Up-to-Date Results and Upgrade Plans of the MEG Experiment

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on behalf of the MEG Collaboration

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Contents

- LFV in Muon
- $\mu \rightarrow e\gamma$ Search
- MEG Experiment
  - Up-to-date Results
  - Upgrade Plans

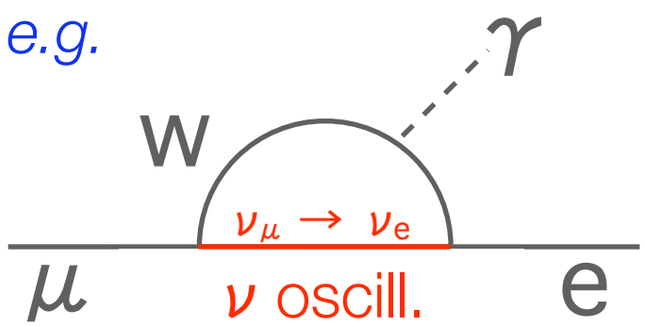
Why charged LFV has never been observed ?

Why ? : Quark/Neutrino Flavour Mixing = ☺ / Charged LFV = ☹ ?

SM + simple ν Oscillation

- charged LFV is possible

e.g.



- but extremely rare

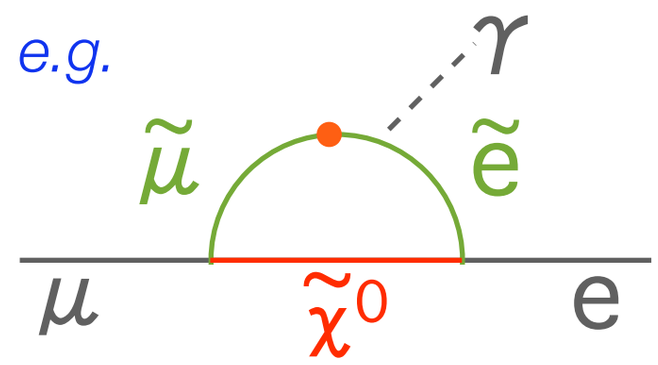
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{m^2_W} \right|^2$$

- B($\mu \to e\gamma$) ≲ 10^{-57} !!!

beyond SM (SUSY-GUT *etc.*)

- charged LFV is largely enhanced

e.g.



- still rare but observable level

$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{\alpha^3 \pi \theta^2_{\tilde{e}\tilde{\mu}}}{G_F^2 \tilde{m}^4}$$

- B($\mu \to e\gamma$) = 10^{-15} ~ 10^{-11} !!!

Why charged LFV has never been observed ?

Why ? : Quark/Neutrino Flavour Mixing = ☺ / Charged LFV = ☹ ?

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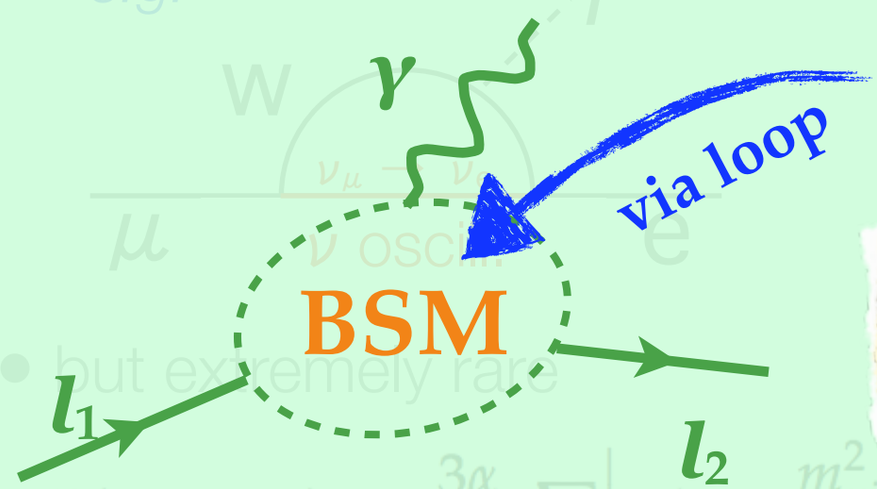
- charged LFV possible

e.g.



- but extremely rare

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

- $B(\mu \to e\gamma) \approx 10^{-57}$!!!

beyond SM (SUSY-GUT *etc.*)

- charged LFV vastly enhanced

e.g.

$$G_F m^4$$

- $B(\mu \to e\gamma) = 10^{-15} \sim 10^{-11}$!!!

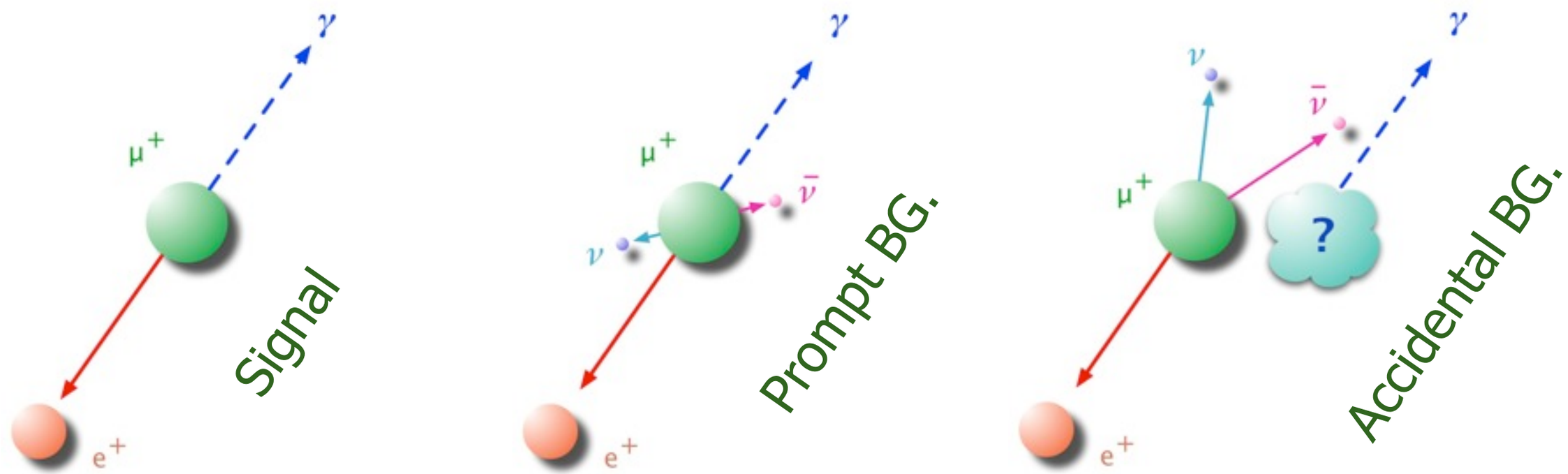
"charged LFV" = "NEW PHYSICS"

TeV-scale New Physics

competitive & complementary to LHC !

Hunting for $\mu \rightarrow e\gamma$ and MEG Features

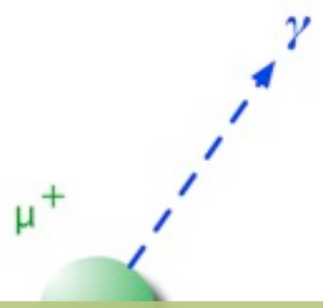
- Signal and Backgrounds

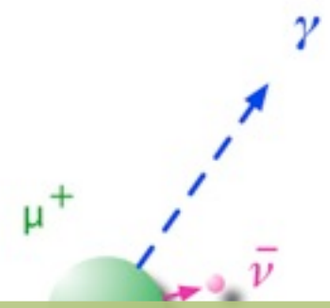


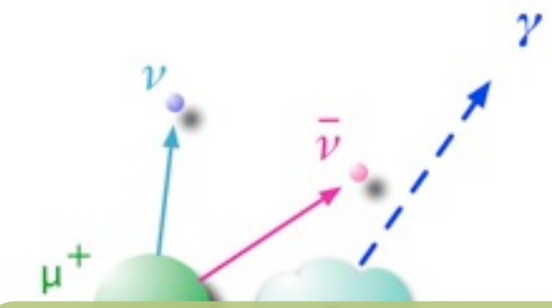
- Clear 2-body kinematics (E_e=E_γ=52.8MeV, $\theta_{e\gamma}$=180°, Time Coincidence)
- Sensitivity is Limited by "Accidental Overlap"
  - **DC muon is the Best Solution**
  - **Good Resolution (Energy, Spacial and Timing) under Very High Rate**

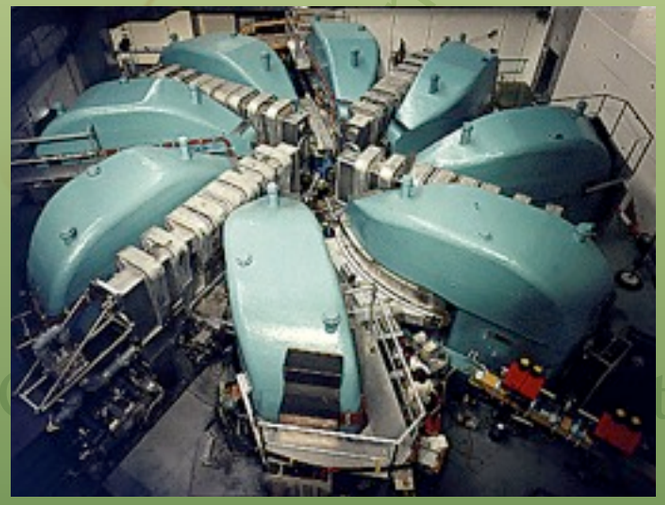
Hunting for $\mu \rightarrow e\gamma$ and MEG Features

- Signal and Backgrounds



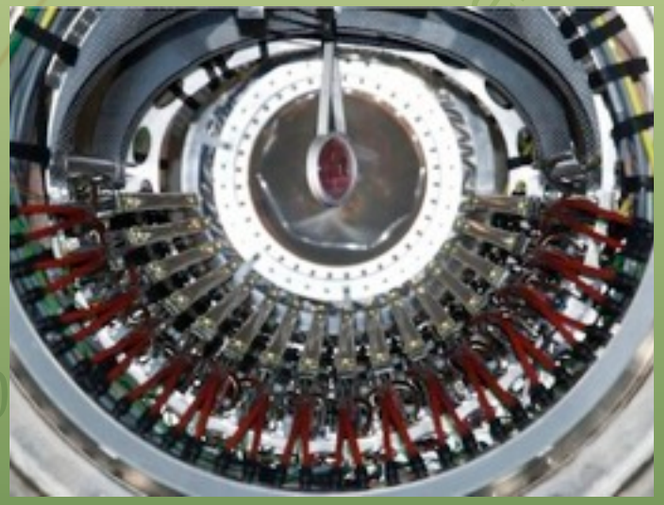






World Most Intense
DC Muon Beam at PSI
10^8 muon/sec

Liquid Xenon
Scintillation Detector
(gamma)

