Near and long term prospects @ FNAL (mu2e and g-2)

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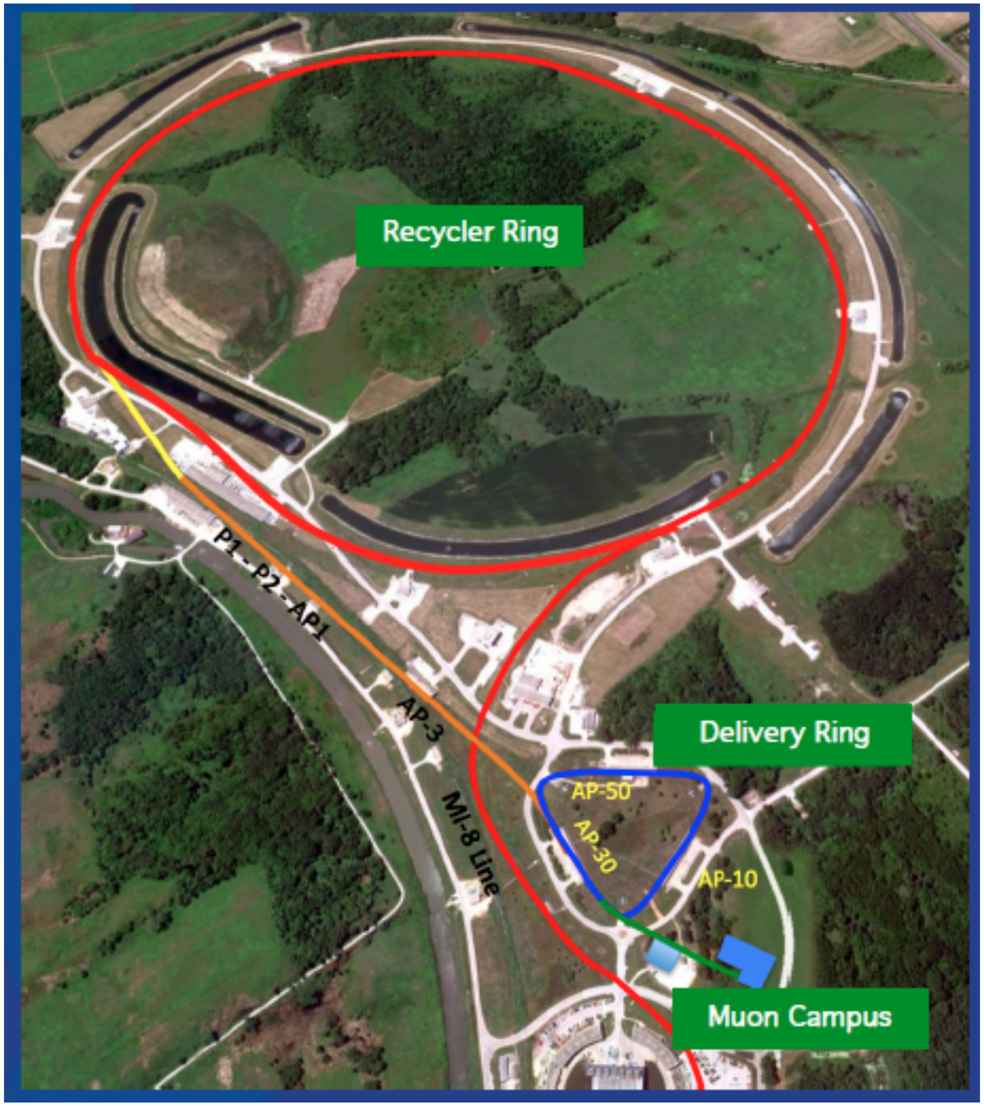
Intensity frontier: the muon campus

Upgrade of infra-structure in progress to convert the anti-proton source to a high intensity muon source

First "planned" users:
→ g-2 (2017)
→ Mu2e (2020)



AIP = Accelerator Improvement Project

Recycler RF AIP:

Adds RF capability to Recycler meeting g-2/ Mu2e specifications

Delivery Ring AIP:

Modify Delivery Ring to deliver custom beams to the muon experiments

Beam Transport AIP:

New connection from Recycler to Delivery Ring, improve apertures

Muon campus optimizes g-2 and Mu2e

✧ Maximize shared Infrastructure
→ 1 CRYO plant
→ 1 new beam tunnel
→ 1 new RF system

✧ It results in a Cost and schedule optimization

✧ It capitalizes the 100 M$ existing equipment

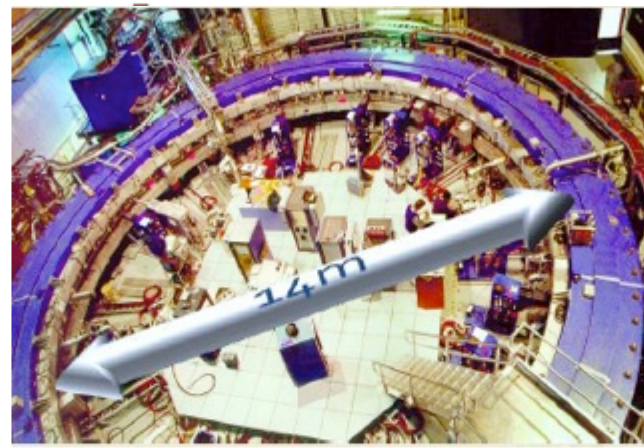
Total cost of Muon Campus: 46 M$ (g-2), 55M$(muon campus), 260 M$ (Mu2e)

What is g-2? Why is needed ?

INFN Istituto Nazionale di Fisica Nucleare

Mu2e

a_μ = (g-2)/2 is derived from the precession of the muon spin in a well-measured magnetic field



- New experiment at FNAL (E989) at magic momentum, Consolidated method.
- **20 x** μ w.r.t. E821 @ BNL.
- **Relocate the BNL storage ring to FNAL.**

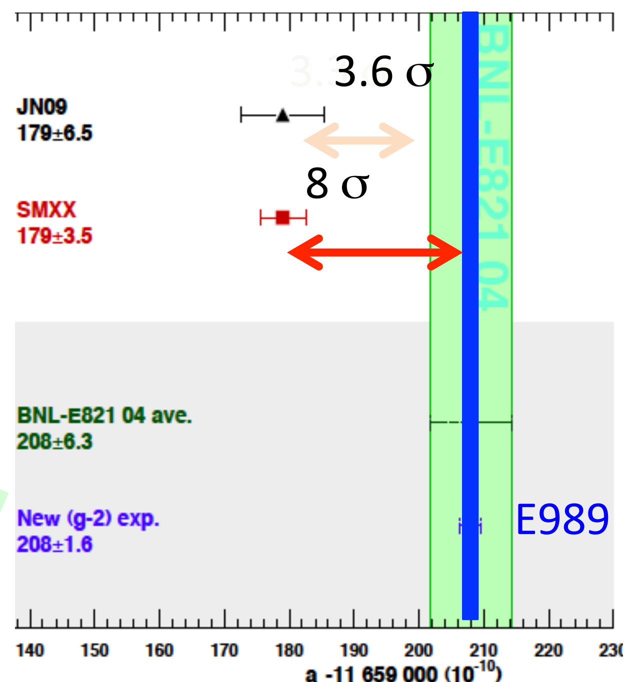
$\Rightarrow$ **a x4 improvement on a_μ (from 540 ppb to 140 ppb)**

If the central value remains the same $\Rightarrow$ 5-8 σ from SM* (enough to claim discovery of New Physics!)

*Depending on the progress on Theory

From G.Venanzoni

Thomas Blum; Achim Denig; Ivan Logashenko; Eduardo de Rafael, ... oberts, B.; Thomas Teubner; Graziano Venanzoni (2013). "The Muon (g-2) ... heory Value: Present and Future". arXiv:1311.2198 [hep-ph].

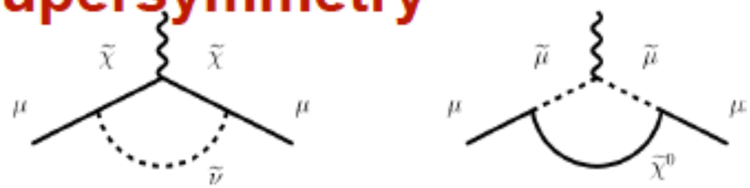


g-2 …

- Error budget – goal $\Delta a_\mu \rightarrow 16\text{x}10^{-11}$
- mu+ first phase
- mu- second phase

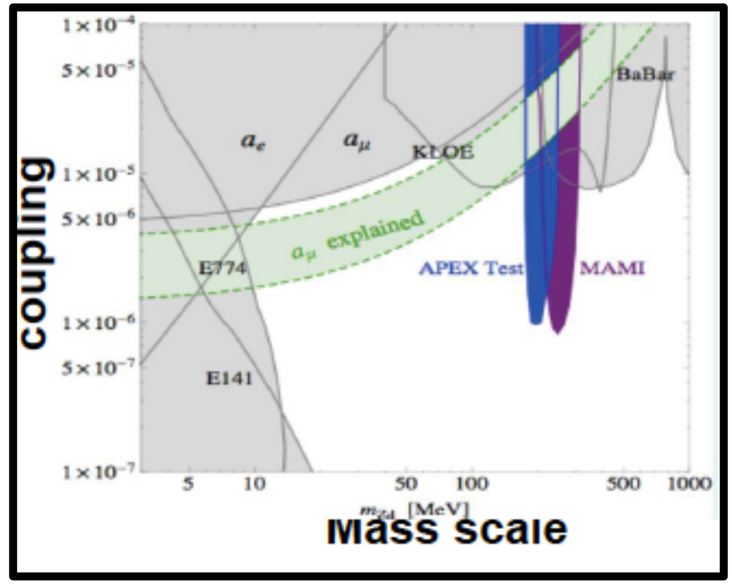
Category	Error (ppb)	vs BNL E821
Statistical	100	x20 events
Field Systematics	70	x2 better
Precession Systematics	70	x3 better

- **Supersymmetry**



$$a_\mu^{SUSY} \approx 130\times10^{-11}\left(\frac{100\ \text{GeV}}{M_{SUSY}}\right)^2 \tan\beta\ \text{sign}(\mu)$$

Difficult to measure at the LHC



DARK PHOTONS:
Light new Vector Particle, U, from Dark sector, kinematically mixed with the photon

g-2 collaboration and INFN

E989 Collaboration: 38 Institutes; >150 Members
20 USA institutions + Italy, China, NL, Japan, Russia, Germany, England, Korea.

