A New Result of $\mu \to e\gamma$ Search by MEG

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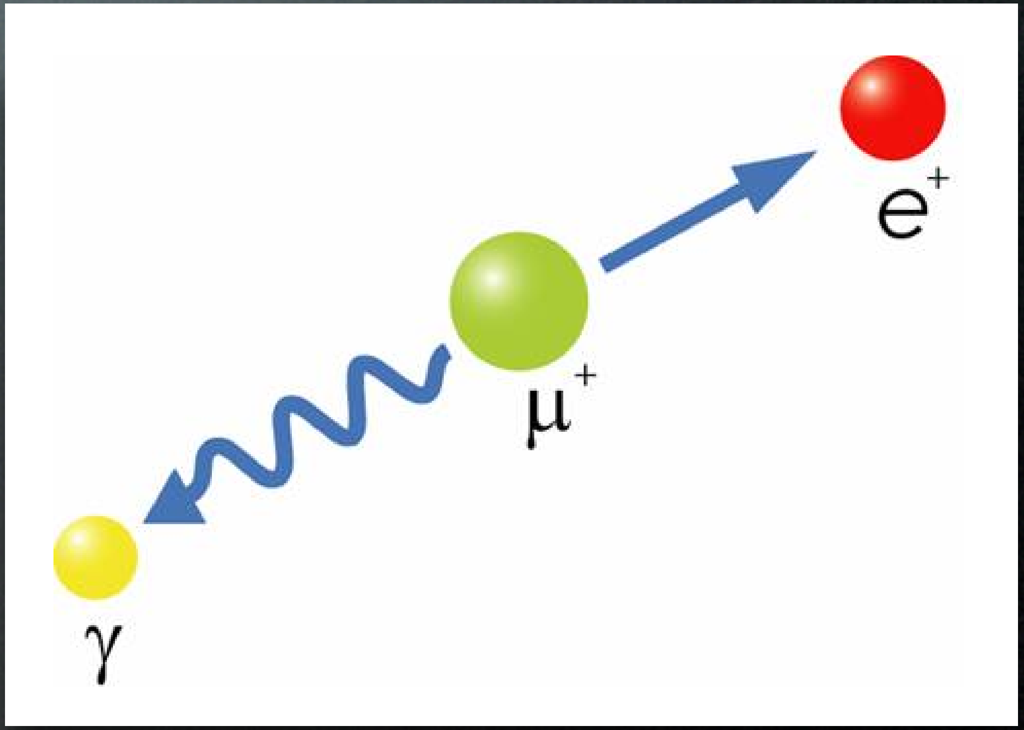
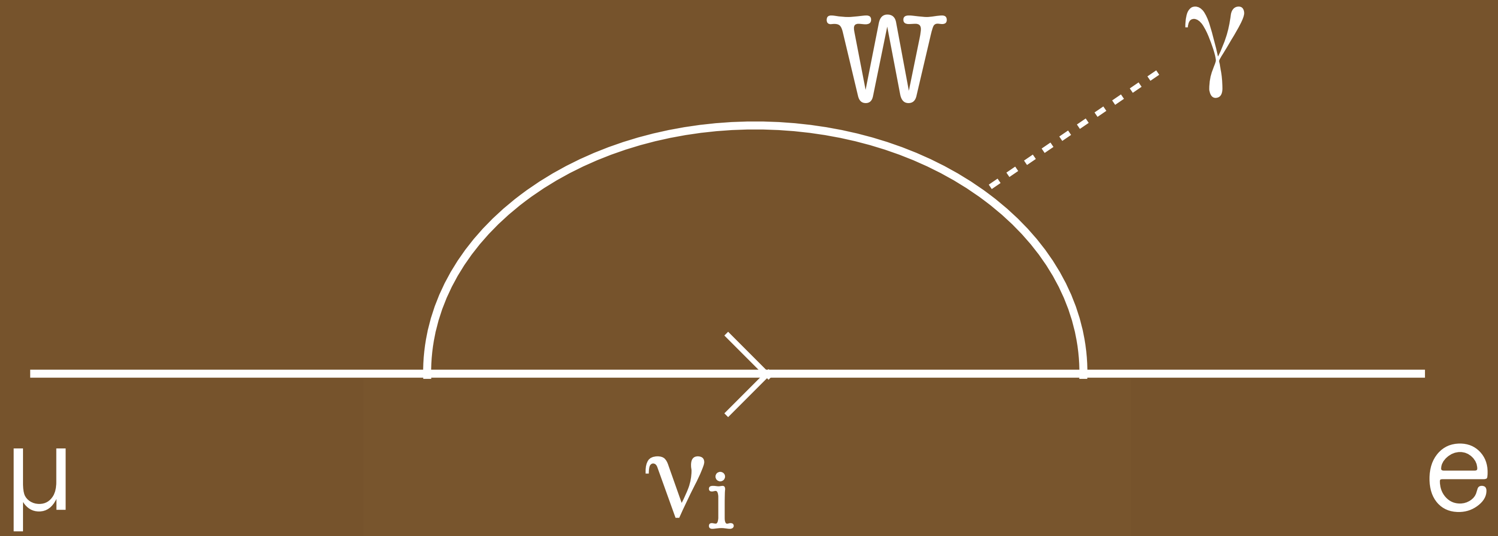
$\mu \rightarrow e\gamma$

- Violates lepton flavor
- Lepton flavor is violated in neutrino mixings



Charged leptons should also mix !

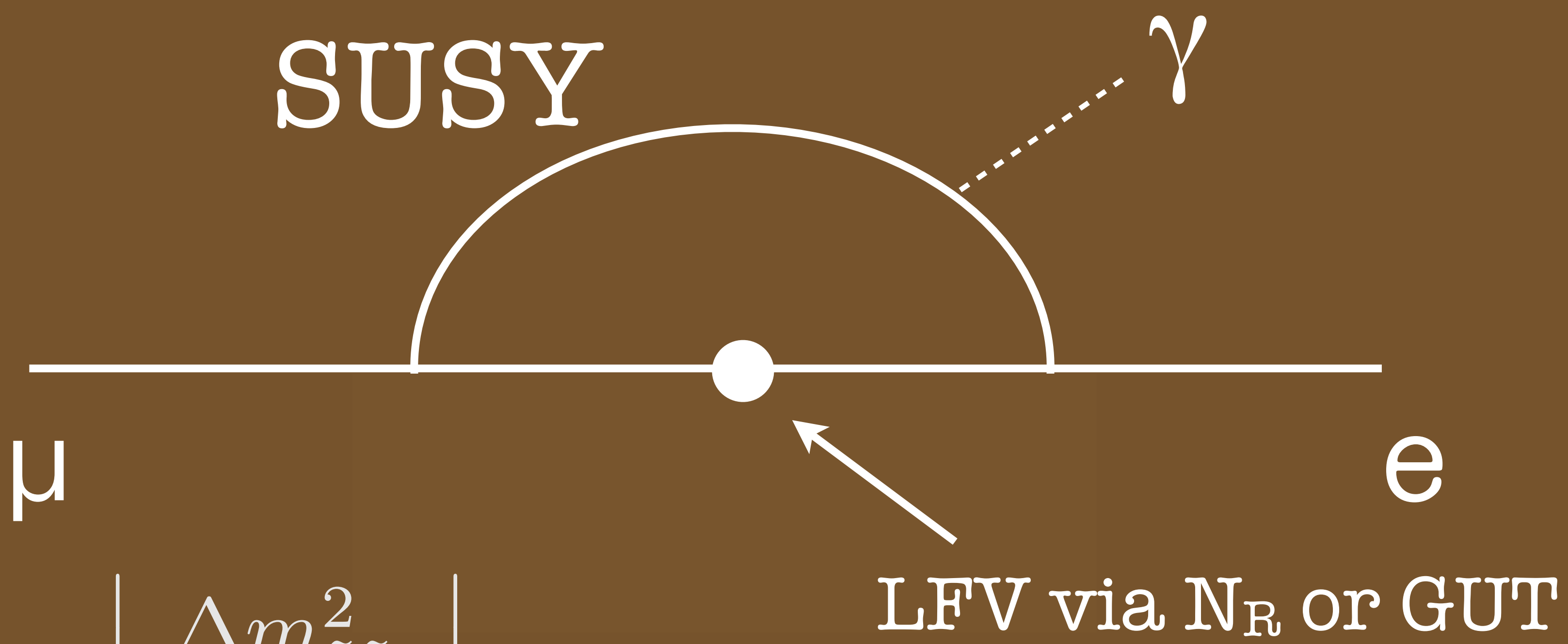


$$\frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}\left(\frac{m^2_{\nu_i}}{M^2_W}\right)U_{ei}\right|^2 \leq 10^{-45}$$

neutrinos are too light

...but practically no mixing

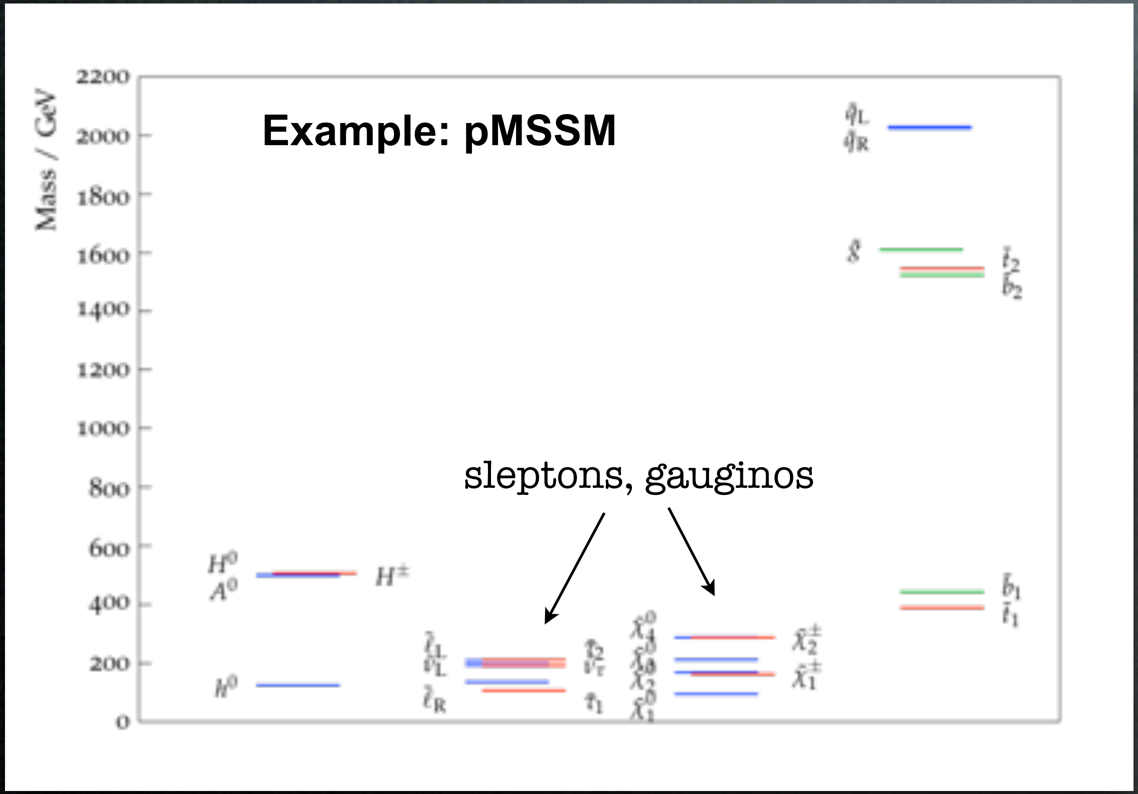
TeV scale physics help them mix !



$$\left|\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{M^2_{SUSY}}\right| \rightarrow \sim 10^{-12}$$

Perhaps we can observe!

TeV scale physics strongly constrained by LHC



- Particle not strongly interacting are NOT strongly constrained
- Dark matter may come from TeV scale physics!

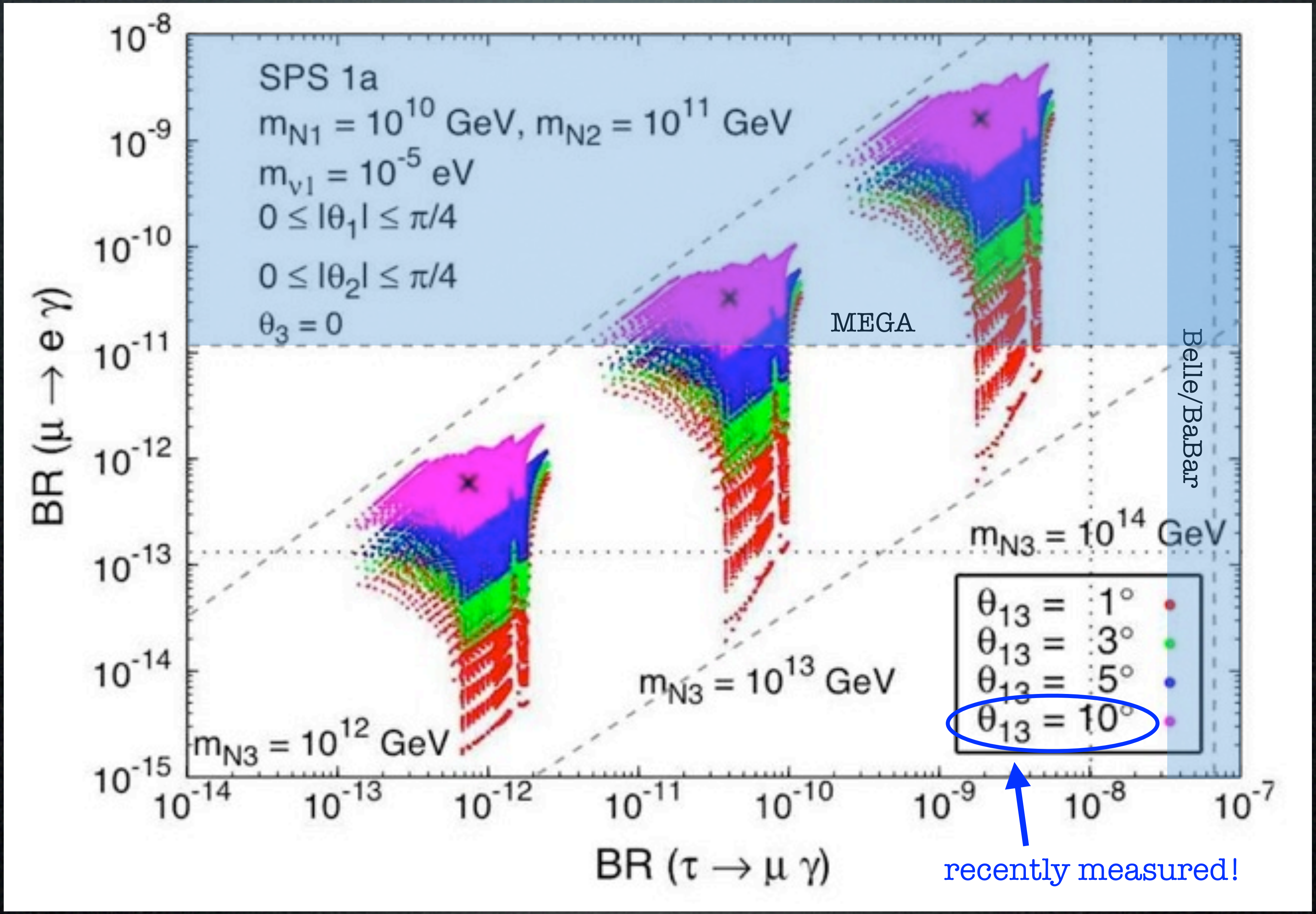
not necessarily SUSY

Complementary to LHC + sources of LFV

GUT , seesaw

Implication of Large θ_{13}

→ larger BR($\mu \to e\gamma$)



S. Antusch et al. JHEP11 (2006) 090

Implication of Large θ_{13}

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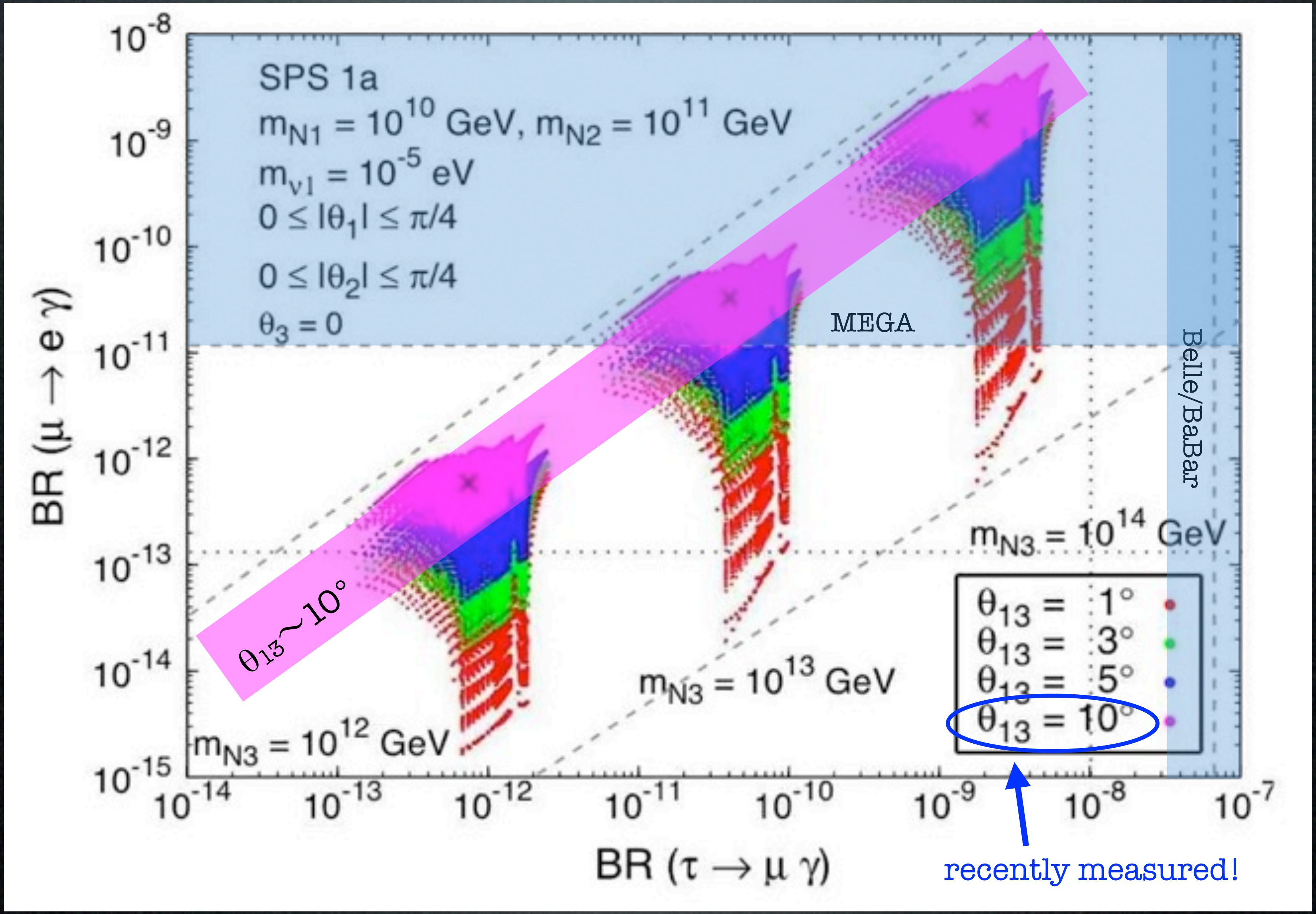

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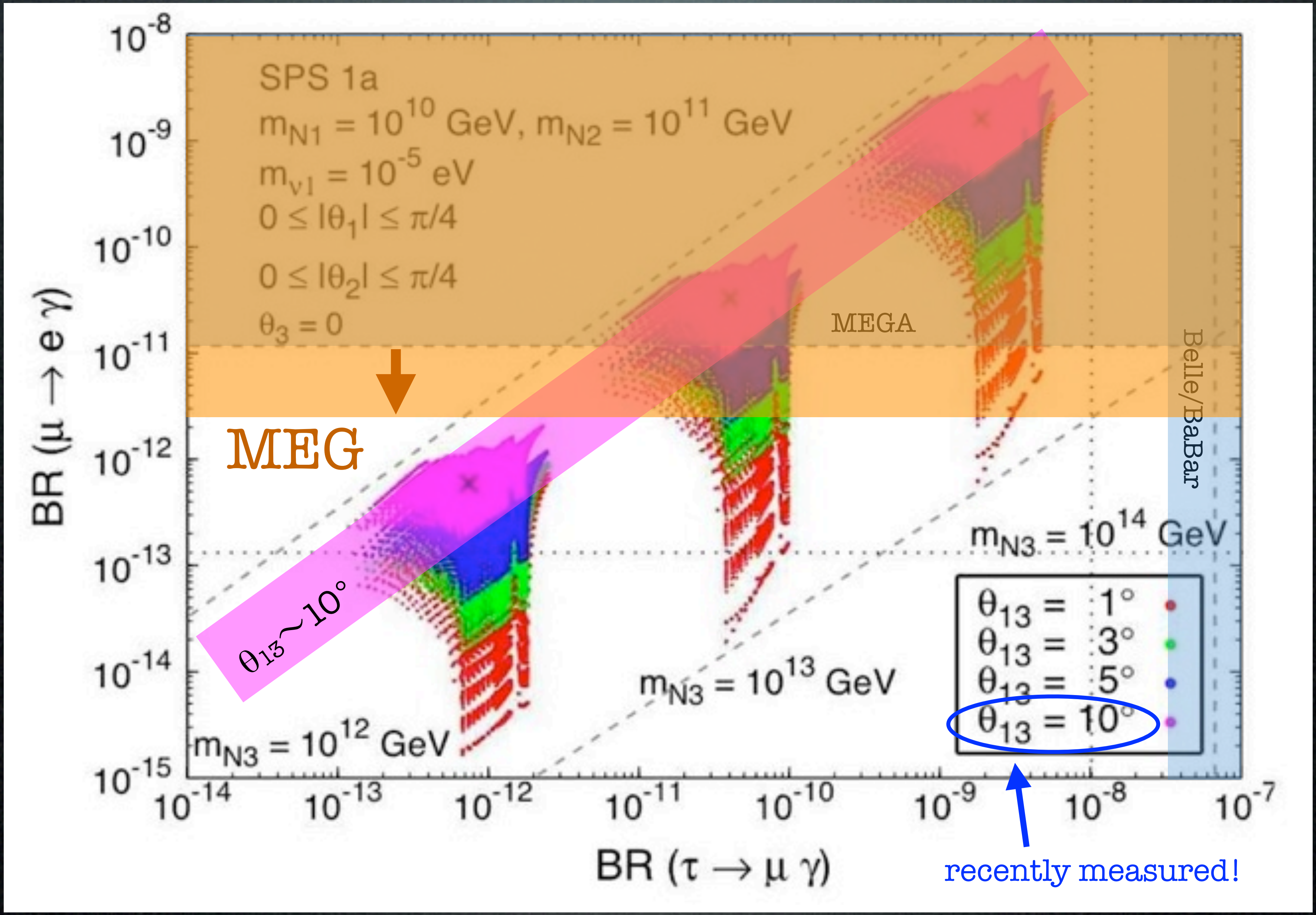

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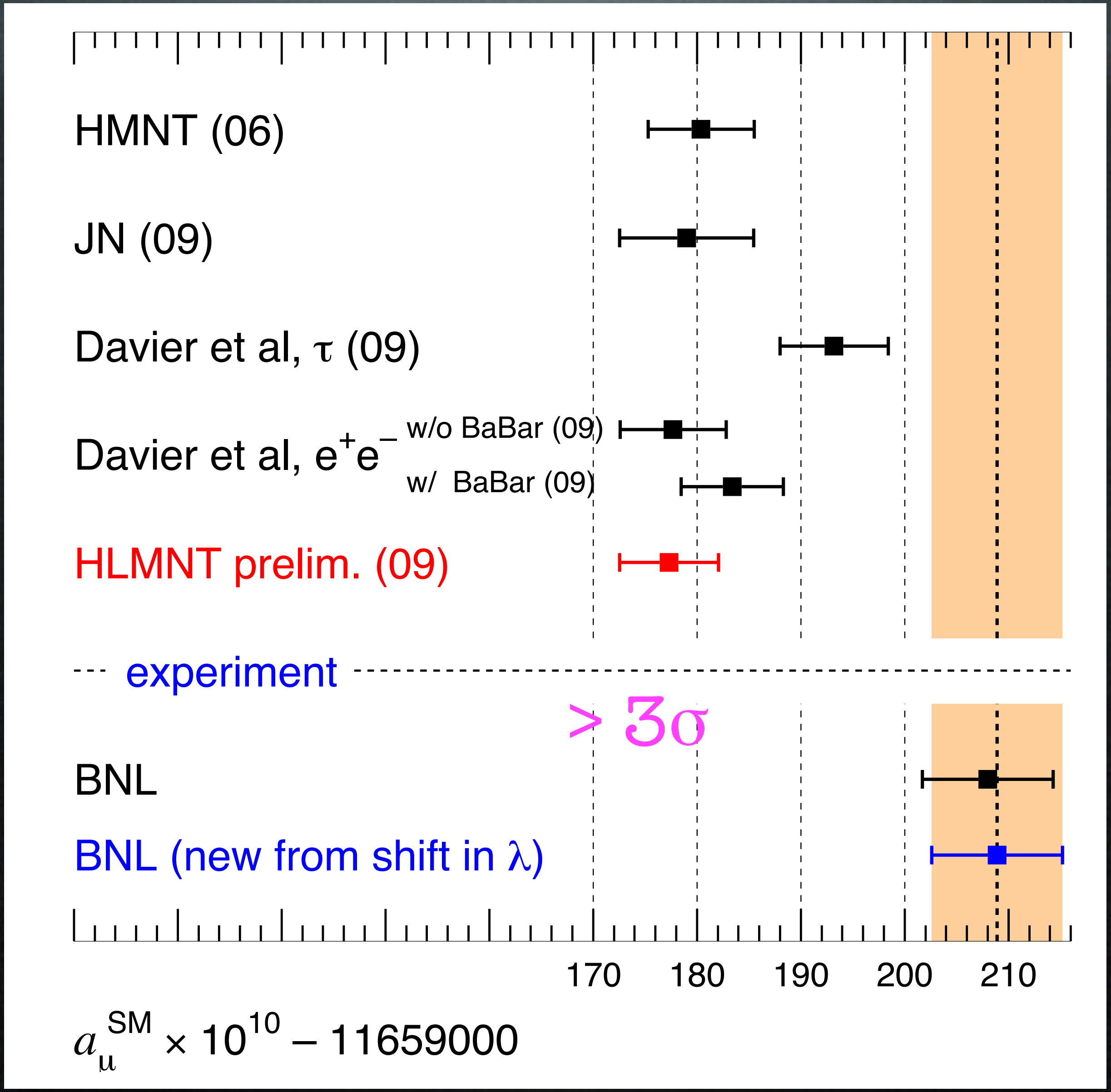
muon (g-2) anomaly



muon's anomalous magnetic moment

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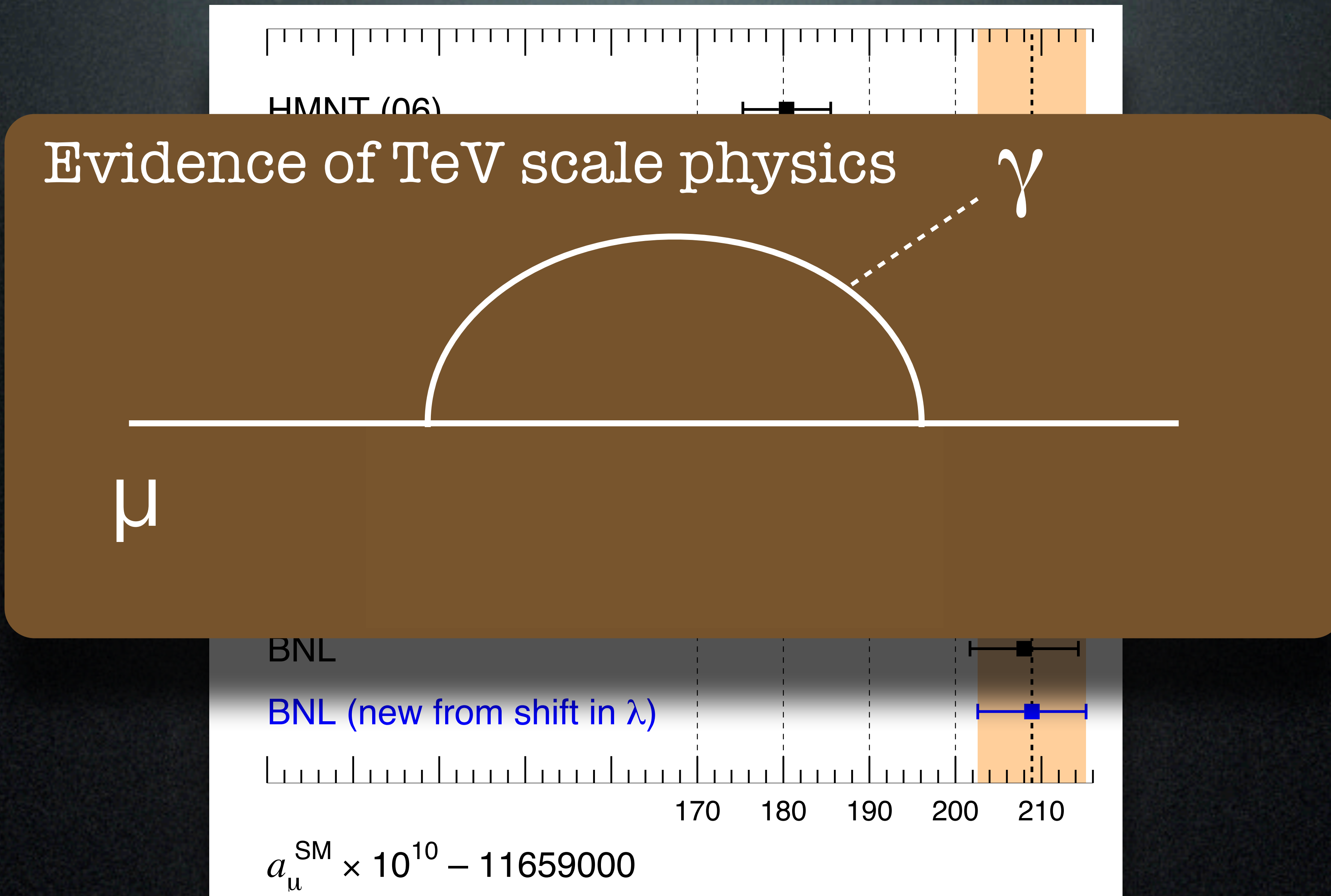

