Lepton flavour violation at COMET

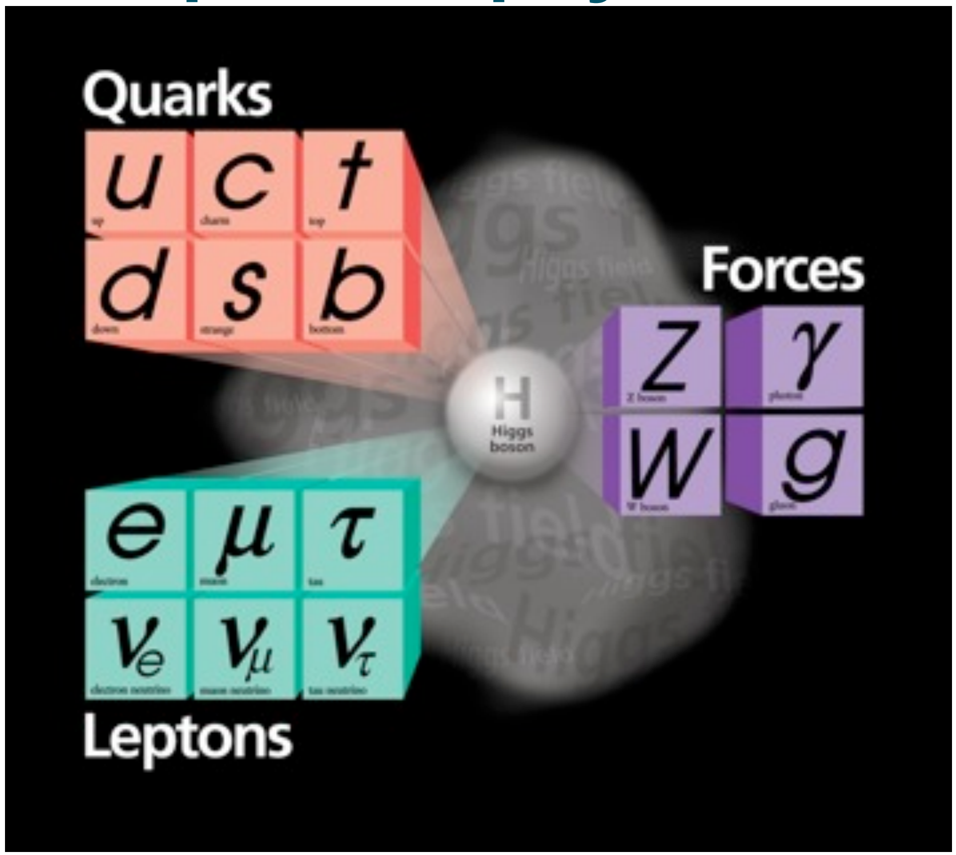
Matthew Wing (UCL)

- Motivation : lepton flavour violation, intensity, exotics
- Experiments on charged lepton flavour violation
- COMET and Mu2e experiments
- Summary

Seminar — DESY HH / Zeuthen — 9 / 10 October 2012

Motivation

Big questions in particle physics



The Standard Model is amazingly successful, but some things remain unexplained :

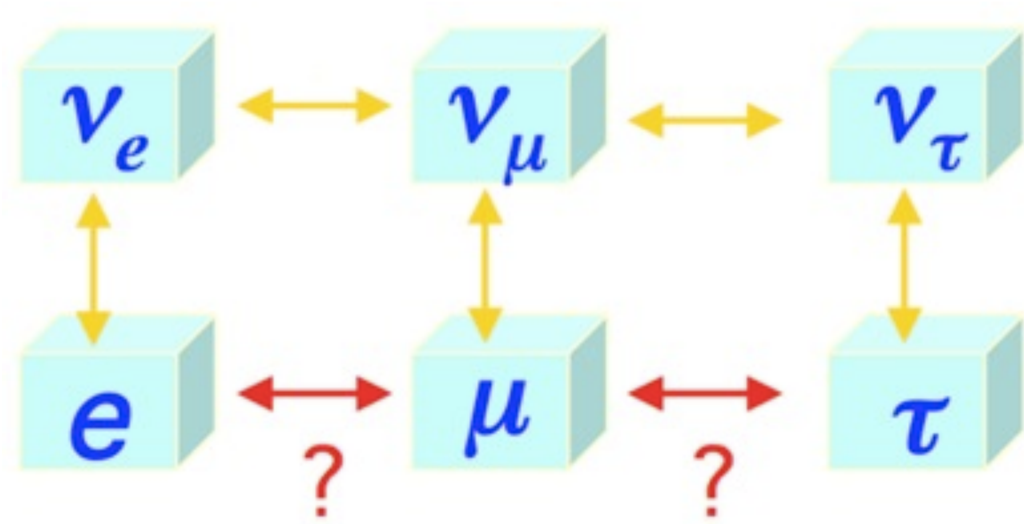
- masses
- why is there so much matter (vs anti-matter) ?
- why is there so little matter (*5%* of Universe) ?
- can we unify the forces ?

Lepton flavour violation

What is the nature of new physics between the TeV and the GUT scale ?

What is the mechanism generating the Universe's baryon asymmetry ?

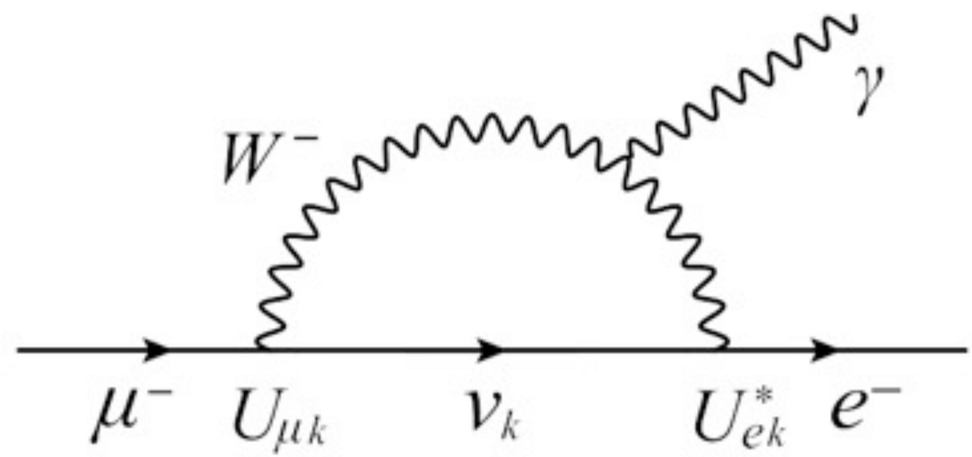
Neutrino oscillations have been observed, what about charge lepton flavour violation ?



- In SM, rate is $O(10^{-50})$.
- In BSM, SUSY and other models give $O(10^{-10}-10^{-20})$.

Considering :

- $\mu^+ \rightarrow e^+ \gamma$
- $\mu^+ \rightarrow e^+ e^- e^+$
- $\mu^- N \rightarrow e^- N$



Intensity / precision frontier

New physics can appear in loops, Standard Model prediction can be tiny ⇒ intensity and precision needed

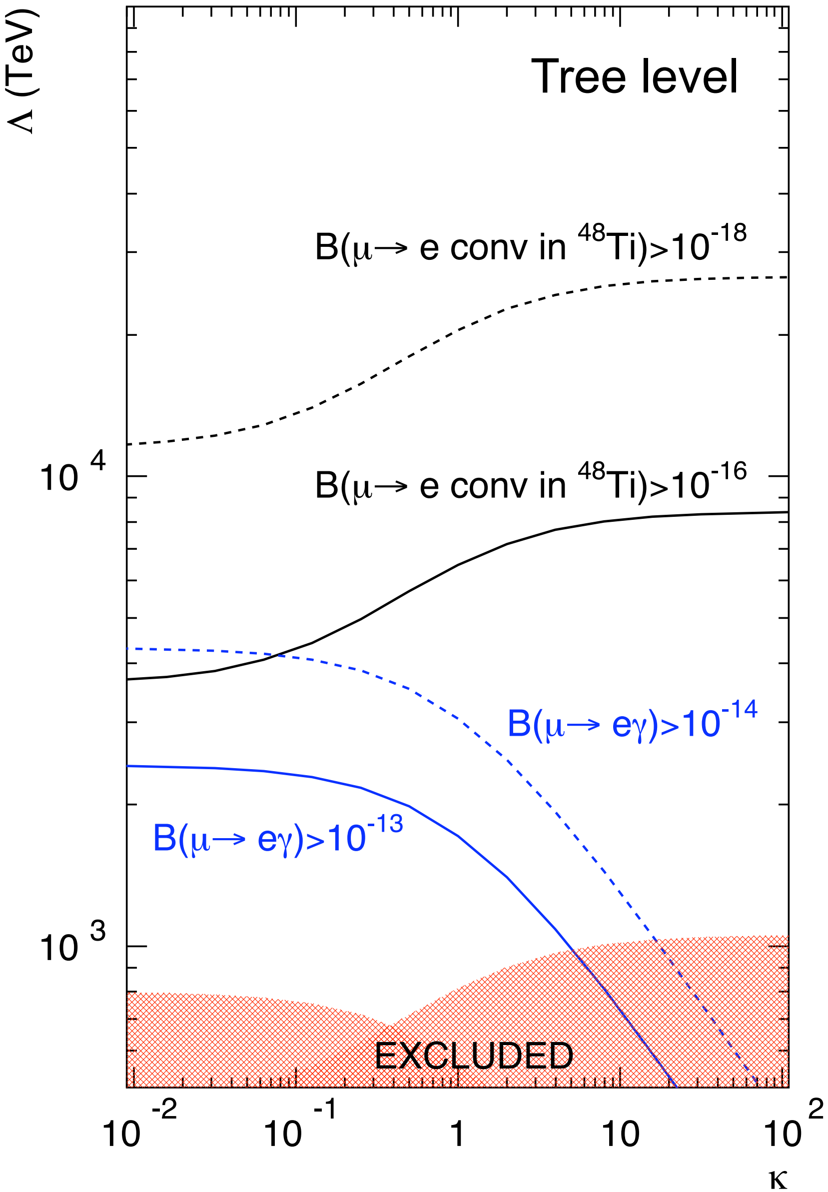
Complements energy frontier searches

Many running and proposed experiments :

- Study of rare Kaon decays : NA62, KOTO, ORKA, ...
- Charm physics programme : BES, SuperB (also tau), ...
- B physics programme : LHCb, Belle-II, SuperB, ...
- Charged lepton flavour violation : MEG, Mu3e, Mu2e, MUSIC, COMET, PRISM, ...
- Electric dipole moments : nEDM, eEDM, ...
- Muon gyromagentic ratio : g-2 (FNAL, J-PARC), ...

Big improvements in sensitivity expected during this decade.

Energy sensitivity reach



Sensitivity to physics scales beyond the LHC

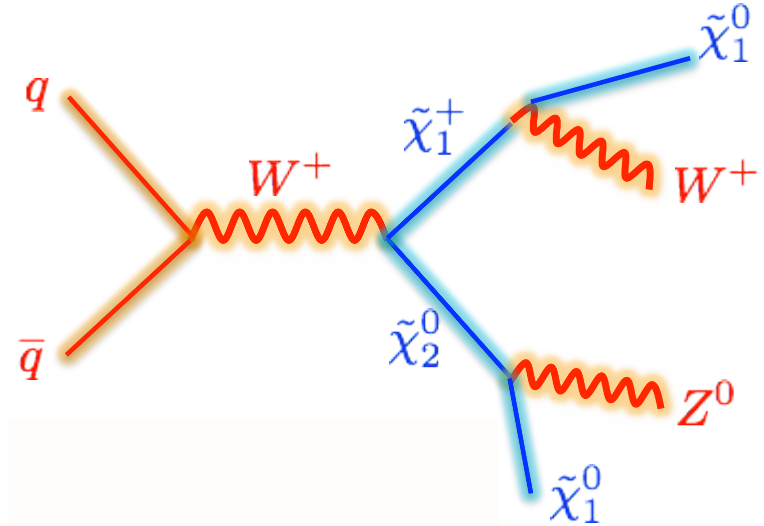
Interpretation of any new physics discovered at the LHC can be aided by other data

Muon-to-electron conversion experiments are most sensitive

If new physics found, important to measure many channels to elucidate its nature

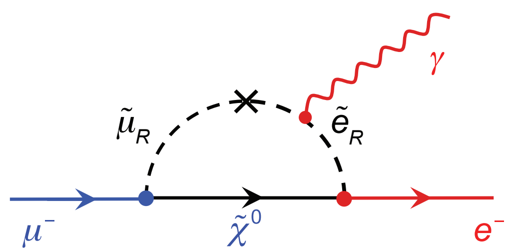
Exotic physics

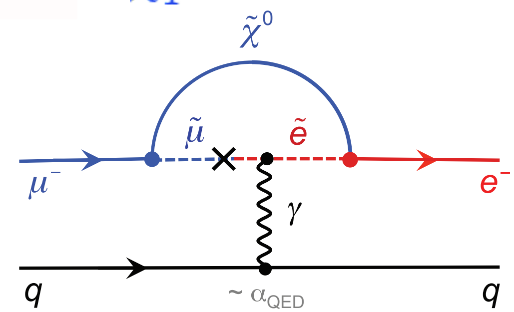
Models contain new particles which could be directly detected at the energy frontier



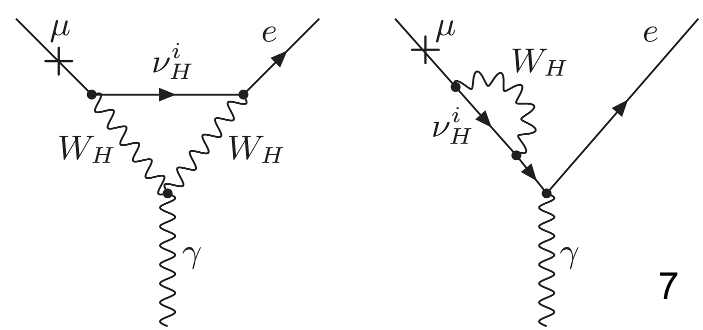
Supersymmetry

Or seen through their contribution to loops at the intensity / precision frontier

