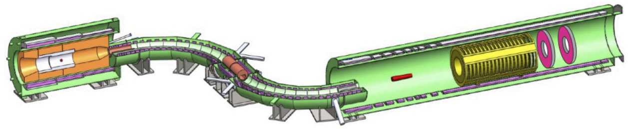
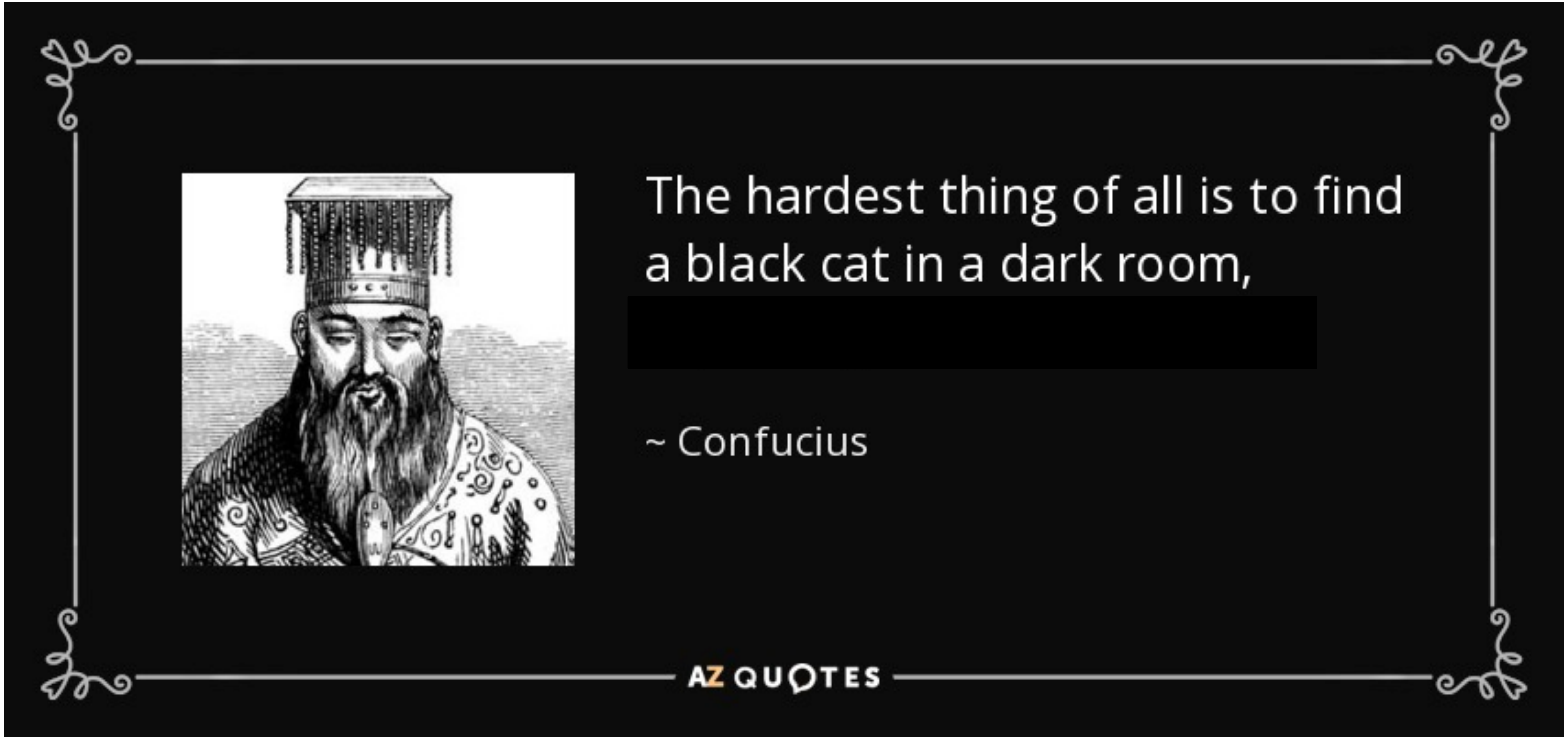
Who ordered that: what lepton flavor may tell us about the Universe

Yury Kolomensky
UC Berkeley/LBNL

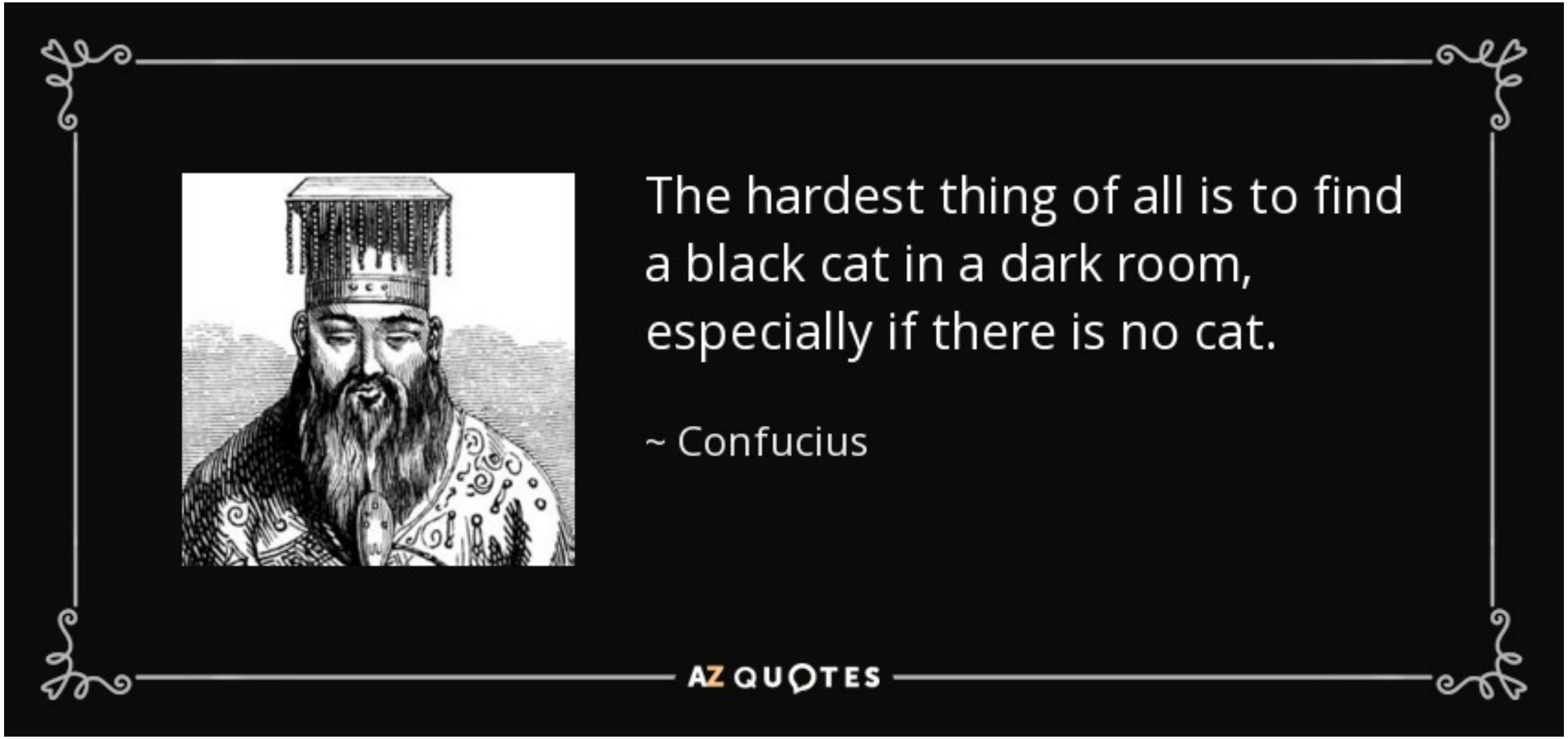


Outline of the Talk

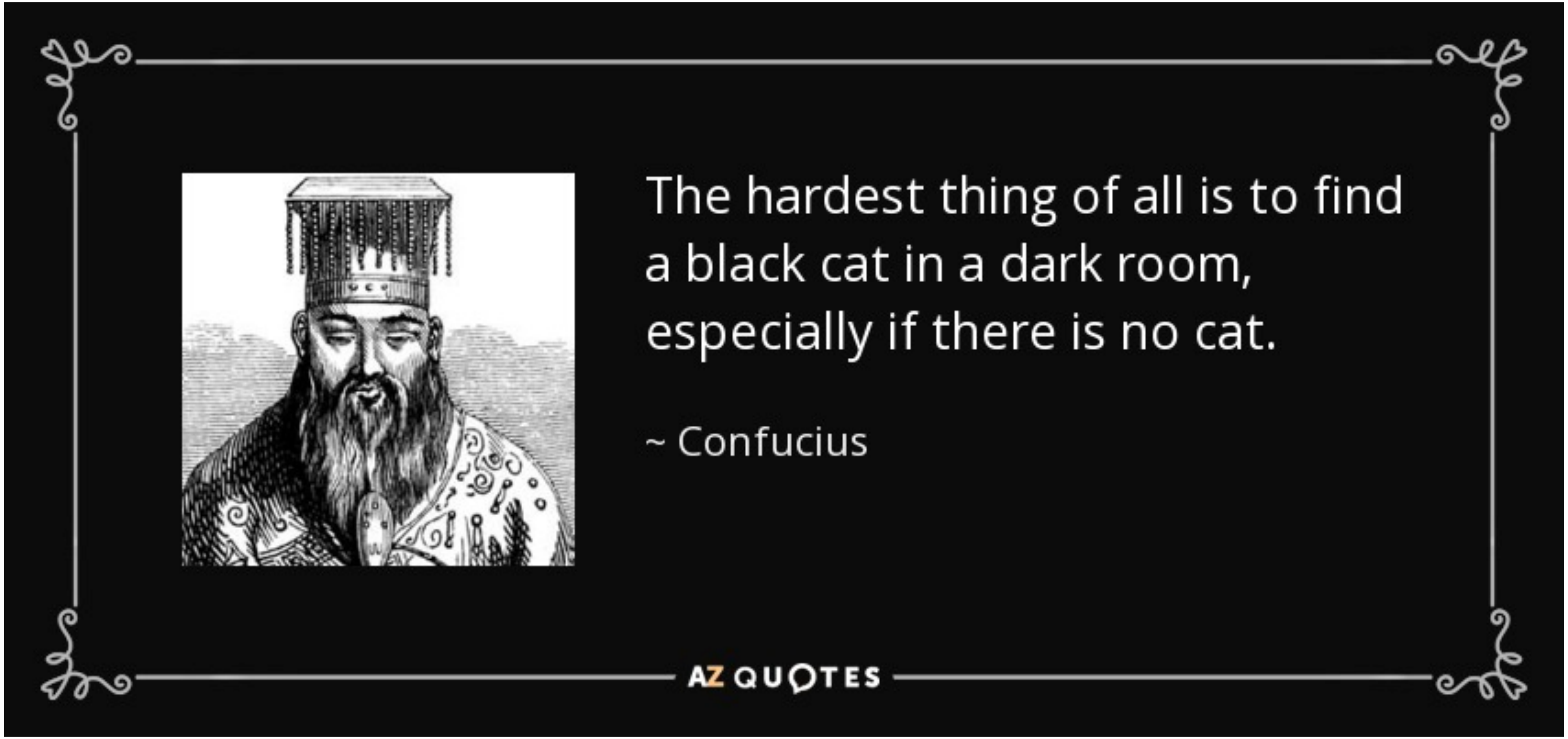
Outline of the Talk



Outline of the Talk



Outline of the Talk



(My sincere apologies if this offends your cultural sensitivities)

Outline

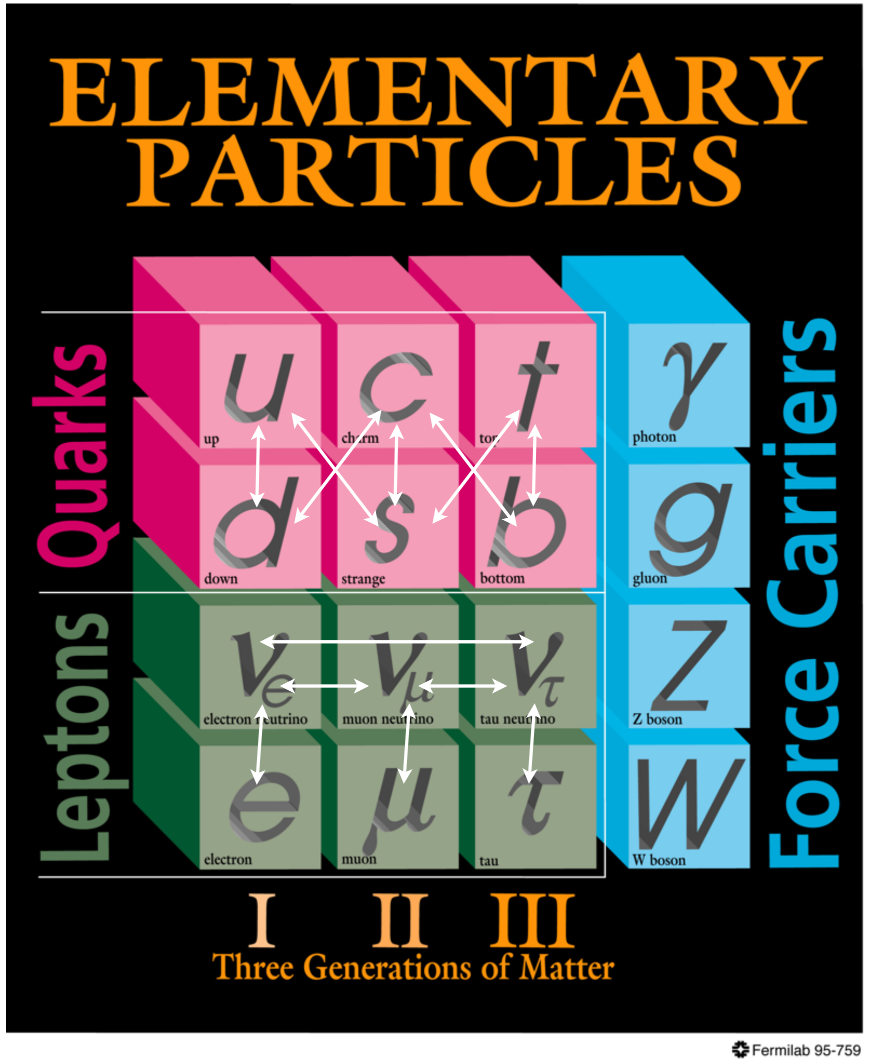
- Brief history of the muon
- Lepton Universality, Lepton Flavor, and Lepton Number
- Charged Lepton Flavor Violation
- Mu2e experiment
- Future Prospects

Standard Model of Particle Physics

Complete description of matter and forces (other than gravity) ?

Three generations (families) of elementary particles

Four force carriers for E&M and weak interactions



Neutrinos mix and change their flavor

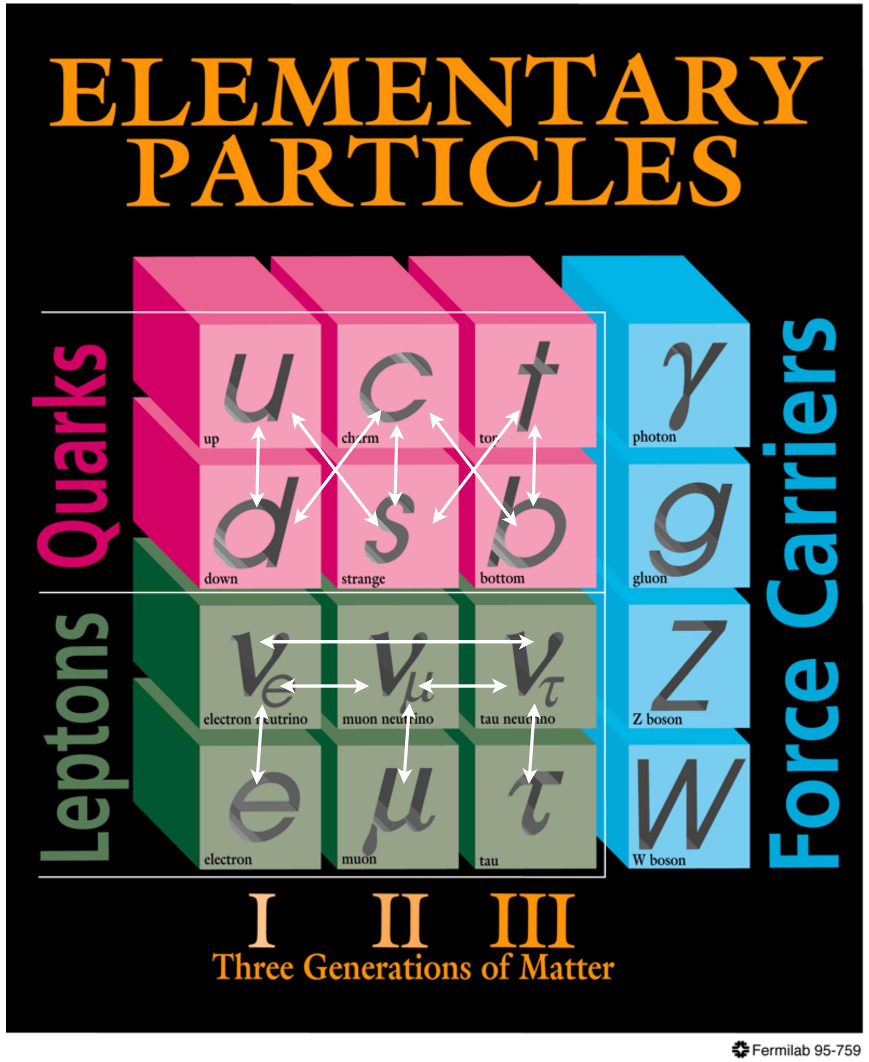
Neutrinos couple to charged leptons by weak interactions

Standard Model of Particle Physics

Complete description of matter and forces (other than gravity) ?

Three generations (families) of elementary particles

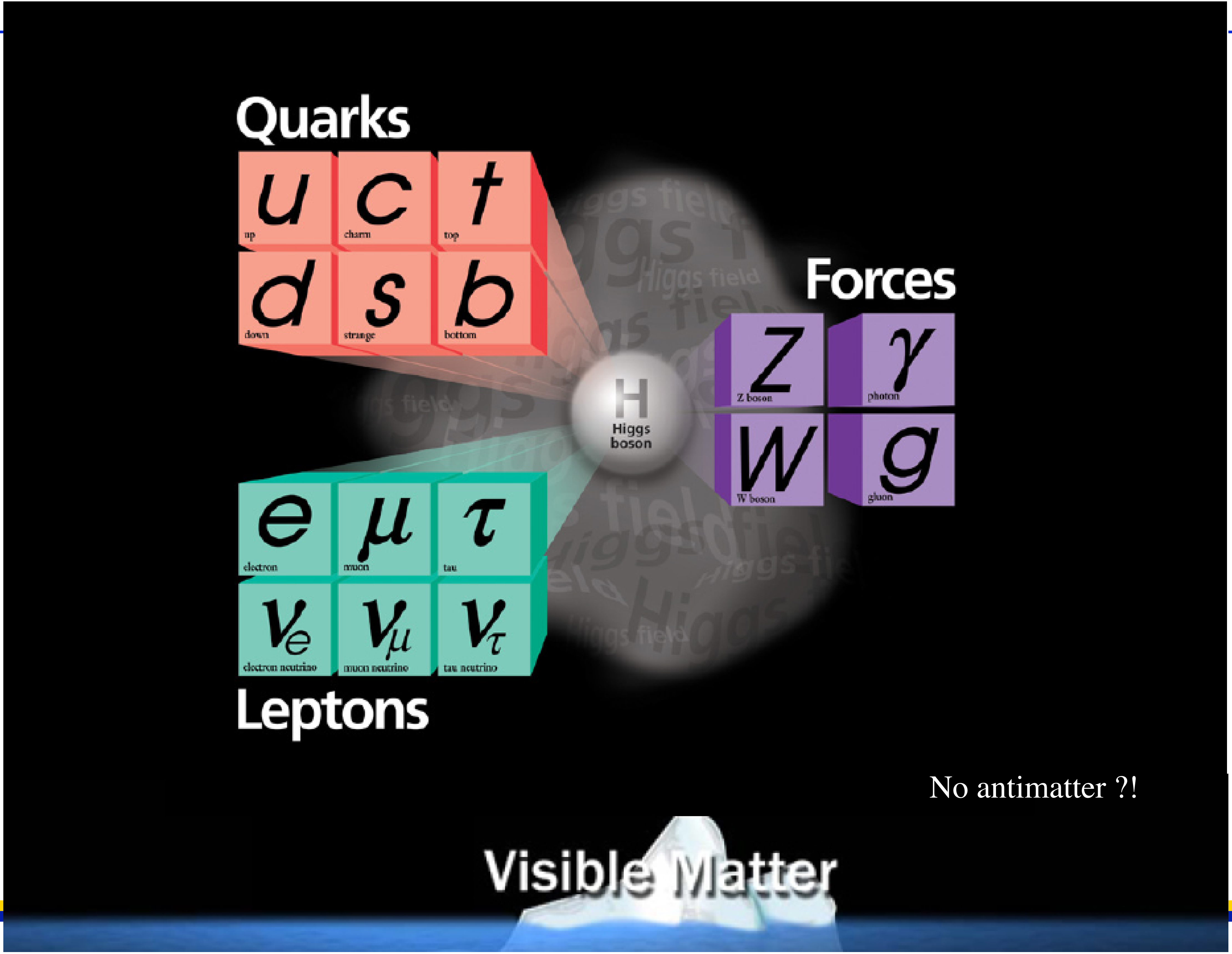
Four force carriers for E&M and weak interactions

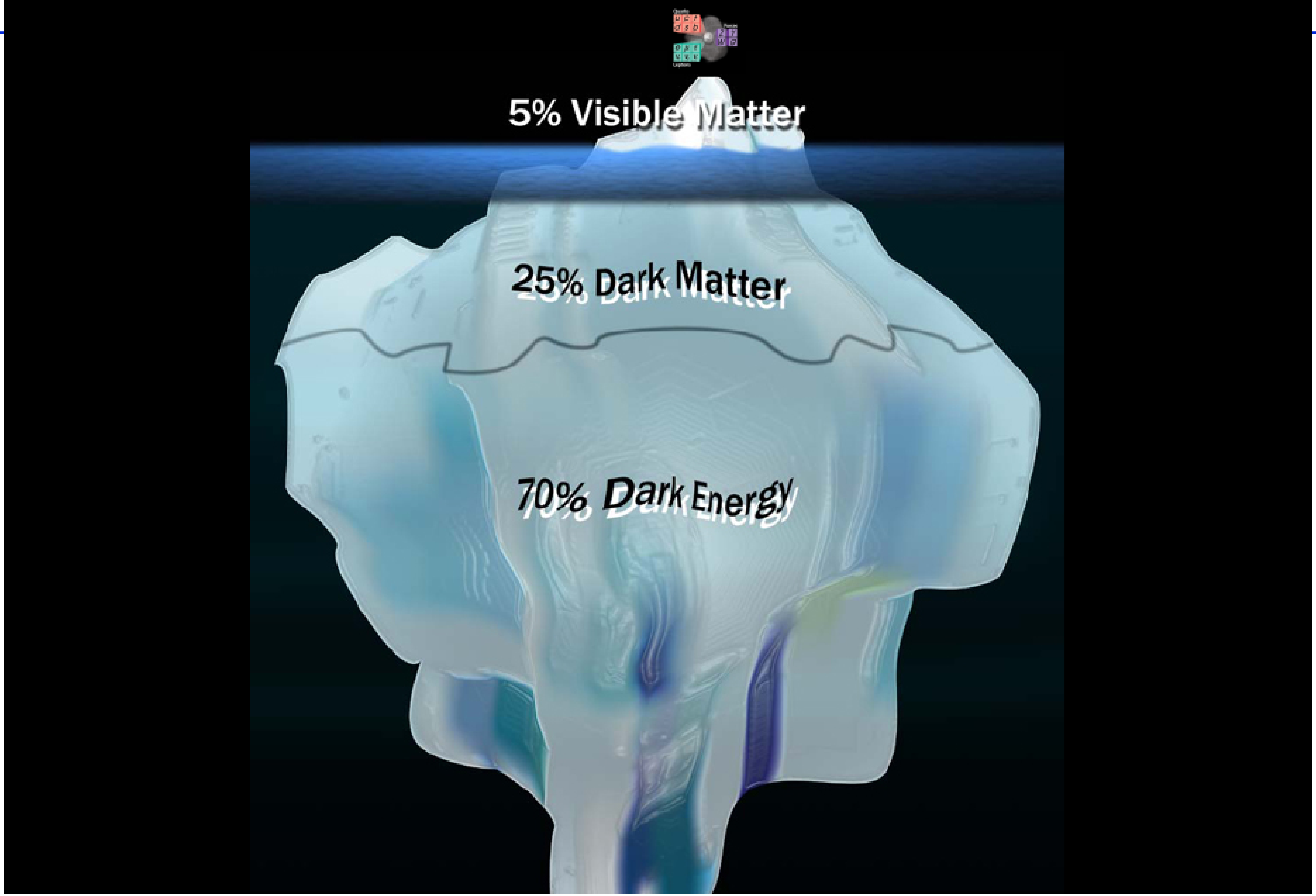


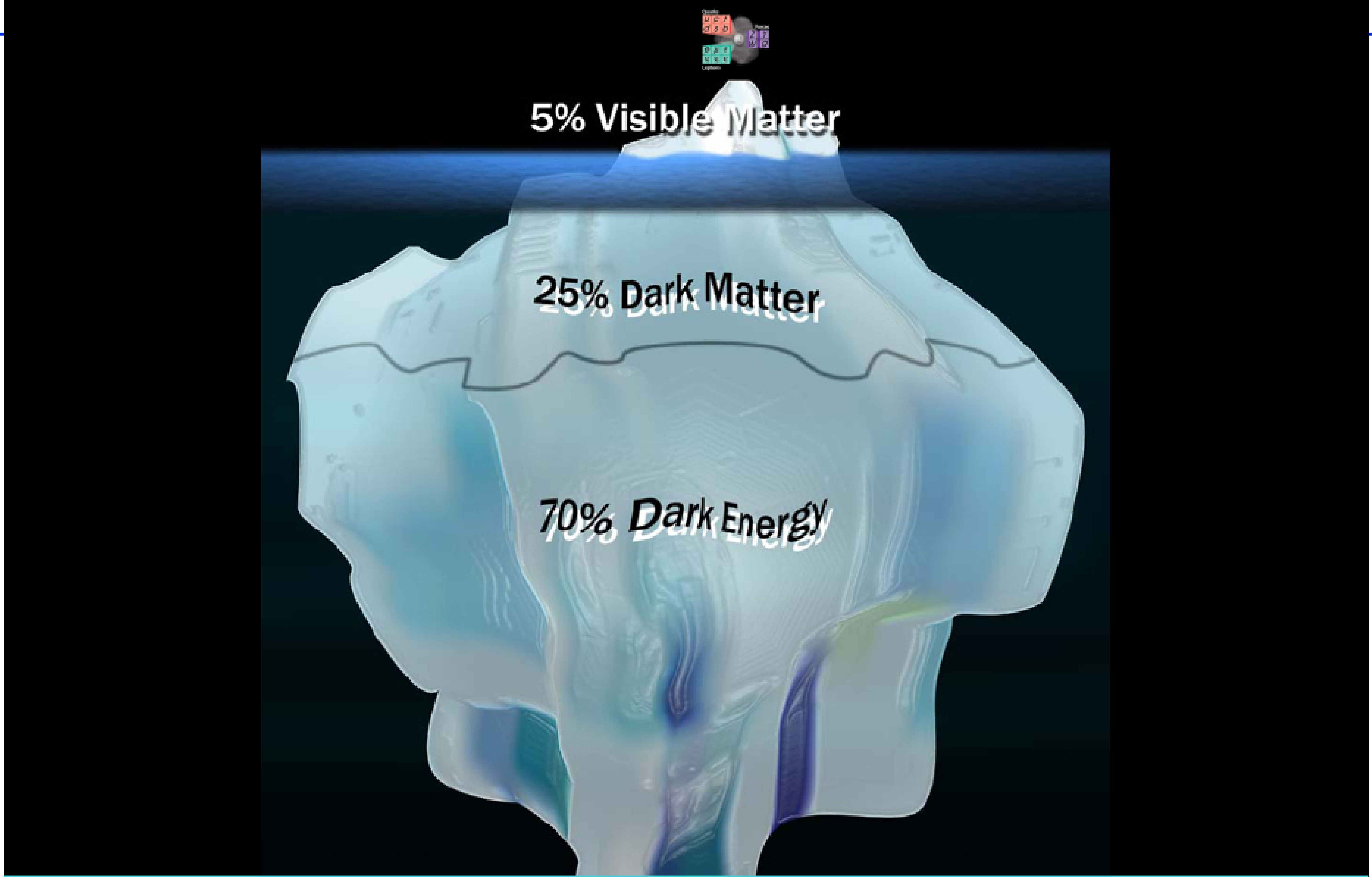
Neutrinos mix and change their flavor

Neutrinos couple to charged leptons by weak interactions

Remaining questions ?


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs
boson
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons
No antimatter ?!
Visible Matter


5% Visible Matter
25% Dark Matter
70% Dark Energy



What is the Dark Stuff ?

What happened to anti-matter ?

Direct vs Indirect Searches

Direct vs Indirect Searches

Direct vs Indirect Searches

Courtesy Bob Cahn

Direct vs Indirect Searches

Courtesy Bob Cahn

Direct vs Indirect Searches

Courtesy Bob Cahn

Direct vs Indirect Searches

Courtesy Bob Cahn

Indirect Searches for New Physics

$\Delta E \Delta t \sim \hbar$

- Precision measurements
  - Look for small deviations from the Standard Model
    - ☞ Deviations go as $\sim \frac{\alpha_{NP}}{\alpha_{SM}} \left(\frac{M_{SM}}{M_{NP}} \right)^n$
    - ☞ Examples: muonic g-2, P and CP violation
- Processes suppressed in the Standard Model
  - Symmetry violations, Rare decays, Forbidden transitions
    - ☞ Small Standard Model background usually implies higher sensitivity
    - ☞ Examples: Neutrinoless Double Beta Decay, Electric Dipole Moments, Charged Lepton Flavor Violation

Matter-Antimatter Asymmetry

- Cosmic microwave background: trace of primordial annihilations
- We exist: not all matter has annihilated !

☞ How did this happen?

☞ Sakharov's recipe (1967): need antimatter to behave (slightly) differently from matter: CP symmetry violation

☞ Difference needed is about 1 part in 10 billion

☞ Leptons (neutrinos) may play an important role in producing matter in the early Universe.

☞ Number of flavors and flavor structure important !

ИЗБРАННЫЕ ТРУДЫ

НАРУШЕНИЕ CP-ИНВАРИАНТНОСТИ, C-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д. Сахаров

(ЖЭТФ. Письма в редакцию. 1967. Т. 5. вып. 1. С. 32 – 35)

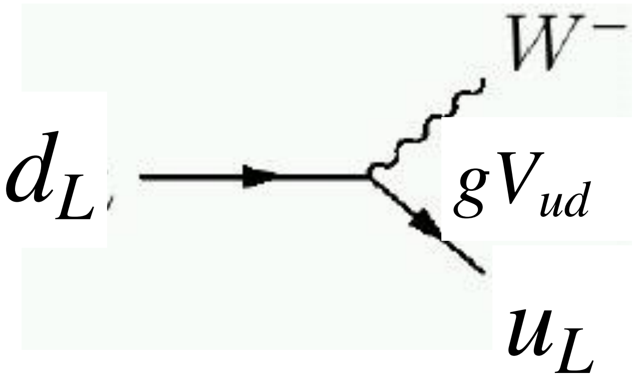
Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

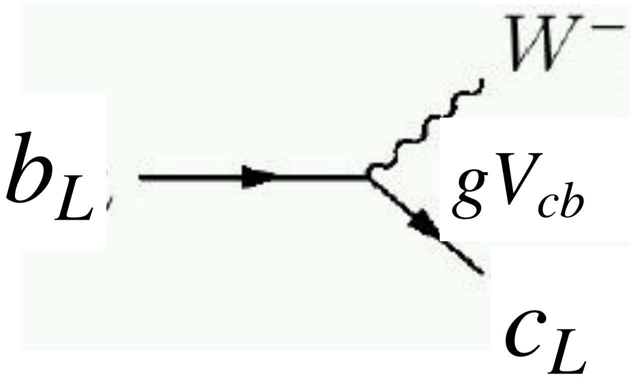
Cabibbo-Kobayashi-Maskawa Mixing Matrix

- Defines mixing between weak and mass states of quarks:

$$\underset{\textbf{\textit{weak eigenstates}}}{} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} Vud & Vus & Vub \\ Vcd & Vcs & Vcb \\ Vtd & Vts & Vtb \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \underset{\textbf{\textit{mass eigenstates}}}{}$$

$$\mathcal{L}_{\mathrm{W}} = -\sqrt{1/2}\; g\; u_{Li}\, \gamma^{\mu}\, V_{ij}\, d_{Lj}\, W^{+}{}_{\mu} + \mathrm{h.c.}$$





Nobel Prizes in Physics

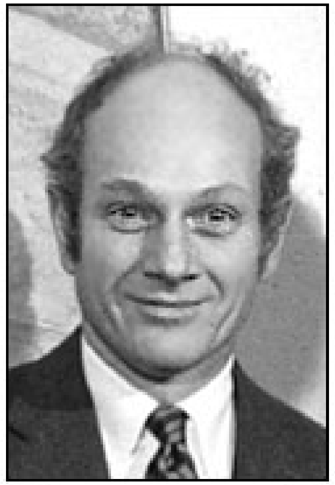
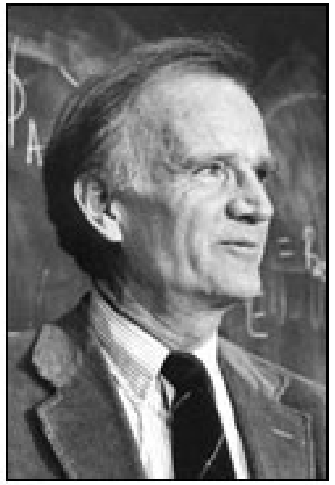


Yoichiro Nambu

Makoto Kobayashi

Toshihide Maskawa

2008: Kobayashi-Maskawa:
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

James Cronin

Val Fitch

1980: Cronin-Fitch
"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"

Omitted but not forgotten:
Nicola Cabibbo
(1935-2010)

Solved Problem ?

