IoP2013, High Energy and Astro Particle Physics, University of Liverpool, 9th April 2013

Precision Physics with leptons: g-2, LFV and EDMs

UNIVERSITY OF LIVERPOOL

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LIVERPOOL THEORETICAL PHYSICS

`A very incomplete experimental overview from a theorist'

[Sorry no time to cover tau physics, eDMs]

Thanks to M. Lancaster, L. Roberts, D. Glenzinski, Y. Kuno, T. Mibe, N. Saito, D. Stoeckinger, D. Nomura for slides and help with the talk

Introduction/Motivation: g-2, LFV, EDMs

Why in one talk?

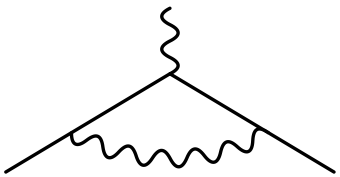
- Low energy, precision, intensity, single-number experiments
- Realistic chance to `see’ physics beyond the SM
- in turn constrain/distinguish between models
- Complementary to high energy searches at the LHC:
  - un-coloured sector so far not strongly constrained
  - leptons ideal for low energy precision studies

We know already:

- ν masses (small) and mixing: point towards some high-scale (GUT) physics, so LFV in neutral sector established, but no Charged LFV seen so far
- No direct signals for BSM from LHC so far: some models like CMSSM are in trouble/excluded already when trying to accommodate LHC exclusion limits and to solve muon g-2

Introduction: Lepton Dipole Moments

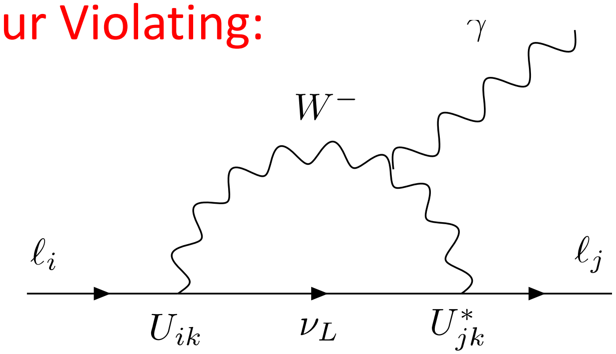
Flavour Conserving:



- Interaction with E and B fields: $\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$
- g-2: $\vec{\mu} = g\frac{e}{2m}\vec{s}$ Dirac: $g = 2$ Schwinger (1948): $a \equiv (g-2)/2 = \alpha/(2\pi)$
- EDM: $\vec{d} = \eta\frac{e}{2mc}\vec{s}$ is CP-violating and very small within the SM

(from quark CKM in 4-loop diagrams $d_e \sim 10^{-38} e\,\mathrm{cm}$, larger from Maj. ν's)

Flavour Violating:



$$B(\mu\to e\gamma) = \frac{\alpha}{2\pi}\left|\sum_k U_{ek}U^*_{\mu k}\frac{m^2_{\nu_k}}{m^2_W}\right|^2 < 10^{-54}$$

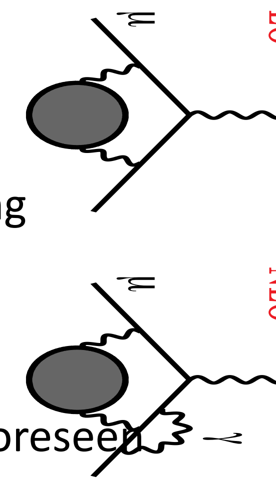
EDM or CLFV measurement ≠ 0
would be a clear signal for NP

Also $\mu\to e\,e^+e^-$ and $\mu\,N\to e\,N$ `conversion', all procs. have similar diagrams

Status of the muon g-2: SM prediction

$$a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{hadronic}} + a_\mu^{\text{NP?}}$$

- QED: Kinoshita et al. 2012: 5-loop completed (12672 diagrams) □
- EW: 2-loop □
- Hadronic: the limiting factor of the SM prediction



L-by-L: - so far use of model calculations, form-factor data will help improving
- in the future: lattice QCD predictions (first results encouraging)
- several groups: USQCD, UKQCD, ETMC, … much increased effort

Vacuum Polarisation: use of e+e- had. cross section data; big improvements foreseen

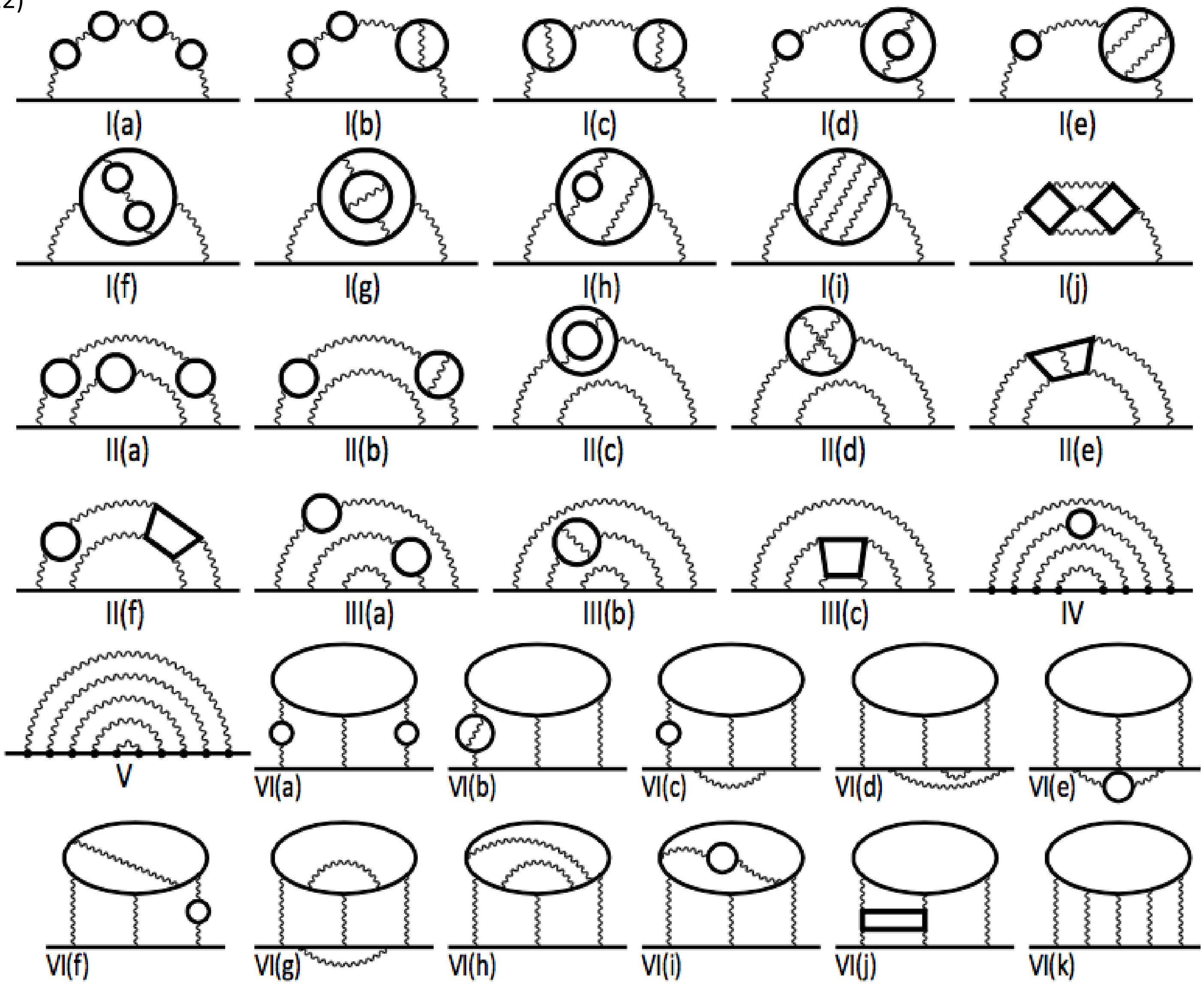
Kinoshita et al: g-2 in QED at 5-loop order

T. Aoyama, M. Hayakawa,
T. Kinoshita, M. Nio (PRL, 2012)

10th

12672

diagrams



Kinoshita et al: g-2 in QED at 5-loop order

A triumph of perturbative QFT and computing [From M. Hayakawa (tau2012)]

$$a_l(\text{QED}) = a_l^{(2)} \times \frac{\alpha}{\pi} + a_l^{(4)} \times \left(\frac{\alpha}{\pi}\right)^2 + a_l^{(6)} \times \left(\frac{\alpha}{\pi}\right)^3 + a_l^{(8)} \times \left(\frac{\alpha}{\pi}\right)^4 + a_l^{(10)} \times \left(\frac{\alpha}{\pi}\right)^5 + \cdots .$$

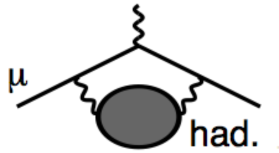
Table: $a_\mu(\text{QED})$ at each order $2n$, scaled by 10^{11}

order $2n$	using $\alpha(\text{Rb})$	using $\alpha(a_e)$
2	116 140 973.318 (77)	116 140 973.213 (30)
4	413 217.6291 (90)	413 217.6284 (89)
6	30 141.902 48 (41)	30 141.902 39 (40)
8	381.008 (19)	381.008 (19)
10	5.0938 (70)	5.0938 (70)
sum	116 584 718.951 (80)	116 584 718.846 (37)

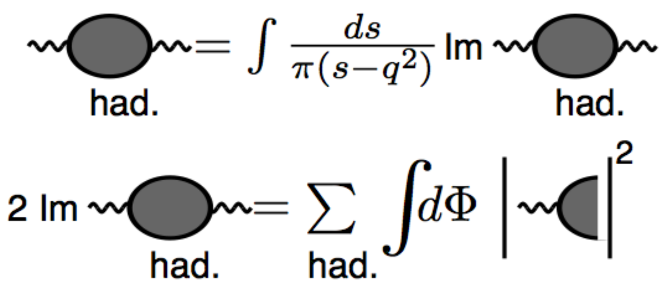
NEW!

Status of the muon g-2 SM prediction: hadronic VP

Use of data compilation for hadr. VP:



pQCD not useful. Use the dispersion relation and the optical theorem.



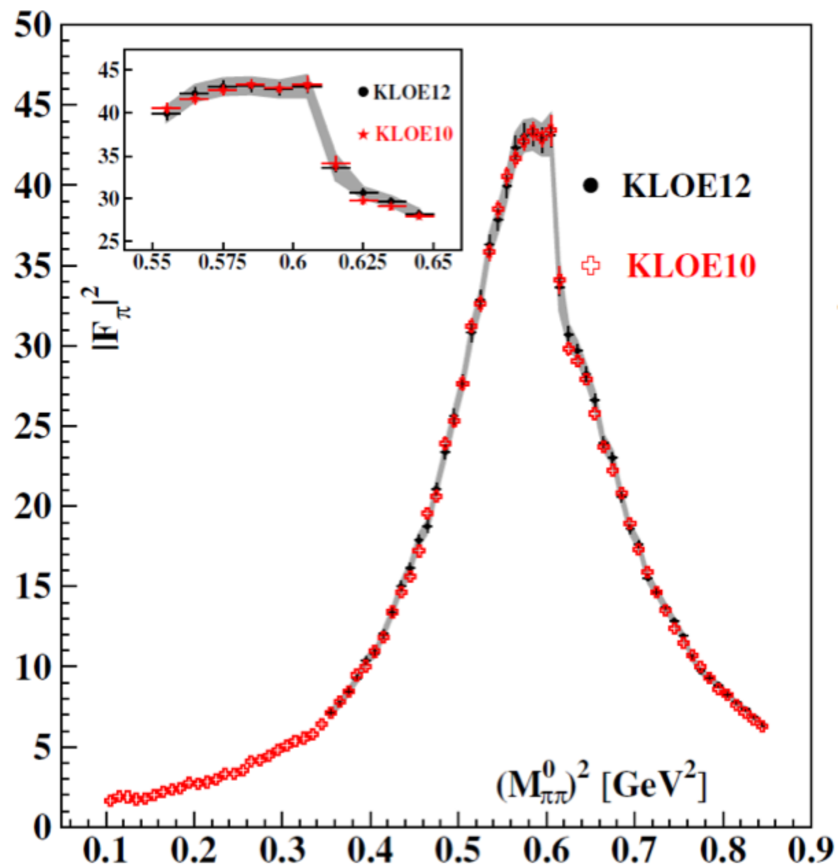
$$a_\mu^{\rm had,LO} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\rm th}}^{\infty} ds\ \frac{1}{s} \hat{K}(s) \sigma_{\rm had}(s)$$

- Weight function $\hat{K}(s)/s = \mathcal{O}(1)/s$

$\Longrightarrow$ Lower energies more important

$\Longrightarrow$ $\pi^+\pi^-$ channel: 73% of total $a_\mu^{\rm had,LO}$

Data from many exps. for many final states from many experiments;
- traditional `scan' (tunable e+e- beams)
- `Radiative Return' at meson factories, eg



Status of the muon g-2 SM prediction

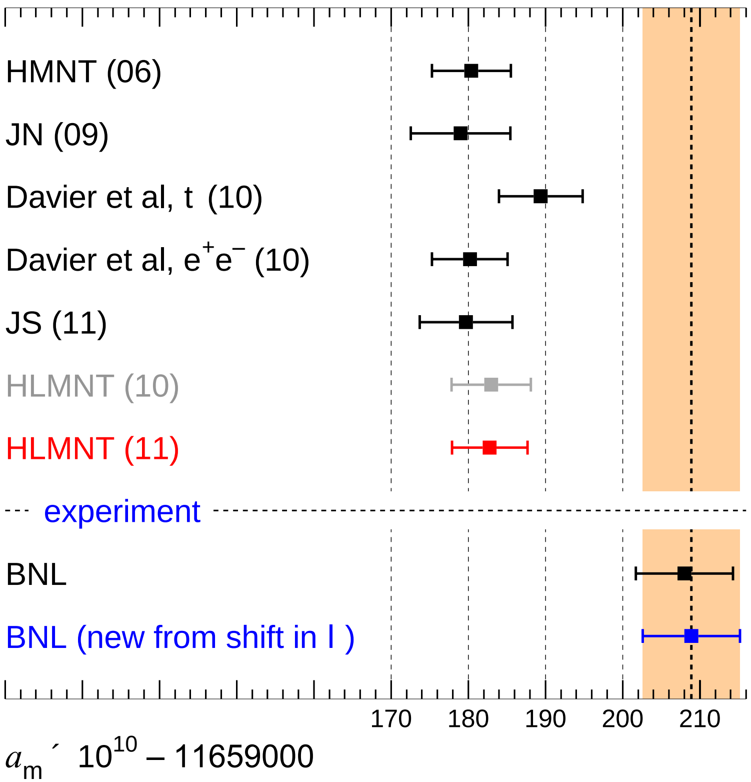
Several groups have produced hadronic compilations over the years.
Here: Hagiwara+Liao+Martin+Nomura+T

QED contribution	11 658 471.808 (0.015) $\times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	**694.9 (4.3)** $\times 10^{-10}$	HLMNT11
NLO hadronic	−9.8 (0.1) $\times 10^{-10}$	HLMNT11
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**

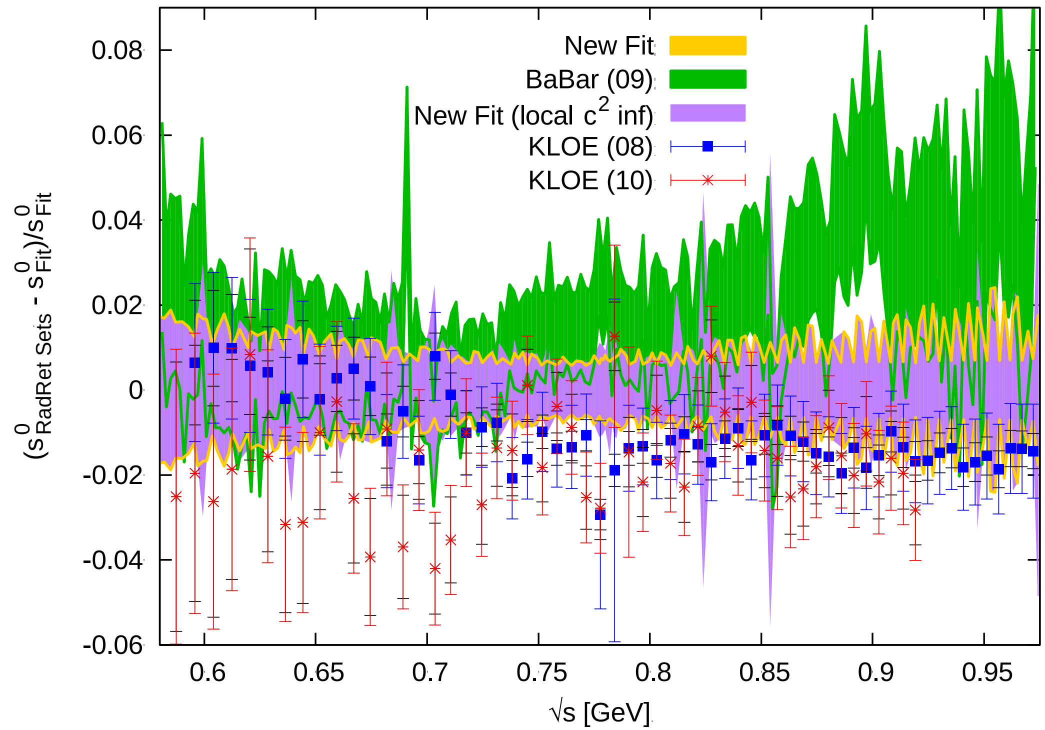
(Numbers taken from HLMNT11, arXiv:1105.3149)

Status of the g-2 SM prediction: $a_\mu^{\mathrm{NP}} = 26 \times 10^{-10}$?!

