Charged Lepton Flavor Violations

CLFV

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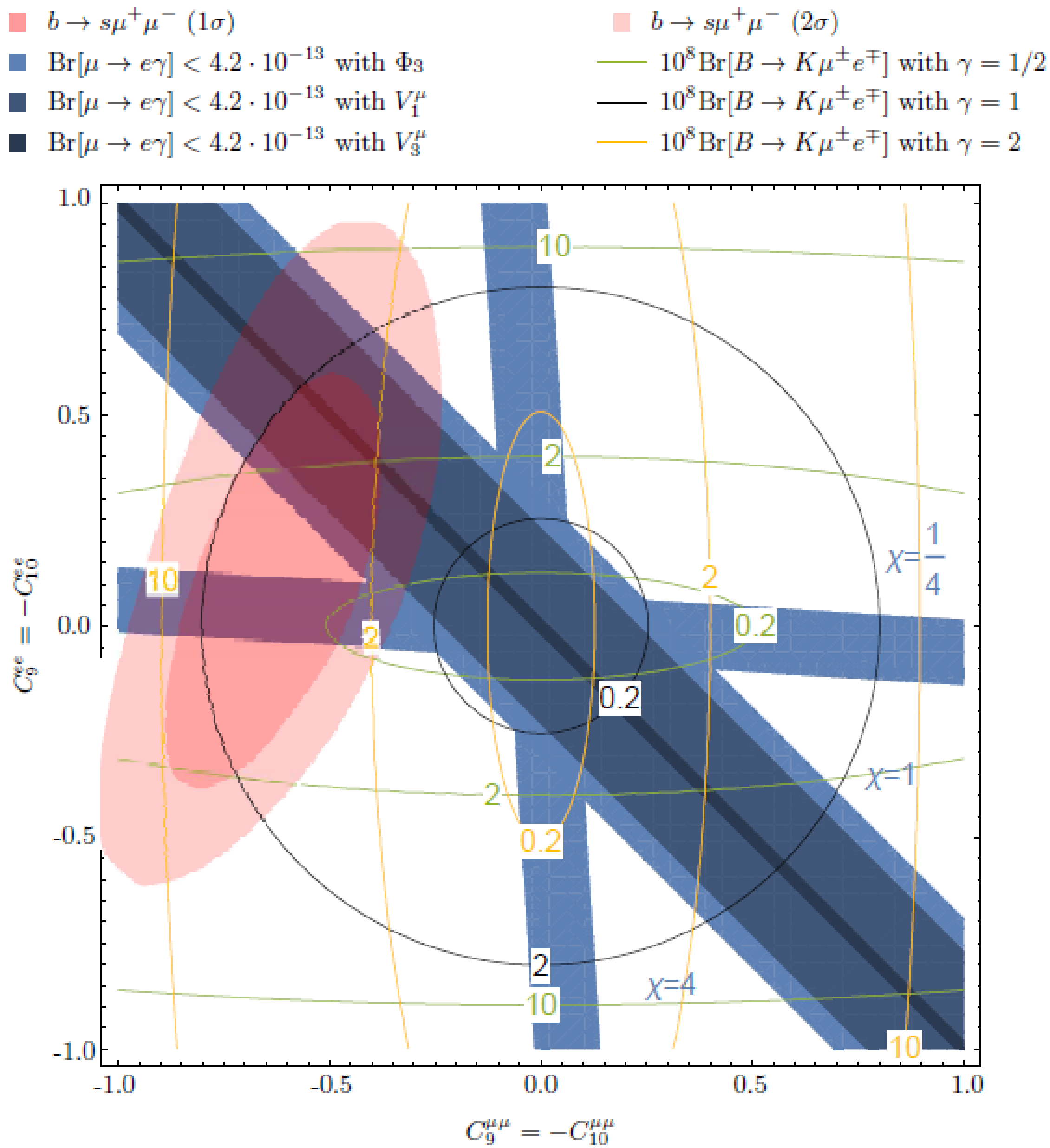
Most stringent LFV upper limits

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8 BaBar	
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8 BaBar	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8 Belle	
$\tau \rightarrow eee$	BR < 3.6 E-8 Belle	
$K_L \rightarrow e\mu$	BR < 4.7 E-12 BNL	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11 BNL	NA62 might improve by O(10)
$B^0 \rightarrow e\mu$	BR < 7.8 E-8 LHCb	Belle II - LHCb
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8 BaBar	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2 E-13 MEG@PSI	10^{-14} (MEG@PSI)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12 SINDRUM@PSI	10^{-16} (PSI)
$\mu N \rightarrow eN$	$R_{\mu e}$ < 7.0 E-13 SINDRUM@PSI	10^{-17} (Mu2e, COMET)

R-parity conserved SUSY: meson decays strongly suppressed by μ constraints
(not true if R –parity is violated): Belayev et al., 2000

The recent LHCb results on possible LFU violations could be a sign of new physics giving rise to LFV: A. Crivellin et al., 2017 (LQ model)



Search for LFV decays of the Higgs boson at LHC

(Phys. Lett. B 763(2016) 472; CMS-PAS-HIG-17-001)

B(H->$\mu\tau$)<0.25%; B(H->eτ)< 0.61%; B(H->eμ)<0.035%

Higgs induced CLFV: parameterized with the following lagrangian

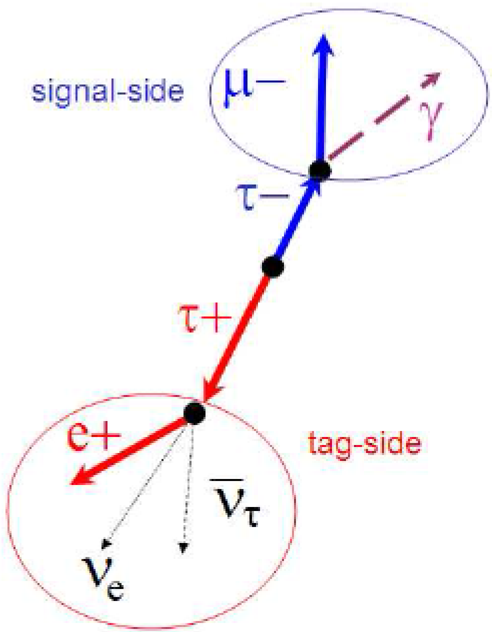
$$-\mathcal{L} \supset (m_e)_i \bar{e}_{L\,i}\, e_{R\,i} + (Y_e^h)_{ij}\, \bar{e}_{L\,i}\, e_{R\,j}\, h + h.c.$$

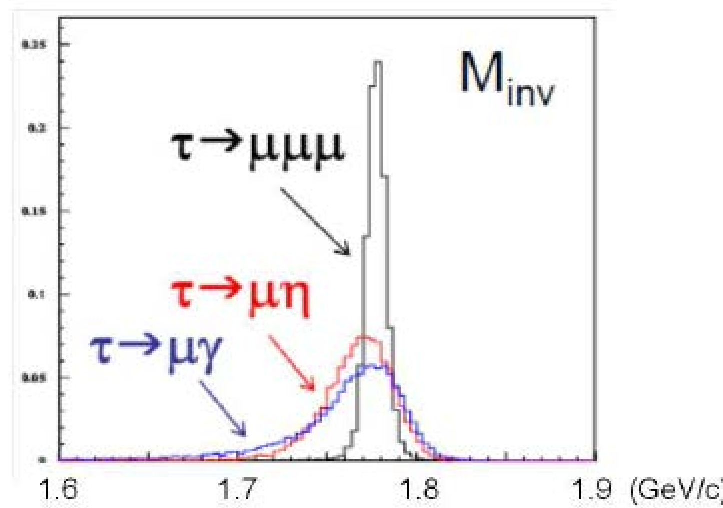
Process	Coupling	Bound	
$h \to \mu e$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2 + \lvert Y^h_{e\mu}\rvert^2}$	$< 5.4 \times 10^{-4}$	LHC
$\mu \to e\gamma$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2 + \lvert Y^h_{e\mu}\rvert^2}$	$< 2.1 \times 10^{-6}$	
$\mu \to eee$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2 + \lvert Y^h_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$	
$\mu\,\mathrm{Ti} \to e\,\mathrm{Ti}$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2 + \lvert Y^h_{e\mu}\rvert^2}$	$< 1.2 \times 10^{-5}$	
$h \to \tau e$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2 + \lvert Y^h_{e\tau}\rvert^2}$	$< 2.3 \times 10^{-3}$	LHC
$\tau \to e\gamma$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2 + \lvert Y^h_{e\tau}\rvert^2}$	< 0.014	
$\tau \to eee$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2 + \lvert Y^h_{e\tau}\rvert^2}$	$\lesssim 0.12$	
$h \to \tau\mu$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2 + \lvert Y^h_{\mu\tau}\rvert^2}$	$< 1.4 \times 10^{-3}$	LHC
$\tau \to \mu\gamma$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2 + \lvert Y^h_{\mu\tau}\rvert^2}$	< 0.016	
$\tau \to \mu\mu\mu$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2 + \lvert Y^h_{\mu\tau}\rvert^2}$	$\lesssim 0.25$	

L. Calibbi, G.Signorelli, 2017

Leptons: τ

τ cLFV sensitivity (BelleII): 1

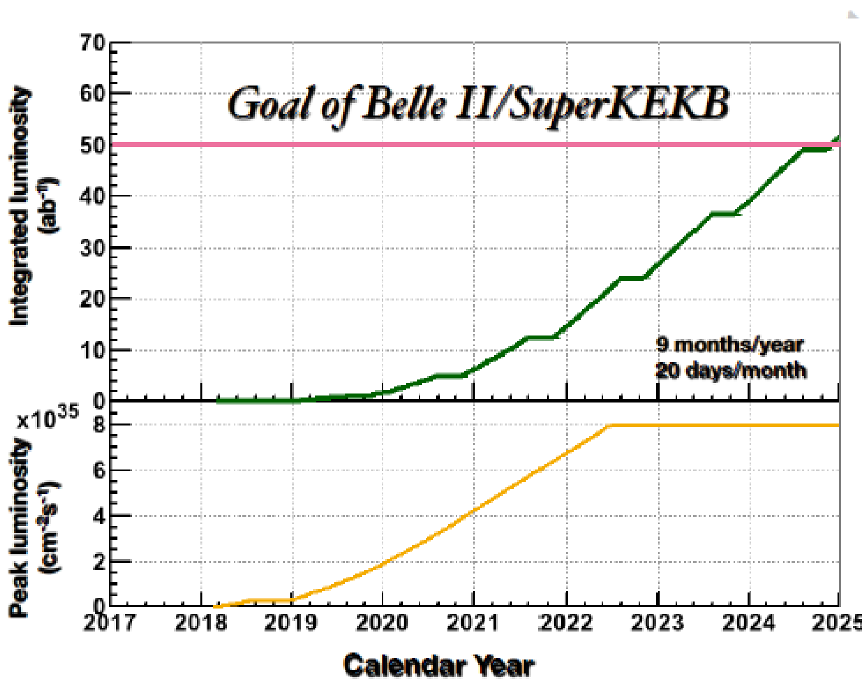


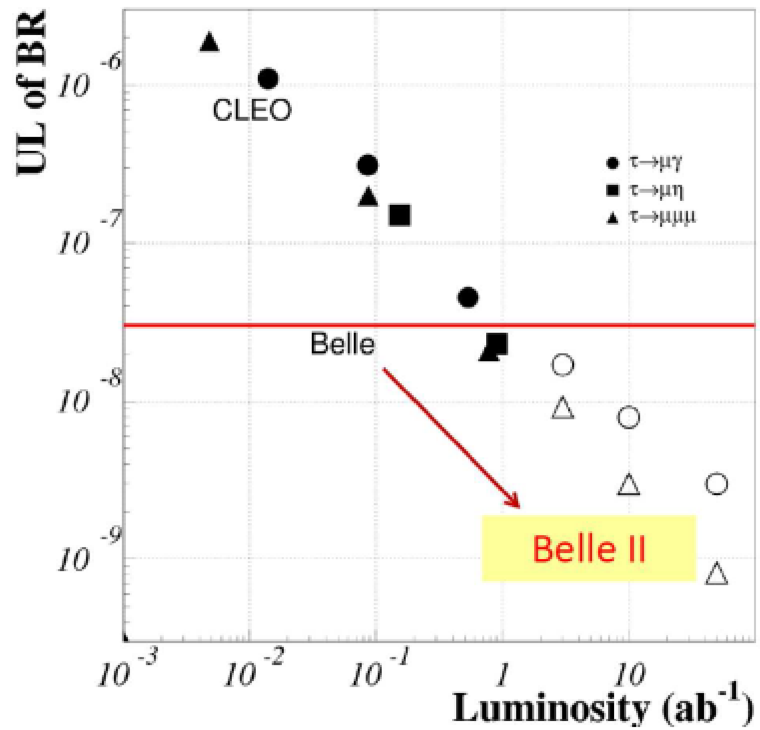


$$m_{\mathrm{inv}} = \sqrt{E_{\mu\gamma}^2 - p_{\mu\gamma}^2} \quad \Delta E = E_{\mu\gamma}^{\mathrm{CM}} - E_{\mathrm{beam}}^{\mathrm{CM}}$$

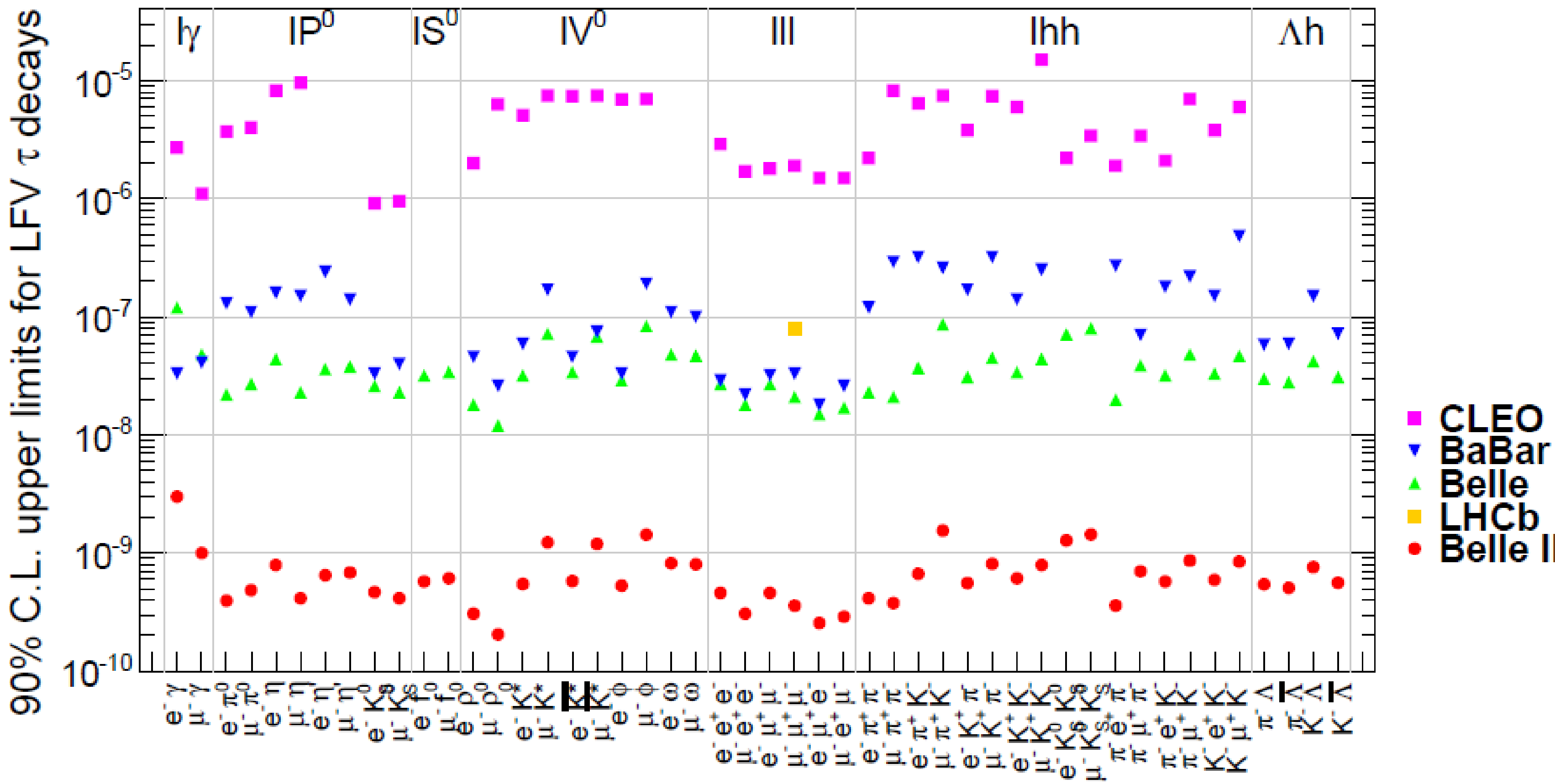
τ cLFV sensitivity (BelleII): 2

- Luminosity of 50 ab^{-1} (5×10^5 $\tau\bar{\tau}$) reachable by 2025
- Golden channels ($\tau \to 3\mu$) might be non background limited