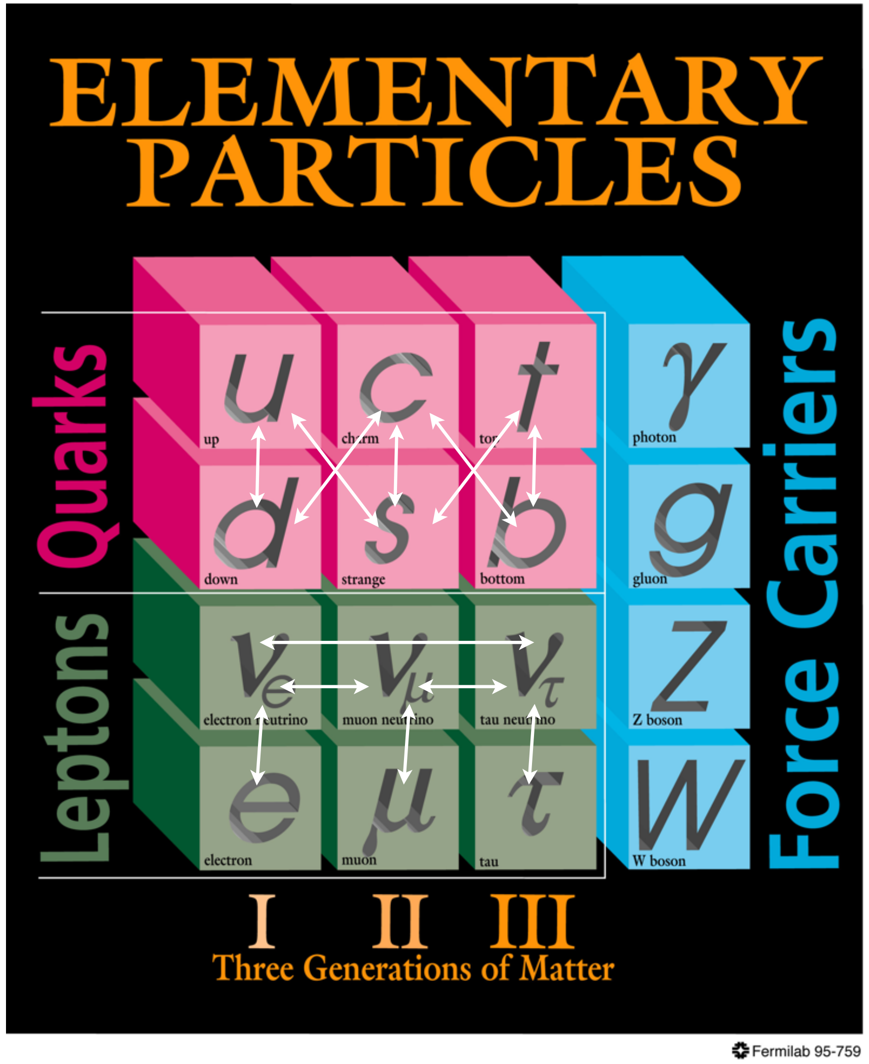
- CKM mechanism has been an incredible success: explain all quark flavor phenomena to date
- But… calculation shows that CKM is not enough to explain matter abundance in the Universe
  - Turn to leptons ?

Standard Model of Particle Physics

Complete description of matter and forces (other than gravity) ?

Three generations (families) of elementary particles

Four force carriers for E&M and weak interactions



Neutrinos mix and change their flavor

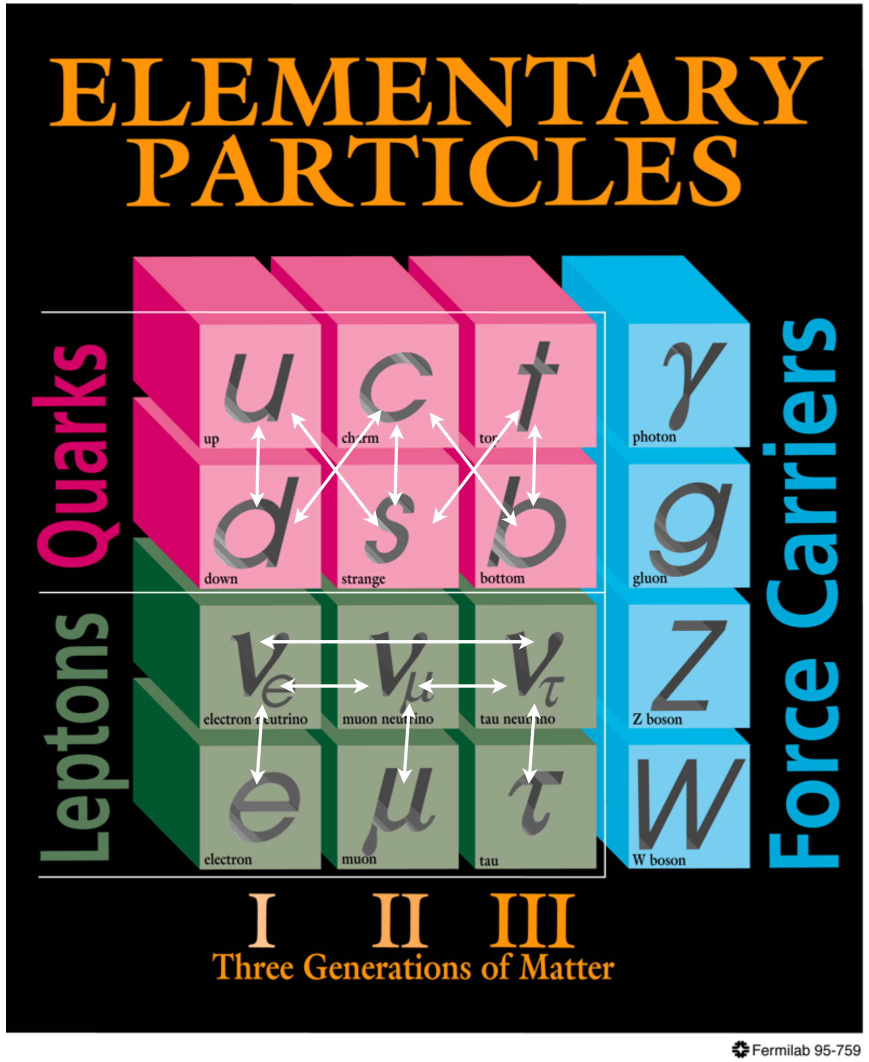
Neutrinos couple to charged leptons by weak interactions

Standard Model of Particle Physics

Complete description of matter and forces (other than gravity) ?

Three generations (families) of elementary particles

Four force carriers for E&M and weak interactions



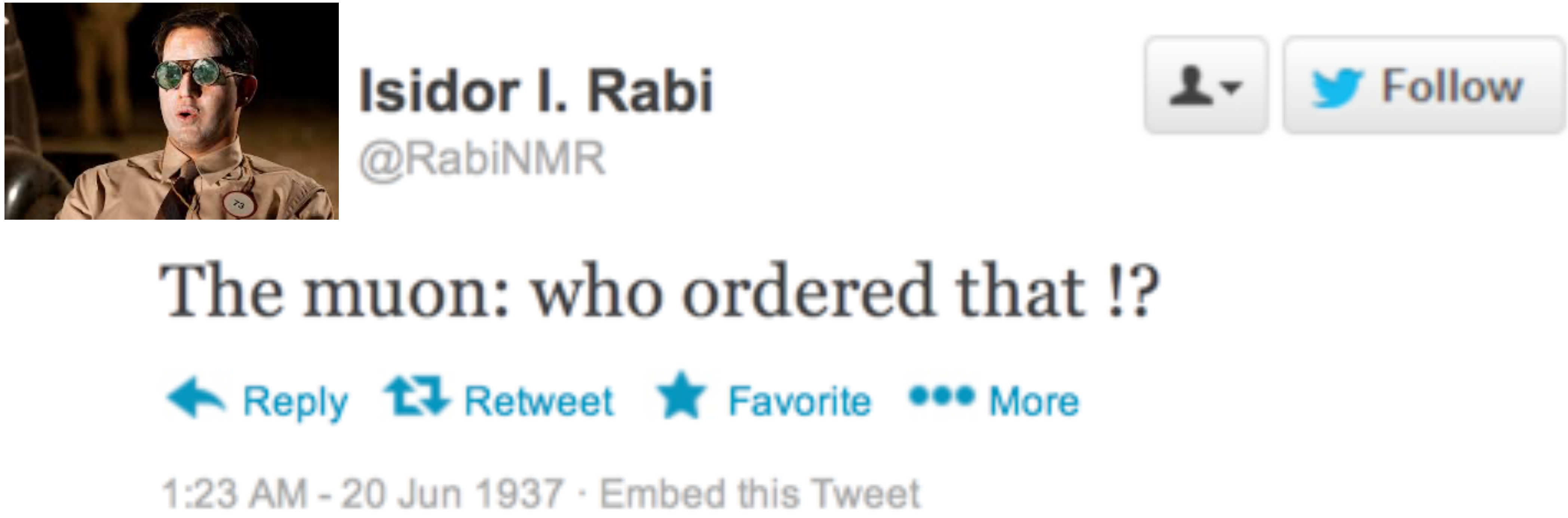
Neutrinos mix and change their flavor

Neutrinos couple to charged leptons by weak interactions

What about charged leptons ?

Long-Standing Question

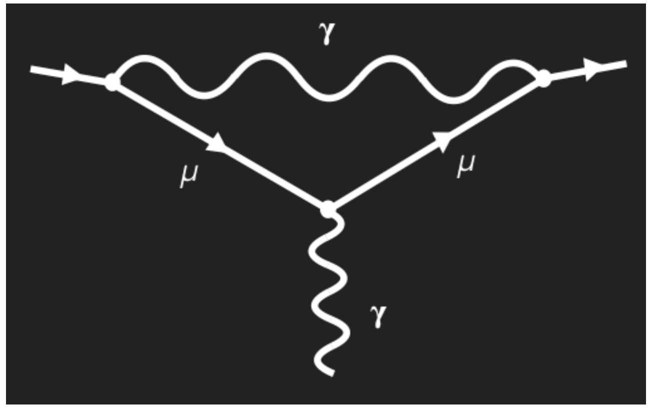
Long-Standing Question



What can we tell about leptons ?

- Weak interactions treat all leptons equally
  - “Lepton universality”
    - ☞ Muons and taus: “heavy cousins" of electrons
- Charged leptons are Dirac fermions: magnetic moment is related to spin as

$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$



    - ☞ g ≈ 2 up to small corrections
- Lepton flavor is (approximately) conserved

Muons: Important Tool

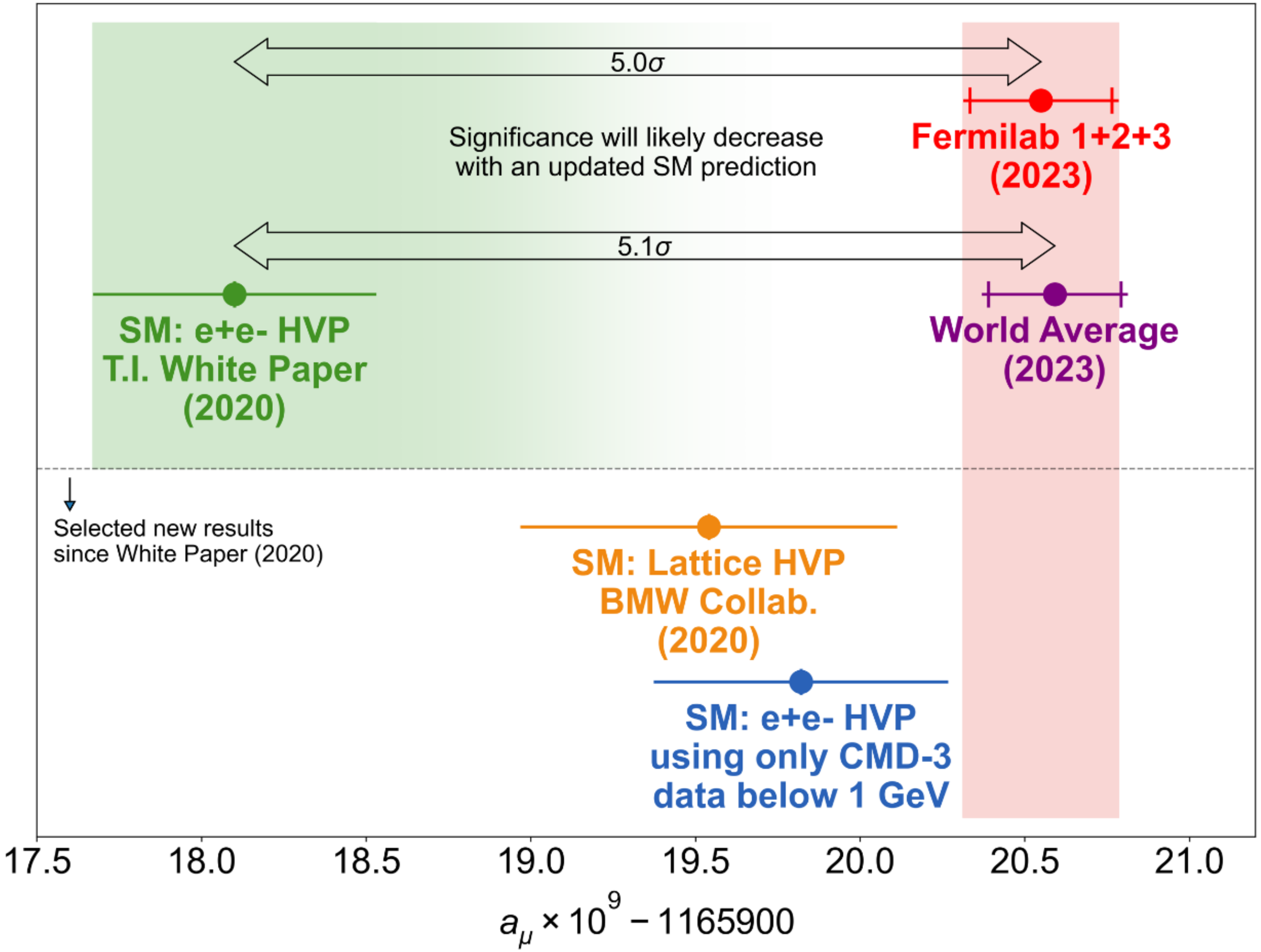
- Muons are here, now
  - ☞ One hits your iris every minute
- Since their discovery in cosmic rays in 1937, muons have provided
  - ❑ The first evidence for fermion generations
    - ☞ Evidence for >1 neutrino: BR($\mu \rightarrow e\gamma$)<10^{-4}
  - ❑ Decisive demonstration of time dilation
  - ❑ Best determination of the Fermi constant and indirect constraint on the W mass
  - ❑ Precision tests of V-A theory of weak interactions
  - ❑ Most precise measurement of the proton charge radius
  - ❑ Tantalizing hints for physics beyond the Standard Model

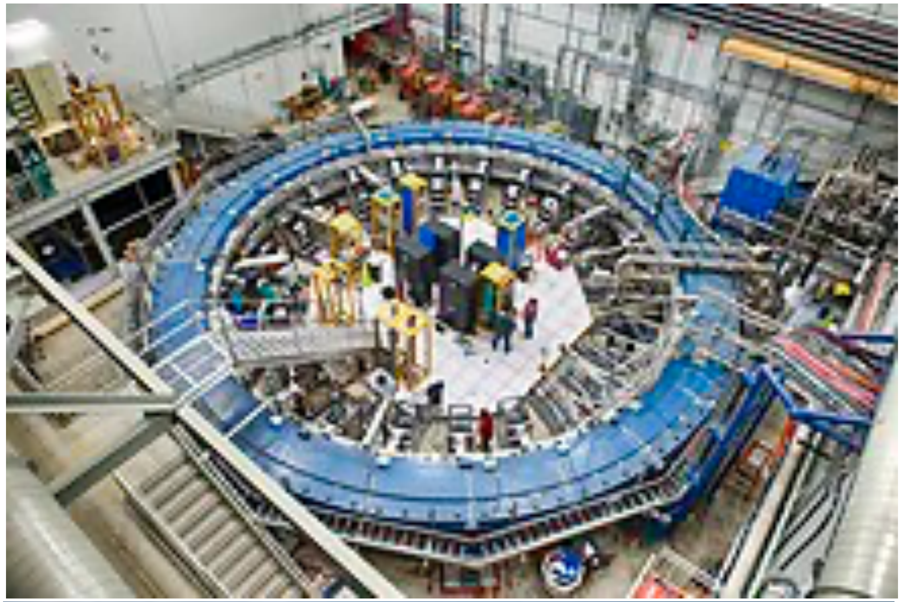
Charged Lepton Puzzles

- Muon anomalous magnetic moment
  - ☞ 5σ discrepancy vs the Standard Model (maybe)
- Proton radius measured with muons vs electrons
  - ☞ Went away
- Possible lepton universality violations in semileptonic B decays into muons and taus
  - ☞ $2\text{-}4\sigma$ effects, e.g. in $B \rightarrow D^{(*)}\tau\nu$

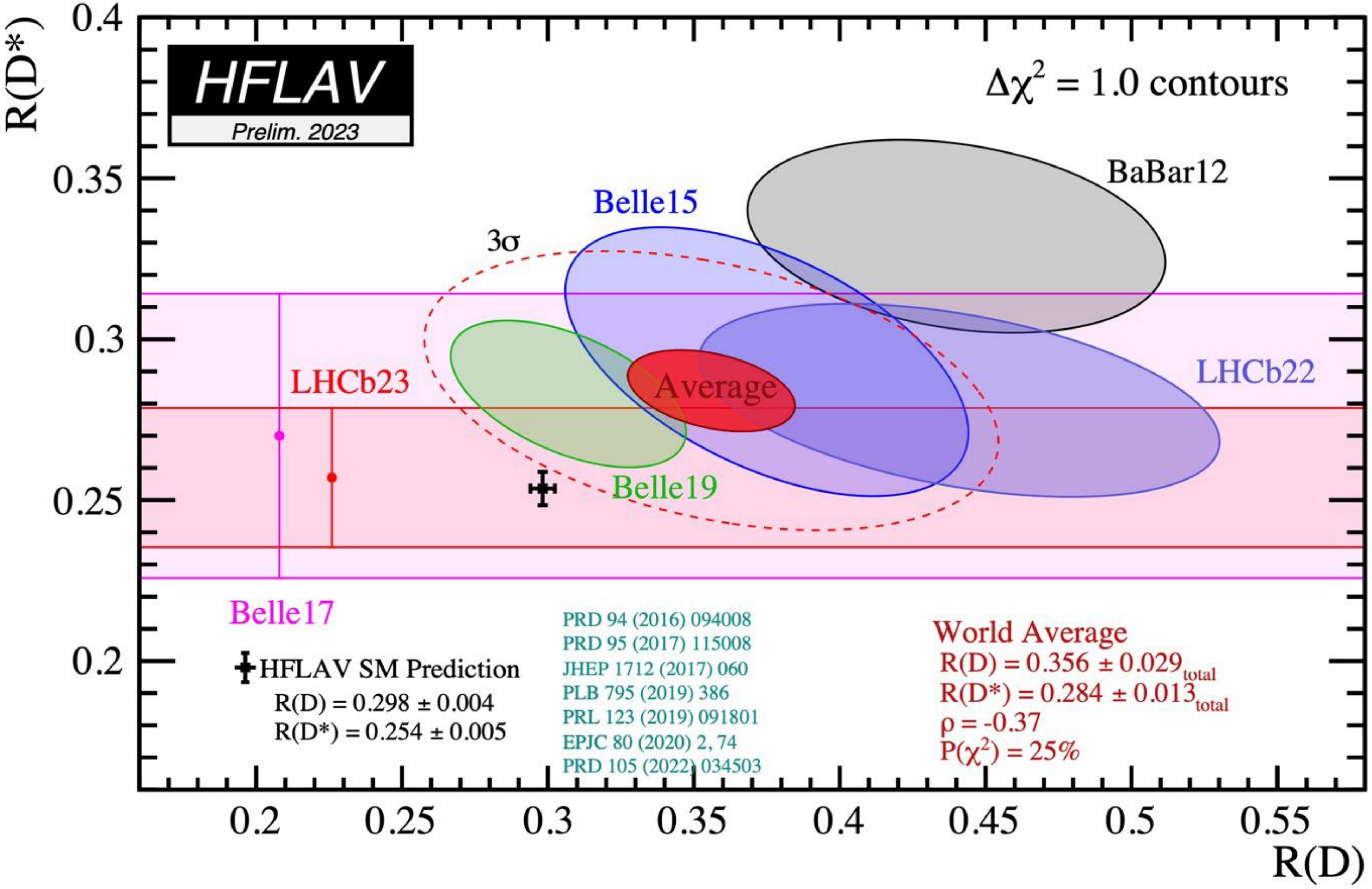
❑ Are studies of Lepton Flavor starting to show hints of New Physics ?

Muon g-2


5.0σ
Significance will likely decrease
with an updated SM prediction
Fermilab 1+2+3
(2023)
5.1σ
SM: e+e- HVP
T.I. White Paper
(2020)
World Average
(2023)
Selected new results
since White Paper (2020)
SM: Lattice HVP
BMW Collab.
(2020)
SM: e+e- HVP
using only CMD-3
data below 1 GeV
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
$a_\mu \times 10^9 - 1165900$

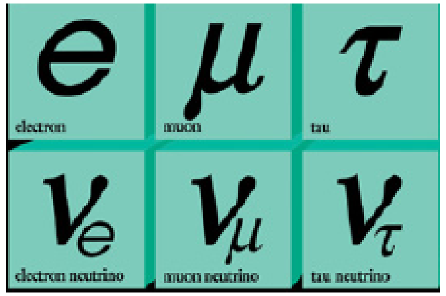


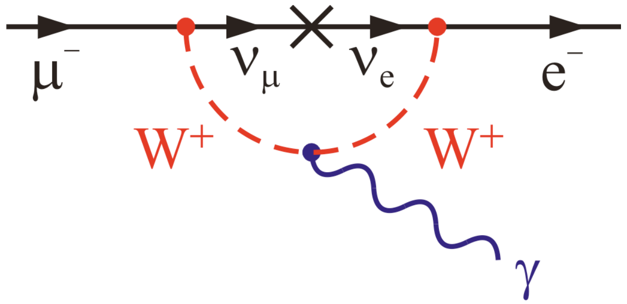
Lepton Universality Violations



$$R\left(D^{(*)}\right) = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\ell\nu)}$$

Charged Lepton Flavor Violation

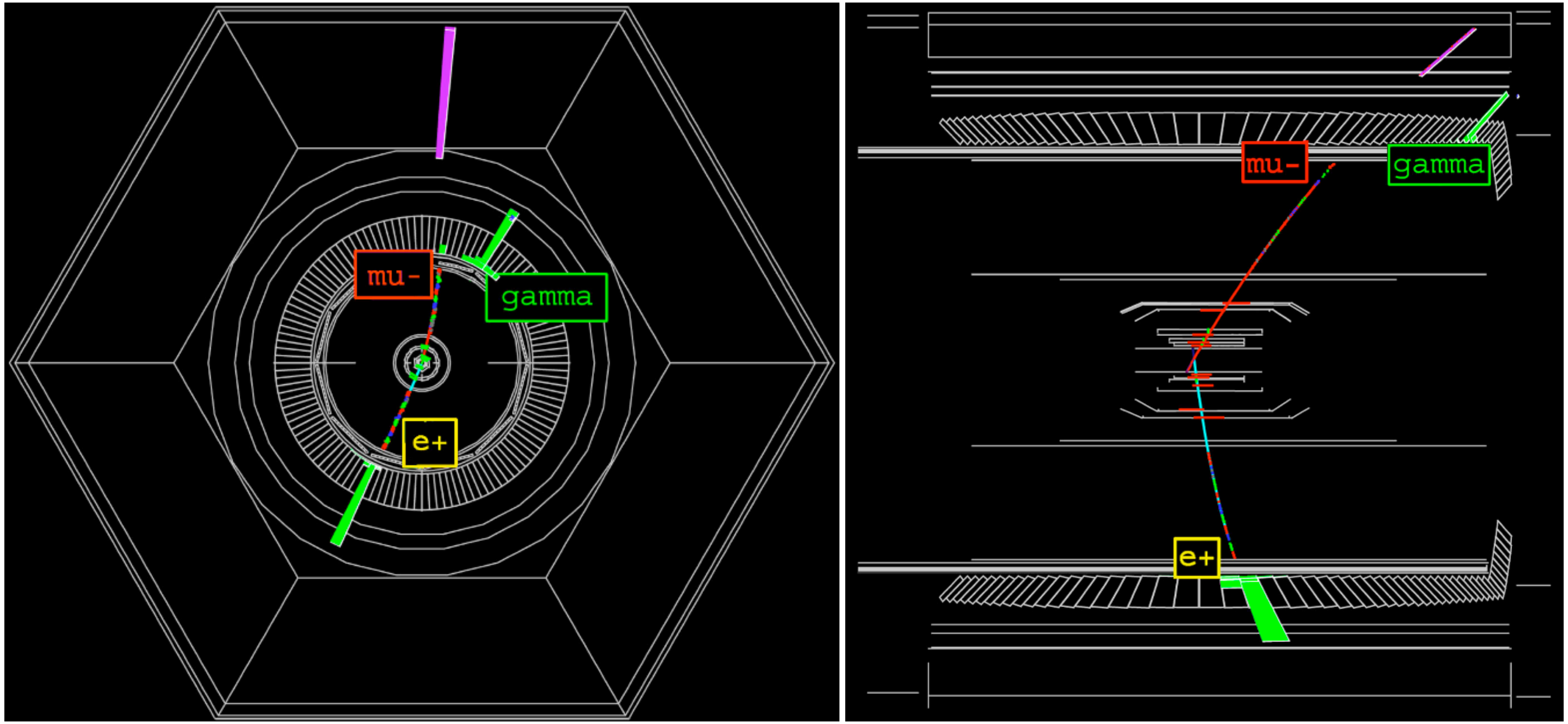




- Charged Lepton flavor: accidental symmetry in the Standard Model
  - Lepton flavor violation forbidden if neutrinos are massless
    - ☞ Very small SM effect due to finite neutrino mass: $BR(\mu \rightarrow e\gamma) \sim 10^{-52}$
- CLFV: an unambiguous signature of new physics
  - ☞ Sensitivity to mass scales far beyond the reach of direct searches
  - ☞ Window into TeV physics and beyond, complementary to the LHC
  - ☞ Next generation experiments will have sensitivity to directly test predictions of many BSM theories, e.g. SUSY

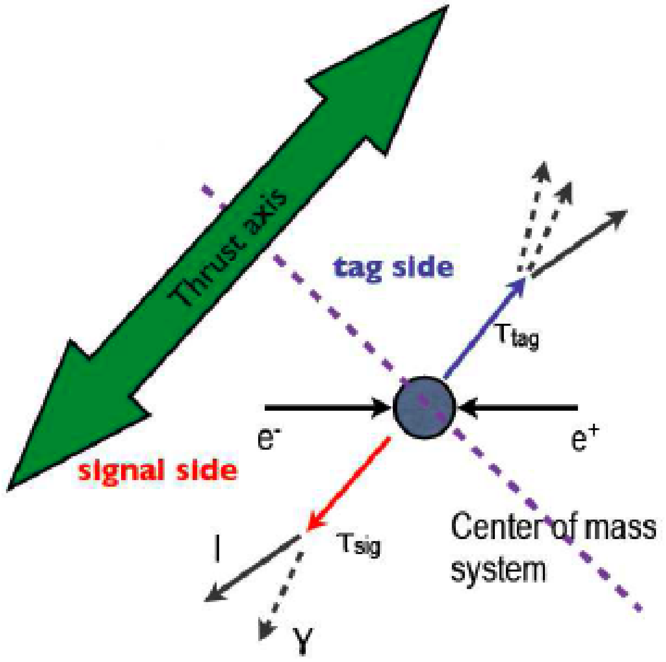
LFV Processes at a Collider

BaBar $\tau \to \mu\gamma$ simulation



Taus produced in pairs: $e^+e^- \to \tau^+\tau^-$, before taus decay. Use one side to tag the process, the other to look for LFV. Obvious signature: two leptons of different flavor in the final state.

Search Strategy



- Select a large clean sample of "tag" tau decays
  - Clean leptonic and hadronic tau decays: "1-prong" and "3-prong"
    - ☞ $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to \pi\nu$, $\tau \to \rho\nu$, $\tau \to 3\pi\nu$
- Look for LFV decays of the "other" τ
  - Typically a fully-reconstructed final state
    - ☞ $\tau \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to lll$, $\tau \to lh^0$
- Take advantage of kinematics (known beam energy): define

$$\Delta E \equiv E^*_{rec} - E^*_{beam};$$

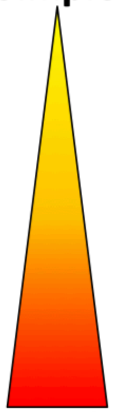
$$\Delta M_{ec} \equiv M_{rec} - m_\tau = \sqrt{\frac{E^{*\,2}_{beam}}{c^4} - \frac{|\vec{p^*_{3l}}|^2}{c^2}} - m_\tau$$

CLFV in Tau Decays

Search various decay modes:

- $\tau \to \ell\ell\ell$
- $\tau \to \ell K_S, \Lambda h$
- $\tau \to \ell V^0(\to hh')$
- $\tau \to \ell P^0\ (\to \gamma\gamma)$
- $\tau \to \ell hh'$
- $\tau \to \ell\gamma$

Simple



Hard

Difficulty of background reduction

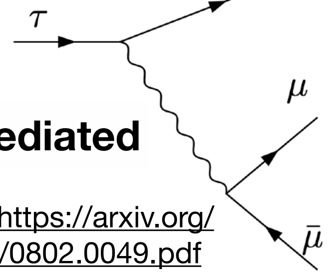
→ Good determination of τ mass and energy + few SM background sources

→ Tough determination of τ mass and energy + irreducible SM backgrounds

Golden channel: $\tau \to \mu\mu\mu$

experimentally the most accessible

ref: https://arxiv.org/pdf/1808.10567.pdf



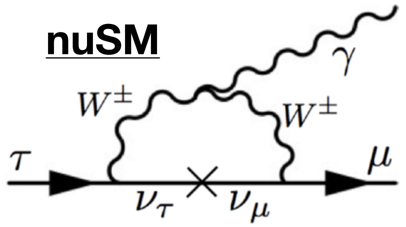
Z' mediated

ref: https://arxiv.org/pdf/0802.0049.pdf

Golden channel: $\tau \to \mu\gamma$

Largest BF in models where a one-loop diagram is involved

nuSM



Ref: https://arxiv.org/pdf/1301.4652.pdf

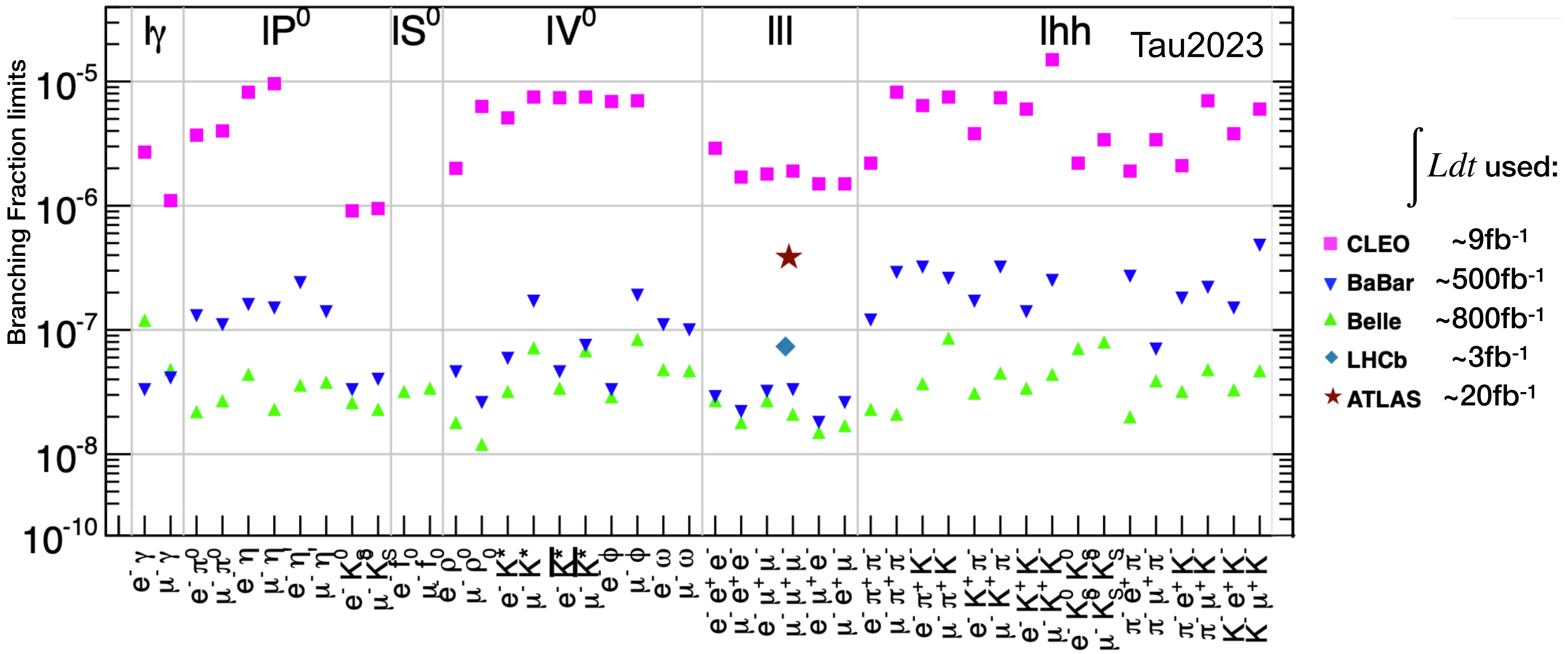
Physics models	$B(\tau \to \mu\gamma)$	$B(\tau \to \mu\mu\mu)$
SM + ν mixing	$10^{-49} \sim 10^{-52}$	$10^{-53} \sim 10^{-56}$
SM+heavy Majorana ν_R	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY SO(10)	10^{-8}	10^{-10}
mSUGRA + seesaw	10^{-7}	10^{-9}
SUSY Higgs	10^{-10}	10^{-7}

Ref: https://arxiv.org/abs/hep-ph/0702136

An observation would be a clear signature of NP!

