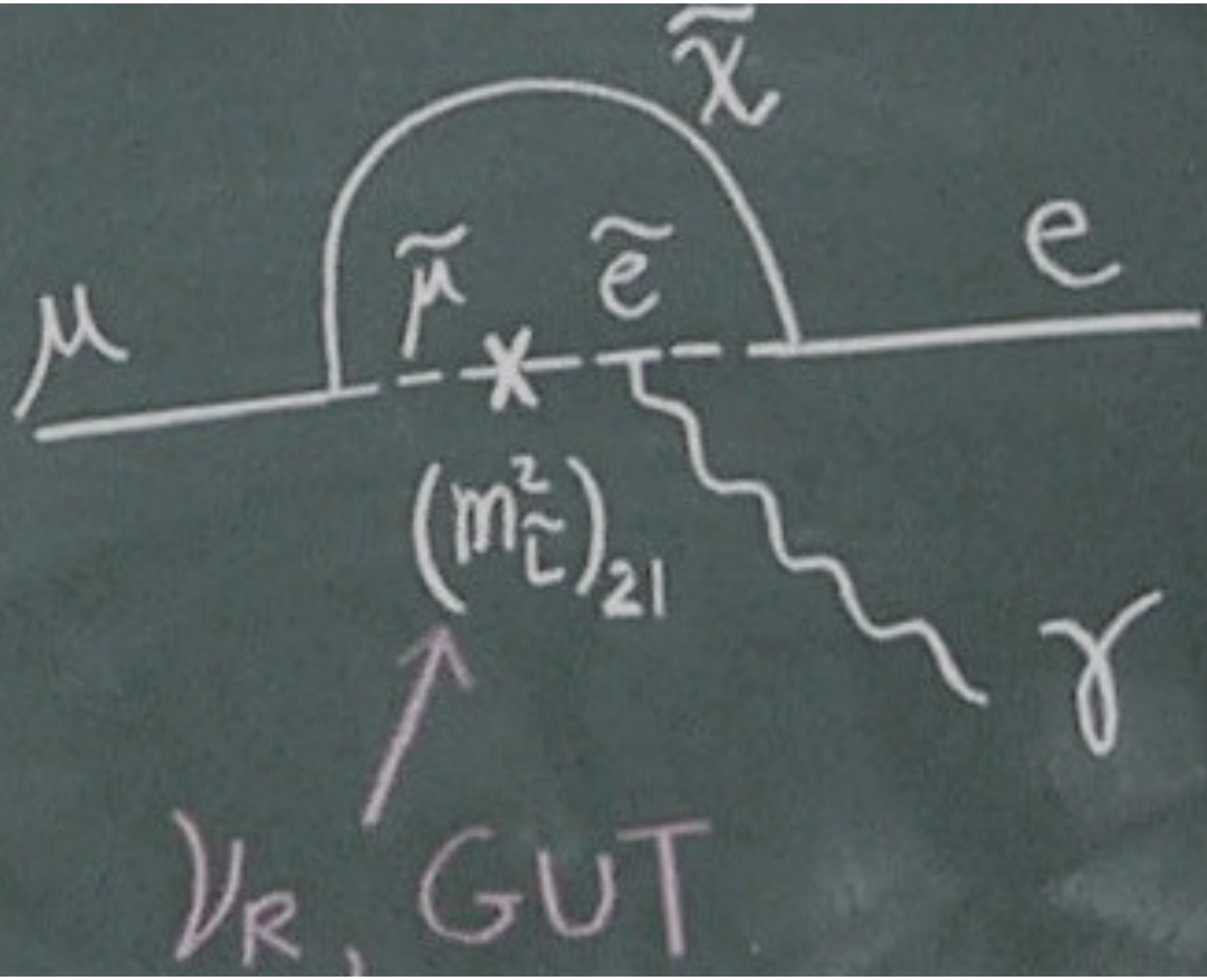
MEG Experiment
- New Result & Prospects -

Hajime NISHIGUCHI, *KEK*
on behalf of MEG Collaboration

NuFact10, 20-25 Oct. 2010, Tata Fundamental Research Institute, Mumbai

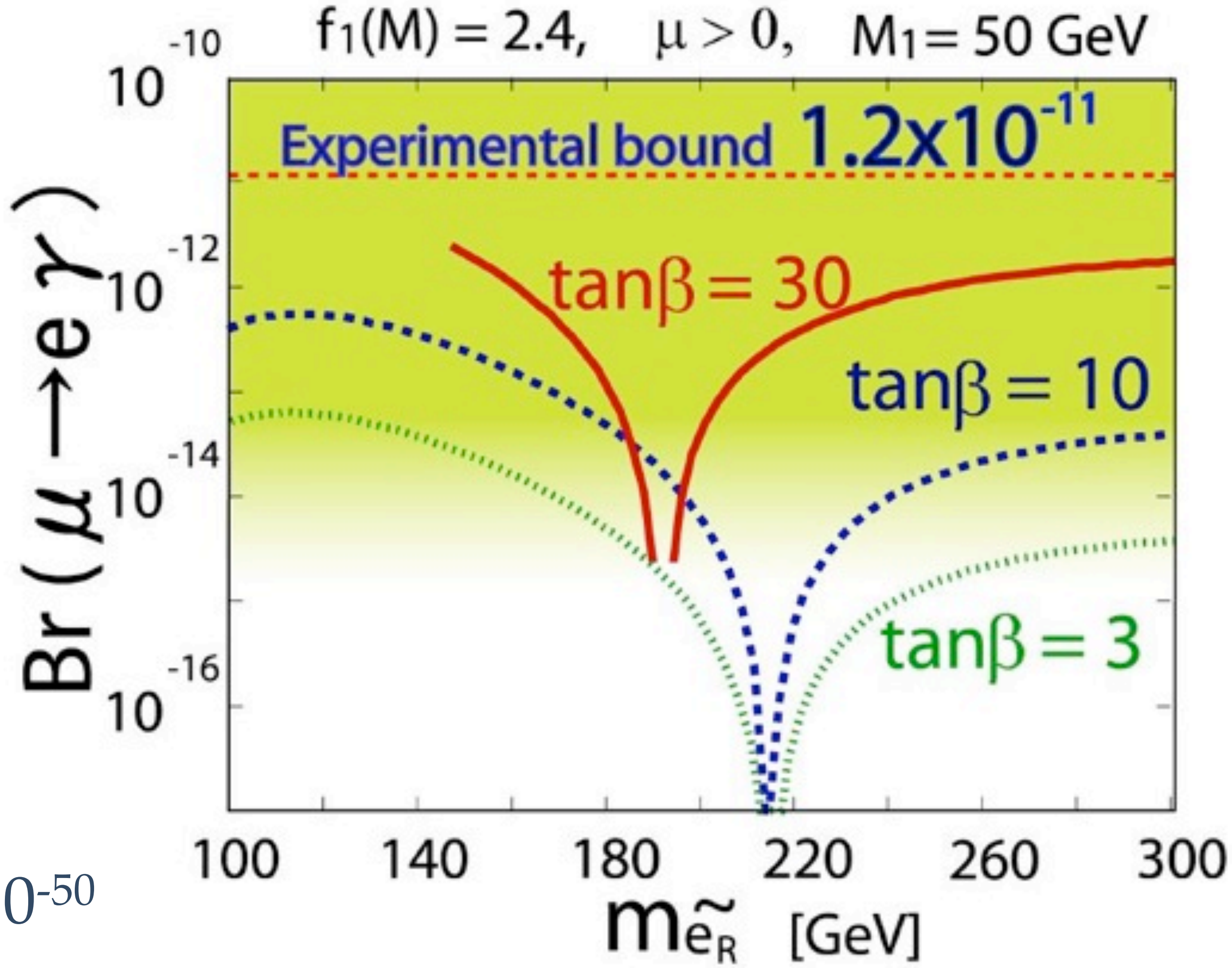


CONTENTS

Introduction - Lepton Flavour Violating Muon Decay -

Lepton Flavour Violating "$\mu \to e\gamma$"

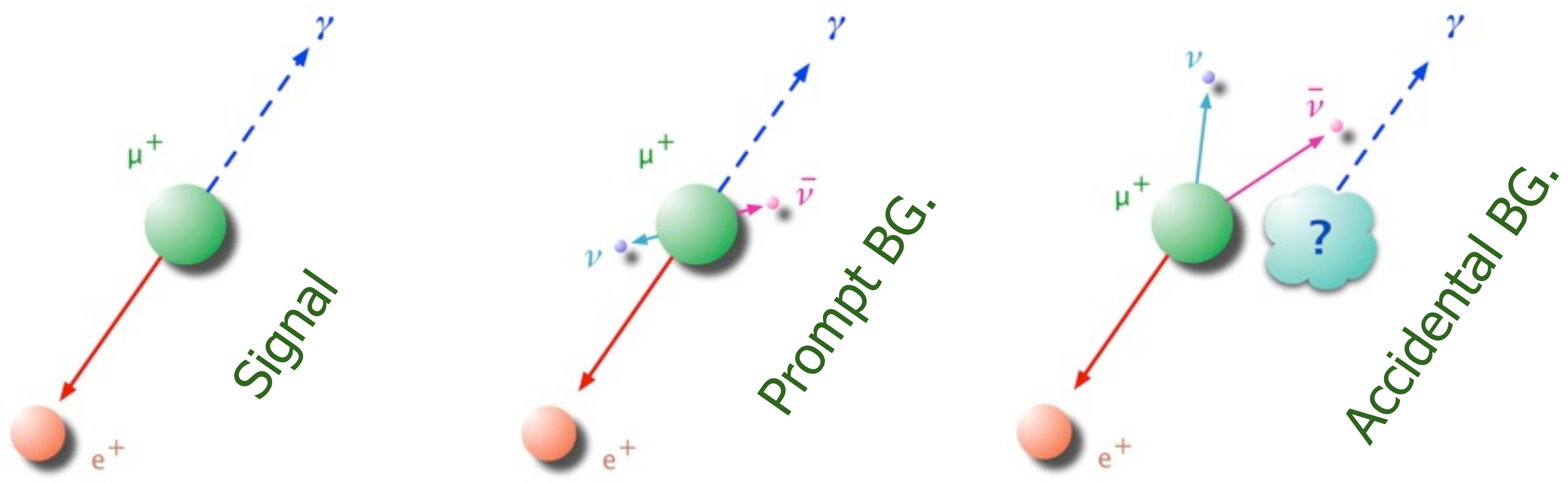
- **Lepton Flavour Violating muon decay --- "$\mu \to e\gamma$" ---**
  - $\mu \to e\nu\nu \sim 100\%$ (normal muon decay in SM, **Michel decay**)
  - $\mu \to e\gamma$ violates Lepton Flavour Conservation
  - Even if we assume "SM" + "Neutrino-Oscillation", $\mathcal{B}(\mu \to e\gamma)$ is calculated to be $< 10^{-50}$
  - Many models of beyond SM, however, predicts large, achievable $\mathcal{B}(\mu \to e\gamma) \sim 10^{-15 \sim -11}$



- Present experimental Upper Limit on $\mathcal{B}$ is 1.2×10^{-11}(90CL.) (MEGA experiment, 1999) *cf*. PRL. 83 (1999) 1521

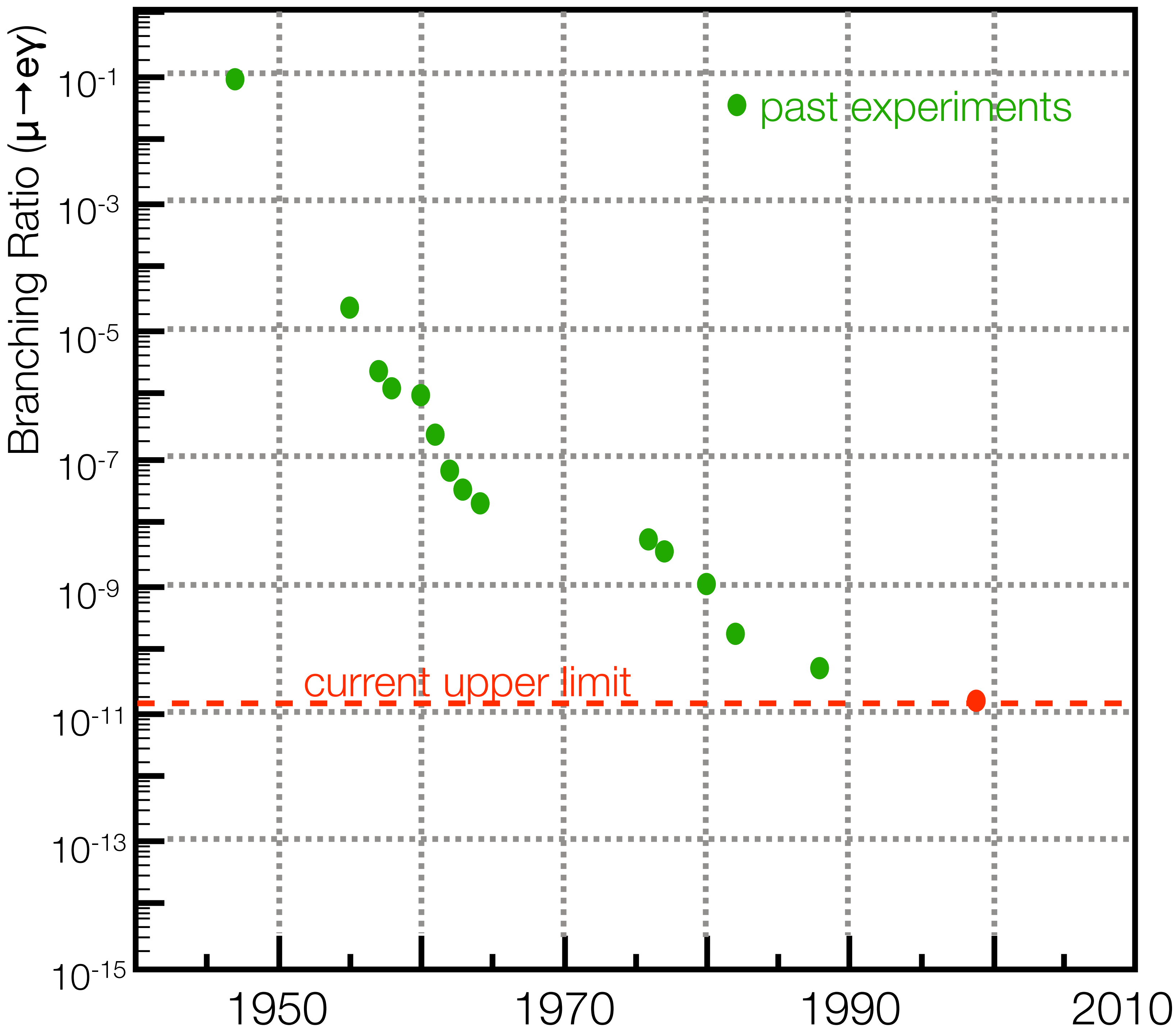
Hunting for $\mu \to e\gamma$

- Signal and Backgrounds



- Clear 2-body kinematics ($E_e = E_\gamma = 52.8$MeV, $\theta_{e\gamma} = 180°$, Time Coincidence)
- Sensitivity is Limited by "Accidental Overlap"
  - **DC muon is the Best Solution**
  - **Good Resolution (Energy, Spacial and Timing) under Very High Rate**

Long History of "$\mu \rightarrow e\gamma$" Search



- **"$\mu \rightarrow e\gamma$" Search Experiment has started right after μ discovery**
  - **Very Long Tradition**
- Now we are approaching the predicted region

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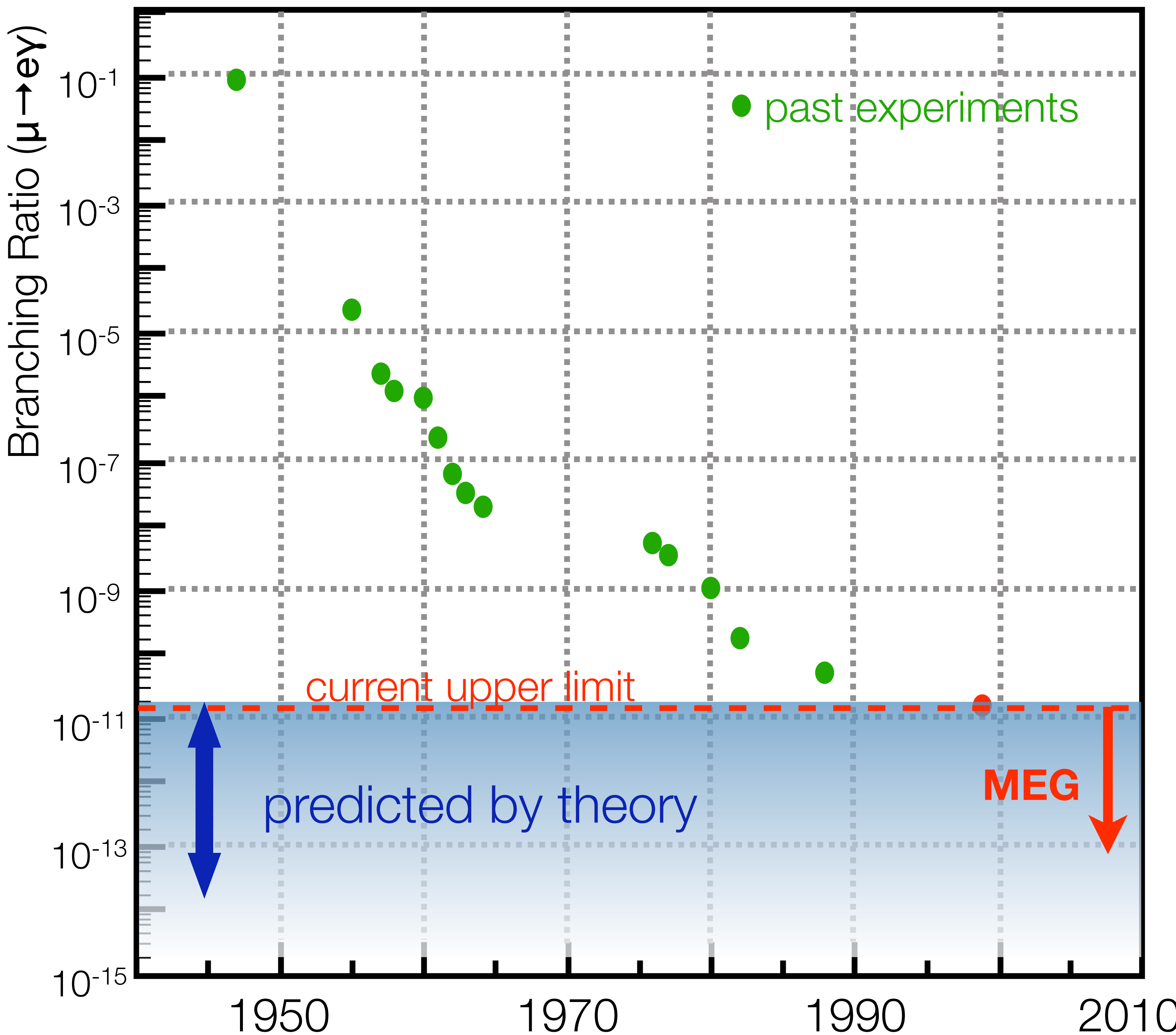

