Searches on
charged Lepton Flavour Violation with muons
and
Time-reversal symmetry Violation with neutrons

SWHEPPS 2016
Angela Papa
Unterägeri, 7-9 June

PAUL SCHERRER INSTITUT

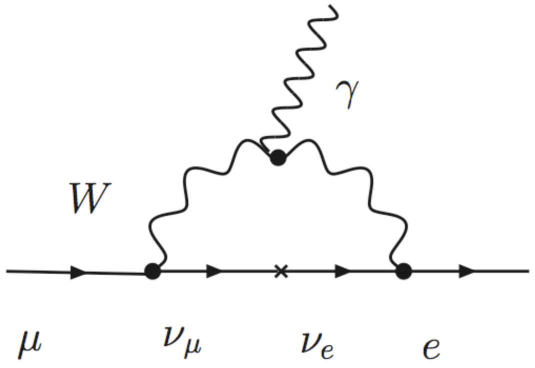
Overview

- charged Lepton Flavour Violation (cLFV) searches with muons
    - MEG/MEGII
    - Mu3e
- Testing time-reversal symmetry searching for the electric dipole moment of neutron
    - nEDM/n2EDM

cLFV motivations

(the $\mu^+ \rightarrow e^+ \gamma$ decay as an example)

SM with massive neutrinos (Dirac)

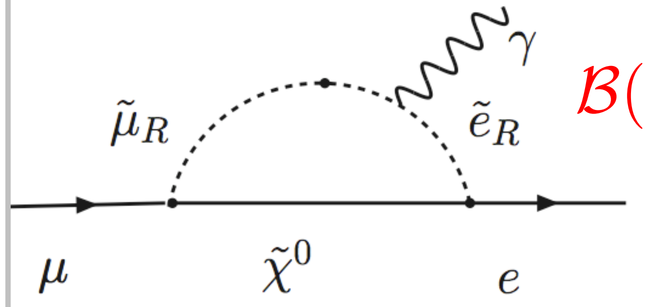


$$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$$

too small to access experimentally:

current upper limit ~ 10^{-13}

i.e. SU(5) SUSY-GUT or SO(10) SUSY-GUT



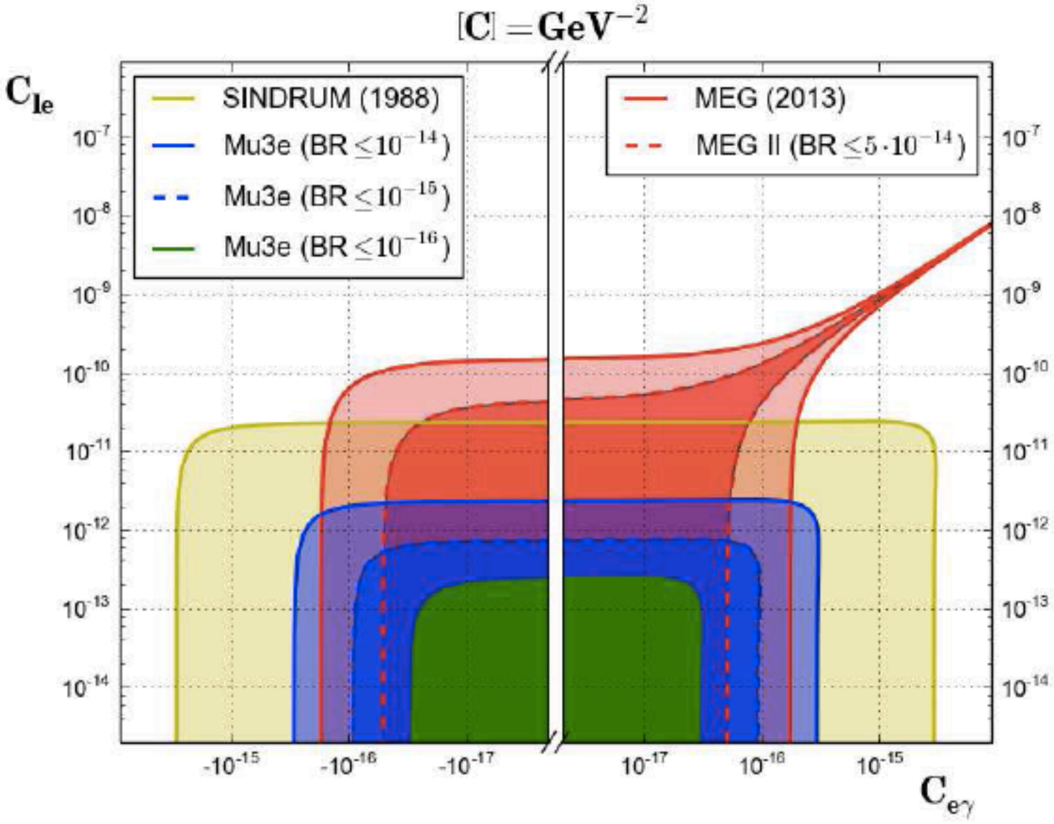
$$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$$

an experimental evidence:
a clear signature of New Physics

The role of low energy physics:
a sensitive tool

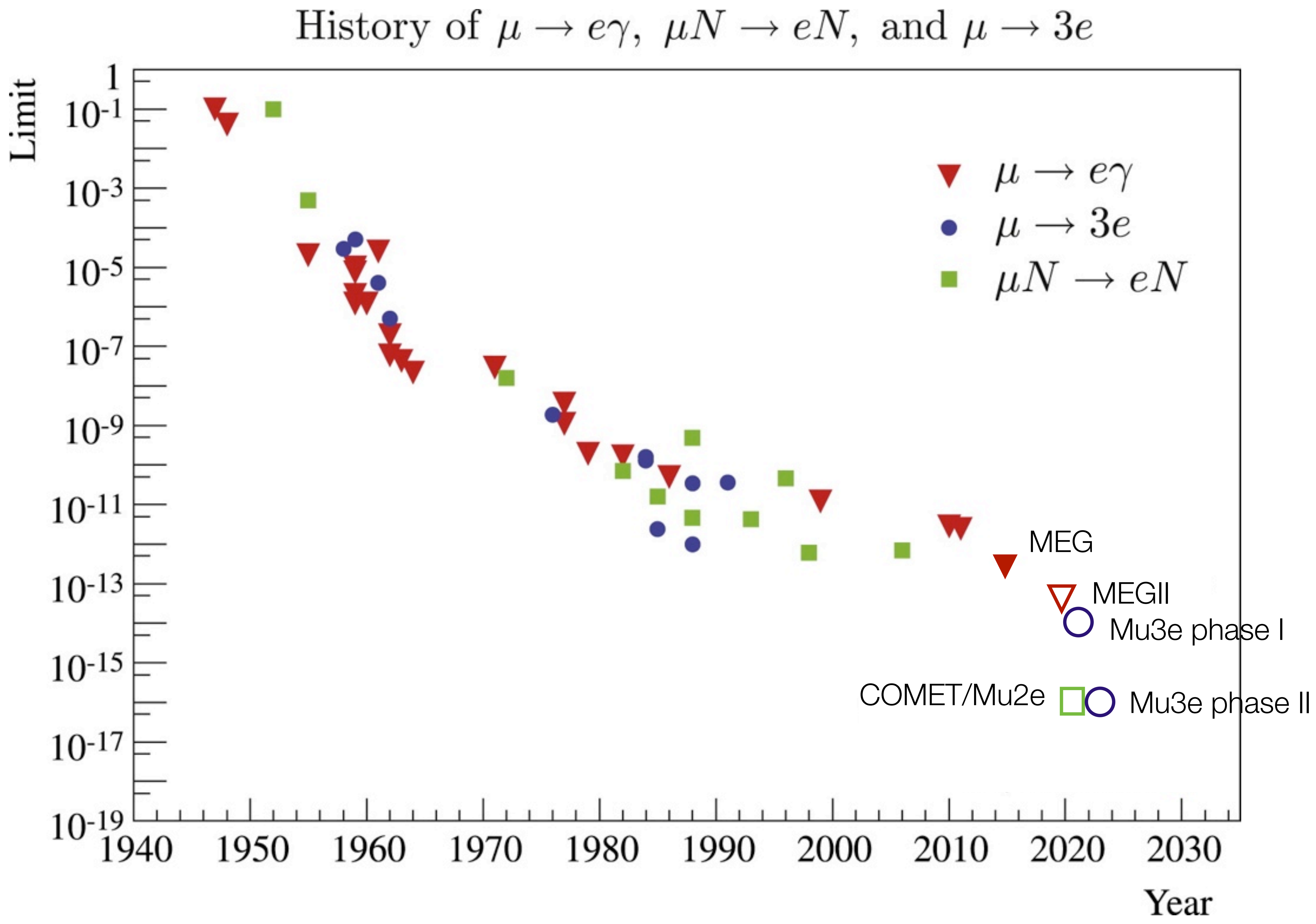
- to unveil behind SM physics (virtual particles)
- effective lagrangian approach
  - high energy scale probe
  - a framework to combine constrains from low-energy (i.e. μ-> eγ) experiments with LFV searches at higher energies (Z bosons or H -> τμ)
  - complementarity among LFV channels

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$



ref.: G.M. Pruna and A. Signer arXiv:1511.04421v1
G.M. Pruna and A. Signer JHEP 10 (2014) 014

cLFV searches with muons: status and future prospects



Why cLFV with muons?

- Even if taus are the ideal probe for new physics via cLFV w. r. t. muons
  - Smaller GIM suppression
  - Expected stronger coupling to new physics
  - Many possible LFV decays
- Muons are currently the most sensitive probe to new physics via cLFV
  - Huge statistics

- **Best upper limit of any particle decay set by the MEG experiment**

$$B(\mu^+ \longrightarrow e^+ \gamma) < 5.7 \times 10^{-13} \quad (2009\text{-}2011)$$

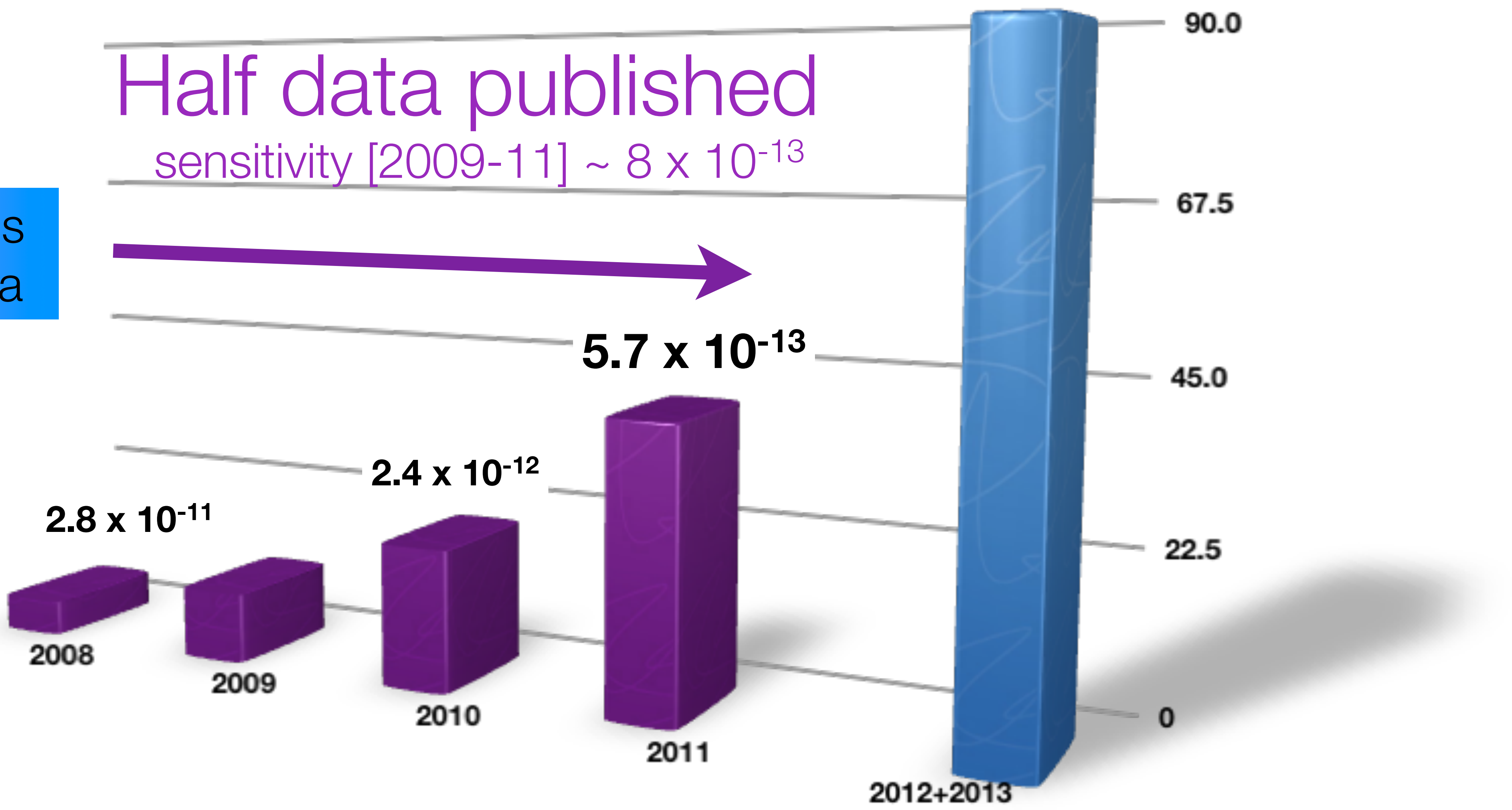
Ref. Phy. Rev. Lett. 110, 201801 (2013)

MEG Analysis status

Unblinded Dec. 2015

sensitivity [2009-13] ~ 5 x 10^{-13}

Improved analysis applied to all data



Half data published

sensitivity [2009-11] ~ 8 x 10^{-13}

Previous upper limit before MEG

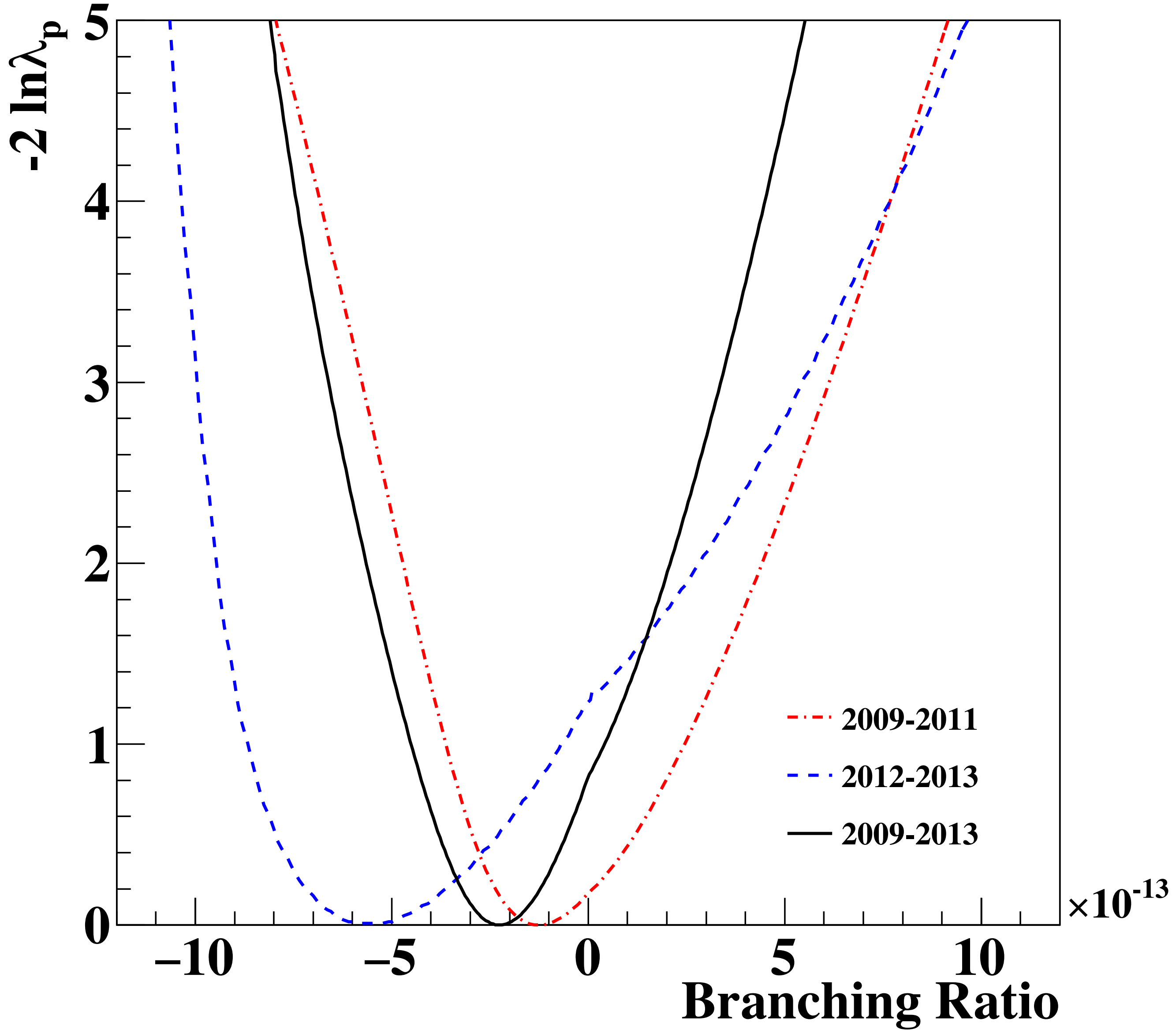
$\mathcal{B}(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$

@ 90% C.L. by the MEGA experiment

MEG full data set result

New since March 8th 2016

- Profile likelihood ratios as a function of the BR: all consistent with a null-signal hypothesis



MEG full data set result

available on ArXiV
submitted to EPJc

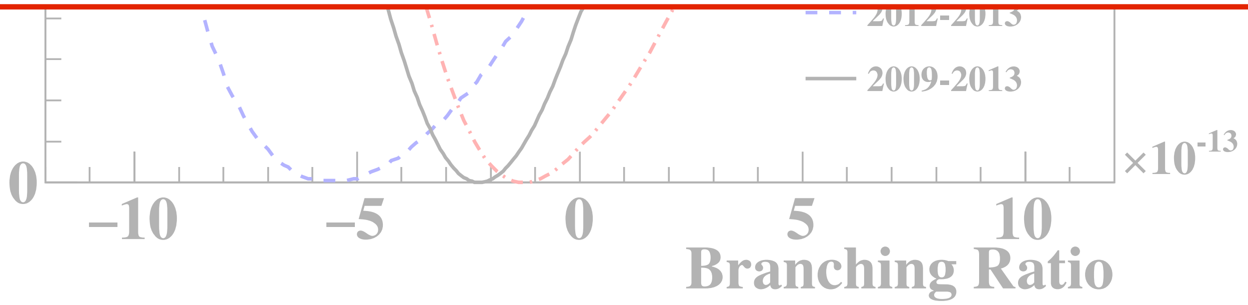
- profile likelihood ratios as a function of the BR: all consistent with a null-signal

Full data sample:
2009-2013
Best fitted branching ratio at
90% C.L.*:

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

(*) from MEGA to MEG:

improvement by a factor ~ ***30***



Muon-cLFV coincidence experiments

Gold channels: the $\mu^+ \rightarrow e^+ \gamma$ and $\mu^+ \rightarrow e^+ e^+ e^-$ decays

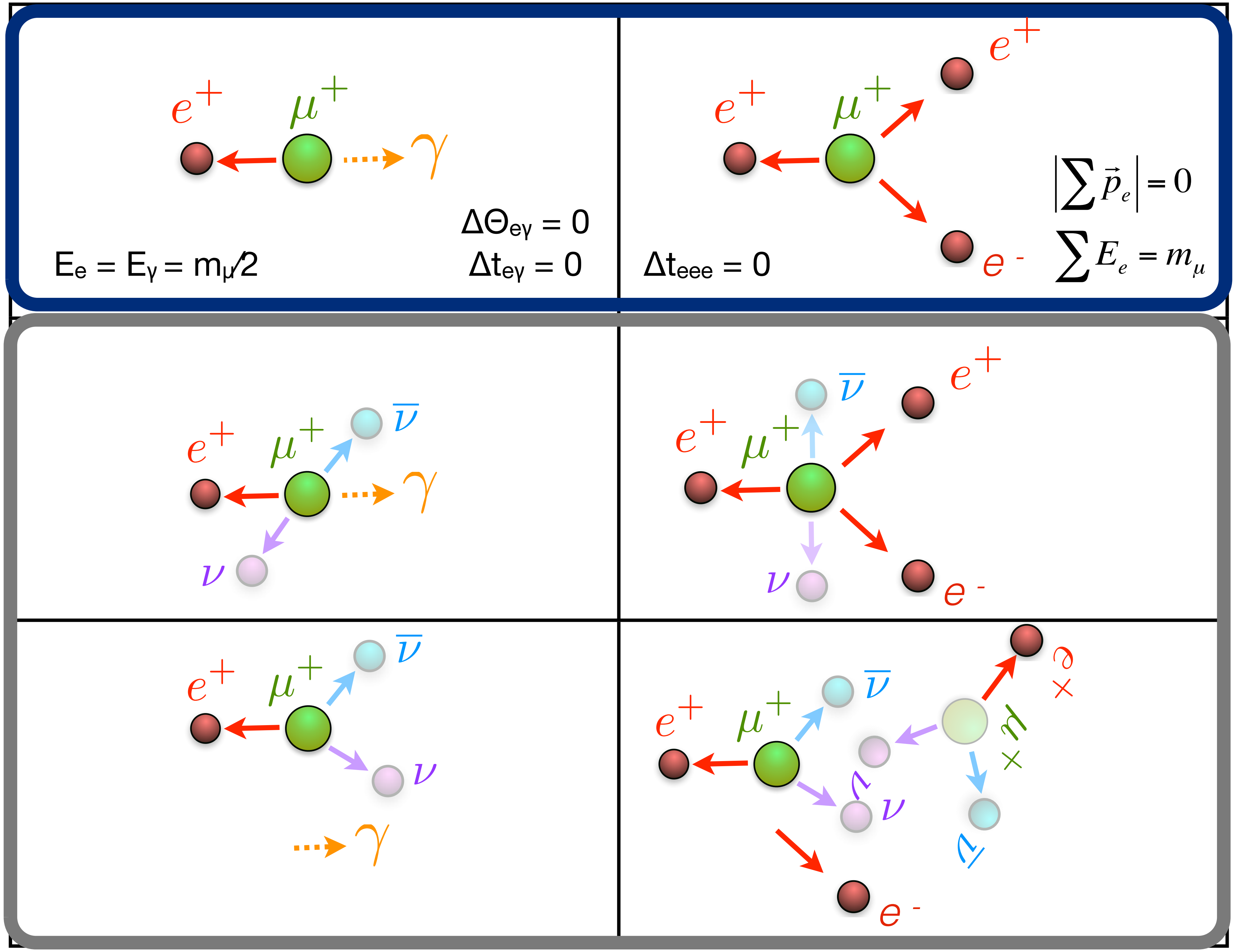
MEG and MEGII (CH)

SINDRUM and Mu3e (CH)

Signature

Correlated Background

Accidental Background



$E_e = E_\gamma = m_\mu/2$

$\Delta\Theta_{e\gamma} = 0$

$\Delta t_{e\gamma} = 0$

$\Delta t_{eee} = 0$

$\left|\sum \vec{p}_e\right| = 0$

$\sum E_e = m_\mu$

How the sensitivy can be pushed down?

