WG4 – Muon Physics Summary

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Questions from 2012

- MEG New results & Upgrade
- μ→eee
- μ-e conversion
  - Mu2e
  - COMET Phase I & II
  - DeeMe
- J-PARC MUSE activities : H-Line
  - Mu HFS
  - ultracold-μ production
  - g-2/EDM
- FNAL g-2
- τ-sector
  - combined Belle and BaBar results
  - Prospects for Belle-II and SuperB
- Precision tests
  - cross sections (MuSUN)
  - MuSIC
  - J-PARC Beam lines
  - Muon production
  - Muon collection / Cooling (MICE...)
  - Work towards muon collider
- p-EDM
- Beyond
  - Project-X
  - PRISM/PRIME
- Theory
  - Reflect LHC results
    - Higgs
    - Supersymmetry
  - Neutrino oscillation parameters
    - ϑ_{13}
    - δ_{CP}

Questions moving forward for 2014

- Three "Big" questions we want to address:

- Expt: What is the ultimate $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ reach once $\mu N \rightarrow eN$ has set the limit.
  - What are the roles of the ratios of cLFV processes and other precision experiments at this point?

- Beams: What are the beam specifications for muon physics? (our requirements)
  - Are these compatible with the NuFact?
  - Are there other options?

- Theory: What else besides cLFV? EDMs?
  - What does theory tell us once we observe cLFV?
  - How do we relate our results to the models?

Muon Physics

- At its heart a Neutrino Factory
  is also a Muon Factory

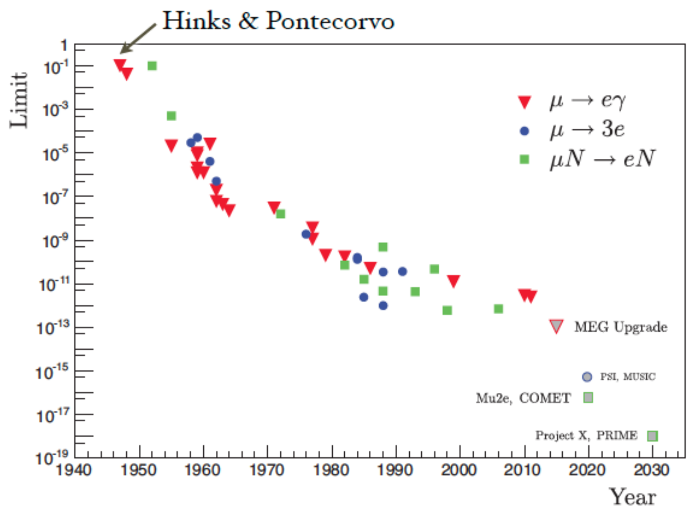
$$p + Target \rightarrow \pi, K \rightarrow \mu\nu$$

- Producing these intense neutrino beams will require new high intensity muon beam lines
- This will greatly increase the number of mu's available to probe for hints of physics beyond the standard Model
- Is there a deeper connection between muon physics and neutrino physics?
  - Fundamental questions of lepton flavor

Bruno Pontecorvo: 100 years

- Centenary of the birth of Bruno Pontecorvo
  - Bruno Pontecorvo was born in Pisa on 22 August 1913
  - Completed his studies in Rome under E. Fermi
  - Went to Paris and then to Canada during WW2

- Muon: discovered 1936 (N&A), Lattes et al. 1947, Conversi et al. 1947



/erse β-process (1946)
- neutrino detection

ıclear capture of mesons (1947)
- universality of Fermi interaction

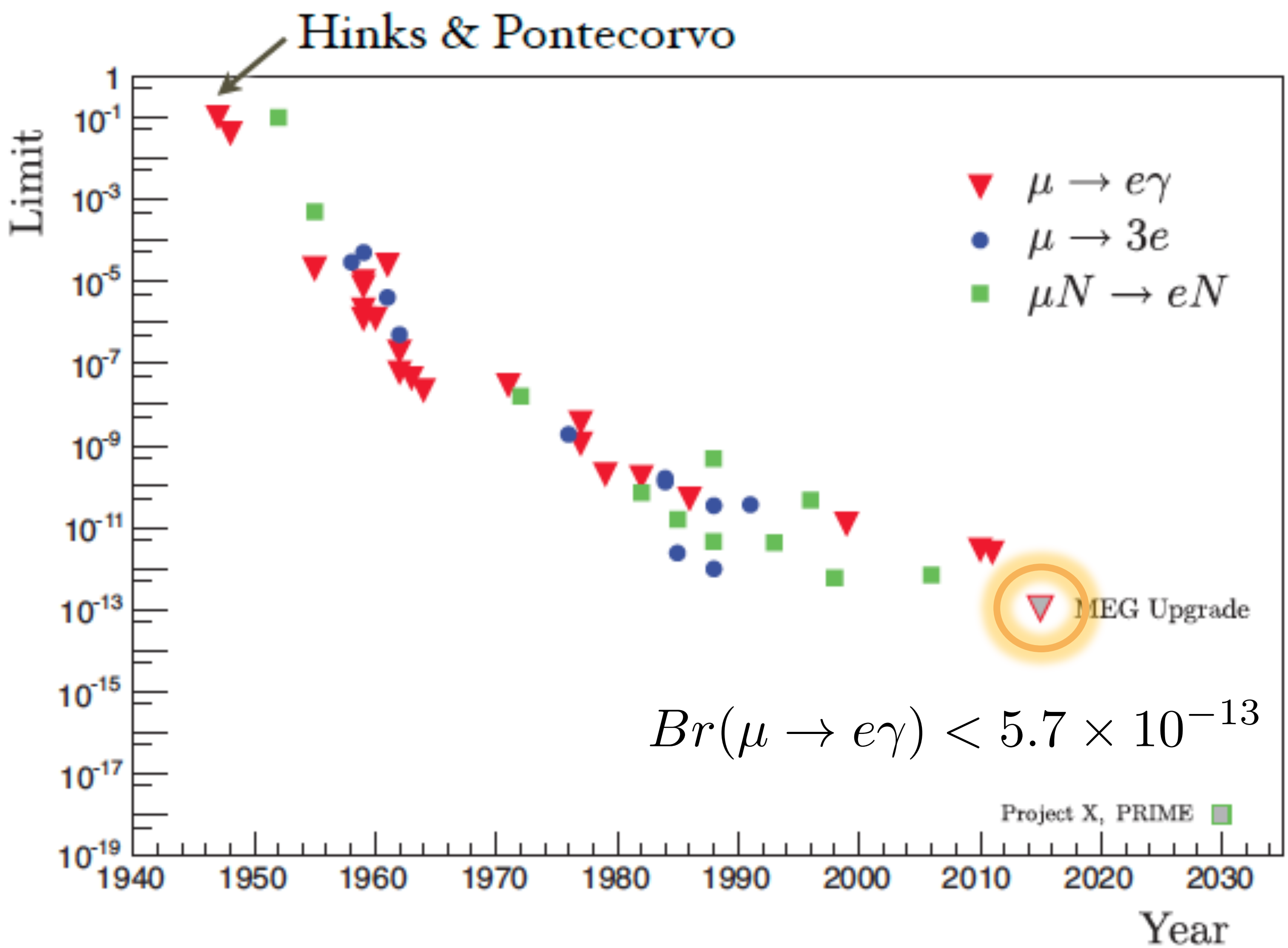
ɔsence of μ→eγ (1948-1950)
- neutrino and muons are connected

ectron and muon neutrinos (1959)
- neutrino beams

eutrino oscillations (1967→)

pton mixing and the solar neutrino puzzle (1977)

Making History



Week in Review

- Charged Lepton Flavor
  - μ→eγ, μ→eee, μN→eN, τ→cLFV
  - Connections to theory

7 talks

- Precision Measurements
  - muon g-2
  - μ hyperfine spliting
  - proton radius
  - μ capture

6 talks

- Muon Facilities
  - Progress on mu cooling
  - New methods for intense mu beams

13 talks

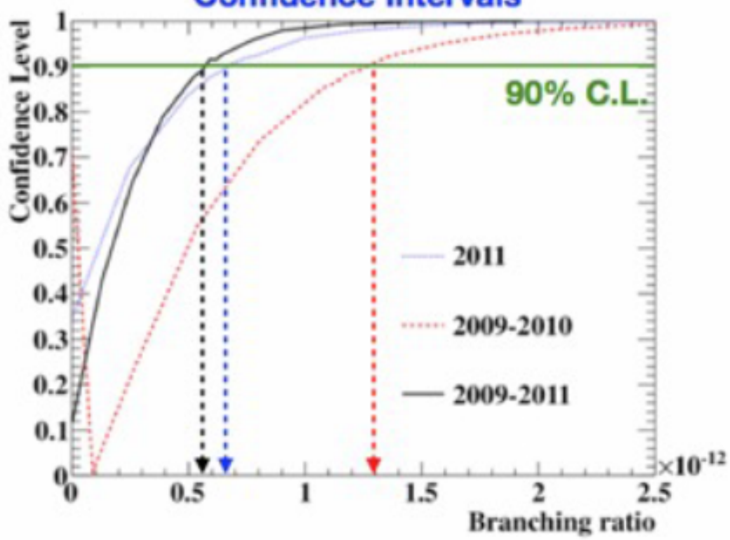
26 talks total including

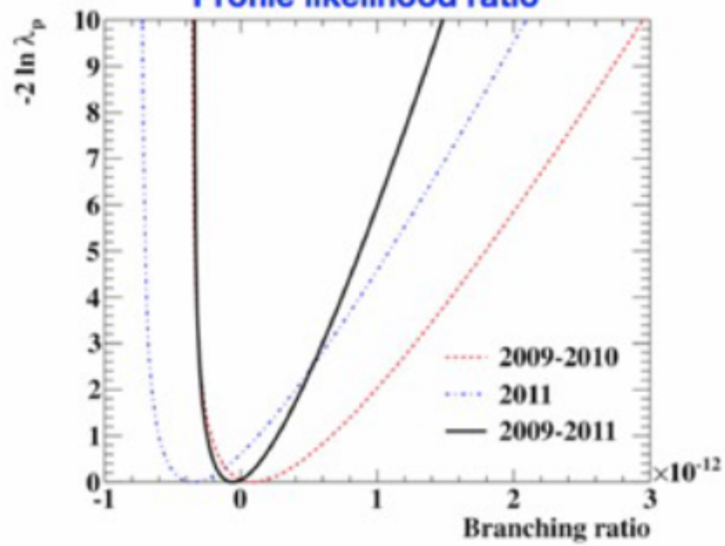
3 joint sessions with WG3 and 1 with WG1

$\mu \to e\gamma$ Results (MEG)

- **Confidence interval** calculated with **Feldman-Cousins** method + **profile likelihood** ratio ordering
  - *result **consistent** with **null-signal** hypothesis*
  - ***consistent** in **all analysis***

BR < 5.7 10^{-13} @90% CL





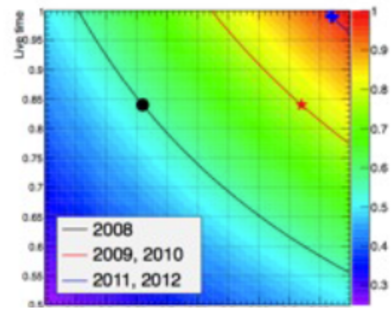
CL curve: Allowed region of branching ratio can be read at given confidence level.

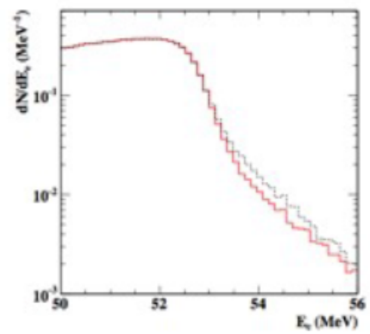
N.B. likelihood curves are not directly used in confidence interval calculation

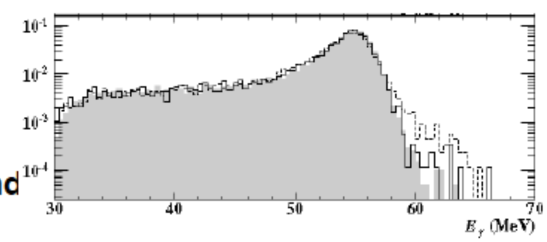
MEG Result

What's new in the last result?

- Hardware
  - *New **DC laser tracker** for alignment*
  - *New **BGO calorimeter** for LXe **calibration** with **CEX***
  - ***Multiple buffer** read out → **DAQ efficiency = 96%***
- Software
  - *e^+ side:*
    - new DC-waveform **noise filtering** → **improved resolution**
    - **new Kalman filter** implementation → **higher efficiency** and **reliable** per event track **fit uncertainties**
      - ***per event PDFs***
  - *γ-detector side:*
    - **improved pile up rejection** algorithm → **steeper background spectrum** close to signal region



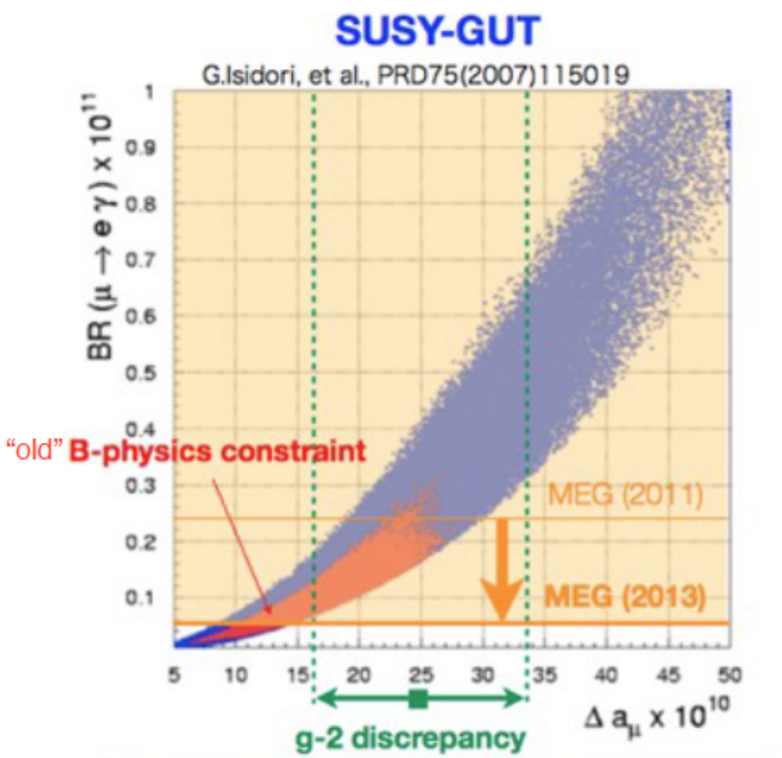




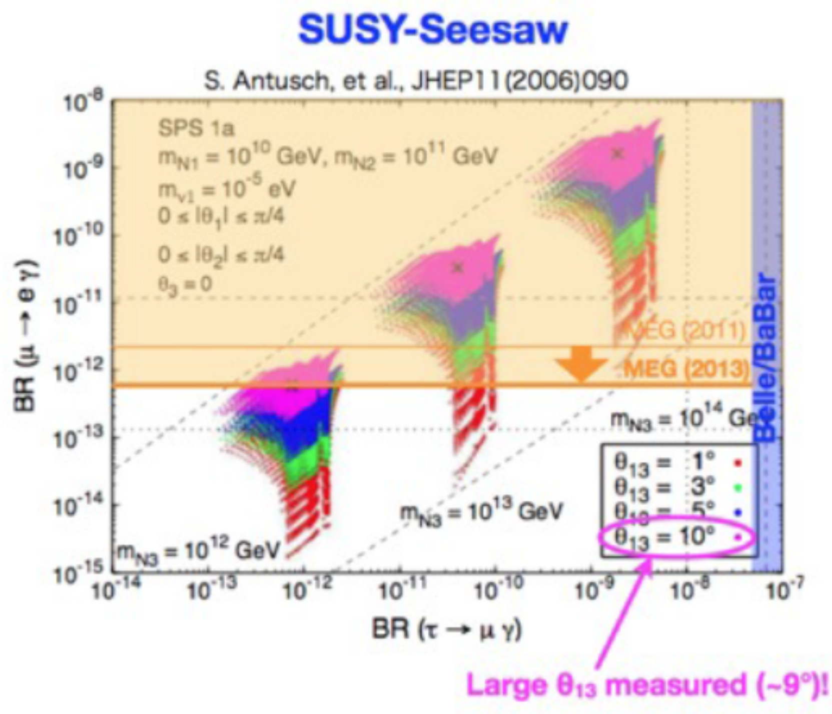
L. Galli, PSI & INFN Pisa

MEG Implications

Constraints on New Physics, two examples



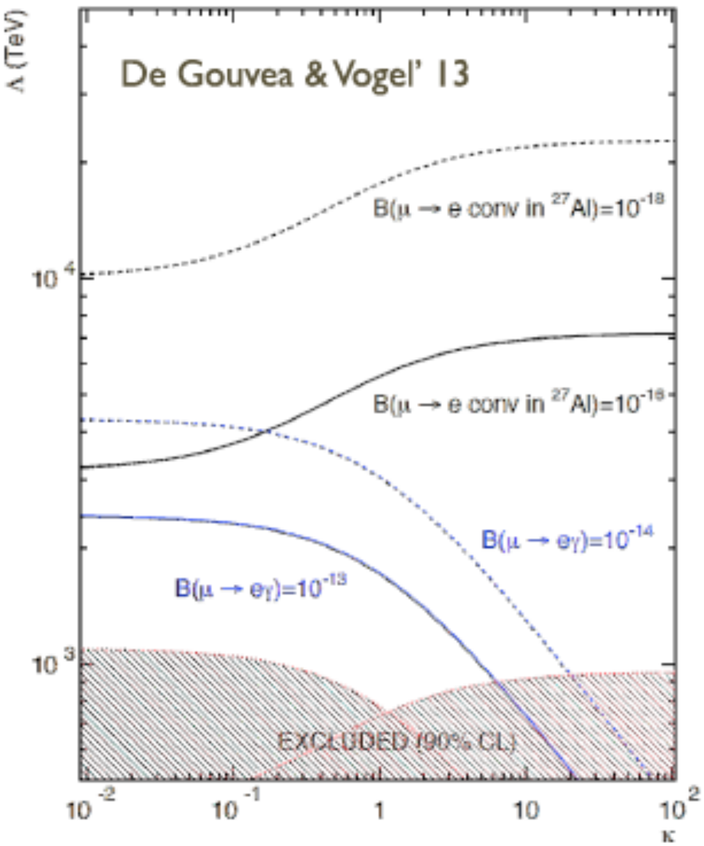
Inconsistency arising... compatibility with LHCb



