Lepton Flavor Violation with muons

Giovanni Signorelli
INFN Sezione di Pisa - Italy

The landscape of flavour physics towards the intensity era
9–10 December, SNS Pisa (Italy)

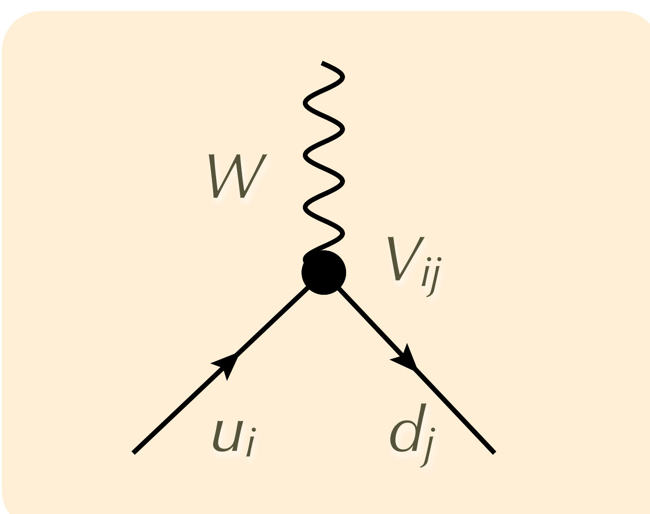
Outline

- (Charged) Lepton Flavour violation search experiments
  - complementary to quark flavor and CP
- Observables towards new physics
- The "classical searches"
  - $\mu \to e\gamma$
  - $\mu \to 3e$
  - $\mu N \to eN$
- Status and perspectives

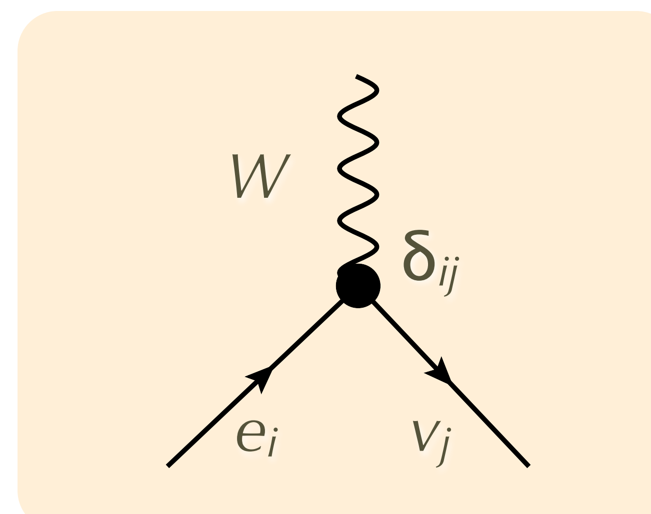
Flavor in the SM

- Unlike the quark sector, lepton flavor transitions are forbidden in the SM due to the vanishing neutrino masses
- Coupling between different generations are present in the charged current and in the mass term
  - possibility to diagonalize simultaneously the lepton part, not the quark

$$J^\mu = \bar{d}'_L \gamma_\mu U_L^{d\,\dagger} U_L^u u'_L + \bar{e}'_L \gamma^\mu U_L^{e\,\dagger} \nu_L \qquad Y_d^{ij} \bar{Q}_{Li} \phi D_{Rj} + Y_u^{ij} \bar{Q}_{Li} \bar{\phi} U_{Rj} + Y_e^{ij} \bar{L}_{Li} \phi E_{Rj}$$



V_{CKM}

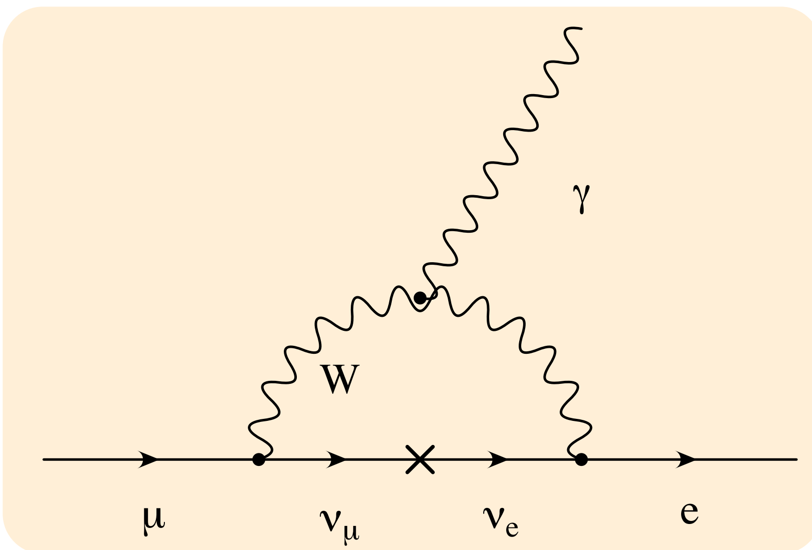


$\mathbb{1}$

- In the SM lepton flavor transition are forbidden
- Nevertheless neutrino oscillations were observed $\nu_i \longrightarrow \nu_j$
  - Flavor transitions in the (neutral) lepton sector
  - νSM

charged Lepton Flavor Violation

- neutrino masses and mixings induces cLFV decays radiatively in the SM is by at a negligible level



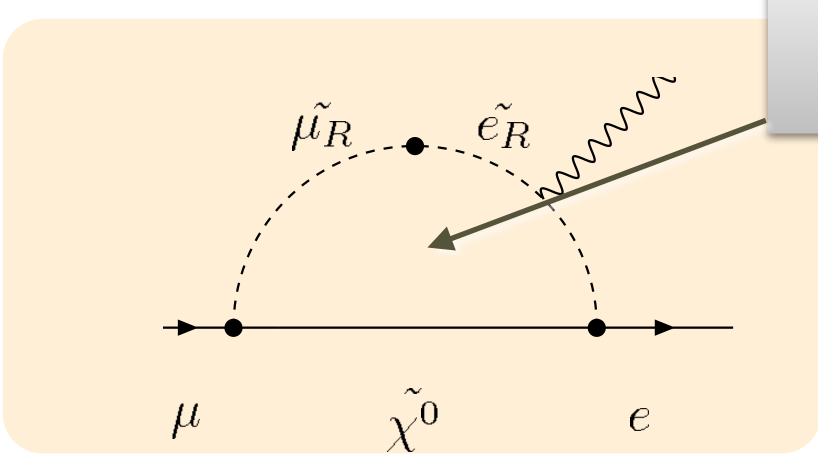
$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

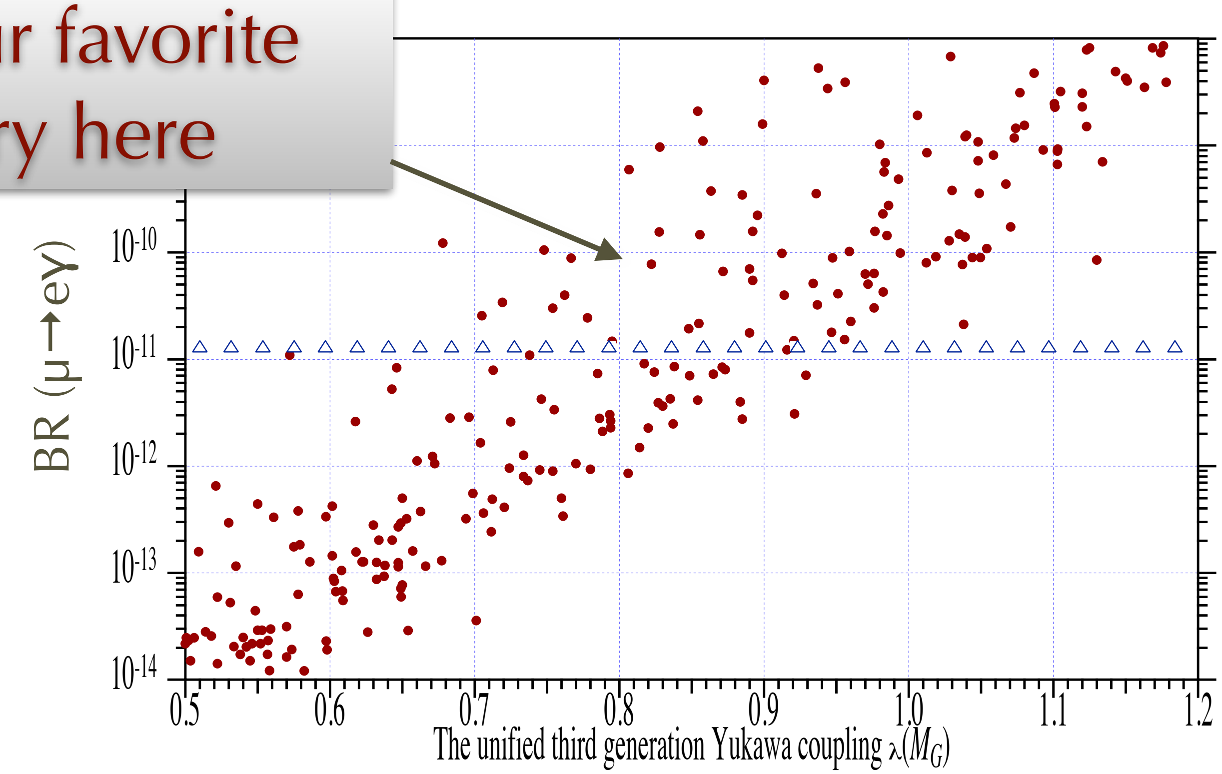
$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{3\alpha}{32\pi} \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

relative probability ~ 10^{-54}

- All SM extensions enhance the rate through mixing in the high energy sector of the theory (other particles in the loop...)

Put your favorite theory here



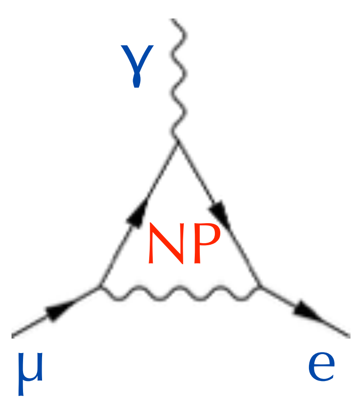


- Clear evidence for physics beyond the SM
  - background-free
- Restrict parameter space of SM extensions

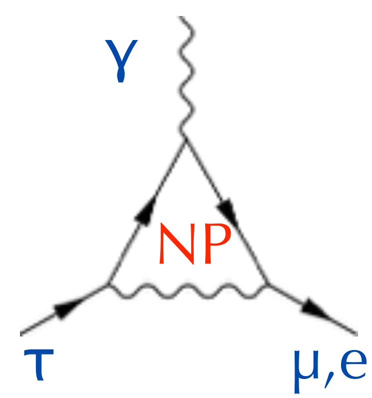
Many processes

- LFV is related to "new" lepton-lepton couplings and effective operators

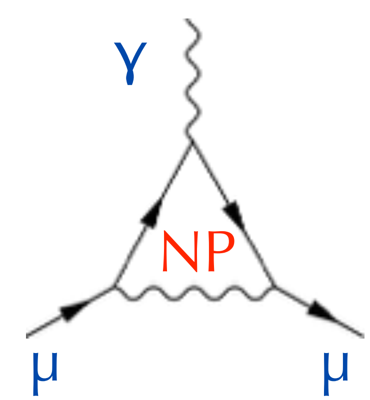
$$\frac{1}{\Lambda}\,\bar{\ell}_i \sigma_{\mu\nu} \ell_j F^{\mu\nu} \qquad\qquad \frac{1}{\Lambda^2}\,\bar{\ell}_i \gamma_\mu \ell_j (\bar{q}_k \gamma^\mu q_m + \bar{\ell}_k \gamma^\mu \ell_m)$$



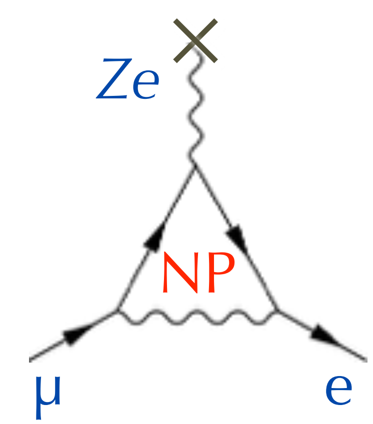
$\mu \to e\gamma$



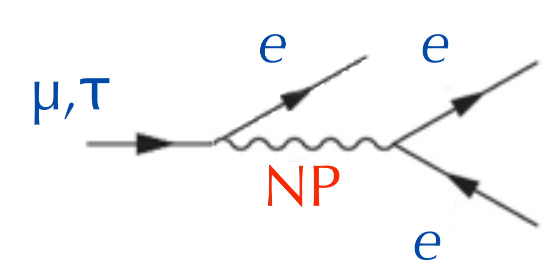
$\tau \to \mu\gamma$
$\tau \to e\gamma$



$(g-2)_\mu$

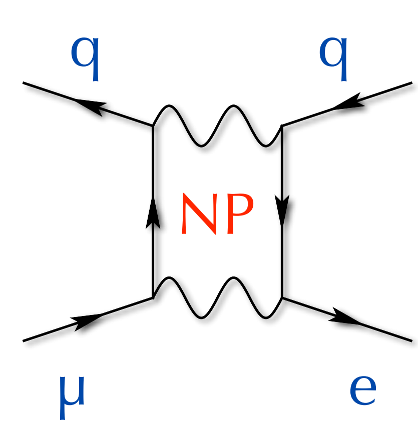


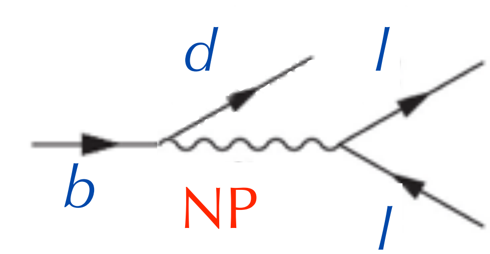
$\mu^- \mathcal{N} \to e^- \mathcal{N}$



$\mu \to eee$

- A wide field of research
  - LFV decays of leptons
  - Anomalous magnetic moment for the μ
  - Muon-to-electron conversion
  - LFV in meson decays