Using the $\mu^+ \rightarrow e^+ \gamma$ search as an example

Current upper limit	future sensitivity
BR $(\mu^+ \rightarrow e^+ \gamma) < 4.2 \times 10^{-13}$ (MEG)	SES $(\mu^+ \rightarrow e^+ \gamma) \sim 5 \times 10^{-14}$ (MEGII)
BR $(\mu^+ \rightarrow e^+ e^+ e^-) < 1.0 \times 10^{-12}$ (SINDRUM)	SES $(\mu^+ \rightarrow e^+ e^+ e^-) \sim 10^{-16}$ (Mu3e)

high statistics

- More sensitive to the signal...

$$\mathrm{SES} = \frac{1}{\boxed{R} \times T \times A_g \times \boldsymbol{\varepsilon}(e^+) \times \boldsymbol{\varepsilon}\,(\mathrm{gamma}) \times \boldsymbol{\varepsilon}(\mathrm{TRG}) \times \boldsymbol{\varepsilon}(\mathrm{sel})}$$

Beam rate

Acquisition time

Geometrical acceptance

Detector efficiency

Selection efficiency

high resolutions

- More effective on rejecting the background...

$$B_{acc} \sim R \times \boxed{\Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta \Theta_{egamma})^2}$$

Momentum resolution

Energy resolution

Relative timing resolution

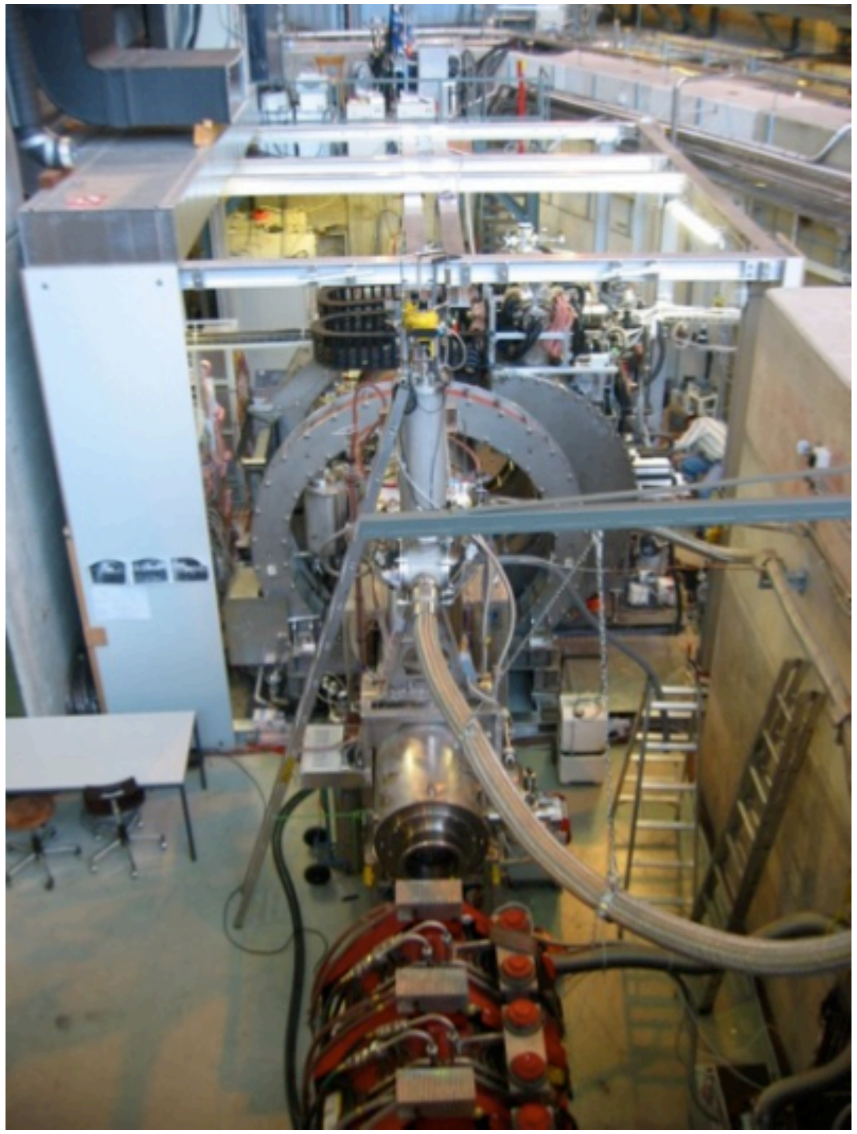
Relative angular resolution

The piE5 beam line

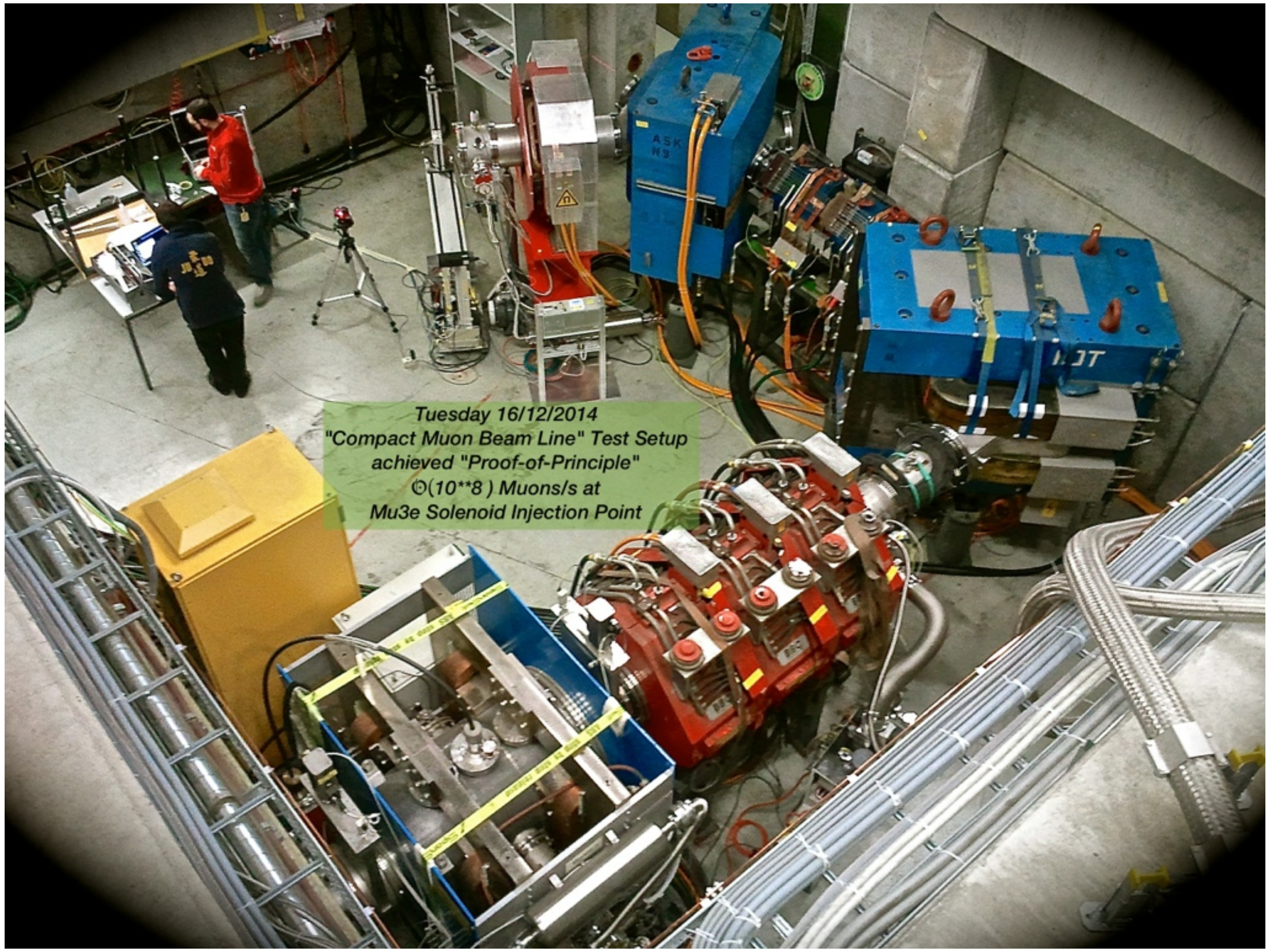
- MEGII and Mu3e (phase I) similar beam requirements:
  - Intensity O(10^8 muon/s), low momentum p = 28 MeV/c
  - Small straggling and good identification of the decay region

Only possible in piE5!

MEG/MEGII Beam Line



Mu3e Compact Muon Beam Line



Tuesday 16/12/2014
"Compact Muon Beam Line" Test Setup
achieved "Proof-of-Principle"
Θ(10**8) Muons/s at
Mu3e Solenoid Injection Point

2013	2014	2015	2016	2017-20
Design	Construction	PreEng Run	Eng. Run	Run

MEGII detector concept

Sensitivity [2017-20] ~ 4 x 10^{-14}

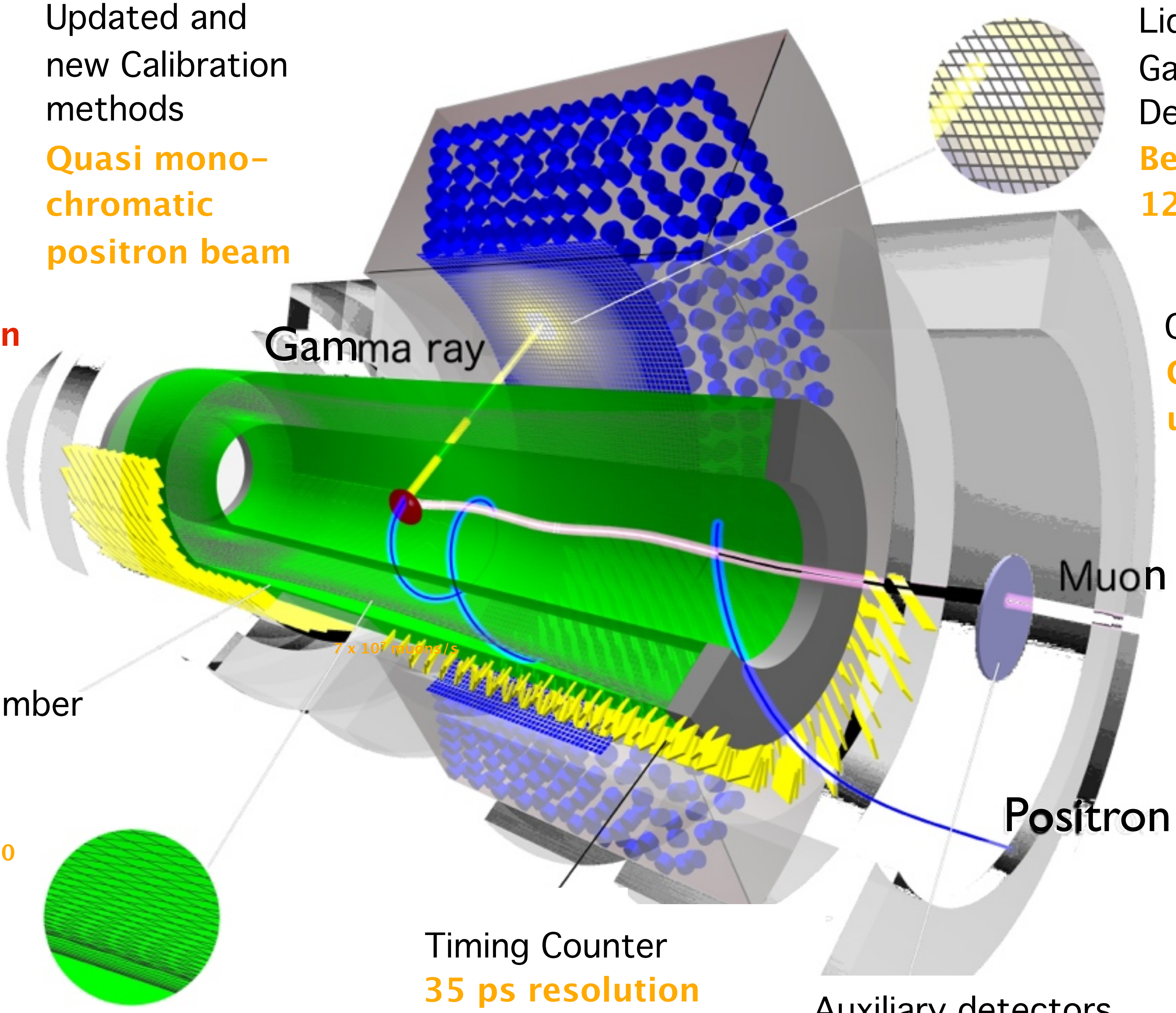
Wavedream
~9000 channels at 5GSPS

Updated and new Calibration methods
Quasi mono-chromatic positron beam

x2 resolution everywhere

Tech. coordination

Drift Chamber
Single volume $He{:}iC_4H_{10}$



Liquid Xenon Gamma-ray Detector
Better uniformity w/ 12x12 VUV SiPM

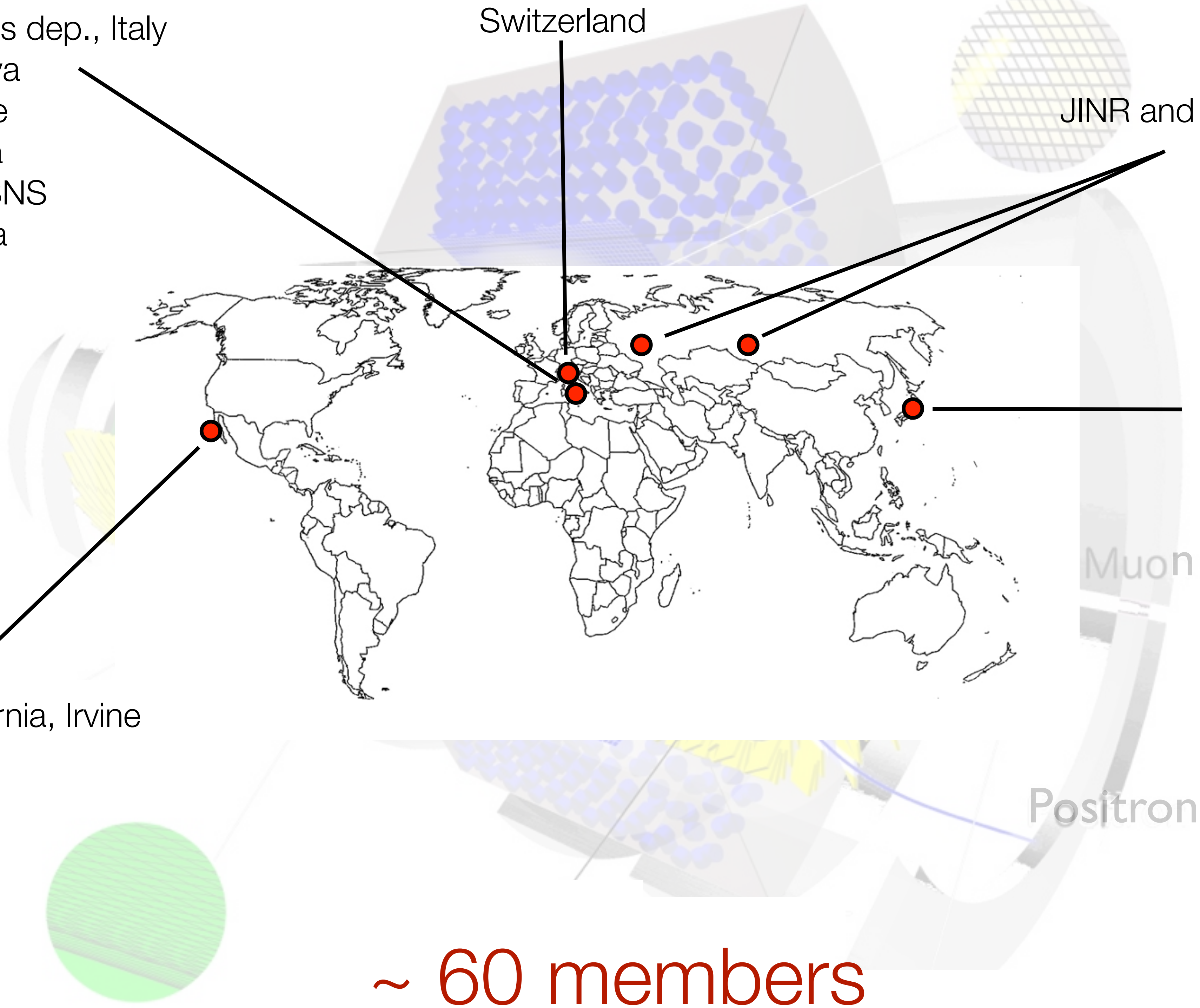
Cobra magnet
Gradient B field up to 1.3 T

Muon Beam and target
Full available stopped beam intensity 7 x 10^7

Timing Counter
35 ps resolution w/ multiple hits

Auxiliary detectors
Background rejection

MEGII collaboration



INFN and physics dep., Italy
Genova
Lecce
Pavia
Pisa & SNS
Roma

PSI and ETH Zurich,
Switzerland

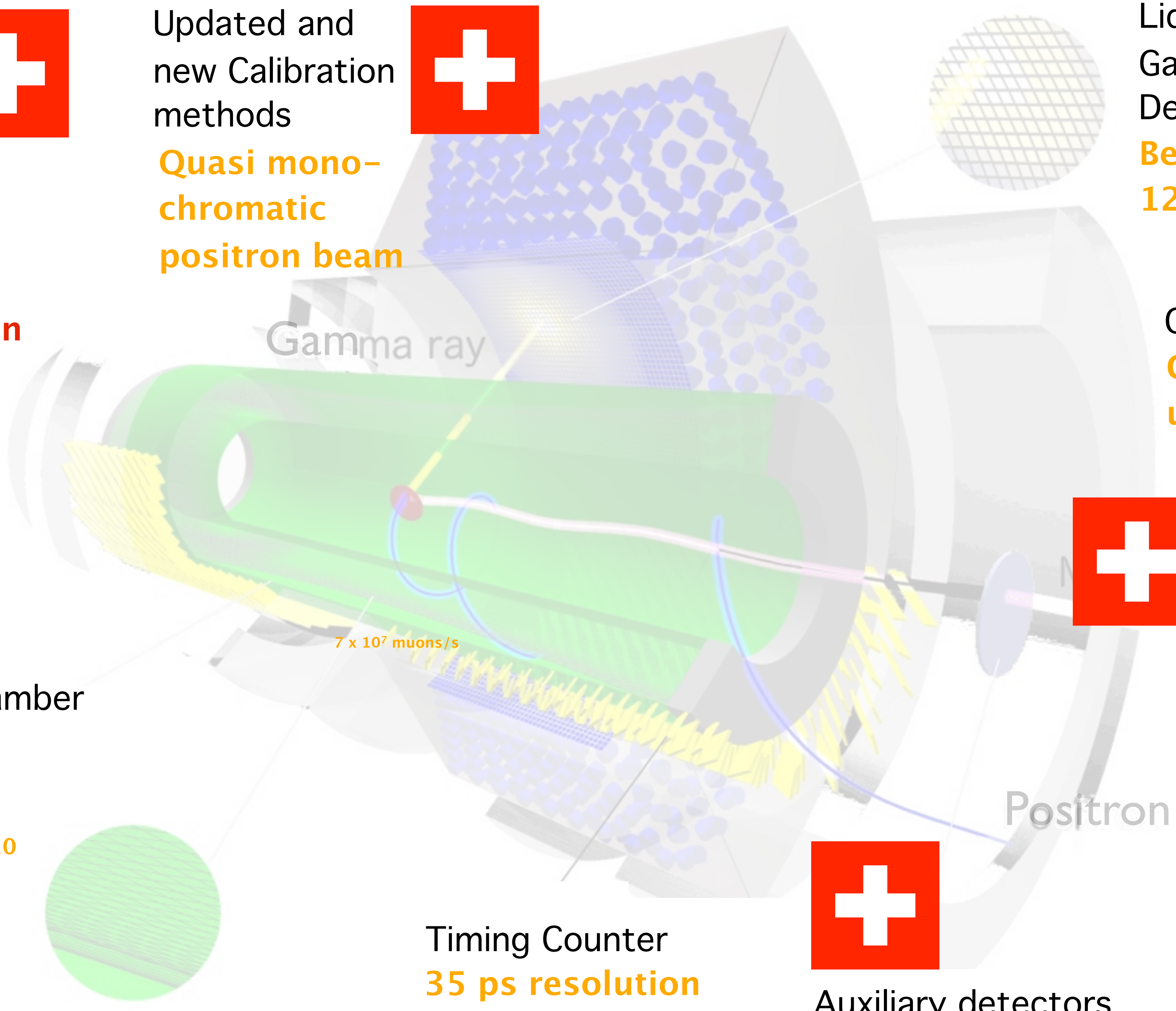
JINR and physics dep., Russia
Dubna
Novosibirsk

ICEPP Tokyo, Japan
KEK Ibaraki, Japan
Waseda Uni. Tokyo,
Japan

University of California, Irvine

~ 60 members

MEGII collaboration and Swiss responsibilities



Wavedream
~9000
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Updated and
new Calibration
methods
Quasi mono-
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Liquid Xenon
Gamma-ray
Detector
Better uniformity w/
12x12 VUV SiPM

x2 resolution
everywhere

Cobra magnet
Gradient B field
up to 1.3 T

Tech. coordination
& Run coordination

Muon Beam and
target
Full available
stopped beam
intensity
7 x 10^7

Drift Chamber
Single
volume
$He{:}iC_4H_{10}$

Timing Counter
35 ps resolution
w/ multiple hits

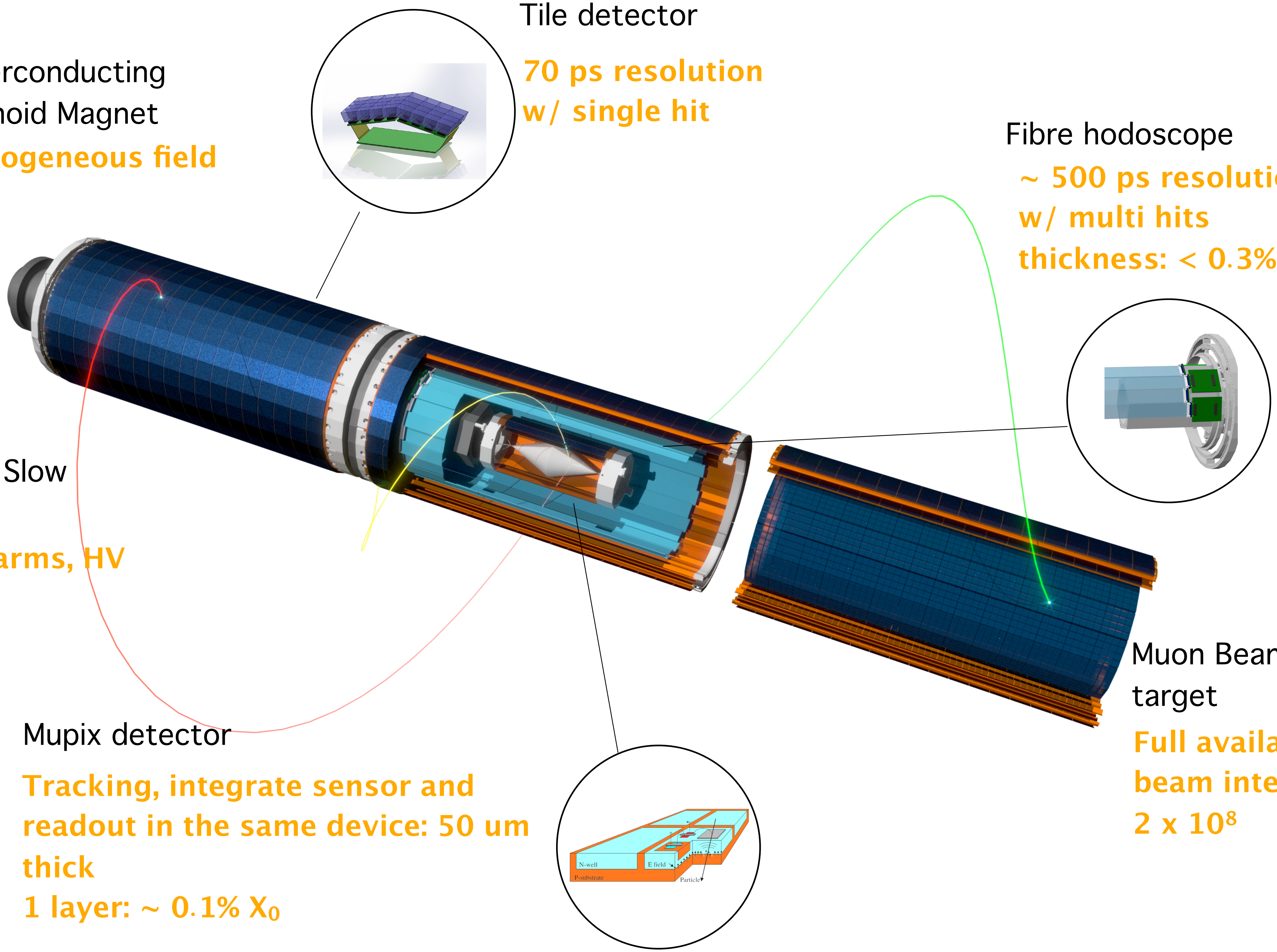
Auxiliary detectors
Background rejection

2013-5	2015-7	2017	2018-20
Design	Construction	Eng Run	Run

Mu3e detector concept

Sensitivity phase I [2018-20] ~ 10^{-15}

(Final sensitivity phase II [202x] ~ 10^{-16} needs 10^{9} muons/s)



