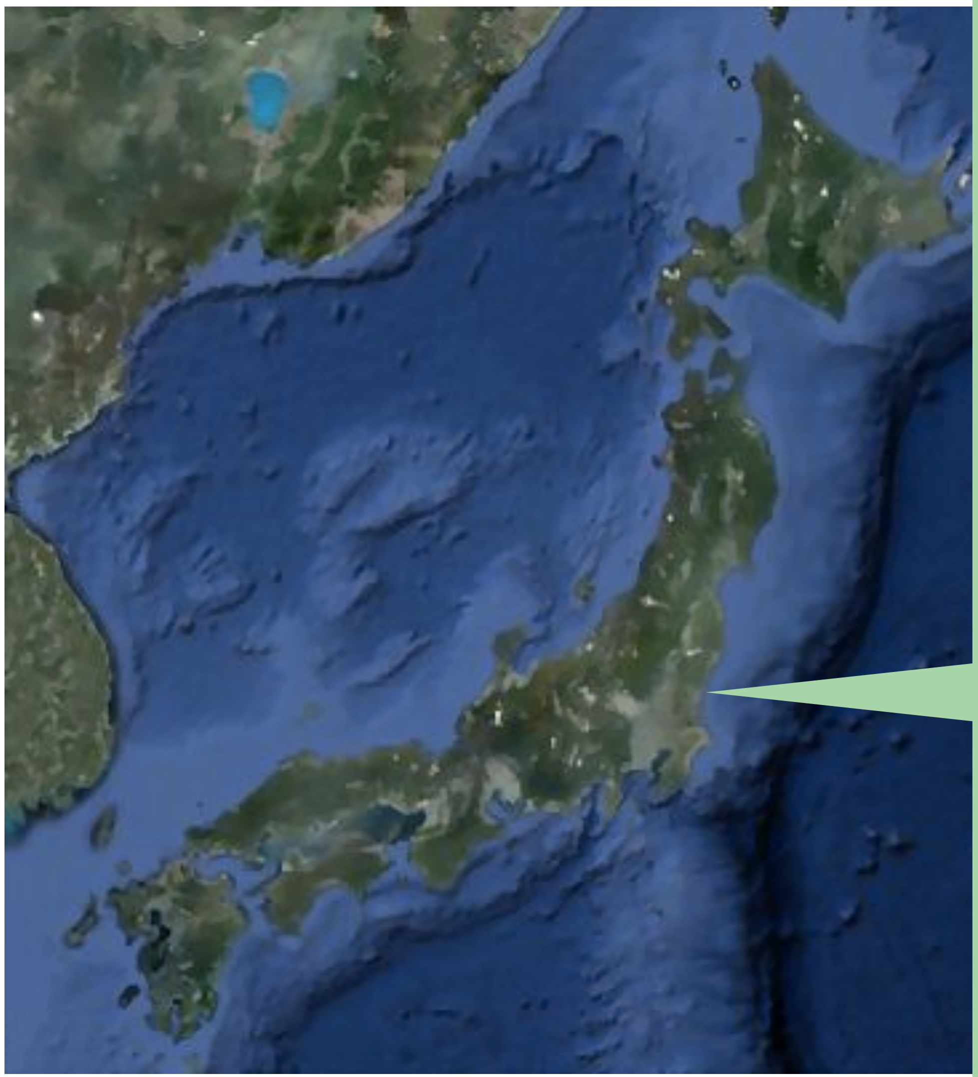
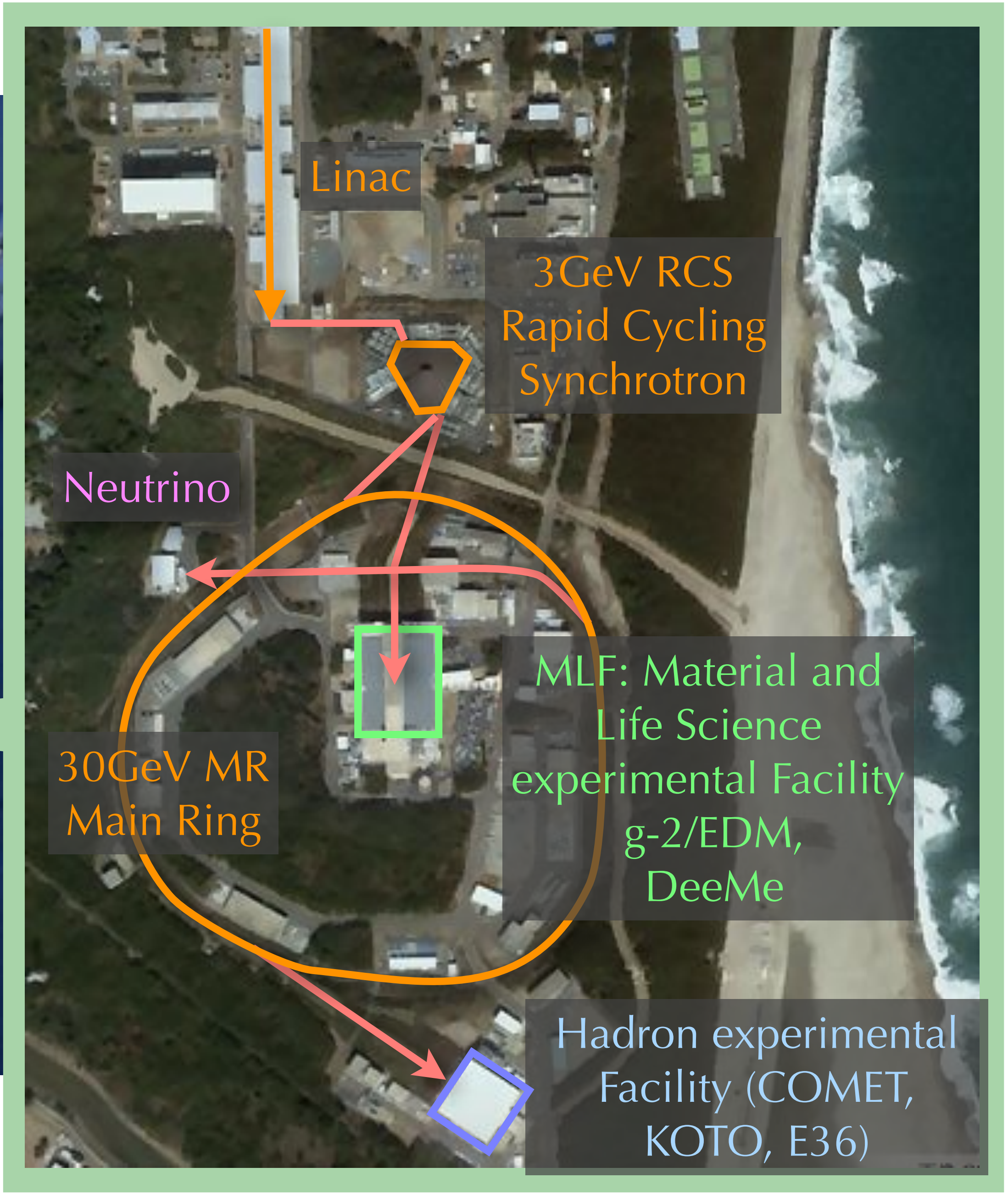
Kaon and Muon Physics at J-PARC

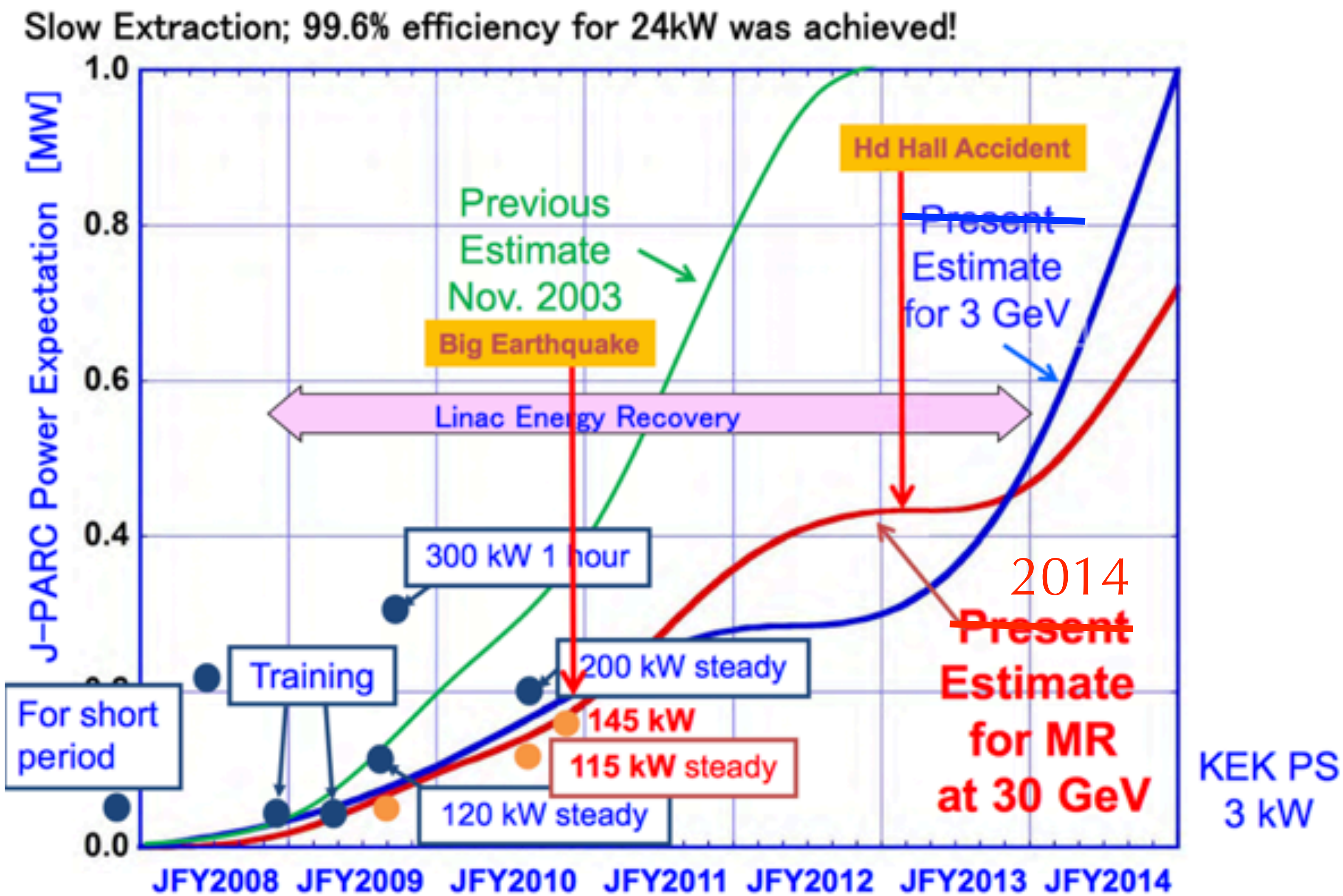
Hiroaki Natori, KEK

Experimental site



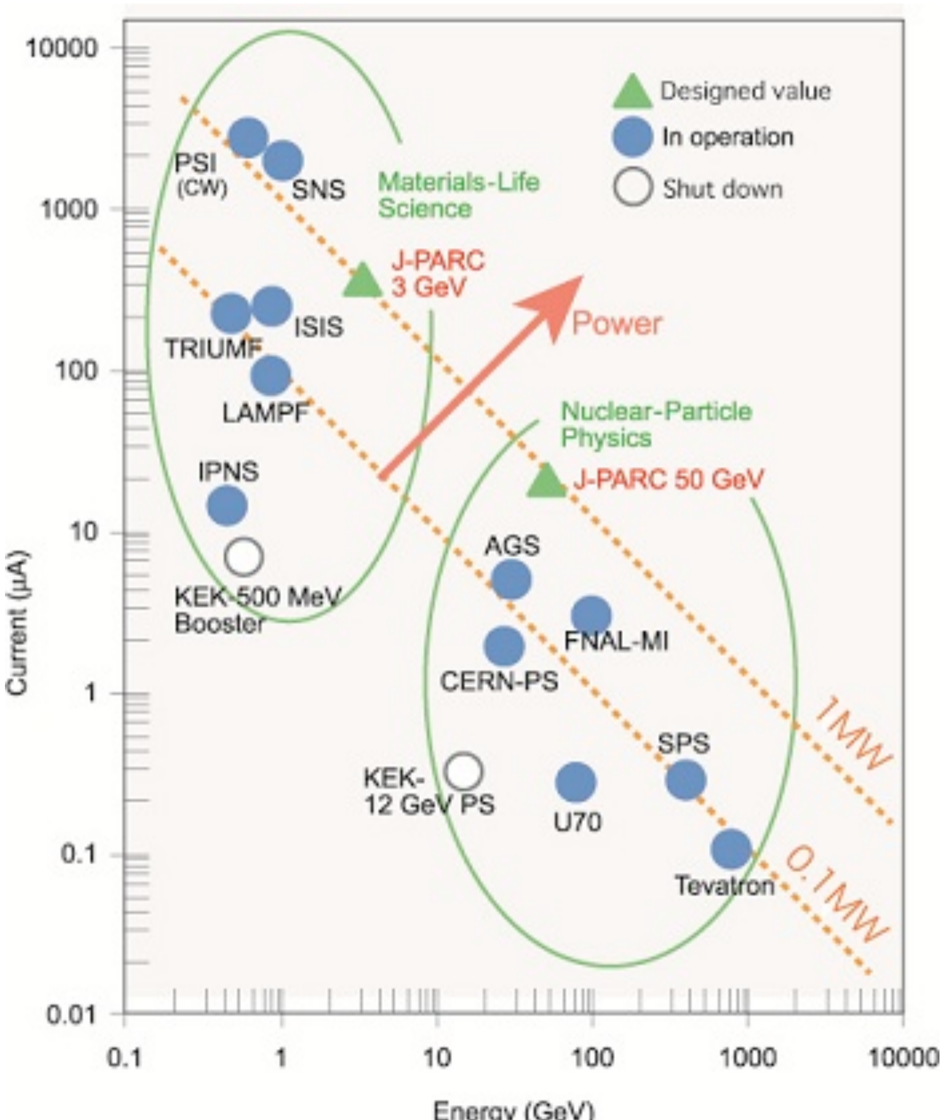


Power Capability of J-PARC



Slide from ISPUN14 by K. Tanaka

Intensity frontier in J-PARC



One of the most powerful beam

- RCS: 3GeV, designed to be 1MW
    - 3GeV 1MW acceleration test succeeded (Feb./2015). 500kW beam delivery in MLF (April/2015).
- Main Ring: 50GeV, designed to be 0.75MW
    - Hadron hall restarted April/2015