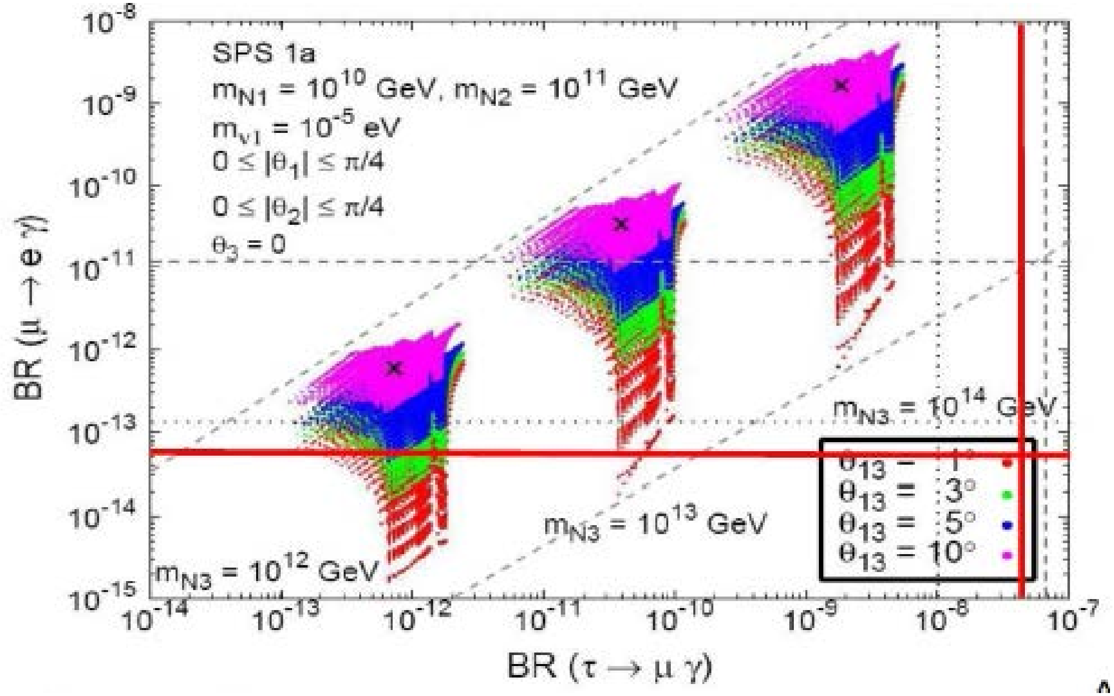


The foreseen improvements on all the CLFV decays

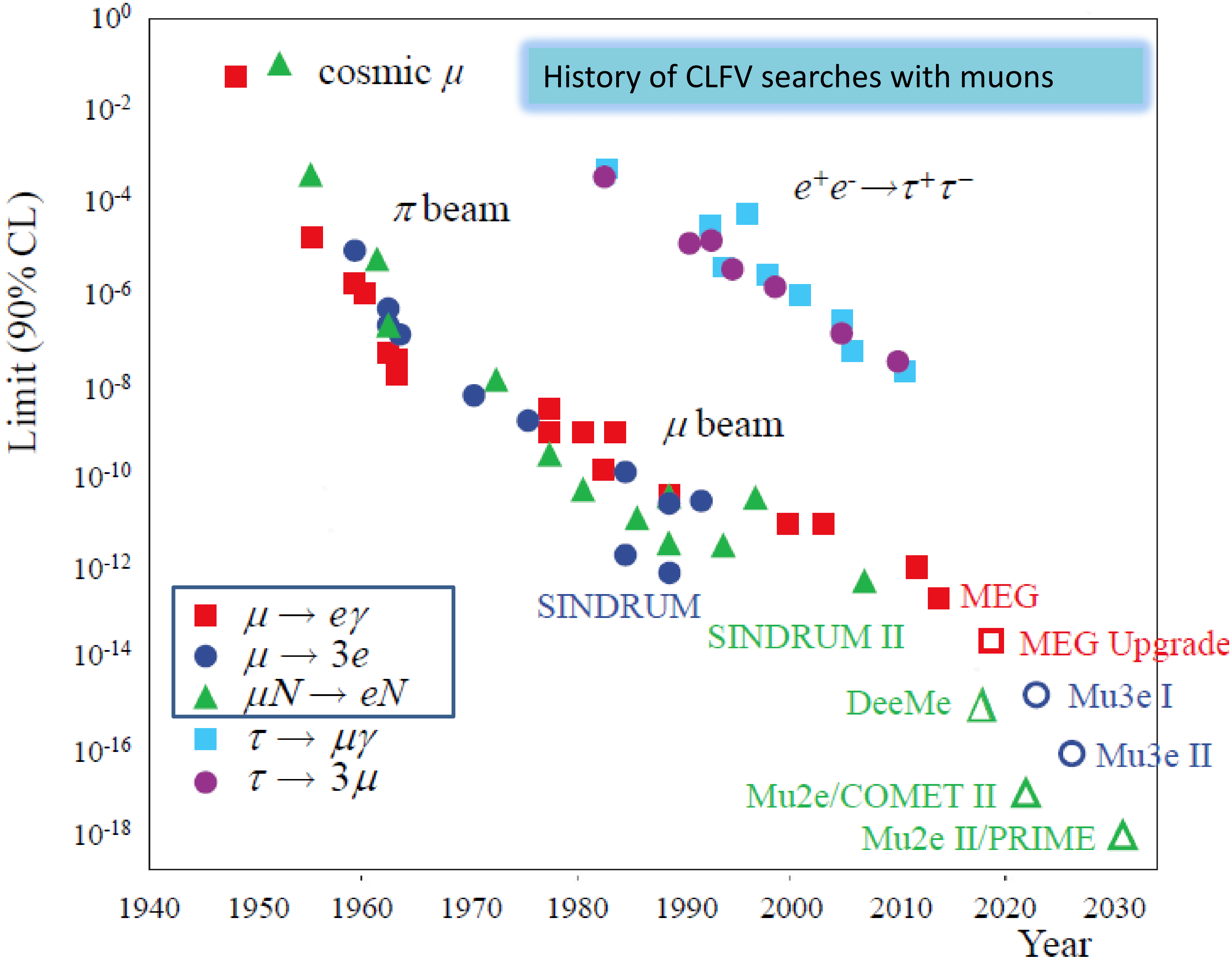


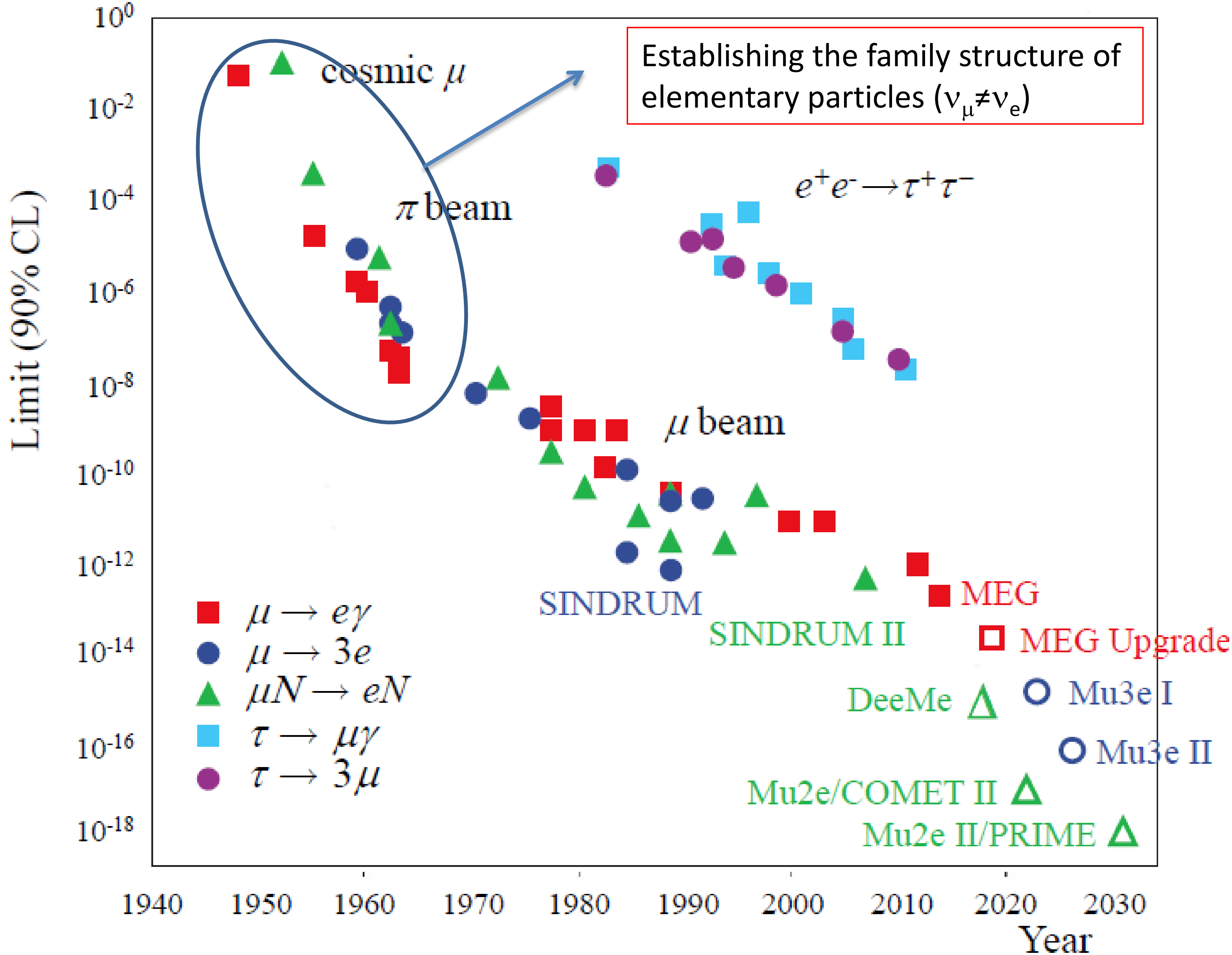
The sensitivity of the τ channels wrt the μ channels again depends very much on the model considered

Antusch et al., 2006

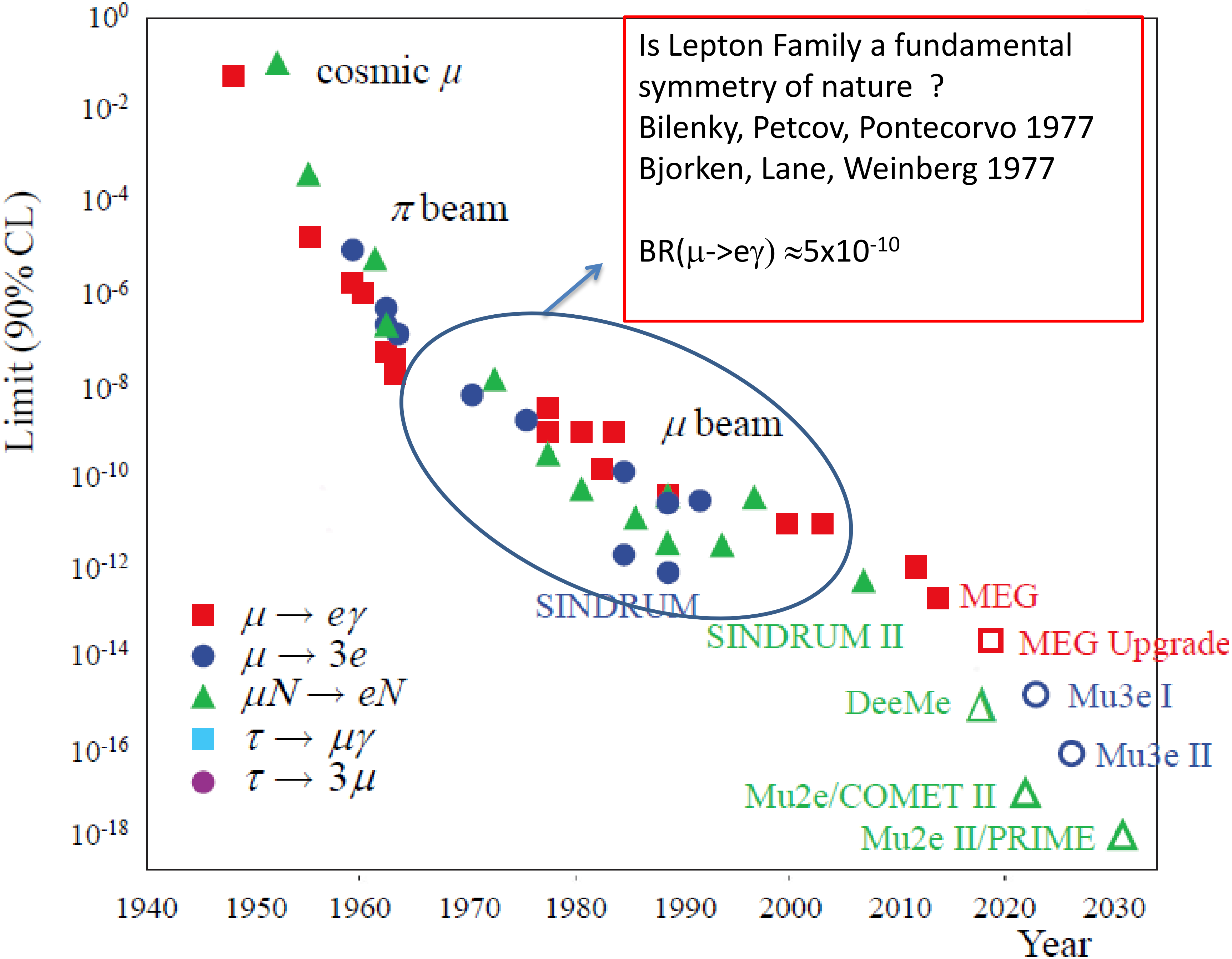


Bu the enhancement of the τ decay can be as large as 10^4: Barbieri et al., 1994

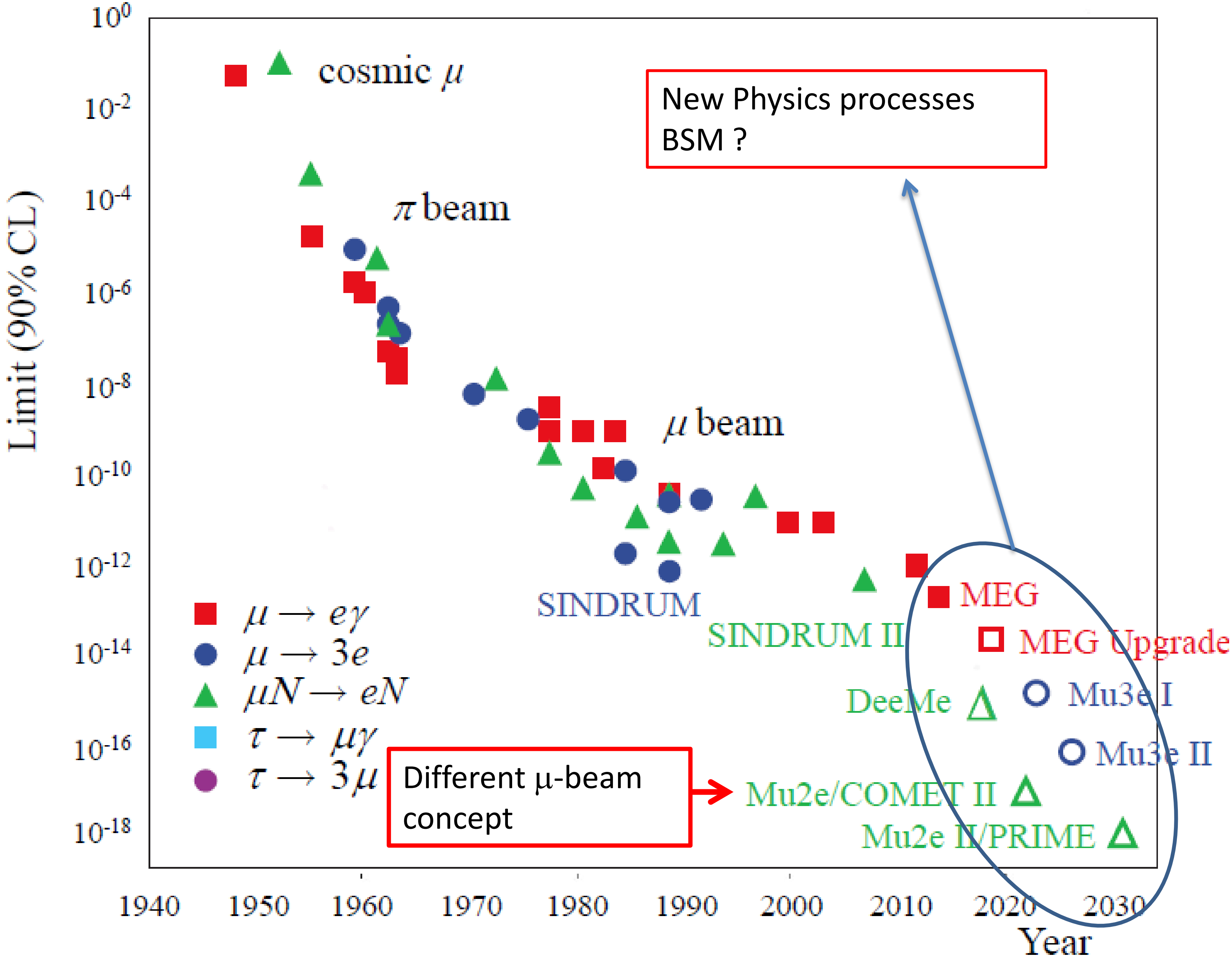

History of CLFV searches with muons
cosmic μ
π beam
μ beam
$e^+e^- \to \tau^+\tau^-$
SINDRUM
SINDRUM II
MEG
MEG Upgrade
DeeMe
Mu3e I
Mu3e II
Mu2e/COMET II
Mu2e II/PRIME
$\mu \to e\gamma$
$\mu \to 3e$
$\mu N \to eN$
$\tau \to \mu\gamma$
$\tau \to 3\mu$
Limit (90% CL)
Year
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030



Establishing the family structure of elementary particles ($\nu_\mu \neq \nu_e$)
cosmic μ
π beam
$e^+e^- \to \tau^+\tau^-$
μ beam
SINDRUM
SINDRUM II
MEG
MEG Upgrade
DeeMe
Mu3e I
Mu3e II
Mu2e/COMET II
Mu2e II/PRIME
$\mu \to e\gamma$
$\mu \to 3e$
$\mu N \to eN$
$\tau \to \mu\gamma$
$\tau \to 3\mu$
Limit (90% CL)
Year
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030



Is Lepton Family a fundamental symmetry of nature ?
Bilenky, Petcov, Pontecorvo 1977
Bjorken, Lane, Weinberg 1977
BR(μ->eγ) ≈5x10^-10
cosmic μ
π beam
μ beam
SINDRUM
SINDRUM II
MEG
MEG Upgrade
DeeMe
Mu3e I
Mu3e II
Mu2e/COMET II
Mu2e II/PRIME
μ → eγ
μ → 3e
μN → eN
τ → μγ
τ → 3μ
Limit (90% CL)
Year



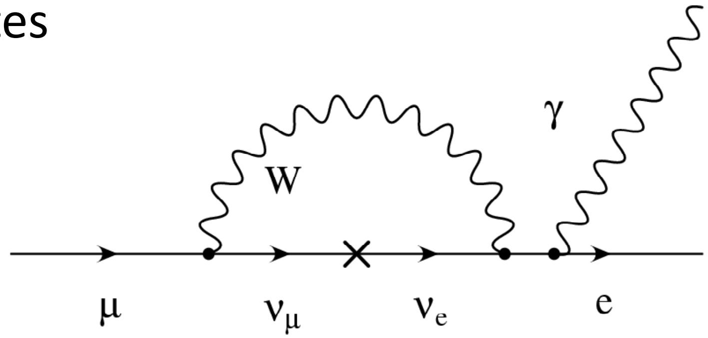
cosmic μ
π beam
μ beam
New Physics processes
BSM ?
SINDRUM
SINDRUM II
MEG
MEG Upgrade
DeeMe
Mu3e I
Mu3e II
Mu2e/COMET II
Mu2e II/PRIME
Different μ-beam concept
μ → eγ
μ → 3e
μN → eN
τ → μγ
τ → 3μ
Limit (90% CL)
Year

Why are these processes so sensitive to BSM ?
First: CLFV in the SM are NOT observable

In the pre-ν oscillations SM cLFV amplitudes are 0 due to the fact that neutrino masses are 0

But even the introduction of conventional neutrino masses to account for oscillations gives negligible rates

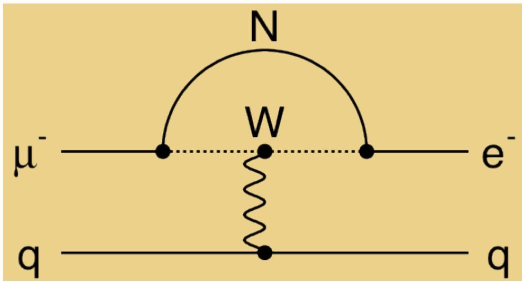
$\mu \rightarrow e\gamma$ rate in the standard model after neutrino oscillations



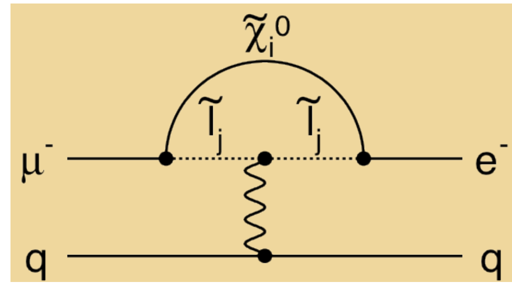
$$BR \sim \left(\frac{\delta m_\nu^2}{M_w^2} \right)^2 \; ; \delta m_\nu^2 \sim 10^{-5} eV^2 \Rightarrow BR \sim 10^{-54}$$

CLFV are VERY clean channels for new physics searches

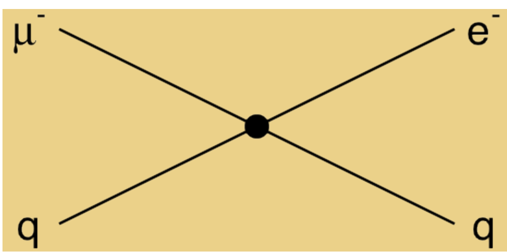
Second: as soon as one starts adding terms to the SM Lagrangian:



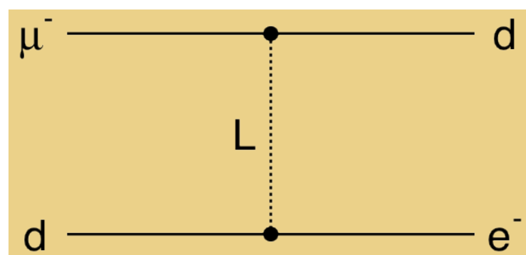
Heavy Neutrinos
(see saw)