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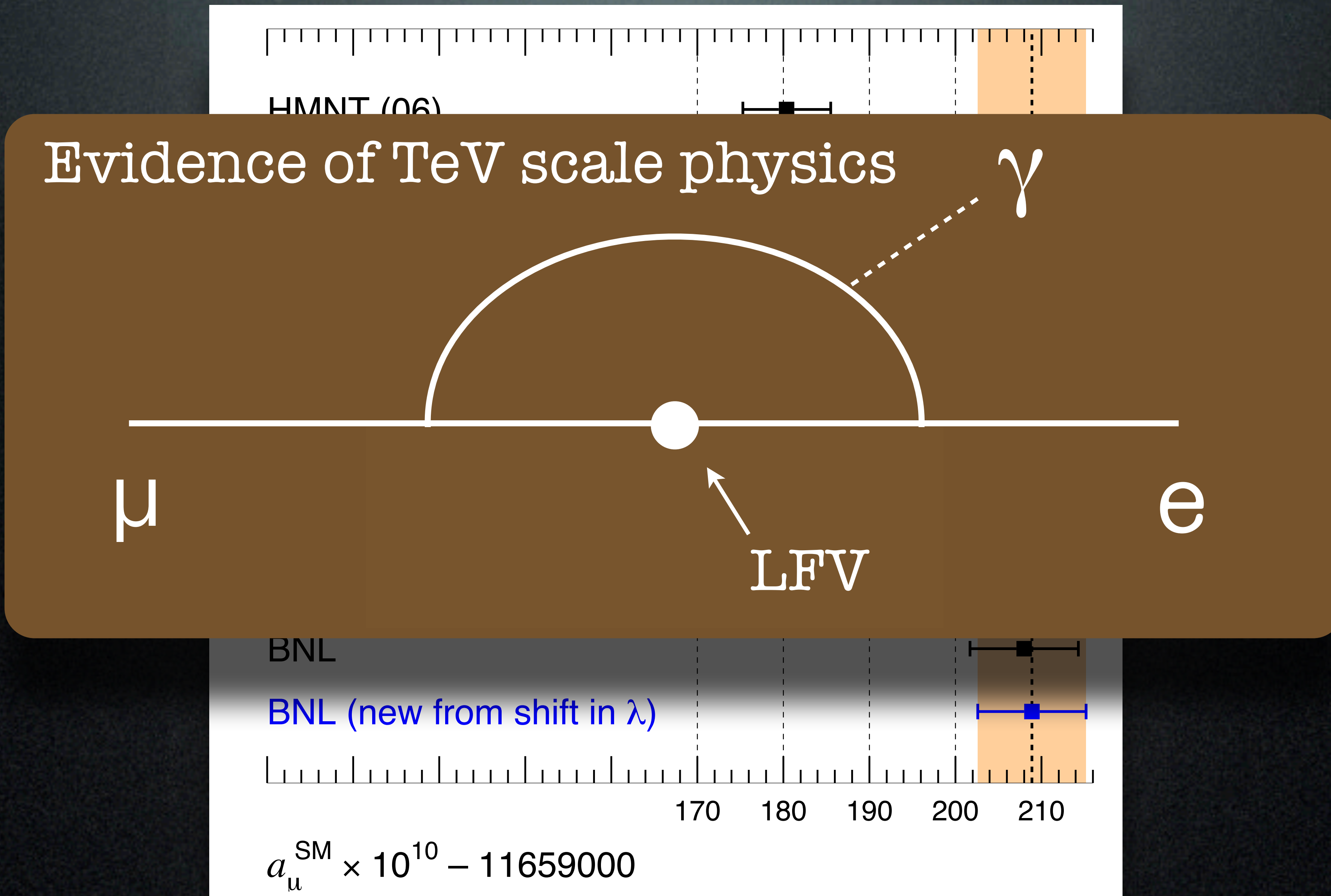

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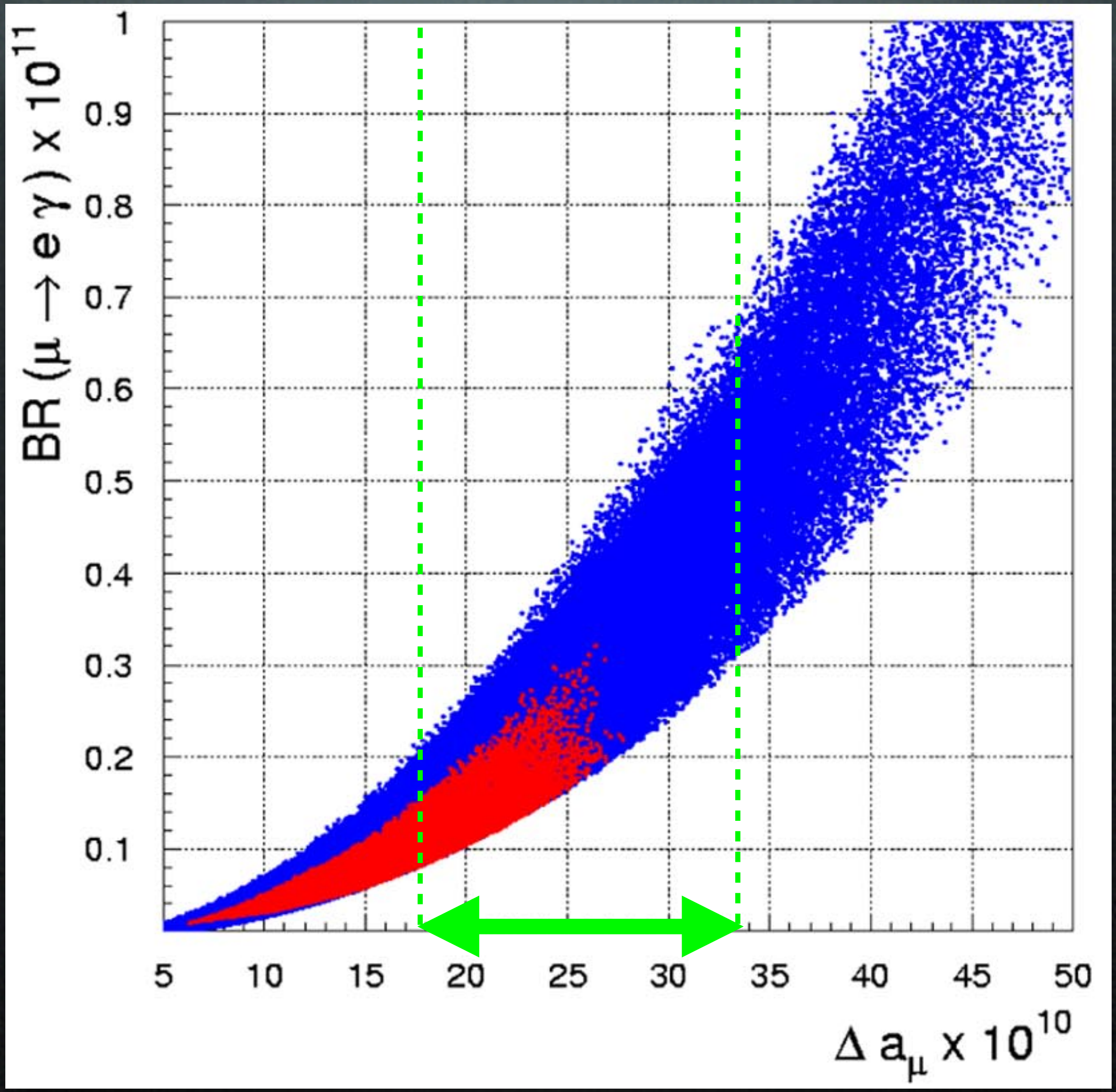

G.Isidori et al. PRD75, 115019

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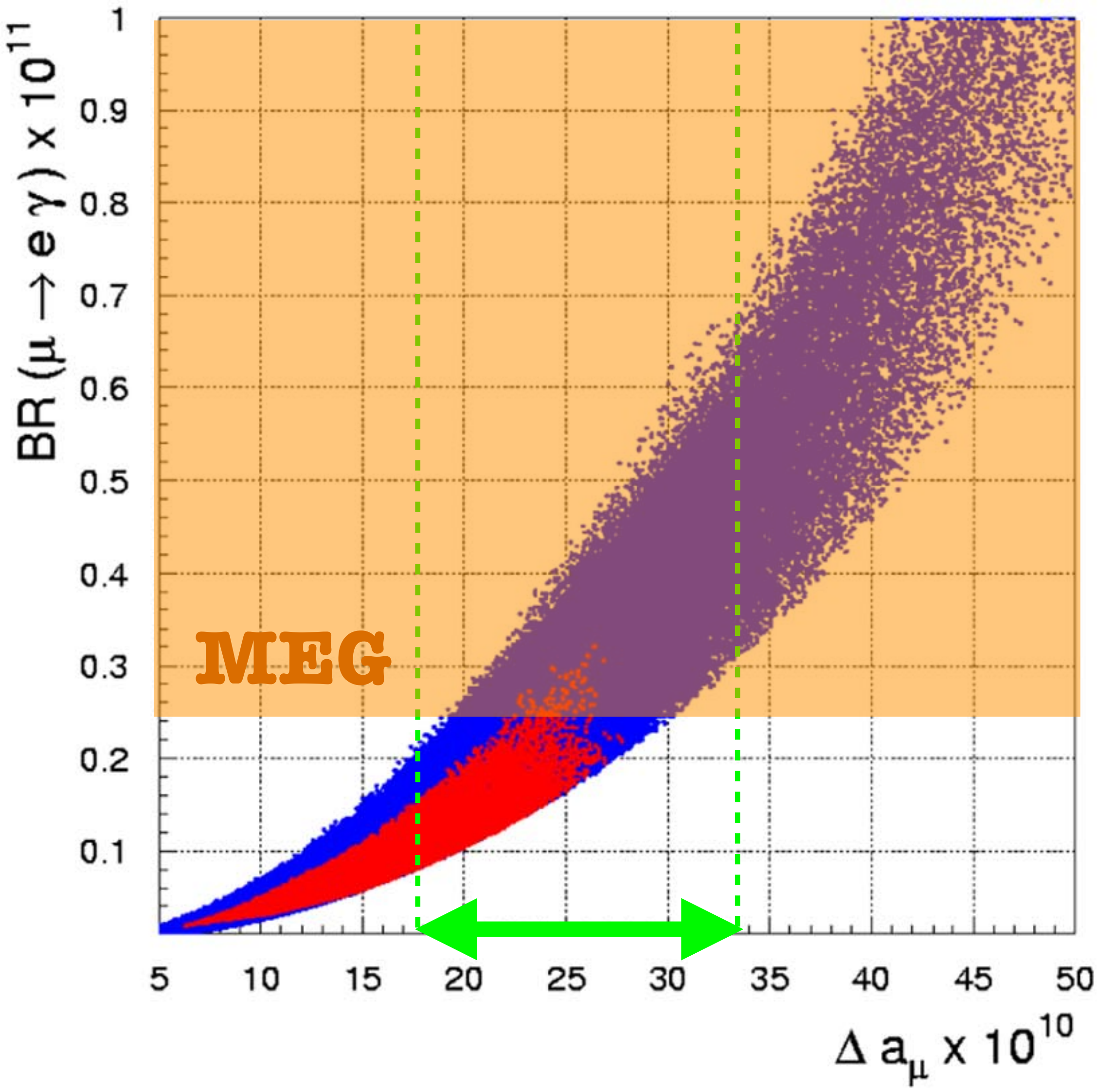
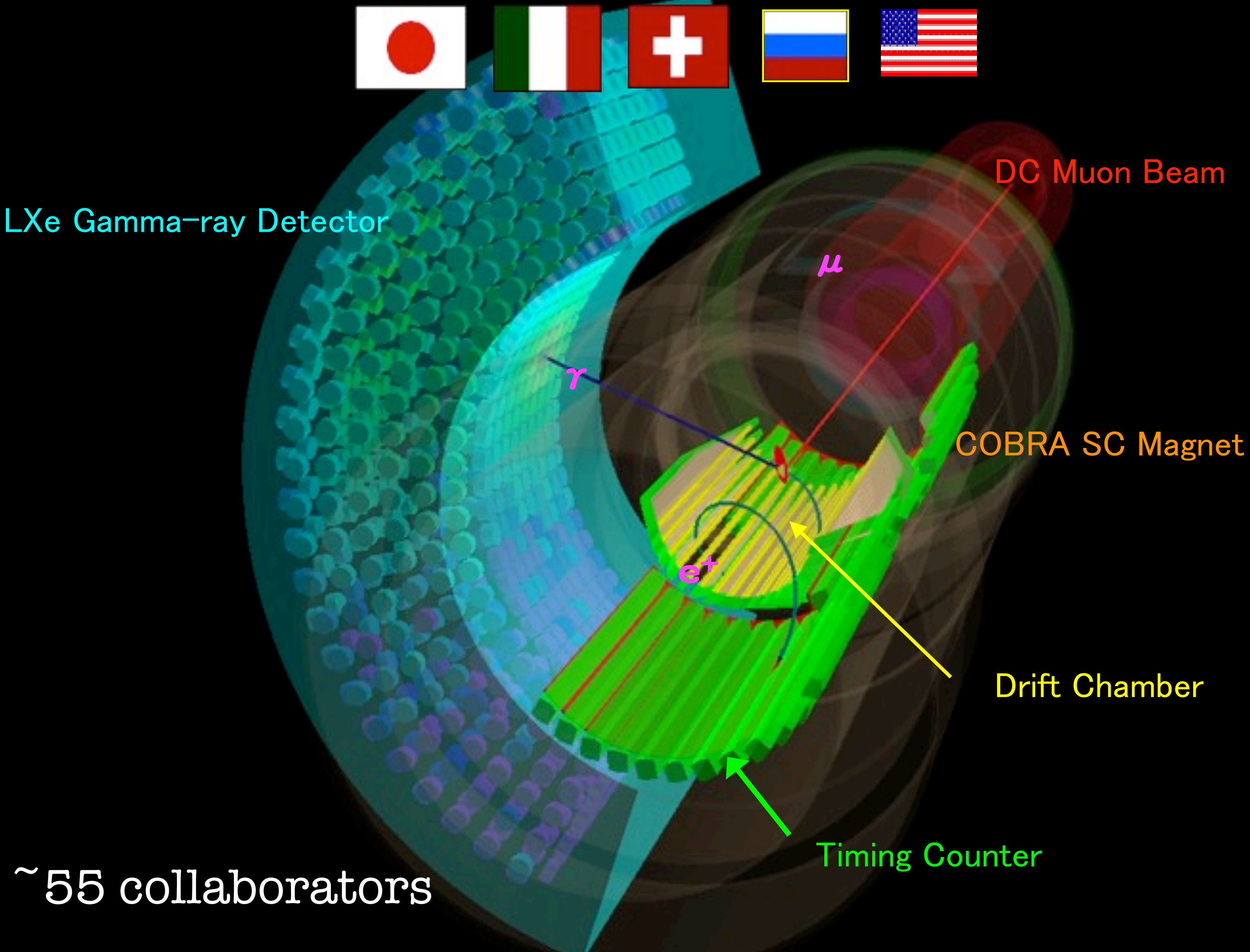


G.Isidori et al. PRD75, 115019

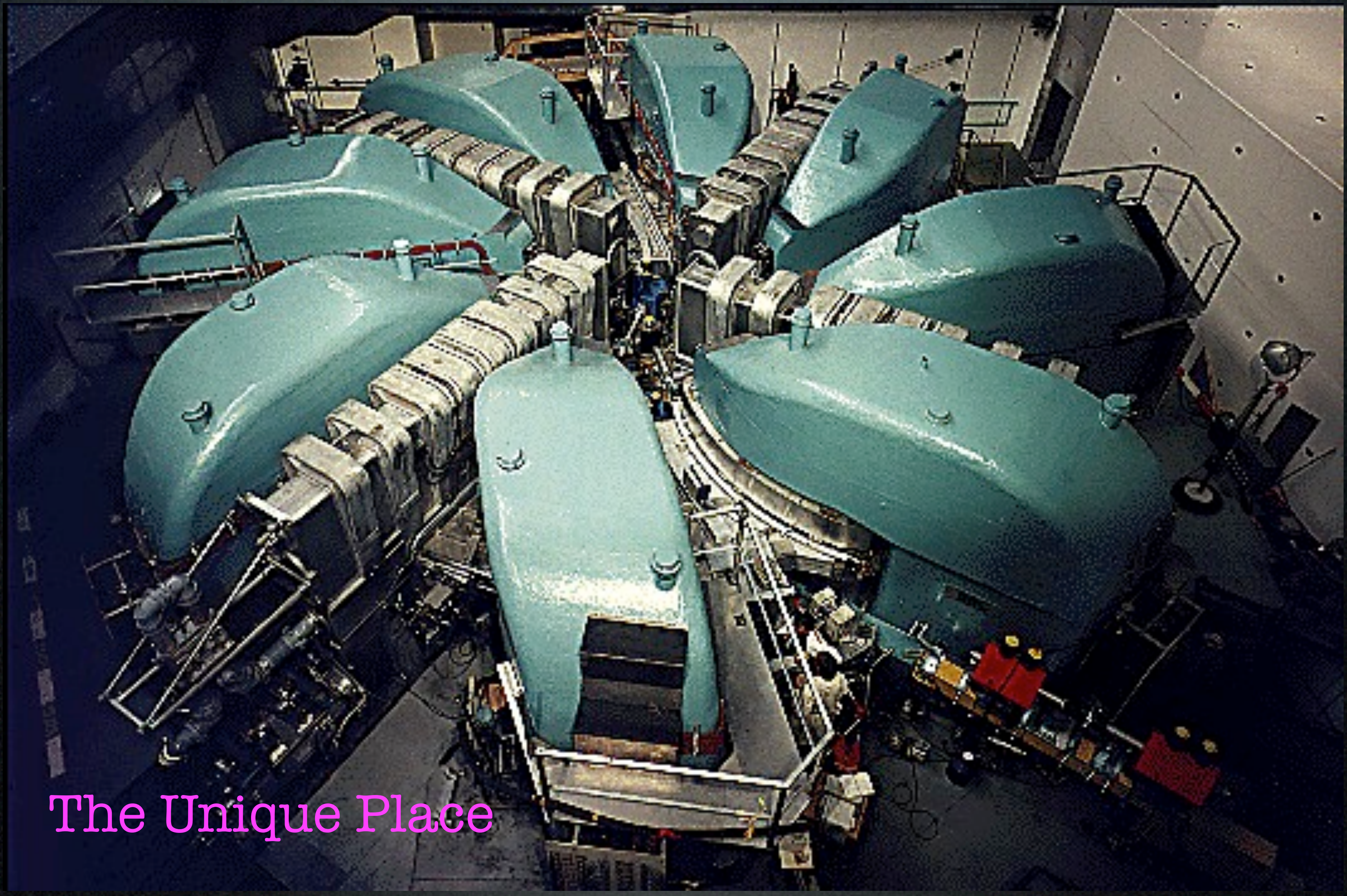
muon's anomalous magnetic moment

The MEG Experiment



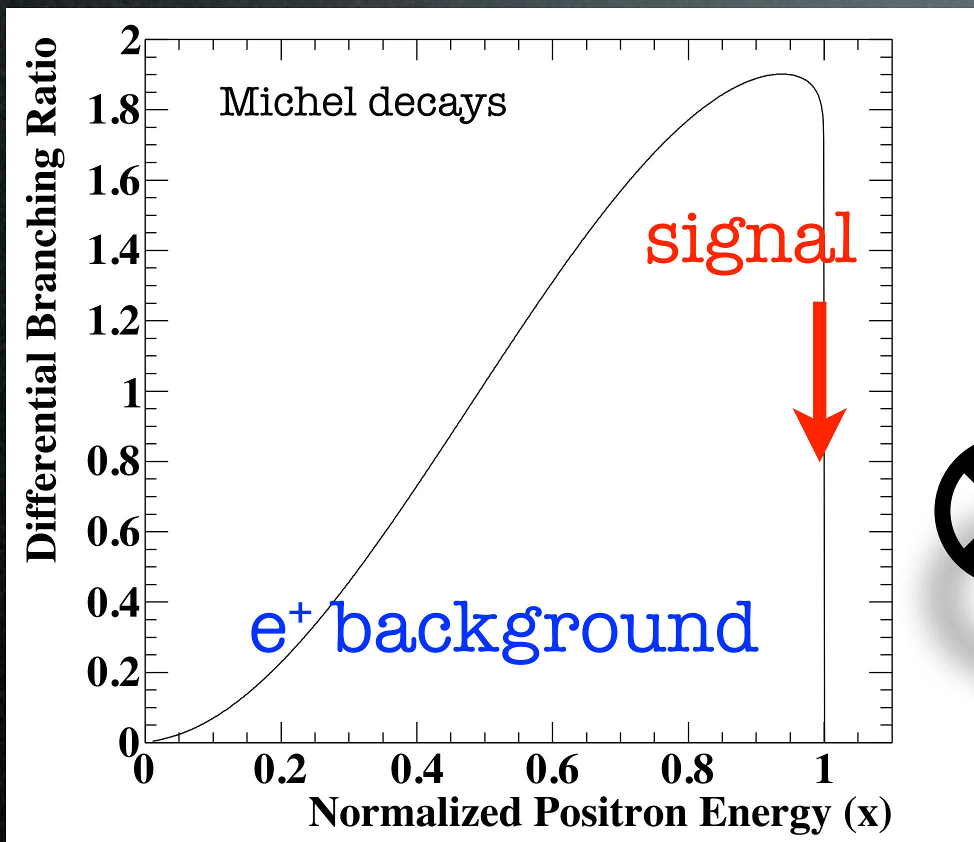
~55 collaborators

1.3MW Proton Cyclotron at PSI

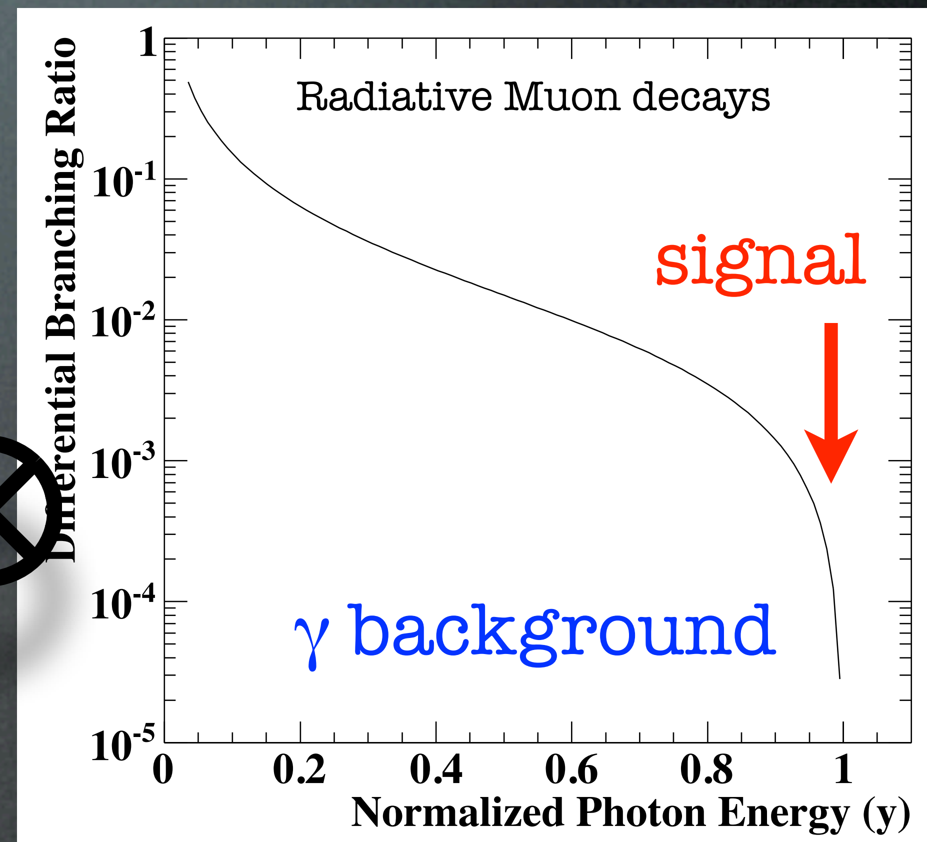


Provides world's most powerful DC muon beam > 10^8/sec

Dominant Background Is Accidental



$\otimes$



must manage high rate e^+

good γ resolution is most important !