      33kW slow extraction
    - 360kW May/2015 fast extraction for neutrino

Suitable experimental site for intensity frontier

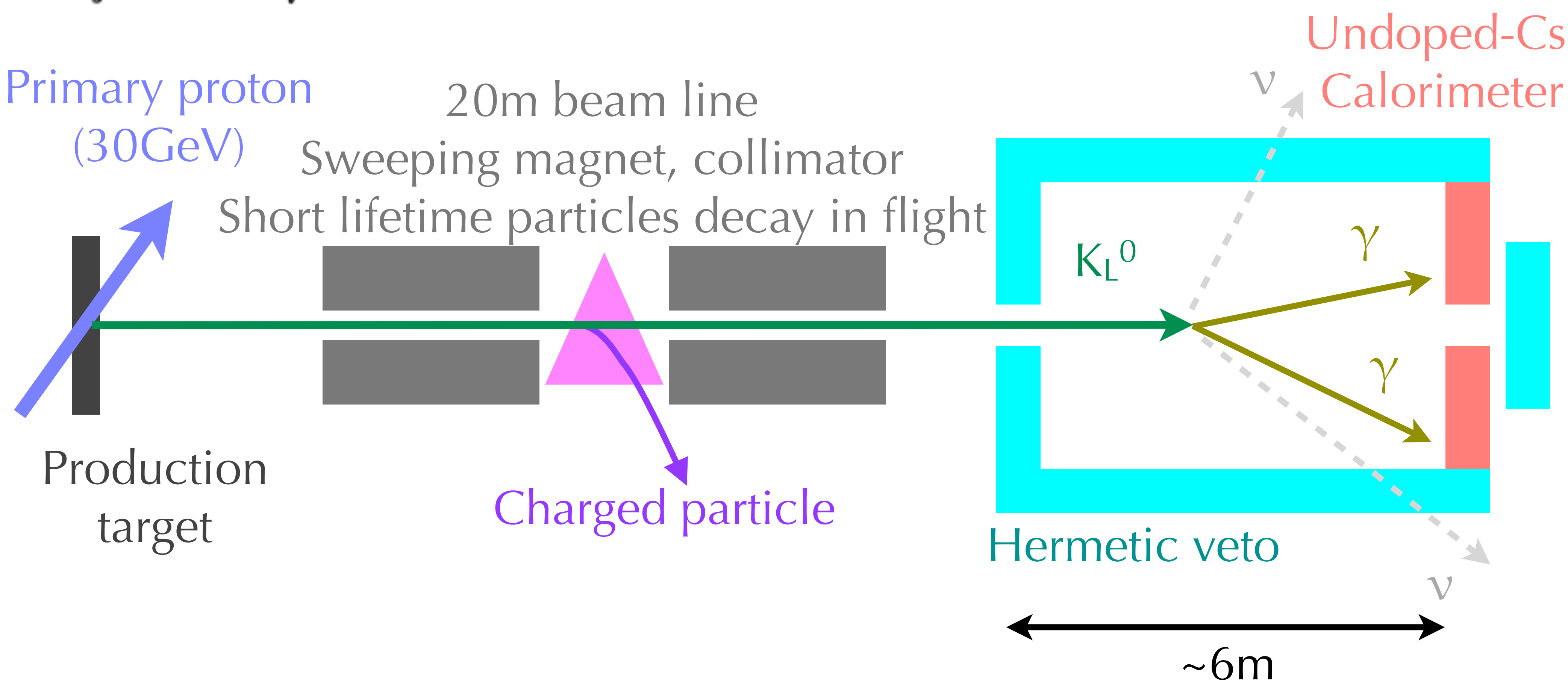
Available secondary particles

- $K^{\pm}$, K_L^0, $\pi^{\pm}$, $\mu^{\pm}$, n, ν have low mass and long life time
    - Easy to generate a lot
        - High intensity secondary beam available
    - Transportation by secondary beam line
        - Various experimental setup, in flight or stopped etc.
        - Reduction of unwanted particle: lower backgrounds

- Important probe of high precision measurement

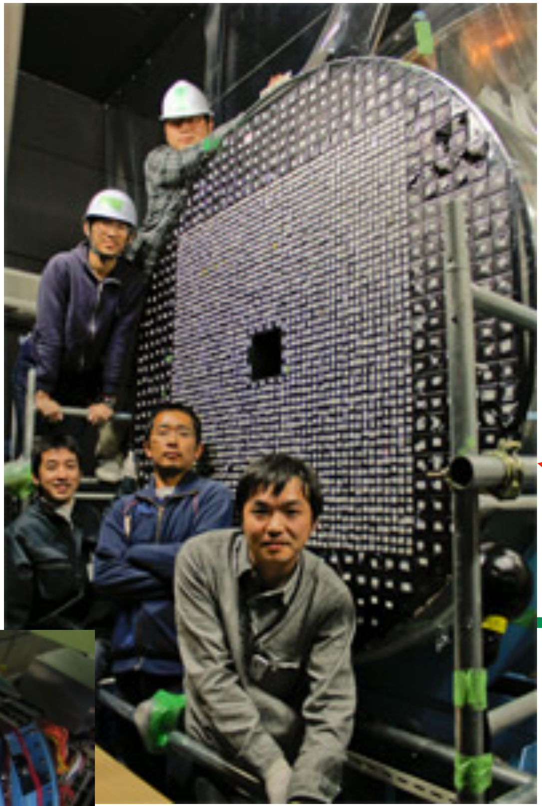
KOTO (K0 at TOkai)

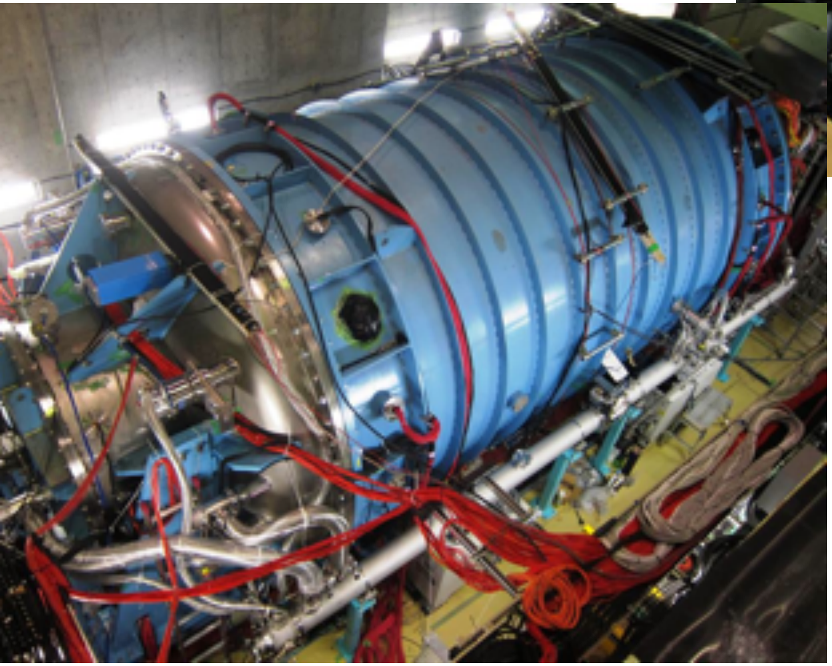
Rare decay, $K_L^0 \to \pi^0 \nu\nu$ search experiment



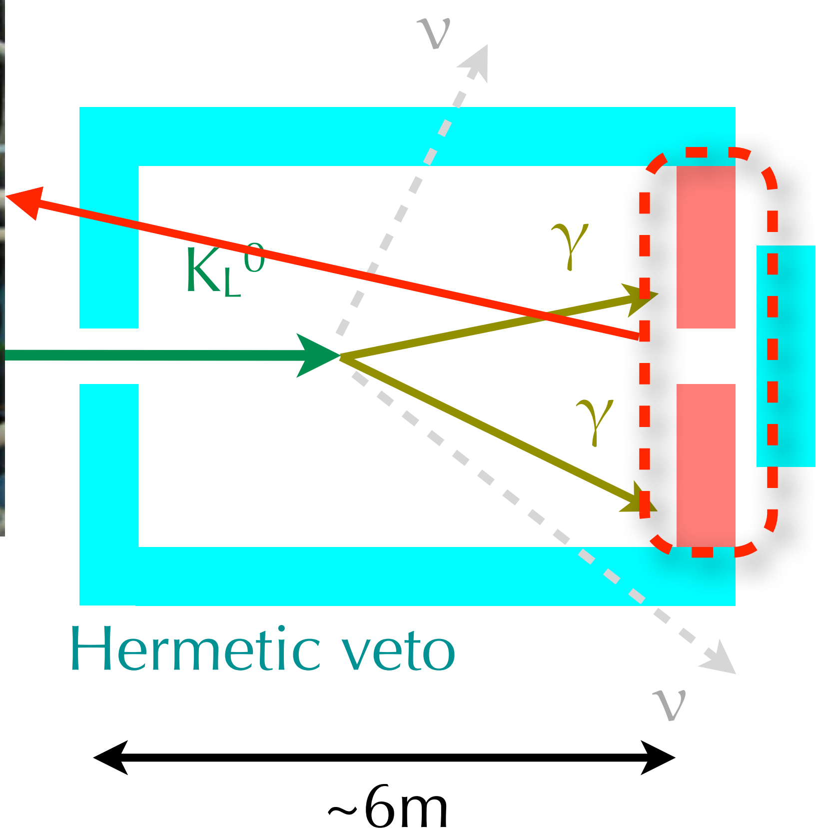
Signal: 2γ + Nothing

KOTO (K0 at TOkai)



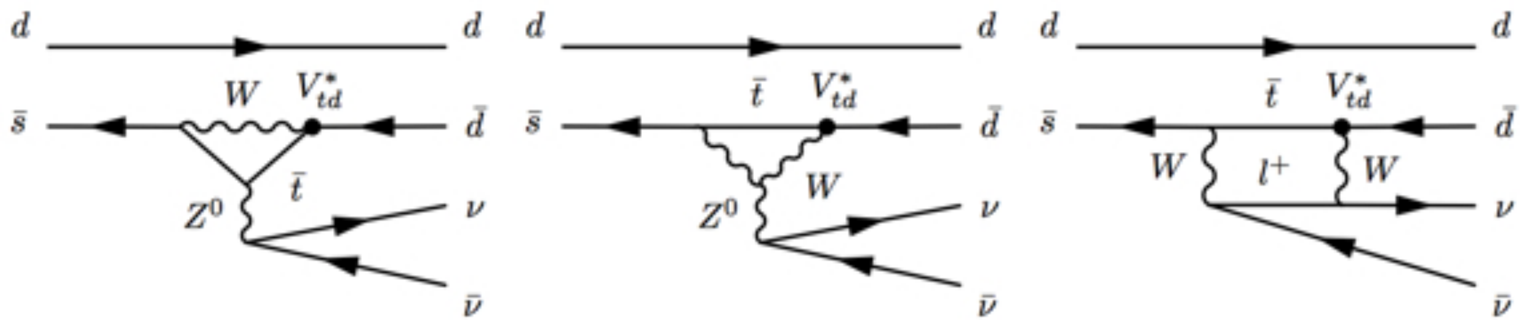


Undoped-CsI Calorimeter



Most of the detectors in this vacuum tank

KOTO (K0 at TOkai)



- Rare kaon decay $K_L^0 \rightarrow \pi^0 \nu\nu$: Flavor changing neutral current process, CP violating
  - $Br(K_L^0 \rightarrow \pi^0 \nu\nu) = 3.00 \pm 0.30 \times 10^{-11}$ (Standard Model, A.J. Buras, *et al*, arXiv:1503.02693)
  - Br $< 2.6 \times 10^{-8}$ (Current experimental limit by E391a)
  - Br $< 1.5 \times 10^{-9}$ (Indirect limit from $K^+ \rightarrow \pi^+ \nu\nu$)
- 5-day run in May/2013, Resumed to take data from April/2015 aiming sensitivity of 10^{-11}, (then O(100) measurement with KOTO-II)

If they find $K_L^0 \rightarrow \pi^0 \nu\nu$ above SM prediction → New Physics!!

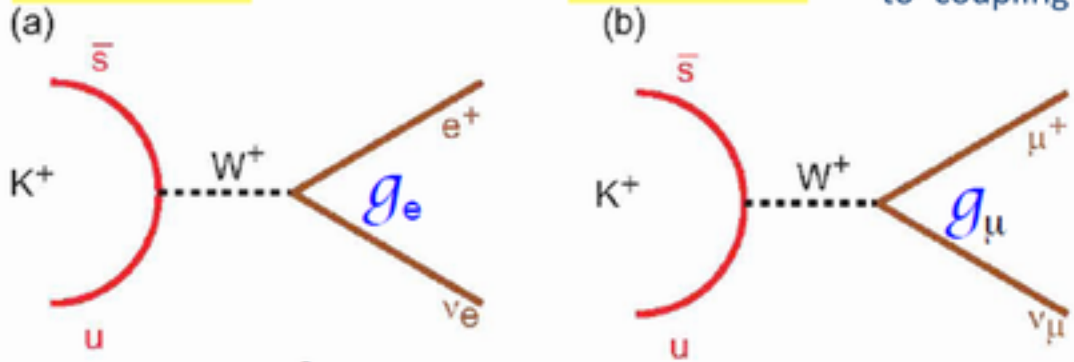
E36: Lepton flavor universality

Do electron and muon have exactly the same properties in the weak interaction world?

If it is true, μ/e universality is realized.

$K \rightarrow e\nu$ $K \rightarrow \mu\nu$

K_{l2} decay width is proportional to coupling constant, g_l.