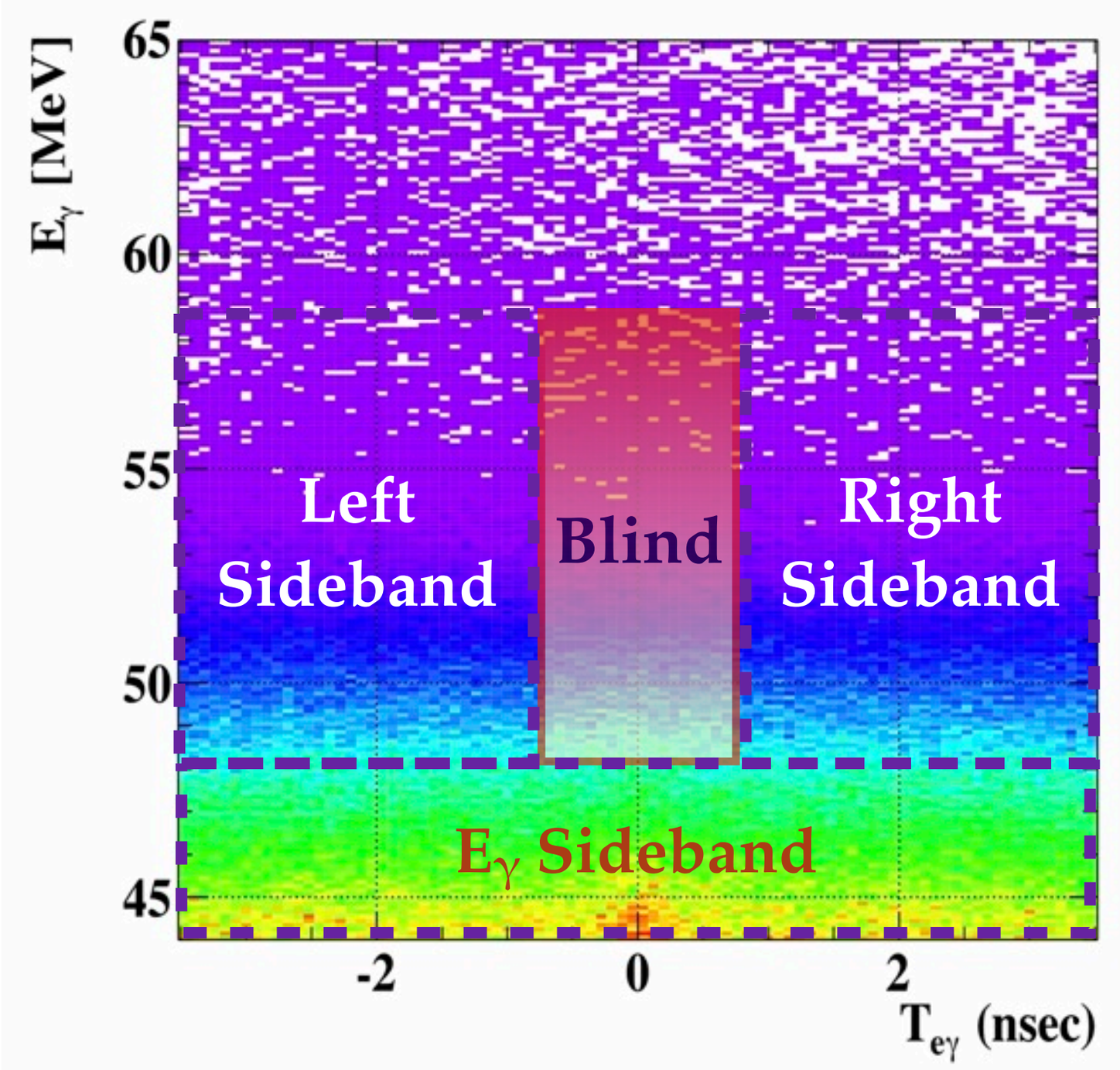


COBRA Spectrometer
(positron)

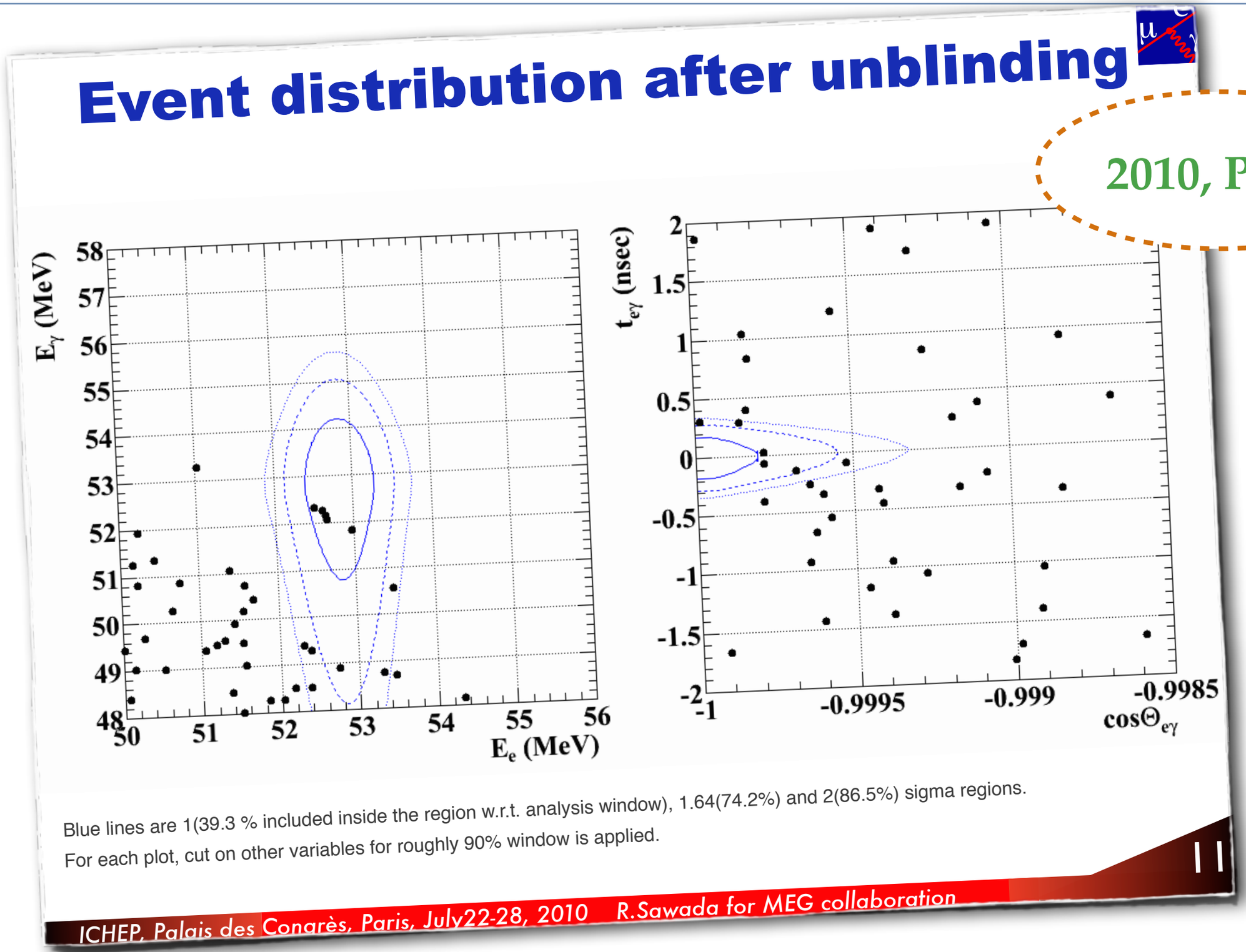
- Kinematics (Momentum, Angle, Time) ~180
- Sensitivity is Limited by "Accidental Overlap"
  - **DC muon is the Best Solution**
  - **Good Resolution (Energy, Spacial and Timing) under Very High Rate**

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_γ, $T_{e\gamma}$)
- **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
- **Maximum likelihood fitting**
  - N_{sig}, N_{RD} and N_{BG} fitted with PDFs extracted from data for E_e, E_γ, $t_{e\gamma}$, $\theta_{e\gamma}$ and $\phi_{e\gamma}$



After the Previous ICHEP



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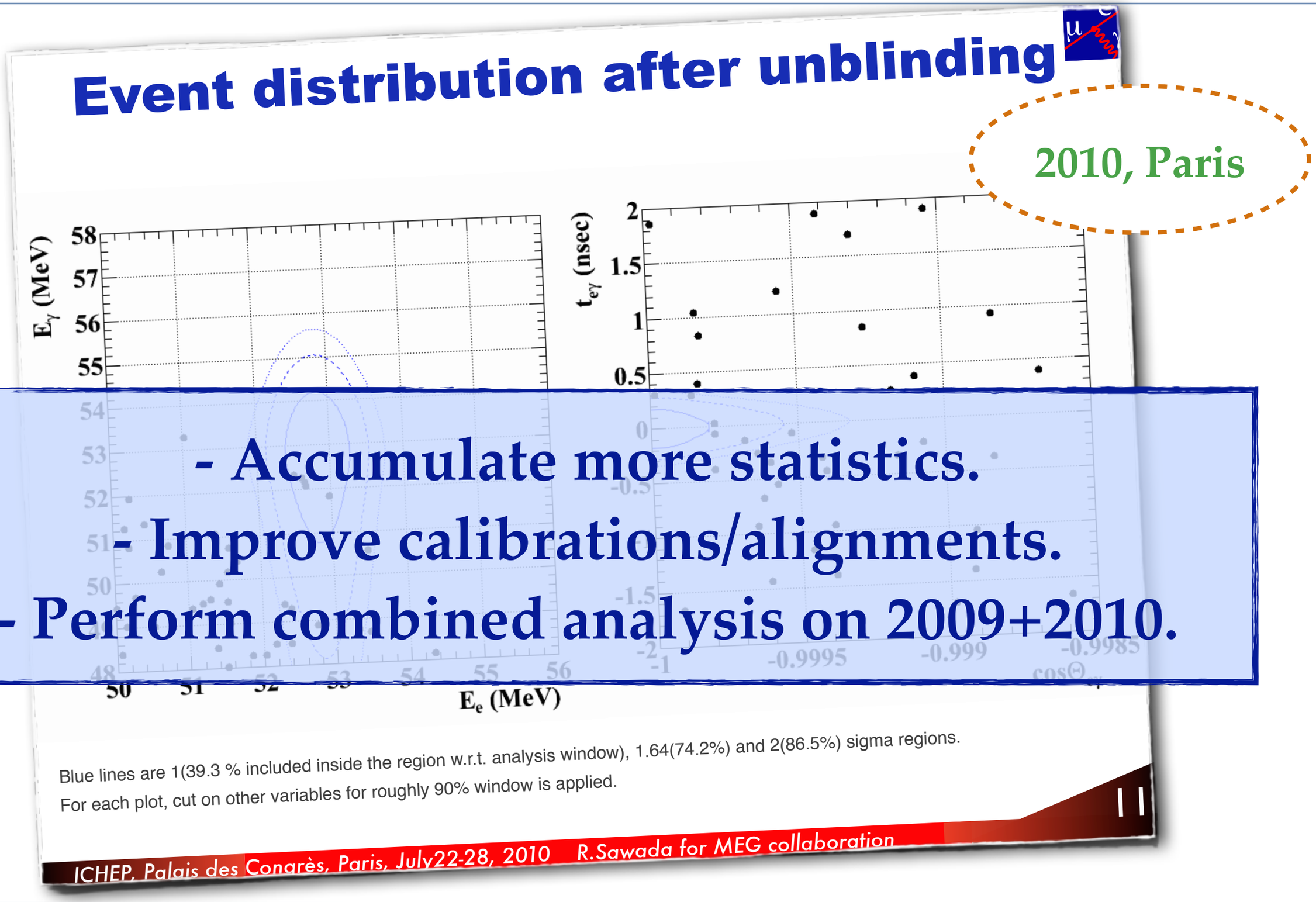
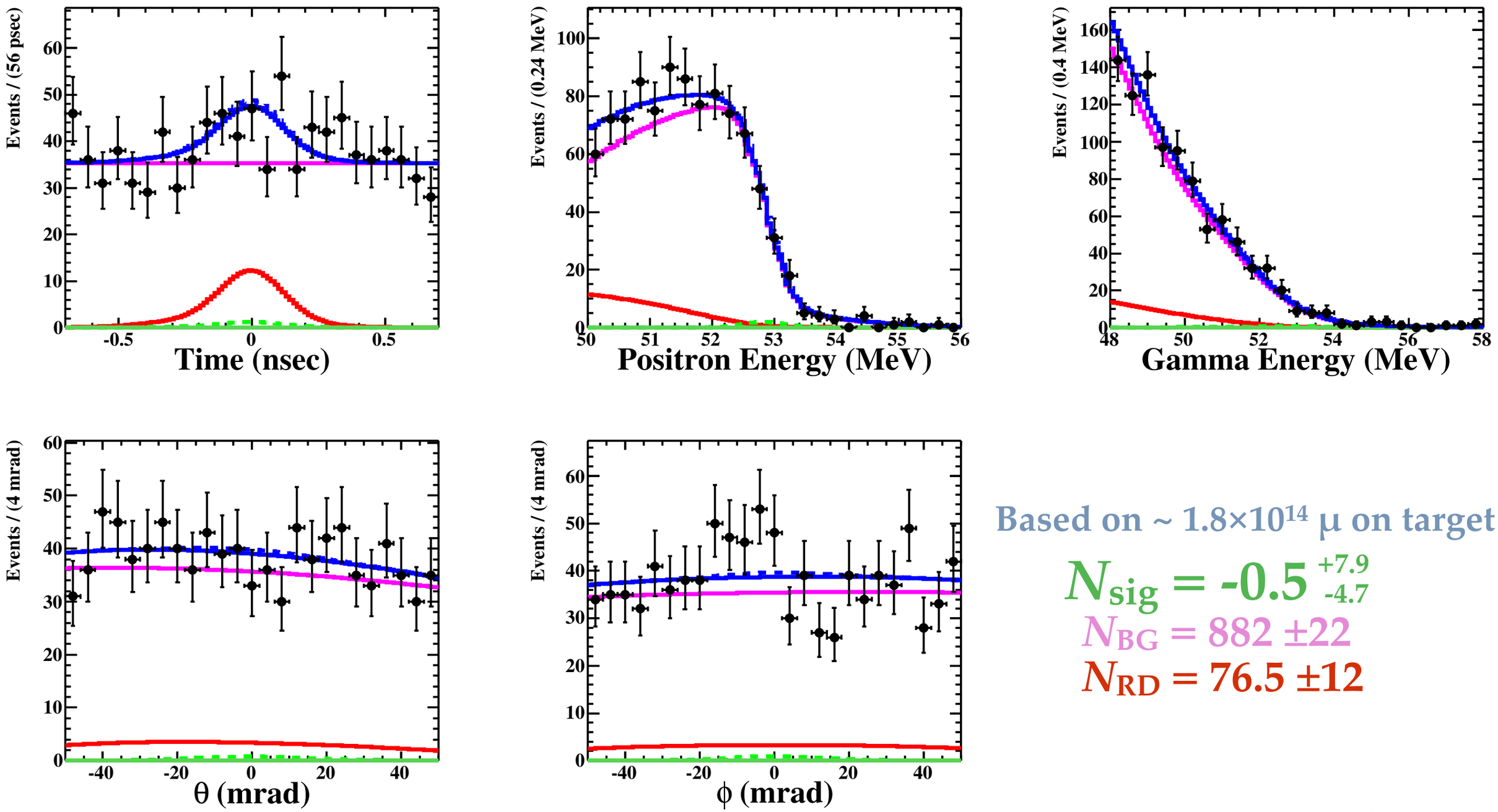