Tile detector

70 ps resolution w/ single hit

Superconducting solenoid Magnet

Homogeneous field 1T

Fibre hodoscope

~ 500 ps resolution w/ multi hits thickness: < 0.3% X_0

MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

Muon Beam and target

Full available beam intensity 2×10^{8}

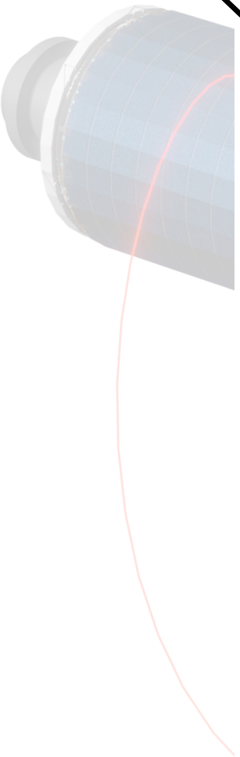
Mupix detector

Tracking, integrate sensor and readout in the same device: 50 um thick

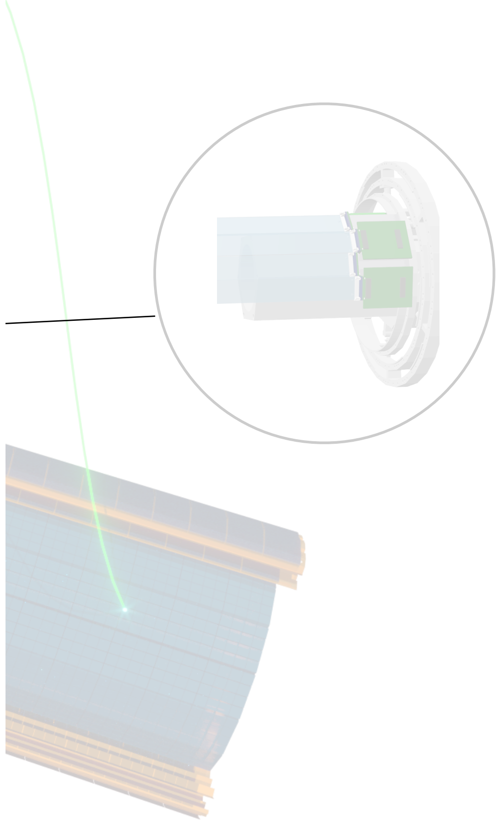
1 layer: ~ 0.1% X_0

Mu3e collaboration

Switzerland:
PSI
ETH Zurich
Uni. of Geneve
Uni. of Zurich

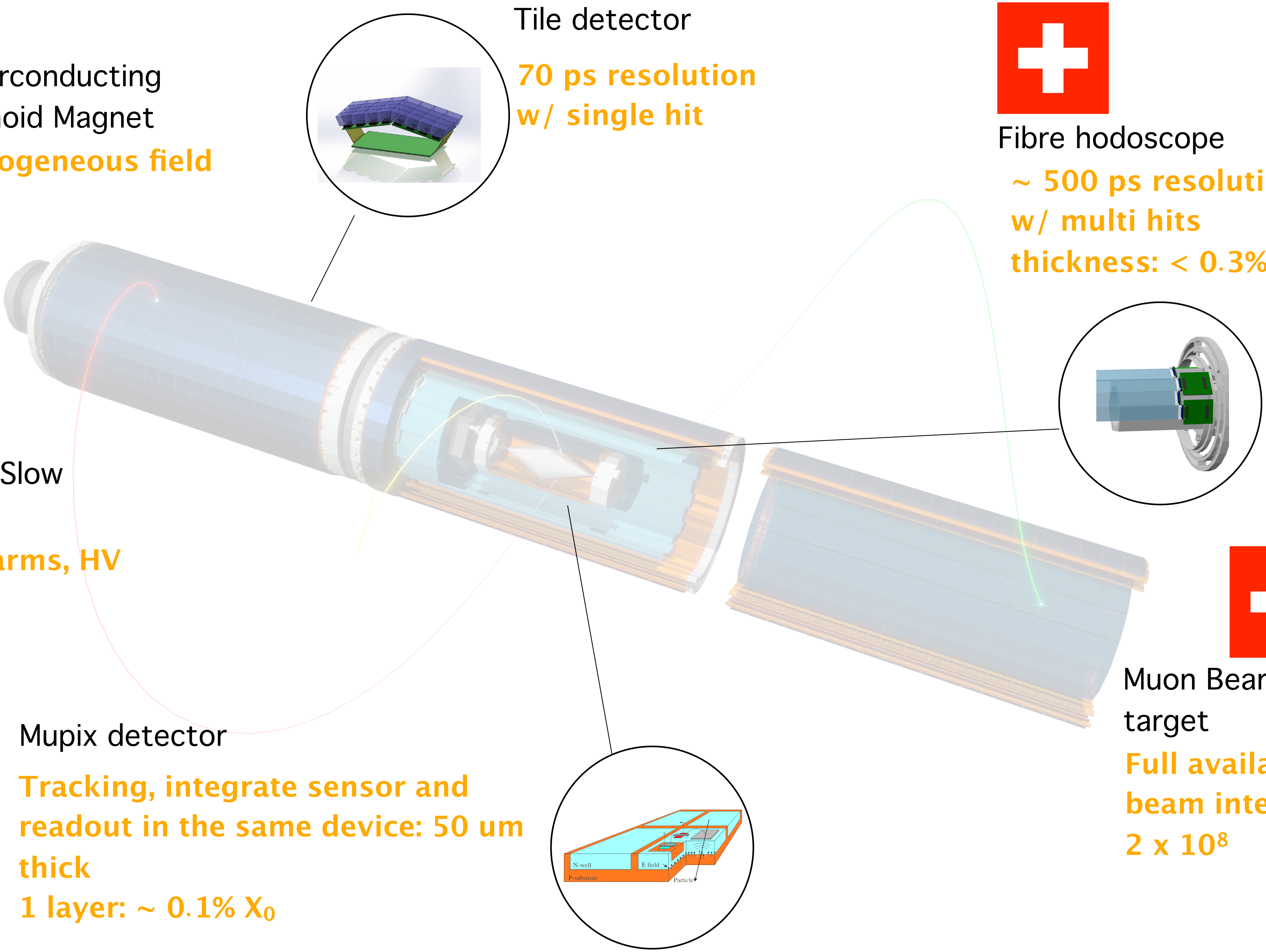


Germany:
Karlsruhe Institut fur Technologie
J.G. Uni. Mainz
Uni. Heidelberg



~ 40 members

Mu3e collaboration and Swiss responsibilities



Superconducting solenoid Magnet

Homogeneous field 1T

Tile detector

70 ps resolution w/ single hit

Fibre hodoscope

~ 500 ps resolution w/ multi hits

thickness: $< 0.3\% X_0$

MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

Mupix detector

Tracking, integrate sensor and readout in the same device: 50 um thick

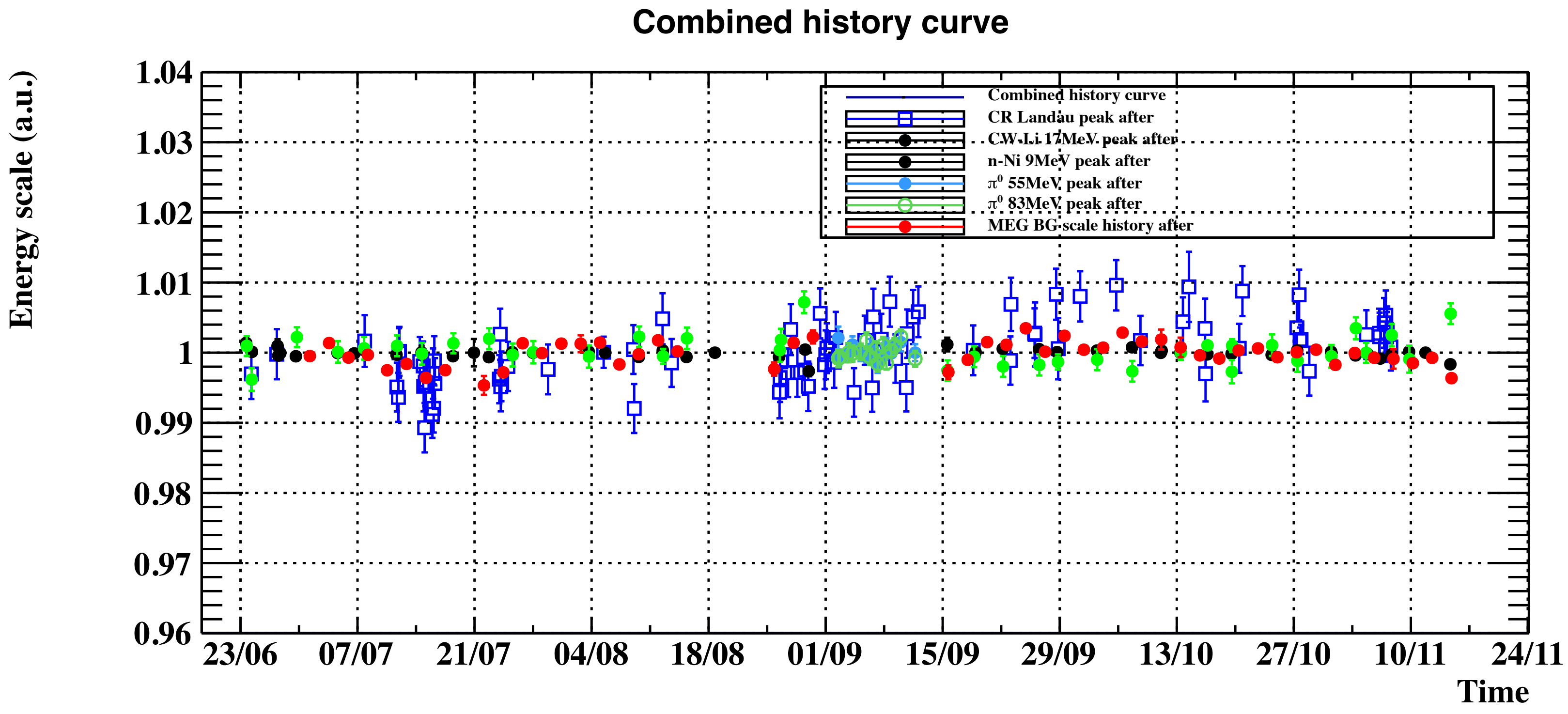
1 layer: $\sim 0.1\% X_0$

Muon Beam and target

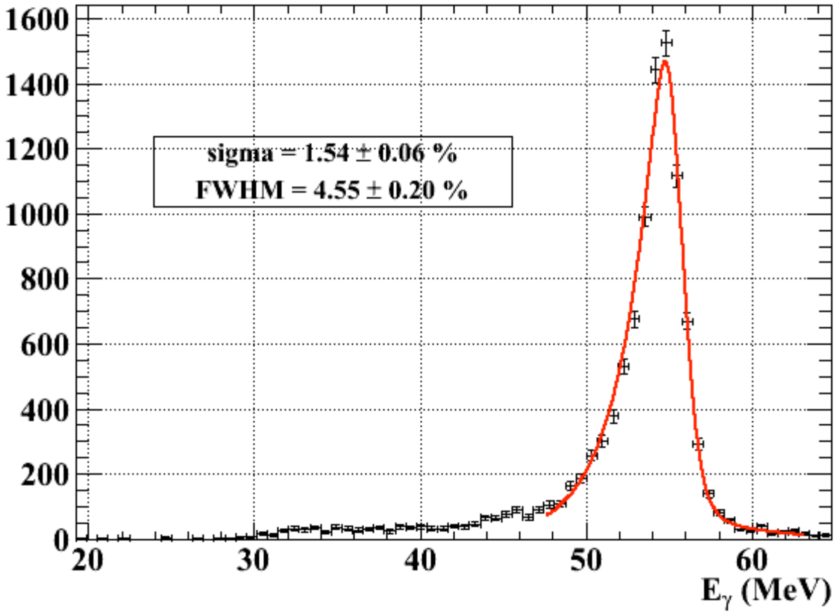
Full available beam intensity 2×10^8

The MEG LXe calorimeter

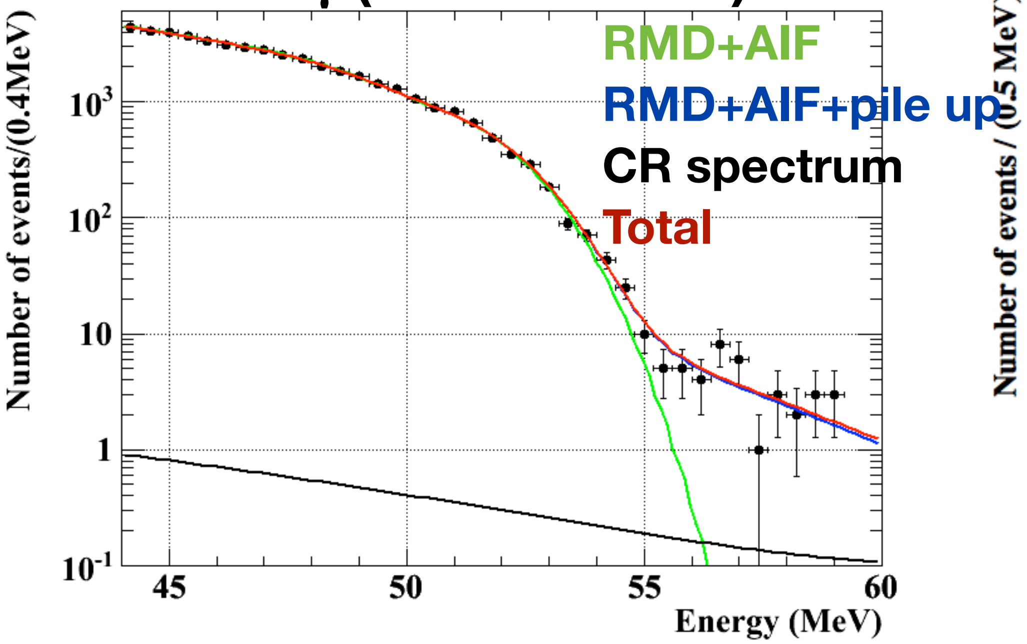
- Purity < 1 ppm and stable conditions over the time
- Energy (σ_E /E <2.5%) and timing resolutions(σ_t < 70 ps) never reached up to now with a unique detector at 52.8 MeV!
- Crucial ingredients:
  - waveform based analysis
  - calibration and monitoring methods


Combined history curve

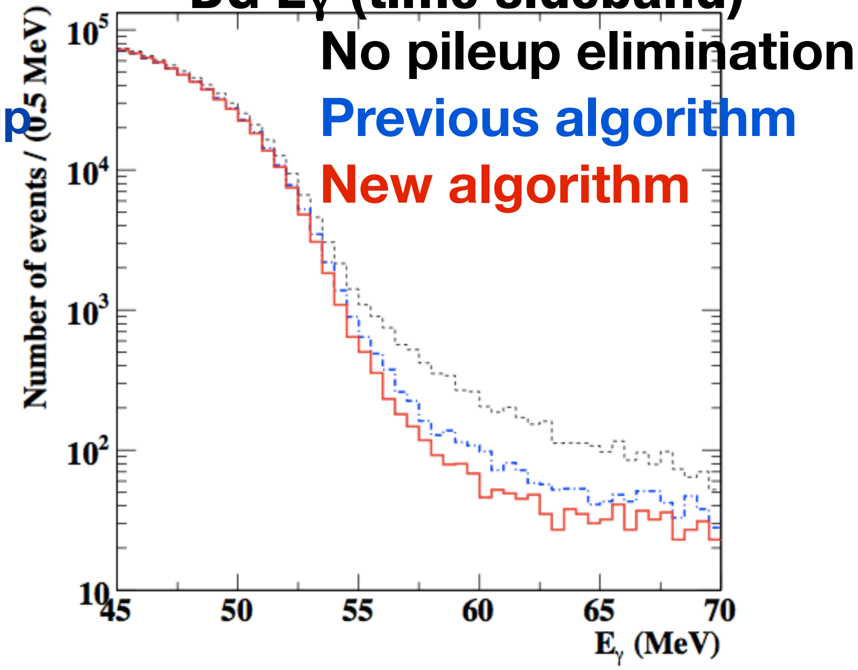
55 MeV spectrum (pi0 run)



BG Eγ (time sideband)

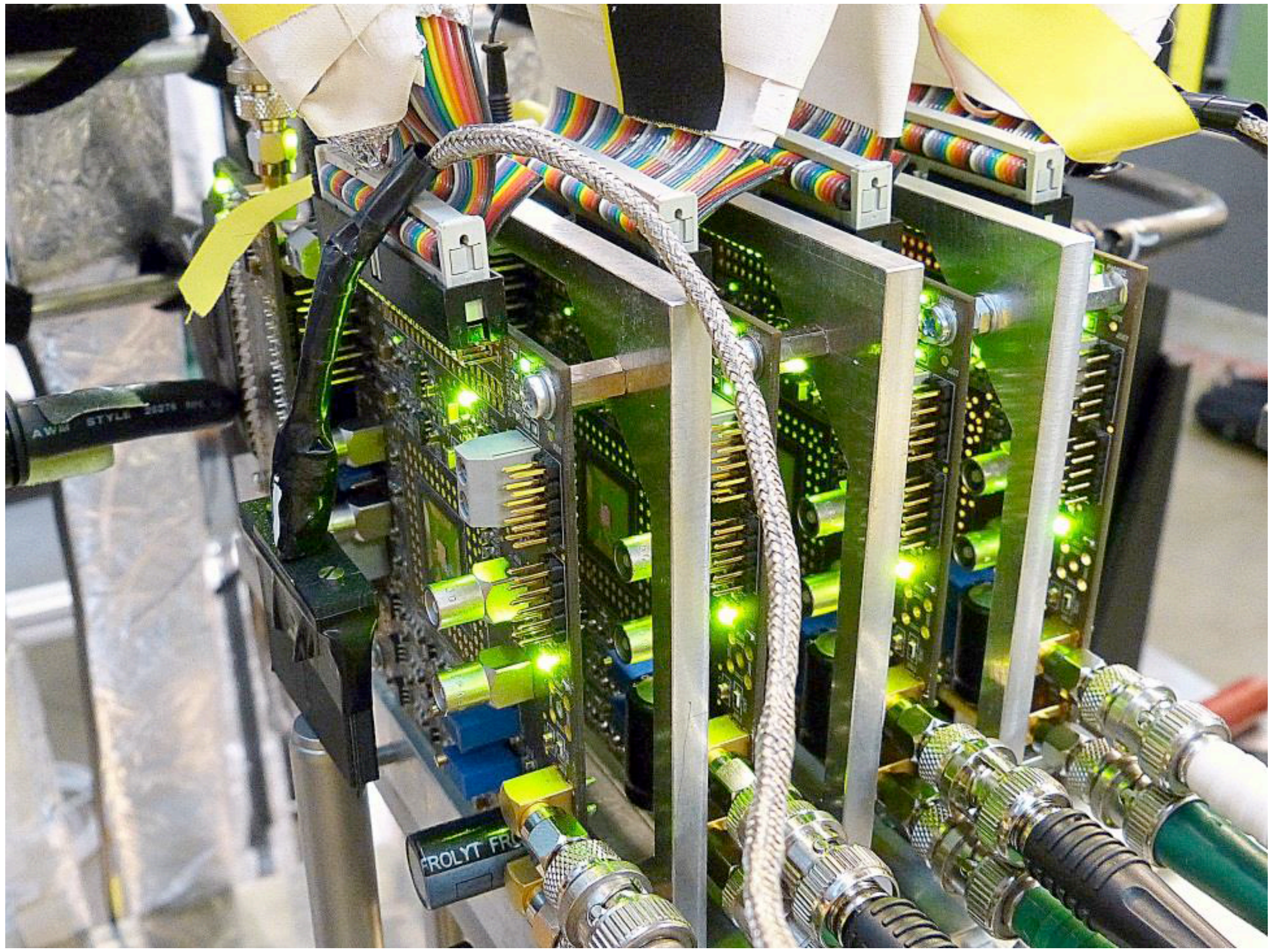


BG Eγ (time sideband)

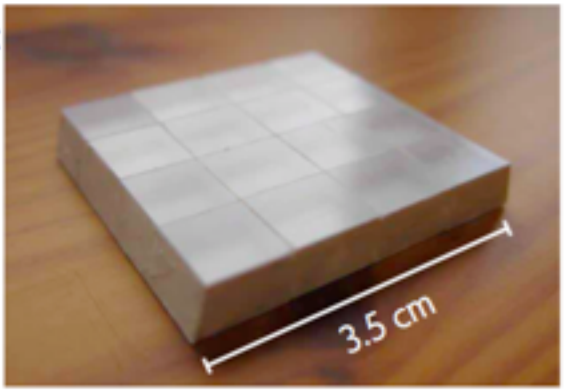


The Mu3e tracker detector: Mupix

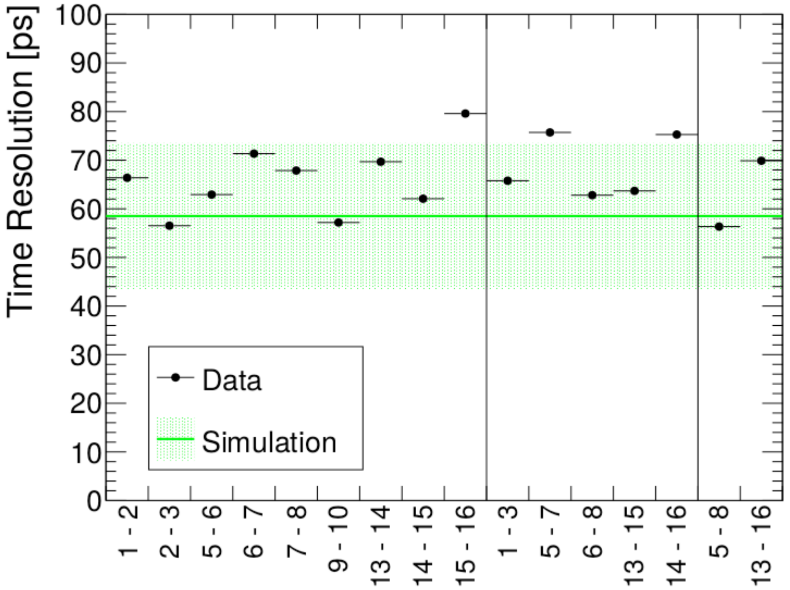
- Based on the High Voltage Monolithic Active Pixel Sensors (HV-MAPs)
- HV-CMOS technology
- Reverserly biased ~60 V
  - charge collection via drift
  - fast <1ns
  - thinning to ~50 μm
- Integrated readout electronics
- Full detection efficiency (> 99%)
- High rate capability (> 1 MHz)
- Timing resolution < 17 ns

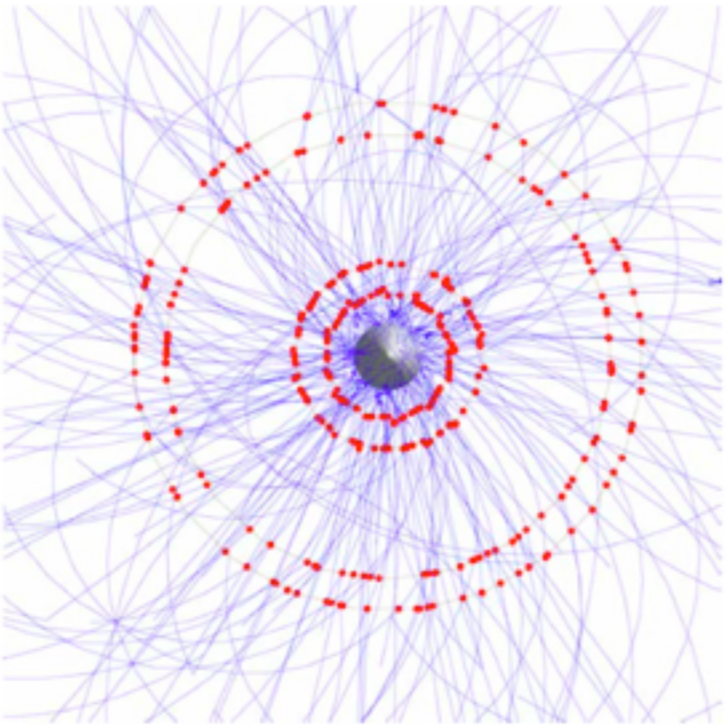


The timing detector: SciFi and Tiles

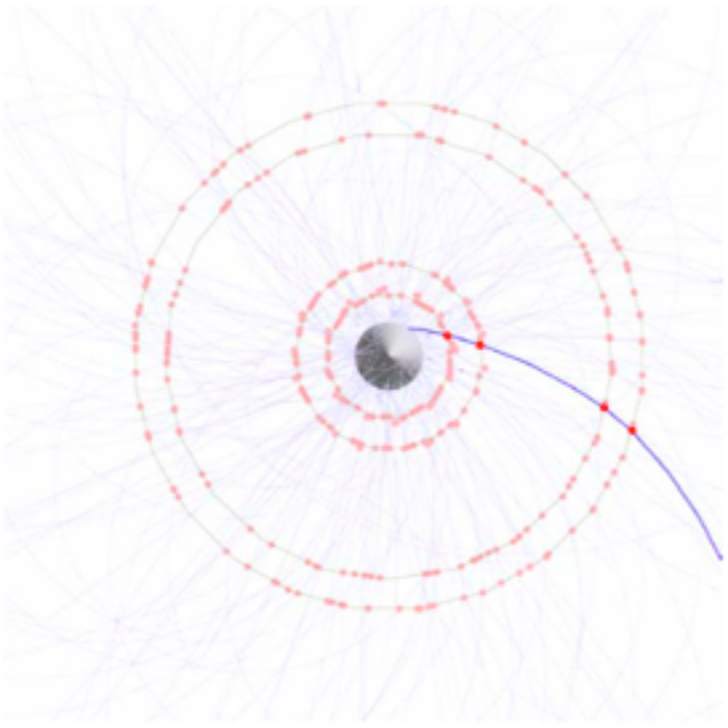


- Precise timing measurement is critical to reduce the accidental BGs
    - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
    - Scintillating tiles O(100 ps), full detection efficiency (>99%)

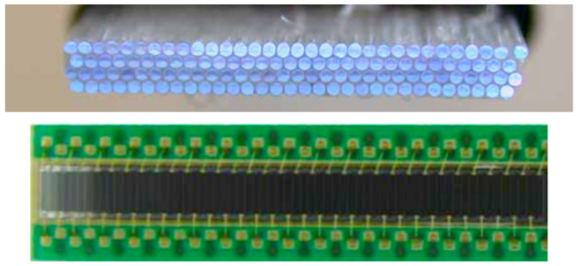


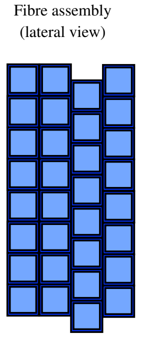


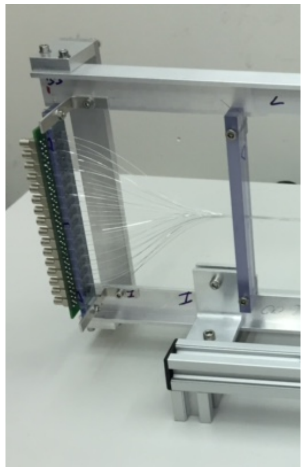
Pixels: O(50 ns)

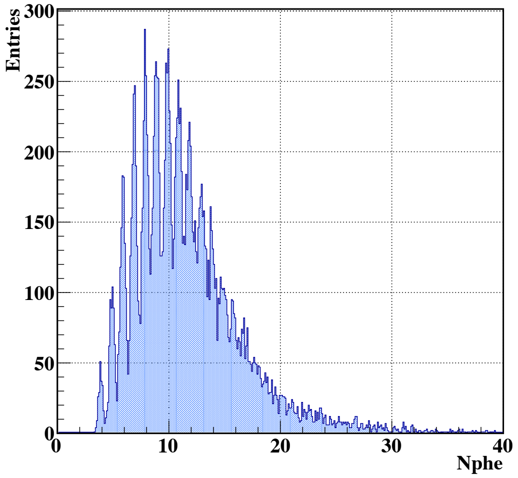


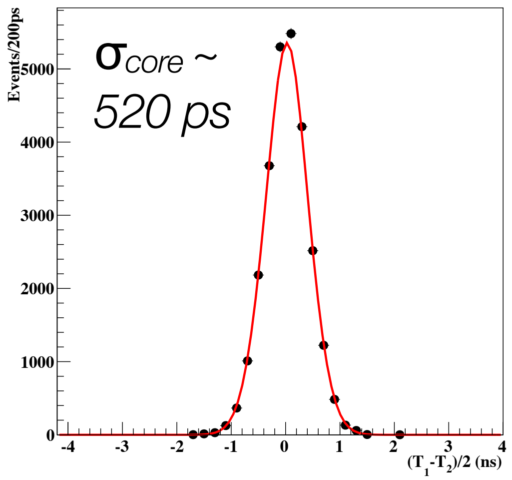
Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)











cLFV search landscape

Rough estimate of numbers of researchers, in total ~ 850 (with some overlap)

● Muons

~ 250

- MEG, PSI
- MEGII, PSI
- Mu3e, PSI
- DeeMee, J-PARC
- MuSiC, Osaka
- Mu2e, FNAL
- COMET, J-PARC
- PROJECT X, FNAL
- PRIME, J-PARC