- ❑ Ring move completed
- ❑ Ring being reassembled.
- ❑ Building practically finished
- ❑ Prototype detectors will be tested in beams
- ❑ Cost of the experiment ~ 40 M$ (Core + Labour)
- ❑ CD-2 review in July

Expected data taking in 2017

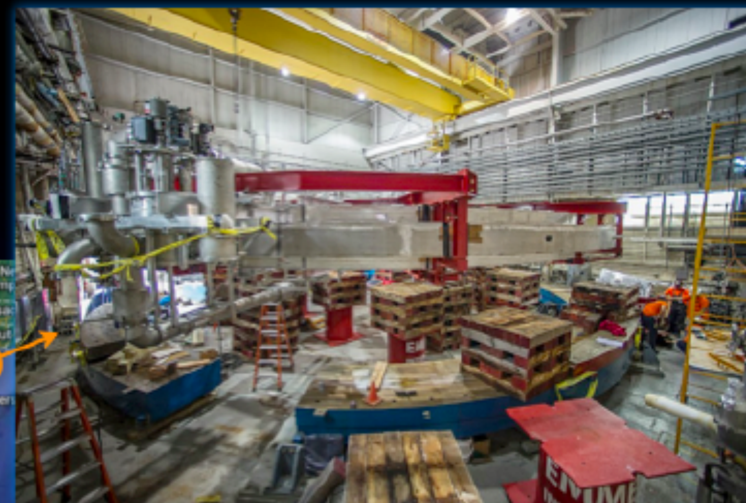
E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher n-value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05[1]	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07

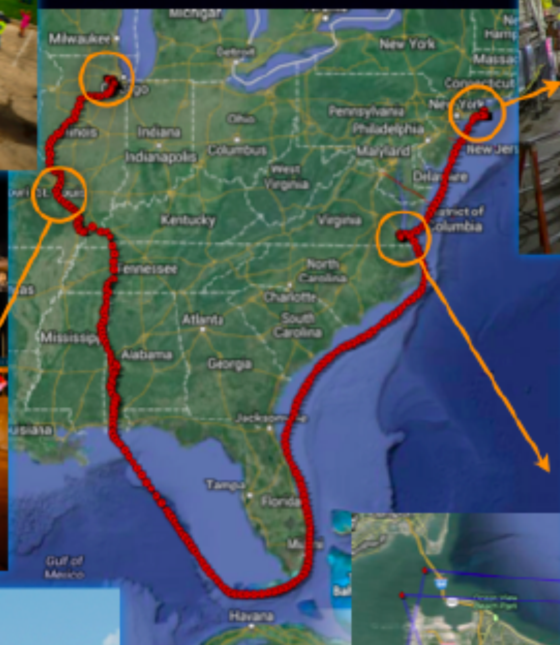
INFN Group (LNF, Na,Rm2,TS, Udine) 20 people , 10 FTE with an important item
→ improve gain calibration with precise monitor system.

Core investment expected O(300 kEuro)

Taking the ring for a spin

L. Gibbons talk PSI2013





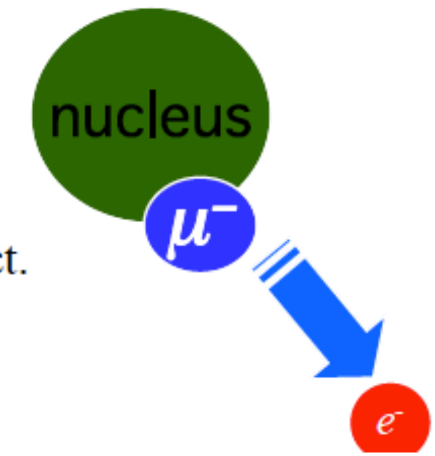
15 m diameter
3 mm flex tolerance

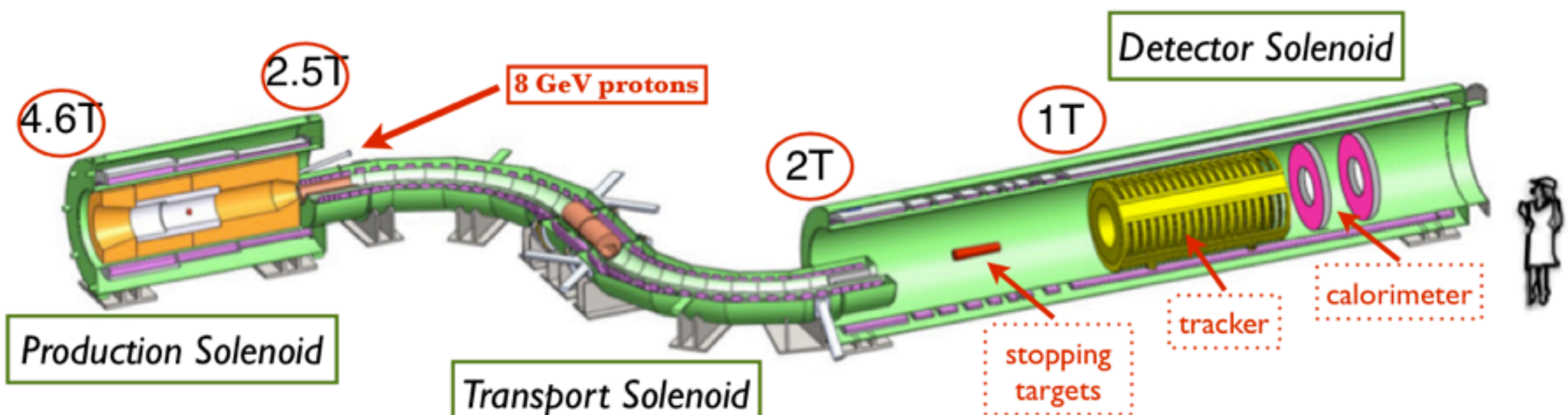
What is Mu2e? Why is needed ?

- Initial state: muonic atom
- Final state:
  - a single mono-energetic electron.
    - the energy depends on Z of target.
  - recoiling nucleus is not observed
    - the process is coherent: the nucleus stays intact.
  - neutrino-less
- Standard Model rate is 10^{-54}

60% Muon Capture
40% DIO

$$\mu N \rightarrow eN$$

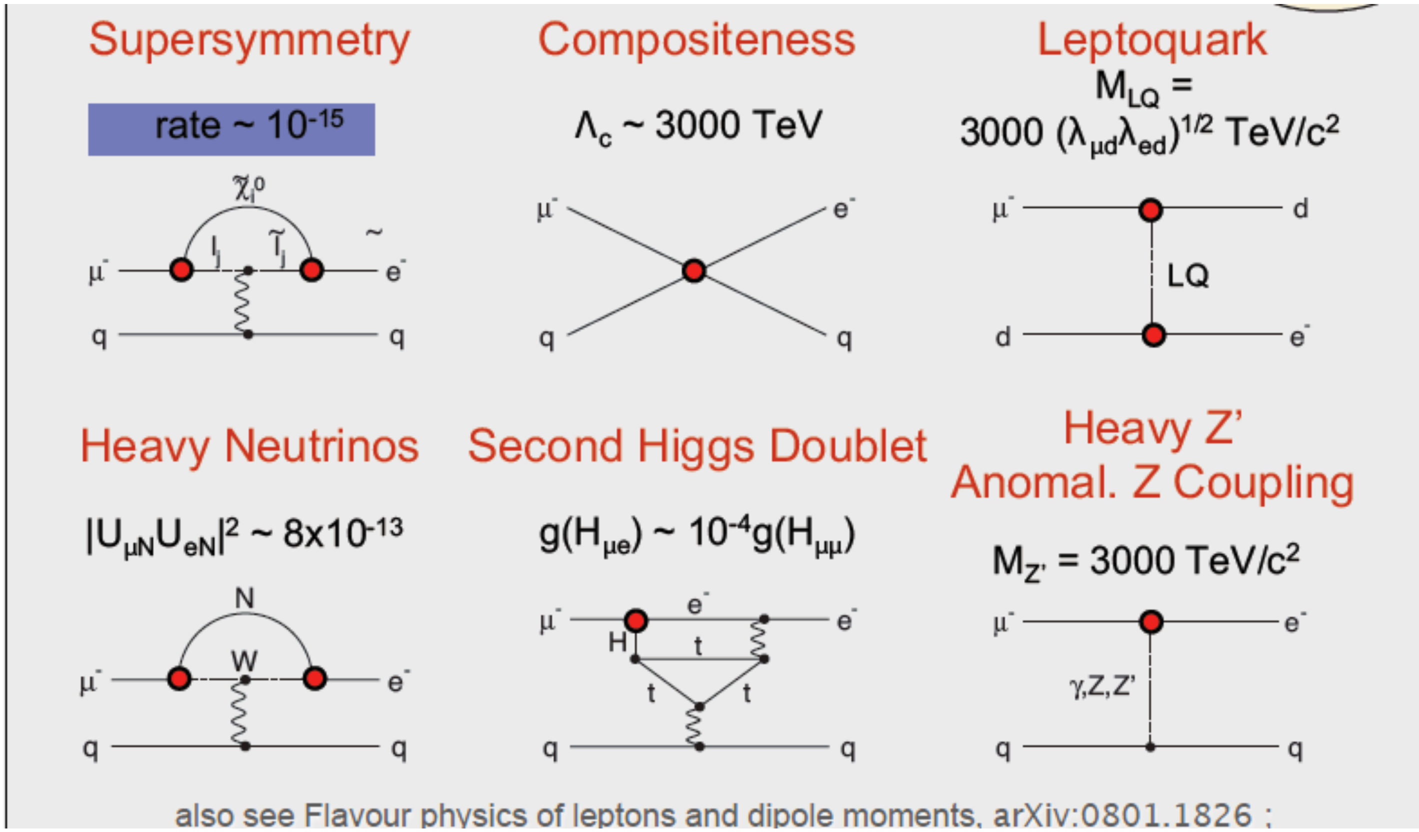




Mu2e….

Sensitivity reach: 10^4 improvement with respect to previous conversion experiment (Sindrum-II)

→ Extinction
→ Delayed gate
→ Precise Resolution

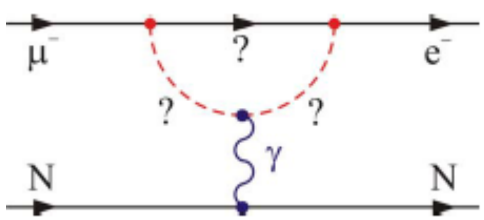


$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \to e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \to \text{ all muon capture})} \leq 6 \times 10^{-17} \text{ (@90\%CL)}$$

Mu2e….

