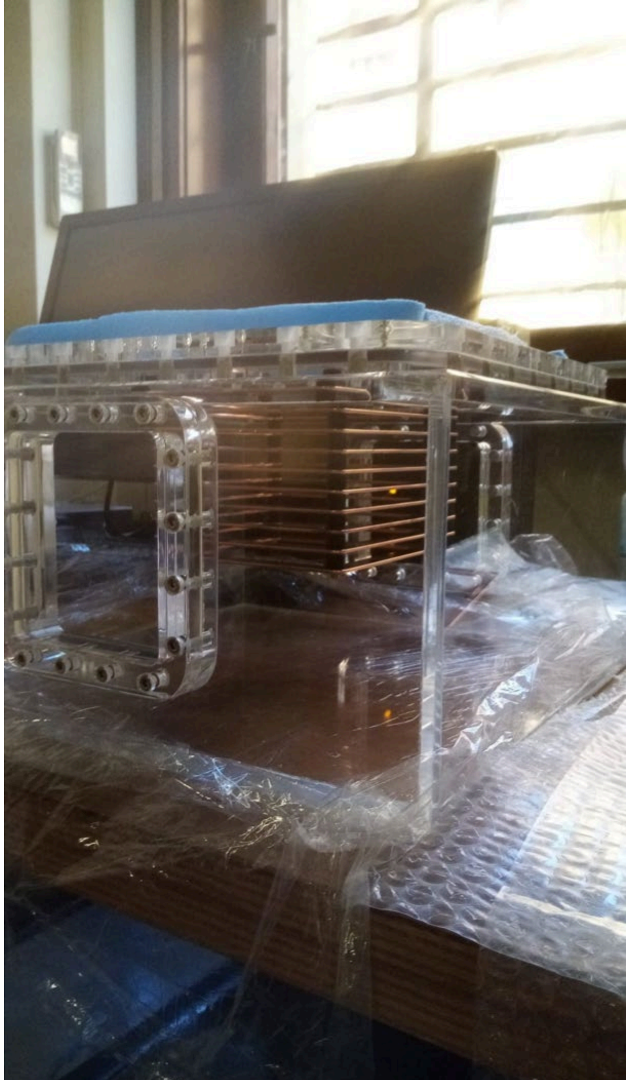


TPC with very high granularity readout based on the GridPix chip

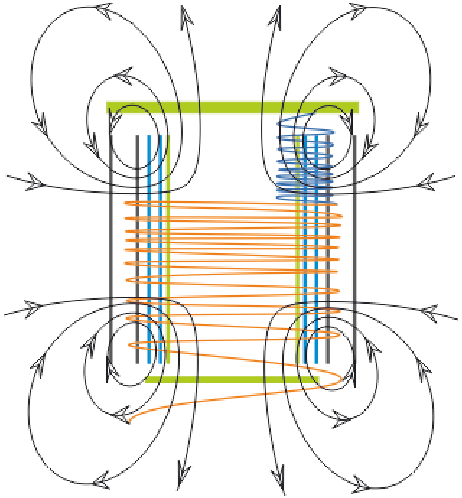
- Helium-based gas mixture
- minimize multiple
- no literature on GridPix with helium mixture

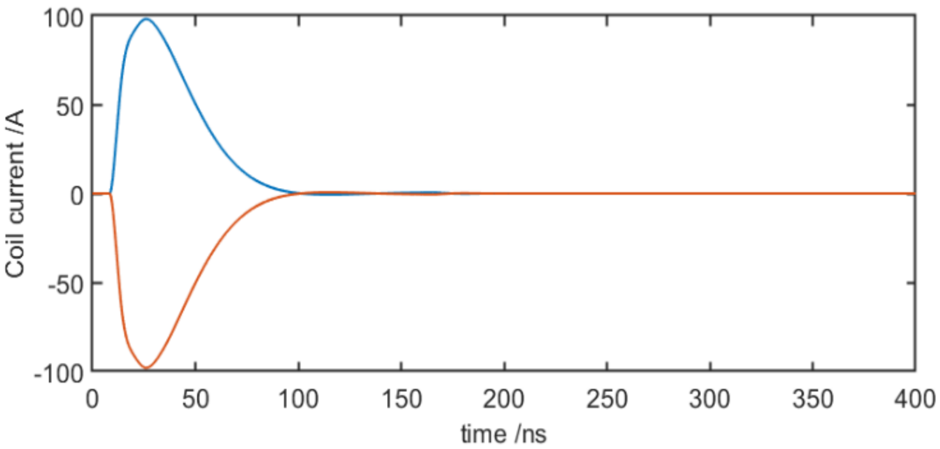
The TPC is under construction at INFN Roma

– gas box, field cage and cathode ready for assembly
– anode and readout board under design in collaboration with Bonn University
– procurement of DAQ electronics (CERN SRS) ongoing