● Taus

~ 250

- BABAR, PEPII
- BELLE/BELLE II, KEKB/SuperKEKB
- LHCb, CERN
- BESIII, Beijing

● Kaons

~ 100

- NA48,CERN
- NA62,CERN
- KOTO, J-PARC

● cLFV @ LHC

~ 250

- ATLAS,CERN
- CMS,CERN

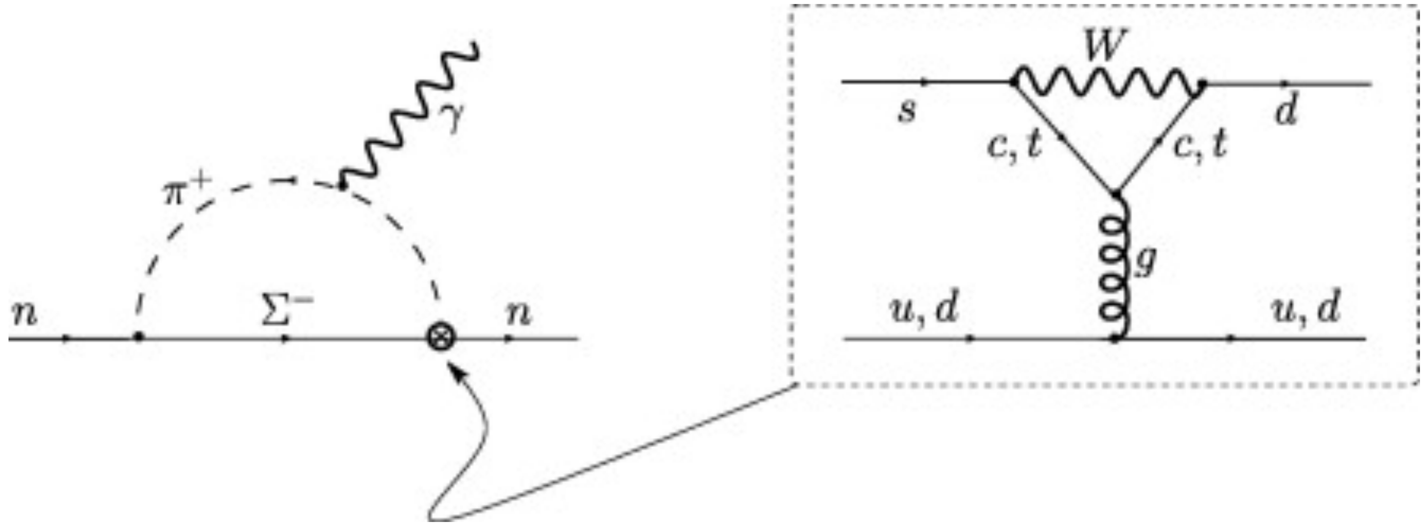
cLFV best upper limits

Process	Upper limit	Reference	Comment
$\mu^+ \to e^+ \gamma$	4.2×10^{-13}	arXiV:1605.05081	MEG
$\mu^+ \to e^+ e^+ e^-$	1.0×10^{-12}	Nucl. Phy. B299 (1988) 1	SINDRUM
$\mu^- N \to e^- N$	7.0×10^{-13}	Eur. Phy. J. c 47 (2006) 337	SINDRUM II
$\tau \to e \gamma$	3.3×10^{-8}	PRL 104 (2010) 021802	Babar
$\tau \to \mu \gamma$	4.4×10^{-8}	PRL 104 (2010) 021802	Babar
$\tau^- \to e^- e^+ e^-$	2.7×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$\tau^- \to \mu^- \mu^+ \mu^-$	2.1×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$\tau^- \to \mu^+ e^- e^-$	1.5×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$Z^0 \to \mu e$	7.5×10^{-8}	Phy. Rev. D 90 (2014) 072010	Atlas ($\mu \to 3e : 10^{-12}$)
$Z^0 \to \mu e$	7.3×10^{-8}	CMS PAS EXO-13-005	CMS
$H \to \tau \mu$	1.85×10^{-2}	JHEP 11 (2015) 211	Atlas (*)
$H \to \tau \mu$	1.51×10^{-2}	Phy. Let. B 749 (2015) 337	CMS
$K_L \to \mu e$	4.7×10^{-12}	PRL 81 (1998) 5734	BNL

* $B(H \to \mu e) < O(10^{-8})$ from $\mu \to e \gamma$

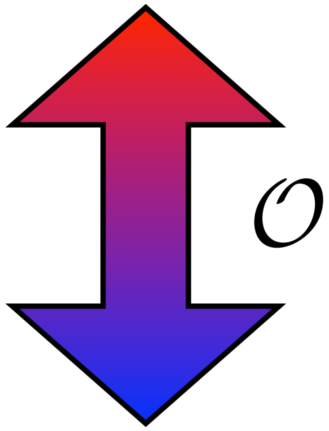
nEDM search - Motivations

- In the search for laboratory manifestations of new CP-violating effects, EDM play a crucial role: nEDM violates T and, assuming CPT conservation, also CP
- Standard Model nEDM predictions are much smaller than current experimental sensitivities
  - an observation of any particle's EDM today would signal discovery of NP
  - if of sufficient strength, such a CP-source could provide an important ingredient for baryon asymmetry



Current Upper Limit

$$d_n < 3 \times 10^{-26}\ e\ cm$$



$$\mathcal{O}(10^{5-6})$$

SM predictions

$$d_n \approx 10^{-32} - 10^{-31}\ e\ cm$$

ref.: M. Pospelov and A. Ritz, Annals of Physics 318 (2005) 119

nEDM status and future perspects

first

$$d_n < 5 \times 10^{-20} e\ cm$$

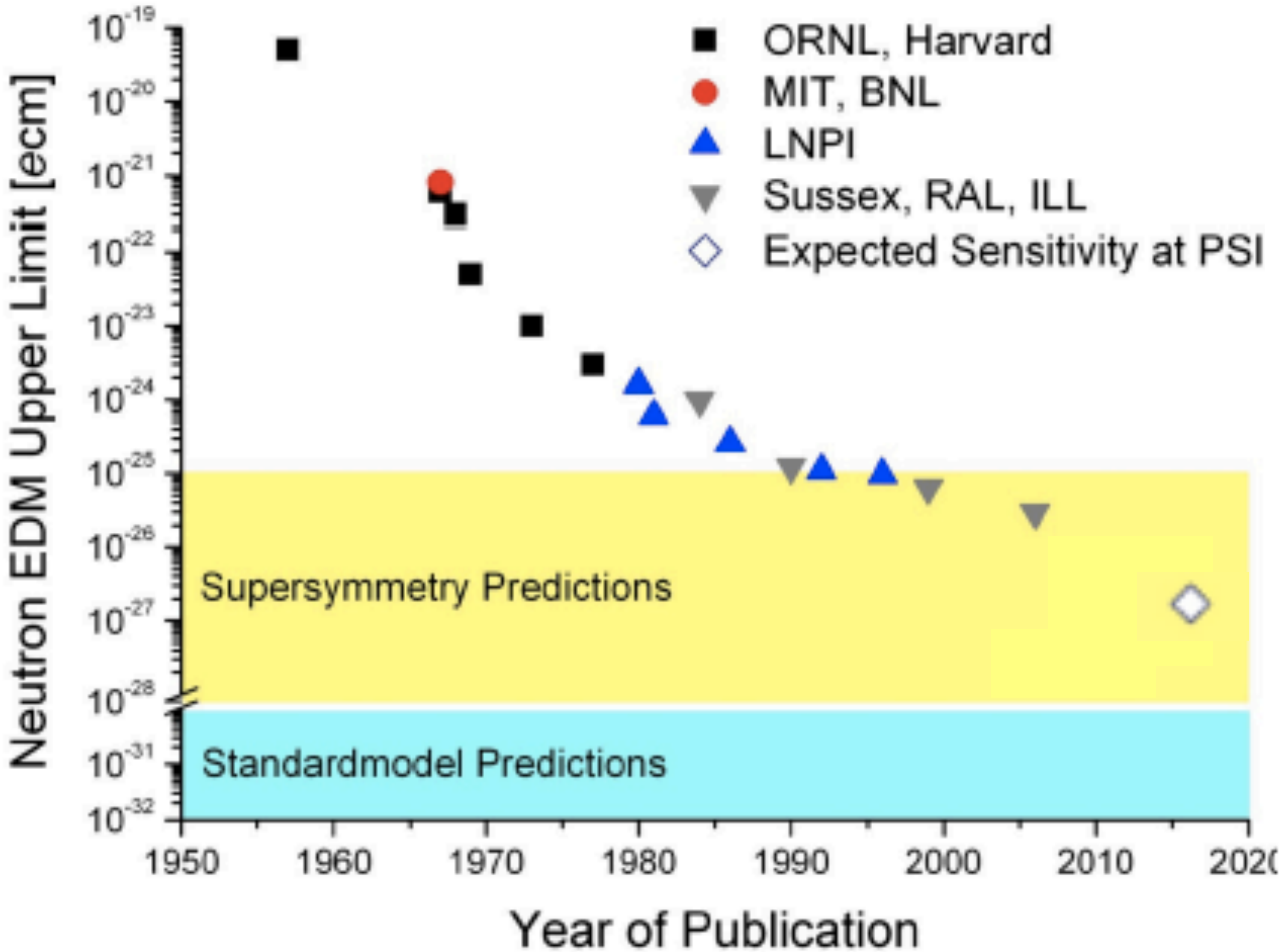
J. H.Smith, E.M. Purcell, and N.F. Ramsey
PR 108 (1957) 120

~ 50 years

last

$$d_n < 3.0 \times 10^{-26} e\ cm$$

C.B. Baker et al., PR. 97 (2006) 131801
J.M. Pendlebury et al., PRD 92 (2015) 092003

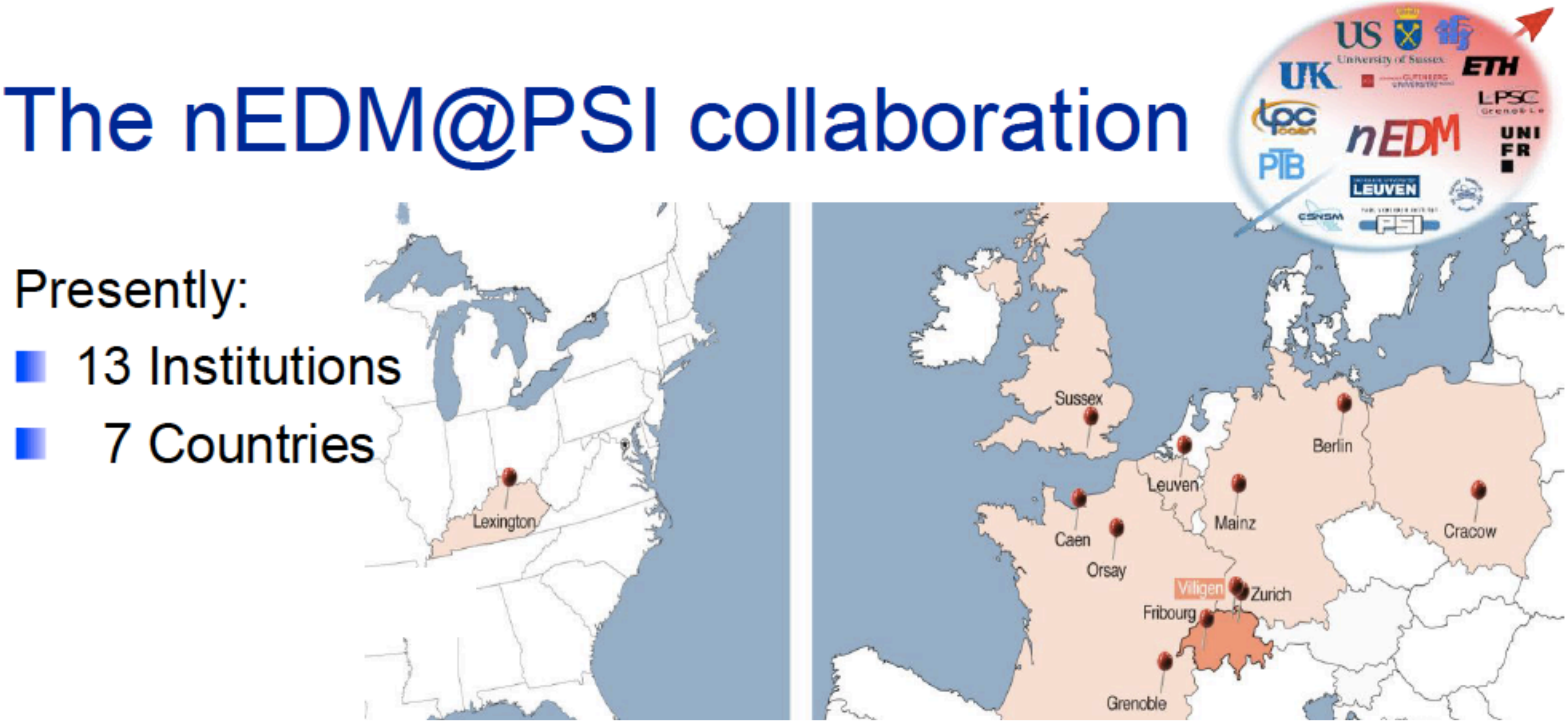


Aimed sensitivity
$d_n \sim 10^{-27}$ e cm

SM prediction
(electroweak)

$$d_n \approx 10^{-31} \mathrm{e \cdot cm}$$

nEDM collaboration



The nEDM@PSI collaboration

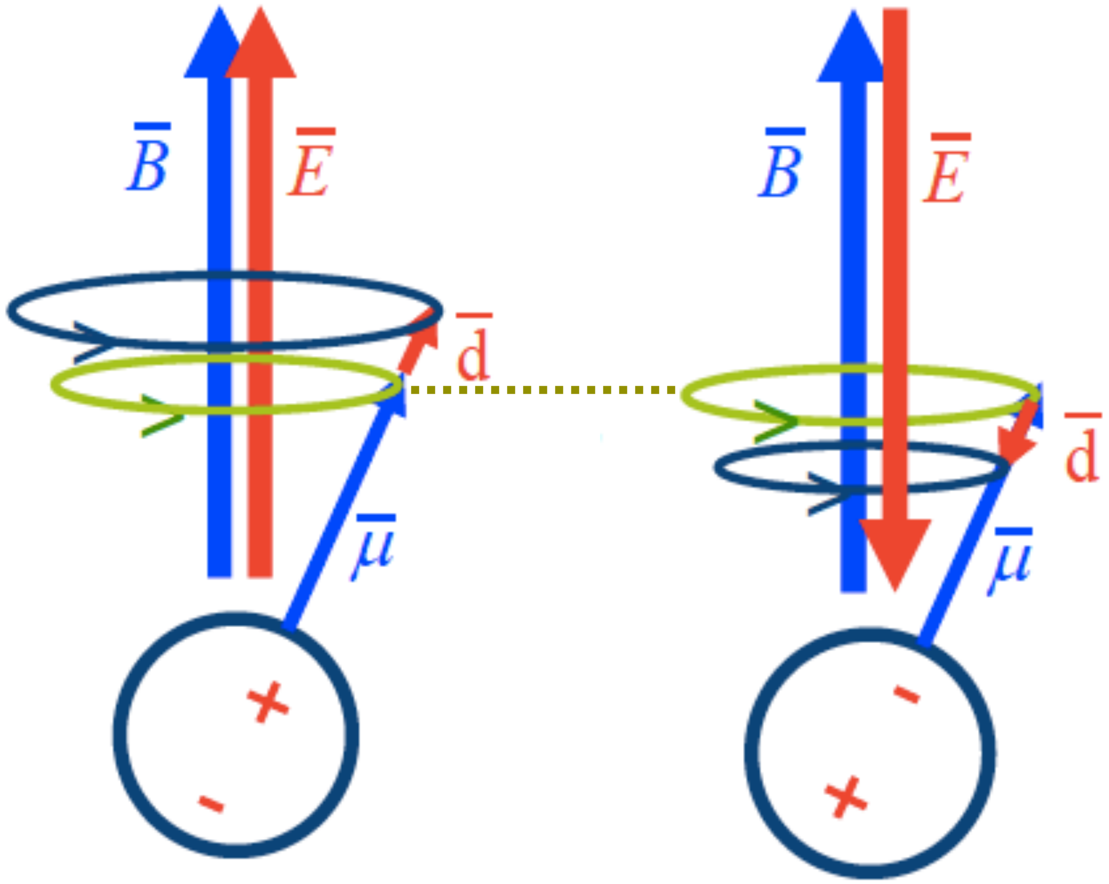
Presently:

- 13 Institutions
- 7 Countries

~ 60 members

Measurement principle

- Ramsey's method of separated oscillatory fields:



1. Measure Larmor precession frequency with parallel E and B

$$\hbar\omega_{\uparrow\uparrow} = 2(\mu_n B_{\uparrow\uparrow} + d_n E_{\uparrow\uparrow})$$

2. Measure Larmor precession frequency with antiparallel E and B

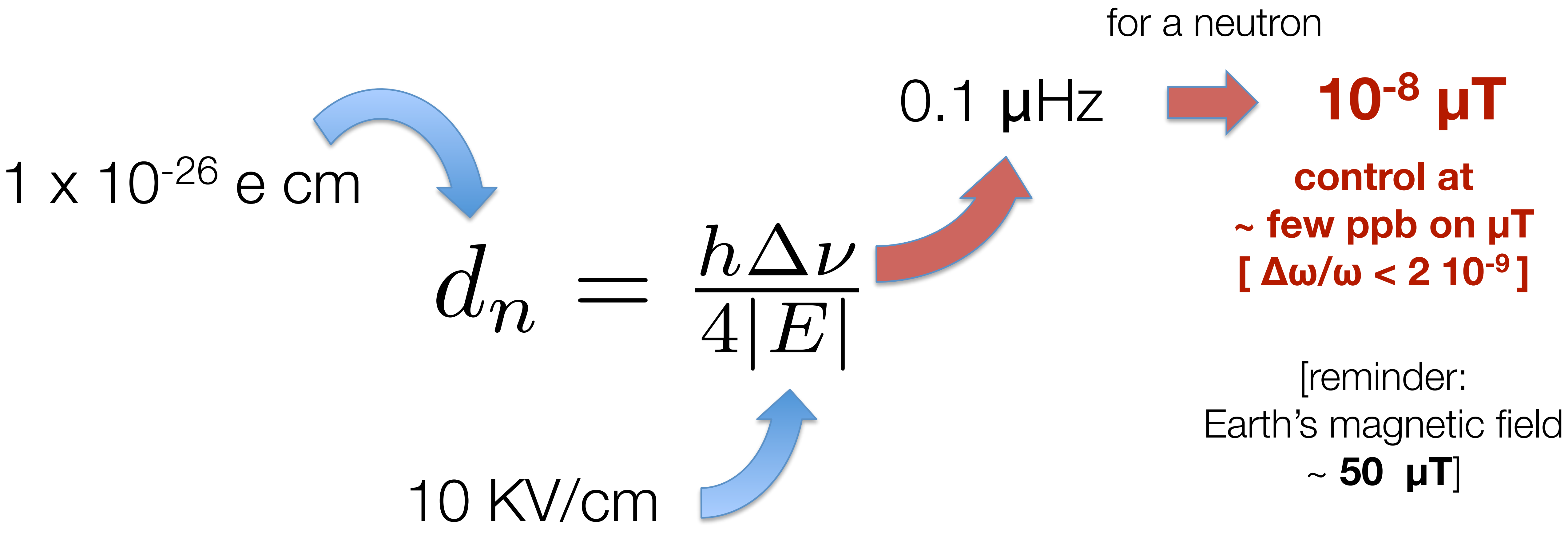
$$\hbar\omega_{\uparrow\downarrow} = 2(\mu_n B_{\uparrow\downarrow} - d_n E_{\uparrow\downarrow})$$

3. Take the difference

$$d_n = \frac{\hbar\Delta\omega - 2\mu_n(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})}{2(E_{\uparrow\uparrow} + E_{\uparrow\downarrow})} = \frac{\hbar\Delta\omega}{4|E|}$$

Measurement principle: In numbers

- Ramsey's method of separated oscillatory fields:



for a neutron

0.1 μHz → **10^{-8} μT**

control at
~ few ppb on μT
[$\Delta\omega/\omega < 2\ 10^{-9}$]

1 x 10^{-26} e cm

$$d_n = \frac{h\Delta\nu}{4|E|}$$

10 KV/cm

[reminder:
Earth's magnetic field
~ **50 μT**]

The control of the magnetic field is crucial for any EDM experiment

Statistical sensitivity

- If all the other contributions are below the counting fluctuations the sensitivity on nEDM is determined by the uncertainty in the measurement of the frequency
    - it corresponds to the fundamental limit sensitivity given by Heisenberg's uncertainty principle

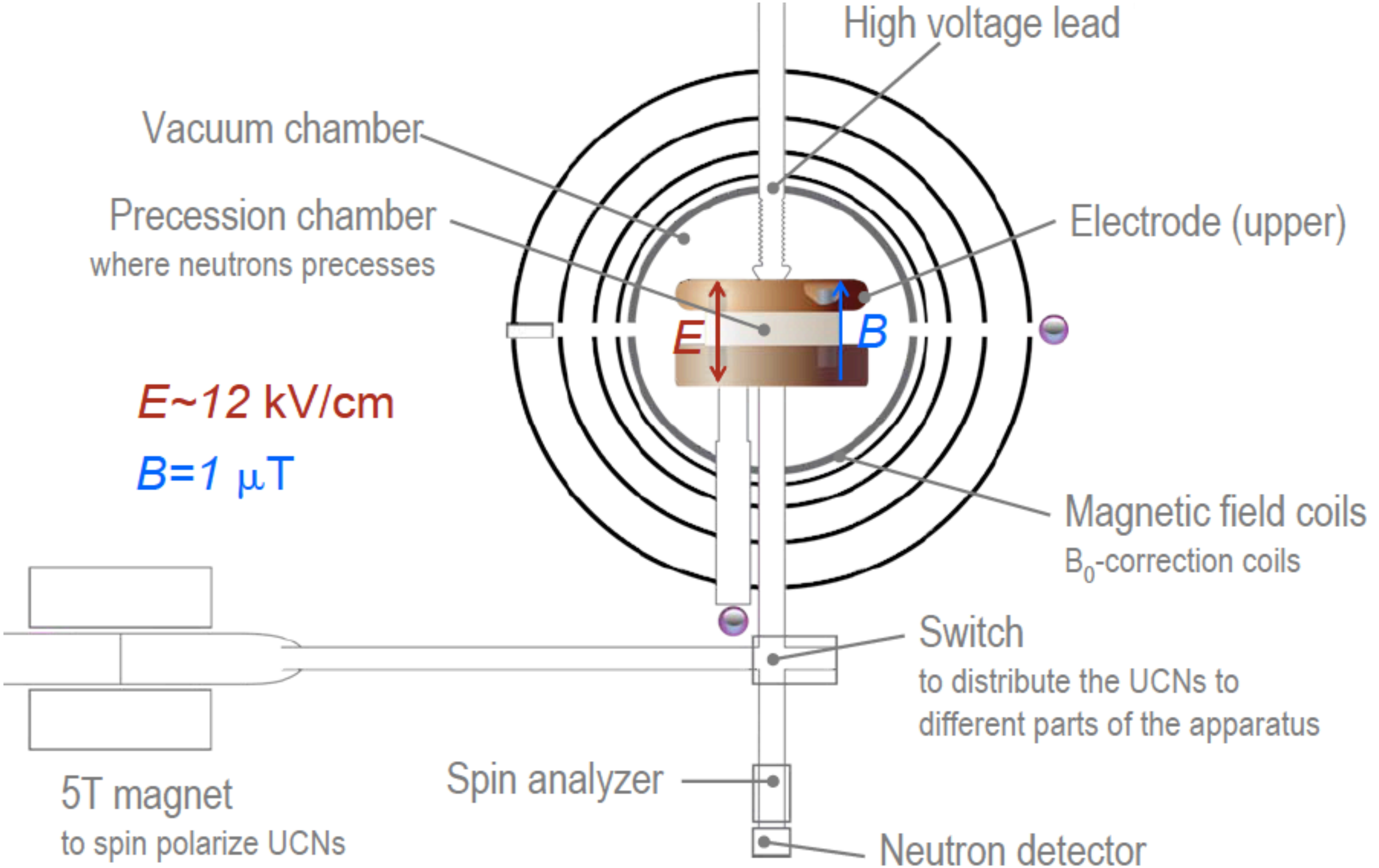
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

α: visibility of resonance
E: electric field
T: free precession time
N: neutrons number

The Experimental Setup

- Ultra cold neutrons (UCN)
  - UCNs definition: neutrons with low energy enough (< 300 neV) that they undergo total reflection from a given surface at any angle of incidence
  - Can be guided and stored in a vessel
  - Speed less than 7 m/s
- Setup moved from ILL to PSI