✓ High intensity (~10^7/sec) DC muon beam

➡ Paul Scherrer Institute's 1.3MW Cyclotron

✓ e^+ spectrometer that can manage high rate

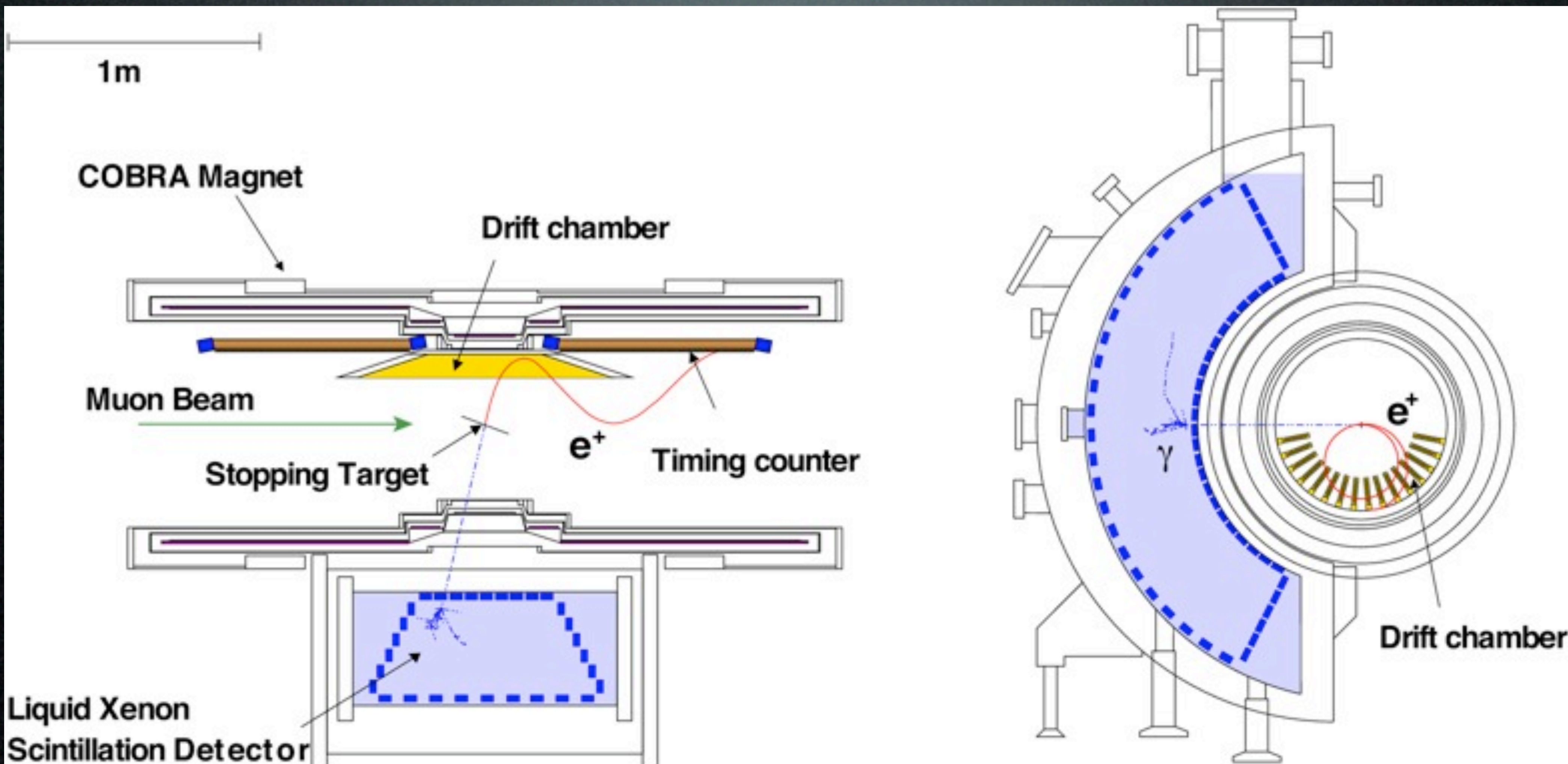
➡ Gradient Magnetic Field Spectrometer

✓ High resolution gamma-ray detector

➡ Liquid Xenon Scintillation Detector

→ MEG Experiment

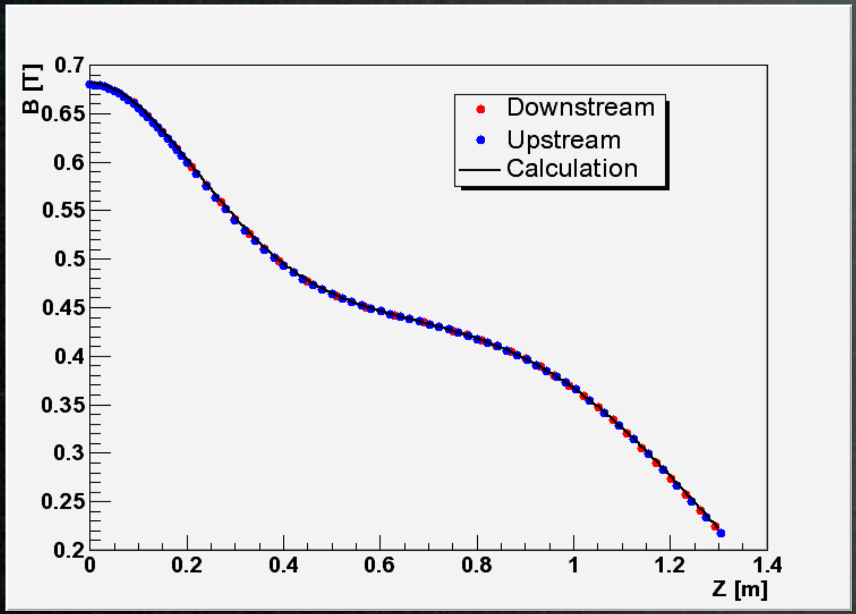
The MEG Experiment

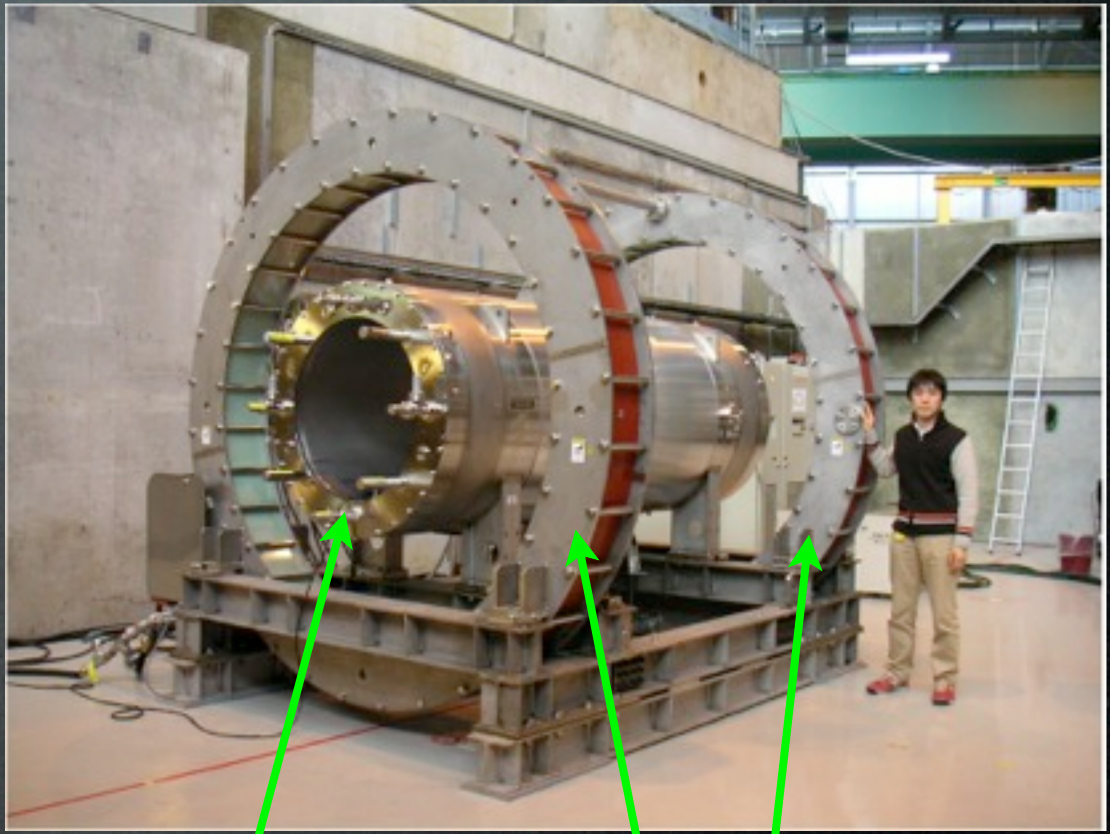


COBRA Positron Spectrometer

Gradient B field helps to manage high rate e^+

- thin-walled SC solenoid with a gradient magnetic field: 1.27 - 0.49 Tesla

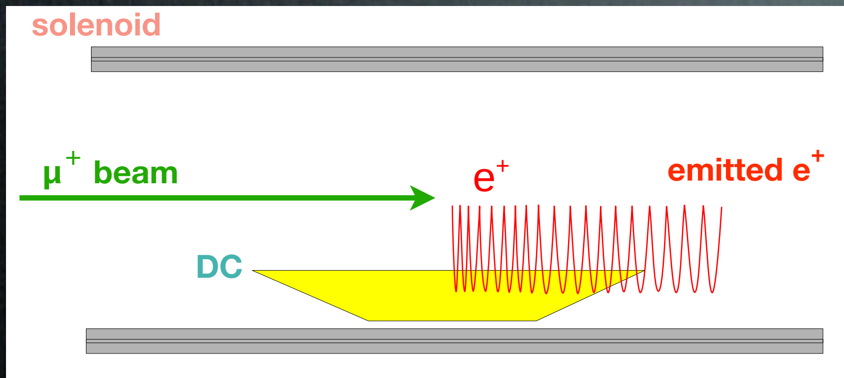


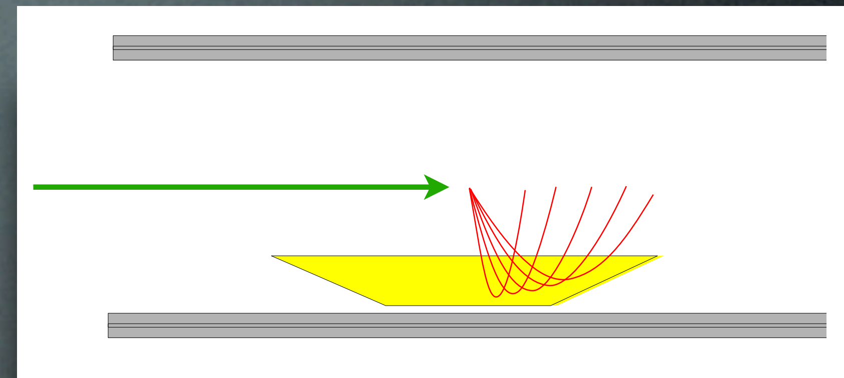


COBRA

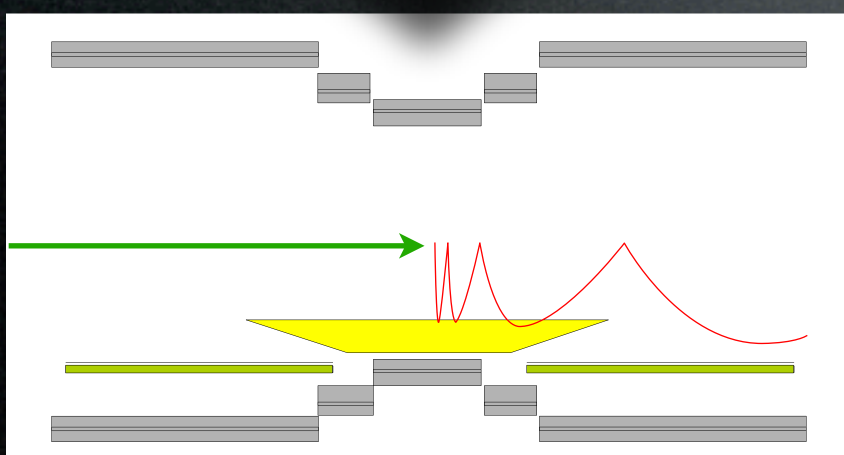
compensation coils

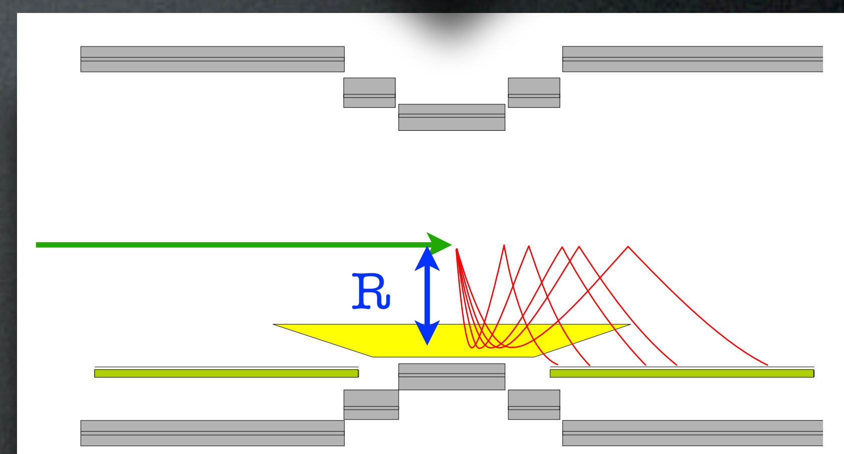
uniform B-field





gradient B-field

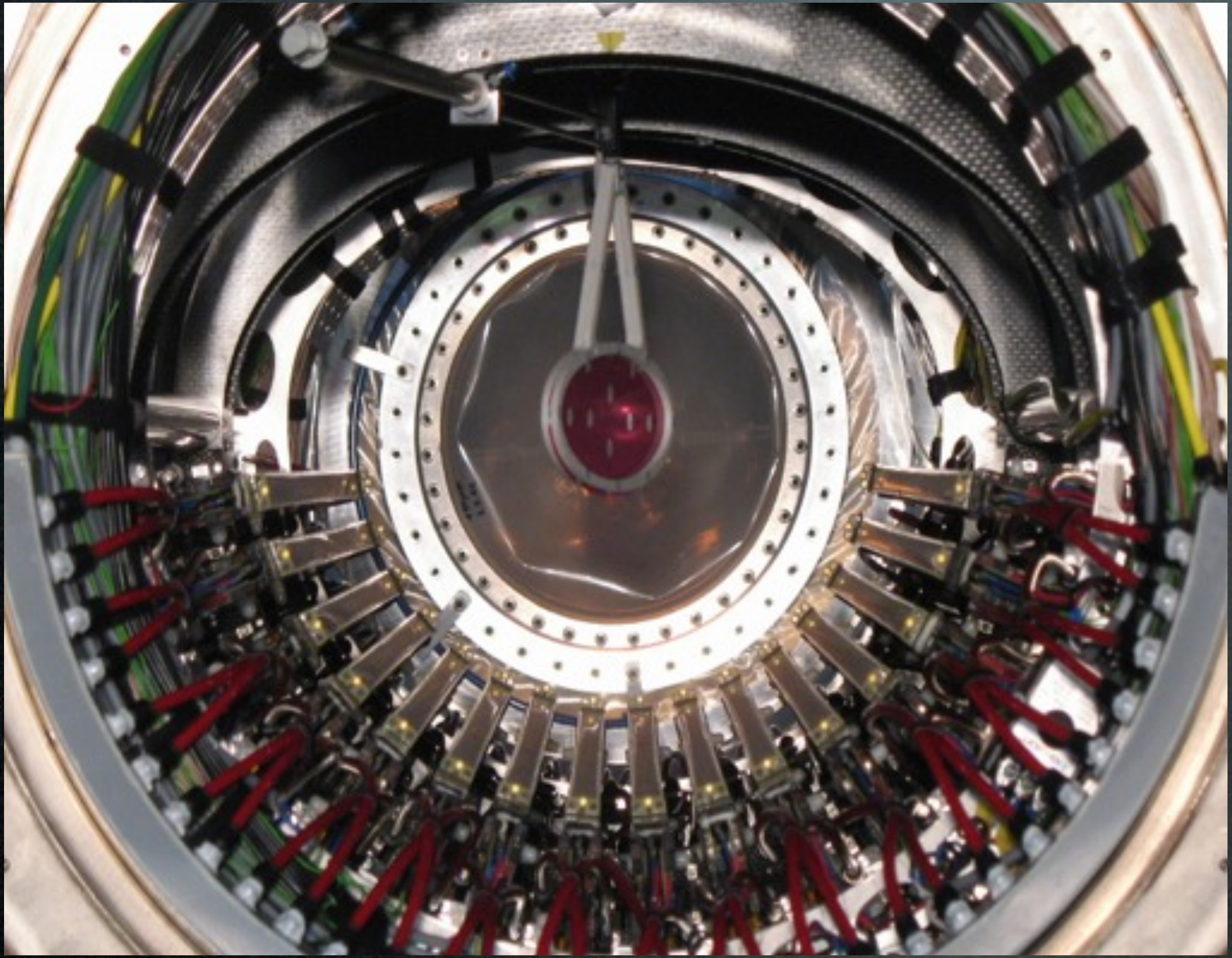




Low energy positrons quickly swept out

Constant bending radius independent of emission angles

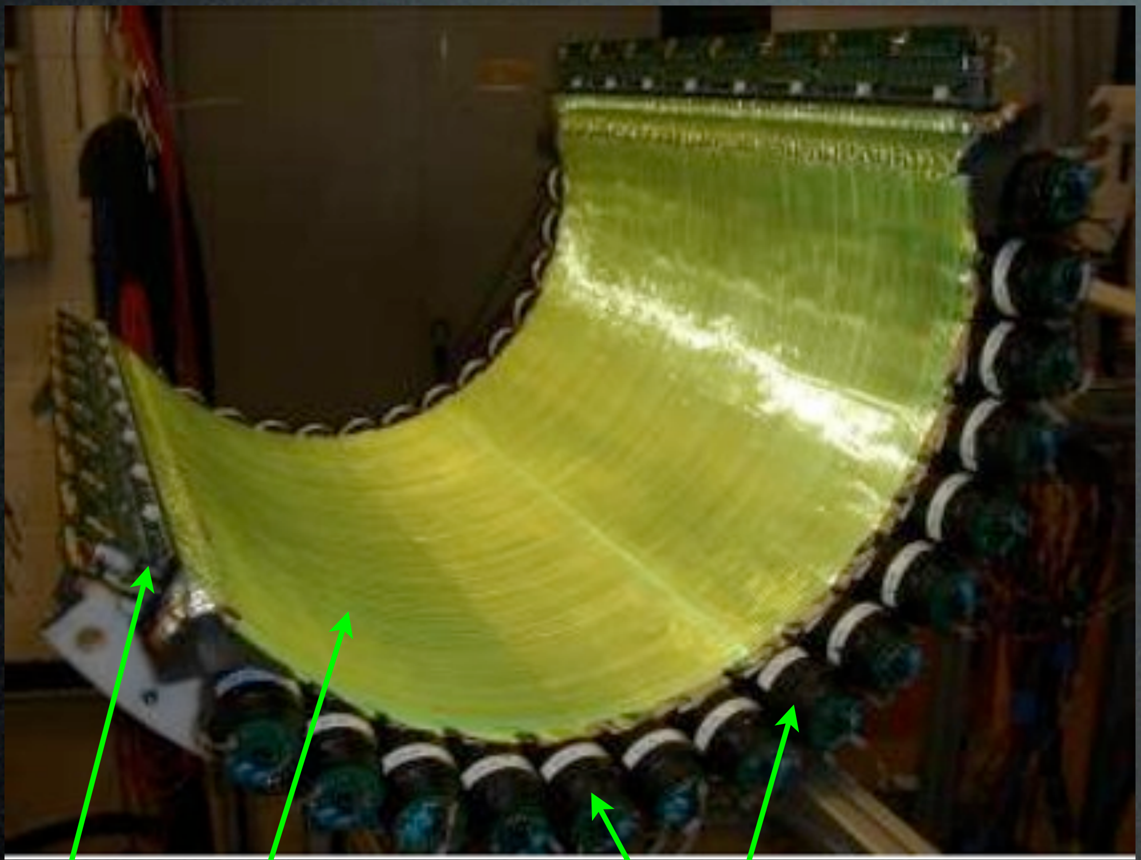
Drift Chambers



filled with He inside COBRA

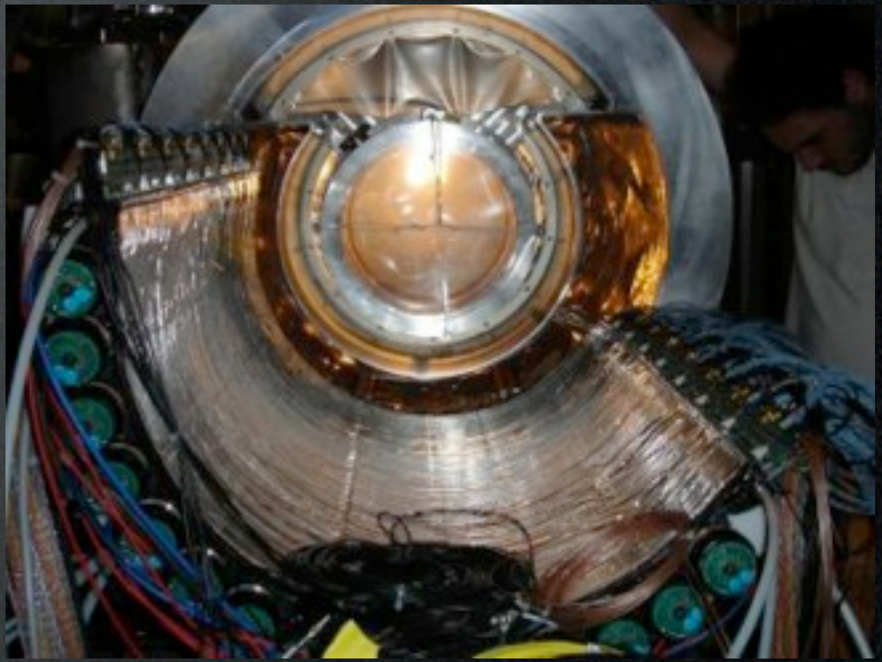
- 16 radially aligned modules, each consists of two staggered layers of wire planes
- 12.5um thick cathode foils with a Vernier pattern structure
- He:ethane = 50:50 differential pressure control to COBRA He environment
- ~2.0×10^{-3} X_0 along the positron trajectory

Timing Counters



< 50 psec

- Scintillator arrays placed at each end of the spectrometer
- Measures the impact point of the positron to obtain precise timing

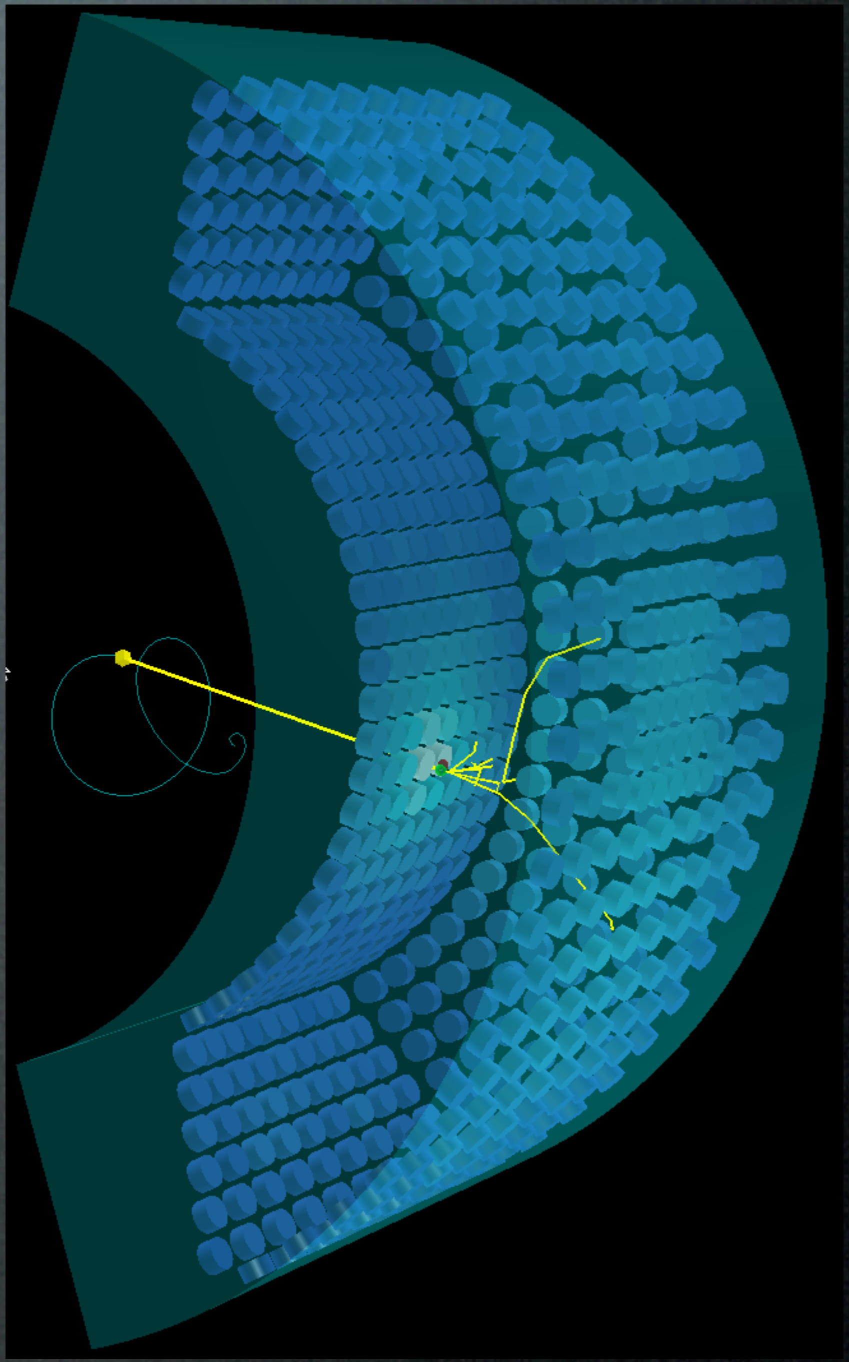


installing inside COBRA

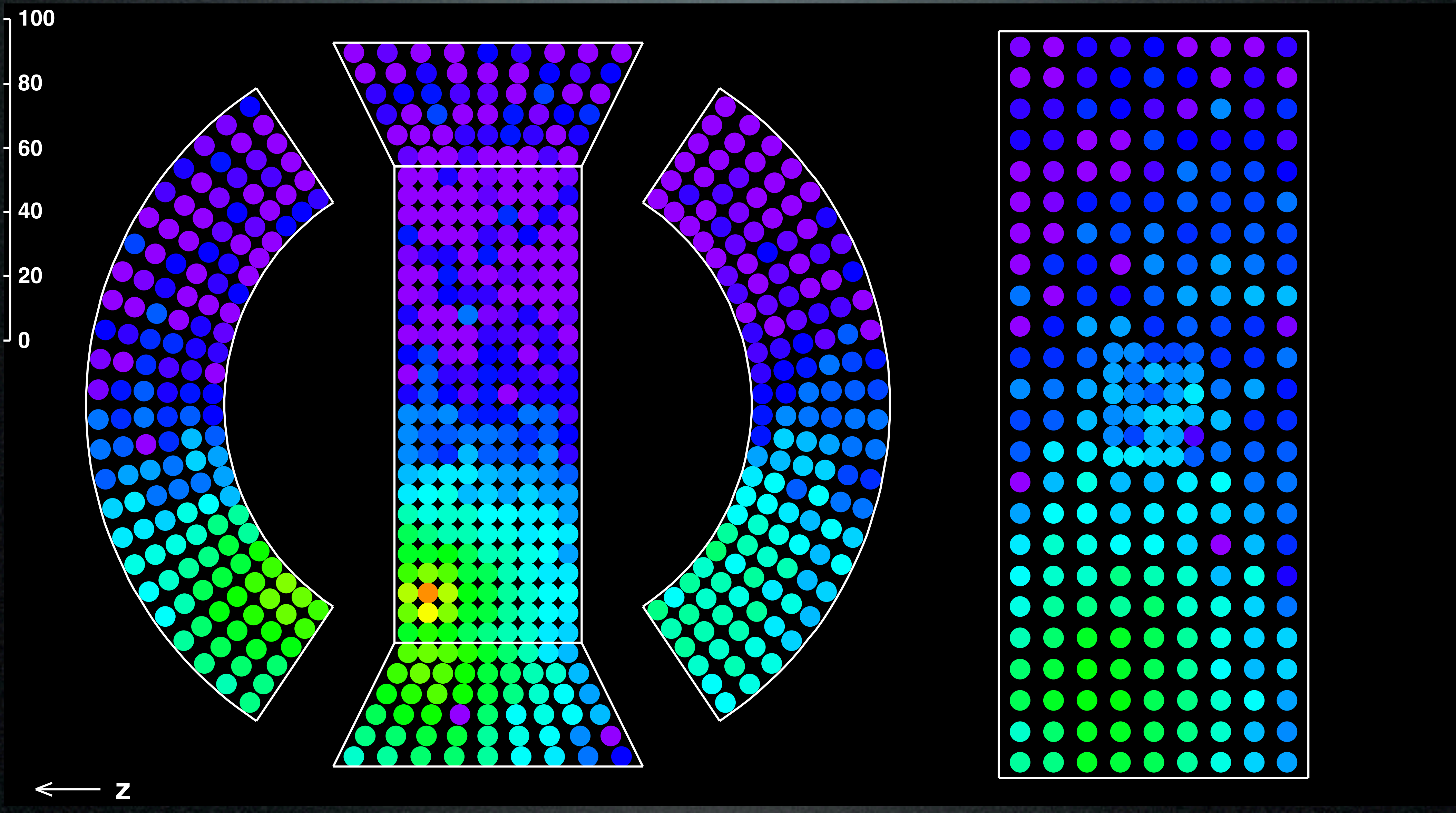
2.7t Liquid Xenon Photon Detector

High resolution detector

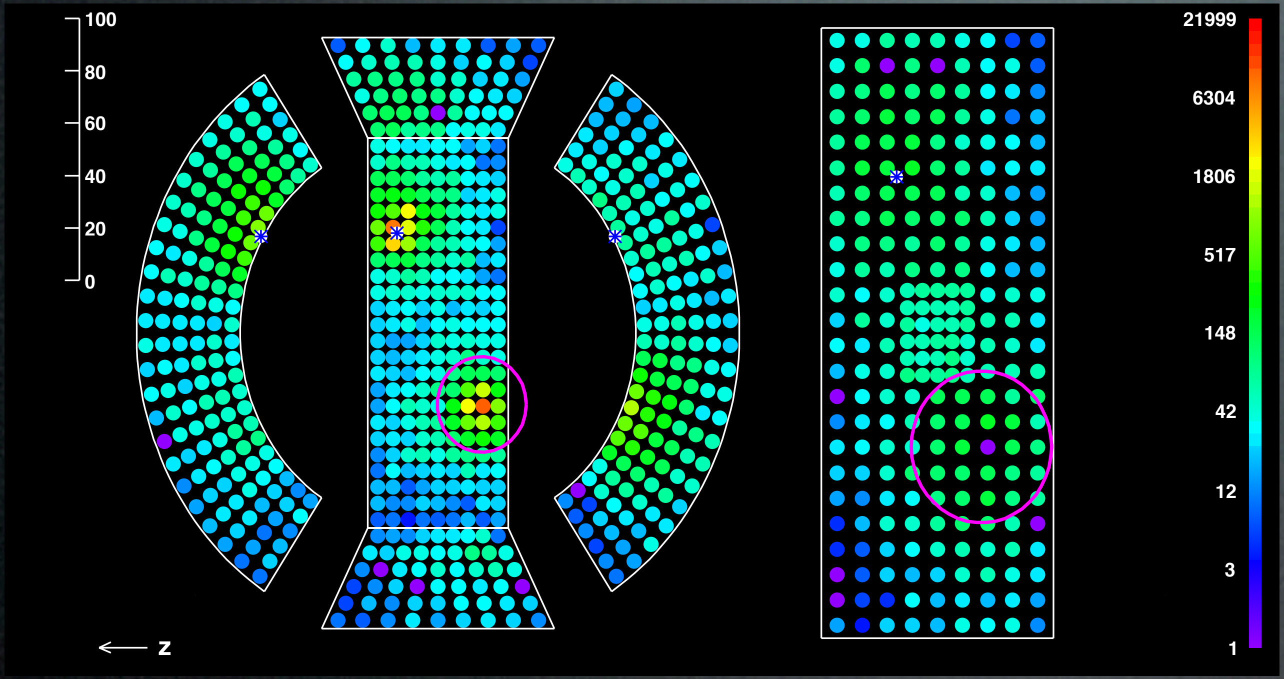
- Scintillation light from 900 liter liquid xenon is detected by 846 PMTs mounted on all surfaces and submerged in the xenon
- fast response & high light yield provide good resolutions of E, time, position
- kept at 165K by 200W pulse-tube refrigerator
- gas/liquid circulation system to purify xenon to remove contaminants

