Experimental status of the muon (g-2) and of the lepton flavor violating decay modes

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Current Trends in Flavor Physics

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Outline

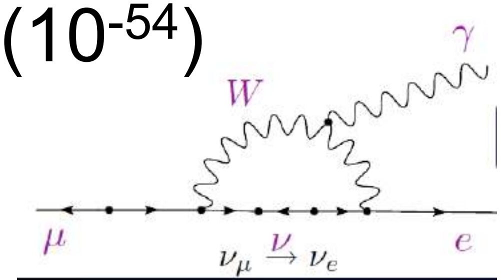
- Introduction to CLFV
- CLFV experiments:
  - $\mu \to e\gamma$ [MEG & MEG II]; $\mu \to 3e$
  - μ-e conversion: Mu2e, COMET, DeeMe
  - Tau LV
- Introduction to g-2
  - g-2 experiments at Fermilab and J-Park
  - New proposal to measure a_μ^{HAD} in the spacelike region
- Conclusion

Introduction to CLFV

- Charged Lepton Flavor violation is forbidden in the Standard Model:
  - $\mu\to e\gamma$, $\mu\to eee$, $\mu^-+A \to e^-+A$,, $\tau\to e(\mu)\gamma$, $\tau\to e(\mu)h$, $K_L\to\mu e$, $K\to\pi\mu e$, **and many others**
- Neutrino oscillation may induce CLFV but very small (due to GIM-like mechanism and neutrino mass)

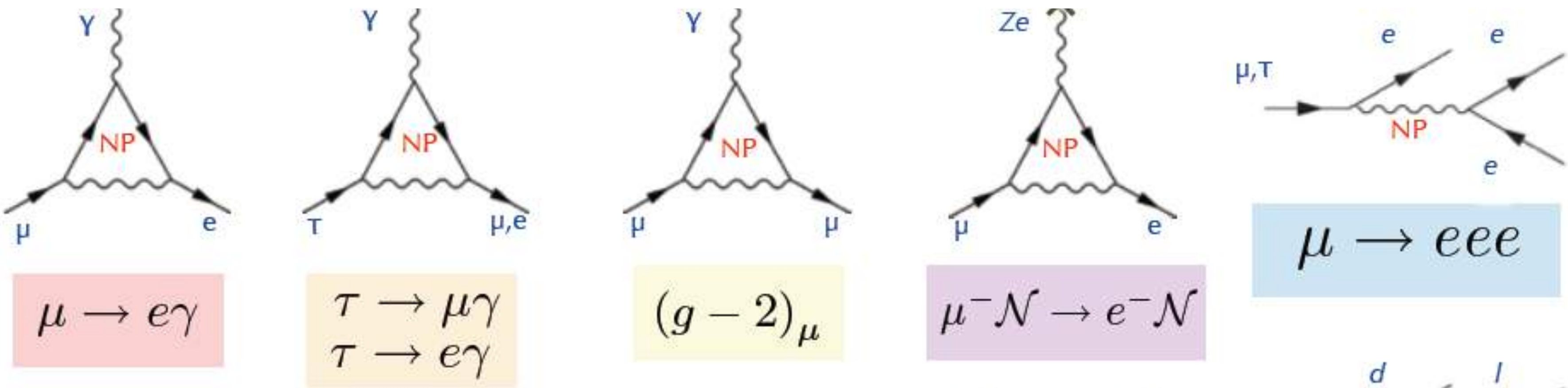
BR($\mu\to e\gamma$)~O(10^{-54})

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\sum_i \left| U_{\mu i}U^*_{ei}\frac{m^2_{\nu_i}}{M^2_W}\right|^2 \simeq 10^{-60}\left(\frac{m_\nu}{10^{-2}\,\mathrm{eV}}\right)^4$$

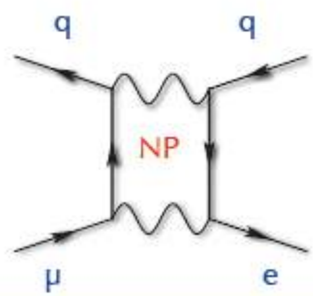


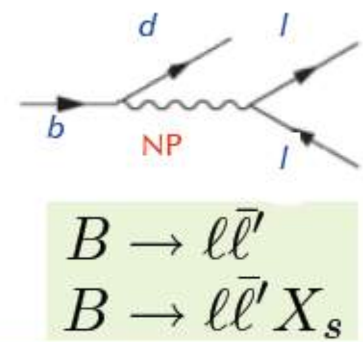
- If CLFV found → Clear evidence of Physics BSM
- Many theories BSM predicts CLFV

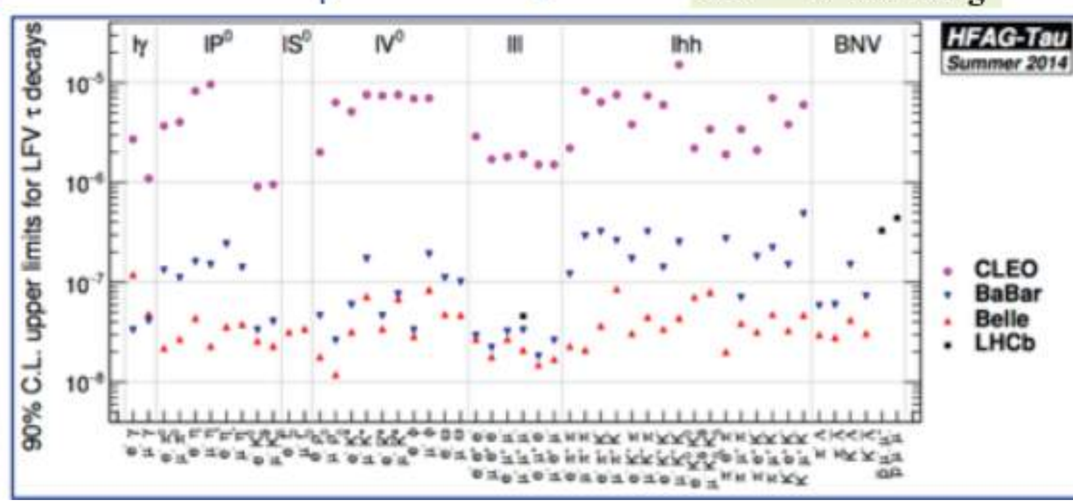
Many CLFV Processes



- A **wide field** of research
  - *LFV decays of leptons*
  - *Anomalous magnetic moment for the μ*
  - *Muon-to-electron conversion*
  - *LFV in meson decays*





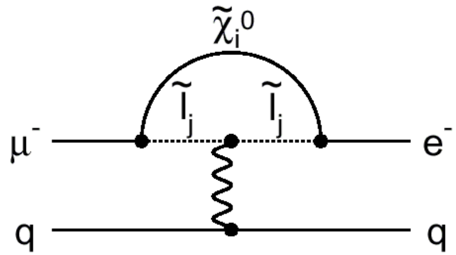


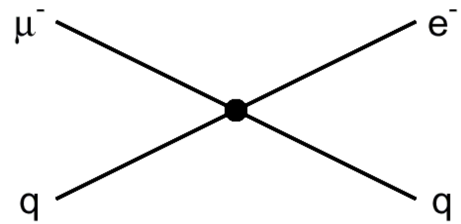
Various models predict CLFV

Sensitivity to different Muon Conversion Mechanism

Supersymmetry

Predictions at 10^{-15}



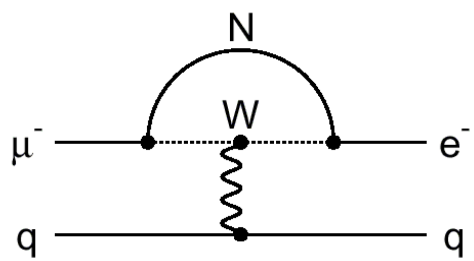


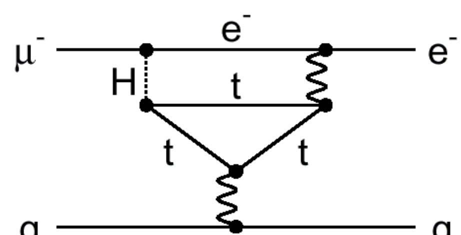
Compositeness

Λ_C=3000 TeV

Heavy Neutrinos

$$\left|U^*_{\mu N} U_{eN}\right|^2 = 8 \times 10^{-13}$$



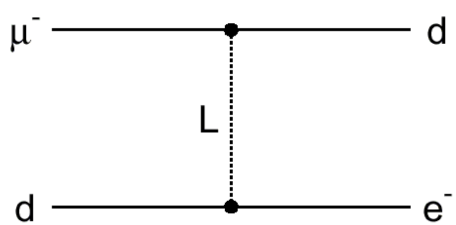


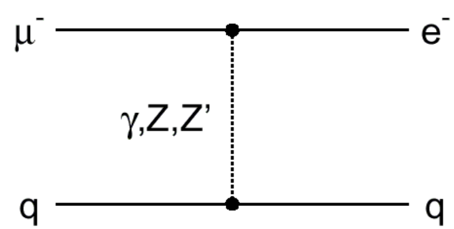
Second Higgs doublet

$g_{H\mu e}=10^{-4} g_{H\mu\mu}$

Heavy Z’ , Anomalous Z coupling

Leptoquarks





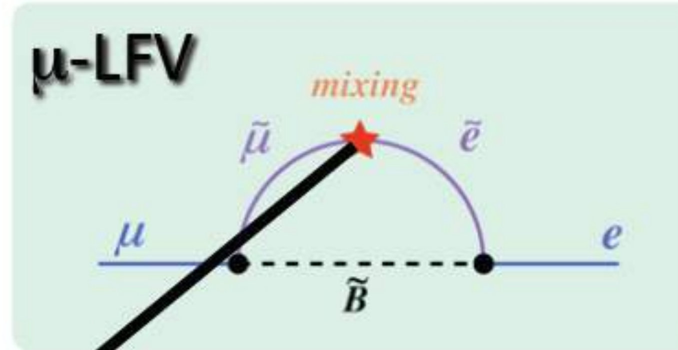
M_Z=3000 Tev/c^2

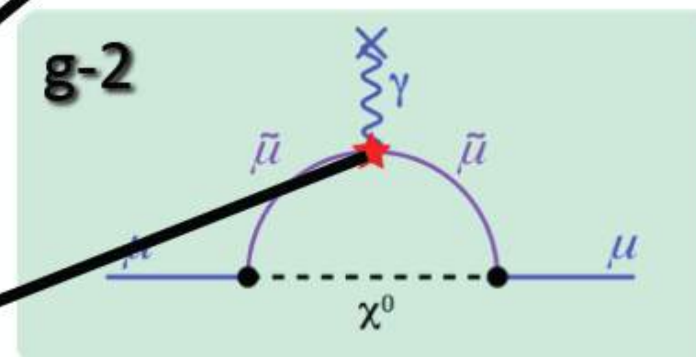
$B(Z \rightarrow \mu e)<10^{-17}$

$M_L=3000(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2

Supersimmetry as source of CLFV

- Supersymmetry (SUSY)
  - Hierarchy Problem
  - Unification of Force
- If SUSY exists
  → SUSY flavor mixing
  → CLFV



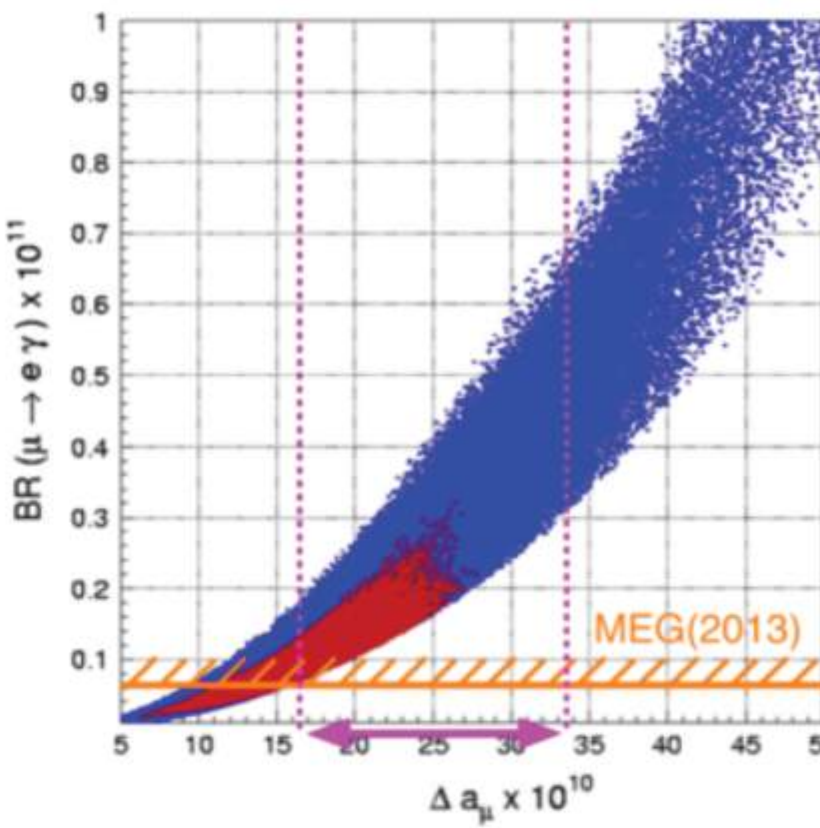


$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} &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

Physics of
slepton mass matrix

Correlations: $\mu \rightarrow e\gamma$ vs $(g\text{-}2)_\mu$

- **3.4 σ discrepancy** w.r.t. Standard Model prediction
  - *possible **hint** of **new physics***
  - *this **would enhance** to **μ->eγ** for example in a **supersymmetric** model*
    - **cLFV coupling $|\delta_{LL}^{12}|^2 \approx 10^{-4}$ almost excluded**
- resolution **improvements** by a **factor 4** from future experiments at **Fermilab** and **J-PARC**
  - *together with **new generation** cLFV **experiments** will be **sensitive** to $|\delta_{LL}^{12}|^2 \approx 10^{-5}$*

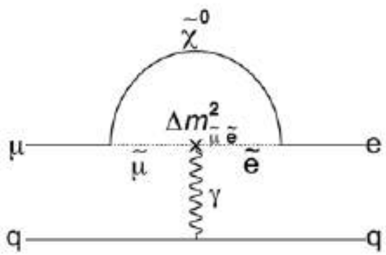


$$\mathcal{B}(\mu \to e\gamma) \approx 10^{-4} \left(\frac{\Delta a_\mu}{200 \times 10^{-11}} \right)^2 |\delta_{LL}^{12}|^2$$

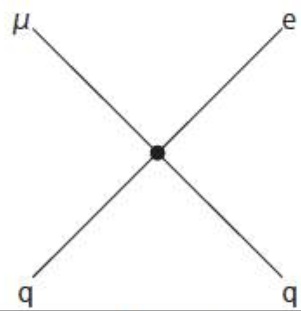
G. Isidori et al., 2007

Correlation μ → eγ & μ-e Conversion

$$\mathcal{L} = \boxed{\frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{e}\sigma^{\mu\nu}F_{\mu\nu}\mu} + \boxed{\frac{\kappa}{(1+\kappa)\Lambda_F^2}\bar{e}\mu(\bar{q}q+\bar{e}e)}$$

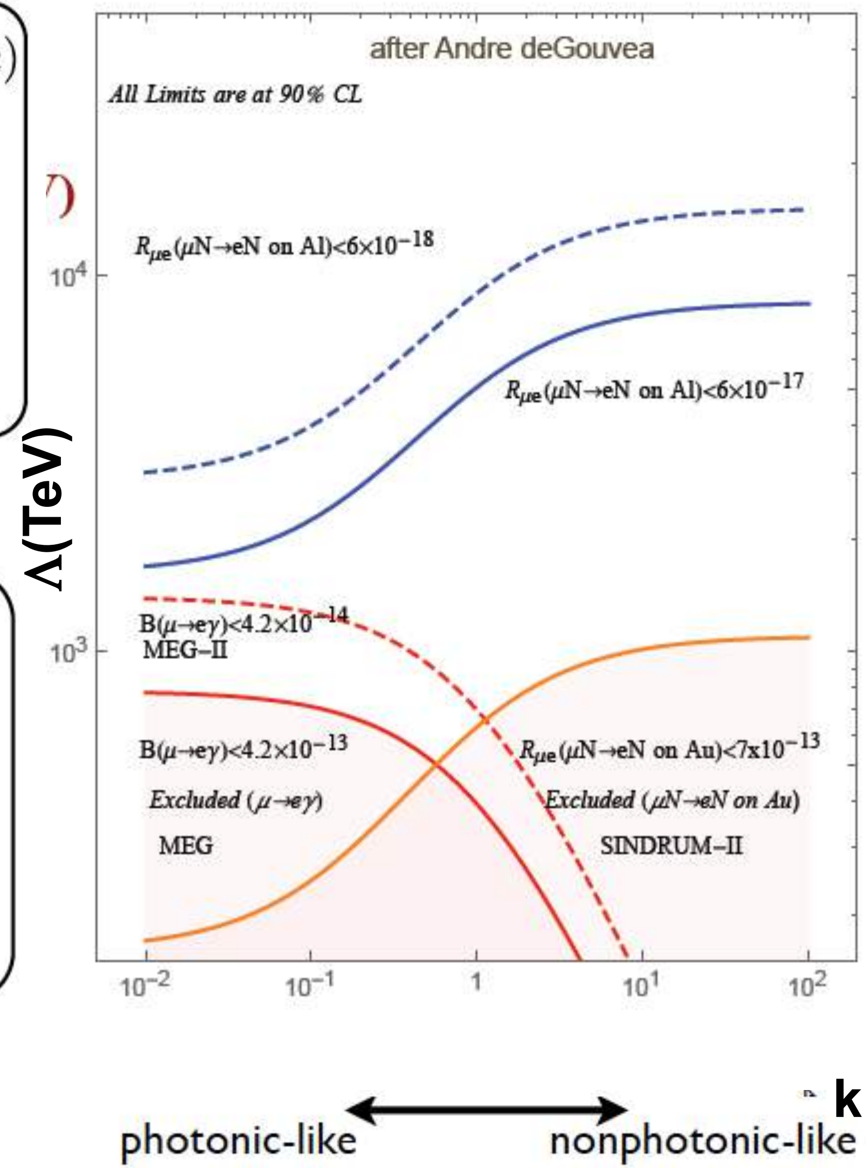


photonic



non-photonic

- SUSY-GUT, SUSY-seesaw
  - higgs mediated processes
- Doubly Charged Higgs Boson (LRS *etc.*)
- Little Higgs Models
- Randall-Sundrum Models
- SUSY with R-parity Violation
- Leptquarks
- Heavy Z'
- Multi-Higgs Models



Correlations

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

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

These are a subset of a subset listed by Buras and Girrbach MFV, CMFV, $2HDM_{\overline{MFV}}$, LHT, SM4, SUSY flavor. SO(10) – GUT, $SSU(5)_{HN}$, FBMSSM, RHMFV, L-R, RS_0, gauge flavor, ……….

The pattern of measurement:

★★★ large effects

★★ visible but small effects

★ unobservable effects

is characteristic,

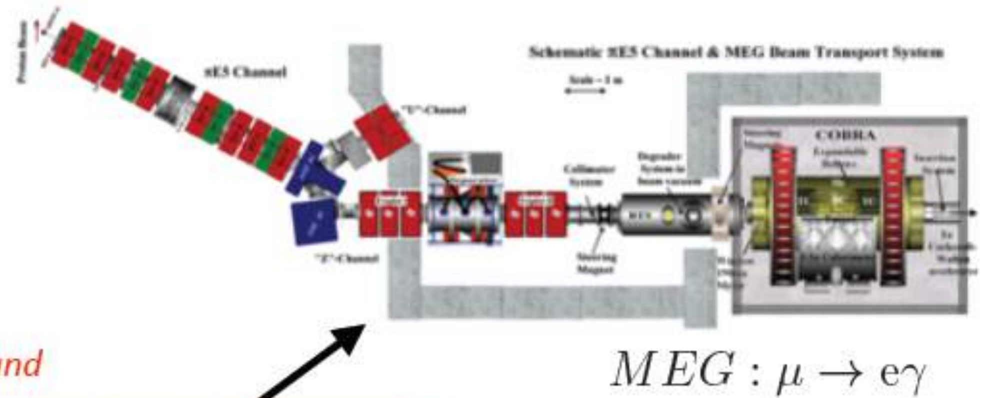
often uniquely so,

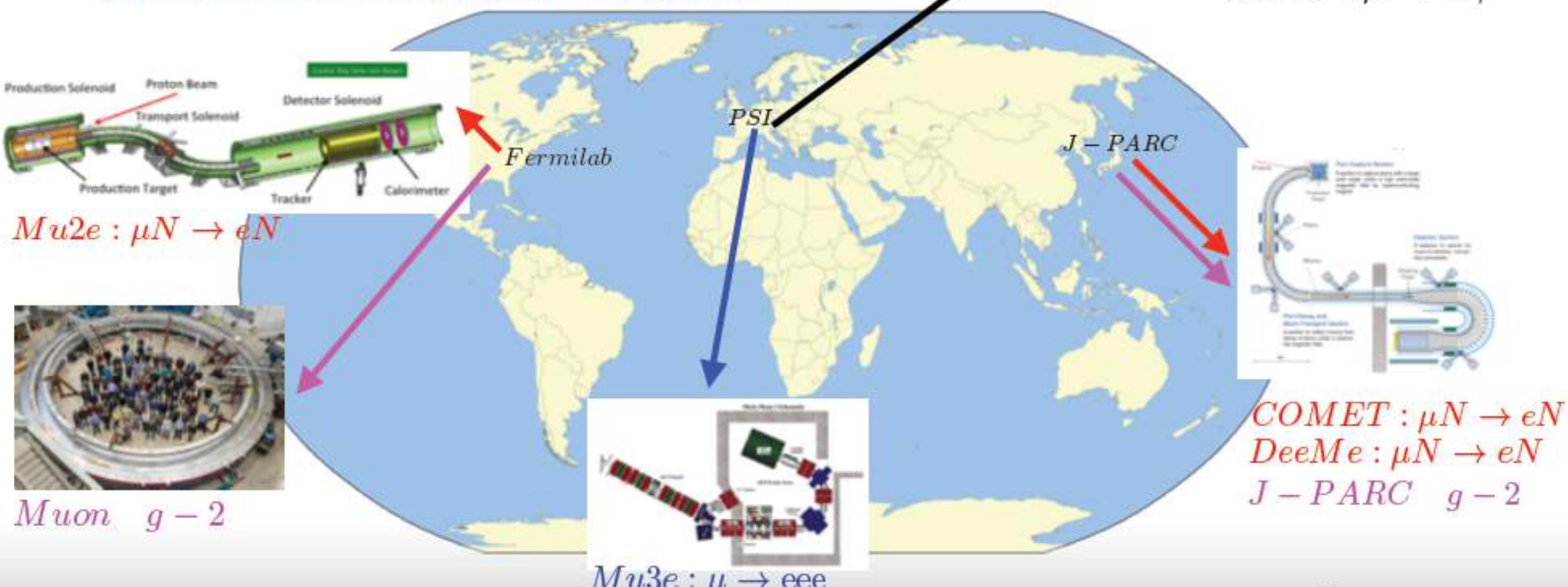
of a particular model

GLOSSARY	
AC [10]	RH currents & U(1) flavor symmetry
RVV2 [11]	SU(3)-flavored MSSM
AKM [12]	RH currents & SU(3) family symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parity
RS [16]	Warped Extra Dimensions

Muon is a golden channel

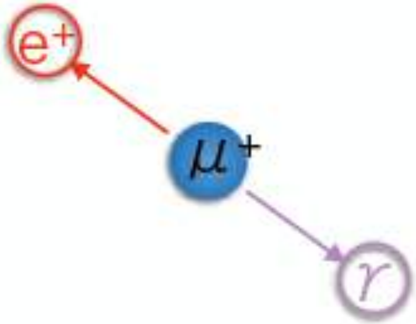
- **High intensity and low energy μ beams**
  - *large statistics possible*
- **long decay time**
  - *beam **transport** to a **target***
- **simple kinematics**
  - ***precise** measurements in a **high rate** background*