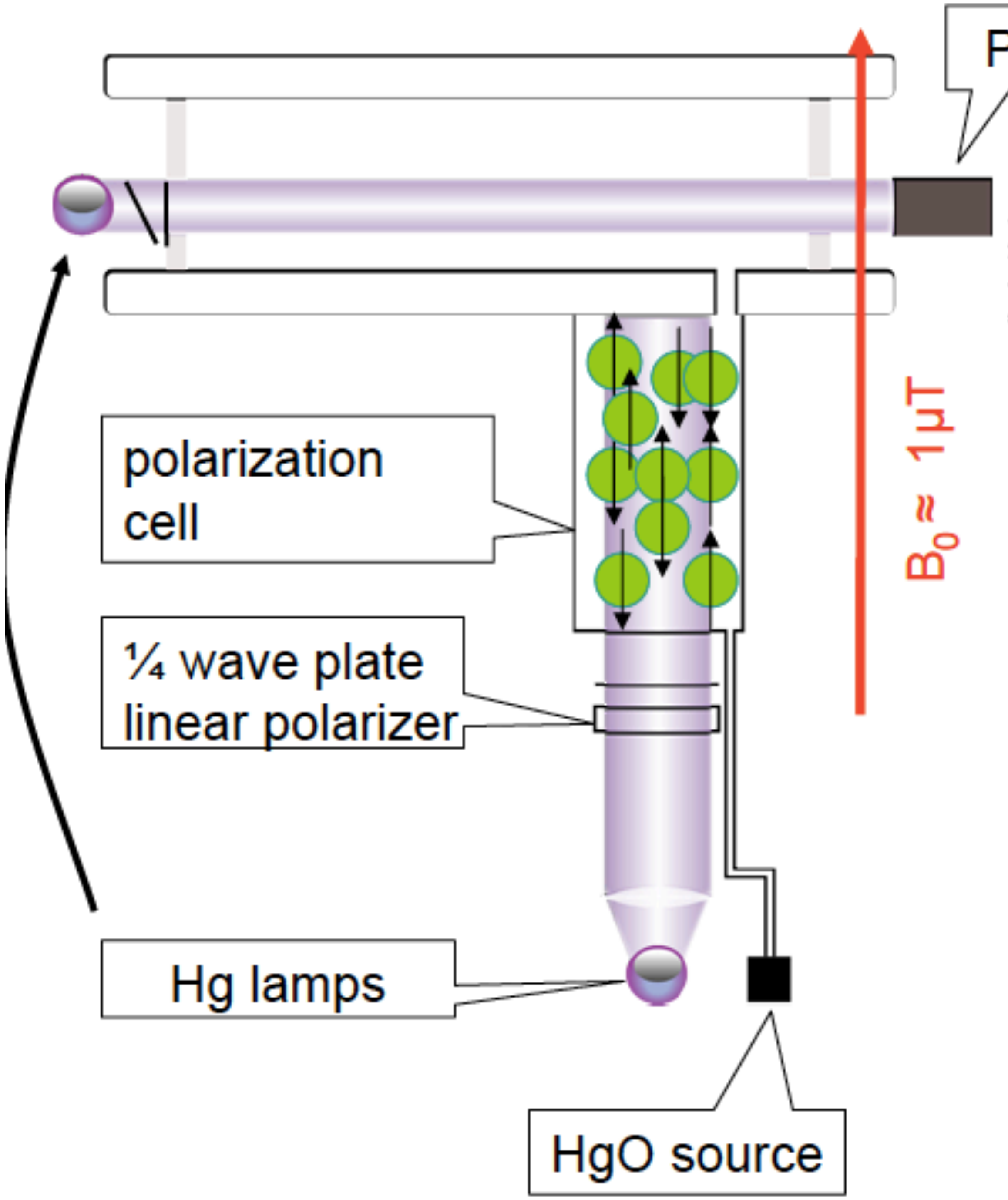
The nEDM Setup

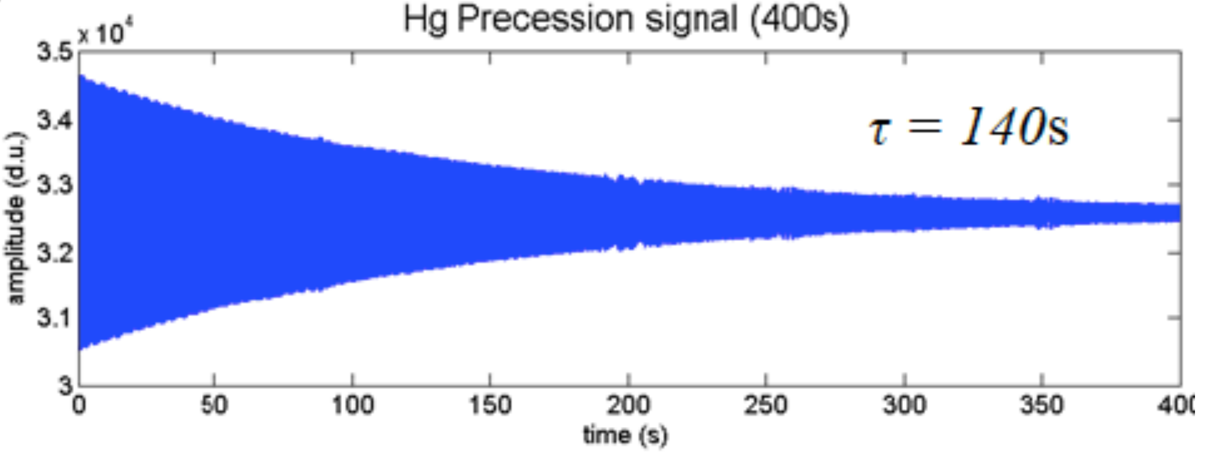


$E \sim 12$ kV/cm

$B = 1\ \mu\text{T}$

Precession magnetic field monitoring: The Hg magnetometer



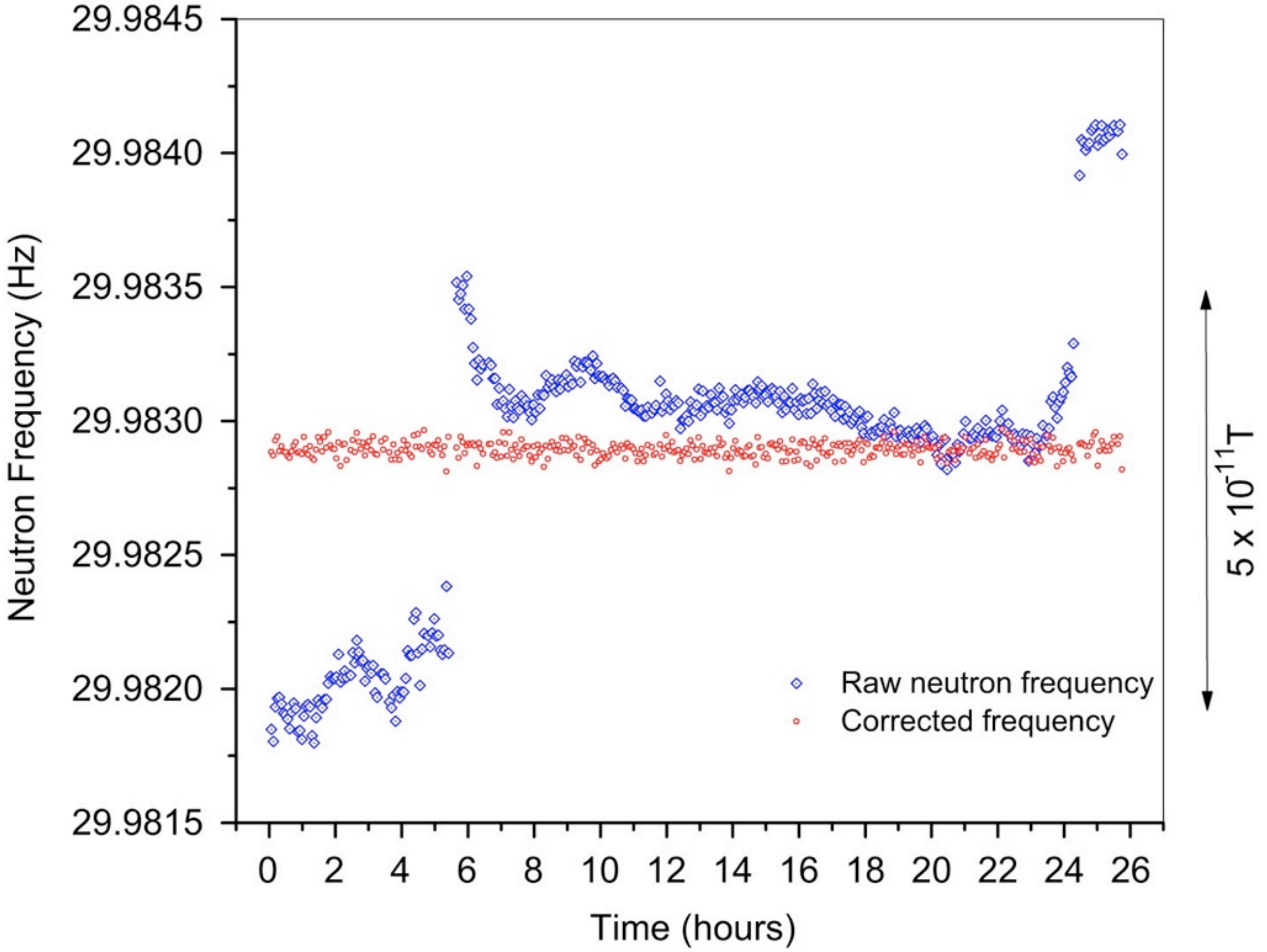


- Average magnetic field (volume and cycle)
- σ(B) ~ **few 10^{-8} μT**
- Center of mass different for UCN
- To be taken into account: **systematic effects due to field gradients**

ref.: C.A. Baker et al. NIMA A 736 (2014) 184

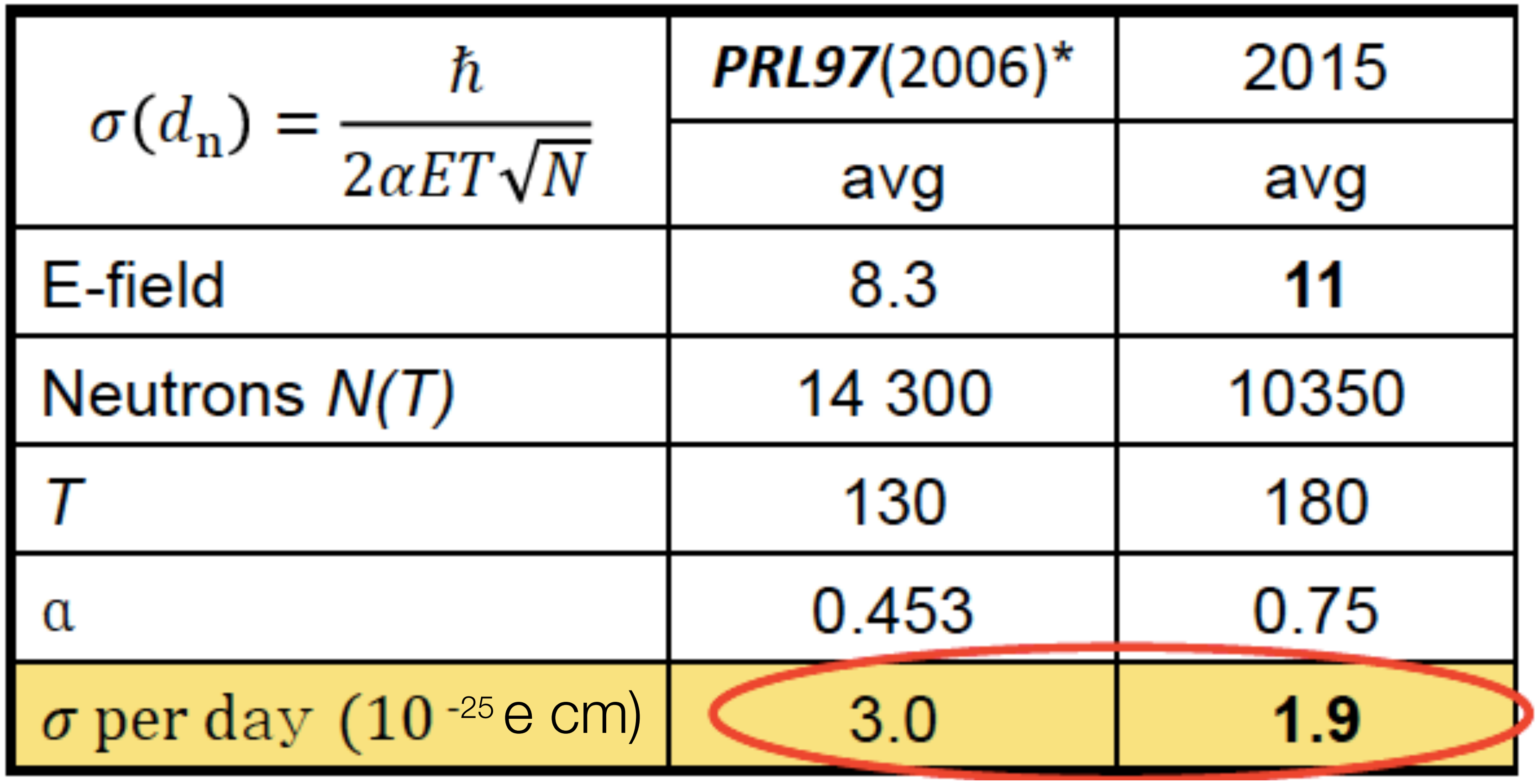
Hg magnetometer: calibration benefit

- Neutron resonance frequency **before** and **after** correction of the effect of the drifting magnetic field

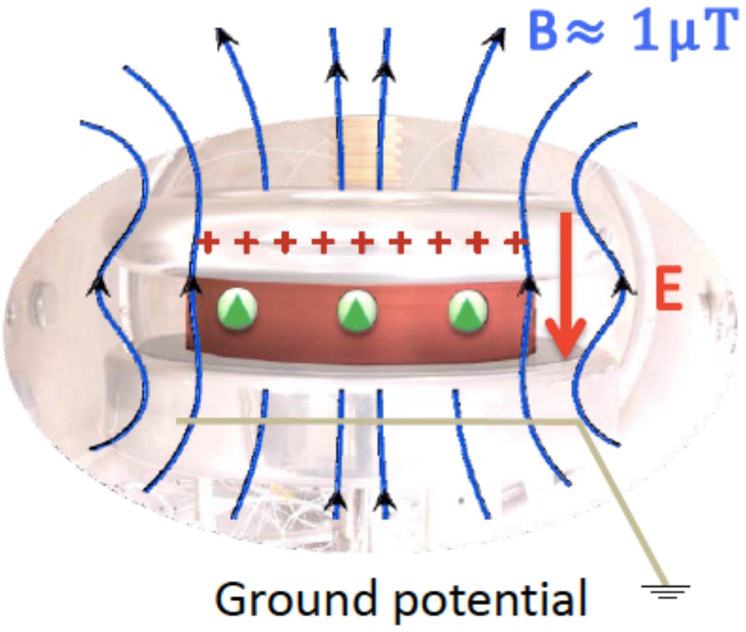


nEDM search: recent results

statistical sensitivity: $\sigma(d_n) = \dfrac{\hbar}{2\alpha E T \sqrt{N}}$



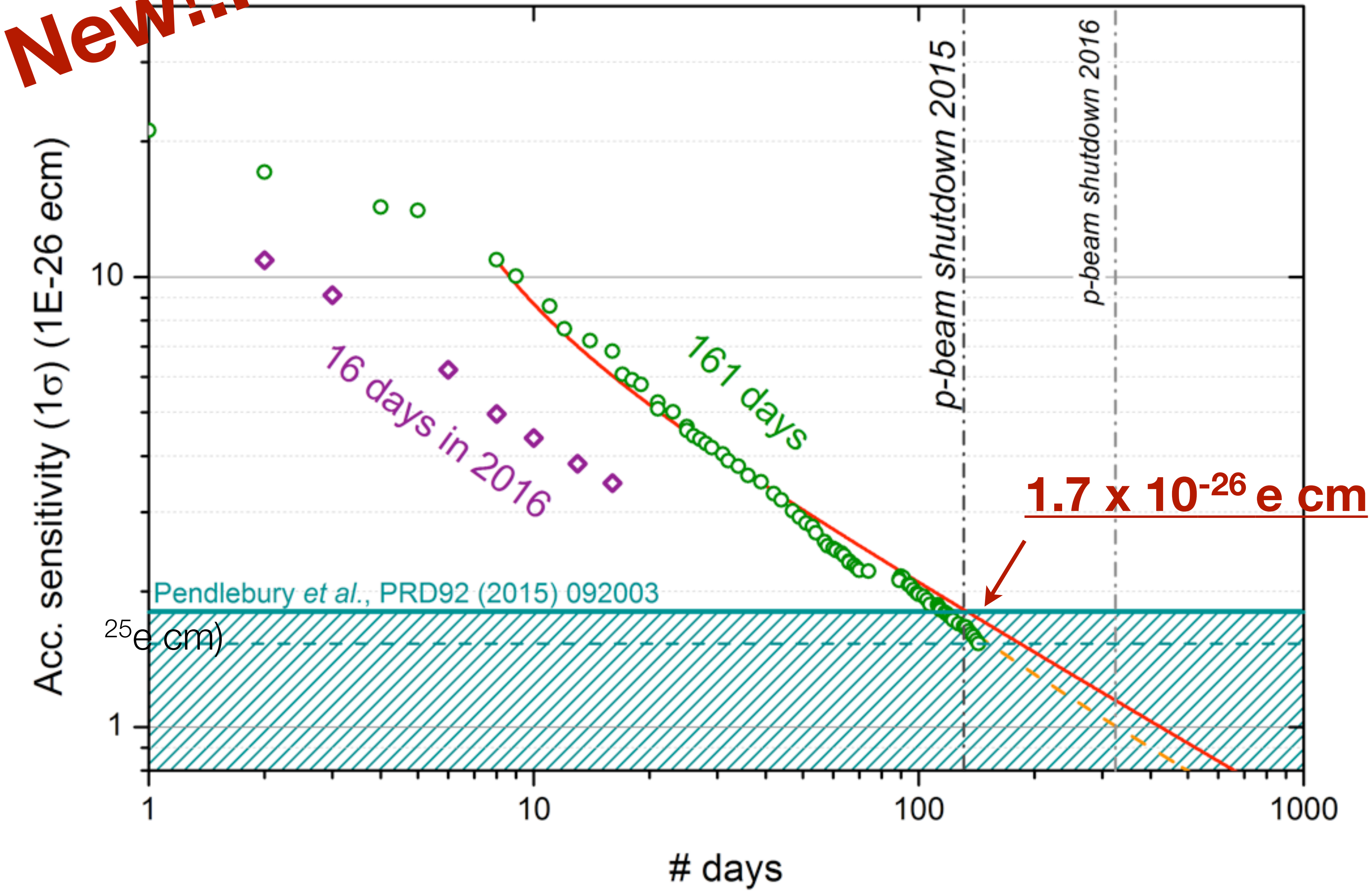
$\sigma(d_\mathrm{n}) = \dfrac{\hbar}{2\alpha E T\sqrt{N}}$	***PRL97***(2006)*	2015
	avg	avg
E-field	8.3	**11**
Neutrons *N(T)*	14 300	10350
T	130	180
α	0.453	0.75
σ per day (10^{-25} e cm)	3.0	**1.9**



* Best ***DIRECT*** *nEDM limit*
[reanalysis in Pendlebury et al. PRD ***92*** *(2015) 092003]*

ref.: S. Afach et al., EPJA ***51*** *(2015) 143*
S. Afach et al., PRL ***115*** *(2015) 162502*

nEDM search: recent results



New!!!

1.7 x 10^{-26} e cm

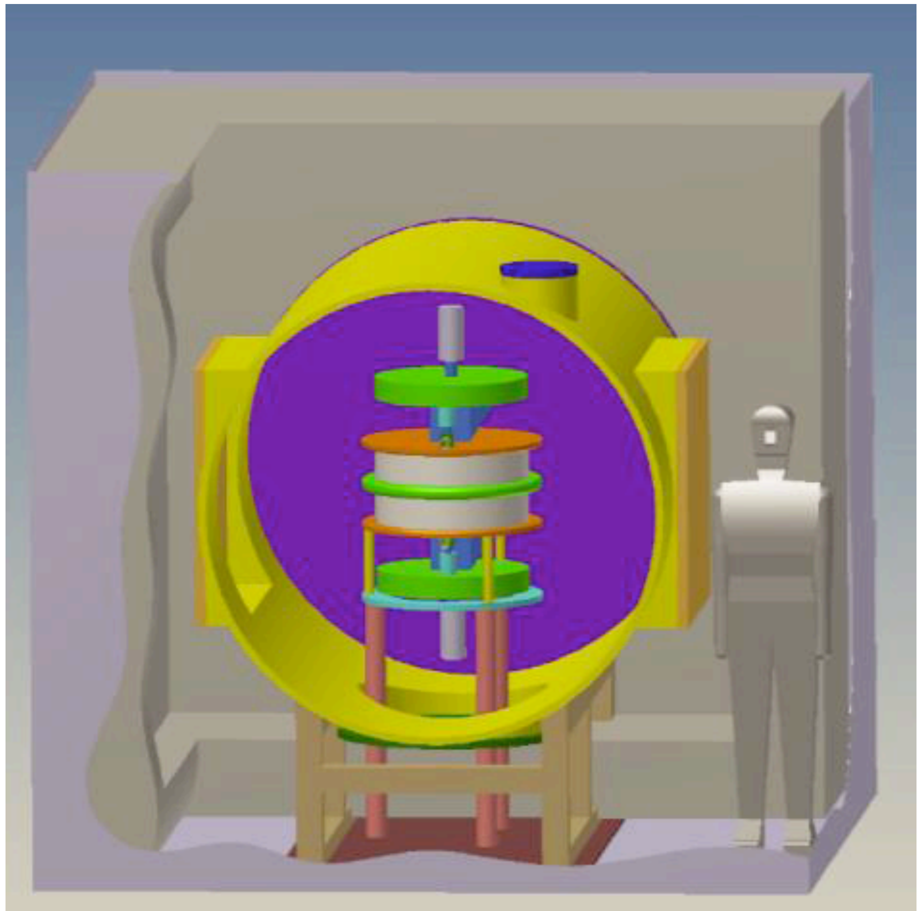
Final nEDM sensitivity $d_n \sim 10^{-26}$ e cm

*ref.: S. Afach et al., EPJA **51** (2015) 143*
*S. Afach et al., PRL **115** (2015) 162502*

Next phase: n2EDM

- Aim: improving the current sensitivity by **one order of magnitude**

- Some elements of the new setup:

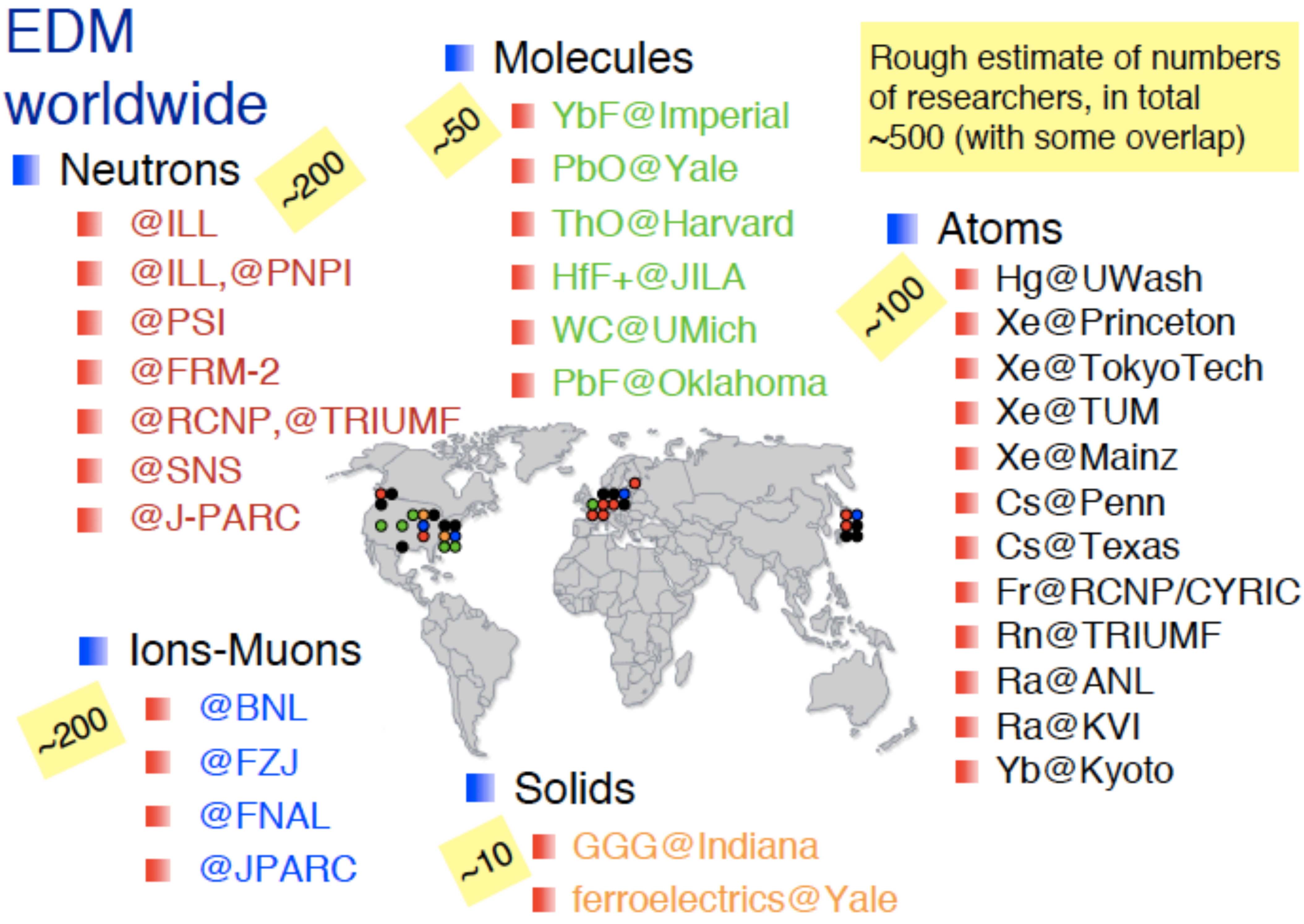


  - Double chamber setup
  - New mu-metal shield
  - He magnetometers
  - Improved Hg magnetometer
  - Vector Cs magnetometers
  - ...
- Schedule: start data taking in ~ end of 2019

- Final Goal:

sensitivity ~ 10^{-27} e cm

EDM search landascape



EDM worldwide

- **Neutrons** ~200
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC

- **Molecules** ~50
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- **Atoms** ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto

- **Ions-Muons** ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC

- **Solids** ~10
  - GGG@Indiana
  - ferroelectrics@Yale

EDM best upper limits

- Present best EDM limits of their kind: bare nucleon, lepton, diamagnetic atom, paramagnetic atom, and molecule. The indirect limit is based on the assumption that it is the sole contribution to the parent EDM

System	upper limit [e cm]	reference	comment
n	3.0×10^{-26} (90% C.L.)	Phy. Rev. D 92 (2015) 092003	best direct limit for n
μ	1.8×10^{-19} (95% C.L.)	Phy. Rev. D 80 (2009) 052008	direct limit
^{199}Hg	7.4×10^{-30} (95% C.L.)	Phy. Rev. Lett. 116 (2016) 161601	best direct limit of any experiment
^{199}Hg (n)	1.6×10^{-26} (95% C.L.)	“	best indirect limit for n
^{199}Hg (p)	2.0×10^{-25} (95% C.L.)	“	best indirect limit for p
^{205}Tl	9.0×10^{-25} (90% C.L.)	Phy. Rev. Lett. 88 (2002) 071805	direct limit
^{205}Tl (e)	1.6×10^{-27} (90% C.L.)	“	indirect limit
^{225}Ra	5.0×10^{-22} (95% C.L.)	Phy. Rev. Lett. 114 (2015) 233002	direct limit
YbF	1.1×10^{-22} (90% C.L.)	Nature 473 (2011) 493	direct limit
YbF (e)	1.05×10^{-27} (90% C.L.)	“	indirect limit
ThO (e)	8.7×10^{-29} (90% C.L.)	Science 343 (2014) 269	best indirect limit for e

Outlook

- cLFV and EDM processes are among the most clean where to search for new physics
  - muon cLFV: most cLFV sensitive channels
  - nEDM searches: a major role looking for laboratory manifestation of new CP-violating effects
  - complementarity for unveling the driven physics associated with them
- PSI/Swiss Institutions are leading such a researches (MEG, MEGII, Mu3e, nEDM, n2EDM, HiMB, muCool...A. Knecht' talks)

- a plethora of fundamental processes can be studied with muons and neutrons
  - we are not allowed to loose such opportunities and leaderships

Acknowledgements

- Thanks to
    - MEG/MEGII, Mu3e and nEDM collaborations for the materials
    - Philipp Schmidt-Wellenburg for the discussions
- and very warm thanks to you for your attention

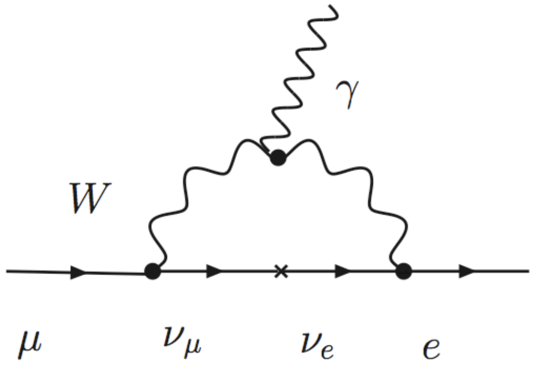
Backup

Outlook

- cLFV processes are among the most clean where to search for new physics
  - muon cLFV: most sensitive channels - complemetarity for unveling the physics driving them
  - PSI/Swiss Institutions are leading such a research (MEG, MEGII, Mu3e, HiMB, muCool...)
- nEDM searches have a major role looking for laboratory manifestation of new CP-violating effects
  - any particle's EDM would signal discovery of new physics
  - PSI/Swiss Institutions are the frontier research (UCN, nEDM, n2EDM)
- a plethora of fundamental processes can be studied with muons and neutrons
  - we are not allowed to loose such opportunities and the leaderships