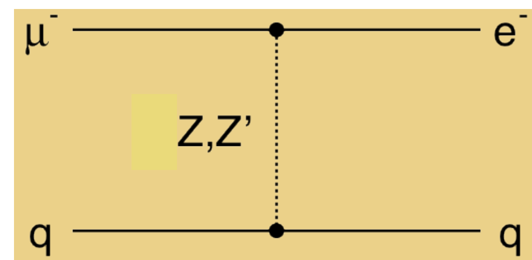
Supersymmetry



Compositeness



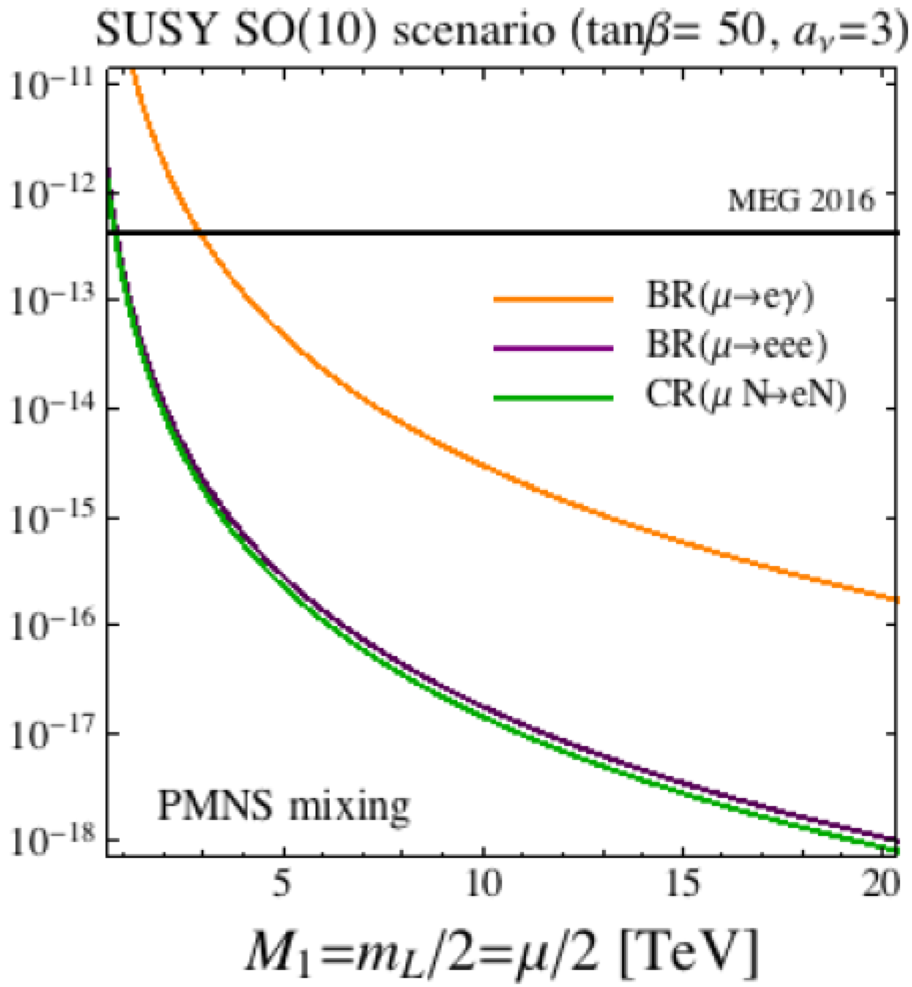
Leptoquarks



New Heavy Bosons /
Anomalous Couplings

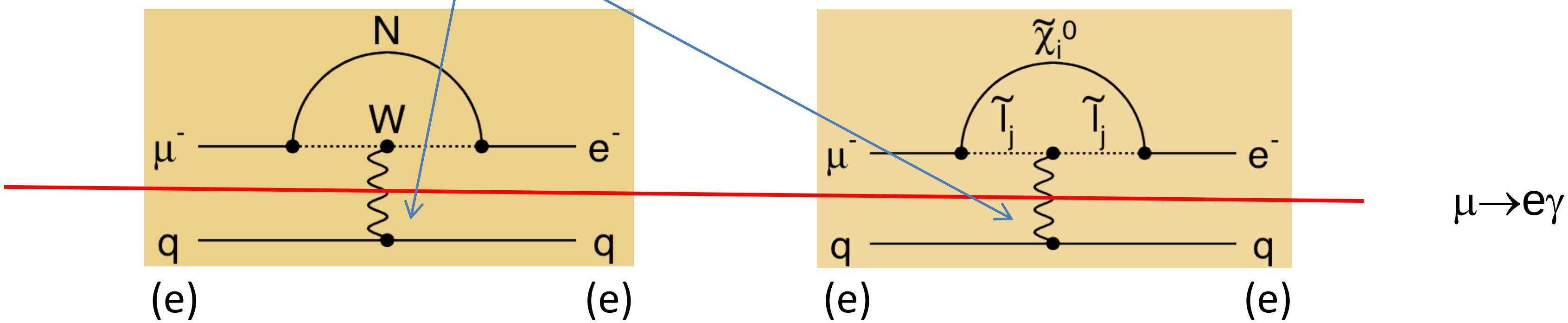
Charged Lepton flavor violating amplitudes arise at measurable levels !!

An example…



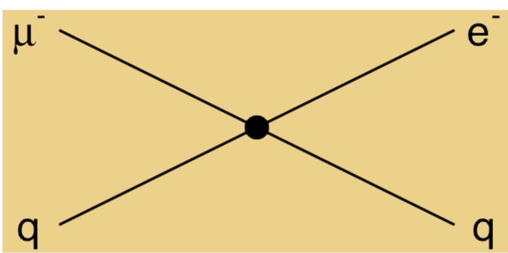
SUSY seesaw SO(10) with PMNS slepton mixing; Calibbi, Signorelli 2017 and references therein.

In case model prefer dipole operator (Supersymmetry) $\mu \rightarrow e\gamma$ is enhanced by roughly a factor $1/\alpha$ wrt $\mu \rightarrow e$ conversion or $\mu \rightarrow 3e$

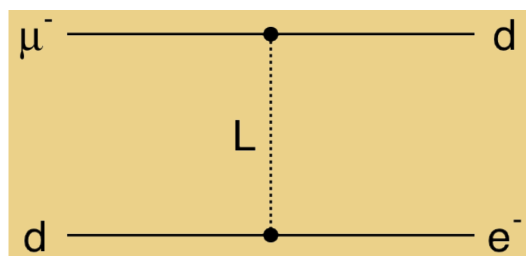


Heavy Neutrinos
(see saw)

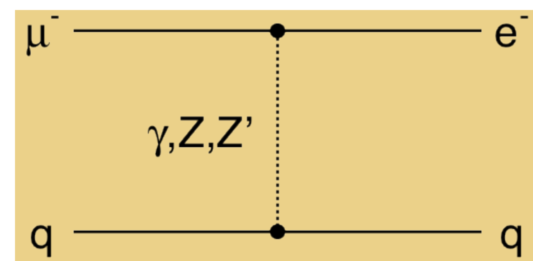
Supersymmetry



Compositeness



Leptoquarks



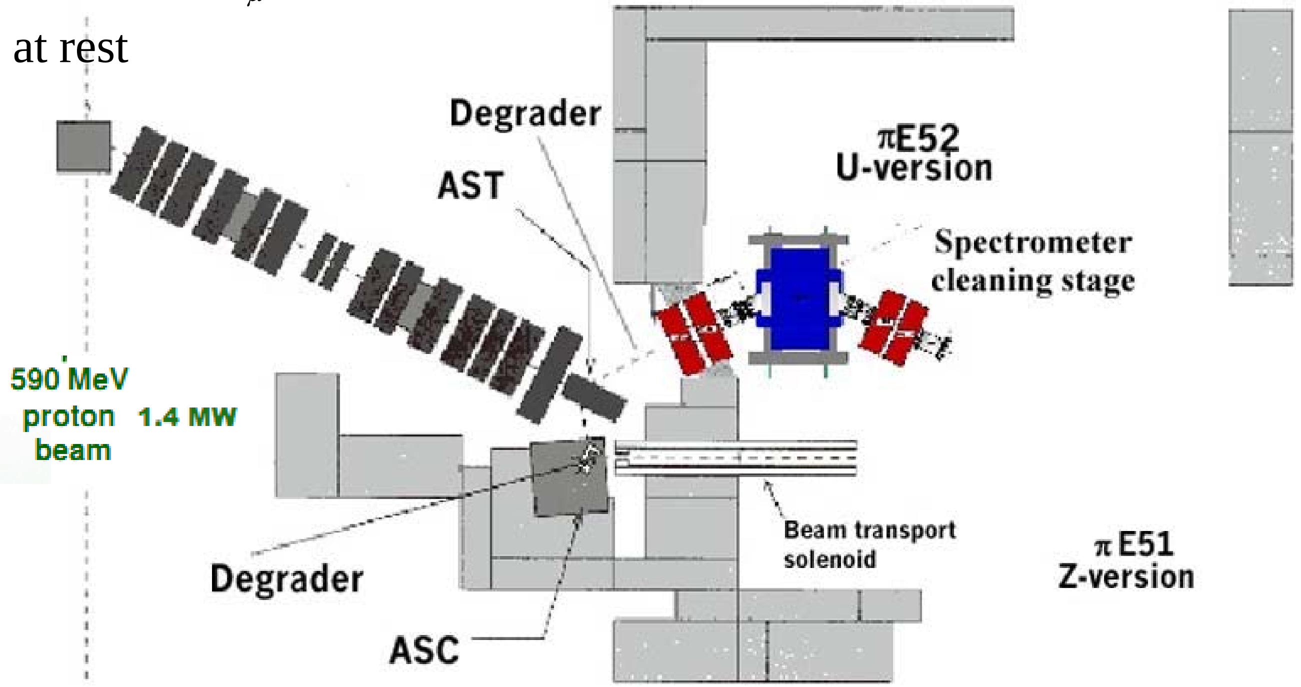
New Heavy Bosons /
Anomalous Couplings

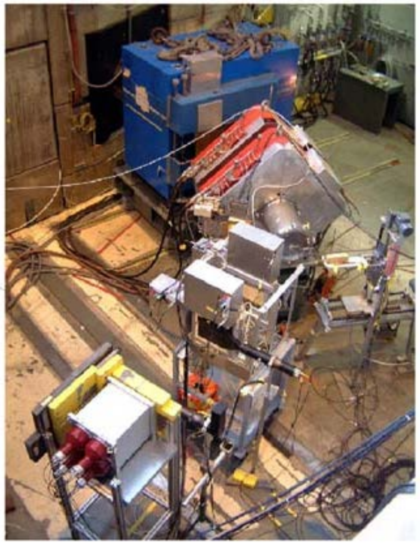
In other cases $\mu \rightarrow e$ conversion or $\mu \rightarrow 3e$ dominate ➔ Complementarity + possibility of distinguishing among different models

The PSI surface muon beam

$\pi \rightarrow \mu\nu$ $P_{\mu} \sim 29 MeV/c$

at rest



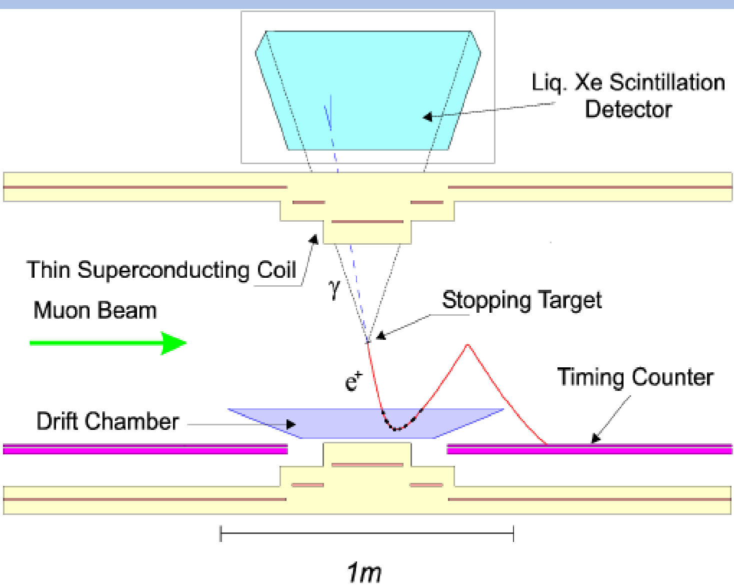


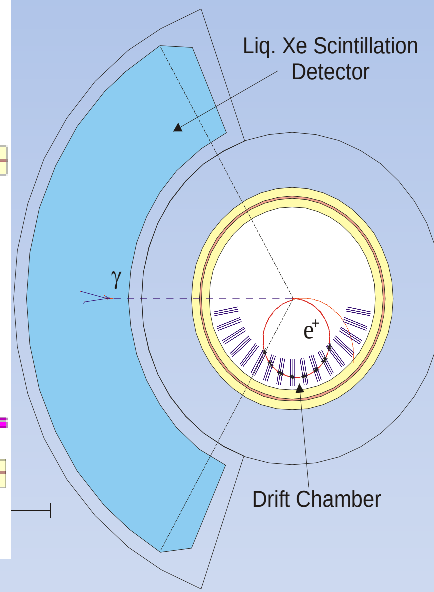
The layout of πE5

- 10^8 μ/s from the decay at rest of π^+ on the target surface (the μ range is approx. .1 gr/cm^3): almost completely polarized

- It is possible to focalize and stop the μ beam in a thin target

Used by the MEG experiment…



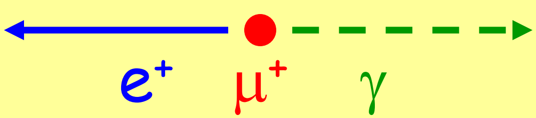


1. Stopped beam of 3 10^7 μ /sec in a 150 μm target
2. Solenoid spectrometer & drift chambers for e^+ momentum
3. Scintillation counters for e^+ timing
4. Liquid Xenon calorimeter for γ detection (scintillation)

Signal and background

signal

$\mu \rightarrow e\,\gamma$



$\theta_{e\gamma} = 180°$

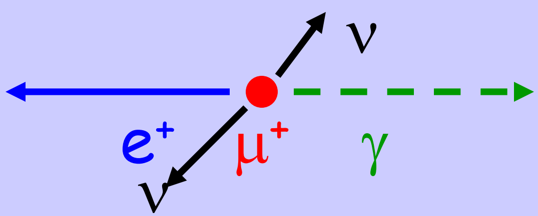
$E_e = E_\gamma = 52.8$ MeV

$T_e = T_\gamma$

background

physical

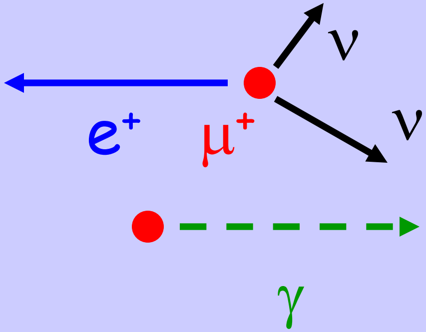
$\mu \rightarrow e\,\gamma\,\nu\,\nu$



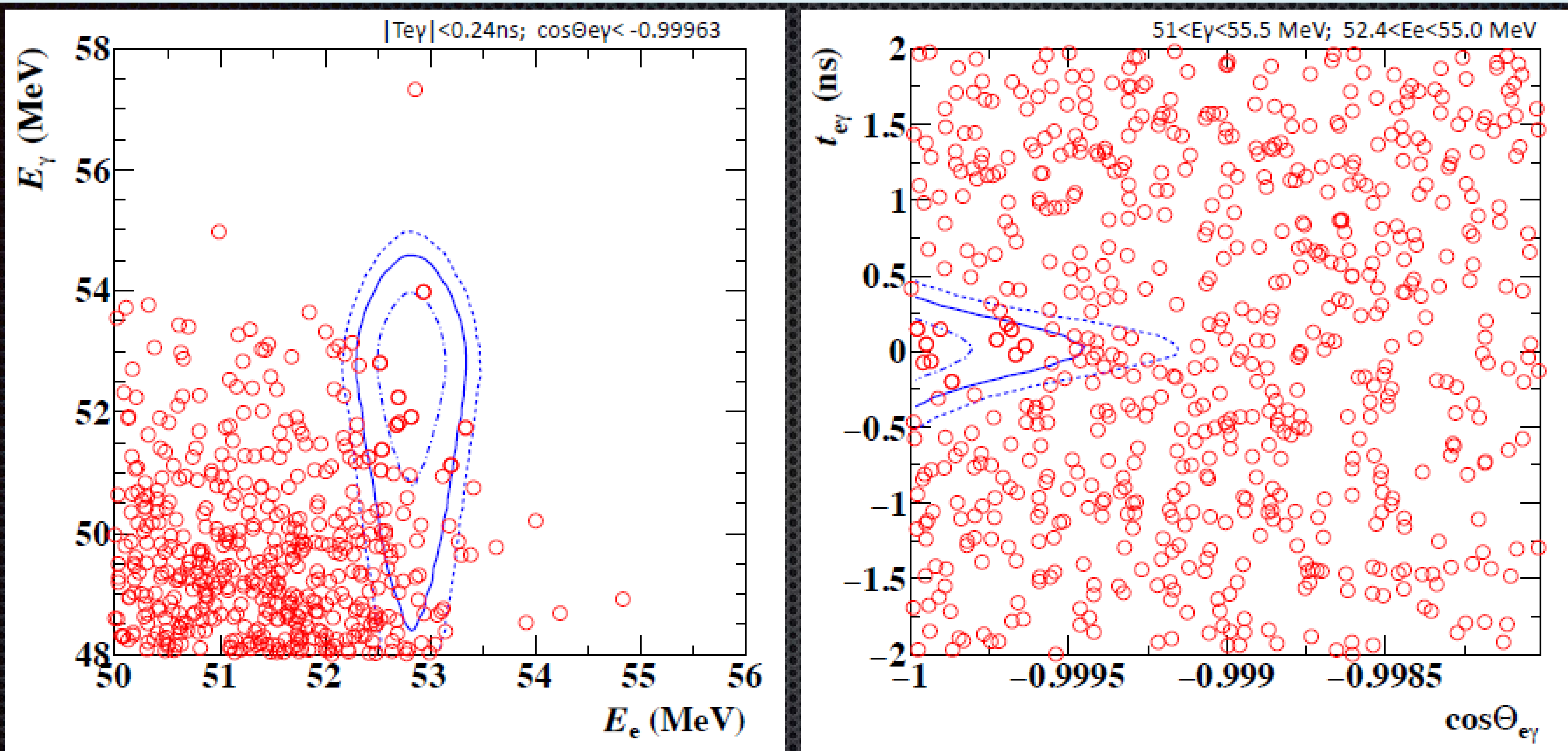
accidental

$\mu \rightarrow e\,\nu\,\nu$

$$\begin{cases} \mu \rightarrow e\,\gamma\,\nu\,\nu \\ ee \rightarrow \gamma\,\gamma \\ eZ \rightarrow eZ\,\gamma \end{cases}$$

