Lepton Flavor Violation: present and future experiments - 2

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- Beyond MEG
- $\mu \rightarrow eee$
- $\mu \rightarrow e$ conversion in nucleus
- Mu2e and PRIME
- τ decay

Beyond MEG

- Which gain in sensitivity can be expected using more intense muon beam ($\geq 10^7$ μ/s) ?
- For a fixed accidental background experiment Rμ can be maximized

$$R_{\mu\max} \propto \left(\Delta E_\gamma \bullet \Delta E_{e\gamma}\right)^{-1} \bullet \left(\sqrt{T \bullet \varepsilon_e \varepsilon_{sel} \varepsilon_\gamma \bullet \Omega / 4\pi \bullet \Delta E_e \bullet \Delta T_{e\gamma}}\right)^{-1}$$

$$SES \propto \Delta E_\gamma \Delta\theta_{e\gamma} \sqrt{\frac{\Delta E_e \bullet \Delta T_{e\gamma}}{T \bullet \varepsilon_e \varepsilon_{sel} \varepsilon_\gamma \bullet \Omega / 4\pi}}$$

- Linear improvements are obtained only with $\Delta E\gamma$ and $\Delta\theta\varepsilon\gamma$
- At PSI $R\mu_{max} \approx 2\times10^8$ as far as $R\mu_{max} > R\mu_{opt}$ rate is not a limitation.
- A factor 10 in the $(R\mu_{max}\, \Delta E\gamma\, \Delta\theta e\gamma)^2$ should be gained to reach BR($\mu \rightarrow e\, \gamma$) $\approx 1 \bullet 10^{-14}$
- Either a detector technology breakthrough or several small improvements (factors 1.5-2.0)

Beyond MEG

- Most limiting factors: performances of LXe calorimeter it is at the state of the art of the technology → how to improve further $\Delta E\gamma$ with a fast (ns) and calorimetric detector?
- Some other possible improvements:
  - thinner target to improve $\Delta\theta$; but exploiting higher intensity muon beam on target

    → off target decay could increase pileup and background;
  - finely segmented active target (to improve $e\gamma$ match),

    → new concept to be developed;
  - high resolution beta spectrometers ($\Delta Ee/Ee$ = 0.1 %) without reducing the geometrical acceptance;
- RD is always needed

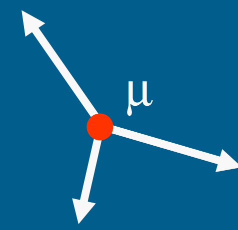
$\mu \rightarrow 3e$

- Theories give

  $BR(\mu \rightarrow 3e) \sim 10^{-1} \div 10^{-2}\, BR(\mu \rightarrow e\gamma)$
- There is a 20 year old limit $BR(\mu \rightarrow 3e) < 10^{-12}$ (SINDRUM Coll., Nucl. Phys. B299 (1988) 1)

  with a limit in $BR_{acc} \approx 10^{-13} \rightarrow R\mu \approx 5 \bullet 10^{6}\ \mu/s$
- This decay channel has not been investigated since many years

$\mu \rightarrow 3e$

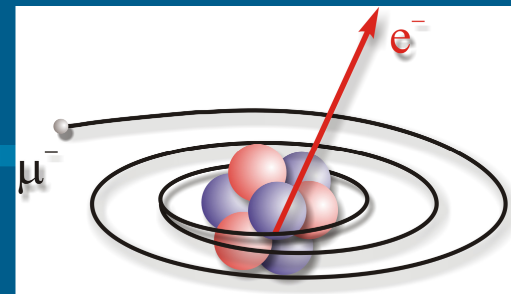


- Exploit Σ Ee = Mμ, time coincidence and co-planarity
- Also limited by accidental background.
  (Michel positron and an e^+e^- pair produced by Bhabha scattering in the target)
- Experimental advantage: no photons
  $\rightarrow$ no EM calorimeter.
- However: very high rate in tracking system
  $\rightarrow$ dead time, trigger & pattern recognition problems;
- need of large modularity.
  $\rightarrow$ large angular and momentum acceptance of the spectrometer

$\mu \to 3e$

- Difficulties:
  - To be competitive with MEG predicted limit BR($\mu \to e\gamma$)<10-13, BR($\mu \to 3e$) $\approx$ 10-15
  - Total efficiency in SINDRUM $\approx 15\%$ Cannot be improved much
  - To match the BR goal, Rμ must increase by 10^3 to Rμ= 5 • 10^9 μ/s
  - The accidental BR_{acc} increases of a factor 10^6
  - Using a timing system MEG-like to improve resolution of factor of 10
  - Recover 10^5 with a fast tracking detector appears extremely difficult.

$\mu N \rightarrow eN$



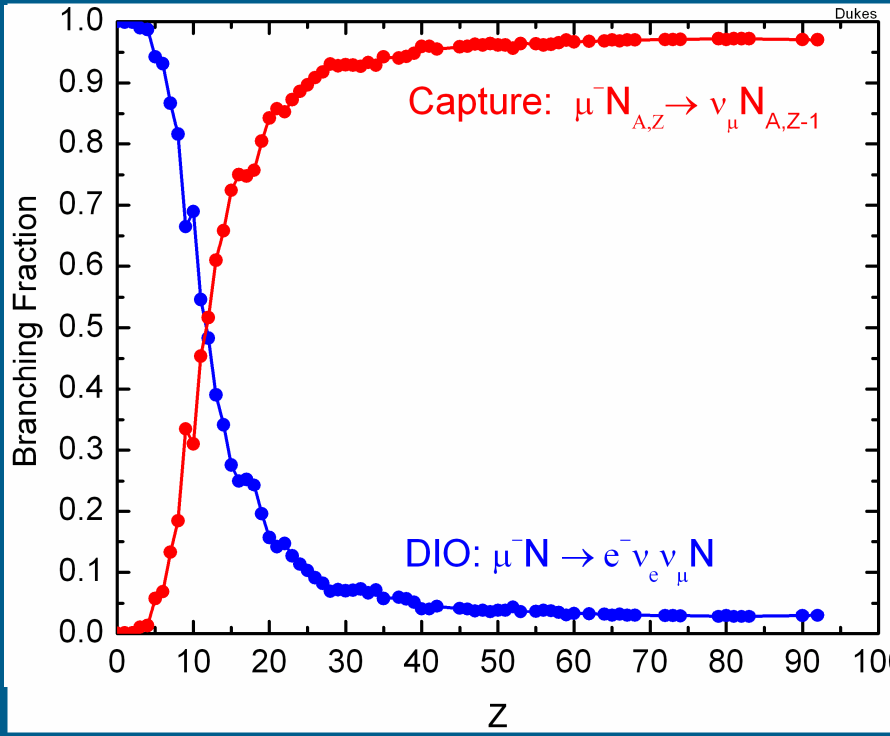
- stop muon in atom
- rapidly (10^{-16}s) cascades down to the 1S state
- circles the nucleus for up to ~2 μs
- two things most likely happen:
  - is captured by the nucleus: $\mu^- N_{A,Z} \rightarrow \nu_\mu N_{A,Z-1}$
  - decays in orbit: $\mu^- N_{A,Z} \rightarrow e^- \nu_\mu \nu_e N_{A,Z}$
- in $\mu^- N \rightarrow e^- N$ the muon coherently interacts with nucleus leaving it in ground state
  - signature single isolated electron
  - $E_e = m_\mu - E_{NR} - E_b \sim 104.97$ MeV (Al)