17th International Workshop on τ Lepton Physics: τ2023 - Alberto Martini for Belle II - 5 December 2023, Louisville Kentucky USA

Summary of LFV in Tau Decays

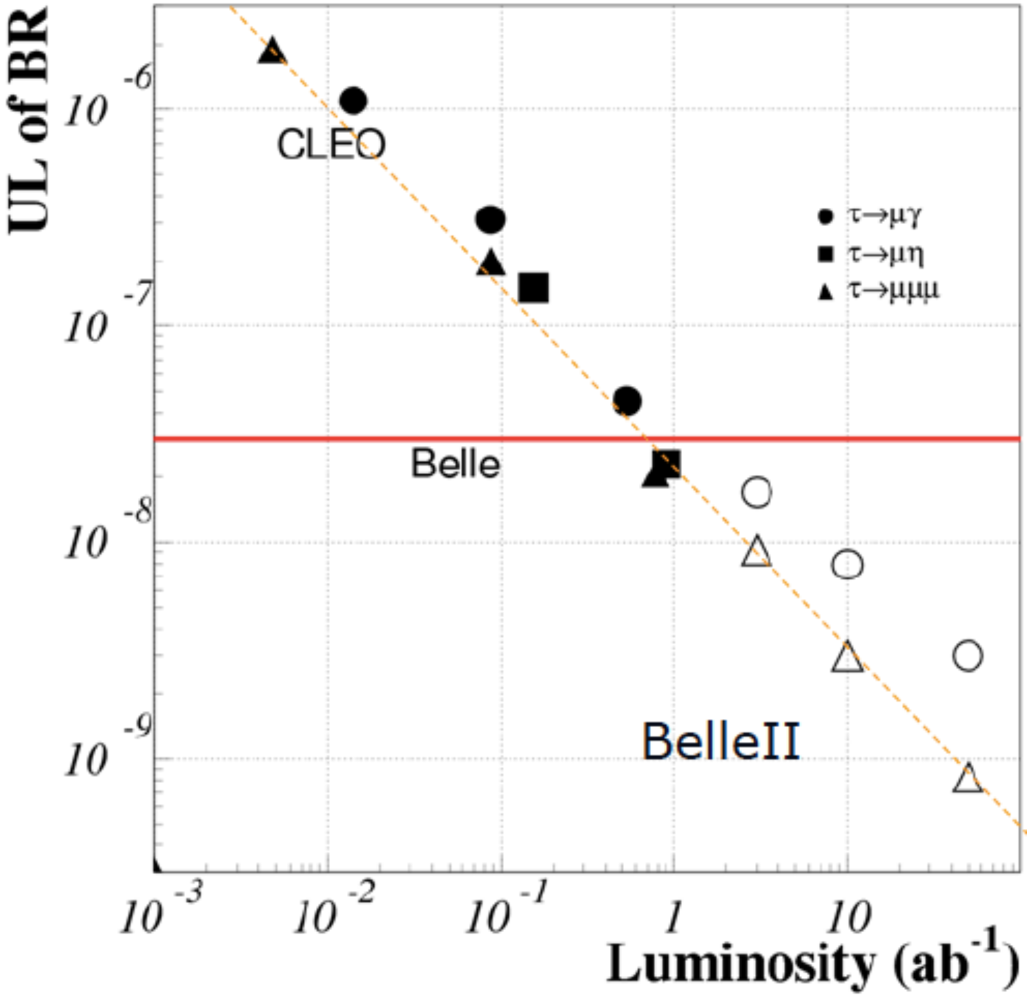


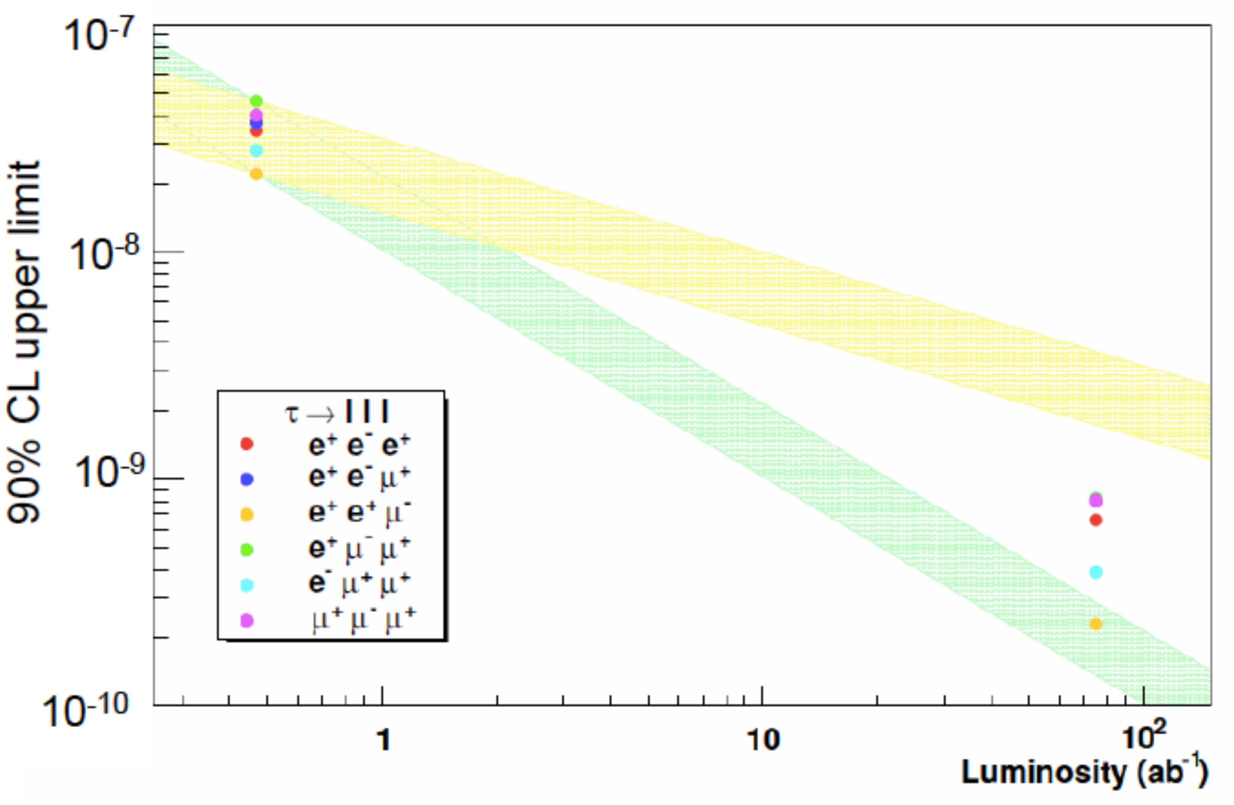
Comprehensive search with 48 decay modes: leptonic and hadronic

Several modes with nearly zero backgrounds

LHCb sensitivity comparable to B-Factories for leptonic modes

Projected Sensitivities





The no-background regime improves as $1/\int L\,dt$

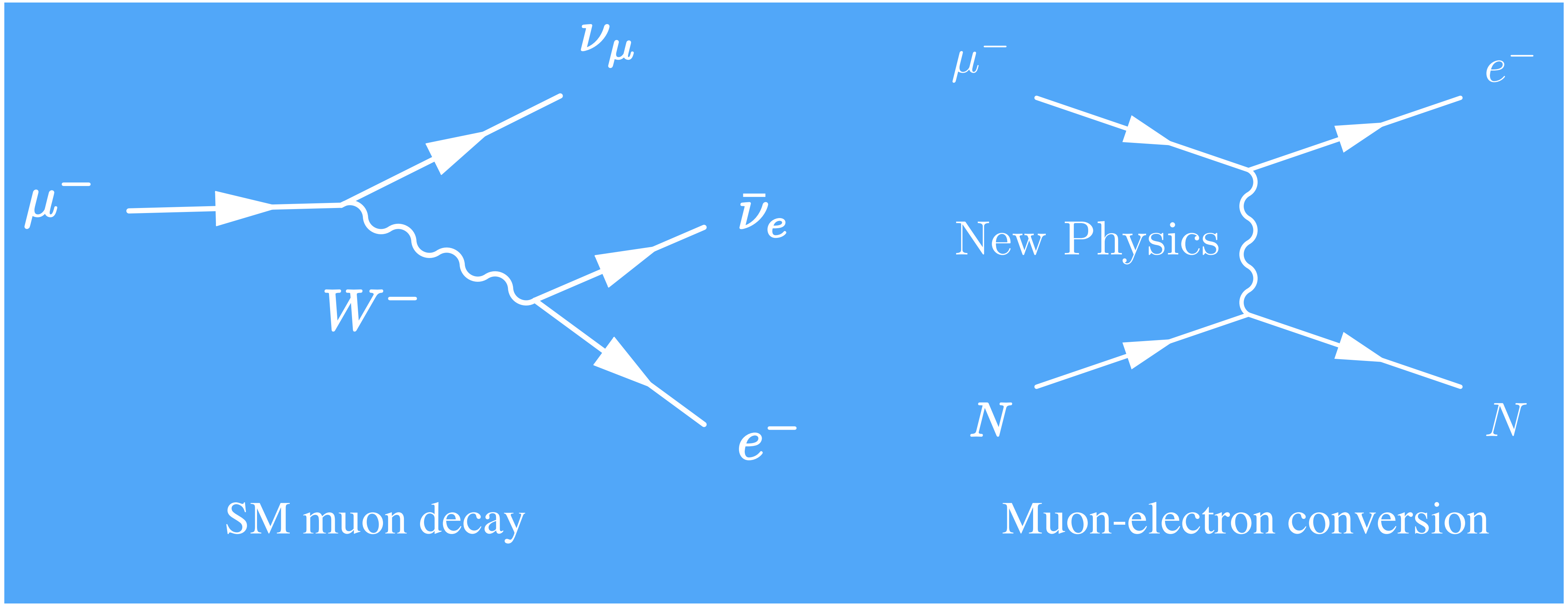
If there are background events, the improvement is $1/\sqrt{\int L\,dt}$

C. Cecci @ NuFact 2015

CLFV in Muon Decays

- Advantage: high-intensity muon sources are available
  - Very large statistical samples
- (Potential) disadvantage: 2nd generation
  - ☞ Typically need to reach significantly lower branching ratios for comparable sensitivity to tau decays
  - ☞ However, statistics is winning at this point
- Several channels of interest
  - ☞ $\mu \rightarrow e\gamma$
  - ☞ $\mu \rightarrow e$ conversion in nuclear field
  - ☞ $\mu \rightarrow eee$

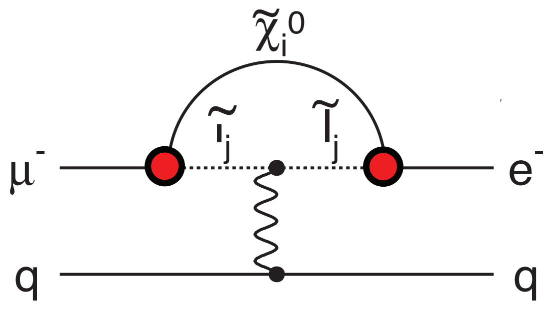
Neutrinoless Muon-Electron Conversion



Possible New Physics Contributions

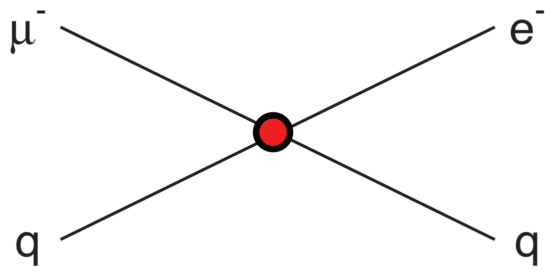
Supersymmetry

rate ~ 10^{-16} - 10^{-15}



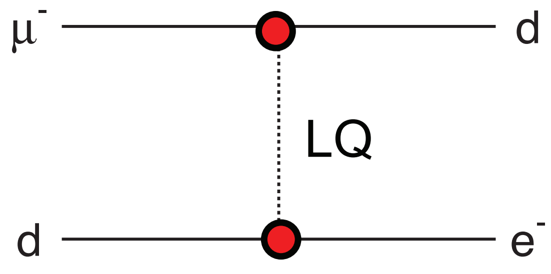
Compositeness

Λ_c ~ 7000 TeV



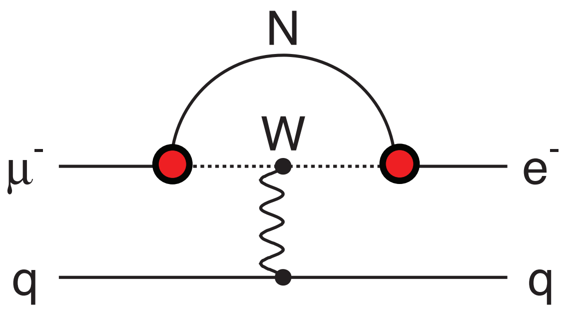
Leptoquark

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



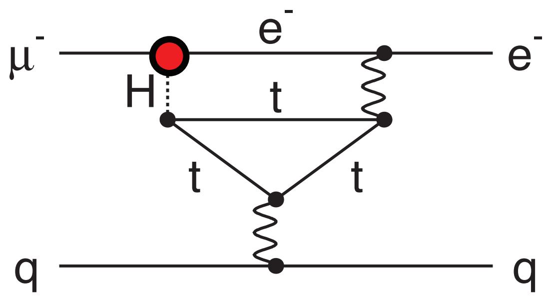
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



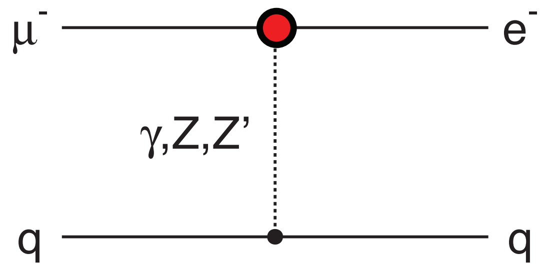
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4} g(H_{\mu\mu})$



Heavy Z' Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/c^2



Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58

Sensitivity to New Physics

★ Vanishingly small effects

★★ Moderate, but visible effects

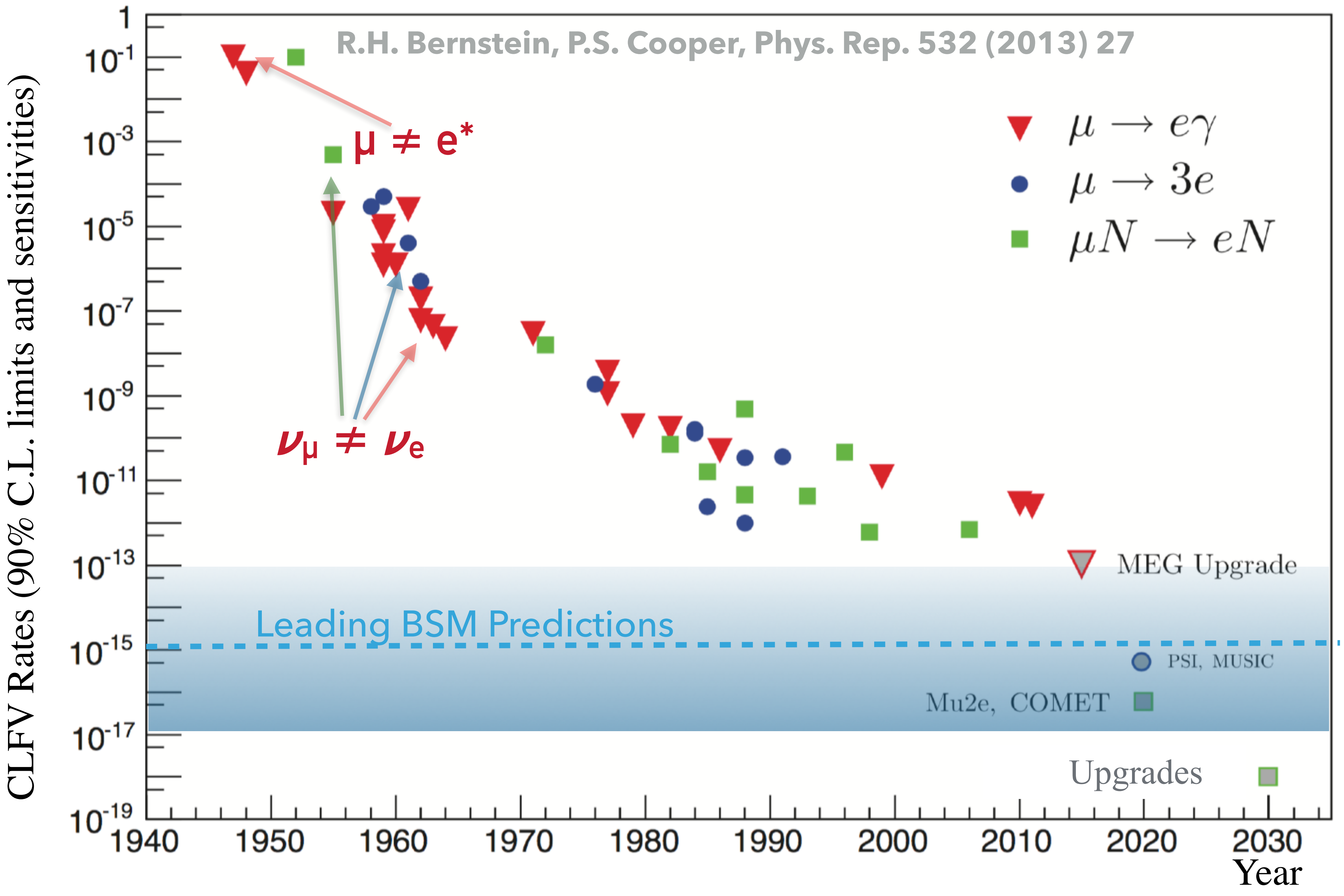
★★★ Large effects

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

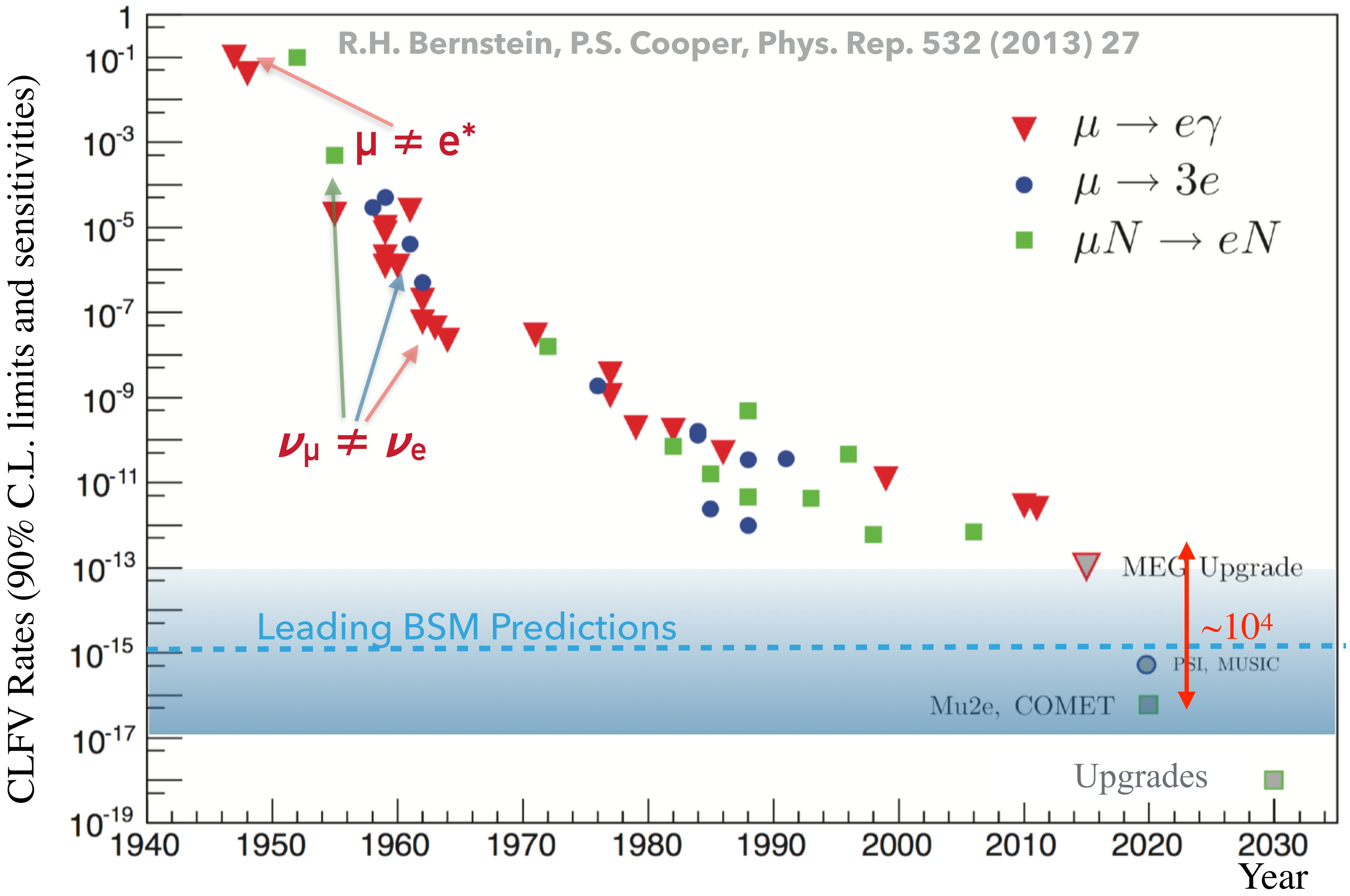
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to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

Altmannshofer, Buras, *et al*, **Nucl.Phys.B830:17-94, 2010**

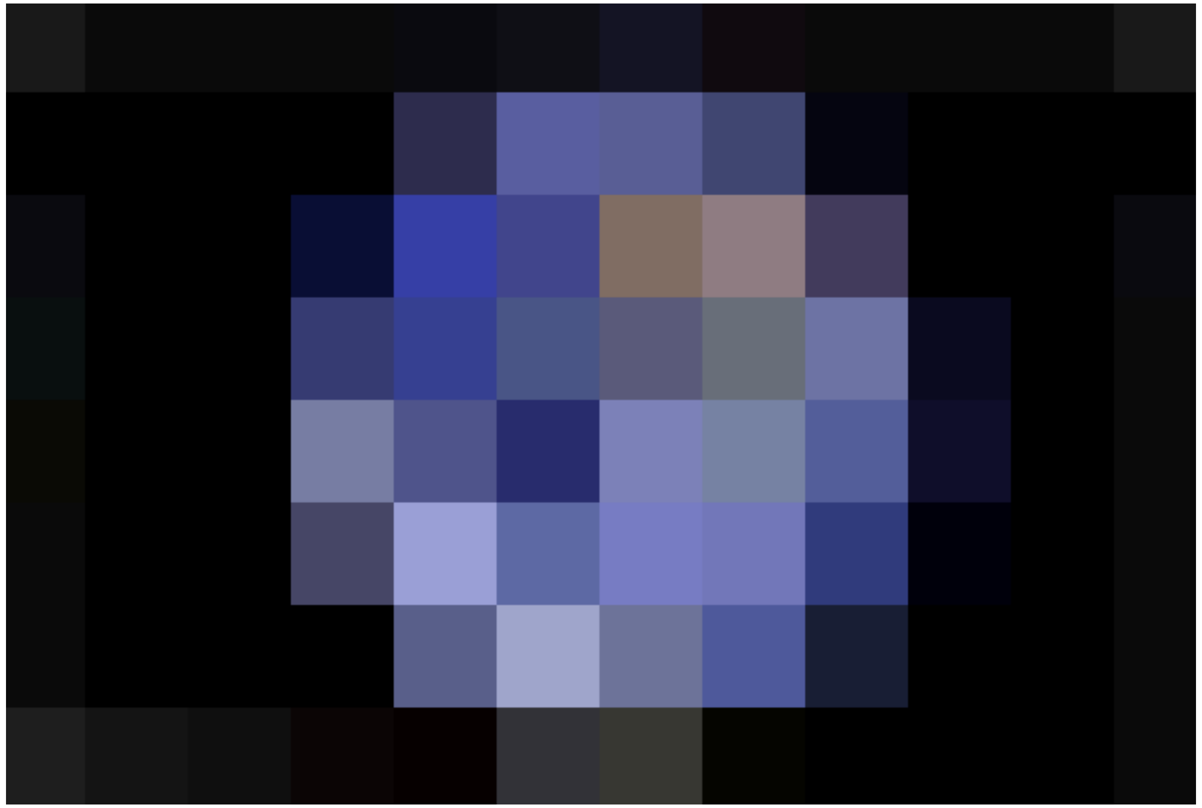
Entering Interesting Regime



Entering Interesting Regime



Four Orders of Magnitude



Credit: Jason Bono, Nina Hazen

Four Orders of Magnitude

Credit: Jason Bono, Nina Hazen

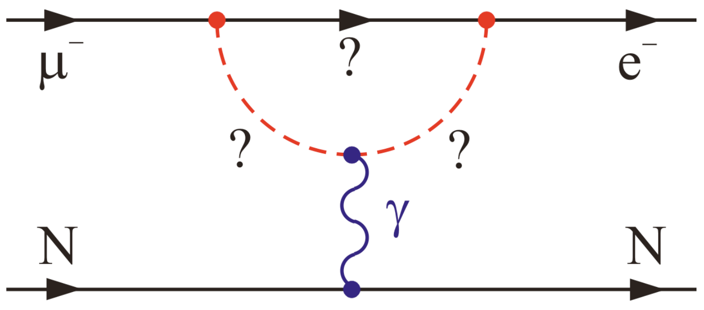
10^4 increase in fidelity reveals rich structure

$\mu^- N \rightarrow e^- N'$ and $\mu^+ \rightarrow e^+\gamma$ Complementary

Model independent CLFV Lagrangian:

(A. de Gouvea)

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma^\mu q_L$$

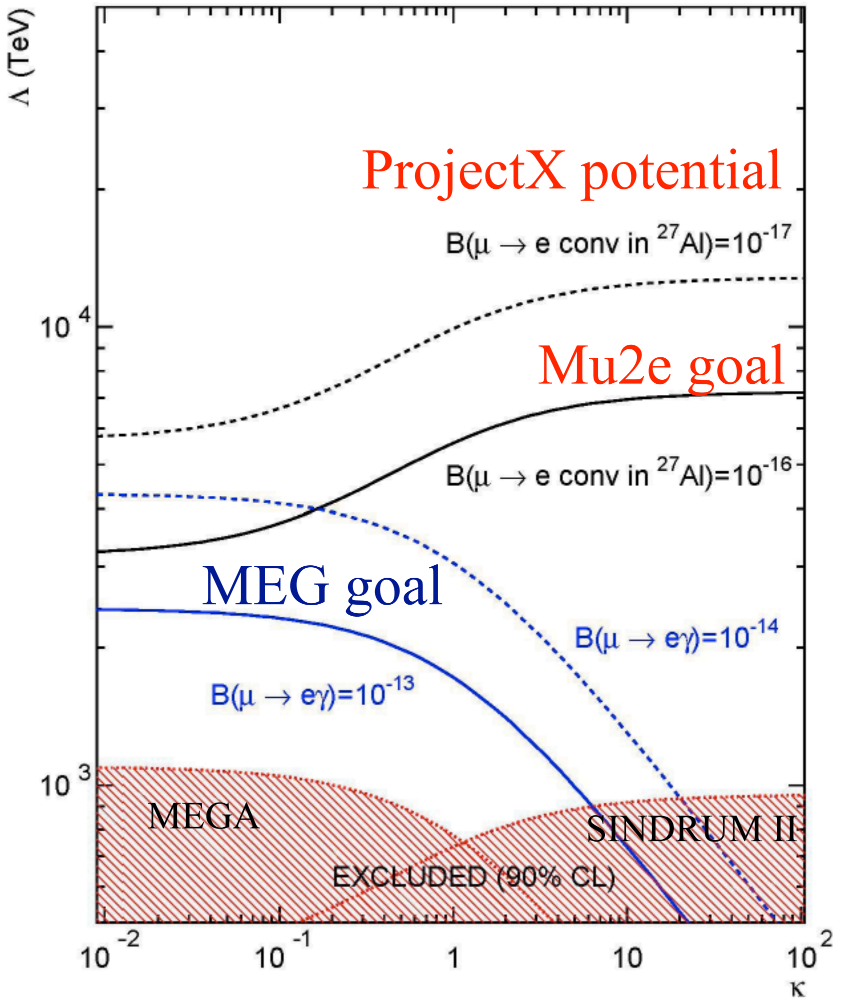


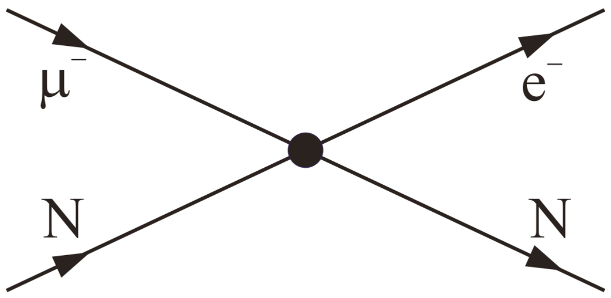
κ<<1

magnetic moment type operator

$\mu \rightarrow e\gamma$ rate ~300x

$\mu N \rightarrow eN'$ rate





κ>>1

four-fermion interaction

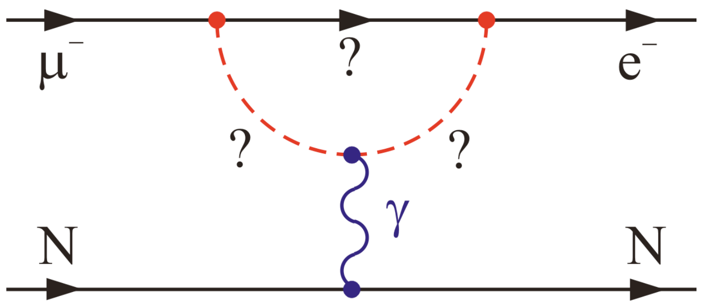
$\mu N \rightarrow eN'$ greatly enhanced over $\mu \rightarrow e\gamma$ rate

μ⁻N→e⁻N' and μ⁺→e⁺γ Complementary

Model independent CLFV Lagrangian:

(A. de Gouvea)

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}R\sigma_{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma^\mu q_L$$

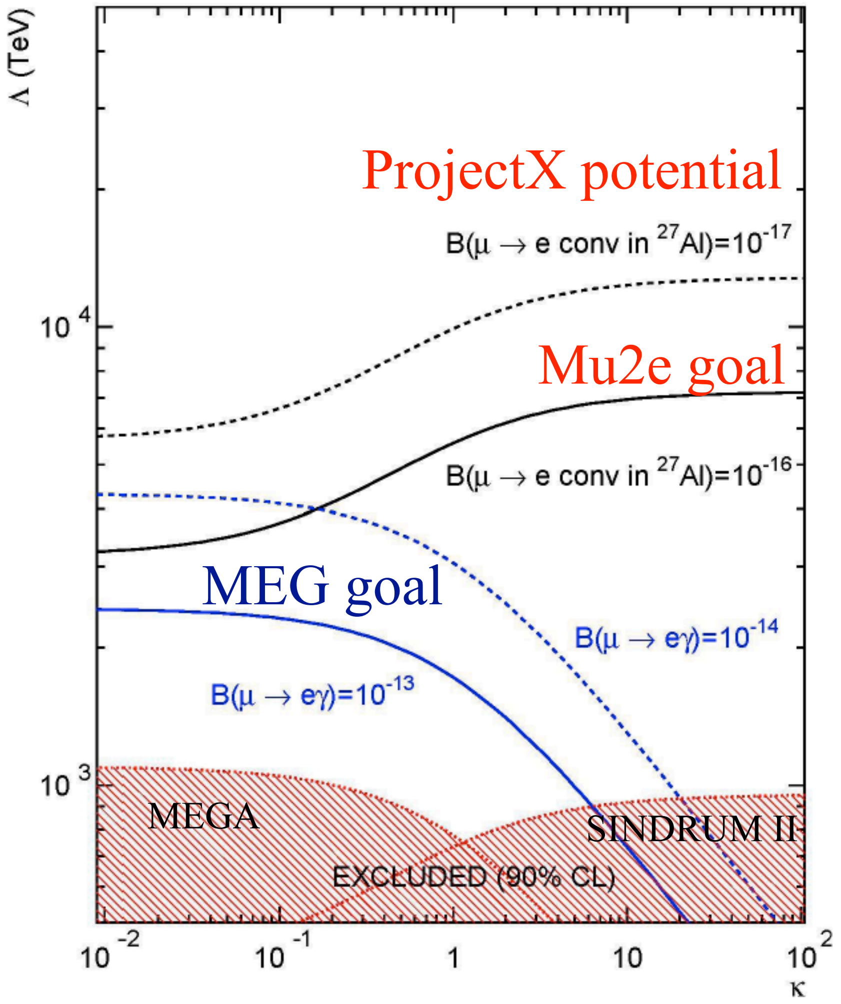


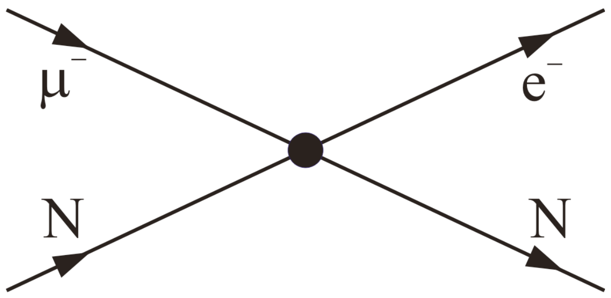
κ<<1

magnetic moment type operator

μ → eγ rate ~300x

μN → eN' rate





κ>>1

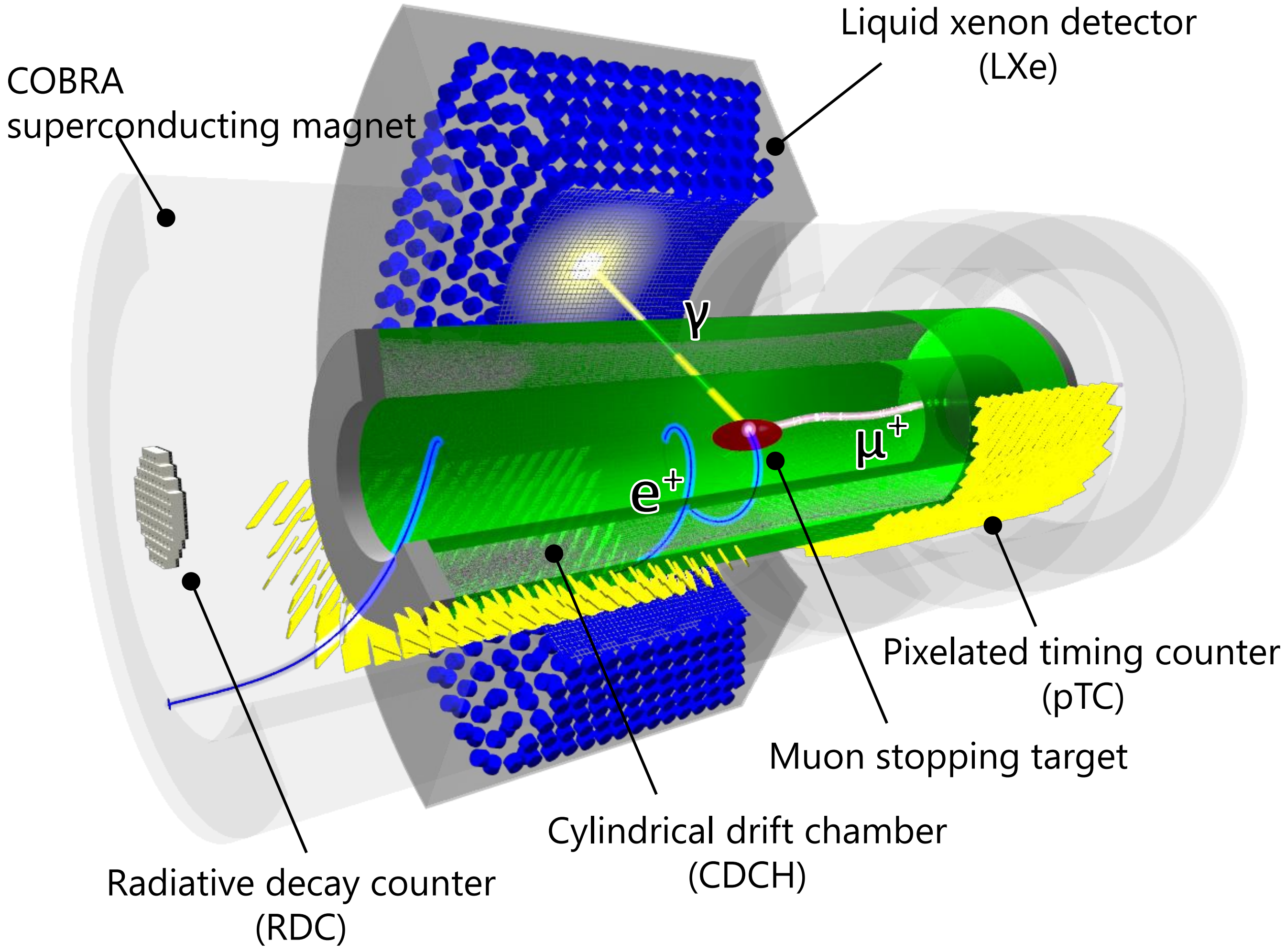
four-fermion interaction

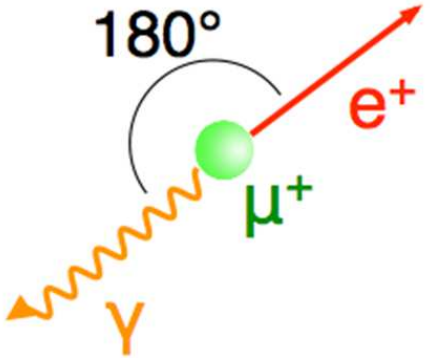
μN → eN' greatly enhanced over μ → eγ rate

Similarly, complementary information from μ and τ searches

MEG: Search for $\mu^+ \to e^+\gamma$

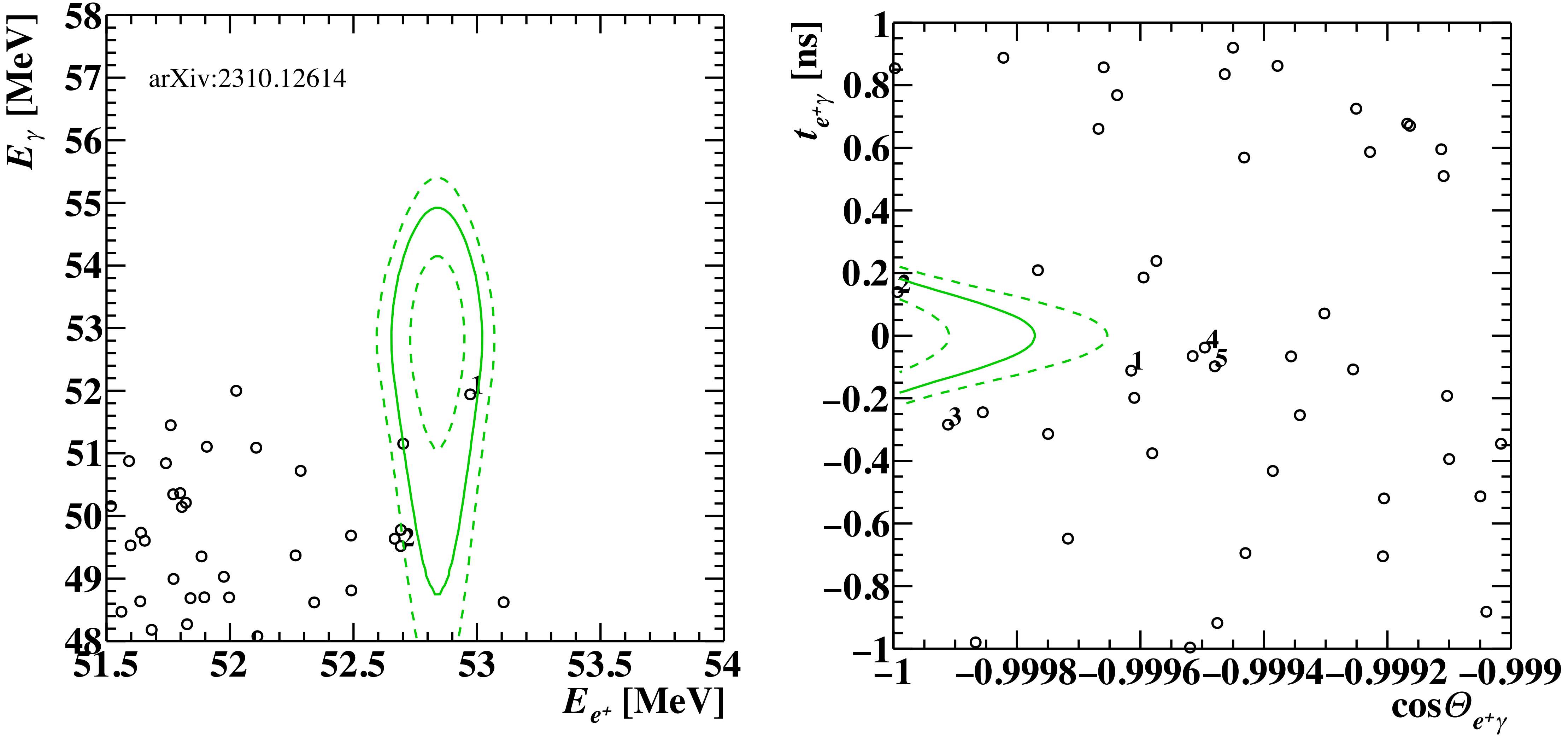
MEG, MEG-II (PSI)





Eur. Phys. J. C (2013) 73:2365

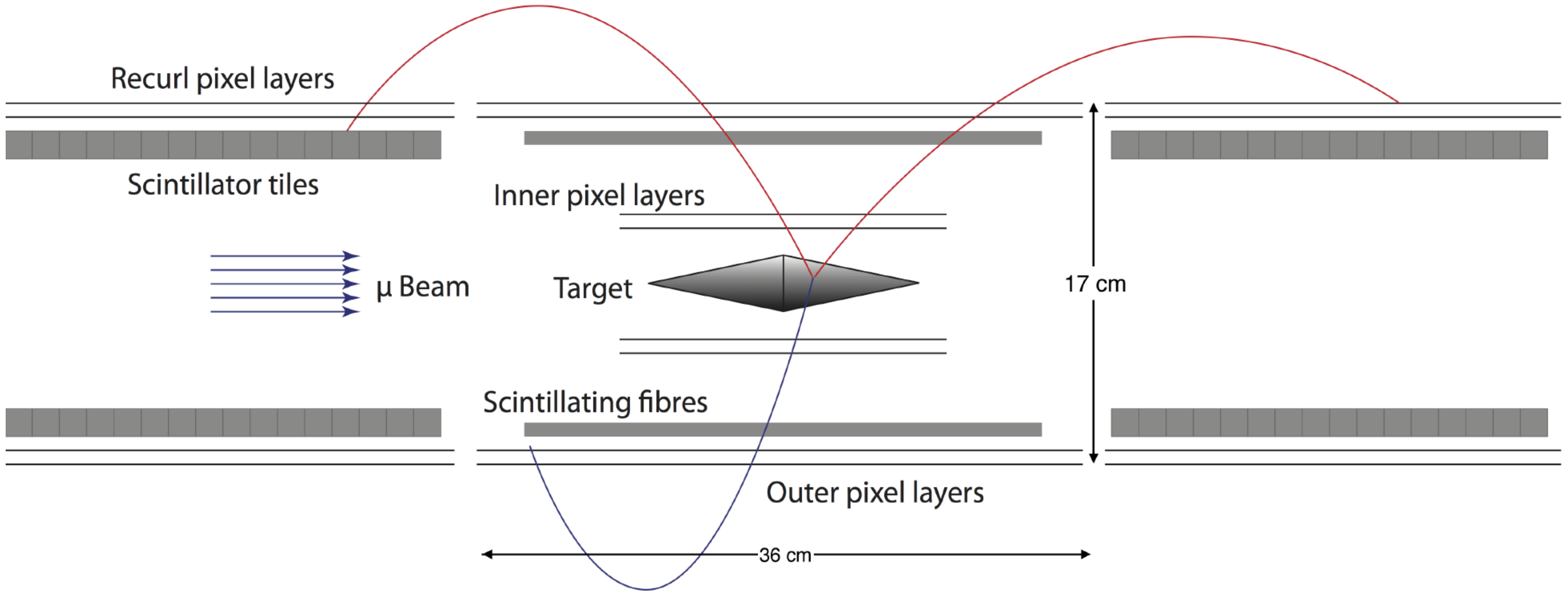
MEG-II Results



$B(\mu^+ \to e^+\gamma) < 3.1\times10^{-13}$ (combined MEG and MEG-II)

$\mu \to$ eee: Mu3e Experiment

- Mu3e is a dedicated experiment searching for $\mu^+ \to e^+e^-e^+$
- aimed sensitivity $\mathcal{B}(\mu \to eee) < 10^{-16}$
- stopped muons per second: 10^9
- main background: $\mu \to eee\nu_e\nu_\mu$, with $\mathcal{B} = 3.4 \cdot 10^{-5}$ and accidentals
  - Phase Ib: muon stopping $\sim 10^8\ \mu^+/s$ (2017)
  - central module upgraded with 250 µm diameter scintillation fibres (three layers)
  - two additional recurl modules including pixel and scintillation tiles $\Rightarrow$ better timing

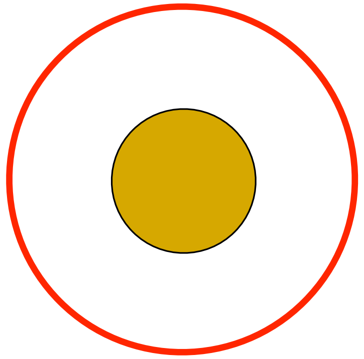


Muon→Electron Conversion

μ^- stops in thin Al foil

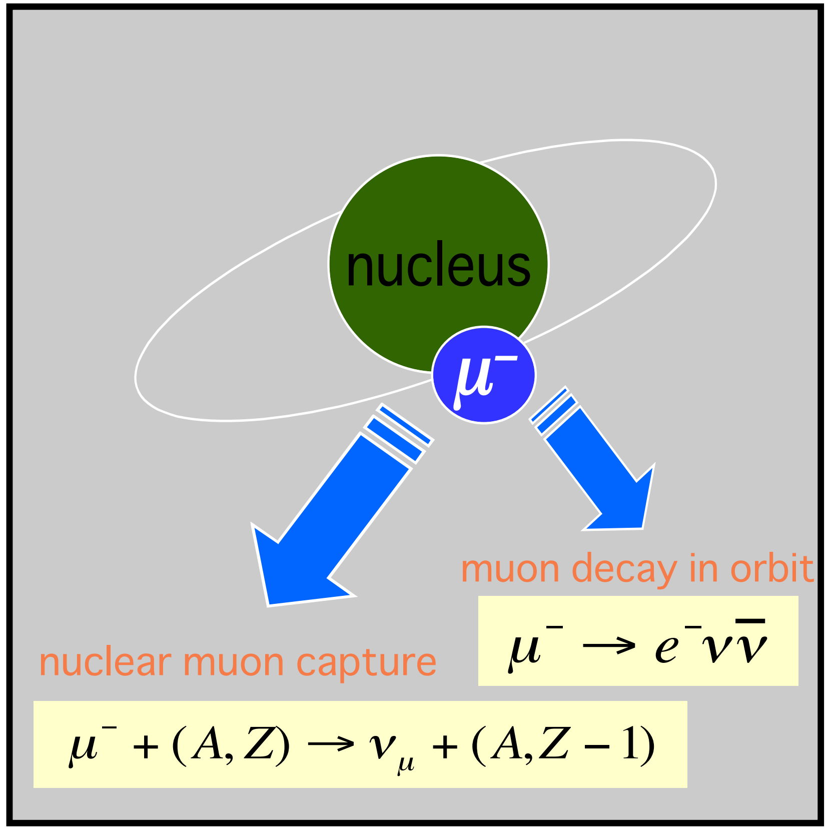
the Bohr radius is ~ 20 fm, so
the μ^- sees the nucleus

μ^- in 1S state



Al Nucleus
~4 fm

muon capture,
muon "falls into"
nucleus:
normalization



60% capture
40% decay

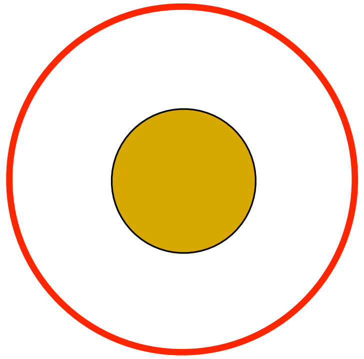
Decay in Orbit:
background

Muon→Electron Conversion

μ^- stops in thin Al foil

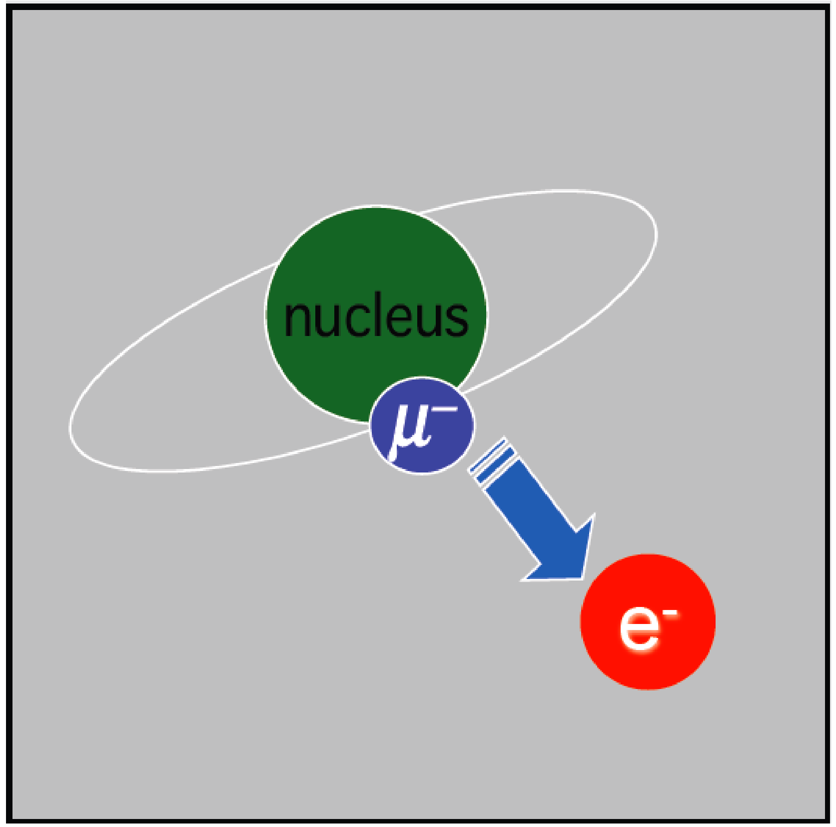
the Bohr radius is ~ 20 fm, so the μ^- sees the nucleus

μ^- in 1S state



Al Nucleus ~4 fm

muon capture, muon “falls into” nucleus: ***normalization***



60% capture
40% decay

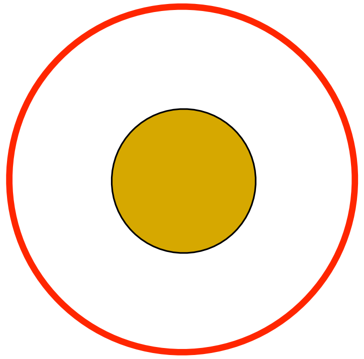
Muon conversion: signal

Muon→Electron Conversion

μ^- stops in thin Al foil

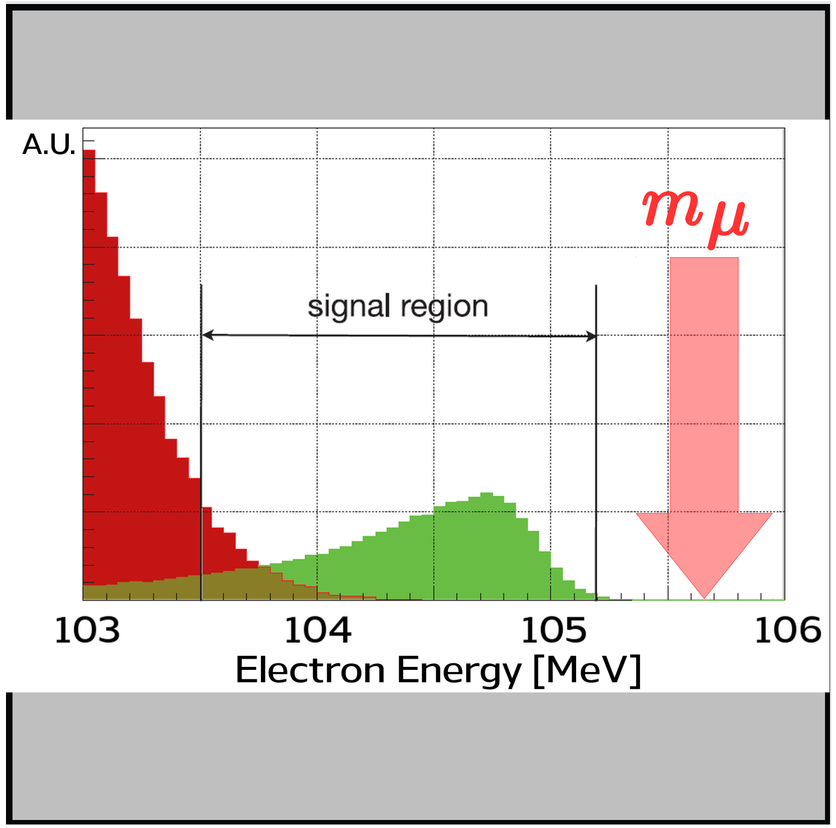
the Bohr radius is ~ 20 fm, so
the μ^- sees the nucleus

μ^- in 1S state



Al Nucleus
~4 fm

muon capture,
muon “falls into” nucleus:
normalization



60% capture
40% decay

Muon conversion:
signal

$\mu \to e$ Conversion Experiments

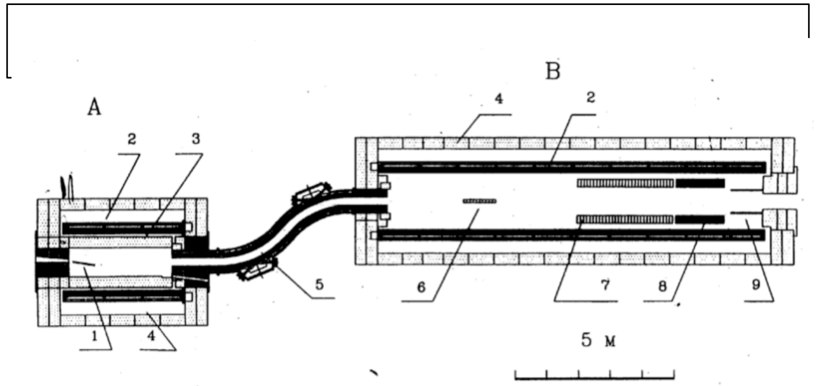
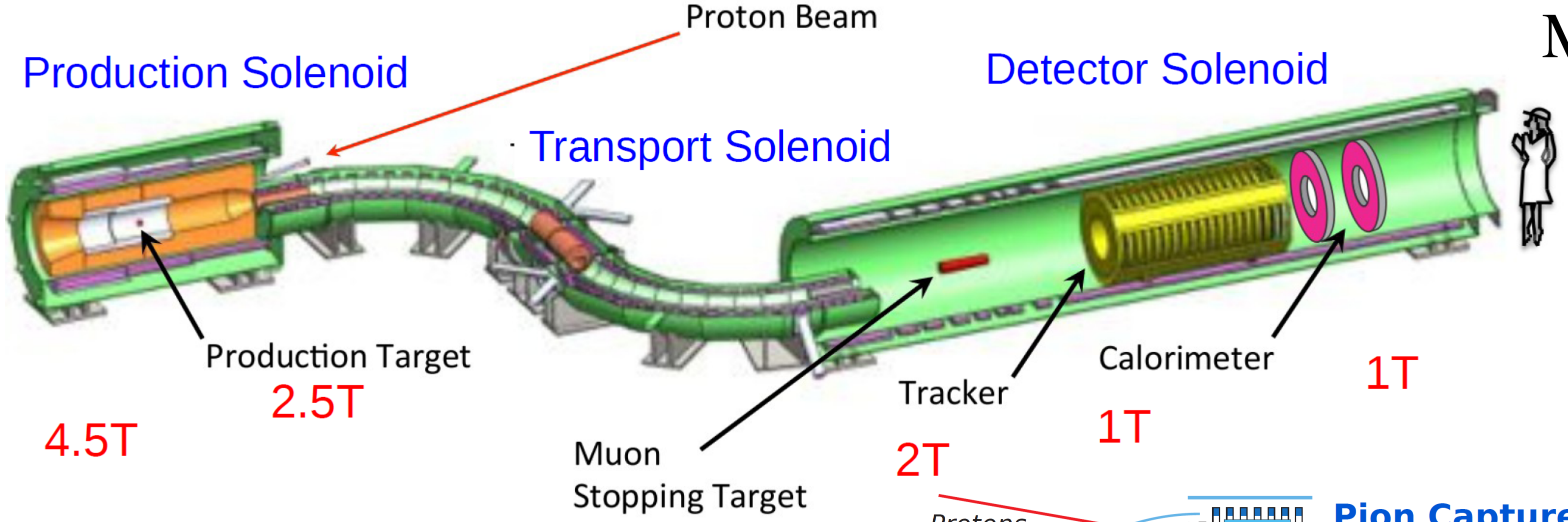


Fig. 1. Set-up MELC: A – meson-production part, B – detector part.
1 – tungsten target of the meson-production part (T_1),
2 – big superconducting solenoids, 3 – protection of the solenoid against radiation,
4 – steel magnetic circuit, 5 – solenoid-collimator,
6 – aluminium-target of the detector part (T_2),
7 – coordinate detector,
8 – total absorption scintillation spectrometer,
9 – protection of the detector against background.

V. Lobashev, MELC 1992

$\mu\rightarrow$e Conversion Experiments

Mu2e (FNAL)



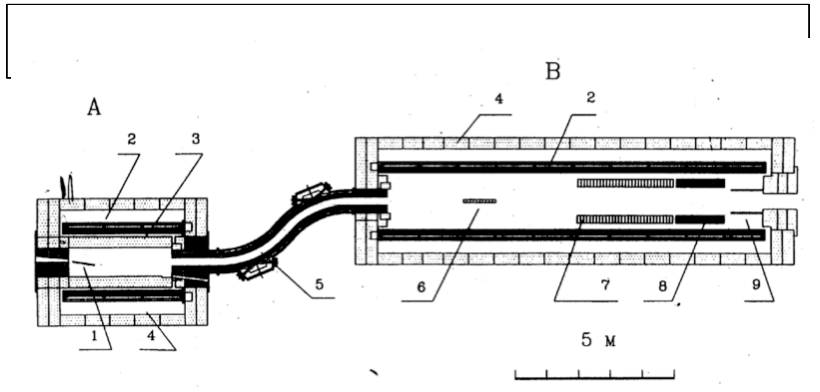
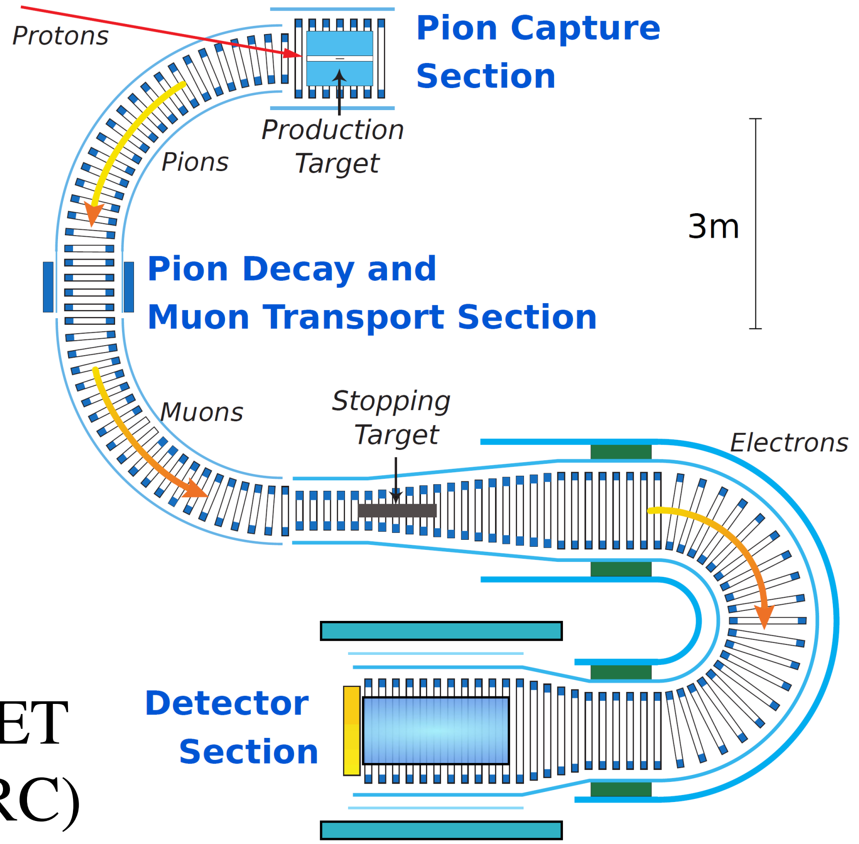


Fig. 1. Set-up MELC: A – meson-production part, B – detector part.
1 – tungsten target of the meson-production part (T_1),
2 – big superconducting solenoids, 3 – protection of the solenoid against radiation,
4 – steel magnetic circuit, 5 – solenoid-collimator,
6 – aluminium-target of the detector part (T_2),
7 – coordinate detector,
8 – total absorption scintillation spectrometer,
9 – protection of the detector against background.

