Recent + future MEG results (and LFV implications) in the “SuperB” era

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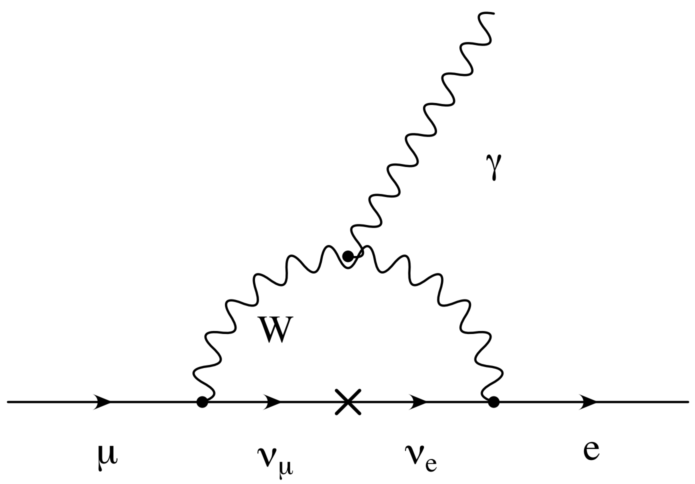
XVII SuperB Workshop and Kick-off Meeting

La Biodola (Isola d’Elba) 1 June 2011

Lepton flavor violation

- LFV decays in the SM is radiatively induced by neutrino masses and mixings at a negligible level

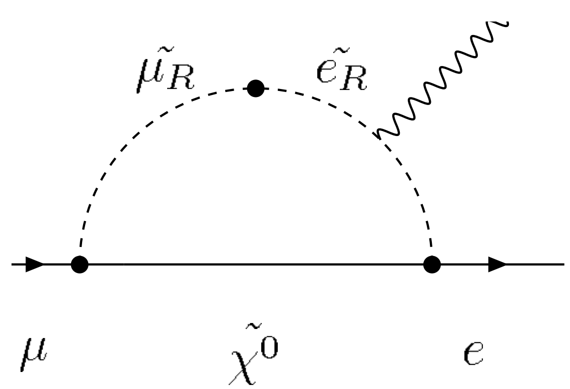


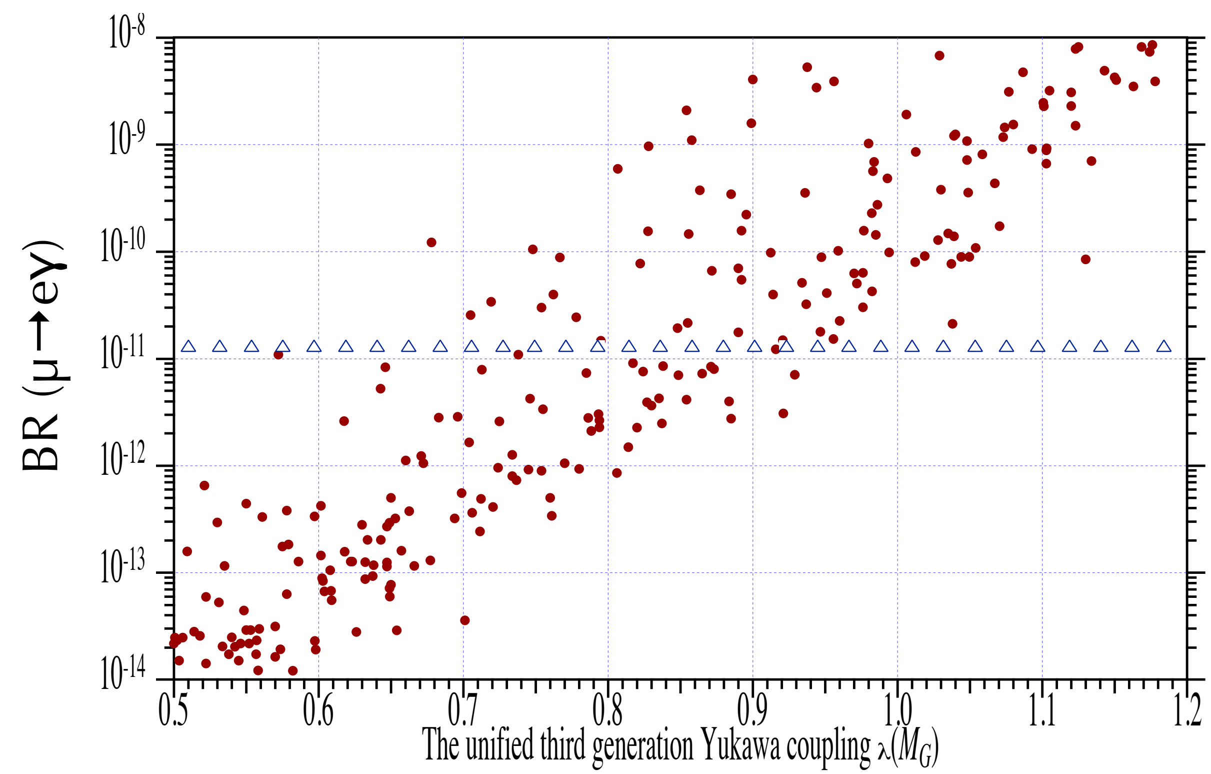
$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

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

relative probability ~ 10^{-54}

- All SM extensions enhance the rate through mixing in the high energy sector of the theory (other particles in the loop...)





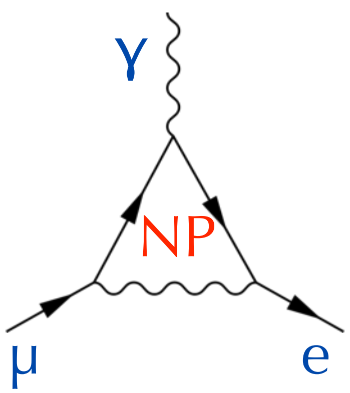
- Clear evidence for physics beyond the SM
  - background-free
- Restrict parameter space of SM extensions

Many processes

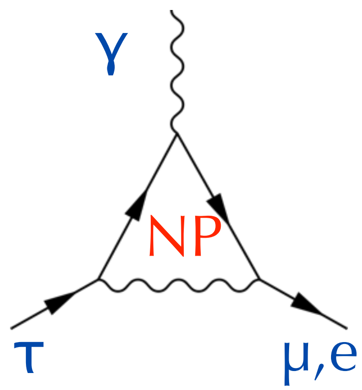
Tau's from B-factory

- LFV is related to a "new" lepton-lepton coupling

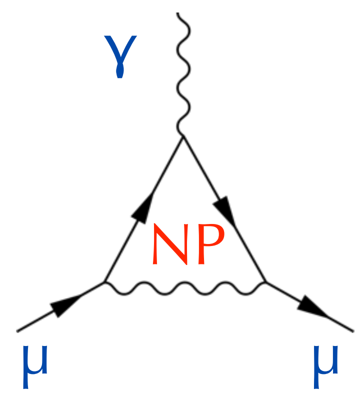
$$y_{ij}\bar{\ell}_i F^{\mu\nu}\ell_j\sigma_{\mu\nu}$$



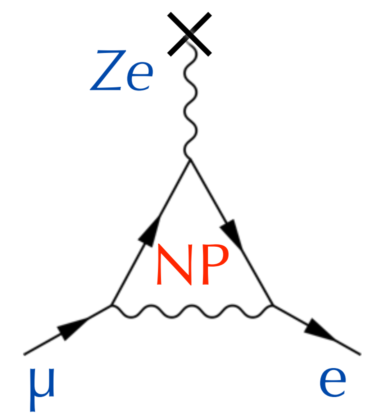
$\mu \to e\gamma$



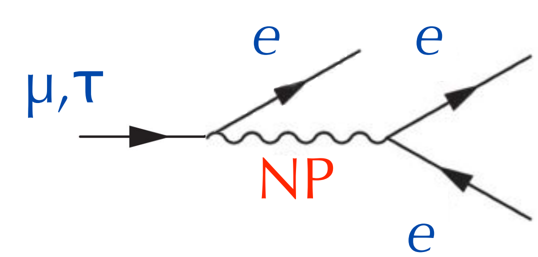
$\tau \to \mu\gamma$
$\tau \to e\gamma$



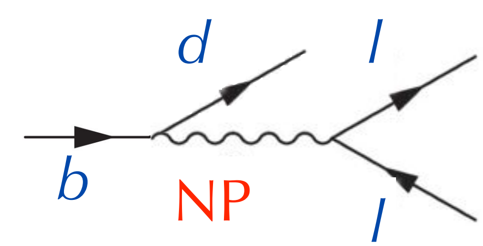
$(g-2)_\mu$



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



$\mu \to eee$



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

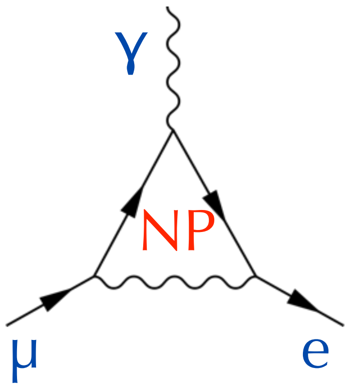
- A wide field of research
  - LFV decays
  - Anomalous magnetic moment for the μ, τ
  - Muon-to-electron conversion
  - (LFV in B-meson decays)

Many processes

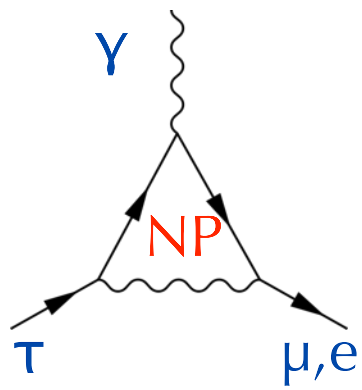
Tau's from B-factory

- LFV is related to a "new" lepton-lepton coupling

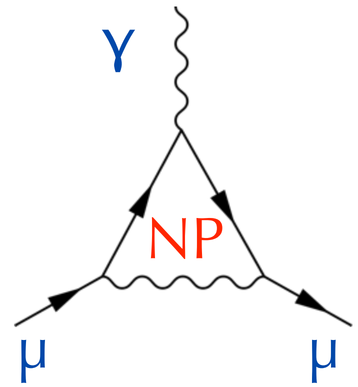
$$y_{ij}\bar{\ell}_i F^{\mu\nu}\ell_j\sigma_{\mu\nu}$$



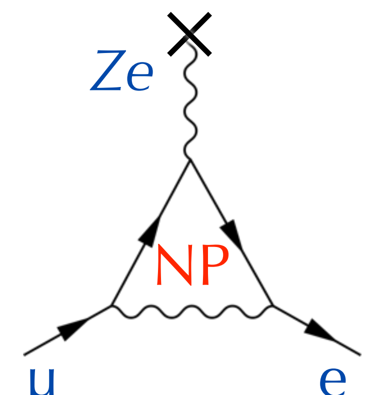
$\mu \to e\gamma$



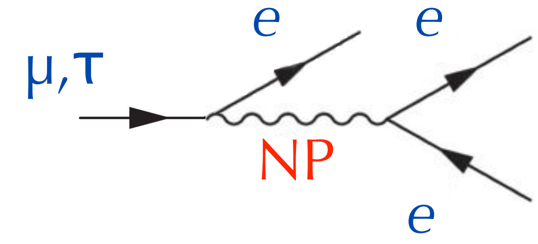
$\tau \to \mu\gamma$
$\tau \to e\gamma$



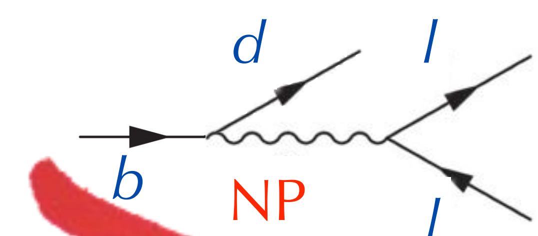
$(g-2)_\mu$



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



$\mu \to eee$

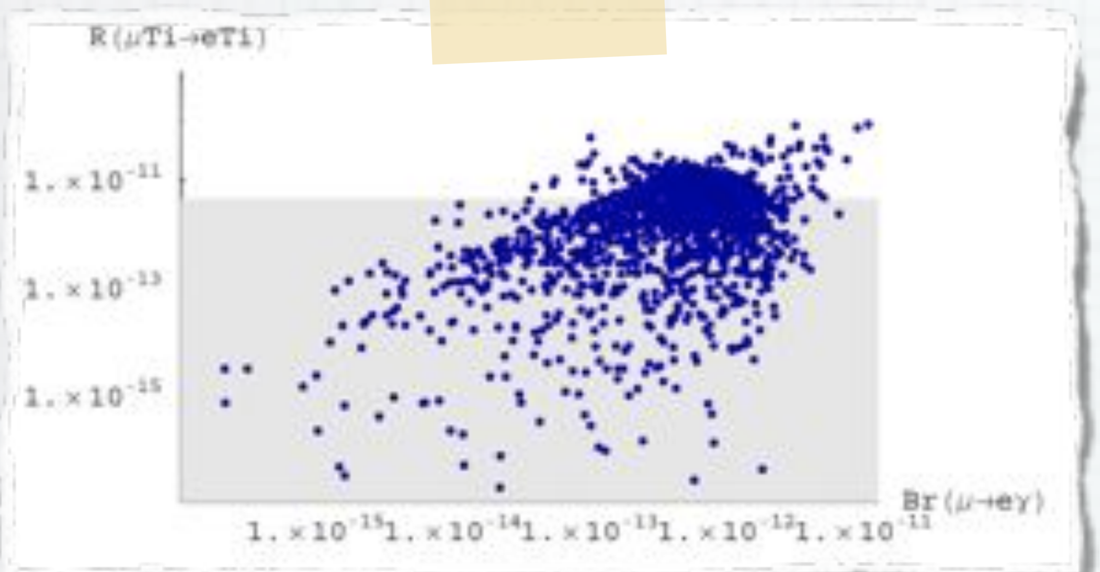


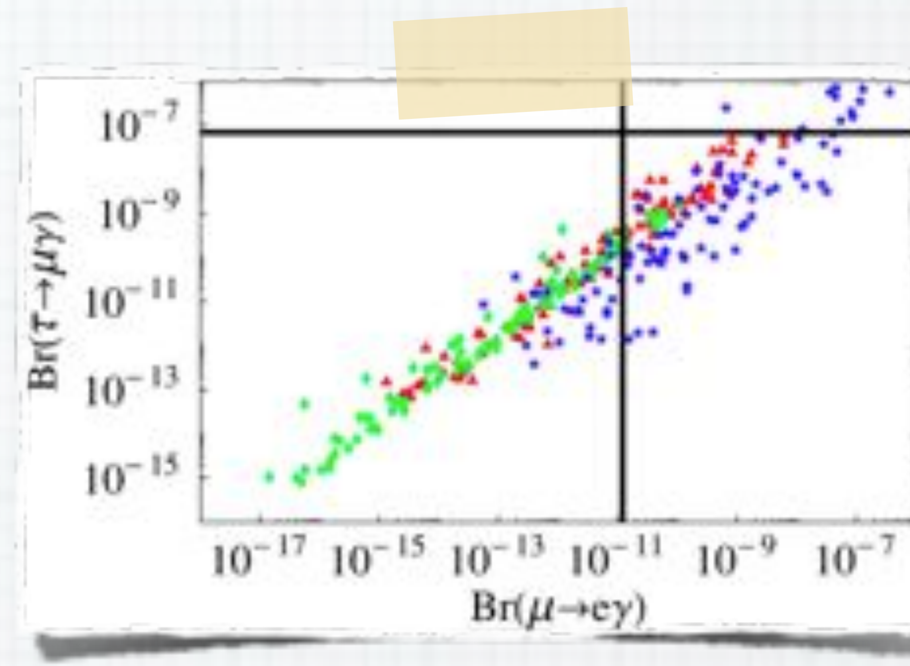
$B \to \ell\bar{\ell}'$
$B \to \ell\bar{\ell}' X_s$