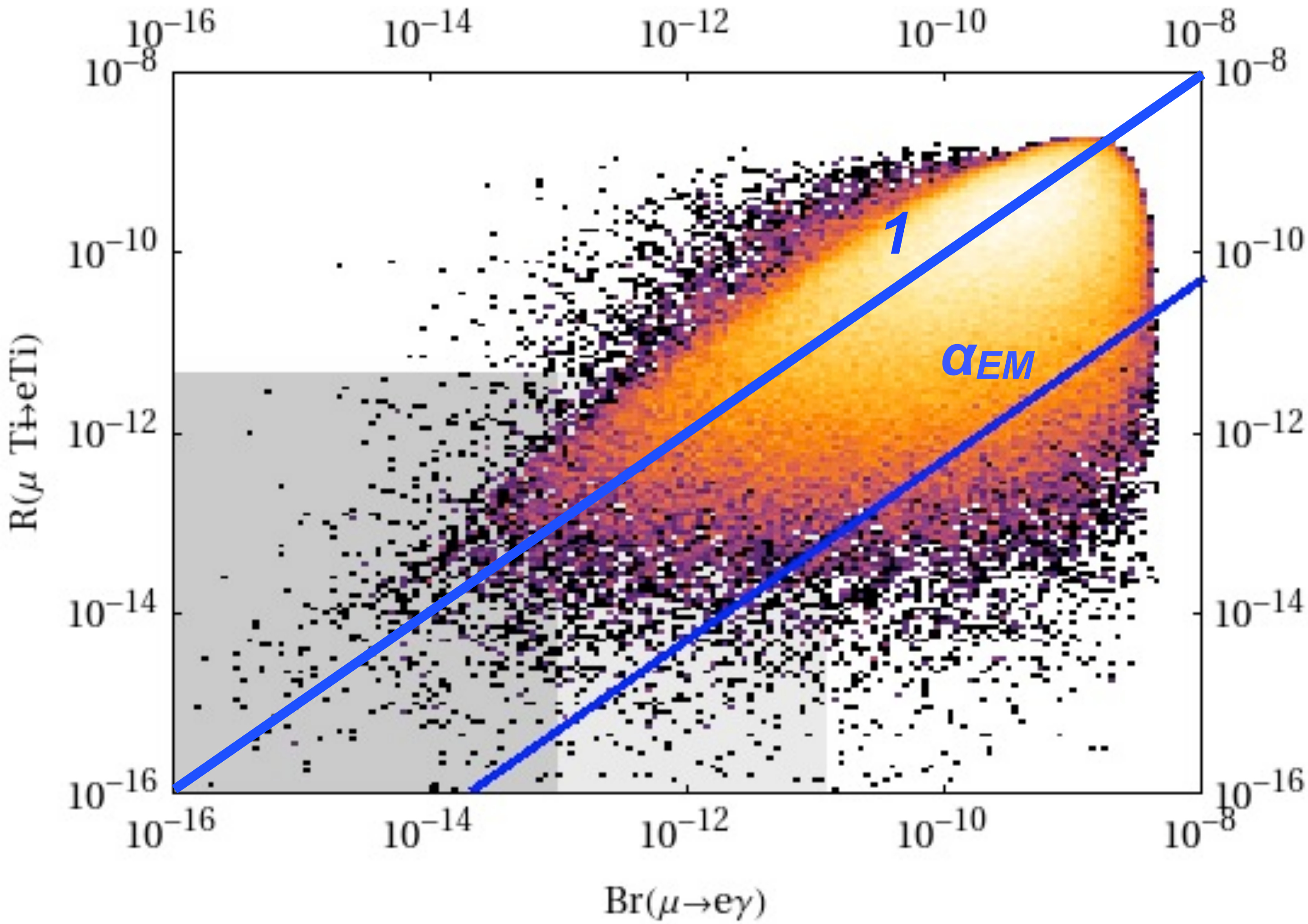




Little Higgs models



Model predictions e.g. Little Higgs

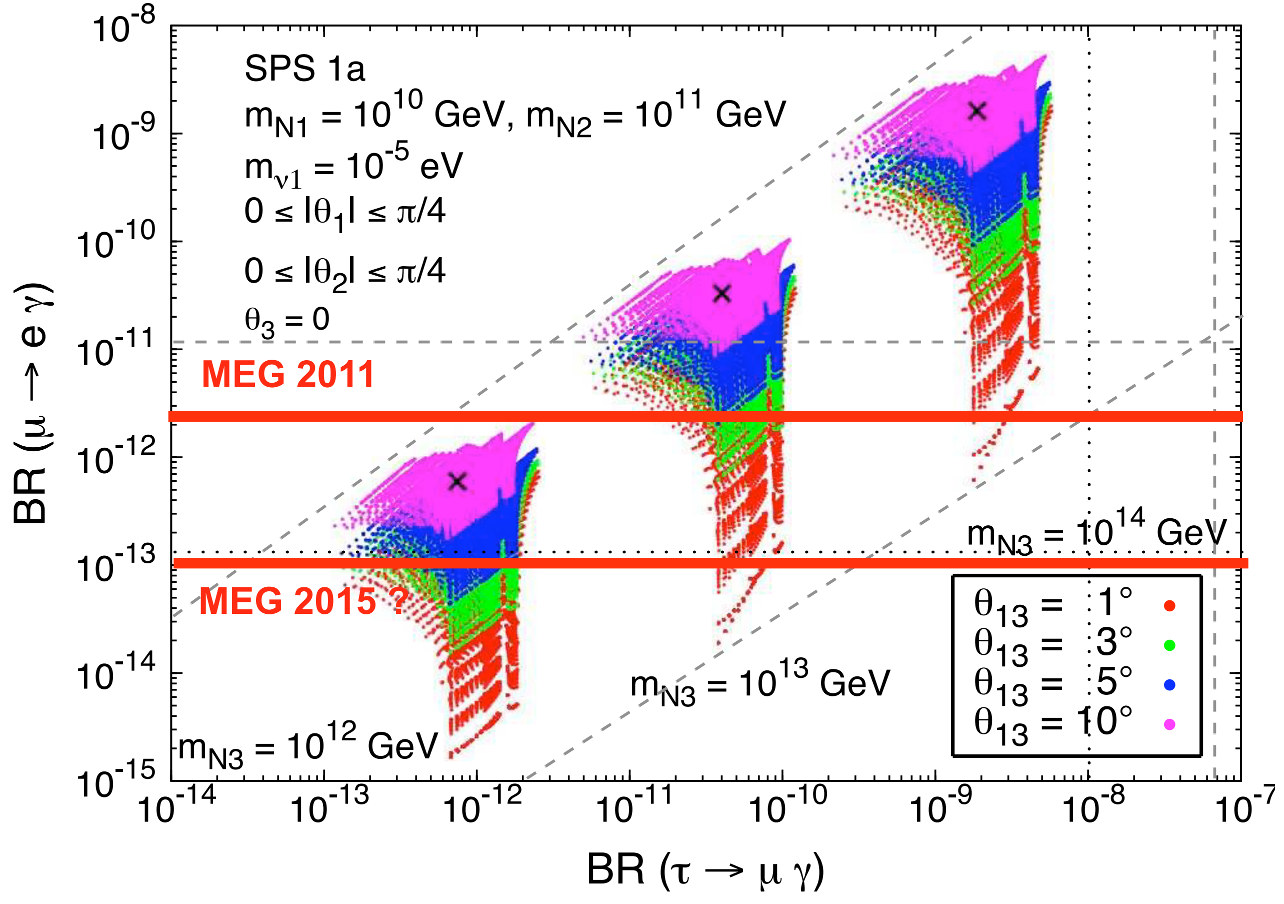


Blanke et al., Acta Phys. Polon. **B 41** (2010) 657

Connection with neutrino physics

Non-GUT SUSY model with seesaw mechanism

Recent Daya Bay / RENO measurement of $\theta_{13} = 8.5^o$



Antush et al., JHEP **11** (2006) 090.

Sensitivity of cLFV to BSM physics

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

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

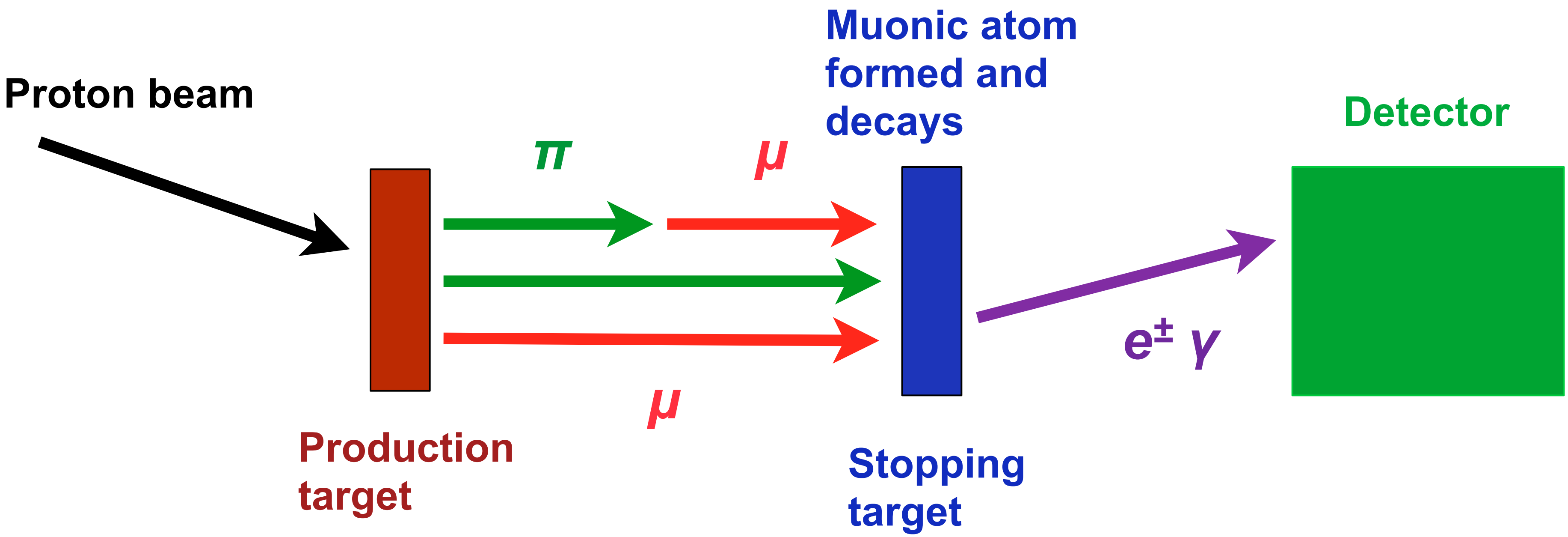
Different SUSY and non-SUSY physics models

All three stars for muon-to-electron conversion in an atom

Altmannshofer et al. Nucl. Phys. **B 830** (2010) 17

Status of charged lepton flavour violation

Basic technique for measuring muon decays

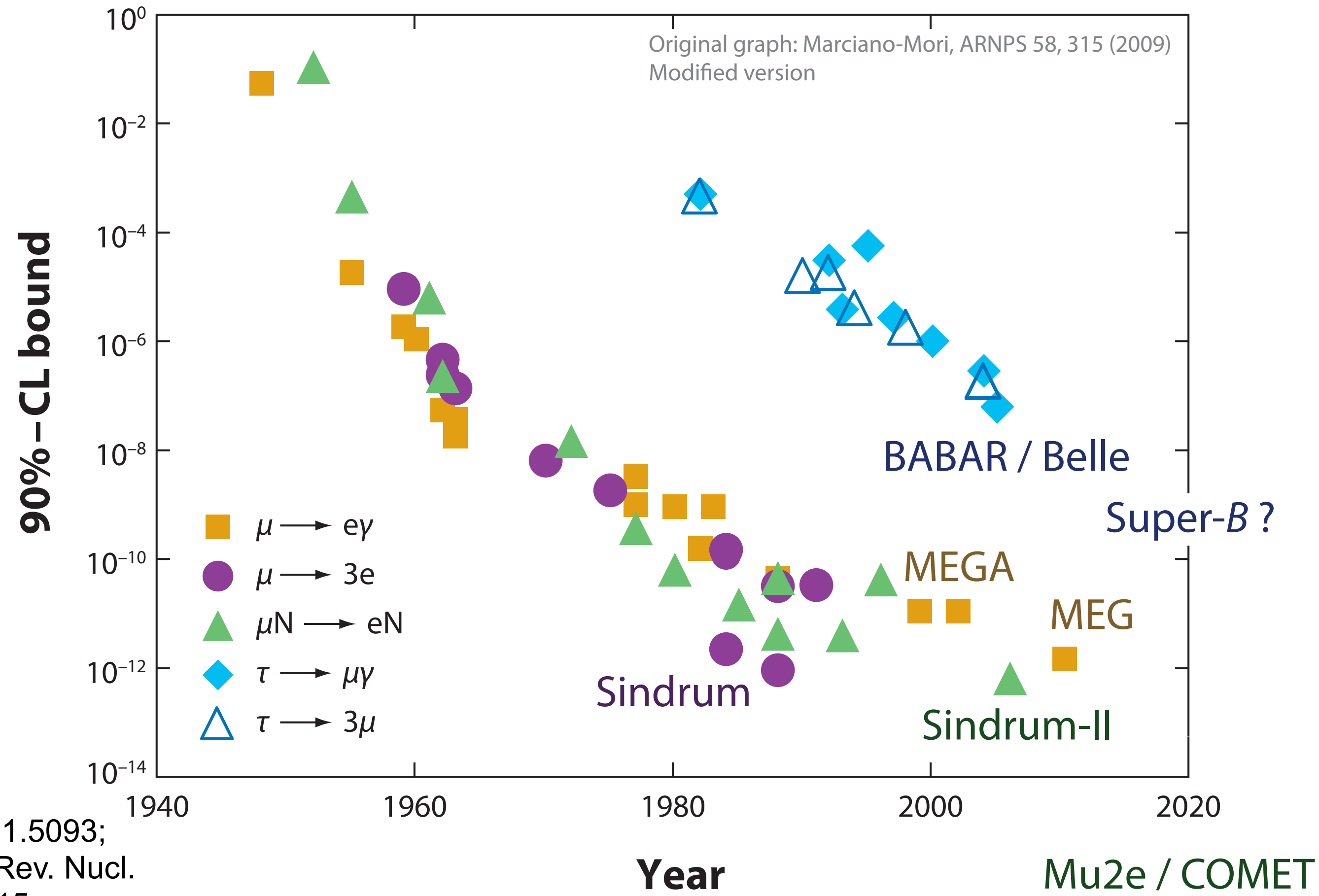


- $\mu \rightarrow e\,\gamma$
- $\mu^{+} \rightarrow e^{+}\,e^{+}\,e^{-}$
- $\mu^{-}\,N \rightarrow e^{-}\,N$