$\mu N \rightarrow eN$

- $R_{\mu e}$ is the ratio of conversion rate to capture rate.

$$R_{\mu e} = \frac{\Gamma(\mu^- Al \rightarrow e^- Al)}{\Gamma(\mu^- Al \rightarrow \nu_\mu Mg)}$$

- Nuclear wavefunctions "cancel," → calculation simpler
- As muon cascades to 1s, X-rays give stop rate
- and Mg →Al yields a 2.6 MeV β followed by γ that can be used to measure capture rate

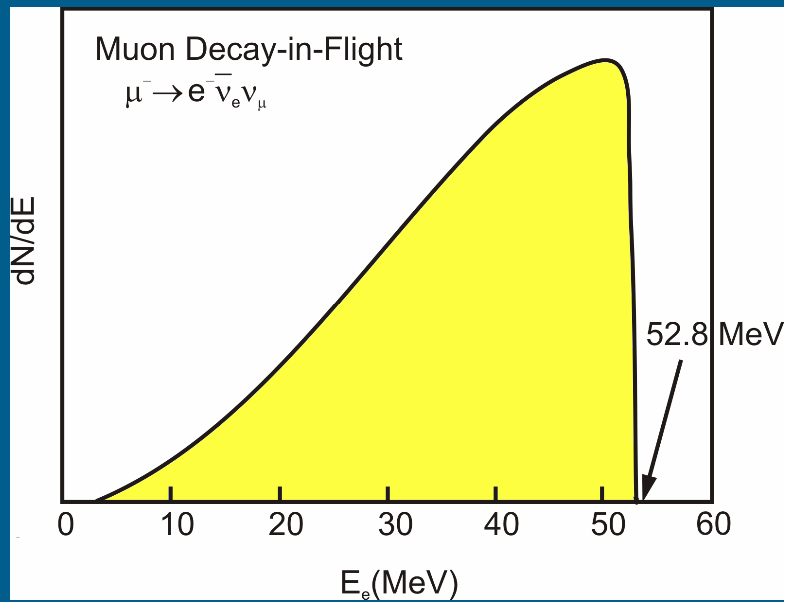


$\mu N \rightarrow eN$ background

- Muon decay in orbit (DIO):

  $\mu^- N_{A,Z} \longrightarrow e^- \nu_\mu \nu_e N_{A,Z}$
  - Note: $E_e < mc^2 - E_{NR} - E_b$
  - require good energy resolution
- Radiative muon capture (RMC):

  $\mu^- N_{A,Z} \longrightarrow \nu_\mu \gamma N_{A,Z-1}$, $\gamma \longrightarrow e^+ e$
  - Note: $E_{\gamma max}(Al) = 102.5$ MeV
  - restricts choice of stopping targets
  - require good energy resolution



$\mu N \rightarrow eN$ background

- Radiative pion capture (RPC):

  $\pi^- N_{A,Z} \rightarrow \gamma N_{A,Z-1}$, $\gamma \rightarrow e^+ e^-$

  - Note: 1.2% have $E_\gamma > 105$ MeV
- Muon decay in flight:

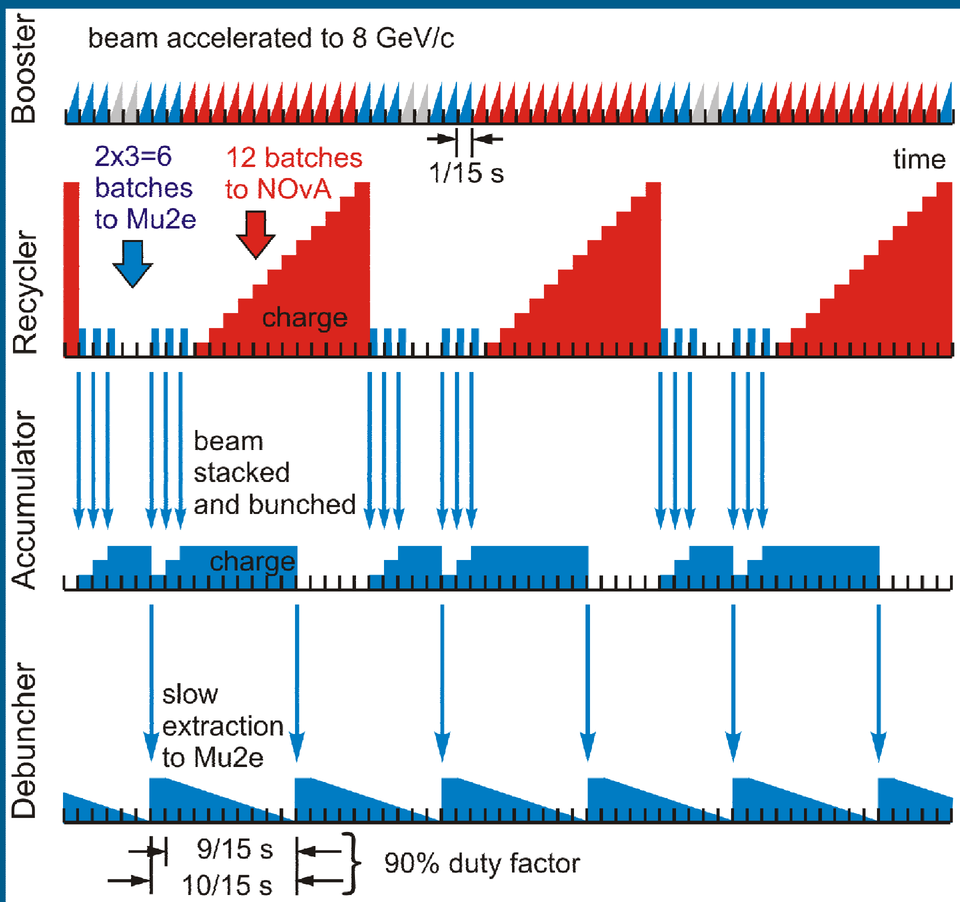
  $\mu^- \rightarrow e^- \nu\nu$

  - Note: since $E_e < m_\mu c^2/2$, $p_\mu > 77$MeV/c
- Beam electrons scattering in target
- Pion decay in flight:

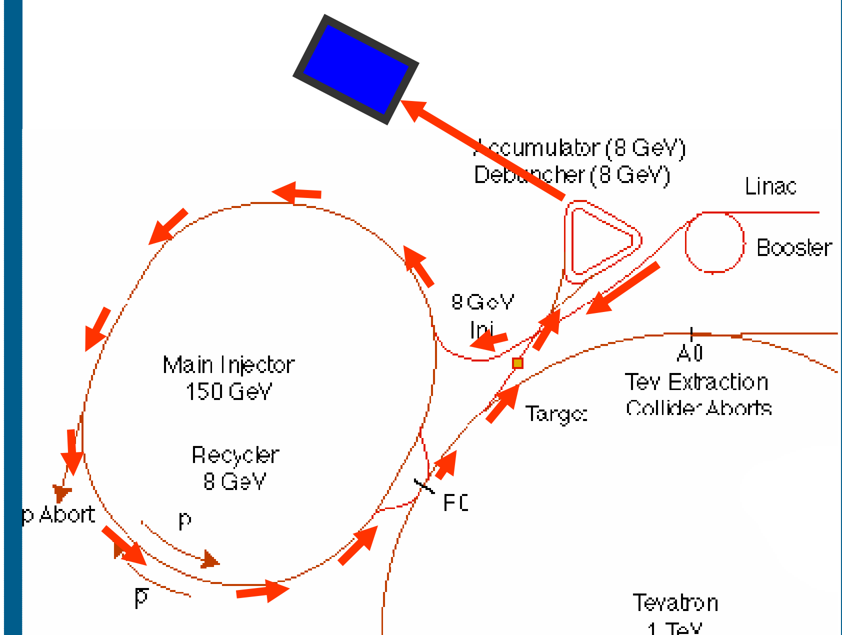
  $\pi^- \rightarrow e^- \nu_e$

  - Need high interbunch extinction!
- Antiprotons annihilating
  - need thin absorber

Mu2e at FNAL



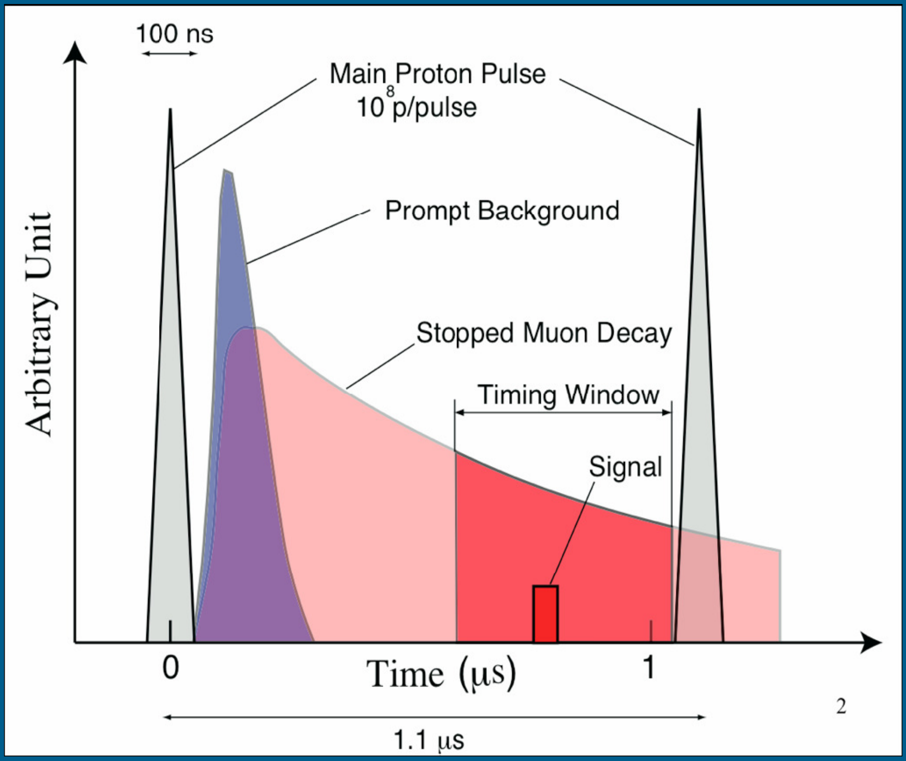
new detector hall and beamline



Mu2e at FNAL

- In Mu2E-type experiments, signals of mu-e conv. events will be searched after waiting for while from the primary proton pulse hitting the production target to suppress prompt backgrounds,

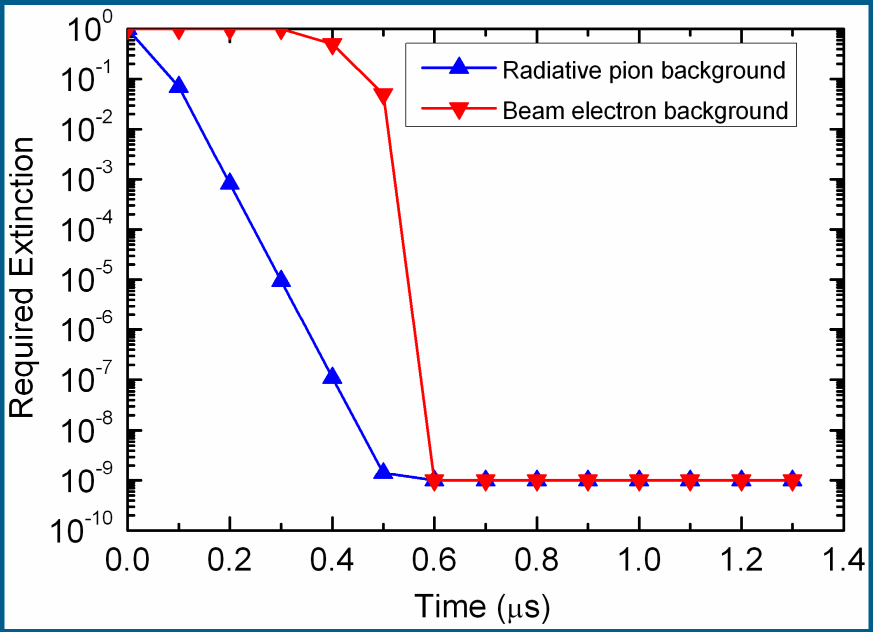
- By doing this, the prompt background events produced by primary proton pulse will be suppressed down to a negligible level. The only remaining backgrounds are the prompt background events produced by off-timing protons coming between main pulses.



