Experimental cLFV search and last results of the MEG experiment

Giovanni Signorelli
INFN Sezione di Pisa

Third International Workshop on Baryon and Lepton Number Violation

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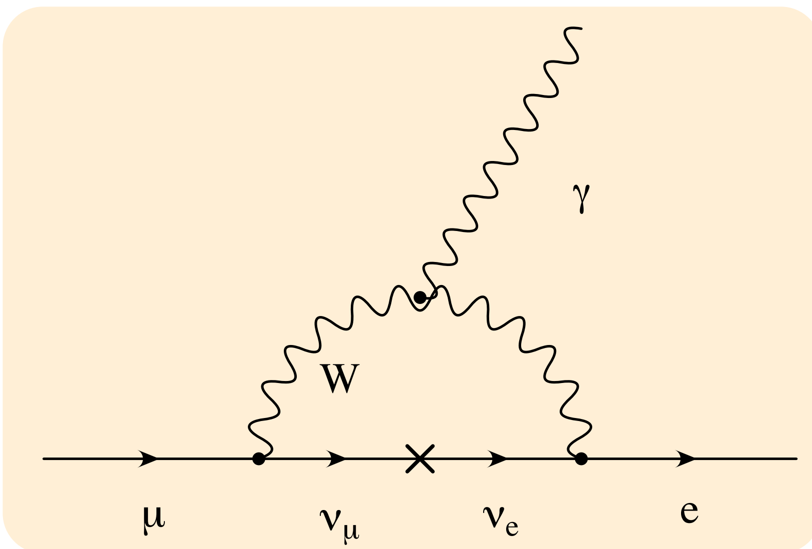
charged Lepton Flavor Violation

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

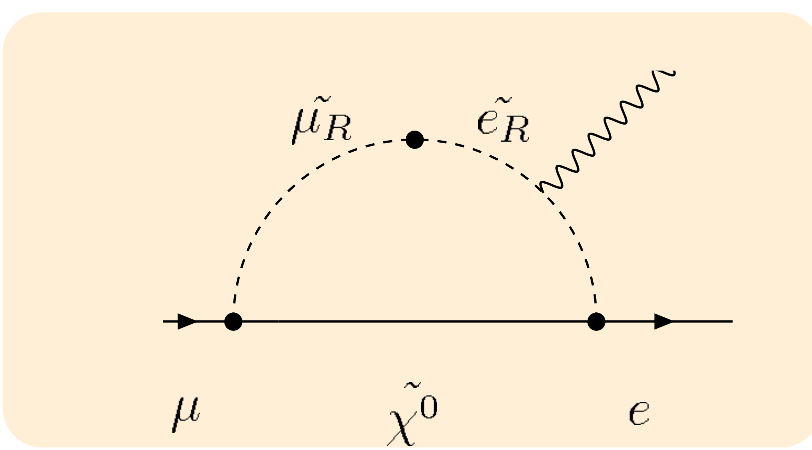


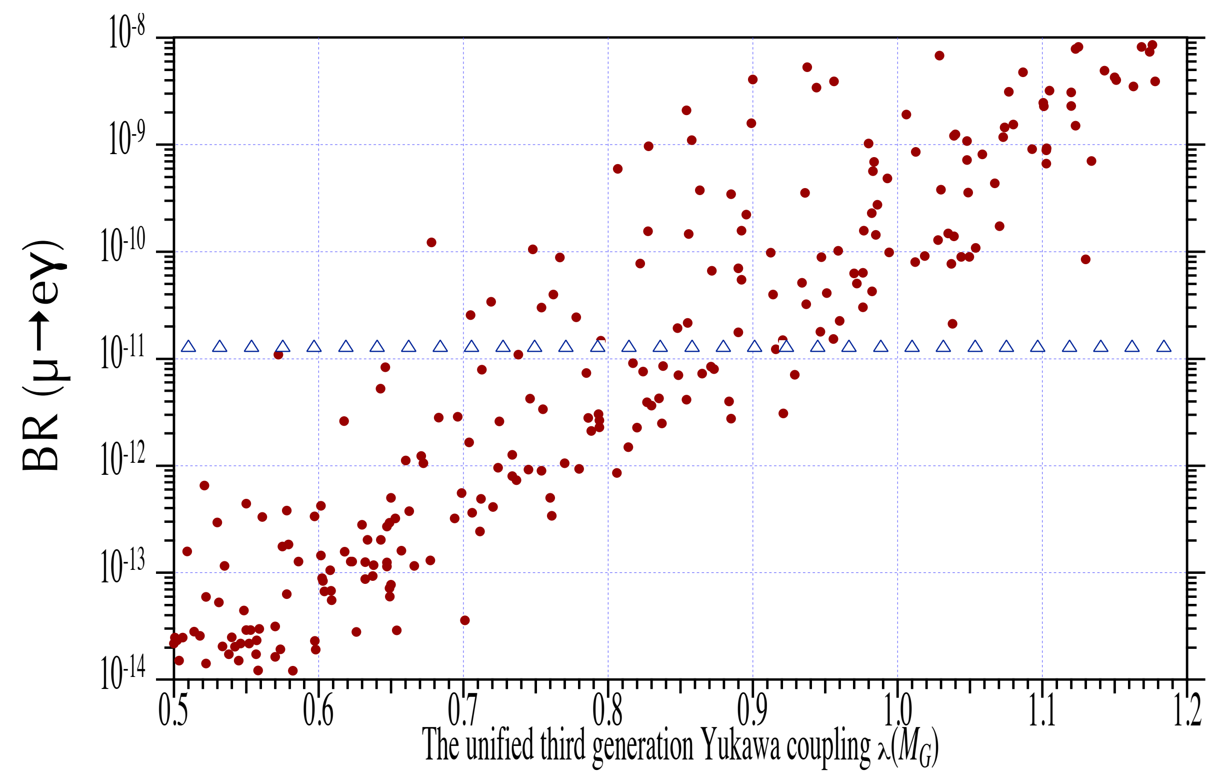
$$\Gamma(\mu \to e\gamma) \approx \underbrace{\frac{G_F^2 m_\mu^5}{192\pi^3}}_{\mu-\text{decay}} \underbrace{\left(\frac{\alpha}{2\pi}\right)}_{\gamma-\text{vertex}} \underbrace{\sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2}{M_W^2}\right)}_{\nu-\text{oscillation}}$$

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

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...)



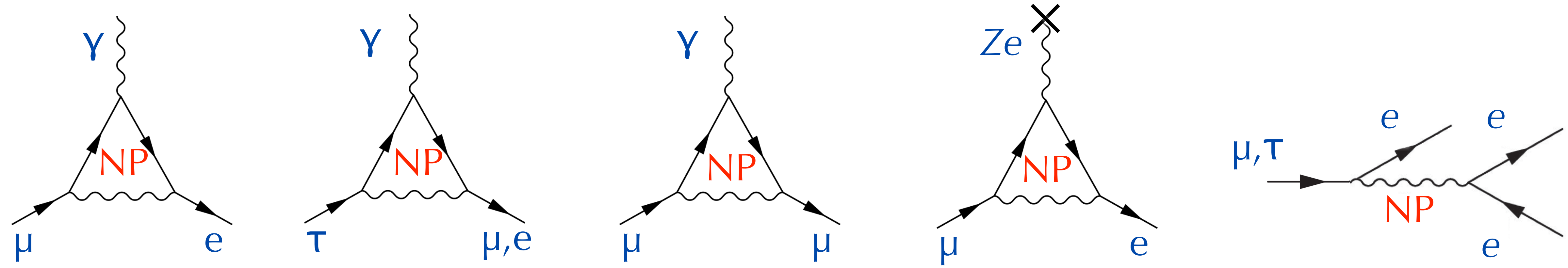


- Clear evidence for physics beyond the SM
  - background-free
- Restrict parameter space of SM extensions

Many cLFV processes

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

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



$\mu \to e\gamma$

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

$(g-2)_\mu$

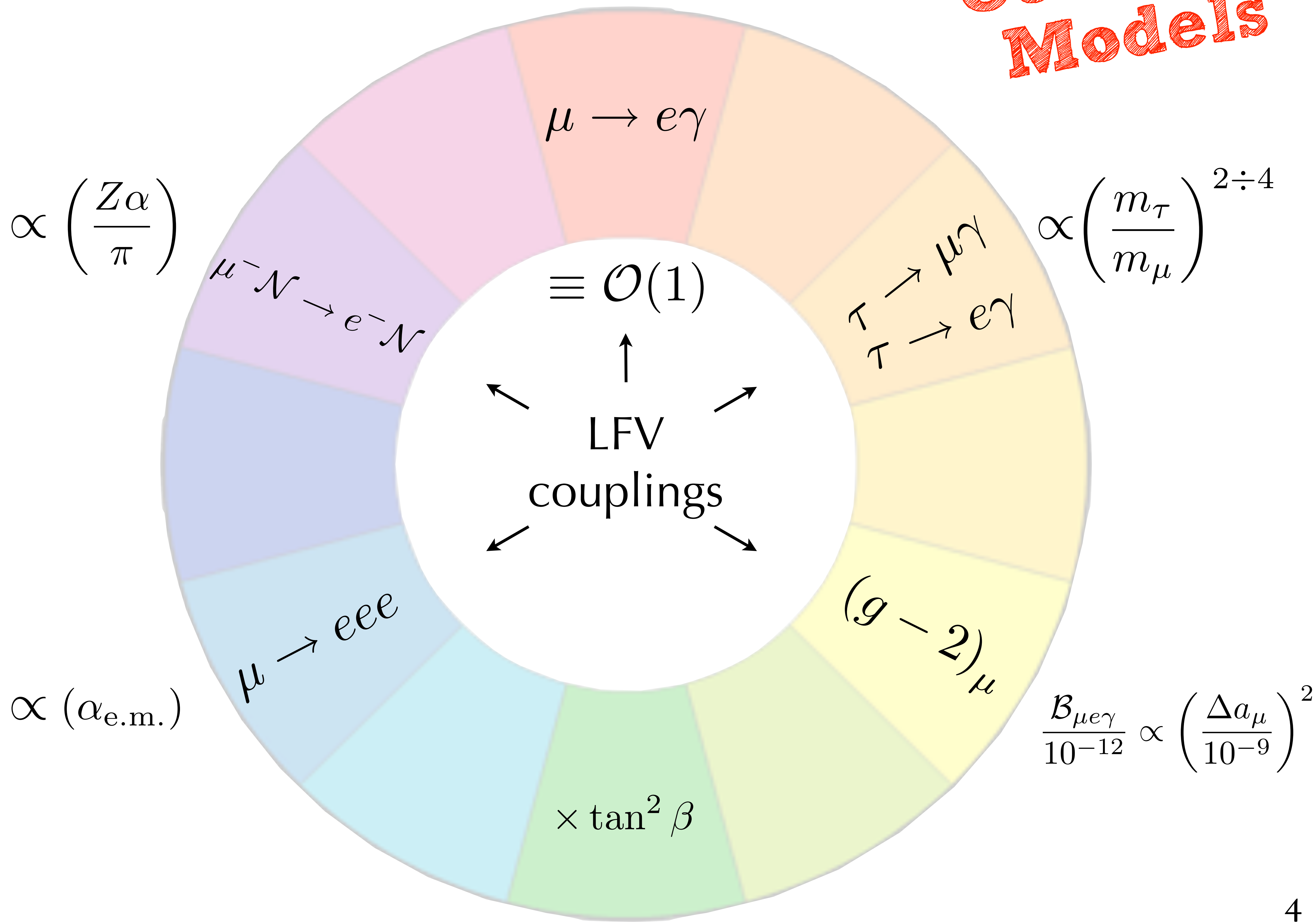
$\mu^- \mathcal{N} \to e^- \mathcal{N}$

$\mu \to eee$

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

The LFV wheel

Common Models



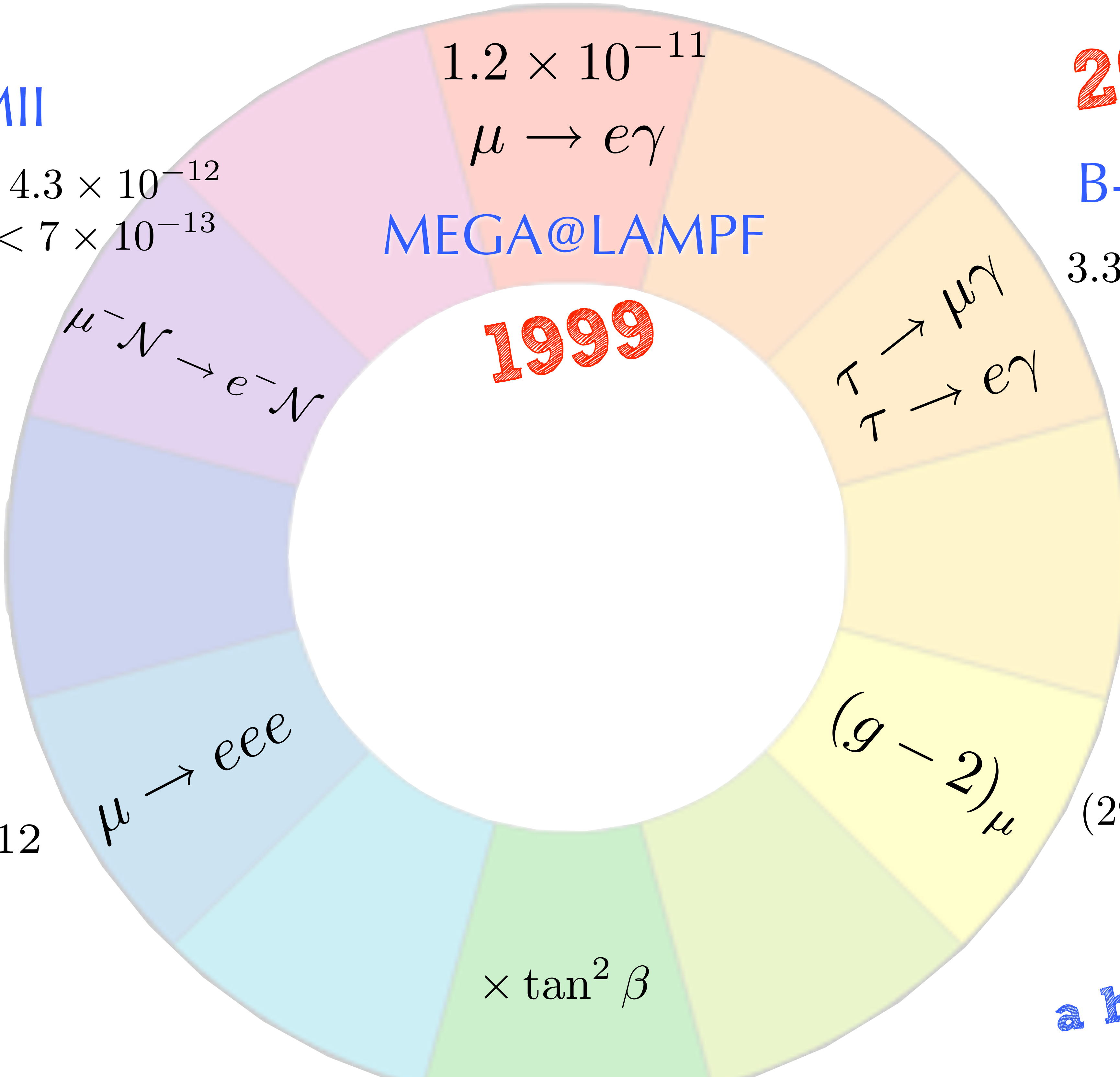
Present limits

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

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

2004

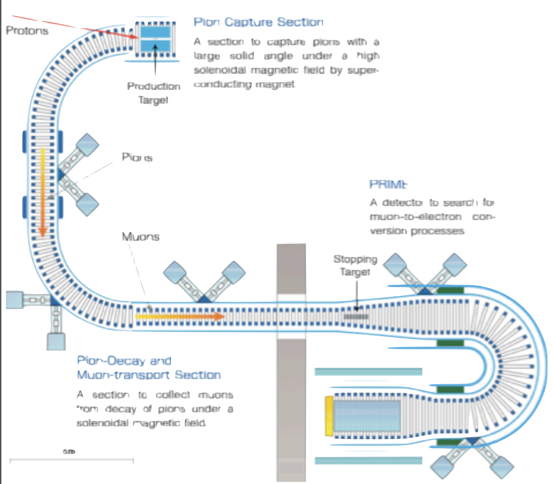
a hint for NP?

SINDRUM

1×10^{-12}

1988

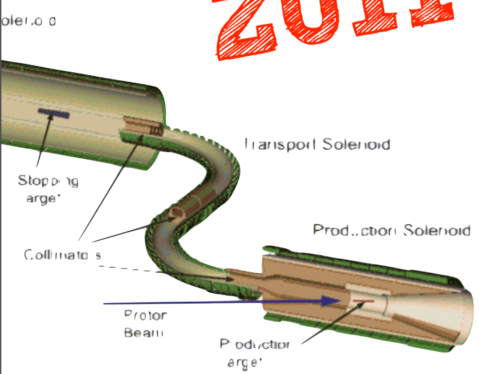
Future prospects



mu2e COMET

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

2017→



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

$\mu \to e\gamma$

MEG

few $\times 10^{-13}$

running →2013

SuperB SuperKEKB

SuperB

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

2015→

$\tau \to \mu\gamma$

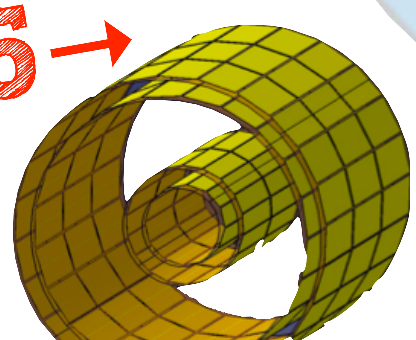
$\tau \to e\gamma$

$\mu \to eee$

Heidelberg

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

2015→



$\times \tan^2 \beta$

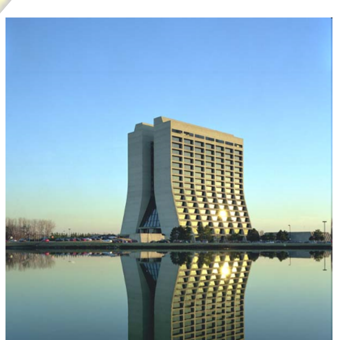
$(g-2)_\mu$

Gm2 FNAL

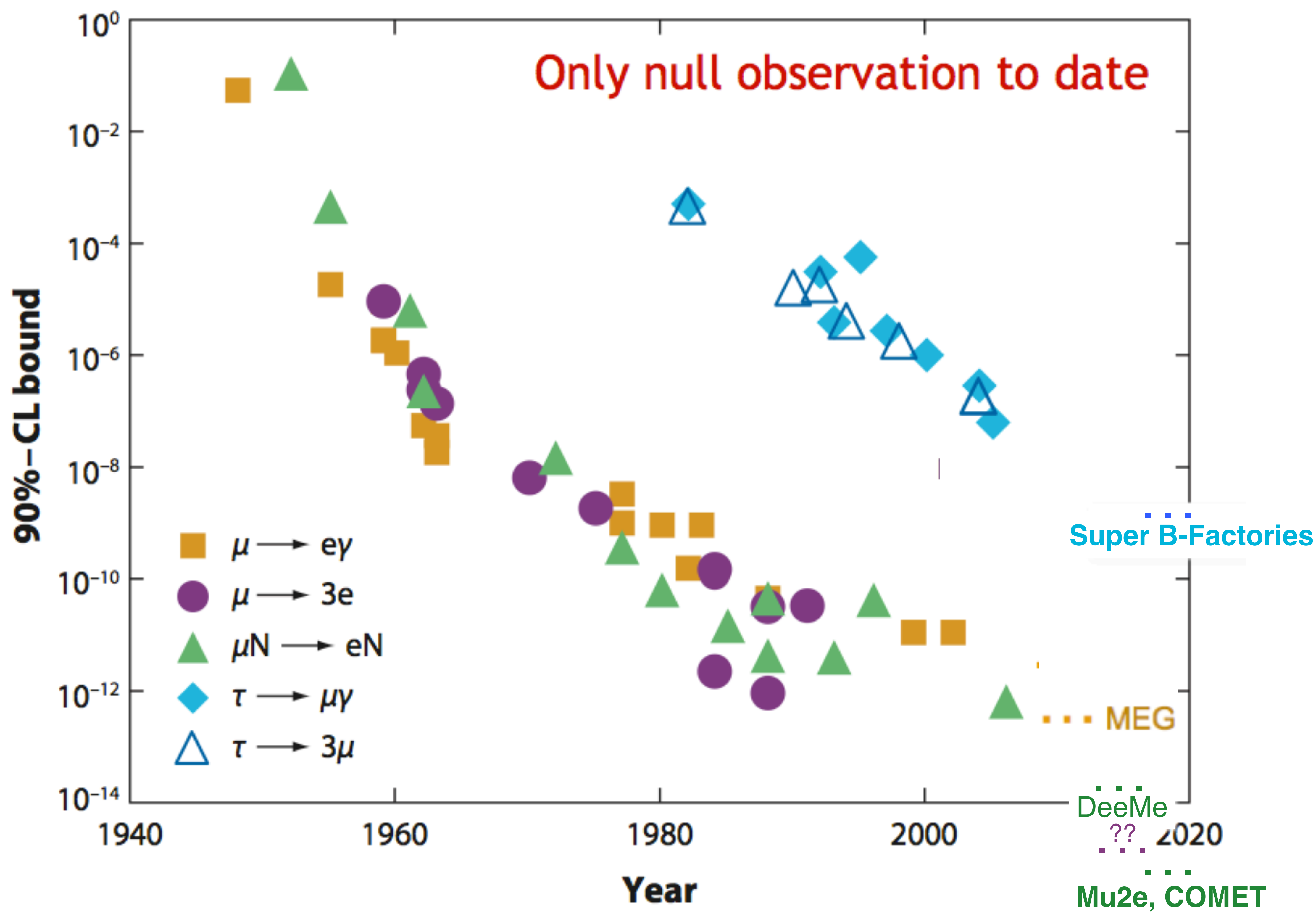
$\Delta a_\mu = (XXX \pm 34) \times 10^{-11}$

$3.6\sigma \to 8\sigma$

2015→



All history in one slide



Marciano, Mori & Roney, Annu. Rev. Nucl. Part. Sci. 2008 58:315–41

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

X. Bai
E. Baracchini
T. Doke
Y. Fujii
T. Haruyama
T. Iwamoto
A. Maki
S. Mihara
T. Mori
H. Natori
H. Nishiguchi
Y. Nishimura
W. Ootani
R. Sawada
Y. Uchiyama
A. Yamamoto

A. Baldini
C. Bemporad
G. Boca
P. W. Cattaneo
G. Cavoto
F. Cei
C. Cerri
A. De Bari
M. De Gerone
S. Dussoni
K. Fratini
L. Galli
F. Gatti
M. Grassi
D. Nicolò
M. Panareo
R. Pazzi†
G. Piredda
F. Renga
M. Rossella
F. Sergiampietri
G. Signorelli
F. Tenchini
C. Voena
D. Zanello

J. Adam
M. Hildebrandt
P.-R. Kettle
O. Kiselev
A. Papa
S. Ritt

B. Golden
G. Lim
W. Molzon

D. N. Grigoriev
F. Ignatov
B. I. Khazin
A. Korenchenko
N. Kravchuk
D. Mzavia†
A. Popov
Yu. V. Yudin

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Waseda U.
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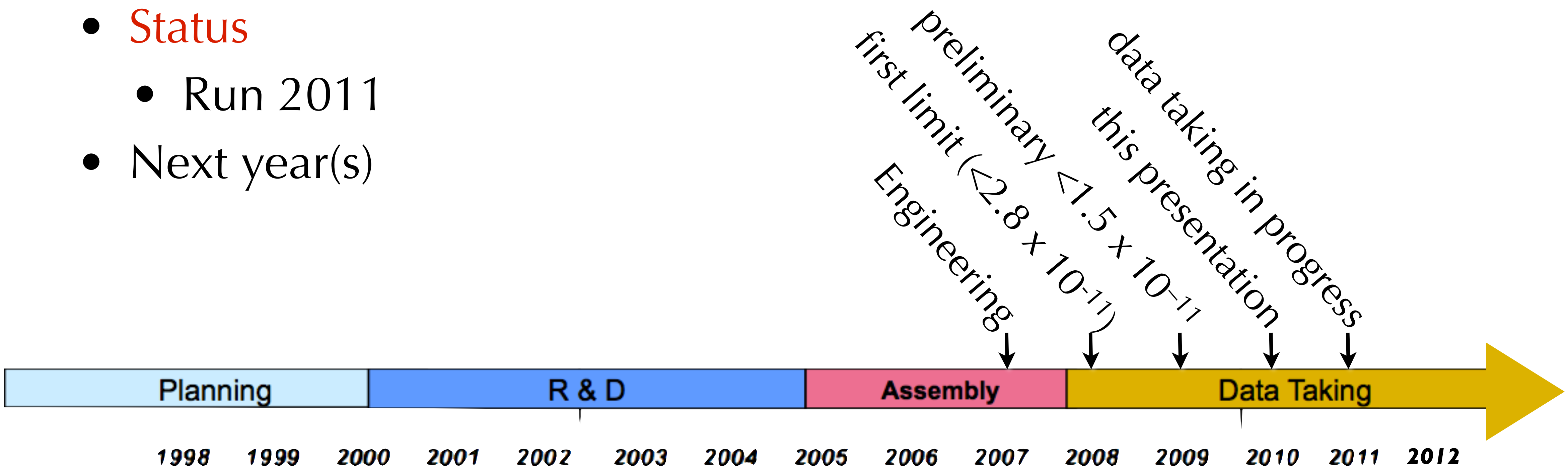
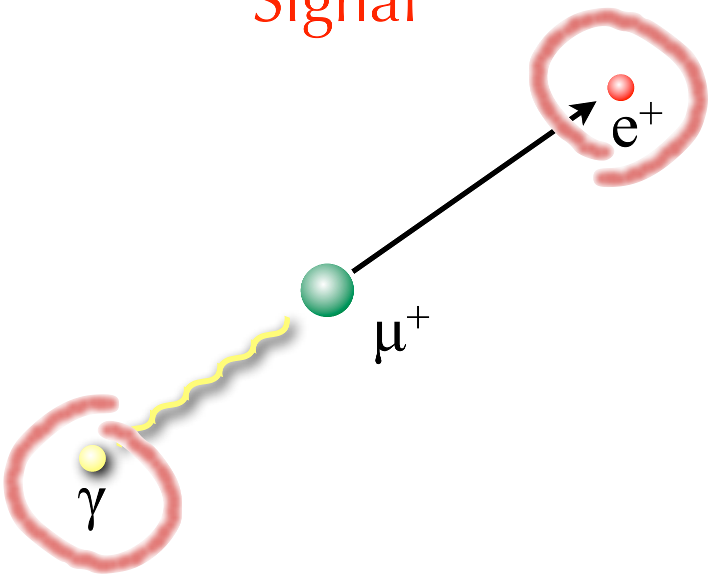
Time scale

- 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 + 2010 run
- Status
  - Run 2011
- Next year(s)



Signal and Background

"Signal"

