μLFV in Europe: MEG μ3e and beyond

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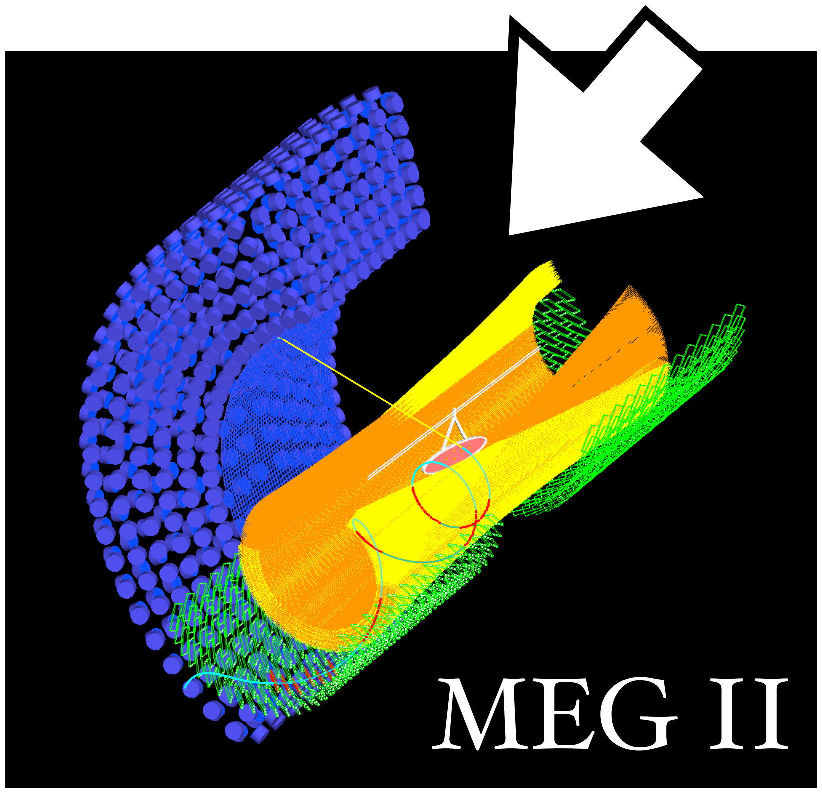
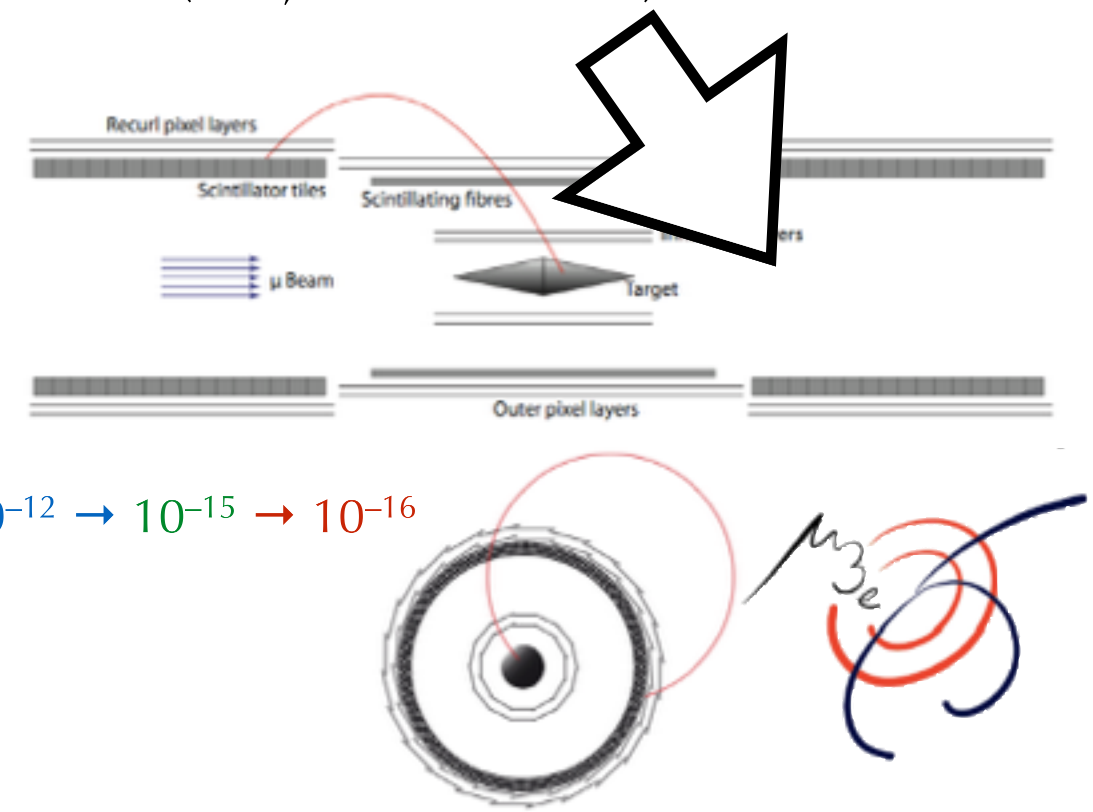
LTS1 2014 Workshop on the long term strategy of INFN-CSN1

Ballistic

- 10^8 μ/sec, 1.2 MW continuous *p* beam. LFV (Sin, SINdrum…)



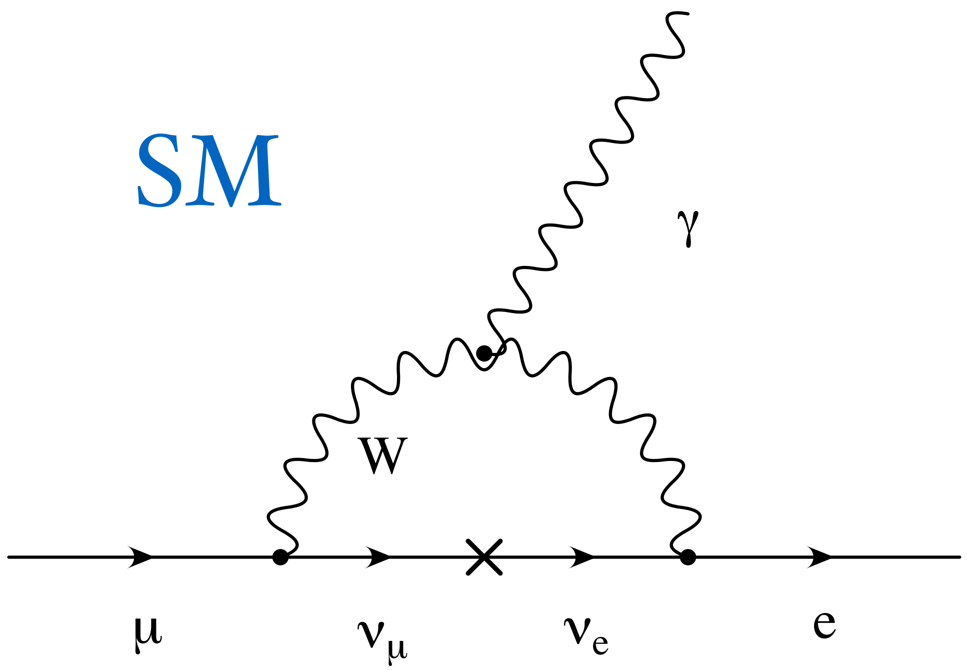


$10^{-12} \rightarrow 10^{-15} \rightarrow 10^{-16}$

$5 \times 10^{-13} \rightarrow 5 \times 10^{-14}$

Non ballistic

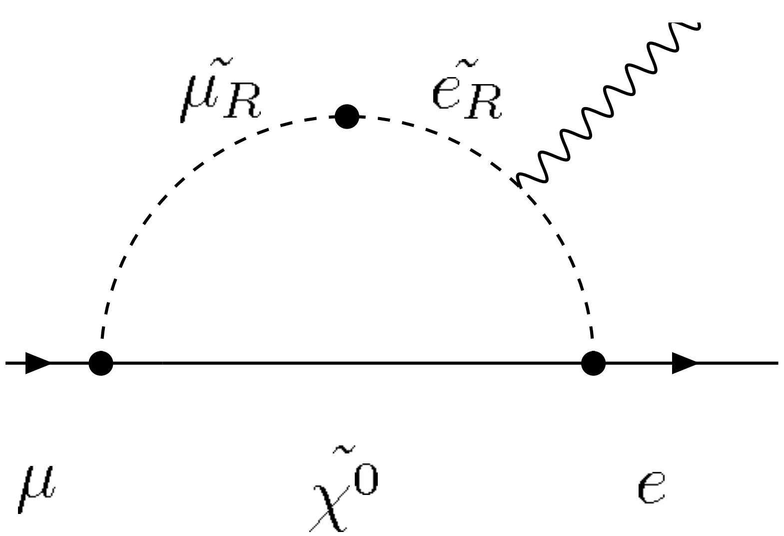
SM

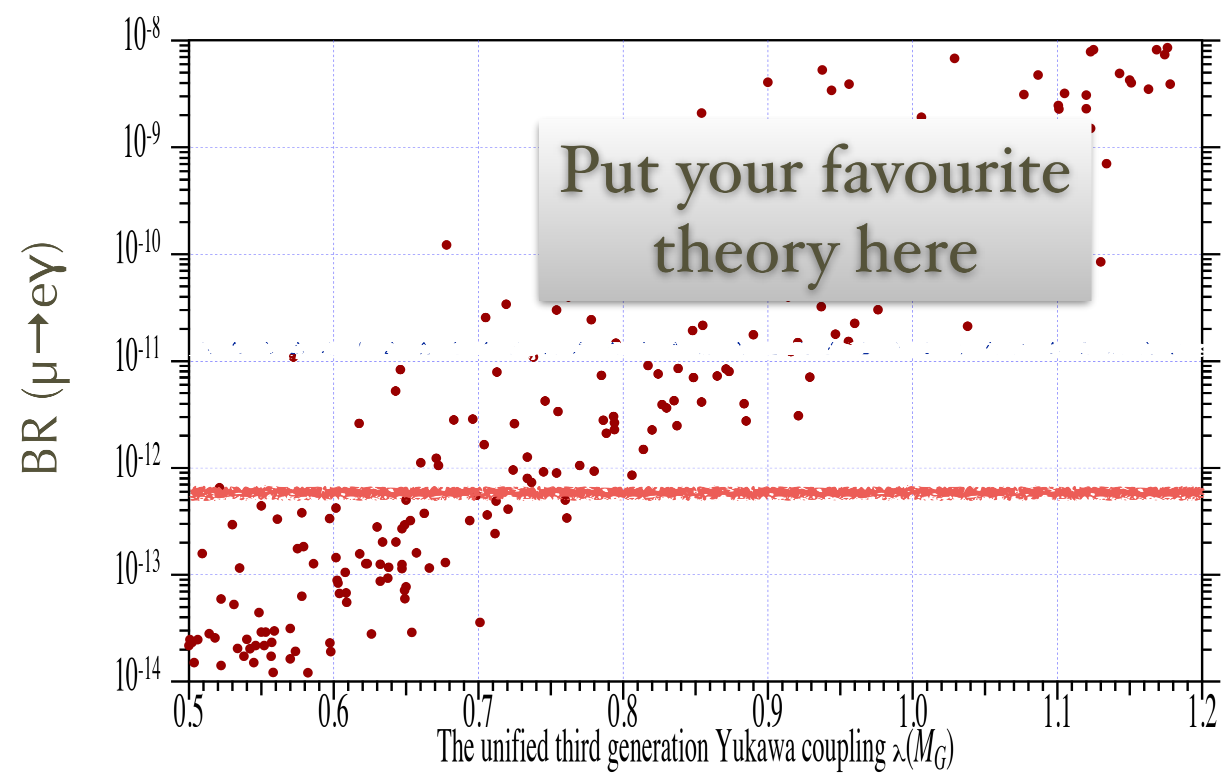


$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \quad \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \quad \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

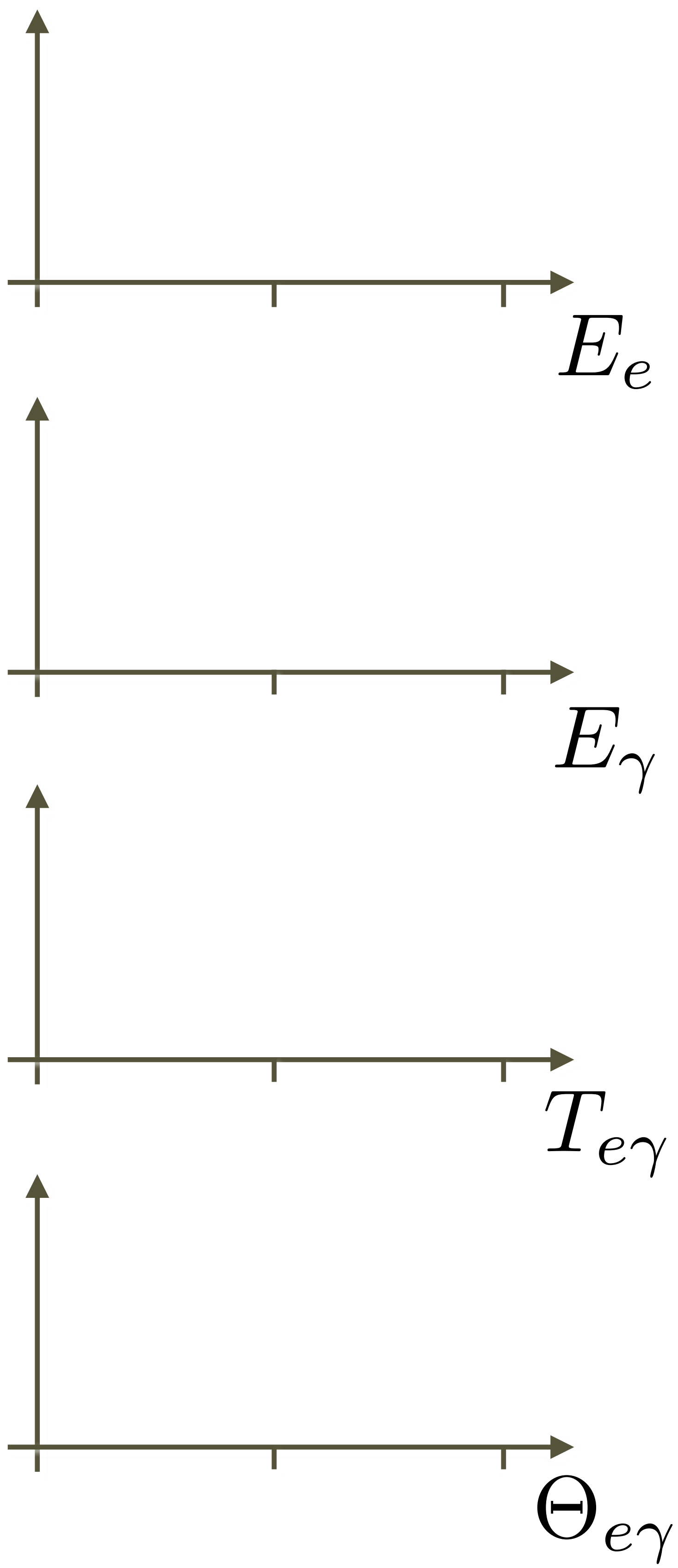
$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{3\alpha}{32\pi} \left(\frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}}{M_W^2}\right)^2$$

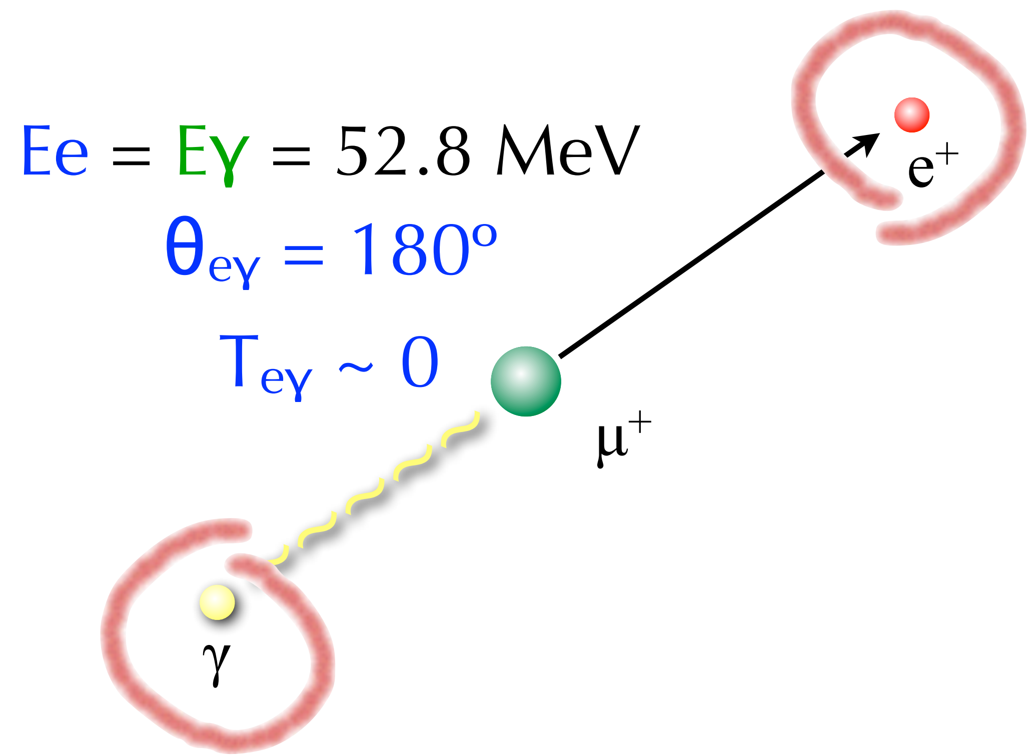
relative probability ~ **10^{-54}**



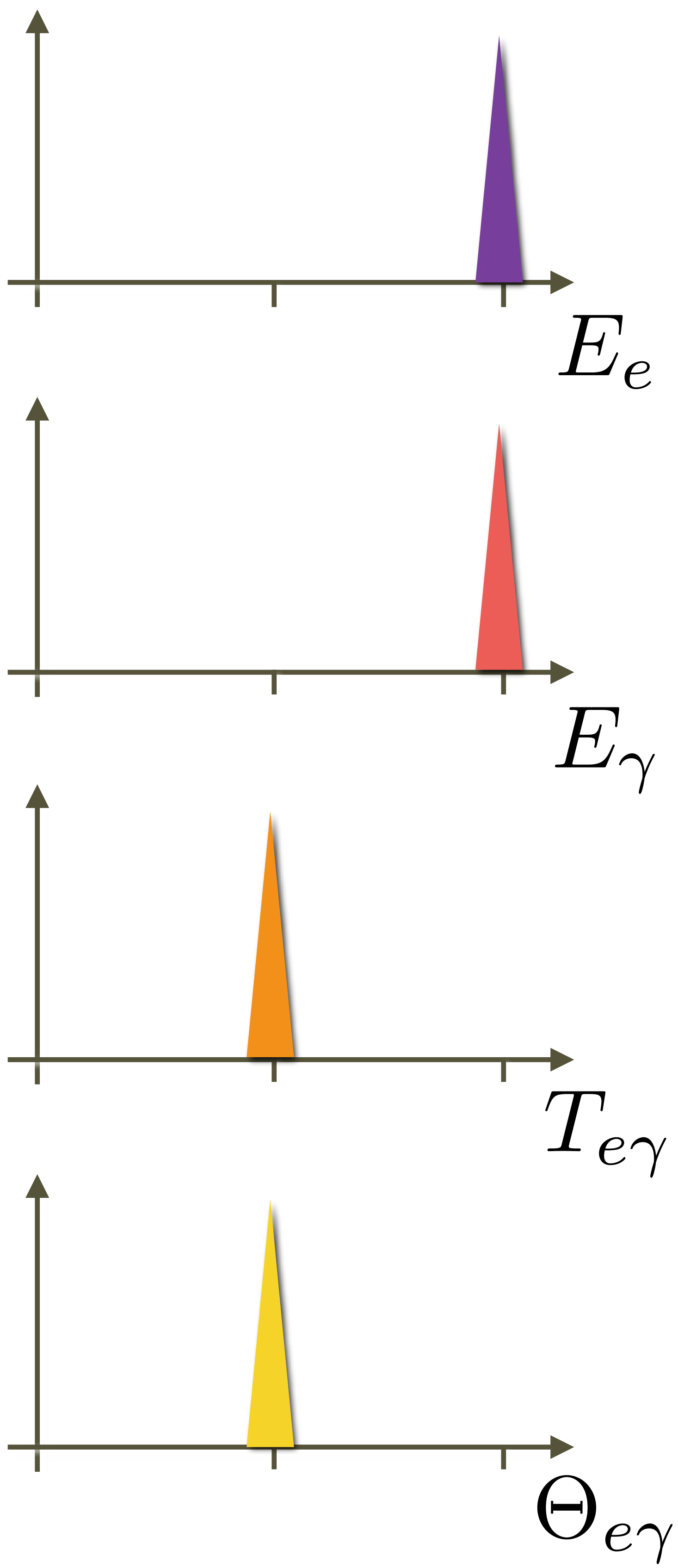


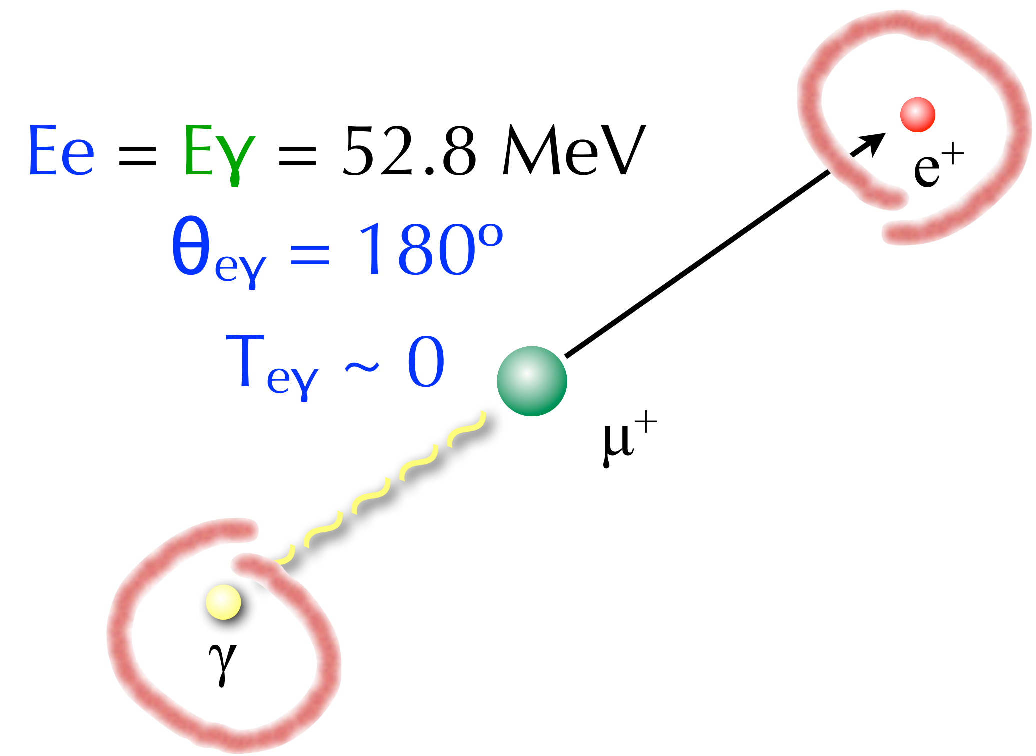
Take $\mu \to e\gamma$: sensitivity



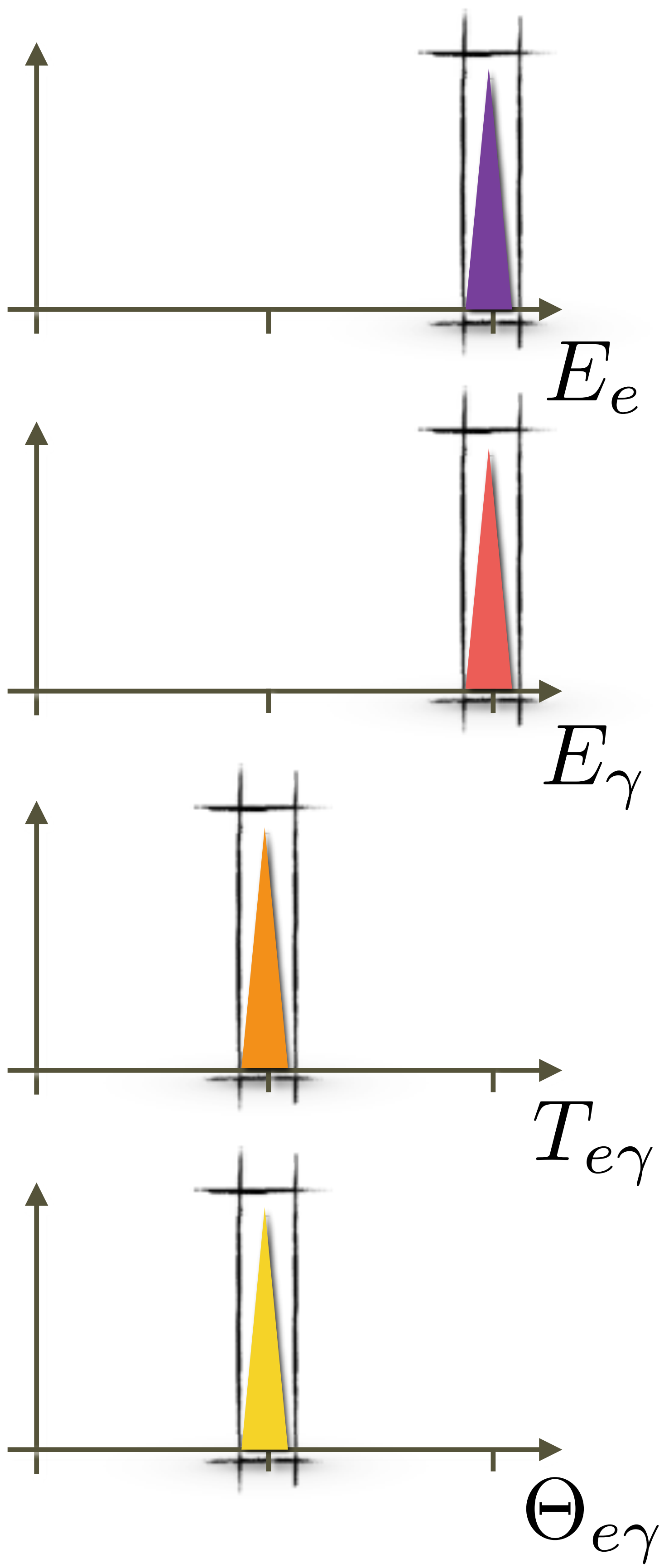


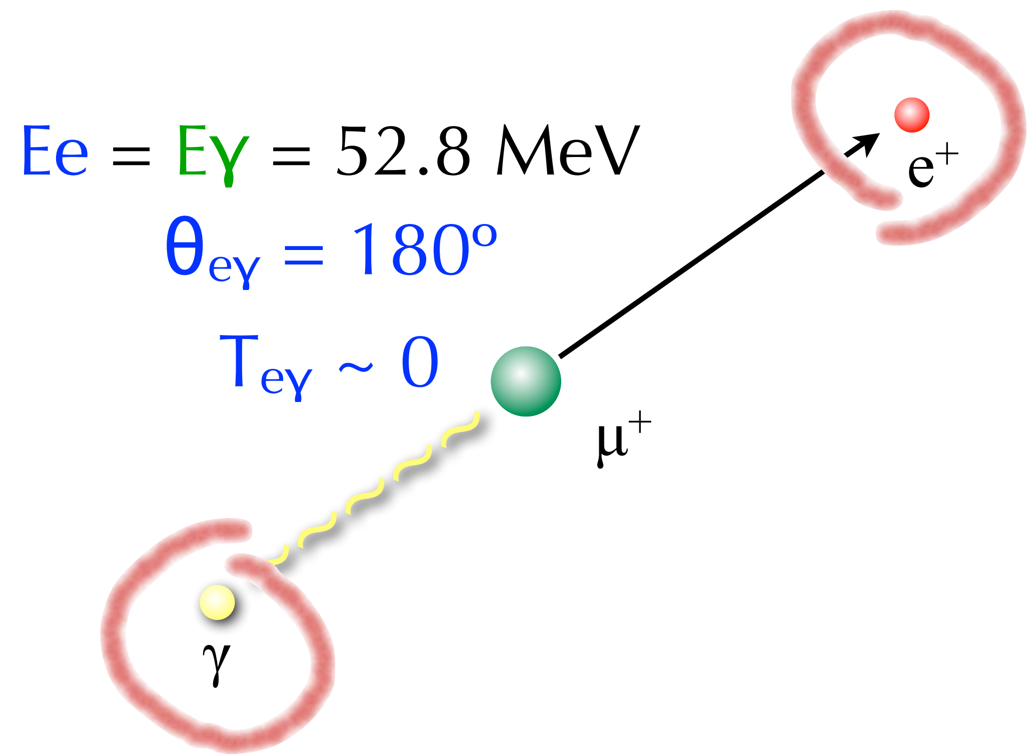
Take $\mu \rightarrow e\gamma$: sensitivity