Muons are excellent for high-precision physics

- Intense continuous and pulsed beams available
- Long-lived
- Simple final states at low energy; small detectors

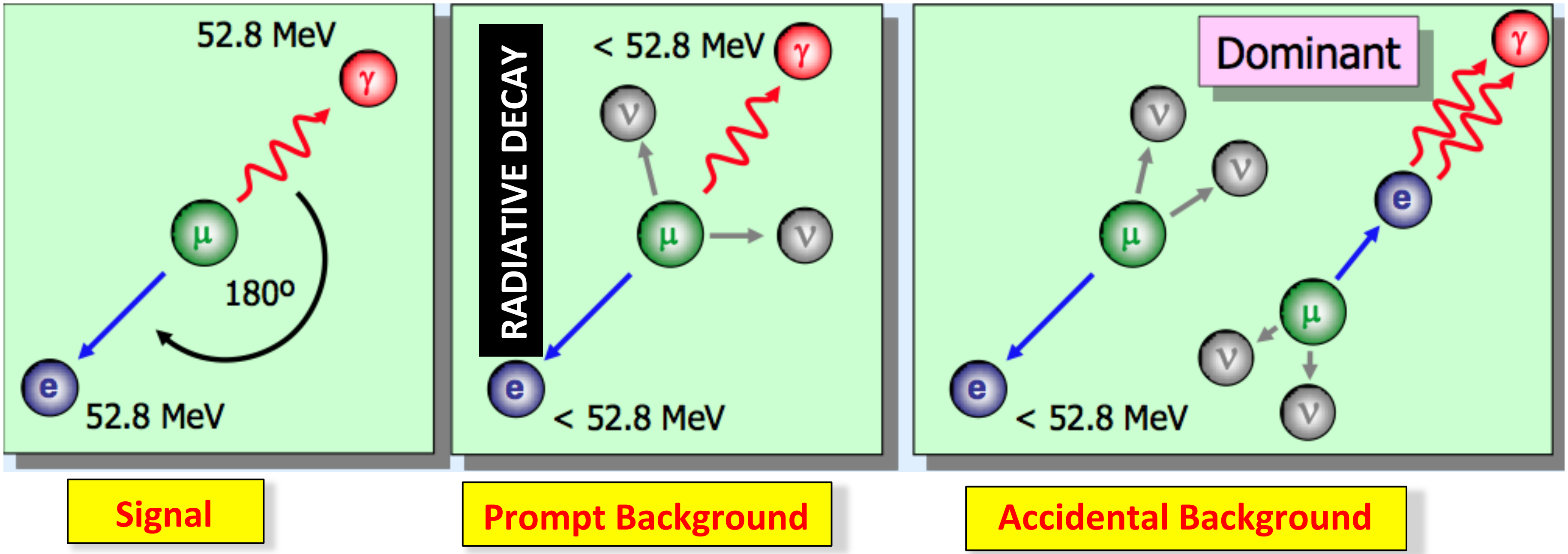
Experimental status of cLFV searches



A. Hoecker, arXiv:1201.5093; Marciano et al., Ann. Rev. Nucl. Part. Sci. **58** (2008) 315

Figure 1. History of searches for selected lepton flavour violating processes. Shown are 90% CL upper limits, and the experiments setting the best current limits and future prospectives for LFV searches in τ decays and μ–e conversion are indicated. This graph has been modified from [5].

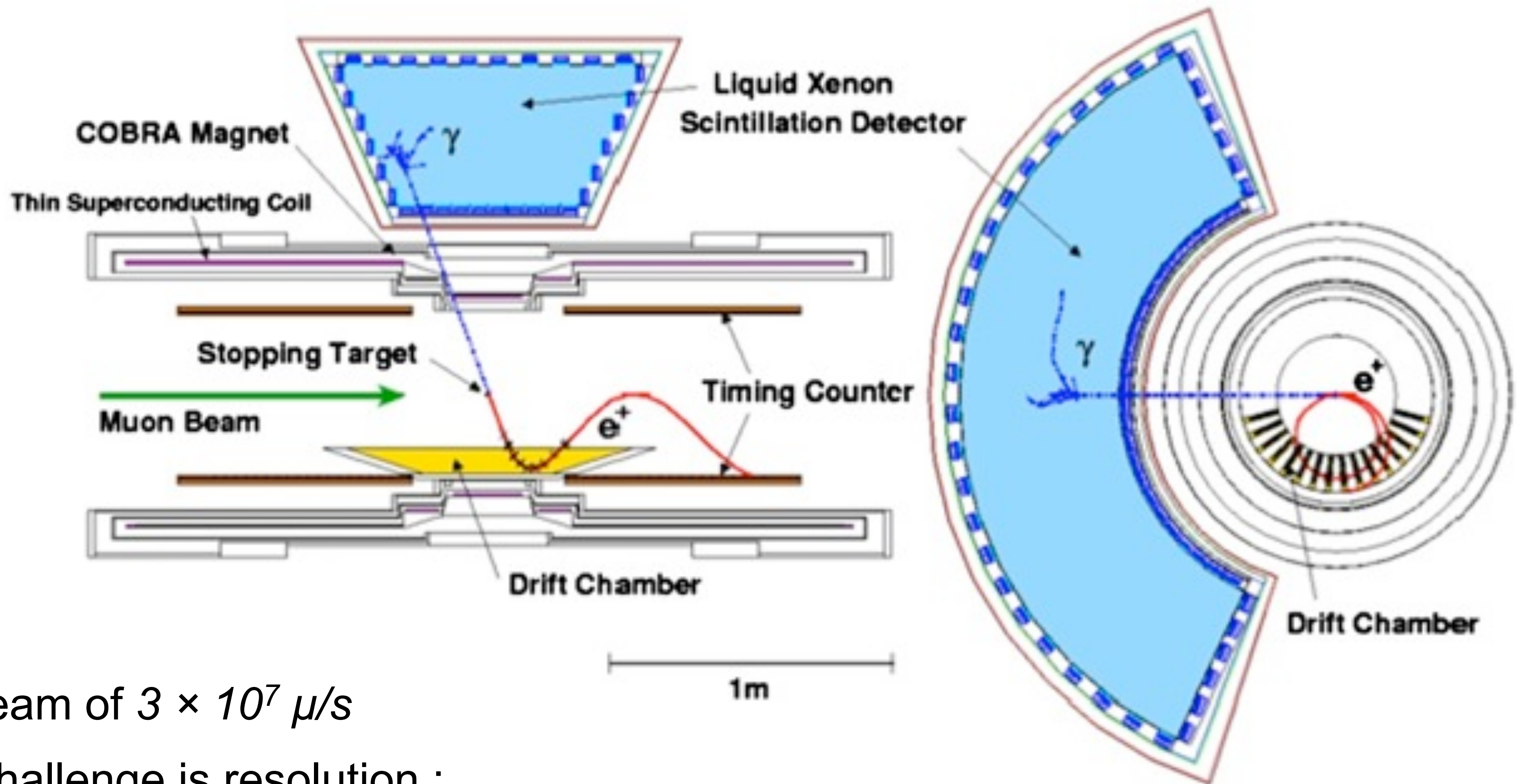
MEG status, $\mu \rightarrow e\ \gamma$



$E_{\gamma} = E_{e+} = 52.8$ MeV
$\theta_{\gamma e} = 180^0$
γ and e^+ in time

Currently running a PSI with a planned upgrade

MEG detector, $\mu \rightarrow e\ \gamma$



DC beam of $3 \times 10^7\ \mu/s$

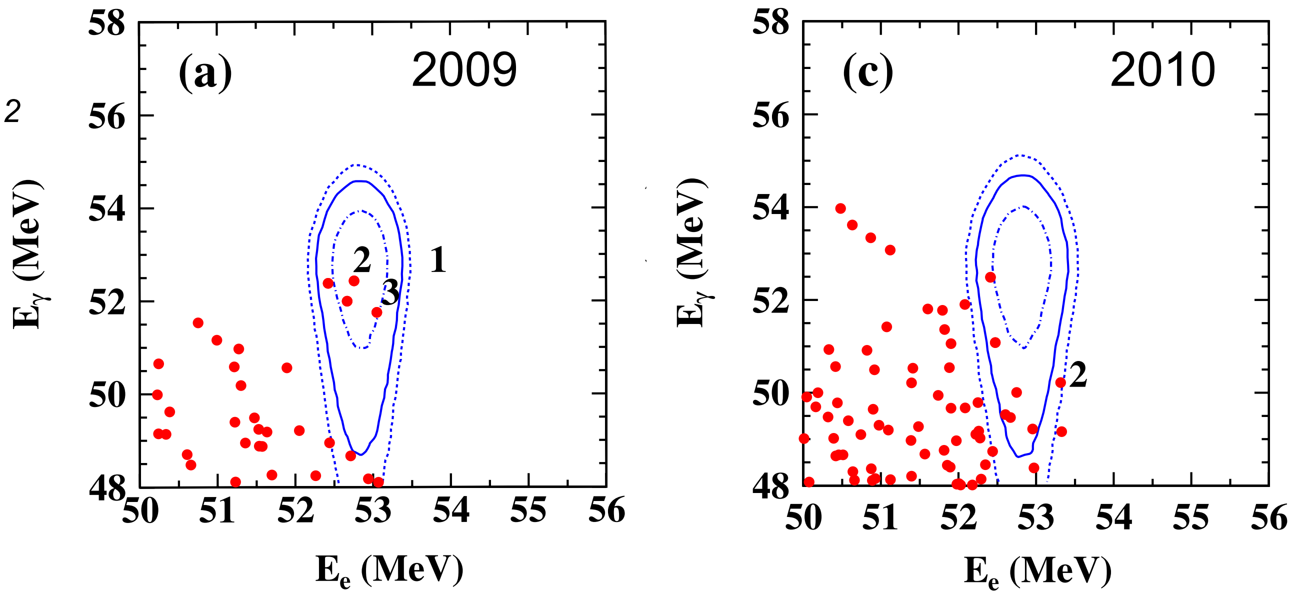
The challenge is resolution :

- Spectrometer and low-mass drift chamber
- Scintillator bars and fibres for e+ timing
- Liquid Xenon calorimeter for photon detection

MEG results and future

*BR (μ → e γ) < 2.4 × 10^−12^*
(at 90% C.L)

Data taking since should improve to ~ *6 × 10^−13^*



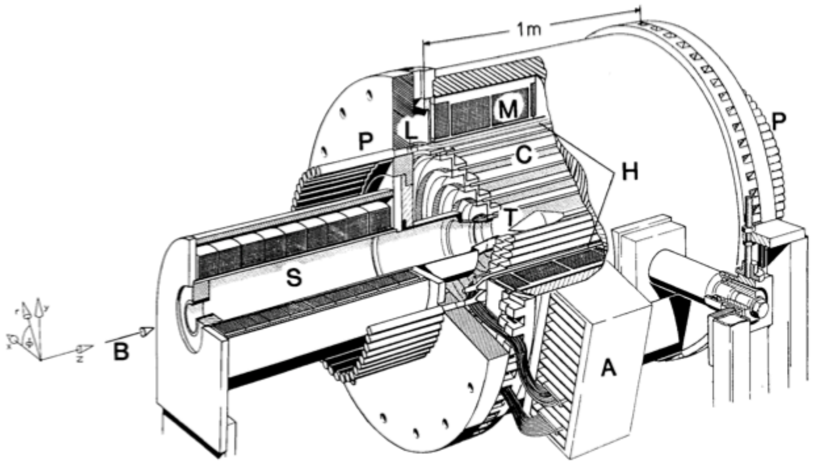
Upgrade :

- Larger tracker with more hits
- Large calorimeter with SiPM rather than PMTs
- To reach *5 × 10^−14^* after 3 years from 2015