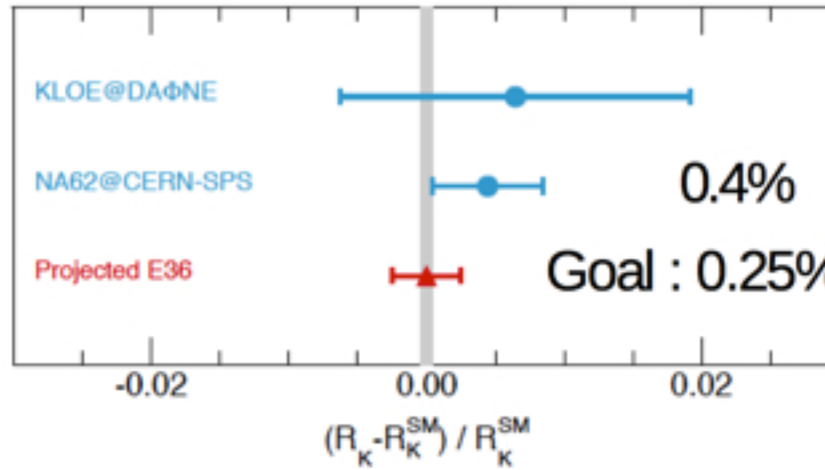


Kl2 decay width: $\Gamma(K_{l2}) = g_l^2\,(G^2/8\pi)\,f_K^2 m_K m_l^2\,\{1-(m_l^2/m_K^2)\}^2$

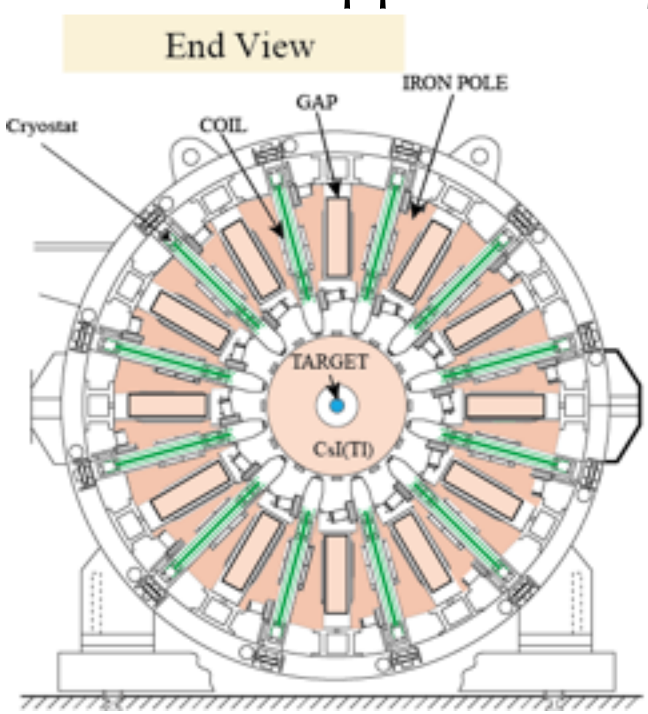
We aim at testing the μ/e universality in the K^+ system by precisely checking whether g_e=g_μ

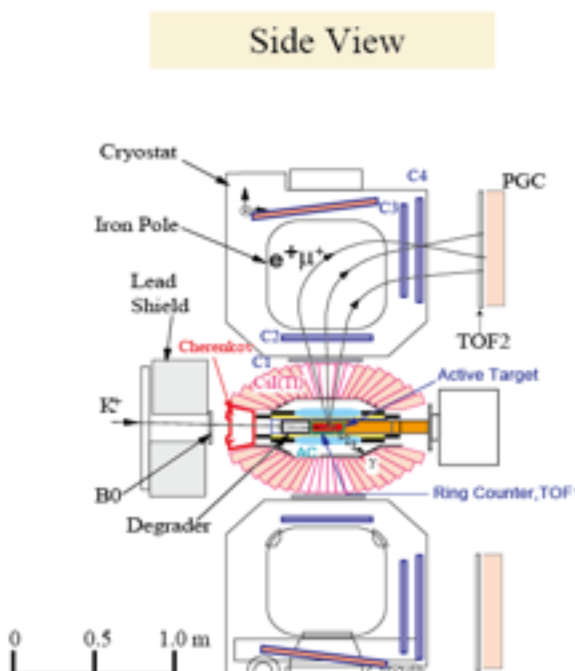
E36: Lepton flavor universality

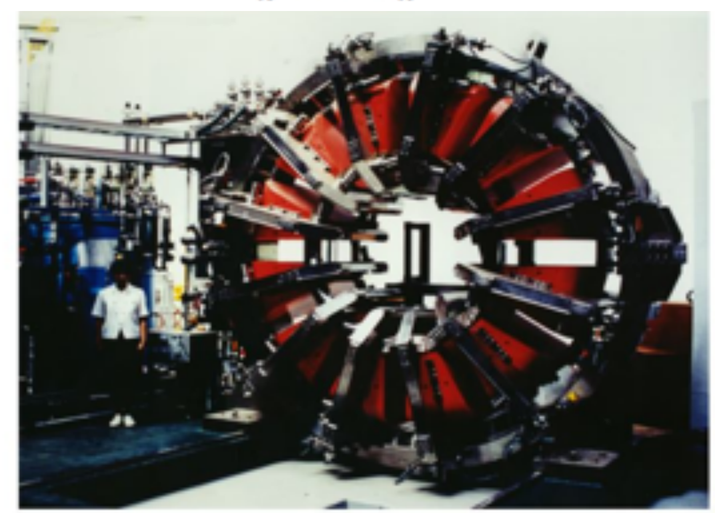
- $R_{K(SM)} = \Gamma(K^+ \rightarrow e^+\nu_e) / \Gamma(K^+ \rightarrow \mu^+\nu_\mu) = 2.477(1)\times10^{-5}$
- E36 accuracy: $(R_K - R_{K(SM)})/R_K = 2.5\times10^{-3}$
- $O(10^{-3})$ deviation from SM in some new physics model



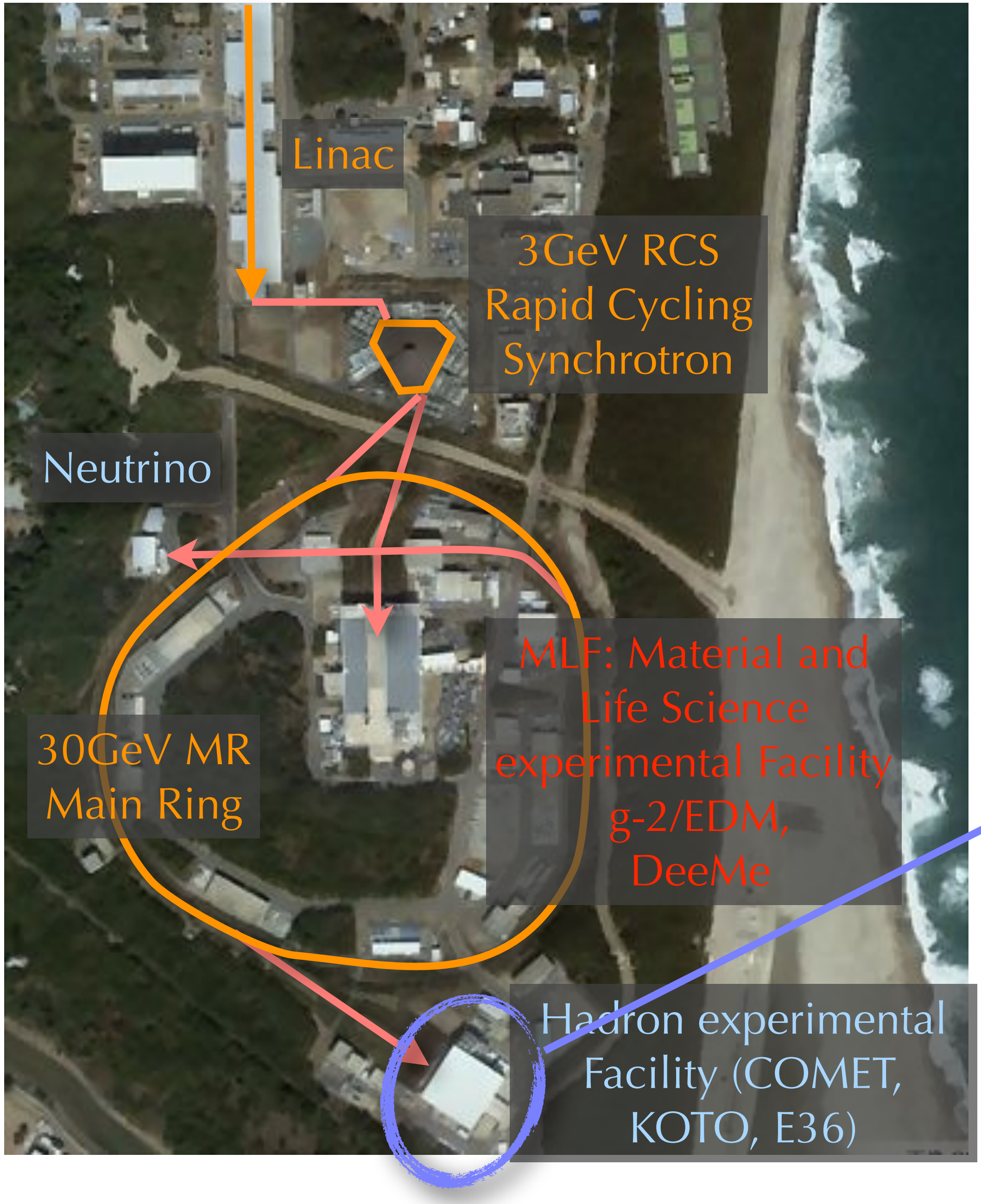
Difference from former experiments:
Stopped K^+ experiment

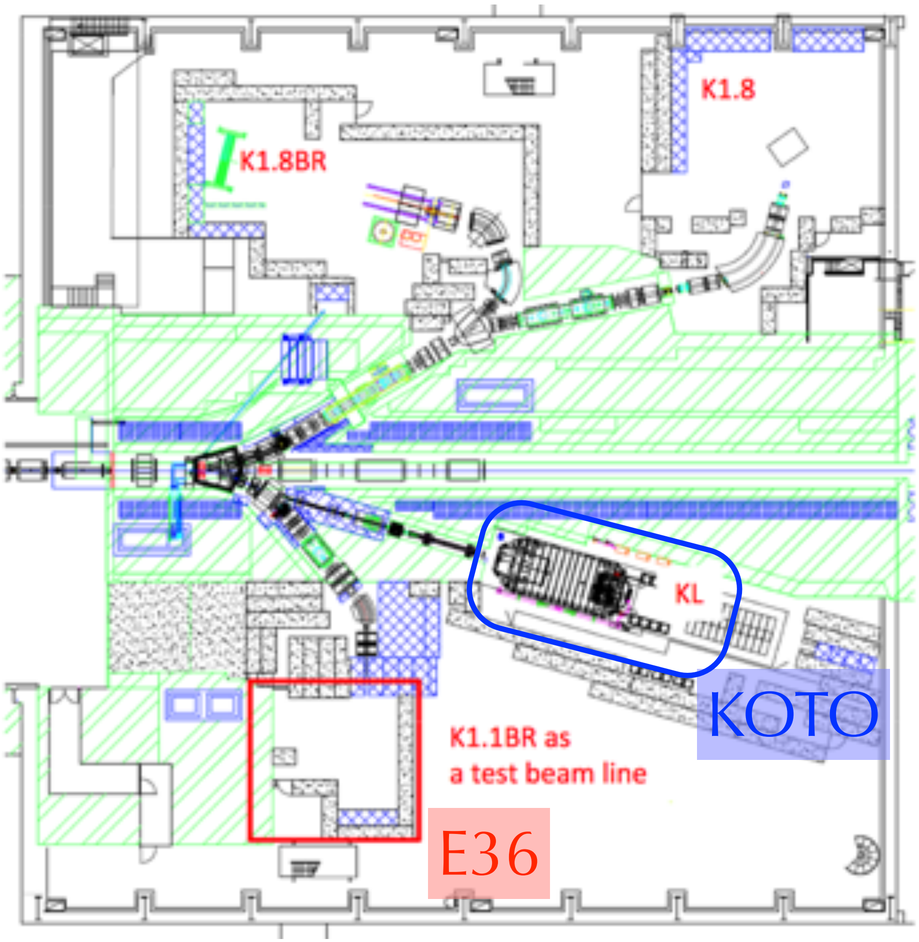




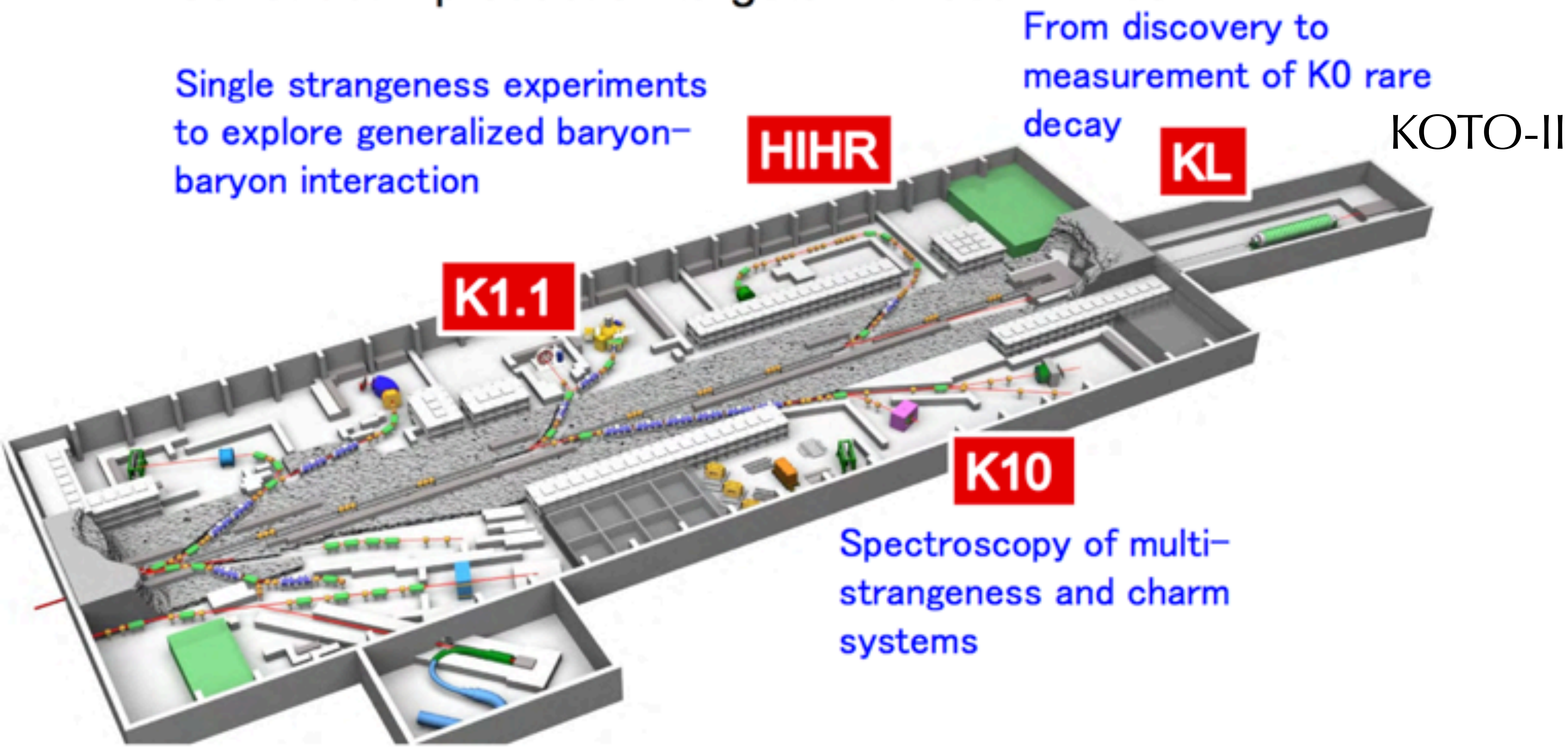


Physics data taking


Linac
3GeV RCS
Rapid Cycling
Synchrotron
Neutrino
30GeV MR
Main Ring
MLF: Material and
Life Science
experimental Facility
g-2/EDM,
DeeMe
Hadron experimental
Facility (COMET,
KOTO, E36)