The $\mu^+ \to e^+ \gamma$ decay as an example

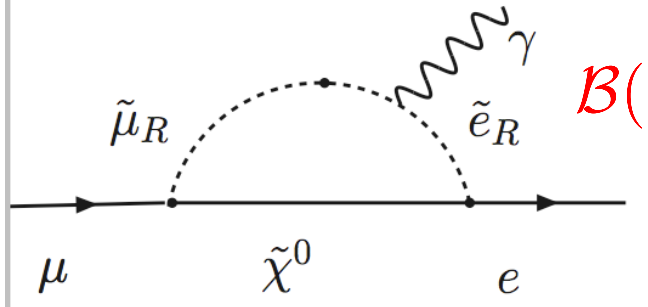
SM with massive neutrinos (Dirac)



$$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$$

too small to access experimentally

i.e. SU(5) SUSY-GUT or SO(10) SUSY-GUT



$$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$$

an experimental evidence:
a clear signature of New Physics

The $\mu^+ \to e^+ \gamma$ decay as an example

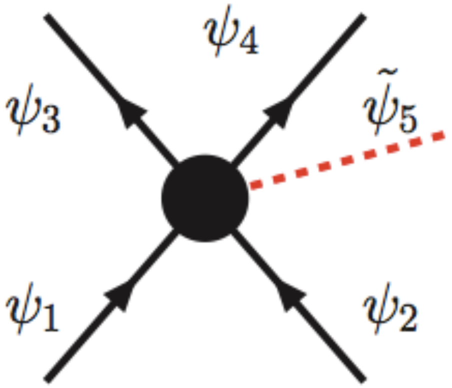
The role of low energy physics:
a sensitive tool

- to unveil behind SM physics (virtual particles)

New Physics

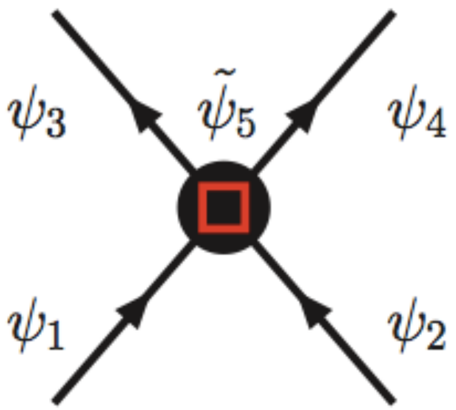
SM with massive neutrinos (Dirac)

Energy frontier

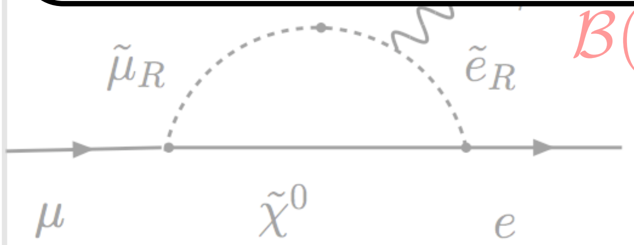


Real BSM
particles

Precision and intensity frontier



Virtual BSM
particles



$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$

an experimental evidence:
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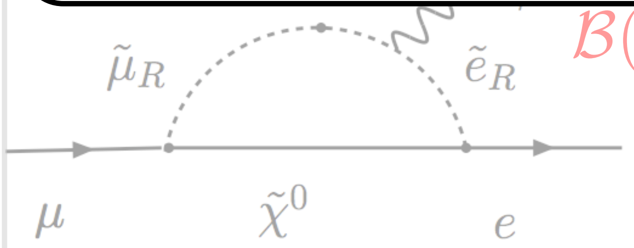
The $\mu^+ \rightarrow e^+ \gamma$ decay as an example

SM with massive neutrinos (Dirac)



$$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) \gg 10^{-54}$$

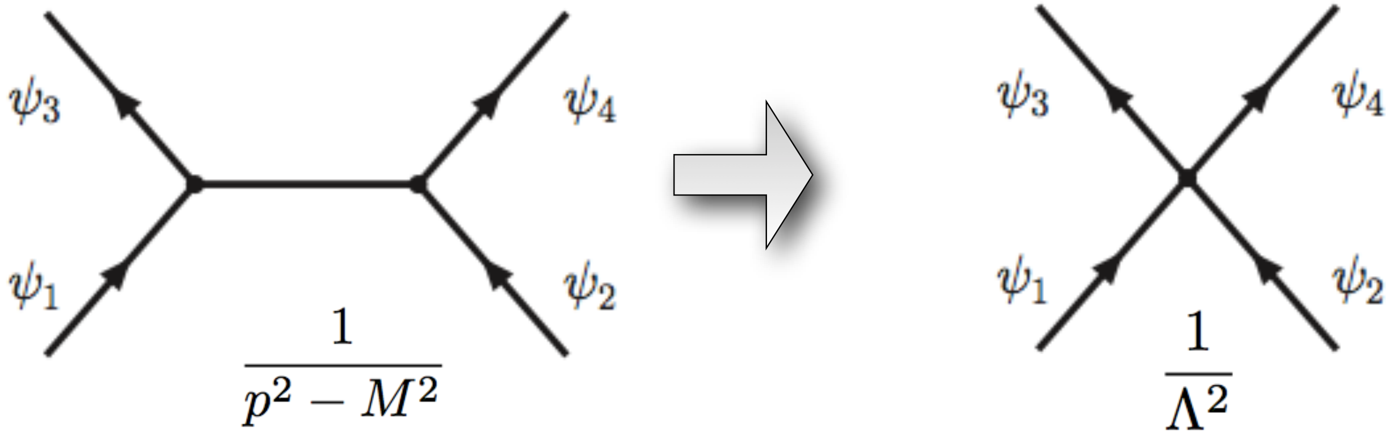
an experimental evidence:
a clear signature of New Physics

The role of low energy physics:
a sensitive tool

- to unveil behind SM physics (virtual particles)
- high energy scale probe (effective lagrangian)

New Physics

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$



The $\mu^+ \to e^+ \gamma$ decay as an example

The role of low energy physics:
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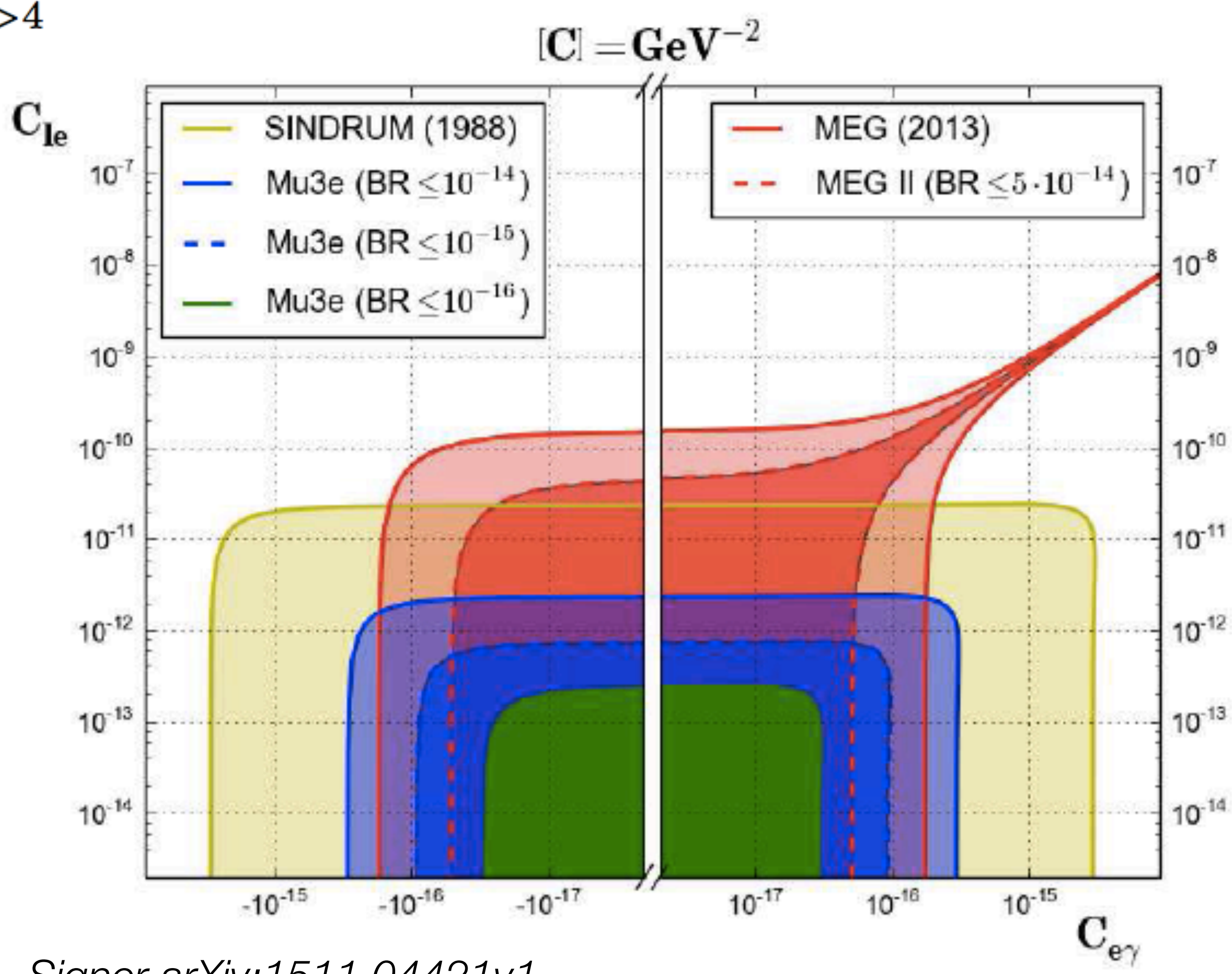
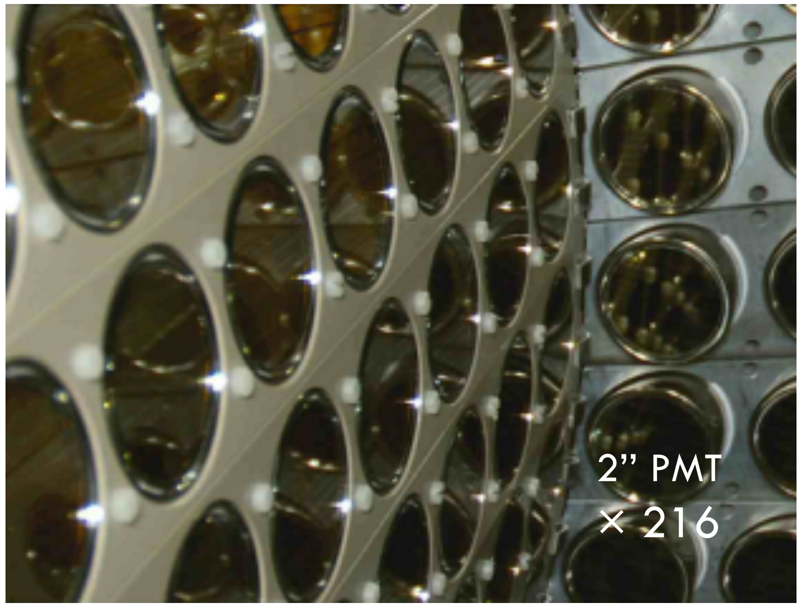
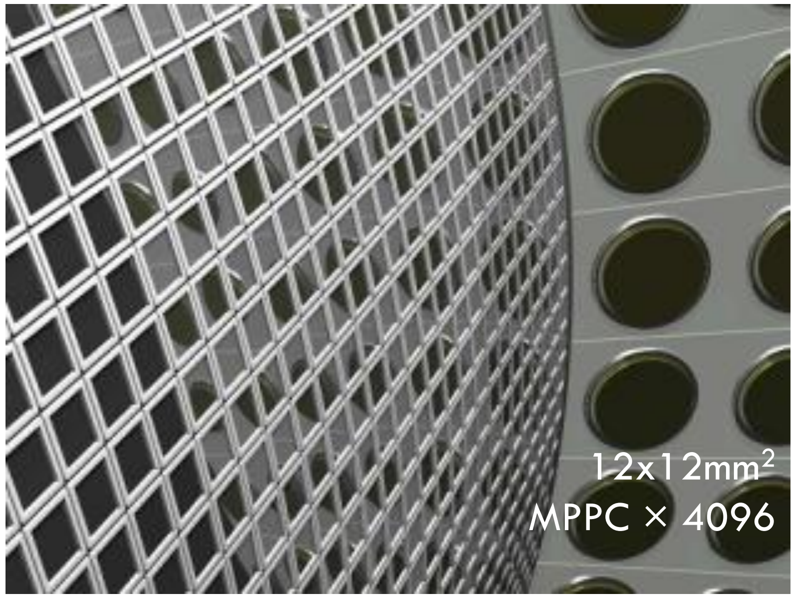


ref.: G.M. Pruna and A. Signer arXiv:1511.04421v1
G.M. Pruna and A. Signer JHEP 10 (2014) 014

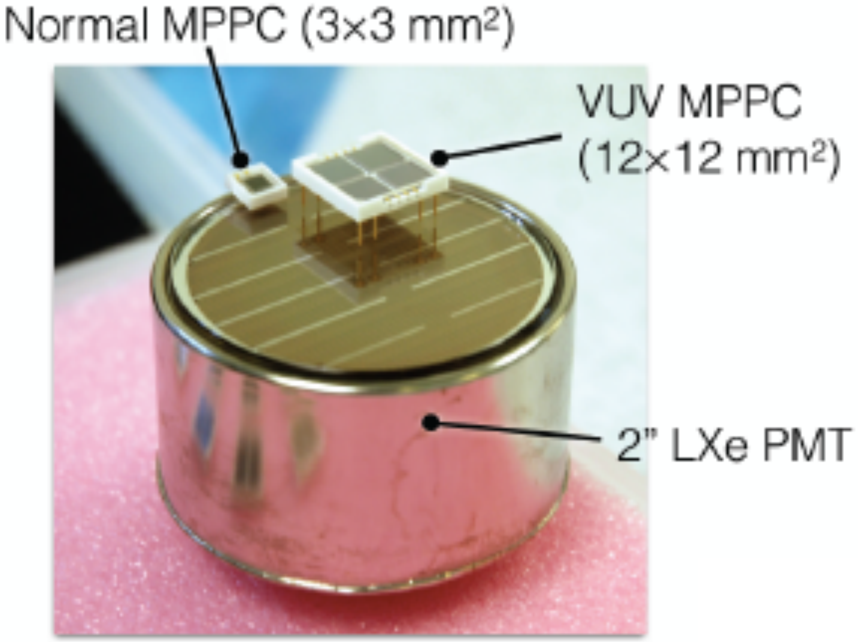
The MEGII calorimeter

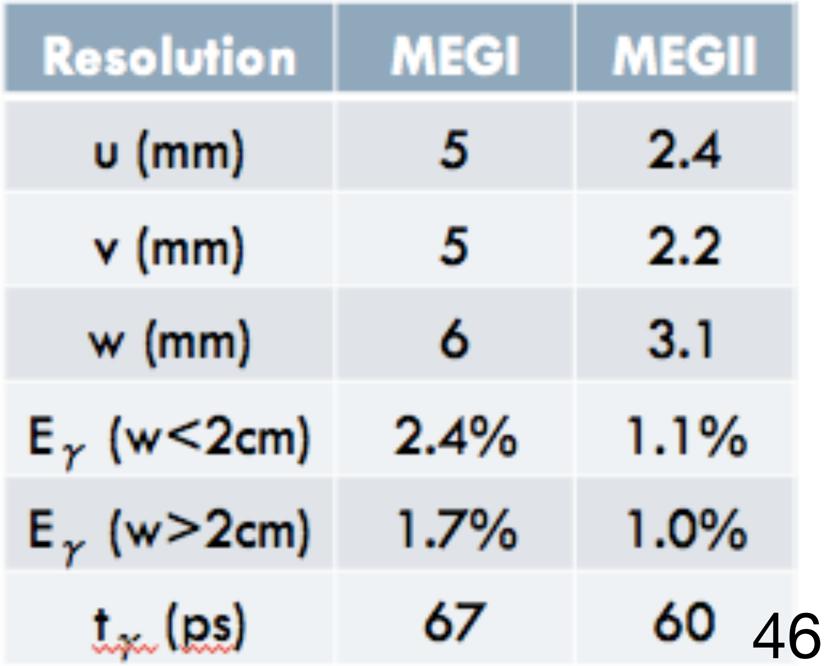




- Increased uniformity/ resolutions
- Increased pile-up rejection capability
- Increased acceptance and detection efficiency

new R&D: VUV SiPM





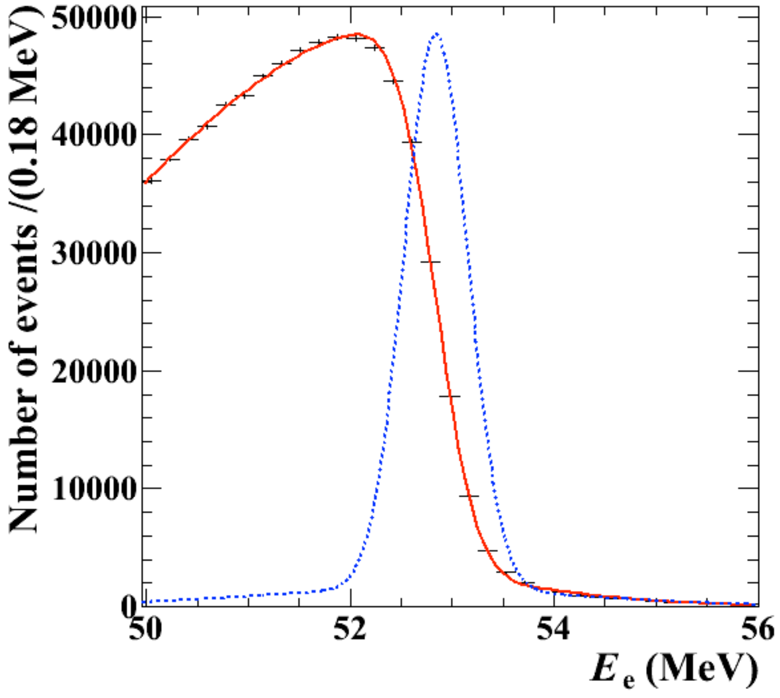
Resolution	MEGI	MEGII
u (mm)	5	2.4
v (mm)	5	2.2
w (mm)	6	3.1
E_γ (w<2cm)	2.4%	1.1%
E_γ (w>2cm)	1.7%	1.0%
t_γ (ps)	67	60

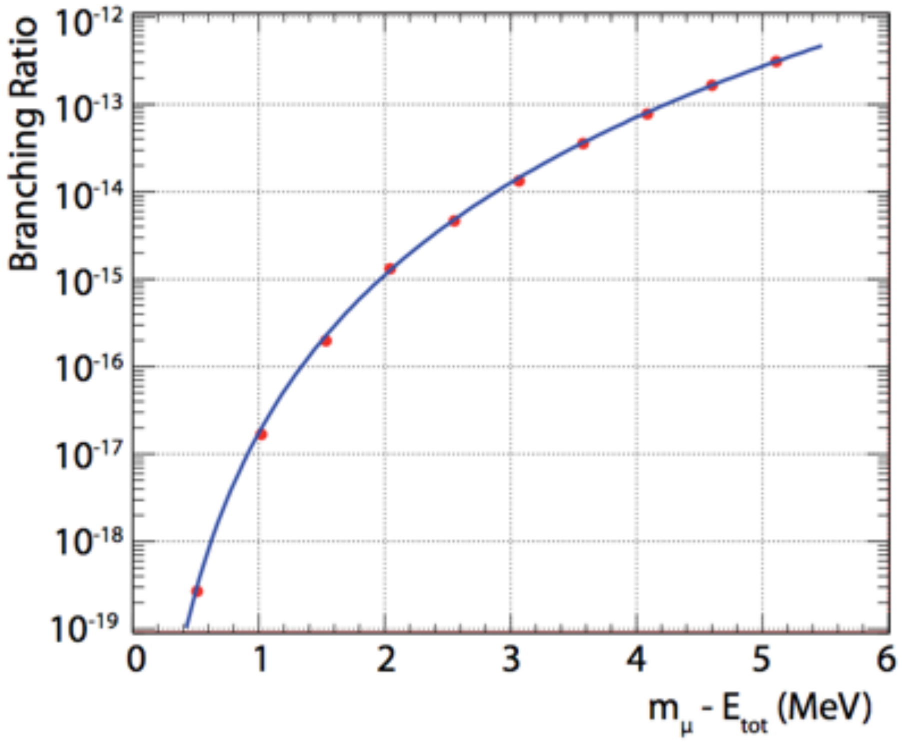
Positron/electron detector requirements

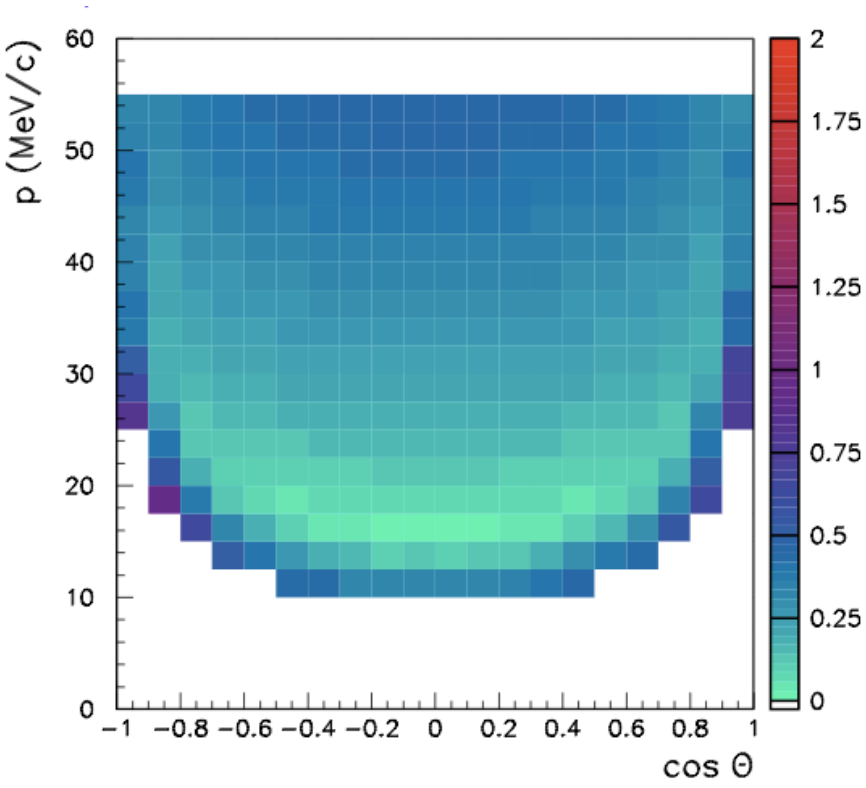
- High detection efficiency and acceptance (10 - 60 MeV/c)
- High rate capability
- High momemtum resolutions
  - good hit resolutions
  - low mass