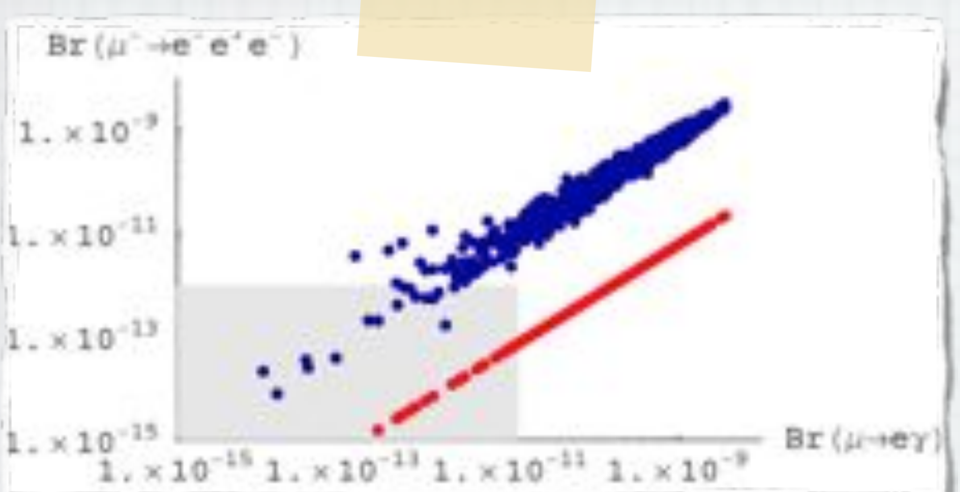
- A wide field of research
  - LFV decays
  - Anomalous magnetic moment for the μ, τ
  - Muon-to-electron conversion
  - (LFV in B-meson decays)

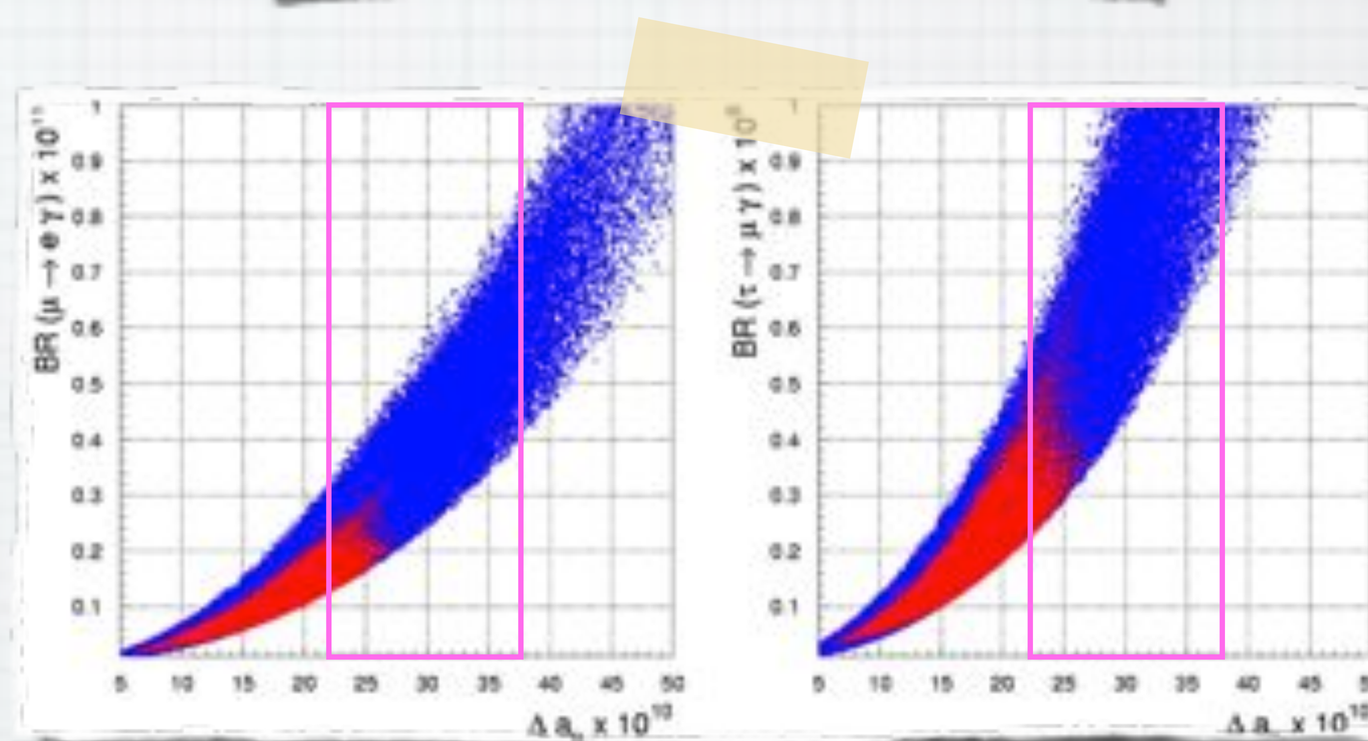
Processes are correlated

Model-dependent correlations



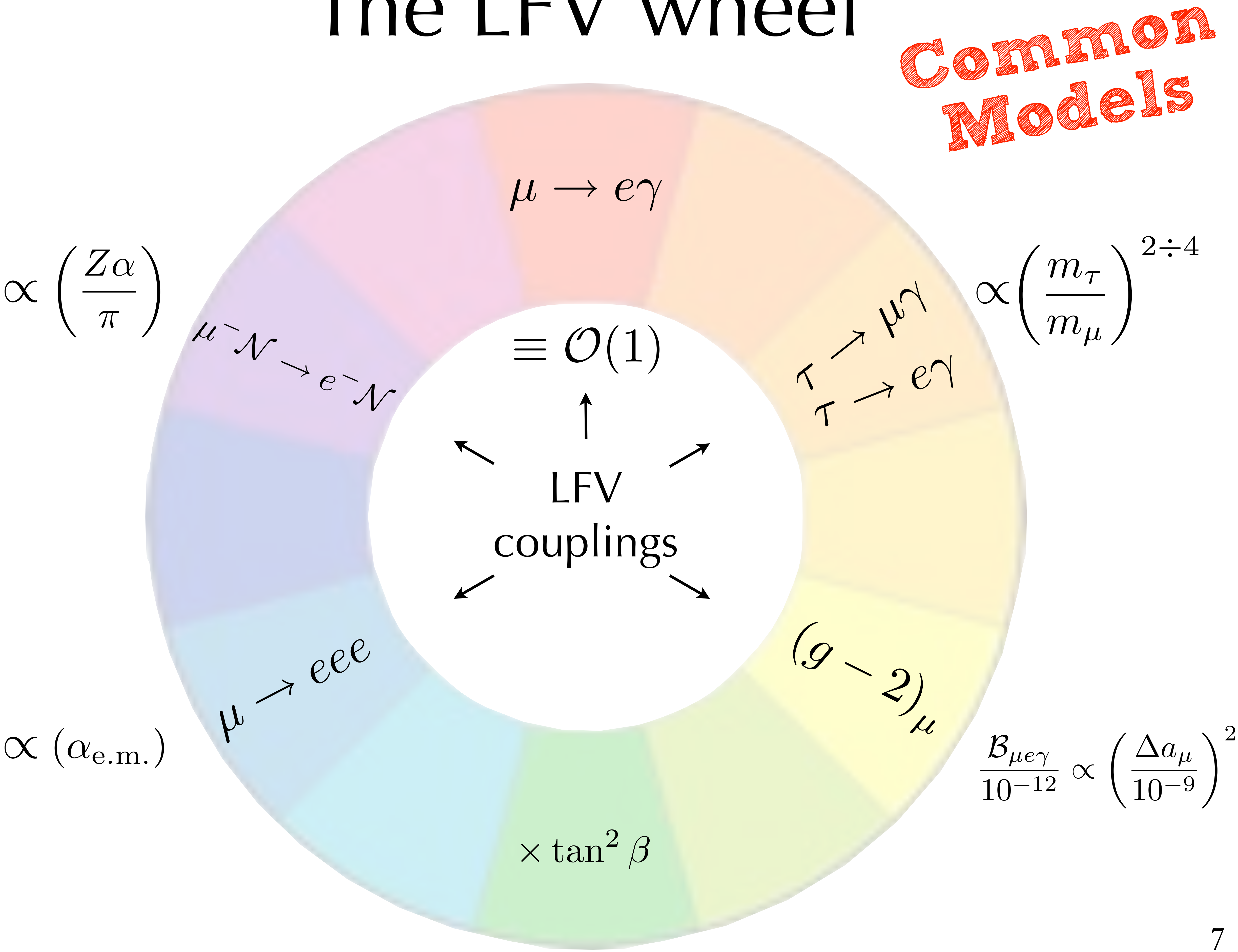






Barbieri *et al*,, Nucl. Phys B445 (1995) 225
Hisano *et al.*, Phys. Lett. B391 (1997) 341
Masiero *et al.*, Nucl. Phys. B649 (2003) 189
Calibbi *et al.*, Phys. Rev. D74 (2006) 116002
Isidori *et al.*, Phys. Rev. D75 (2007) 115019
...

The LFV wheel



Present limits

SINDRUMII

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

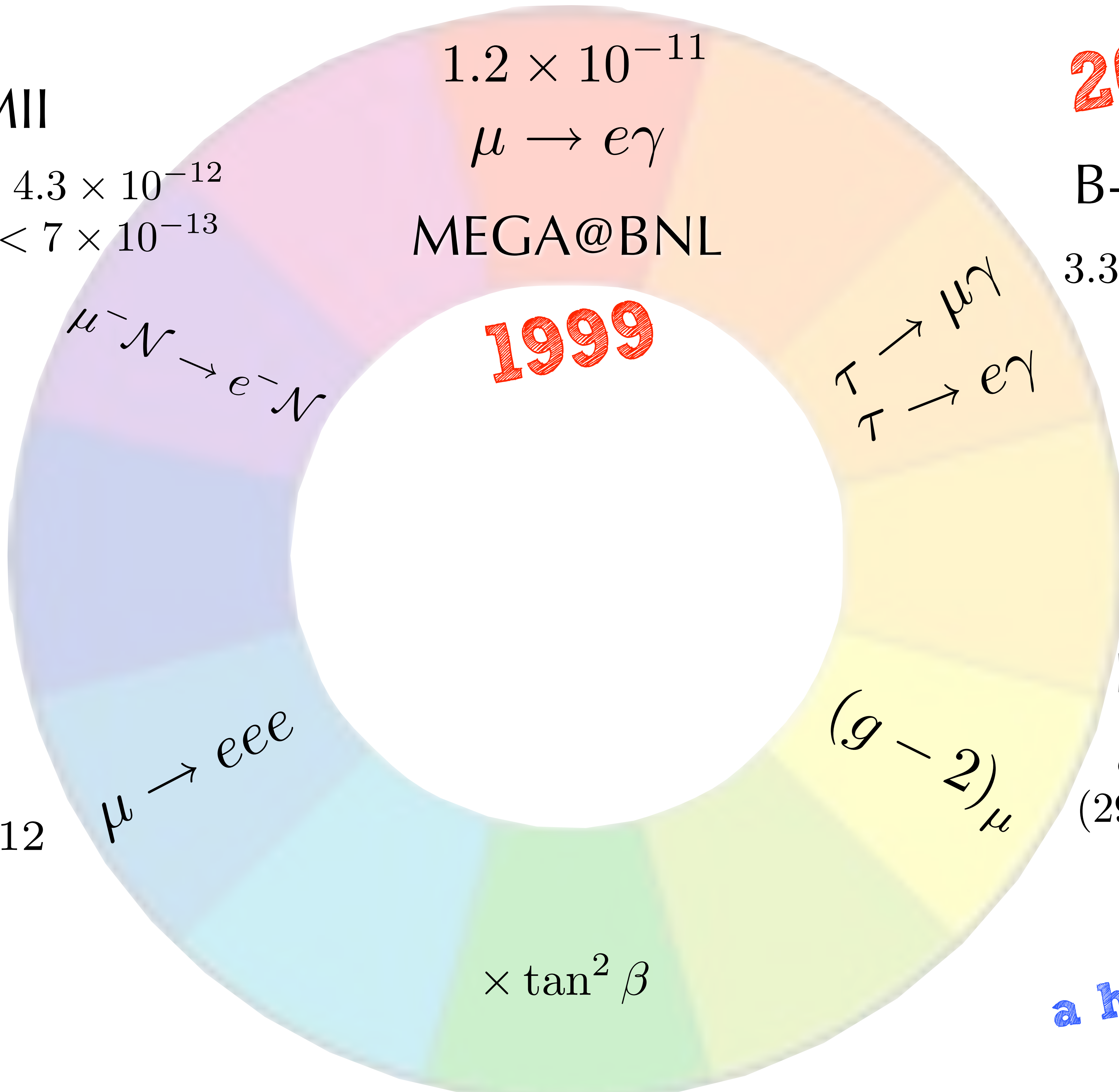
$\mathcal{B}(\mu\mathrm{Au} \to e\mathrm{Au}) < 7 \times 10^{-13}$

2006

2010

B-factories

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



BNL E821

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

SINDRUM

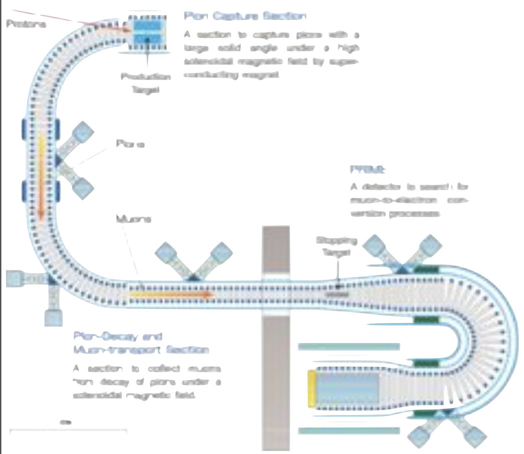
1×10^{-12}

1988

2004

a hint for NP?