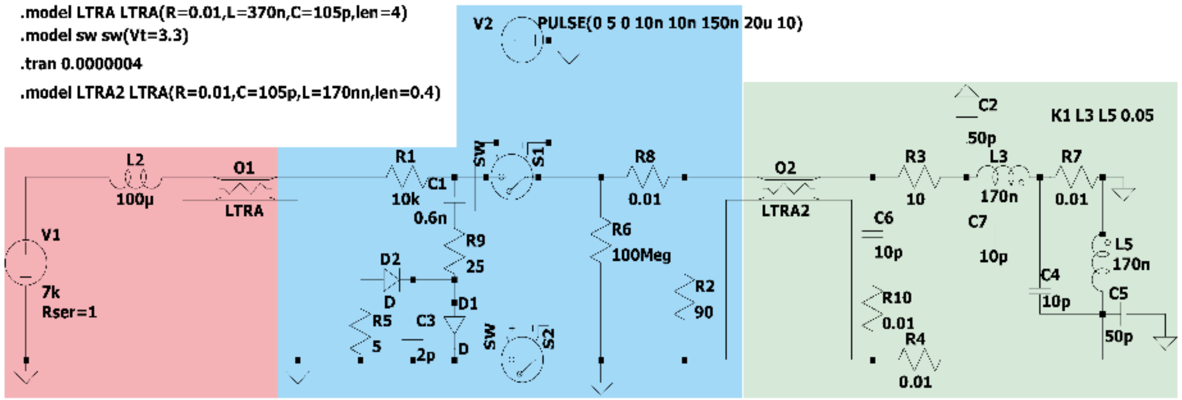


Radial magnetic field pulse to kick muons

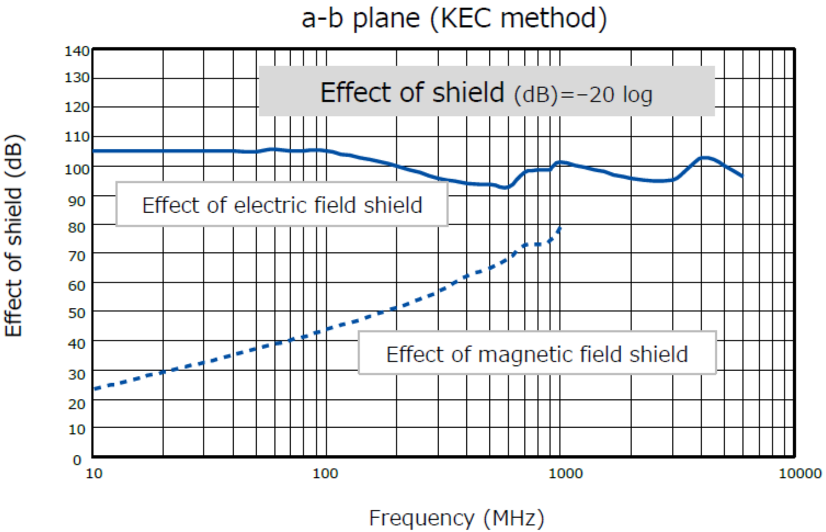




- Pulse width $\Delta t \approx 100$ ns
- Delay between trigger and pulse peak $\Delta t_d \approx 105$ns
- Peak current 60A
- Eddy current damping by electrodes?



Eddy current damping of magnetic pulse



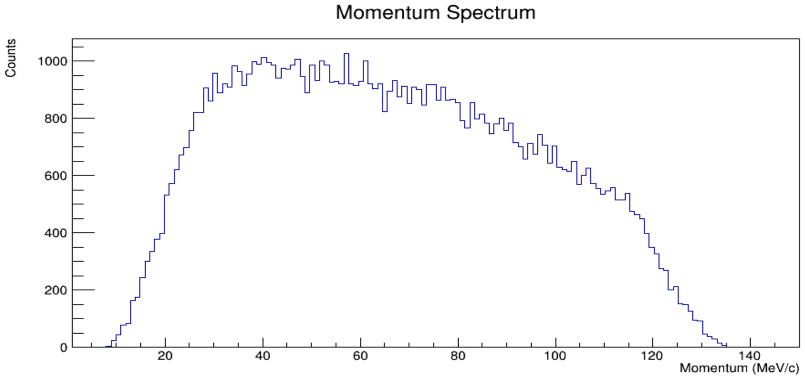
- Exist off the shelf without substrate down to **17µm**
- Still considerable damping of magnetic pulse possible
- Tests requires
- Alternative one dimensional wires (carbon fibers / tungsten)