MEG/MEGII

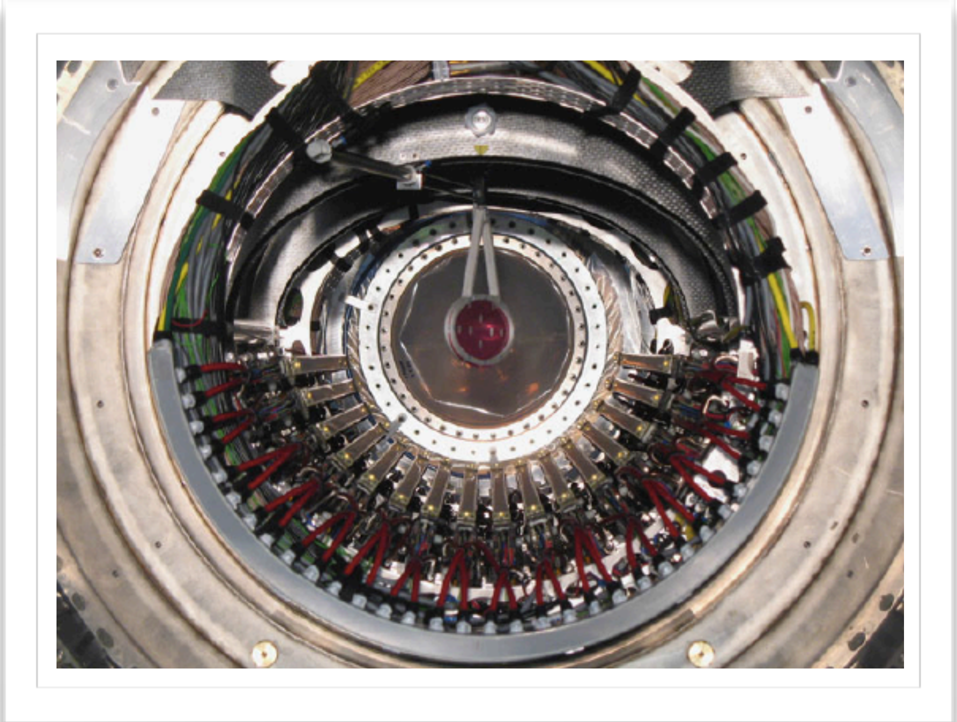
Mu3e

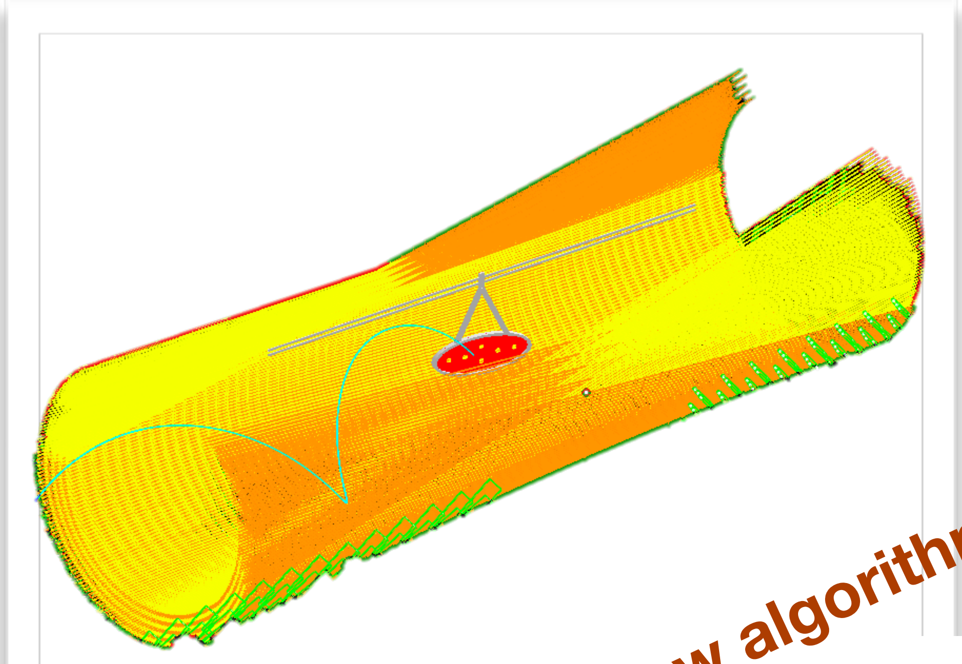




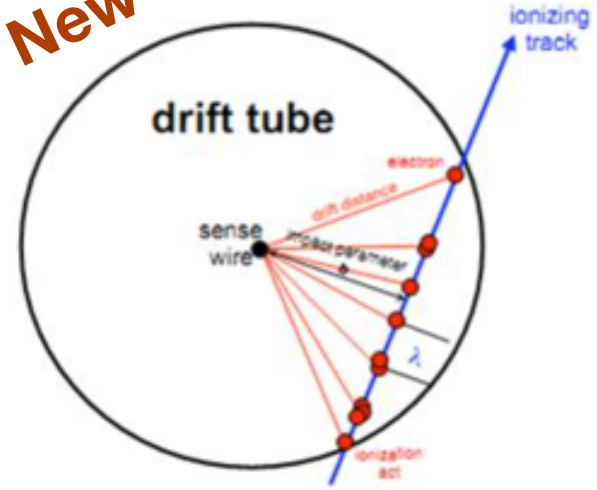


The MEGII spectrometer: a single volume chamber





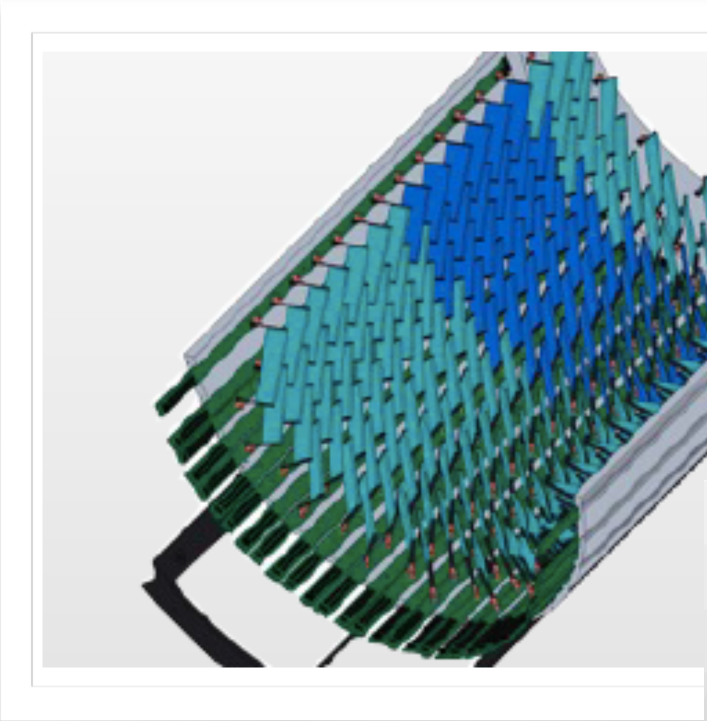
New algorithms



- Improved hit resolutions σ_r = 120 um, σ_z = 170 um (210, 800 um)
- High granularity/Increased number of hits per track/cluster timing technique
- Less material (helium:isobutane = 85:15, $1.6\times10^{-3}\,X_0$)
- High transparency towards the TC

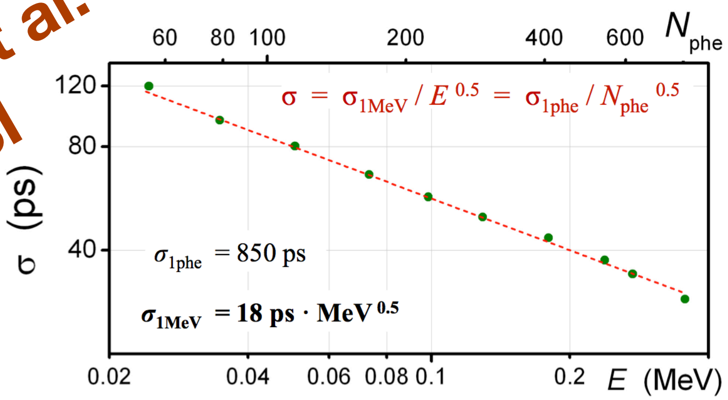
Resolutions	MEG	MEG II
p_e (keV)	306	130
ϑ_e(mrad)	9.4	5.3
φ_e(mrad)	8.7	4.8
e^+ efficiency (%)	40	88

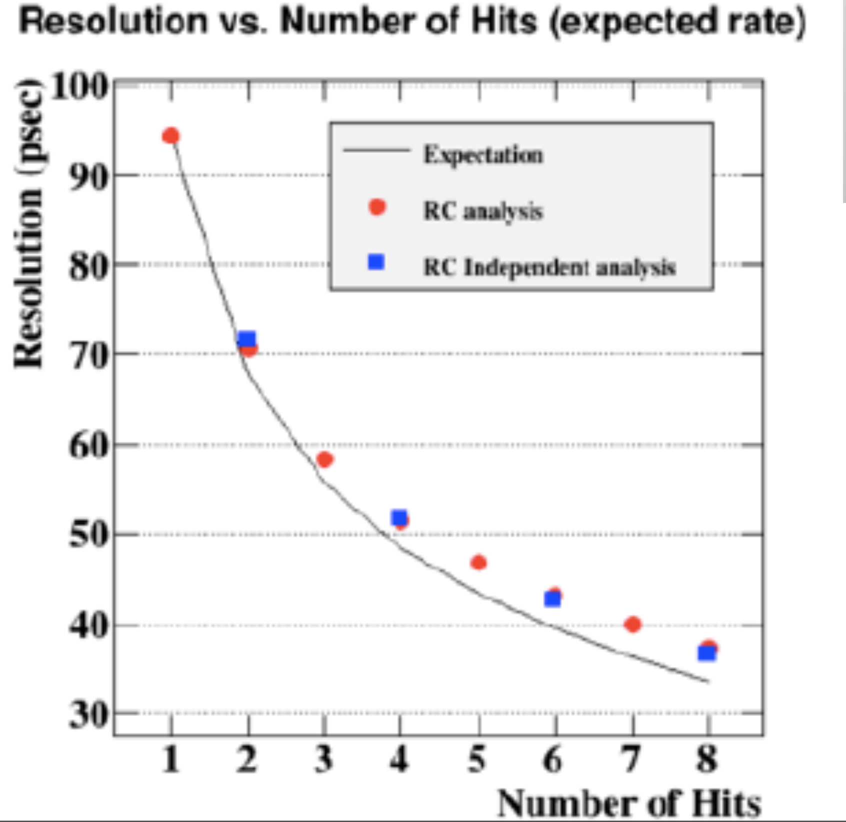
The MEGII spectrometer: the pixelized Timing Counter



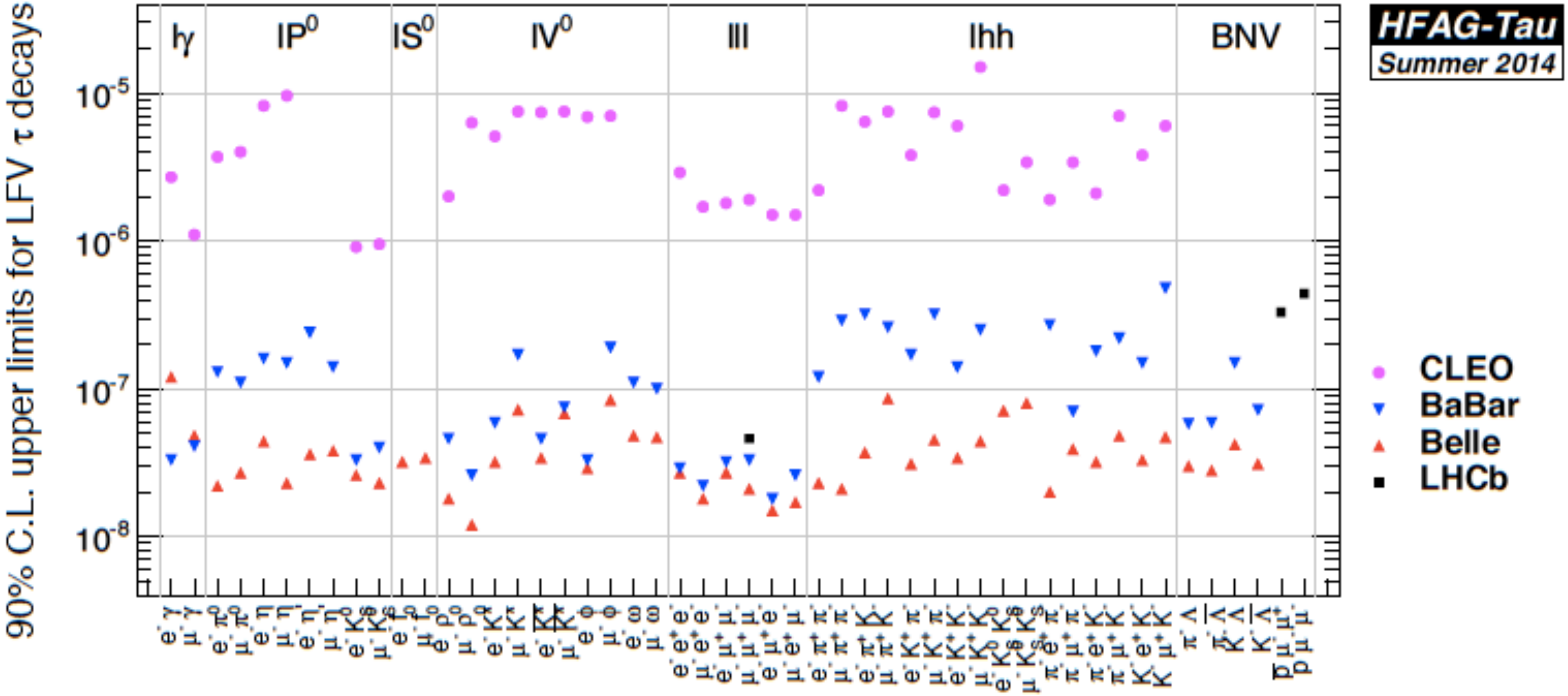
- Higher granularity: 2 x 256 of scintillator plates ($120 \times 50 \times 5$ mm^3) readout by SiPMs
- Improved timing resolution: from 70 ps to 35 ps
- Less multiple scattering and pile-up

A. Stoykov et al.
μSR PSI





cLFV with Taus



nEDM search - Motivations

- One of the outstanding open question in contemporary particle physics and cosmology is finding an explanation for the observed matter-antimatter asymmetry of our universe
- A much greater degree of CP-violation than provided by SM is requested
- New Physics (NP) could provides such a CP-violating sources

Baryon asymmetry

Observed:

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

SM predicted:

$$\approx 10^{-18}$$

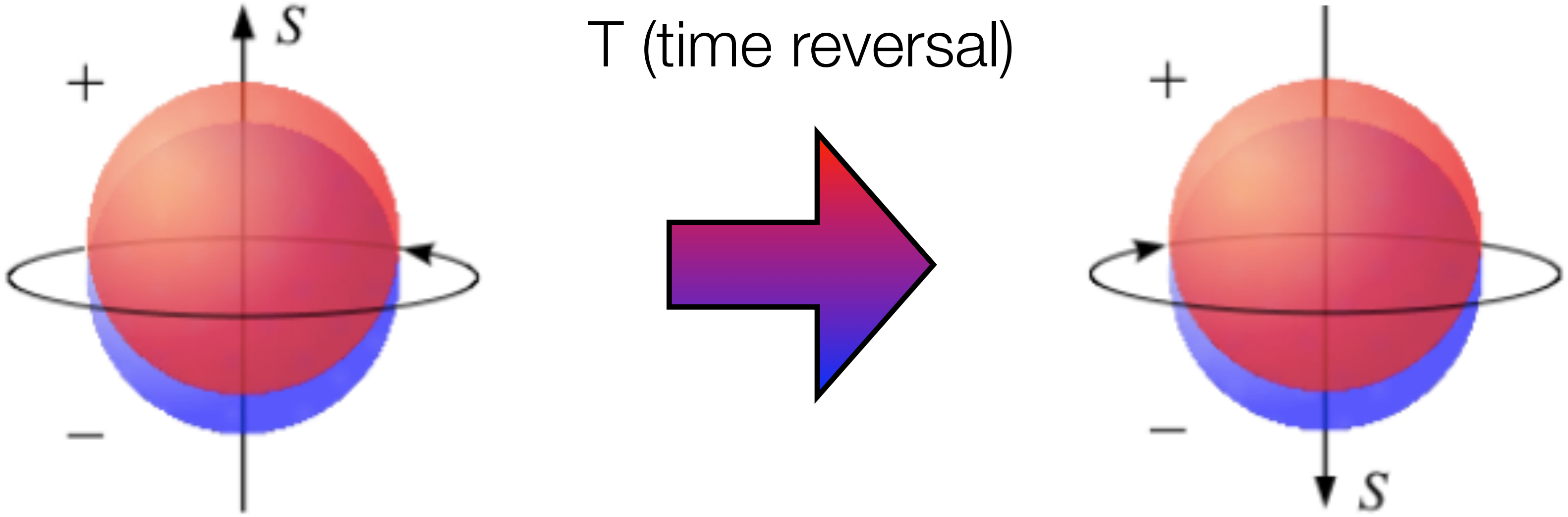
Sakharov criteria

Baryon asymmetry origin:

- B-violating interactions
- Departude from local equilibrium
- C and **CP violation**

nEDM search - Motivations

- In the search for laboratory manifestations of new CP-violating effects, EDM plays a crucial role: nEDM violates T and, assuming CPT conservation, also CP
- Standard Model EDM predictions are much smaller than current experimental sensitivities
    - an observation of any particle's EDM today would signal discovery of NP
    - if of sufficient strength, such a CP-source could provide a possible explanation for baryogenesis



$$T|n> \neq \alpha|n> \xrightarrow{\text{CPT theorem}} CP|n> \neq \alpha|n>$$

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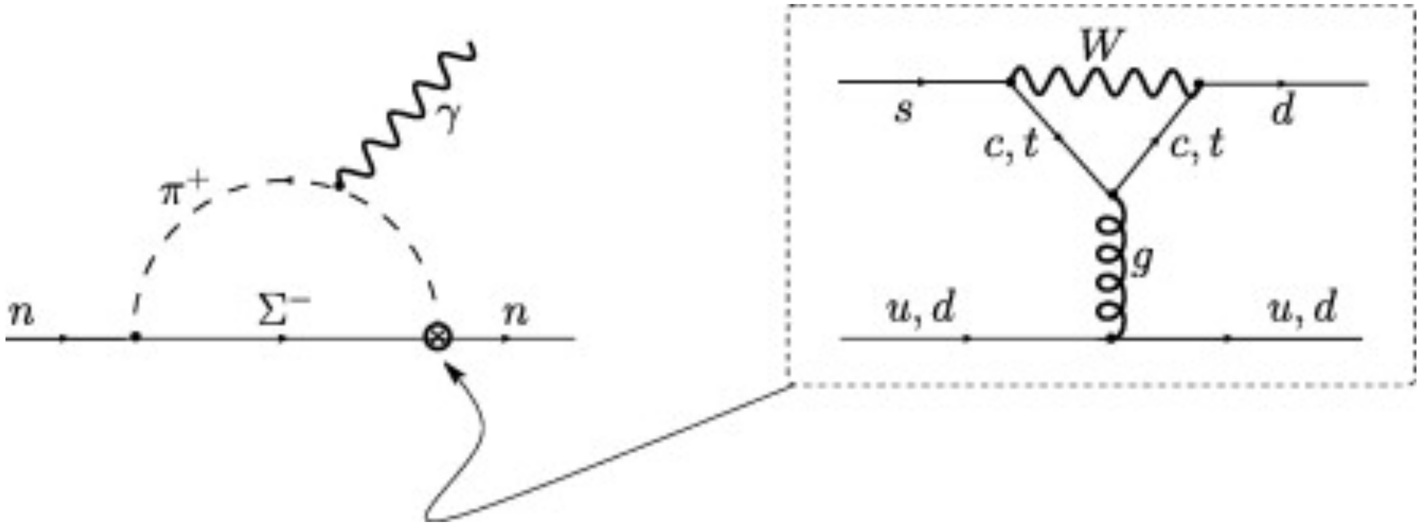
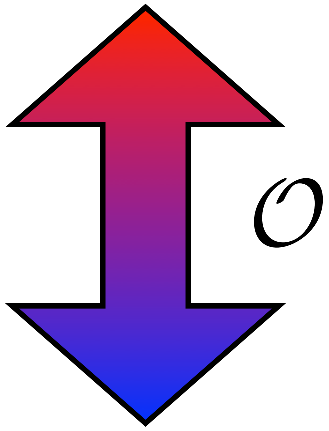


Current Upper Limit

$$d_n < 3 \times 10^{-26}\ e\ cm$$



$$\mathcal{O}(10^{5-6})$$

SM predictions

$$d_n \approx 10^{-32} - 10^{-31}\ e\ cm$$

ref.: M. Pospelov and A. Ritz, Annals of Physics 318 (2005) 119

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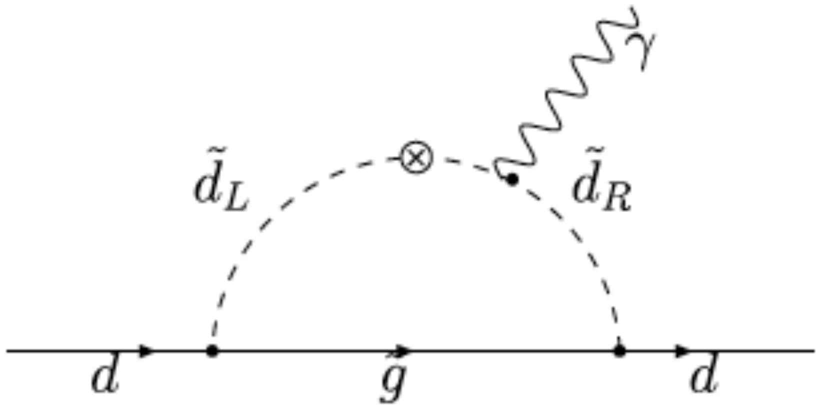

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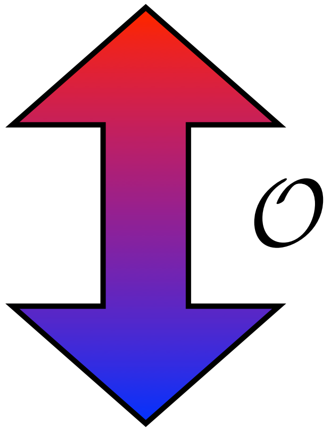

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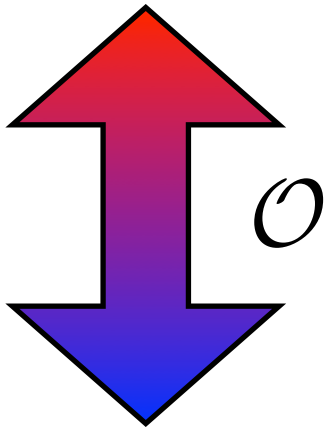

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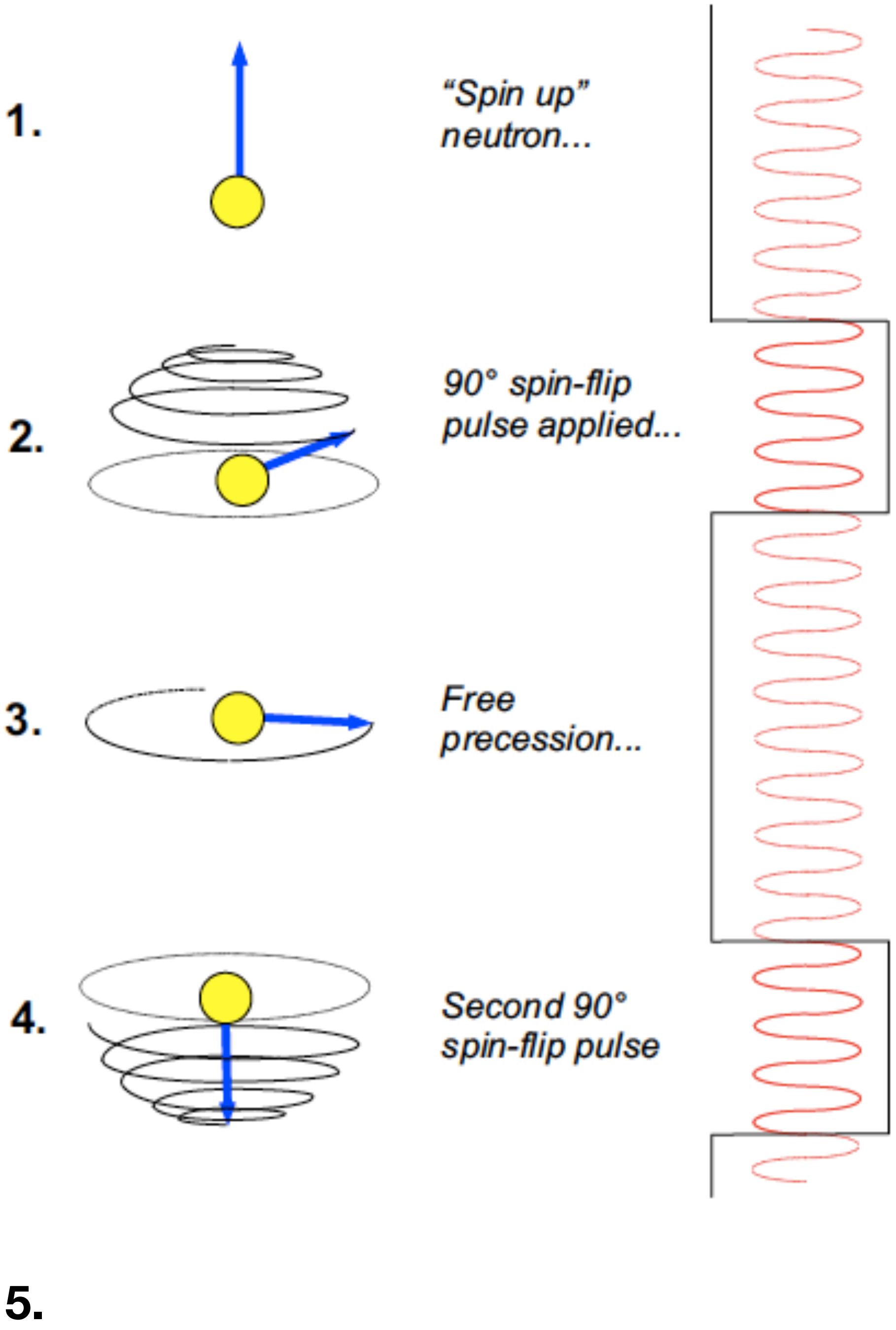
Experimental method

- Ramsey's method of separated oscillatory fields:



Polarize neutrons along B_0 direction

Choose a frequency for the external clock (**$\nu_1 \sim \nu_{Larmor}$**)
Apply oscillating (ν_1) magnetic field perpendicular to B_0 for a short time τ
Neutron spin is flipped

Neutrons precess freely during T

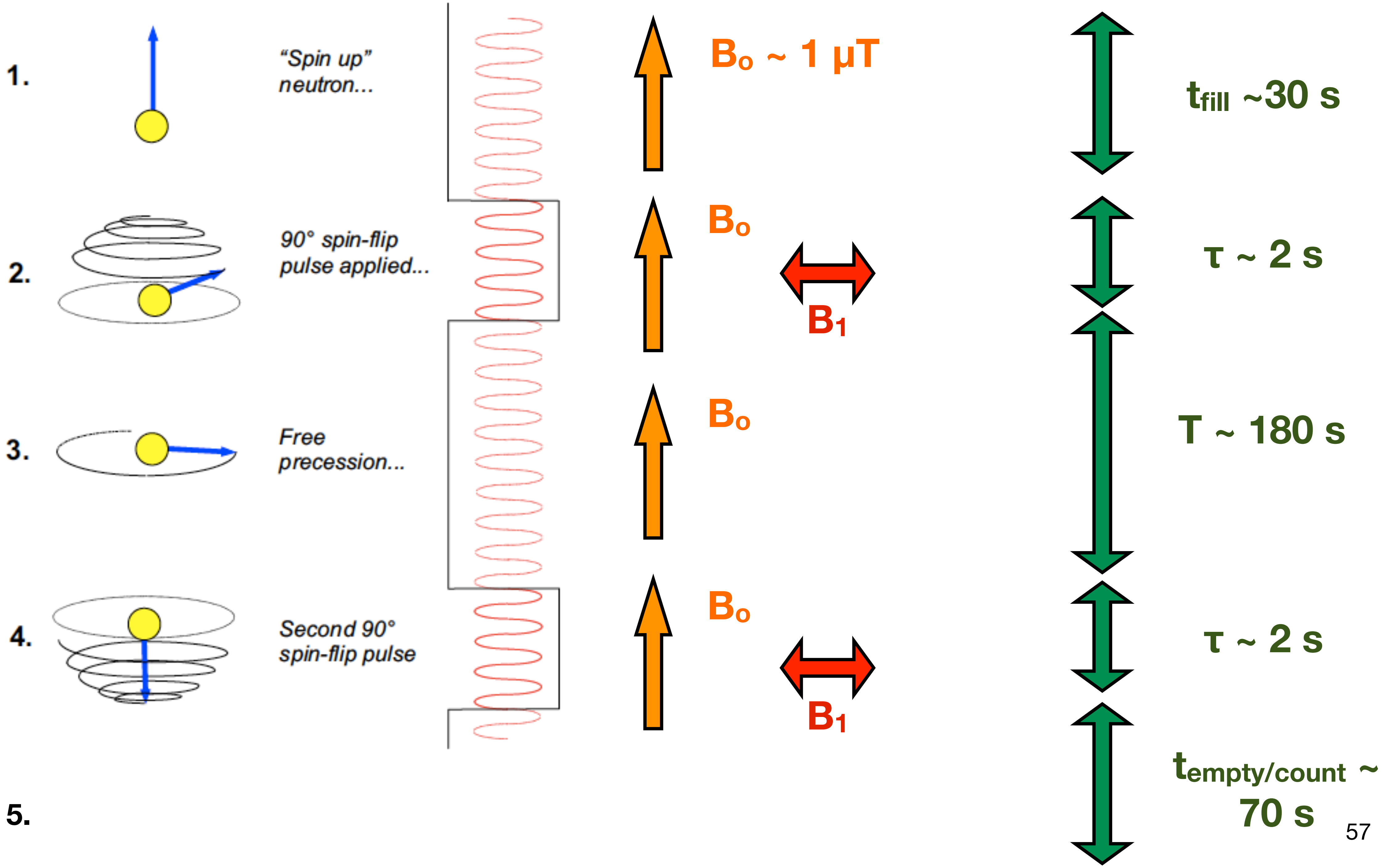
Re-Apply oscillating (ν_1 - **in phase with the first one**) magnetici field perpendicular to B_0 for the time τ
Neutron spin is flipped again