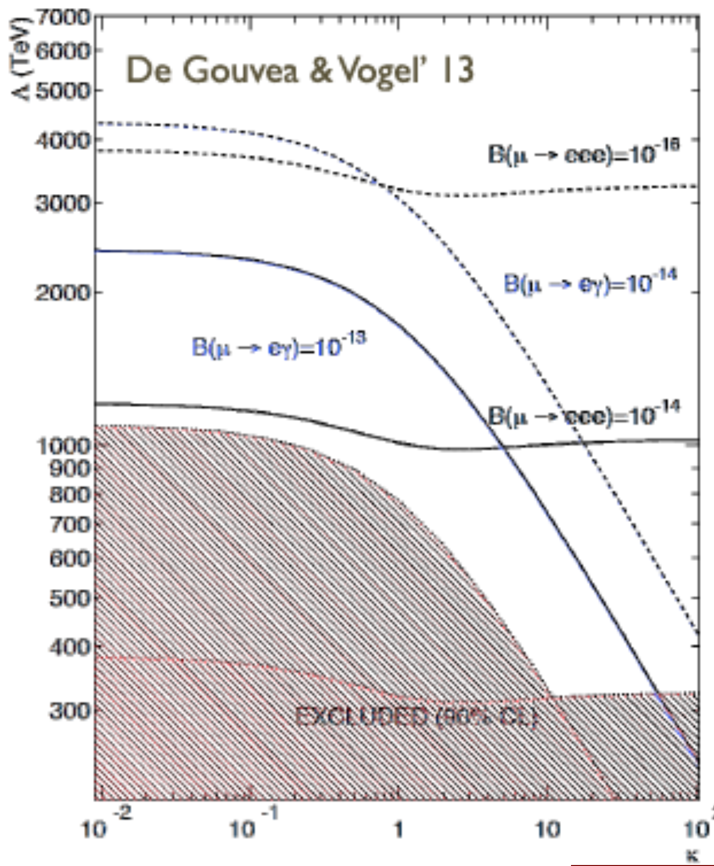
Willing for one more order of magnitude!!!!

Theory & Experiment

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$
$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + h.c.\,.$$

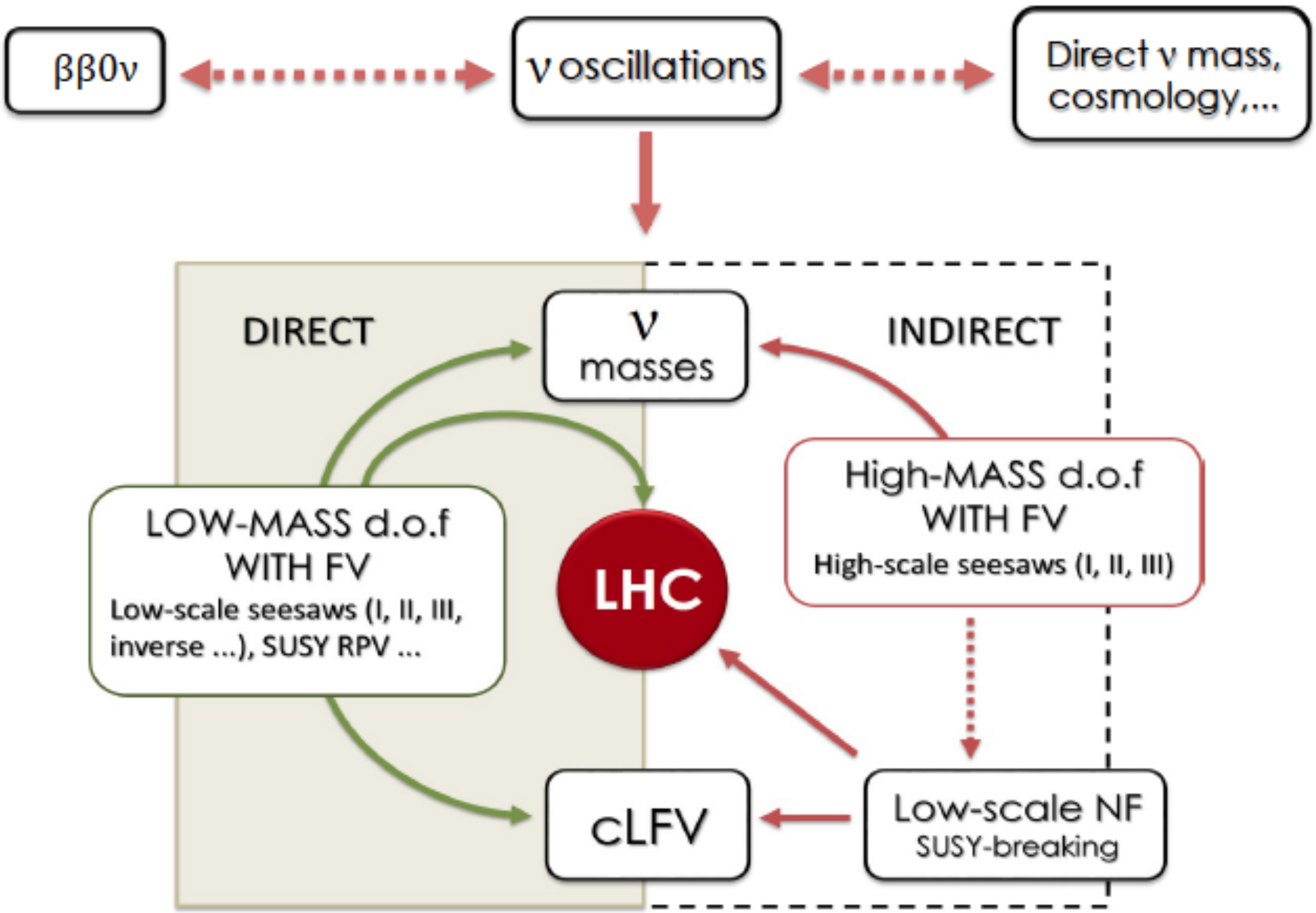


$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$
$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{e}\gamma^\mu e\right) + h.c.\,.$$



Filipe Joaquim

Connection with Seesaw



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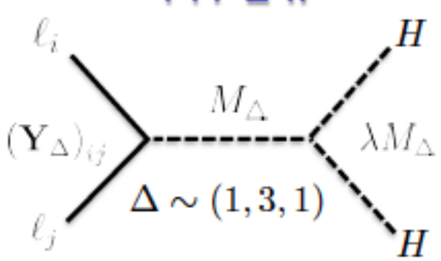
Connection w/ cLFV Expt.

TYPE II



Neutrino masses:

$$\mathbf{m}_\nu \simeq -\lambda \frac{v^2}{2} \frac{\mathbf{Y}_\Delta}{M_\Delta}$$

Roughly: $\mathrm{BR}(\ell_j \to \ell_i + \gamma) \simeq \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m}_{\tilde{L}}^2)_{ji}|^2}{m_S^8} \tan^2\beta \, \mathrm{BR}(\ell_j \to \ell_i \nu_j \bar{\nu}_i)$

What is Important are the RATIOS of the cLFV channels

One gets rid of the non-flavoured parameter dependence.

$$R_{\tau\mu} \equiv \frac{\mathrm{BR}(\tau \to \mu\gamma)}{\mathrm{BR}(\mu \to e\gamma)} \simeq \left| \frac{(\mathbf{m}_{\tilde{L}}^2)_{\tau\mu}}{(\mathbf{m}_{\tilde{L}}^2)_{\mu e}} \right|^2 \frac{\mathrm{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}{\mathrm{BR}(\mu \to e\nu_\mu\bar{\nu}_e)} \quad , \quad \frac{\mathrm{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}{\mathrm{BR}(\mu \to e\nu_\mu\bar{\nu}_e)} = 0.1737$$

$$R_{\tau e} \equiv \frac{\mathrm{BR}(\tau \to e\gamma)}{\mathrm{BR}(\mu \to e\gamma)} \simeq \left| \frac{(\mathbf{m}_{\tilde{L}}^2)_{\tau e}}{(\mathbf{m}_{\tilde{L}}^2)_{\mu e}} \right|^2 \frac{\mathrm{BR}(\tau \to e\nu_\tau\bar{\nu}_e)}{\mathrm{BR}(\mu \to e\nu_\mu\bar{\nu}_e)} \quad , \quad \frac{\mathrm{BR}(\tau \to e\nu_\tau\bar{\nu}_e)}{\mathrm{BR}(\mu \to e\nu_\mu\bar{\nu}_e)} = 0.1784$$

These are the perdictions of the model

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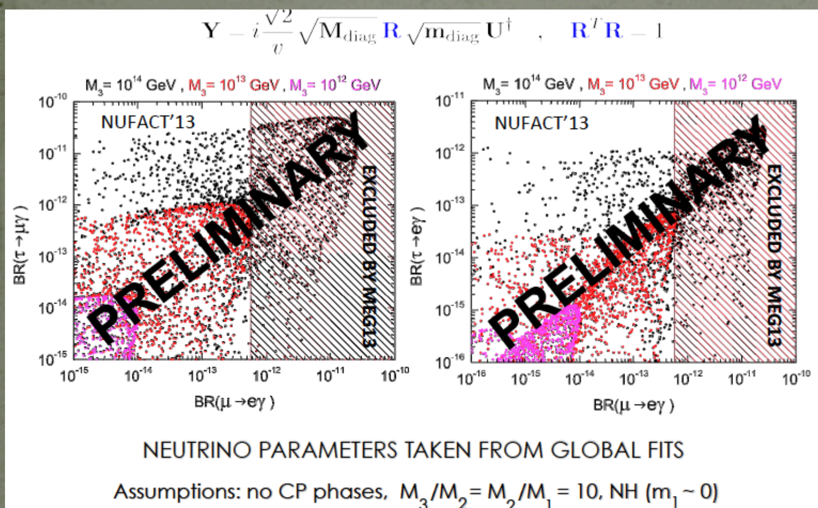
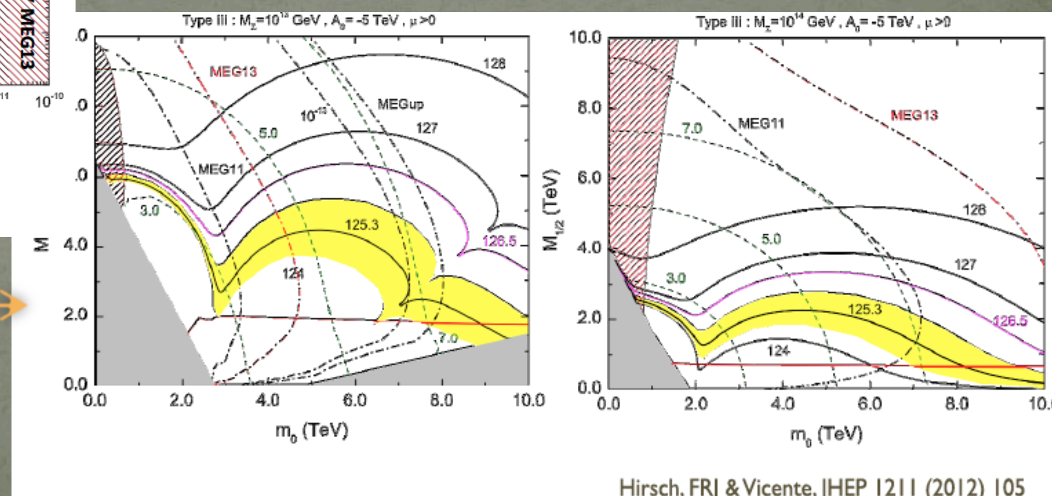
Connection w/ Expt

Shortcoming of type I and III seesaws:
HARD* to disentangle the flavour structure of the couplings in the neutrino sector
IN A MODEL-INDEPENDENT WAY



So you can look at the ratio prediction for differ R matrix parameter space

But there is an instinct dependence on the energy scale that affects whether you are really constraining the model with MEG



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MEG2013 Data and MEG2

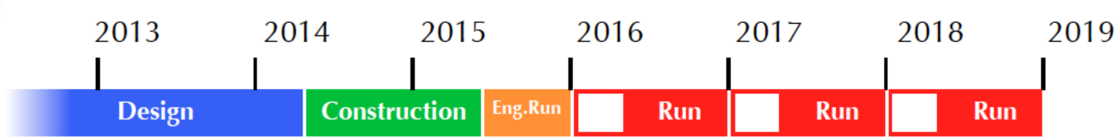
- The **2012 run already performed**
  - ***10% more statistics*** *w.r.t.* ***2011*** *run,* ***analysis ongoing***
- The **2013 run ready** to start in the **middle of May** until to **end of August, together** with **2012** will **double** this **seminar statistics**

Data statistics will be doubled with 2012+2013 (est.)

Final MEG $S = 5\ 10^{-13}$

Doubling of current statistics

- It is an **upgrade**, **NOT** a **new experiment**!
  - ***improving*** *the final MEG sensitivity* ***by an order of magnitude ~ 5x10^{-14}***
- Limited to a **reasonable time span**
- Make the **best usage** of existing
  - ***infrastructures***
    - **beam line, magnet, cryostat, calibrations** (CW)
  - ***knowledge*** *accumulated in these 12 years*
  - ***expertise*** *inside the collaboration*
- **MEG2 approved and financed** by funding agencies.

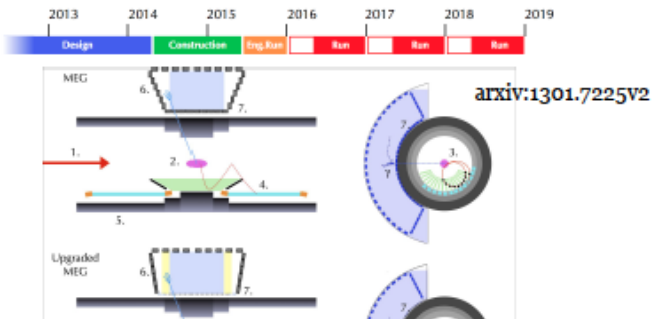


Pushing to 10^{-14} Sensitivites

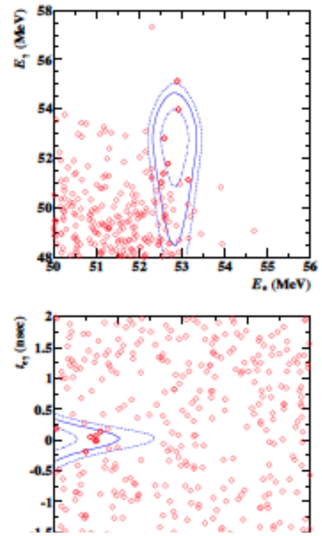
Beyond MEG

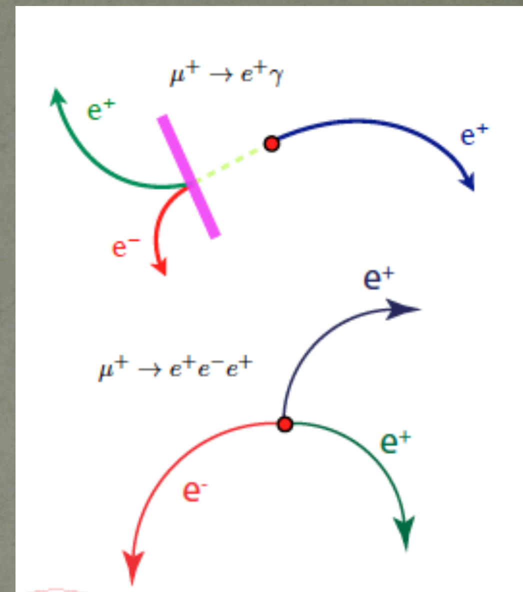
- Current limit: $\mathcal{B}(\mu^+ \to e^+\gamma) < 5.7 \times 10^{-13}$ using 3.6×10^{14} stopped muons.
- Background is dominated by accidentals.

  $N_{acc} \propto R_\mu^2 \times \Delta E_\gamma{}^2 \times \Delta P_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$
- Upgrade: target sensitivity ~ 6×10^{-14} based on ~ 3.3×10^{15} stopped muons.



arxiv:1301.7225v2





How to improve beyond MEG upgrade?