Recent history plot:



Data combination can be non-trivial:



SM prediction consolidated, though `the devil is in the detail';

- EXP+TH will have to work hard to match planned exp. improvements (see below):

- More hadronic cross section data from: KLOE, BaBar, Belle(II), CMD-3, SND, BESIII
- Radiative corrections/Monte Carlos
- Improved model predictions for l-by-l
- Lattice QCD

g-2 and BSM physics

Many physics models probed by g-2

Large change wrt SM prediction

Extended technicolor (muon mass generated radiatively)

SUSY (natural, gauge-mediated, …), RS, large ED, dark γ

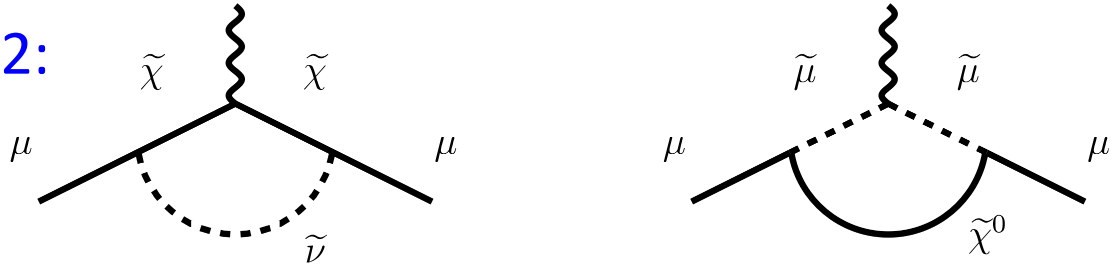
Z’, W’, Little Higgs, Universal ED, 2HDM

SM prediction changed little

g-2 and BSM physics: SUSY?

SUSY could easily explain g-2:

Main 1-loop contributions:



Simplest case:

$$a_\mu^{\rm SUSY} \simeq sgn(\mu)\, 130 \times 10^{-11}\, \tan\beta \left(\frac{100\,{\rm GeV}}{\Lambda_{\rm SUSY}}\right)^2$$

- Needs $\mu>0$, \`light' SUSY-scale Λ and/or large tan β to explain 260×10^{-11}

- This is already \`excluded' by LHC searches in the simplest SUSY scenarios (like CMSSM); causes large χ^2 in simultaneous SUSY-fits with LHC data and g-2

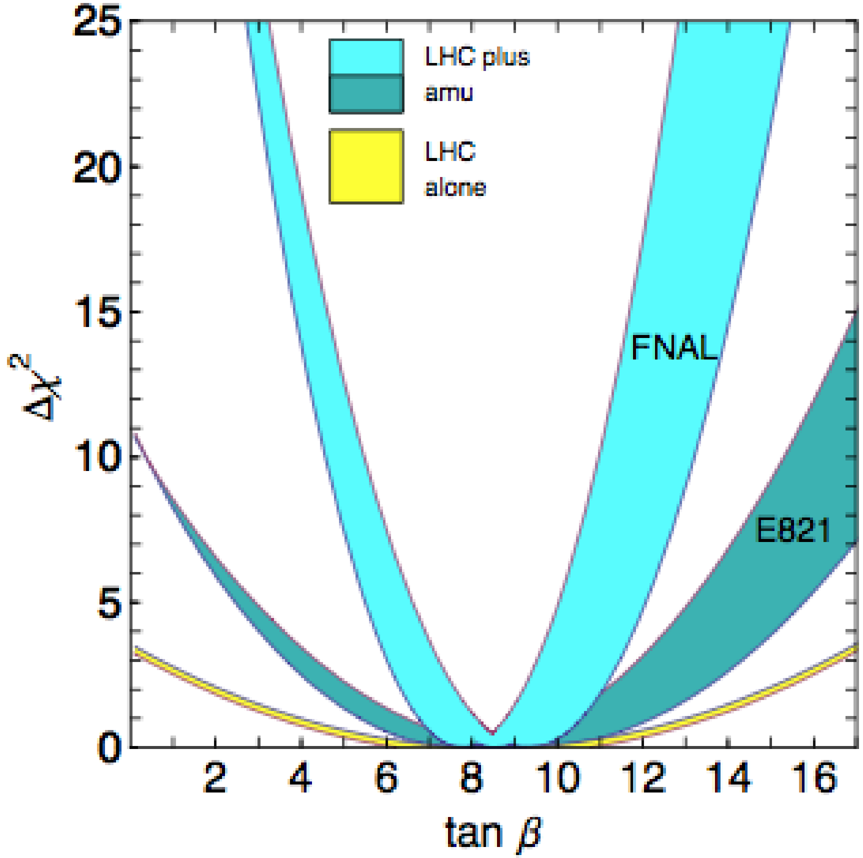
- However note: SUSY does not have to be minimal (w.r.t. Higgs),
  could have large mass splittings (with lighter sleptons), or
  corrections (to g-2 and Higgs mass) different from simple models,
  or not be there at all

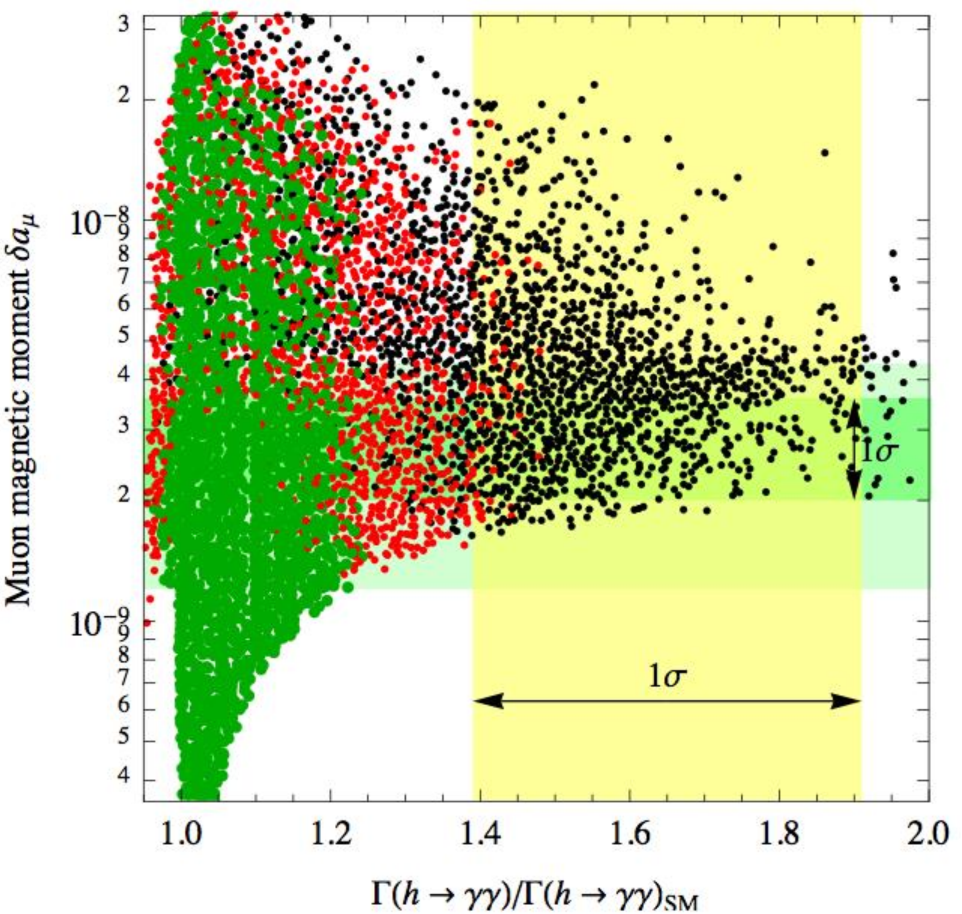
- g-2 constrains params, distinguishes between NP models \`degenerate' for LHC

g-2 constrains SUSY

LHC with (100 fb^{-1}) can determine tan(β) to 50%, with g-2 to 10%

g-2 complements LHC data selecting in the vast SUSY (param/model) space

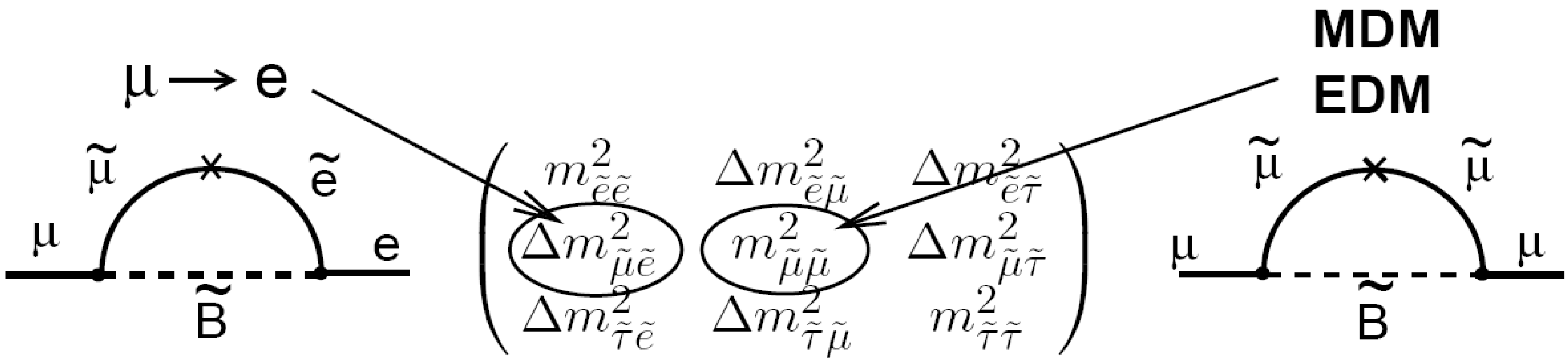




Guidice, Paradisi, Strumia JHEP 1210, 186

SUSY in CLFV and dipole moments

Contributions to CLFV and DMs related to elements of slepton mixing matrix:



$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

Large contributions to g-2 ➔ large LFV, but:

bound from MEG on μ -> eγ rules out most of the parameter space of certain SUSY models:

SUSY in CLFV and dipole moments [From Tsutomu Mibe]

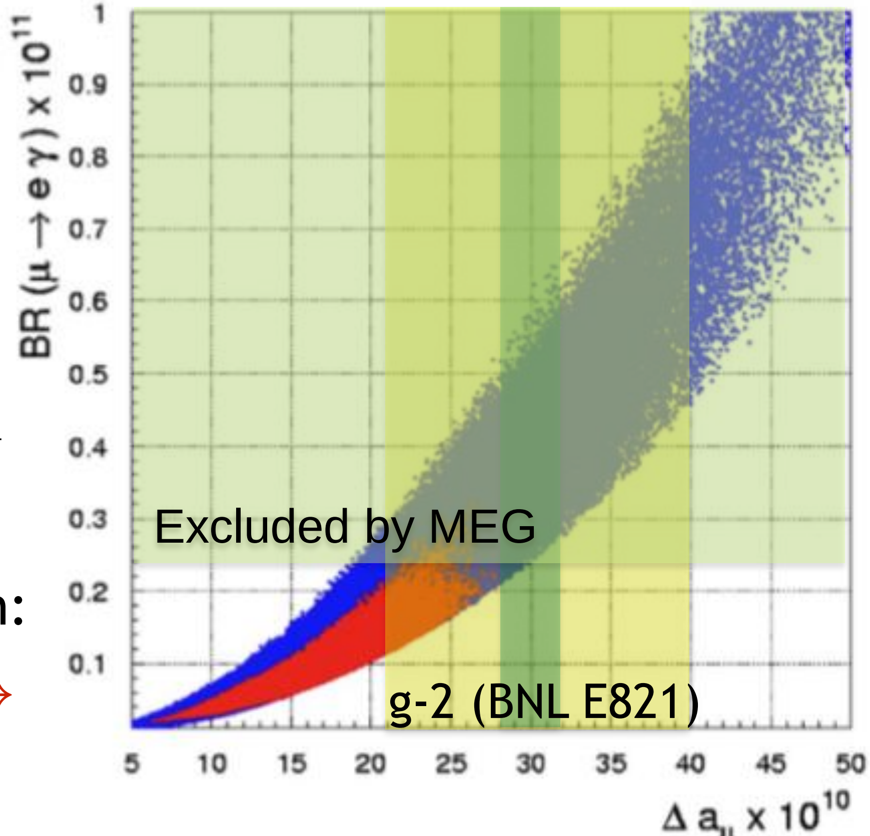
- **Large g-2 → Large cLFV**

G. Isidori, F. Mescia, P. Paradisi, and D. Temes, PRD 75 (2007) 115019

$Br(\mu \to e\gamma) \times 10^{11}$

MEG limit now even:

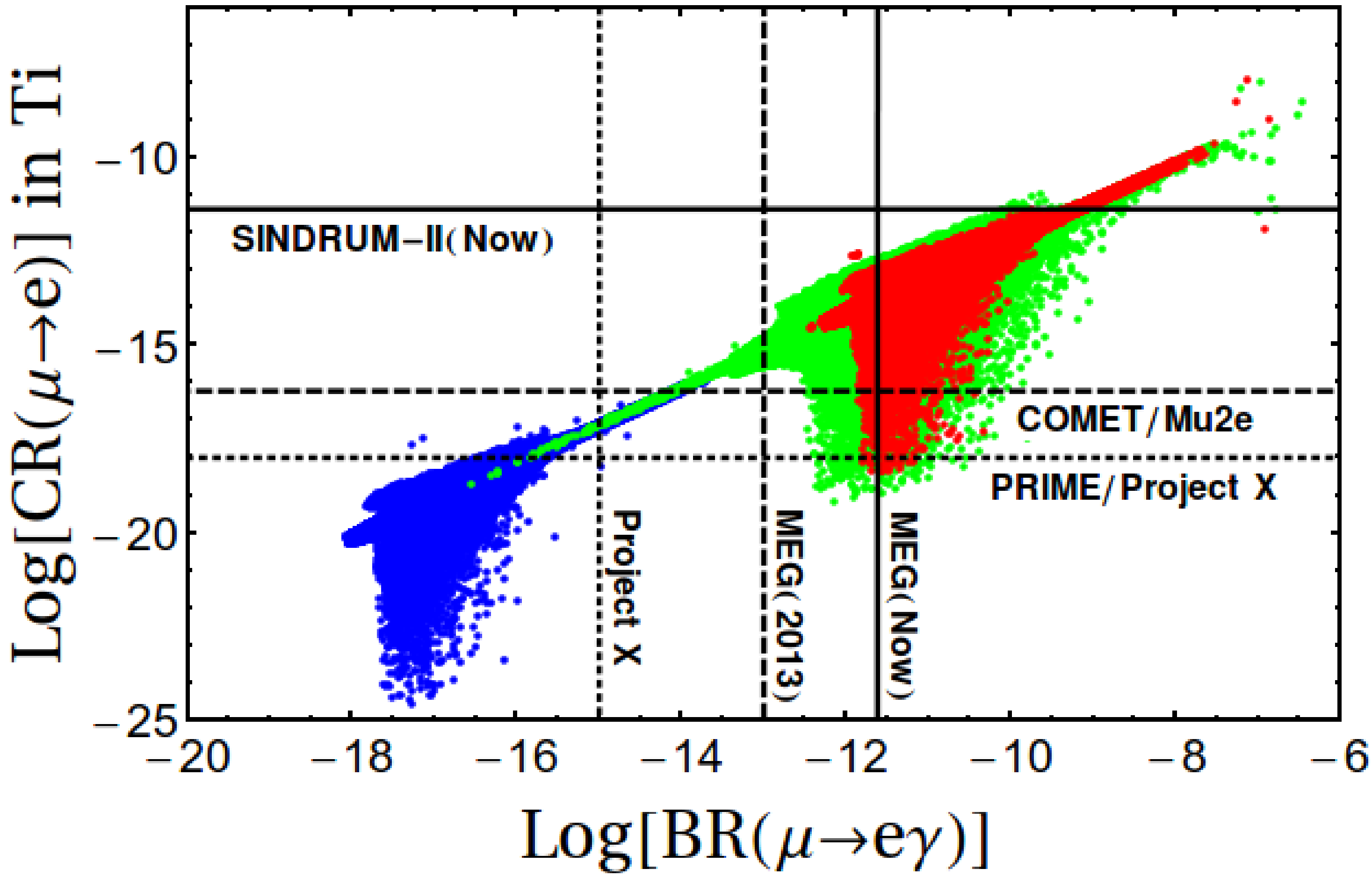
$5.7 \times 10^{-13} \longrightarrow$



deviation from SM (g-2)