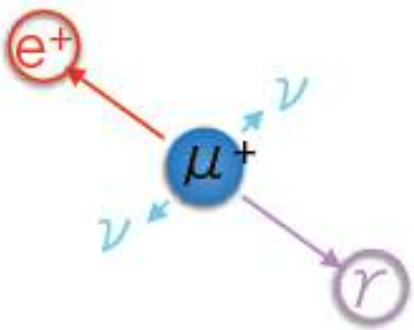
$\mu \rightarrow e\gamma$: Signal and Background

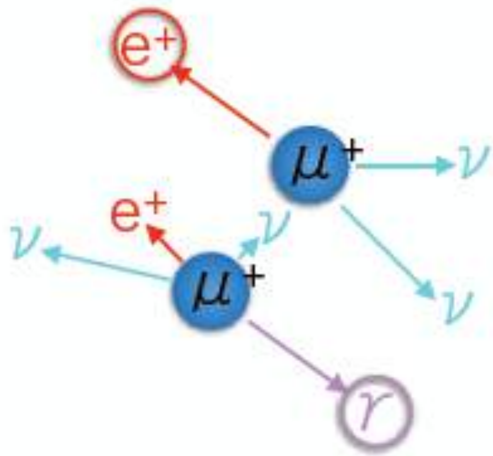
Signal



- $E_{e^+} = 52.8$ MeV
- $E_\gamma = 52.8$ MeV
- $\theta_{e\gamma} = 180°$
- $T_{e\gamma} = 0$ s

Backgrounds





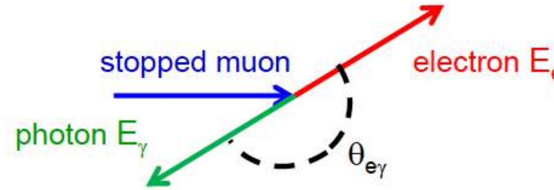
- $E_{e^+} < 52.8$ MeV
- $E_\gamma < 52.8$ MeV
- $\theta_{e\gamma} <= 180°$

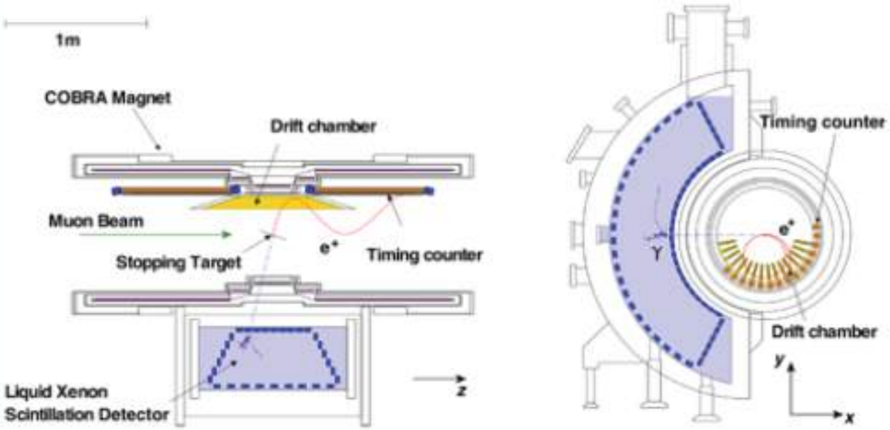
- $T_{e\gamma} = 0$ s
- $T_{e\gamma}$ = flat-distribution

Accidental Background dominate:

$\propto R_\mu \times \Delta E_e \times \Delta E_\gamma^2 \times \Delta\theta_{e\gamma}^2 \times \Delta T_{e\gamma}$

MEG@PSI



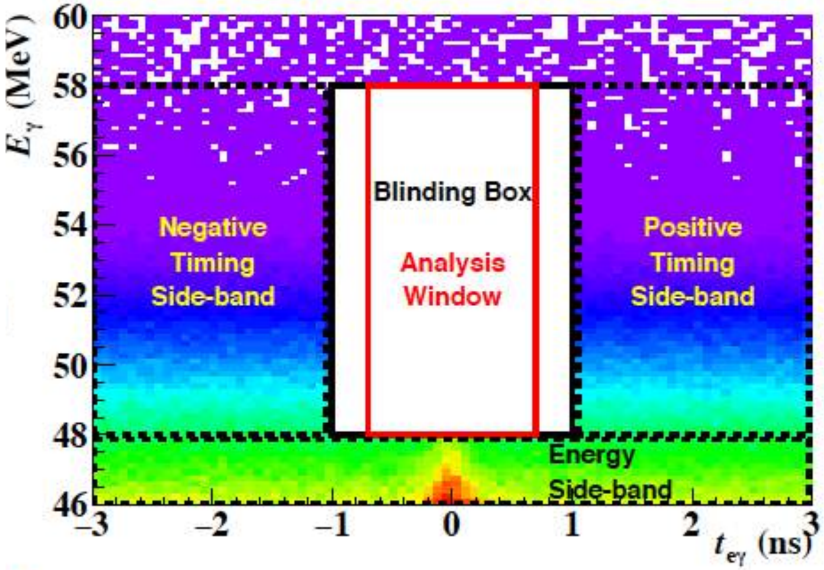


- MEG
  - DC muon beam, $R_\mu{}^+ = 3 \times 10^7$ /sec
  - LXe photon detector
  - ultra-light DC, Gradient B-field
  - DAQ: 2008 ~ 2013
  - Final Result: BR < 4.2×10^{-13} (90% C.L.)
- MEG II
  - Run 2017 ~ 2020
  - Sensitivity: 4×10^{-14}

- **μ decay** at **rest**
  - *Beam rate:* ***3×10^7 μ/s***
  - *μ stopped in* ***205 μm target***
- **γ** detection
  - ***Liquid Xenon*** *calorimetry with* ***scintillation light***
    - **fast**: 4/22/45 ns
    - **high LY**: ~0.8 NaI
    - **short X_0**: 2.77 cm
- **positron** detection
  - ***magnetic spectrometer***
    - **non-uniform B field → constant bending radius** and **e swept rapidly away**
    - **ultra-thin drift chambers** to **limit matter effects (X_0 ~ 0.0003 per module)**
  - ***TC detector***
    - **time of flight** with **plastic scintillator counters**

MEG@PSI; result

- Decided to extract **CL to B(μ→eγ)** from a **likelihood analysis** in a **wide signal box**
- Each **event** is described in terms of **5 kinematic variables**
  - $x_i = (E_\gamma, E_e, t_{e\gamma}, \varphi_{e\gamma}, \vartheta_{e\gamma})$
- **resolutions** and **PDFs** evaluated **on data outside the signal box**
  - *signal box* ***closed*** *until* ***analysis is fixed***
- Use of **sidebands**
  - ***accidental background*** *from* ***Left and Ri sidebands***
  - ***Radiative Muon Decay*** *(RMD) studied in the* E_γ ***sideband***



$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}) = \frac{e^{-N}}{N_{\rm obs}!} \boxed{e^{-[(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2/2\sigma^2_{\rm RMD}]}} \times \boxed{e^{-[(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2/2\sigma^2_{\rm BG}]}} \prod_{i=1}^{N_{\rm obs}} [N_{\rm sig}S(\vec{x}_i) + N_{\rm RMD}R(\vec{x}_i) + N_{\rm BG}B(\vec{x}_i)],$$

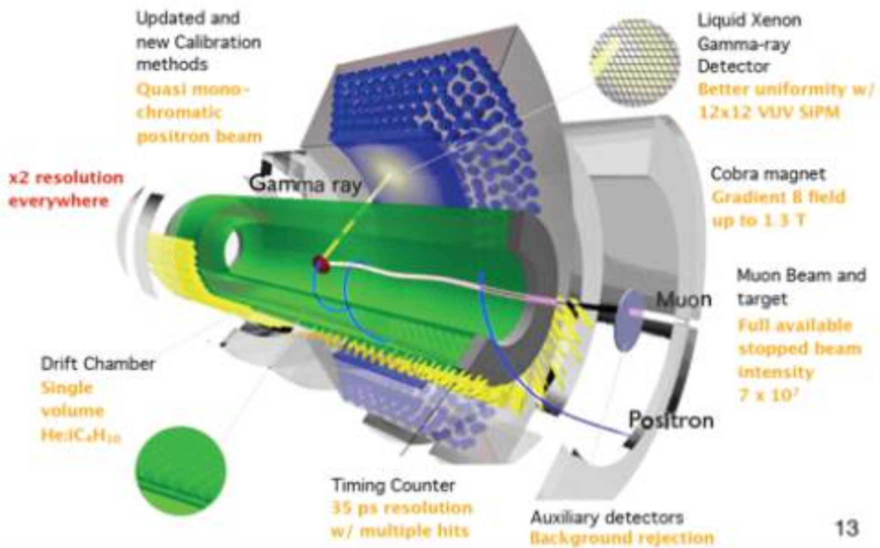
Number

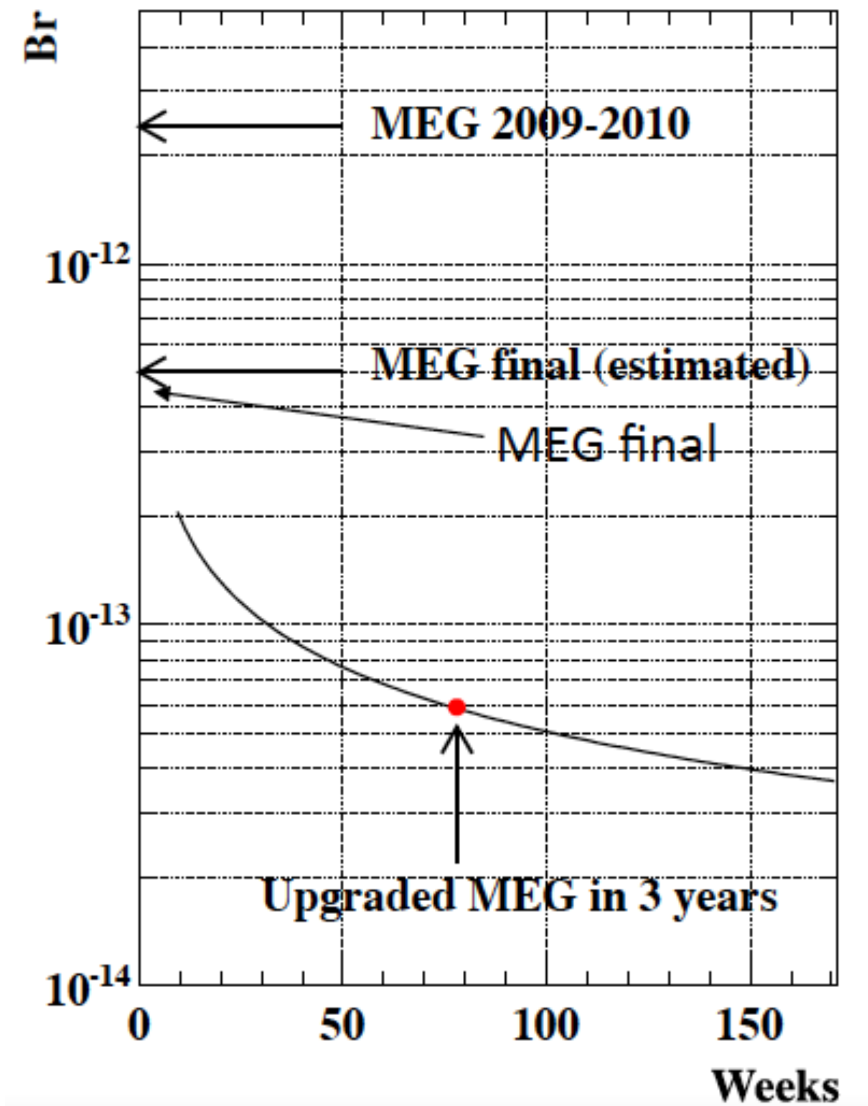
Likelihood function in terms of Signal, Radiative muon decays and accidental background number events and PDFs

BR(μ→eγ)<4.2 10^-13 @90% CL

MEGII @PSI

Going to improve the sensitivity by one order of magnitude





Resolution	MEG	MEGII
γ-position (mm)	5~6	2.2~3.1
E_γ	1.7~2.4%	1.0~1.1%
t_γ (ps)	67	60
p_e (keV)	306	130
θ_e (mrad)	9.4	5.3
ϕ_e (mrad)	8.7	4.8

Mu3e@PSI

search for $\mu^+ \to e^+ e^- e^+$ with sensitivity BR ~ 10^{-16} (PeV scale)

$\tau_{(\mu \to eee)}$ > 700 years (τ_μ = 2.2 μs)

using the most intense DC (surface) muon beam in the world (p ~ 28 MeV/*c*)

suppress backgrounds below 10^{-16}

find or exclude $\mu^+ \to e^+ e^- e^+$ at the 10^{-16} level
4 orders of magnitude over previous experiments (SINDRUM @ PSI)

Aim for sensitivity
10^{-15} in Phase I
10^{-16} in Phase II
(i.e. find one $\mu^+ \to e^+e^-e^+$ decay in 10^{16} muon decays)

$\to$ observe ~10^{17} μ decays (over a reasonable time scale)
rate ~ 2×10^9 μ decays / s
$\to$ build a detector capable of measuring 2×10^9 μ decays / s
minimum material, maximum precision

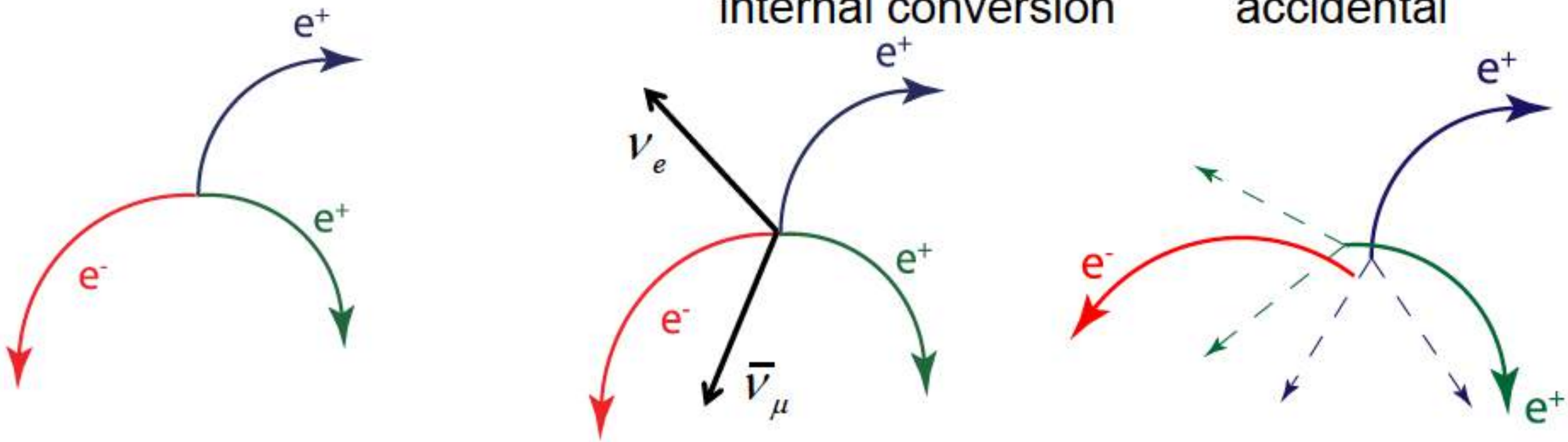
project (Phase I) approved in January 2013

Mu3e@PSI

signal

backgrounds

internal conversion accidental



BR ($\mu^+ \to e^+ e^- e^+ \nu_e \nu_\mu$) = 3.5 x 10^{-5}

Features

common vertex	common vertex	no common vertex
$\Sigma \mathbf{p}_i = 0$, $\Sigma E_i = m_\mu$	$\Sigma \mathbf{p}_i \neq 0$, $\Sigma E_i < m_\mu$	$\Sigma \mathbf{p}_i \neq 0$, $\Sigma E_i \neq m_\mu$
in time	in time	out of time

Rejecting the background requires

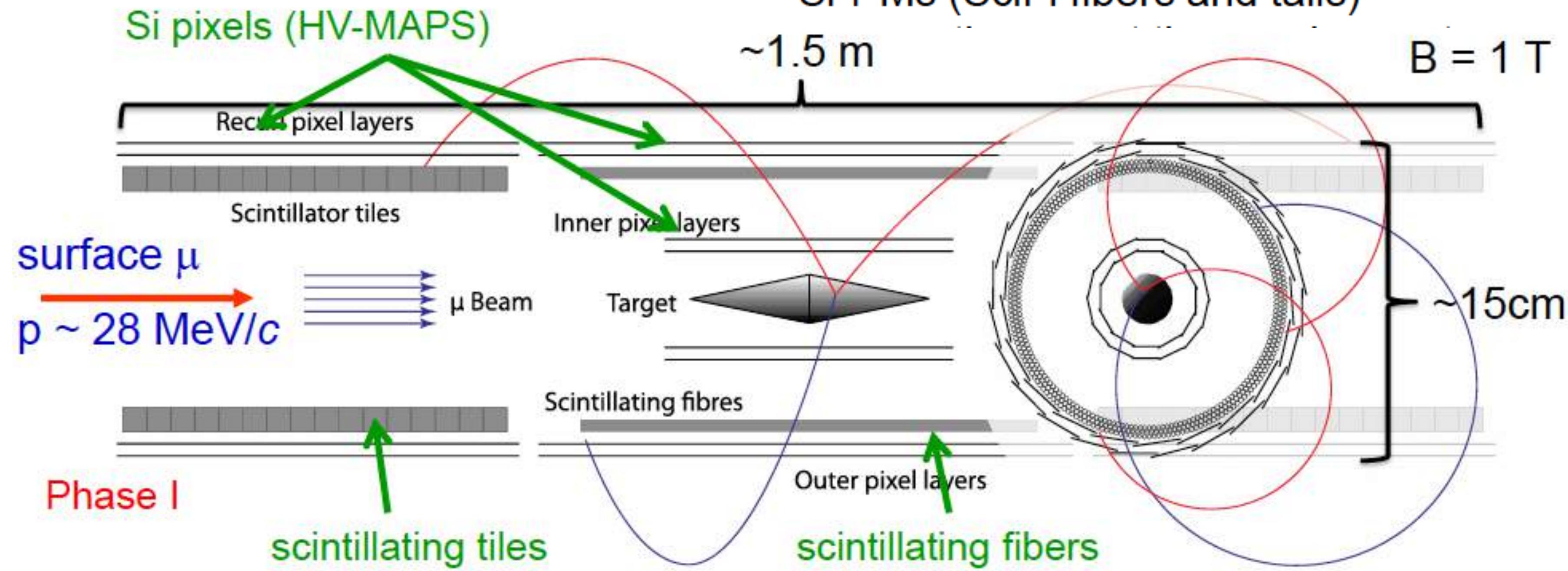
$\sigma_{vtx} < 300\ \mu m$
$\sigma_p < 0.5$ MeV/c
$\sigma_t < 0.5$ ns

Mu3e@PSI

Novel technologies:

HV-MAPS (Si pixels, 50 μm thickness)

Si-PMs (SciFi fibers and tails)



Staged approach

Stage I (2018 – 2020)

$\sim 10^8$ μ decays / s $\quad$ BR($\mu \to eee$) < 10^{-15}

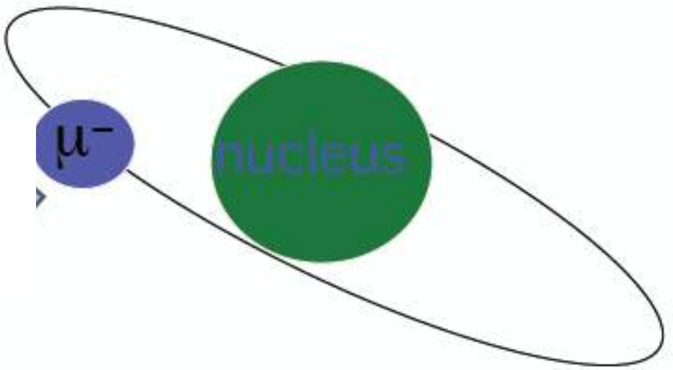
approved in January 2013

Stage II (> 2020)

$\sim 2 \times 10^9$ μ decays / s $\quad$ BR($\mu \to eee$) < 10^{-16}

HiMB feasibility study already started

μ-e Conversion in Nuclear Field



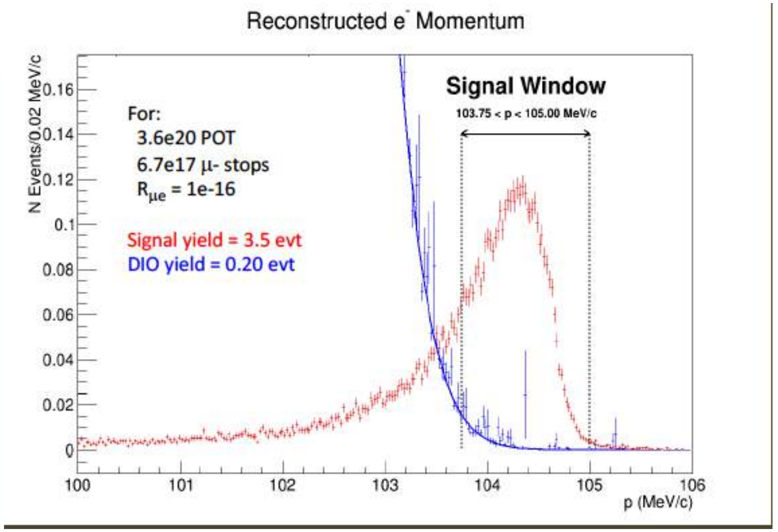
- Muonic Atom (1S state)
  - Muon Capture (MC)

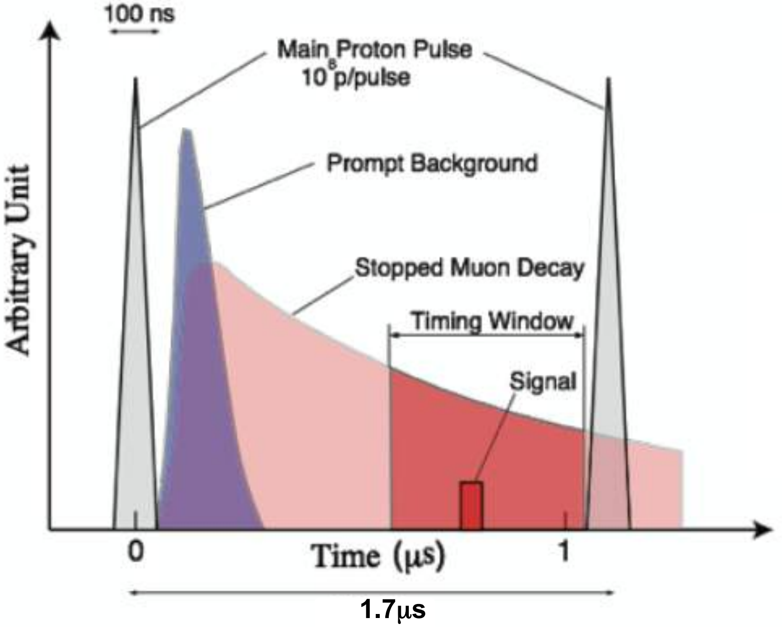
    $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1)$
  - **Muon Decay in Orbit (DIO):**
    - **$\mu^- \rightarrow e^- \nu\ \nu$**
  - **MC: DIO = 1:1000(H), 2:1(Si), 13:1(C)**
  - **$\tau\mu$ = 2.2 μs**
  - **$\tau\mu$ (Si) = 0.76 μs**
- **Charged Lapton Flavor Violation (μ-e conversion in nuclear field)**
  - $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$

$$\mathrm{BR}[\mu^- + (A,Z) \to e^- + (A,Z)] \equiv \frac{\Gamma[\mu^- + (A,Z) \to e^- + (A,Z)]}{\Gamma[\mu^- + (A,Z) \to \nu_\mu + (A, Z-1)]}$$