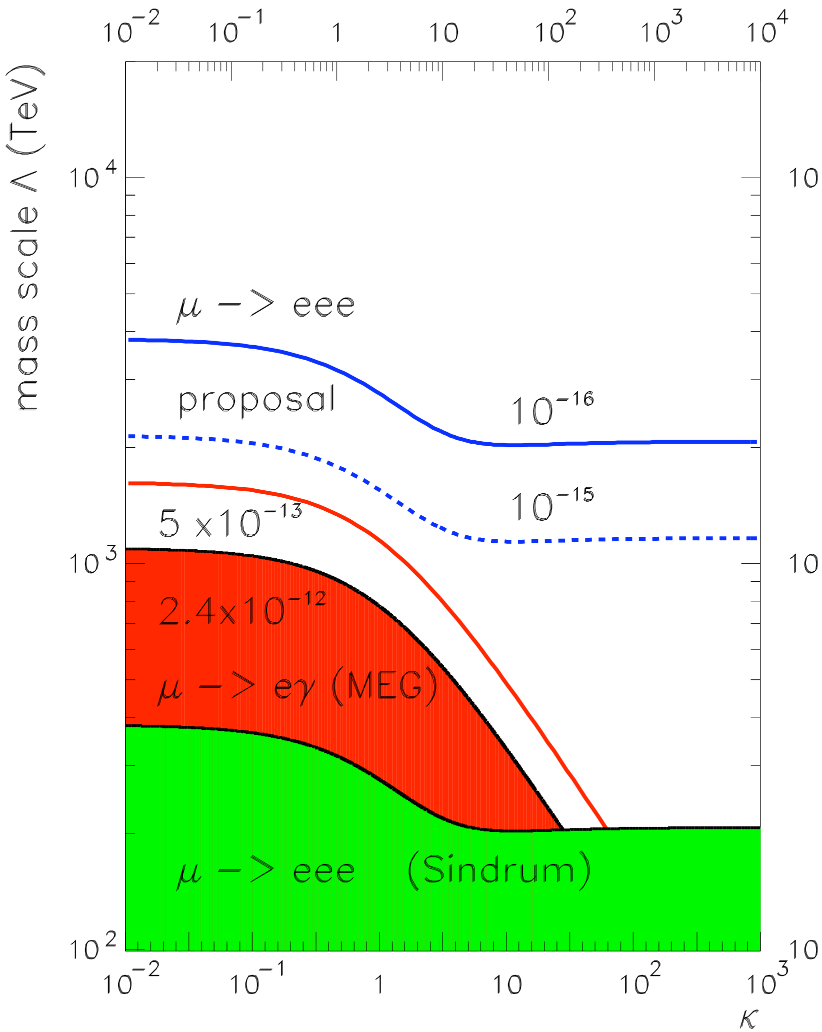
J. Adam et al., Phys. Rev. Lett. 107 (2011) 171801

$\mu^+ \rightarrow e^+ e^+ e^-$ search by SINDRUM-I

Current limit from SINDRUM-I at PSI of 10^{-12}



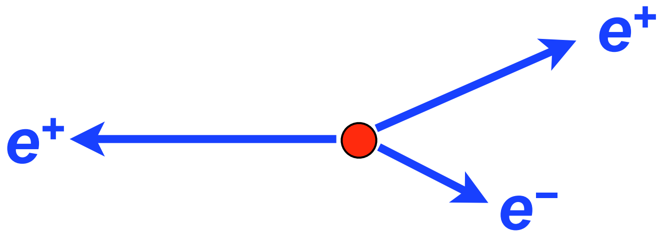
Sindrum-I @ PSI

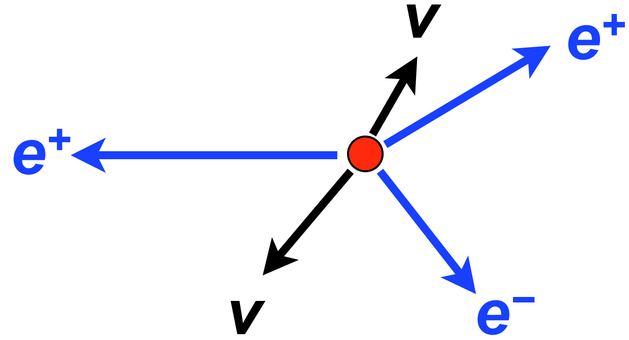


Given the MEG, $\mu \rightarrow e\,\gamma$, results, need significant step in $\mu \rightarrow e\,e\,e$ sensitivity

U. Bellgardt et al., Nucl. Phys. **B 299** (1988) 1.

Mu3e at PSI, $\mu^+ \rightarrow e^+ e^+ e^-$, status





Three-body signal has backgrounds from radiative and overlay events

Letter of Intent submitted to PSI in 2012

Sensitivity goals :

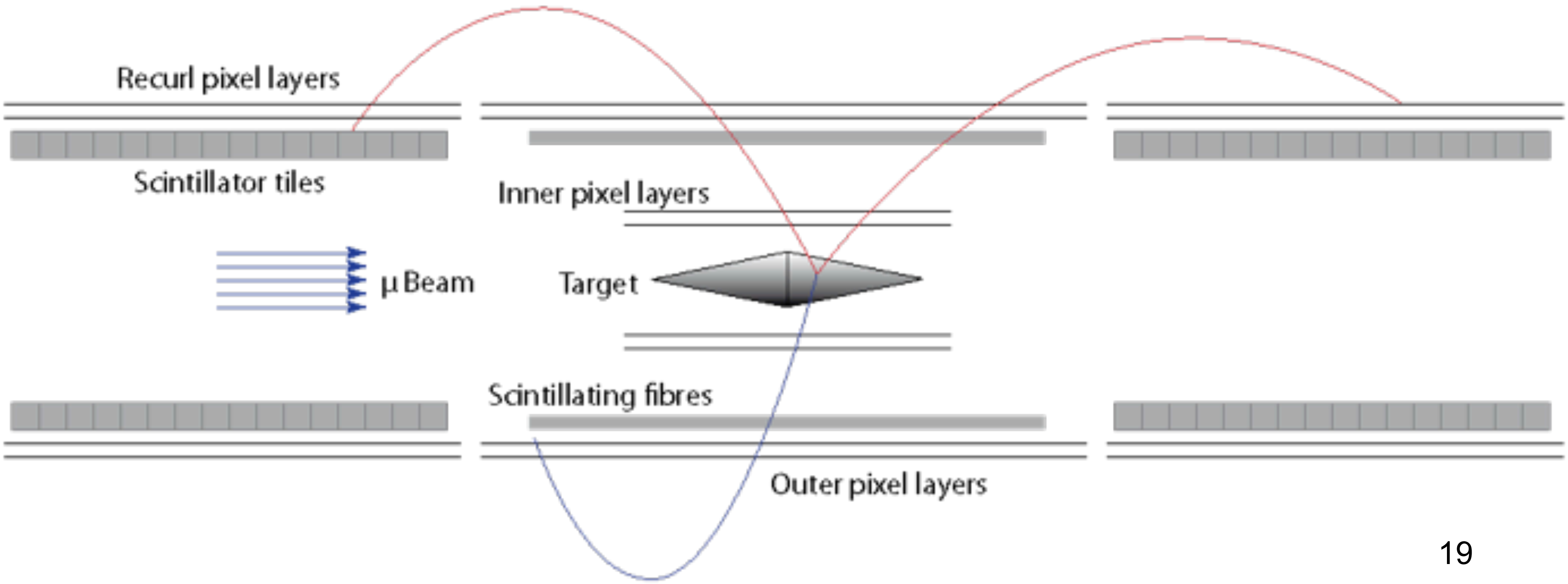
- Phase I (2014−17) : 10^{-15}
- Phase II (> 2017) : 10^{-16}

Mu3e at PSI, $\mu^+ \rightarrow e^+ e^+ e^-$, plans

Needs excellent momentum and timing resolution

- Tracker using HV-MAPS
- Timing using scintillating fibres and high resolution hodoscope

Challenging detector and schedule



Muon-to-electron conversion

Processes considered so far suffer, at high rates, from accidental background

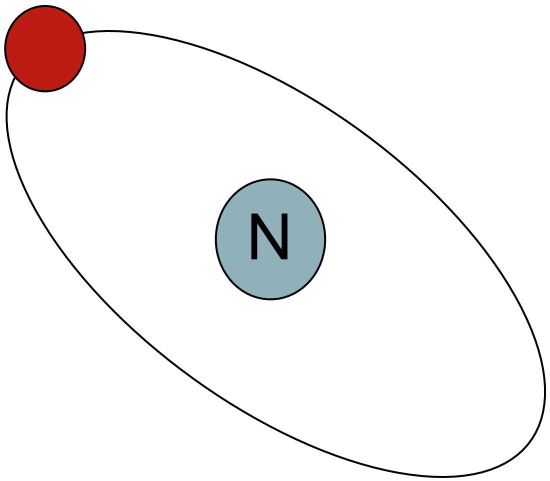
- $\mu^+ \rightarrow e^+ \gamma$
- $\mu^+ \rightarrow e^+ e^- e^+$

The conversion process has a simple one-particle signature

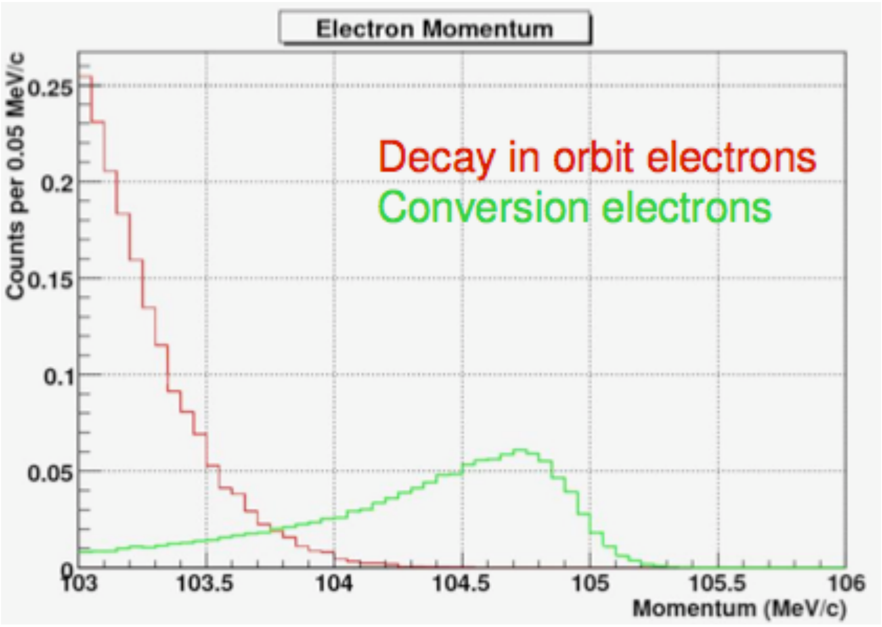
- $\mu^- N \rightarrow e^- N$

Best route to high sensitivity at high muon rates

$\mu^- \rightarrow e^-$



$E_e = m_\mu - B_\mu \approx 105\ MeV\ (Al)$

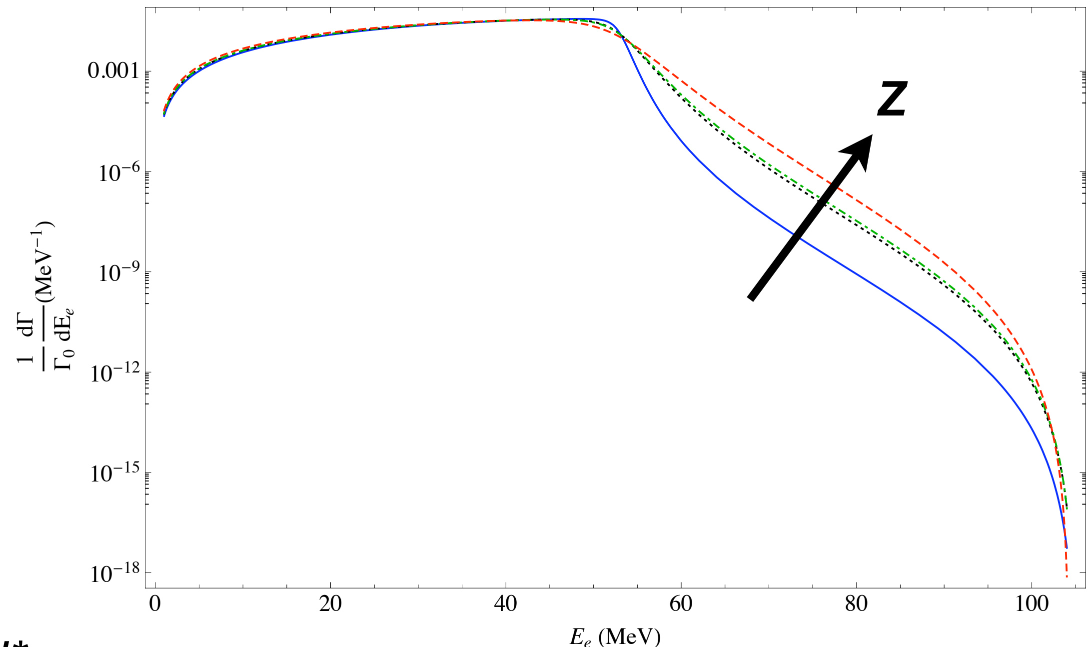


Backgrounds to $\mu^- N \rightarrow e^- N$

1. Decay-in-orbit, $\mu^- N \rightarrow e^- \overline{\nu}_e \nu_\mu N$.
Normal decay where atom allows electron to be above end-point.