SUSY in CLFV: conversion vs μ->eγ

Expected limits from current and future CLFV experiments (conversion vs μ->eγ)
[from Calibi et al, arXiv:1207.7227]



tan β = 10

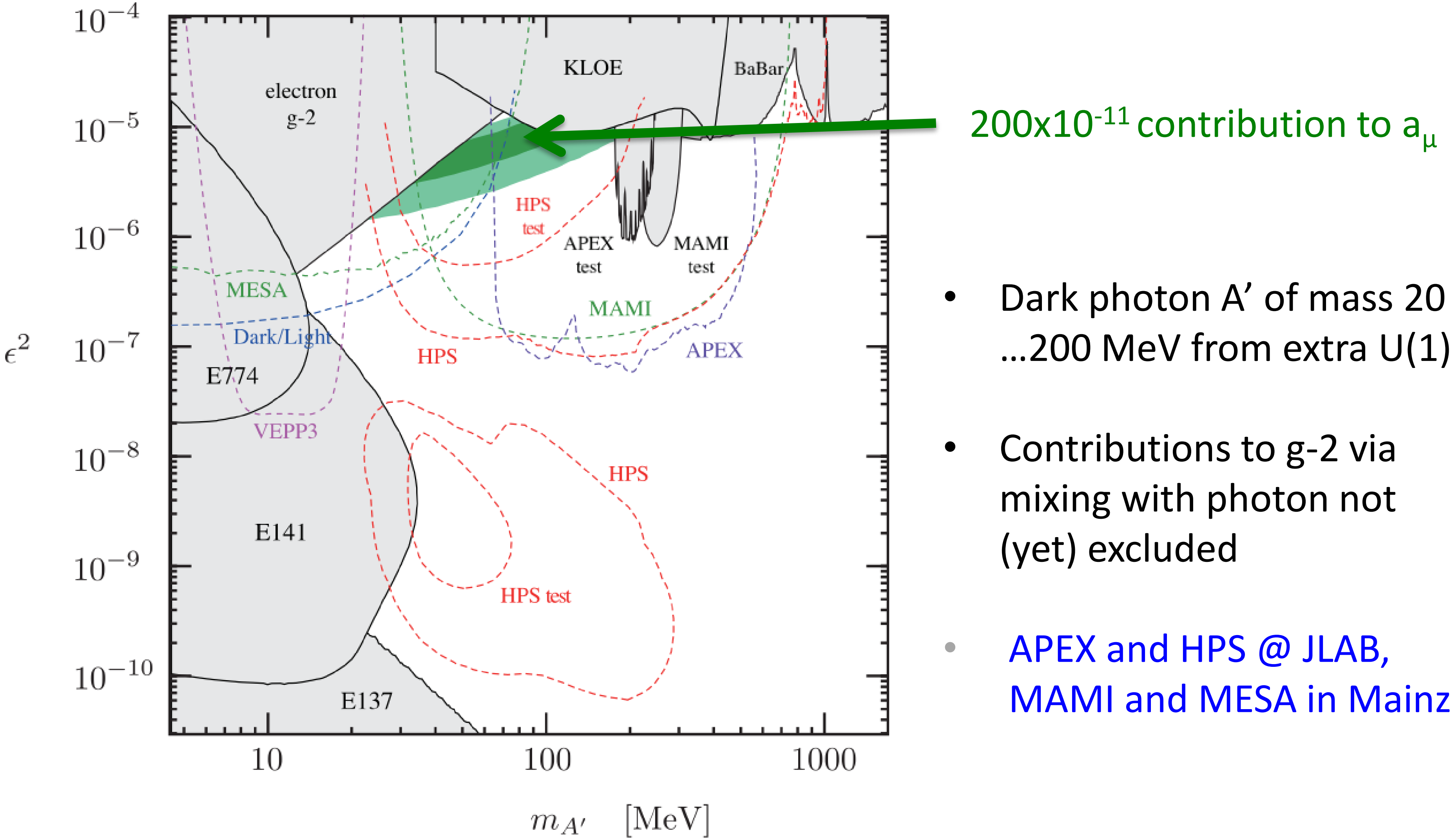
red: PMNS in mSUGRA

green: NUHM

blue: `CKM' (small mixing)

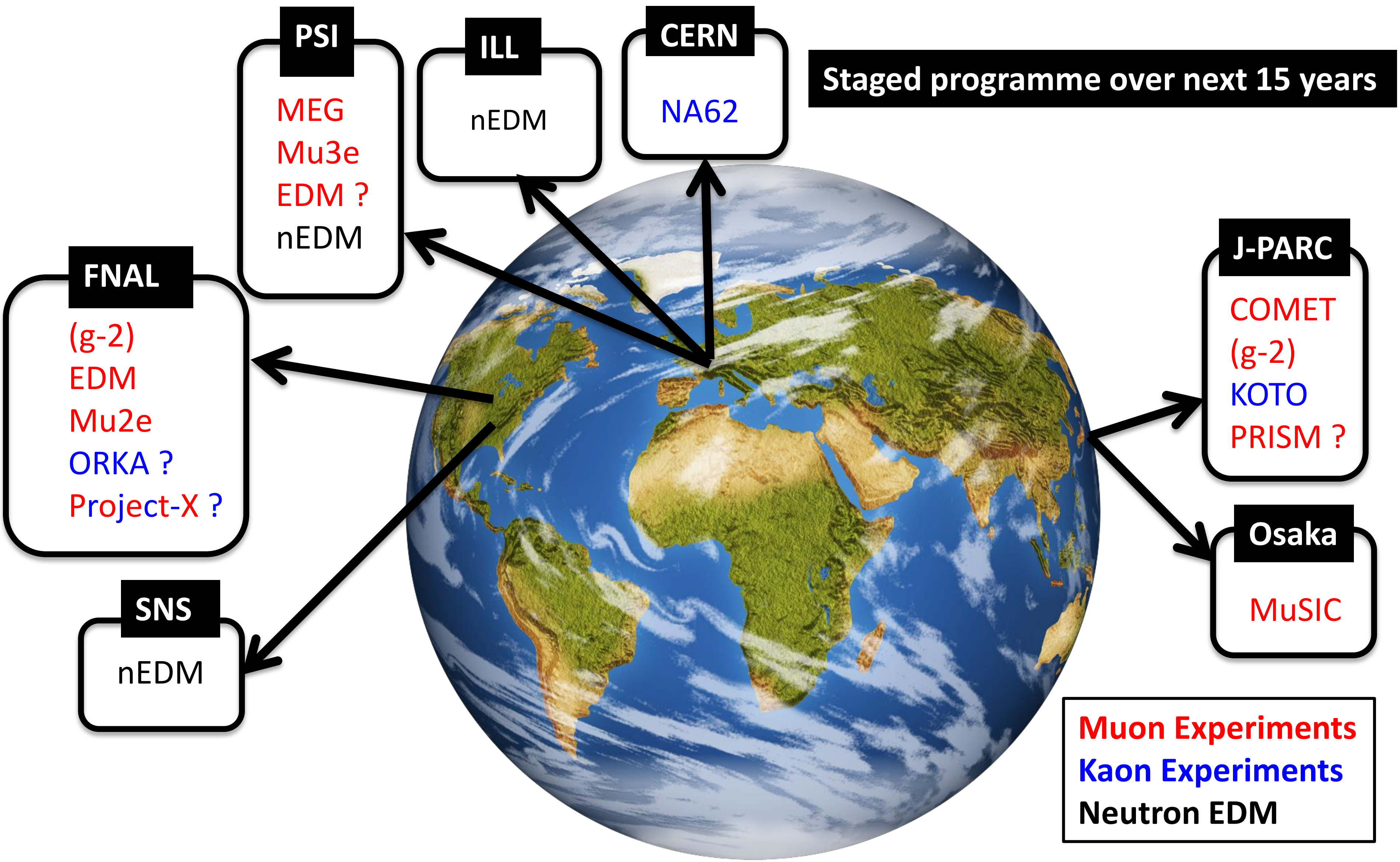
g-2 and low scale NP: probing `dark photons'

$$\mathcal{L}_{A'} = -\frac{1}{4}F^{A'}_{\mu\nu}F^{A'\mu\nu} + \frac{1}{2}m^2 A'_\mu A'^\mu - e\epsilon A'_\mu J^\mu_{\rm em} + g\epsilon \tan\theta_W \frac{m^2}{m_Z^2} A'_\mu J^\mu_Z$$



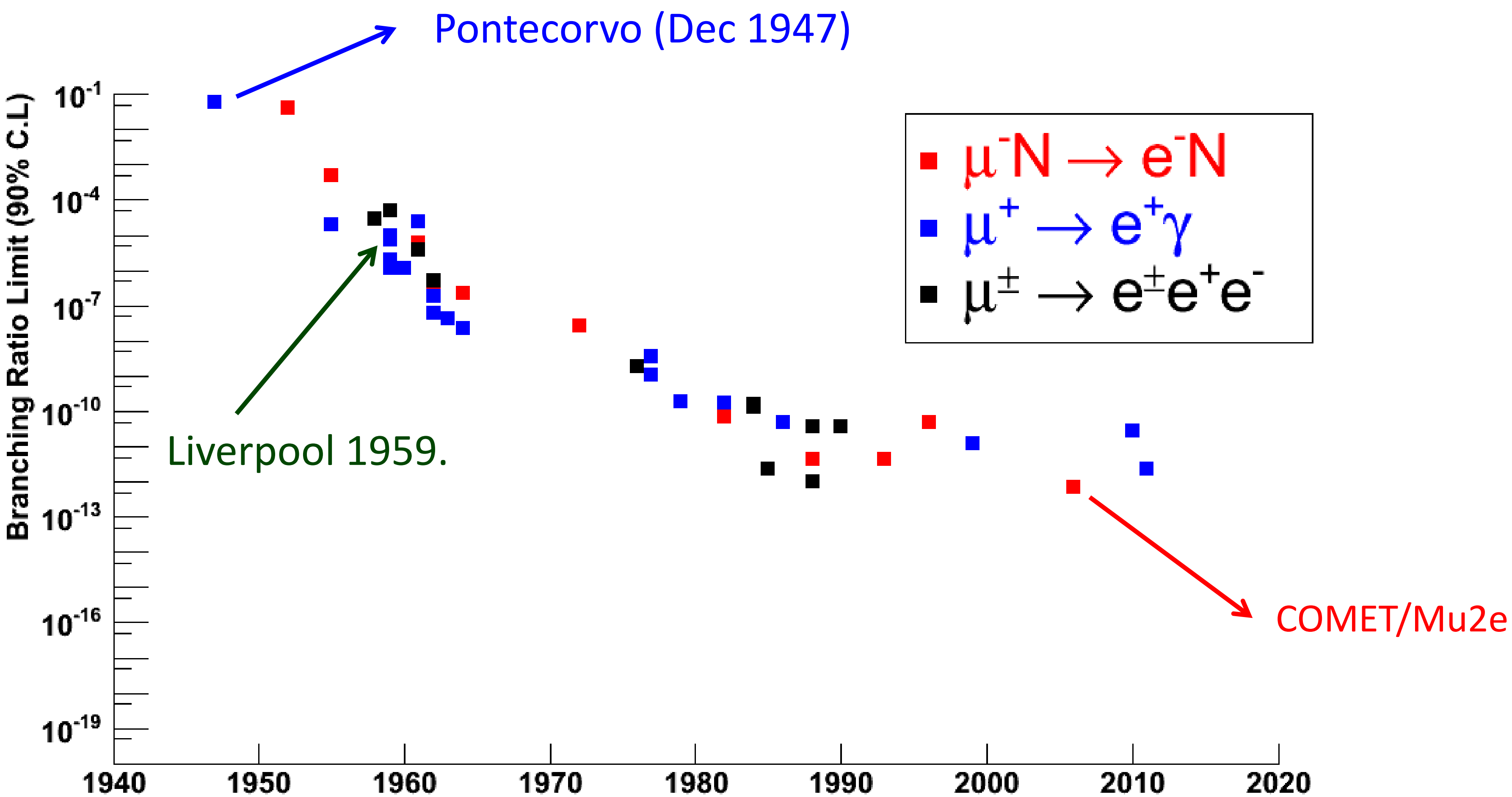
- Dark photon A' of mass 20 …200 MeV from extra U(1)
- Contributions to g-2 via mixing with photon not (yet) excluded
- APEX and HPS @ JLAB, MAMI and MESA in Mainz

Experiments at the high precision/intensity frontier

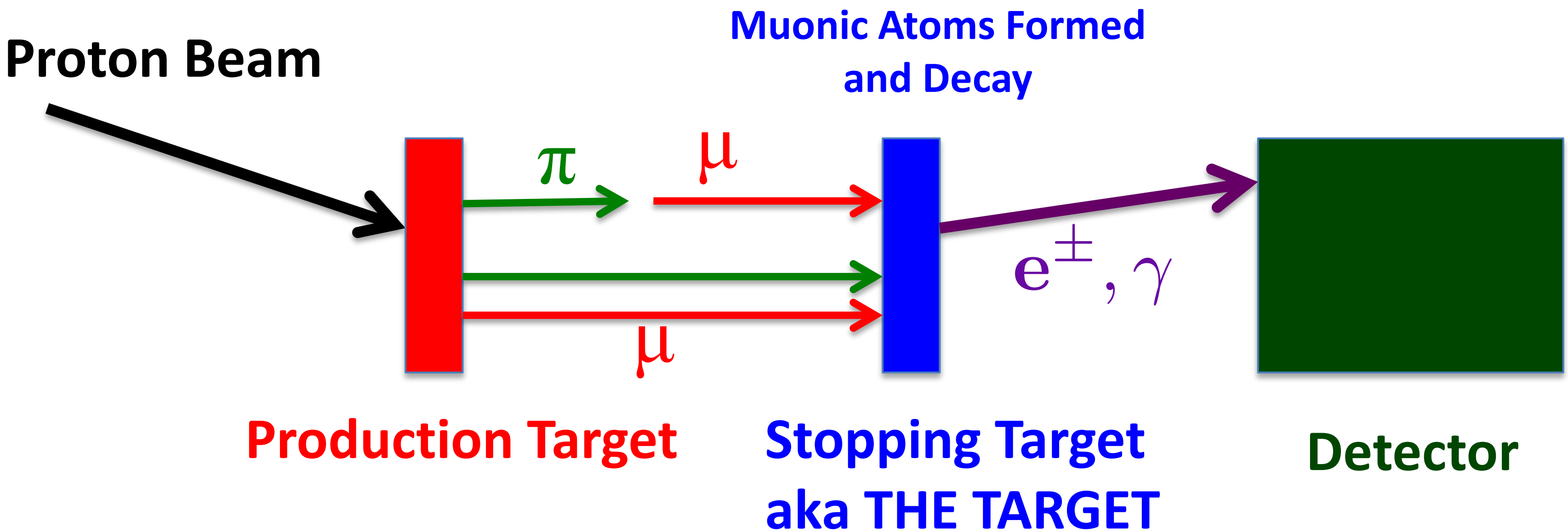


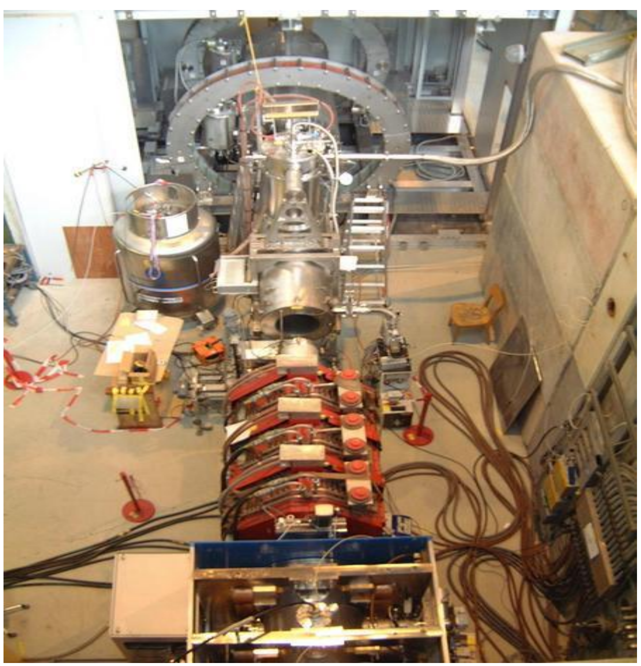
CLFV: Limits in different processes

Muon to electron conversion experiments aiming for single event sensitivity of $2x10^{-17}$



CLFV: Experimental Technique. MEG limits

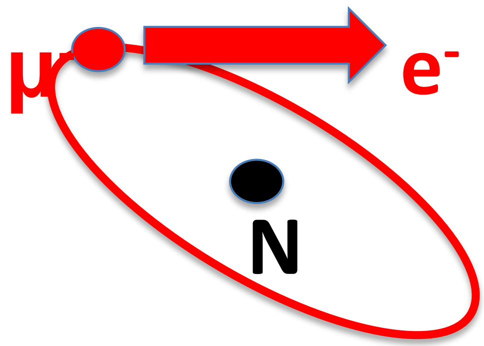




- MEG at PSI: 10^8 `stopped' **μ+**/sec
- Limit with 2011 data: Br(μ->eγ) < 5.7 x 10^{-13}
  (90% CL Excl.)
- `Eliminates' SUSY models, fitting g-2 and CLFV
- With naïve power counting: $\Lambda_{\rm NP} > \mathcal{O}(10^5\ \mathrm{TeV})$
- Doubled statistics expected his summer
- Upgrade aiming at 6 x 10^{-14}

CLFV: Conversion vs decay processes

$$\mu^- + (\mathbf{A},\mathbf{Z}) \rightarrow \mathbf{e}^- + (\mathbf{A},\mathbf{Z})$$



vs

$$\mu^+ \longrightarrow e^+\gamma$$

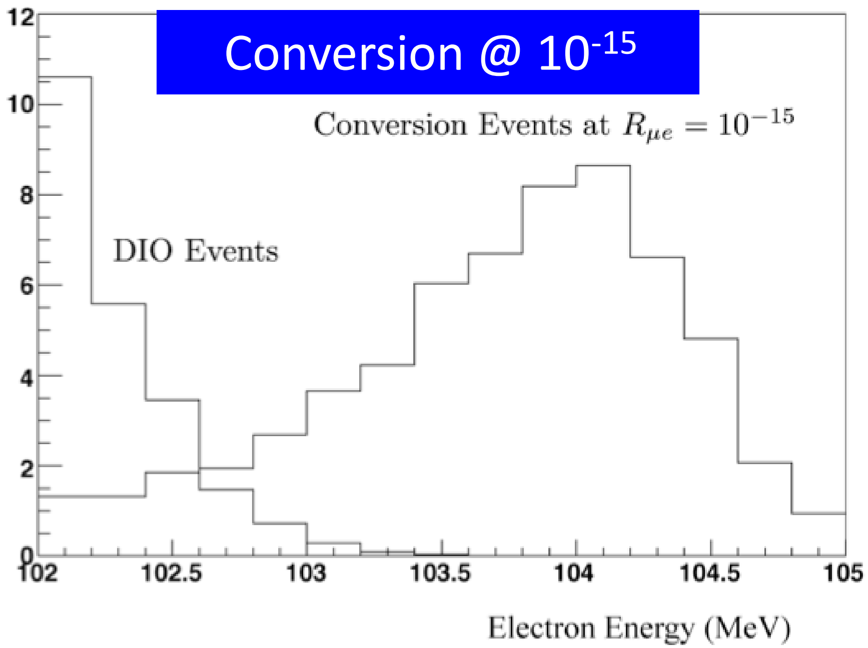
$$\mu^+ \longrightarrow e^+e^-e^+$$

Suffer, at the highest rates, from accidental backgrounds that scale as muon rate[2]

`Conversion' process can occur due to

- `dipole like' diagrams (like decays)
- four fermion operators,
- leptoquark or Z' exchanges…

Signals in reach in many models!