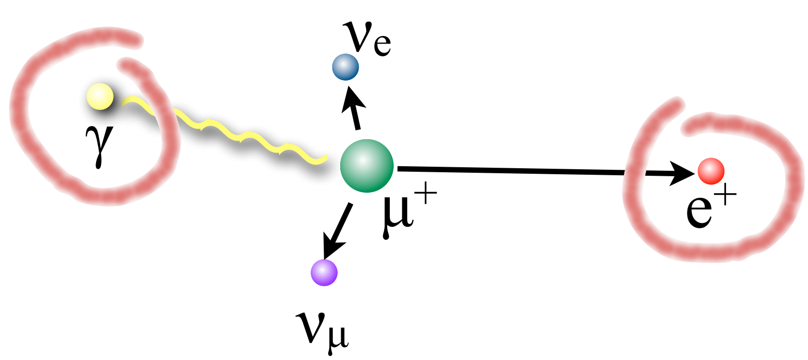


$E_e = E_\gamma = 52.8$ MeV

$\theta_{e\gamma} = 180°$

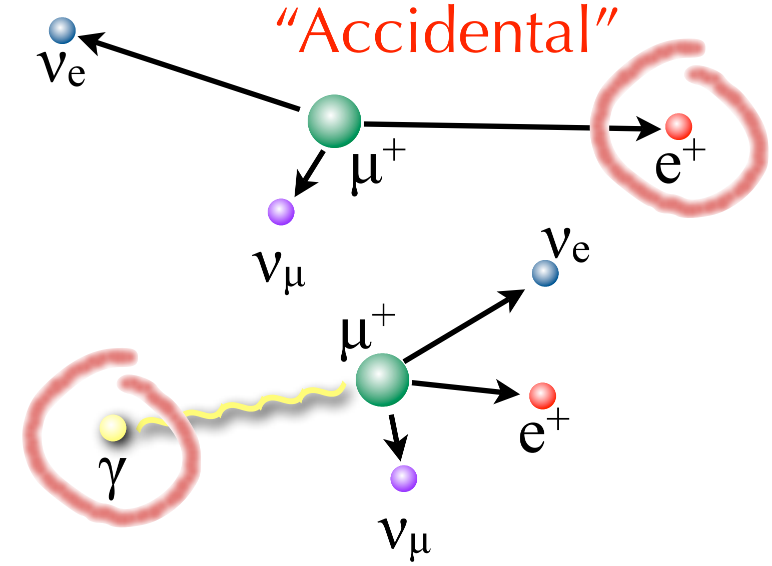
$t_{e\gamma} \sim 0$

"RMD"



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

"Accidental"



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

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

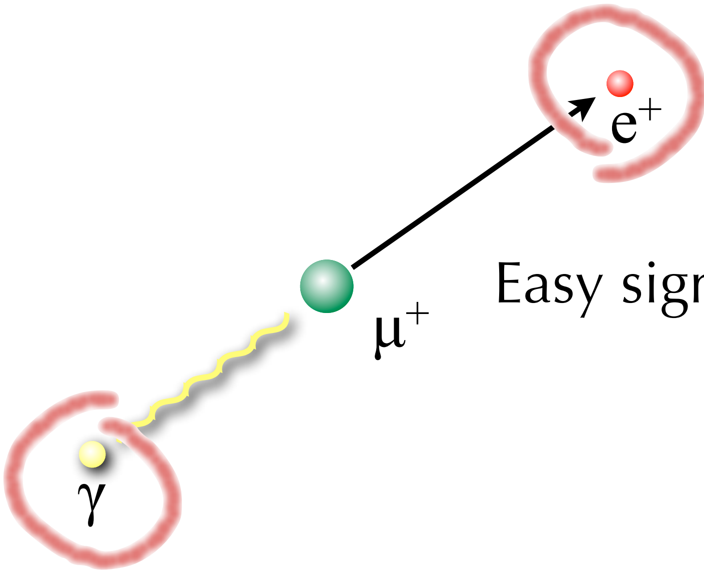
$e^+e^- \to \gamma\gamma$

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

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

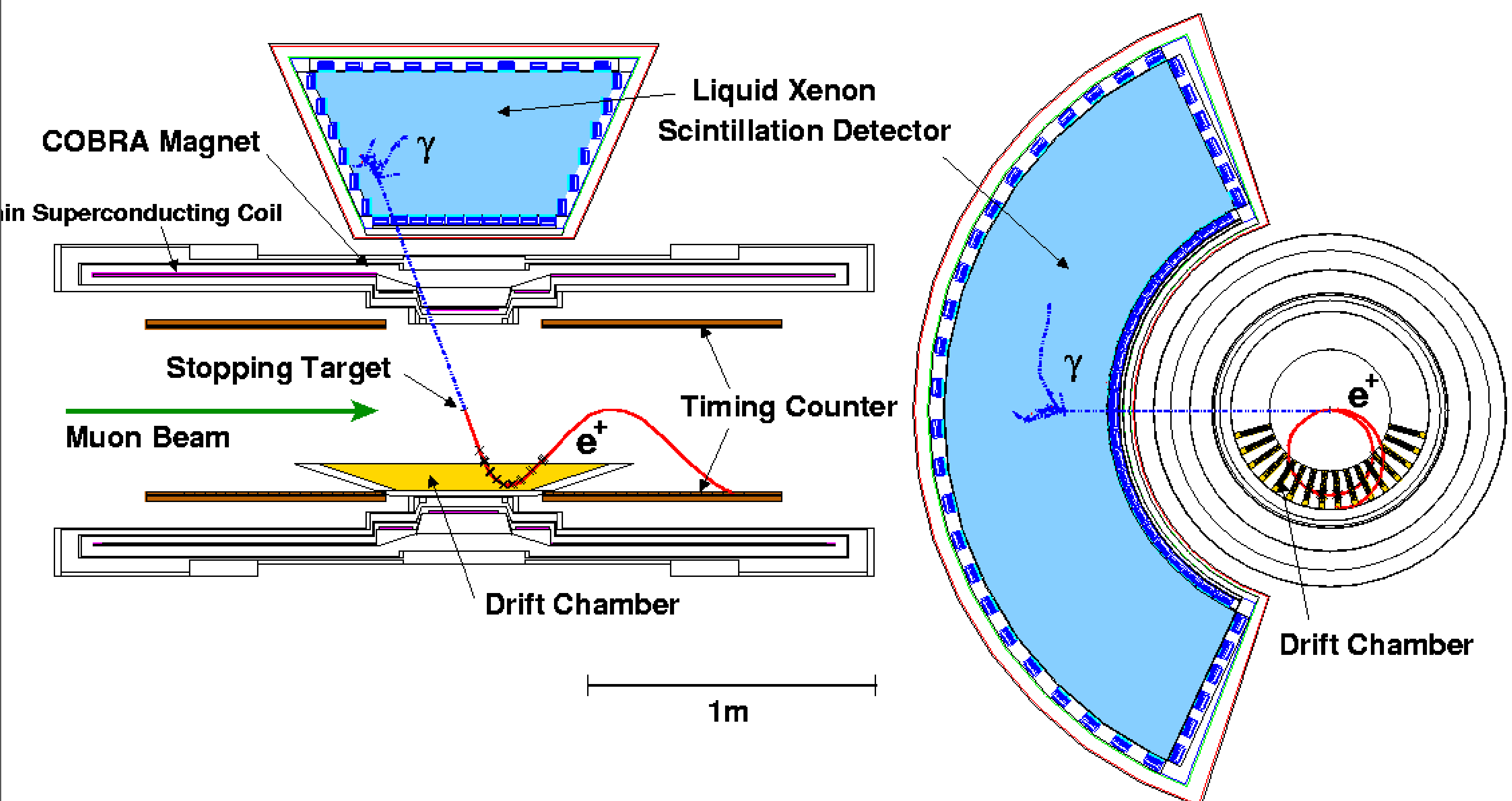
The accidental background is dominant and it is determined by the experimental resolutions

MEG experimental method



Easy signal selection with
μ+ at rest

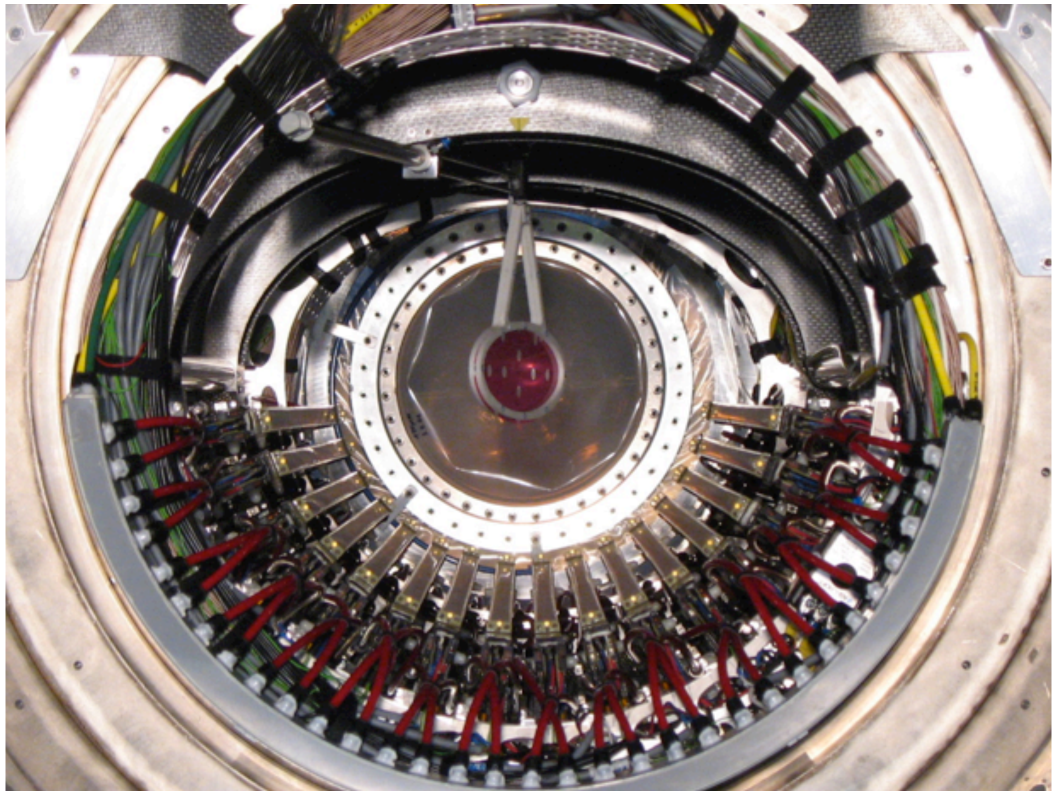
- μ: stopped beam of 3 x 10^7 μ /sec in a 205 μm polyethylene target
  - PSI πE5 beam line
- e^+ detection
  magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum
  plastic counters for timing
- γ detection
  Liquid Xenon detector based on the scintillation light
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm



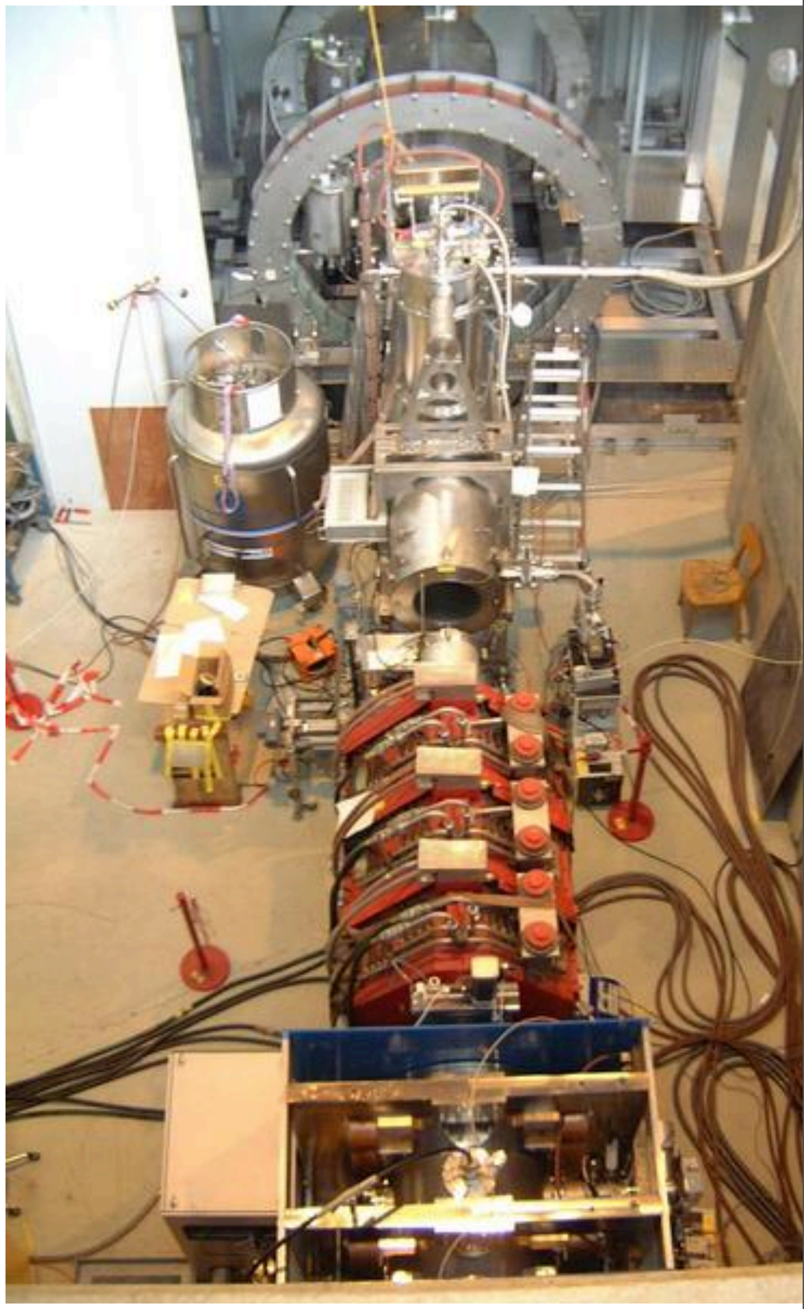
Some detector pictures

LXe detector

DC system



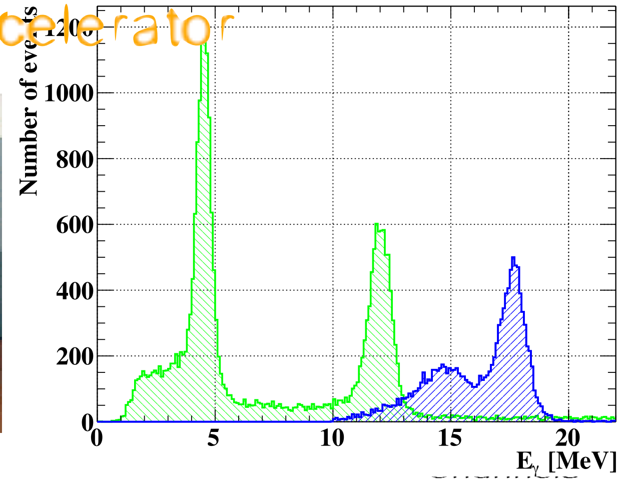
Beam Line



Calibration & Monitoring

Detector Calibration

Proton Accelerator



<u>Li(p,γ)Be</u>

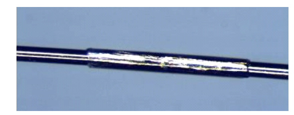
LiF target at COBRA center

17.6MeV γ

~daily calib.

also for initial setup

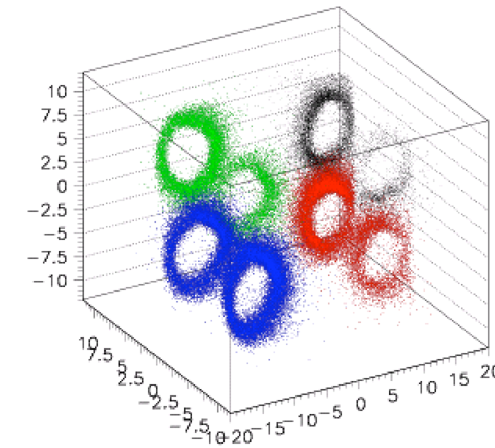
Alpha on wires



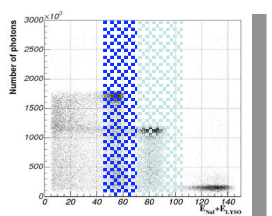
<u>PMT QE & Att. L</u>

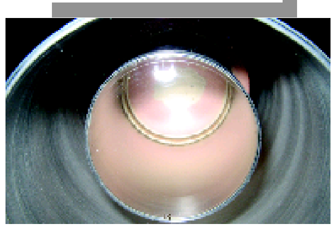
Cold GXe

LXe



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



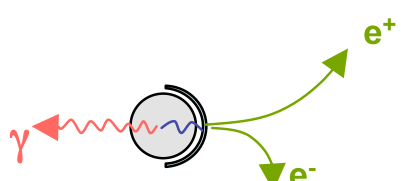


$\pi^- + p \rightarrow \pi^0 + n$

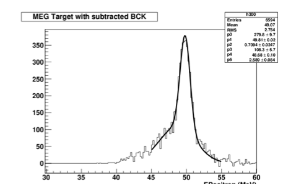
$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

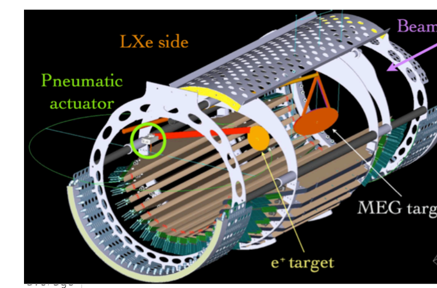
$\pi^- + p \rightarrow \gamma + n$ (129MeV)

LH_2 target

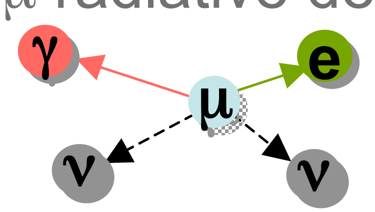


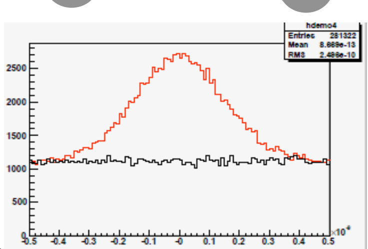
Mott e+ scattering





μ radiative decay



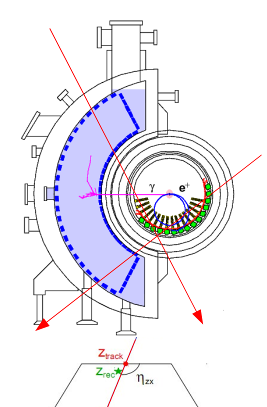


Lower beam intensity < 10^7

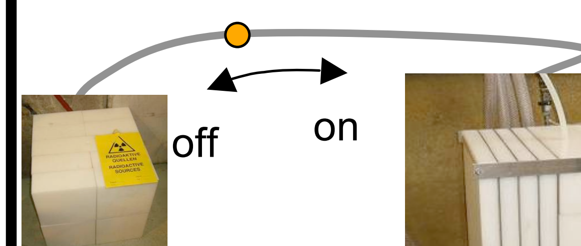
Is necessary to reduce pile-ups

A few days ~ 1 week to get enough statistics

Cosmic ray alignment

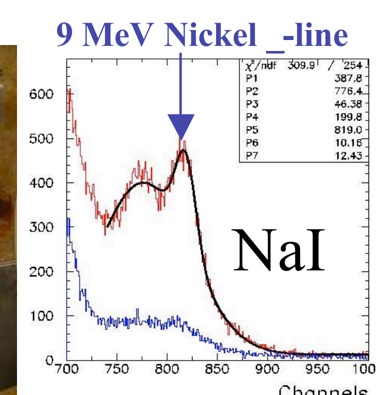


Nickel γ Generator



Illuminate Xe from the back

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



Analysis principle

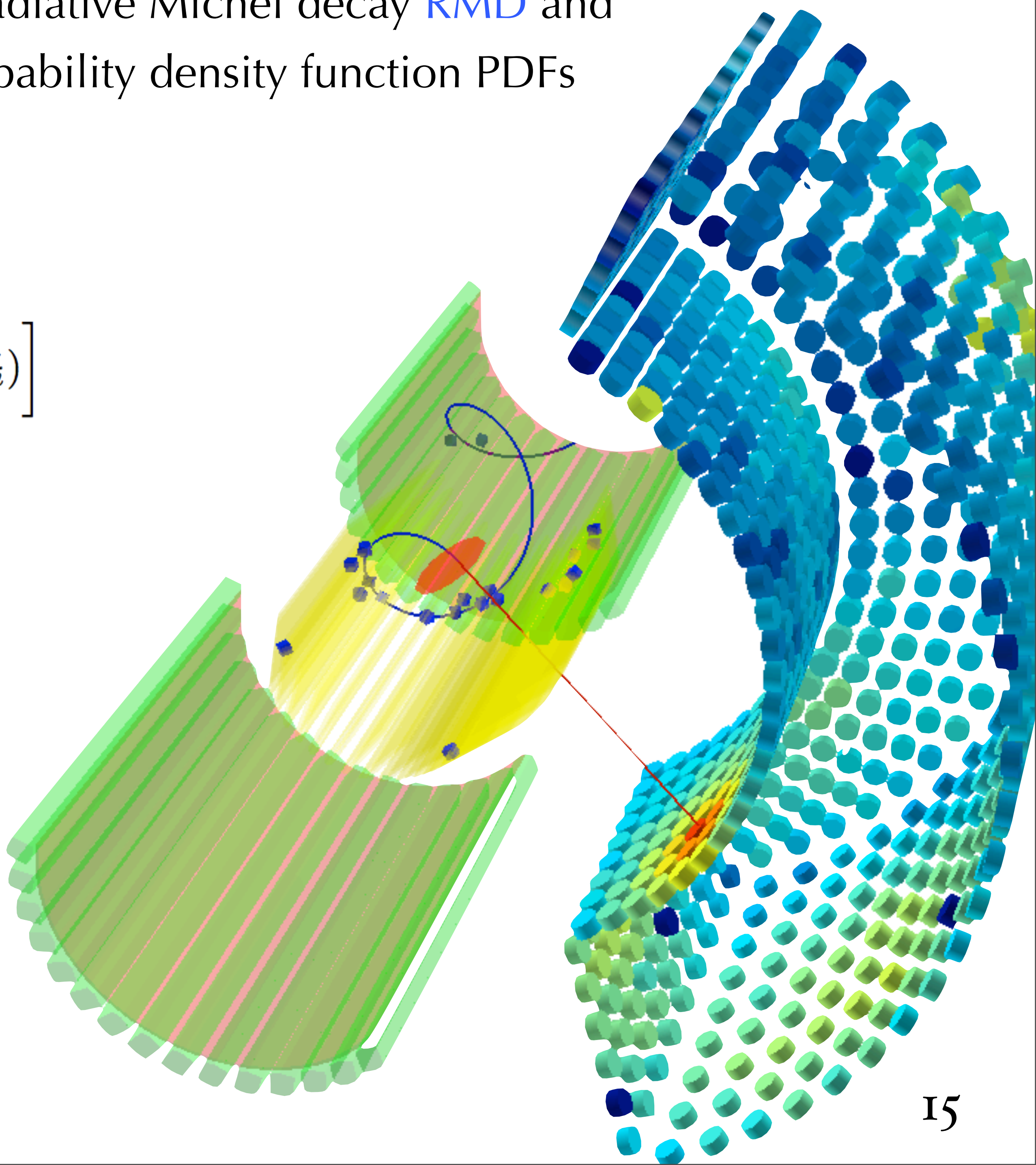
- A $\mu \to e\gamma$ event is described by 5 kinematical variables

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

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

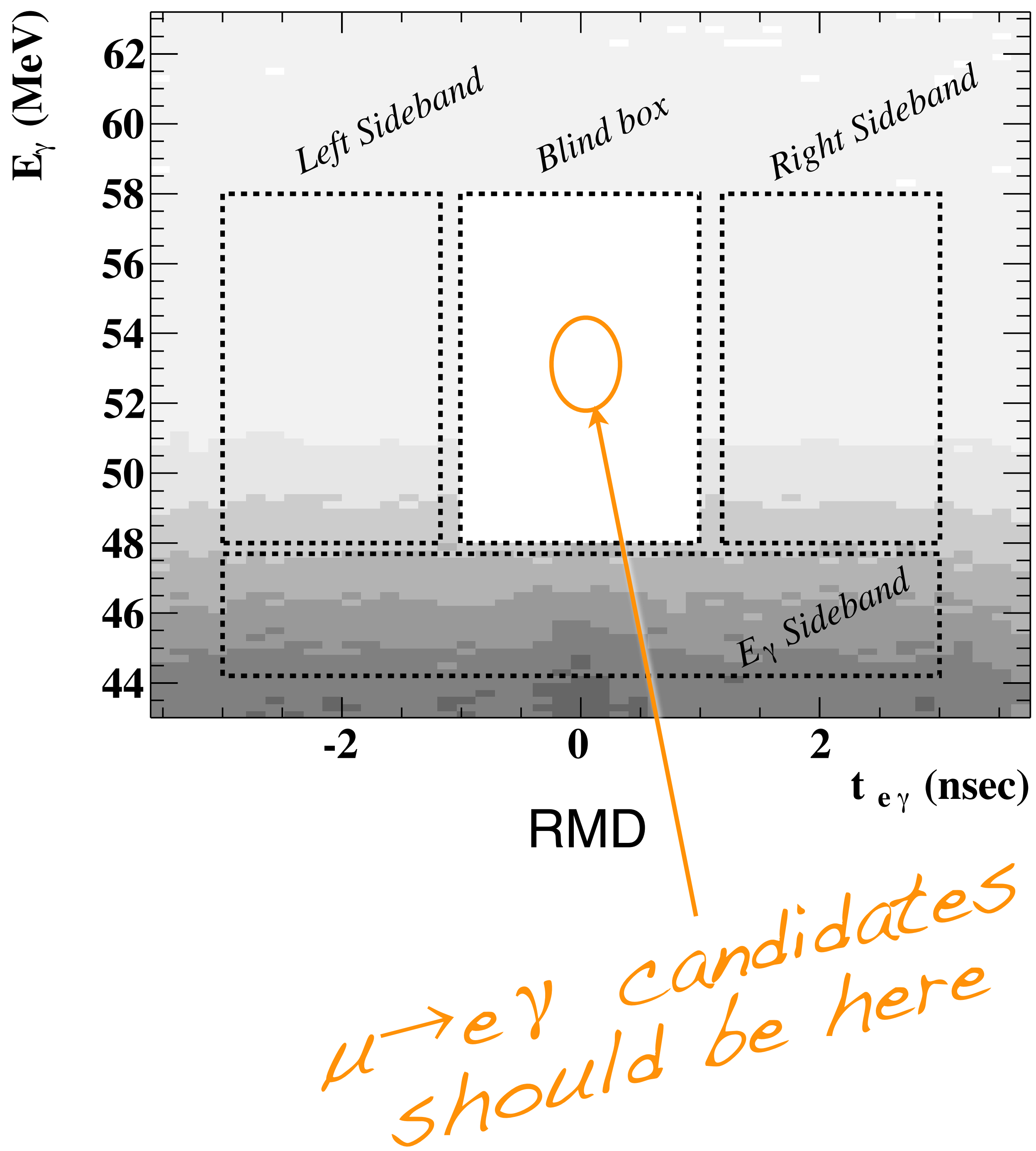
$$\begin{aligned} &-\ln \mathcal{L}\left(N_{\rm sig}, N_{\rm RMD}, N_{\rm BG}\right) \\ &= N_{\rm exp} - N_{\rm obs} \ln\left(N_{\rm exp}\right) \\ &\quad - \sum_{i=1}^{N_{\rm obs}} \ln\left[\frac{N_{\rm sig}}{N_{\rm exp}} S(\vec{x_i}) + \frac{N_{\rm RMD}}{N_{\rm exp}} R(\vec{x_i}) + \frac{N_{\rm BG}}{N_{\rm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

