$\mu \rightarrow e\gamma$ detector using $\gamma \rightarrow ee$ conversion

Chih-hsiang Cheng
Caltech

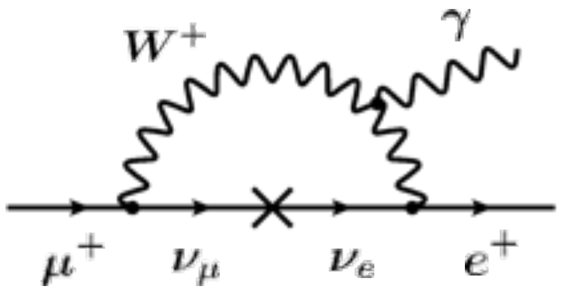
International Workshop on Neutrino Factories, Super Beams and Beta Beams (NuFact2013)

IHEP, Beijing, China
2013/08/19–24

Physics motivation

- Observing charged lepton violation is a clear sign of new physics.

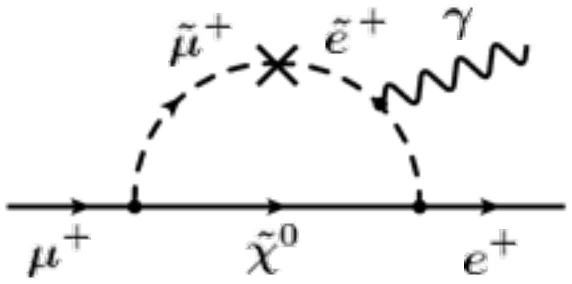
Standard Model:
through neutrino mixing



$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{m^2_W} \right|^2$$

$$\approx 10^{-54}$$

Beyond Standard Model:
e.g., SUSY-GUT



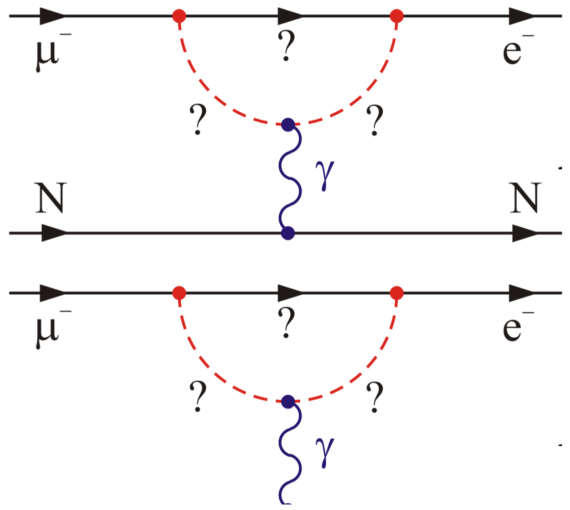
$$\mathrm{Br}(\mu \to e\gamma) \approx \frac{\alpha^3}{G_F^2} \frac{(\delta_{\mathrm{LL}})^2_{e\mu}}{m^4_{\mathrm{SUSY}}} \tan^2(\beta)$$

$$\approx 10^{-11} \sim 10^{-14}$$

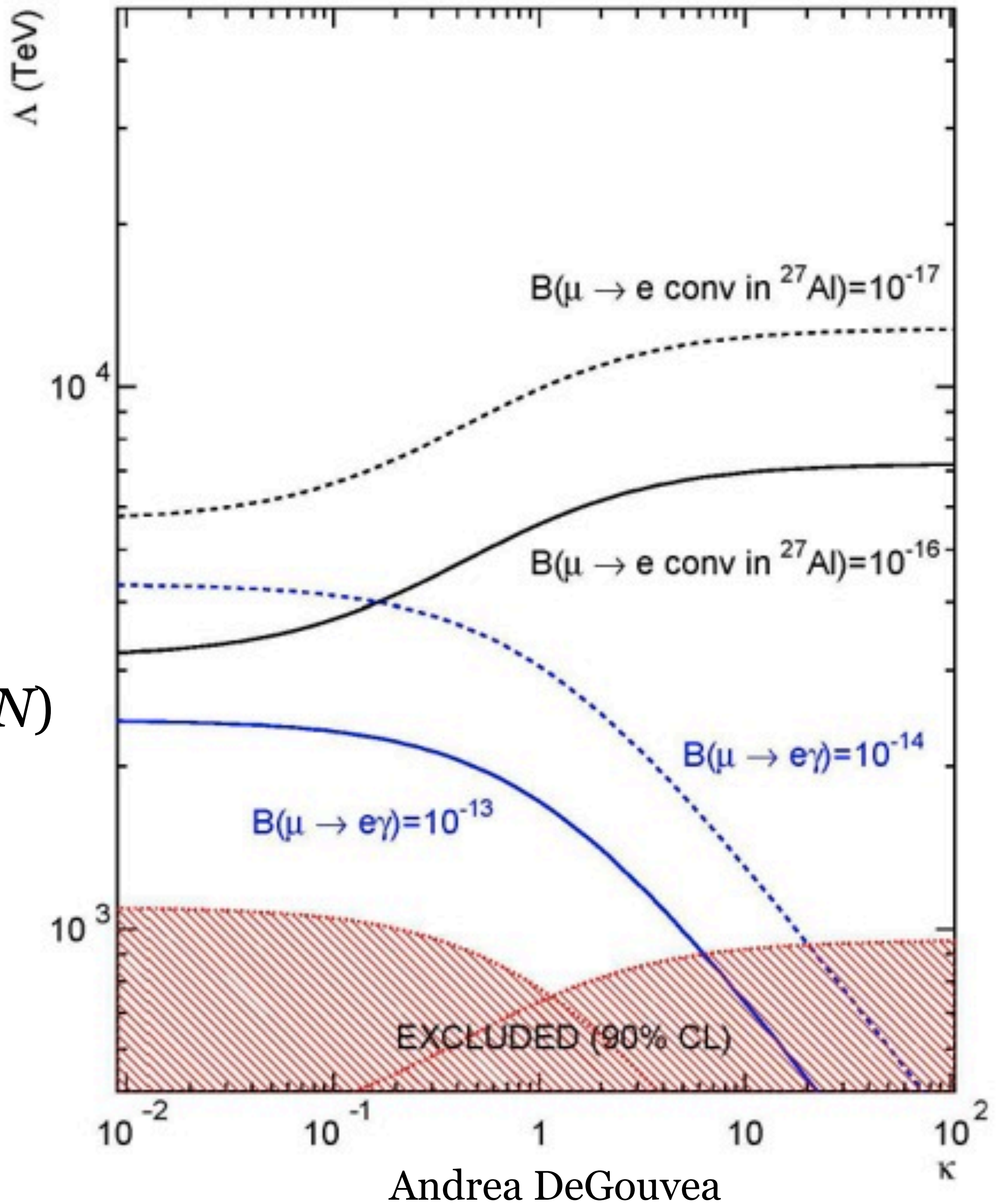
Sensitive to high mass scales

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

κ≪1 Loops

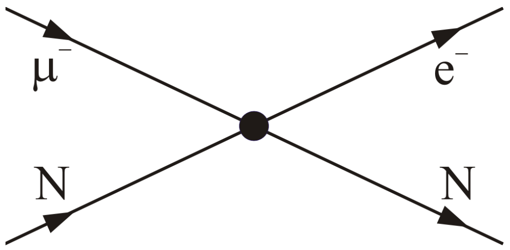


$\Gamma(\mu\to e\gamma) \approx 300\ \Gamma(\mu N\to eN)$



Andrea DeGouvea

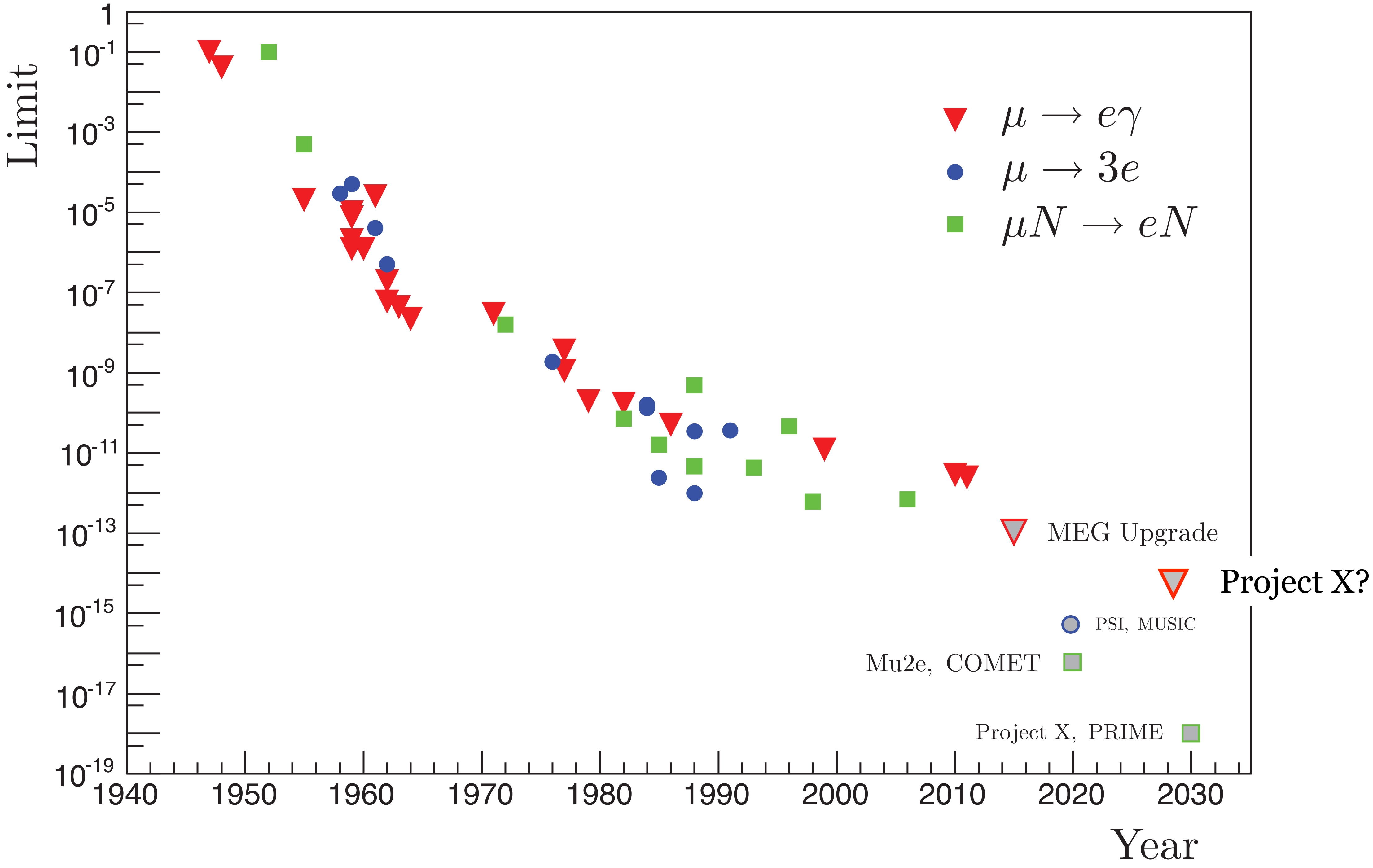
κ≫1 Contact terms



$\Gamma(\mu N\to eN) \gg \Gamma(\mu\to e\gamma)$

μ→*eee* is also sensitive to both ends of the spectrum.

History of muon CLFV search



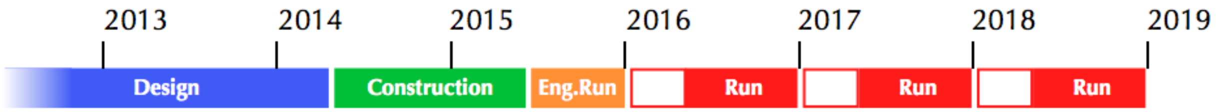
Marciano et al, Annu.Rev. Nucl. Part. Sci. 2008. 58:315; and Bernstein/Cooper arXiv:1307.5787

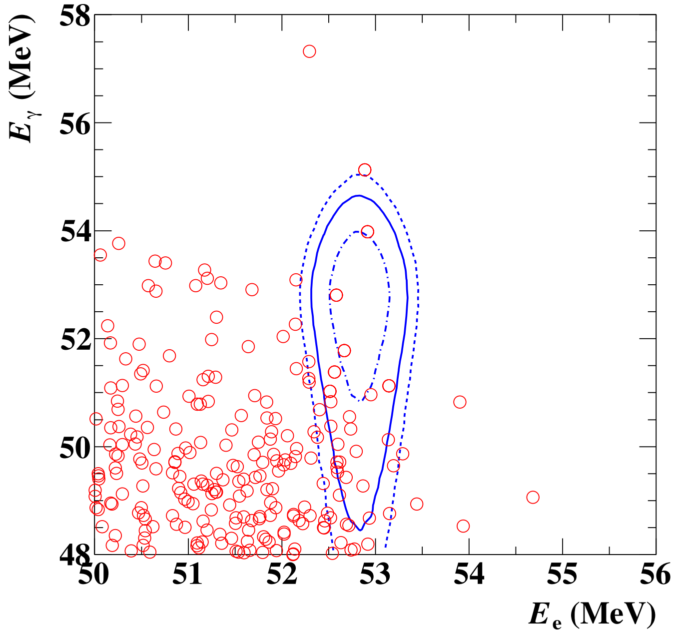
MEG result and upgrade

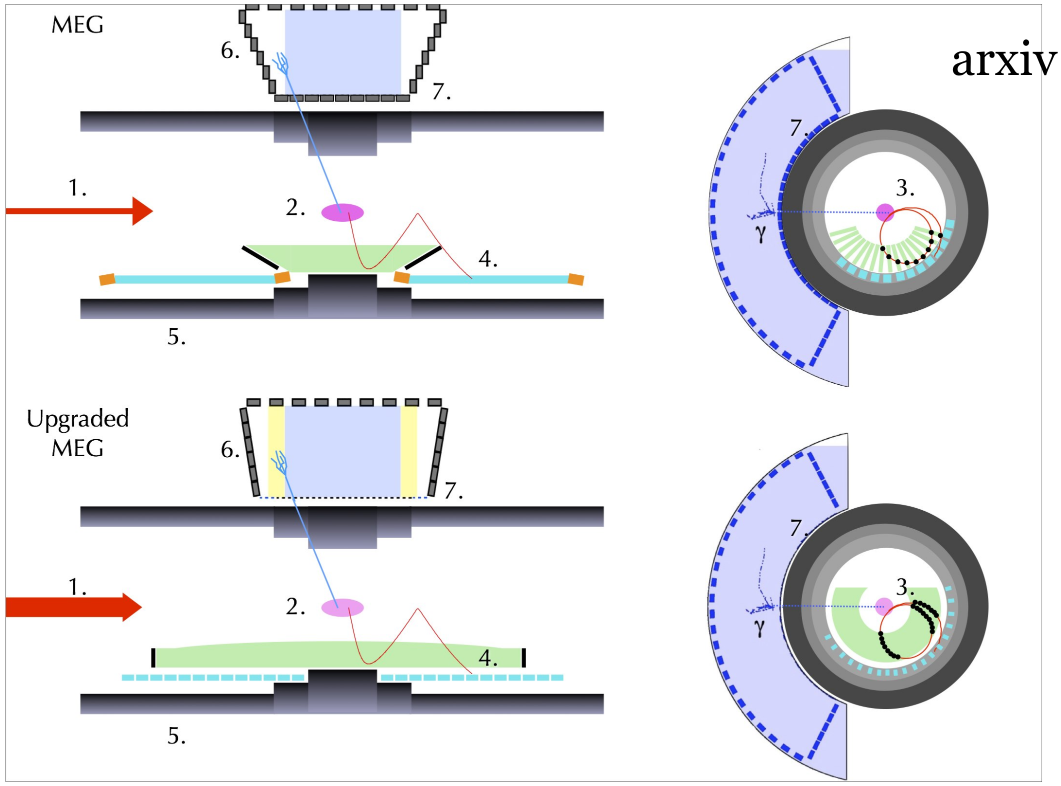
- Current limit: $\mathcal{B}(\mu^+ \to e^+\gamma) < 5.7 \times 10^{-13}$ using 3.6×10^{14} stopped muons.
- Background is dominated by accidentals.

