Charged Lepton Flavor Violation & Dipole Moments

T. Mori
The University of Tokyo

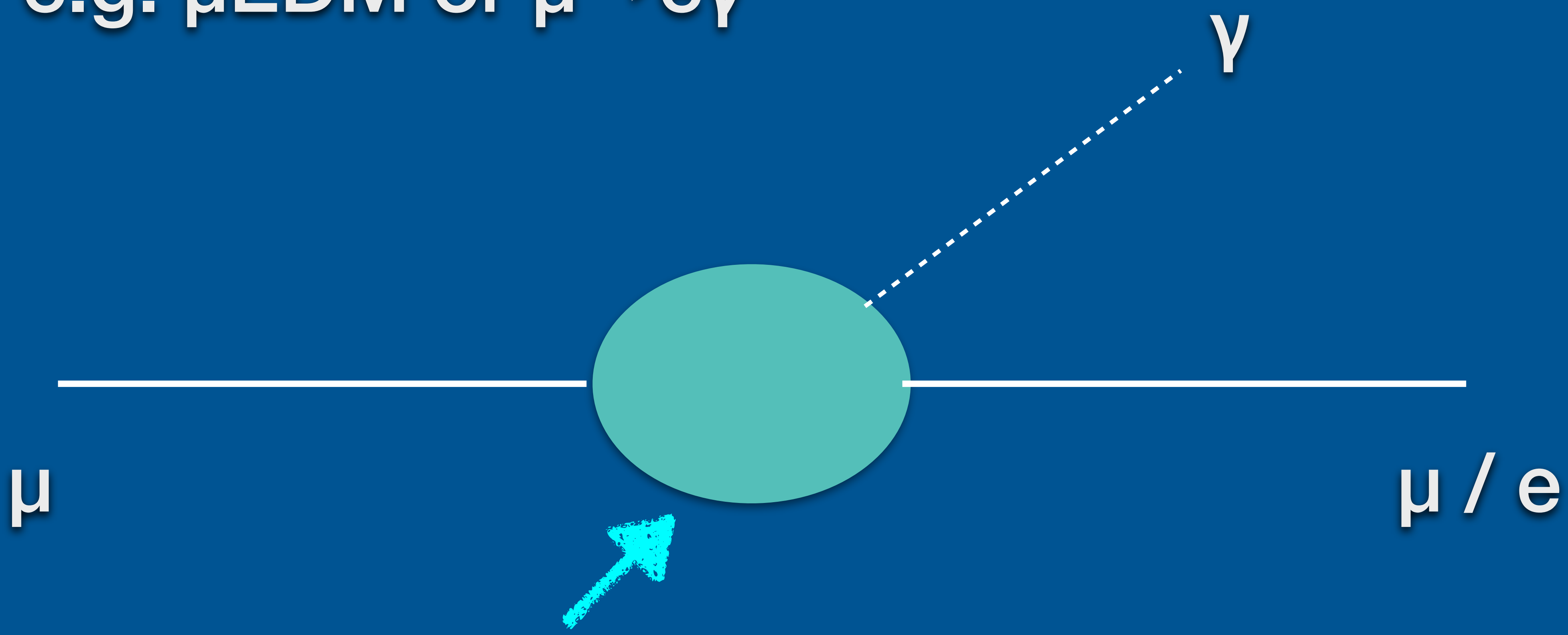
ICFA Seminar 2014, Beijing

- This talk reviews the experimental searches for new physics through the extensive studies of:
  - charged lepton flavor violation (cLFV) of muons,*
  - electric dipole moments (EDM),
  - and magnetic dipole moments (g-2)

* cLFV of taus are not discussed.

What are cLFV and EDM ?

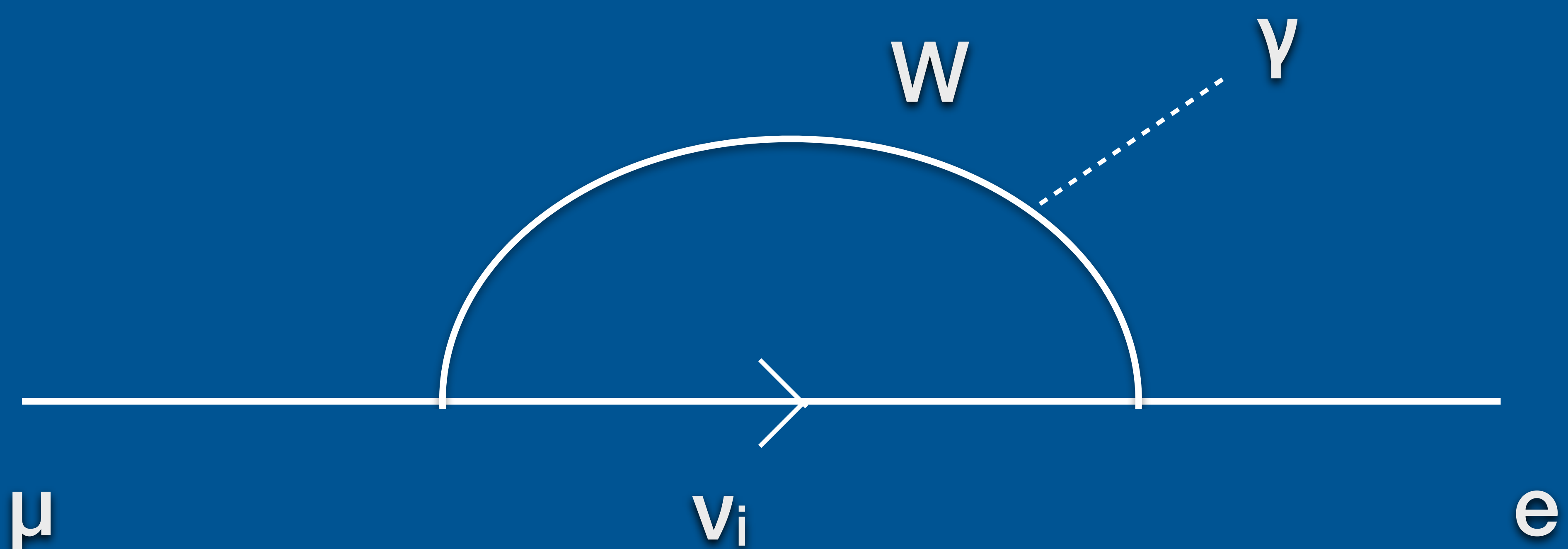
e.g. μEDM or $\mu \to e\gamma$



CP Violation (CPV) or LFV

We know LF & CP are violated: so this should occur!

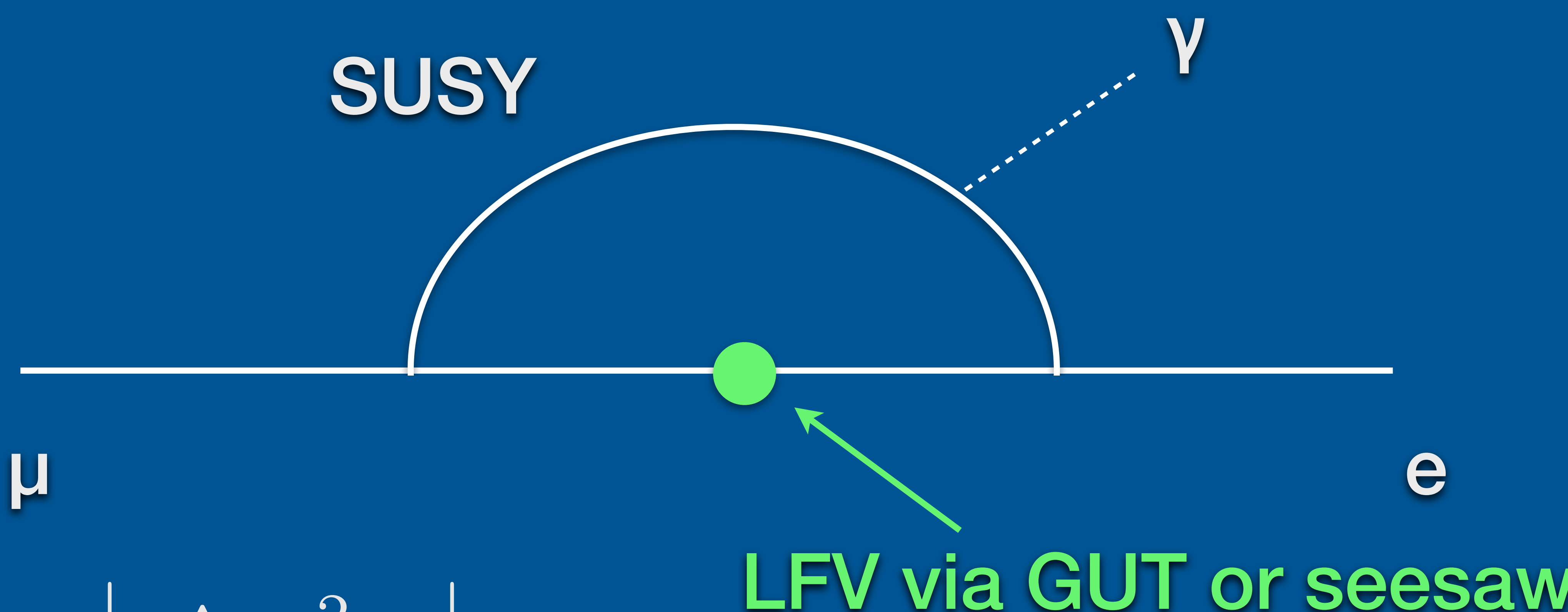
...but practically no cLFV or EDM in SM



$$\frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}\left(\frac{m^2_{\nu_i}}{M^2_W}\right)U_{ei}\right|^2 \leq 10^{-50}$$

neutrinos are too light

TeV scale new physics help them occur !

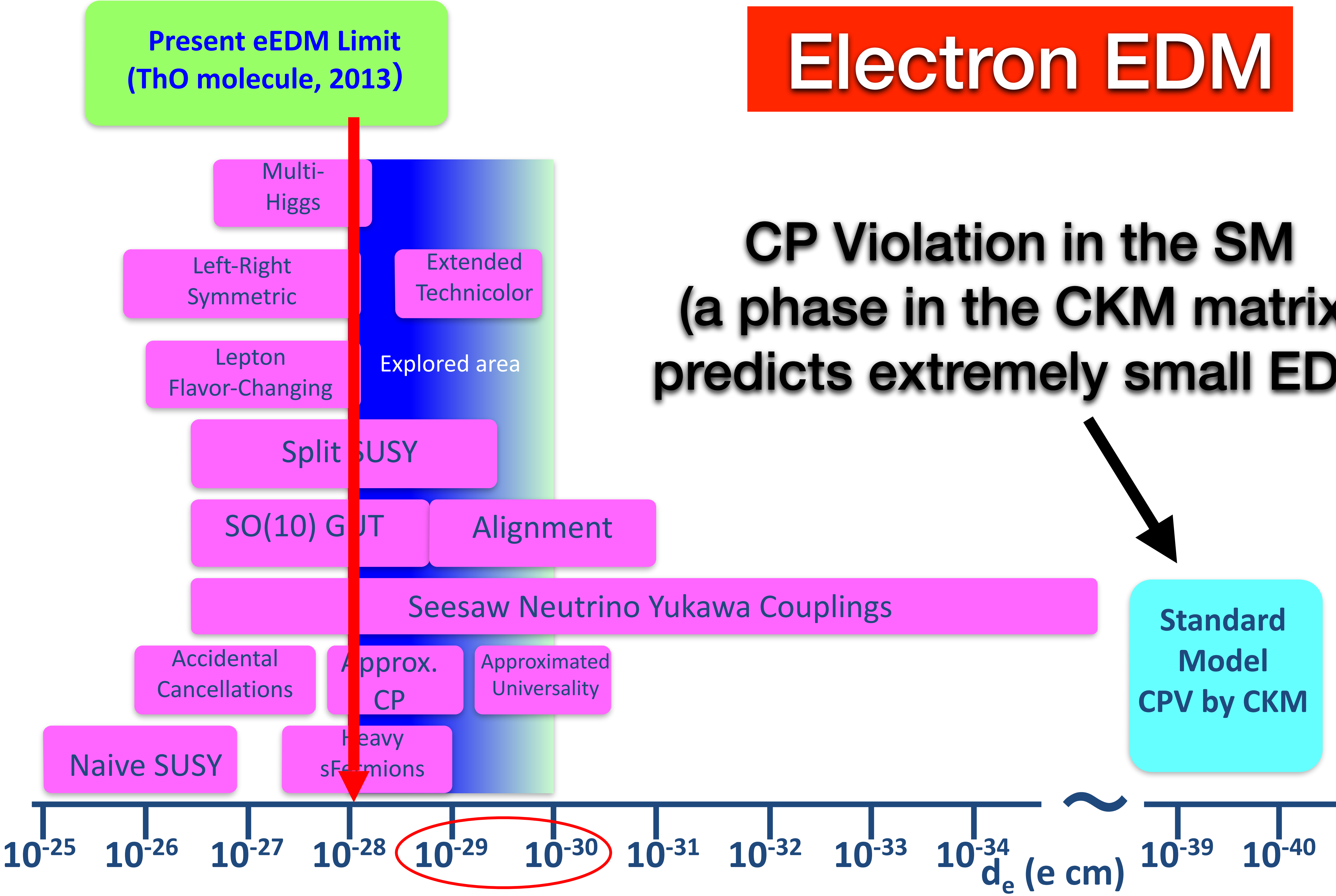


$$\left| \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{M^2_{SUSY}} \right| \rightarrow \sim 10^{-12}$$

We can probably observe them!

Electron EDM

CP Violation in the SM (a phase in the CKM matrix) predicts extremely small EDM



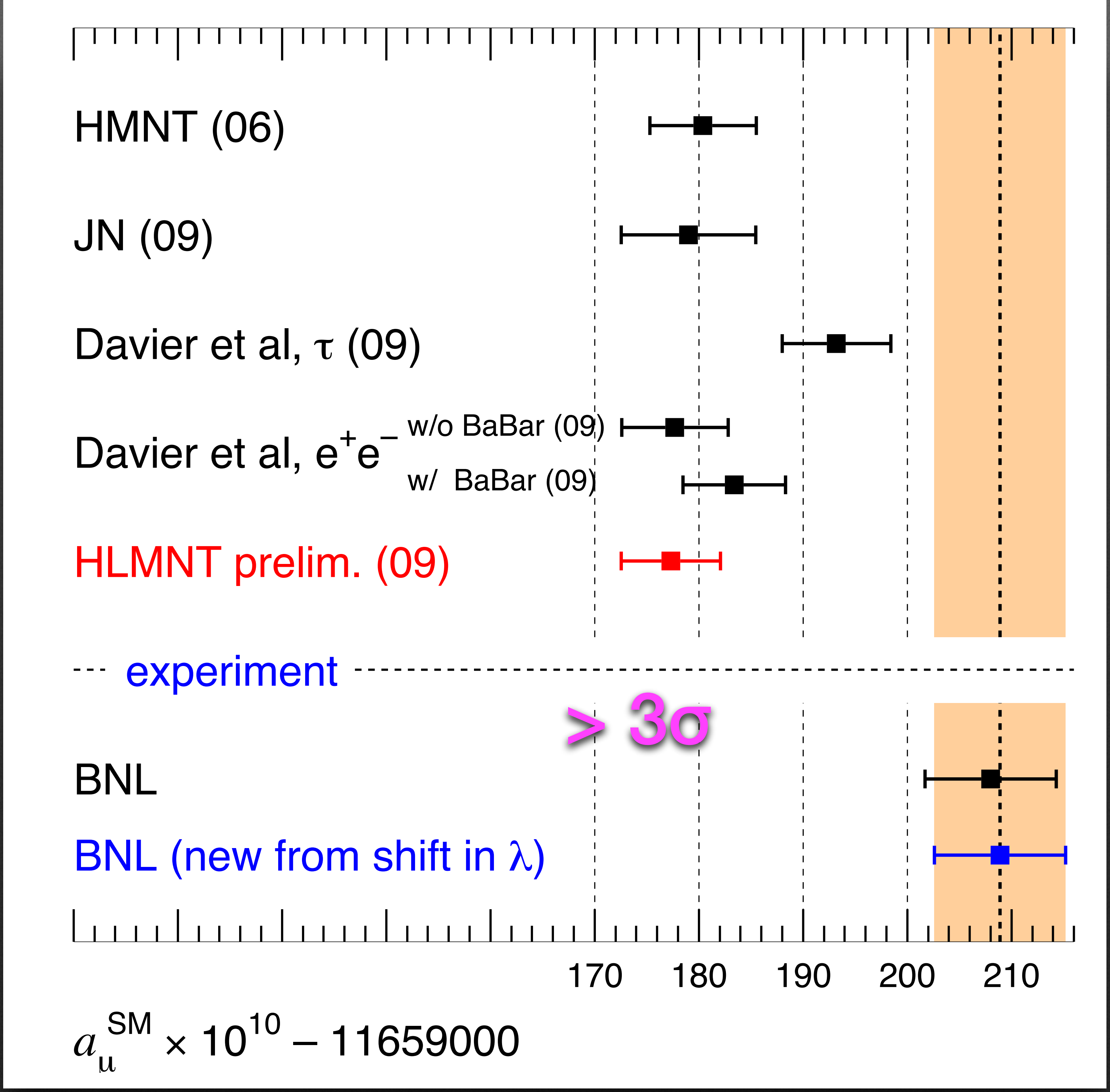
A new source of CPV must exist for the birth of our Universe!

cLFV & EDM

- Definite evidence of new physics if discovered
  - can probe very early stages of Universe (matter-antimatter asymmetry, GUT, seesaw)
  - A complementary and similar (or better) sensitivity to new physics than the LHC experiments

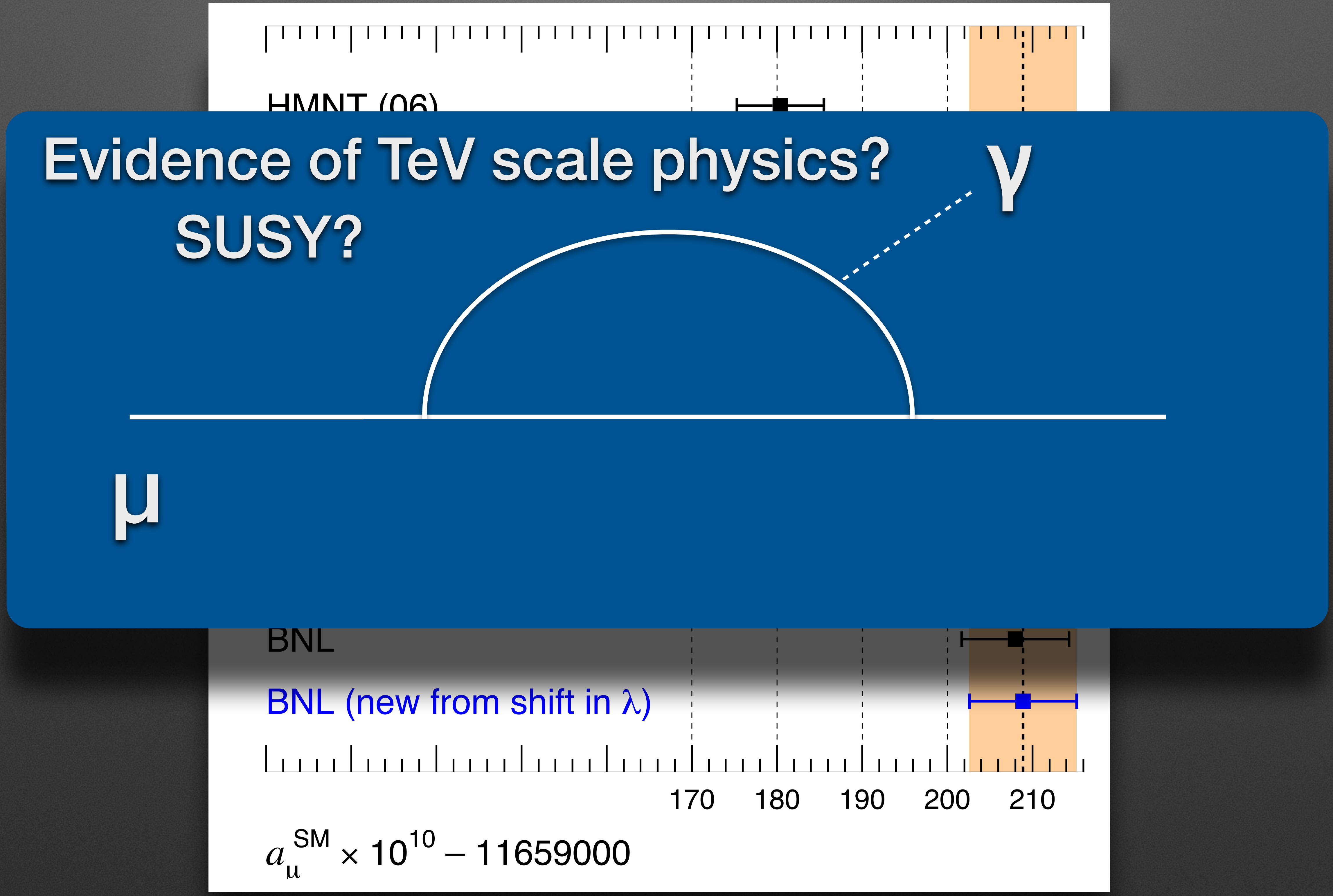
How could New Physics have hidden herself without leaving any trace anywhere?

There is a >3σ evidence!



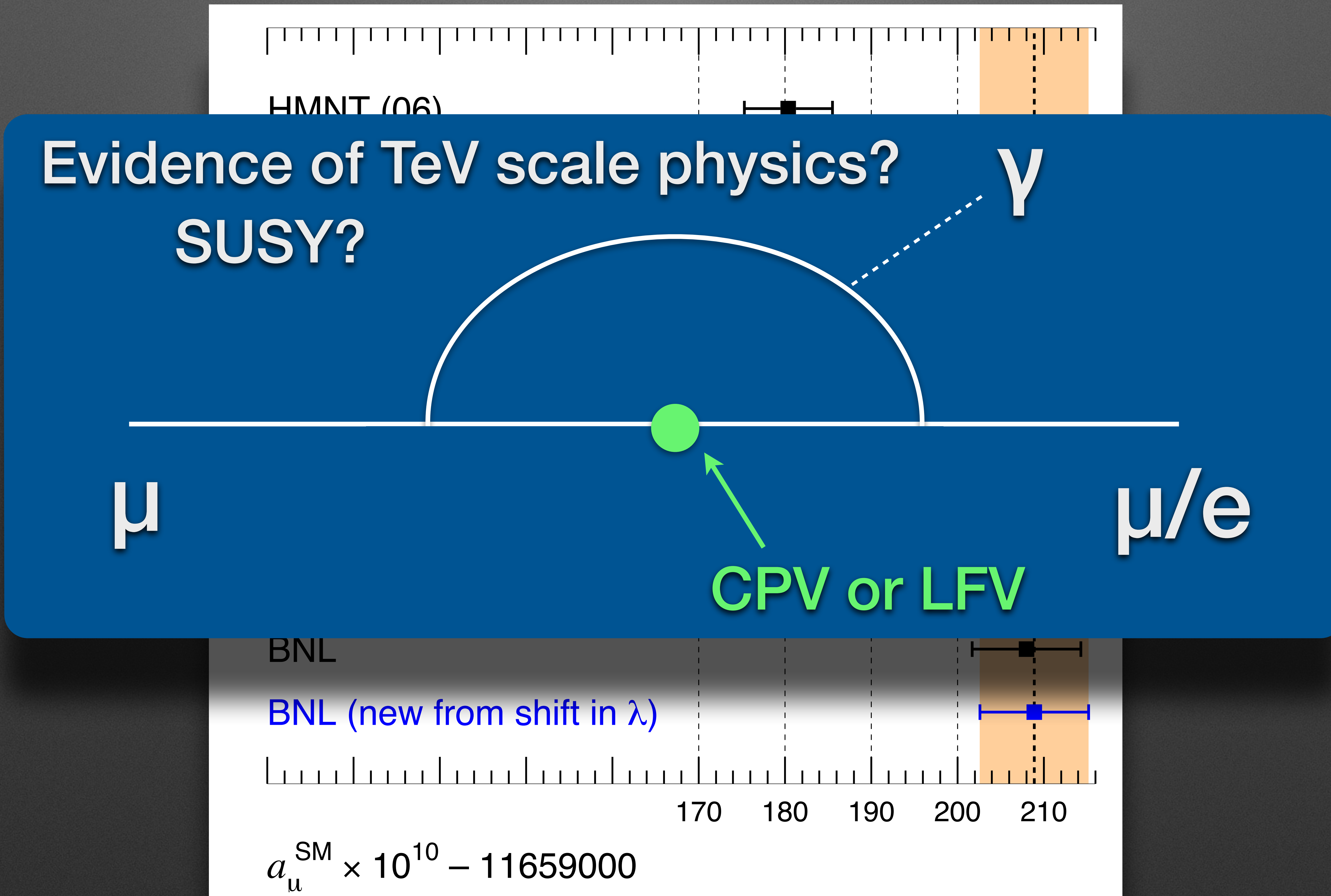
muon's anomalous magnetic moment g_μ-2

There is a >3σ evidence!



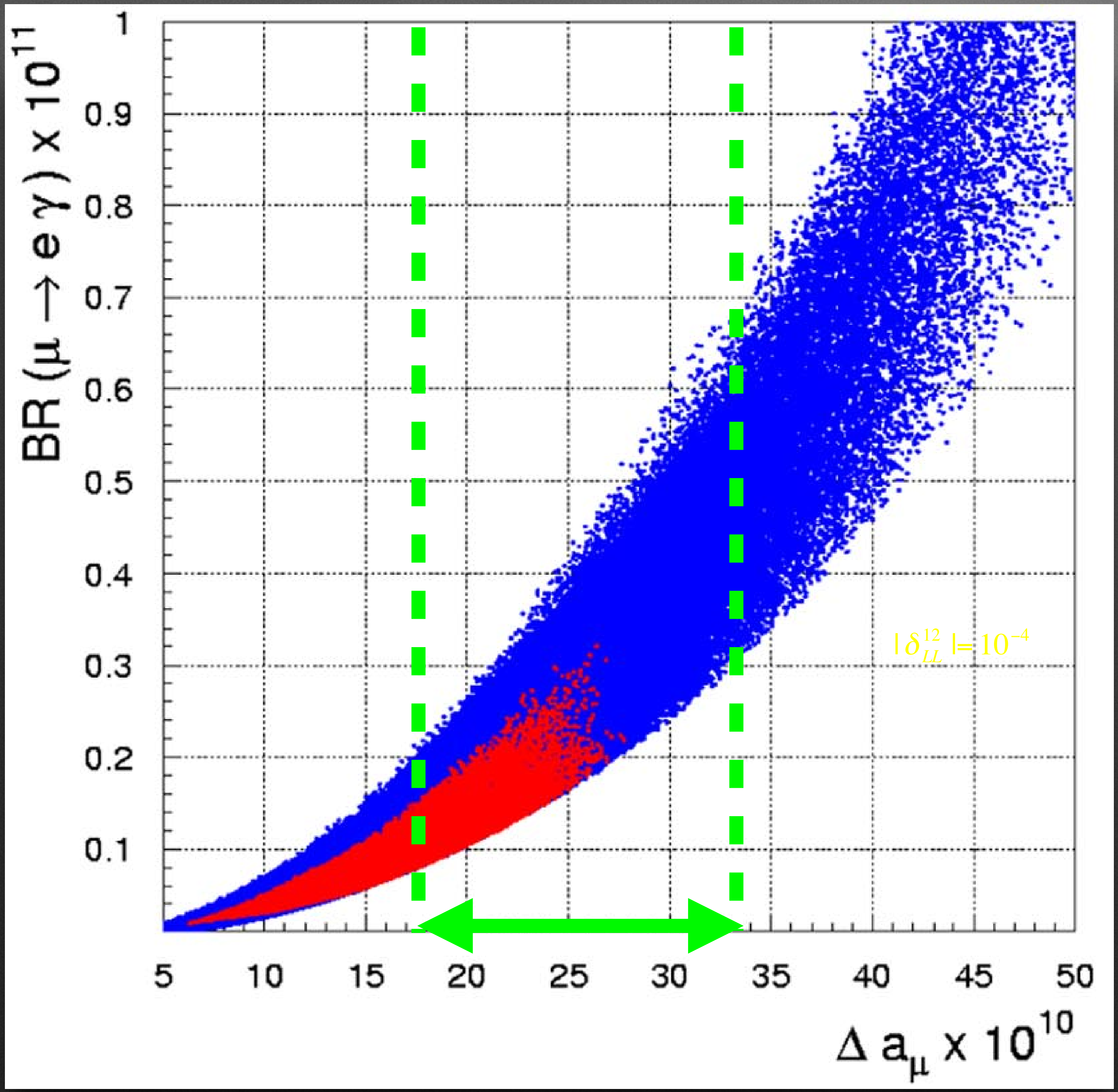
muon's anomalous magnetic moment g_μ-2

There is a >3σ evidence!



muon's anomalous magnetic moment g_μ-2

muon (g-2) anomaly



G.Isidori et al. PRD75, 115019

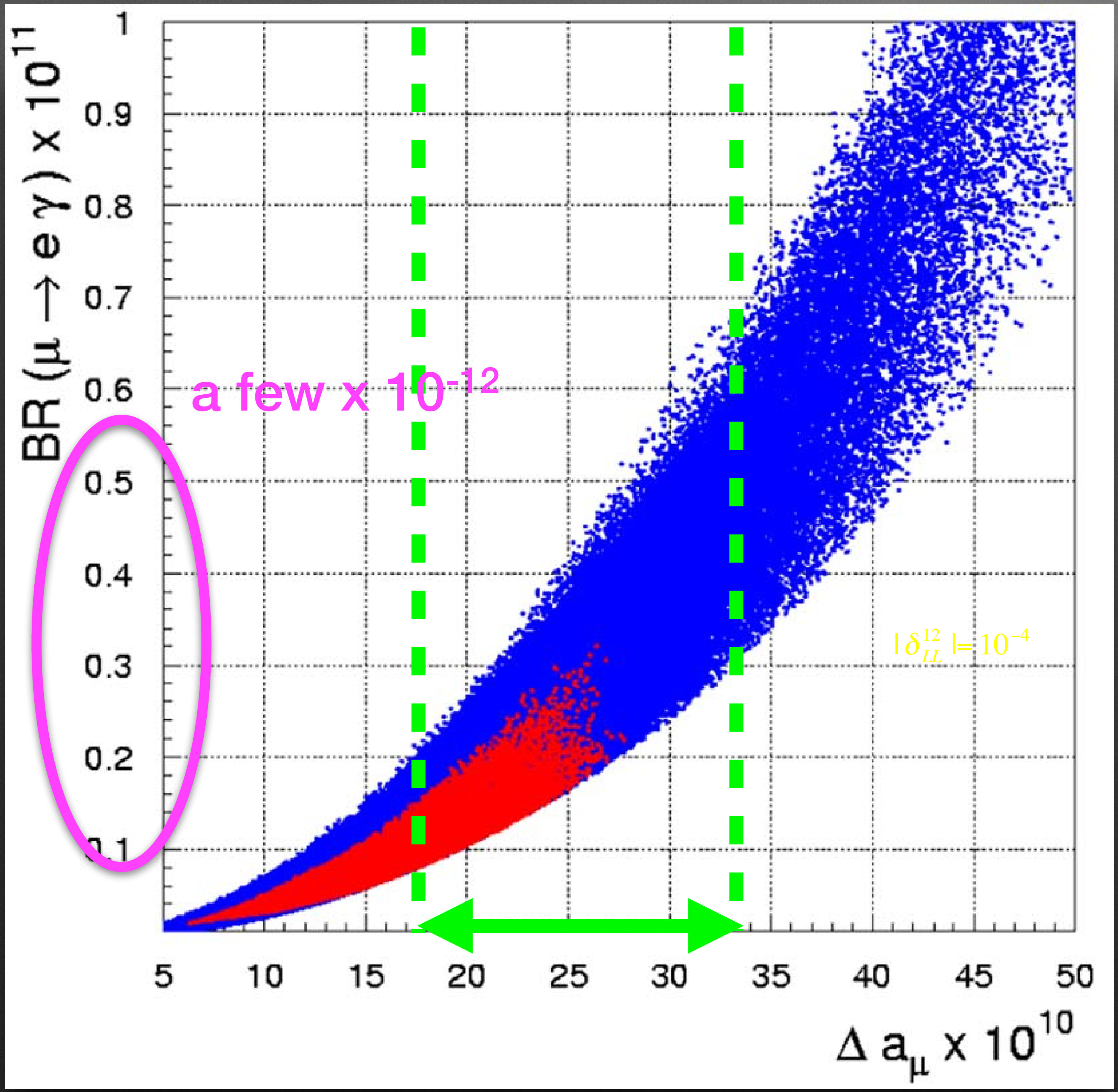
There is a generic relation with BR(μ→eγ) :

$$\mathcal{B}(\mu \to e\gamma) \approx 10^{-4} \left(\frac{\Delta a_\mu}{200 \times 10^{-11}} \right)^2 |\delta_{LL}^{12}|^2$$

unknown cLFV constant

$|\delta_{LL}^{12}| = 10^{-4}$ assumed here

muon (g-2) anomaly



G.Isidori et al. PRD75, 115019

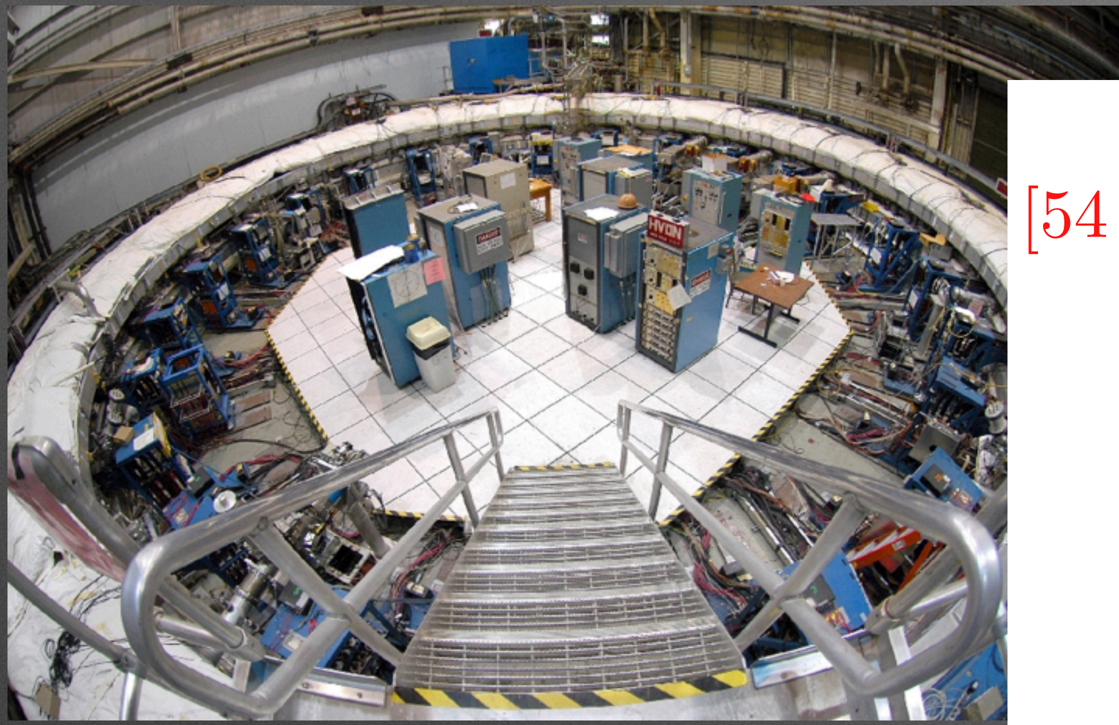
There is a generic relation with BR(μ→eγ) :

$$\mathcal{B}(\mu \to e\gamma) \approx 10^{-4} \left(\frac{\Delta a_\mu}{200 \times 10^{-11}} \right)^2 |\delta_{LL}^{12}|^2$$