- Extended unbinned likelihood fit
  - fit (N_{sig}, N_{RMD}, N_{BG}) in a wide region
    - $48 \le E_\gamma \le 58$ MeV
    - $50 \le E_e \le 56$ MeV
    - $|T_{e\gamma}| \le 0.7$ ns
    - $|\phi_{e\gamma}|, |\theta_{e\gamma}| \le 50$ mrad
- PDFs taken from
  - data
  - MC tuned on data

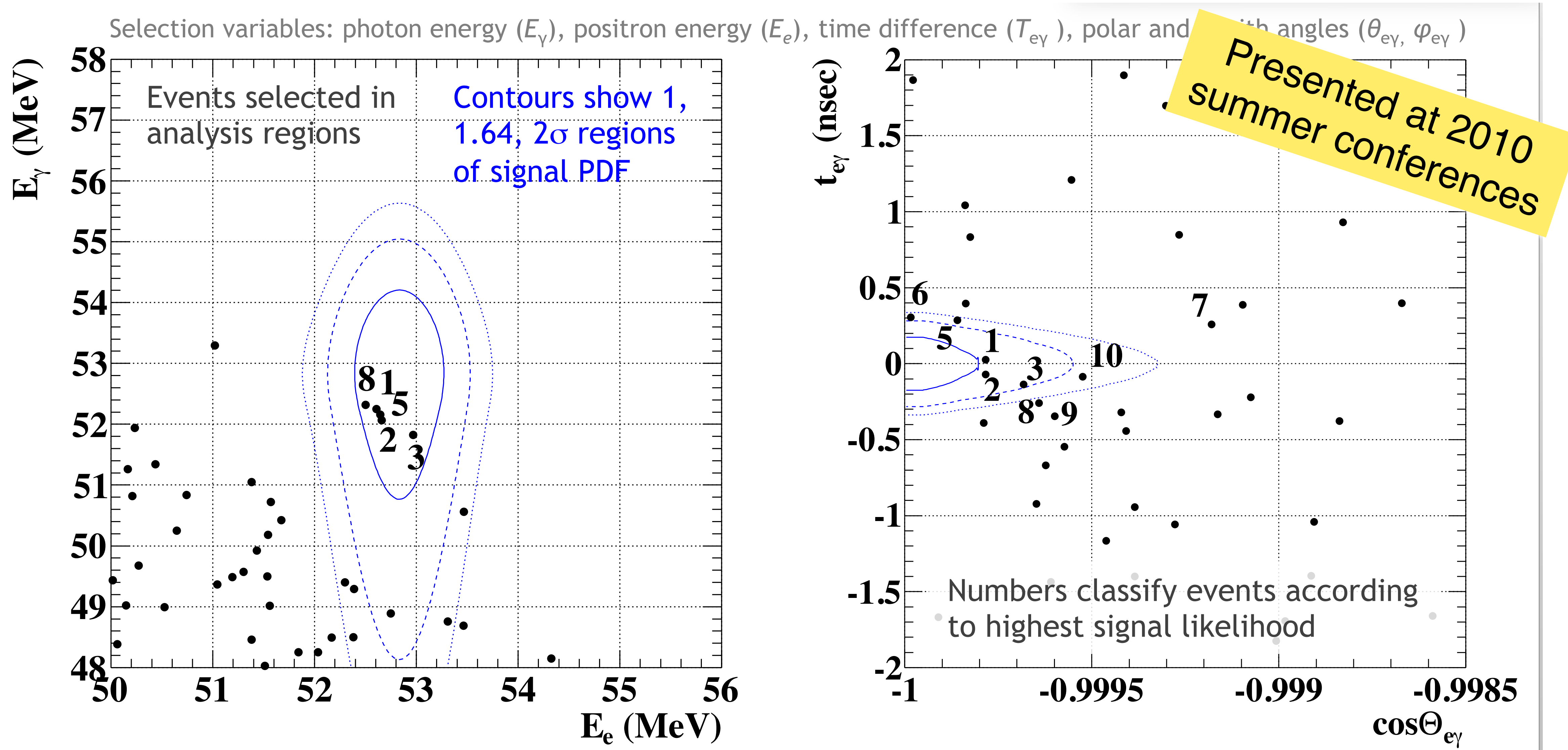


Analysis principle

- 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



Preliminary analysis of 2009



Unbinned maximum likelihood fit gave slight signal excess and 90% CL upper limit:

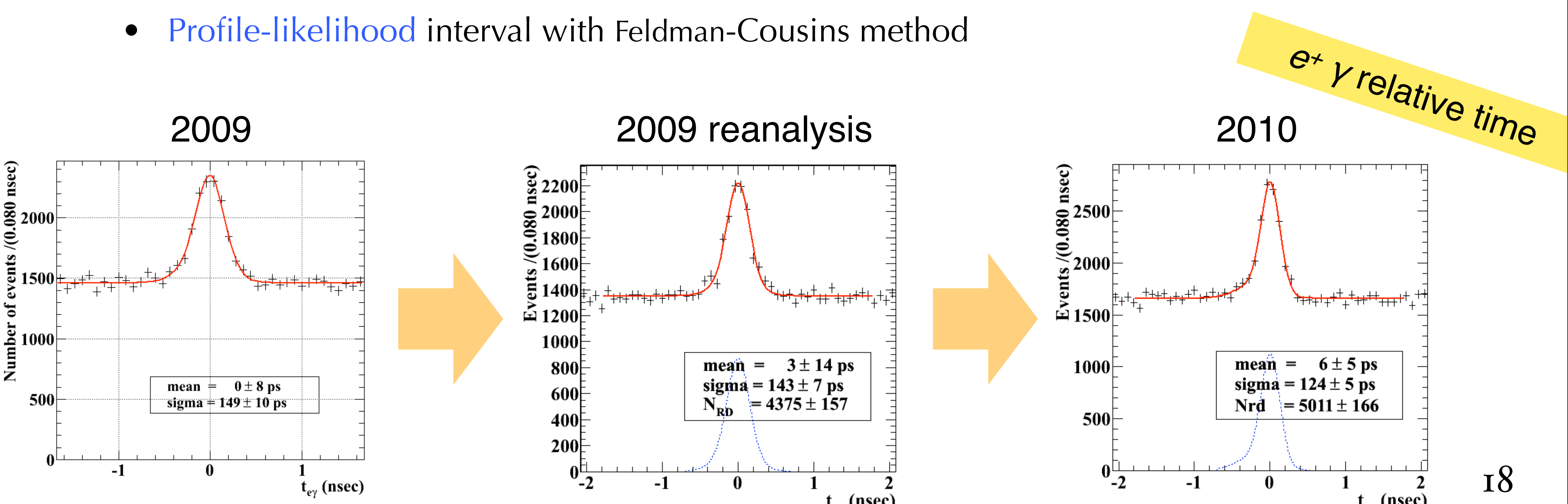
$$BR(\mu^+ \to e^+\gamma) < \begin{cases} 1.5 \cdot 10^{-11} & \text{(observed)} \\ 6.1 \cdot 10^{-12} & \text{(expected for no signal)} \end{cases}$$

Analysis improvements

- New data
  - 2010 data = 2 x 2009 data
  - Combine 2009 and 2010

- Better understanding of the detector
  - Alignment inside/among detectors
  - Implement correlations among variables
    - reduce systematic uncertainty

- Analysis method
  - N_{BG} constrained from sideband data
  - Profile-likelihood interval with Feldman-Cousins method

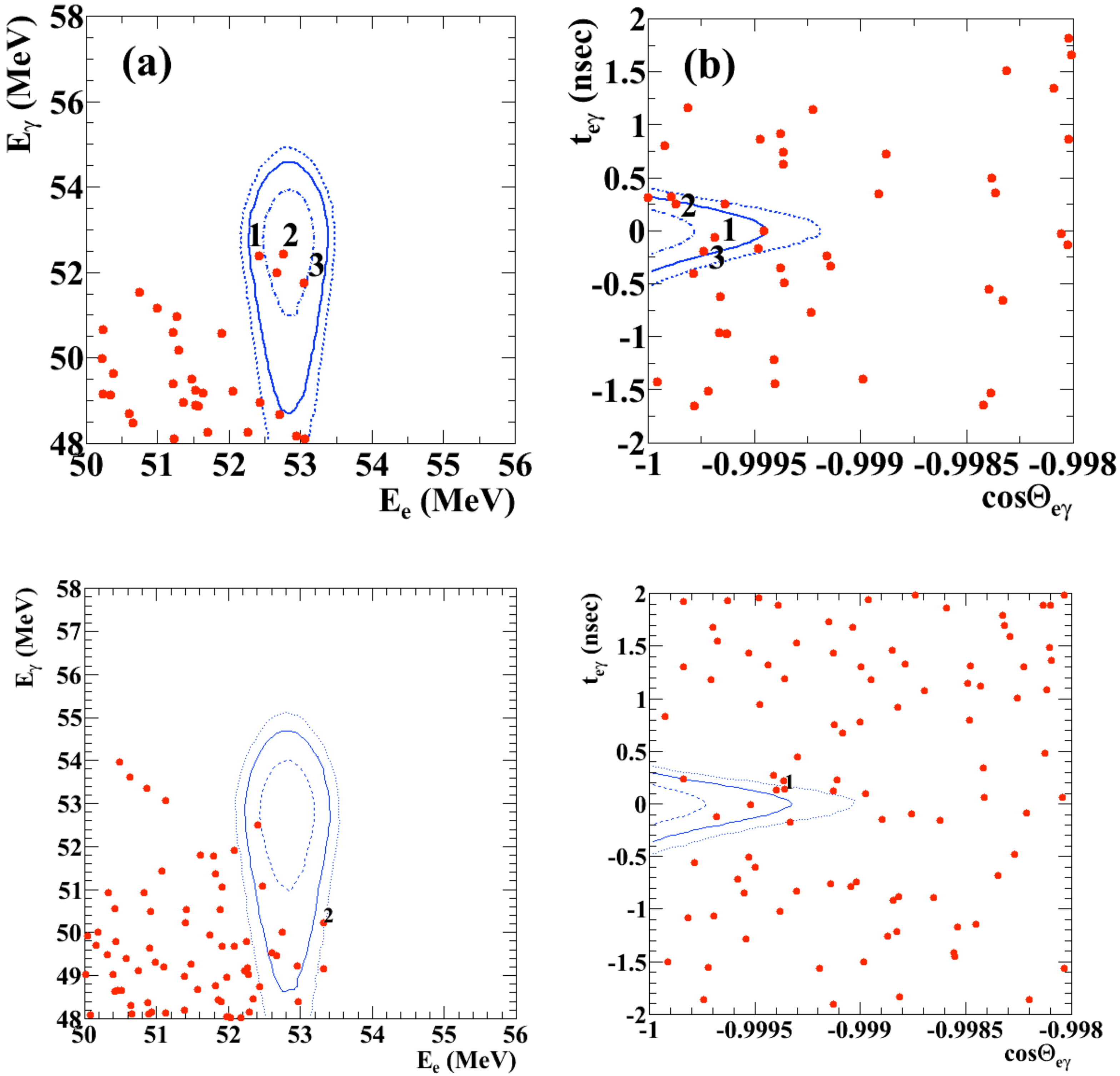


2009 reloaded, 2010

~ 1.8 x 10^{12} μ^+ on target.   2010 statistics ~ 2 x 2009

2009

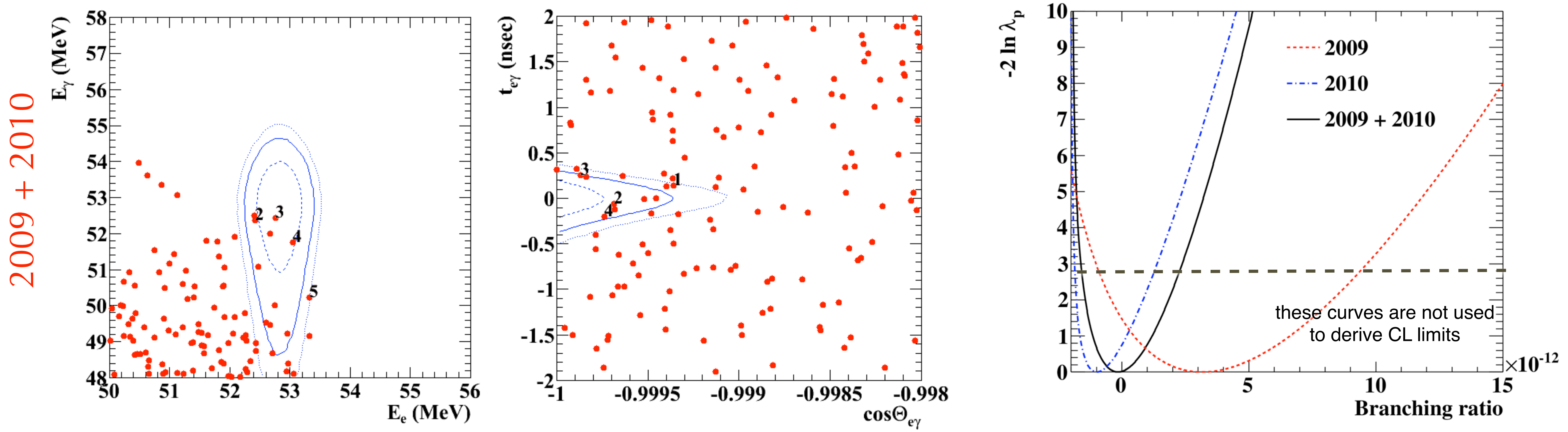
2010



- Excess in 2009 data confirmed by reanalysis
  - (background only p-value ~ 8%)

- However not reproduced in 2010 data

Combined 2009 + 2010



- 90% C.L. Feldman-Cousins upper limit

$$\frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma(\mu^+ \to e^+\nu\bar{\nu})} \leq 2.4 \times 10^{-12}$$

5 times better than previous limit!

  - 1.6×10^{-12} expected for no signal (sensitivity)

Data set	$\mathcal{B}_{\rm fit}$	LL	UL
2009	3.2×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-13}	–	1.7×10^{-12}
2009 + 2010	-1.5×10^{-13}	–	2.4×10^{-12}

Cornell University Library

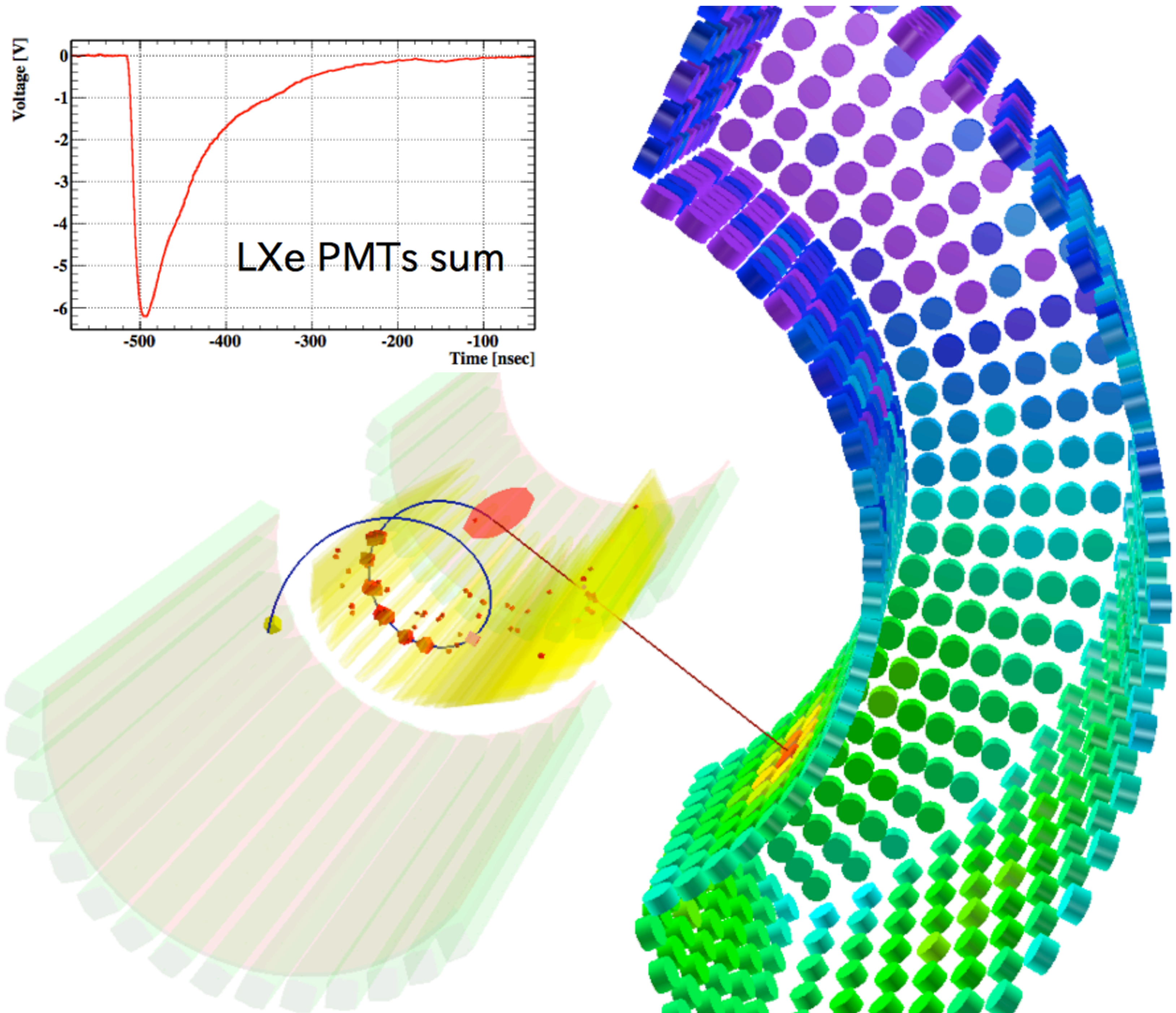
arXiv.org > hep-ex > arXiv:1107.5547

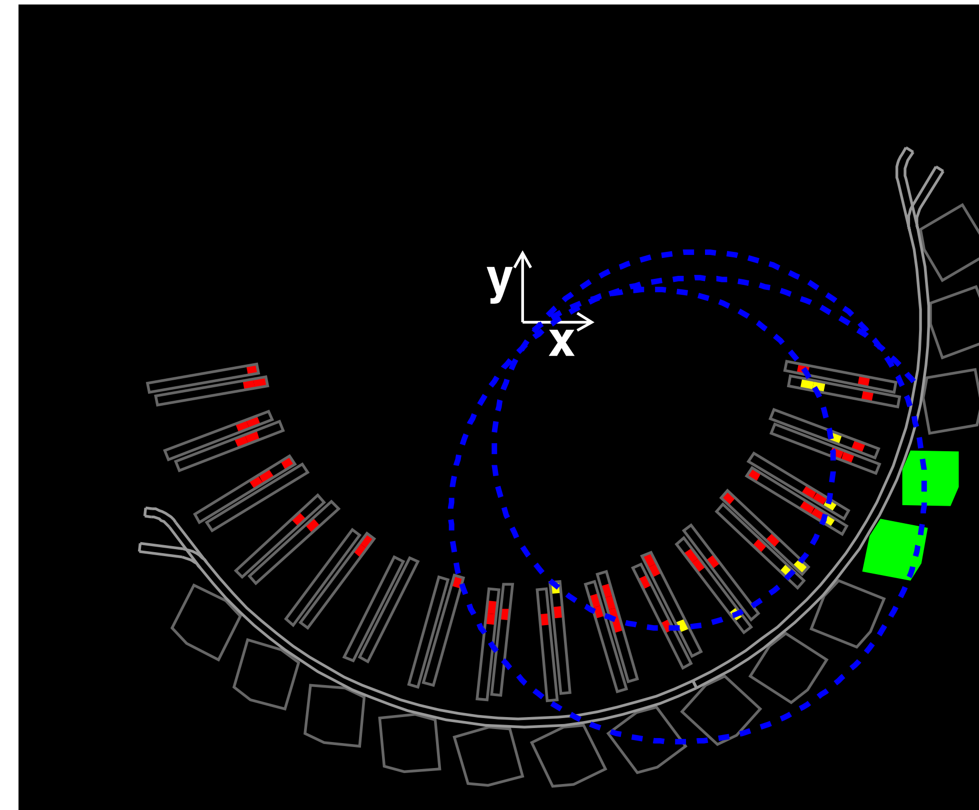
High Energy Physics – Experiment

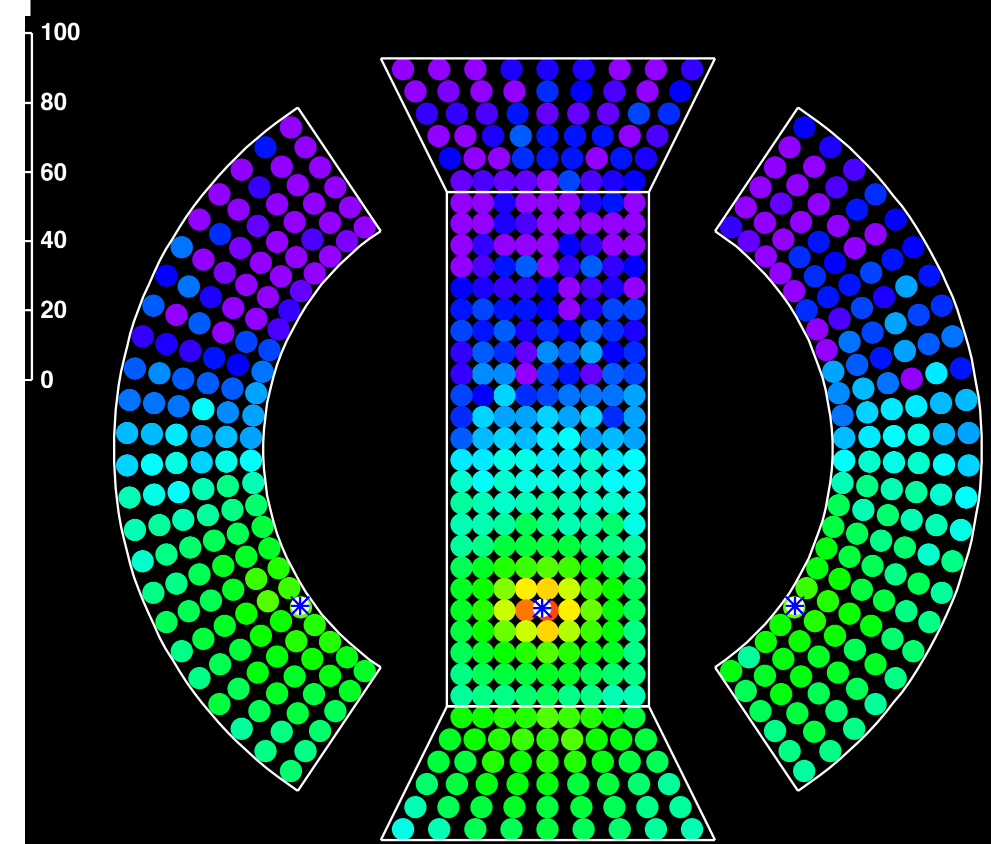
New limit on the lepton-flavour violating deca

Event display

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

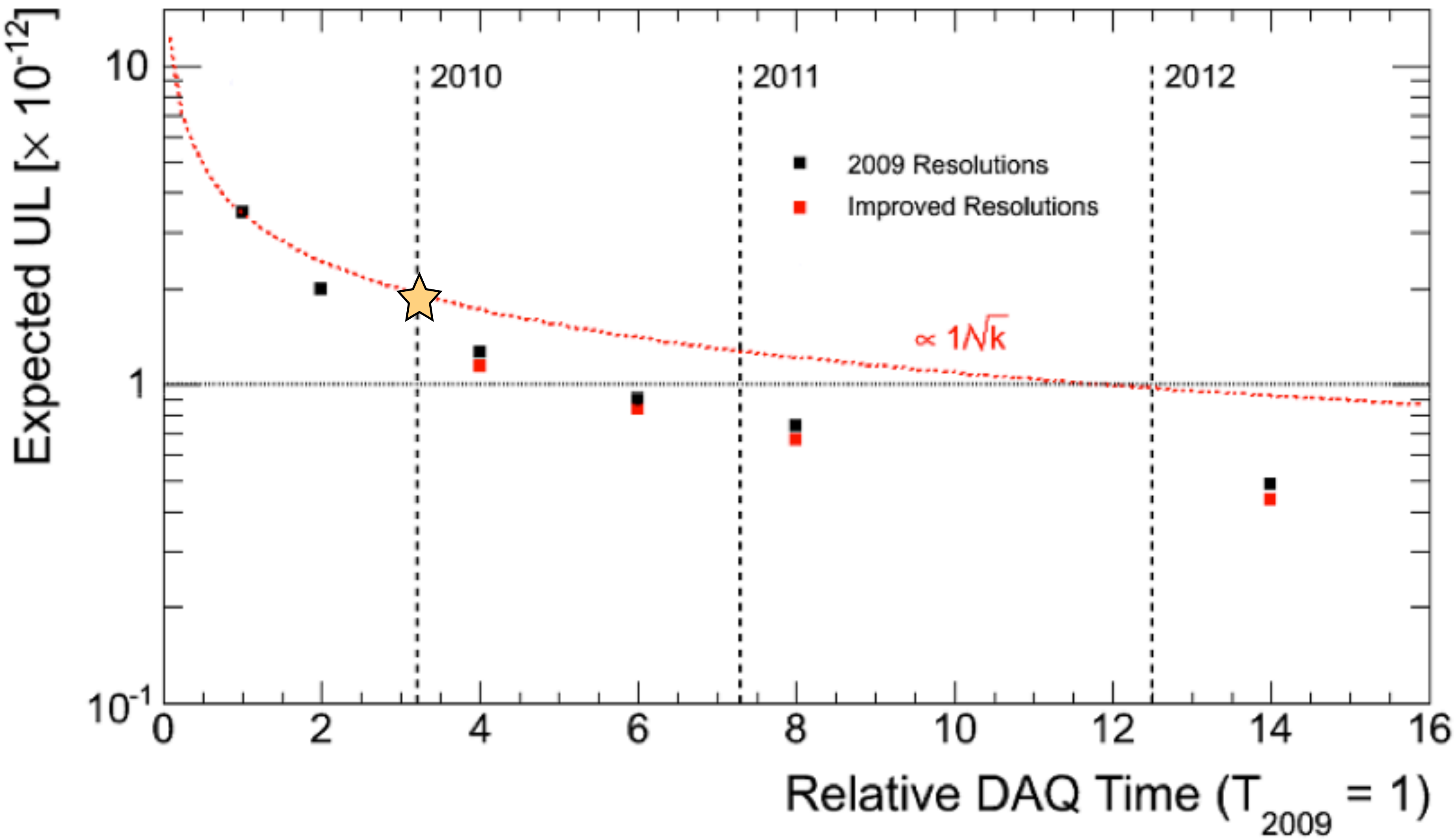


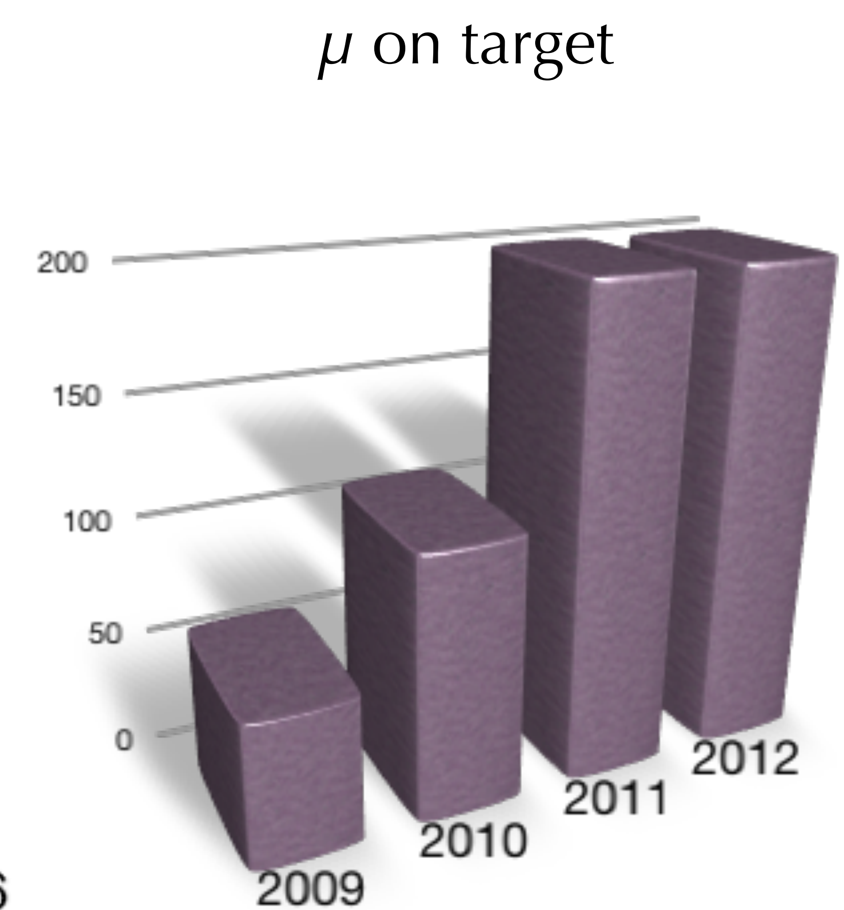




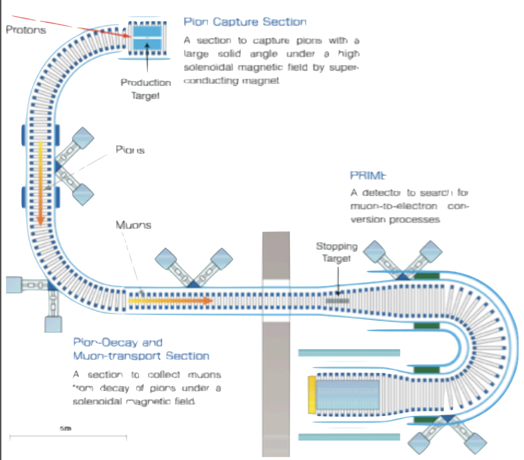
Sensitivity prospect

- Data from the combined 2009+2010 runs of the MEG experiment give the best limit to the $\mu \rightarrow e\gamma$ decay to date
- Plans to reach its design sensitivity (few x 10^{-13}) within 2013