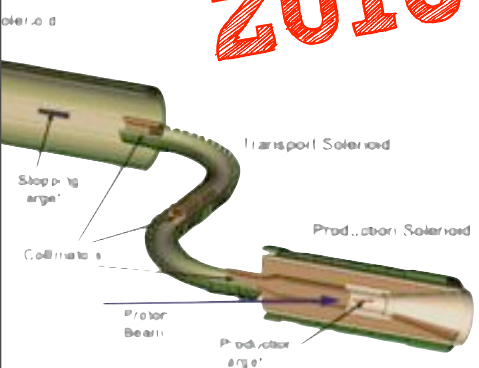
Future prospects



mu2e COMET

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

2016→



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

$\mu \rightarrow e\gamma$

MEG

few $\times 10^{-13}$

running

→2013

SuperB

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

2015→

$\tau \rightarrow \mu\gamma$

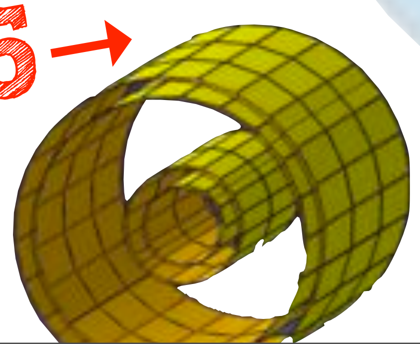
$\tau \rightarrow e\gamma$

$\mu \rightarrow eee$

Heidelberg

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

2015→



$\times \tan^2 \beta$

$(g-2)_\mu$

Gm2 FNAL

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

$3.6\sigma \rightarrow 8\sigma$

2015→

The MEG collaboration

Tokyo U.
Waseda U.
KEK

INFN & U Pisa
INFN & U Roma
INFN & U Genova
INFN & U Pavia
INFN & U Lecce

PSI

UCIrvine

JINR Dubna
BINP Novosibirsk

The MEG collaboration

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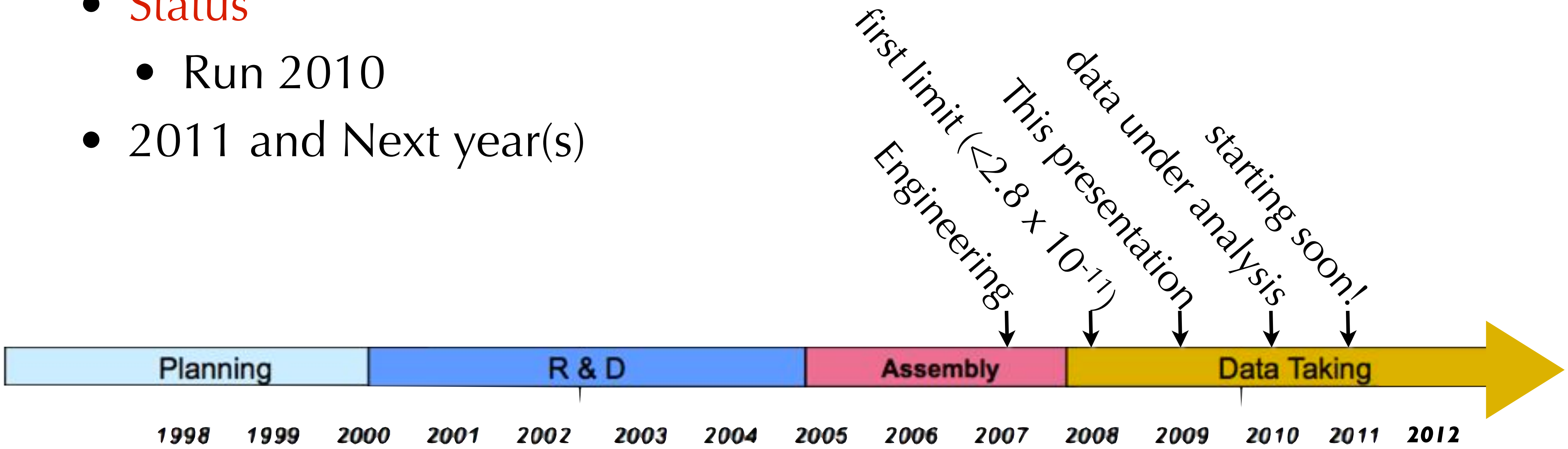
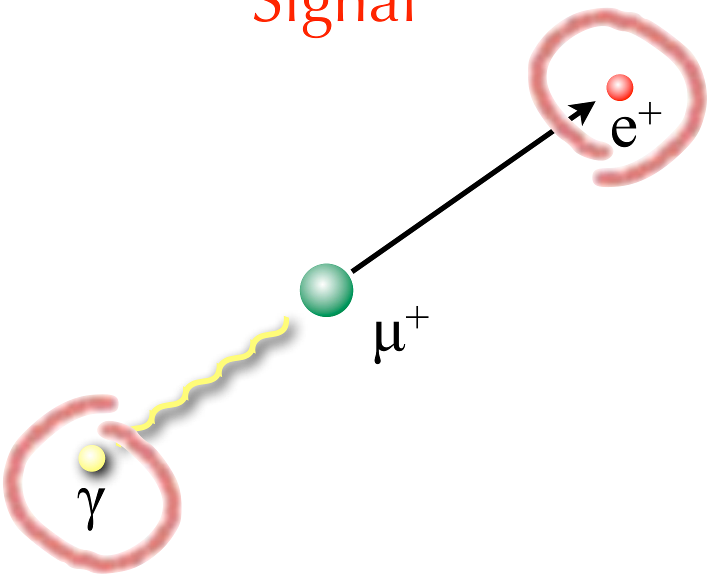
Time scale

- A $\mu \to e\gamma$ experiment at the Paul Scherrer Institut (PSI)
- The $\mu \to e\gamma$ decay
- The detector
  - Overview of sub-detectors
  - Calibration methods
- Analysis of 2009 run
- Status
  - Run 2010
- 2011 and Next year(s)



Signal and Background

"Signal"

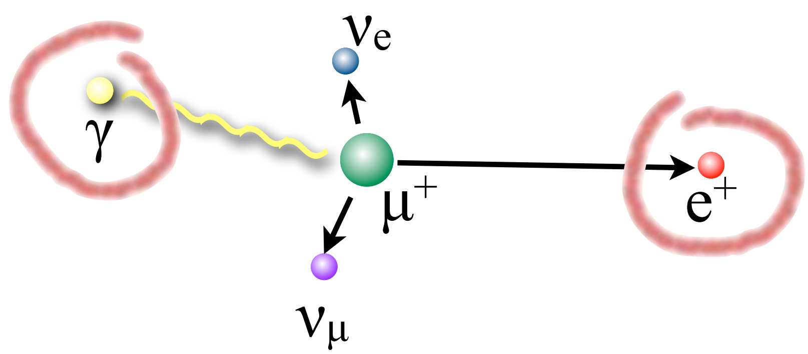


$E_e = E_\gamma = 52.8$ MeV

$\theta_{e\gamma} = 180^o$

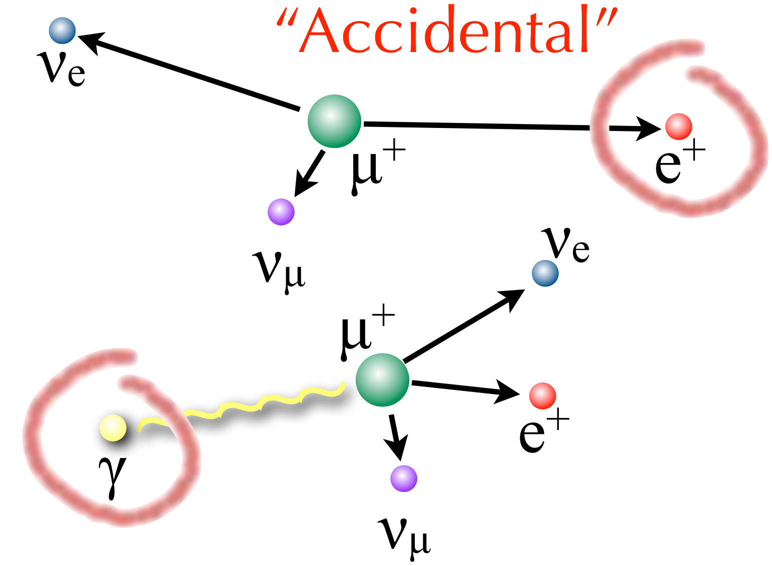
$t_{e\gamma} \sim 0$

"RMD"



$\mu \to e\bar{\nu}\nu\gamma$

"Accidental"



$\mu \to e\bar{\nu}\nu$

$\mu \to e\bar{\nu}\nu\gamma$

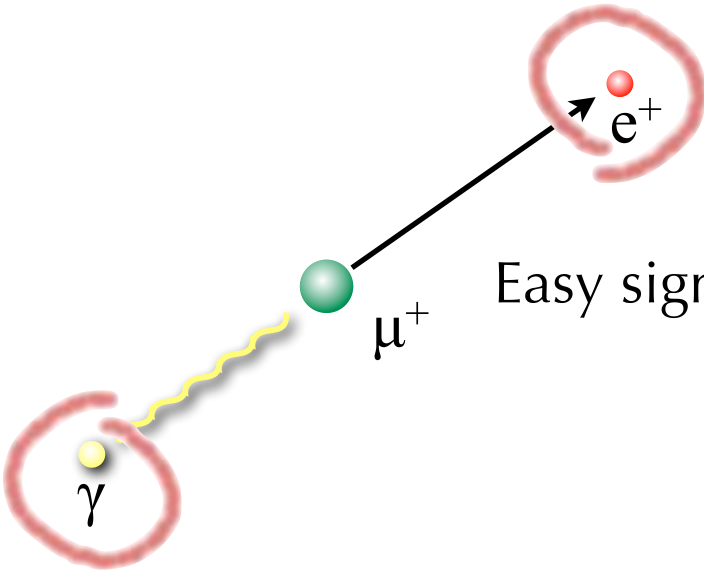
$e\mathcal{N} \to e\mathcal{N}\gamma$

$e^+e^- \to \gamma\gamma$

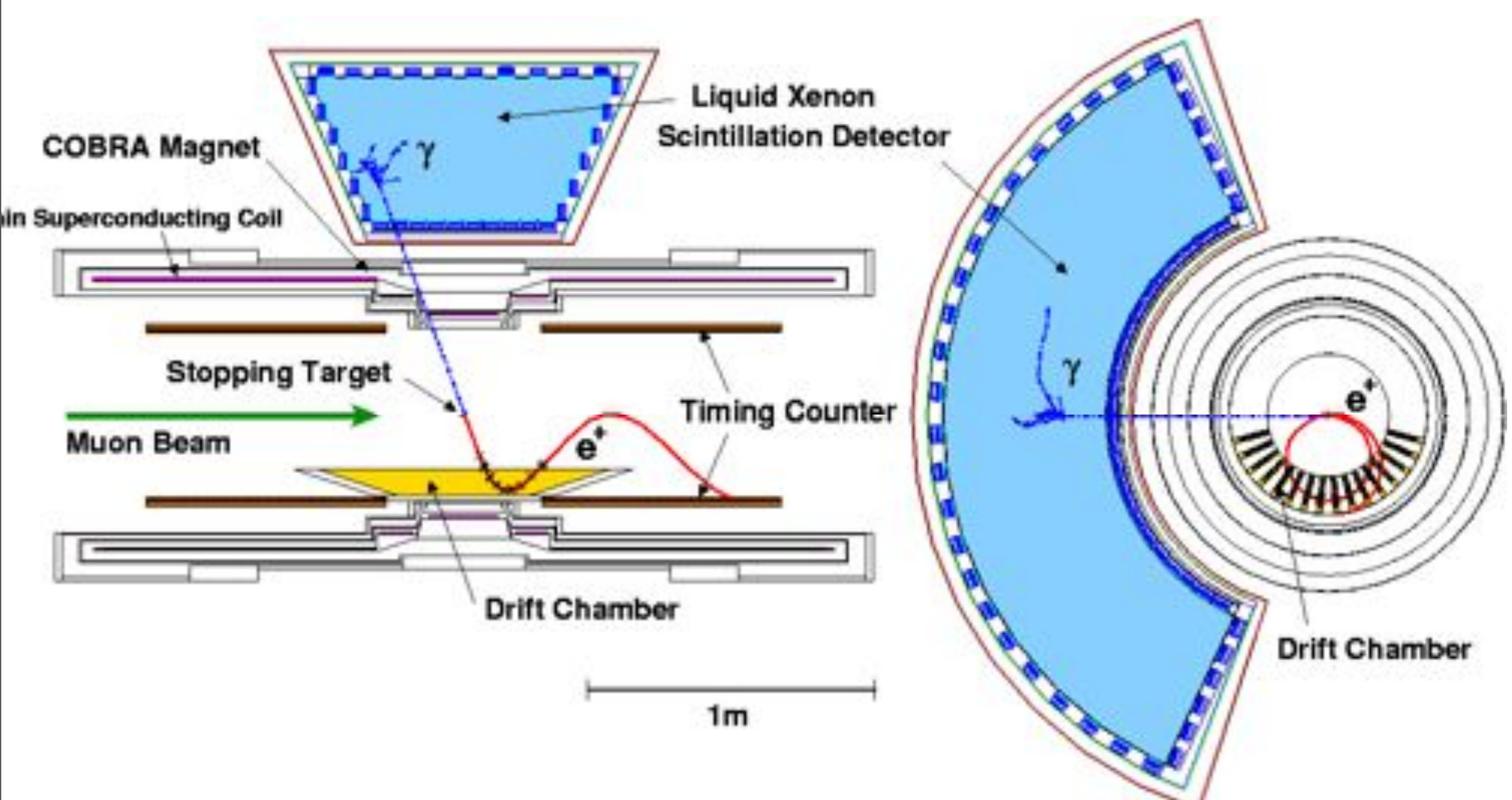
$$B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}} \qquad B_{\text{acc}} \approx R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\theta^2 \Delta t$$

The accidental background is dominant and it is determined by the experimental resolutions