unknown cLFV constant

$|\delta_{LL}^{12}| = 10^{-4}$ assumed here

New FNAL g_μ-2 Experiment

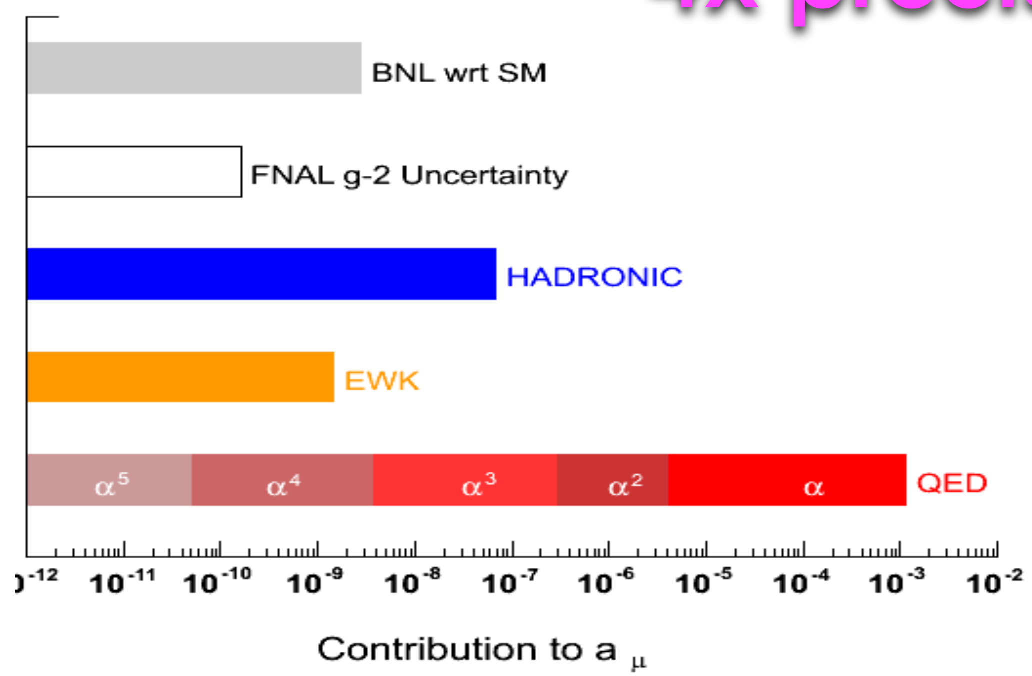


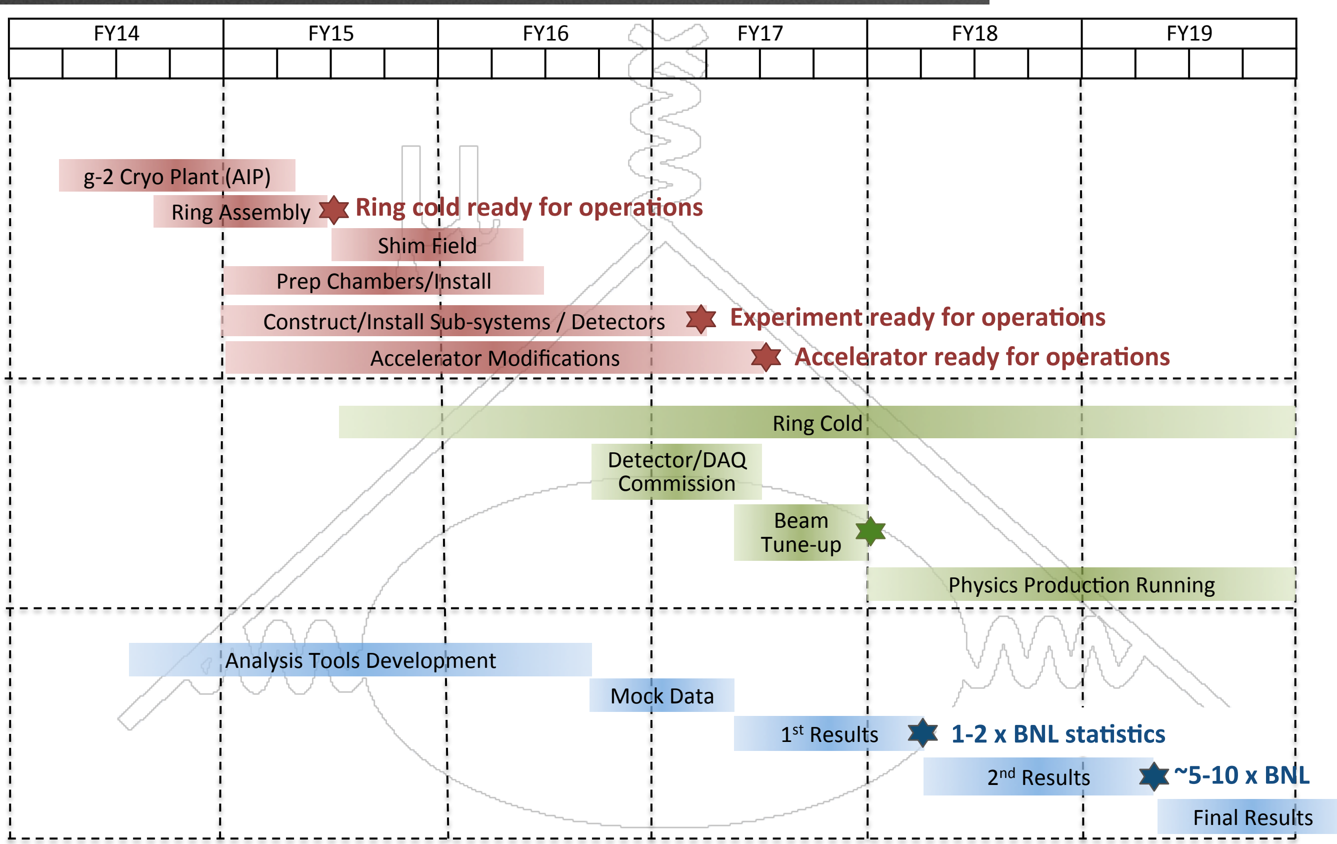
BNL → FNAL

$$[54\ (\text{stat.}) \oplus 33\ (\text{syst.}) \rightarrow 11\ (\text{stat.}) \oplus 11\ (\text{syst.})] \times 10^{-11}$$

$$0.54\ \text{ppm} \rightarrow 0.14\ \text{ppm}$$

4x precision





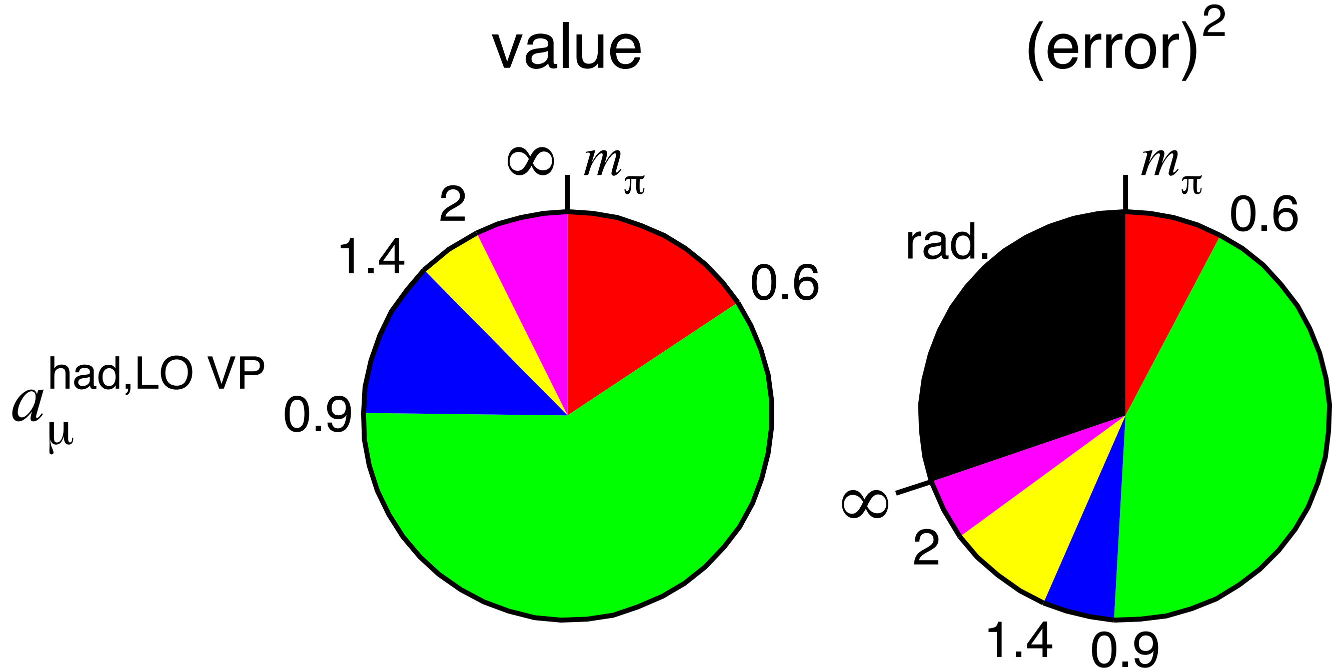
Need improvements in theoretical prediction: hadronic vacuum polarization expected to improve by x2

Future improvements for a_μ^{HVP}:

T. Teubner @Lepton Moments 2014

- Most important 2π:
  - close to threshold important; possible info also from space-like
  - better and more data
  - understand discrepancy between sets, especially `BaBar puzzle'
  - possibility of direct scan & ISR in the same experiment(s)
- √s > 1.4 GeV:
  higher energies will improve with input from SND, CMD-3, BESIII, BaBar
- With channels more complete, test/ replace iso-spin corrections
- Very good prospects to significantly squeeze the dominant HLO error!

Pie diagrams from HLMNT 11:

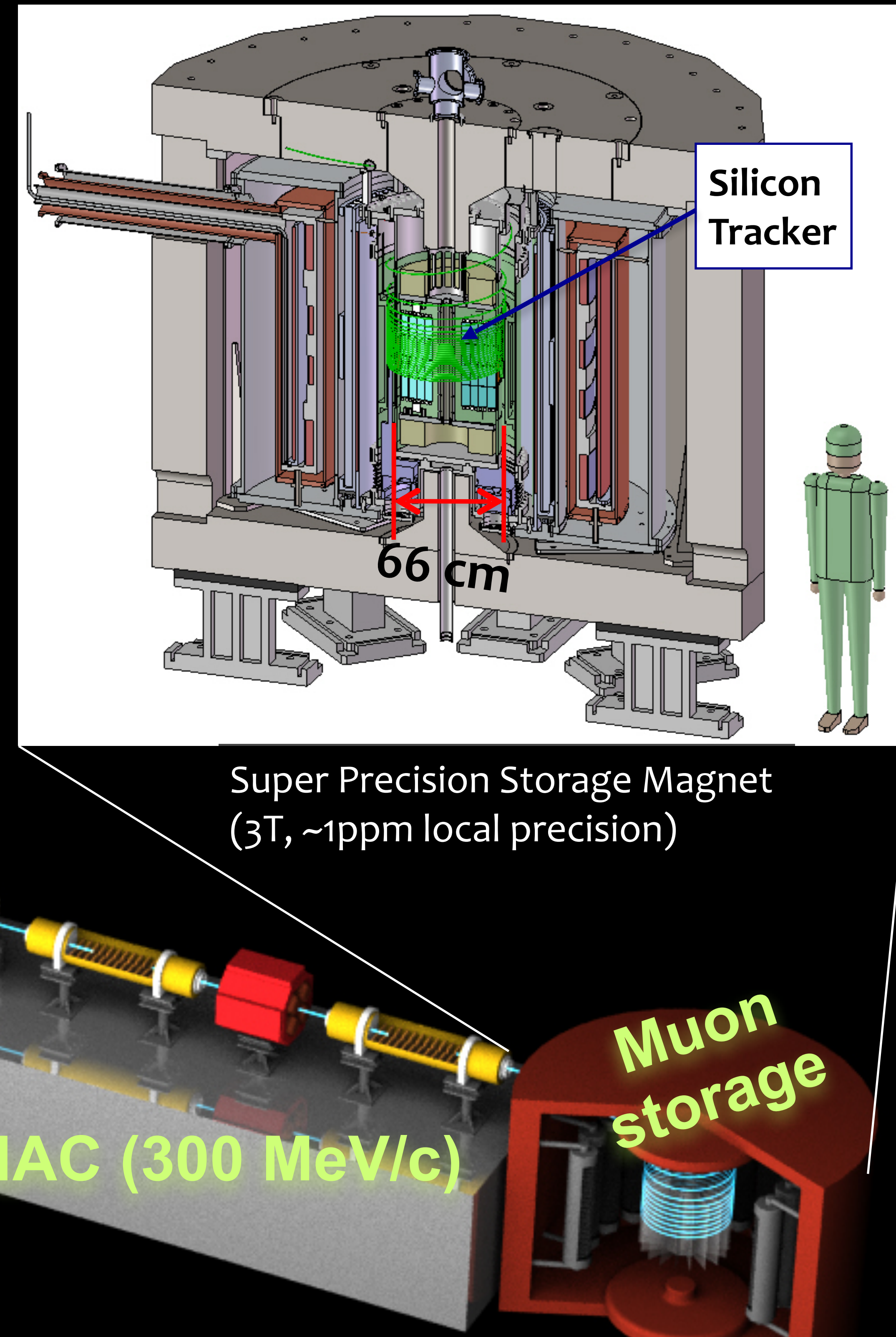


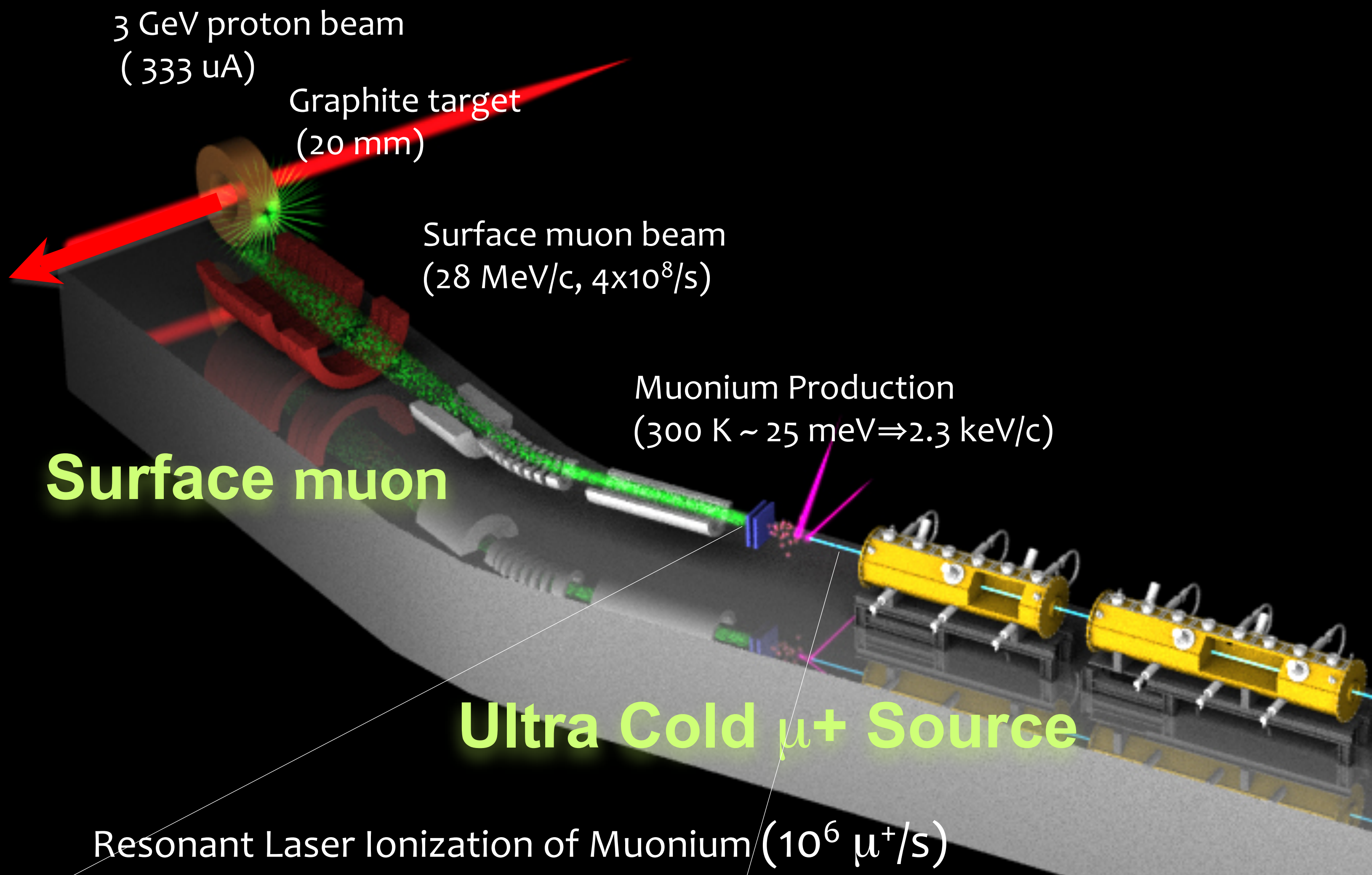
Can expect significant improvements:

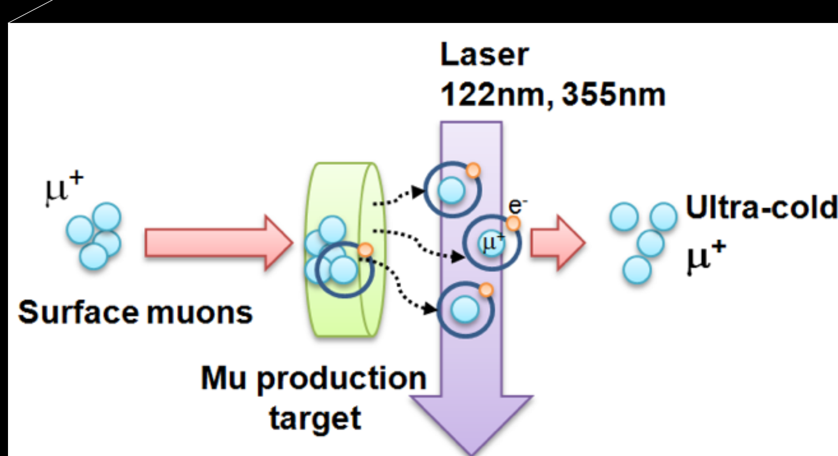
- 2π: error down by about 30-50%
- subleading channels: by factor 2-3
- √s > 2 GeV: by about a factor 2

→ I believe we can half the HVP error in time for the new g-2

New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam







1. Ultra-cold μ^+ beam is injected to storage magnet.
2. Pulse kicker stops muons in storage area
3. Positron tracker measures e+ from $\mu^+ \rightarrow e^+ \nu\nu$ decay for the period of 33μs (5 x lifetime)

N. Saito

Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL/Fermilab Approach

J-PARC Approach

N. Saito

Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL/Fermilab Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

J-PARC Approach

N. Saito

Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL/Fermilab Approach

J-PARC Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$

N. Saito

Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL/Fermilab Approach

J-PARC Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\eta \approx 0$$

$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$

N. Saito

■ Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL/Fermilab Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\eta \approx 0$$

$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$

J-PARC Approach

N. Saito

Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

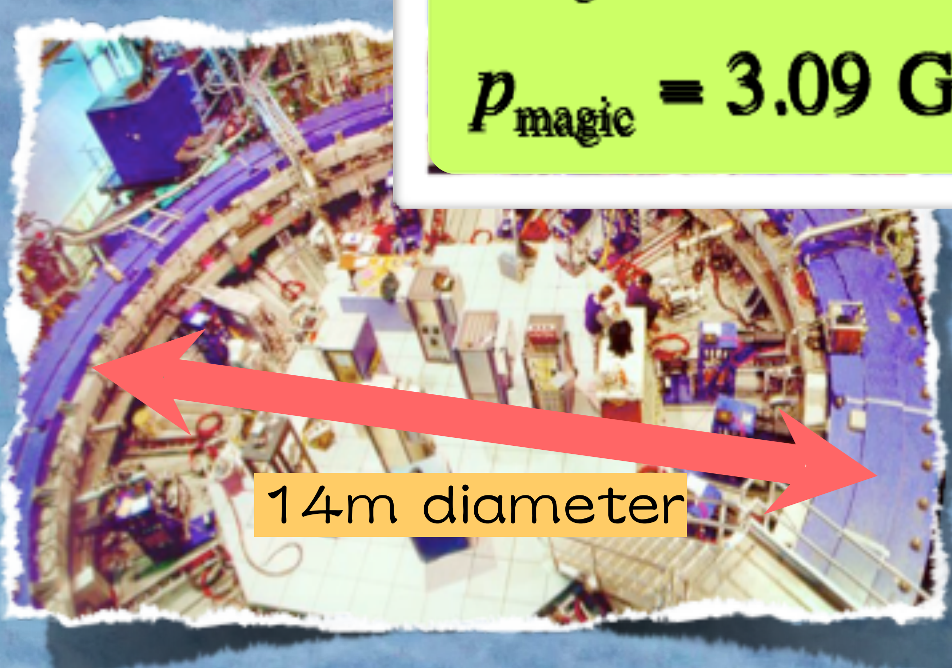
BNL/Fermilab Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\eta \approx 0$$

$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$



J-PARC Approach

N. Saito

Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL/Fermilab Approach

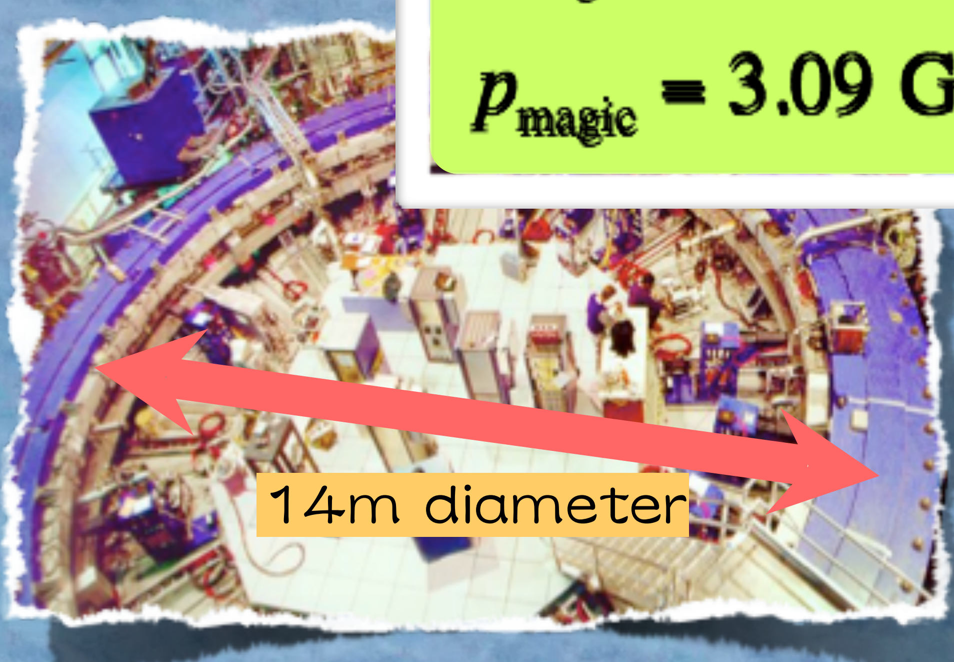
J-PARC Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\eta \approx 0$$

$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$



$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

N. Saito

■ Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL/Fermilab Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

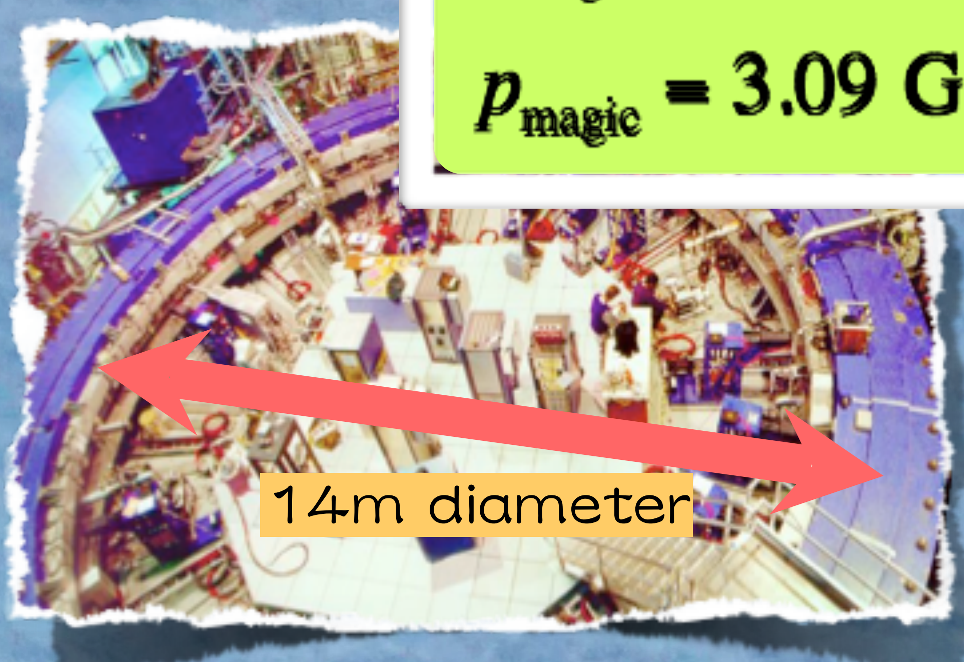
$$\eta \approx 0$$

$$\gamma_{magic} = 29.3$$

$$p_{magic} = 3.09 \text{ GeV}/c$$

J-PARC Approach

$$\vec{E} = 0$$



$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

N. Saito

Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL/Fermilab Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\eta \approx 0$$

$$\gamma_{magic} = 29.3$$

$$p_{magic} = 3.09 \text{ GeV}/c$$

J-PARC Approach

$$\vec{E} = 0$$

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

N. Saito

Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

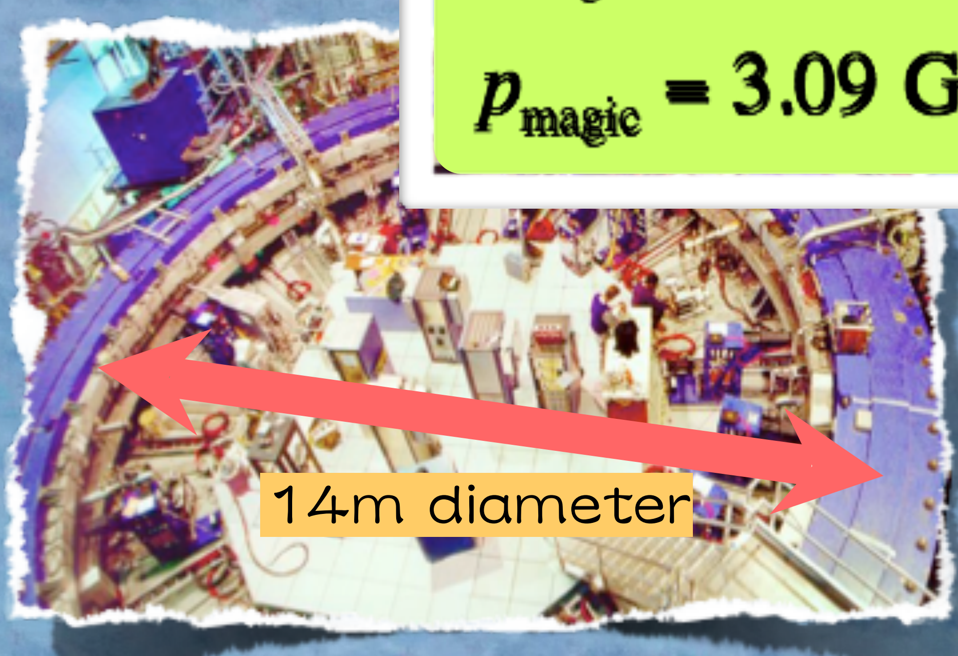
BNL/Fermilab Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\eta \approx 0$$

$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$



J-PARC Approach

$$\vec{E} = 0$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

N. Saito

Complimentary Approaches

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL/Fermilab Approach

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$

$$\eta \approx 0$$

$$\gamma_{magic} = 29.3$$

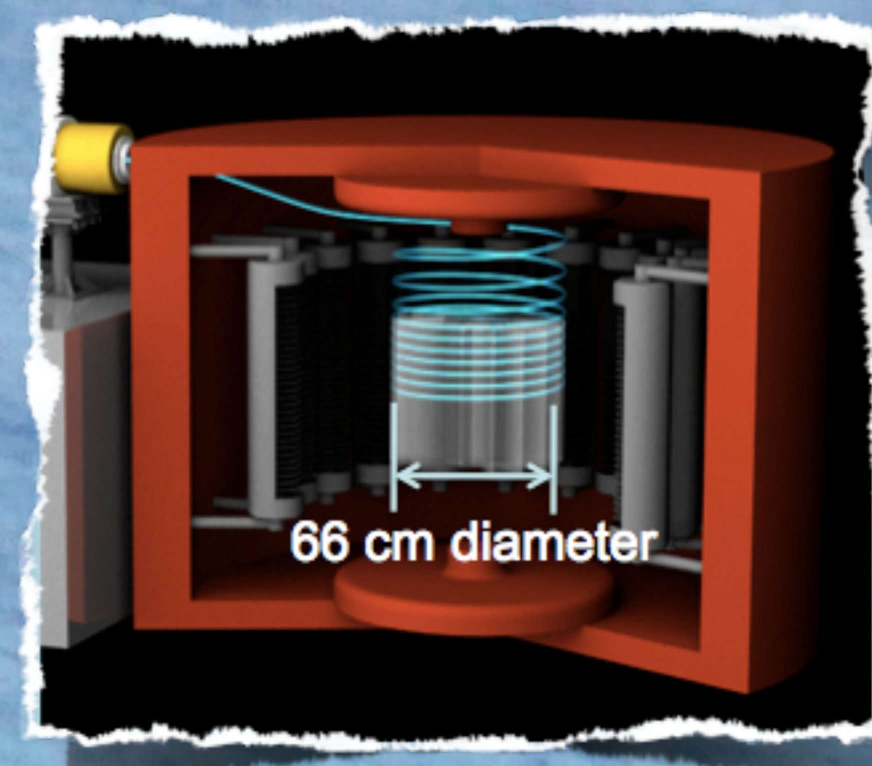
$$p_{magic} = 3.09 \text{ GeV}/c$$

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

J-PARC Approach

$$\vec{E} = 0$$

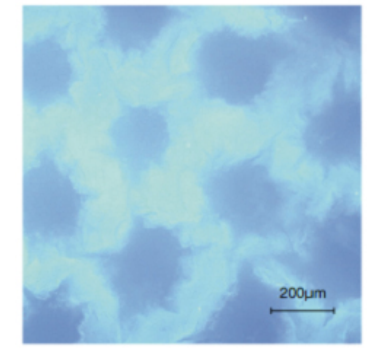
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

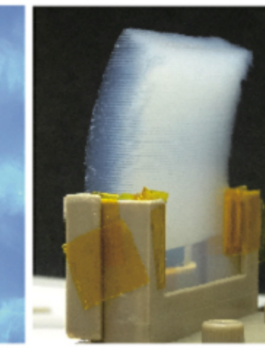


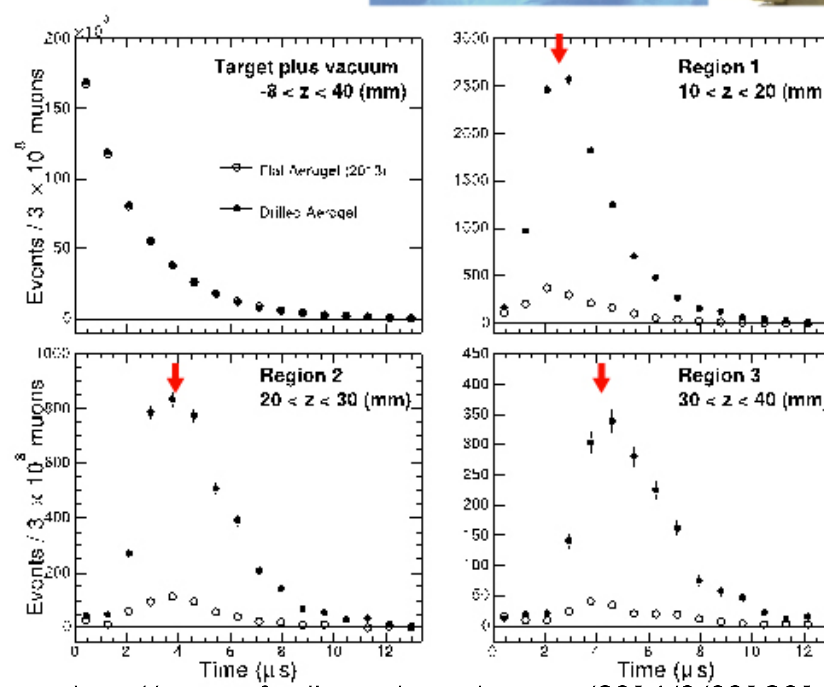
Status of J-PARC muon g-2/ EDM expriment

- Efficient muonium production target was developed
  - 10 times more yield than before
- Preparation of Mu- acceleration test
  - using J-PARC LINAC RFQ around 2015
- Muon storage magnet design being finalized
  - 1ppm local uniformity
  - verified in Muon Hyper-fine experiment in 2015 at J-PARC

Laser-ablated silica aerogel in vacuum



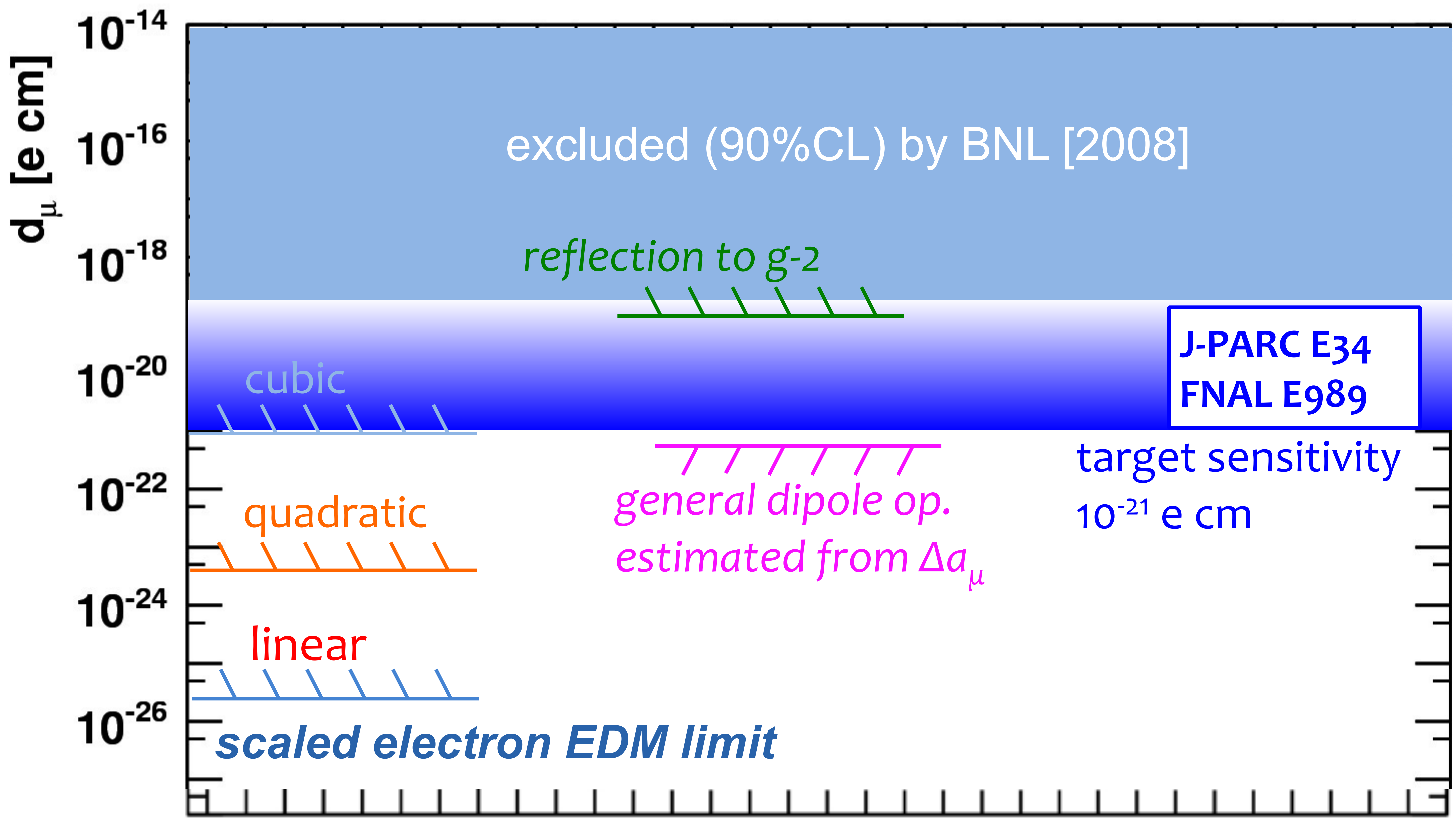




http://ptep.oxfordjournals.org/content/2014/9/091C01.full?sid=d0dc7d4c-5362-4016-8d2d-bbb168980010

N. Saito

muon EDM experimental reach



Standard model < 10^{-36} ecm

Main motivation driven by g-2 anomaly (from BNL E821).

→ The g-2 anomaly should be checked as well as EDM search

g_e-2 to check g_μ-2 ?

$$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = 2.90\,(90) \times 10^{-9}$$

PRA 89, 52118 (2014)

$$\left|\frac{\Delta a_e}{\Delta a_\mu}\right| = \frac{m_e^2}{m_\mu^2}\frac{\Lambda_\mu^2}{\Lambda_e^2}$$

The case where $\Lambda_\mu \equiv \Lambda_e$

Present: $\Delta a_e/a_e$ = 0.24 ppb

X 4 only !