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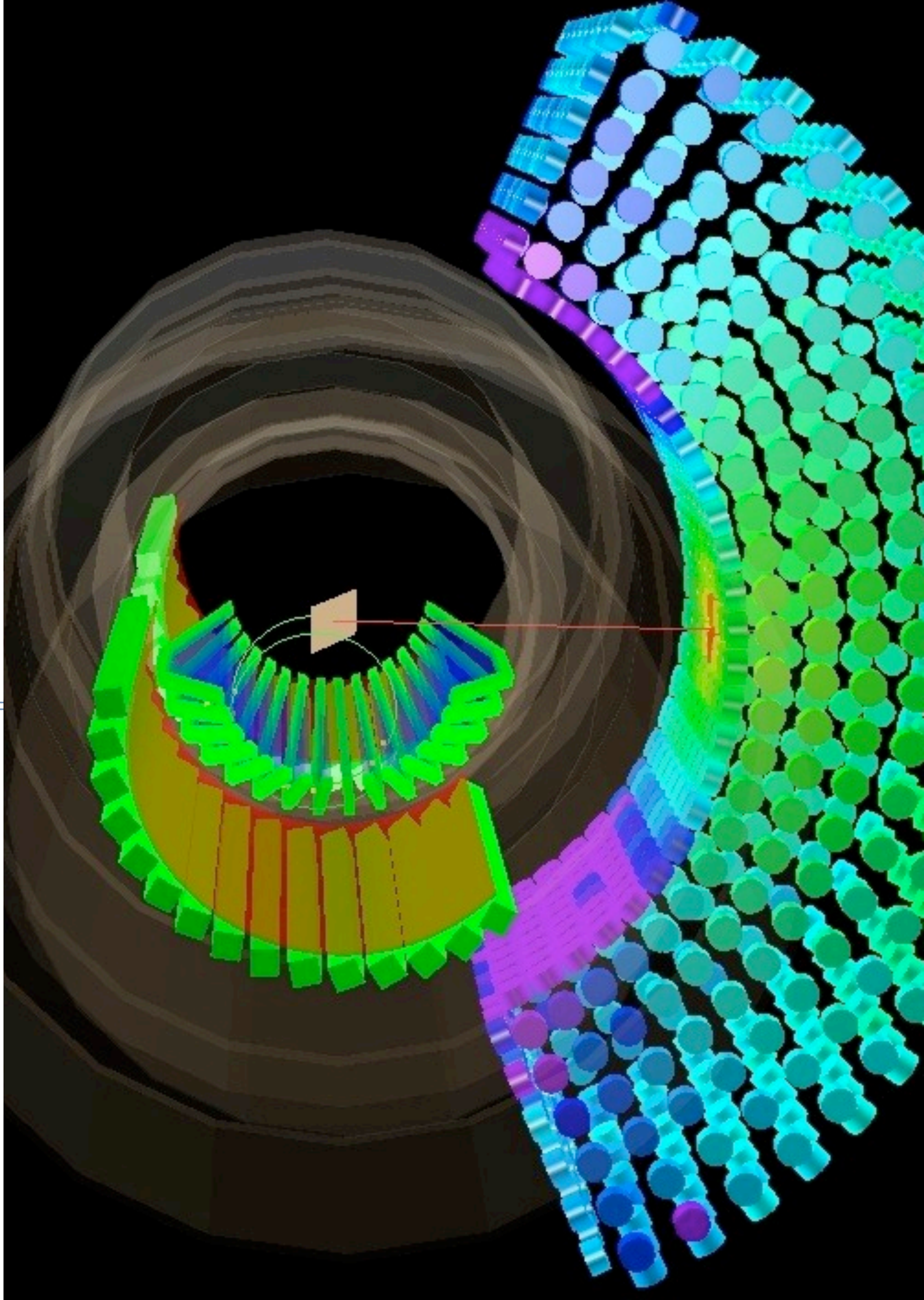
MEG Started !

(physics run from 2008)

MEG Experiment



Three Features of MEG

- Sensitivity is Limited by "Accidental Overlap"
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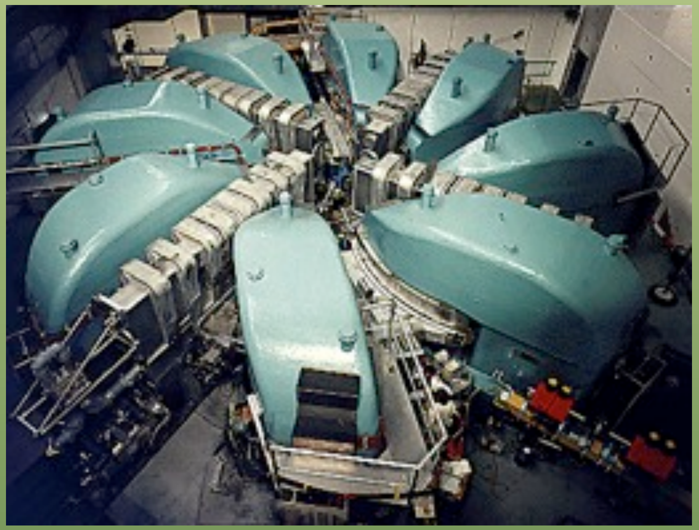

World Most Intense
DC Muon Beam at PSI
10^8 muon/sec

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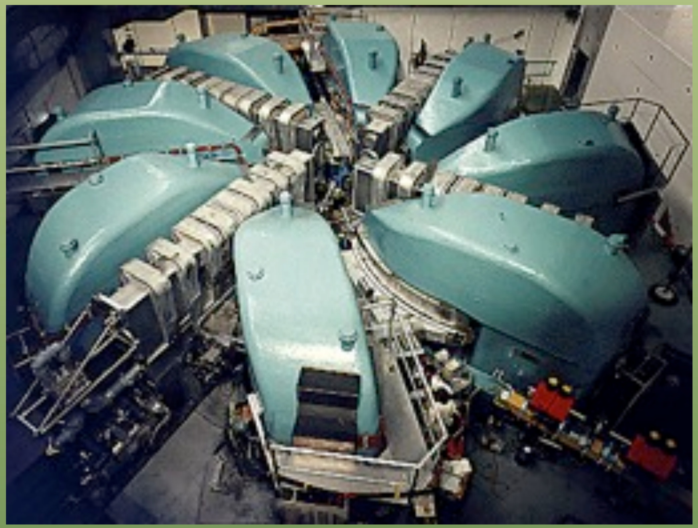

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Liquid Xenon
Scintillation Detector
(gamma)

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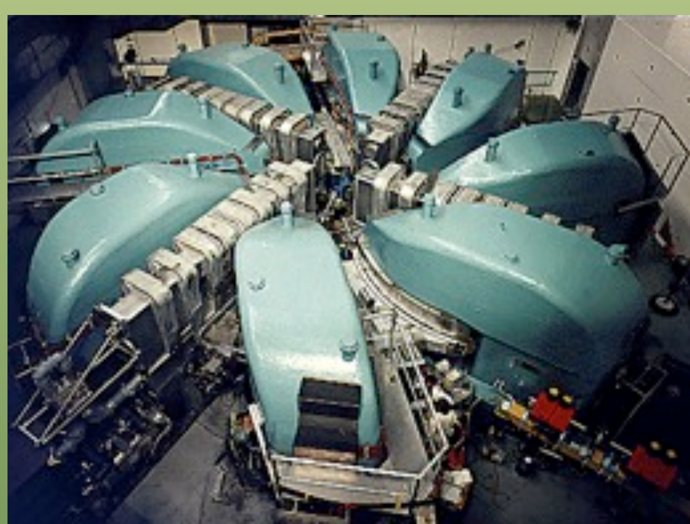

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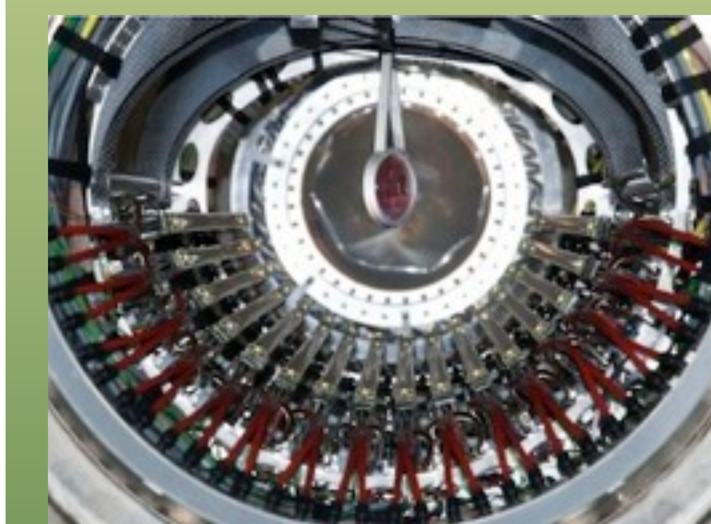
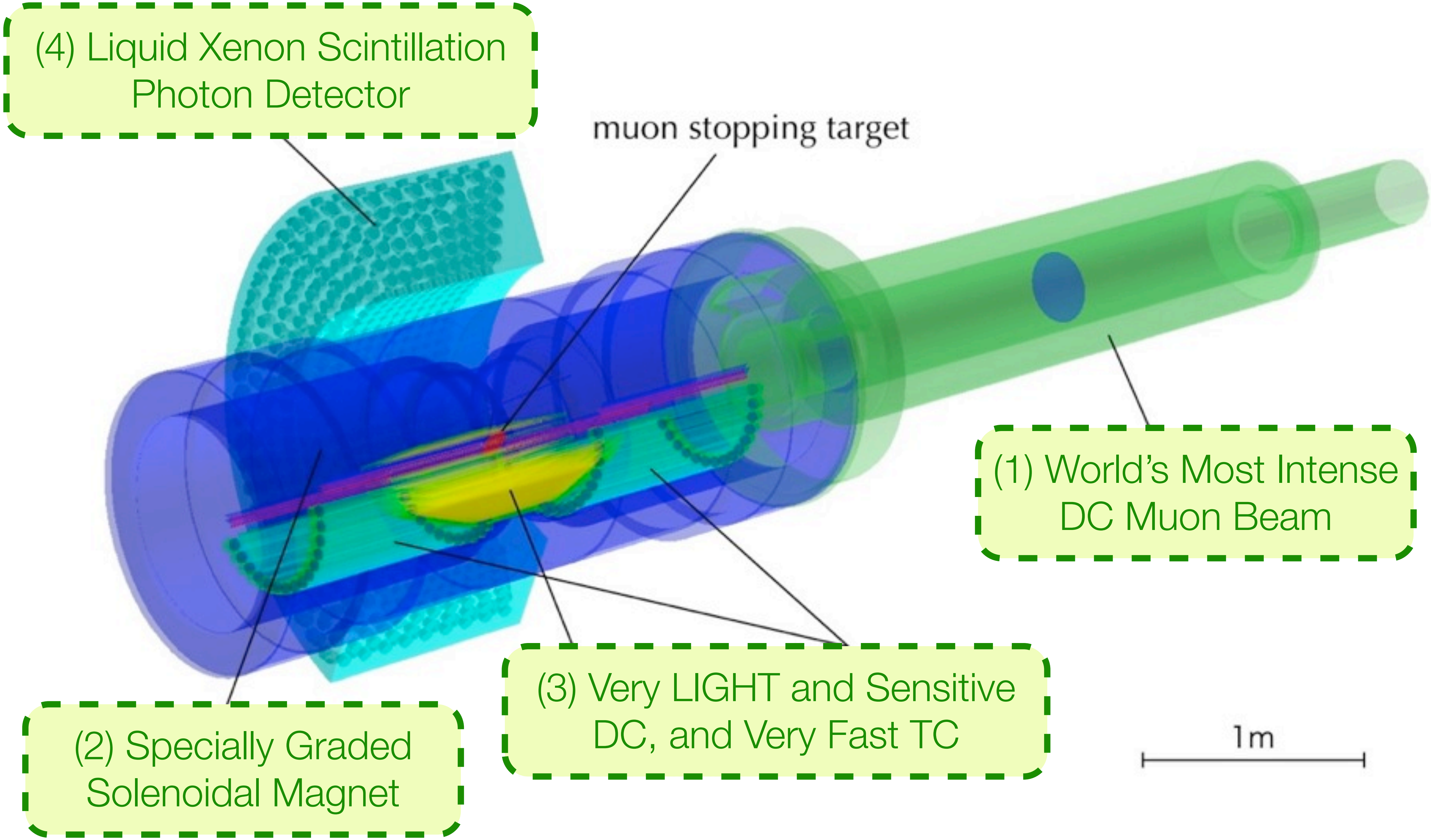


COBRA Spectrometer
(positron)

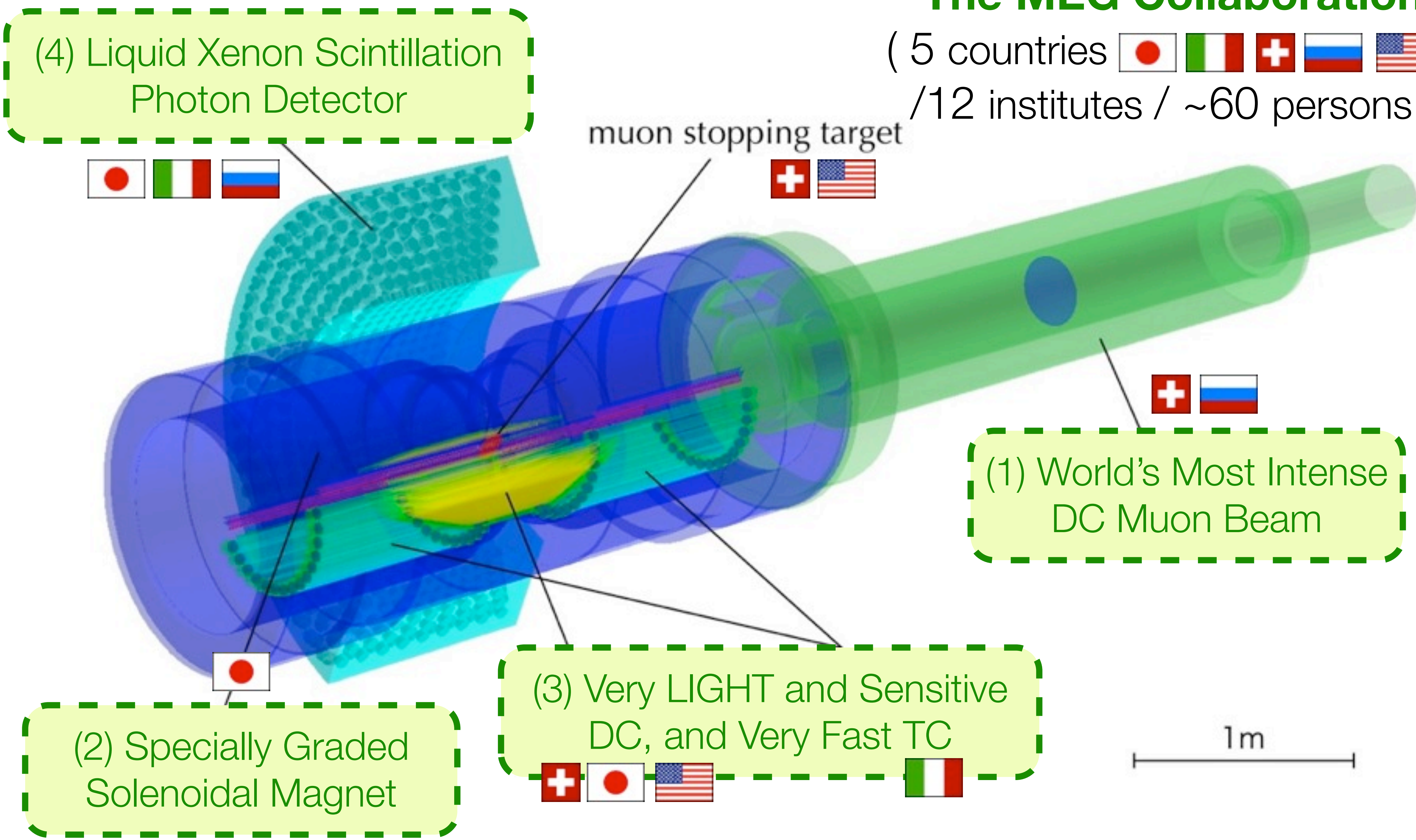
MEG Detector Apparatus



MEG Detector Apparatus

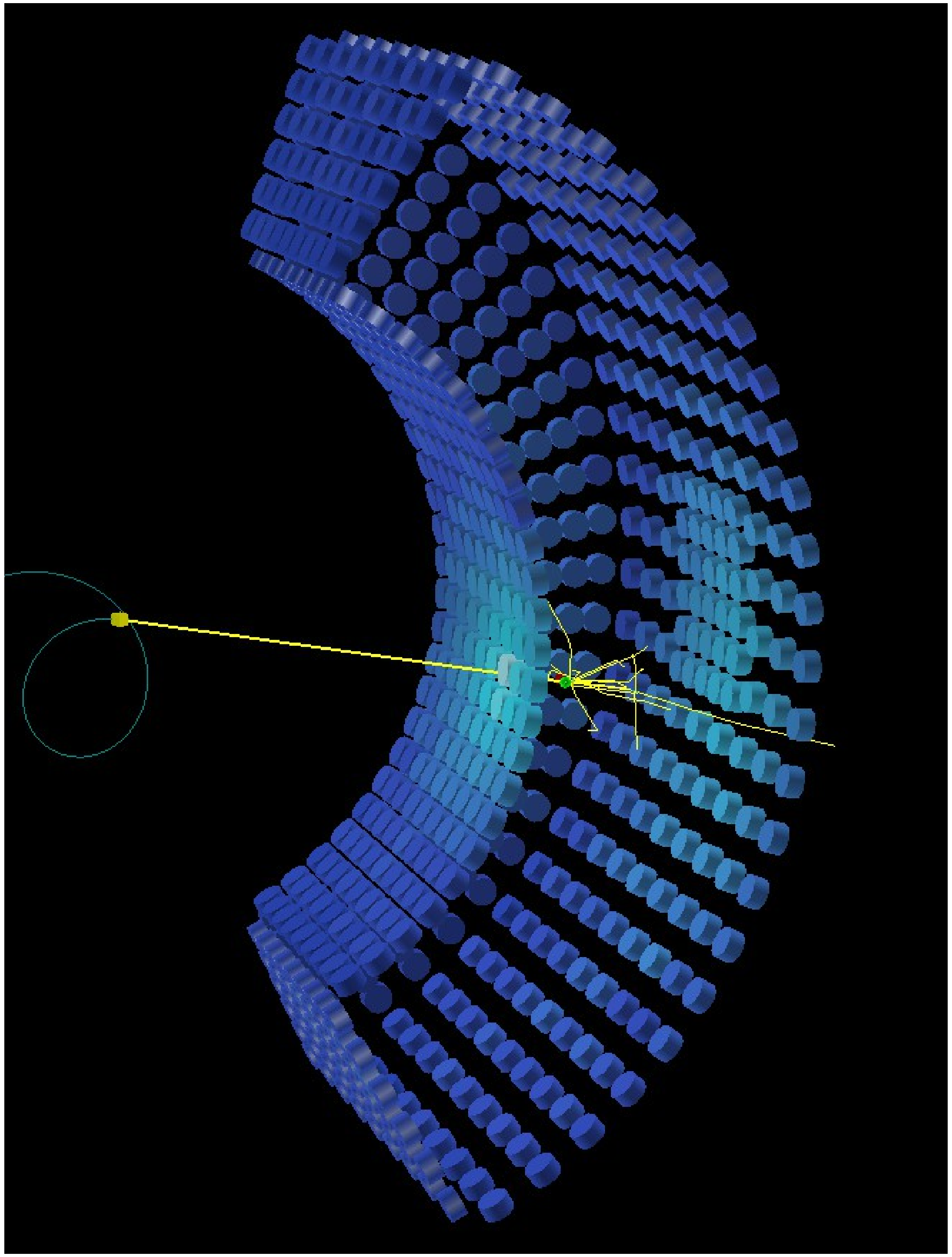
The MEG Collaboration

(5 countries , /12 institutes / ~60 persons)