$$N_{\mathrm{acc}} \propto R_\mu^2 \times \Delta E_\gamma{}^2 \times \Delta P_\mathrm{e} \times \Delta\Theta_{\mathrm{e}\gamma}^2 \times \Delta t_{\mathrm{e}\gamma} \times T$$

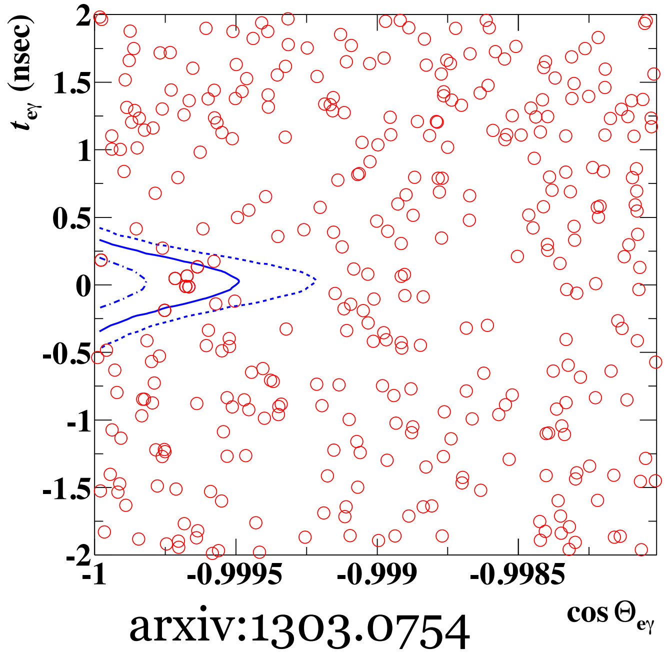
- Upgrade: target sensitivity ~ 6×10^{-14} based on ~ 3.3×10^{15} stopped muons.







arxiv:1301.7225v2



arxiv:1303.0754

How to improve beyond MEG upgrade?

- One of the limiting factors of $\mu \rightarrow e\gamma$ search is the photon energy resolution in calorimeter.
  - ✦ Accidental background dominates: $N_{\mathrm{acc}} \propto R_{\mu}^{2} \times \Delta E_{\gamma}{}^{2} \times \Delta P_{\mathrm{e}} \times \Delta\Theta_{\mathrm{e}\gamma}^{2} \times \Delta t_{\mathrm{e}\gamma} \times T$ (e^{+} from Michel decay, γ from radiative muon decay)
- A pair spectrometer (reconstructing $e^{+}e^{-}$ pair tracks from photon conversion) can improve photon energy resolution significantly.
- Other improvement such as fiducial volume, positron/photon angular resolutions, muon decay vertex detection ability, etc. should also be considered.
- The use of converted photon were recently mentioned by Fritz DeJongh in his talk at 2012 summer study. Here we use the Super*B* FastSim framework to take a detail look.

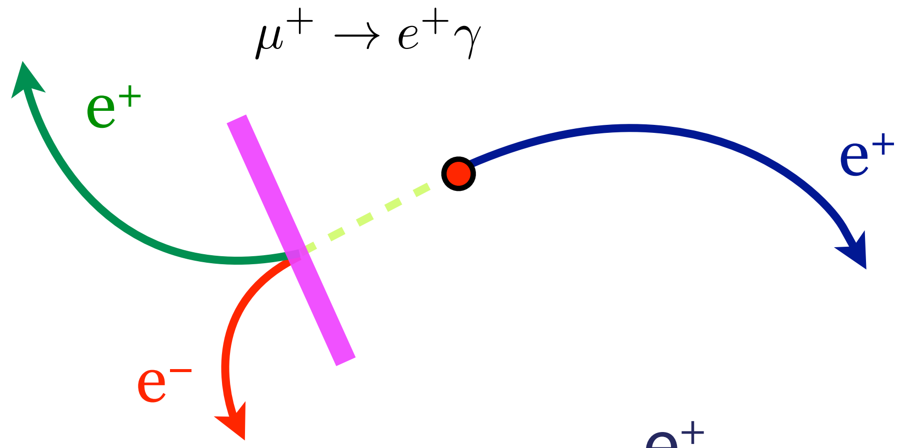
Brief introduction to FastSim

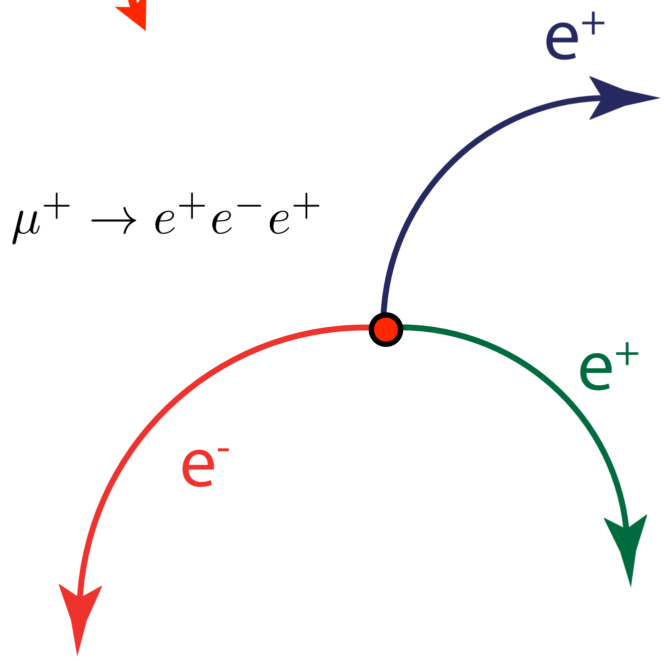
- Born from *BABAR* offline software framework.
- Developed primarily for Super*B*; extensively used for physics studies and detector optimization.
- Detectors are modeled with 2D shells of cylinders, planes, and cones; configured by xml files, very easy and quick to modify.
- Event 4-momenta are generated by EvtGen
- Particle scattering, energy loss, secondary particles, etc. (Compton, Bremsstrahlung, conversion, EM/hadron showers), are simulated at the intersection of particle at each shell.
- Tracks are reconstructed with a Kalman filter into piece-wise trajectories. No pattern recognition, but can artificially confuse hits to mimic inefficiencies.
- High level physics candidates are built and analyzed with *BABAR* framework.

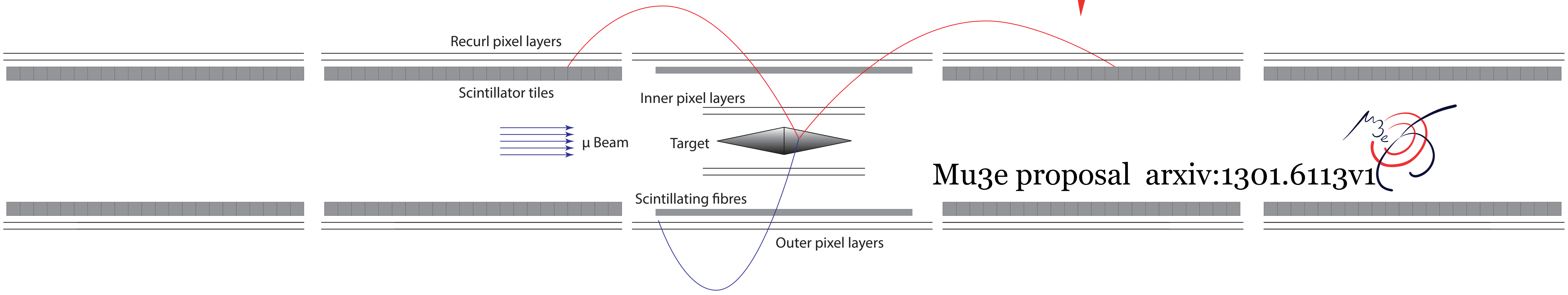
Detector geometry

- Take note from Mu3e proposal:
  - ✦ Similar event topology
- Cylinders of thin silicon sensors
- Thin cone-shape target
- Scintillator timing devices (not implemented yet in this study).

- We need to add thin and dense materials to convert photons.





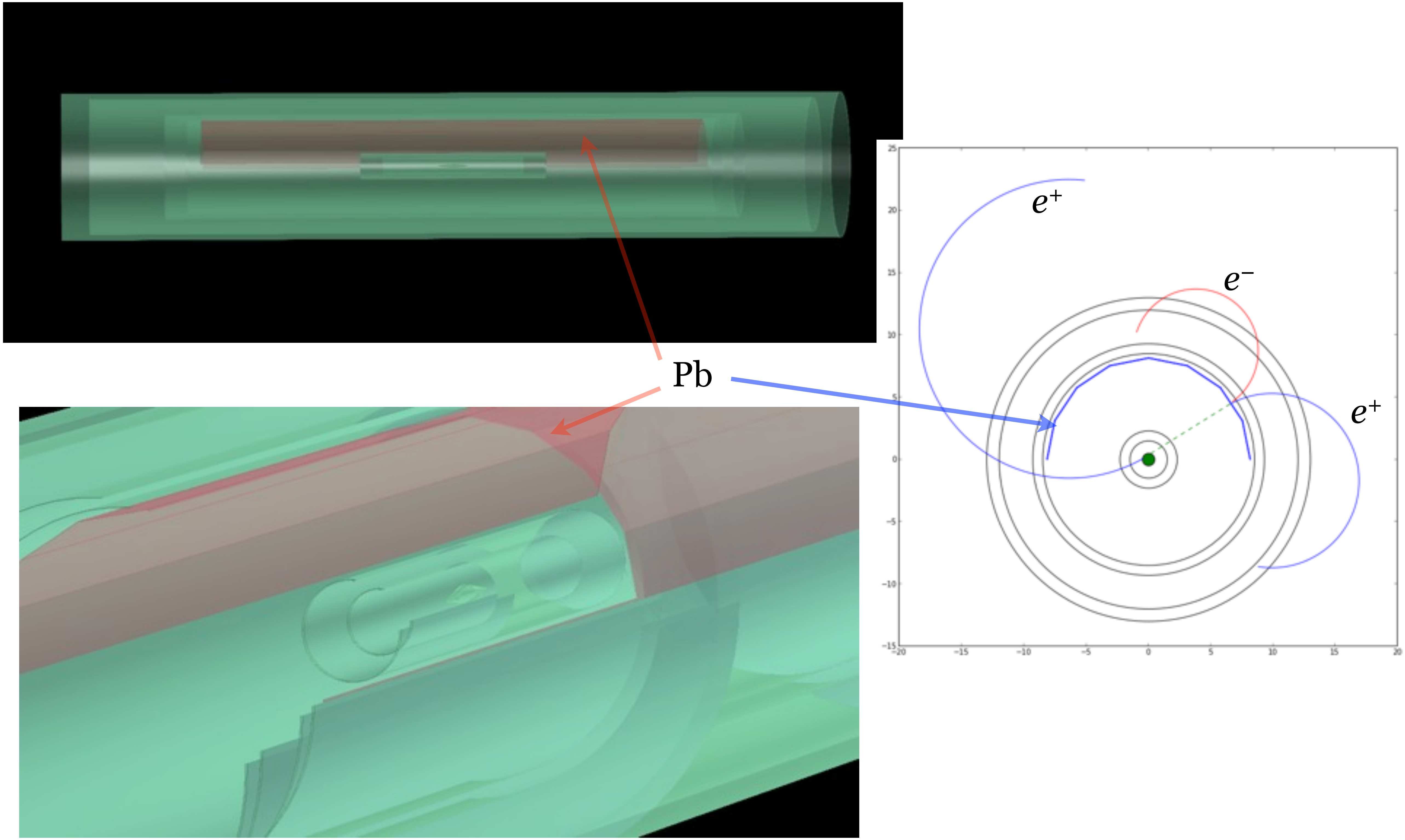


Mu3e proposal arxiv:1301.6113v1

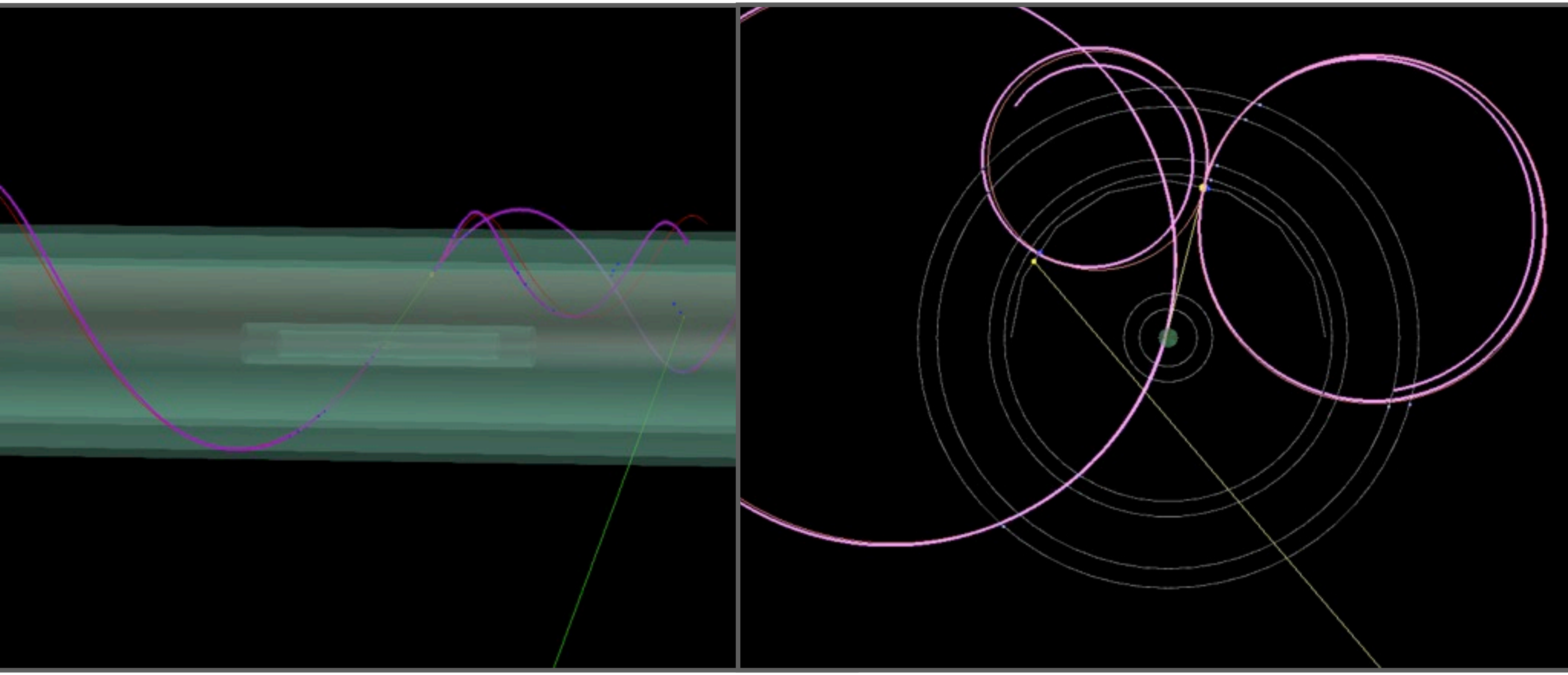
FastSim setup

- 6 layers: R= 1.5, 2.3, 8.5, 9.3, 12.0, 13.0 cm
- Si thickness= 50 µm, plus 50 µm kapton.
- Pb photon converter: 0.56 mm thick (~10% X_0) at R=8.0 cm, covering 180° azimuthal angle.
- Target: double-cone Aluminum. Z vertices at ±5 cm; R=0.5 cm centered at z=0; thickness= 50 µm.
  - Muons are generated just inside the surface of the target.
- Polar angle coverage: [0.2, π−0.2] rad
- B Field= 1.0 T
- Silicon layers are modeled after Super*B* double-sided striplets.
  - Hit resolution: 8 µm, plus some fraction of a 20 µm tail.
  - Hit efficiency: 90%.