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

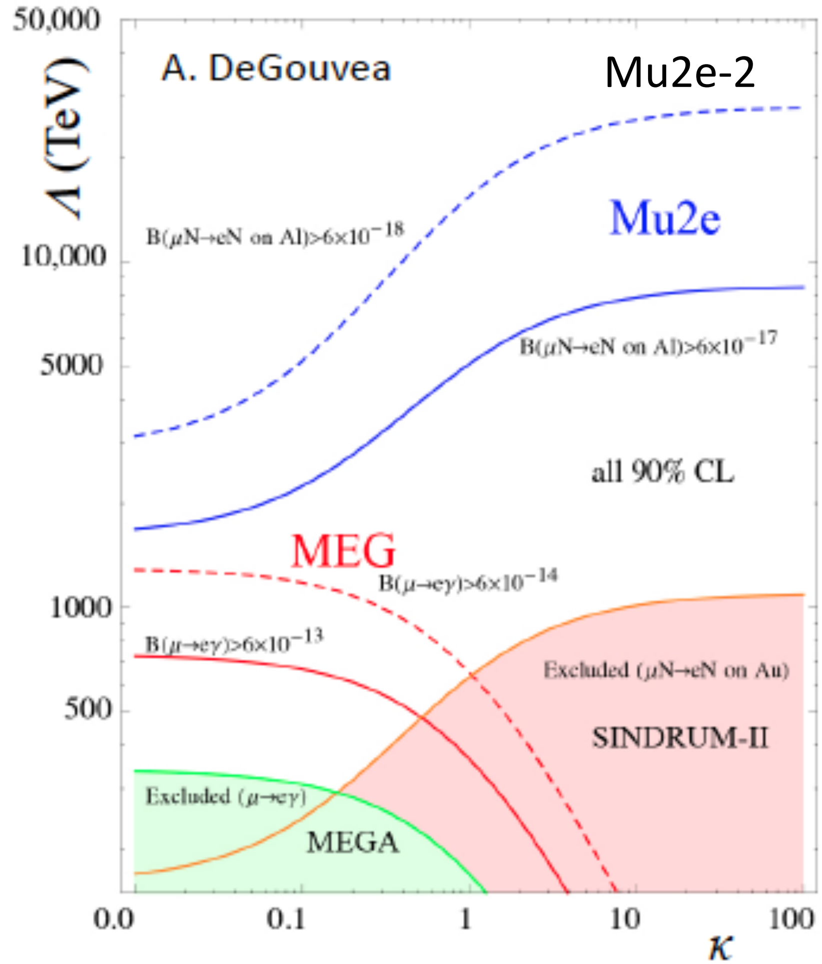
Loops dominate for $\kappa << 1$



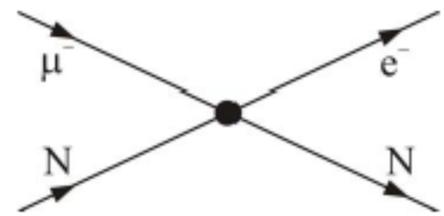
$\mu \rightarrow e\gamma$

$\mu N \rightarrow eN$

$\mu \rightarrow eee$



Contact terms dominate for $\kappa >> 1$



~~$\mu \rightarrow e\gamma$~~

$\mu N \rightarrow eN$

$\mu \rightarrow eee$

Sensitive to mass scales up to $\mathcal{O}(10^4$ TeV)

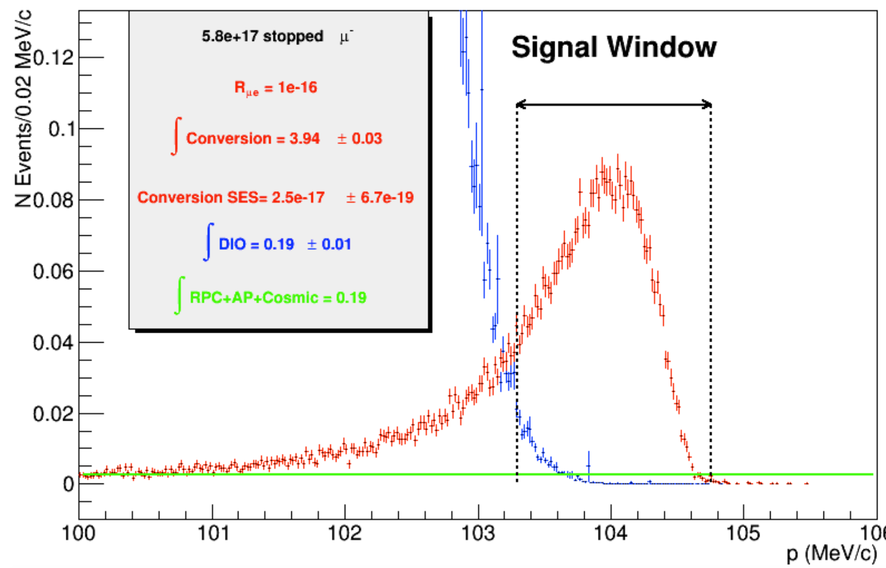
Mu2e Background Classes

- **DIO**

Muons stops and forms muonic atom
→ 60% fall in nucleus (Capture)
→ 40% decay in orbit
→ **NEED high Resolution**

- **Cosmics**

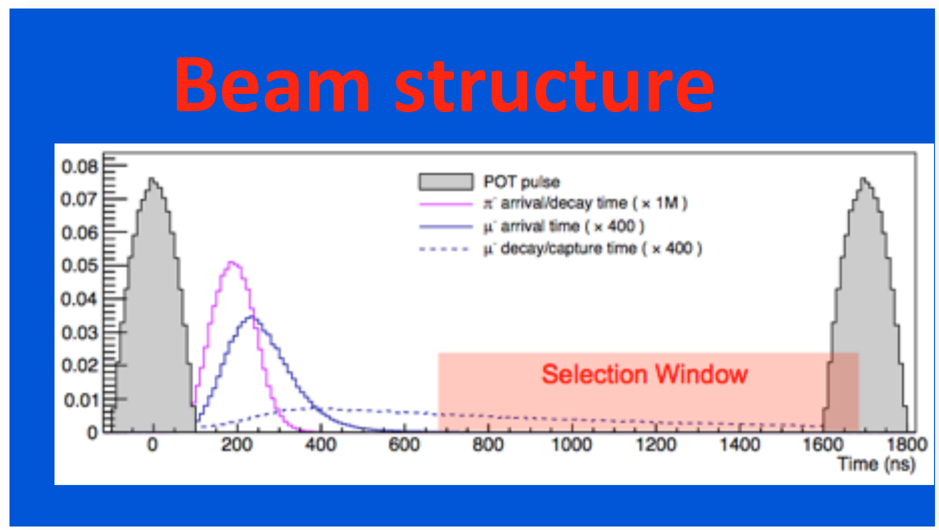
→ **Need CRV and PID**



1) Radiative pion/muon capture
2) Muon/pion decay in flight
3) Beam electrons
4) Antiprotons

Some bkg sources can become a problem for our of time protons or long transit-time for secondaries.

→**Need beam structure**
→**Extinction @ 10^{-10}**
→**Thin-window for pbar absorption**



Mu2e Schedule and plans

- CD-0 in November 2009, CD-1 in July 2012
- **CD-3a in FY2014-Q2 → Done**
  - Order production lengths of solenoid superconductor (long lead item)
- **Scheduled CD2/3 in August 2014**
- Start on building, proceed expeditiously with solenoid fabrication

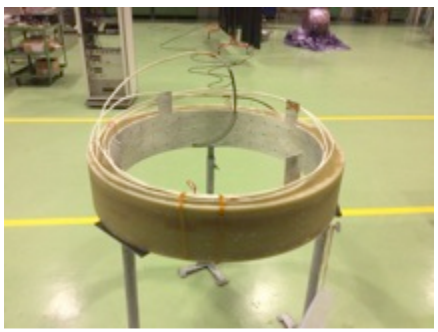
- Obtain R&D lengths of all conductor types →
  Done and tested @ INFN Genova
- Develop a Reference Design for the solenoids and solicit bids from industry for their Final Design & Fabrication → **bid almost completed**

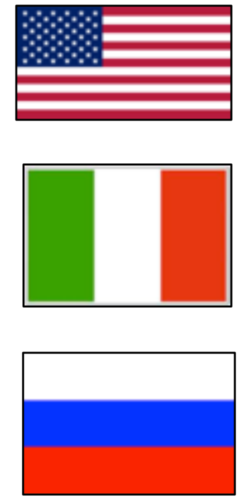
- Complete necessary studies to specify baseline
  - Shielding designs & building drawings completed
  - Detector R&D and test beam studies in progress

Mu2e collaboration & INFN

138 members, 3 countries, 25 USA institutions

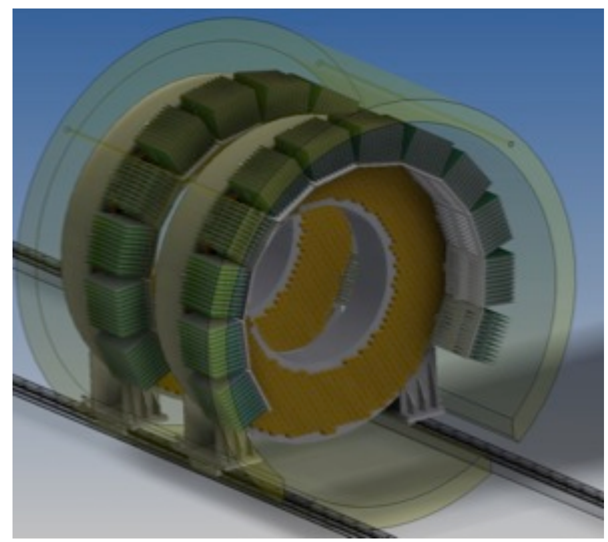
MU2E DOE COST:
→ 260 M$, 80 M$ core





Strong involvement of INFN group in two fields:
1) Project leadership for the calorimeter system
2) Construction of prototypes for the TS magnet

INFN group size extrapolated to 2017, 30 people, O(20 FTE)
Contribution so far: 500 kEuro for magnet proto, 300 kEuro R&D
Expected Core contribution O(2.5 MEuro)



The P5 “message”

3 Budget Scenarios:
→ A) flat + 2% increase/year
→ B) flat + 3% increase/year
→ C) unconstrained

◆ It is really OK for the Muon Campus.
◆ It is also OK for the next phase!
❑ The message is clear: **Complete Mu2e and g-2**

Summary of Scenarios

Project/Activity	Scenarios: Scenario A	Scenario B	Senario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, [illegible]	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, [illegible]	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, [illegible]	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, [illegible]	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I

The P5 “message”