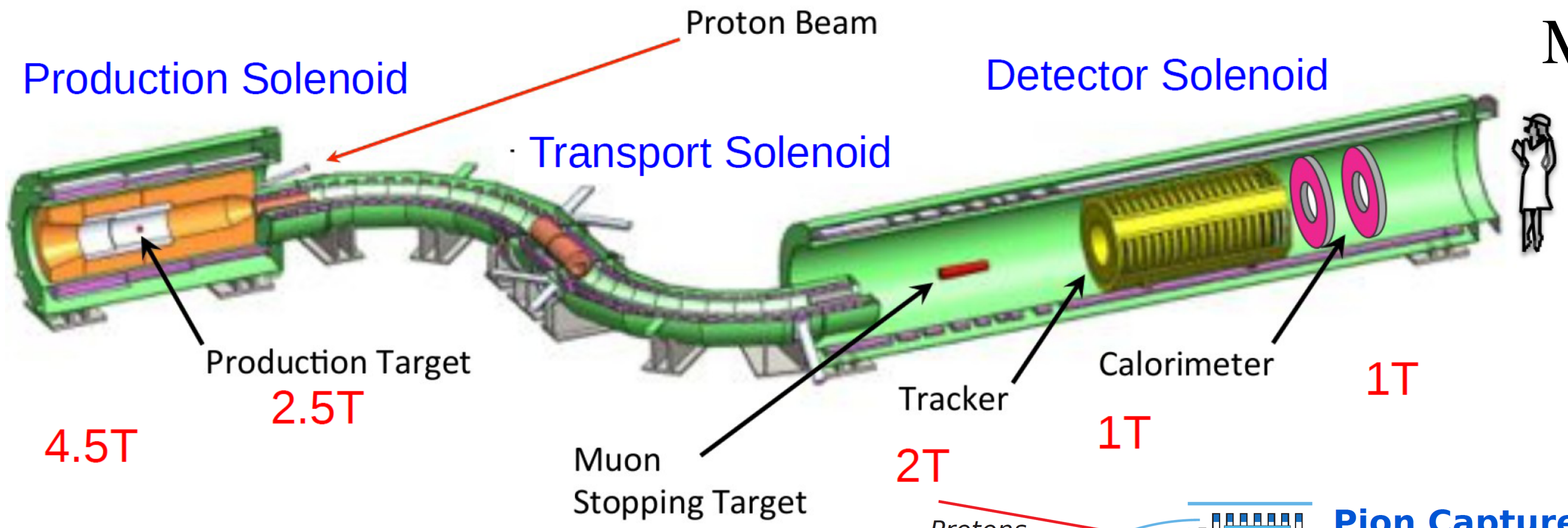
V. Lobashev, MELC 1992



COMET
(J-PARC)

$\mu \rightarrow e$ Conversion Experiments

Mu2e (FNAL)



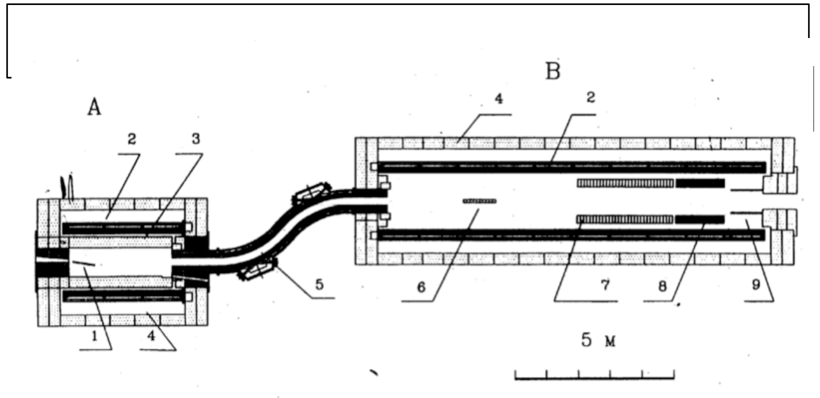
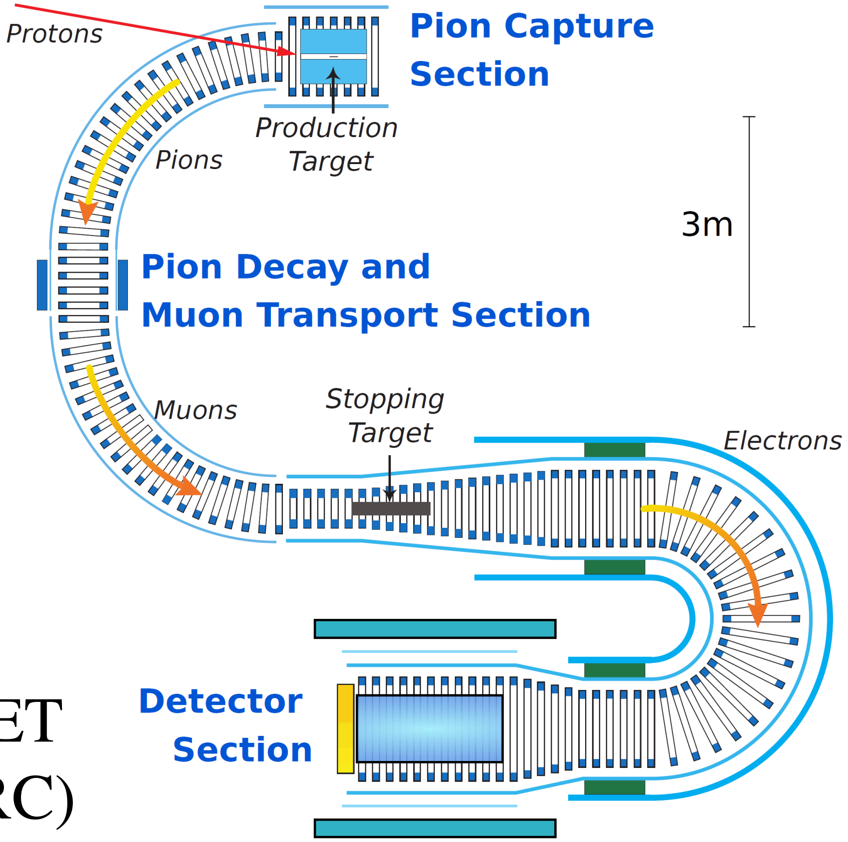


Fig. 1. Set-up MELC: A – meson-production part, B – detector part.
1 – tungsten target of the meson-production part (T_1),
2 – big superconducting solenoids, 3 – protection of the solenoid against radiation,
4 – steel magnetic circuit, 5 – solenoid-collimator,
6 – aluminium-target of the detector part (T_2),
7 – coordinate detector,
8 – total absorption scintillation spectrometer,
9 – protection of the detector against background.

V. Lobashev, MELC 1992



COMET
(J-PARC)

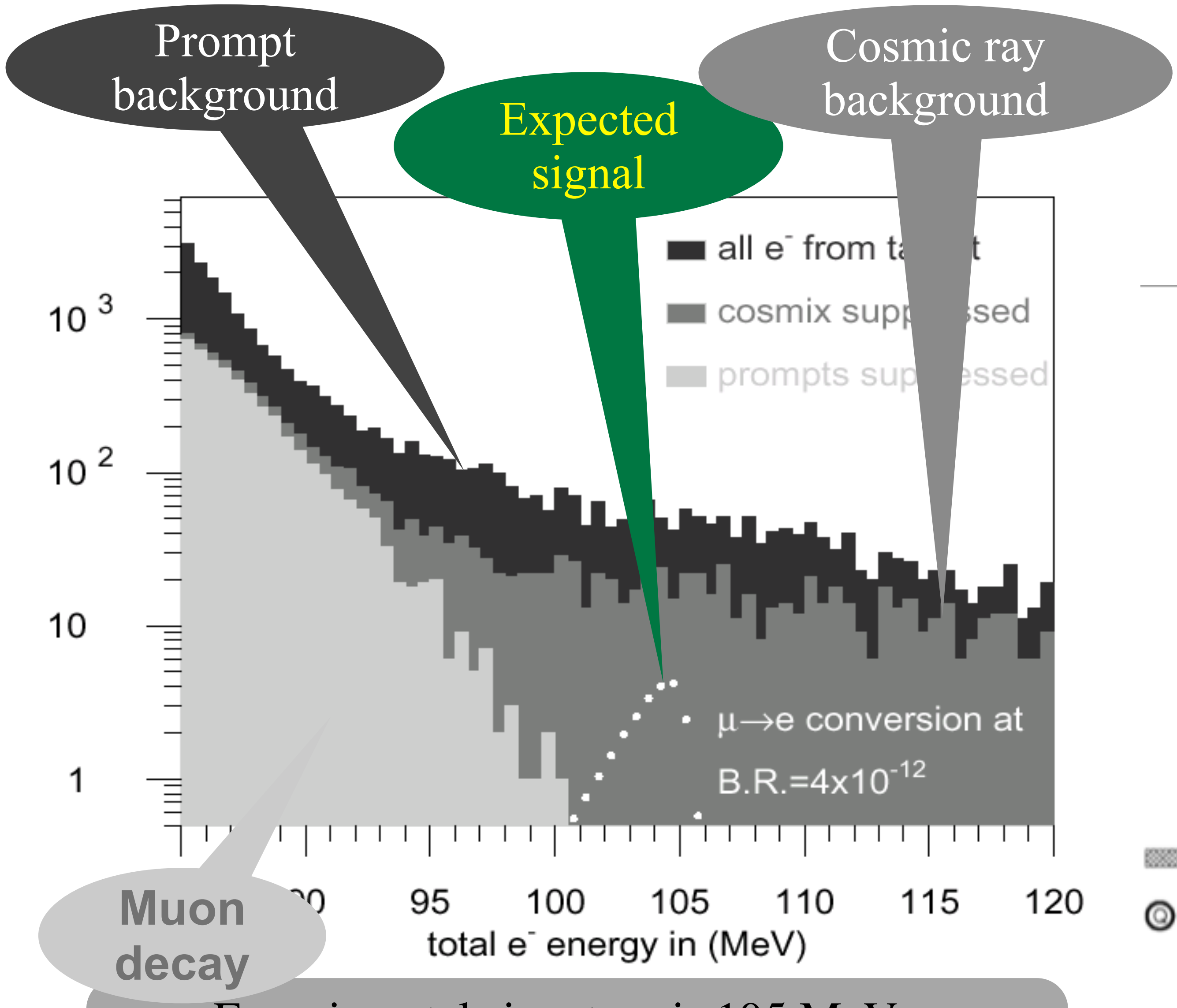
Goal: single event sensitivity of 3×10^{-17}

Rare Processes

Probability of…	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

E. Prebys, R. Bernstein

Previous Best Experiment



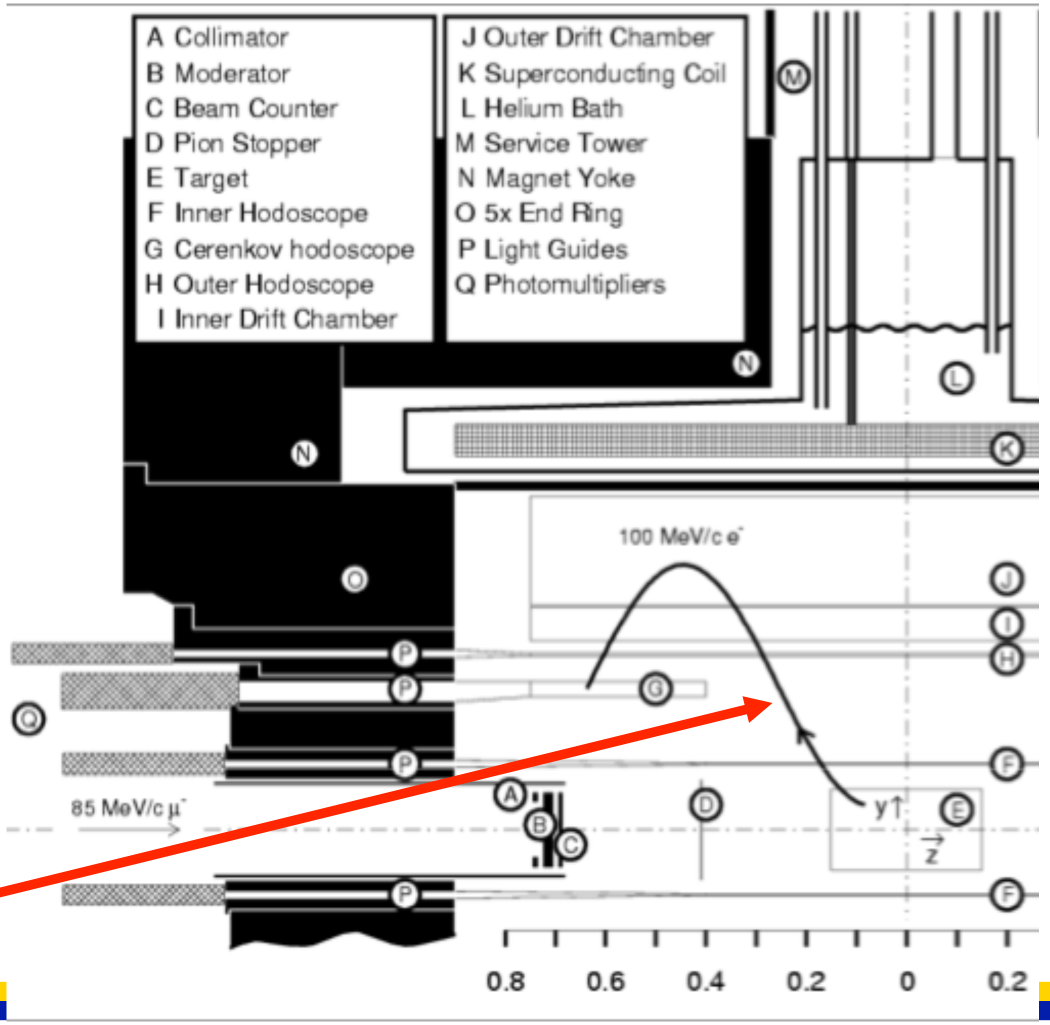
Experimental signature is 105 MeV e- originating in a thin stopping target.

Little time separation between signal and bkg

SINDRUM-II currently has the best limit on this process:

$$B^{\rm Au}_{\mu e} \quad < \quad 7 \times 10^{-13} \text{ @ } 90\% \text{ CL}$$

Limitation: CW beam



Mu2e Background Goals

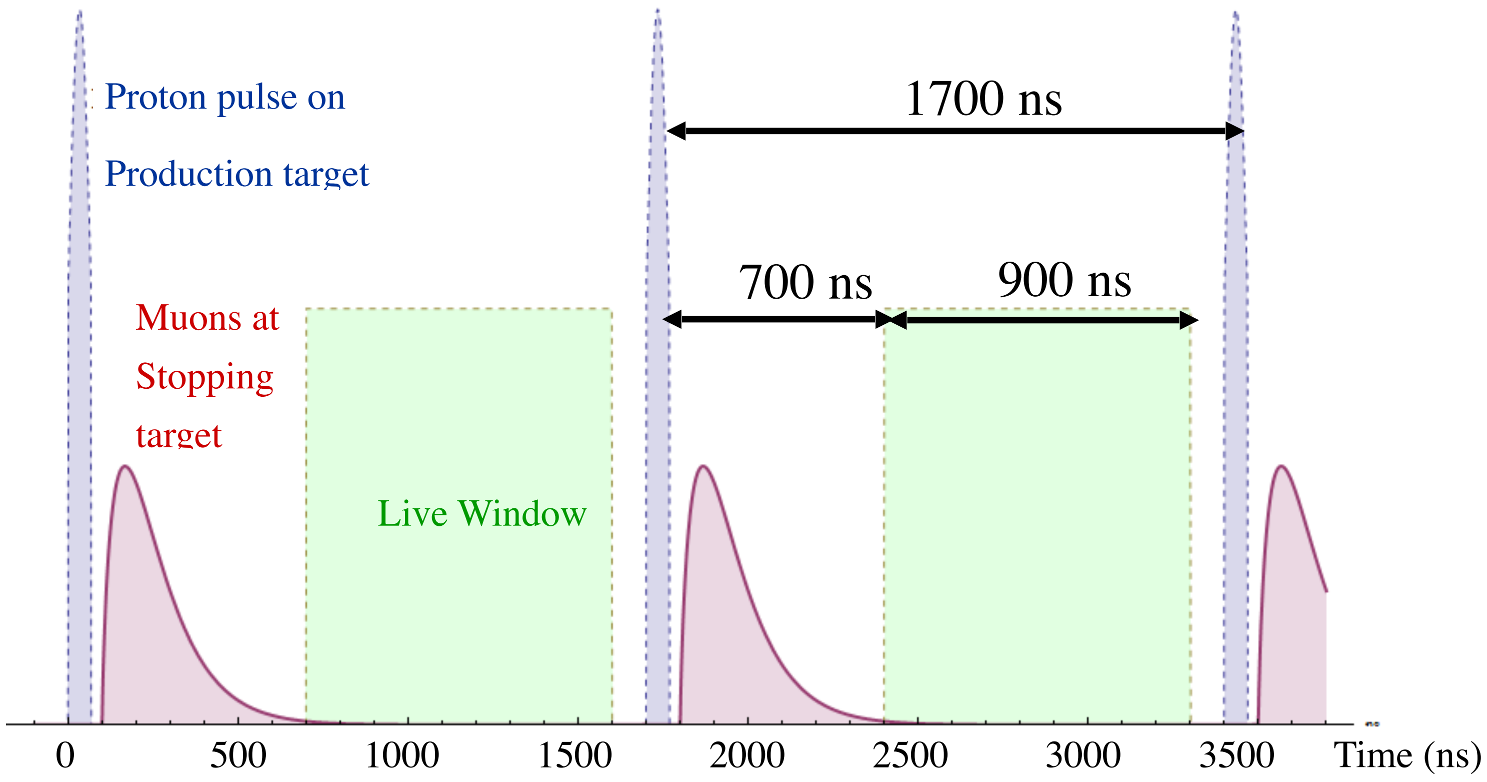
Discovery sensitivity accomplished by suppressing backgrounds to <1 event total

SES=$(3.0\pm0.4)\times10^{-17}$

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.14± 0.10
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.025±0.001
	Beam electrons	0.0025±0.0010
	μ Decay in Flight	<0.003
	π Decay in Flight	<0.001
Miscellaneous	Antiproton induced	0.047±0.005
	Cosmic Ray induced	0.247±0.005
	Pat. Recognition Errors	<0.01
Total Background		0.46±0.10

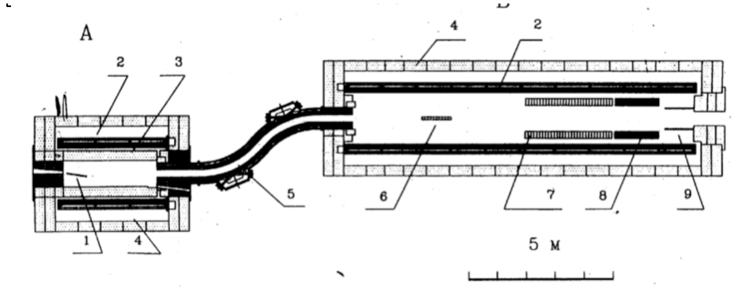
Mu2e @ FNAL

- High-intensity pulsed beam of low momentum muons
  - 8 GeV protons from Fermilab complex (10^3 increase over SINDRUM)
- Stop the muons in orbit around a nucleus
  - Aluminum stopping target ($\tau_\mu^{Al} = 864$ ns)
  - Time structure suppressed background
- Detect outgoing electrons consistent with the signal

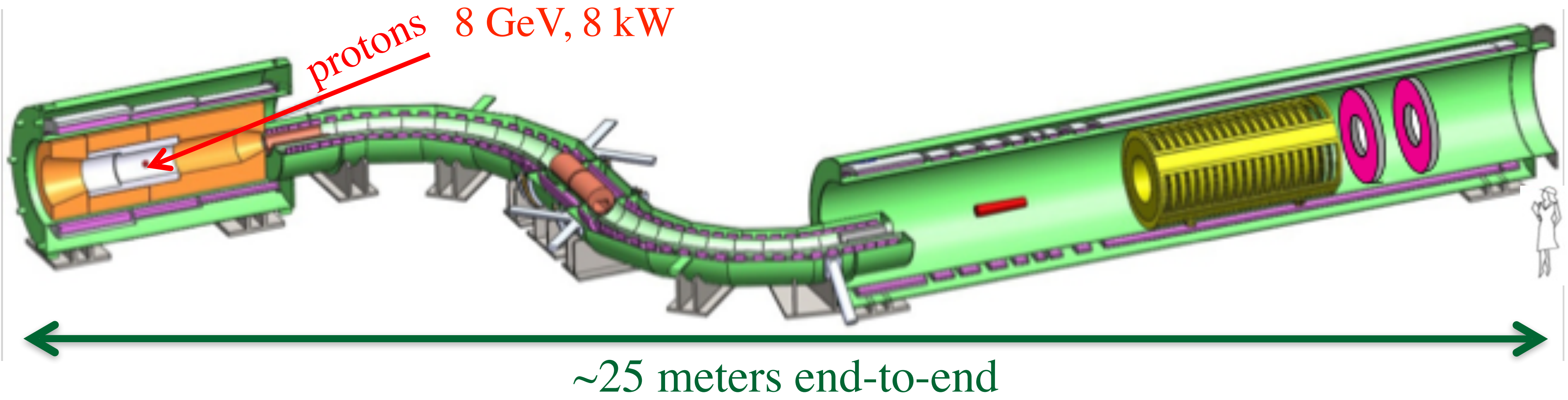


Mu2e @ FNAL

V. Lobashev, MELC 1992:



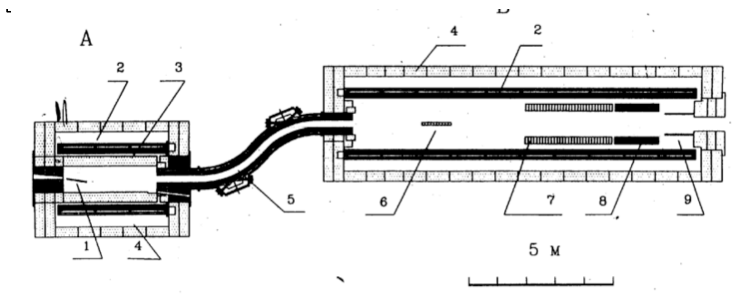
- *Production*: Magnetic bottle traps π's, which decay into accepted μ's



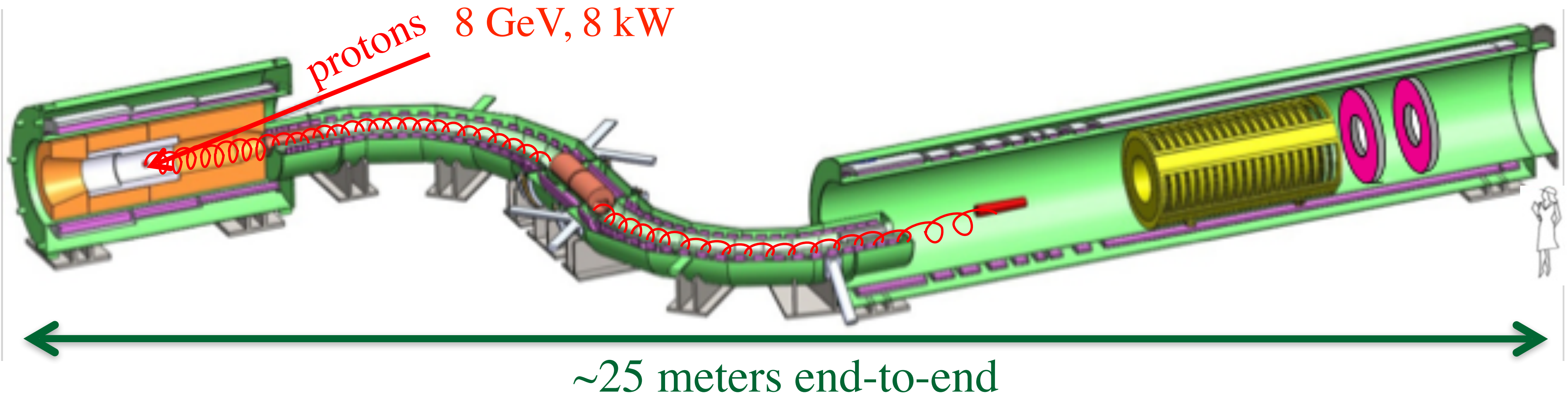
Not shown: Cosmic Ray Veto, Extinction Monitor

Mu2e @ FNAL

V. Lobashev, MELC 1992:



- *Production*: Magnetic bottle traps π's, which decay into accepted μ's

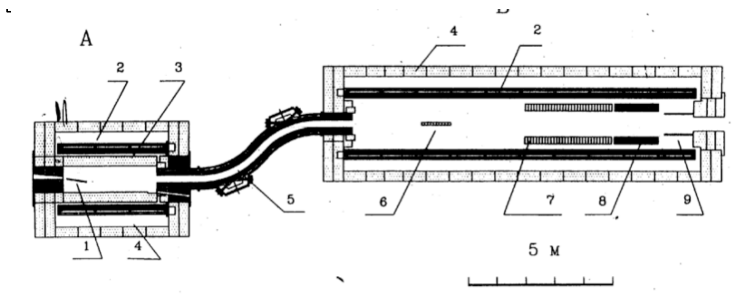


- *Transport:* S-curve eliminates backgrounds and sign-selects

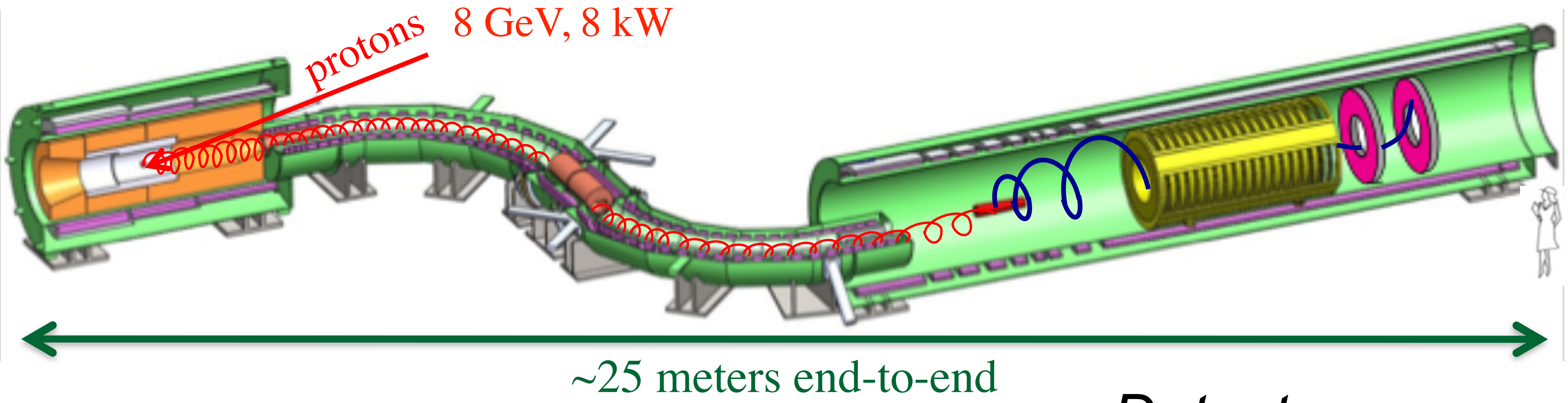
Not shown: Cosmic Ray Veto, Extinction Monitor

Mu2e @ FNAL

V. Lobashev, MELC 1992:



- *Production*: Magnetic bottle traps π's, which decay into accepted μ's



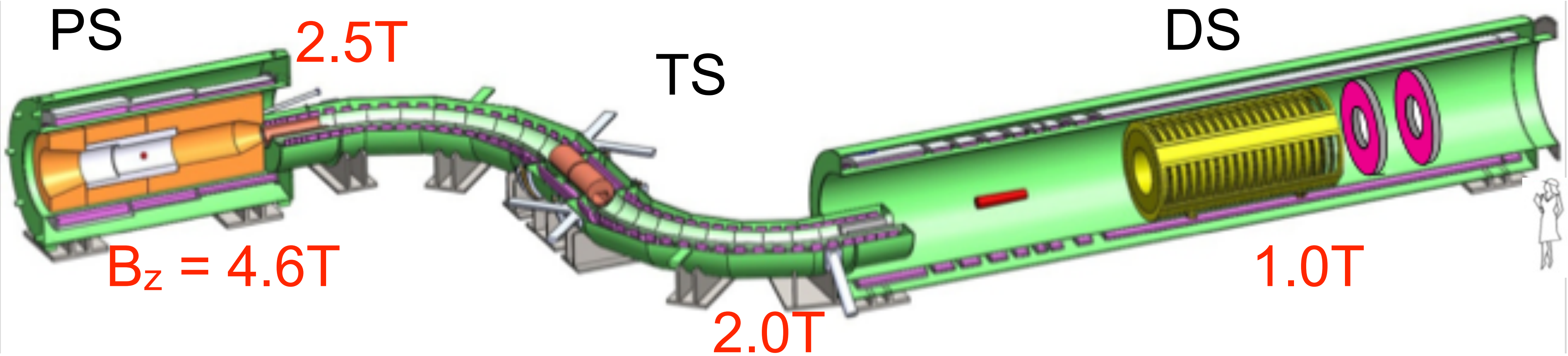
- *Transport:* S-curve eliminates backgrounds and sign-selects

- *Detector:* Stopping Target, Tracking and Calorimeter

Not shown: Cosmic Ray Veto, Extinction Monitor

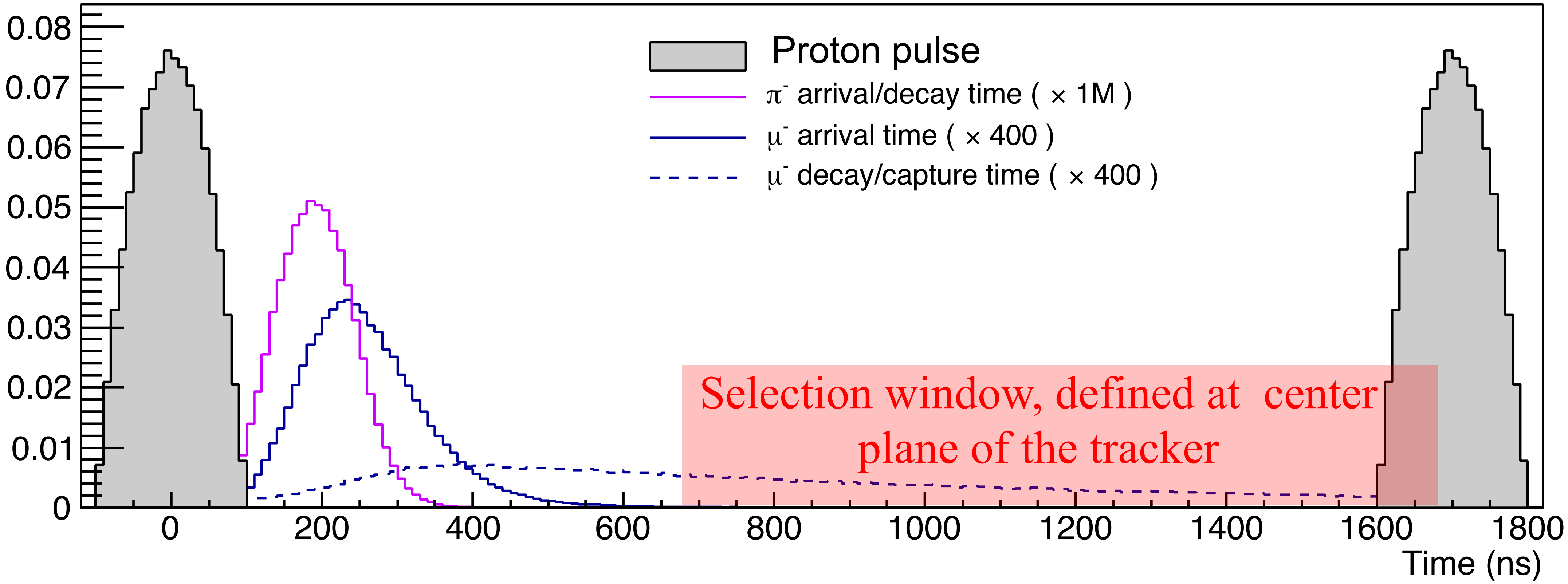
Gradient Fields in Mu2e

- Play a vital role throughout the design
- Drives cost and schedule



- "push" muons out of PS into TS and into DS towards stopping target
- keep particles from spiraling around, arriving late
- conversions are isotropic in stopping target; the gradient over stopping target "reflects" backward going muons and nearly doubles the acceptance