- Accumulate more statistics.
- Improve calibrations/alignments.
- Perform combined analysis on 2009+2010.

Results (2009+2010)



Based on ~ 1.8×10^{14} μ on target

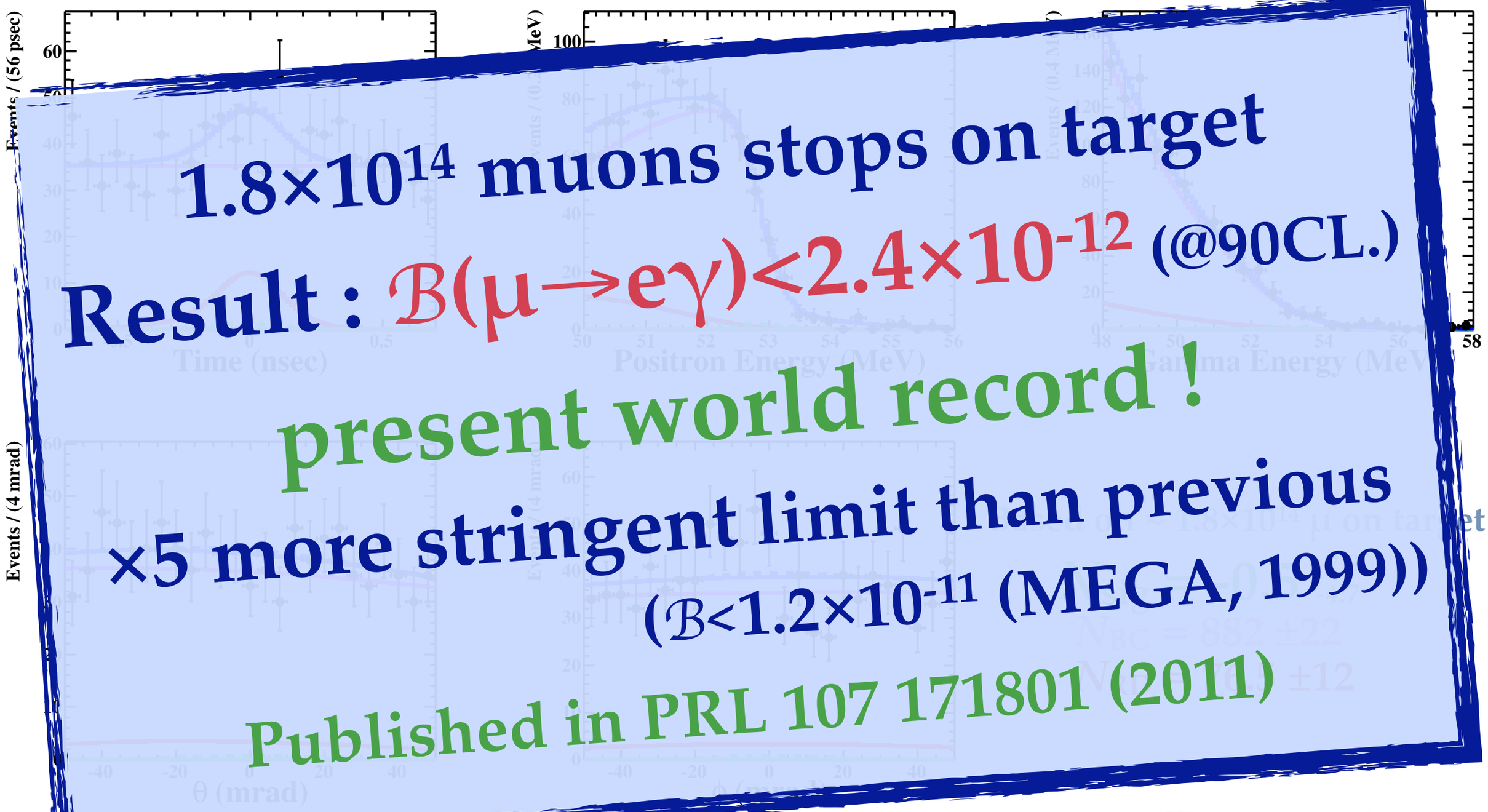
$N_{sig} = -0.5^{+7.9}_{-4.7}$

$N_{BG} = 882 \pm 22$

$N_{RD} = 76.5 \pm 12$

un-binned likelihood fitting on 5 discriminating observables

Results (2009+2010)



1.8×10^{14} muons stops on target

Result : $\mathcal{B}(\mu\to e\gamma)<2.4\times10^{-12}$ (@90CL.)

present world record !

×5 more stringent limit than previous

($\mathcal{B}<1.2\times10^{-11}$ (MEGA, 1999))

Published in PRL 107 171801 (2011)

un-binned likelihood fitting on 5 discriminating observables

Run 2011

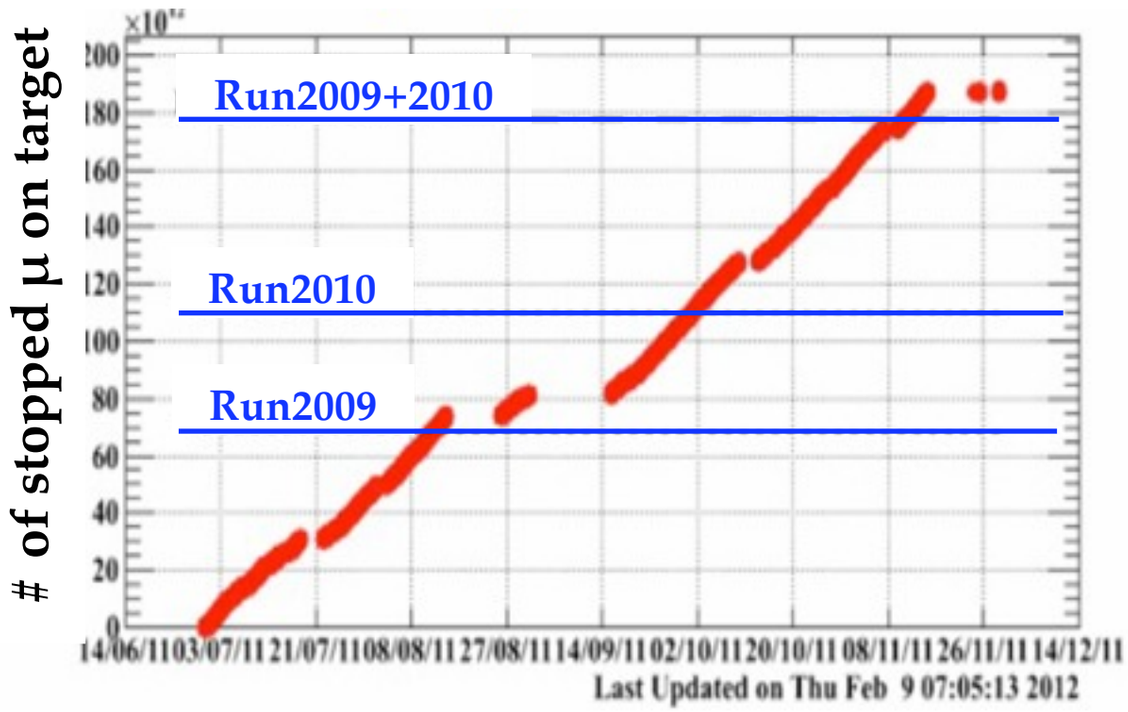
- **Run 2011 was successful. First long DAQ period.**
- All subsystems were operational with reasonable performances during entire data-taking period.

New DC HV

New DC alignment

More efficient LXe calibration

Higher DAQ efficiency



Data Statistics Doubled !!

1.9×10^{14} μ stopped

(1.75×10^{14}μ in 2009+2010)

Analysis Status of Run 2011

- Analysis on data 2011 is in a good shape.
- Calibration/Alignment and optimization of analysis are almost finished.
- Estimated detector performance is comparable (even better) to previous years.