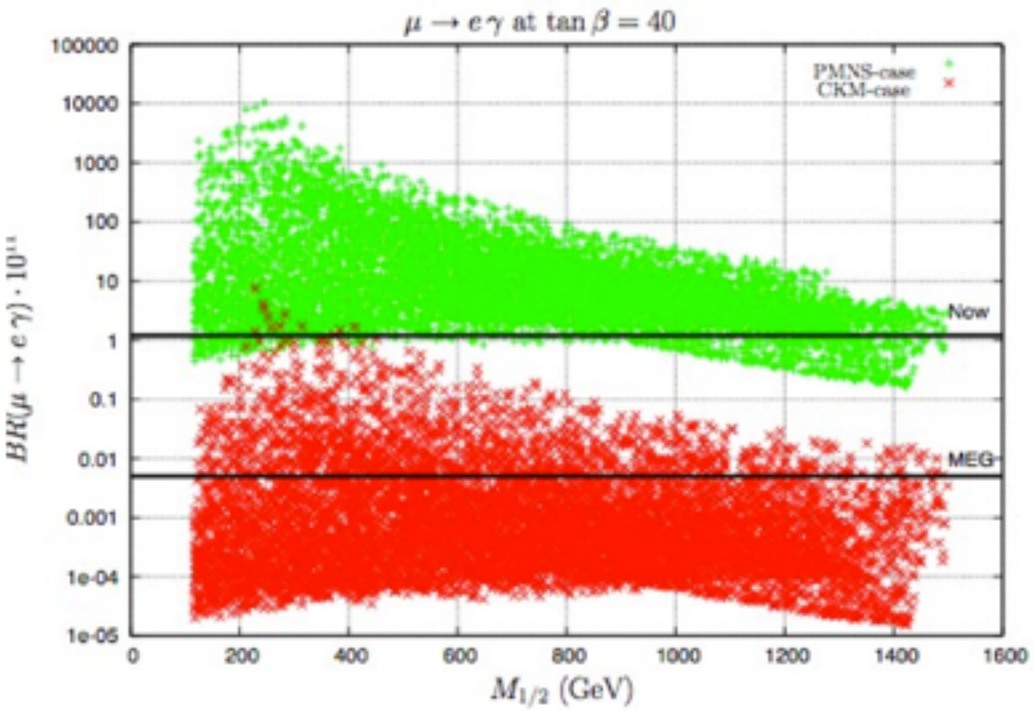


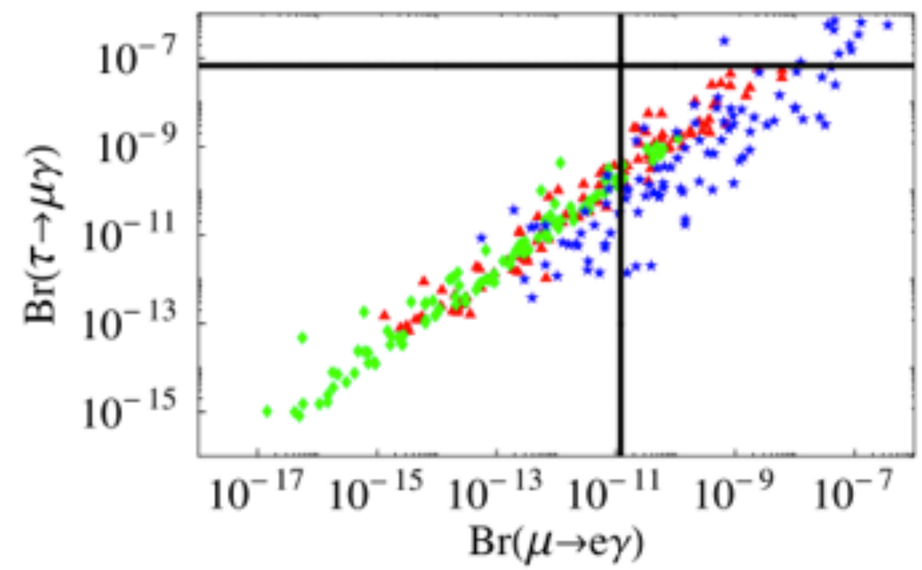


$B \to \ell\bar{\ell}'$
$B \to \ell\bar{\ell}' X_s$

Processes are correlated

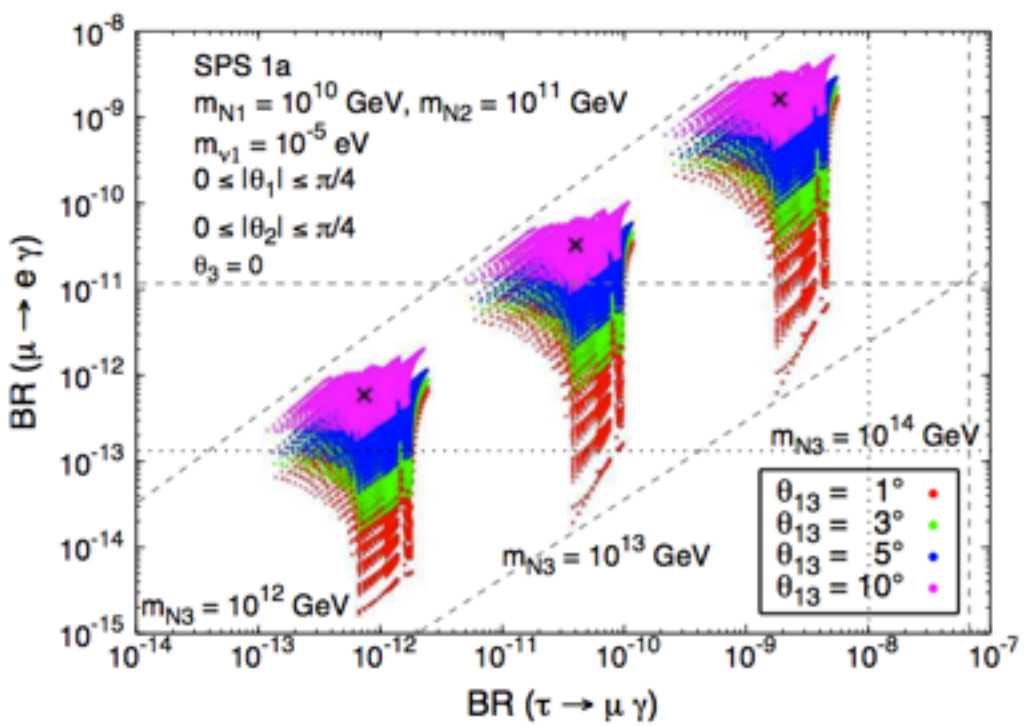
- Model-dependent correlations

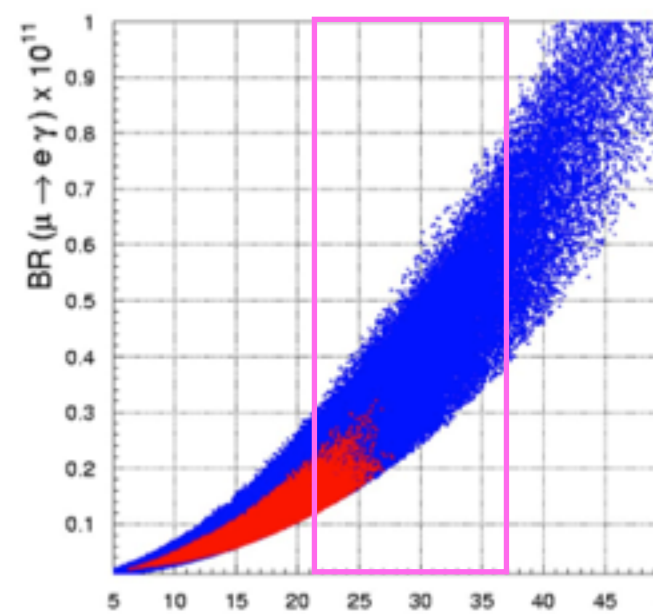




Large ϑ_{13}

Higgs & No Susy

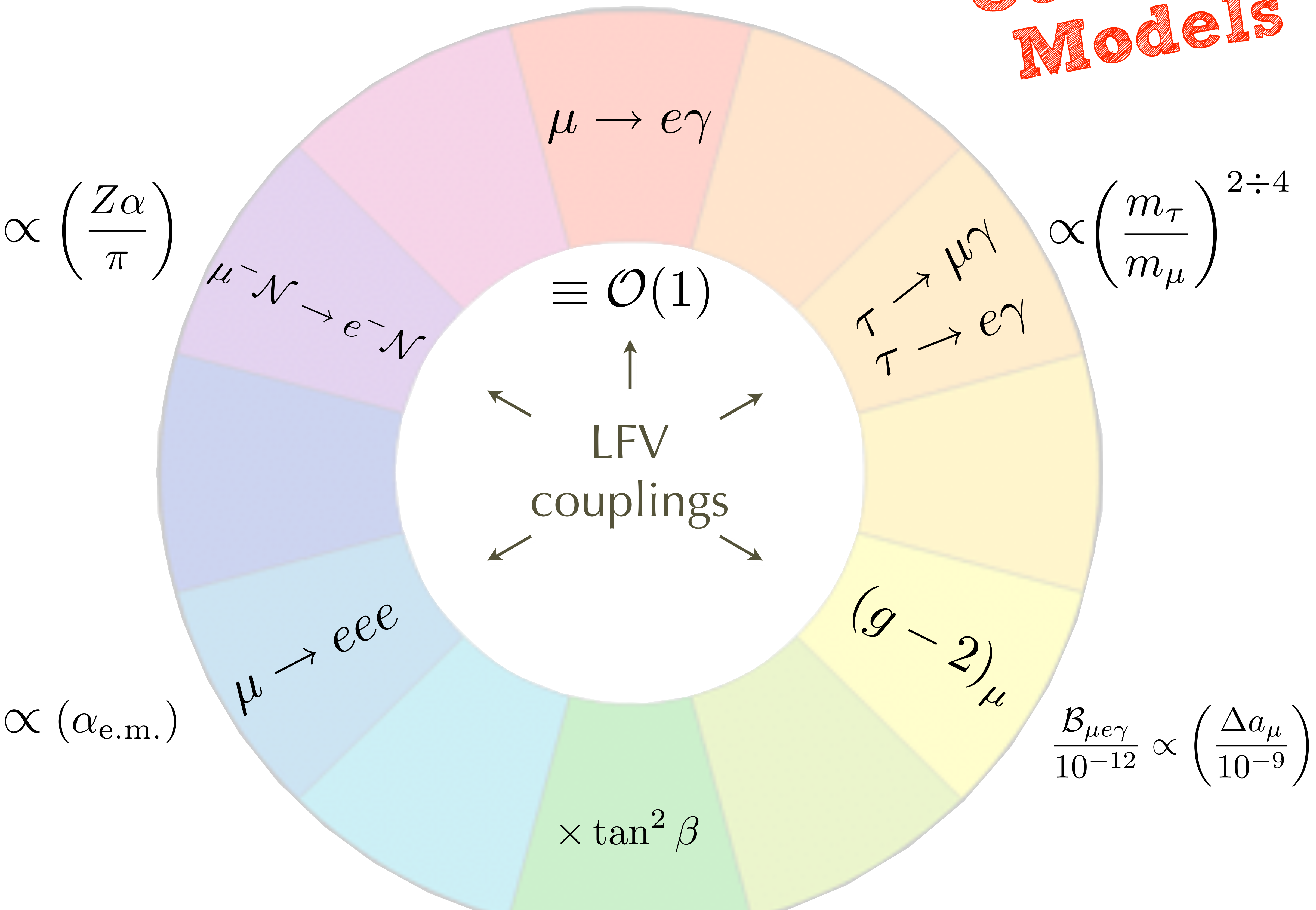




Barbieri *et al,*, Nucl. Phys B445 (1995) 225
Hisano *et al.*, Phys. Lett. B391 (1997) 341
Masiero *et al.*, Nucl. Phys. B649 (2003) 189
Calibbi *et al.*, Phys. Rev. D74 (2006) 116002
Isidori *et al.*, Phys. Rev. D75 (2007) 115019
...

The CLFV wheel

Common Models



Present limits

SINDRUMII

$\mathcal{B}(\mu\mathrm{Ti} \to e\mathrm{Ti}) < 4.3 \times 10^{-12}$

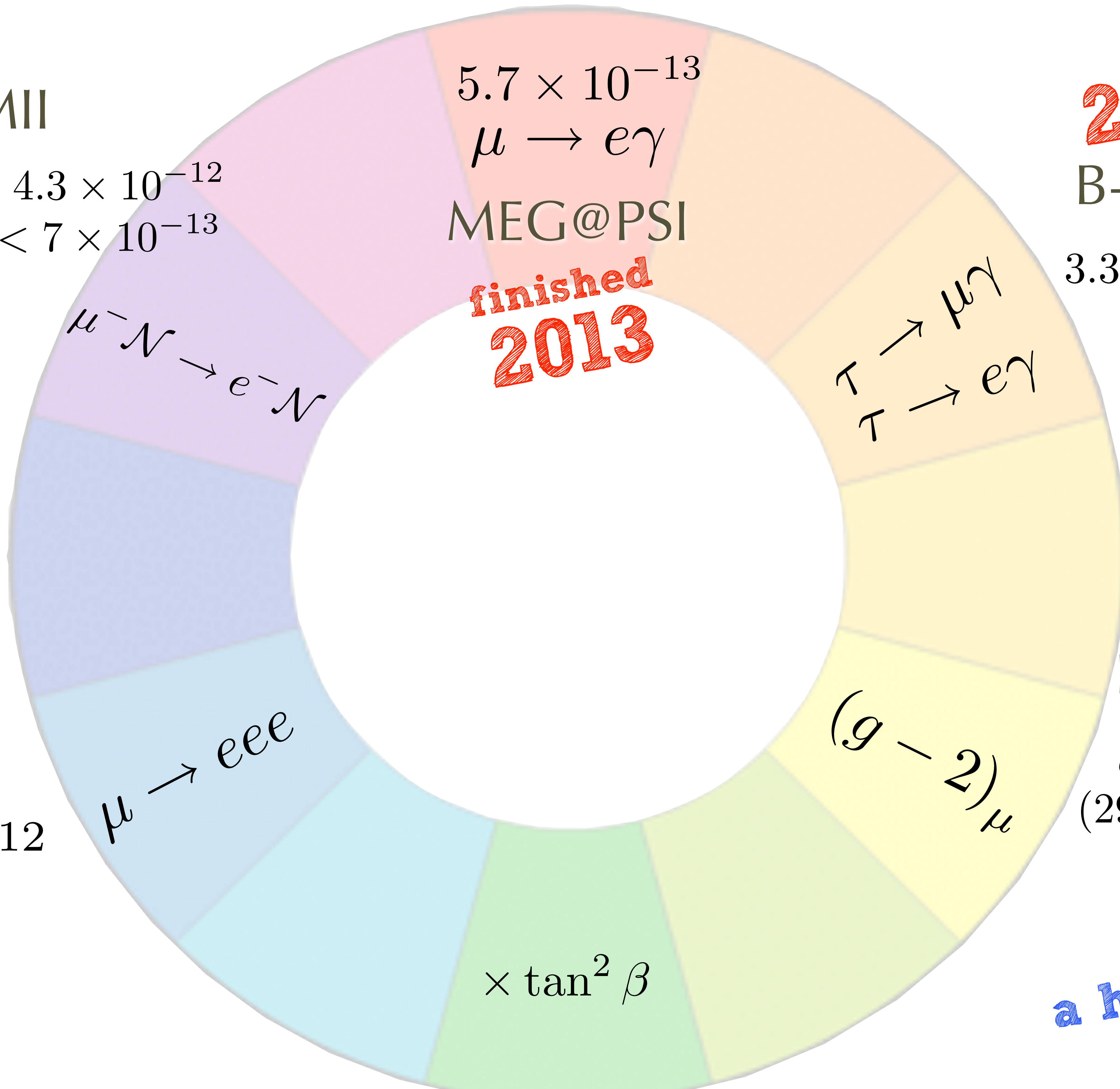
$\mathcal{B}(\mu\mathrm{Au} \to e\mathrm{Au}) < 7 \times 10^{-13}$

2006

2012

B-factories

$3.3 \div 4.5 \times 10^{-8}$



BNL E821

$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (296 \pm 81) \times 10^{-11}$

2004

a hint for NP?

SINDRUM

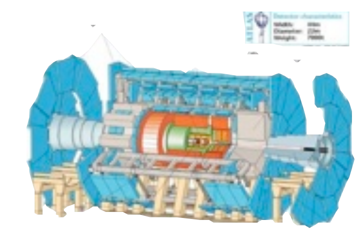
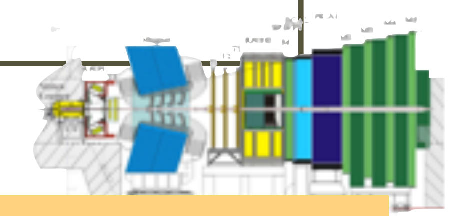
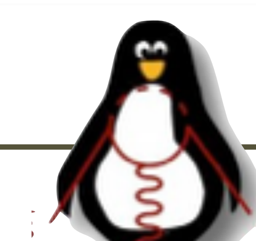
1×10^{-12}

1988

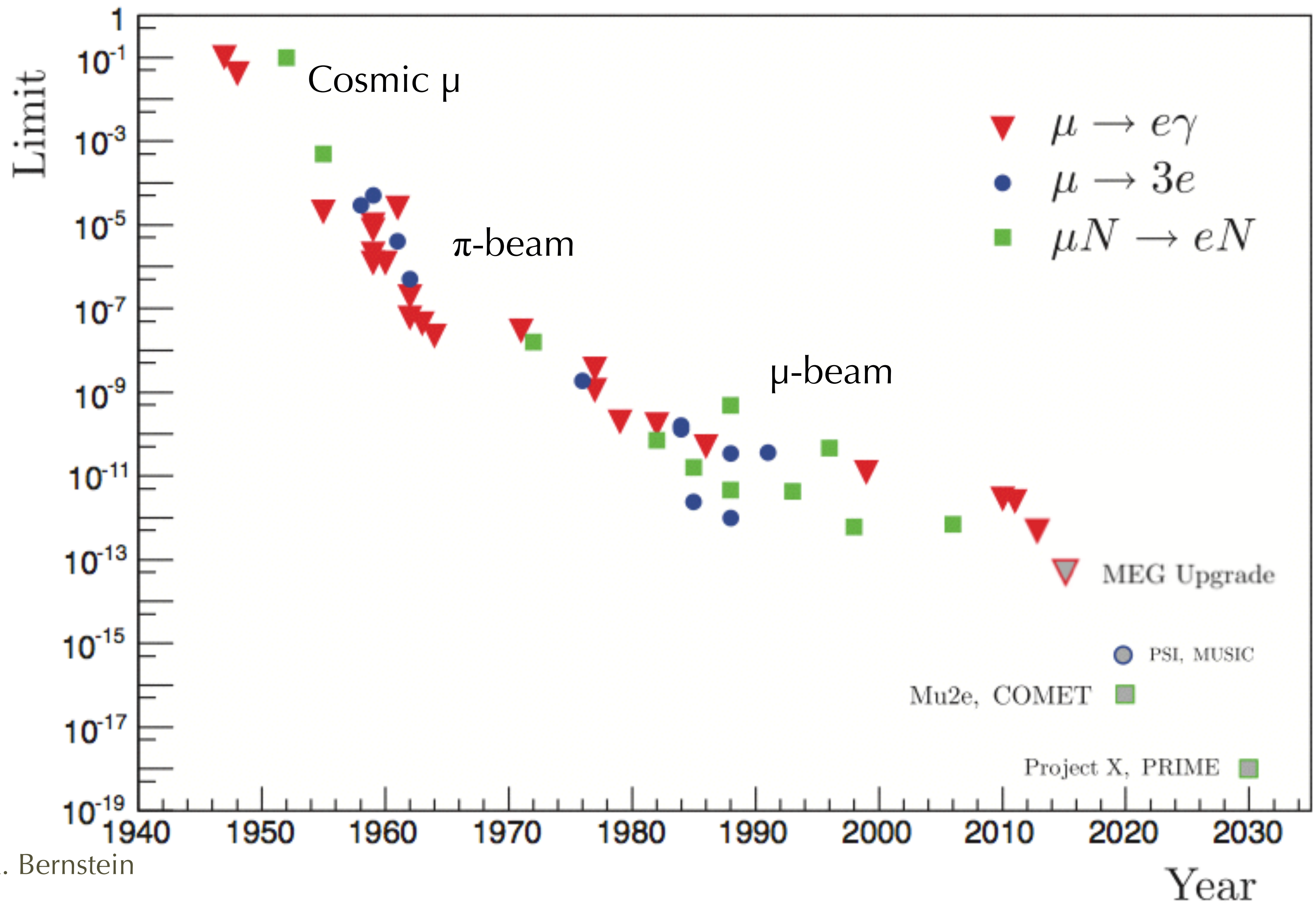
Experimental effort

	Dedicated experiment	Multi-purpose experiment
Exotic Searches New Physics Experiment	$\mu \to e\gamma$ $\mu \to eee$ $\mu^- N \to e^- N$	$\tau \to \mu\gamma$ $\tau \to e\gamma$ $K_L^0 \to \mu e$ $Z' \to e\mu$ $\tau \to 3\ell$
BSM physics NP SM Theory	e, μ, n edm $(g-2)_\mu$ $(g-2)_e$ $\frac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}$ $K_L^0 \to \pi^0\nu\nu$	$B \to \mu\mu$ $b \to s\gamma$ $\frac{\tau \to e\nu\nu}{\tau \to \mu\nu\nu}$ $K^+ \to \pi^+\nu\nu$

Experimental effort

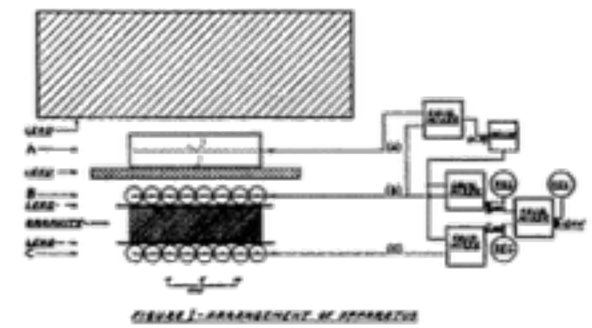
	Dedicated experiment	Multi-purpose experiment
Exotic Searches New Physics Experiment	$\mu \to e\gamma$ $\mu \to eee$ $\mu^- N \to e^- N$	$\tau \to \mu\gamma$ $\tau \to e\gamma$ $K_L^0 \to \mu e$ $Z' \to e\mu$ $\tau \to 3\ell$  
BSM physics NP SM Theory	e, μ, n edm $(g-2)_\mu$ $(g-2)_e$ $\frac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}$ $K_L^0 \to \pi^0 \nu\nu$ 	 $B \to \mu\mu$ I will concentrate on the "classical" searches $K^+ \to \pi^+ \nu\nu$ 

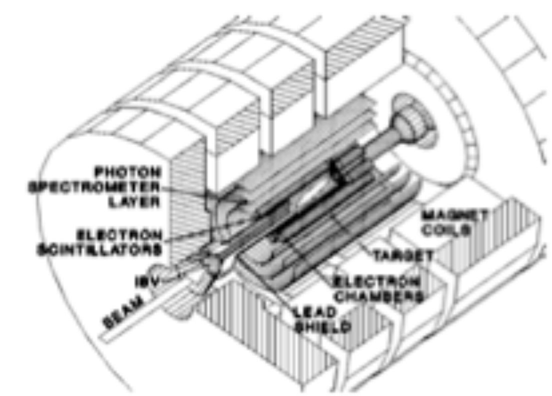
65 years of searches



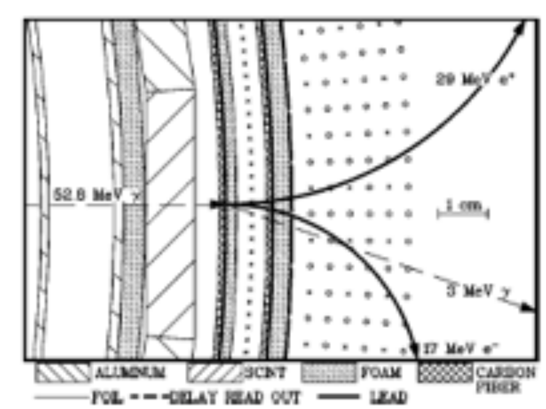
R. Bernstein

Hinks & Pontecorvo



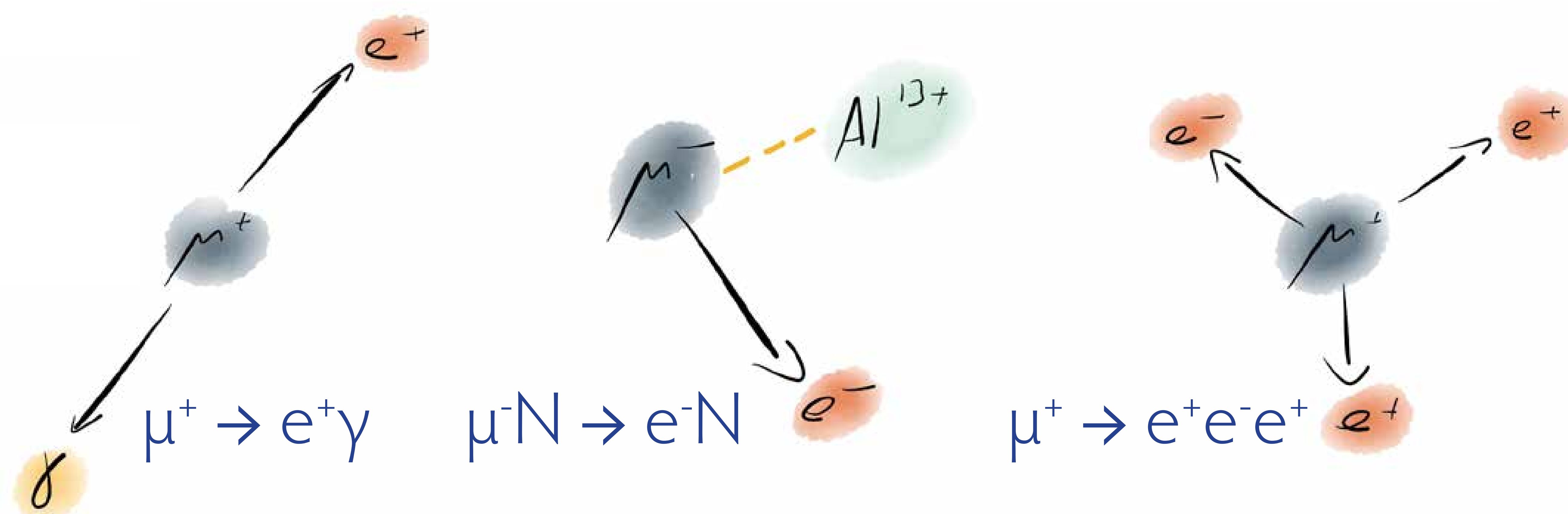


MEGA



- Each improvement linked to beam and detector technology
- Trade-off between sub-detectors to achieve the best “sensitivity”

Kinematics



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

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

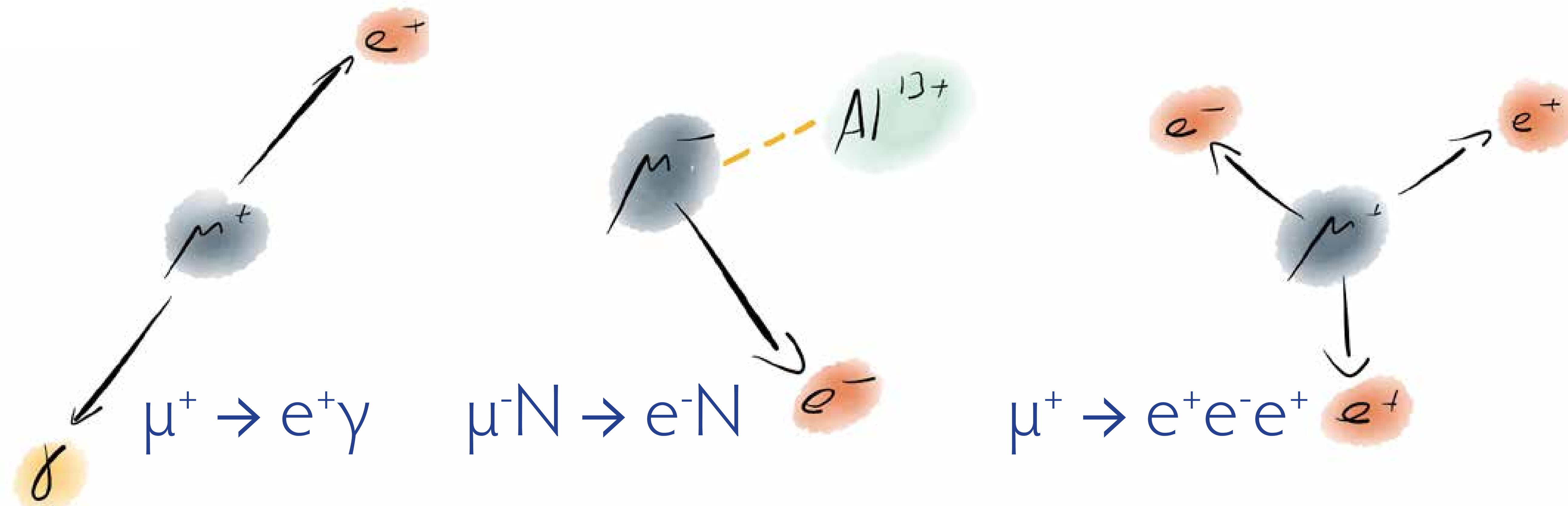
Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma\, p_i = 0$