Schematic of One Beam Cycle



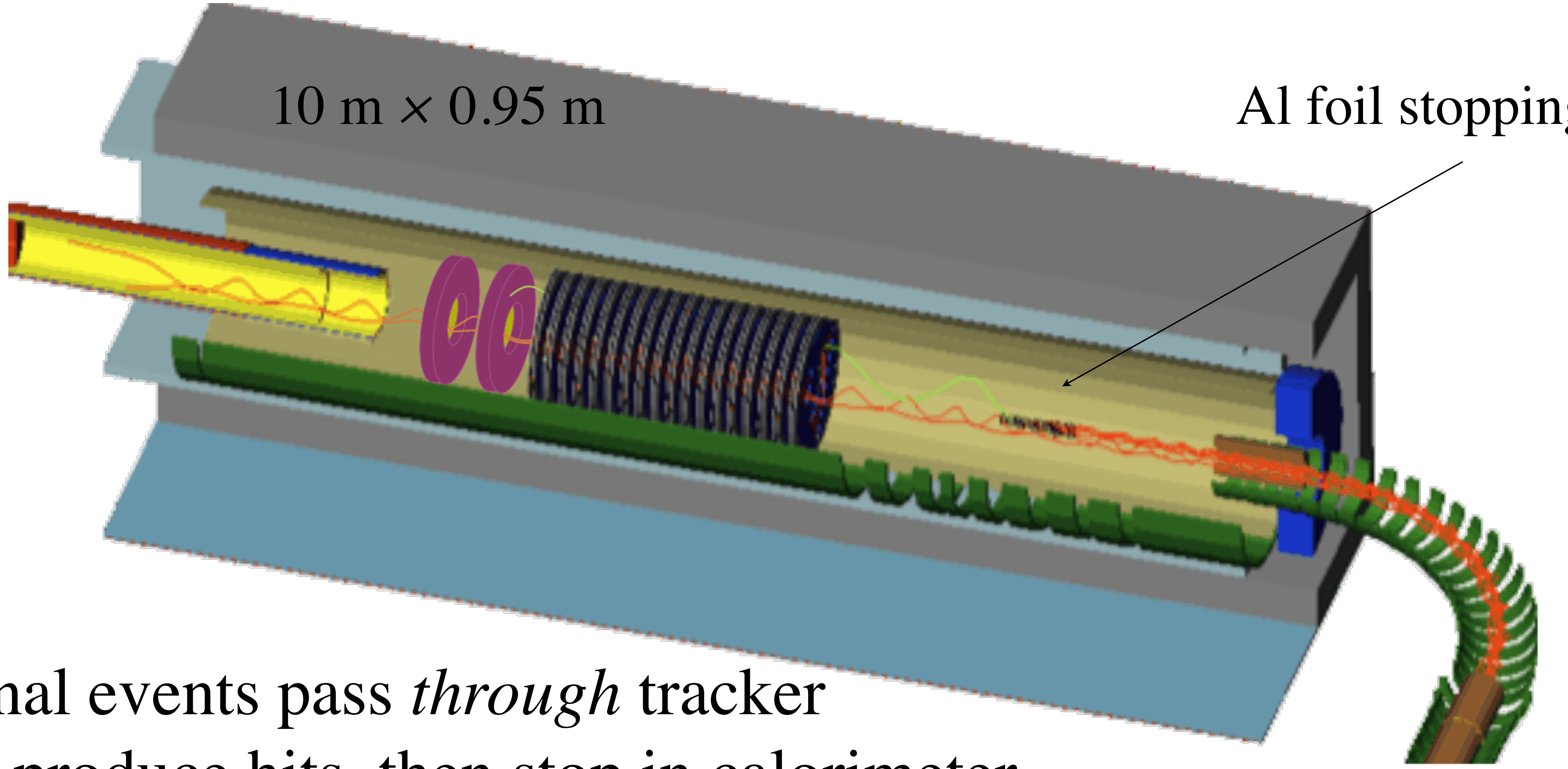
- No real overlap between selection window and the second proton pulse!
  - Proton times: when protons arrive at production target
  - Selection window: measured tracks pass the mid-plane of the tracker
  - Suppress late-arriving backgrounds (e.g. radiative pion capture) by requiring high proton extinction, i.e. no protons between beam bunches

Tracking Detector

Transverse tracker surrounding central region:
radius of helix proportional to momentum, p=qBR

low momentum particles and almost all DIO background passes down center

18 stations of 5 mm diameter straws (~20k total)
0.2% momentum resolution



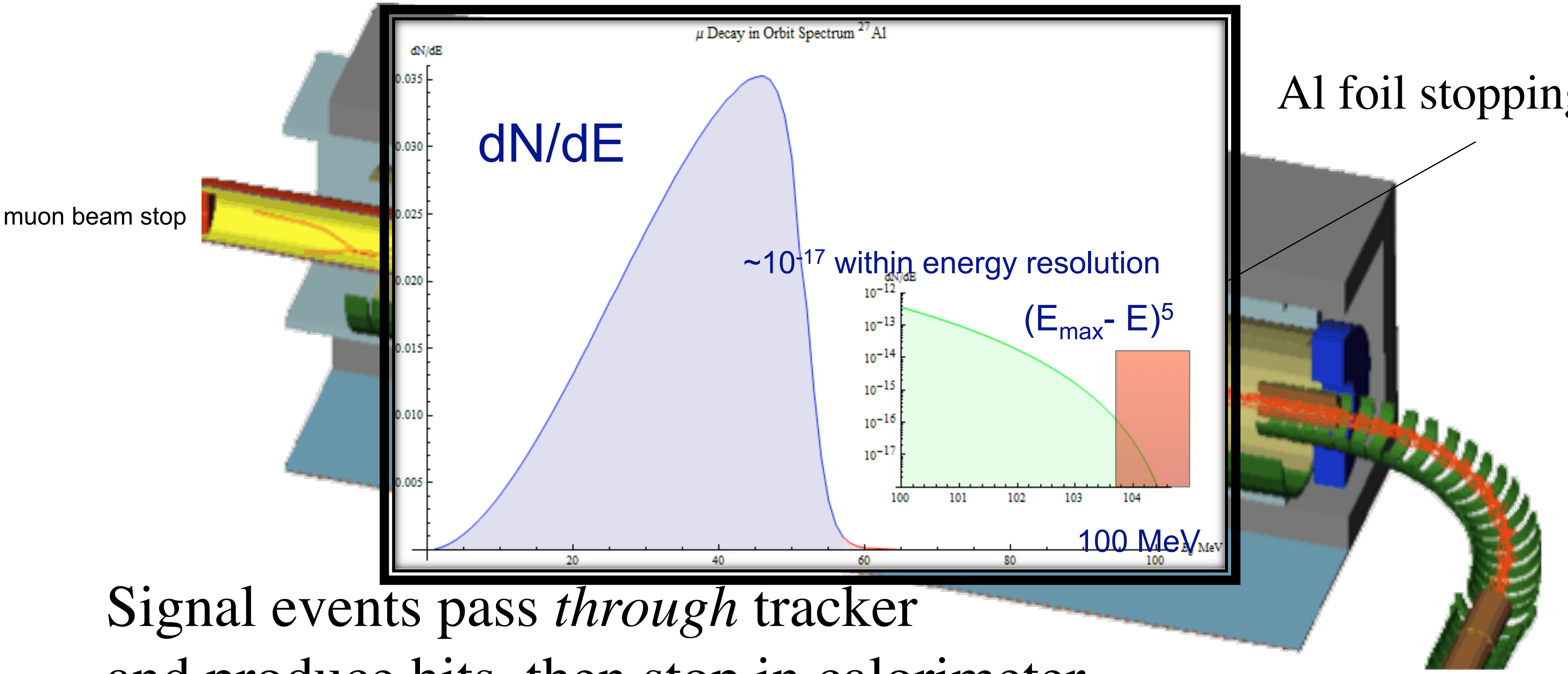
Signal events pass *through* tracker
and produce hits, then stop in calorimeter

Tracking Detector

Transverse tracker surrounding central region:
radius of helix proportional to momentum, p=qBR

low momentum particles and almost all DIO background passes down center

18 stations of 5 mm diameter straws (~20k total)
0.2% momentum resolution



Signal events pass *through* tracker and produce hits, then stop in calorimeter

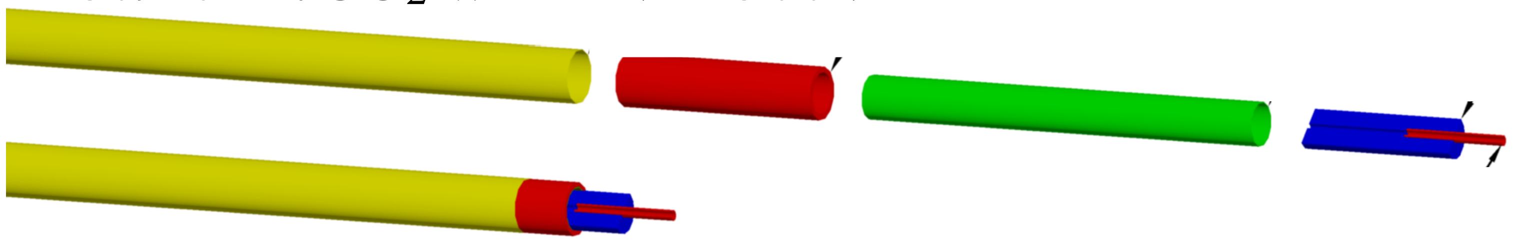
Tracker: Straw Tubes in Vacuum

1

Straws: 5 mm OD; 15μm metalized mylar wall; 25μm Au-plated W wire

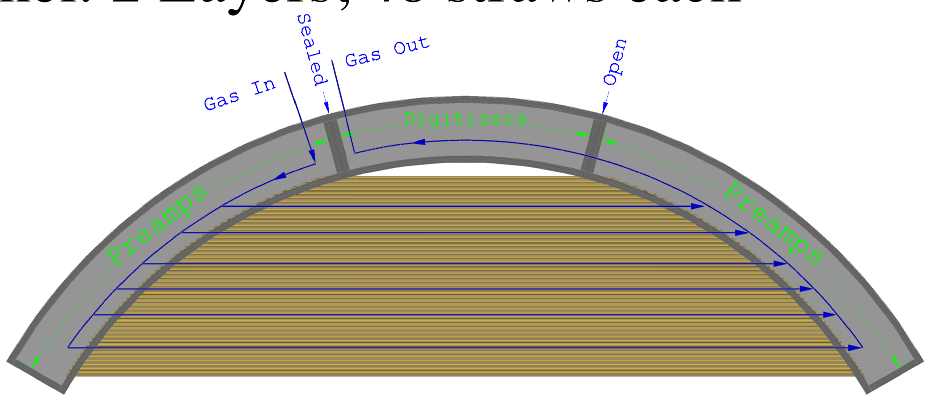
Read out at both ends (time division to provide 3d spacepoints)

80/20 Ar/CO_2 with HV<1500V



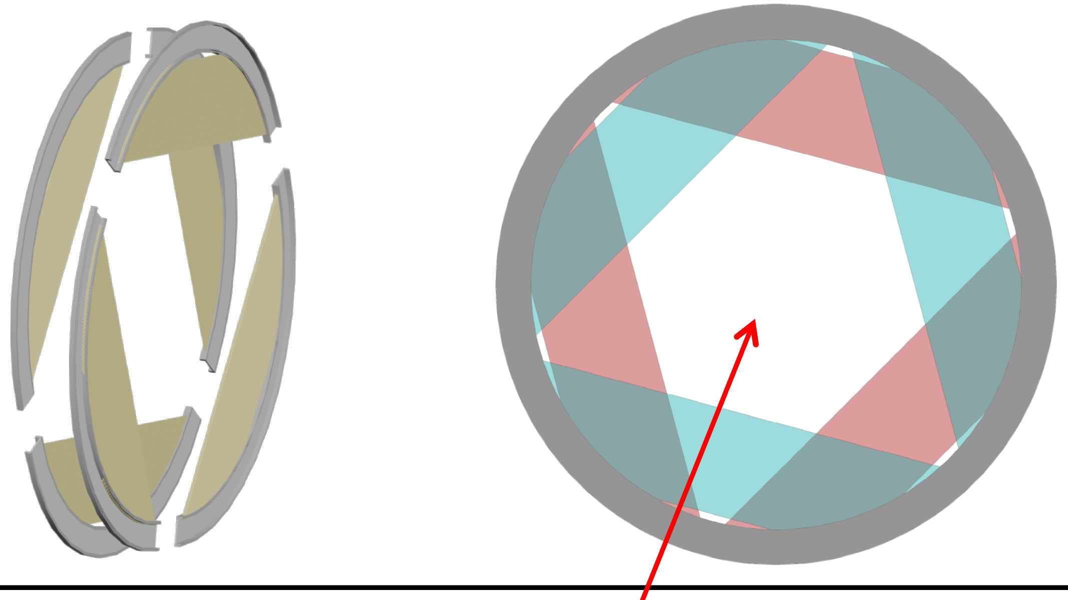
2

Panel: 2 Layers, 48 straws each



3

Plane: 6 panels; self supporting



Tracker sits in Vacuum

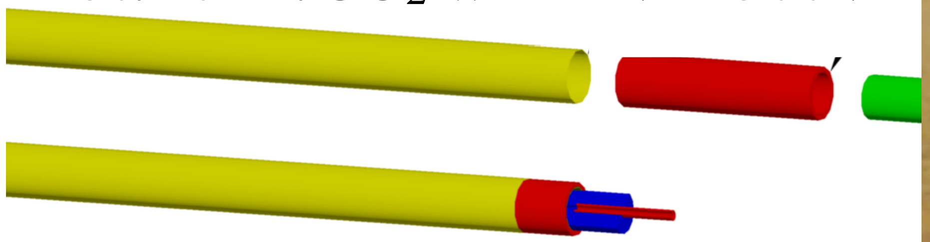
Tracker: Straw Tubes in Vacuum

1

Straws: 5 mm OD; 15μm metaliz

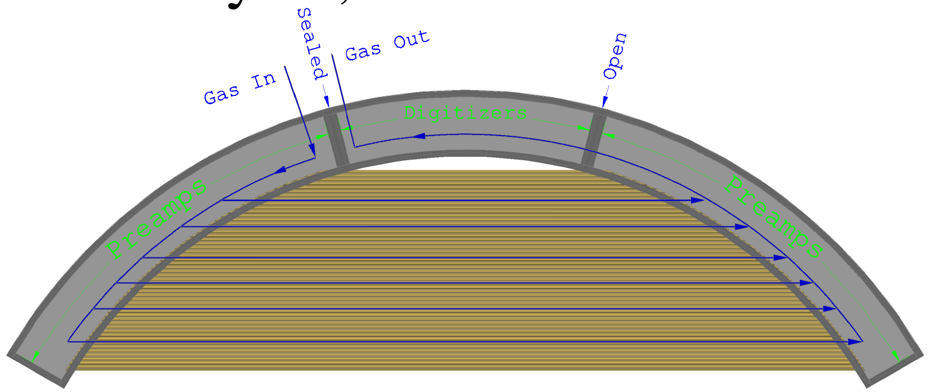
Read out at both ends (time divis

80/20 Ar/CO_2 with HV<1500V



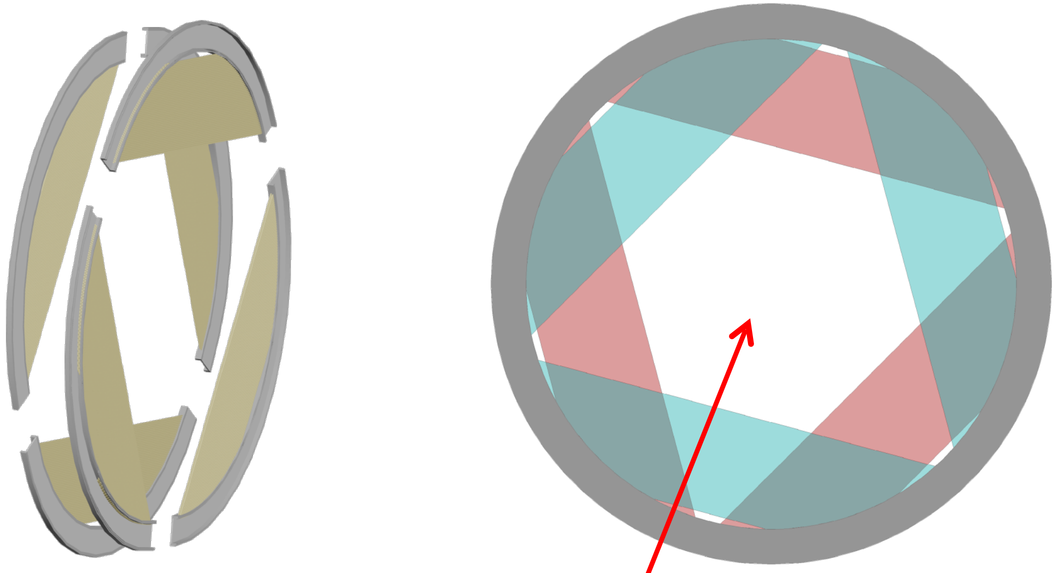
2

Panel: 2 Layers, 48 straws each



3

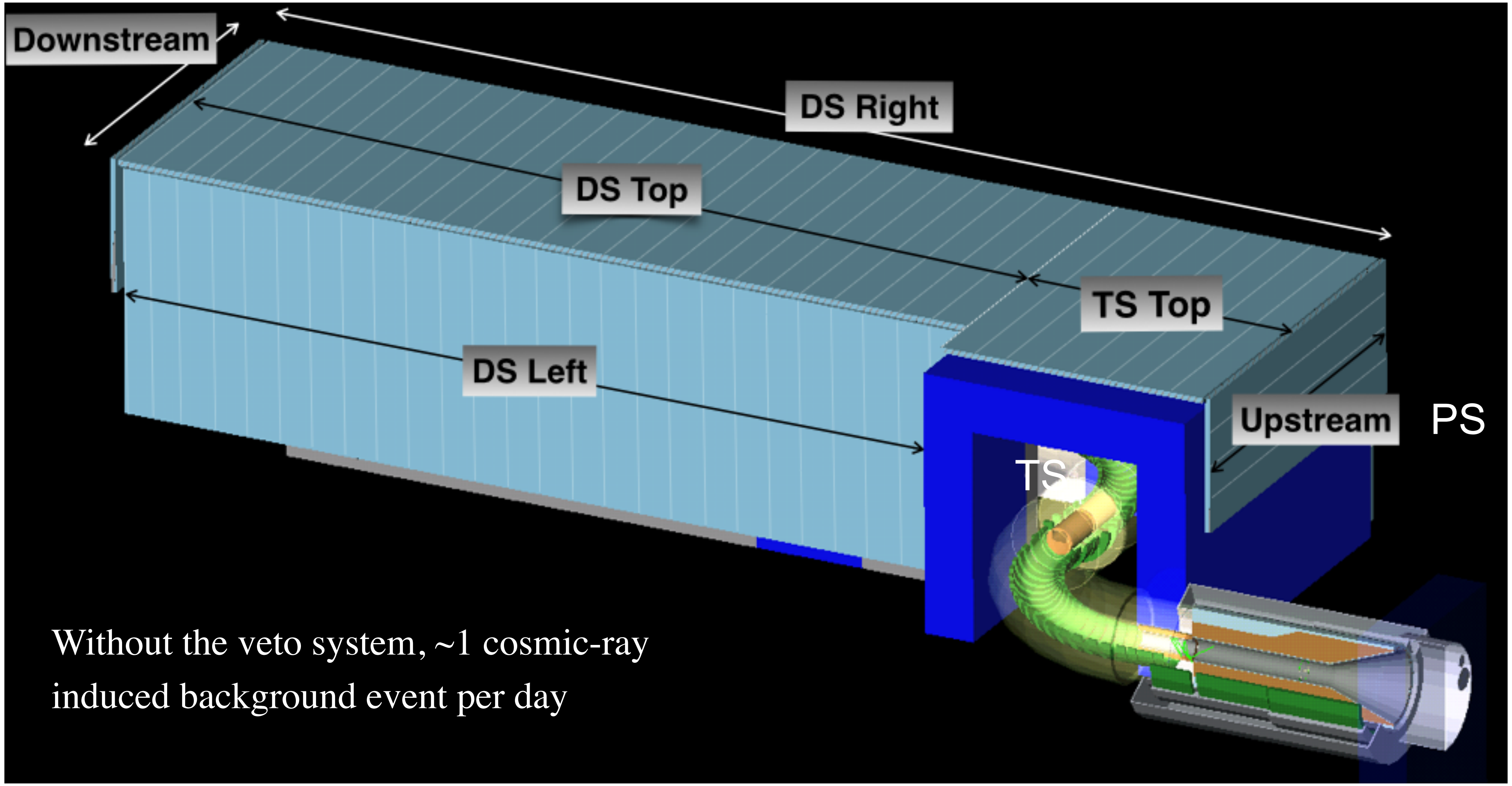
Plane: 6 panels; self supporting



Tracker sits in Vacuum

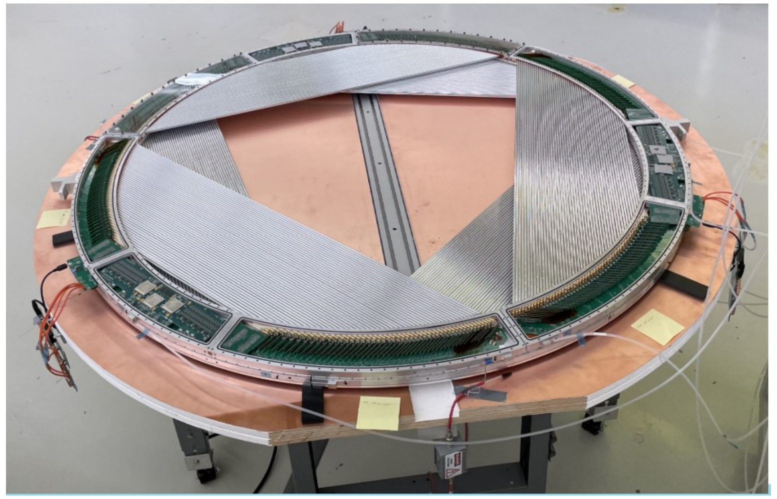
Mu2e Cosmic Ray Veto

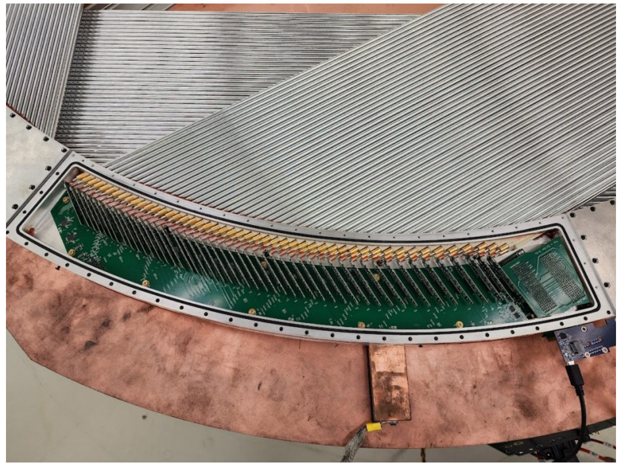
- Covers entire DS and half the TS
- 99.99% CR rejection efficiency required



Mu2e Progress

Tracker

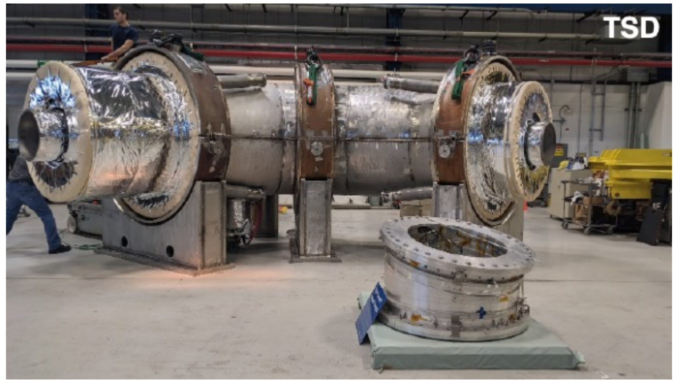




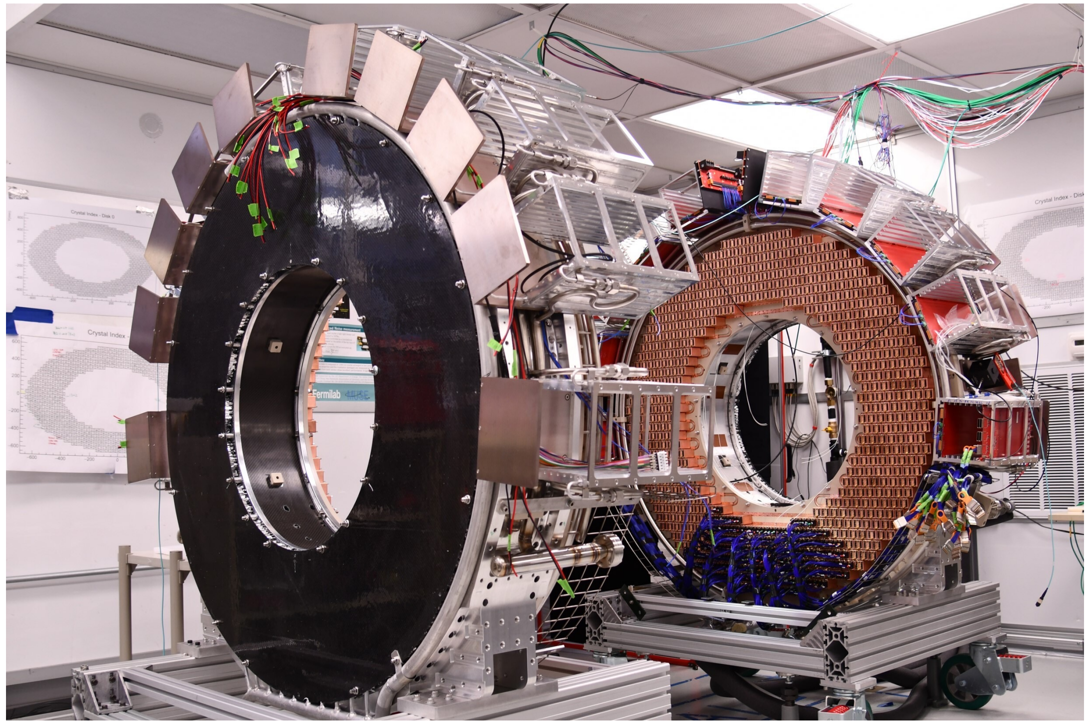
Now installing MLI around cold mass

Outer thermal shield panels now installed with MLI and interconnected

Production solenoid



Transport solenoid



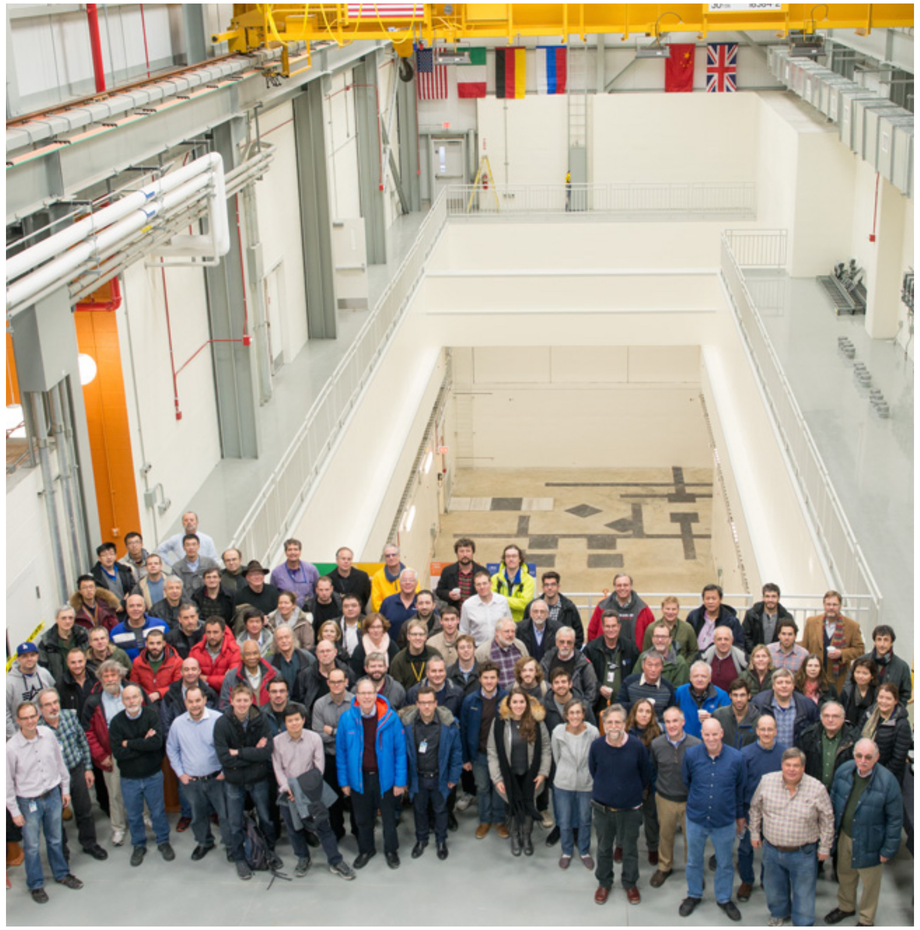
Calorimeter

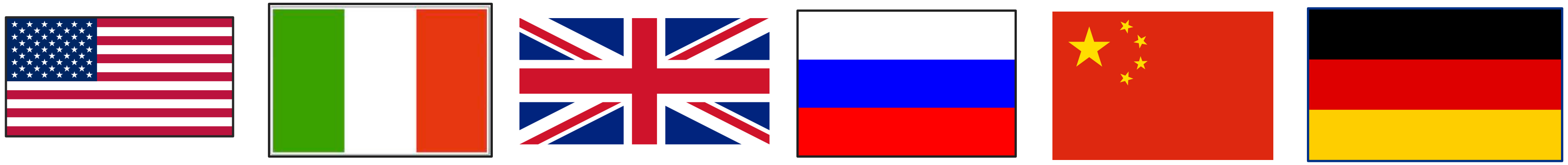
Muon Complex

Mu2e Collaboration

Over 200 Scientists from 37 Institutions

Argonne National Laboratory, Boston University, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionale di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, INFN Genova, Institute for High Energy Physics, Protvino, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Minnesota, Muon Inc., Northwestern University, Institute for Nuclear Research Moscow, INFN Pisa, Northern Illinois University, Purdue University, Rice University, Sun Yat-Sen University, University of South Alabama, Novosibirsk State University/Budker Institute of Nuclear Physics, University of Virginia, University of Washington, Yale University





Mu2e is a Program

+ If we have a signal:
  – Study Z dependence: distinguish among theories
– If we have no signal:
  – Up to to 10 × Mu2e physics reach, $R_{\mu e} < \text{a few} \times 10^{-18}$
  – Will require modest upgrades to detector (arXiv:1802.02599)
- Both could be done faster with more protons from PIP II

➡ Mu2e-II

$\mu^- \to e^+$ Conversion in Nucleus

- Transition

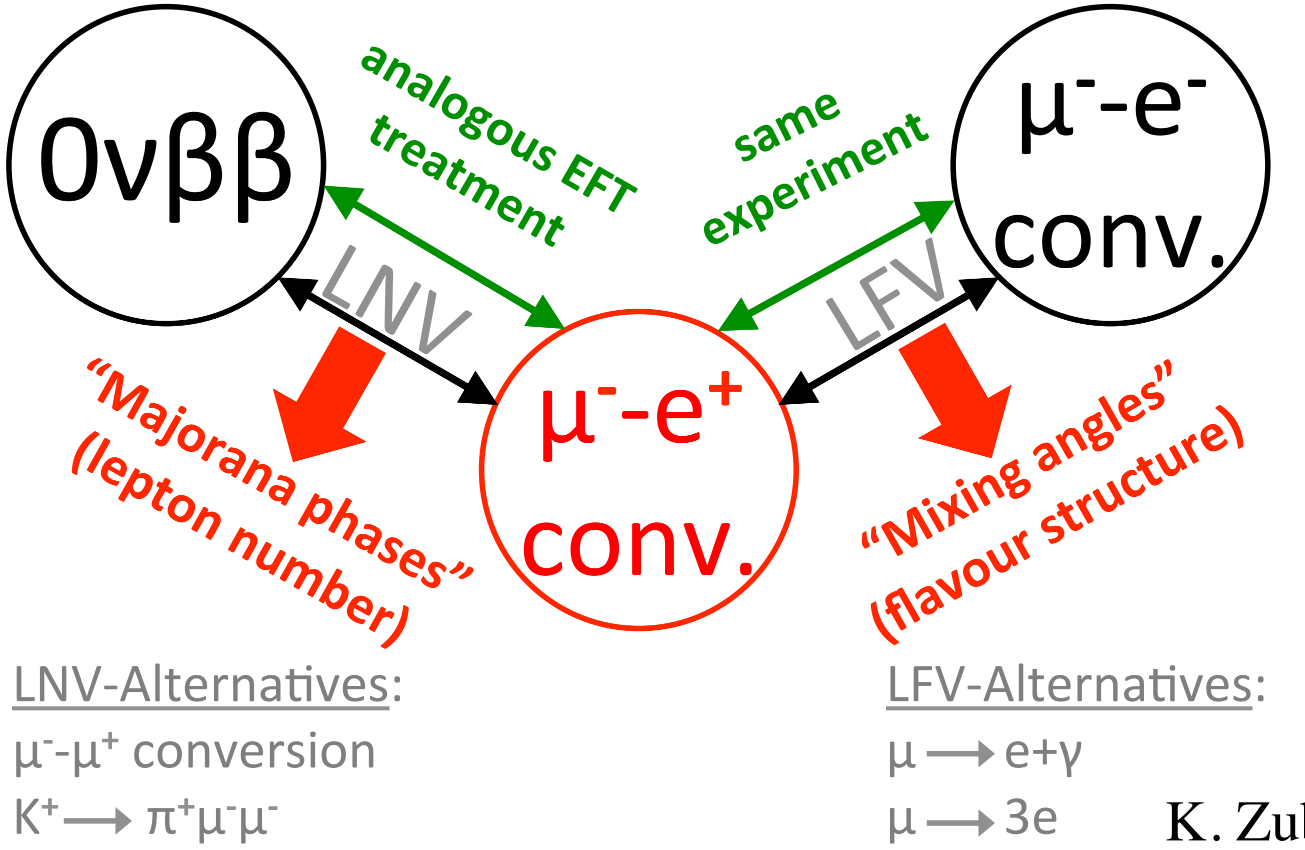
$$\mu^- + A(Z,N) \;\to\; e^+ + A(Z-2, N+2)$$