	2010	**2011**
γ Energy σE_γ (%)	1.9 (depth>2cm)	1.7 (depth>2cm)
γ Position σx_γ (mm)	5/6	←
γ Efficiency ε_γ (%)	59	63
e^+ Mom. σp_e (%)	0.61(core 79%)	0.61(core 86%)
e^+ Angle $\sigma\theta_e$ (mrad)	7.2(ϕ)/11(θ)	6.5(ϕ)/10.8(θ)
e^+ Efficiency ε_e (%)	41	←
γ-e^+ Timing σ_T (ps)	126(core)	133
μ^+ decay vertex (mm)	2.0/1.1	1.9/1.0
Trigger Efficiency (%)	92	95
# of stopped μ	1.1×10^{14}	**1.9×10^{14}**
Sensitivity	2.2×10^{-12}	**next slide !**

PRELIMINARY

3 major updates on analysis

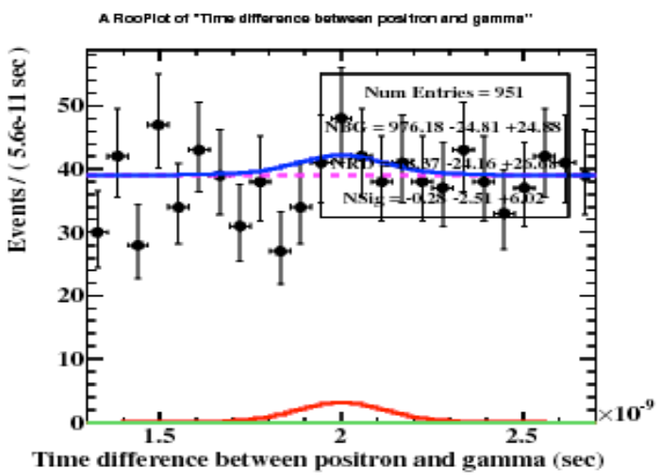
new pile-up rejection

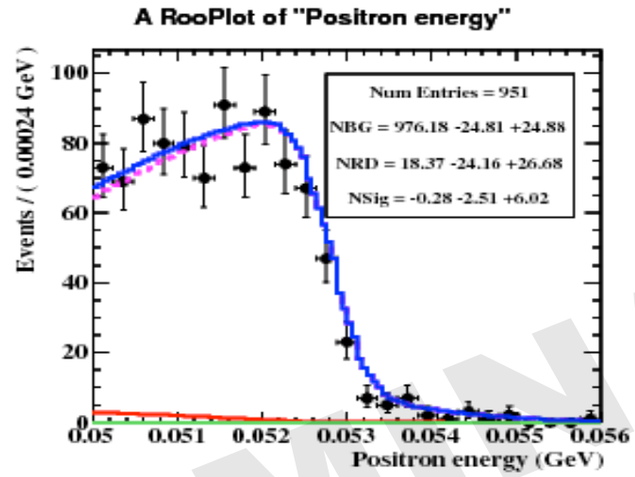
noise reduction at offline

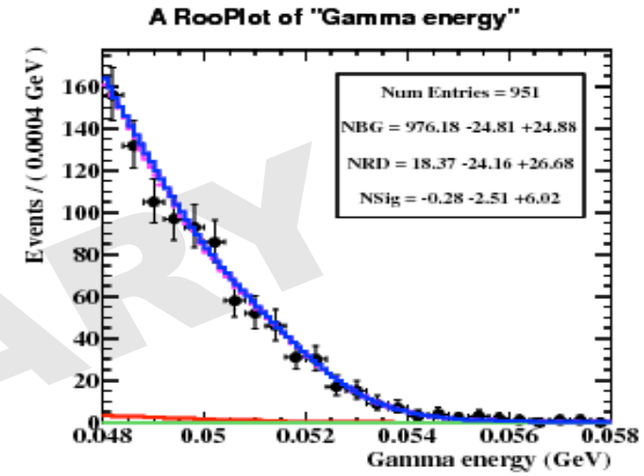
new tracking code and PDF for e^+

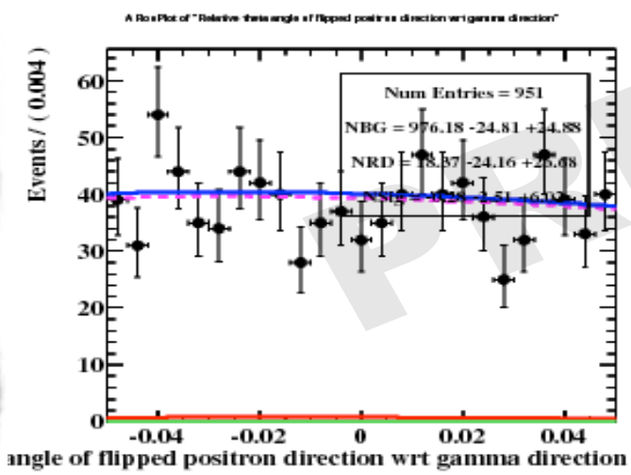
Potential of Run2011 (preliminary)

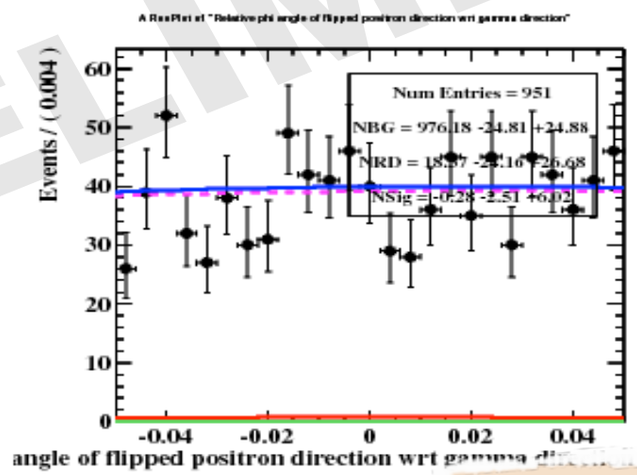
Likelihood Fitting on Sideband Samples











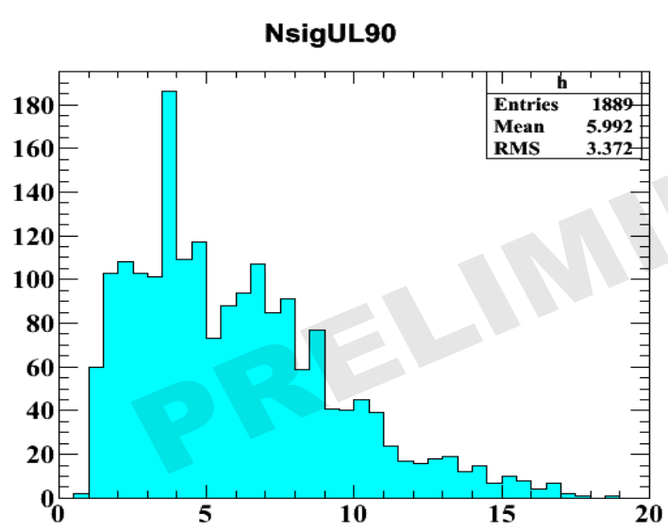
(1.645σ)

$N_{sig} = -0.3^{+6.0}_{-2.5}$

$N_{acc} = 951^{+25}_{-25}$

$N_{RMD} = 18^{+27}_{-24}$

N_{sig} UL (90% CL.)



median Nsig UL = 5.4

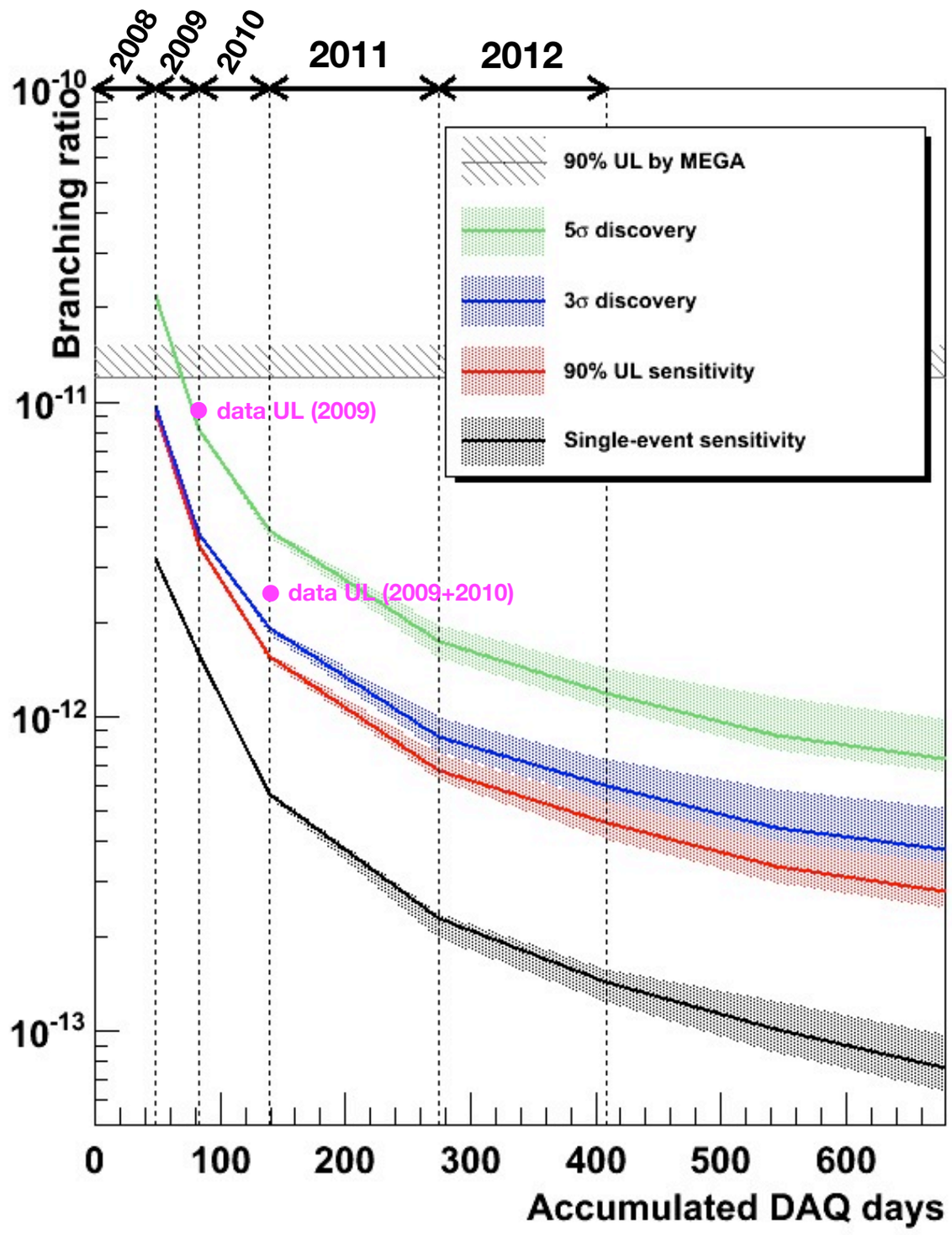
Sensitivity : 1.5×10^{-12}

Expected Sensitivity

$\sim 1\times10^{-12}$

(2011 data only)