Background



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

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Background

- Accidental background

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

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Background

- Decay in orbit
- Antiprotons, pions

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

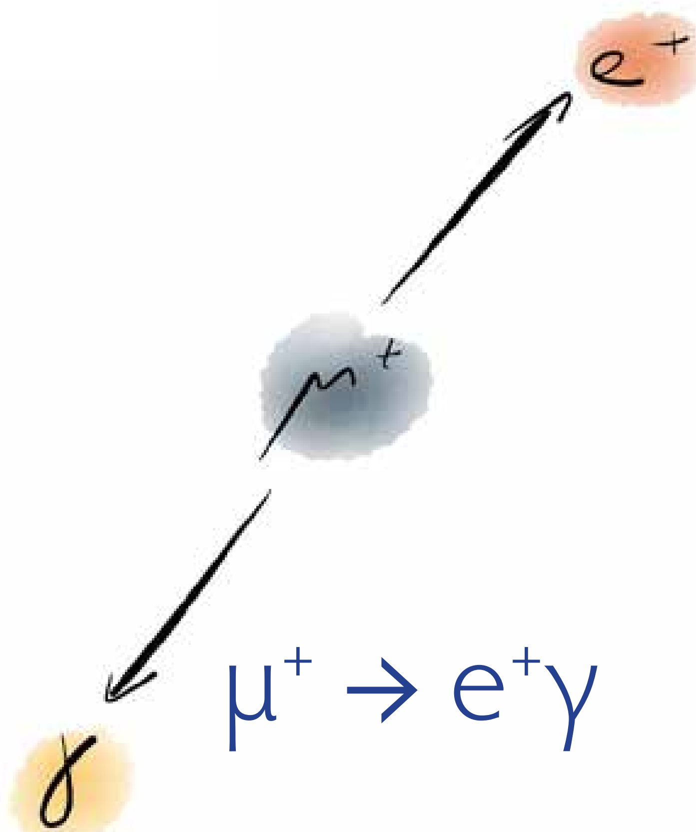
Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma p_i = 0$

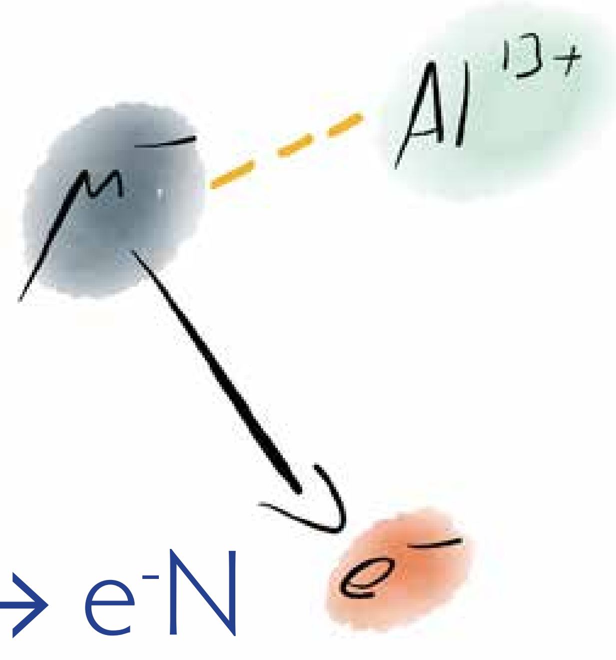
Background

- Radiative decay
- Accidental background

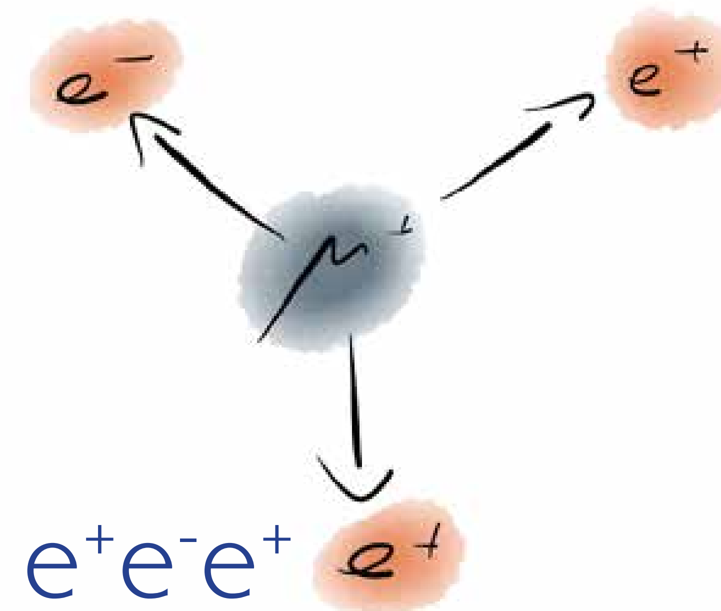
Beam requirements



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



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



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

Continuous Beam

Kinematics

- 2-body decay
- Monoenerge
- Back-to-b

Backgro

- A ...al background

Pulsed Beam

Kinematics

- Quasi 2-body d
- Monoenerge
- Single p ... etected

Backgro

- D ... orbit
- A ... protons, pions

Continuous Beam

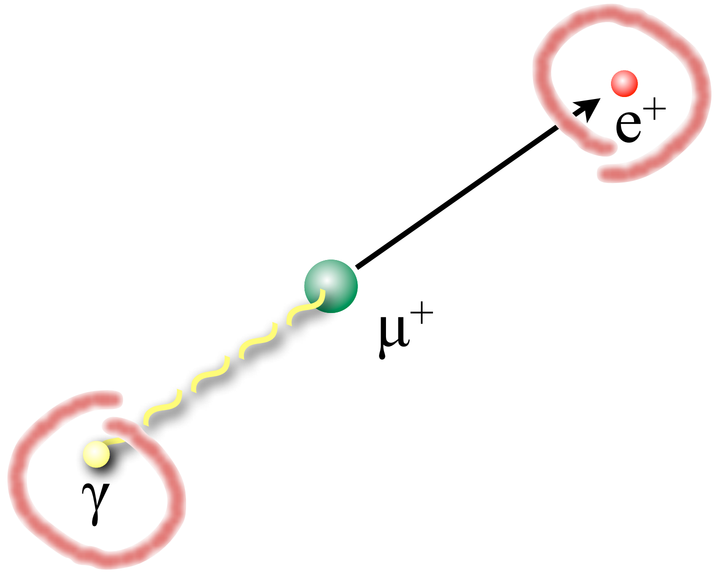
Kinematics

- 3-body decay
- Invariant mas ... aint
- $\Sigma p_i = 0$

Backgro

- R ... decay
- Ac ... ental background

MEG experimental method



PDF parameters	Present MEG
e^+ energy (keV)	306 (core)
e^+ θ (mrad)	9.4
e^+ ϕ (mrad)	8.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7
γ position (mm) $u/v/w$	5 / 5 / 6
γ-e^+ timing (ps)	122

PAUL SCHERRER INSTITUT

- μ: stopped beam of 3 x 10^7 μ /sec in a 205 μm polyethylene target

  - PSI πE5 beam line: 29 MeV μ^+

- e^+ detection

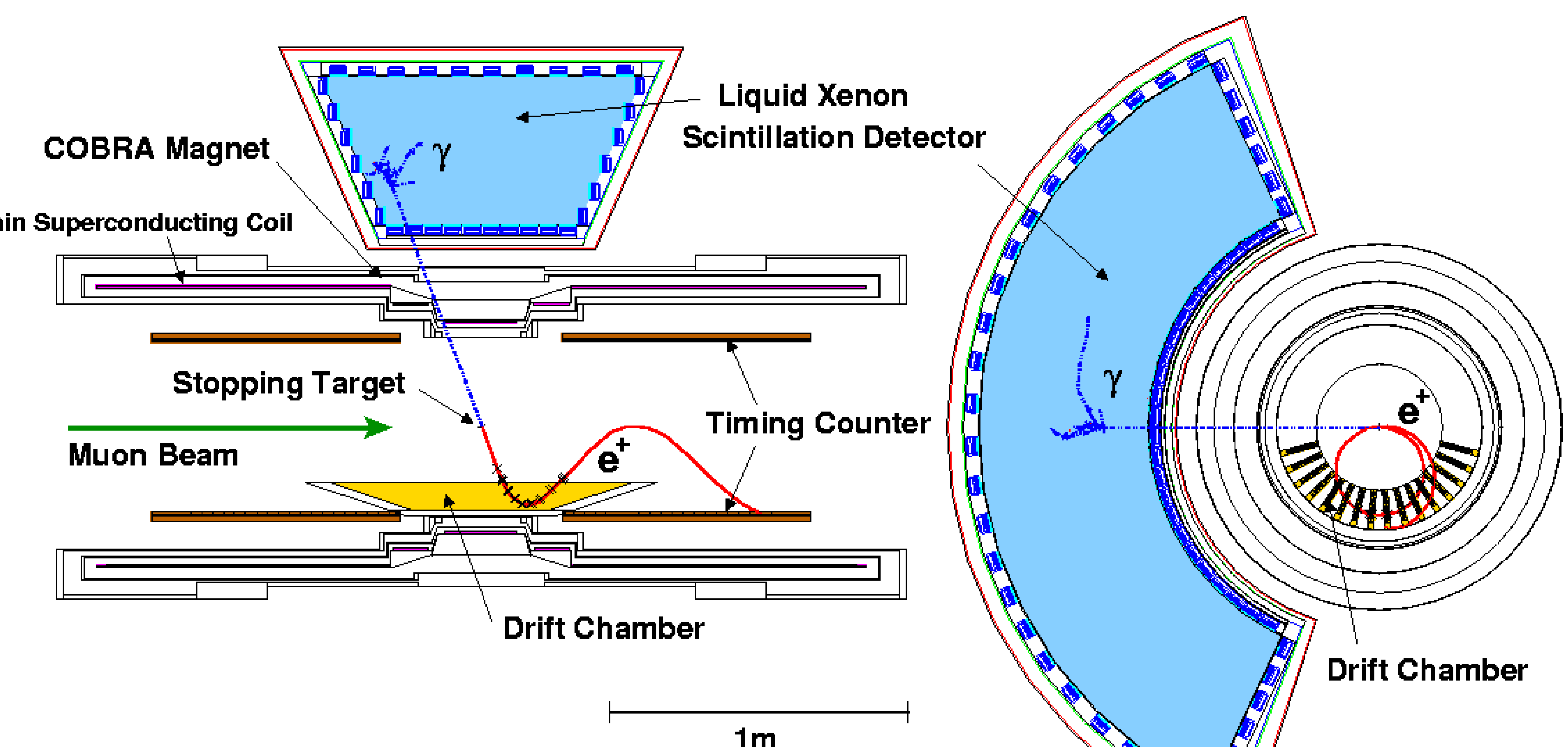
  magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum

  plastic counters for timing

- γ detection

  Liquid Xenon detector based on the scintillation light

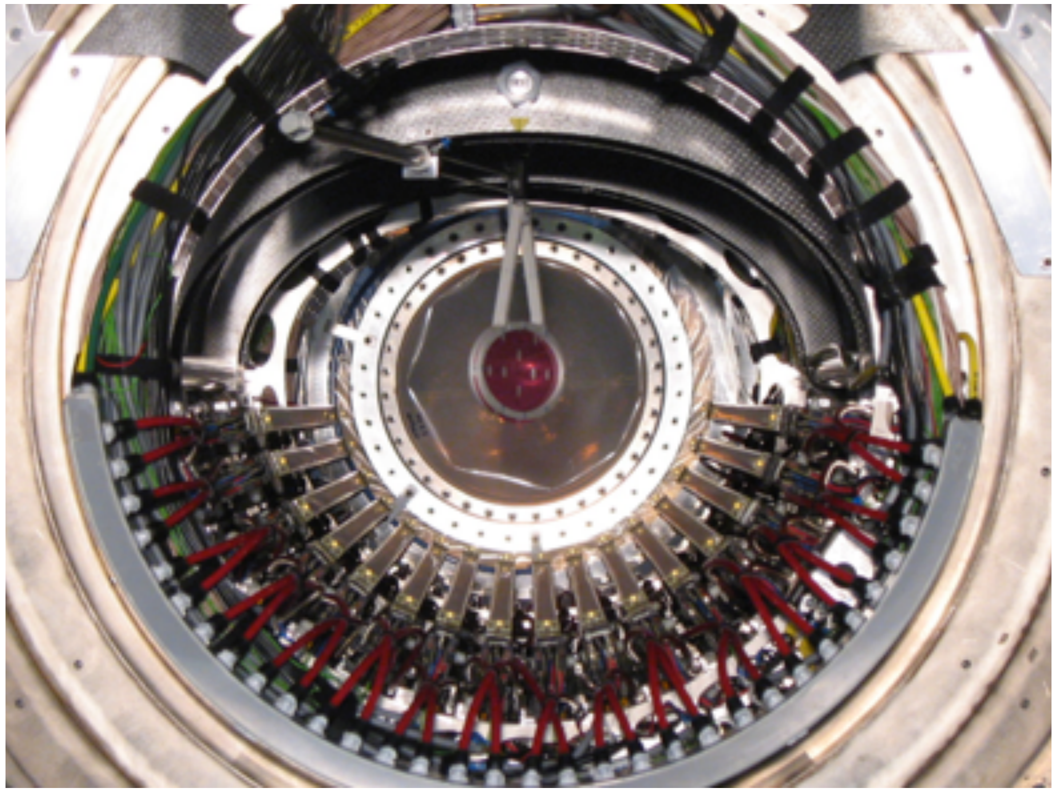
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm



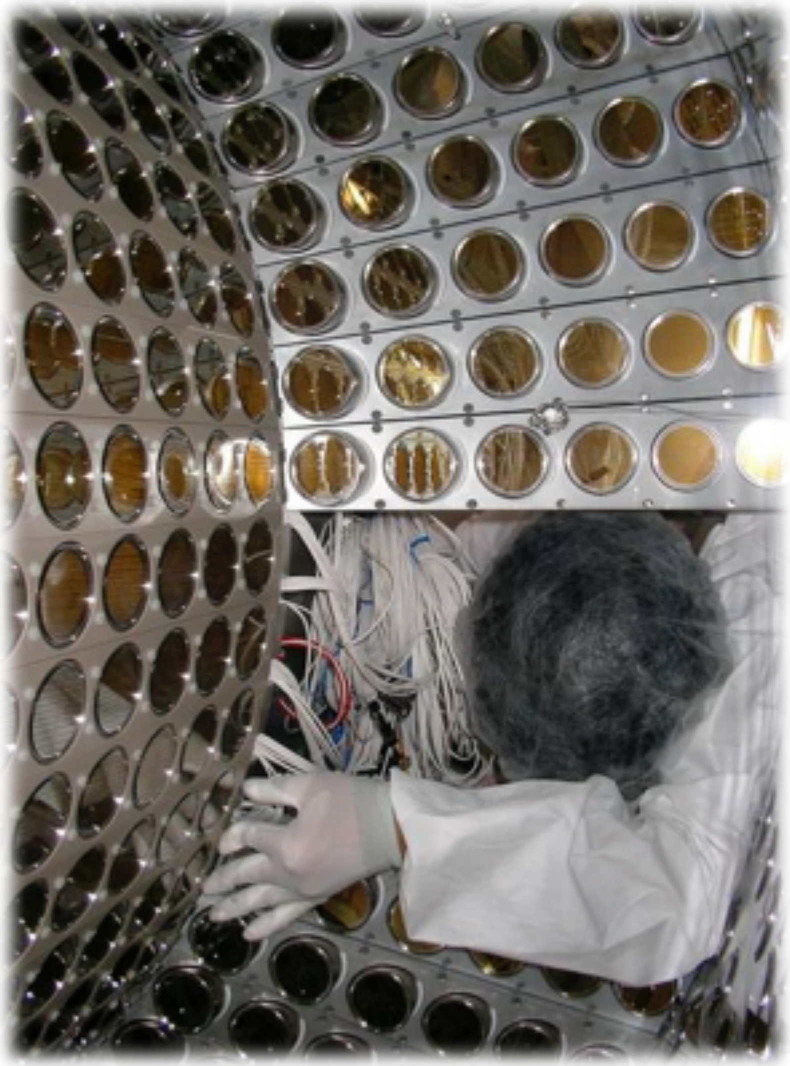
Easy signal selection with
μ^+ at rest

Some detector pictures

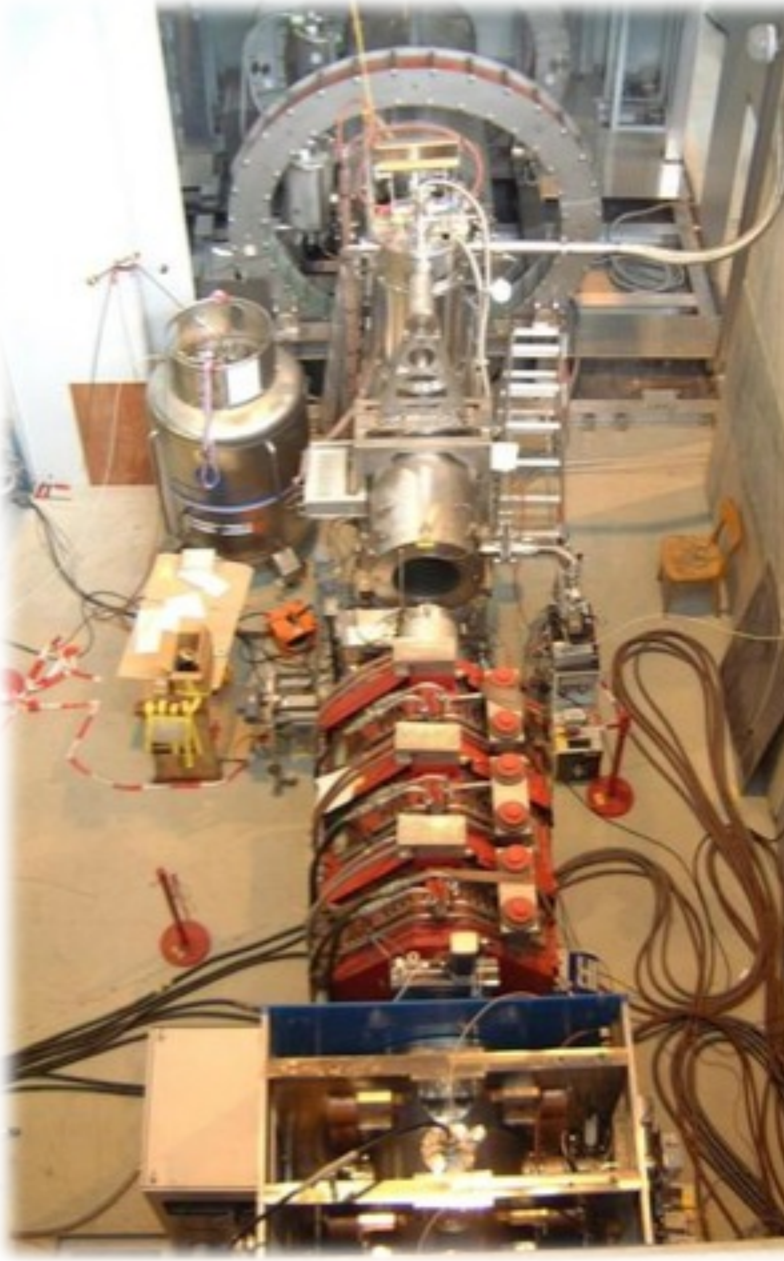
DC system



LXe detector



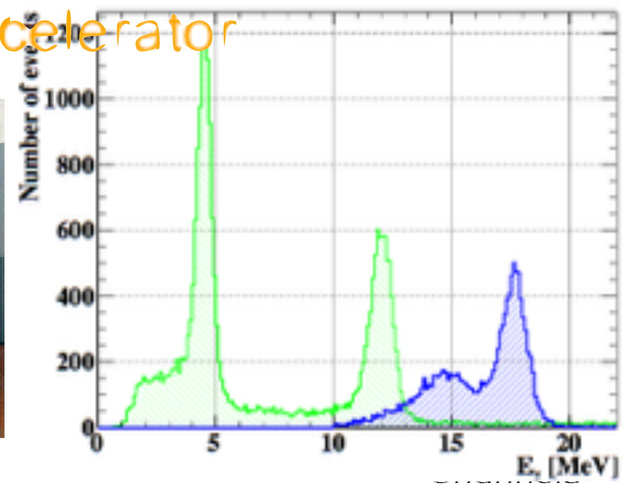
Beam Line



Calibration & Monitoring

Detector Calibration

Proton Accelerator



Li(p,γ)Be

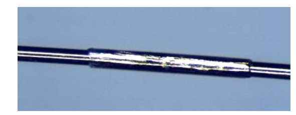
LiF target at COBRA center

17.6MeV γ

~daily calib.