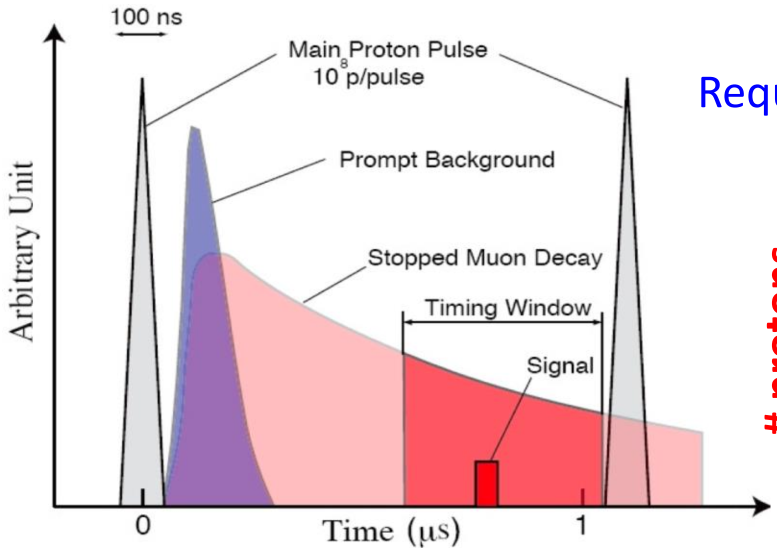
Sindrum-II (PSI) 2004:

$$\mathbf{Br}(\mu^- + \mathrm{Au} \rightarrow \mathbf{e}^- + \mathrm{Au}) < \mathbf{7} \times \mathbf{10^{-13}}$$

Conversion has a simple one particle signature: E_e <~ m_μ , easy to separate from `normal' Decay In Orbit

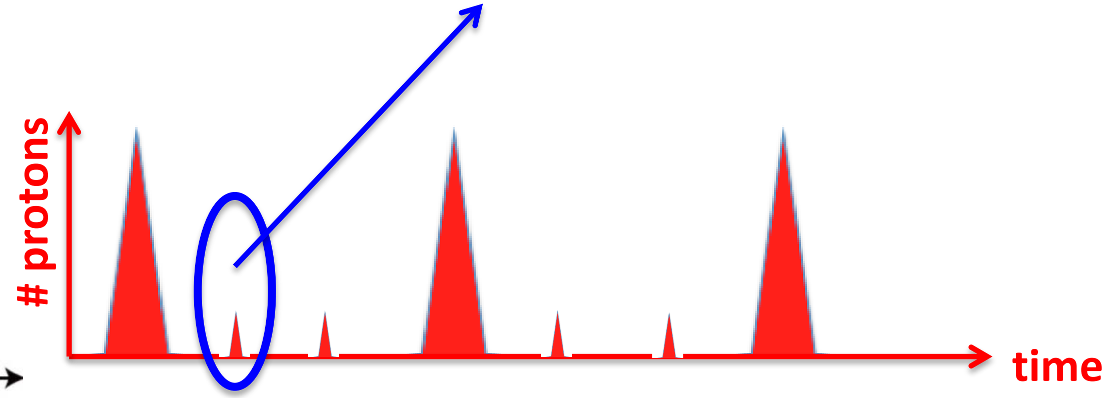
Arguably best route to highest sensitivity at high muon rates

CLFV: the route to SES of 10^{-17}: Pulsed proton beam

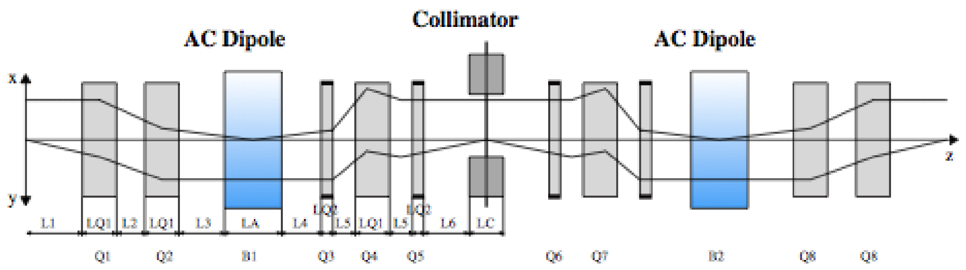


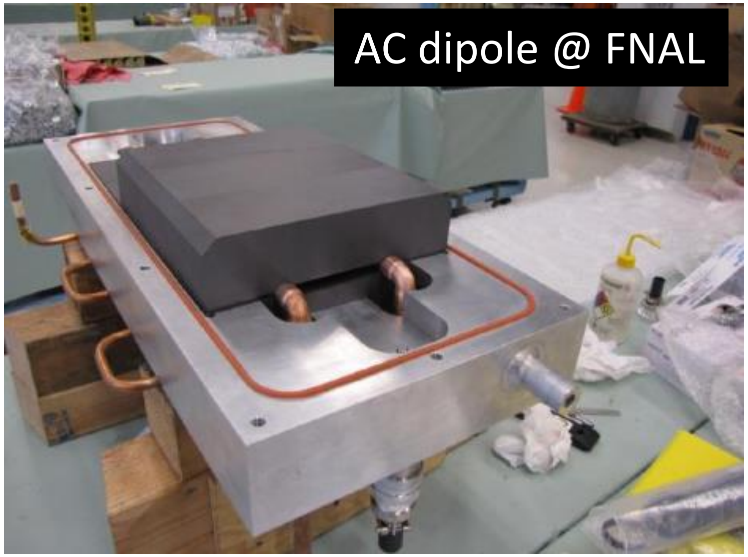
[Comet: 10^{11} muons/sec, up from 10^{8} at MEG.]

Requirement (mue2/COMET) that < 10^{-9} of primary pulse



AC dipole/collimator system kicks out the out-of-time particles

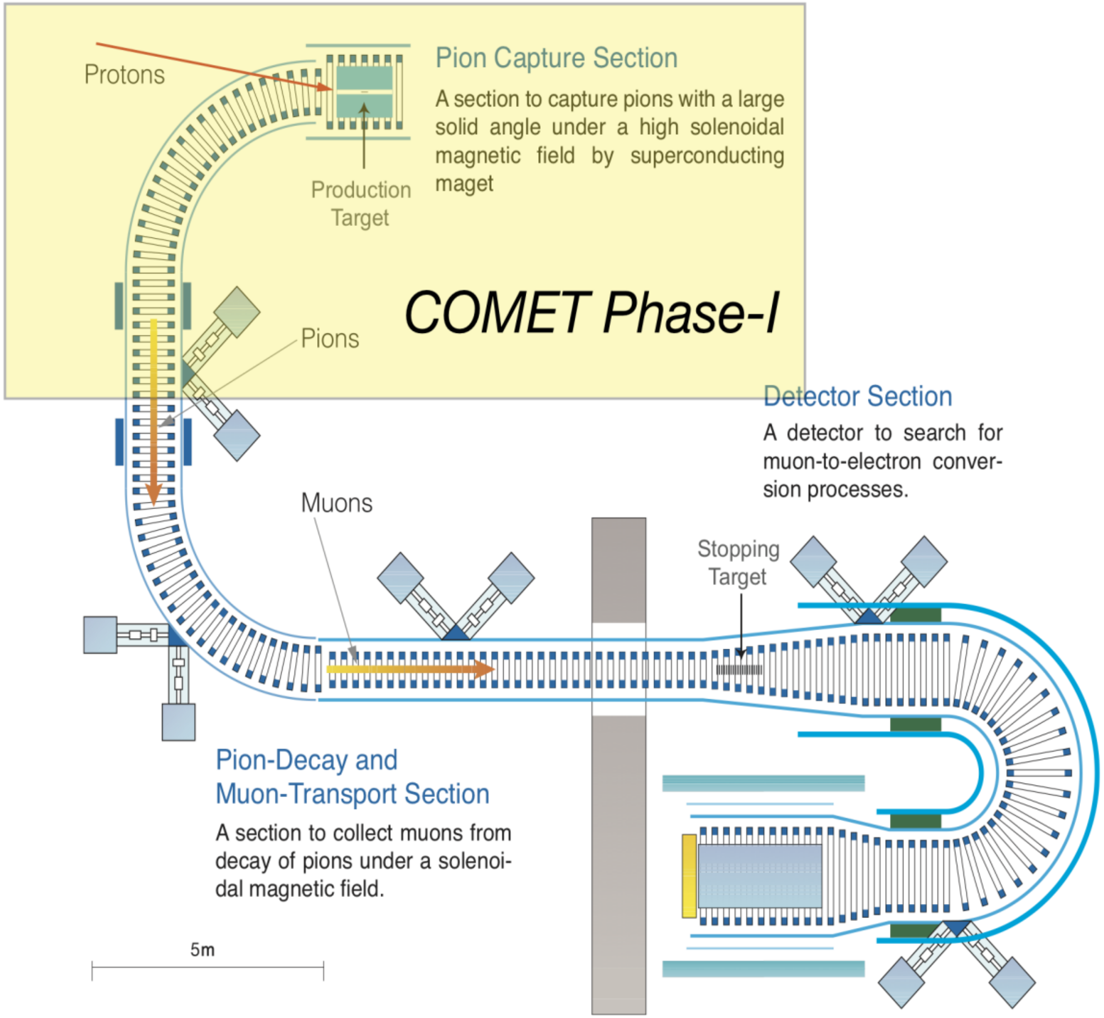




CLFV: COMET @ JPARC

COMET to be built in two phases
- Phase-I : now – 2016
- Phase-II : 2017 – 2020

Current Mu2e/COMET sensitivity estimates of BR < 10^{-16} extrapolate current background knowledge over 4 orders of magnitude…



COMET Phase-I Aims:

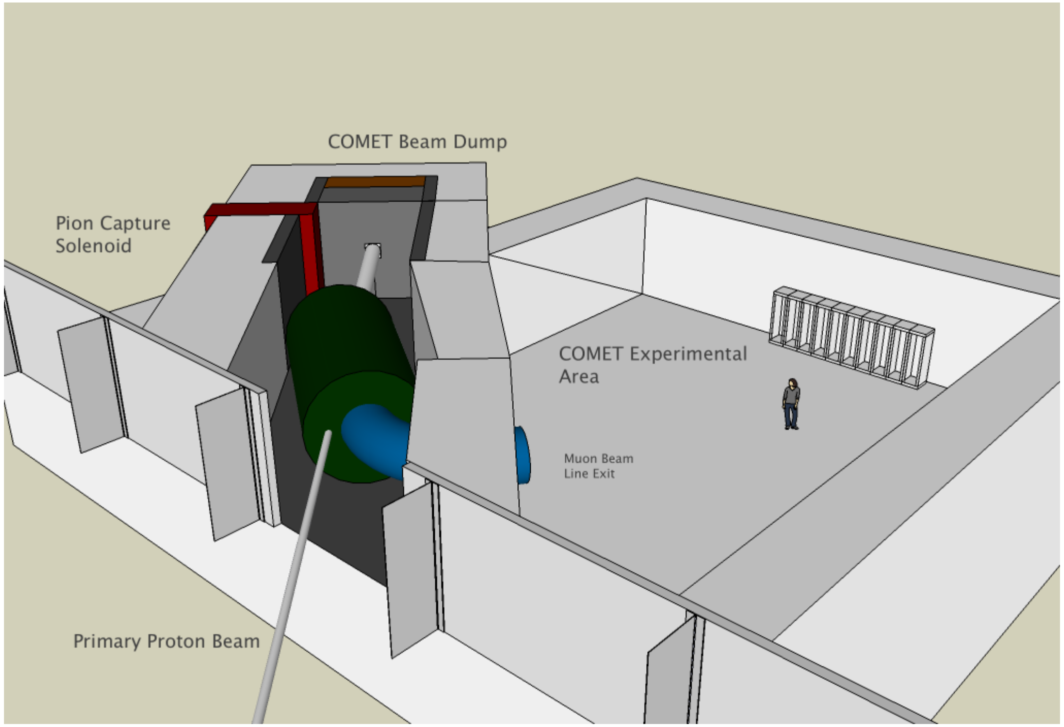
1. Demonstrate that beam extinction >=10^{-9} can be achieved

2. Measure in-situ backgrounds: neutrons, anti-p, nuclear capture products and so refine/optimise the simulation.

3. Test final/prototype detectors

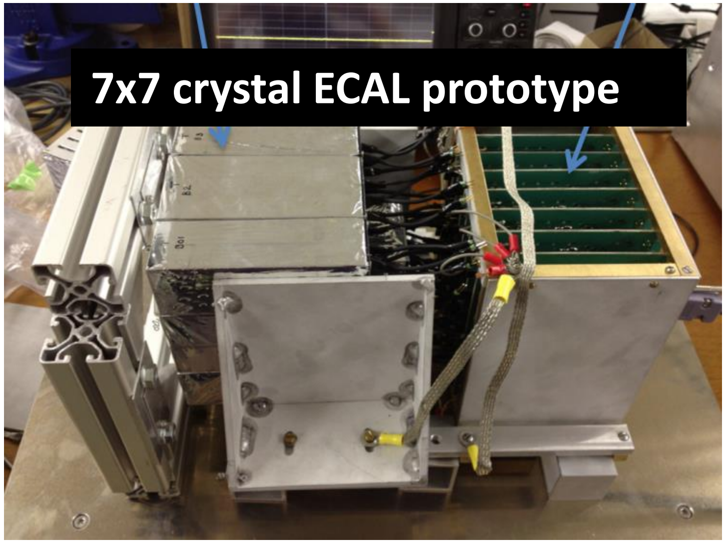
4. Measure conversion process with sensitivity **x100 that of SINDRUM-II** ie go below 10^{-14} : physics-wise comparable to the MEG (2013) limit.

