Status of Lepton Flavor

Experimental Searches for Charged Lepton Flavor Violation

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UC Berkeley/LBNL

SUSY-2015
Granlibakken, Tahoe City, CA
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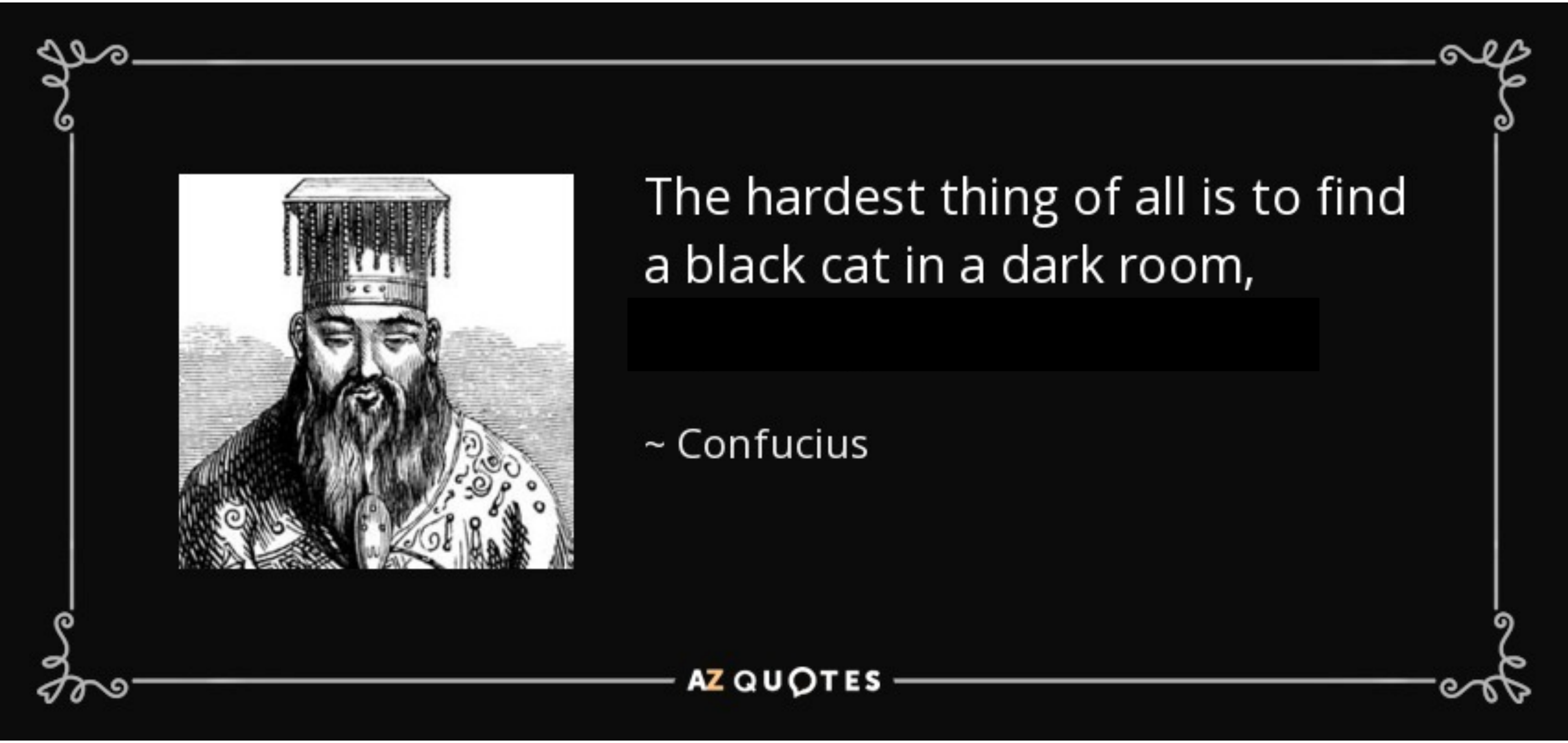
Status of Lepton Flavor



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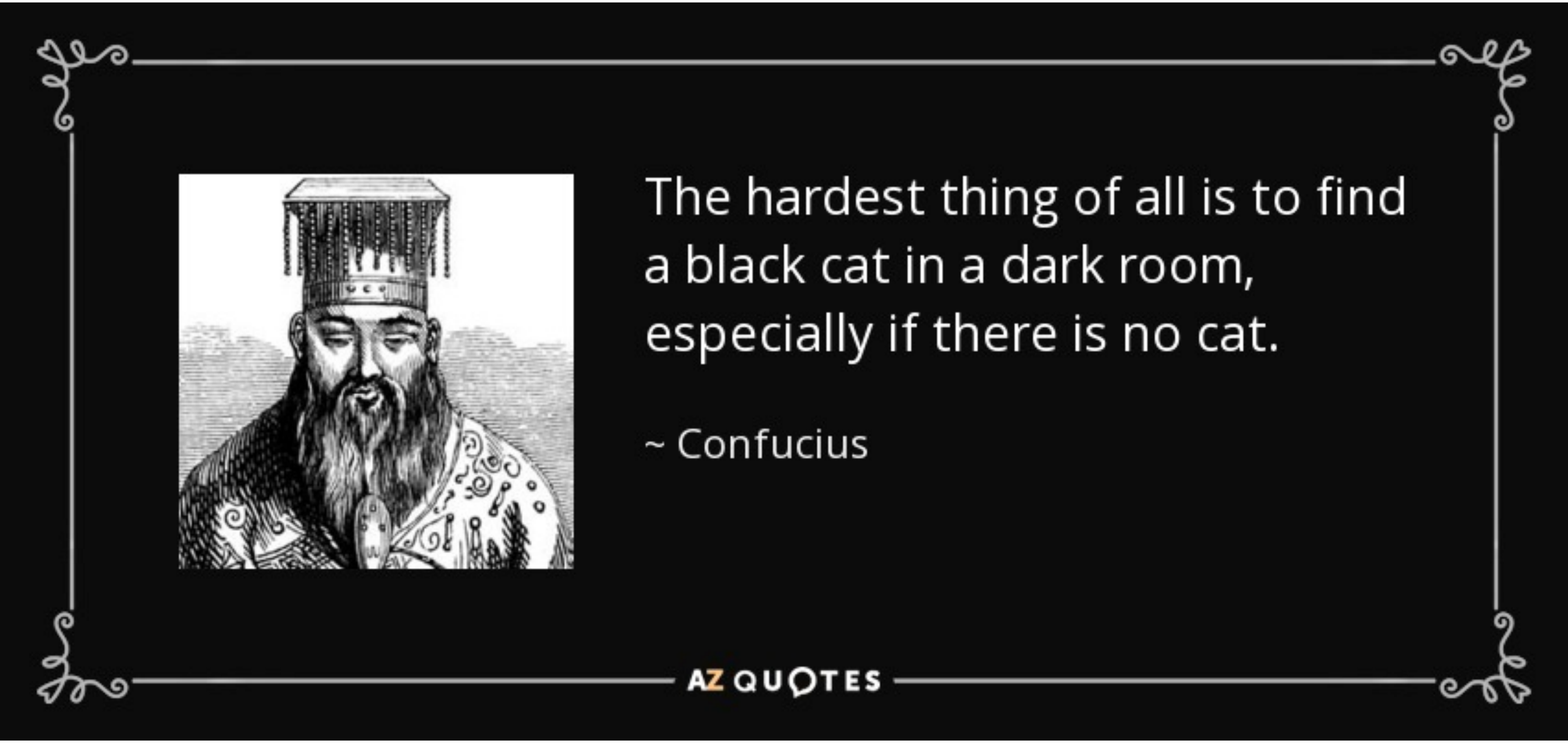
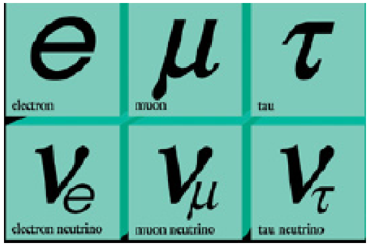


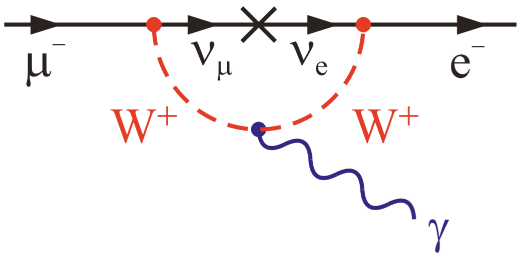
Outline

- Charged Lepton Flavor Violation (short intro)
- Current Status
  - CLFV in Muon Decays (stopped μ beams)
  - CLFV in Tau Decays (e^+e^- colliders, LHCb)
  - CLFV in Higgs and Z Decays (LHC)
- Future Prospects

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: $BR(\mu \rightarrow e\gamma) \sim 10^{-52}$

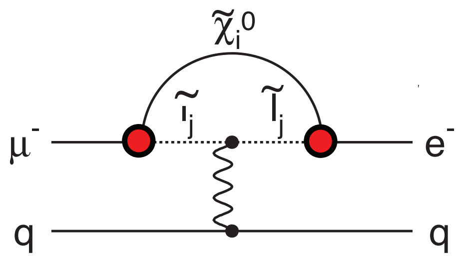


- CLFV: an unambiguous signature of new physics
  - ☞Sensitivity to mass scales far beyond the reach of direct searches
  - ☞Window into TeV physics and beyond
  - ☞Next generation experiments will have sensitivity to directly test predictions of many BSM theories, e.g. SUSY

Possible New Physics Contributions

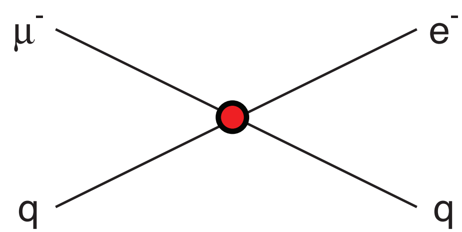
Supersymmetry

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



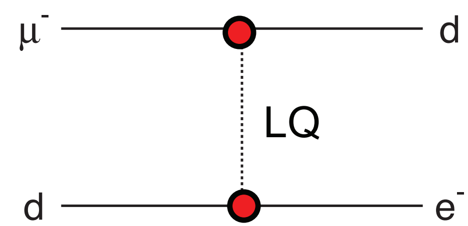
Compositeness

$\Lambda_c \sim 7000$ TeV



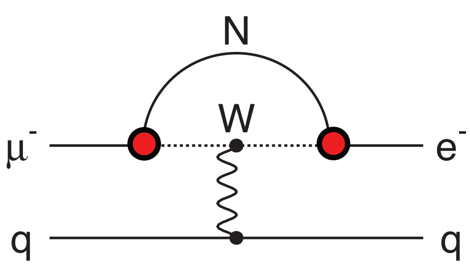
Leptoquark

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



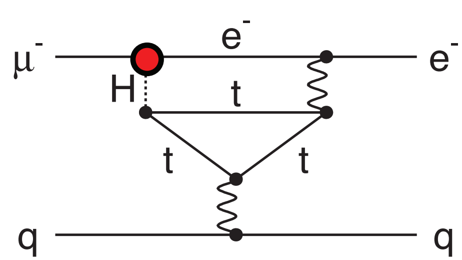
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\text{x}10^{-13}$



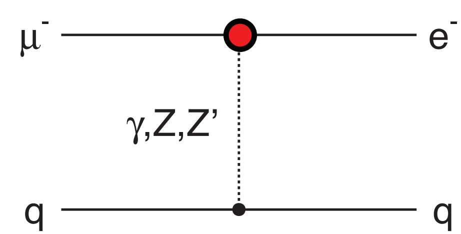
Second Higgs Doublet

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



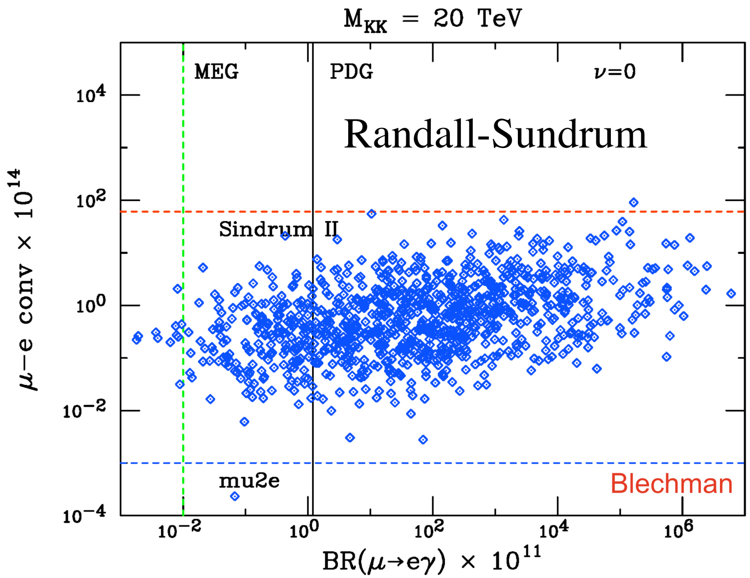
Heavy Z' Anomal. Z Coupling

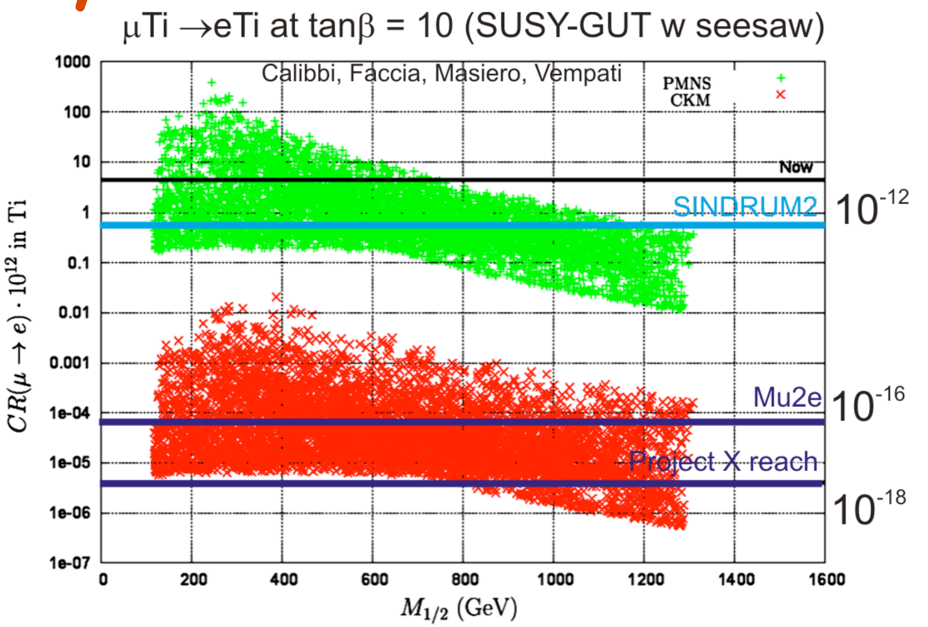
$M_{Z'} = 3000$ TeV/c^2

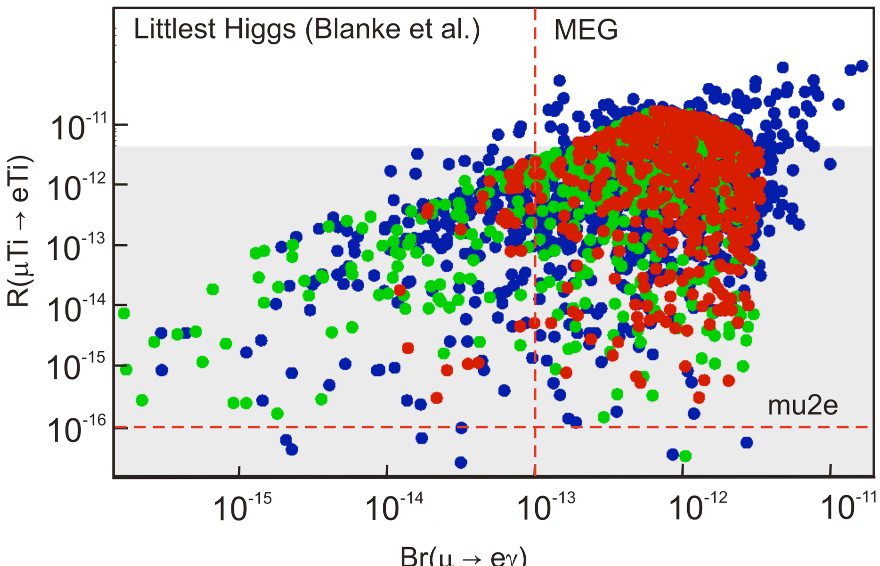


Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58

What Sensitivity is Needed?