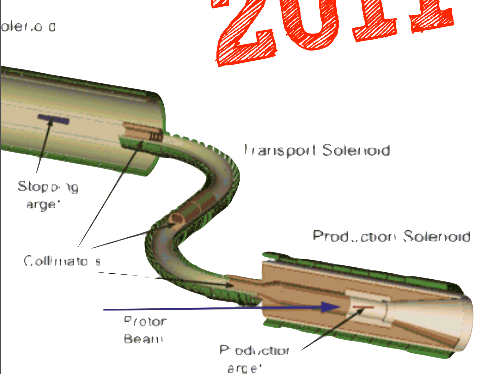
Back to the wheel...



mu2e COMET

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

2017 →



2.4×10^{-12}

$\mu \longrightarrow e\gamma$

MEG

few $\times\, 10^{-13}$

running

→ 2013

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

$\tau \to \mu\gamma$

$\tau \to e\gamma$

SuperB

2×10^{-9}

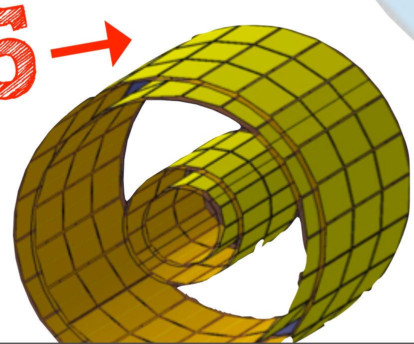
2015 →

$\mu \to eee$

Heidelberg

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

2015 →



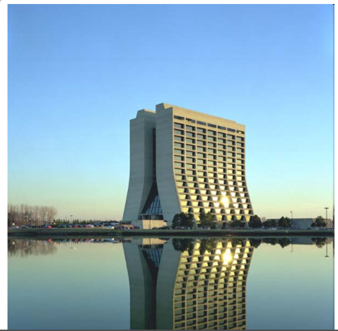
$\times \tan^2 \beta$

$(g-2)_\mu$

Gm2 FNAL

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

$3.6\sigma \to 8\sigma$



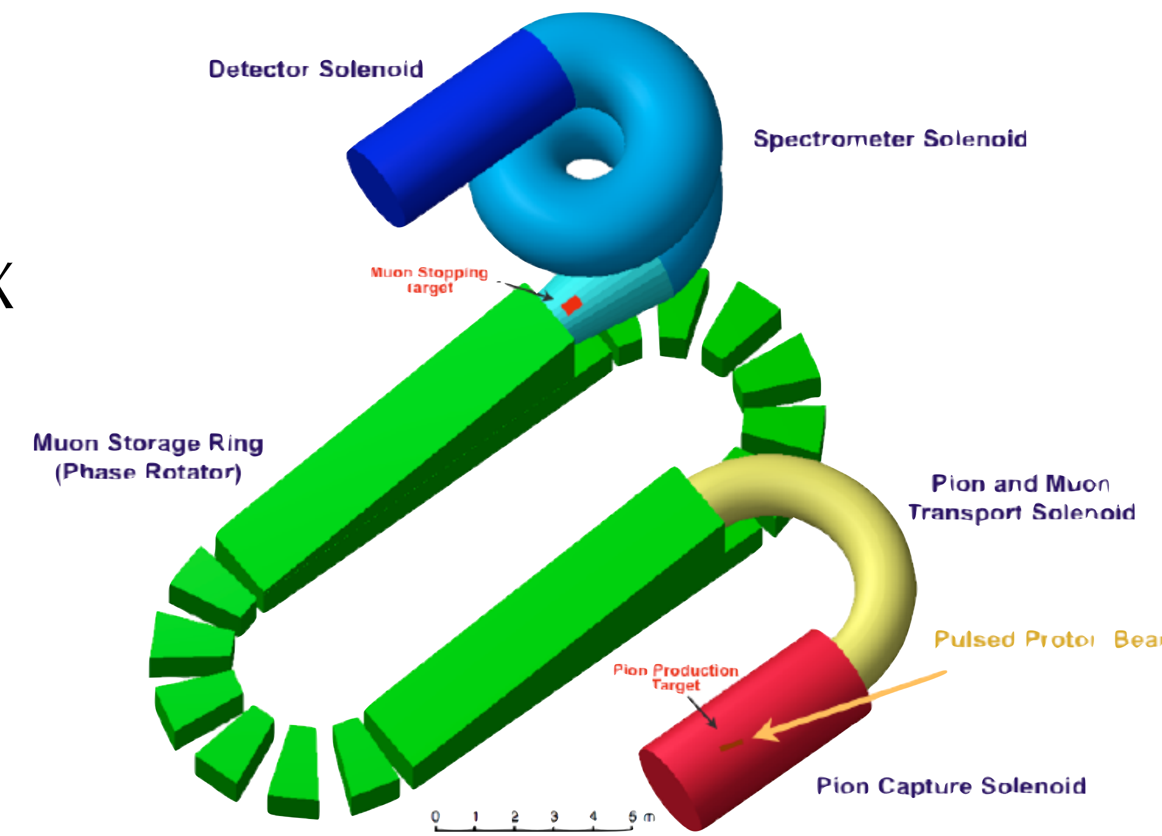
2015 →

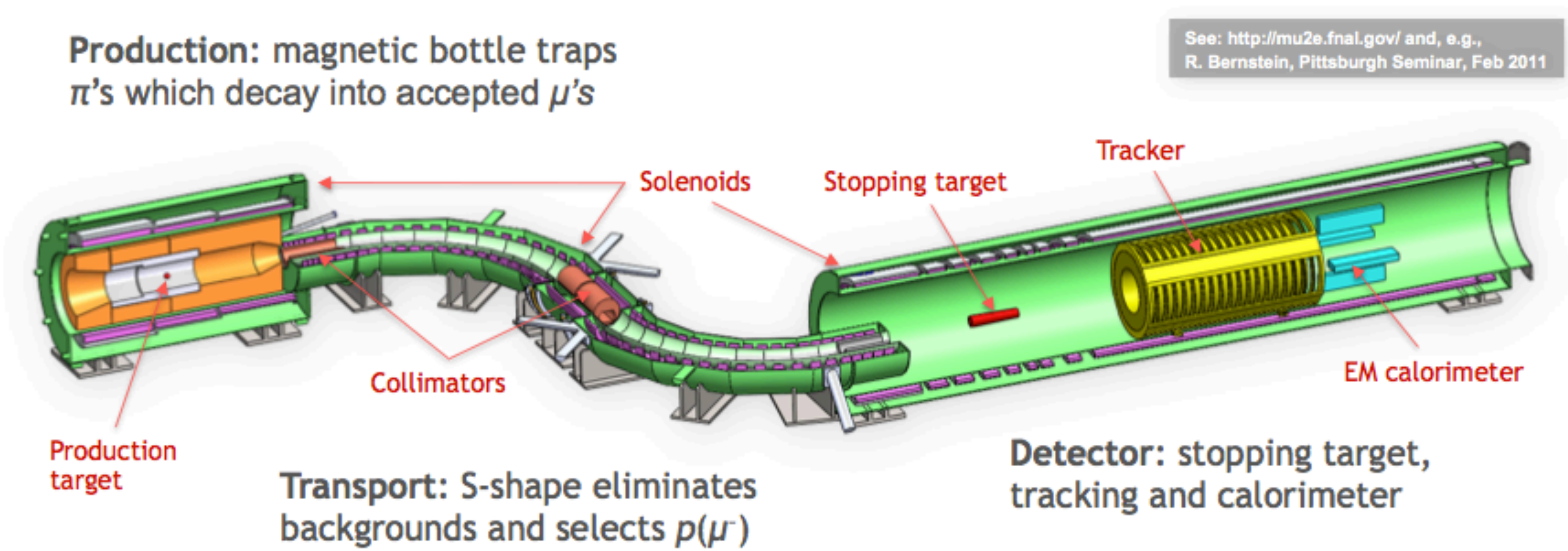
Thank you

Back-up slides

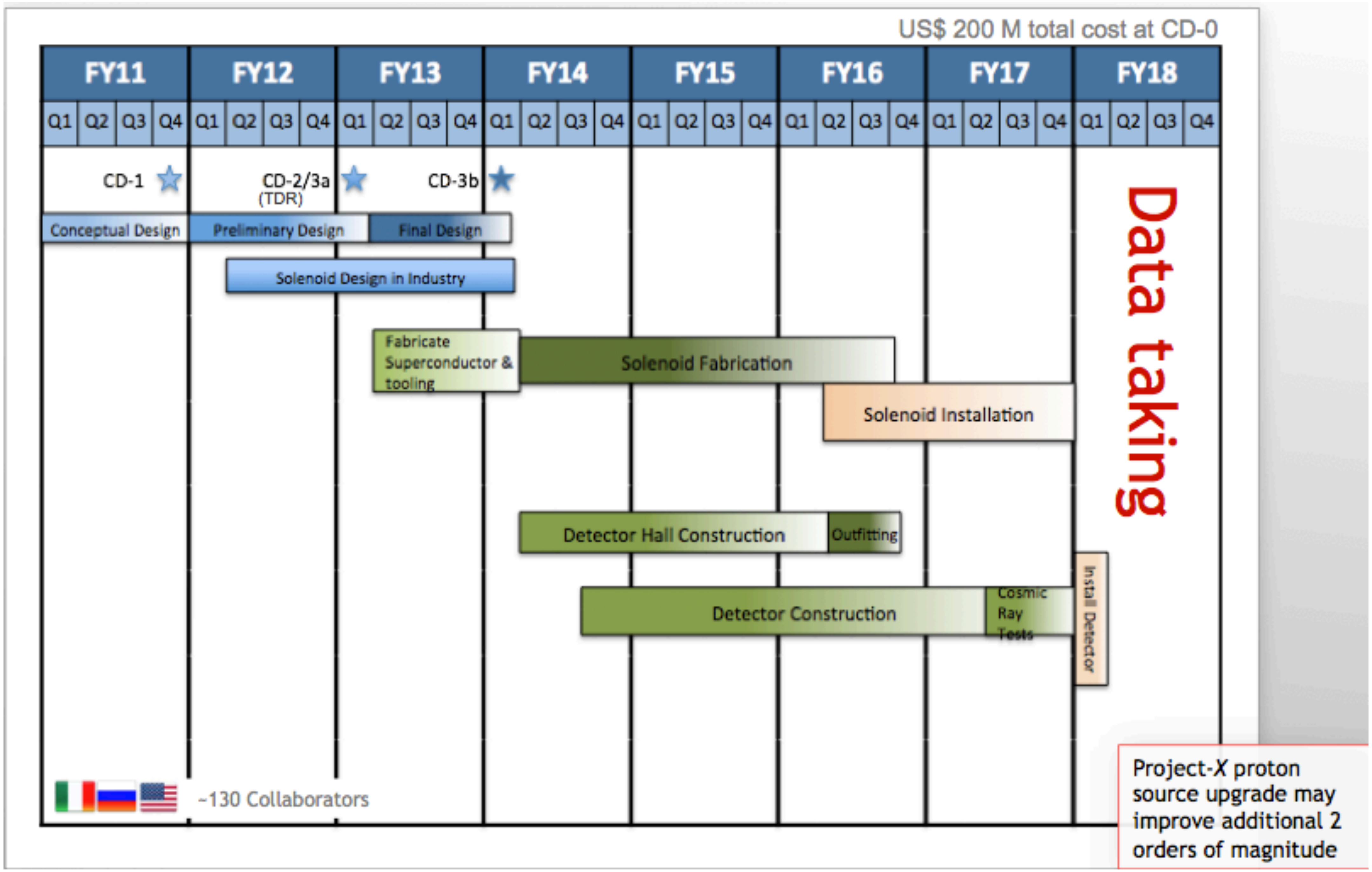
Mu2e @ FNAL

- S-shaped
- CD1 (Conceptual design OK) in Q4 2011
- R(μe) → 10^{-16} down to 10^{-18} with ProjectX
- Data taking starts in 2017





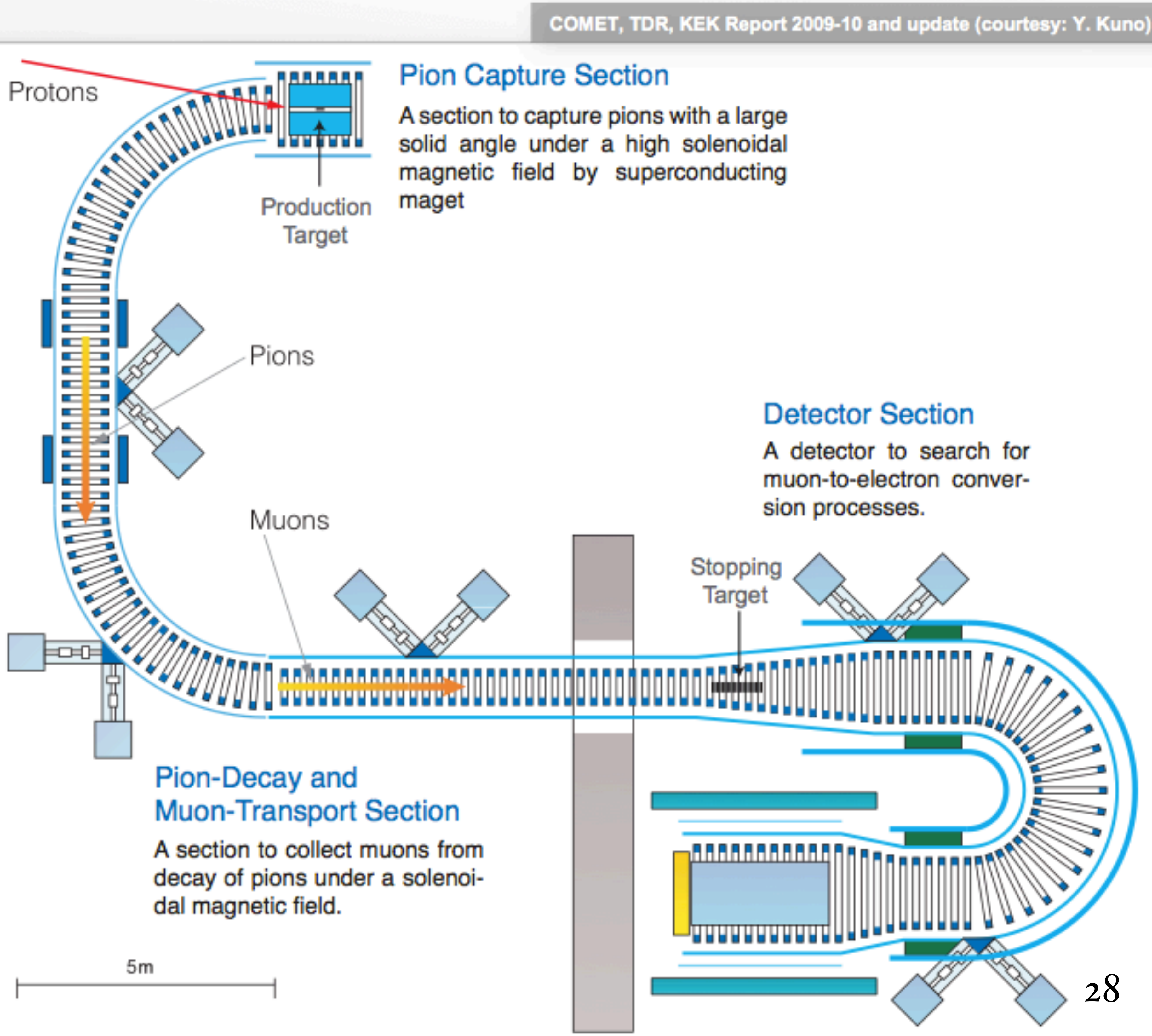
Mu2e @ FNAL schedule



J-parc

Similar design features as Mu2e:

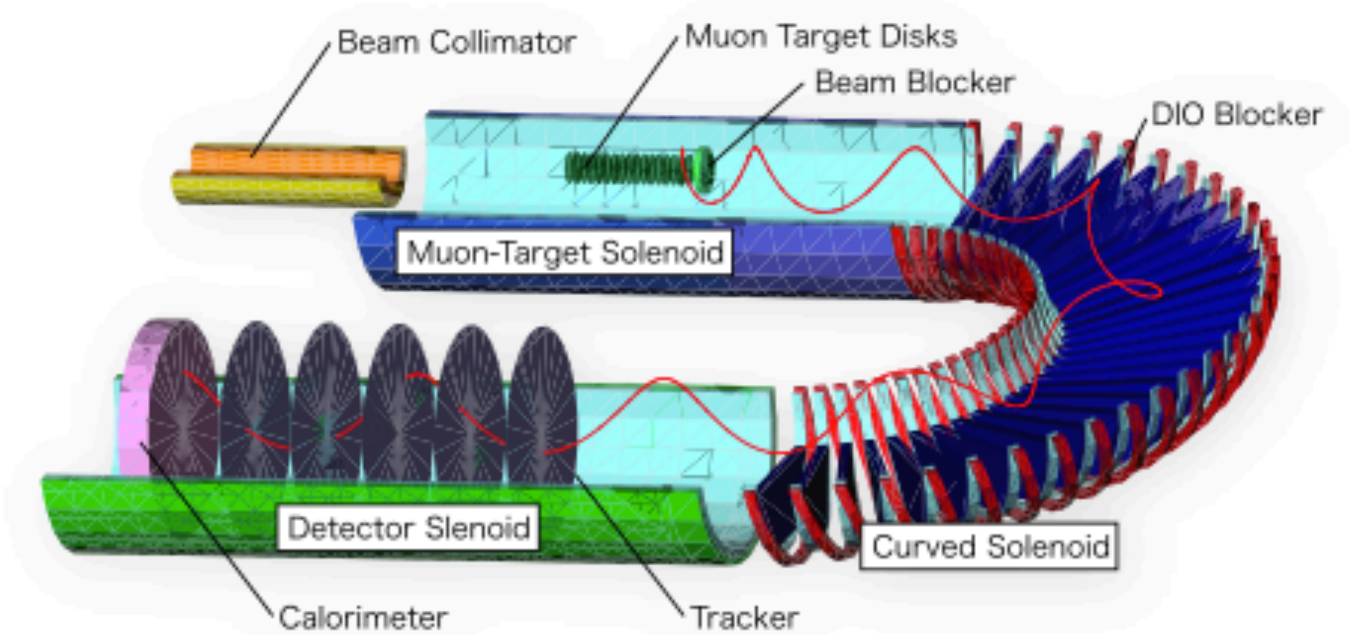
- Sensitivity: $R_{\mu e}$ ~ 3×10^{-17}
- **Pulsed proton beam**
- **Efficient π collection around proton target**
  (~850 protons with 8 GeV required to produce 1 muon)
- Curved solenoids for muon charge and momentum selection
- C-shaped (as opposed to S-shaped) transport for better p_μ selection
- C-shaped detector section eliminates low-E DIO e and protons



COMET schedule

Schedule:

- Stage-1 approval obtained in 2009 (CDR)
- TDR expected end of 2011
- Superconducting magnet design biggest challenge
- Pion capture tested with MuSIC (Osaka)
- Request funding in 2014/2015
- Data taking in 2018
- Upgrade project to PRISM (with muon storage ring) expecting sensitivity of $R_{\mu e}$ ~ 3×10^{-19}



Future g–2

Final E989 proposall: http://gm2.fnal.gov/public_docs/proposals/Proposal-APR5-Final.pdf

Proposal for new experiment E989 at Fermilab with precision target of $1.6 \cdot 10^{-10}$ (factor ~20 increase in statistics)

Fermilab E989
http://gm2.fnal.gov

- Relocate E821 (BNL) storage ring to Fermilab (12 T weight)
- Continue "magic-gamma" technique
- Interlink several proton rings at Fermilab
  - Higher proton rate, less protons per bunch than at BNL
  - 900 m pion decay line (BNL: 80 m) → less pion "flash" at muon ring injection
  - Zero-degree muons → 5—10 times larger muon yield per proton as BNL
  - 5—10 times as many muons stored per hour as BNL
- Improved detectors against signal pileup, new electronics, better shimming to reduce *B*-field variations, more improvements over BNL

  → Expect ~2.5 (3) times reduced systematic error on *B*-field (ω_a)
- Can run parasitic to main injector experiments (e.g. NOVA)
- Experiment approved Jan 2011

Summary of performance

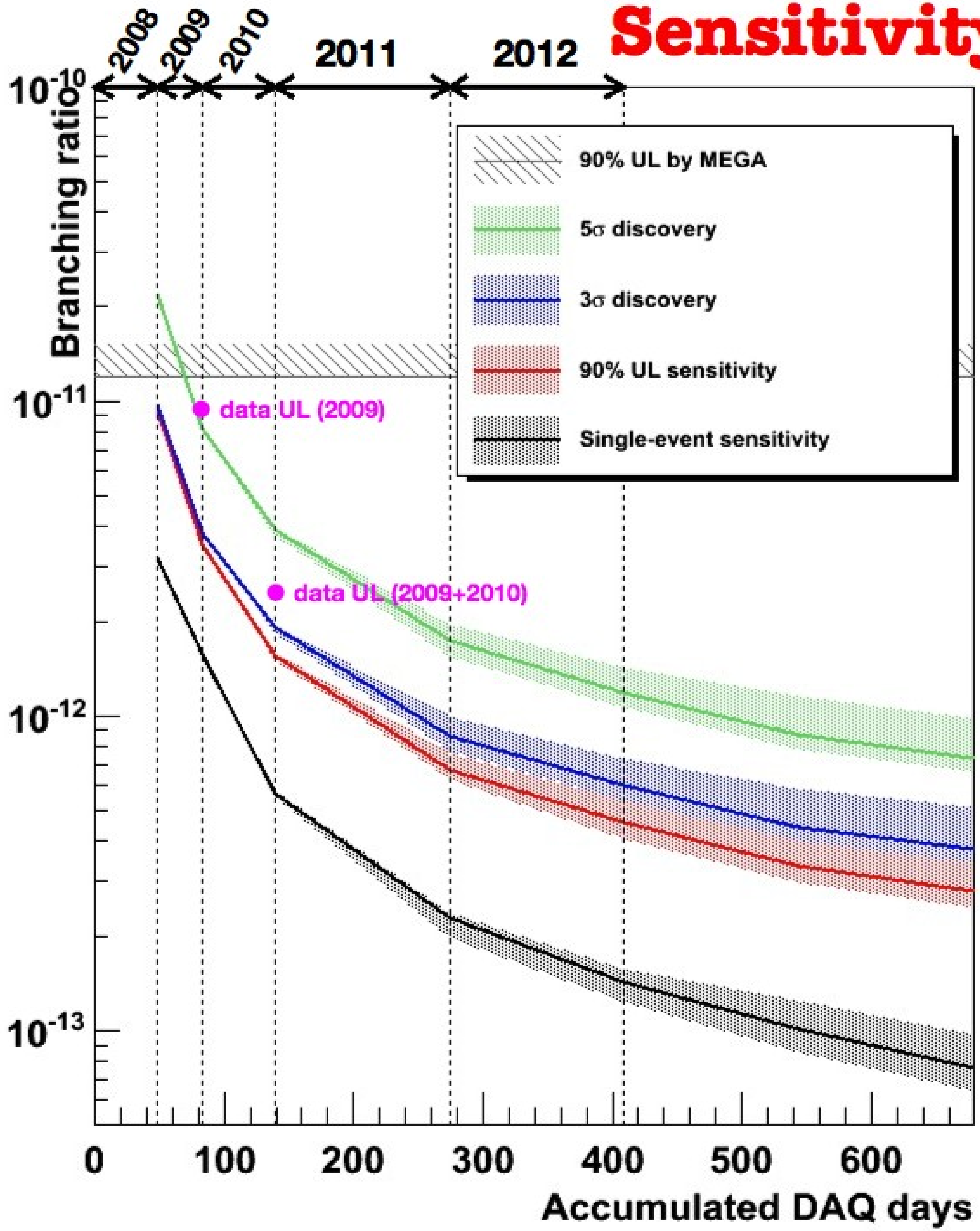
MEG
Mu-E-Gamma Collaboration

	2009	2010
γ energy	1.9%($w>2$cm) 2.4%(($w<2$cm)	1.9%($w>2$cm) 2.4%(($w<2$cm)
γ timing	96ps	67ps
γ position	5mm(u,v), 6mm(w)	5mm(u,v), 6mm(w)
γ efficiency †	58%	59%
e^+ timing	107ps	107ps
e^+ energy	0.31MeV (core 80%)	0.32MeV (core 79%)
e^+ angle (θ)	9.4mrad	11.0mrad
e^+ angle (ϕ)	6.7mrad	7.2mrad
e^+ vertex (Z/Y)	1.5mm/1.1mm(core)	2.0mm/1.1mm(core)
e^+ efficiency	40%	34%
$e^+-\gamma$ timing	146ps	122ps
Trigger efficiency	91%	92%
$e^+-\gamma$ angle (θ)	14.5mrad	17.1mrad
$e^+-\gamma$ angle (ϕ)	13.1mrad	14.0mrad
Stopping μ rate	$2.9\times10^{7}s^{-1}$	$2.9\times10^{7}s^{-1}$
DAQ time/ Real time	35days/43days	56days/67days
Total μ stops on target	6.5×10^{13}	1.1×10^{14}

e^+ tracking slightly worse in 2010 due to noise problem

improvement by waveform digitizer upgrade in 2010

Sensitivity Prospects



Systematic uncertainties

Systematic effects are taken into account in the calculation of confidence interval by profiling on (N_{RD},N_{BG}) and by fluctuating PDFs according to the uncertainty values

- all the results shown so far already contain systematic effect.