also for initial setup

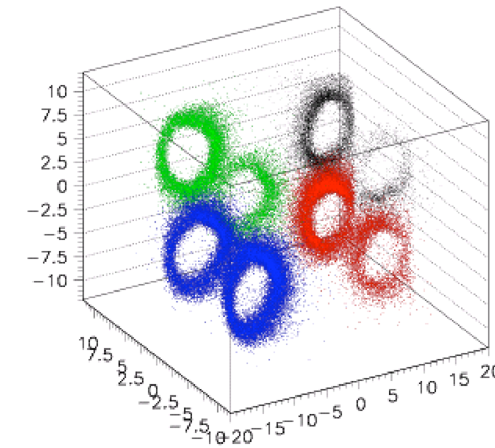
Alpha on wires



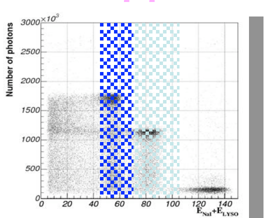
PMT QE & Att. L

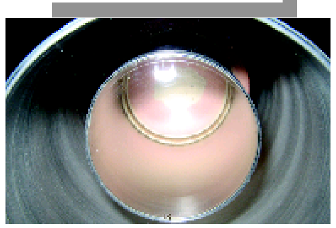
Cold GXe

LXe



$\pi^0 \rightarrow \gamma\gamma$



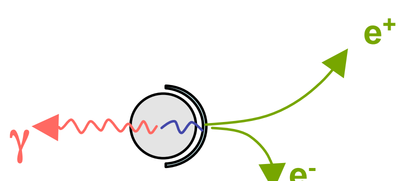


$\pi^- + p \rightarrow \pi^0 + n$

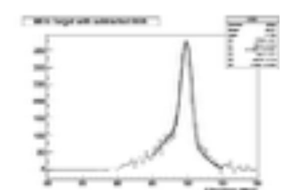
$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

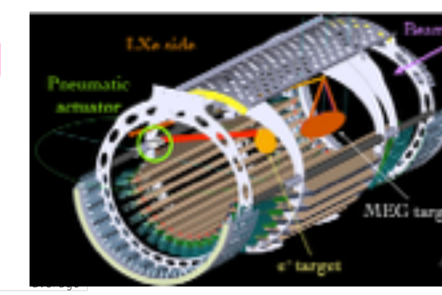
$\pi^- + p \rightarrow \gamma + n$ (129MeV)

LH_2 target

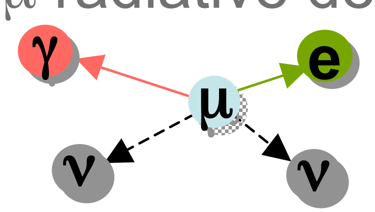


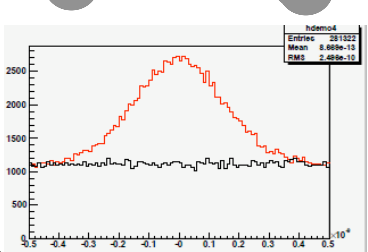
Mott e+ scattering





μ radiative decay



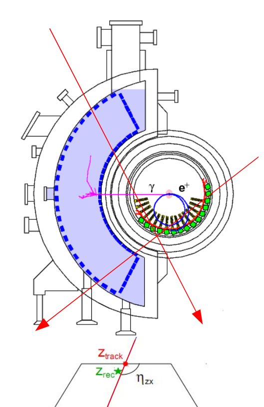


Lower beam intensity < 10^7

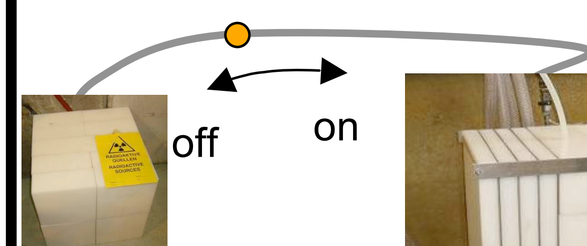
Is necessary to reduce pile-ups

A few days ~ 1 week to get enough statistics

Cosmic ray alignment

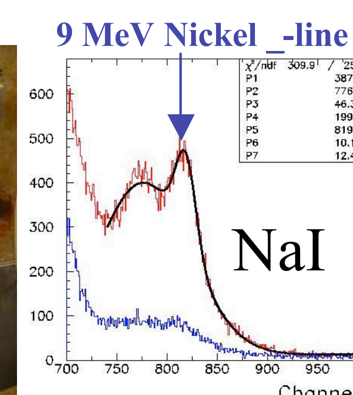


Nickel γ Generator

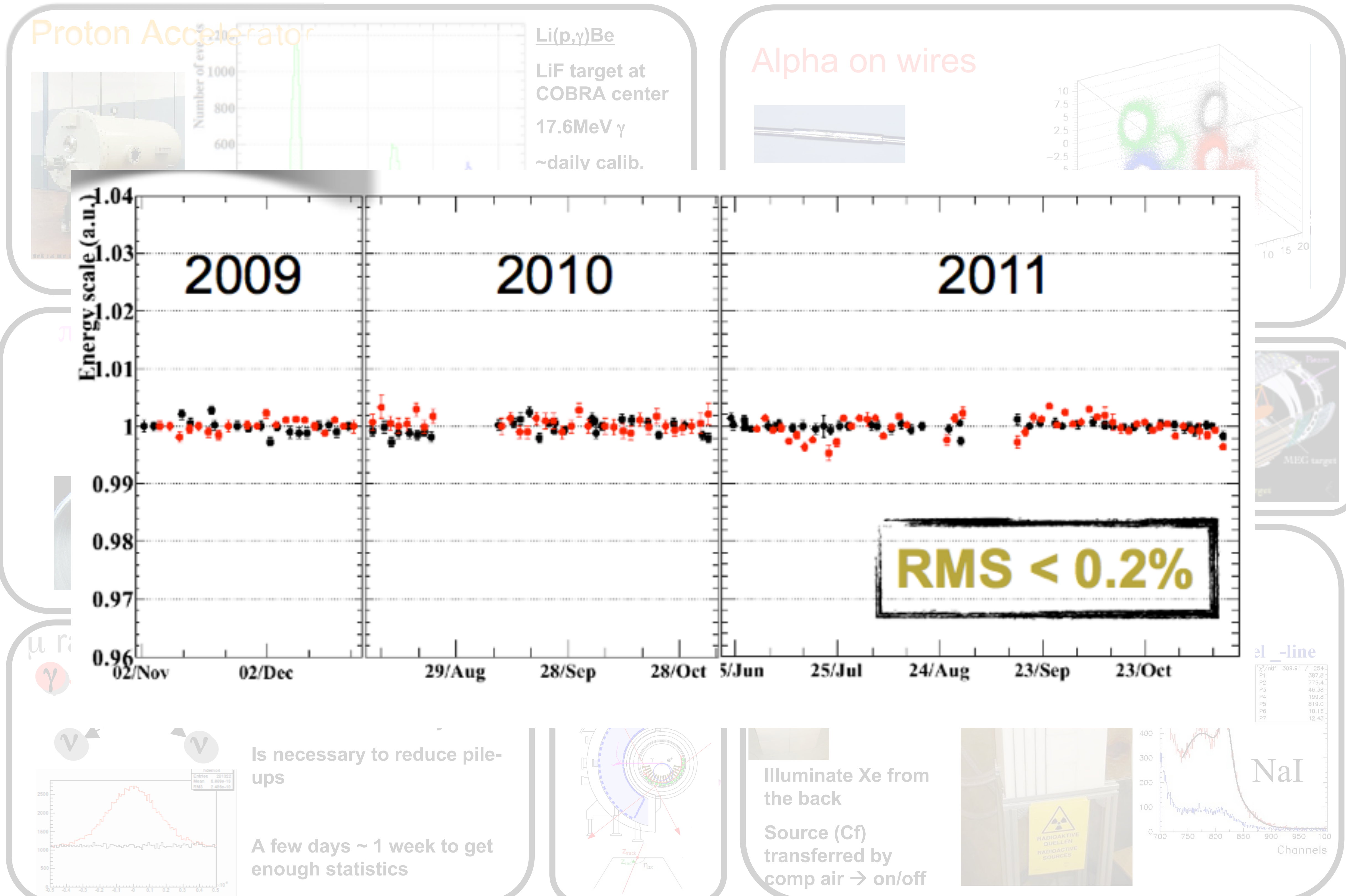


Illuminate Xe from the back

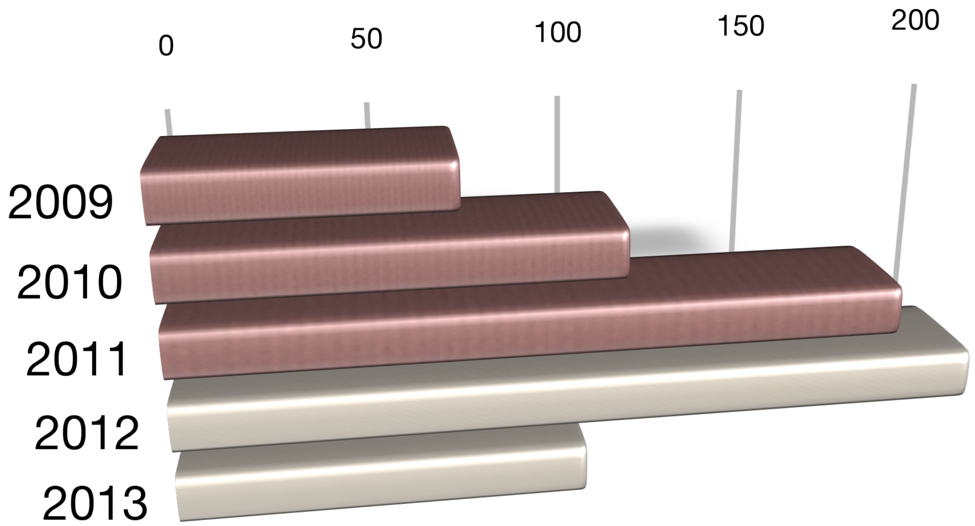
Source (Cf) transferred by comp air → on/off

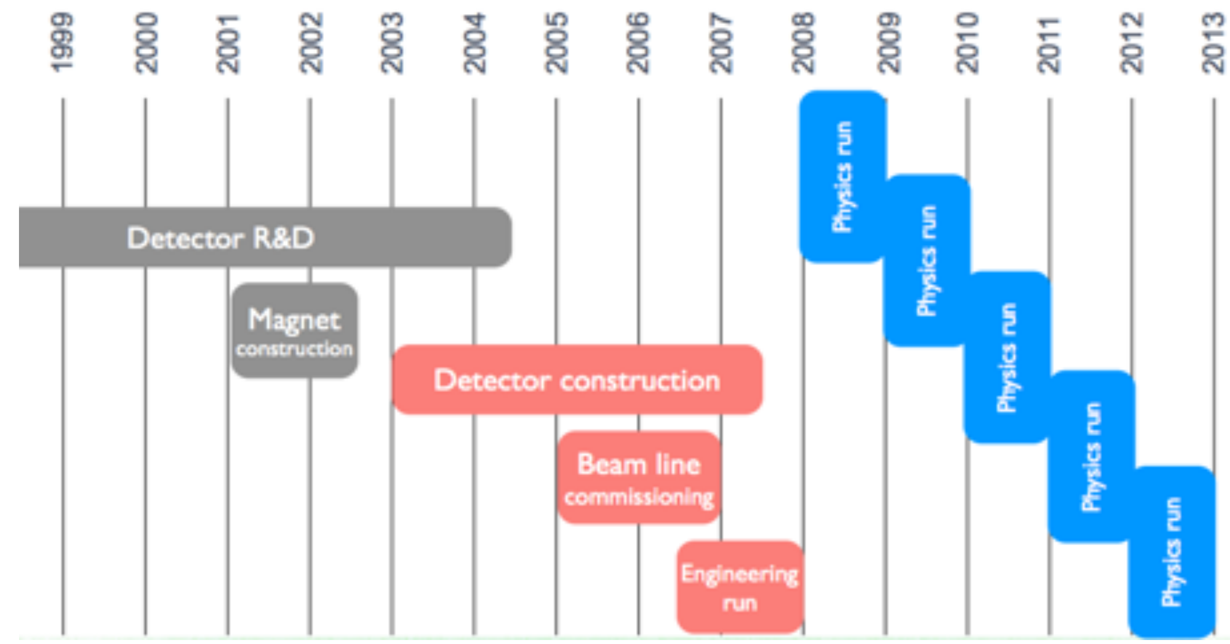


Calibration & Monitoring

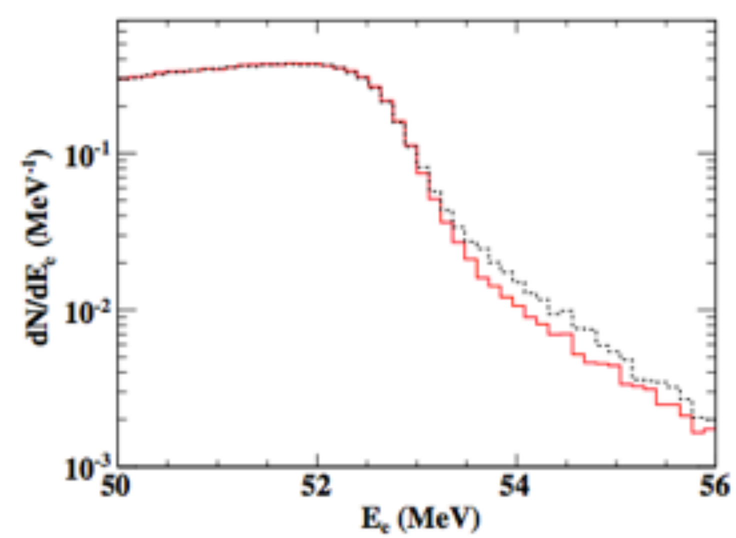


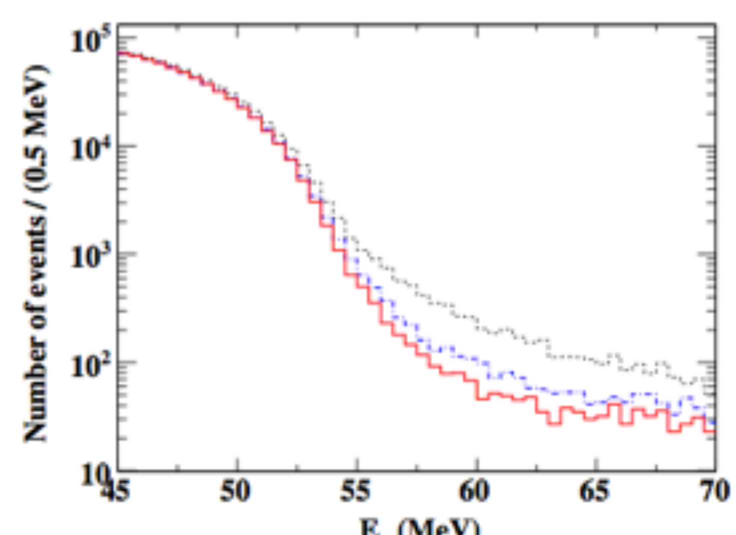
MEG schedule



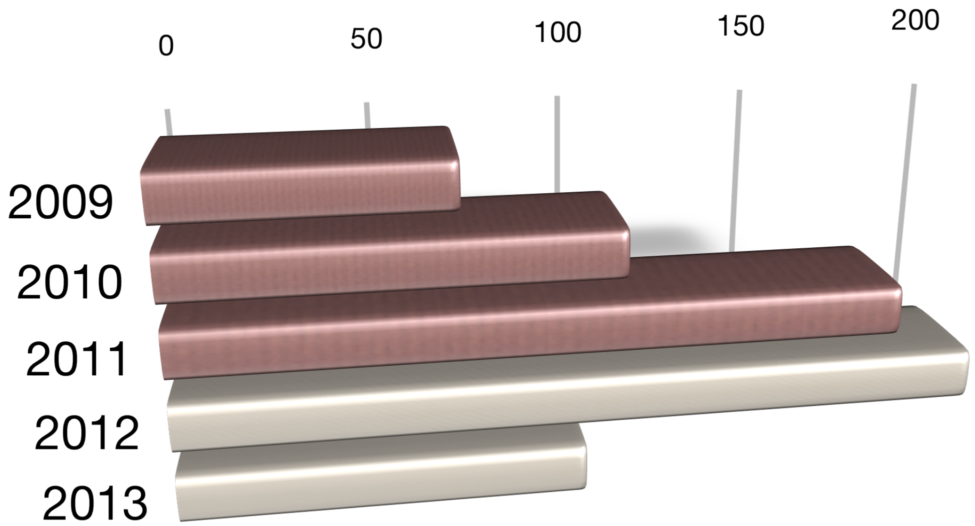


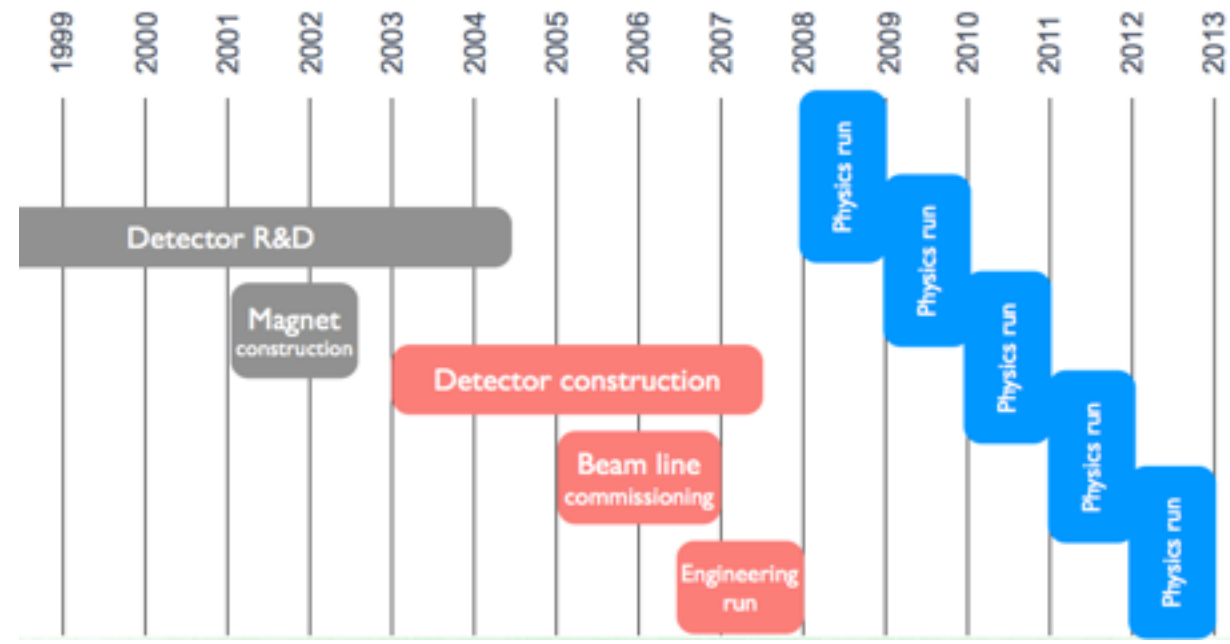
- 2009+2011 analysis: BR($\mu \rightarrow e\gamma$)< 5.7×10^{-13} @ 90%C.L.
- 2009-2011 Analysis improvements
  - Reconstruction improvements
    - γ-ray pileup unfolding
    - e^+ waveform FFT noise reduction + revised track fitter
- 2012-2013 data taken
- Analysis of full data set (2009-2013) in progress
- 2009-2013 Analysis improvements
  - Re-measurement of magnetic field
  - AIF γ-ray identification



