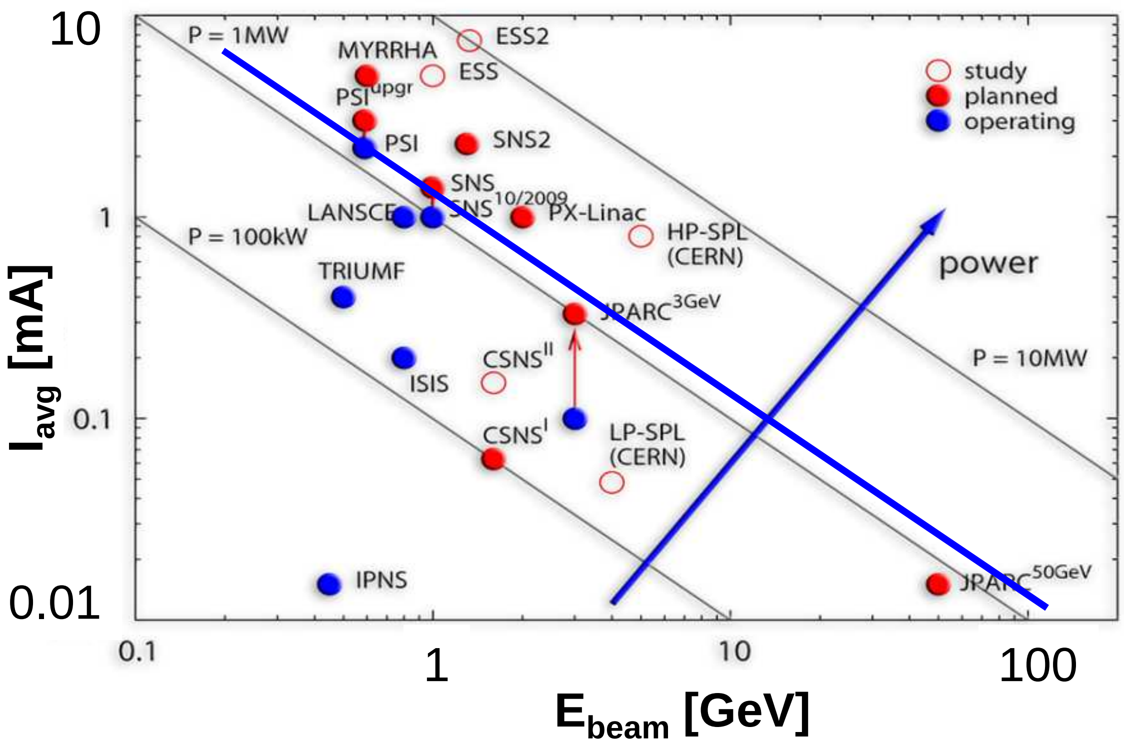
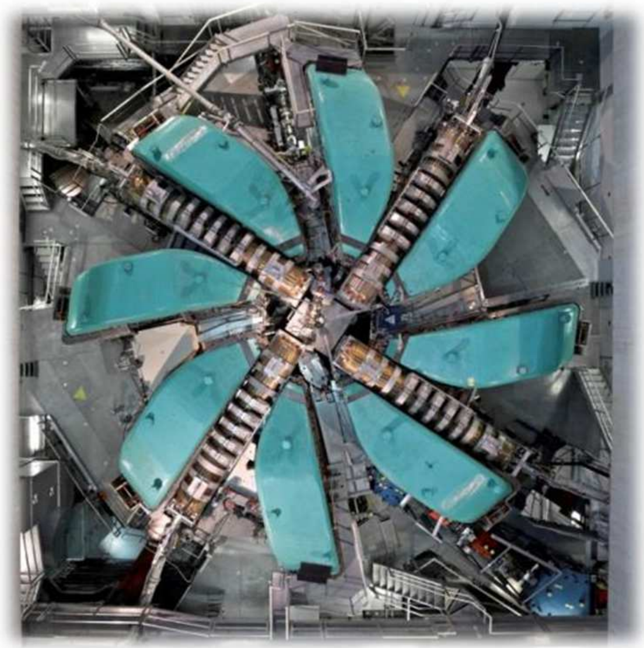
Charged Lepton Flavor and Dipole Moments

K.Kirch, ETH Zurich – PSI Villigen, CH





The 1.4 MW ring cyclotron at PSI

Setting the scene

- Conservation of lepton flavor is a mystery
  - Besides quark mixing, we have neutrino mixing
  - Why wouldn't we expect charged lepton mixing?
  - Theories beyond SM naturally provide LFV

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  - To explain the observed BAU
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- Non-SM precision physics, finite observables
  - Some uniquely sensitive areas

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  - Why ect charged lepton mixing?
  - The naturally provide LFV

Search for charged LFV e.g. $\mu \rightarrow e \gamma$

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Setting the scene

- Conservation of lepton flavor is a mystery
  - Bes **Search for** g, we have neutrino mixing
  - Why **charged LFV** pect charged lepton mixing?
  - The **e.g. $\mu \rightarrow e \gamma$** naturally provide LFV

- Non-SM CP violation seems necessary
  - To explain **Search for CPV**
  - Theories b **e.g. measure EDMs, e, n, μ, …**

- Non-SM precision physics, finite observables
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Setting the scene

- Conservation of lepton flavor is a mystery
  - Bes… …g, we have neutrino mixing
  - Why… …pect charged lepton mixing?
  - The… naturally provide LFV

Search for charged LFV

e.g. $\mu \rightarrow e\gamma$

- Non-SM CP violation seems necessary
  - To explain
  - Theories b…

Search for CPV

e.g. measure EDMs, e, n, μ, …

- Non-SM precision physics, finite observables
  - Some uniquely …

e.g. measure MDMs, e, μ, …

Setting the scene

- Not clear what new non-SM physics will be
  - **Search for LFV in all accessible channels**
  - Some are more promising than others
  - But who knows? → need all to disentangle physics

- Not clear what new non-SM physics will be
  - **Search for CPV in all accessible channels**
  - In particular, search for EDMs in many systems

- Not clear what new non-SM physics will be
  - **Measure with ultimate precision** where theory can accurately calculate

This talk …

- … can't cover all cLFV searches like, e.g. $K_L \rightarrow \mu e$, …
  (or other decays of π, K, D, B, W, Z, H)
- … only touches on important τ decays (dominated by Belle, LHCb entering, future: Belle-II and LHCb upgrade)
- … has LFV searches with muons (@PSI, FNAL, J-PARC) **LFV**
- … has muon g-2 (@BNL, FNAL, J-PARC) but only mentions electron g-2 **MDM**
- … has EDM searches (many systems @many places) **EDM**

$\tau \to \mu\gamma$
$\to e\gamma$

$\mu \to e\gamma$

$\tau \to \mu\mu\mu$
$\to eee$

$\mu \to eee$

$\pi^0 \to \mu e$

$\mu \to e$
e.g. Al

$(g-2)_e$

$(g-2)_\mu$

d_μ

d_e

d_n

d_p , d_d

d_{Hg}

$d_{Xe,Ra,...}$

d_{YbF}

$d_{Tl,Fr,...}$

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e.g. Al

$(g\text{-}2)_e$

$(g\text{-}2)_\mu$

Particle Physics

Nuclear Physics

Atomic Physics

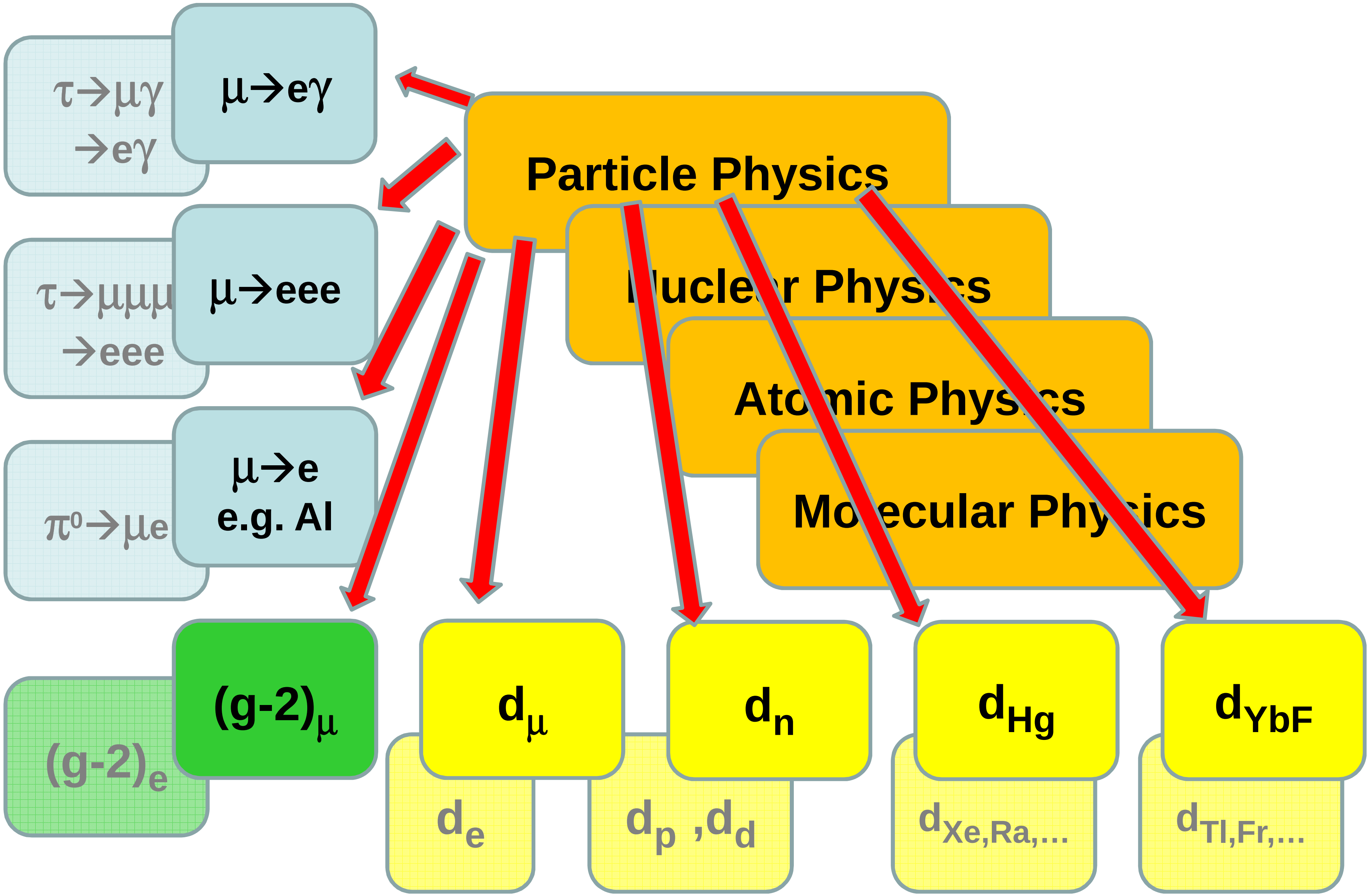
Molecular Physics

d_μ d_e

d_n d_p ,d_d

d_{Hg} $d_{Xe,Ra,\ldots}$

d_{YbF} $d_{Tl,Fr,\ldots}$



$\tau \rightarrow \mu\gamma$
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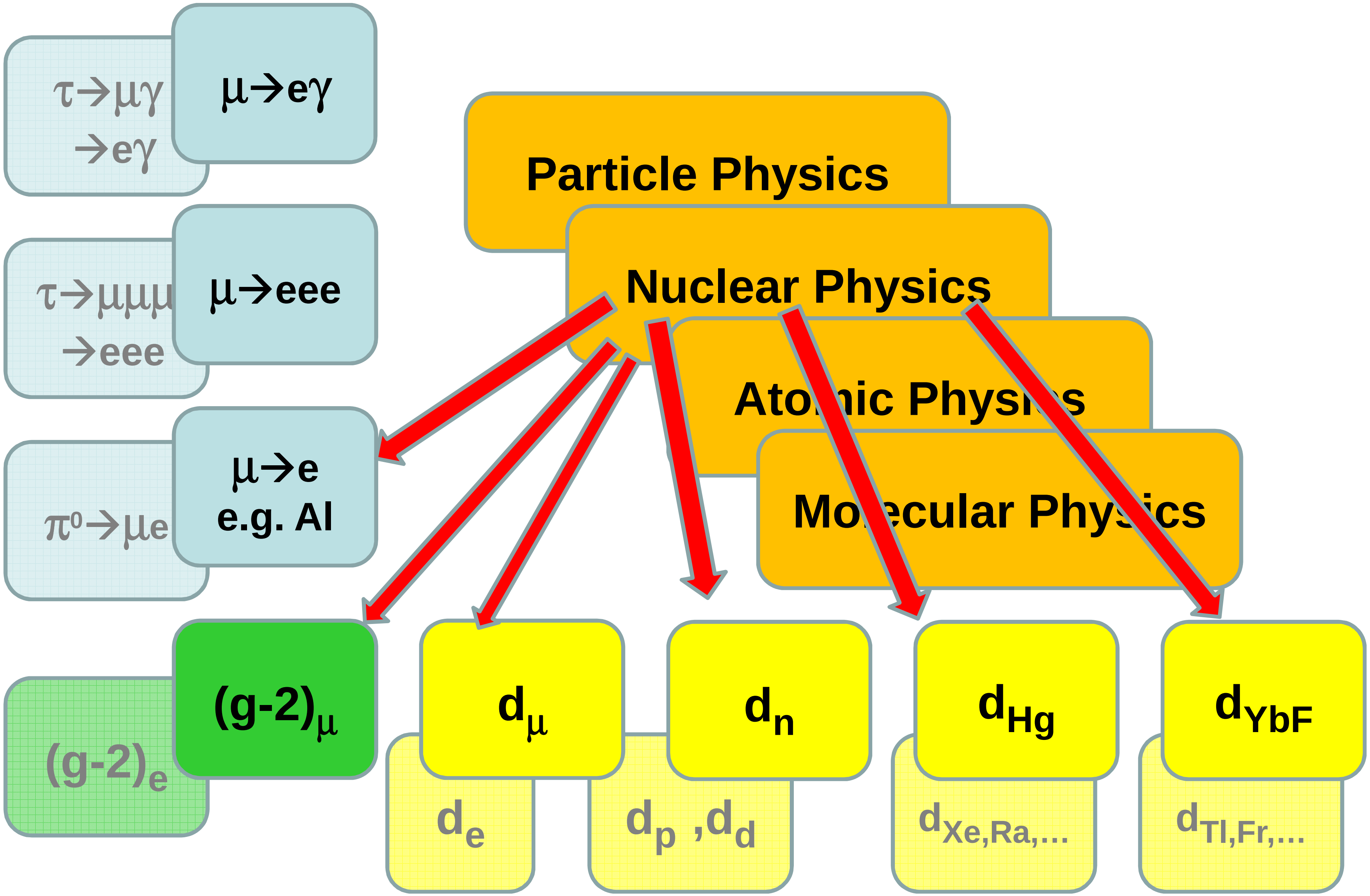
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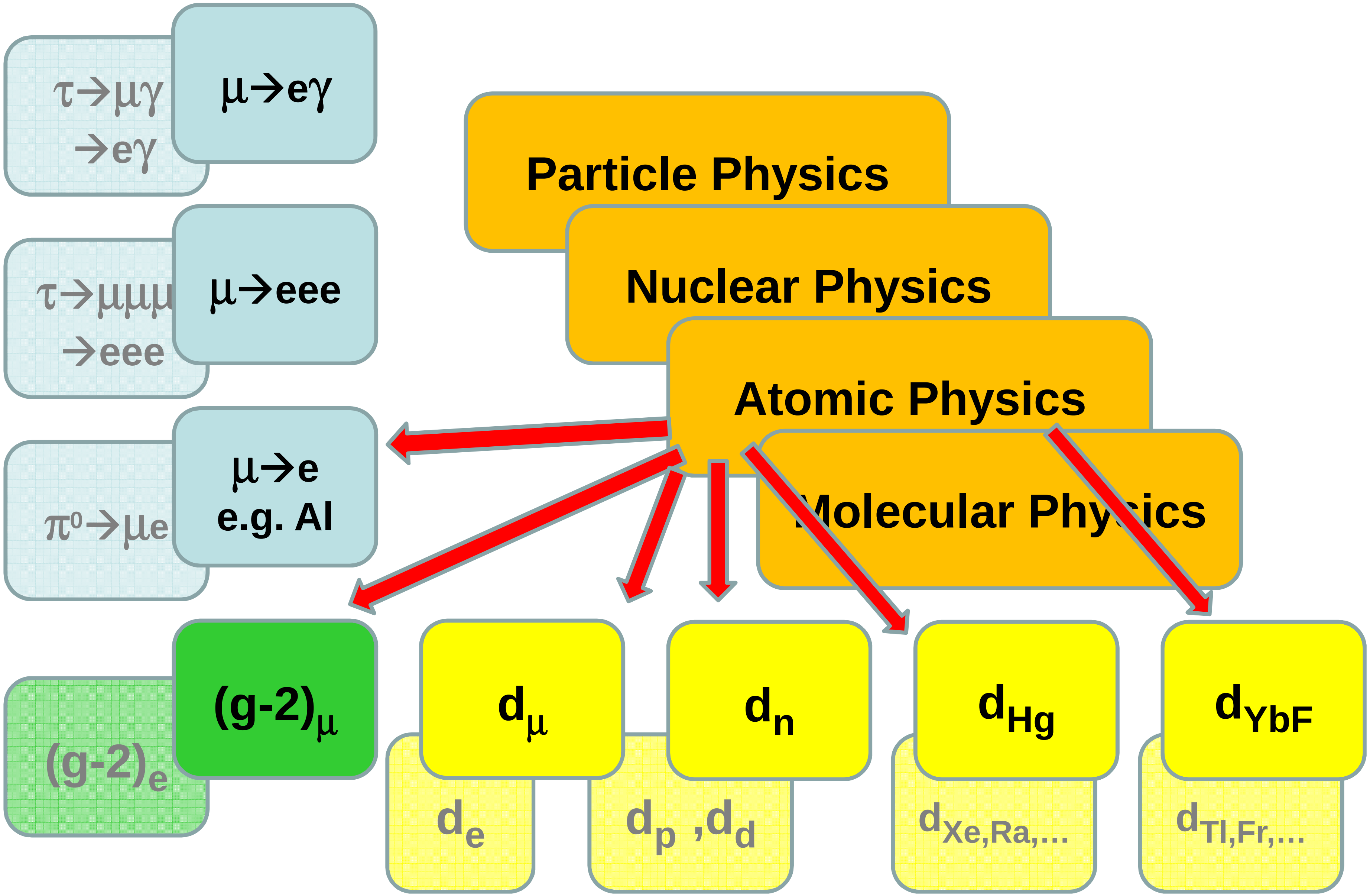
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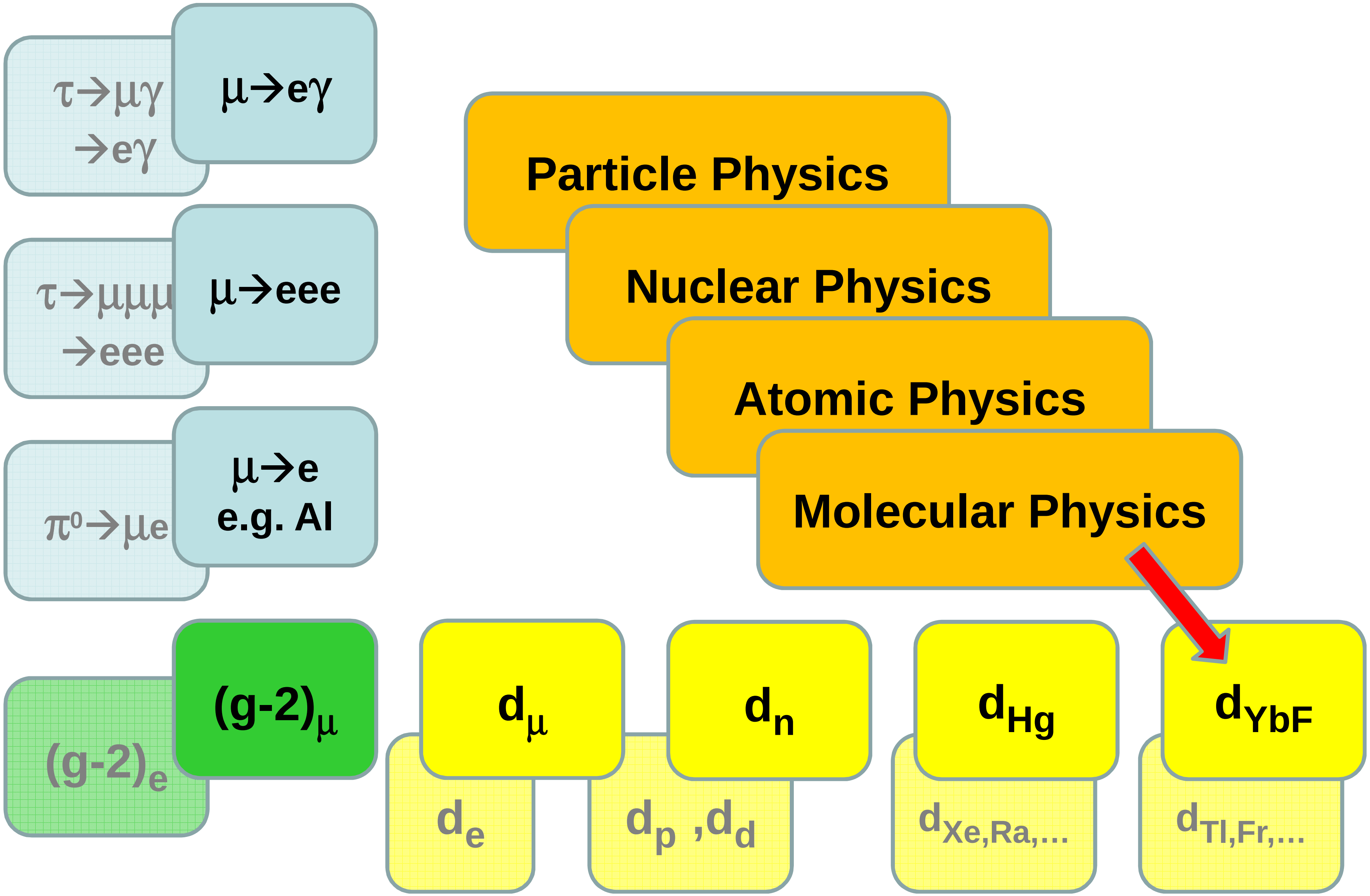
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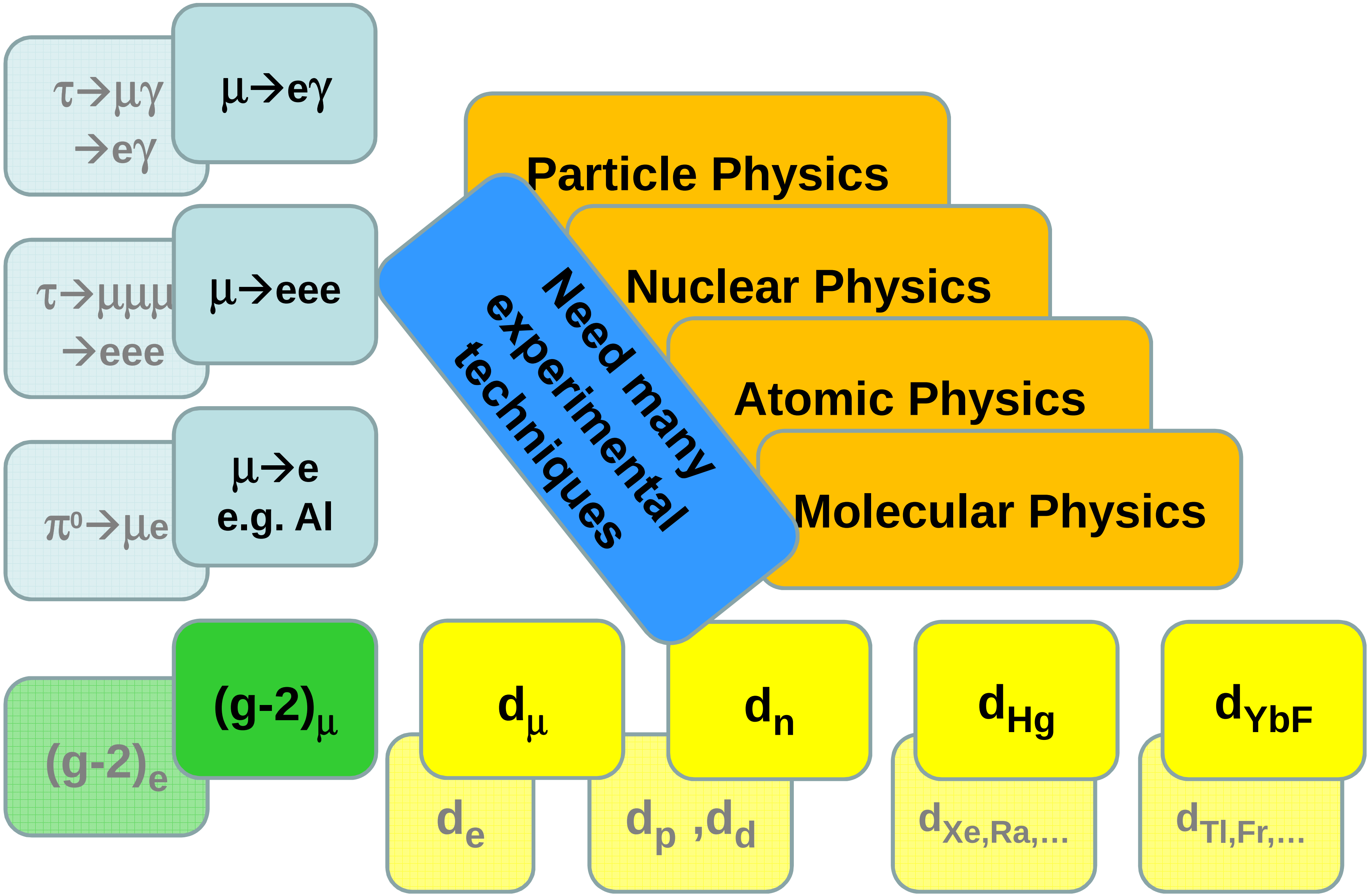
d$_{Tl,Fr,...}$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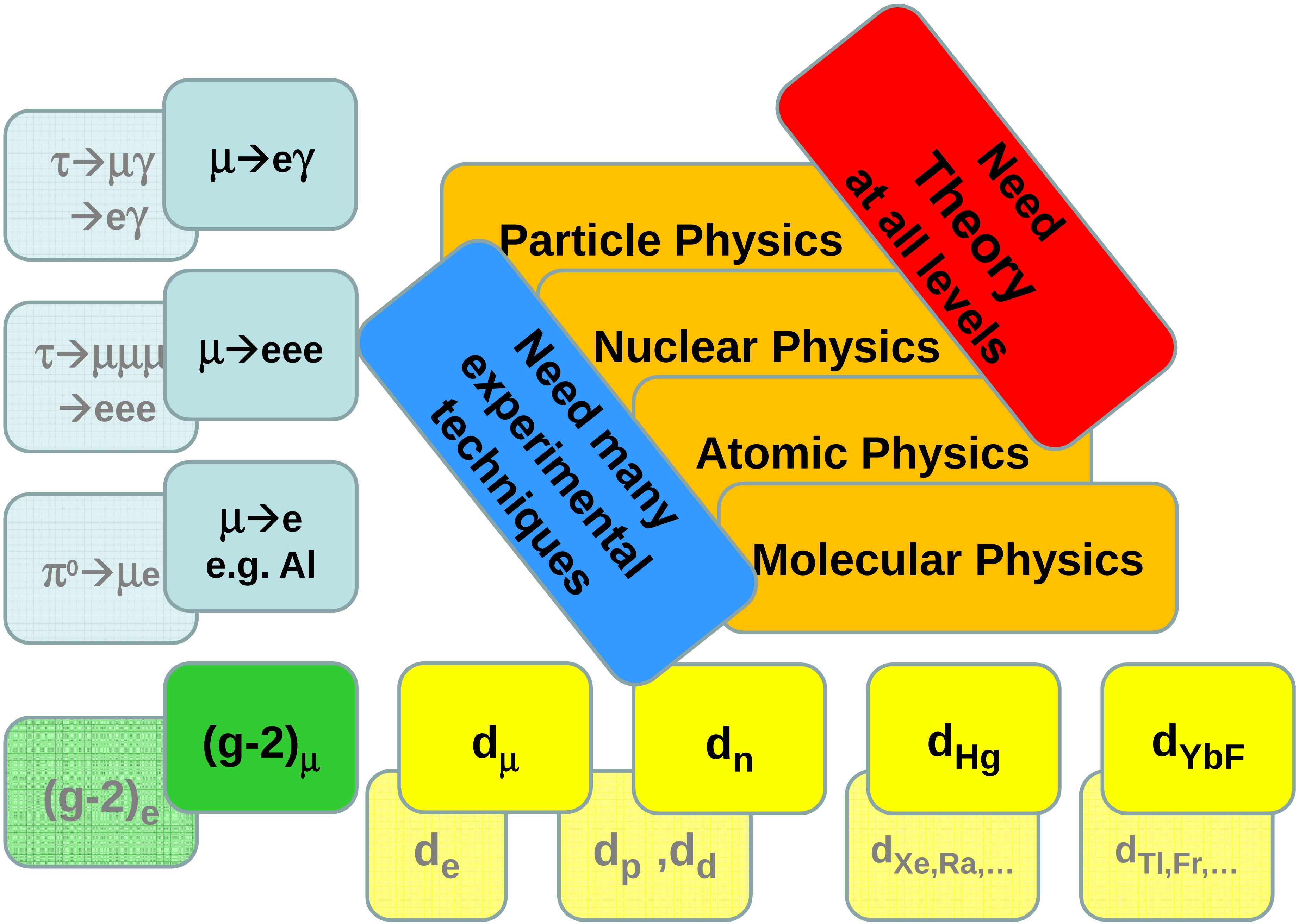
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Need many experimental techniques
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General concept: constrain effective operator coefficients