MEG experimental method



Easy signal selection with μ^+ at rest



- μ: stopped beam of 3×10^7 μ /sec in a 205 μm polyethylene target
  - PSI πE5 beam line
- e^+ detection

  magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum

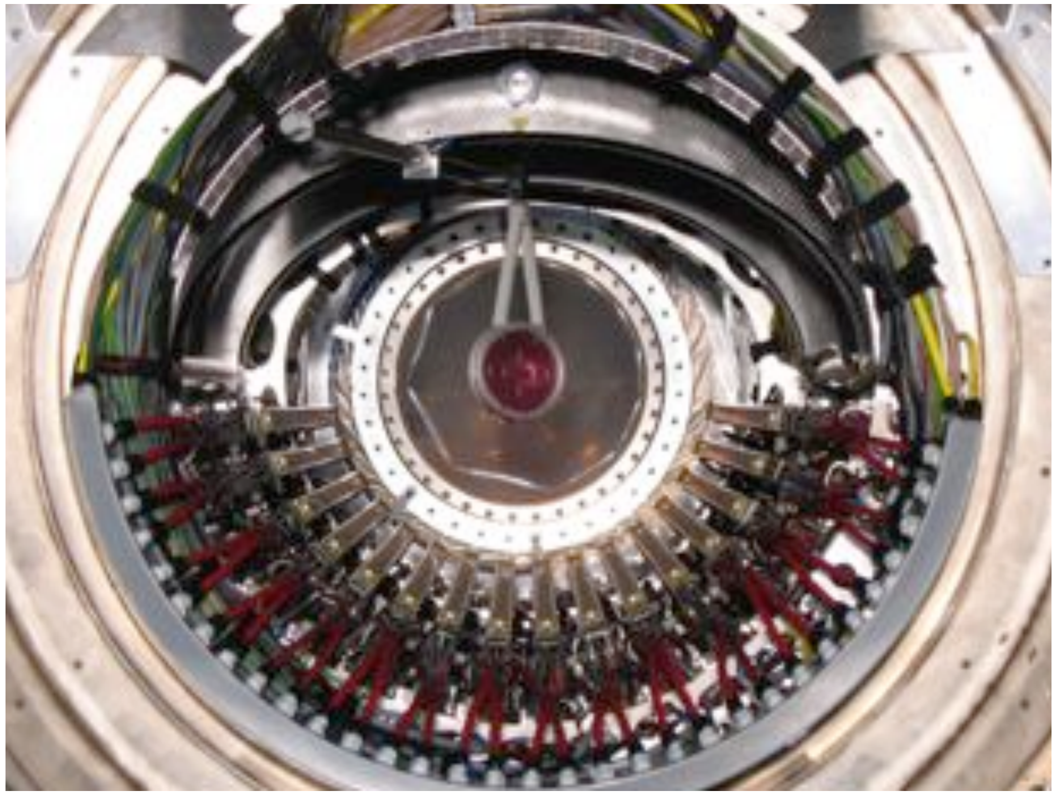
  plastic counters for timing
- γ detection

  Liquid Xenon detector based on the scintillation light
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm

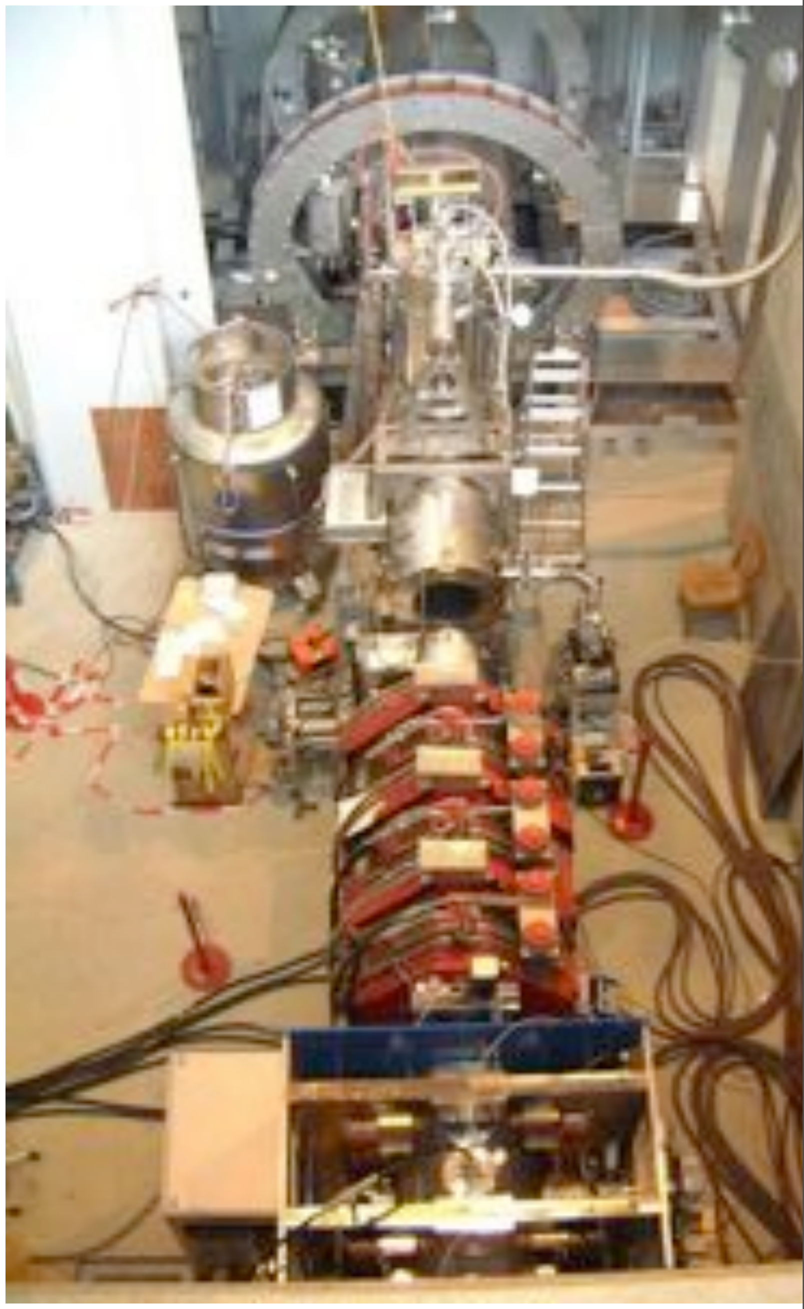
Some detector pictures

LXe detector

DC system

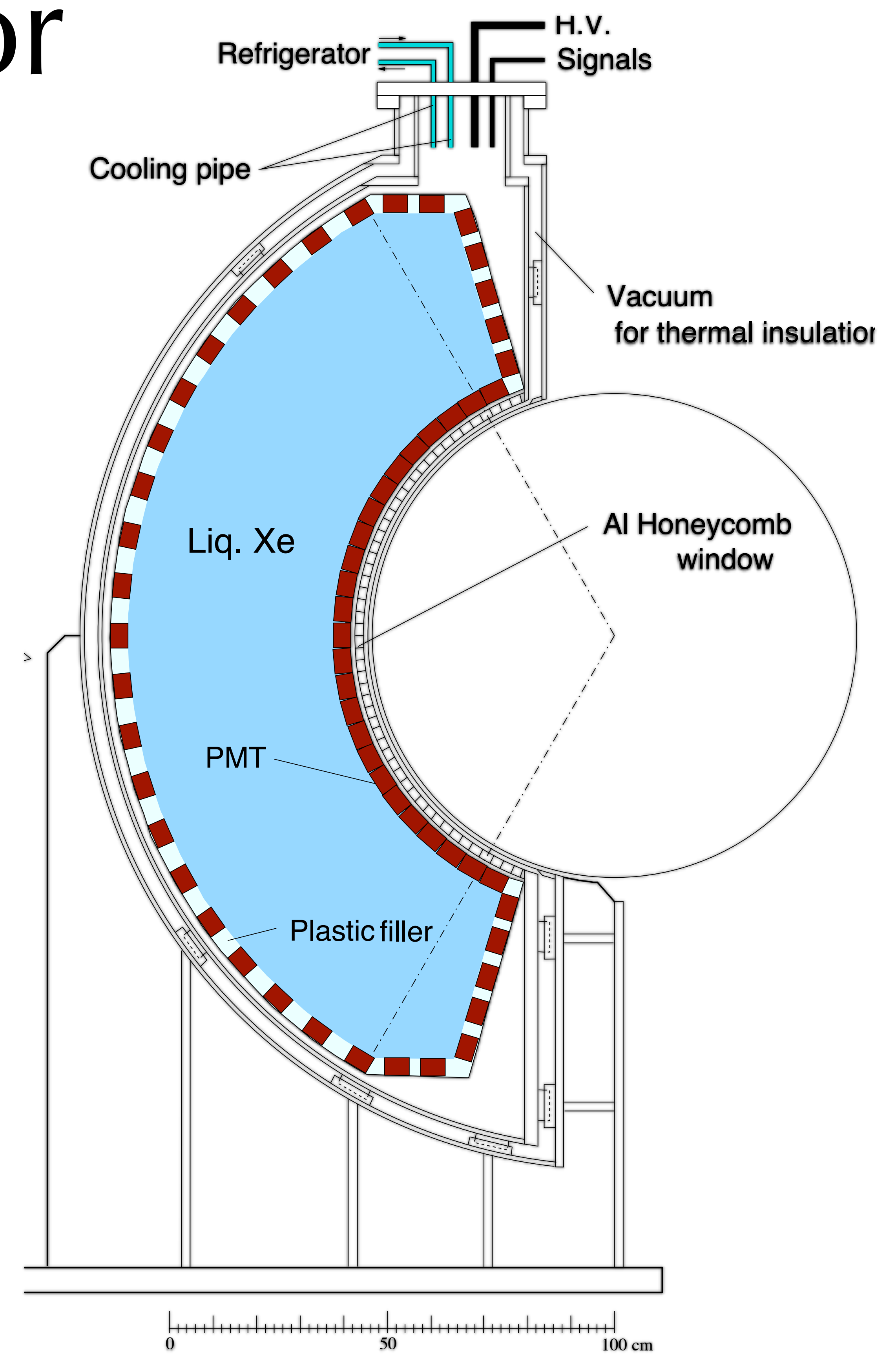


Beam Line



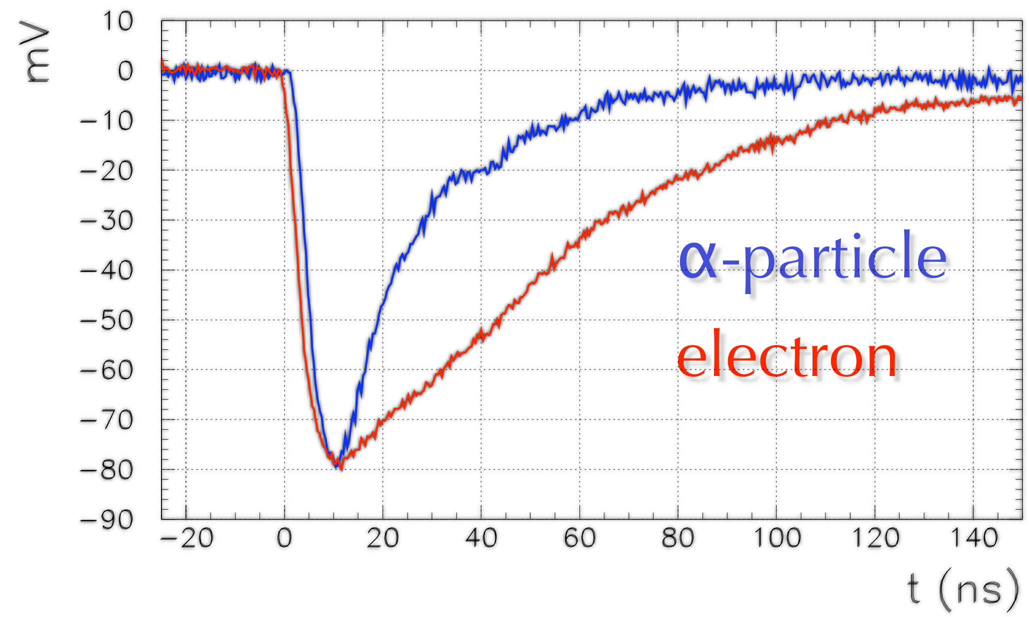
The photon detector

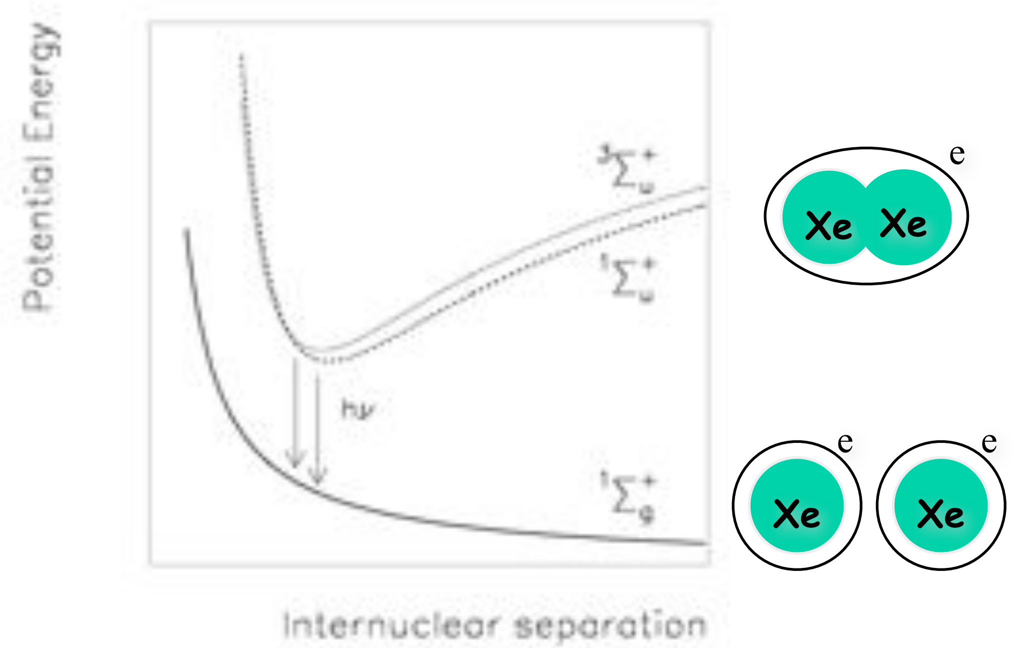
- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe
    - 10 % solid angle
    - 65 < r < 112 cm
    - $|\cos\theta| < 0.35$ $|\phi| < 60^o$
- Only scintillation light
- Read by 848 PMT
    - 2″ photo-multiplier tubes
    - Maximum coverage FF (6.2 cm cell)
    - Immersed in liquid Xe
    - Low temperature (165 K)
    - Quartz window (178 nm)
- Thin entrance wall
- Singularly applied HV
- Waveform digitizing @2 GHz
    - Pileup rejection



Xe properties

- Liquid Xenon was chosen because of its unique properties among radiation detection active media
- Z=54, ρ=2.95 g/cm^3 (X_0=2.7 cm), R_M=4.1 cm
- High light yield (similar to NaI)
  - 40.000 phe/MeV
- Fast response of the scintillation decay time
  - $\tau_{singlet}$= 4.2 ns
  - $\tau_{triplet}$= 22 ns
  - τ_{recomb}= 45 ns
- Particle ID is possible
  - α ~ singlet+triplet, γ ~ recombination
- Large refractive index n = 1.65
- No self-absorption (λ_{Abs}=∞)