  - Incoherent conversion (2p→2n): no coherent enhancement
  - Large momentum transfer: transition to ground or excited state of the nucleus
    - Ground state branching fraction estimated to be ~41%
    - Most dominant excited state is a broad Giant Dipole Resonance

- Previous best measurement: SINDRUM-II

$$R_{\mu e+} \equiv \frac{\Gamma(\mu^- + {}^{48}\mathrm{Ti} \to e^+ + {}^{48}\mathrm{Ca}^{\mathrm{GS}})}{\Gamma(\mu^- + {}^{48}\mathrm{Ti} \to \nu_\mu + {}^{48}\mathrm{Sc}^*)} < 1.7 \times 10^{-12} \;(@90\%\ \mathrm{C.L.})$$

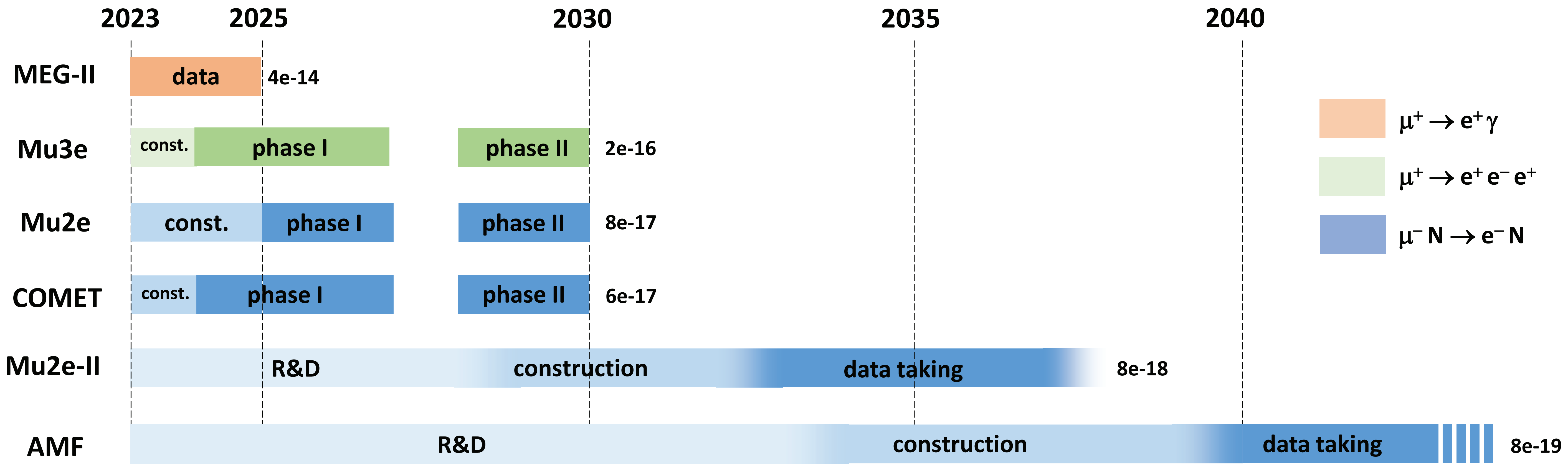
$\mu^- \rightarrow e^+$ Conversion: Complementarity



K. Zuber et al.

Complementarity between LFV and LNV measurements
Complementarity between nuclear (DBD) and particle physics (Mu2e) measurements
Complementarity between nuclear calculations (nuclear matrix elements)

Future of CLFV Searches



Summary

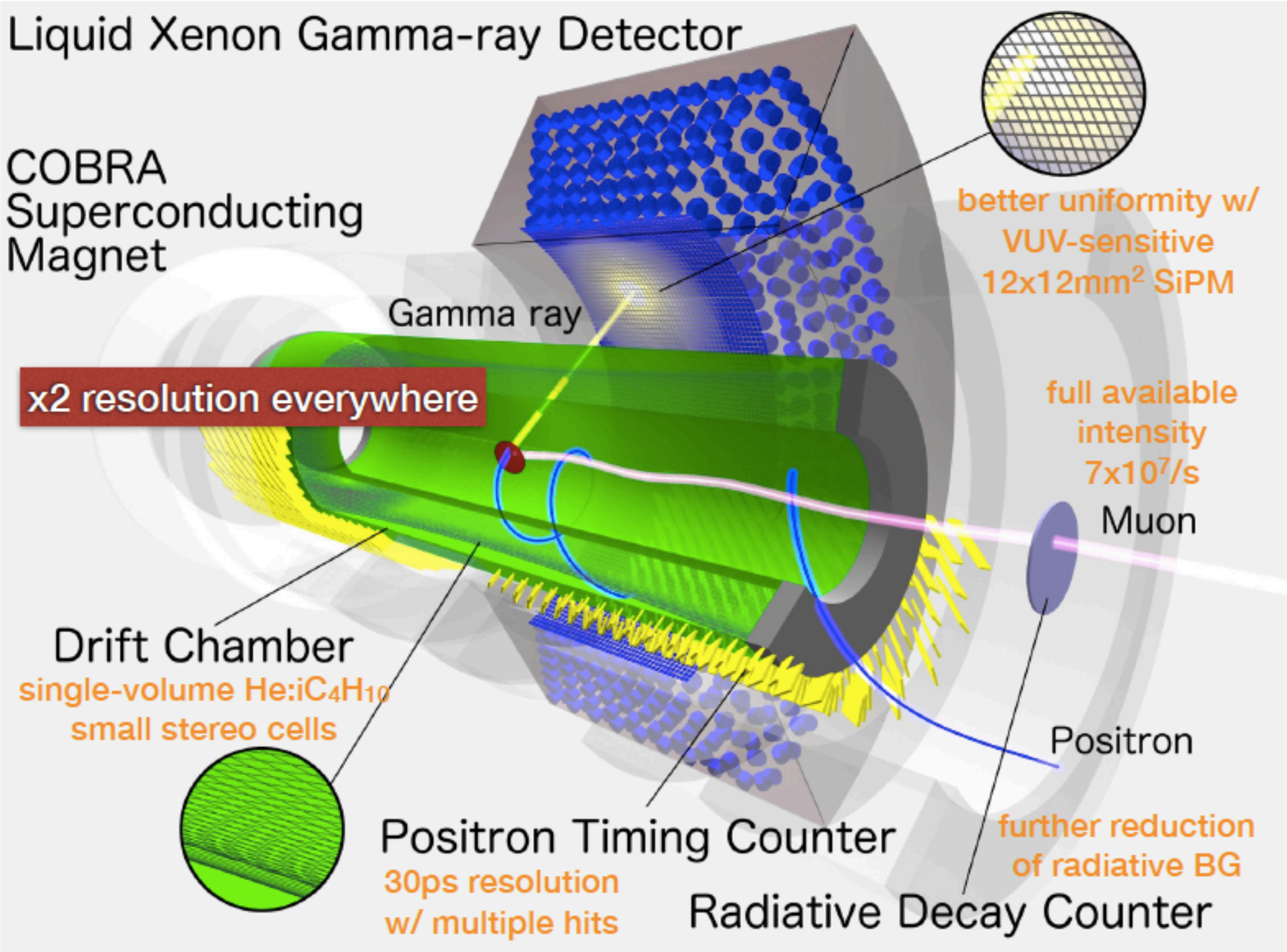
- CLFV offers unique sensitivity to new physics effects
- Aims at understanding the role of leptons, and leptonic transitions in early Universe
  - ❑ Complementary to LHC discovery potential
  - ❑ Can potentially reach significantly higher mass scales
    - ☞ Bridge between Terrascale and GUT
  - ❑ Complementary to other rare decays and precision measurements
    - ☞ Muon g-2, $0\nu\beta\beta$, EDM
- Multiple experiments pushing the sensitivity frontier
  - ☞ Stay tuned !

Summary

- CLFV offers unique sensitivity to new physics effects
- Aims at understanding the role of leptons, and leptonic transitions in early Universe
  - ❑ Complementary to LHC discovery potential
  - ❑ Can potentially reach significantly higher mass scales
    - ☞ Bridge between Terrascale and GUT
  - ❑ Complementary to other rare decays and precision measurements
    - ☞ Muon g-2, $0\nu\beta\beta$, EDM
- Multiple experiments pushing the sensitivity frontier
  - ☞ Stay tuned !

Backup

MEG-II

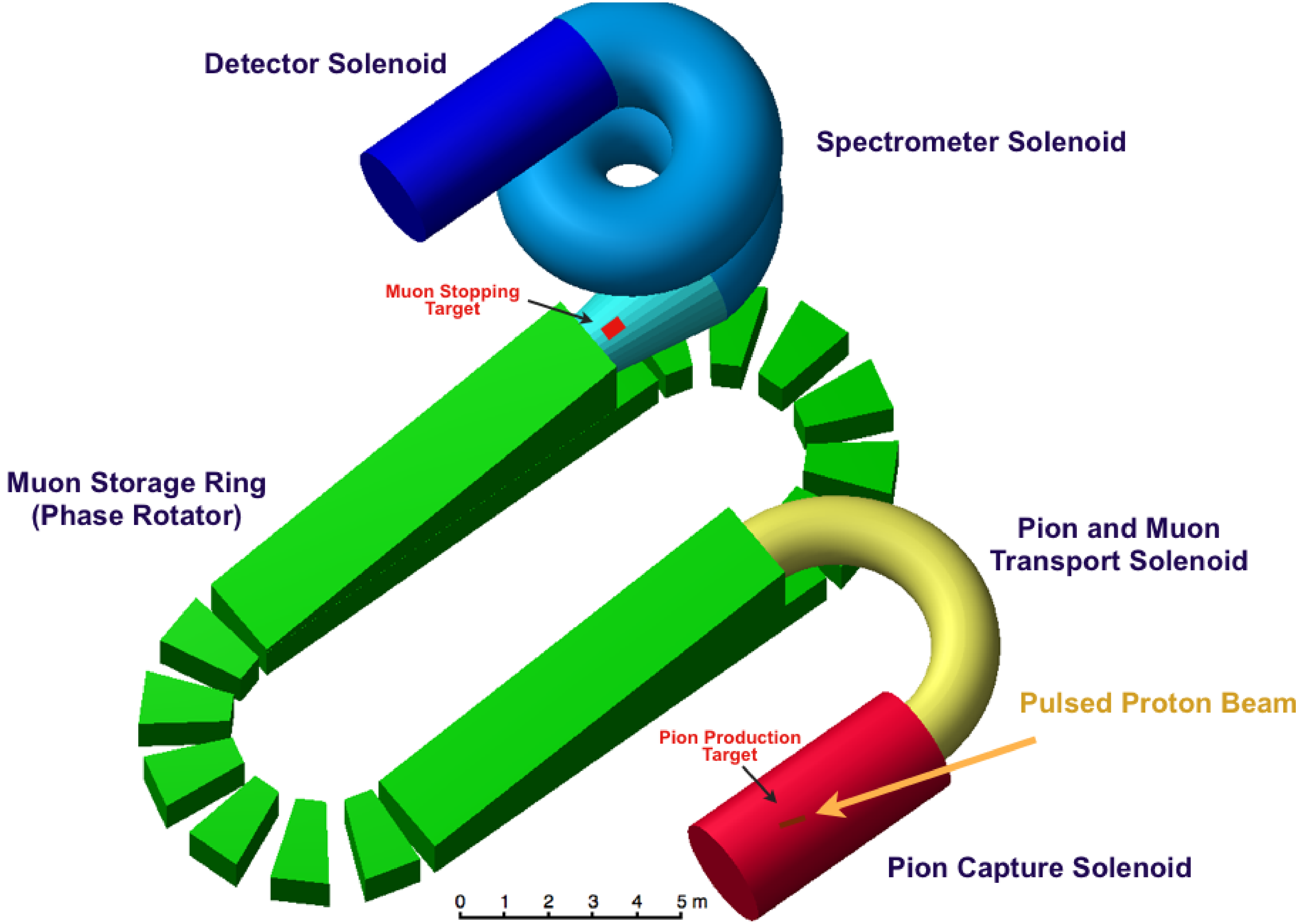


Liquid Xenon Gamma-ray Detector
COBRA
Superconducting
Magnet
Gamma ray
x2 resolution everywhere
better uniformity w/
VUV-sensitive
12x12mm² SiPM
full available
intensity
7x10⁷/s
Muon
Drift Chamber
single-volume He:iC4H10
small stereo cells
Positron
Positron Timing Counter
30ps resolution
w/ multiple hits
further reduction
of radiative BG
Radiative Decay Counter

MUSIC @ Osaka


Pion capture solenoid
Max. Bsol: 3.5 T
Pion-Muon transport solenoid (36deg.)
Max. Bsol: 2.0 T
Max. Bdipole: 0.04 T
Muons
WSS proton beam line
392MeV, 1μA
2 Aug. 2010

PRISM



Detector Solenoid
Spectrometer Solenoid
Muon Stopping Target
Muon Storage Ring (Phase Rotator)
Pion and Muon Transport Solenoid
Pulsed Proton Beam
Pion Production Target
Pion Capture Solenoid
0 1 2 3 4 5 m

PRISM

PRISM - Phase Rotated Intense Slow Muon beam

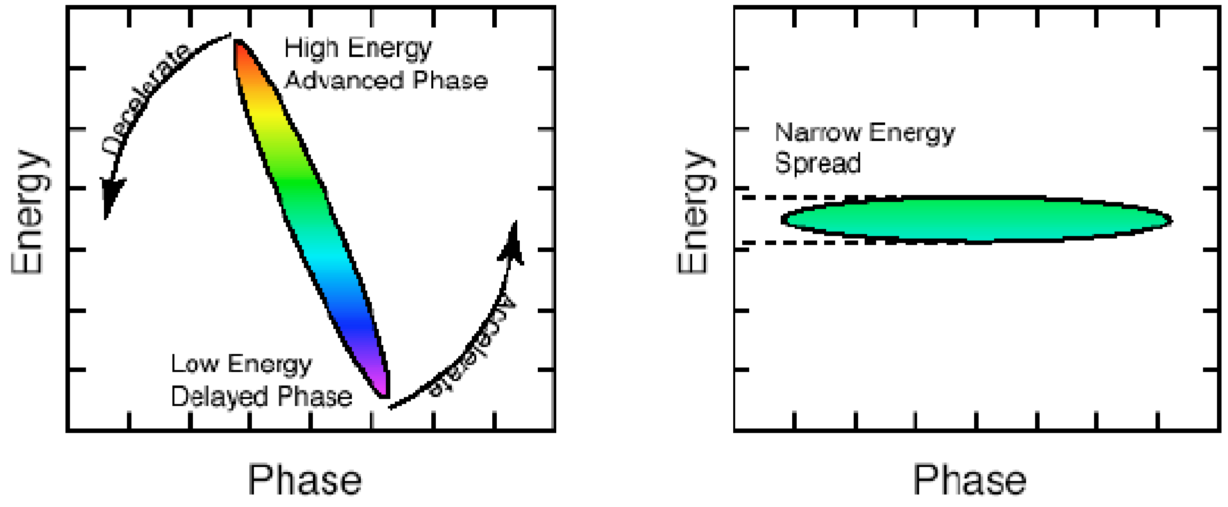
•The PRISM/PRIME experiment based on FFAG ring was proposed (Y. Kuno, Y. Mori) for a next generation cLFV searches in order to:

- reduce the muon beam energy spread by phase rotation,
- purify the muon beam in the storage ring.

• PRISM requires a compressed proton bunch and high power proton beam

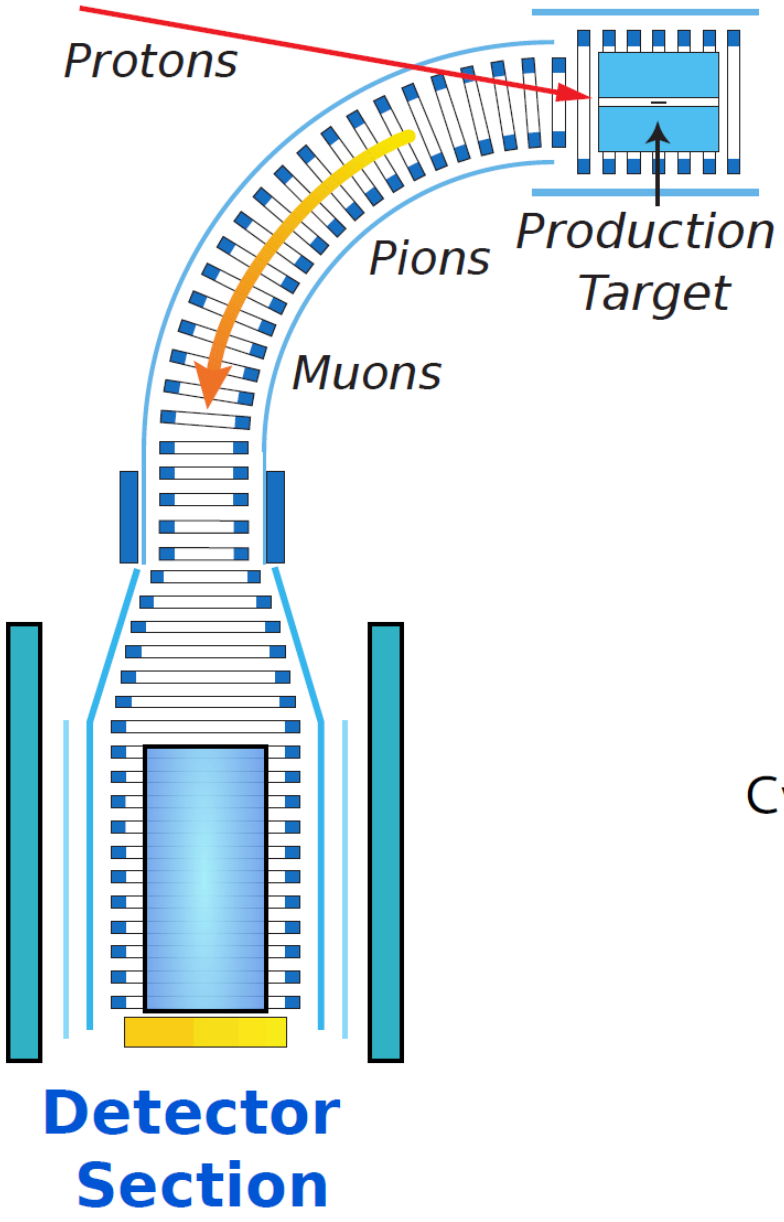
  - It needs a new proton driver!

• This will allow for a single event sensitivity of 3×10^{-19}



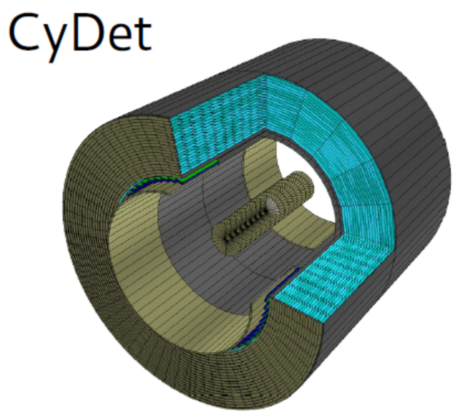
J. Pasternak

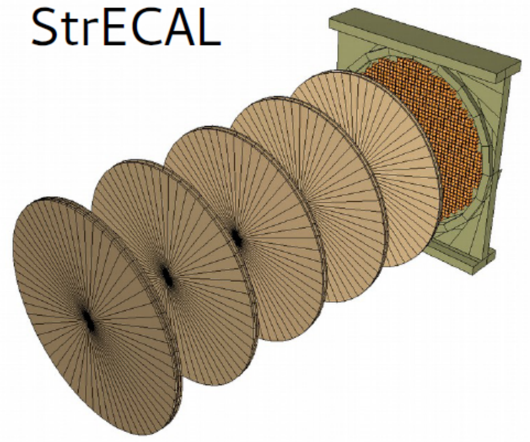
COMET: Phase-I



Goals of Phase–I

- Understand production system
- Understand bent solenoid dynamics
- Prototype the detector
- μ-e conversion search at: 3×10^{-15}

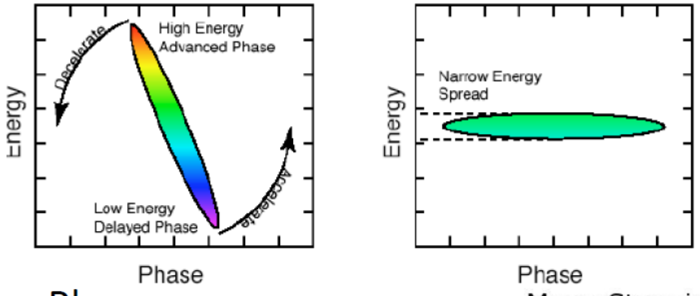




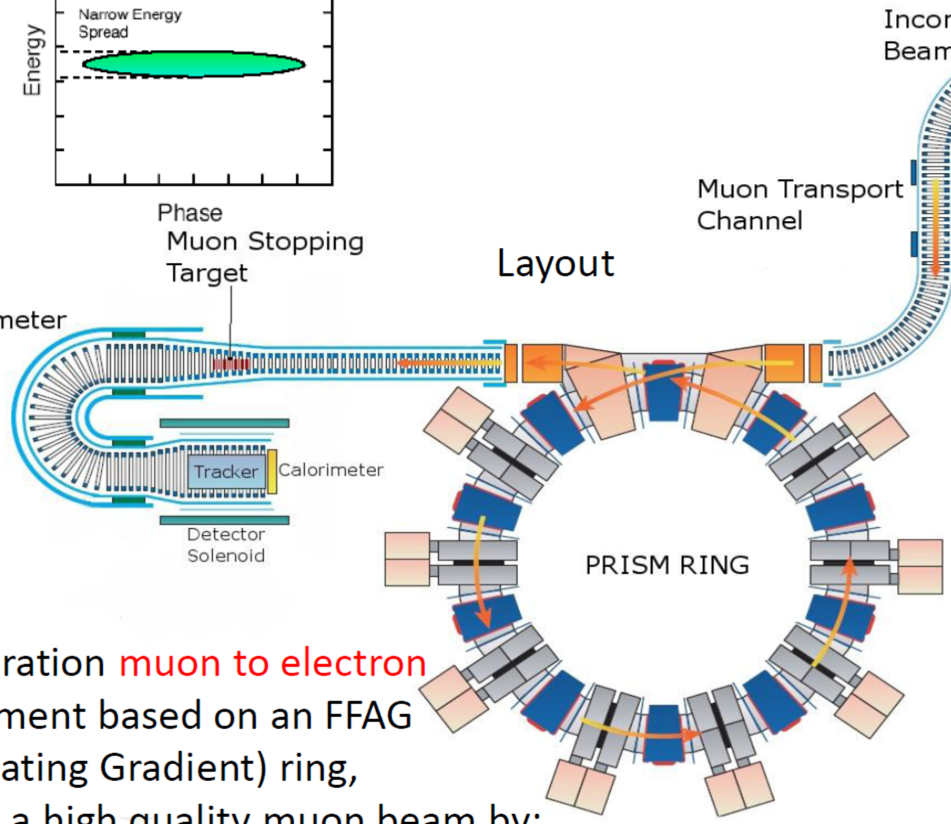
Next-Generation: PRISM/PRIME

PRISM - Phase Rotated Intense Slow Muon beam

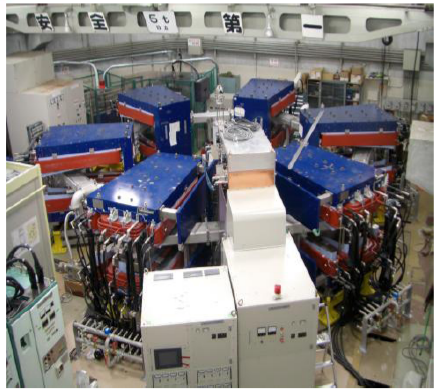
J. Pasternak @ NuFact 2015



Phase Rotation



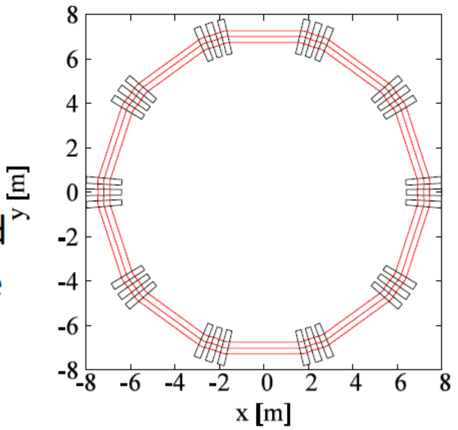
Test ring in Osaka



PRISM:

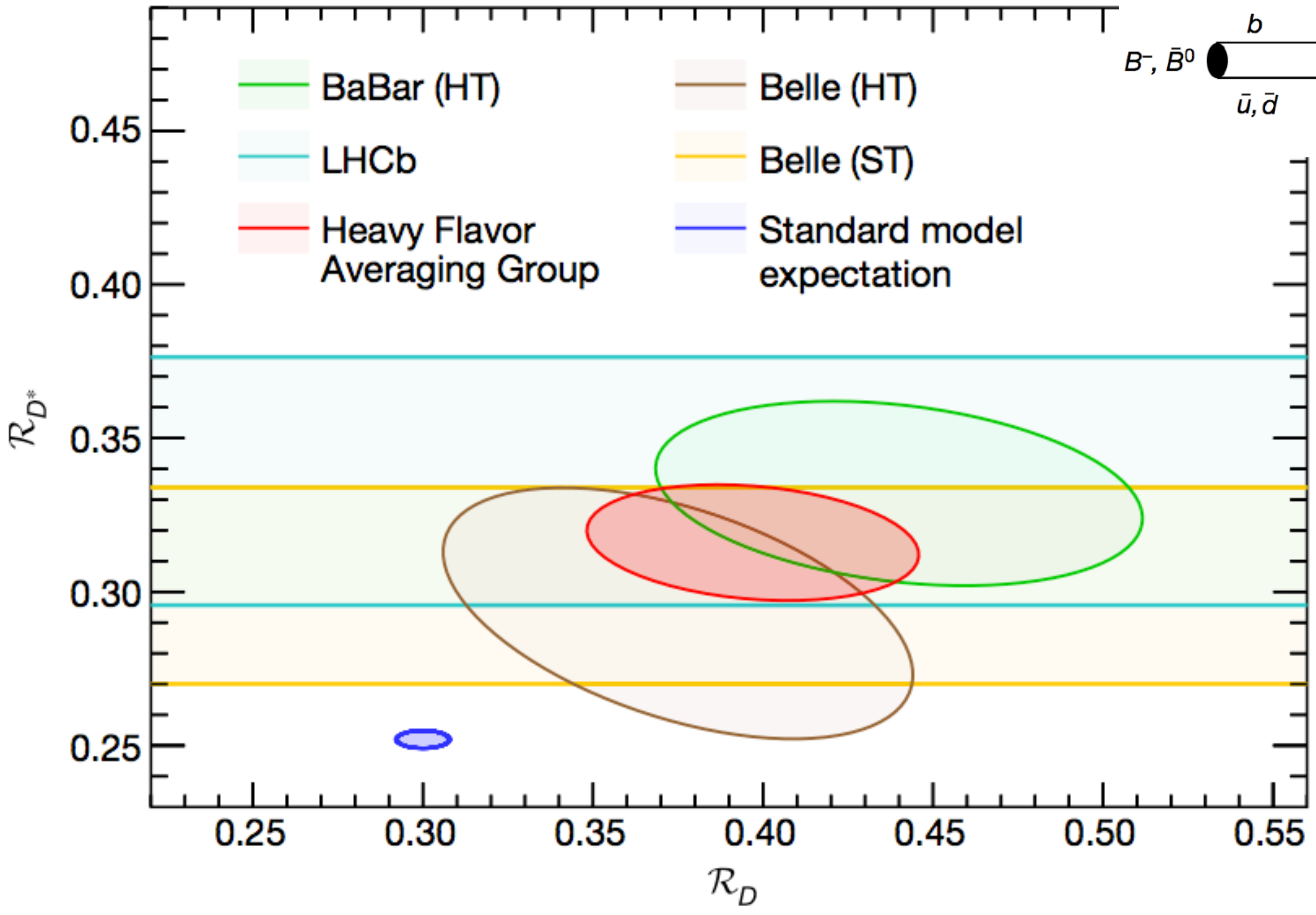
- It is the next generation muon to electron conversion experiment based on an FFAG (Fixed Field Alternating Gradient) ring,
- It allows to create a high quality muon beam by:
  - reducing the muon beam energy spread by RF phase rotation,
  - purifying the muon beam in the storage ring.
- It will have single event sensitivity – 3×10^{-19}
- Design details are being addressed by the Task Force led by Jaroslaw Pasternak (contact him for more details).