- One of the limiting factors of $\mu \to e\gamma$ search is the photon energy resolution in calorimeter.
  - Accidental background dominates: $N_{acc} \propto R_\mu^2 \times \Delta E_\gamma{}^2 \times \Delta P_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$ (e^+ from Michel decay, γ from radiative muon decay)
- A pair spectrometer (reconstructing e^+e^- pair tracks from photon conversion) can improve photon energy resolution significantly.

Chih-hsiang Cheng

μ→eγ + converter

- Comparison with MEG, MEG upgrade and Mu3e.

	This work	MEG
p_e	200 keV	305 keV
E_γ	0.37%	1.7–2.4 %
$m_{e\gamma}$	340 keV	
$\varphi_{e\gamma}$	10 mrad	9 mrad
$\theta_{e\gamma}$	9 mrad	16 mrad
efficiency	1.25%	~2%

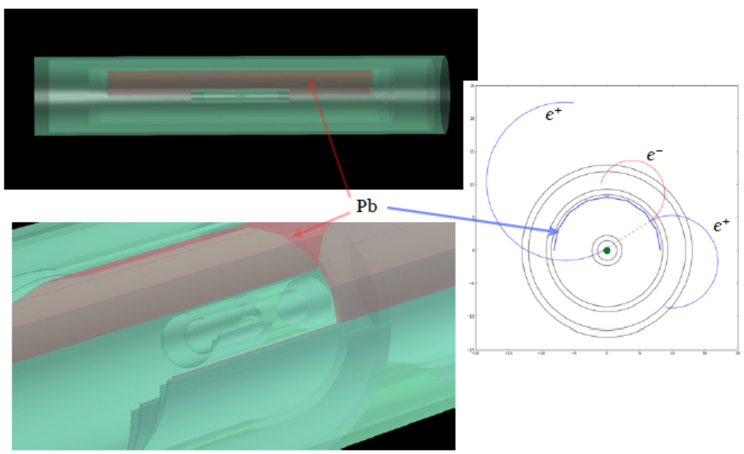
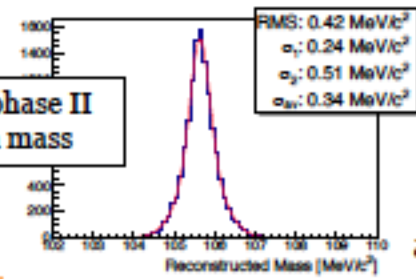


TABLE XI: Resolution (Gaussian σ) and efficiencies for MEG upgrade

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) ($w<2$ cm)/($w>2$ cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88

arxiv:1301.7225v2

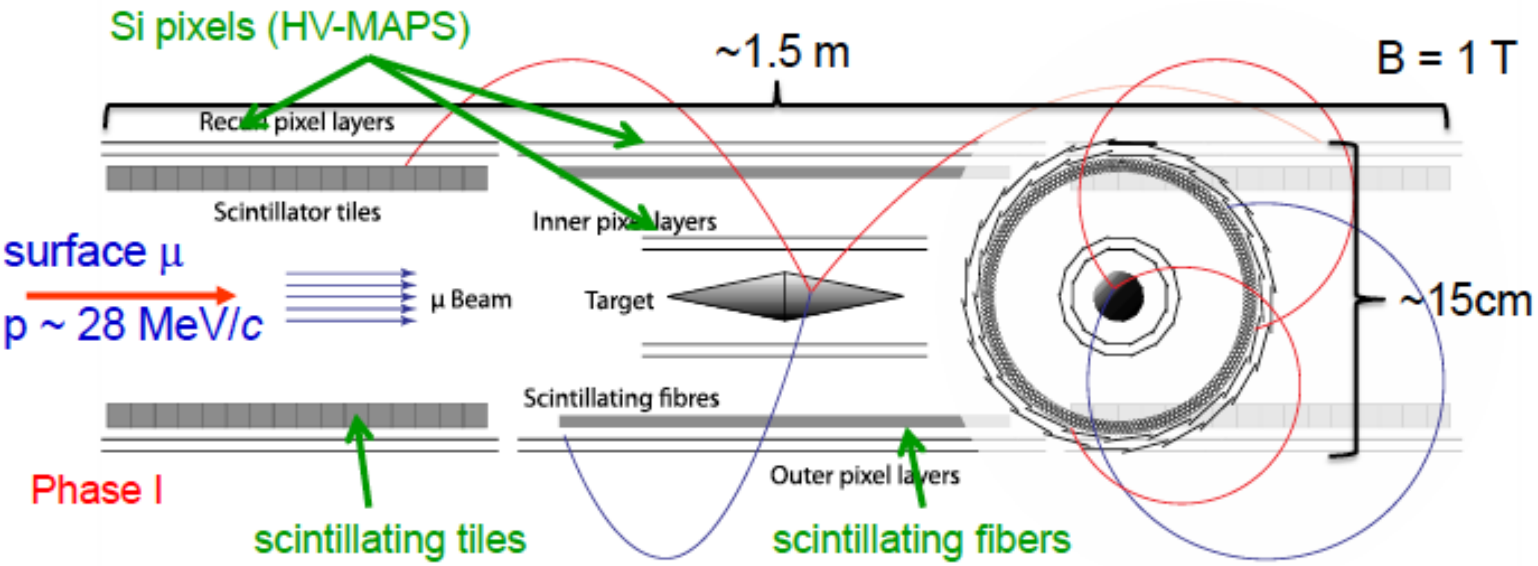
Mu3e phase II muon mass



arxiv:1301.7225v2

Chih-hsiang Cheng

Mu3e

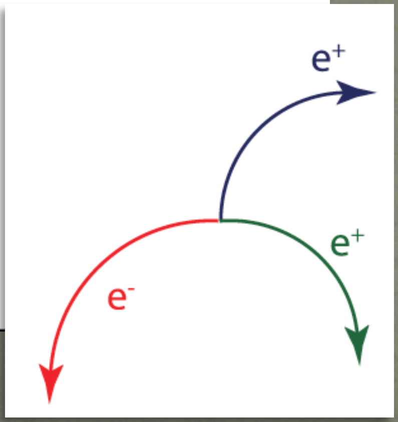


acceptance ~ 70% for $\mu^+ \to e^+ e^- e^+$ decay (3 tracks!)

thin, fast, high resolution detectors
(minimum material, maximum precision)

275 M HV-MAPS (Si pixels w/ embedded ampli.) channels

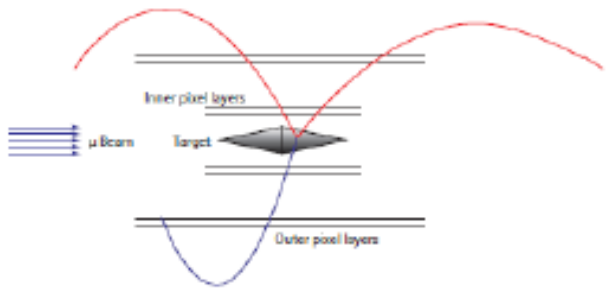
~ 10 k ToF channels (SciFi and Tiles)



A.Bravar

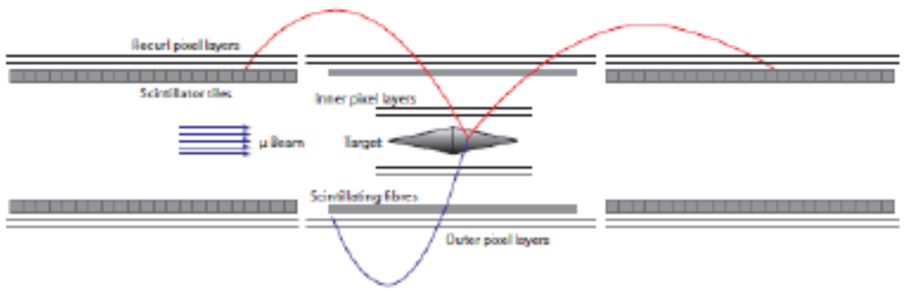
Mu3e Staging

Phase IA
rate $\leq 10^7$ μ / s



only central pixel

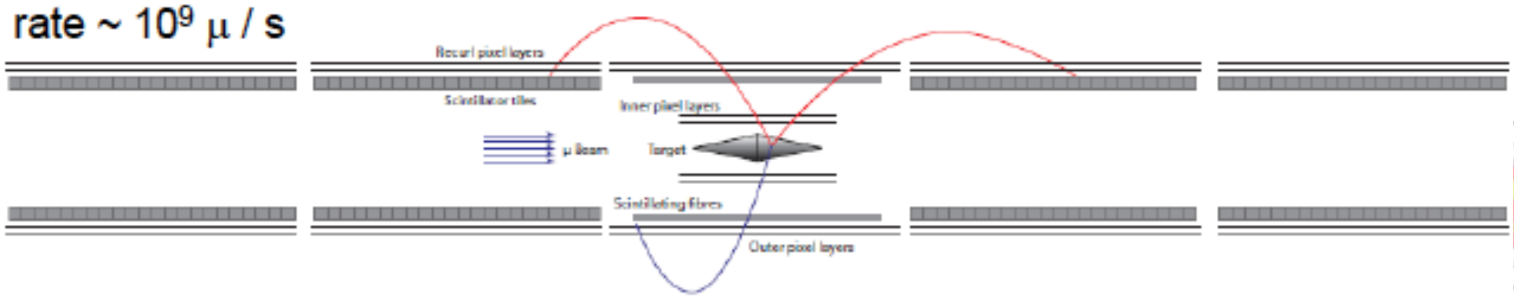
Phase IB
rate ~ 10^8 μ / s



+ inner recurl sta.
+ time of flight

Phase II
rate ~ 10^9 μ / s

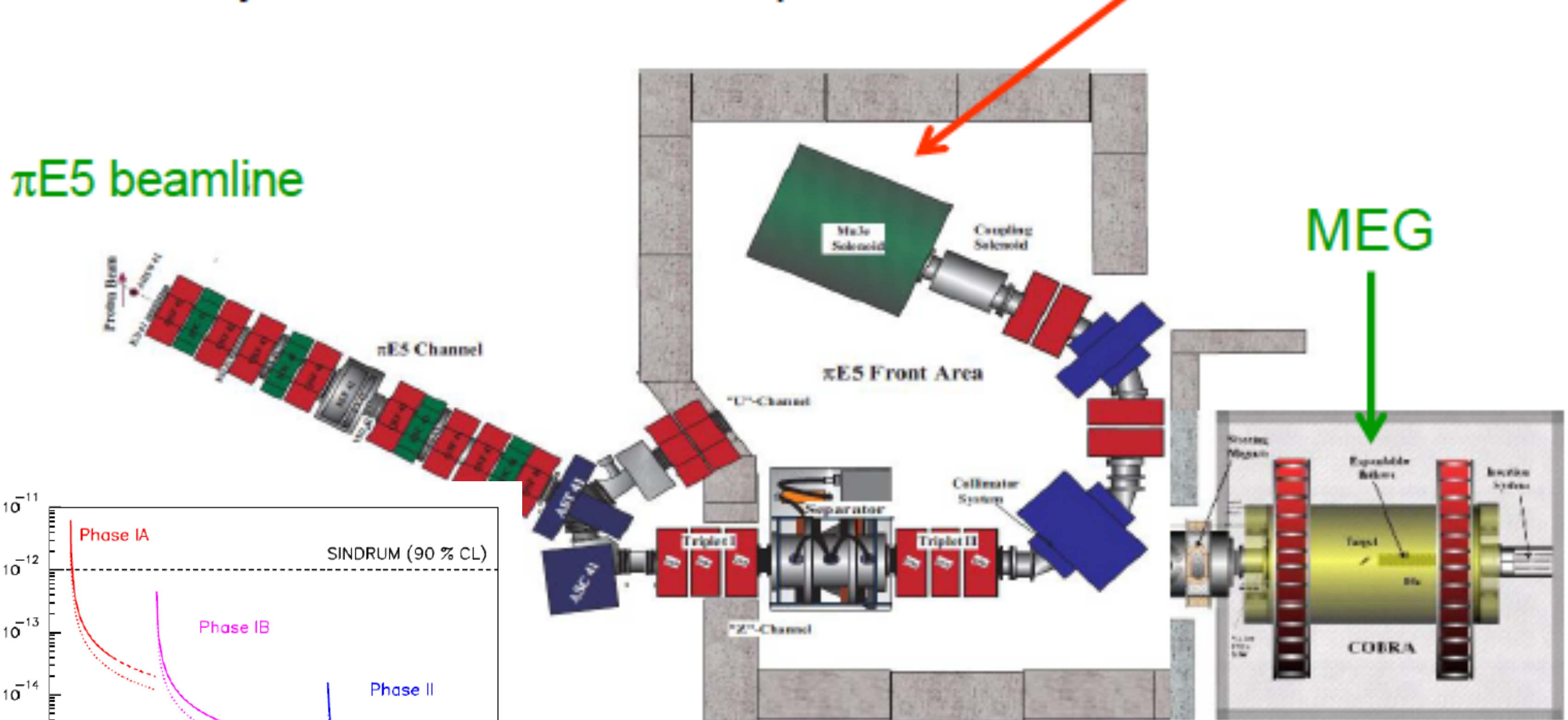
+ outer recurl sta.

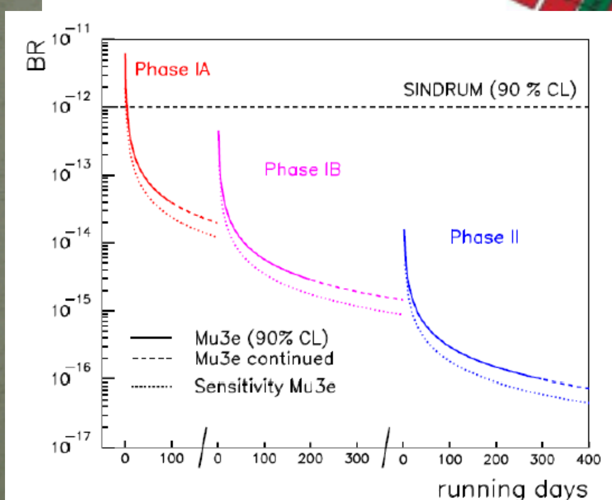


A.Bravar

Mu3e Staging

MEG and Mu3e to share same beamline
can easily switch between the two experiments





A.Bravar

Mu3e Staging

The High-intensity Muon Beamline (HiMB)

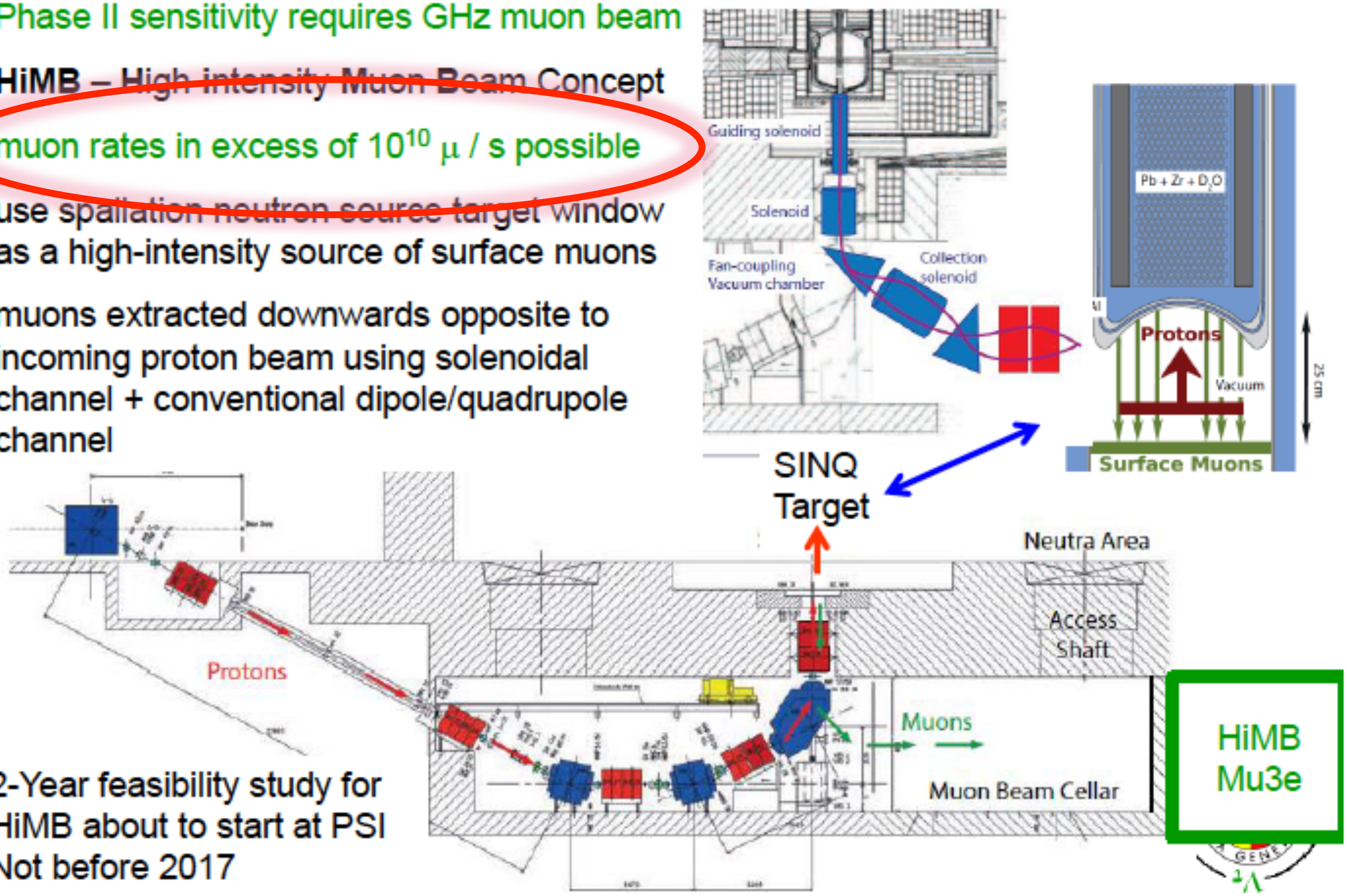
Phase II sensitivity requires GHz muon beam

HiMB – High intensity Muon Beam Concept

muon rates in excess of 10^{10} μ / s possible

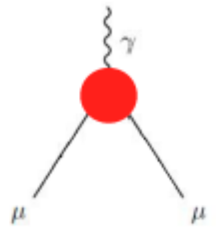
use spallation neutron source target window as a high-intensity source of surface muons

muons extracted downwards opposite to incoming proton beam using solenoidal channel + conventional dipole/quadrupole channel



2-Year feasibility study for HiMB about to start at PSI
Not before 2017

Muon g-2



Anomalous magnetic moment

$g = 2\,(1 + a_\mu)$

$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

All interactions, *including ones we don't know*, appear in quantum loops, and add up to contribute a_μ

Requires precision calculations of the standard model contributions to enable the next generation of experiments

Requires higher precision Measurements of uHFS

T.Mibe

Muon g-2 Theory Improvements

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

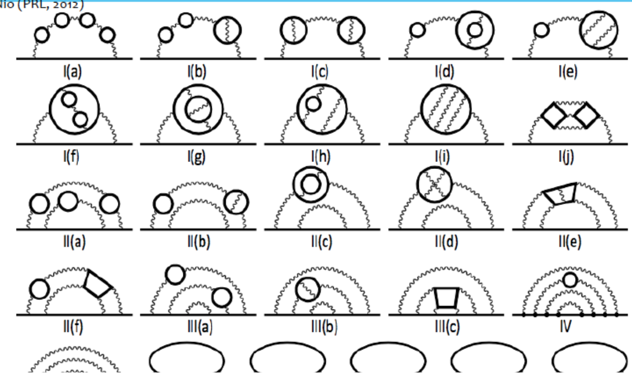
Table: $a_\mu(\text{QED})$ at each order $2n$, scaled by 10^{11}

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

NEW!