3 Budget Scenarios:
→ A) flat + 2% increase/year
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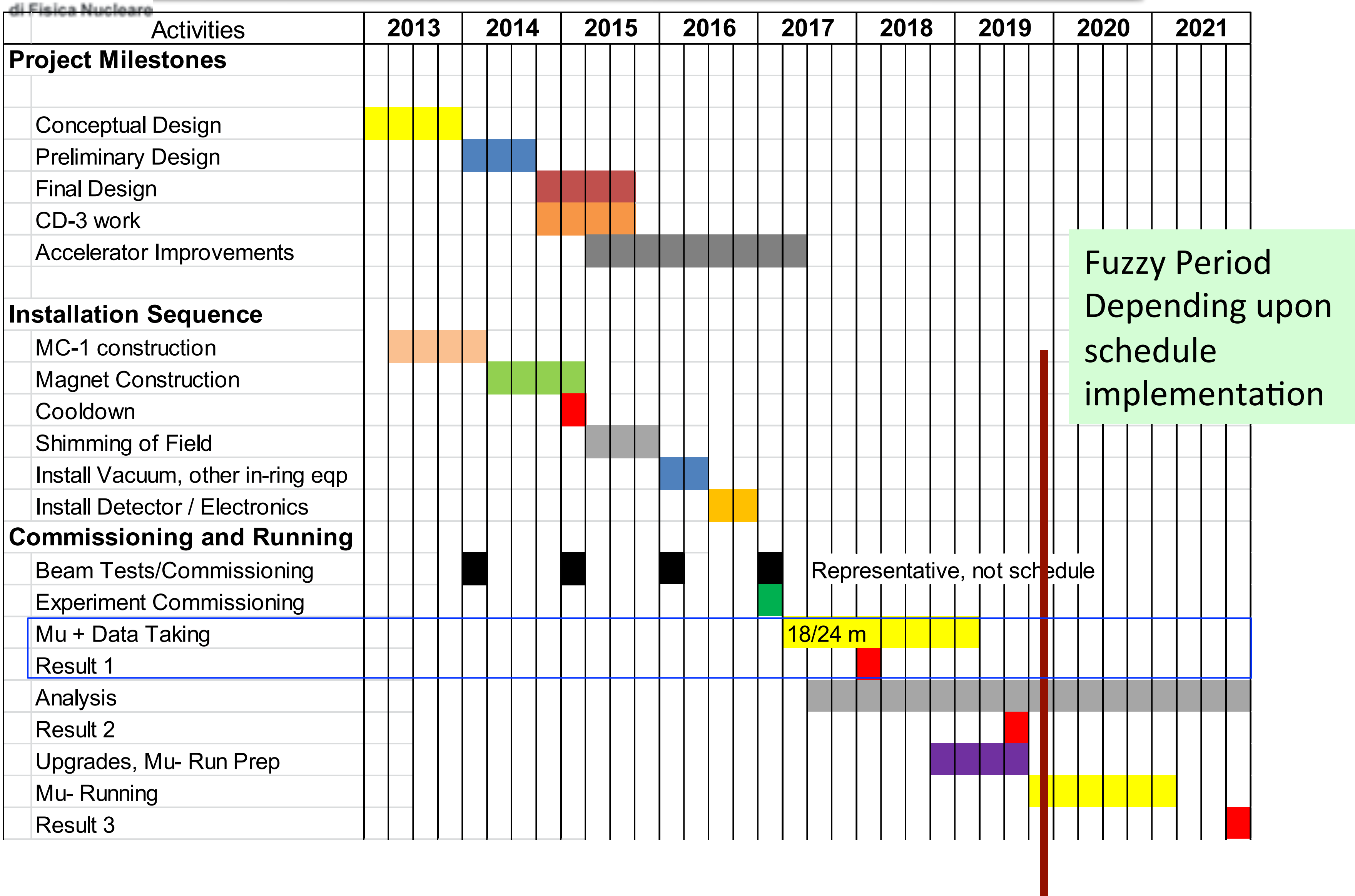
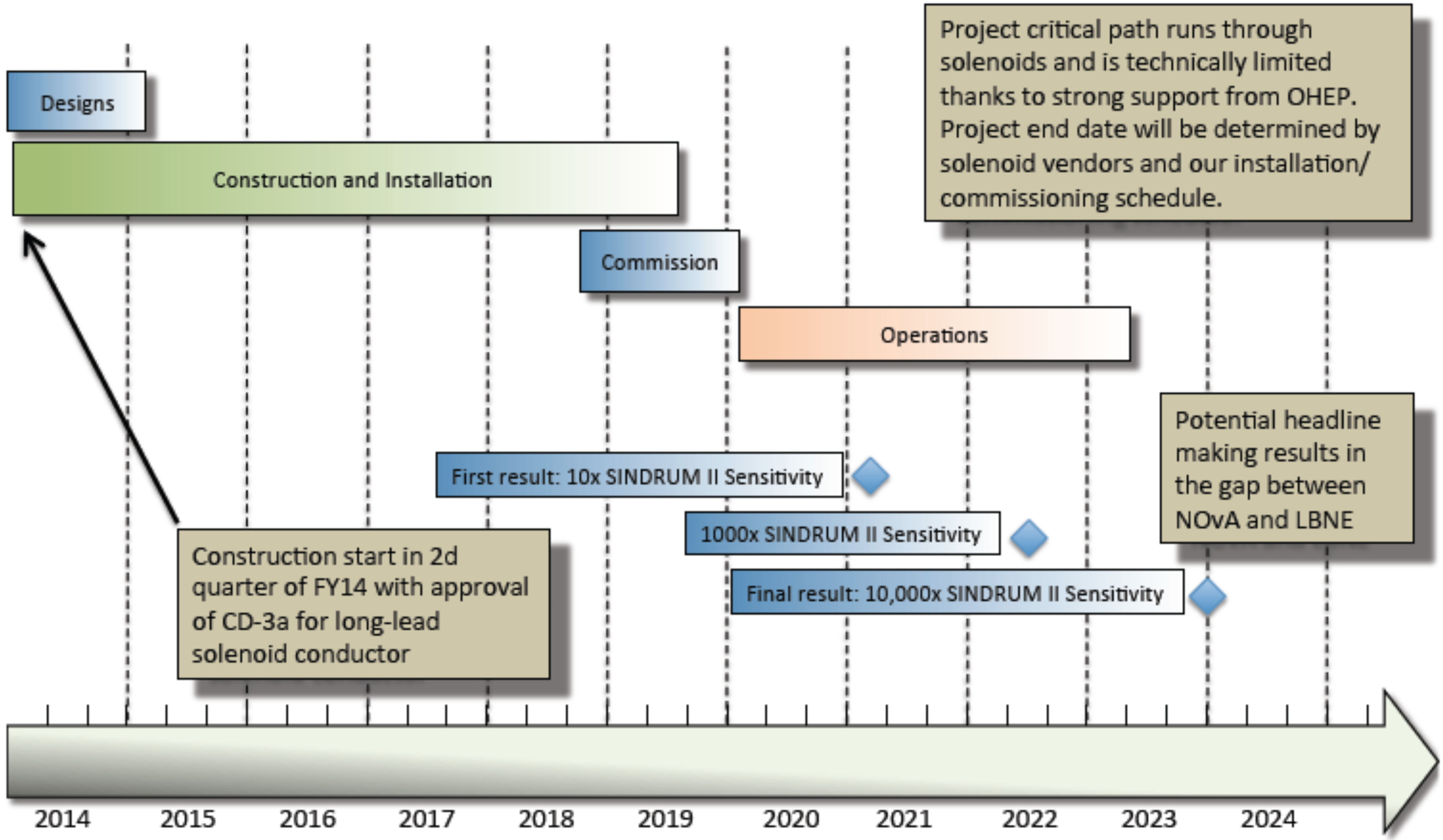
❑ The mes
Complete I

- The Mu2e and muon g-2 projects represent a large fraction of the budget in the early years. These are immediate targets of opportunity in the drive to search for new physics, and they will help inform future choices of direction. The science case is undiminished relative to their earlier prioritization. The programmatic impacts of large changes at this point were also discussed and determined to be generally unwise, although the Mu2e profile could be adjusted by a small amount if needed.
- **Recommendation 22: Complete the Mu2e and muon g-2 projects.**

Schedule g-2


Activities
2013
2014
2015
2016
2017
2018
2019
2020
2021
Project Milestones
Conceptual Design
Preliminary Design
Final Design
CD-3 work
Accelerator Improvements
Installation Sequence
MC-1 construction
Magnet Construction
Cooldown
Shimming of Field
Install Vacuum, other in-ring eqp
Install Detector / Electronics
Commissioning and Running
Beam Tests/Commissioning
Experiment Commissioning
Mu + Data Taking
Result 1
Analysis
Result 2
Upgrades, Mu- Run Prep
Mu- Running
Result 3
Representative, not schedule
18/24 m
Fuzzy Period Depending upon schedule implementation

Schedule Mu2e



g-2 vs Mu2e interaction

❑ g-2 and Mu2e both use the Delivery Ring in their beam lines, however, they use it in very different ways (g-2 transports ~3 GeV muons, Mu2e transports 8 GeV protons) → **They can not run simultaneously.**

❑ Current plan is that Mu2e performs some amount of beam line installation & commissioning while g-2 is running. There are pieces that can't get done until the g-2 run is finished. **The Mu2e "current" schedule includes these interferences.**

❑ If the g-2 run gets **significantly delayed or stretched → it can affect when Mu2e starts**. However → it would be possible for the accelerator to split time between g-2 and Mu2e:

(i) for example few months of data with g-2, then several months with Mu2e;

(ii) it will take ~ 4 weeks to swap between the two experiments when modifying the Delivery Ring.

(WhatNext?) Mu2e … Mu2e-2

Project-X re-imagined to match Budget constraints:

1) PIP-2 plans:

→ 1 MW at LNBF at start (2025)
→ 2 MW at regime at LNBF
→ **x 10 at Mu2e**

Projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232
CLVF-snowmass →Arxiv.1311.5278
Mu2e-2 → Arxiv.1307.1168v2.pdf

2) **Depending on the beam Structure available:**
study Z dependence
if signal is observed

3) If no signal is observed
Use x 10 events in Mu2e-2
Minor modifications of the detector → **BR < 6 x 10^{-18}**

V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon., arXiv:0904.0957 [hep-ph]; Phys.Rev. D80 (2009) 013002

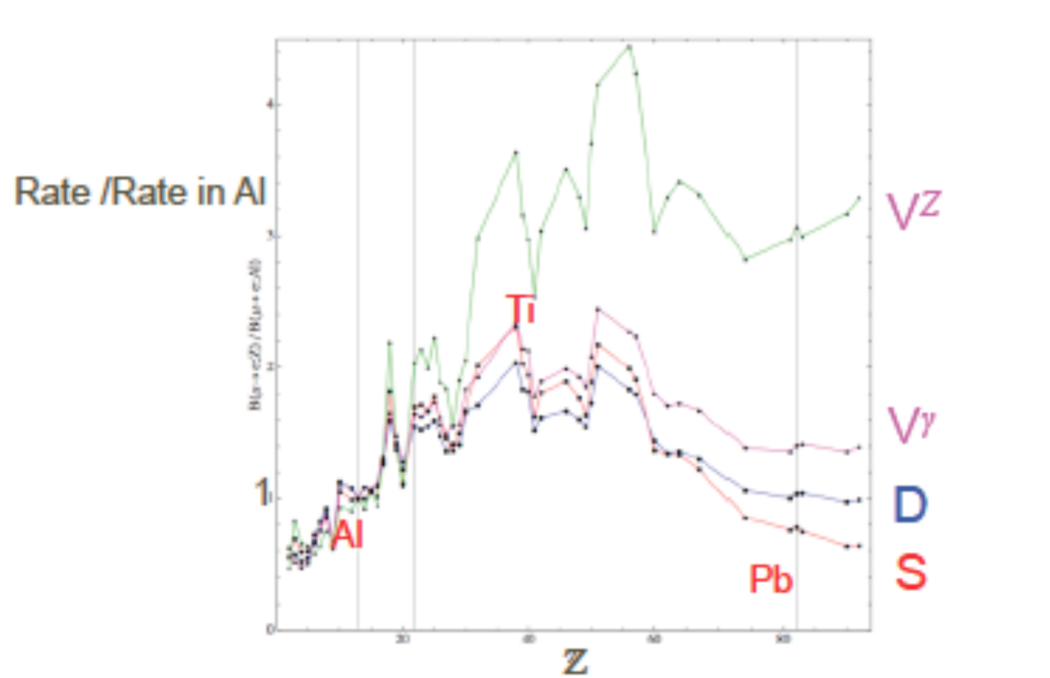


Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

Conclusions

- The muon campus at FNAL is a world class program for two high precision experiments searching for deviation from SM:
  g-2 and Mu2e (at a cost of one).