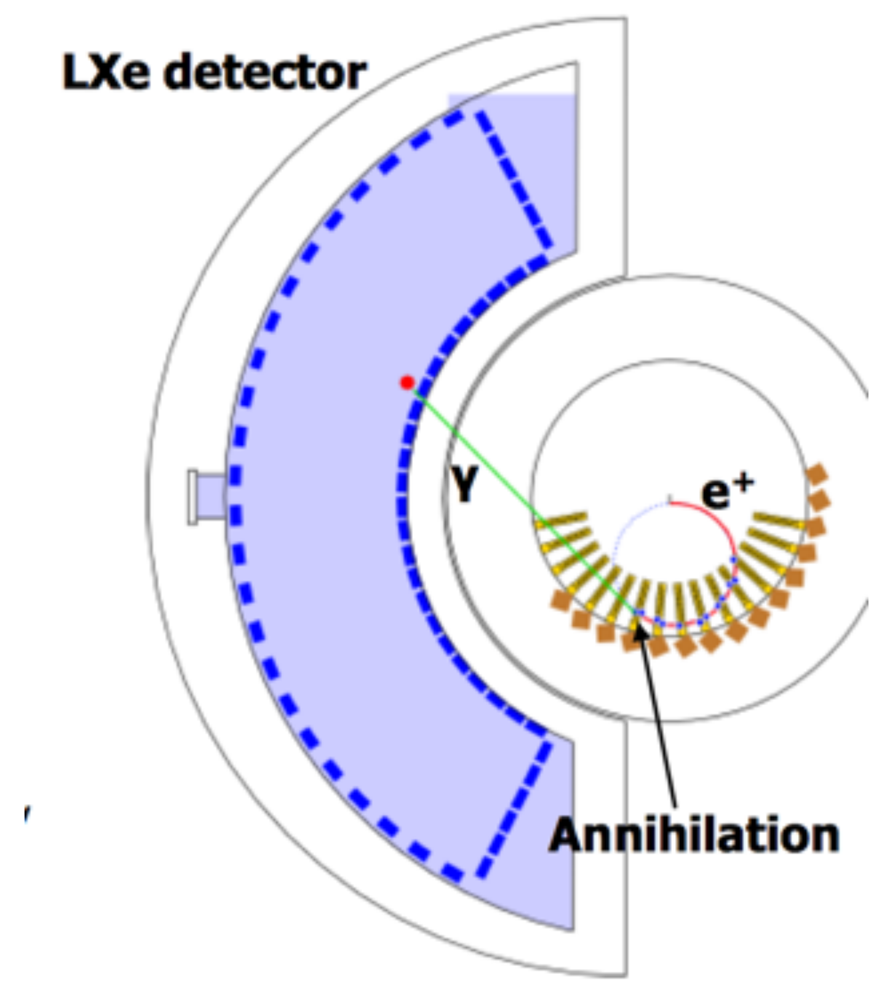


MEG schedule





- 2009+2011 analysis: BR($\mu \rightarrow e\gamma$)< 5.7×10^{-13} @ 90%C.L.
- 2009-2011 Analysis improvements
  - Reconstruction improvements
    - γ-ray pileup unfolding
    - e^+ waveform FFT noise reduction + revised track fitter
- 2012-2013 data taken
- Analysis of full data set (2009-2013) in progress
- 2009-2013 Analysis improvements
  - Re-measurement of magnetic field
  - AIF γ-ray identification



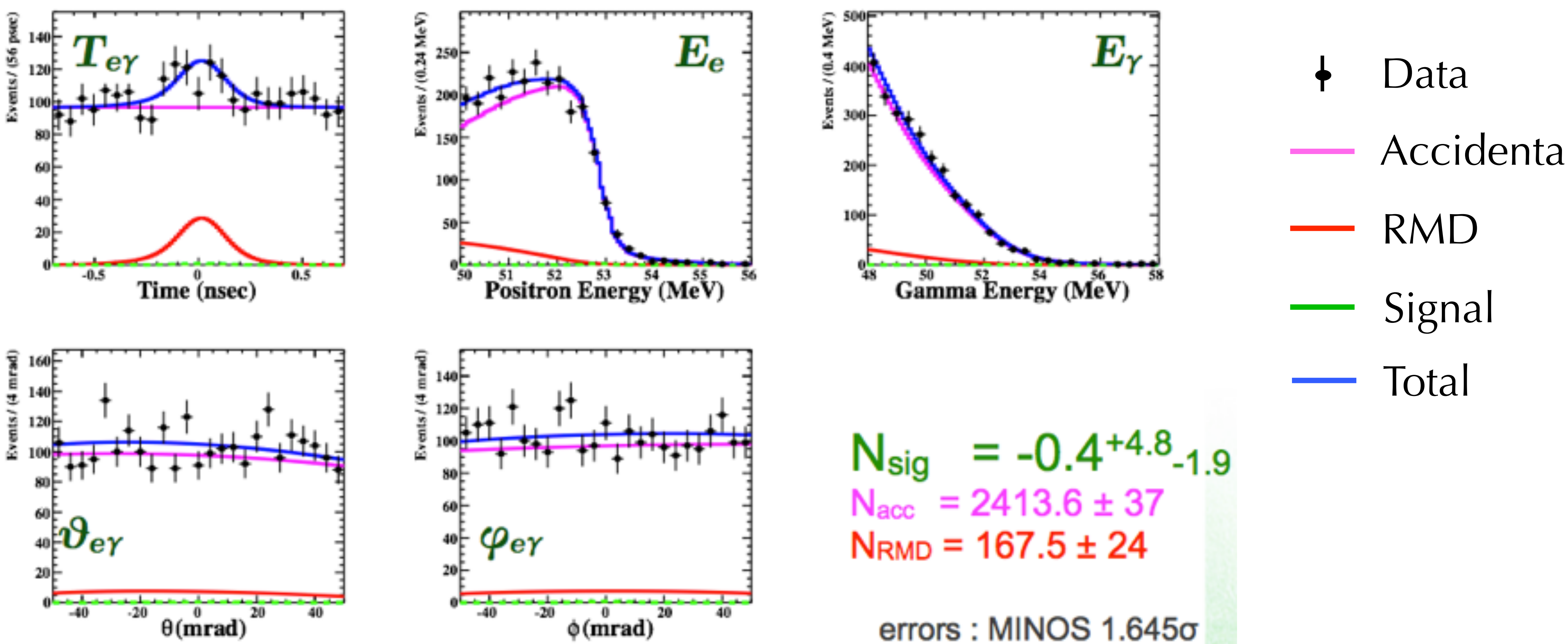
2009-2011 fit result

- A μ→eγ event is described by 5 kinematical variables

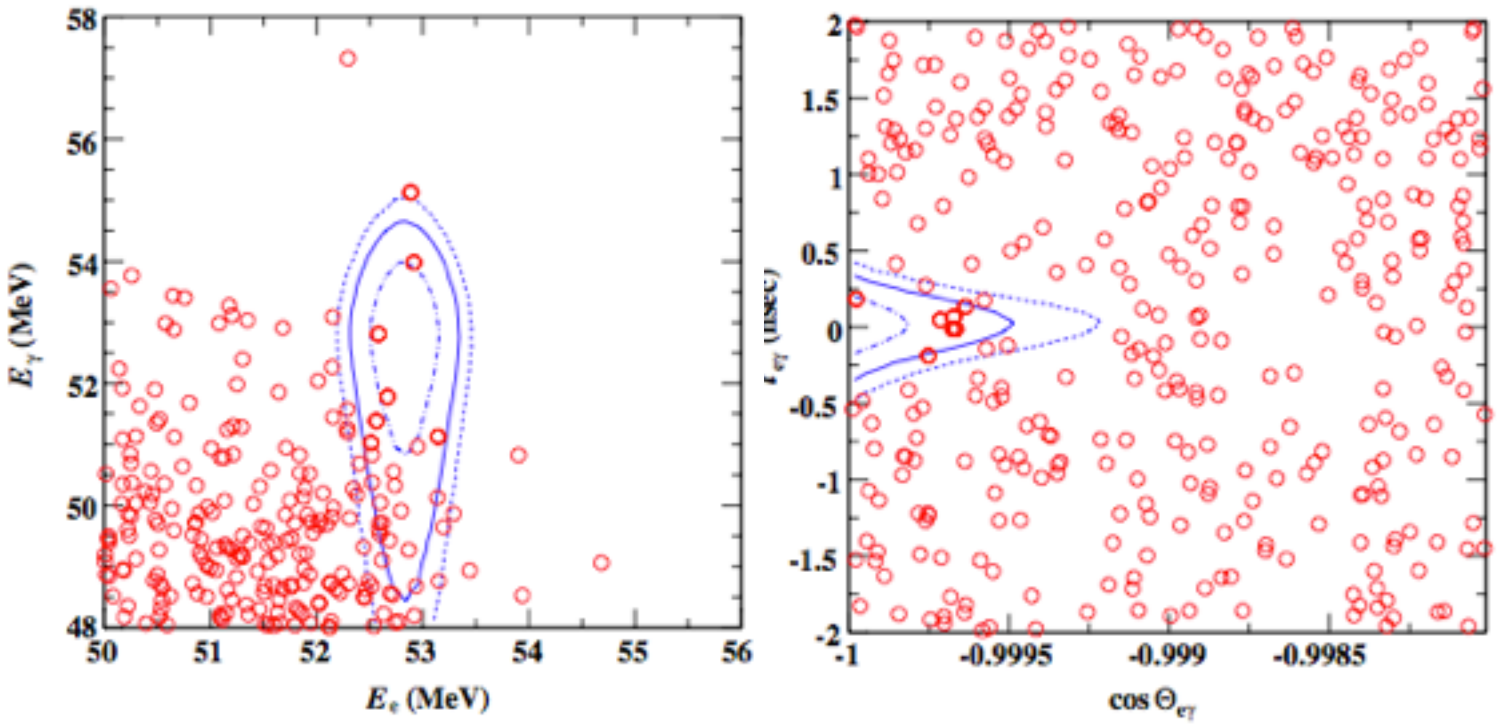
  $\vec{x_i} = (E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$

- Likelihood function is built
  - in terms of Signal, RMD and BG
- Blind- box analysis strategy
  - Use of the sidebands
  - our main background comes from accidental coincidences
  - RMD can be studied in the low E_γ sideband

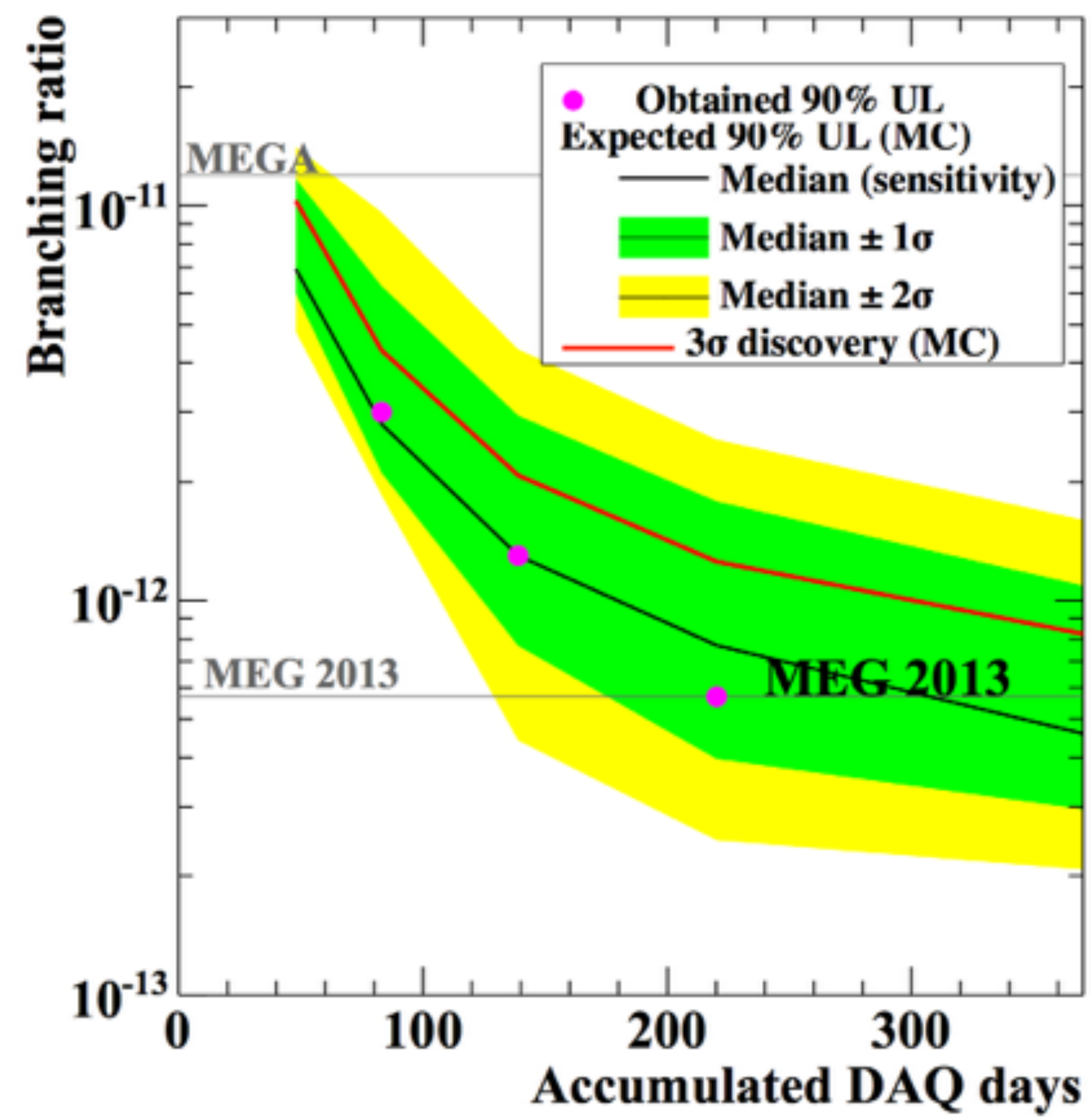
$$-\ln\mathcal{L}\left(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}\right) = N_{\text{exp}} - N_{\text{obs}}\ln\left(N_{\text{exp}}\right) - \sum_{i=1}^{N_{\text{obs}}}\ln\left[\frac{N_{\text{sig}}}{N_{\text{exp}}}S(\vec{x_i}) + \frac{N_{\text{RMD}}}{N_{\text{exp}}}R(\vec{x_i}) + \frac{N_{\text{BG}}}{N_{\text{exp}}}B(\vec{x_i})\right]$$



Combined 2009 -2011



J. Adam et al (MEG Collaboration) PRL 17 May 2013



- 90% C.L. Feldman-Cousins upper limit
  - 8×10^{-13} expected for no signal (sensitivity)

$$\frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma(\mu^+ \to e^+\nu\bar{\nu})} \leq 5.7 \times 10^{-13}$$

Present & Future

- We have just finished the 2013 data-taking (last year)
- MEG is expected to saturate its sensitivity.
- In the meanwhile an upgrade was presented and accepted by PSI laboratory

μ

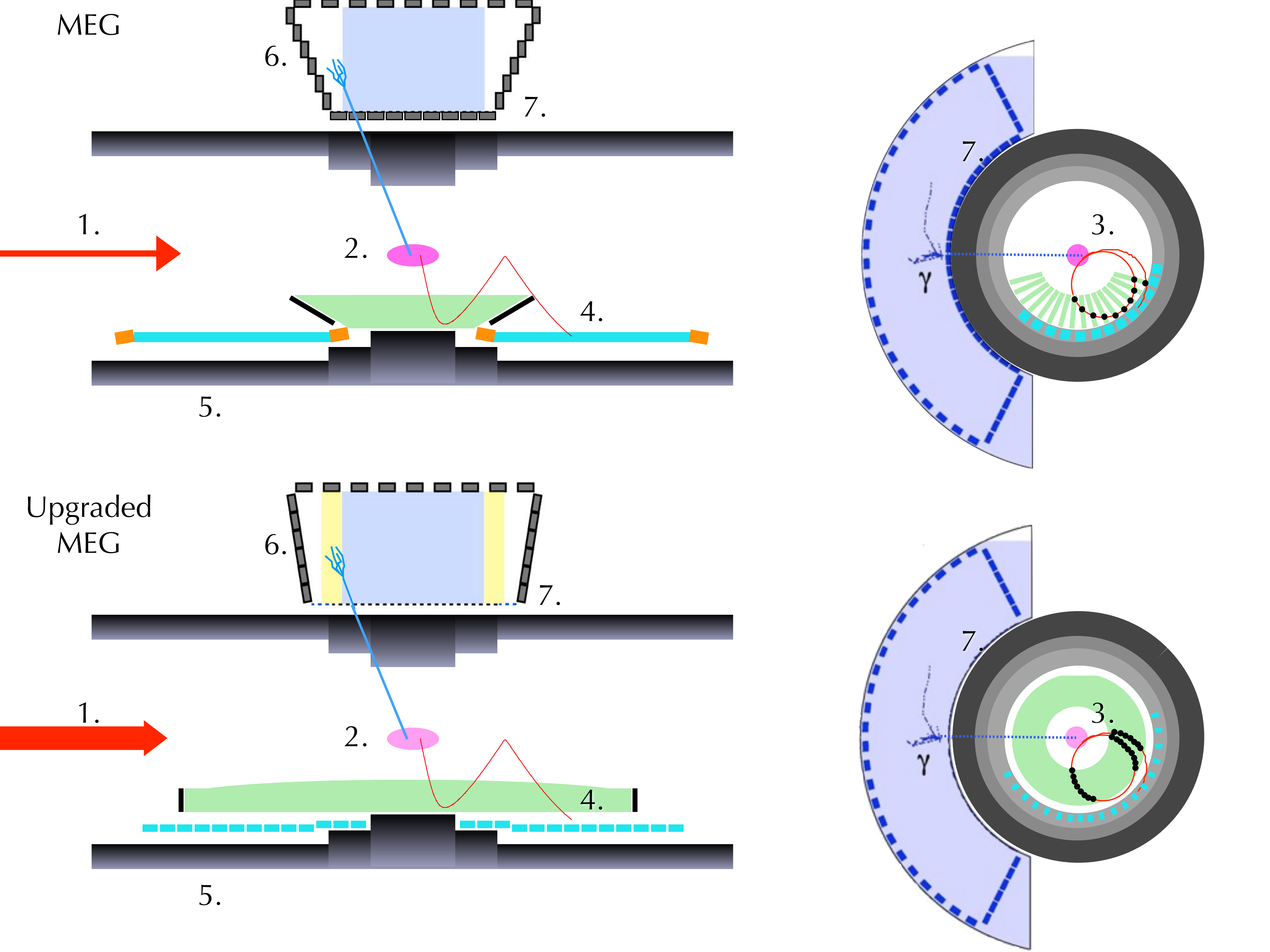
1. Increasing μ^+–stop on target
2. Reducing target thickness to minimize e+ MS & brehmsstrahlung

e

3. Replacing the e+ tracker reducing its radiation length and improving its granularity and resolutions
4. Improving the timing counter granularity for better timing and reconstruction
5. Improving the positron tracking-timing integration by measuring the e+ trajectory up to the TC interface

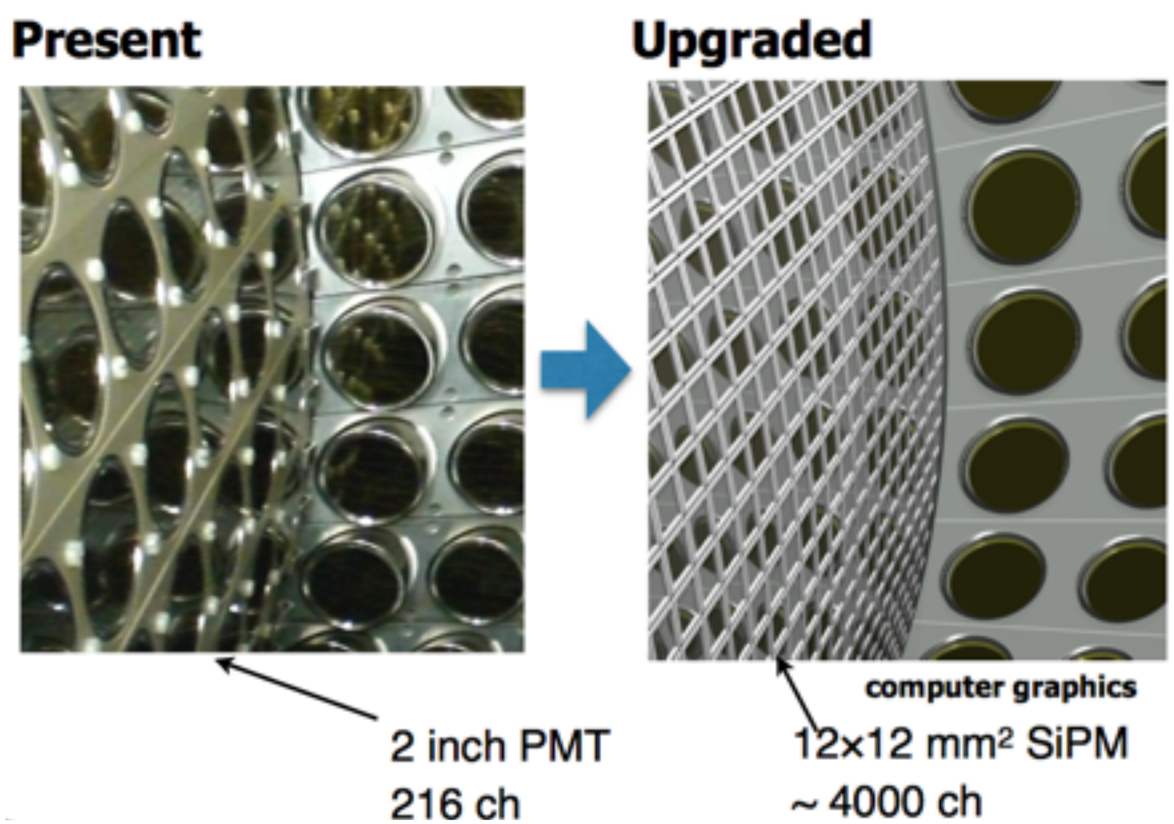
γ

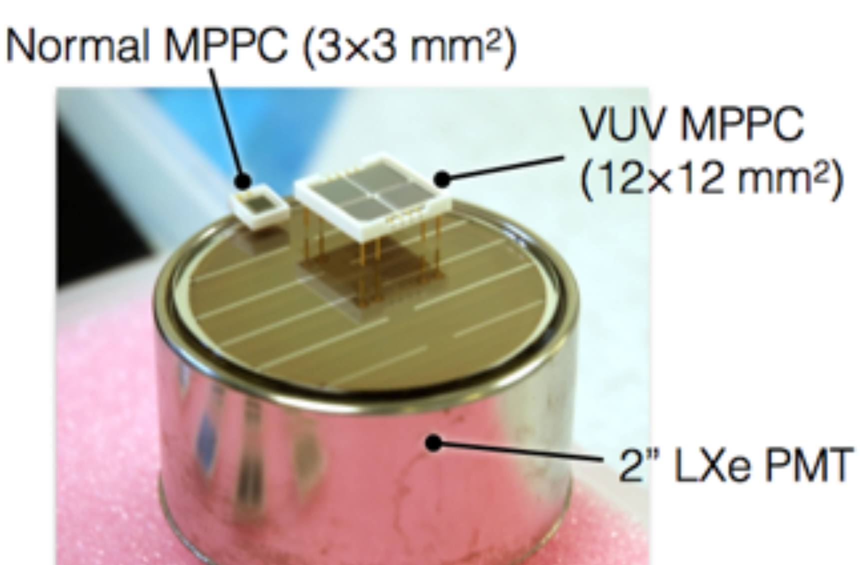
6. Extending the γ–ray detector acceptance
7. Improving the γ-ray energy and position resolution for shallow events
8. Integrating splitter, trigger and DAQ maintaining a high bandwidth