FastSim geometry


Pb

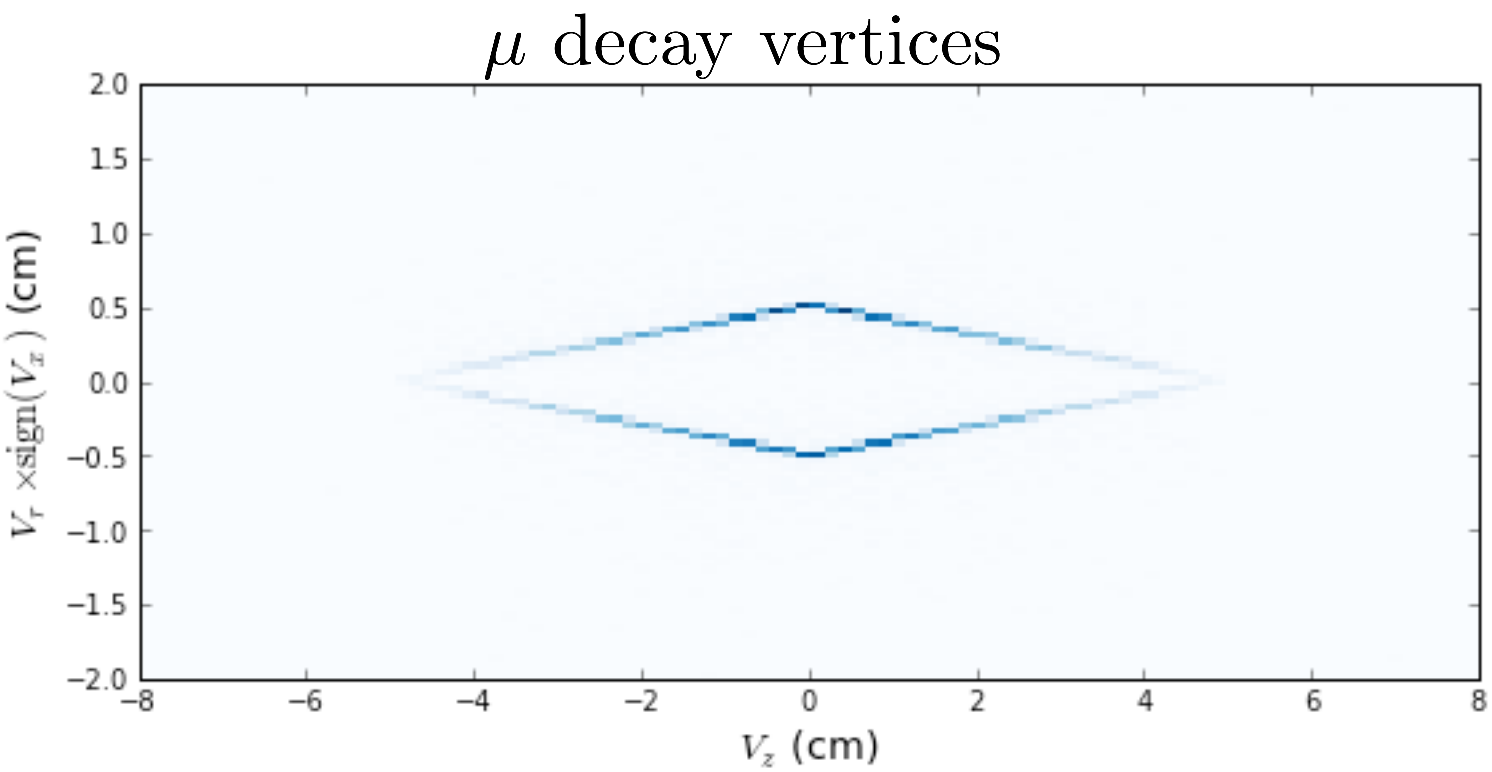
Event display

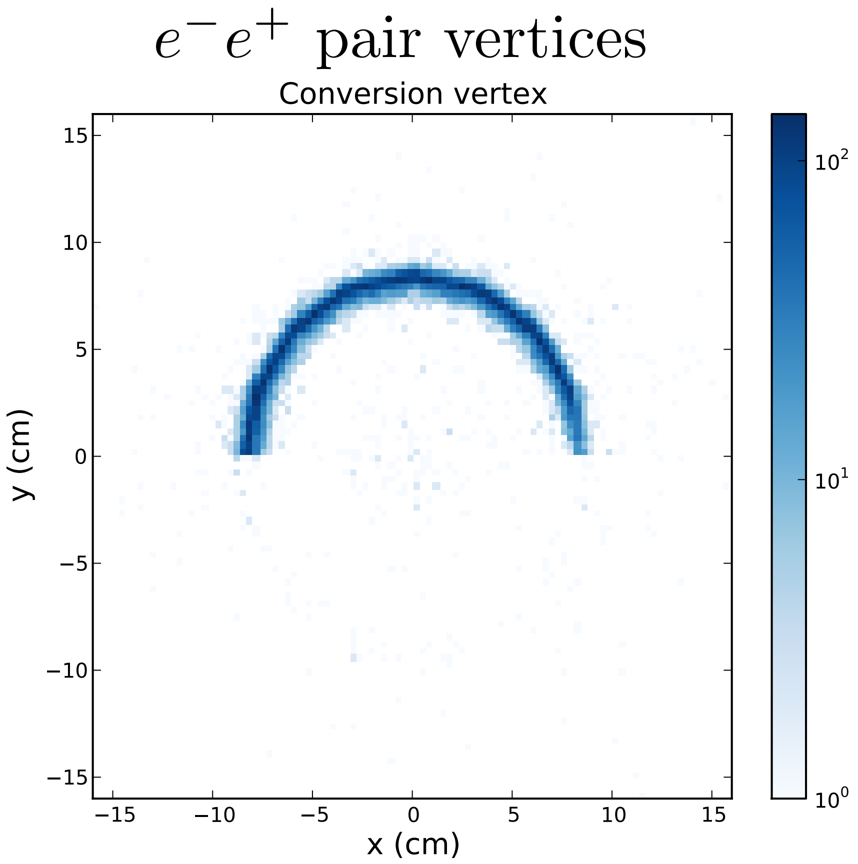


Thin red curves: generated helices; magenta curves: fitted trajectories

Analysis

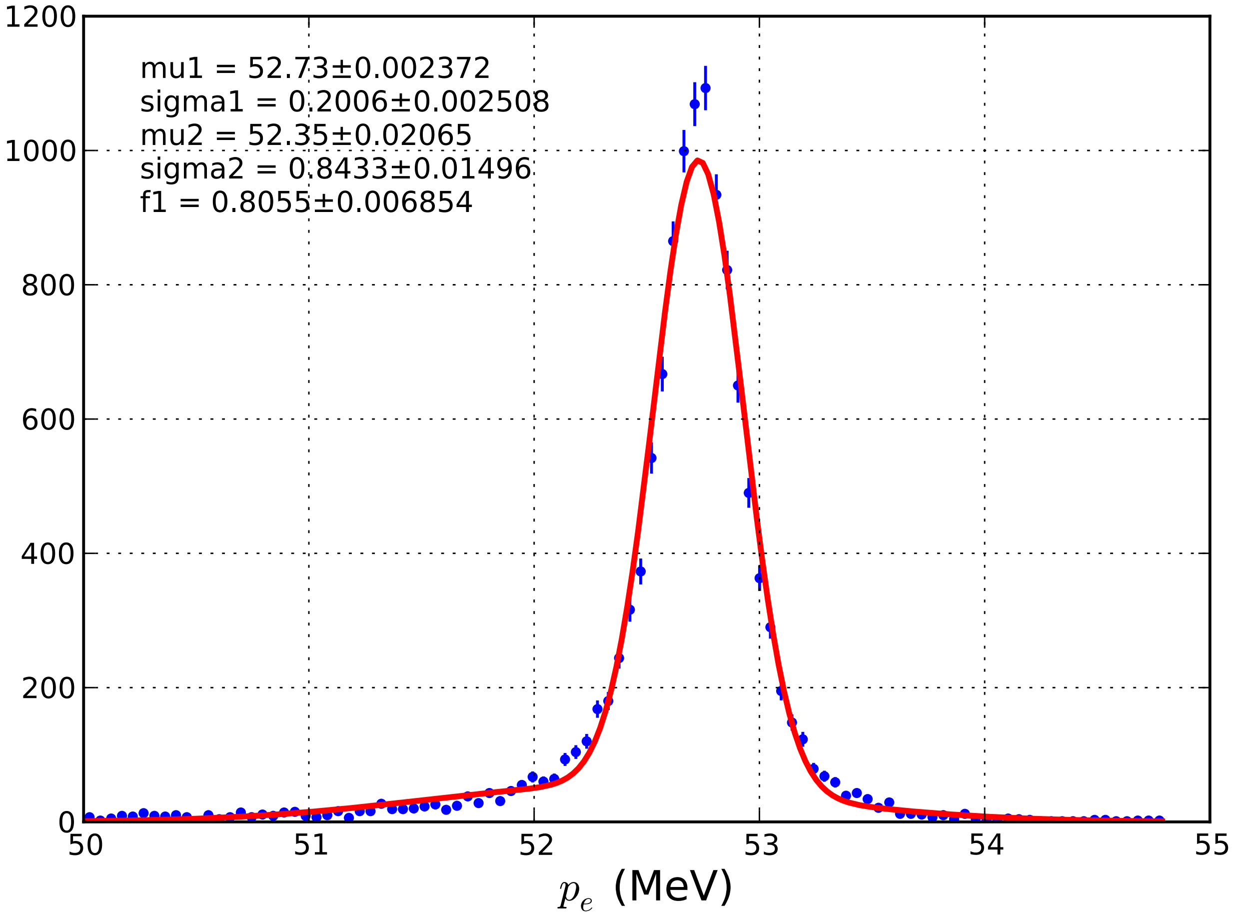
- Generate 10^6 $\mu^+ \rightarrow e^+\gamma$ uniformly under the surface of target.
- *BABAR* algorithm to find/vertex converted $\gamma \rightarrow e^+e^-$ pairs.
- Extrapolate primary e^+ onto the target surface; use the intersection to constrain the muon candidate decay vertex and refit the decay.
  - ✦ If more than one intersection is found, choose the one such that e^+ and γ have a largest opening angle (closest to back-to-back).
- ~1.8% are reconstructed.



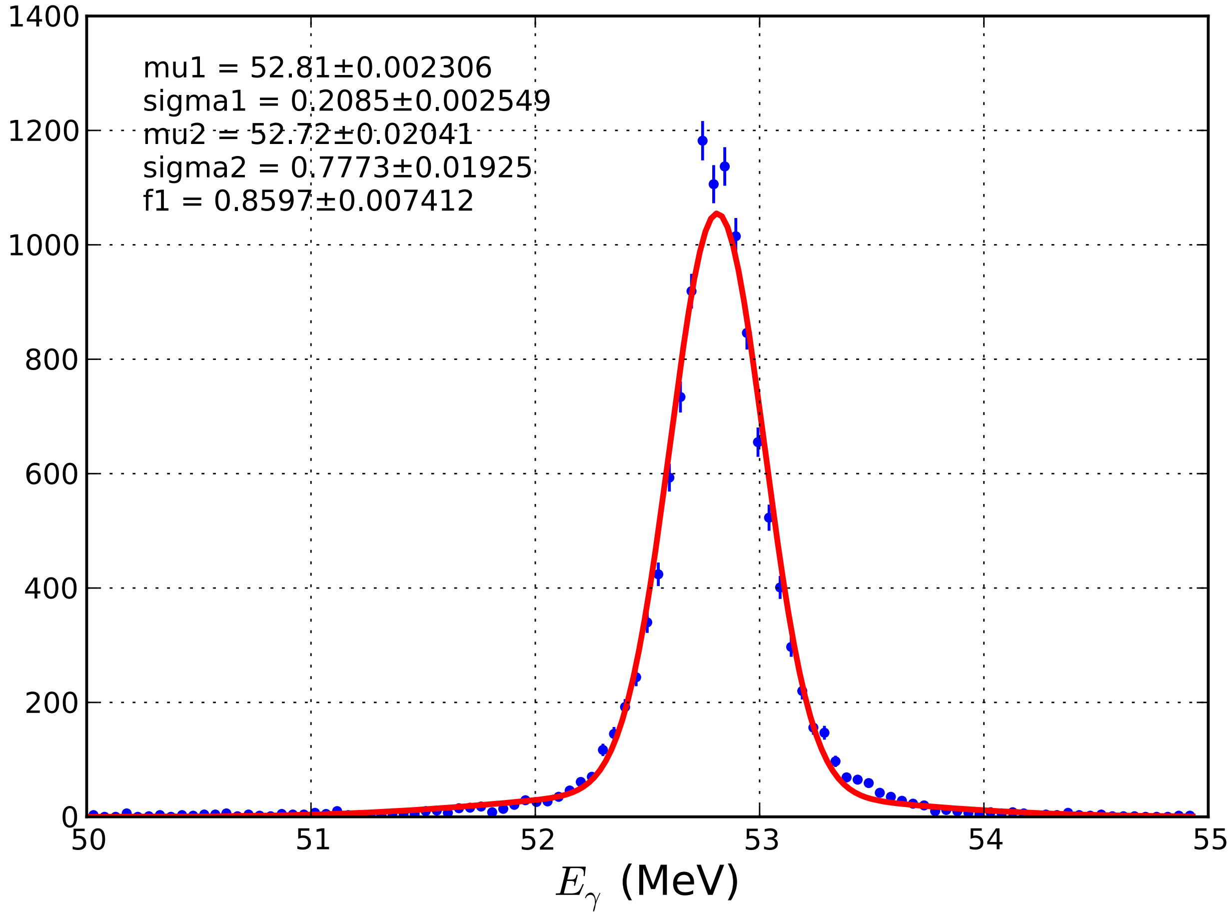


Energy momentum resolutions

- Selection: $|\cos\theta_e|<0.7$; $|\cos\theta_\gamma|<0.7$; $-3<\varphi_e<0$; $\varphi_\gamma>0$
- Efficiency ~ 1.25%.