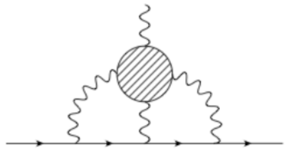
T. Aoyama, M. Hayakawa, T. Kinoshita, M. Nio (PRL, 2012)

10^{th} 12672 diagrams



- Lattice efforts making progress by Tom Blum et. al and other groups (UKQCD, ETMC, Mainz).
- Lattice is especially important for evaluation of light-by-light term, which no measurement can be done.

QED contribution	11 658 471.808 (0.015) $\times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	694.9 (4.3) $\times 10^{-10}$	HLMNT11 (in consistent with DHMZ10)
NLO hadronic	-9.8 (0.1) $\times 10^{-10}$	HLMNT11 (in consistent with DHMZ10)
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg ~BNL E821 (0.5ppm)
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**



Blobs: all possible hadronic states

Courtesy Tom Blum

HLMNT11 : J.Phys.G38:085003,2011

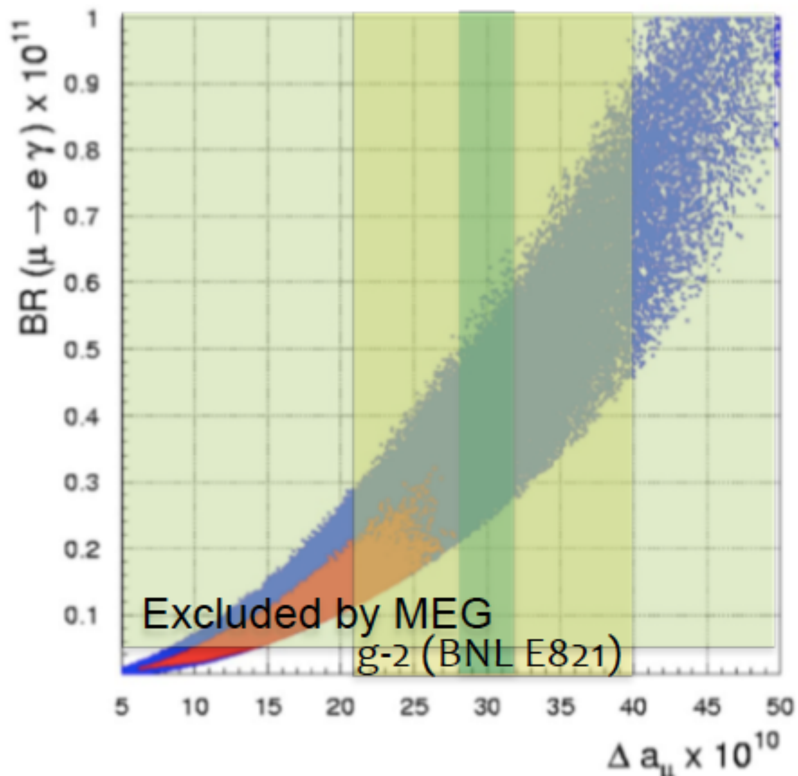
T.Mibe

g-2/μEDM SUSY Tension

Large g-2 → Large cLFV

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

Combining g-2 with μ→eγ (cLFV) is already starting to provide tension for SUSY models



deviation from SM (g-2)

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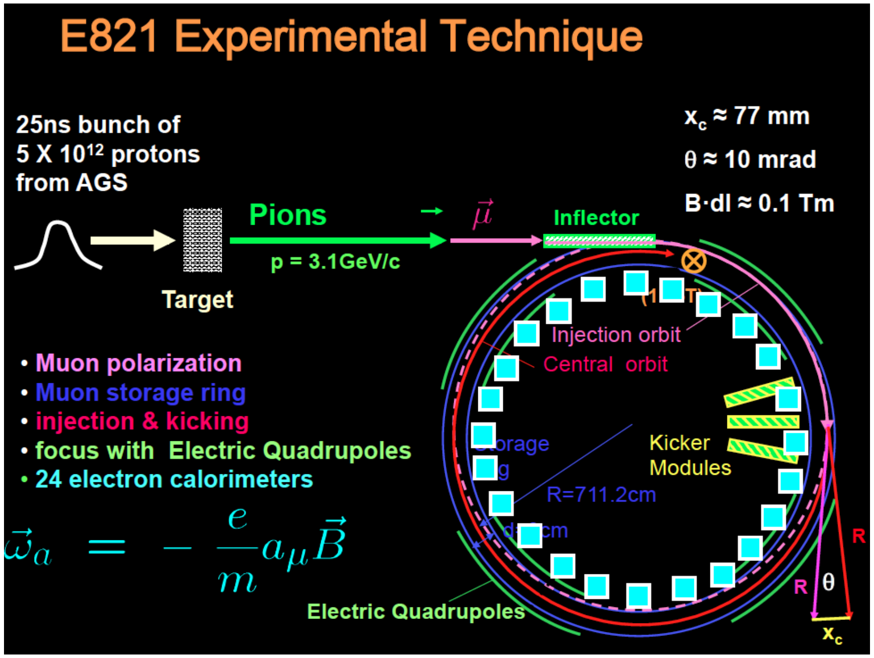
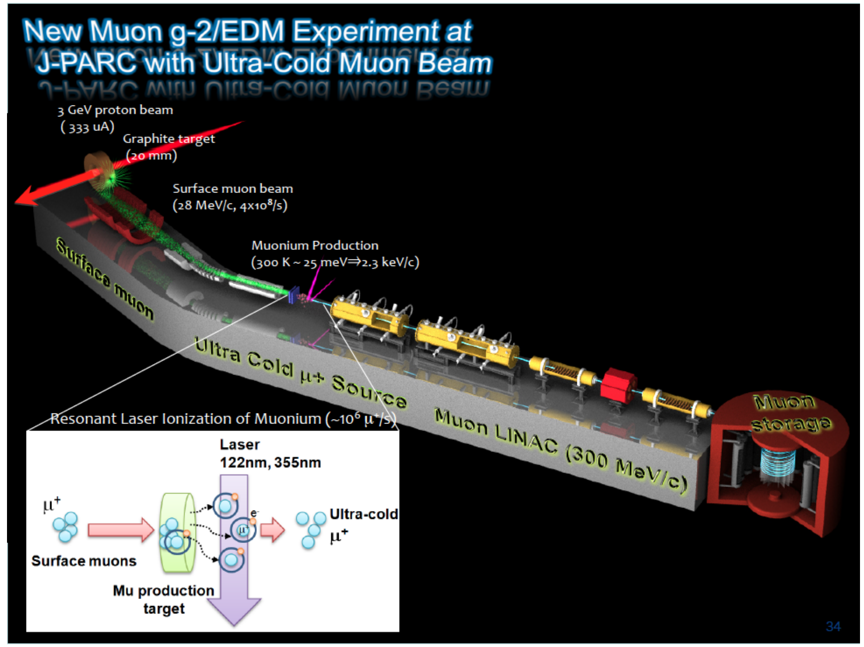
g-2 Techniques

Brookhaven/FNAL Magic Momentum

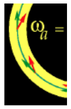
J-PARC Ultra Cold E=0





general form of spin precession vector:

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



BNL E821 approach
$\gamma=30$ (P=3 GeV/c)

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

Continuation at FNAL with 0.1ppm precision

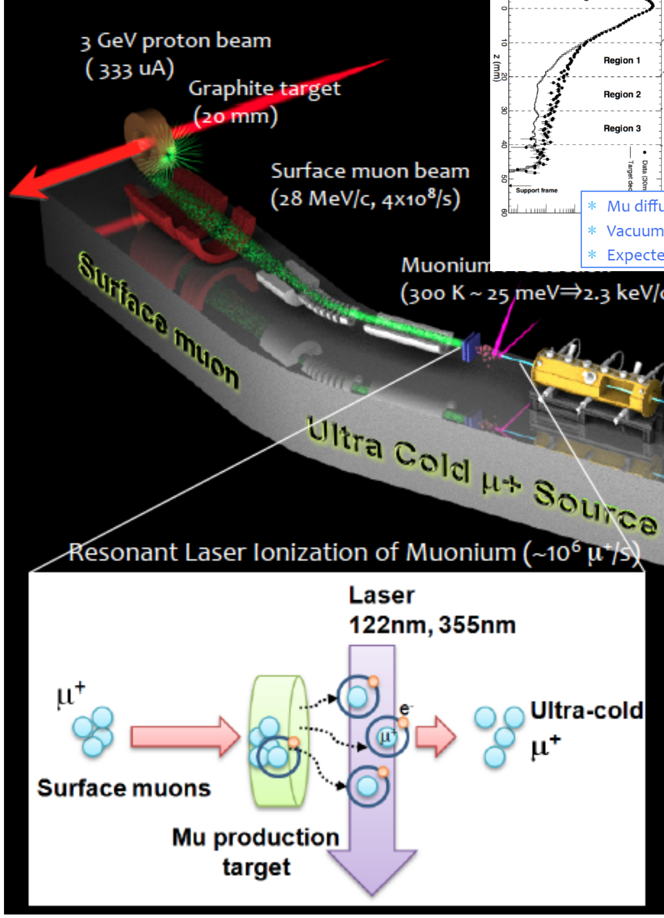
J-PARC approach
$E = 0$ at any γ

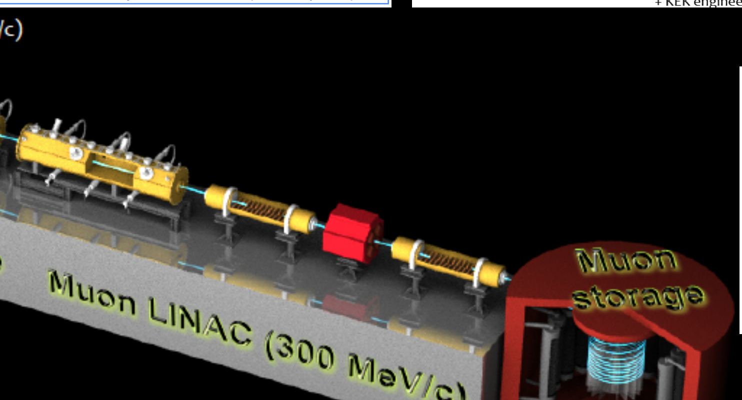
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

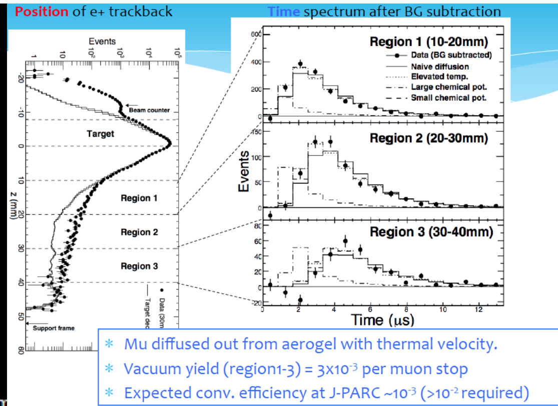
Proposed at J-PARC with 0.1ppm precision

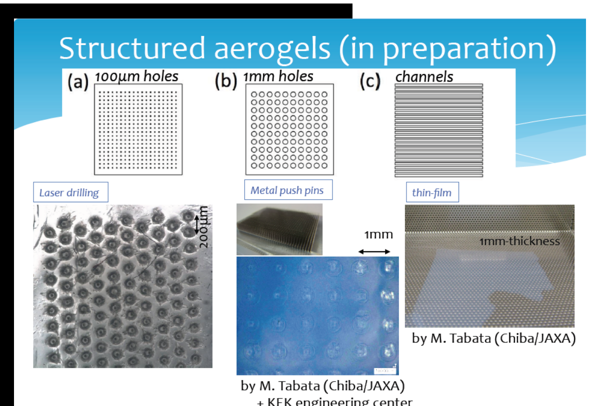
T.Mibe

g-2 Cold Technique Progress



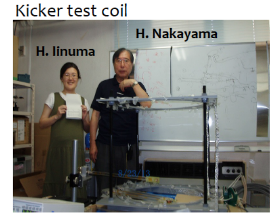






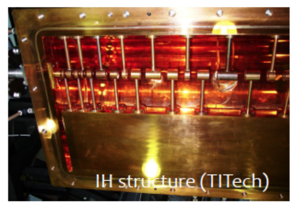
Performance of pulsed power supply and coil is being evaluated with a test coil.

Kicker test coil

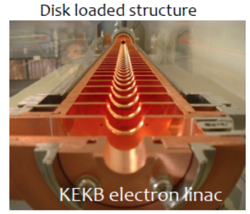


RFQ

IH linac



Disk loaded structure



T.Mibe

KEKB/J-PARC accelerator group + TITech + Kyoto
Beam simulations in progress. Muon acceleration test being planned at J-PARC

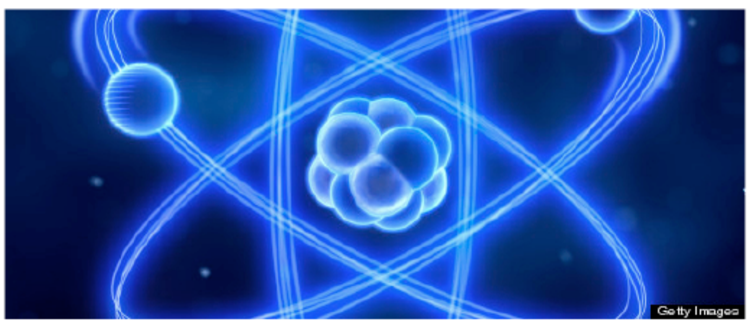
Proton radius problem

April 20, 2013

HUFF POST SCIENCE

Proton Size Smaller Than Physicists Thought, Puzzling New Measurements Suggest

Posted: 04/14/2013 10:16 am EDT



FOLLOW: Video, American Physical Society, Electrons, Physicists, Physics, Proton, Proton

- It has raised public interest!
- Not just interesting:

→ Tests our theoretical understanding of proton

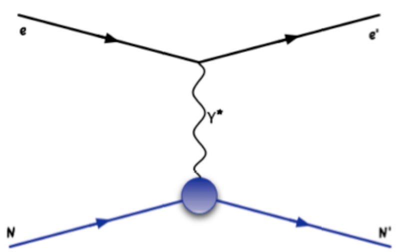
→ Radius of proton is dominant uncertainty in many QED processes

W. J. Briscoe

Proton radius problem

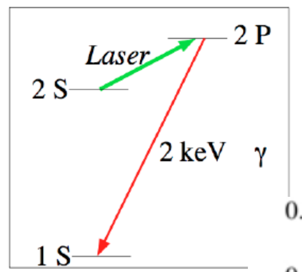
- What is a radius? How do we measure it?
- Classical physics: $r^2 = \int \rho(r) r^2 d^3r$
- Non-relativistic quantum mechanics: $r^2 = \int < \psi^*(r) | r^2 | \psi(r) > d^3r$
- Relativistic quantum mechanics: $r^2 = -6dG(Q^2)/dQ^2|_{Q^2=0}$

Electron Scattering



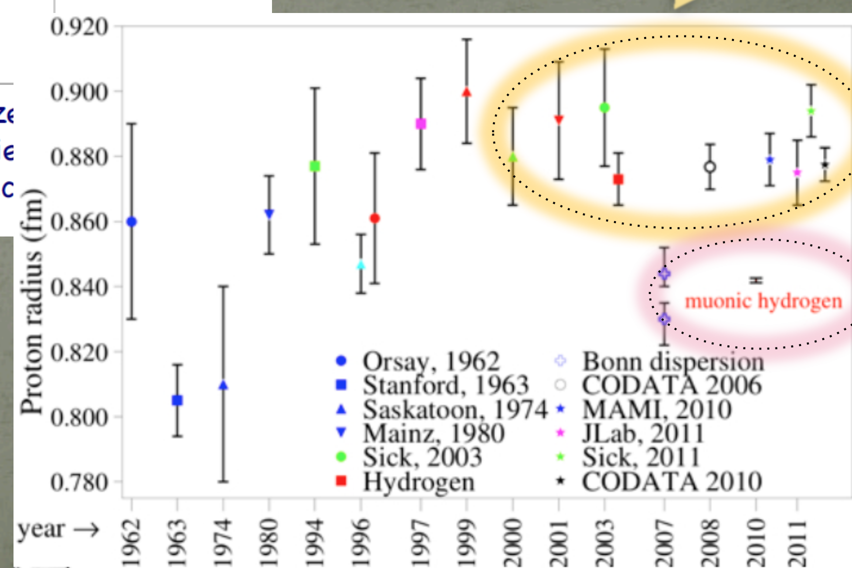
Fit form factor trend with q^2 to data, find slope as $q^2 \to 0$

Atomic Energy Levels



NRQM: finite size perturbs energie << r_{atomic}, so effec ψ $^2{}_a(r=0)$.