μ-e Conv. Signal & Backgrounds

- Process : $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - A single mono-energetic electron
    - 105 MeV
    - Delayed : ~1μS
- <u>No accidental backgrounds</u>
- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - $E_e > 102.5$ MeV (BR:10^{-14})
    - $E_e > 103.5$ MeV (BR:10^{-16})
  - **<u>Beam Pion Capture</u>**
    - $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
      $\gamma \rightarrow e^+ e^-$
    - <u>Prompt timing</u>

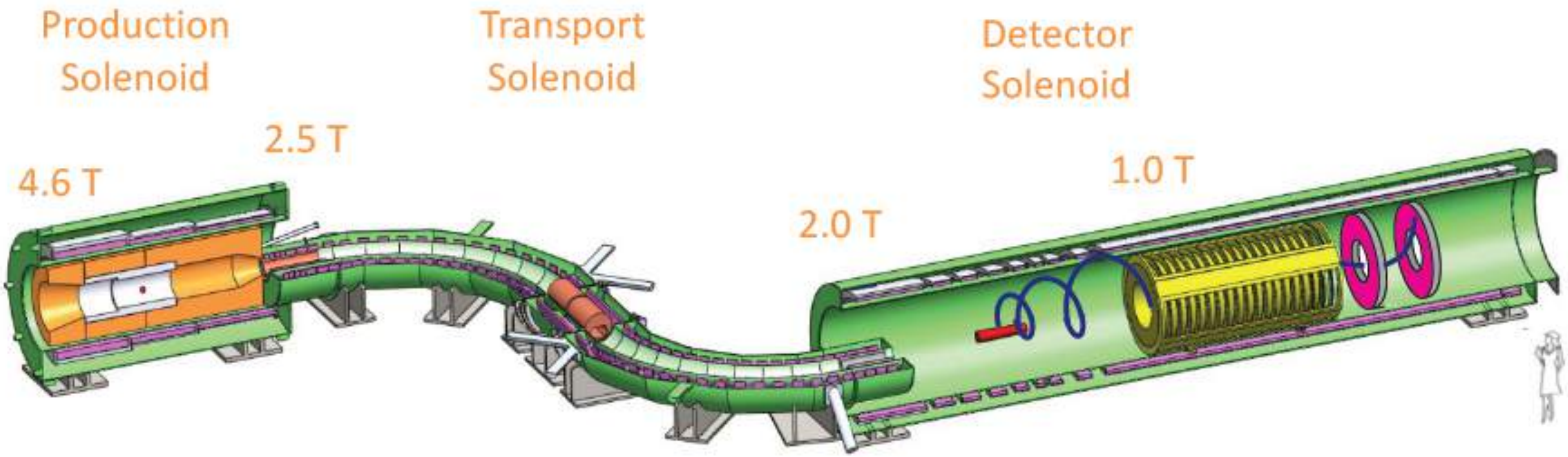




Pulsed proton beam

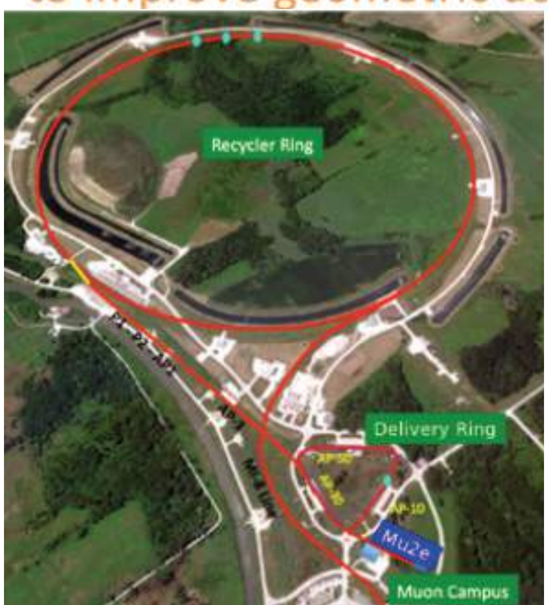
+ Extremely high muon rate w/ state-of-the-art tech.

Mu2e@FNAL



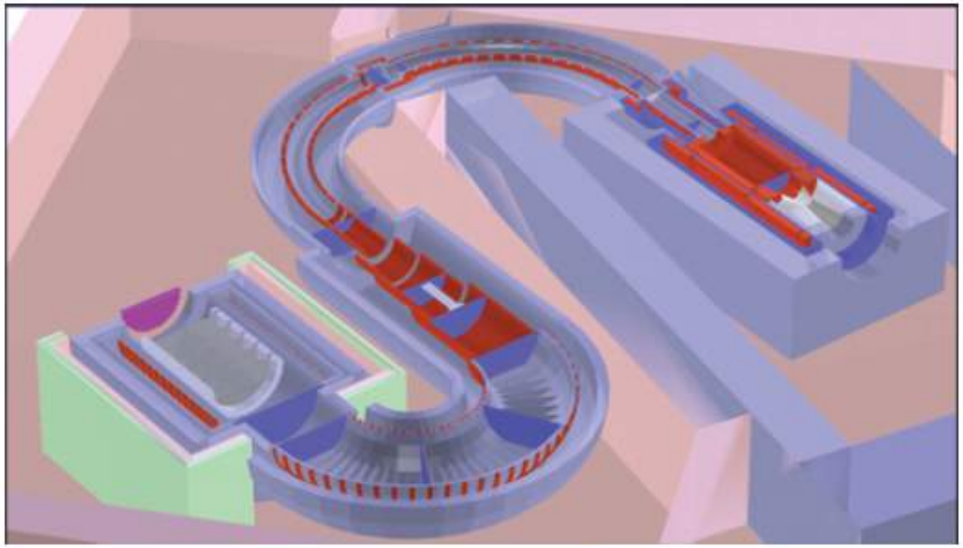
Graded fields important to suppress backgrounds, to increase muon yield, and to improve geometric accept

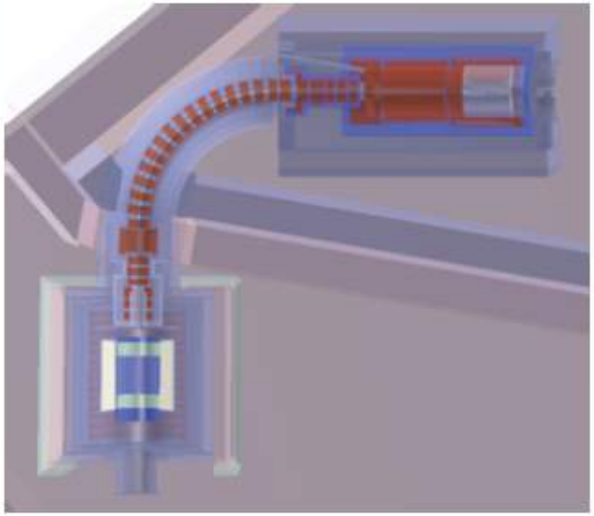
- Long superconducting solenoid: $R_{\mu^-} > 10^{10}$ /sec
  - S.E.S = 2.5×10^{-17}
- Convert FNAL Tevatron rings: pulsed proton
  - Backgrounds < 0.5
- >$200M Project. Physics run 2021~



COMET@JPARC

- a long superconducting solenoid
- Phase-I
  - Beam BG Study
  - S.E.S. = 3×10^{-15}
  - 2018 ~ 2020
- Phase-II
  - S.E.S. = 2.6×10^{-17}
  - 2022 ~

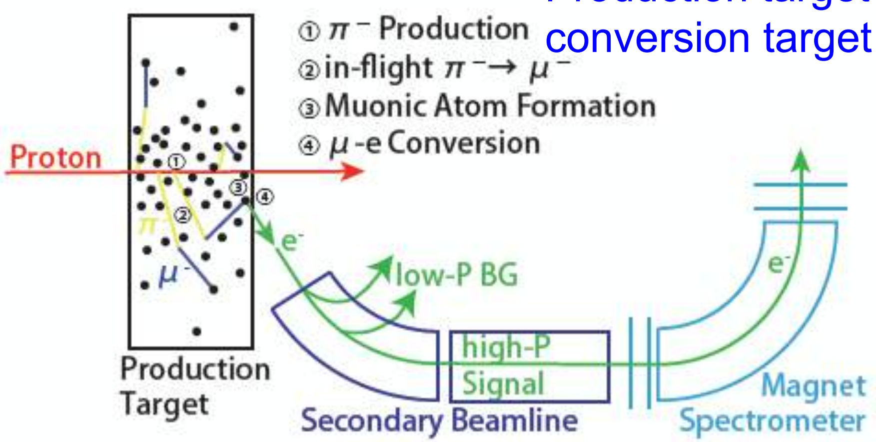


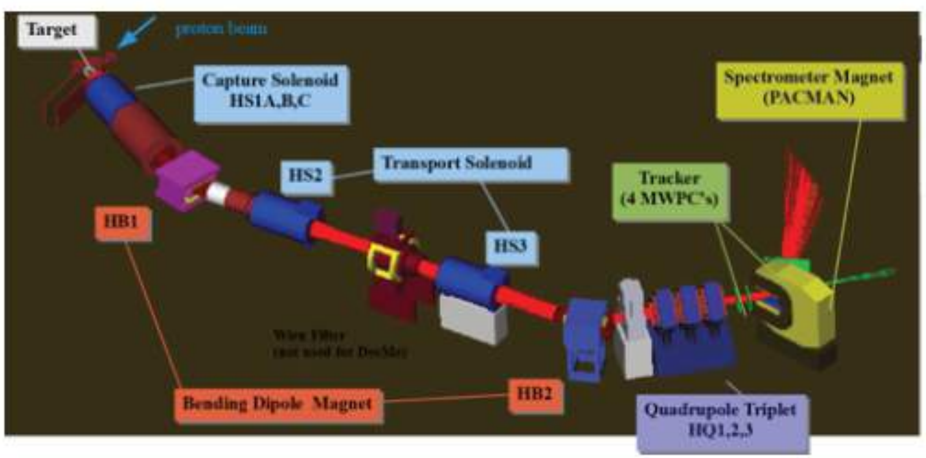


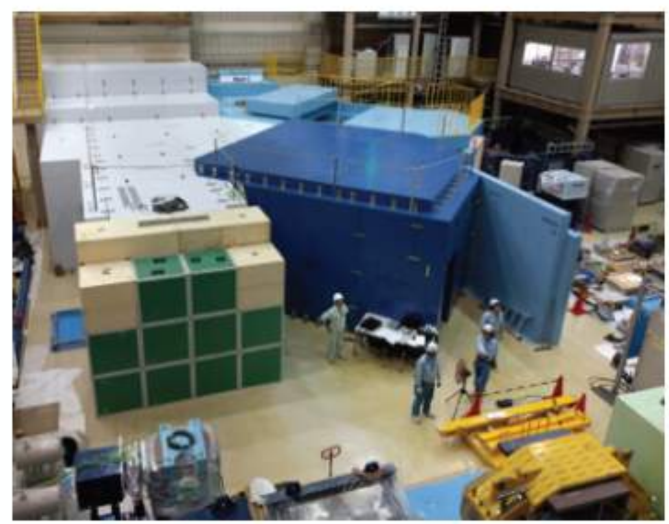
DeeMe@JPARC

- MELC → MECO → Me2e, COMET
- DeeMe: Completely different idea
- S.E.S. = 10^{-13} (C) ~ 5×10^{-14} (SiC)

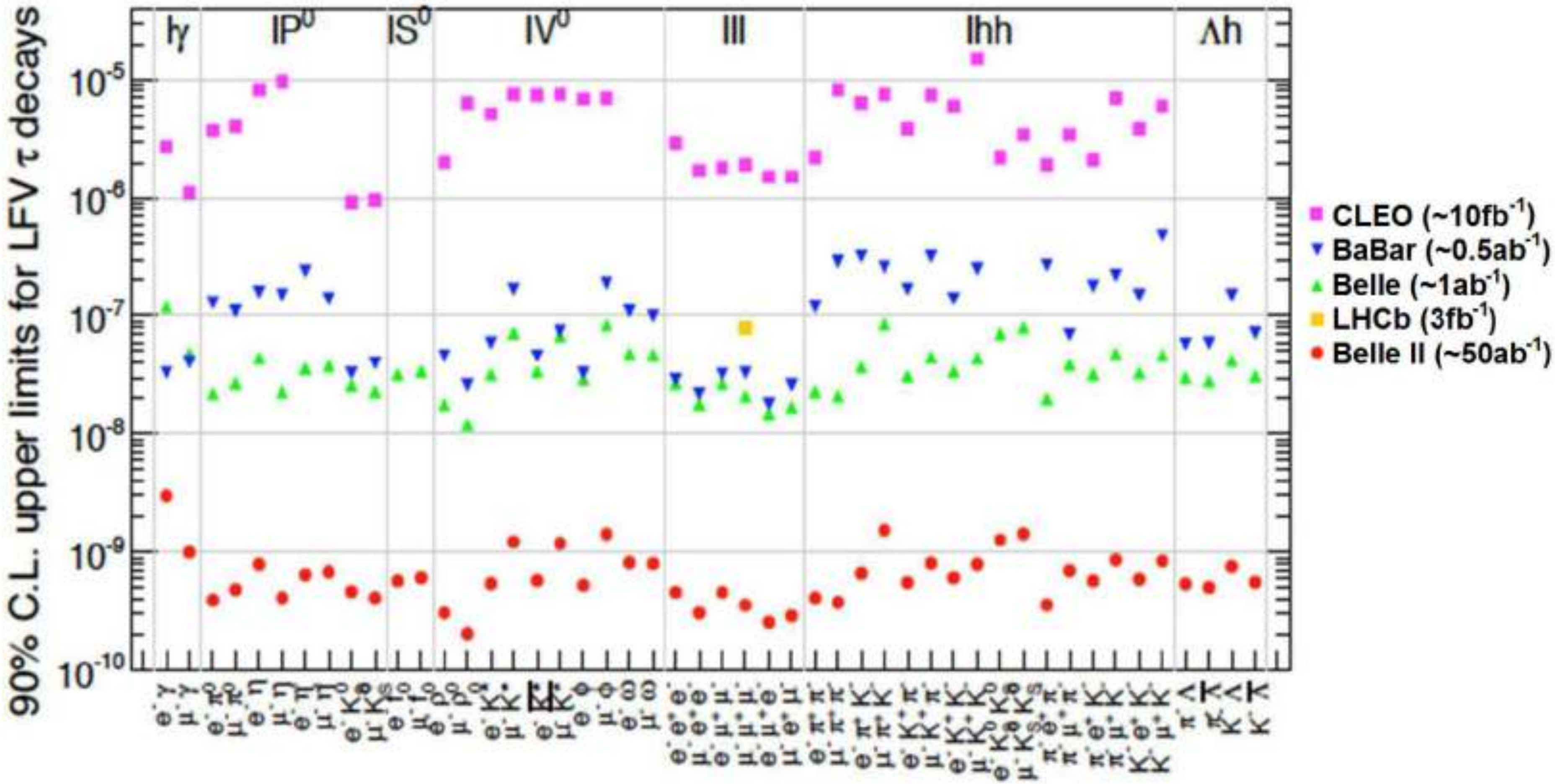
Production target and conversion target the same







Current upper limits on LFV τ decays



Status of $\tau \rightarrow \mu^- \gamma$

Group	Date	$\mathcal{L}, \mathrm{fb}^{-1}$	$N_{\tau\tau}, 10^6$	B_{UL}^{90}
MARK II	1982	0.017	0.048	5.5×10^{-4}
ARGUS	1992	0.387	0.374	3.4×10^{-5}
DELPHI	1995	0.07	0.081	6.2×10^{-5}
CLEO	2000	13.8	12.6	1.1×10^{-6}
Belle	2004	86.3	78.5	3.1×10^{-7}
BaBar	2005	232.2	207	6.8×10^{-8}
Belle	2006	535	477	4.5×10^{-8}
BaBar	2010	515.5	481.5	4.4×10^{-8}
BaBar & Belle	2006	767.2	684	1.6×10^{-8}

Summary of LFV searches

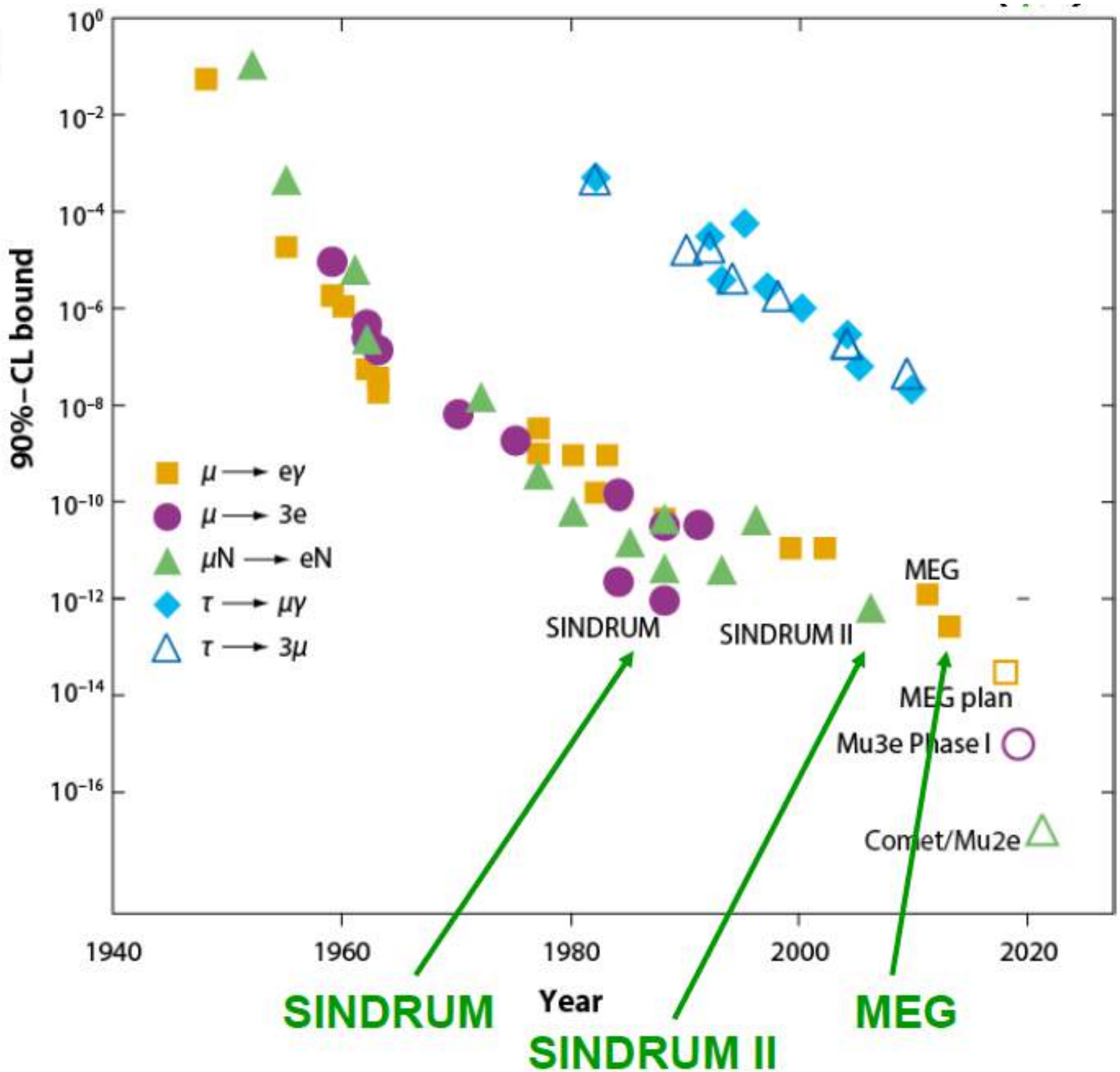
The best limits on LFV come from PSI muon experiments

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

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

$\mu^+ \rightarrow e^+ + \gamma$
BR $< 4.2 \times 10^{-13}$
MEG 2016

Mu3e $\mu^+ \rightarrow e^+e^-e^+$
Phase I : BR $< 10^{-15}$
Phase II: BR $< 10^{-16}$



Muon g-2: summary of the present status

- E821 experiment at BNL has generated enormous interest:

$$a_\mu^{E821} = 11659208.9(6.3)\times 10^{-10} \quad \text{(0.54 ppm)}$$

- Tantalizing ~3σ deviation with SM (persistent since >10 years):

$$a_\mu^{SM} = 11659180.2(4.9)\times 10^{-10}\,(DHMZ)$$

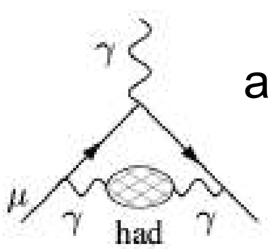
M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C71 (2011)

$$\boxed{a_\mu^{E821} - a_\mu^{SM} \sim (28 \pm 8)\times 10^{-10}}$$

- Current discrepancy limited by:
  - Experimental uncertainty→ New experiments at FNAL and J-PARC **x4** accuracy
  - Theoretical uncertanty→ limited by hadronic effects

$$a_\mu^{SM} = a_\mu^{QED} + \boxed{a_\mu^{HAD}} + a_\mu^{Weak}$$

Hadronic Vacuum polarization (HLO)



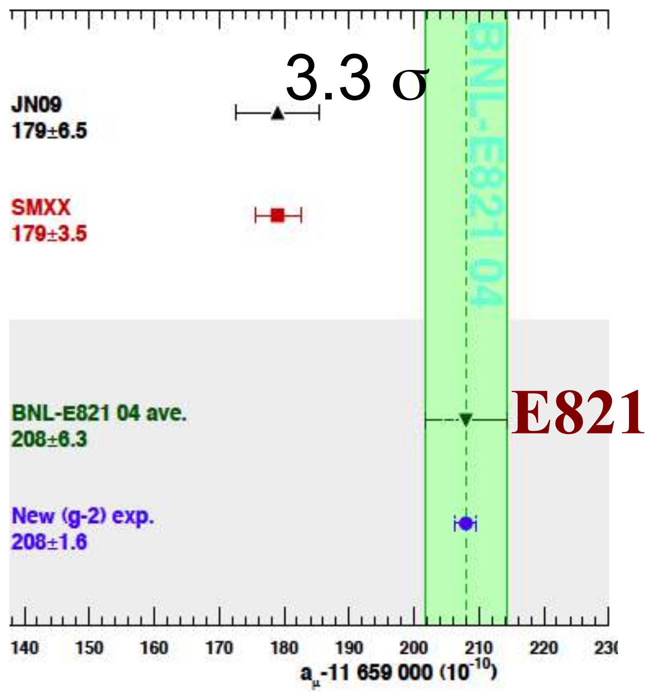
$a_\mu^{HLO} = (692.3 \pm 4.2)10^{-10}$

$\delta a_\mu / a_\mu \sim 0.6\%$

(g-2)$_\mu$: a new experiment at FNAL (E989)

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

→ δa_μx4 improvement (0.14ppm)



$(g\text{-}2)_\mu$: a new experiment at FNAL (E989)