MEG
6.
7.
1.
2.
4.
5.
7.
3.
γ
Upgraded MEG
6.
7.
1.
2.
4.
5.
7.
3.
γ

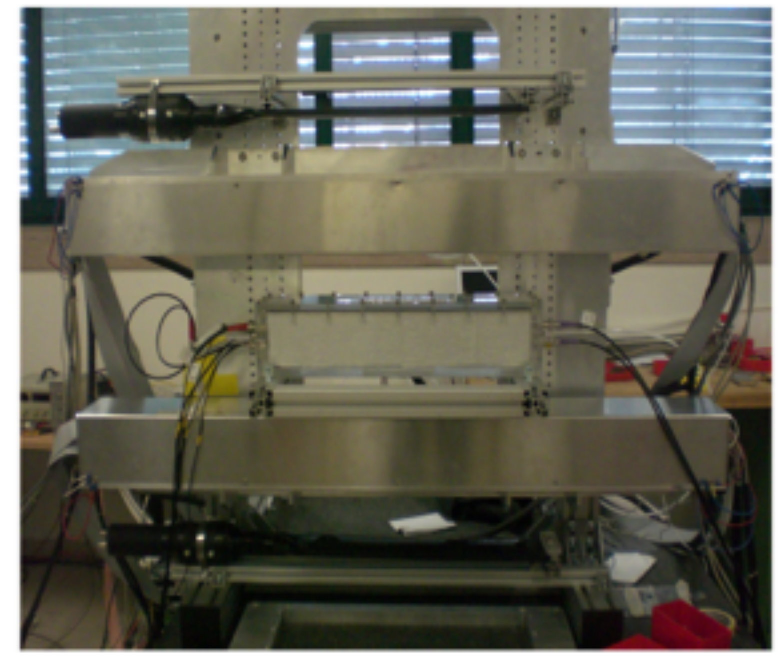
Upgrade highlights

- LXe calorimeter
  - x2 better energy/position resolution
  - 10% higher efficiency

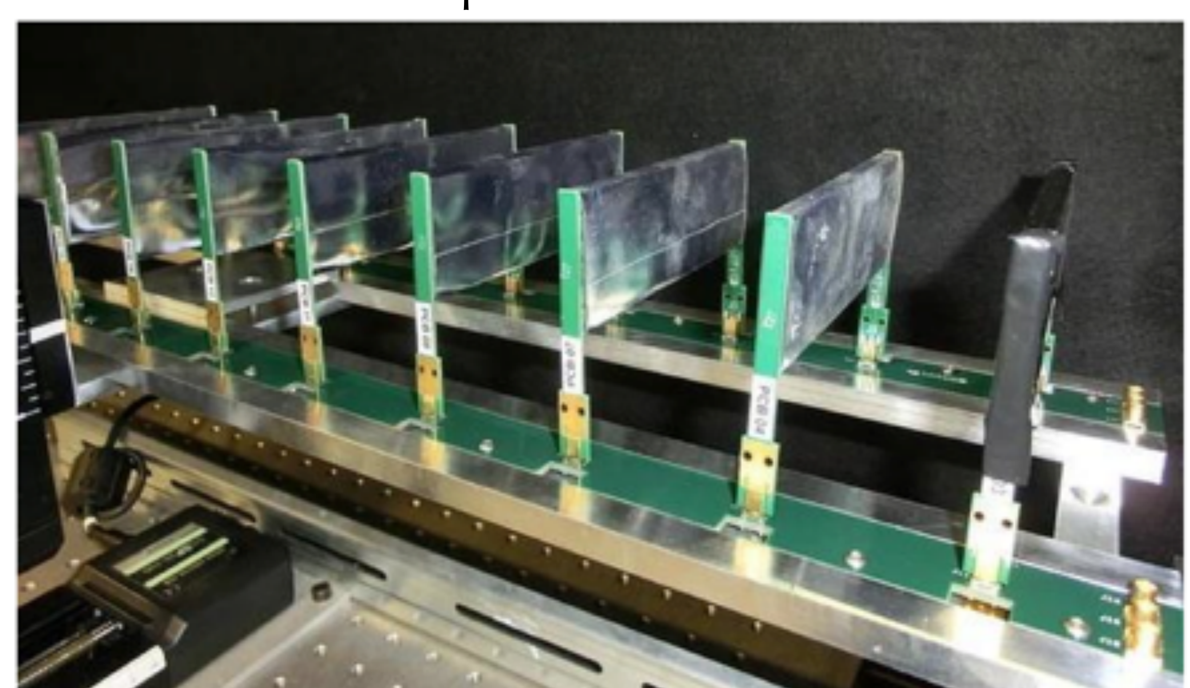




- DC
  - single hit resolution ~120 μm



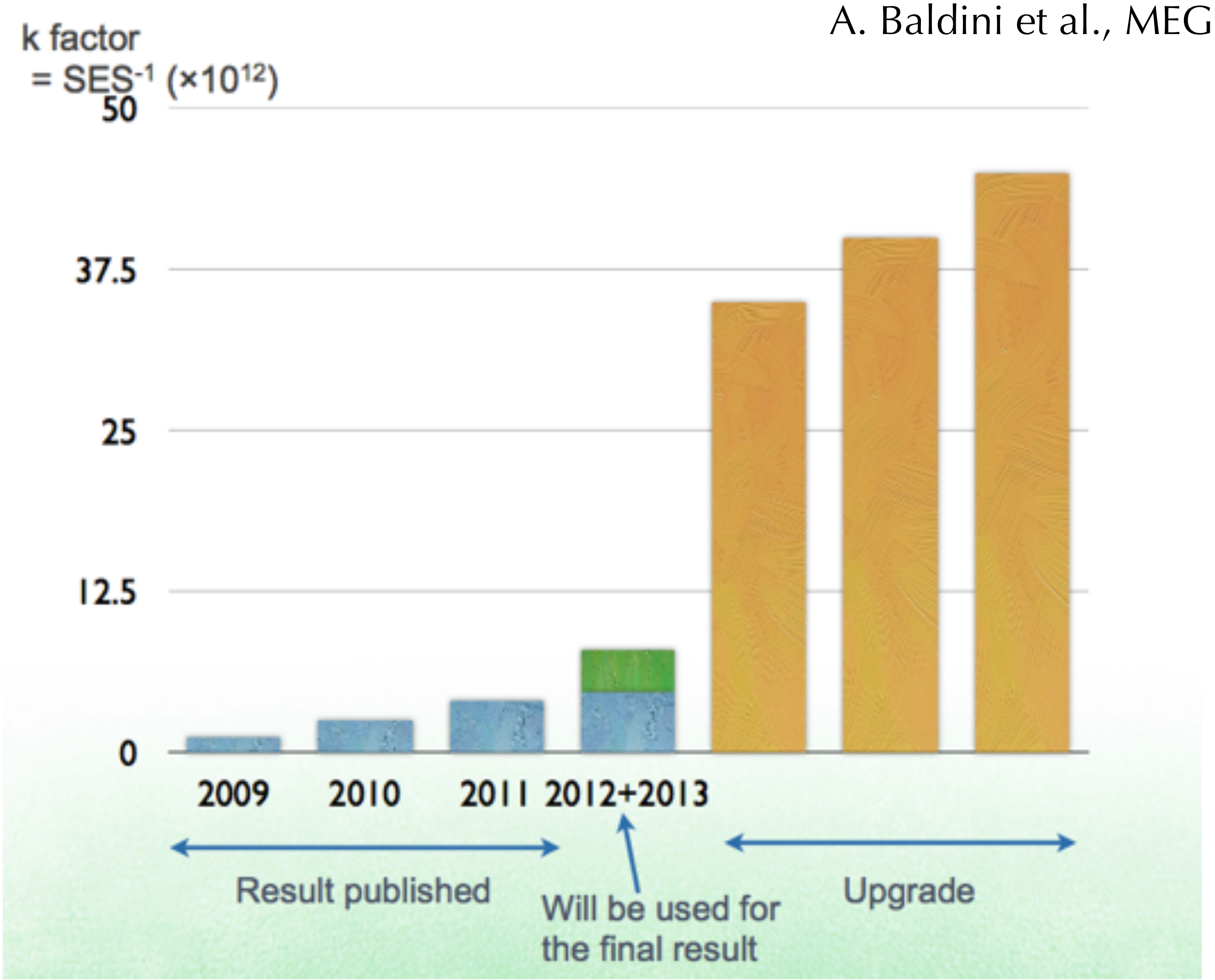
- Tile timing counters
  - σ ~ 40 ps

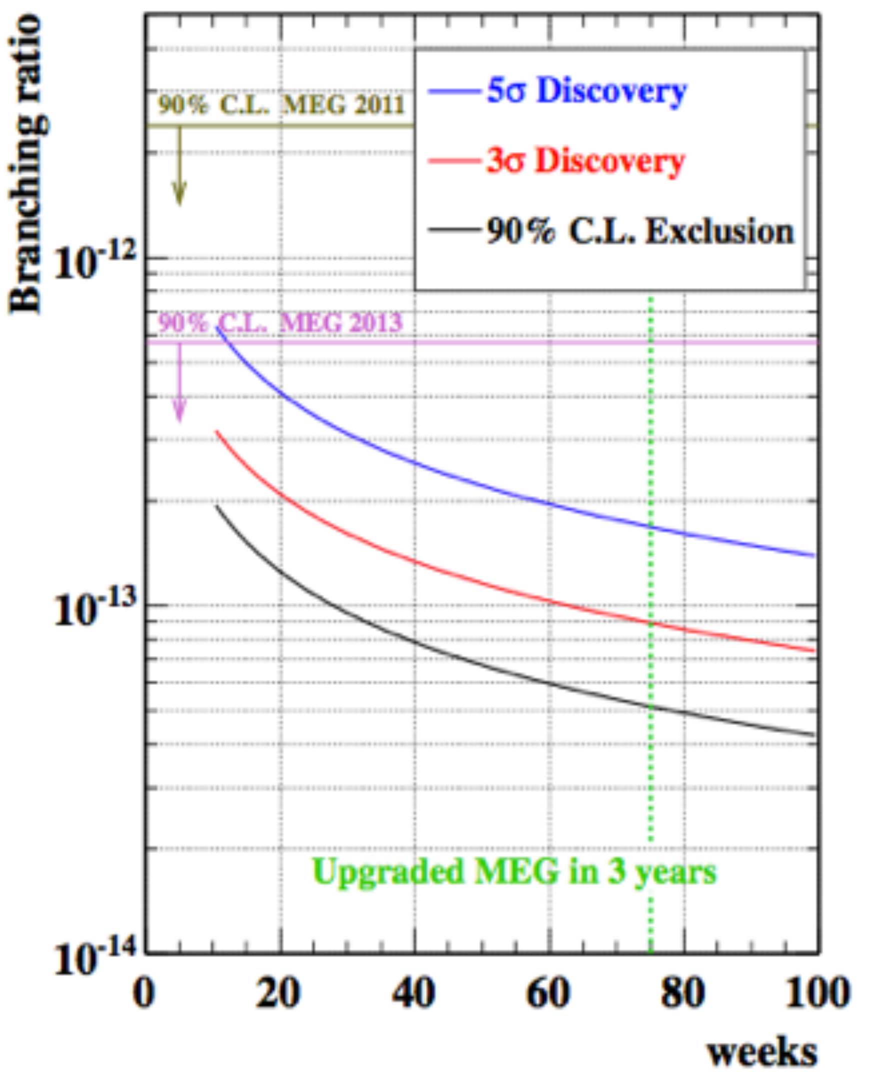


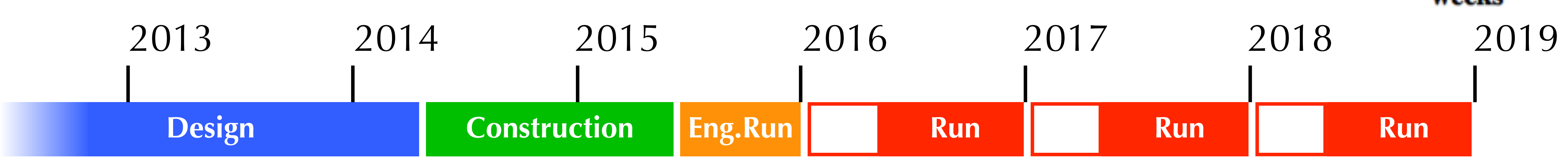
MEGII sensitivity

- Ultimate sensitivity at the few x 10^{-14} level
- Engineering run 2015
- Data taking 2016-2018

A. Baldini et al., MEG Upgrade Proposal, arXiv:1301.7225 [physics.ins-det] |

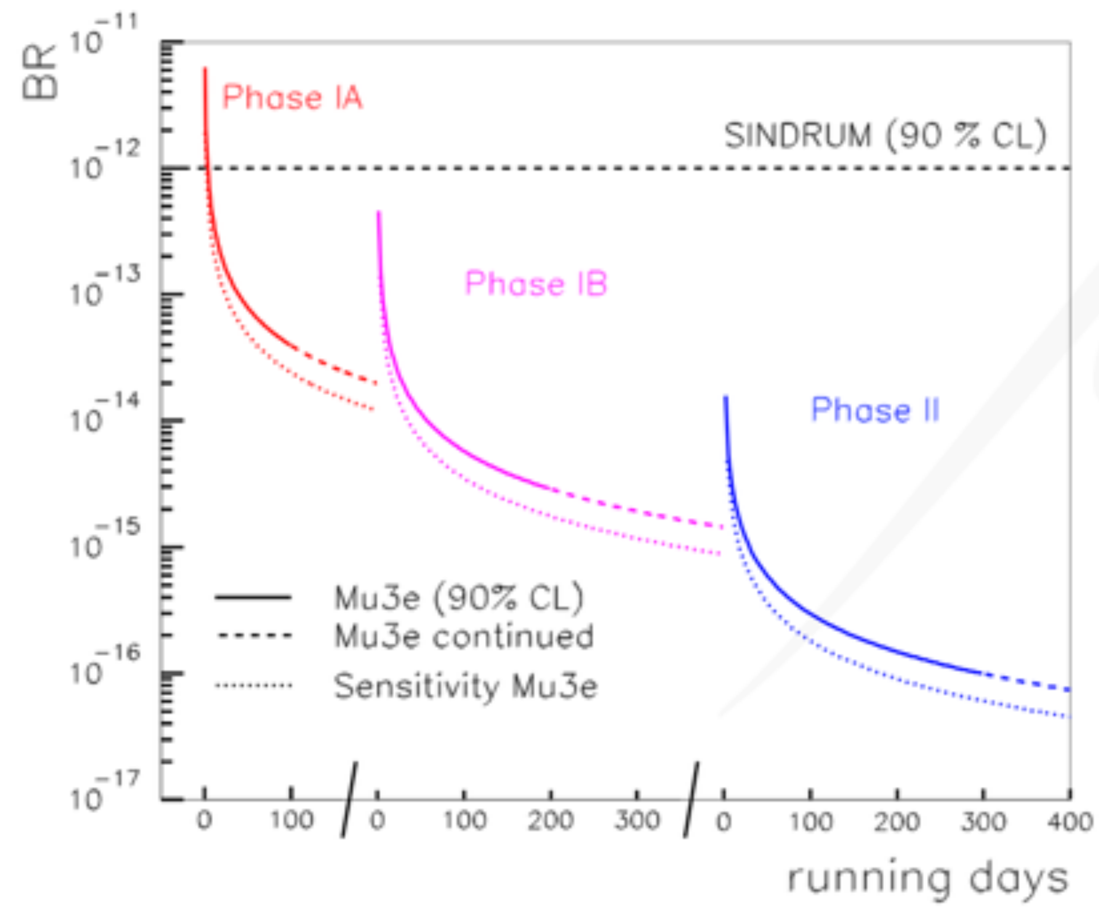


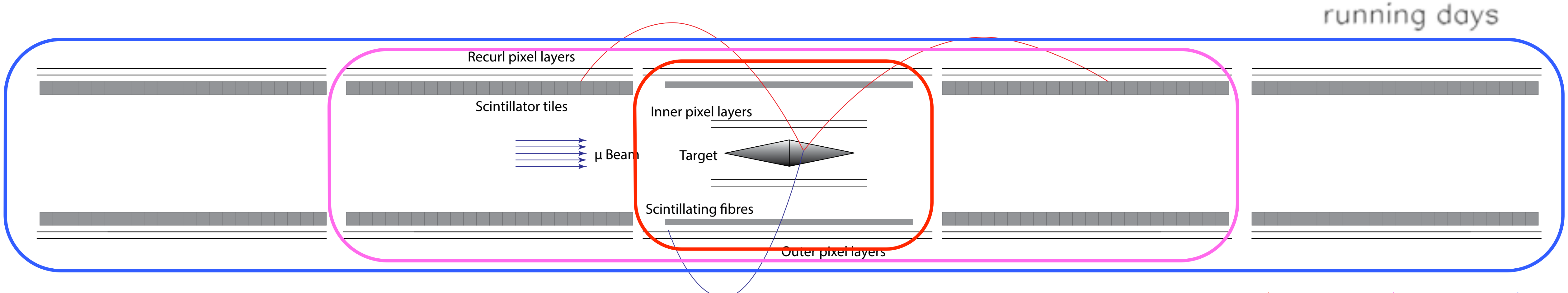




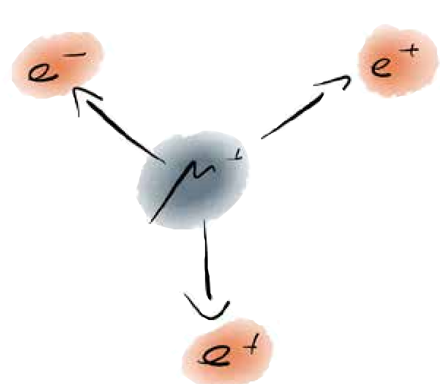
Mu3e at PSI

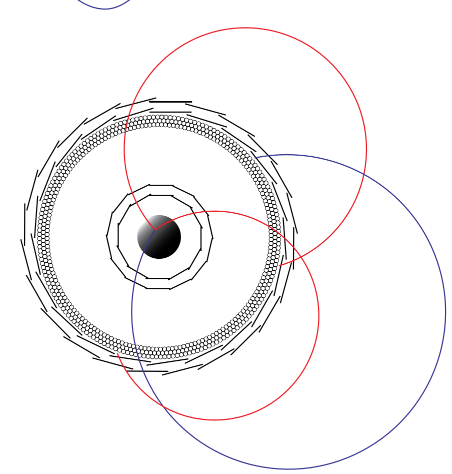
- Search for $\mu \to e\,e\,e$
  - 10^{-15} sensitivity in phase IA / IB
  - 10^{-16} sensitivity in phase II
- Project approved in January 2013
  - Double cone target
  - HV-MAPS ultra thin silicon detectors
  - Scintillating fibers timing counter (from phase IB)





2015 2016 2018



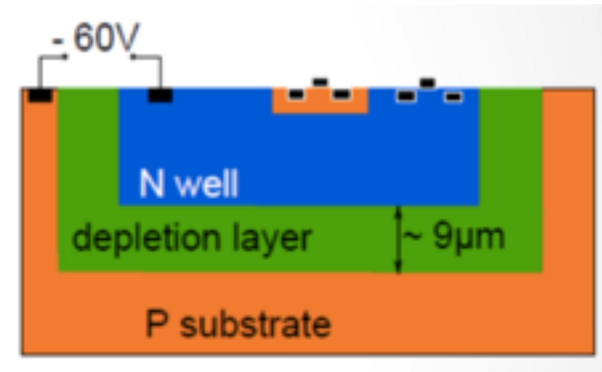


PAUL SCHERRER INSTITUT

www.psi.ch/mu3e

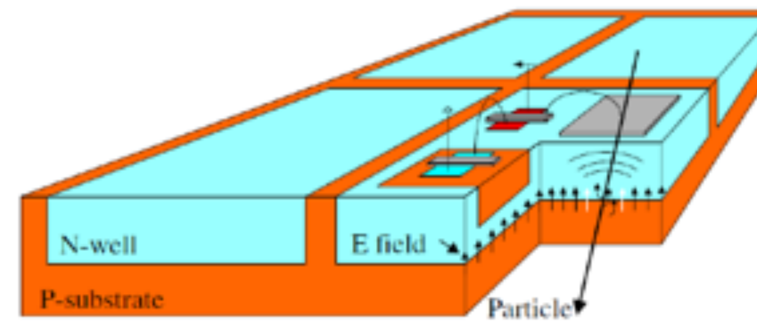
Mu3e detector technology

- Ultra-thin devices are necessary to suppress multiple scattering
- HV-MAPS
  - thinned down to 50 μm
  - amplification and digitization on chip
  - fast readout to get a <50 ns timestamp