CLFV: COMET construction has begun

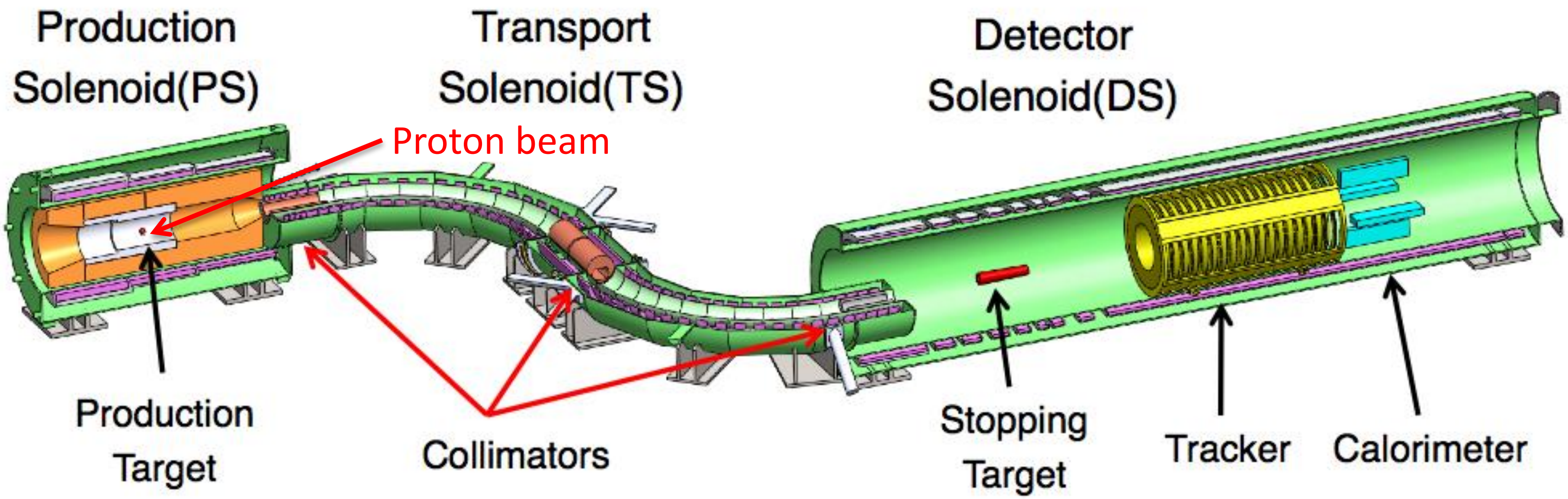


UK Groups (Imperial, Manchester, Oxford, UCL, RAL)

- production target
- trigger / DAQ
- offline simulation and framework
- late arriving particle tagger



CLFV: Mu2e @ FNAL

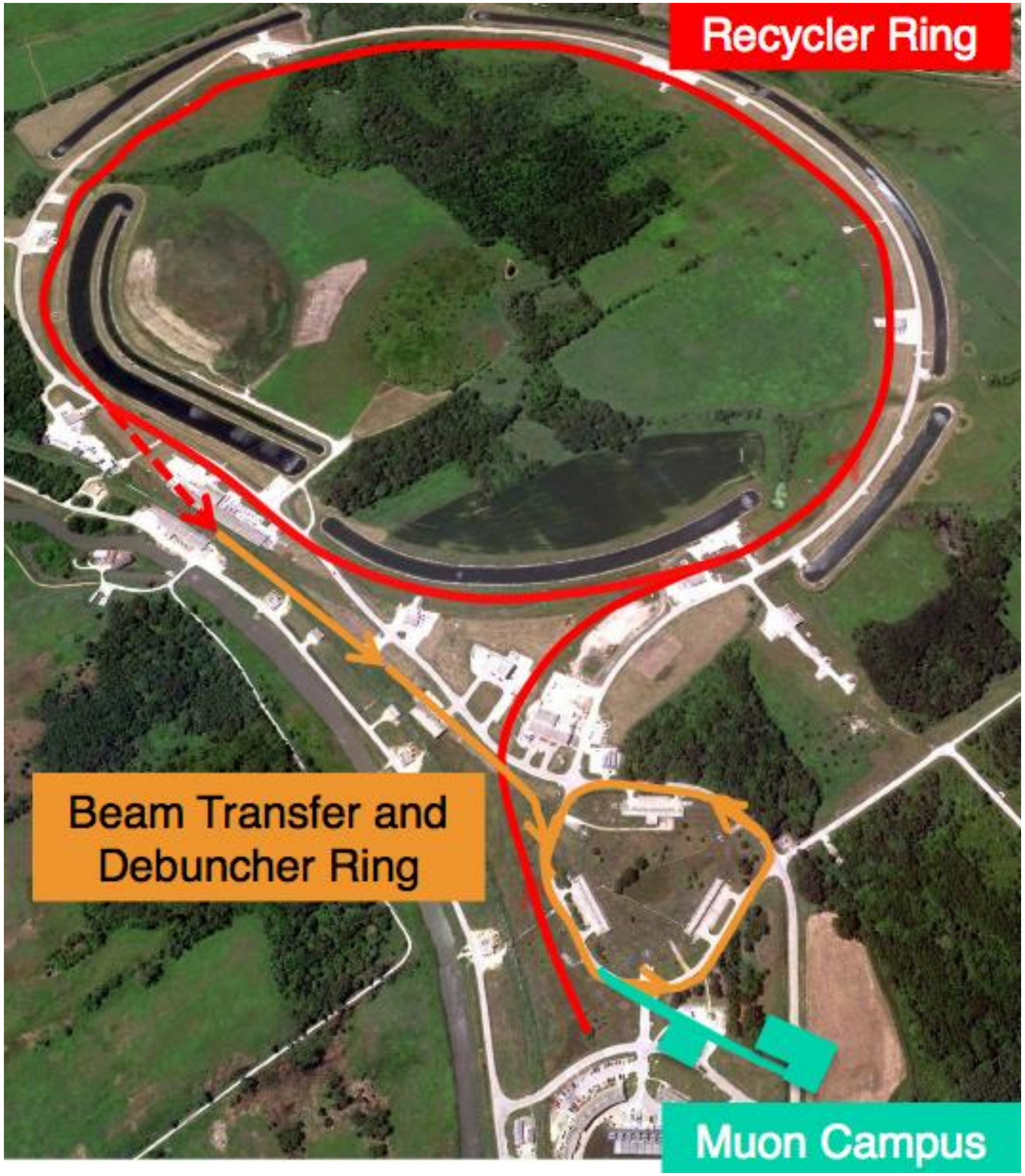


Same physics reach as COMET Phase-II

Consists of 3 superconducting solenoid systems

DOE CD1 approval granted in 2012

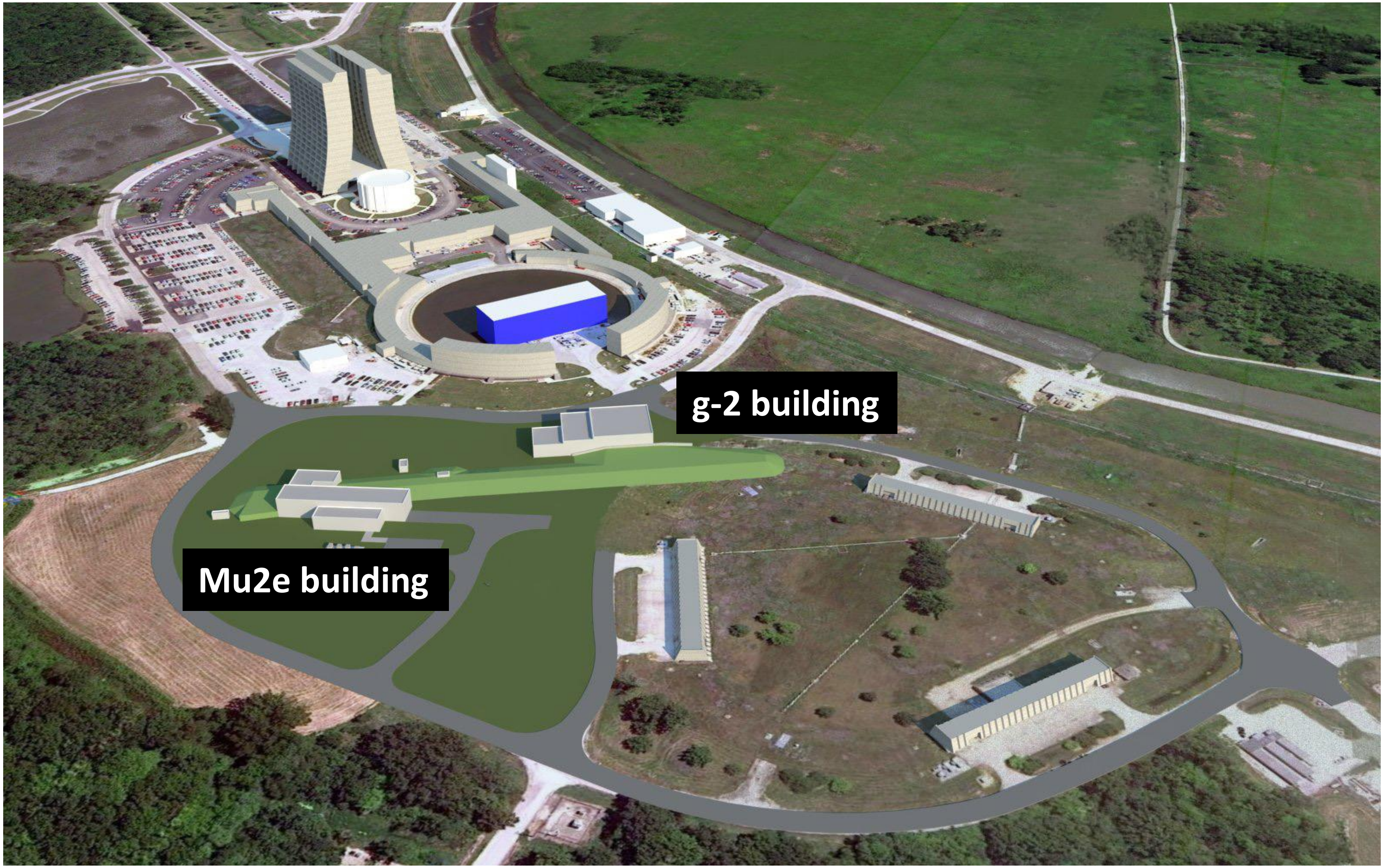
Mu2e and g-2 @ FNAL: Proton Beam Delivery



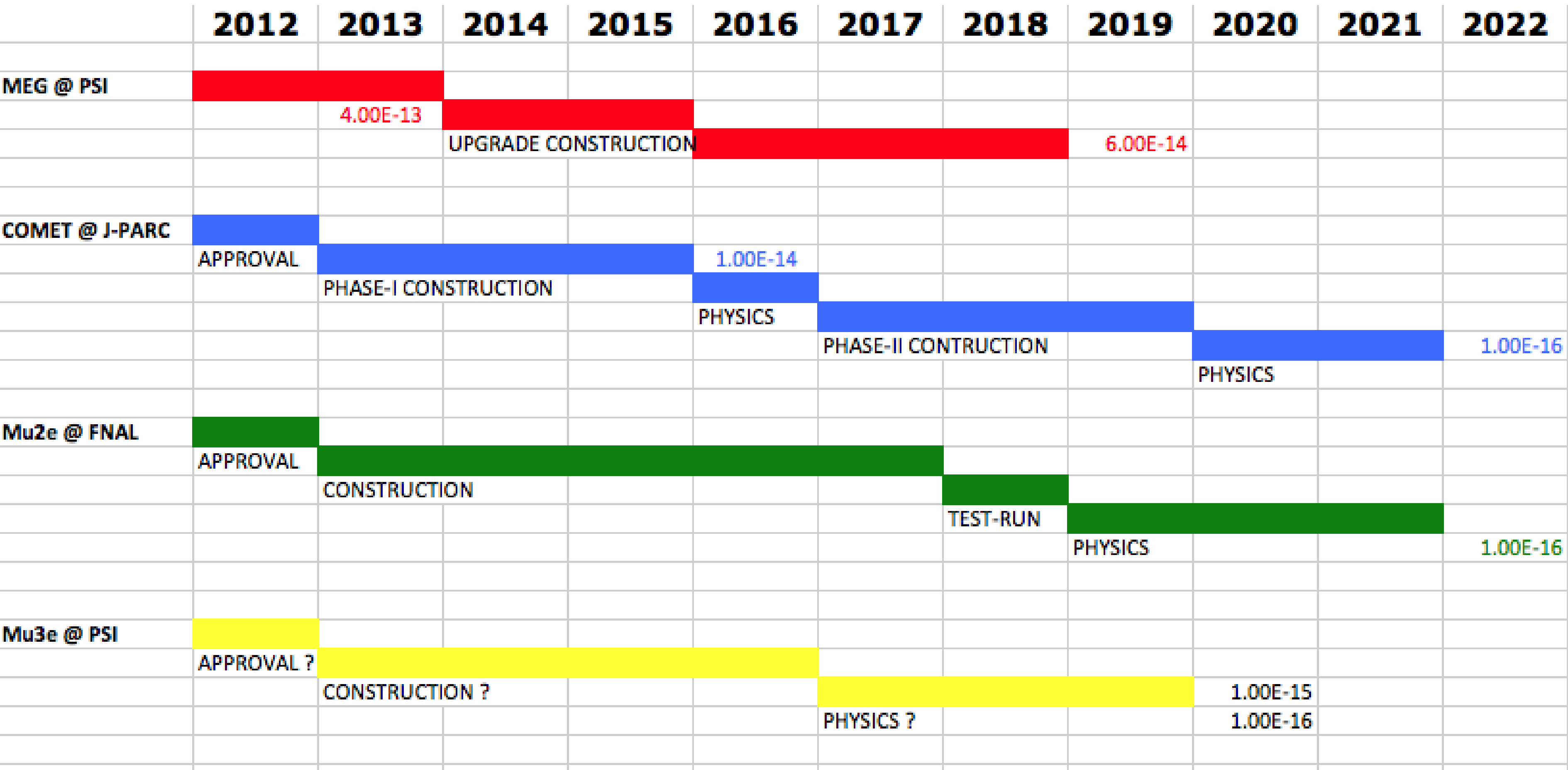
Many components shared between g-2 and Mu2e

Mu2e and g-2 @ FNAL: Muon Campus

Construction of the g-2 building has begun



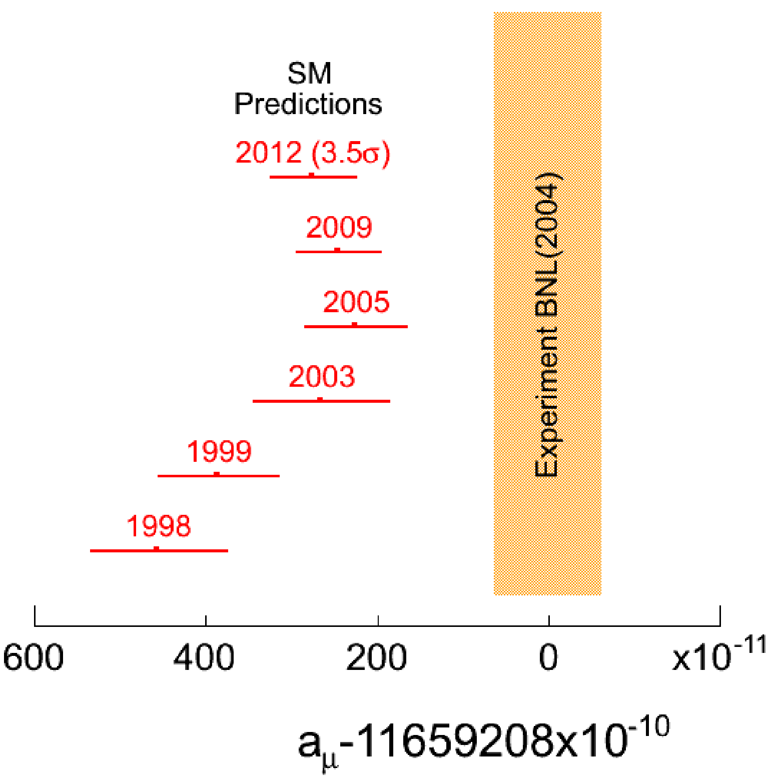
CLFV: Timelines and expected sensitivities

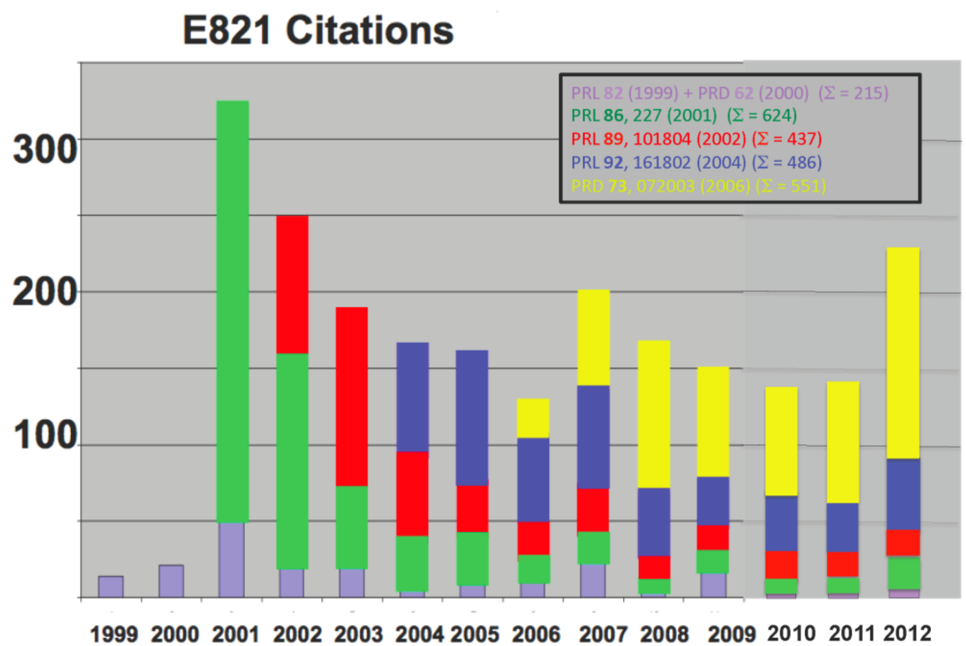


[Scientific case for Mu3e accepted by PSI. First tests of prototype sensors at DESY.]
[Budget for COMET Phase-I beam line approved.]

g-2: the story has just begun…

BNL measurement differs from SM prediction by about 280 x 10^{-11} (~ 3.5 σ)