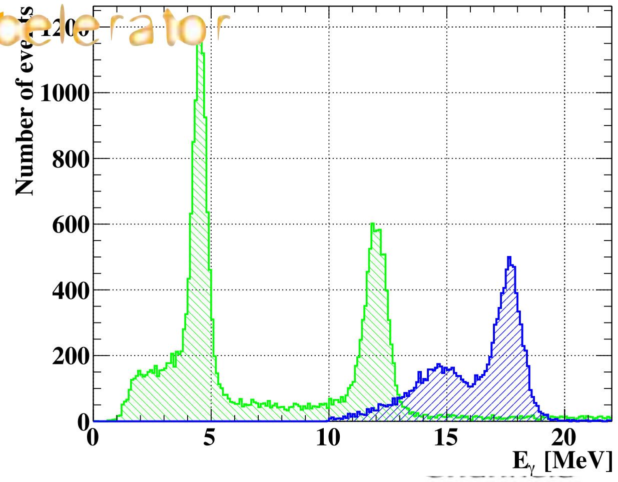




Calibrations

Xenon Calibration

Proton Accelerator



Li(p,γ)Be

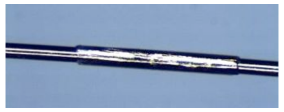
LiF target at COBRA center

17.6MeV γ

~daily calib.

also for initial setup

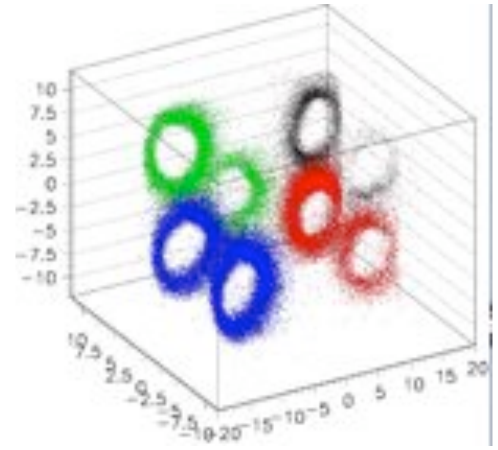
Alpha on wires



PMT QE & Att. L

Cold GXe

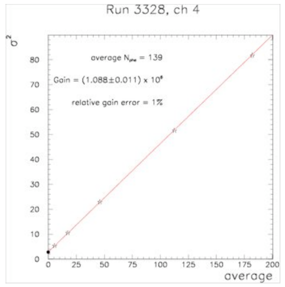
LXe

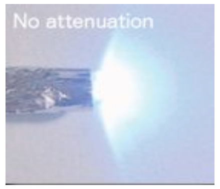


LED

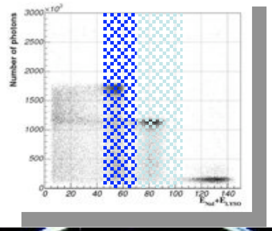
PMT Gain

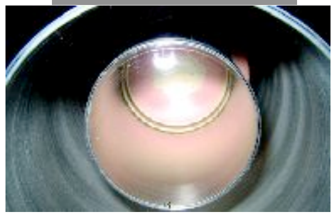
Higher V with light att.





$\pi^0 \rightarrow \gamma\gamma$



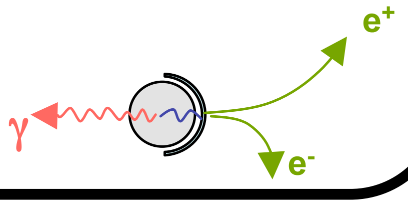


$\pi^- + p \rightarrow \pi^0 + n$

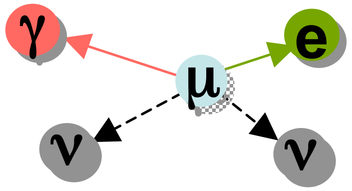
$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

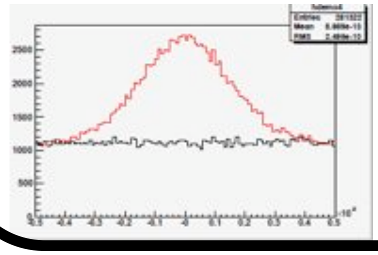
$\pi^- + p \rightarrow \gamma + n$ (129MeV)

LH_2 target



μ radiative decay





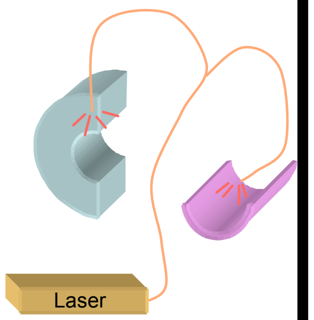
Lower beam intensity < 10^7

Is necessary to reduce pile-ups

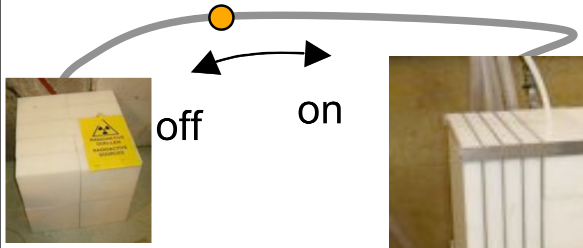
A few days ~ 1 week to get enough statistics

Laser

relative timing calib.

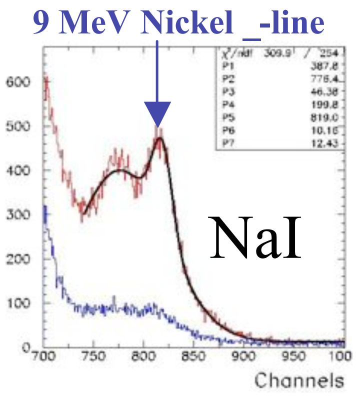


Nickel γ Generator

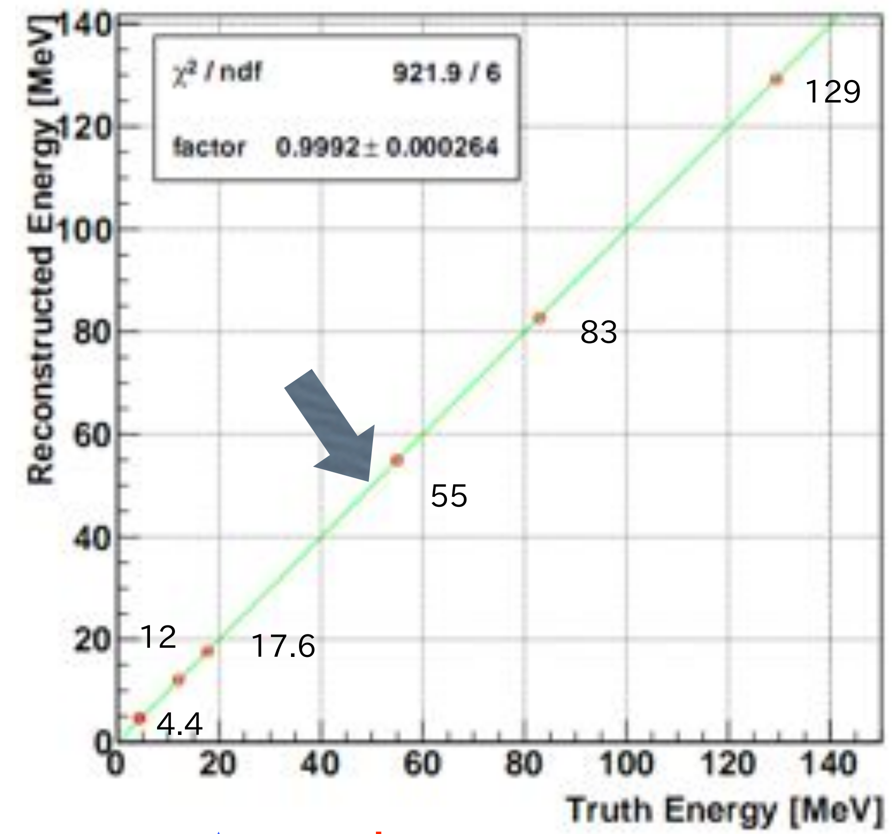


Illuminate Xe from the back

Source (Cf) transferred by comp air → on/off

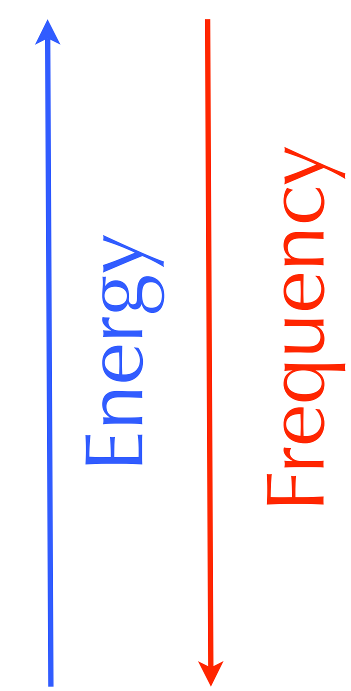


γ-energy scale calibration



- The precise knowledge of the calorimeter energy scale is crucial for the experiment
- constant check of Xe light yield and purity
  - trigger threshold
  - systematic error on energy scale
- Different calibrations have different time-scales

Process		Energy	Frequency
Charge exchange	$\pi^- p \rightarrow \pi^0 n$ $\pi^0 \rightarrow \gamma\gamma$	55, 83, 129 MeV	year - month
Proton accelerator	$^7\mathrm{Li}(p, \gamma_{17.6})^8\mathrm{Be}$	14.8, 17.6 MeV	week
Nuclear reaction	$^{58}\mathrm{Ni}(n, \gamma_9)^{59}\mathrm{Ni}$	9 MeV	daily
Radioactive source	$^{60}\mathrm{Co}$, AmBe	1.1 -4.4 MeV	daily



2009: efficient physics run

- 2008 run BR<2.8 x 10^{-11}
Nucl. Phys. B834, 1–12 (Apr. 2010)

January - October

- detector dismantling
- improvement (after run 2008)
  - -DCH
  - -Electronic
- re – installation
- LXe purification
- CW calibration
- another experiment in the area had "exciting results" (μp)

October

- π^o calibration

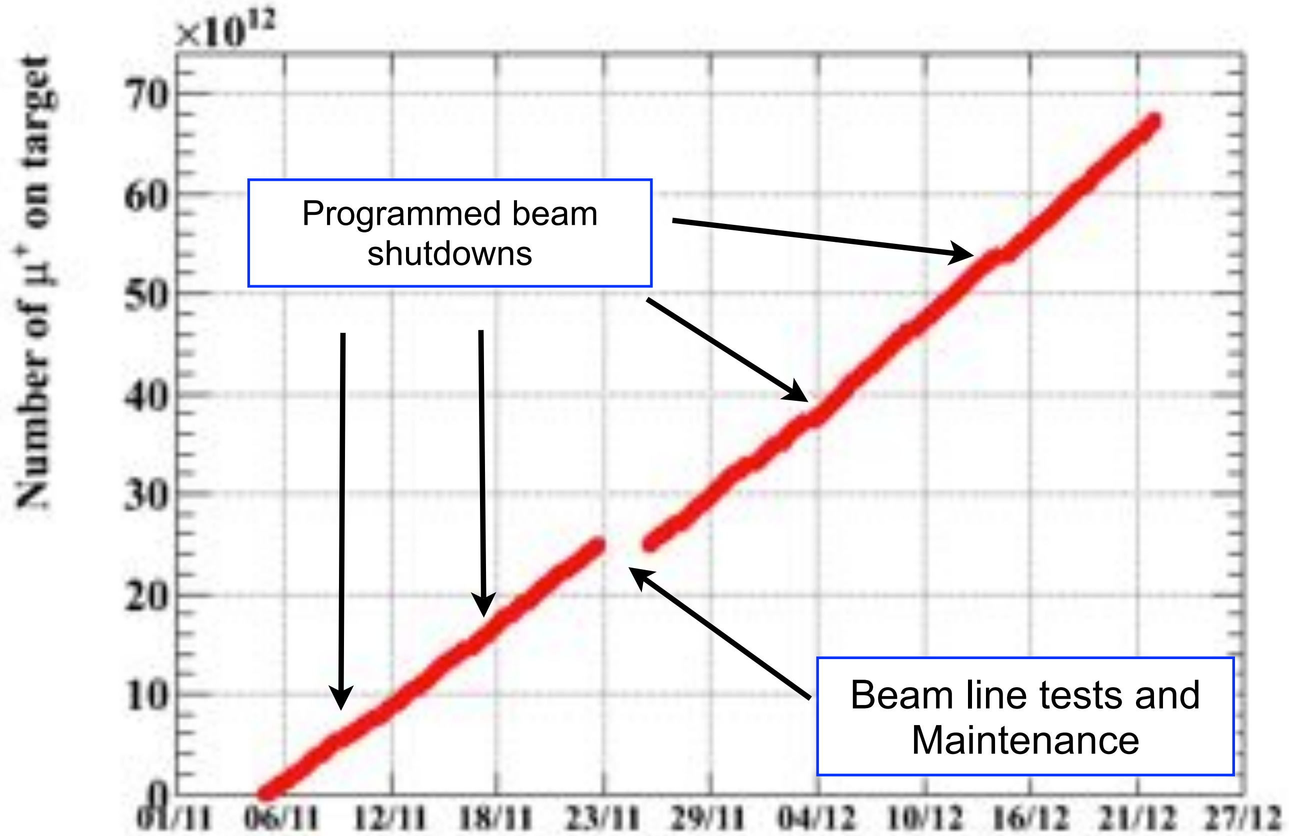
November – December

- MEG run

Running conditions

MEG run period

– Live time ~84% of total time
– Total time ~ 7 weeks
– μ stop rate: 3×10^7 μ/s
– Trigger rate 6.5 ev/s ;
– Total data taken: 93 TB