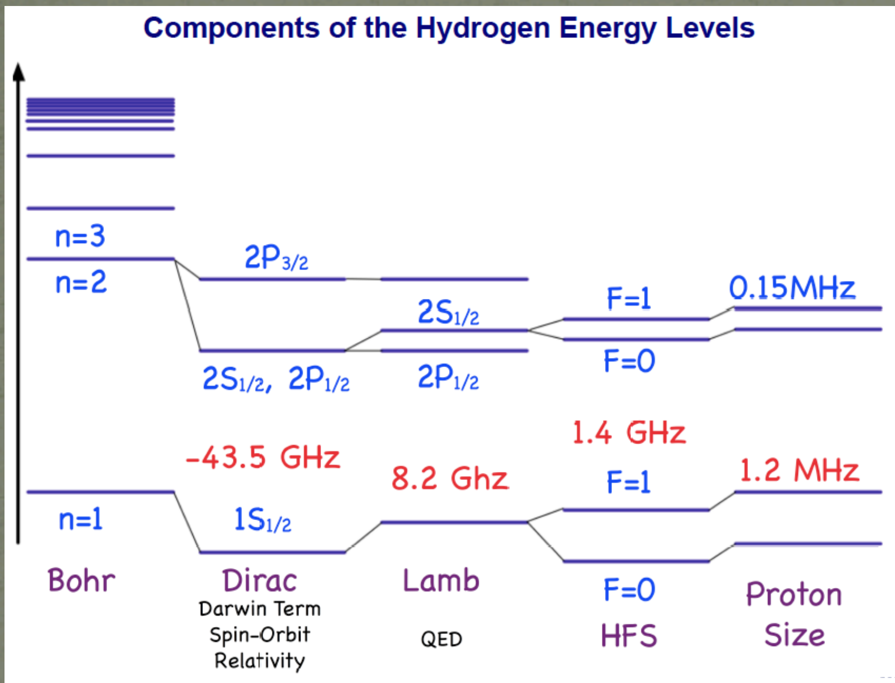
Major disagreement between eP scattering data/hydrogen energy levels and muonic hydrogen E levels

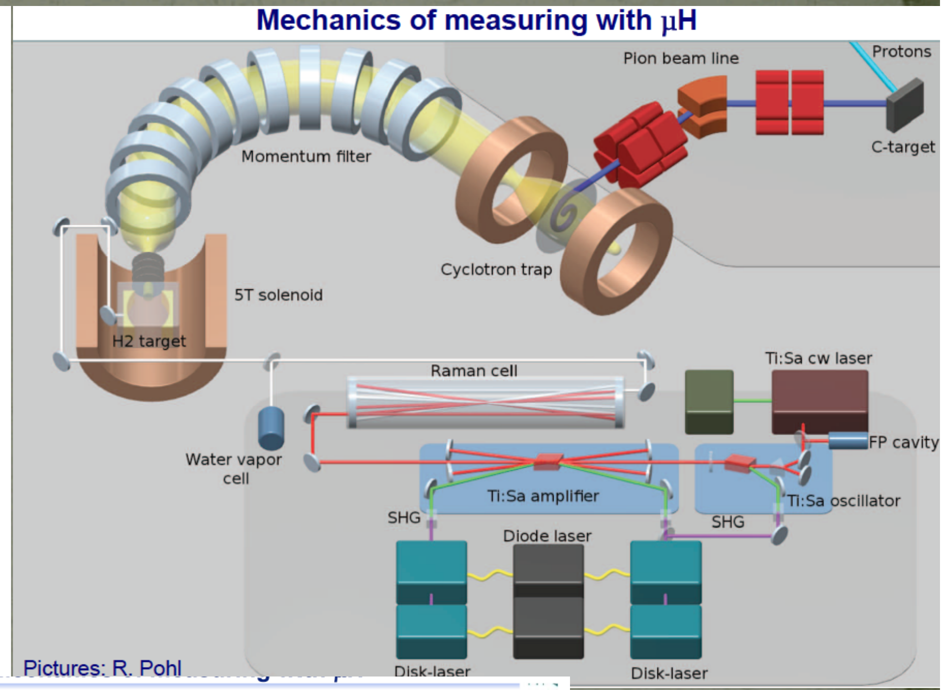


Two Distinct Methods for Measuring

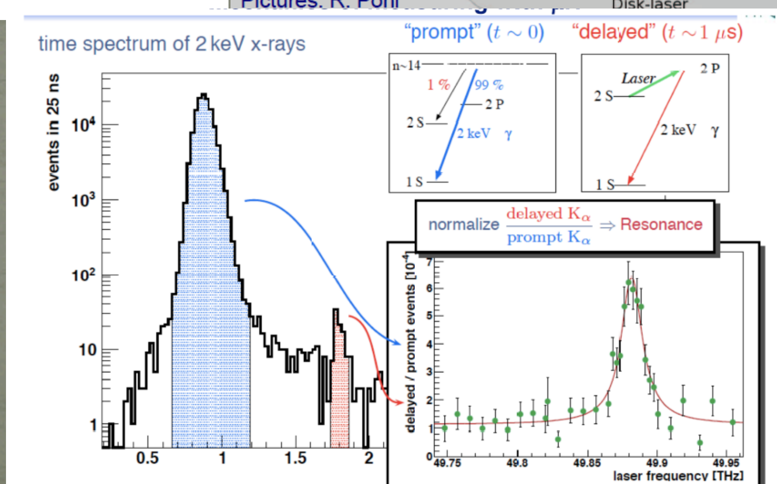
W. J. Briscoe

Proton radius problem





- Simple, but technically challenging
- Form μH
- Excite from 2S to 2P
- Vary laser freq to find transition peak
- Extremely precise



$$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \text{ [meV]}$$

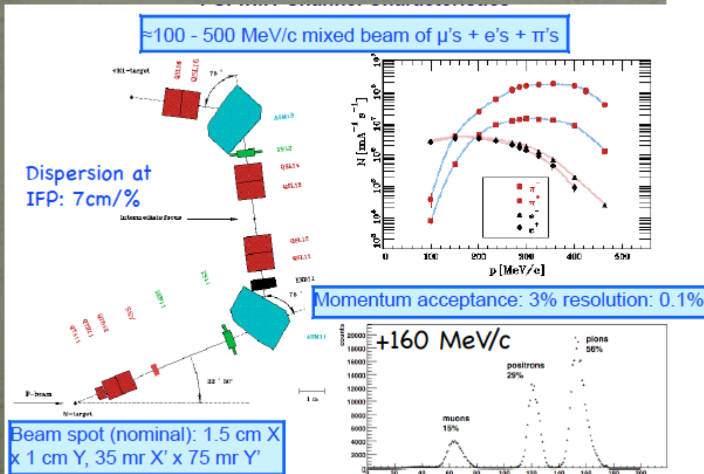
W. J. Briscoe

Why do μ's & e's give different radii?

- Assuming the experimental results are not bad, what are viable theoretical explanations of the Radius Puzzle?
- Novel Beyond Standard Model (BSM) Physics: Pospelov, Yavin, Carlson, ...: the electron is measuring an EM radius, the muon measures an (EM+BSM) radius
- Novel Hadronic Physics: G. Miller: currently unconstrained correction in proton polarizibility affects μ, but not e (effect∝m_l^4)
- Basically everything else suggested has been ruled out - missing atomic physics, structures in form factors, anomalous 3rd Zemach radius, ...
- See Trento Workshop on PRP for more details:

http://www.mpg.mpg.de/~rnp/wiki/pmwiki.php/Main/WorkshopTrento

Need to do μ p and e p scattering side by side



Spots from 0.7x0.9 cm² up to 16x10 cm², Δp/p from 0.1-3.0%, used previously.

MUSE Experiment

r_p(fm)	ep	μp
atom	0.877±0.007	0.841±0.0004
scattering	0.875±0.006	?

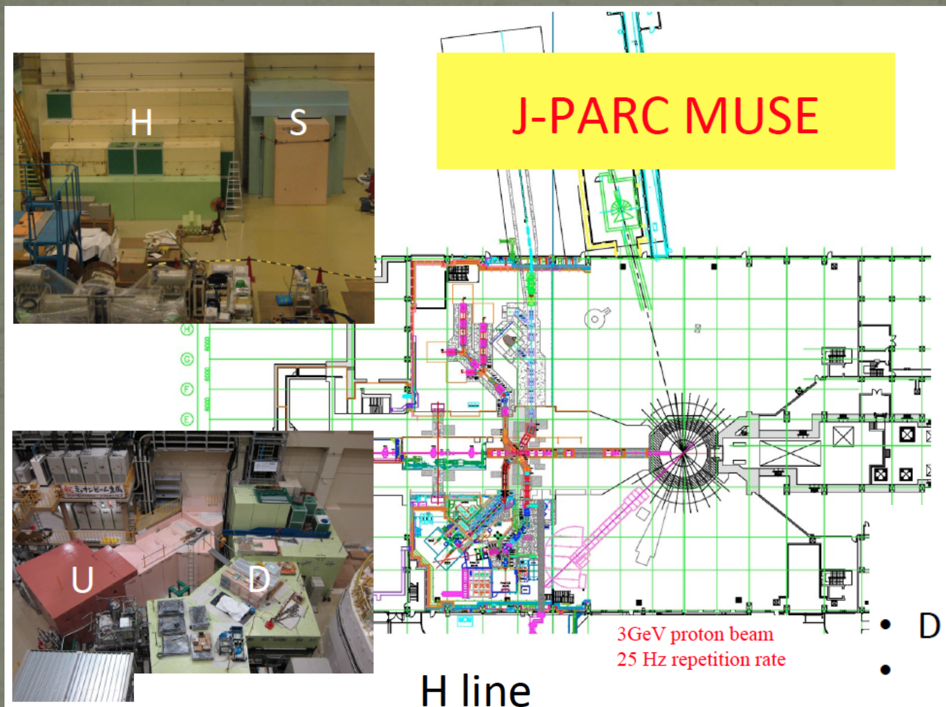
Simultaneous measurement of e^+/μ^+ e^-/μ^- elastic scattering on the proton at beam momenta of 115, 153, 210 MeV/c in pM1 channel at PSI allows:

➔ Determination of two photon effects

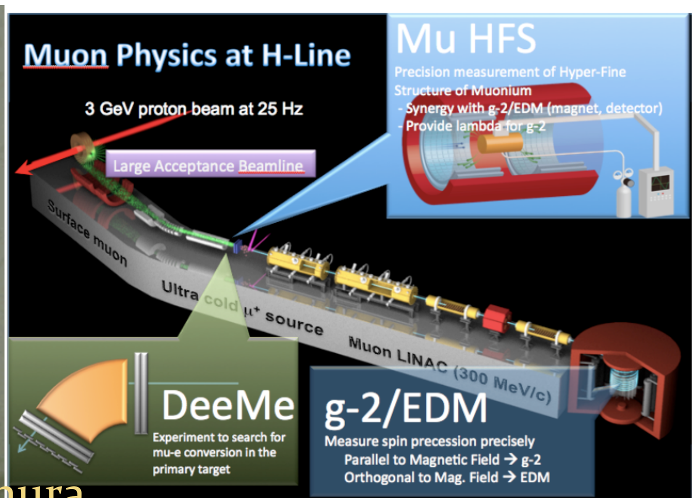
➔ Test of Lepton Universality

➔ Simultaneous determination of proton radius in both eP and mP scattering

JPARC MUSE Program



H line



Multiple intense μ beamlines for cLFV, precsion measurements, ultra cold μ production etc...

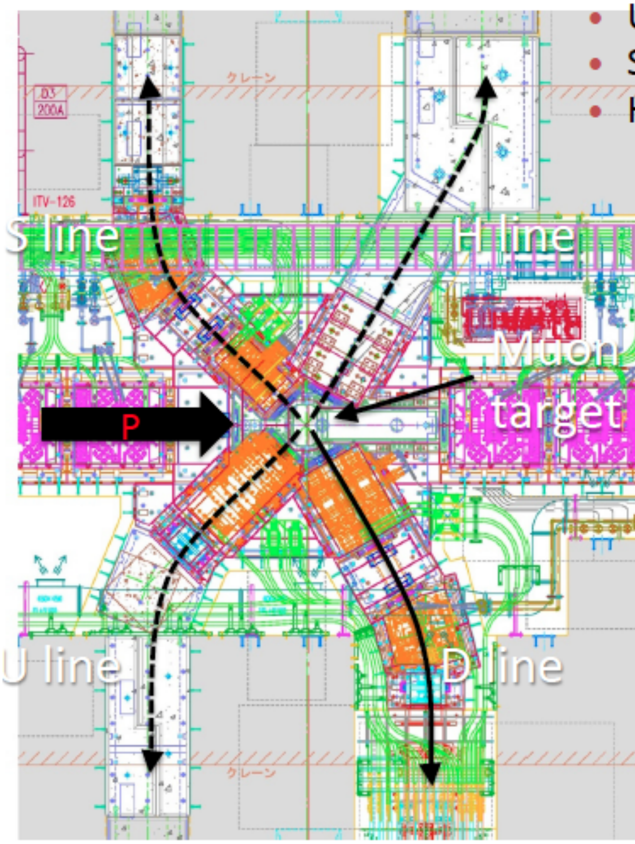
4 Beam line

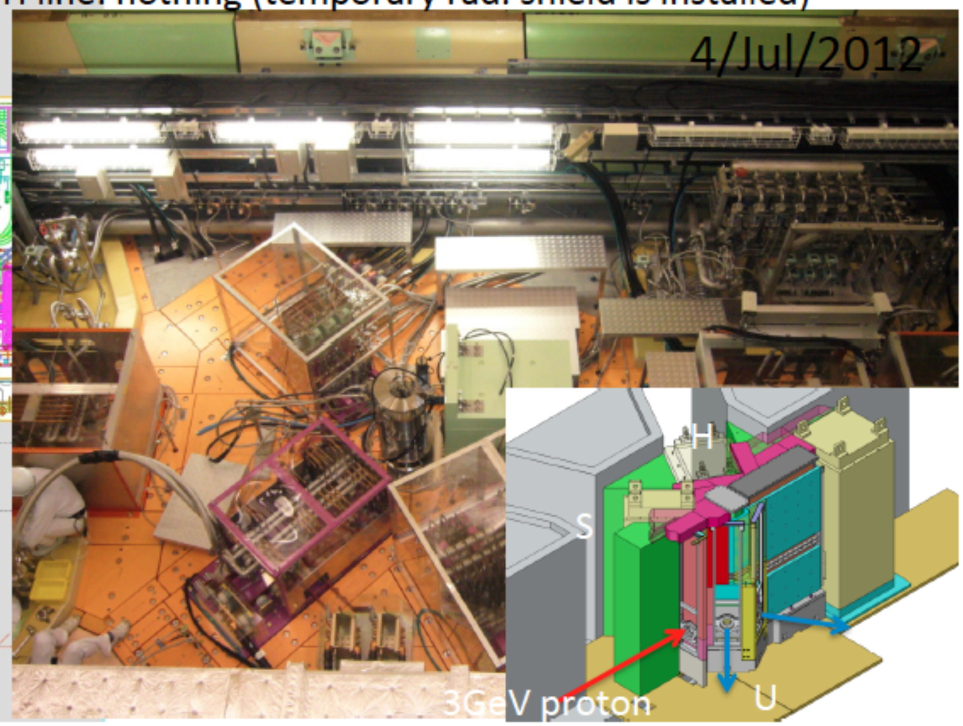
- D line (In operation)
- μ^+, μ^- (10 ~120MeV/c) ~3×10^7/s
- μSR non-destructive element analysis so on
- U line (construction finished in 2013)
- μ^+, μ^- (30MeV/c) ~4×10^8/s
- Ultra Slow Muon
- S line (In construction, 2104?)
- μ^+ (30MeV/c) ~10^7/s
- 4 μSR experiments simultiniusly
- H line (In construction, 2104?)
- μ^+ (30MeV/c) ~10^8/s
- Fundumental physics