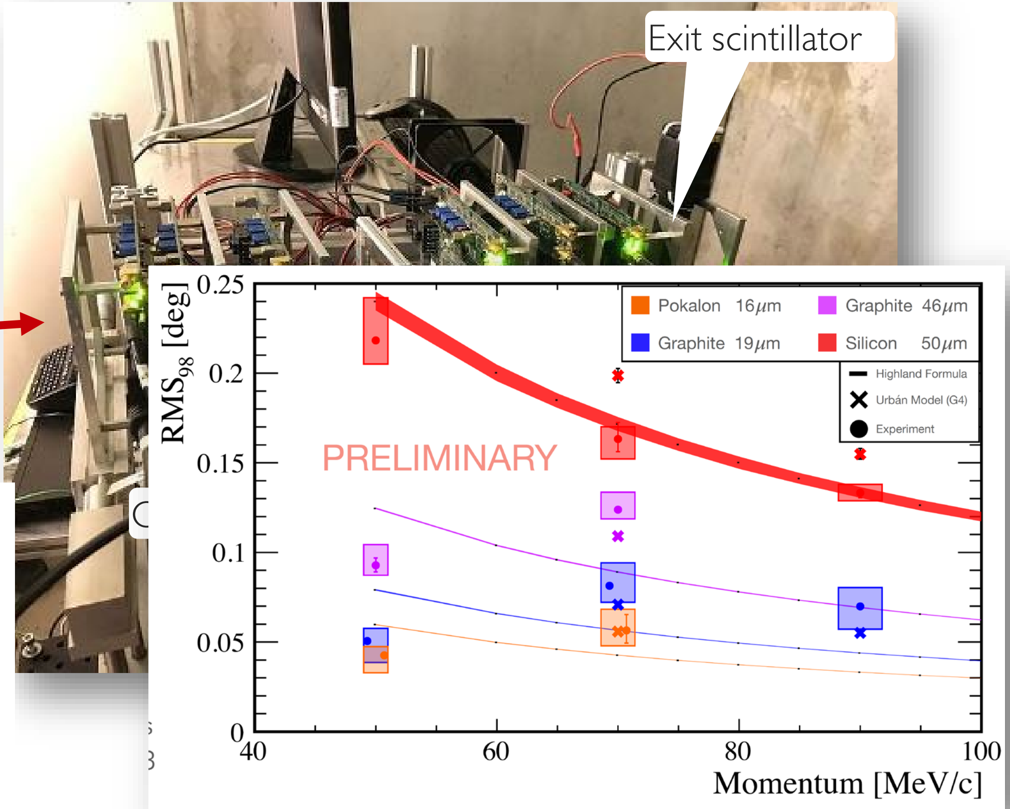
Multiple scattering measurement on carbon

- Characterization of potential electrode material with positrons and muons

μ^+, e^+

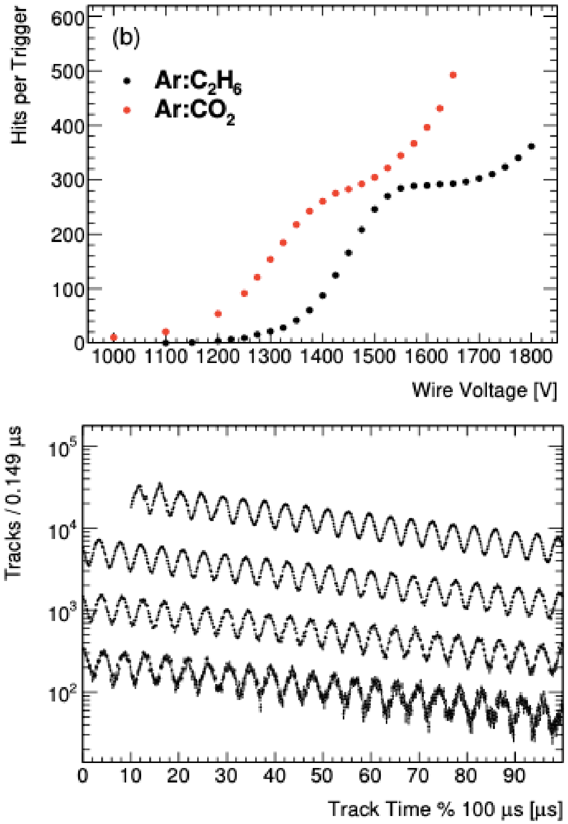
$$50\ \mathrm{MeV}/c < p < 145\ \mathrm{MeV}/c$$





Straw Trackers - Motivation

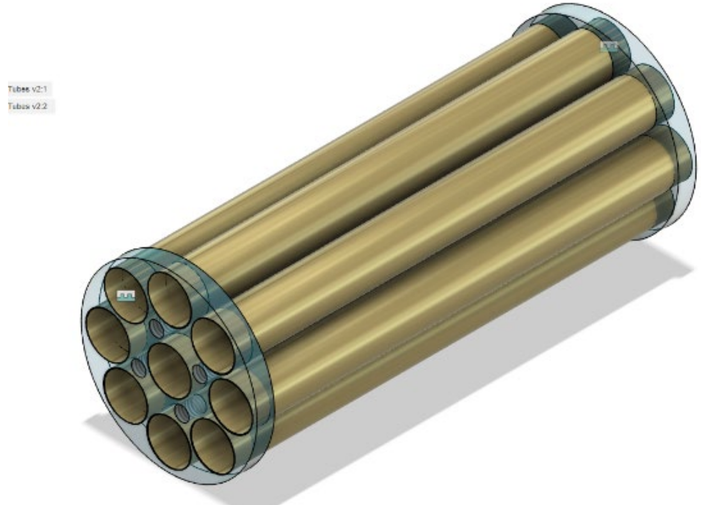
- Use straw tracking detector to confirm g-2 oscillation is frozen out
- 100mm length straws in centre of storage ring, additional layers outside
- 15µm mylar walls, filled with either Argon-Ethane or Argon-CO_2
- Demonstrated observation of g-2 oscillation using reconstructed tracks
- Momentum and vertical angle measurement to improve EDM limit