Take $\mu \to e\gamma$: sensitivity



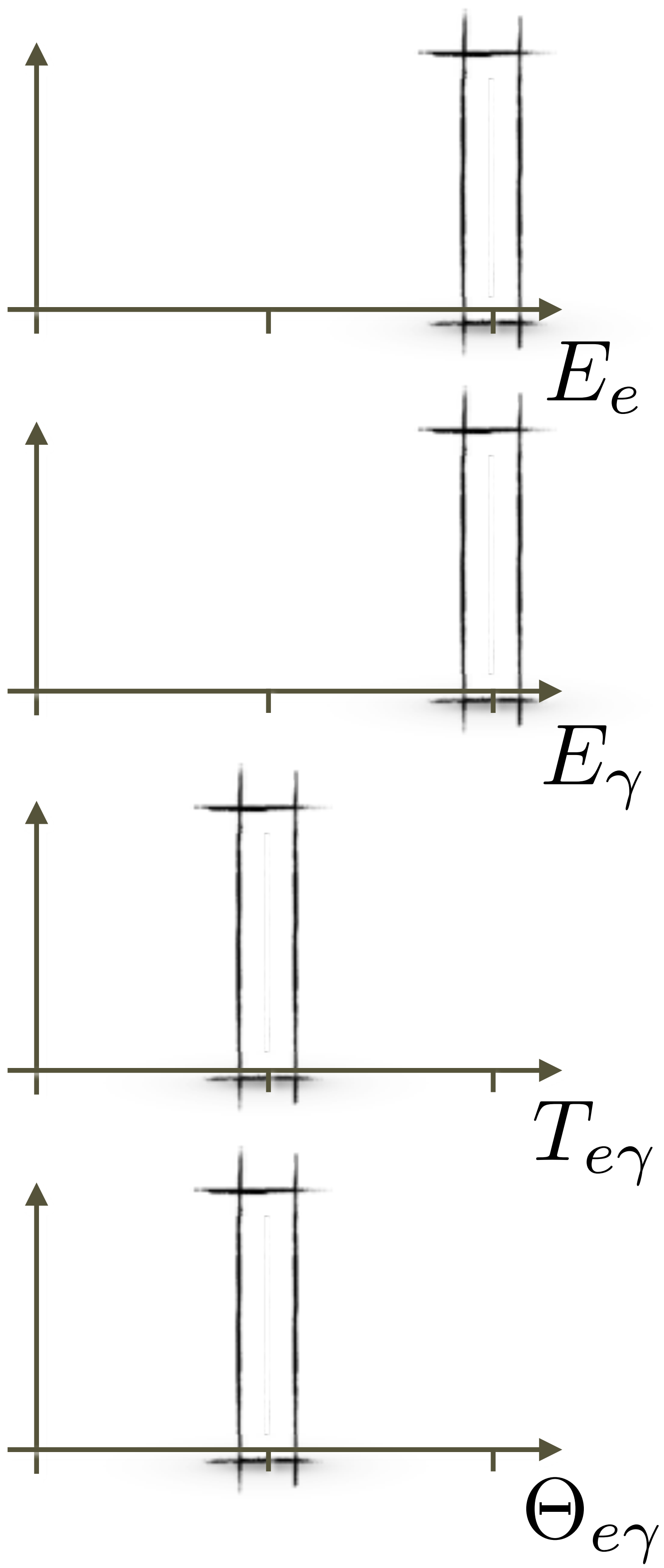


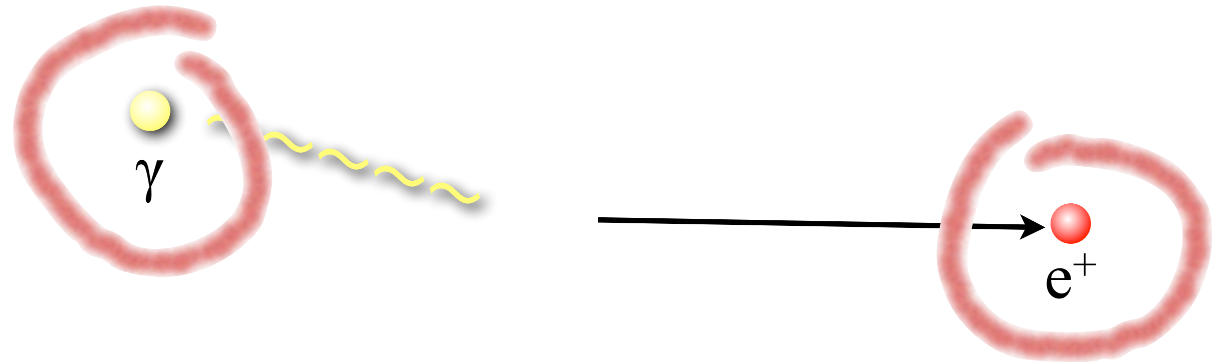
$$SES^{-1} \propto N_\mu \cdot T \cdot (\Omega/4\pi) \cdot \epsilon_e \cdot \epsilon_\gamma \cdot \epsilon_{\rm sel}$$

$$\propto 10^8 \mu/\text{sec} \cdot 5 \times 10^7 \text{sec} \cdot 10\% \cdot 50\%$$

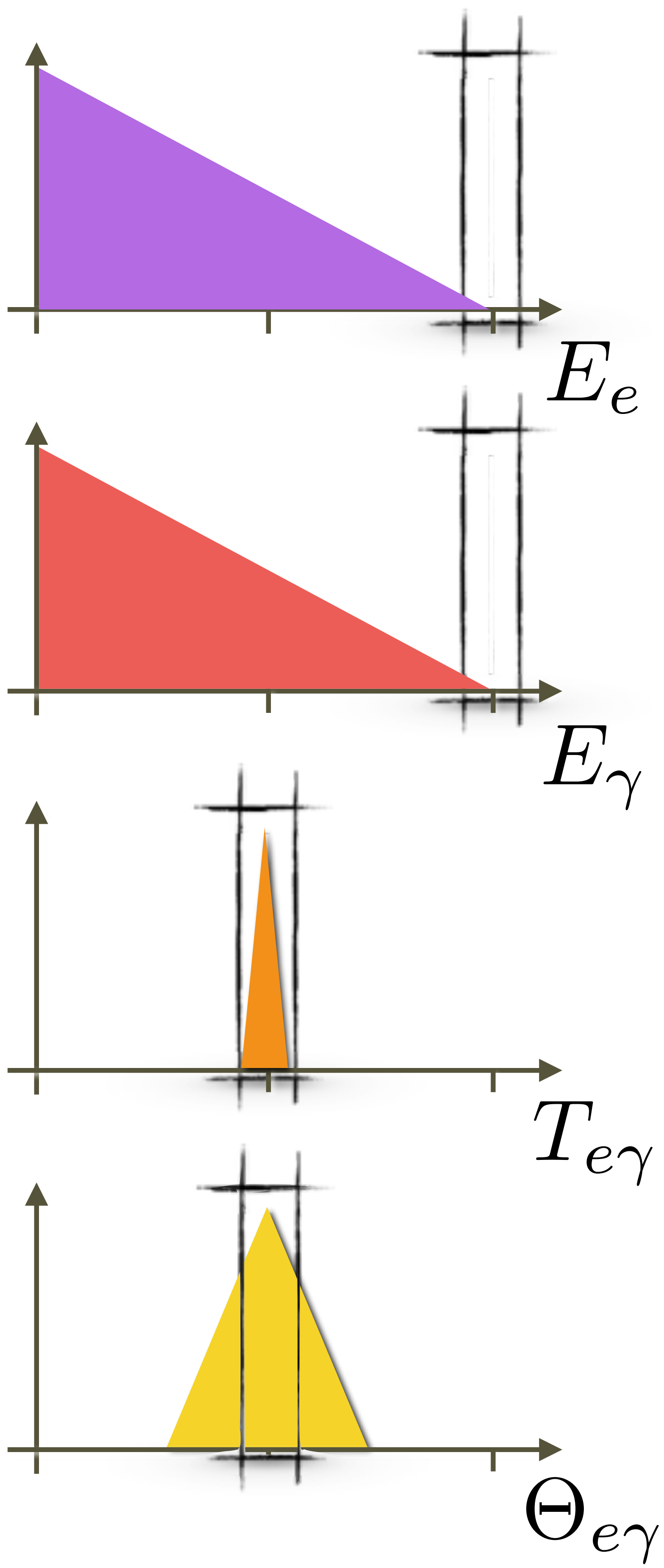
$$SES \approx 10^{-13} \div 10^{-15}$$

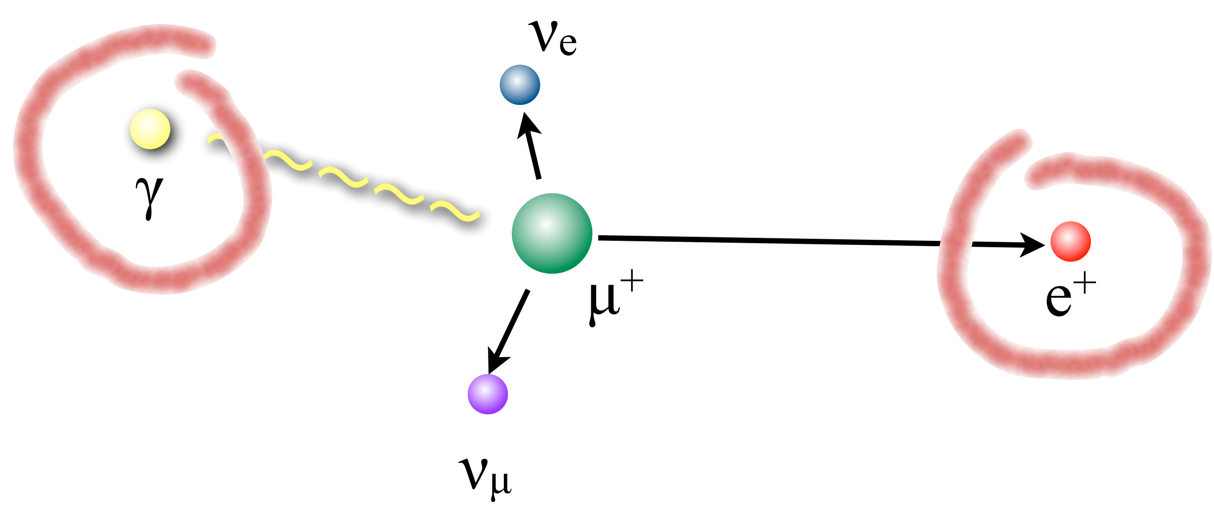
Take $\mu \to e\gamma$: sensitivity

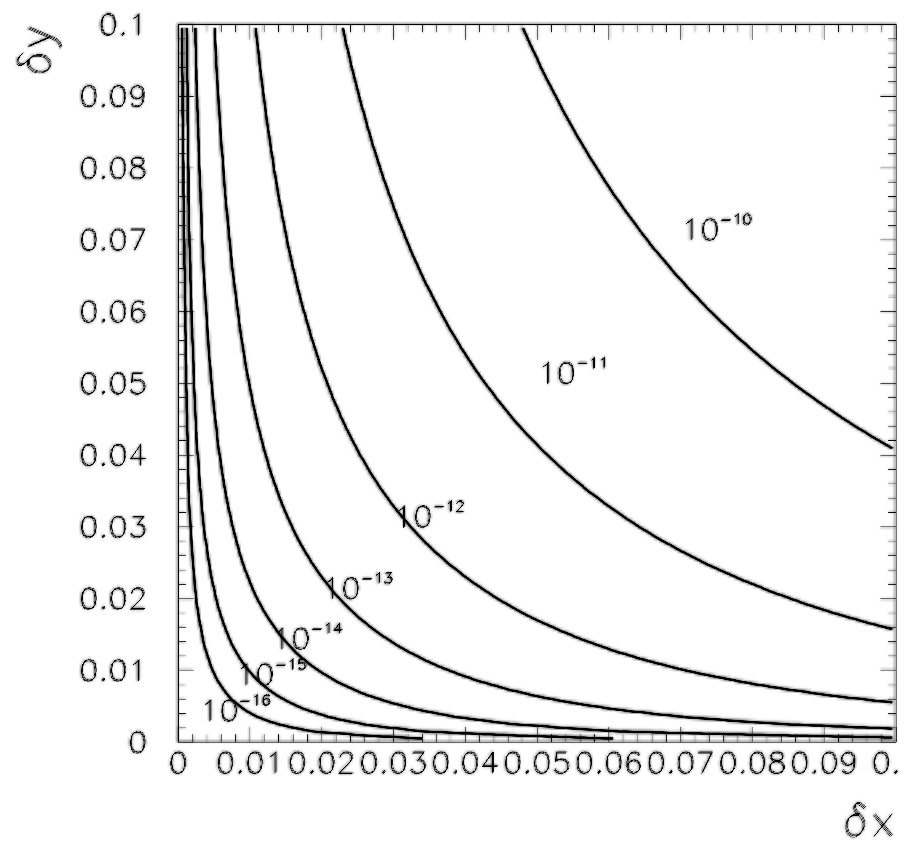




$\mu \to e\gamma$ RMD background





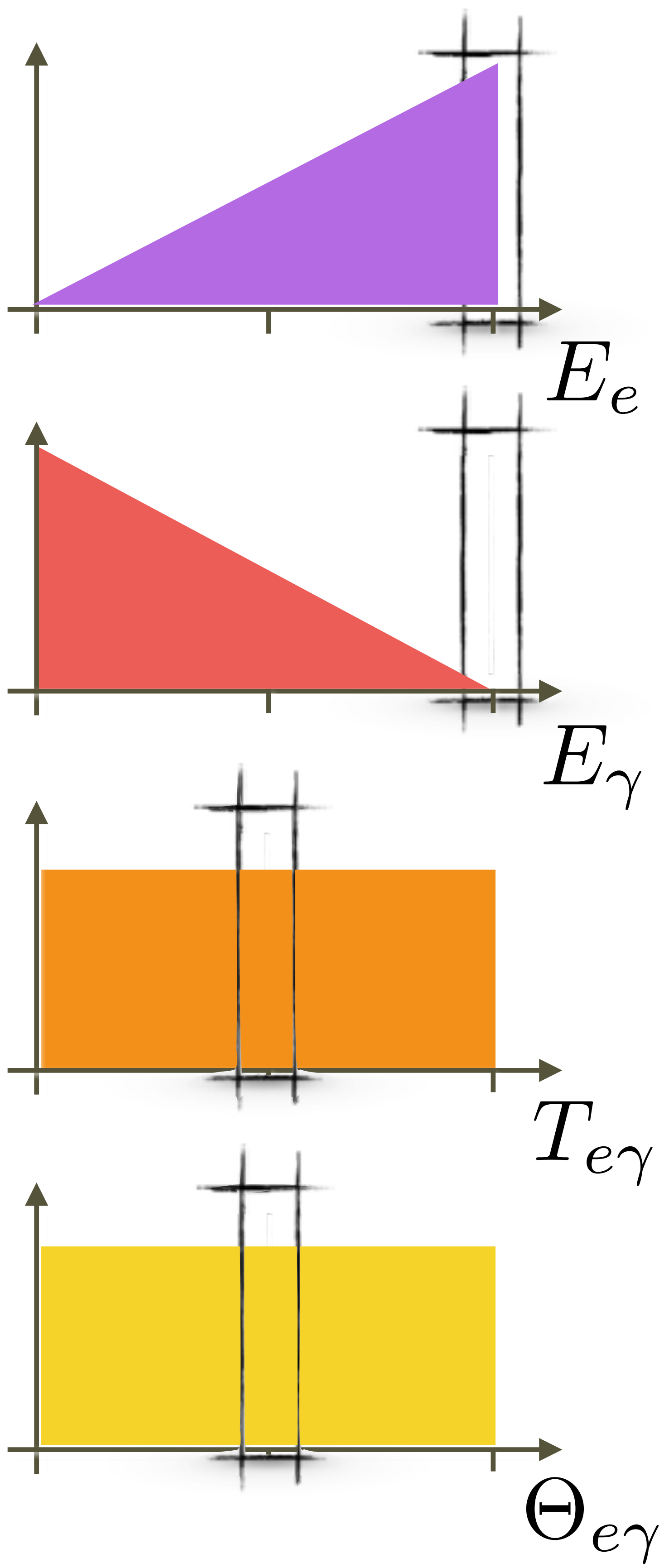


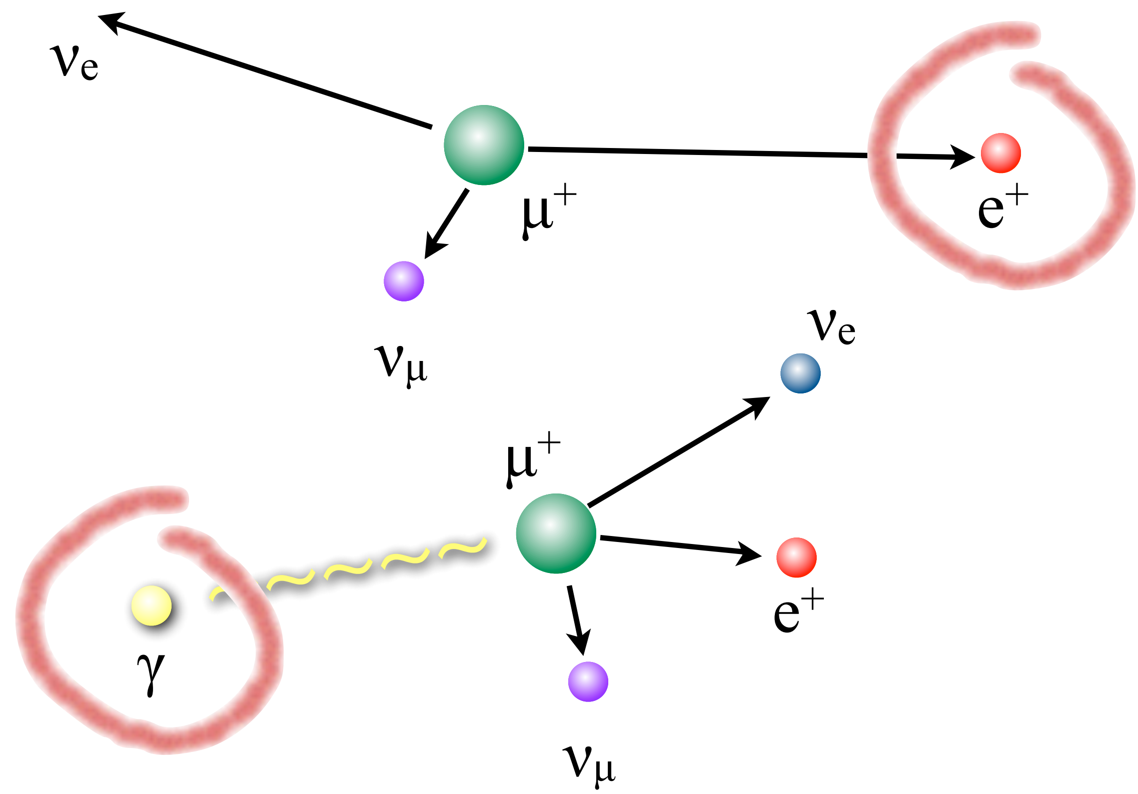
$$y = \frac{E_\gamma}{m_\mu/2}$$

$$x = \frac{E_e}{m_\mu/2}$$

$$dB(\mu^+ \to e^+\nu\bar{\nu}\gamma) = \frac{1}{\Gamma(\mu^+ \to e^+\nu\bar{\nu})} \int_{1-\delta x}^{1} dx \int_{1-\delta y}^{1} dy \int_{0}^{\min(\delta z, 2\sqrt{(1-x)(1-y)})} dz \; \frac{d\Gamma(\mu^+ \to e^+\nu\bar{\nu}\gamma)}{dx\,dy\,dz}$$

$\mu \to e\gamma$ accidental background





$$N_{\text{acc}} \approx R_\mu^2 \cdot \Delta E_e \cdot \Delta E_\gamma^2 \cdot \Delta\Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma}$$

The total background grows quadratically with the muon rate *provided that* the RMD background is negligible

Take $\mu\rightarrow e\gamma$: sensitivity

- The sensitivity to the decay is the best compromise between resolution, acceptance and efficiency

Place	Year	ΔE_e	ΔE_γ	$\Delta t_{e\gamma}$	$\Delta\theta_{e\gamma}$	Upper limit
SIN	1977	8.7%	9.3%	1.4 ns	–	$< 1.0 \times 10^{-9}$
TRIUMF	1977	10%	8.7%	6.7 ns	–	$< 3.6 \times 10^{-9}$
LANL	1979	8.8%	8%	1.9 ns	37 mrad	$< 1.7 \times 10^{-10}$
LANL	1986	8%	8%	1.8 ns	87 mrad	$< 4.9 \times 10^{-11}$
LANL	1999	1.2%*	4.5%*	1.6 ns	17 mrad	$< 1.2 \times 10^{-11}$
PSI	2014	1.4 %*	4.5 %*	280 ps*	20 mrad*	$< 5.7 \times 10^{-13}$

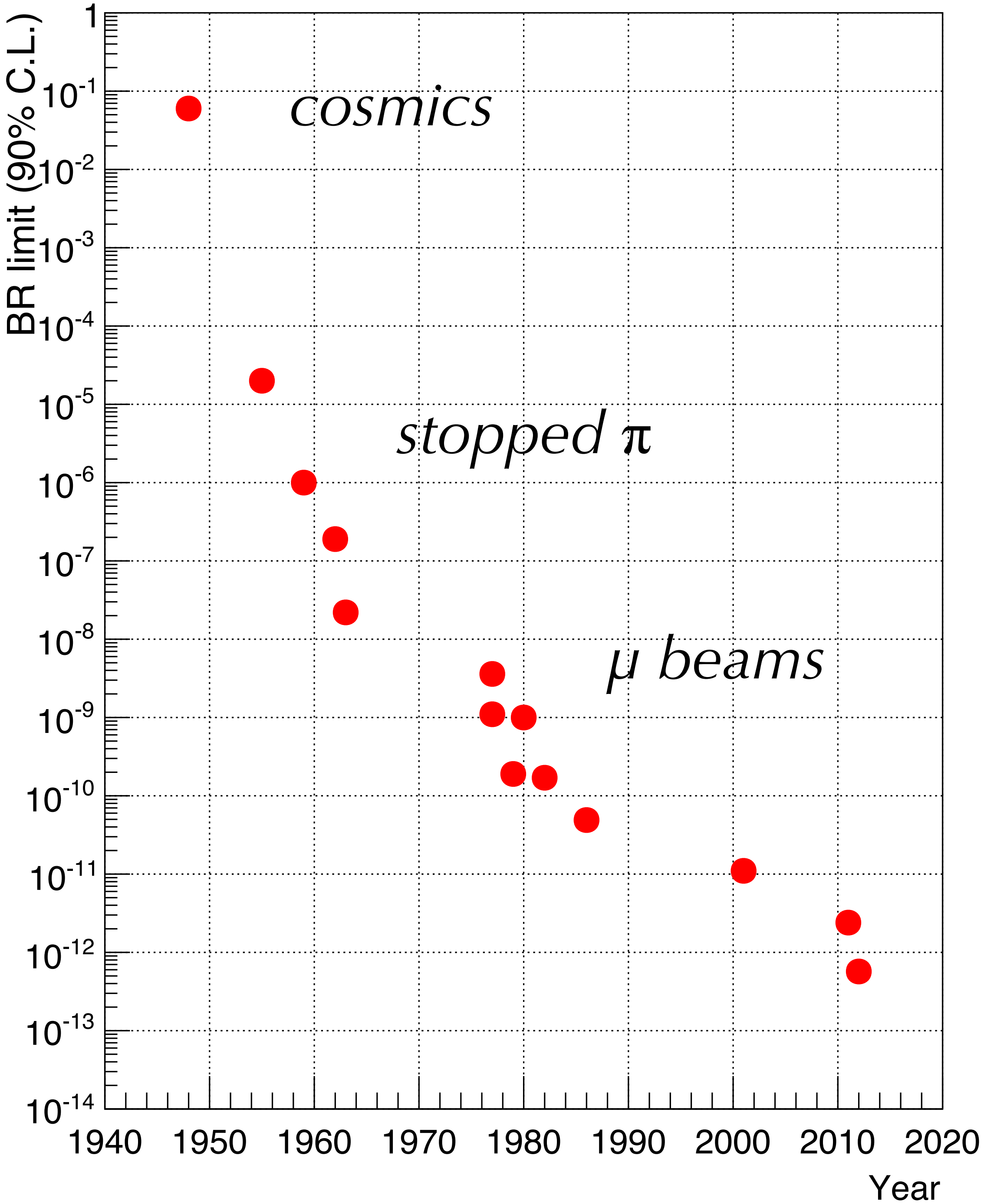
  - (*) FWHM resolutions, averaged over several years