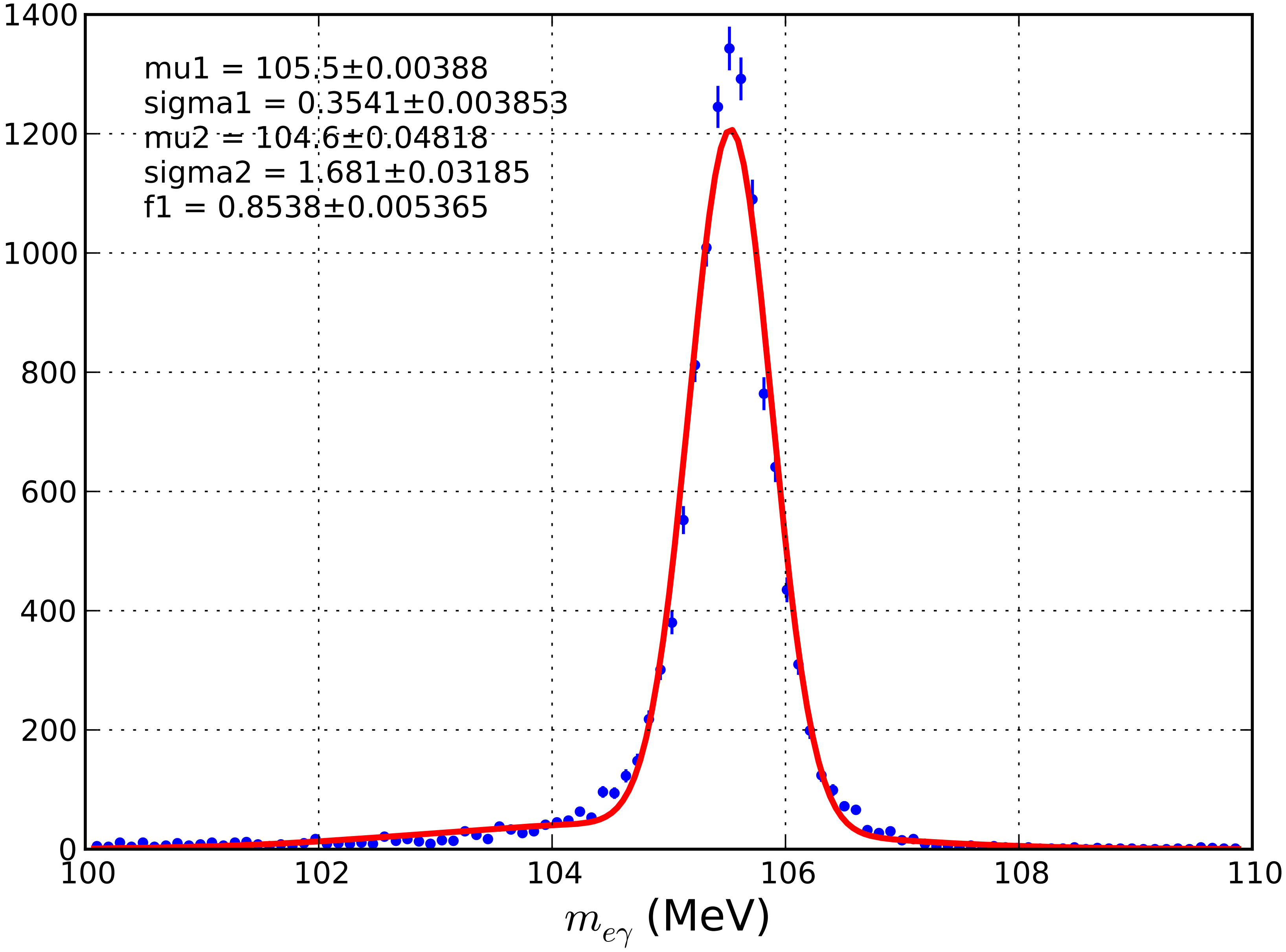


e^+ momentum:
σ_1= 200 keV
σ_2= 840 keV
f_1 = 81%



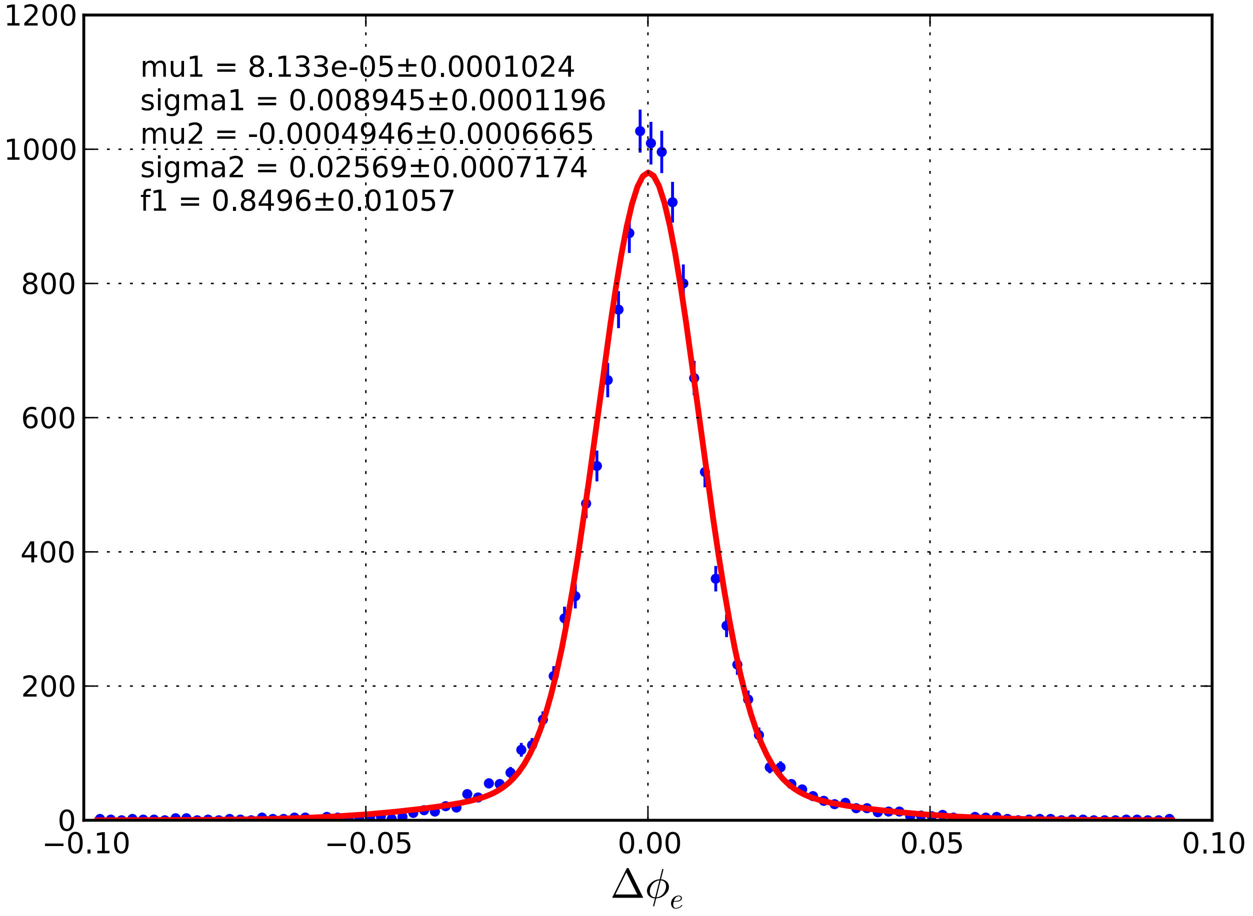
photon energy
σ_1= 208 keV
σ_2= 777 keV
f_1 = 86%