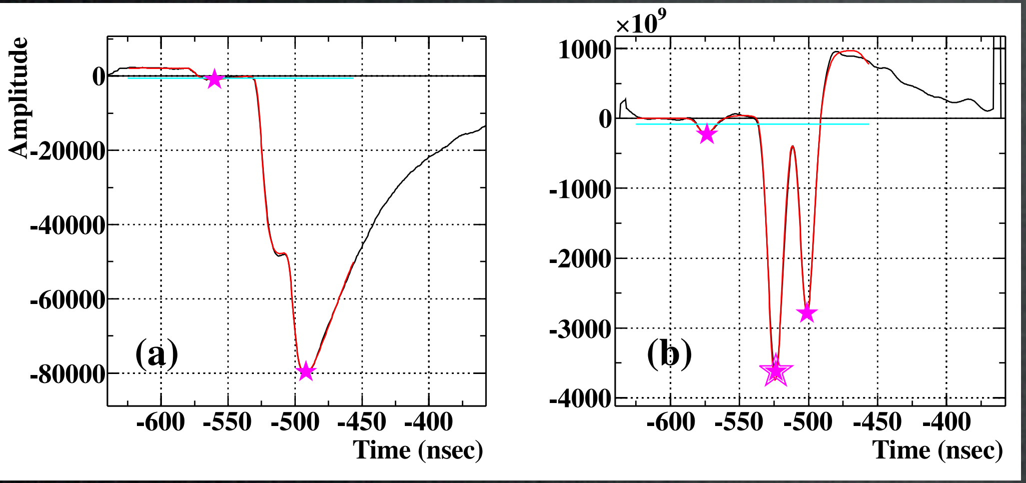


Energy = total light yield
Position = light peak



Pile-up Photon Removal

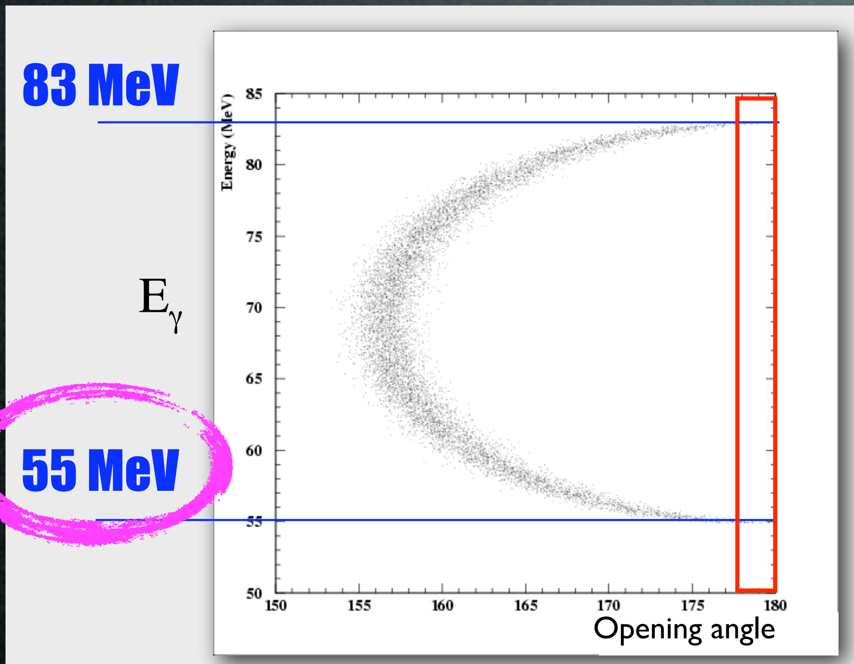




- Good position/timing resolutions enable to remove pile-up photons
- All the PMTs are read out by waveform digitizers (DRS)
- Events are not thrown away

better algorithms implemented for this analysis

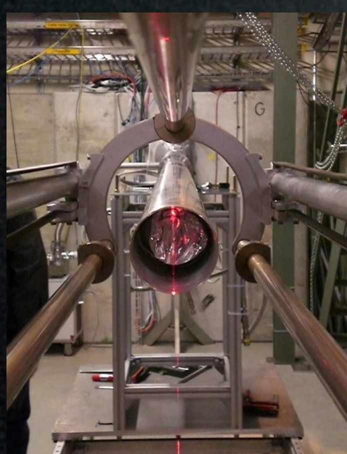
Absolute γ Energy Calibration



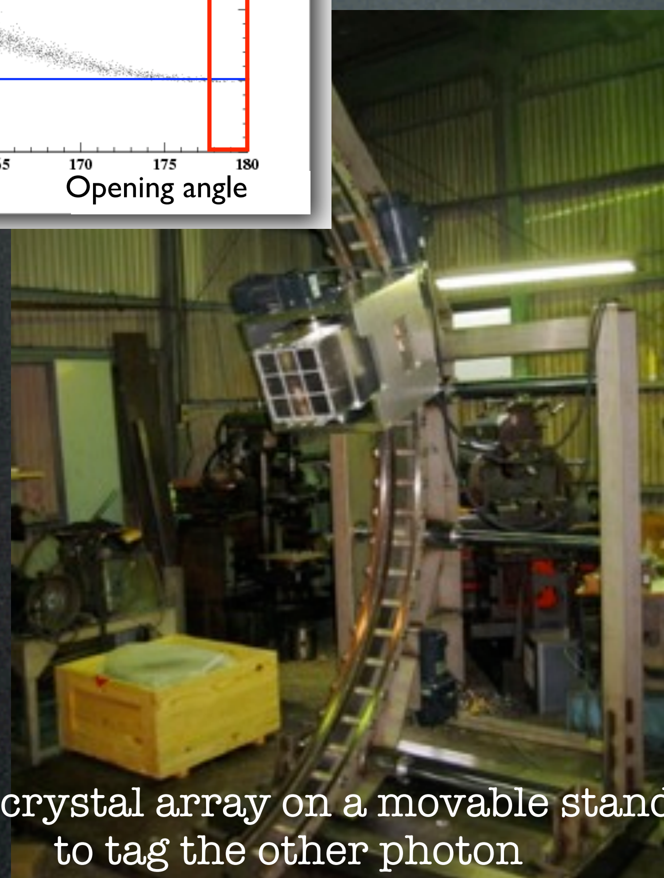
$$\pi^- p \to \pi^0 n \to \gamma\gamma n$$

"CEX"

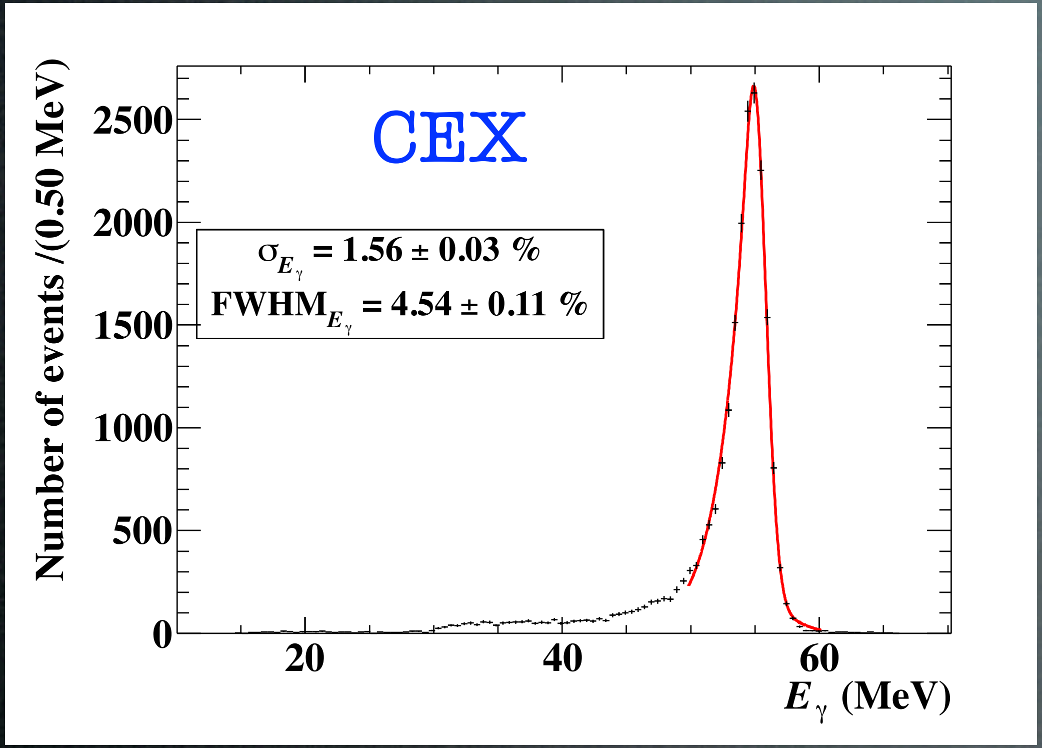
- negative pions stopped in liquid hydrogen target
- Tagging the other photon at 180° provides monochromatic photons
- Dalitz decays were used to study positron-photon synchronization and time resolution $\pi^0 \to \gamma e^+ e^-$
- new BGO crystal to tag the other photons w/ better resolution

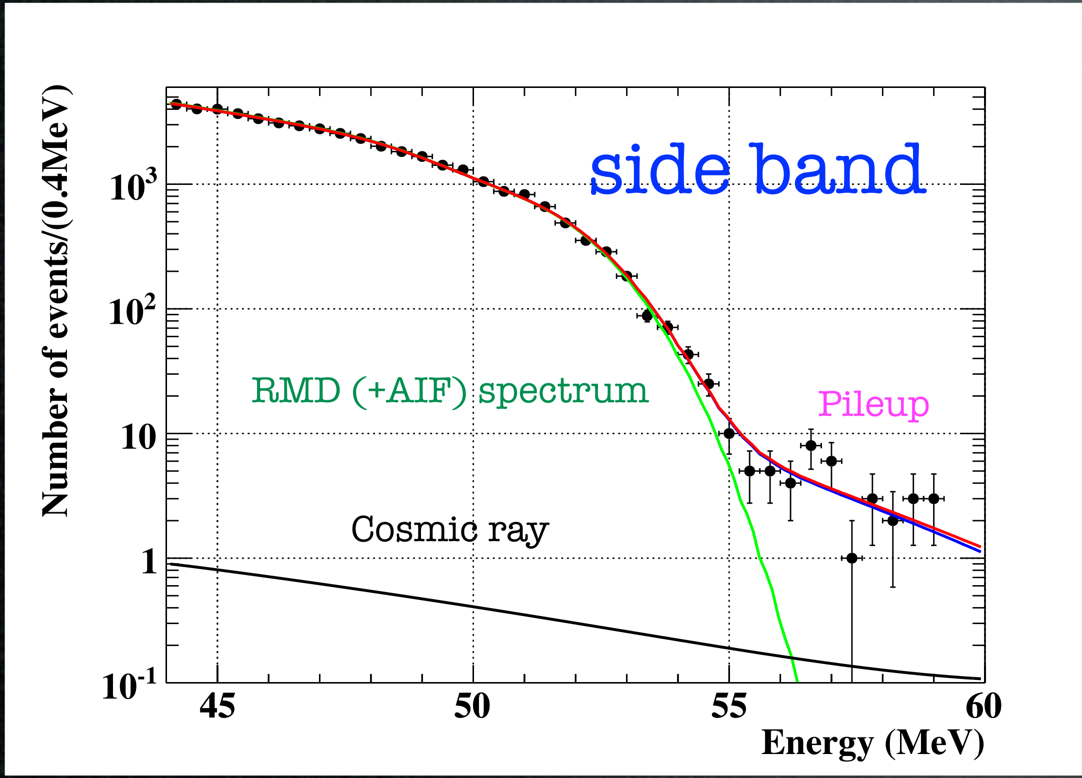


LH_2 target



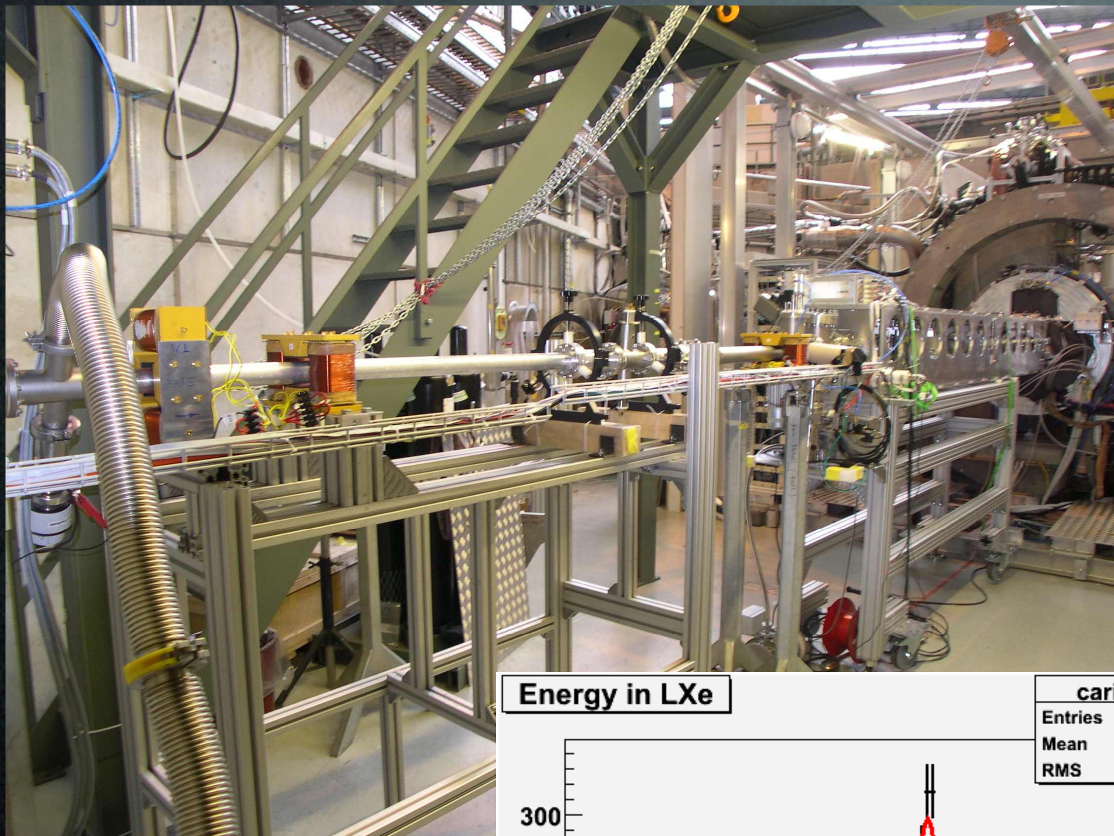
BGO crystal array on a movable stand to tag the other photon



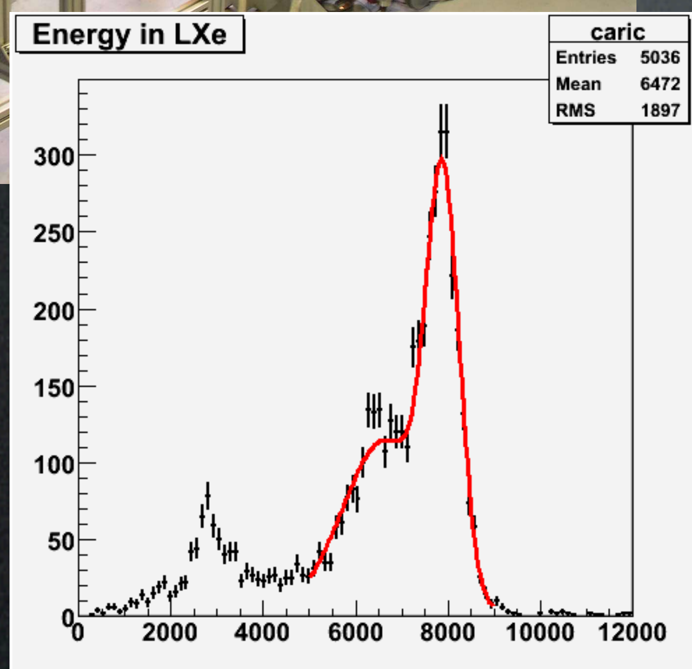


- Gamma ray energy
  - Signal PDF from the CEX calibration data
  - Accidental PDF from the side bands
  - Scale & resolutions verified by radiative decay spectrum
  - systematic uncertainty on energy scale: 0.3%

Monitor E_γ during Run



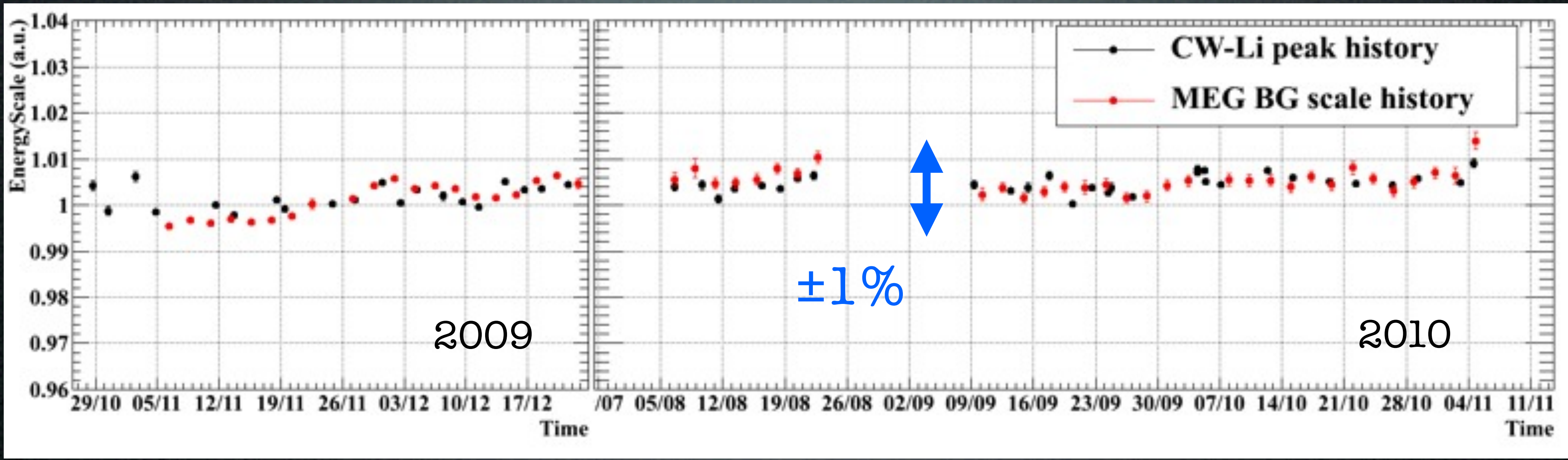
remotely extendable beam pipe of CW proton beam (downstream of muon beam line)

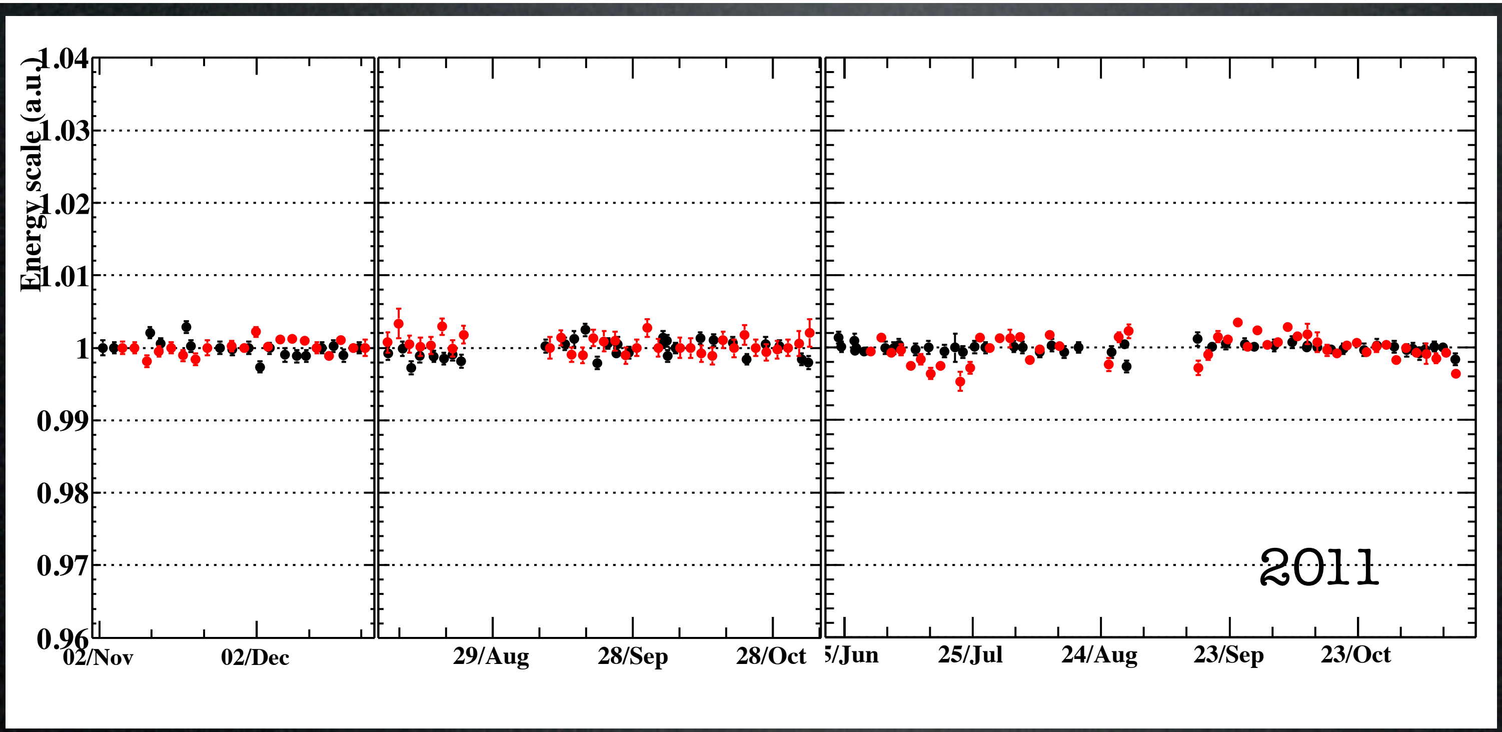


17.67MeV Li peak

- sub-MeV proton beam from a dedicated Cockcroft-Walton accelerator are bombarded on $Li_2B_4O_7$ target.
- 17.67MeV from ^{7}Li
- 2 coincident photons (4.4, 11.6) MeV from ^{11}B: synchronization of LXe and TC
- Short runs two-three times a week