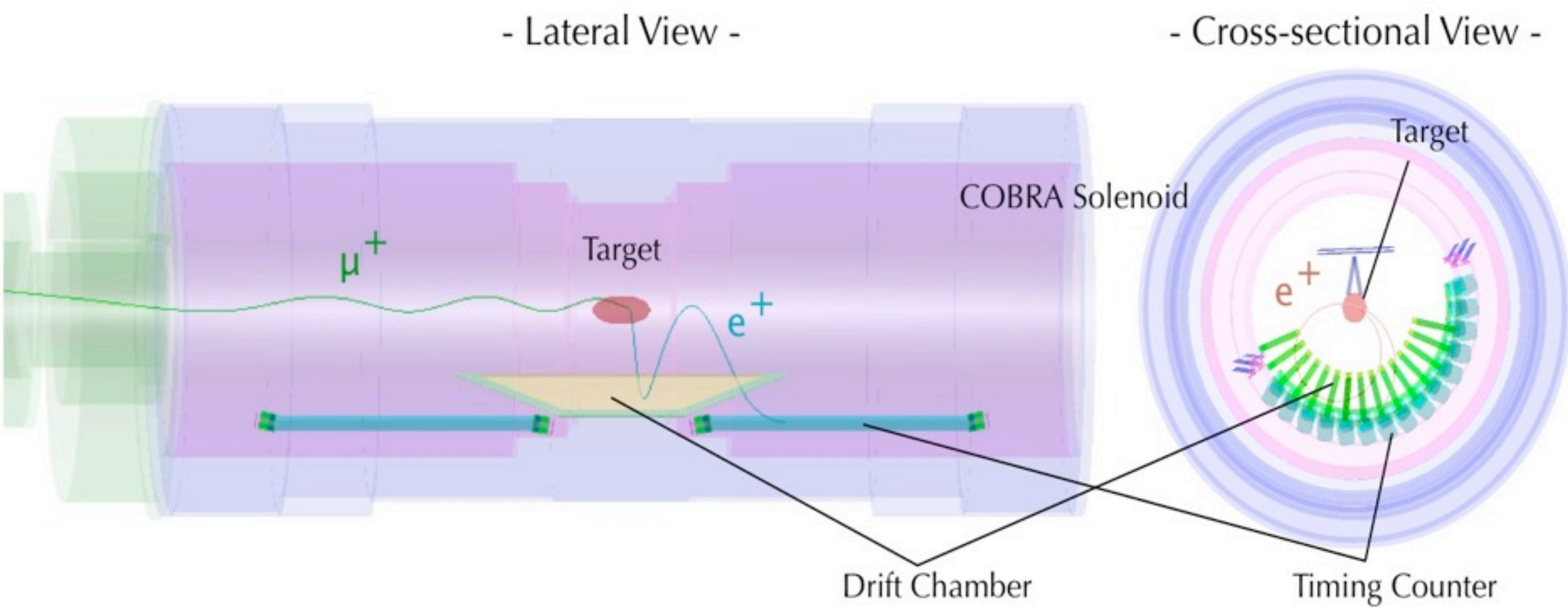


Liquid Xenon Scintillation Detector

- Homogeneous Volume (~800*l*) is surrounded by PMTs on all faces
- 846 PMTs submerged in the liquid
- Energy Measurement
  - All PMT outputs
  - σ_E/E ~ 2% (@52.8MeV)
- Position Measurement
  - PMTs on the inner face
  - σ_x = 5-6 mm (@52.8MeV)
- Timing Measurement
  - Averaging of signal arrival time of selected PMTs
  - σ_t ~ 70 ps (@52.8MeV)



COBRA Positron Spectrometer



Solenoid

superconducting solenoid
gradient B-field (0.5-1.7 T)
very thin conductor and
cryostat wall ($0.2X_0$)

Drift Chamber

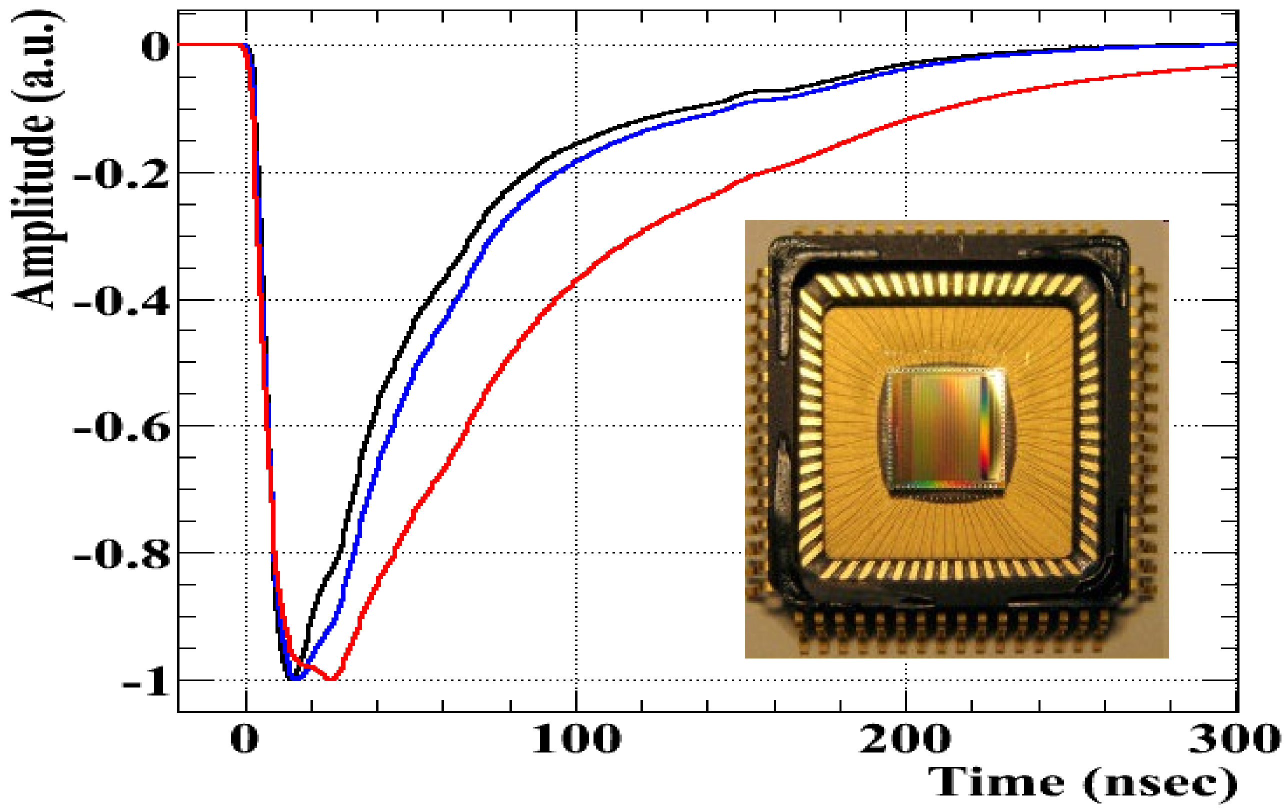
segmented radially (16 sectors)
helium:ethane (50:50)
opened-frame
very thin cathode foil with pads

Timing Counter

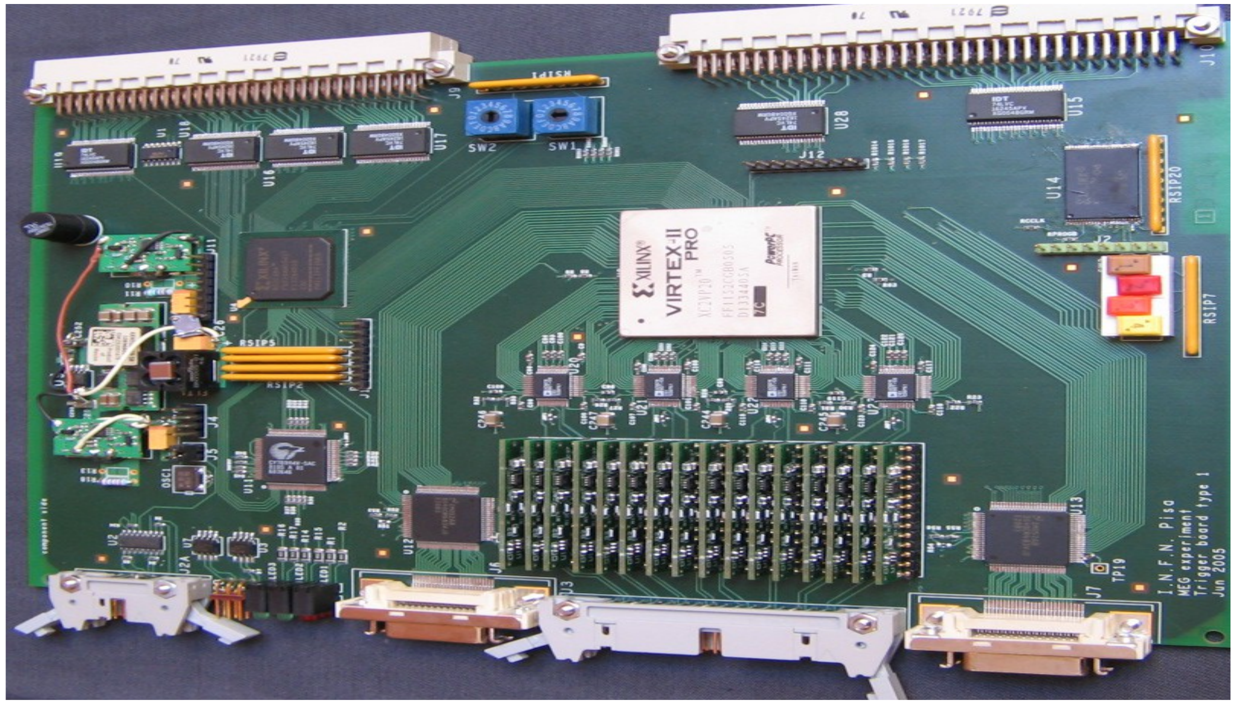
2-layers of scintillators
- scintillator bars (outer)
- scintillator fibres (inner)

Electronics & Trigger

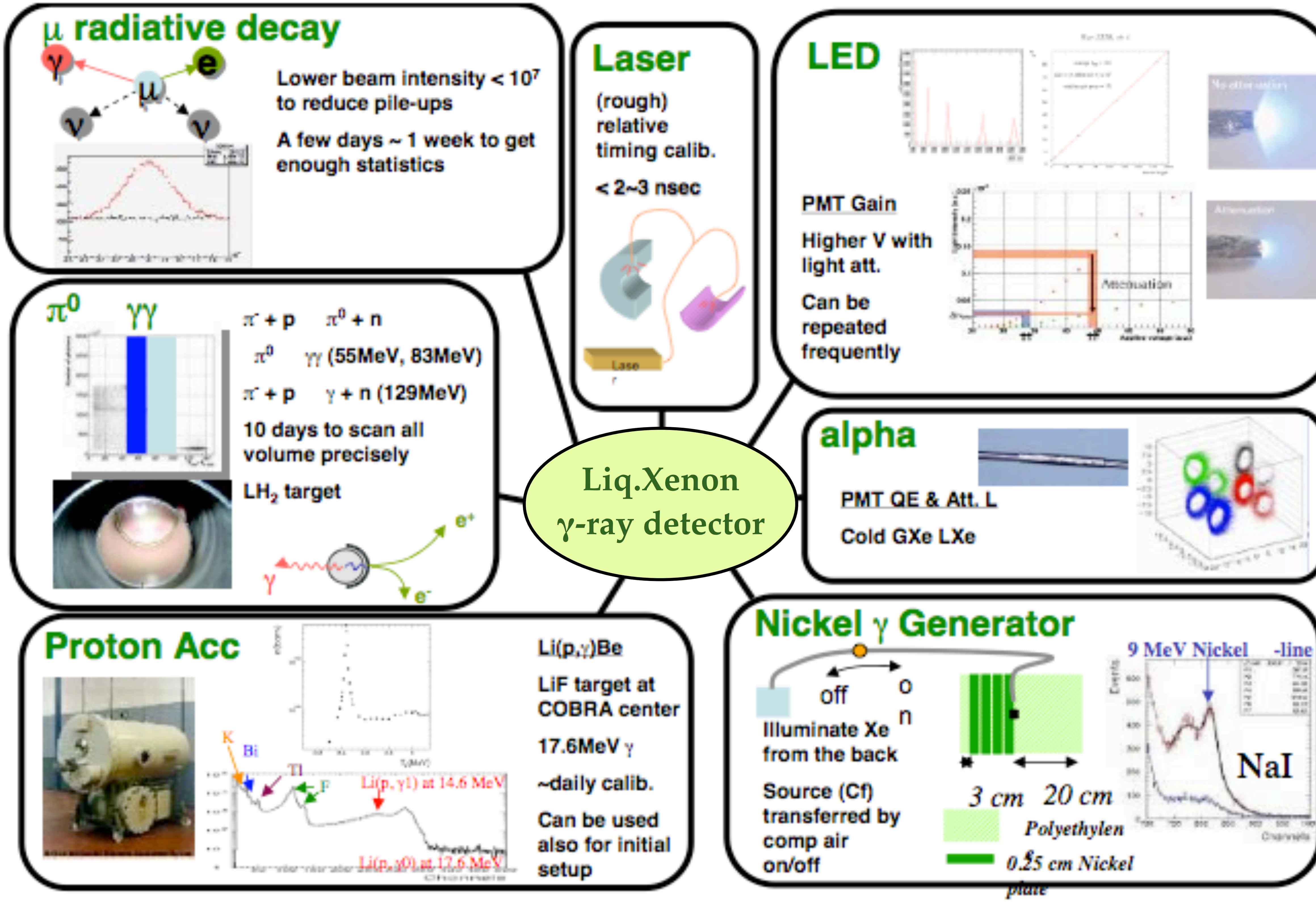
- Waveform Digitizer (DRS)
  - Up to 5GHz sampling, 12bits
  - Essential to remove pileup
  - 1.6GHz sampling for Lig.Xe/TC
  - 0.8GHz sampling for DC



- MEG Trigger
  - FADC-FPGA architecture
  - Liq.Xe charge & TC charge
  - Direction match & coincidence
  - 6Hz DAQ rate @ physics run



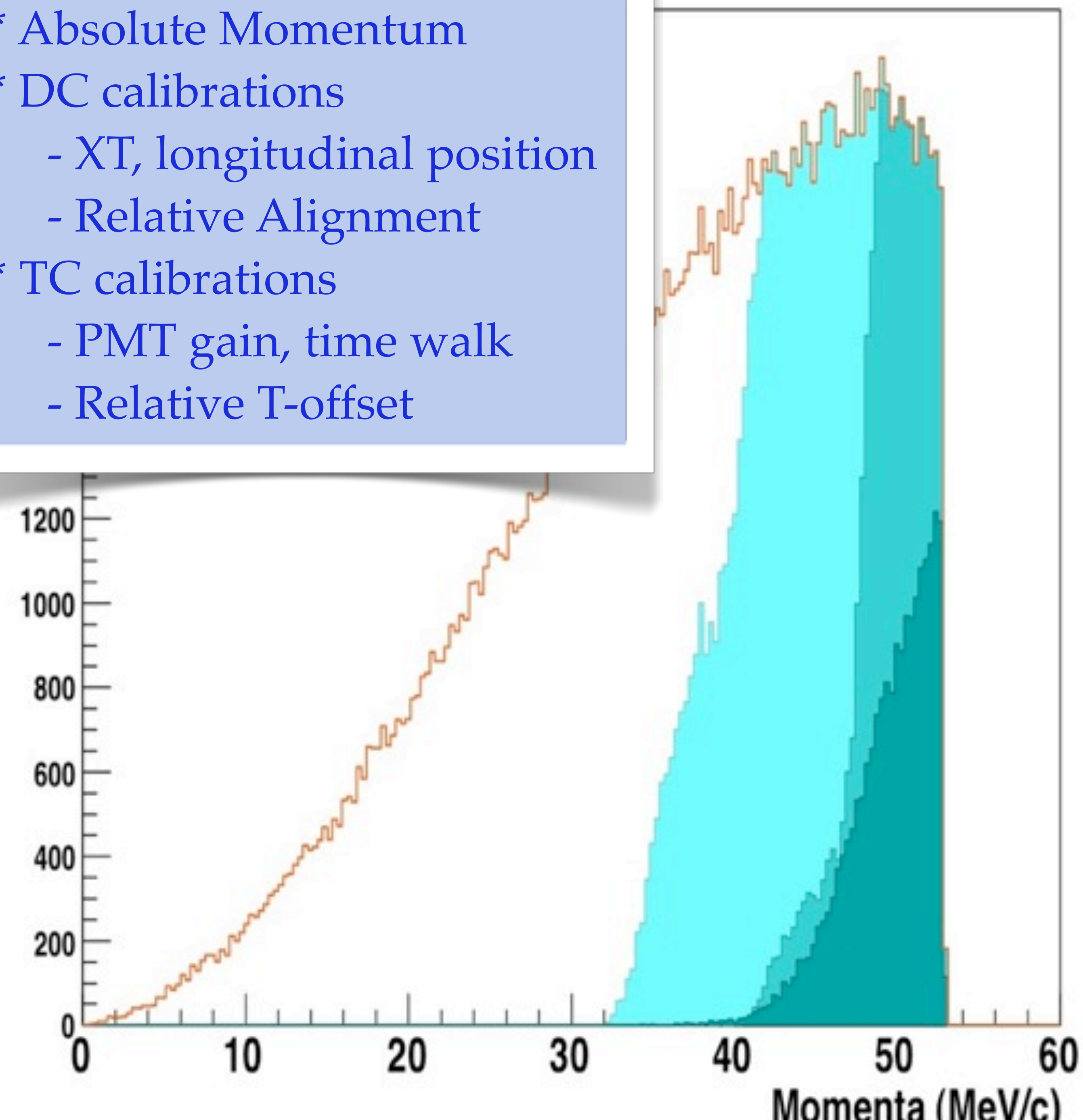
Calibrations for Liq.Xe γ-ray Detector



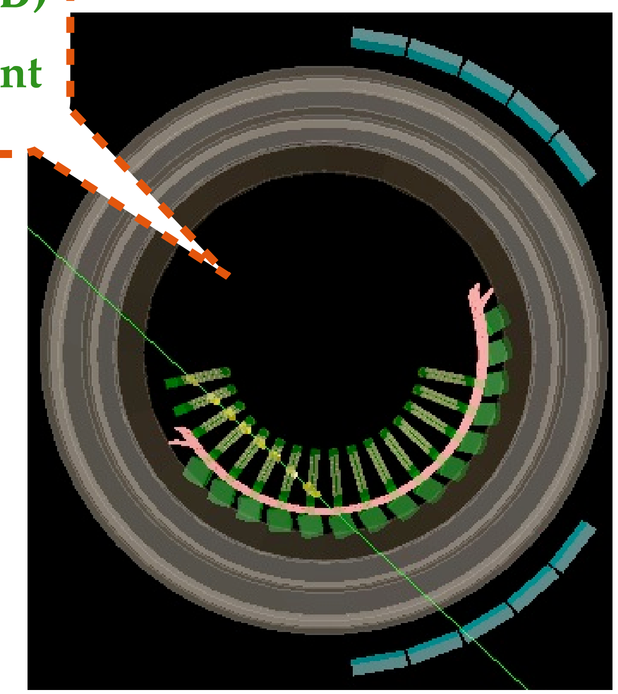
Calibrations for Positron Spectrometer

Mainly Using Michel e^+

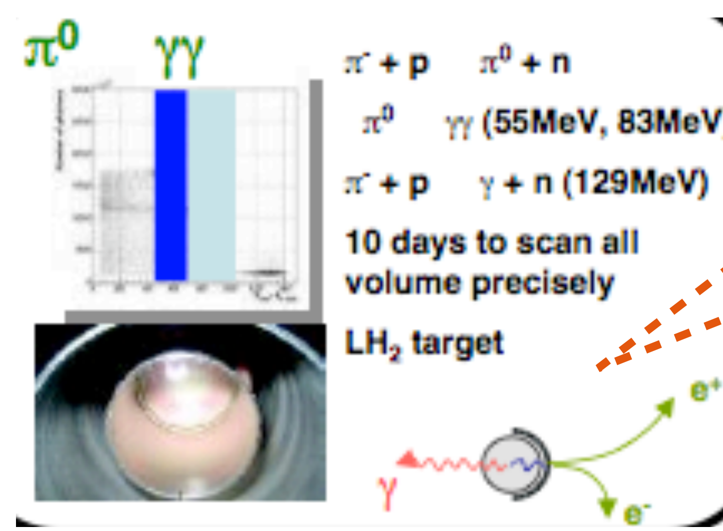
* Absolute Momentum
* DC calibrations
  - XT, longitudinal position
  - Relative Alignment
* TC calibrations
  - PMT gain, time walk
  - Relative T-offset