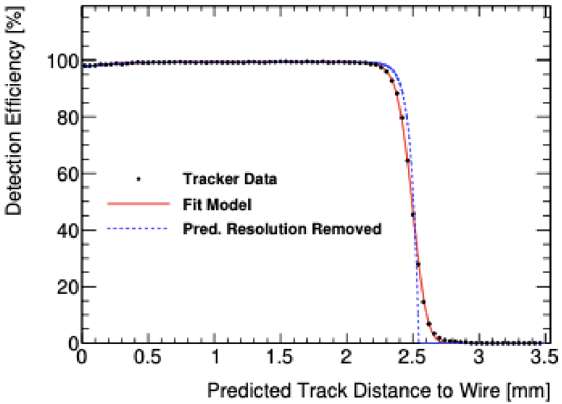


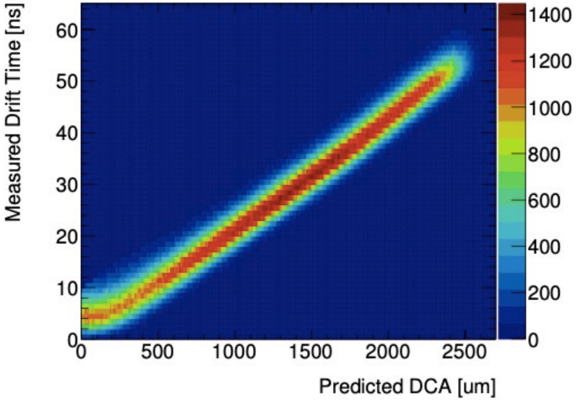
@FNAL g-2

Straw Trackers – Single hit

- Highly efficient across straw radius (2.5mm)
- Straw hit resolution ~110μm
- Single straw ready to read out again after ~100ns, capable of 10MHz rate
- Design, construction, testing and readout expertise at Liverpool, Manchester and UCL
- Optimization of tracker geometry for muEDM ongoing







Systematic effects

- Systematic effects: all effects that lead to a *real* or *apparent* precession of the spin around the radial axis that are not related to the EDM
- The work by Farley et al. used as a starting point:

VOLUME 93, NUMBER 5 PHYSICAL REVIEW LETTERS week ending 30 JULY 2004

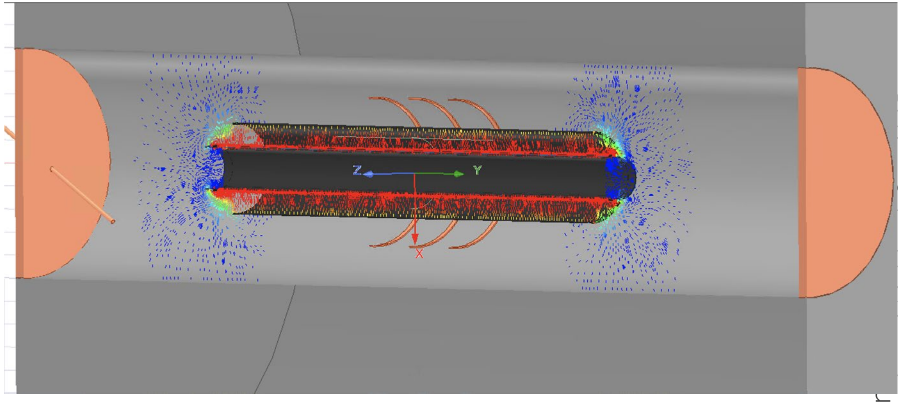
New Method of Measuring Electric Dipole Moments in Storage Rings

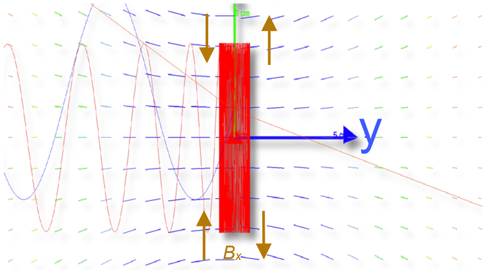
F. J. M. Farley,[7] K. Jungmann,[4] J. P. Miller,[2] W. M. Morse,[3] Y. F. Orlov,[5] B. L. Roberts,[2] Y. K. Semertzidis,[3] A. Silenko,[1] and E. J. Stephenson[6]

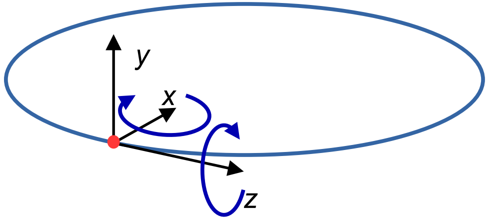
- Major sources of systematic effects in the frozen spin technique:
  - Early to late variation of detection efficiency of the EDM detectors (apparent)
  - Coupling of the anomalous magnetic moment with the EM fields of the experimental setup (real)