Table 1 Bounds on CP- or flavor violating effective operators, expressed as upper limits on their dimensionless coefficients ϵ, scaled to the strength of weak interactions. For more details, in particular the overall normalization convention for the effective operators, see Sect. 3.1.2

Needs update

Observable	Operator	Limit on ϵ
eEDM	$\overline{e_L}\sigma^{\mu\nu}\gamma_5 e_R F_{\mu\nu}$	$\leq 2.1 \times 10^{-12}$
$B(\mu \to e\gamma)$	$\overline{\mu}\sigma^{\mu\nu} e F_{\mu\nu}$	$\leq 3.4 \times 10^{-12}$
$B(\tau \to \mu\gamma)$	$\overline{\tau}\sigma^{\mu\nu} \mu F_{\mu\nu}$	$\leq 8.4 \times 10^{-8}$
$B(K_L^0 \to \mu^\pm e^\mp)$	$(\overline{\mu}\gamma^\mu P_L e)(\overline{s}\gamma^\mu P_L d)$	$\leq 2.9 \times 10^{-7}$

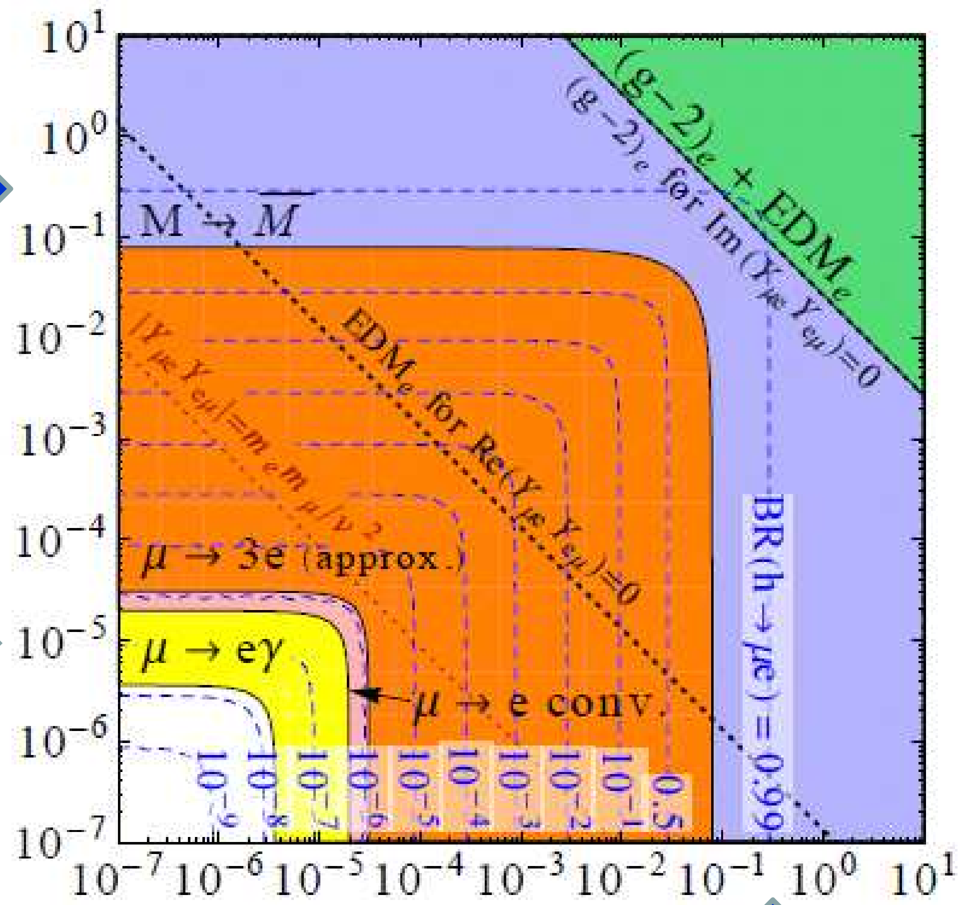
From:
Raidal, van der Schaaf et al.,
Flavor physics of leptons and dipole moments,
Eur. Phys. J. C 57(2008)13

To illustrate complementarity

Flavor violating Higgs decays

$|Y_{\mu e}|$

MEG

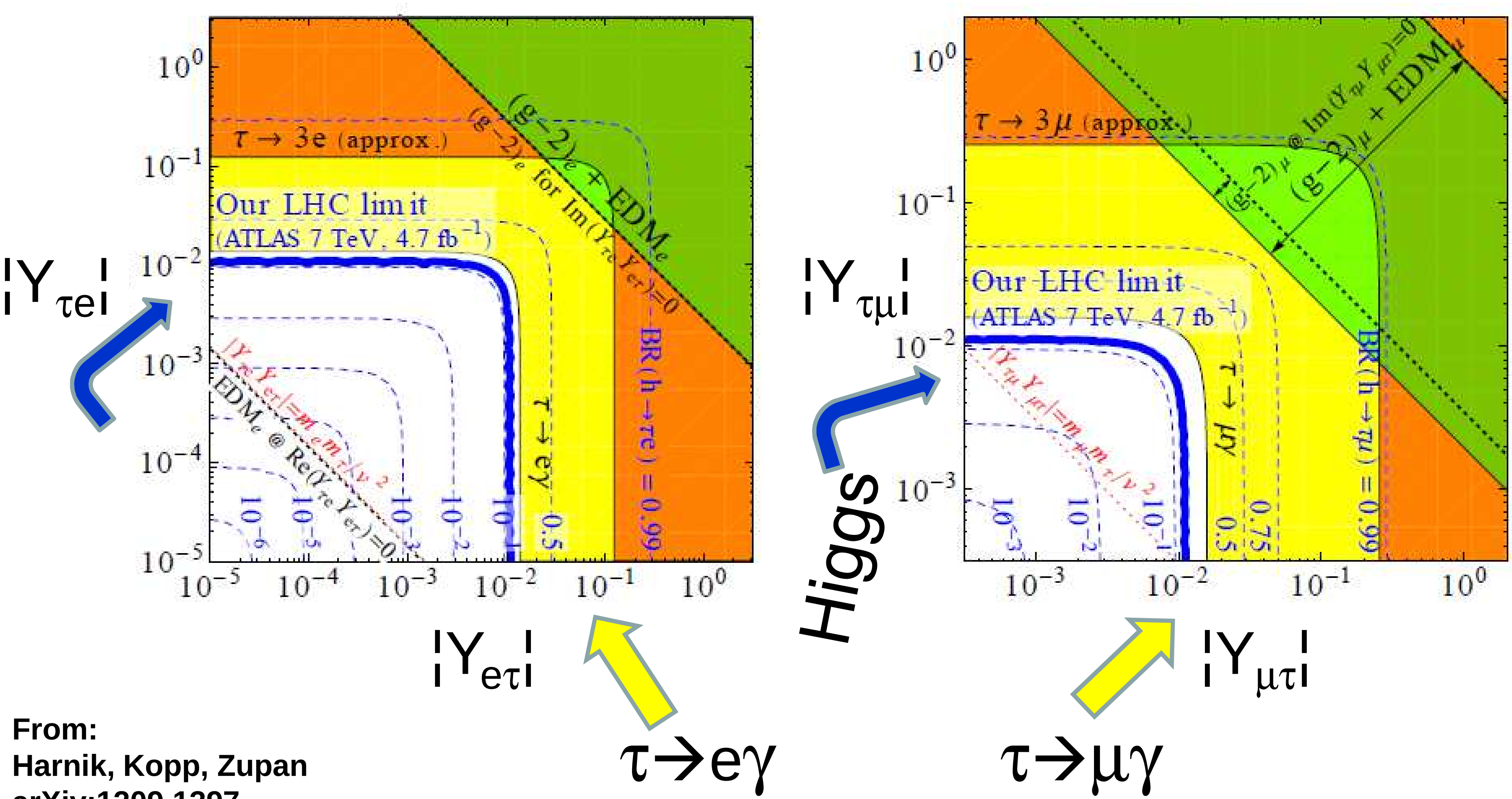


$|Y_{e\mu}|$

Higgs

From:
Harnik, Kopp, Zupan
arXiv:1209.1397

Flavor violating Higgs decays

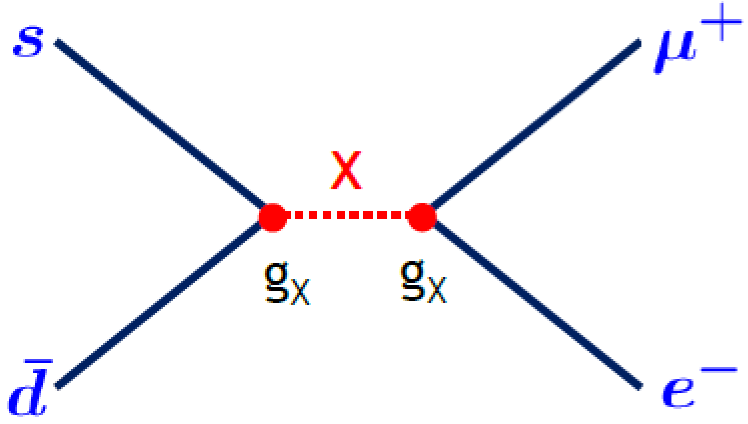


From:
Harnik, Kopp, Zupan
arXiv:1209.1397

One slide on kaons

High NP mass scales accessible for tree-level contributions

Example: $K_L \to \mu^+ e^-$



Dimensional argument:

$$\frac{\Gamma_X}{\Gamma_{SM}} \sim \left(\frac{g_X}{g_W} \cdot \frac{M_W}{M_X}\right)^4$$

For $g_X \approx g_W$ and $\mathcal{B} \sim 10^{-12}$,

$$M_X \sim 100\ \text{TeV}$$

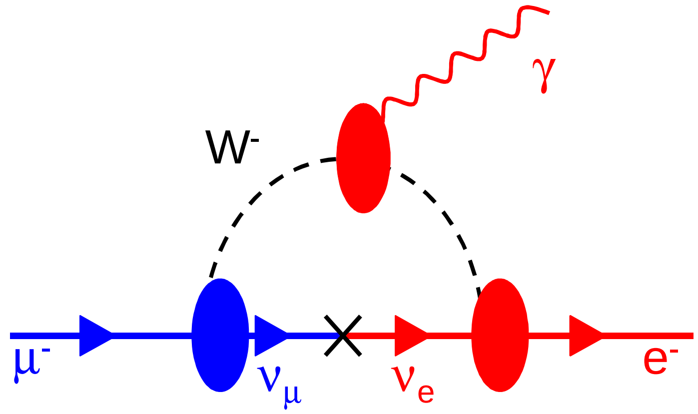
To illustrate the mass reach

See also: European Strategy for PP – unique mass reach
also in other rare decays, cLFV and EDMs

Goudzovski, Lecce, 2013

Reminder: cLFV is small in SM

- Only known LFV so far: neutrino mixing
- Suppressed by $(\delta m_\nu/m_W)^4$ and thus smaller than 10^{-50}
  → SM not observable
- Plenty of room for new physics



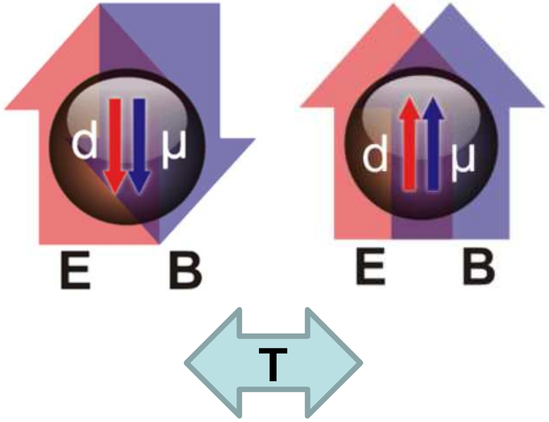
Expect from SM:

BR(μ-eγ) < 10^{-50}

Experimentally so far:

< 5.7×10^{-13}

Reminder: EDM are small in SM



- Leptons: 4th order electro-weak

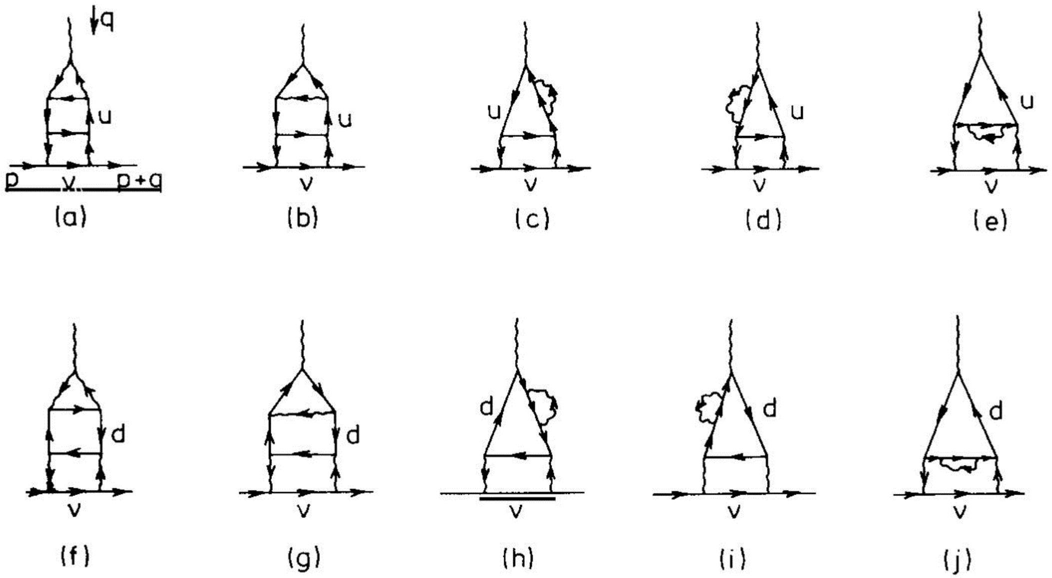


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

F. Hoogeveen:
The Standard Model Prediction for the Electric Dipole Moment of the Electron,
Nucl. Phys. B 241 (1990) 322

Expect from SM, approximately:

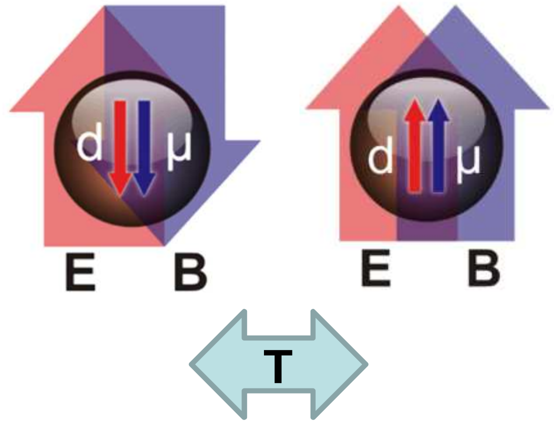
$d_e \leq 10^{-38}$ e•cm
$d_\mu \leq 10^{-36}$ e•cm
$d_\tau \leq 10^{-35}$ e•cm

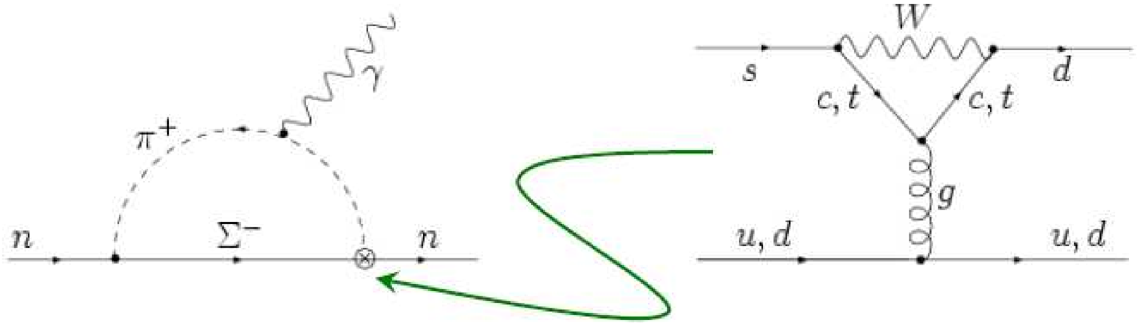
Experimentally so far:

$d_e < 1 \times 10^{-27}$ e•cm
$d_\mu < 2 \times 10^{-19}$ e•cm
$d_\tau < 3 \times 10^{-17}$ e•cm

Reminder: EDM are small in SM

- Neutron, Proton, ..





$$d_n \sim 10^{-32} - 10^{-34} e\ cm$$

[Khriplovich & Zhitnitsky '86]

Expect from SM:

$d_n < 10^{-30}$ e•cm

Experimentally so far:

$< 2.9 \times 10^{-26}$ e•cm

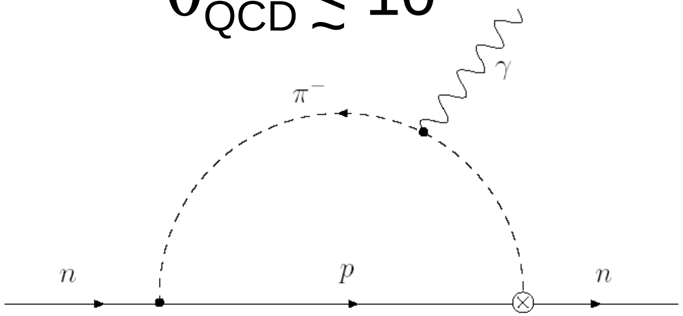
Caveat:

The strong CP problem

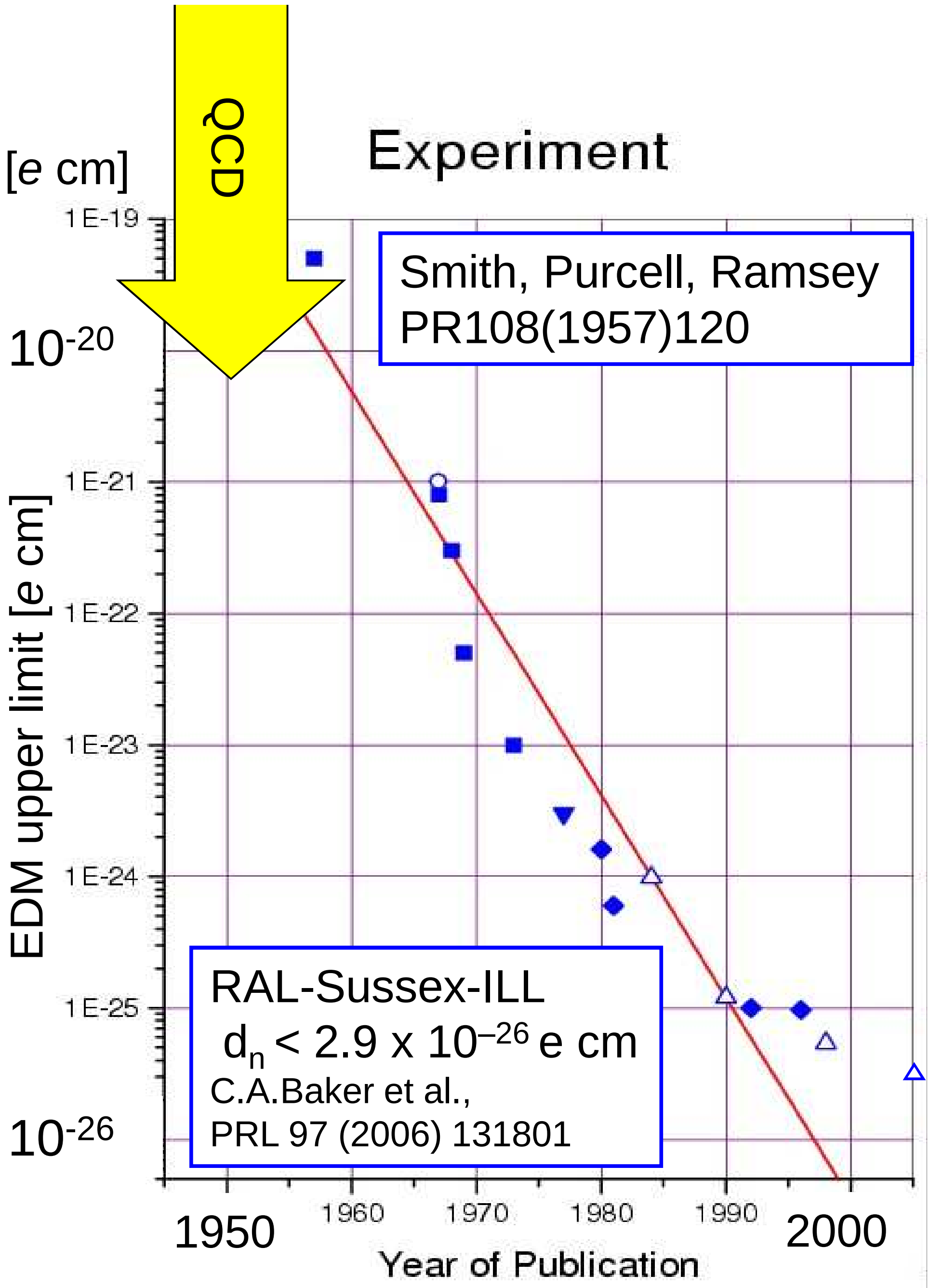
$$L_{QCD} \approx L_{QCD}^{\theta_{QCD}=0} + g^2/(32\pi^2)\,\theta_{QCD} G\tilde{G}$$

$$d_n \approx 10^{-16}\, e\,\mathrm{cm} \cdot \theta_{QCD}$$

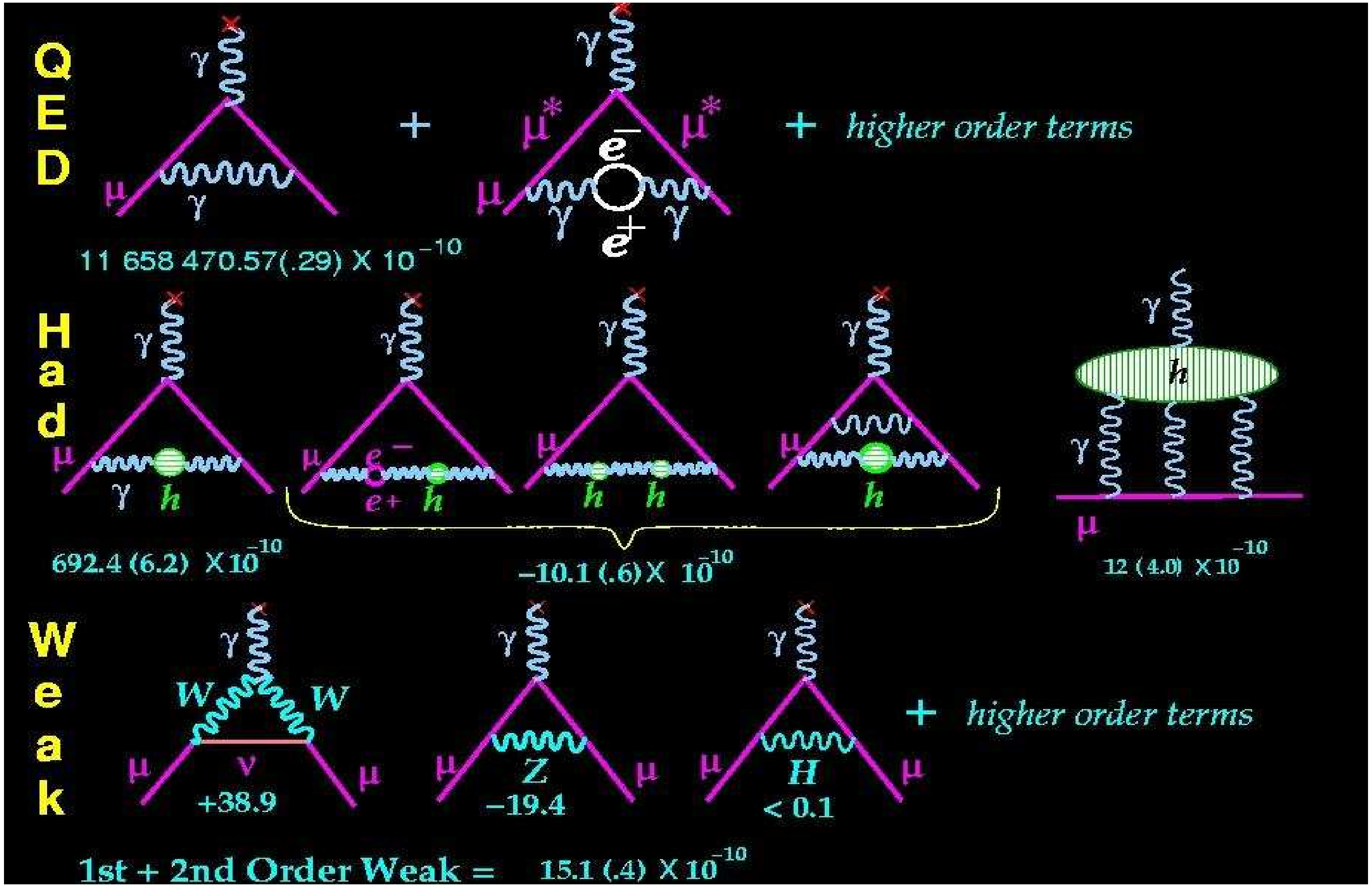
$$\theta_{QCD} \lesssim 10^{-10}$$



Why is θ_{QCD} so small ?

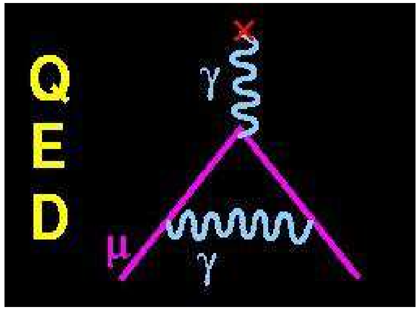


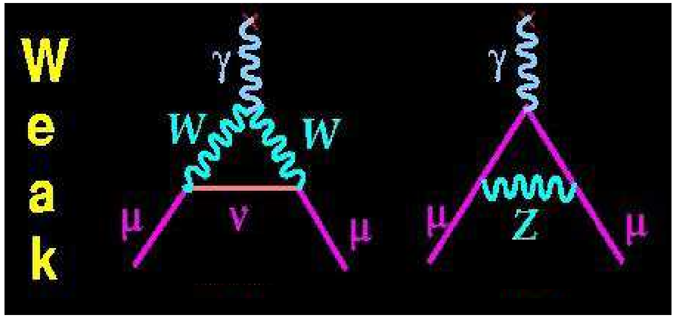
Reminder: g-2 is calculable in SM
(with remarkable precision)

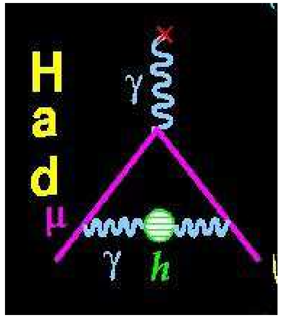


Courtesy: L. Roberts

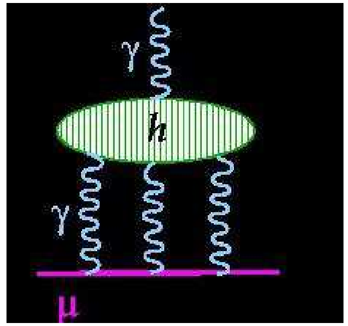
Standard Model Theory Status







lowest order hadronic

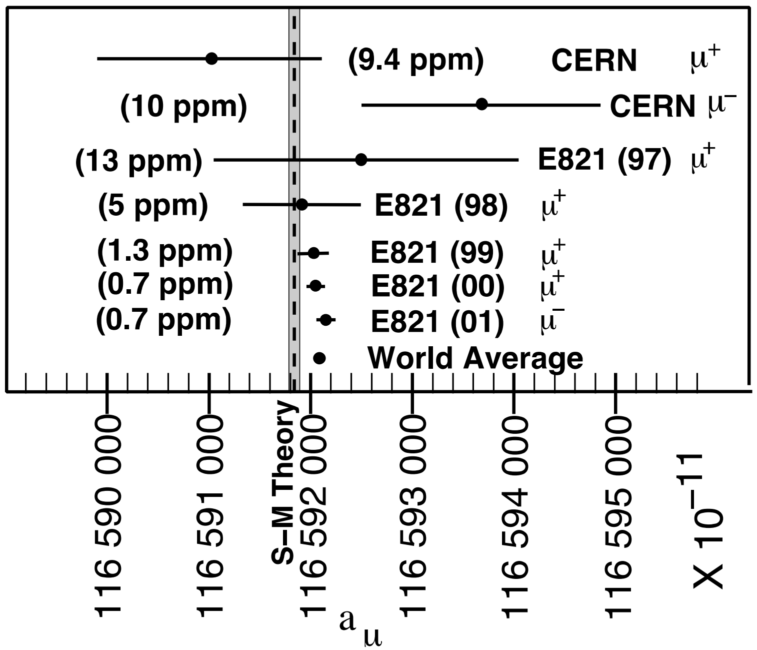


hadronic-light-by-light

well known

significant work ongoing

- International effort continues on the Standard-Model theory value
  - more e^+e^- data for lowest order hadronic contribution (using a dispersion relation)
  - Lattice calculations are underway for both contributions
  - Two photon program at Frascati and BES to help with H-LBL
- **Present difference is between 3 and 4 σ**



cLFV Searches: Current Situation

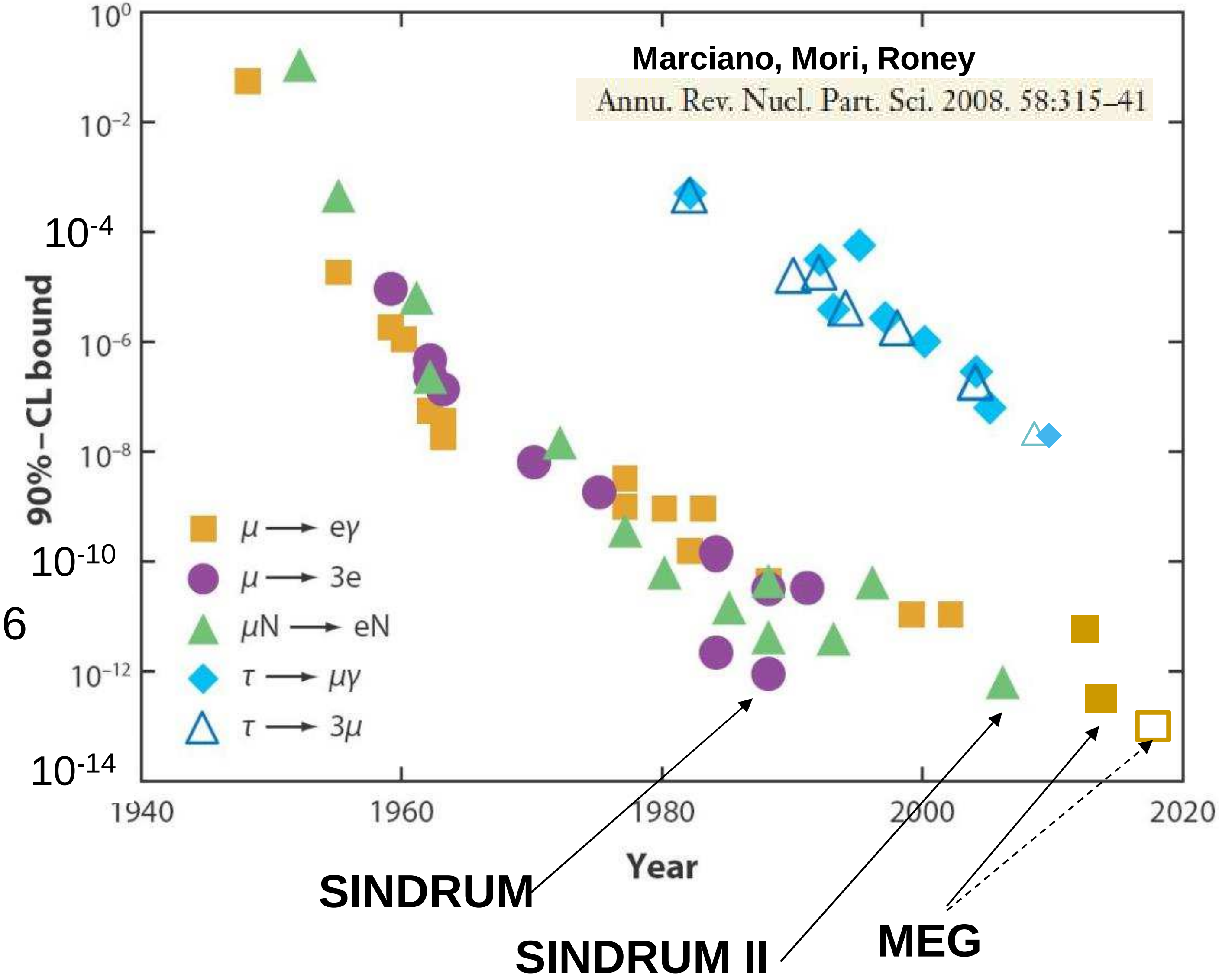
The present best limits on LFV come from PSI muon experiments

$\mu^+ \rightarrow e^+ee$
BR < 1×10^{-12}
SINDRUM 1988

$\mu^- + Au \rightarrow e^- + Au$
BR < 7×10^{-13}
SINDRUM II 2006

$\mu^+ \rightarrow e^+ + \gamma$
BR < 5.7×10^{-13}
MEG 2013

[90 % C.L.]