Cosmic Ray (w/o B)
DC relative alignment



auxiliary calibration sources



"$\pi^0 \to e^+e^-\gamma$"
(Absolute Time offset e^+ and γ)

MEG History

1999	**Proposal submitted to the PSI committee, approved**
1999 - 2007	**Detector R&D and Construction**
2007 Sep.	**Detector Construction completed**
2007 Nov. - Dec.	**Beam Commissioning and Engineering Run**
2008 Sep. - Dec.	**1st Physics Data Acquisition**
2009 Jan. - Sep.	**Hardware Maintenances and Upgrades**
	Analysis of Run-2008 Data
Nov. - Dec.	**2nd Physics Data Acquisition**
	Analysis of Run-2009 Data
2010 Jan. - Jul	**Maintenances**
Aug. -	**3rd Physics Data Acquisition (planned to continue till December)**

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Published in
NP B834 (2010) 1
Sensitivity : 1.3×10^{-11}
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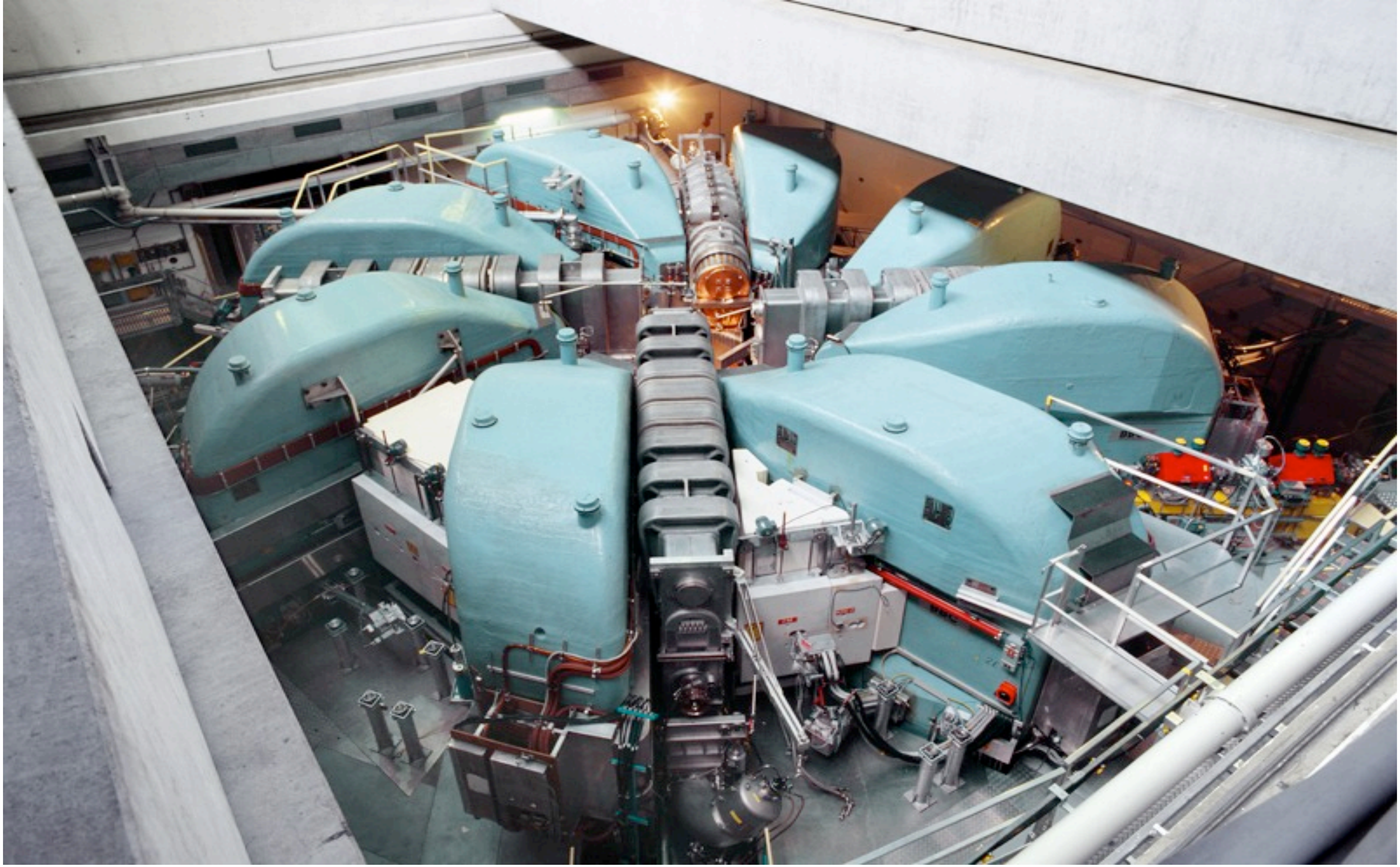
Coming Soon



MEG 2009

Updates before the Physics Run

- **Run-2008**
  - Low Efficiency (70% loss of expected) due to HV discharge on DC.
    - Bad tracking resolution was also resulted.
  - Low Light Yield (45% less than expected) on Liq.Xe photon detector due to impurity of xenon.
  - Lack of Scintillation fibre on Timing Counter
- **Run-2009**
  - Most of Problems were solved before Run-2009 in the shutdown period
  - Problem with the DCs was identified and solved, all DCs were modified and have since been successfully in operation throughout the 2009 run.
  - Xenon was purified during liquefaction and recovered full performance
  - Front-end electronics read-out boards were also upgraded with a new version of the digitizing chip (DRS4)

Timeline and Operation

Jan.	Detector Maintenances (Beam line was used by another experiment group)
Feb.	
Mar.	
Apr.	
May	
Jun.	
Jul.	Installation & Conditioning
Aug.	
Sep.	Electronics Upgrade
Oct.	Engineering / Calibration
Nov.	Physics Data Acquisition
Dec.	

- Stopping Rate 2.9×10^7 / sec
- 43 days physics data taking
- 22.3 M Triggers
- 93 TB data taken

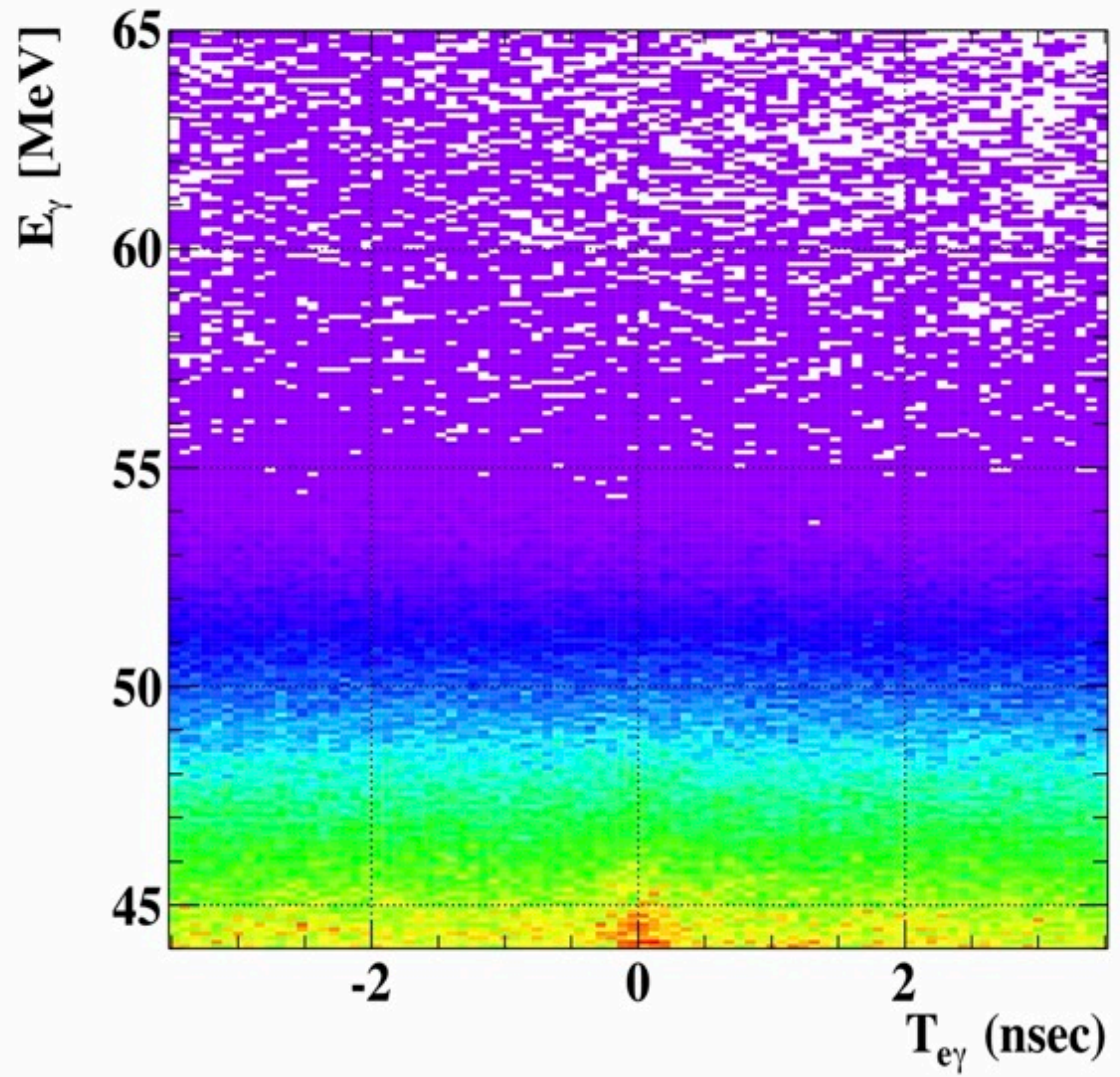
Performances in 2009

	2008	PRELIMINARY 2009
γ Energy σE_γ (%)	2.0 (depth>2cm)	2.1 (depth>2cm)
γ Timing σt_γ (ps)	80	>67
γ Position σx_γ (mm)	5/6	5/6
γ Efficiency ε_γ (%)	63	58
e^+ Mom. σp_e (%)	1.6	0.74
e^+ Timing σt_e (ps)	<125	<125
e^+ Angle $\sigma\theta_e$ (mrad)	10(ϕ)/18(θ)	7.4(ϕ)/11.2(θ)
e^+ Efficiency ε_e (%)	14	40
γ-e^+ Relative Timing	148	142
μ^+ decay vertex (mm)	3.2/4.5	2.3/2.8
Trigger Efficiency (%)	66	84
μ^+ Stopping Rate (Hz)	3×10^7	2.8×10^7
DAQ Time (days)	48	35
Sensitivity	1.3×10^{-11}	**coming soon**
BR Upper Limit	2.8×10^{-11}	**coming soon**

- Several Big Improvements
  - e+ efficiency / resolution
    - Thanks to solving discharge problem
  - Trigger efficiency
- DAQ time is shorter than 2008 due to other experiment sharing area
- Statistics-2009 : ∼2×2008
  - Compensated by efficiency improvements

Analysis Procedure

- **Blind Analysis**
  - Signal region was hidden until analysis fixed
  - Any study (calibration, BG estimation, performance evaluation) can be done with events outside the box
  - Hidden parameters $(E_{\gamma}, T_{e\gamma})$
- **Sideband Data**
  - Accidental BG can be studied with off-timing sideband data
  - Radiative decay can be studied with low energy sideband data
- **Normalization**
  - Unbiased Michel data mixed in physics data
- **Wide Analysis Region**
  - for likelihood fitting



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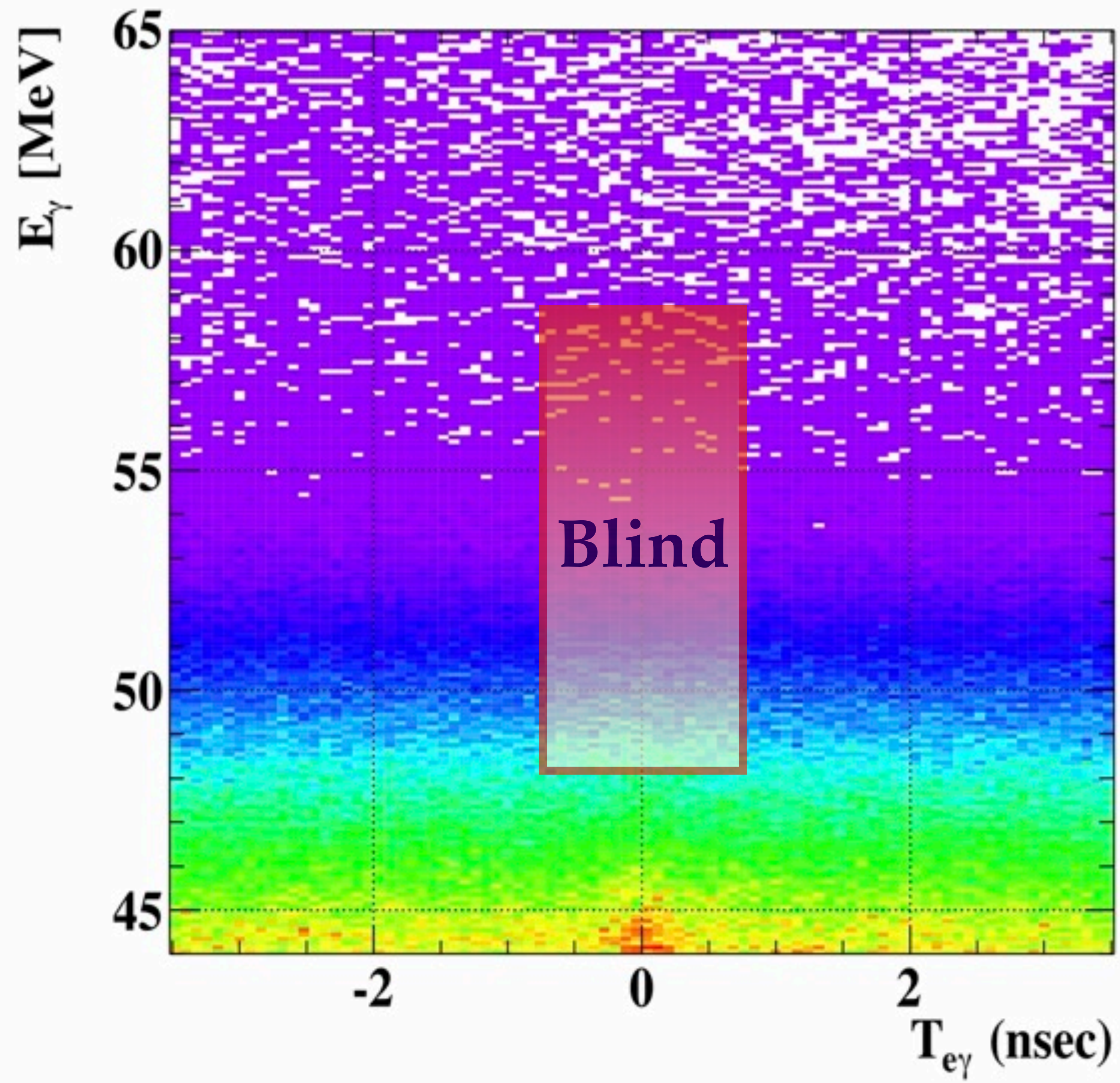