Coupling of the MDM to EM fields

- Main EM fields in the experiment:
  - Main solenoid
  - Coaxial electric freeze field
  - Weakly focusing field
  - Magnetic kick (time varying)
- Rotations that could mimic the EDM:
  - Radial around *x*
  - Azimutal around *z*





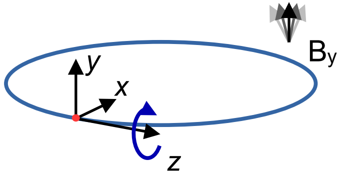


$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{e}{m_0}\left[a\vec{B} - a\frac{\gamma-1}{\gamma}\frac{(\vec{\beta}\cdot\vec{B})\vec{\beta}}{\beta^2} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

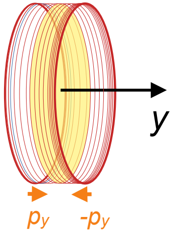
Oscillating and constant terms

- Using the T-BMT equation one can describe analytically the spin precession due to the MDM in the EM fields of the experiment

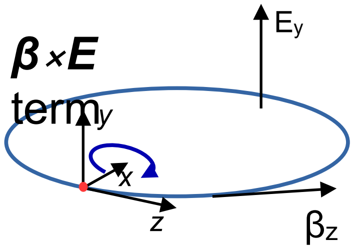
$$\left(\vec{\Omega}_{\mathrm{MDM}}\right)_z = -\frac{ea}{m_0}\left[\frac{p_{y_0}}{p_z}\sin\left(\omega_\beta t\right)\left(\frac{\beta_z}{c}\left(1-\frac{1}{a(\gamma^2-1)}\right)E_{ex}-\left(\frac{\gamma-1}{\gamma}\right)B_y\right)+B_z\right]$$

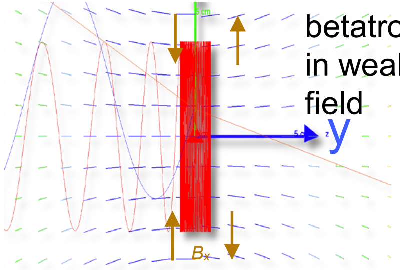


oscillations due to the projection of the main solenoid field along the momentum



$$\left(\vec{\Omega}_{\mathrm{MDM}}\right)_x = -\frac{ea}{m_0}\left[\frac{\beta_z}{c}\left(1-\frac{1}{a(\gamma^2-1)}+\frac{1}{\beta_z^2}\right)E_y+\Phi_0\cos(\omega_\beta t+\phi_0)\rho y_0+B_x\right]$$





betatron oscillations in weakly focusing field

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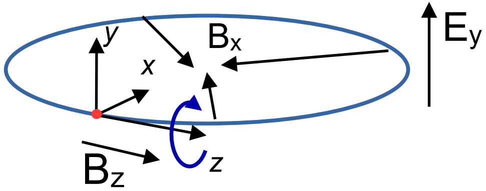
Average over all orbits

- If we take the average over all muon orbits the periodic oscillations disappear and we are left with three terms that could lead to a false EDM signal:

$$\langle \Omega_{\hat{z}} \rangle = -\frac{ea}{m_0}\langle B_z \rangle \qquad \langle \Omega_{\hat{x}} \rangle = -\frac{ea}{m_0}\langle B_x \rangle$$

$$\langle \Omega_{\hat{z}\times\hat{y}} \rangle = -\frac{ea}{m_0 c}\left(\frac{1}{a(\gamma^2-1)} - 1 + \frac{1}{\beta_z^2}\right)\langle \beta_z E_y \rangle$$



- Net *B*-field component along the momentum B_z → non-zero if there is current flowing through the muon orbit

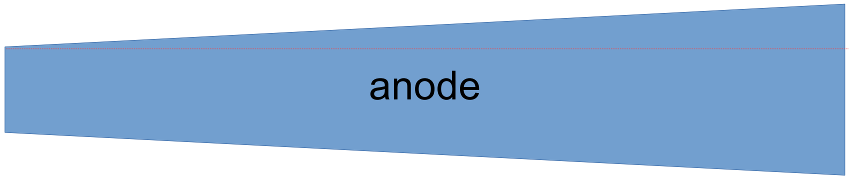
- Net radial *B*-field component B_x → can be non-zero due to residual fields from the magnetic kick

- Radial magnetic field in the reference frame of the muon due to a $\boldsymbol{\beta} \times \boldsymbol{E}$ term → non-zero if there is E-field prependicular to the muon orbit