JPARC MUSE Program Progress

Before summer shutdown 2012

- D line: complete
- U line: complete and under commissioning.
- S line: only frontend magnet was installed .
- H line: nothing (temporary rad. shield is installed)

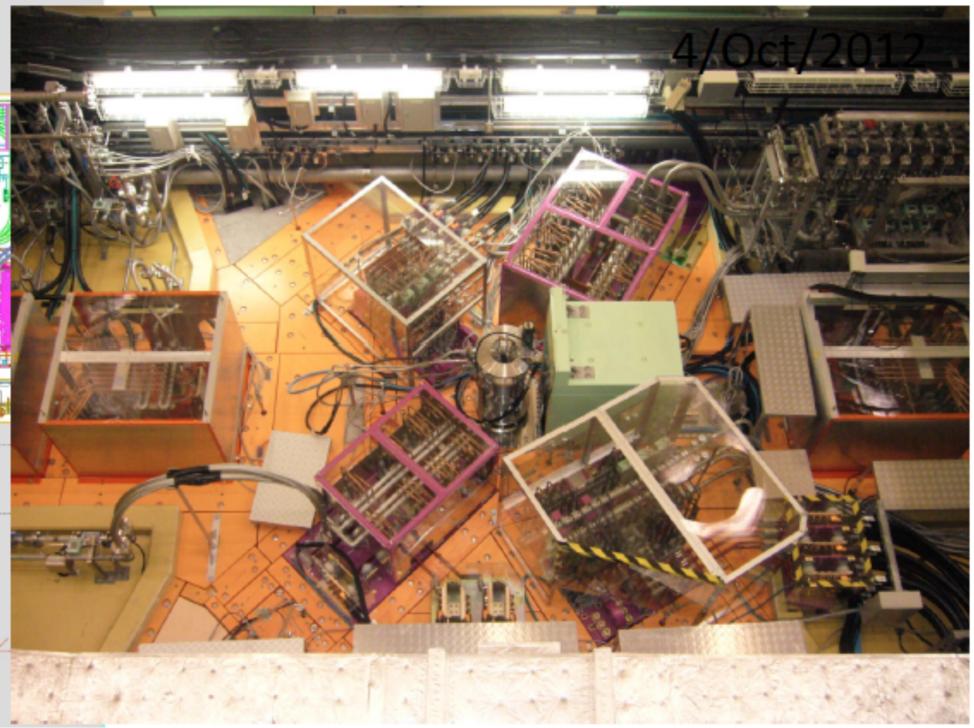




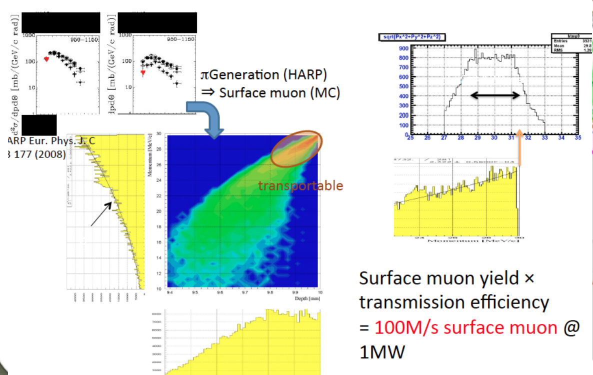
JPARC MUSE Program Progress

After summer shutdown 2012

- U line: installation of curved solenoid
- S line: installation of SQ456.
- H line: installation of frontend magnets



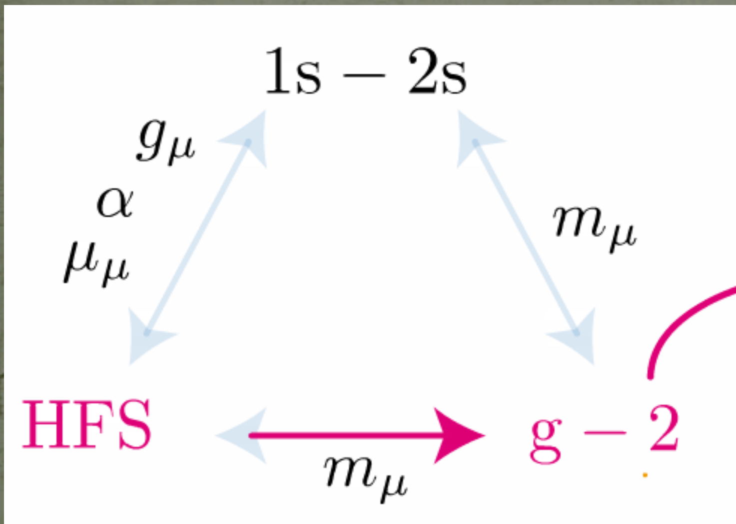
Muon beam intensity

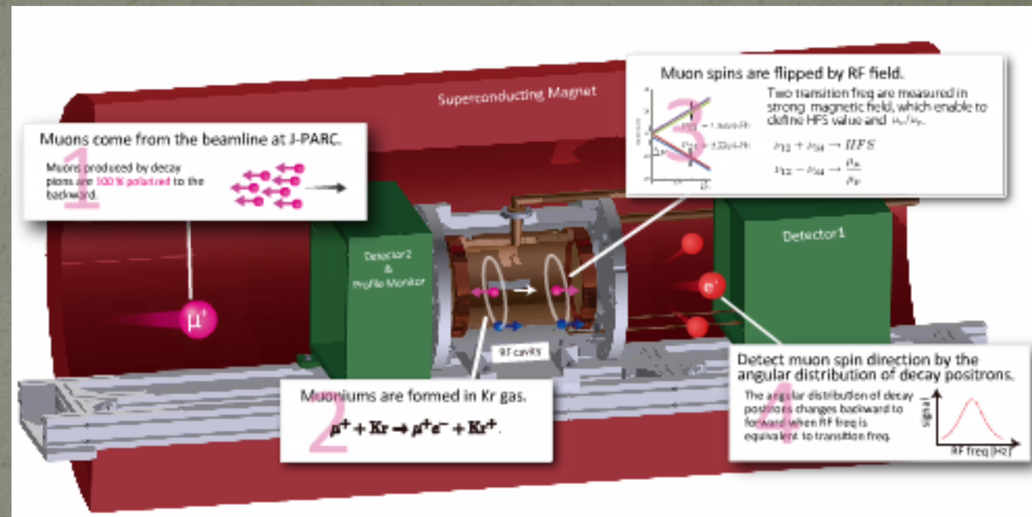


Surface muon yield × transmission efficiency = 100M/s surface muon @ 1MW

Tremendous progress on all lines

Muon Hyper Fine Splitting (JPARC)





2. Determine fundamental values.

magnetic moment

$$\frac{\mu_\mu}{\mu_p} = 3.183345107(84)$$

mass

$$\frac{m_\mu}{m_e} = 206.7682823(52)$$

Theory

4.46330288(55) GHz

Nucl. Phys. B (Proc. Suppl.) 162 (2006) 260-263

Measurement (LAMPF)

4.463302765(53) GHz

Phys. Rev. Lett. 82, 711

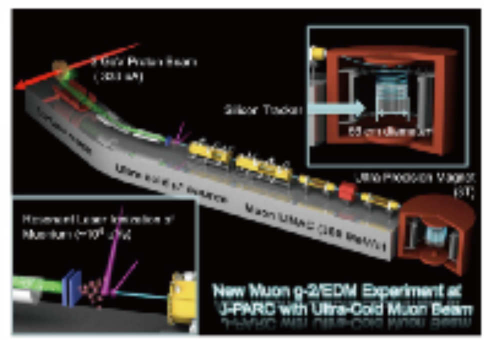
Our goul is one more digit higher

magnetic moment contributes to a precision of g-2 value.

$$g - 2 = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

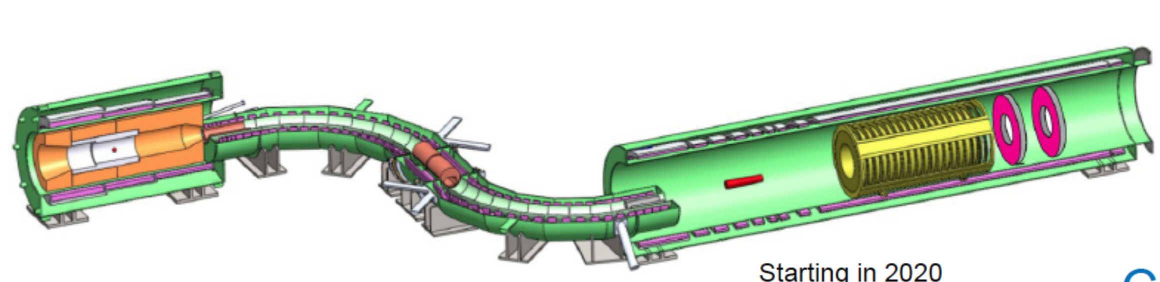
defined by g-2 exp
3.183345107(84)

defined by Mu-HFS
0.0037072083(26)



μN→eN Conversion

The Mu2e experiment

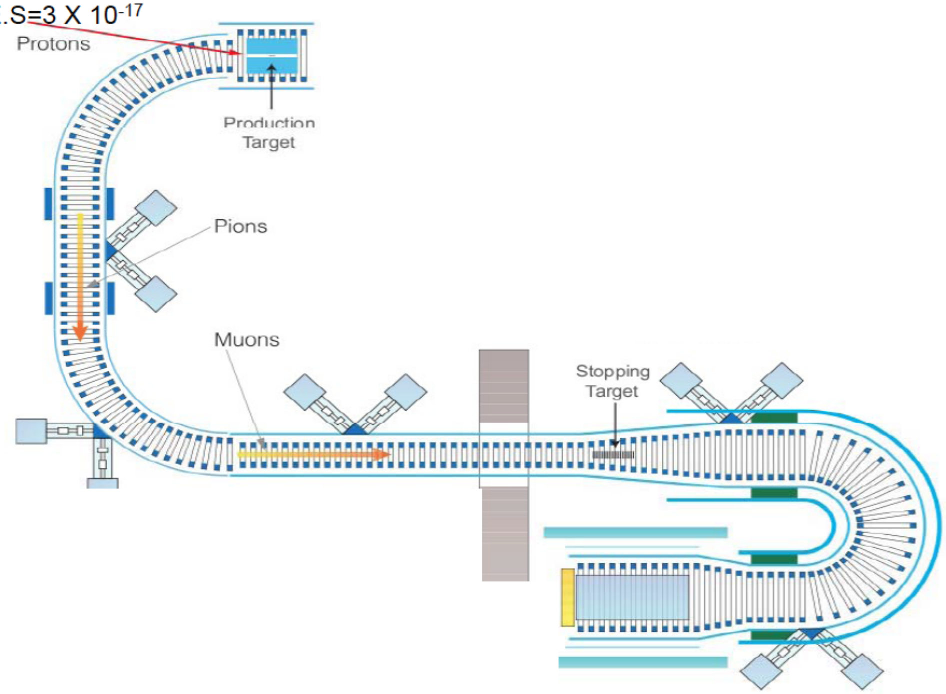


Z.You

Y.Yuan

Starting in 2020
Measurement in 2022
S.E.S=3 X 10^{-17}

COMET(Phase-II)

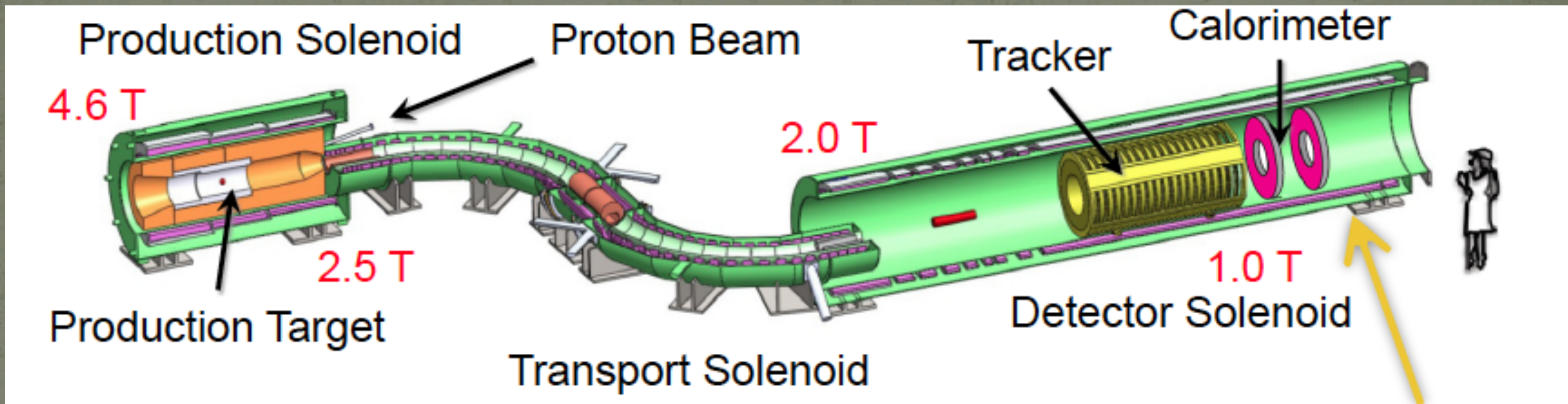


	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to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

A.J.Buras

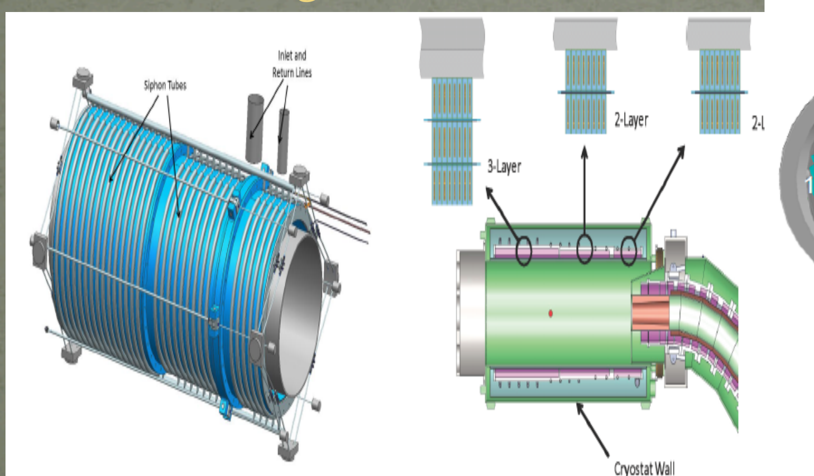
Mu2e

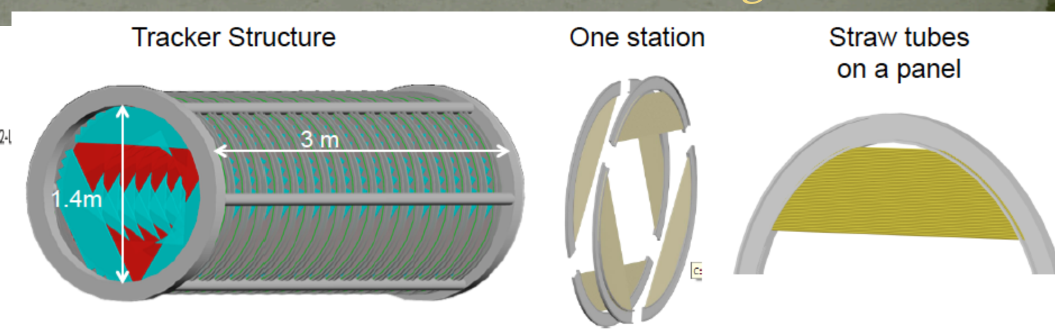
Z.You

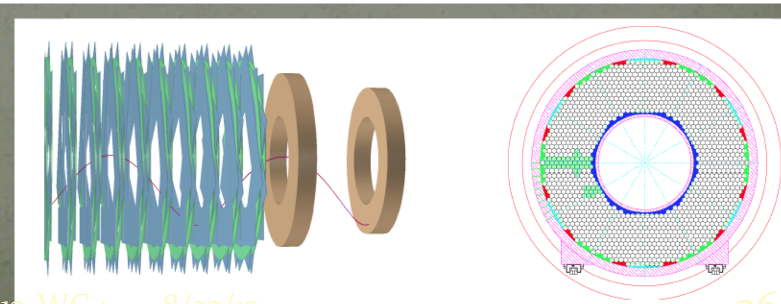


Advanced production solenoid designs

Updated tracking & New calorimeter designs







Charge symmetric calorimeter allows for improved track reconstruction and bkg rejection

Mu2e

Background & Sensitivity

Category	Source	Events	Error
Muon-Induced	μ decay in orbit	0.20	±0.06
	radiative π capture	0.04	±0.02
Prompt	Beam electrons	0.001	±0.001
	μ decay in flight	0.01	±0.005
Miscellaneous	Anti-proton induced	0.10	±0.05
	Cosmic ray induced	0.05	±0.013
Total		**0.4**	**0.1**