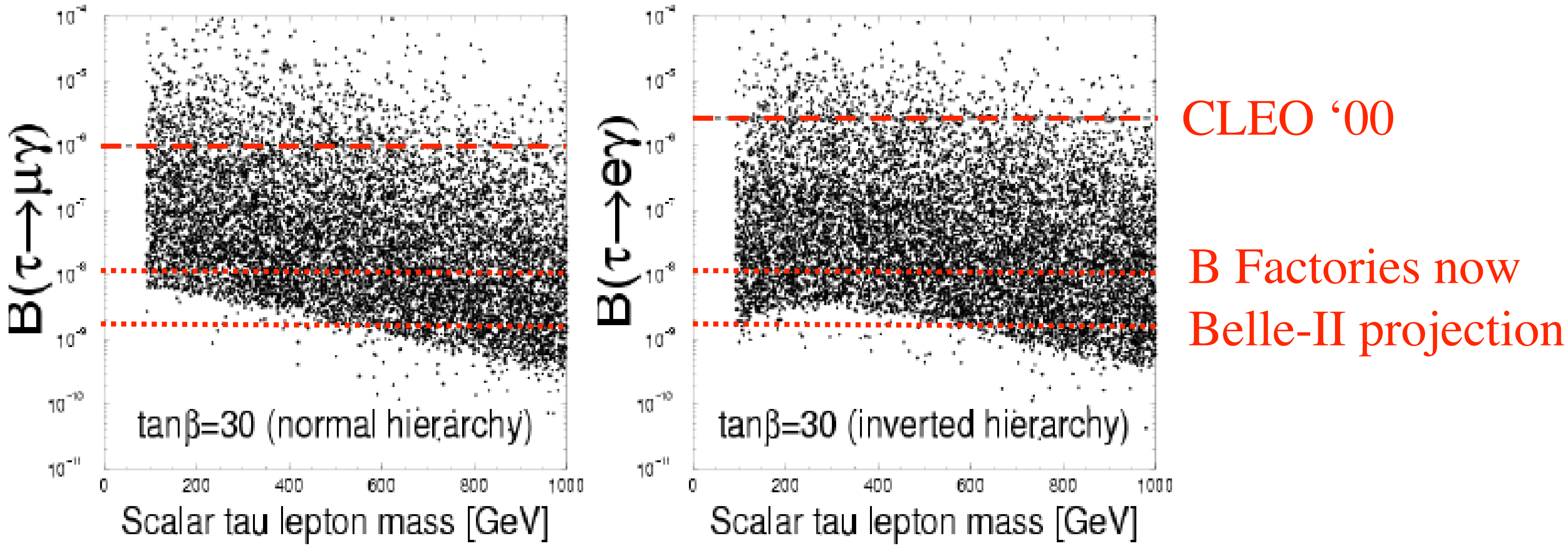




~10^{-16} constrains many models

~10^{-18} ultimate goal

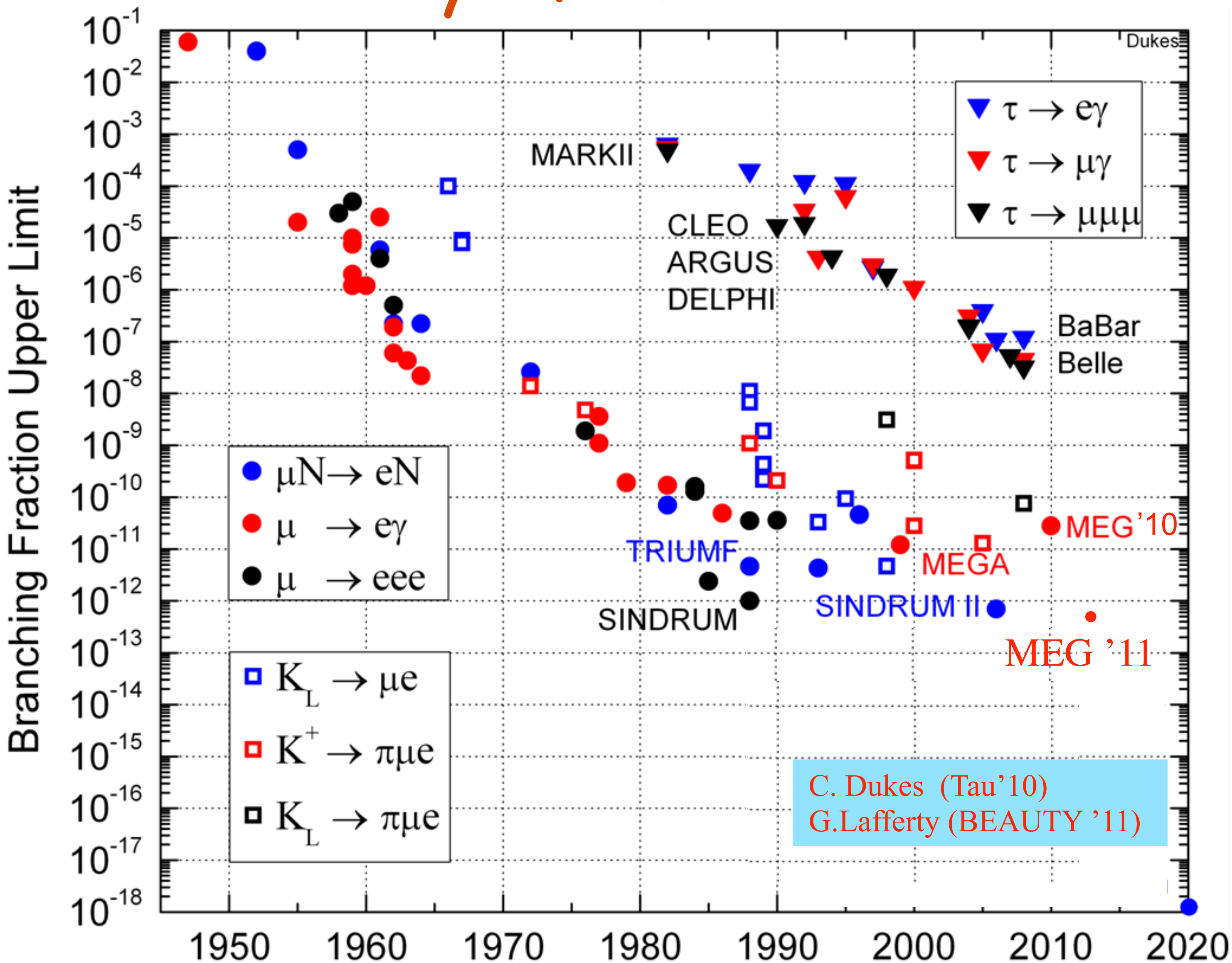
LFV in Tau Decays



Model examples:

	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}
Non-Universal Z' (PLB547(2002)252)	10^{-9}	10^{-8}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-7}	10^{-9}

History of LFV Searches

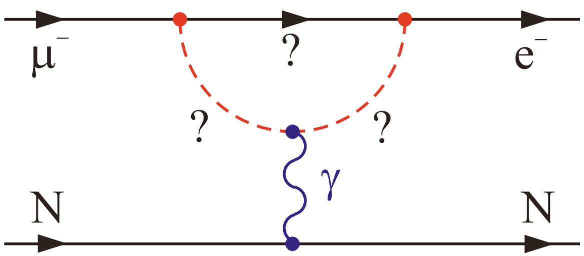


$\mu^- N \rightarrow e^- N'$ and $\mu^+ \rightarrow e^+\gamma$ Complementary

Model independent CLFV Lagrangian:

(A. de Gouvea)

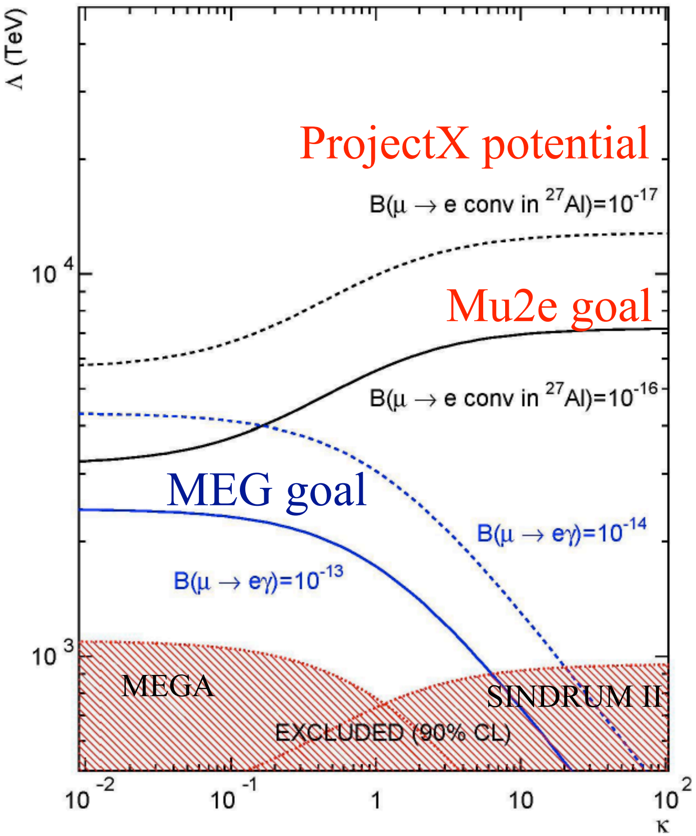
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu} R \sigma_{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma^\mu q_L$$

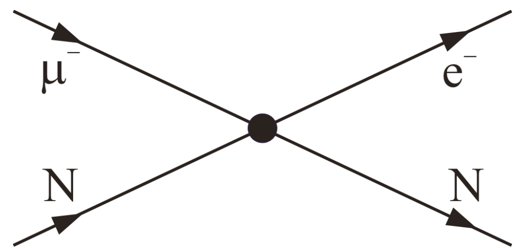


κ<<1

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

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

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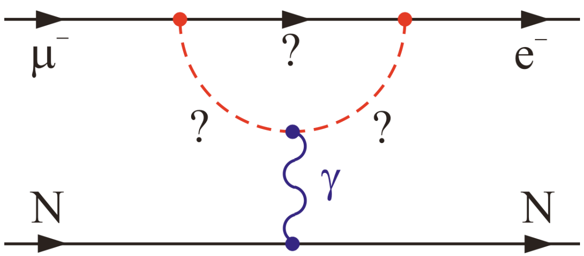

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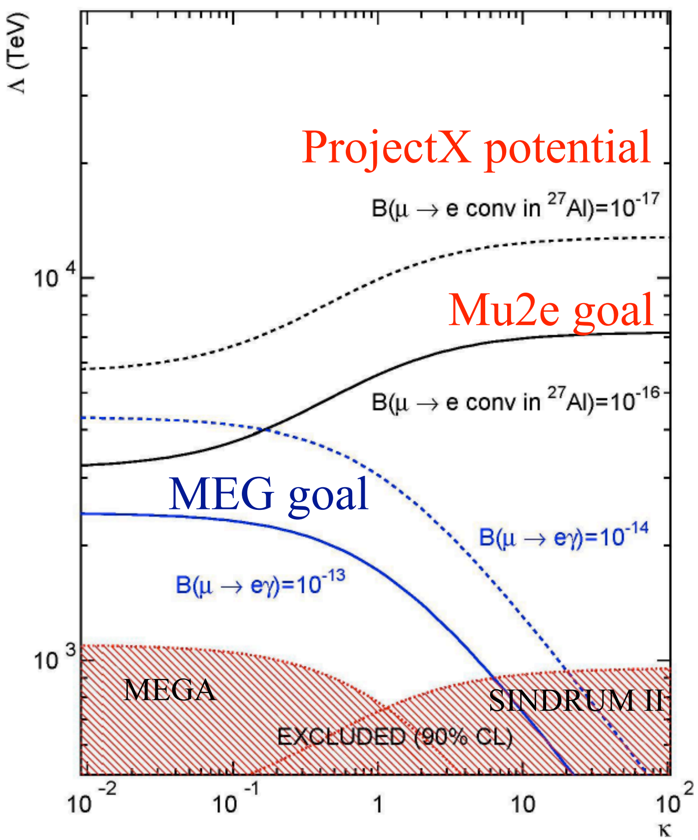

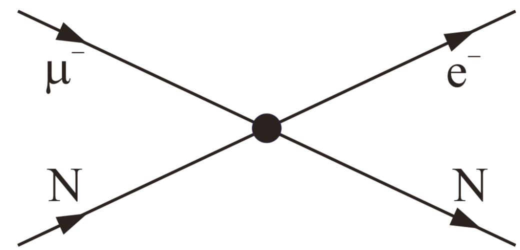

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$\mu N \rightarrow eN'$ greatly enhanced over $\mu \rightarrow e\gamma$ rate

Similarly, complementary information from μ and τ searches

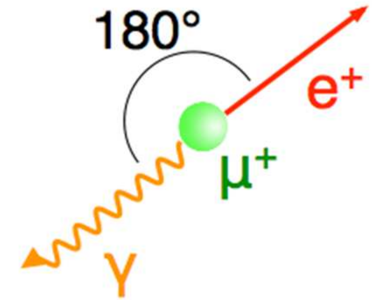
CLFV in Muon Decays

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

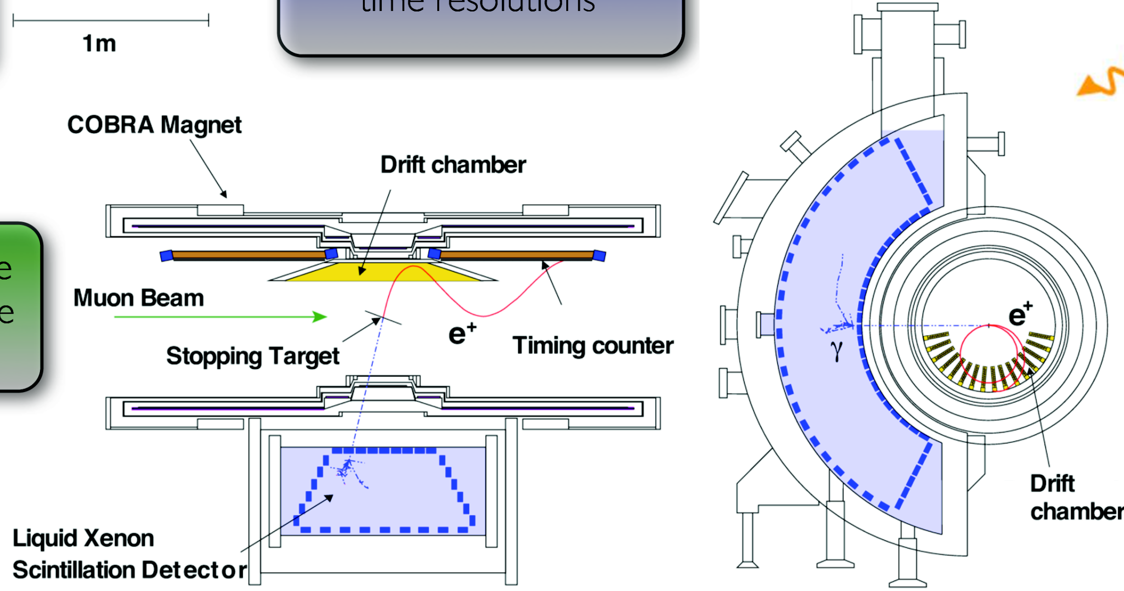
MEG (PSI)

The most intense DC muon beam

Gamma High energy and time resolutions



Positron Very precise momentum and time resolutions



High efficiency event selection and frequency signal digitization

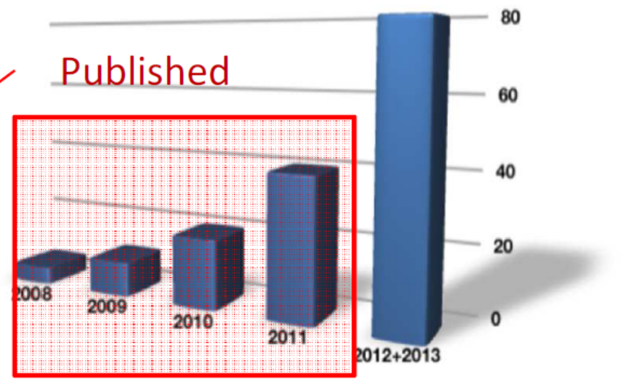
Complementary calibration and monitoring methods

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

MEG Results and Prospects

D. Grigoriev @ NuFact 2015

Phy. Rev. Lett. 110, 201801 (2013)



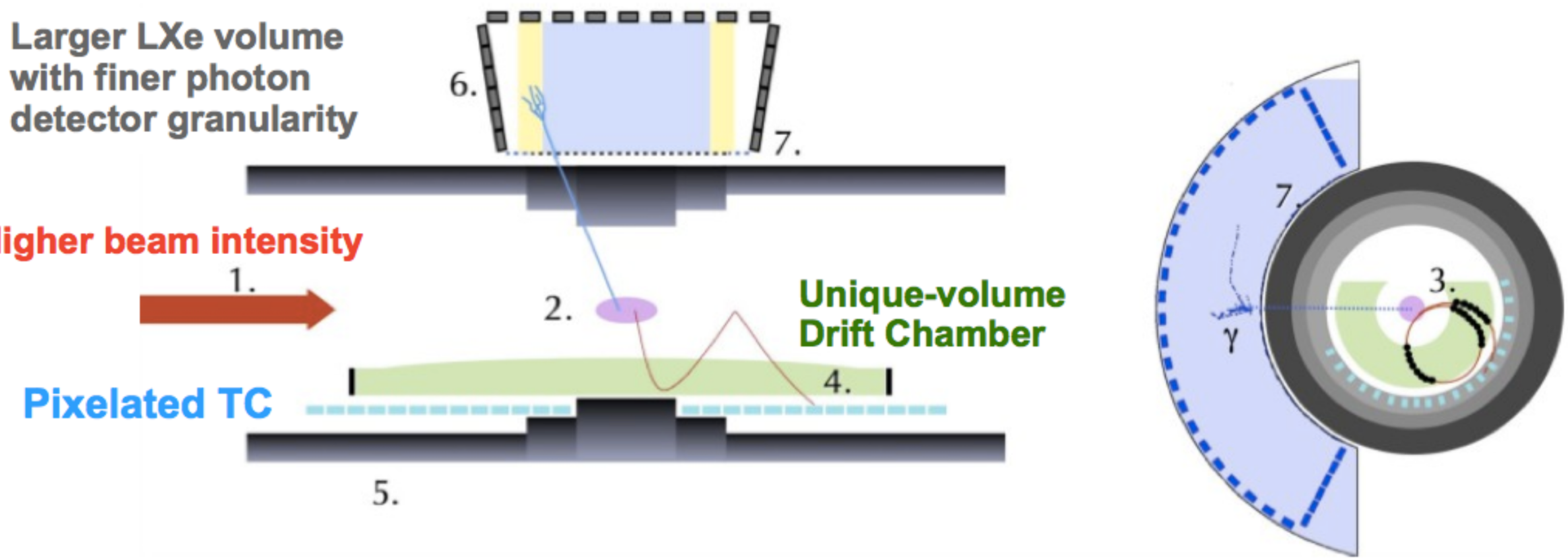
Data taking finished at 31.08.2013
Statistics is doubled compare to published

year	Nstop μ, $x10^{13}$	Sensitivity, $x10^{-13}$	Br, Upper limit (CL 90%), $x10^{-13}$
2009+2010	17.5	13	13
2011	18.5	11	6,7
2009+2010+2011	36.0	7.7	**5.7** (20 times better
All data (expected)	~80	~5	than MEGA)

Final result of analysis is expected by the end of 2015 with the improved analysis. The data are reprocessed now.