Required precision is,

$$\sigma_{a_e} = 2.9 \times 10^{-9} \times \left(\frac{m_e}{m_\mu}\right)^2 = 6.8 \times 10^{-14}\ (0.06\ \mathrm{ppb})$$

relative precision

New m_e measurement $8\mathrm{x}10^{-11}$ (Nature 506, 467 (2014)) important

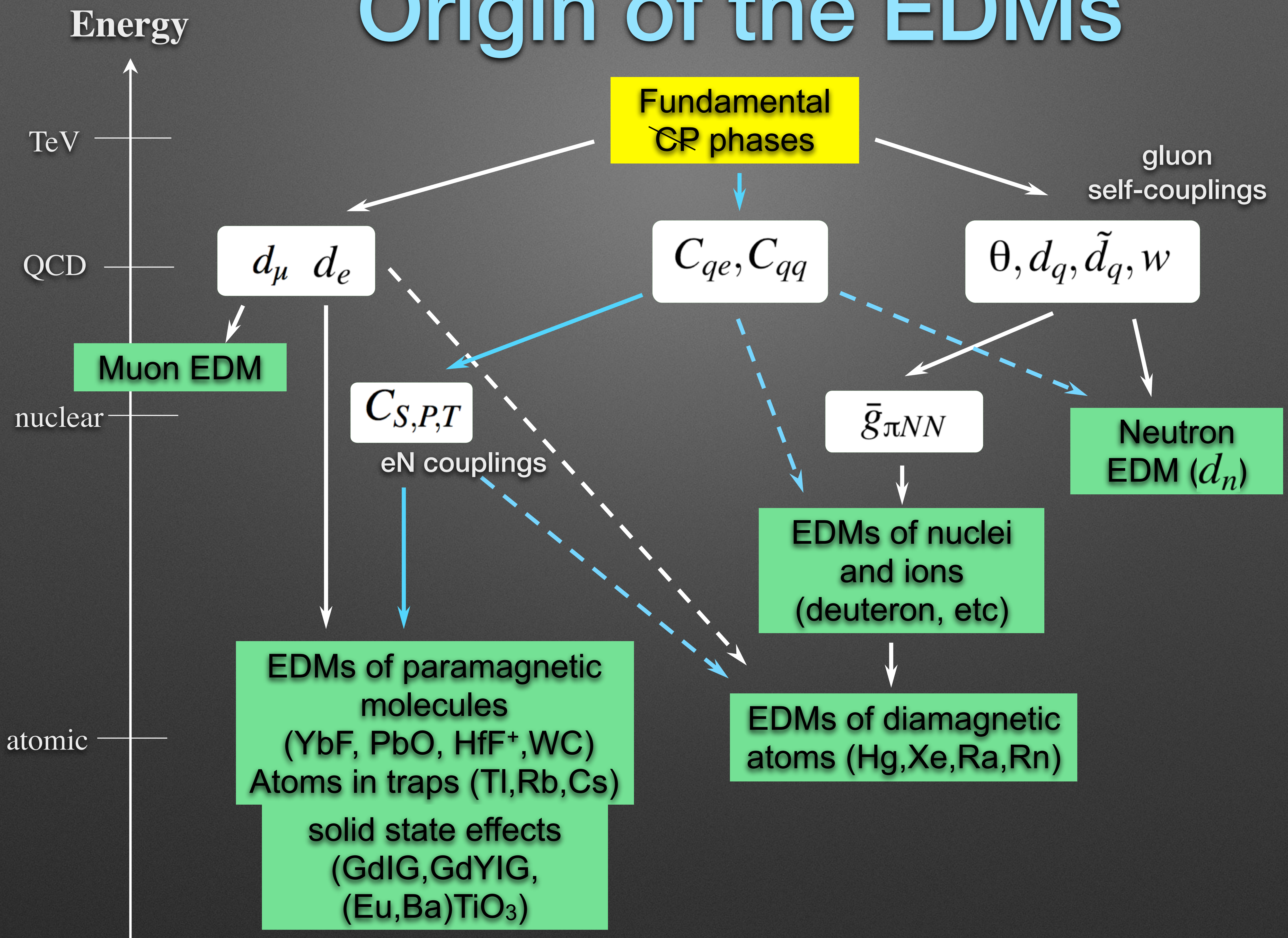
---

In case of SUSY with $m_{\tilde{e}} \neq m_{\tilde{\mu}}$

$\Delta a_e \approx 10^{-12}$ can be predicted,
(saturates the current limit, 0.24 ppb)

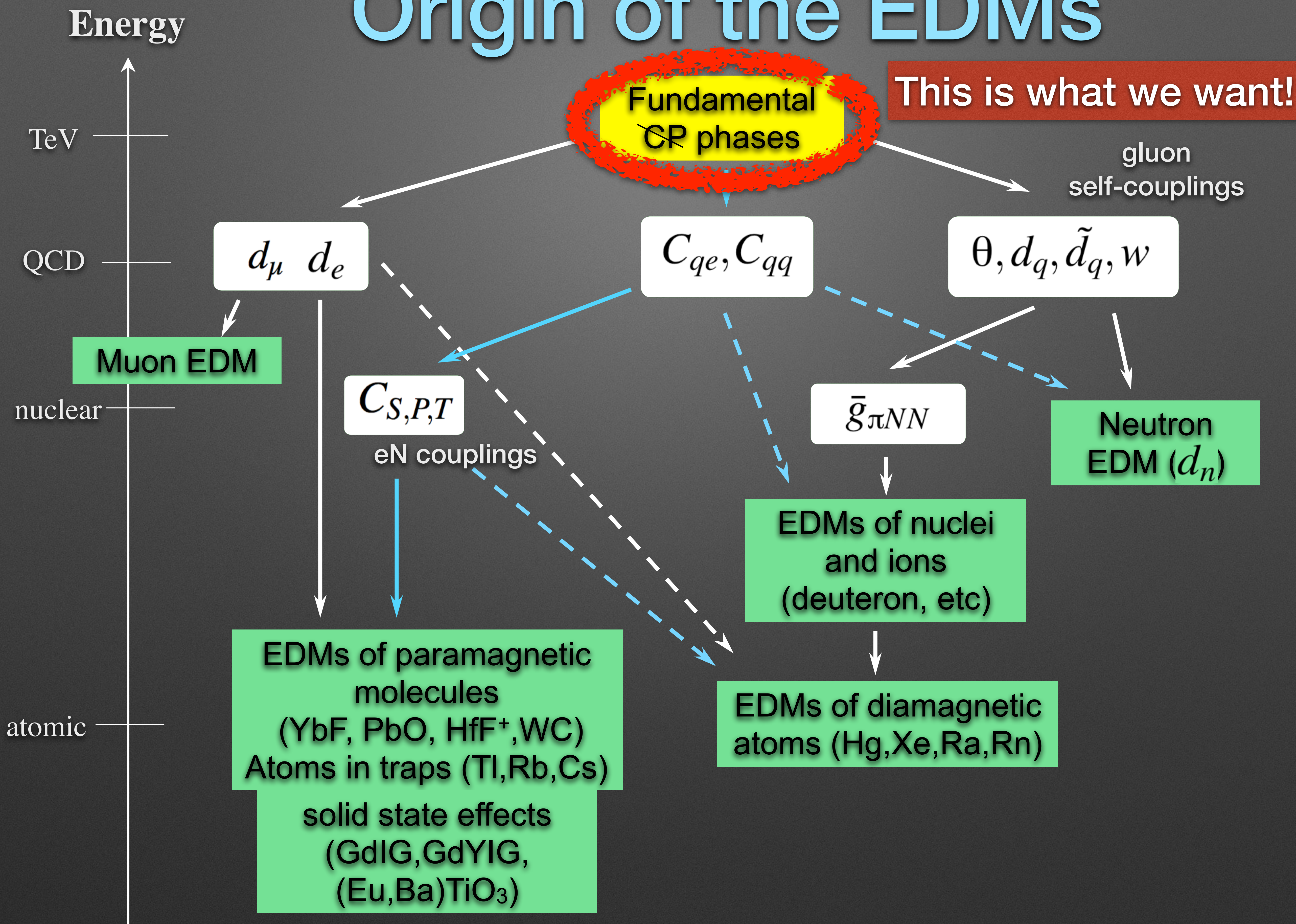
Electric Dipole Moment
(EDM)

Origin of the EDMs



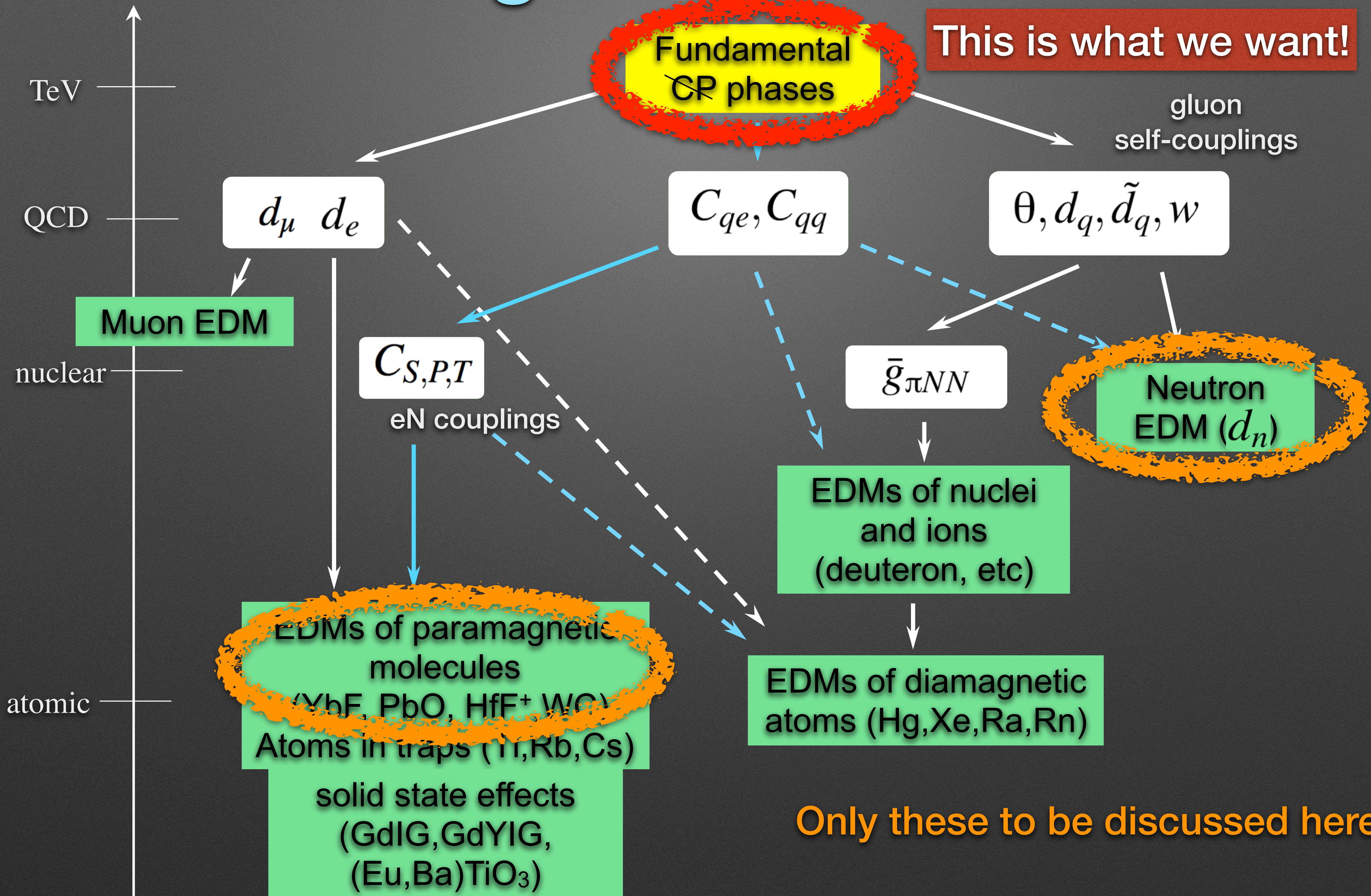
P. Ritz, Ann Phys 318 (05) 119 [updated by TM]

Origin of the EDMs



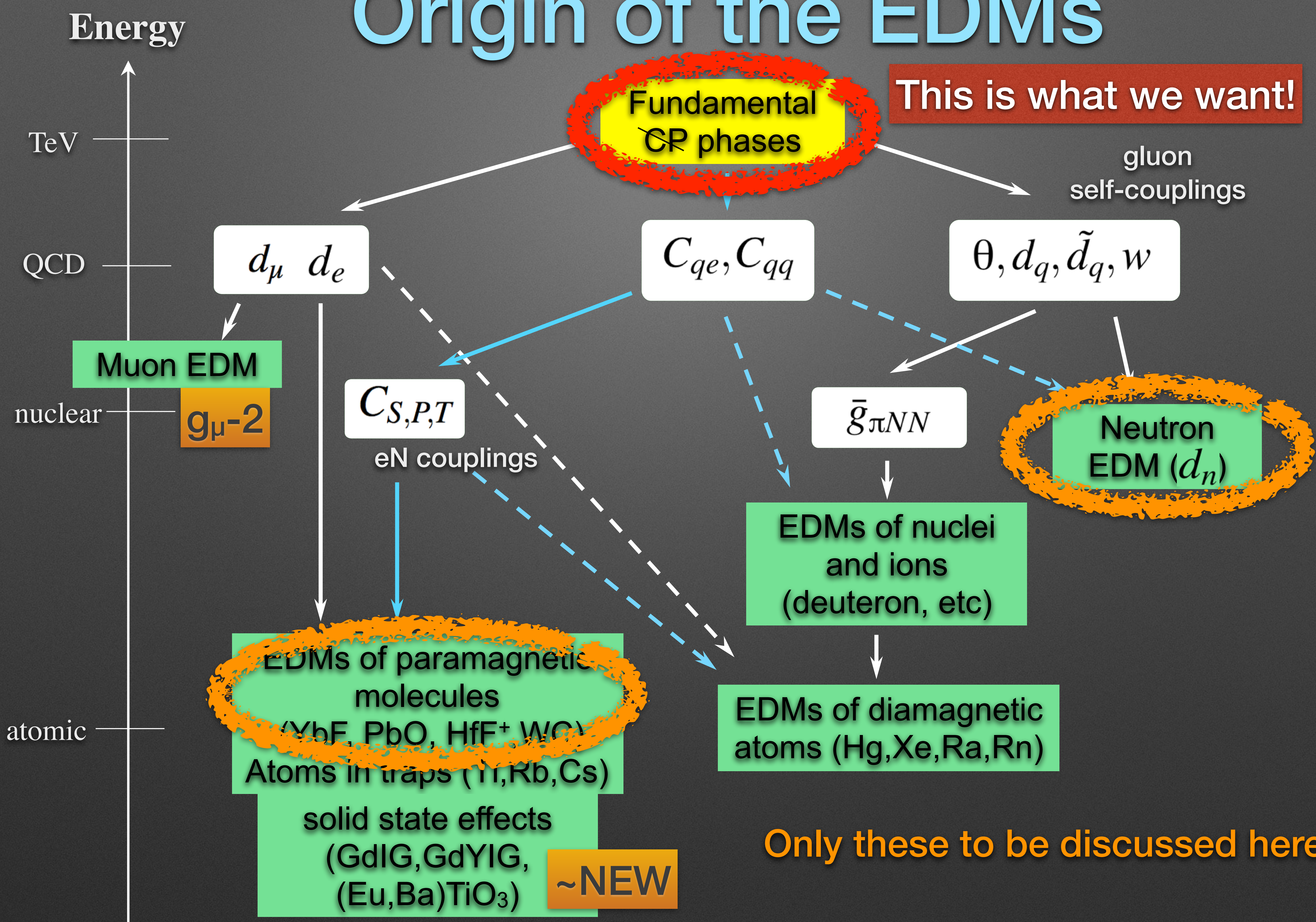
P. Ritz, Ann Phys 318 (05) 119 [updated by TM]

Origin of the EDMs



P. Ritz, Ann Phys 318 (05) 119 [updated by TM]

Origin of the EDMs



P. Ritz, Ann Phys 318 (05) 119 [updated by TM]

Many Research Activities Going on Various EDMs

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

Neutrons

~200

- @ILL
- @ILL,@PNPI
- @PSI
- @FRM-2
- @RCNP,@TRIUMF
- @SNS
- @J-PARC

Molecules

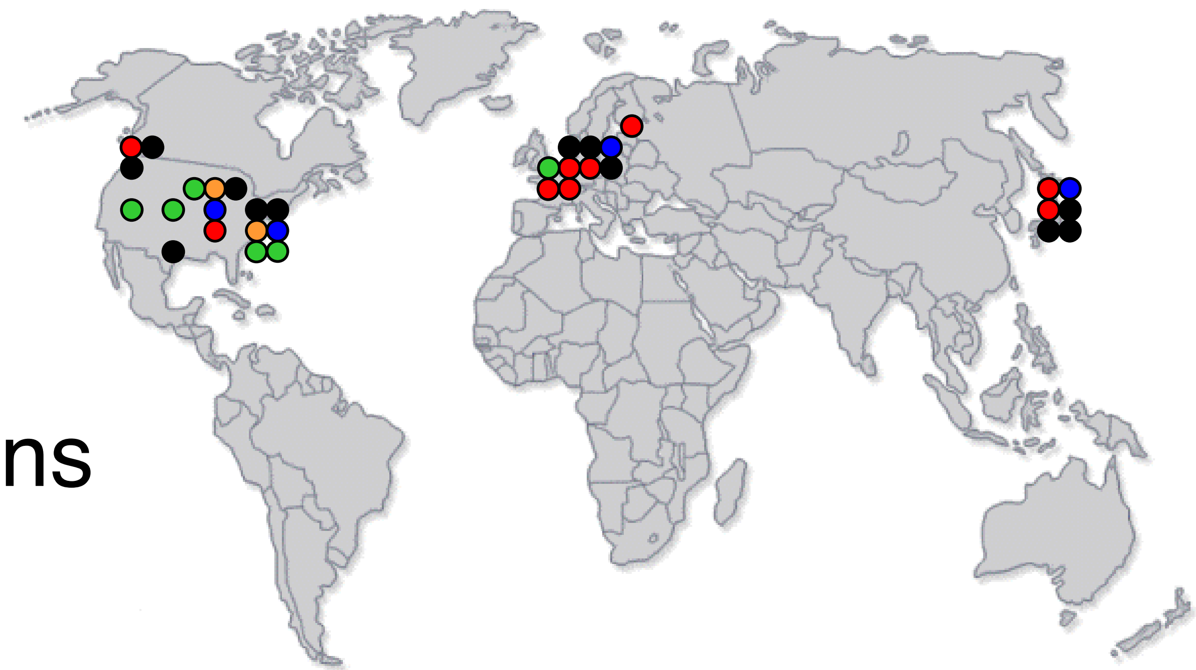
~50

- YbF@Imperial
- PbO@Yale
- ThO@Harvard
- HfF+@JILA
- WC@UMich
- PbF@Oklahoma

Atoms

~100

- Hg@UWash
- Xe@Princeton
- Xe@TokyoTech
- Xe@TUM
- Xe@Mainz
- Cs@Penn
- Cs@Texas
- Fr@CYRIC,Tohoku
- Rn@TRIUMF
- Ra@ANL
- Ra@KVI
- Yb@Kyoto



Ions-Muons

~200

- @BNL
- @FZJ
- @FNAL
- @JPARC

Solids

~10

- GGG@Indiana
- ferroelectrics@Yale

Many Research Activities Going on Various EDMs

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

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

Atoms

~100

- Hg@UWash
- Xe@Princeton
- Xe@TokyoTech
- Xe@TUM
- Xe@Mainz
- Cs@Penn
- Cs@Texas
- Fr@CYRIC,Tohoku
- Rn@TRIUMF
- Ra@ANL
- Ra@KVI
- Yb@Kyoto

Diversity is important

Ions-Muons

~200

- @BNL
- @FZJ
- @FNAL
- @JPARC

Solids

~10

- GGG@Indiana
- ferroelectrics@Yale

Many Research Activities Going on Various EDMs

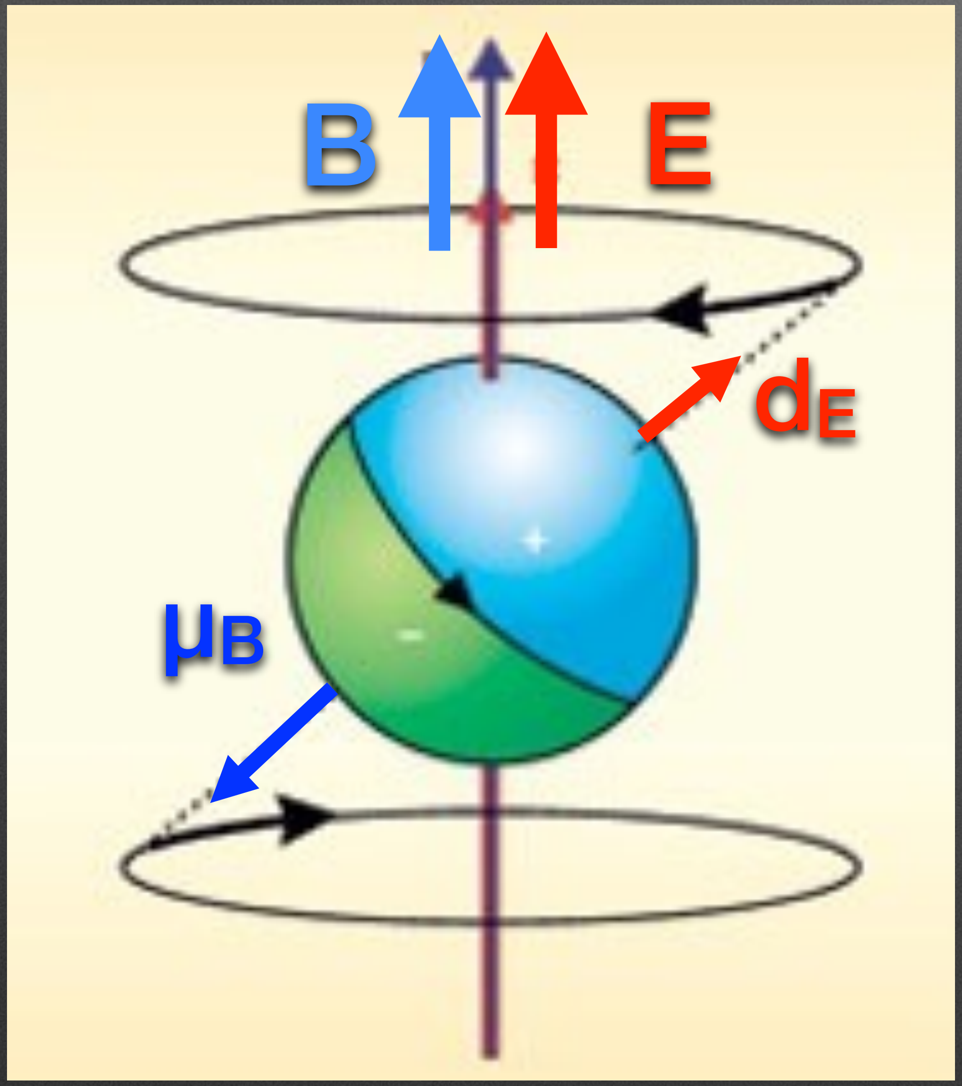
Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- 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
- Atoms ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@CYRIC,Tohoku
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto
- Ions-Muons ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC
- Solids ~10
  - GGG@Indiana
  - ferroelectrics@Yale

Diversity is important

No way to cover all…

Technique to measure EDM



- precesses with Larmor freq

$$\omega_B = -\frac{2\mu_B B}{\hbar}$$

- additional precession

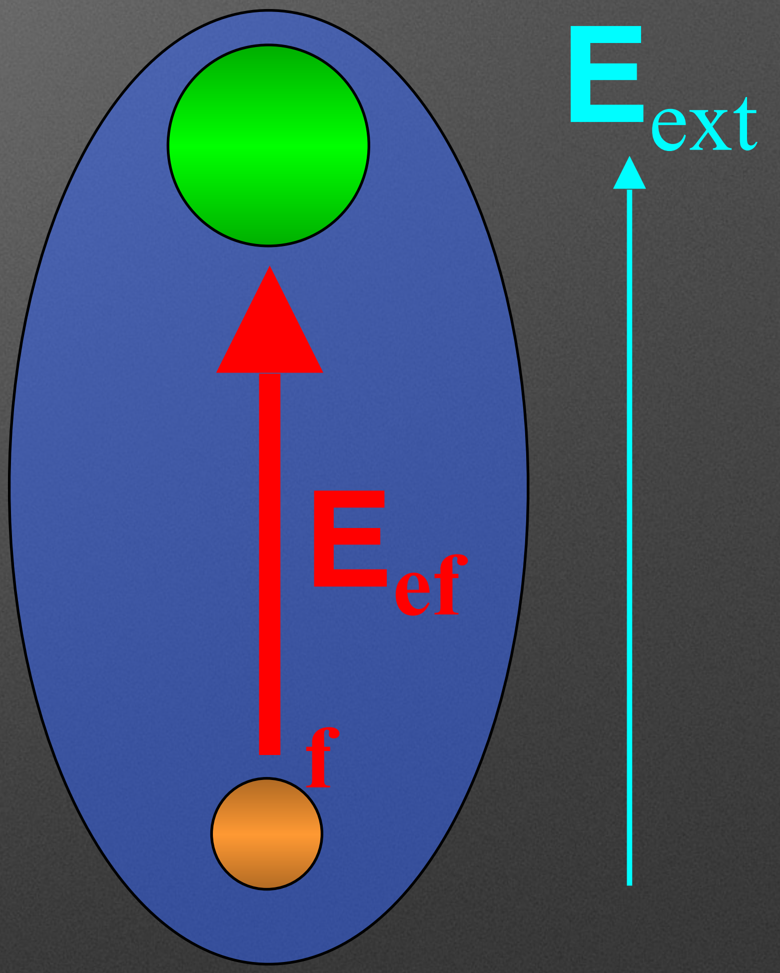
$$\omega_E = \frac{2d_E E}{\hbar}$$

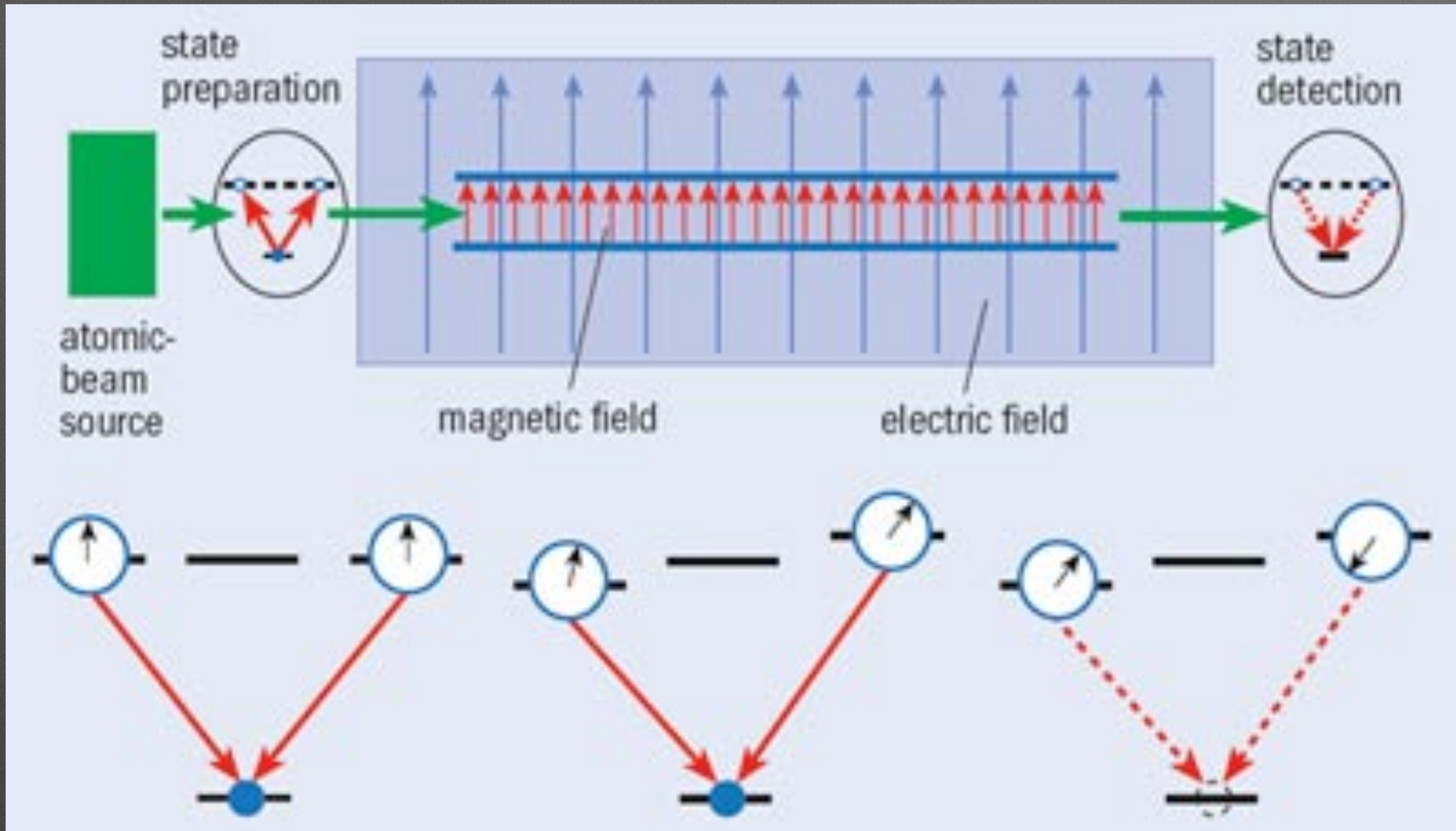
- flip E and measure the difference

$$\omega_{E\|B} - \omega_{E\,anti-\|B} \equiv \Delta\omega = \frac{4d_E E}{\hbar}$$

EDM of dipolar molecules

- Easier to polarize molecules than atoms
- Enhances effective E field seen by the unpaired electron by a factor up to 10^5 (~84GV/cm for ThO*)
- Look for interferometer phase shift of the two spin states (hyperfine levels of the ground state) when E reversed
- “Schiff shielding” strongly violated by relativistic effects especially in heavy atoms



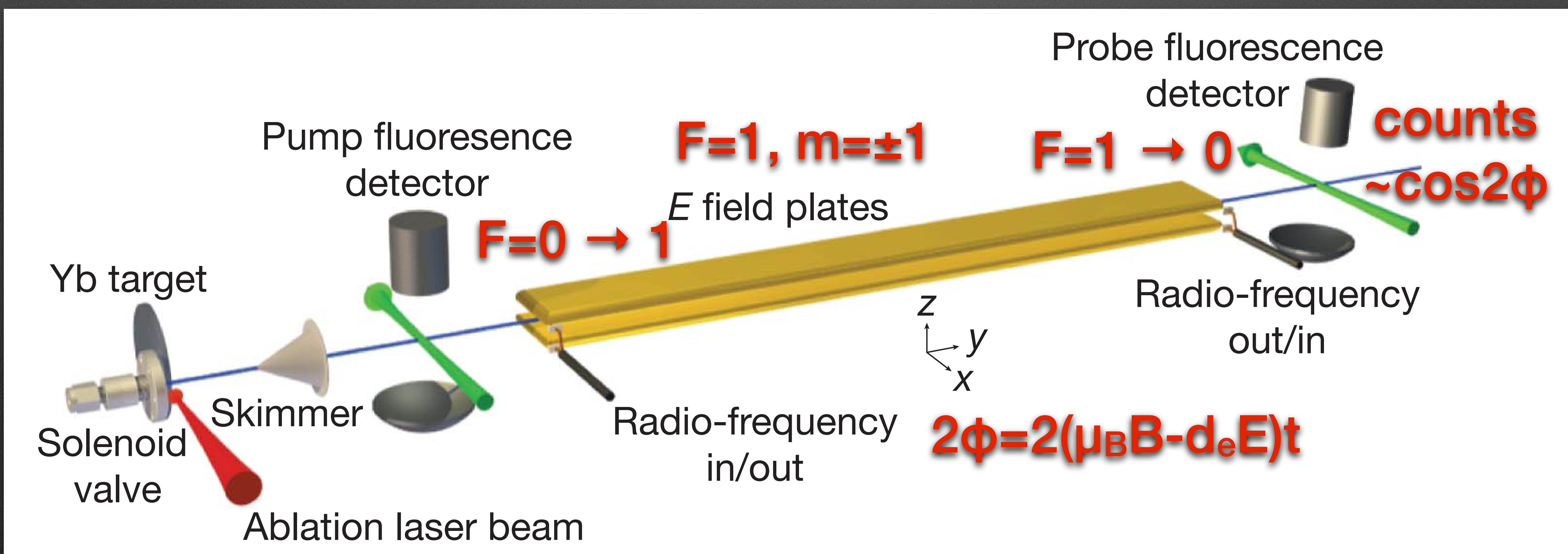


YbF

ICL, 2011

$$|d_e| < 10.5 \times 10^{-28} ecm$$

(90% C.L.)



Nature 473 (2011) 493

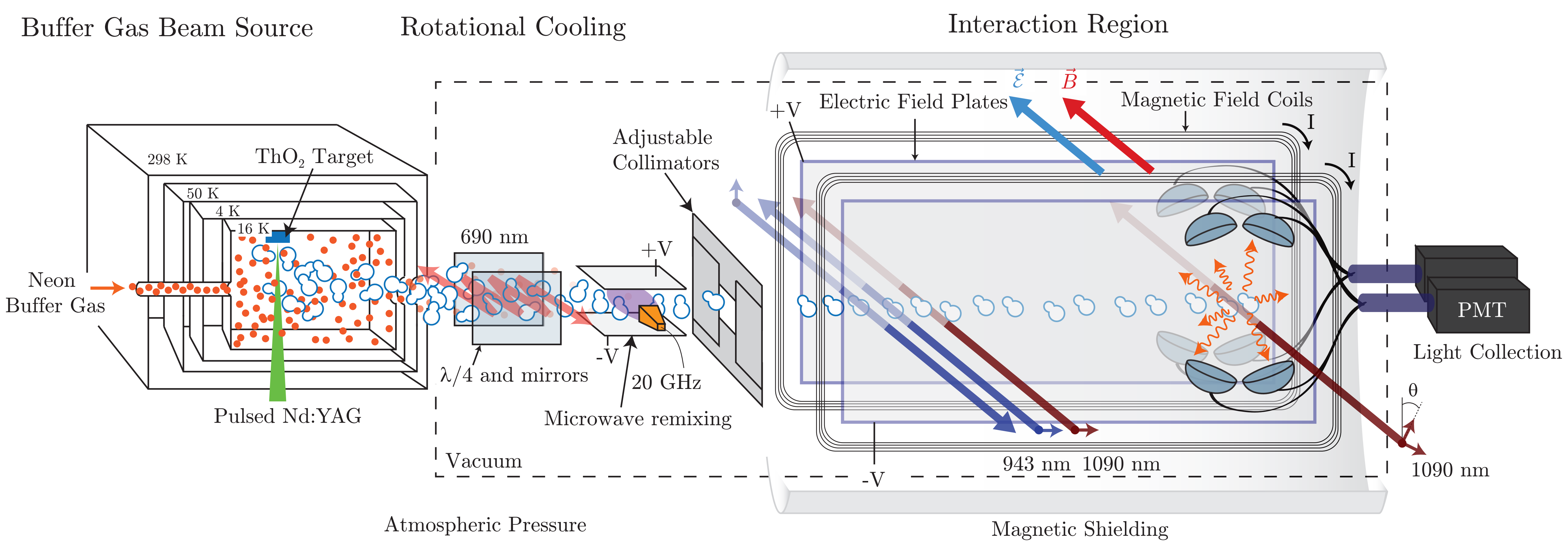
- a pioneering work of the new method, though a modest 1.5× improvement over the previous Tl experiment
  - still statistically limited
- ×10 improvement within a few years;
  ×100 expected eventually
  - several groups working

an excerpt from my review talk at EPS 2011

- a pioneering work of the new method, though a modest 1.5× improvement over the previous Tl experiment
    - still statistically limited
- ×10 improvement within a few years; ×100 expected eventually → YES !
    - several groups working

an excerpt from my review talk at EPS 2011

$|d_e| < 8.7 \times 10^{-29}$ e cm (90% C.L.)



by ACME collaboration using ThO*

Nature 343 (2014) 269

- a pioneering work of the new method, though a modest 1.5× improvement over the previous Tl experiment
    - still statistically limited
- ×10 improvement within a few years; ×100 expected eventually
    - several groups working

Very hopeful

many improvements foreseen: molecule beam, spin state preparation, etc

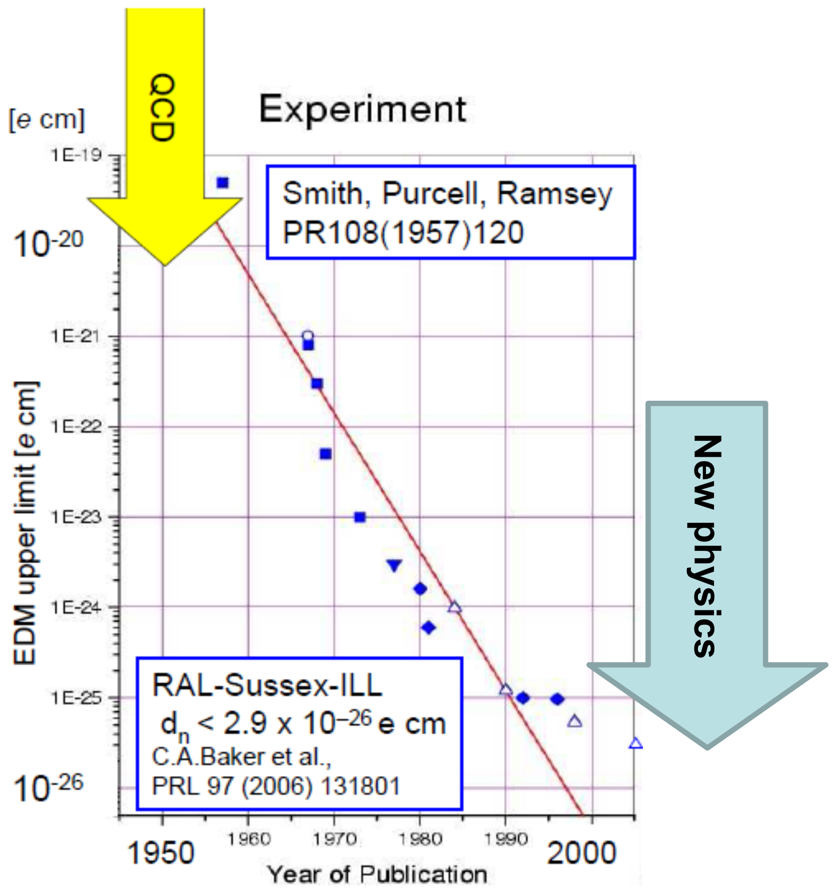
an excerpt from my review talk at EPS 2011