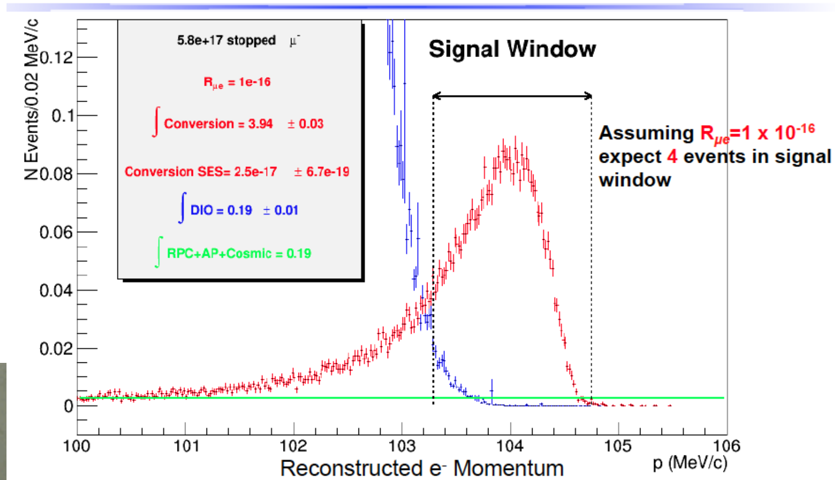
Preliminary Values

Z.You

Backgrounds for 3 years run

Single event sensitivity $R_{\mu e} = 2.5 \times 10^{-17}$

90% C.L. (if no signal) $R_{\mu e} < 6 \times 10^{-17}$



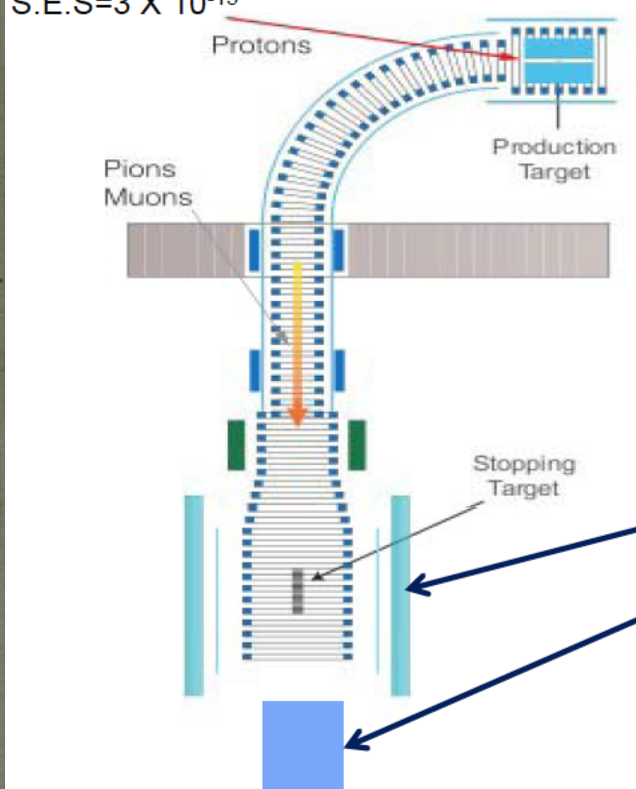
Full Geant4 simulation, background overlay and reconstruction

Improved background estimates and potential sensitivities

COMET

Starting in 2016
Measurement in 2017
S.E.S=3 X 10^{-15}

COMET(Phase-I)

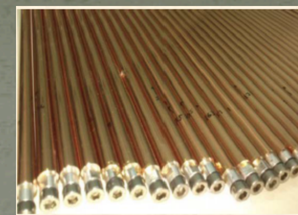


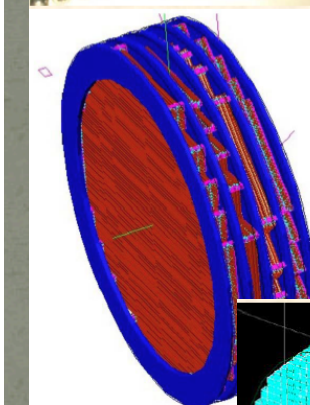
Pion Capture Section
Has a high(5T) magnetic field to collect the low momentum, backwards travelling pions

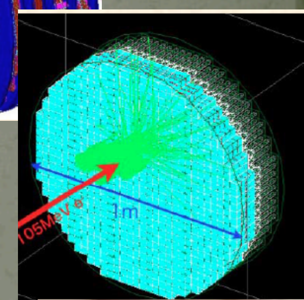
Phase-I Aims
Search for $\mu \to e$ conversion process with a S.E.S. of 3 X 10^{-15}
Study the backgrounds for Phase-II

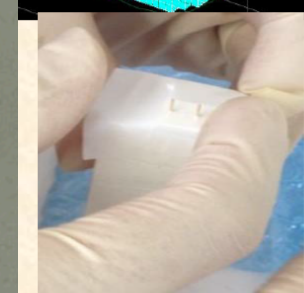
Phase-I Detector
A cylindrical drift chamber (CDC) for the $\mu \to e$ conversion search
A prototype ECAL and straw tube tracker for the background studies

Y.Yuan









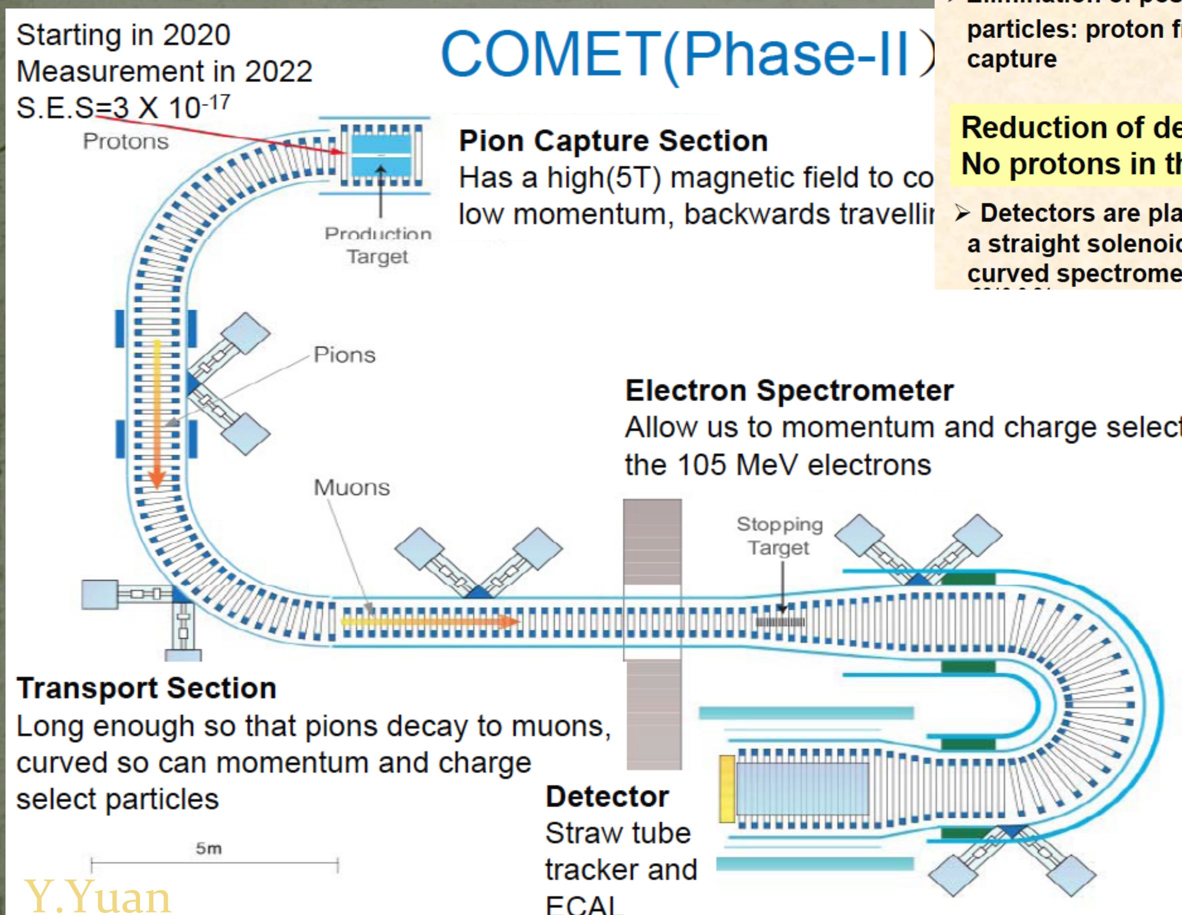
- Phase I is now under construction
- S.E.S ≈3x10^{-15}

- Measure real backgrounds
- Advanced work detector components (straws & calor)

Ye Yuan

COMET Phase II

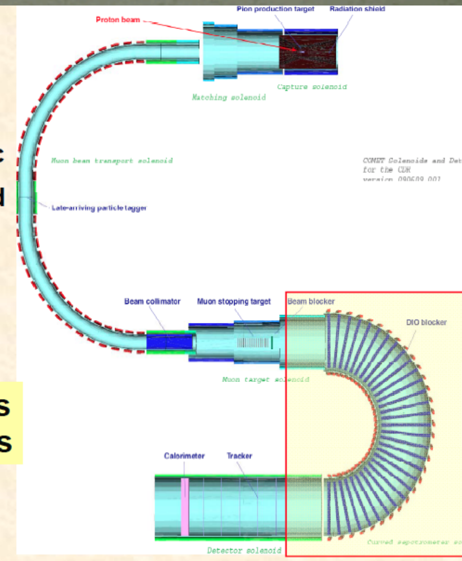
- Improves on stage one by two orders of magnitude
- S.E.S≈10^{-17}



- The electron transport:
  - bore: 700 mm
  - magnetic field: 1 T
  - bending angle: 180 degrees
- Electron momentum: 105 MeV/c
- Elimination of negative-charged particles less than 80 MeV/c
- Elimination of positive-charged particles: proton from muon capture

Reduction of detector rates
No protons in the detectors

- Detectors are placed in a straight solenoid after the curved spectrometer.

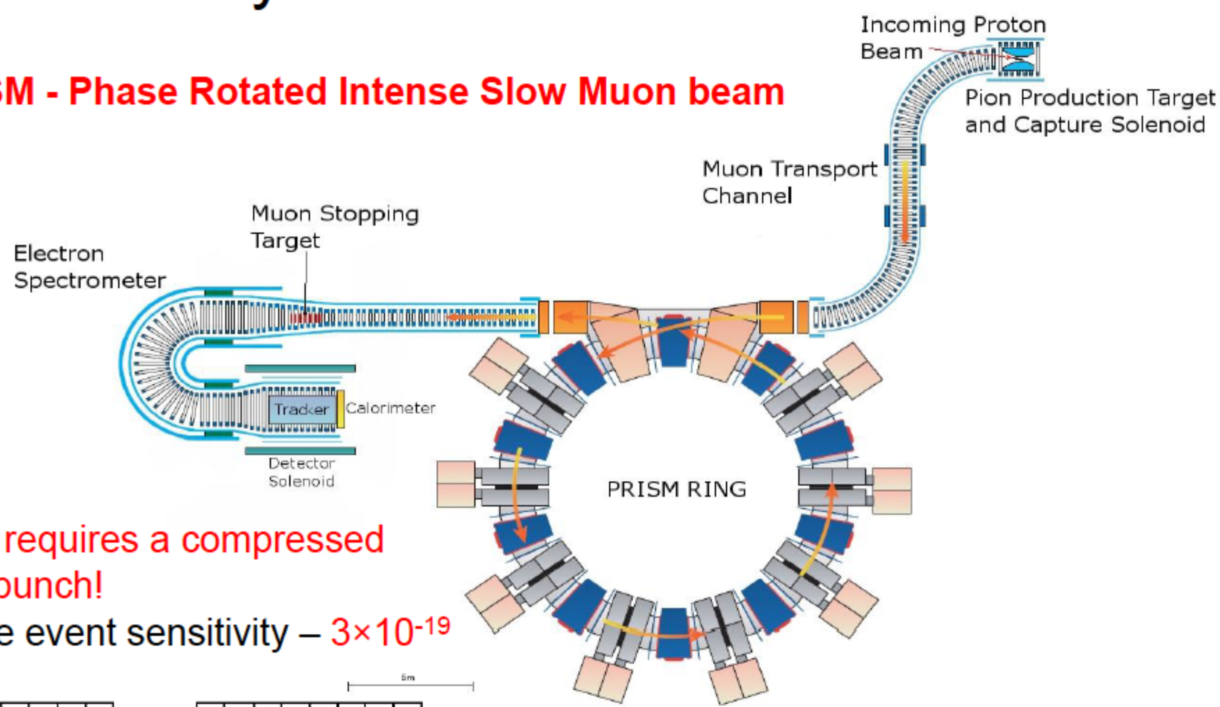


- Significantly reduces backgrounds compared to Phase I detector

Ye Yuan

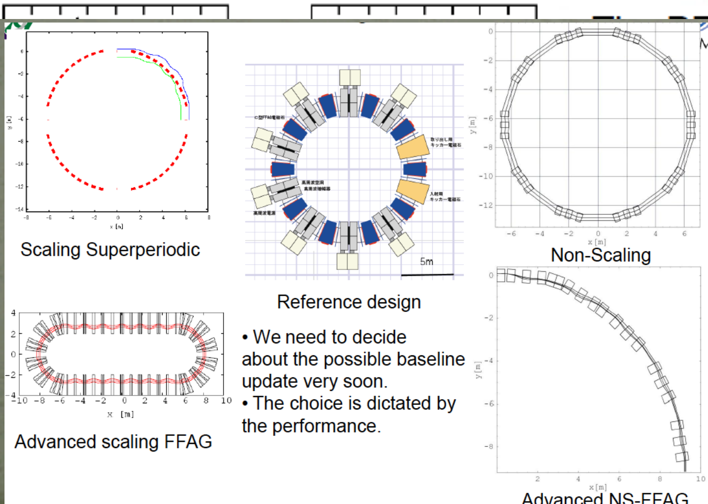
Prism/Prime

PRISM - Phase Rotated Intense Slow Muon beam



PRISM requires a compressed proton bunch!

Single event sensitivity – 3×10^{-19}

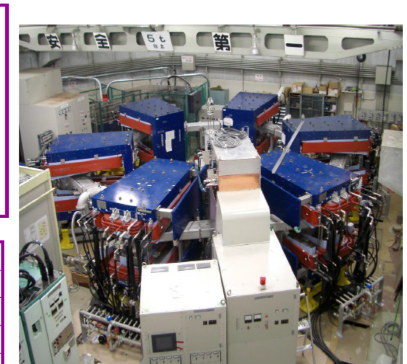


Demonstration Experiment at Osaka

PRISM

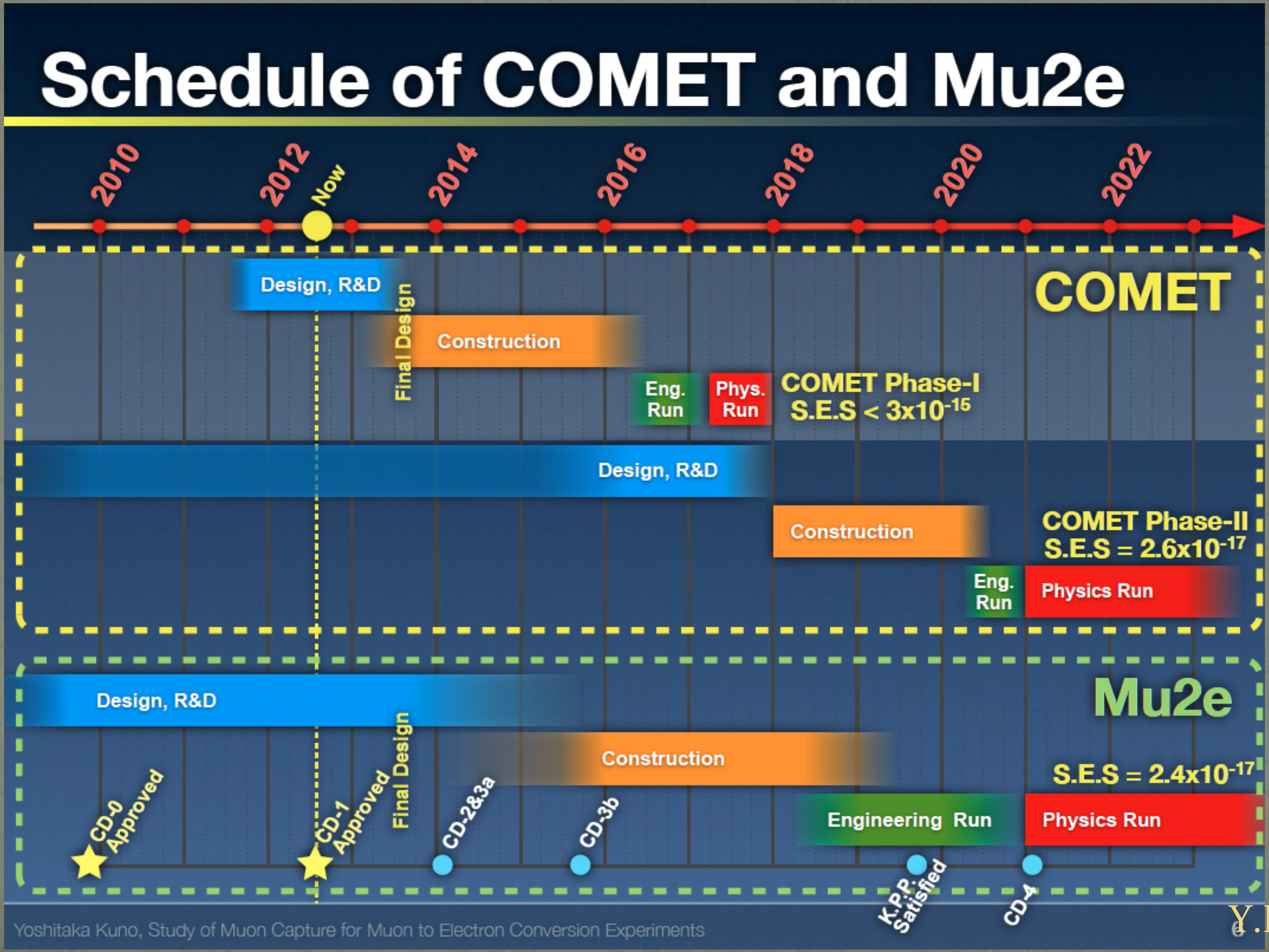
- Original design uses 10 cells. Demonstration experiment used 6 cells.
- Use ^{241}Am alpha source (200 MeV/c degraded to 100 MeV/c with Al foil).
- Can locate position and angle of source.
- Study closed orbits, dynamic aperture and tune.