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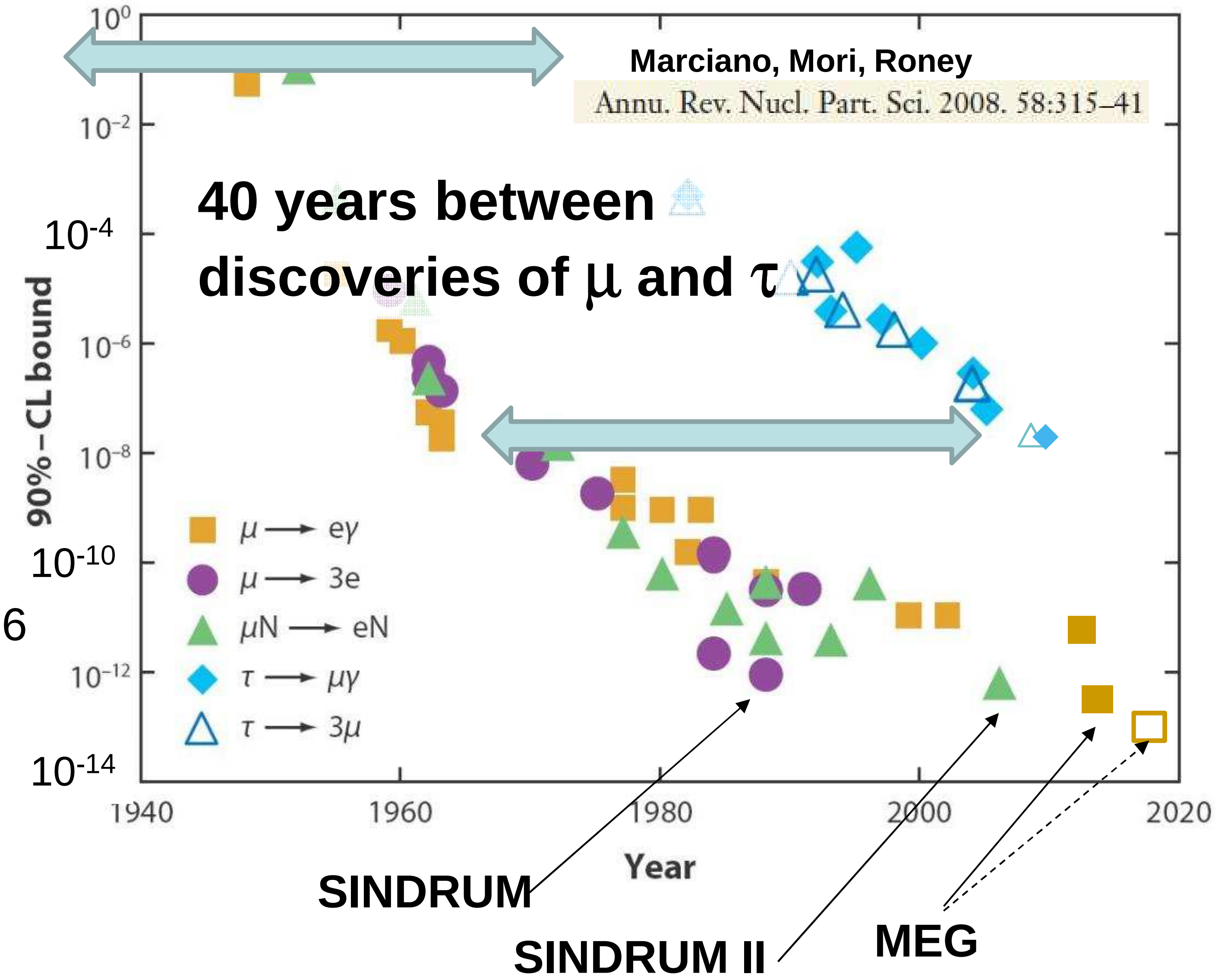
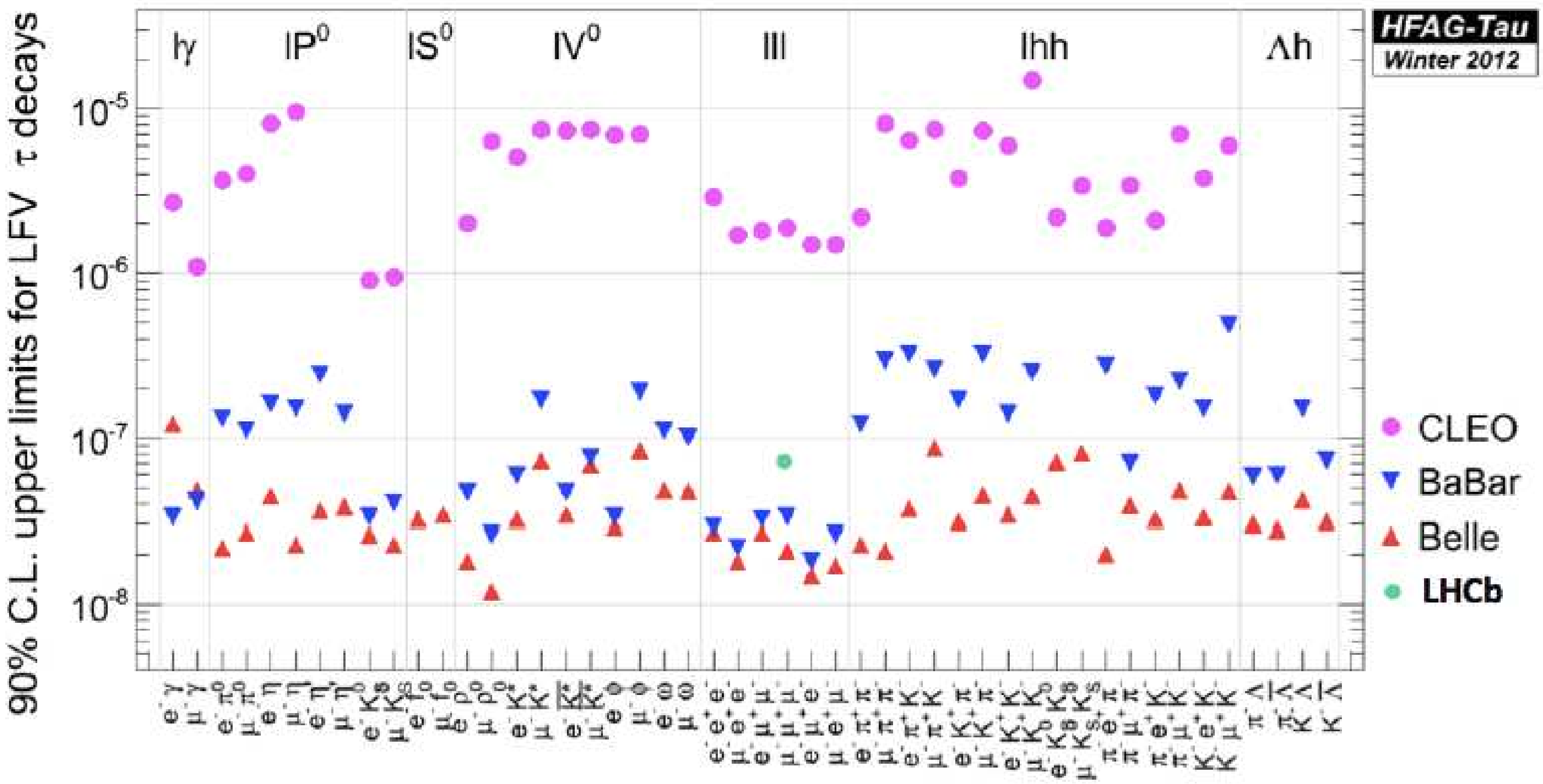


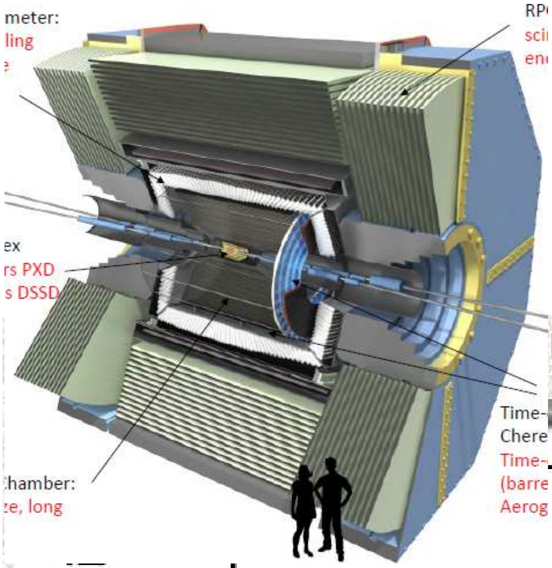
Summary Belle τ LFV results

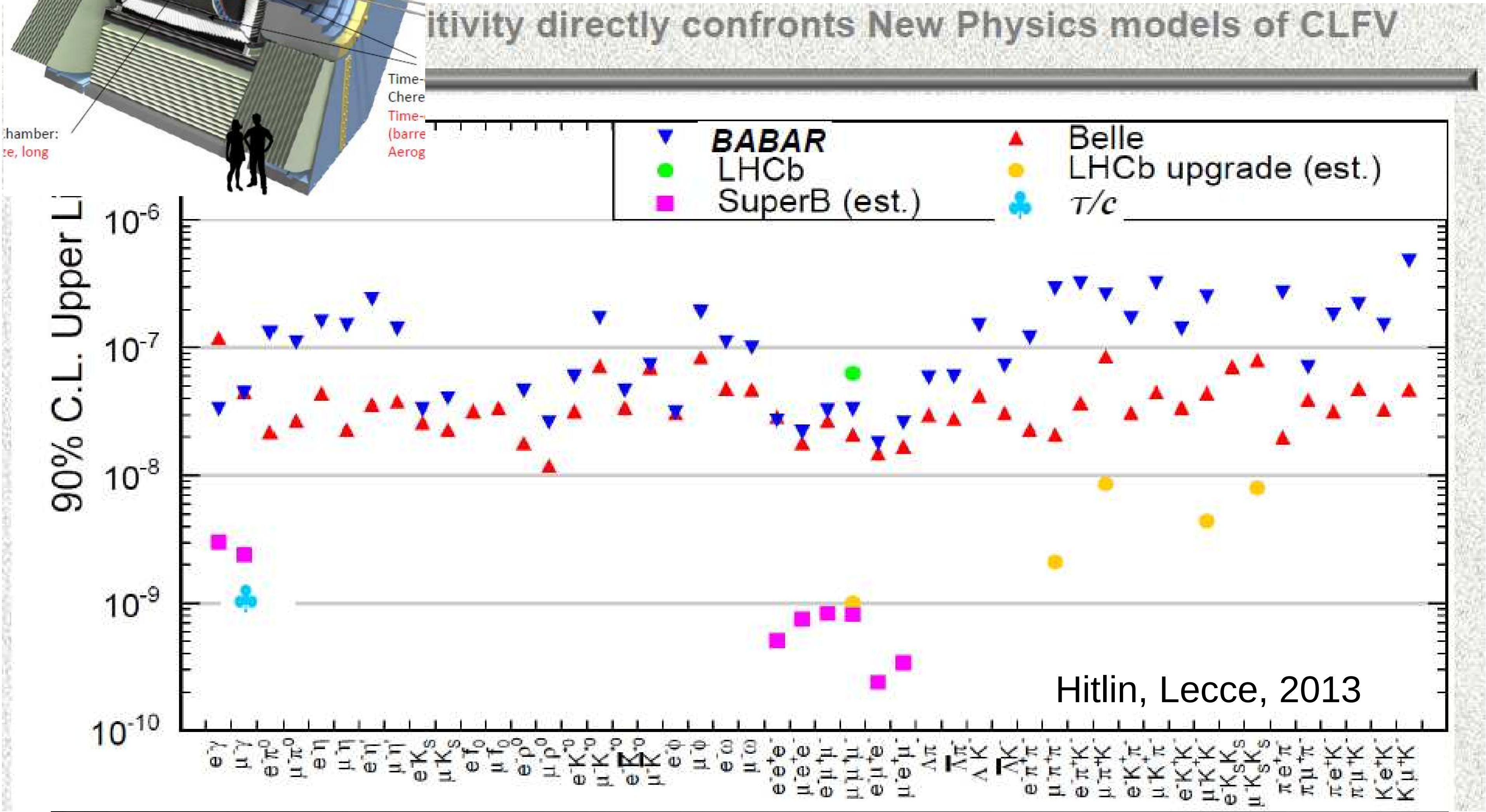


48 modes searched for, U.L.s around $\sim 10^{-8}$

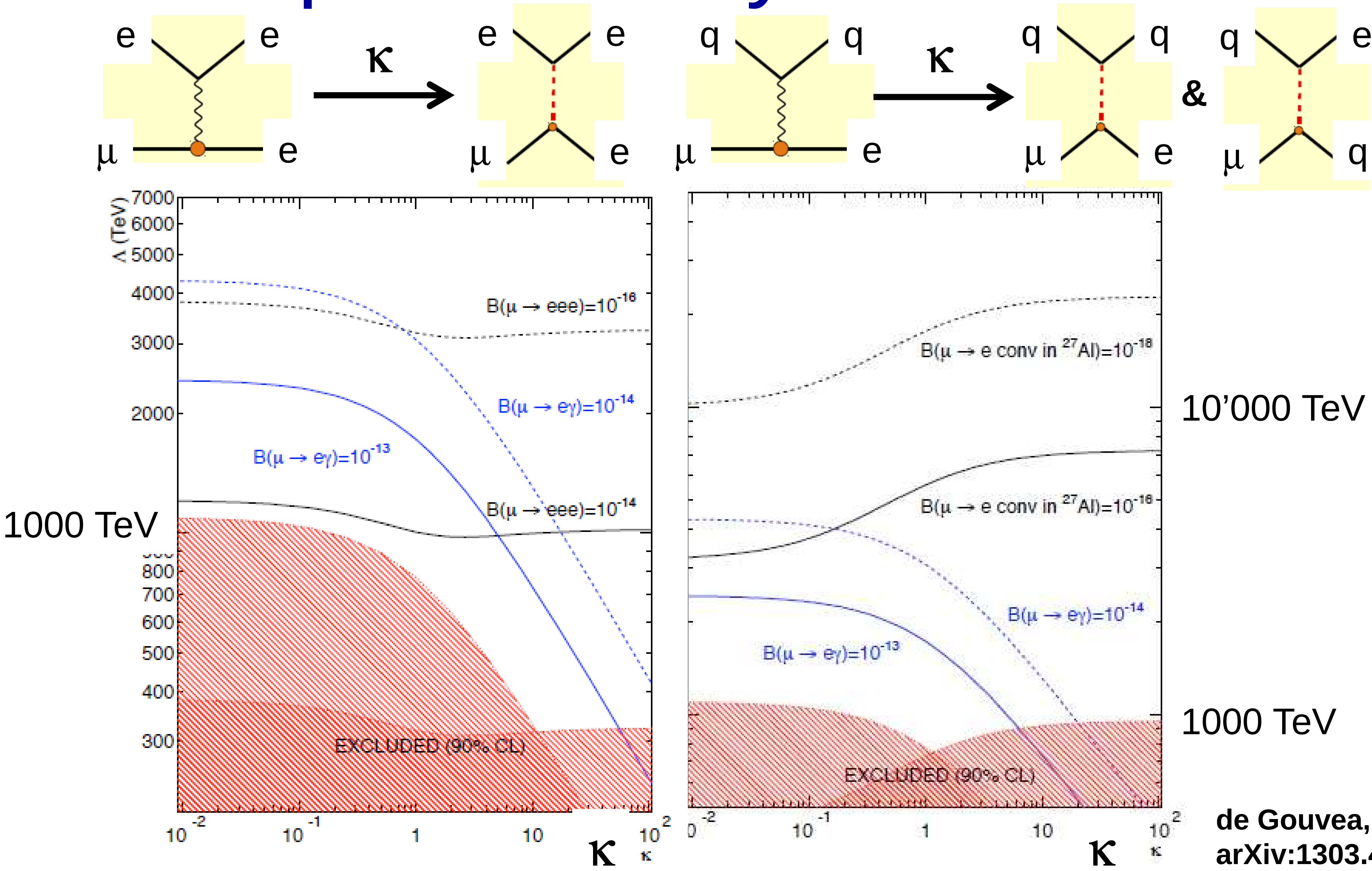
Schwanda, Lecce, 2013

Belle-II and LHCb upgrade



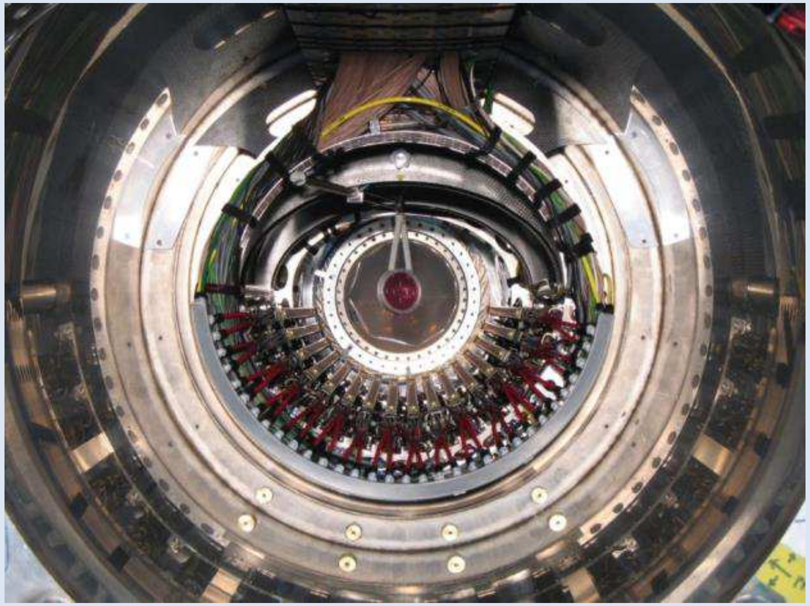


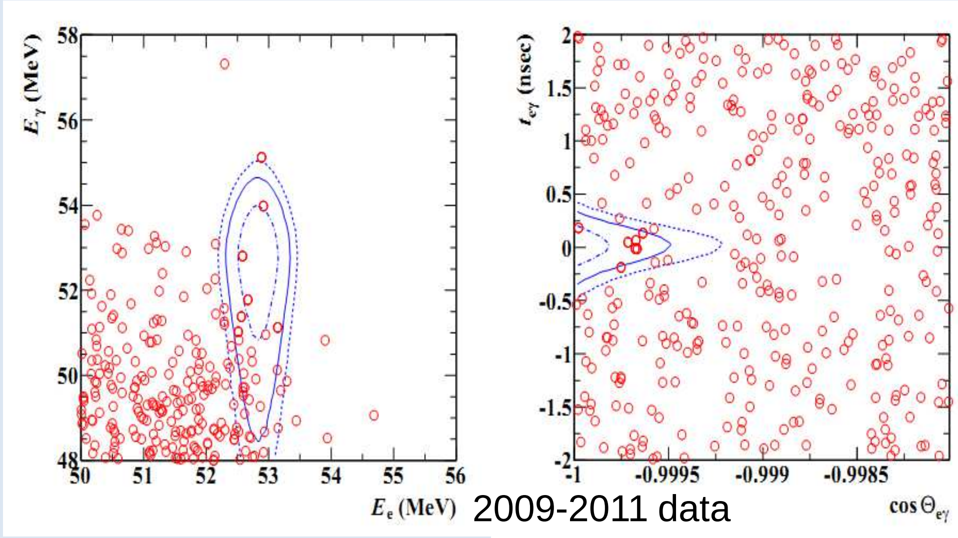
Complementarity in muon cLFV



de Gouvea, Vogel
arXiv:1303.4097

The MEG experiment at PSI (μ->e γ decay search at rest)





2009-2011 data

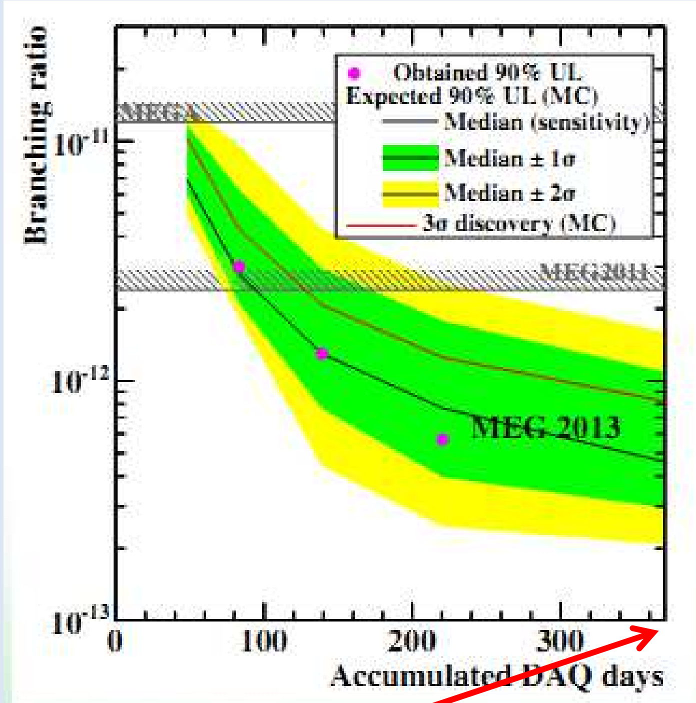
New results ! < 5.7 x 10^{-13} (90% CL)

PRL **110**, 201801 (2013) PHYSICAL REVIEW LETTERS week ending 17 MAY 2013

New Constraint on the Existence of the $\mu^+ \to e^+\gamma$ Decay

TABLE I. Best fit values ($\mathcal{B}_{fit}$'s), branching ratios ($\mathcal{B}_{90}$) and sensitivities ($\mathcal{S}_{90}$).