MEG-II Upgrade

- An upgrade of MEG, aiming at a sensitivity improvement of one order of magnitude (**down to 5 x 10^{-14}**) approved by PSI and funding agencies is ongoing



A. Papa @ NuFact 2015

MEG-II Sensitivity

- More sensitive to the signal...

high statistics

$$SES = \frac{1}{R \times T \times A_g \times \varepsilon(e^+) \times \varepsilon\,(gamma) \times \varepsilon(TRG) \times \varepsilon(sel)}$$

beam rate
acquisition time
geometrical acceptance
detector efficiency
selection efficiency

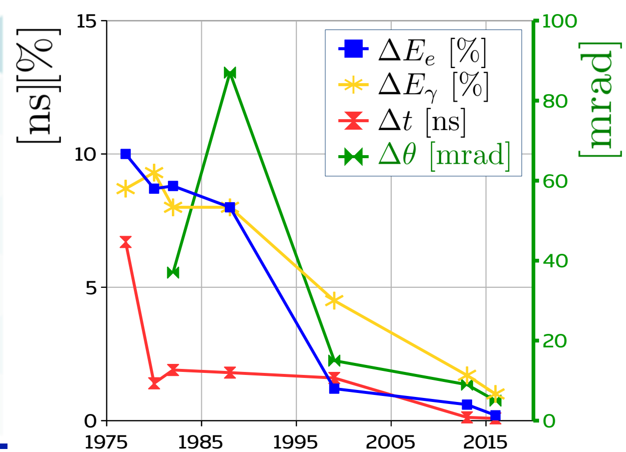
- More effective on rejecting the background...

high resolutions

$$B_{acc} \sim R \times \Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta \Theta_{egamma})^2$$

momentum resolution
Energy resolution
Relative timing resolution
Relative angular resolution

Resolution	MEGI	MEGII
u (mm)	5	2.4
v (mm)	5	2.2
w (mm)	6	3.1
E_γ (w<2cm)	2.4%	1.1%
E_γ (w>2cm)	1.7%	1.0%
$t_{e\gamma}$ (ps)	67	60

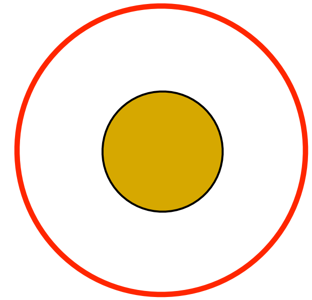


Muon→Electron Conversion

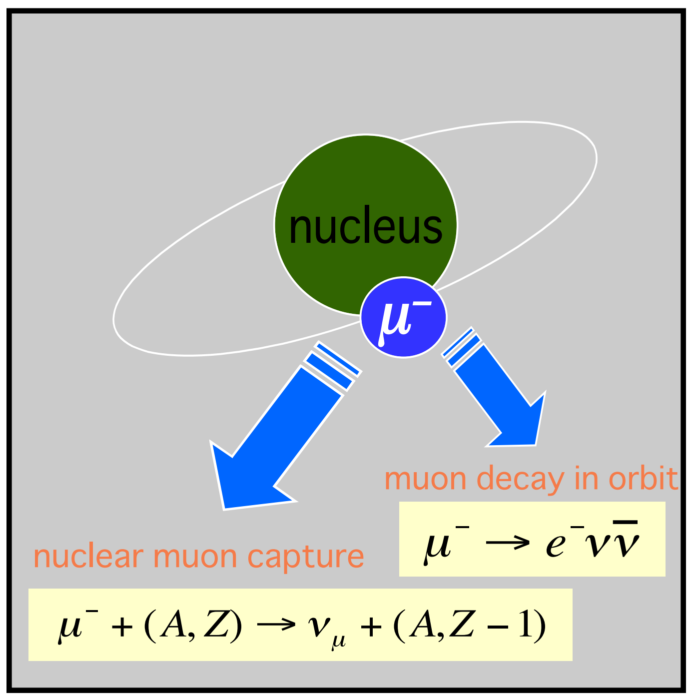
μ^- stops in thin Al foil

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

μ^- in 1S state



Al Nucleus
~4 fm



60% capture
40% decay

muon capture,
muon "falls into"
nucleus:
normalization

Decay in Orbit:
background

Muon→Electron Conversion

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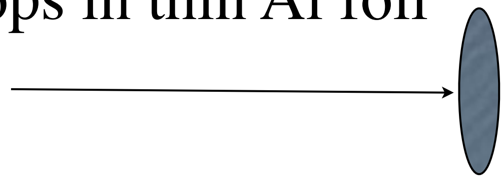

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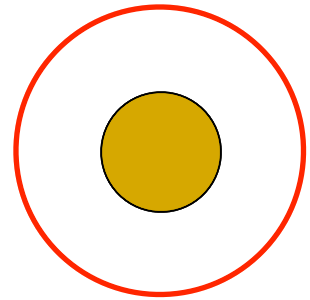

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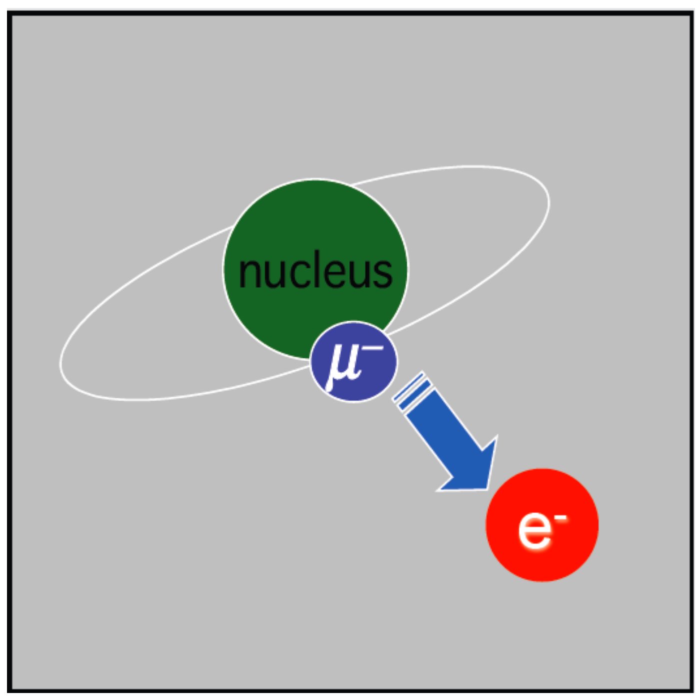

60% capture
40% decay

Muon conversion:
signal

Muon→Electron Conversion

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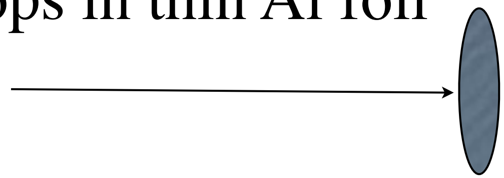

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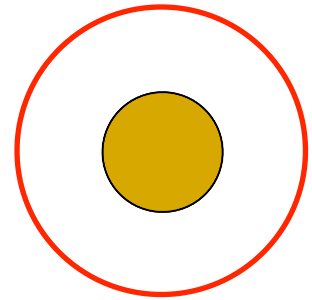
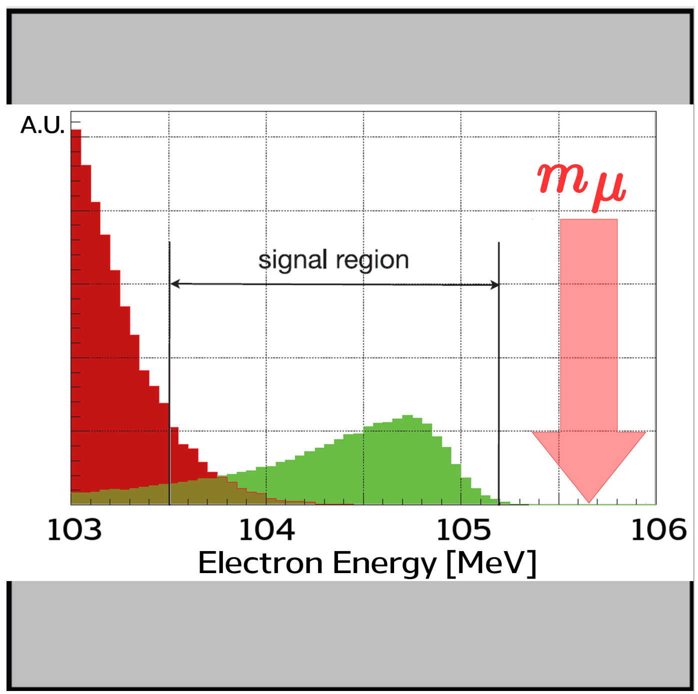


Al Nucleus
~4 fm

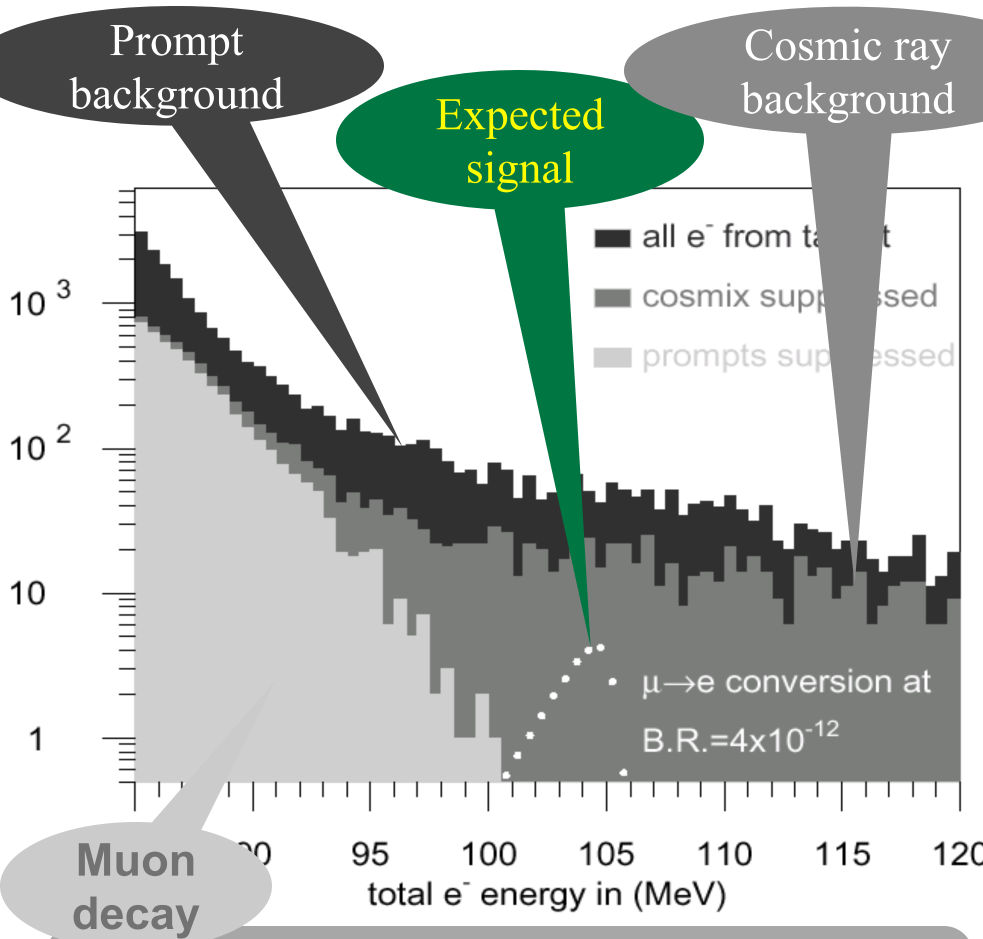


60% capture
40% decay

muon capture, muon "falls into" nucleus: ***normalization***

Muon conversion: signal

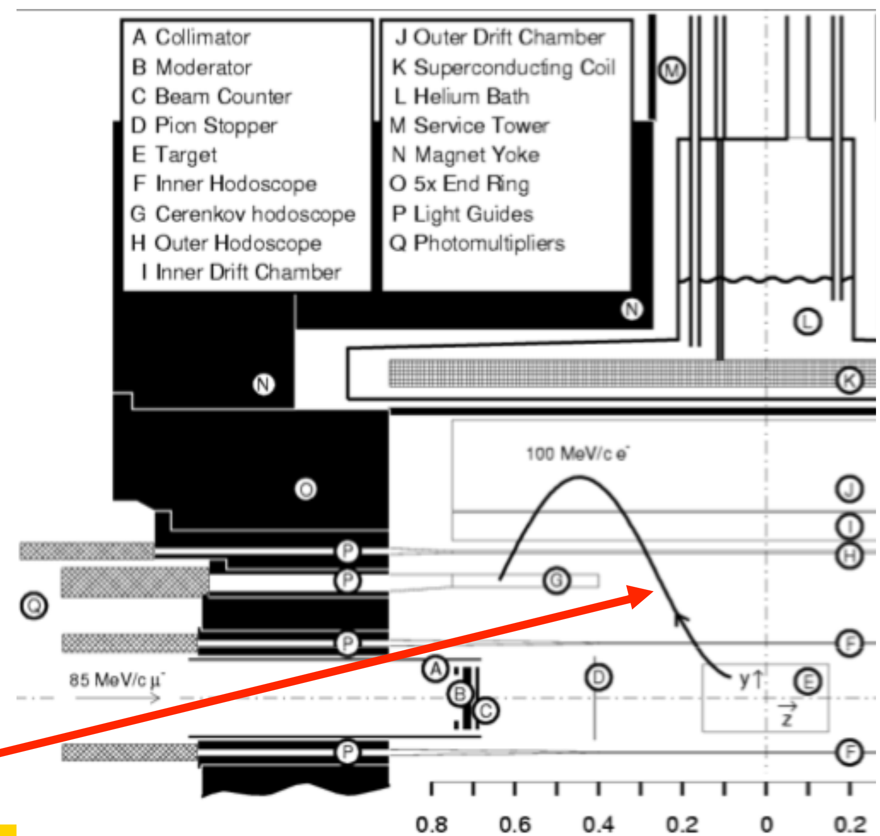
Previous Best Experiment



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

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

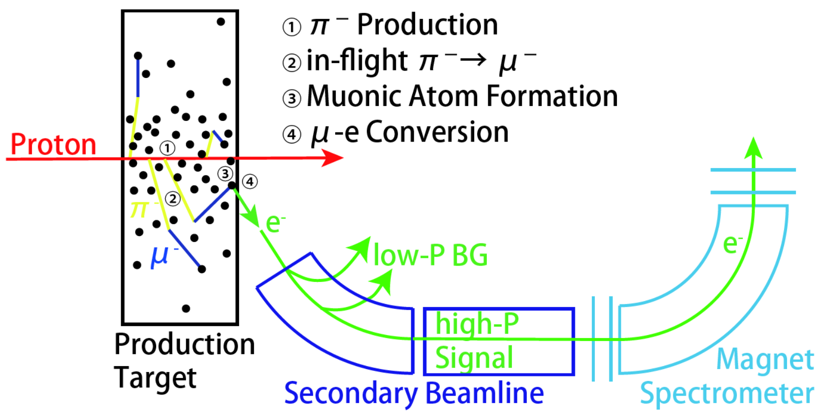
Limitation: CW beam



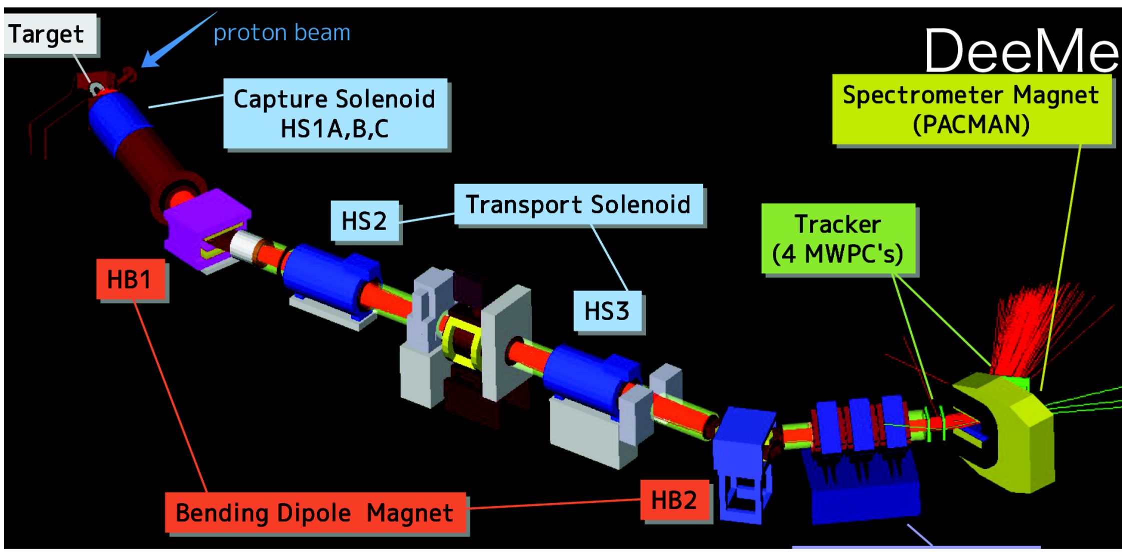
Experimental signature is 105 MeV e- originating in a thin stopping target.

Little time separation between signal and bkg

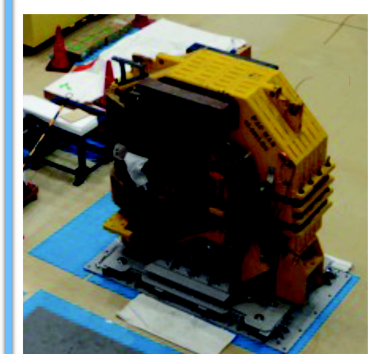
Near Term: DeeMe



- **IMSS/Muon PAC: Stage-2 Approved**
- **J-PARC/RCS**: High-Power High-Purity Pulsed Proton Beam.
- **Production Target as μ-stopping target**.
- **H-Line/MLF**: Large-Acceptance Beam line.
- **State-of-the-Art MWPC** Technology
- **S.E.S. — BR~5 x 10^{-15}**
  (8 x 10^7 sec of data taking with SiC target)
- Start the physics run with graphite target
  - S.E.S. — 1 x 10^{-13} (2 x 10^7 sec)
- Aiming to start the engineering run in **2016**.