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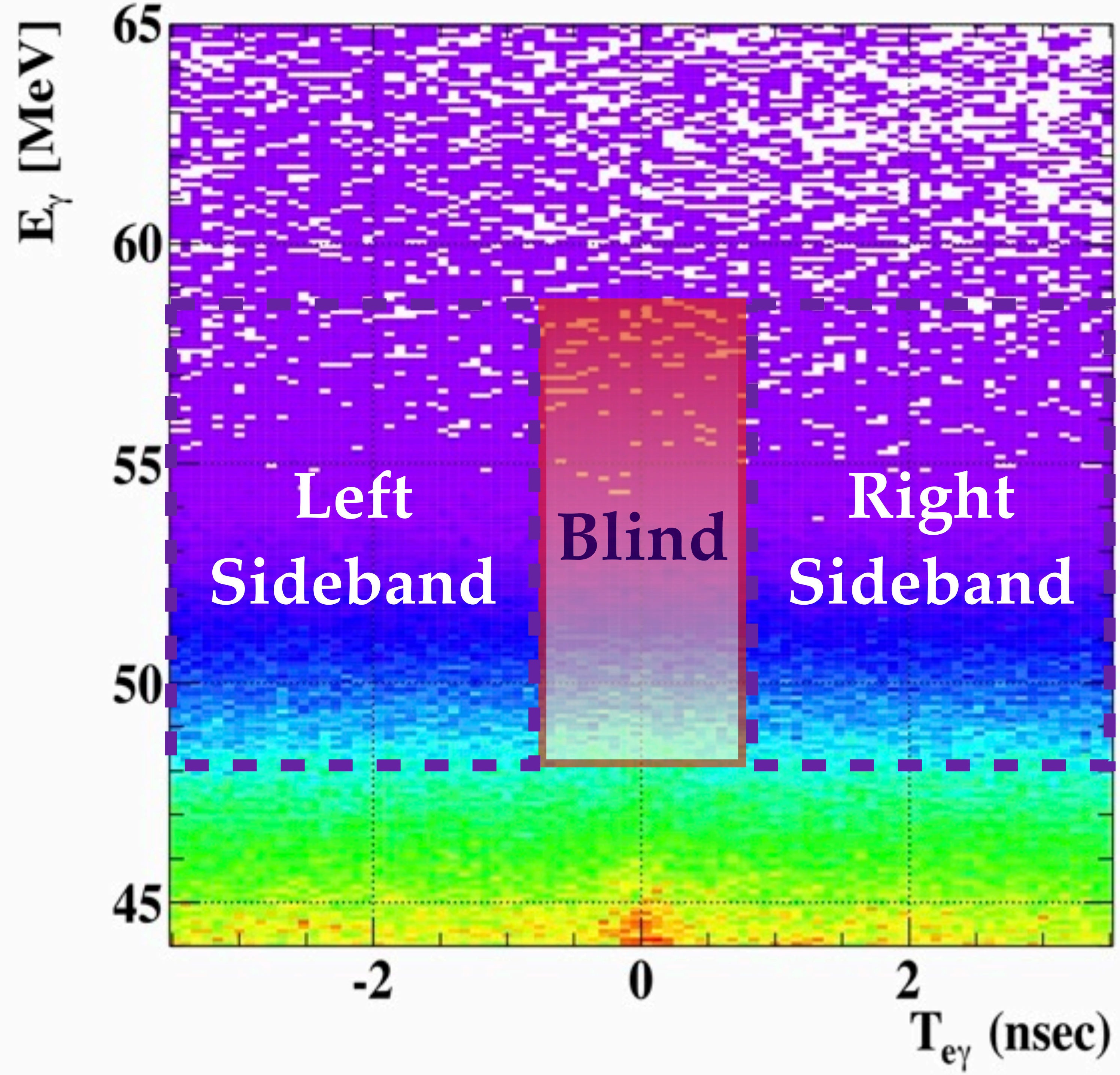

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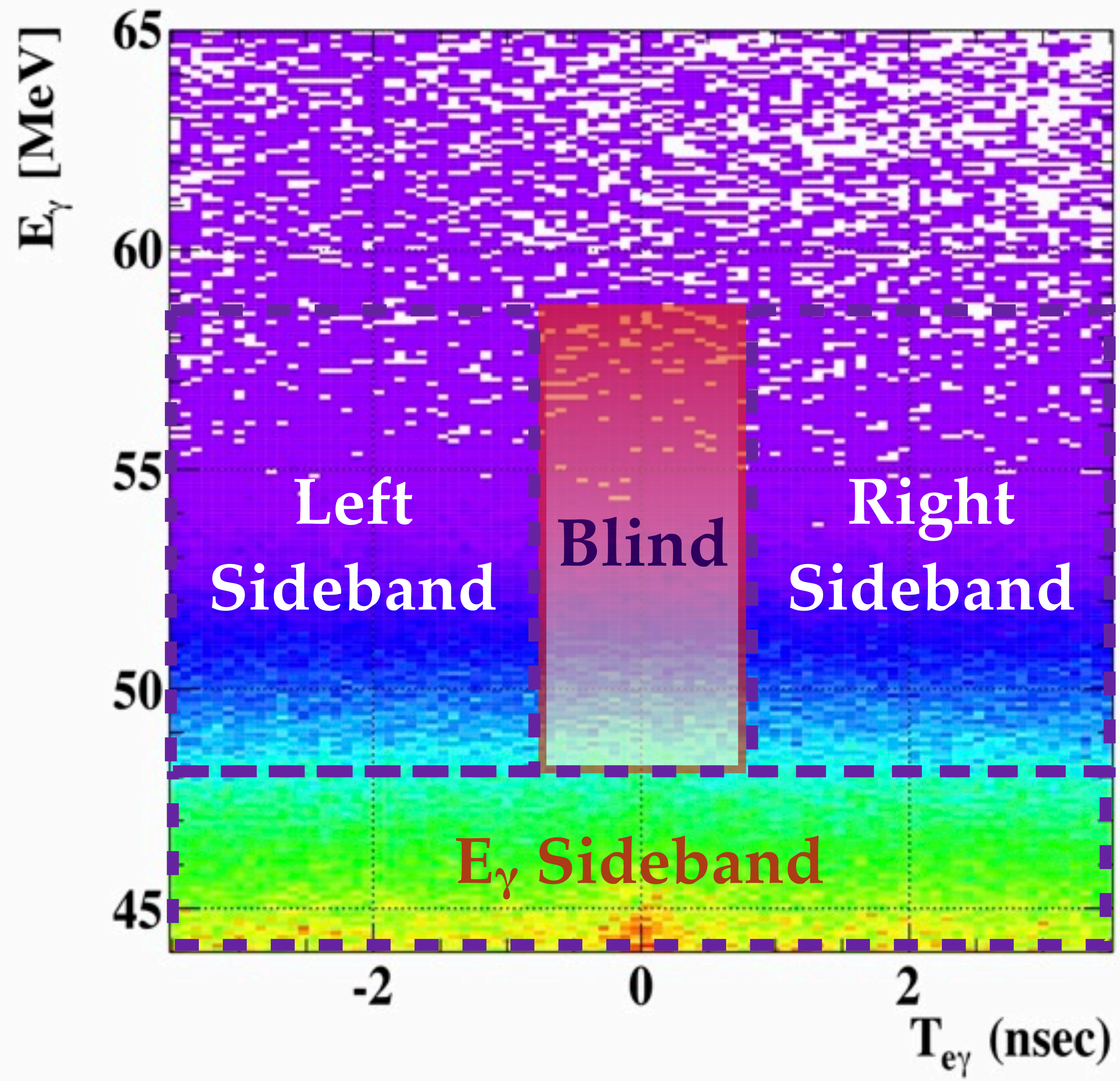


Likelihood Analysis

- Extended unbinned maximum likelihood analysis on number of events

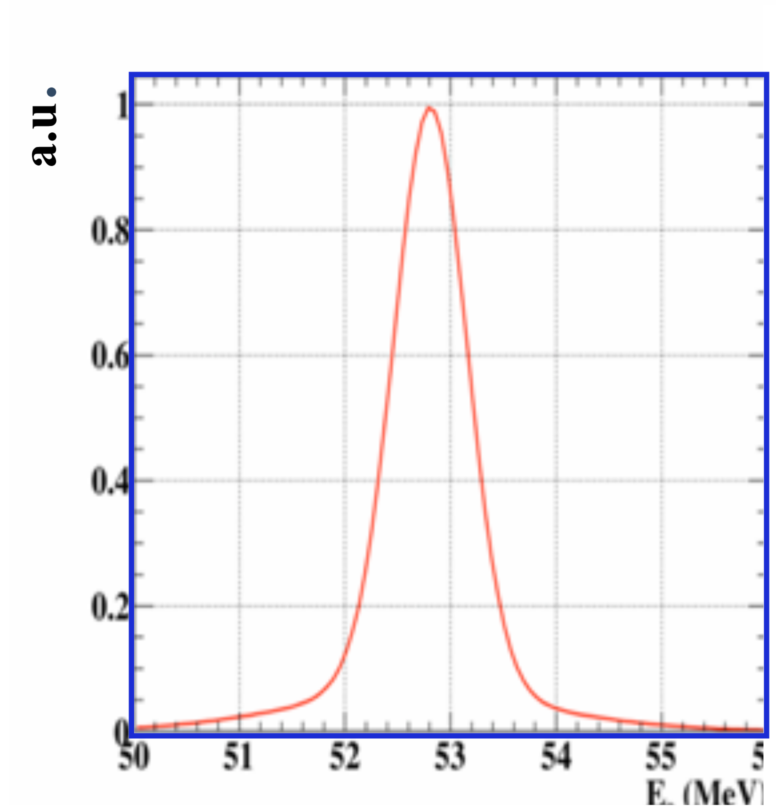
$$\mathcal{L}(N_{sig}, N_{RD}, N_{BG}) = \frac{N^{N_{obs}} e^{-N}}{N_{obs}} \prod_{i=i}^{N_{obs}} \left[\frac{N_{sig}}{N} S + \frac{N_{RD}}{N} R + \frac{N_{BG}}{N} B \right]$$

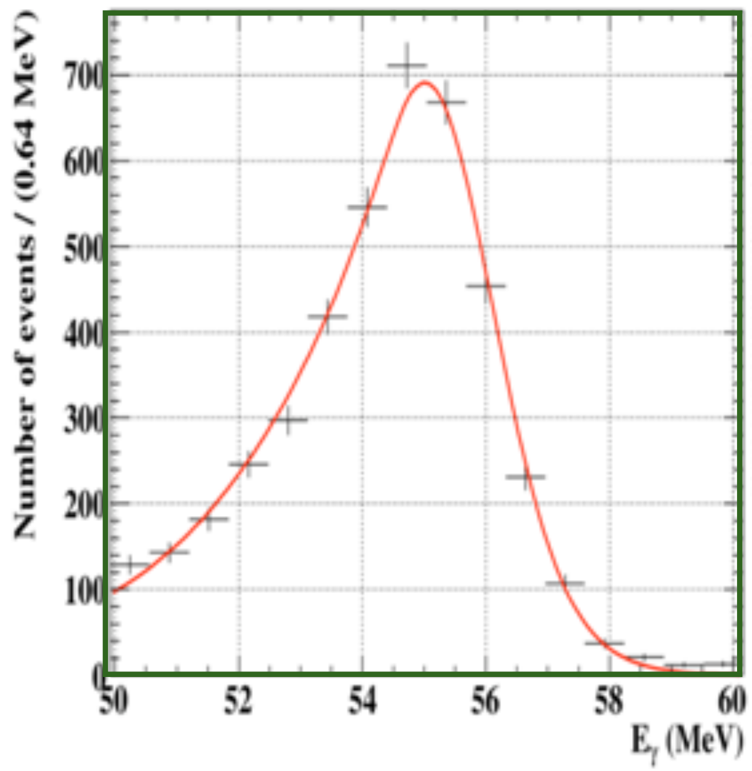
- Fit Parameters : # of events N_{sig}, N_{RD} and N_{BG} ($N = N_{sig} + N_{RD} + N_{BG}$)
- Observables : Energy E_γ, E_e, Relative time $T_{e\gamma}$ and Opening angle $\theta_{e\gamma}$, $\phi_{e\gamma}$
- Probability Density Function for each event type (**S, R, B**)
  - PDFs are extracted from data
- Fit in Wide region (10σ)
  - Fit Signal and Background simultaneously
- Three Independent Analysis Tools

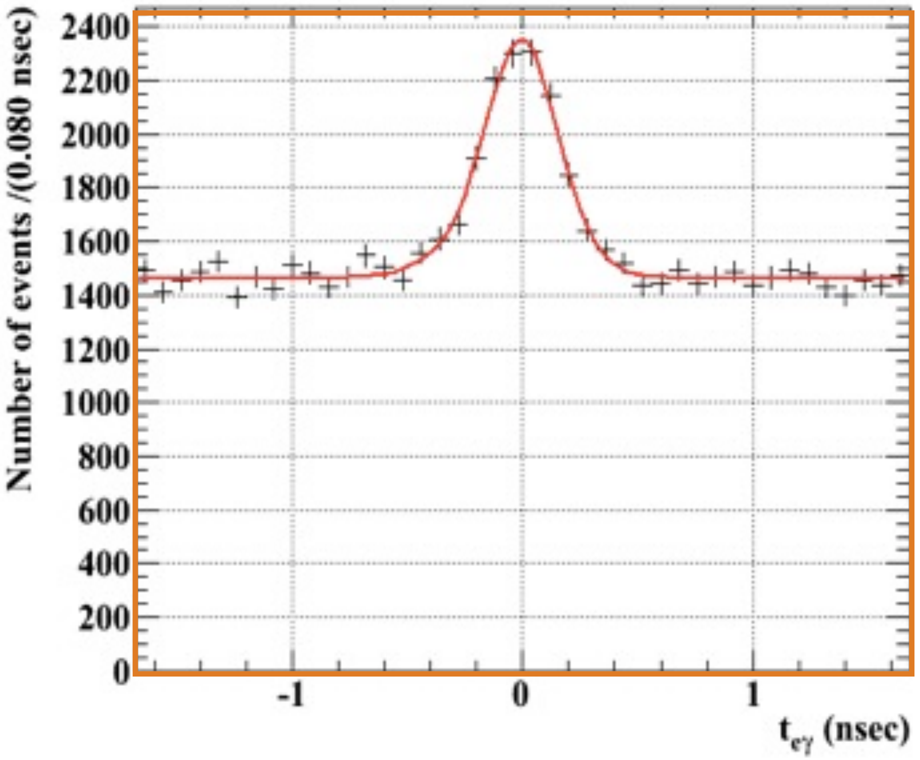
check, understanding or find bug

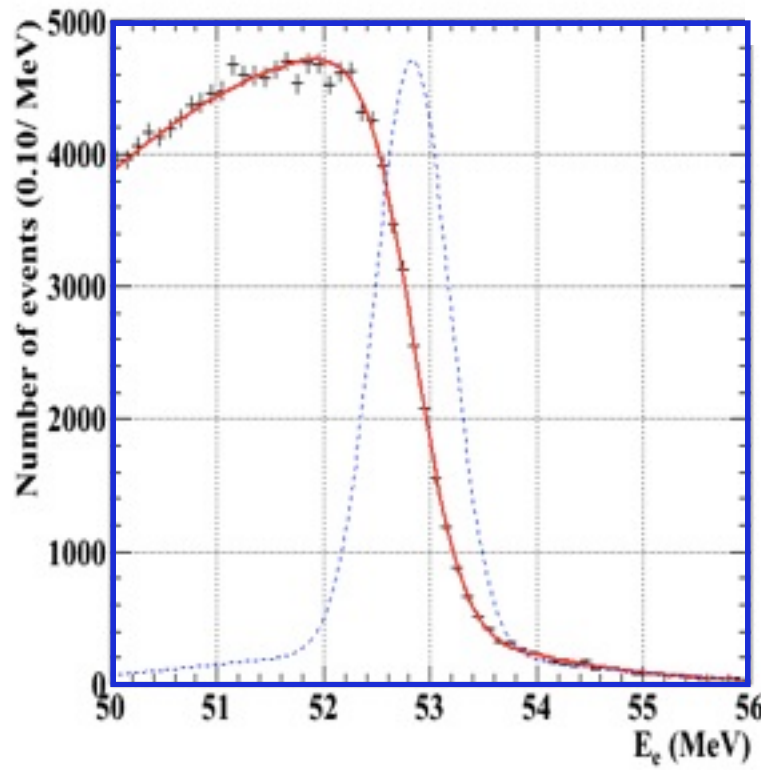
Different PDF implementation	Fit or Input N_{RD}	Different Statistical treatment (Frequentist or Bayesian)

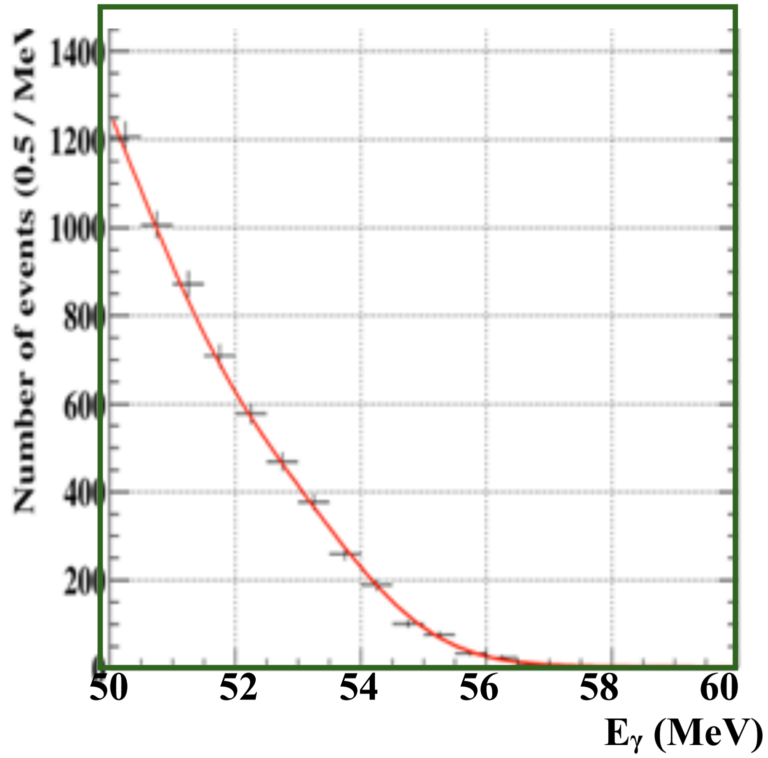
PDFs - Energies, Angles and Timing -











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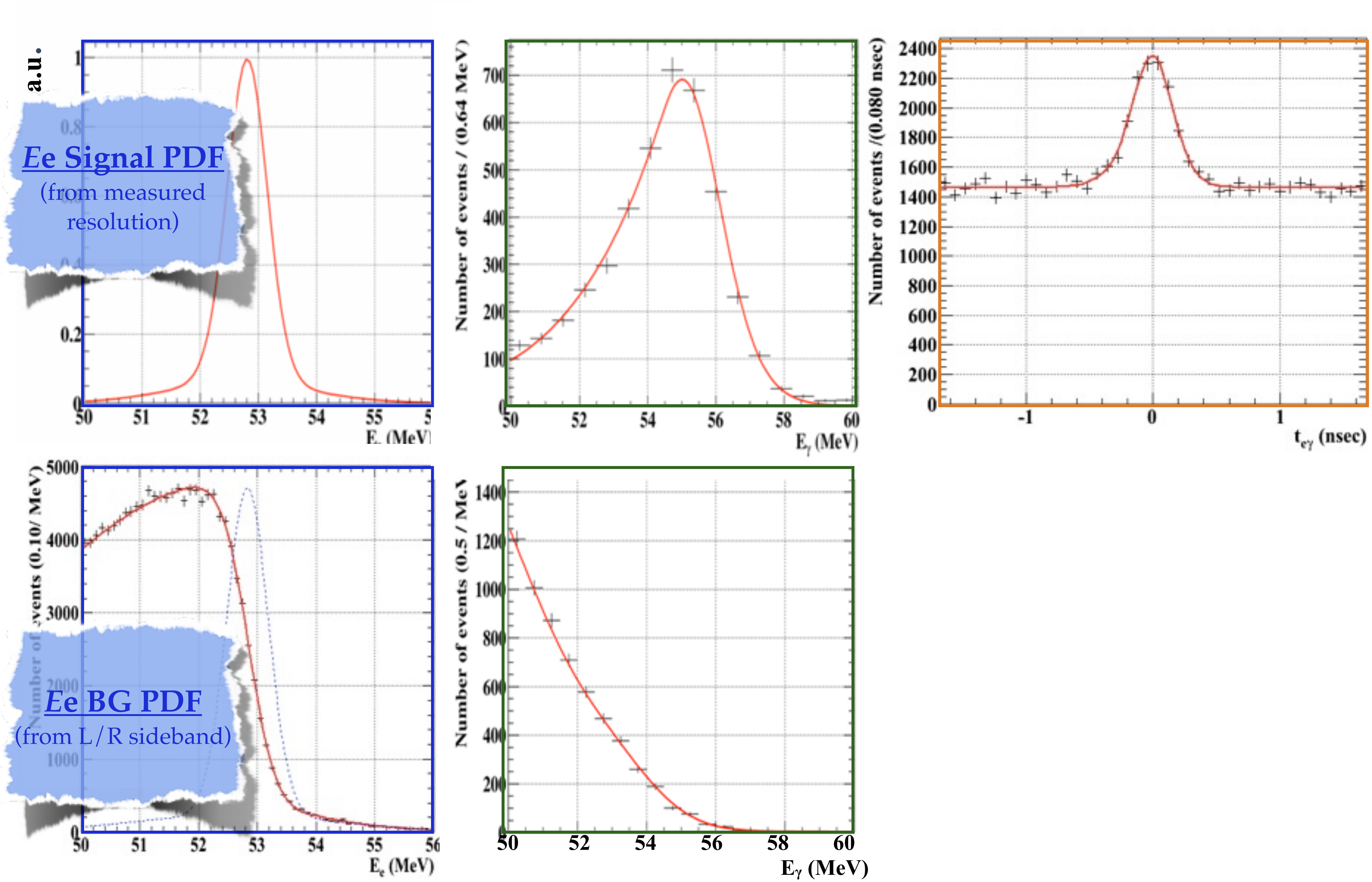