Mu2e at FNAL

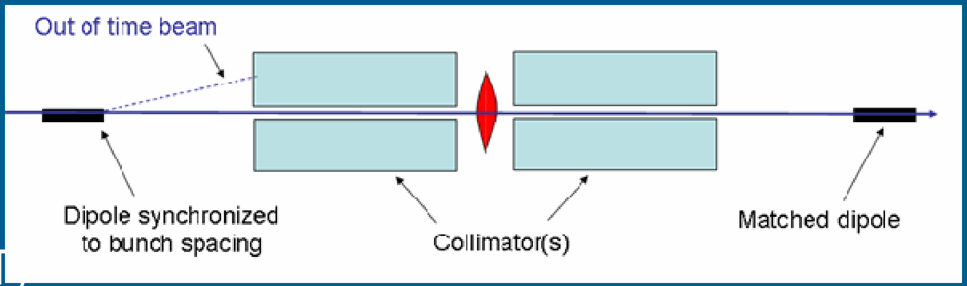
Inter-bunch protons cause backgrounds

1. Muon decay in flight:
   - $\mu^- \to e^-\nu\nu$
   - Since $E_e < m_\mu c^2/2$, $p_\mu > 77$ MeV/c
2. Radiative π^- capture:
   - $\pi^- N \to N^*\gamma$, $\gamma Z \to e^+e^-$
3. Beam electrons
4. Pion decay in flight:
   - $\pi^- \to e^-\nu_e$

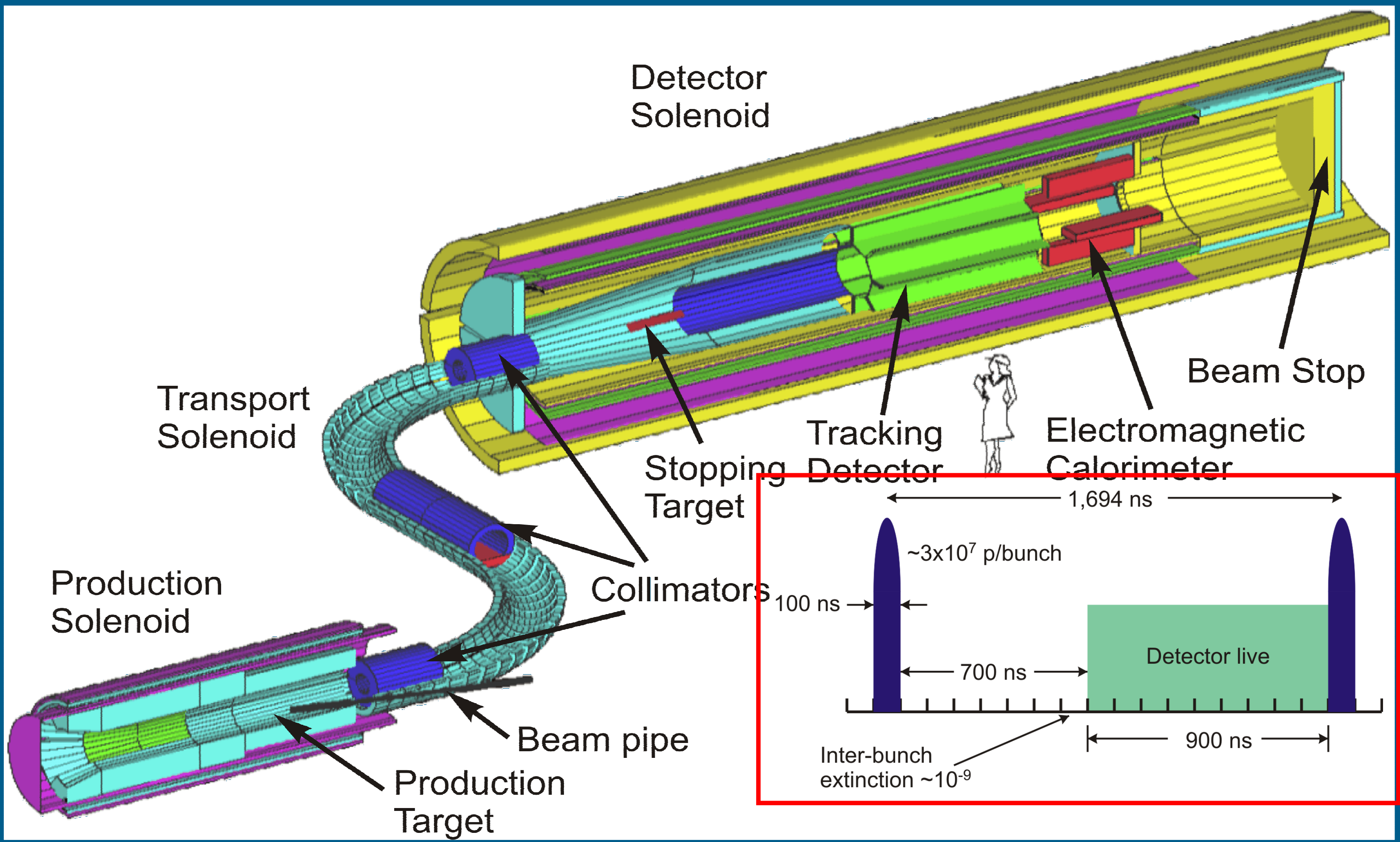


Suppressed by minimizing beam between bunches

- Need $\lesssim 10^{-9}$ extinction
- Get 10^{-3} for free
- Special kickers needed for rest
- US-JAPAN collaboration on R&D (similar proposal in Japan: COMET)