+ updates

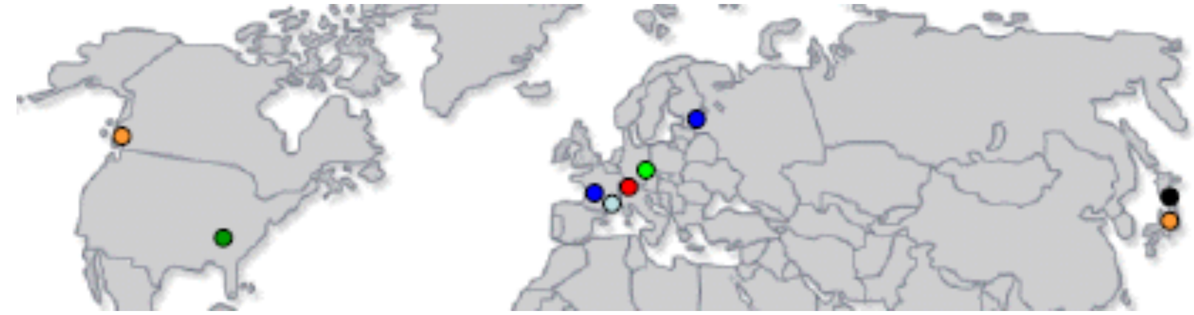
Neutron EDM projects

(Essentially all of them aiming at 1-2 orders of magnitude improvement)

- Operating:
  - PNPI, ILL@ILL
    (result 2013/14, upgrading)
  - nEDM@PSI
    (2017 upgrade to n2EDM)



- R&D and construction
  - cryoEDM@ILL
  - @RCNP/TRIUMF
  - @FRM-2
  - @SNS
  - @PNPI
  - @LANL
- Possible future projects
  - @J-PARC
  - @PIK
  - @ESS



UCN sources
[some belong to specific experiments]

- Operating:
  - ILL PF-2 (turbine)
  - LANL (sD2)
  - PSI (sD2)
  - TRIGA Mainz (sD2)
  - RCNP (SF-He)
  - ILL SUN (SF-He)
  - [ILL: GRANIT, cryoEDM]
  - [NIST: lifetime]
- R&D and construction
  - ILL SuperSUN
  - TRIUMF/RCNP
  - PNPI WWR-M
  - NCSU PULSTAR
  - FRM-2
  - SNS-EDM
- Possible projects
  - J-PARC
  - PIK
  - ESS

neutron EDM - Prospects

- Sensitivity is expected to improve
  - by a factor of 5 in a couple of years
  - by two orders of magnitude within the next decade

an excerpt from my review talk at EPS 2011

neutron EDM - Prospects

- Sensitivity is expected to improve
  - by a factor of 5 in a couple of years
  - by two orders of magnitude within the next decade

Perhaps I meant ~5 years here

an excerpt from my review talk at EPS 2011

Updated

Neutron EDM Status & Prospects

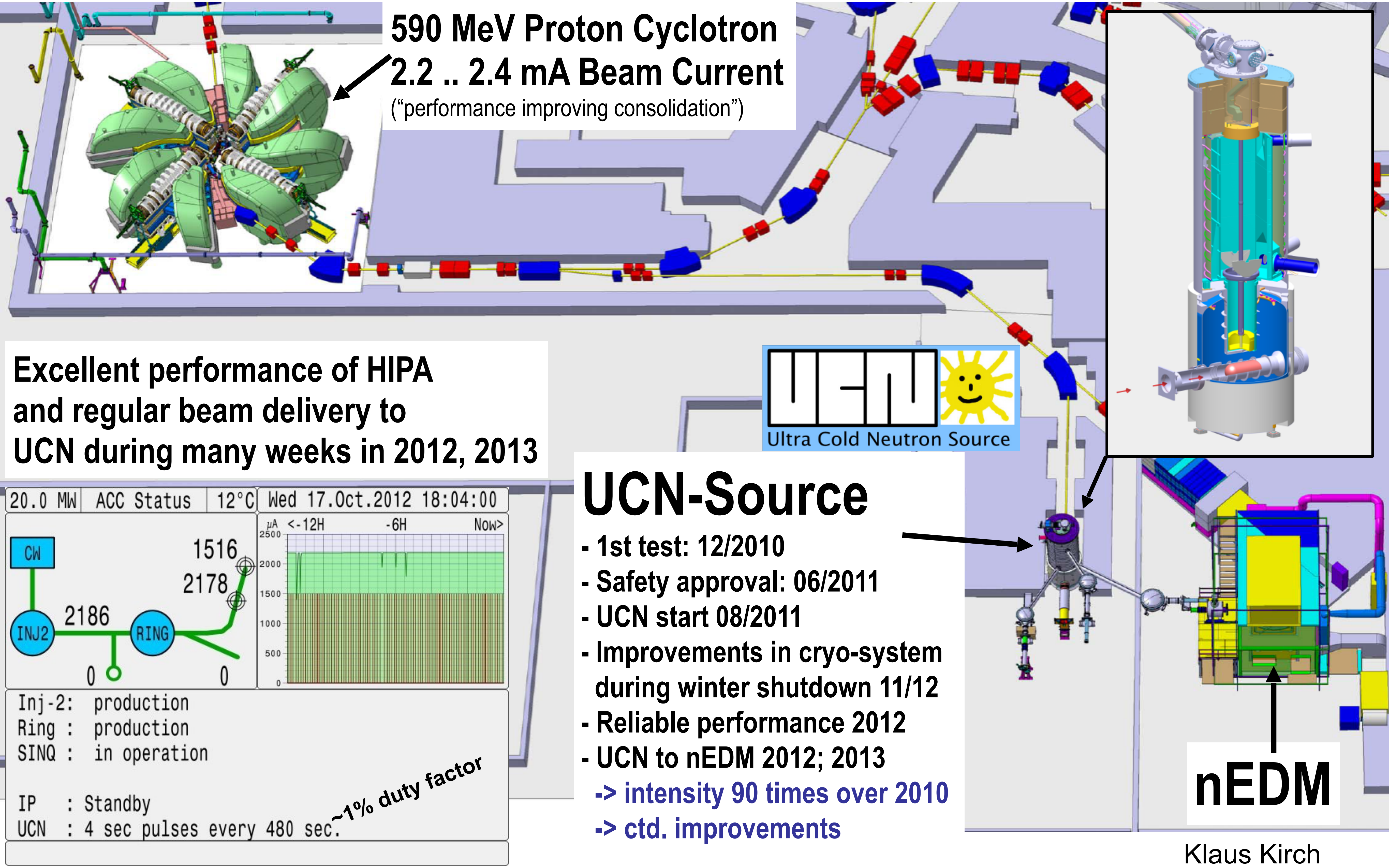
- Presently ~3 UCN sources worldwide (ILL, LANL, PSI, etc) in a user mode (state of the art is still below 100 cm^{-3} in reasonable volumes; potential improvements up to 1000 cm^{-3})
- Around 5-10 more projects and ideas for improved sources, some of which aim at the order of 10'000 cm^{-3}
- 2 nEDM experiments are taking data, 5 or more may come online in the next 5 years
  - nEDM@PSI may hopefully deliver an improved result in 2016? if things go well.
- These are complex installations and difficult experiments – experience tells us that they need time.
- Some efforts may join forces in the future.

High Intensity Proton accelerator & UCN Source at the Paul Scherrer Institut

Solid D_2

590 MeV Proton Cyclotron
2.2 .. 2.4 mA Beam Current
("performance improving consolidation")

Excellent performance of HIPA and regular beam delivery to UCN during many weeks in 2012, 2013



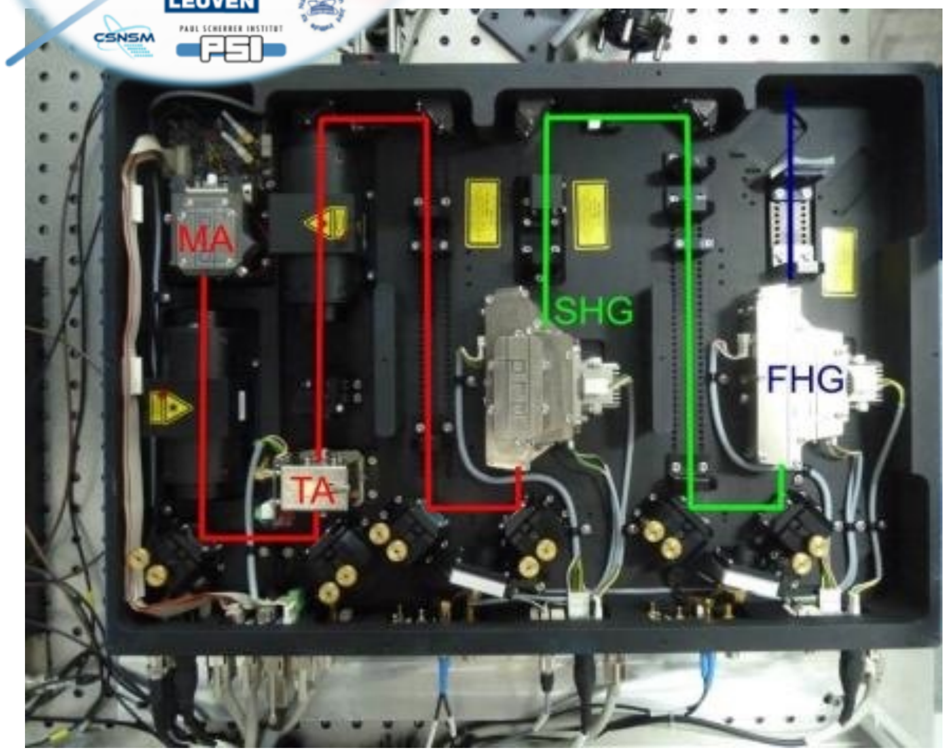
Ultra Cold Neutron Source

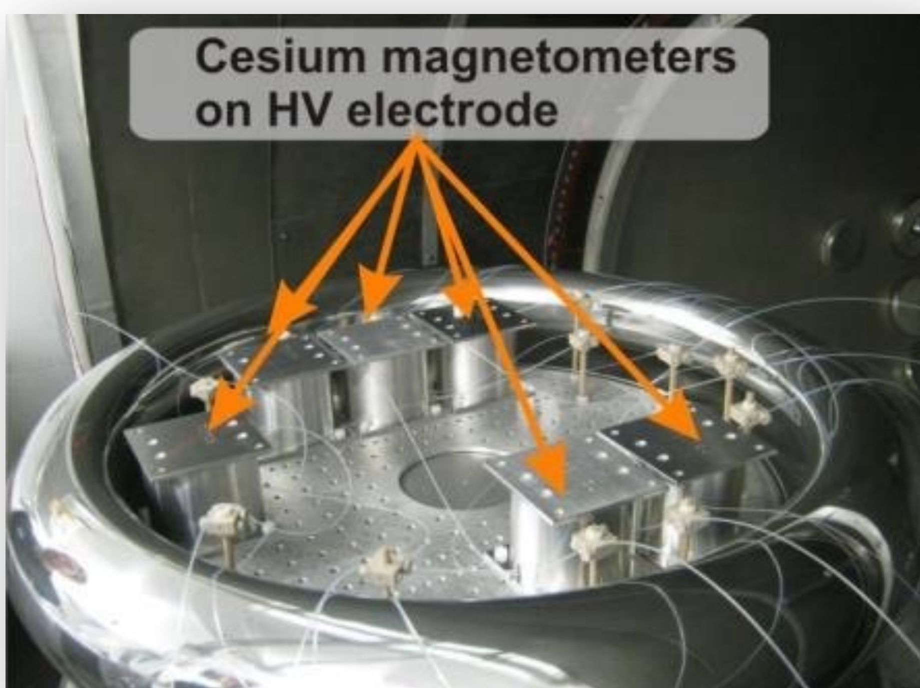
UCN-Source

- 1st test: 12/2010
- Safety approval: 06/2011
- UCN start 08/2011
- Improvements in cryo-system during winter shutdown 11/12
- Reliable performance 2012
- UCN to nEDM 2012; 2013
  - -> intensity 90 times over 2010
  - -> ctd. improvements

Klaus Kirch

Features of nEDM@PSI





- Hg-199 co-magnetometer
  - improved S/N by factor >4
  - laser read-out proven, being implemented
- CsM array
  - 16 scalar sensors in operation (6 HV)
  - vector CsM proven
- B-field
  - homogeneity (T2~1000s)
  - reproducibility (~50pT), after degaussing (~200pT)
- Simultaneous spin analysis
- Known systematics well under control down to ~2 x 10^{-27} ecm

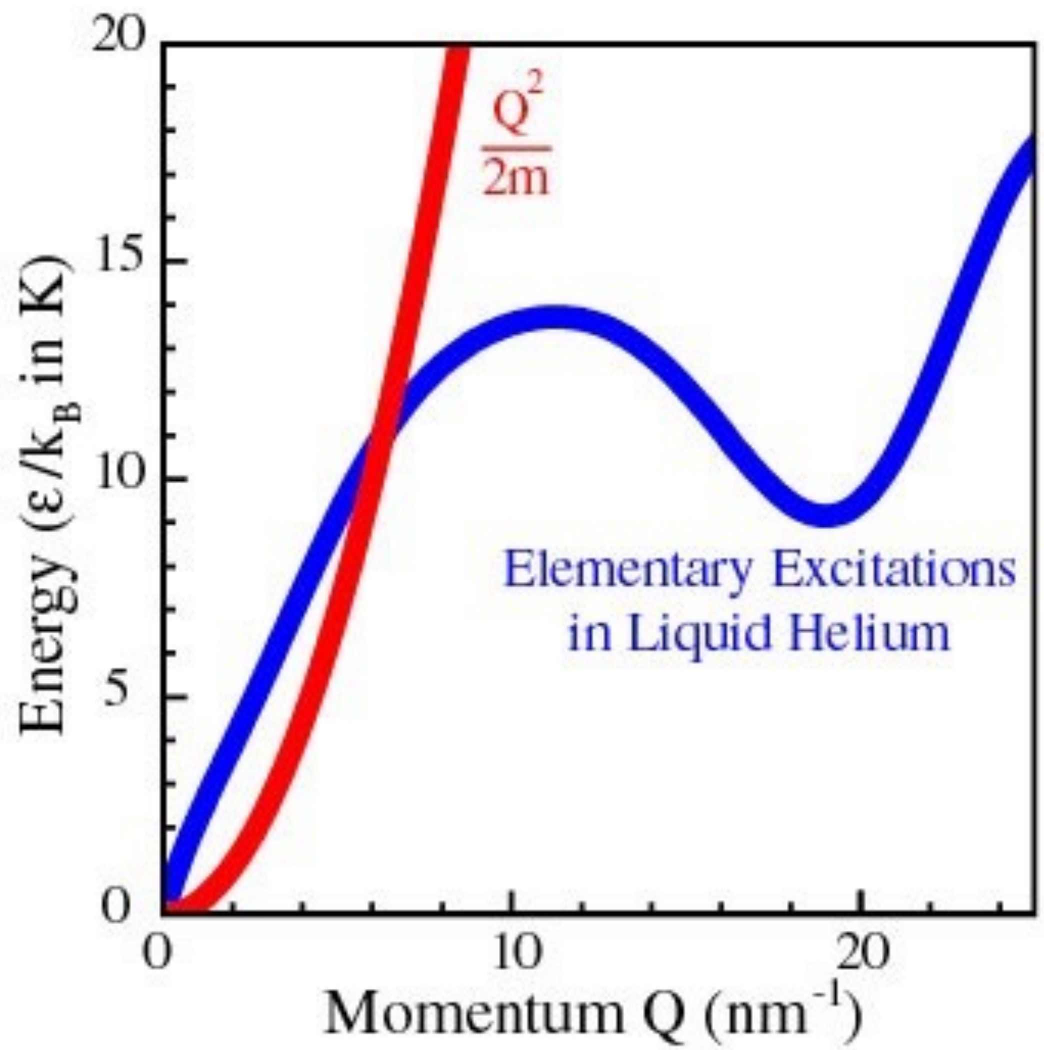
Klaus Kirch

Superthermal Production of UCN

R.Golub and J.M.Pendlebury, Phys.Lett.A **62**,337,(77)

- 8.9 Å cold neutrons get down-scattered in superfluid ^4He by exciting elementary excitation
- Up-scattering process is

  suppressed by a large Boltzman factor
- No nuclear absorption



- Expect a production of ~ 0.2-0.3 UCN/cc/s
- With a 500 second lifetime, ρ_{UCN}~100-150/cc and N_{UCN}~3-4x10^5 for each of the two 3 liter cells

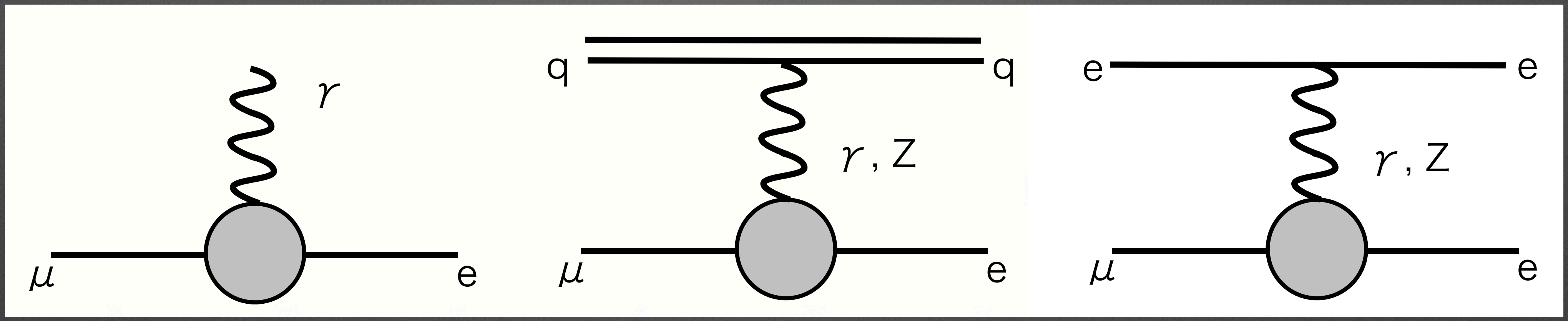
Charged Lepton Flavor Violation
(cLFV)
in *Muons*

Muon cLFV
Sensitivity comparisons

$\mu \to e\gamma$ $\mu N \to eN$ $\mu \to 3e$

"dipole" dominant

(SUSY etc)