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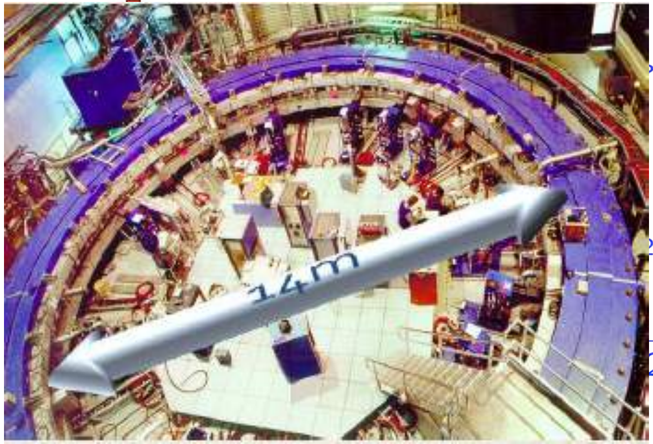
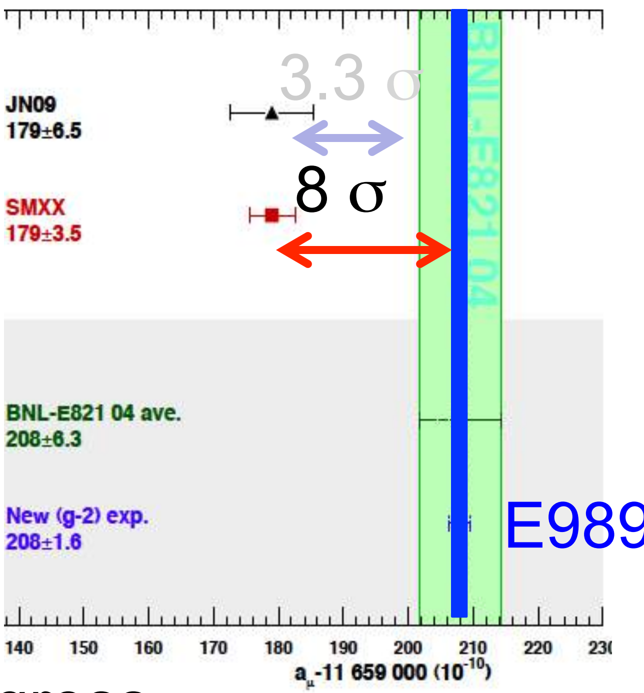


$\rightarrow \delta a_\mu$x4 improvement (0.14ppm)



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

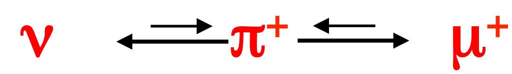
***Depending on the progress on Theory**

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

Complementary proposal at J-PARC in progress

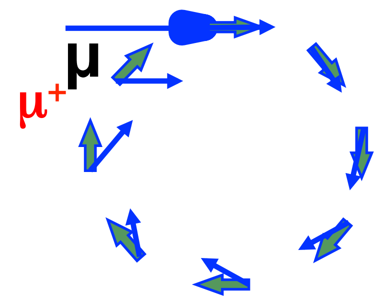
How to measure g-2 in a storage ring

(1) Polarized muons



~97% polarized for forward decays

(2) Precession proportional to (g-2)



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

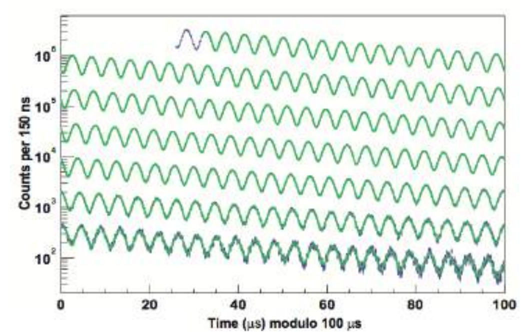
(3) P_μ magic momentum = 3.094 GeV/c

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

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

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

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



How to measure g-2 in a storage ring

(1) Polarized muons

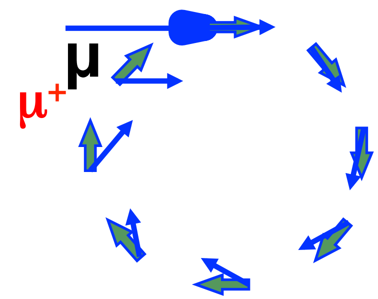
$\nu \longleftarrow \pi^+ \longrightarrow \mu^+$

~97% polarized for forward decays

(2) Precession proportional to (g-2)

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

Measure 2 quantities



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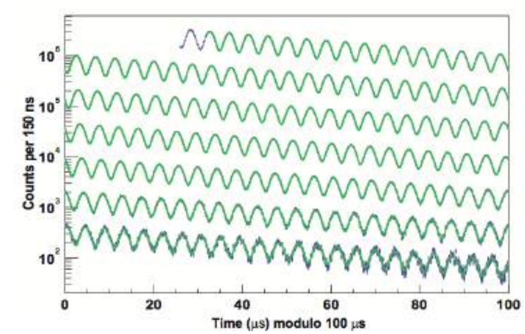


4 key elements for E989 at FNAL

- Consolidated method
- More muons (x20)
- Reduced systematics (ring and detector)
- New crew

- **E821 at Brookhaven**

$$\left.\begin{array}{l}\sigma_{\text{stat}} = \pm 0.46 \text{ ppm} \\ \sigma_{\text{syst}} = \pm 0.28 \text{ ppm}\end{array}\right\} \sigma = \pm 0.54 \text{ ppm}$$

$\hookrightarrow$ $0.2\omega_a \oplus 0.17\omega_p$

- **E989 at Fermilab**

$$\left.\begin{array}{l}\sigma_{\text{stat}} = \pm 0.1 \text{ ppm} \\ \sigma_{\text{syst}} = \pm 0.1 \text{ ppm}\end{array}\right\} \sigma = \pm 0.14 \text{ ppm}$$

$\hookrightarrow$ $0.07\omega_a \oplus 0.07\omega_p$

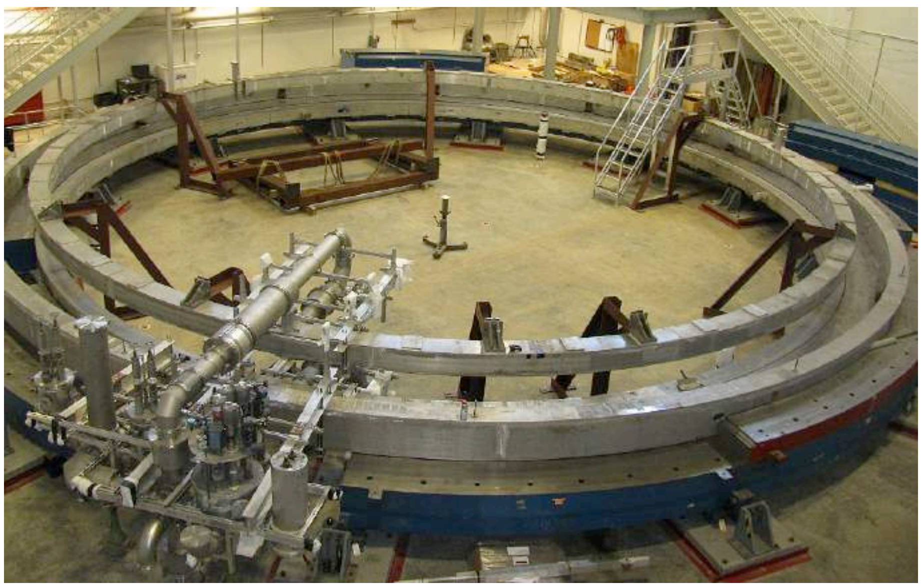
Fermilab Muon Campus Vision, circa 2012

- **Convert FNAL anti-proton source to produce customized muon beams for experiments like Muon g-2 and Mu2e**

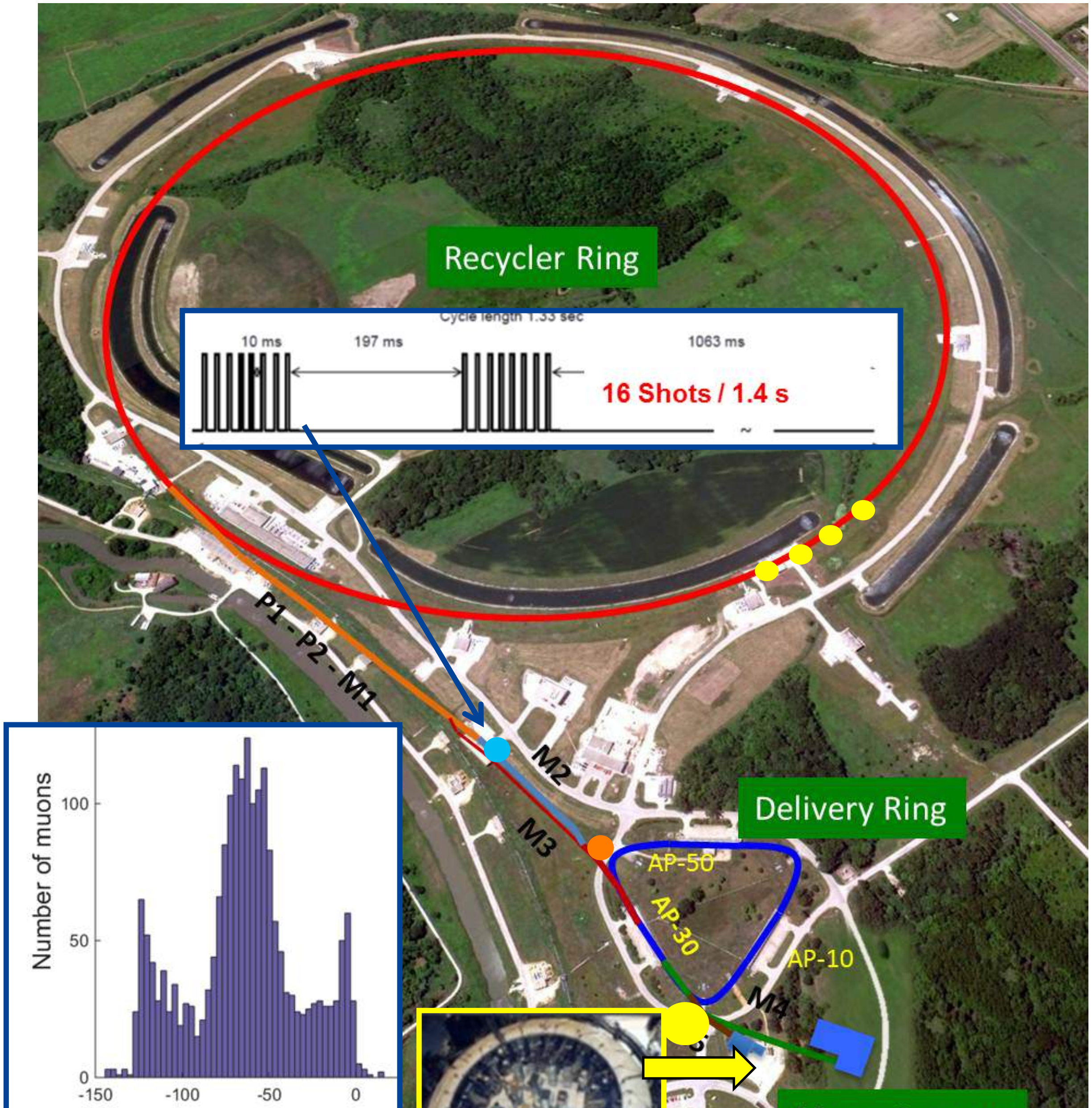
Muon Campus Reality – View from Wilson Hall Today

- Muon g-2 hall complete, BNL storage ring installed and operational
- Mu2e civil construction complete, building outfitting underway
- Conversion of accelerator complex to muon source nearing completion

Ring Reassembling (July 2014 – June 2015)



Achieved full power in September 2015



Intensity profile is 120 ns wide with “W” shape

Creating the Muon Beam for g-2

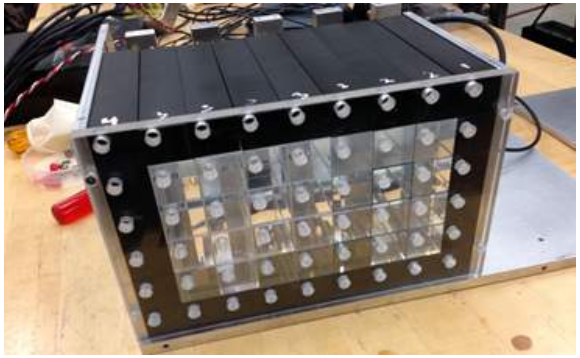
- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract 1 by 1 to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- p/π/μ beam enters DR; protons kicked out; π decay away
- **μ enter storage ring**

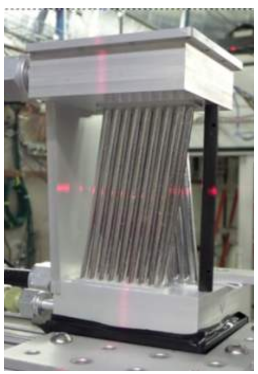
Second challenge – ω_a systematics

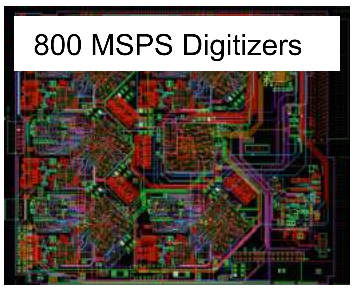
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

- Tackling each of the major systematic errors with knowledge gained from BNL E821 and improved hardware

New detector systems to be installed by March 2017

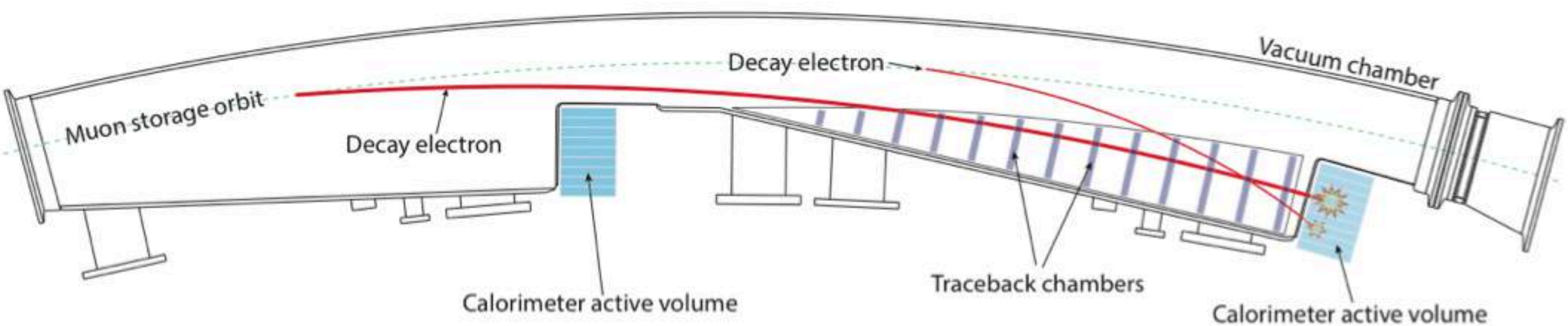






- Calorimeters 24 6x9 PbF2 crystal arrays with SiPM readout, segmentation to reduce pileup
- New electronics and DAQ, 800MHz WFDs and a greatly reduced threshold
- Three 1500 channel straw trackers to precisely monitor properties of stored muon beam via tracking of Michel decay positrons, significant UK contributions
- New laser calibration system from INFN crucial for untangling gain from other systematics

Top view of 1 of 12 vacuum chambers

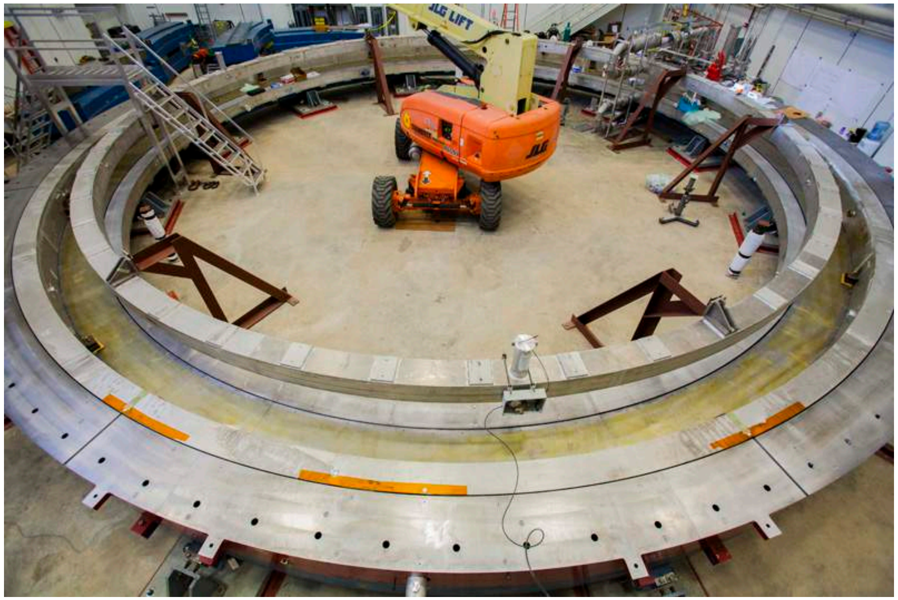


Third challenge – ω_p systematics

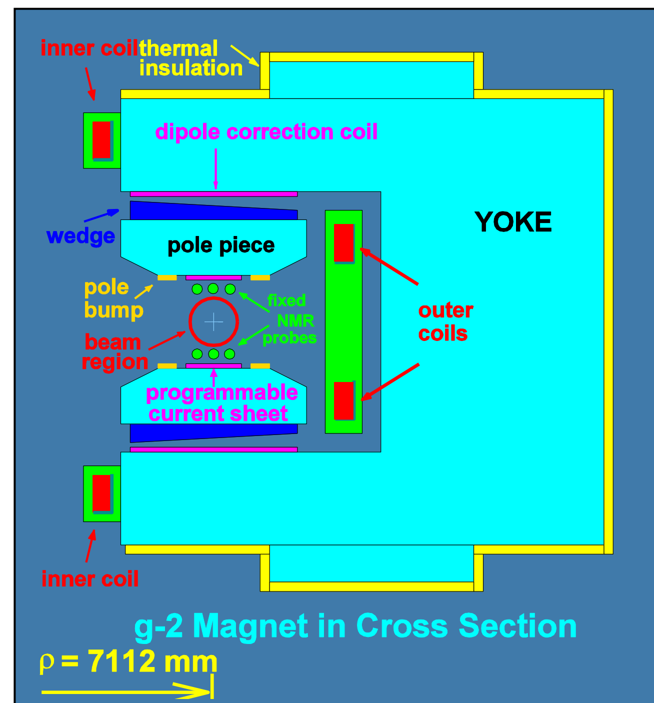
Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Improved T stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes	35
Trolley probe calibrations	90	3-axis motion of plunging probe, higher accuracy position determination by physical stops/optical methods, more frequent calibration, smaller field gradients, smaller abs cal probe to calibrate all trolley probes	30
Trolley measurements of B_0	50	Reduced/measured rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	30
Fixed probe interpolation	70	Better temp. stability of the magnet, more frequent trolley runs, more fixed probes	30
Muon distribution	30	Improved field uniformity, improved muon tracking	10
External fields	–	Measure external fields; active feedback	5
Others †	100	Improved trolley power supply; calibrate and reduce temperature effects on trolley; measure kicker field transients, measure/reduce O_2 and image effects	30
Total syst. unc. on ω_p	170		70

- Need to know the average field observed by a muon in the storage ring absolutely to better than 70 ppb, many hardware improvements
- Very challenging…first major step is making the field as uniform as possible
  - Has been our main thrust over the last 9 months

Field stability and uniformity improvements

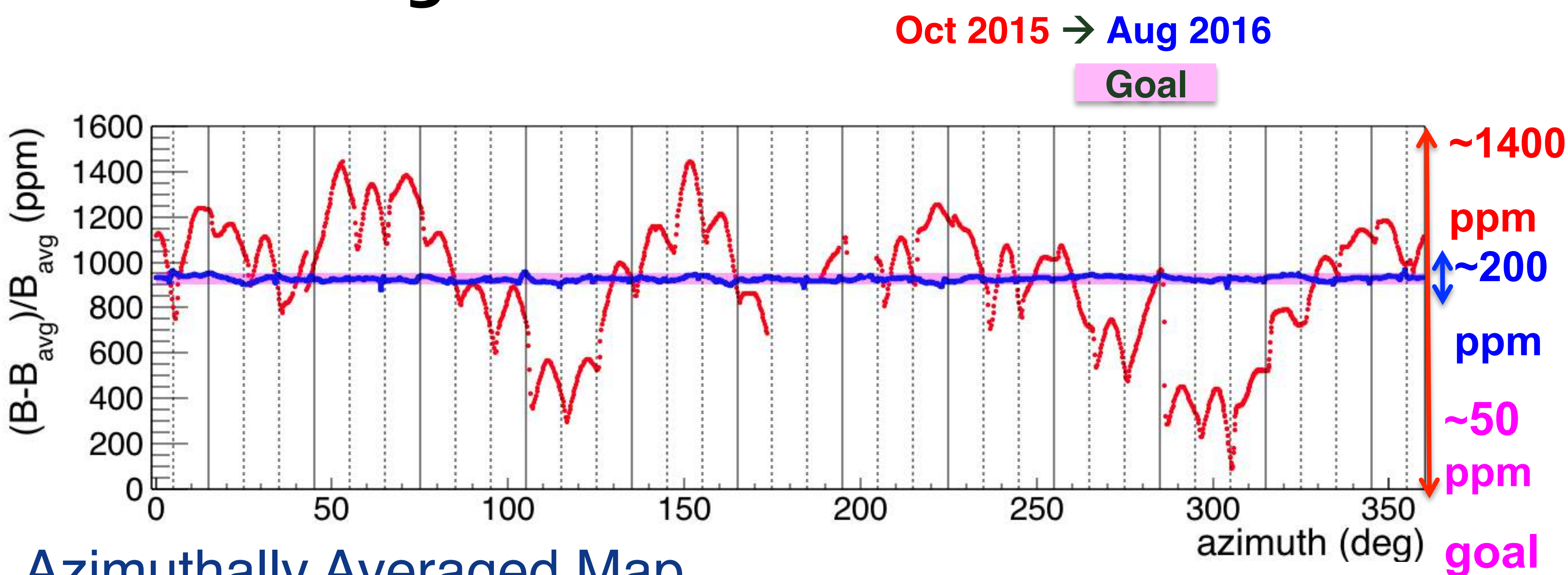


- Environmental
  - 2'9" heavily-reinforced floor installed on 12' deep excavation of undisturbed soil
  - Temperature control to +/- 1C

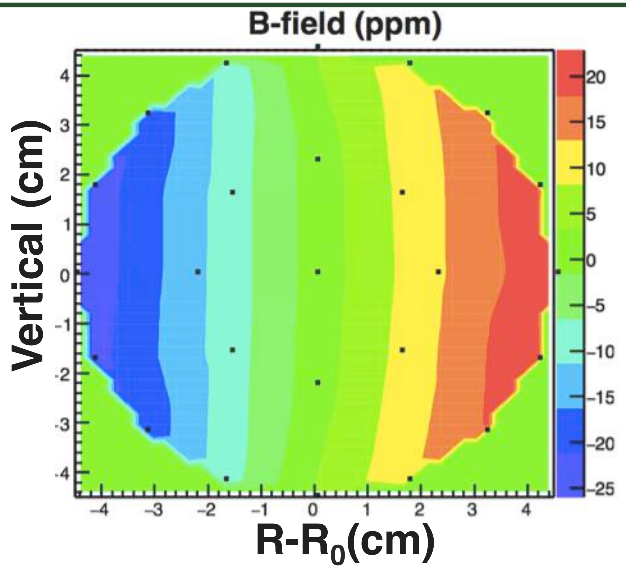


- Construction tolerances
  - 26 ton pieces of yoke steel (30 of them) placed to 125 micron tolerance
  - Pole pieces aligned to 25 micron
- 10 months of interactively shimming B-field with bits of steel and current loops (just ended last month)