- **10 years Timeline for completion.**

- Both experiments are getting ready for the DOE CD-2 reviews (July/August 2014).

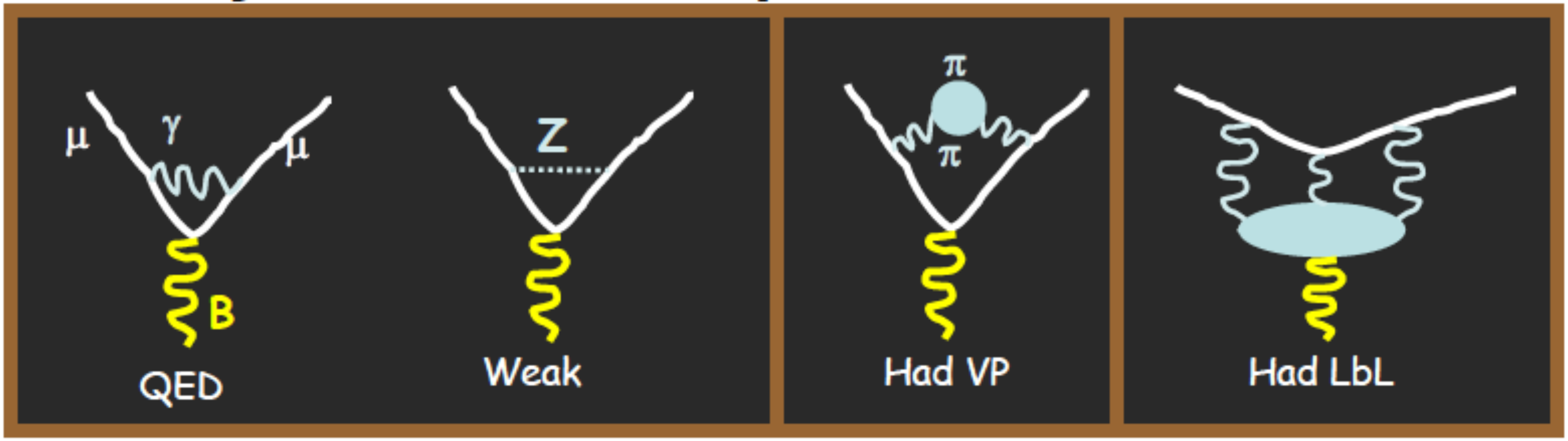
- For Mu2e, the construction of the solenoids will start next year. Detector engineering review end of 2015.

- **P5 report is positive for the baseline Muon Campus plan.**

- A long term plan is feasible. New Mu2e-2 detector being discussed for a second (x 10) phase. **This is now becoming more realistic since the P5 panel has also approved the PIP-2 accelerator upgrade.**

Additional Material

$a_\mu = (g - 2)/2$ can be calculated and measured very precisely to test the completeness of the SM

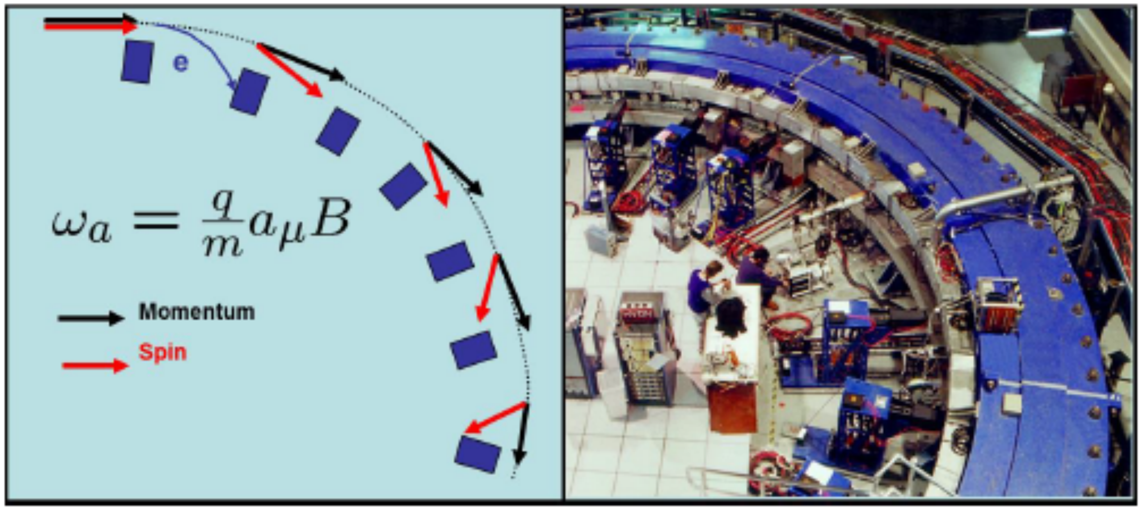


Known well **Theoretical work ongoing**

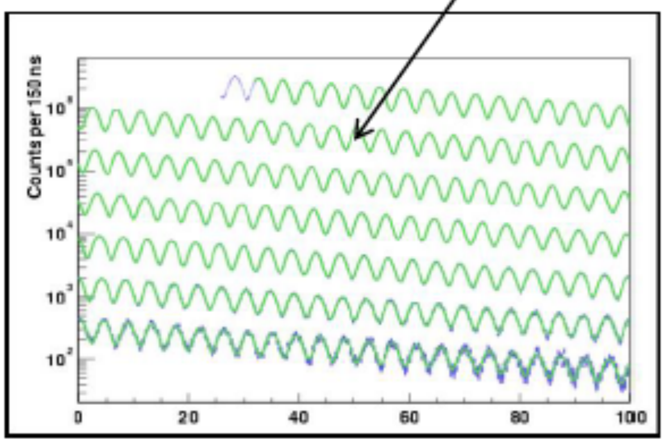
	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

Δa_μ(Expt – Thy) = 287 ± 80 x 10^{-11} 3.6 σ

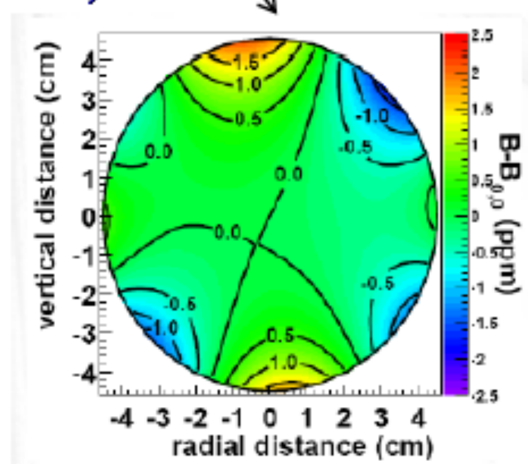
a_μ = (g-2)/2 is derived from the precession of the muon spin in a well-measured magnetic field



$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$



Precession frequency

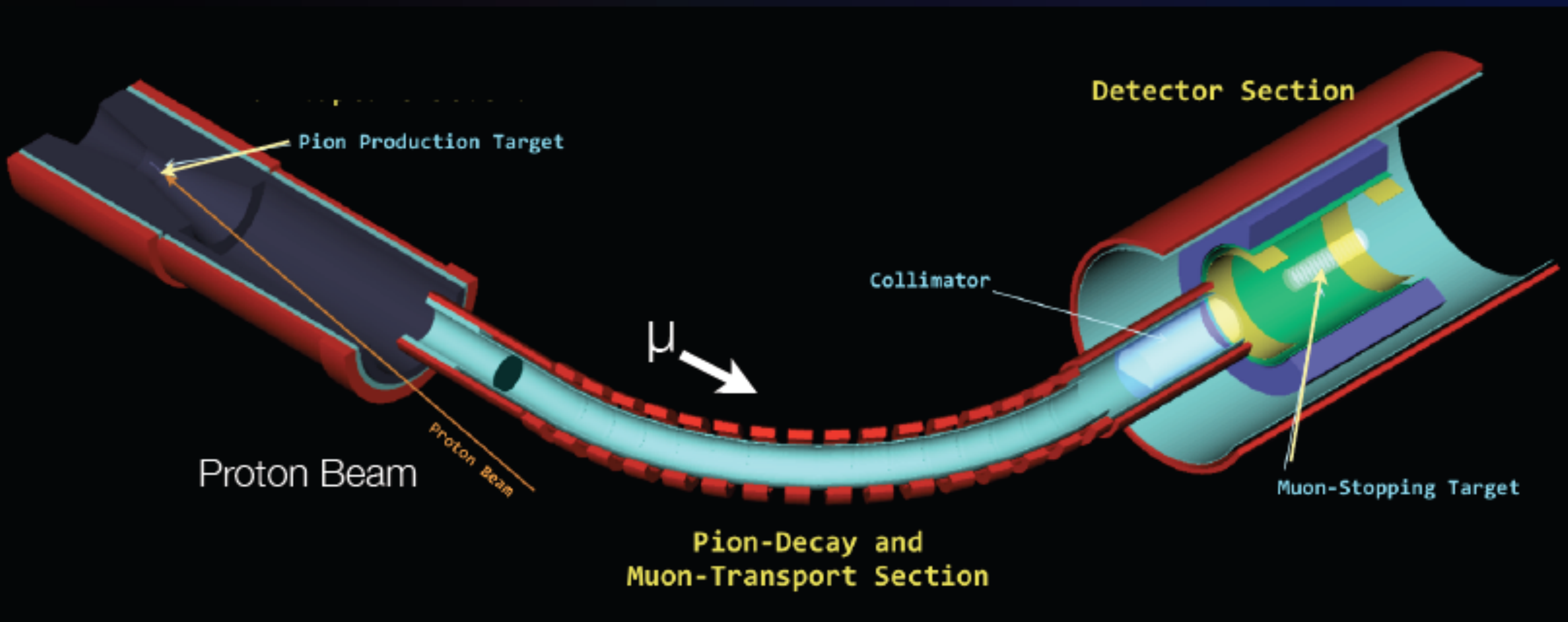


Average Magnetic Field

physics case coupled with the explicit scope of the experiment

COMET Phase-I Experimental Layout

Osaka University



COMET muon beam-line :