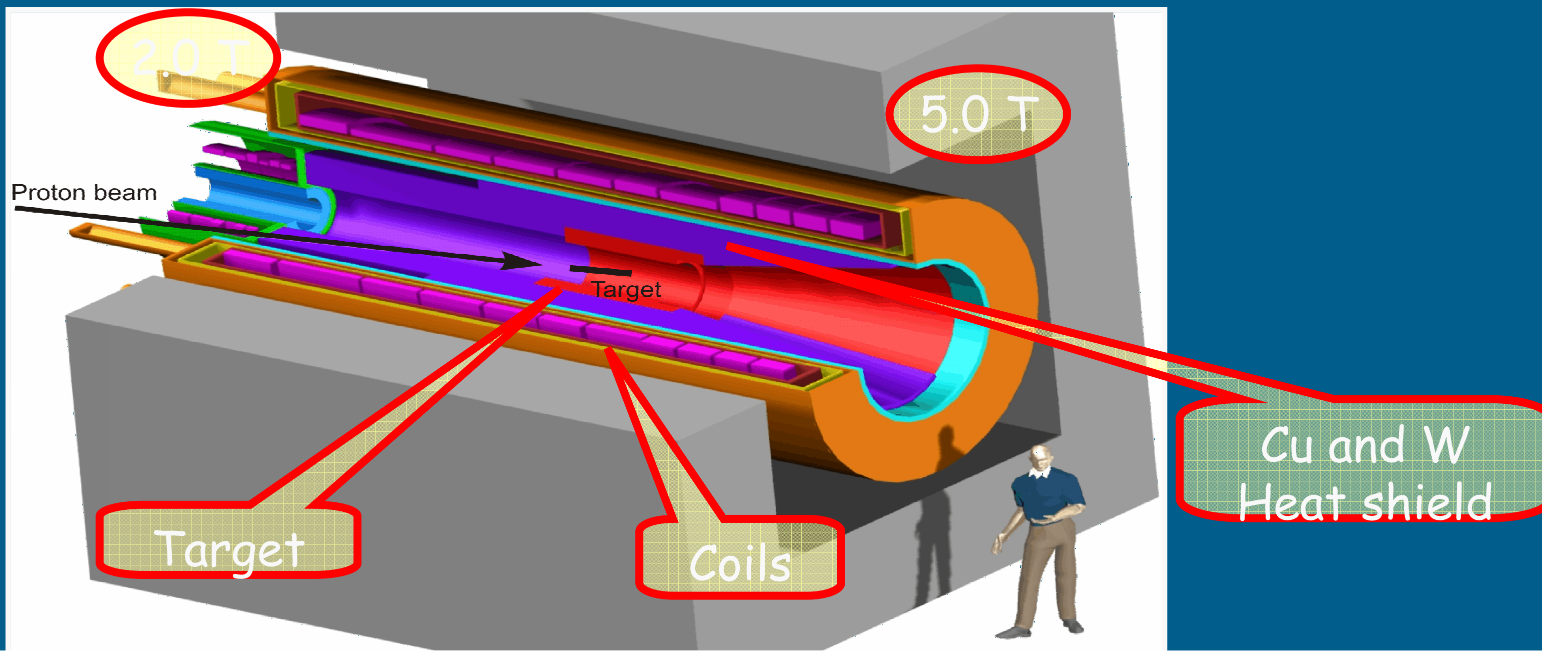


Mu2e apparatus



Mu2e p target side

- Graded solenoidal field to maximize pion capture:2.5T – 5.0T graded magnetic field
- 2.5x10-3 μ-/p
- R = 75 cm
- 23kW beam
- 0.8 mm x 160 mm gold target
- Forward moving pions and muons with $\theta > 30°$ and pz < 180 MeV/c reflected back in graded field