Data set	$\mathcal{B}_{fit} \times 10^{12}$	$\mathcal{B}_{90} \times 10^{12}$	$\mathcal{S}_{90} \times 10^{12}$
2009–2010	0.09	1.3	1.3
2011	−0.35	0.67	1.1
2009–2011	−0.06	0.57	0.77

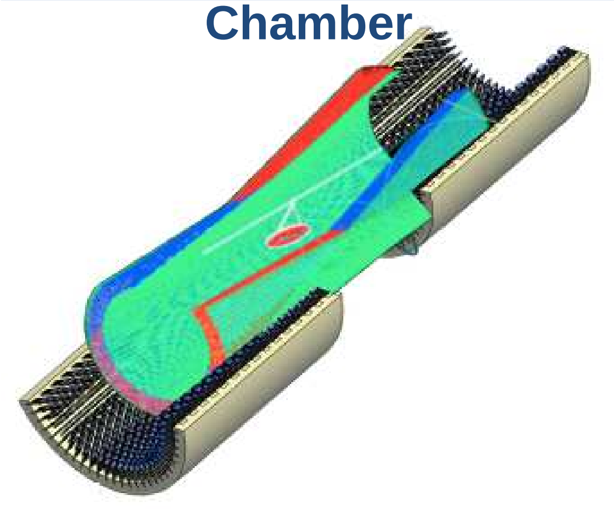


Courtesy: A. Baldini

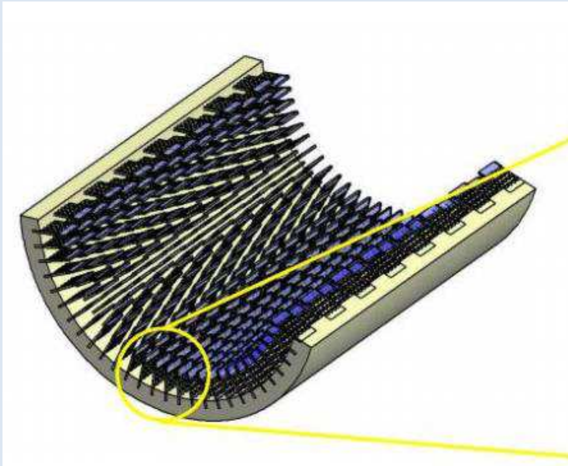
End of data taking: September this year

The MEG UPgrade project (approved)

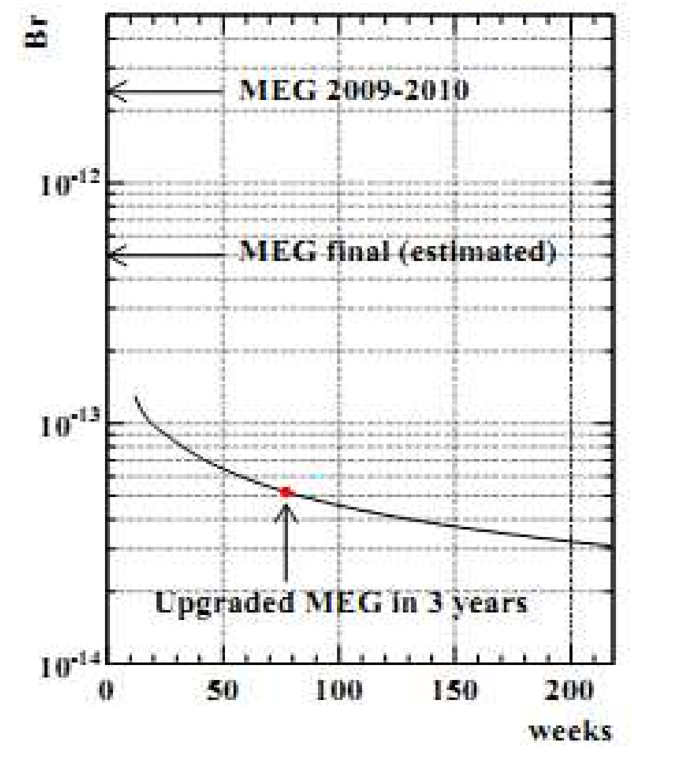
New positron Drift Chamber



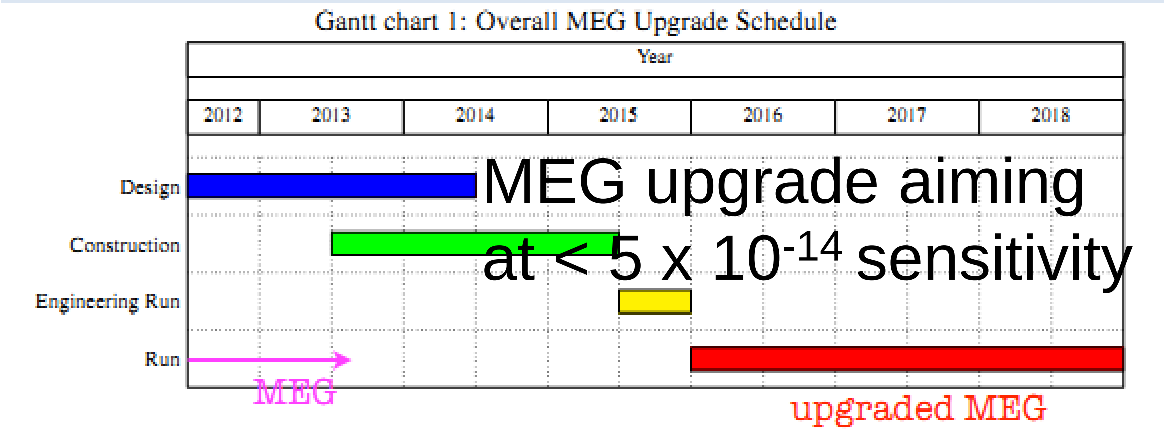
New positron Timing counter



Smaller photosensors for the photon detector



Further: improved electronics and full exploitation of the PSI muon beam intensity



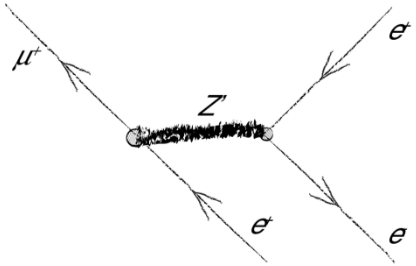
MEG upgrade aiming at < 5 x 10^{-14} sensitivity

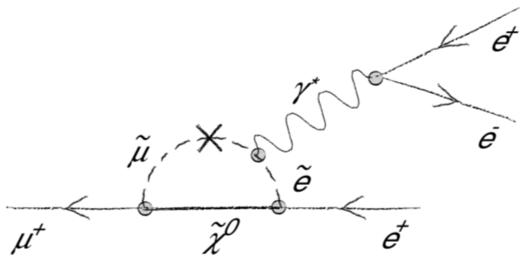
Courtesy: A. Baldini

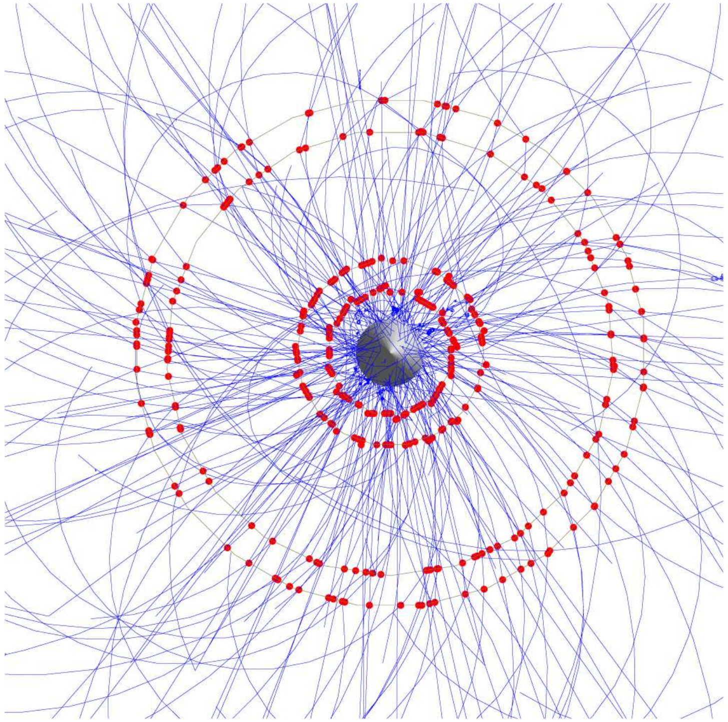
Mu3e Experiment at PSI

Experiment:

- Search for LFV decay: μ → eee
- Single event sensitivity better than 10^{-16}
- Muon rate $>10^9$ per second
- 100 electron tracks within 50ns

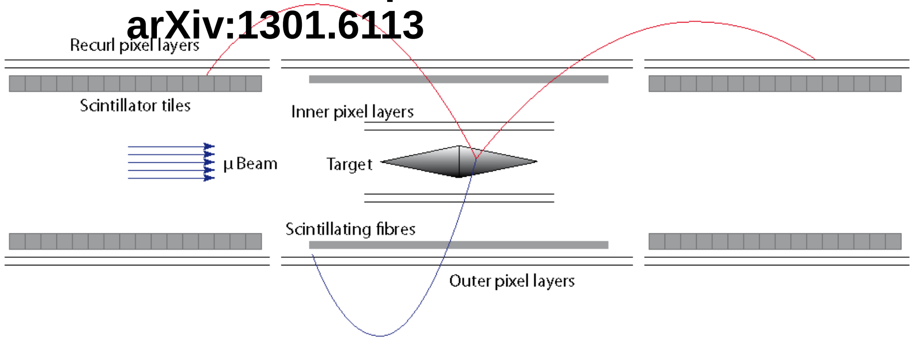






all silicon HV-MAPS silicon detector

Research Proposal: arXiv:1301.6113

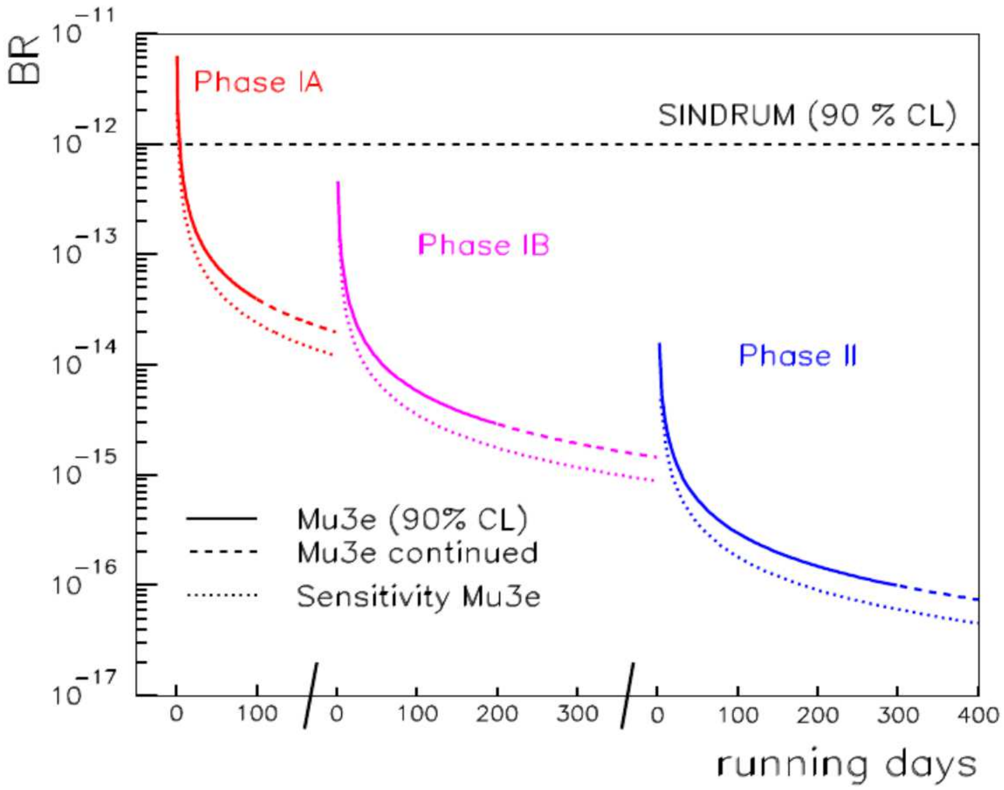


Courtesy: A. Schoening

Detector Requirements:

- good momentum resolution (B=1 T)
- good vertex resolution (→ accidentals)
- good timing resolution (→ accidentals)

Mu3e Experiment at PSI



Mu3e Schedule:

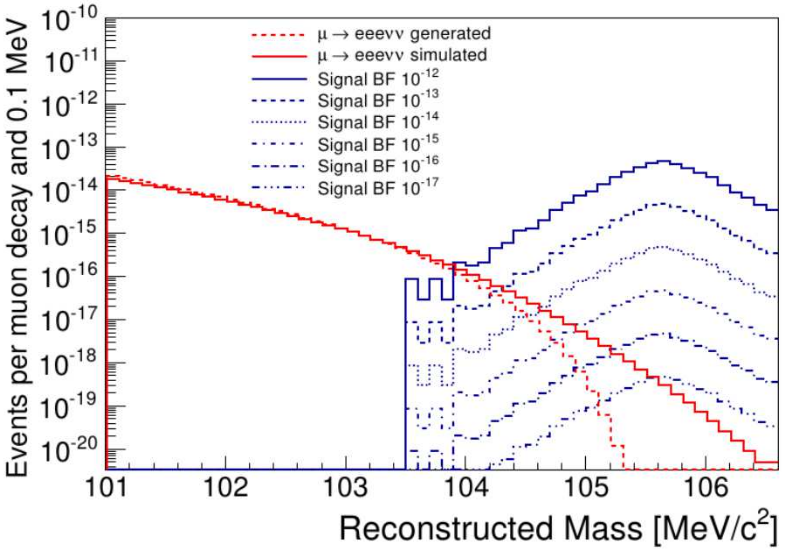
>2012 prototyping

>2014 construction

>2015 first measurements (phase I)

>2017 full experimental setup (phase II)

Mu3e Phase 2 sensitivity:



- Phase 2 requires installation of the proposed HiMB High Intensity Muon Beamline at PSI to provide muon rates > $2 \cdot 10^9$ per second

Courtesy: A. Schoening

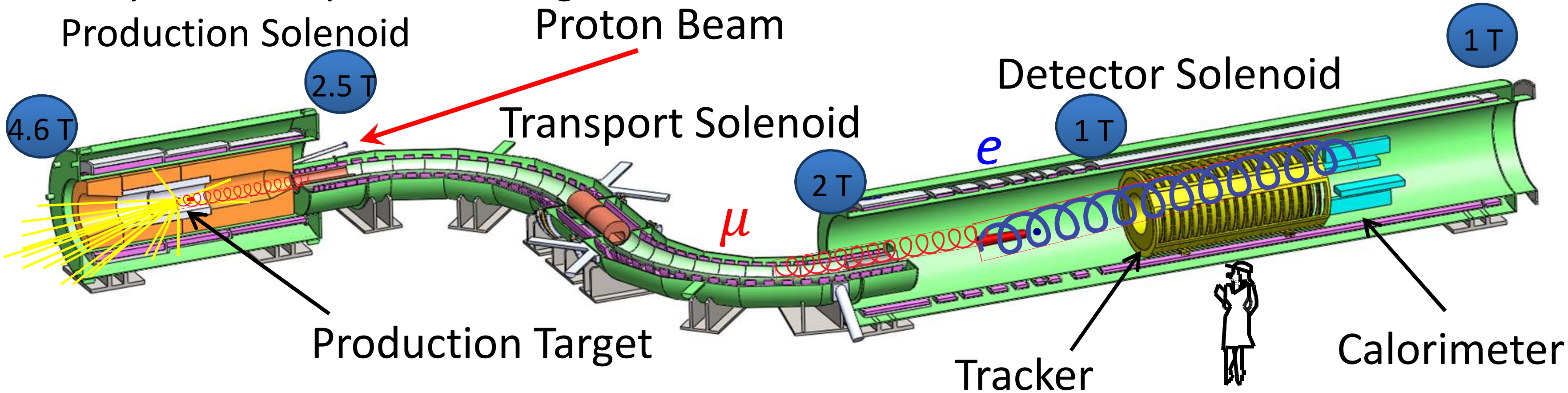
Mu2e at FNAL

Starts with FNAL Booster; upgrades at Project X

X10,000 improvement over previous measurements

mu2e.fnal.gov

System of superconducting solenoids and world's most intense muon beam

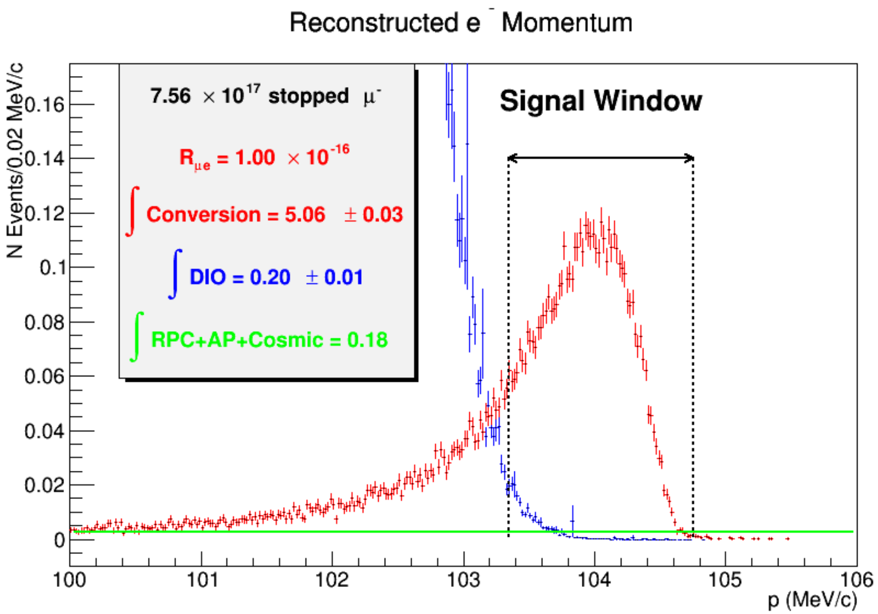


- **Charged Lepton Flavor Violation: Search for $\mu N \rightarrow eN$ at 6×10^{-17}**
  - Quarks and neutrinos violate flavor: why don't the charged leptons?
  - Uniquely sensitive to both SUSY and non-SUSY new physics
  - Complements LHC and probes mass scales to 10^4 TeV/c^2
  - A powerful discriminator among models
- **Prototyping of Detector and Tests of Superconducting Cable Underway**
- **Civil Construction to start late 2014**
- **Physics data-taking to start early 2020 for 2-3 years**

Courtesy: R. Bernstein

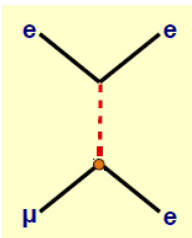
Mu2e Signal Sensitivity

Full G4 detector simulation, background overlay, reconstruction

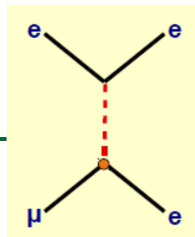


Source	Events
Anti-proton capture	0.1 ± 0.06
Radiative π^- capture	0.04 ± 0.02
Beam electrons	0.001 ± 0.001
μ decay in orbit	0.2 ± 0.06
Cosmic ray induced	0.025 ± 0.025
μ decay in flight	0.01 ± 0.005
Total	0.4 ± 0.1

$$R_{\mu e}\ \text{SES} = 2 \times 10^{-17}$$



&



Courtesy: R. Bernstein

COMET (I<10^{-14}; II < 10^{-16})

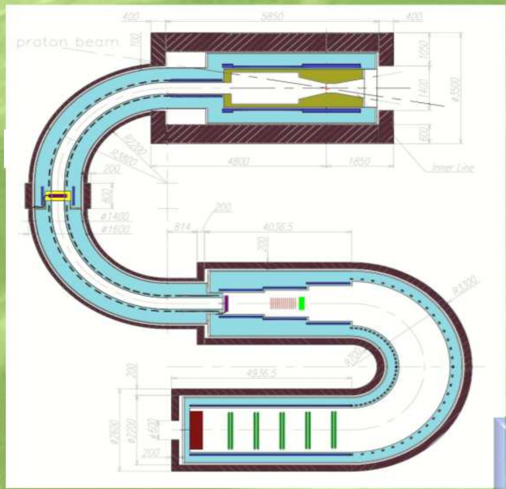
Search for muon to electron conversion

Adopted staging approach

Phase-I: < 10^{-14}

Phase-II: < 10^{-16}

Budget for phase-I is approved !! to start the measurement in 2016.