Magnet leased from TRIUMF



M. Aoki @ NuFact 2015

$\mu \rightarrow e$ Conversion Experiments

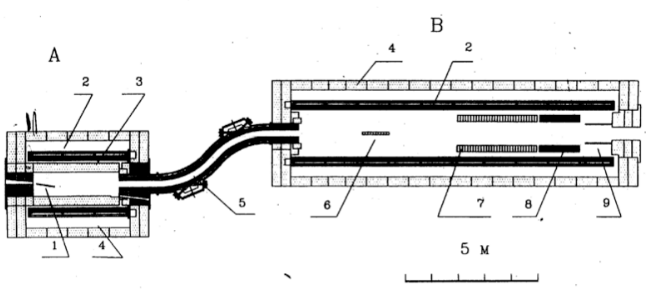
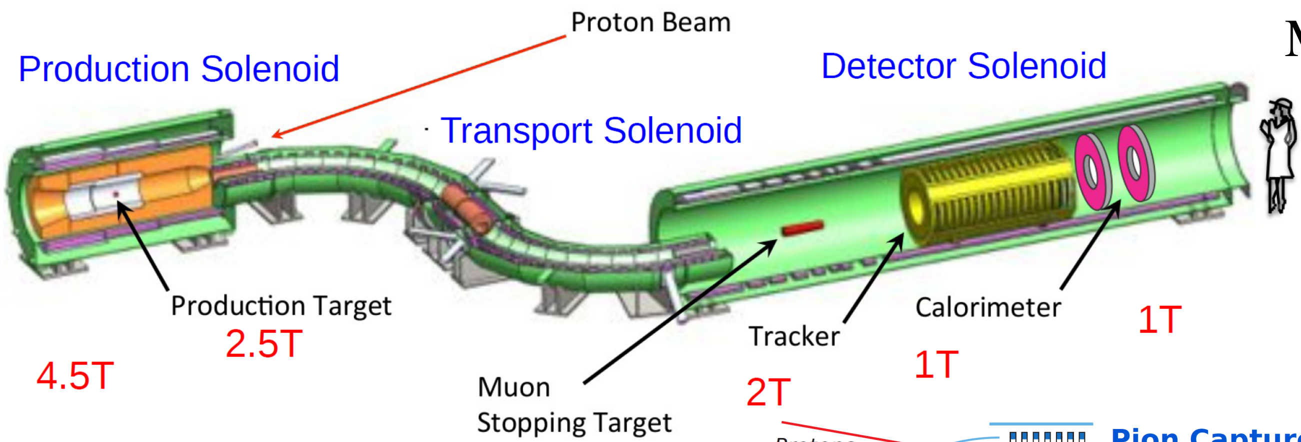


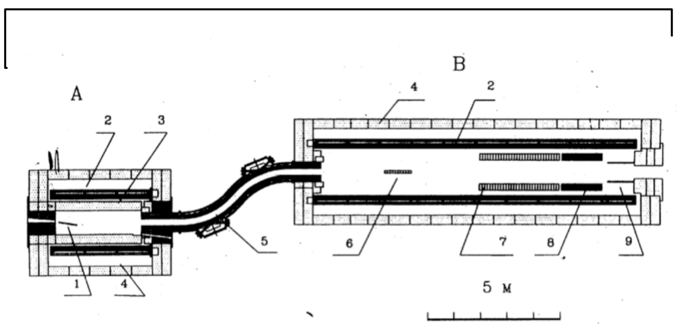
Fig. 1. Set-up MELC: A – meson-production part, B – detector part.
1 – tungsten target of the meson-production part (T_1),
2 – big superconducting solenoids, 3 – protection of the solenoid against radiation,
4 – steel magnetic circuit, 5 – solenoid-collimator,
6 – aluminium-target of the detector part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





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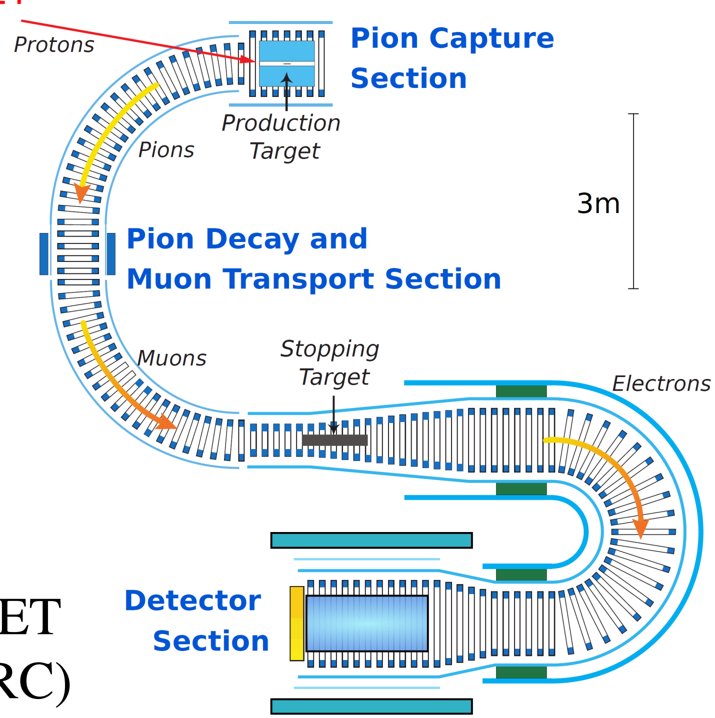
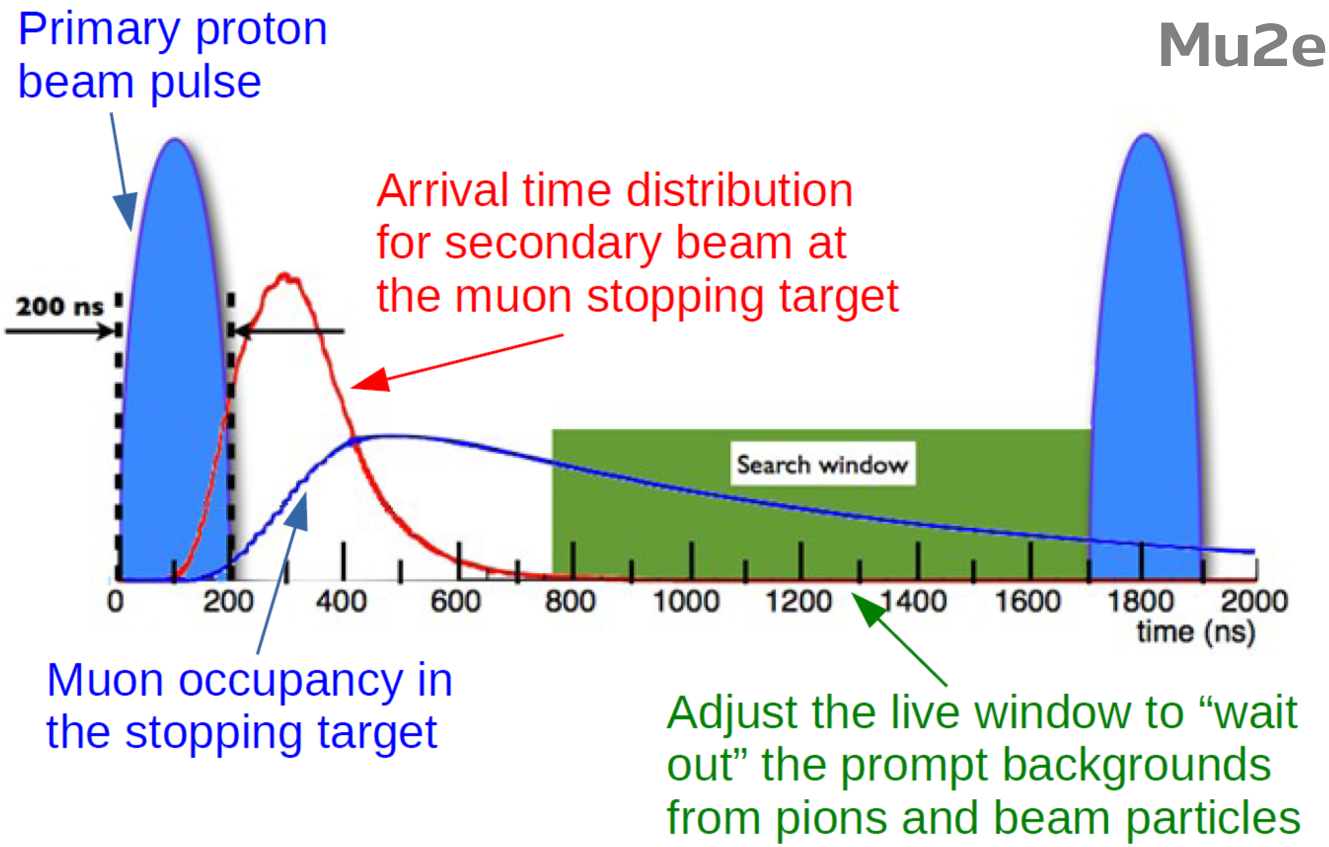


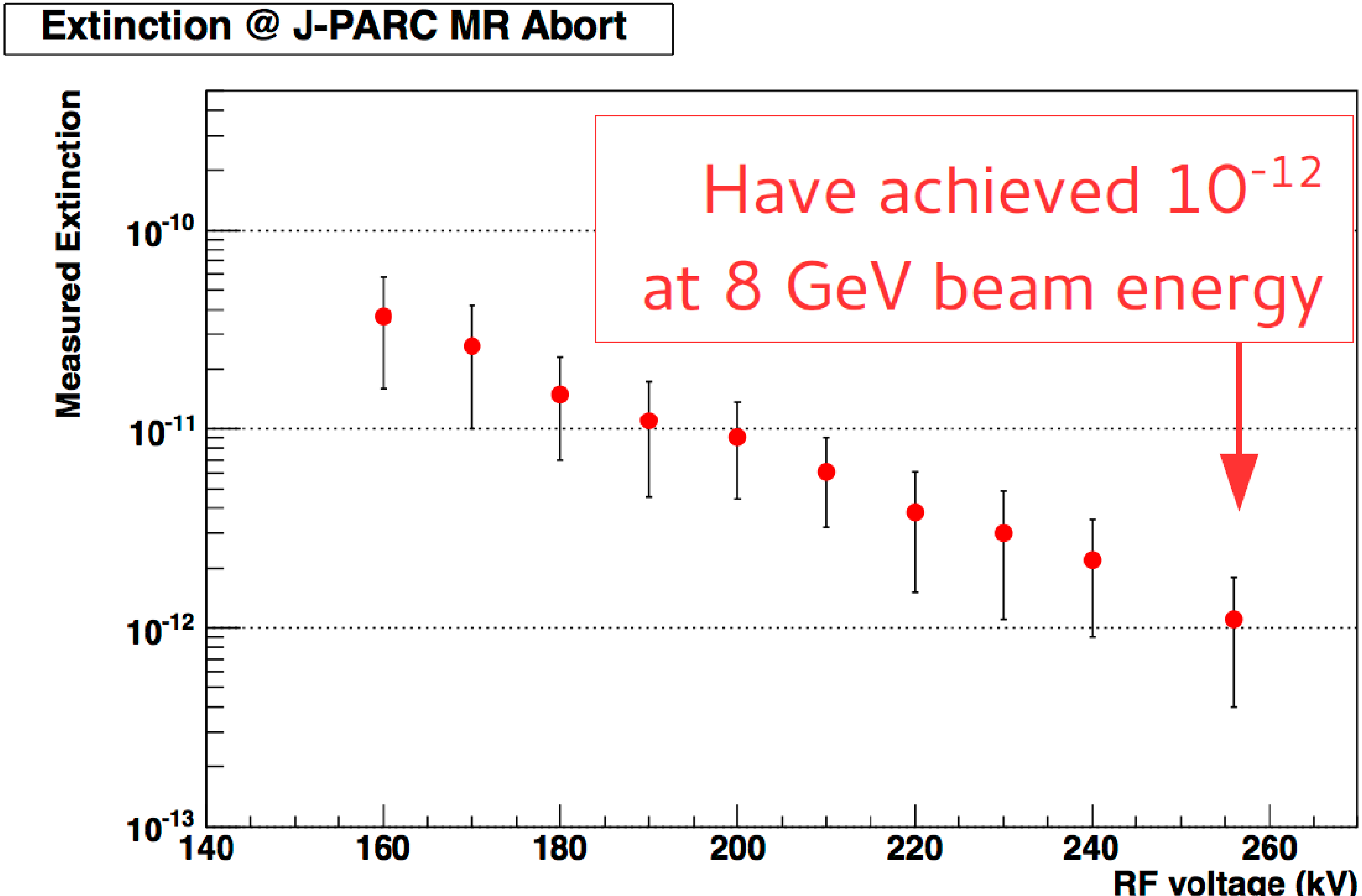
COMET (J-PARC)

Critical Issue: Proton Beam Timing



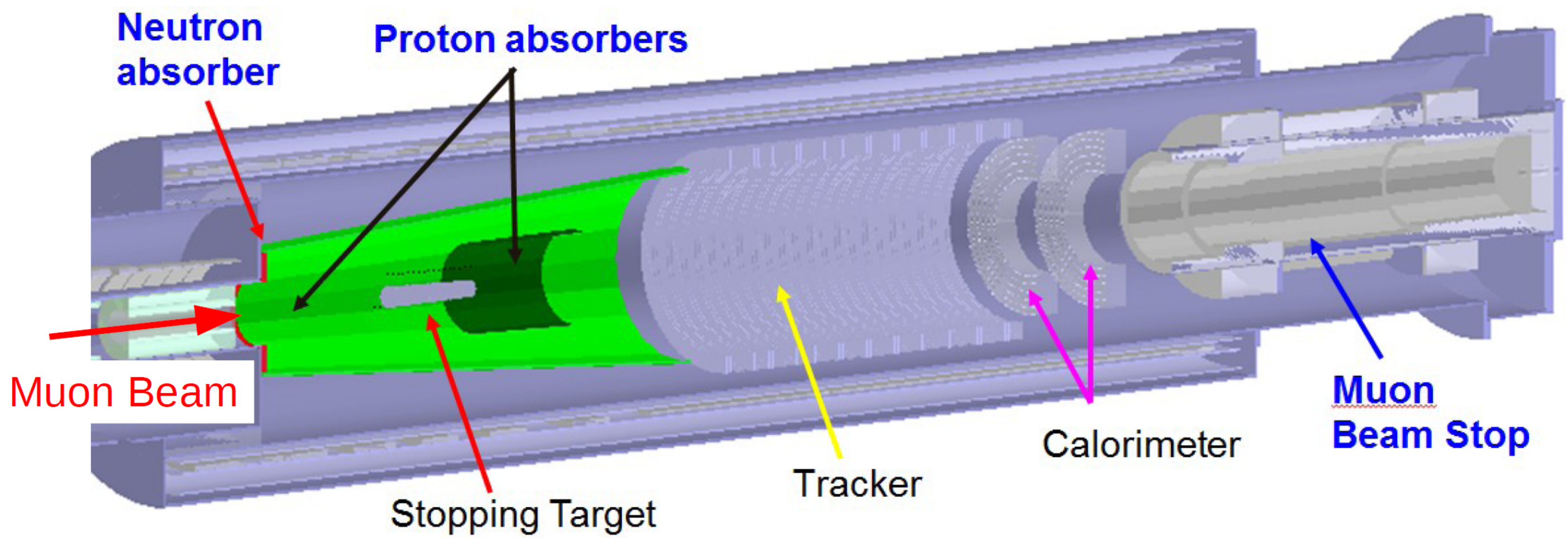
Critical parameter: beam extinction between pulses ($<10^{-10}$ required)

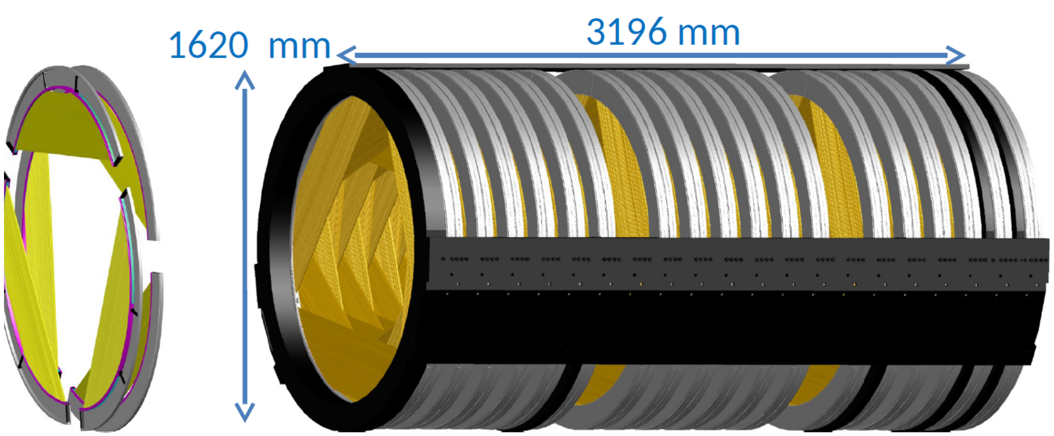
Critical Issue: Proton Beam Timing



B. Krikler @ NuFact 2015

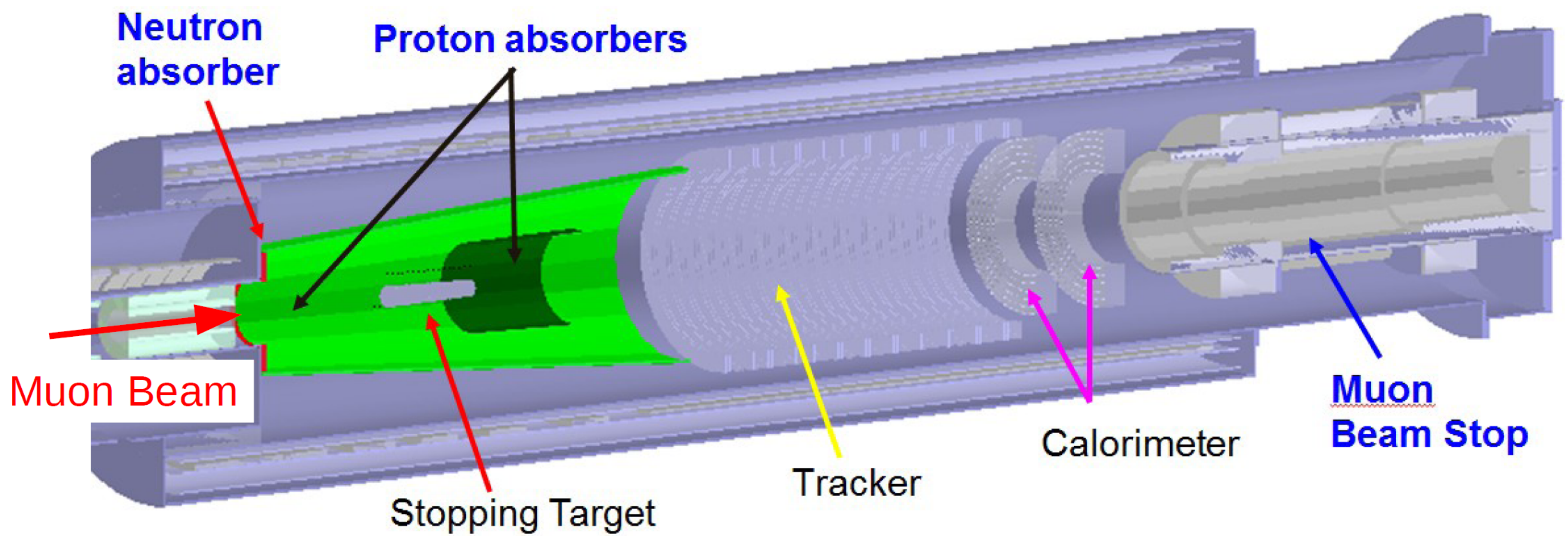
Detectors: Mu2e

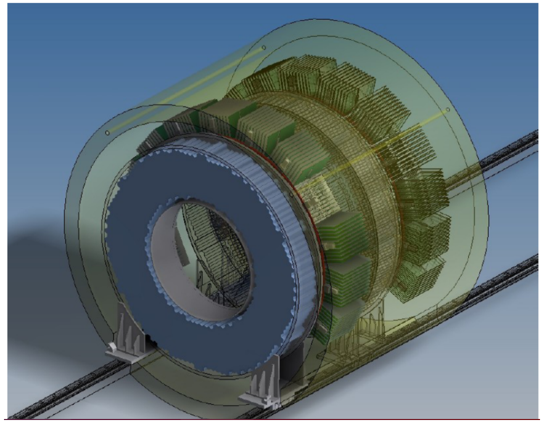




- Electron tracker: low-mass straw tubes
- 18 planes of 5-mm diameter straws transverse to beam, 0.1% momentum resolution
- Time-division readout to seed pattern recognition