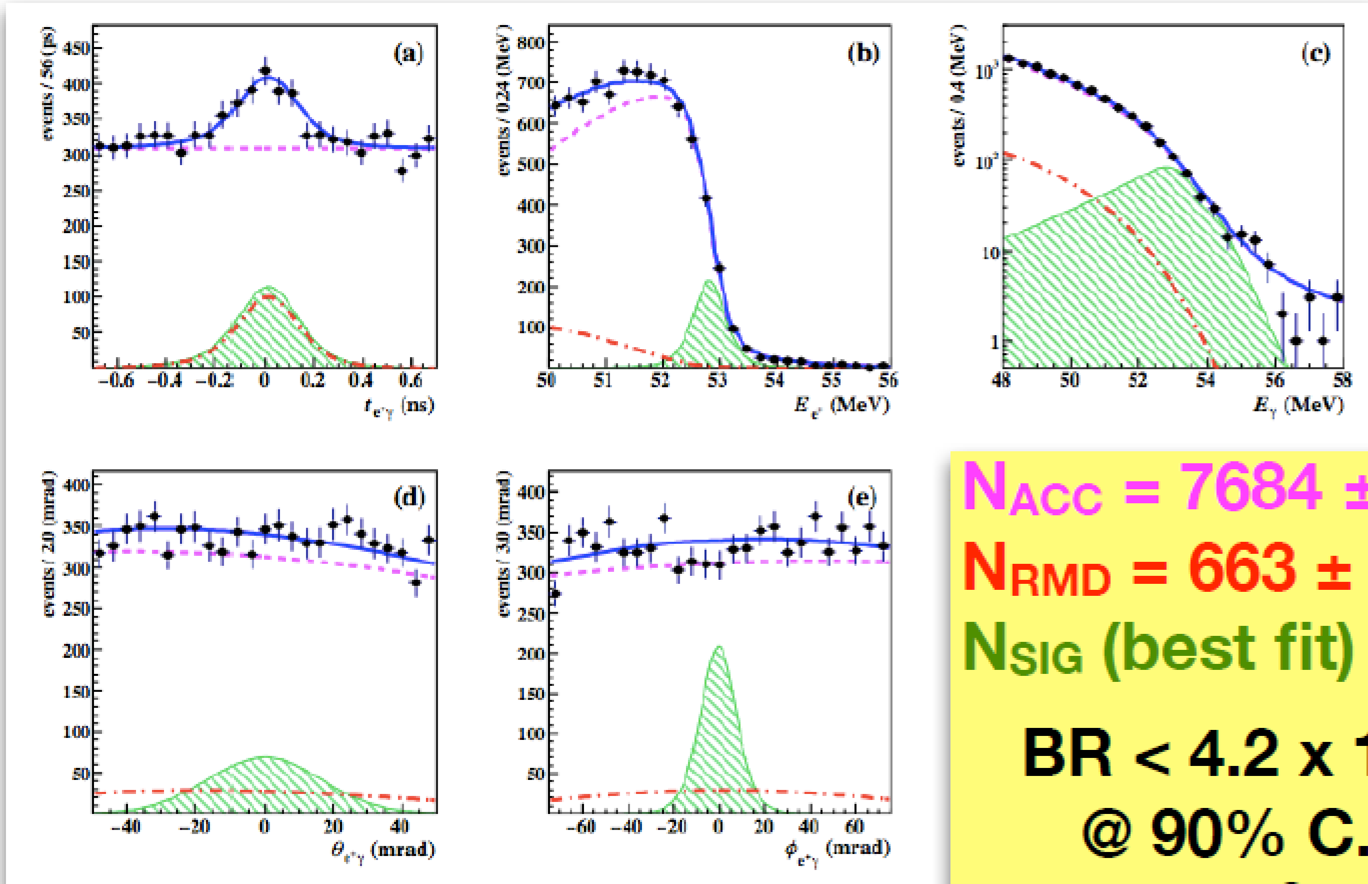


The interesting 4D region split in 2 bidimensional plots



signal contours of 1, 1.64, 2σ are shown

A more quantitative comparison…



N_{ACC} = 7684 ± 103

N_{RMD} = 663 ± 59

N_{SIG} (best fit) = -2.2

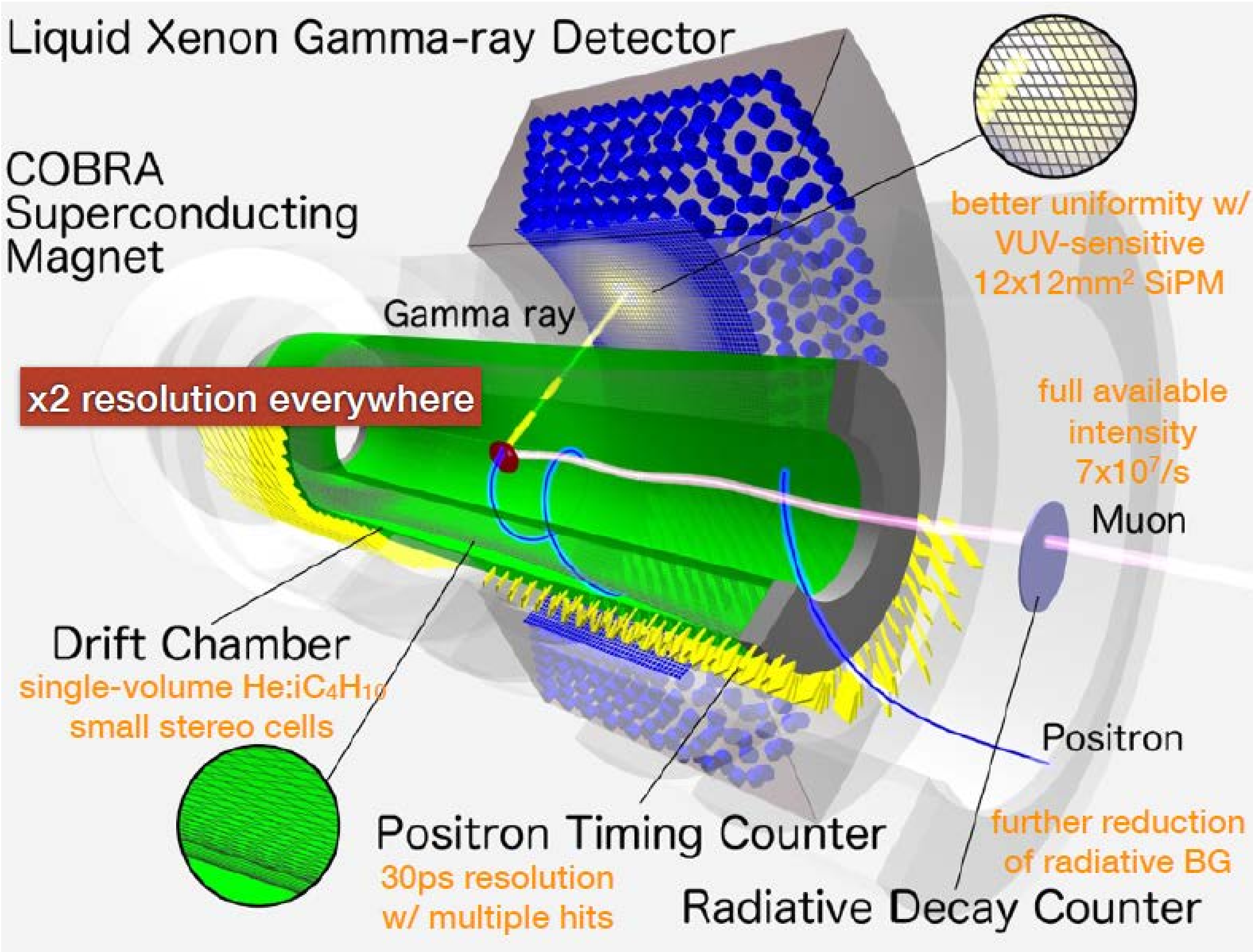
BR < 4.2 x 10^{-13} @ 90% C.L.

Eur. Phys. J. C76 (2016)

Magnified signal (BR = 4 x 10^{-11})

The relative angle is split into zenith and azimuth

The MEG II detector



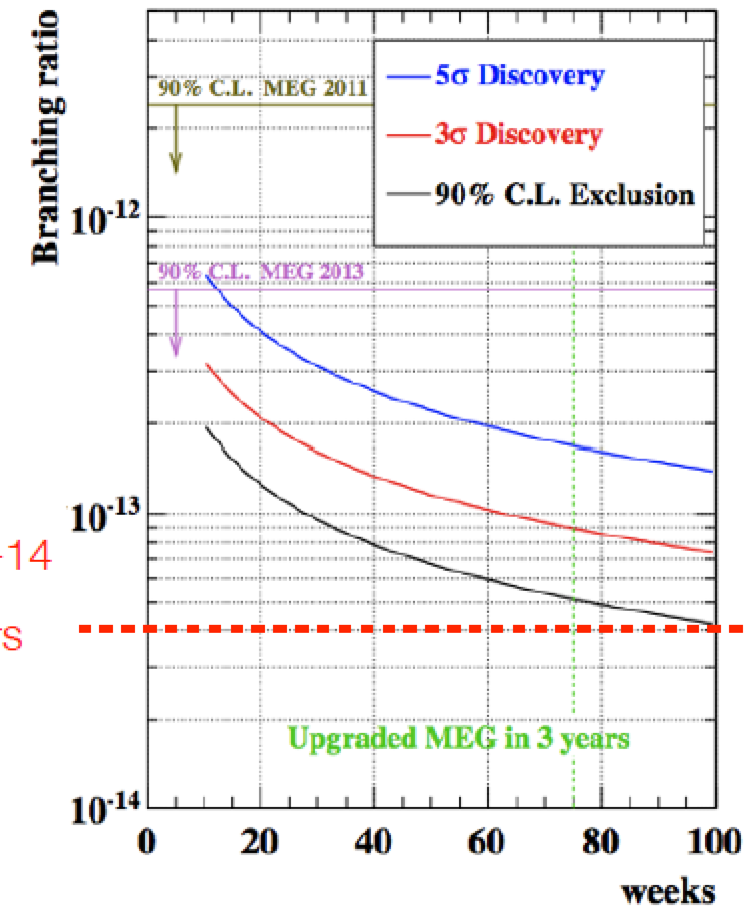
For a final sensitivity of 4×10^{-14}

- MEG-II is expected to start taking data with the full detector next year
- x10 improvement in sensitivity w.r.t. MEG

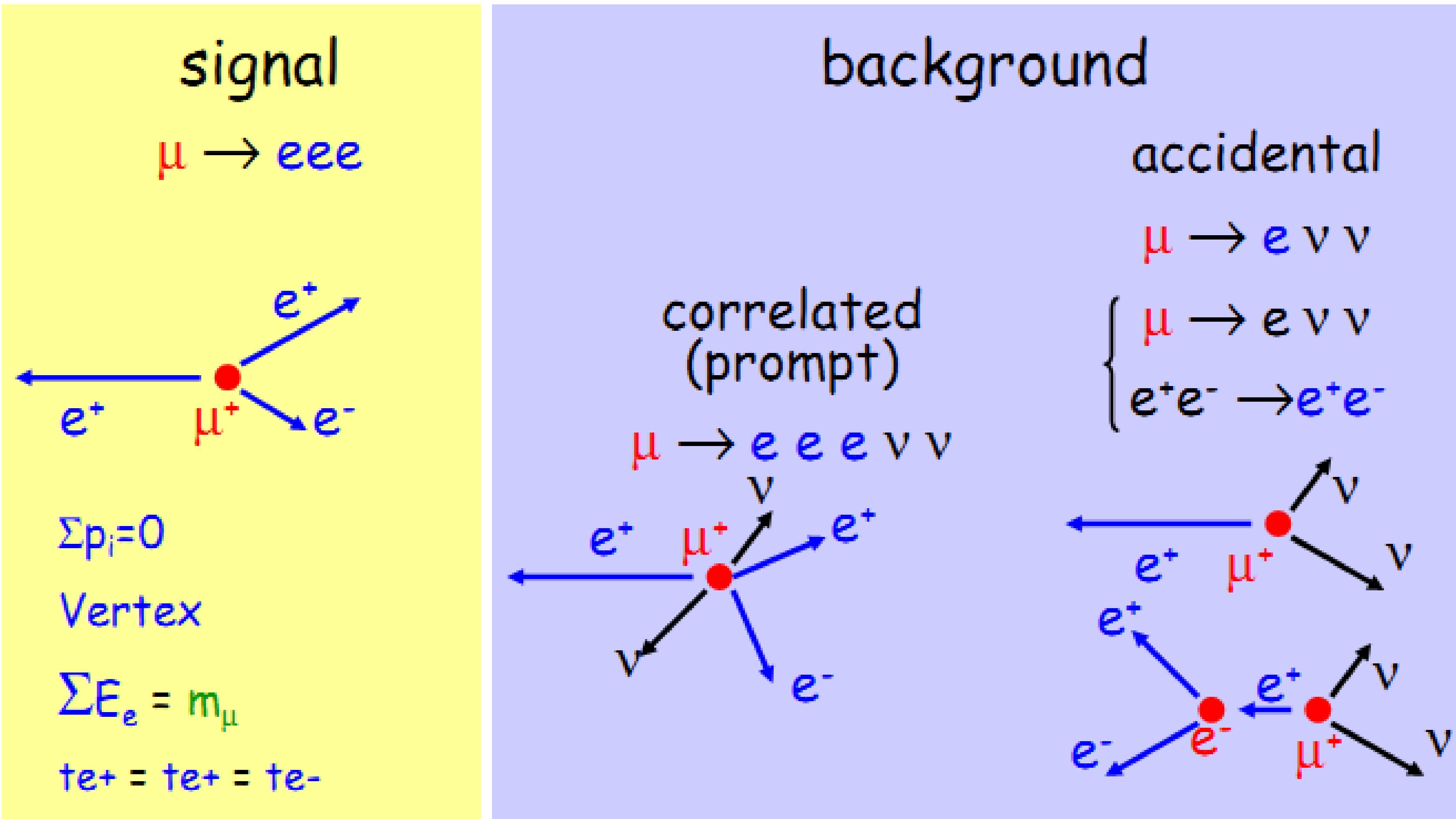
TABLE VIII: Resolution (Gaussian σ) and efficiencies for MEG upgrade

PDF parameters	Present MEG	Upgrade scenario
$\sigma_{E_{e^+}}$ (keV)	380	110
e^+ σ_θ (mrad)	9	5
e^+ σ_ϕ (mrad)	11	5
e^+ σ_Z / σ_Y(core) (mm)	2.0/1.0	1.2/0.7
$\frac{\sigma_{E_\gamma}}{E_\gamma}$ (%) w>2 cm	1.6	1.0
γ position at LXe $\sigma_{(u,v)}$-σ_w (mm)	4	2
γ-e^+ timing (ps)	120	80
Efficiency (%)		
trigger	≈ 99	≈ 99
γ reconstruction	60	60
e^+ reconstruction	40	95
event selection	80	85

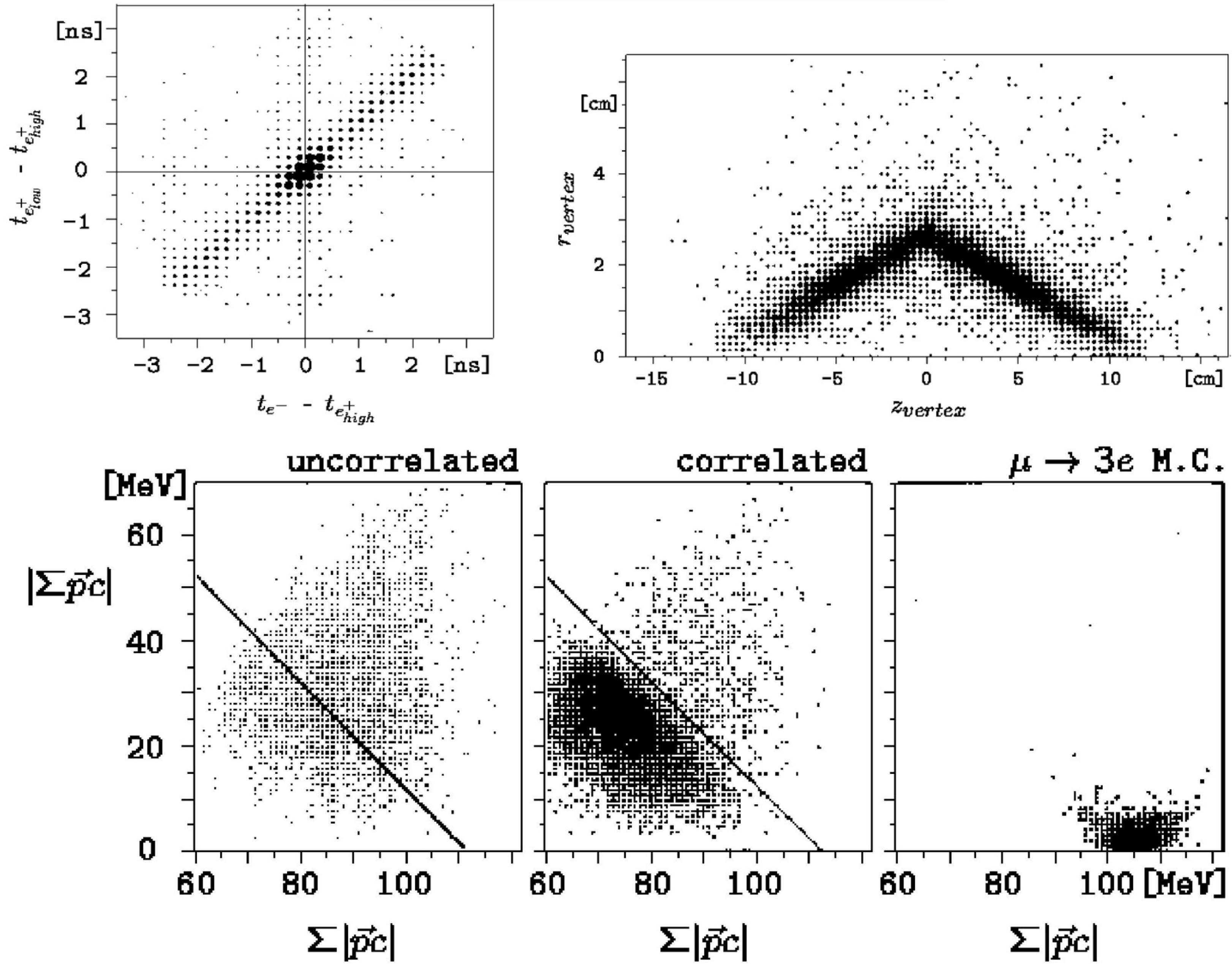
4×10^{-14}
in 4 years



The same μ beam will be used by μ->3e



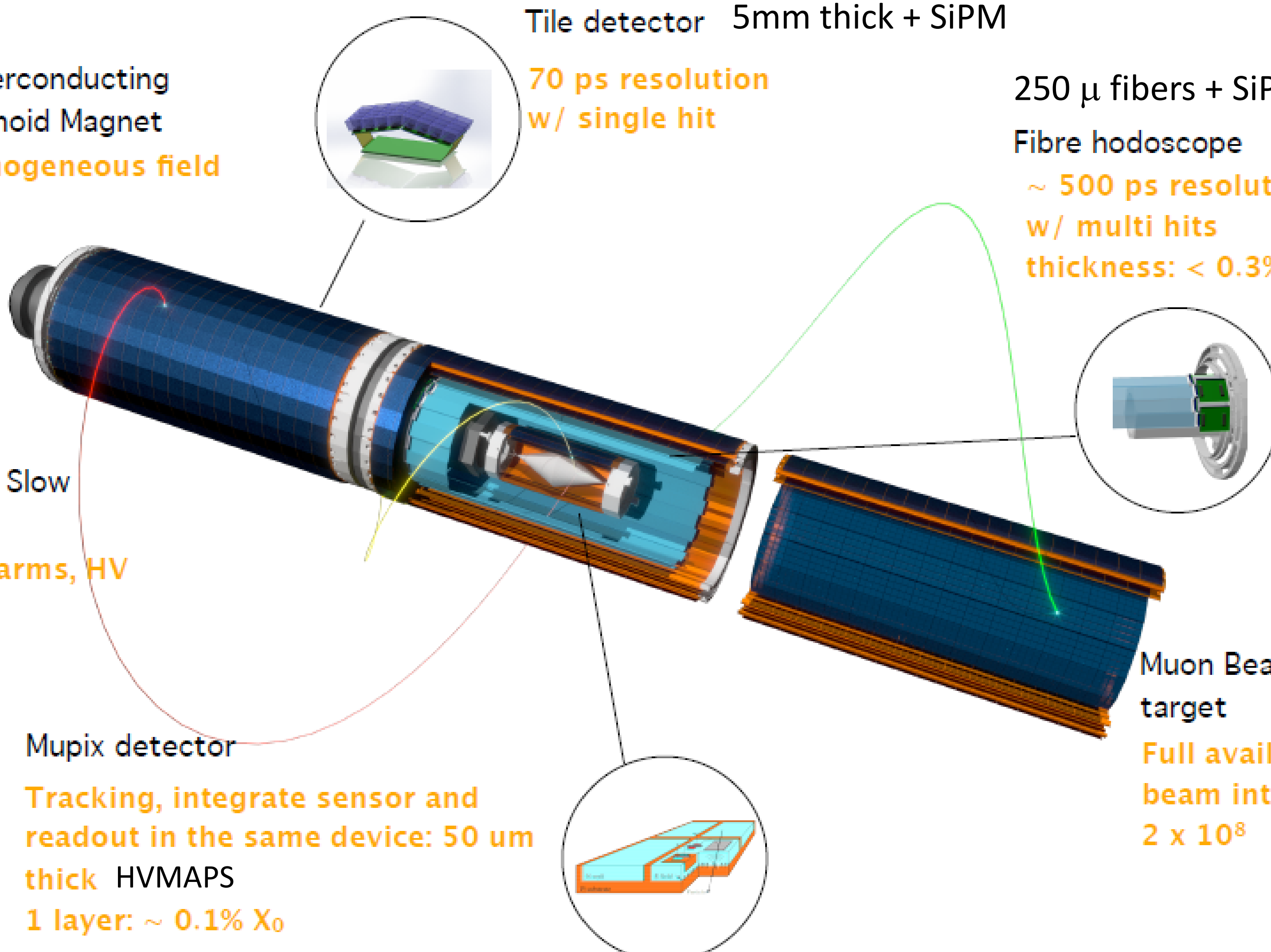
Data from SINDRUM I



2013-5	2015-7	2017	2018-20
Design	Construction	Eng Run	Run

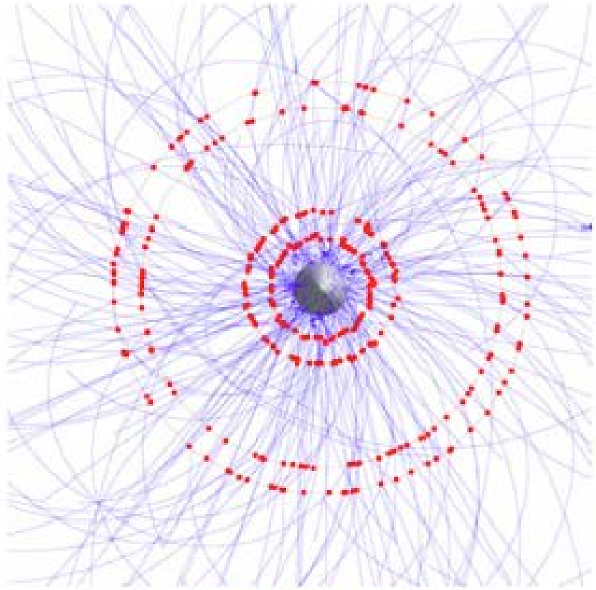
The detector concept

Sensitivity phase I >2020 ~ 10^{-15}
(Final sensitivity phase II [202x] ~ 10^{-16} needs 10^9 muons/s)