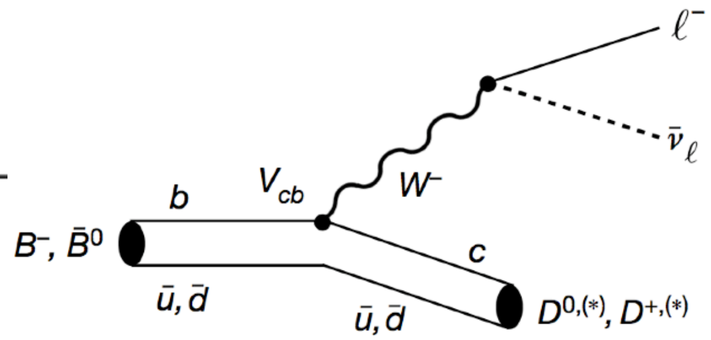
Alternative ring designed by Task Force



R_D Measurements

doi:10.1038/nature22346





R_K Measurement

$$\mathcal{R}_K^{SM} = \frac{\mathcal{B}(\bar{B} \to K^+ \mu^- \bar{\nu}_\mu)}{\mathcal{B}(\bar{B} \to K^+ e^- \bar{\nu}_e)} \approx 1$$

$$\mathcal{R}_K^{\mathrm{LHCb}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

A 2.6σ departure from unity

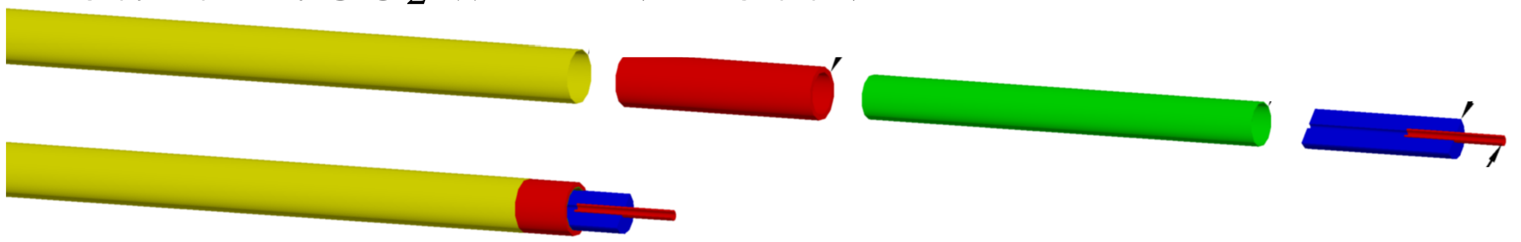
Tracker: Straw Tubes in Vacuum

1

Straws: 5 mm OD; 15μm metalized mylar wall; 25μm Au-plated W wire

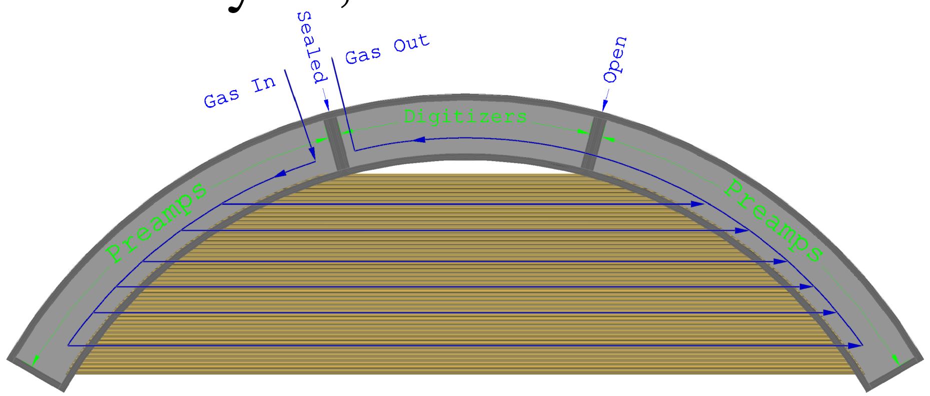
Read out at both ends (time division to provide 3d spacepoints)

80/20 Ar/CO_2 with HV<1500V



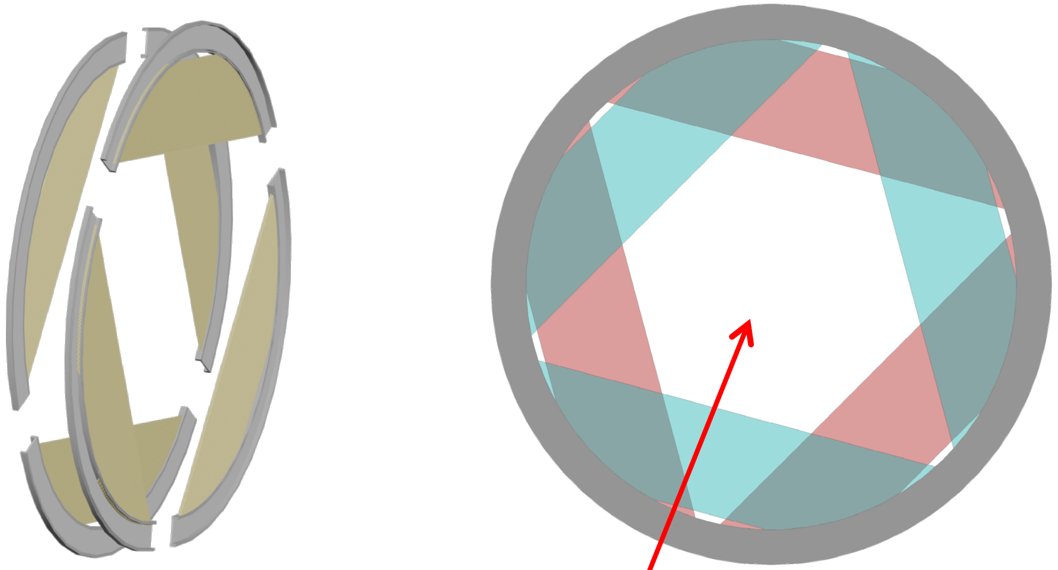
2

Panel: 2 Layers, 48 straws each



3

Plane: 6 panels; self supporting



Tracker sits in Vacuum

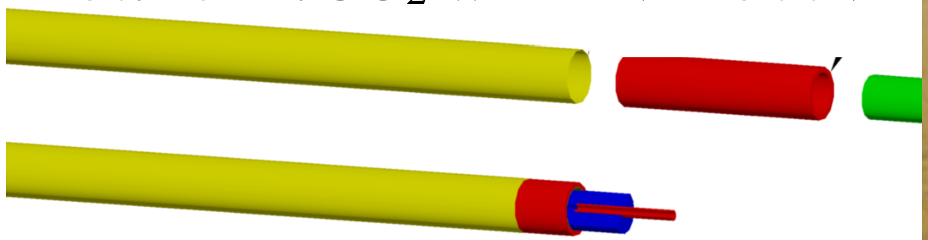
Tracker: Straw Tubes in Vacuum

1

Straws: 5 mm OD; 15μm metaliz

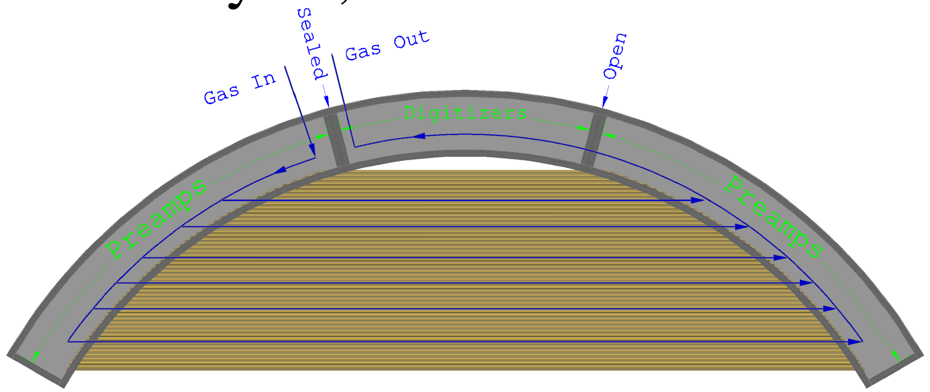
Read out at both ends (time divis

80/20 Ar/CO_2 with HV<1500V



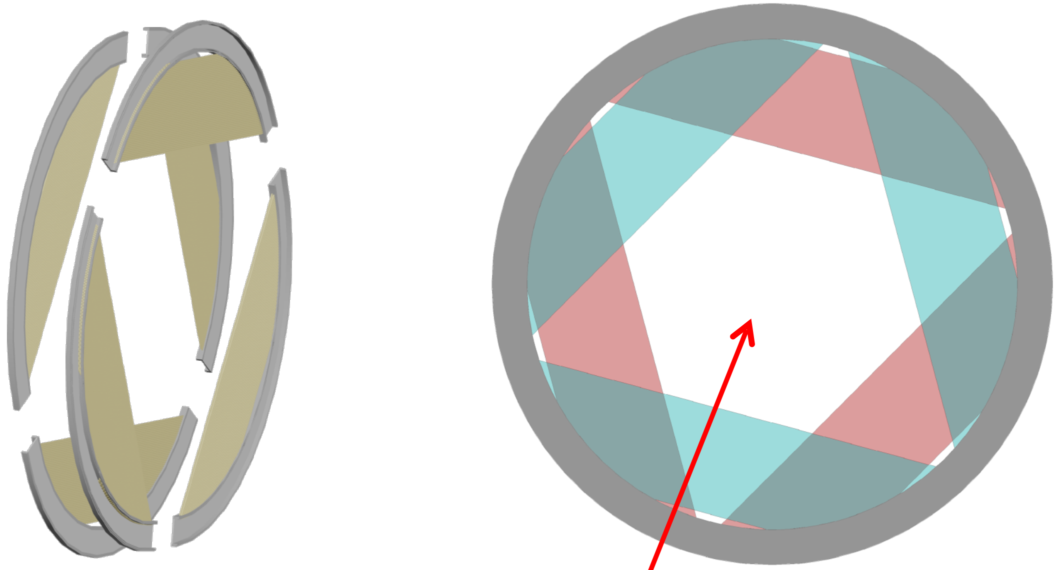
2

Panel: 2 Layers, 48 straws each



3

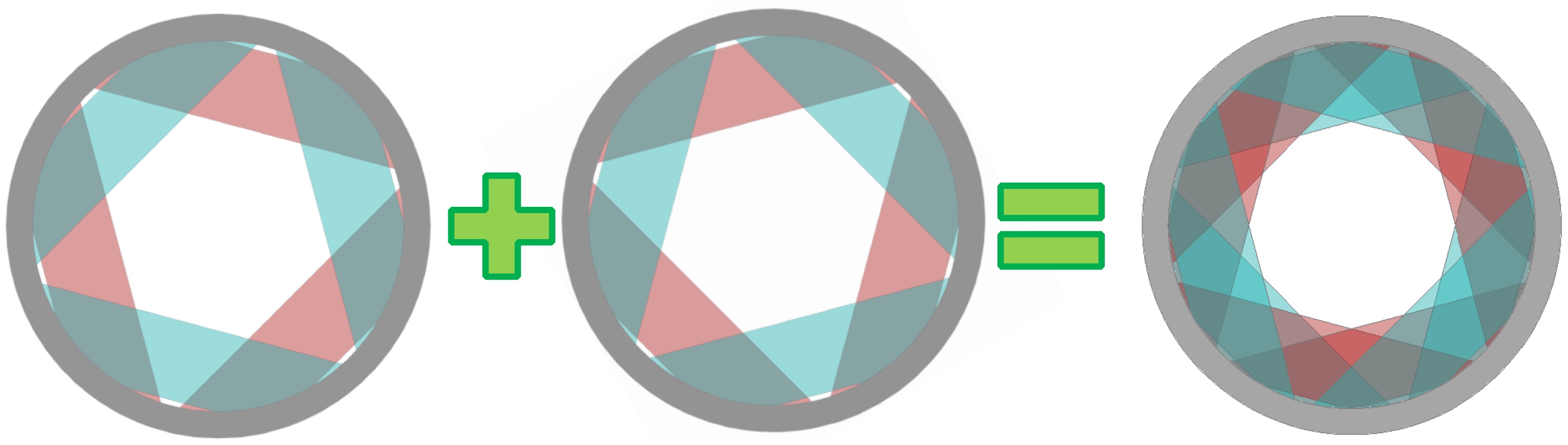
Plane: 6 panels; self supporting



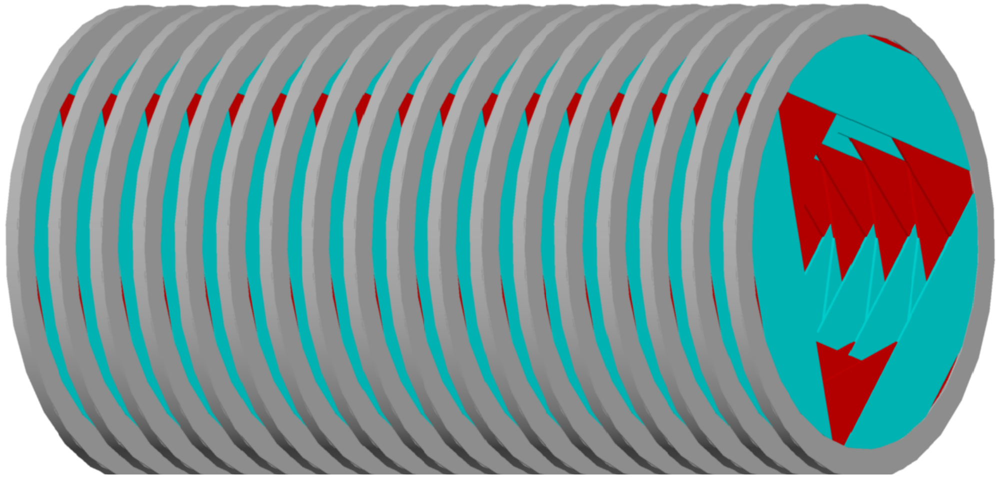
Tracker sits in Vacuum

Tracker: Straw Tubes in Vacuum

4 Station: 2 planes; relative rotation provides stereo info

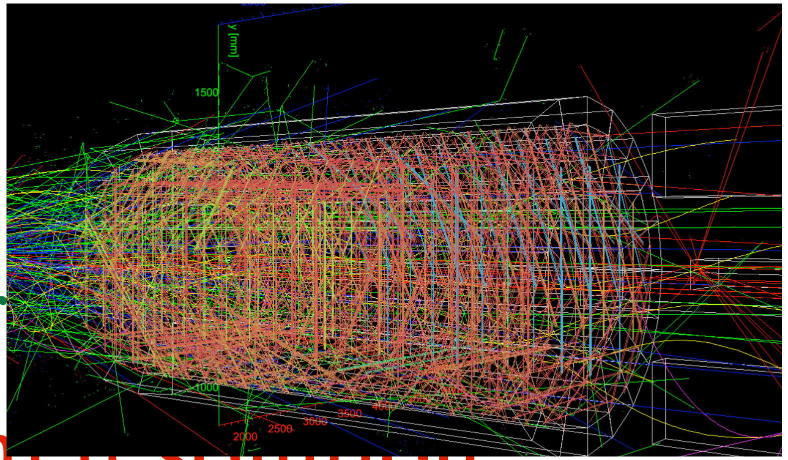


5 Tracker: 18 stations (# being optimized), ~20k straws

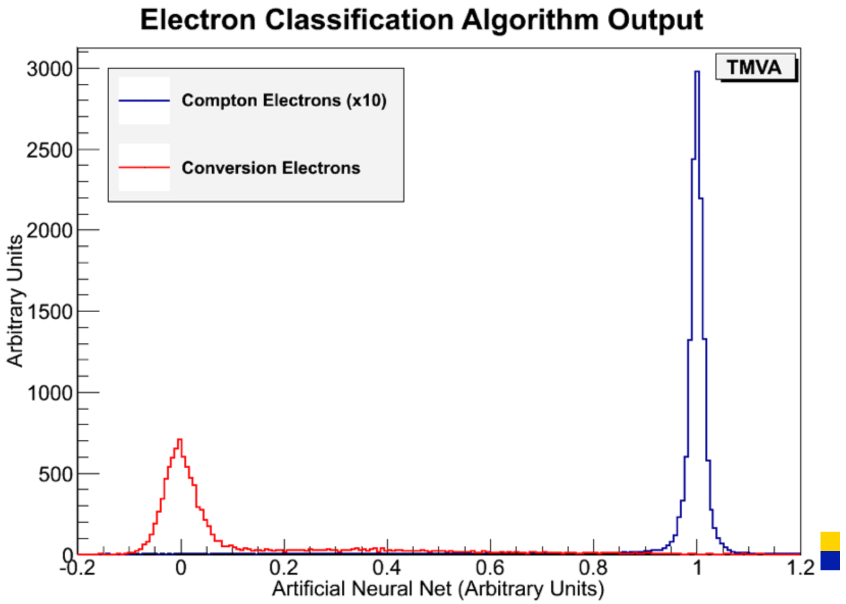


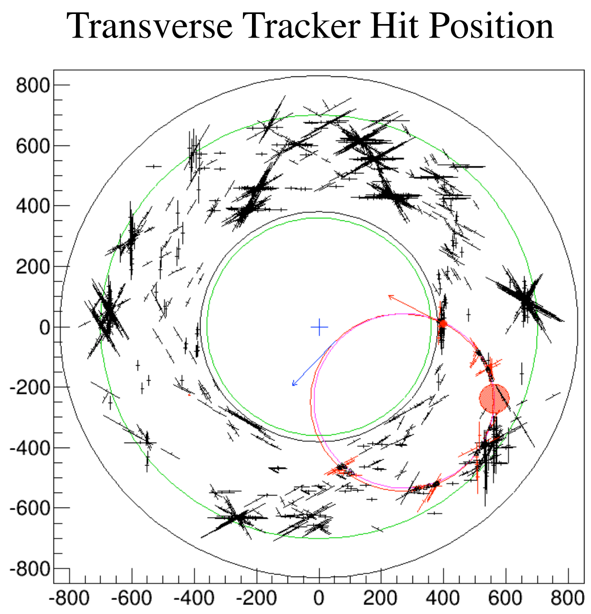
Mu2e Track Reconstruction

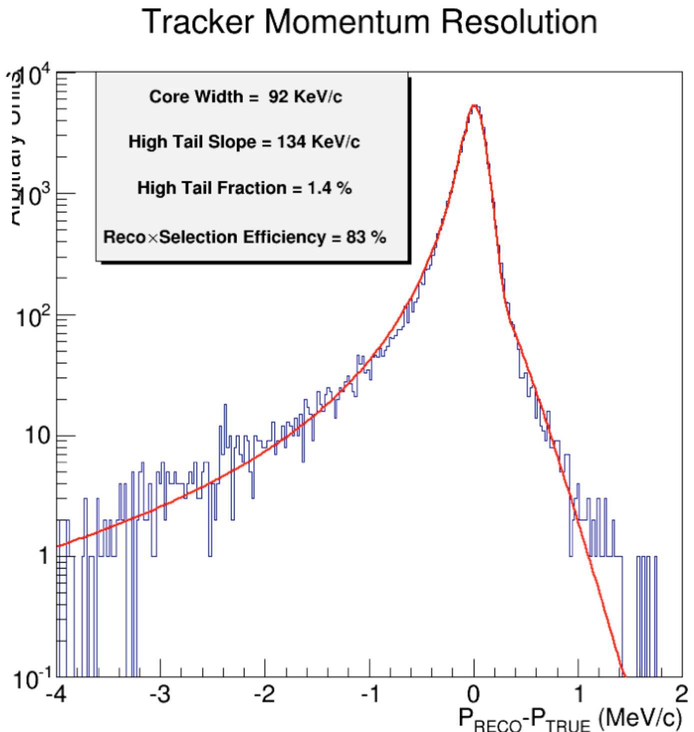
- High backgrounds, single track, no t_0
  - Challenging pattern recognition problem!
  - Time division: define 3d points along the tr
- Need high efficiency, < 2‰ momentum resolution
- Multi-stage solution



Low-energy Background removal → Robust Helix Fit (requires Time Division) → Kalman Fit (import from BaBar)

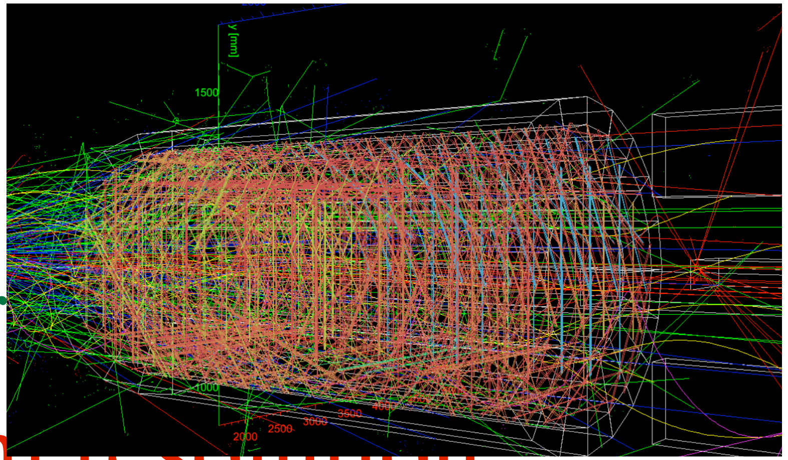






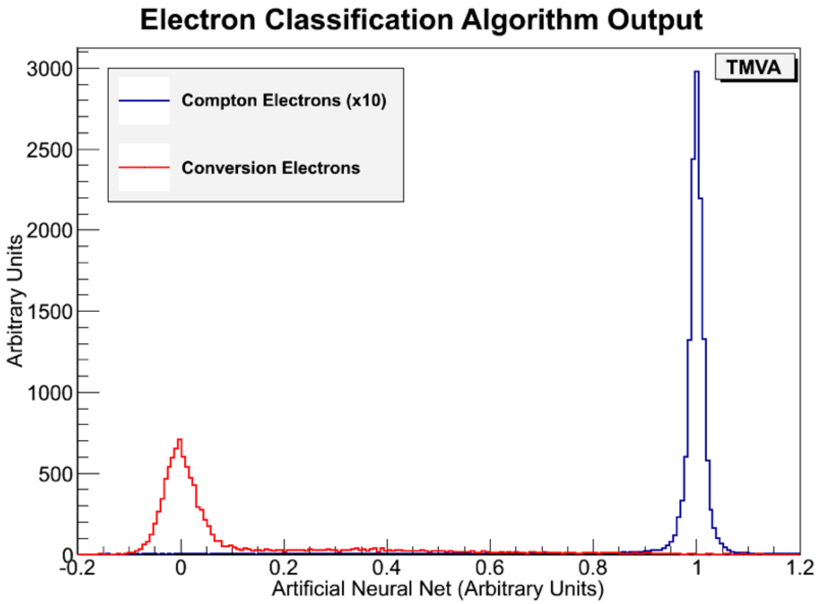
Mu2e Track Reconstruction

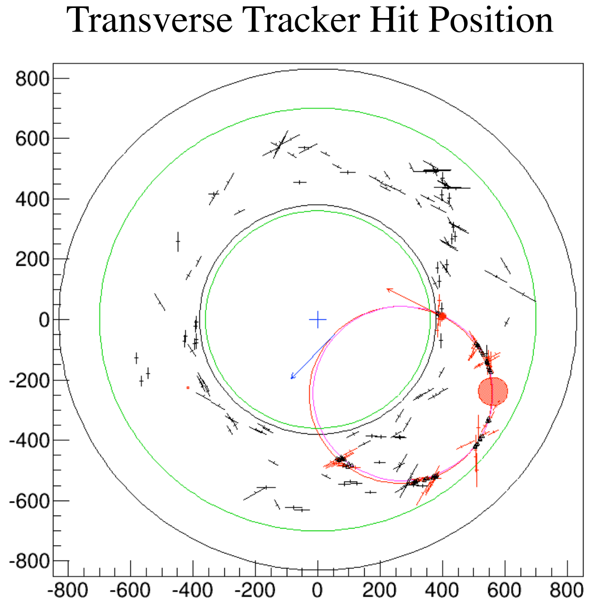
- High backgrounds, single track, no t_0
  - Challenging pattern recognition problem!
  - Time division: define 3d points along the tr

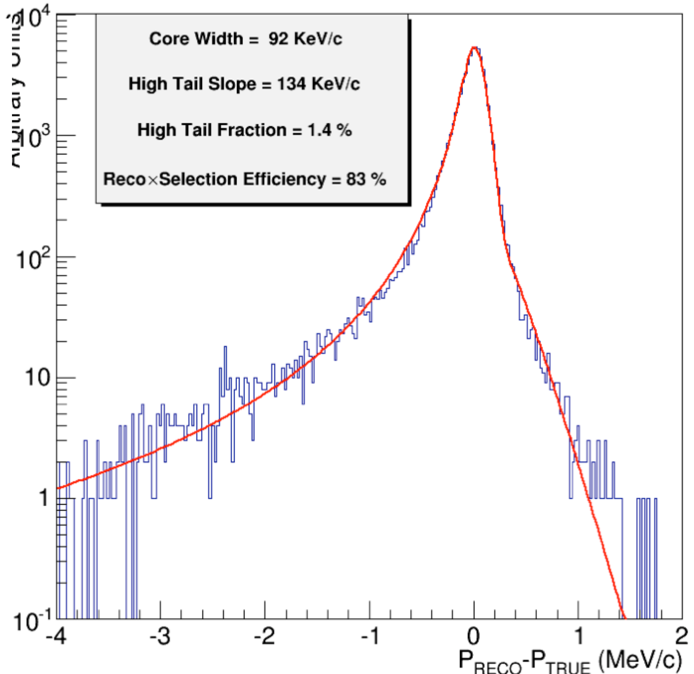


- Need high efficiency, < 2‰ momentum resolution
- Multi-stage solution

Low-energy Background removal → Robust Helix Fit (requires Time Division) → Kalman Fit (import from BaBar)

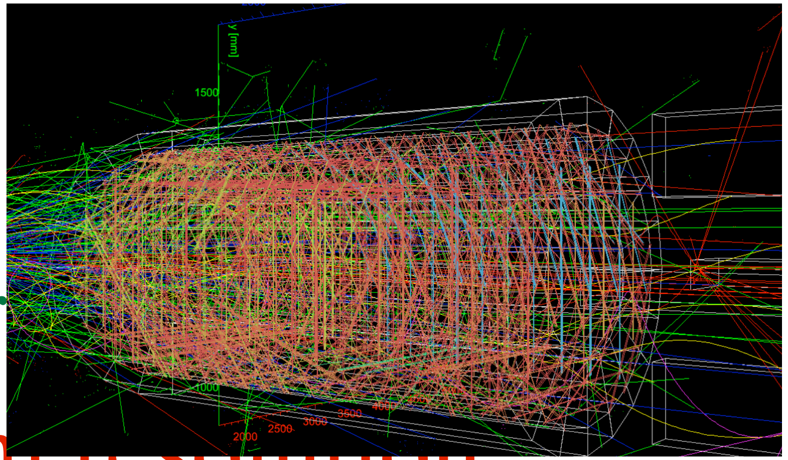




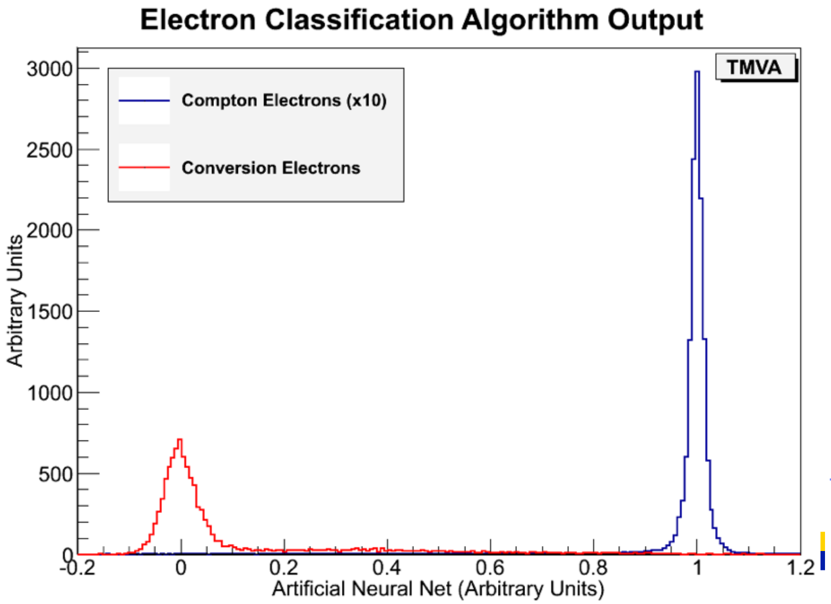


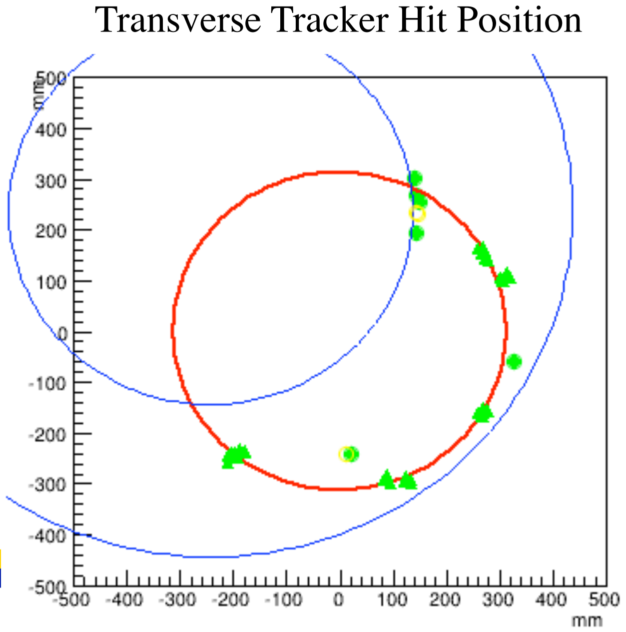
Mu2e Track Reconstruction

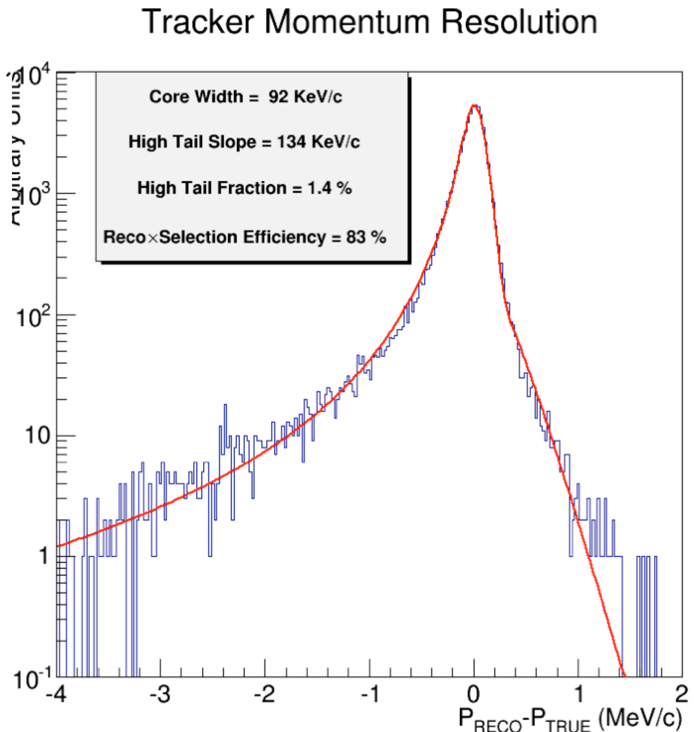
- High backgrounds, single track, no t_0
  - Challenging pattern recognition problem!
  - Time division: define 3d points along the tr
- Need high efficiency, < 2‰ momentum resolution
- Multi-stage solution



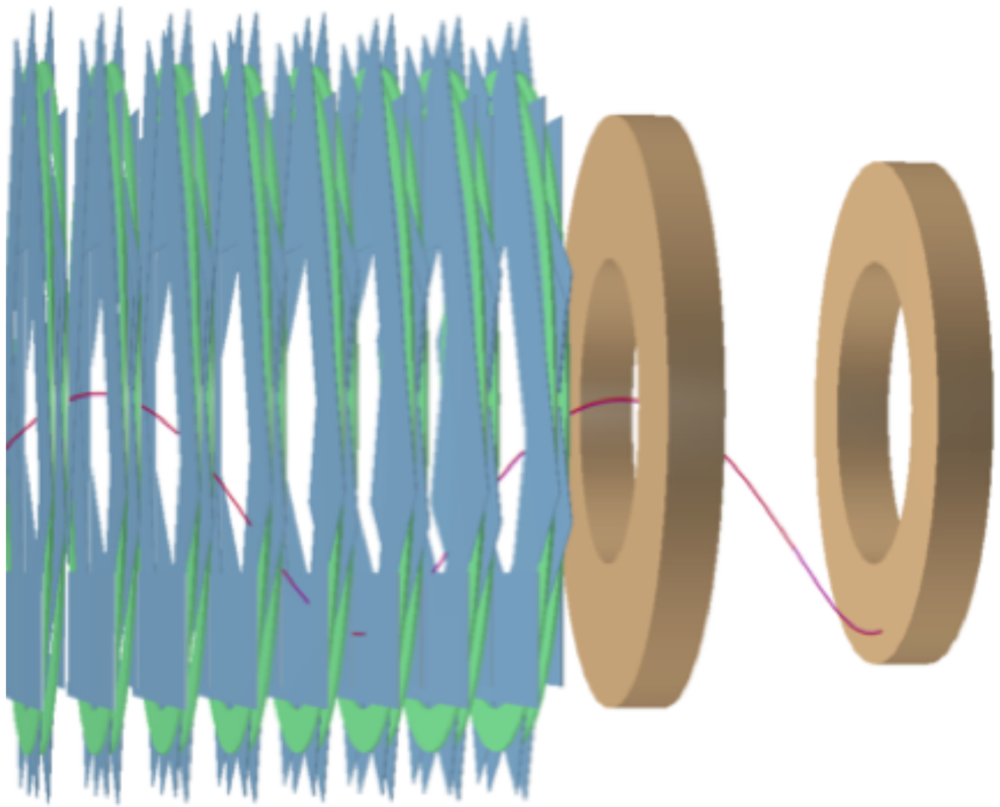
Low-energy Background removal → Robust Helix Fit (requires Time Division) → Kalman Fit (import from BaBar)

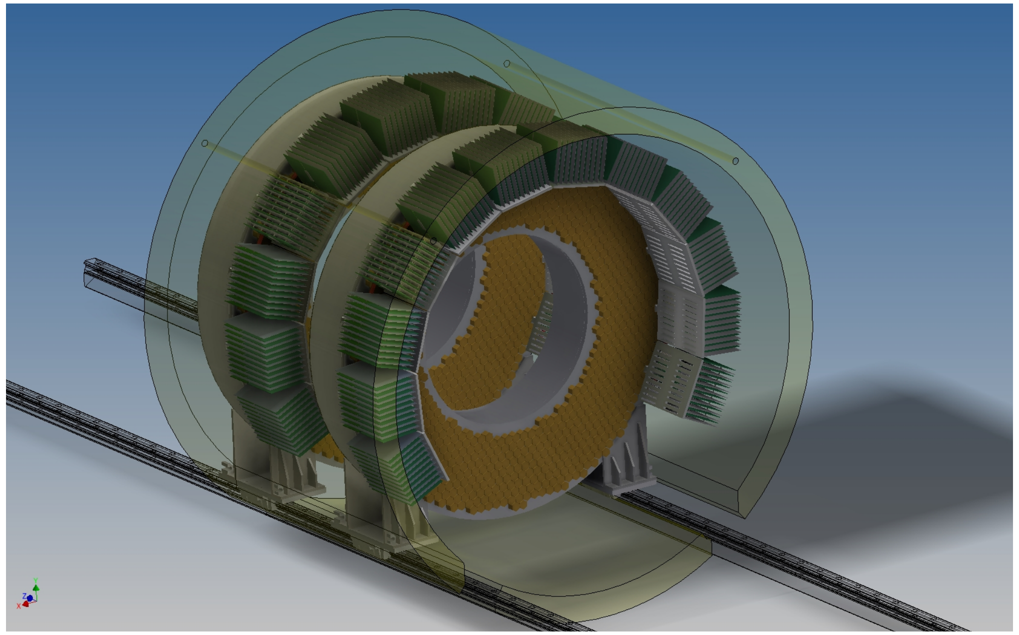




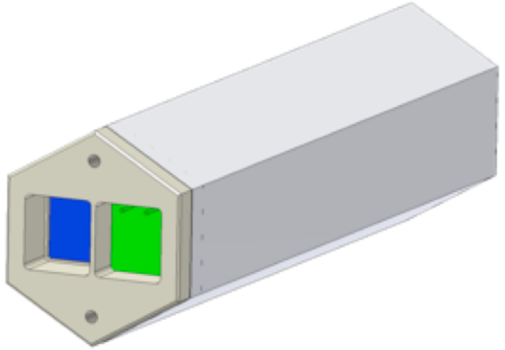


Calorimeter





- Two disk geometry
- Hex BaF_2 crystals; APD or SiPM readout
- Provides precise timing, PID, background rejection, alternate track seed, and possible calibration trigger.



Cosmic Ray Backgrounds