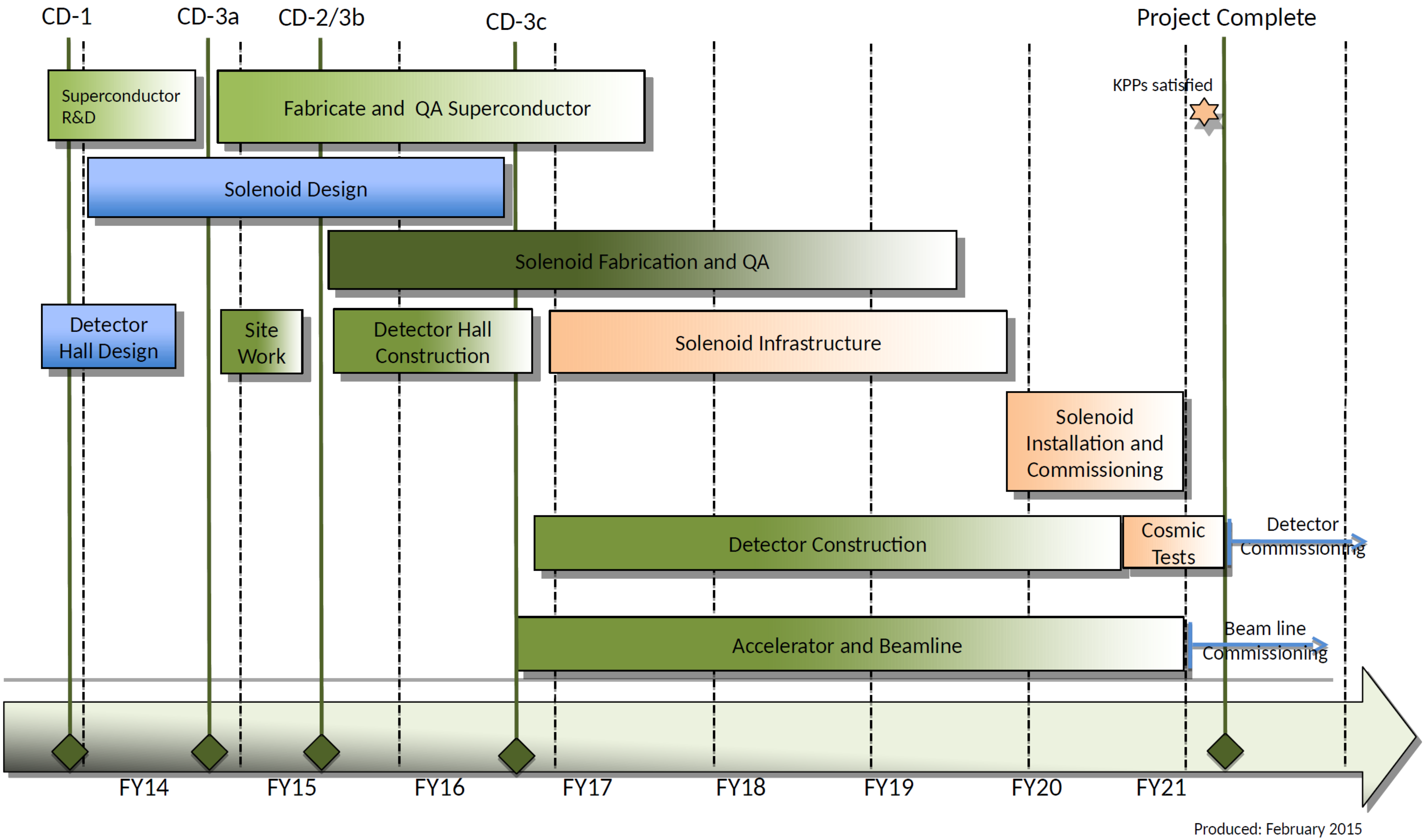
Detectors: Mu2e





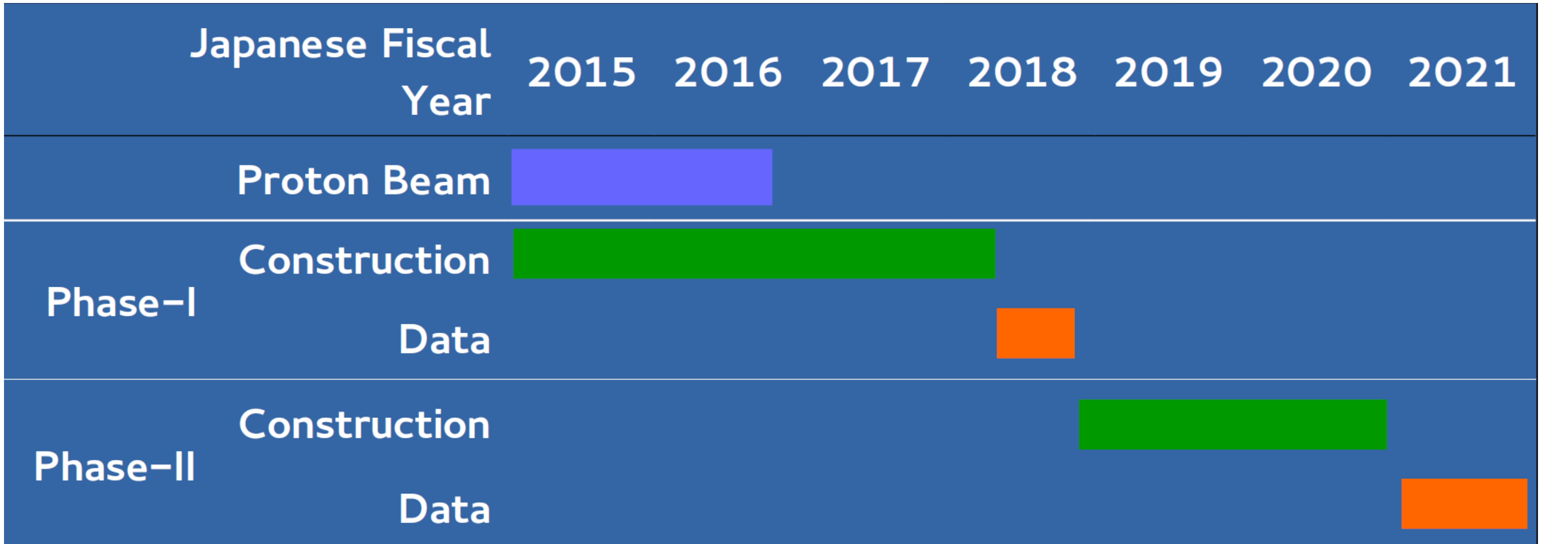
- Calorimeter: disk geometry
- Hex BaF_2 crystals; APD or SiPM readout
- Provides precise timing, PID, background rejection, alternate track seed, and possible calibration trigger.

Mu2e Schedule

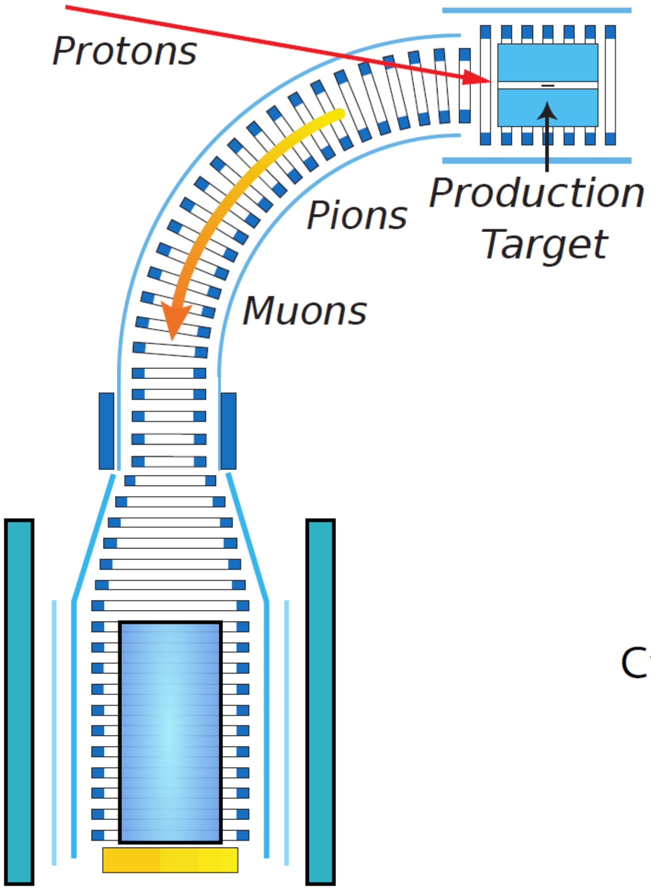


Mu2e Progress

COMET Schedule



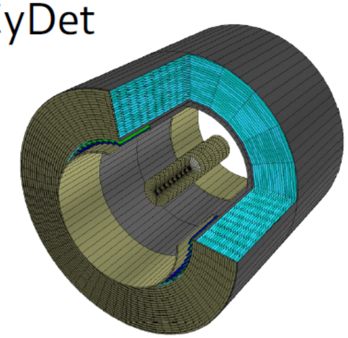
COMET: Phase-I



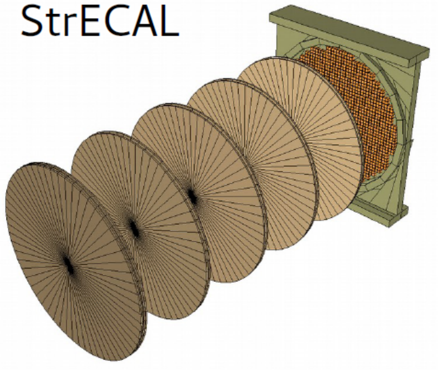
Goals of Phase−I

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

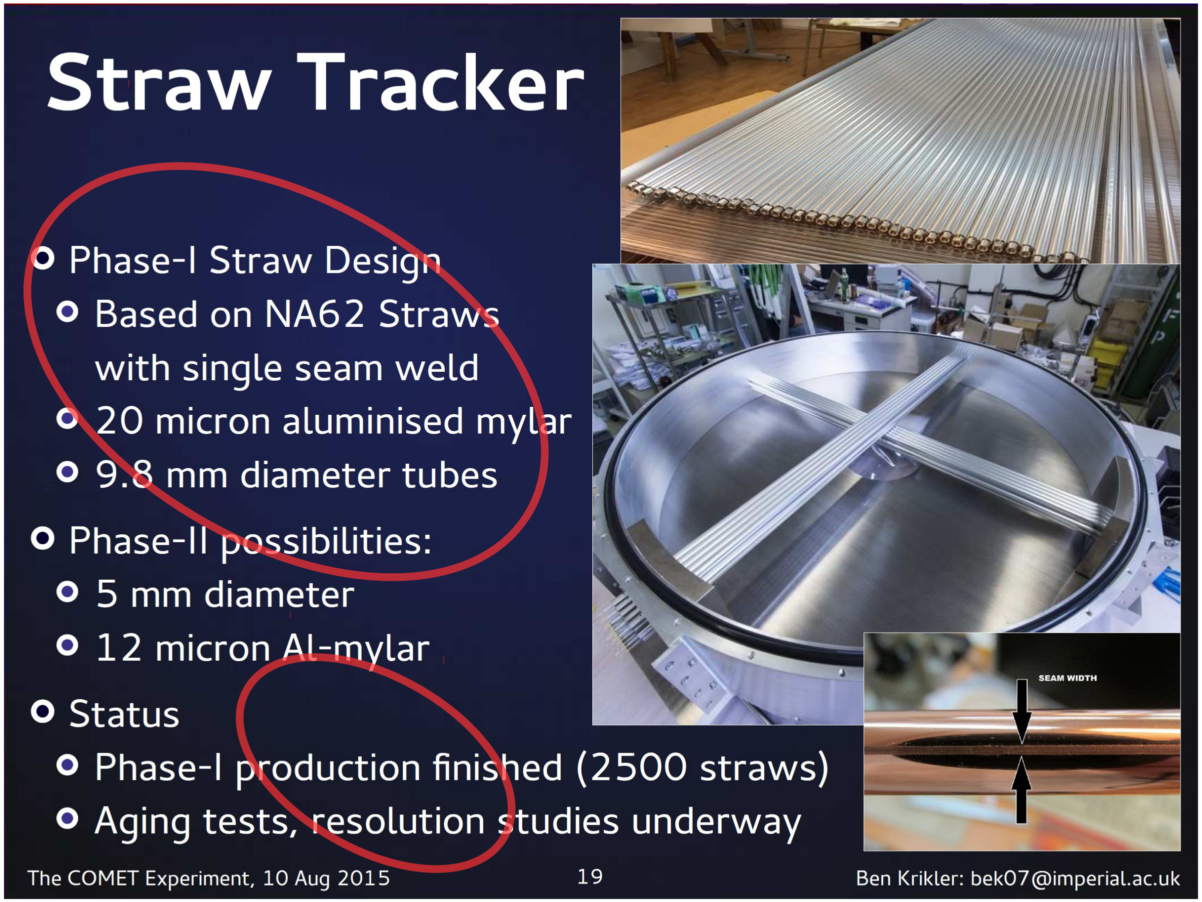
CyDet



StrECAL



COMET Progress



COMET Phase-I
2018
Sensitivity < 3×10^{-15}
110 days
3.2 kW proton beam

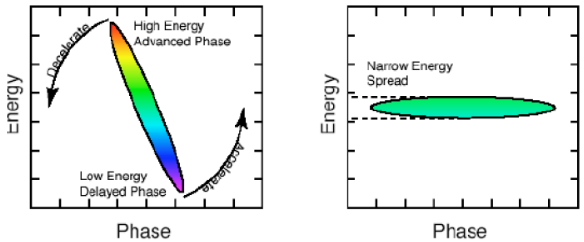
COMET Phase-II
2021
Sensitivity < 3×10^{-17}
1 Year
56 kW proton beam

The future:
PRISM / PRIME
Sensitivity $\ll 10^{-18}$

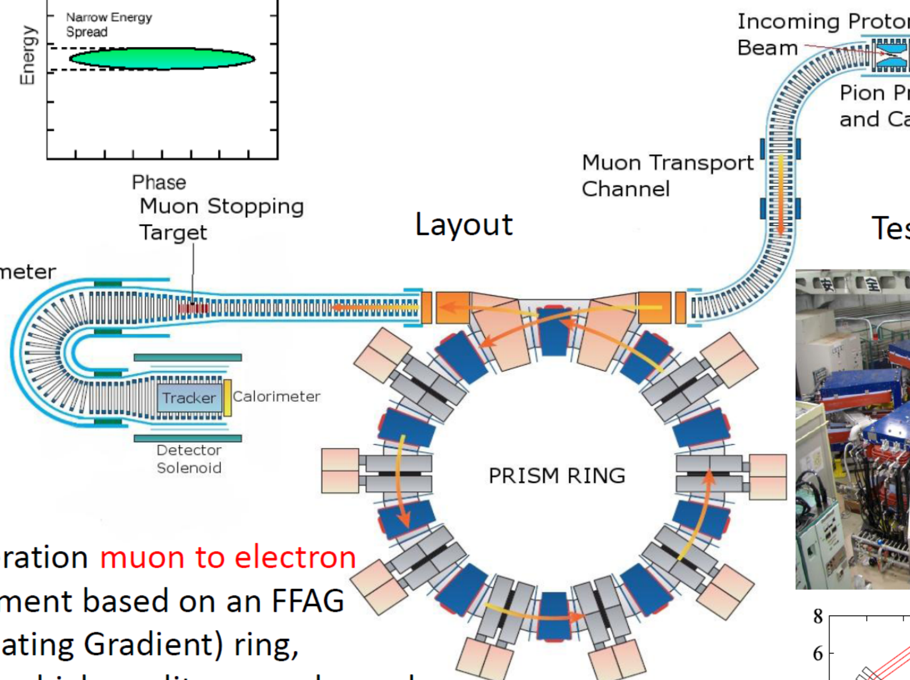
Next-Generation: PRISM/PRIME

PRISM - Phase Rotated Intense Slow Muon beam

J. Pasternak @ NuFact 2015

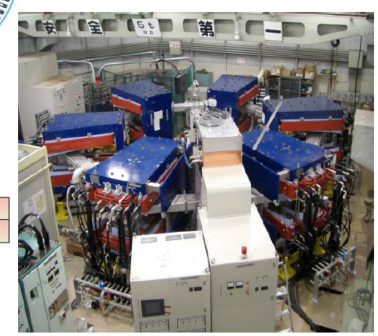


Phase Rotation



Layout

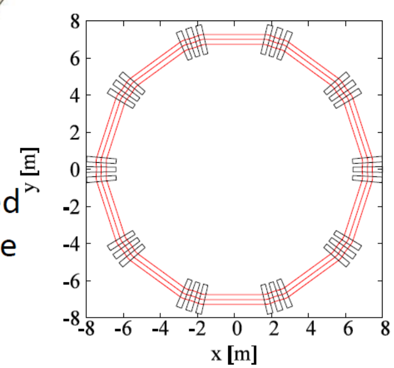
Test ring in Osaka



PRISM:

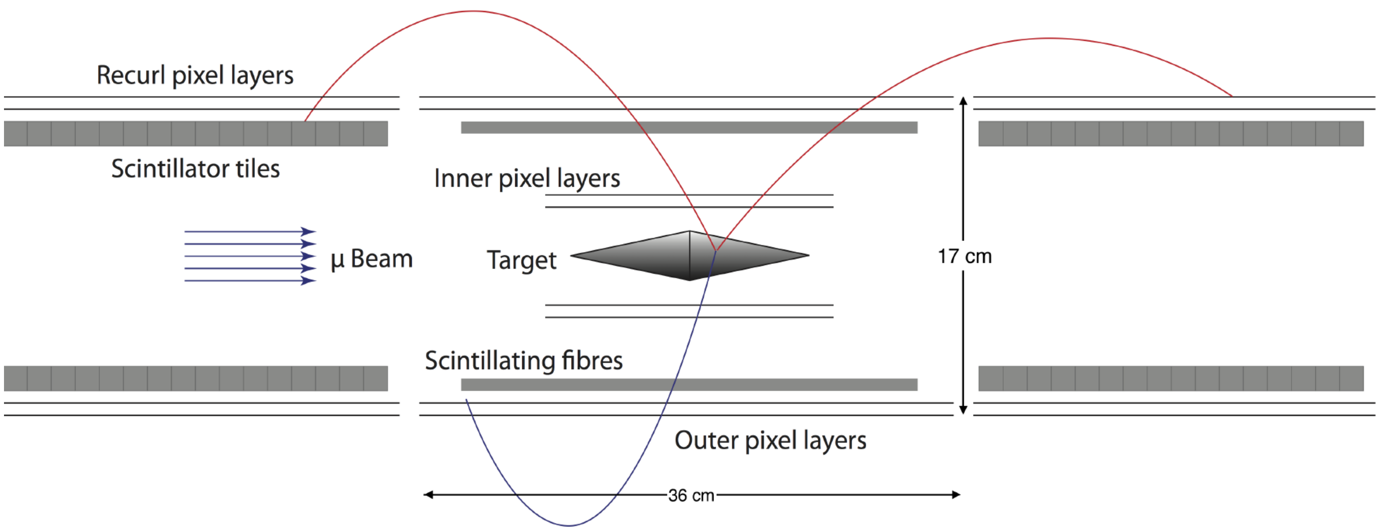
- It is the next generation muon to electron conversion experiment based on an FFAG (Fixed Field Alternating Gradient) ring,
- It allows to create a high quality muon beam by:
  - reducing the muon beam energy spread by RF phase rotation,
  - purifying the muon beam in the storage ring.
- It will have 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



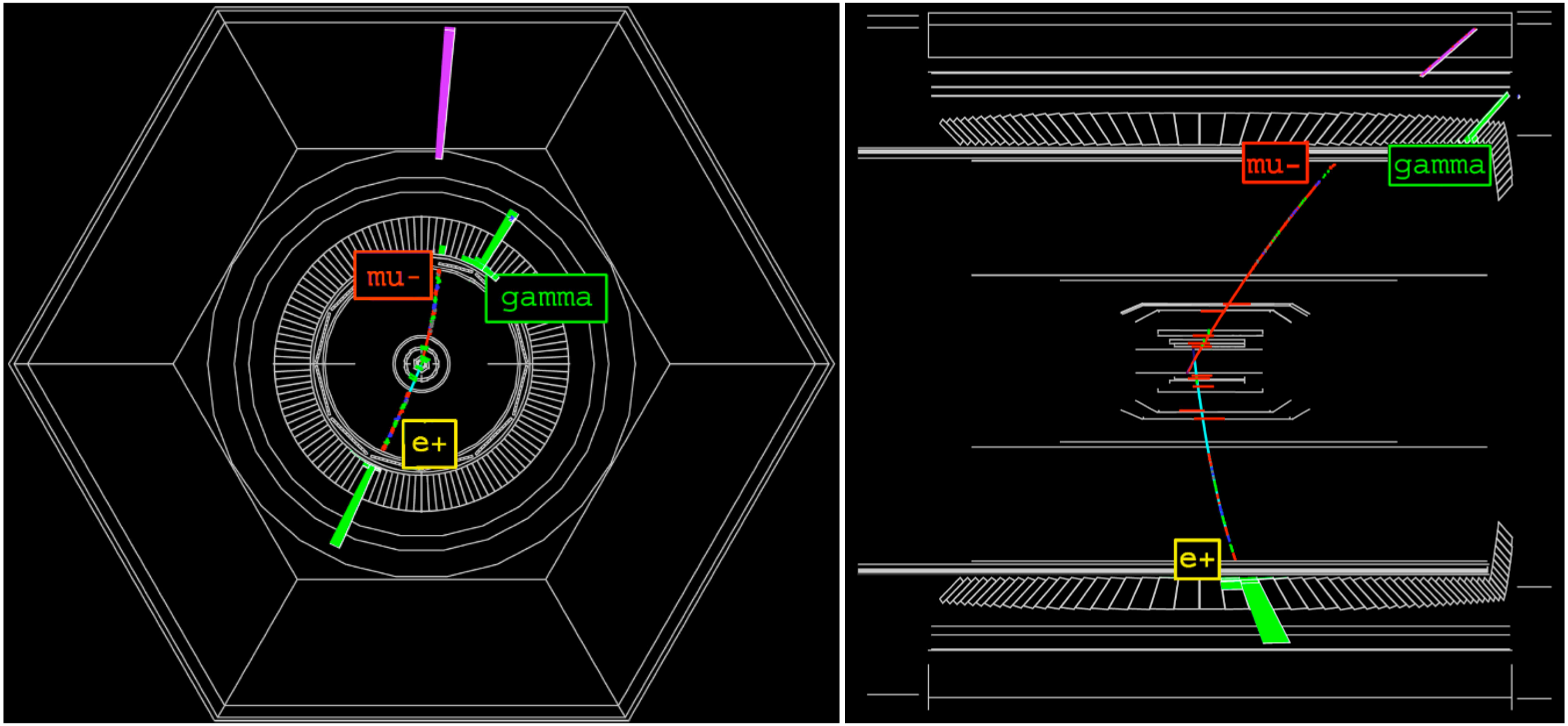
$\mu \to$ eee: Mu3e Experiment

- 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



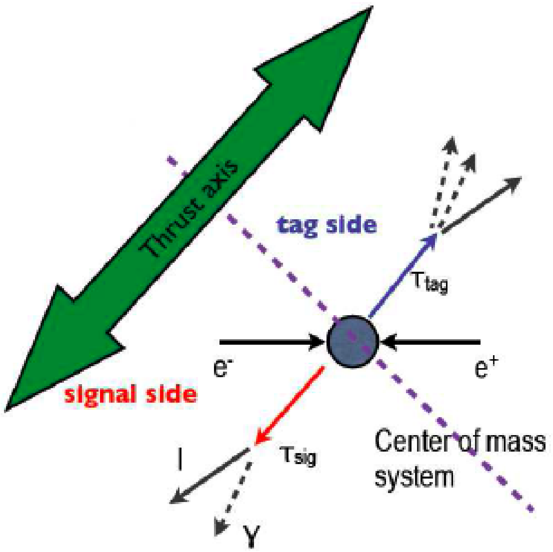
LFV Processes at a Collider

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

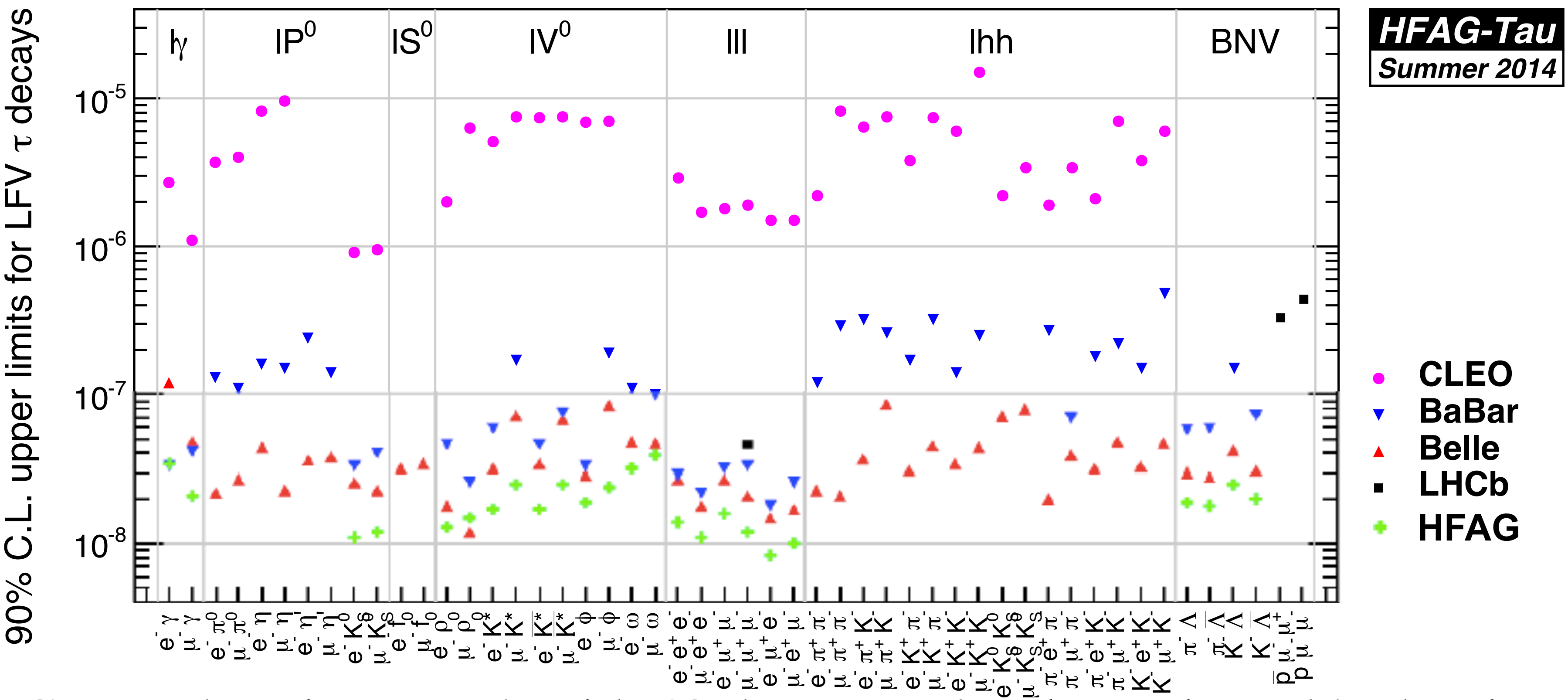


- Select a large clean sample of "tag" tau decays
  - Clean leptonic and hadronic tau decays: "1-prong" and "3-prong"
    - ☞ $\tau\to e\nu\nu$, $\tau\to\mu\nu\nu$, $\tau\to\pi\nu$, $\tau\to\rho\nu$, $\tau\to 3\pi\nu$
- Look for LFV decays of the "other" τ
  - Typically a fully-reconstructed final state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

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

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

Summary of LFV in Tau Decays



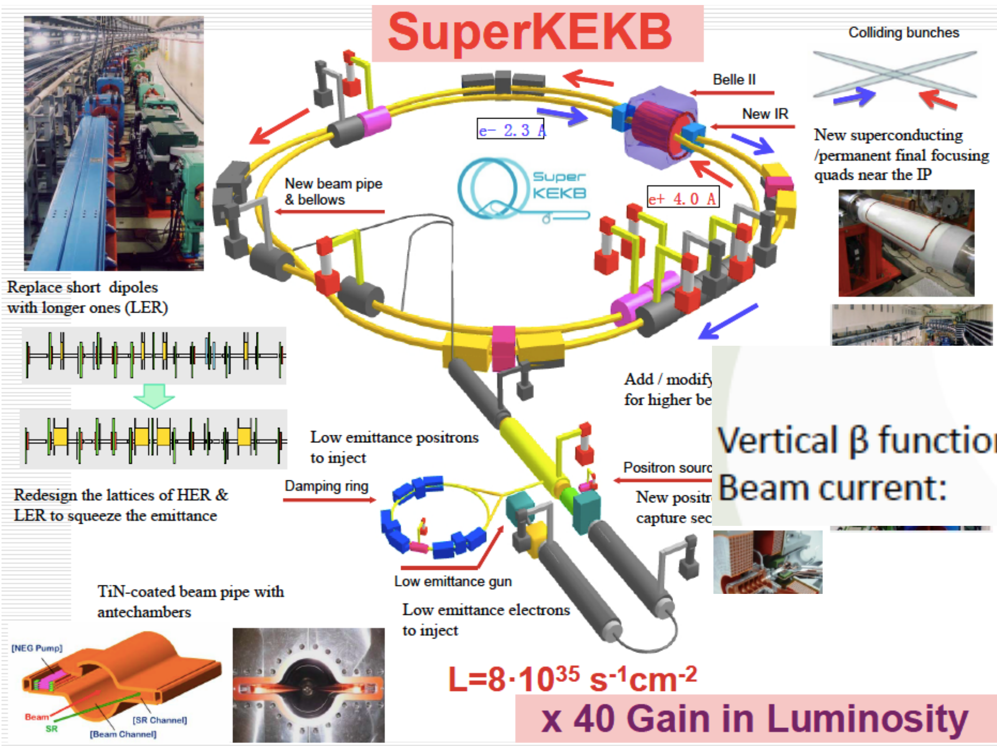
Comprehensive search with 48 decay modes: leptonic and hadronic

Several modes with nearly zero backgrounds

~x100 better sensitivity wrt CLEO

LHCb sensitivity comparable to B-Factories for leptonic modes

Future: SuperKEKB & Belle-II



	KEKB	superKEKB
Vertical β function:	5.9 mm	→ 0.27/0.30 mm (x20)
Beam current:	1.7/1.4 A	→ 3.6/2.6 A (x2)

NANO-BEAM scheme:
- Smaller β_y^*
- Increase beam current
- Increase ξ_y

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

Beam current

Beam-beam parameter

Lumi. reduction factor (crossing angle)& Tune shift reduction factor (hour glass effect) 0.8 ~ 1 (short bunch)

Classical electron radius

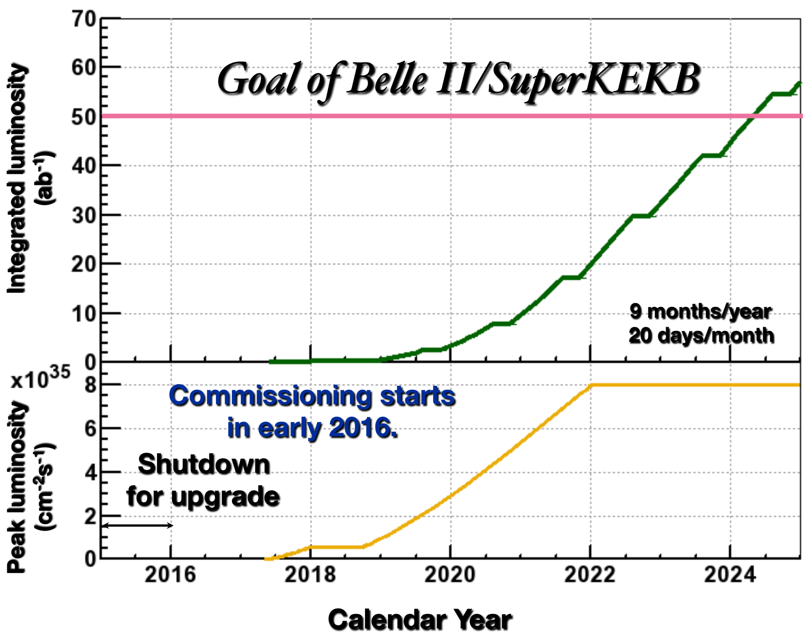
Beam size ratio@IP 1 ~ 2 % (flat beam)