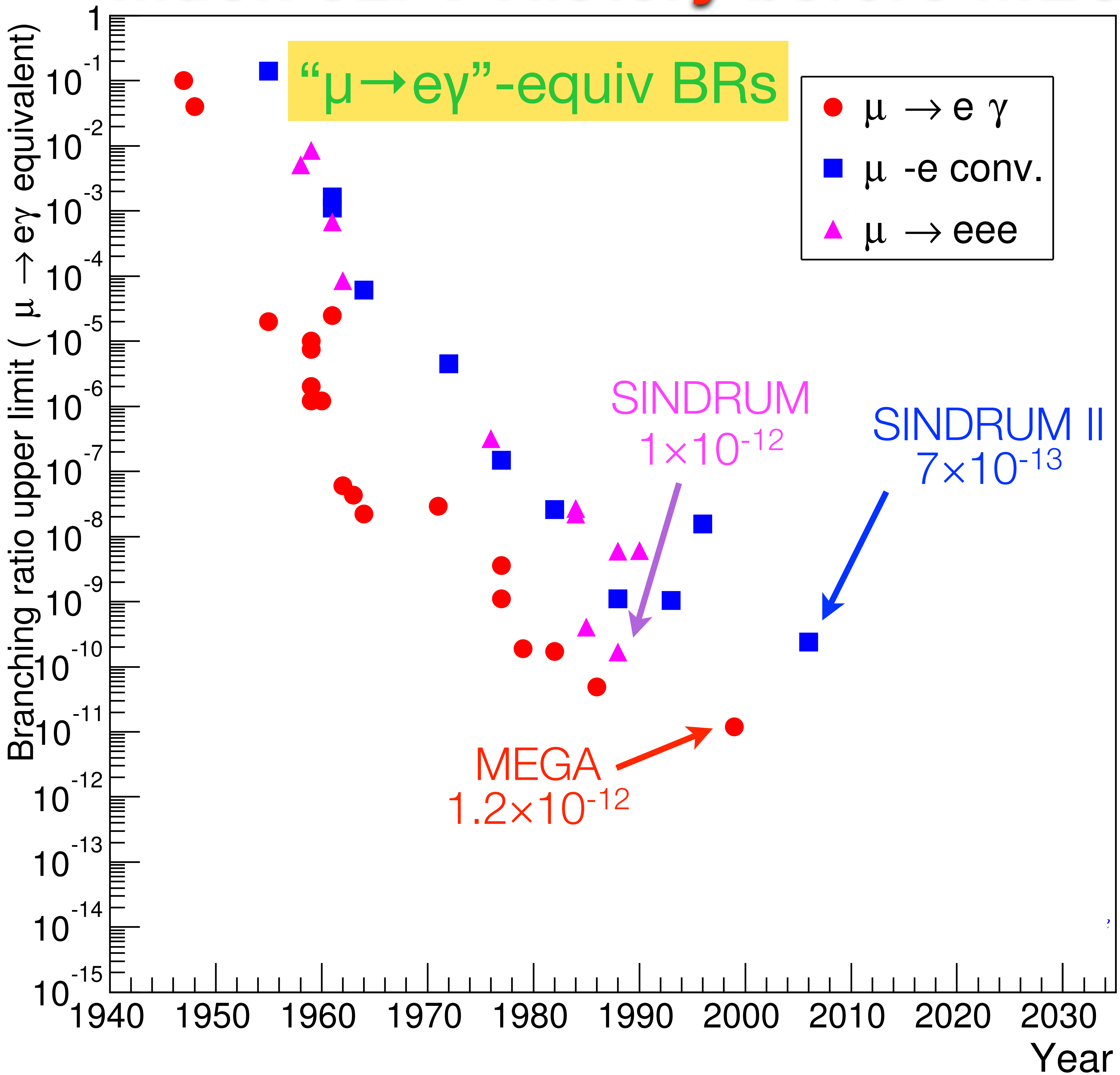
1 : 1/390 : 1/170

BR = 4×10^{-14} : 1×10^{-16} : 2×10^{-16}

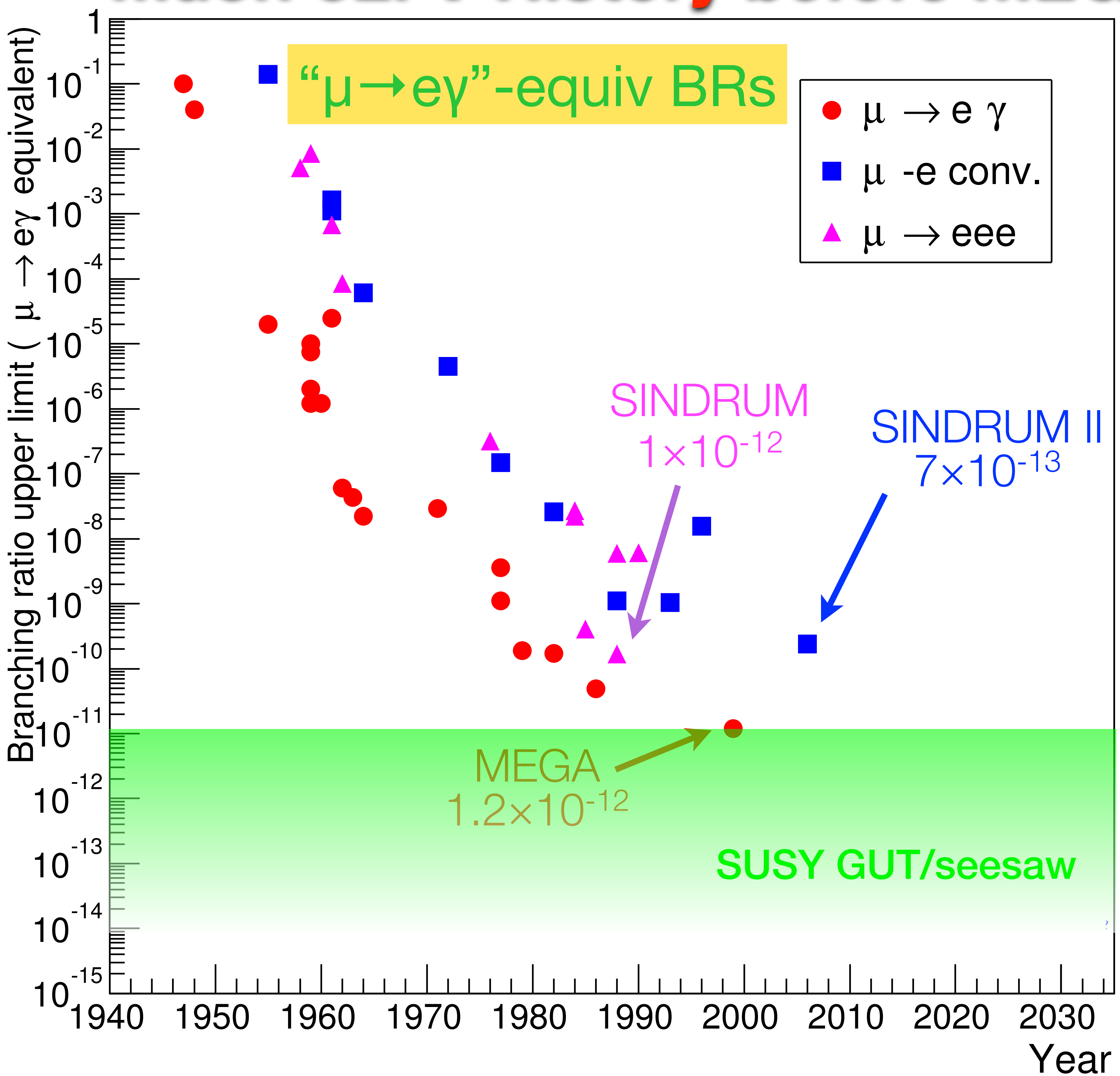
~MEG II goal

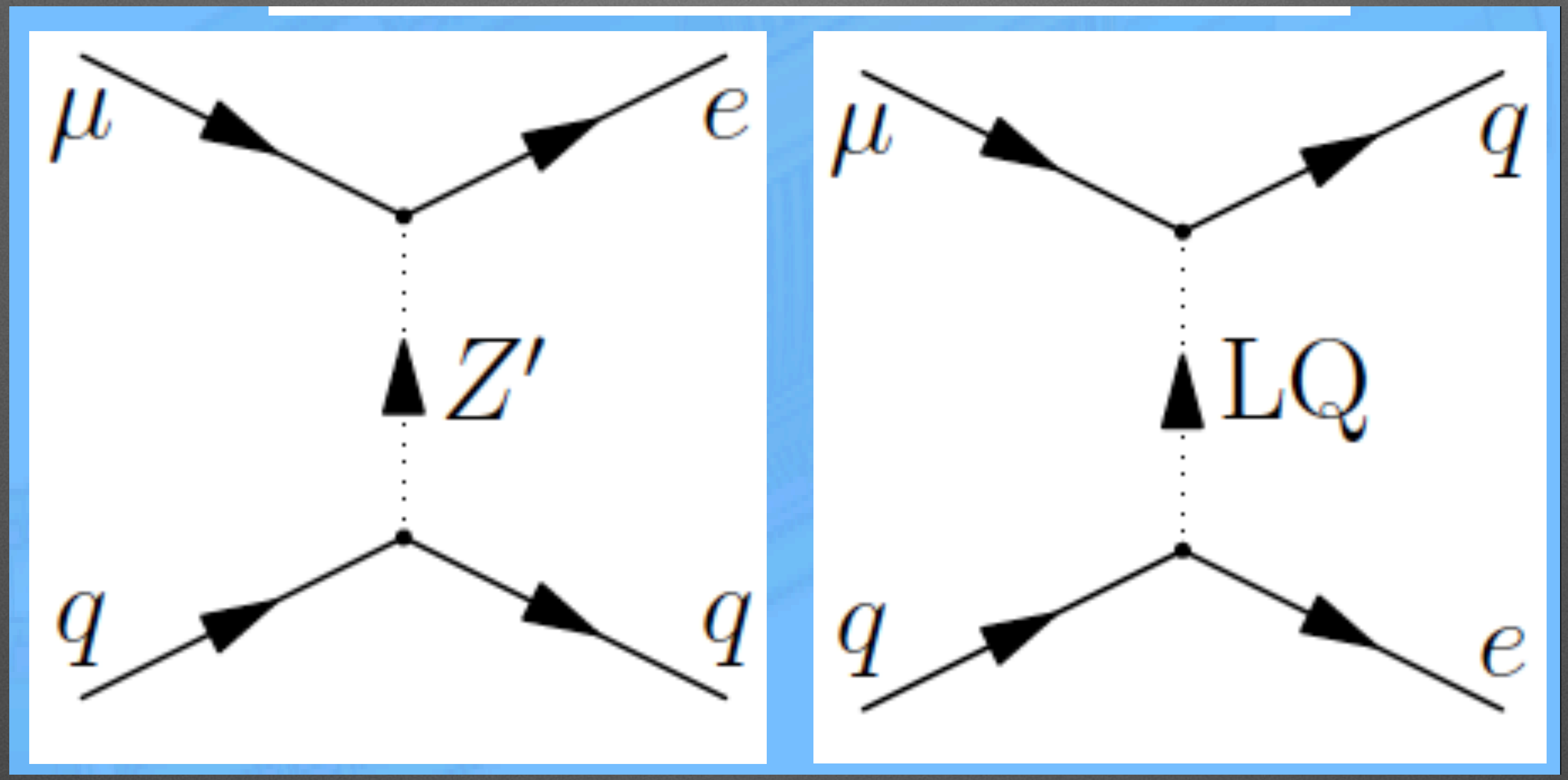
for Al target

Muon cLFV History before MEG



Muon cLFV History before MEG

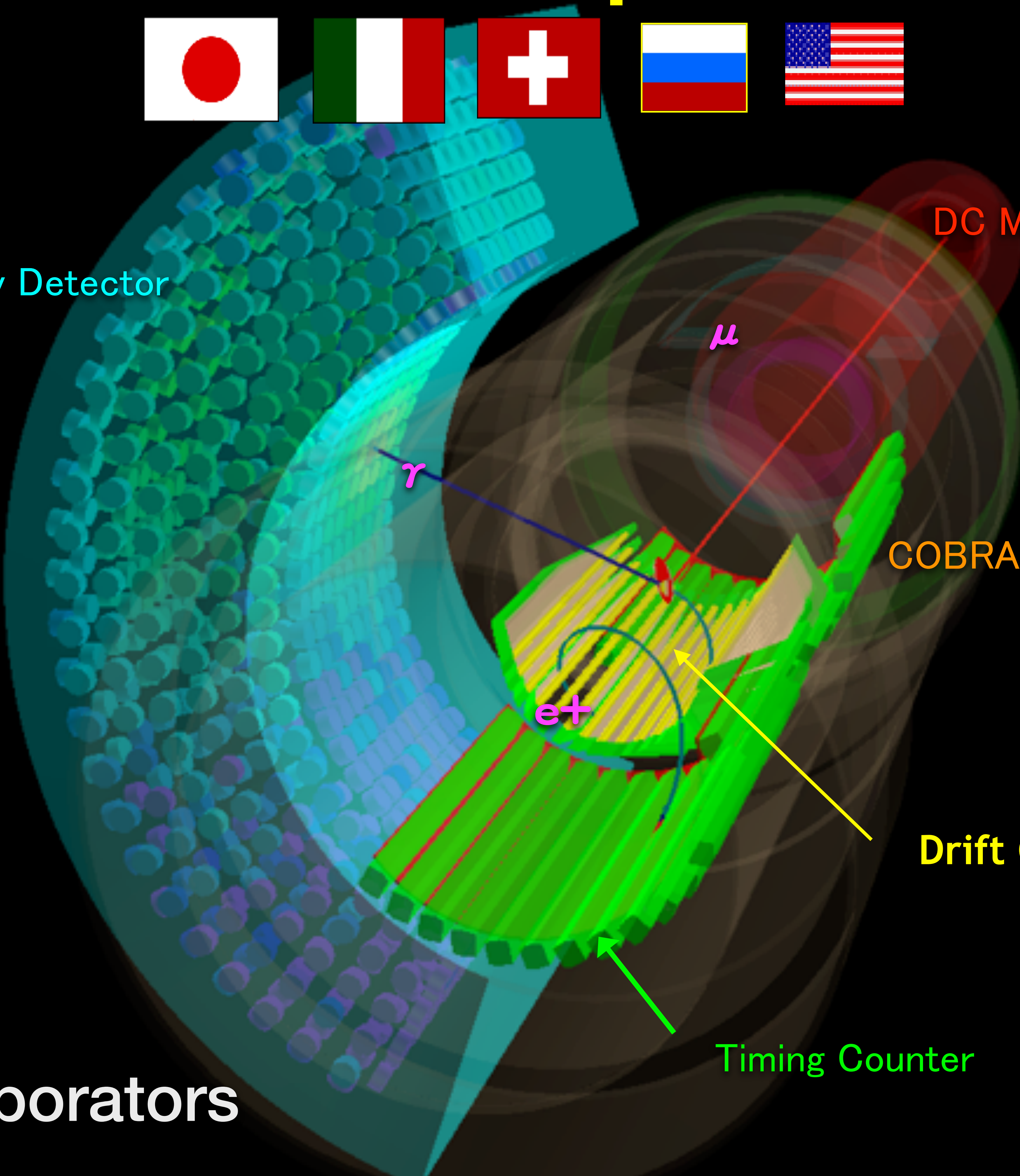




Some models have “four-fermion” terms which strongly enhance

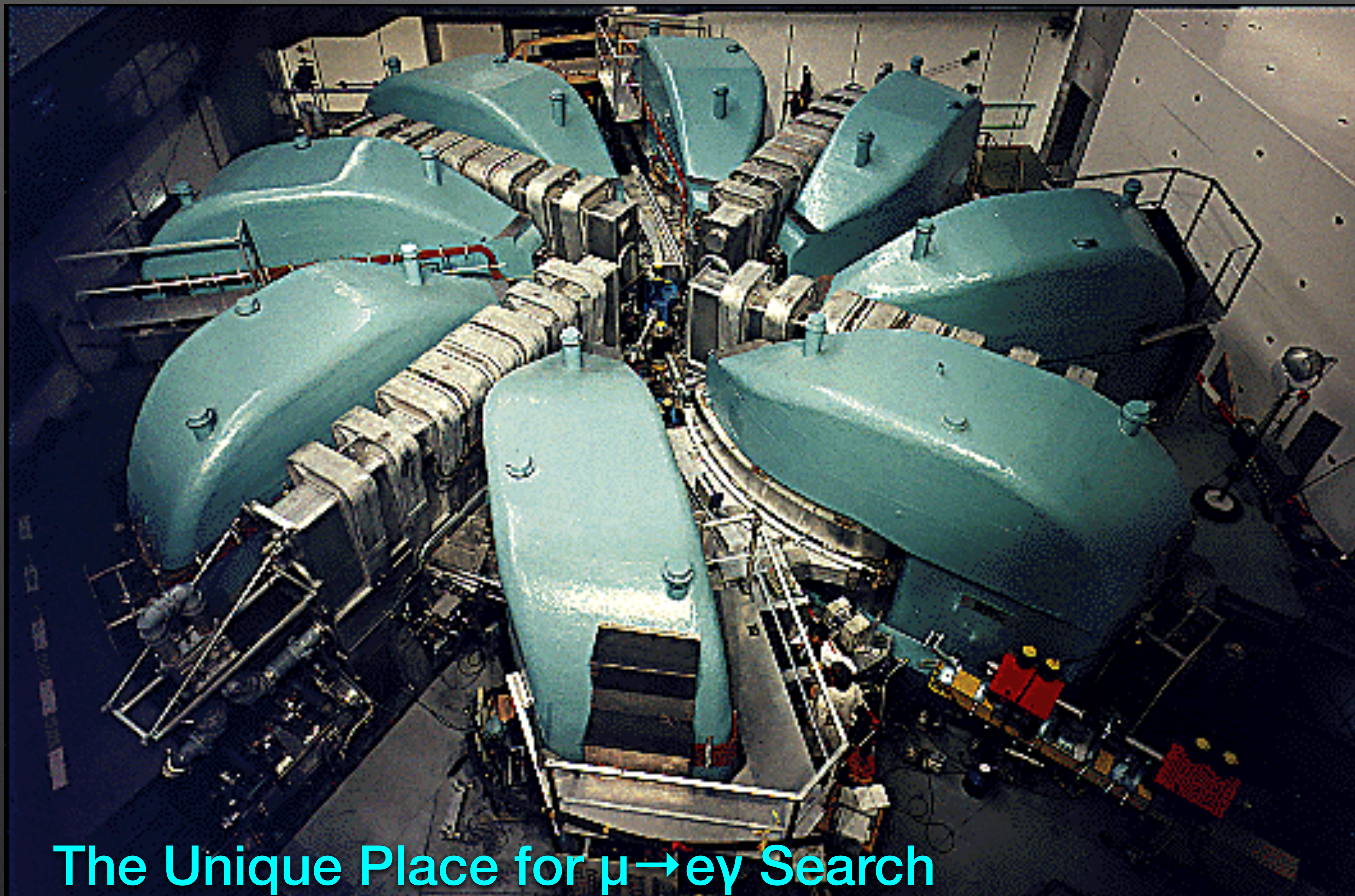
$\mu N \to eN \qquad \mu \to 3e$

The MEG Experiment



~60 collaborators

1.3MW Proton Cyclotron at PSI

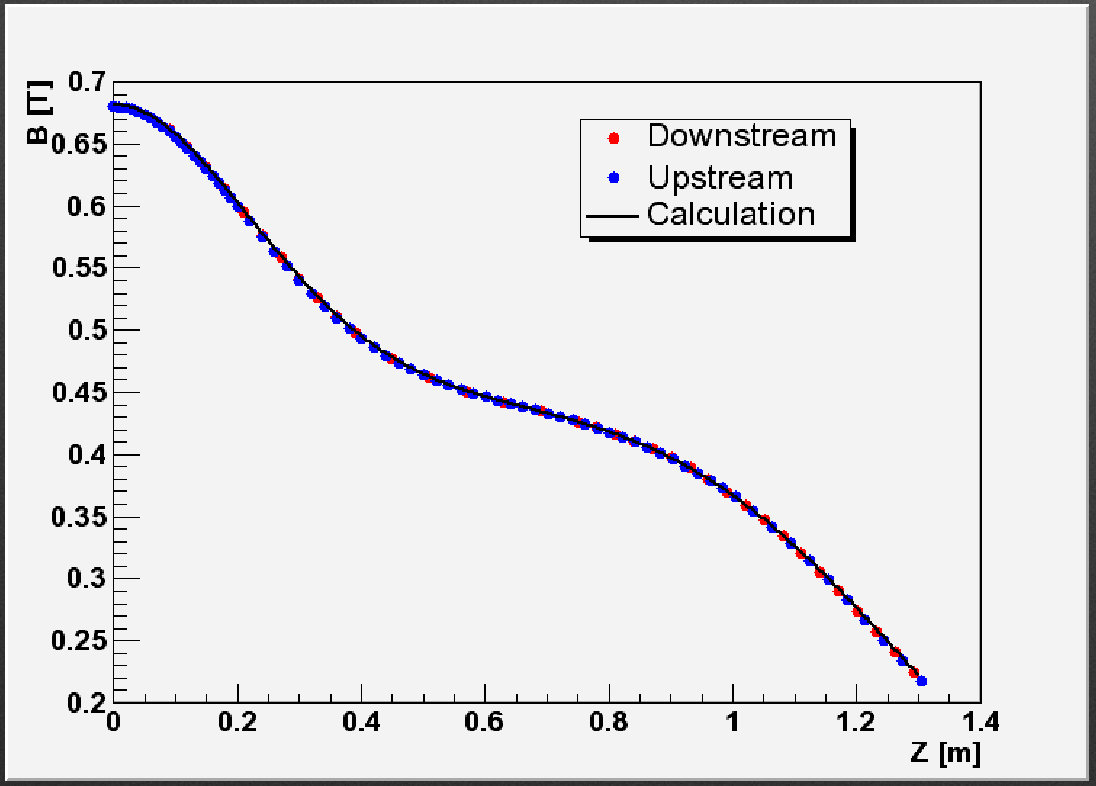


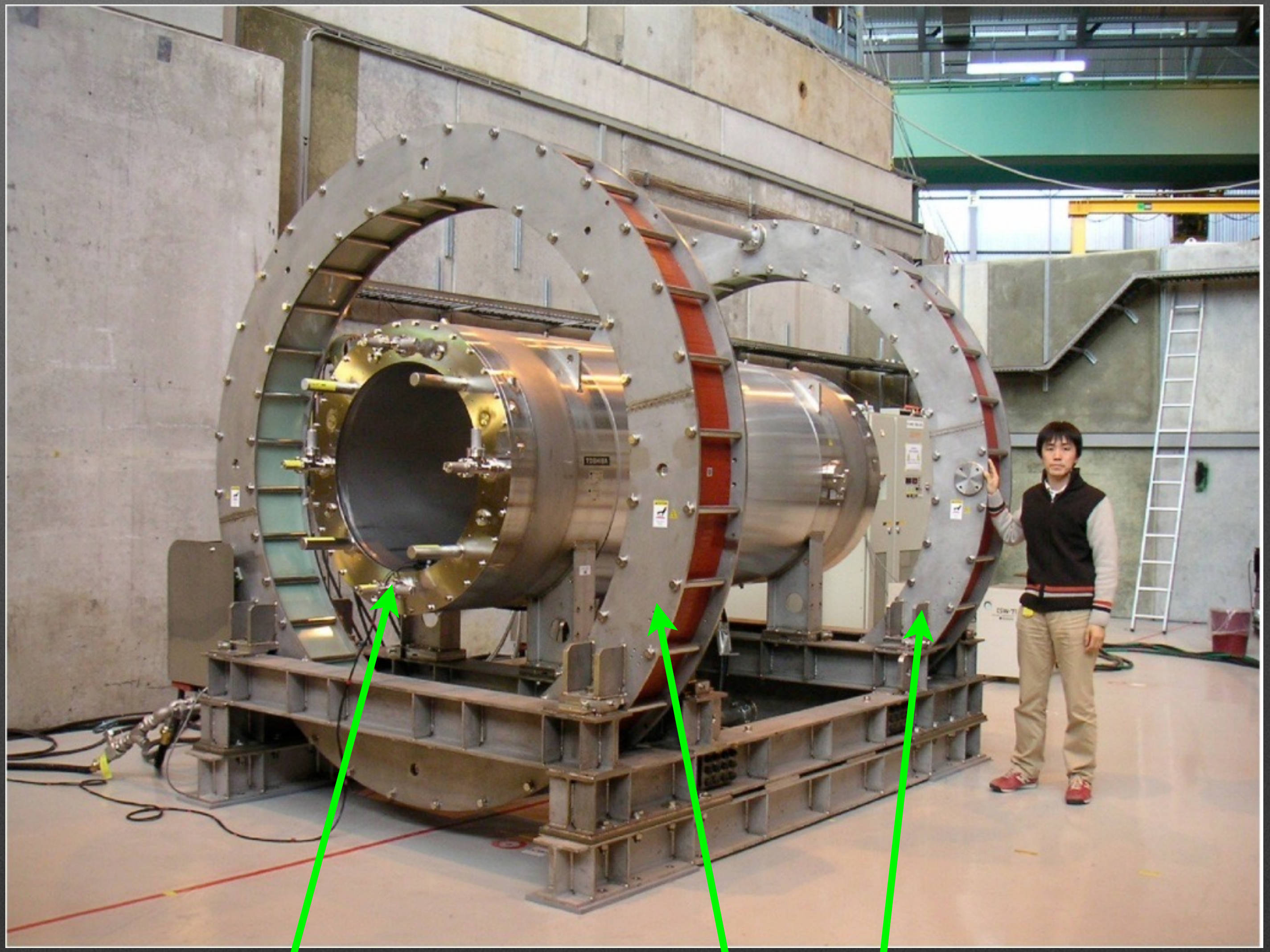
Provides world's most powerful DC muon beam > 10^8/sec

COBRA Positron Spectrometer

Gradient B field helps to manage high rate e^+

- thin-walled SC solenoid with a gradient magnetic field: 1.27 - 0.49 Tesla

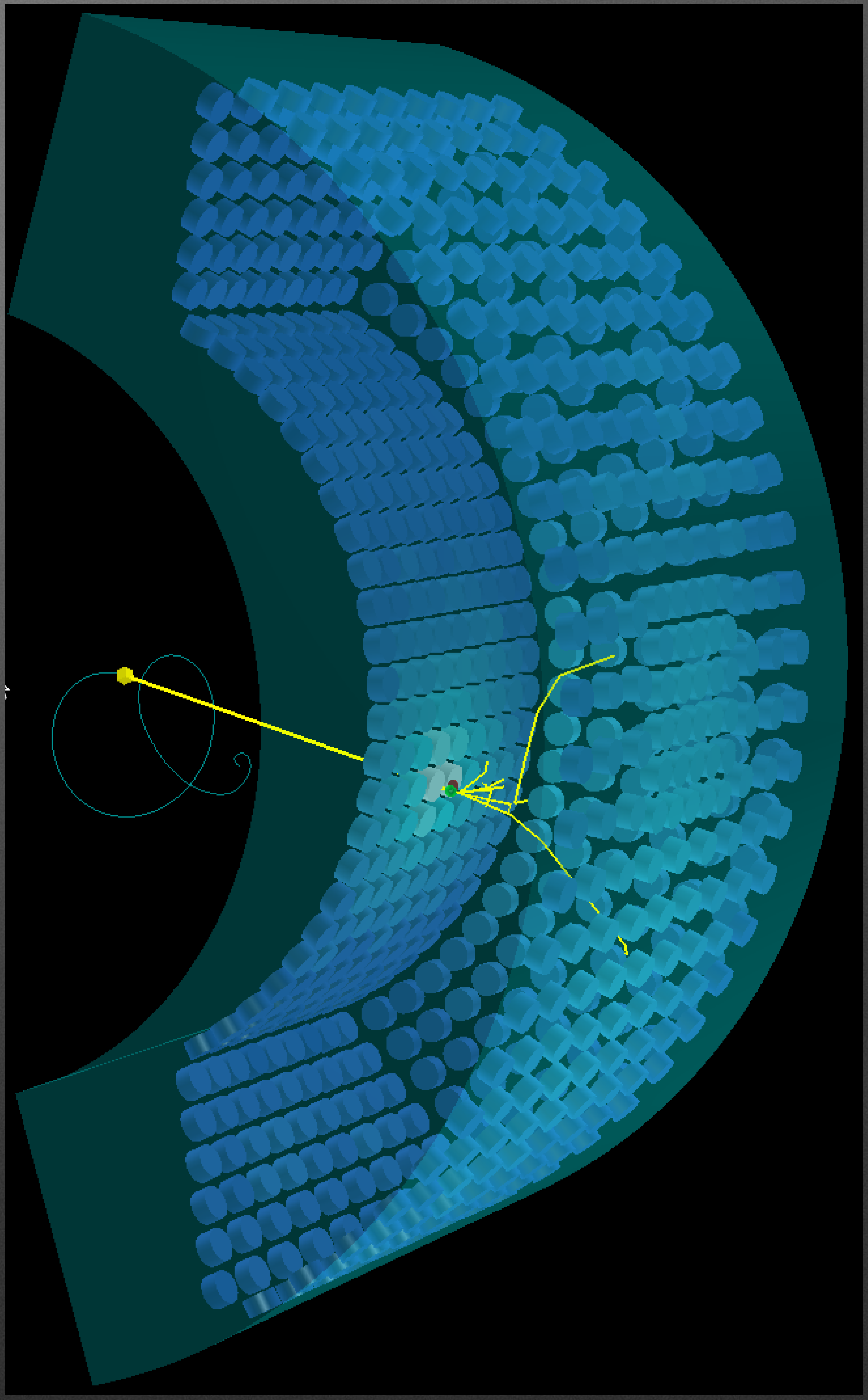




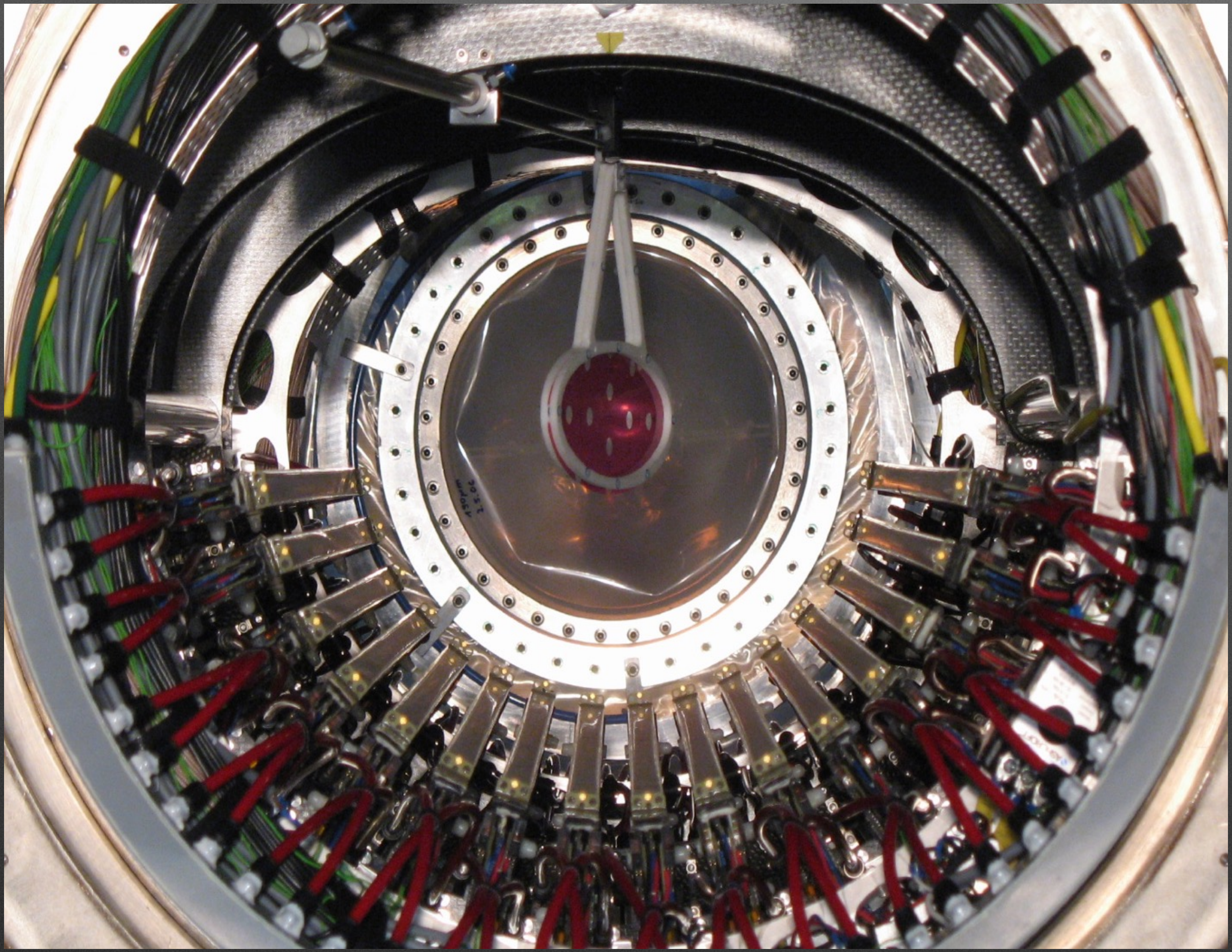
2.7t Liquid Xenon Photon Detector

High resolution detector

- Scintillation light from 900 liter liquid xenon is detected by 846 PMTs mounted on all surfaces and submerged in the xenon
- fast response & high light yield provide good resolutions of E, time, position
- kept at 165K by 200W pulse-tube refrigerator
- gas/liquid circulation system to purify xenon to remove contaminants



Drift Chambers



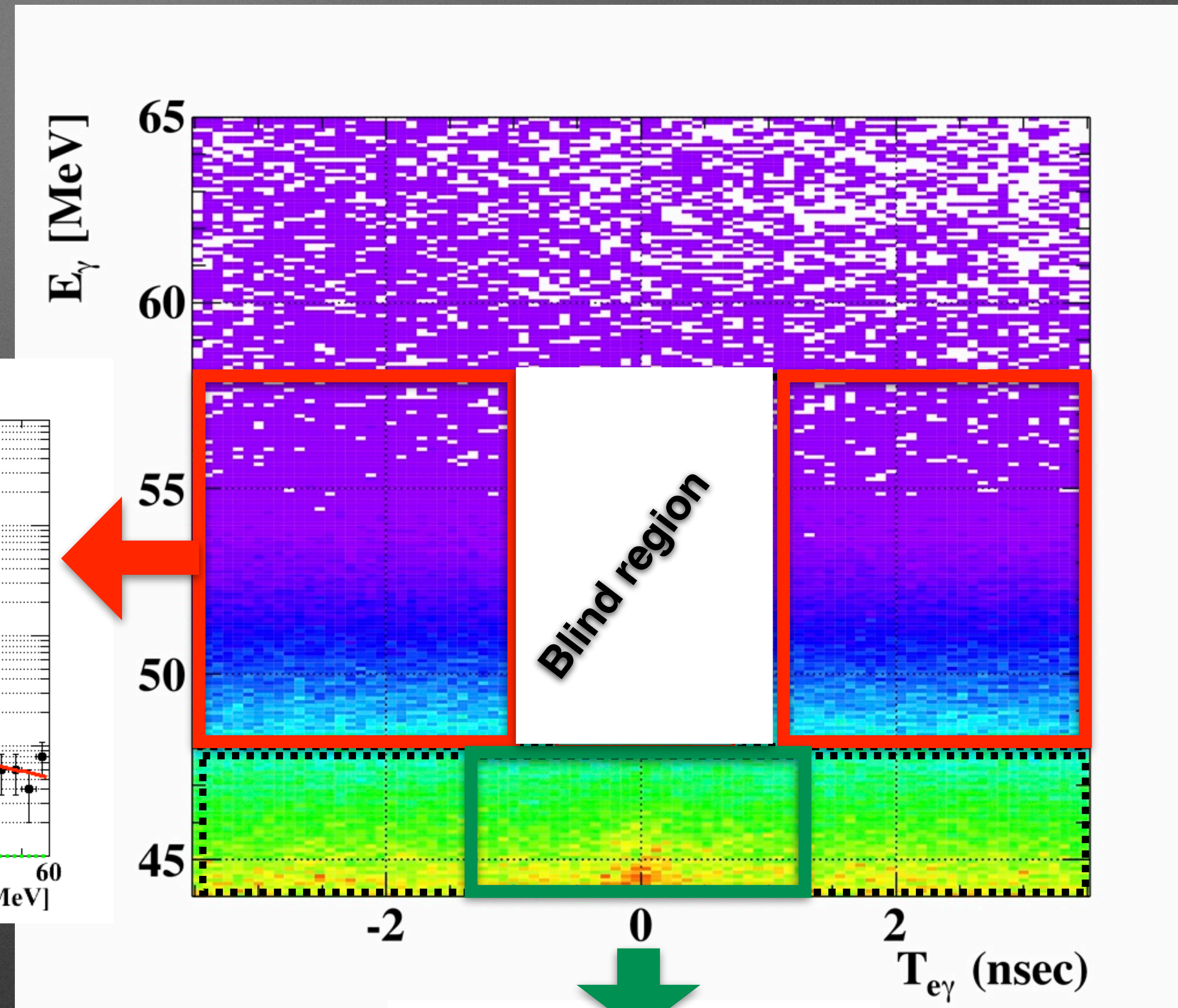
- 16 radially aligned modules, each consists of two staggered layers of wire planes
- 12.5um thick cathode foils with a Vernier pattern structure
- He:ethane = 50:50 differential pressure control to COBRA He environment
- ~2.0 x 10^{-3} X_0 along the positron trajectory

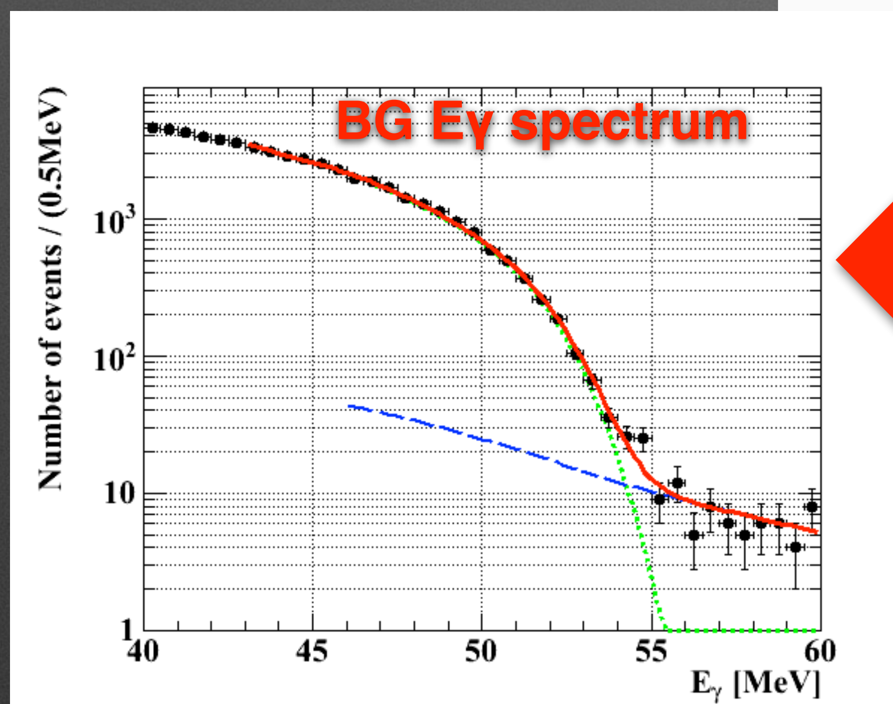
filled with He inside COBRA

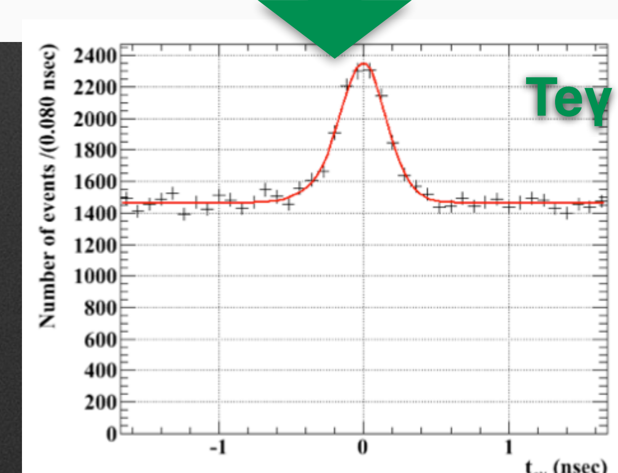
Blind & Likelihood Analysis

$(E_\gamma, E_e, T_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$ → signal, acc BG, RD BG