Progress on Field

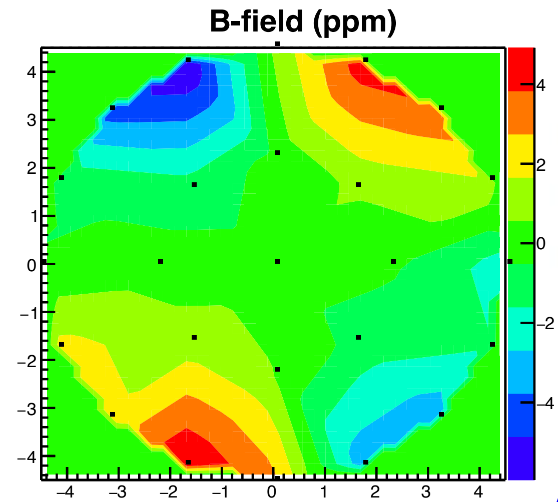


Azimuthally Averaged Map



	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

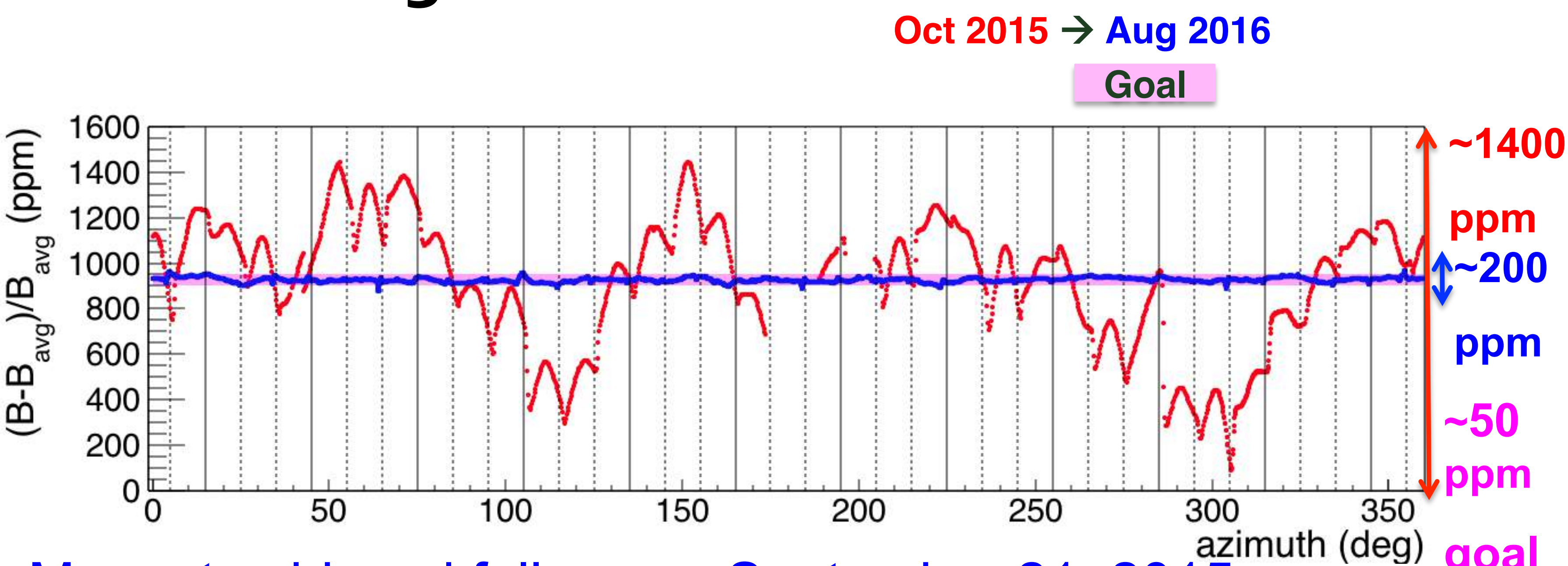
Oct 2015



	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

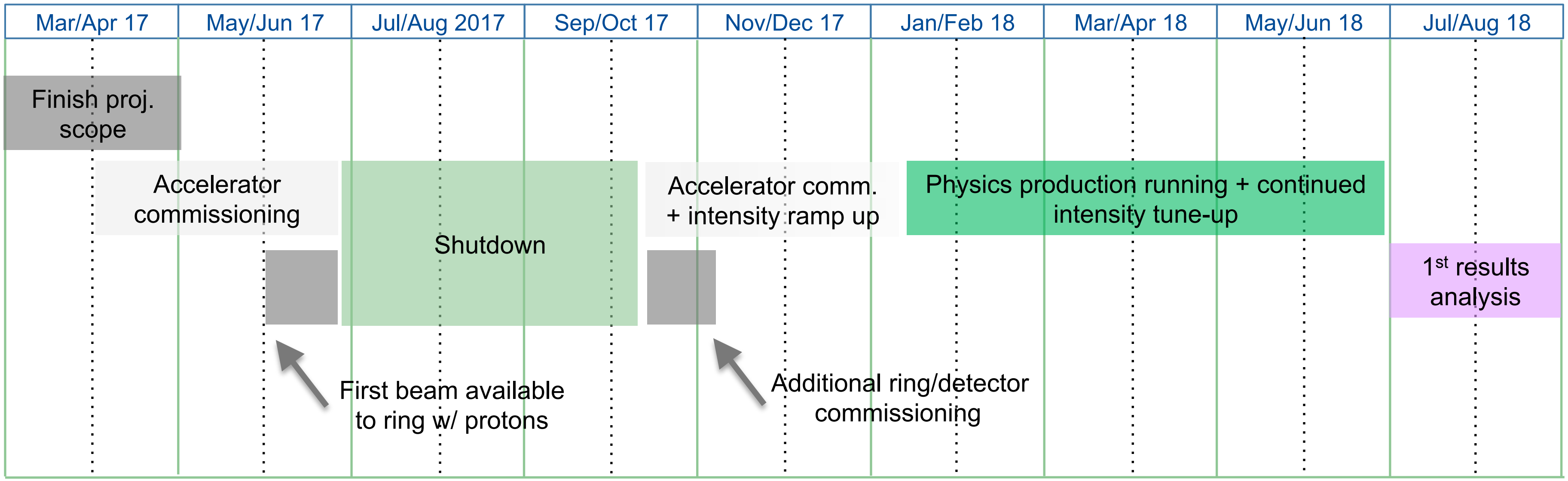
Aug 2016

Progress on Field



- Magnet achieved full power September 21, 2015
- Field started out with a peak variation of 1400 ppm
- June 2016 peak to peak variation was reduced to 200 ppm
- The goal of shimming is 50 ppm with a muon weighted systematic uncertainty of 70 ppb
- BNL achieved 100 ppm with an averaged field uniformity of +- 1ppm. They estimated their systematic uncertainty of 140 ppb. We would like to improve of a factor 2!

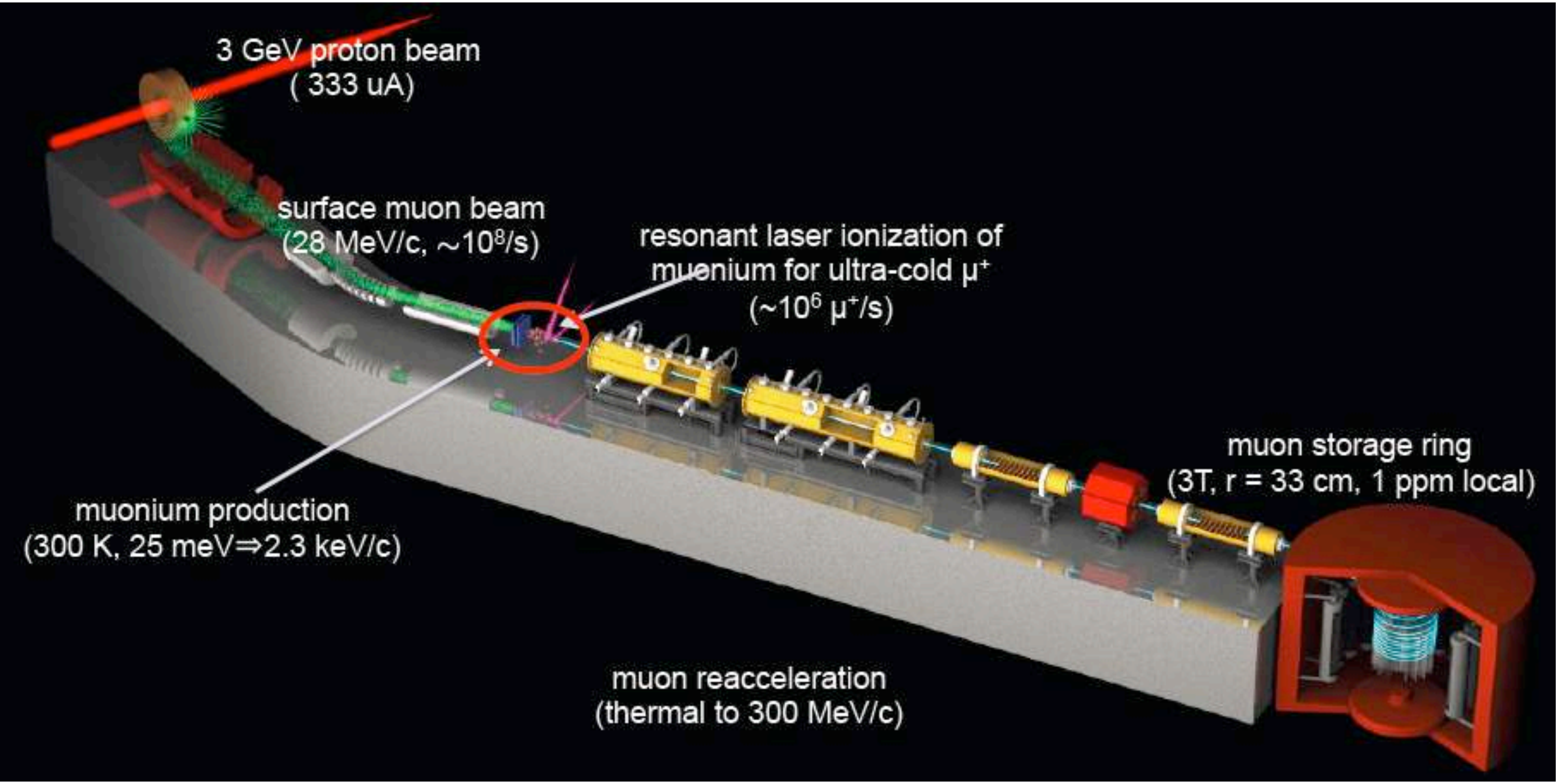
Short term schedule



- After many years of design and construction, we are essentially ready for beam
- June: Commissioning
- Fall: Commission Delivery Ring and optimize Muon Storage
- CY2018: Efficient data taking
- Summer 2018: Our goal is a "BNL level" 1st result
- 2 years run for 4x reduction of error (final result expected ~2020)

The J-PARC approach

Injection of an ultra-cold, low-energy, muon beam into a small, but highly uniform magnet



What makes them different?

- Eliminate electric focusing removes $\beta \times E$ term

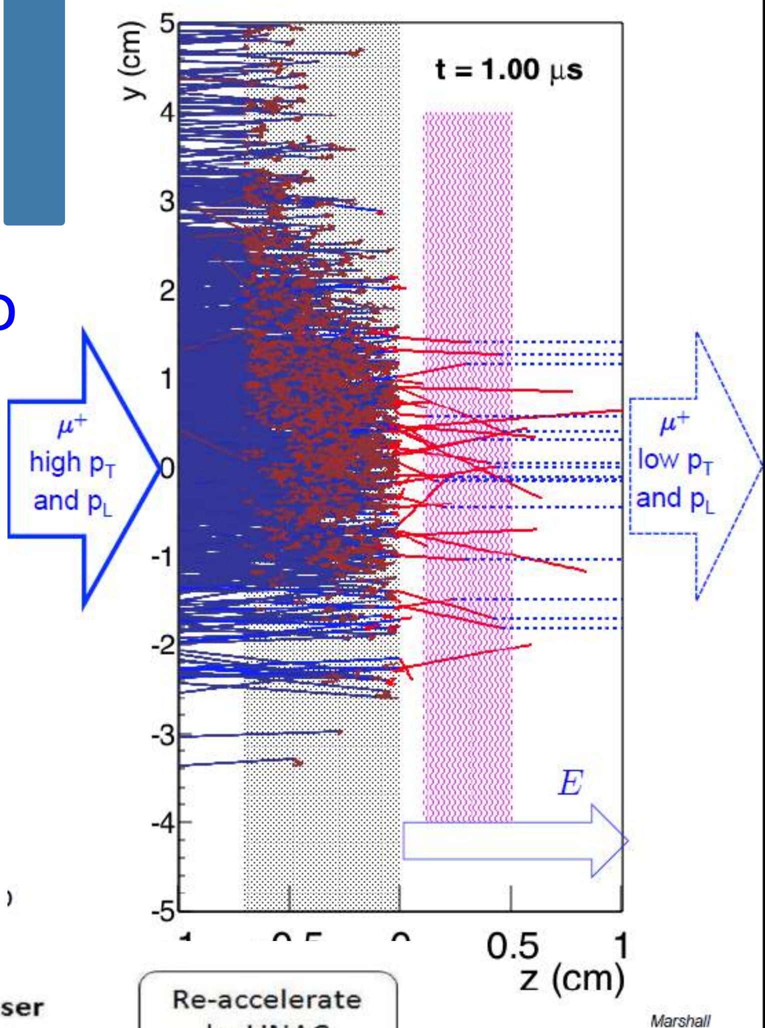
$$\vec{\omega}_a = \frac{e}{mc}\left[a\vec{B} - \cancel{\left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}}\right]$$

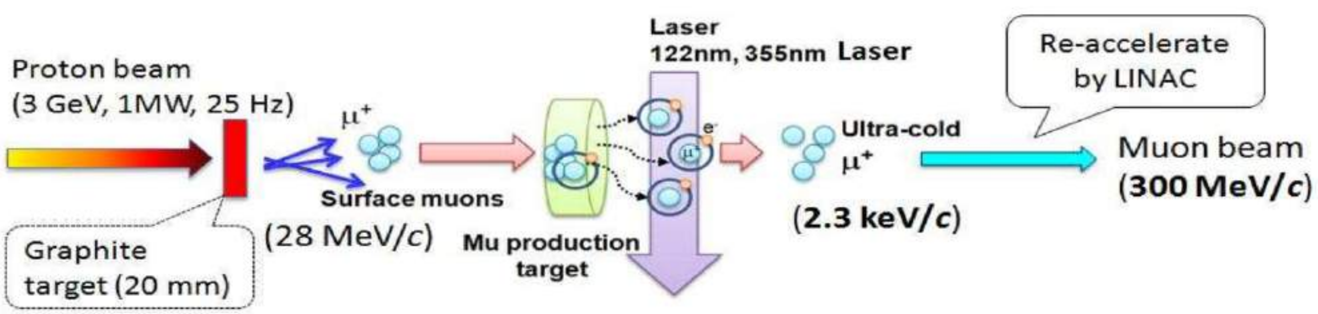
Do need ~zero P_T to store muons

- → Not constrained to run at the "magic momentum"
- Create "ultra-cold" muon source; accelerate, and inject into compact storage ring.
- Consequences are quite interesting …
  - Smaller magnet; intrinsically more uniform
- Aim for BNL level precision as an important check

Ultra-cold Muons

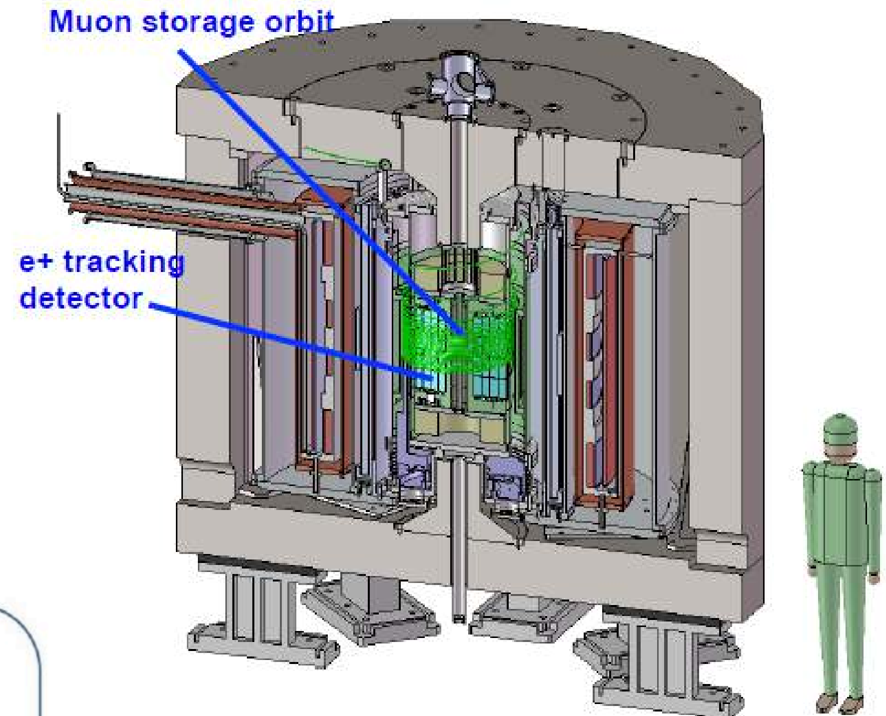
- Surface μ^+
- Stop in Aerogel
- Diffuse Muonium (μ^+e^-) atoms into vacuum
- Ionize
  - 1S → 2P→unbound
  - **Max Polarization 50%**
- Accelerate
  - E field, RFQ, linear structures
  - P = 300 MeV/c



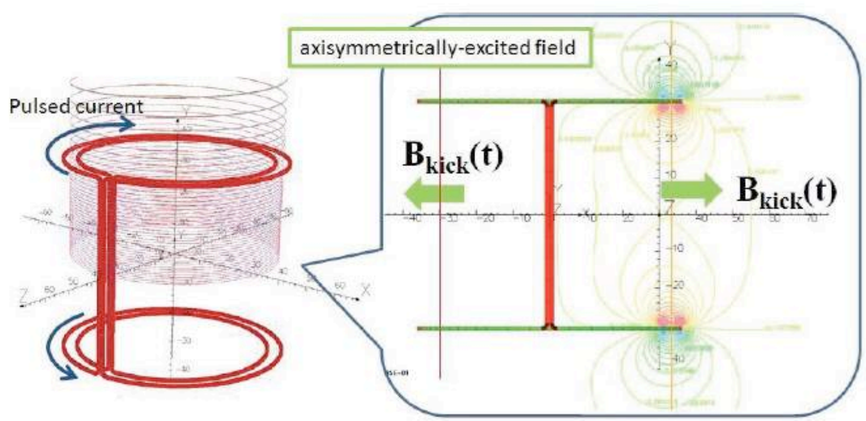


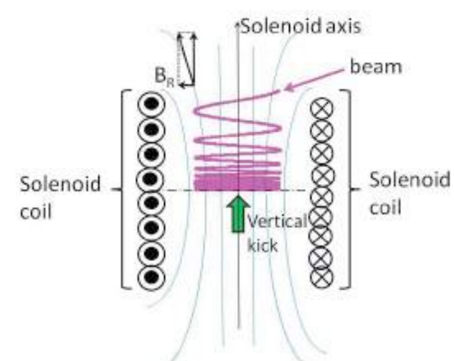
Muon storage magnet

- Superconducting solenoid
  - cylindrical iron poles and yoke
  - vertical B = 3 Tesla, <1ppm locally
  - storage region r = 33.3$\pm$1.5 cm, h = $\pm$5 cm
  - tracking detector vanes inside storage region
  - storage maintained by static weak focusing
    - $n = 1.5 \times 10^{-4}$, $rB_r(z) = -n\, zB_z(r)$ in storage region



a trapped orbit





Continuous detector system of silicon trackers

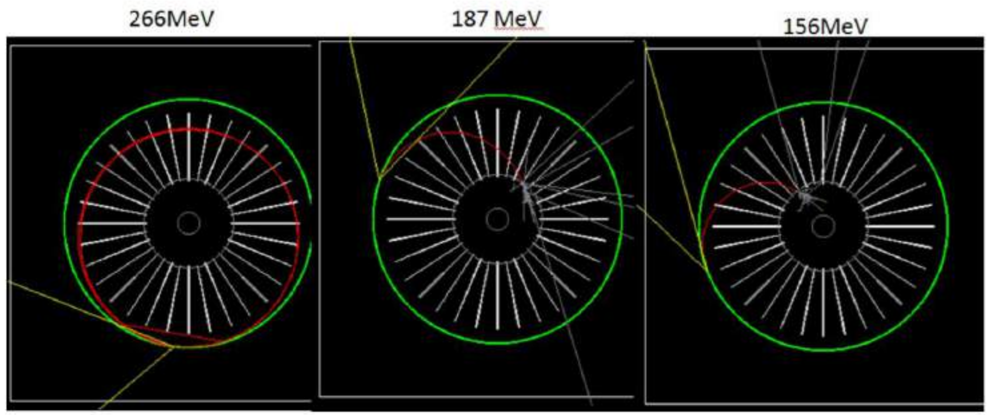
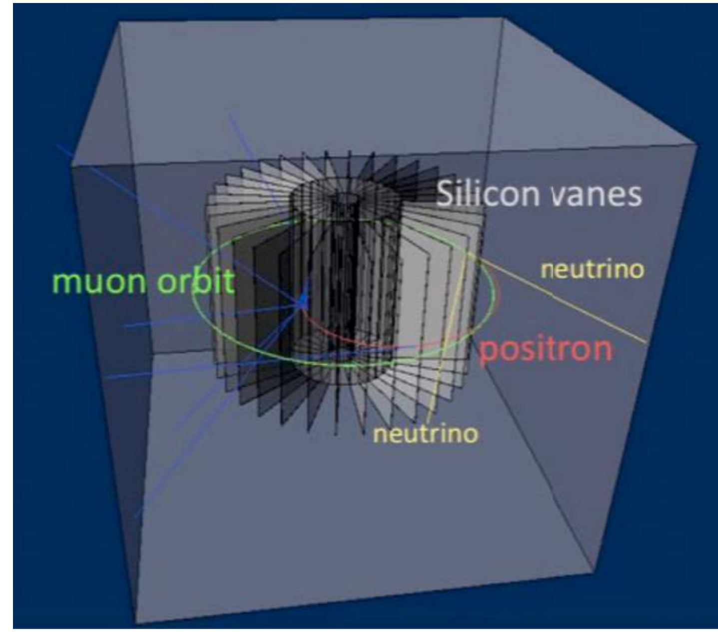
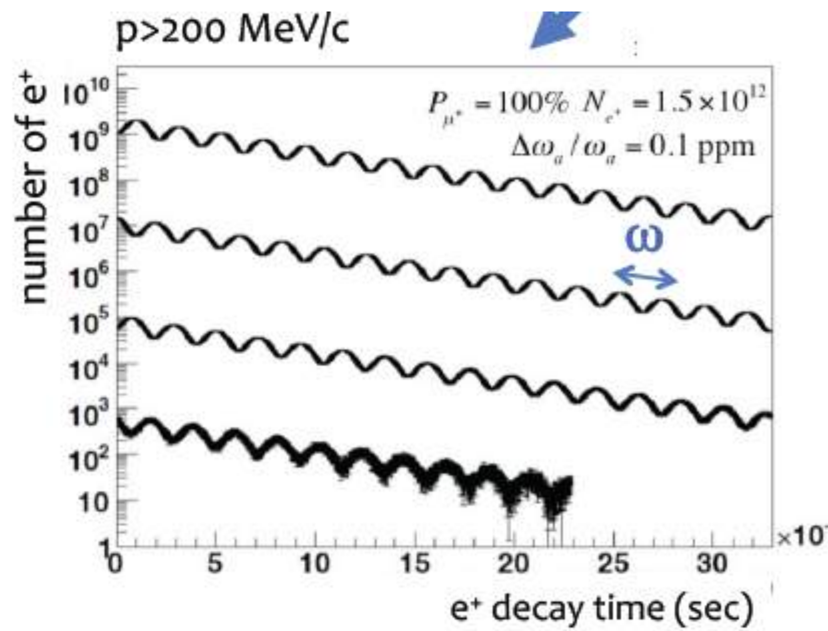


Figure 6: Example positron trajectories in the detector system at three different energies of positrons. The green circle is the muon beam orbit. The red trajectory is the trace of the positron track. The white tracks are photons.