DeeMe (Br<10^{-14})

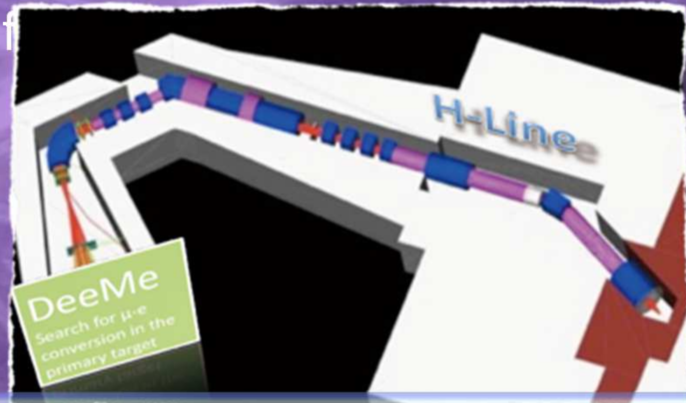
Search for muon to electron conversion

Share H-Line at MLF with g-2/EDM

Partially f

from

TRIUMF



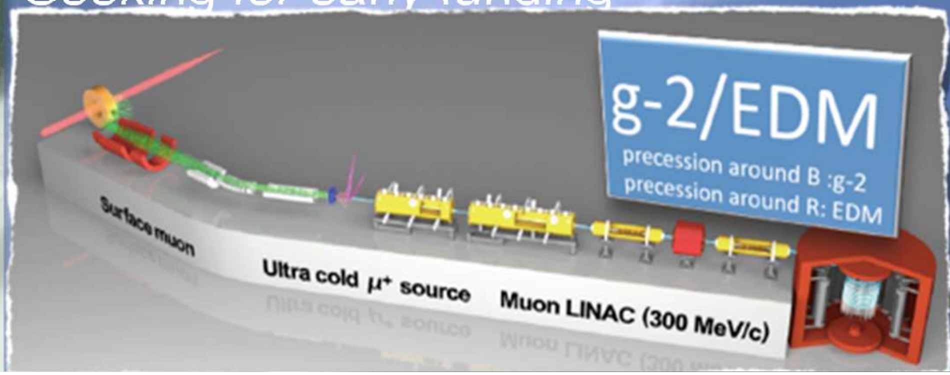
g-2/EDM (0.1ppm/10^{-21} e cm)

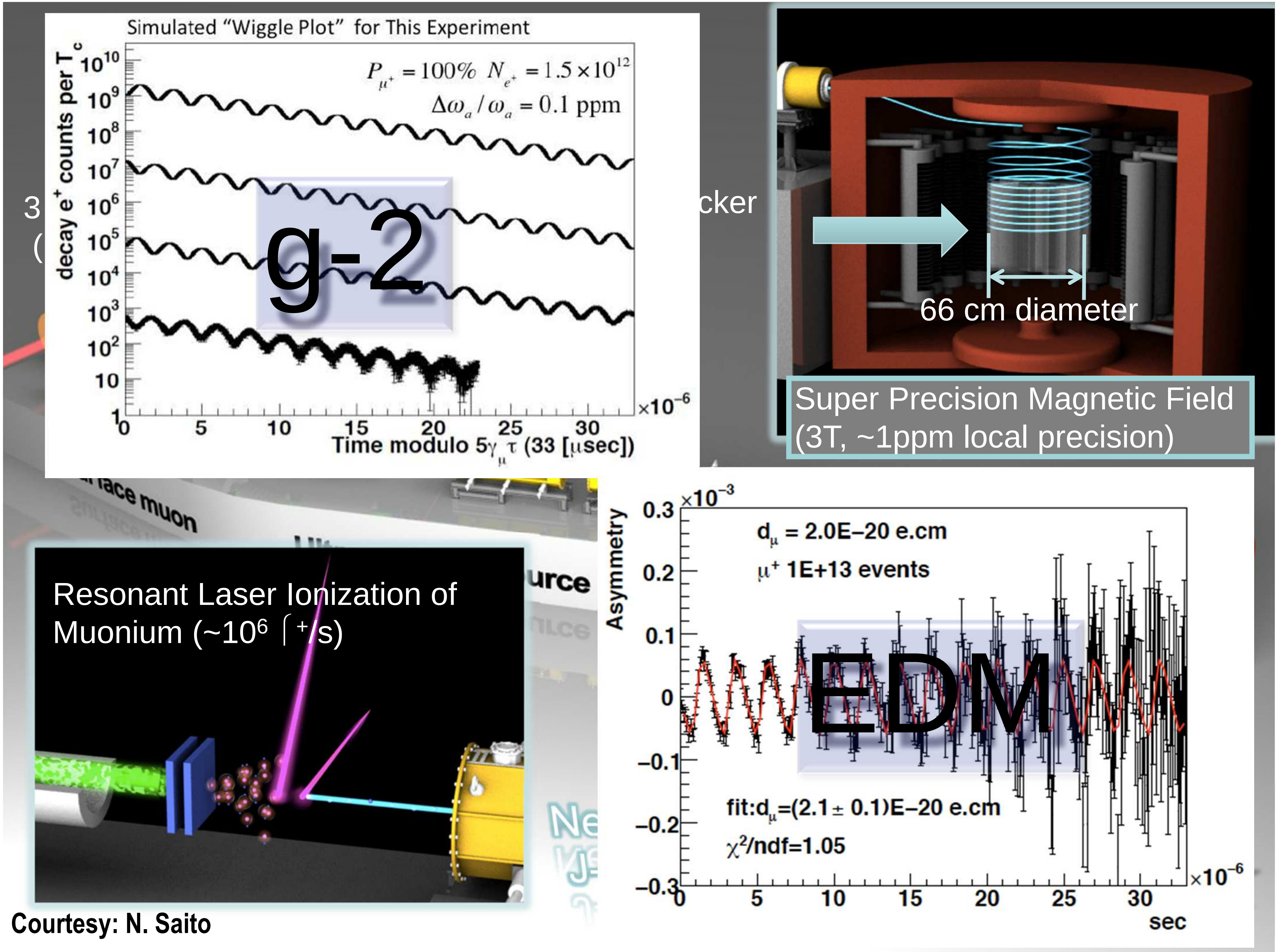
Ultra-Cold Muon Beam

Ultra-Precision Magnetic Field

g-2 and EDM SIMULTANEOUSLY !!

Seeking for early funding

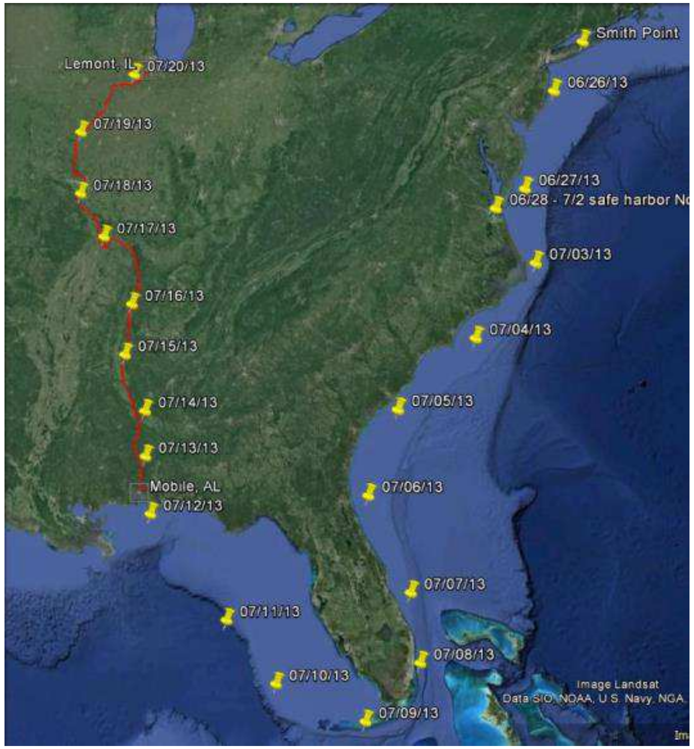



Simulated "Wiggle Plot" for This Experiment
$P_{\mu^+} = 100\%$ $N_{e^+} = 1.5\times10^{12}$
$\Delta\omega_a/\omega_a = 0.1$ ppm
decay e+ counts per T_c
Time modulo $5\gamma_\mu\tau$ (33 [μsec])
g-2
66 cm diameter
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Resonant Laser Ionization of
Muonium (~10^6 ⌠+/s)
d_μ = 2.0E−20 e.cm
μ^+ 1E+13 events
fit:d_μ=(2.1 ± 0.1)E−20 e.cm
χ^2/ndf=1.05
Asymmetry
sec
EDM
Courtesy: N. Saito

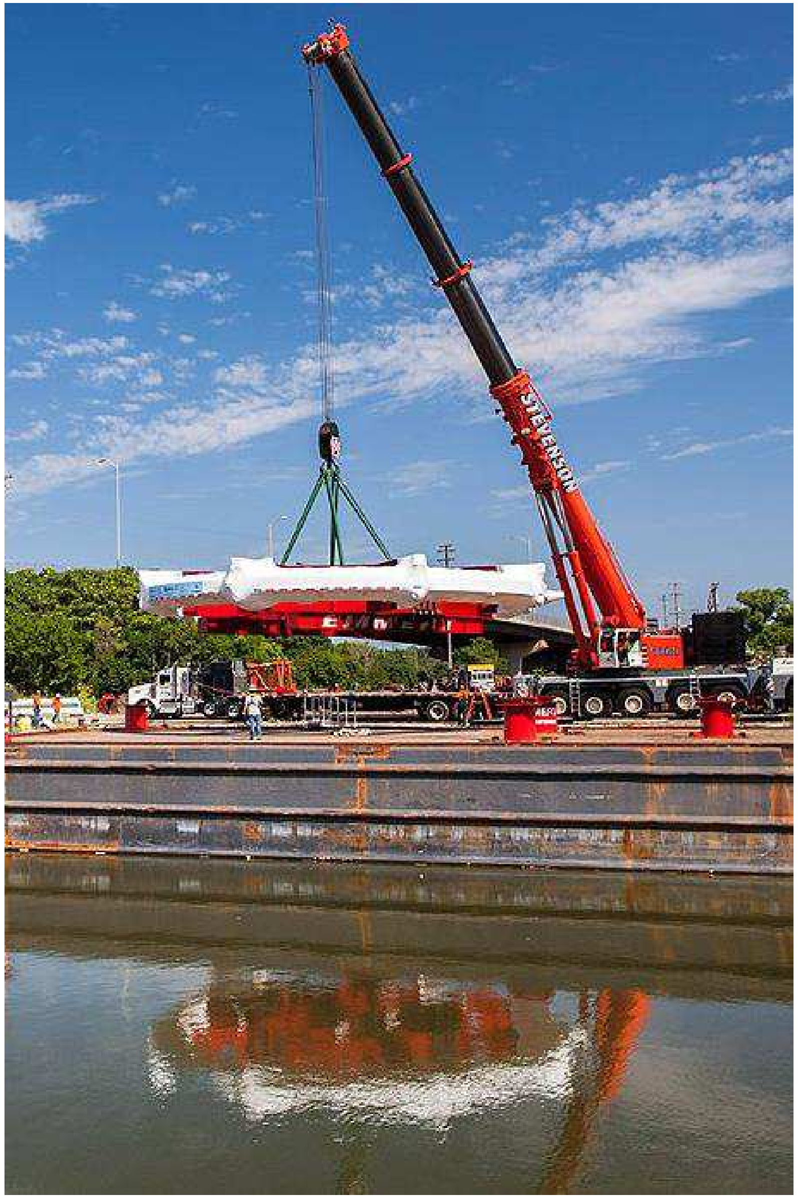
Courtesy: L. Roberts

FNAL muon g-2 status

- Superconducting coils are now in Illinois, will arrive at Fermilab on Friday 26/7
- Building under construction
- Half the steel is at Fermilab



http://muon-g-2.fnal.gov/bigmove/



Unloading the barge in Lemont Illinois

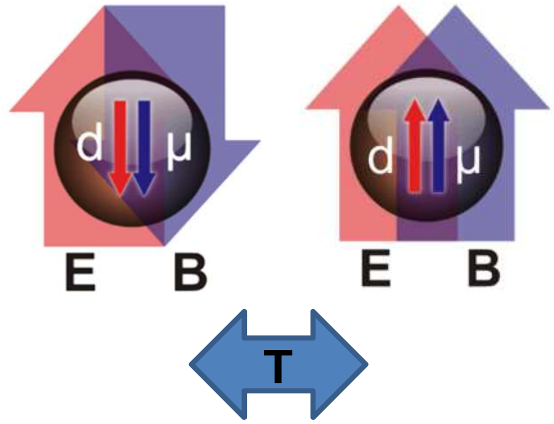
Courtesy: L. Roberts

Timeline

- Building completed 1/2014
- Remaining steel will arrive just after the building is complete
- Re-assembly will take between 12-18 months
- Ring together and powered early 2015
  - magnet shimming expected to take 6 to 12 months
- Beamline construction begins in 2015
- **Data collection 2016**

EDM Searches: Current Situation

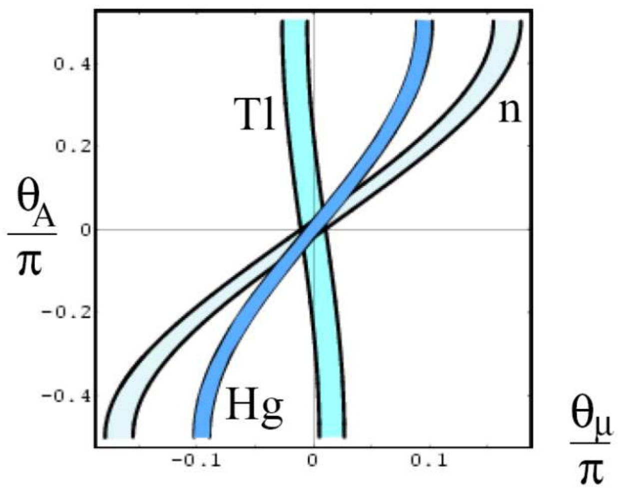
- neutron **d_n < 2.9 x 10^{-26} e cm** PRL97(2006)131801
- Hg-199 **d_{Hg} < 3.1 x 10^{-29} e cm** PRL102(2009)101601
  → d_p < 8 x 10^{-25} e cm*
- Xe-129 d_{Xe} < 6 x 10^{-27} e cm PRL86(2001)22
- Tl-205 d_{Tl} < 9 x 10^{-25} e cm
  → d_e < 1.6 x 10^{-27} e cm* PRL88(2002)071805
- YbF → **d_e < 1.05 x 10^{-27} e cm*** Nature473(2011)493
- muon d_μ < 1.8 x 10^{-19} e cm PRD80(2009)052008



* using the ‚1-miracle assumption‘, i.e. no cancelations with other CP-odd effects.

Only for one fundamental fermion, the muon, a direct EDM-limits exist.

Many people consider the neutron almost fundamental -- so we may perhaps count two direct basic EDM limits.



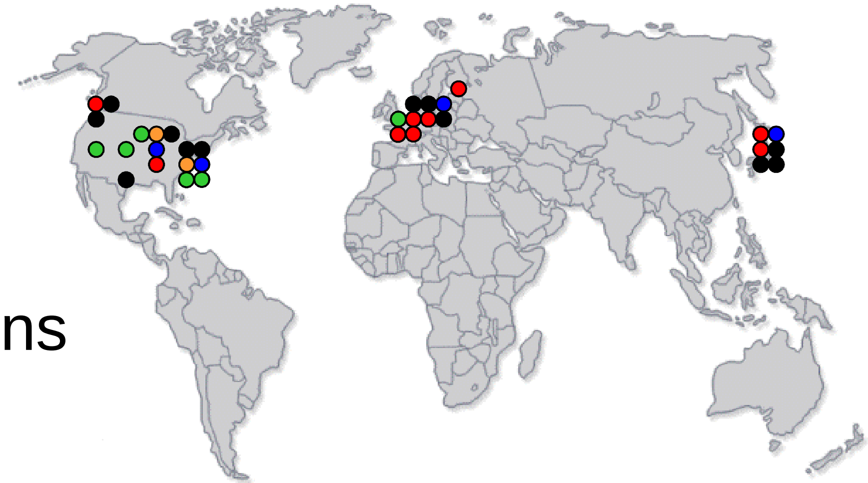
Pospelov, Ritz, Ann. Phys. 318(2005)119
for M_{SUSY} = 500GeV, tan β = 3

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@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



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

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

In conclusion: experiments with unique reach

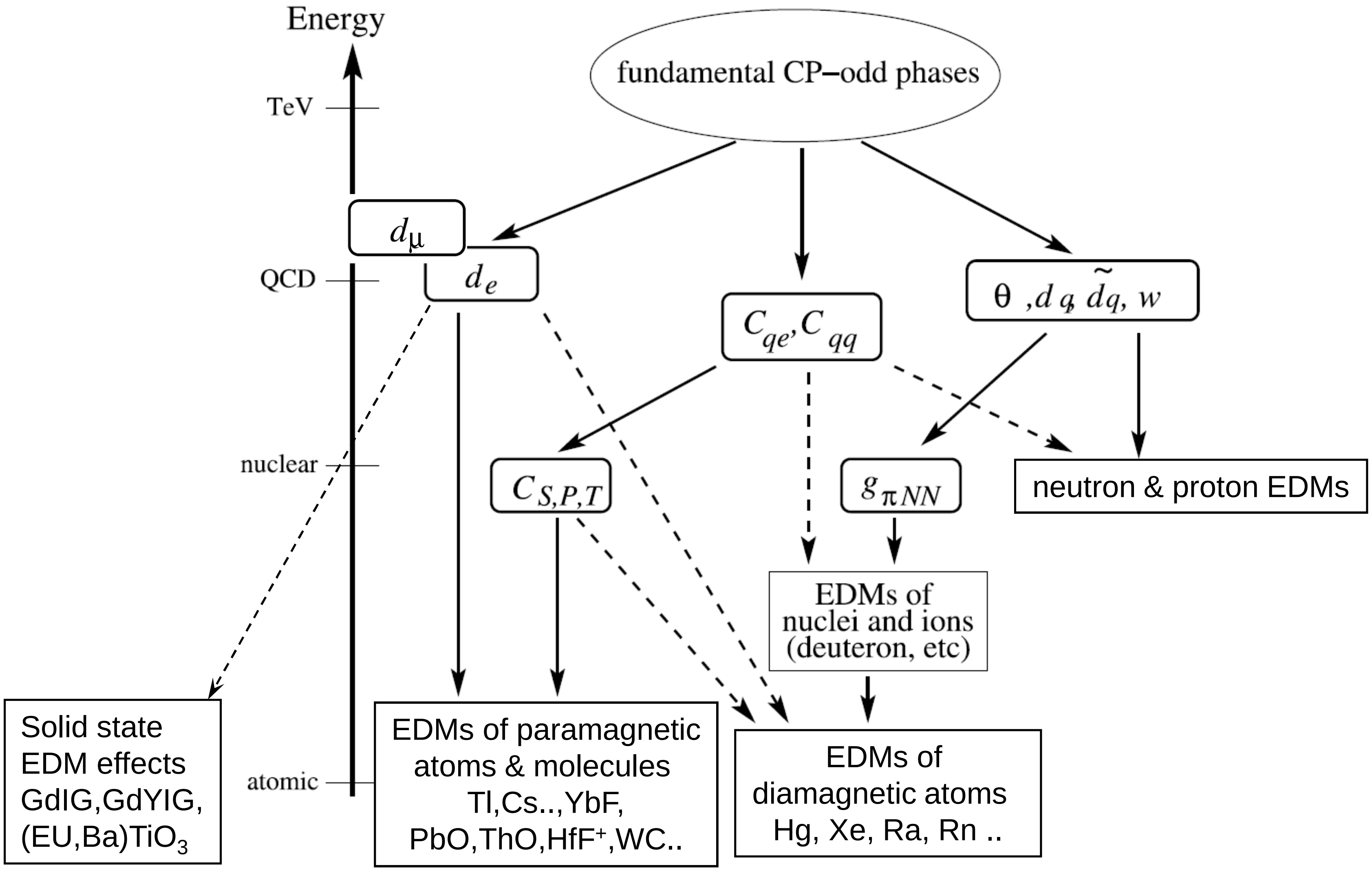
- cLFV with taus will be boosted with Belle-II and LHCb upgrade **→10^{-9}**
- cLFV with muons will see a major step forward in the next years @PSI, J-PARC, FNAL **→$5x10^{-14}$,10^{-16},$10^{-14...18}$**
- muon g-2 will be improved @FNAL, J-PARC (need experiment and theory) **→ 0.1 ppm**
- many EDM experiments around the world hold promise for improved sensitivities

  →n< $5x10^{-28}$ecm, e< 10^{-28}ecm, Hg< $5x10^{-30}$ecm, p< $5x10^{-29}$ecm ….

- Need more work on consistent theoretical framework for relevant and more global comparisons of HE and LE

Backup

Origin of EDMs



Adapted from:
Pospelov, Ritz, Ann. Phys. 318 (2005) 119
M. Raidal et al., Eur. Phys. J. C 57 (2008) 13

Complex composite systems have constituents and interactions

Paramagnetic atoms

$$d_{\text{para}}(d_e) \sim 10\alpha^2 Z^3 d_e \Longrightarrow d_{\text{Tl}} = -585 d_e - 43\ \text{GeV} \times e\, C_S^{\text{singlet}}$$ enhancement

Paramagnetic molecules

additional enhancement from large internal electric fields of order 10 GV/cm or more, influenced by molecular level structure

Diamagnetic atoms

$$d_{\text{dia}} \sim 10 Z^2 (R_N/R_A)^2 \tilde{d}_q$$ suppression of order 10^3

$$\Longrightarrow d_{\text{Hg}} = 7 \times 10^{-3}\, e\,(\tilde{d}_u - \tilde{d}_d) + 10^{-2}\, d_e + \mathcal{O}(C_S, C_{qq})$$

enhancement factors possible due to atomic state mixing and nuclear deformation.

International context (nEDMs)

Project	Goal (en *e*.cm)	Result expected
nEDM@PSI n2EDM@PSI	~ 5 x 10^{-27} ~ 5 x 10^{-28}	2014 2020
PNPI@ILL	~ 1 x 10^{-26}	2014
CryoEDM@ILL	~ 3 x 10^{-27}	2016
nEDM@SNS	~ 3 x 10^{-28}	2020
nEDM@TRIUMF	~ 3 x 10^{-27} ~ 1 x 10^{-28}	2017 2020
nEDM@TUM	~ 5 x 10^{-28}	2018

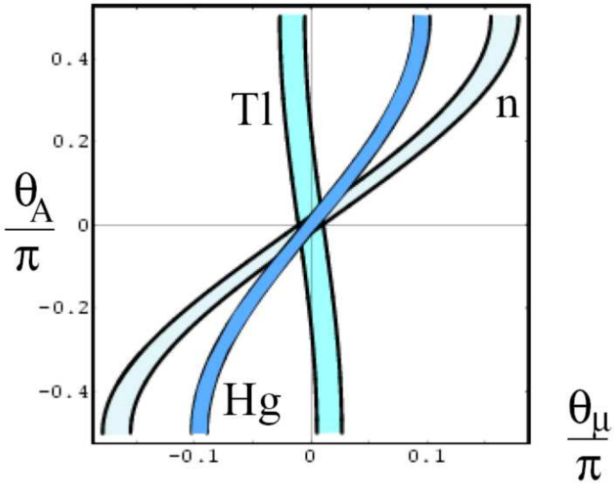
The SUSY CP problem

(for neutron and electron!)