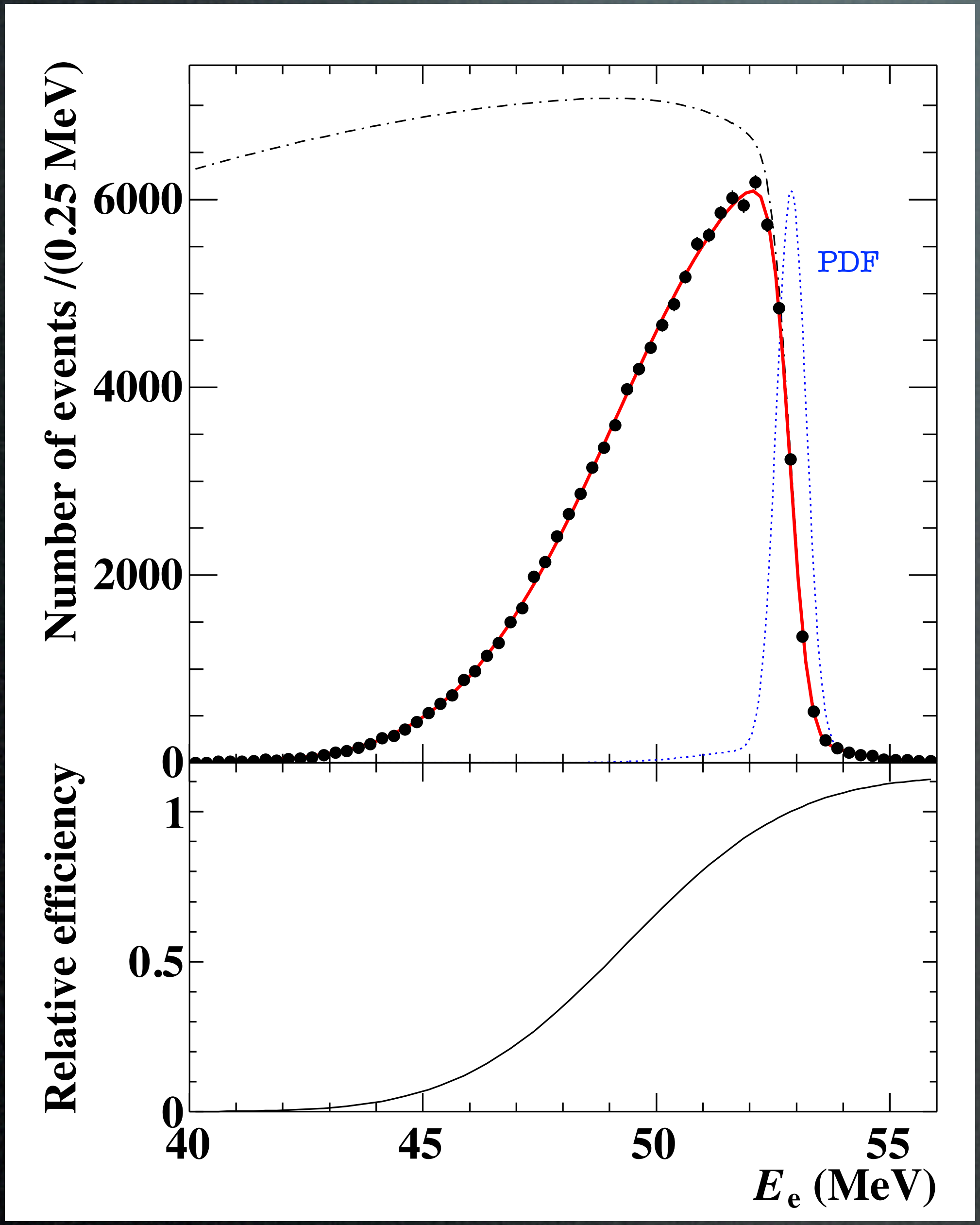
Stability of E_γ Scale





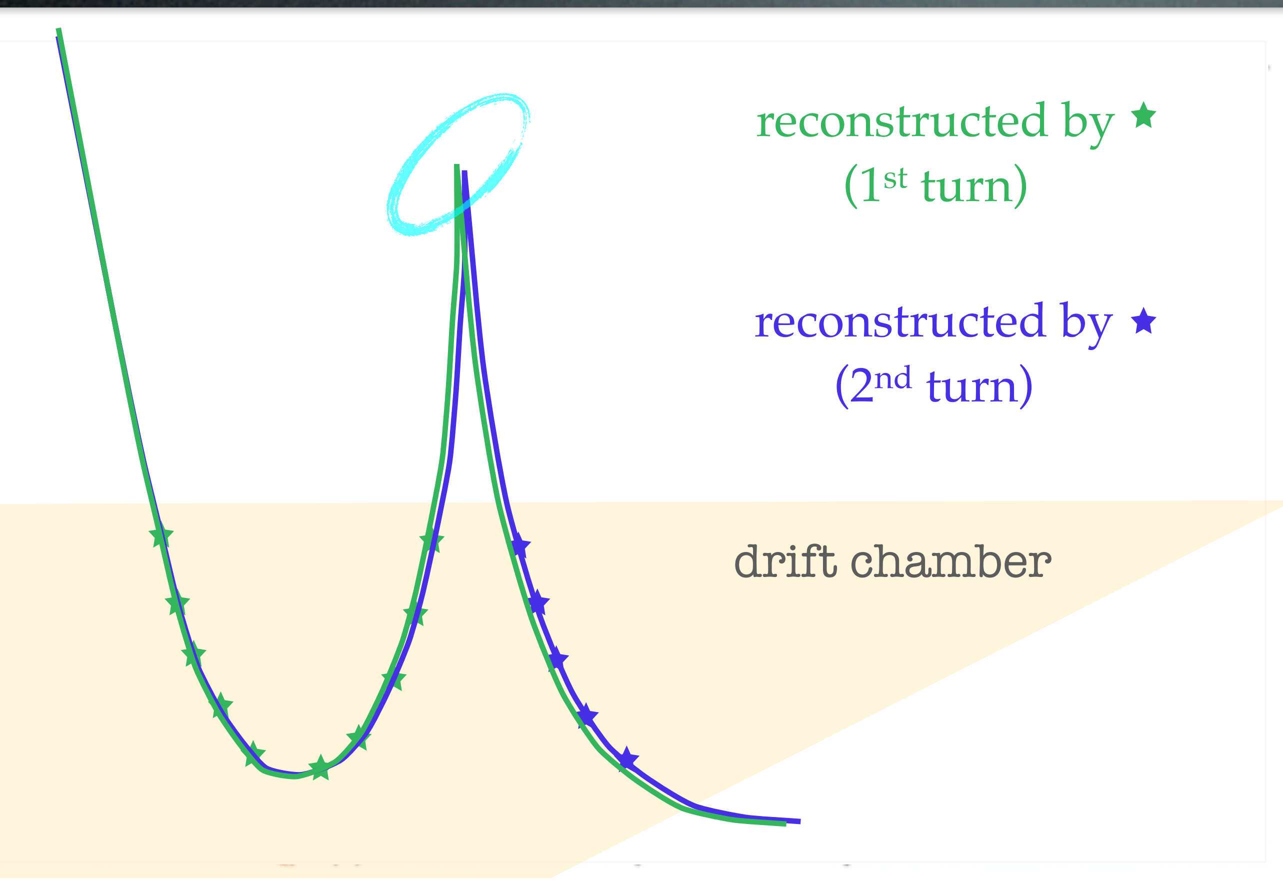
rms ~0.2%

Positron PDFs

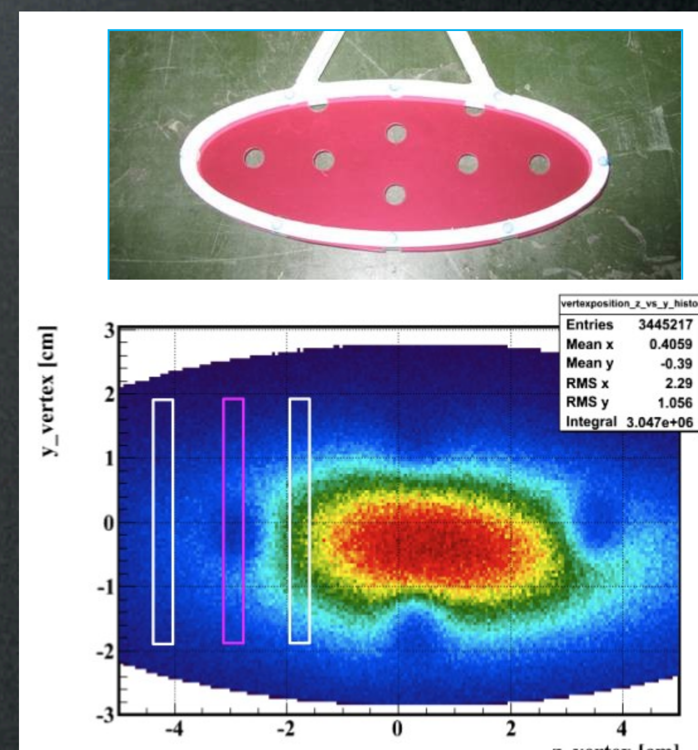


- Positron energy scale and resolution are evaluated by fitting the kinematic edge of the Michel positron spectrum at 52.8MeV
- new Kalman filter for track fits w/ better modeling of hits & materials
- improved technique for survey + alignment by cosmic ray
- fast Fourier transform filtering to reduce DC noise
  → better resolutions

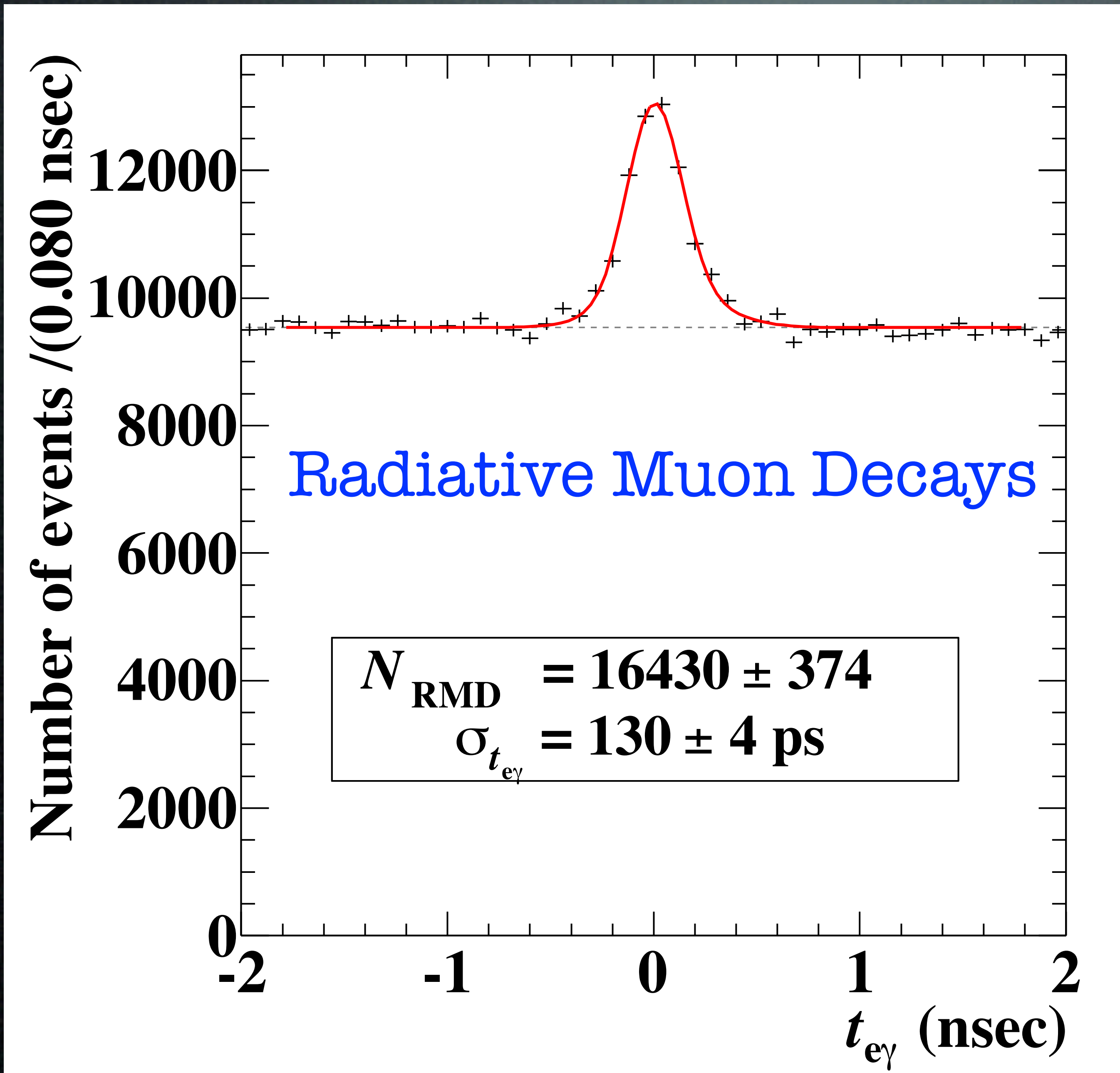
Positron Angle & μ Decay Point



- Angular resolutions were evaluated by the double turn tracks inside the DC
- holes of the muon stopping target



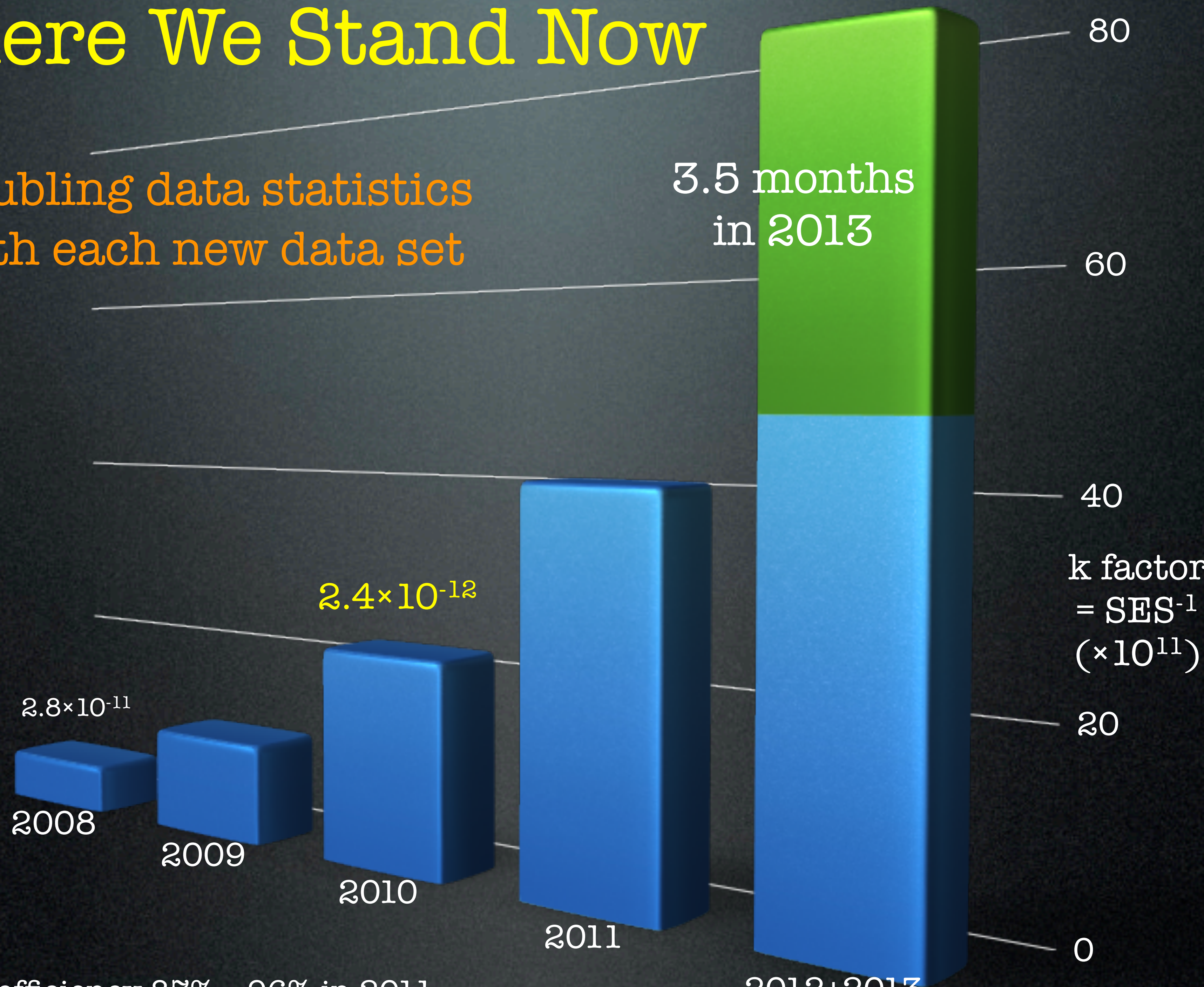
Positron - Photon Timing



- Positron time measured by TC and corrected by ToF (DC trajectory)
- LXe time corrected by ToF to the conversion point
- RMD peak in a normal physics run corrected by small energy dependence; stable < 20ps

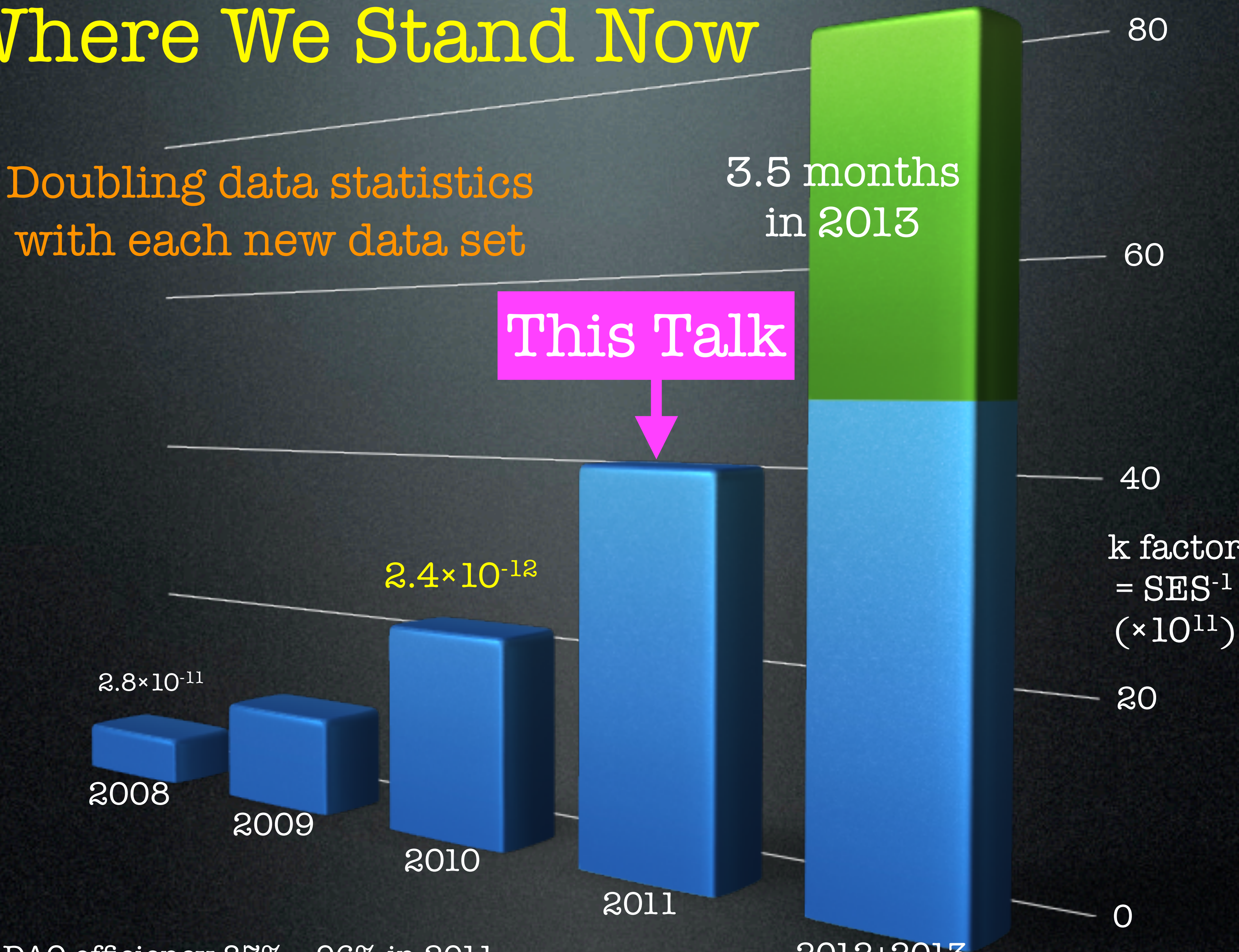
Where We Stand Now

Doubling data statistics
with each new data set



DAQ efficiency 87%→96% in 2011

Where We Stand Now

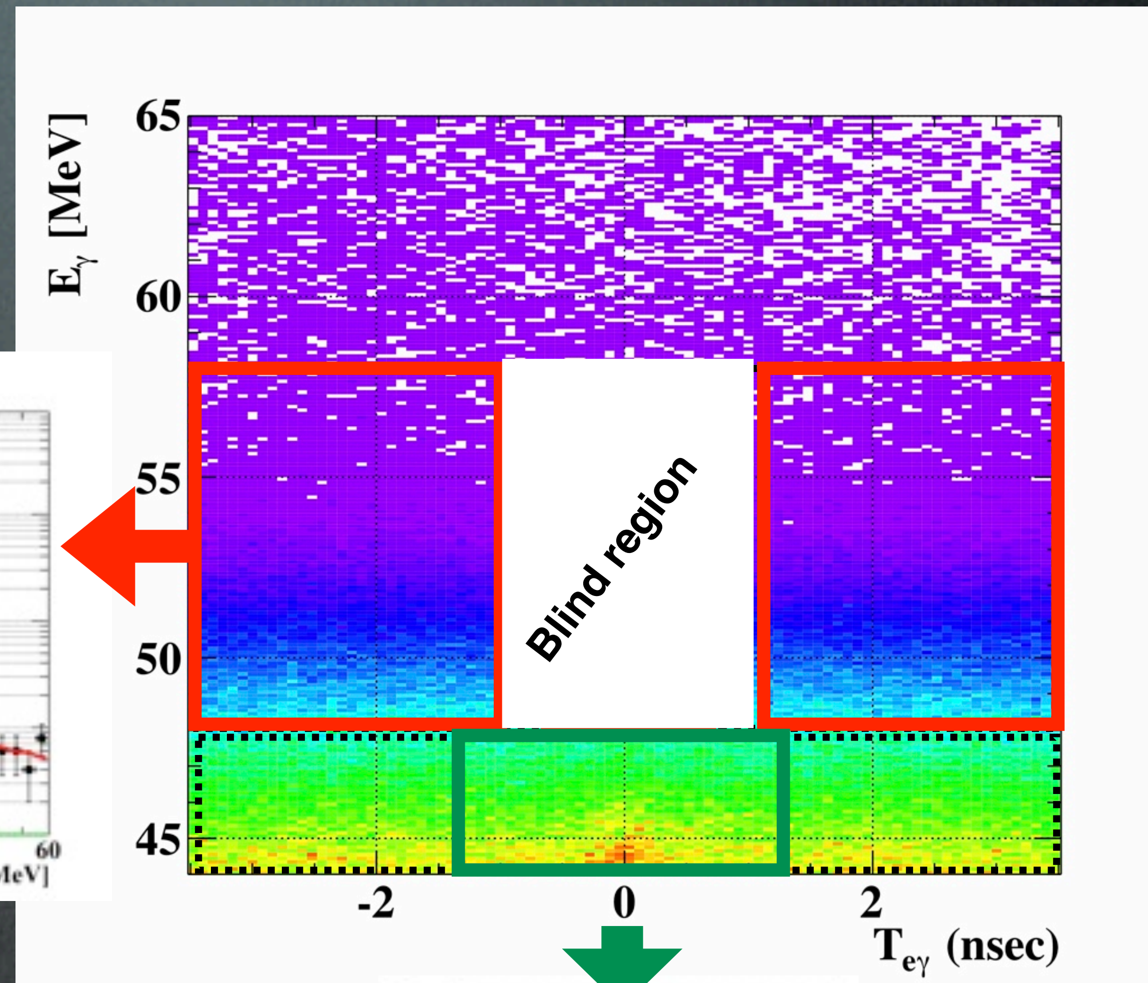


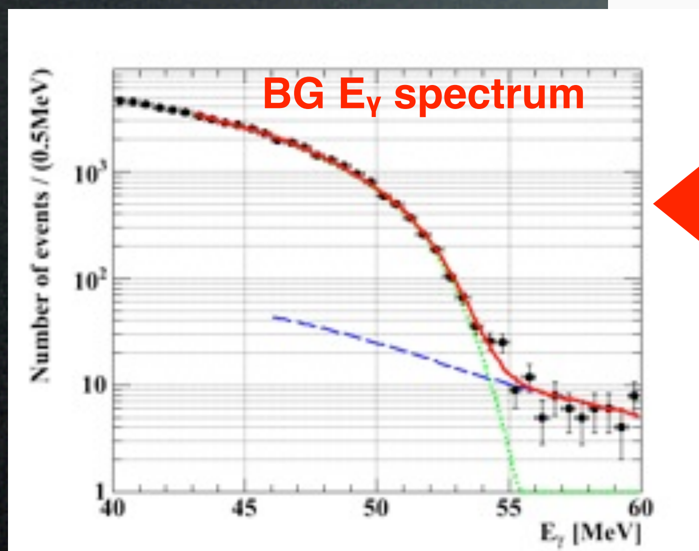
DAQ efficiency 87%→96% in 2011

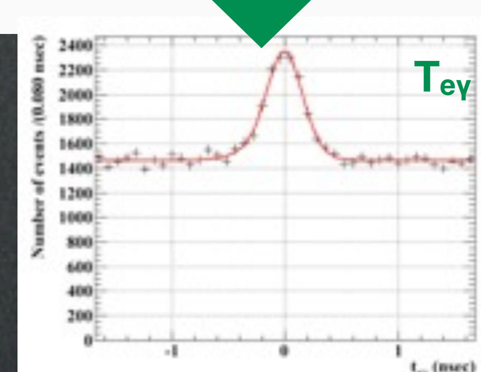
Blind & Likelihood Analysis

$(E_\gamma, E_e, T_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$

→ signal, acc BG, RD BG







PDFs mostly from data

- accidental BG: side bands
- signal: measured resolution
- radiative BG: theory + resolution

Likelihood Fit

- fully frequentist approach (Feldman & Cousins) with profile likelihood ratio ordering

$$\mathcal{L}\left(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}\right) = \frac{e^{-N}}{N_{\rm obs}!} e^{-\frac{1}{2}\frac{(N_{\rm BG}-\langle N_{\rm BG}\rangle)^2}{\sigma_{\rm BG}^2}} e^{-\frac{1}{2}\frac{(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2}{\sigma_{\rm RMD}^2}} \times \prod_{i=1}^{N_{\rm obs}} \left(N_{\rm sig}S(\vec{x}_i) + N_{\rm RMD}R(\vec{x}_i) + N_{\rm BG}B(\vec{x}_i)\right),$$

$$LR_p(N_{\rm sig}) = \frac{\max_{N_{\rm BG},N_{\rm RMD}} \mathcal{L}(N_{\rm sig}, N_{\rm BG}, N_{\rm RMD})}{\max_{N_{\rm sig},N_{\rm BG},N_{\rm RMD}} \mathcal{L}(N_{\rm sig}, N_{\rm BG}, N_{\rm RMD})}.$$

New: per-event PDFs introduced also for positrons
→ sensitivity improvement

Normalization

Conversion factor from Nsig to B.R.

$$N(\mu \rightarrow e\gamma) = \boxed{N_\mu} \cdot Br(\mu \rightarrow e\gamma) \cdot (\Omega/4\pi) \cdot \epsilon_\gamma \cdot \boxed{\epsilon_e} \cdot \epsilon_{\mathrm{trig}} \cdot \epsilon_{\mathrm{sel}}$$

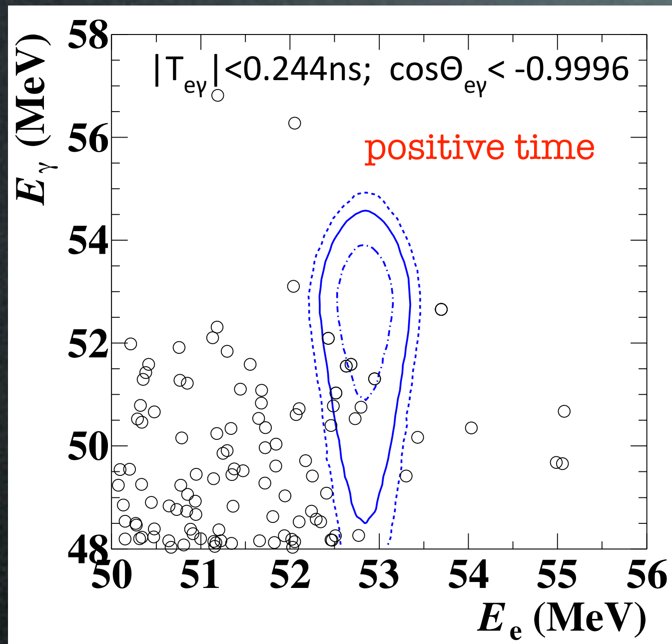
$$N(Michel) = \boxed{N_\mu} \cdot (\Omega/4\pi) \cdot \boxed{\epsilon'_e} \cdot \epsilon'_{\mathrm{trig}} \cdot P(Michel)$$

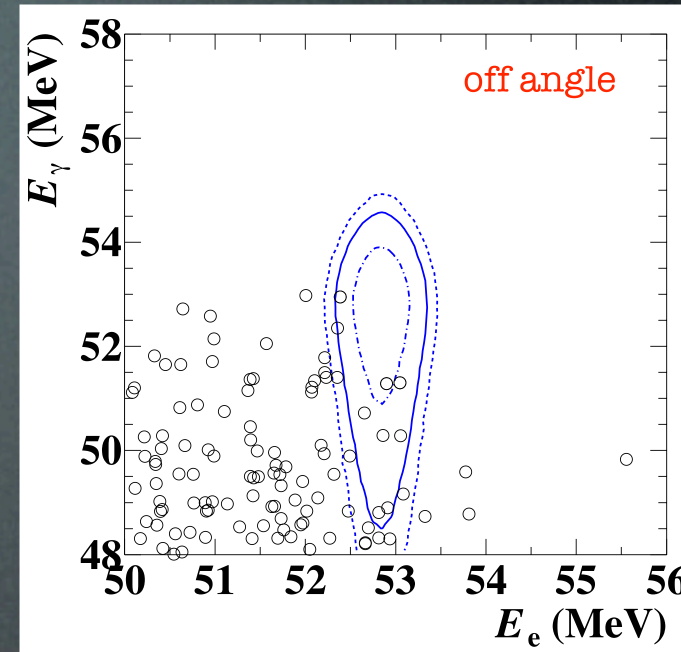
Efficiency for Michel   Trigger preselection

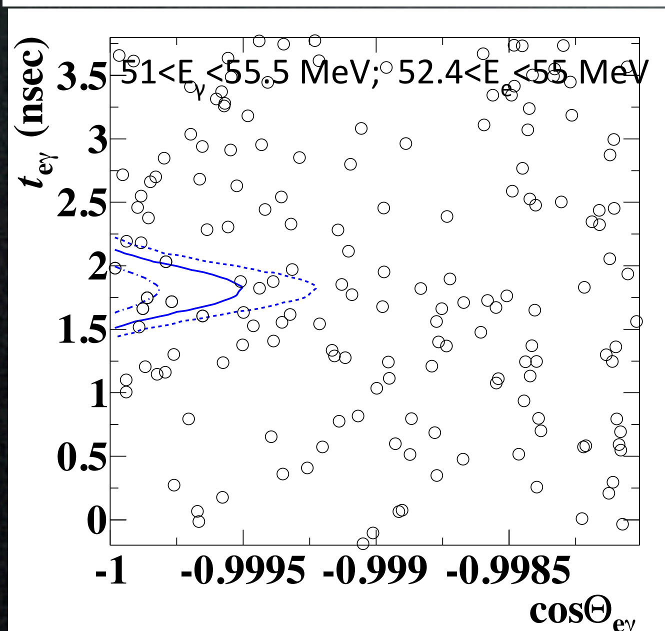
- Use Michel decay as normalization channel
    - Michel samples mixed in normal data taking
    - Count reconstructed high momentum Michel positrons
    - In the branching ratio calculation, the positron efficiency is cancelled out in the first order. Rather precise evaluation should be possible in spite of the varying positron efficiency during the run.