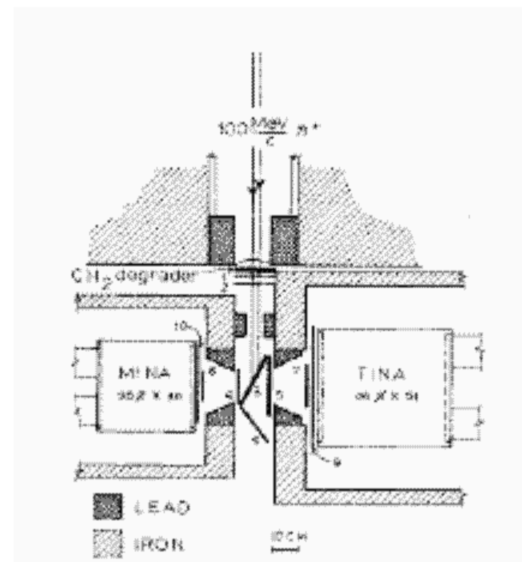
- The background rejection capability is the best compromise between subdetector resolutions and acceptances

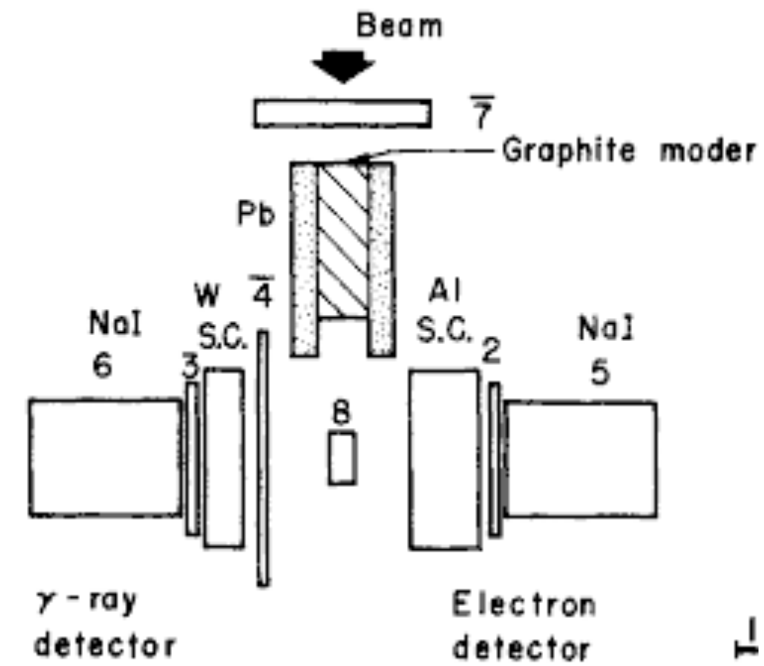
$$N_{\rm acc} \approx R_\mu^2 \cdot \Delta E_e \cdot \Delta E_\gamma^2 \cdot \Delta\Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma}$$

What we learned

1) We need a continuous, 29 MeV/c muon beam stopped on a thin target (100 μm)

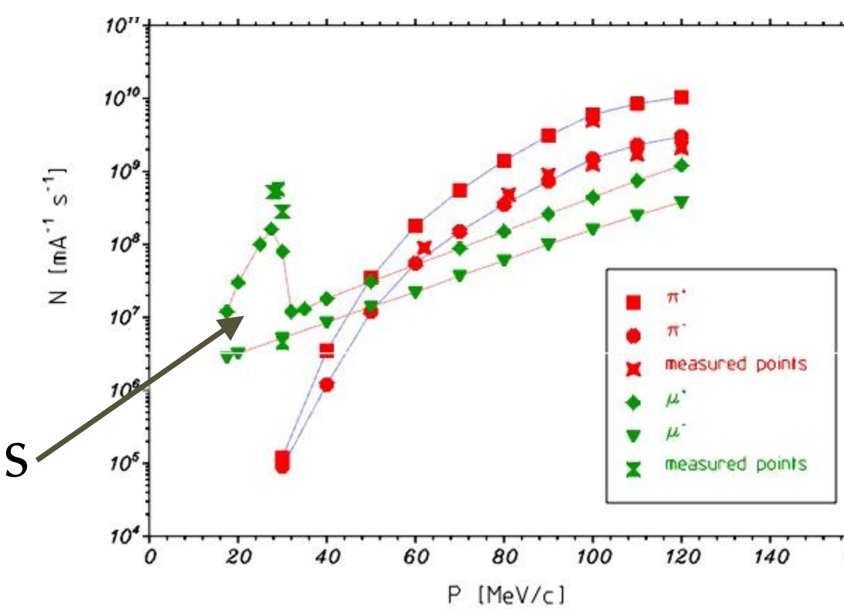






1 cm plastic target → 2 MeV → 4%

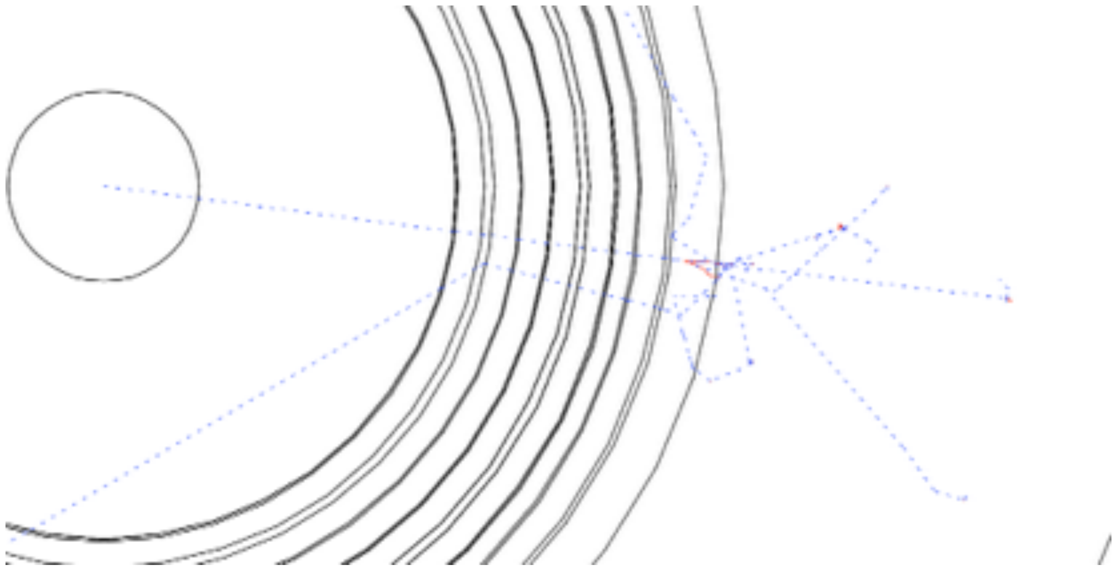
“surface” muons

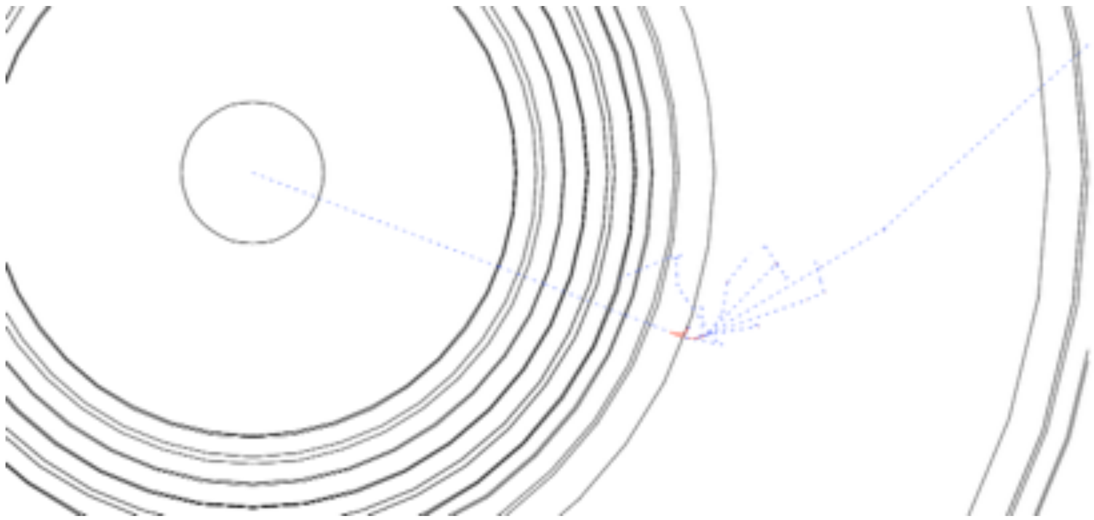


What we learned

2) 52.8 MeV photons and positrons have different behavior from that at “high” energy

- no e.m. shower
- lots of multiple scattering



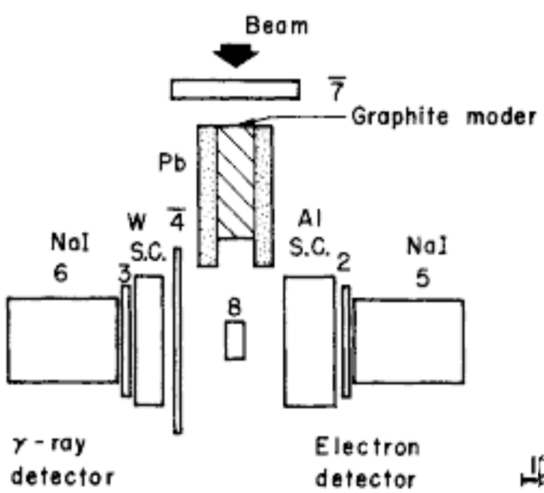


$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

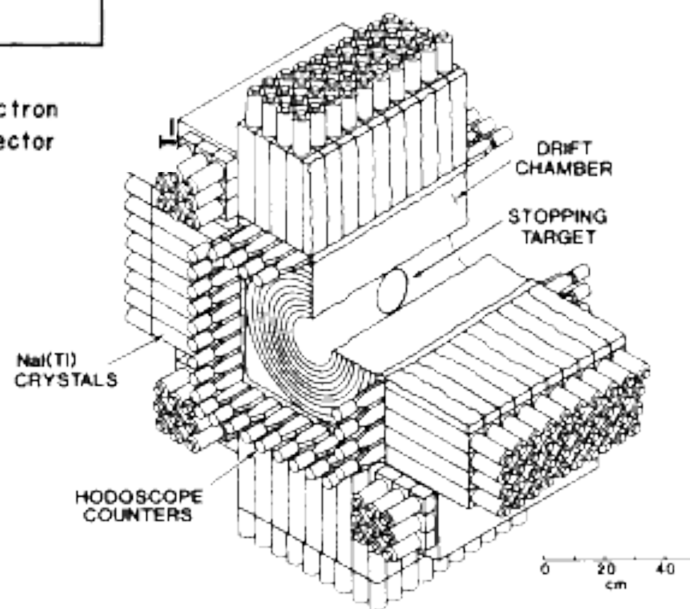
- MEG-II $1.7 \times 10^{-3}\ X_0$ per track

What we learned

3) Need for specialized detectors…. (or not?) or “how to achieve back-to-back”

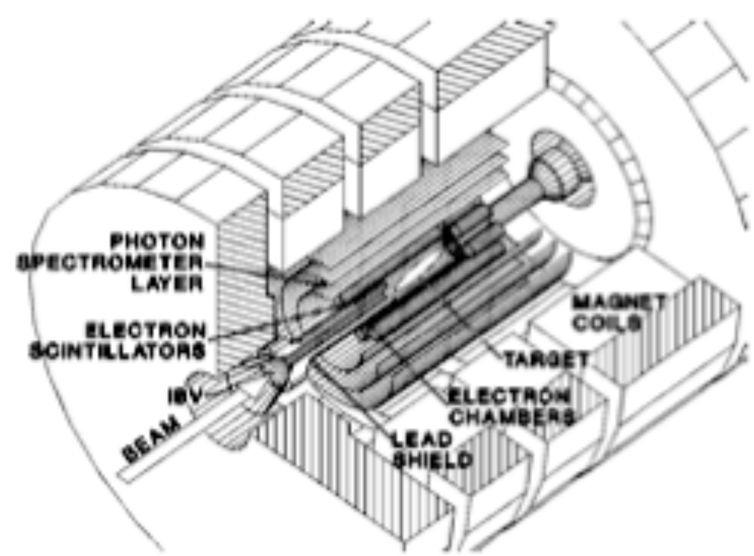


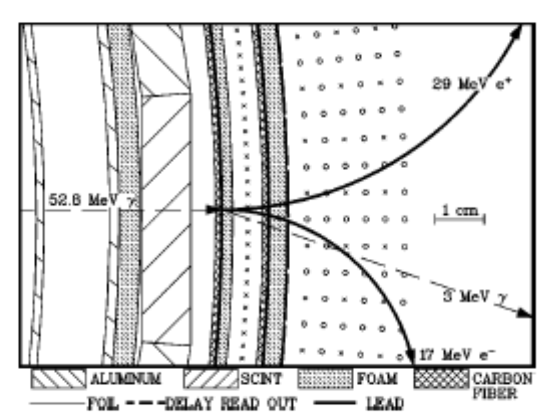
SIN



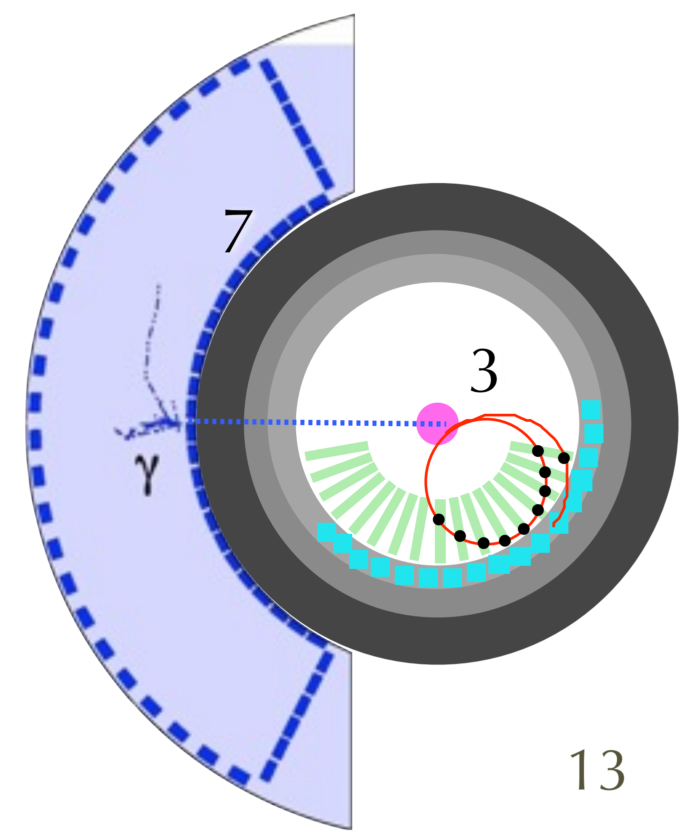
Crystal Box

MEGA



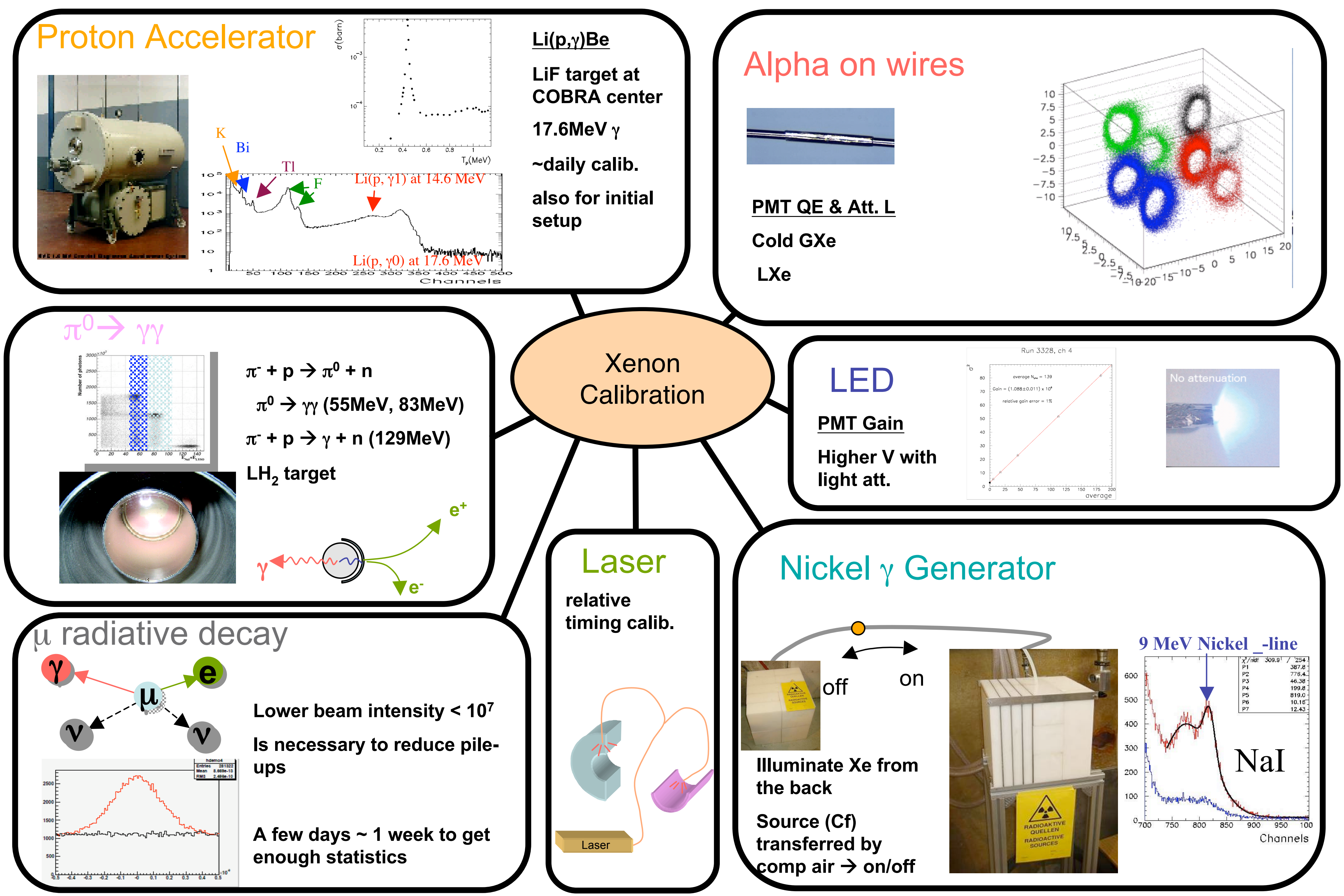


MEG/ MEG II



What we learned

4) We need a LOT of CALIBRATIONS to continuously monitor the status of the experiment and of all subdetectors



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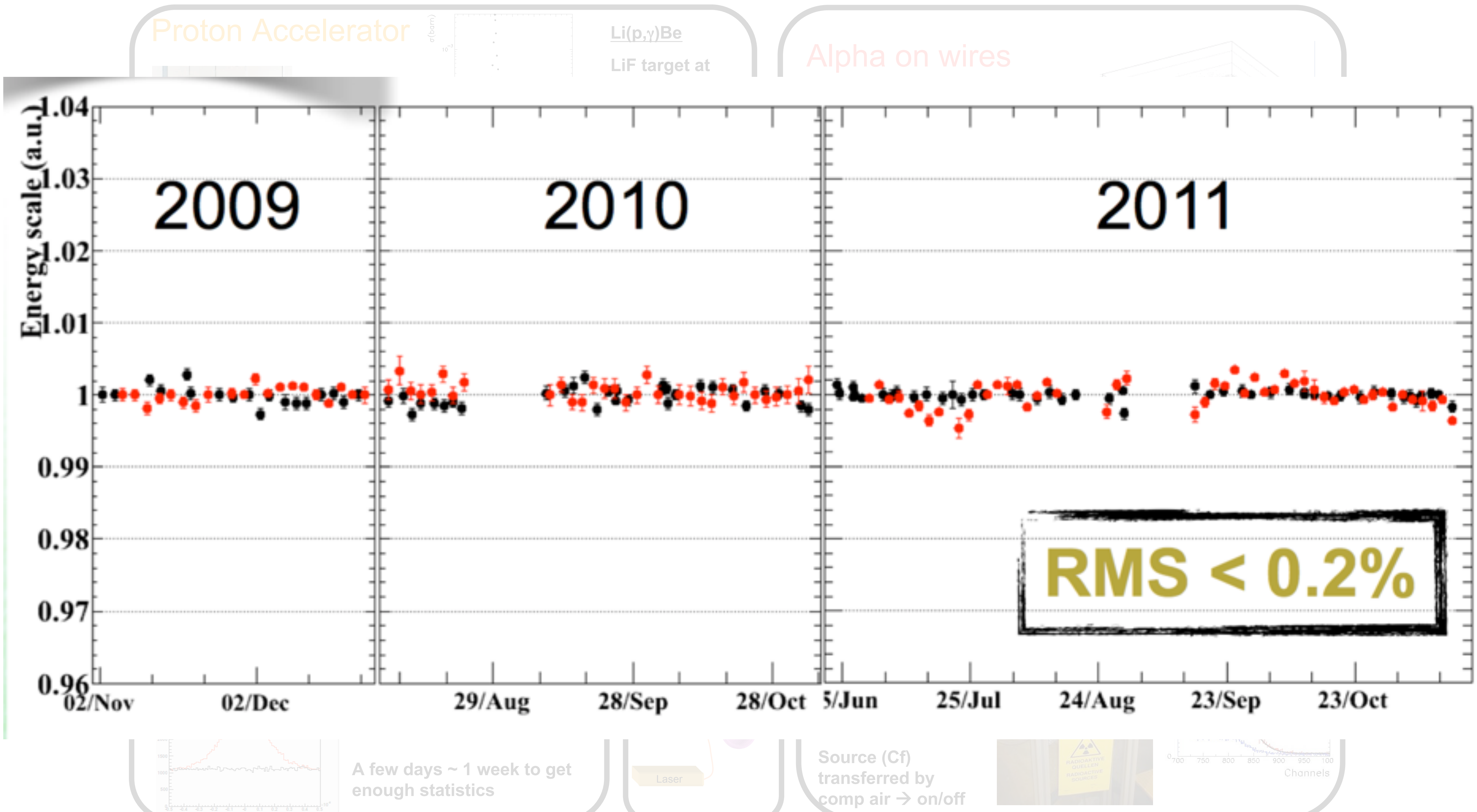


Key elements to MEG II

μ

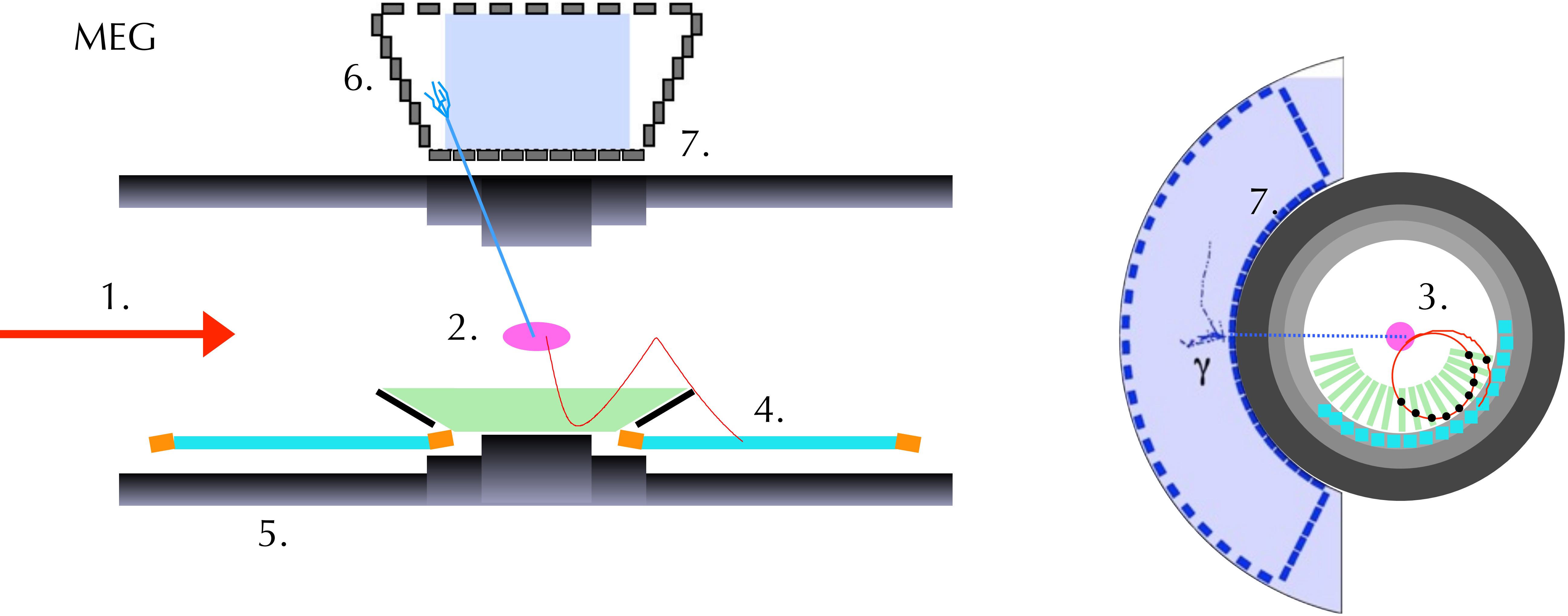
1. Increasing μ^+–stop on target
2. Reducing target thickness to minimize e+ MS & brehmsstrahlung