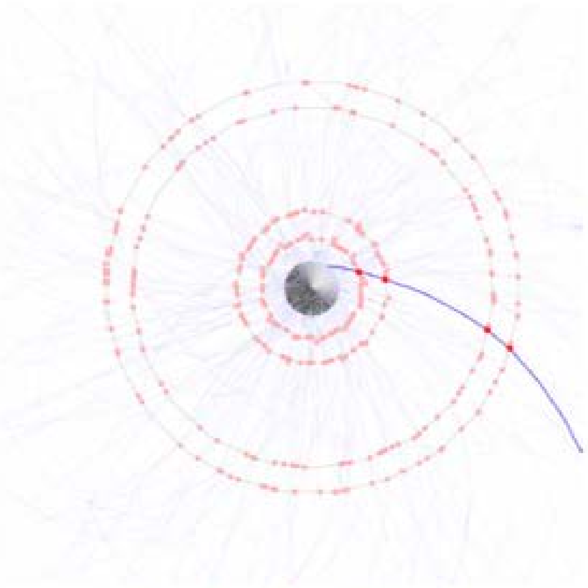


Precise timing is critical to reduce the accidental background

- Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
- Scintillating tiles O(100 ps), full detection efficiency (>99%)

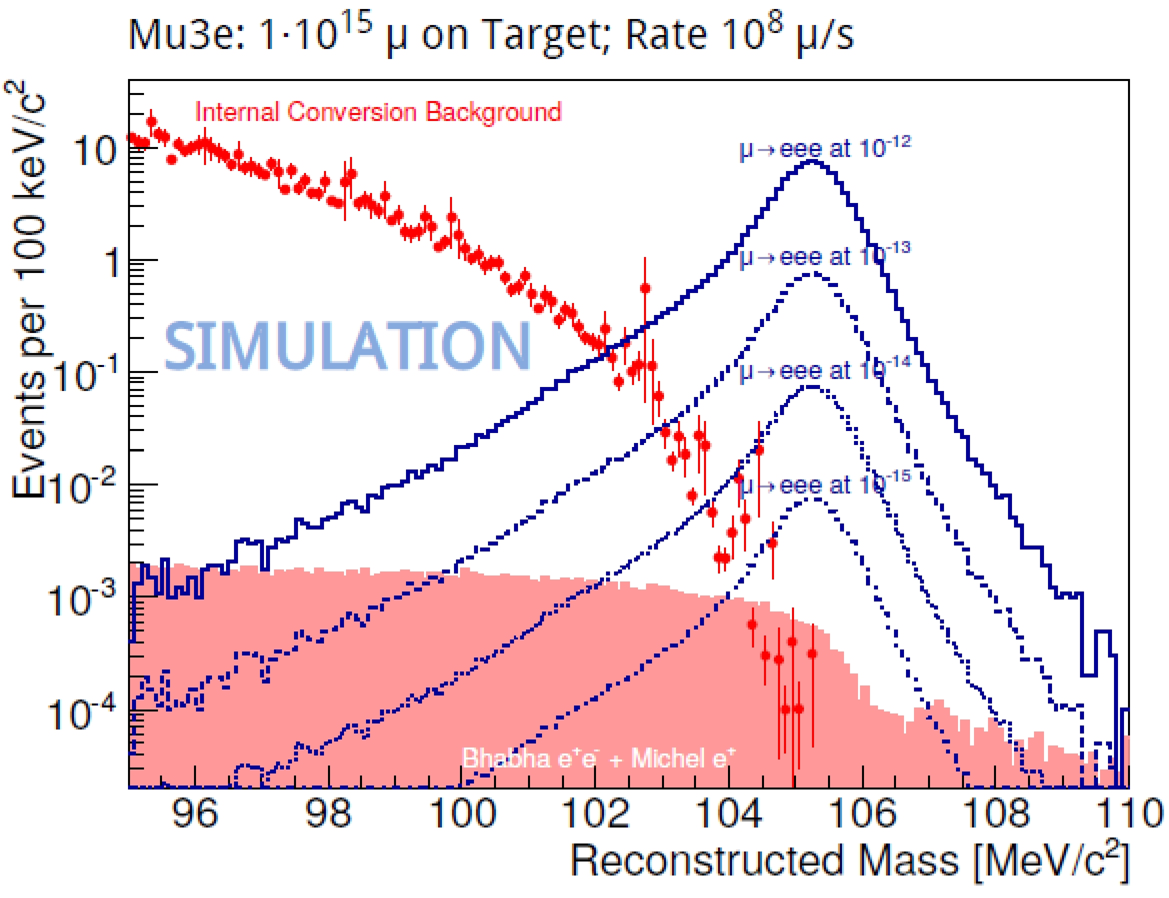


Pixels: O(50 ns)



Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

Reconstruction simulation



μ→e conversion

$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$

Signature: single monoenergetic e^-

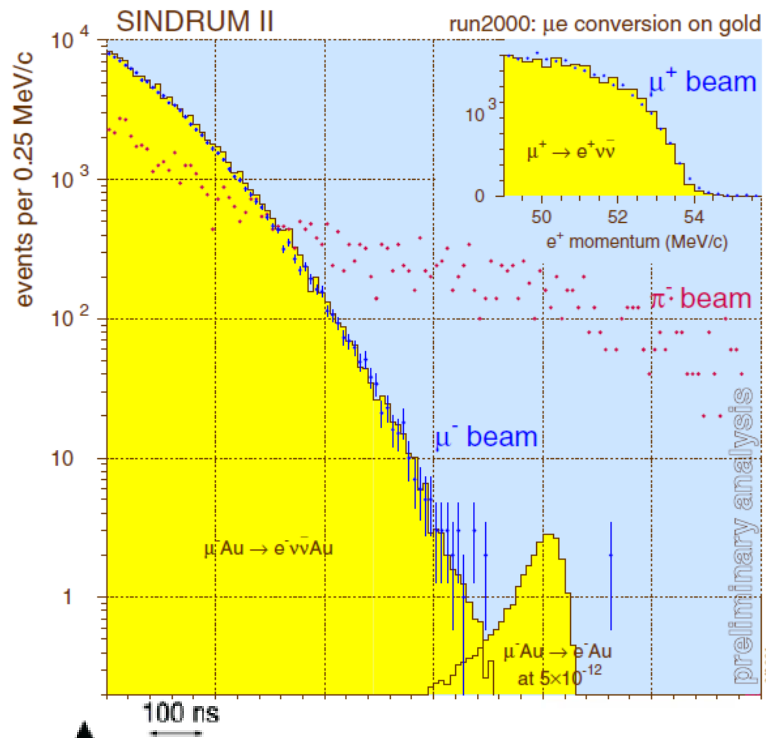
$E = m_\mu - B_\mu$: 105 MeV in Al

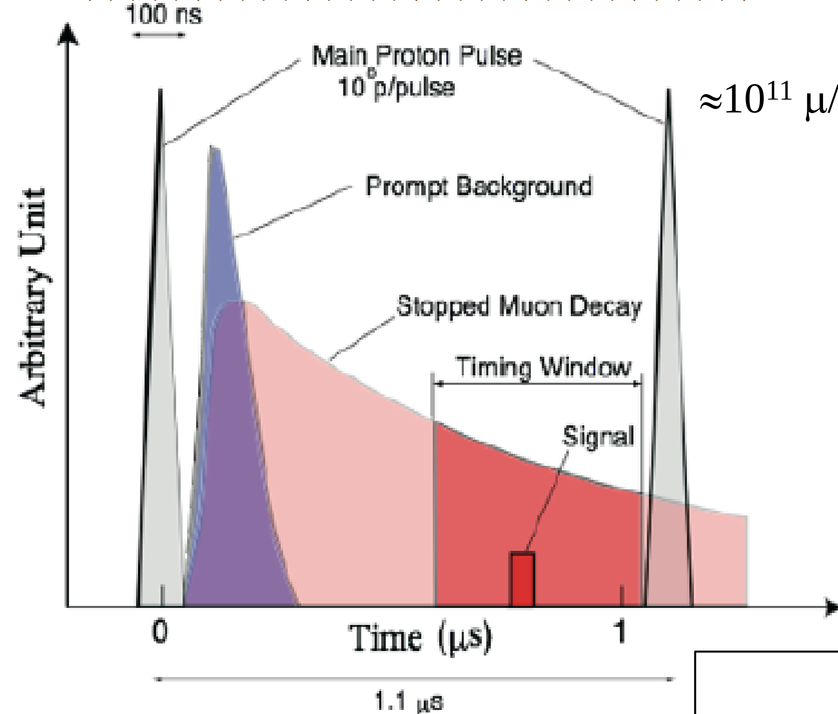
Lifetime ≈1 μs

No accidental backgrounds!

- Physics backgrounds
  - Muon Decay in Orbit (DIO)
    - $E_e > 102.5$ MeV (BR:10^{-14})
    - $E_e > 103.5$ MeV (BR:10^{-16})
  - Beam Pion Capture
  - $\pi^- + (A,Z) \rightarrow (A,Z\text{-}1)^* \rightarrow \gamma + (A,Z\text{-}1)$
    $\gamma \rightarrow e^+ e^-$

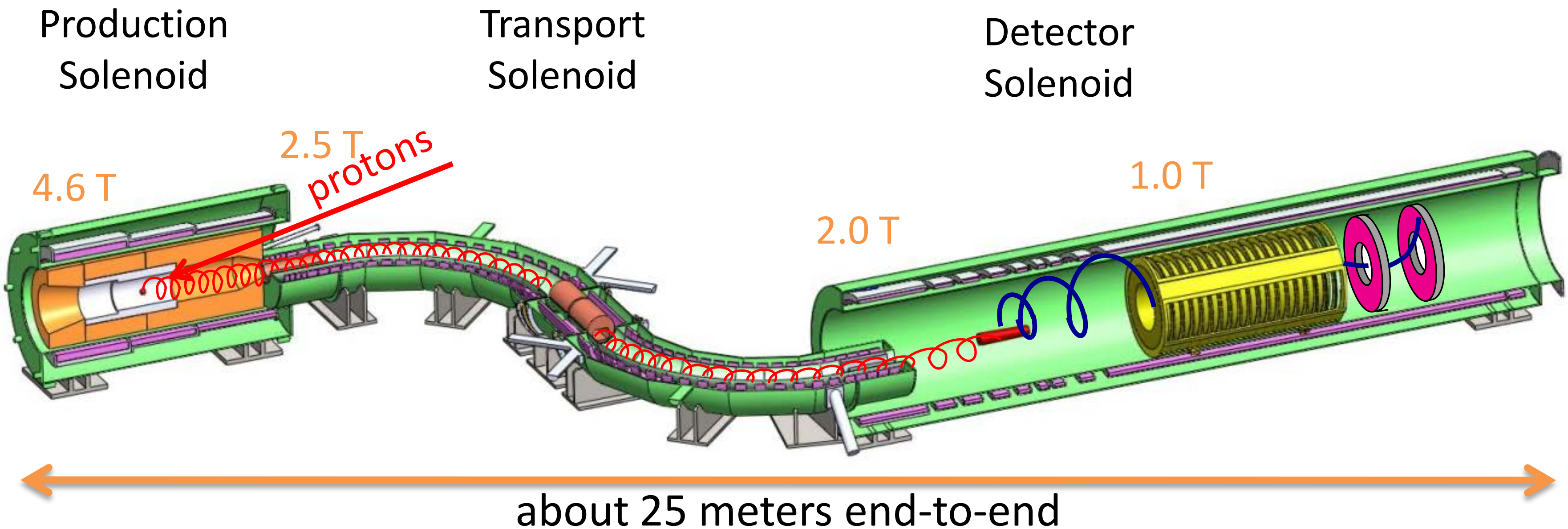
$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$





≈10^{11} μ/s

Mu2e beam line elements



Production Solenoid:

8 GeV protons interact with a tungsten target to produce μ- (from π- decay)

Transport Solenoid:

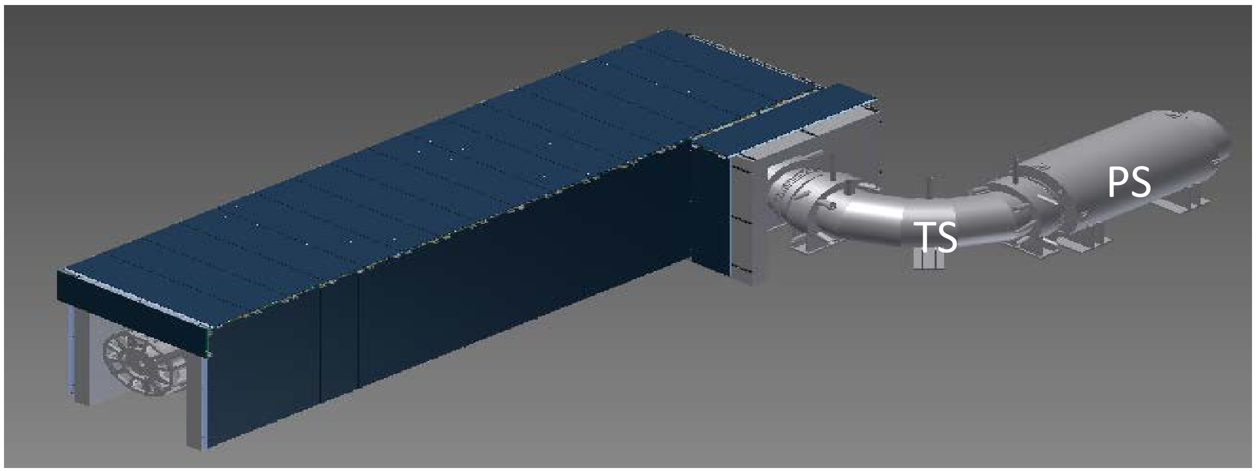
Captures π- and subsequent μ-; momentum- and sign-selects beam

Detector Solenoid:

Upstream – Al. stopping target, Downstream – tracker, calorimeter

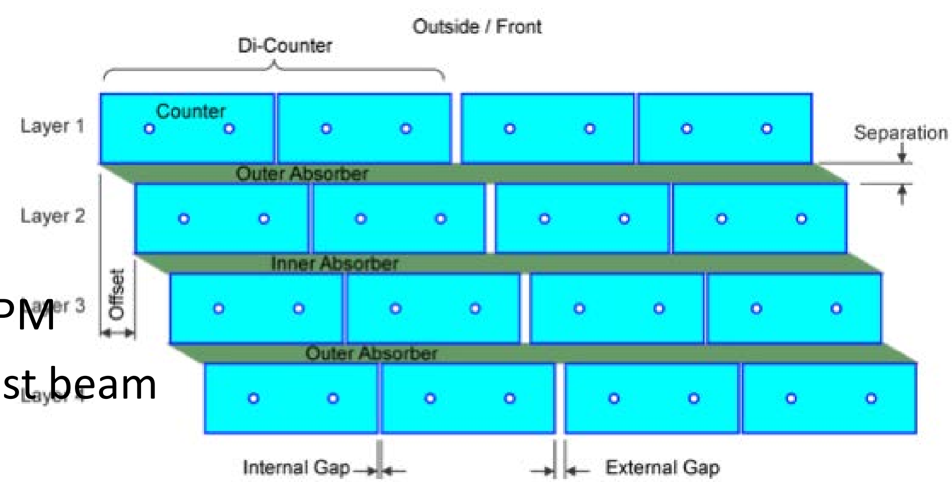
(not shown – cosmic ray veto system, extinction monitor, target monitor)

Mu2e Cosmic-Ray Veto

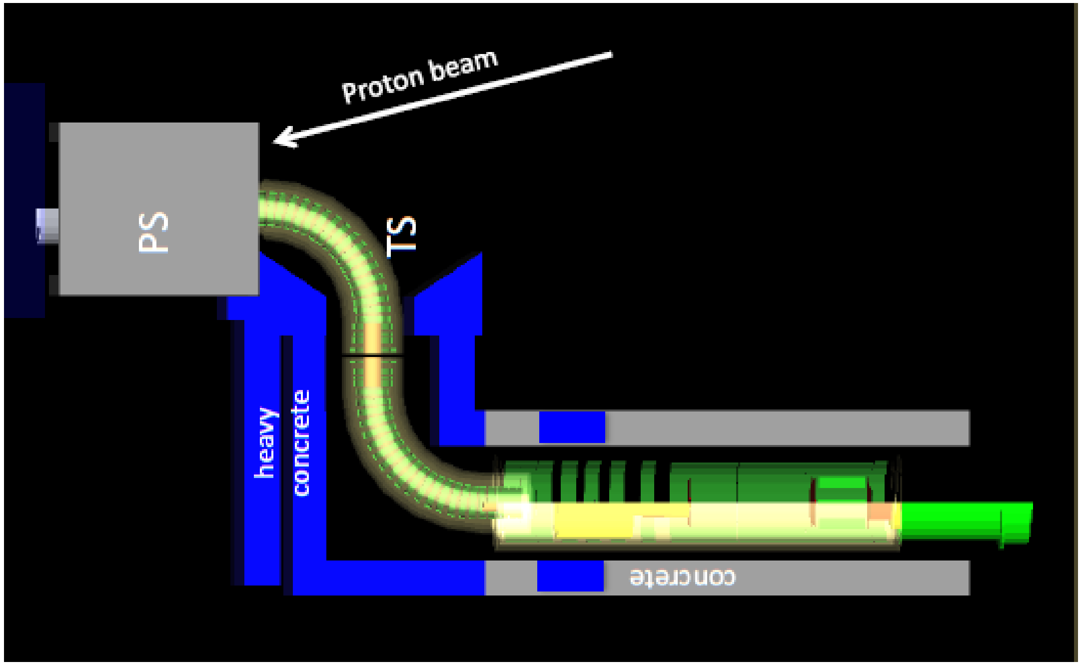


Without the veto system, ~1 cosmic-ray induced background event per day

- 4 overlapping layers of scintillator
  - Each bar is 5 x 2 x ~450 cm^3
  - 2 WLS fibers / bar
  - Read-out both ends of each fiber with SiPM
  - Have achieved e > 99.4% (per layer) in test beam

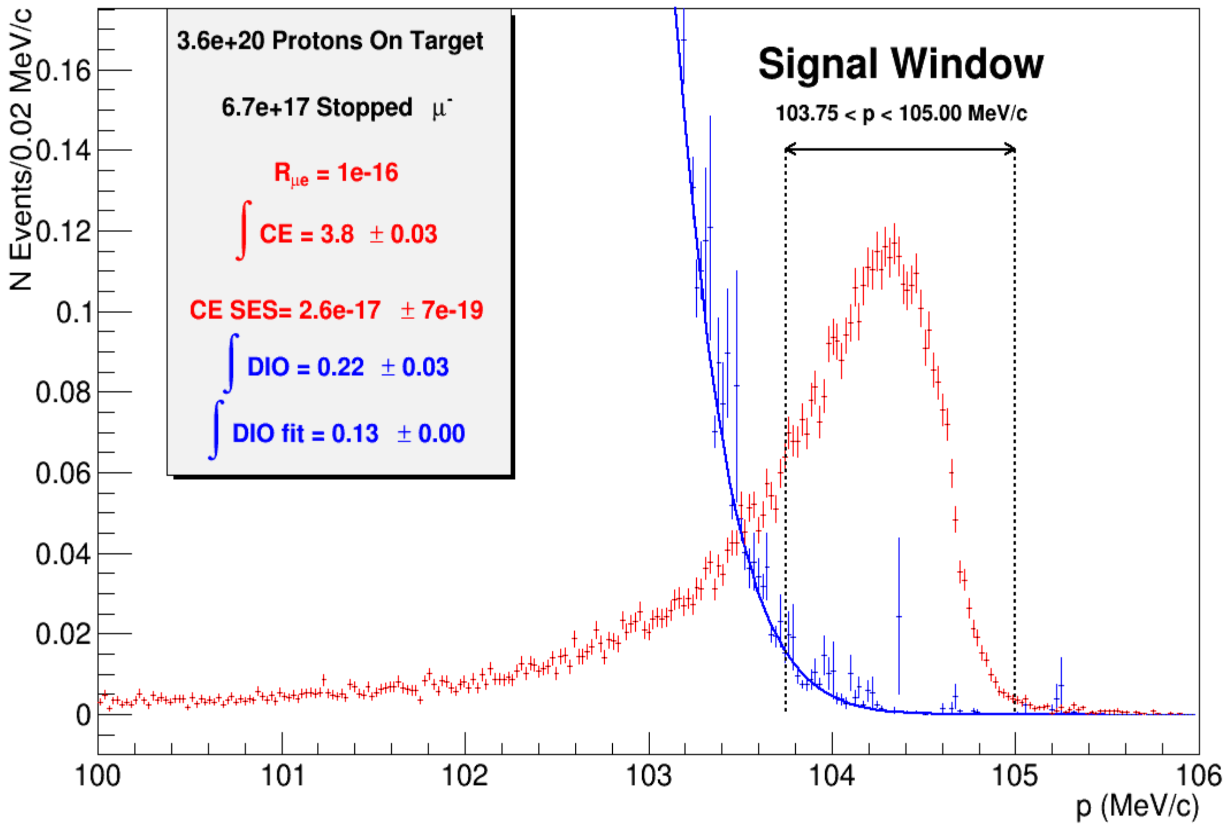


Plus a neutrons shielding of the detectors' area



…and joint effort Mu2e and Comet to study the proton emission due to muon capture in Al which may significantly contribute to the detectors hit rate: **AlCap experiment at PSI**