K1.8
K1.8BR
KL
KOTO
K1.1BR as
a test beam line
E36

- Extend the Hadron Hall for ~105m.
- Construct 2 production targets with beam lines.



Slide from ISPUN14 by K. Tanaka

Kaon summary

- Kaon rare decay, lepton universality: A good probe for beyond the SM
- Two kaon programs in J-PARC are running
    - J-PARC KOTO ($K_L^0 \rightarrow \pi^0 \nu\nu$)
    - J-PARC E36 (Lepton flavor universality in K12 decays, $\Gamma(K^+ \rightarrow e^+ \nu_e) / \Gamma(K^+ \rightarrow \mu^+ \nu_\mu)$)
- Look forward to see good results in near future!

Muon g-2

Anomalous magnetic moment (g-2)

a_μ = (g-2)/2 = 0.00116592089(63) (BNL E821 ~2001) 0.5ppm

= 0.00116591828(49) (Standard Model)

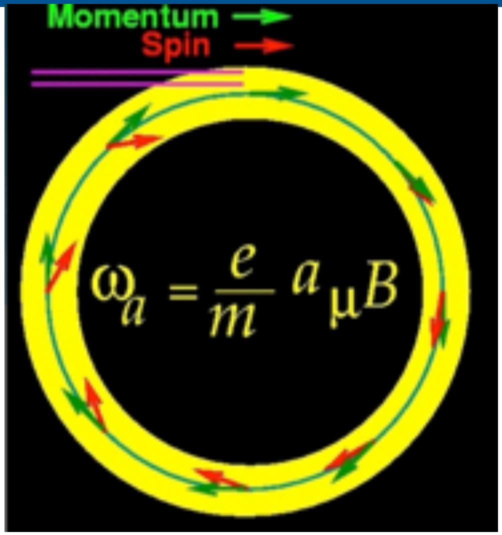
Δa_μ = Exp - SM = 26.1 (8.0) × 10^{-10} 3.3σ deviation

We may have already see the sign of new physics beyond the SM.

But only a single experimental data ...

→ Verifications with better sensitivity are planned

g-2 measurement



Muon spin rotates in uniform B due to g-2≠0

Spin precession vector

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

γ=30
(P=3GeV/c)

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

BNL E821 (0.5ppm)
FNAL E989 (0.1ppm)

E = 0 at
any γ

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

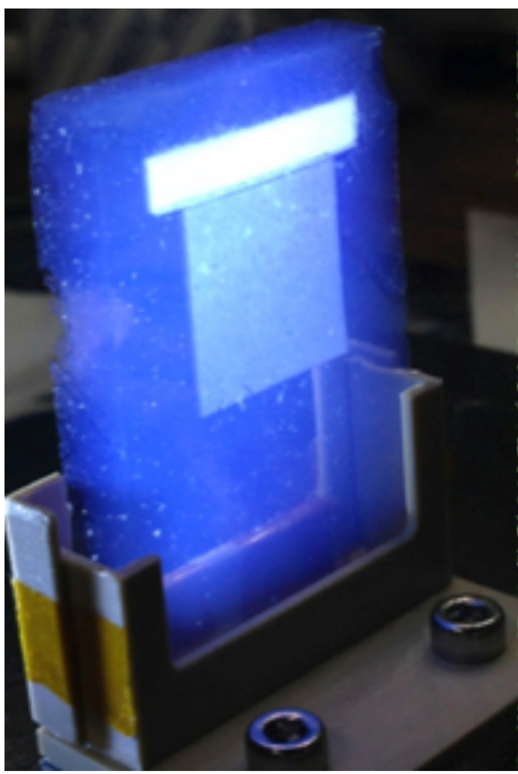
J-PARC E34 (0.1ppm)

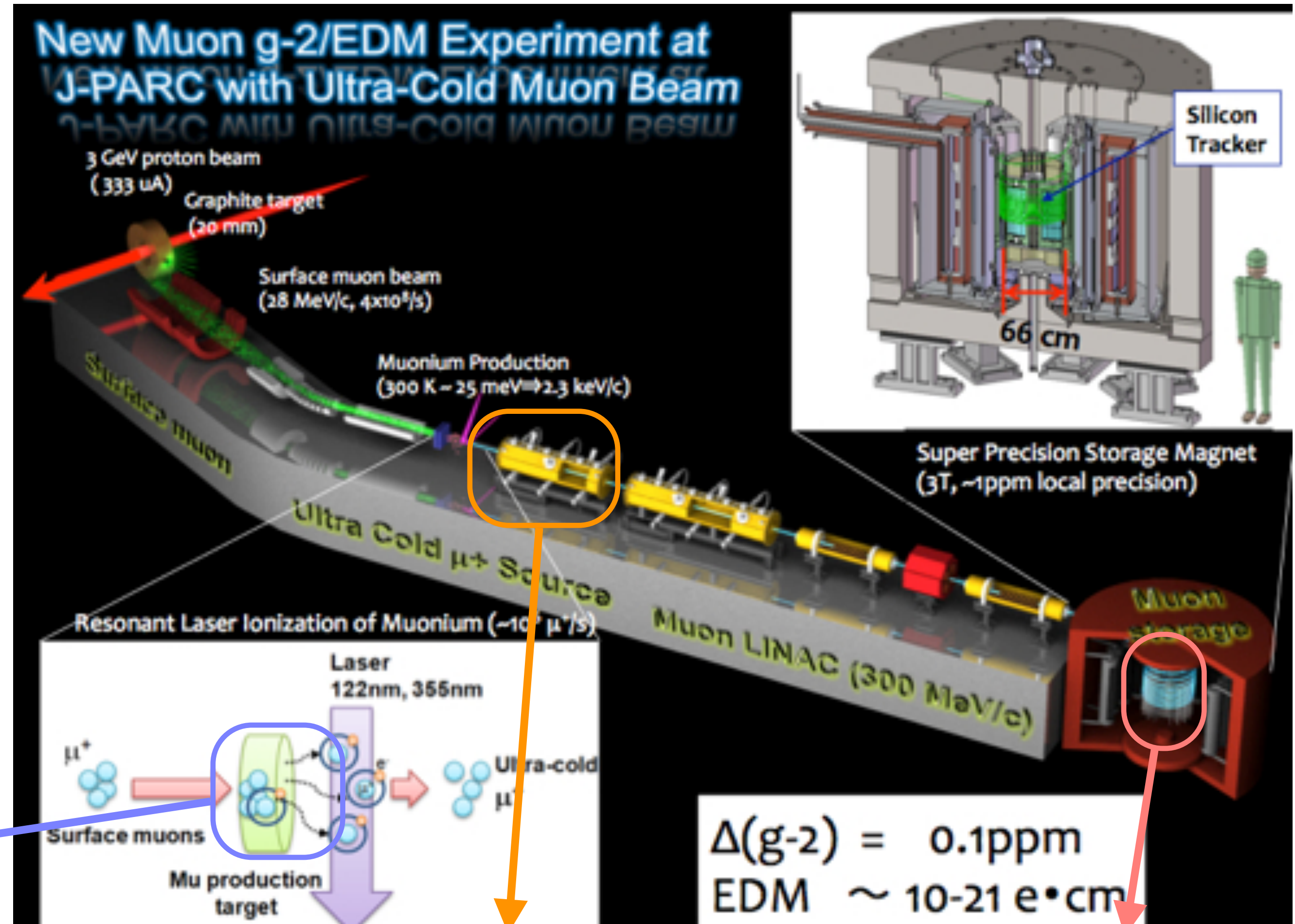
Completely different systematics than BNL E821 or FNAL989

Some of g-2 R&D status

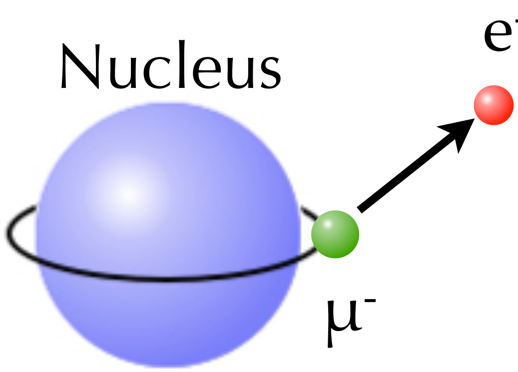
Enhancement of muonium emission by silica aerogel with micro-pattern surface

Prog. Theor. Exp. Phys. (2014) 091C01

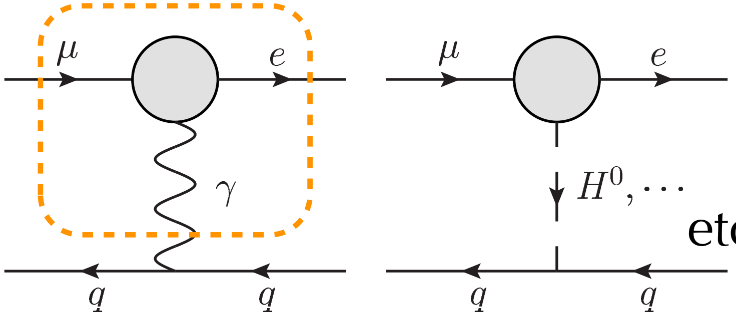




μ-e conversion $\mu^- + (A, Z) \to e^- + (A, Z)$



Common diagram with $\mu^+ \to e^+\gamma$ (Br<5.7x10^{-13})

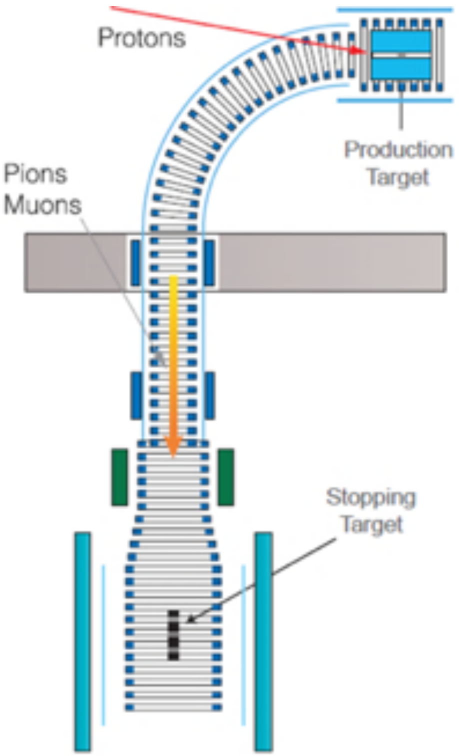


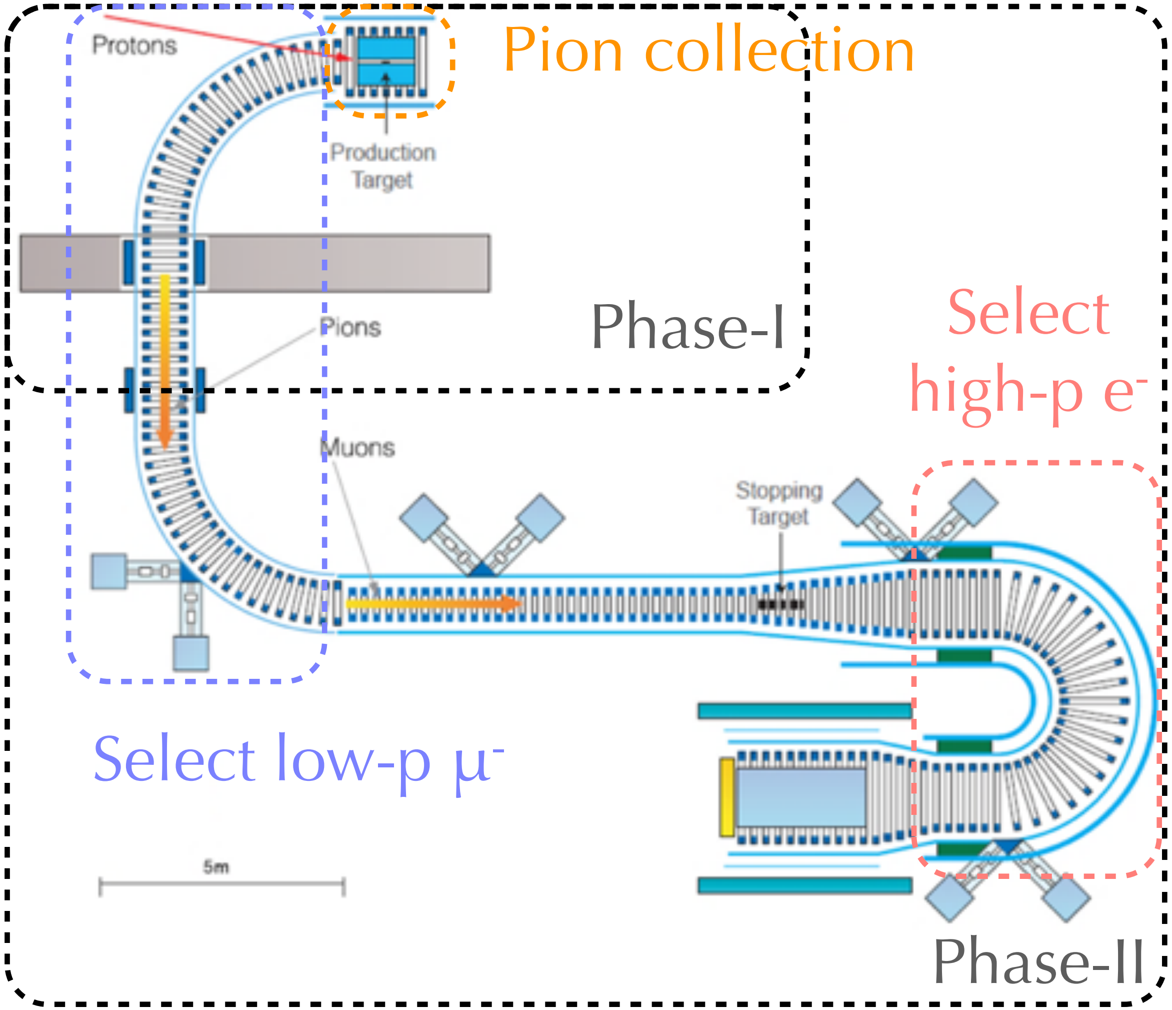
etc.