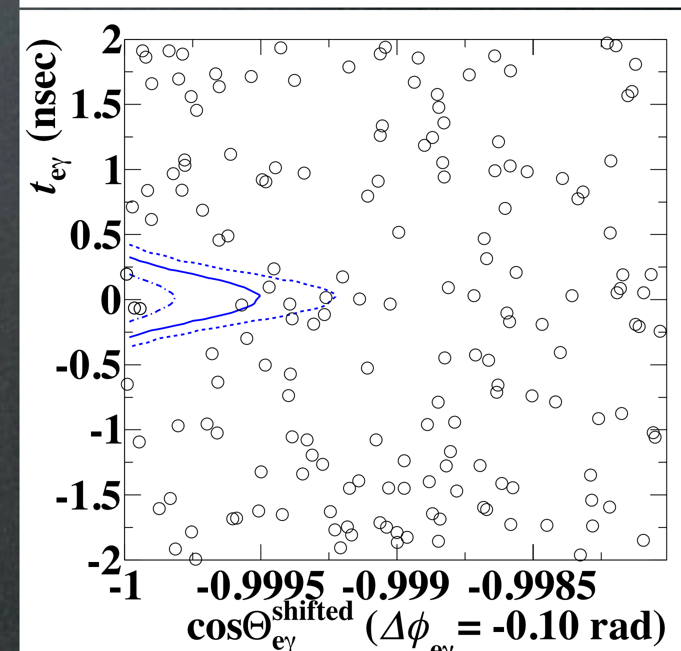
also checked by radiative muon events

2011 Side band data





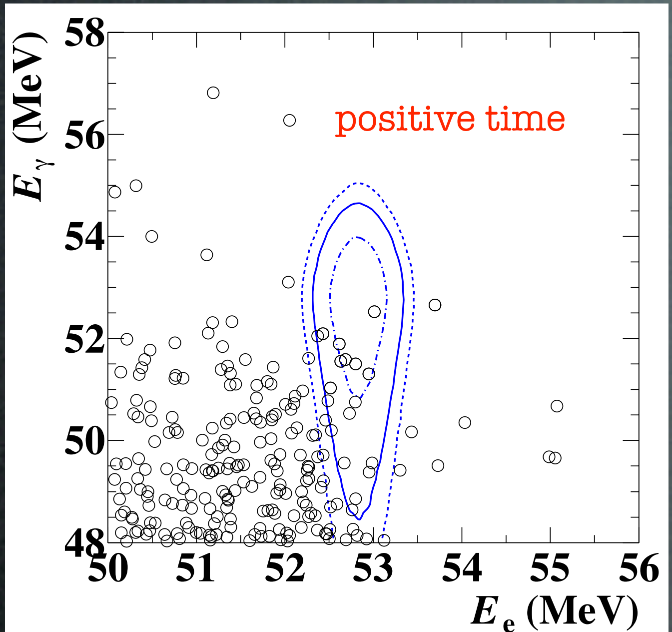


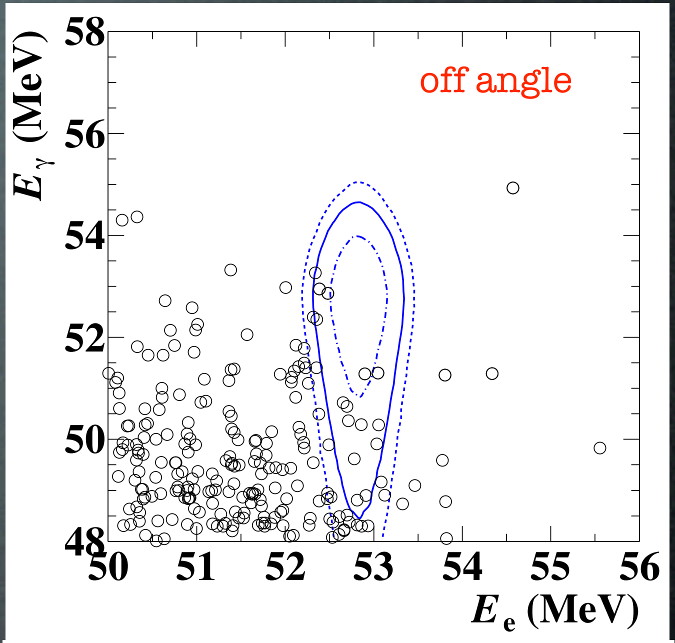


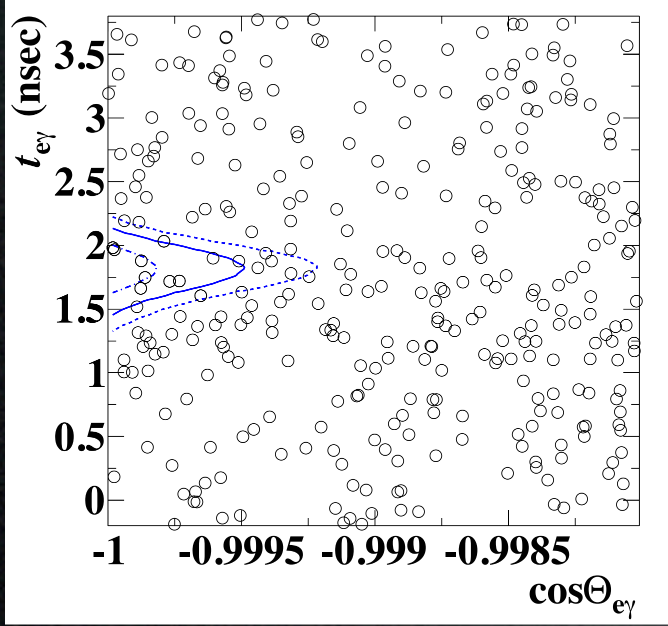
1, 1.64, 2σ contours

side band BG rates are consistent with the expected sensitivity for 2011 data = 1.1×10^{-12} @90% C.L.

2009-2011 Side band data

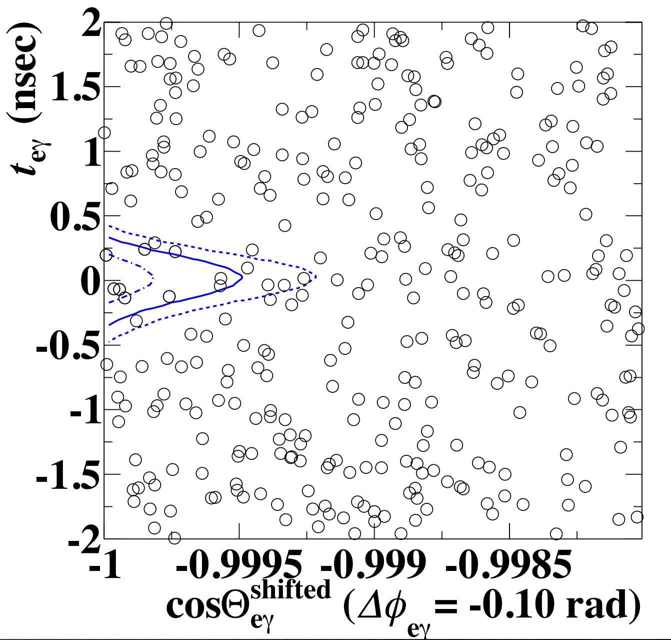






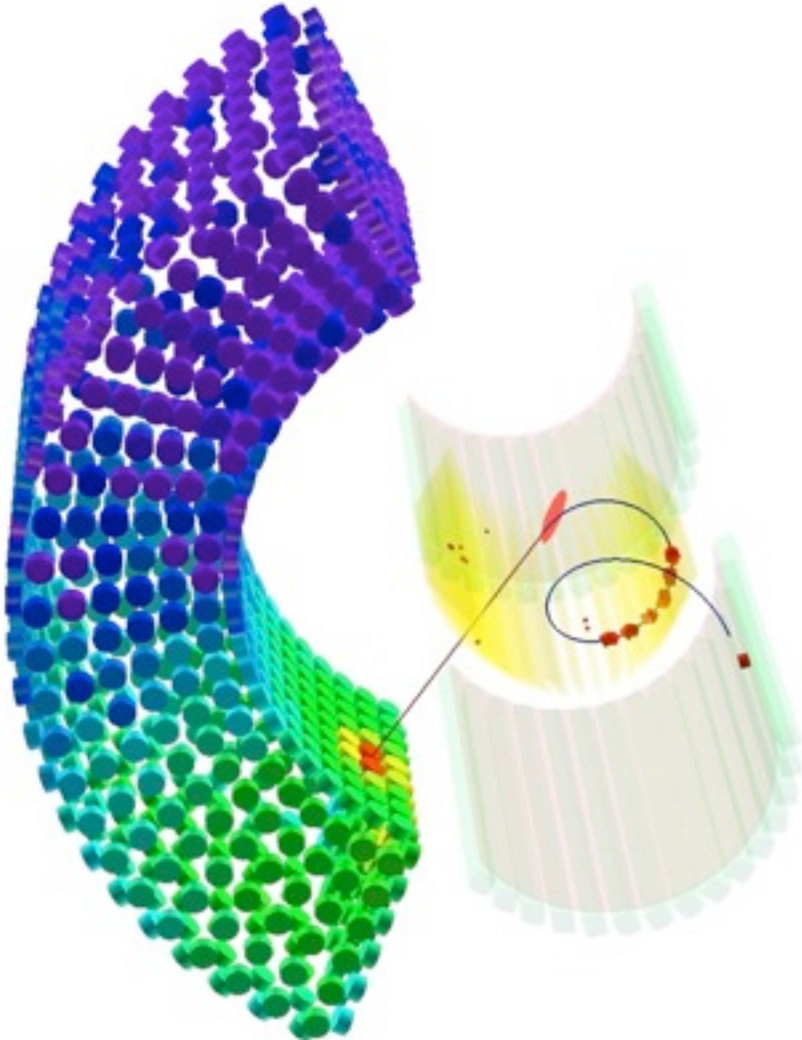
2009-2010 reprocessed ~20% better sensitivity

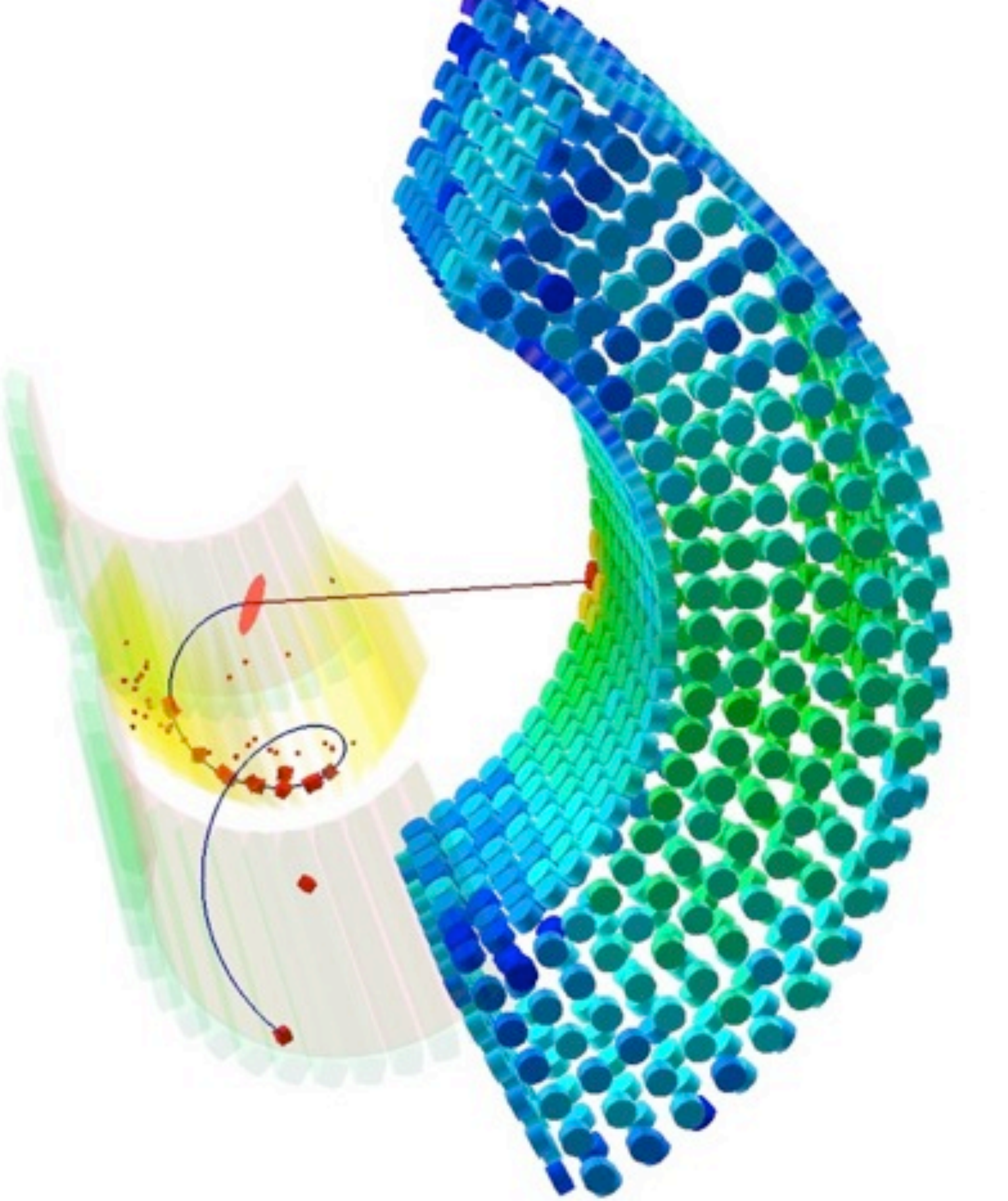
1, 1.64, 2σ contours



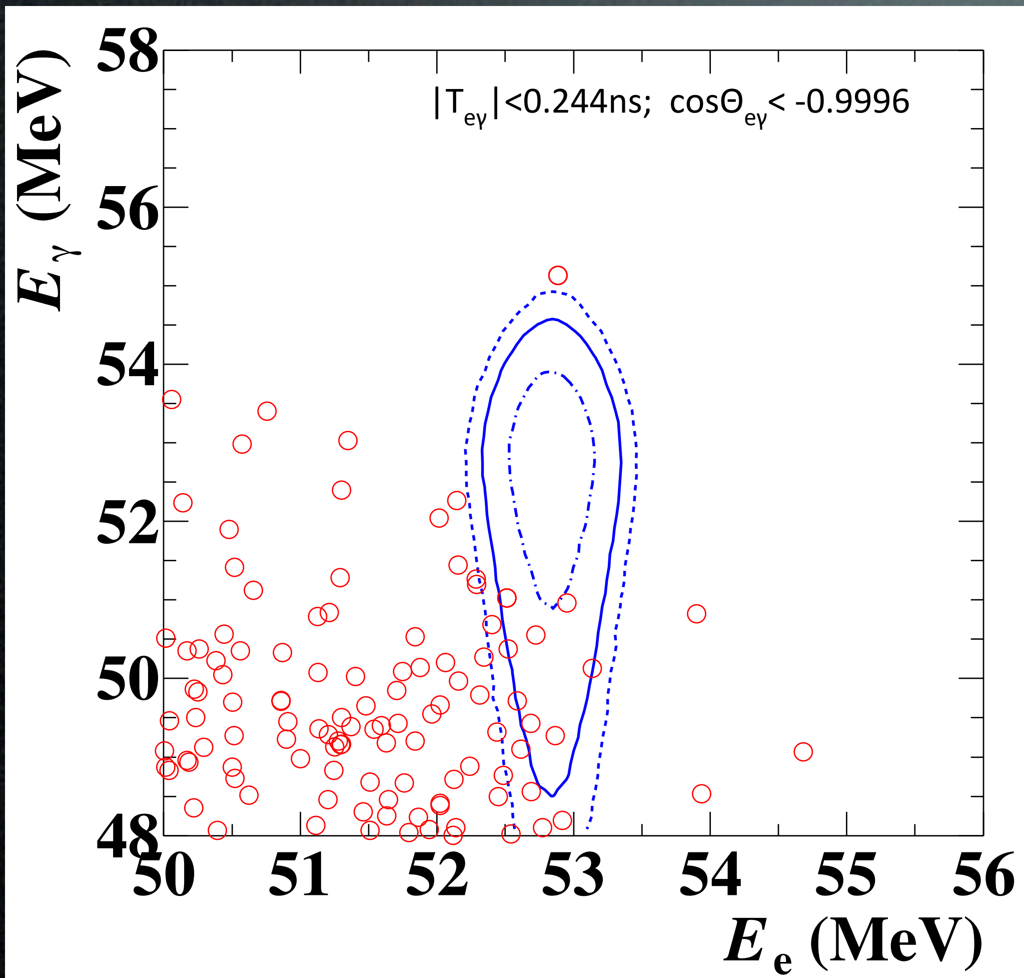
side band BG rates are consistent with the expected sensitivity for 2009-11 data = 7.7×10^{-13} @90% C.L.