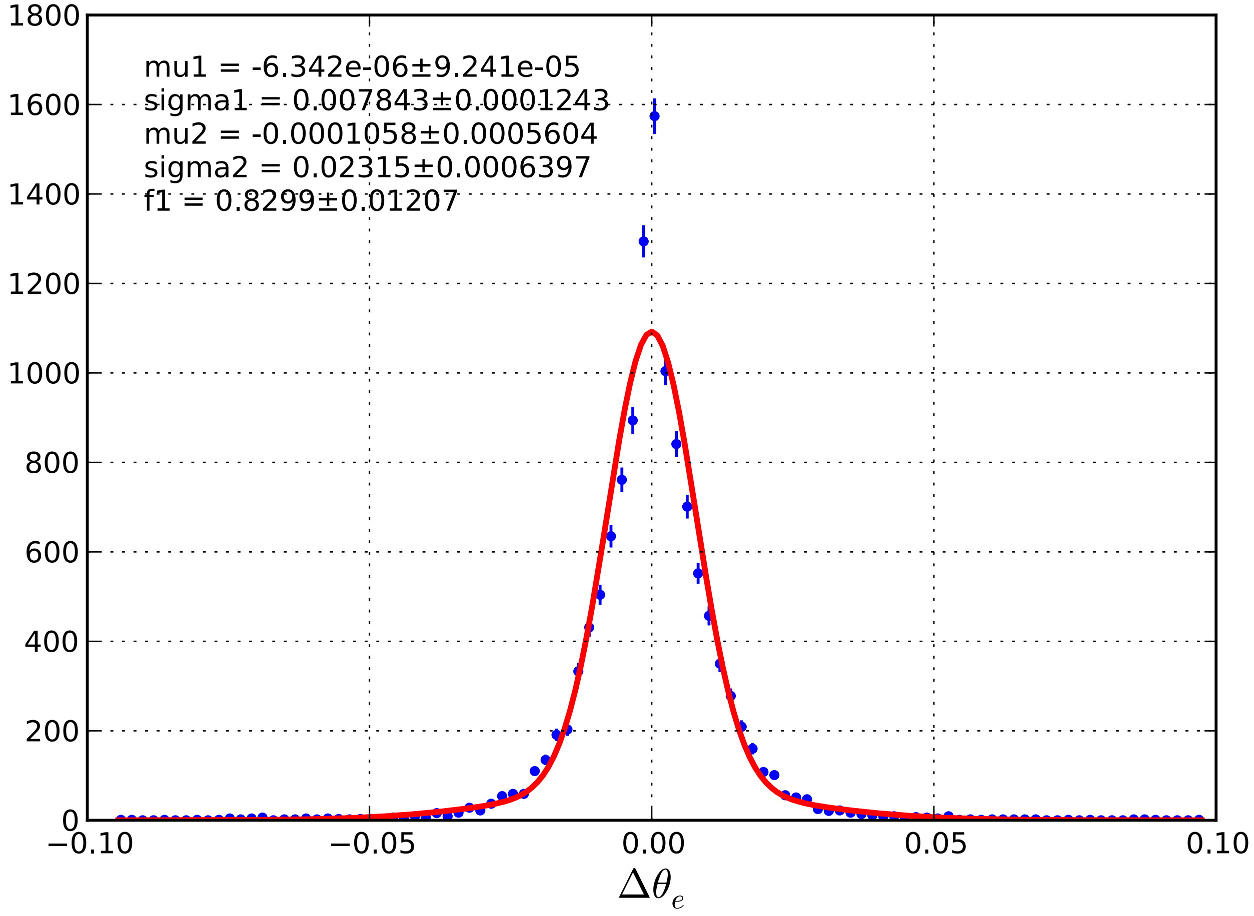
$e^+\gamma$ invariant mass resolution



σ_1= 354 keV
σ_2= 1681 keV
f_1 = 85%

Positron angular resolution



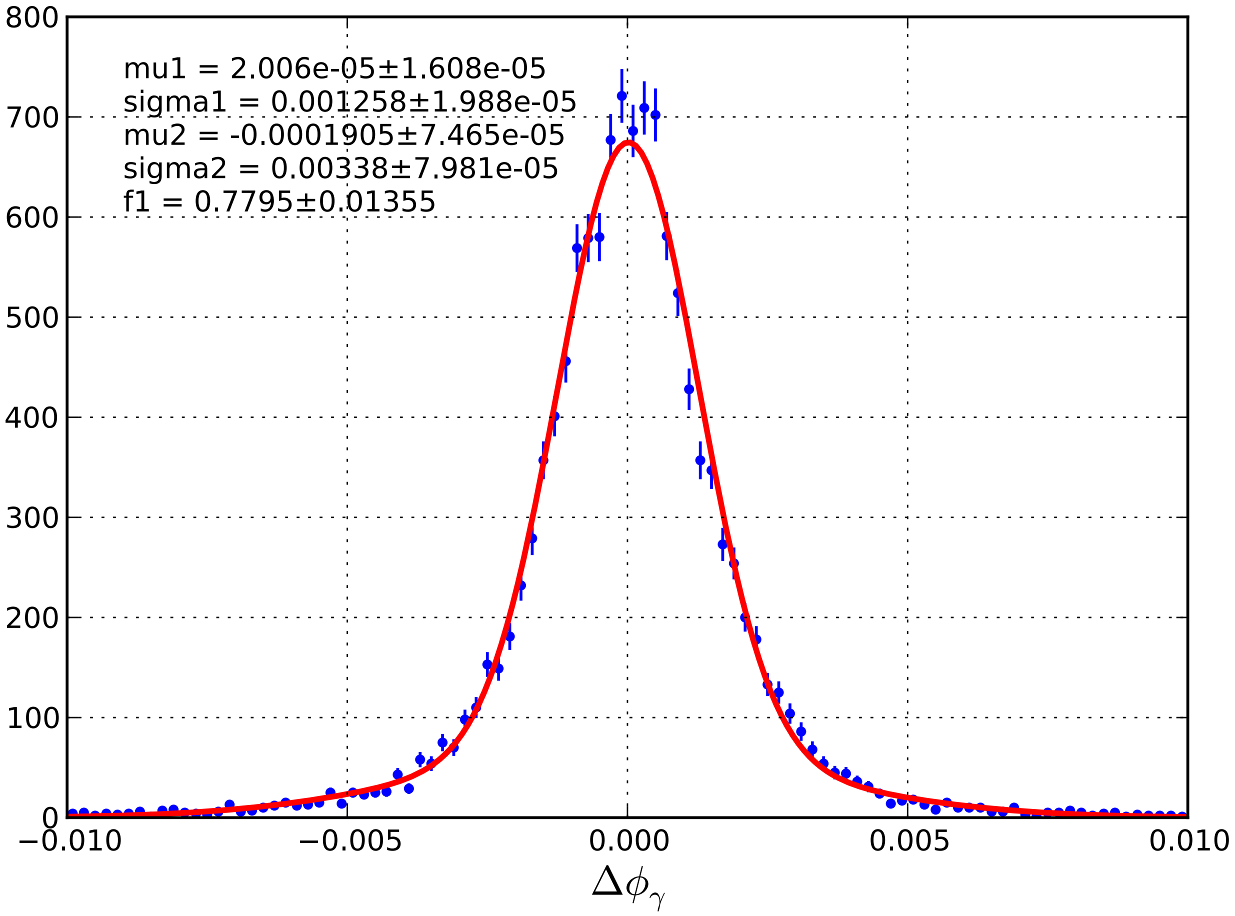


φ_e resolution
σ_1= 9 mrad
σ_2= 26 mrad
f_1 = 85%

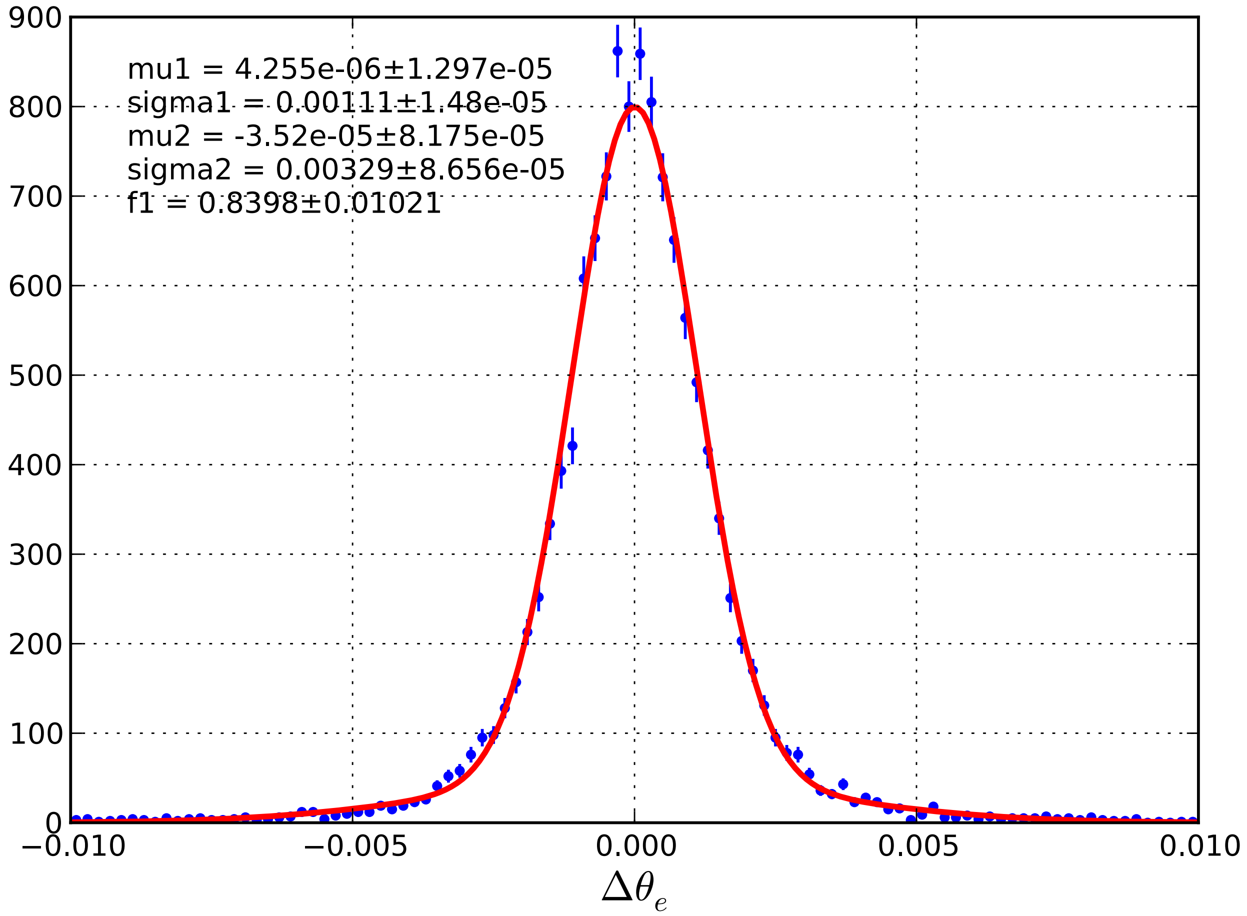
θ_e resolution
σ_1= 8 mrad
σ_2= 23 mrad
f_1 = 83%

Photon angular resolution

- After vertex constraint: ~7 time better than positron angular resolution.
  - (Before vertex constraint: similar to positron.)



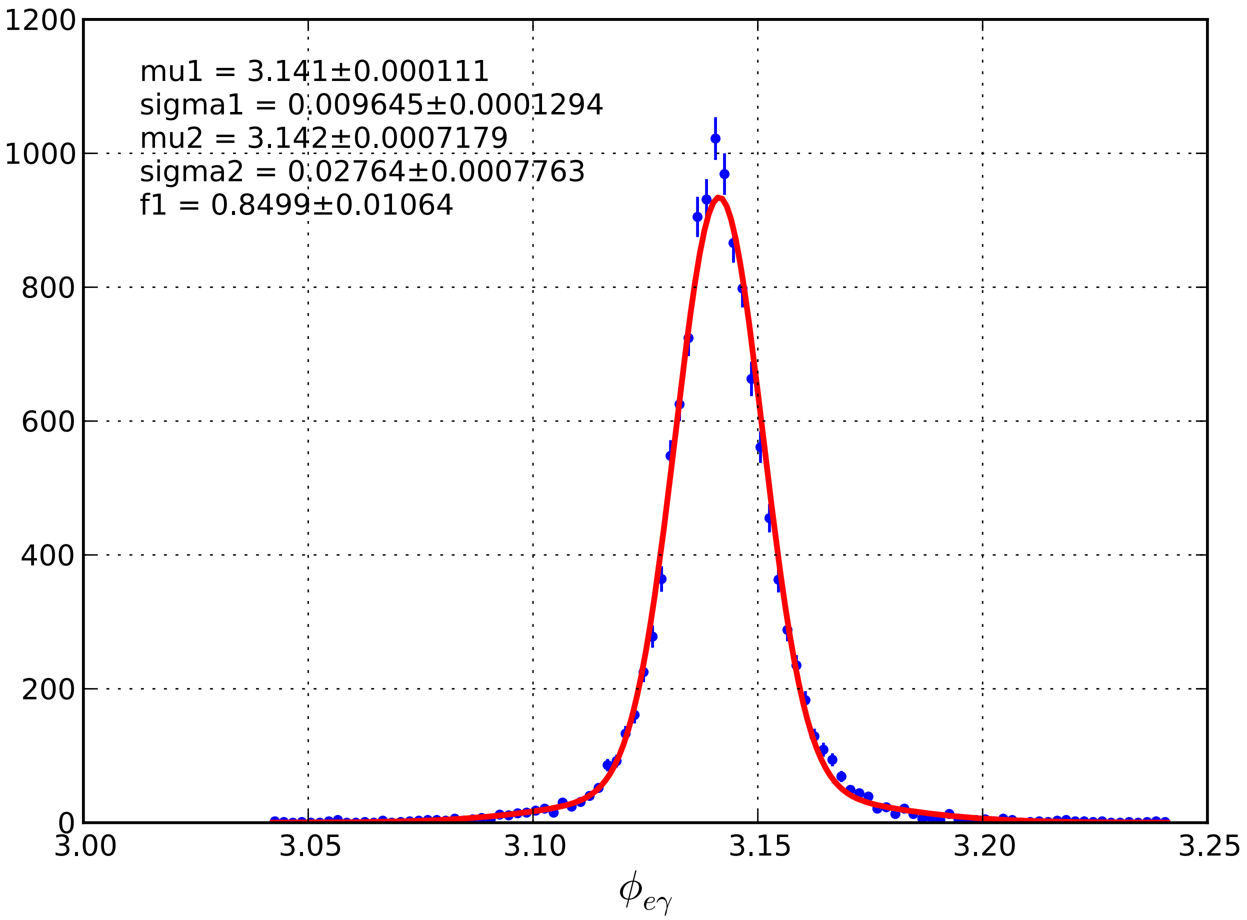
φ_γ resolution
σ_1= 1.3 mrad
σ_2= 3.4 mrad
f_1 = 78%



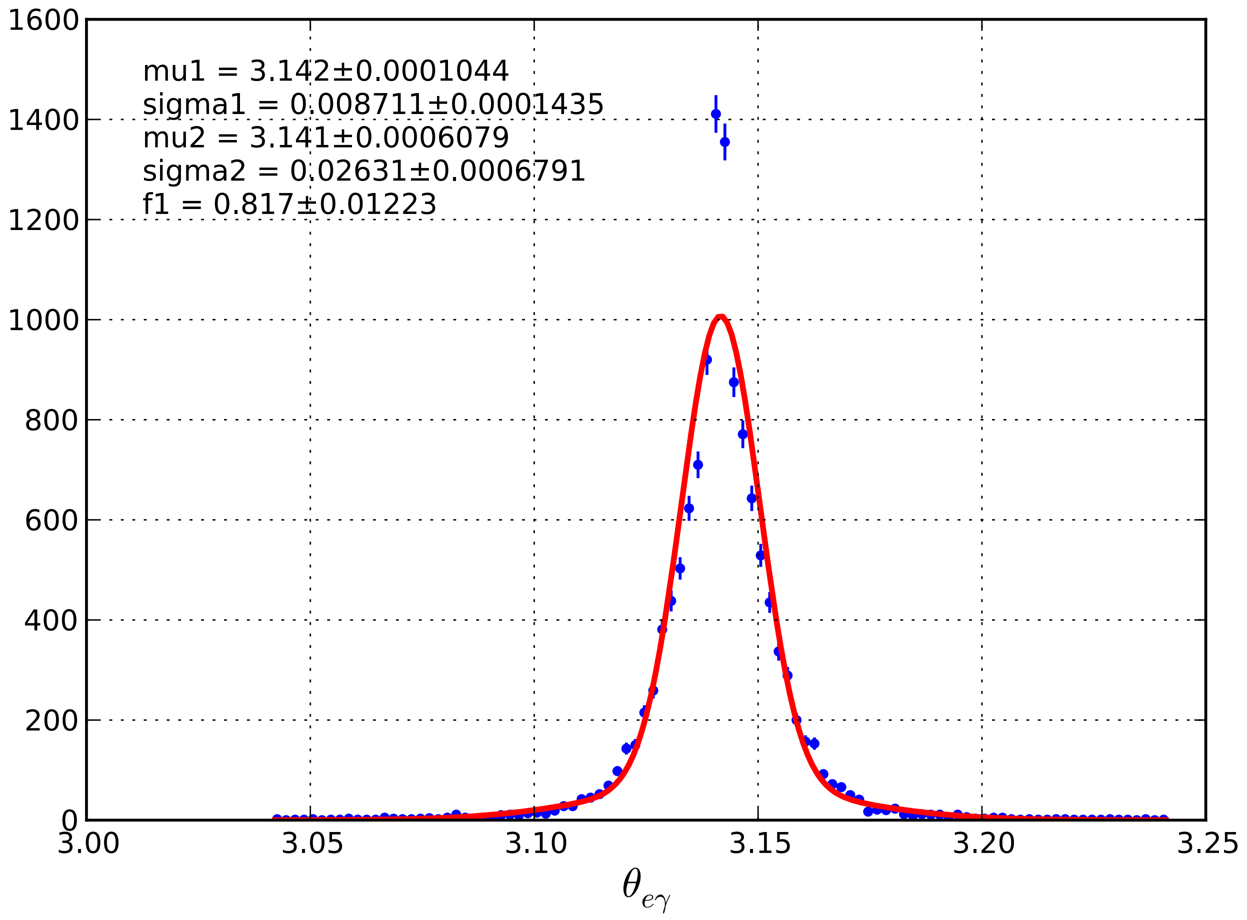
θ_γ resolution
σ_1= 1.1 mrad
σ_2= 3.3 mrad
f_1 = 84%

Resolution of *e*-*γ* angle

- Dominated by positron angular resolution.



$\varphi_{e\gamma}$ resolution
σ_1= 9.6 mrad
σ_2= 28 mrad
f_1 = 85%



$\theta_{e\gamma}$ resolution
σ_1= 8.7 mrad
σ_2= 26 mrad
f_1 = 82%

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%

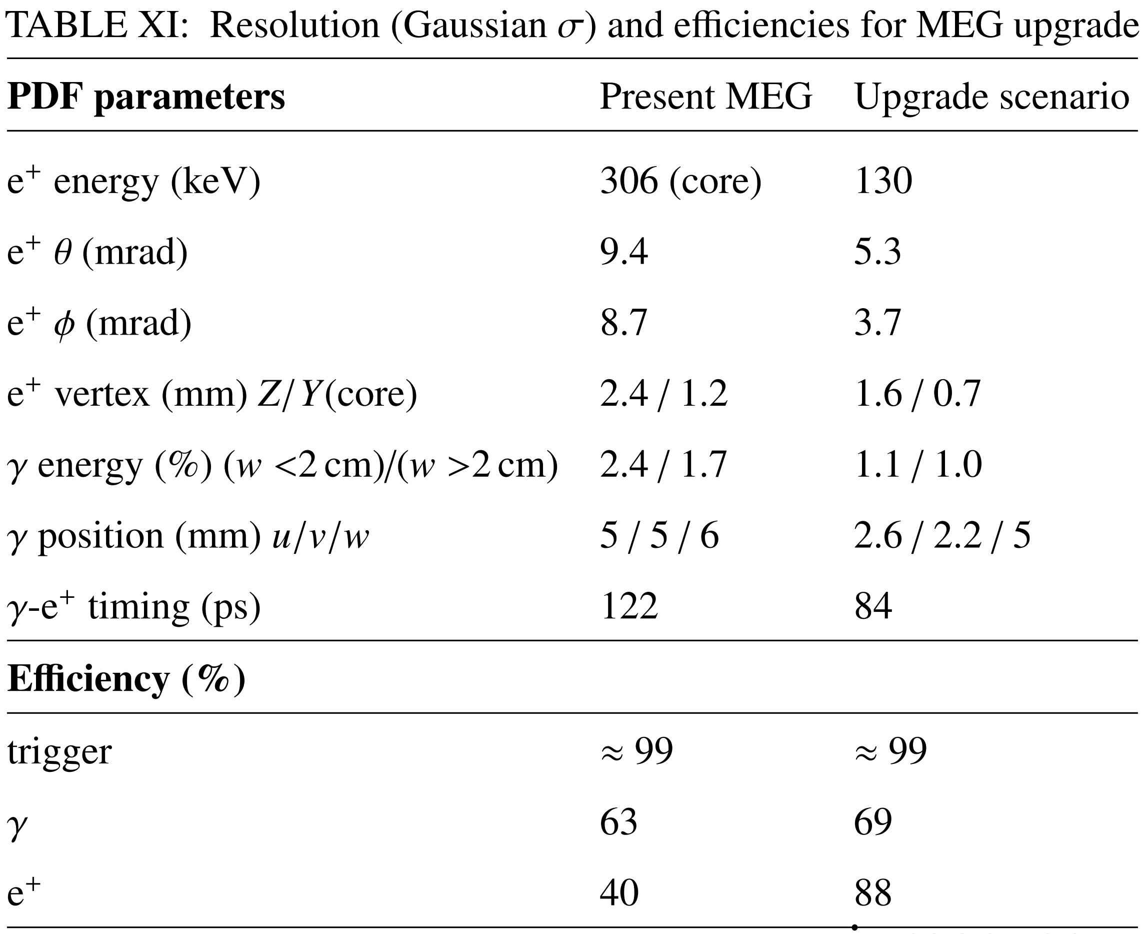
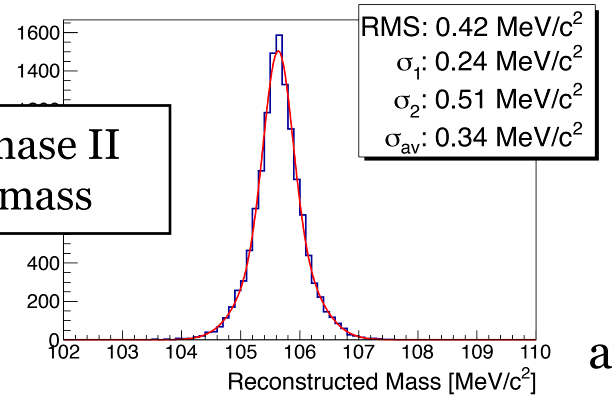