Count spin up/down neutrons as a function of ν_1
Neutron counts is sensitive to the accumulated precession phase: the difference between the polarization vector and the oscillator

ref.: C.A. Baker et al. NIMA A 736 (2014) 184

Experimental method: In numbers

- Ramsey's method of separated oscillatory fields:

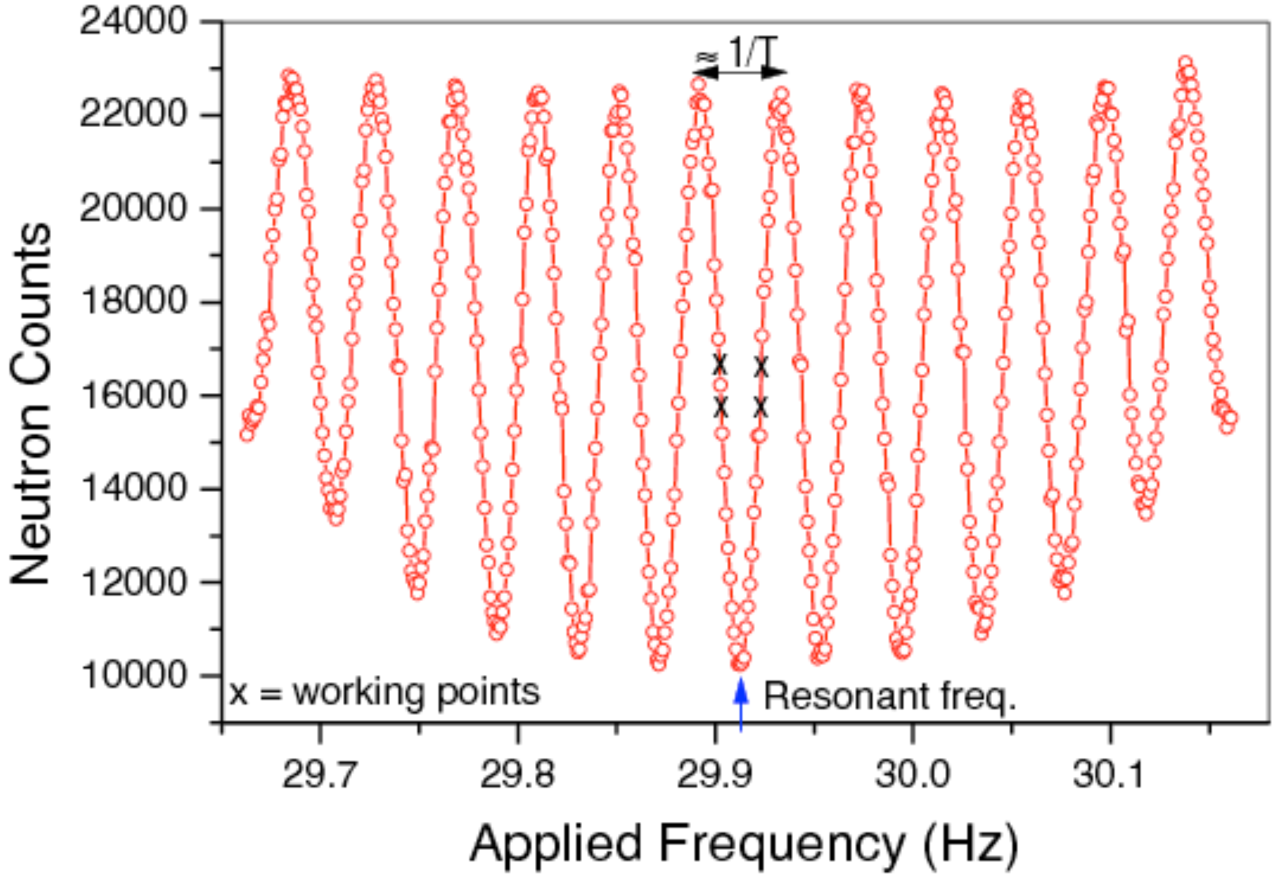


1. *"Spin up" neutron...* — $B_o \sim 1\ \mu T$ — $t_{fill} \sim 30\ s$
2. *90° spin-flip pulse applied...* — B_o, B_1 — $\tau \sim 2\ s$
3. *Free precession...* — B_o — $T \sim 180\ s$
4. *Second 90° spin-flip pulse* — B_o, B_1 — $\tau \sim 2\ s$
5. $t_{empty/count} \sim 70\ s$

ref.: C.A. Baker et al. NIMA A 736 (2014) 184

Experimental method: The Ramsey path

- Ramsey's method of separated oscillatory fields:



1. Four working points in the frequency domain
2. Ramsey's method with parallel and anti-parallel Electric field E_0 ~ 10 KV/cm
3. Looking for:

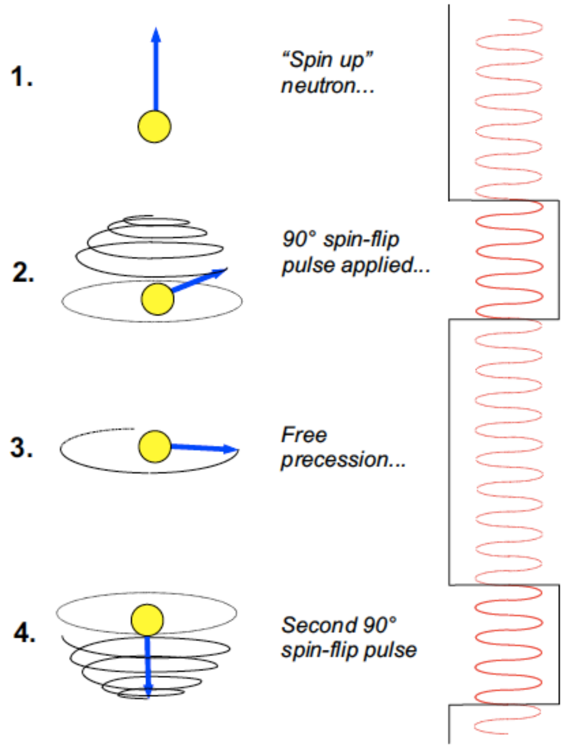
$$\delta\nu_0 = -\frac{4d_n E_0}{h}$$

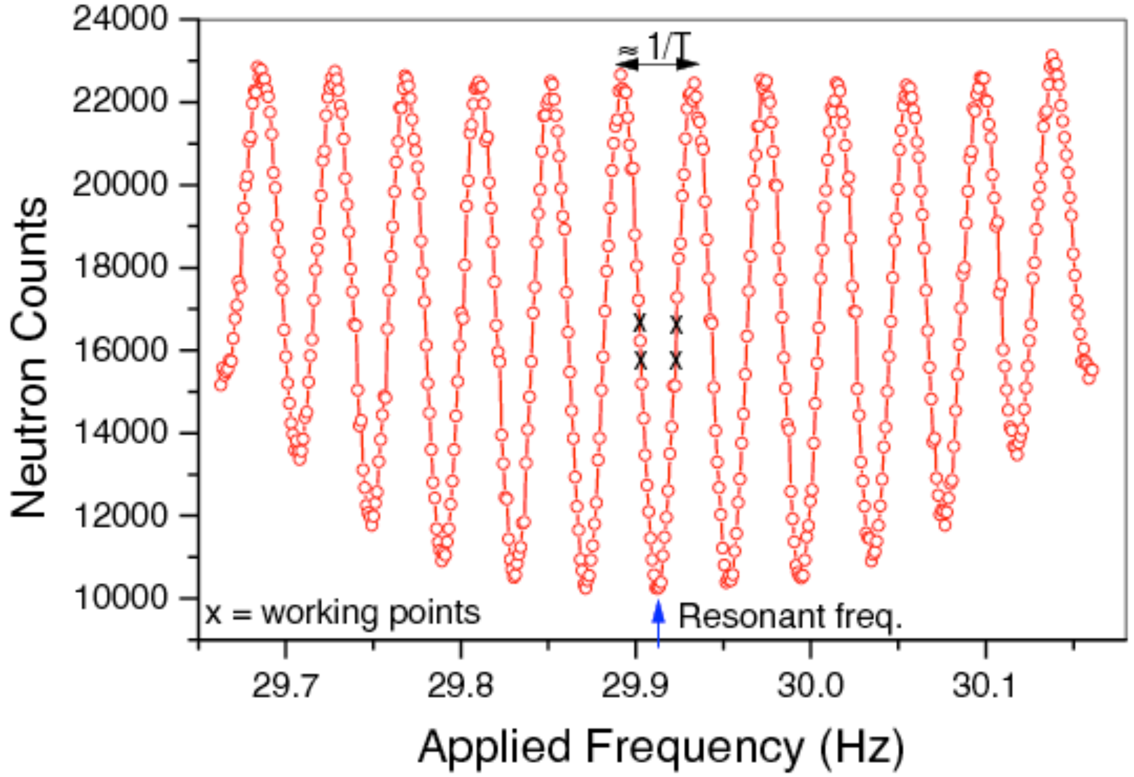
$$\sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

ref.: C.A. Baker et al. NIMA A 736 (2014) 184

Experimental method: The Ramsey path

- Ramsey's method of separated oscillatory fields:





1. Four working points in the frequency domain
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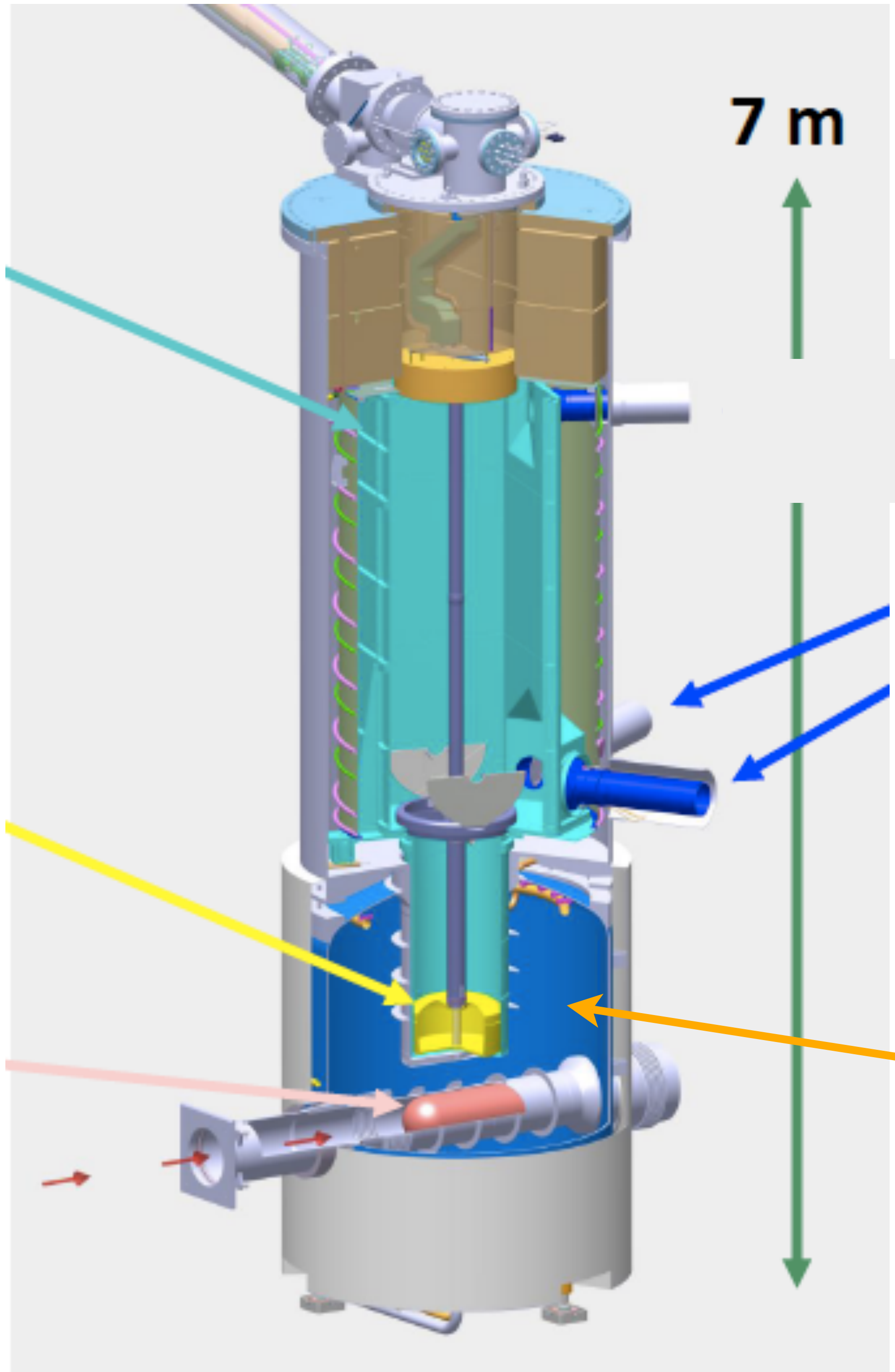
$$\boxed{\delta\nu_0 = -\frac{4d_n E_0}{h}}$$

The UltraCold Neutron (UCN) source at PSI



UCN storage vessel

UCN guides towards
experimental areas

Solid D_2 converter
(ultra-cold neutrons)

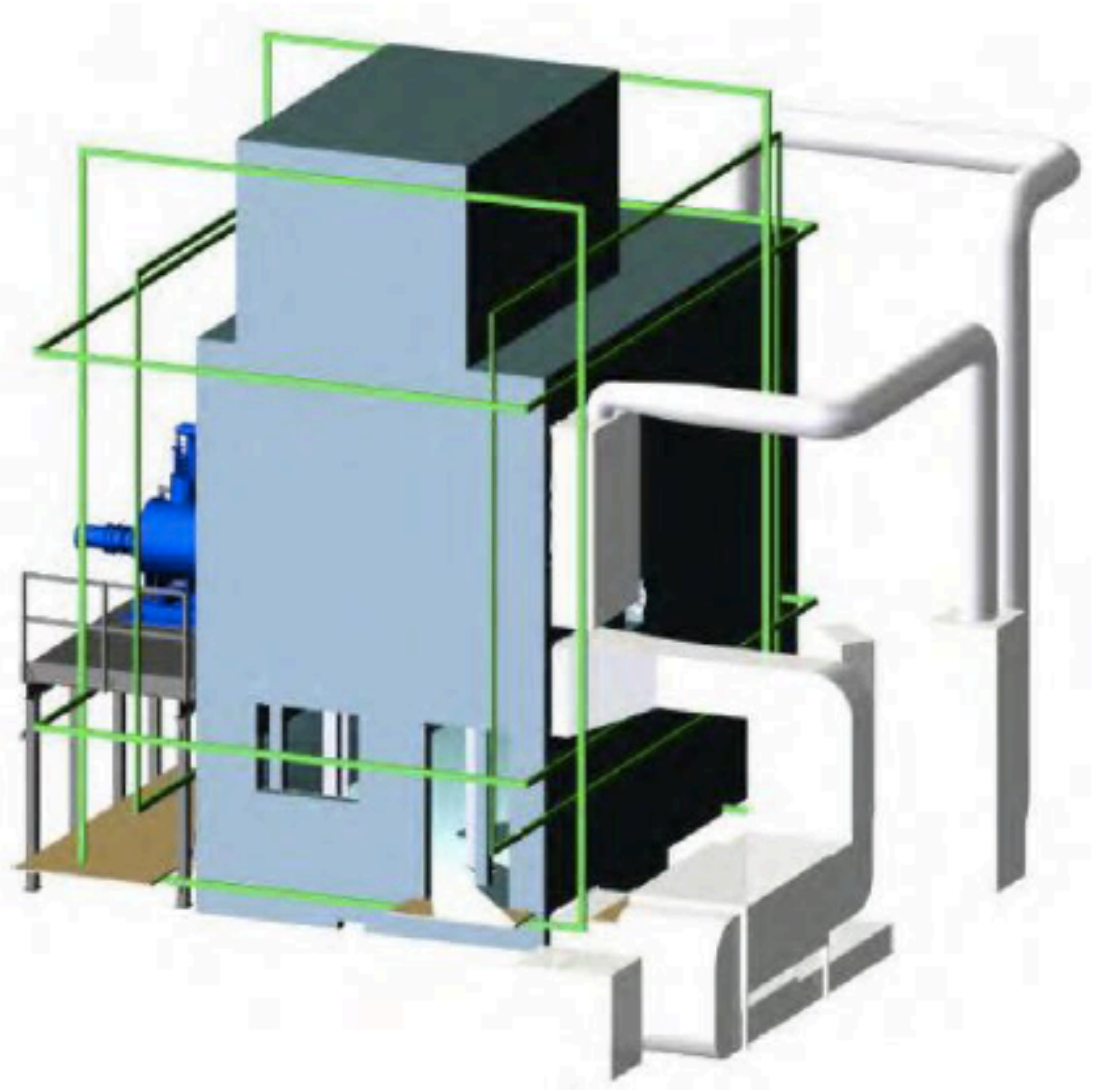
Spallation target (Pb/Zr)
8 n/incident proton

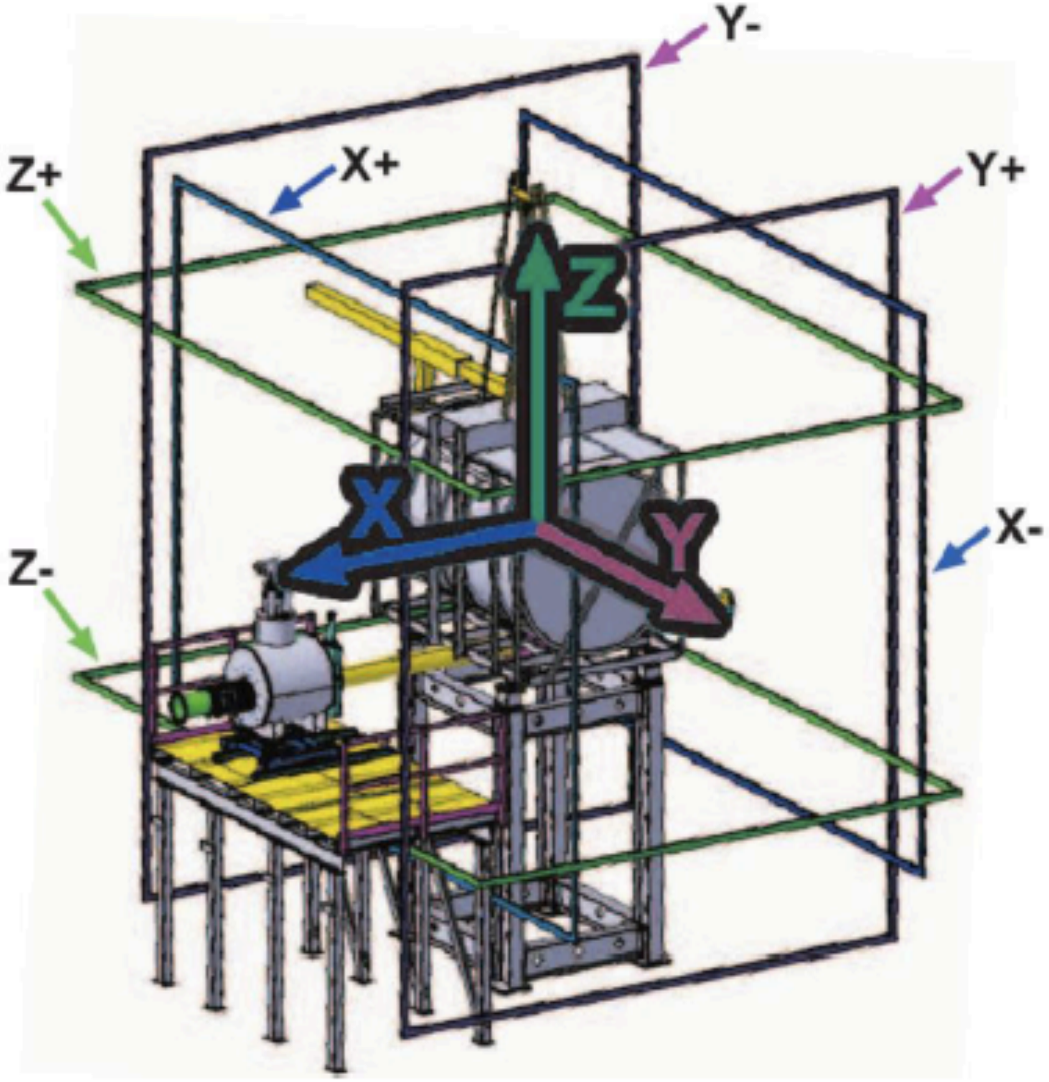
Heavy water moderator
(thermal neutrons)

Full proton beam:
1.3 MW, 590 MeV, 2.2 mA,
pulses up to 8 s on target

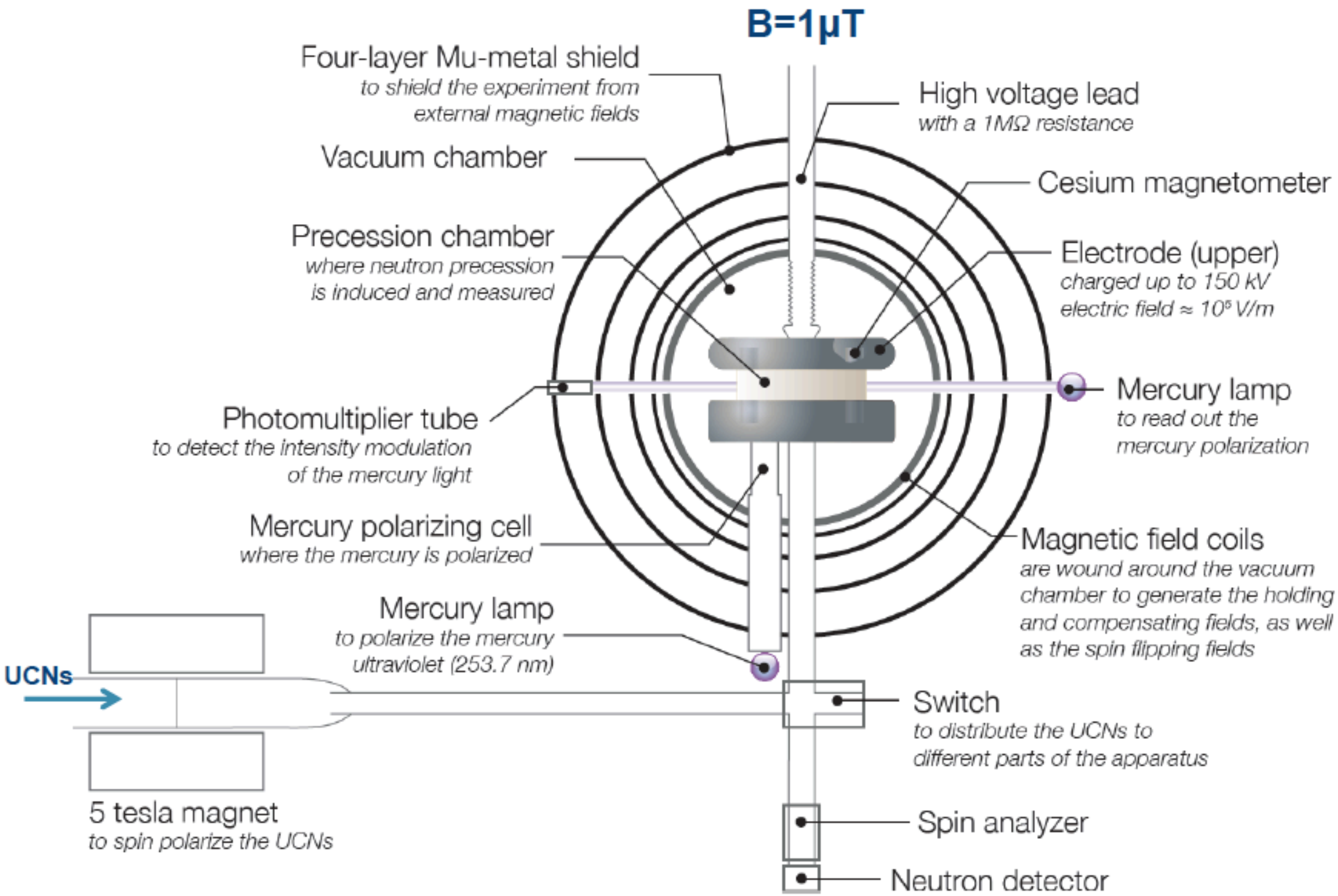
ref: B. Blau et al., NIM A 807 (2016) 30
H. Becker et al., NIM A 777 (2015) 20

Field compensation and Temperature stabilisation





The nEDM Setup - more details



B=1μT

Four-layer Mu-metal shield
to shield the experiment from external magnetic fields

Vacuum chamber

Precession chamber
where neutron precession is induced and measured

Photomultiplier tube
to detect the intensity modulation of the mercury light

Mercury polarizing cell
where the mercury is polarized

Mercury lamp
to polarize the mercury ultraviolet (253.7 nm)

UCNs

5 tesla magnet
to spin polarize the UCNs

High voltage lead
with a 1MΩ resistance

Cesium magnetometer

Electrode (upper)
charged up to 150 kV electric field ≈ 10^6 V/m

Mercury lamp
to read out the mercury polarization

Magnetic field coils
are wound around the vacuum chamber to generate the holding and compensating fields, as well as the spin flipping fields

Switch
to distribute the UCNs to different parts of the apparatus

Spin analyzer

Neutron detector

Which value for B_0 ?

- It does not enter directly in the sensitivity but has been choosen to be 1 μT in order to satisfy the following requirements
    - it should be large compared any residuals inside the chamber (< 2 nT) to guarantee the neutron quantization axis being the same everywhere
    - it should be large to prevent depolarization of neutron passing into the shields
    - it should be homogeneous (field gradients increase linearly with the field itself)
    - it should be stable: a more easy achivement for lower fields
    - it should be such that the neutron precession frequency is away from the 50 Hz mains frequency

The neutron mirror

Statistical sensitivity evaluation