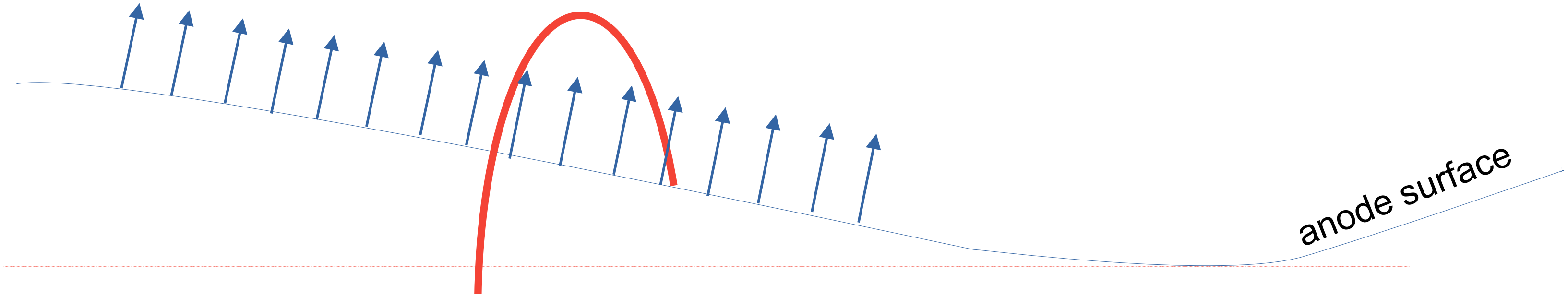
Sources of E_y field: electrode non-uniformity

- None constant radius of cylindrical anode (cone)

$$E_y \approx E_f \frac{\Delta_R}{L} \approx E_f \alpha$$



- Smoothness of the electrodes close to the muon orbit (few centimeters)



- Generally sub-micrometer surface smoothness is possible with common machining and polishing techniques

- Cylindricity in the order of 50 nm is measurable even on large samples

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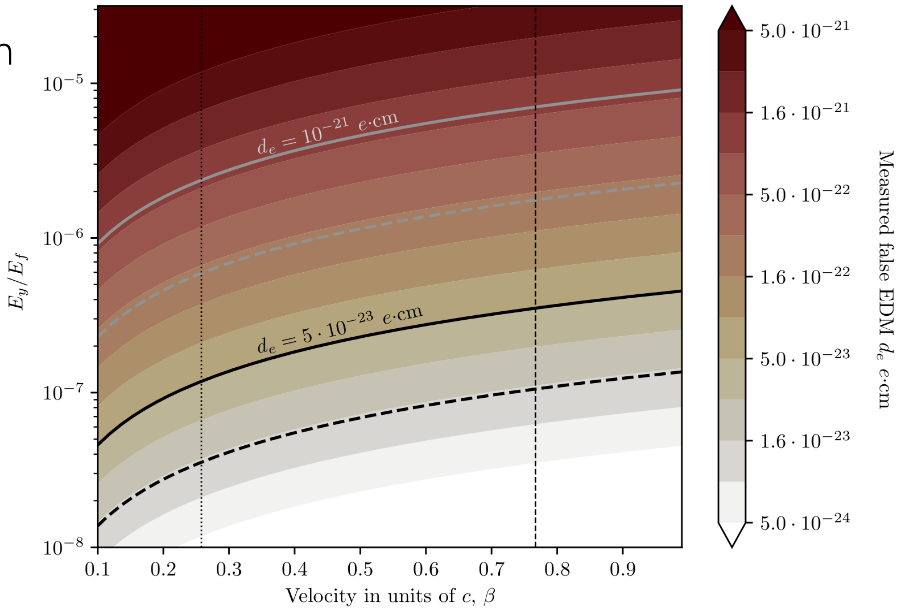
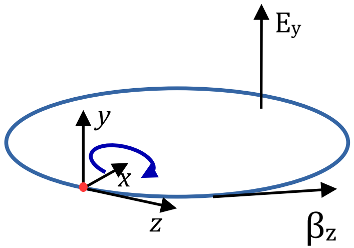
Constraints on the average horizontal E-field

- Limit on the average E_y field as a function of the muon velocity shown as a fraction of the radial component
- The limit is 0.5 ppm for the precursor experiment and 0.1 ppm for the final experiment
- This effect can be largely cancelled if particles are injected alternatively CW and CCW and subtracting counts in the detectors