TABLE XI: Resolution (Gaussian σ) and efficiencies for MEG upgrade

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

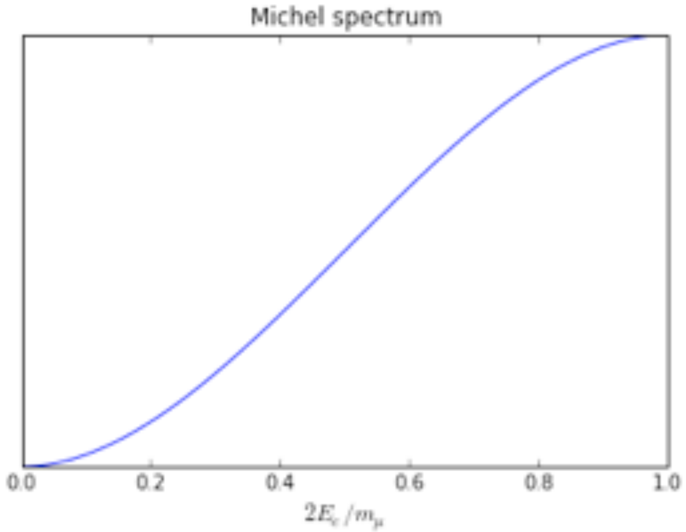


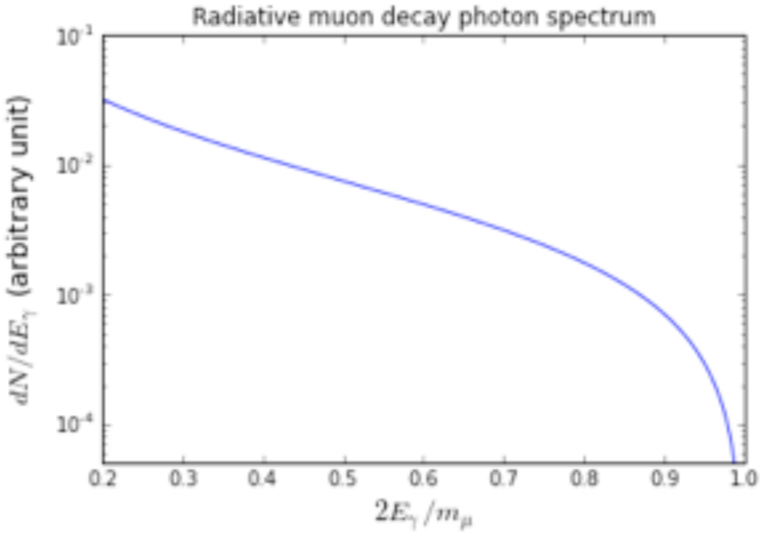
Mu3e phase II
muon mass

arxiv:1301.7225v2

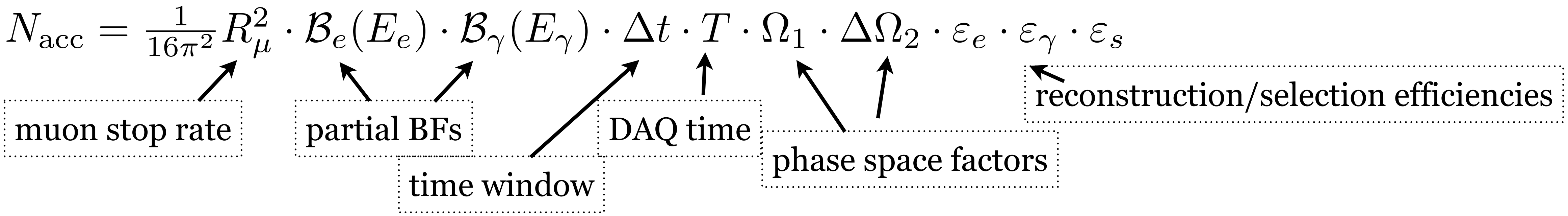
Background study

- The dominant background in MEG is accidental background (>90%).
  - ✦ Positron from normal Michel decay; photon from radiative muon decay.


Michel spectrum


Radiative muon decay photon spectrum

- BF(Michel)~100%; BF($\mu^-\rightarrow e^-\bar{\nu}_e\nu_\mu\gamma$; E_γ>10 MeV)= (1.4 ± 0.4)%.
- We can generate uncorrelated pairs of e^+ and γ (assuming no polarization), limiting ourselves to around the signal-like phase space, to simulate the equivalent background from 10^{16} stopped muons in a short time.



$$N_{\text{acc}} = \frac{1}{16\pi^2} R_\mu^2 \cdot \mathcal{B}_e(E_e) \cdot \mathcal{B}_\gamma(E_\gamma) \cdot \Delta t \cdot T \cdot \Omega_1 \cdot \Delta\Omega_2 \cdot \varepsilon_e \cdot \varepsilon_\gamma \cdot \varepsilon_s$$

muon stop rate

partial BFs

time window

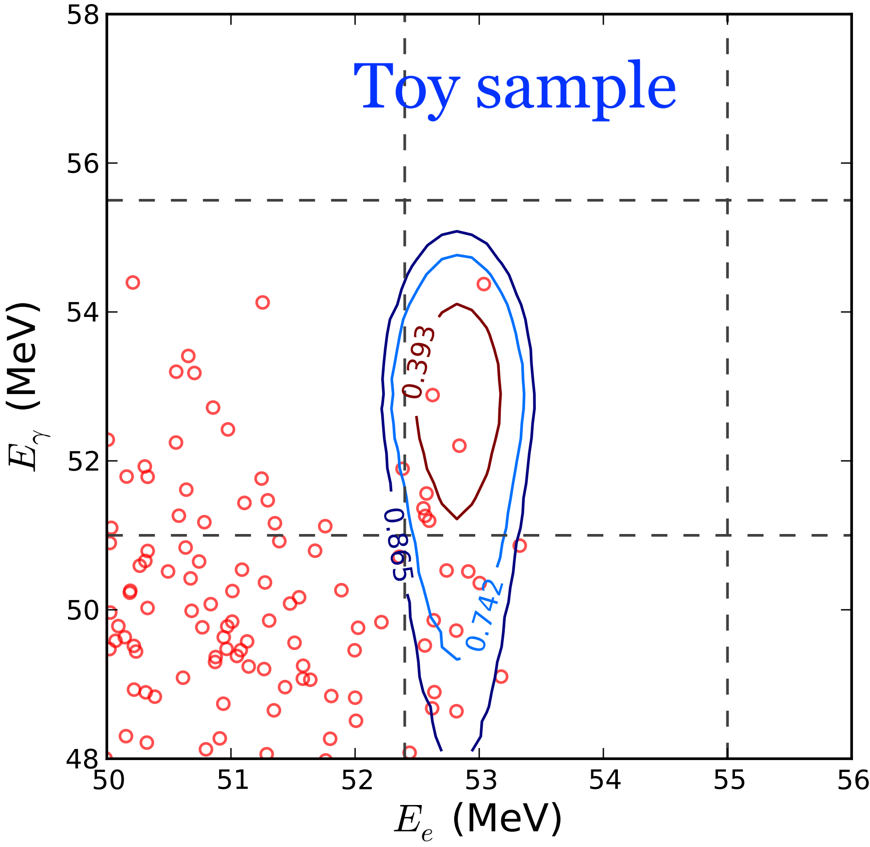
DAQ time

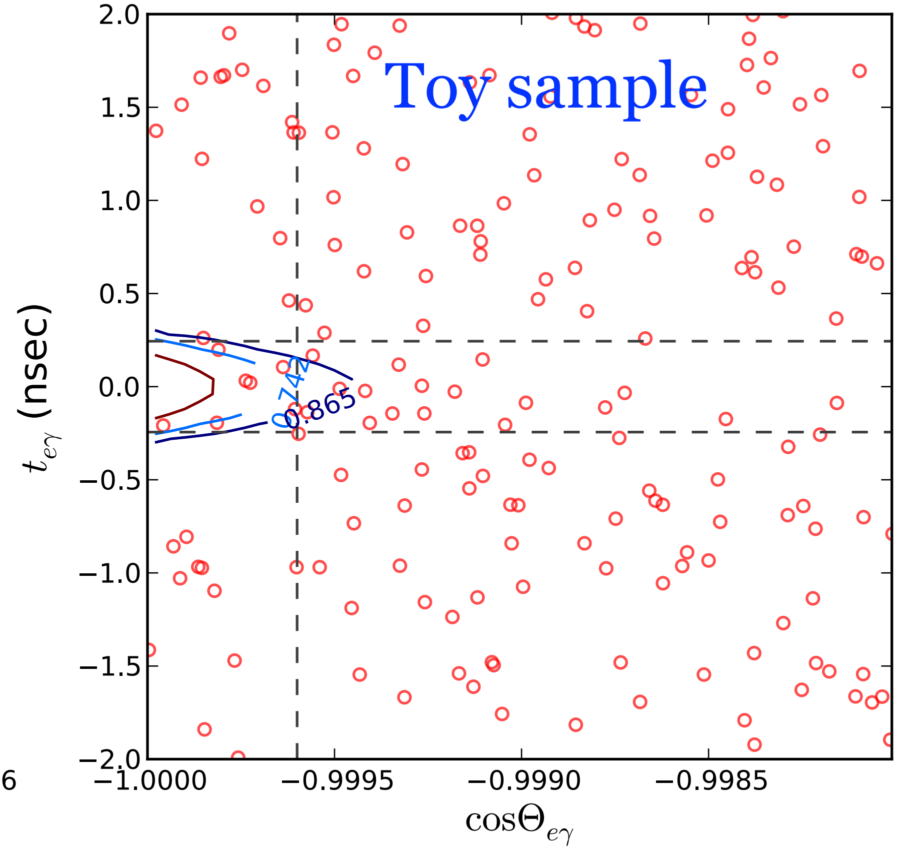
phase space factors

reconstruction/selection efficiencies

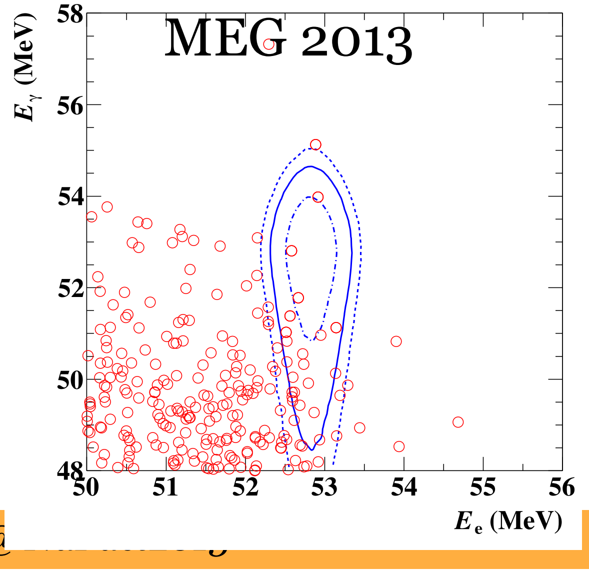
Toy validation with MEG

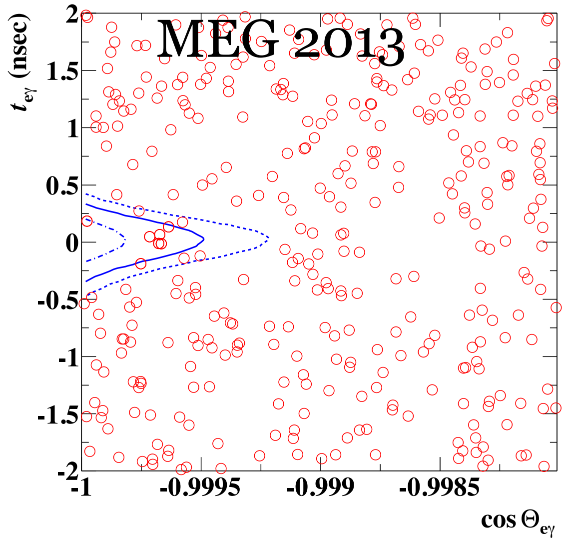
- Use $R_\mu = 3 \times 10^7/\mathrm{s}$, $R_\mu T = 3.6 \times 10^{14}$, **2.2% overall efficiency, and MEG's resolutions to generate accidental background toy events**





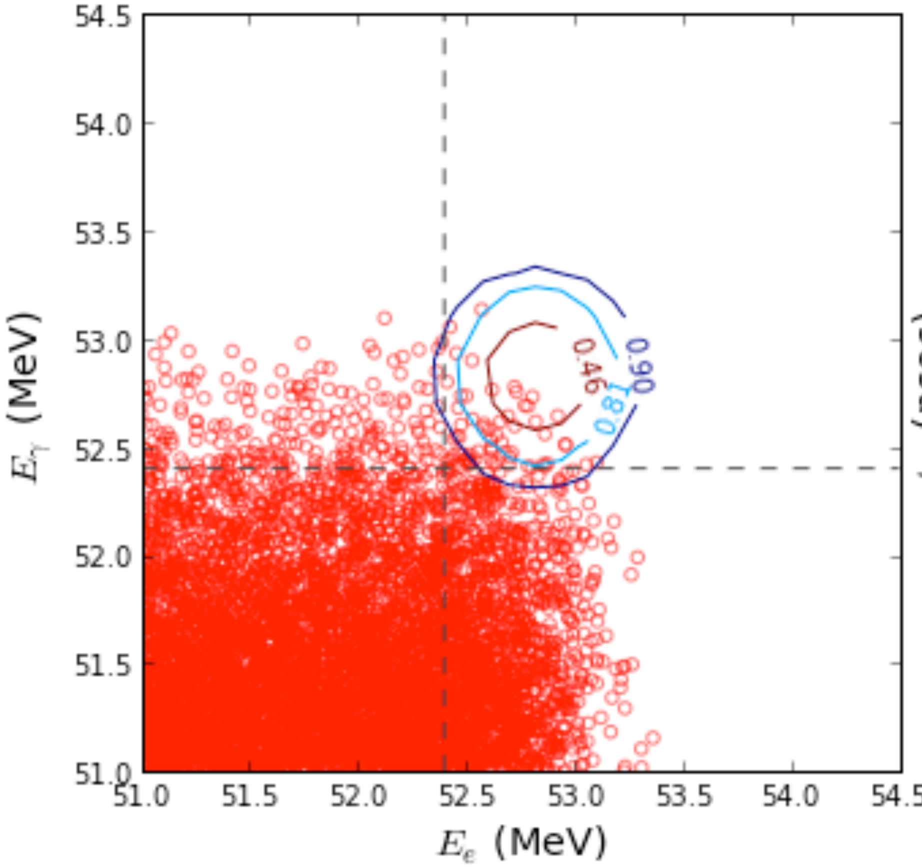
Count events in ±1.64-σ windows (90% for a Gaussian distribution) in E_e, E_γ, $\theta_{e\gamma}$, $\varphi_{e\gamma}$, and Δt. Found 3.3±0.2 background events.