- Blind analysis
  - Optimization of analysis and BG study are done in sidebands







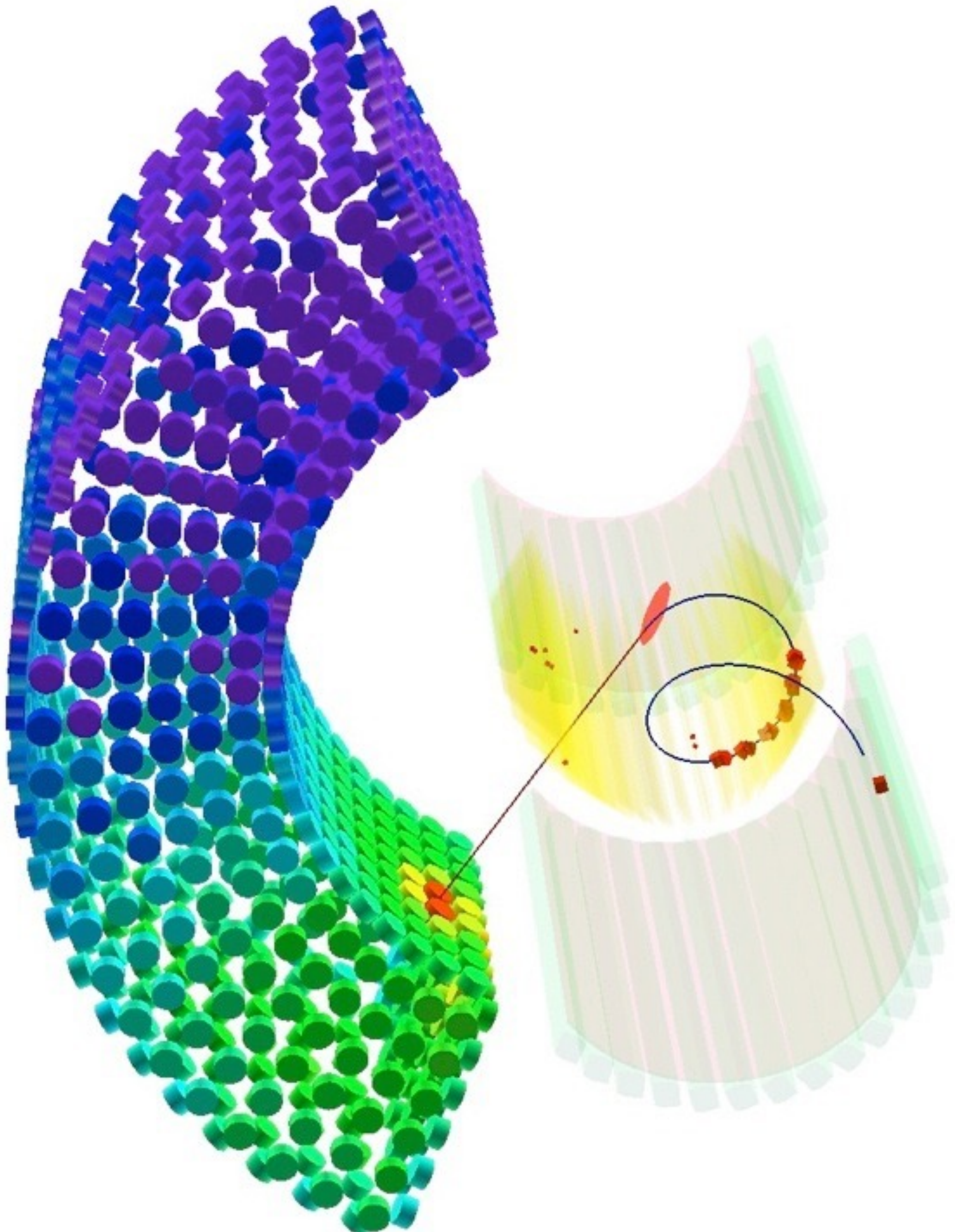
PDFs mostly from data

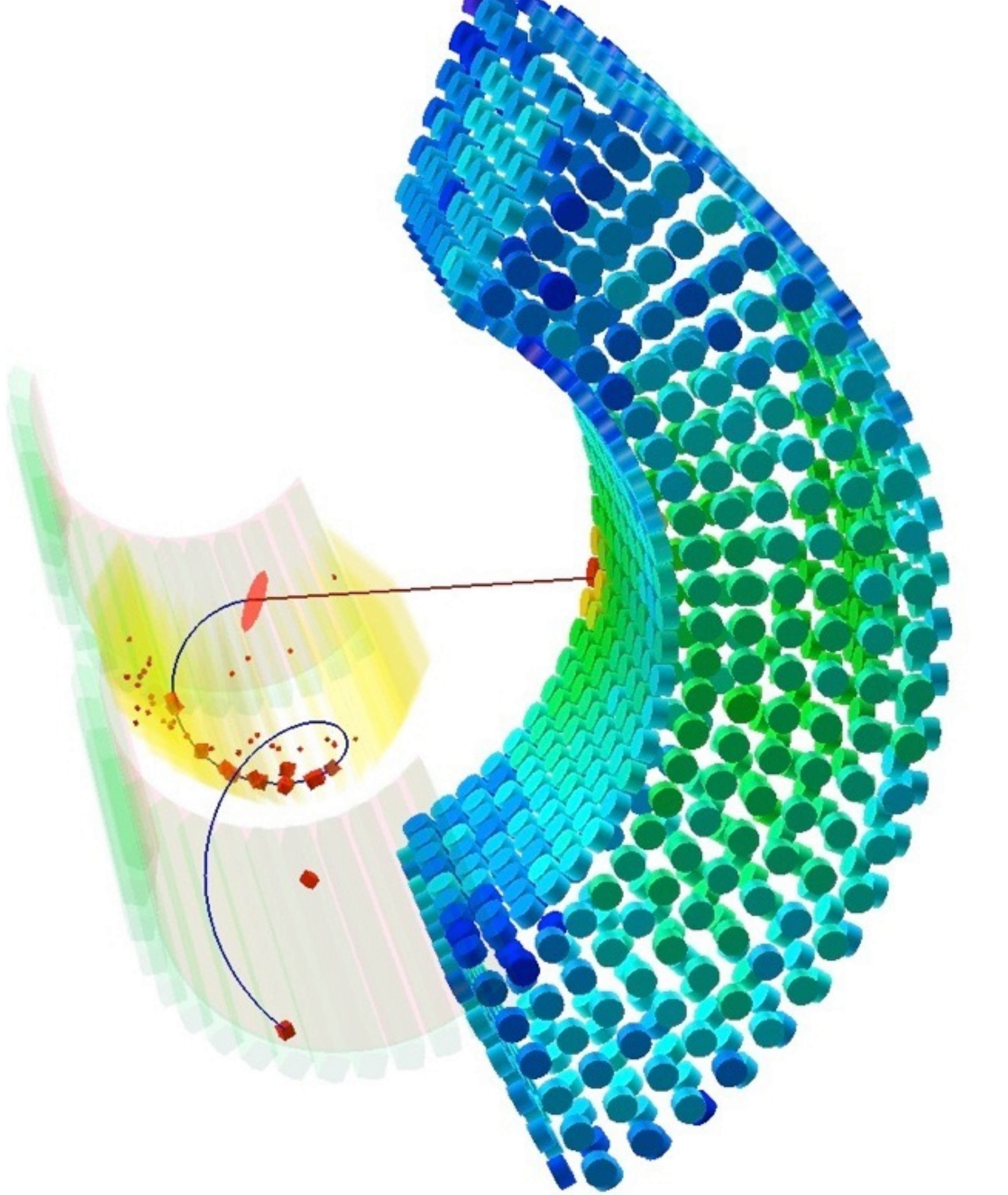
accidental BG: side bands

signal: measured resolution

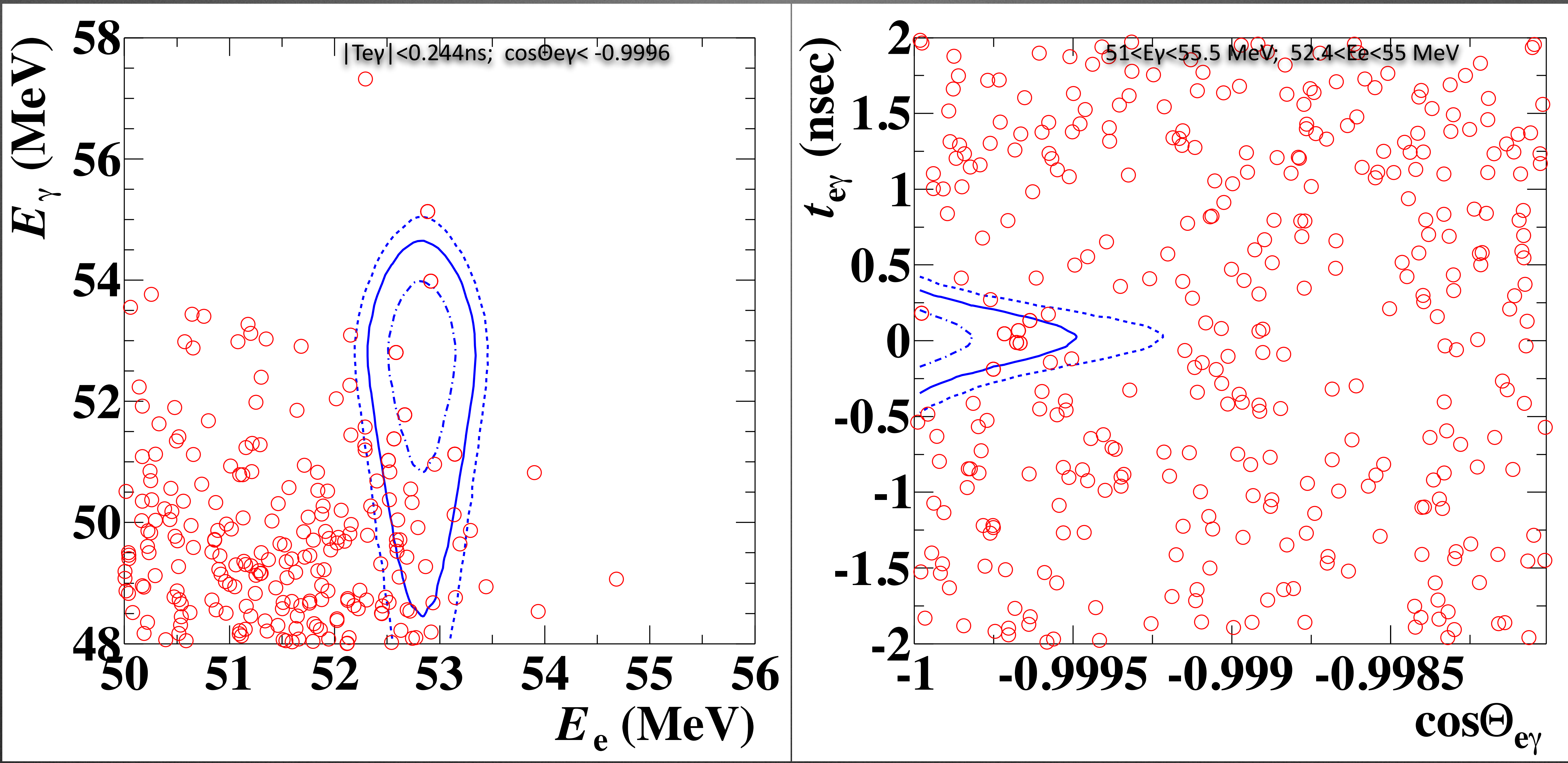
radiative BG: theory + resolution

a few examples of events



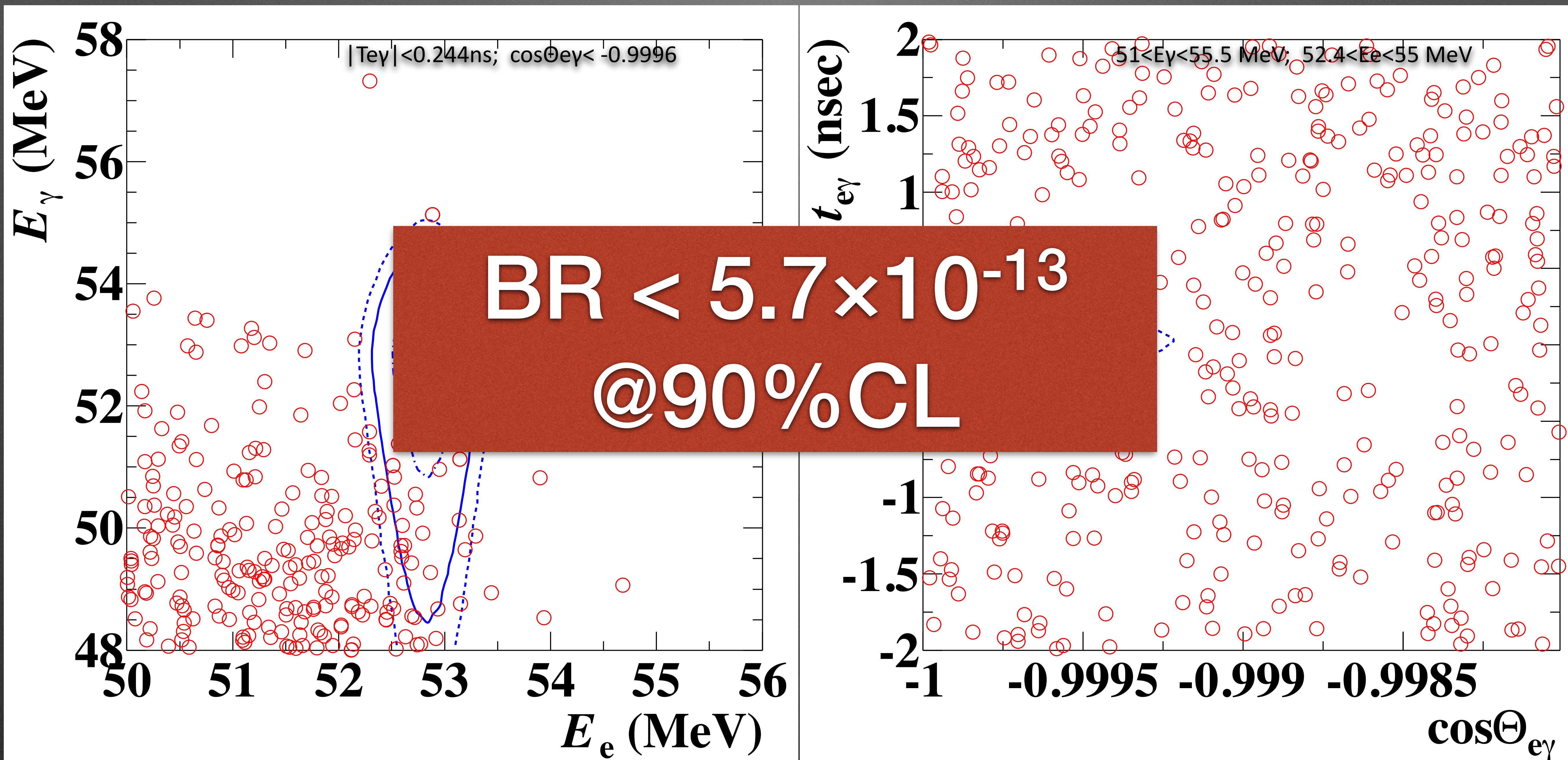


2009-2011 Combined MEG Data



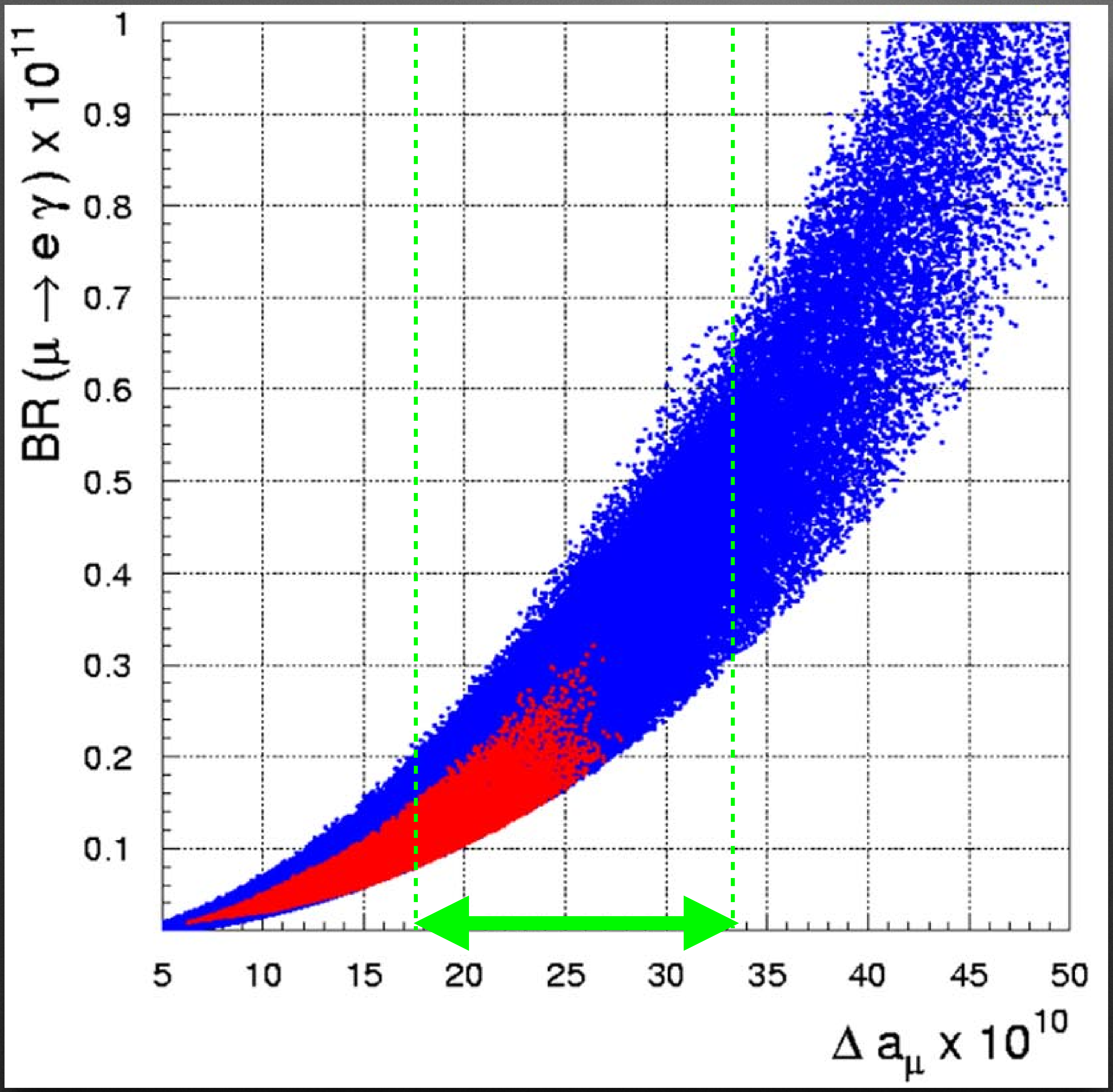
1, 1.64, 2σ contours

2009-2011 Combined MEG Data



1, 1.64, 2σ contours

muon (g_μ-2) anomaly

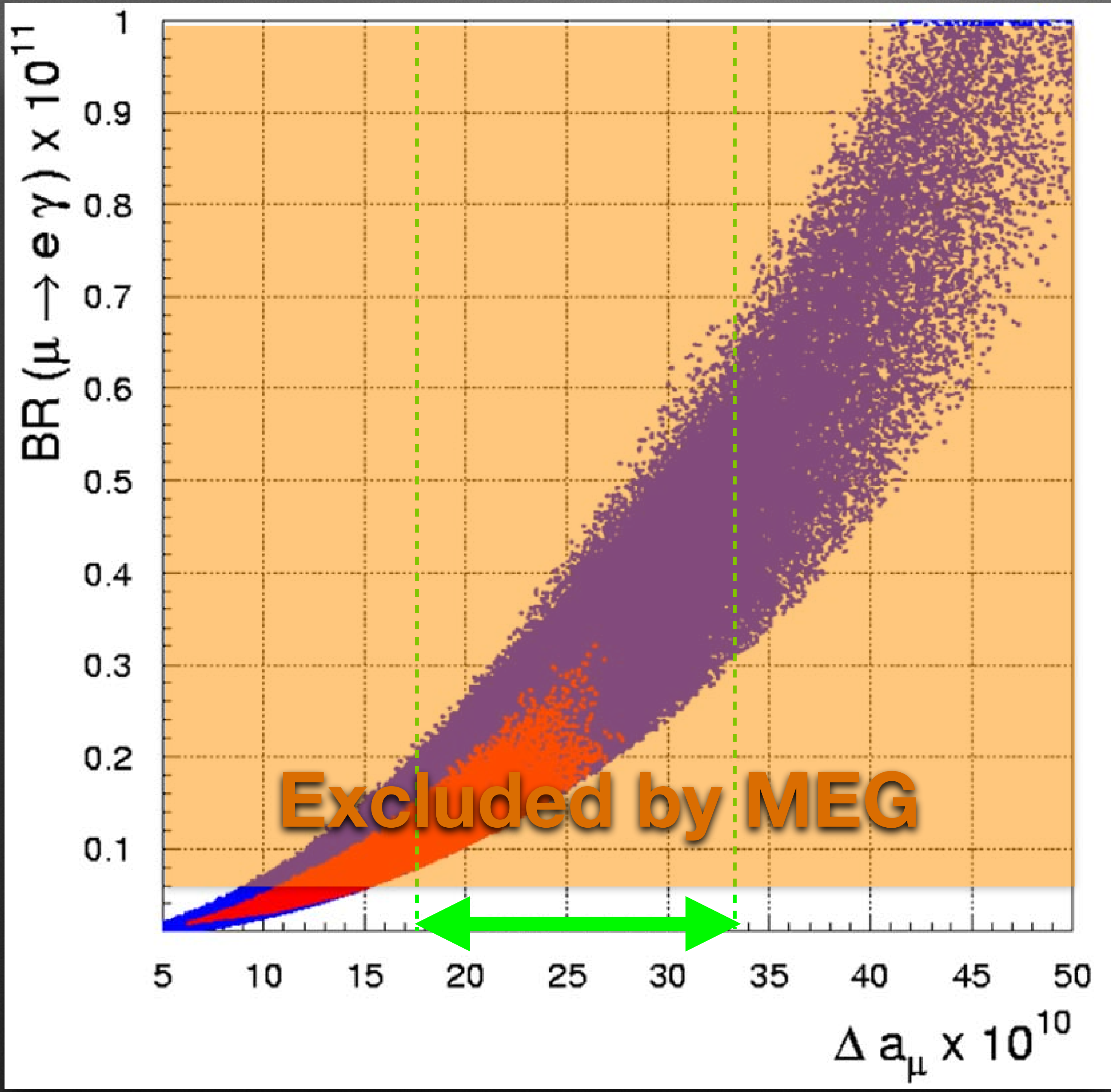


G.Isidori et al. PRD75, 115019

$|\delta_{LL}^{12}| = 10^{-4}$ assumed

muon's anomalous magnetic moment

muon (g_μ-2) anomaly

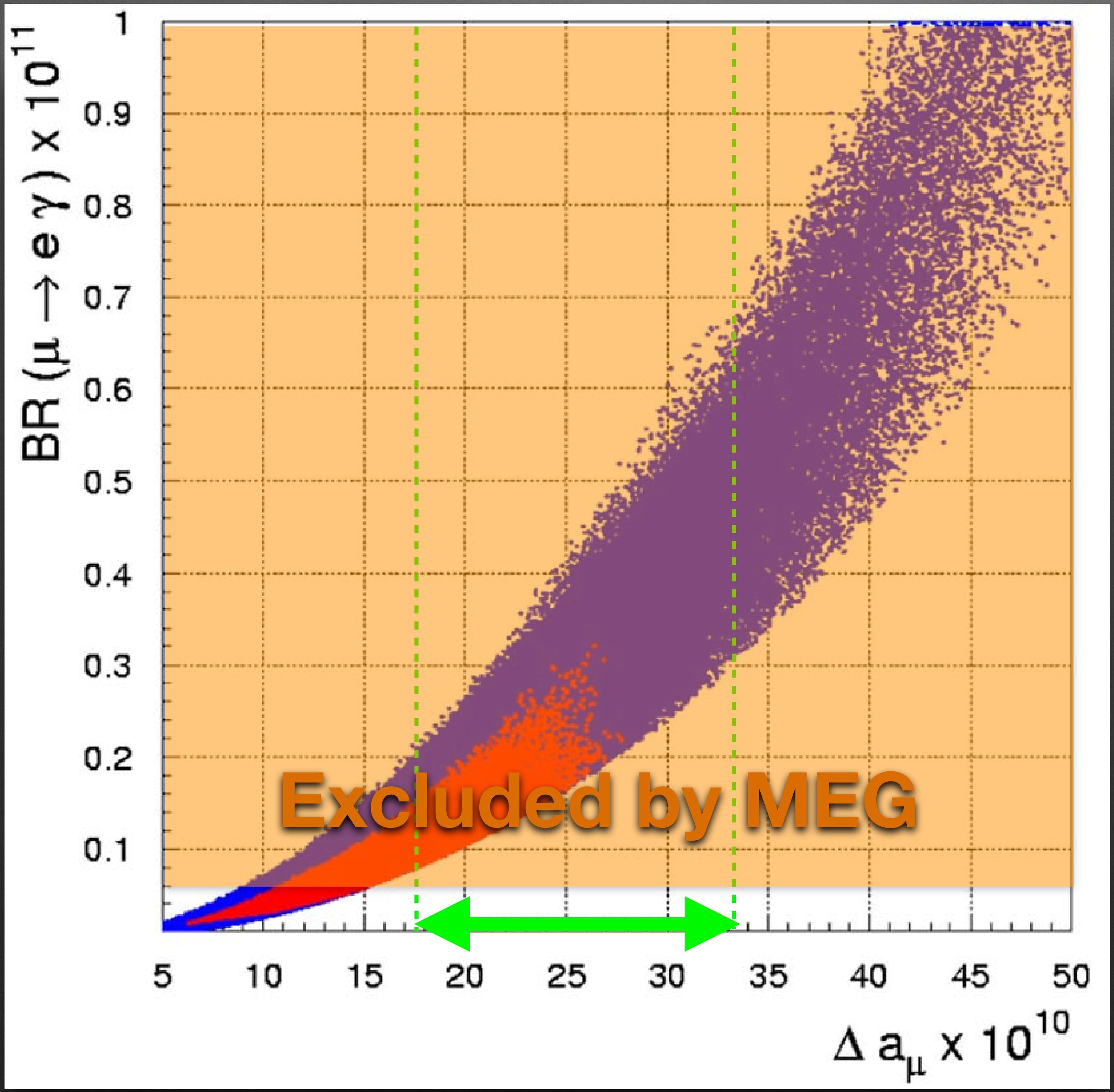


$|\delta_{LL}^{12}| = 10^{-4}$ assumed

G.Isidori et al. PRD75, 115019

muon's anomalous magnetic moment

muon (g_μ-2) anomaly

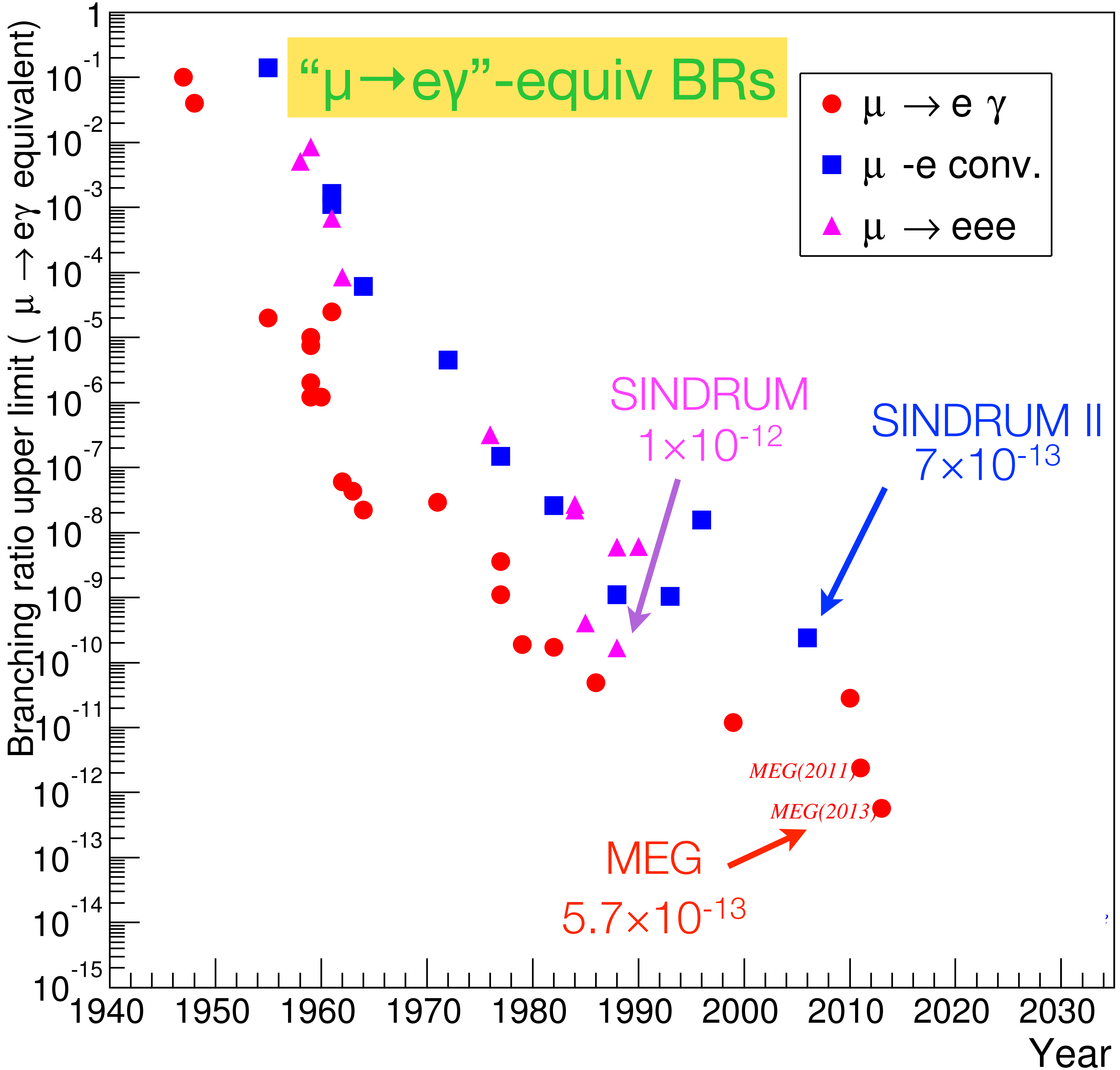


G.Isidori et al. PRD75, 115019

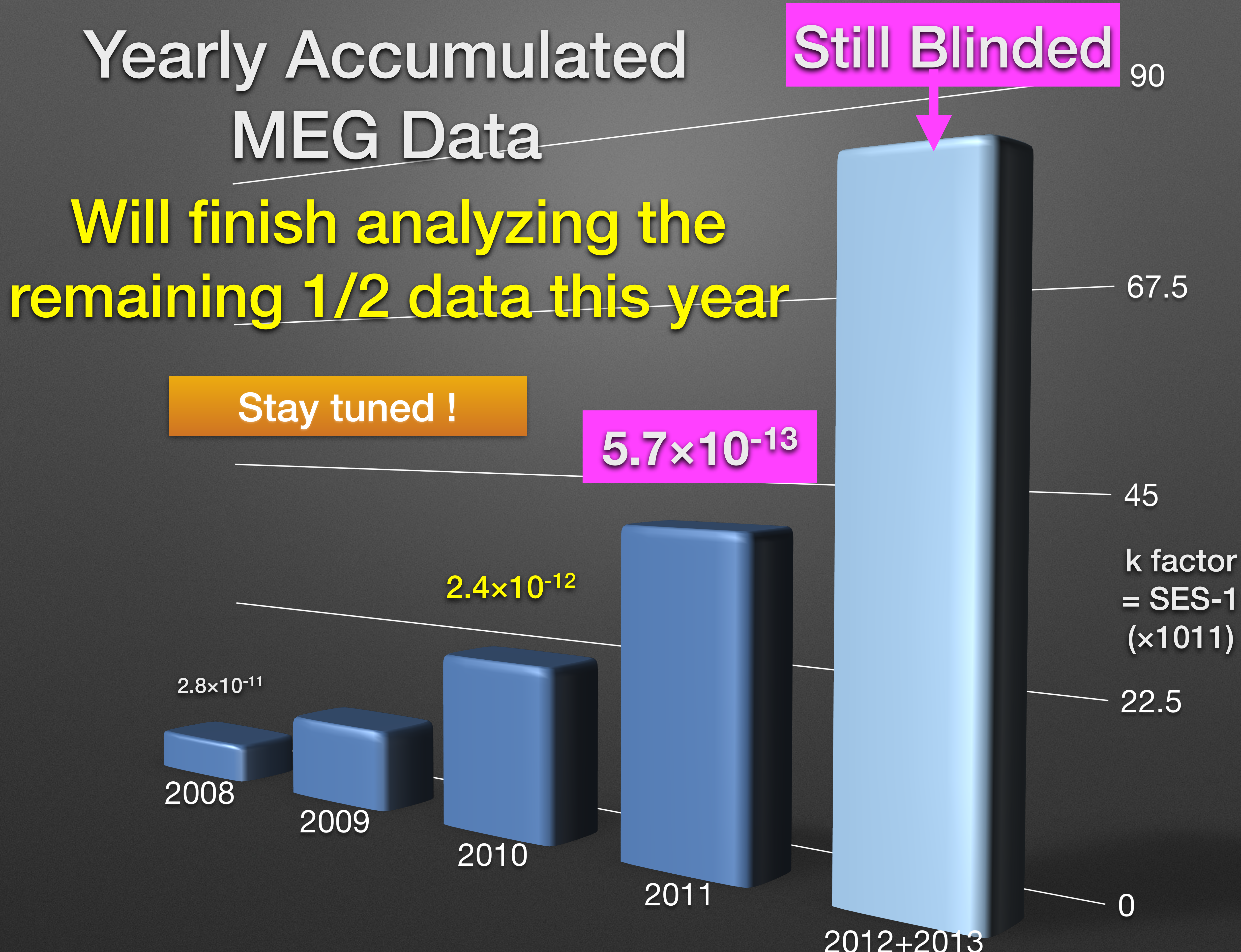
tighter limit on this

$|\delta_{LL}^{12}| = 10^{-4}$ assumed

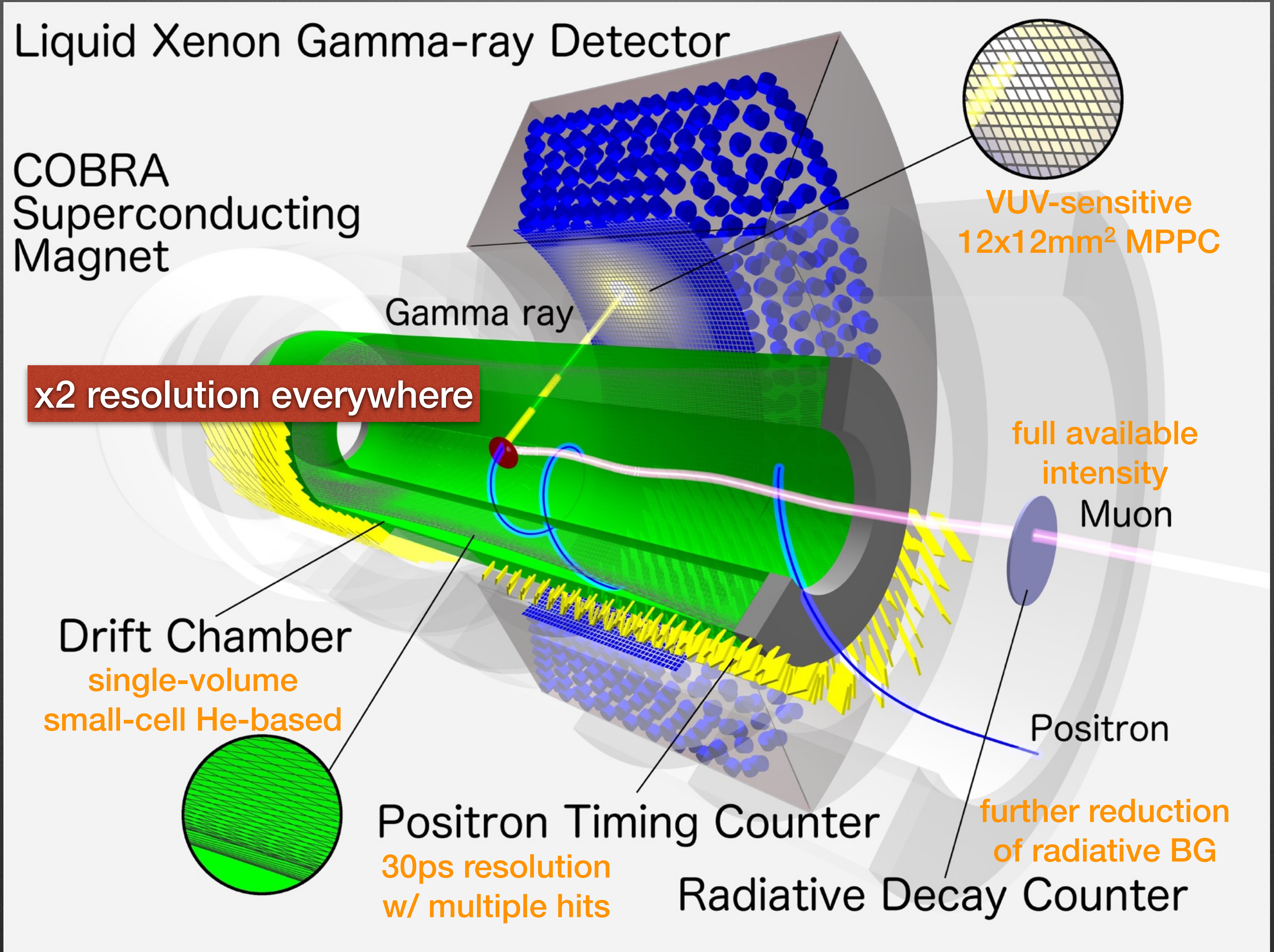
muon's anomalous magnetic moment



"μ→eγ"-equiv BRs
μ → e γ
μ -e conv.
μ → eee
SINDRUM
1×10-12
SINDRUM II
7×10-13
MEG(2011)
MEG(2013)
MEG
5.7×10-13
Branching ratio upper limit (μ → eγ equivalent)
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10-14
10-15
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
Year


Yearly Accumulated
MEG Data
Still Blinded
Will finish analyzing the
remaining 1/2 data this year
Stay tuned !
5.7×10-13
2.4×10-12
2.8×10-11
90
67.5
45
k factor
= SES-1
(×1011)
22.5
0
2008
2009
2010
2011
2012+2013

MEG II to start in 2016

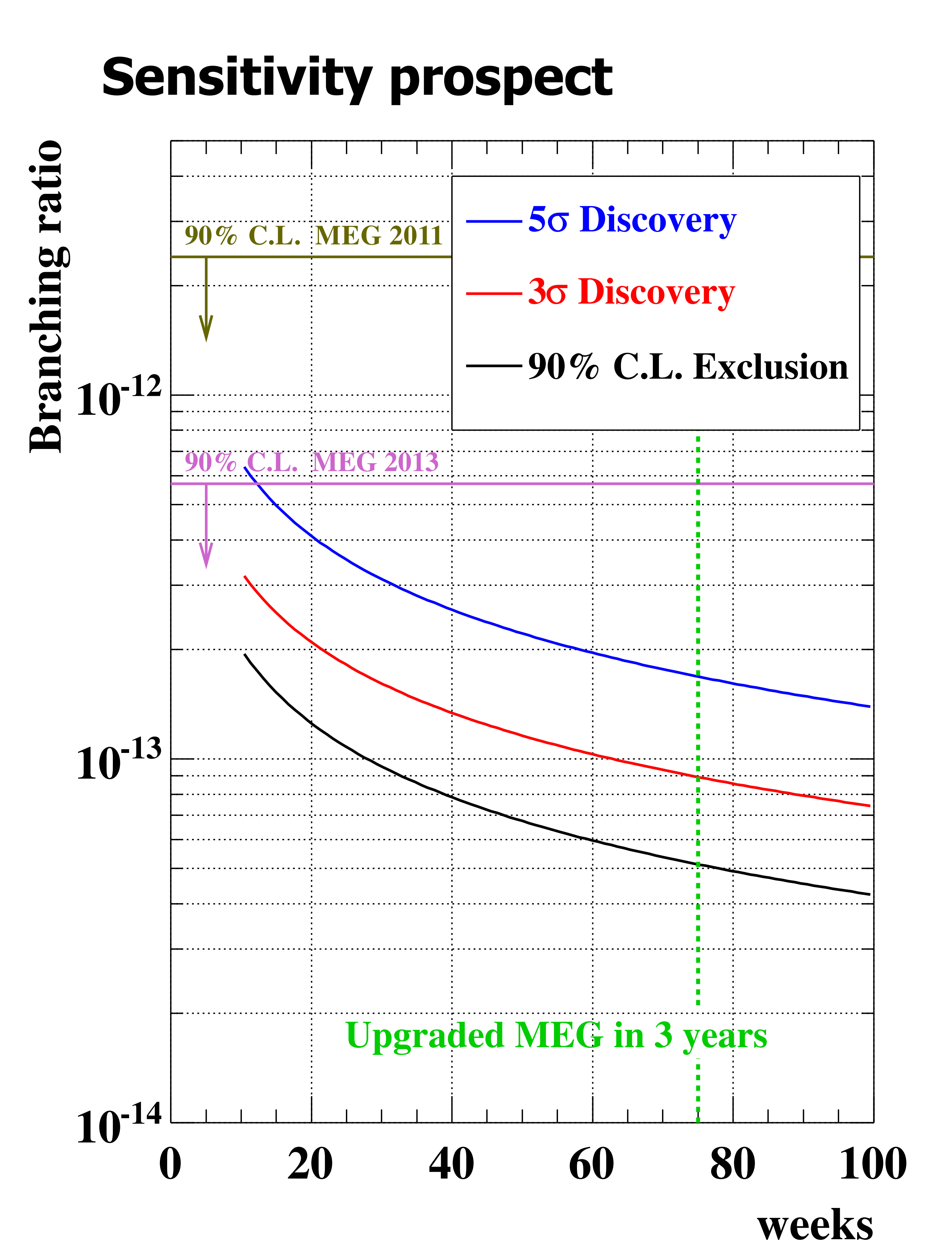


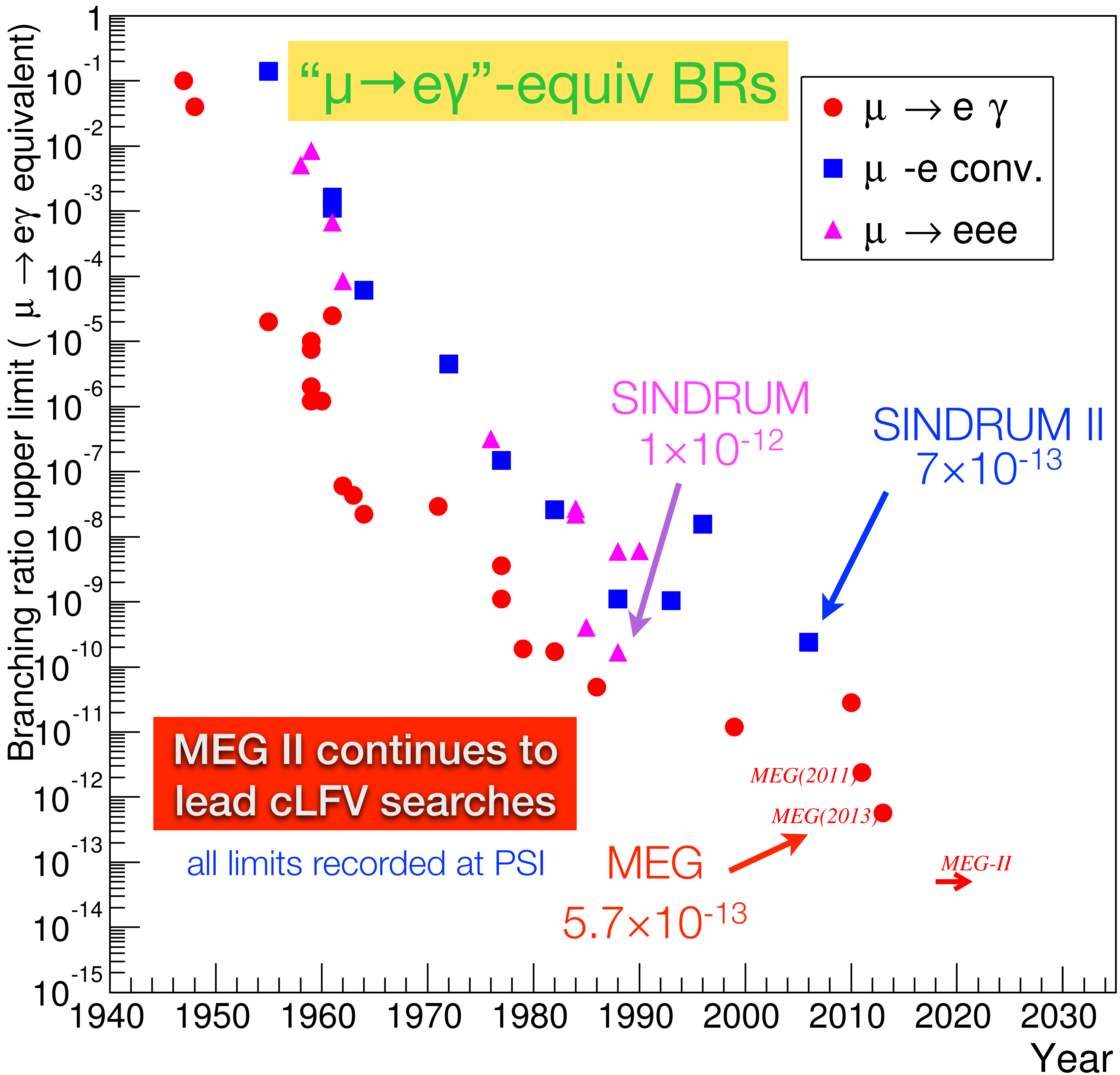
Expected performance and sensitivity

$5x10^{-14}$ in 3 years DAQ

Resolution (Gaussian σ) and efficiencies for MEG upgrade

PDF parameters	Present MEG	Upgrade scenario
$\sigma_{E_{e^+}}$ (keV)	380	110
e^+ σ_θ (mrad)	9	5
e^+ σ_ϕ (mrad)	11	5
e^+ σ_Z / σ_Y(core) (mm)	2.0/1.0	1.2/0.7
$\frac{\sigma_{E_\gamma}}{E_\gamma}$ (%) w>2 cm	1.6	1.0
γ position at LXe $\sigma_{(u,v)}$-σ_w (mm)	4	2
γ-e^+ timing (ps)	120	80
Efficiency (%)		
trigger	≈ 99	≈ 99
γ reconstruction	60	60
e^+ reconstruction	40	95
event selection	80	85

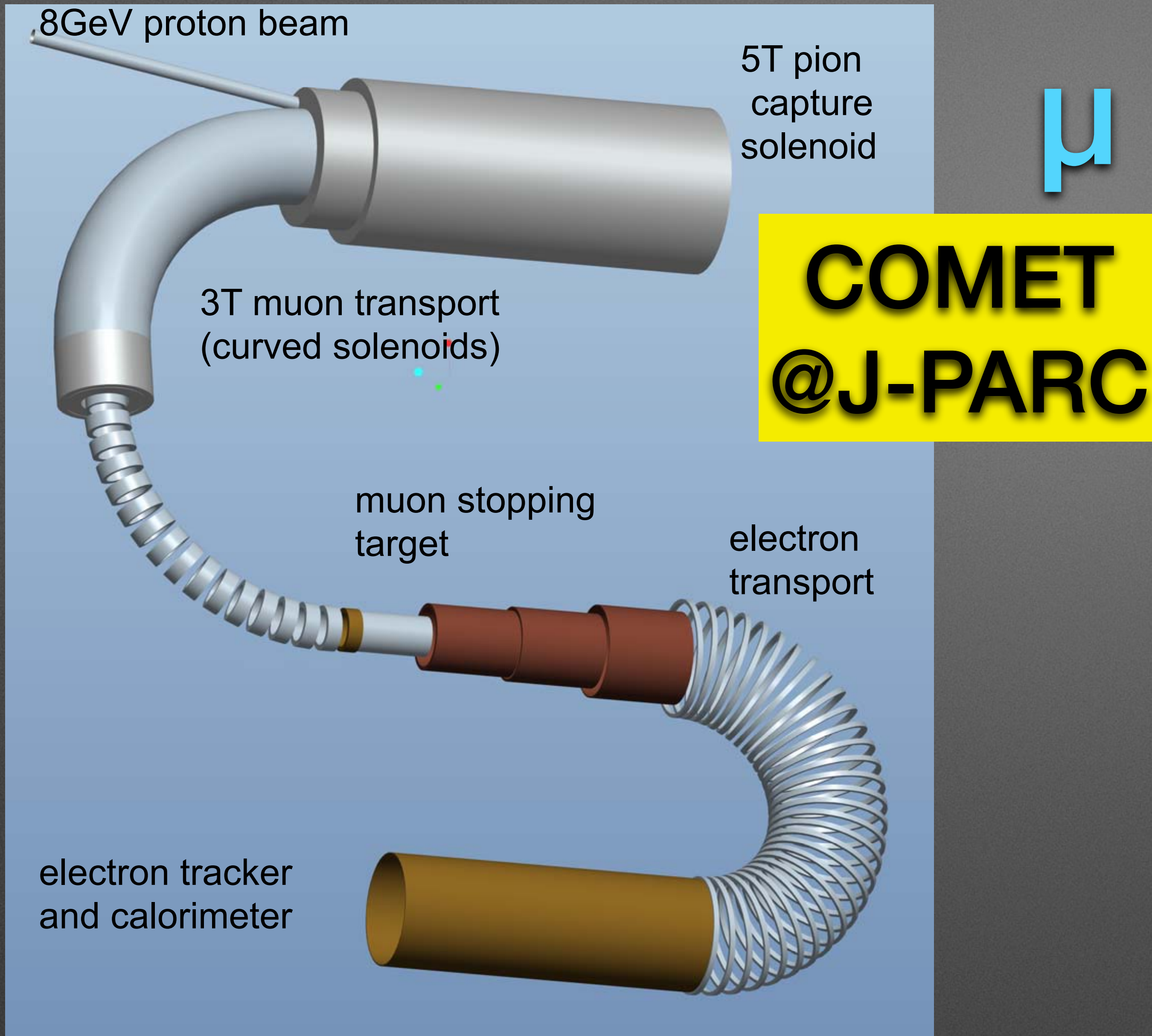


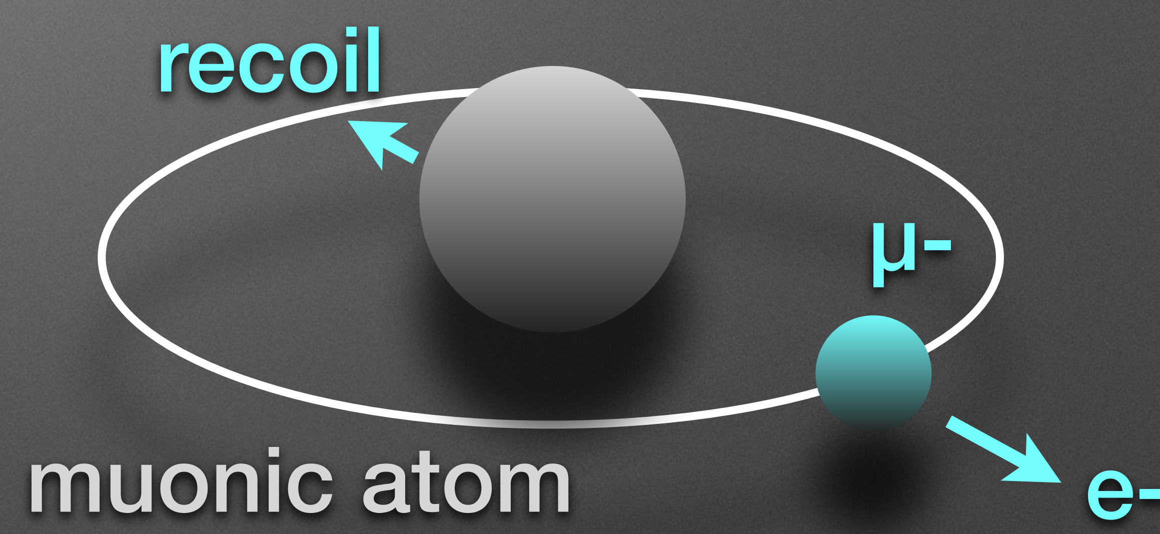


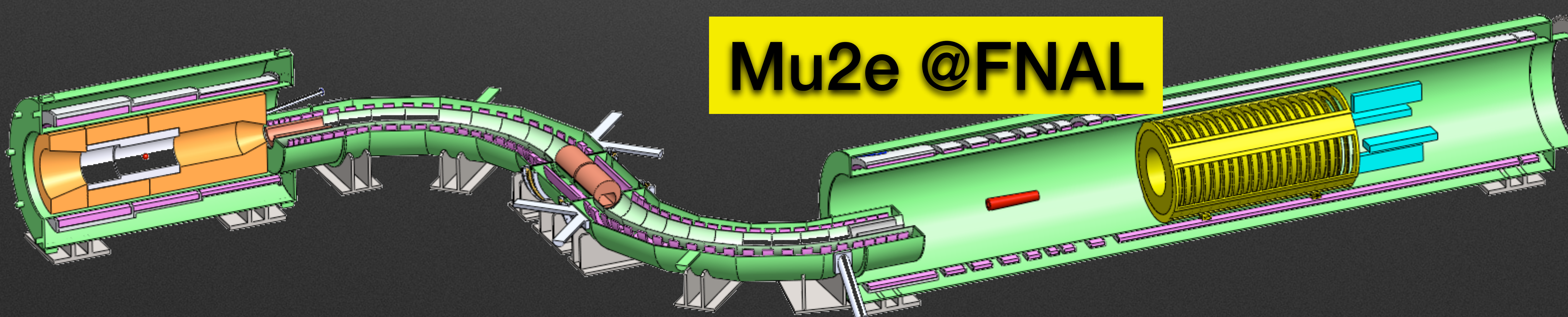
"μ→eγ"-equiv BRs
μ → e γ
μ -e conv.
μ → eee
SINDRUM
1×10^-12
SINDRUM II
7×10^-13
MEG II continues to lead cLFV searches
all limits recorded at PSI
MEG
5.7×10^-13
MEG(2011)
MEG(2013)
MEG-II
Branching ratio upper limit (μ → eγ equivalent)
Year