Size of effect of systematic uncertainty is in total 2% on the UL.

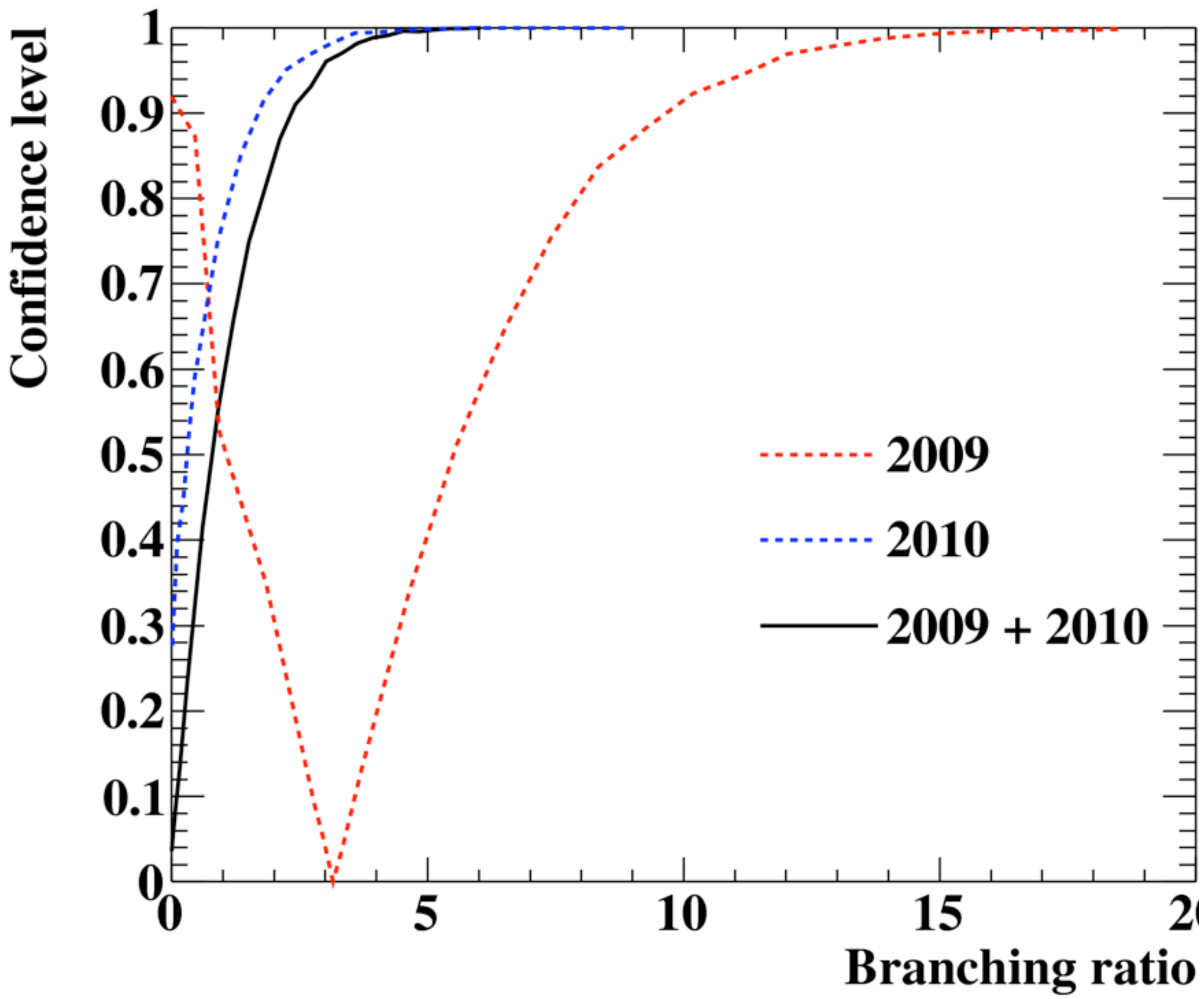
- $2.3\times10^{-12} \rightarrow 2.4\times10^{-12}$ for combined result

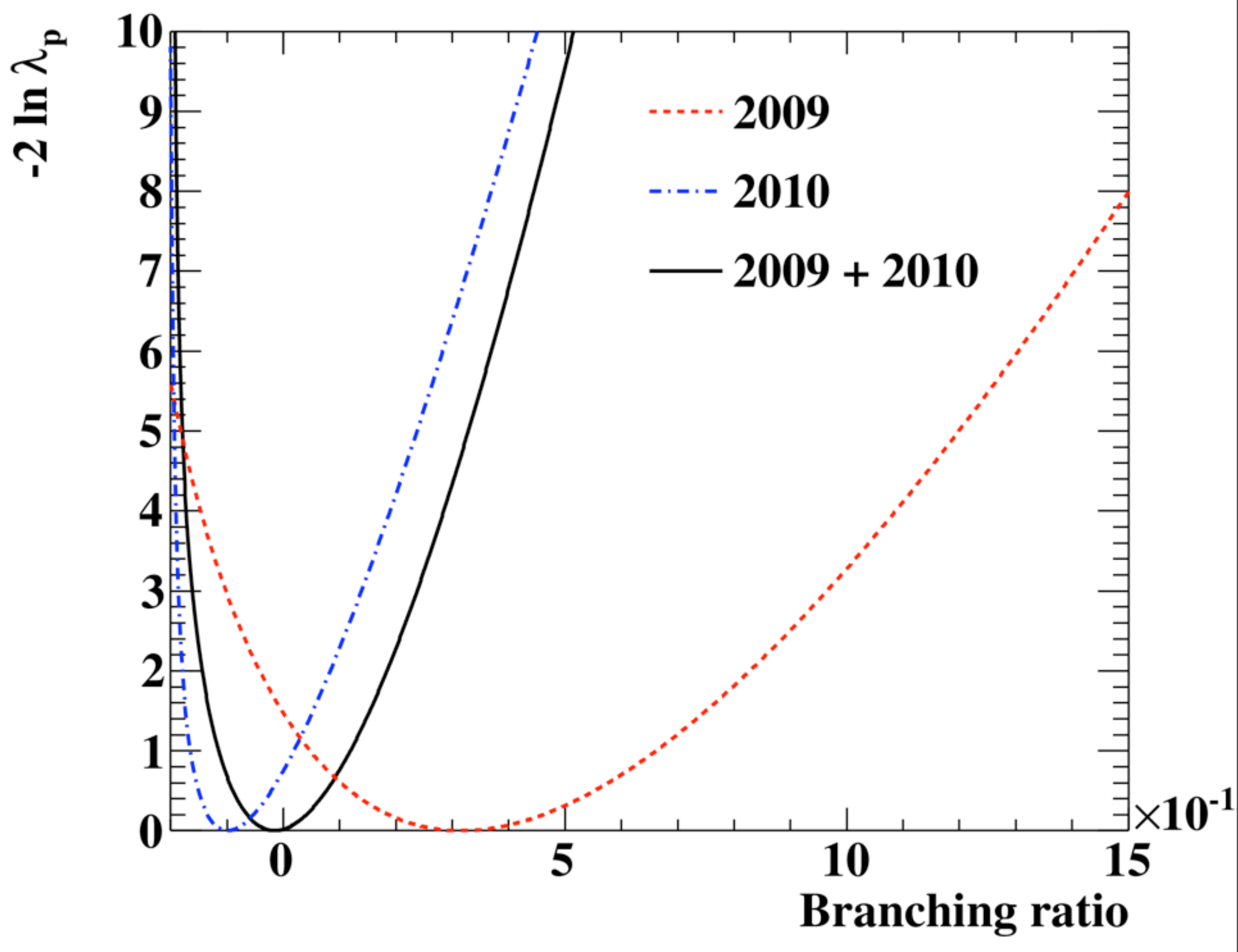
Contribution of each item was studied with toy-experiment by comparing the result with nominal PDF and that with fluctuated one.

Relative contributions on UL

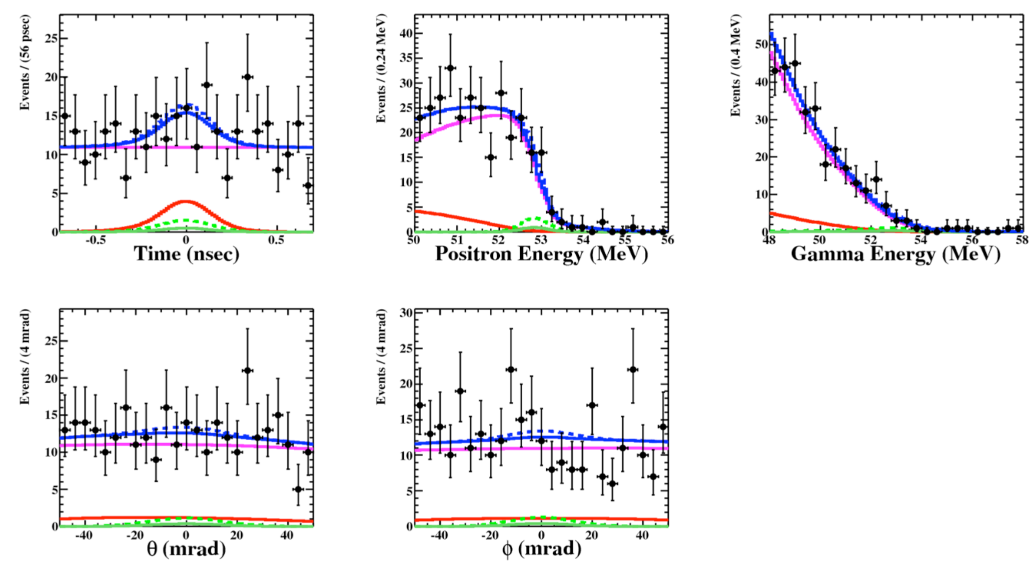
Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.16
Normalization	0.13
E_γ scale	0.07
E_e bias, core and tail	0.06
$t_{e\gamma}$ center	0.06
E_γ BG shape	0.04
E_γ signal shape	0.03
Positron angle resolutions (θ_e, ϕ_e, z_e, y_e)	0.02
γ angle resolution (u_γ, v_γ, w_γ)	0.02
E_e BG shape	0.02
E_e signal shape	0.01

FC Profile curves

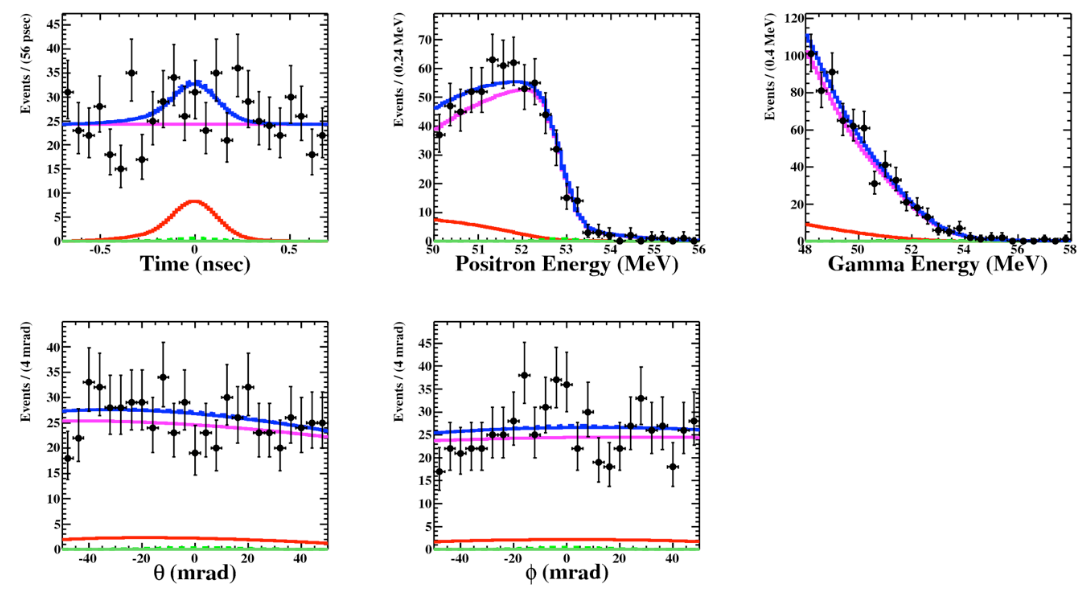


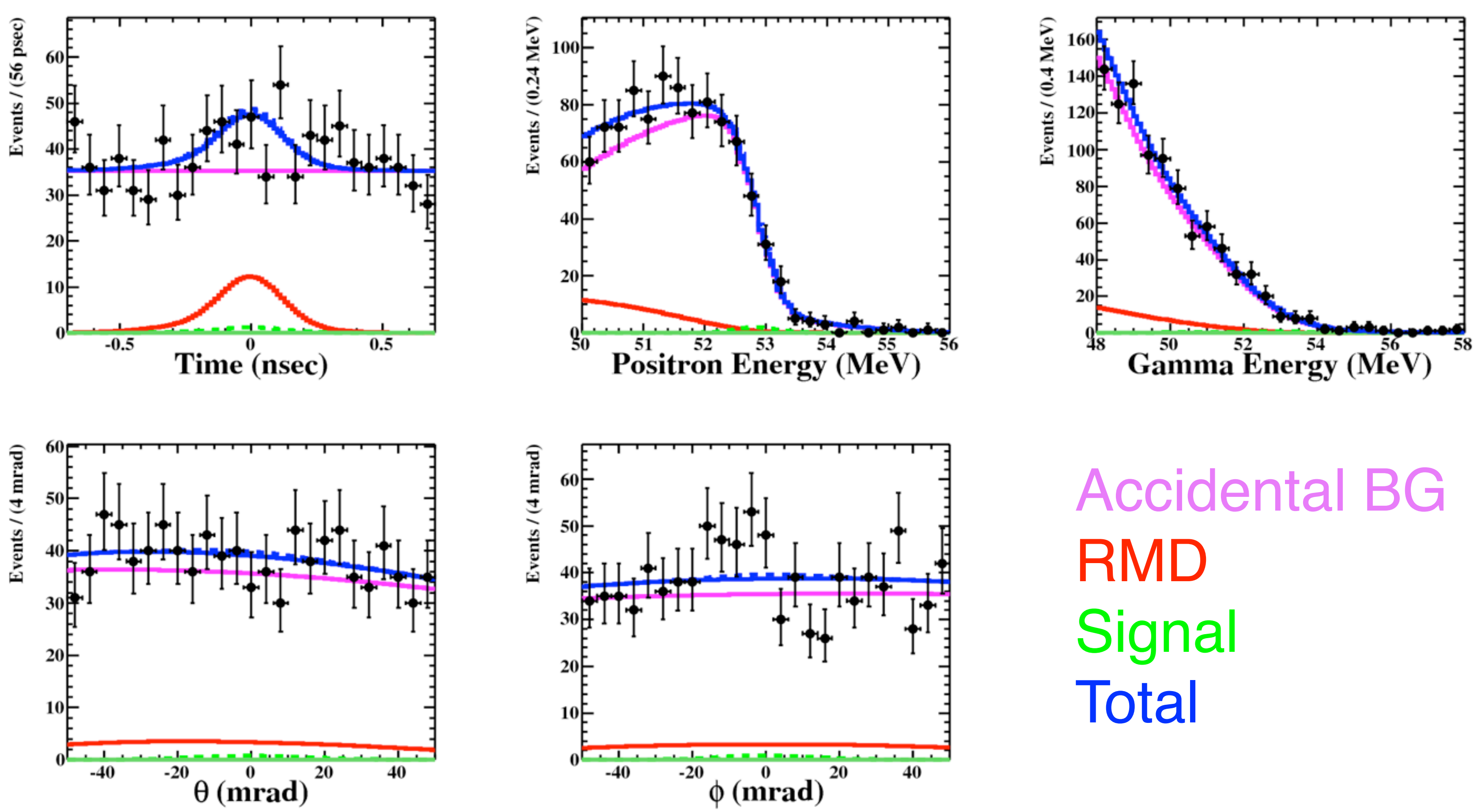


2009



2010



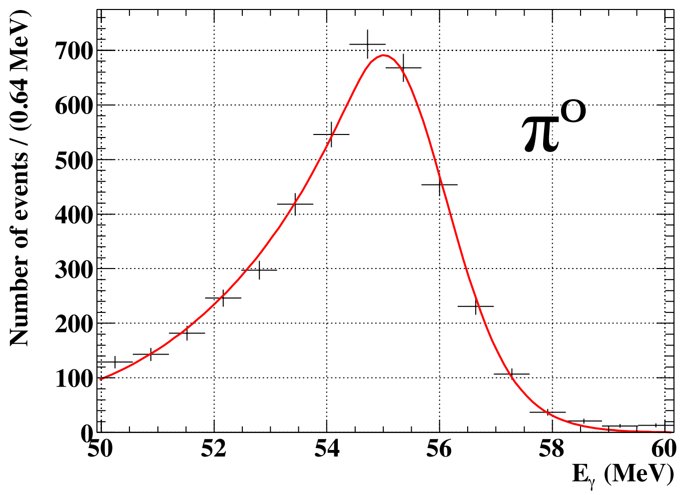


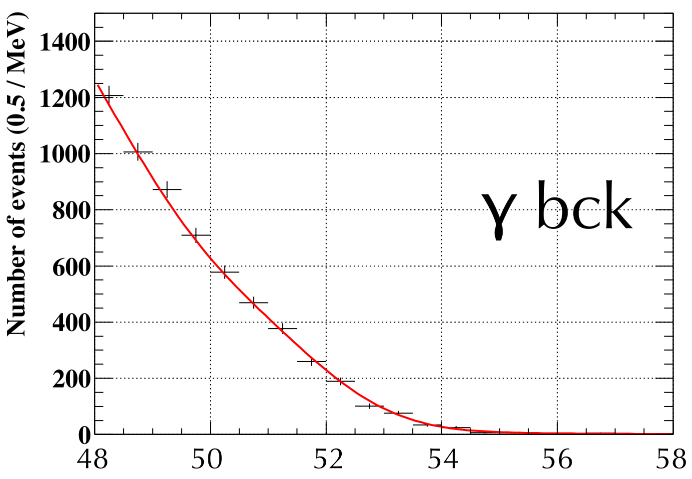
Accidental BG
RMD
Signal
Total

Dashed lines : 90% C.L. UL of Nsig

Pdfs and resolutions

E_γ

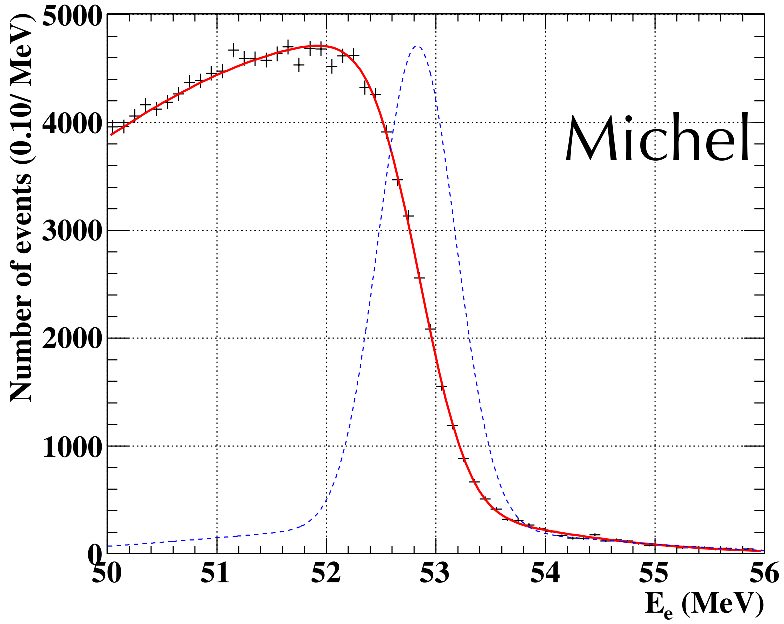




- Average upper tail for deep conversions
  - σ_R = (2.1 ± 0.15) %
- Systematic uncertainty on energy scale < 0.6%

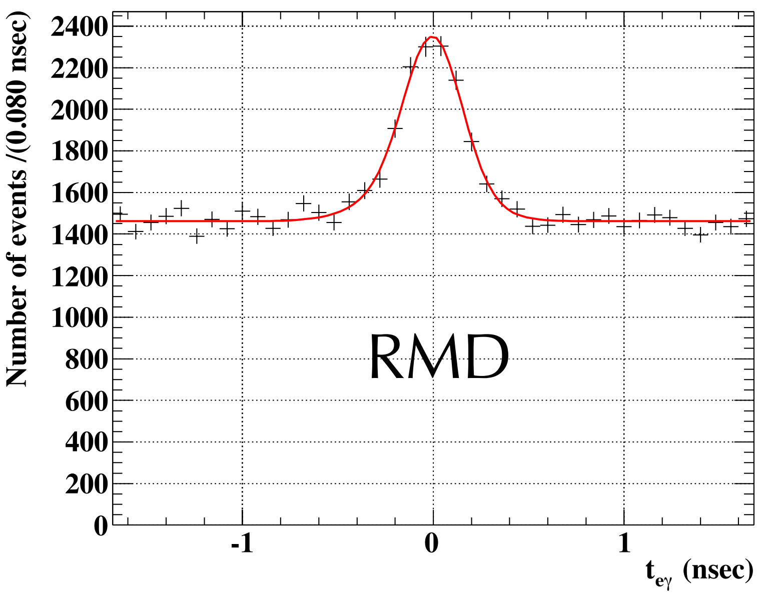
E_{e^+}

- 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

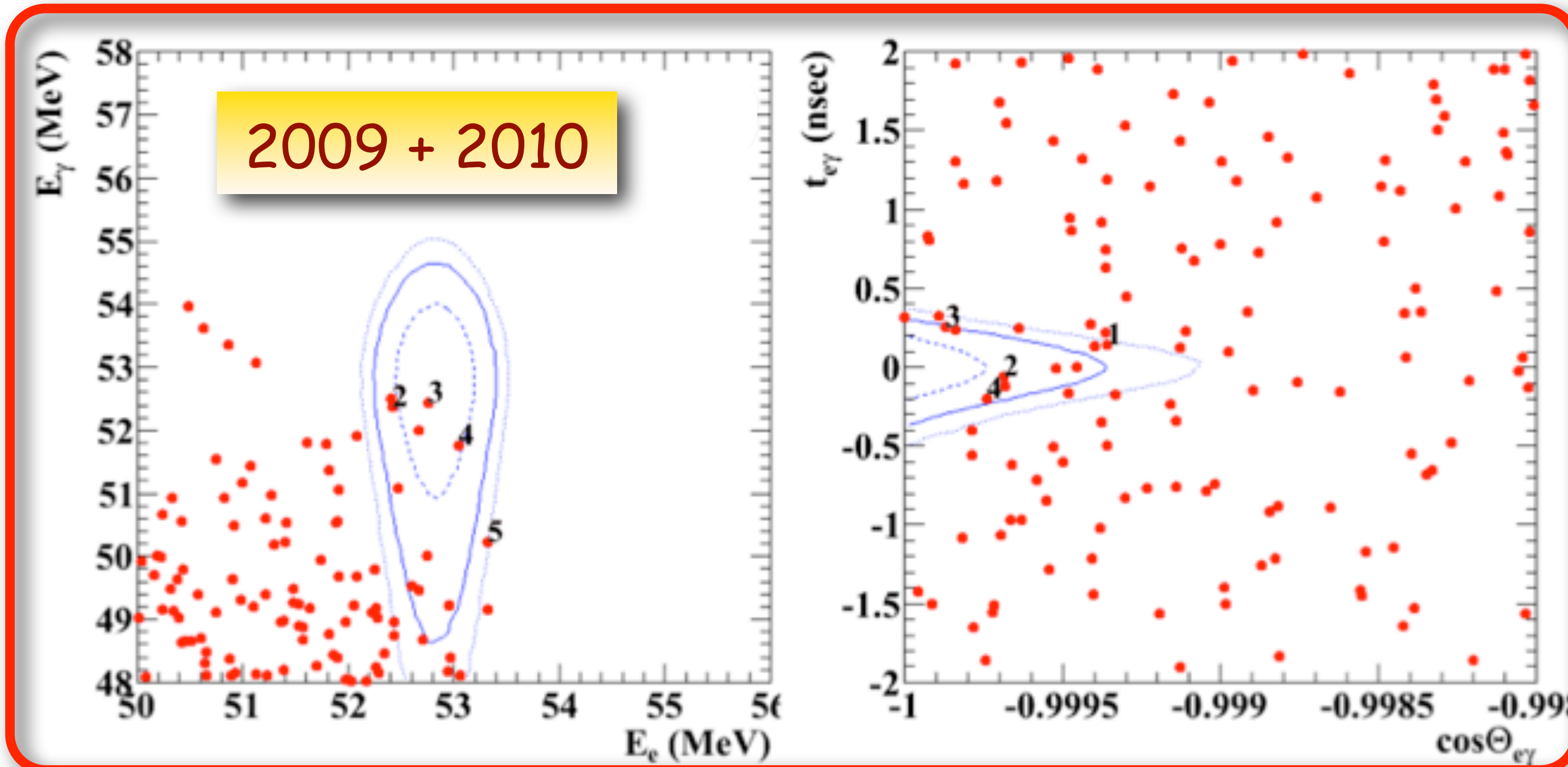


- Overall angular resolution combining
  - XEC+DCH+target
    - $\sigma(\varphi)$ = 12.7 mrad (core)
    - $\sigma(\vartheta)$ = 14.7 mrad