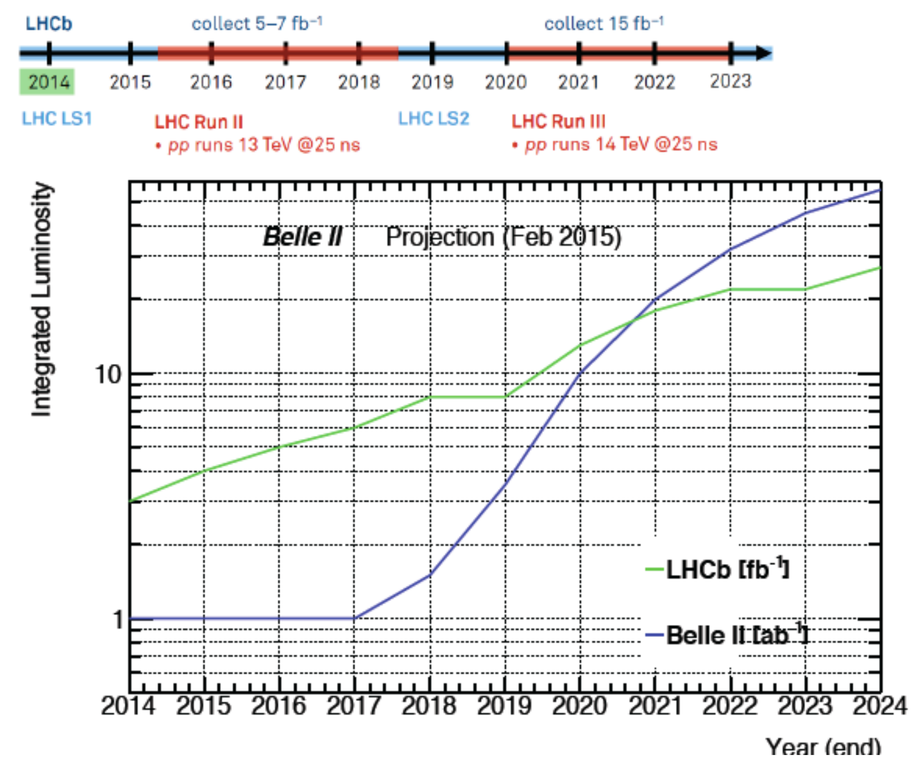
Vertical beta function@IP

8/12/15 C. Cecchi 14

Belle-II vs LHCb

SuperKEKB luminosity projection



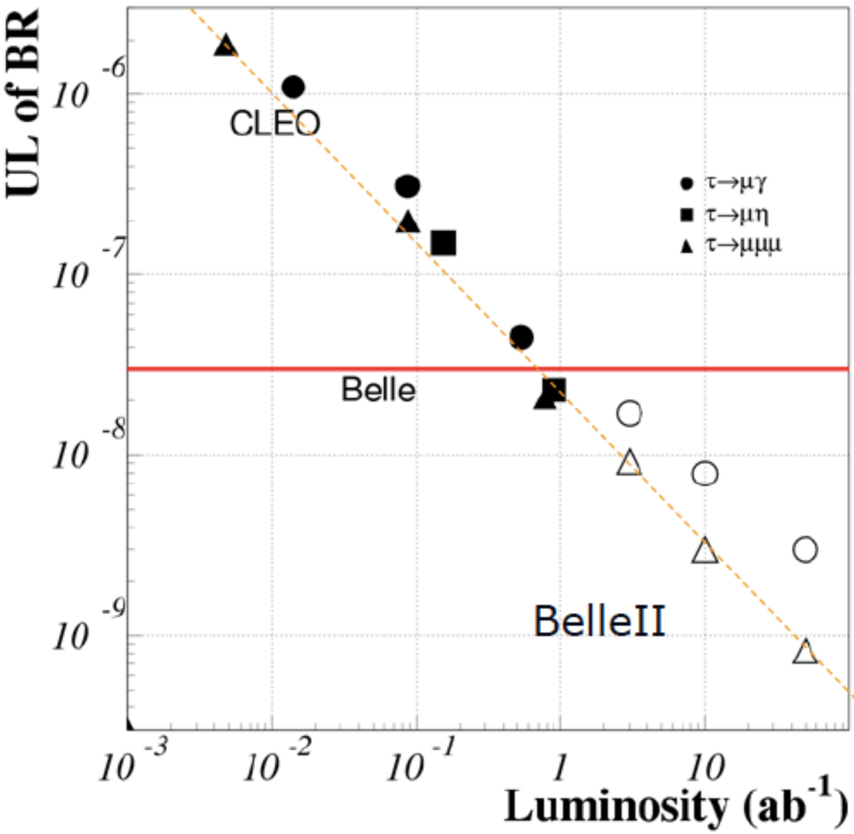


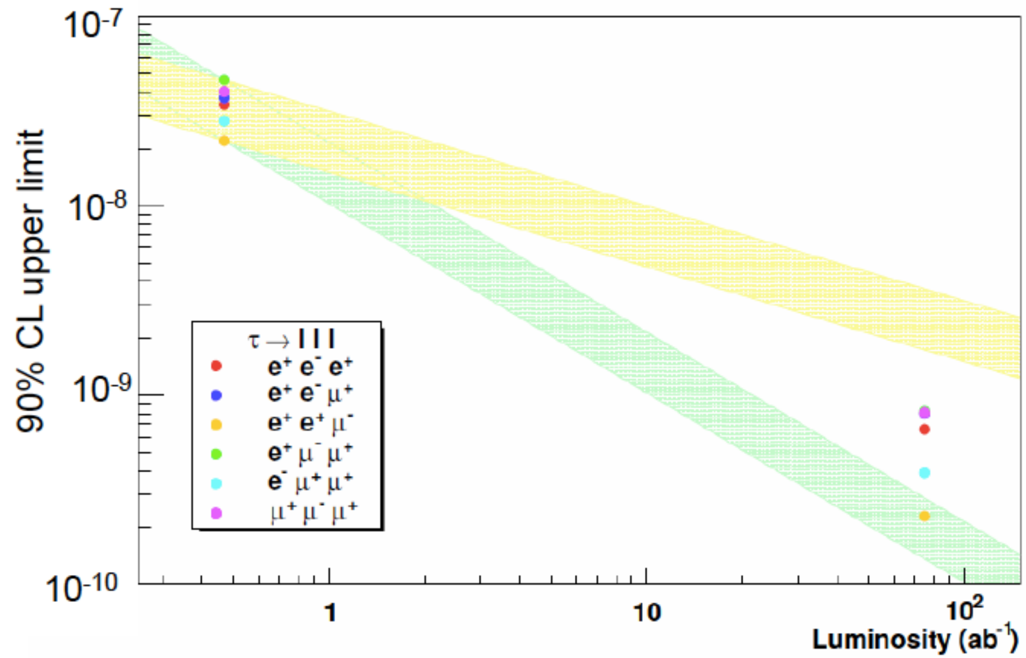
O(10^{11}) τ sample by 2024

Complementary sensitivity for Belle-II and LHCb

C. Cecci @ NuFact 2015

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 CMS

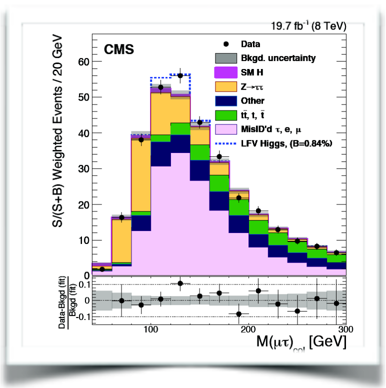
- $H \to \mu\tau$:
  - 2.4σ deviation from SM observed
  - Limits on branching fraction & LFV Yukawa couplings set:

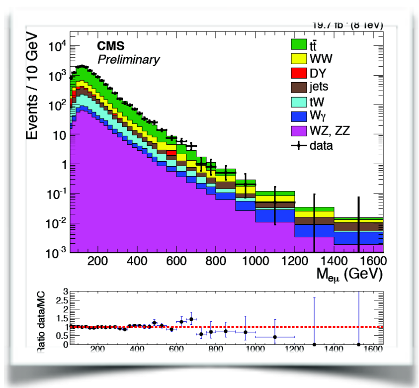
$$\mathcal{B}(H \to \mu\tau) < 1.51\%$$

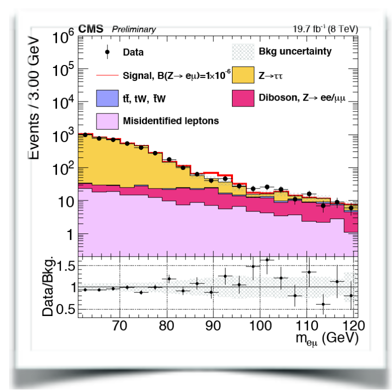
$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \cdot 10^{-3}$$

- Heavy states:
  - Model-independent analysis
    - τ sneutrino: m < 1.28 (2.11) TeV for $\lambda_{132} = \lambda_{311} = 0.01$ ($\lambda_{132} = 0.05$, $\lambda_{311} = 0.1$)
    - QBHs: m < 1.99 - 3.63 TeV for $n_{\text{extra dim.}} = 0 - 6$
    - Z'/a': no sensitivity, yet

- $Z \to e\mu$:
  - Obtained most stringent direct limit on branching fraction: $\mathcal{B}(Z \to e\mu) < 7.3 \cdot 10^{-7}$







A. Nehrkorn @ NuFact-2015
S. Dasu, D. Kobayashi @ SUSY-2015

CLFV in ATLAS ($H^0 \to \mu\tau$)

Events with μ and hadronically decaying τ.

Use τ kinematics and missing Et to correct for undetected ν.

Two signal regions

SR1: $m_T(\mu, E_T^{miss}) > 40$ GeV and
$m_T(\tau_{had}, E_T^{miss}) < 40$ GeV

SR2: $m_T(\mu, E_T^{miss}) < 30$ GeV and
$m_T(\tau_{had}, E_T^{miss}) < 60$ GeV

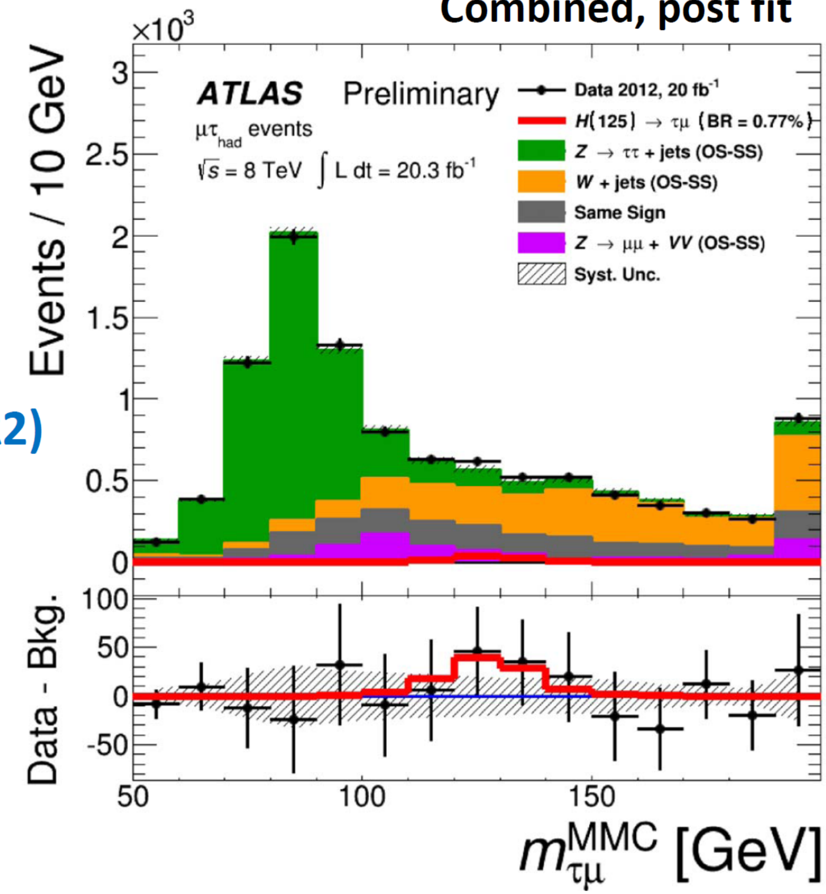
Dominant backgrounds are $Z/\gamma^* \to \tau\tau$ (SR2) and W + jets (SR1)

BR < 1.85% (95% CL)

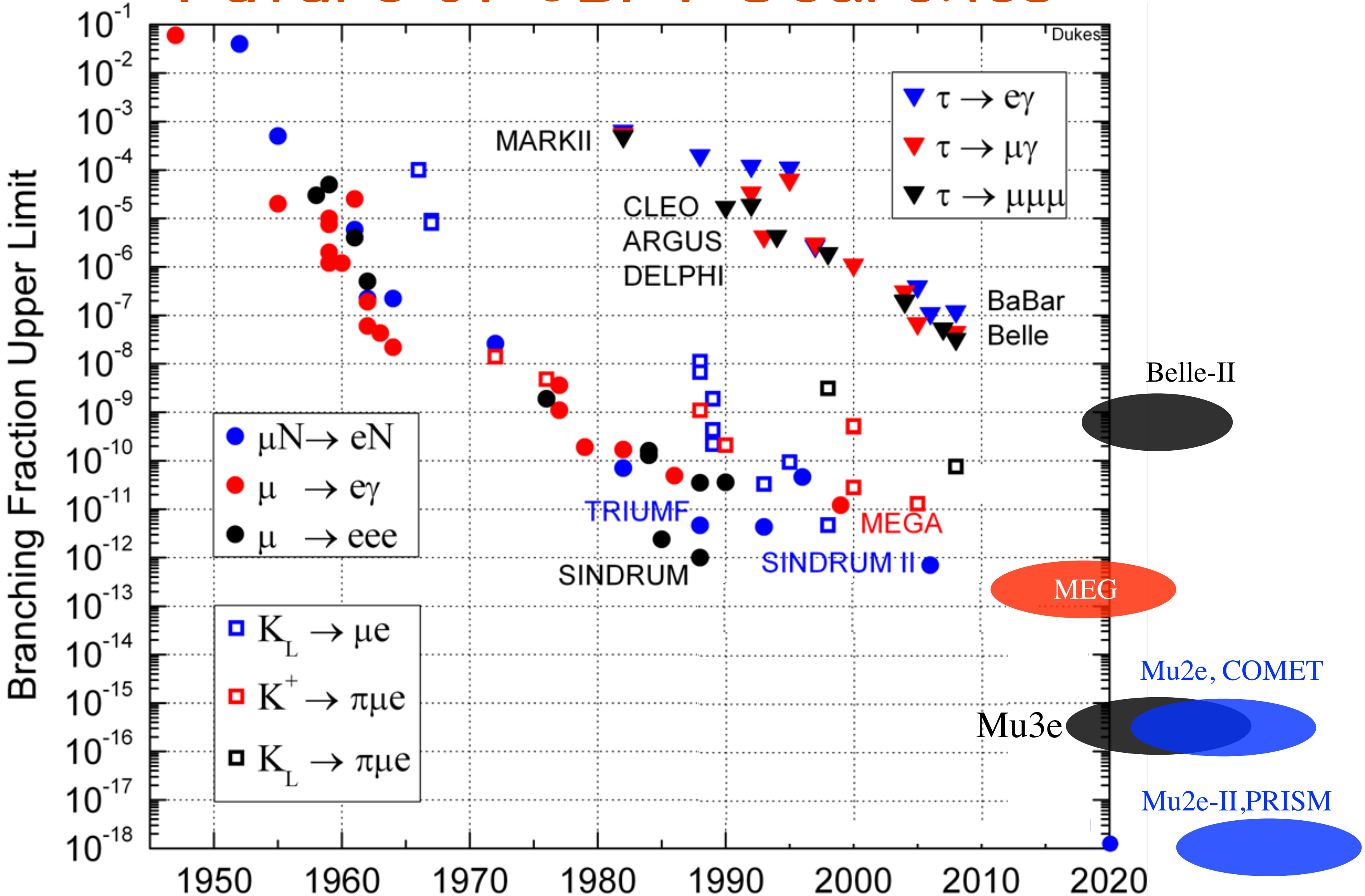
Theory: BR < ~10% from $\tau \to \mu\gamma$ and $(g\text{-}2)_{e,\mu}$

C. Blocker @ NuFact-2015
S. Palestini @ SUSY-2015

Combined, post fit



Future of CLFV Searches



Summary

- CLFV offers unique sensitivity to new physics
  - ❑ Complementary to LHC in SUSY parameter space
  - ❑ 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
- Current sensitivities in TeV range for CLFV
- Multiple experiments pushing the sensitivity frontier
    - ☞ SUSY-2025 will be exciting !

Summary

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Backup

MEG Analysis

Blind likelihood Analysis:

Data Sample defined by 5 Observables:

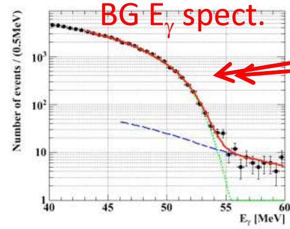
E_{e^+}, E_γ, $\theta_{e\gamma}$, $\phi_{e\gamma}$, $T_{e\gamma}$

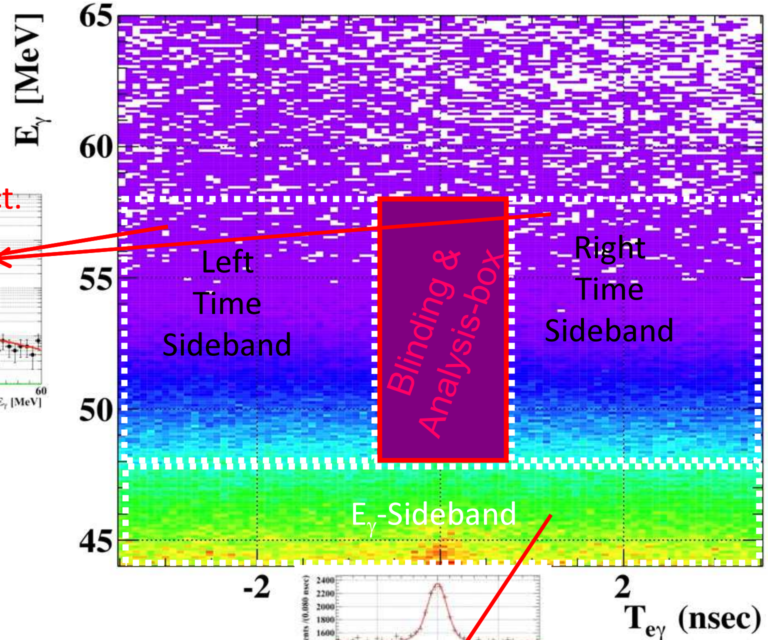
Analysis-box for Likelihood fit
Defined in 5D-space as:

Analysis Box vs 5 Observables

(~10σ wide windows cf. res.)
$48 \le E_\gamma \le 58$ MeV
$50 \le E_e \le 56$ MeV
$|T_{e\gamma}| \le 0.7$ ns
$|\phi_{e\gamma}|, |\theta_{e\gamma}| \le 50$ mrad
(angles between e^+ & flipped γ vec.)