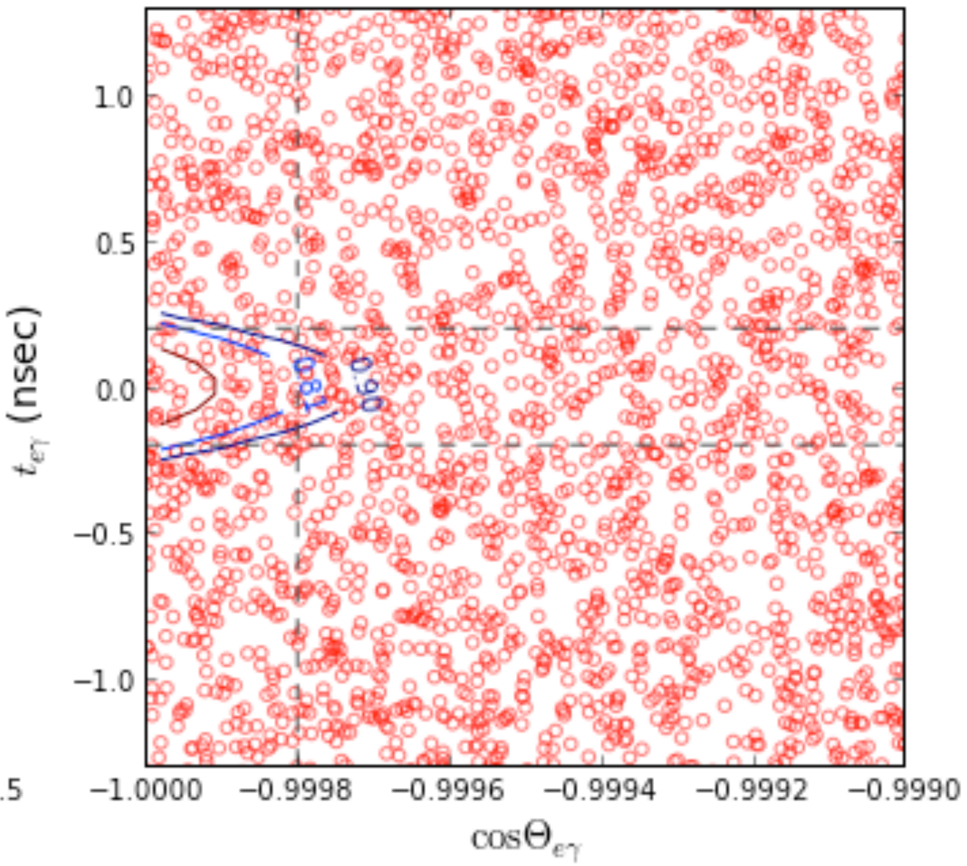




Background in future facility

- 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_μ=8.4×10^8/s.
- Use resolutions similar to those found in FastSim, and timing resolution of 100 ps.

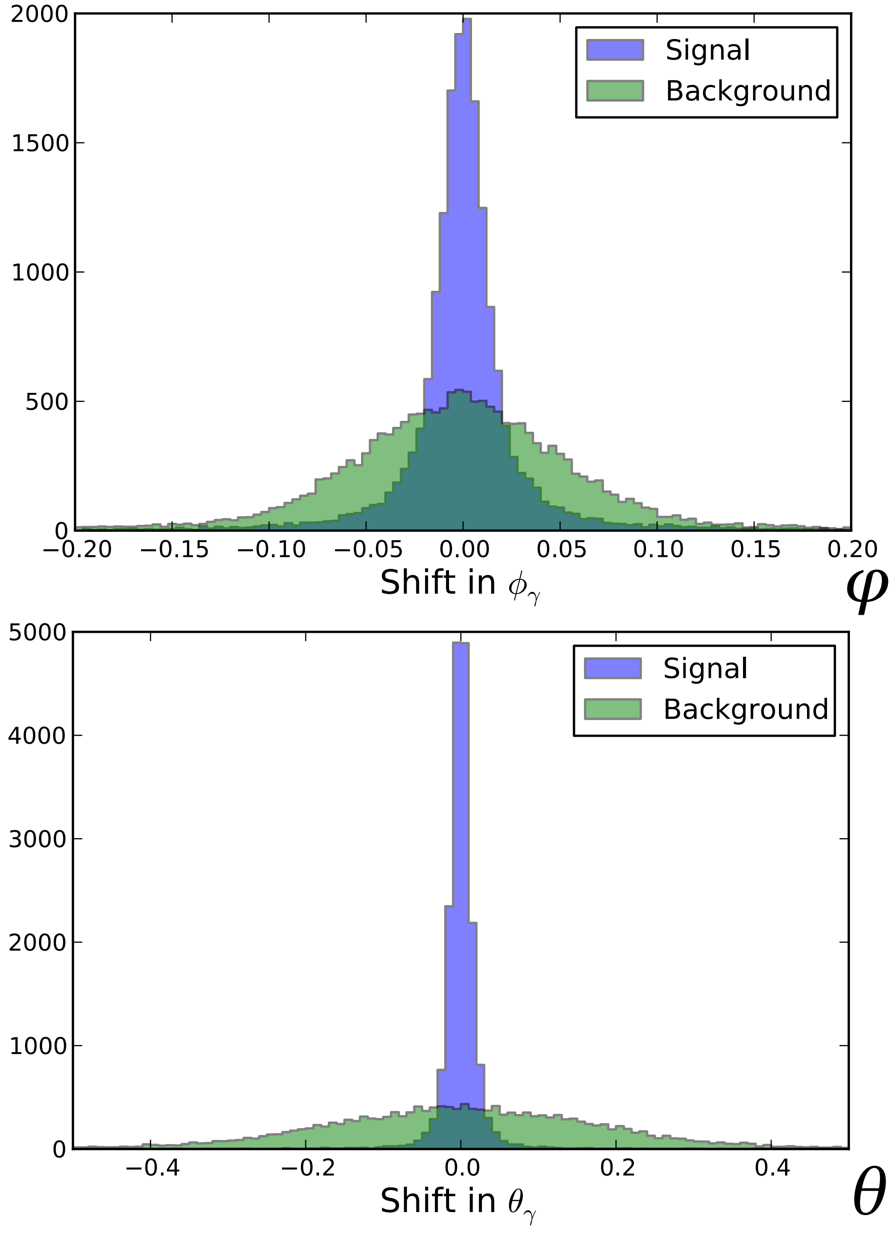




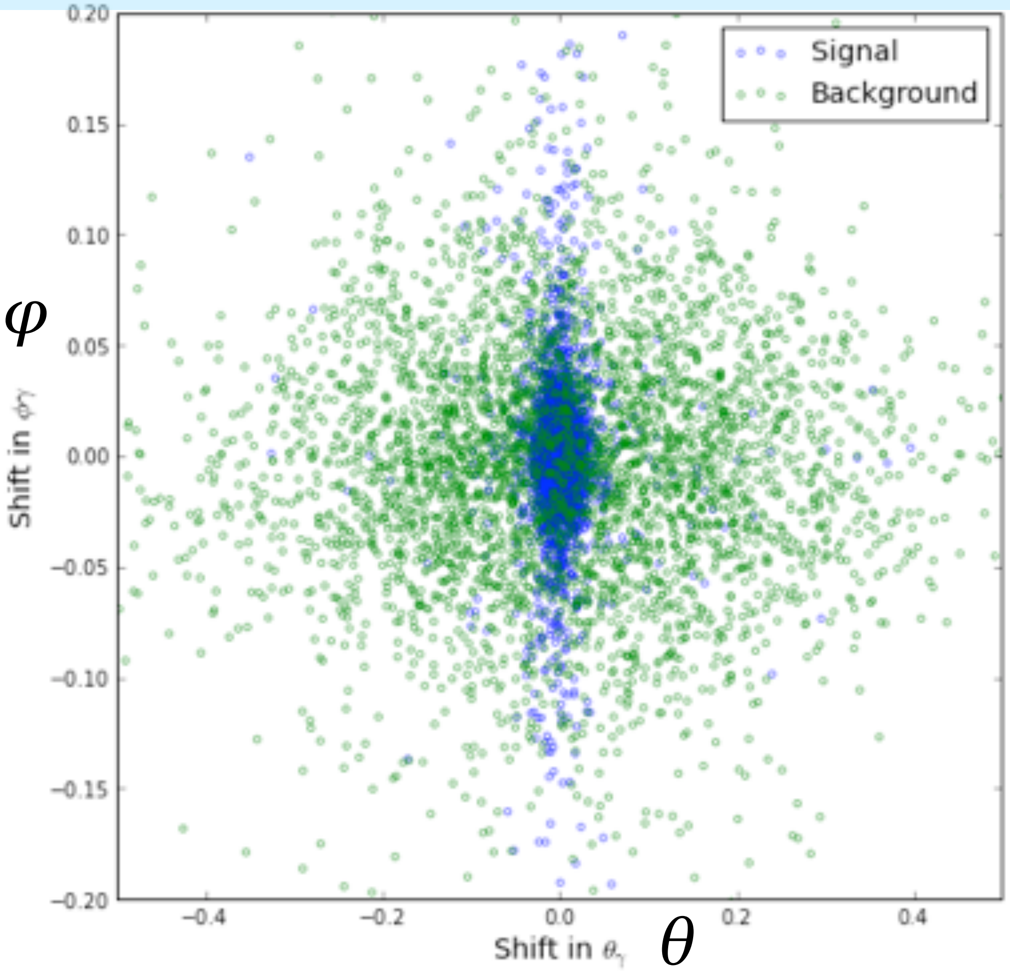
Count events in ±1.64-σ windows (90% for a Gaussian distribution) in E_e, E_γ, $\theta_{e\gamma}$, $\varphi_{e\gamma}$, and Δt. Found 20±3 background events. => one order of magnitude to go.

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

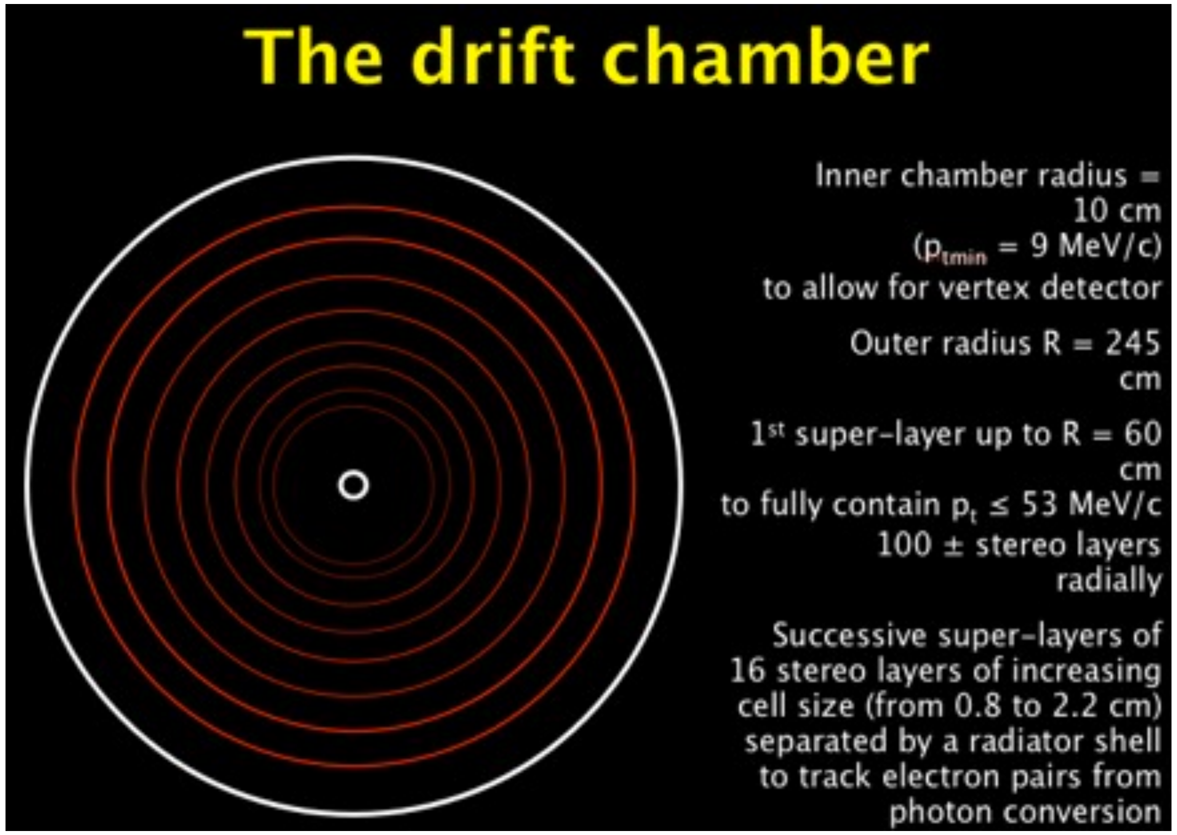


In ±30 mrad box,
85% signal, 5% background are selected

Another approach: large drift chamber

Franco Grancagnolo
presentation at CSS2013 Snowmass

- Consider a large volume solenoid, such as KLOE, run at 0.6 T.
- Fill it with a low mass drift chamber, subdivided in concentric stereo super-layers separated by thin shells of W photon converter.