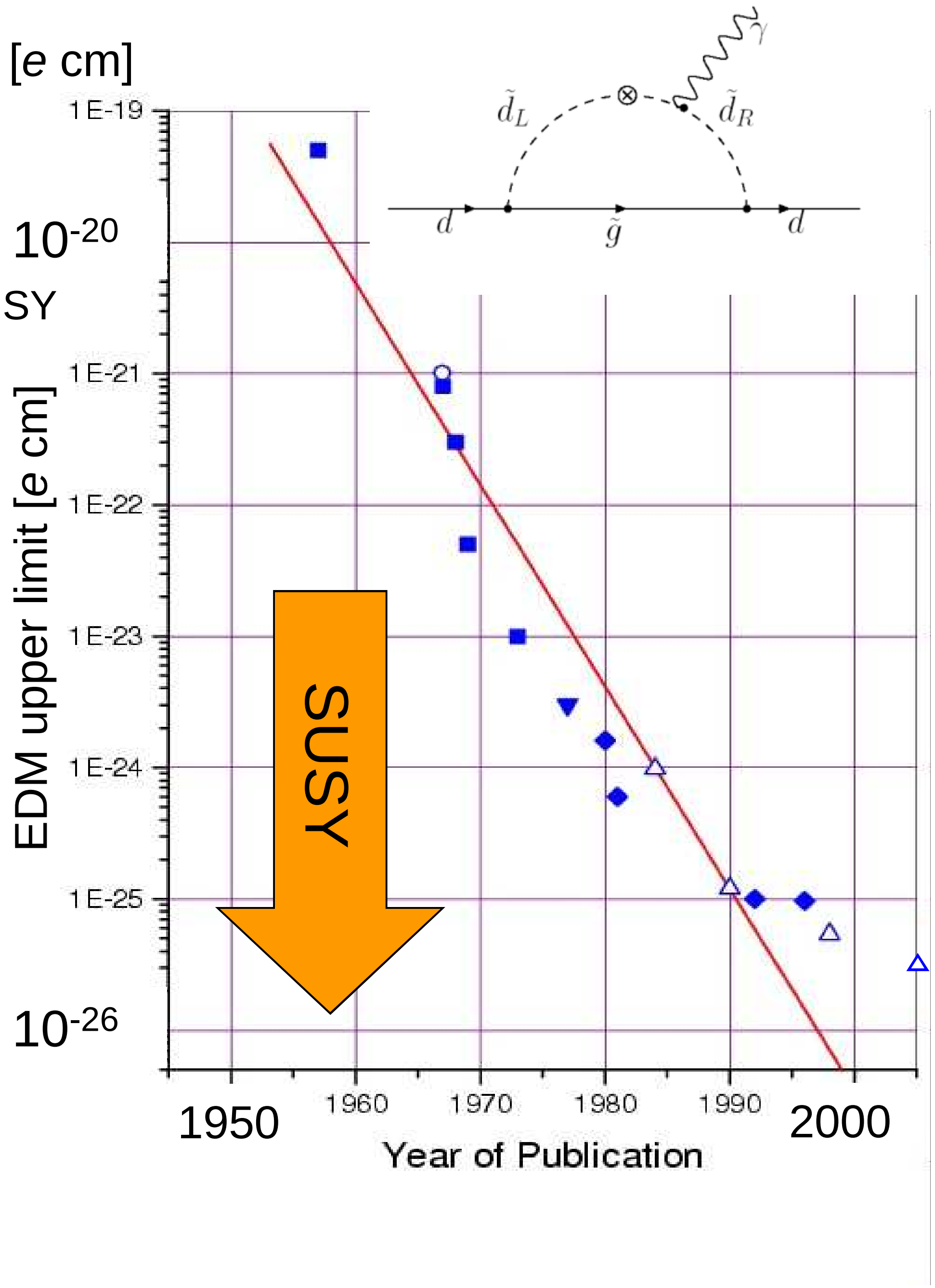
$$d_n \approx 10^{-23}\, e\text{ cm} \left(\frac{300\text{ GeV/c}^2}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

Why is ϕ_{SUSY} so small ?

(this is testing M already to 10TeV and you may also ask: why are the masses so huge?)

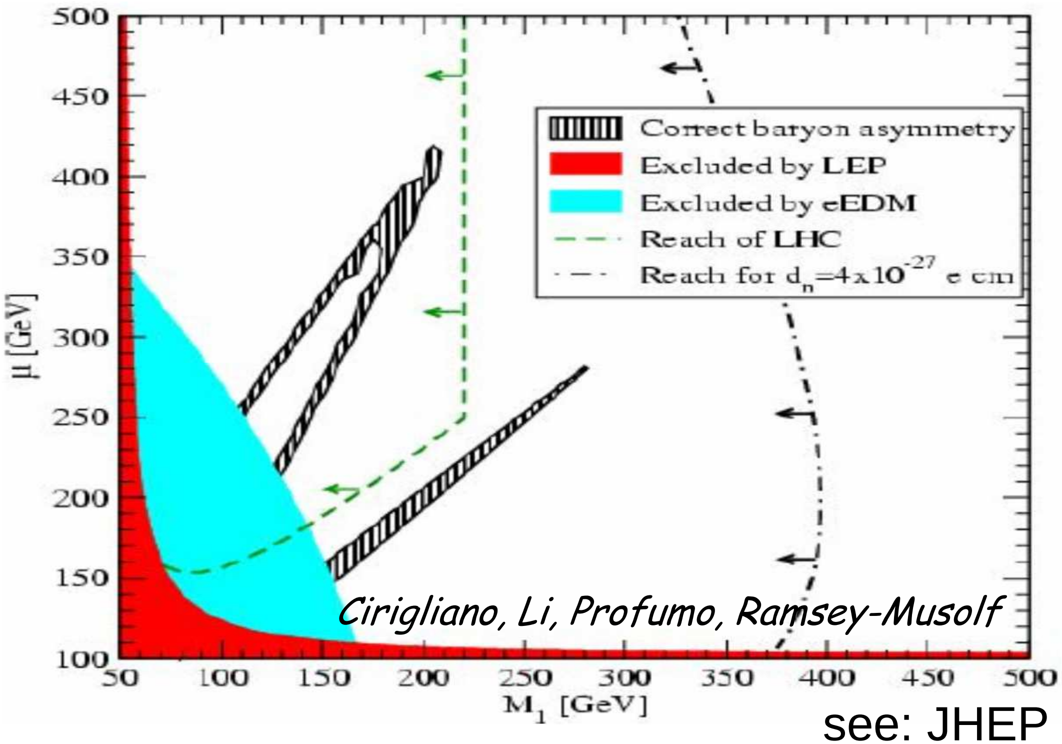


Pospelov, Ritz, Ann. Phys. 318(2005)119
for M_{SUSY} = 500GeV, tan β = 3



Complementarity with high energy:

Electroweak baryogenesis in MSSM



see: JHEP 1001:002,2010

could eventually become completely excluded by LHC plus next generation nEDM

Muon cLFV: Status

Mode	Upper limit (90% C.L.)	Year	Exp./Lab.
$\mu^+ \to e^+\gamma$	5.7×10^{-13}	2013	MEG / PSI
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	1988	SINDRUM I / PSI
$\mu^+e^- \leftrightarrow \mu^-e^+$	8.3×10^{-11}	1999	PSI
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$	6.1×10^{-13}	1998	SINDRUM II / PSI
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^*$	3.6×10^{-11}	1998	SINDRUM II / PSI
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$	4.6×10^{-11}	1996	SINDRUM II / PSI
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	7×10^{-13}	2006	SINDRUM II / PSI

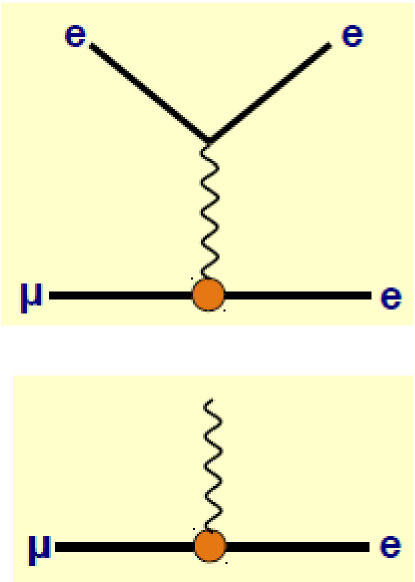
Adapted from:
Raidal, van der Schaaf et al.,
Flavor physics of leptons and dipole moments,
Eur. Phys. J. C 57(2008)13

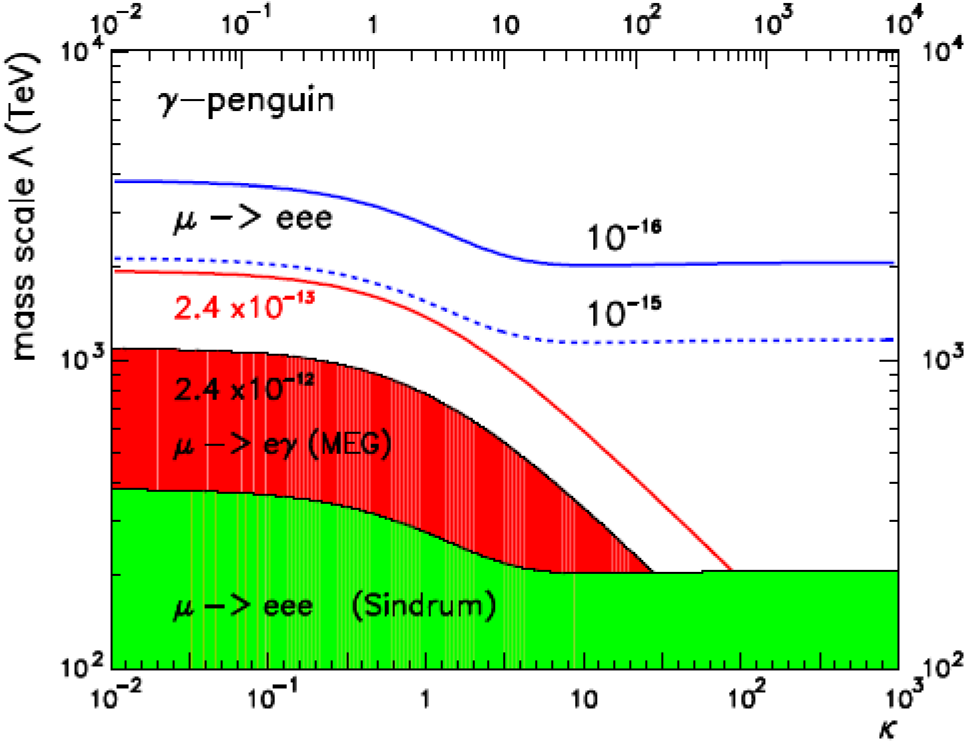
Model Comparison (μ → eγ and μ → eee)

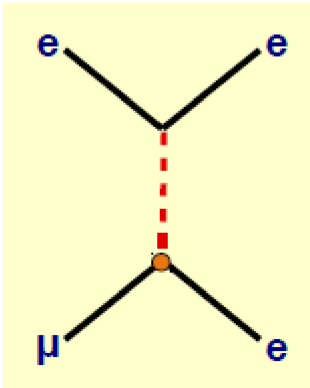
Effective charge LFV Lagrangian ("toy" model) (Kuno and Okada)

$$L = \frac{m_\mu}{\Lambda^2(1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2(1+\kappa)} J_\sigma^{e\mu} J^{\sigma,ee}$$

Λ = effective mass scale
κ = "parameter" of toy model





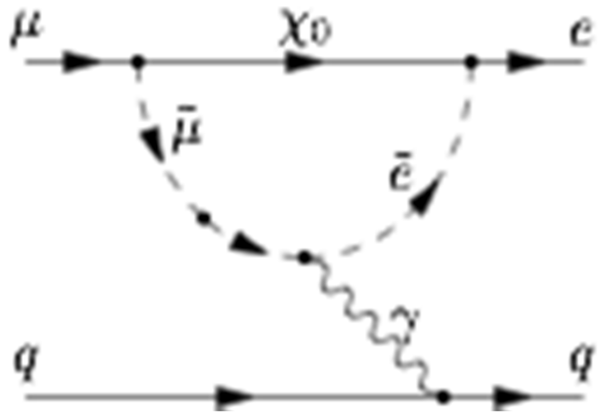


$\kappa \to 0$ $\kappa \to \infty$

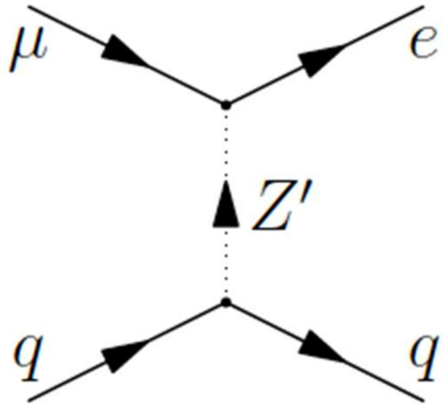
$$\frac{BR(\mu^+ \to e^+e^-e^+)}{BR(\mu^+ \to e^+\gamma)} \sim 0.006$$

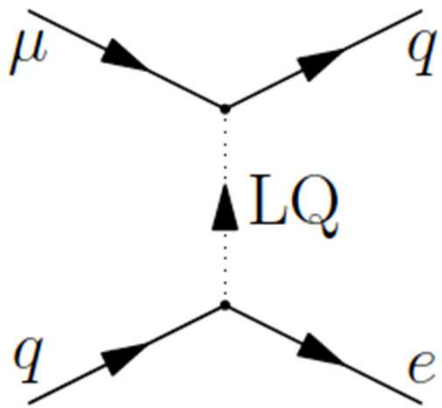
μ→e Conversion

- **'Dipole' terms**
  - i.e. SUSY
  - Also mediates μ→eγ



- **'Contact' terms**
  - Direct coupling between quarks and leptons
  - Only accessible by μN→eN





- **Effective Lagrangian**
  - contact κ, mass scale Λ

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu} R \sigma_{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma^\mu q_L$$

R. Bernstein

Table 4 Bounds at 90% CL on selected lepton flavor violating decays of pseudoscalar mesons

Channel	Upper limit	Experiment	Reference
$\pi^0 \to \mu^\pm e^\mp$	3.59×10^{-10}	KTeV	75
$\eta \to \mu^\pm e^\mp$	6×10^{-6}	Saturne SPES2	76
$K_L^0 \to \pi^0\mu^\pm e^\mp$	7.56×10^{-11}	KTeV	75
$K_L^0 \to 2\pi^0\mu^\pm e^\mp$	1.64×10^{-10}	KTeV	75
$K_L^0 \to \mu^+ e^-$	4.7×10^{-12}	BNL E871	74
$K^+ \to \pi^+\mu^+ e^-$	1.3×10^{-11}	BNL E865, E777	73
$D^+ \to \pi^+\mu^\pm e^\mp$	3.4×10^{-5}	Fermilab E791	77
$D^+ \to K^+\mu^\pm e^\mp$	6.8×10^{-5}	Fermilab E791	77
$D^0 \to \mu^\pm e^\mp$	8.1×10^{-7}	BaBar	78
$D_s^+ \to \pi^+\mu^\pm e^\mp$	6.1×10^{-4}	Fermilab E791	77
$D_s^+ \to K^+\mu^\pm e^\mp$	6.3×10^{-4}	Fermilab E791	77
$B^0 \to \mu^\pm e^\mp$	9.2×10^{-8}	BaBar (347 fb^{-1})	79
$B^0 \to \tau^\pm e^\mp$	1.1×10^{-4}	CLEO (9.2 fb^{-1})	80
$B^0 \to \tau^\pm \mu^\mp$	3.8×10^{-5}	CLEO (9.2 fb^{-1})	80
$B^+ \to K^+ e^\pm \mu^\mp$	9.1×10^{-8}	BaBar (208 fb^{-1})	81
$B^+ \to K^+ e^\pm \tau^\mp$	7.7×10^{-5}	BaBar (348 fb^{-1})	82
$B_s^0 \to e^\pm \mu^\mp$	6.1×10^{-6}	CDF (102 pb^{-1})	83

Marciano, Mori, Roney

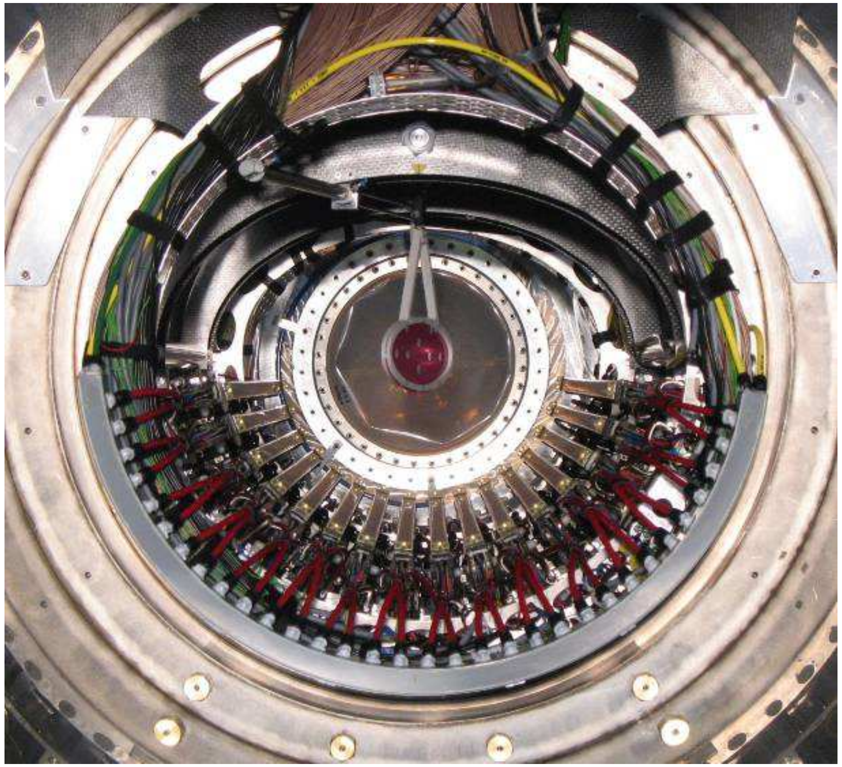
Annu. Rev. Nucl. Part. Sci. 2008. 58:315–41

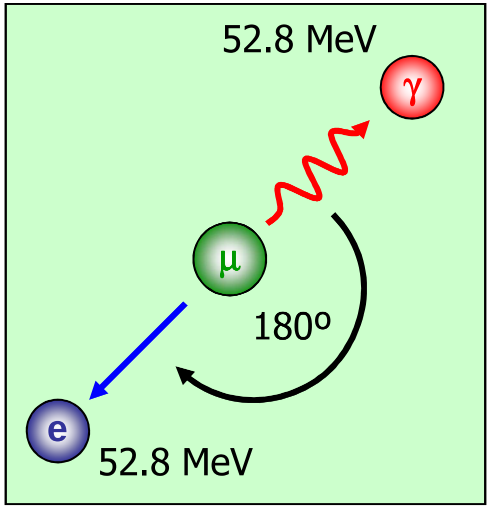
Searching for μ→eγ :

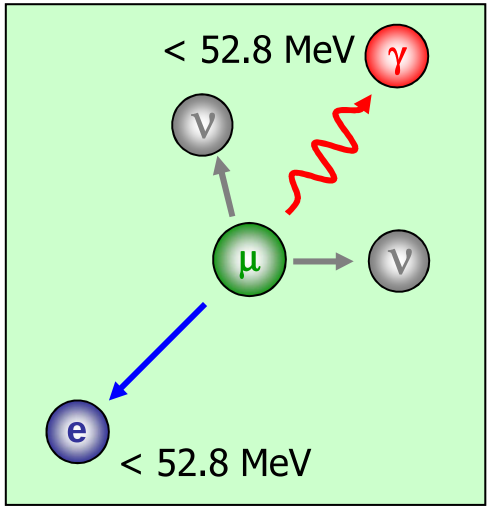
MEG collaboration

< 5.7 x 10^{-13} (90% CL)