Analysis principle

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

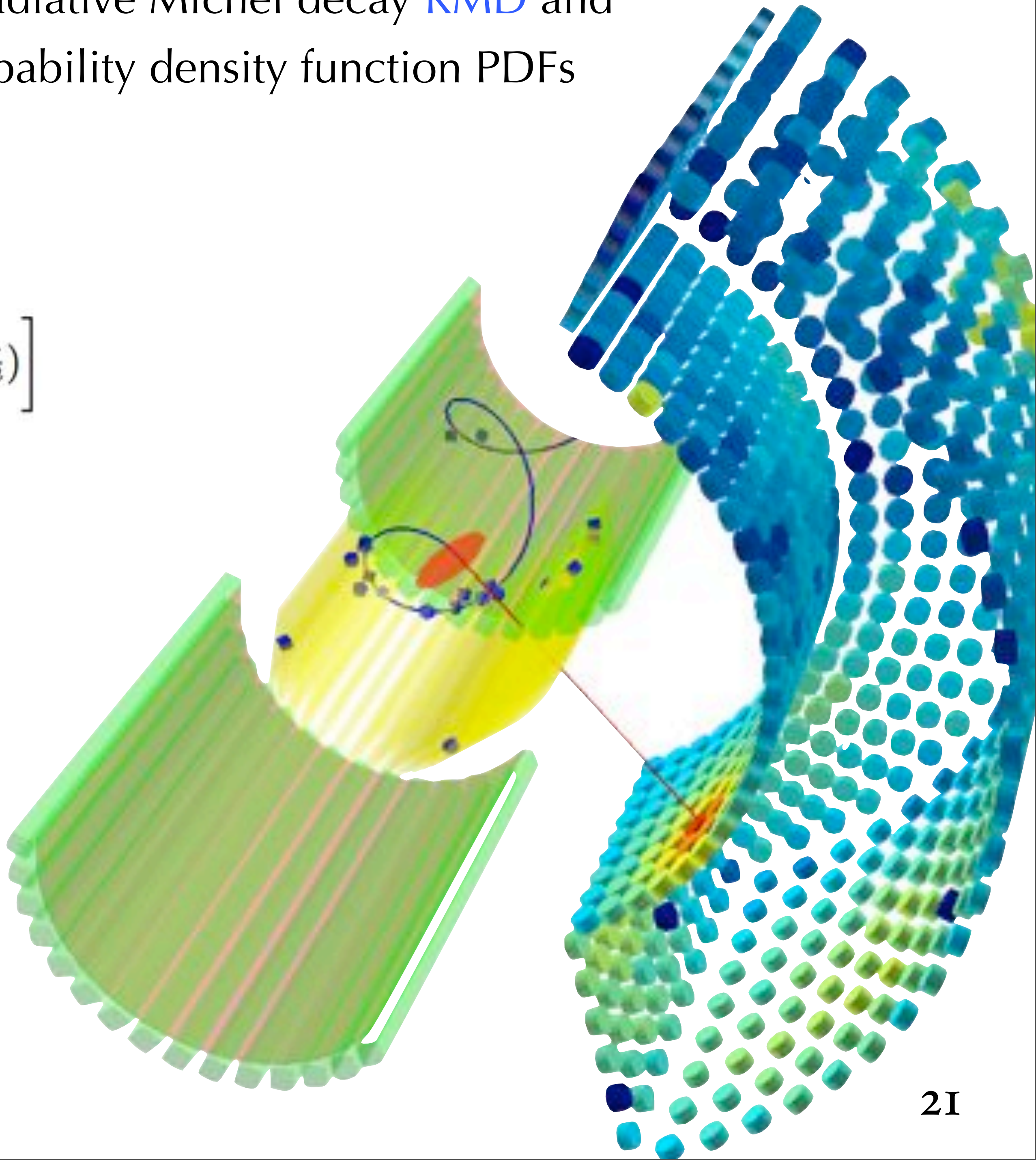
$$\vec{x_i} = (E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$$

- Likelihood function is built in terms of Signal, radiative Michel decay RMD and background BG number of events and their probability density function PDFs

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

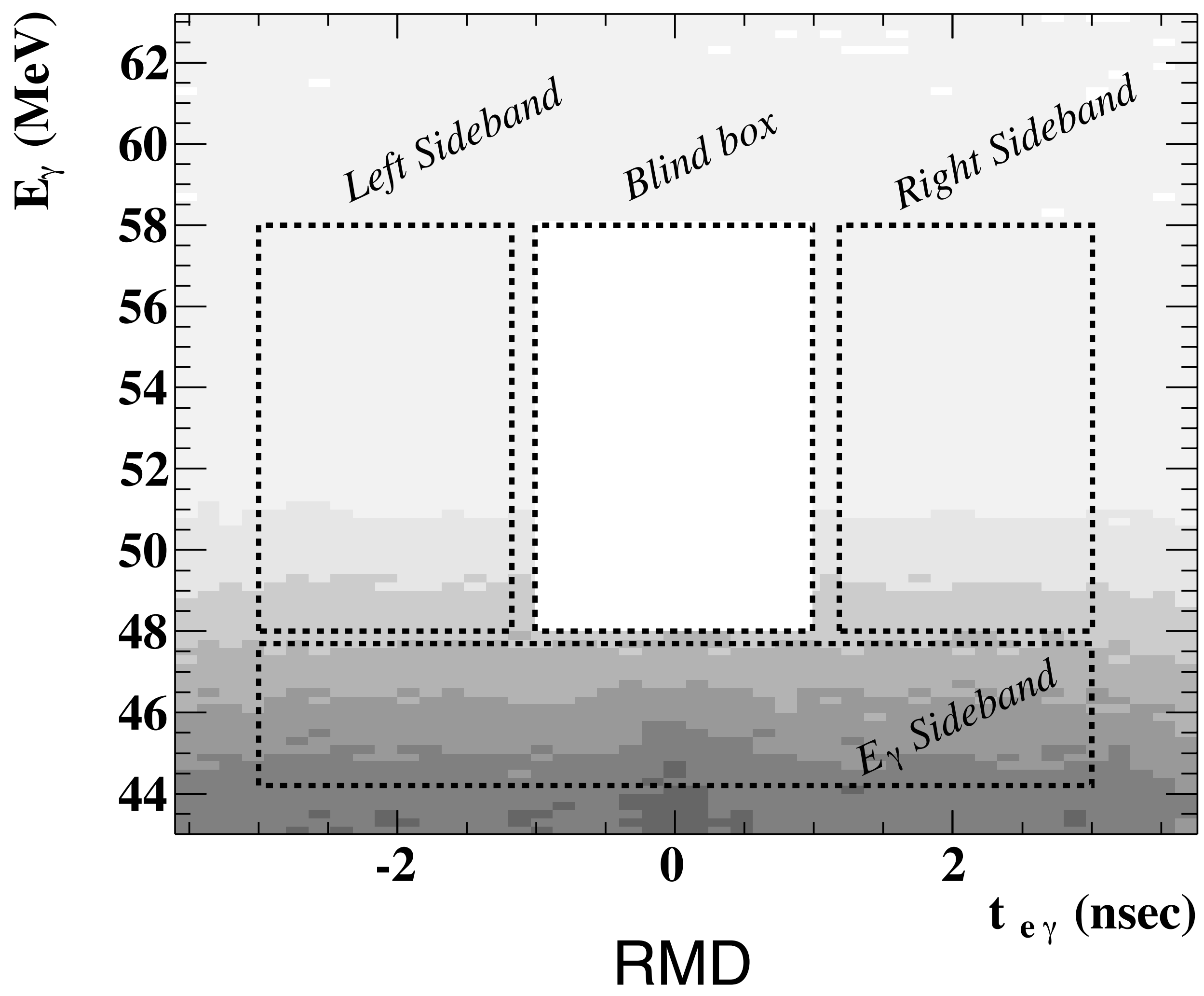
- Extended unbinned likelihood fit
  - fit (N_{sig}, N_{RMD}, N_{BG}) in a wide region
- PDFs taken from
  - data
  - MC tuned on data

- $48 \leq E_\gamma \leq 58$ MeV
- $50 \leq E_e \leq 56$ MeV
- $|T_{e\gamma}| \leq 0.7$ ns
- $|\phi_{e\gamma}|, |\theta_{e\gamma}| \leq 50$ mrad



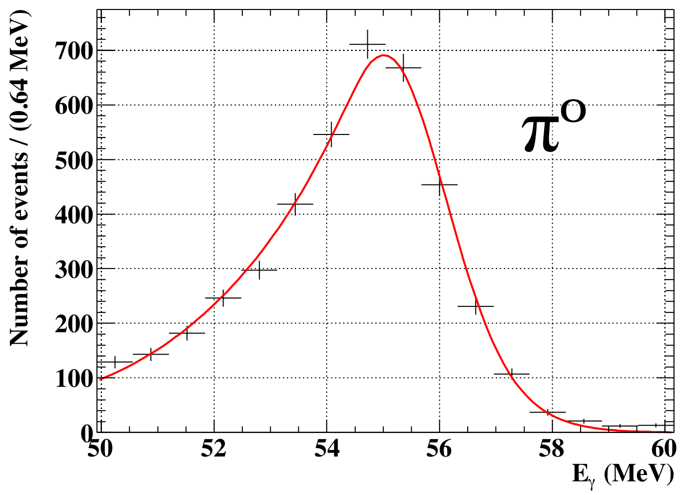
Analysis principle

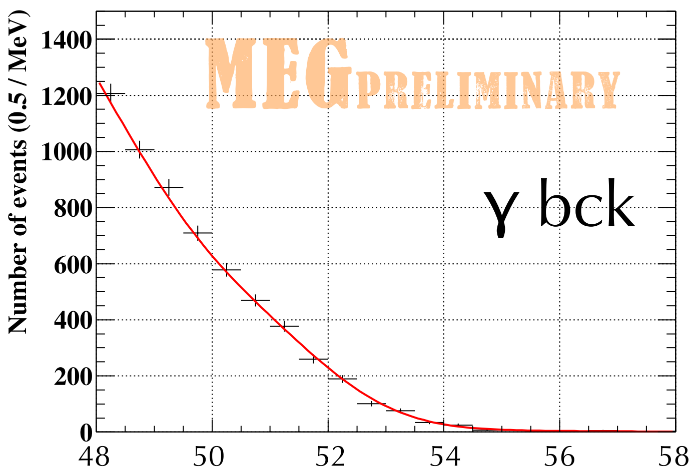
- We adopt a blind-box likelihood analysis strategy
- The blinding variables are E_γ and $t_{e\gamma}$
  - Hidden until analysis is fixed
- Three independent analyses
  - different *pdf* implementation
  - Fit or input N_{RMD}, N_{BG}
  - Different statistical treatment (Freq. or Bayes)
- Use of the sidebands
  - our main background comes from accidental coincidences
  - RMD can be studied in the low E_γ sideband



Pdfs and resolutions

E_γ

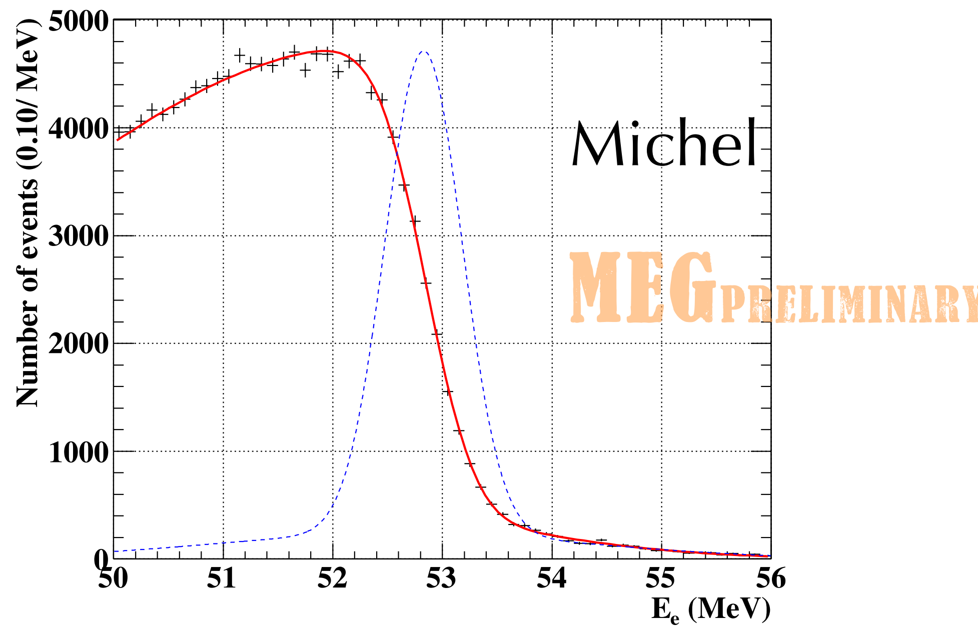




- Average upper tail for deep conversions
  - σ_R = (2.1 ± 0.15) %
- Systematic uncertainty on energy scale < 0.6%

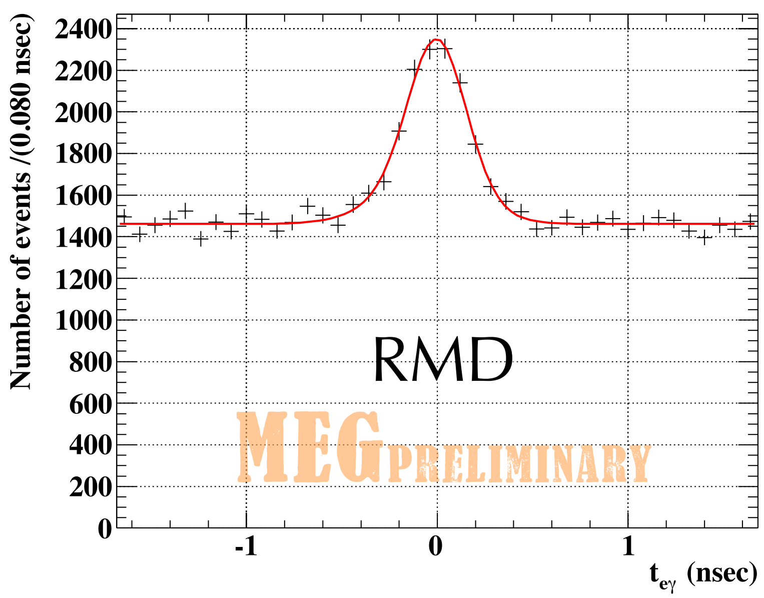
E_{e^+}

- Resolution functions of core and tail components
  - core = 390 keV (0.74%)
- Positron angle resolution measured using multi-loop tracks
  - $\sigma(\varphi)$ = 7.1 mrad (core)
  - $\sigma(\vartheta)$ = 11.2 mrad



- Overall angular resolution combining
  - XEC+DCH+target
    - $\sigma(\varphi)$ = 12.7 mrad (core)
    - $\sigma(\vartheta)$ = 14.7 mrad

$t_{e\gamma}$



- 40 MeV < E_γ < 48 MeV
- σ_t is corrected for a small energy-dependence
  - (142 ± 15) ps
  - stable within 15 ps along the run
- MEGA had on RMD
  - 700 ps resolution

Normalization

- The normalization factor is obtained from the number of observed Michel positrons taken simultaneously (pre-scaled) with the μ→eγ trigger
- Cancel at first order
  - Absolute e+ efficiency and DCH instability
  - Instantaneous beam rate variations

O(1)