cLFV in further future

$\mu \rightarrow e$ conversion at 5×10^{-17}

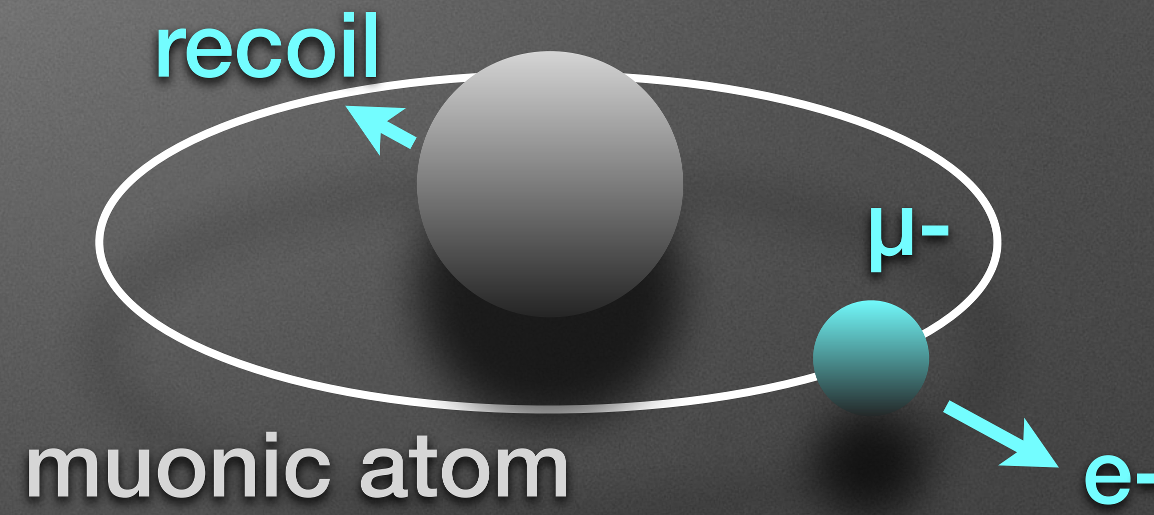


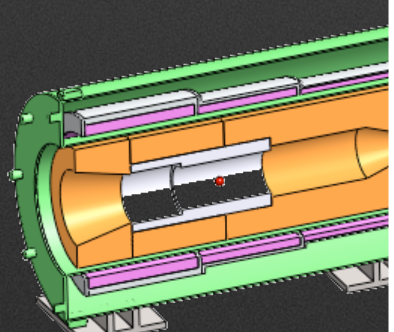


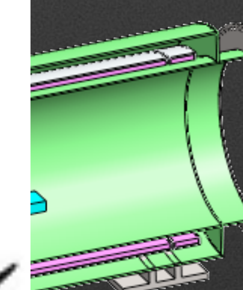


cLFV in further future

$\mu \rightarrow e$ conversion at 5×10^{-17}



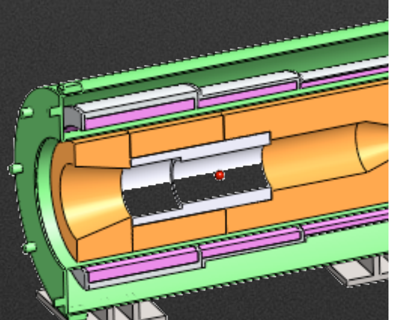


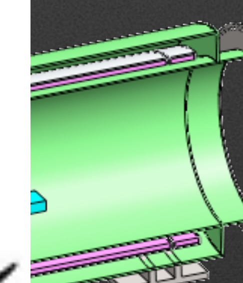



COMET
@J-PARC


Two dragons fighting for the orb
双竜争珠

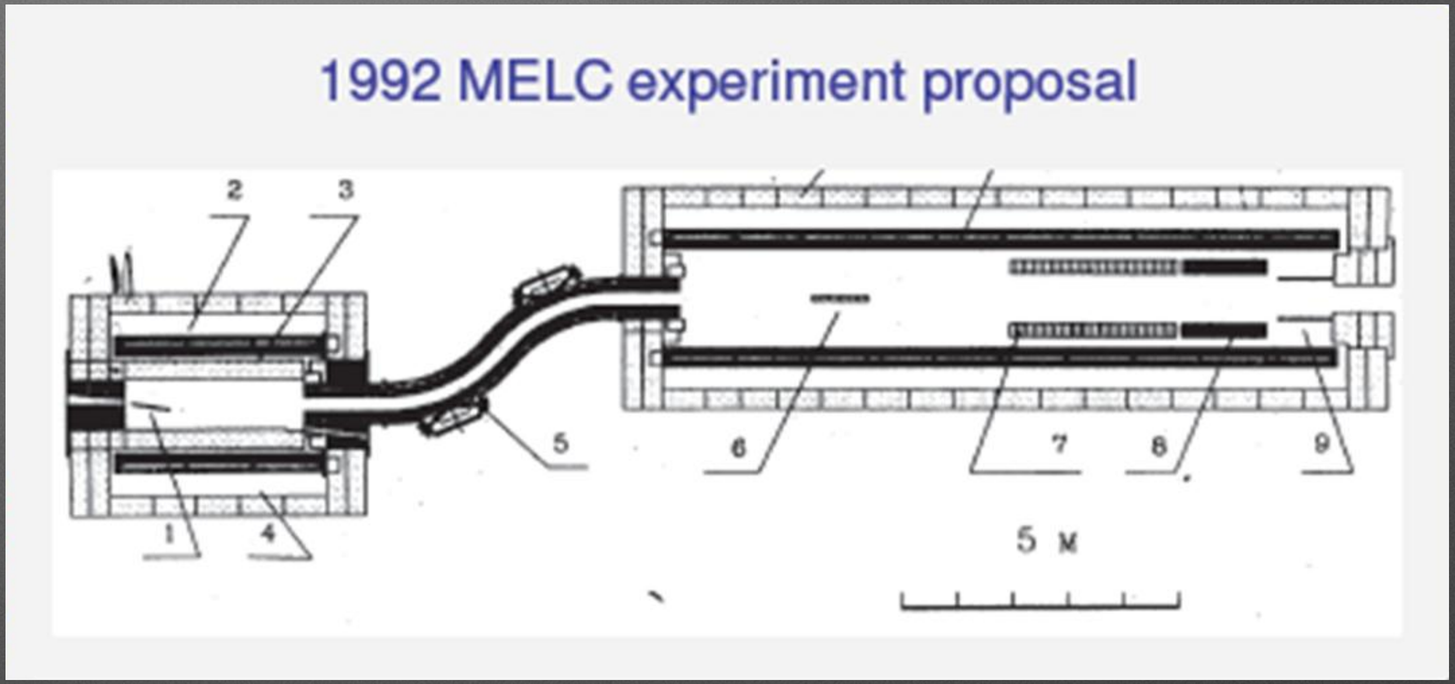

Mu2e @FNAL

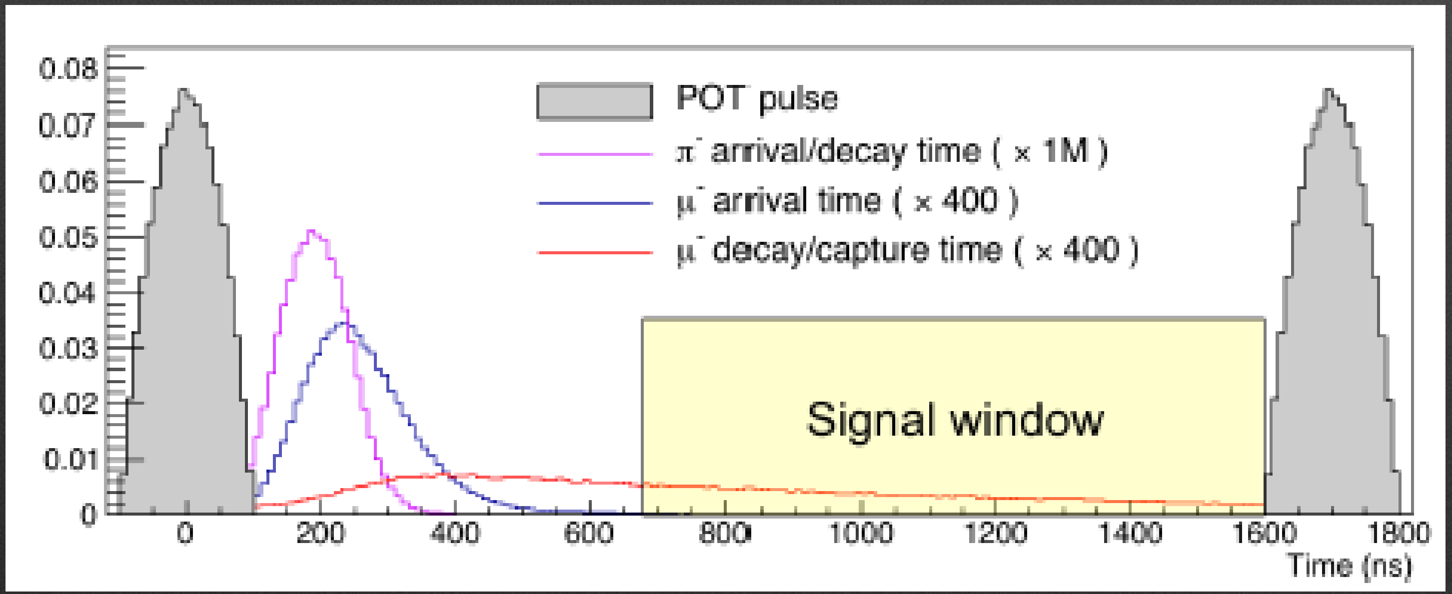




Experimental Concept

- Graded-field solenoid to collect pions w/ 10^3 times higher muon intensity (~10^{11}/sec)
- Curved solenoid to transport and select low energy negative muons

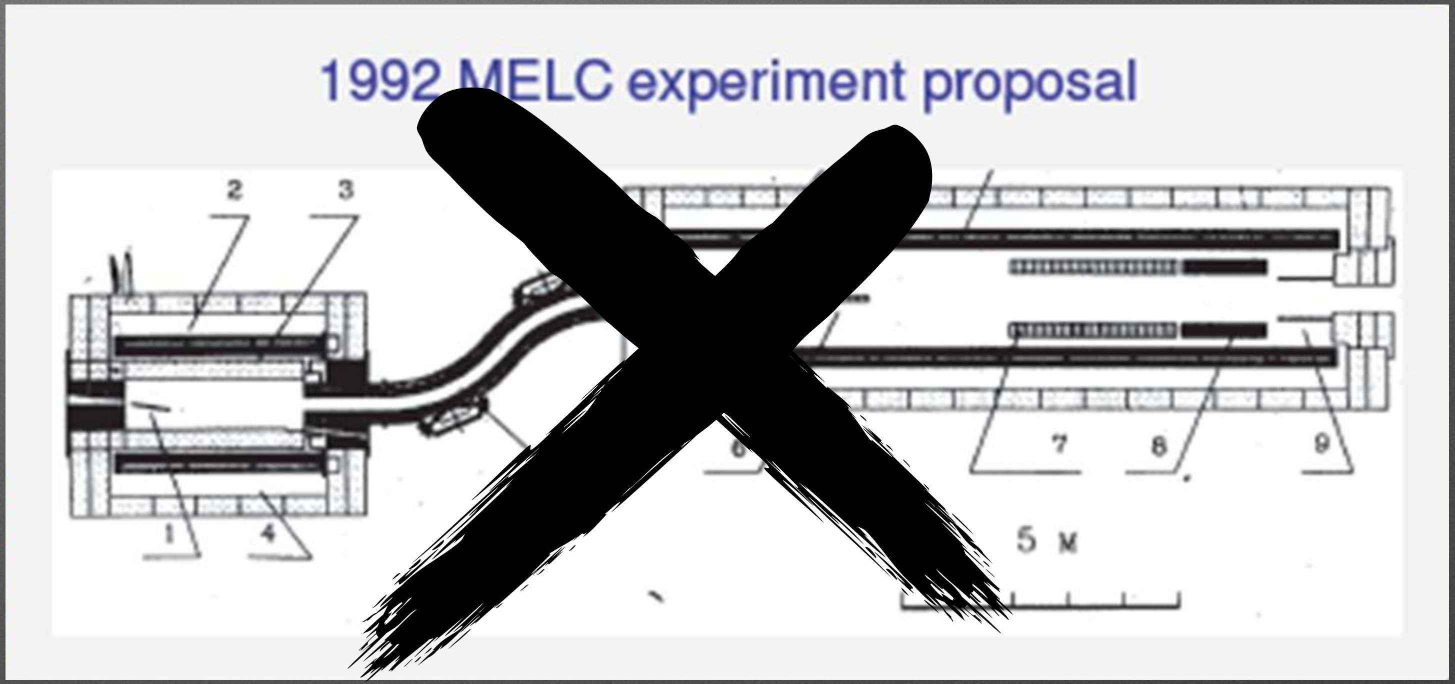


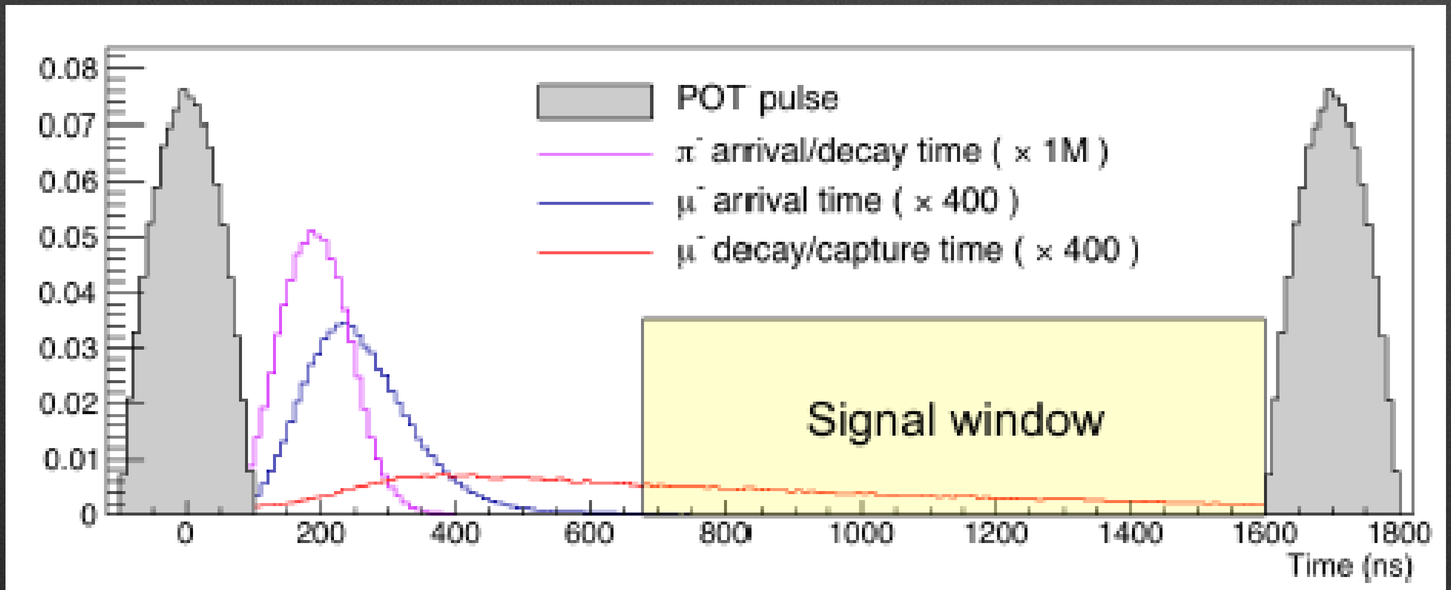


- Short pulsed beam that matches capture lifetime
- Data taken in a delayed time window to avoid beam-related BG
- “beam extinction”

Experimental Concept

- Graded-field solenoid to collect pions w/ 10^3 times higher muon intensity (~10^{11}/sec)
- Curved solenoid to transport and select low energy negative muons

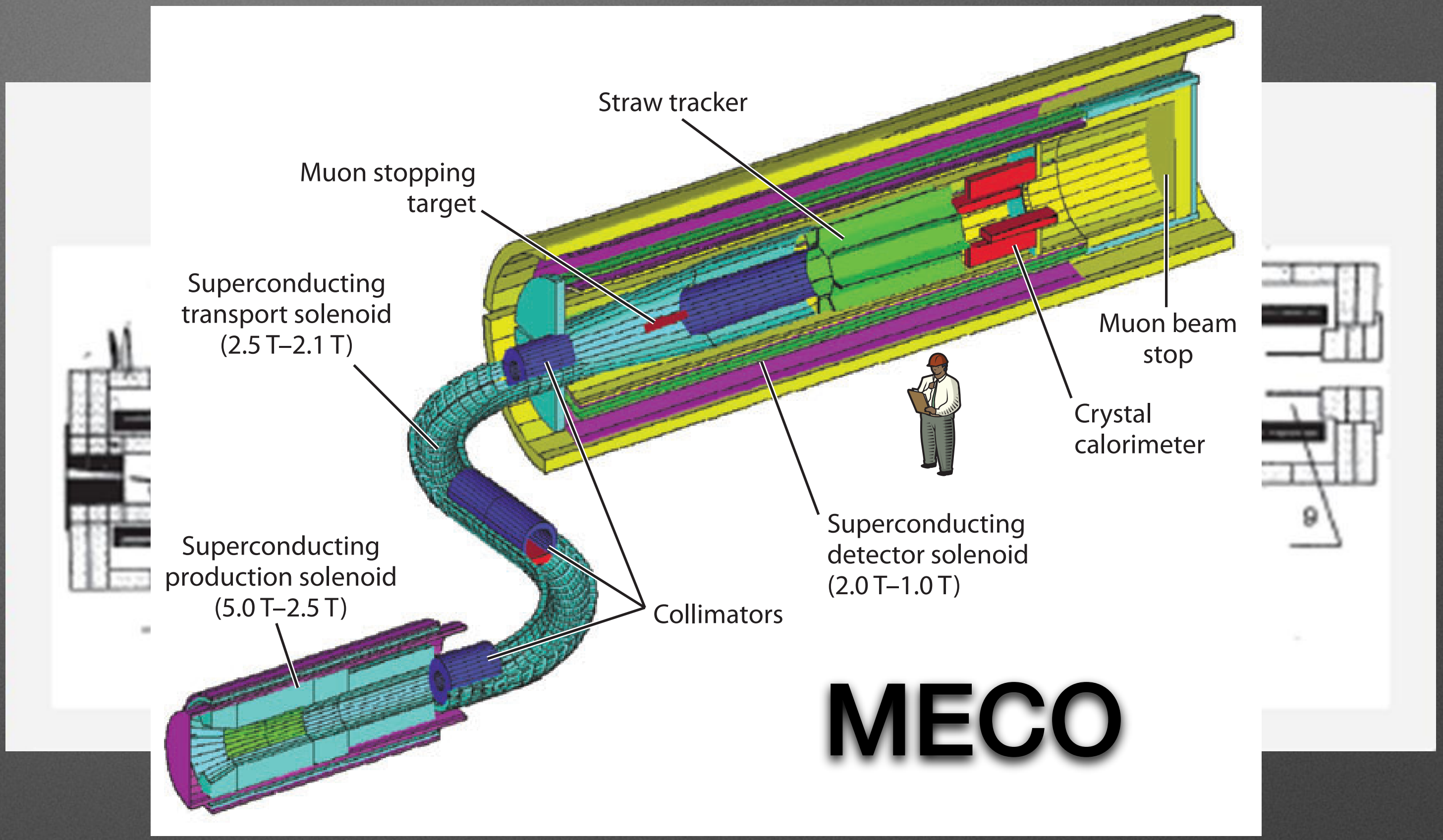


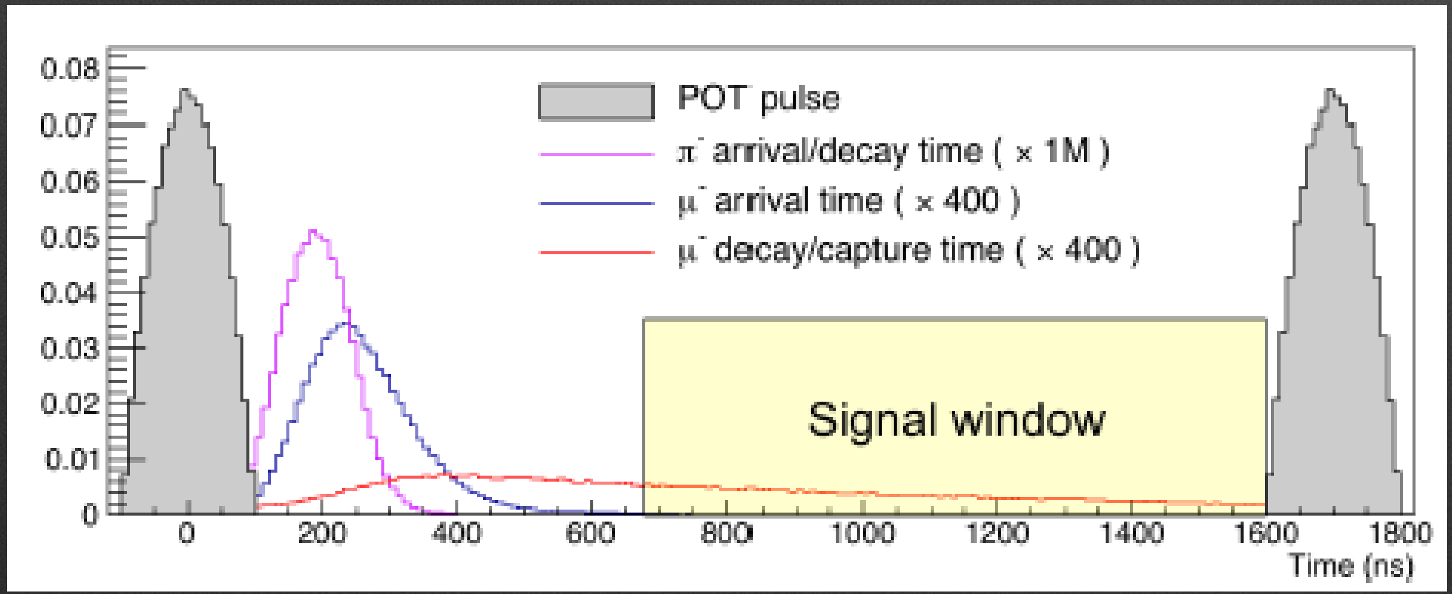


- Short pulsed beam that matches capture lifetime
- Data taken in a delayed time window to avoid beam-related BG
- "beam extinction"

Experimental Concept

- Graded-field solenoid to collect pions w/ 10^3 times higher muon intensity ($\sim 10^{11}$/sec)
- Curved solenoid to transport and select low energy negative muons

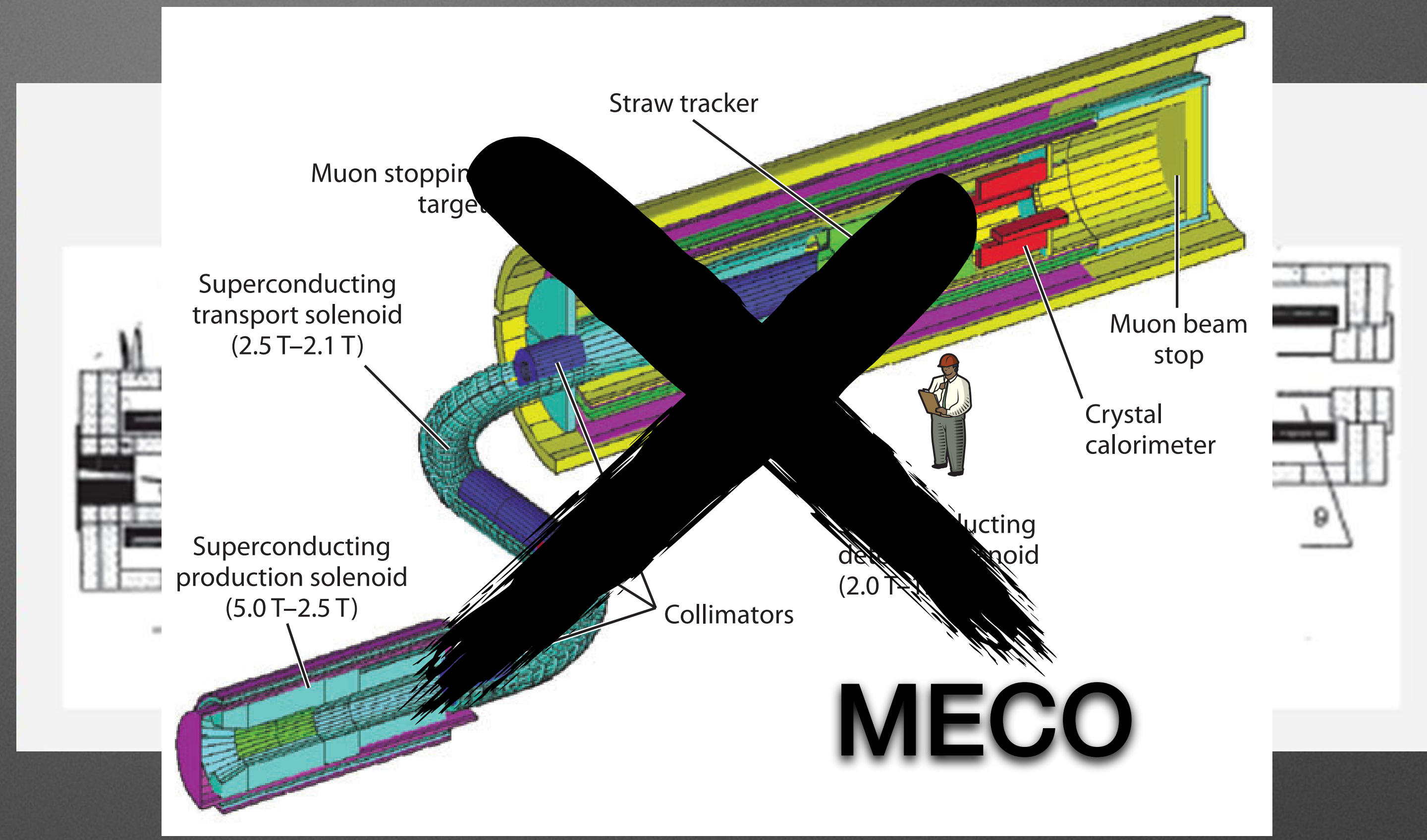


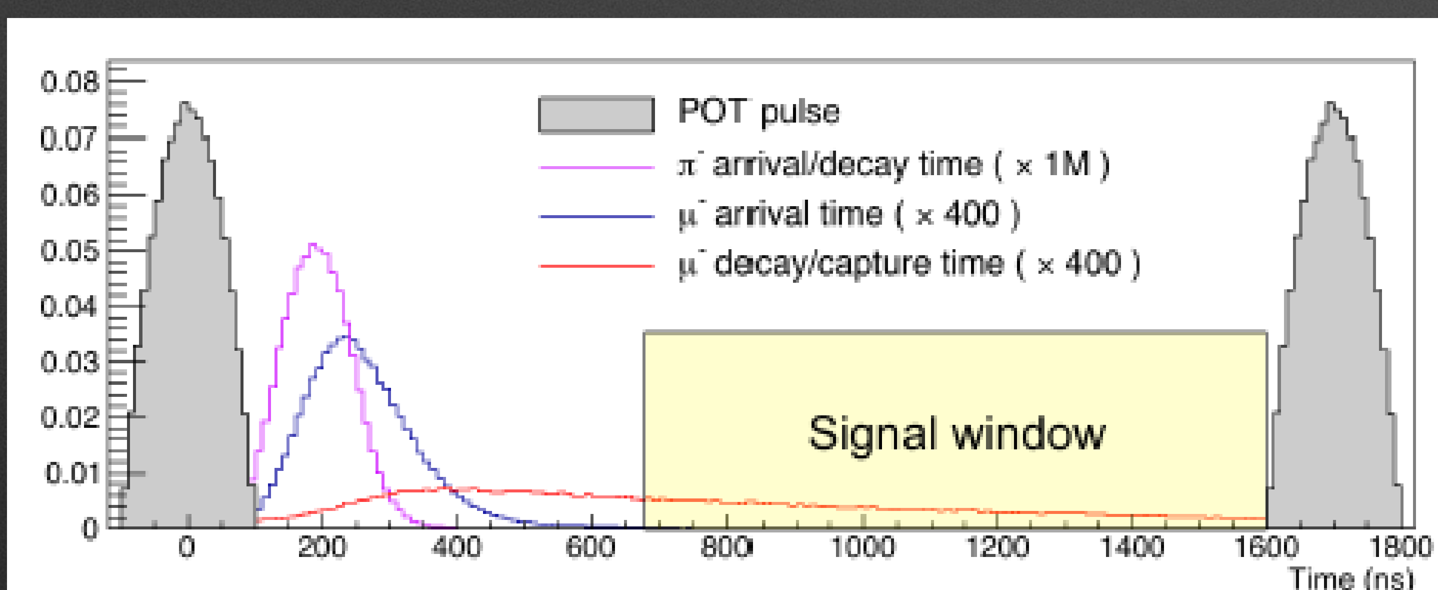


- Short pulsed beam that matches capture lifetime
- Data taken in a delayed time window to avoid beam-related BG
- “beam extinction”

Experimental Concept

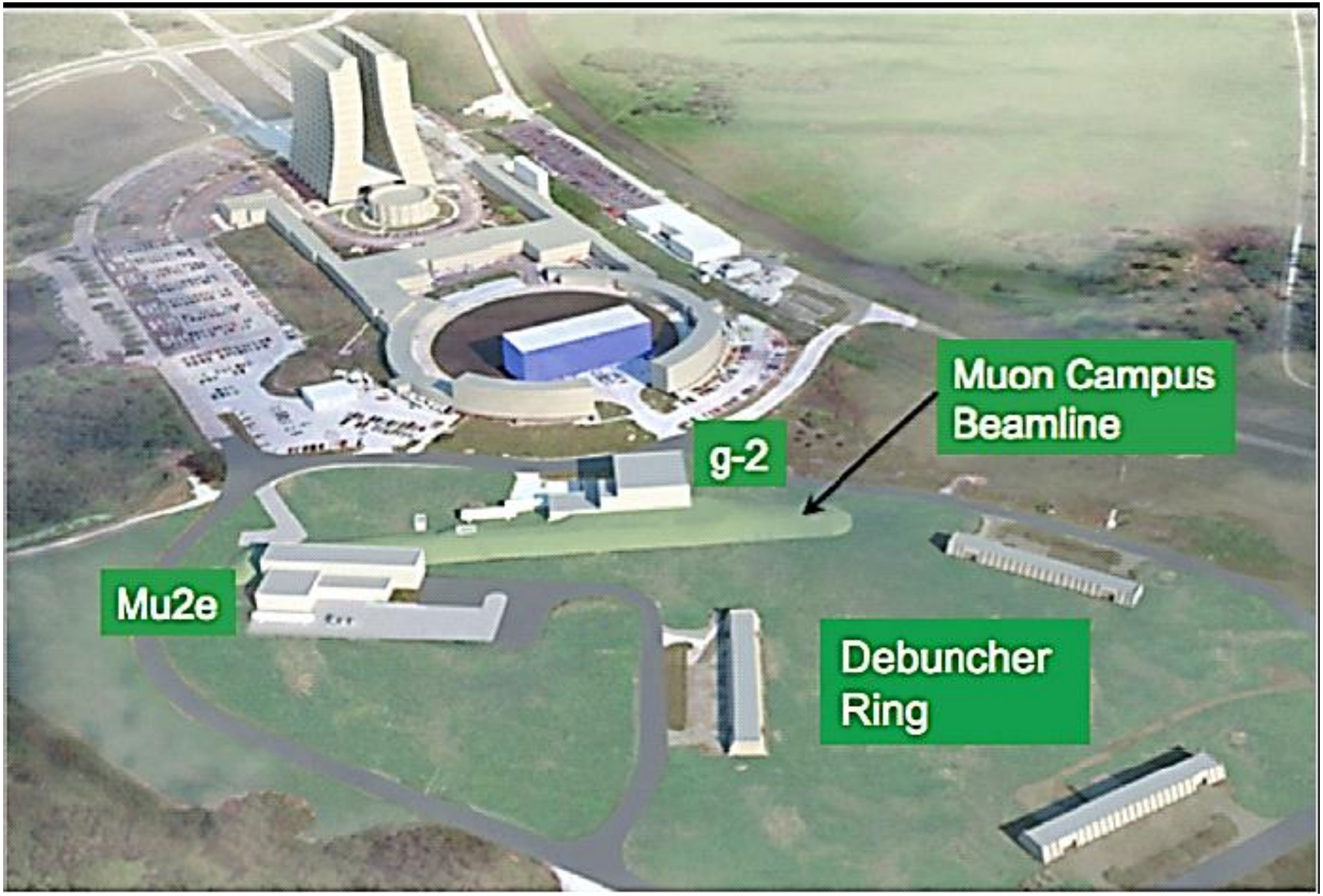
- Graded-field solenoid to collect pions w/ 10^3 times higher muon intensity (~10^{11}/sec)
- Curved solenoid to transport and select low energy negative muons



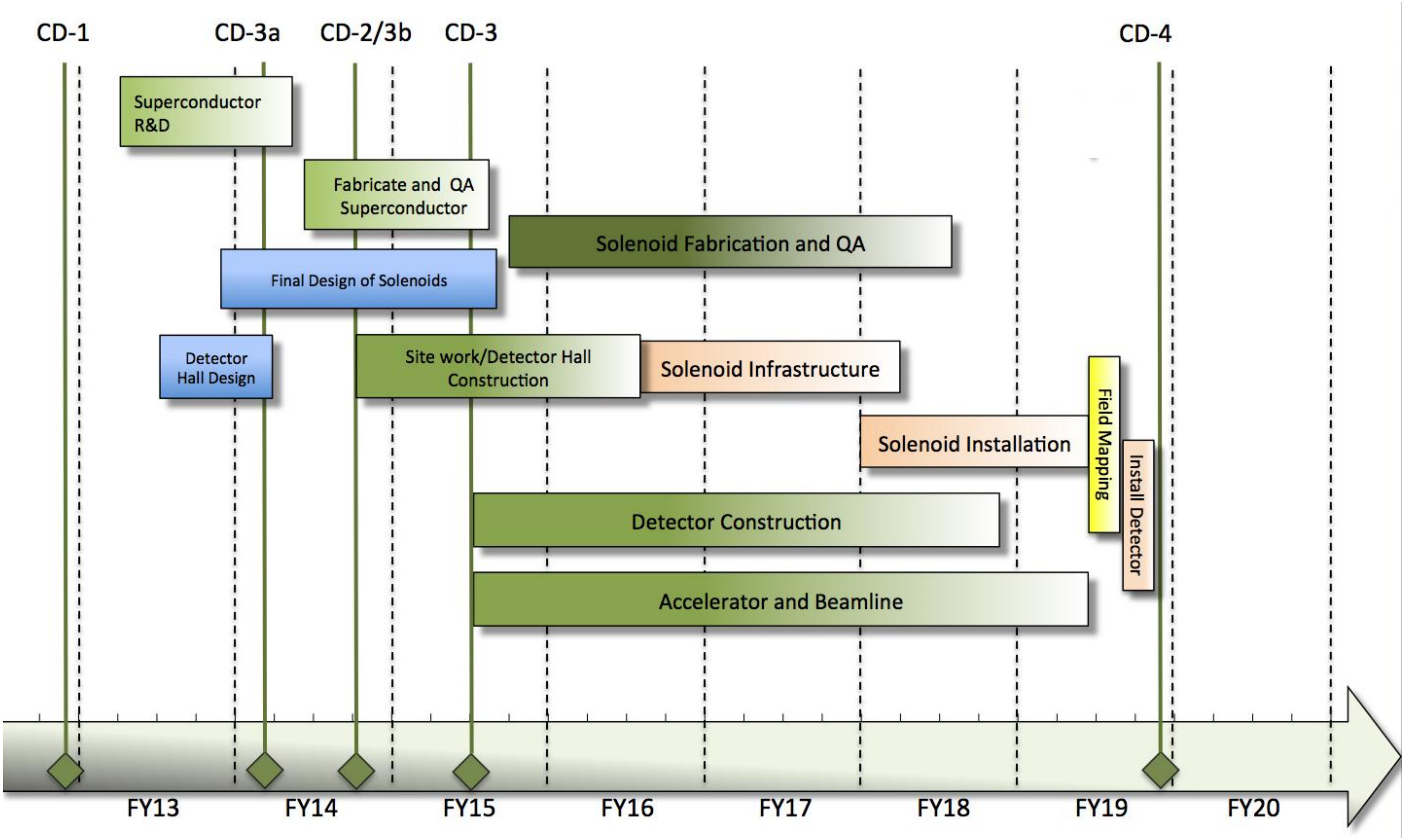


- Short pulsed beam that matches capture lifetime
- Data taken in a delayed time window to avoid beam-related BG
- "beam extinction"