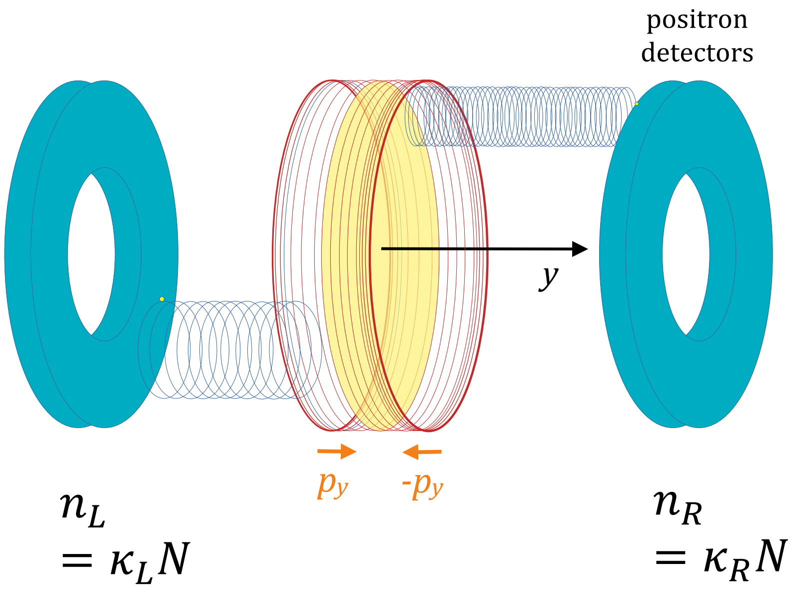




$$\langle \Omega_{\hat{z}\times\hat{y}} \rangle = -\frac{ea}{m_0 c}\left(1 - \frac{1}{a(\gamma^2 - 1)} - \frac{1}{\beta_z^2}\right)\langle \beta_z E_y \rangle$$

Detection efficiency asymmetry

- The EDM will be deduced from the accumulation of asymmetry between the upstream and downstream detectors that increases with time
- Static differences in the detection efficiency of one detector compared to the other is not a problem
- Change of the detection efficiency with time is a problem as it will introduce time dependent asymmetry



Constraints on the total detection efficiency

- Let us assume that there is some effect that changes the total detection efficiency of both detectors and it is exponential in nature

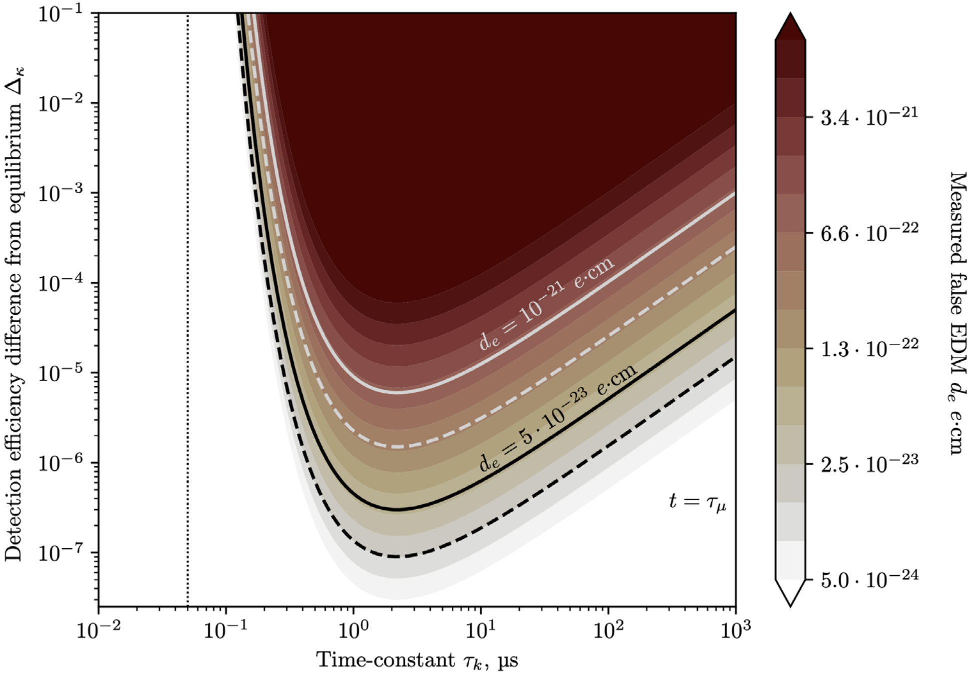
- Detection efficiency of up and downstream detectors:

$$\kappa_u = \kappa_{u0} - \Delta_\kappa e^{-t/\tau_k},$$

$$\kappa_d = \kappa_{d0} + \Delta_\kappa e^{-t/\tau_k},$$

- Change in measured asymmetry with time:

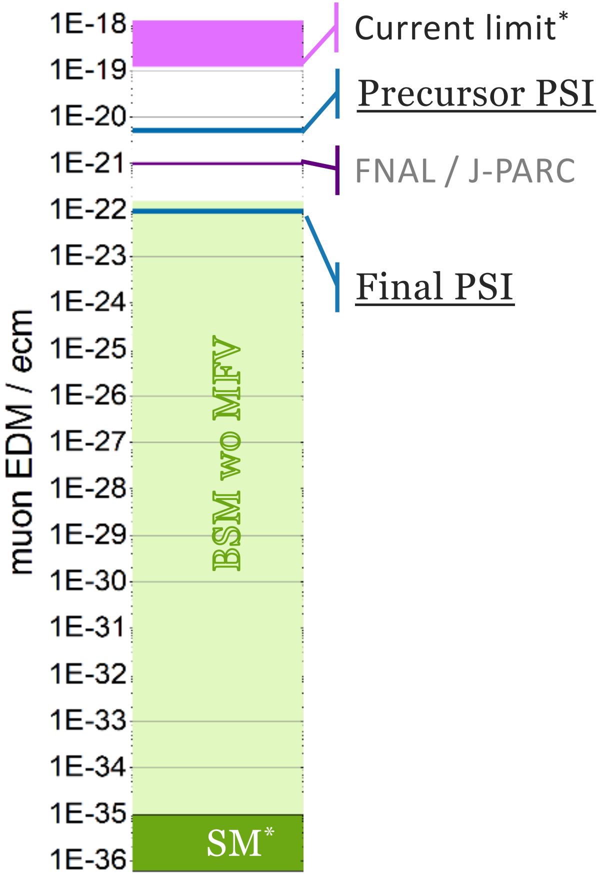
$$\dot{A}_m = \frac{2}{\tau_k} \Delta_\kappa e^{-t/\tau_k}$$