$t_{e\gamma}$

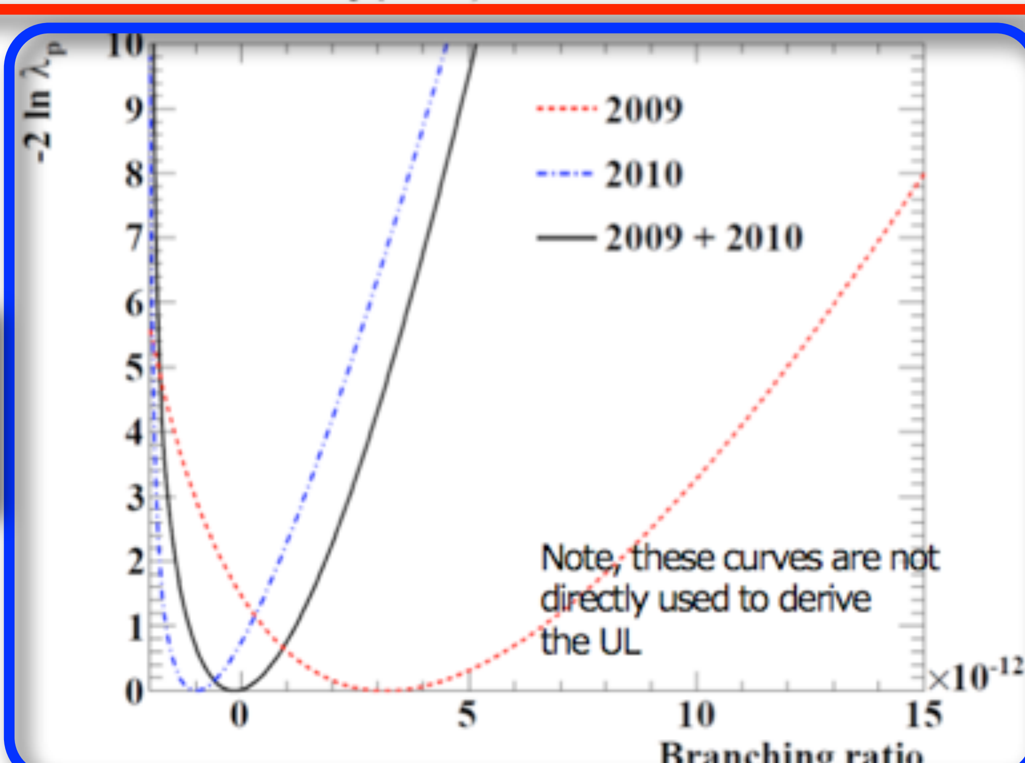


- 40 MeV < E_γ < 48 MeV
- σ_t is corrected for a small energy-dependence
  - (142 ± 15) ps
  - stable within 15 ps along the run
- MEGA had on RMD
  - 700 ps resolution



	expected	best fit
N_{sig}		-0.5
N_{RMD}	79.4 ± 7.9	76 ± 12
N_{bkg}	881.7 ± 15.1	882 ± 22

Profile Likelihood



UL @ 90% CL

BR < 2.4×10^{-12}

Data set	$\mathcal{B}_{fit}$	LL	UL
2009	3.2×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-13}	–	1.7×10^{-12}
2009 + 2010	-1.5×10^{-13}	–	2.4×10^{-12}

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)

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

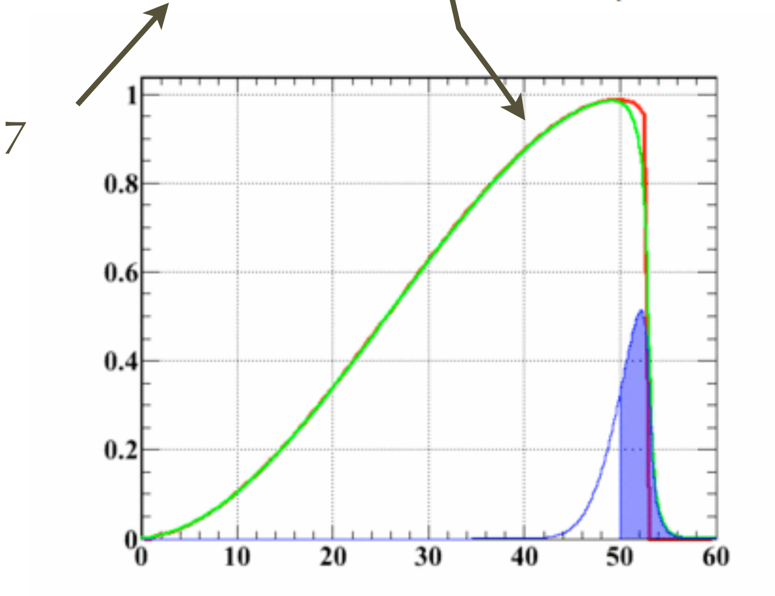
~18k

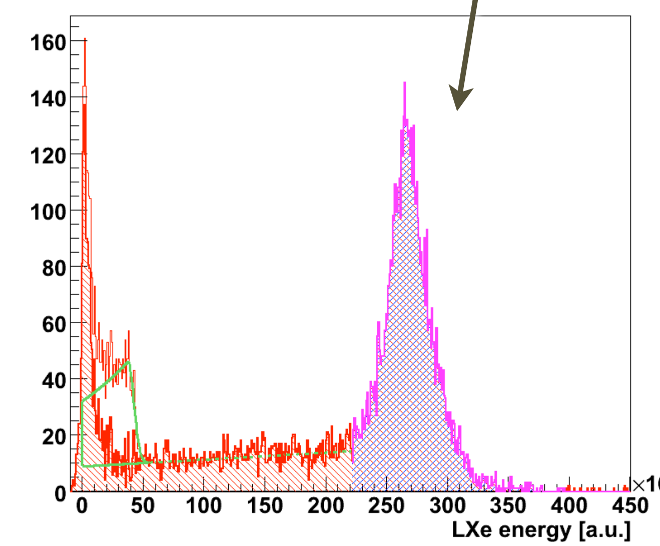
10^7

theory

resolution

acceptance

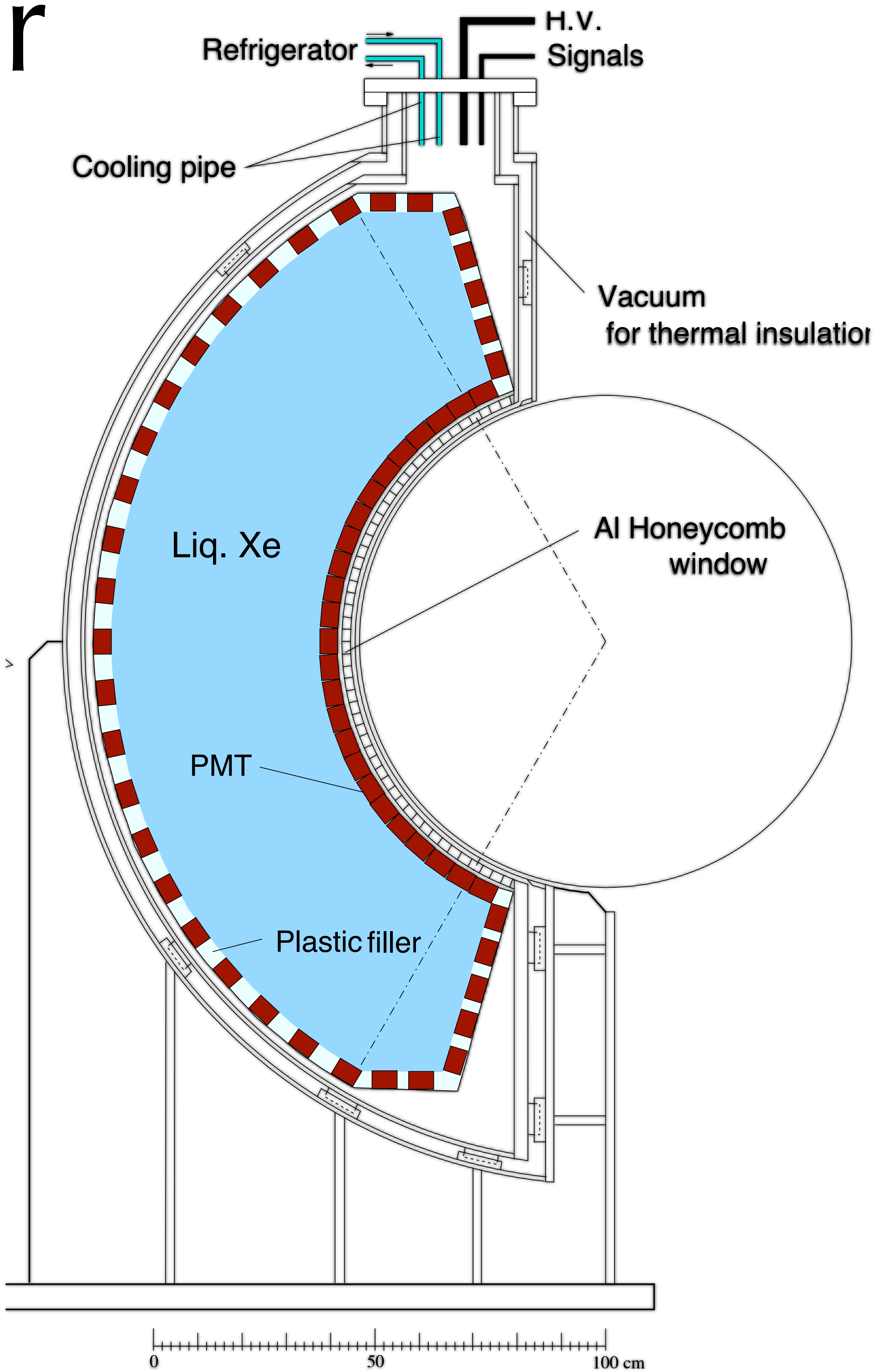




B.R. = $N_{\rm sig}$ x (1.01 ± 0.08) × 10^{-12}

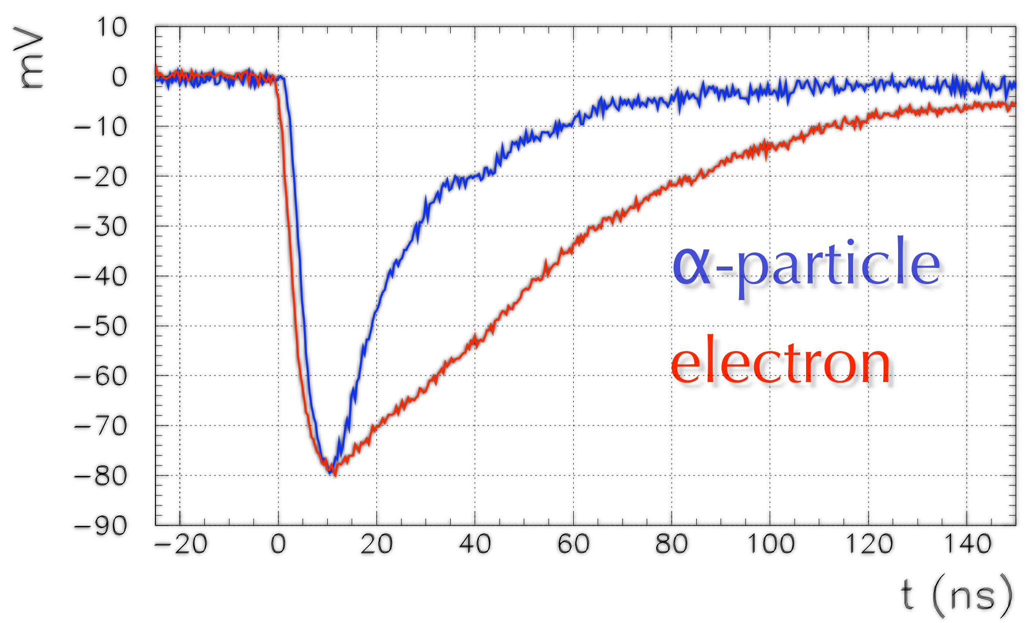
The photon detector

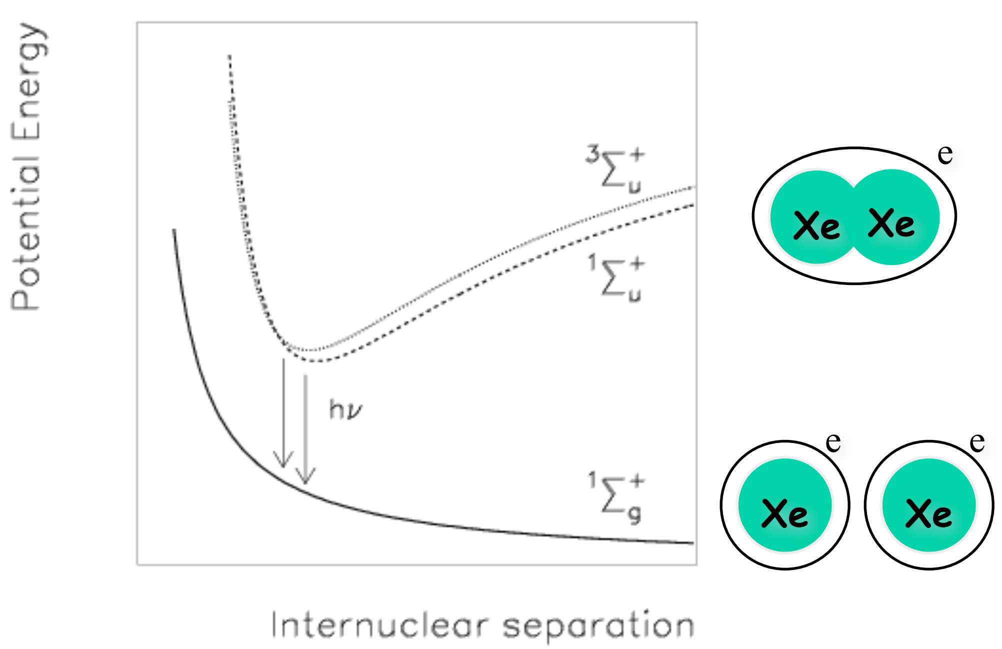
- γ Energy, position, timing
- Homogeneous 0.8 m^3 volume of liquid Xe
    - 10 % solid angle
    - $65 < r < 112$ cm
    - $|\cos\theta| < 0.35$ $|\phi| < 60^o$
- Only scintillation light
- Read by 848 PMT
    - 2″ photo-multiplier tubes
    - Maximum coverage FF (6.2 cm cell)
    - Immersed in liquid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

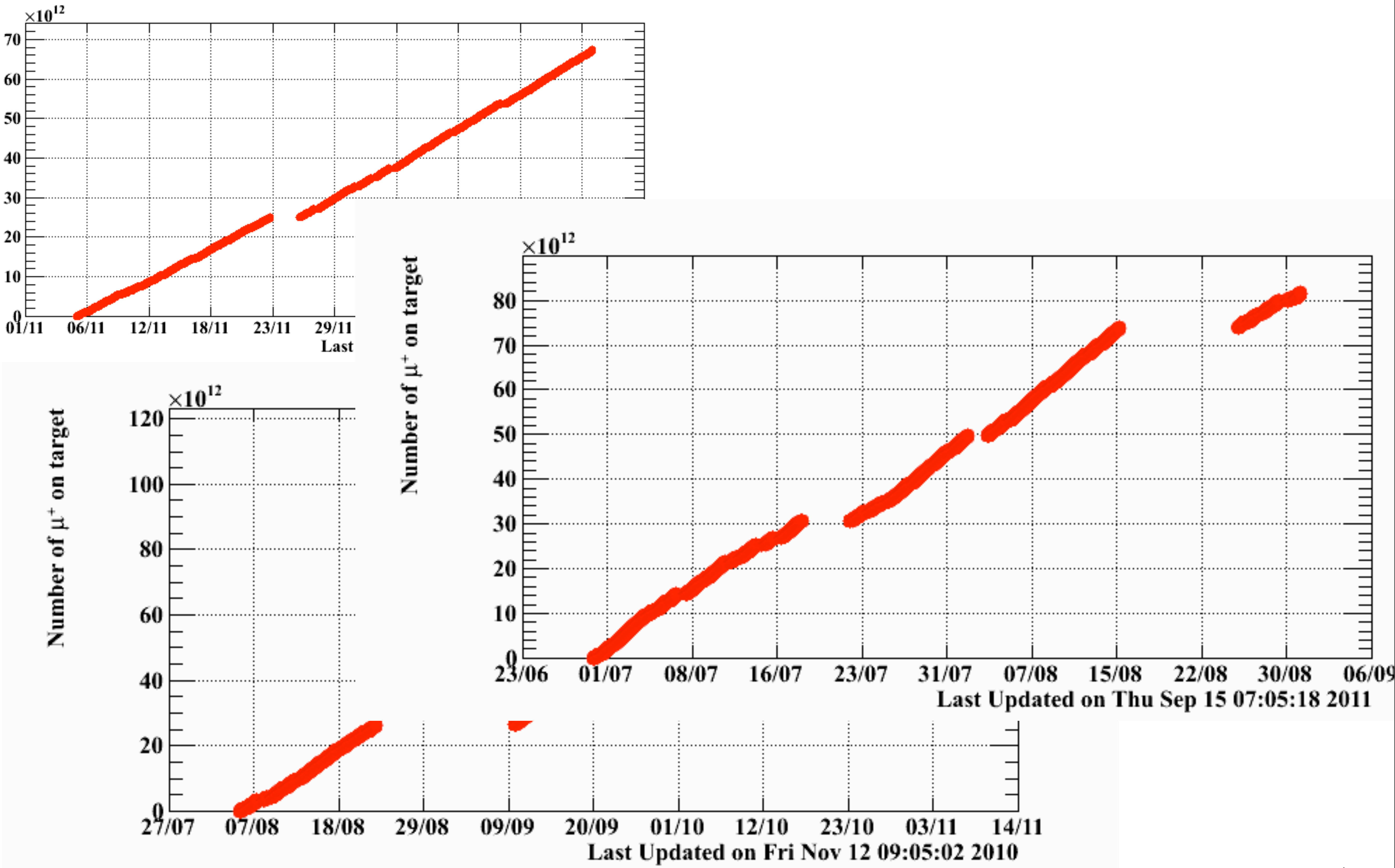


Xe properties

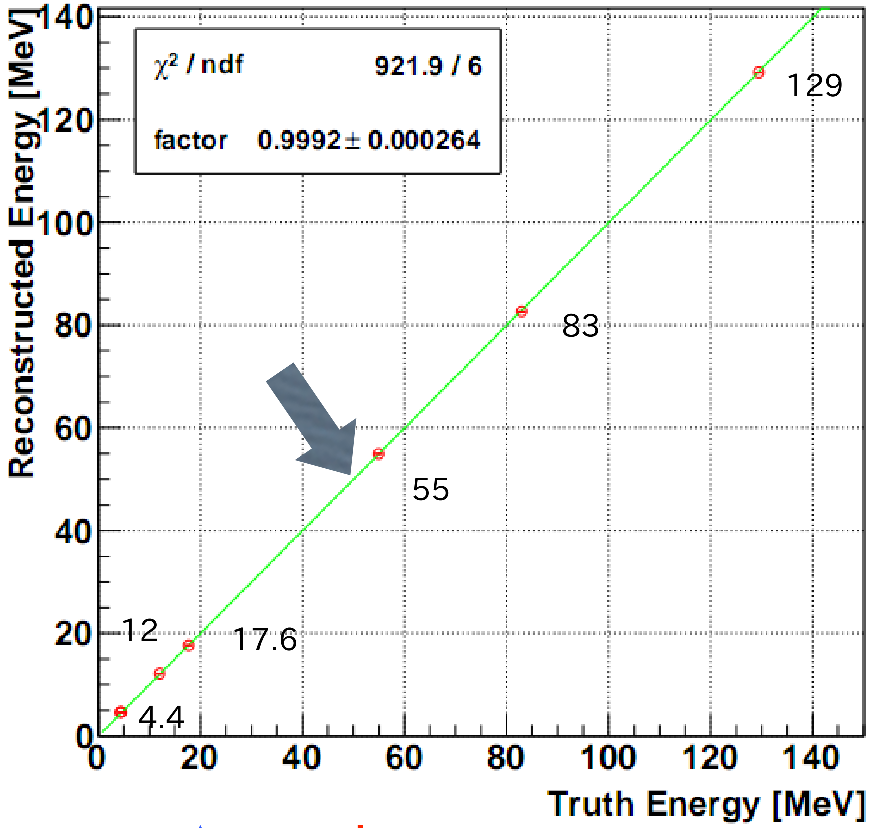
- Liquid Xenon was chosen because of its unique properties among radiation detection active media
- Z=54, ρ=2.95 g/cm^3 (X_0=2.7 cm), R_M=4.1 cm
- High light yield (similar to NaI)
  - 40.000 phe/MeV
- Fast response of the scintillation decay time
  - $\tau_{singlet}$= 4.2 ns
  - $\tau_{triplet}$= 22 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}=∞)





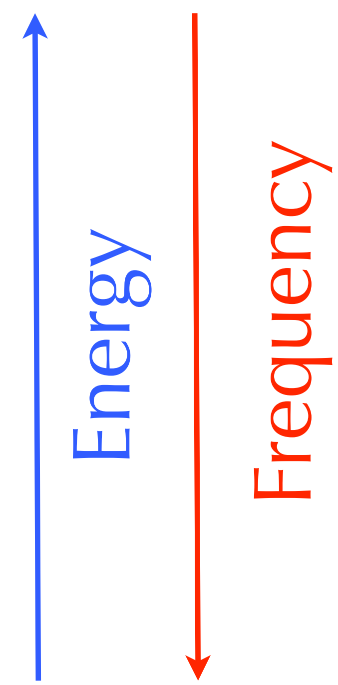

×10¹²
70
60
50
40
30
20
10
0
01/11
06/11
12/11
18/11
23/11
29/11
Last
Number of μ⁺ on target
×10¹²
120
100
80
60
40
20
0
27/07
07/08
18/08
29/08
09/09
20/09
01/10
12/10
23/10
03/11
14/11
Last Updated on Fri Nov 12 09:05:02 2010
Number of μ⁺ on target
×10¹²
80
70
60
50
40
30
20
10
0
23/06
01/07
08/07
16/07
23/07
31/07
07/08
15/08
22/08
30/08
06/09
Last Updated on Thu Sep 15 07:05:18 2011

γ-energy scale calibration

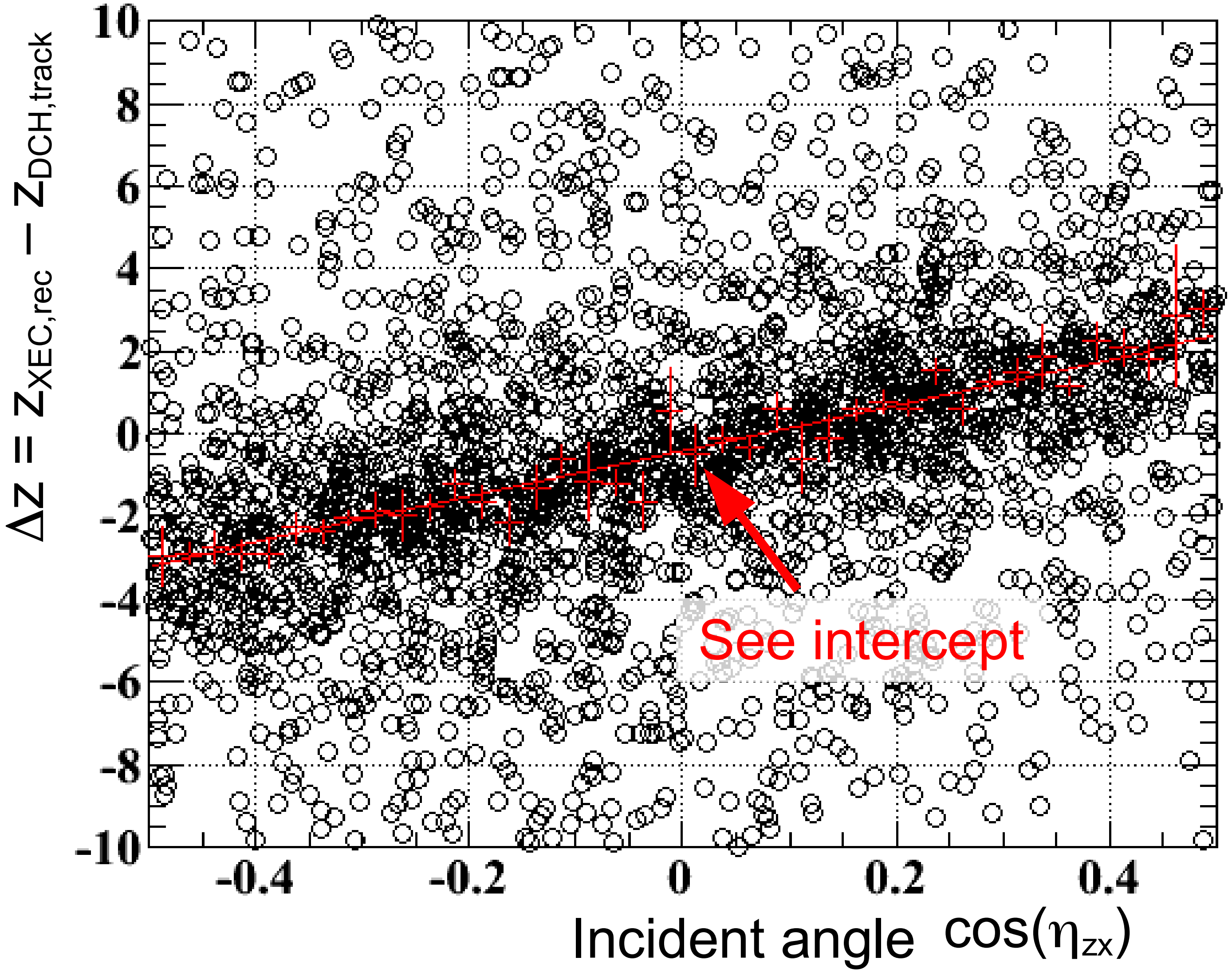


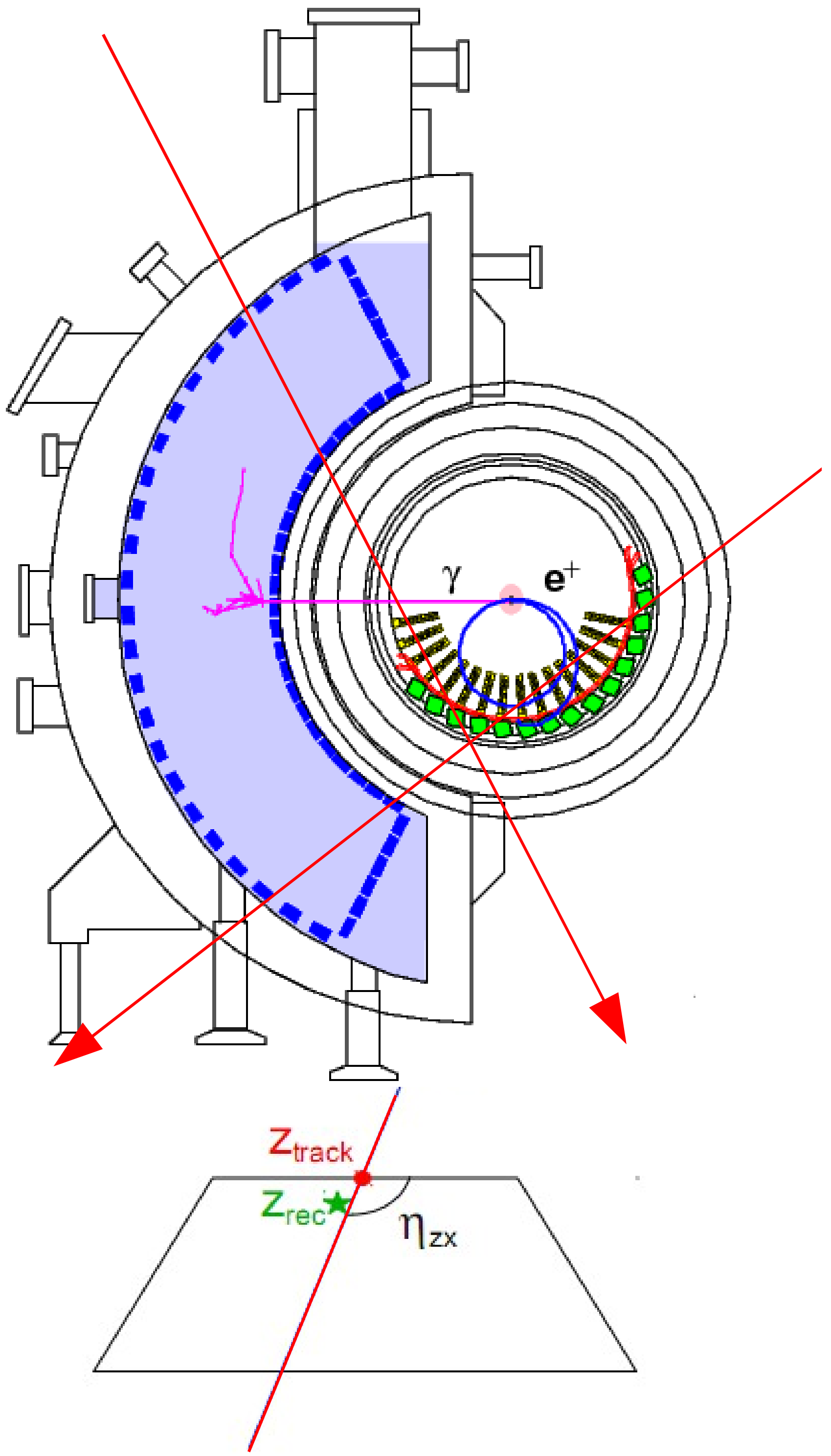
- The precise knowledge of the calorimeter energy scale is crucial for the experiment
- constant check of Xe light yield and purity
  - trigger threshold
  - systematic error on energy scale
- Different calibrations have different time-scales