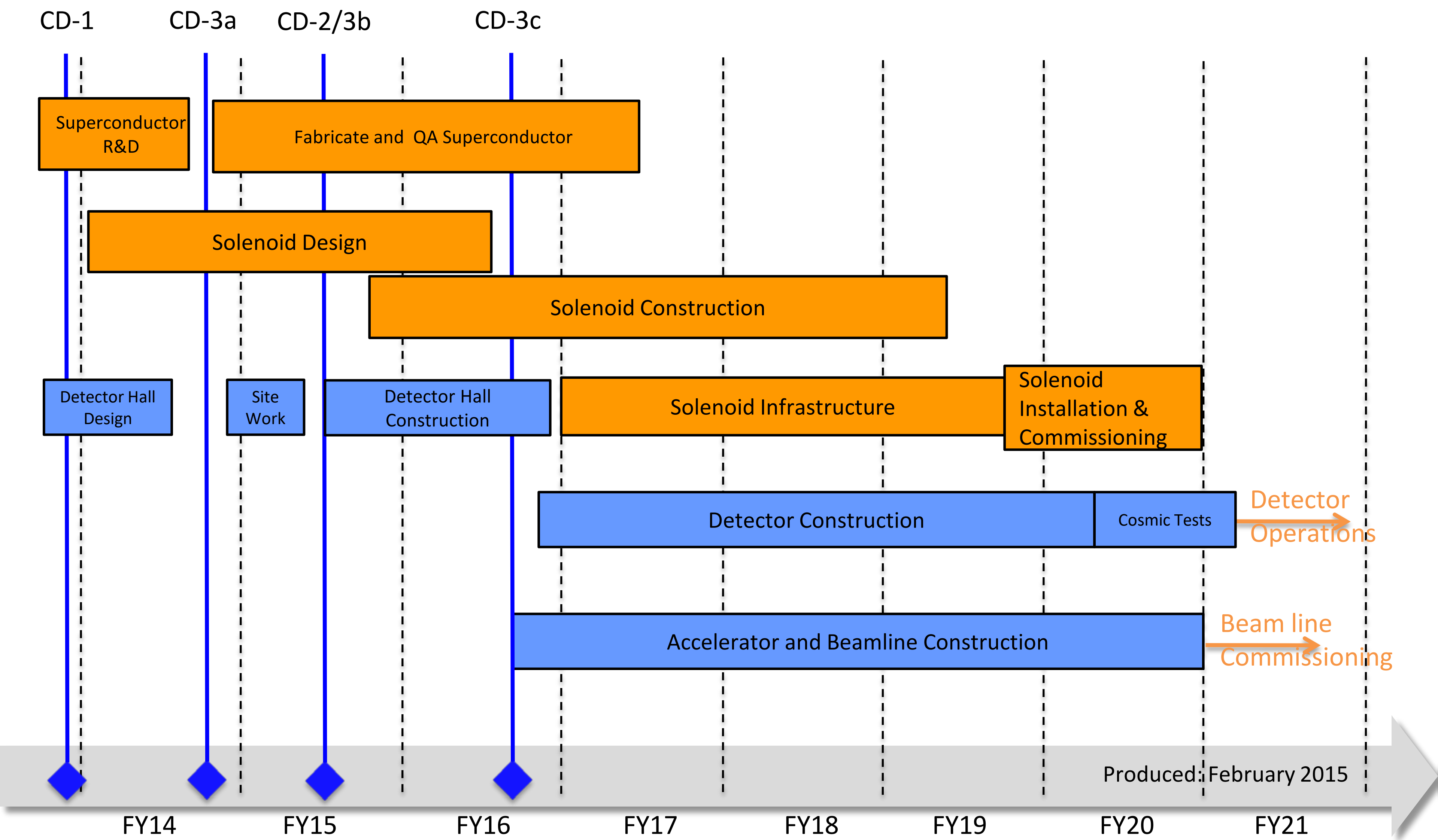
Detailed simulation of the electron momentum at the signal region



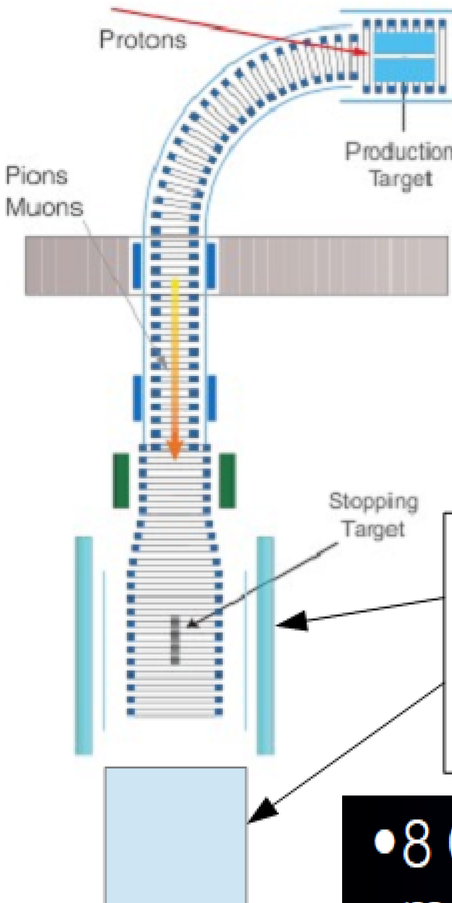
- Single-event-sensitivity = 2.6 x 10^{-17}

  (SES goal 2.4 x 10^{-17})
- Total background < 0.5 events

Mu2e Schedule



COMET Phase I



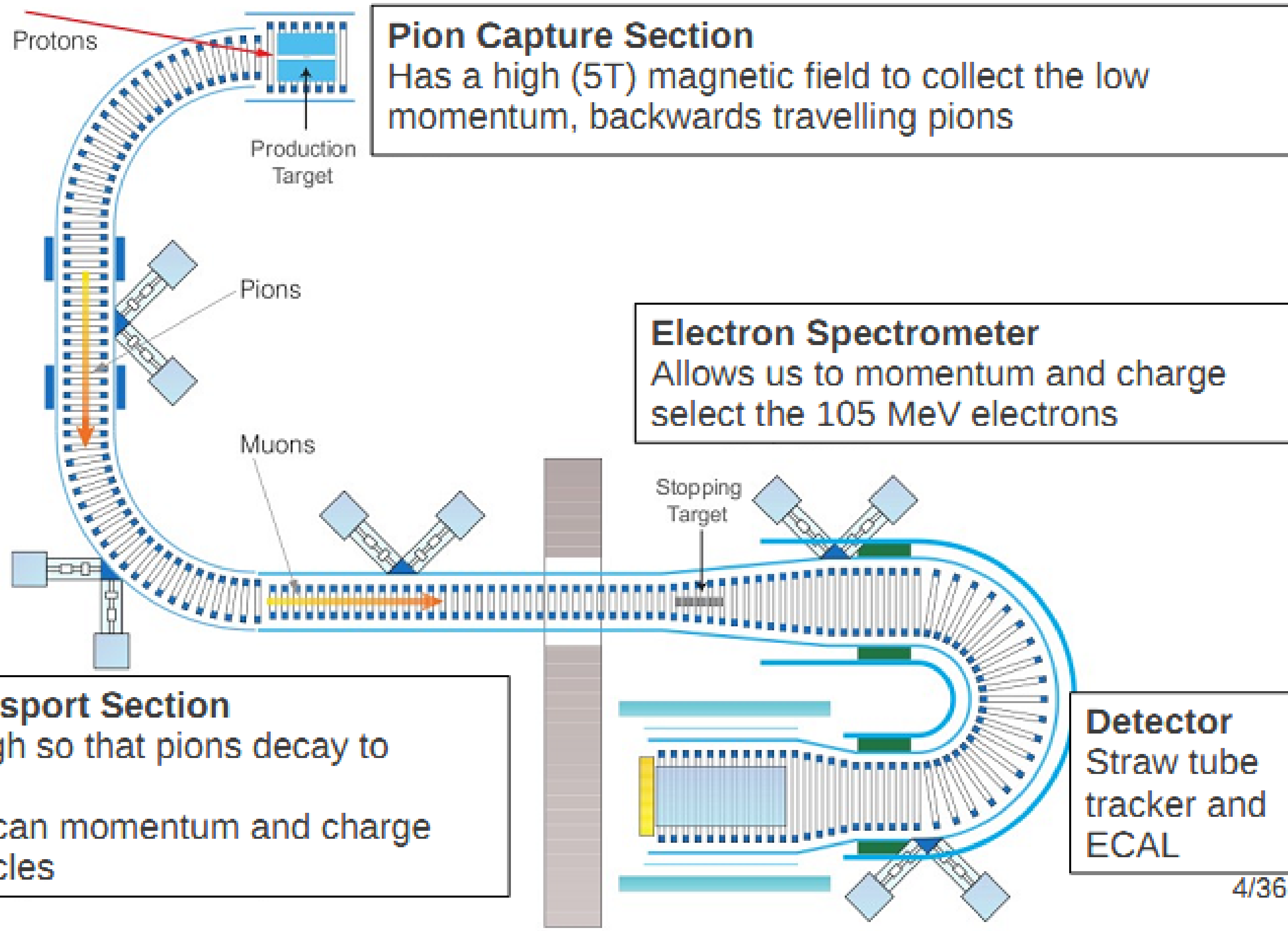
Phase-I Aims
Search for μ-e conversion process with a S.E.S of 3×10^{-15}
Study the backgrounds for Phase-II

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

- 8 GeV commissioning and proton extinction measurements is foreseen in 2017

COMET Phase II

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



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

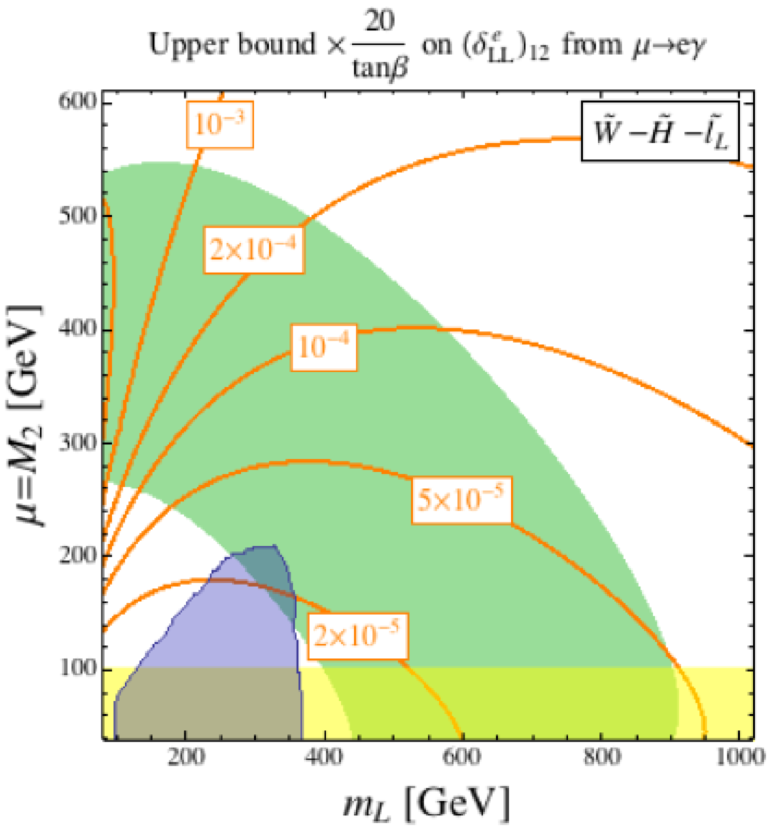
Electron Spectrometer
Allows us to momentum and charge select the 105 MeV electrons

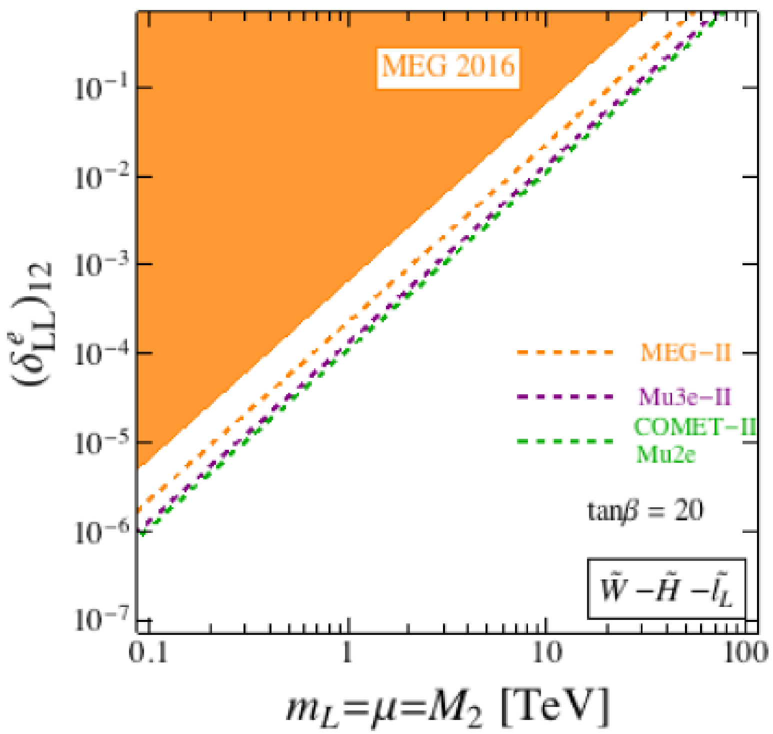
Muon Transport Section
Long enough so that pions decay to muons
Curved so can momentum and charge select particles

Detector
Straw tube tracker and ECAL

Comparison with SUSY searches at LHC

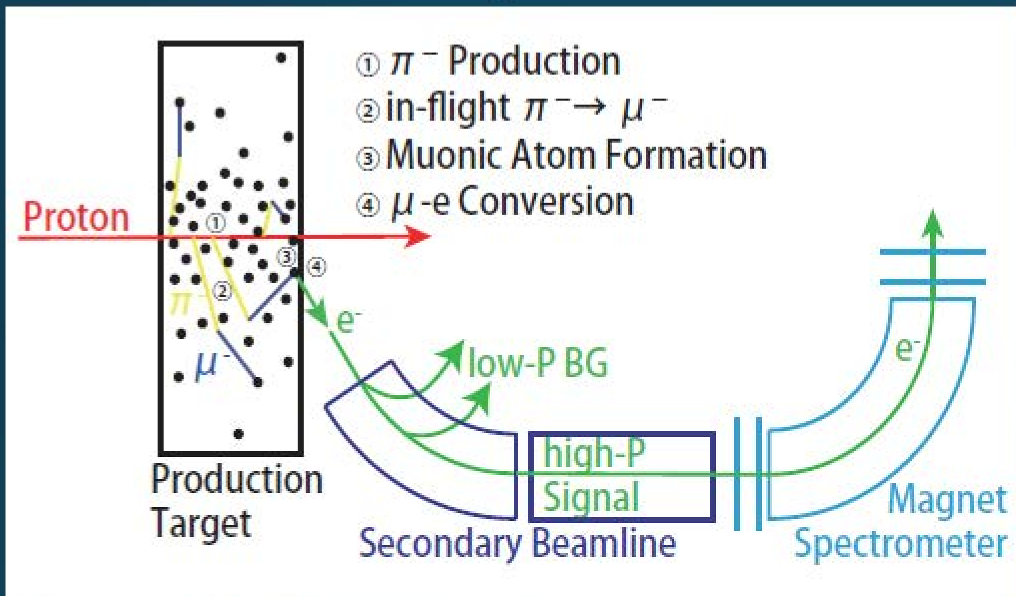
$$(\delta_{\rm LL})_{ij} = \frac{(\Delta_{\rm LL})_{ij}}{\sqrt{(\tilde{m}_L^2)_{ii}(\tilde{m}_L^2)_{jj}}},$$





Calibbi, Signorelli, NC 2017

DeeMe experiment



$\mu N \to eN$

signal electron

- single
- mono energetic
- delayed

The signal electron is identified by measuring their momentum

Start with Carbon target

- Lifetime of muonic atom ~ 2 μs
- Energy of electron from μ-e conversion = 105 MeV
- Single event sensitivity (1 year = $2{\times}10^7$ sec)
  - $1{\times}10^{-13}$
  - $2.5{\times}10^{-14}$ (4 years)

Upgrade to SiC

- $2{\times}10^{-14}$
- $5{\times}10^{-15}$ (4 years)

Summary

CLFV: excellent probe for search for physics Beyond the Standard Model

Complementarity among the different channels enabling to check the different New Physics models

Complementarity of intensity (and precision) frontier wrt to the high energy frontier

We would need some luck, soon or later…

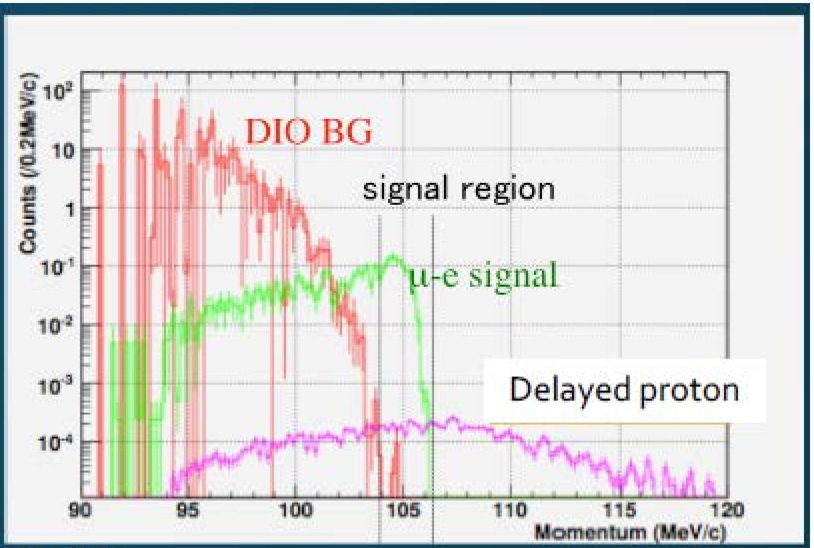
Background

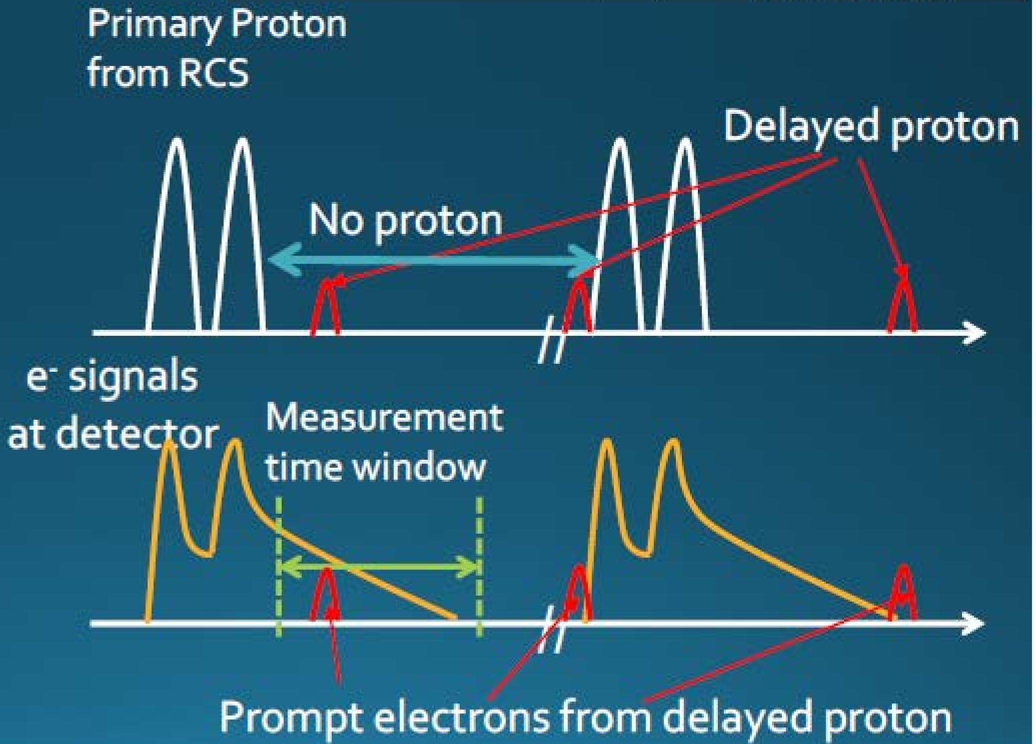
- Decay In Orbit 0.015
  in the signal region