The drift chamber

Inner chamber radius = 10 cm
(p_{tmin} = 9 MeV/c)
to allow for vertex detector

Outer radius R = 245 cm

1st super-layer up to R = 60 cm
to fully contain $p_t \leq 53$ MeV/c
100 ± stereo layers radially

Successive super-layers of 16 stereo layers of increasing cell size (from 0.8 to 2.2 cm) separated by a radiator shell to track electron pairs from photon conversion

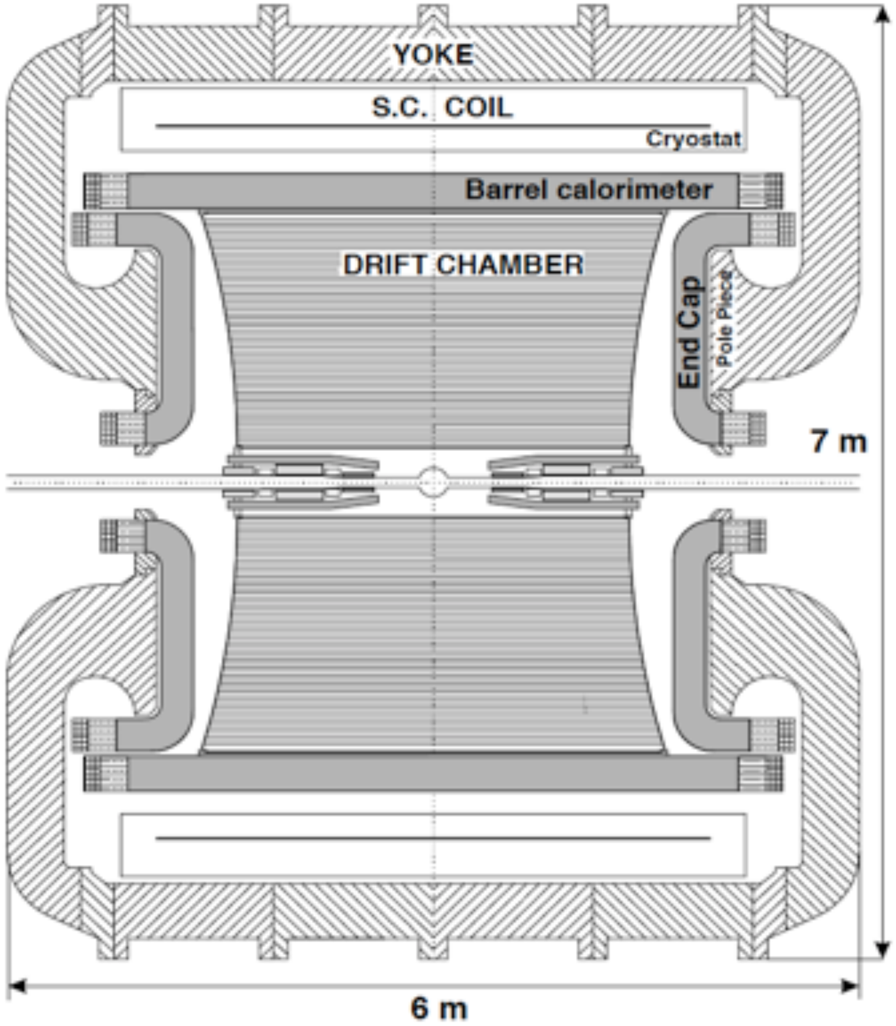
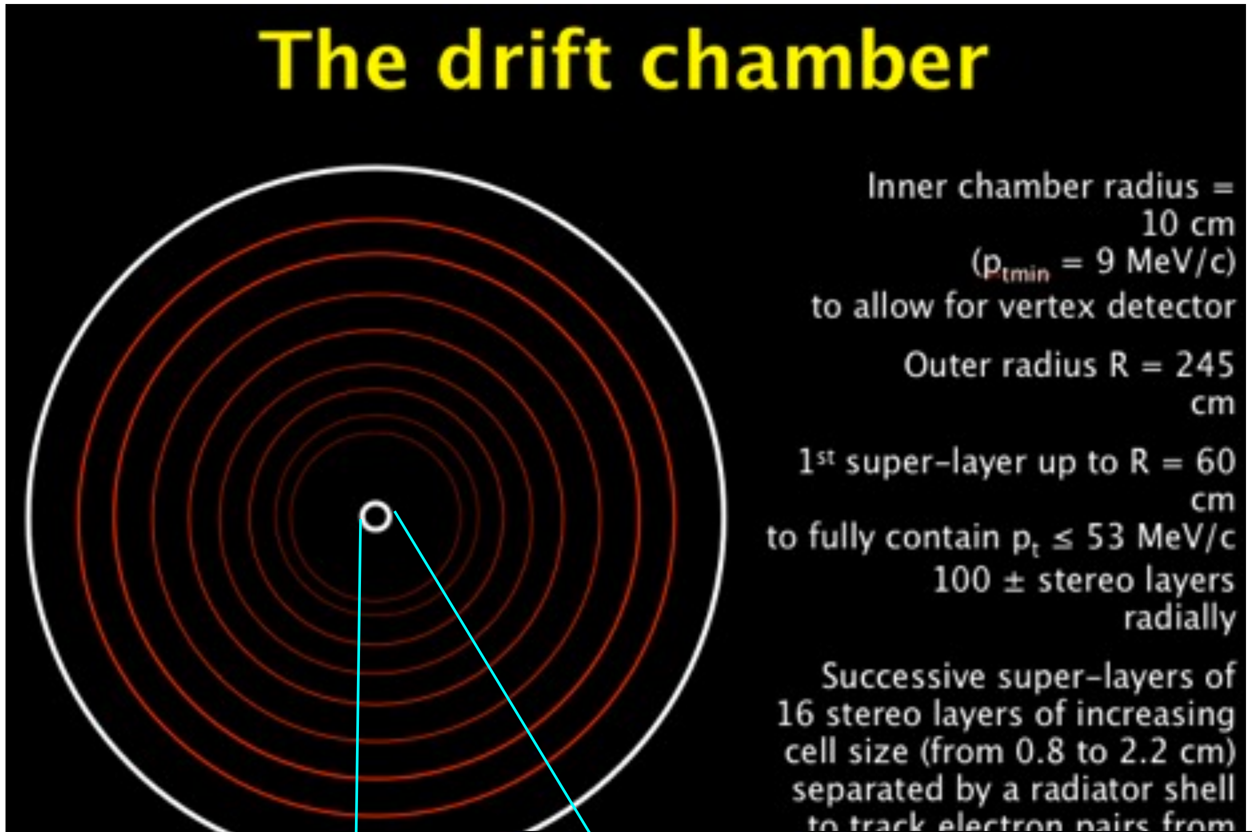


Fig. 1. Vertical cross-section of the KLOE detector along the beam line.

Large drift chamber approach



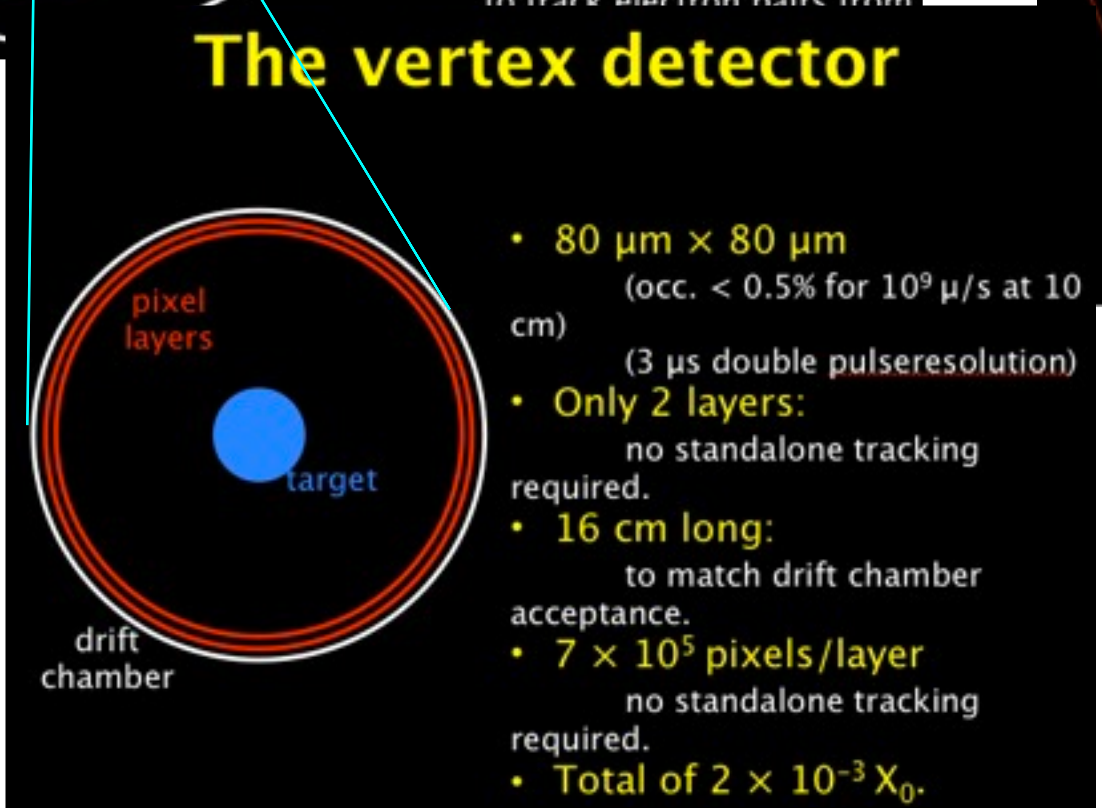
The drift chamber

Inner chamber radius = 10 cm (p_{tmin} = 9 MeV/c) to allow for vertex detector

Outer radius R = 245 cm

1st super-layer up to R = 60 cm to fully contain $p_t \leq$ 53 MeV/c 100 ± stereo layers radially

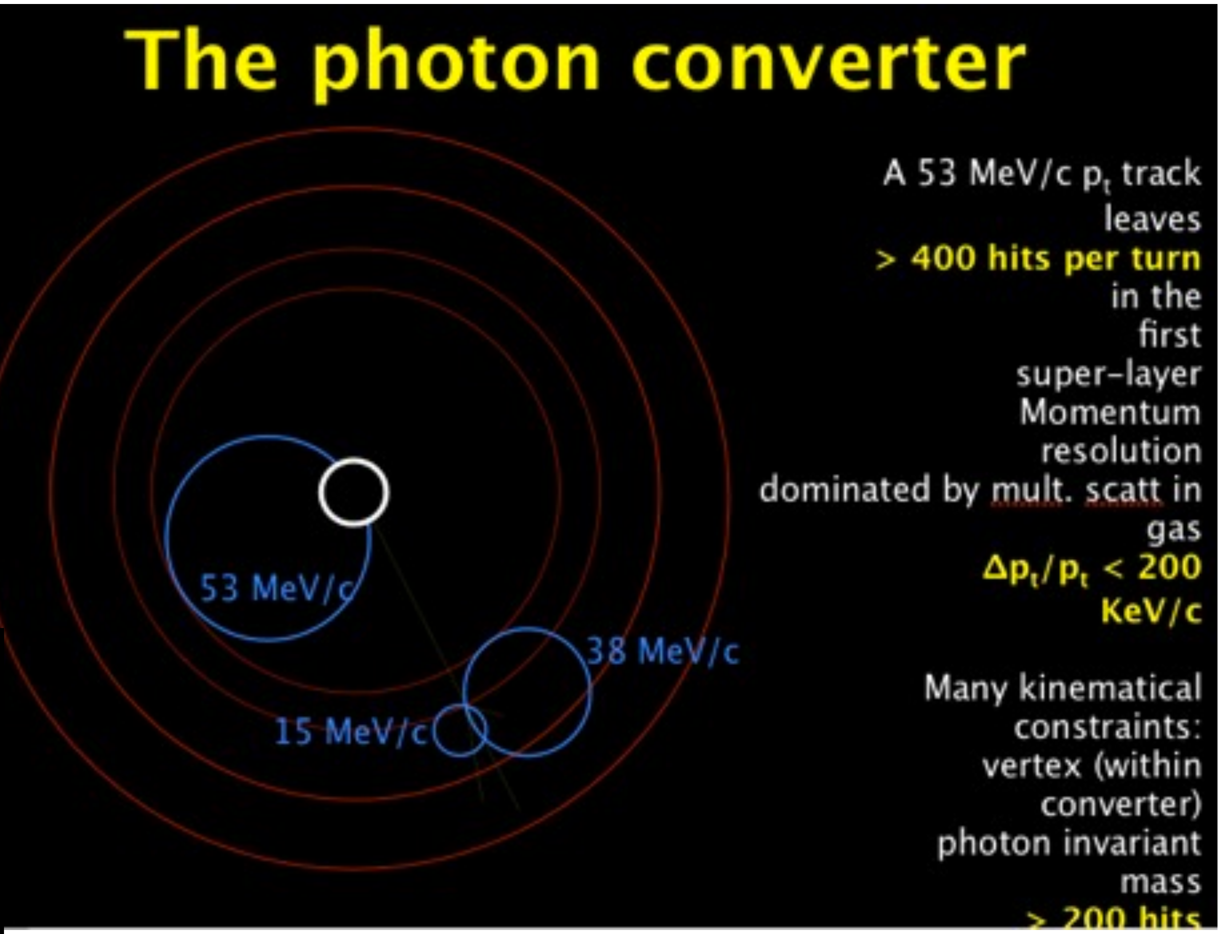
Successive super-layers of 16 stereo layers of increasing cell size (from 0.8 to 2.2 cm) separated by a radiator shell to track electron pairs from



The vertex detector

- 80 μm × 80 μm
  (occ. < 0.5% for 10^9 μ/s at 10 cm)
  (3 μs double pulseresolution)
- Only 2 layers:
  no standalone tracking required.
- 16 cm long:
  to match drift chamber acceptance.
- 7 × 10^5 pixels/layer
  no standalone tracking required.
- Total of 2 × 10^{-3} X_0.

Franco Grancagnolo
presentation at CSS2013 Snowmass



The photon converter

A 53 MeV/c p_t track leaves **> 400 hits per turn** in the first super-layer
Momentum resolution dominated by mult. scatt in gas
$\Delta p_t/p_t$ < 200 KeV/c

Many kinematical constraints: vertex (within converter) photon invariant mass
> 200 hits

- Much higher photon conversion efficiency ~90% (many converters).
- Great p_e and angular resolutions.
- Could reach <10^{-15} limit.

Summary

- Reconstructing e^+e^- tracks from converted photons can significantly improve photon energy resolution, and can provide photon direction independently; both improve $\mu \to e\gamma$ search sensitivity significantly. FastSim study demonstrates the principle.
- Toy study shows that an order of magnitude improvement from MEG upgrade sensitivity is possible (as long as the muon stopping rate is achievable, and target/detector can tolerate it).
- Further improvement:
  - ✦ Loss of efficiency due to photon conversion probability could be partially recovered by adding more layers of converters.
  - ✦ Target optimization; active (silicon) target.
  - ✦ Detector layout optimization.
  - ✦ Optimize for both $\mu \to e\gamma$ and $\mu \to eee$ simultaneously fro Project-X.