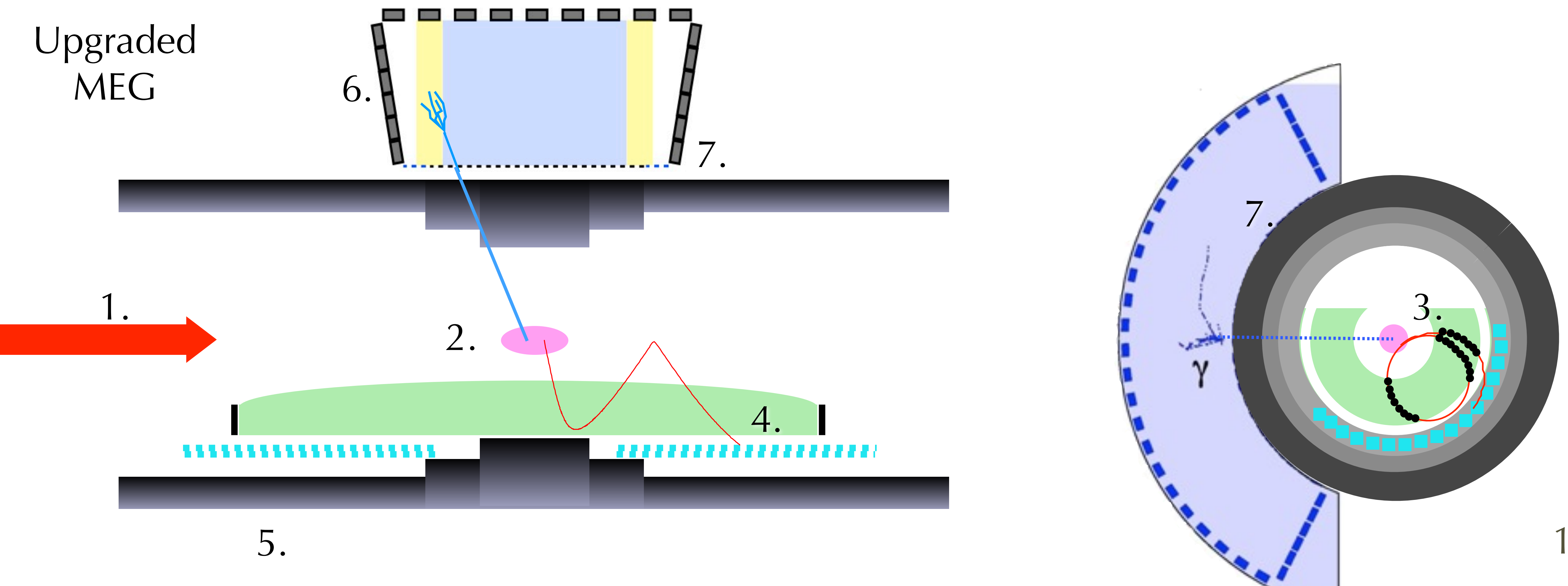
e

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

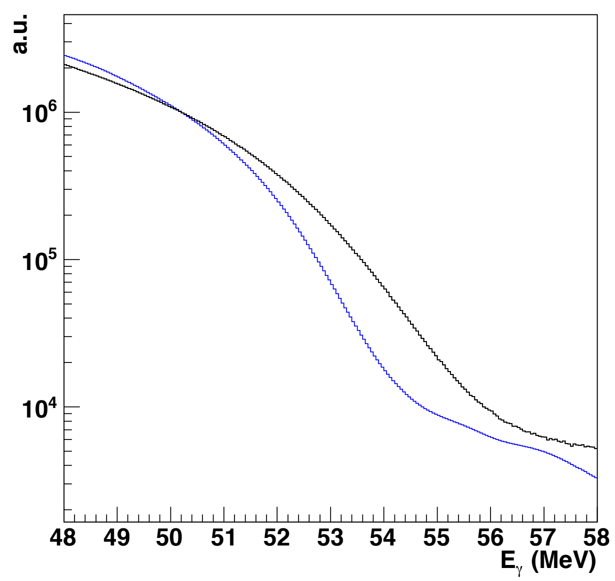
6. Extending the γ–ray detector acceptance
7. Improving the γ-ray energy and position resolution for shallow events
8. Integrating splitter, trigger and DAQ maintaining a high bandwidth

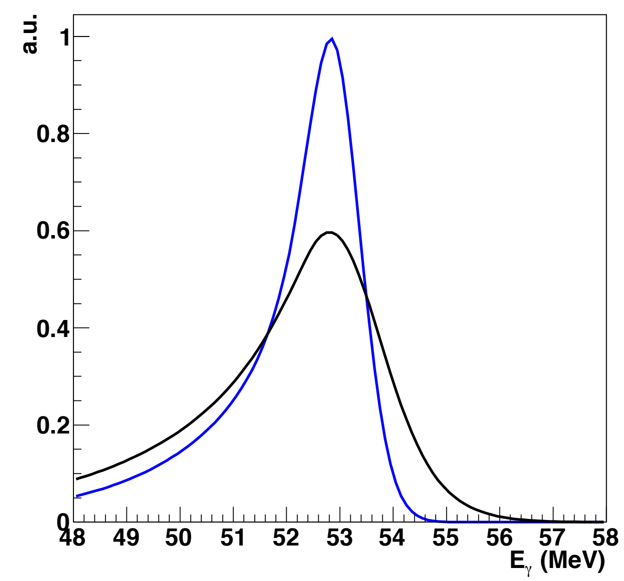

MEG
6.
7.
1.
2.
4.
5.
7.
3.
γ


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

MEG^{UP} sensitivity

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88



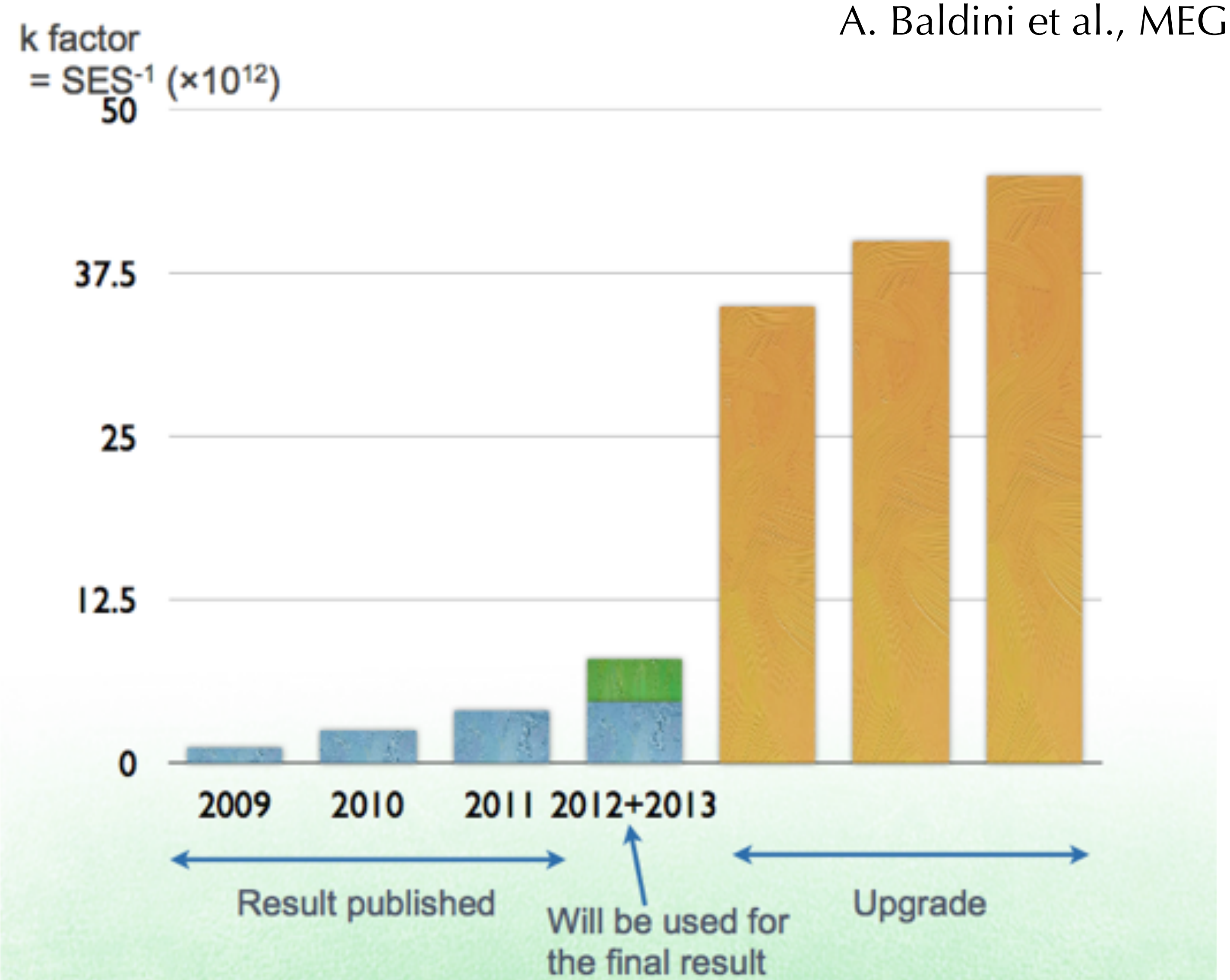


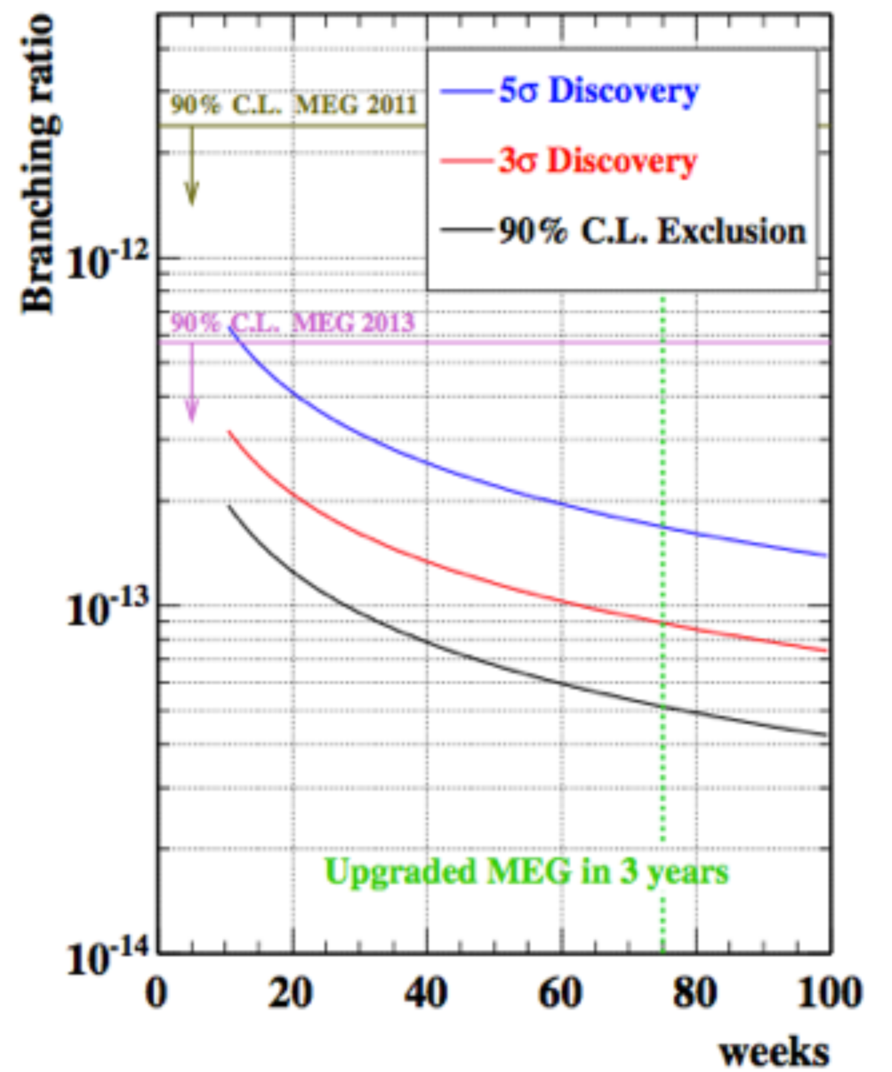
$$5.7 \times 10^{-13}$$

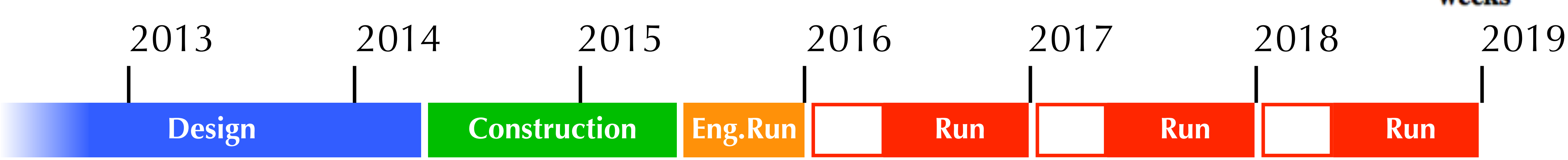
MEG^{UP} sensitivity

- 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] |





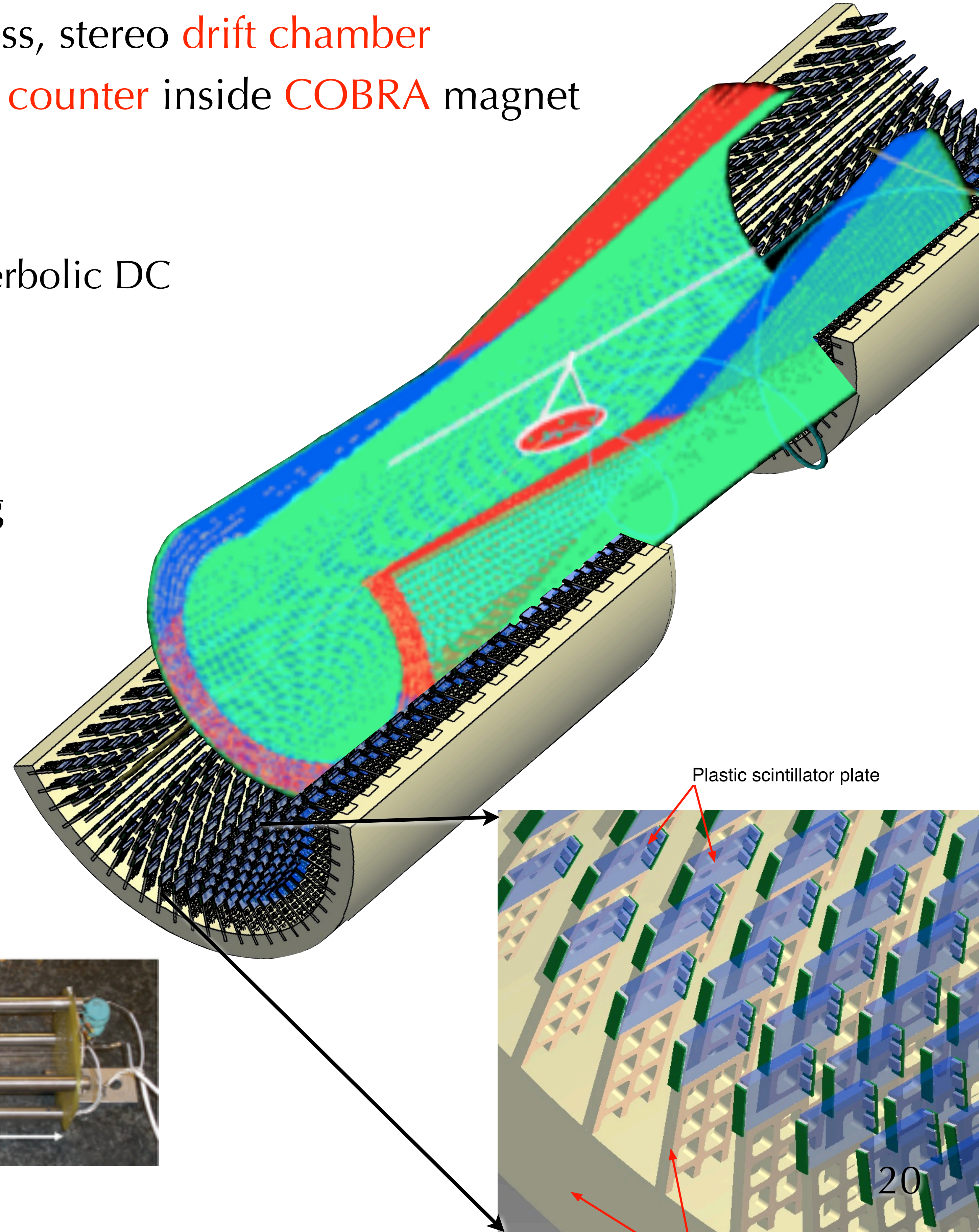


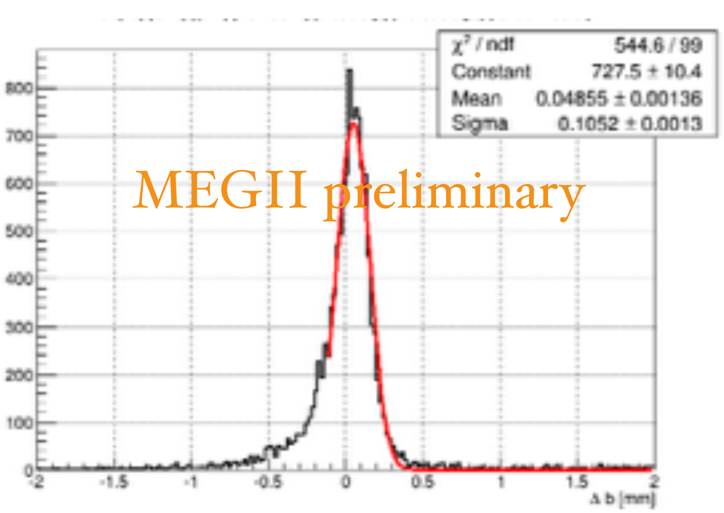
Positron tracker

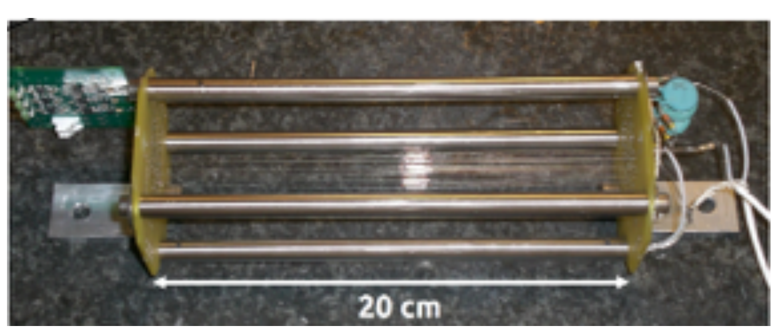
single volume, low mass, stereo drift chamber

+ multi-tile scintillation timing counter inside COBRA magnet

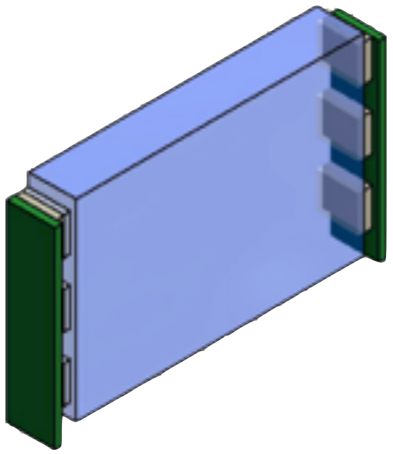
- Drift Chamber
  - Single volume gas detector
  - U-V stereo reconstruction (8º) → hyperbolic DC
  - low mass (85:15 $He:iC_4H_{10}$)
  - Low X_0 ($<1.7 \times 10^{-3}$ X_0)
  - >80% Transparency towards TC
  - Ultra-fast electronics for cluster timing
- performance from MC + Protoypes
  - > 50 hits/track
  - Single hit resolution ~120 μm
  - Momentum resolution ~150 keV
  - Angular resolution ~5÷7 mrad



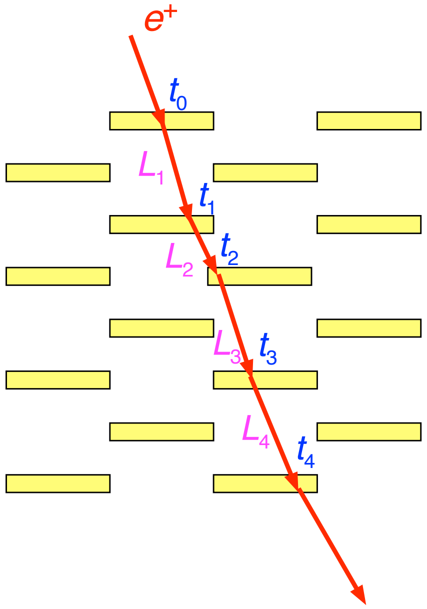


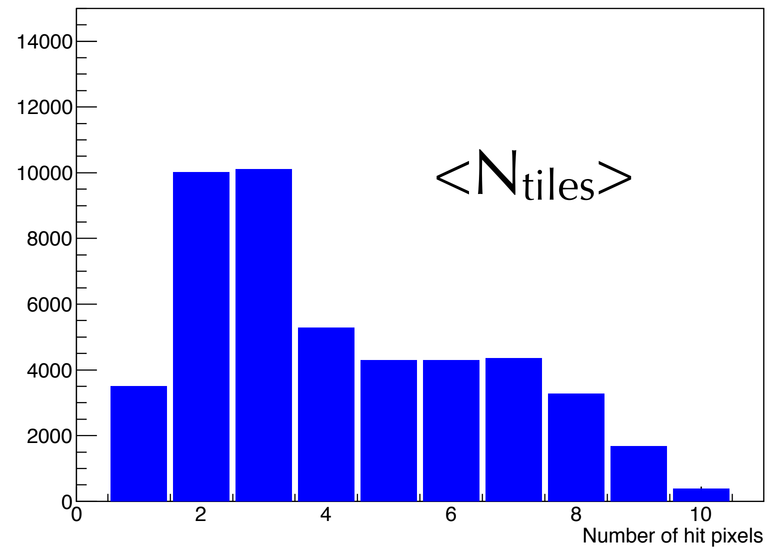


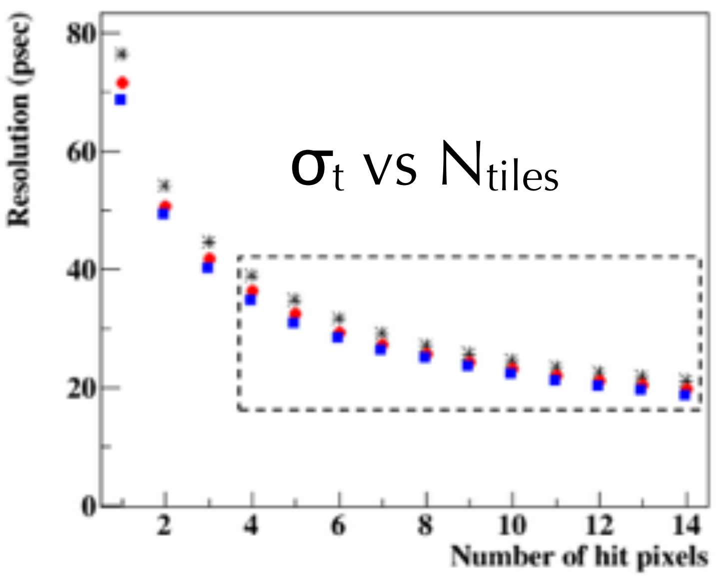
Timing Counter

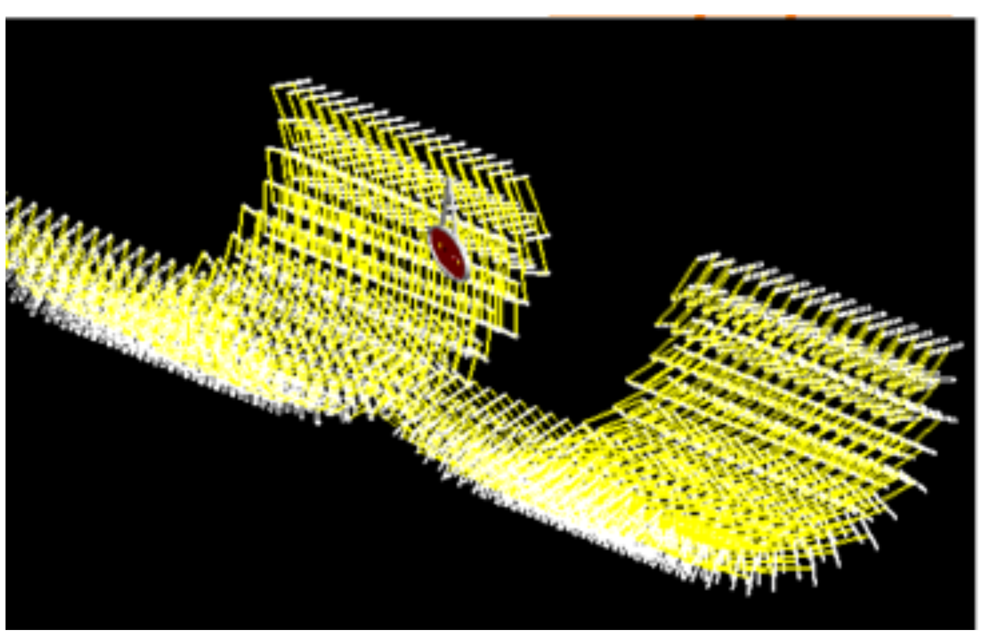


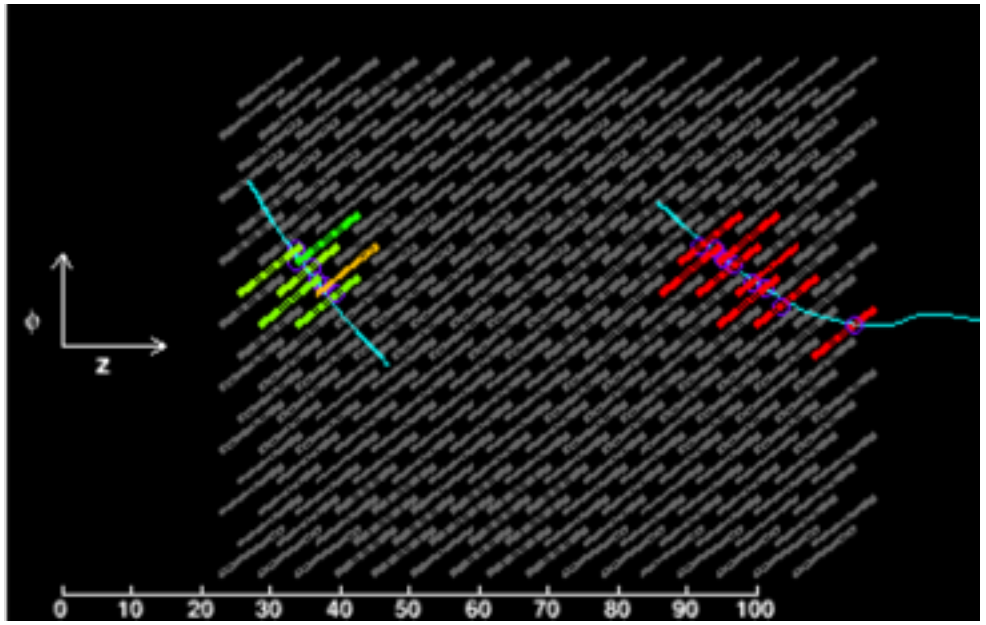
- Timing Counter
  - Increased muon flux → Reduce hit-rate and pile-up
  - (3 x 6 x 0.5) cm^3 plastic scintillator tiles, read by MPPC
  - improve timing resolution by combining several tiles