Process		Energy	Frequency
Charge exchange	$\pi^- p \to \pi^0 n$ $\pi^0 \to \gamma\gamma$	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



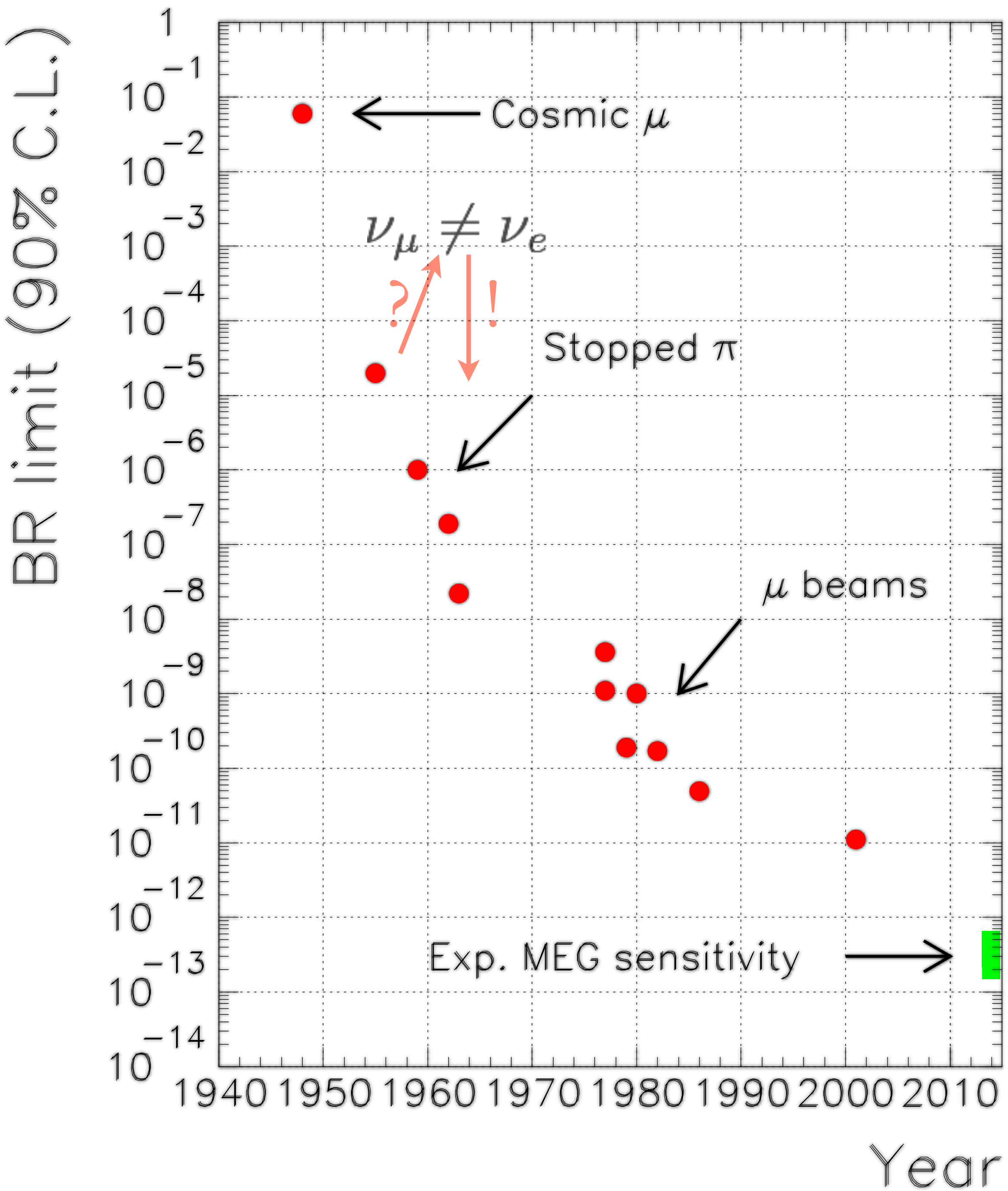
- Alignment of detectors
  - Relative alignment b/w XEC and spectrometer
    - Took CR w/o magnetic field June & November 2010



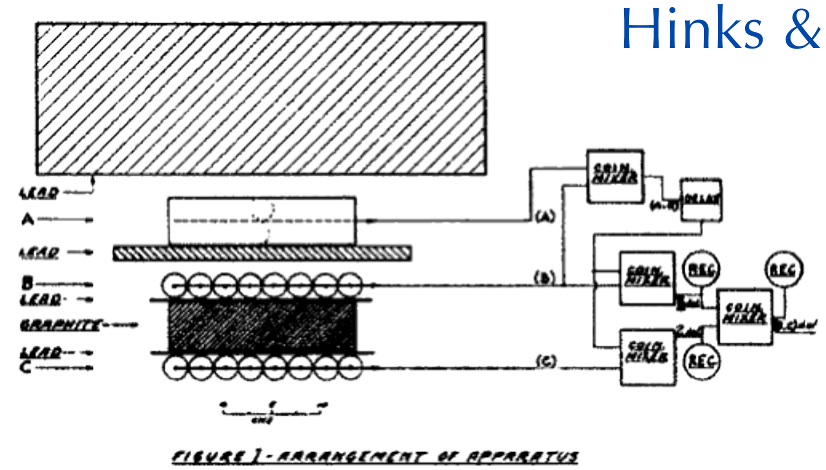


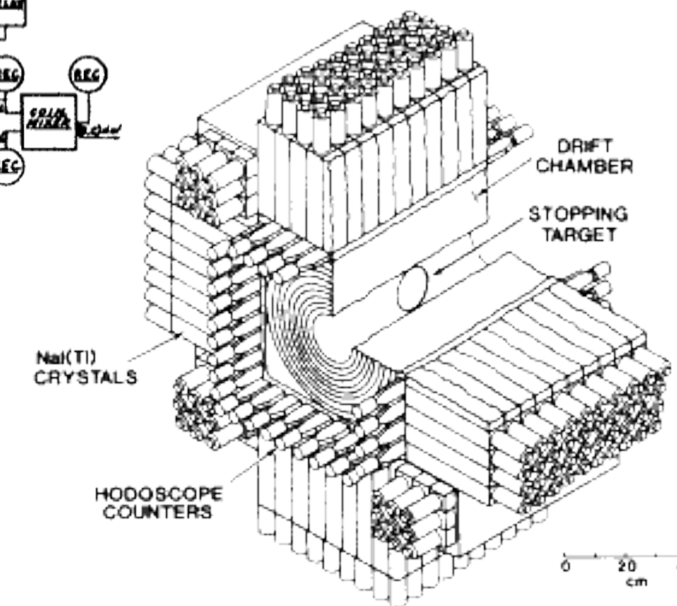
$\Delta z = z_{rec} - z_{track} = -4.3 \pm 0.6$ mm

Historical perspective

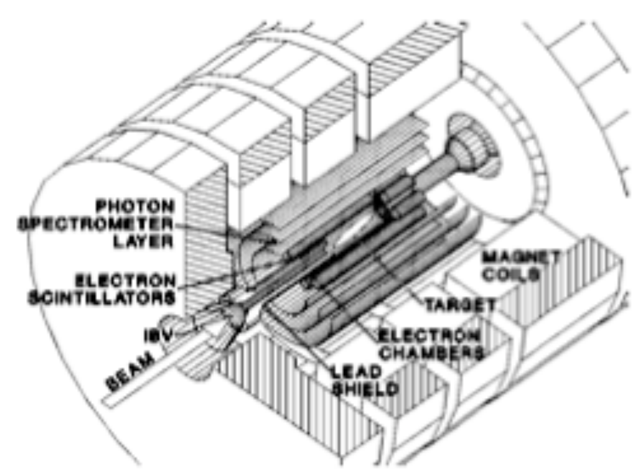


Hinks & Pontecorvo

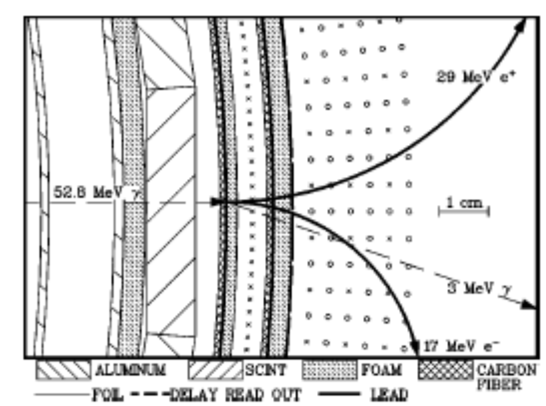




Crystal Box



MEGA

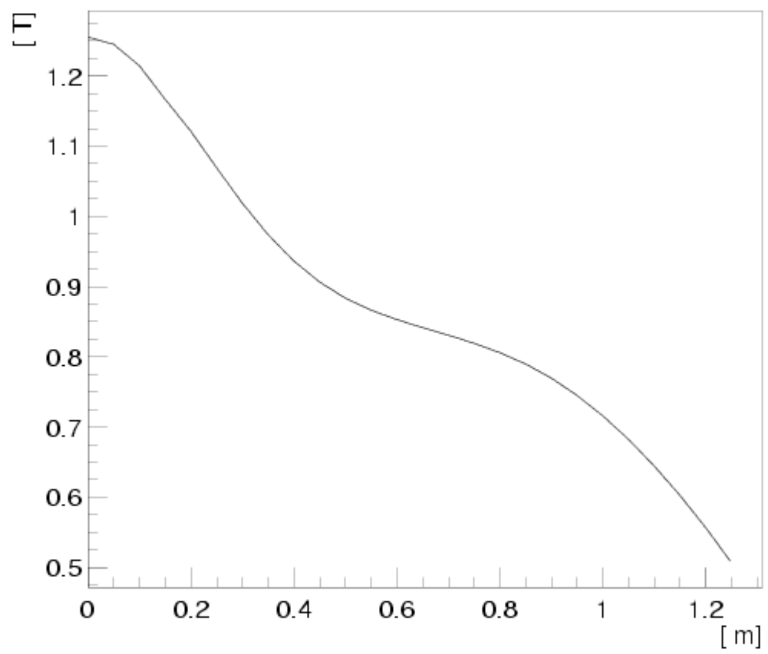


Each improvement linked to the technology either in the beam or in the detector

Always a trade-off between various elements of the detector to achieve the best "sensitivity"

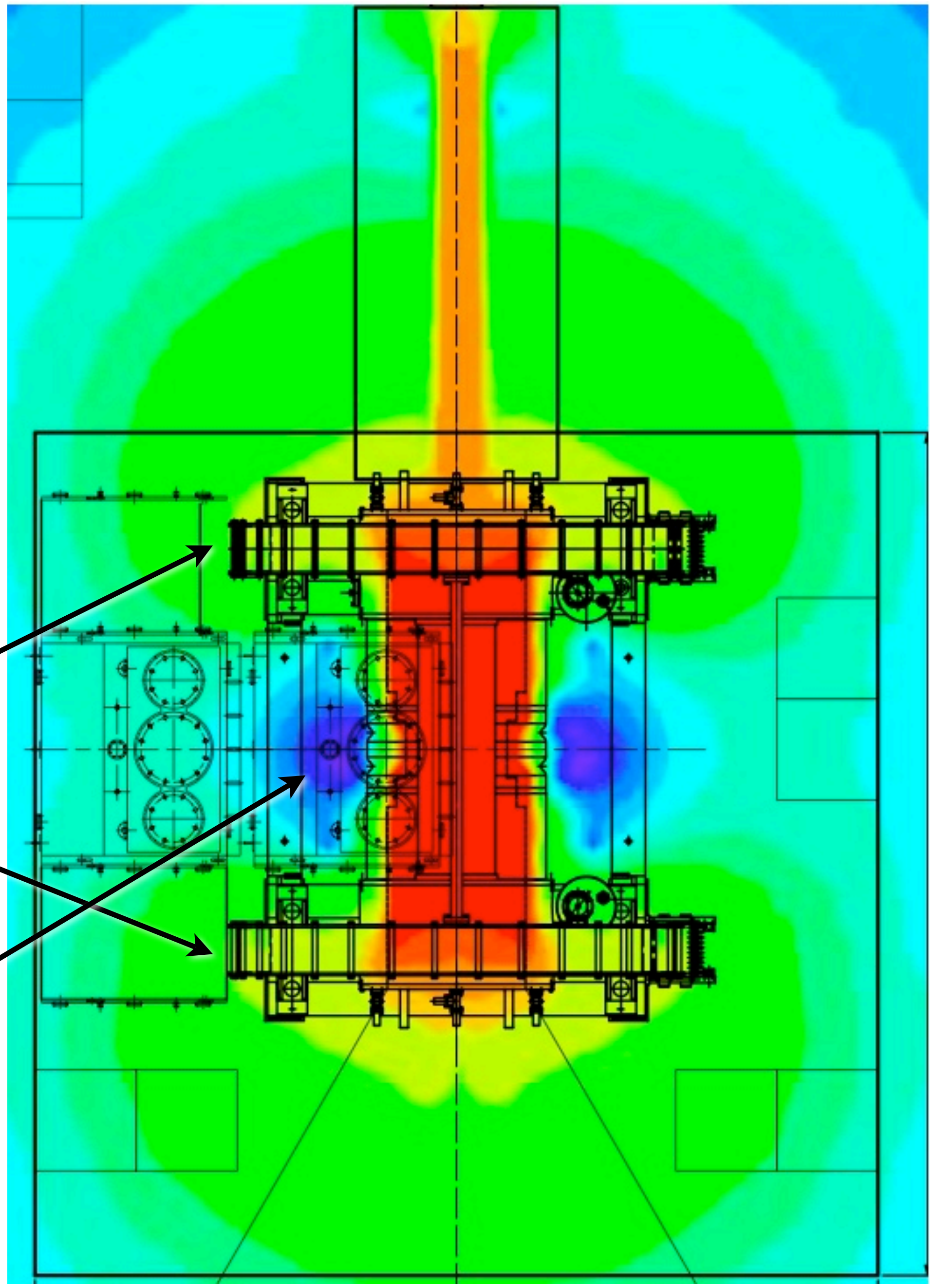
COBRA spectrometer

Non uniform magnetic field decreasing from the center to the periphery

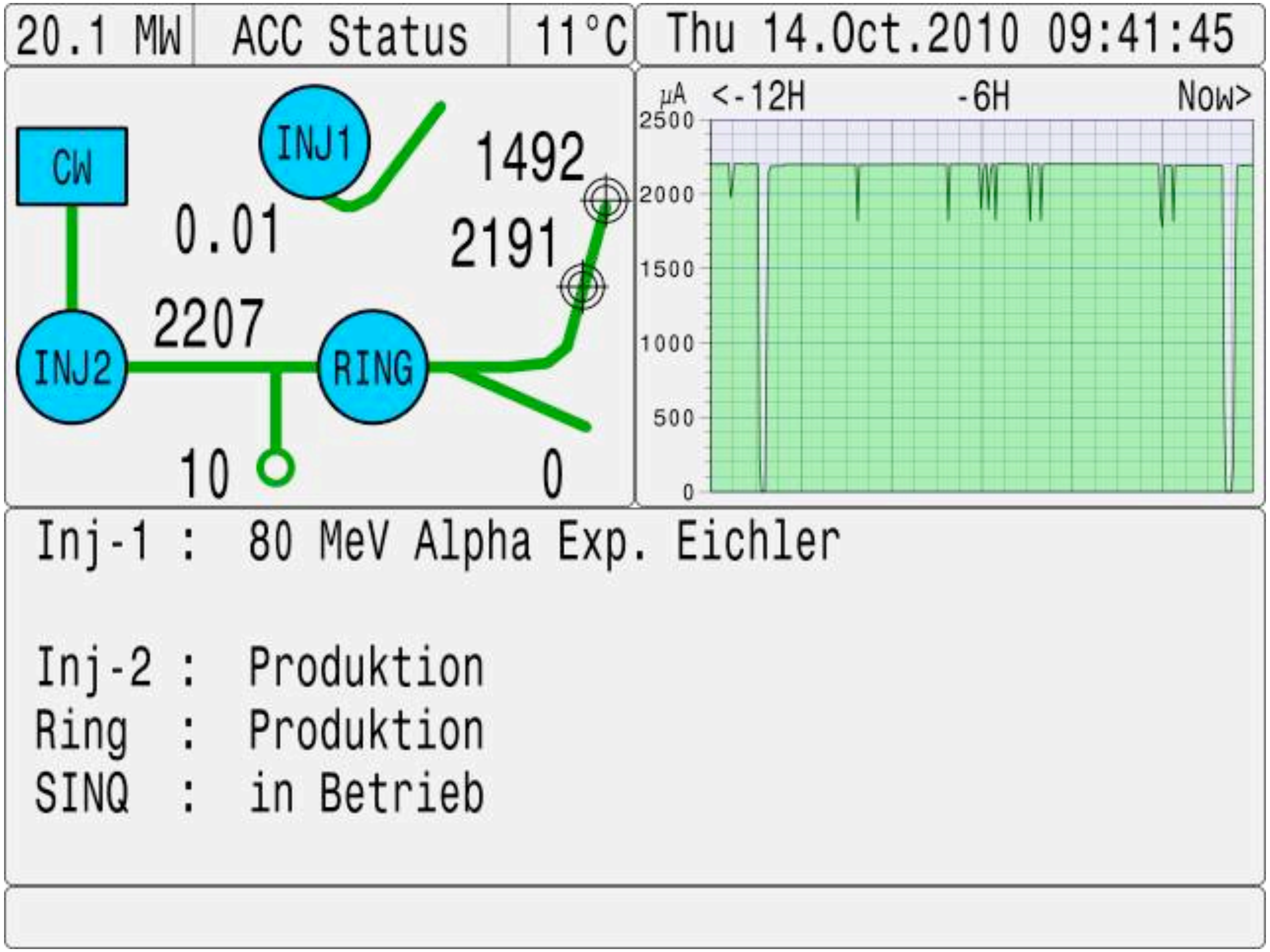


Compensation coil for LXe calorimeter

$$|\vec{B}| < 50\ G$$

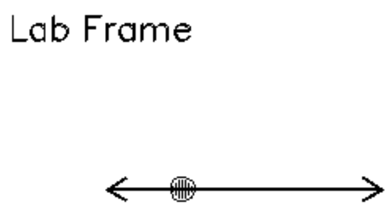


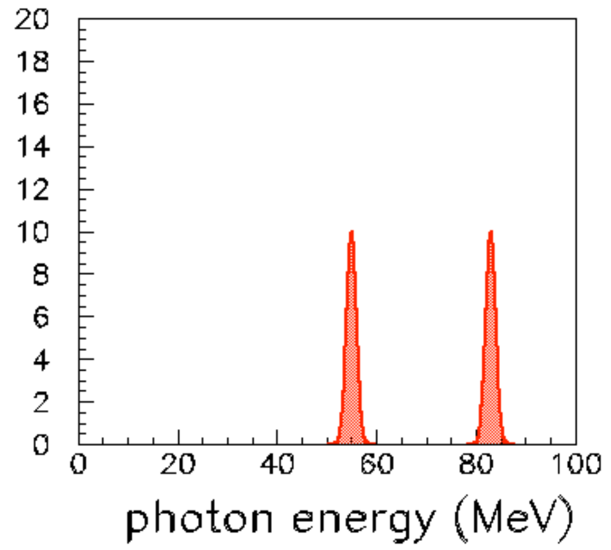
- The superconducting magnet is very thin (0.2 X_0)
- Can be kept at 4 K with GM refrigerators (no usage of liquid helium)


20.1 MW
ACC Status
11°C
Thu 14.Oct.2010 09:41:45
CW
INJ1
INJ2
RING
0.01
1492
2191
2207
10
0
µA
<-12H
-6H
Now>
2500
2000
1500
1000
500
0
Inj-1 : 80 MeV Alpha Exp. Eichler
Inj-2 : Produktion
Ring : Produktion
SINQ : in Betrieb

CEX measurement

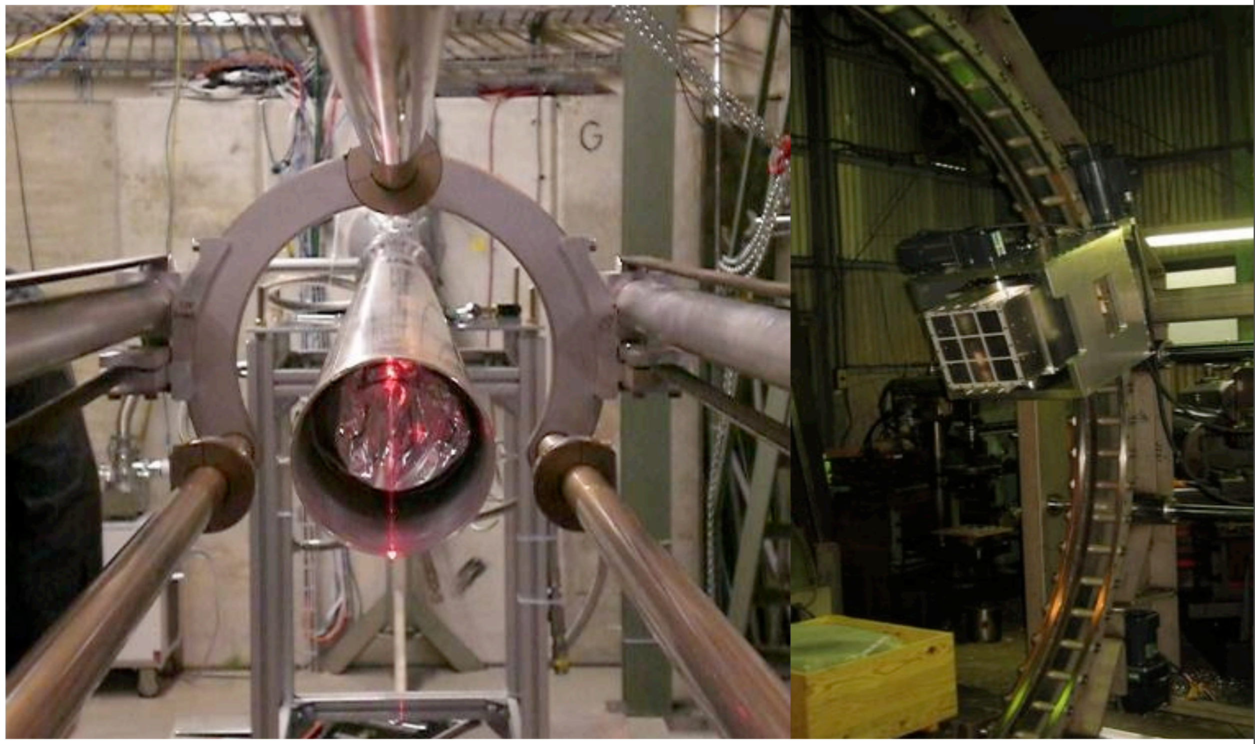
$$\pi^- p \rightarrow \pi^0 n$$
$$\pi^0 \rightarrow \gamma\gamma$$



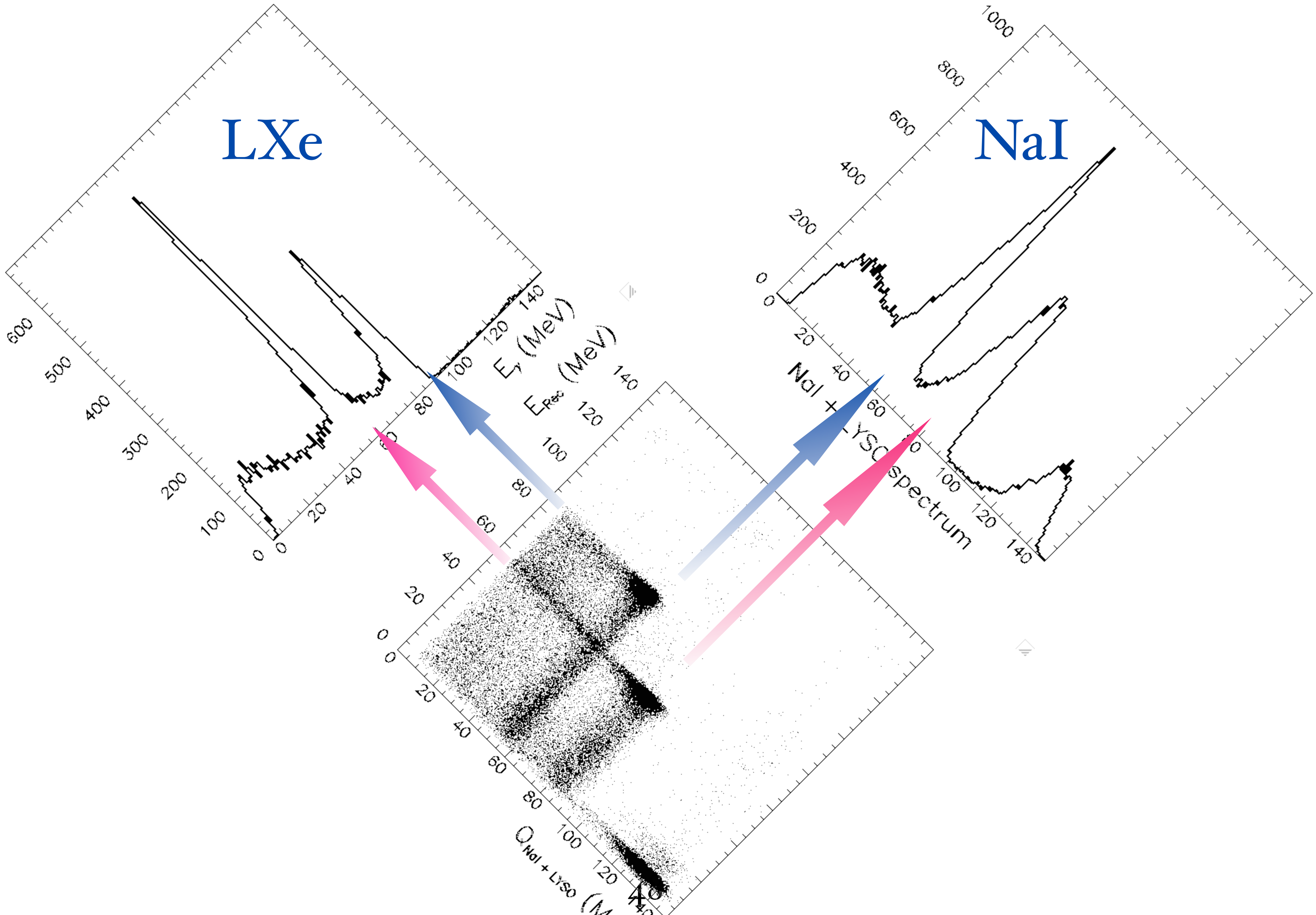


- The monochromatic spectrum in the pi-zero rest frame becomes flat in the Lab
- In the back-to-back configuration the energies are 55 MeV and 83 MeV