- If found, ~10^{40} × (SM +ν oscillation prediction)
  - Clear evidence of the new physics
- Recent upper limits
  - SINDRUM-II @PSI: Br(μ-e conv. w/ Au) < 7 × 10^{-13}

    Br(μ-e conv. w/ Ti) < 4.3 × 10^{-12}
  - TRIUMF: Br(μ-e conv. w/ Ti) < 4.6 ×10^{-12}
- Br(μ→eγ) / Br(μ-e conv.) would give information what mediates them: comprehensive

COMET

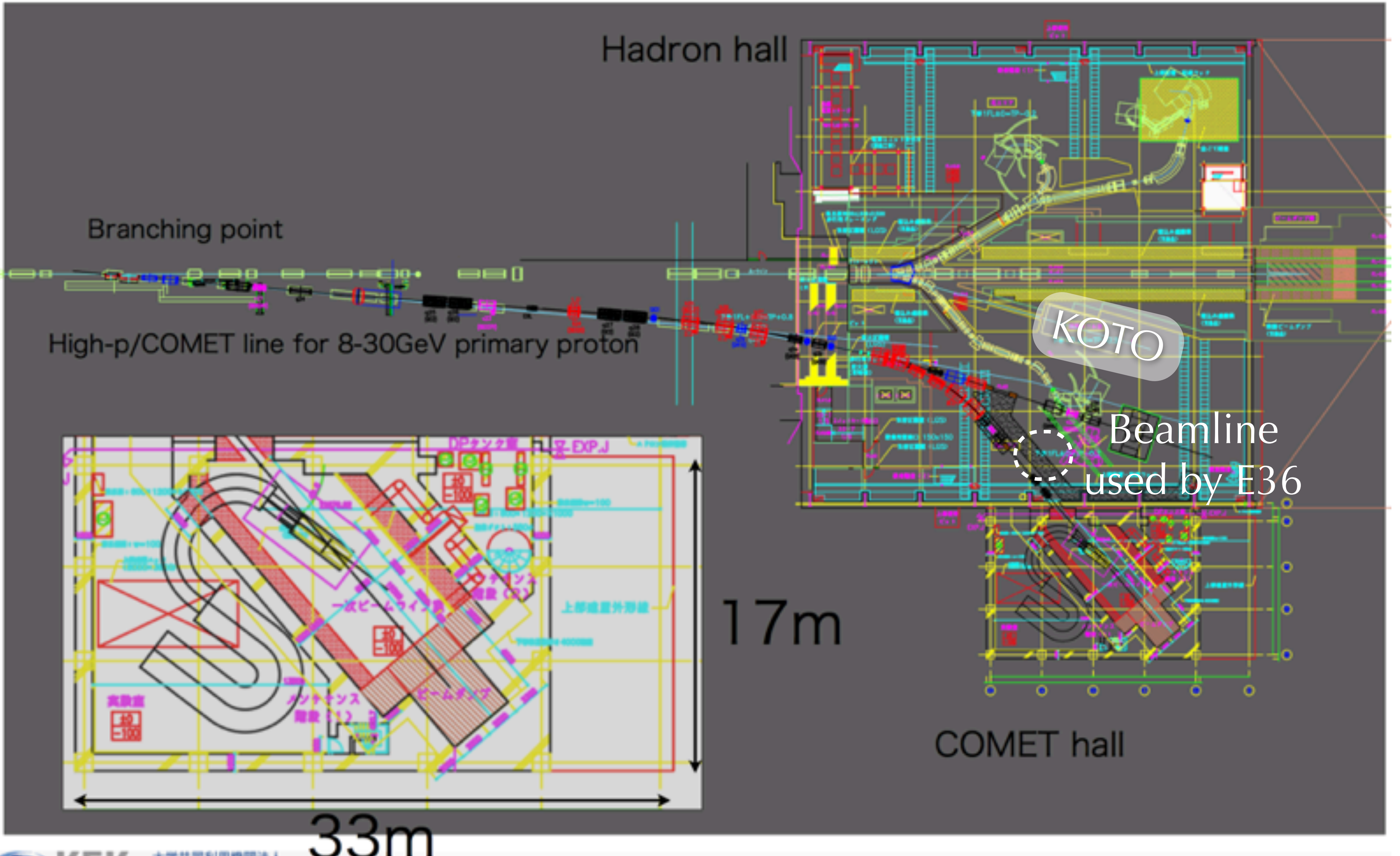




Search μ-e conv. (Al) with staging approach

- Background study in Phase-I
- Full μ-e conversion search in Phase-II

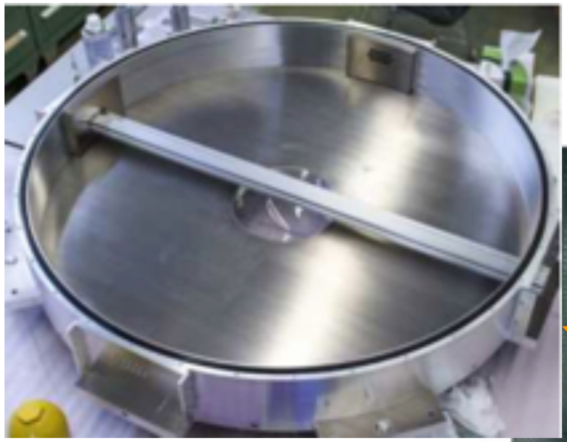
S.E.S.=3.1×10^{-15} (Phase-I 2017), 2.6×10^{-17}(Phase-II)

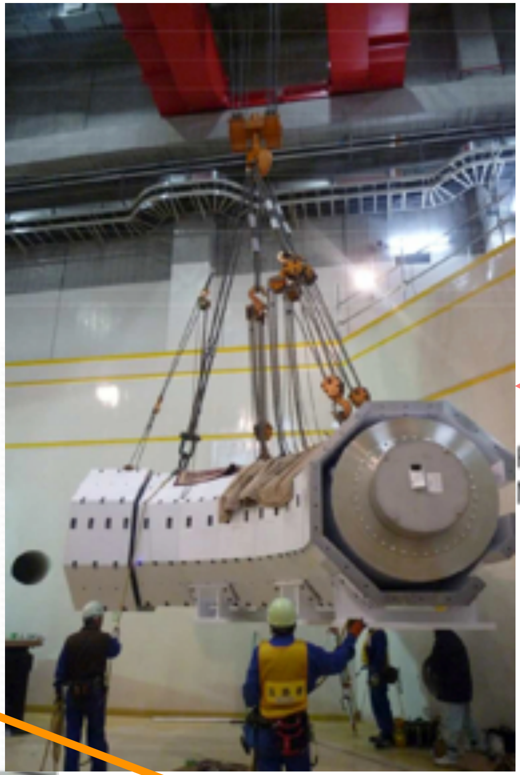


Hadron hall
Branching point
High-p/COMET line for 8-30GeV primary proton
KOTO
Beamline
used by E36
17m
33m
COMET hall

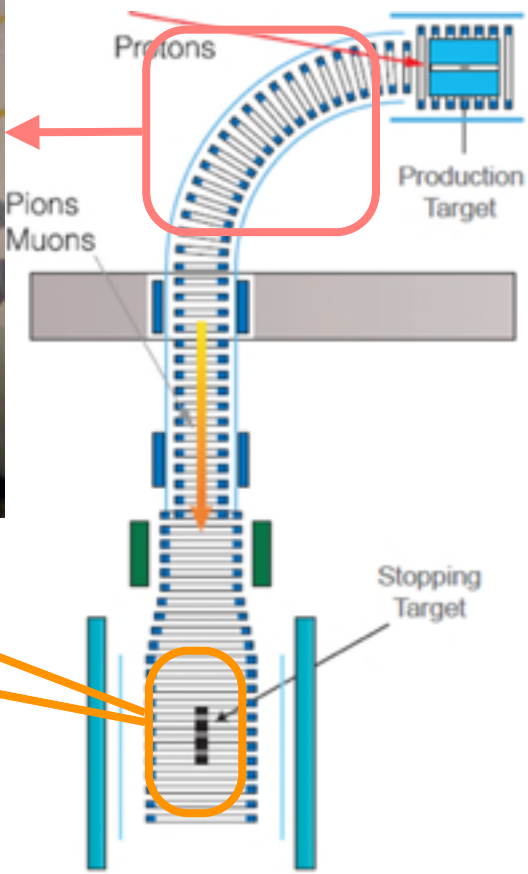
COMET Some pictures from preparation status

Straw tracker
production on going





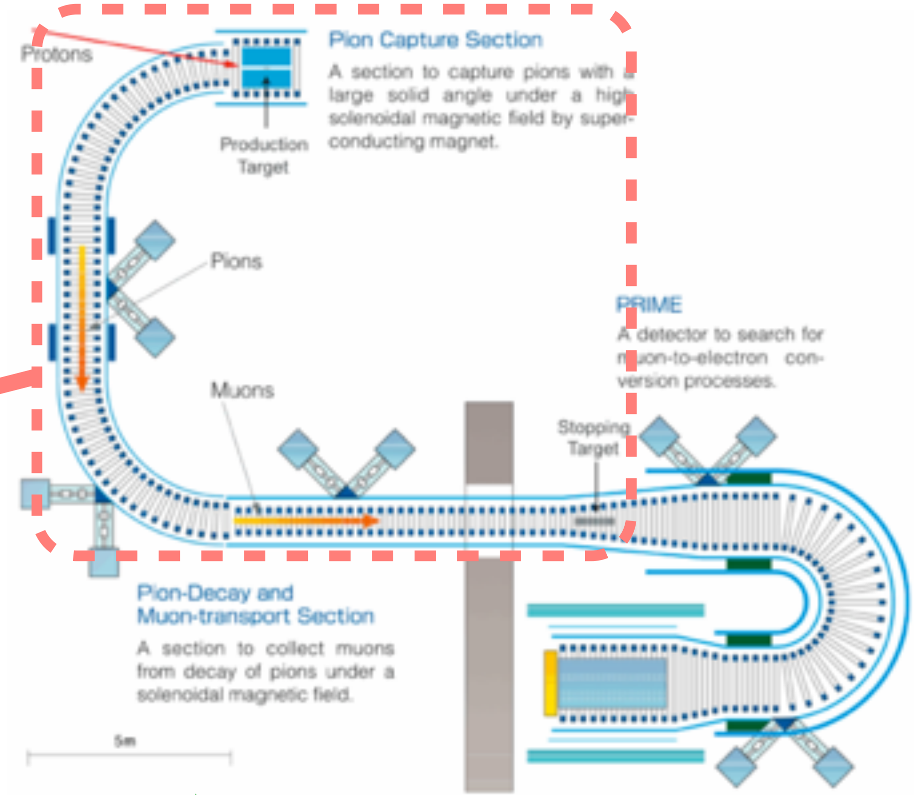
Transport solenoid
Installed



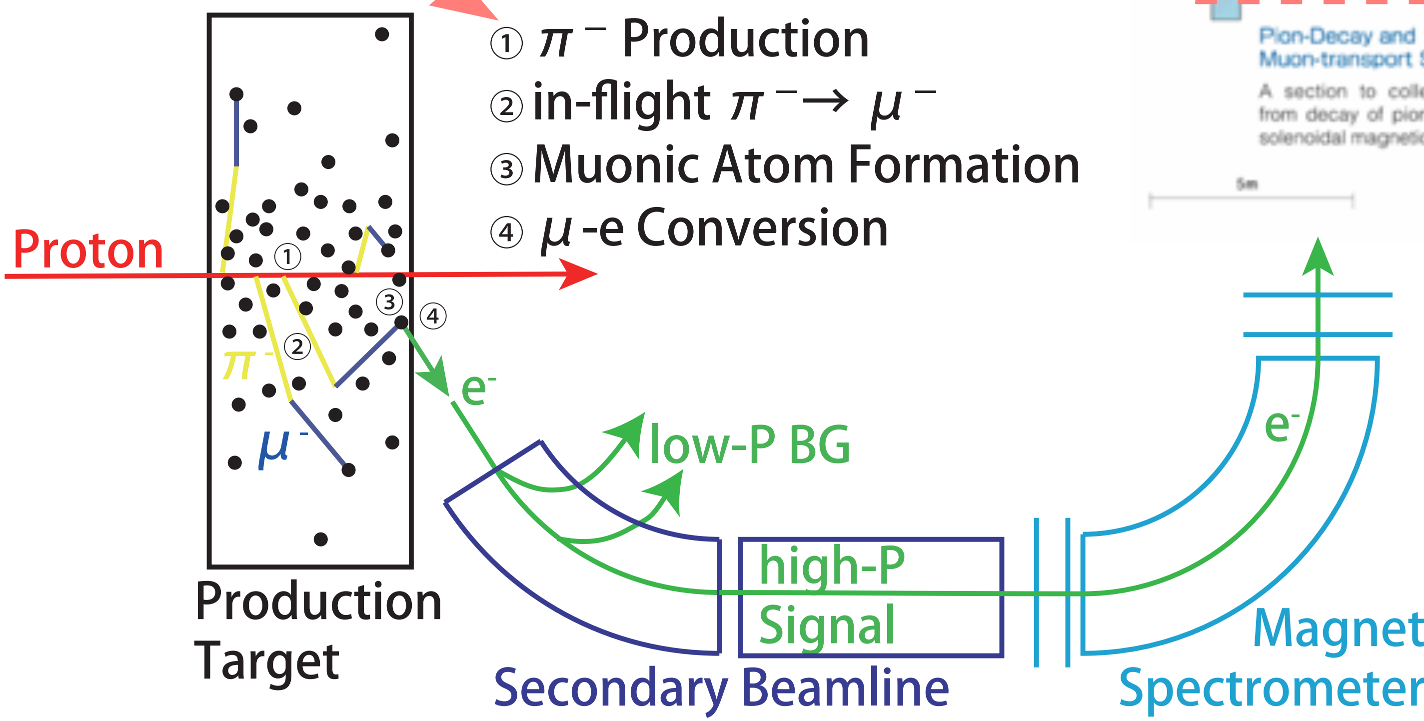
Cylindrical drift chamber
for Phase-I constructing