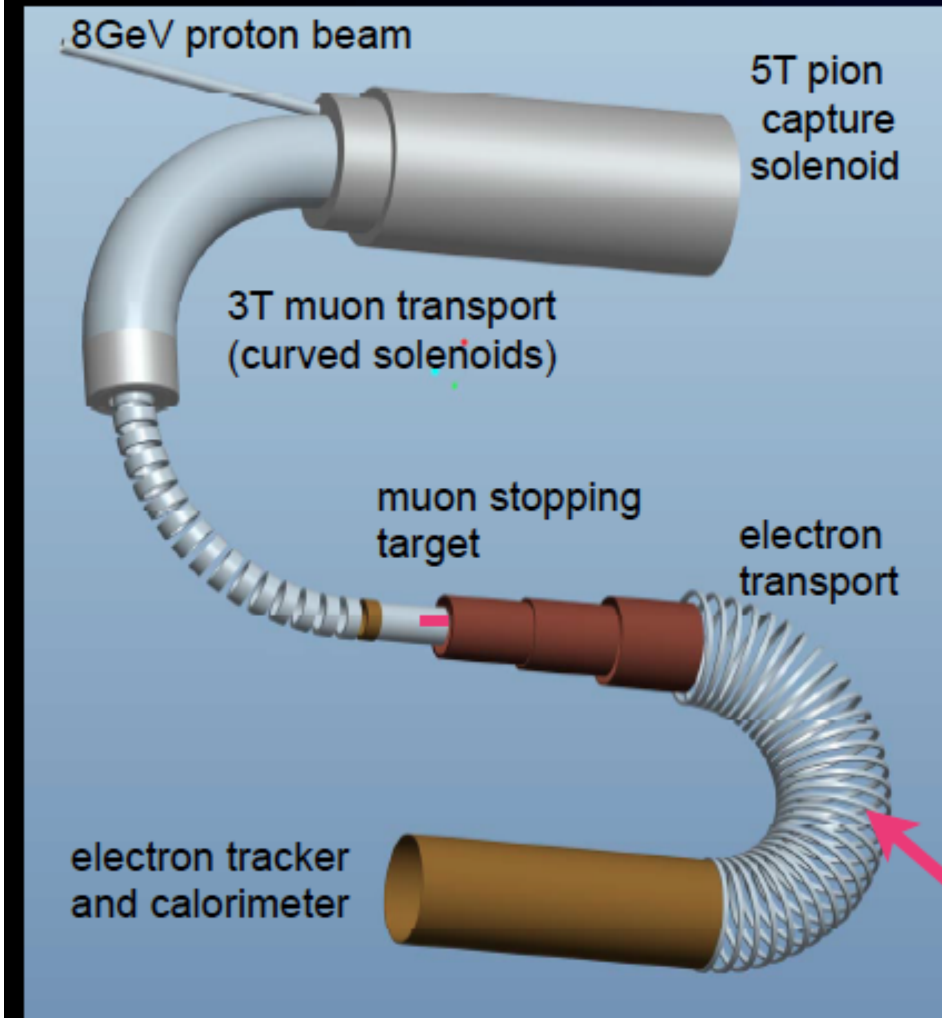
$(1\sim3)\times10^9$ muon/sec with 3kW beam produced. The world highest intensity.

COMET Phase-I detector :

Cylindrical drift chamber (CDC) for μ-e conversion is used. Straw chamber and ECAL are for beam studies.

Q:physics case coupled with the explicit scope of the experiment

What is COMET (E21) at J-PARC



Experimental Goal of COMET

$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

- 10^{11} muon stops/sec for 56 kW proton beam power.
- 2×10^7 running time (~1 year)
- C-shape muon beam line
- C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

Electron transport with curved solenoid would make momentum and charge selection.

COMET vs Mu2e

- ❑ Similar capabilities as physics reach
- ❑ COMET designed to operate at 56 kW, Mu2e 8 kW
  - → COMET will use all JPARC beam
  - → Mu2e runs simultaneously with neutrino beam
- ❑ Final bend after COMET stopping target efficiently transmits Conversion e- and provides rate suppression in detector.
- ❑ It does not transmit positrons

- COMET solenoids ~ 10 m longer than Mu2e
- Higher beam -> higher cost (solenoid shieldling, neutron shielding)
- Longer solenoids carry "cost"

Phase-1 could be useful if successful to study background rate
→ Path to Phase-2 is still difficult.

Construction Funds (not ops)

	Source	$ M	Comment
	DOE OHEP	46.4	CD-1 guidance; $9 M obligated; **$12 M contingency on remaining (40%)**
Awarded	DOE Early Career	0.5	Casey: trackers ($2.5 M award)
Awarded	NSF MRI	3.6	Consortium Proposal; Detectors; Electronics, DAQ, Including 30% match (mostly from Universities)
Awarded	ITALY: INFN	0.40	Laser calibration
Awarded	UK: STFC	0.40	Trackers, NMR
Awarded	China: Shanghai	0.25	PbF2 crystals *
Awarded	Texas Instruments	0.20	Digitizer chips*
	Additionally E821 Components And most of the Pbar Complex	**50 – 100 M**	**Storage Ring, Vacuum, Power supplies, Pbar (now muon) target system, Beamline elements, … Debuncher, etc etc,**

*part of MRI match formula

Neutrino Oscillation Experiments (PIP-II)

- The PIP-II project at Fermilab is a necessary investment in physics capability, enabling the world's most intense neutrino beam, providing the wideband capability for LBNF, as well as high proton intensities for other opportunities, and it is also an investment in national accelerator laboratory infrastructure. The project has already attracted interest from several potential international partners.
- **Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.**

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Neutrino Oscillation Experiments (LBNF)

- Key preparatory activities will converge over the next few years: in addition to the international reformulation described above, PIP-II design and project definition will be nearing completion, as will the necessary refurbishments to the Sanford Underground Research Facility. Together, these will set the stage for the facility to move from the preparatory to the construction phase around 2018. The peak in LBNF construction will occur after HL-LHC peak construction.

- **Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.**

Muons and Kaons

- The Mu2e and muon g-2 projects represent a large fraction of the budget in the early years. These are immediate targets of opportunity in the drive to search for new physics, and they will help inform future choices of direction. The science case is undiminished relative to their earlier prioritization. The programmatic impacts of large changes at this point were also discussed and determined to be generally unwise, although the Mu2e profile could be adjusted by a small amount if needed.
- **Recommendation 22: Complete the Mu2e and muon g-2 projects.**

- The ORKA kaon experiment would provide an opportunity to make measurements of a process with very small theoretical uncertainties in the Standard Model with discovery potential for multi-TeV scale new physics. It has the potential for significant improvement over CERN experiment NA62, which uses a complementary technique and which has a head start. The suite of measurements with ORKA would provide excellent training for students and postdocs, and this mid-size project offers additional balance to the large-scale projects in the field. Unfortunately, due to resource constraints and anticipated conflicts with the highest priority items in the Fermilab program, P5 cannot recommend moving ahead with ORKA at this time.

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budget guidance but an exercise to help confront choices and identify priorities.

- Scenario B is defined in the Charge as a constant level of funding ("flat-flat") for three years, followed by increases of 3% per year with respect to the FY2014 President's budget request for HEP. Scenario A is defined in the Charge as a constant level of funding for three years, followed by increases of 2% per year with respect to the FY2013 budget for HEP. The two budgets start at somewhat different values, though they are similar in that they are flat-flat until FY2018. With the 1% difference in escalation rate and the different starting values, the two budgets differ by approximately $500M summed over a decade. The recommended programs in the three Scenarios are shown in Table 1.

- Hard choices were required. While Scenario B allows for a balanced program, based on our Criteria, excellent projects will not be fiscally possible. Moreover, the constant funding level in the early years, coupled with the urgently needed 20%–25% project construction fraction, implies an erosion of research effort. The early years are particularly constrained, given existing projects that are recommended for completion (muon g-2, Mu2e, LSST) and the urgent need to

Scenarios B and A

- Scenario A is much more challenging. The reduction relative to Scenario B, which is approximately $30M per year until FY2018 and then grows over time, would have very large impacts:
  - DESI would not be possible
  - Accelerator R&D and advanced detector R&D would be reduced substantially
  - Extension of flat-flat research program funding would result in further personnel reductions and loss of research capability
  - Ramp up of funding for LBNF would be delayed relative to Scenario B (preliminary work would proceed immediately in both scenarios)
  - Third-generation direct detection dark matter capabilities would be reduced or delayed
  - A small change in the funding profile of Mu2e would be required.
- DESI should be the last project to be cut if moving from Scenario B toward Scenario A.
  - A small, limited-time increment above Scenario A would make this very important small project possible.

The return on the investment of the relatively small increment from Scenario A to Scenario B is large. It provides excellent science per incremental dollar by enabling the outstanding opportunity of DESI, sets a faster course for the long-baseline neutrino program, and preserves the long-term investments in R&D and the research program. As valuable as each of these items is, they simply do not fit in Scenario A.

Why Mu2e is unique?

Muon to electron conversion is a unique probe for BSM:

- **Broad discovery sensitivity across all models:**

  → Sensitivity to the same physics of MEG but with better mass reach

  → Sensitivity to physics that MEG is not

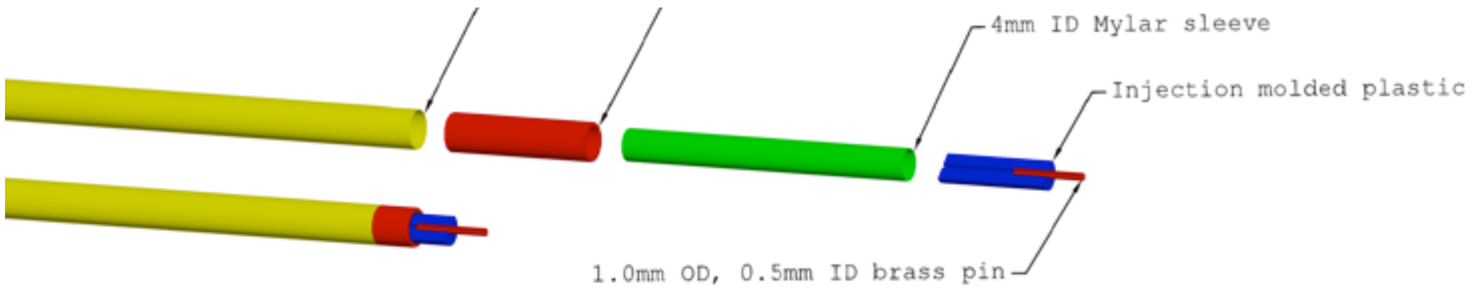
  → If MEG observes a signal, MU2E does it with improved statistics.
  Ratio of the BR allows to pin-down physics model

  → If MEG does not observe a signal, MU2E has still a reach to do so.
  In a long run, it can also improve further with PIP-2

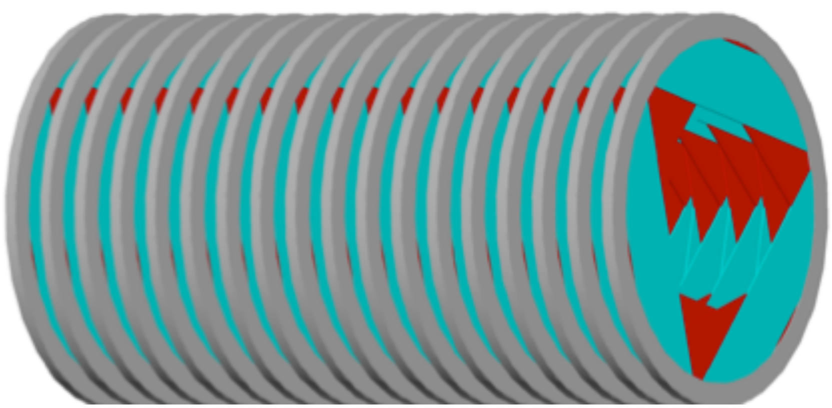
- **Sensitivity to λ up to 10.000 TeV beyond any imaginable accelerator**

Straws: 5 mm OD; 15 μm metalized mylar wall.