Expected data. Note shorter lifetime at this momentum, and lower asymmetry owing to polarization of source



J-PARC g–2 goals (Stage 1)

Statistics

- Running time
  - measurement only: 2×10^7 s
- Muon rate from H-line
  - 1MW, SiC target: 3.32×10^8 s^{-1}
- Conversion efficiency to ultra-slow muons
  - Mu emission (S1249), laser ionization, $\mathcal{P} = 0.5$
  - 2.25×10^{-3} (stage 2 goal is 0.01)
- Acceleration efficiency including decay
  - RFQ, IH, DAW, and high-β: 0.52
- Storage ring injection, decay, and kick
  - 0.92
- Stored muons
  - 3.34×10^5 s^{-1} , total 6.68×10^{12}

Systematics

- Estimations still in progress
  - simulations
  - need experience with prototypes and first stages
  - need running experience to make assessments similar to E989
- ω_p (B measurement)
  - + smaller stored volume, higher local precision that E821
  - + all tracks to storage region
- ω_a (decay time measurement)
  - + all tracking detectors
  - – high rate differences between early and late decay times
    - + polarization flip
- Learning curve could be long and steep
  - we haven't done this experiment before…

Summary of expected sensitivities

Quantities	Description	Value
T	Running time	2×10^7 s
P	Muon polarization	0.5
$\frac{dN_\mu}{dt}$	Average muon rate in the storage magnet	$0.334 \times 10^6/\mathrm{s}$
N_μ	Total number of muon in the storage magnet	0.668×10^{13}
ϵ_{acc}	Acceptance of the e^+ detector and momentum cut	0.133
ϵ_{trk}	Track reconstruction efficiency	0.9
N_{e+}	Total number of positrons ($N_\mu \epsilon_{acc} \epsilon_{trk}$)	0.80×10^{12}
$\frac{\Delta\omega_a}{\omega_a}$	Uncertainty on anomalous spin precession frequency	0.36 ppm
Δd_μ	Uncertainty on EDM	$1.3 \times 10^{-21} e \cdot \mathrm{cm}$

- Statistical uncertainty estimates
  - $\Delta\omega_a/\omega_a$ = 0.36 ppm ($0.163/PN^{1/2}$)
    - BNL E821 σ_{stat} = 0.46 ppm
  - $\Delta d_\mu = 1.3\times10^{-21}$ $e \cdot$ cm sensitivity
    - BNL E821 $(-0.1\pm0.9)\times10^{-19}$ $e \cdot$ cm
    - $\Delta d_e < 1.05\times10^{-27}$ $e \cdot$ cm

Comparison

$$\delta\omega_a/\omega_a = \frac{1}{\omega_a \gamma \tau_\mu}\sqrt{\frac{2}{NA^2\langle P\rangle^2}},$$

Table 4: Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.8×10^{11}	8.1×10^{11}

Gorringe and Hertzog, Progress in Nuclear and Particle Physics, *Volume 84 (2015) September 2015*

Summary

- ***FNAL: status and the plan going forward …***
  - Design complete and implementation well along
  - Beam on; magnetic field ready
  - Detector almost ready; starting commissioning
  - Beam expected in late 2017
  - Goal remains **140 ppb (or 16 x 10^{-11}) on a_μ**
  - EDM parasitically

- ***J-PARC: novel method being developed***
  - Working out key new issues: source; magnet; detectors, etc.
  - Concept has greater reach for EDM owing to detector coverage
  - Aiming at 2019 Phase 1 start with
    - **g-2 to ~400 ppb**

Measurement of a_μ^{HLO} with a 150 GeV μ beam on e^- target at CERN

Physics Letters B 746 (2015) 325–329

Contents lists available at ScienceDirect

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ELSEVIER

A new approach to evaluate the leading hadronic corrections to the muon g-2

CrossMark

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Phys. Lett. B **746** (2015) 325

Eur. Phys. J. C (2017) 77:139
DOI 10.1140/epjc/s10052-017-4633-z

The European Physical Journal C

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Regular Article - Experimental Physics

Measuring the leading hadronic contribution to the muon g-2 via μe scattering

G. Abbiendi[1,a], C. M. Carloni Calame[2,b], U. Marconi[3,c], C. Matteuzzi[4,d], G. Montagna[2,5,e], O. Nicrosini[2,f], M. Passera[6,g], F. Piccinini[2,h], R. Tenchini[7,i], L. Trentadue[8,4,j], G. Venanzoni[9,k]

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Eur. Phys. J C **77** (2017) 139

Muon g-2: summary of the present status

- E821 experiment at BNL has generated enormous interest:

$$a_\mu^{E821} = 11659208.9(6.3)\times 10^{-10} \quad \text{(0.54 ppm)}$$

- Tantalizing ~3σ deviation with SM (persistent for >10 years):

$$a_\mu^{SM} = 11659180.2(4.9)\times 10^{-10}(DHMZ)$$

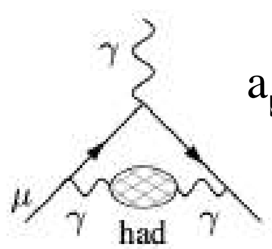
M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C71 (2011)

$$\boxed{a_\mu^{E821} - a_\mu^{SM} \sim (28\pm 8)\times 10^{-10}}$$

- Current discrepancy limited by:
  - Experimental uncertainty→ New experiments at FNAL and J-PARC **x4** accuracy
  - Theoretical uncertainty→ limited by hadronic effects

$$a_\mu^{SM} = a_\mu^{QED} + \boxed{a_\mu^{HAD}} + a_\mu^{Weak}$$

Hadronic Vacuum polarization (HLO)

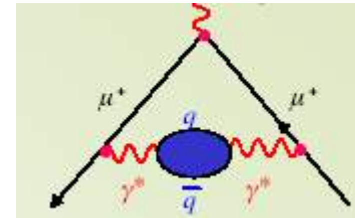


$$a_\mu^{HLO} = (692.3\pm 4.2)10^{-10}$$

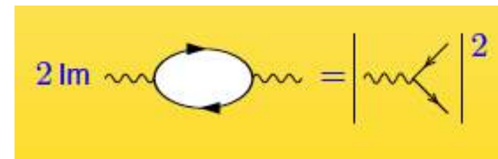
$$\delta a_\mu^{HLO}/a_\mu^{HLO} \sim 0.6\%$$

a_μ^{HLO} calculation, traditional way: time-like data

a_μ=(g-2)/2



$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^-\to hadr}(s)K(s)\,ds$$

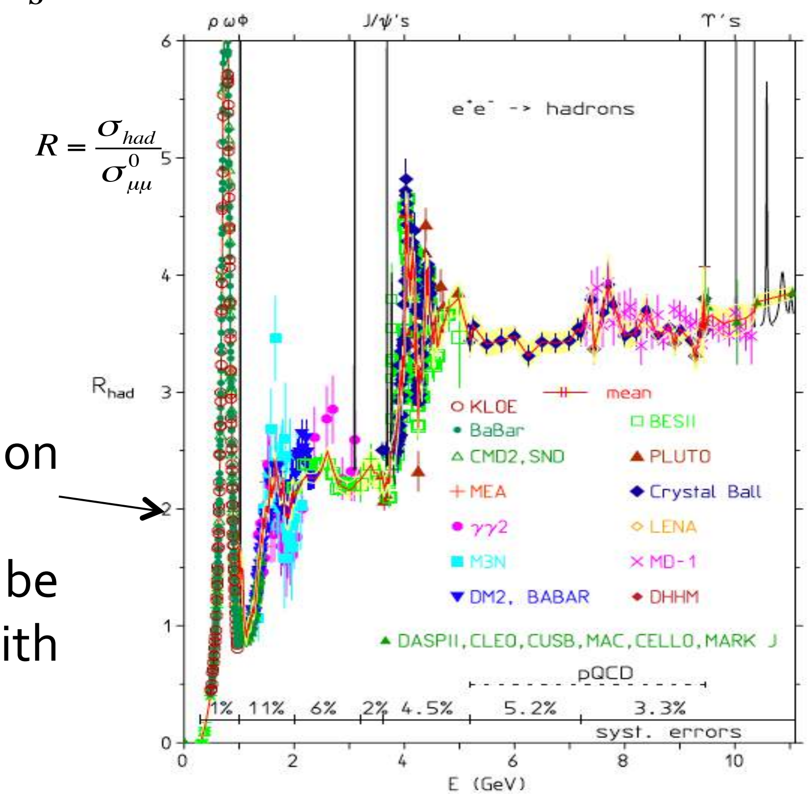


$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)(s/m^2)} \sim \frac{1}{s} \qquad \sigma_{e^+e^-\to hadr}(s) = \frac{4\pi}{s}\,\mathrm{Im}\,\Pi_{had}(s)$$

Traditional way: based on precise experimental (time-like) data:

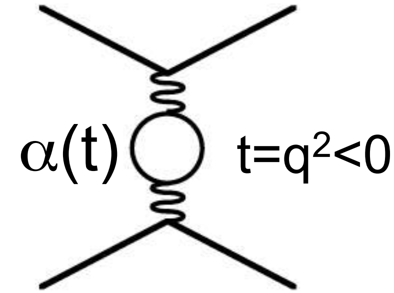
a_μ^{HLO} = (692.3±4.2)10^{-10} (DHMZ)

- Main contribution in the low energy region (**highly fluctuating!**)
- Current precision at 0.6% → needs to be reduced by a factor ~2 to be competitive with the new **g-2** experiments



a_μ^{HLO} from space-like region

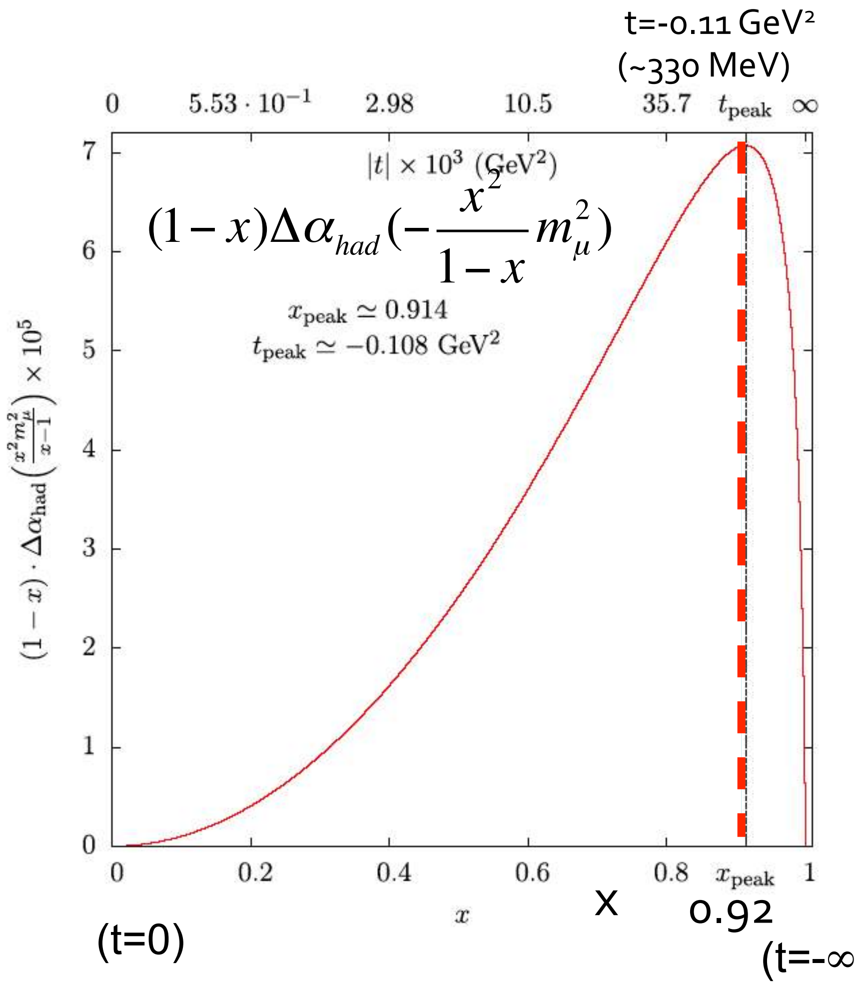
$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$



$$t = \frac{x^2 m_\mu^2}{x-1} \qquad 0 \le -t < +\infty$$

$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \qquad 0 \le x < 1;$$

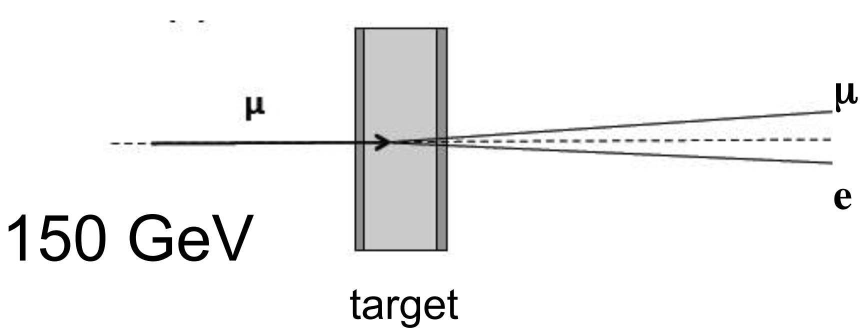
- **a_μ^{HLO} is given by the integral of the curve** (smooth behaviour)
- **It requires a measurement of** the hadronic contribution to the effective electromagnetic coupling in the space-like region **$\Delta\alpha_{had}(t)$ ($t=q^2<0$)**
- **It enhances** the contribution from **low** q^2 region (below 0.11 GeV²)
- **Its precision** is determined by the **uncertainty** on $\Delta\alpha_{had}(t)$ in this region

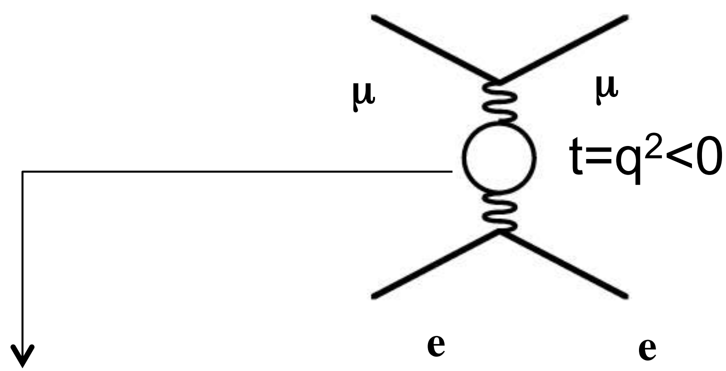


Experimental approach:

High precision measurement of a_μ^{HLO} with a 150 GeV μ beam on Be target at CERN

(through the elastic scattering $\mu e \to \mu e$)





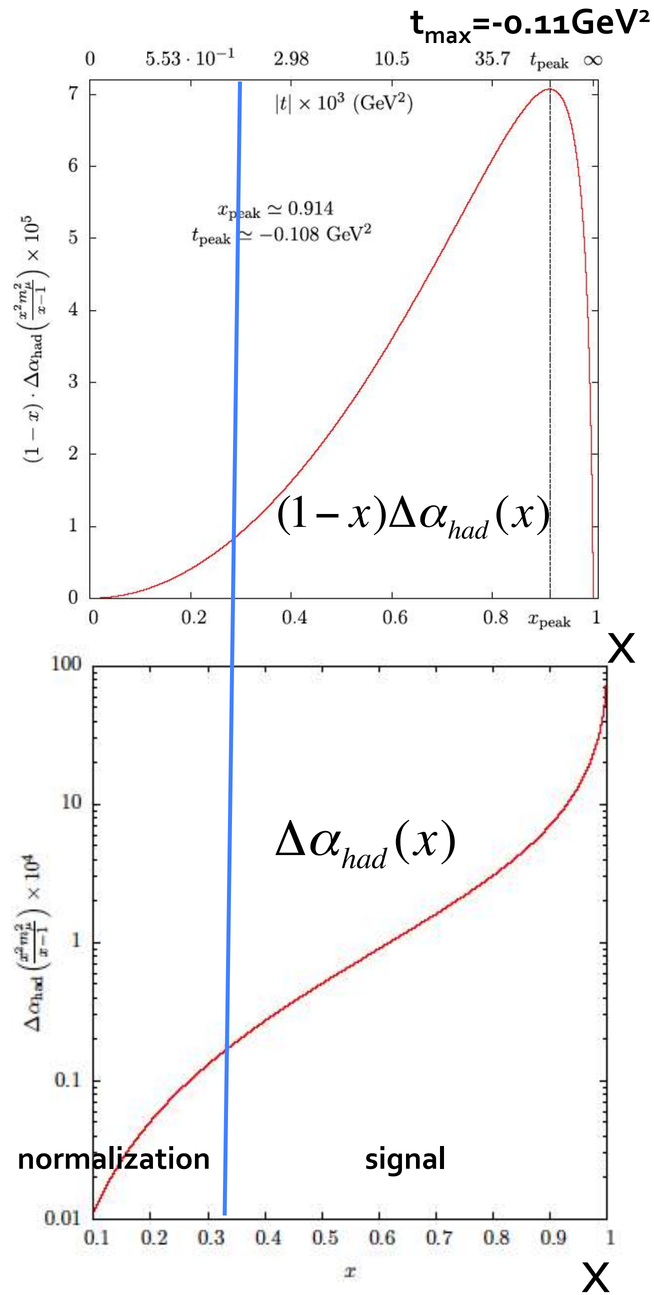
$$\left|\frac{\alpha(t)}{\alpha_0}\right|^2 = \left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

Why measuring $\Delta\alpha_{had}(t)$ with a 150 GeV μ beam on e^- target ?

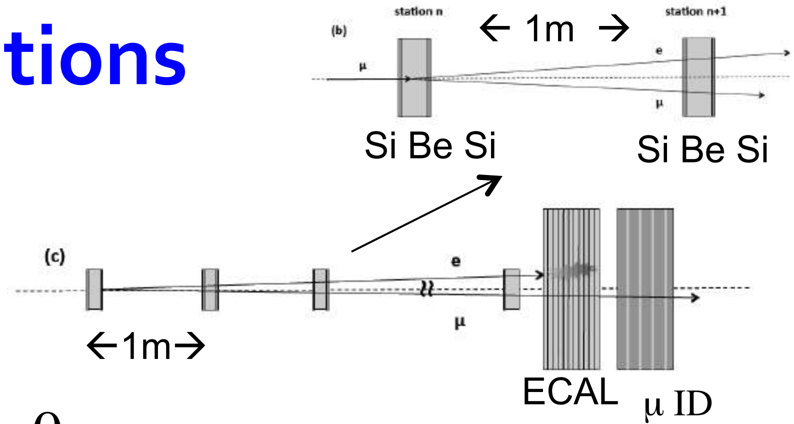
It looks an ideal process!

- $\mu\, e \rightarrow \mu\, e$ is pure t-channel (at LO)
- It gives $0<-t<0.161$ GeV² ($0<x<0.93$)
- The kinematics is very simple: $t=-2m_eE_e$
- High boosted system gives access to all angles (t) in the cms region

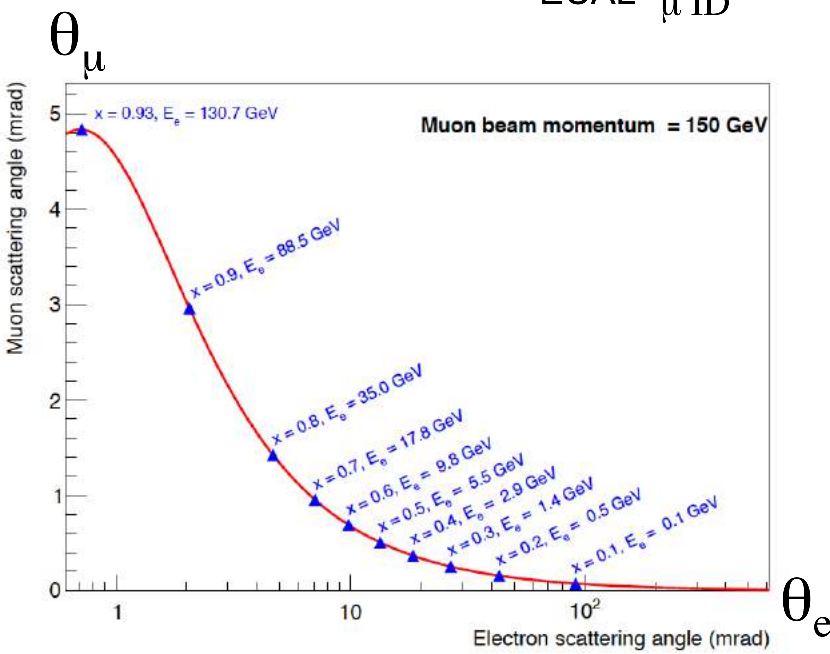
  $\theta_e^{LAB}<32$ mrad ($E_e>1$ GeV)
  $\theta_\mu^{LAB}<5$ mrad
- It allows using the same detector for signal and normalization
- Events at $x\sim0.3$ ($t\sim-10^{-3}$ GeV²) can be used as normalization ($\Delta\alpha_{had}(t)<10^{-5}$)

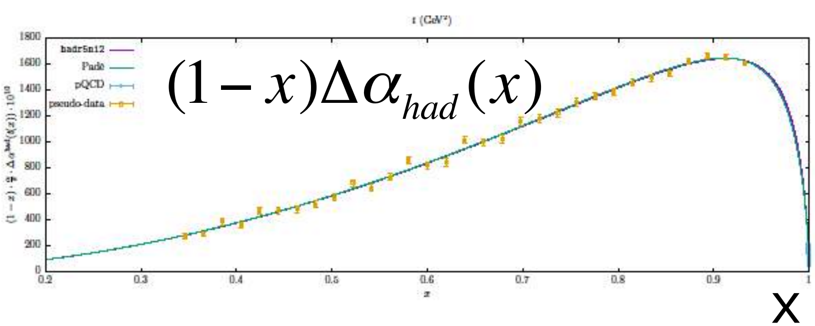


Detector considerations



- Modular apparatus: 20 layers of 3 cm Be (target), each coupled to 1 m distant Si (0.3 mm) planes. It provides a 0.02 mrad resolution on the scattering angle
- The $t=q^2<0$ of the interaction is determined by the electron (or muon) scattering angle (a\` la NA7)
- ECAL and μ Detector located downstream to solve PID ambiguity below 5 mrad. Above that, angular measurement gives correct PID
- It provides uniform full acceptance, with the potential to keep the systematic errors at 10^{-5} (main effect is the multiple scattering for normalization which can be studied by data)
- Statistical considerations show that a **0.3%** error can be achieved on a_μ^{HLO} in 2 years of data taking with 2×10^7 μ/s





μ-e proposal: plans (next 2 years)

- Focus on Multiple Scattering (MSC) effects:
  - How non gaussian tails affects our measurement and can be monitored/ controlled (2D plots and acoplanarity)

- Background subtraction and modeling in GEANT

- Optimization of target/detector and full detail simulation

- Test beam(s) and proto-experiment with a realistic module

- NNLO MC generation of μe process

- Design possible implementation in M2

- Consolidate the collaboration and write a CDR

Proposal part of the Physics Beyond Collider Working Group!

http://pbc.web.cern.ch/

Conclusions

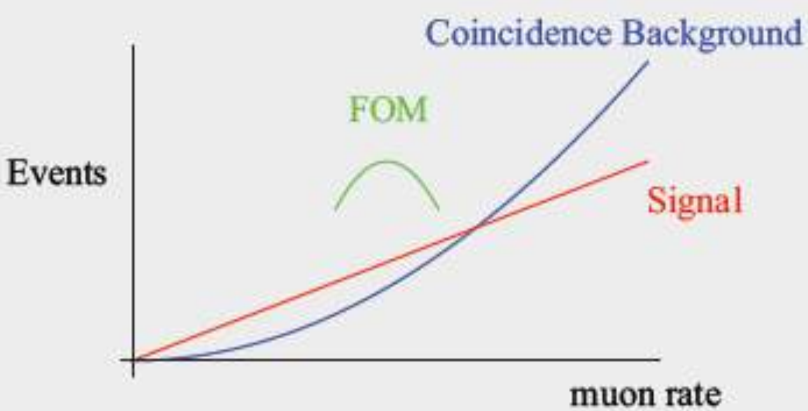
- Lepton Flavor Violation is one of the most important gateways to phyisics BSM
- $\mu \rightarrow e\gamma$ already provides constraints to new physics thanks to MEG (and an upgraded MEGII is under going)
- Mu3e experiment in preparation
- μ-e conversions experiment Mu2e and COMET will reach 10^{-17} in few years from now.
- Many results from τ from B factories and LHCb
- Important inter-connection between g-2 & LFV
- New muon g-2 experiments undergoing at Fermilab (E989) and in J-Parc (E34). E989 expected to take data by the end of this year.
- New proposal for a_μ^{HLO} with a 150 GeV μ beam on e- target