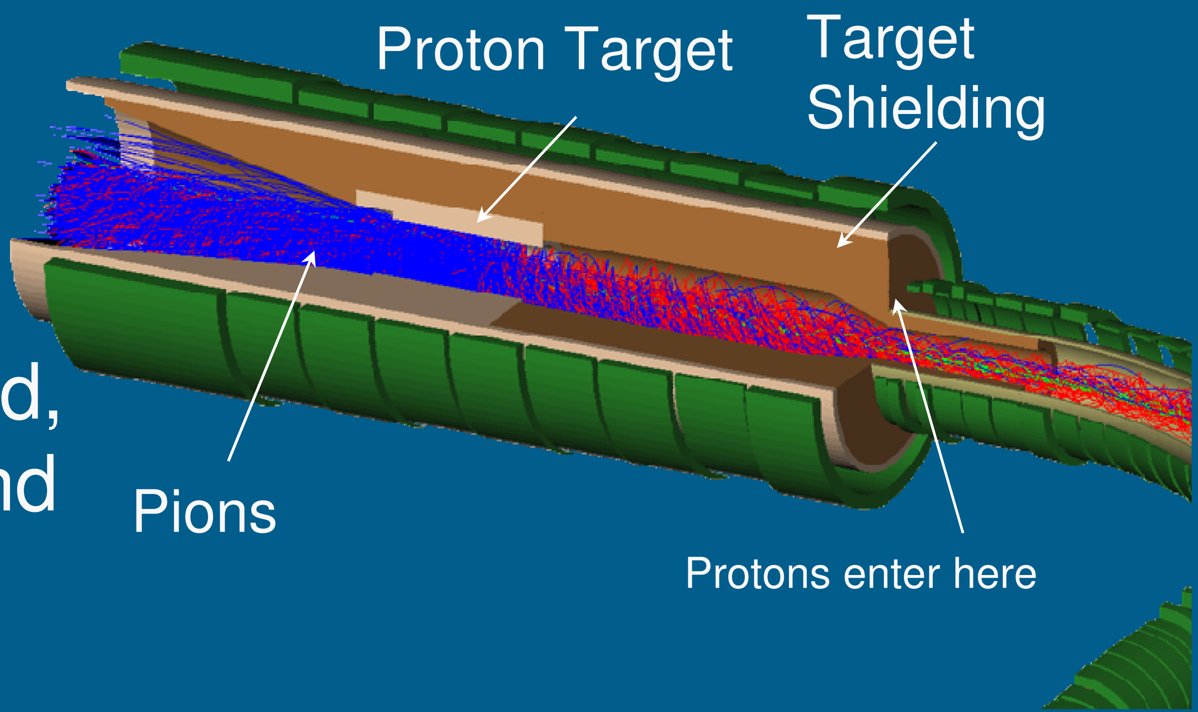


Mu2e p target side

Protons leave through thin window

π's are captured, spiral around and decay

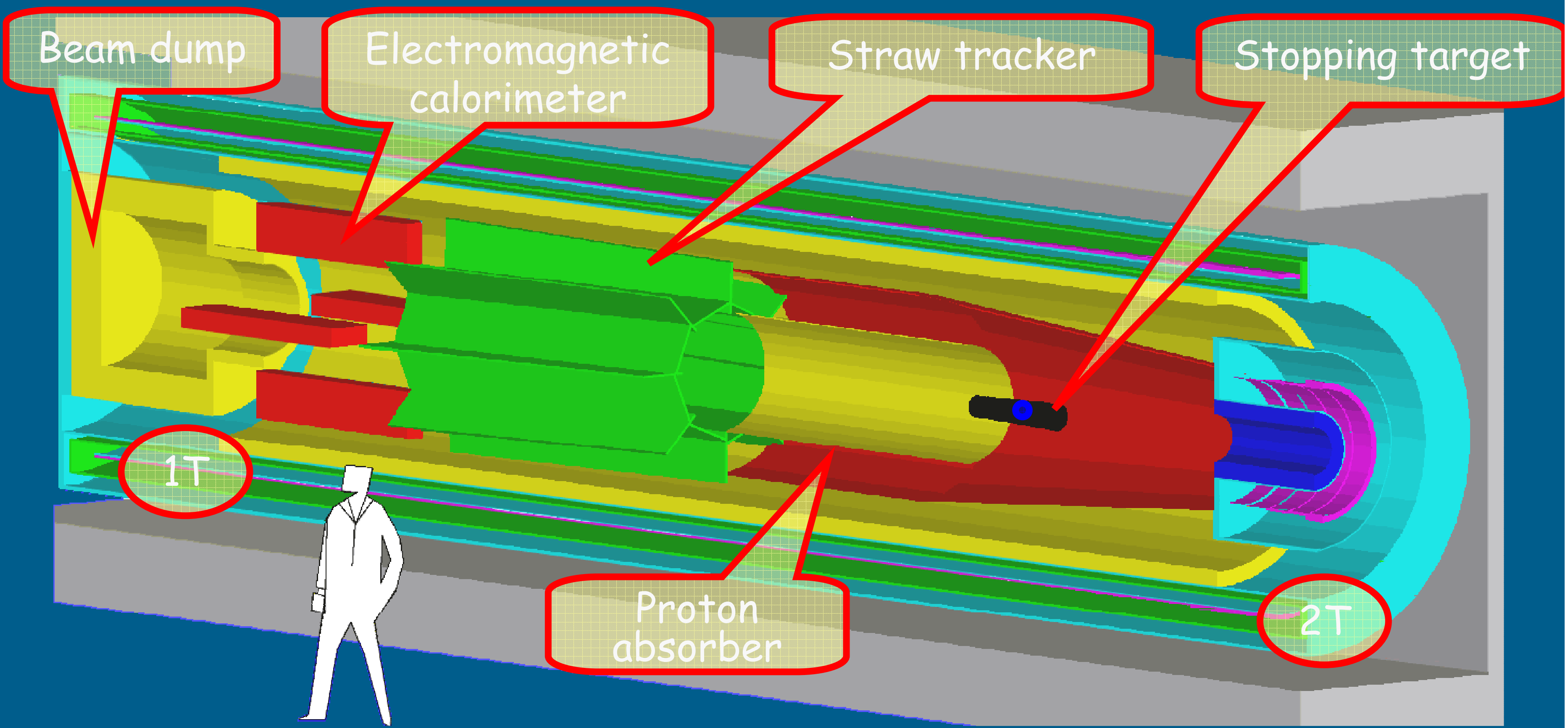
muons exit to right



4 m X 0.75 m

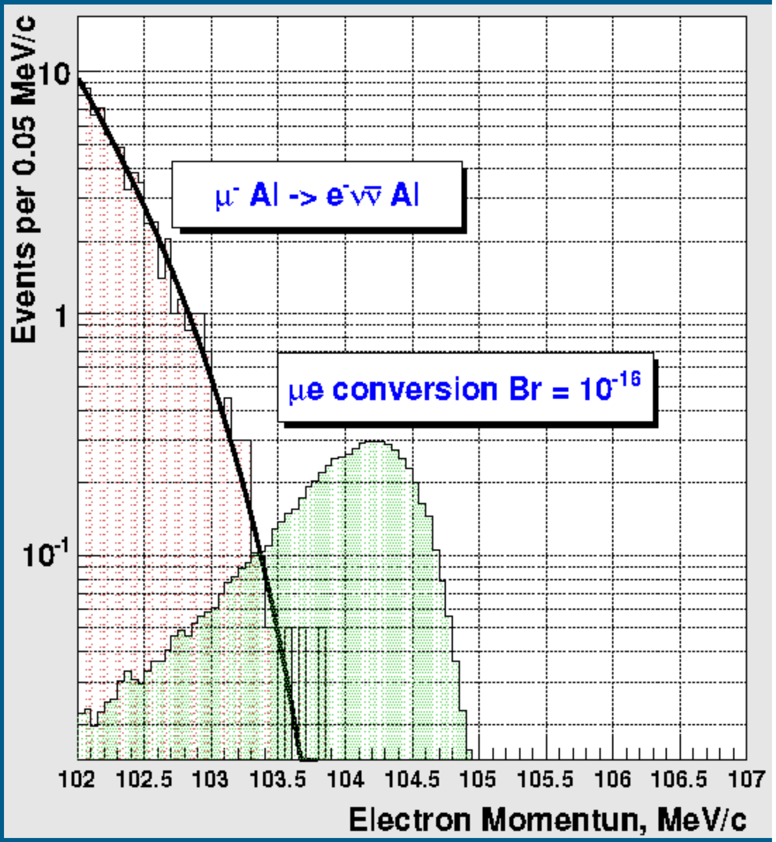
Mu2e - muon decay side

- No detector element in region of transported beam
- Small acceptance for DIO electrons
- Minimal amount of material ⇨ detector elements in vacuum



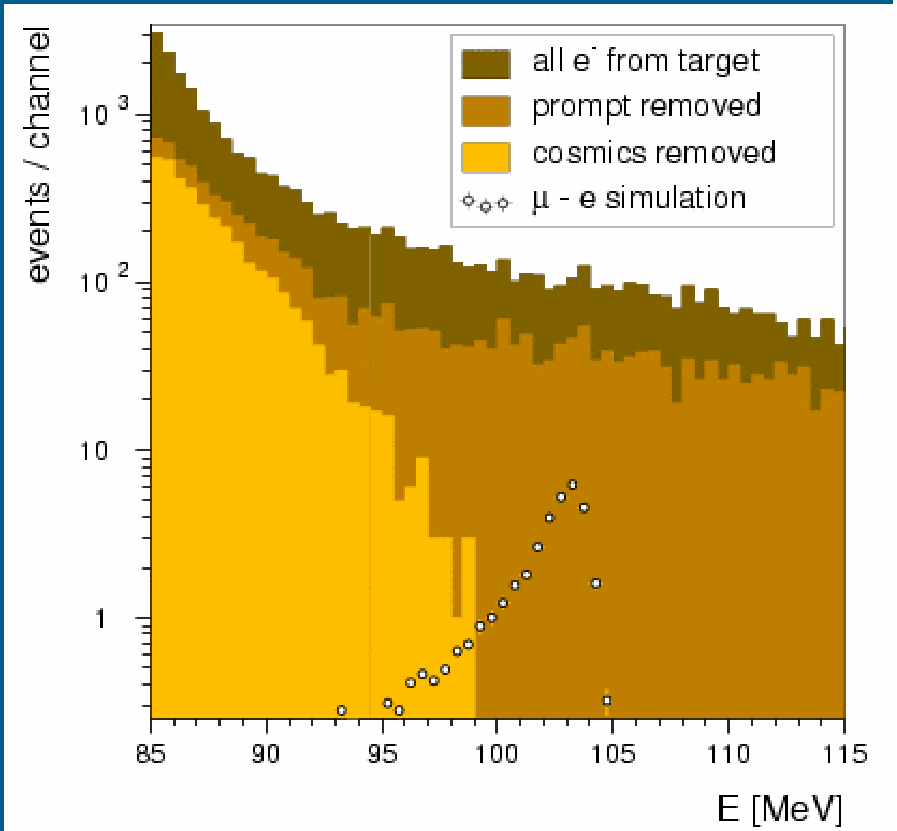
Mu2e

- Must operate in rates up to 200 kHz in individual detector elements
- Must operate in vacuum: < 10-3 Torr
- Must have low acceptance for DIO electrons
- Straw tubes: 2,800, 5 mm diam., 2.6 m long, 25mm thick
- Cathode strips: 17,000
- 50% geometrical acceptance: 90°±30°
- 0.2 MeV intrinsic energy resolution
- Resolution dominated by multiple scattering



Mu2e

- CR Muons cause two types of backgrounds:
1. Muon decay-in-flight
2. Delta electrons from target or tracker
- Cosmics have been the main SINDRUM external background



Mu2e performance

Proton flux	1.8×10^{13} p/s
Running time	2×10^{7} s
Total protons	3.6×10^{20} p/yr
μ^- stops/incident proton	0.0025
μ^- capture probability	0.61
Time window fraction	0.49
Electron trigger efficiency	0.90
Reconstruction and selection efficiency	0.19
Sensitivity (90% CL)	5×10^{-17}
Detected events for $R_{\mu e} = 10^{-16}$	5