- Need good detector resolution
- Minimise energy loss

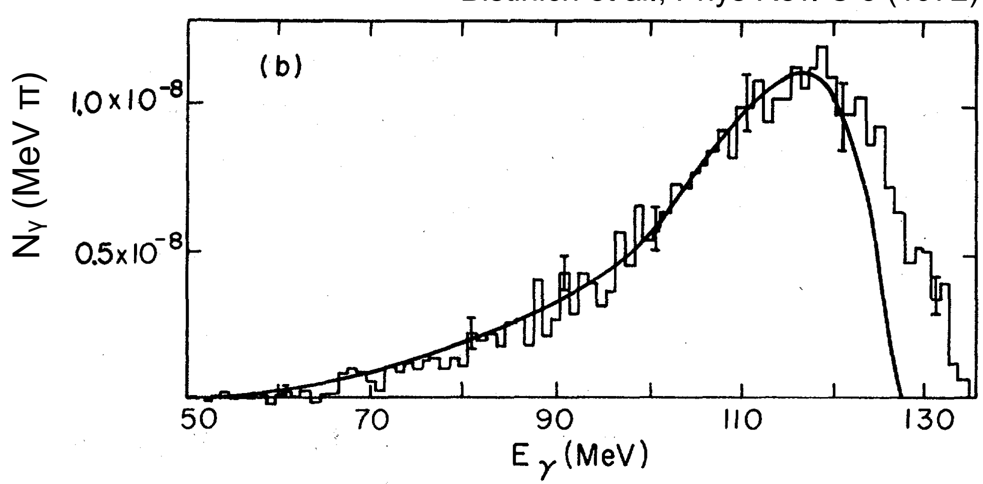
Czarnecki et al., arXiv:1111.4237



2. Radiative pion capture, $\pi^- N \rightarrow \gamma N^*$ and $\gamma \rightarrow e^+ e^-$ or $\pi^- N \rightarrow e^+ e^- N$

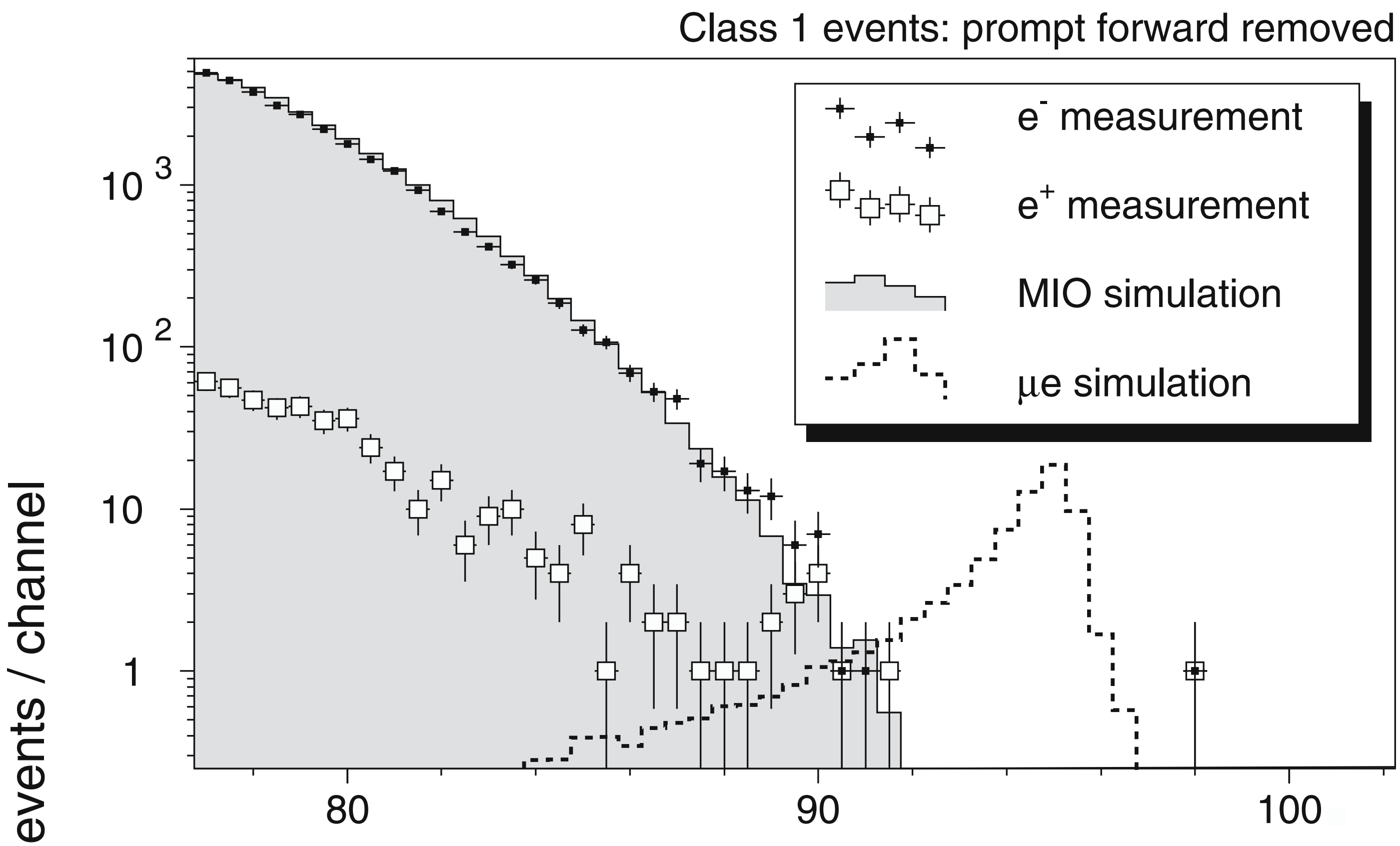
- Timing in beam

Bistirlich et al., Phys Rev. C 5 (1972) 1867



Muon-to-electron conversion limit

Current best measurement from SINDRUM-II at PSI



Limit : 7 × 10^{-13} (Gold target)

W.H. Bertl et al., Euro. Phys. J. **C 47** (2006) 337.

COMET and Mu2e experiments

COMET Collaboration

> 100 collaborators
24 institutes
11 countries

The COMET Collaboration

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New Collaborators welcome !

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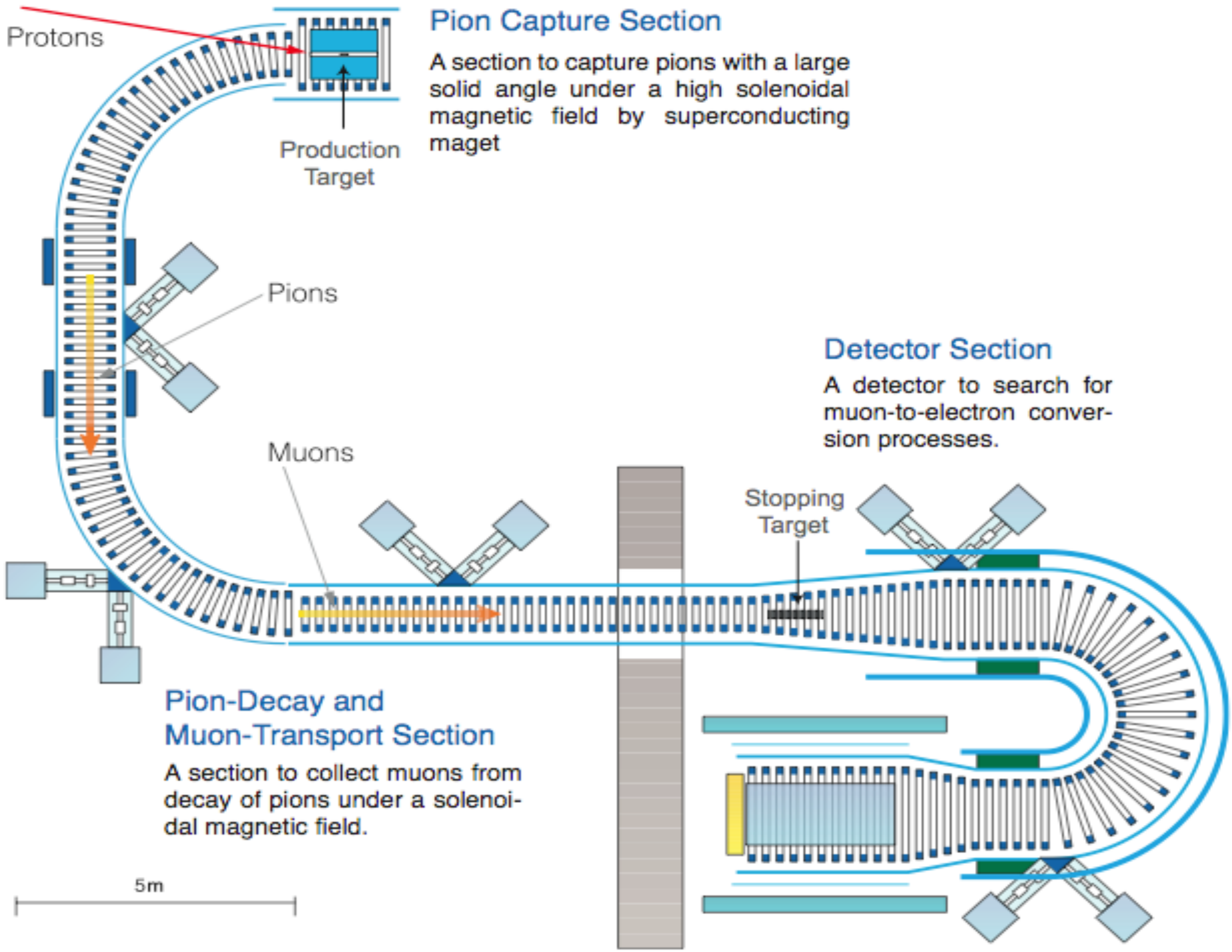
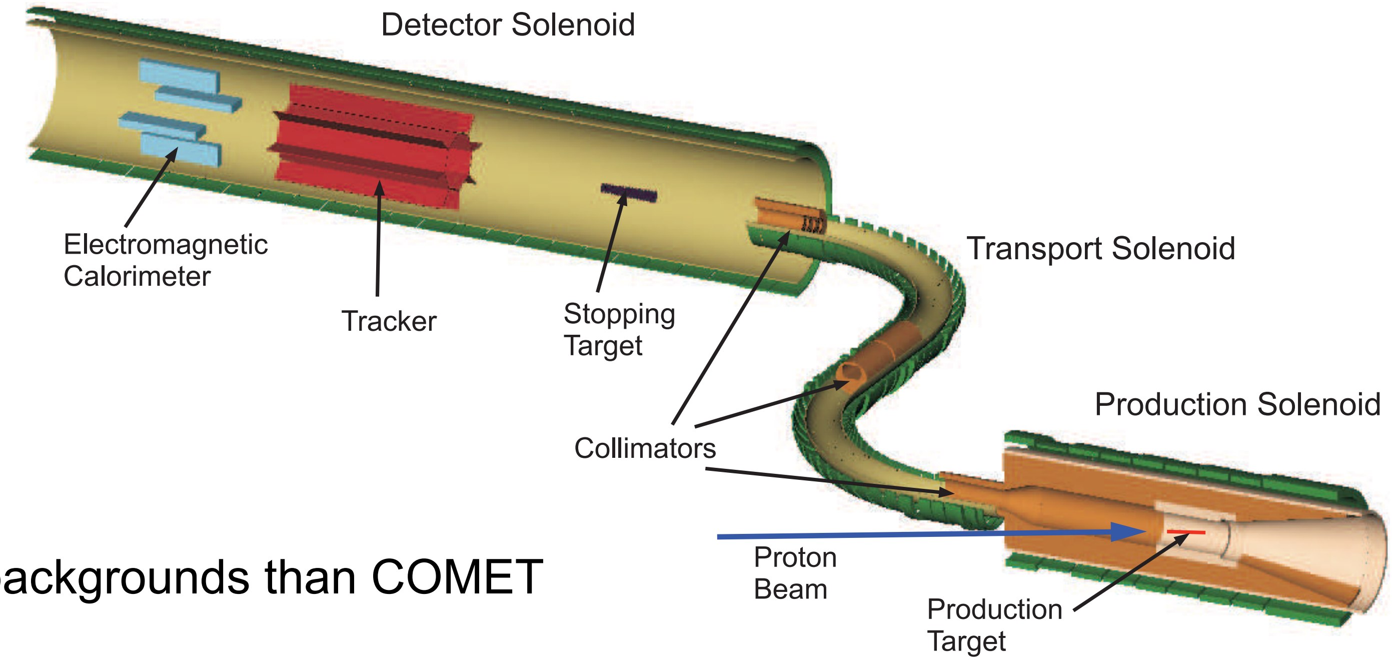
The COMET (J-PARC / E21) experiment



The Mu2e experiment



Higher backgrounds than COMET

Concurrent with Nova rather dedicated running

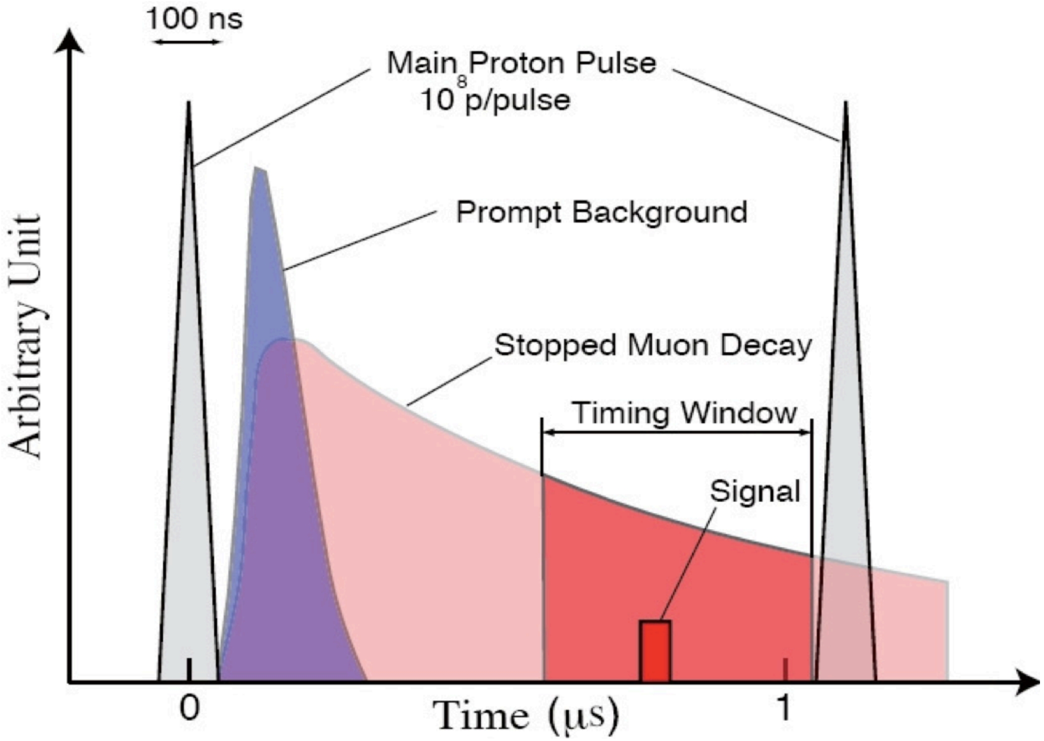
To be built and run in one go rather than staged into two Phases.