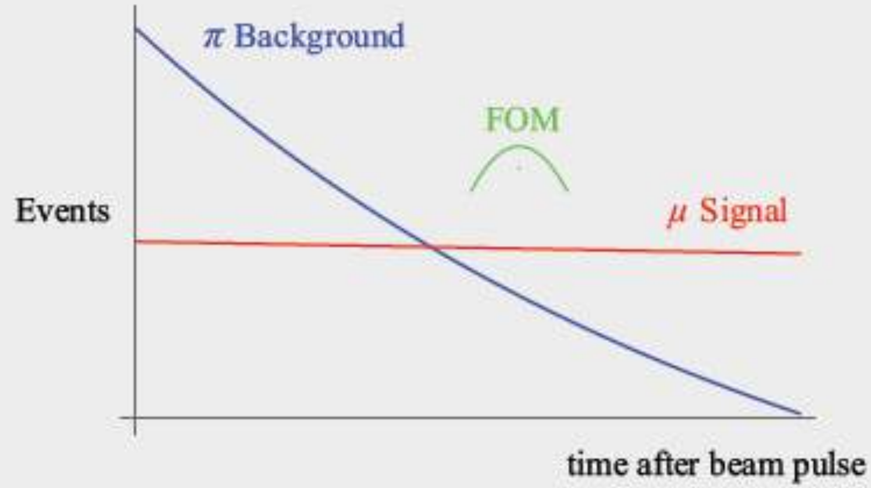
SPARES

Pulsed vs. DC Beam

- $\mu \rightarrow e\gamma$ or $\mu \rightarrow eee$ want a steady beam: PSI
  - backgrounds from coincidences of two decays dominate
  - $(\text{Rate})^2$ bkg vs Rate(signal)

- muon-electron conversion wants a pulsed beam: FNAL/J-PARC
  - Many pion-induced backgrounds after proton pulse
  - Take advantage of 26 nsec lifetime to "wait it out"





Pulsed vs. DC Beam

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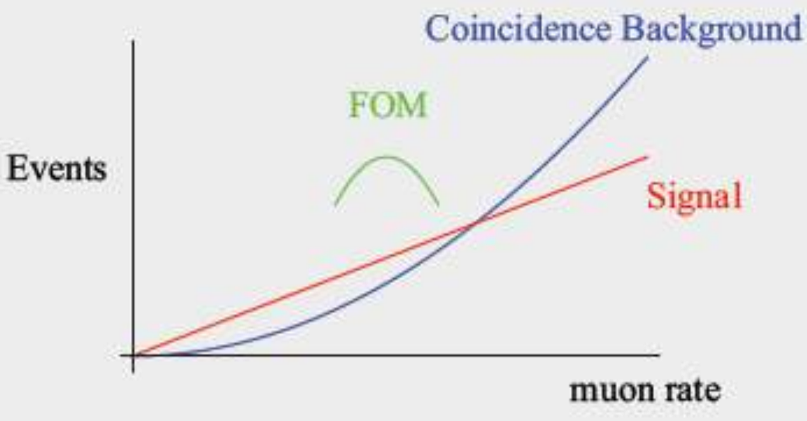

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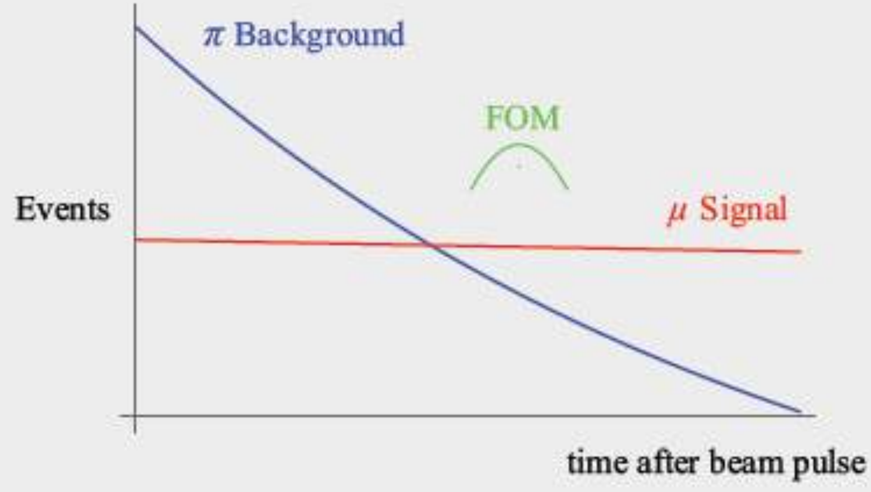
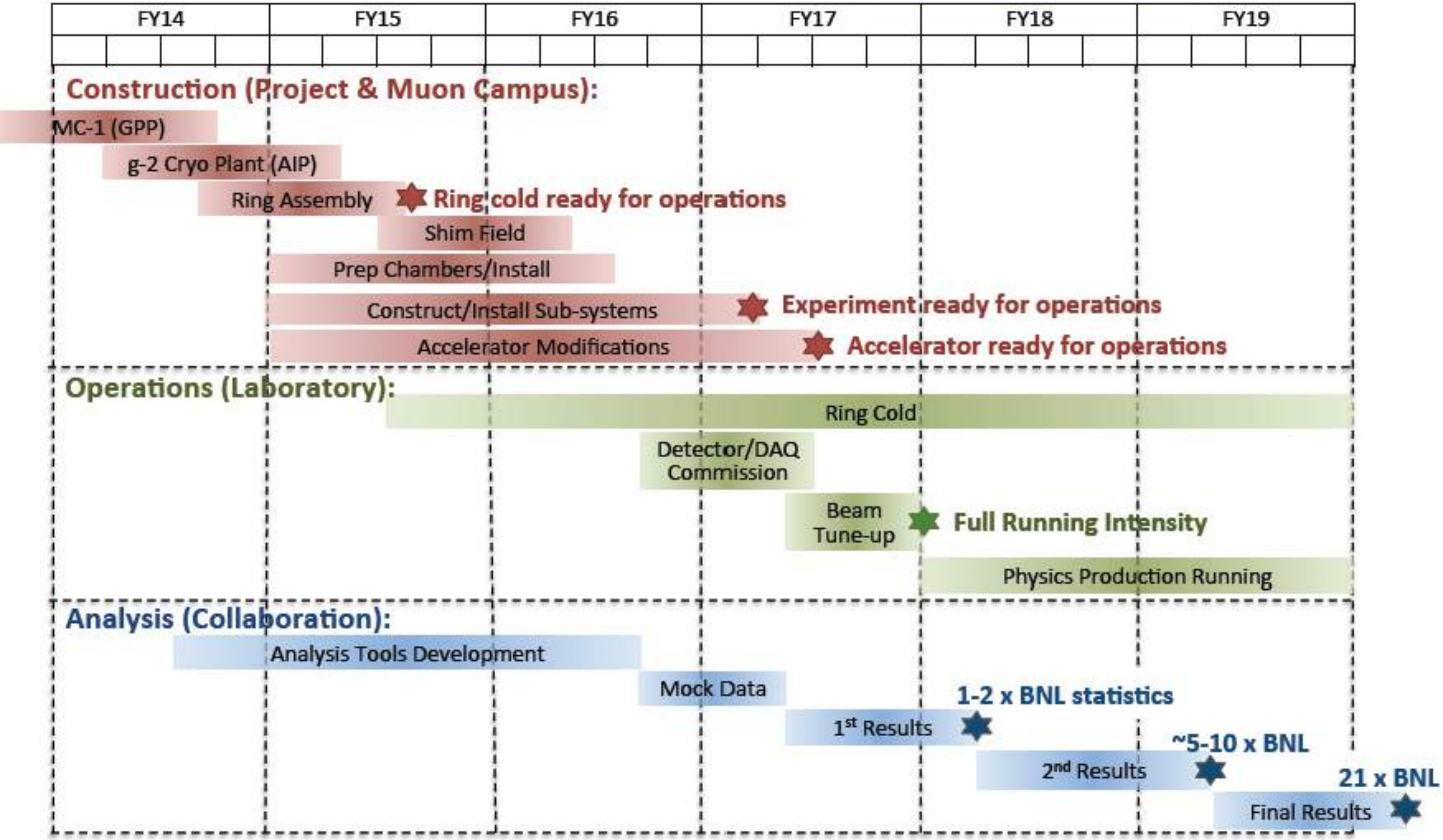
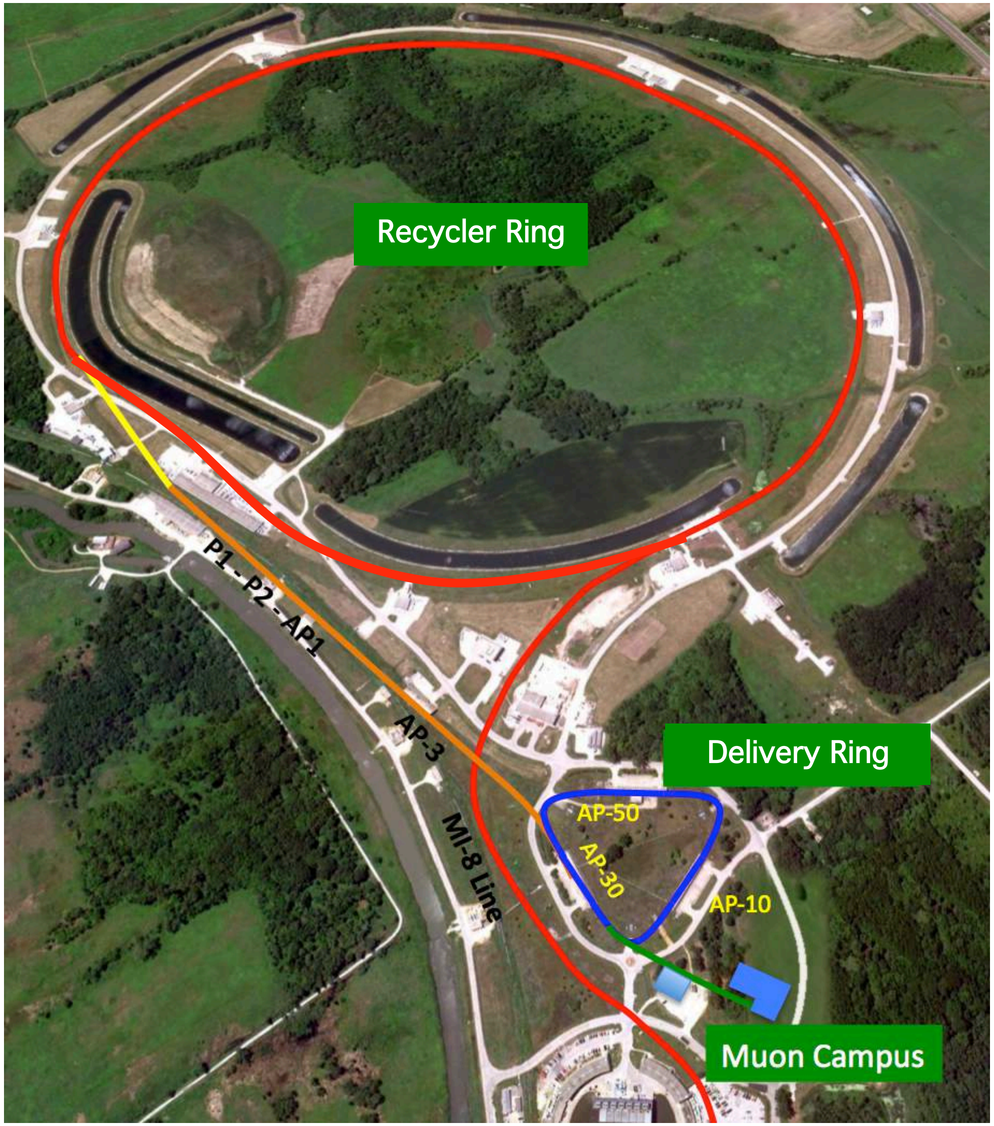


Schedule overview



First challenge - statistics



Achieving required statistics is a primary concern
- Need a factor 21 more statistics than BNL
- Beam power reduced by 4

Need a factor of 85 improvement in integrated beam coming from many other factors
- Collection of pions from Li lens
- Capture of decay muons in FODO channel
- p_{π} closer to magic momentum
- Longer decay channel
- Increased injection efficiency
- Earlier start time of fits
- Longer runtime (~18 months for production running + systematics)

Mu2e@FNAL

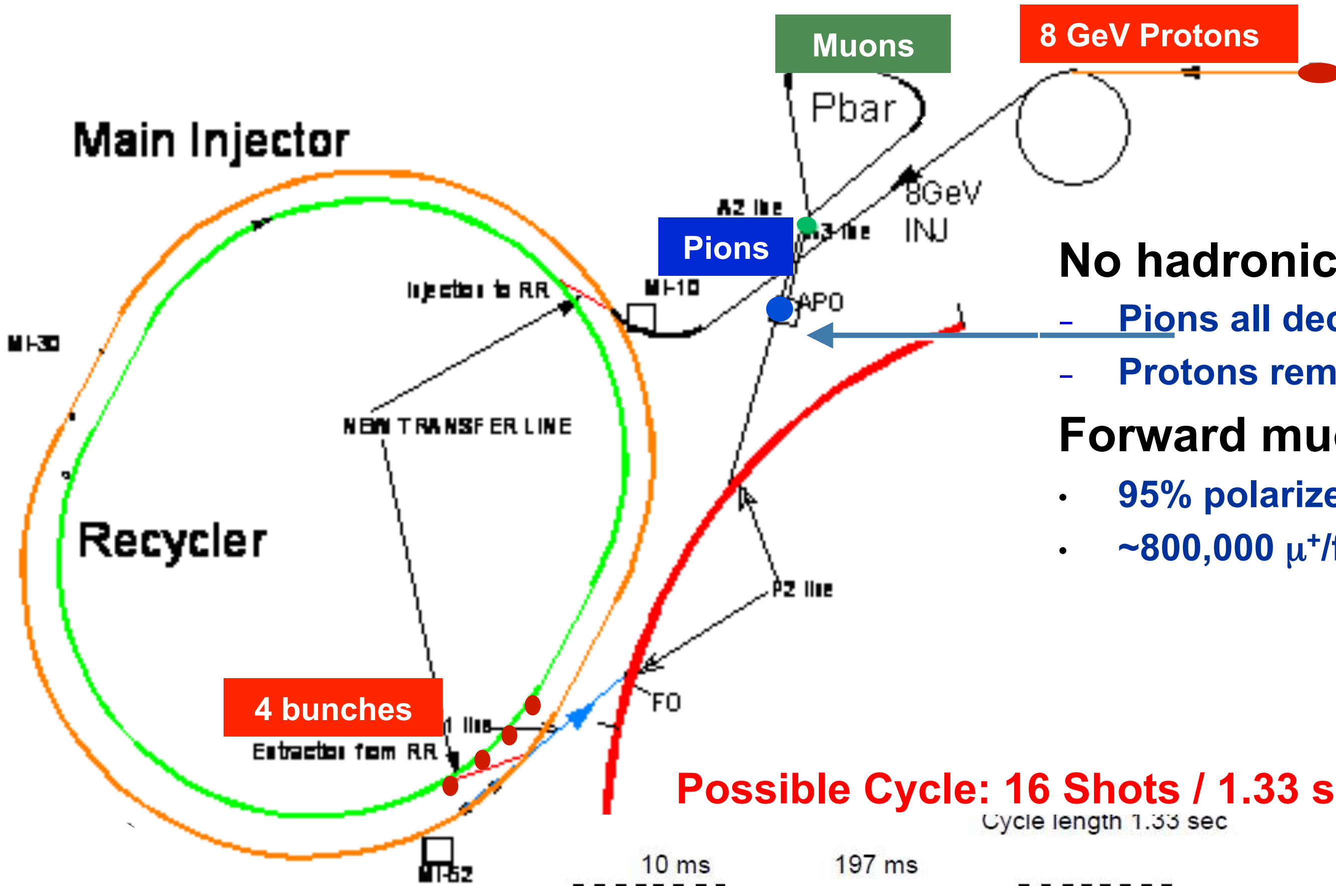
- Target protons at 8 GeV inside superconducting solenoid at 8kW
- Capture muons and guide through S-shaped region to Al stopping target
- Stop muons, let them fall into a “1s” state
- Check for outgoing electrons

mu2e.fnal.gov

FNAL

- >$200M Project. Physics run 2021~

A pure muon beam of 3.1 GeV



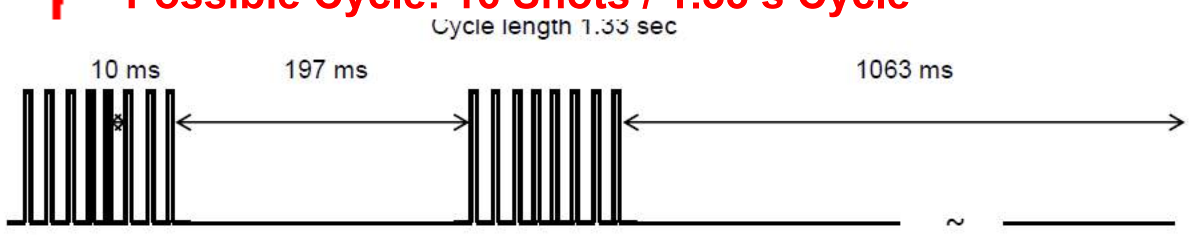
No hadronic flash

- Pions all decay
- Protons removed by a DR kicker

Forward muons collected

- 95% polarized
- ~800,000 μ^+/fill ($\delta P/P$ 2%) at ring

Possible Cycle: 16 Shots / 1.33 s Cycle



All protons are "excess" from those used for NOvA ν

Conclusions

- KLOE has pioneered the ISR method, performing in the last 15 years factor a series of precision measurements with ISR which confirmed a 3σ discrepancy between a_μ^{SM} and the BNL measured value
- The running of the e.m. coupling constant α has been measured in the process $e^+e^- \rightarrow \mu^+\mu^-\gamma$ in the 0.6 - 0.98 GeV $M_{\mu\mu}$ invariant mass range at 1.7 fb^{-1}.
- Clear contribution of the $\rho-\omega$ interference to the photon propagator with 6σ statistical significance.
- Imaginary and Real part of Δa extracted for the first time.
- By a fit of the real part of $\Delta a(s)$ and assuming lepton universality the branching ratio of $\omega \rightarrow \mu^+\mu^-$ has been extracted.
- New proposal to measure a_μ^{HLO} in the space-like region using a high energy muon beam (E~150 GeV) at CERN (**μ e →μ e**)

Conclusion

- During the last ten years the muon (g-2) provided one of the strongest tests of the SM, thanks to the impressive accuracy of BNL experiment (δa_μ^{EXP} = 0.54 ppm). Important interplay with LHC!

- At present a discrepancy of more than 3 “standard deviations” between SM and Experiment; uncertainty dominated by BNL experiment. Possible sign of New Physics?

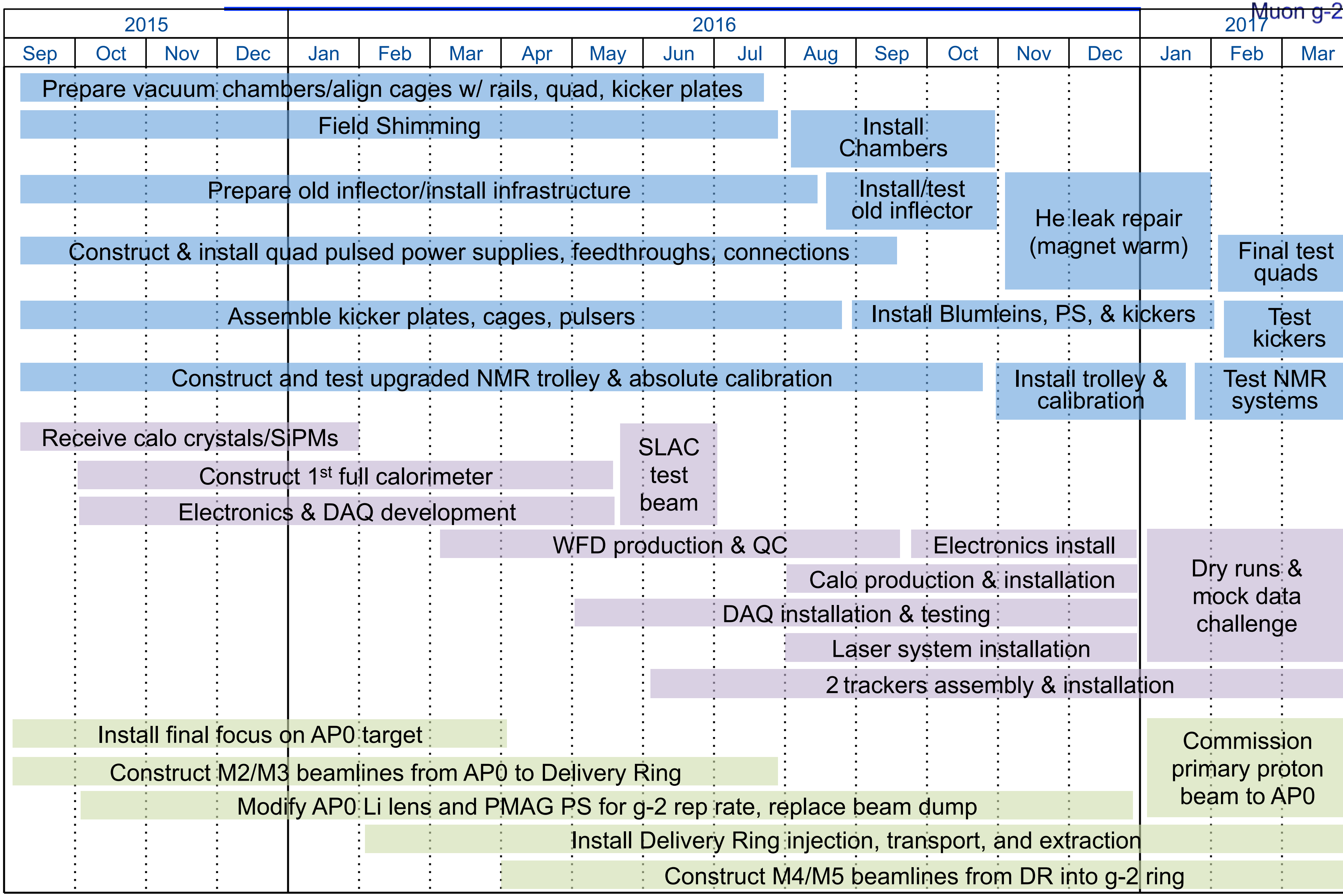
- New $(g\text{-}2)_\mu$ experiment at Fermilab with a fourfold reduction δa_μ^{EXP} = 0.14 ppm . Data taking expected in 2017.

- Field shimming is finished, now moving into period where rest of experiment is under construction through March 2017

- First muons stored in mid-2017…first result (with comparable accuracy of BNL) in 2018!

Stay Tuned!