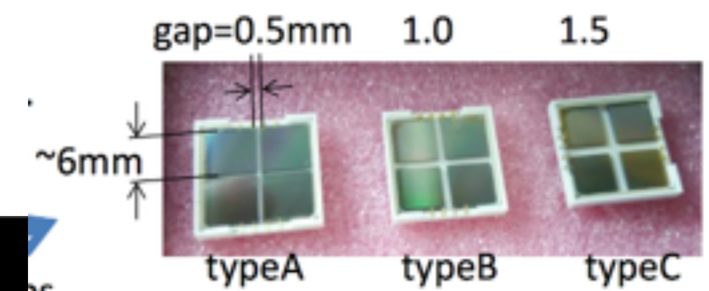


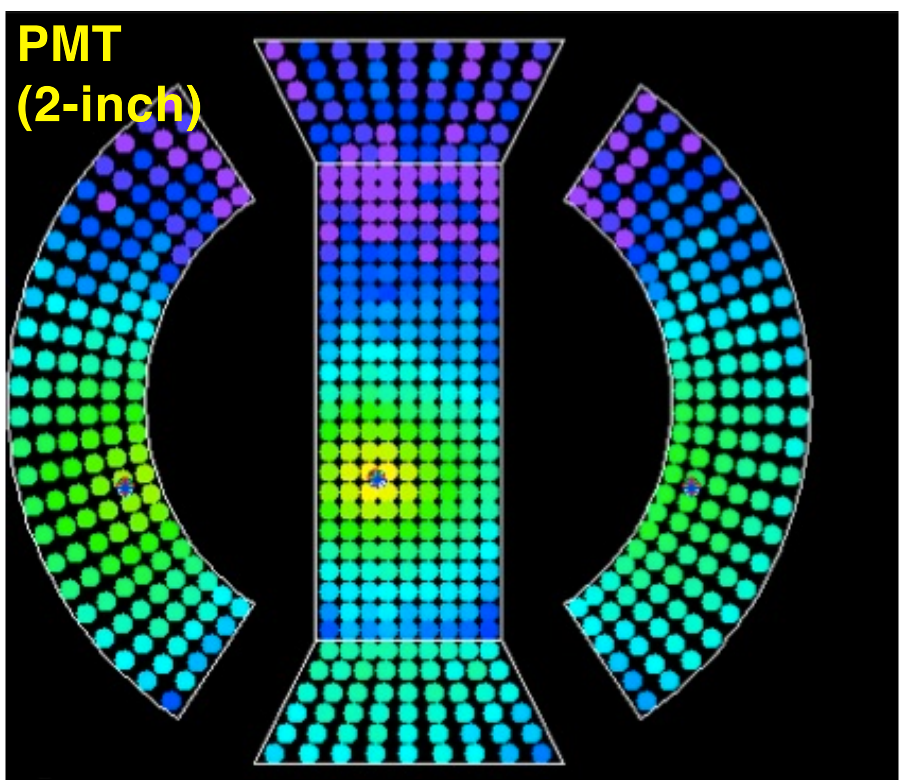


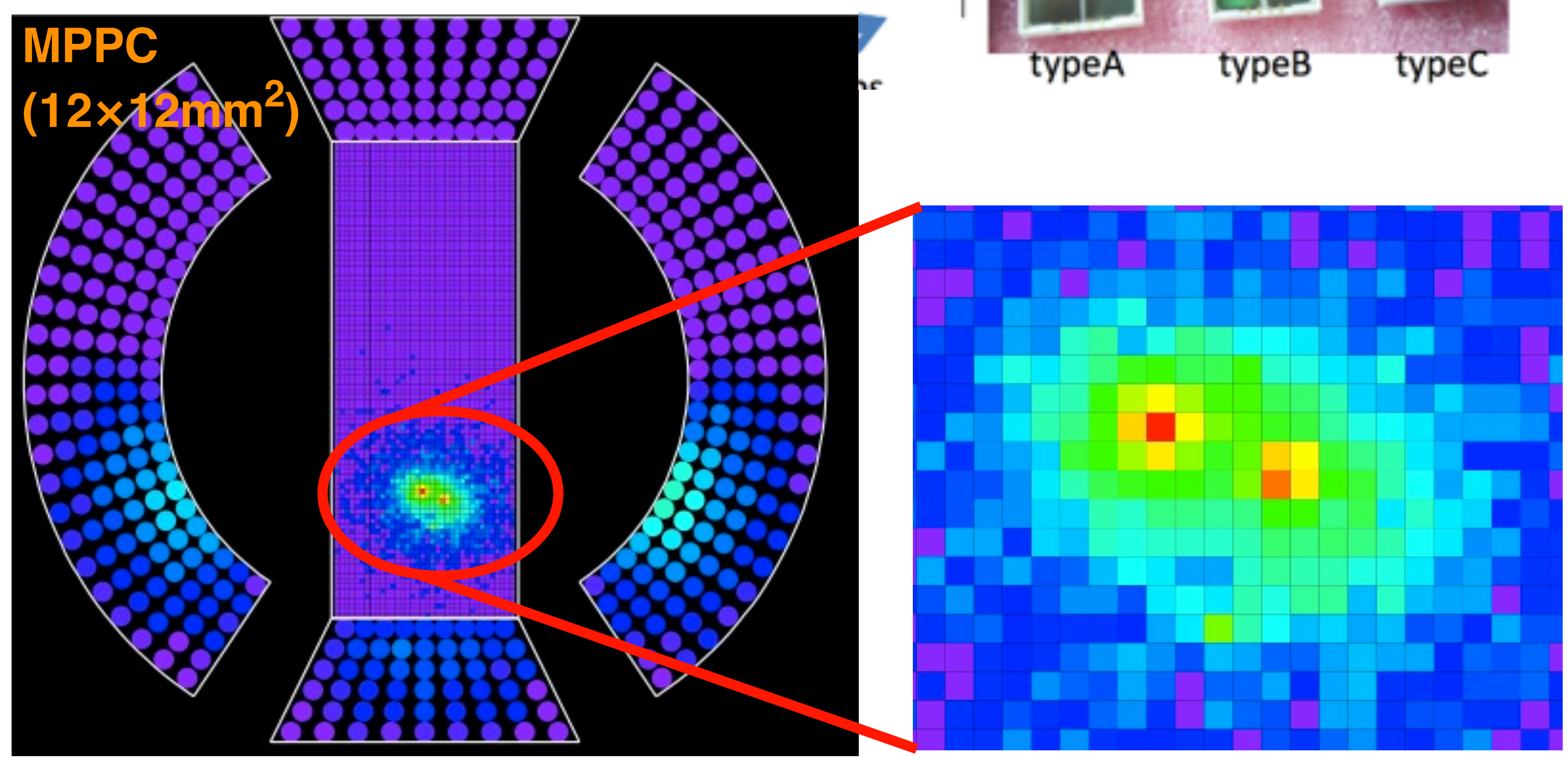


γ-detector improvements

- Use the same cryostat, most mechanics, + 620 PMTs
- Use of 1 cm² SiPM (MPPC)
  - O(3500)
  - +9% detector transparency to 52.8 MeV γ–rays
  - Better granularity for depth reconstruction/pile-up rejection
    - position reconstruction
    - timing





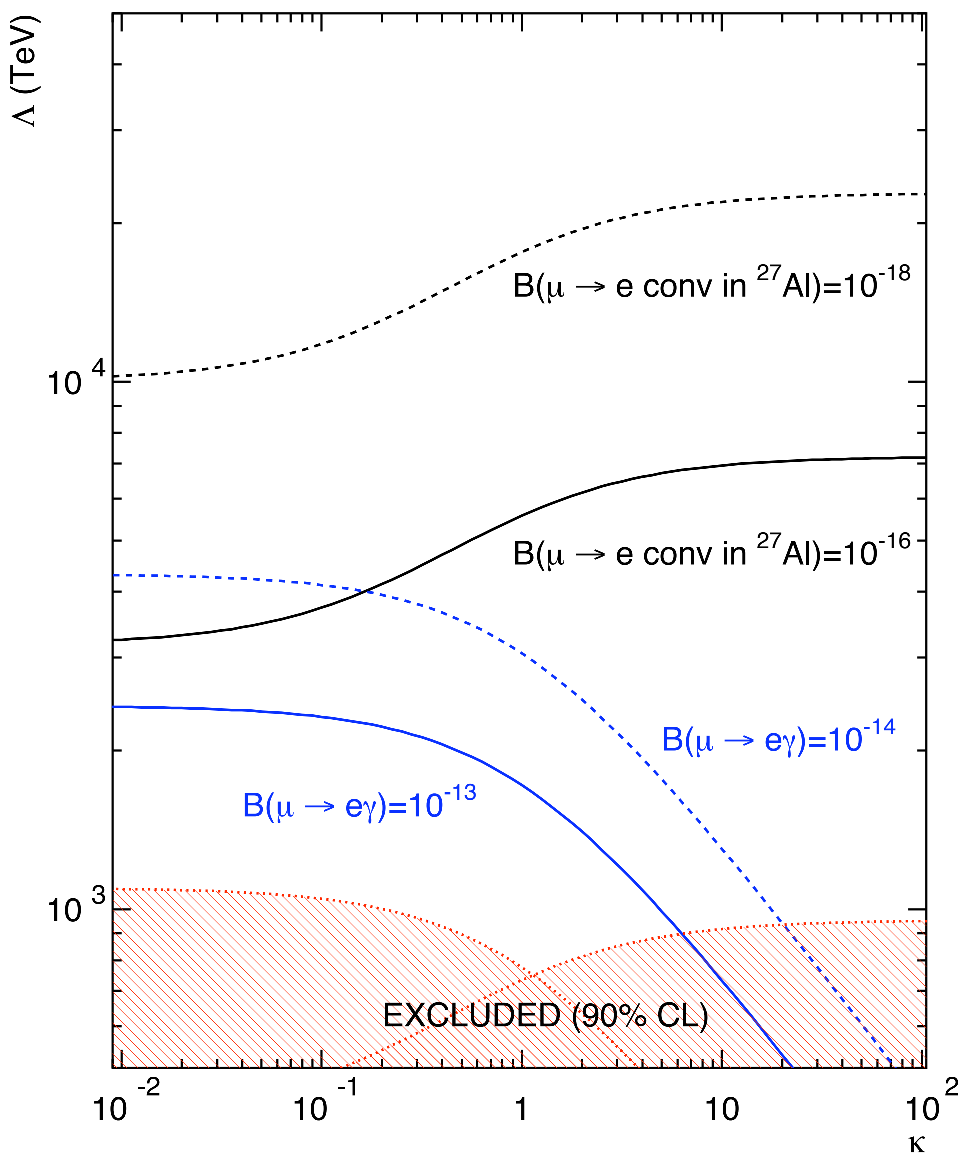


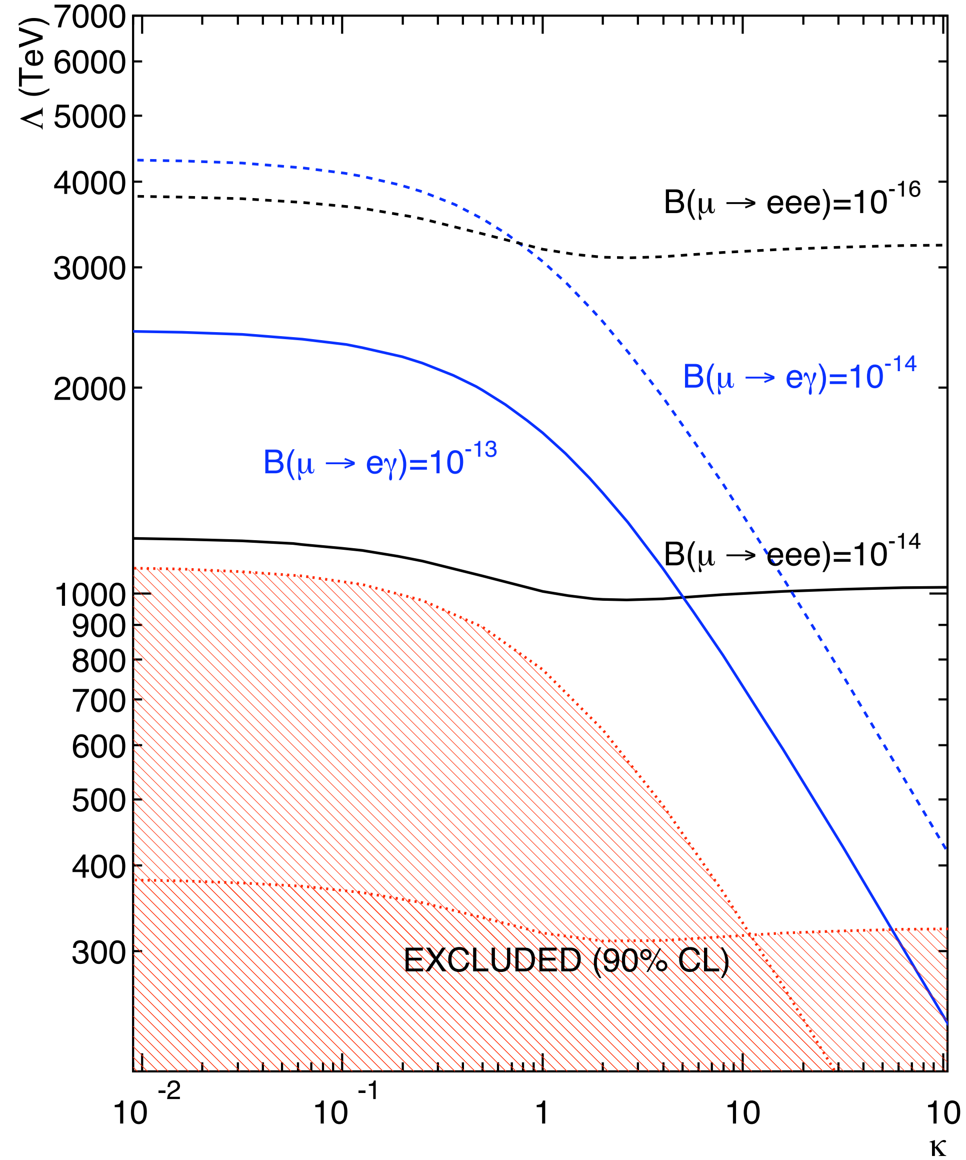
- Different geometry for the lateral faces
  - +10% acceptance (Xenon)

Complementarity

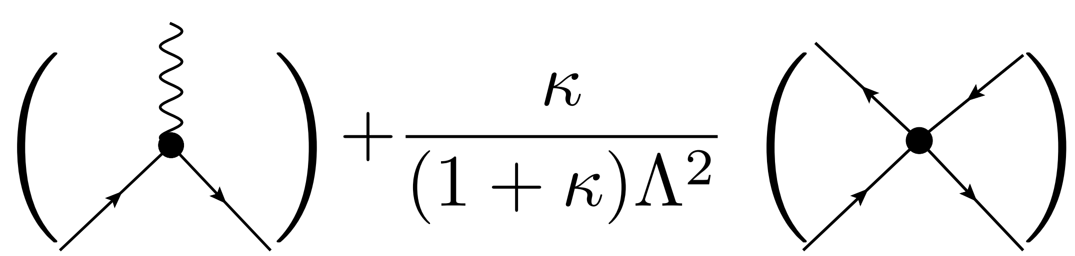
- Capability of different measurements to discriminate between models

de Gouvea and Vogel, 2013



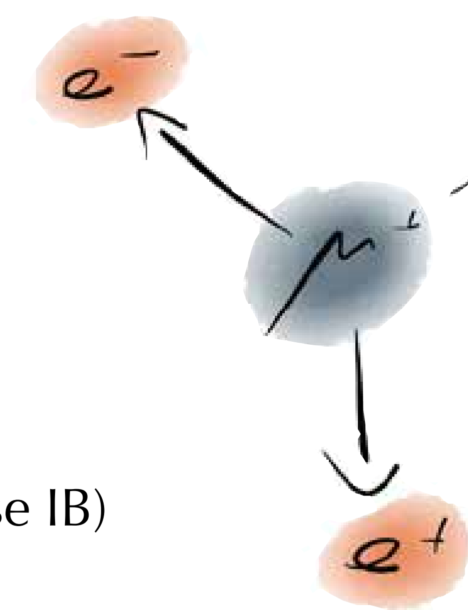


$$\frac{m_\mu}{(1+\kappa)\Lambda^2}\left(\quad \right) + \frac{\kappa}{(1+\kappa)\Lambda^2}\left(\quad \right)$$



Mu3e at PSI

- Search for μ→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)



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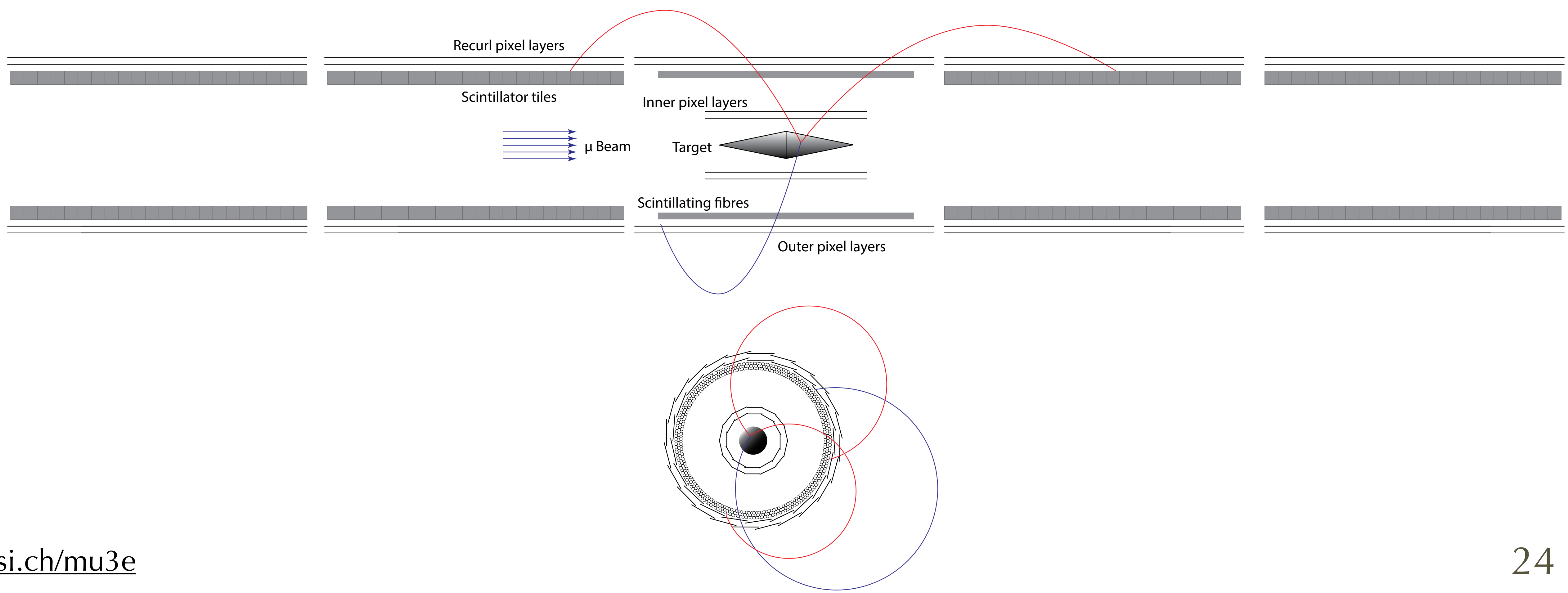
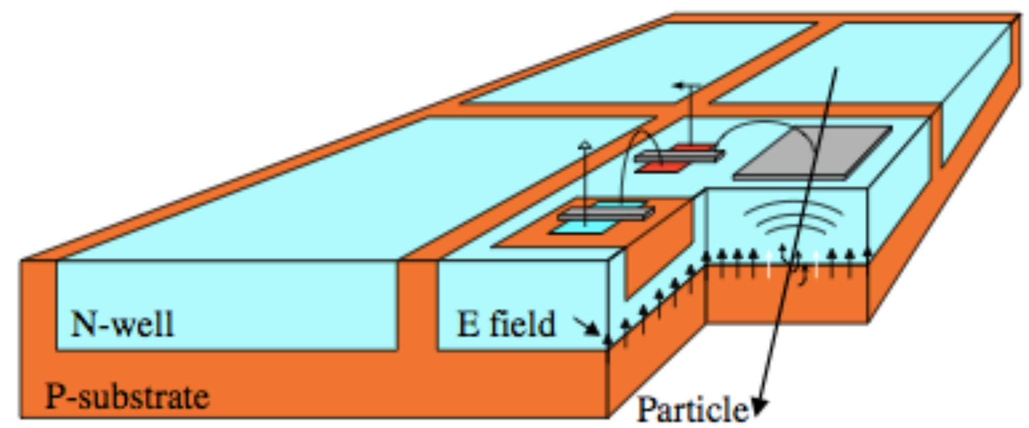
PSI

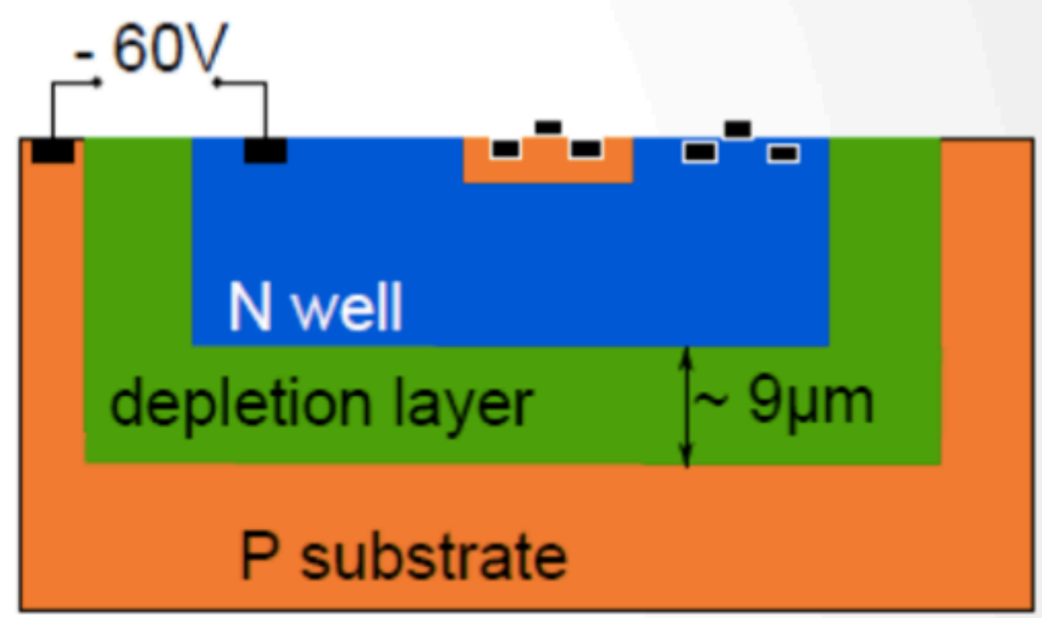


The pixel detector

HV-MAPS

- **Key elements**
- based on HV-MAPS
  - Pixel dimension: 80 x 80 μm^2
  - Thinning to 50 µm
  - The sensor and readout are integrated on the same device
  - Drift charge collection: < 10ns
  - Sensor size: 1x 2 cm^2 or 2 x 2 cm^2
  - Power consumption : 150 mW/cm^2



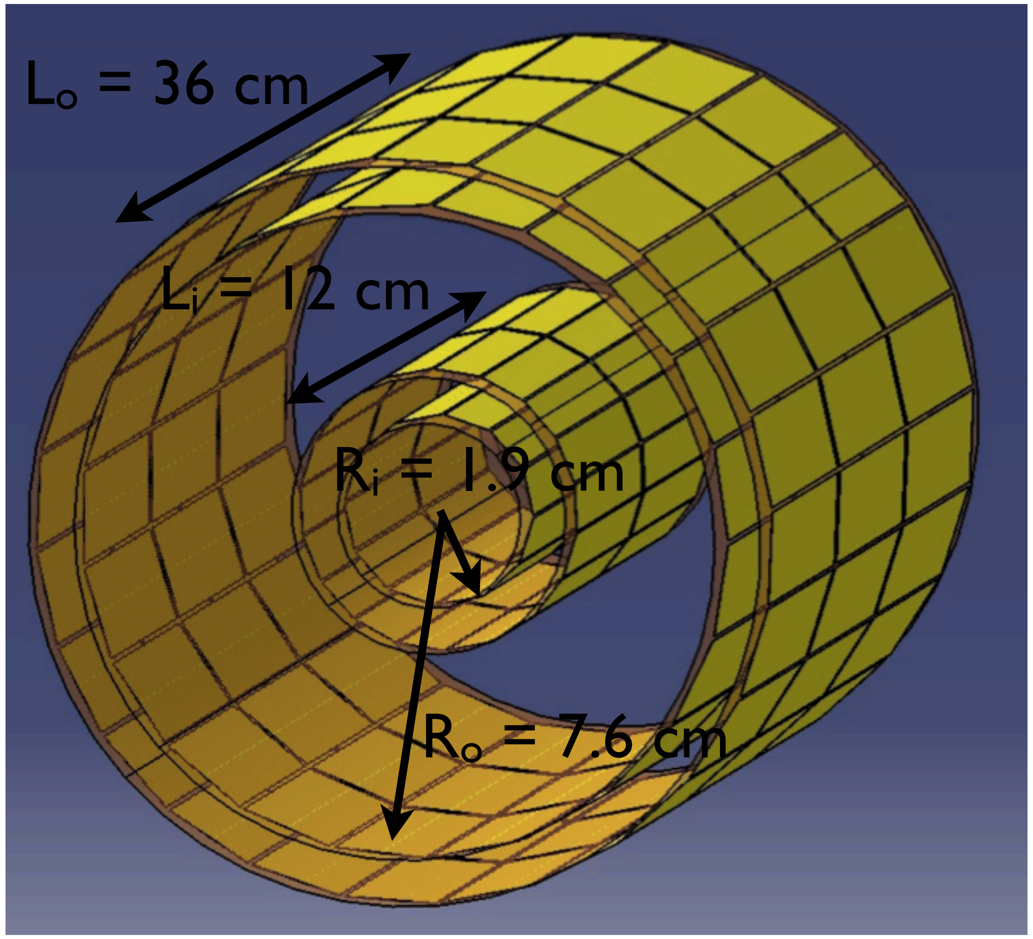


by Ivan Perić

I. Perić, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology Nucl.Instrum.Meth., 2007, A582, 876

The pixel detector

- **Performances**
  - Precise hit Position: 80 x 80 μm^2 (c.t. multiple scattering σ_{MS} ~ 150μm)
  - Momentum resolution < 0.5 MeV/c over a large phase space
  - Geometrical acceptance ~ 70%
  - X/X_0 per layer ~ 0.044%
  - Vertex resolution < 200 μm suppressing the accidental background
  - Internal conversion background is limiting
  - Sensitivity down to 10^{-16} achievable with < 0.5 MeV/c momentum resolution