Custom ASIC for time division: $\sigma \approx 5$ mm at straw center

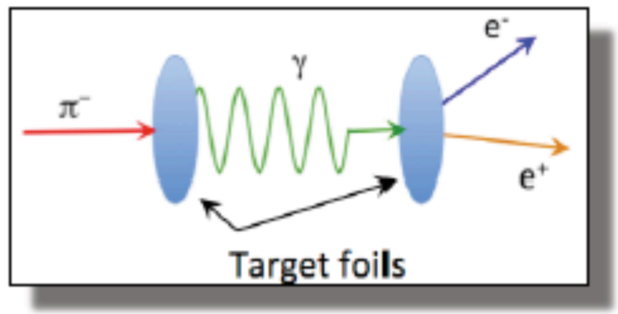


Tracker: 22 stations (# and rotations still being optimized)



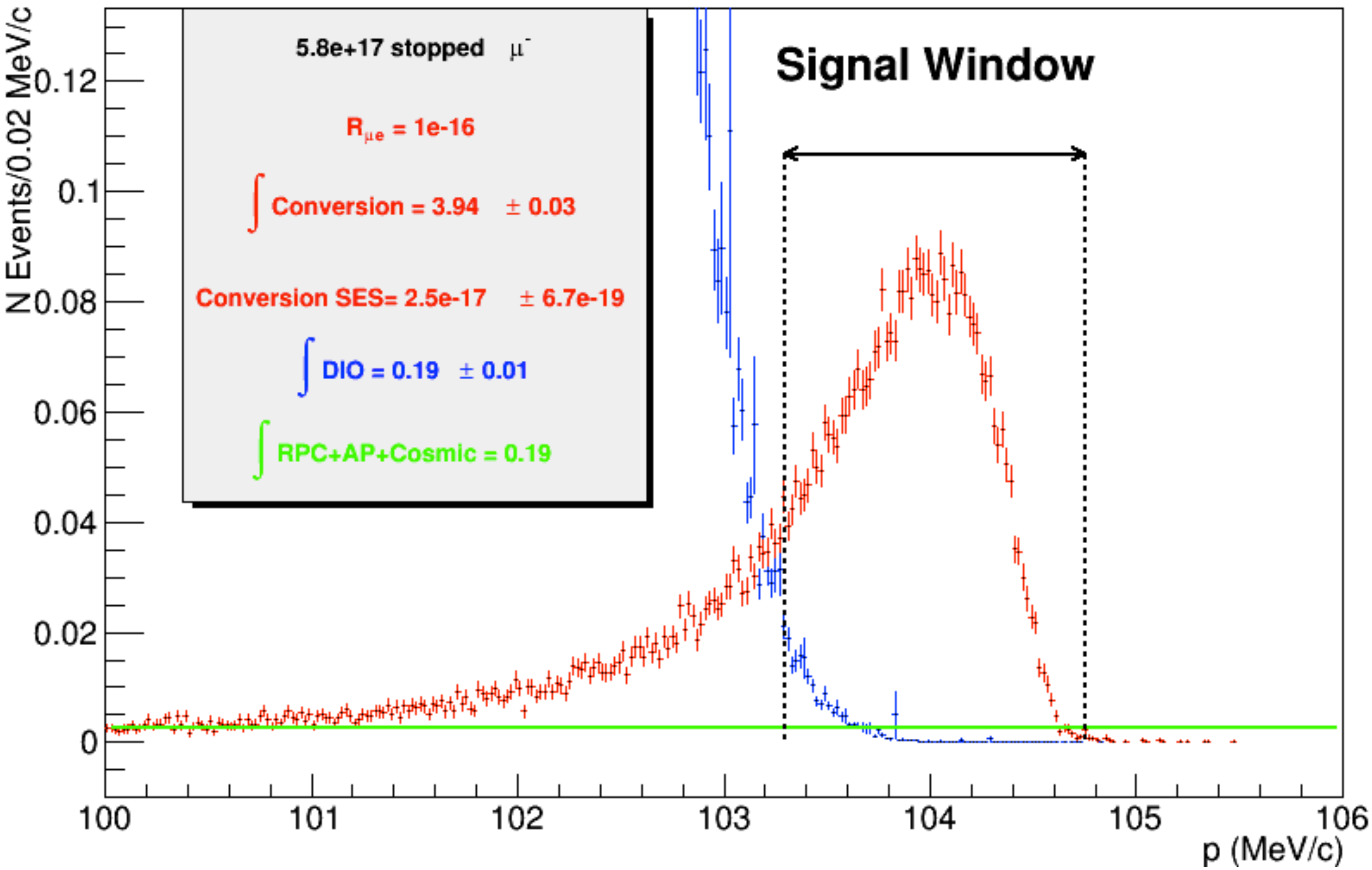
Mu2e-2

- Mu2e can simultaneously see electrons and positrons from the stopping target
  - Access to additional physics mode: $\mu^- N(Z,A) \rightarrow e^+ N(Z-2,A)$
    - ($\Delta L=2$ transition – charged analog of neutrinoless double beta decay)
  - High energy positrons are an additional handle on radiative backgrounds with converted photons



- Mu2e is the fastest, cheapest path to broad discovery sensitivity in CLFV sector.

DIO final count with Simulation



Mu2e Expected Background

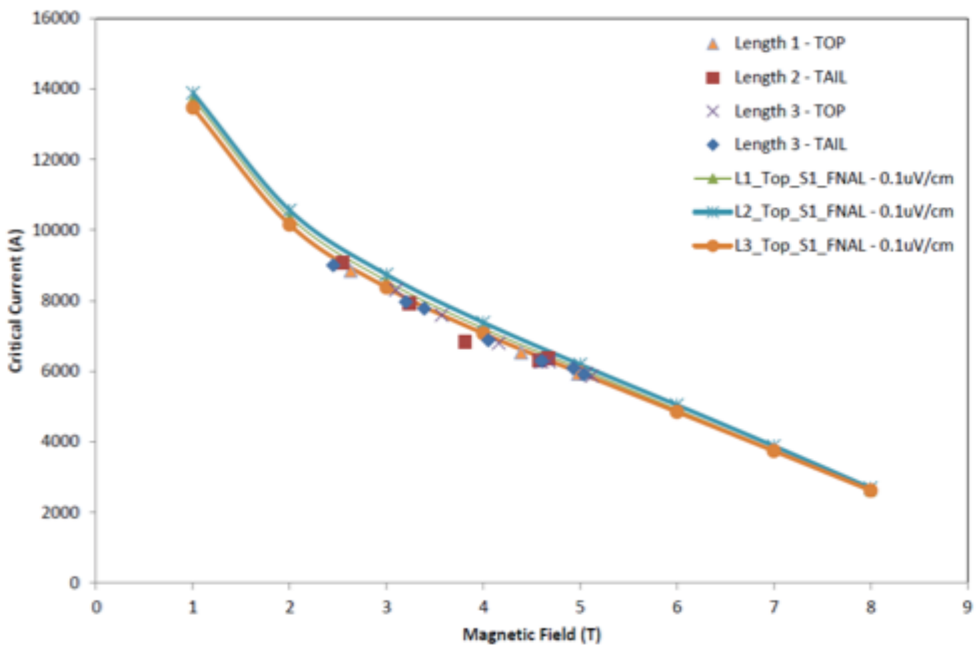
(assuming ~30 GHz muon beam, 6E17 captured muons in 6E7 s of beam time)

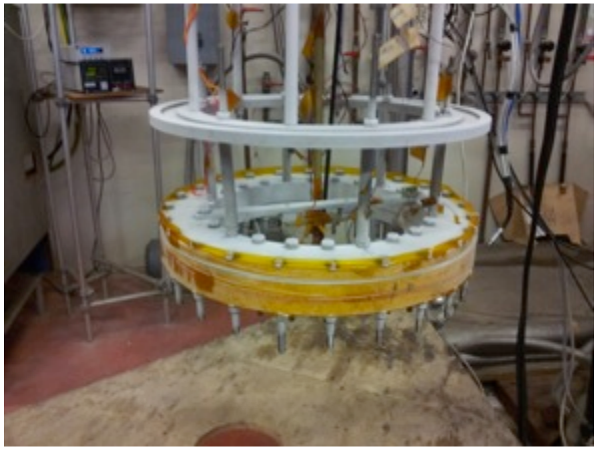
Category	Source	Events
	μ Decay in Orbit	0.22
Intrinsic	Radiative μ Capture	<0.01
	Radiative π Capture	0.03
	Beam electrons	<0.01
	μ Decay in Flight	0.01
Late Arriving	π Decay in Flight	<0.01
	Anti-proton induced	0.10
	Cosmic Ray induced	0.05
Miscellaneous	Pat. Recognition Errors	<0.01
Total Background		0.41

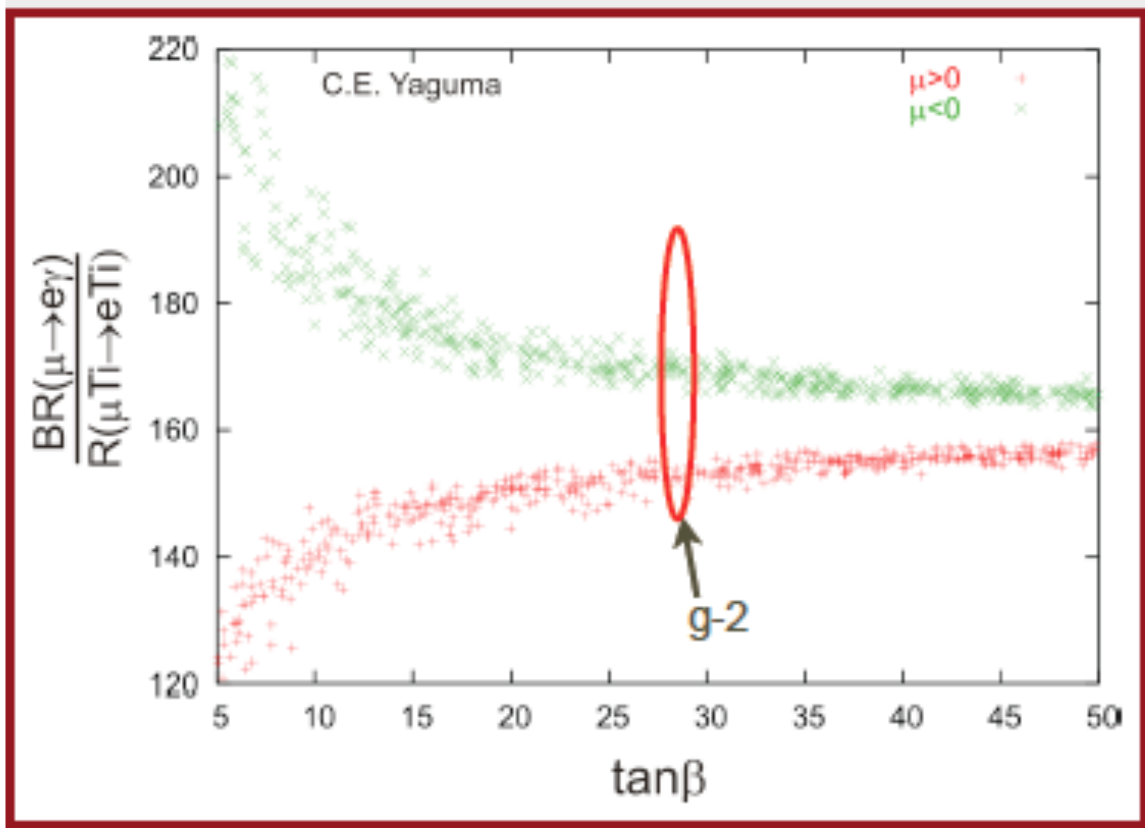
Discovery sensitivity accomplished by suppressing backgrounds to < 0.5 event total