DeeMe experiment

Roll of all these parts in a production target

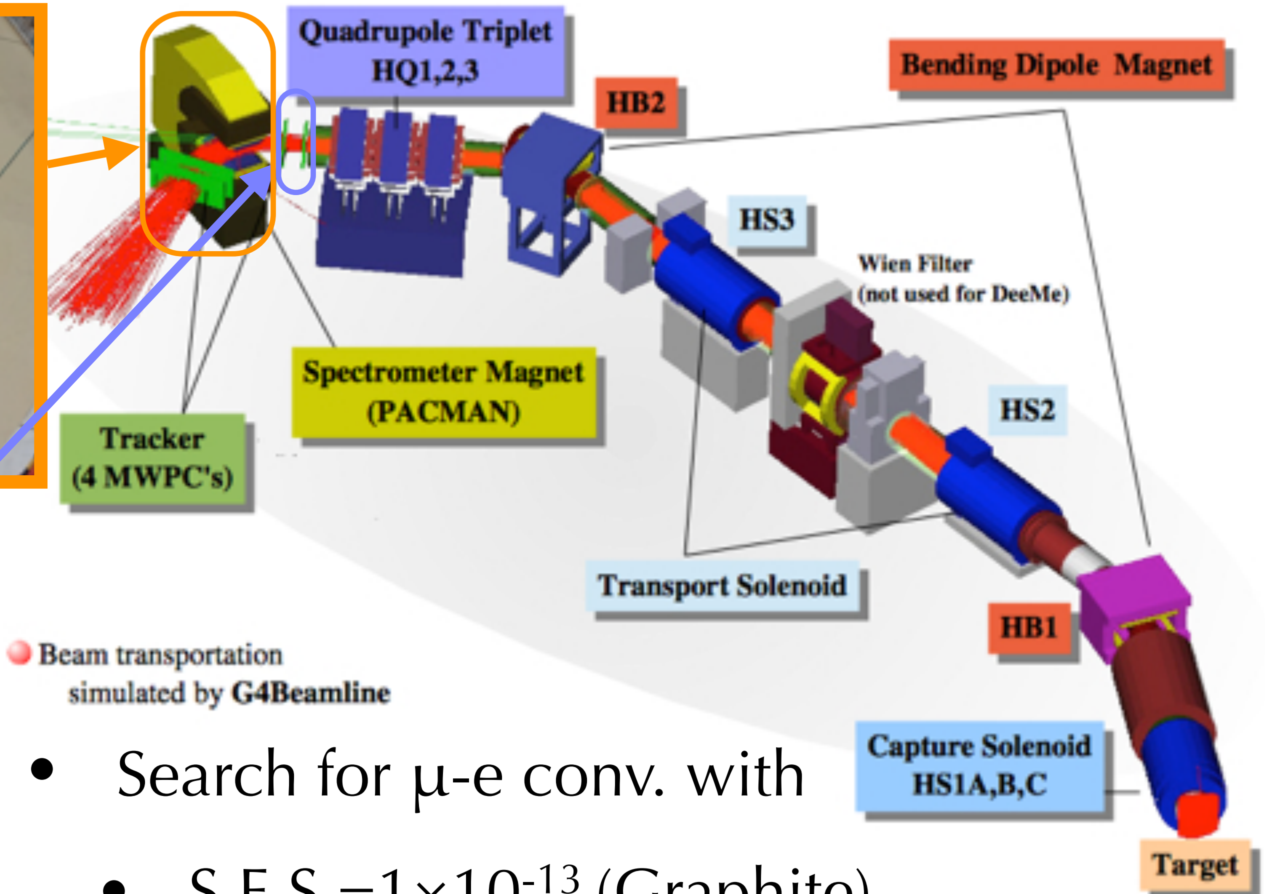


① π^- Production
② in-flight $\pi^- \rightarrow \mu^-$
③ Muonic Atom Formation
④ μ-e Conversion



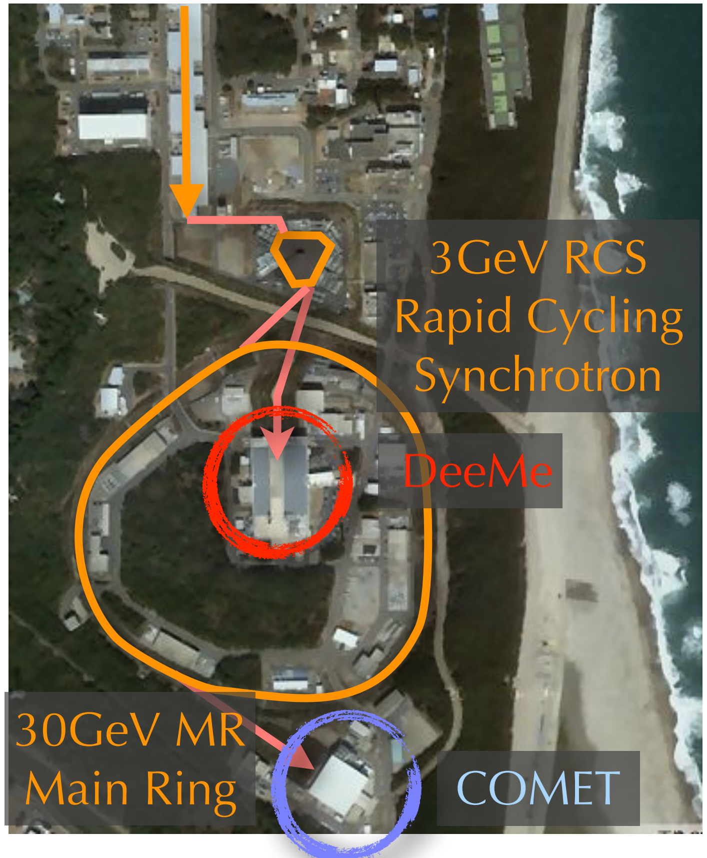
Simpler beamline
Simpler detector

DeeMe



- Search for μ-e conv. with
  - S.E.S.=1×10^{-13} (Graphite)
  - S.E.S.=2×10^{-14}(SiC)
- Unique idea in role of production target
- Early realization

COMET and DeeMe



Advantages of DeeMe
As I'm working on DeeMe ;)

	COMET	DeeMe
Anti-proton background	Possible (8GeV initial proton)	No (3GeV initial proton)
B.G. by off-timing proton	Possible (Slow extraction)	No in principle (Fast extraction)
Cosmic-ray B.G.		Strong (Small duty factor, horizontal track)
Run start	Phase-I ~2017 Phase-I ~2019	A.S.A.P after beamline construction (2015-2016)
S.E.S.	3.1×10^{-15} (Phase-I) 2.6×10^{-17}(Phase-II)	1×10^{-13}(Carbon) 2×10^{-14}(SiC)

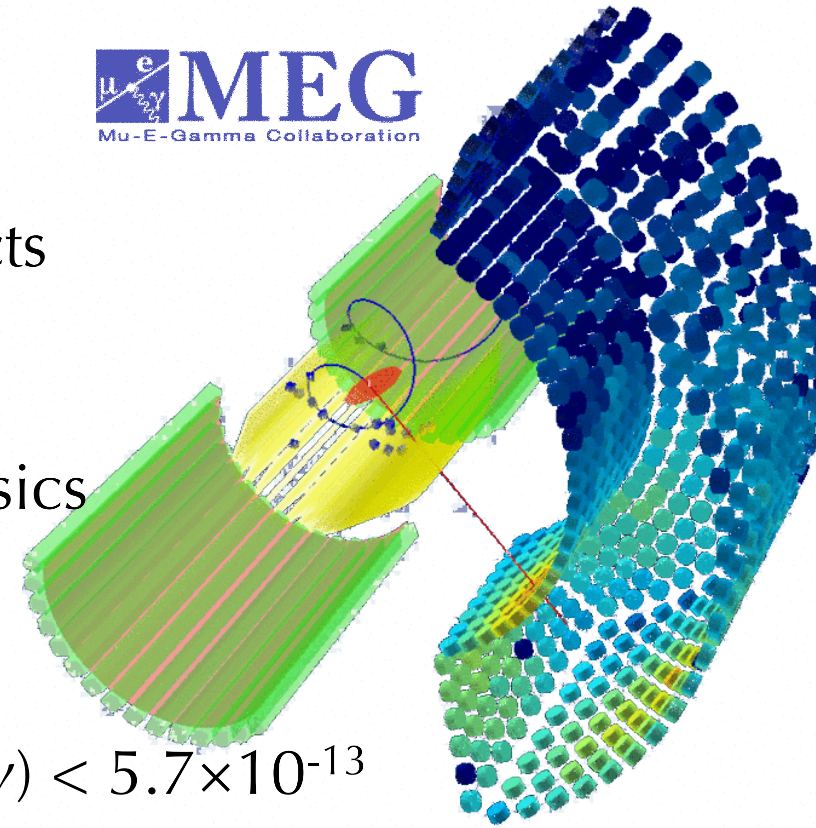
Muon Summary

- Muon physics is important as probe for beyond the SM
- Three muon experiments in J-PARC are introduced in this talk
  - g-2 E34 (muon anomalous magnetic moment measurement with new approach)
  - COMET, DeeMe (mu-e conversion search)
- These experiments will produce exciting results in near future
- Aside from I mentioned, further future plans (PRISM/PRIME at J-PARC, Project-X at Fermilab, MEG-II in PSI etc.)

Summary

- J-PARC is suited for intensity frontier by its high intensity proton beam.
- Several flavor physics experiments with kaon or muon are running, or going to run soon in J-PARC
- Stay tuned!!

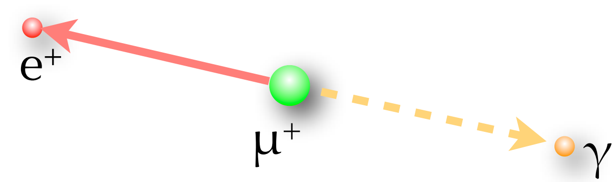
MEG at PSI



$\mu^+ \to e^+\gamma$ is strictly forbidden in the SM
SM with neutrino oscillation extension predicts
$Br(\mu^+ \to e^+\gamma)_{SM} \sim 10^{-50}$ (nearly zero)

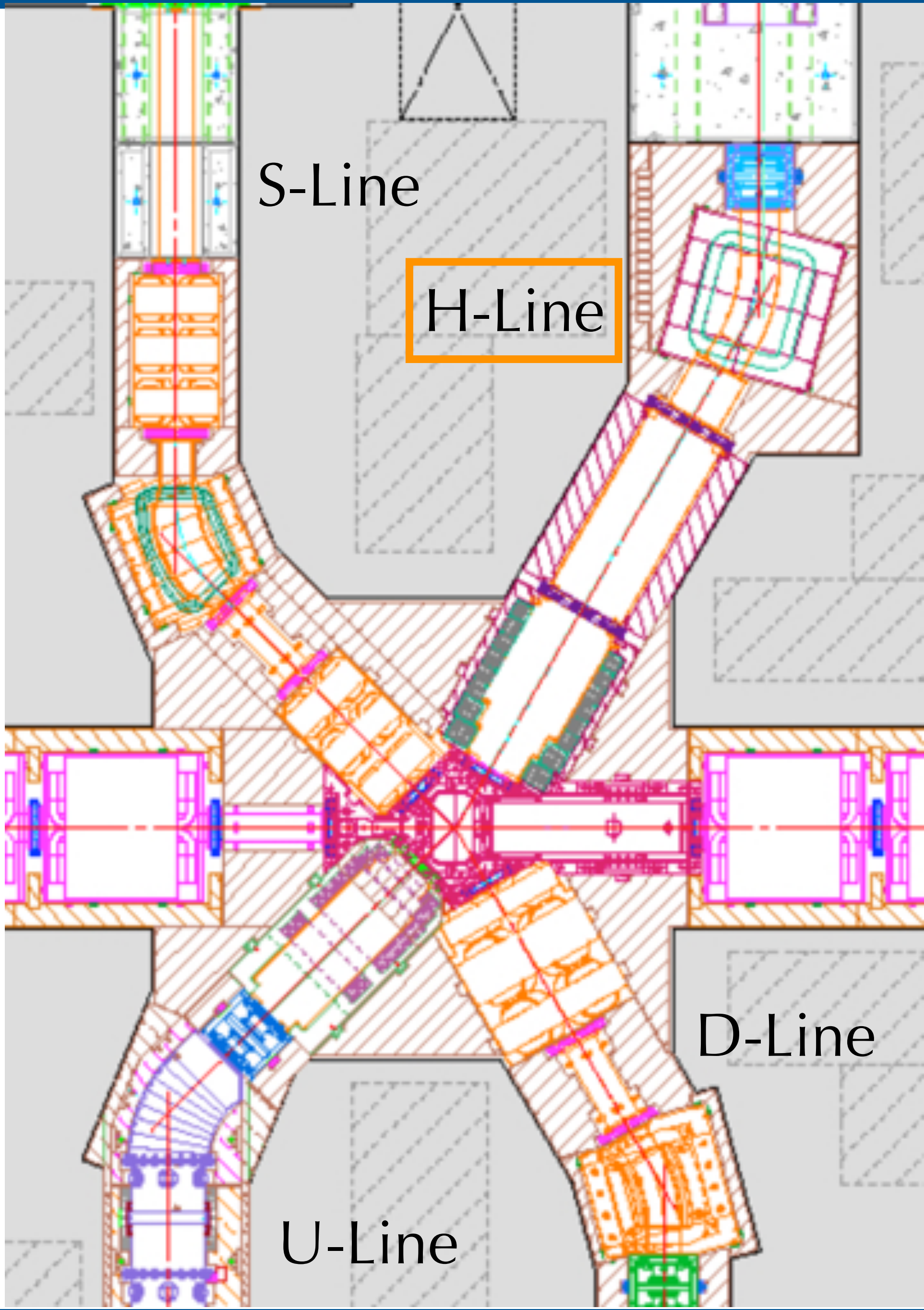
Discovery of it is a clear evidence for new physics