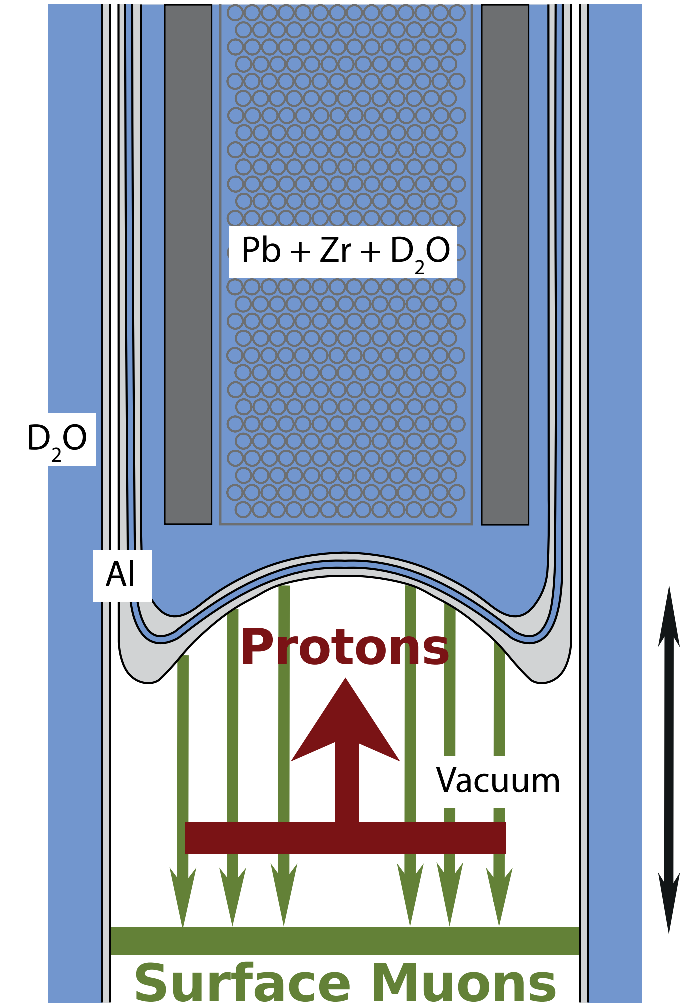


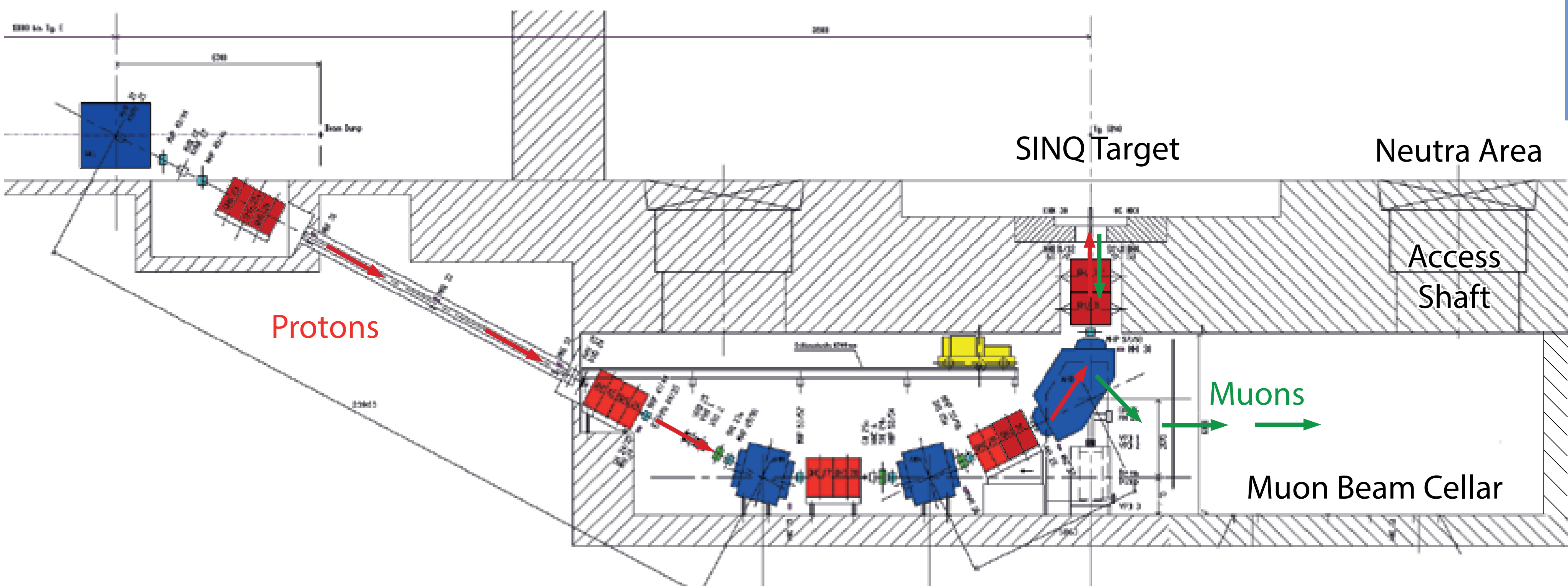
State of the art

- **The beam**
  - Compact beam-line solution in PiE5 able to deliver up to ~10^8 mu/s (Mu3e Phase I)
  - HiMB feasibility study is ongoing with the aim of providing up 10^{10} mu/s (Mu3e Phase II)
- **The pixel detector**
  - Mupix4 prototype
  - Active area: 9,42 mm^2 -- Pixel size: 92 x 80 um^2 -- Pixel Matrix: 40 x 32 pixels
  - Detection efficiency: 99% -- Spatial Resolution: (RMS) 28 um -- Timing: O (10ns)
- **The fiber hodoscope**
  - Multi-layer square/round fibre
  - Detection efficiency: > 99% -- Timing resolution: < 700 ps -- Spatial resolution: 150 um
- **The Tile detector**
  - Detection efficiency: > 99% -- Timing resolution: ~ 70 ps
- **The DAQ**
  - DRS4 abundant used. DRS5 Wavedream available soon
  - STiC v.2

HIMB at PSI

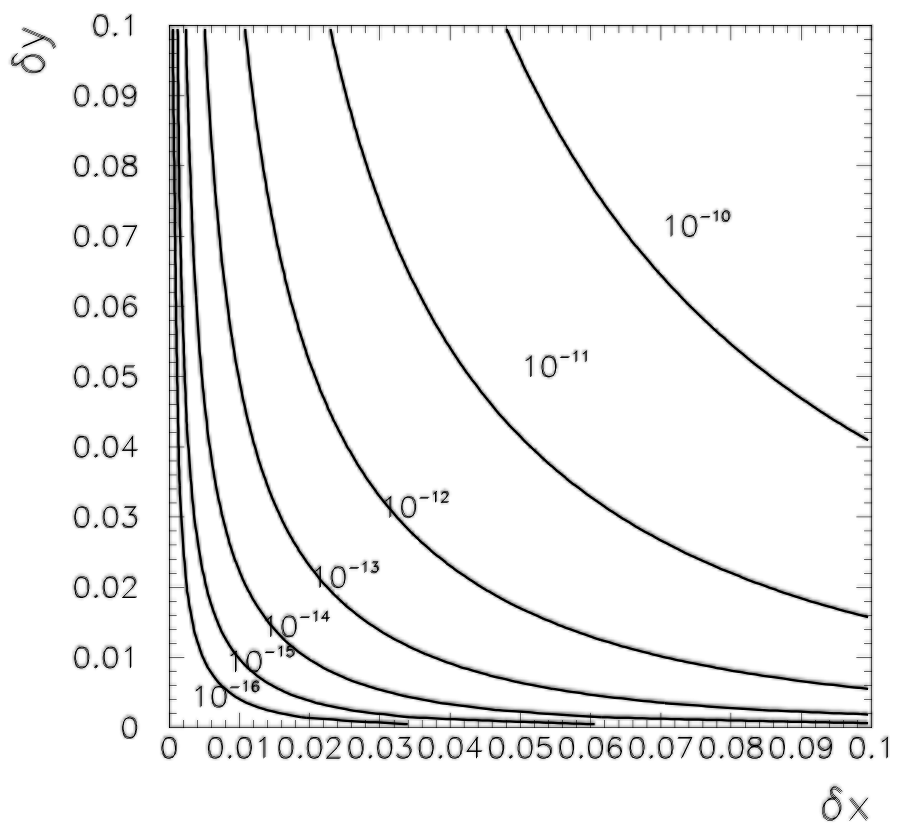
- Muon rates in excess of 10^{10}/s in acceptance
- $2 \cdot 10^{9}$/s needed for $\mu \rightarrow eee$ at 10^{-16}
- Not before 2017





Towards an ultimate $\mu \to e\gamma$

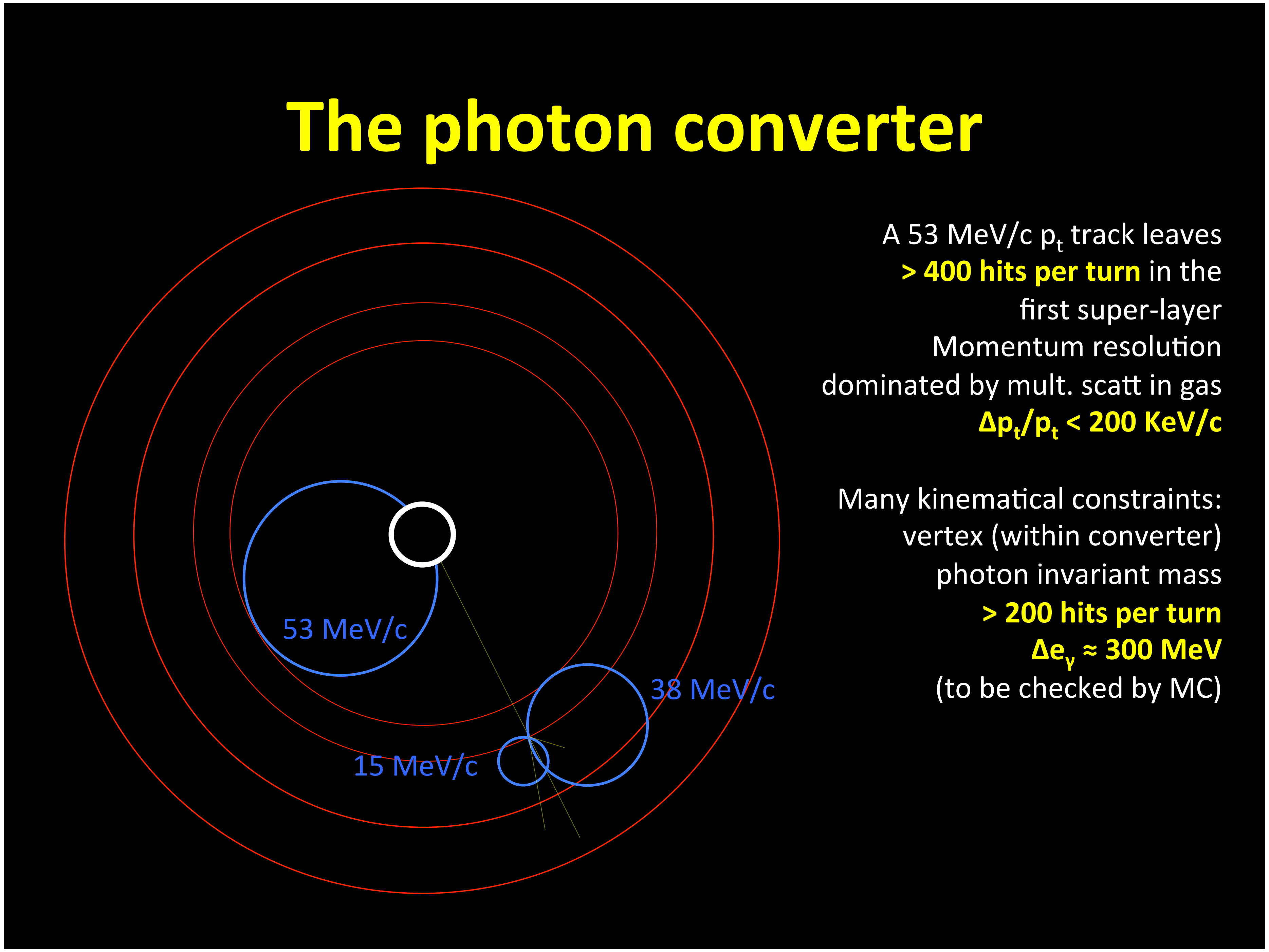
- It is interesting to start thinking if there is a physical limit to the measurement of the $\mu \to e\gamma$ / $\mu \to eee$ decays (no SM background)
- If accidentals are the limit:
  - Track photons
    - pair spectrometer
    - identify photon starting point (multiple targets)
- If resolutions are the limit
    - Improved beams → restrict acceptance
    - focussing spectrometer



- At some point the prompt background will dominate → stop

Some futuristic ideas

- by F. Grancagnolo *et al.*



- by F. Grancagnolo *et al.*

Conclusions 1

We have presented a different approach at searching for evidence of CLFV in the muon sector.

The approach requires an apparatus made of three sub-detectors:

- A very large volume, low mass, all stereo drift chamber with the order of **10^5 sense wires**. The drift chamber is used also for the determination of the radiative photon energy through its conversion in thin W radiators placed in the active volume.
- A very thin, fast response time, high granularity two layers pixel detector based on HV MAPS for defining the vertex of the decays. It makes use of **7×10^5 pixels per layer**.
- A system of scintillating fibers for setting the trigger of photon conversion and defining a crude position of the conversion point. It uses of the order of **6×10^4 readout channels**.

Comparison

- We use Super*B* FastSim and *BABAR* framework to study a conceptual design of a detector for $\mu^+ \to e^+\gamma$ ($\to e^+e^-$)

- Comparison with MEG, MEG upgrade and Mu3e.

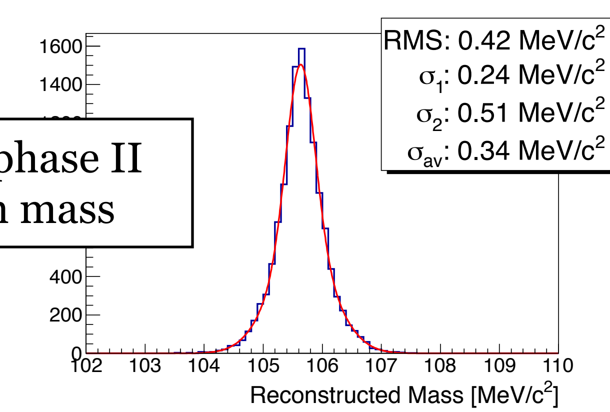
	This work	MEG
p_e	200 keV	305 keV
E_γ	0.37%	1.7–2.4 %
$m_{e\gamma}$	340 keV	
$\varphi_{e\gamma}$	10 mrad	9 mrad
$\theta_{e\gamma}$	9 mrad	16 mrad
efficiency	1.25%	~2%

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

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88

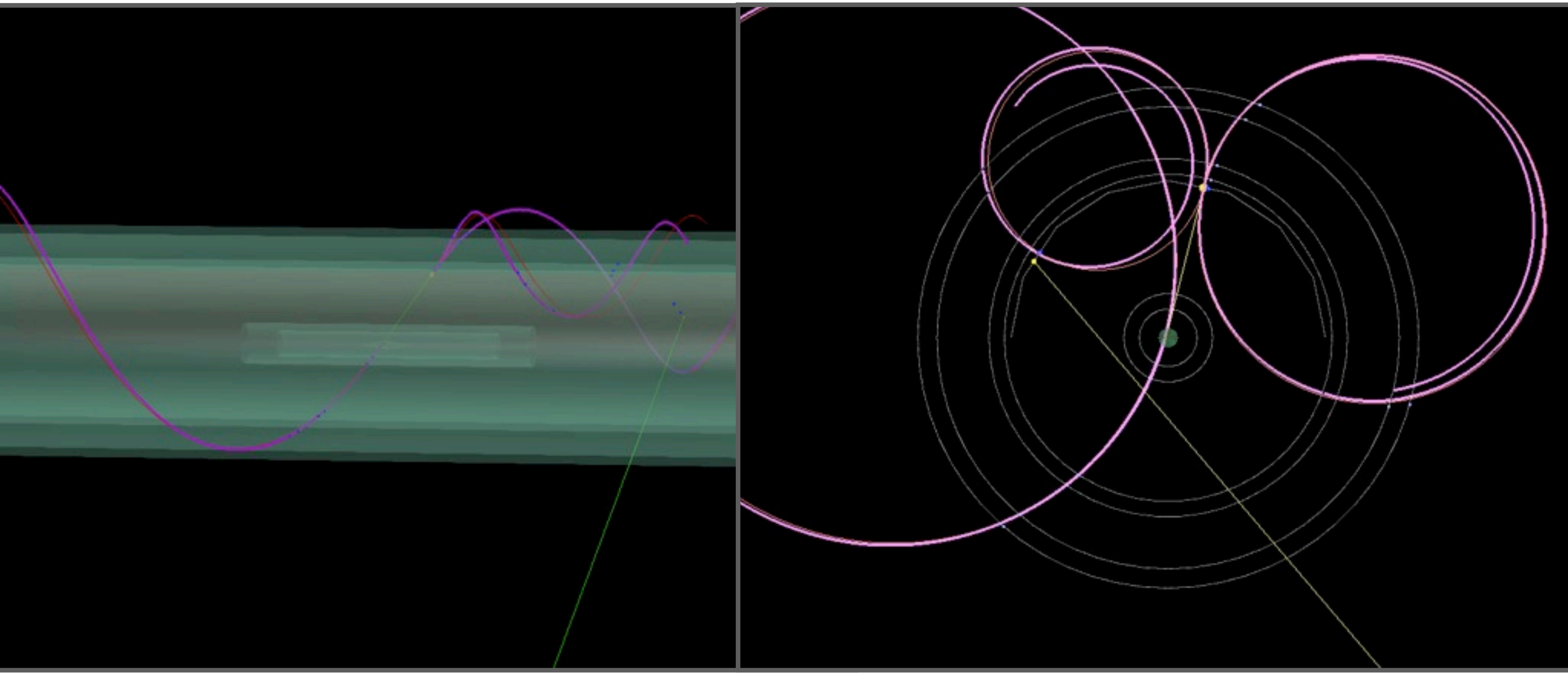
arxiv:1301.7225v2

Mu3e phase II
muon mass



arxiv:1301.7225v2

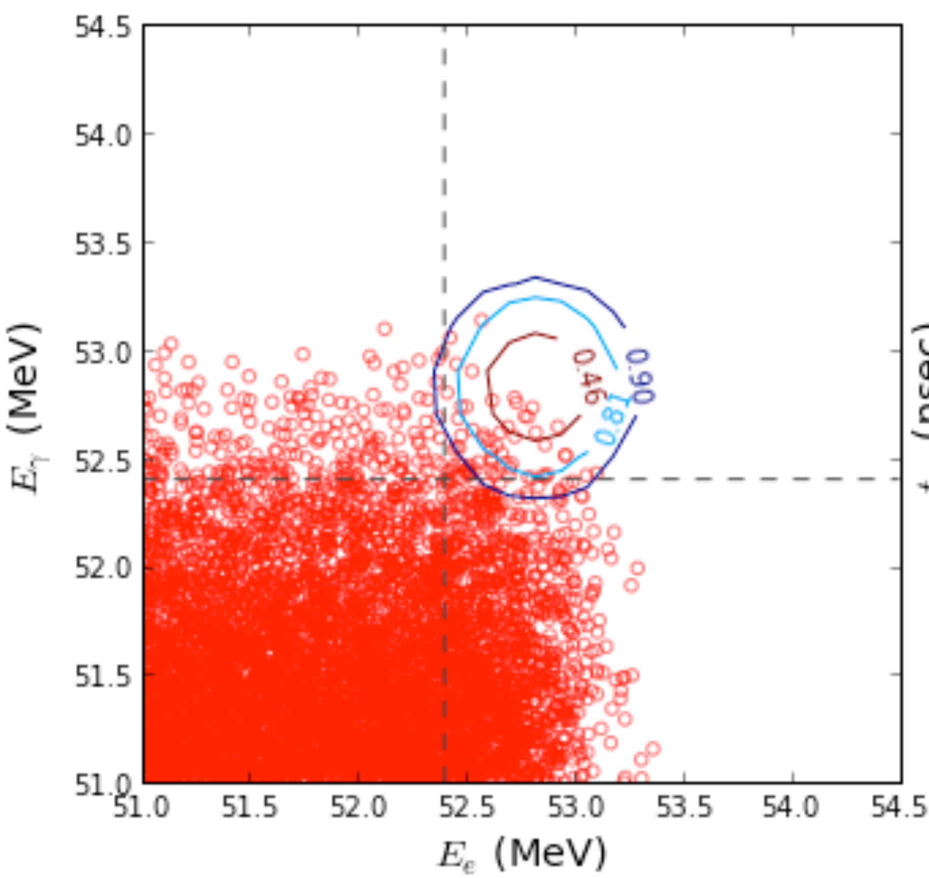
Event display

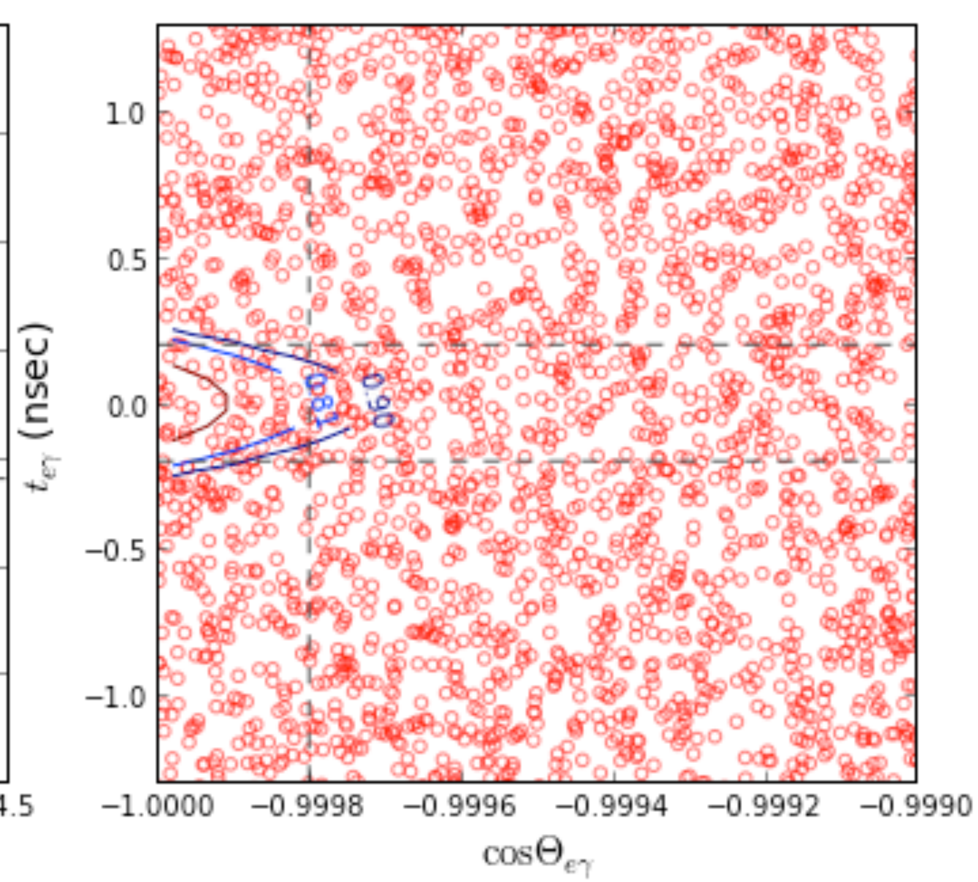


Thin red curves: generated helices; magenta curves: fitted trajectories

Background in future facility

- Assume single event sensitivity ~2×10^{-15}.
- Signal efficiency 1.25%.
- Need ~4×10^{16} stopped muons.
- Assuming data taken in 1.5 DAQ years ⇒ $R_{\mu}=8.4\times10^{8}$/s.
- Use resolutions similar to those found in FastSim, and timing resolution of 100 ps.

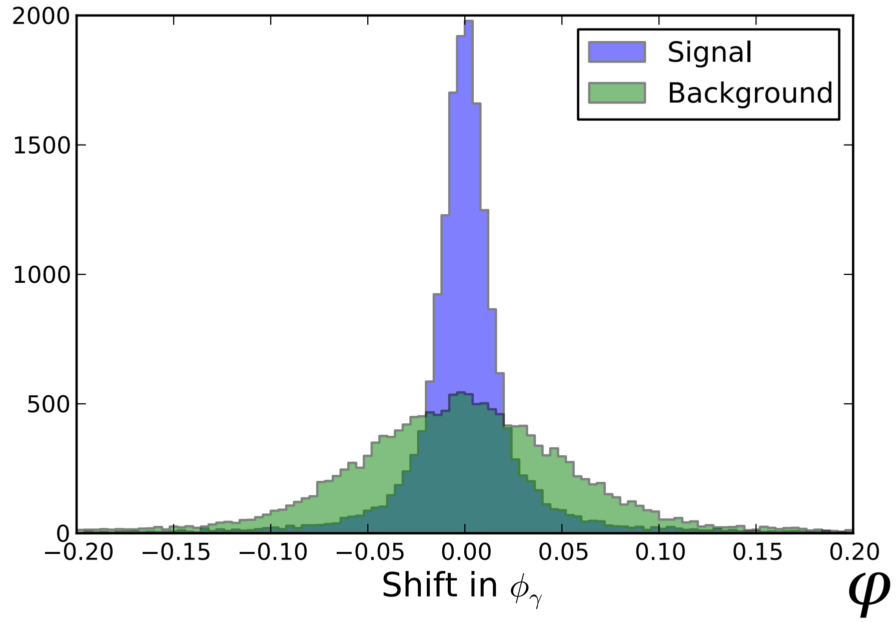


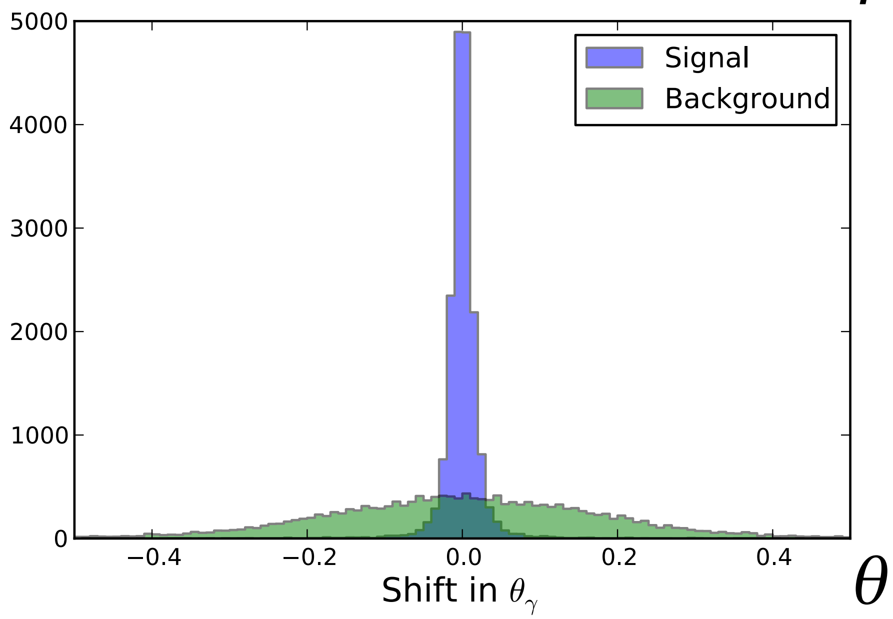


Count events in ±1.64-σ windows (90% for a Gaussian distribution) in E_e, E_γ, $\theta_{e\gamma}$, $\varphi_{e\gamma}$, and Δt. Found 20±3 background events. => one order of magnitude to go.