Critical Current Measurements

- FNAL awarded a contract to Hitachi for three lengths of TS conductor (1000 m)
- INFN Genova received six samples (head and tail of production)
- Critical currents of five sample were measured. Except a case (bad soft soldering of the sample) four runs went well.
- Measured critical currents compare very well with the ones performed at Fermilab on extracted strands
- **After these results Fermilab is asking INFN Genova to test all 60 cables involved in Mu2e solenoids.**





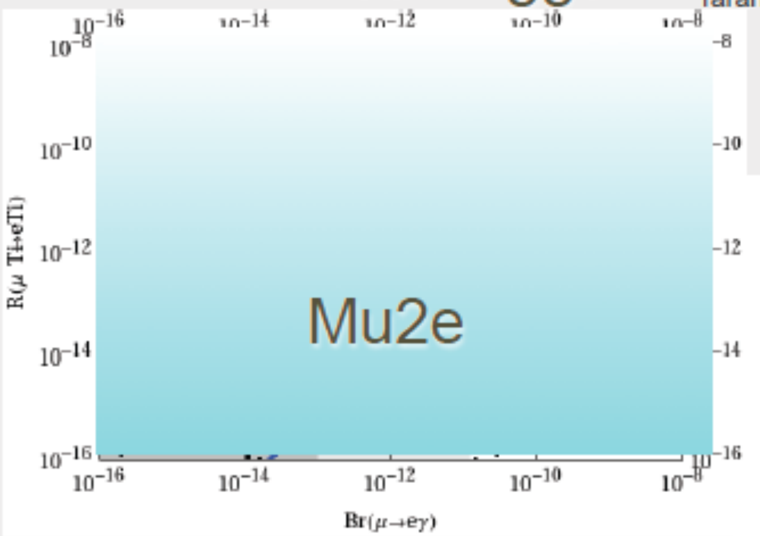


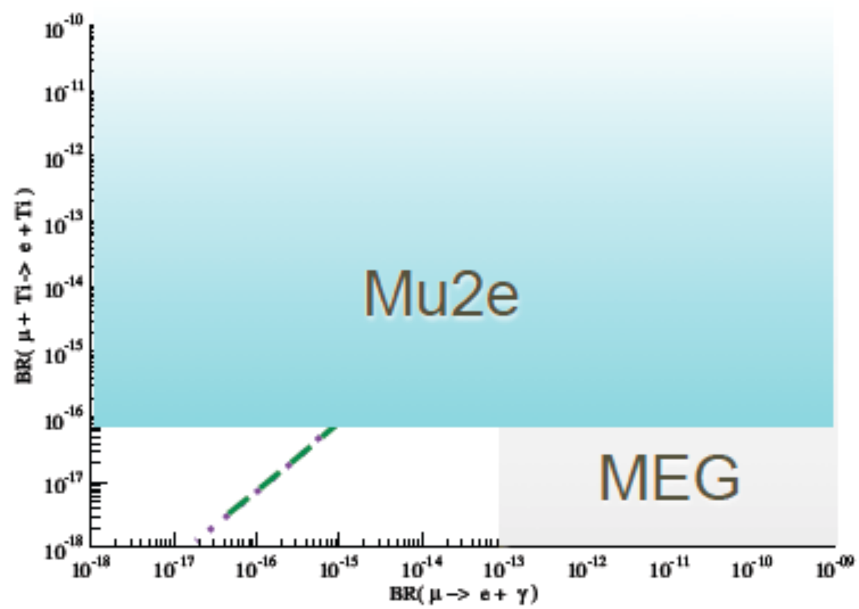
Yaguna, hep-ph/0502014v2

Combining μ→eγ with μ→e Conversion

Littlest Higgs

Monika Blanke, Andrzej J. Buras, Bjoern Duling, Stefan Recksiegel, Cecilia Tarantino, Acta Phys.Polon.B41:657,2010,arXiv:0906.5454v2 [hep-ph]





SO(10) models:

C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.

CLFV Predictions

M.Blanke, A.J.Buras, B.Duling, S.Recksiegel, C.Tarantino

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2.0$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$

arXiv:0909.5454v2[hep-ph]

Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\mathrm{TeV}$) and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

- Relative rates are model dependent
- Measure ratios to pin-down theory details

Mu2e Physics Reach

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

★★★ = Discovery Sensitivity

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

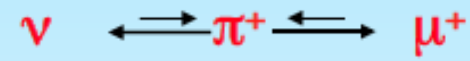
arXiv:0909.1333[hep-ph]

Next Generation Proton Source

- Proton Improvement Plan (PIP)
  - Improve beam power to meet NOνA requirements
  - Essentially complete.
- PIP-II design underway
  - Project-X reimagined to match funding constraints
  - 1+ MW to LBNE at startup (2025)
  - Flexible design to allow future realization of the full potential of the FNAL accelerator complex
    - ~2 MW to LBNE
    - 10× the protons to Mu2e
    - MW-class, high duty factor beams for rare process experiments

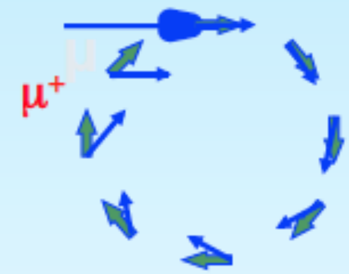
4 Key elements of modern storage-ring g-2 measurements

(1) Polarized muons



~97% polarized for forward decays

(2) Precession proportional to (g-2)

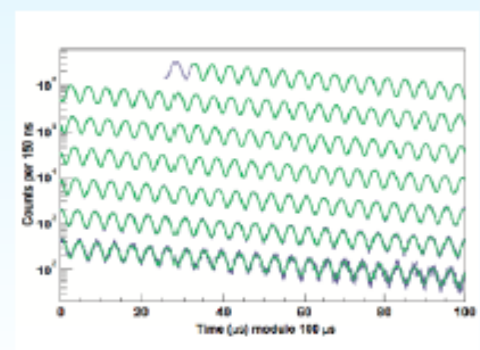


$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

(3) P_μ magic momentum = 3.094 GeV/c

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

E field doesn't affect muon spin when γ = 29.3



(4) Parity violation in the decay gives average spin direction

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Why Fermilab?

- The existence of many storage rings that are interlinked permits us to make the “ideal” beam structure.
  - proton bunch structure:
    - BNL 4 X 10^{12} p/fill: repetition rate 4.4 Hz
    - FNAL 10^{12} p/fill: repetition rate 15 Hz
  - using antiproton rings as an 900m pion decay line
    - 20 times <u>**less**</u> pion flash at injection than BNL
  - 0^o muons
    - ~5-10x increase μ/p over BNL
  - Can run parasitic to main injector experiments (e.g. to NOVA) or take the booster cycles

Flash compared to BNL

parameter	FNAL/BNL
p / fill	0.25
π / p	0.4
π survive to ring	0.01
π at magic P	50
Net	0.05

Stored Muons / POT

parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx$ 2.7E-5	$\approx$ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 $\pm$ 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band	$\pm$0.5%	$\pm$2%	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

Expected data taking end of 2016/2017

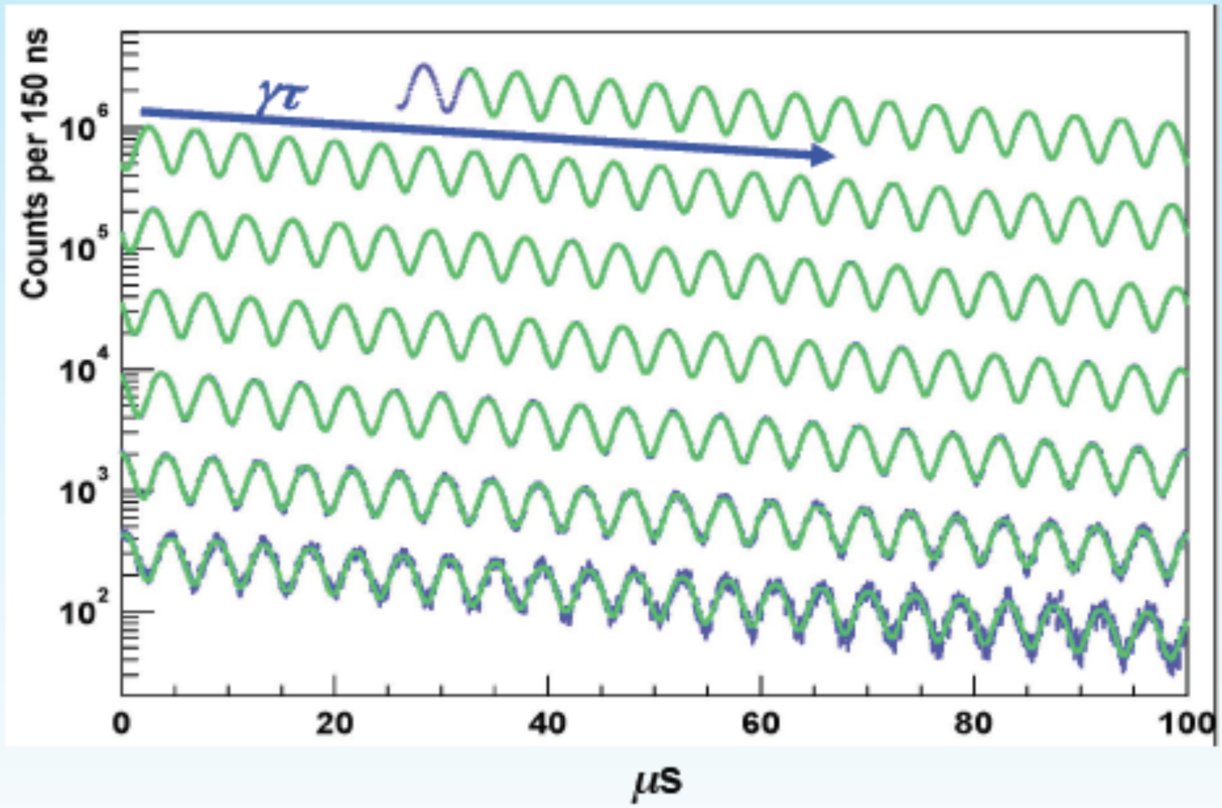
The arrival time spectrum of high-energy e⁻ ω_a

$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos\omega_a t + \phi)]$$

$3.6 \times 10^9\ e^-$

$E_e \geq 1.8$ GeV

$\gamma\tau_\mu$ = 64.4 μs;
(g-2): τ_a = 4.37 μs;
Cyclotron: t_C = 149 ns



Systematic uncertainty on ω_a expected to be reduced by 1/3 at E989 (compared to E821) thanks to **reduced** pion contamination,the **segmented** detectors, and an **improved** storage ring kick of the muons onto orbit.