2nd most cited paper(s) in experimental particle physics

Have to firmly establish discrepancy and find/constrain NP models

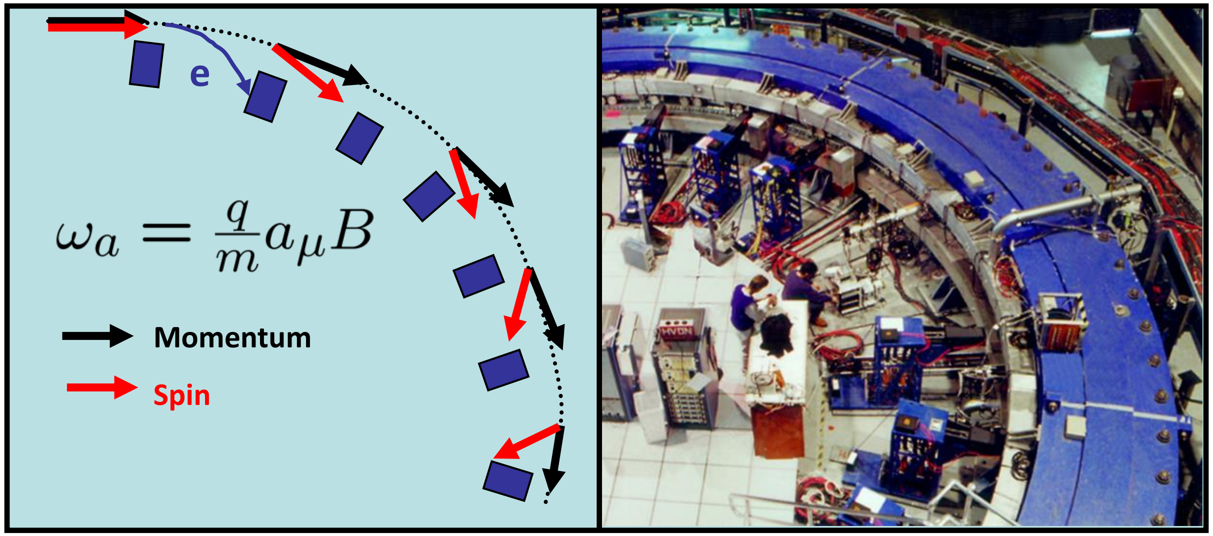
g-2 @ FNAL: aiming for 0.14 ppm precision

1. Use established technique (& apparatus)

2. Increase # of muons by factor of 21 to reduce statistical error by over 4

3. Reduce systematics by factor of 3

$$\omega_a = \omega_{\text{spin}} - \omega_{\text{cyclotron}}$$



BNL uncertainty (10^{-11})

Proposed FNAL uncertainty (10^{-11})

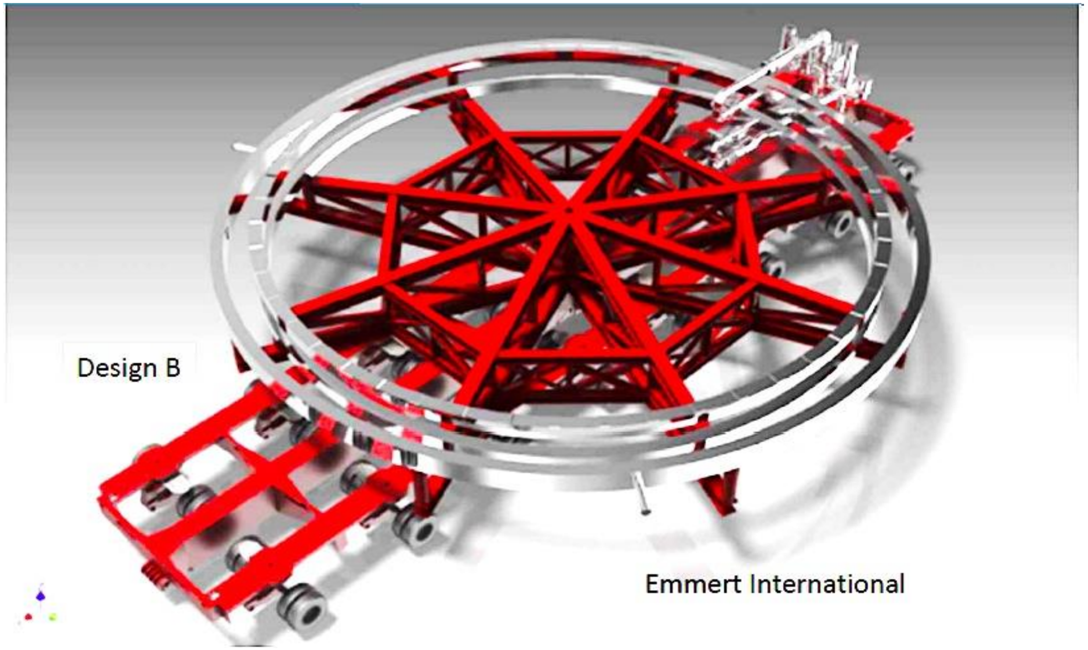
$$54\ (\text{stat}) \oplus 33\ (\text{sys}) \rightarrow 11\ (\text{stat}) \oplus 11\ (\text{sys})$$

SM uncertainty (10^{-11}) now

SM uncertainty (10^{-11}) 2017

$$42\ (\text{HVP}) \oplus 26\ (\text{HLBL}) \rightarrow 15 \oplus 15$$

g-2 @ FNAL: work has begun



Must be shipped in one piece

g-2 @ FNAL: planned transport of the ring

4 week journey of the ring from BNL to FNAL to begin June 2013

CDR being finalised now

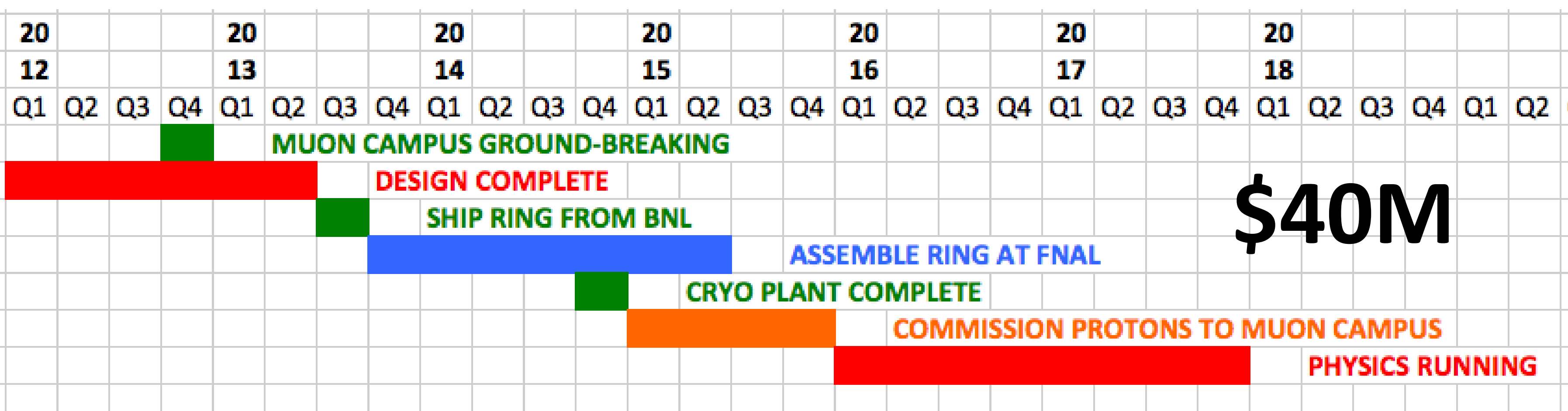
Expect DOE CD1 in summer

g-2 @ FNAL: UK contributions

Proposed contributions from 5 institutes in 5 areas:

- Construction of straw trackers (Liverpool)
- Squid Magnetometer (Oxford)
- DAQ (UCL/Oxford)
- Injection system (STFC RAL TD/STFC Cockcroft)
- Physics optimisation (hadronic SM contribution)

First beam in muon storage ring @ FNAL in 2016.



g-2: BNL/FNAL AND J-PARC

[From Naohito Saito]

■ Complementary!

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

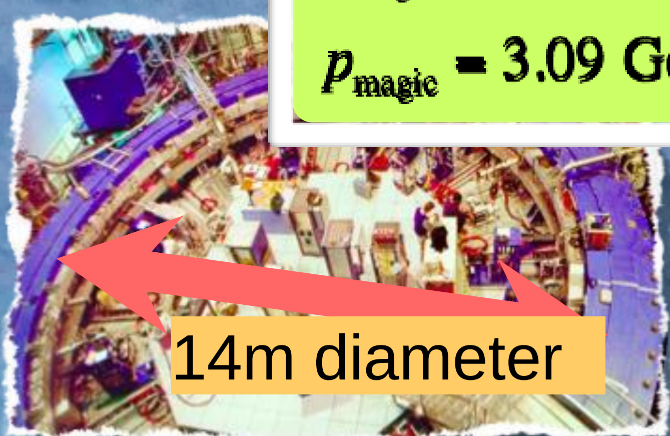
BNL/Fermilab Approach

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

$$\eta \approx 0$$

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

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

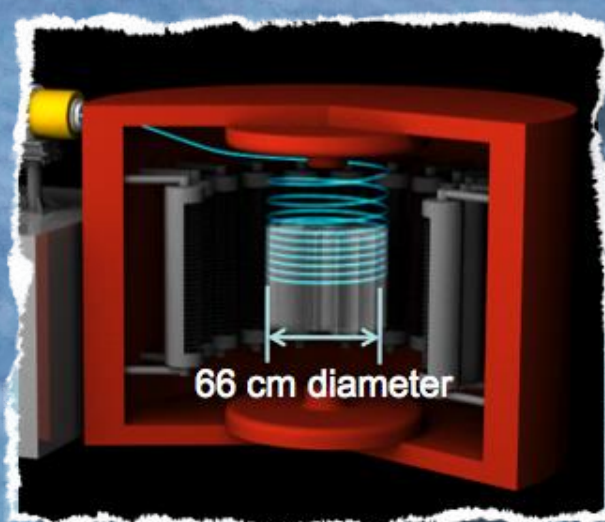


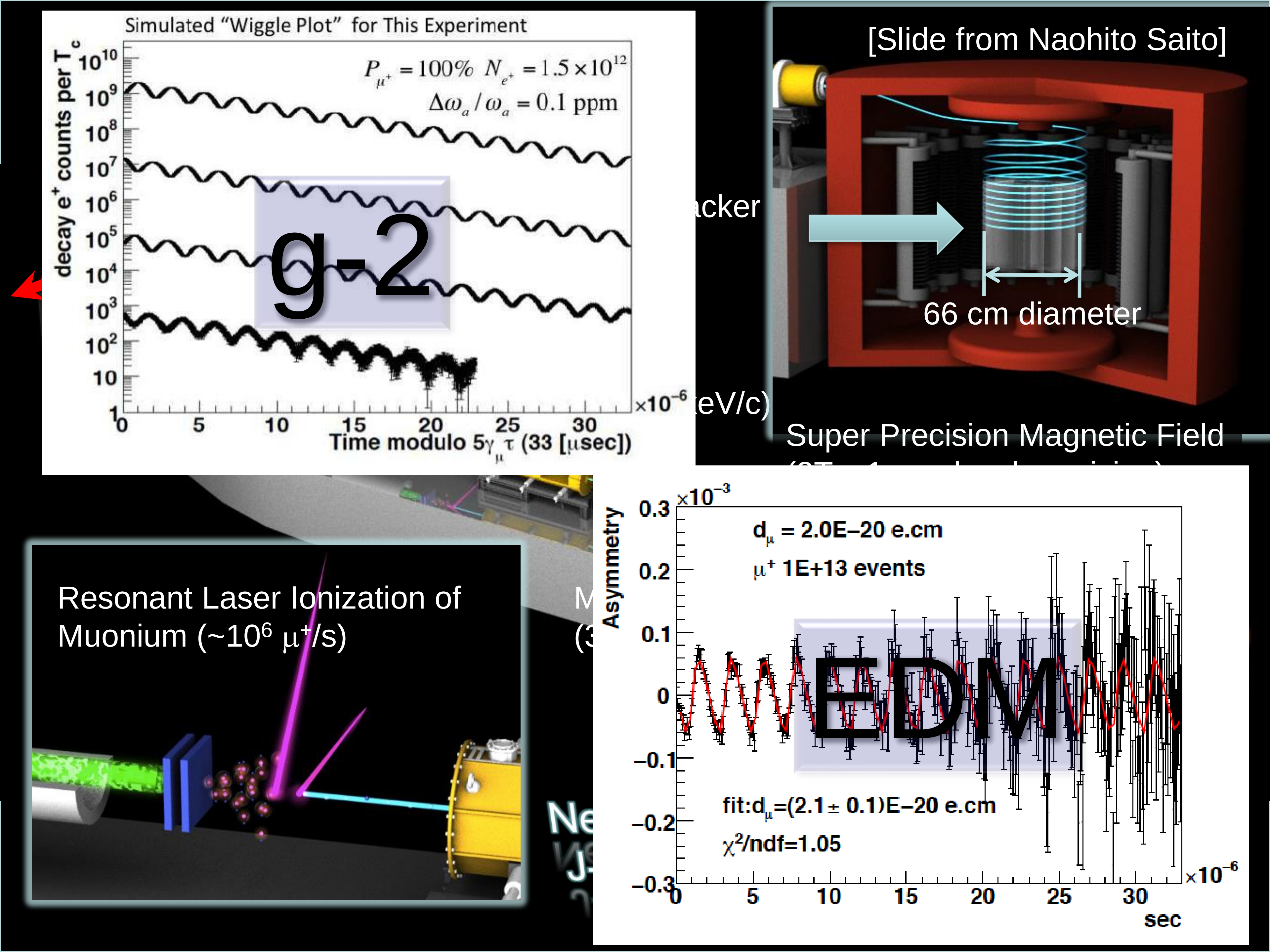
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

J-PARC Approach

$$\vec{E} = 0$$

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





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 Tc
Time modulo 5γμτ (33 [μsec])
g-2
[Slide from Naohito Saito]
acker
66 cm diameter
eV/c)
Super Precision Magnetic Field
Resonant Laser Ionization of
Muonium (~10^6 μ+/s)
dμ = 2.0E−20 e.cm
μ+ 1E+13 events
fit:dμ=(2.1 ± 0.1)E−20 e.cm
χ2/ndf=1.05
Asymmetry
sec
EDM

g-2: BNL/FNAL vs J-PARC

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		Very weak magnetic
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm

[From Tsutomu Mibe]

Conclusions

- Low energy precision experiments with leptons strongly test the SM and already exclude/constrain many BSM scenarios

- g-2, CLFV and EDMs often complementary to direct searches; rich experimental programme involving many facilities

- Muon g-2 discrepancy consolidated at $> 3\ \sigma$, but no signs for SUSY at the LHC so far

- Big improvements in sensitivity for future projects, eg
  g-2 and Mu2e @ FNAL, g-2 and COMET @ J-PARC

- Groups from UK hope to contribute significantly to this!

Stay tuned

Thank you.

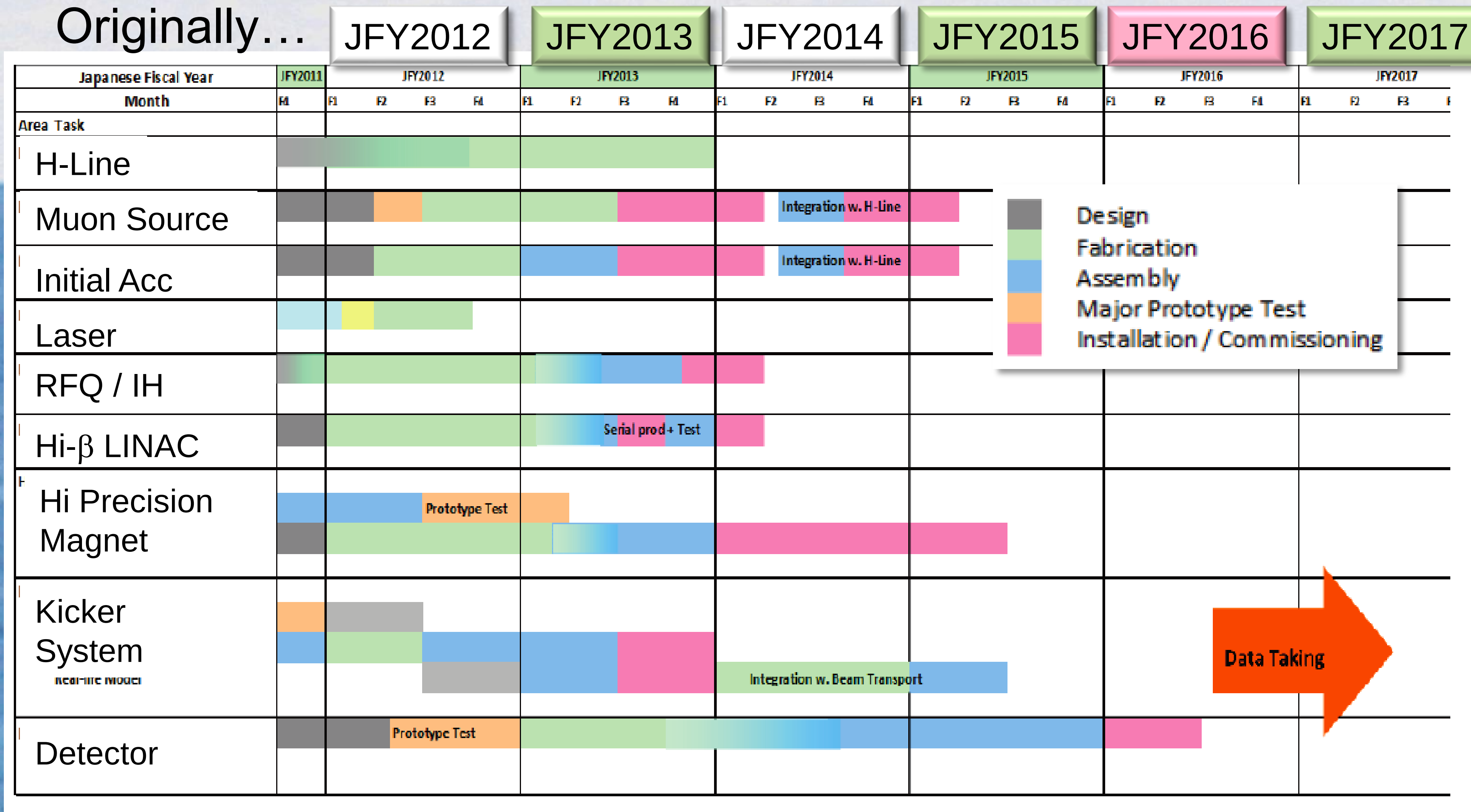
Spares

g-2 @ J-PARC: schedule

[From Naohito Saito]