- Run finished in 2013
- 2009-2012 data analysis gives $Br(\mu^+ \to e^+\gamma) < 5.7\times10^{-13}$
  - Giving a strong constraint on models of new physics
  - New result will come soon
- Upgrade R&D for 10^{-14} sensitivity in progress



J-PARC MUSE beamlines

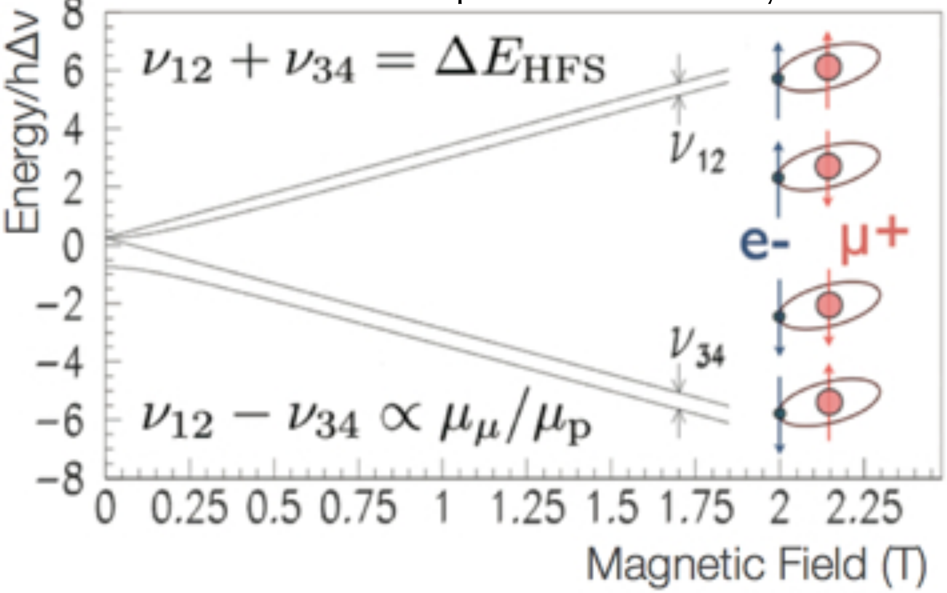
- D-Line (Decay Muon Line)
  - Operating
- U-Line (Ultra Slow Muon Line)
  - Under commissioning
- S-Line (Surface Muon Line)
  - Under construction
- H-Line (High Momentum Line)
  - Large acceptance (130msr)
  - Momentum tunable
  - Mu HFS, g-2, DeeMe mu-e conversion experiments are proposed
  - Planed to be constructed



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

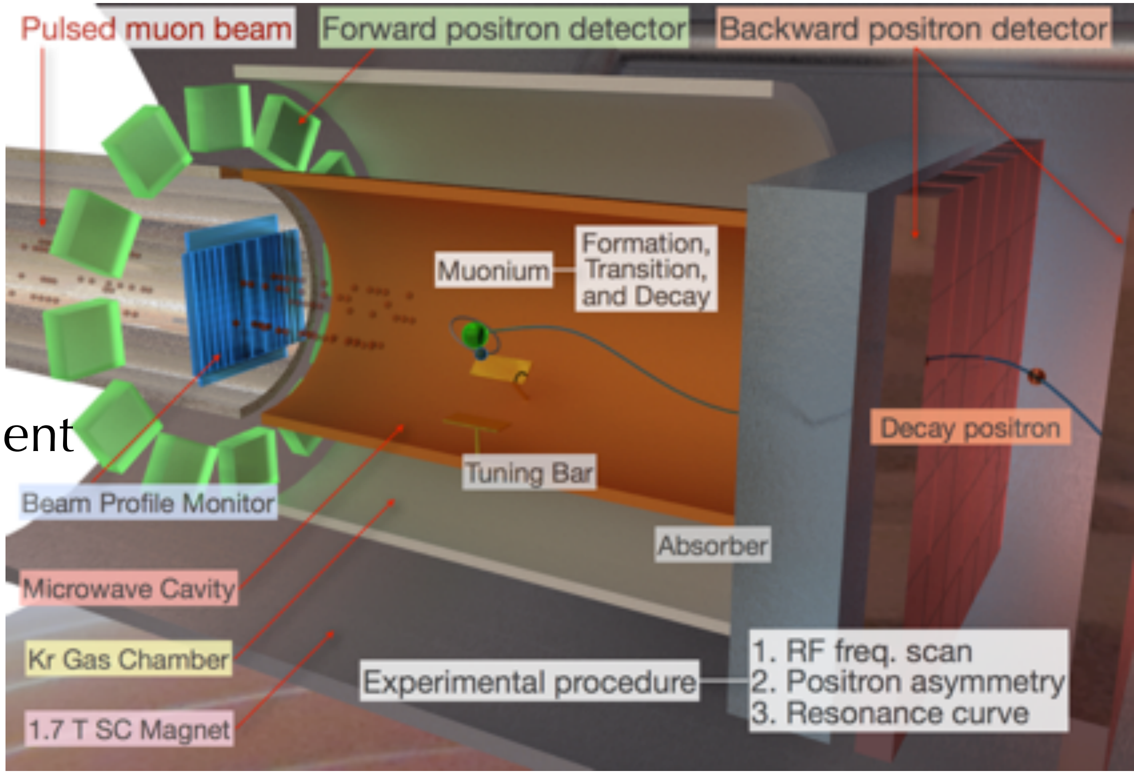
Muonium Hyperfine splitting

(Captured from Slide by S. Kanda)



Liu et al., PRL. 82, 711 (1999) @LAMPF

ΔE_{HFS} = 4463302765(53) Hz (12ppb)
μ_μ/μ_p = 3.18334513(39) (120ppb)



Limited by statistics in the former experiment
improve with× 200 statistics

Will contribute to
CPT & Lorentz invariance test
Muon mass determination
g-2 = R/(λ-R) where $R=\omega_a/\omega_p$ and $\lambda=\mu_\mu/\mu_p$

Details: PM-15-PM1 14:55-, H. Torii

Aim of particle physics

- To explore a fundamental principle of the nature

We have constructed the Standard Model of elementary particle physics (SM) which well describes behavior of forces and particles so far

▪ Energy Frontier

Study of collision of high energy particles

Check of the SM in high energy region

Study properties of heavy particle

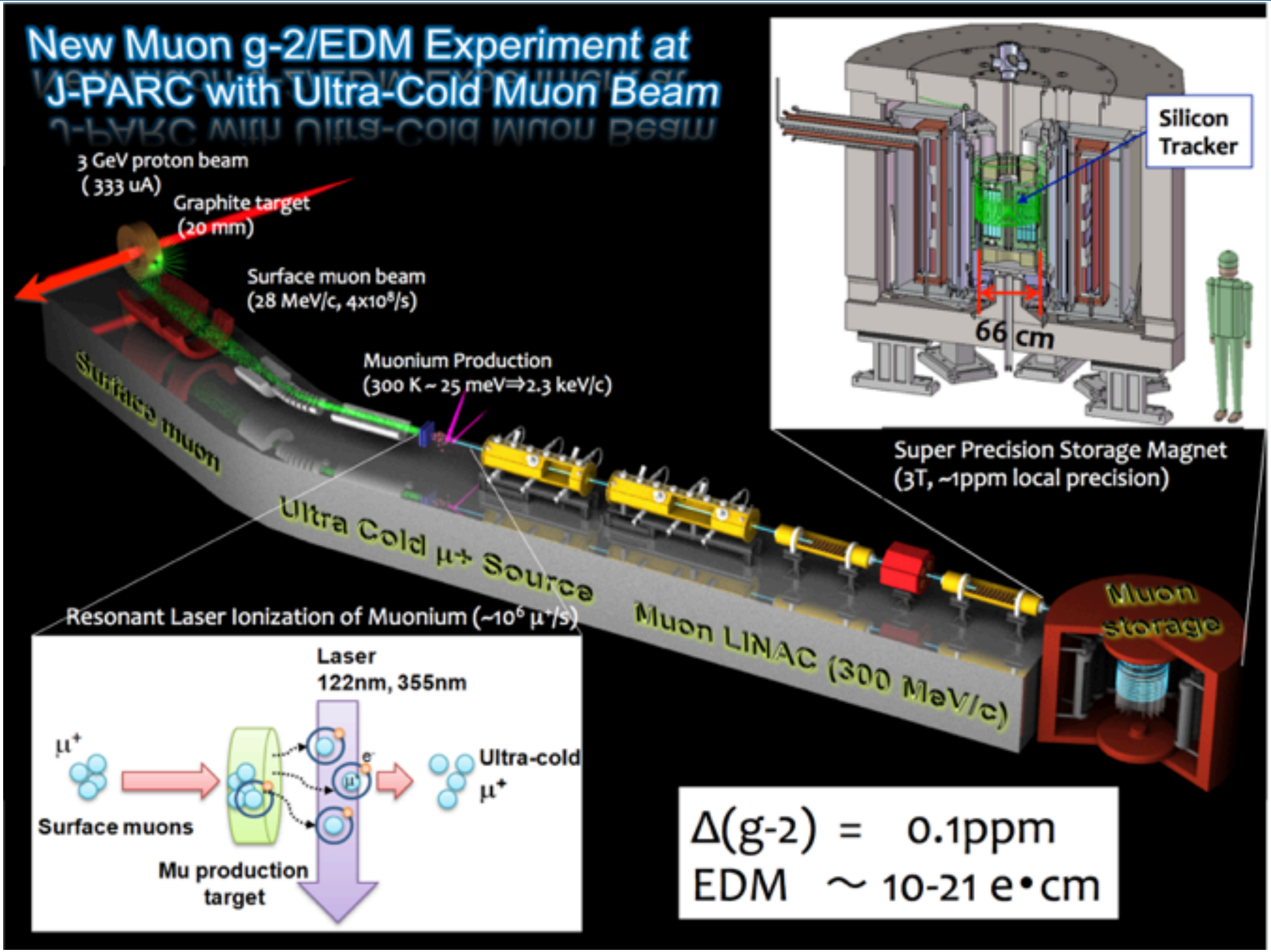
Generate undiscovered heavy particles that the SM do not predict

▪ Intensity Frontier

Precise study of known particles

Measure physics parameters of the SM, or verify the SM precisely with high statistics

Investigate deviation from the SM, which would be mediated by virtually appeared undiscovered particles (uncertainty principle)

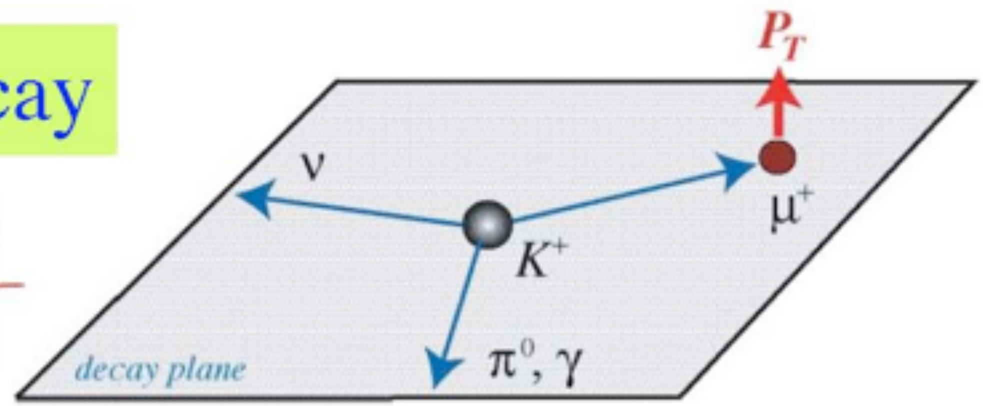


New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam
3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10⁸/s)
Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)
Surface muon
Ultra Cold μ+ Source
Muon LINAC (300 MeV/c)
Muon storage
Silicon
Tracker
66 cm
Super Precision Storage Magnet
(3T, ~1ppm local precision)
Resonant Laser Ionization of Muonium (~10⁶ μ⁺/s)
Laser
122nm, 355nm
μ⁺
Surface muons
e⁻
Ultra-cold
μ⁺
Mu production
target
Δ(g-2) = 0.1ppm
EDM ~ 10-21 e•cm

E06 TREK (Time Reversal Experiment with Kaons)

$K^+ \rightarrow \pi^0 \mu^+ \nu$ decay

$$P_T = \frac{\sigma_\mu \cdot (p_{\pi^0,\gamma} \times p_{\mu^+})}{|(p_{\pi^0,\gamma} \times p_{\mu^+})|}$$



- Same spectrometer as E36
- Transverse μ polarization measurement
  - T-odd product -> sensitive to CP-violating new physics
  - SM contribution < 10^{-7}
  - Effect of final state interaction < 10^{-5}
- Goal: 10^{-4} (270kW beam, 1.4×10^{7} sec)