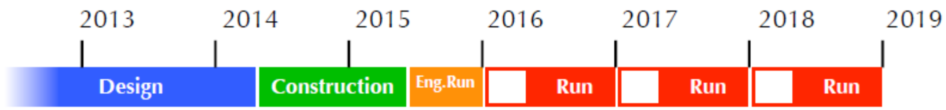
PRL110(2013)201801



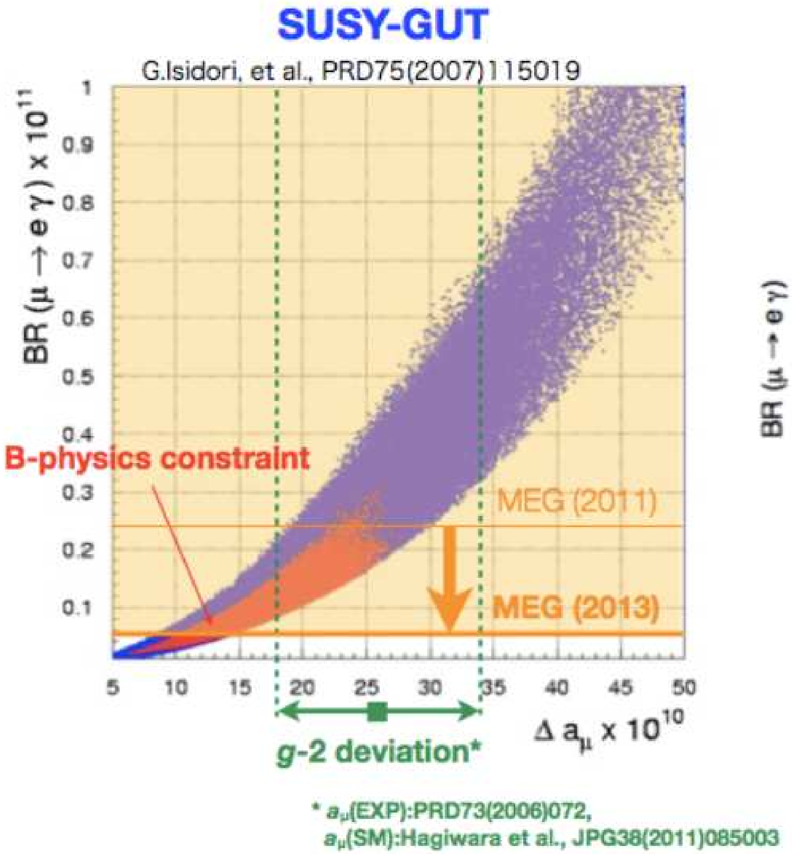


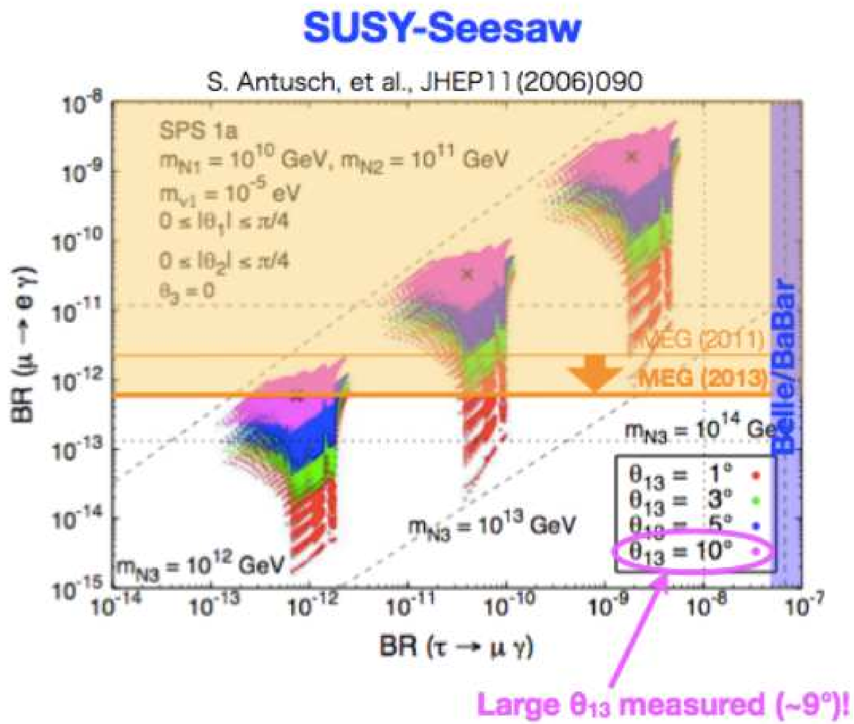


MEG upgrade aiming at < 5 x 10^{-14} sensitivity



Impact on NP Models

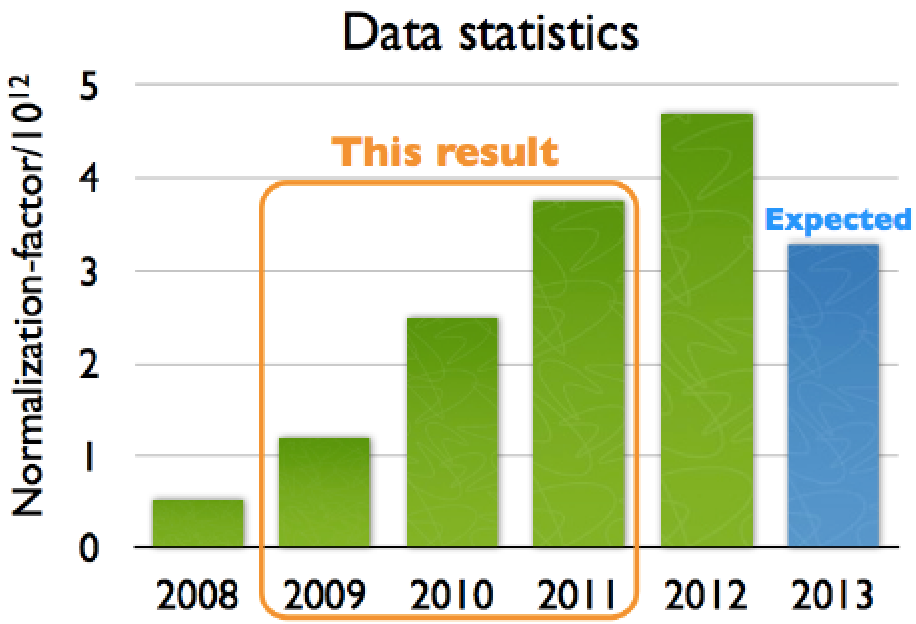




MEG
Detector performance and Data sample

New 2011

	Resolutions (σ)
Gamma Energy (%)	1.7(depth>2cm), 2.4
Gamma Timing (psec)	67
Gamma Position (mm)	5(u,v), 6(w)
Gamma Efficiency (%)	63
Positron Momentum (KeV)	305 (core = 85%)
Positron Timing (psec)	108
Positron Angles (mrad)	7.5 (Φ), 10.6 (θ)
Positron Efficiency (%)	40
Gamma-Positron Timing (psec)	127
Muon decay point (mm)	1.9 (z), 1.3 (y)

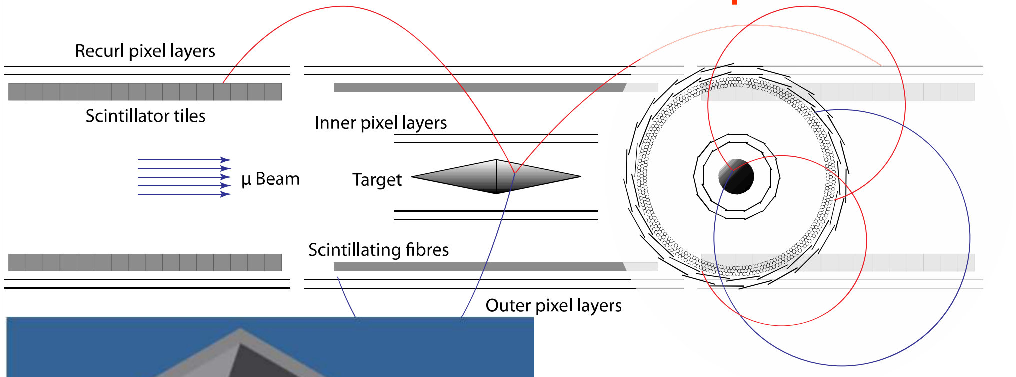


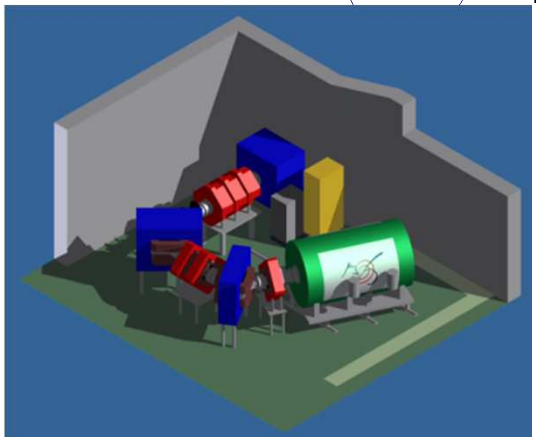
	μ stopped	sensitivity
2009+10	1.75×10^{14}	1.3×10^{-12}
2011	1.85×10^{14}	1.1×10^{-12}
2009+10+11	3.60×10^{14}	7.7×10^{-13}

Searching for μ→eee :

Mu3e collaboration

search for $\mu^+ \rightarrow e^+ e^- e^+$ with sensitivity ~10^{-16} (PeV scale)
using the most intense DC muon beam (p ~ 28 MeV/*c*) in the world
→ observe ~10^{17} μ decays   (over a reasonable time scale)
rate ~ 2×10^9 μ decays / sec
→ build a detector capable of measuring 2×10^9 μ decays / sec





R-12-03.1_BV44

Research Proposal for an Experiment to Search for the Decay $\mu \rightarrow eee$

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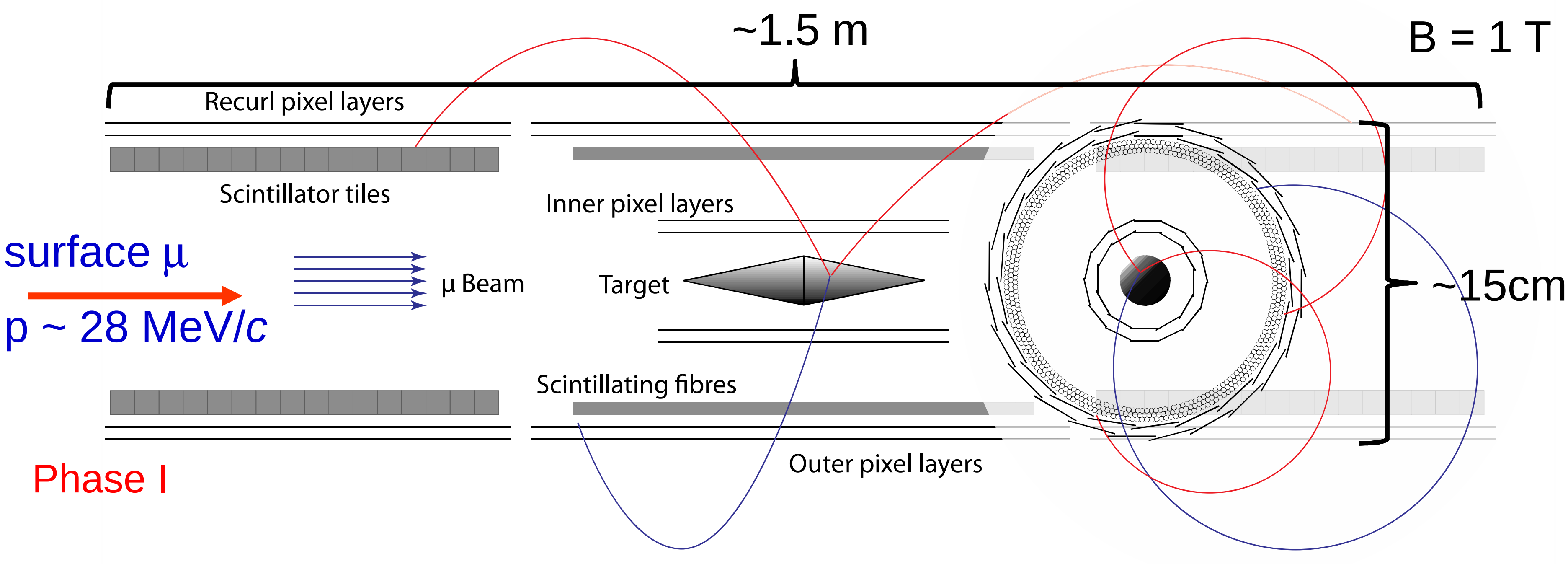
December 10^{th}, 2012

Staged approach:
first measurement 2015-17
aiming at 10^{-15}

Mu3e Baseline Design

search for $\mu^+ \to e^+ e^- e^+$ with sensitivity ~10^{-16} (PeV scale)
using the most intense DC muon beam (p ~ 28 MeV/*c*) in the world
$\to$ observe ~10^{17} μ decays (over a reasonable time scale)
rate ~ 2×10^9 μ decays / sec
$\to$ build a detector capable of measuring 2×10^9 μ decays / sec

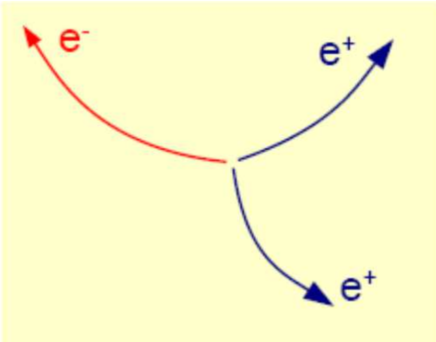


acceptance ~ 70% for $\mu \to eee$ decay (3 tracks!)

200 M HV-MAPS (Si pixels w/ embedded ampli.) channels
~ 10 k ToF channels (SciFi and Tiles)

Backgrounds

signal

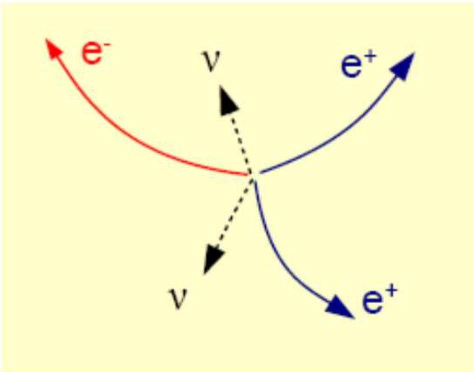


$$\sum_i \vec{p}_i = 0$$

$$\sum_i E_i = m_\mu$$

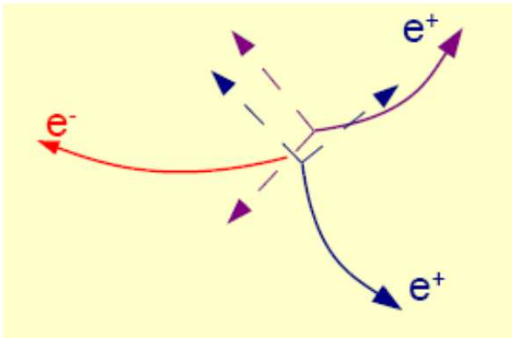
$$\Delta t_{tracks} \sim 0$$

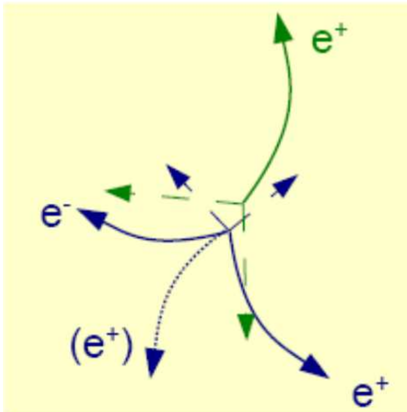
irreducible backgrounds



$BR(\mu \rightarrow ee e\nu\nu) = 3.4 \times 10^{-5}$

accidental backgrounds



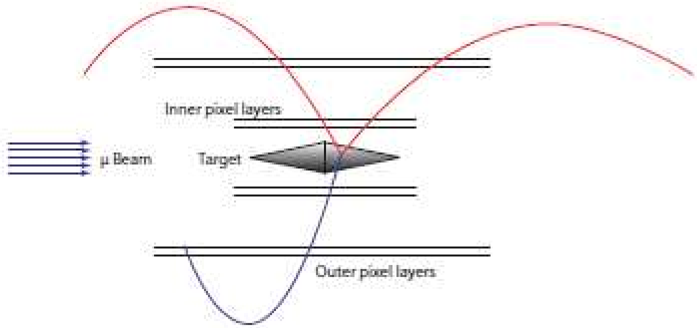


to suppress backgrounds

- precise kinematics (p and E_{TOT} resolution): $\Delta m_\mu < 0.5$ MeV/c^2
- precise timing (ToF): $\Delta t \sim 100$ ps
- precise vertexing: $\Delta x \sim 0.1$ mm

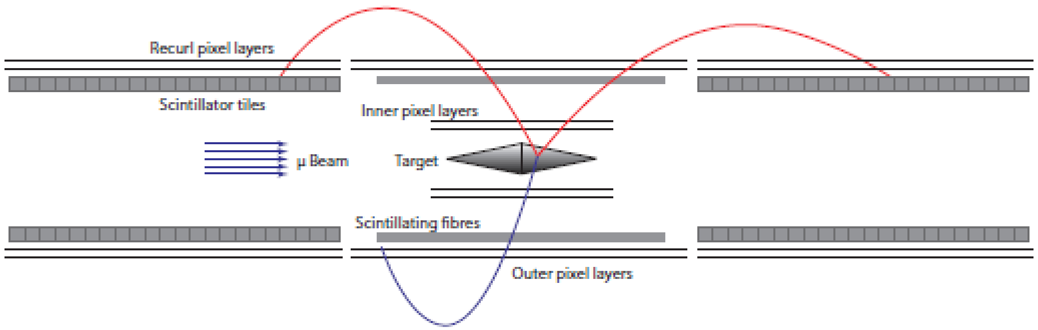
Staged Approach

Phase IA
rate ≤ 10^7 μ / s



only central pixel

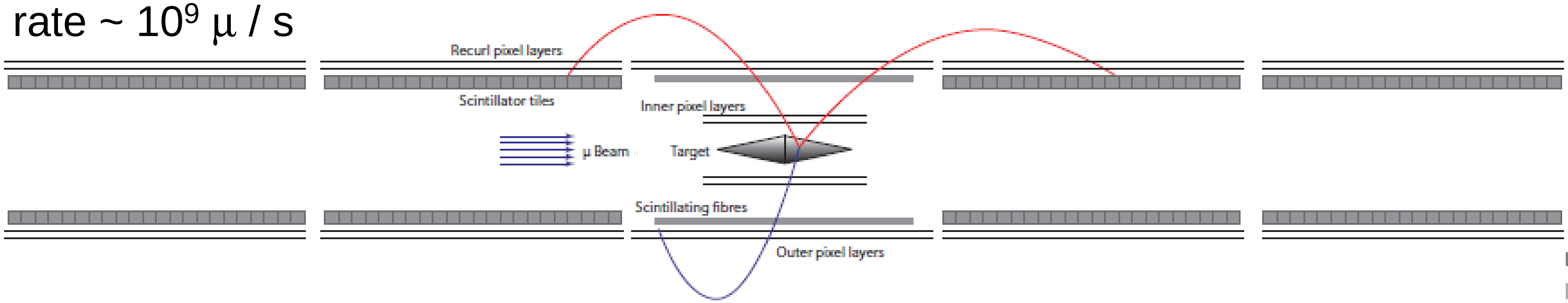
Phase IB
rate ~ 10^8 μ / s



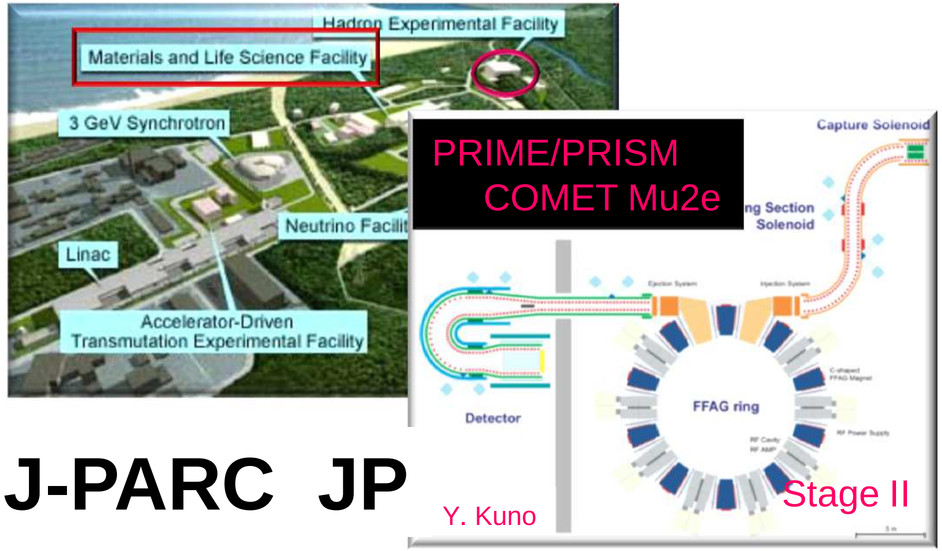
+ inner recurl sta.
+ time of flight

Phase II
rate ~ 10^9 μ / s

+ outer recurl sta.



Next Generation Facilities & cLFV experiments

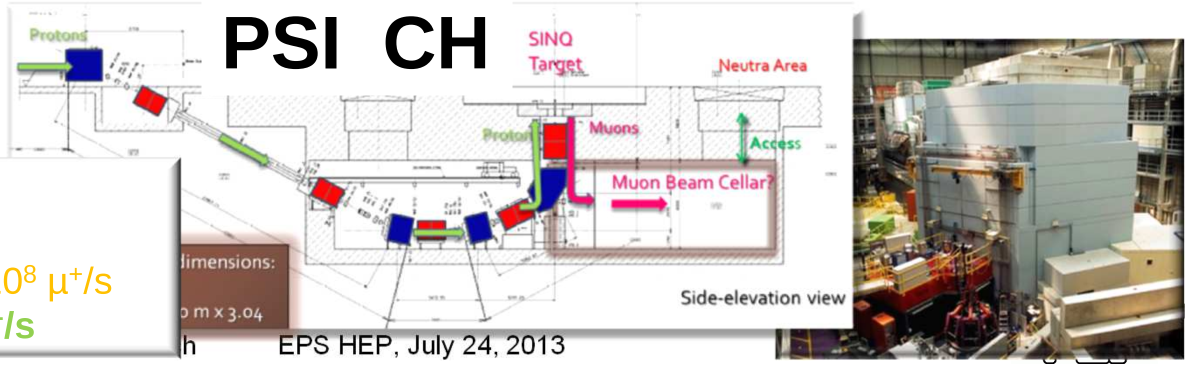


J-PARC JP

J-PARC cLFV μ→e Conversion **(Pulsed!)**
Staged Expt:
(i)COMET (2019-2020) ⇒**10^{11} μ^-/s**
(ii)PRIME/PRISM (>2020) 10^{11-12} μ^-/s

FNAL cLFV μ→e Conversion **(Pulsed!)**
Staged Expt:
(i)Mu2e (2019-2020) ⇒**$5\cdot10^{10}$ μ^-/s**
(ii)Project X Mu2e (>2022) $2\cdot10^{12}$ μ^-/s

HiMB@PSI



PSI cLFV μ→eγ μ→3e **(DC)**
Staged Expt:
(i) Mu3e I (2014-2017) πE5 ⇒$2\cdot10^{8}$ μ^+/s
(ii) Mu3e II (>2017) SINQ **>10^{10} μ^+/s**

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www.psi.ch/psi2013

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- Searches for new forces
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- Searches for permanent electric dipole moments
- Exotic atoms and molecules
- Precision magnetometry
- Advanced muon and ultracold neutron sources
- Advanced detector technologies

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