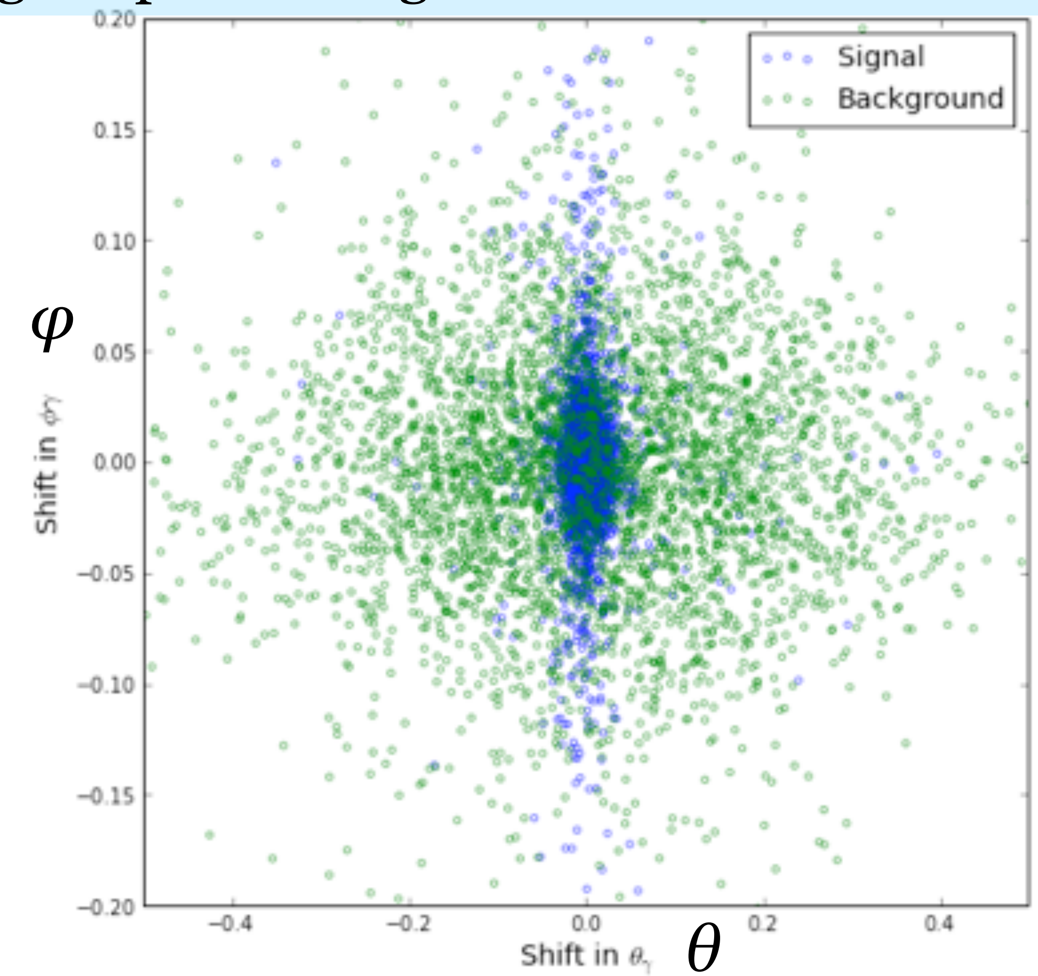
Vertexing power

- Converted photon has an angular resolution ~10 mrad in φ and θ (before vertex constraint).
- Positron and photon in accidental background come from different points on the target. Forcing the production point of the photon to be that of the positron will change the photon direction.





Change in photon angles after vertex constrained fit



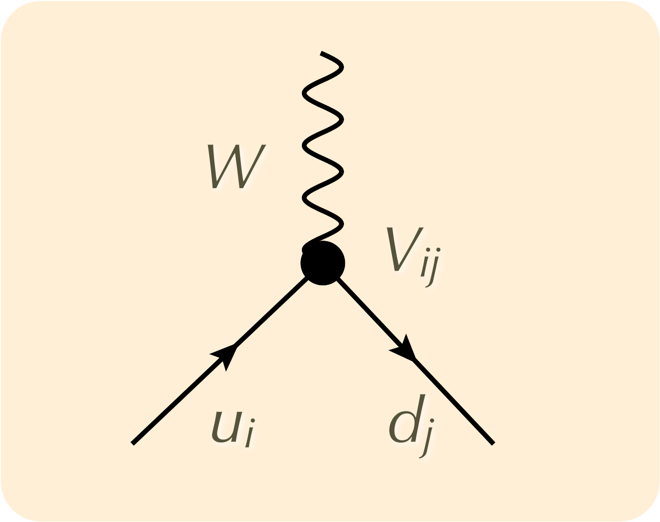
In ±30 mrad box,
85% signal, 5% background are selected

Models - Wheel - Flavour

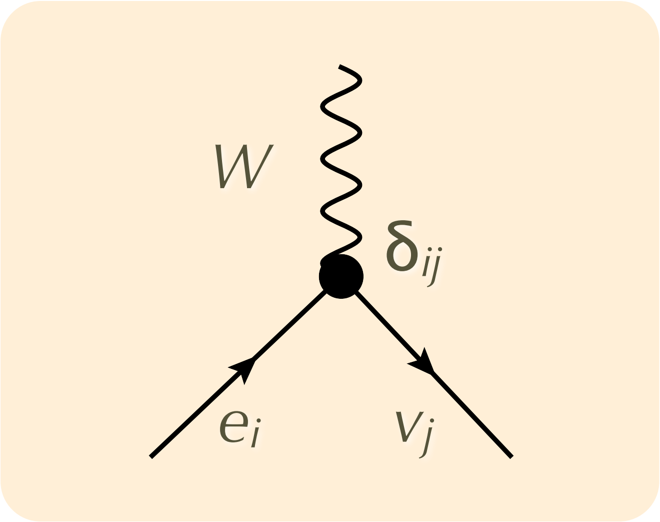
Flavor in the SM

- 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}



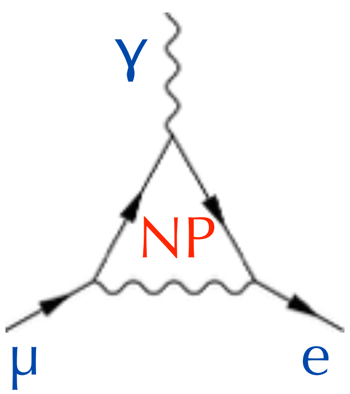
$\mathbb{1}$

- 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

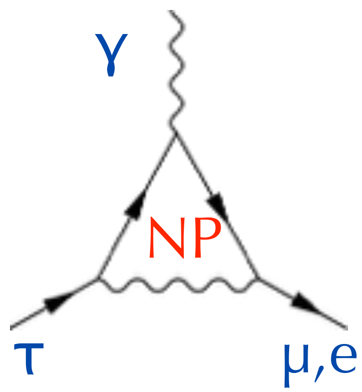
Many processes

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

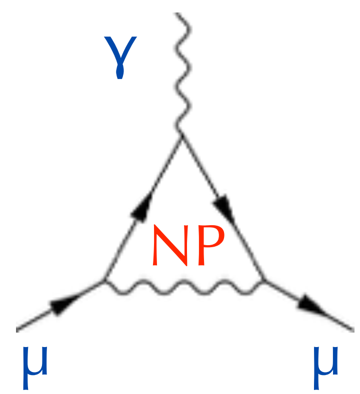
$$\frac{1}{\Lambda}\,\bar{\ell}_i \sigma_{\mu\nu} \ell_j F^{\mu\nu} \qquad\qquad \frac{1}{\Lambda^2}\,\bar{\ell}_i \gamma_\mu \ell_j (\bar{q}_k \gamma^\mu q_m + \bar{\ell}_k \gamma^\mu \ell_m)$$



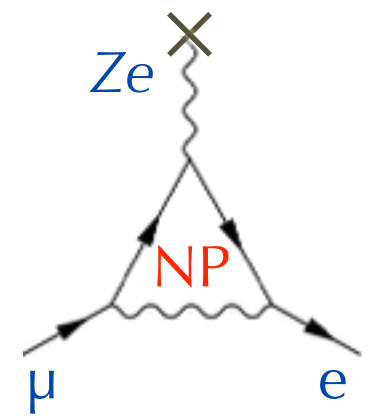
$\mu \to e\gamma$



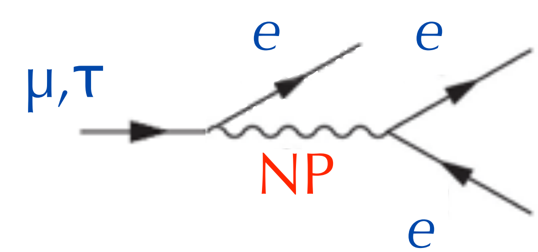
$\tau \to \mu\gamma$
$\tau \to e\gamma$



$(g-2)_\mu$

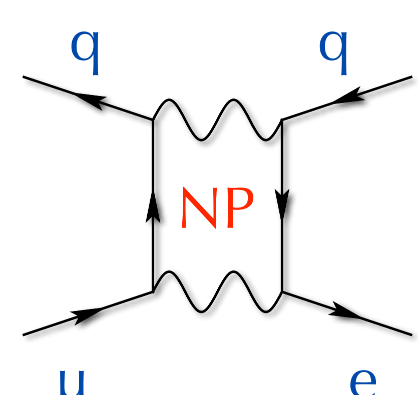


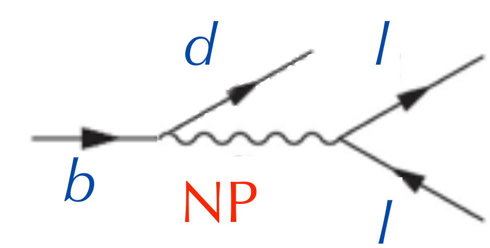
$\mu^- \mathcal{N} \to e^- \mathcal{N}$



$\mu \to eee$

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

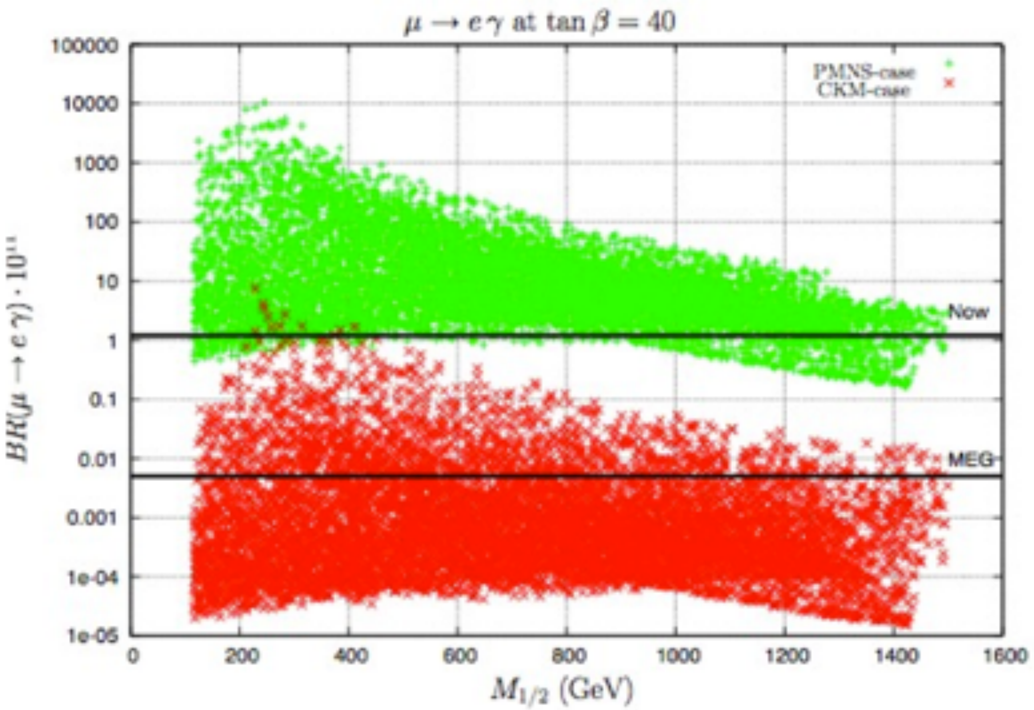


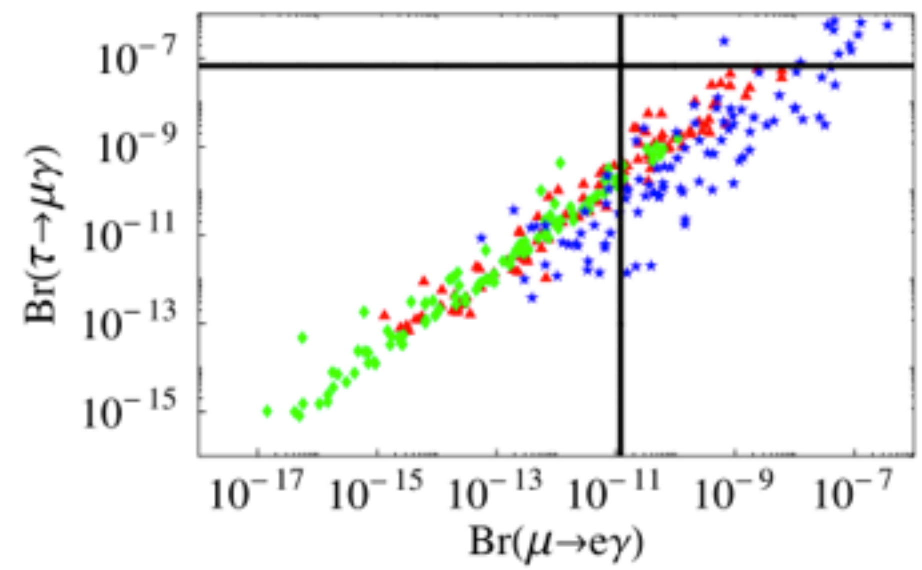


$B \to \ell\bar{\ell}'$
$B \to \ell\bar{\ell}' X_s$

Processes are correlated

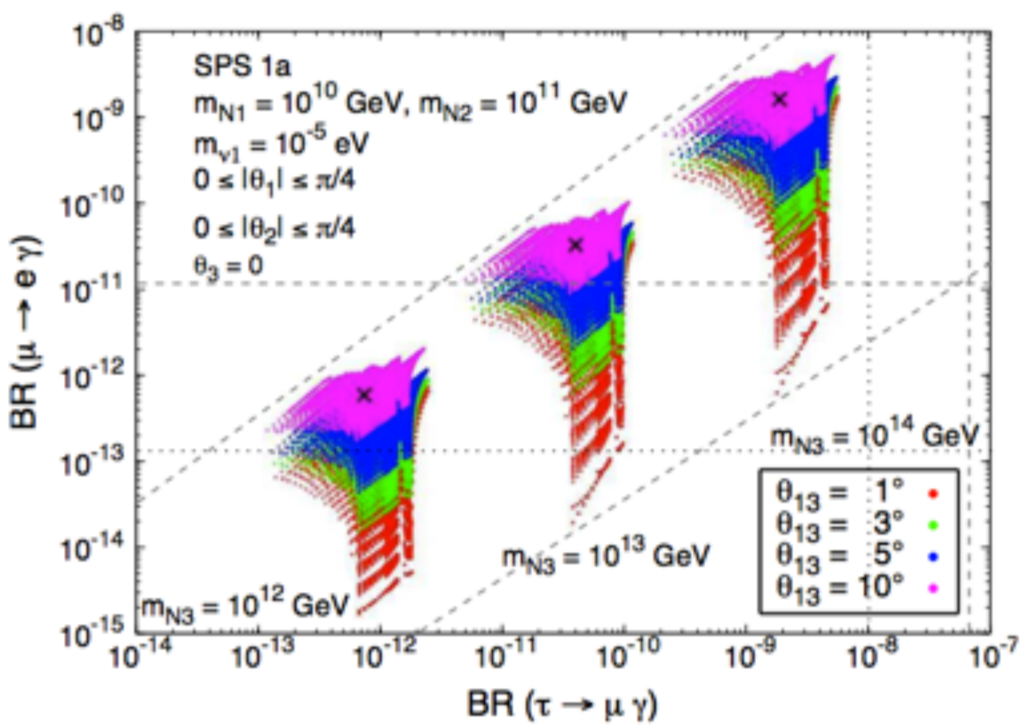
- Model-dependent correlations

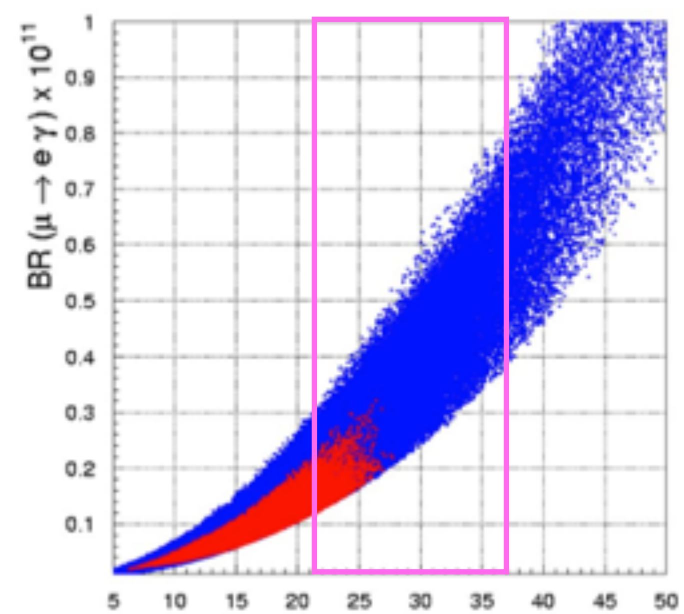




Large ϑ_{13}

Higgs & No Susy

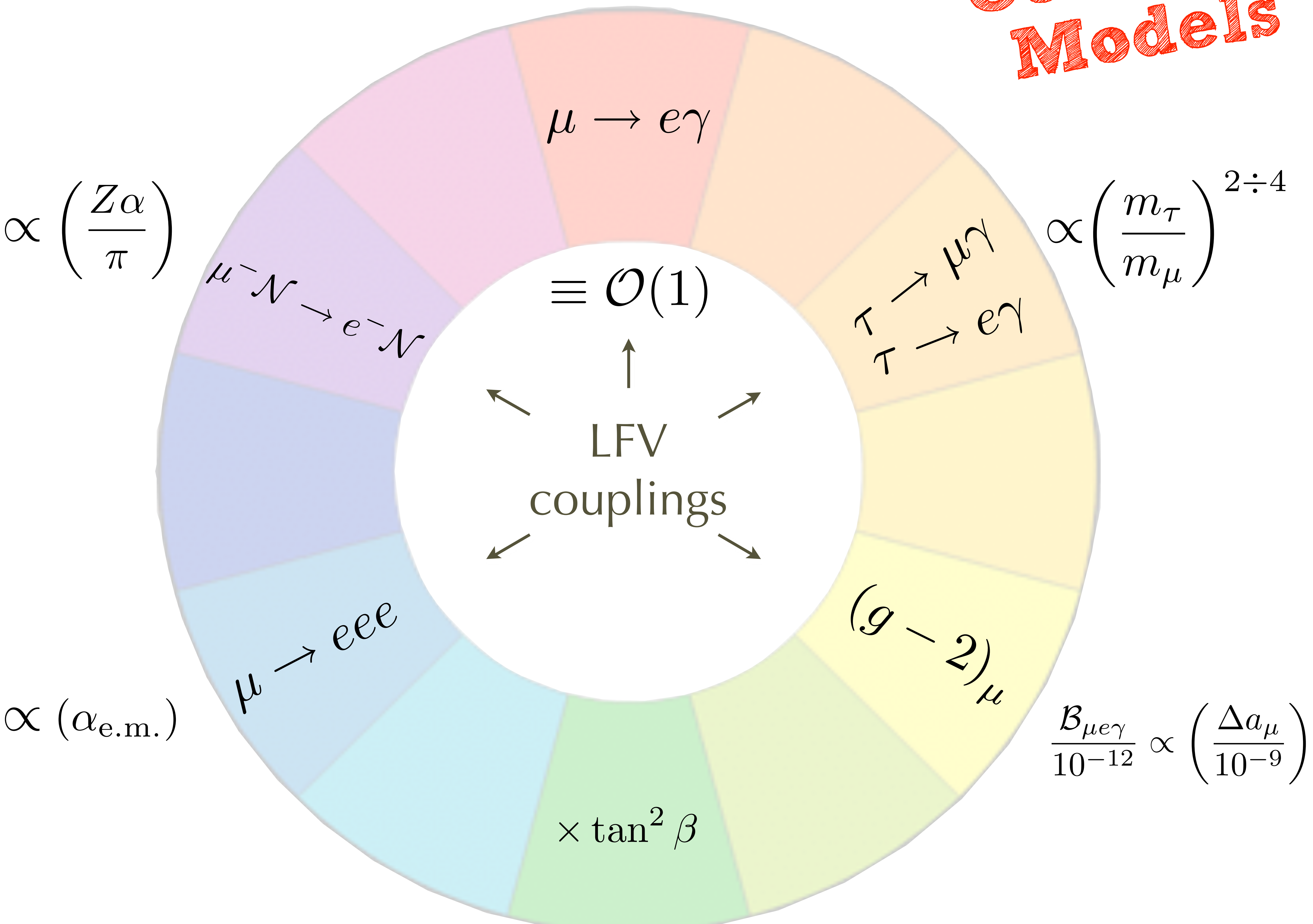




Barbieri *et al,*, Nucl. Phys B445 (1995) 225
Hisano *et al.*, Phys. Lett. B391 (1997) 341
Masiero *et al.*, Nucl. Phys. B649 (2003) 189
Calibbi *et al.*, Phys. Rev. D74 (2006) 116002
Isidori *et al.*, Phys. Rev. D75 (2007) 115019
...

The CLFV wheel

Common Models



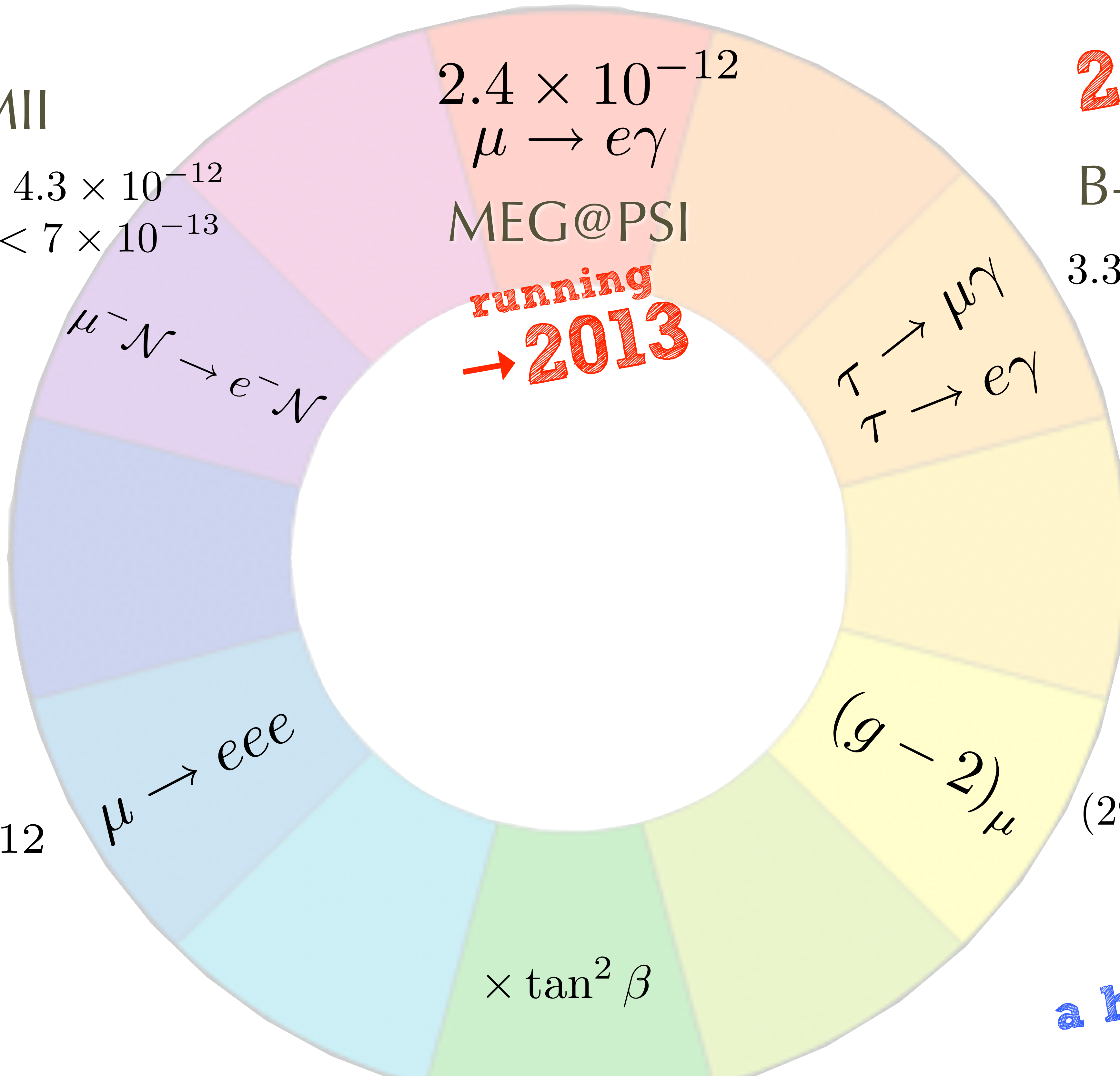
Present limits

SINDRUMII

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

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

2006



2011

B-factories

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

BNL E821

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

2004

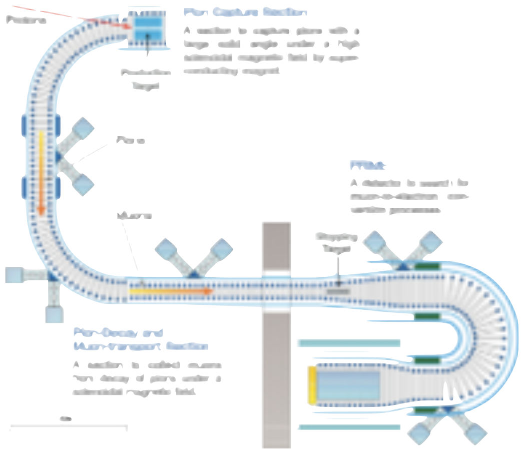
a hint for NP?