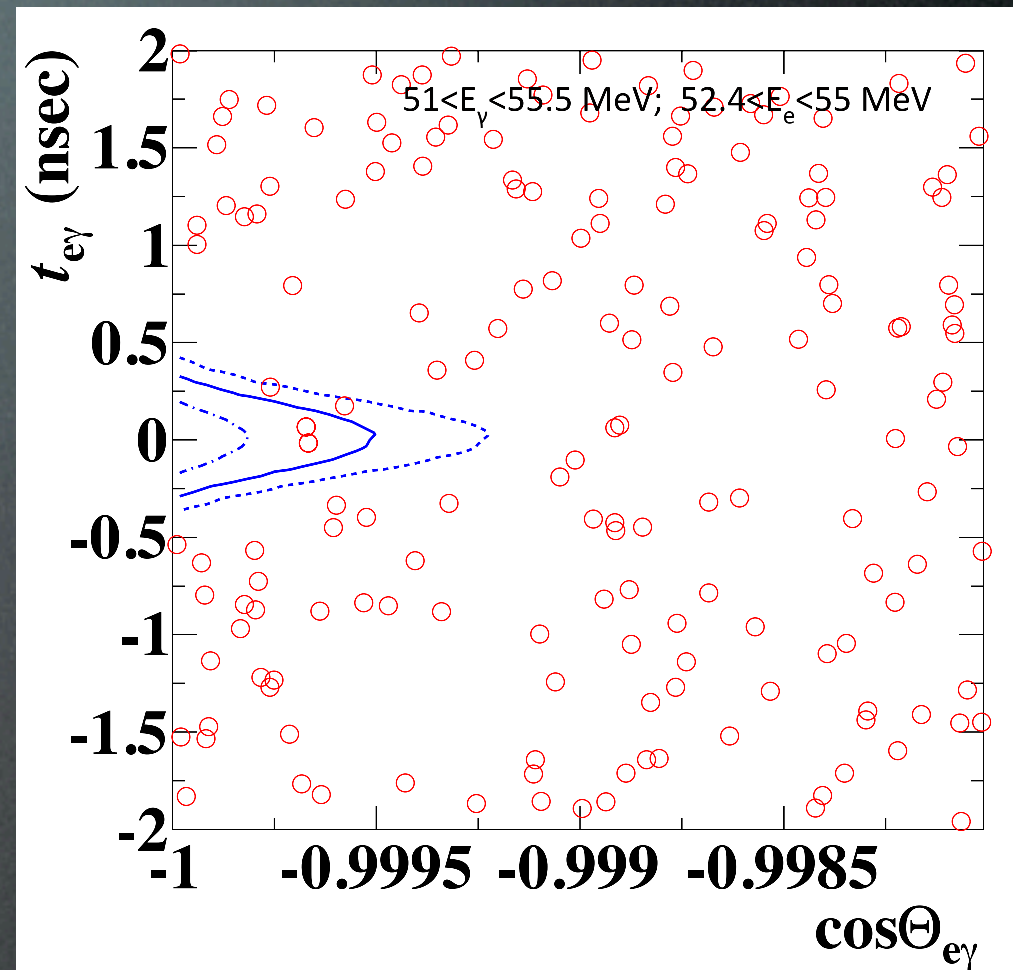
Blind box opened





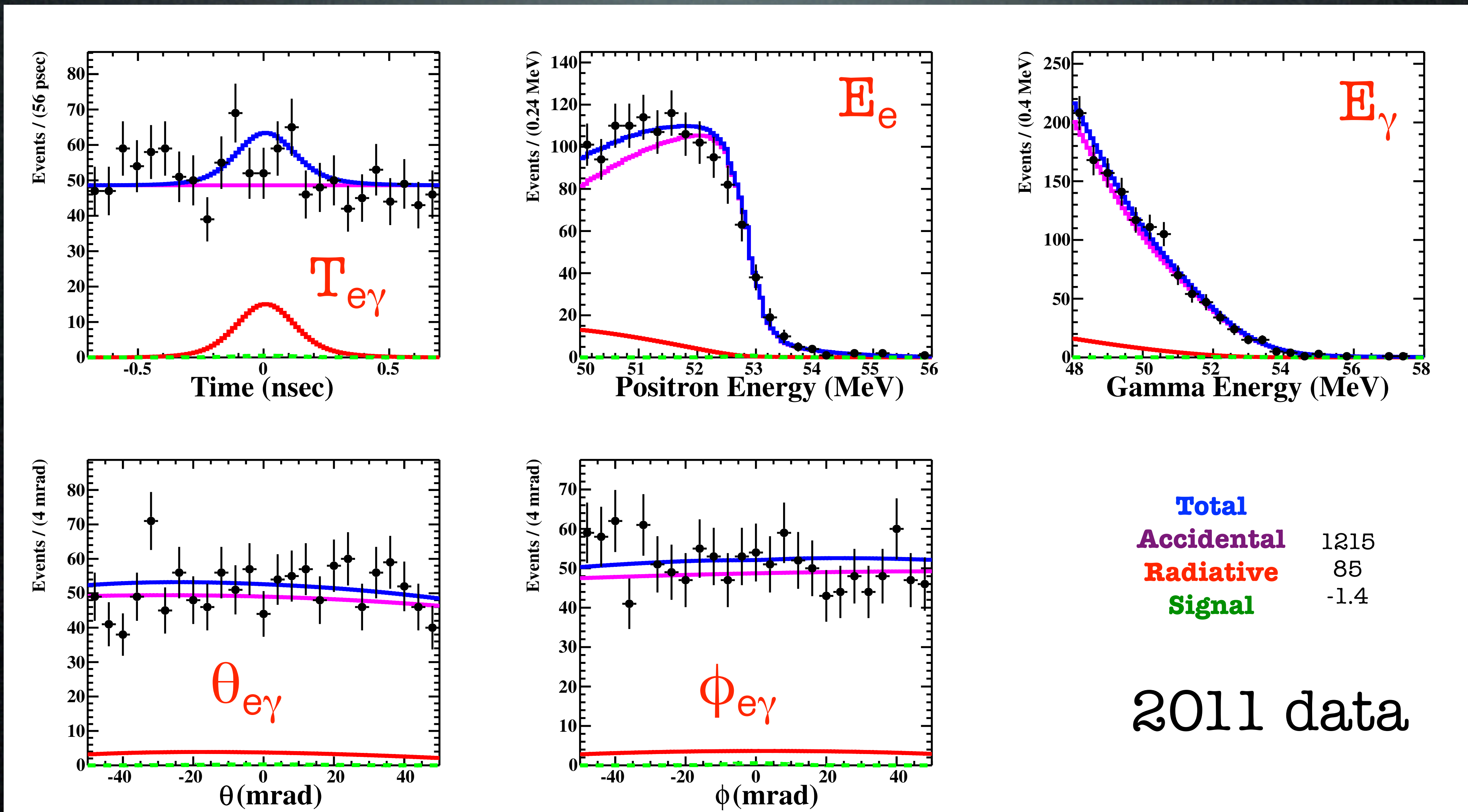
2011 data



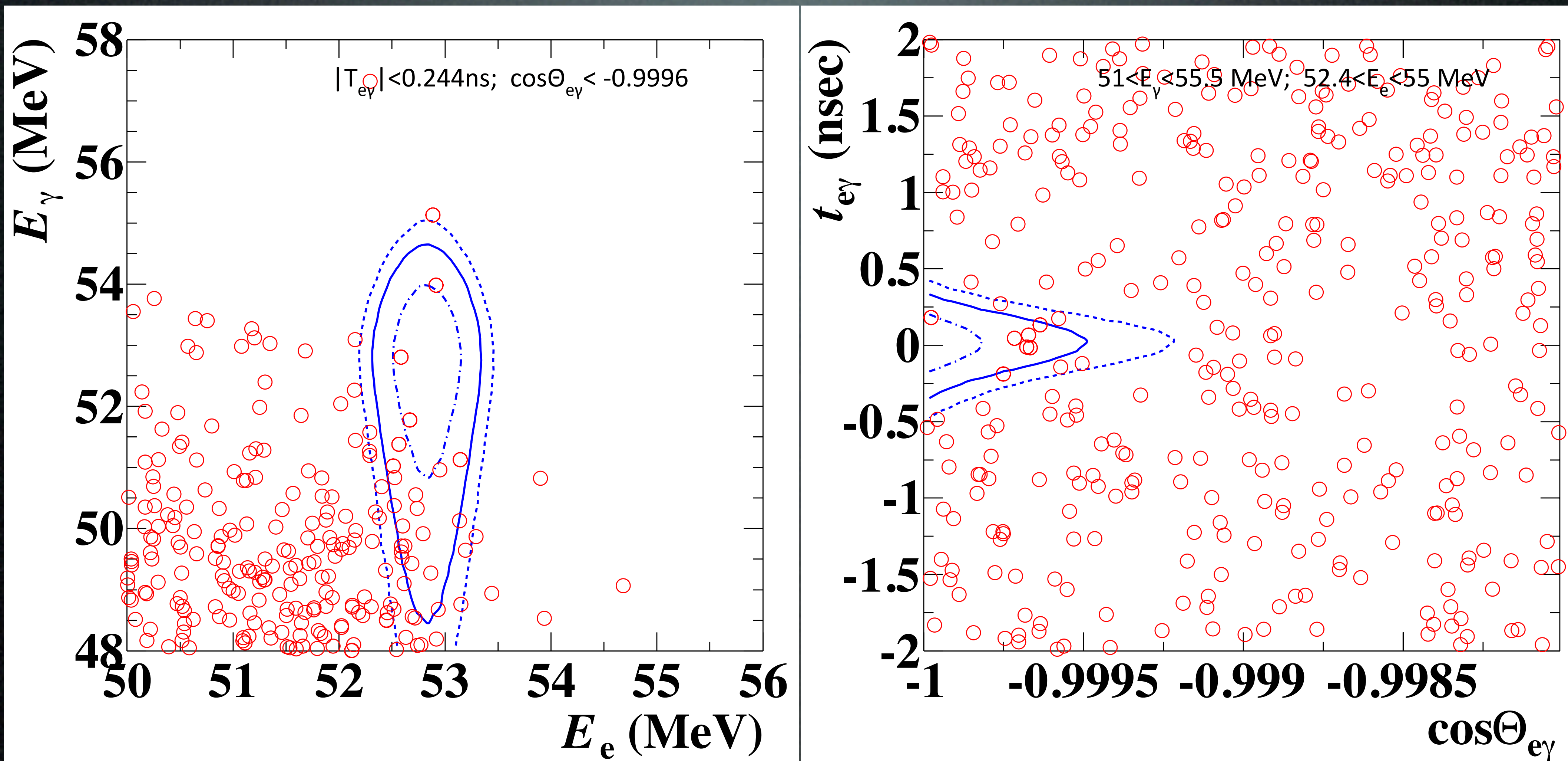


1, 1.64, 2σ
contours

Likelihood Fit - 2011 Data

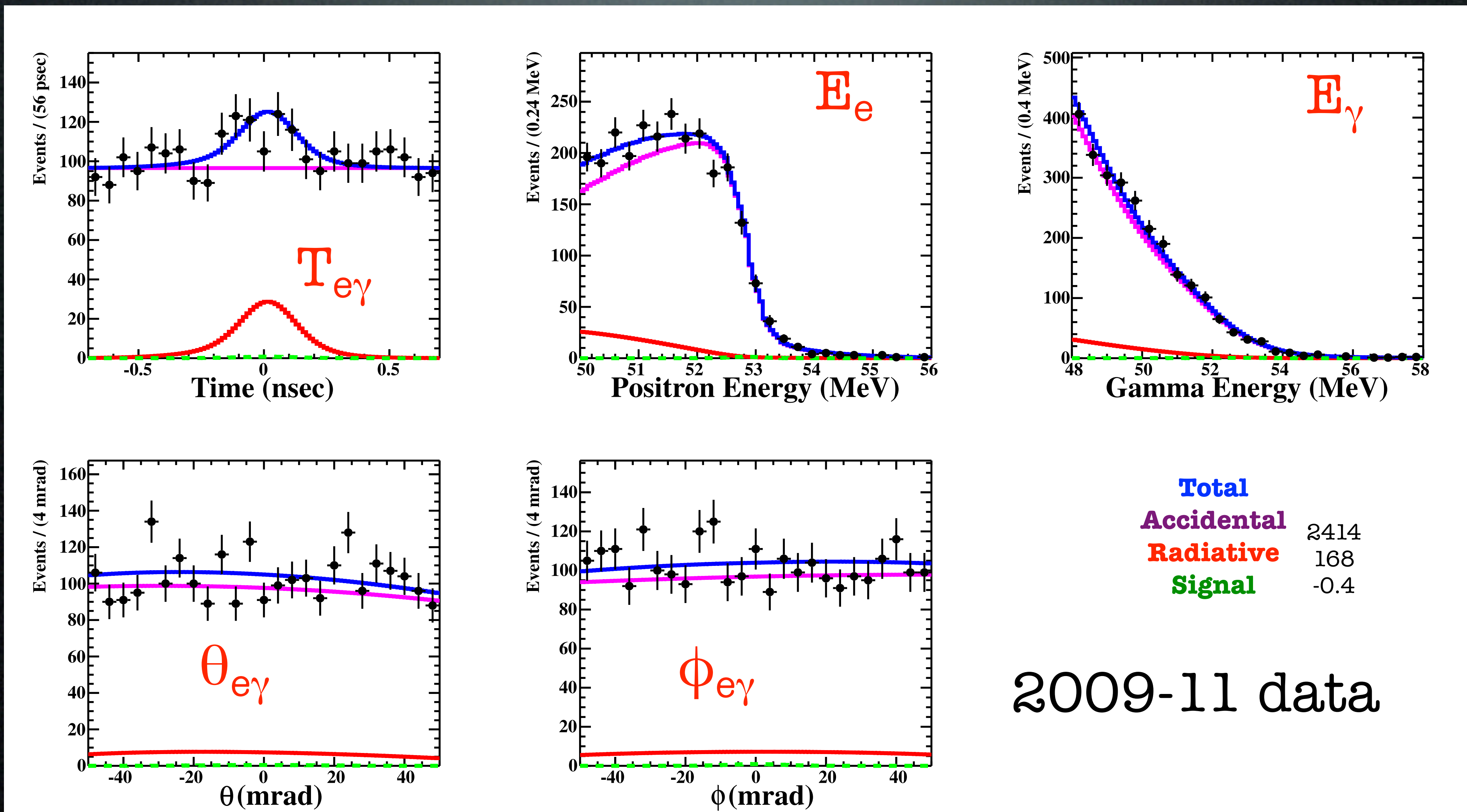


2009-2011 data

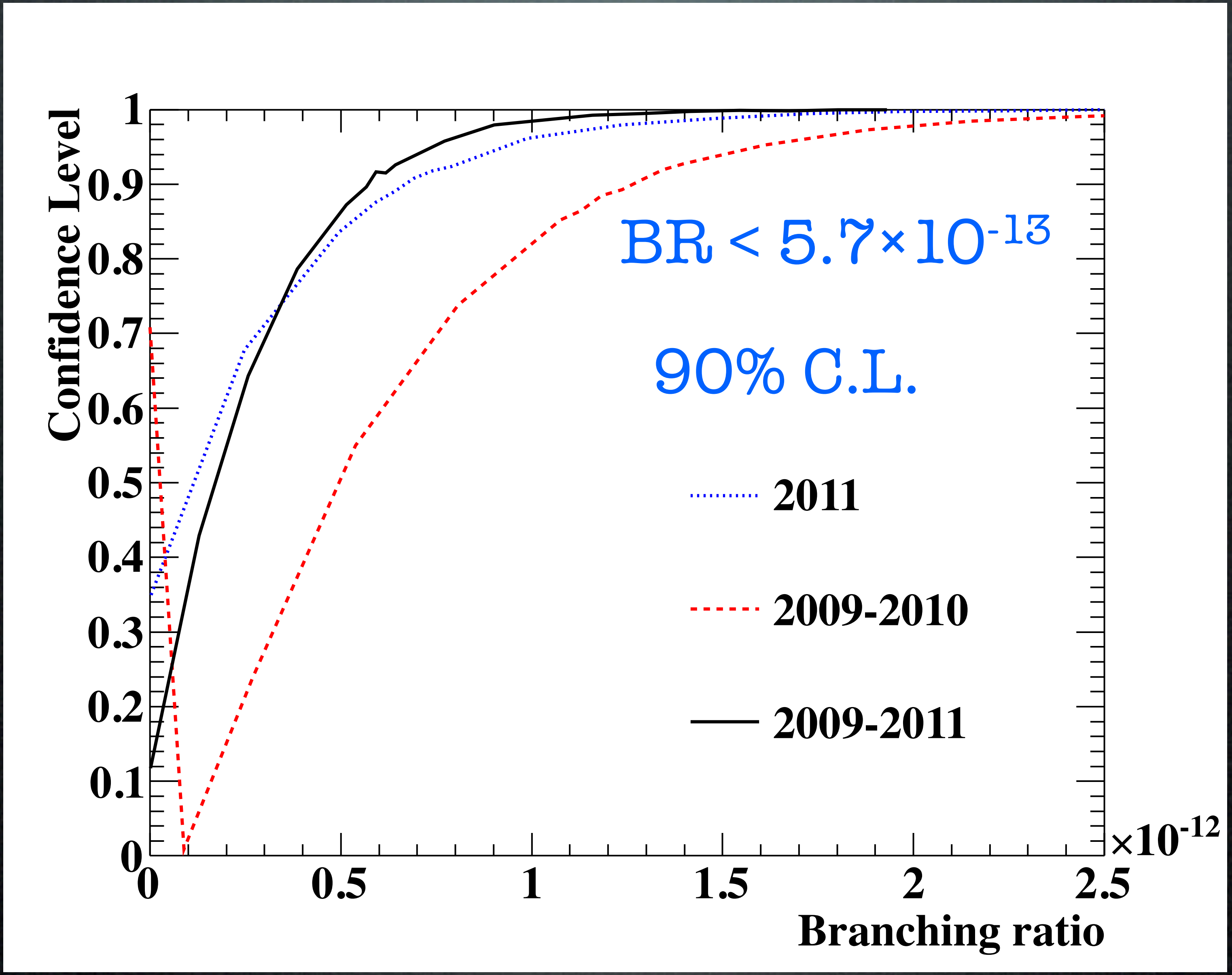


1, 1.64, 2σ contours

Likelihood Fit - 2009-2011 Data



Likelihood Analysis



Likelihood Analysis Results

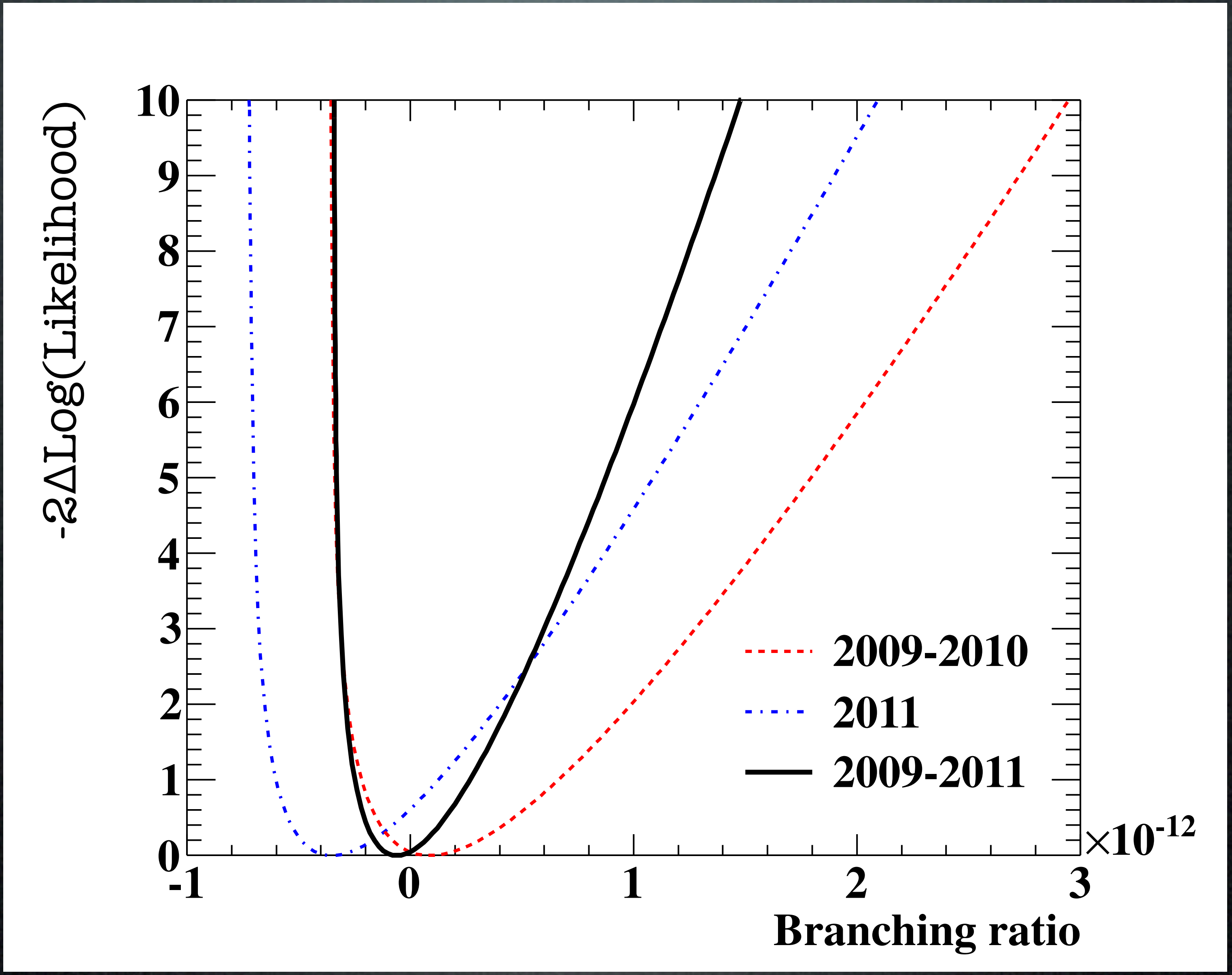
	BR(fit)	90% UL	sensitivity
2009+2010	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	0.67×10^{-12}	1.1×10^{-12}
2009-2011	-0.06×10^{-12}	0.57×10^{-12}	0.77×10^{-12}

combined result

4× improved upper limit than previous 2.4×10^{-12}

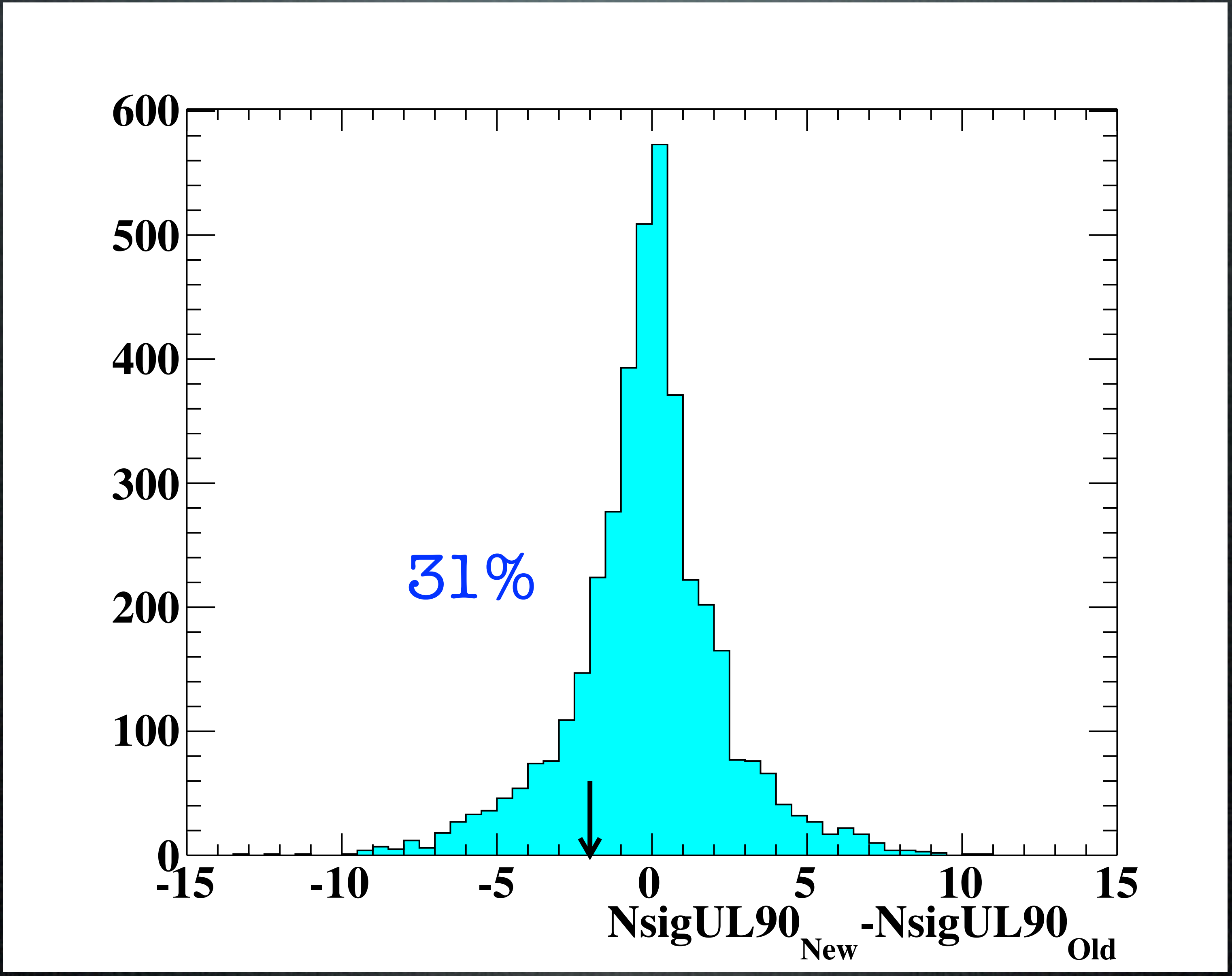
the preprint to be submitted to arXiv today

Profile Likelihood Curves

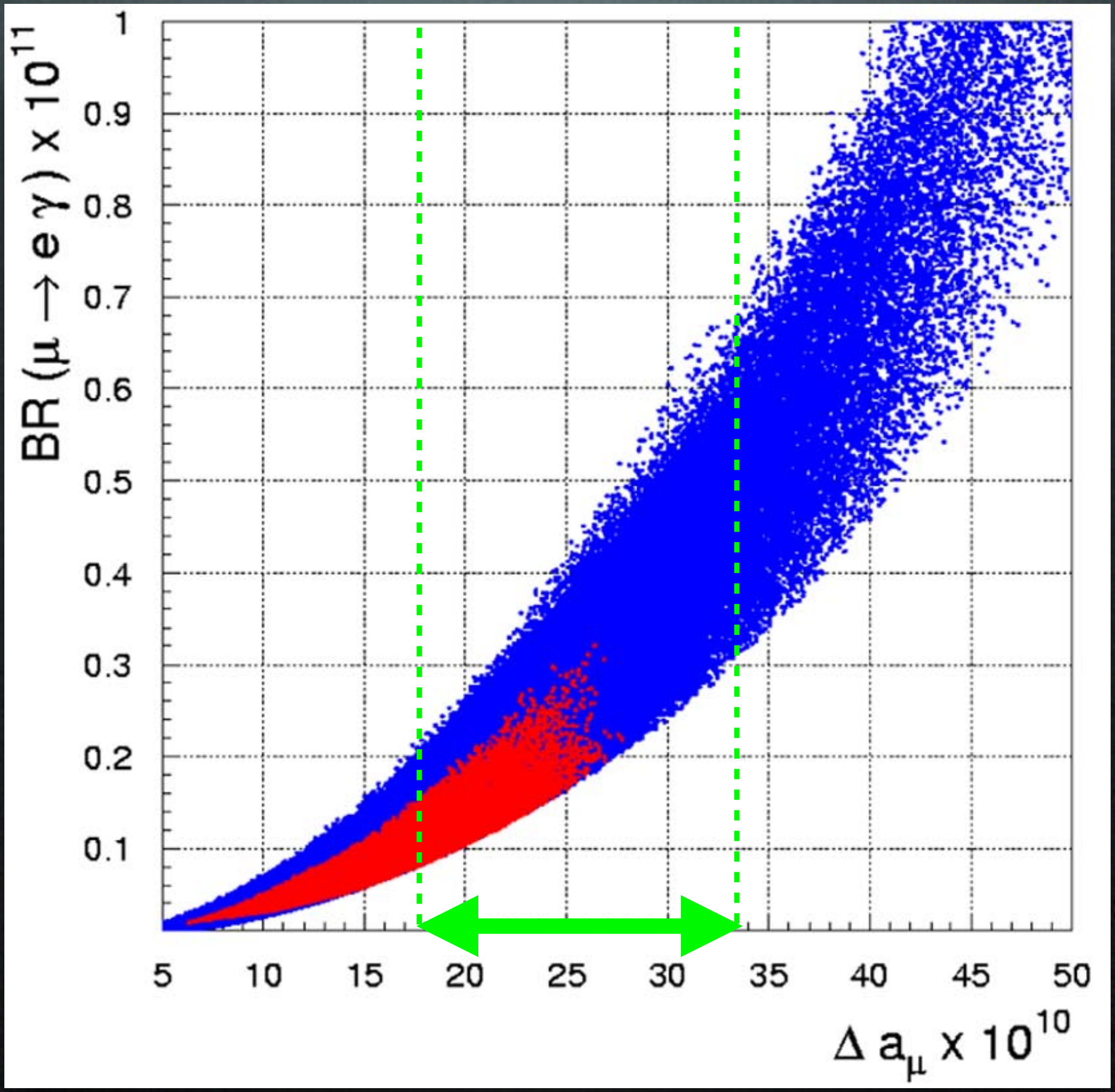


Note these curves are not directly used to derive the U.L. which are obtained in a frequentist approach.

Compatibility Test for 2009+2010 Data before/after re-process



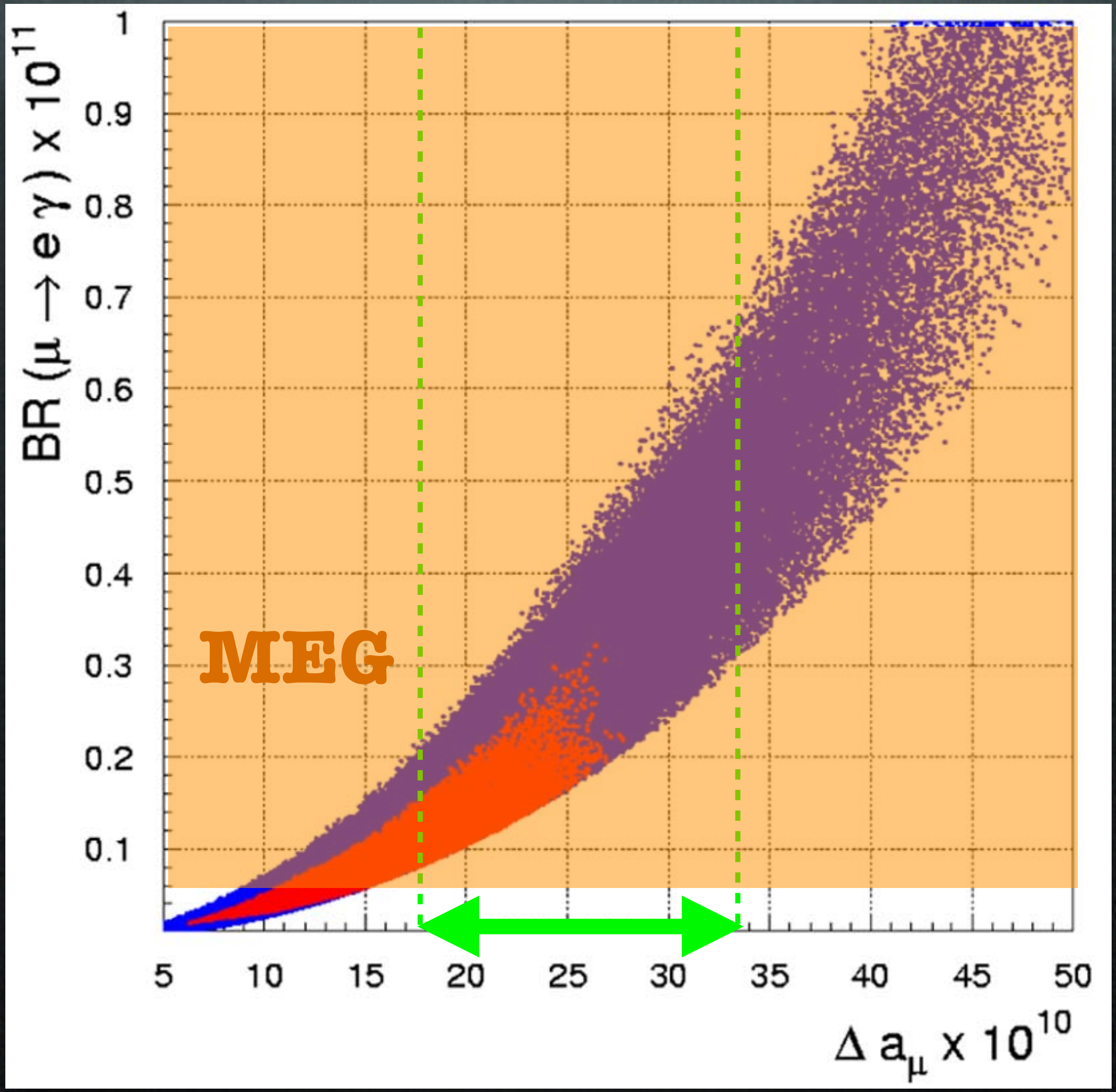
muon (g-2) anomaly



G.Isidori et al. PRD75, 115019

muon's anomalous magnetic moment

muon (g-2) anomaly

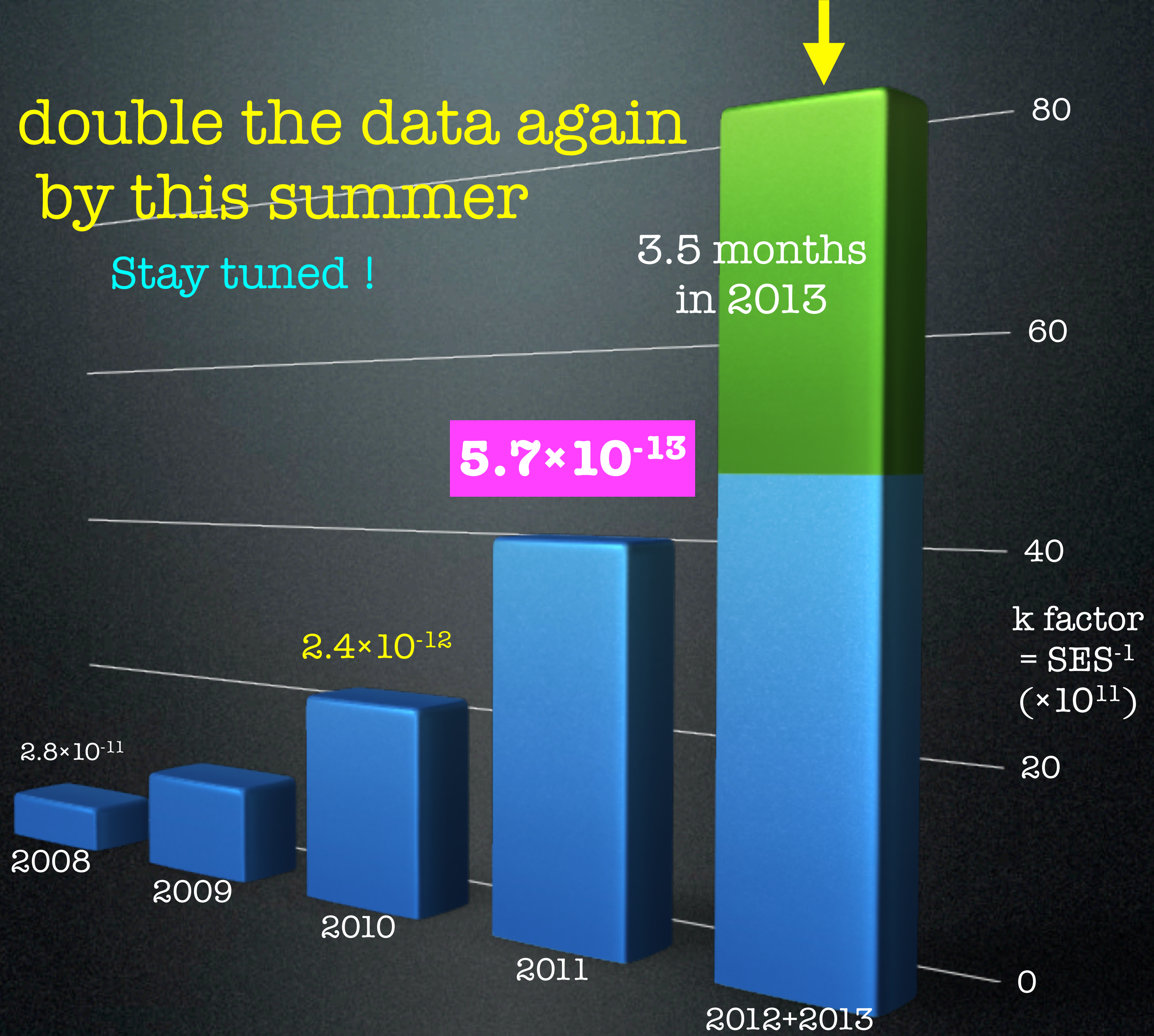


G.Isidori et al. PRD75, 115019

muon's anomalous magnetic moment

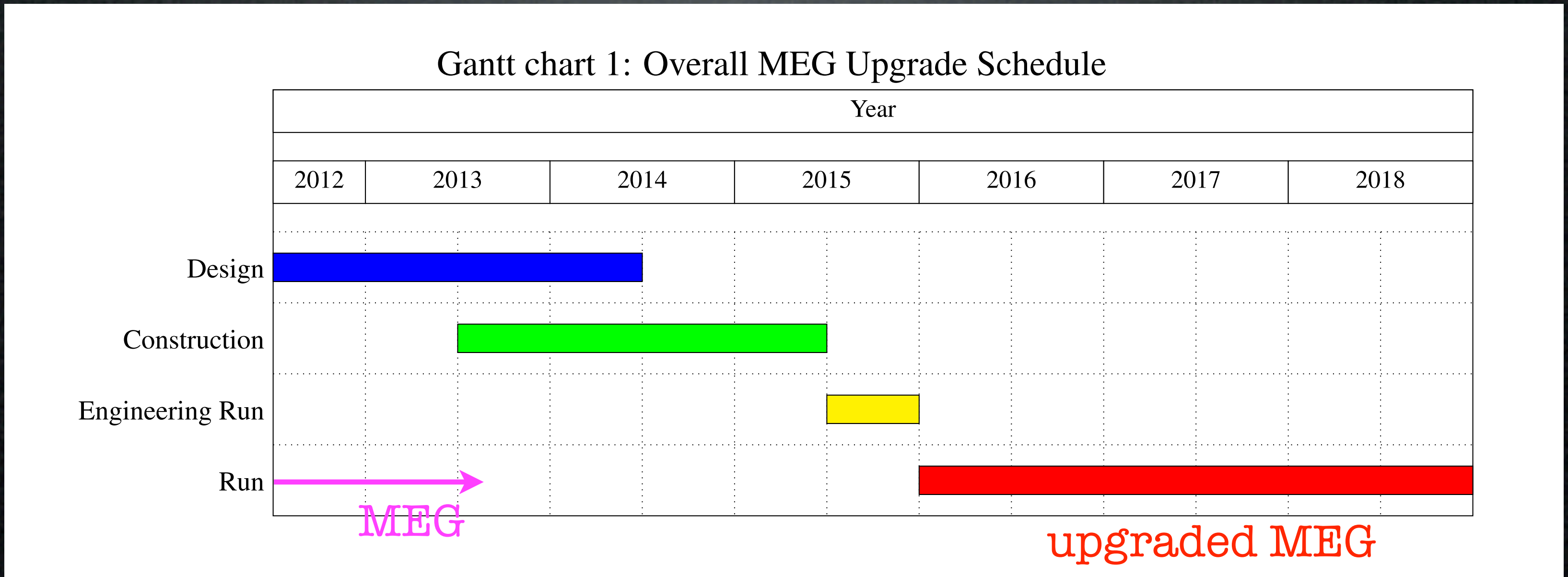
Will double the data again by this summer

Stay tuned !