Both Mu2e and COMET have single event sensitivities of 3×10^{-17}

Extending beyond SINDRUM-II

Mu2e and COMET need :

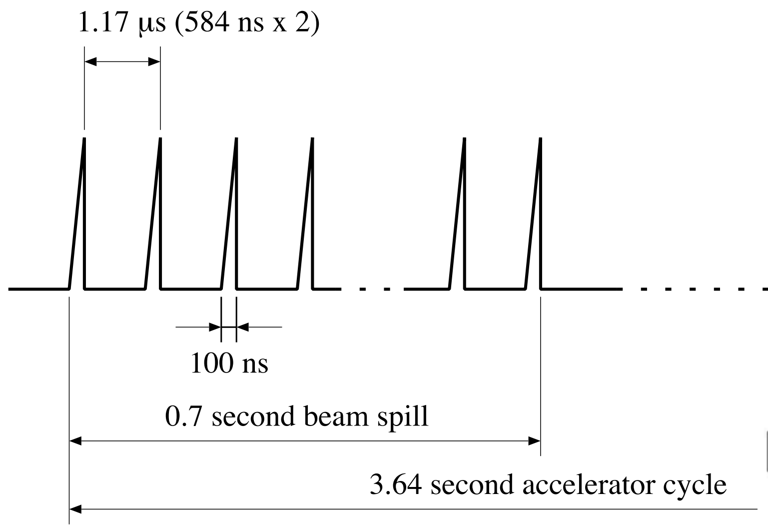
- High rate of muons
- High resolution measurement of decayed electron
- Minimised energy loss of electron in target
- Reduction of prompt backgrounds



Use pulsed beam and measure after prompt background subsided

To achieve single-event sensitivity of 10^{-17}, need 10^{11} μ/s (at $56\ kW$ power) for 10^{7} s

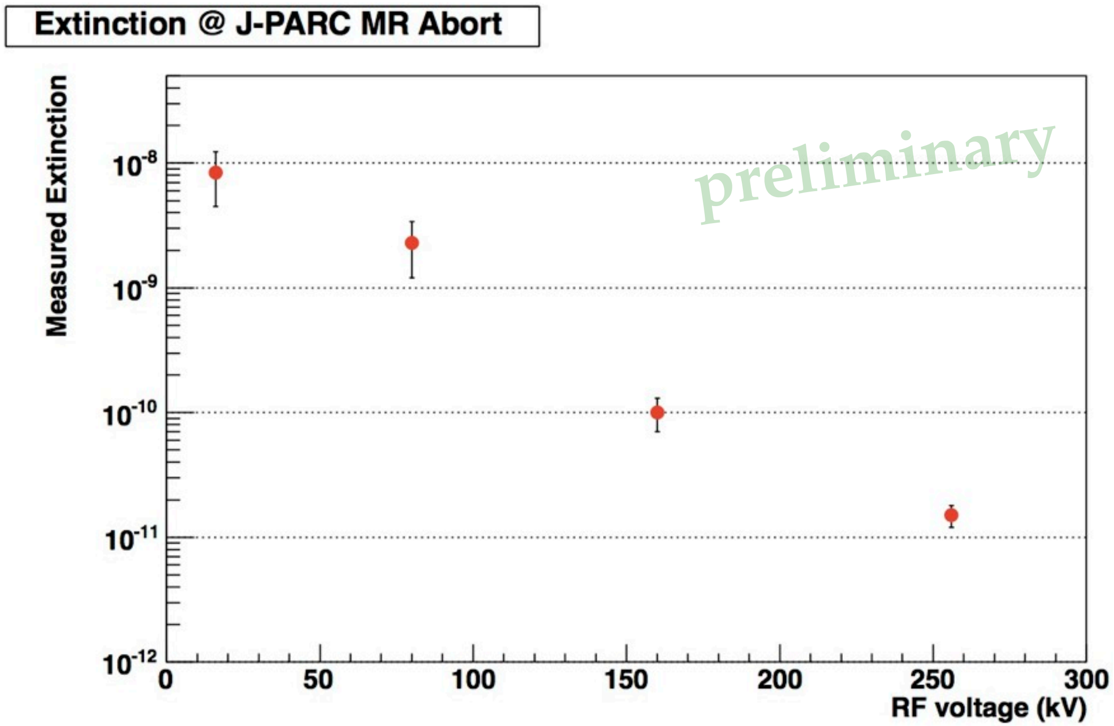
Proton beam at J-PARC and extinction



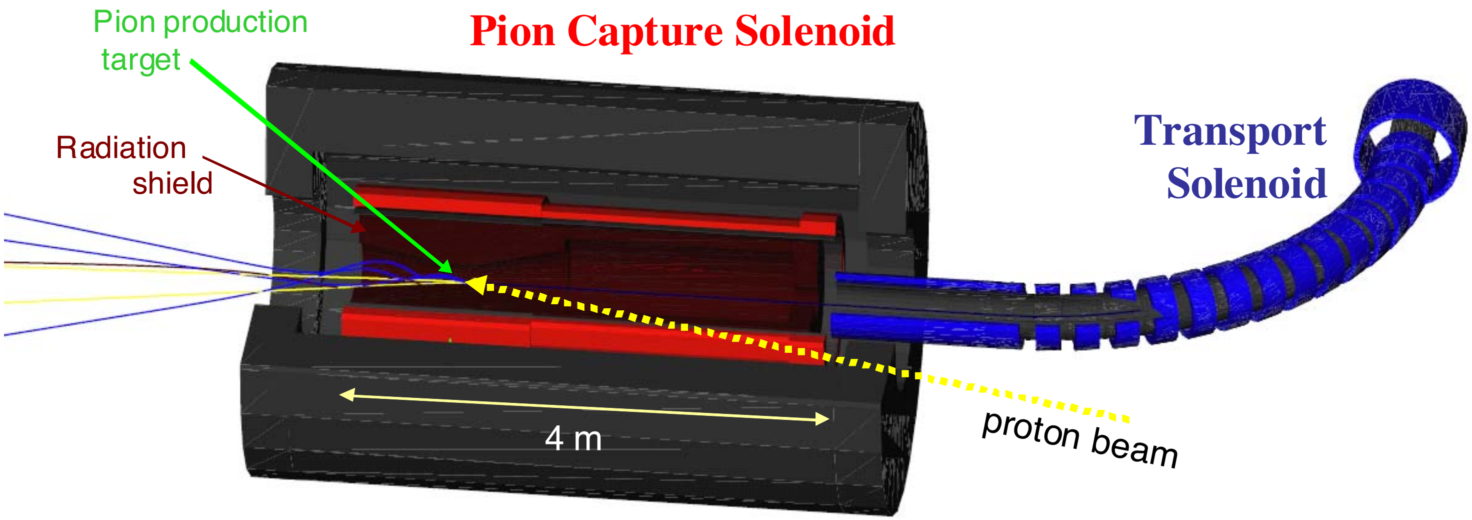
Pulsed beam from slow extraction

Need low number of beam particles between bunches < 10^{-9}

Factor of 3×10^{-11} achieved



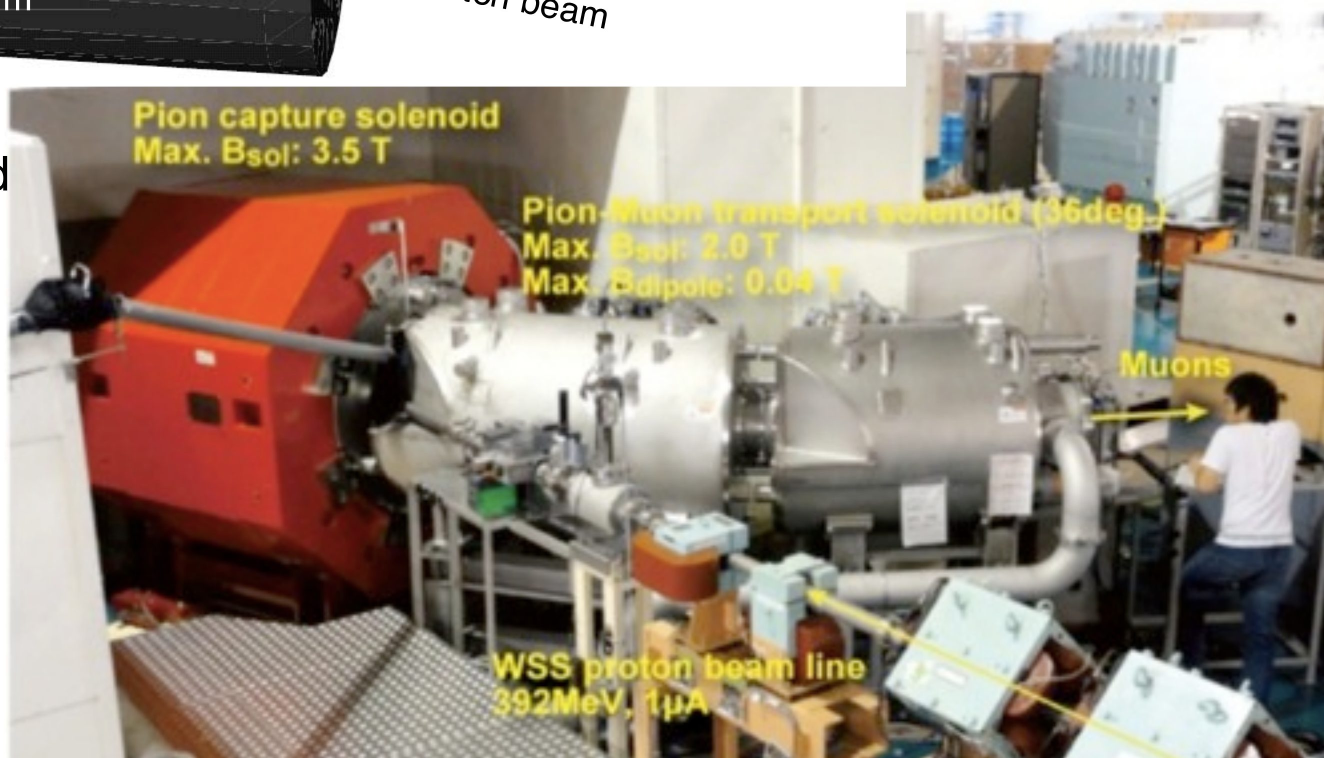
Stopped muon yield



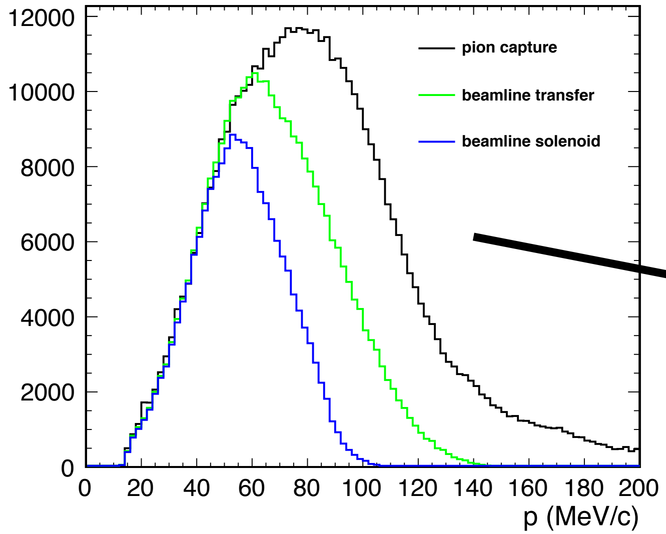
• High field solenoid magnets capture backward and low-p forward pions

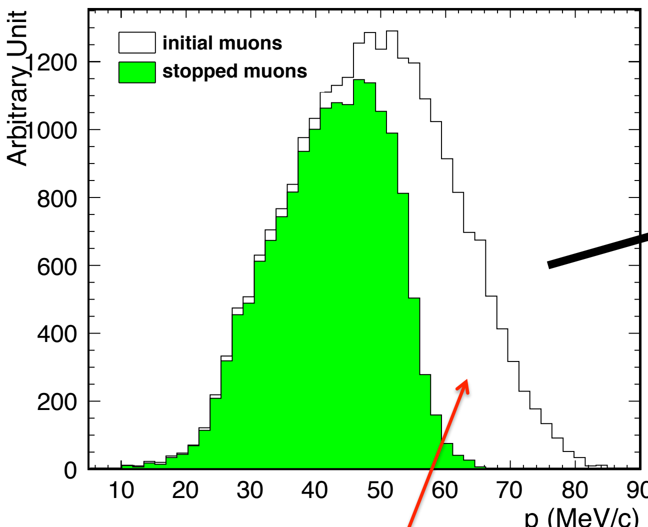
• Factor 1000 increase in efficiency

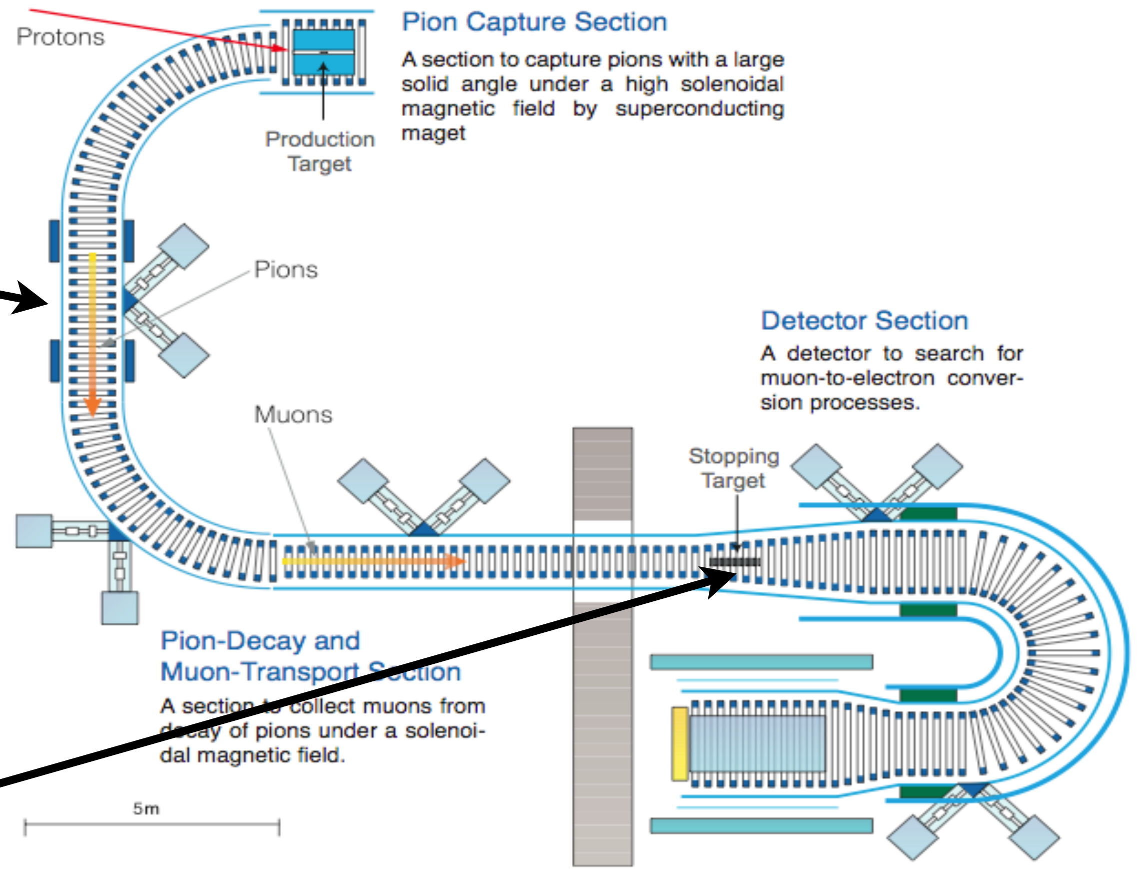
• Demonstrated at MuSIC experiment in Osaka