SINDRUM

1×10^{-12}

1988

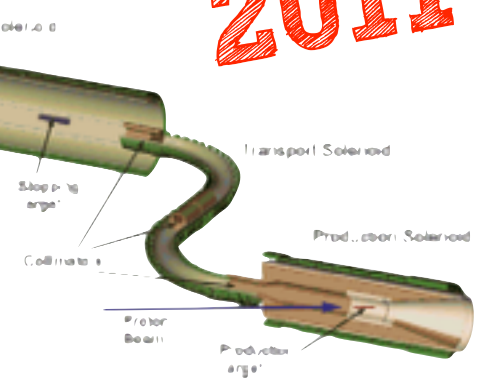
Back to the wheel



mu2e COMET

$10^{-16} \to 10^{-18}$

2017 →



$\mu \to e\gamma$

MEG^{UP}

few $\times\ 10^{-14}$

2015 →

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

$\tau \to \mu\gamma$

$\tau \to e\gamma$

BelleII

LHC

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

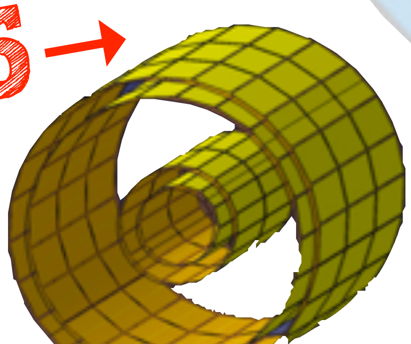
2015 →

$\mu \to eee$

Mu3e

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

2015 →



$\times \tan^2\beta$

$(g-2)_\mu$

Gm2 FNAL

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

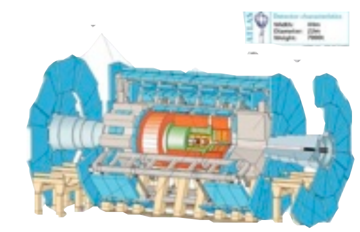
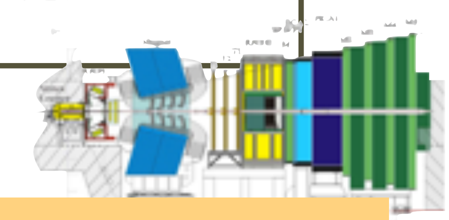
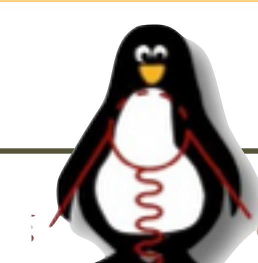
$3.6\sigma \to 8\sigma$

2015 →

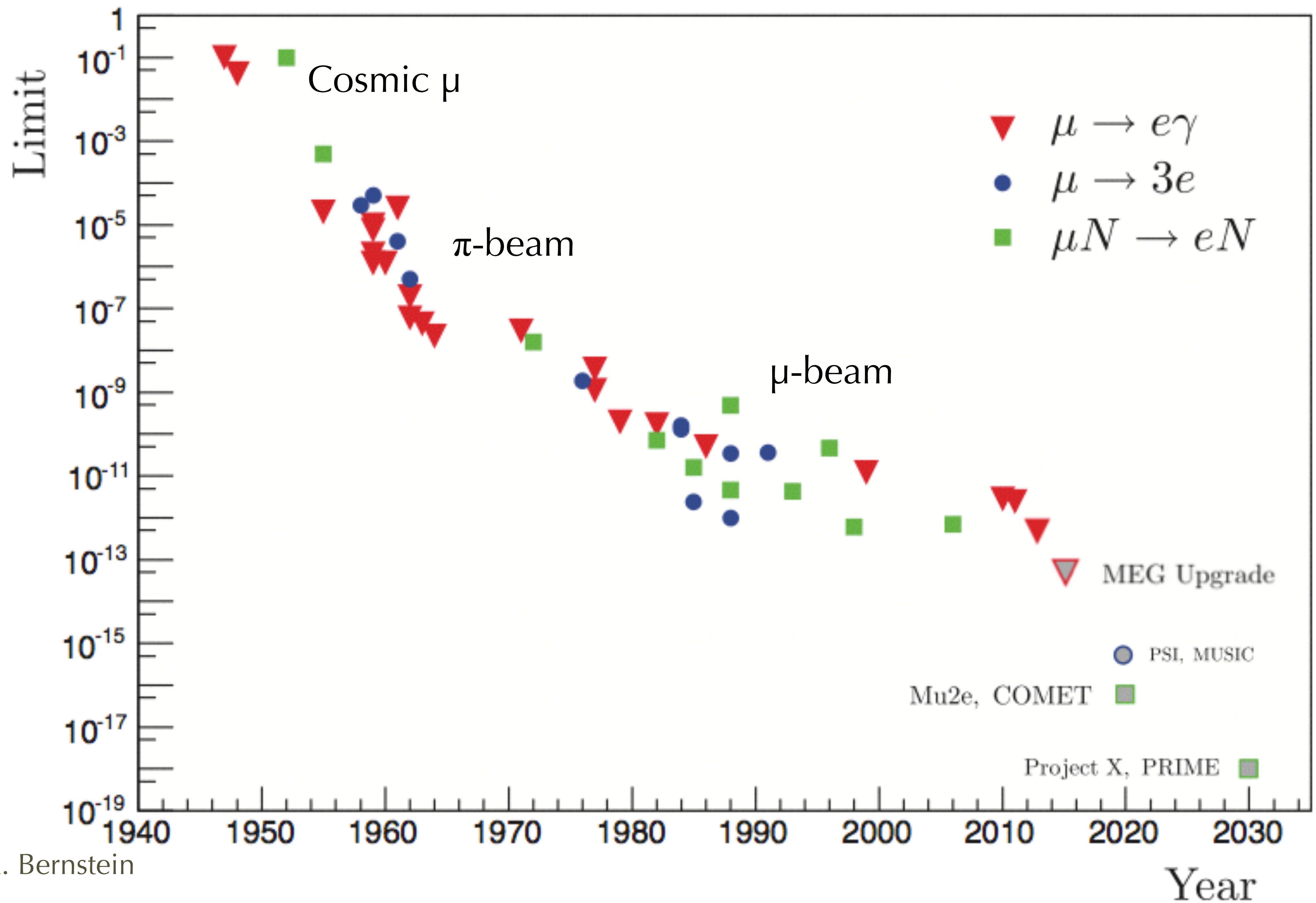
Experimental effort

	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

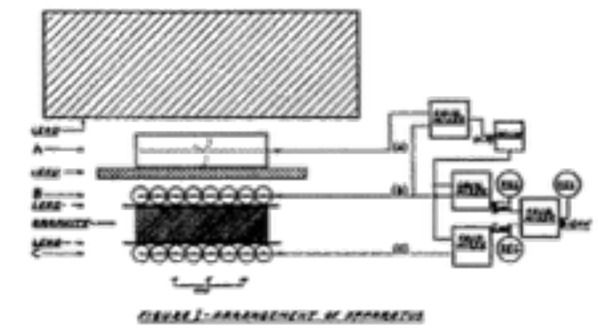
	Dedicated experiment	Multi-purpose experiment
Exotic Searches New Physics Experiment	$\mu \to e\gamma$ $\mu \to eee$ $\mu^- N \to e^- N$	$\tau \to \mu\gamma$ $\tau \to e\gamma$ $K_L^0 \to \mu e$ $Z' \to e\mu$ $\tau \to 3\ell$  
BSM physics NP SM Theory	e, μ, n edm $(g-2)_\mu$ $(g-2)_e$  $\frac{\pi^+(K^+)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

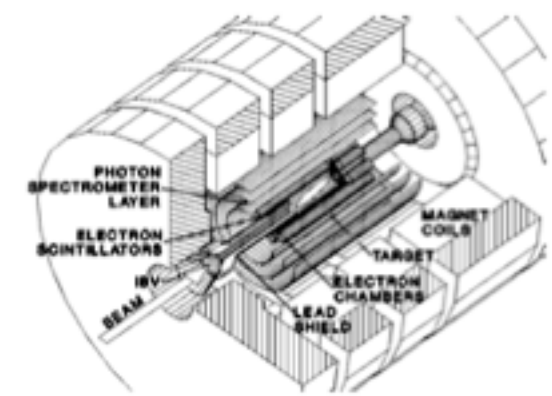
65 years of searches



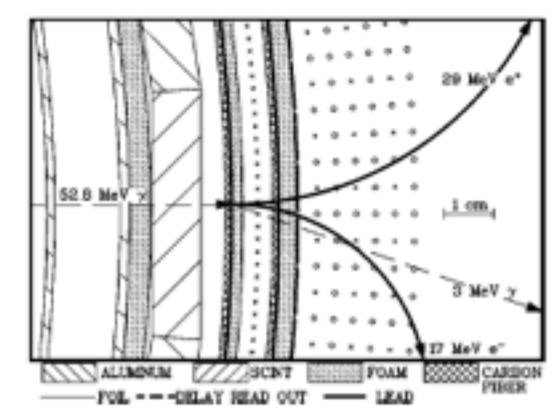
R. Bernstein

Hinks & Pontecorvo





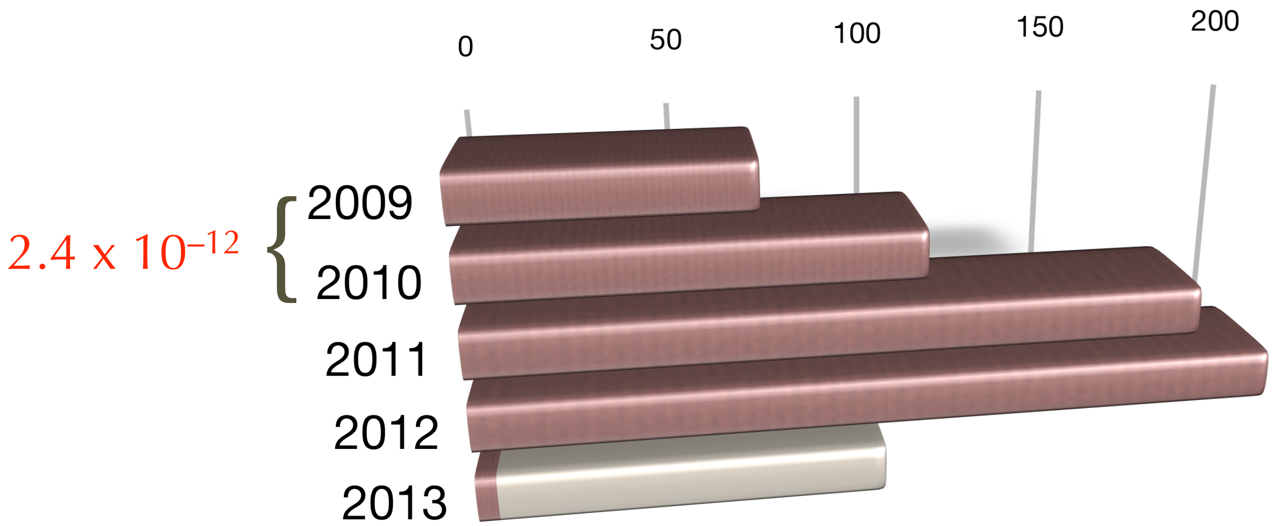
MEGA

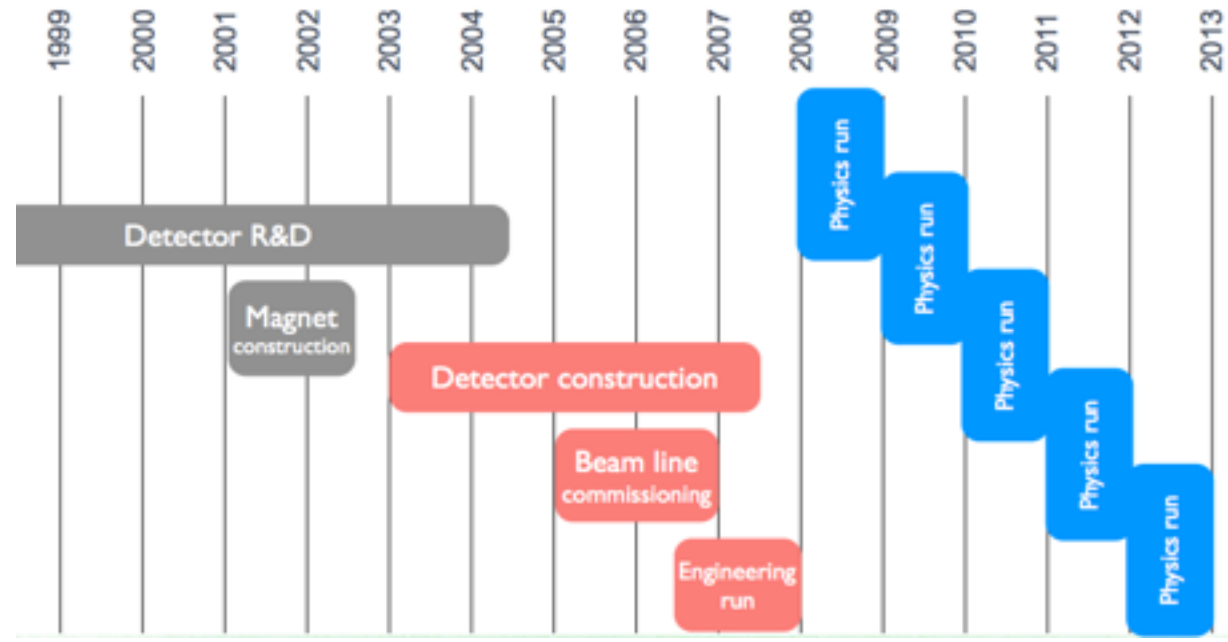


- Each improvement linked to beam and detector technology
- Trade-off between sub-detectors to achieve the best "sensitivity"

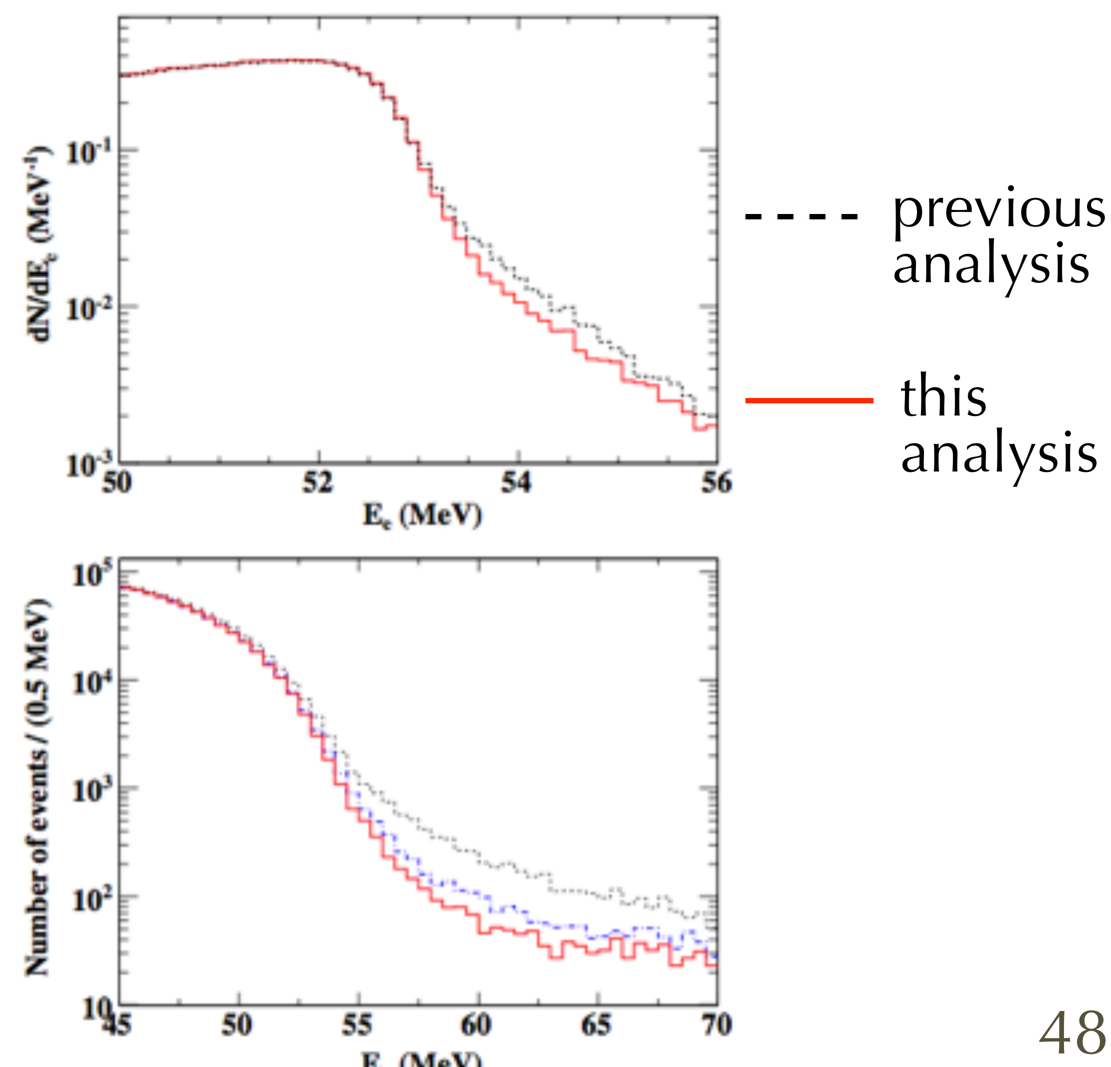
MEG status

MEG schedule





- 2009+2010 analysis: BR(μ→eγ)< 2.4 x 10^{-12} @ 90%C.L.
- 2011 data
  - Doubled the statistics
    - Improved trigger and reconstruction efficiency
  - Hardware modification
    - BGO for calibration
    - Laser tracker system for drift chamber alignment
- 2009-2011 Analysis improvements
  - Reconstruction improvements
    - γ-ray pileup unfolding
    - e^+ waveform FFT noise reduction + revised track fitter
- 2012 + 2013 analysis in progress



2009-2011 fit result

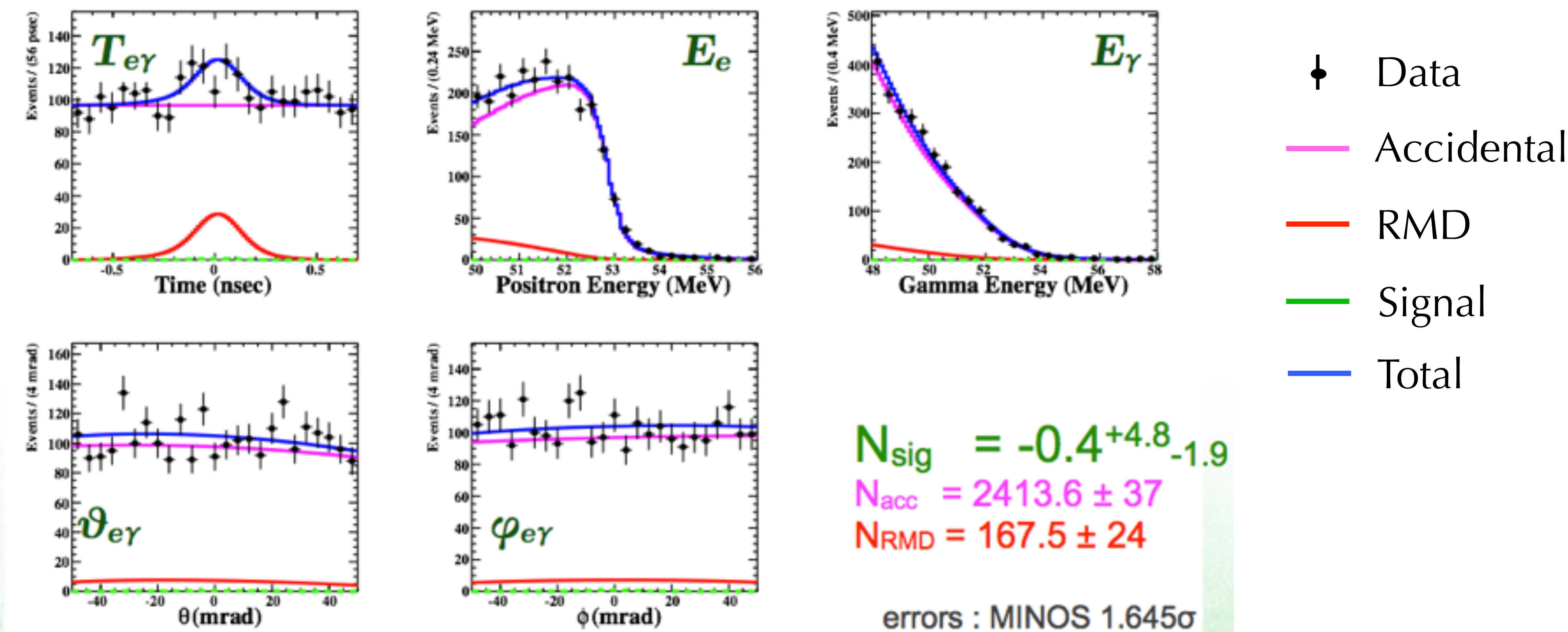
- A μ→eγ event is described by 5 kinematical variables

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

- Likelihood function is built
  - in terms of Signal, RMD and BG

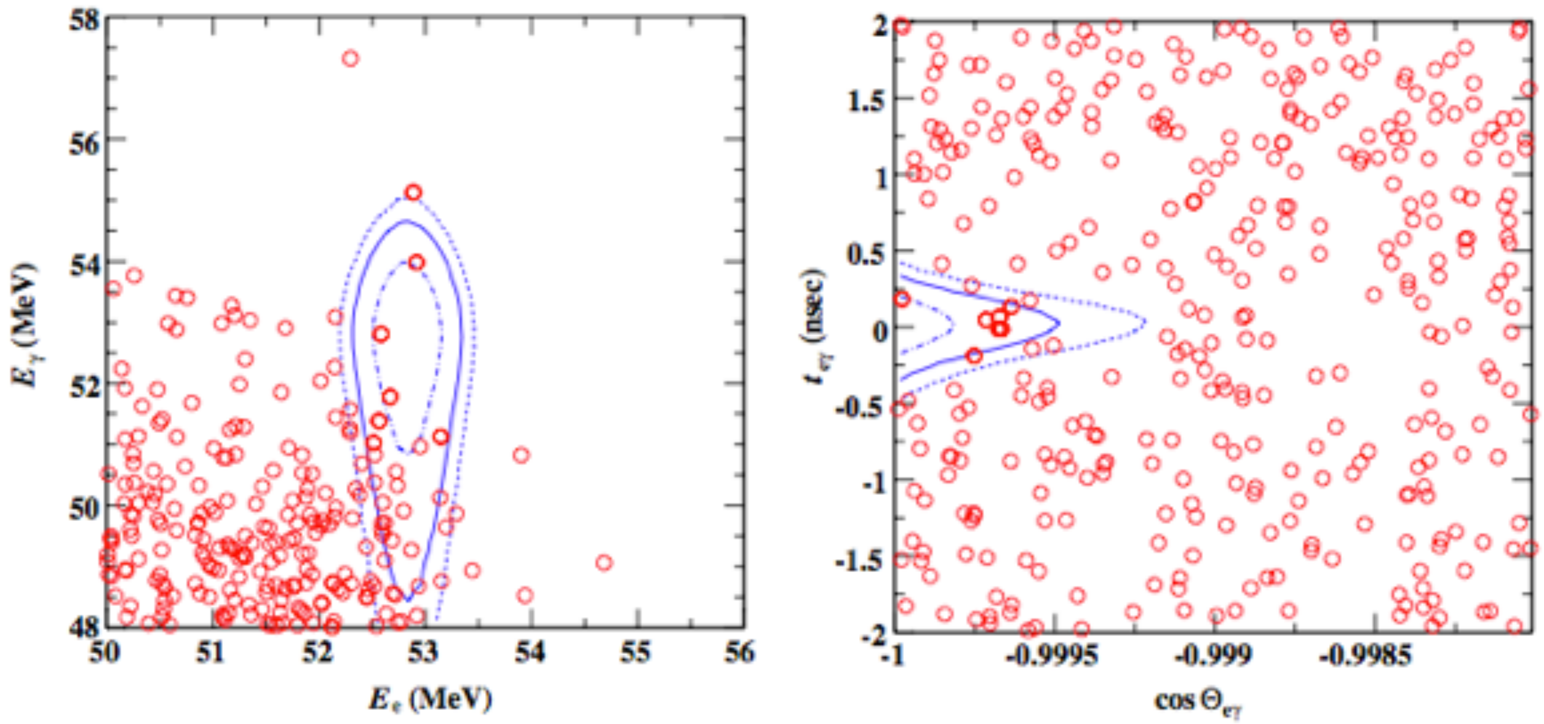
$$-\ln \mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = N_{\text{exp}} - N_{\text{obs}} \ln(N_{\text{exp}}) - \sum_{i=1}^{N_{\text{obs}}} \ln\left[\frac{N_{\text{sig}}}{N_{\text{exp}}} S(\vec{x_i}) + \frac{N_{\text{RMD}}}{N_{\text{exp}}} R(\vec{x_i}) + \frac{N_{\text{BG}}}{N_{\text{exp}}}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

- 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



Combined 2009 + 2010

2009 – 2011



Data set	$\mathcal{B}_{\rm fit} \times 10^{12}$	$\mathcal{B}_{90} \times 10^{12}$	$\mathcal{S}_{90} \times 10^{12}$
2009–2010	0.09	1.3	1.3
2011	−0.35	0.67	1.1
2009–2011	−0.06	0.57	0.77

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

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

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