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

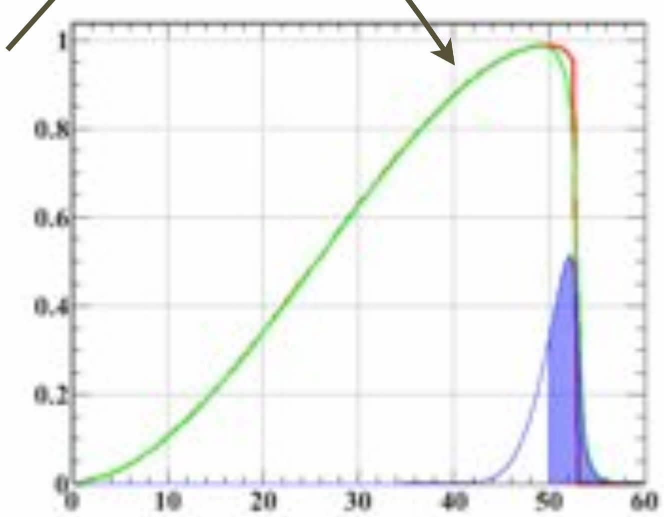
~18k

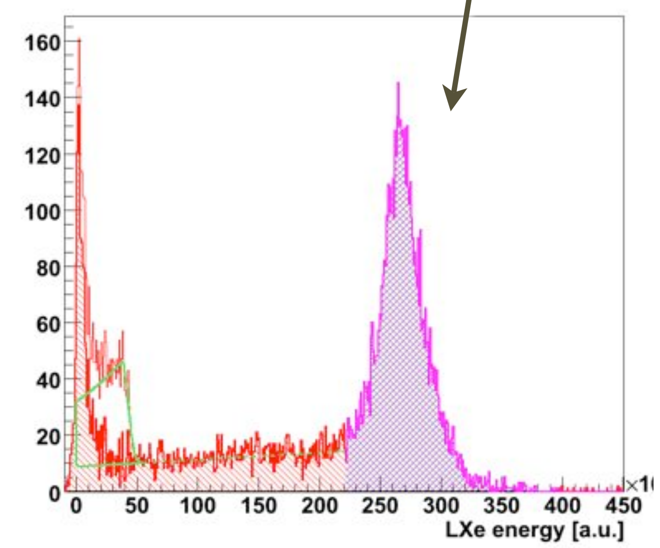
10^7

theory

resolution

acceptance

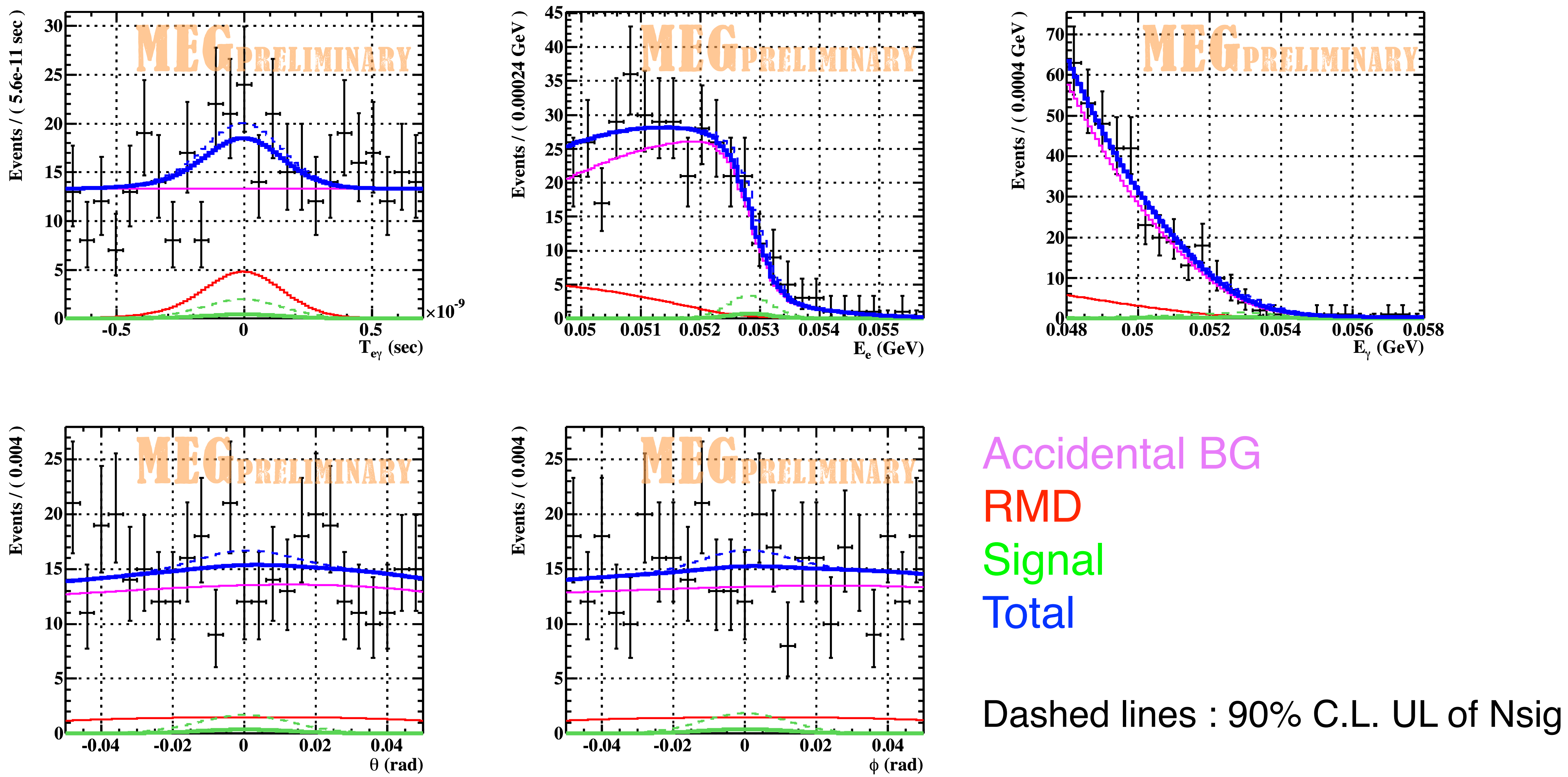




B.R. = N_{sig} x (1.01 ± 0.08) × 10^{-12}

Likelihood fit result

- $N_{sig} < 14.5$ @ 90% C.L., N_{sig} best–fit value = 3.0
- $N_{sig} = 0$ is in 90% confidence region
  - C.L @0: 40÷60% depending on the statistical approach



Fitting was done by three groups with different parametrization, analysis window and statistical approaches, and confirmed to be consistent (Nsig best fit = 3.0-4.5, UL = 1.2-1.5×10^{-11})

Upper limit

- From the analysis of the 2009 data our limit on the BR is the following:

$$\frac{\mathcal{B}(\mu^+ \to e^+\gamma)}{\mathcal{B}(\mu^+ \to e^+\nu\bar{\nu})} < 1.5 \times 10^{-11}$$

Preliminary

at 90% C.L.

MEG PRELIMINARY

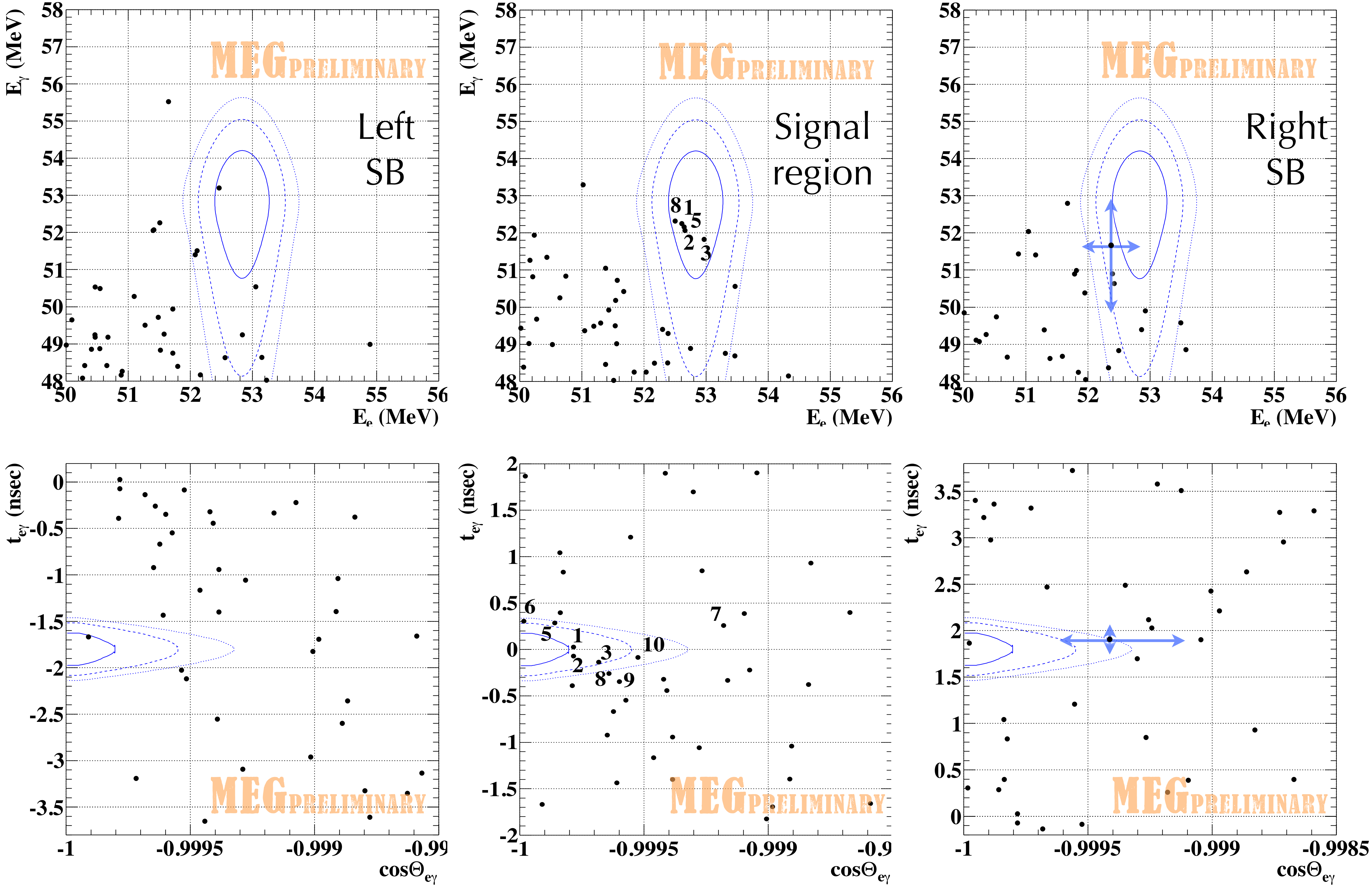
  - cfr. MEGA limit BR < 1.2×10^{-11} @ 90% C.L.

- Sensitivity:
  - 6.1×10^{-12} average 90% upper limit on null-signal toy experiments
  - BR < $(4 \div 6) \times 10^{-12}$ from the SideBands

- On going activity
  - better understanding of the spectrometer
  - reduction of systematics on back-to-back alignment
  - better usage of sideband information in the likelihood