Schedule


2015
2016
2017
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
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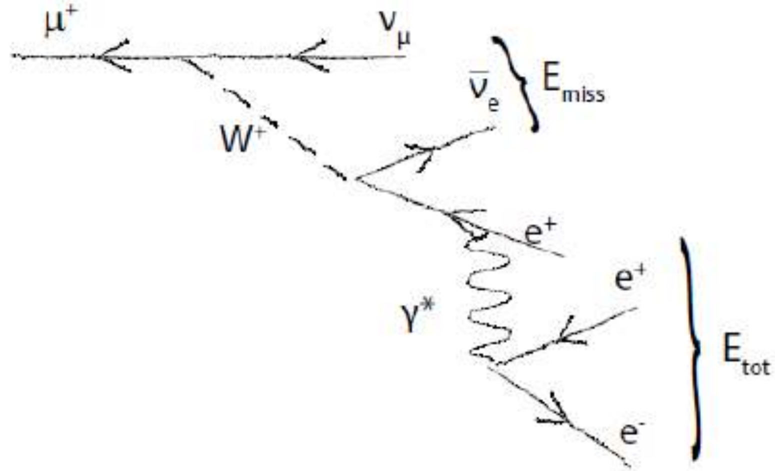
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Prepare vacuum chambers/align cages w/ rails, quad, kicker plates
Field Shimming
Install Chambers
Prepare old inflector/install infrastructure
Install/test old inflector
He leak repair (magnet warm)
Construct & install quad pulsed power supplies, feedthroughs, connections
Final test quads
Assemble kicker plates, cages, pulsers
Install Blumleins, PS, & kickers
Test kickers
Construct and test upgraded NMR trolley & absolute calibration
Install trolley & calibration
Test NMR systems
Receive calo crystals/SiPMs
Construct 1st full calorimeter
Electronics & DAQ development
SLAC test beam
WFD production & QC
Electronics install
Calo production & installation
DAQ installation & testing
Laser system installation
Dry runs & mock data challenge
2 trackers assembly & installation
Install final focus on AP0 target
Construct M2/M3 beamlines from AP0 to Delivery Ring
Modify AP0 Li lens and PMAG PS for g-2 rep rate, replace beam dump
Commission primary proton beam to AP0
Install Delivery Ring injection, transport, and extraction
Construct M4/M5 beamlines from DR into g-2 ring

The New Muon g-2 experiment at Fermilab (E989)

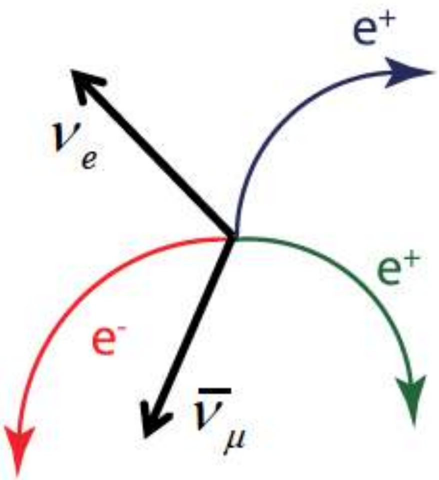
Mu3e@PSI

Irreducible background

μ radiative decay with internal conversion

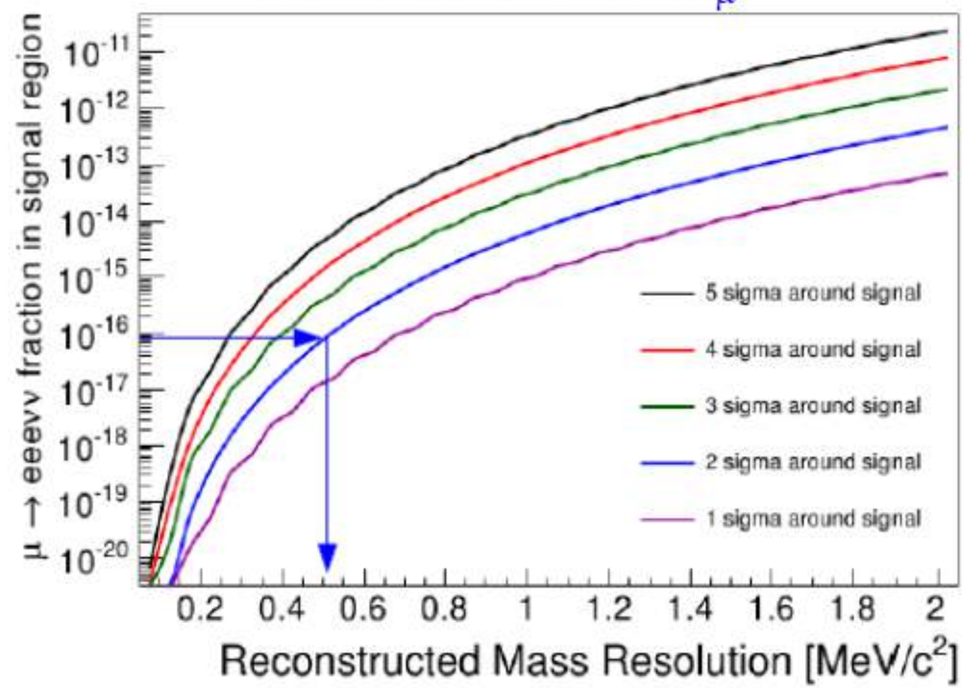


BR ($\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu$) = 3.5×10^{-5}



$\Sigma \mathbf{p}_i \neq 0, \quad \Sigma E_i \neq m_\mu$

$\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu$ fraction in signal region as a function of Δm_μ



high momentum and energy resolution required to suppress this background

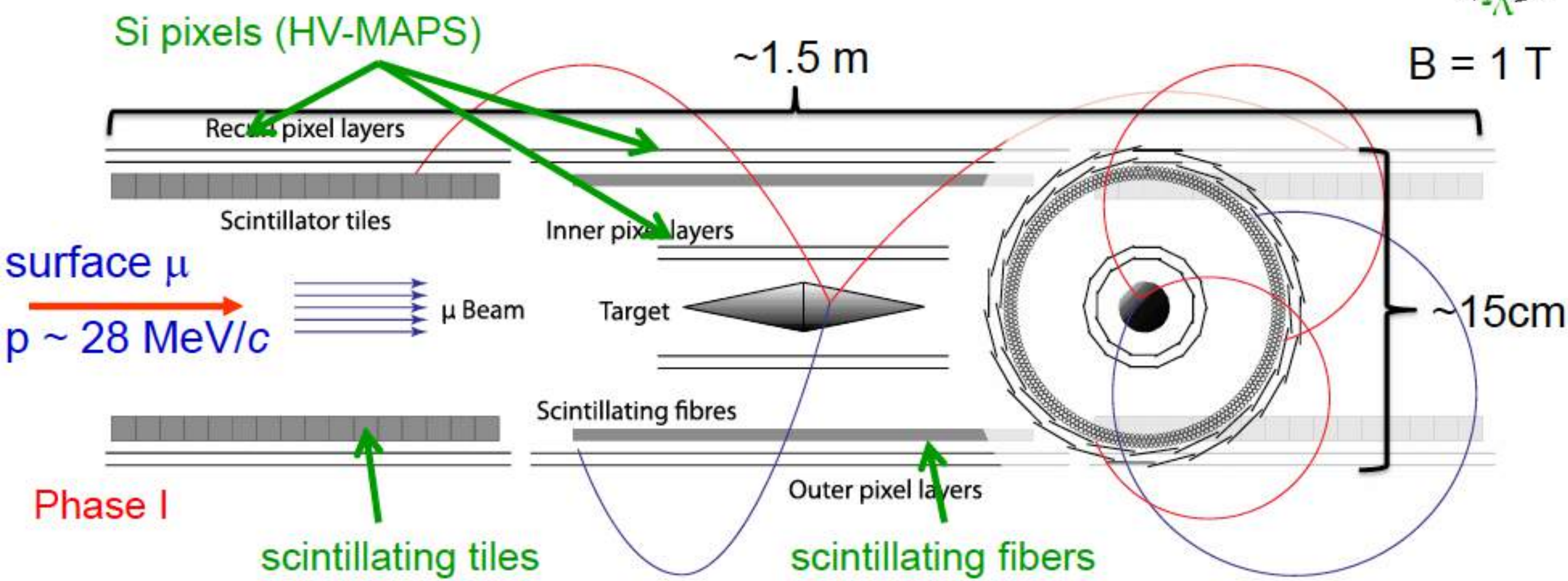
$\sigma_p < 0.5$ MeV/c and $\Delta m_\mu < 0.5$ MeV/c^2

Mu3e@PSI

search for $\mu^+ \rightarrow e^+ e^- e^+$ with sensitivity BR ~ 10^{-16} (PeV scale)

$\tau_{(\mu \rightarrow eee)}$ > 700 years (τ_μ = 2.2 μs)

suppress backgrounds below 10^{-16}



Kinematics: 3-body decay; coplanarity $\Sigma p=0$, $\Sigma E=m_\mu$

disegni

background: radiative decays; accidentals

beam: continuouos

Mu3e@PSI

search for $\mu^+ \to e^+ e^- e^+$ with sensitivity BR ~ 10^{-16} (PeV scale)

$\tau_{(\mu \to eee)} > 700$ years ($\tau_\mu = 2.2\ \mu s$)

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Kinematics: 3-body decay; coplanarity $\Sigma p=0$, $\Sigma E=m_\mu$

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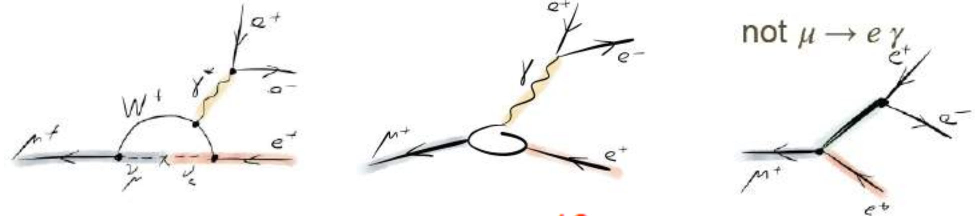
Mu3e@PSI



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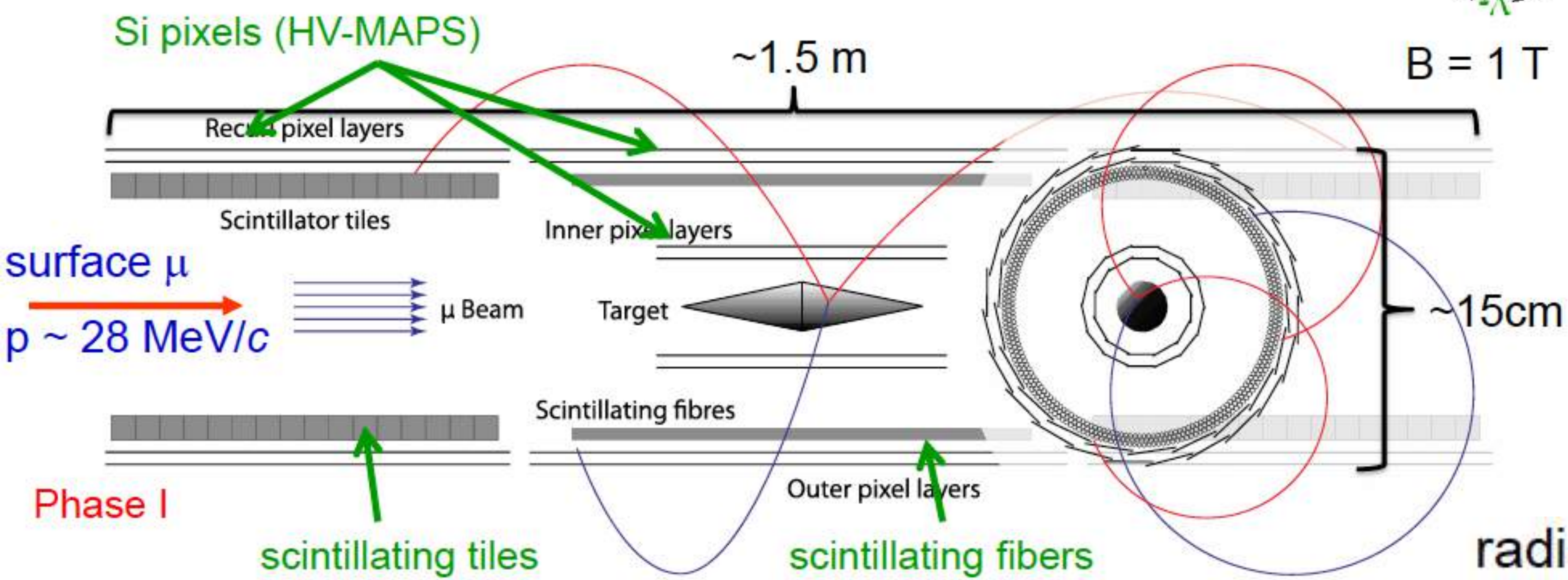


radia

accic

Kinematics: 3-body decay; coplanarity Σp=0, ΣE=m_μ

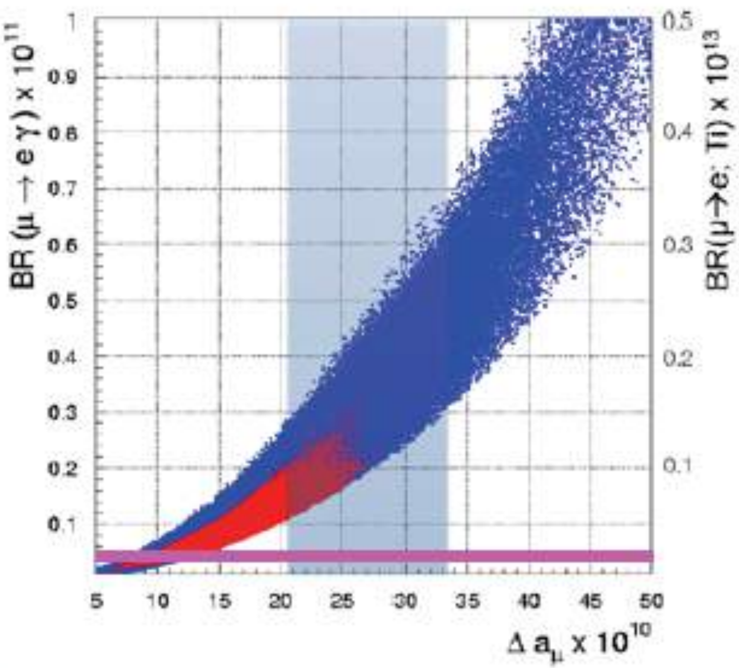
disegni

background: radiative decays; accidentals

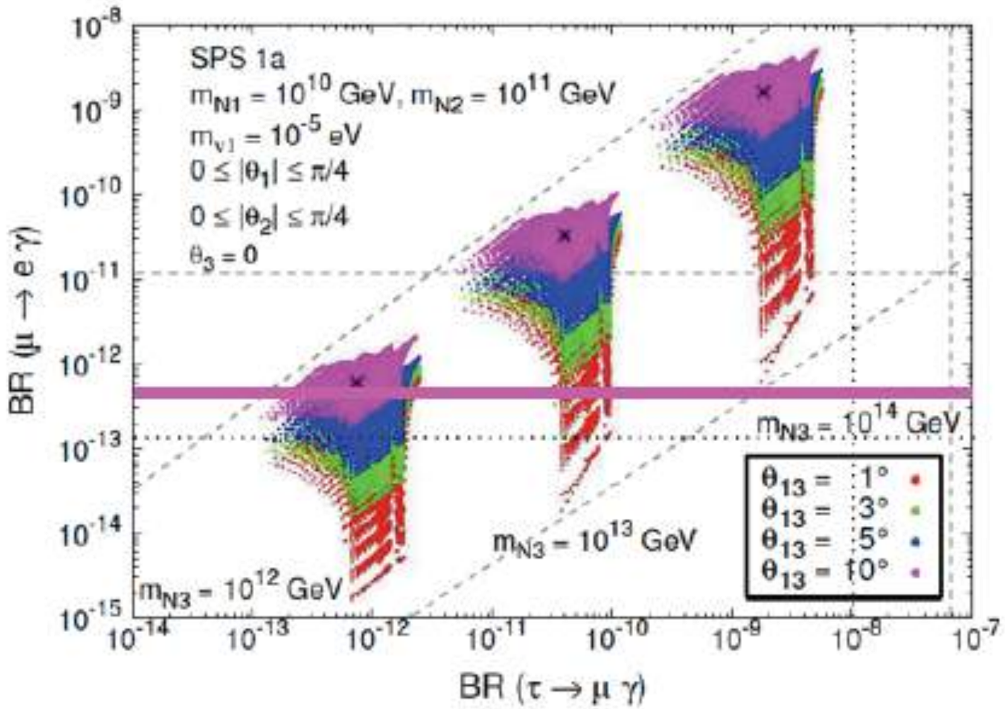
beam: continuouos

$(g\text{-}2)_\mu$, ν-Oscillations & μ-LFV

G. Isidori *et al.*, PRD 75 (2007) 115019



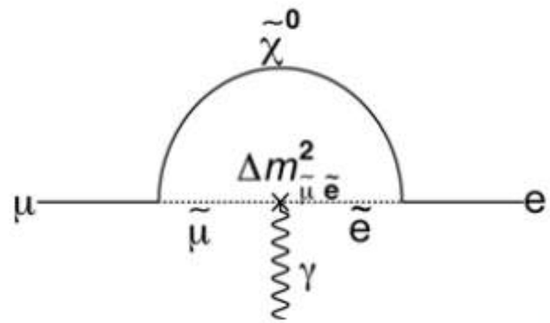
S. Antusch *et al.*, JHEP11(2006)090

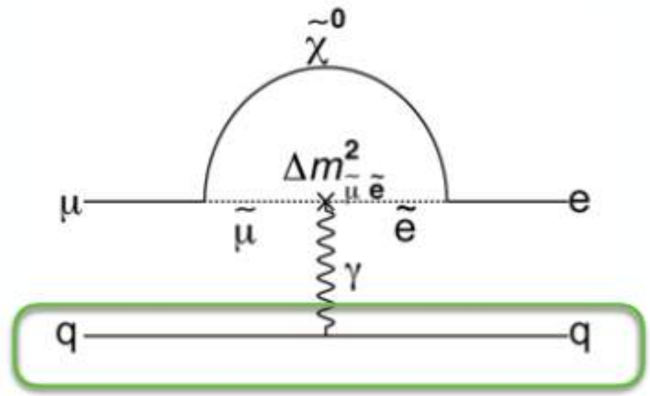


T2K (2011): $0.03 < \sin^2 2\theta_{13} < 0.3$ (90%C.L.)
$\to 5° < \theta_{13} < 15°$
Daya Bay (2012): $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$
$\to \theta_{13} > 8°$

Discovery of μLFV (possibly) around the corner

$\mu \rightarrow e\gamma$ & μ-e Conversion (II)





$B[\mu \rightarrow e\gamma]$

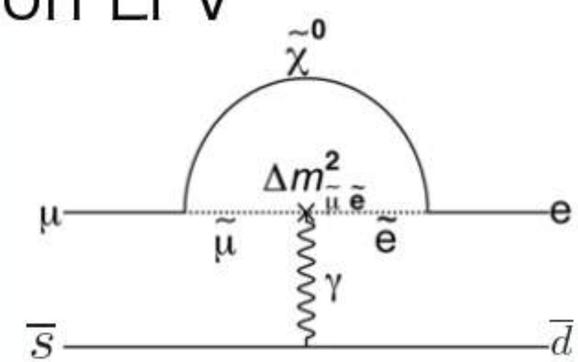
$\rightarrow$ MEG II: 4×10^{-14}

$B[\mu\text{-e conv.}] = \alpha \times B[\mu \rightarrow e\gamma]$

$\rightarrow 2 \times 10^{-16}$

$\rightarrow$ Mu2e: 2.5×10^{-17}

Kaon LFV



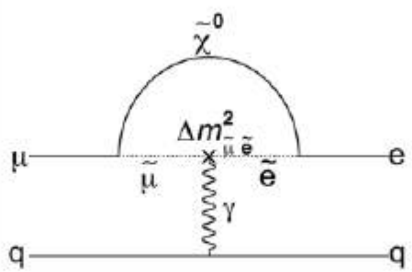
$B = \varepsilon_{FCNC} \times \alpha \times BR[\mu \rightarrow e\gamma]$

$\rightarrow 10^{-25}$

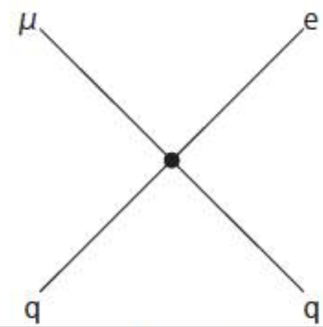
$\varepsilon_{FCNC} \sim B[K^+ \rightarrow \pi^+\nu\nu]/B[K^+ \rightarrow \pi^0 e\nu]$

μ → eγ & μ-e Conversion

$$\mathcal{L} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{e}\sigma^{\mu\nu}F_{\mu\nu}\mu + \frac{\kappa}{(1+\kappa)\Lambda_F^2}\bar{e}\mu(\bar{q}q+\bar{e}e)$$

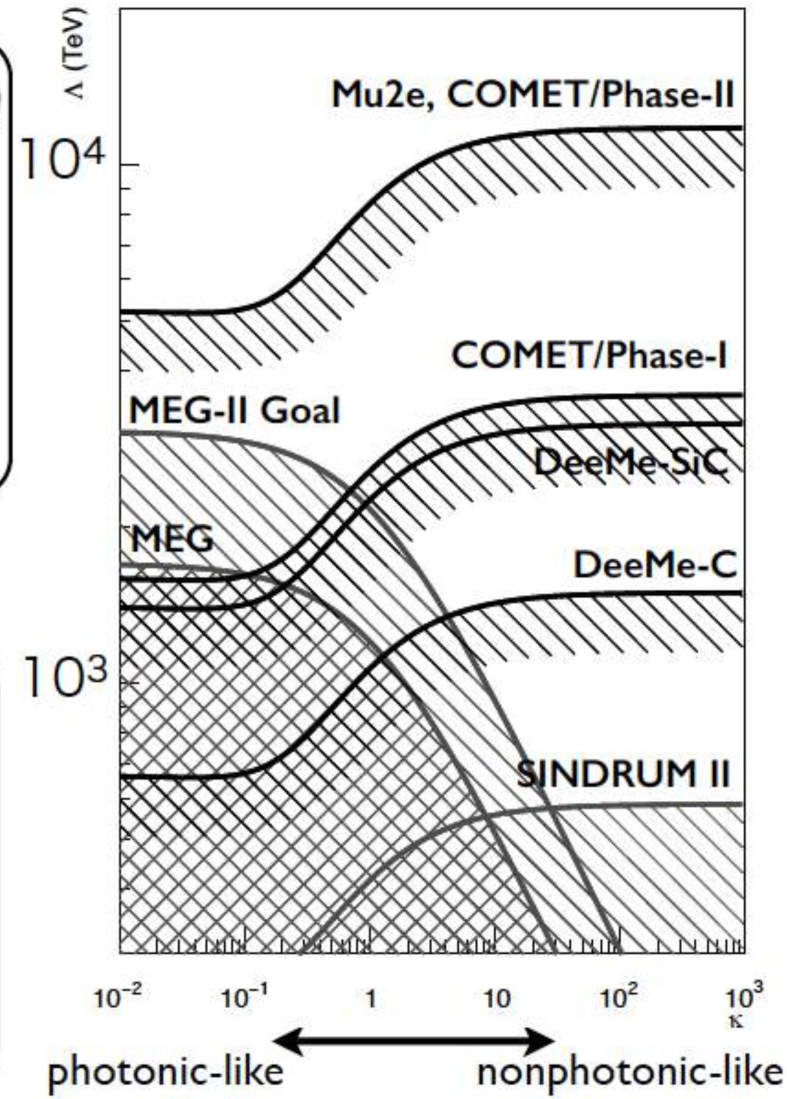


photonic



non-photonic

- SUSY-GUT, SUSY-seesaw
  - higgs mediated processes
- Doubly Charged Higgs Boson (LRS *etc.*)
- Little Higgs Models
- Randall-Sundrum Models
- SUSY with R-parity Violation
- Leptquarks
- Heavy Z'
- Multi-Higgs Models



original plot by Andre de Gouvea