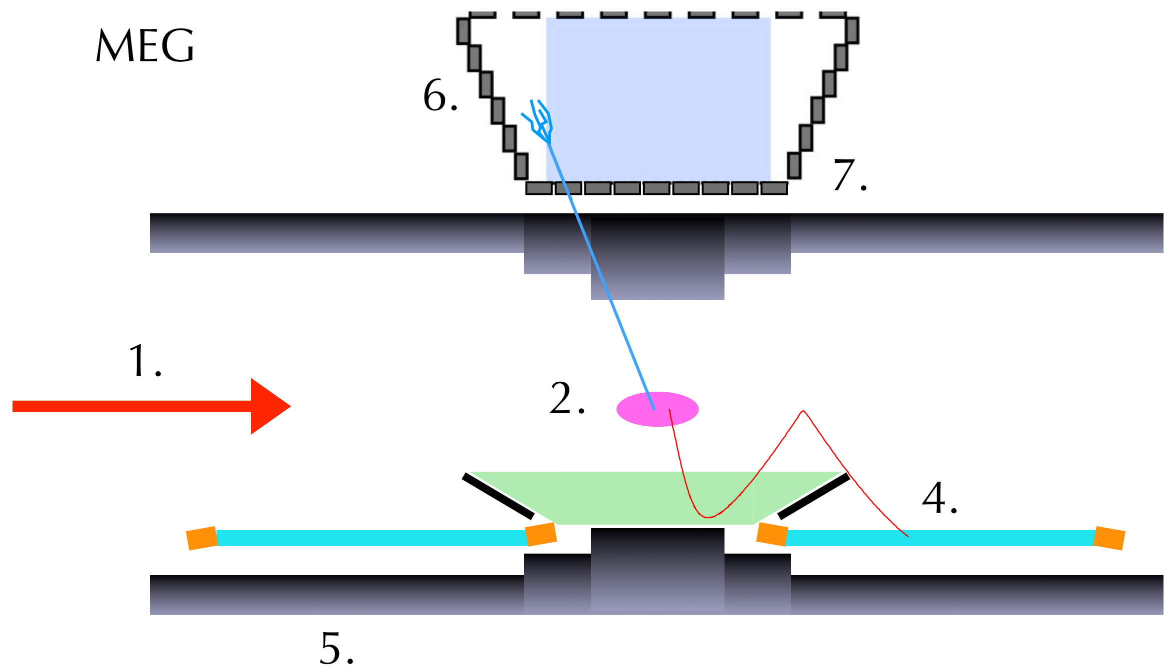


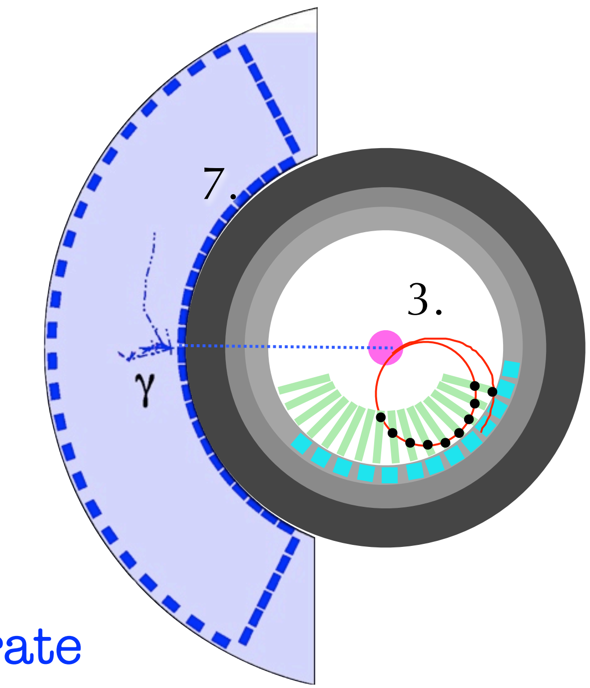
MEG upgrade

- MEG upgrade proposal was submitted to PSI, December 2012
- Approved by PSI committee, January 2013

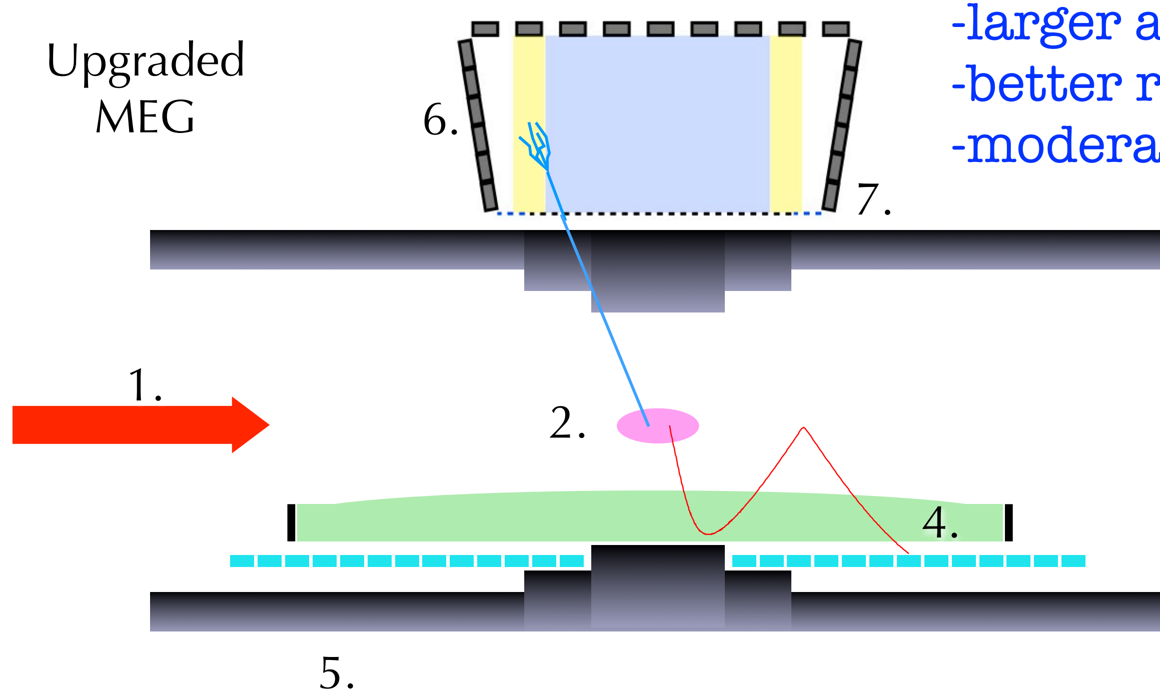


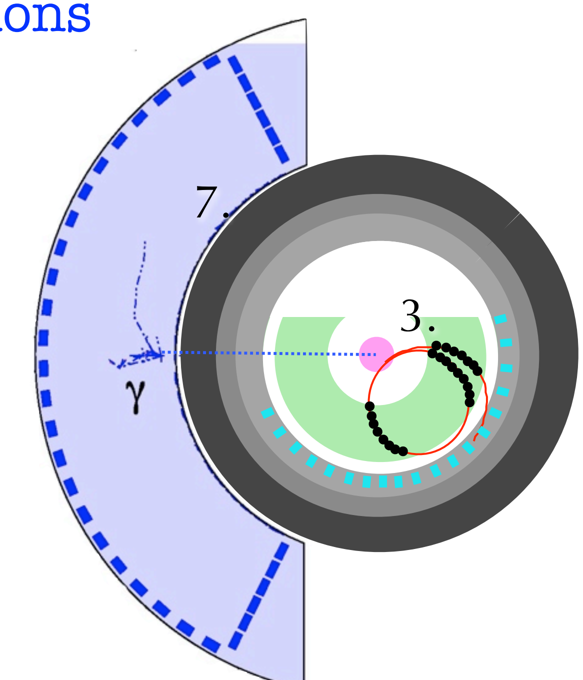
upgrade design based on our long time experience





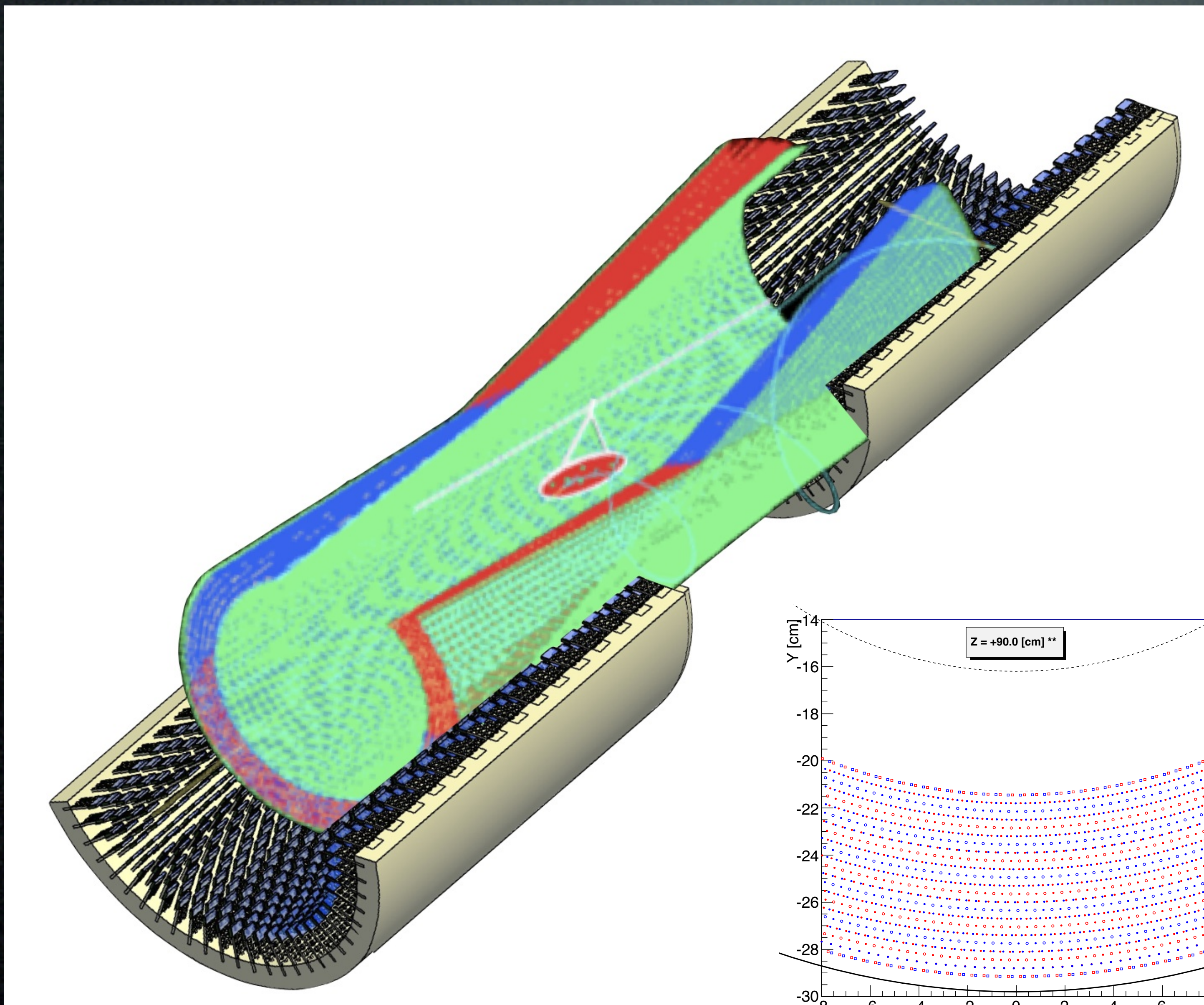
- higher beam rate
- larger acceptance
- better resolutions
- moderate cost





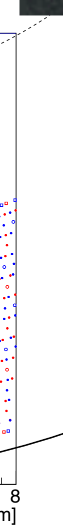
Drift Chamber

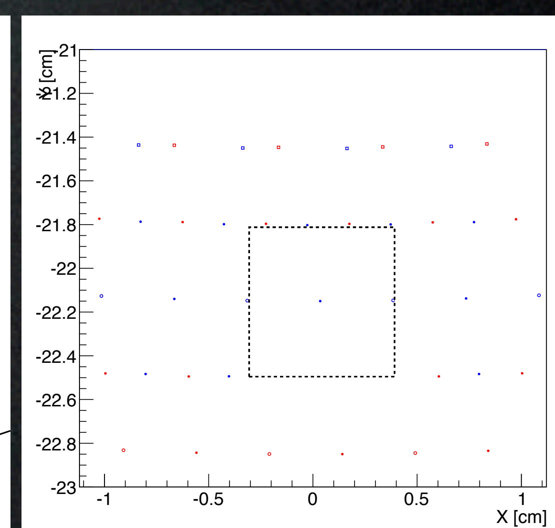
- sustain higher muon rate & ageing
- finer granularity & better resolution
- lager combined DC+TC acceptance



single volume
He-based gas
small cell size
stereo wires
~130μm hit resolution

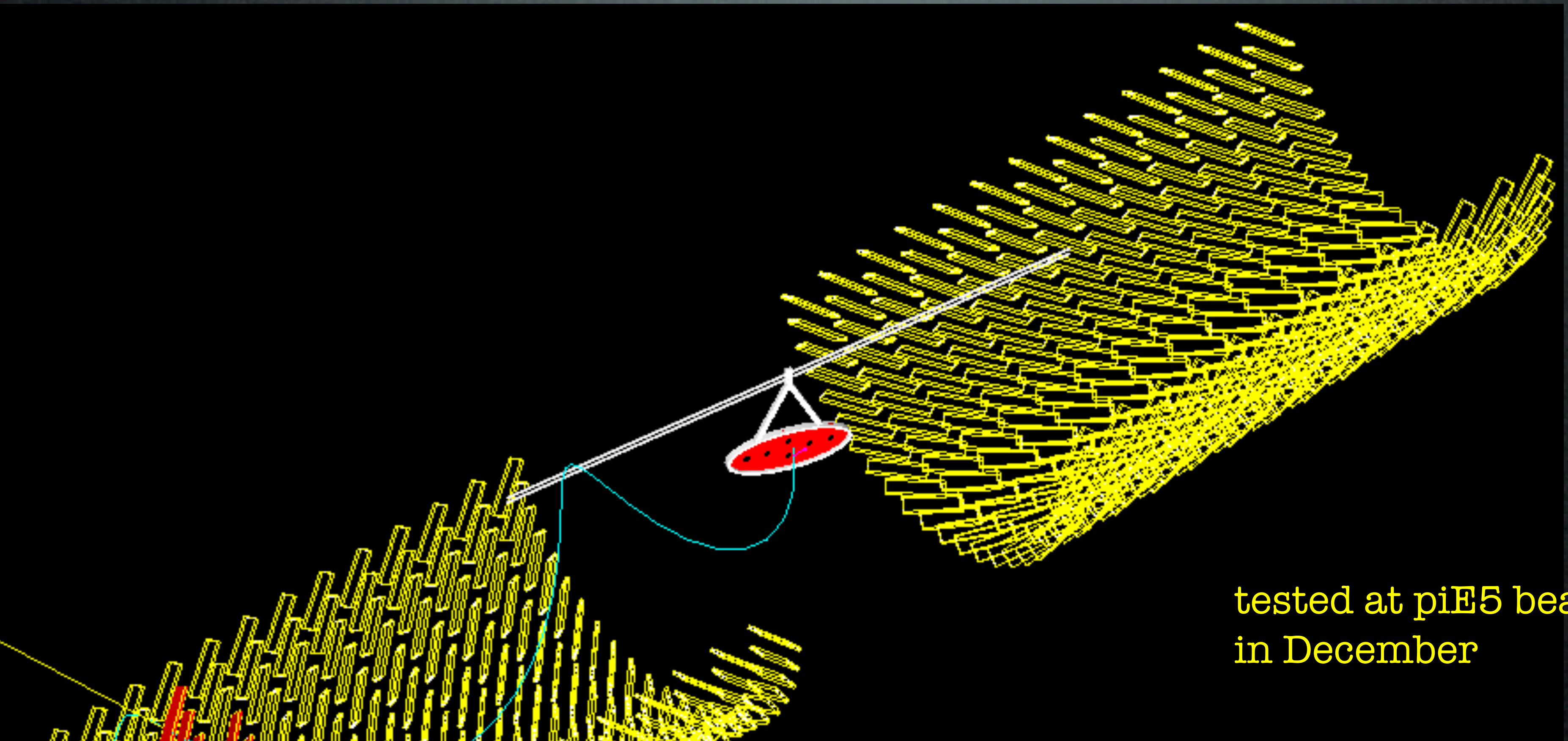
most challenging
element of upgrade



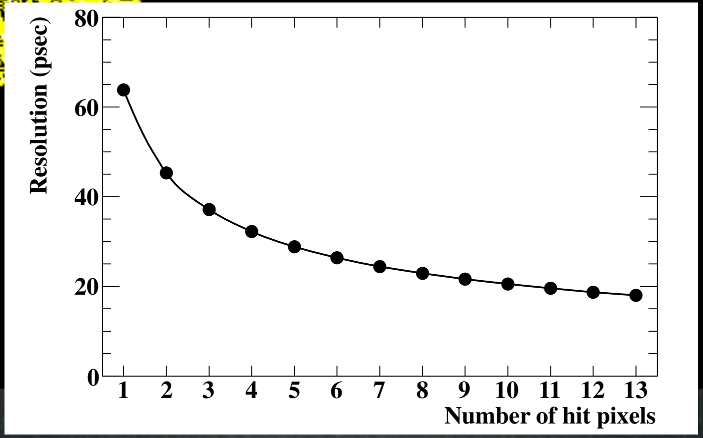


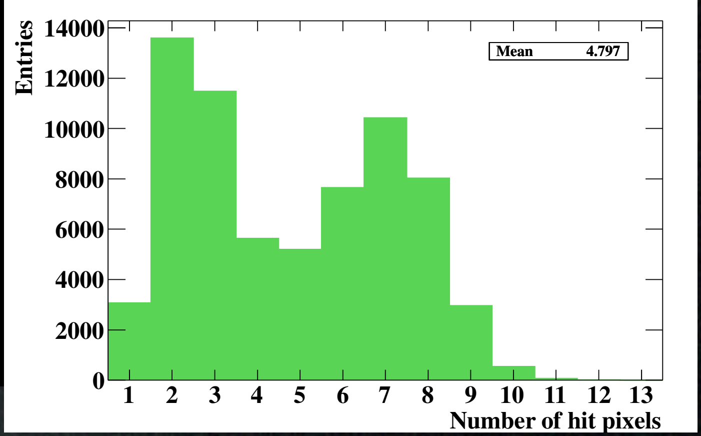
Timing Counters

- proven technology using SiPM
- excellent resolutions expected using multiple counters



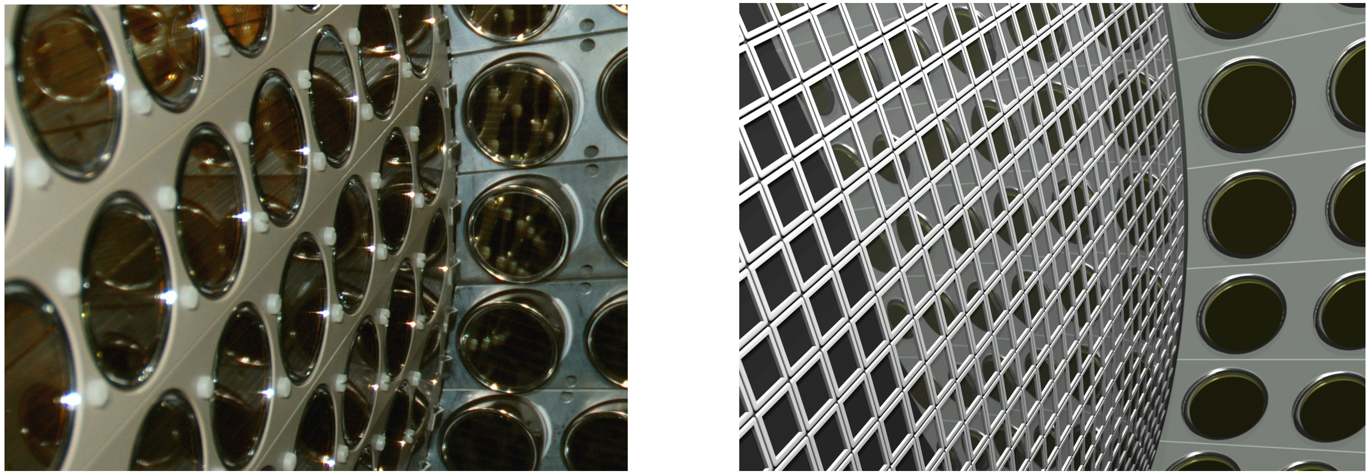
tested at piE5 beam line in December





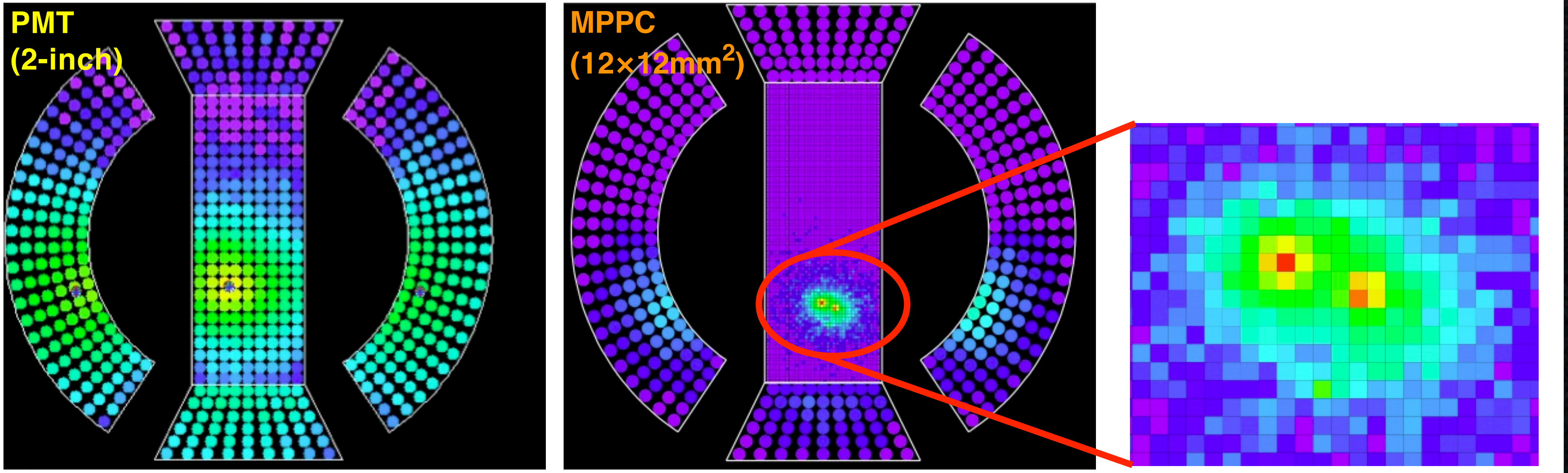
LXe Detector

- finer photon sensors at entrance face
- better uniformity - better resolution
- better handles for pile ups



(a) Present detector (b) Upgraded detector (CG)

LXe detector proved to work at 10^8 muons/s w/o pileup issues

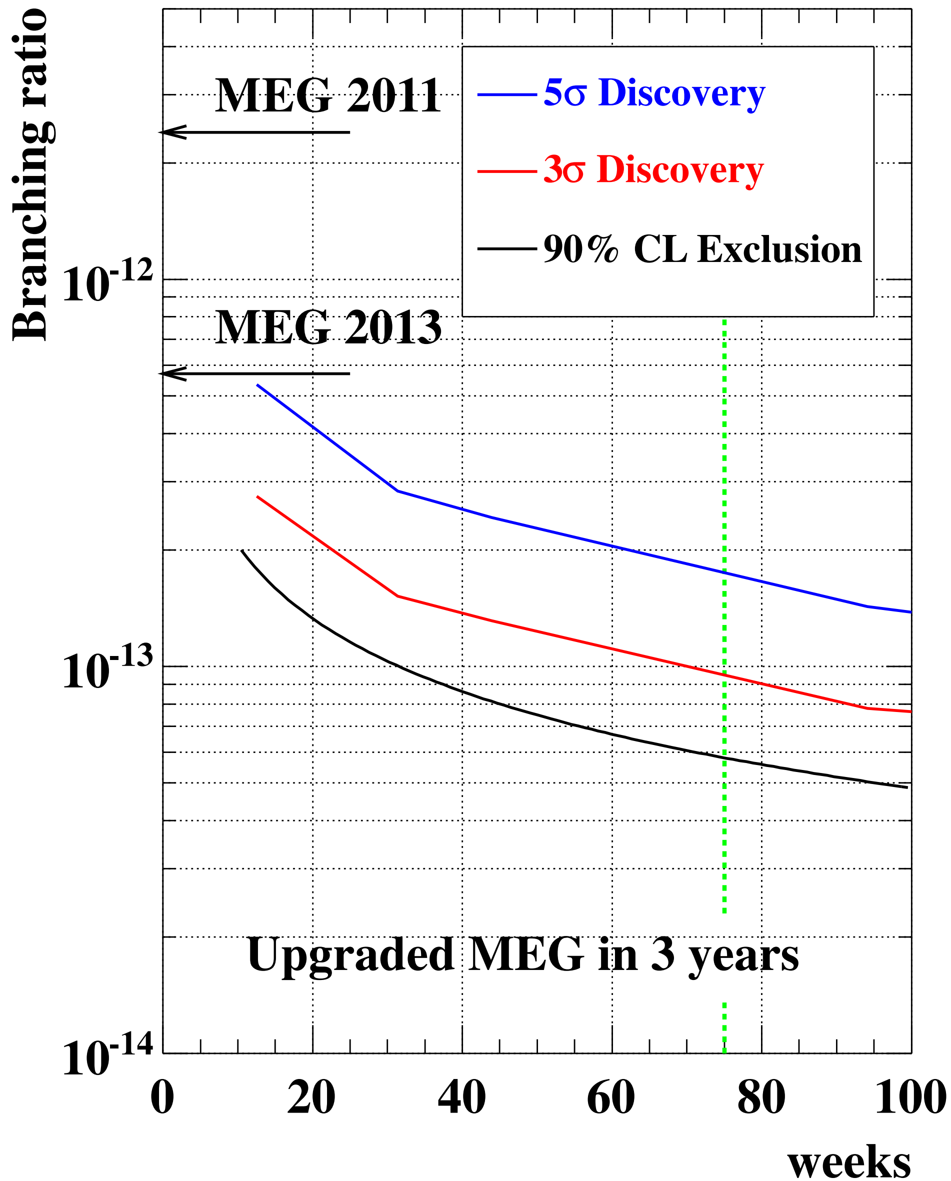


Resolutions, Efficiencies, & Sensitivity

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

muon rate	$3.3\text{x}10^7$/sec	$7\text{x}10^7$/sec



Where We Will Be

Summary

- No $\mu \to e\gamma$ event found in the new 2011 data, which more than doubled data statistics
- New physics is 4× more strongly constrained: $BR(\mu \to e\gamma) < 5.7\times10^{-13}$ @90% C.L. getting higher tension w/ muon g-2
- MEG plan to double the data again by summer 2013; So stay tuned!
- MEG upgrade approved & underway: 10× higher sensitivity expected in future