- Delayed proton <0.027 (zero in principle)
  Synchrotron is empty at the delayed timing by fast extraction

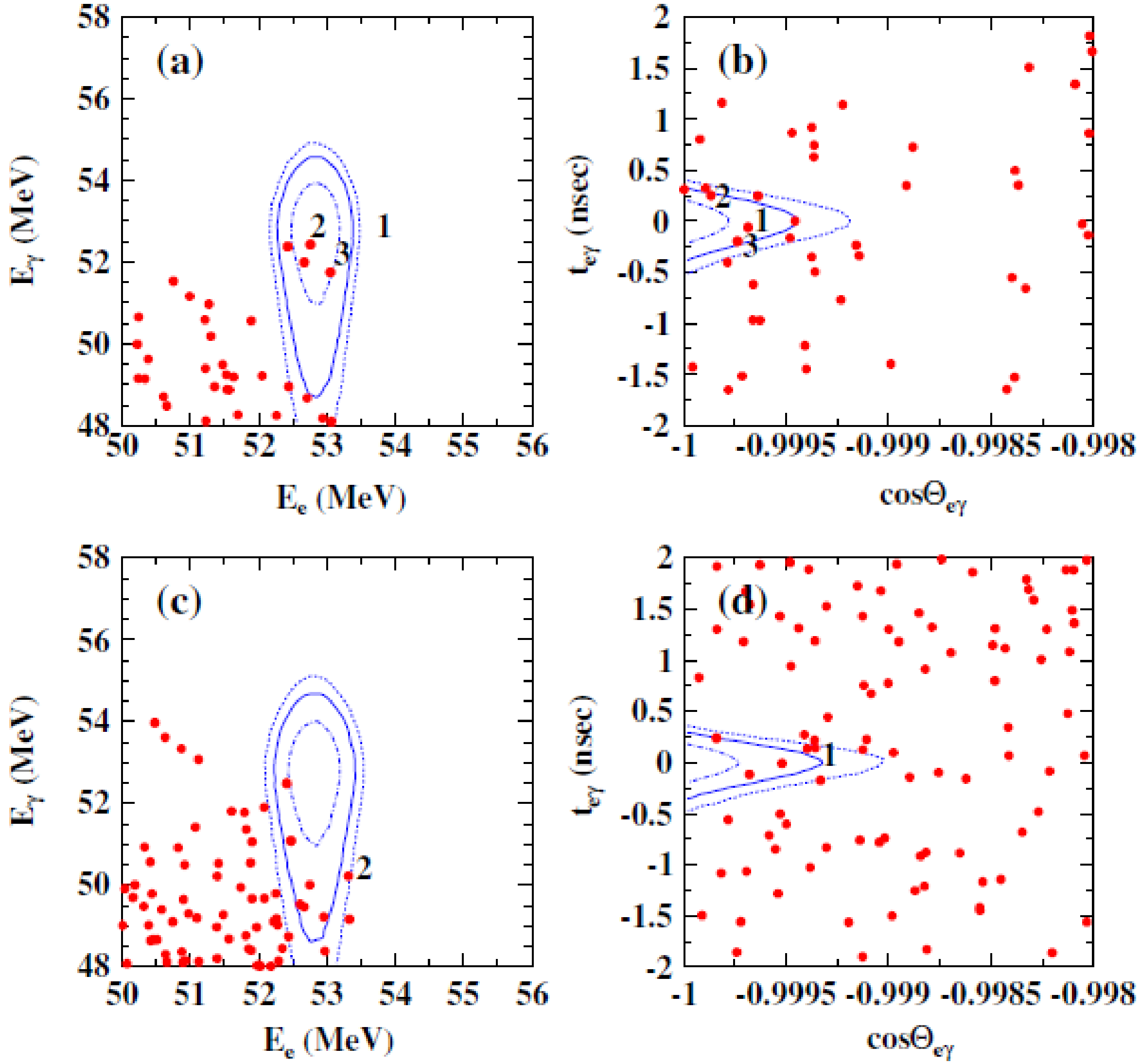
- Cosmic-ray induced
  e: <0.018, μ: <0.001
  duty factor = 1/20000
  Horizontal tracking direction

- Anti-Proton zero
  beam energy(=3 GeV)
  < $\bar{p}$ production threshold





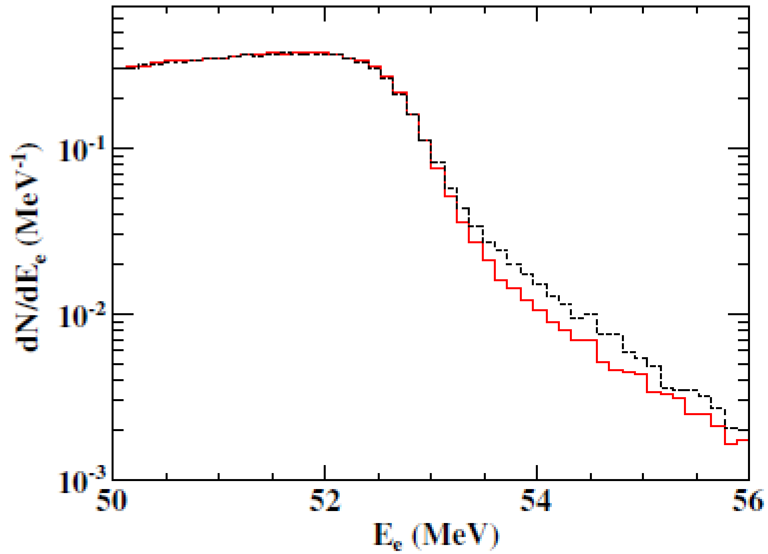
Aiming to start DeeMe experiment from 2017!



2011 paper

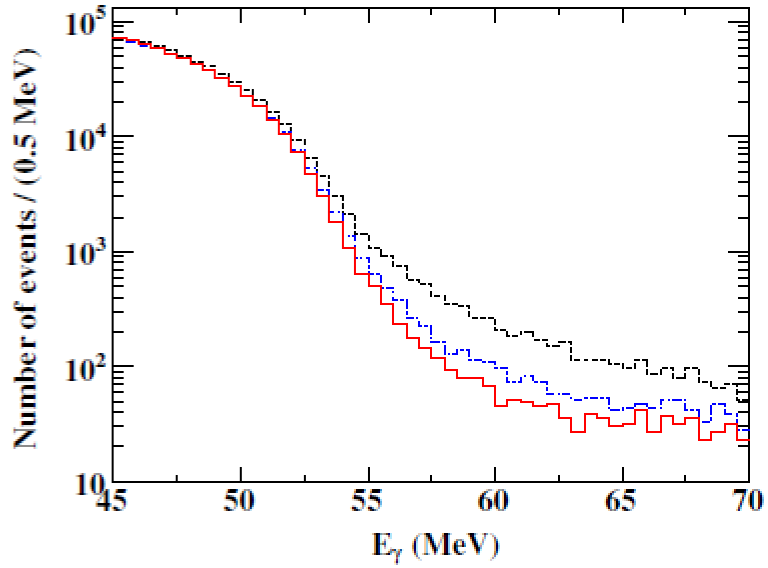
Data set	$\mathcal{B}_{\mathrm{fit}}$	LL	UL
2009	3.2×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-13}	$\cdots$	1.7×10^{-12}
2009 and 2010	-1.5×10^{-13}	$\cdots$	2.4×10^{-12}

New Kalman filter



2013

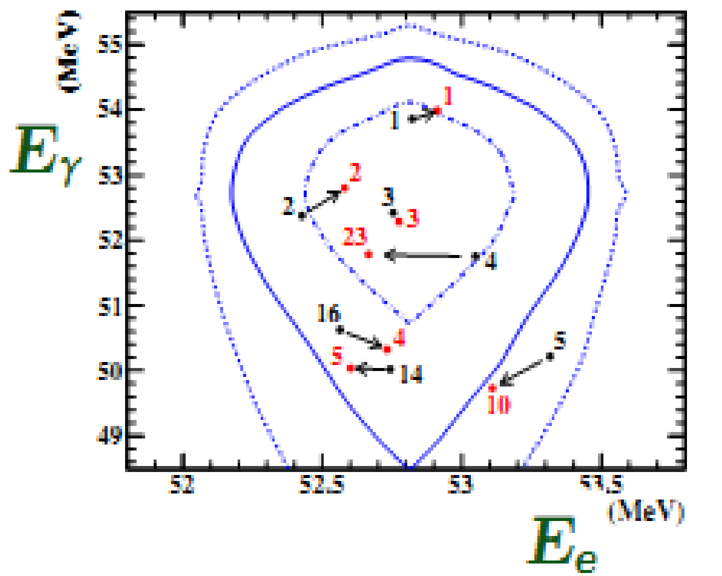
Better pile-up rejection

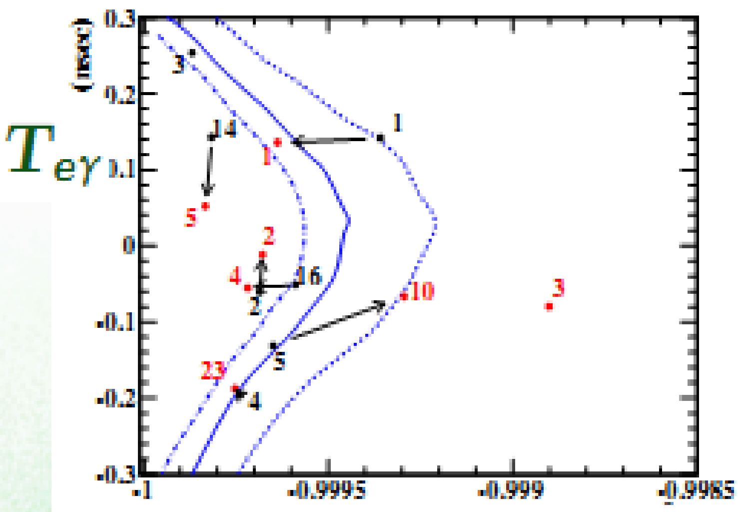


Comparison with previous analysis

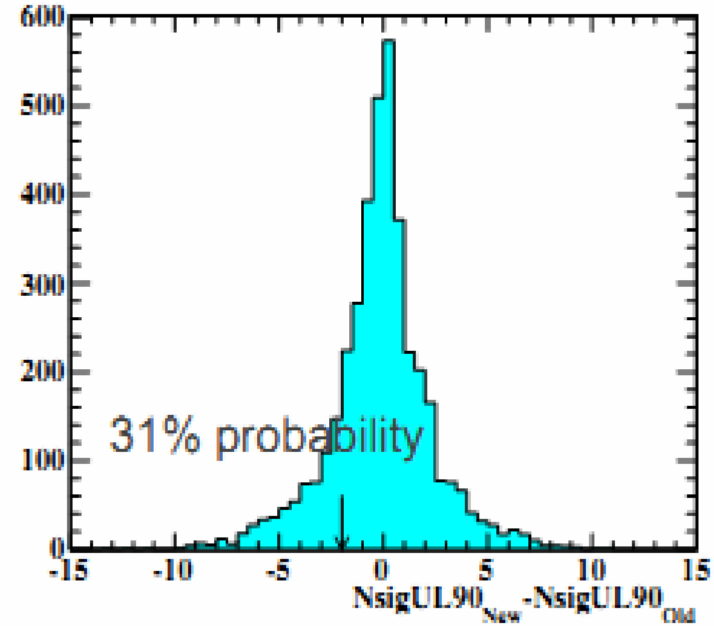
- Previous analysis
- New analysis

Numbers : rank in each dataset

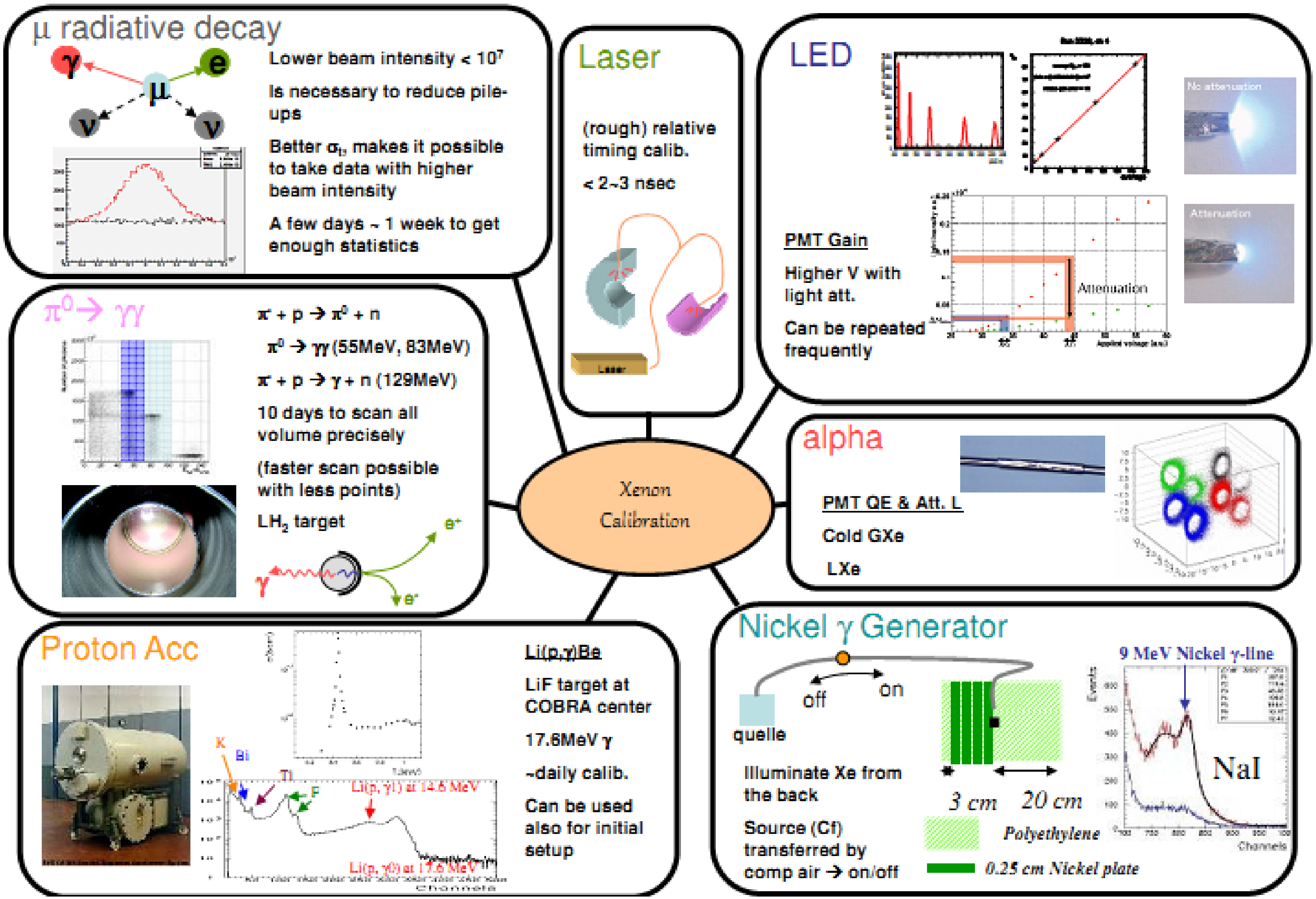




Change of UL by modifications of reconstruction algorithms. (MC)

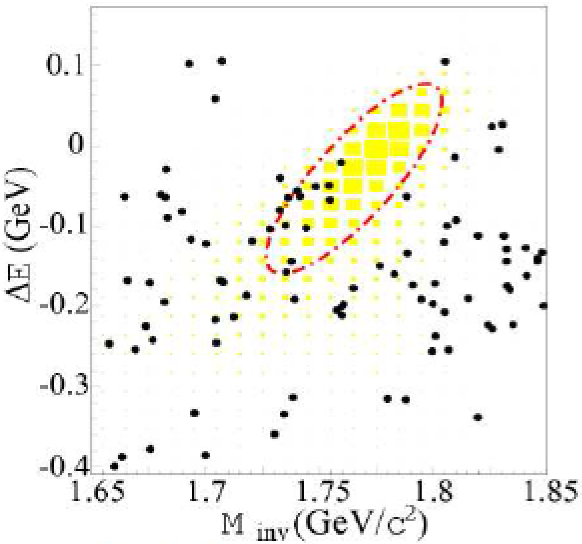


- High ranked events are stable
- Differences of observables by modifications of reconstruction algorithms are smaller than resolutions.


Xenon Calibration
μ radiative decay
Lower beam intensity < 10^7
Is necessary to reduce pile-ups
Better σ_t, makes it possible to take data with higher beam intensity
A few days ~ 1 week to get enough statistics
Laser
(rough) relative timing calib.
< 2~3 nsec
Laser
LED
PMT Gain
Higher V with light att.
Can be repeated frequently
Attenuation
No attenuation
π0 → γγ
π- + p → π0 + n
π0 → γγ (55MeV, 83MeV)
π- + p → γ + n (129MeV)
10 days to scan all volume precisely
(faster scan possible with less points)
LH2 target
e+
e-
γ
alpha
PMT QE & Att. L
Cold GXe
LXe
Proton Acc
Li(p,γ)Be
LiF target at COBRA center
17.6MeV γ
~daily calib.
Can be used also for initial setup
K
Bi
Tl
F
Li(p, γ1) at 14.6 MeV
Li(p, γ0) at 17.6 MeV
Channels
Nickel γ Generator
quelle
off
on
Illuminate Xe from the back
Source (Cf) transferred by comp air → on/off
3 cm
20 cm
Polyethylene
0.25 cm Nickel plate
9 MeV Nickel γ-line
NaI
Events
Channels

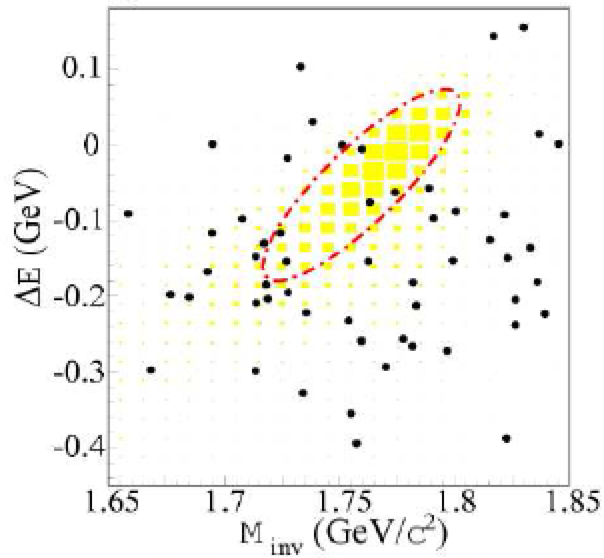
Belle

$\tau \rightarrow \mu\gamma$



– Br<4.5x10^{-8} at 90%C.L.

$\tau \rightarrow e\gamma$



– Br<1.2x10^{-7} at 90%C.L.