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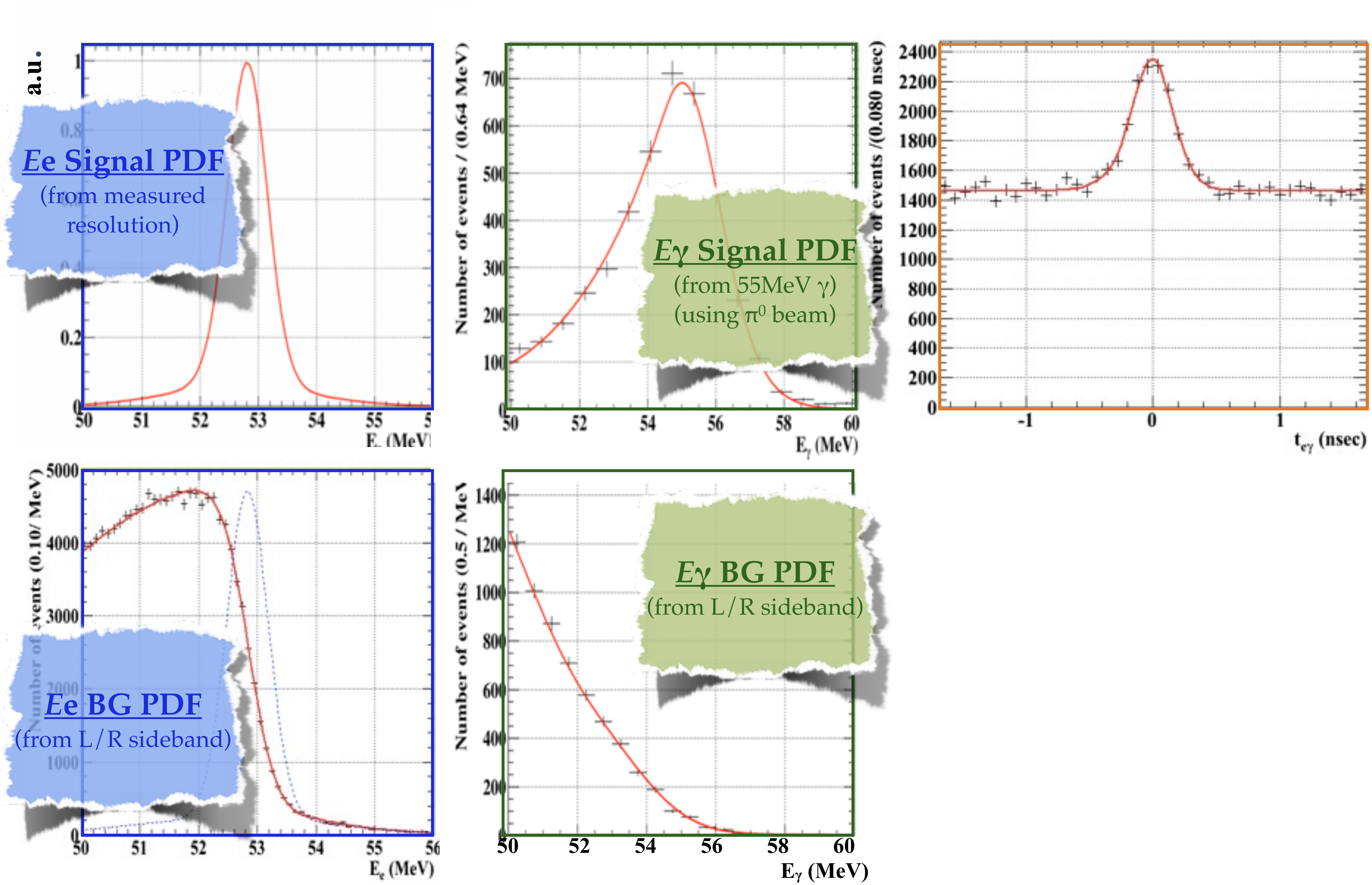

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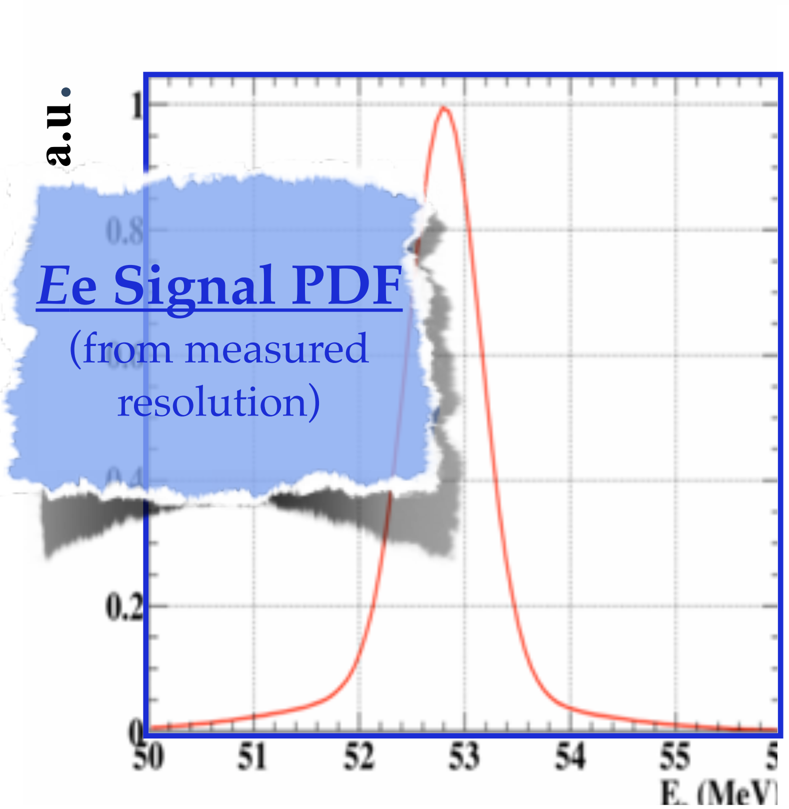

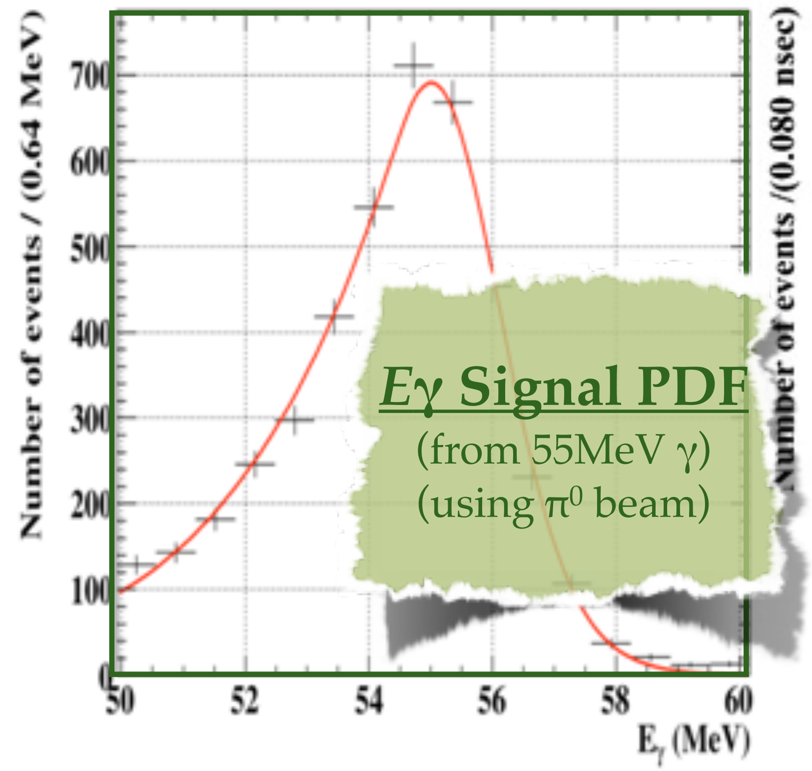

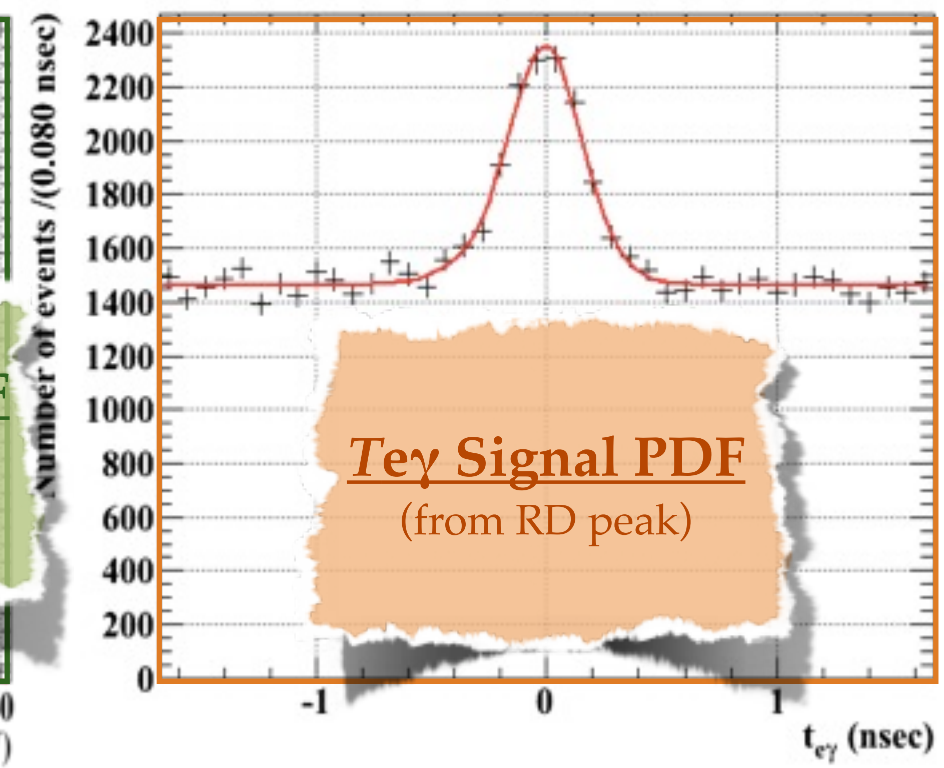

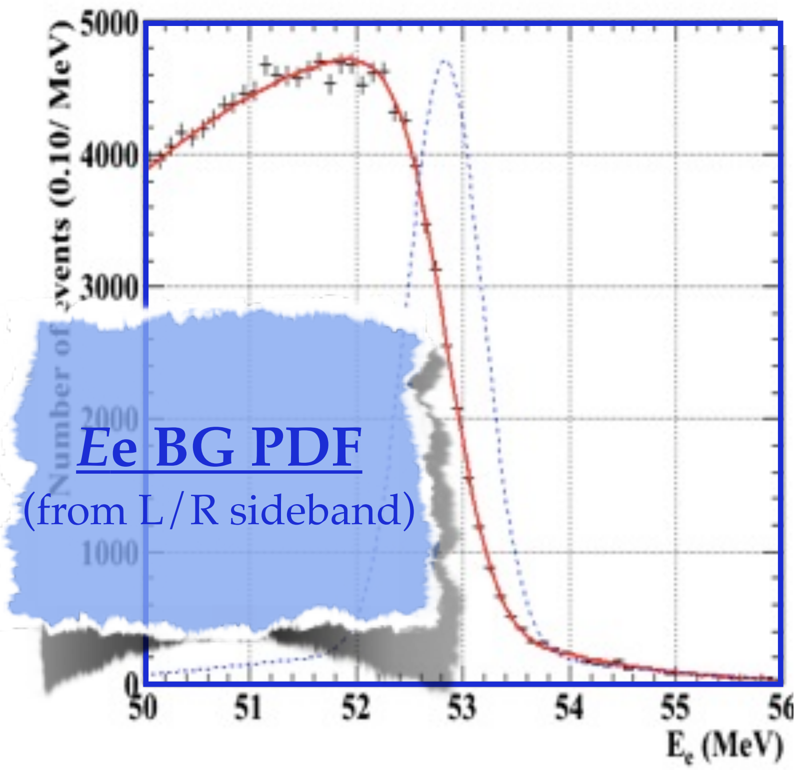

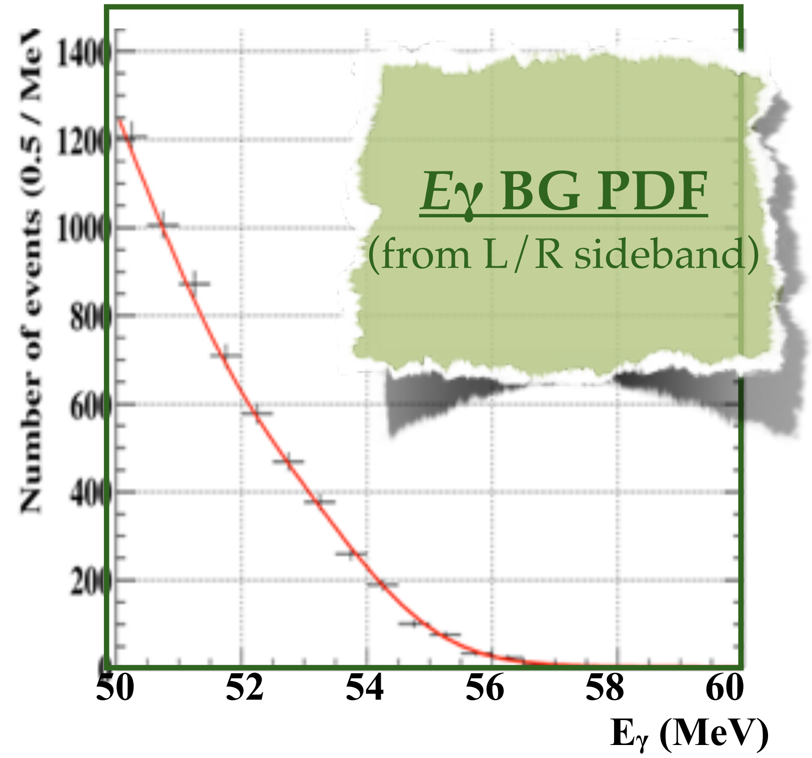

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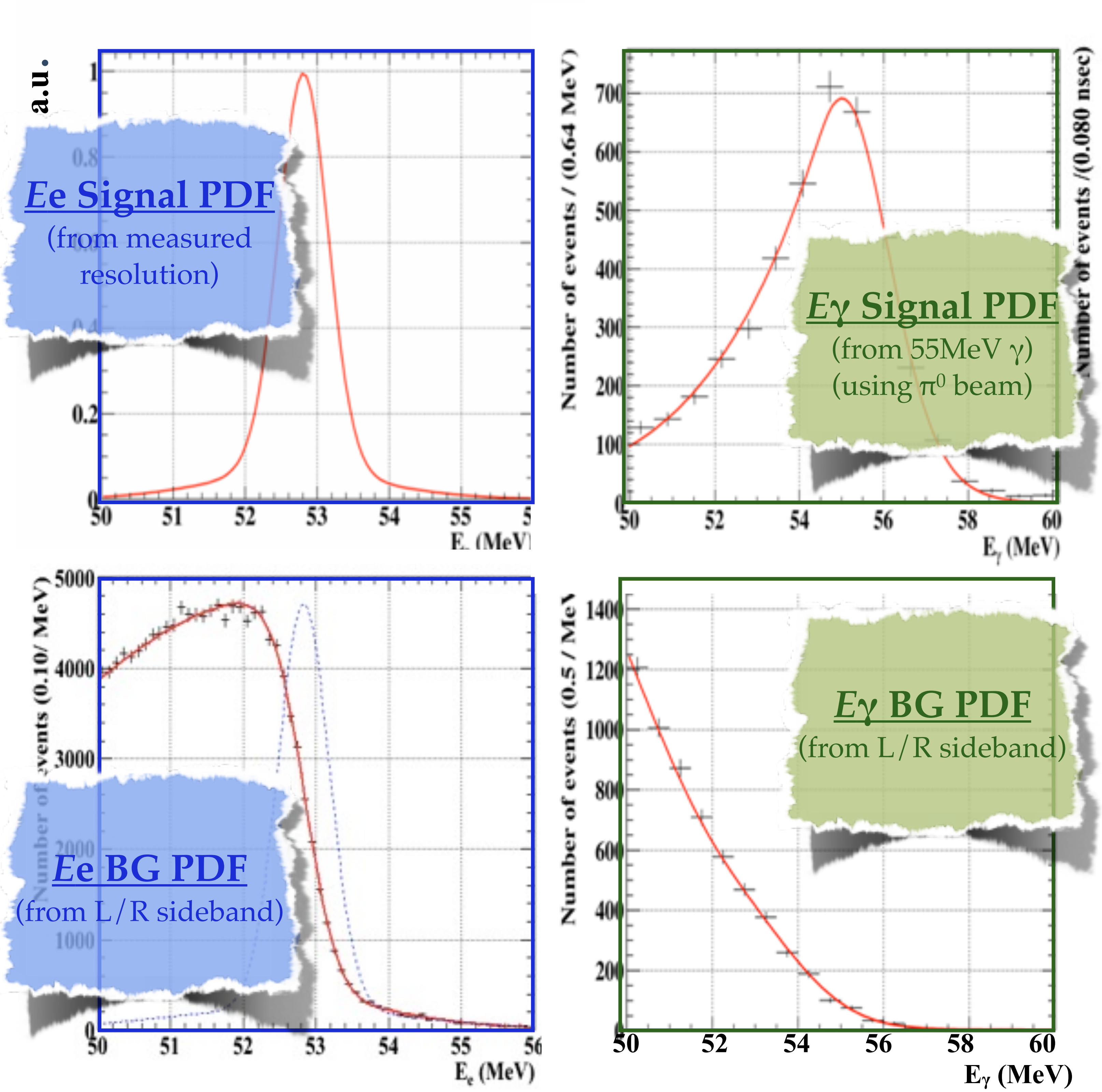


Relative Angle ($\theta_{e\gamma}$, $\phi_{e\gamma}$) PDF

Signal : from measured resolution

Background : from L/R sideband

Normalization - # of Muon Decay -

$$\frac{\mathcal{B}(\mu^+ \to \mathrm{e}^+\gamma)}{\mathcal{B}(\mu^+ \to \mathrm{e}^+\nu\bar{\nu})} = \frac{N_{sig}}{N_{\mathrm{e}\nu\nu}} \times \frac{f^{\mathrm{e}}_{\mathrm{e}\nu\nu}}{P \cdot \epsilon_{\mathrm{pu}}} \times \frac{\epsilon^{\mathrm{trig}}_{\mathrm{e}\nu\nu}}{\epsilon^{\mathrm{trig}}_{\mathrm{e}\gamma}} \times \frac{\epsilon^{\mathrm{DC}}_{\mathrm{e}\nu\nu}}{\epsilon^{\mathrm{DC}}_{\mathrm{e}\gamma}} \times \frac{1}{A^{geo}_{\mathrm{e}\gamma}} \times \frac{1}{\epsilon_{\mathrm{e}\gamma}}$$

- # of Michel Positrons is counted simultaneously using highly pre-scaled trigger applying the same event selection as for the ***physics*** data sample.
- Advantage: Independent of beam-rate & in 1st-order insensitive to acceptances & efficiencies (ratios)
- Branching ratio is represented by obtained normalization factor "***k***" and the # of signal which will be obtained by the final analysis

$$\mathcal{B}(\mu^+ \to \mathrm{e}^+\gamma) = \frac{k}{N_{sig}}$$

- Obtained normalization factor **"*k*" = (1.0±0.1)×10^{12}**

Sensitivity

- Mean Upper Limit (90%C.L.) on ensemble of toy-MC experiments
  - Generate events with obtained PDFs assuming Null-Result Hypothesis
  - Repeat toy-MC experiments and calculate Upper Limit for each experiment in the same way as real data

Mean Sensitivity of Run2009 : 6.1×10^{-12} (90CL.)