PRIME

Source	Events	Comments
μ decay in orbit	0.25	S/N = 20 for $R_{\mu e} = 10^{-16}$
Tracking errors	< 0.006	
Radiative μ decay	< 0.005	
Beam e^-	< 0.04	
μ decay in flight	< 0.03	Without scattering in stopping target
μ decay in flight	0.04	With scattering in stopping target
π decay in flight	< 0.001	
Radiative π capture	0.07	From out of time protons
Radiative π capture	0.001	From late arriving pions
Anti-proton induced	0.007	Mostly from π^-
Cosmic ray induced	0.004	Assuming 10^{-4} CR veto inefficiency
Total Background	0.45	Assuming 10^{-9} inter-bunch extinction

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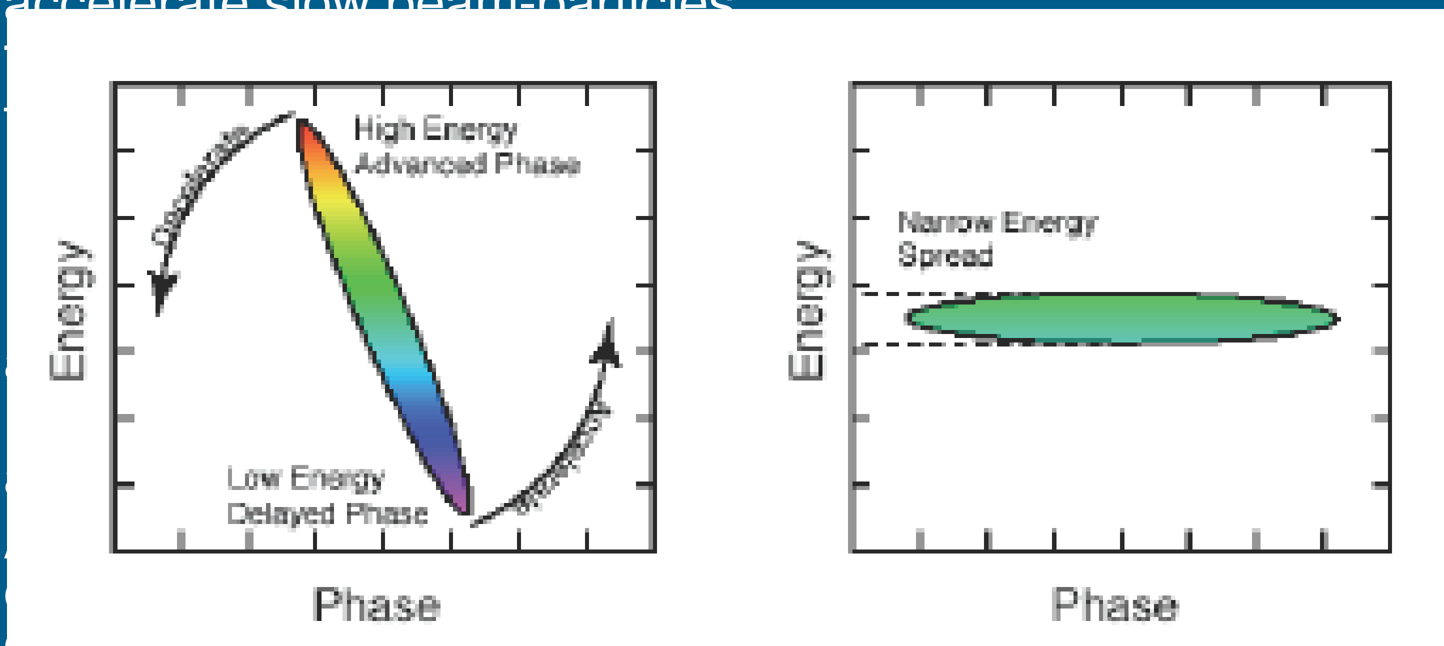
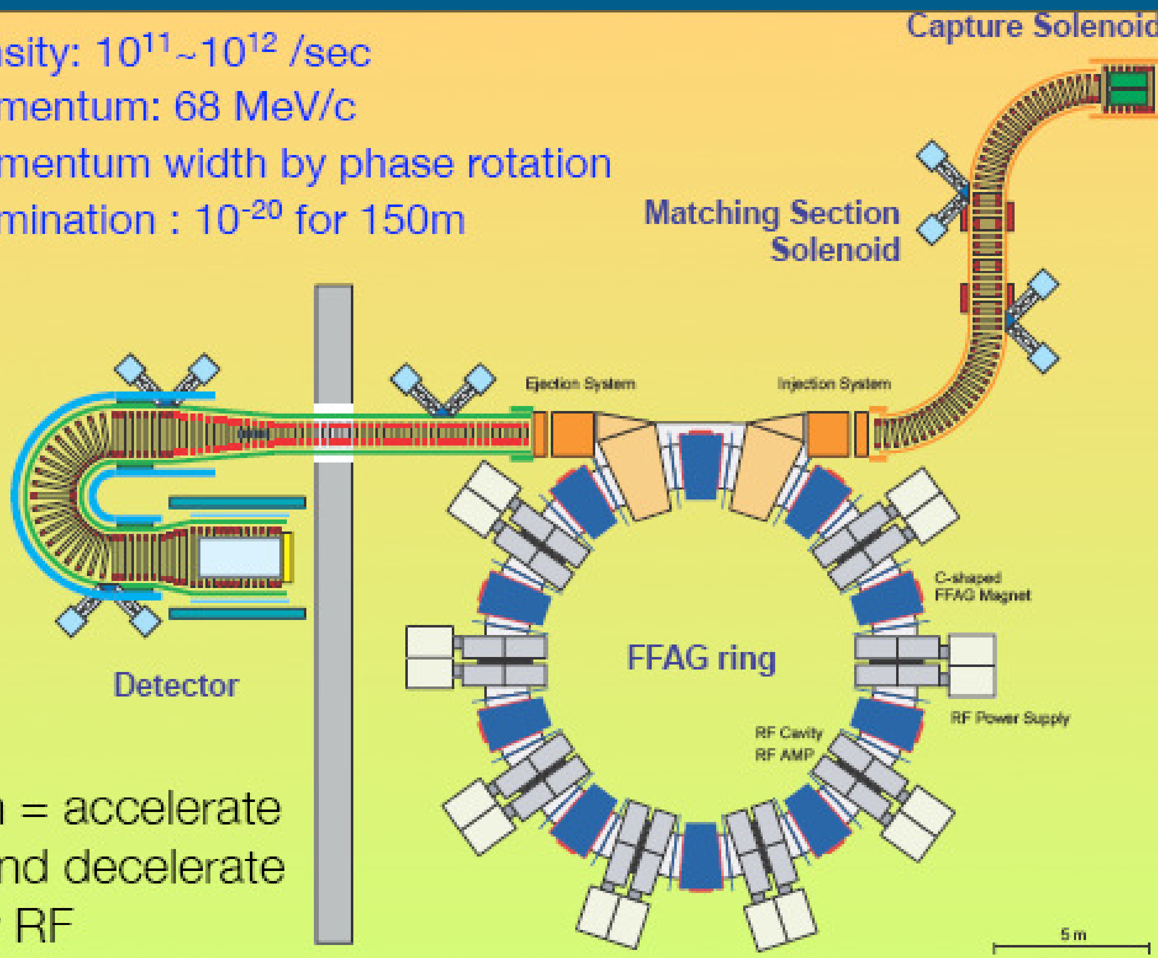
PRIME

- A technique of phase rotations adopted.
- The phase rotation is to decelerate fast beam particles and accelerate slow beam-particles.