- **Need to be competitive with Fermilab g-2 which starts in 2016.**

Originally…

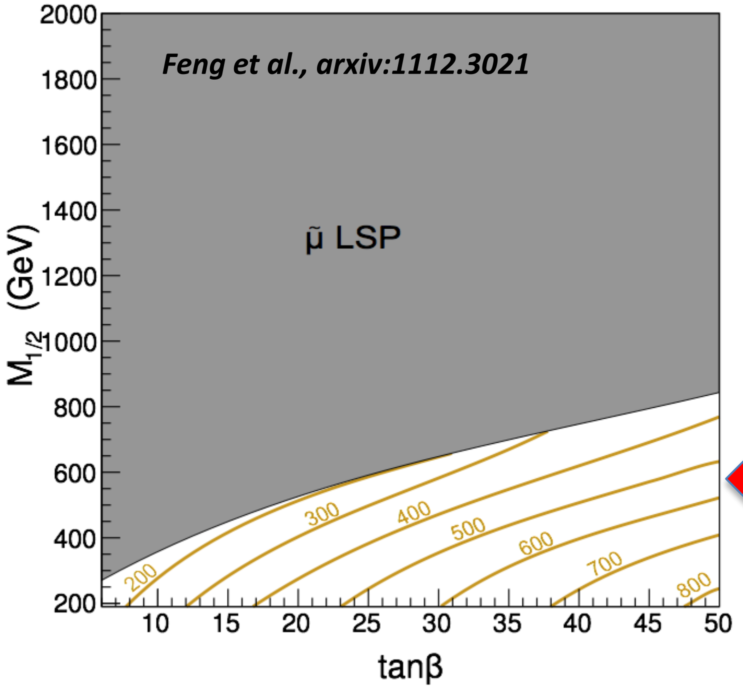


g-2 and SUSY

LHC/Dark Matter data rule out much of light squarks / gluino param.-space, but light sleptons (best limits from LEP) still not excluded

“Looking to (SUSY) models with a different connection between the coloured and uncoloured sector, not only seems timely now, but mandatory.”

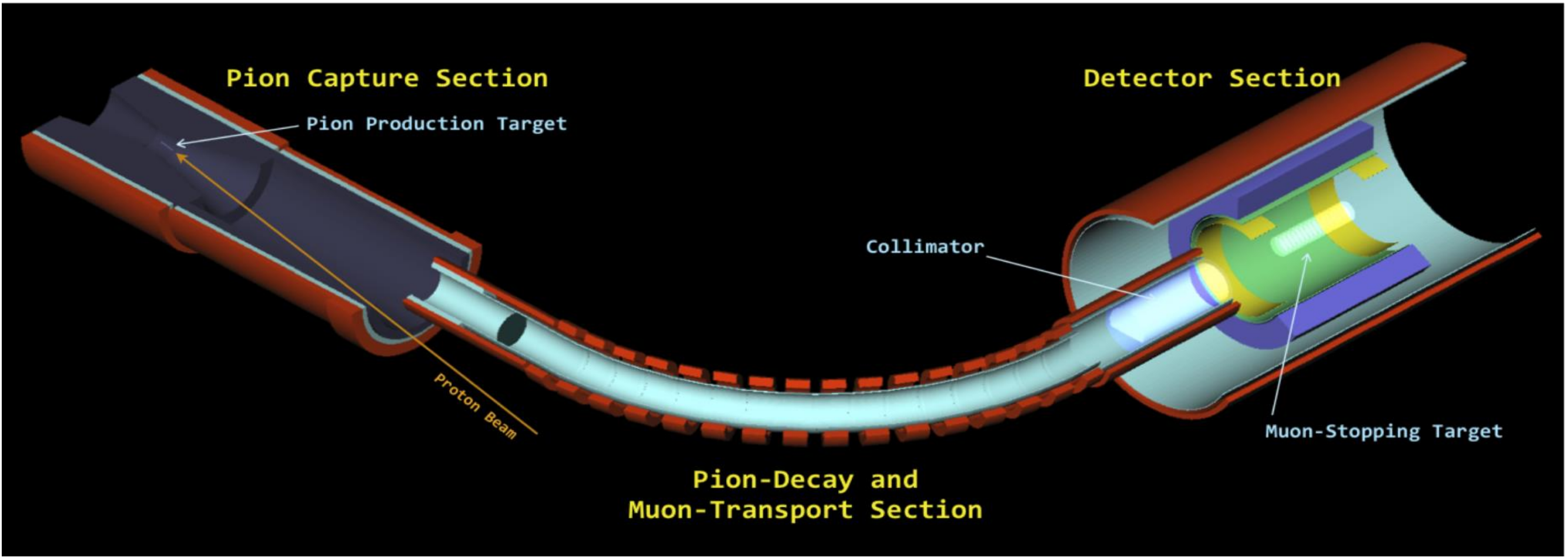
John Ellis et al, arxiv:1207.7315



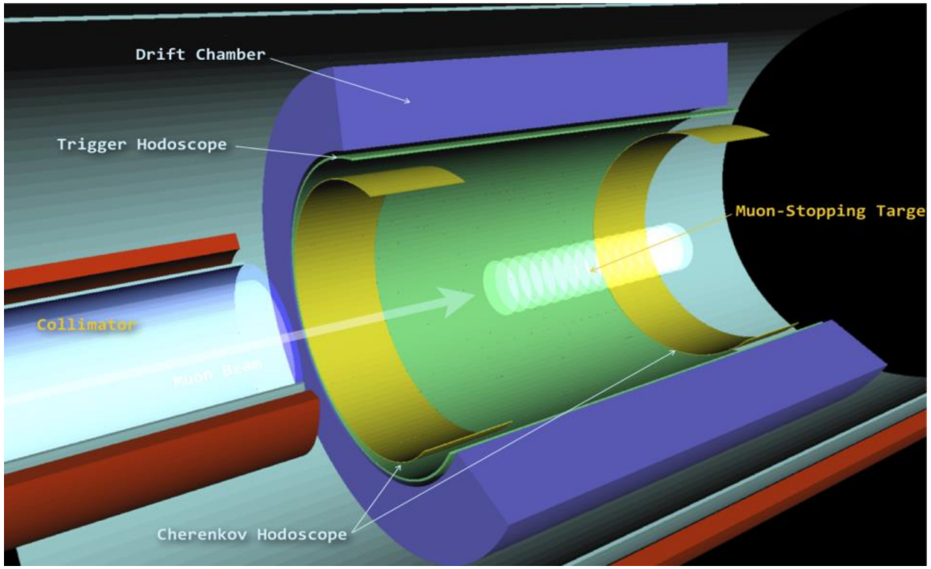
SUSY contribution to g-2 determined by smuon, sneutrino, chargino and neutralino masses

Smuon masses contributing 280×10^{-11} to a_μ

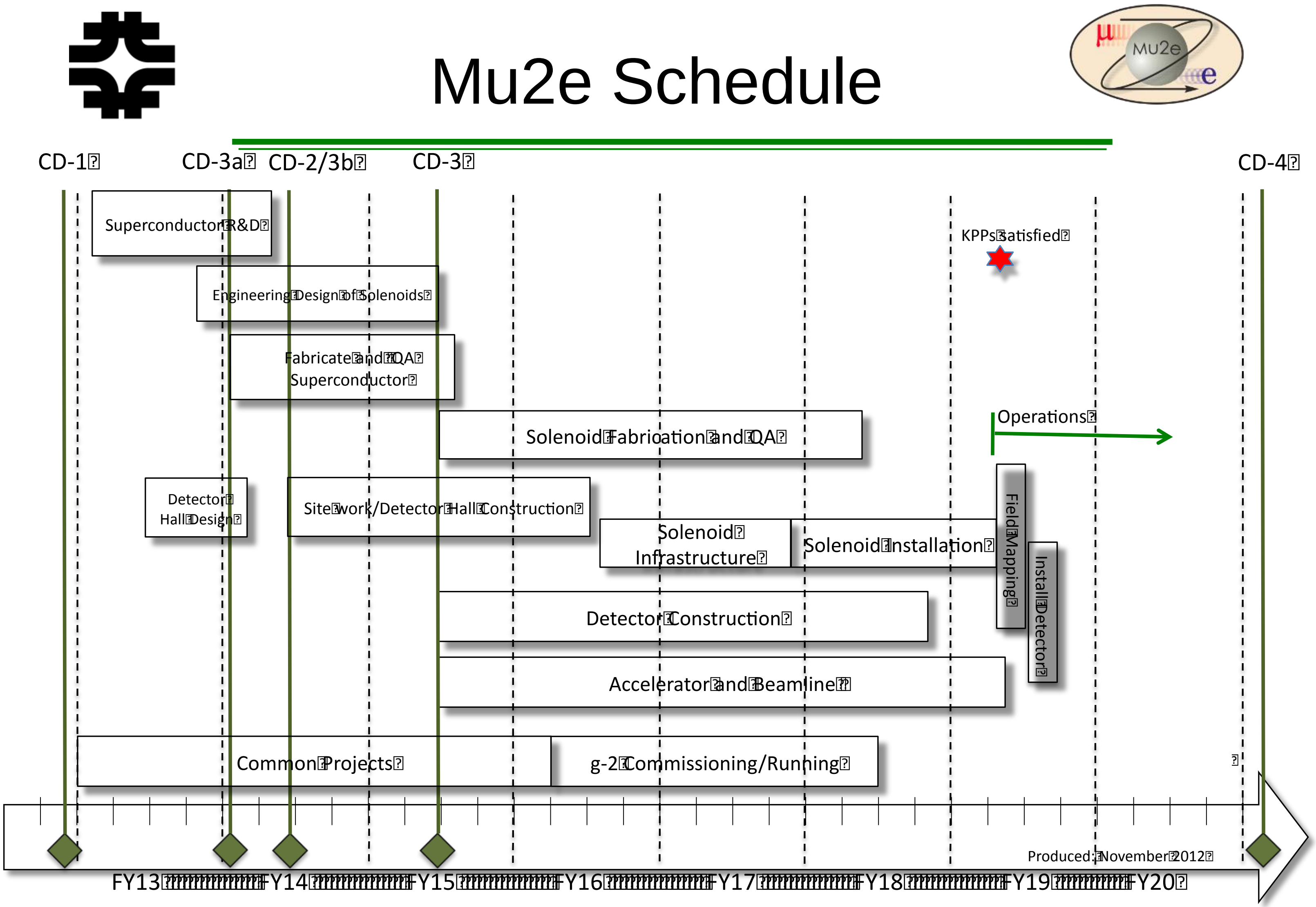
CLFV: COMET Phase-I



Cylindrical detector
has higher acceptance but poorer resolution compared to transverse/phase-II detector



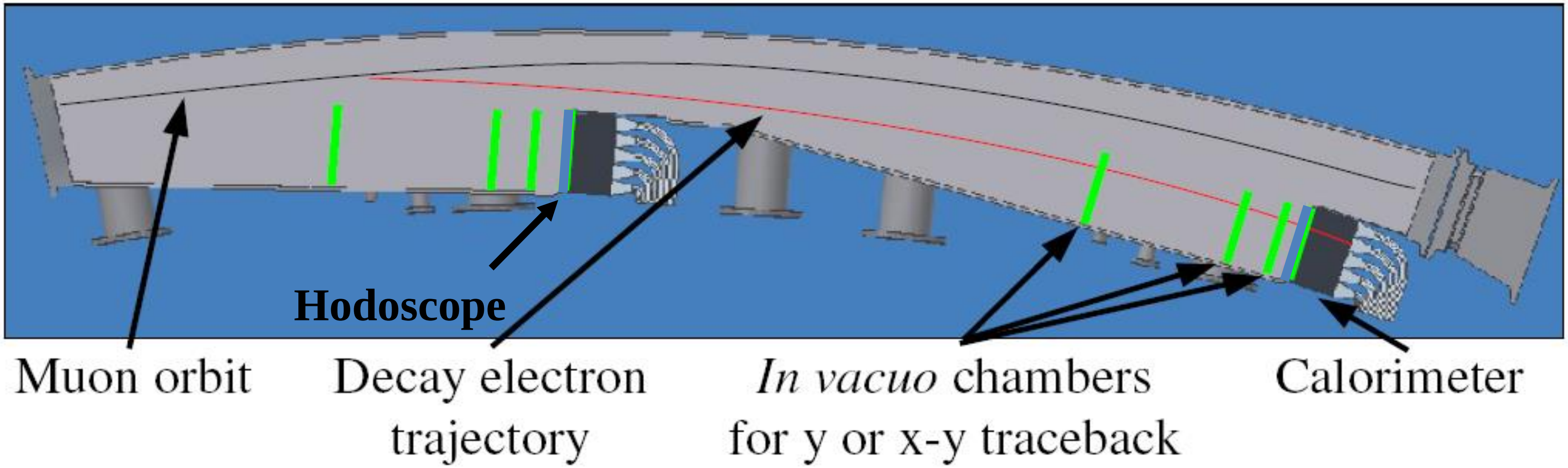
Mu2e: Schedule



g-2 @ FNAL: UK Contributions

Construction / design of straw trackers with FNAL

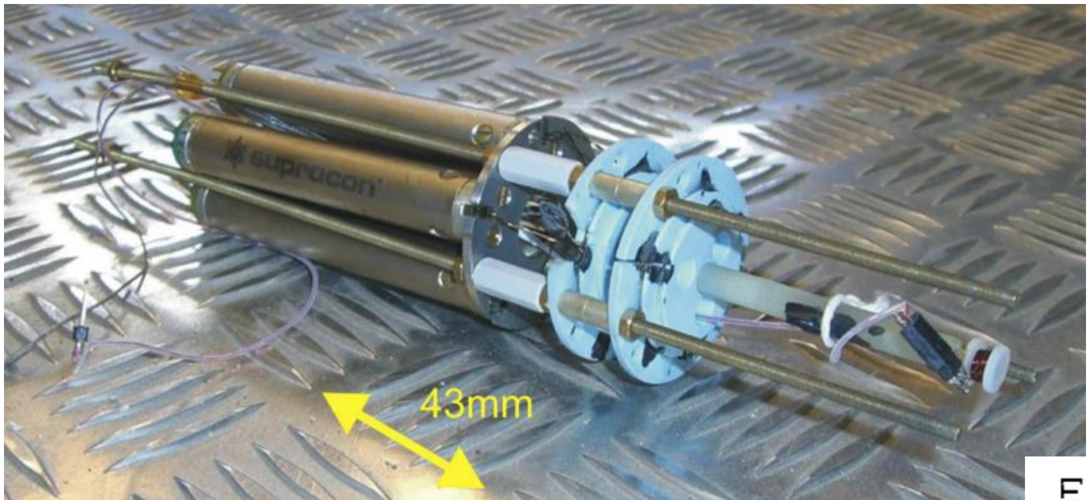
Straw trackers:
- understand and correct for pileup effects in calorimeter
- monitor beam trajectory / losses
- measure muon electric dipole moment



g-2 @ FNAL: UK Contributions

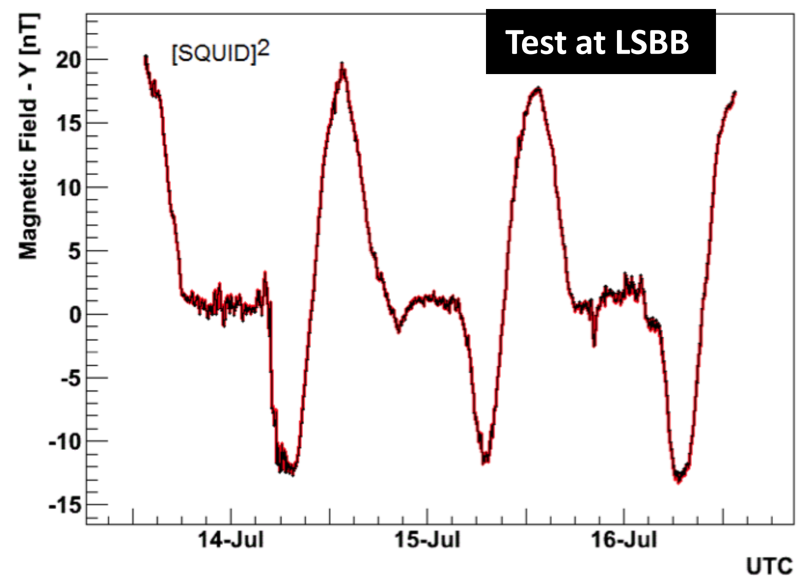
Squid Magnetometer

- to improve magnetic field monitoring



Prototype developed for cryoEDM experiment

Pickup-loops and SQUID inside superfluid ^{3}He

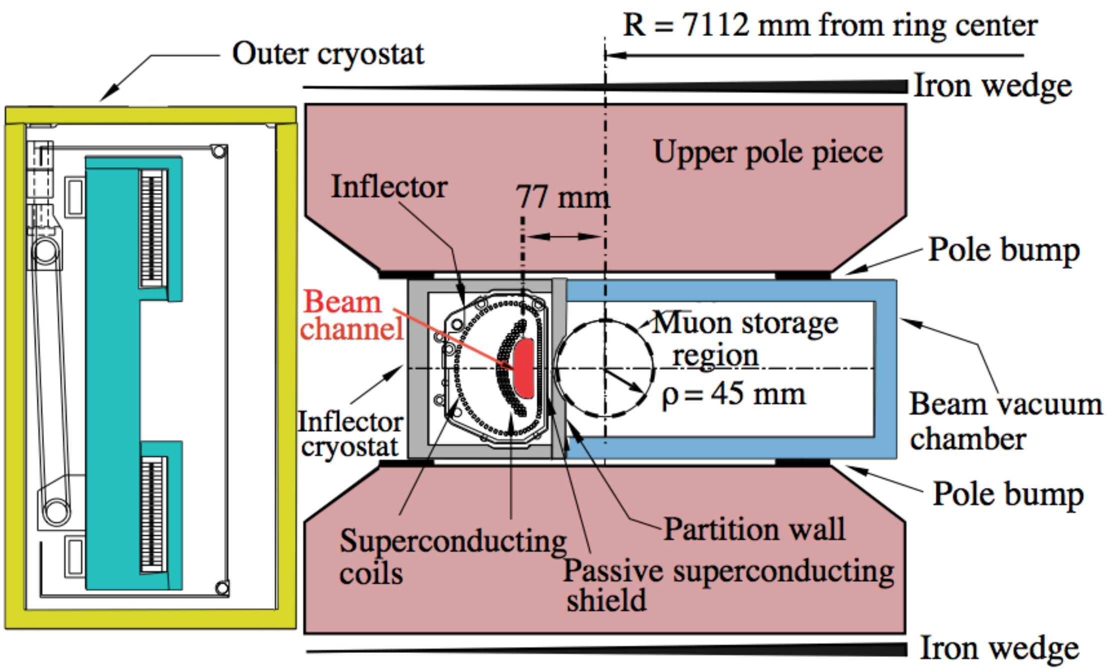


g-2 UK Contributions

Modeling of injection/kicker system (software)