- 50 μm Silicon sensor
- 25 μm Kapton flexprint
- 25 μm Kapton support frame

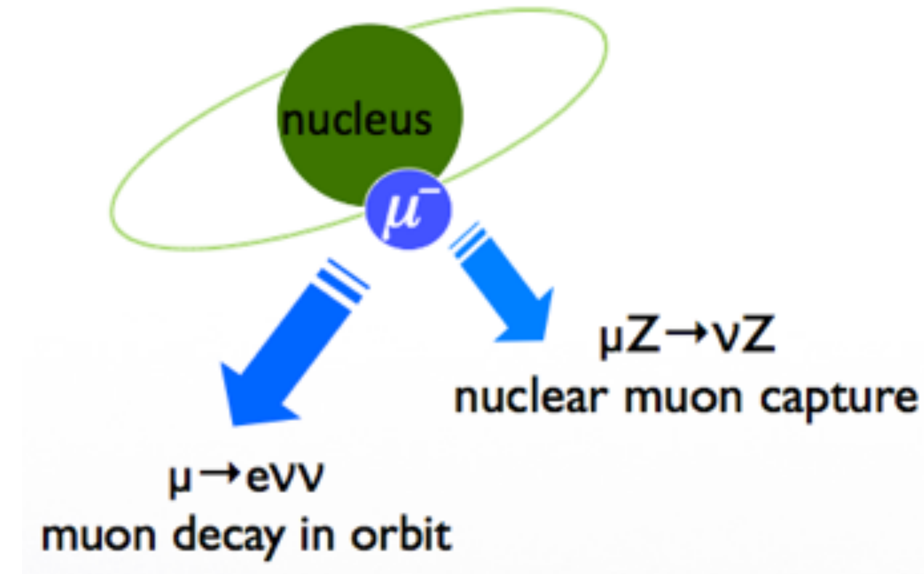
→ ~ 1 ‰ Radiation length



(High voltage monolithic active pixel sensors)
I. Peric et.al. NIMA 582 (2007) 876

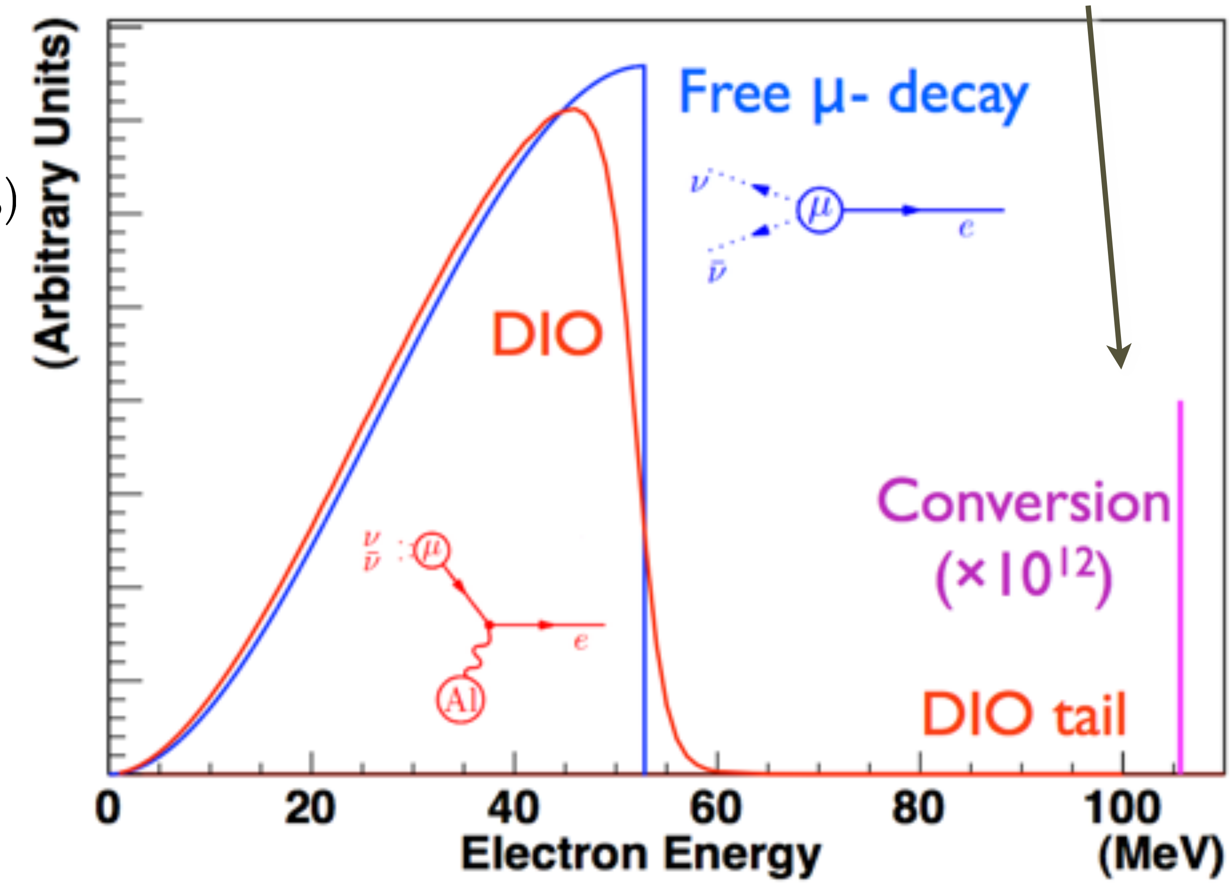
μN → eN

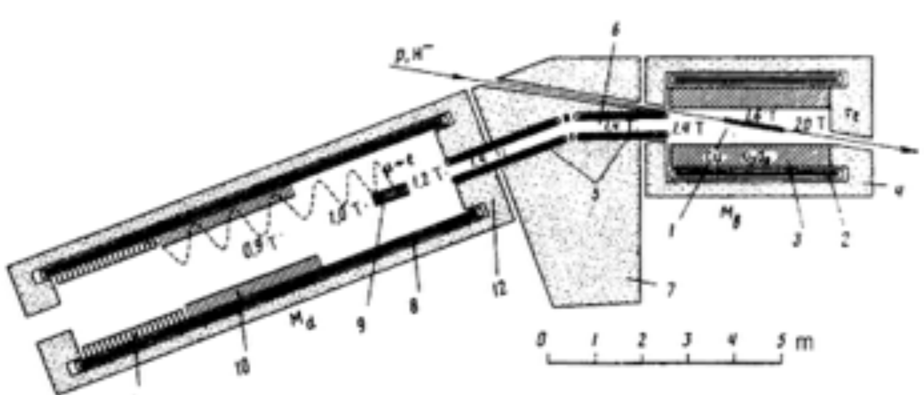
- Coherent muon capture on nucleus (Al is the candidate)
- Single mono-energetic electron
  - $E_e = m_\mu - B_\mu$ –recoil
- Only one particle in final state
  - No (accidental) background limited
  - Unlike $\mu \to e\gamma$ and $\mu \to 3e$ there is no experimental “wall” until conversion rates $O(10^{-18})$
  - It is anticipated that will provide the ultimate sensitivity to CLFV
- Background comes from
  - μ decay-in-orbit (DIO)
  - radiative muon capture
    - bkg n and γ-rays are produced
  - beam related background (π and e contaminations)
    - high purity environment
    - curved solenoid (Dzhilkibaev and Lobashev, 1989)
    - pulsed beam with challenging extinction



$(E_\mu - E_e)^5$

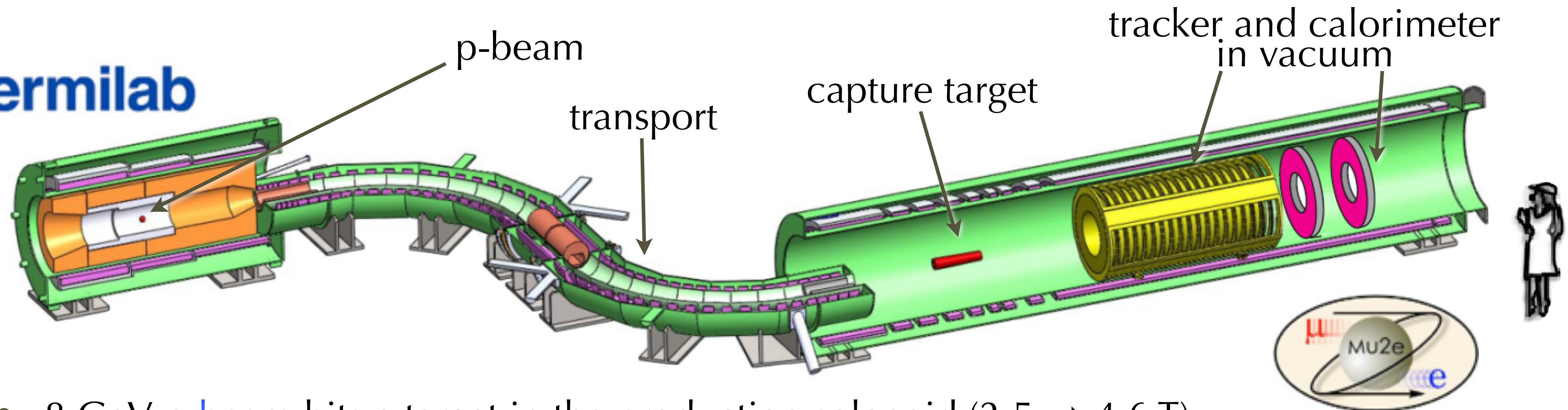
~10^{-17} of the spectum wihin the last MeV



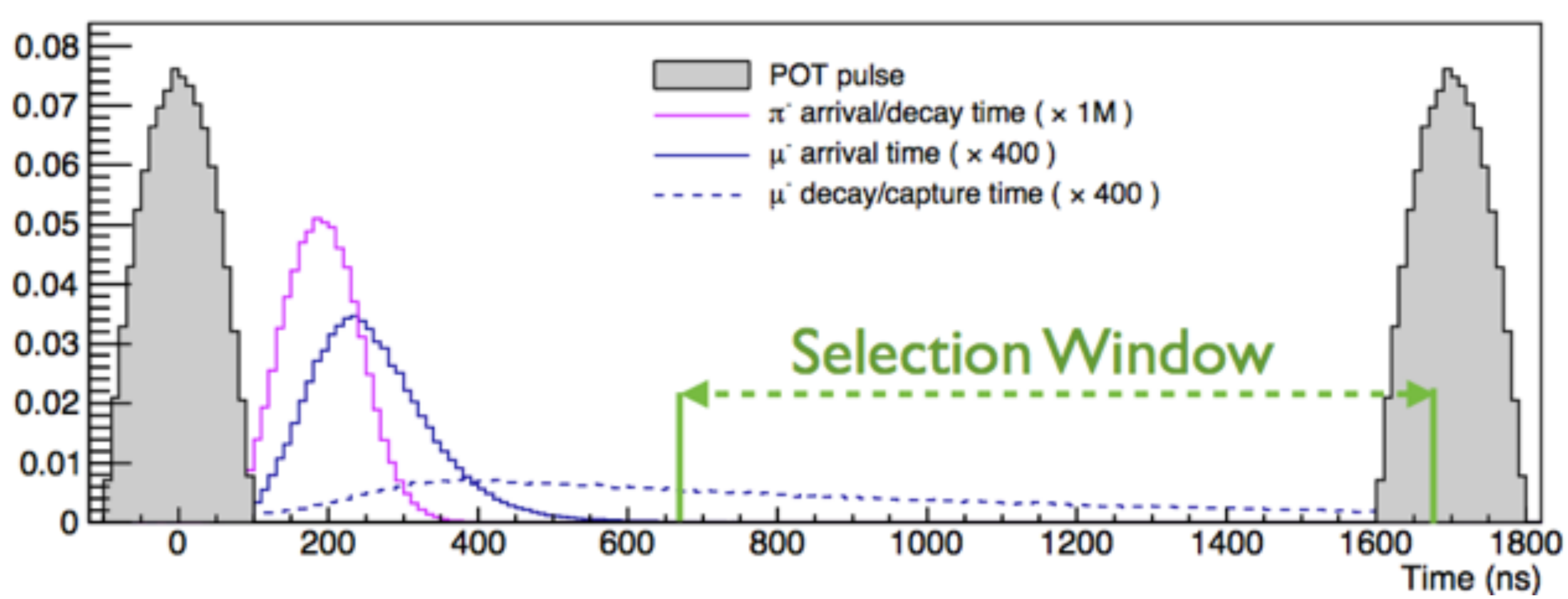


μN→eN experiments: mu2e

- Mu2e @ FNAL and COMET @ J-PARC are quite similar in the outline



- 8 GeV p-beam hits a target in the production solenoid (2.5 → 4.6 T)
- solenoid collects (lenses) π^- and let them decay to μ^-
- μ^- are transported to the capture target inside the detector solenoid (2 → 1 T)
- A pulsed beam allows a time window for events ⇒ needs high extinction