(including no systematics)

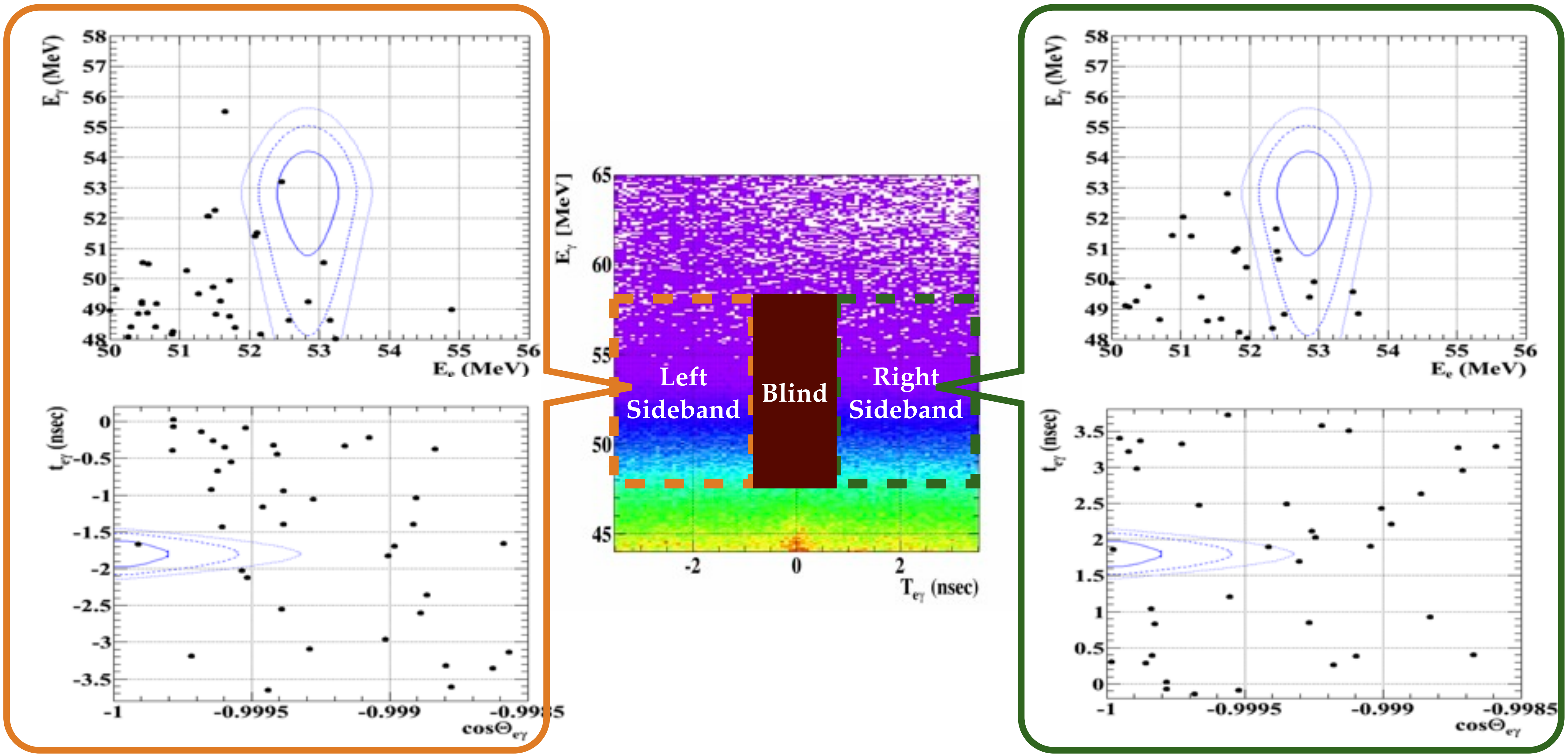
Sensitivity Run2008 : 1.3×10^{-11} (90CL.)

Present Upper Limit : 1.2×10^{-11} (90CL.)

- Signal-detection power of our likelihood analysis was also checked by dedicated toy-MC with mixed $\mu\rightarrow e\gamma$ signal events

Sideband fits

- To confirm the final analysis, Off-timing Sideband data is fitted



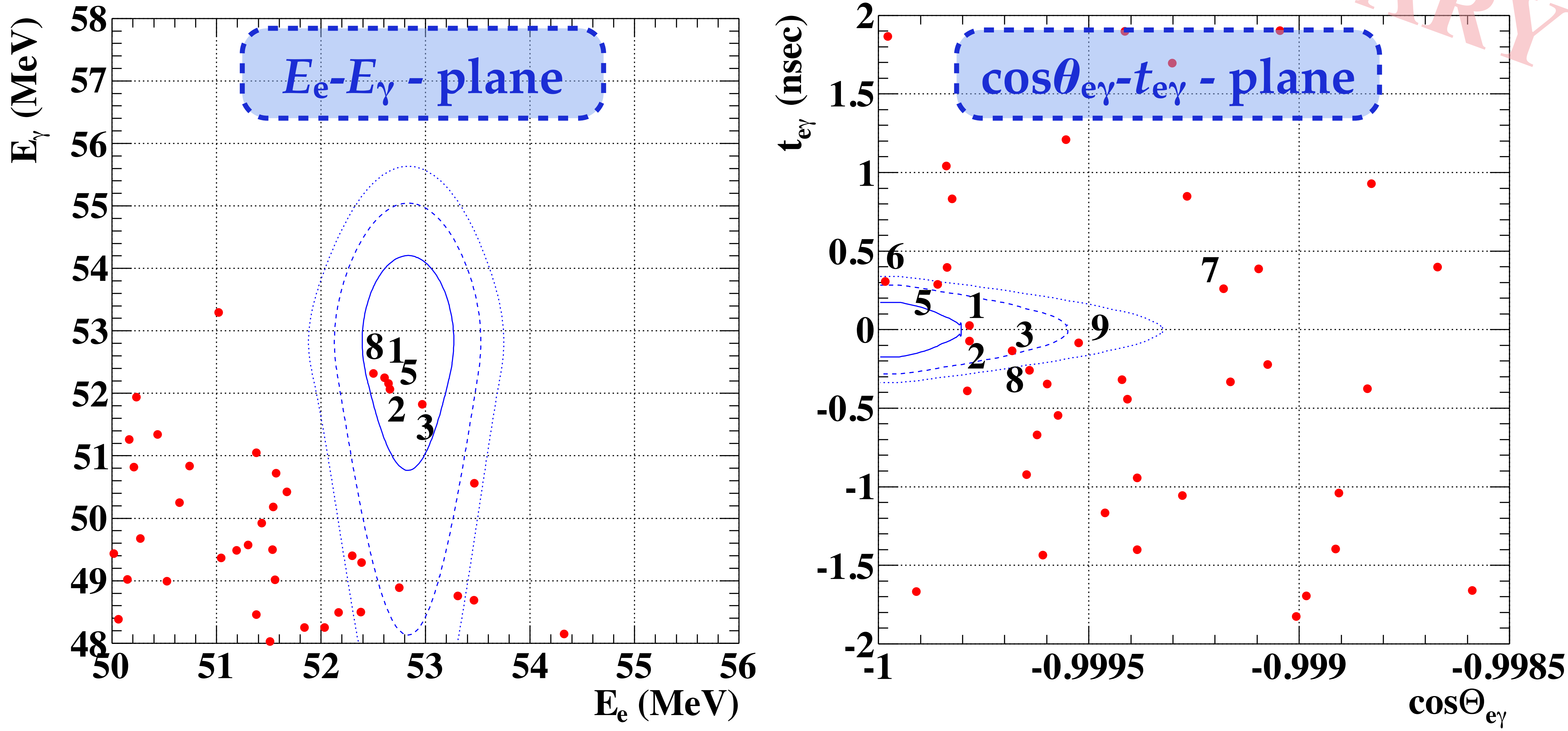
- Sideband-fit results : **<u>BR UL Sensitivity < 4~6×10^{-12}</u>**
- No Signal in Sideband / Sideband Fit is consistent with obtained Sensitivity

Finally......

Now Ready to Open the BOX !!

Event Distribution

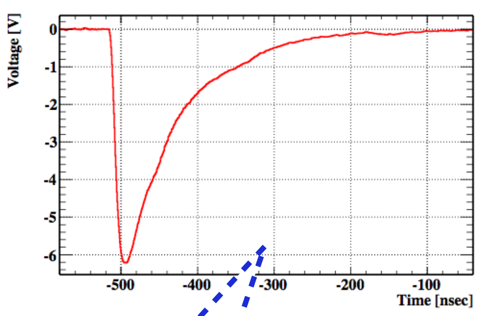
We opened the blind box on 06/July/2010



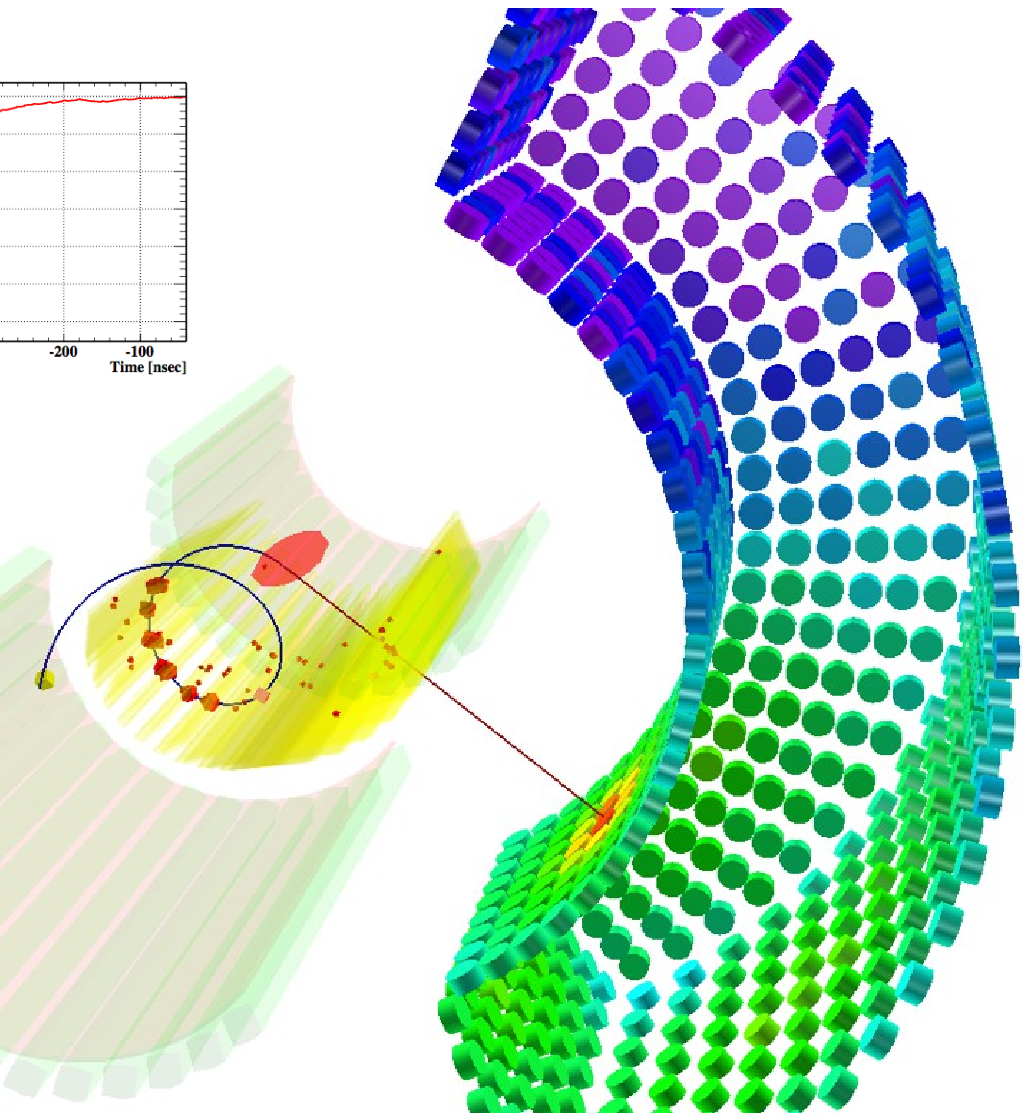
- Contours of the PDFs (**1σ, 1.64σ** & **2σ**) are shown
- Same events in two plots are numbered correspondingly, by decreasing ranking in terms of relative signal likelihood ($S(R+B)$)

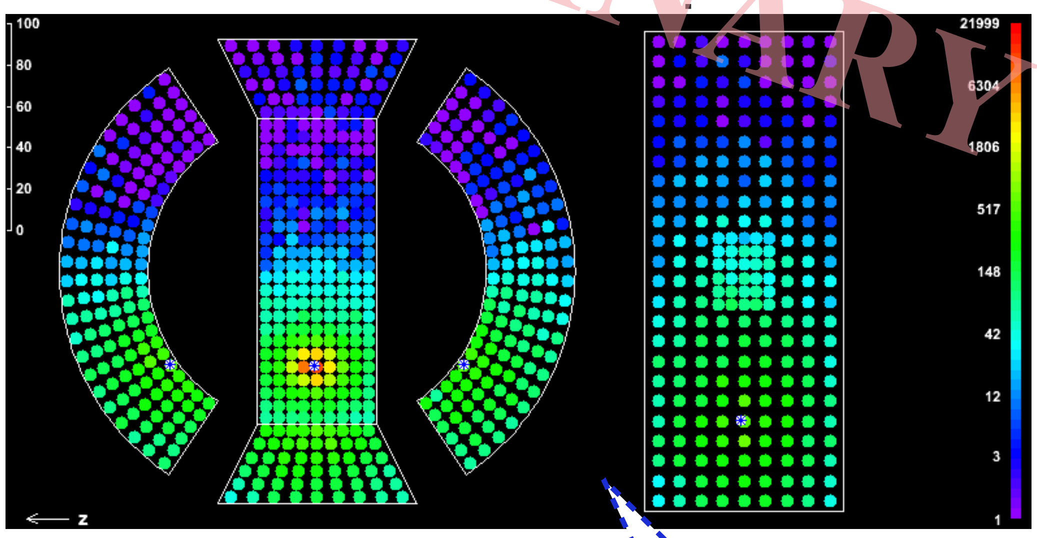
Sample Event Display

PRELIMINARY

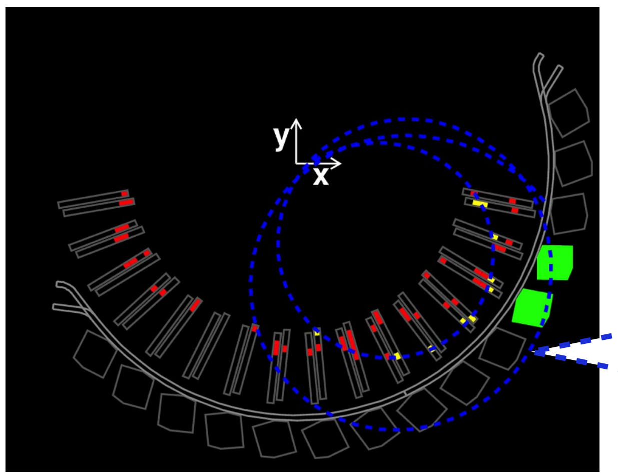


PMT sum WF





calorimeter PMT hit map

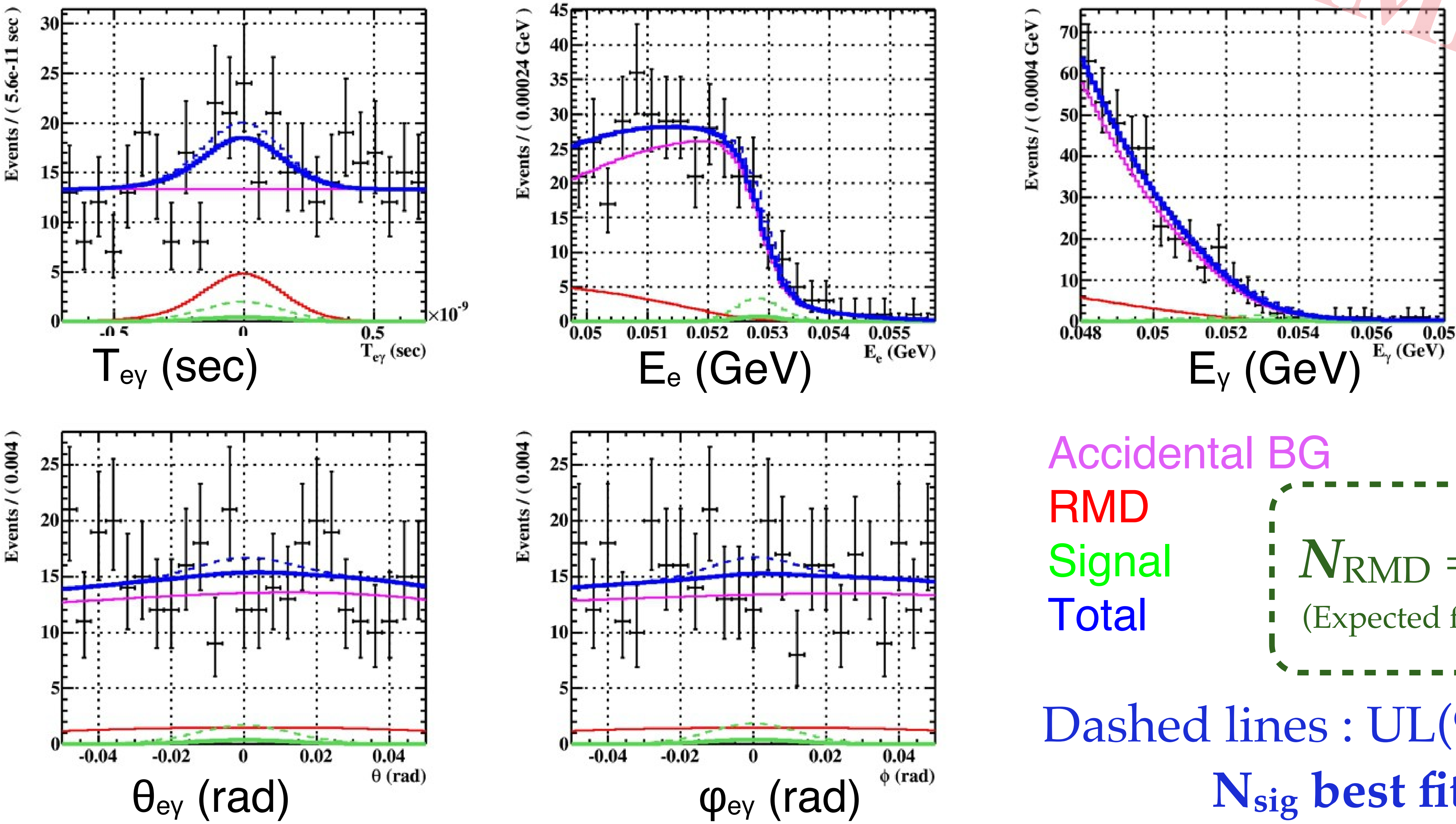


spectrometer hit & track

- Highest Ranked (=most signal-like) Event
- No pileup, Relative Angle and Relative Timing are checked.
- Every highly ranked events are checked carefully.