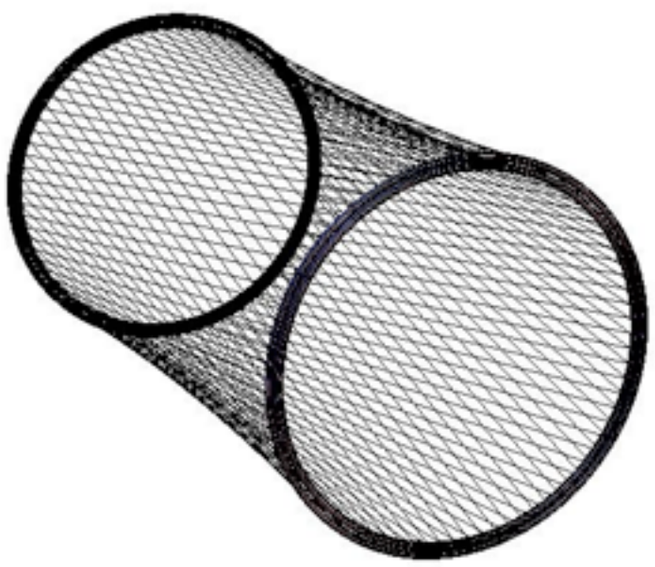
MEG Upgrade → MEG-2

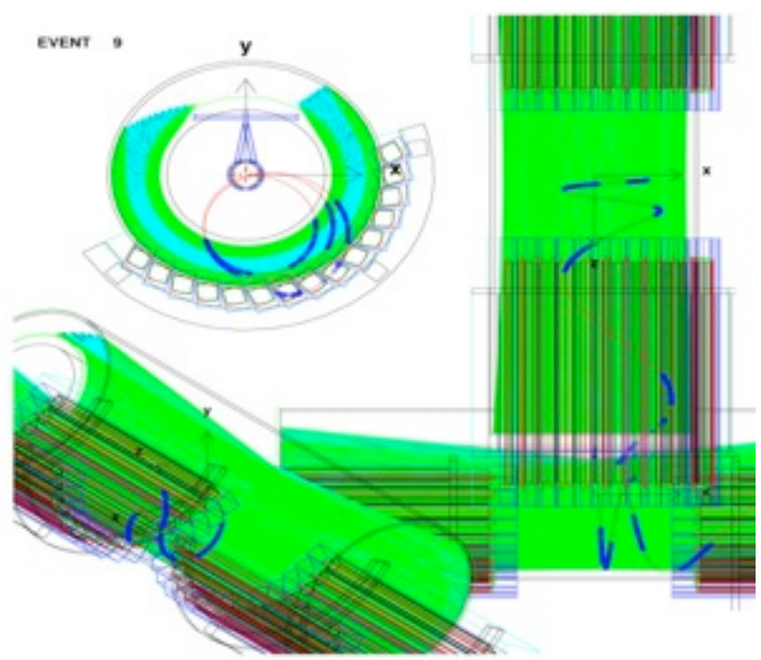


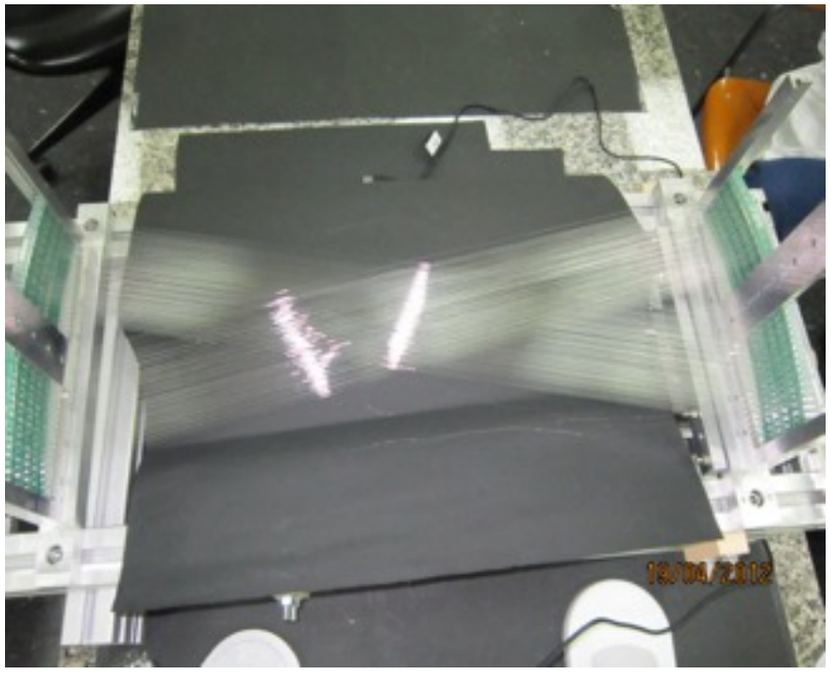
- **MEG sensitivity is surely and steadily improving,**
  - **2009+2010+2011→Enter to *O*(-13)**
  - Exploring ***O*(-13)** region by adding 2012 data holds **3-σ discovery potential**, if $\mathcal{B} \gtrsim 10^{-12}$
- but is moderately slowing down...
- Now it's a time to consider the major upgrade of experiment !!
- Several R&Ds are ongoing to perform the experiment with
  - **"×3 higher beam intensity"**
  - **"improved resolution/efficiency"**

e^+-detector upgrade (tracker)

- **Unique volume cylindrical DC concept**, with very small cell & all stereo
  - Avoid any material along the e^+ path → **improve efficiency/resolution**
  - Track e^+ until the timing counter hit → **improve timing resolution**



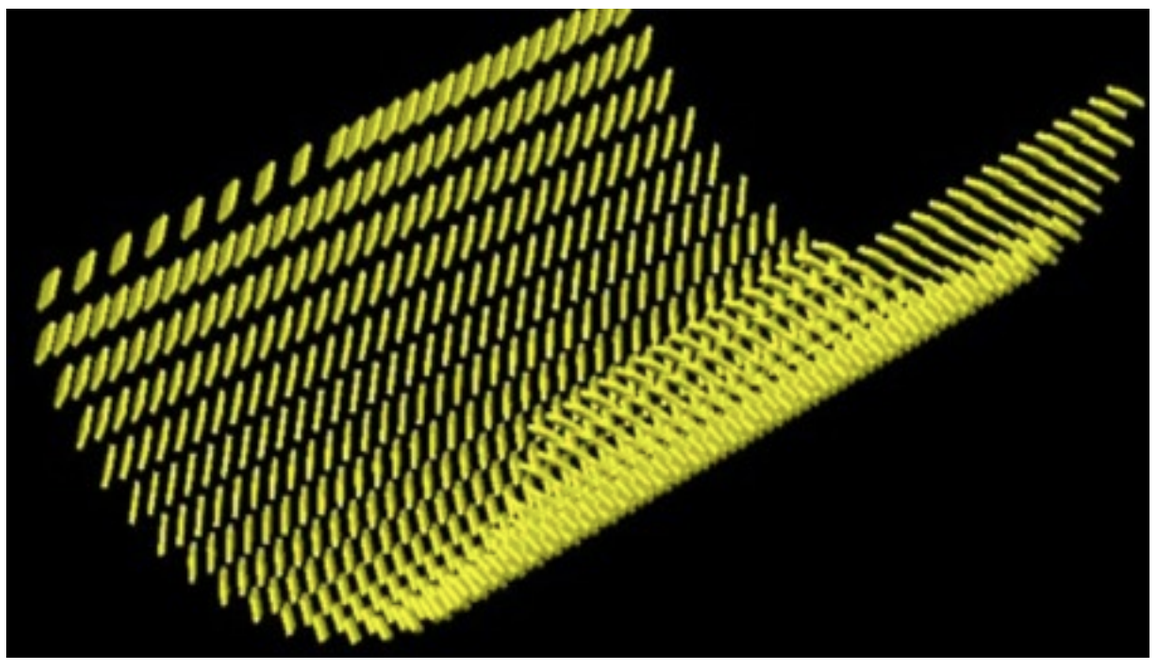


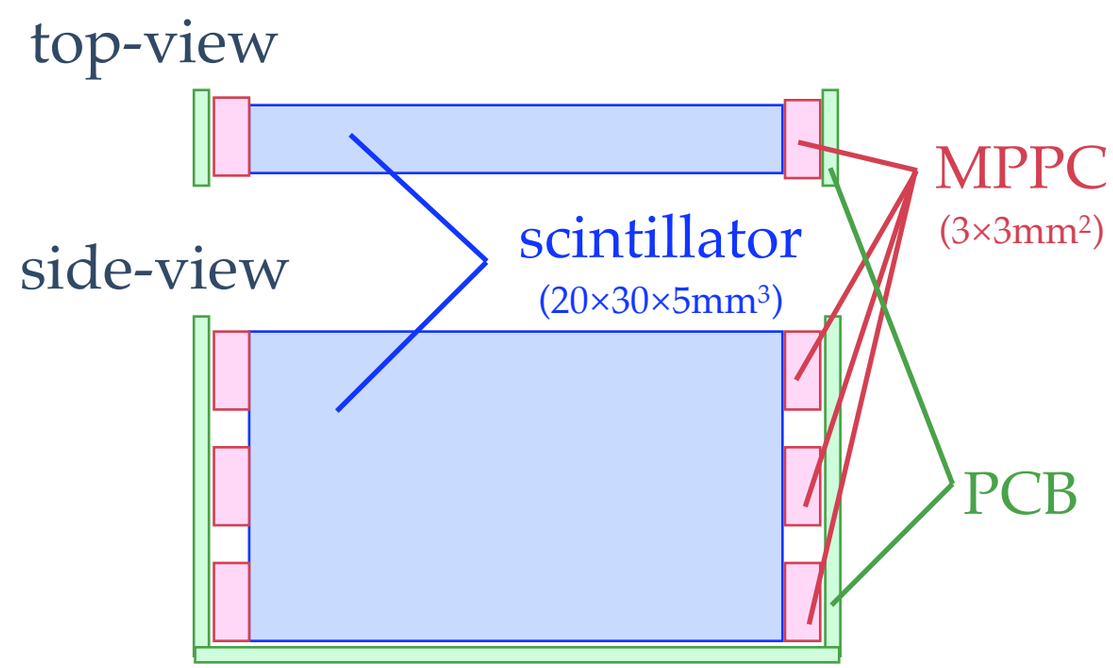


- Intensive simulation work / prototyping are ongoing.
  - Expected Performances; $\varepsilon_{e+} = 91\sim92\%$, $\sigma_p = 140$keV, $\sigma_{\theta,\phi} = 6\sim8$mrad.
  - Prototyping ; Machinery Studies, Aging Study and Performance R&D

e^+-detector upgrade (timing counter)

- **Scintillator pixel detector concept**
  - With small scintillator pixel (~20×30×5 mm^3), Total # of pixels ~ 1500
  - Each pixel is readout by MPPCs from both ends.
  - **Less pileup, Improved time resolution** using multiple hits info.