Design of new inflector magnet

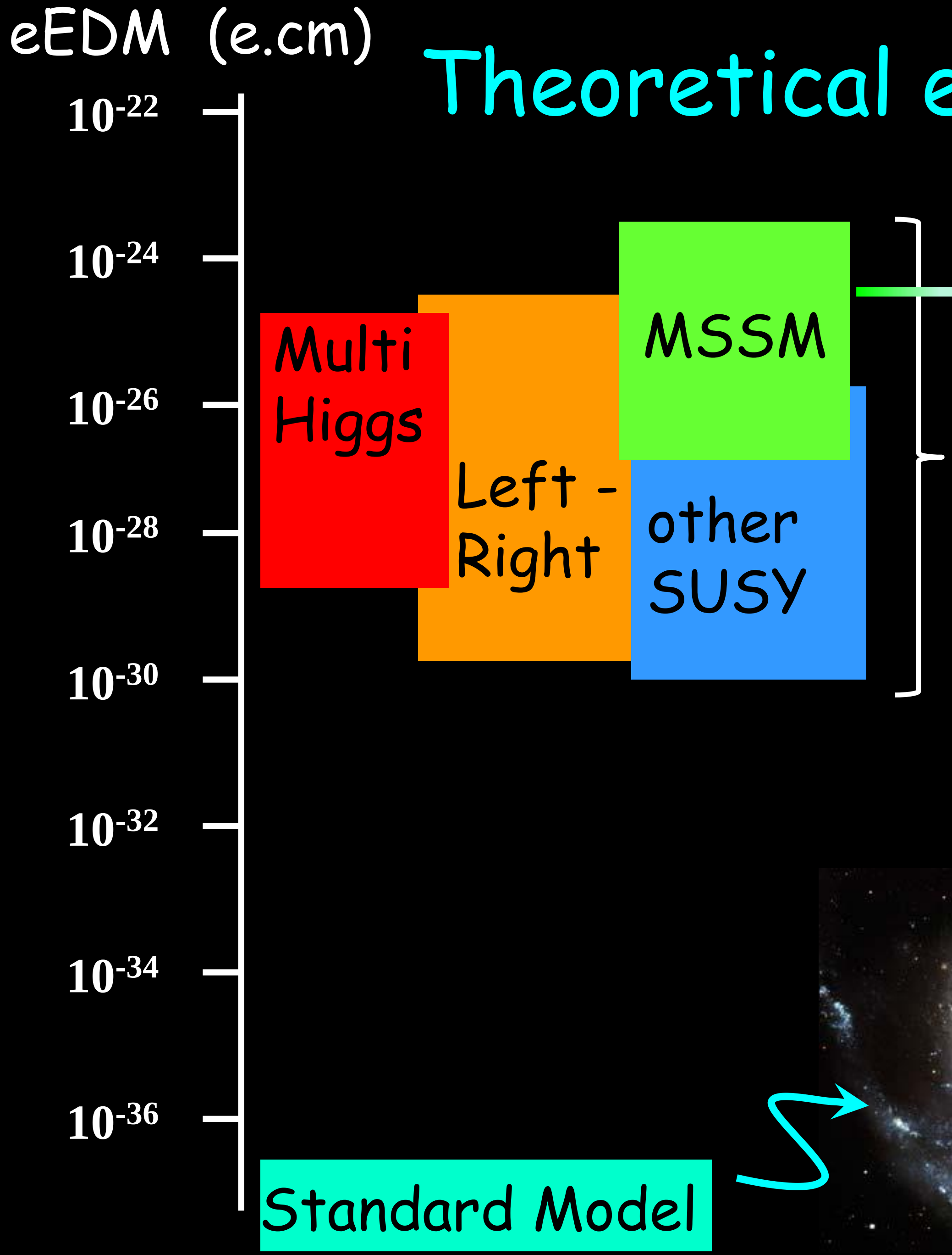
- reduce muon loss on injection

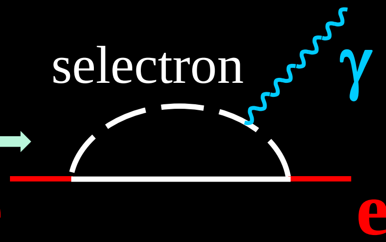


- Non-ferromagnetic, static with no flux leakage into storage ring
- Null storage ring field

[From Ed Hinds' talk @ Liverpool 2013]

Theoretical estimates of eEDM





$$\frac{\alpha}{\pi}\frac{m_e}{m_s^2}\sin\phi$$

The interesting region of sensitivity

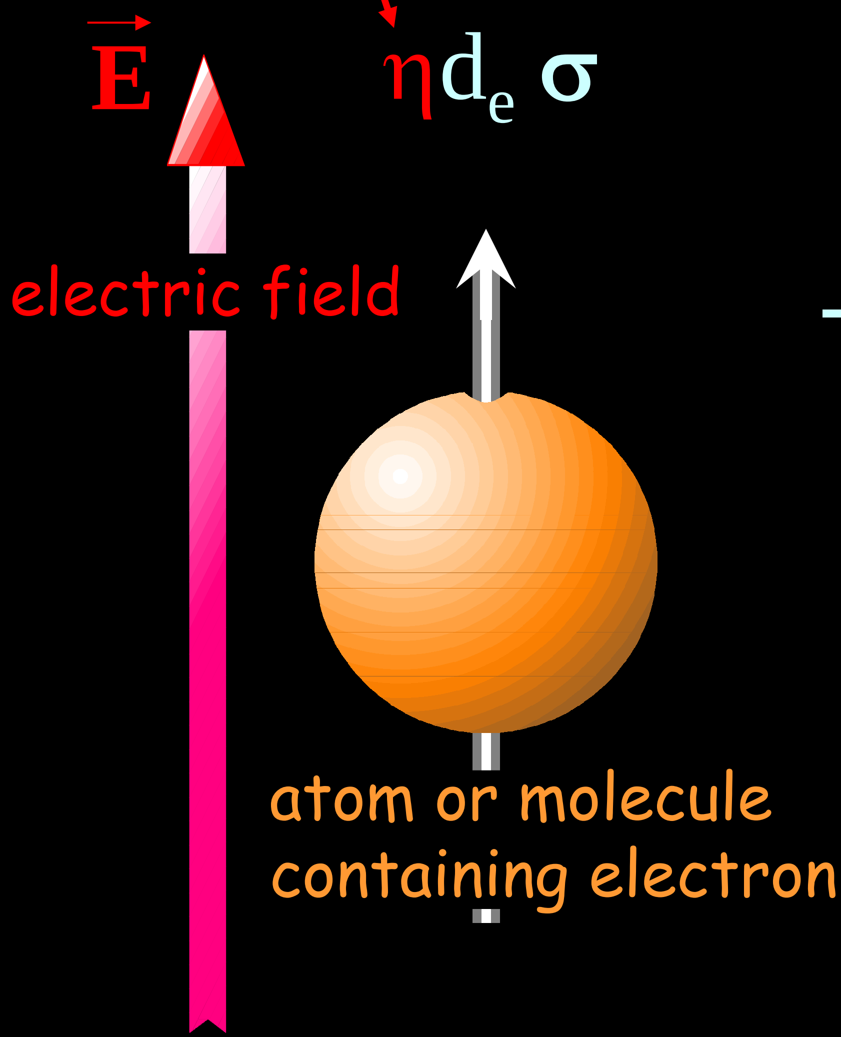
Insufficient ~~CP~~ to make universe of matter

A clever solution

For more details, see E. A. H. Physica Scripta T70, 34 (1997)

amplification (Sandars)

$\eta d_e \sigma$



Interaction energy

$$-d_e\, \eta \vec{E} \cdot \vec{\sigma}$$

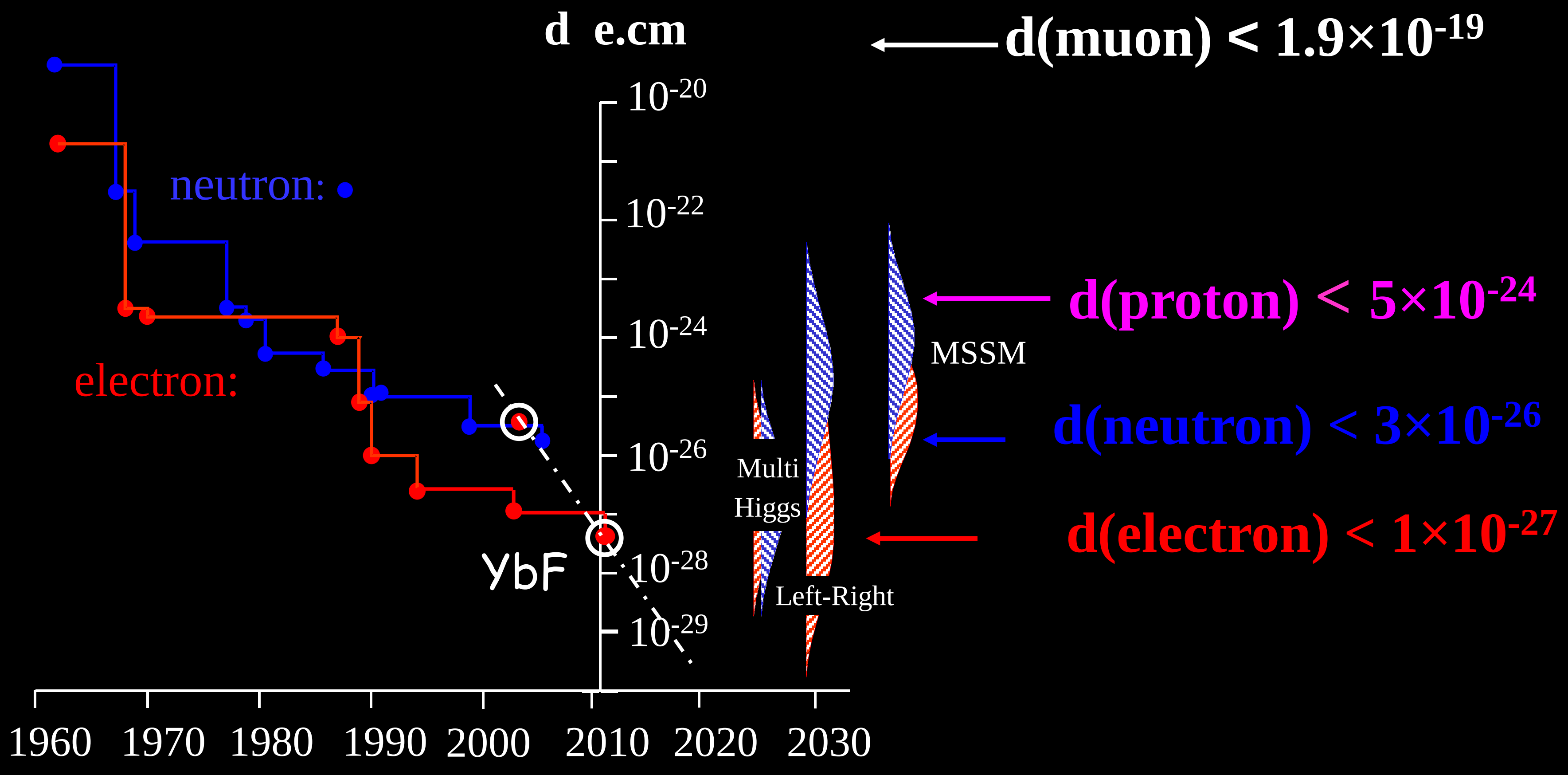
η → $F\,P$

P → Polarization factor

F → Structure-dependent relativistic factor $\propto Z^3$

[From Ed Hinds' talk @ Liverpool 2013]

Current status of EDMs



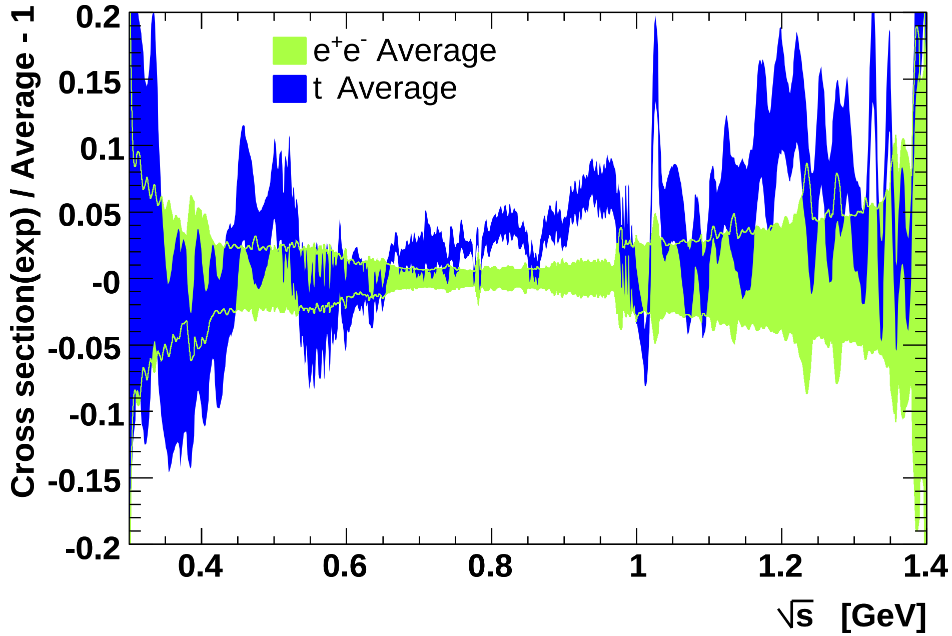
[From Ed Hinds' talk @ Liverpool 2013]

What about the τ 'puzzle'?

- CVC hypothesis (Isospin-symm.) connects $\tau^- \to \pi^- \pi^0 \nu_\tau$ to $e^+ e^- \to \rho, \omega \to \pi^+ \pi^-$
- Sizeable Isospin-symmetry violations [from radiative corrections, mass differences ($m_{\pi^-} \neq m_{\pi^0}$), $\rho - \omega$ interf.] (→ Cirigliano+ Ecker+ Neufeld)
- Role of possible $\rho^0 - \rho^\pm$ mass difference?
- Width difference $\Gamma_{\rho^0} \neq \Gamma_{\rho^\pm}$?

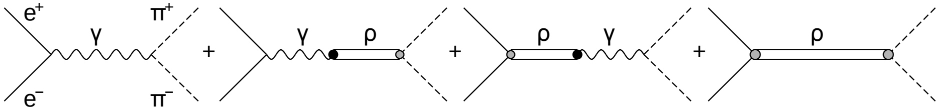
  Large effects possible!
  Are the model calculations reliable?

Davier et al. [0908.4300]: τ compared to $e^+ e^-$ data



→ Benayoun et al. [EPJC55 (2008) 199; C65 (2010) 211, C68 (2010) 355]: τ ok with $e^+ e^-$
[mixing + isospin breaking effects in model based on 'Hidden Local Symmetry']

→ Jegerlehner+ Szafron [EPJC71(2011)1632]: crucial role of $\rho - \gamma$ mixing!



↪ τ compatible with and confirm $e^+ e^-$, but limited gain in accuracy for a_μ!