Analysis Region shown in 2D
(No Selection)





Analysis box
"Blinded" in the
E_γ vs $T_{e\gamma}$ plane
during calibration
and
optimization of
physics analysis

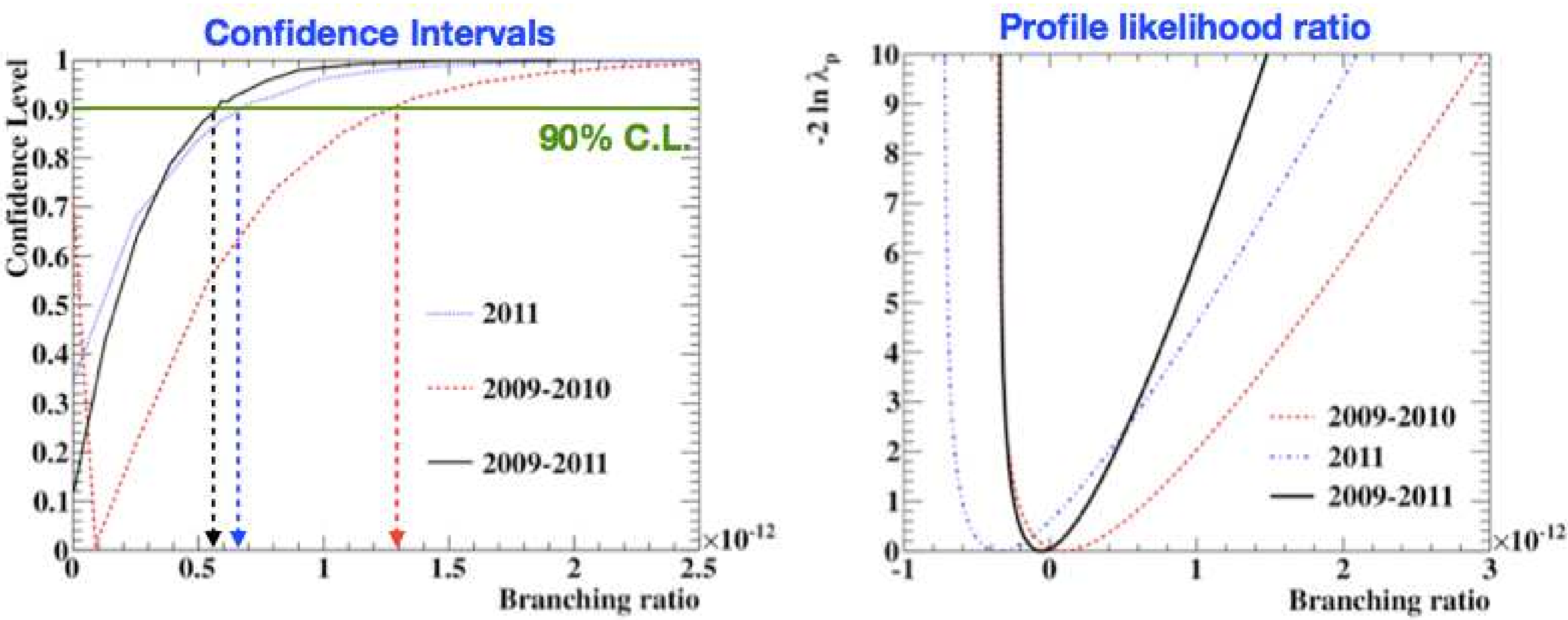
!!! Time and E_γ sidebands Important Ingredient to Analysis also angular sidebands introduced

⇨ Since our background is dominated by "accidentals" the side bands can be used to estimate the background in the signal region, check of experimental sensitivity & measure the timing resolution using RMD in the E_γ-sideband

D. Grigoriev @ NuFact 2015

MEG Results

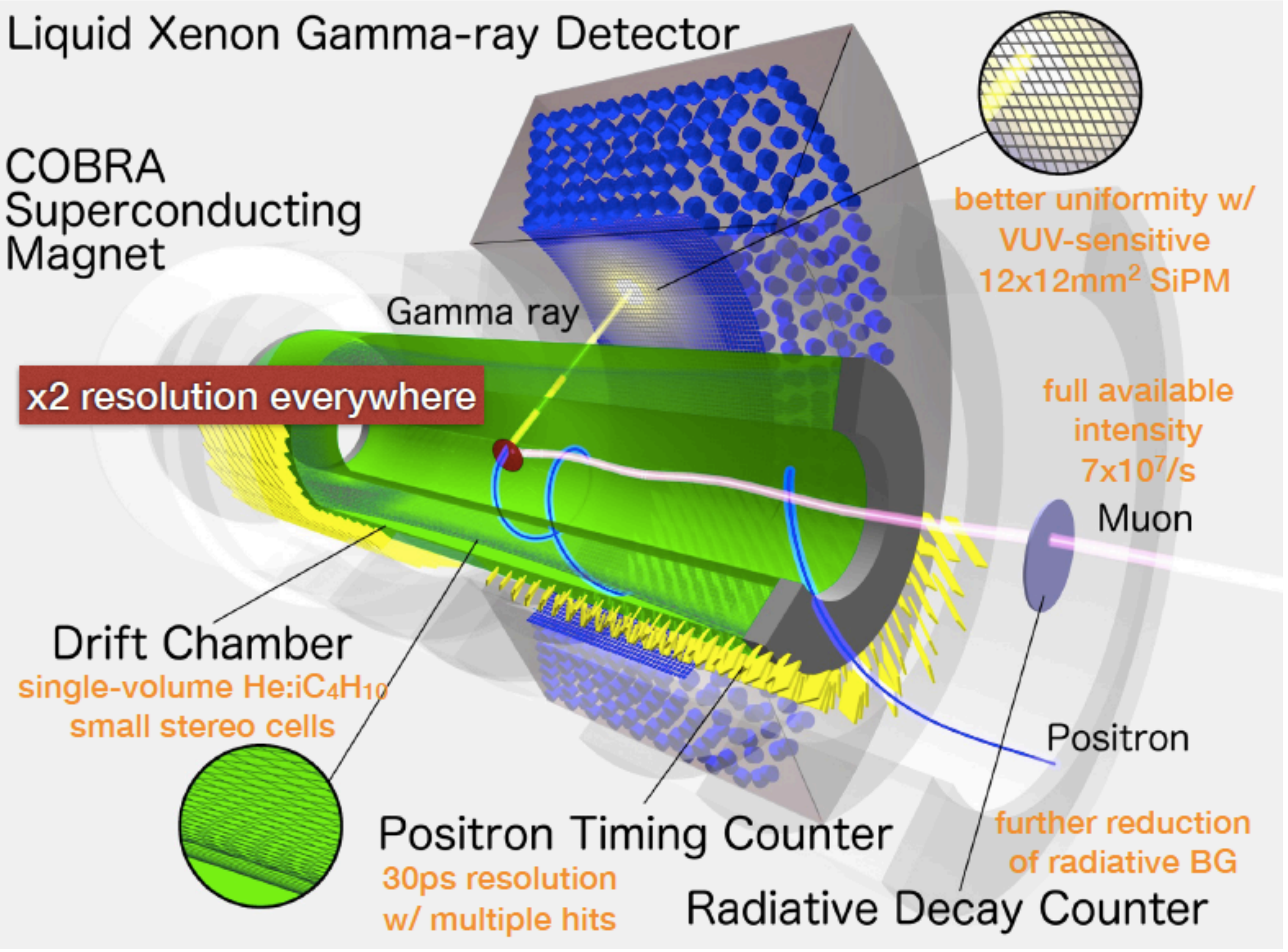
- Confidence interval calculated with Feldman-Cousins method + profile likelihood ratio ordering



Consistent with null-signal hypotesis

D. Grigoriev @ NuFact 2015

MEG-II



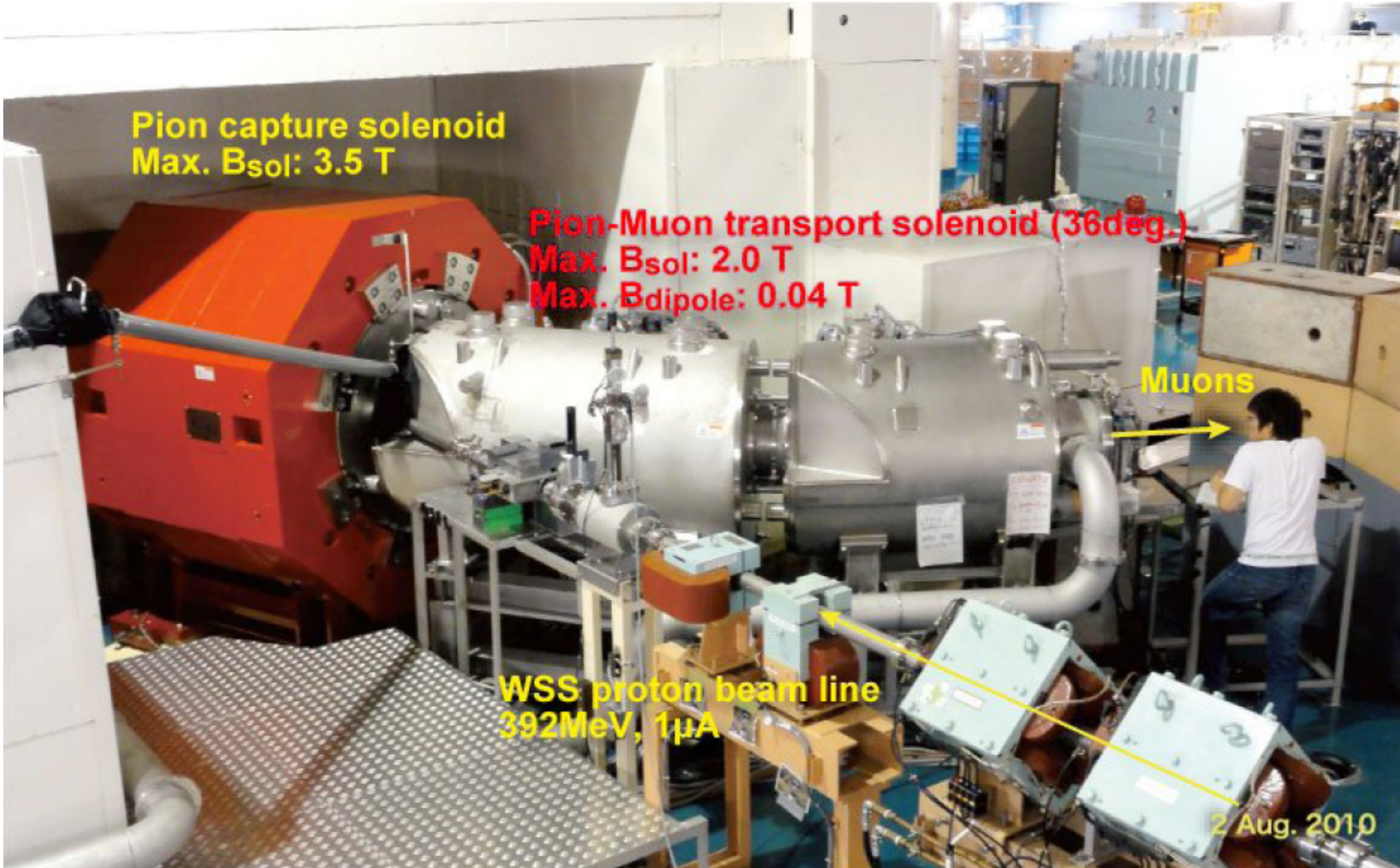
Liquid Xenon Gamma-ray Detector
COBRA Superconducting Magnet
Gamma ray
better uniformity w/ VUV-sensitive 12x12mm^2 SiPM
x2 resolution everywhere
full available intensity 7x10^7/s
Muon
Drift Chamber
single-volume He:iC$_4$H$_{10}$ small stereo cells
Positron
further reduction of radiative BG
Positron Timing Counter
30ps resolution w/ multiple hits
Radiative Decay Counter

Mu2e Progress

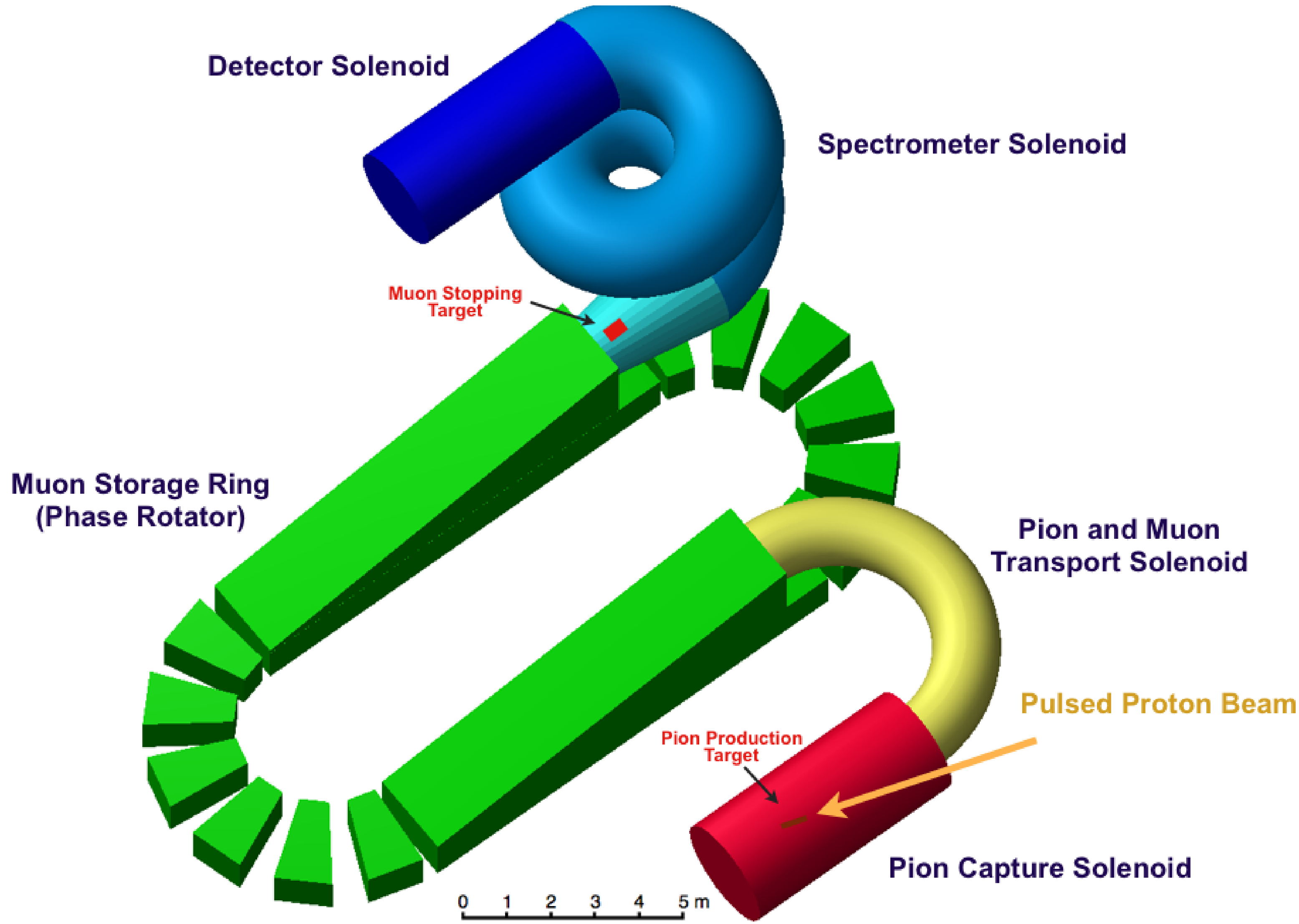
Groundbreaking April 18, 2015,

Final floor pour on July 28, 2015

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

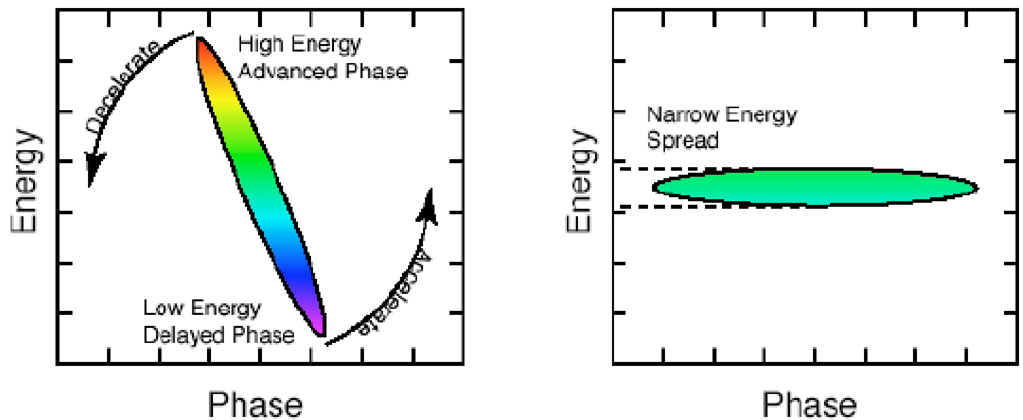
PRISM

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.

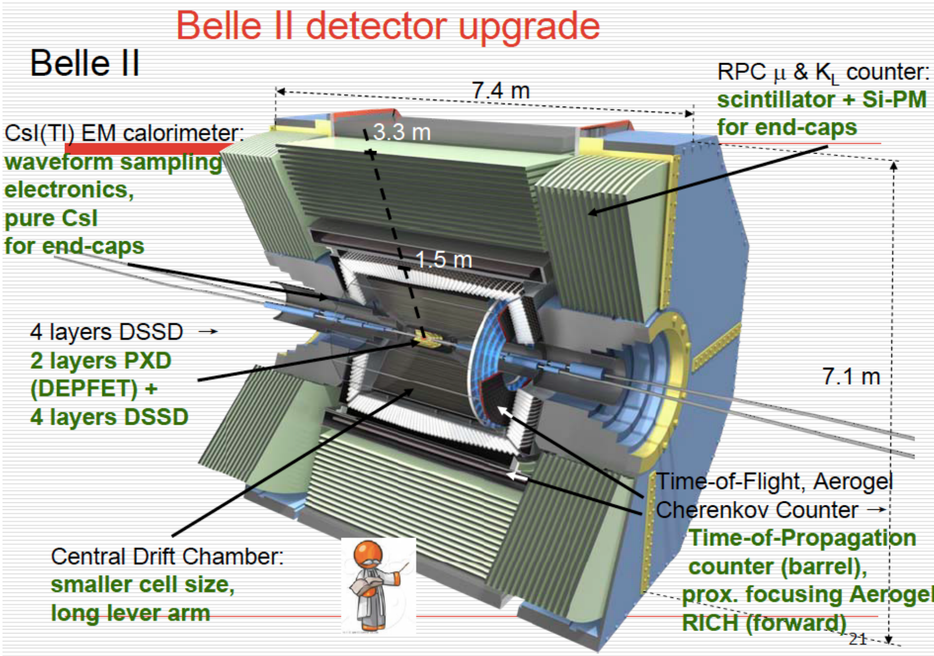
• PRISM requires a compressed proton bunch and high power proton beam
  - It needs a new proton driver!

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



J. Pasternak

Belle-II Detector Upgrade



Critical issues @8x10^{35} s^{-1}cm^{-2}

-Higher background (x10-20)

- radiative Bhabha dominate
- radiation damage, occupancy
- pile-up in ECL

-Higher event rates (x10)

- higher trigger rates (0.5 → 3KHz)
- DAQ

-IMPROVEMENTS

- hermeticity (kπ-ID μ-ID endcap)
- IP and secondary vertex resolution
- Ks and π^0 efficiency
- K/π separation
- μ-ID and PID endcaps

TDR arXiv: 10110352

Low-Energy Searches for New Physics

- 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, parity violation measurements
- Processes suppressed in the Standard Model
  - Symmetry violations, Rare decays, Forbidden transitions
    - ☞ Little Standard Model background usually implies higher sensitivity
    - ☞ Examples: $0\nu\beta\beta$, EDM, LFV searches