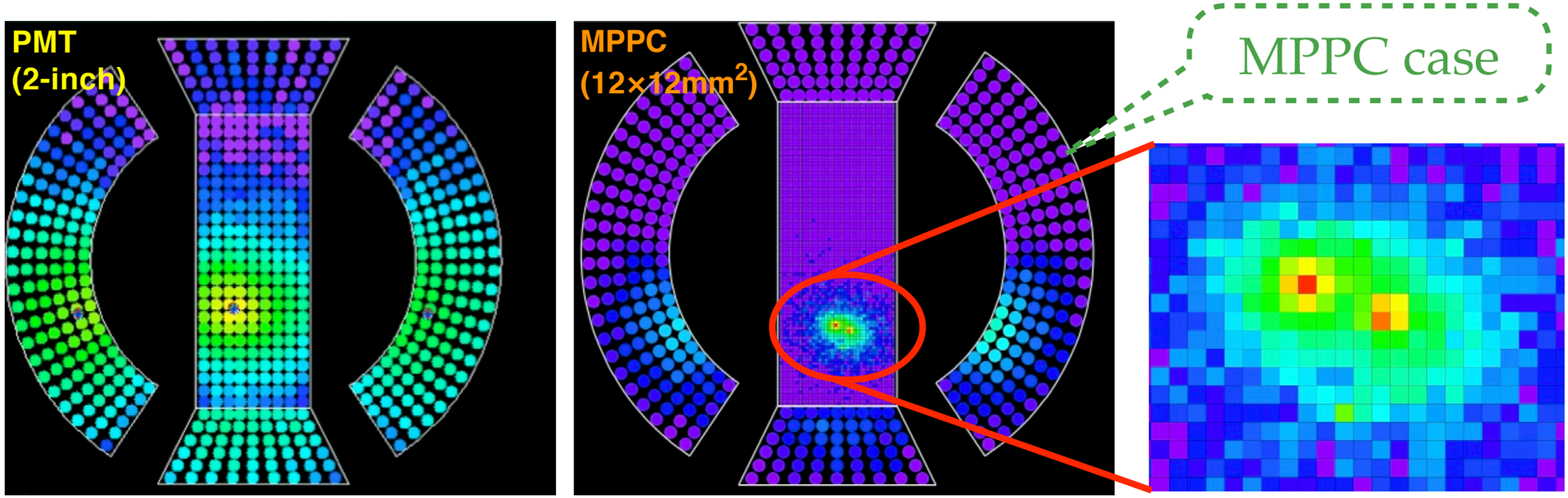




- Simulation works are ongoing
  - Optimization of scintillator size, tilt, layout, and MPPC studies
  - Expected timing resolution = ~35 psec.

γ-detector upgrade

- **Replace inner face PMTs by smaller photosensors in the present LXe detector**
  - candidate-1 : MPPC
  - candidate-2 : 1″ square shape PMT
  - candidate-3 : 2″ flat panel multi-anode PMT
  - **Good pile-up elimination power and resolutions are expected.**

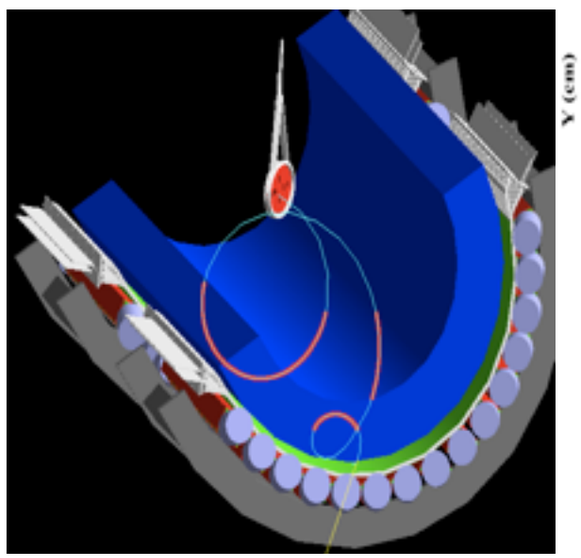


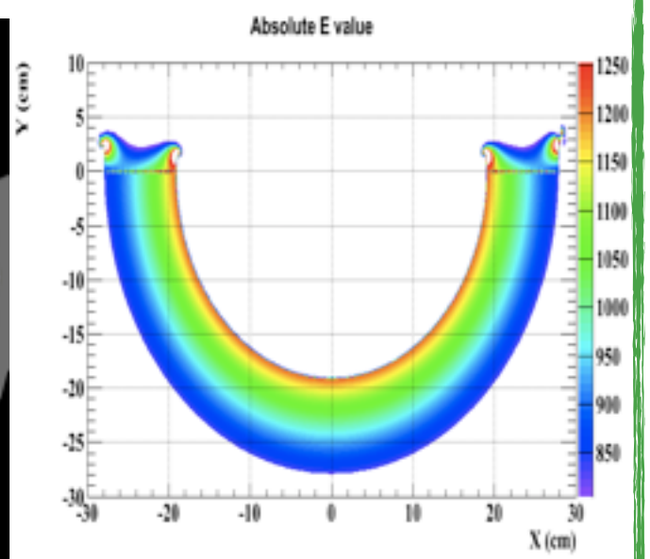
- Simulation works and photosensor R&Ds are ongoing.
  - Estimated resolutions; $\sigma_E = 0.7\sim0.9\%$, $\sigma_x = 2\sim4$mm

Alternative Upgrade R&Ds

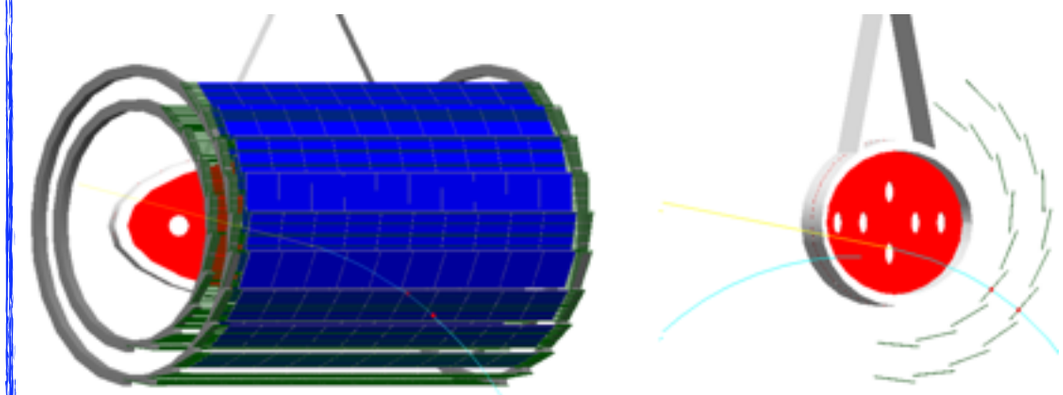
- **Many alternatives are under studies, for example...**

Radial TPC base e^+ tracker

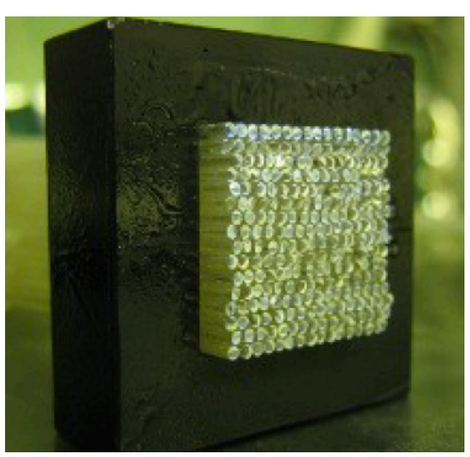




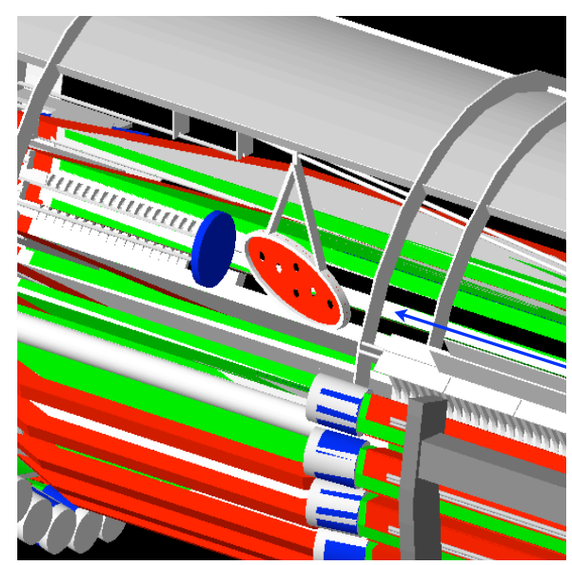
SVD option

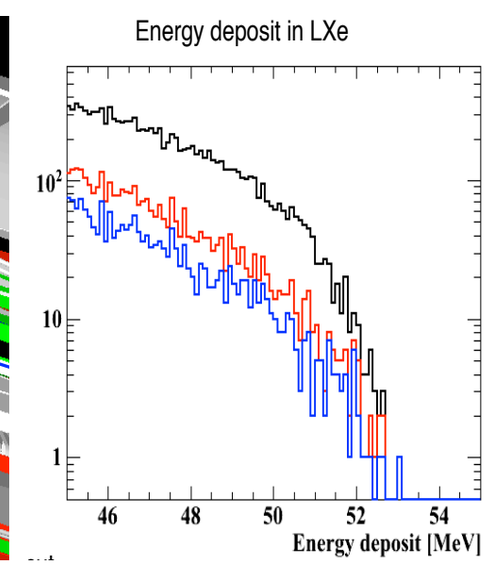


Active Target idea



Radiative decay Veto





MEG prospects

1. Analysis

- Almost Finished
- Box will be opened in this Autumn

- Improved analysis is applied on 2009+2010, and then it will be re-processed.
- After reprocess, blind box will be opened with old data
- All combined analysis (2009+2010+2011) will be published in this autumn → $O(-13)$!!

2. Physics Run

- Will Re-Start Soon
- Long Shutdown will start in 2013

- Detector Maintenance is almost finished.
- Extra run (3 months) are planned at begin of 2013 → Enough statistics to achieve 6×10^{-13}
- Long Shutdown (~2 y) for Major Upgrade

3. Upgrade

- R&D Started
- Goal : 5×10^{-14} Sensitivity

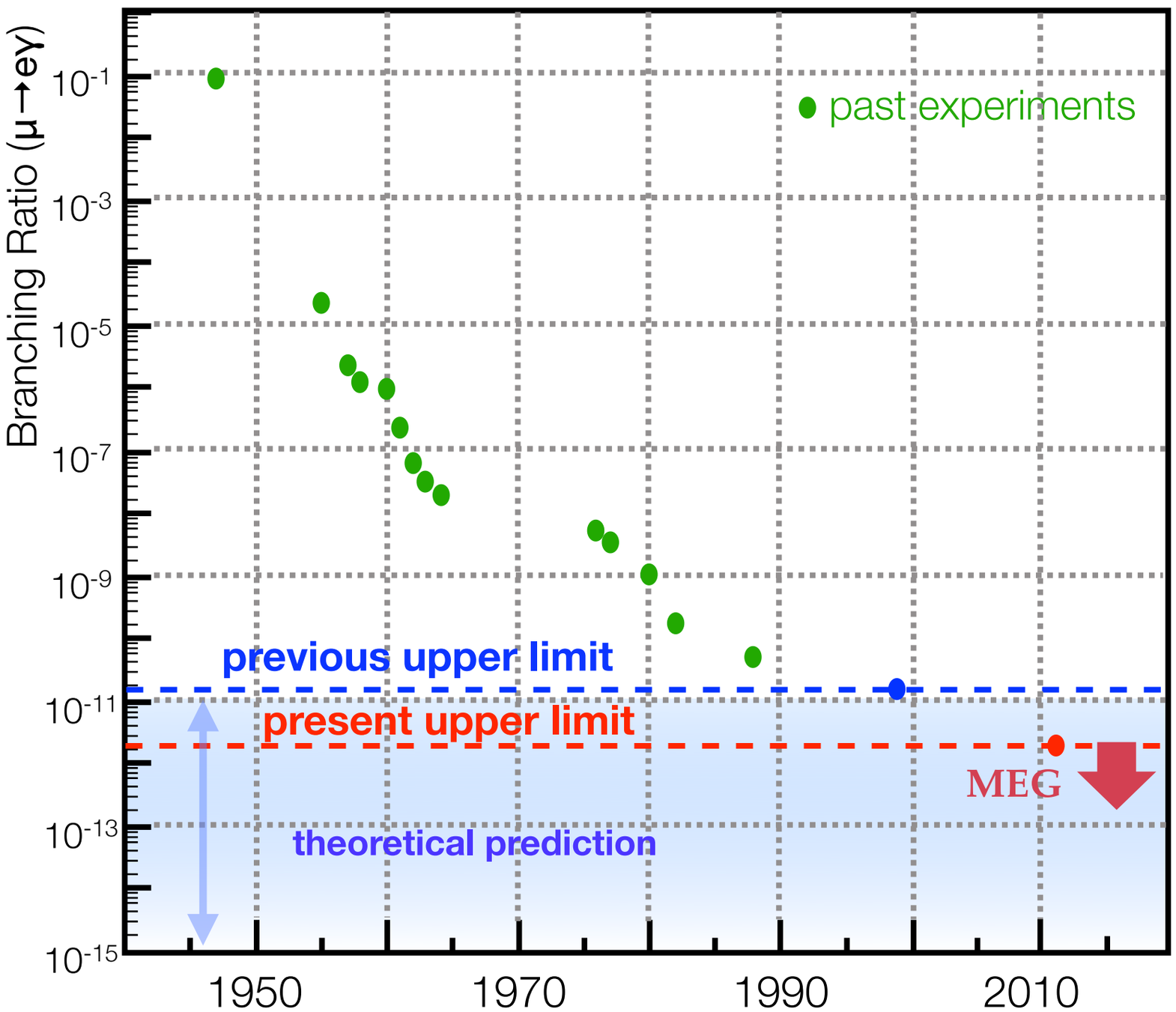
- Many Activities are ongoing for upgrade
- Proposals are under preparation for INFN (Jul.) and PSI (Dec.)
- MEG-II will start ~2015(16) and run ~3 y