	10-cell Ring	6-cell Ring
Particle	muon	alpha
Momentum (MeV/c)	68	100
Radius (m)	6.5	3.5
Number of cavities	8	1
Number of field clamps	20	2



J. Pasternak

Mu2e & COMET



Y.Kuno

AlCap

The AlCap Collaboration Joint force

- Osaka University
  - **Y. Kuno**, H. Sakamoto, T. Itahashi, Y. Hino, A. Sato. T. Yai, T.H. Nam
- Univ. College London
  - M. Wing, M. Lancaster, A. Edmonds
- Imperial College London
  - B. Krikler, A. Kurup, Y. Uchida

COMET

- Univ. Washington
  - **P. Kammel**, D. Hertzog, F. Wauters, M. Murray
- Boston University
  - J. Miller, E. Barnes, A. Kolarkar
- Univ. Massachusetts Amherst
  - D. Kawall, K. Kumar
- FermiLab
  - R. Bernstein, V. Rusu
- Pacific North National Laboratory
  - D. M. Asner, R. Bonicalzi, M. Schram, G.Warren, L. Wood

Mu2e

Y.Kuno

ALCap

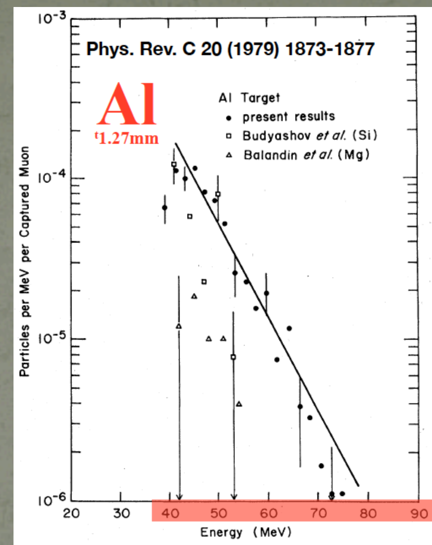
Three Work Packages

- WP1: Charged Particle Emission after Muon
  - Kammel (Washington) and Kuno (Osaka)
  - Rate and spectrum with precision 5% down
- WP2: Gamma and X-ray Emission after Muon
  - Lynn (PNNL) and Miller (Boston)
  - X-ray and gamma-ray for normalization (by muon decay (by a NaI detector)
- WP3: Neutron Emission after Muon Capture
  - Hungerford (Houston) and Winter (ANL)
  - rate and spectrum from 1 MeV up to 10 Me
  - BG for calorimeters and cosmic-ray veto, da

scheduled in Dec. 2013

in 2014

Yoshitaka Kuno, Study of Muon Capture for Muon to Electron Conversion Experiments 8



Measuring E spectrum down below current data (<40MeV)

Table 4.14 D.F Measday, Phys. Rep. 354 (2001) 243–409

Probabilities in units of 10^{-3} per muon capture for the reaction ${}^A_Z X(\mu, \nu p)^{A-1}_{Z-2}Y$ and for inclusive proton emission calculated by Lifshitz and Singer [343,348]. The experimental data are from Wyttenbach et al. [333], except when otherwise referenced. For $\Sigma(\mu, \nu p(xn))$ the experimental figures are lower limits, determined from the actually measured channels. The figures in crescent parentheses are estimates for the total inclusive rate derived from the measured exclusive channels by the use of the approximate regularity noted in Ref. [333], viz: $(\mu, \nu p):(\mu, \nu pn):(\mu, \nu p2n):(\mu, \nu p3n) = 1:6:4:4$

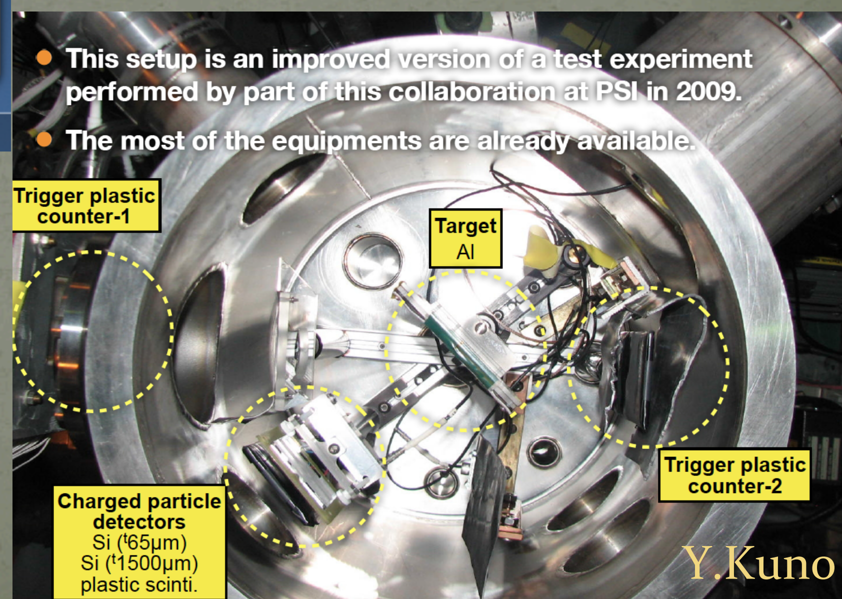
Capturing nucleus	$(\mu, \nu p)$ calculation	Experiment	$\Sigma(\mu, \nu p(xn))$ calculation	Experiment	Est.
${}^{27}_{13}$Al	9.7	(4.7)	40	> 28 ± 4	(70)
${}^{28}_{14}$Si	32	53 ± 10[a]	144[b]	150 ± 30[c]	
${}^{31}_{15}$P	6.7	(6.3)	35	> 61 ± 6	(91)
${}^{39}_{19}$K					
${}^{41}_{19}$K					
${}^{51}_{23}$V					
${}^{55}_{25}$Mn					
${}^{59}_{27}$Co					
${}^{60}_{28}$Ni					
${}^{63}_{29}$Cu					
${}^{65}_{29}$Cu					
${}^{75}_{33}$As					
${}^{79}_{35}$Br					
${}^{107}_{47}$Ag					
${}^{115}_{49}$In					
${}^{133}_{55}$Cs					
${}^{165}_{67}$Ho					
${}^{181}_{73}$Ta	0.15	0.26 ± 0.04	2.8	> 0.7 ± 0.1	(3.0)
^{208}Pb	0.14	0.13 ± 0.02	1.1	> 3.0 ± 0.8	(4.1)

no Ti data

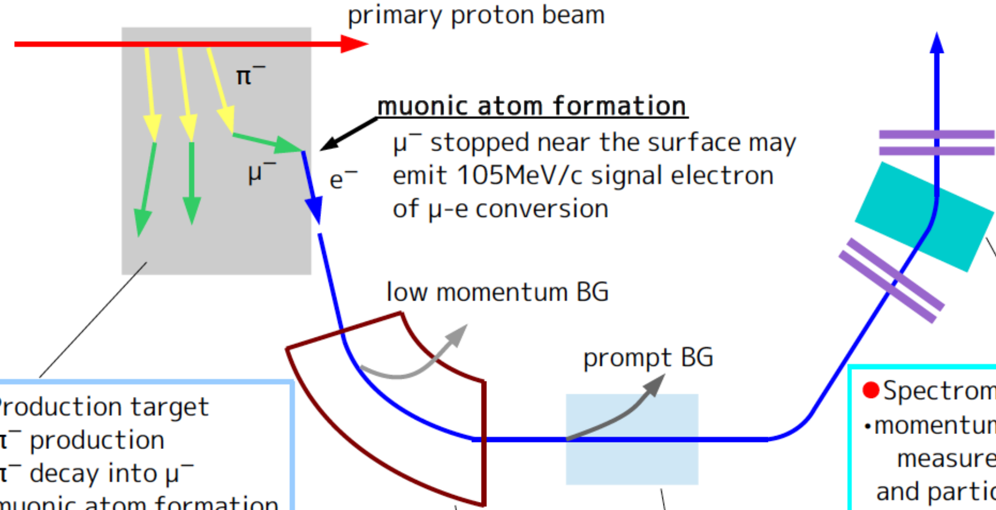
Activation experiment A. Wyttenbach, et al, Nucl. Phys. A294 (1978) 278-292

Reaction probabilities per captured muon [a])

Target A, Z	Product Reaction Factor / target purity (%)	A−1, Z−2 (μ^-, p) (10^{-4})	A−2, Z−2 (μ^-, pn) (10^{-3})	A−3, Z−2 $(\mu^-, p2n)$ (10^{-3})	A−4, Z−2 $(\mu^-, p3n)$ (10^{-3})	A−4, Z−3 (μ^-, α) (10^{-3})
${}^{23}_{11}$Na	> 99.5					11 ±1.5 (3)
${}^{27}_{13}$Al	99.99	no data	28 ±4 (2)	no data	no data	7.6 ±1.1 (2)
${}^{31}_{15}$P	99.5		38 ±5 (2)	23 ±3 (2)		13 ±2 (2)



DeeMee

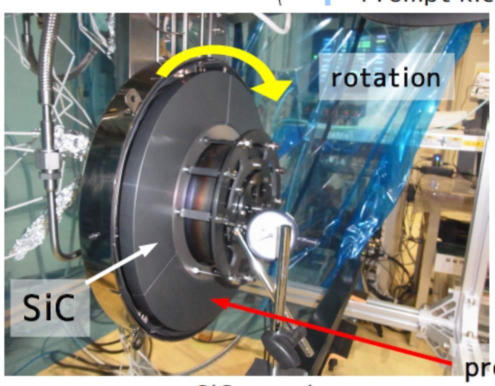


- Production target
  - π^- production
  - π^- decay into μ^-
  - muonic atom formation inside the production target

- Spectrometer
  - momentum measurement and particle ID
  - measure delayed electrons

- Prompt kicke

- Beamlin
  Low mom
  → sup



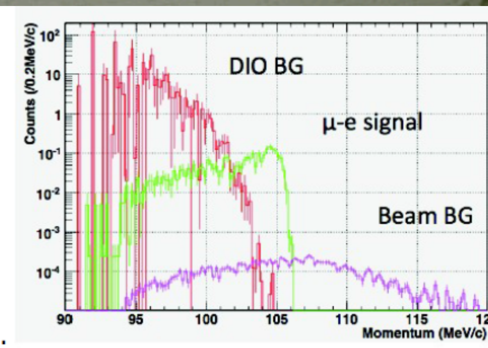
prototype SiC rotating target

- **Signal Sensitivity**
  S.E.S (single event sensitivity) = **2 x 10^{-14}**
  (1MW proton beam, 2x10^{7}sec)

- **Backgrounds**

- After proton rate (R_{AP}) < 9 x10^{-19}
- Detector live-time duty = 1/20000
  → Cosmic ray backgrounds are suppressed.
- No anti-protons

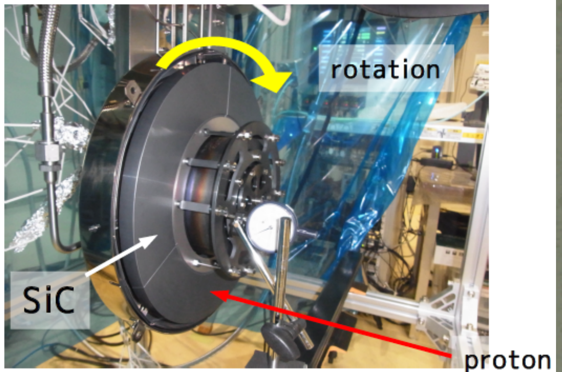
Decay in Oribit	0.09
After proton	< 0.027 (0.05 90% C.L.)
Cosmic induced e	< 0.018 (MC stat. limited)
Cosmic induced μ	< 0.001
Radiative muon capture	< 0.0009



Y.Nakatsugawa

DeeMee

- Experimental search for μ-e conversion in nuclear field is planned at J-PARC/MLF/MUSE (DeeMe) .
  - single event sensitivity = 2×10^{-14}
- DeeMe already has Stage-1 approval from KEK/IMSS/MUSE PAC.
- Beamline is under construction.
  - J-PARC/MLF/MUSE H-Line
  - beamline design
  - Magnets at entrance port has been installed.
- Production target R&D is ongoing.
  - rotating SiC target
- Preparations of detectors at spectrometer are in progress.
  - MWPC
    final design, prototype beam test
- Updated Monte Carlo simulation study is under way.
- Physics data taking is planned to start from 2015.



prototype SiC rotating target

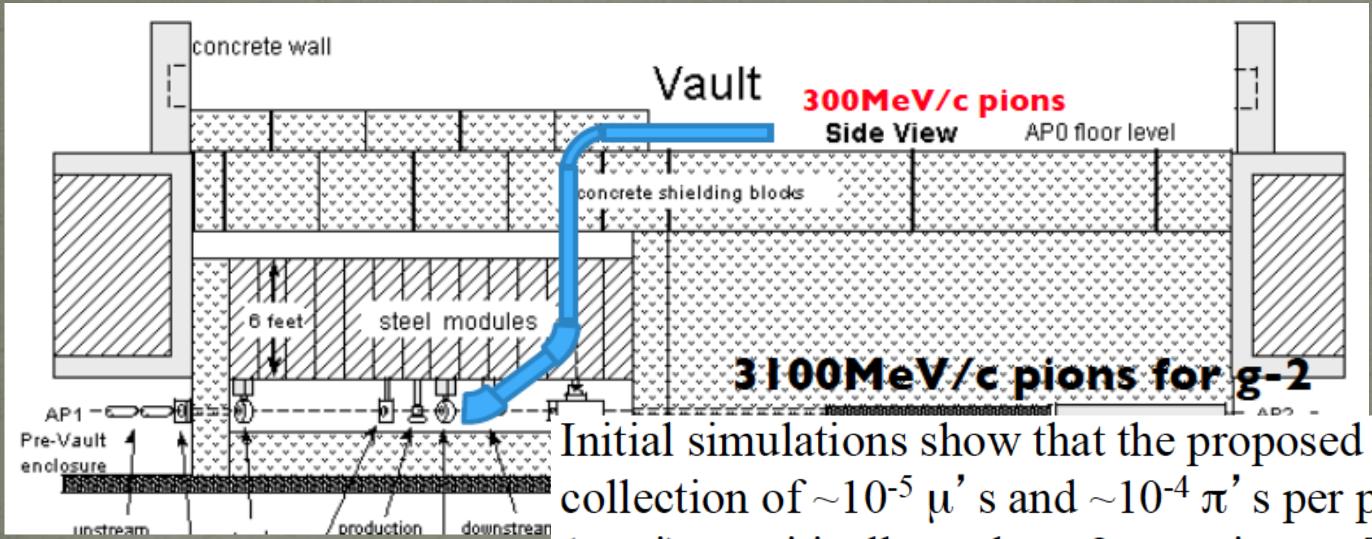

PACMAN @ TRIUMF

Well under way for 2015 data taking

Y.Nakatsugawa

Beam Ideas (using g-2 @ FNAL)

- Extract low energy π's and μ's from AP0 target without degradation of the π fluxed used by g-2
- Beam produces μ's with momentum up to ~300 MeV/c
- Allows for parasitic running of μ cooling experiments and materials science experiments



Initial simulations show that the proposed scheme allows collection of $\sim 10^{-5}$ μ' s and $\sim 10^{-4}$ π' s per proton running (semi)parasitically to the g-2 experiment. The g-2 beam will have $\sim 10^{13}$ protons per second on target, so the Muon Laboratory in the AP0 Hall would have $\sim 10^{8}$ μ 's per second with momentum centered at 300 MeV/c. This beam can be used for Muon Cooling experiments.

M. Popovic

Questions moving forward for 2014

- Three "Big" questions we want to address:
  - Expt: What is the ultimate $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ reach once $\mu N \rightarrow eN$ has set the limit.
    - What are the roles of the ratios of cLFV processes and other precision experiments at this point?
  - Beams: What are the beam specifications for muon physics? (our requirements)
    - Are these compatible with the NuFact?
    - Are there other options?
  - Theory: What else besides cLFV? EDMs?
    - What does theory tell us once we observe cLFV?
    - How do we relate our results to the models?