CERN NA62

Concerning experiment

- $Br(K_L^+ \to \pi^+ \nu\nu) = 9.11 \pm 0.72 \times 10^{-11}$ (SM)
- $Br(K_L^+ \to \pi^+ \nu\nu) = (1.73 +1.15 -1.05) \times 10^{-10}$ (BNL E787/949)

- CERN NA62 2014 pilot run, run 2015 starts in July
  - Search with sensitivity of O(100) signal events, determine Br within 10% error

Muon Beams

TRIUMF
Continuous
500MeV, 75kW
Surface muon: $10^6 \mu^+/s$

RIKEN
Pulsed
Surface muon: $1.5\times10^6 \mu^+/s$ @200kW

MUSIC (MUon Science Innovative Commission at RCNP, Osaka University)
Continuous
$10^8 \mu^+/s$@0.4kW

PAUL SCHERRER INSTITUT PSI
Continuous
Surface muon:$1.6\times10^8 \mu^+/s$ @1.3kW

HiMB $4\times10^{10} \mu^+/s$ in the future

Fermilab
Pulsed
Mu2e 8GeV, 25kW, $5\times10^{10} \mu^-/s$(2019/20)
Project X Mu2e 2×10^{12} μ^-/s (>2022)

J-PARC
Pulsed

MUSE 3GeV 1MW (currently 500kW)
Surface muon rate: $6.4\times10^7 \mu^+/s$@212kW

COMET 8GeV 56kW $10^{11} \mu^-/s$(2019/20)
PRISM/PRIME 8GeV 300kW $10^{11\text{-}12}$ (>2020)

J-PARC offers the world's most intense pulsed muon now

- g-2 @BNL reports deviation from the SM
    - Verification with better sensitivity are planned
- Charged Lepton Flavor violation (not discovered yet) is expected as another important probe for the new physics
    - Most recent result reported from MEG @PSI
    - Mu2e(Fermilab), COMET(J-PARC), DeeMe(J-PARC), μ3e(PSI) in the future

Muon g-2

Anomalous magnetic moment (g-2)

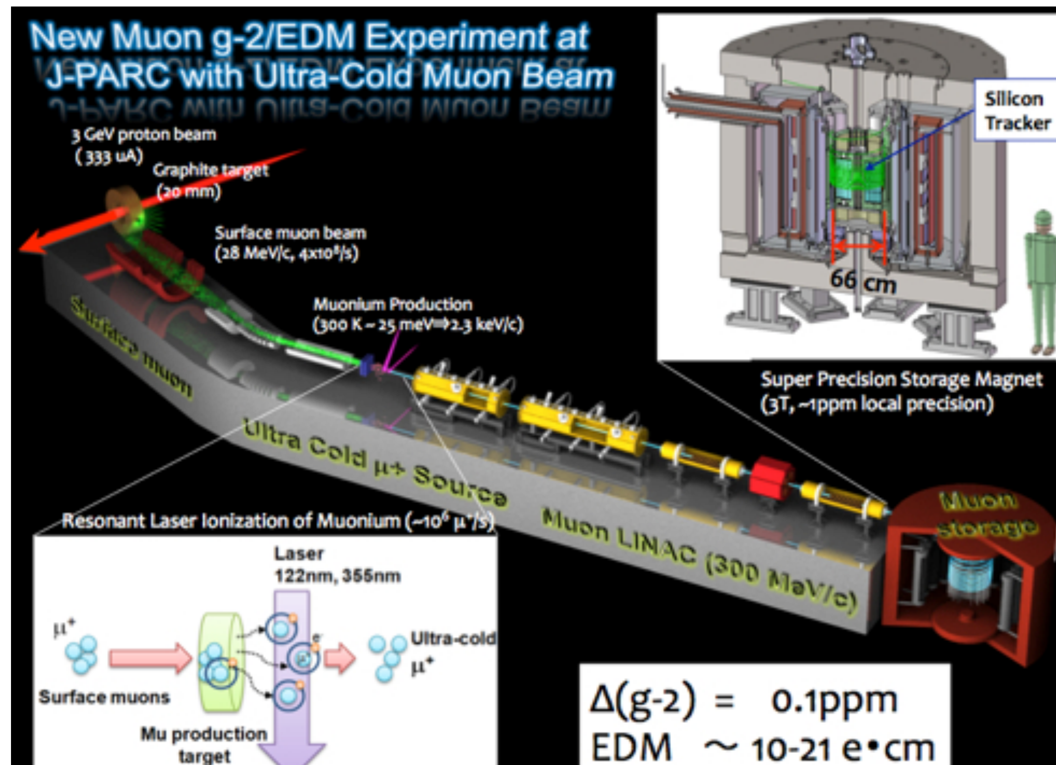
$a_\mu = (g\text{-}2)/2 = 0.00116592089(63)$ (BNL E821 ~2001) 0.5ppm

$= 0.00116591828(49)$ (Standard Model)

$\Delta a_\mu = \text{Exp} - \text{SM} = 26.1\ (8.0) \times 10^{-10}$ 3.3σ anomaly

J-parc muon g-2/EDM

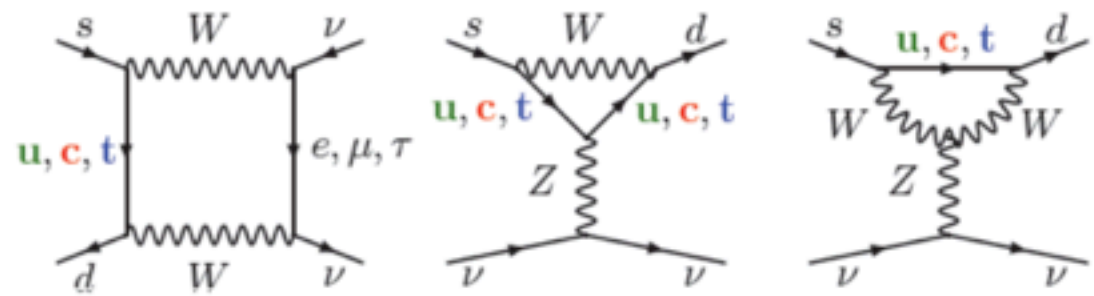
FNAL-E989



Upgrade former experiment to ~0.1ppm

Perform with brand new approach, different systematics with sensitivity ~0.1ppm

- FCNC process
- Loop diagram



- Neutral : CP violating, top loop dominated

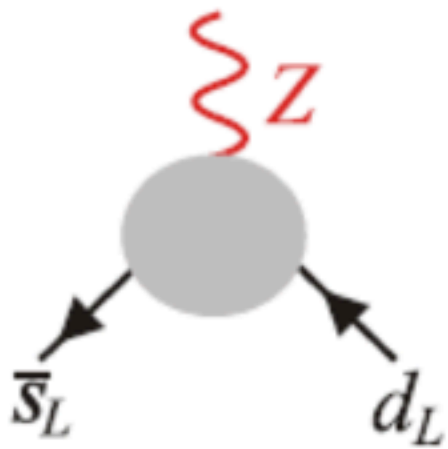
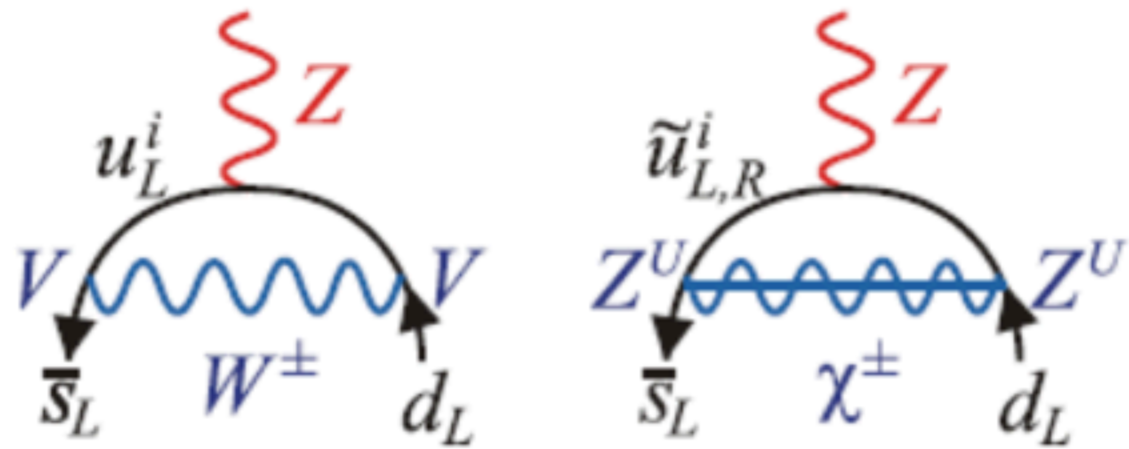
$$\mathcal{B}r(K_L \to \pi^0 \bar{\nu}\nu) = \kappa_L \left(\frac{\mathrm{Im}(V_{ts}^* V_{td})}{\lambda^5} X(x_t) \right)^2$$

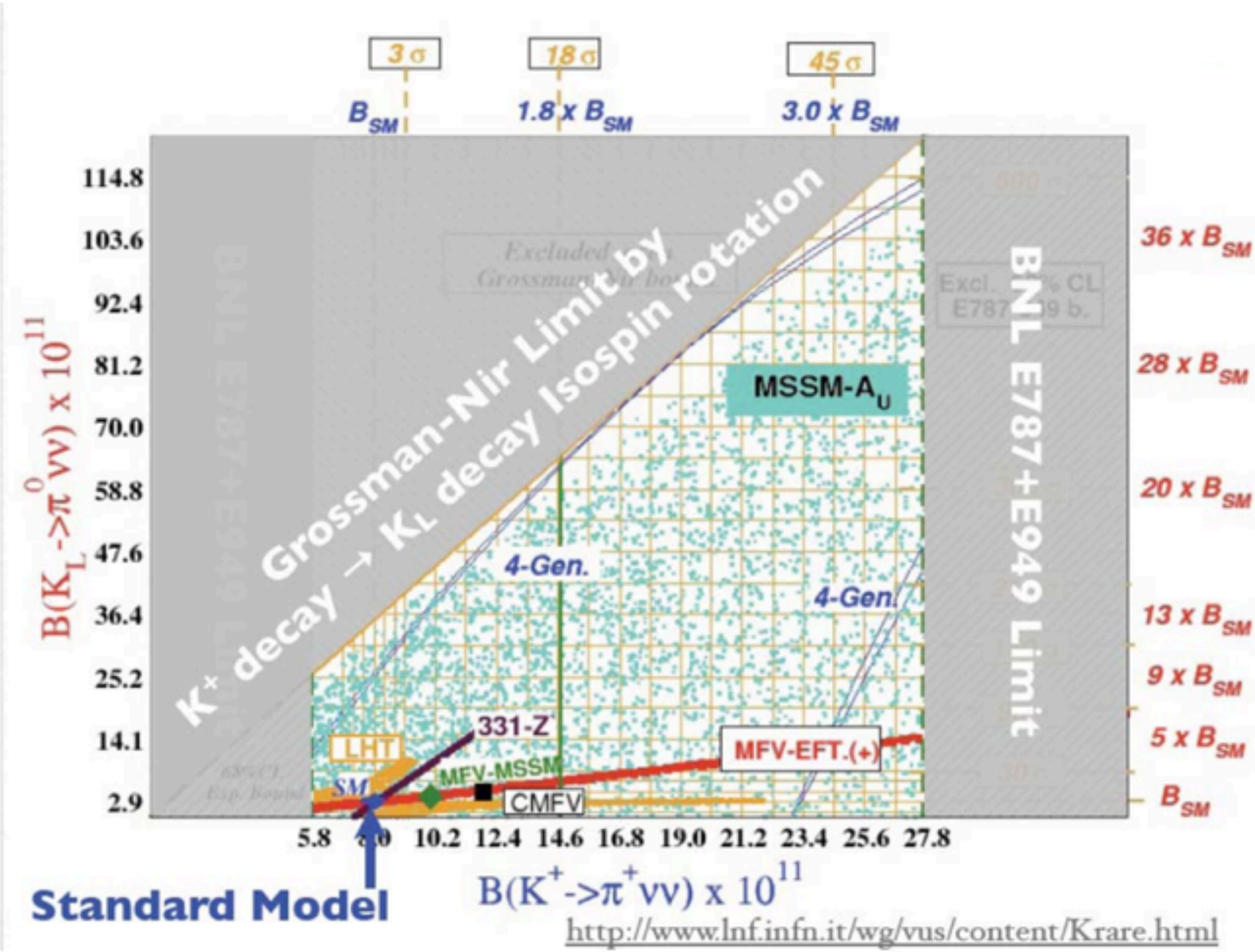
- Charged: CP conserving, top and charm loop

$$\mathcal{B}r\left(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)\right) = \kappa_+ (1 + \Delta_{EM})$$
$$\times \left| \frac{V_{ts}^* V_{td} X_t(m_t^2) + \lambda^4 \mathrm{Re} V_{cs}^* V_{cd} \left(P_c(m_c^2) + \delta P_{c,u} \right)}{\lambda^5} \right|^2$$

Uncertainty of hadron can be cancelled by normalizing with well measured $Br(K^+ \to \pi^0 e^+ \nu)$

K→πνν beyond SM

EW Penguin	SM and/or example of SUSY diagram
	


3 σ
18 σ
45 σ
B_{SM}
1.8 x B_{SM}
3.0 x B_{SM}
114.8
103.6
92.4
81.2
70.0
58.8
47.6
36.4
25.2
14.1
2.9
B(K_L->π^0 νν) x 10^11
Grossman-Nir Limit by
K+ decay → KL decay Isospin rotation
MSSM-A_U
BNL E787+E949 Limit
4-Gen.
4-Gen.
331-Z
LHT
MFV-MSSM
SM
CMFV
MFV-EFT.(+)
36 x B_{SM}
28 x B_{SM}
20 x B_{SM}
13 x B_{SM}
9 x B_{SM}
5 x B_{SM}
B_{SM}
5.8
10.2
12.4
14.6
16.8
19.0
21.2
23.4
25.6
27.8
B(K^+->π^+ νν) x 10^11
Standard Model
http://www.lnf.infn.it/wg/vus/content/Krare.html