Conclusions

- After the previous ICHEP (2010, Paris), MEG renewed the Upper limit of **$\mathcal{B}(\mu\to e\gamma)$ as 2.4×10^{-12} (@90CL.)** which is **×5 more stringent** than previous limit 1.2×10^{-11} (MEGA, 1.2×10^{-11}, 1999)
  - MEG 2009+2010 data (~1.75×10^{14} μ stops) were analyzed for that result.
- **MEG 2011 was successfully done**, and analysis is almost verging to a close.
  - According to the side-band samples, **~1×10^{-12} of sensitivity is expected**
  - Improved analysis will also be applied on 2009/2010 data.
  - **All combined analysis will be published this autumn → *O*(-13)**
- MEG 2012 will start soon.
  - To compensate the shorter DAQ period, extra runs will be performed at the beginning of 2013, and then we will have a long break for upgrade.
- **MEG Upgrade**
  - **Many upgrade R&Ds are ongoing in parallel with MEG 2012 run**
  - **Aiming ~5×10^{-14} of UL sensitivity, can be a good competitor for LHC.**

appendix

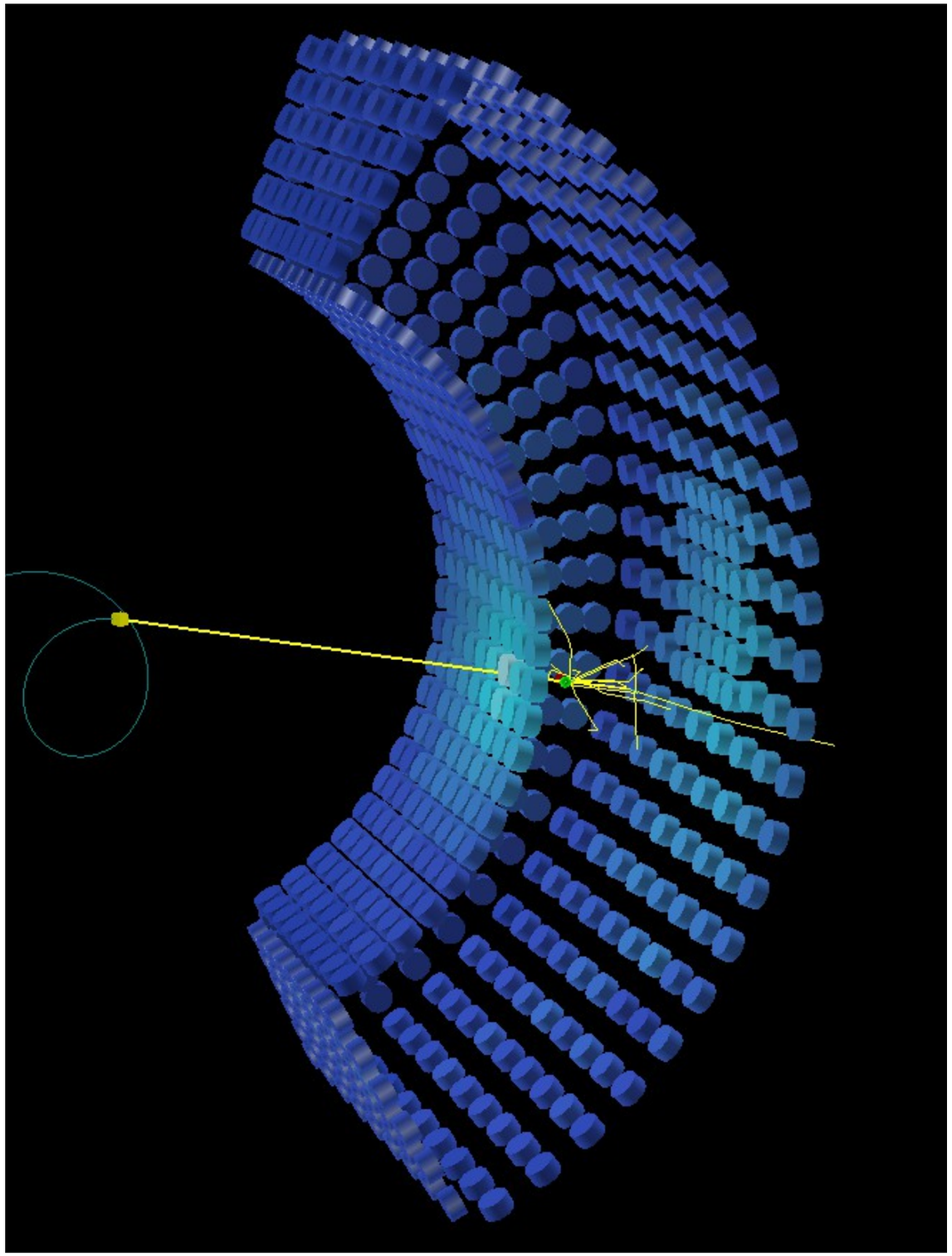
Long History of "$\mu \to e\gamma$" Search



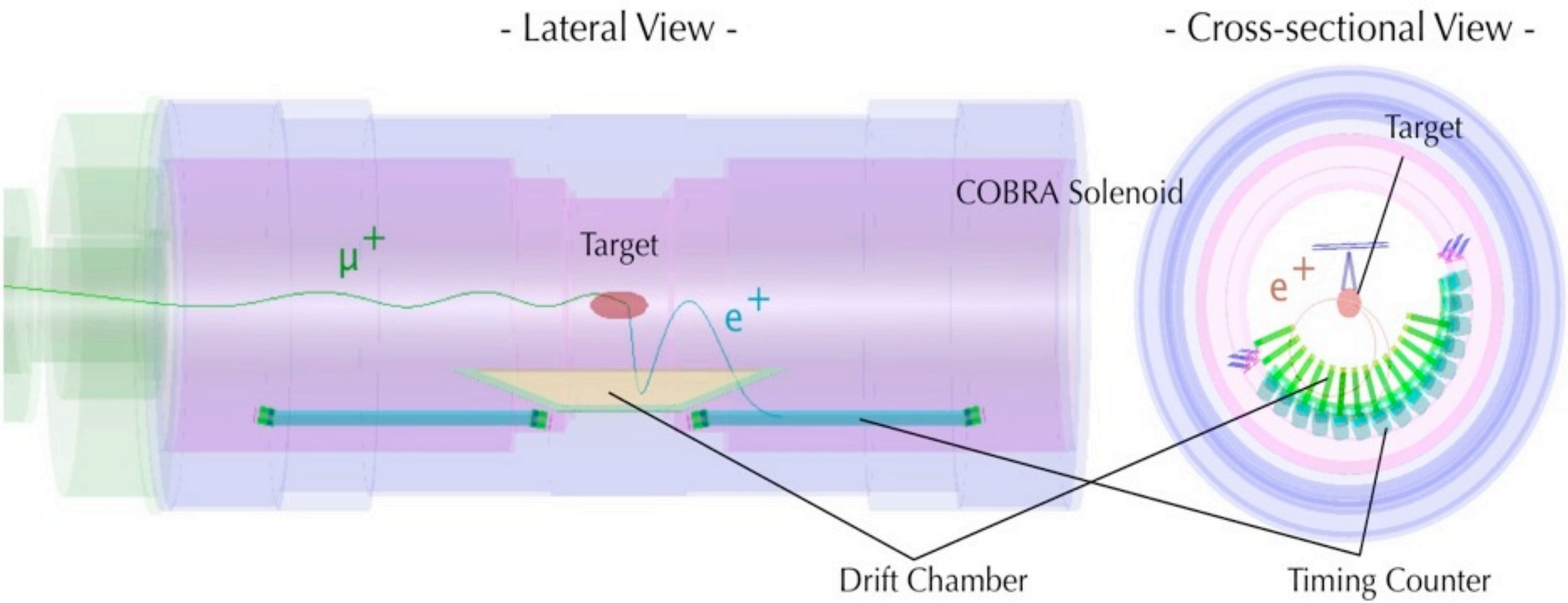
- "$\mu \to e\gamma$" Search Experiment has started right after μ discovery
  - Very Long Tradition
- Now already sensitive to the predicted region.
  - MEG reseted UL on $\mathcal{B}(\mu \to e\gamma) < 2.4 \times 10^{-12}$ in 2011, and is aiming to improve it down to the order of 10^{-13}

Liquid Xenon Scintillation γ Detector

- Homogeneous Volume (~800l) 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 ($0.2X_0$)