Conclusion

Preparation of proposal for muEDM in two phases:

- Precursor muEDM better than $3 \times 10^{-21} ecm$
- Final muEDM search better than $6 \times 10^{-23} ecm$



*Bennet et al, PRD **80**, 052008 (2009) **Ghosh et al, PLB **777**, 335 (2018) selected for funding, funded by SBFI

The muEDM – collaboration

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18 TUM
19 BROOKHAVEN NATIONAL LABORATORY "a passion for discovery"
20 UNIVERSITÀ DI PISA

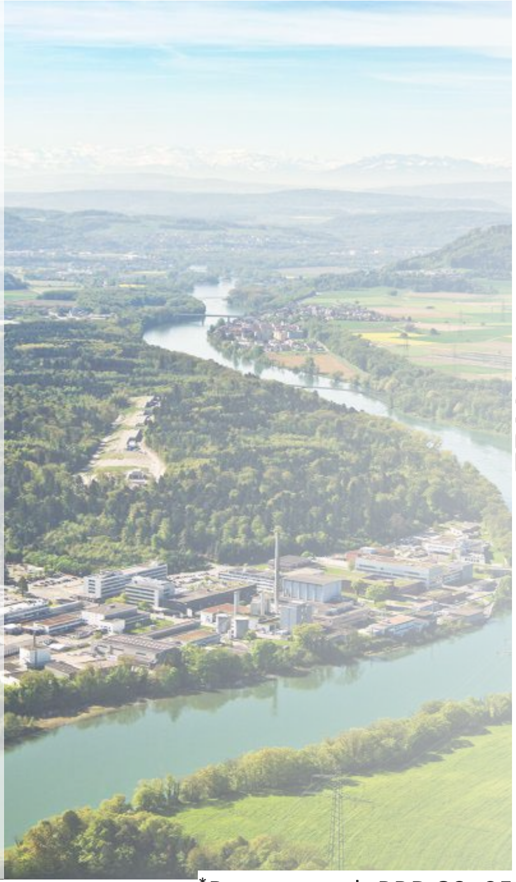
Conclusions

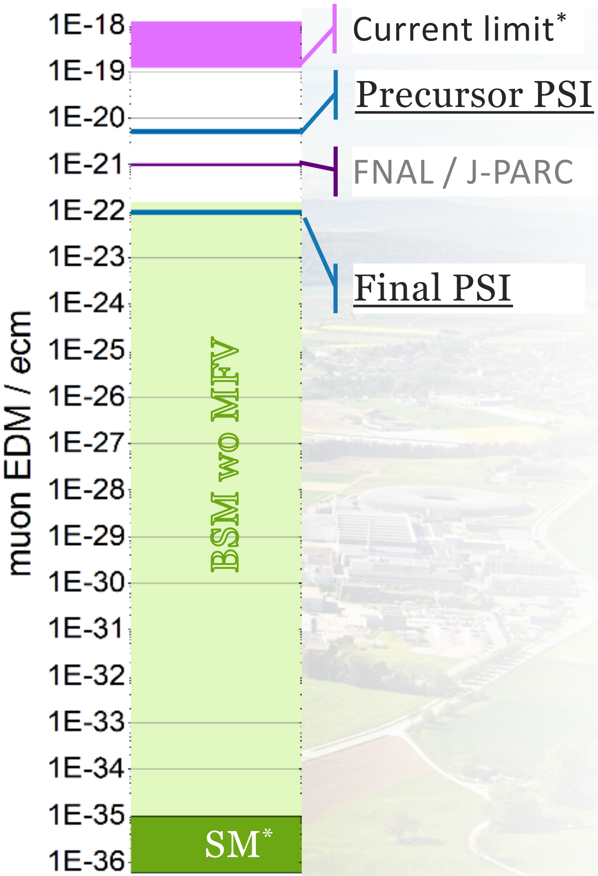
- EDM are excellent probes to search for new physics
- PSI is currently preparing two experiments to improve the current best limits of the neutron and muon EDM in the next decade to better than:

$$\sigma(d_{\mathrm{n}}) \sim 1 \times 10^{-27} ecm$$

and

$$\sigma(d_{\mu}) \sim 6 \times 10^{-23} ecm$$





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