Muon transport and stopping target



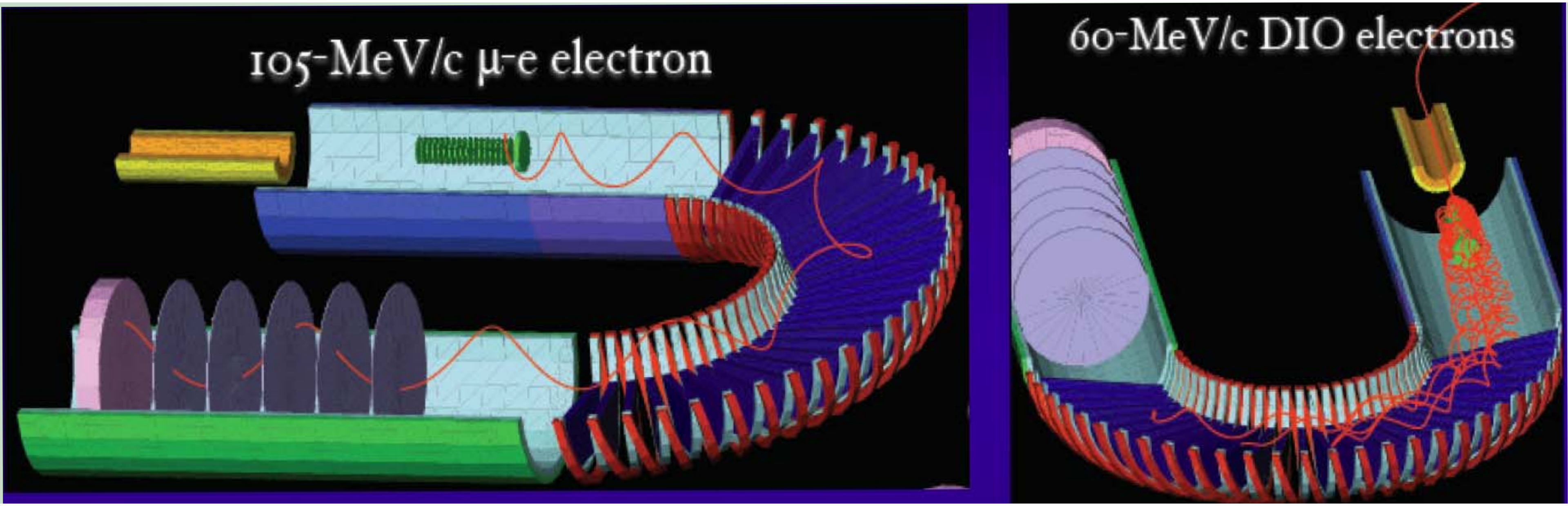




Stopping target : series of 17 Al disks

Only ~ 30% muons not stopped

Electron spectrometer



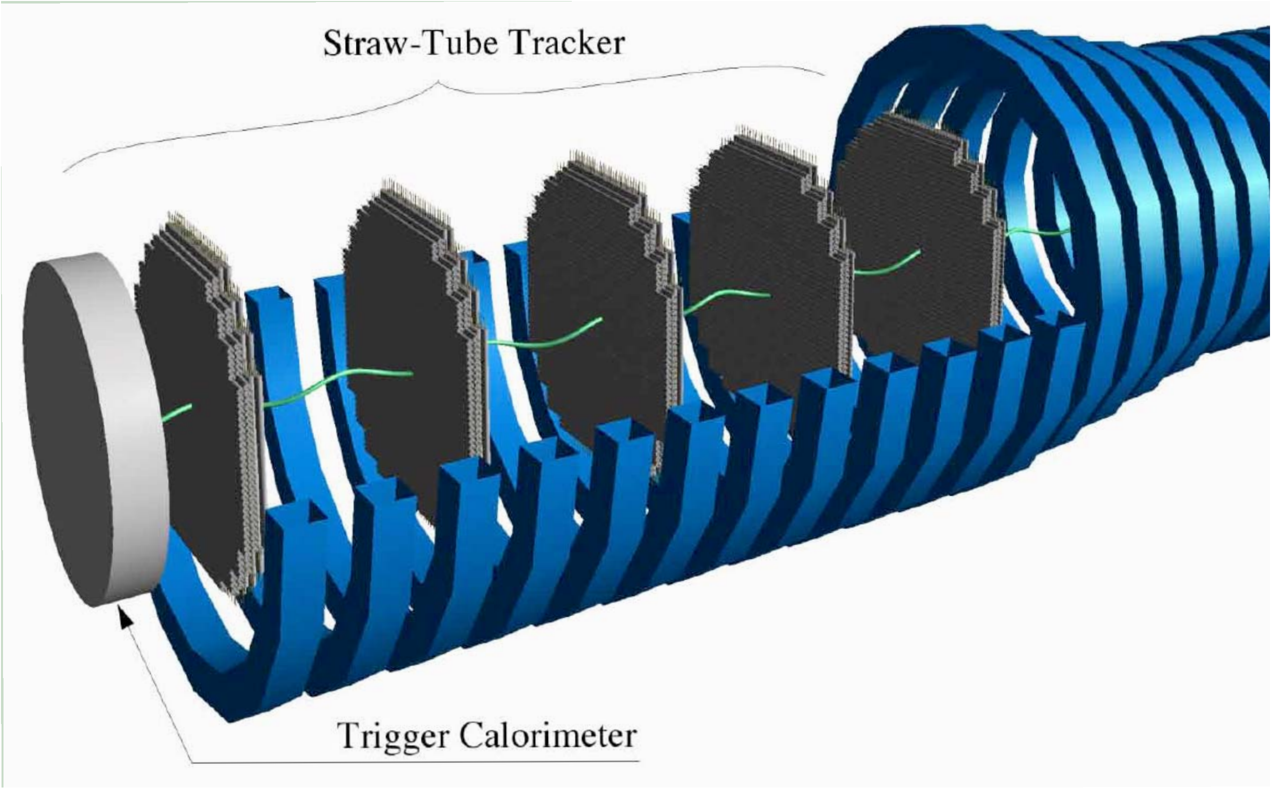
Difference between COMET and Mu2e

Reduce background from low-energy electrons

- Cleaner signal
- Lower detector rate

Electron detection

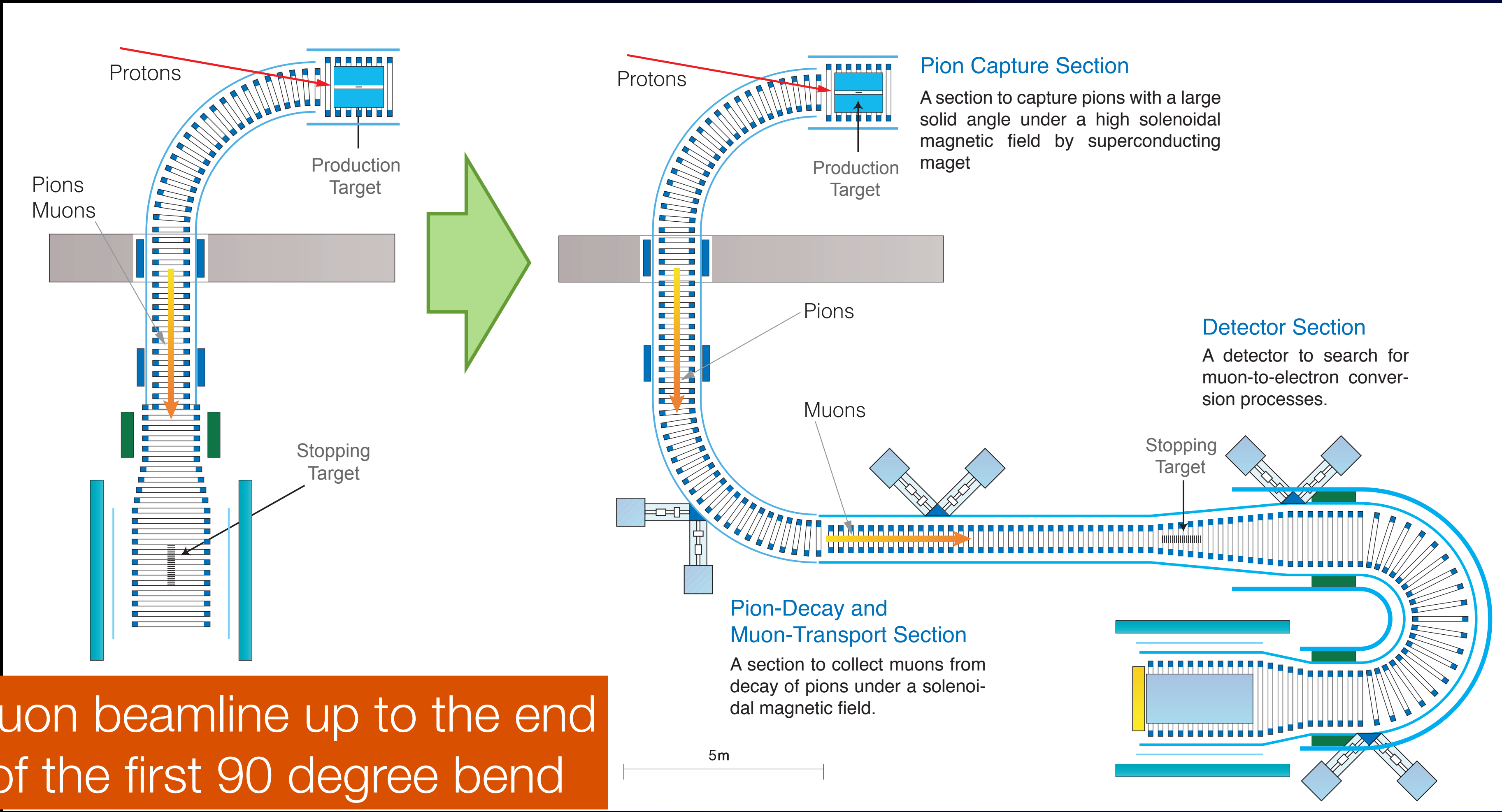
Five planes of straw tubes giving 0.4% momentum resolution



Crystal (e.g. LYSO, GSO) calorimeter with < 5% energy resolution

COMET staged approach

COMET Phase-I — COMET Phase-II



muon beamline up to the end of the first 90 degree bend

Goals of COMET Phase-I

1. Measurements of backgrounds for Phase II

   Poorly known, model dependent, have real measurements, reduce extrapolation, use actual beamline.

2. Search for cLFV via muon-to-electron conversion

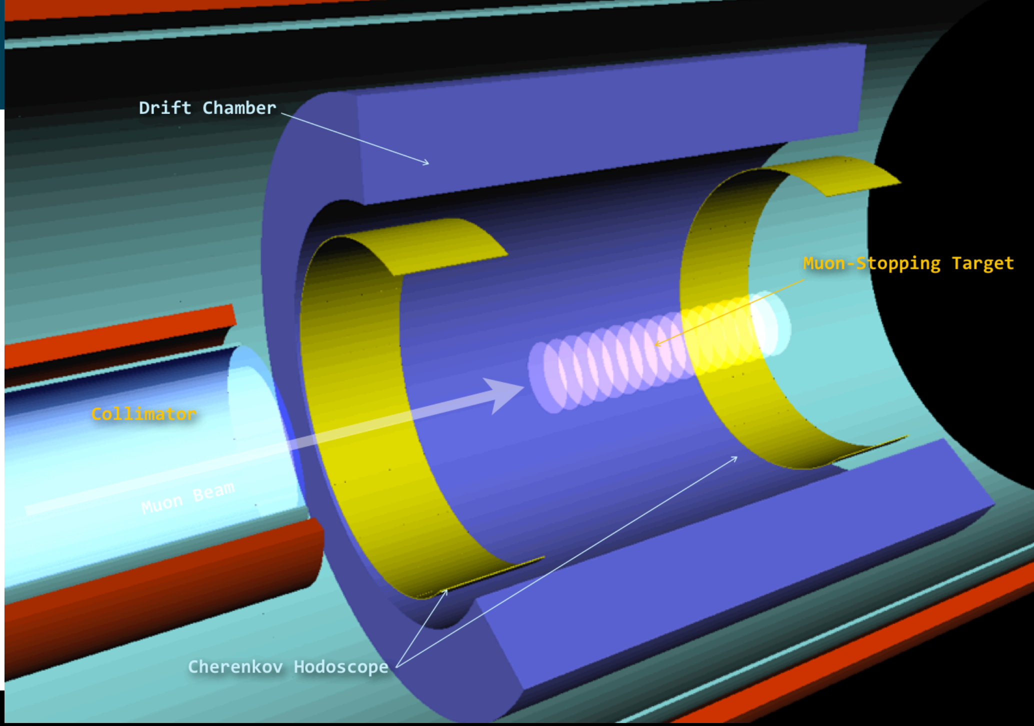
   Sensitivity 100 times better than SINDRUM-II limit with ~ 20 days running.