PRIME concept design

- muon intensity: $10^{11} \sim 10^{12}$ /sec
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination : 10^{-20} for 150m



Phase rotation = accelerate slow muons and decelerate fast muons by RF

LFV τ decay

- The τ channel is in principle very interesting for studying LFV because of the τ large mass ($m\tau \approx 17\ m\mu$)
- -->Many decay channels;
- BR's enhanced in respect with $\mu \to e\gamma$ by $(m\tau/m\mu)^{\alpha}$ with $\alpha \sim 3$
-

$$\frac{Br(\tau->\mu\gamma)}{Br(\mu->e\gamma)} \approx 10^{4}$$

- Experimental problem: production & detection of τ large samples.
- To be competitive with dedicated experiments one must reach
- $BR(\tau \to \mu\gamma) < 10^{-(8\div 9)}$
- Significant improvements obtained by B-factories (BELLE,BABAR).

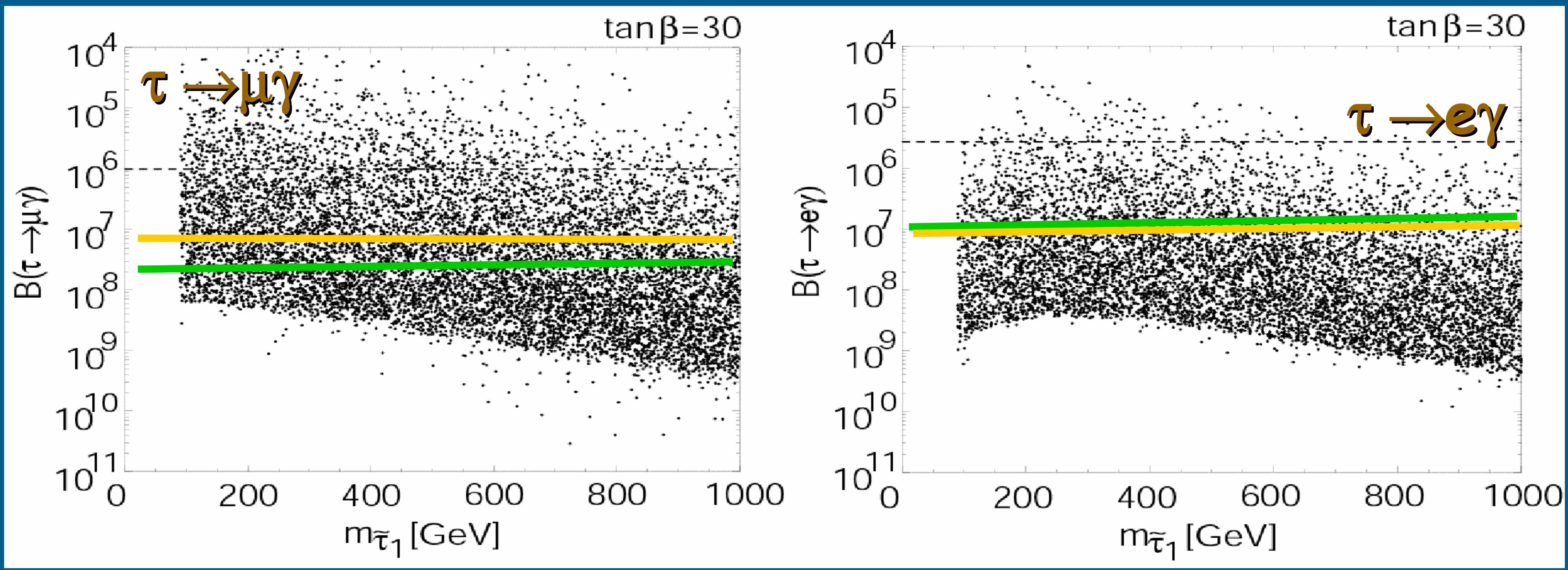
LFV τ decay

Predicted by many new physics models

- Normal models enhance $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow \mu l^+ l^-$
- Some models may enhance other modes
- $\tau \rightarrow e\gamma$ and $\tau \rightarrow e l^+ l$ are similar

	Reference	$\tau \rightarrow \mu\gamma$	$\tau \rightarrow \mu\mu\mu$
SM+ ν mixing	EPJ C8(1999)513	10^{-40}	10^{-14}
SM + heavy Maj ν_R	PRD 66(2002)034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547(2002)252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68(2003)033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66(2002)115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566(2003)217	10^{-10}	10^{-7}

Present limit of $\tau \to l\gamma$



Green: Belle (2008)
Yellow: BaBar (2008)

- **$Br(\tau\mu ee) / Br(\tau\mu\gamma) \cong 1/94$**
- **$Br(\tau\mu\mu\mu) / Br(\tau\mu\gamma) \cong 1/440$**
- **$Br(\tau eee) / Br(\tau e\gamma) \cong 1/94$**
- **$Br(\tau e\mu\mu) / Br(\tau e\gamma) \cong 1/440$**

Current status for several τ decay channels

	Belle		BaBar			Belle		BaBar	
	UL90 (10^{-7})	Lum (fb^{-1})	UL90 (10^{-7})	Lum (fb^{-1})		UL90 (10^{-7})	Lum (fb^{-1})	UL90 (10^{-7})	Lum (fb^{-1})
$\mu\gamma$	0.5	535	0.7	232	$e\pi^0$	0.8	401	1.3	339
$e\gamma$	1.2	535	1.1	232	3l	0.2-0.4	535	0.4-0.8	376
$\mu\eta$	0.7	401	1.5	339	lhh	2-16	158	1-5	221
$\mu\eta'$	1.3	401	1.3	339	μV^0	0.6-1.3	543	1.0($\mu\omega$)	384
$\mu\pi^0$	1.2	401	1.5	339	eV^0	0.6-1.8	543	1.1($e\omega$)	384
$e\eta$	0.9	401	1.6	339	μf_0	0.33	671		
$e\eta'$	1.6	401	2.4	339	ef_0	0.34	671		

Towards Super B factory

- Int. Luminosity at B-factories >1.3 ab^{-1}
  - ~1.2x10^{9} τ-pairs
- Super B-factory 10 ab^{-1}/year (50 ab^{-1})
- BR sensitivity
  - It depends on background.
  - $\tau \rightarrow l\gamma$; scale as $\sim 1/\sqrt{L}$
    - $e^+e^- \rightarrow \tau^+\tau^-\gamma$ is irreducible BG.
    - ~10^{-8} level at super B-factory
  - $\tau \rightarrow lll$, lX^0; scale as ~1/L
    - O(10^{-9}) level at super B-factory