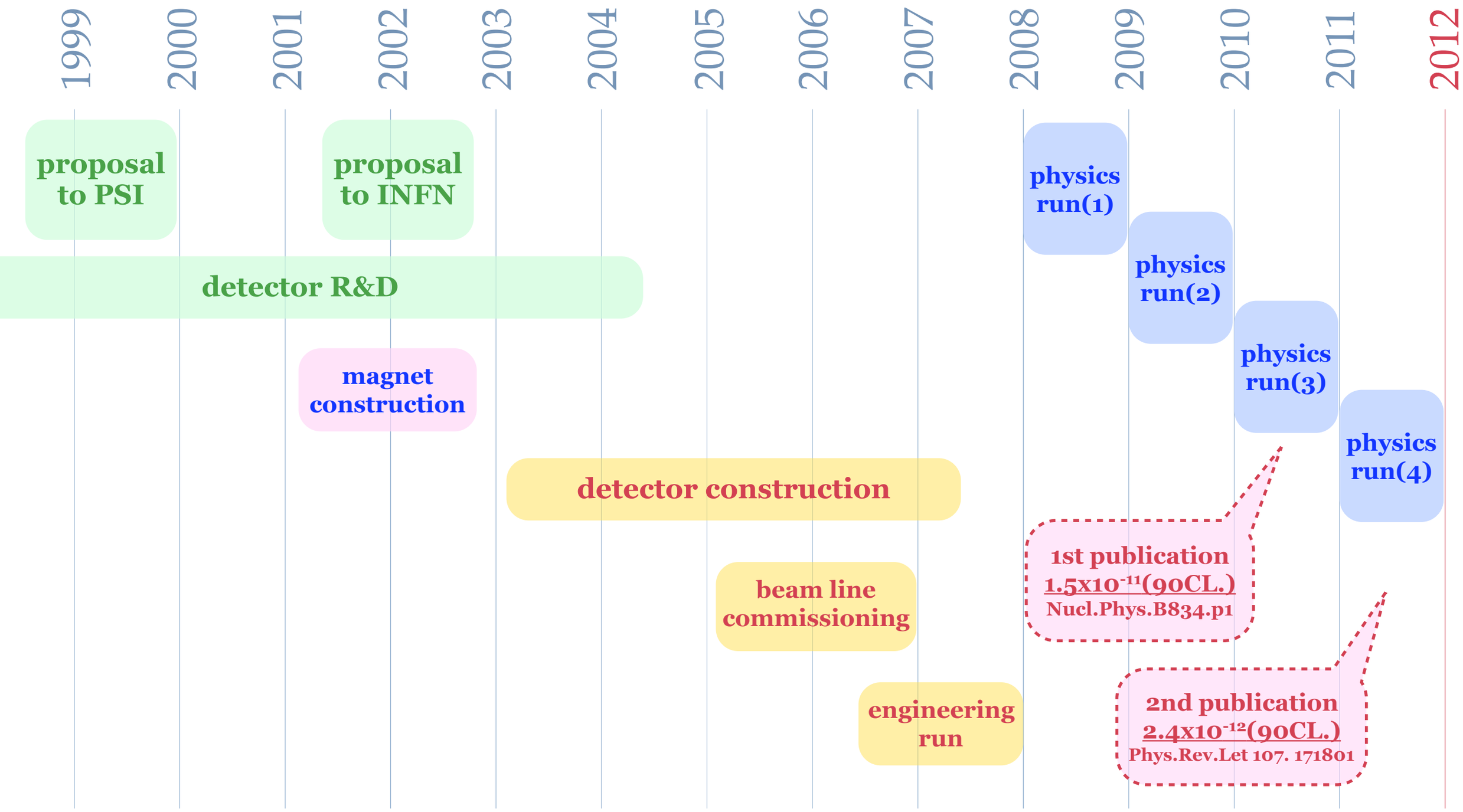
Drift Chamber

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)

MEG Time line



Likelihood Analysis

- Extended unbinned maximum likelihood analysis on number of events

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

- 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

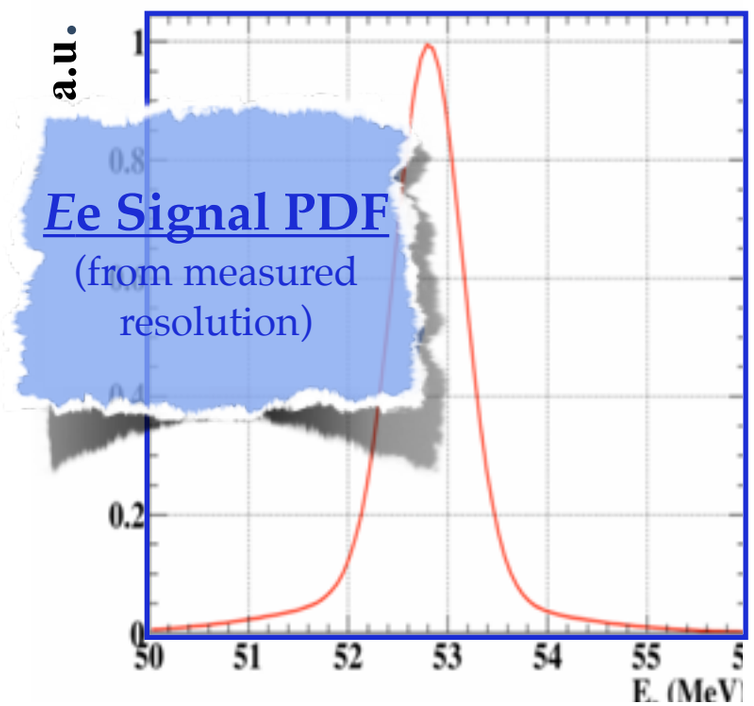
check, understanding or find bug

Different PDF implementation

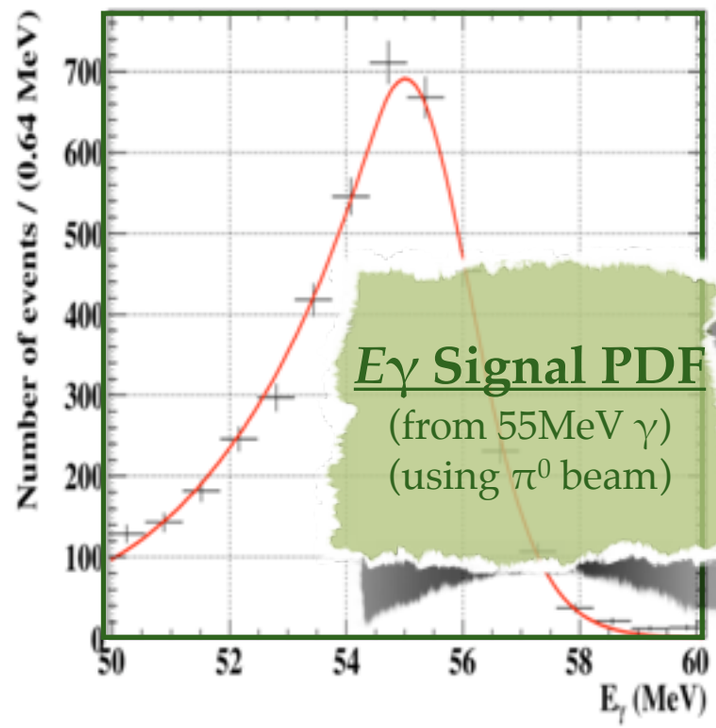
Fit or Input N_{RD}

Different Statistical treatment (Frequentist or Bayesian)

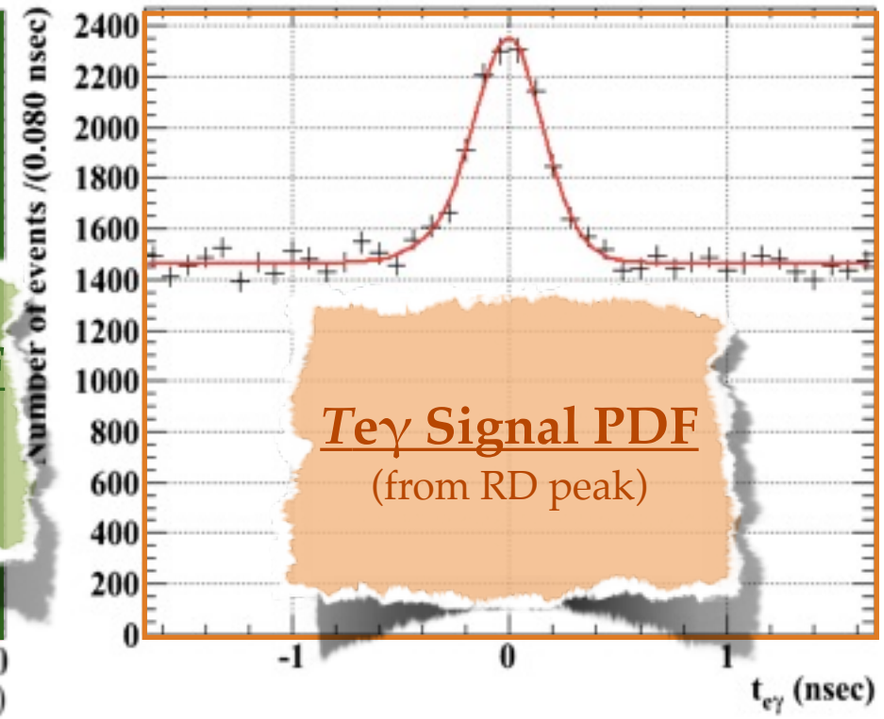
PDFs - Energies, Angles and Timing -



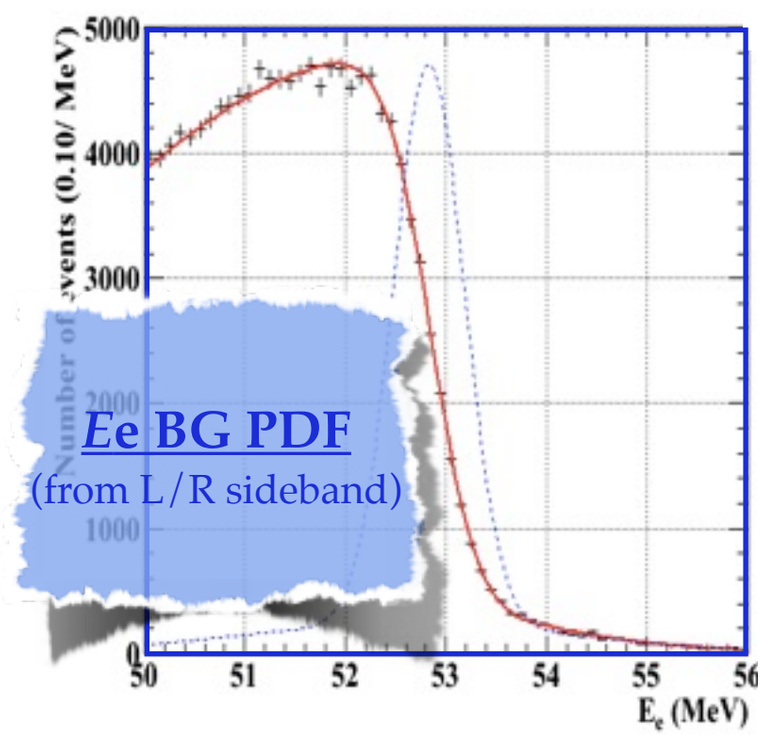
E_e Signal PDF
(from measured resolution)



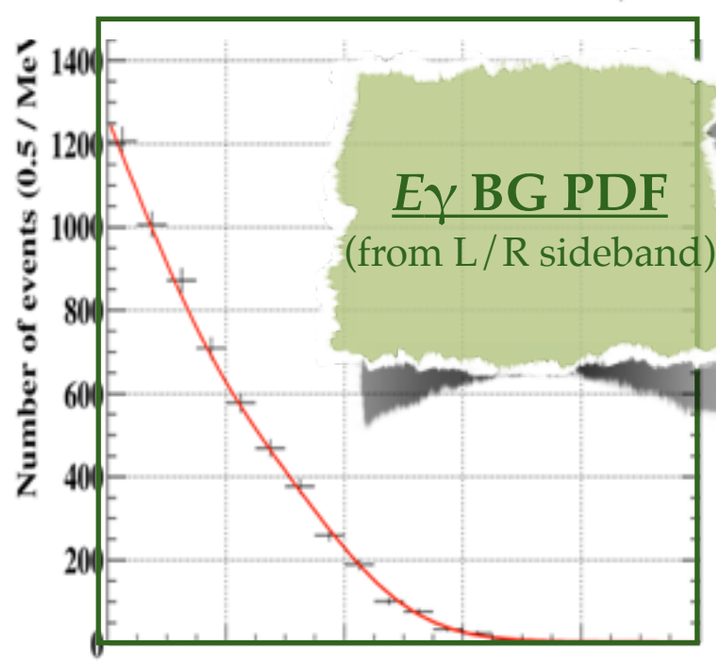
E_γ Signal PDF
(from 55MeV γ)
(using π^0 beam)



$T_{e\gamma}$ Signal PDF
(from RD peak)



E_e BG PDF
(from L/R sideband)



E_γ BG PDF
(from L/R sideband)

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

Signal : from measured resolution

Background : from L/R sideband

Normalization - # of Muon Decay -

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

- # 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

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