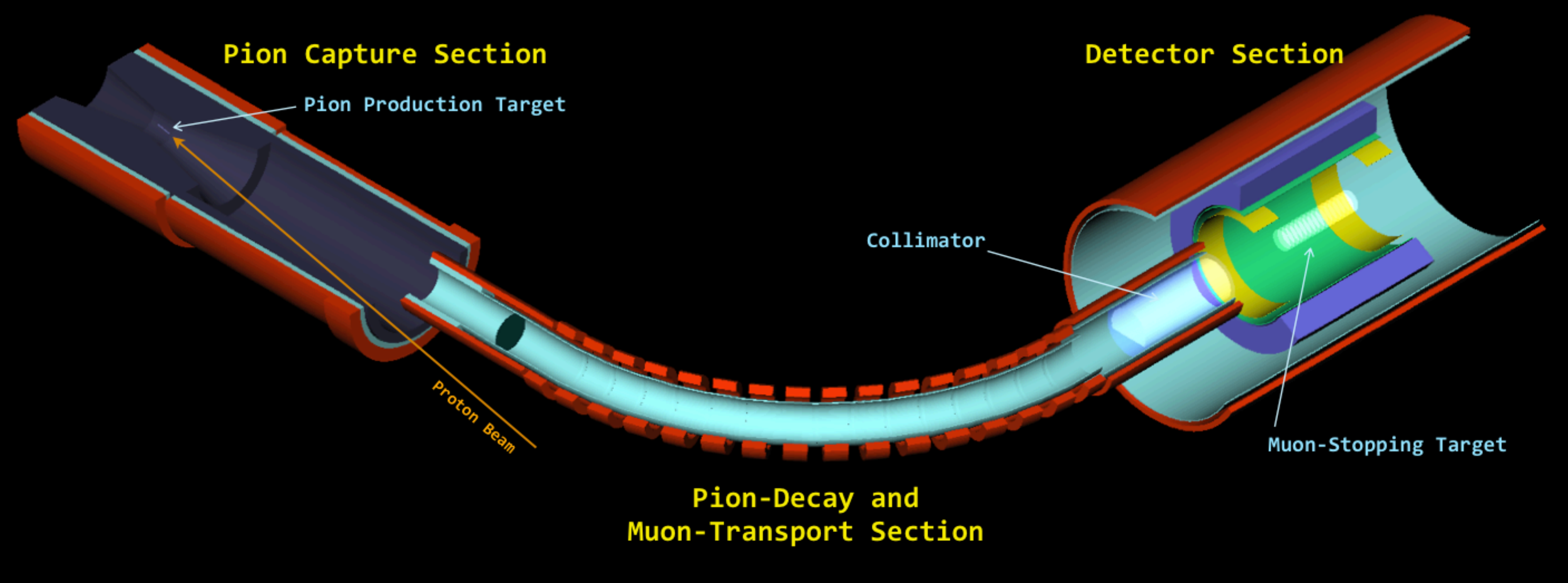
3. Demonstration of extinction below 10^{-9}

4. Testing final / prototype detectors

COMET Phase-I

Cylindrical detector gives lower backgrounds and larger acceptance to compensate the poorer resolution





COMET Phase-I sensitivity

Single event sensitivity

$$B(\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}) \quad = \quad \frac{1}{N_\mu^{\mathrm{stop}} \cdot f_{\mathrm{cap}} \cdot A_{\mu\text{-}e}}$$

N_μ = 8.7×10^{15}, number of muons stopped

f_{cap} = 0.6 is fraction of muons captured

$A_{\mu\text{-}e}$ = 0.06 is detector acceptance

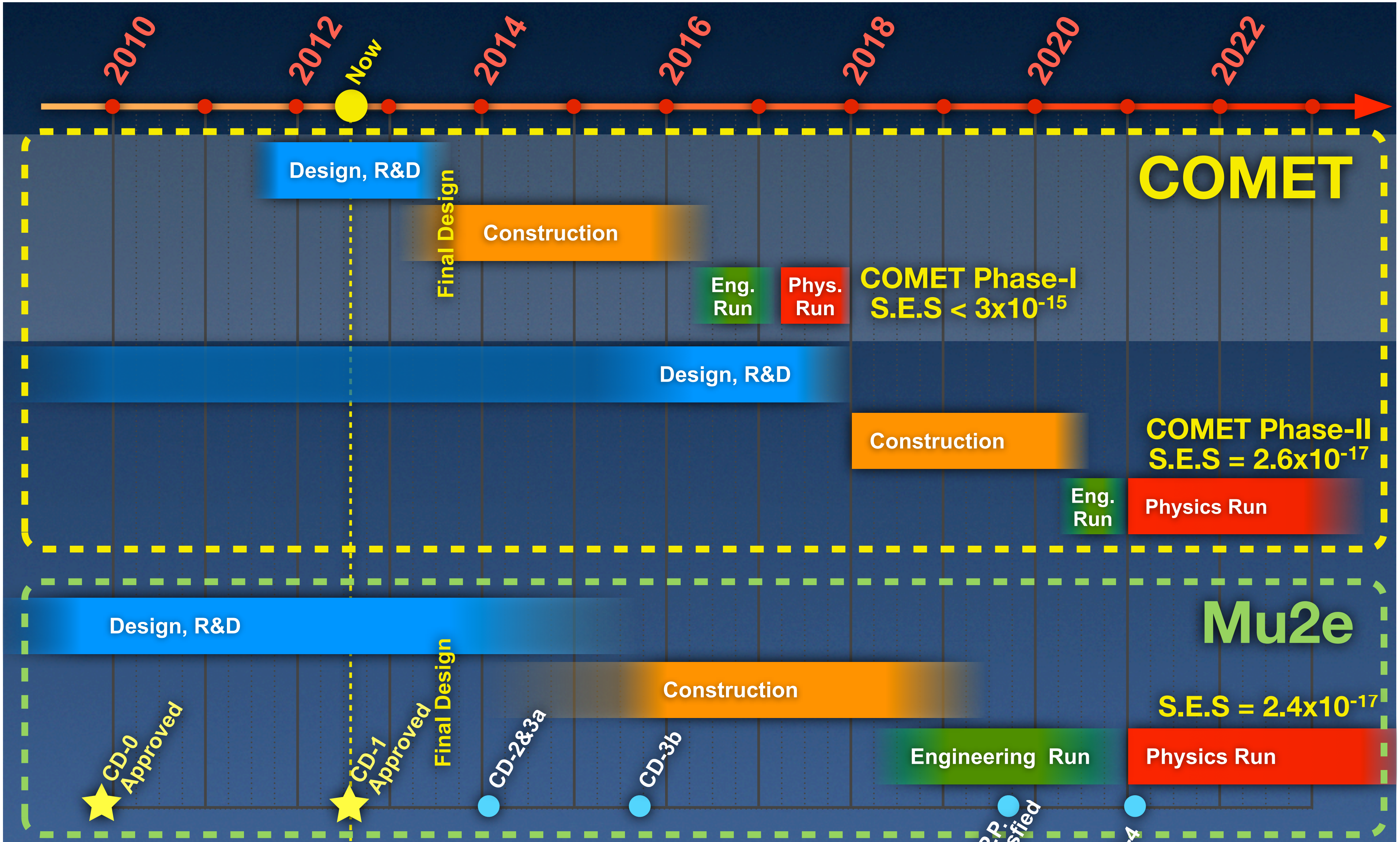
Event selection	Value	Comments
Geometrical acceptance	0.24	tracking efficiency included
Momentum selection	0.74	104.1 MeV/c < P_e <106 MeV/c
Timing selection	0.39	same as COMET
Trigger and DAQ	0.9	same as COMET
Total	0.06	

$$B(\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}) = 3.1 \times 10^{-15}.$$

Recall SINDRUM-II limit, 7×10^{-13}.

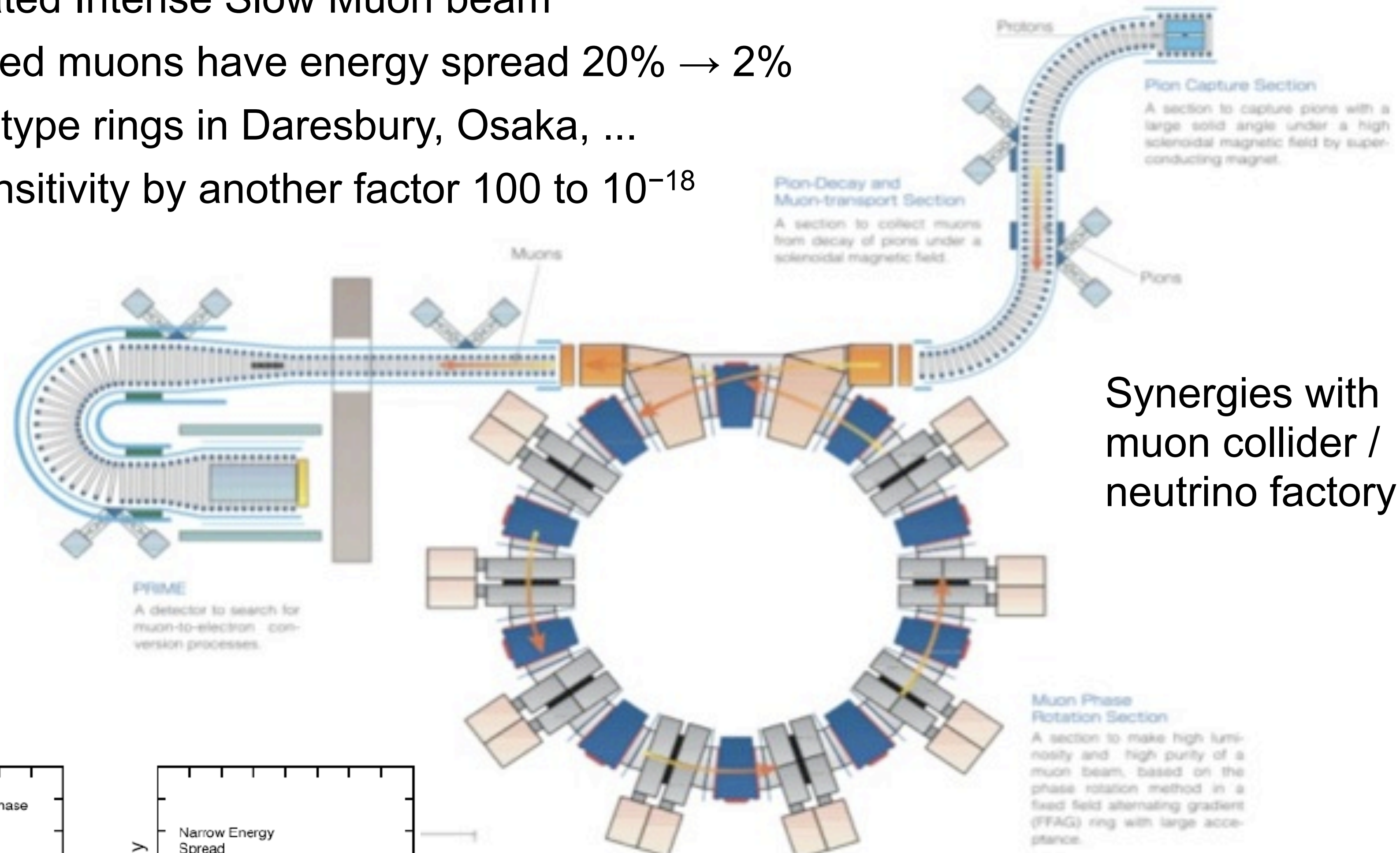
COMET Phase-I is an approved J-PARC project. Construction to start in 2013 and data-taking in 2016/17.

Schedule of COMET and Mu2e

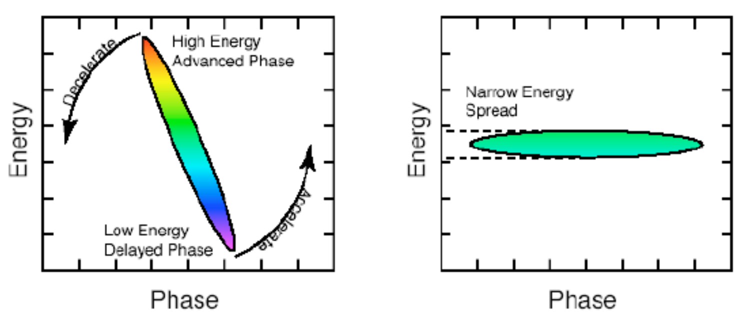


PRISM / PRIME experiment

- Phase Rotated Intense Slow Muon beam
- Phase rotated muons have energy spread 20% → 2%
- FFAG prototype rings in Daresbury, Osaka, ...
- Improve sensitivity by another factor 100 to 10^{-18}



Synergies with muon collider / neutrino factory



Site undecided : J-PARC, Project-X, ...

Summary

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There are a lot of exciting experiments at the intensity / precision frontier : rare *K* decays, EDMs, *B* physics, cLFV, etc.

Several planned experiments looking for charged lepton flavour violation : guaranteed BSM physics if understand backgrounds

COMET and Mu2e experiments a factor 10,000 better than previous experiment

COMET is following a staged approach to get new results sooner

New Collaborators are welcome

Back-up