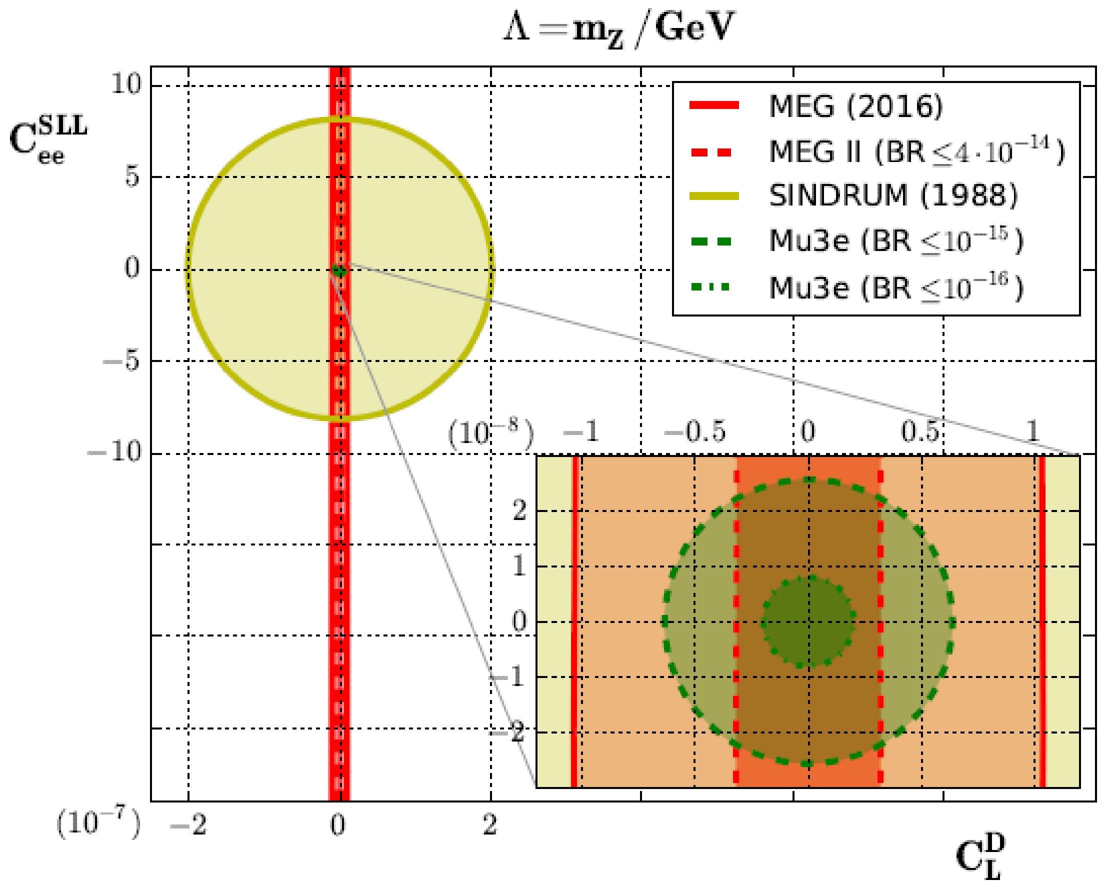
Efficiencies: 5.1% for $\mu^-\gamma$ and 3.0% for $e^-\gamma$

K. Hayasaka et al., Phys. Lett. B666 (2008) 16

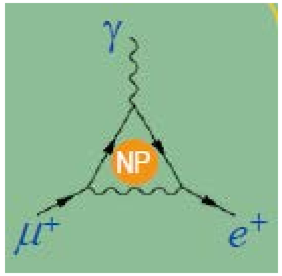
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

$$O_L^D = e\, m_\mu \left(\bar{e}\sigma^{\mu\nu} P_L \mu\right) F_{\mu\nu}$$

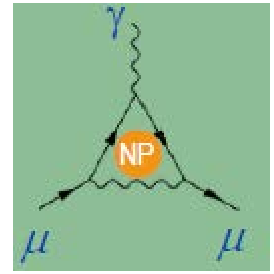
$$O_{ff}^{S\,LL} = \left(\bar{e} P_L \mu\right)\left(\bar{f} P_L f\right)$$



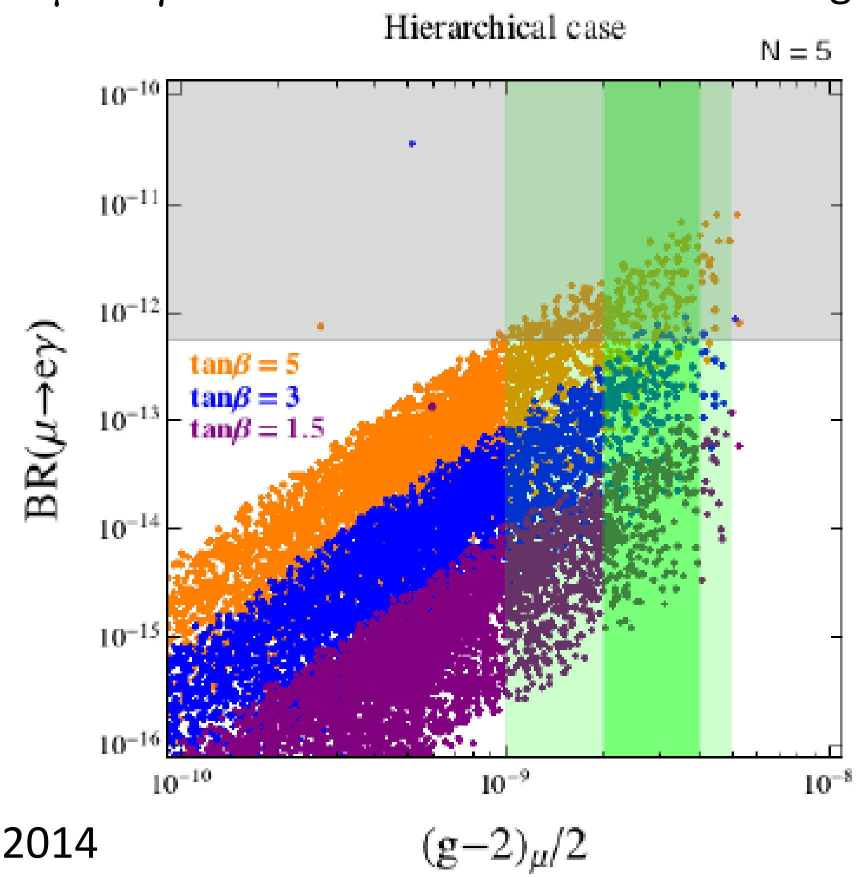
Crivellin et al., 2016



μ->e γ



g-2



Calibbi et al., 2014

The sensitivity is limited by the accidental background

$$n_{sig} \propto R_\mu \ , n_{phys.b.} \propto R_\mu \ , \ n_{acc.b.} \propto R_\mu^2$$

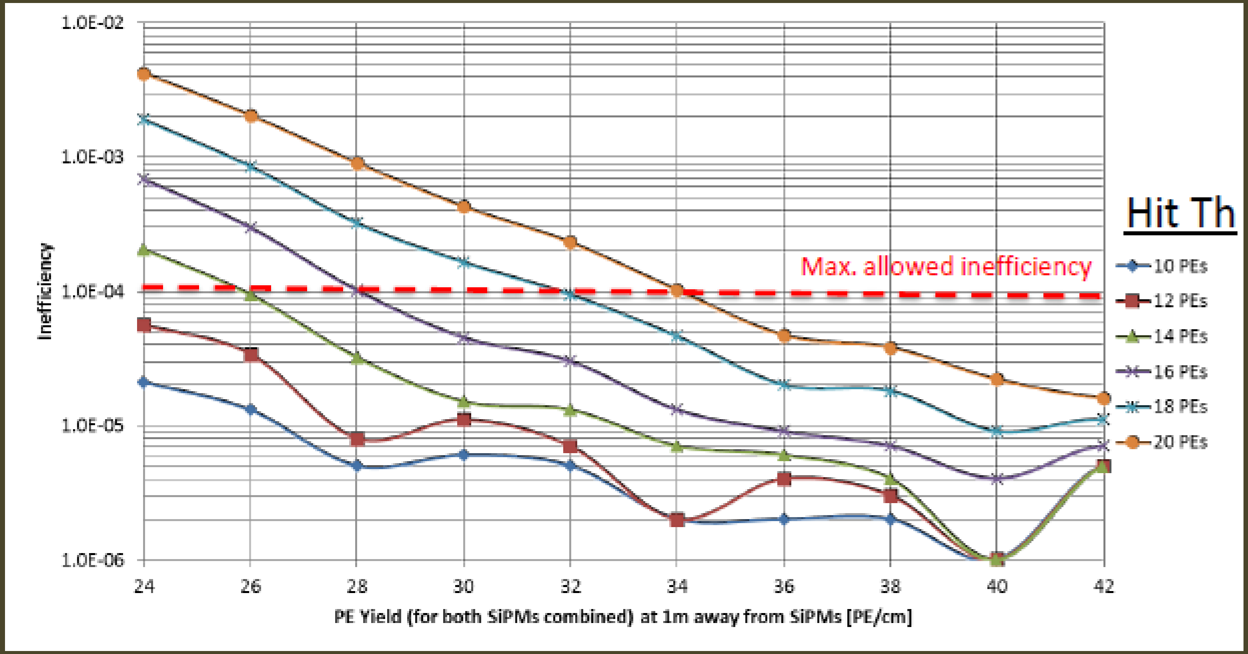
The n. of acc. backg events ($n_{acc.b.}$) depends quadratically on the muon rateand on how well we measure the experimental quantities: e-γ relative timing and angle, positron and photon energy

Effective BRback ($n_{back}/R\mu$ T)

$$BR_{acc} \propto R_\mu \times \Delta t_{e\gamma} \times \Delta\theta_{e\gamma}^2 \times \Delta E_e \times \Delta E_\gamma^2$$

Integral on the detector resolutions of the Michel and radiative decay spectra

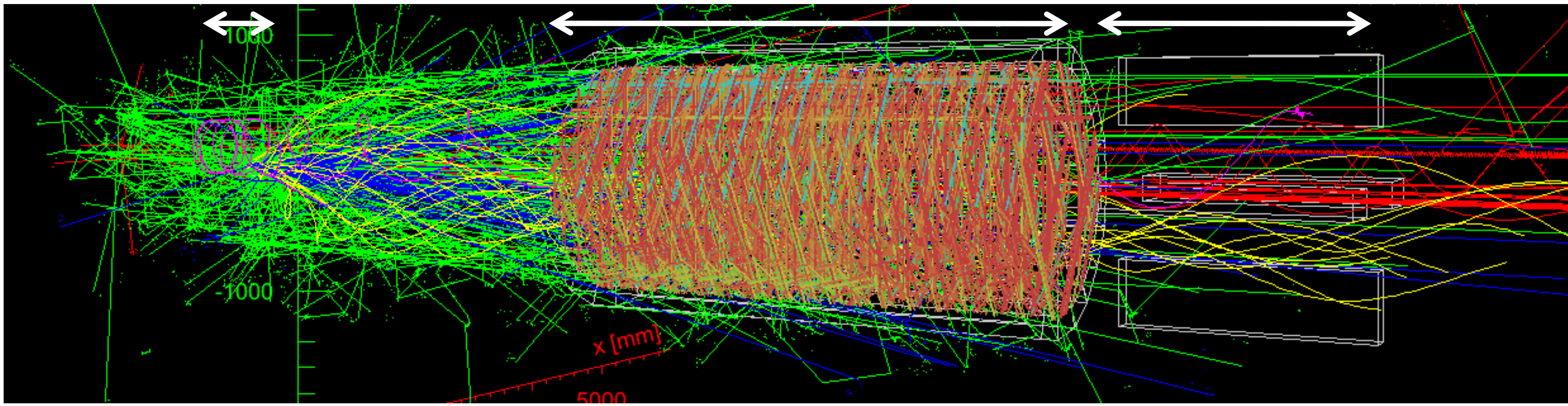
Cosmic Ray Veto

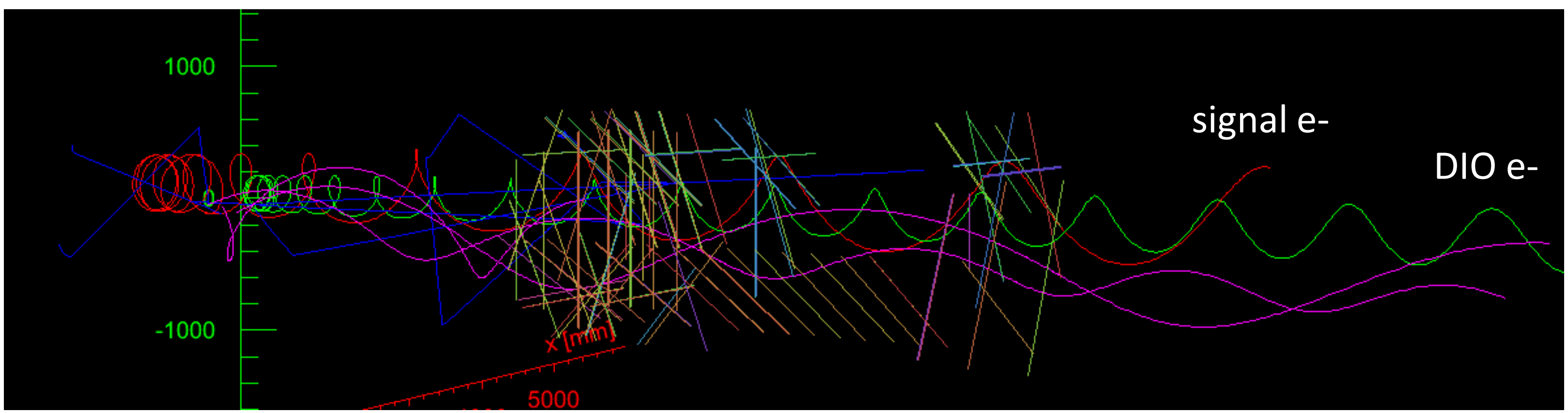


- Use detailed simulation and reconstruction to convince ourselves we can reasonably achieve the required veto efficiency

Mu2e Pattern Recognition

Stopping Target Straw Tracker Crystal Calorimeter

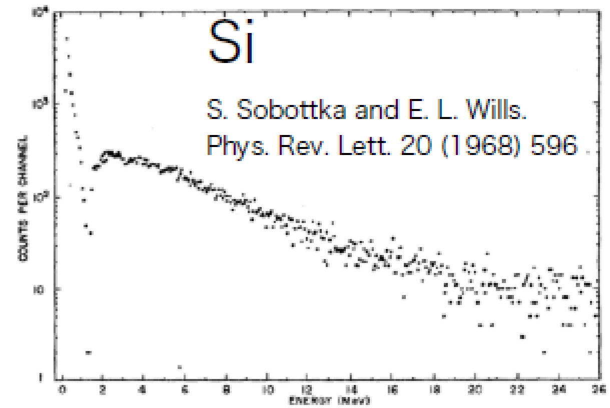




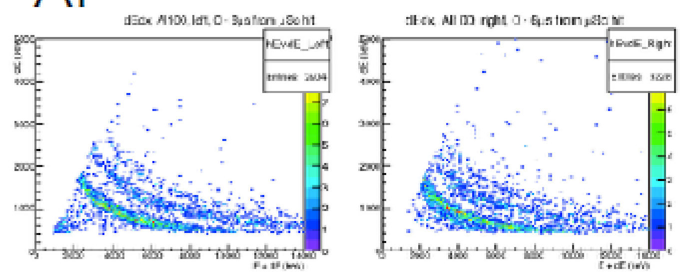
(particles with hits within +/-40 ns of signal electron t_{mean})

Backgrond Assessment

- Proton emission from muon captures
- No data available for Al
  - Si data only (near Al)
    - 15% proton emission / muon capture on ^{28}Si
    - 50MeV/c < p < 200MeV/c
- Significant contribution to the detector hit rate
- AlCap experiment at PSI
  - **Joint effort between COMET/ Mu2e**



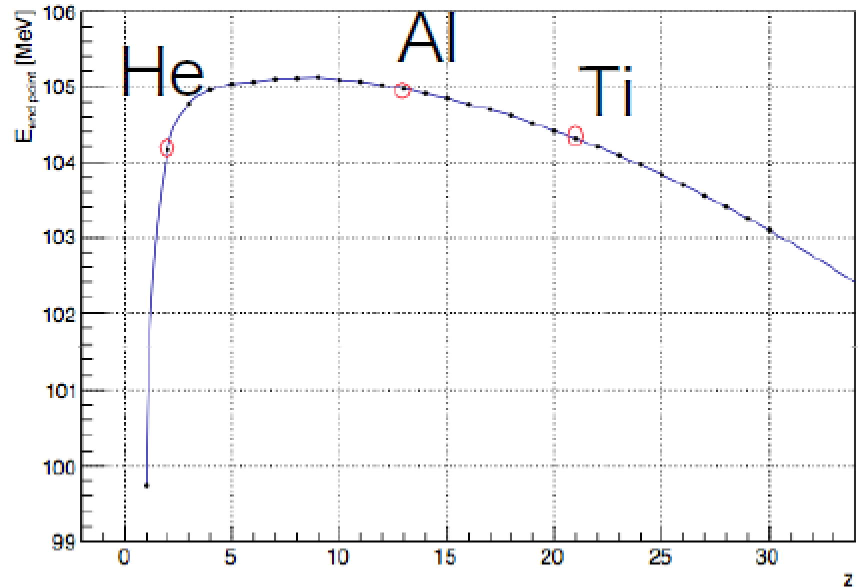
Al



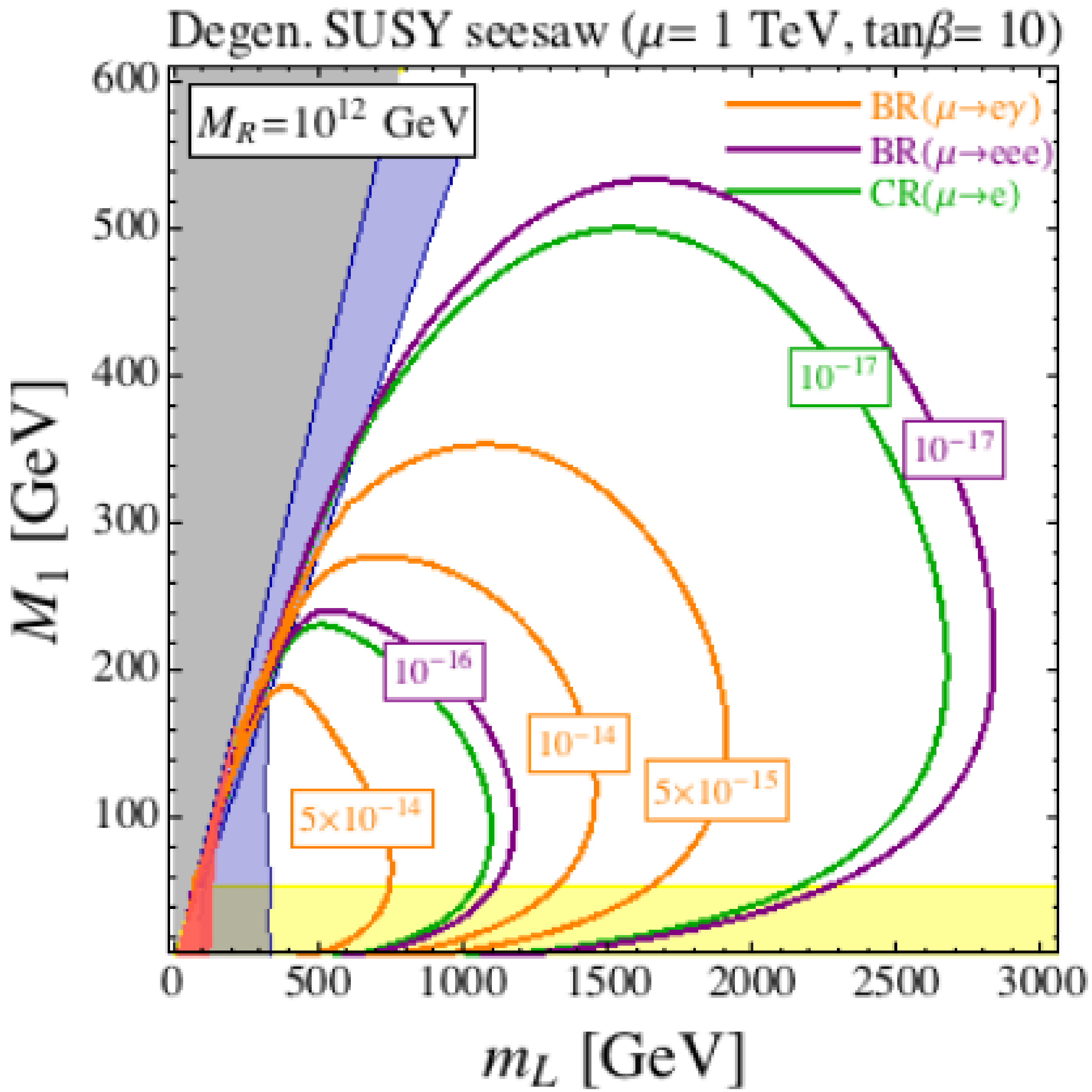
- 0.05 protons/ muon capture
- Tran Hoai Nam (Osaka Univ.) PhD

Selection of the Target Material

- DIO $E_{endpoing}$ extends to the $E_{\mu\text{-}e}$
  - Recoil energy
  - Muon binding energy
- Select the target material with high $E_{\mu\text{-}e}$ and avoid using the material with larger $E_{endpoint}$ around the target
  - When the target is made of aluminium, we should avoid using materials from Z=5 to Z=12.
  - He (Z=2) is OK to use around the target
- Lifetime of muon in muonic atoms
  - Shorter in larger Z because of the larger nuclear muon capture rate



	Al	Ti
lifetime	864 ns	330 ns
time window	0.3	0.2
signal	1	1.5
net	0.3	0.3



Degen. SUSY seesaw (μ= 1 TeV, tanβ= 10)
M_R=10^{12} GeV
BR($\mu \to e\gamma$)
BR($\mu \to eee$)
CR($\mu \to e$)
10^{-17}
10^{-17}
10^{-16}
10^{-14}
5×10^{-15}
5×10^{-14}
600
500
400
300
200
100
0
500
1000
1500
2000
2500
3000
M_1 [GeV]
m_L [GeV]