- We plan to present a combined 2009/2010 analysis this summer

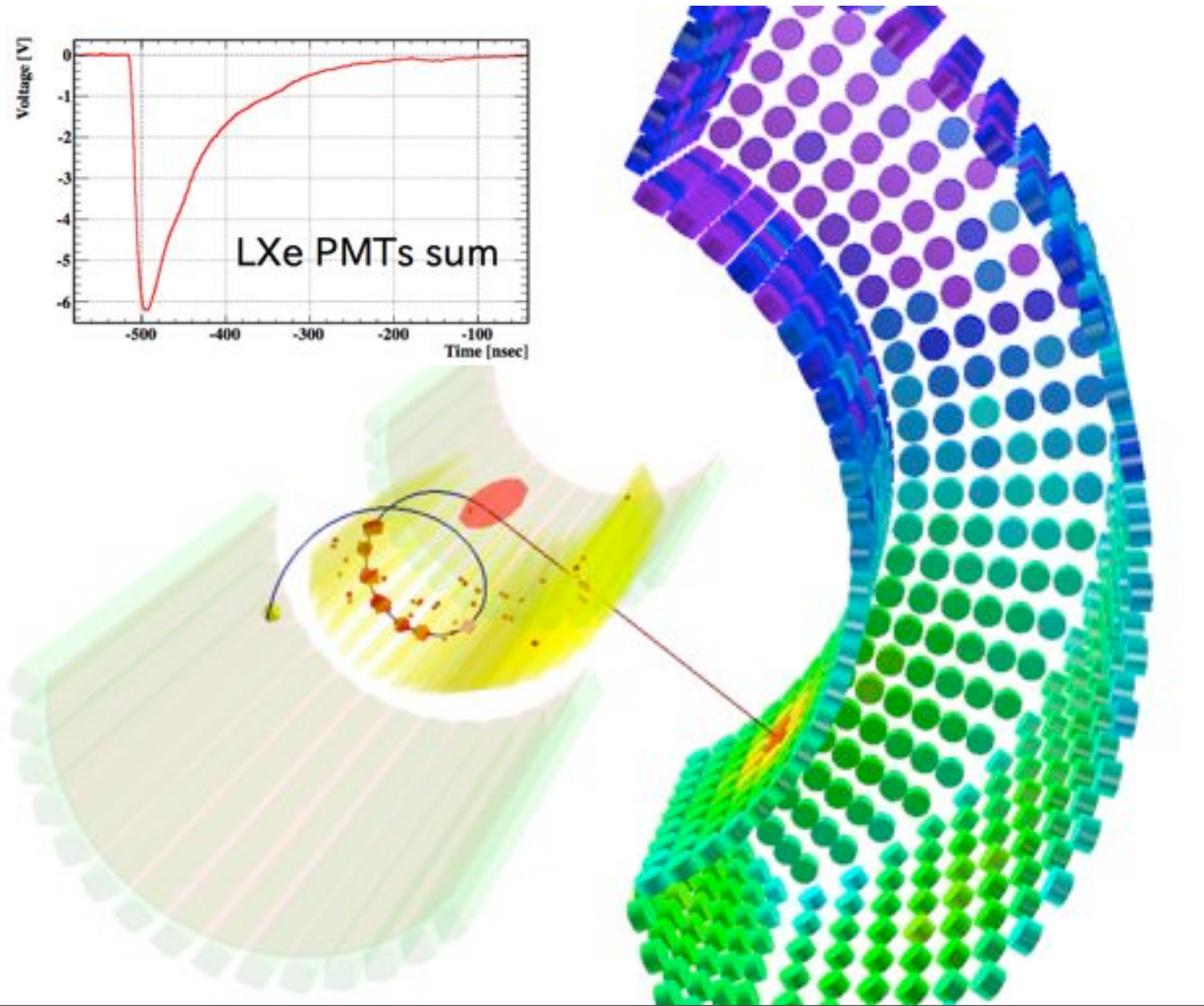
Event distibution

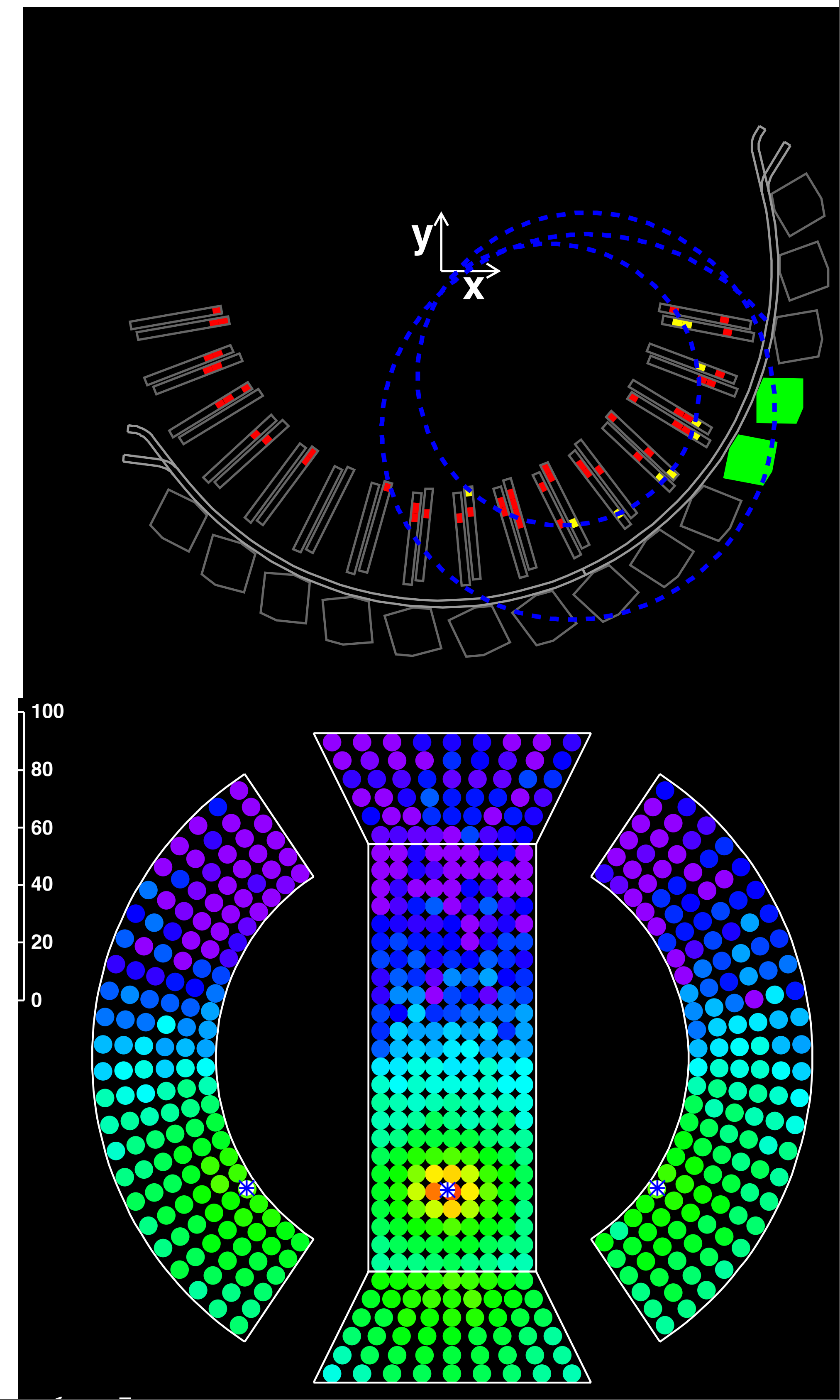


Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions.
For each plot, cut on other variables for roughly 90% window is applied.

Event display

- Events in the signal region were checked carefully
- An event in the signal region

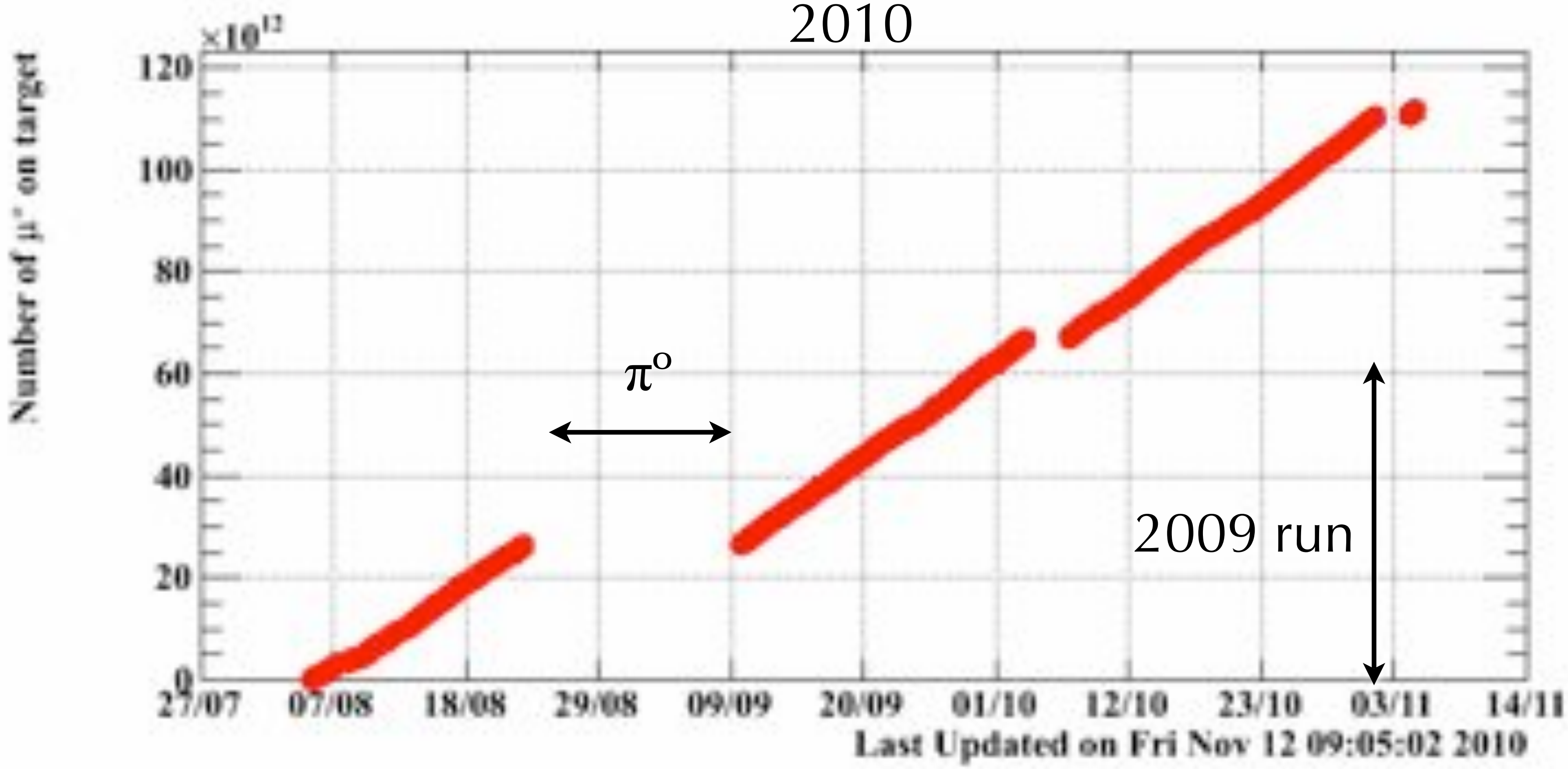




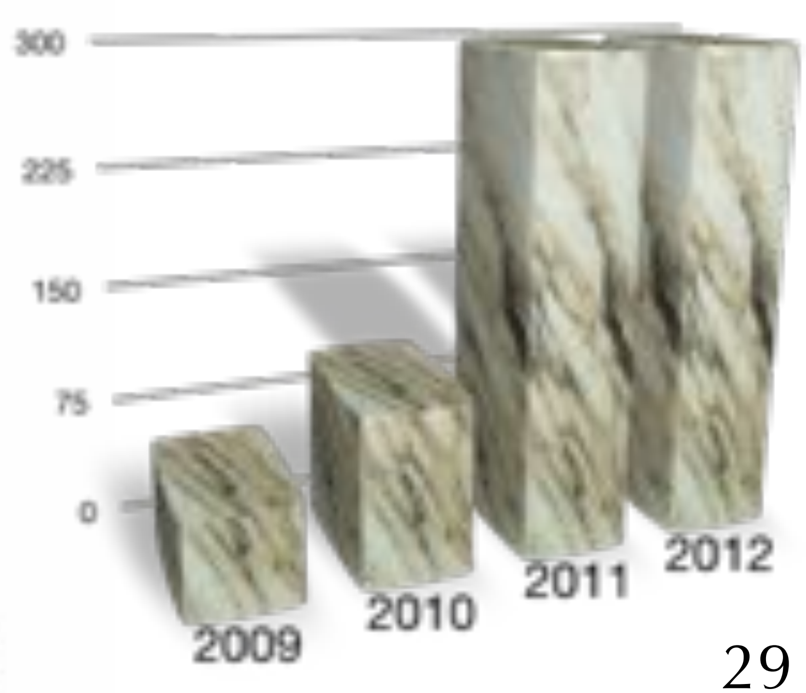
What's next?

- Data taking was restarted from Aug. 5 to Nov. 6 2010
  - π^o calibration from 23/8 to 9/9
  - accident to the beam transport solenoid on Nov. 6
  - ~ 2 x 2009 statistics
- An accident on Nov. 6 put a premature end to the 2010 run
- Analysis ongoing
  - 2009 & 2010 data together
- Run 2011 soon starting
  - physics data taking from June to December

2010

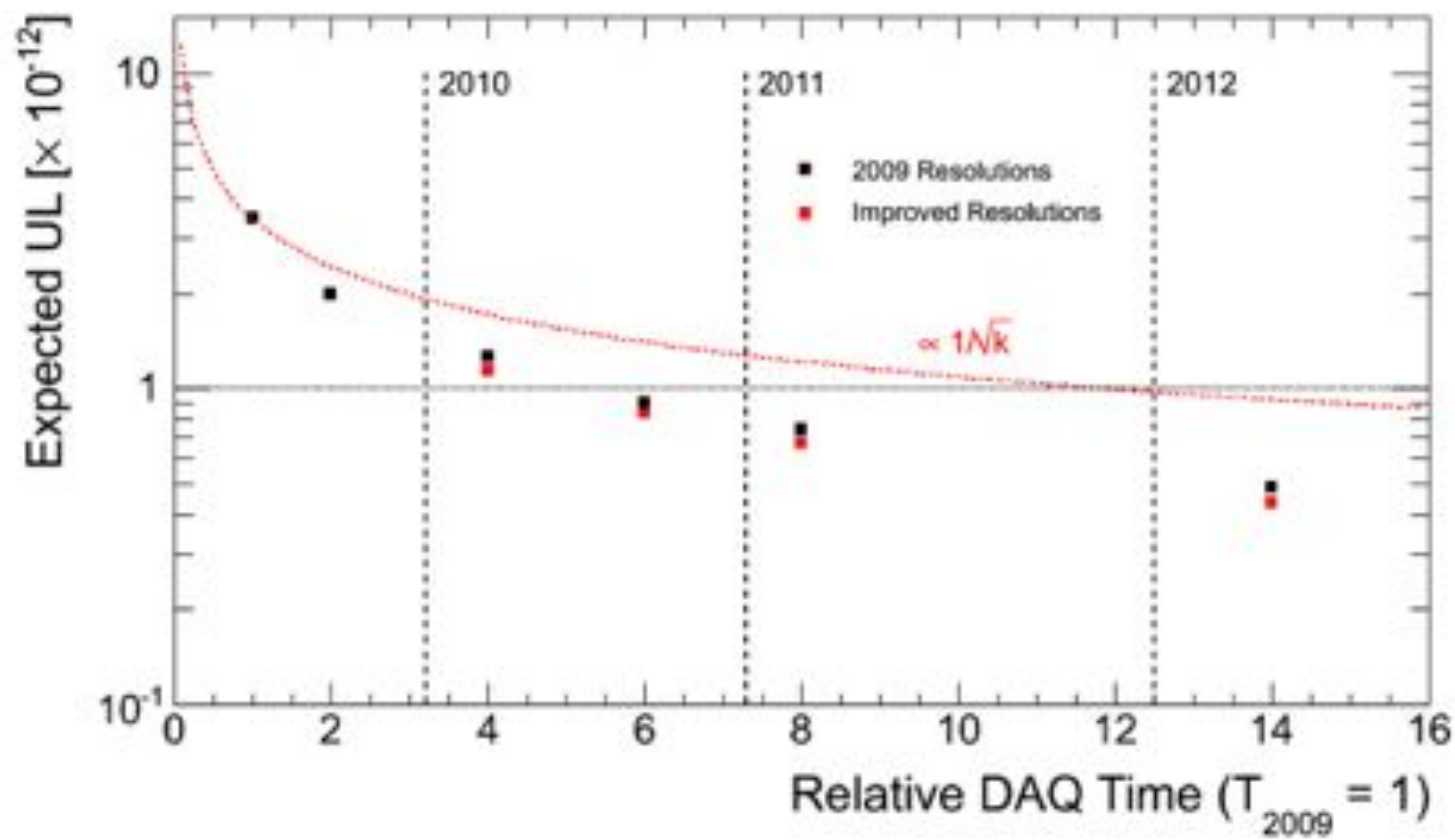


μ on target

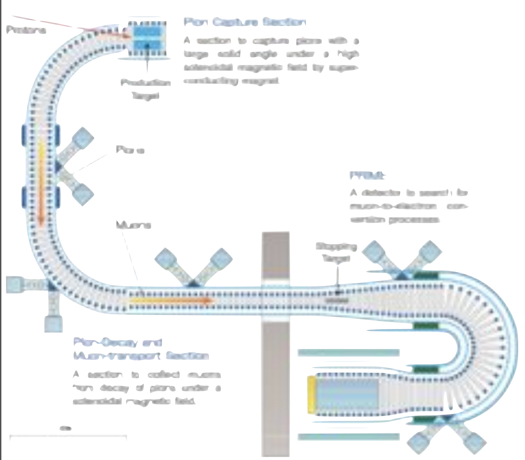


Sensitivity prospect

- Data from the two months of stable data taking of the MEG experiment in 2009 give a result competitive with the previous limit
- Plans to reach its design sensitivity (few x 10^{-13}) within 2013



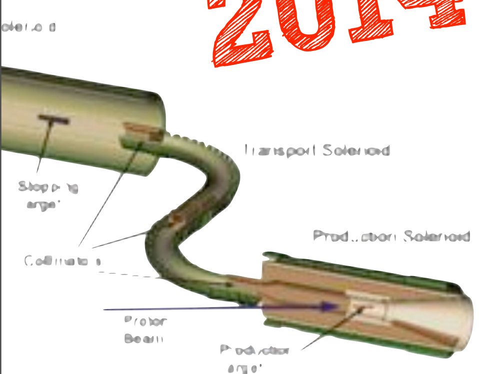
Back to the wheel...



mu2e COMET

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

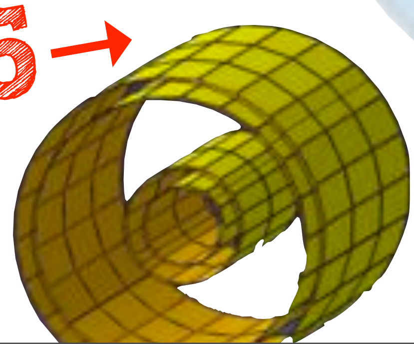
2014→



Heidelberg

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

2015→



$\mu \to e\gamma$

MEG

few $\times 10^{-13}$

running

→2013

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

$\tau \to \mu\gamma$

$\tau \to e\gamma$

$\mu \to eee$

$(g-2)_\mu$

$\times \tan^2\beta$

SuperB

2×10^{-9}

2015→

Gm2 FNAL

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

$3.6\sigma \to 8\sigma$

2015→

Thank you

Back-up slides