Likelihood-Fitting Result

PRELIMINARY



Accidental BG
RMD
Signal
Total

$N_{RMD} = 35\ (+24/-22)$

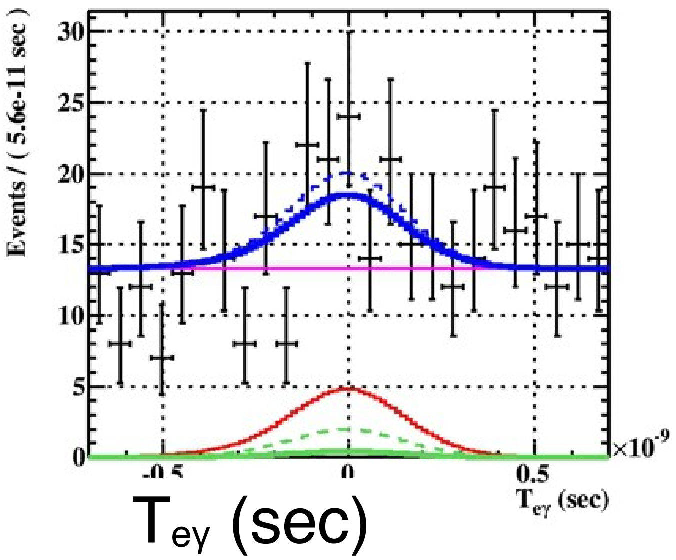
(Expected from sideband = 32±2)

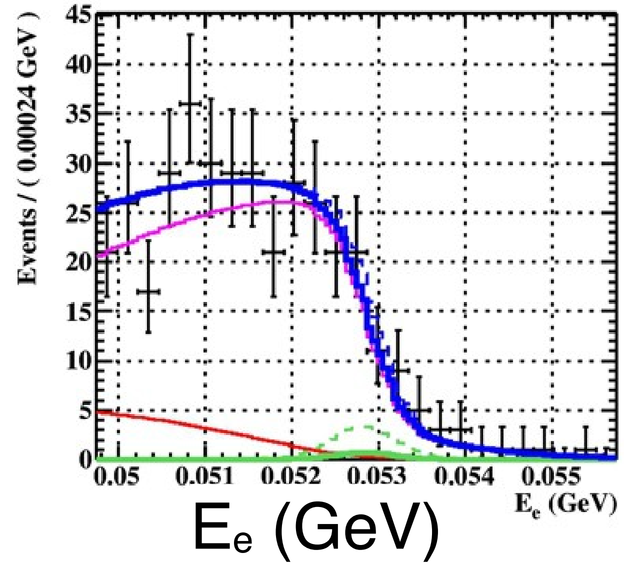
Dashed lines : UL(90CL.) of N_{sig}

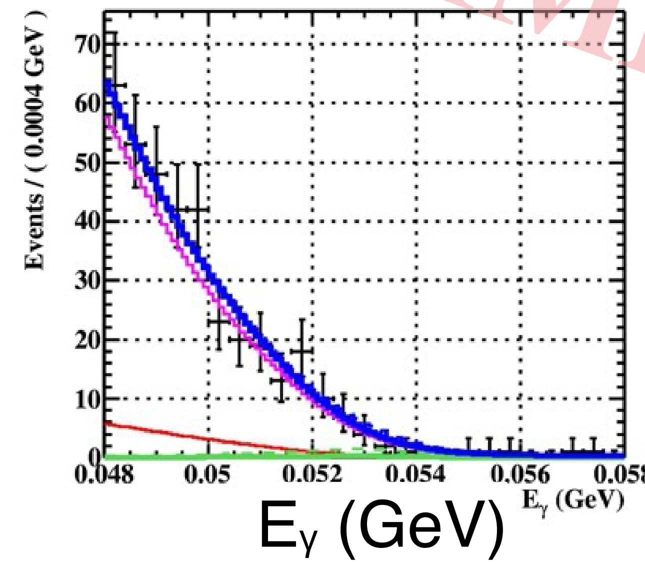
N_{sig} best fit = 3.0

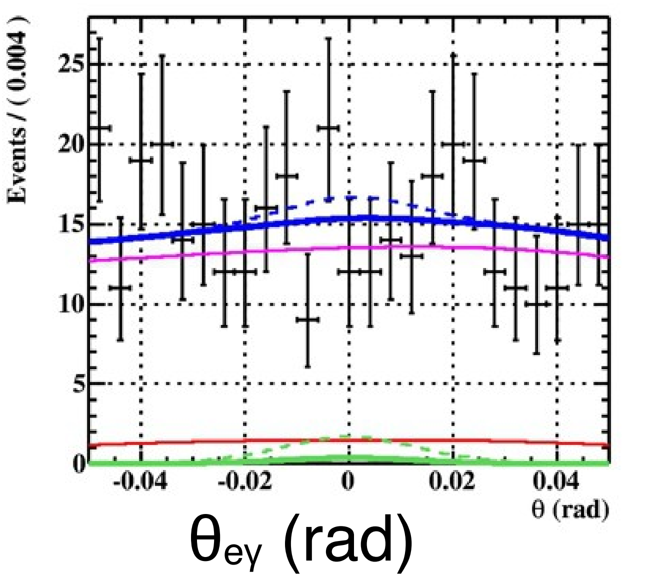
Likelihood-Fitting Result

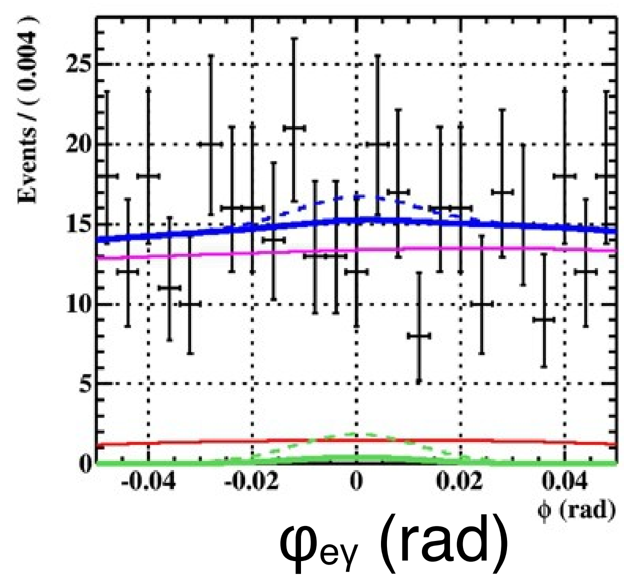
PRELIMINARY











Accidental BG
RMD
Signal
Total

N_{RMD} = 35 (+24/-22)
(Expected from sideband = 32±2)

Dashed lines : UL(90CL.) of N_{sig}

N_{sig} best fit = 3.0

- N_{sig} < 14.5 (90CL.) → **$\mathcal{B}(\mu^+ \to e^+\gamma)^{2009} < 1.5\times10^{-11}$ (90CL.)**
- **N_{sig}=0 is in 90% confidence region**

Systematic Uncertainties

- Systematic Effect is taken into account in the calculation of confidence region **by fluctuating PDFs** according to the uncertainty values.

Normalization	8%	E_e dep. $\oplus\ \varepsilon^{\gamma} \oplus \varepsilon^{trig}$
E_γ Scaling	0.4%	Light Yield & Gain Stability
E_γ Resolution	7%	
E_e Scaling	50 keV	From Michel edge
E_e Resolution	15%	
$T_{e\gamma}$ Centering	15 ps	
$T_{e\gamma}$ Resolution	10%	Radiative Peak
Angle	7.5 mrad	Tracking $\oplus$ LXe Position
Angular Resolution	10%	
E_e-ϕ_e Correlation	50%	MC evaluation

- Effect of each component is evaluated by looking at the change of best-fit value when the parameter is changed according to the uncertainty.
- Effect is enough small compared to the statistical uncertainties

Prospects

Provisional Performances in 2010

	2009 PRELIMINARY	2010 PROVISIONAL
γ Energy σE_γ (%)	2.1 (depth>2cm)	1.5 (depth>2cm)
γ Timing σt_γ (ps)	>67	←
γ Position σx_γ (mm)	5/6	←
γ Efficiency ε_γ (%)	58	←
e^+ Mom. σp_e (%)	0.74	0.7
e^+ Timing σt_e (ps)	<125	95
e^+ Angle $\sigma\theta_e$ (mrad)	7.4(ϕ)/11.2(θ)	8(ϕ)/8(θ)
e^+ Efficiency ε_e (%)	40	←
γ-e^+ Relative Timing	142	120
μ^+ decay vertex (mm)	2.3/2.8	1.4/2.5
Trigger Efficiency (%)	84	84-94%
μ^+ Stopping Rate (Hz)	2.8×10^{7}	2.9×10^{7}
DAQ Time (days)	35	95
Sensitivity	6.1×10^{-12}	**$(2.0\text{-}2.5)\times10^{-12}$**
BR Upper Limit	1.5×10^{-11}	**???**

- Possible Improvements
  - σ_T will be improved by better synchronization of digitizer
  - Possible better calibration with monochromatic e^+ beam and improve positron tracking
  - Noise reduction and electronics modification for DC
  - Refinement of calorimeter analysis
  - TC-fibres in Trigger

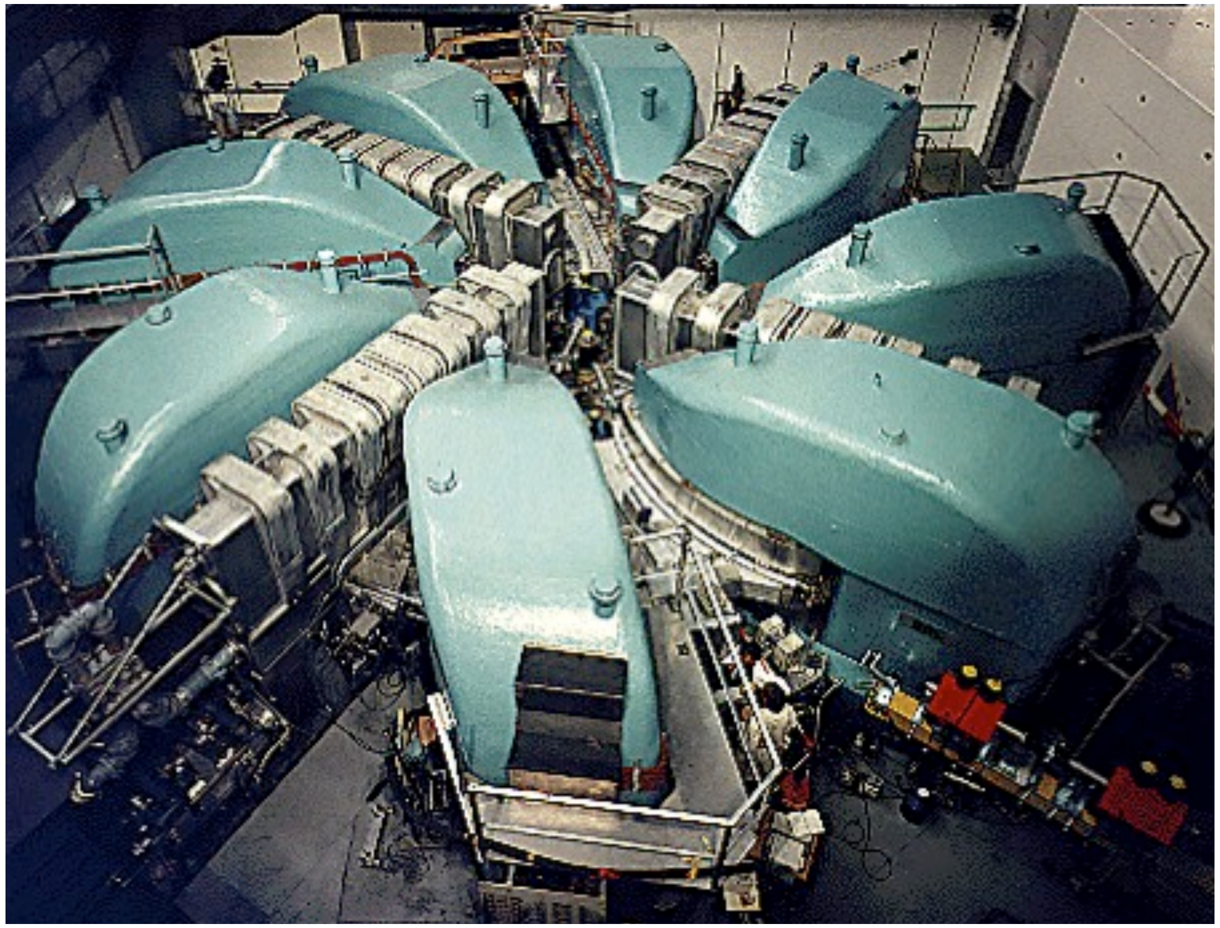
Future Prospects

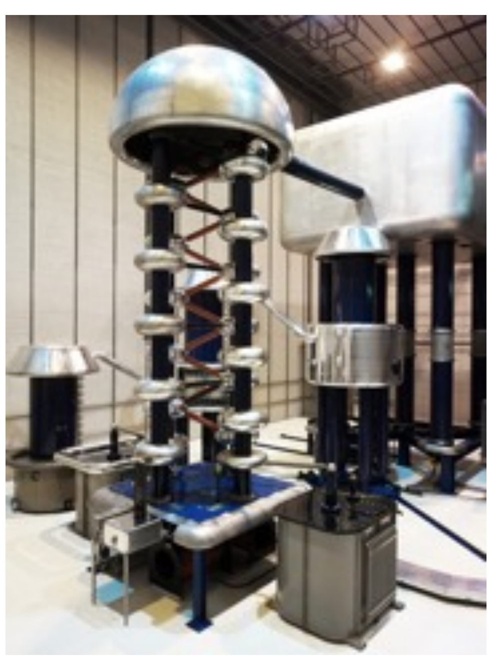
- MEG2010 is now running (physics run resumed August 2010)
  - Will accumulate **×3 statistics** in this year, with improved performances
  - Sensitivity will be improved accordingly
- MEG Physics Run continues until 2012 (at least, guaranteed by committee)
  - Another two years full run
  - **2009 Results will be clarified by ourselves** with long term stable run
- MEG is aiming a sensitivity of **a few × 10^{-13}** level

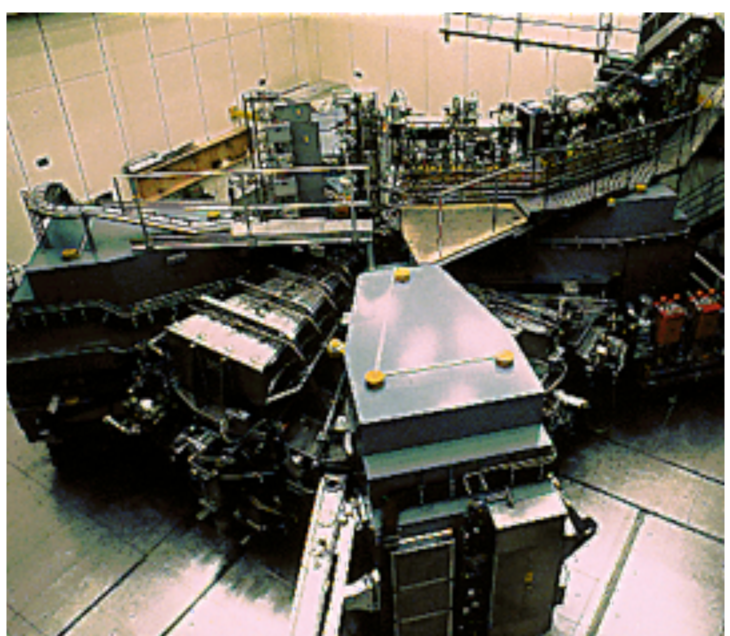
Conclusions

- In 2009, MEG carried out 2 months physics run successfully
  - All the major problems that were occurred in 2008 was fixed
  - Performances (resolution & efficiency) were improved accordingly
  - Stable detector operation over whole data-taking period
- Preliminary Result from 2009 data analysis:
  - **Sensitivity : 6.1×10^{-12}**
  - **Upper Limit : 1.5×10^{-11} (90CL.)**
  - **"$N_{sig} = 0$" is still contained in 90% confidence region**
  - (Best fit is "N_{sig}=3", probability of this result is approx. 2-3% in toy MC)
- **MEG is currently running at close to full efficiency and is expected to continue data taking in the next years. Its sensitivity to the decay will be improved by more than one order of magnitude, therefore it is expected to either place the strongest constraints on new physics models or have a great chance to make a discovery.**

PSI Proton Cyclotron







- The cyclotron facility contains a cascade of three accelerators that deliver a proton beam of 590 MeV energy at a current up to **2 mA (1.2 MW)**.
- Pre-accelerated in a C-W column to an energy of 870 keV, secondary-accelerated in the 4-sector Injector 2 cyclotron up to 72 MeV.
- Final acceleration of the main beam to 590 MeV occurs in the large 8-sector Ring Cyclotron, from which the beam is transported through the experimental hall in a shielded tunnel.