The Muon Facility

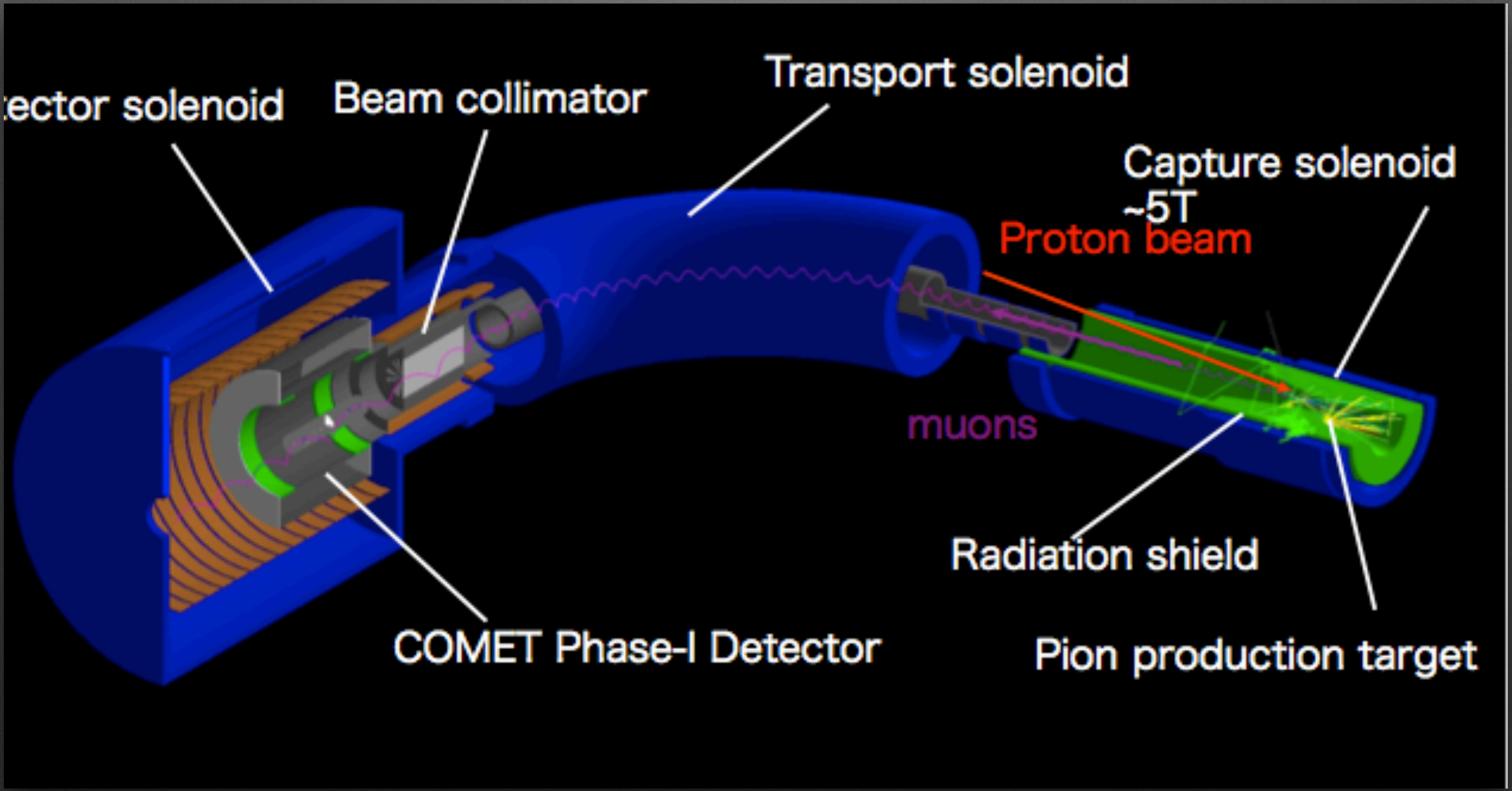


Schedule



CD-1
CD-3a
CD-2/3b
CD-3
CD-4
Superconductor R&D
Fabricate and QA Superconductor
Solenoid Fabrication and QA
Final Design of Solenoids
Detector Hall Design
Site work/Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation
Field Mapping
Install Detector
Detector Construction
Accelerator and Beamline
FY13
FY14
FY15
FY16
FY17
FY18
FY19
FY20

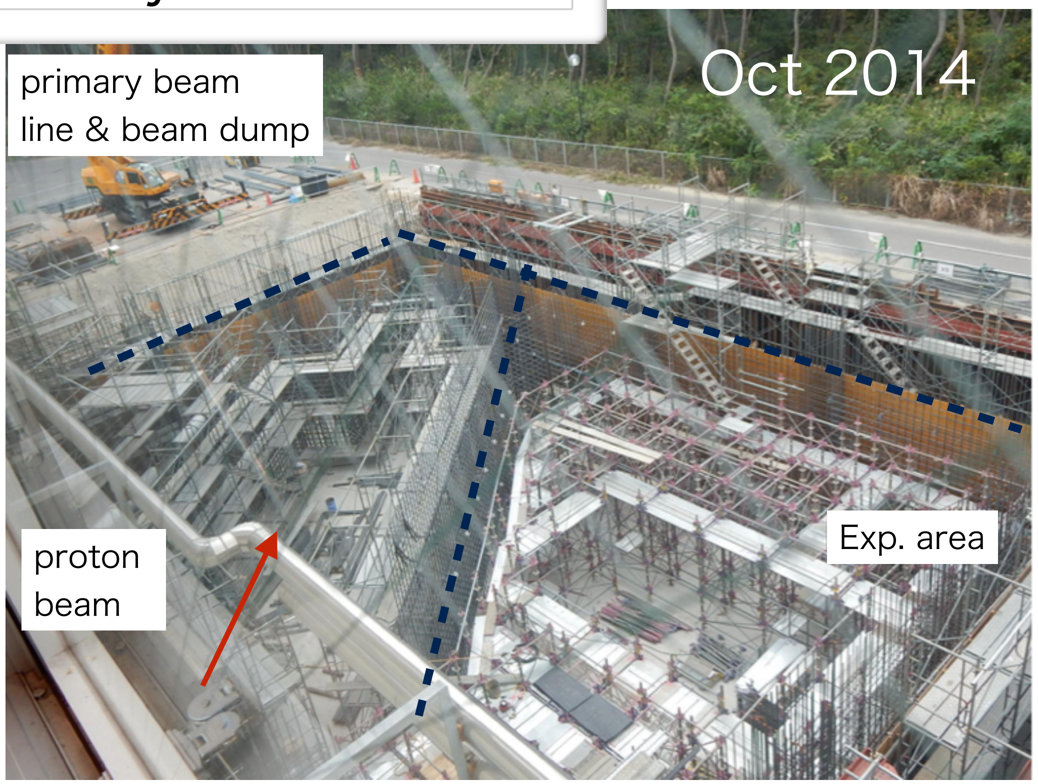
COMET Phase-I



- Staged approach
  - Phase-I 10^{-14} sensitivity, 3.2kW 90 days DAQ in 2017 +BG study
  - Phase-II 10^{-16} sensitivity, 56kW 1 year DAQ around 2020

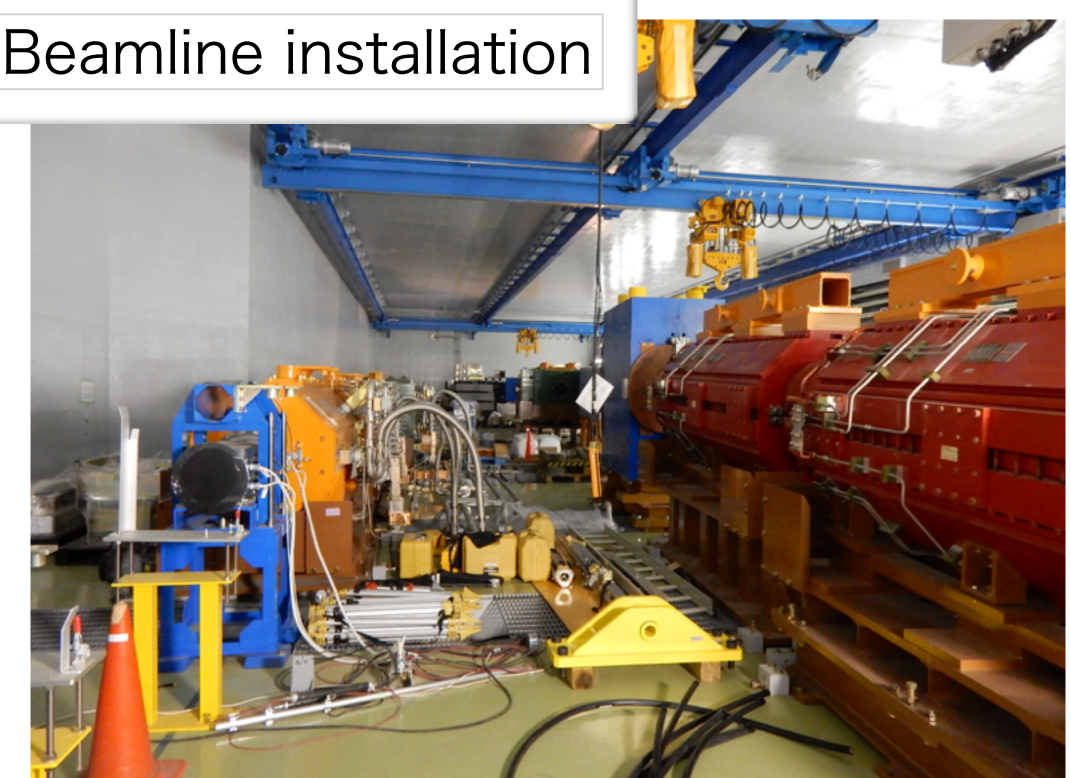
COMET Status

Facility construction

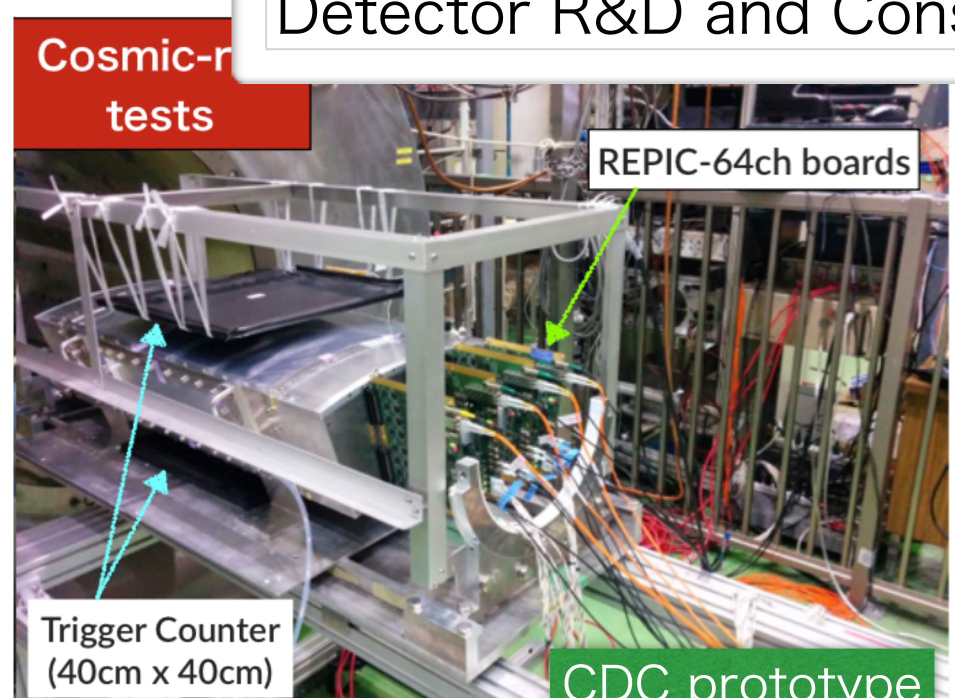


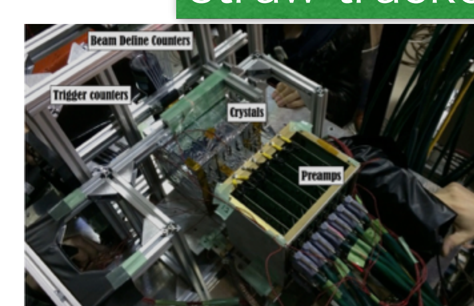
SC coil winding

Beamline installation

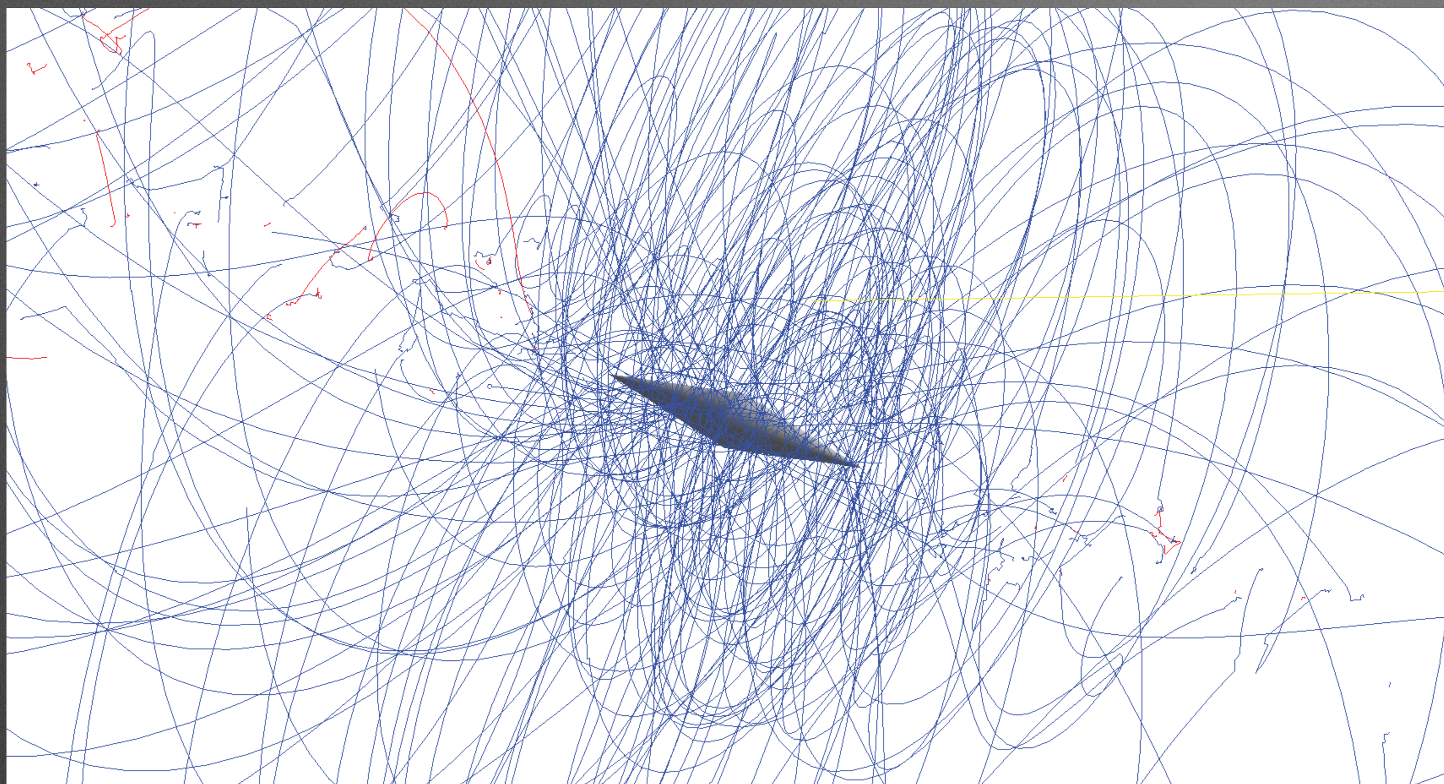


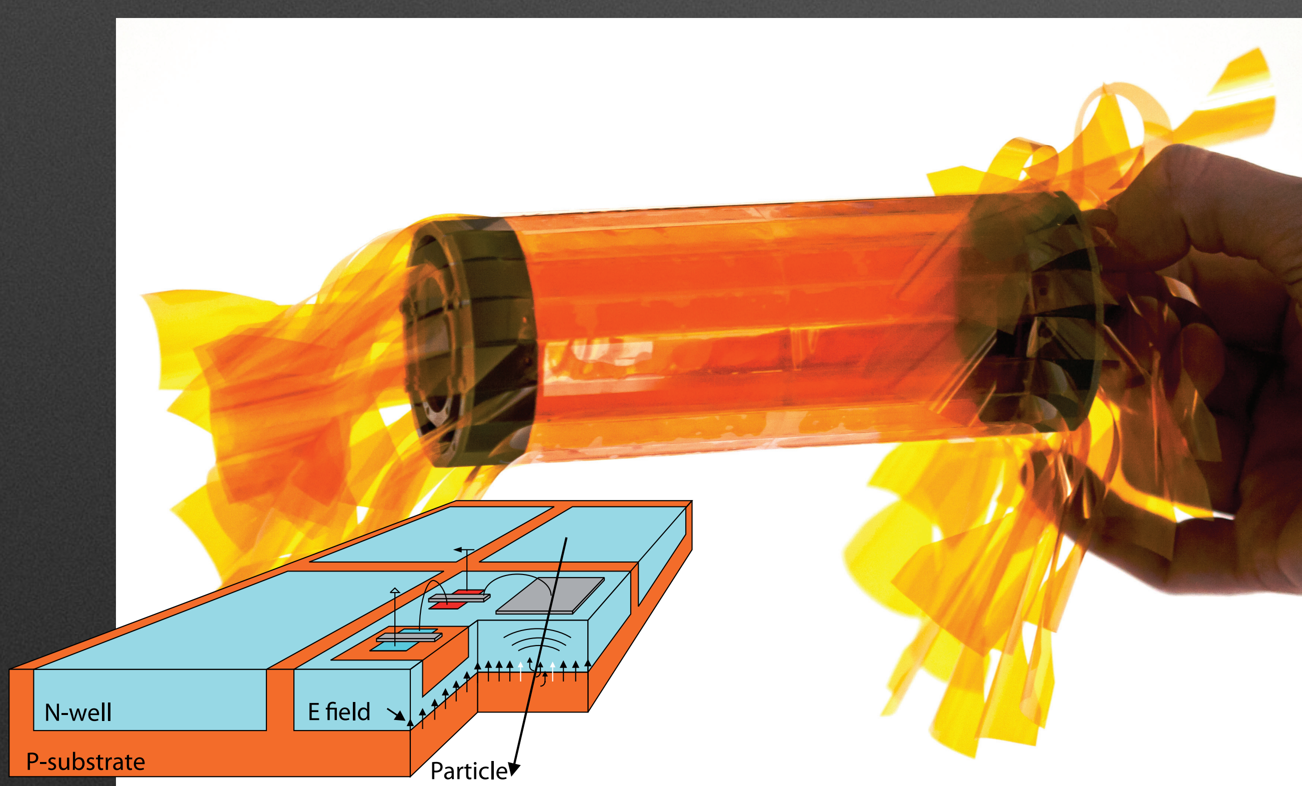
Detector R&D and Construction





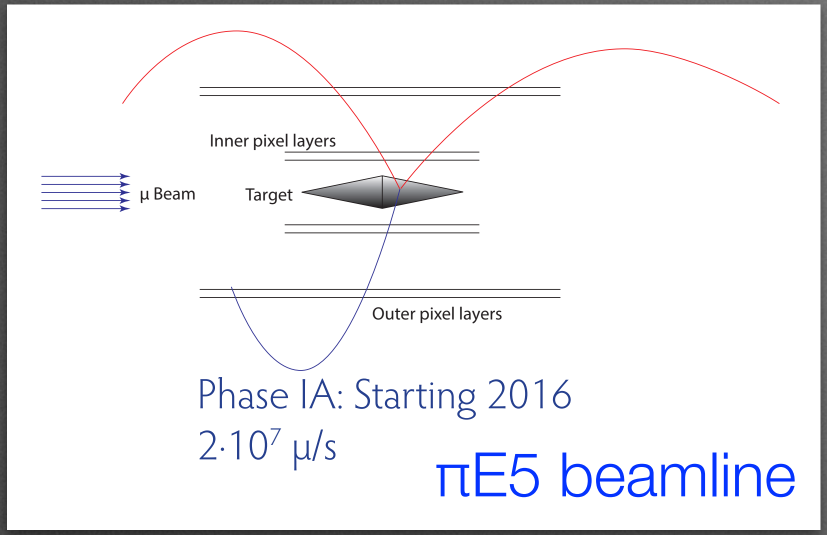
Mu3e - Enabling Technology

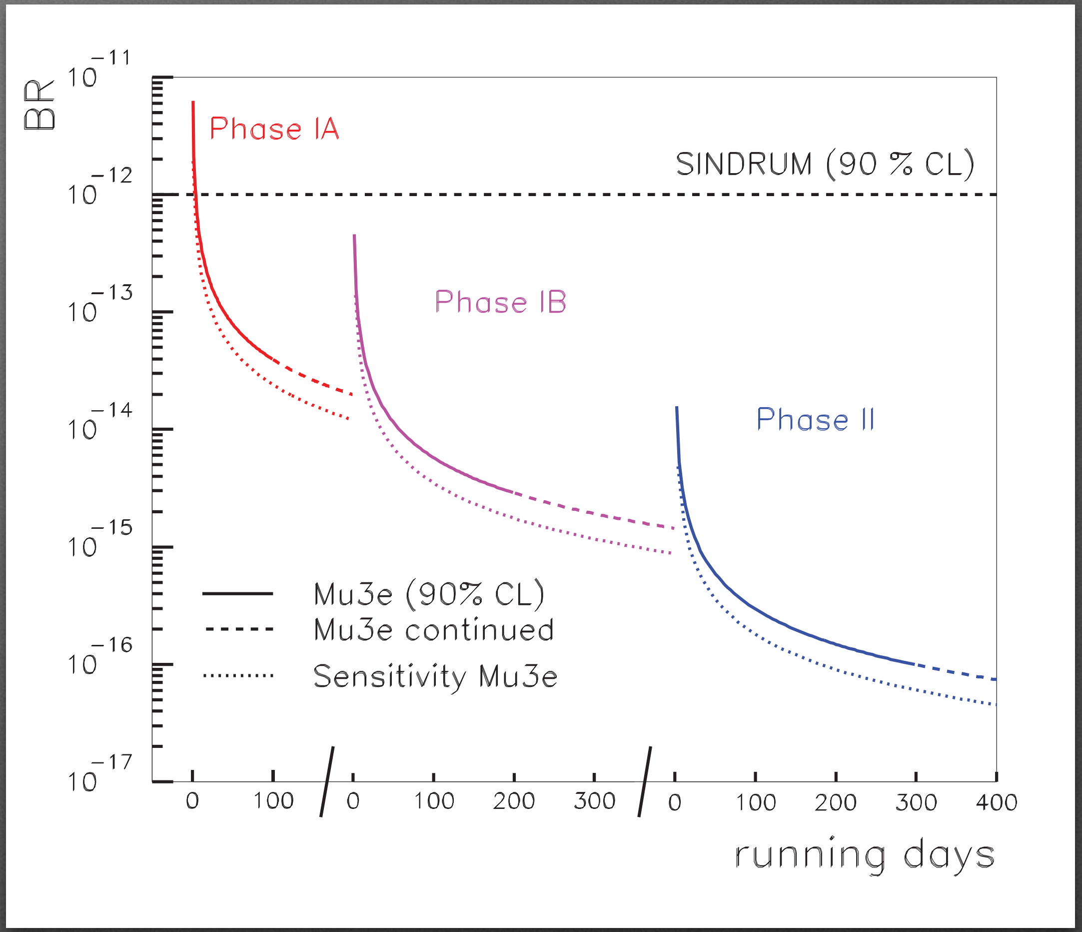


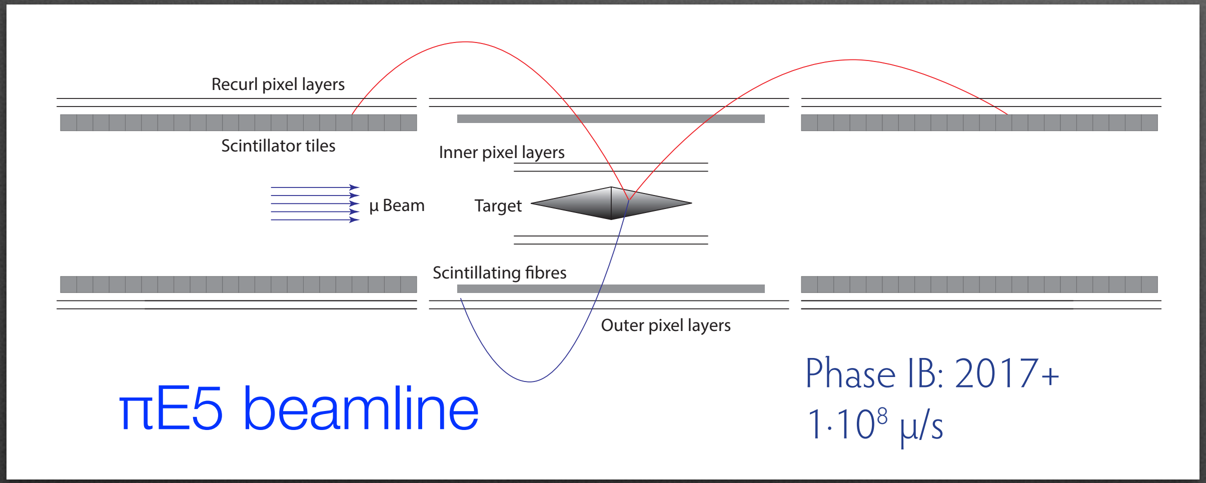


- No experiment since ~a quarter century
- Precision reconstruction of 3-body decay $\mu \rightarrow 3e$ in high rate environment of 2×10^9 muons/sec sounds daunting.
- Scattering & E loss dominate — Minimum material required for O(10 MeV) tracking.
- HV-MAPS: < 50μm possible, Advanced R&D underway

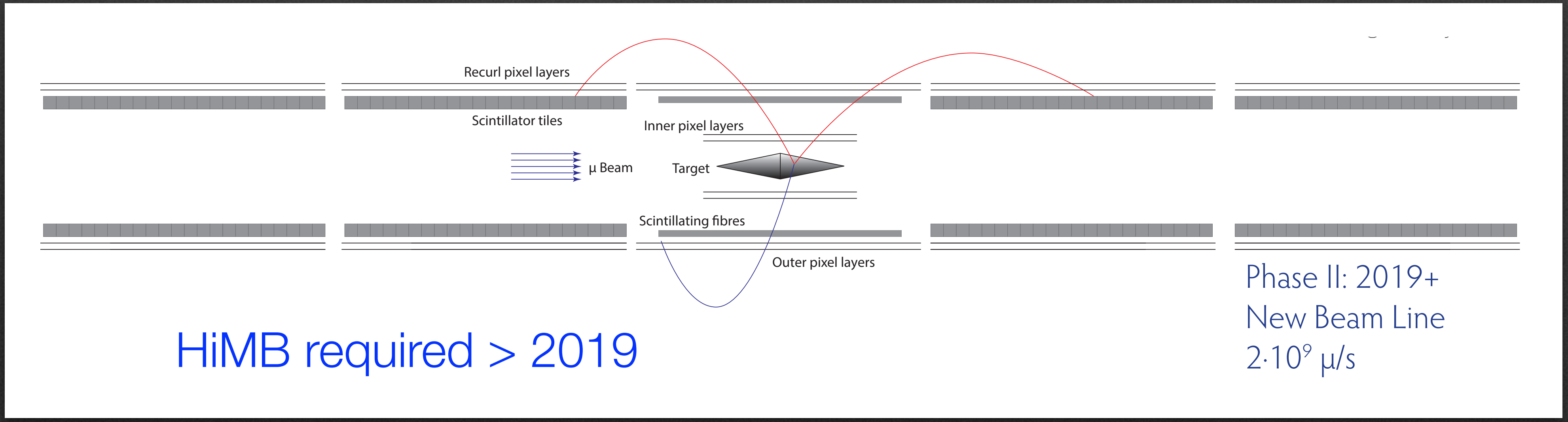
Staged Program







Eventual goal of 10^{-16}



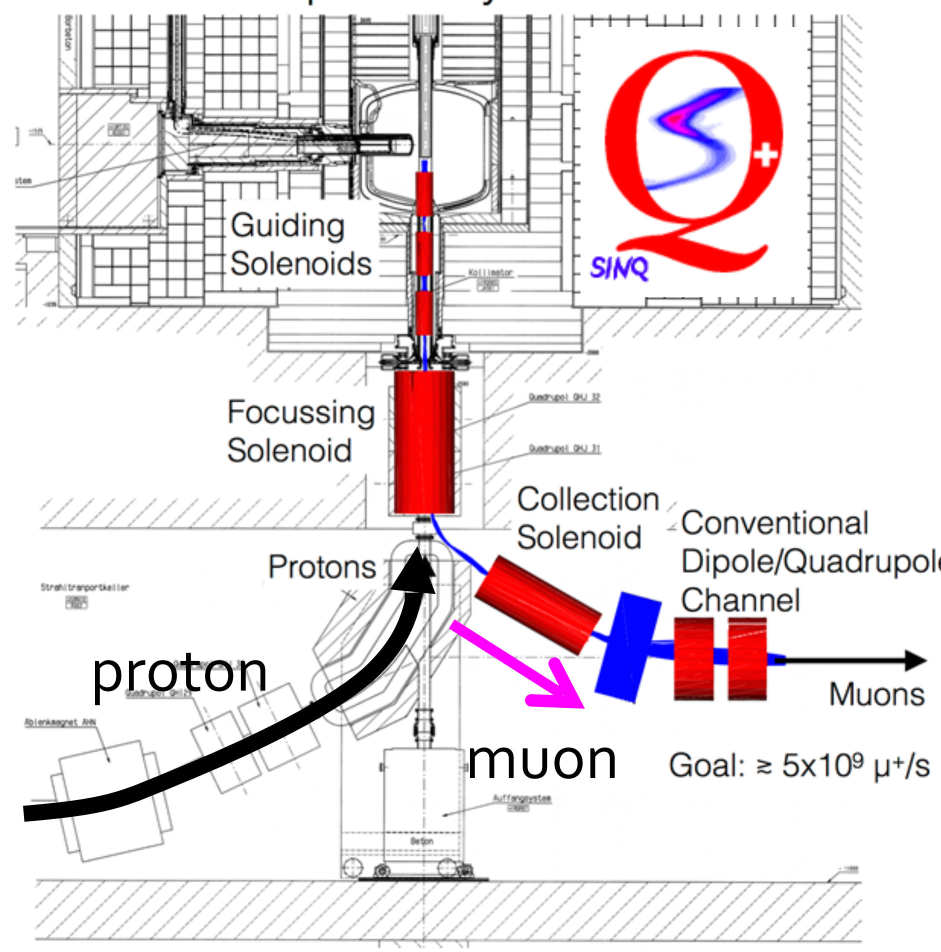
HiMB project @PSI

PAUL SCHERRER INSTITUT

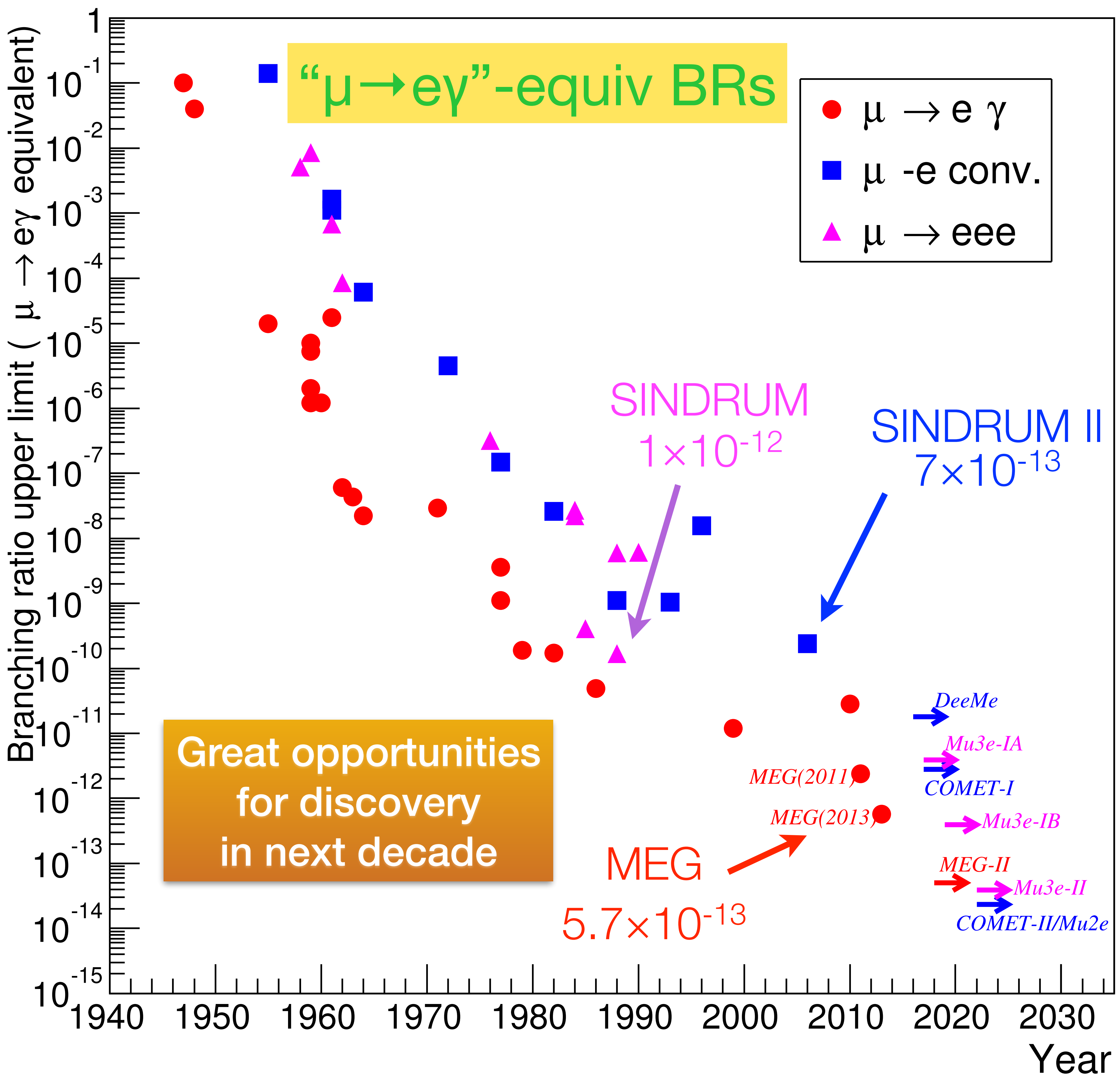
- Next generation High intensity Muon Beam project

- ☐ Extract muon produced at the target of spallation neutron (SINQ)
- ☐ in excess of O(10^{10}) surface μ^+/s
- ☐ Feasibility study going on
- ☐ **Operation not before 2019**

HiMB Conceptual Layout



- A must for Mu3e to achieve 10^{-16}
- An opportunity for "MEG III" for O(10^{-15}) $\mu\to e\gamma$?
  - A preliminary study is underway.
  - A design used in a Snowmass study (arXiv1309.7679) does *not* seem feasible → Needs a much better design!



"μ→eγ"-equiv BRs
μ → e γ
μ -e conv.
μ → eee
SINDRUM
1×10-12
SINDRUM II
7×10-13
MEG
5.7×10-13
MEG(2011)
MEG(2013)
DeeMe
Mu3e-IA
COMET-I
Mu3e-IB
MEG-II
Mu3e-II
COMET-II/Mu2e
Great opportunities
for discovery
in next decade
Branching ratio upper limit (μ → eγ equivalent)
Year

Beyond Mu2e/COMET

- $\mu \rightarrow e\gamma$ experiment for $O(10^{-15})$ at HiMB (PSI) ?
  - Needs a clever experimental design based on new technology
- $\mu \rightarrow 3e$ needs a higher intensity source than HiMB
  - Mu3e-type experiment still feasible?
- $\mu \rightarrow e$ conversion experiments have a potential for a higher sensitivity if a higher intensity muon source becomes available.
  - Perhaps better to think after looking at what will happen at Mu2e/COMET

Summary

- No cLFV / EDM has been found yet.
- A great progress in electron EDM: $d_e < 8.7\times10^{-29}$ @90% C.L.
  - Further improvement expected
  - Other EDM searches continue to move ahead
- MEG /MEG II leading cLFV: $BR(\mu\to e\gamma) < 5.7\times10^{-13}$ @90% C.L.
  - Final MEG result (x2 statistics) by end of this year
  - A full lineup of cLFV experiments in next decade:
    MEG II / DeeMe / Mu3e / COMET / Mu2e
- Stay tuned for the outcome of the new Muon g-2 experiments
- Great opportunities for Discoveries waiting ahead

backup