Starts in 2020

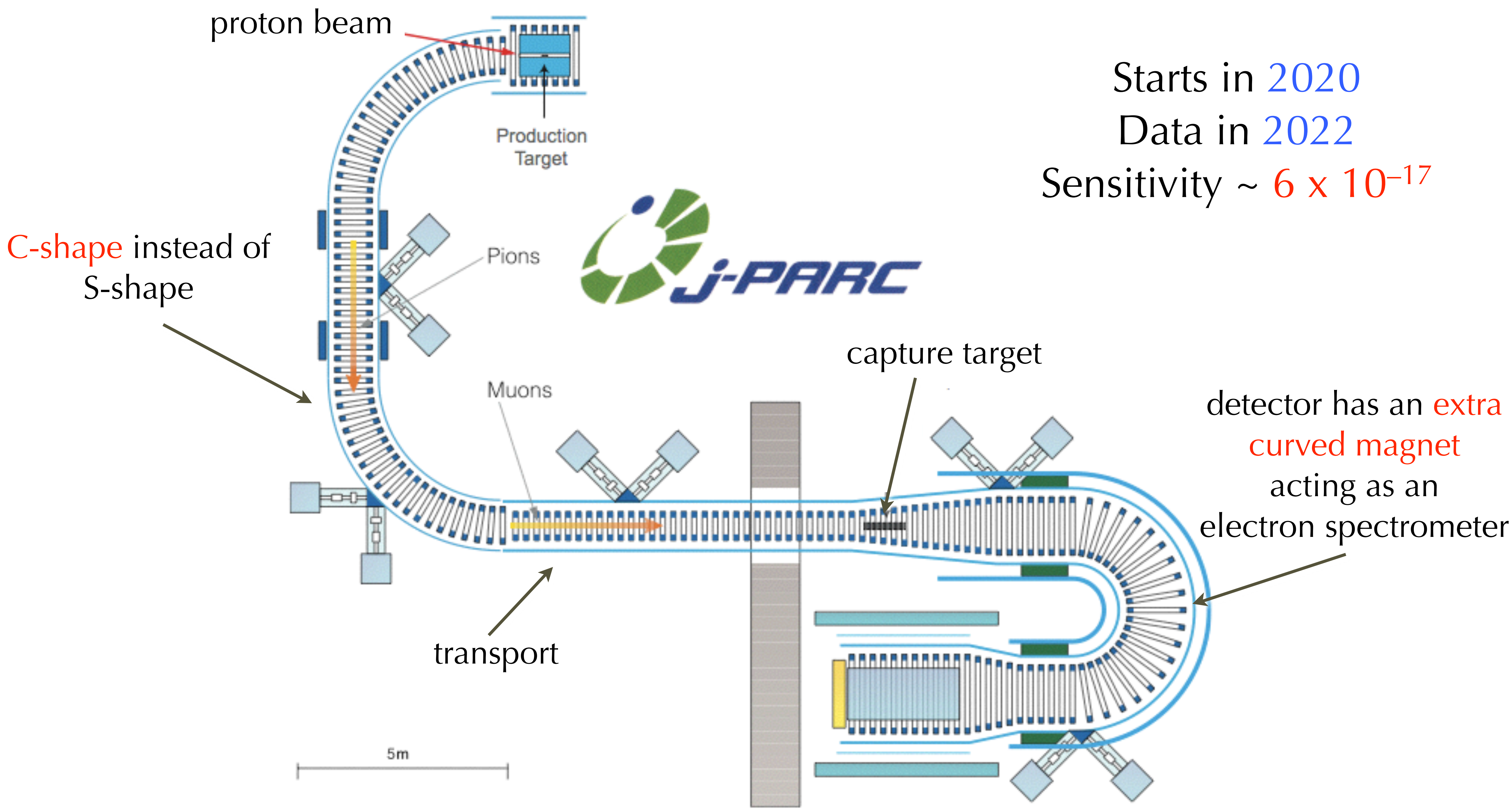
Data in 2022

Sensitivity

~ 6×10^{-17}

COMET: phase II

- COMET @ J-PARC has some differences



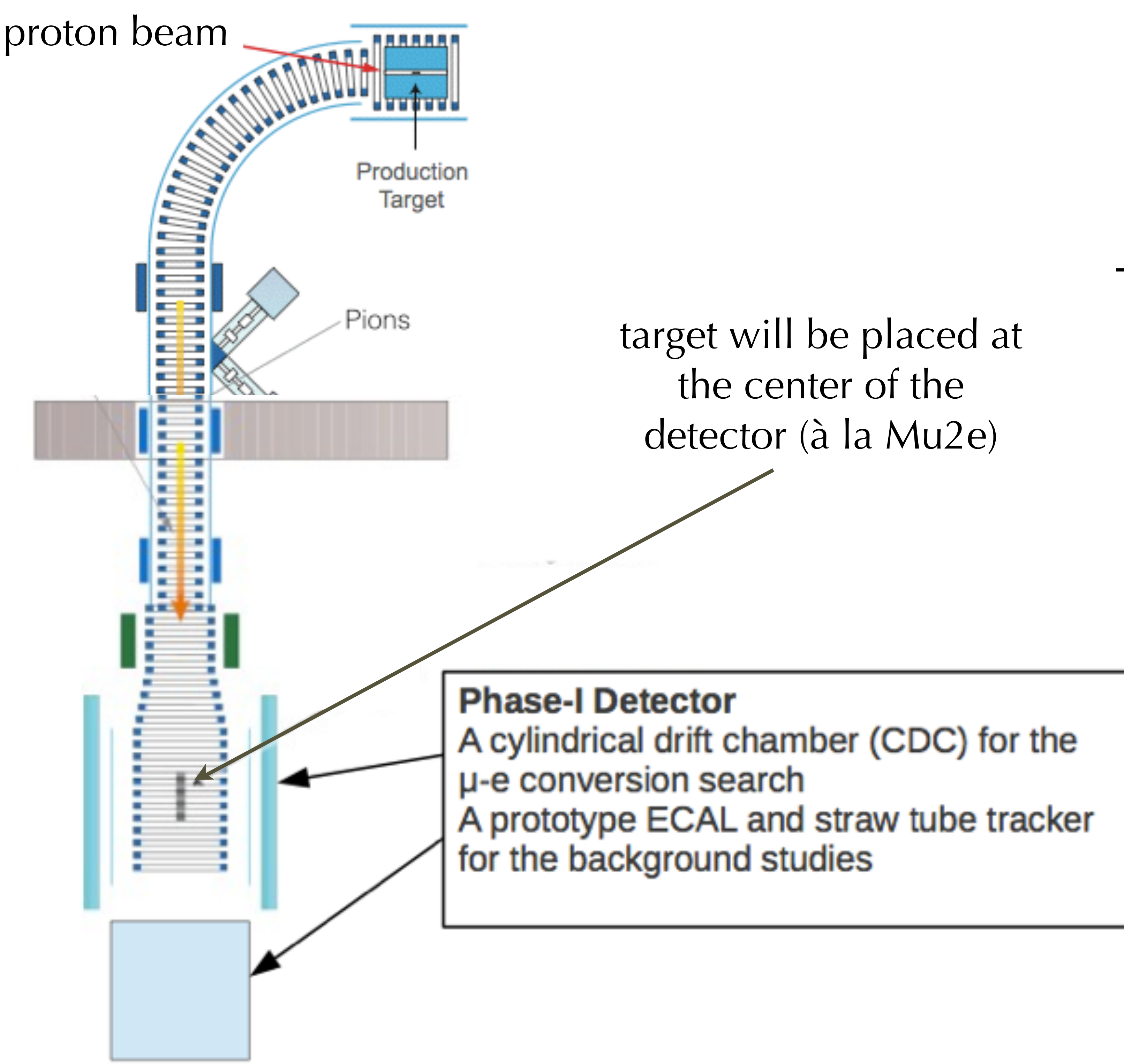
Starts in 2020

Data in 2022

Sensitivity ~ 6×10^{-17}

COMET: phase I

- COMET @ J-PARC has some differences

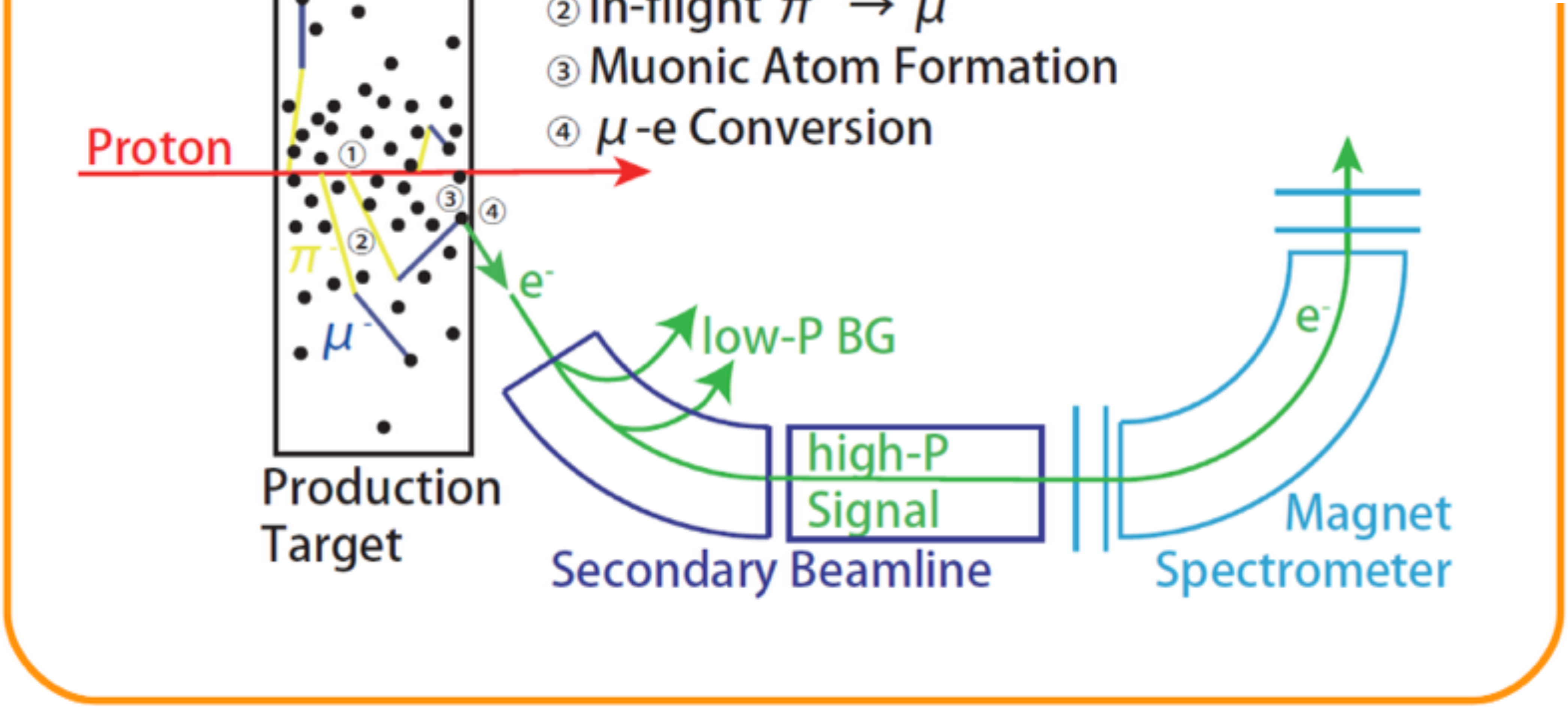


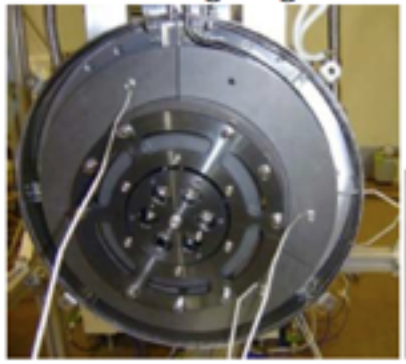
Starts in 2016
~1 month of data taking

-Study backgrounds
-Sensitivity ~ 10^{-15}

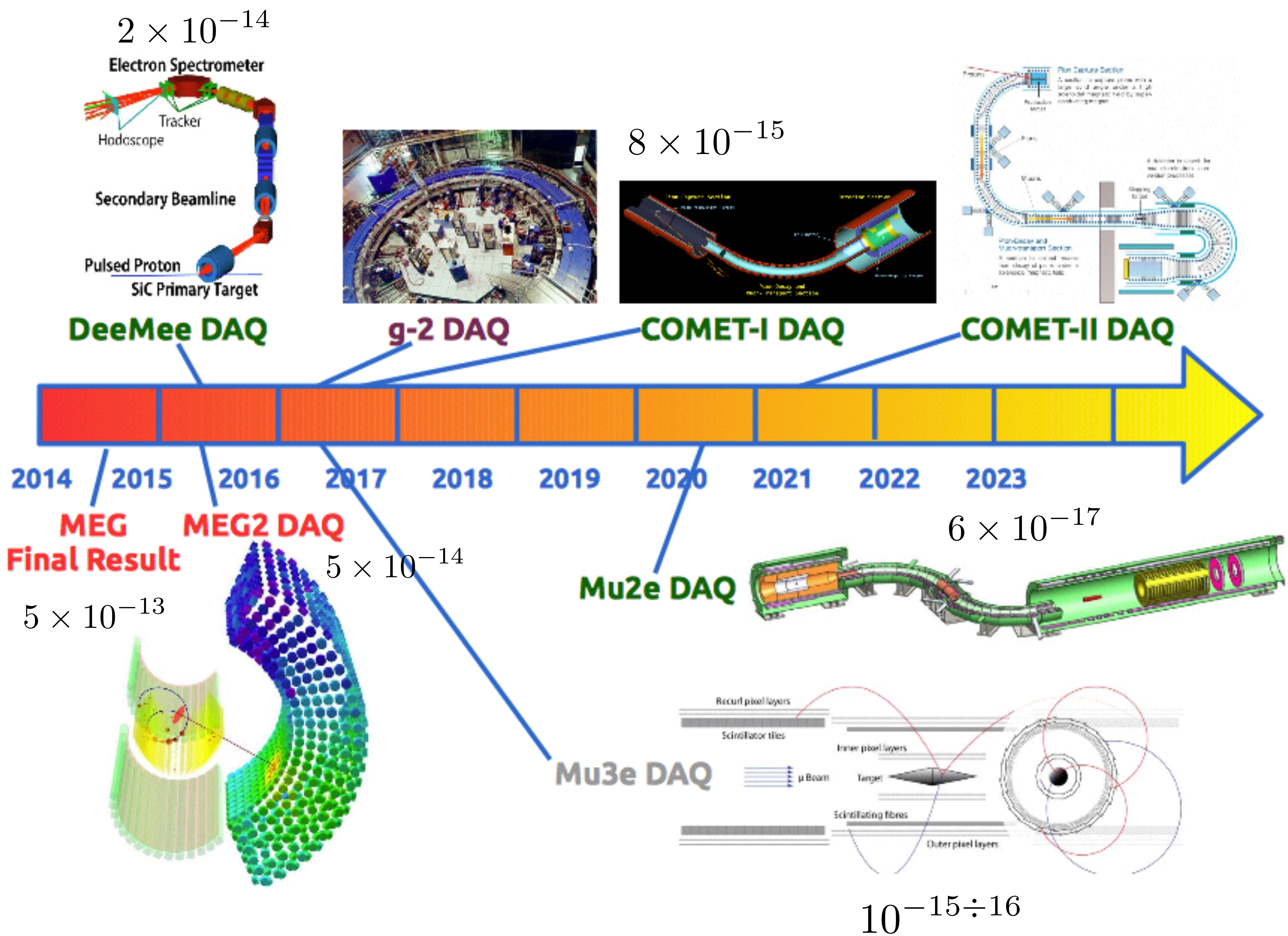
In the meanwhile: DeeMe

- DeeMe at J-PARC H-line aims at searching for μN→eN with a 2×10^{-14} sensitivity
- production target and conversion target are the same
- rotating Silicon Carbide target
- physics data taking planned to start in 2015





SiC sample



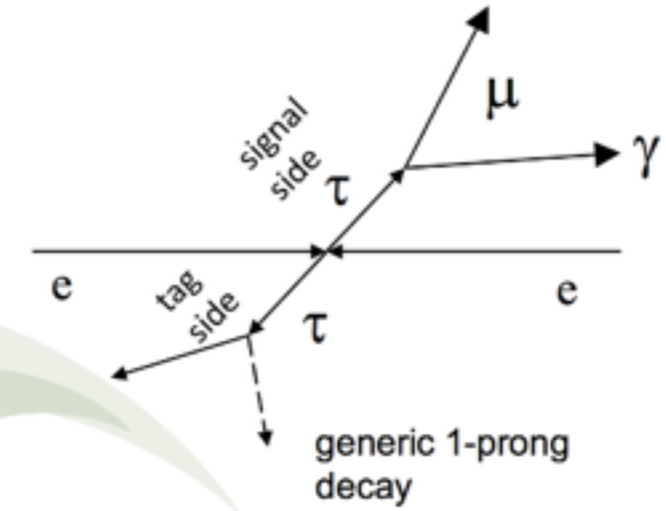
2×10^{-14}
Electron Spectrometer
Tracker
Hodoscope
Secondary Beamline
Pulsed Proton
SiC Primary Target
8×10^{-15}
DeeMee DAQ
g-2 DAQ
COMET-I DAQ
COMET-II DAQ
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
MEG
Final Result
MEG2 DAQ
5×10^{-14}
5×10^{-13}
6×10^{-17}
Mu2e DAQ
Recurl pixel layers
Scintillator tiles
Inner pixel layers
μ Beam
Target
Scintillating fibres
Outer pixel layers
Mu3e DAQ
$10^{-15 \div 16}$

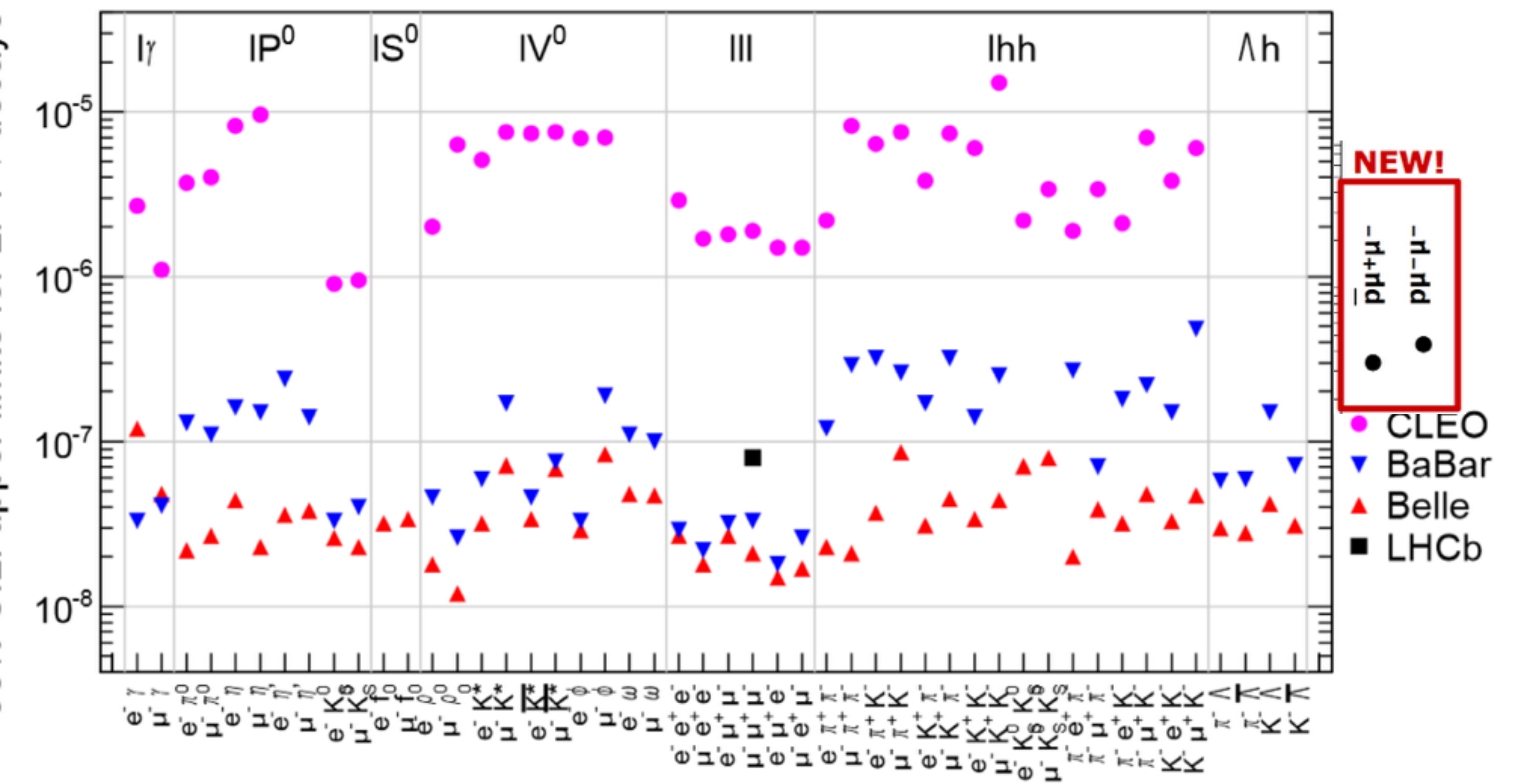
Tau LFV

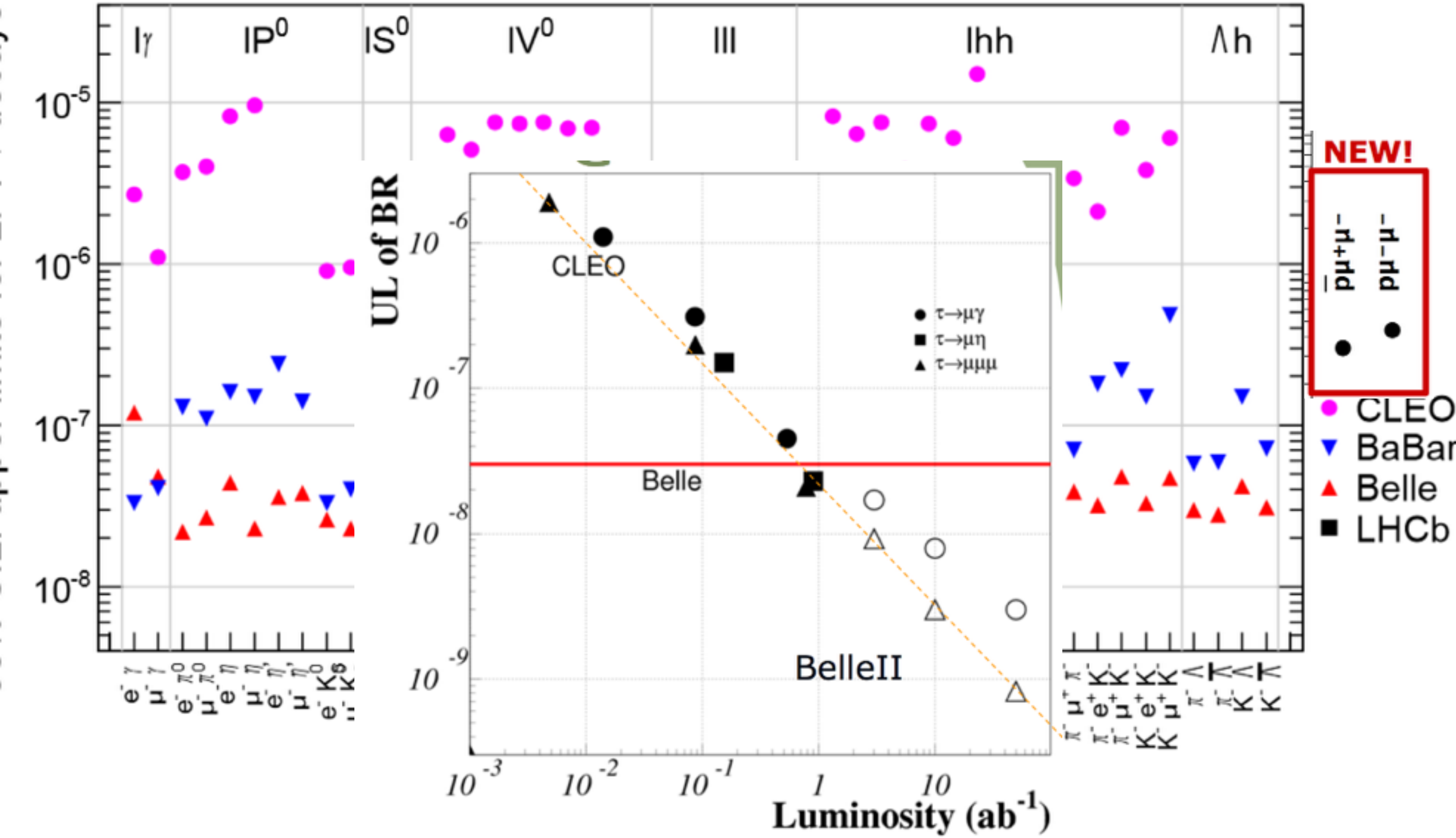
- PROS
  - Amongst the cleanest probes of new physics at high luminosity flavour factories
  - Larger branching ratio compared to μ
  - Many possible final states ⇒ possibility to test different models within one experiment

	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z' boson
$\left(\frac{\tau\to\mu\mu\mu}{\tau\to\mu\gamma}\right)$	~2 × 10^{-3}	0.06~0.1	0.4~2.3	~16
$\left(\frac{\tau\to\mu ee}{\tau\to\mu\gamma}\right)$	~1 × 10^{-2}	~1 × 10^{-2}	0.3~1.6	~16
Br(τ→μγ) @Max	$<10^{-7}$	$<10^{-10}$	$<10^{-10}$	$<10^{-9}$

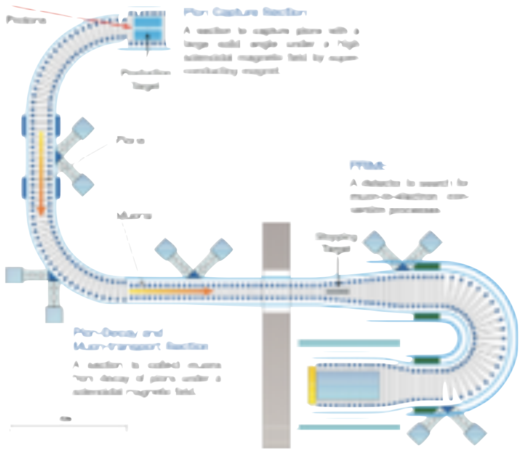
- CONS
  - Smaller number of produced τ
  - Larger experimental background
    - τ→μγ
    - τ→LLL cleaner




lγ
lP0
lS0
lV0
lll
lhh
Λh
10-5
10-6
10-7
10-8
NEW!
CLEO
BaBar
Belle
LHCb


lγ
lP0
lS0
lV0
lll
lhh
Λh
10-5
10-6
10-7
10-8
NEW!
pμ+μ-
pμ-μ-
CLEO
BaBar
Belle
LHCb
UL of BR
τ→μγ
τ→μη
τ→μμμ
CLEO
Belle
BelleII
Luminosity (ab-1)

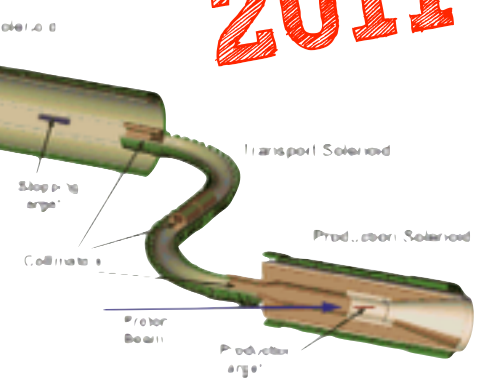
Back to the wheel



mu2e COMET

$10^{-16} \to 10^{-17}$

2017→



$\mu \longrightarrow e\gamma$

MEG[II]

few $\times 10^{-14}$

2015→

BelleII

LHC

$1 \div 2 \times 10^{-9}$

2015→

$\mu^- \mathcal{N} \to e^- \mathcal{N}$

$\tau \to \mu\gamma$

$\tau \to e\gamma$

$\mu \to eee$

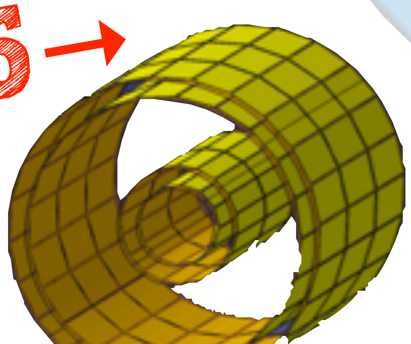
$(g-2)_\mu$

$\times \tan^2 \beta$

Mu3e

$\sim 10^{-15 \div 16}$

2015→



Gm2 FNAL

$\Delta a_\mu = (XXX \pm 34) \times 10^{-11}$

$3.6\sigma \to 8\sigma$

2015→

Summary

- CLFV activities in the World
- Complements flavor physics from the lepton sector
- MEG improved the limit on $\mu \to e \gamma$
    - 5.7×10^{-13} @ 90% C.L.
    - Final result expected for spring 2015
- MEG II
    - Down to 6×10^{-14}
- Mu3e @ PSI
    - Staged approach
    - $<10^{-16}$ level
- Mu2e, DeeMe and COMET
    - intensive R&D for the realization of the experiments
    - Staged setup to test part of the techniques
    - 10^{-17} level
    - towards 10^{-18} with future muon campuses (Project-X and PRISM/PRIME)
- Complementarity with τ, meson and exotic CLFV