- Even a modest collimation guarantees a sufficient monochromaticity
- Liquid hydrogen target to maximize photon flux
- An "opposite side detector" is needed (NaI array)

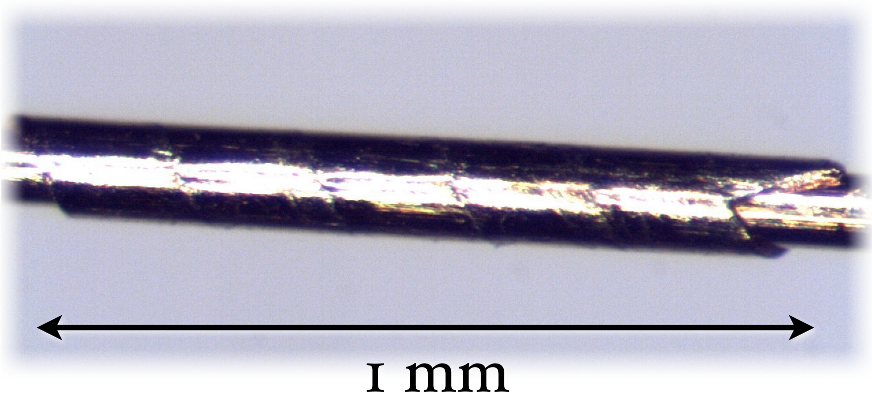


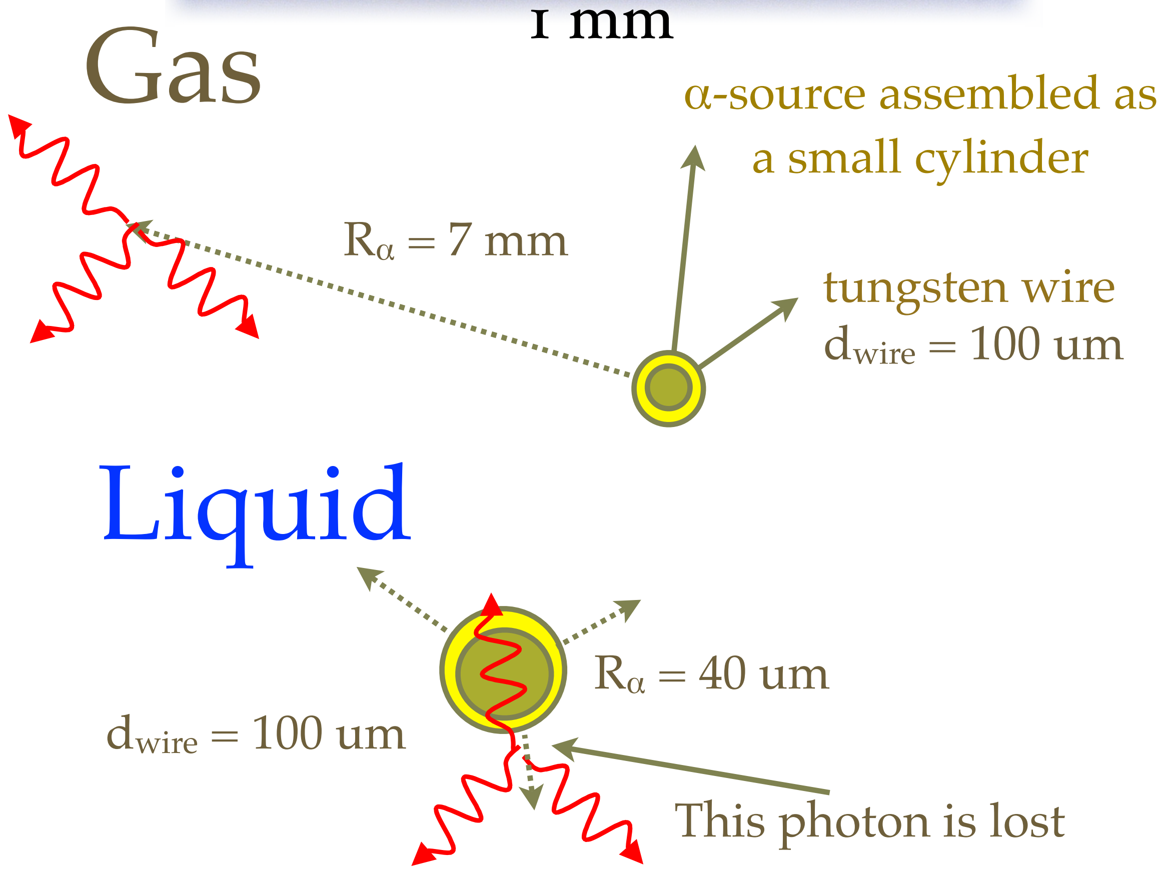
- In the back-to-back raw spectrum we see the correlation
  - 83 MeV ⇔ 55 MeV
  - The 129 MeV line is visible in the NaI because Xe is sensitive to neutrons (9 MeV)

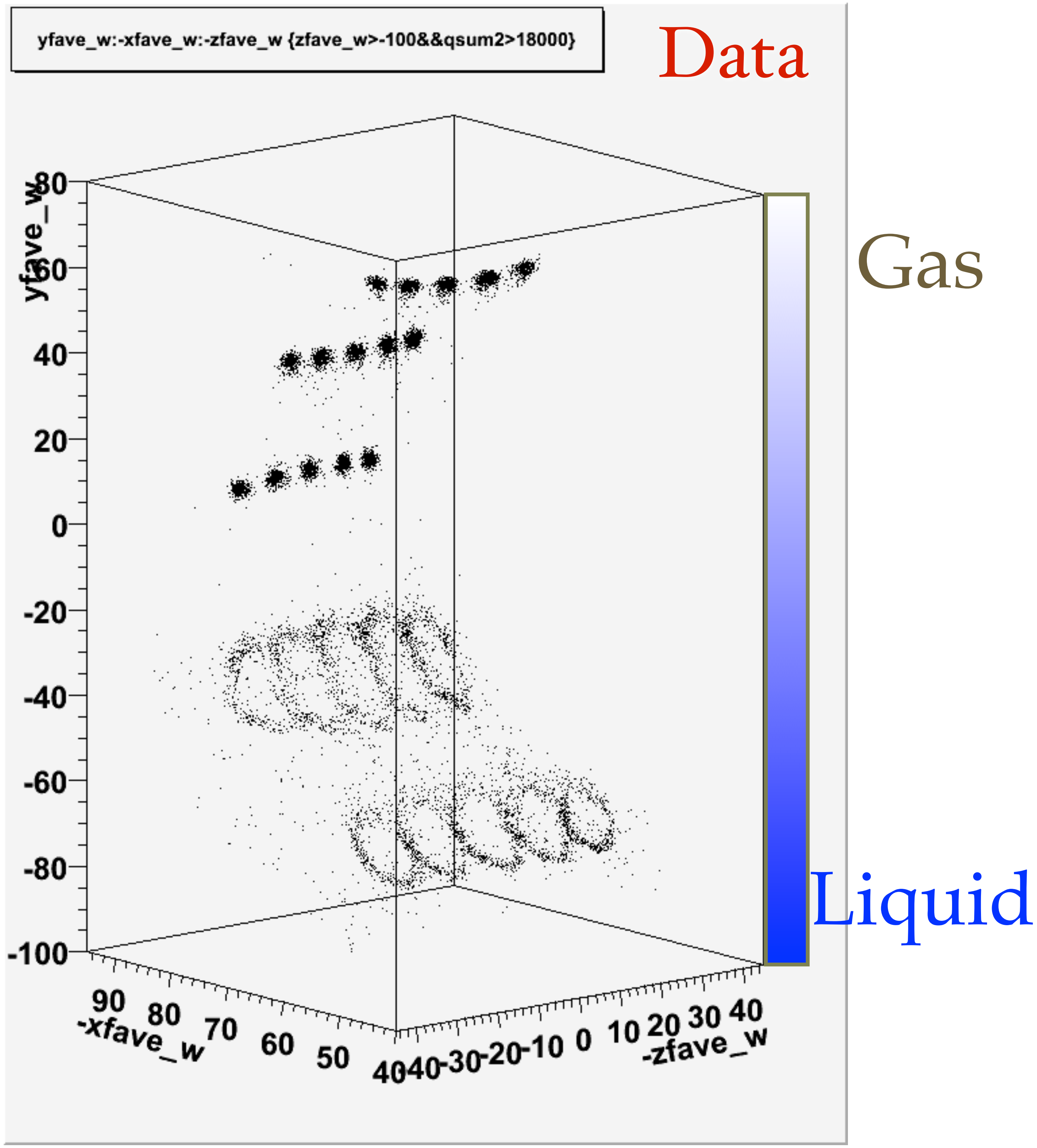


Example: α-sources in Xe

- Specially developed Am sources:
  - 5 dot-sources on thin (100 μm) tungsten wires
  - SORAD Ltd. (Czech Republic)

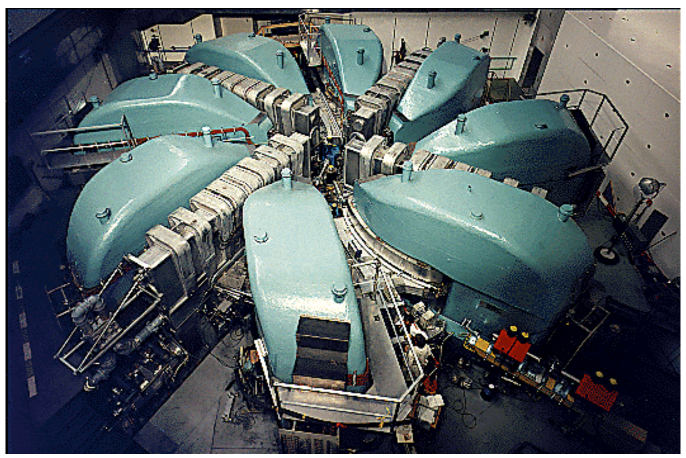


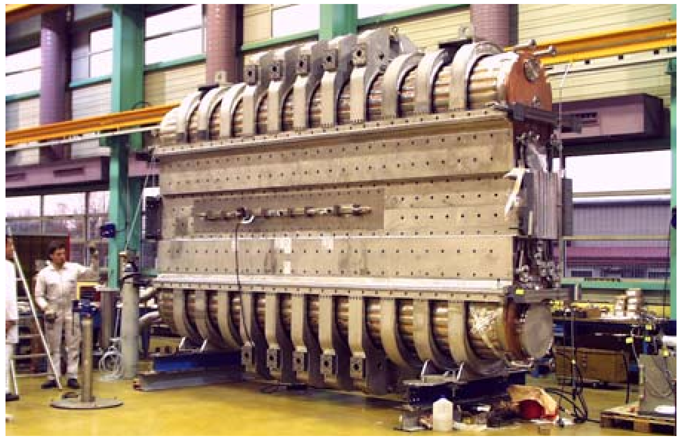




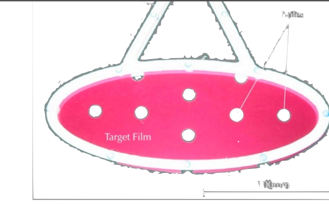
Machine

- "Sensitivity" proportional to the number of muons observed
- Find the most intense (continuous) muon beam: Paul Scherrer Institut (CH)
- 1.6 MW proton accelerator
  - 2 mA of protons - towards 3 mA (replace with new resonant cavities)!
  - extremely stable
  - > 3 x 10^8 muons/sec @ 2 mA





Beam line

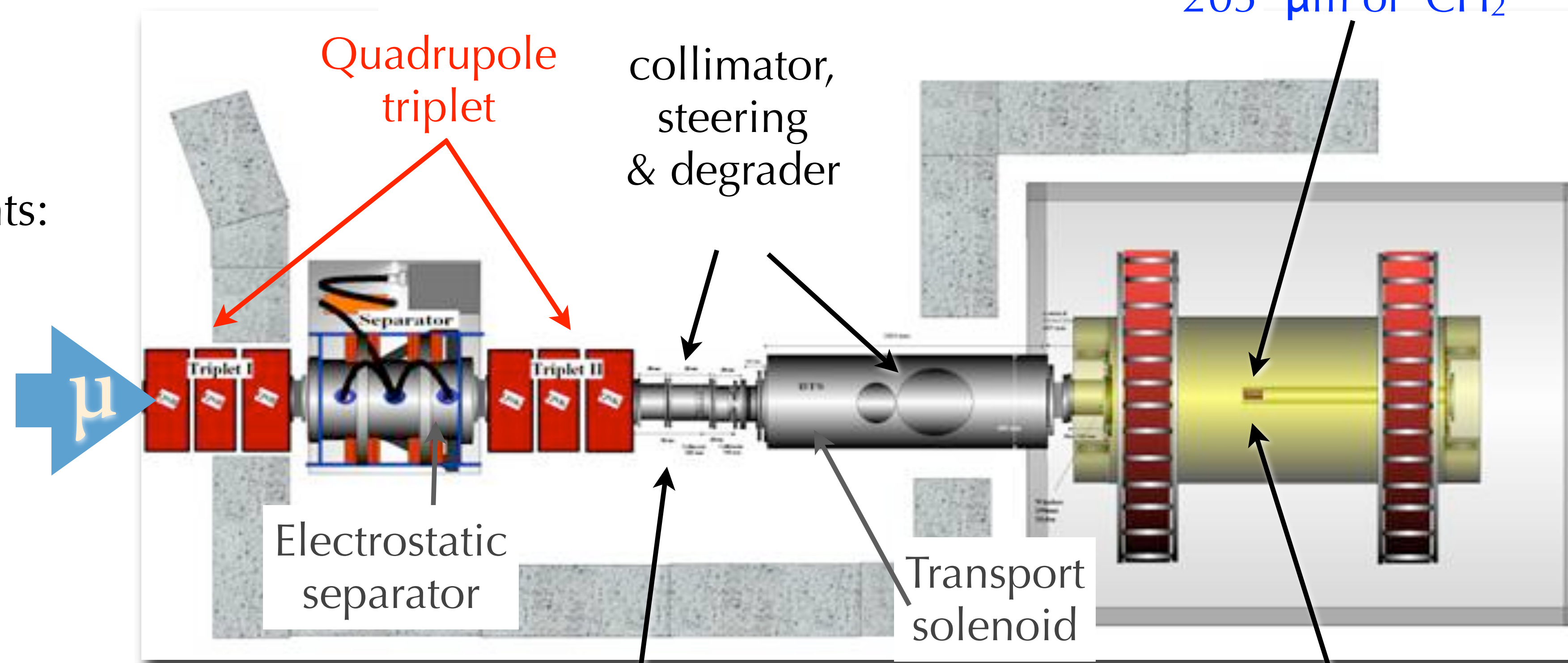


target
205 μm of CH_2

πE5 beam line at PSI

Optimization of the beam elements:

- Muon momentum ~ 29 MeV/c
- Wien filter for μ/e separation
- Solenoid to couple beam and spectrometer (BTS)
- Degrader to reduce the momentum for a 205 μm target

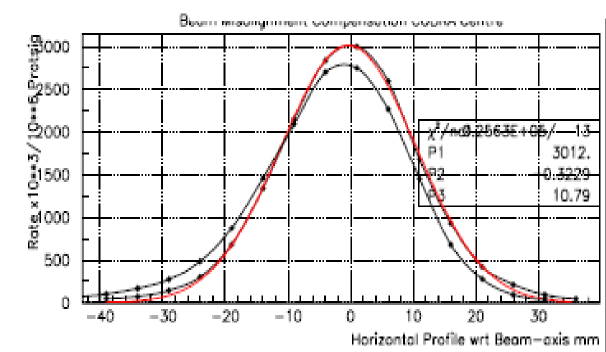


μ/e separation 11.8 cm (7.2 σ)

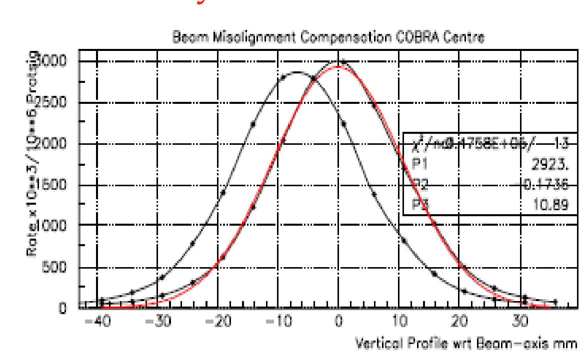
R_μ (exp. on target) $3 \times 10^7\ \mu^+/s$

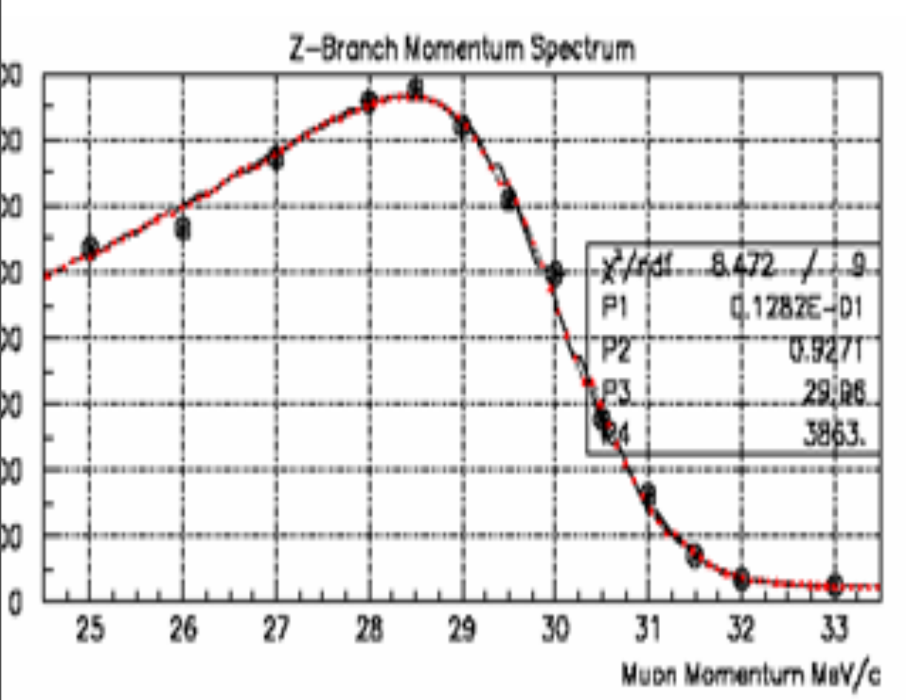
μ spot (exp. on target) $\sigma_V \approx \sigma_H \approx 11$ mm

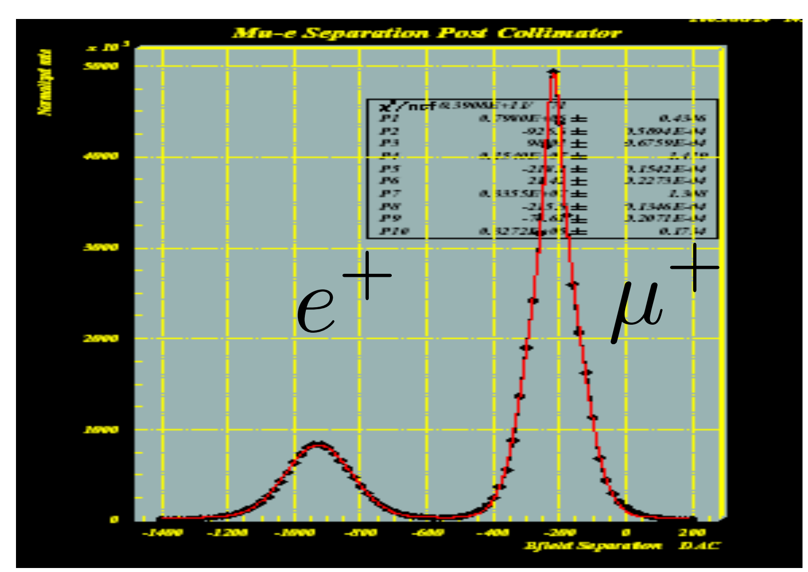
$\sigma_x = 11$ mm



$\sigma_y = 11$ mm

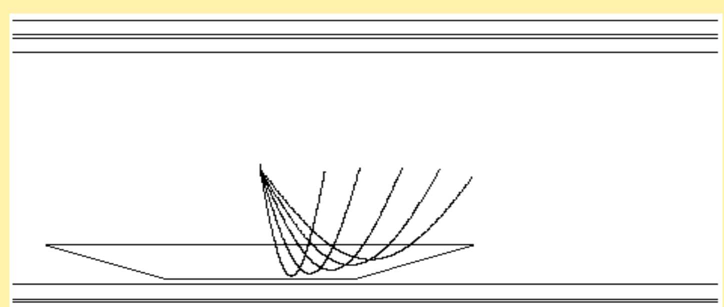
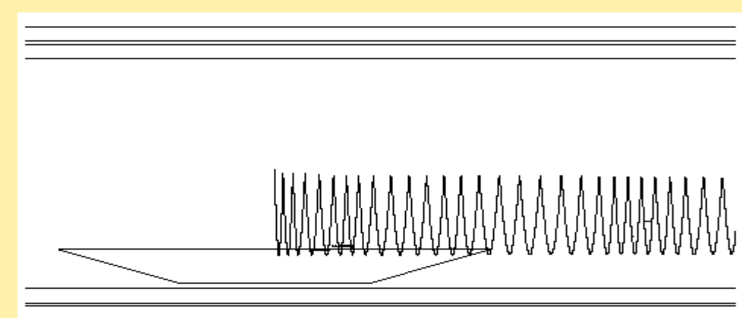
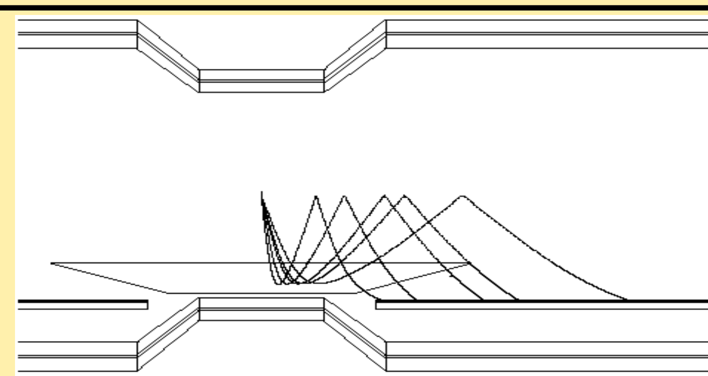
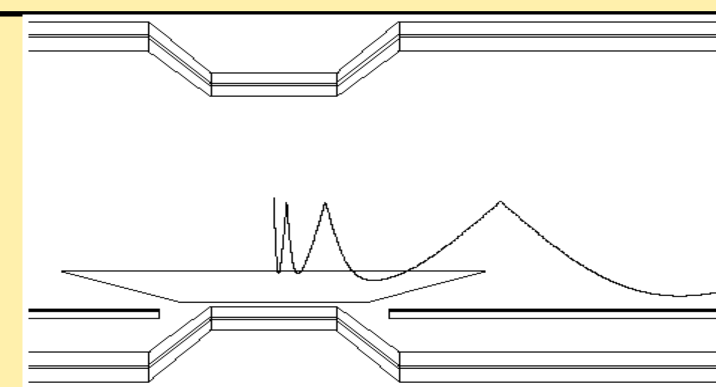




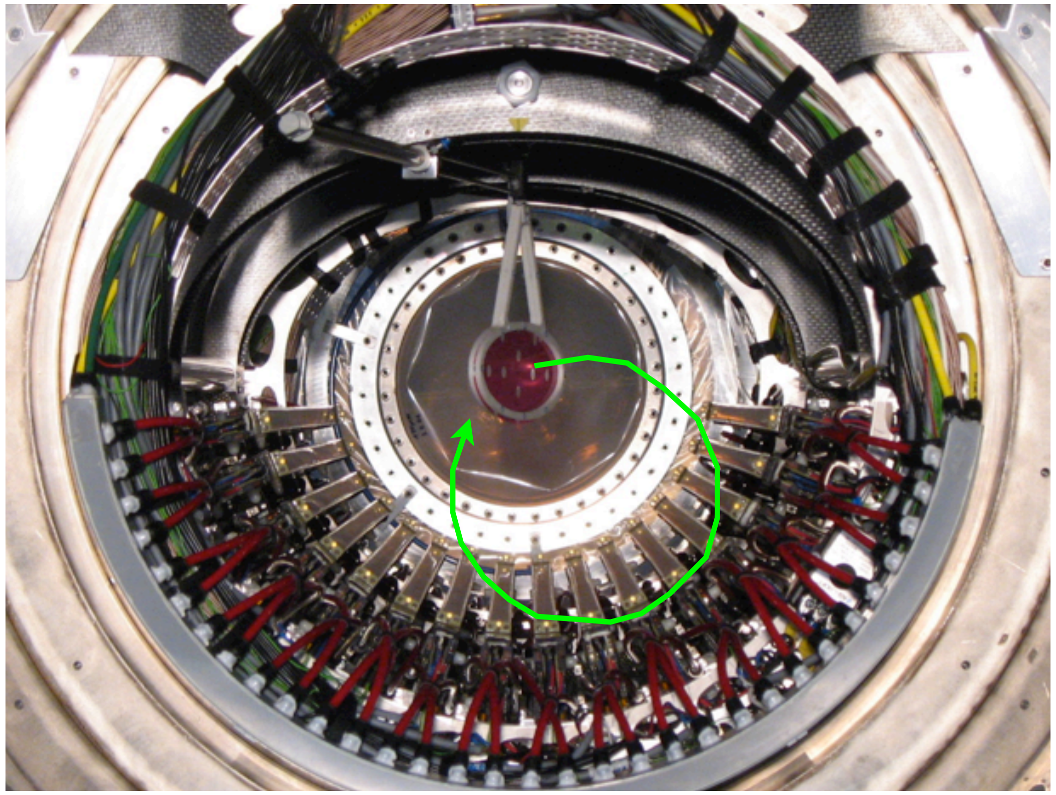


COBRA spectrometer

- The emitted positrons tend to wind in a uniform magnetic field
  - the tracking detector becomes easily “blind” at the high rate required to observe many muons
- A non uniform magnetic field solves the rate problem
- As a bonus: COnstant Bending RAdius

	Constant $|p|$ track	High p_T track
Uniform field		
CoBRa: Constant bending quick sweep away		

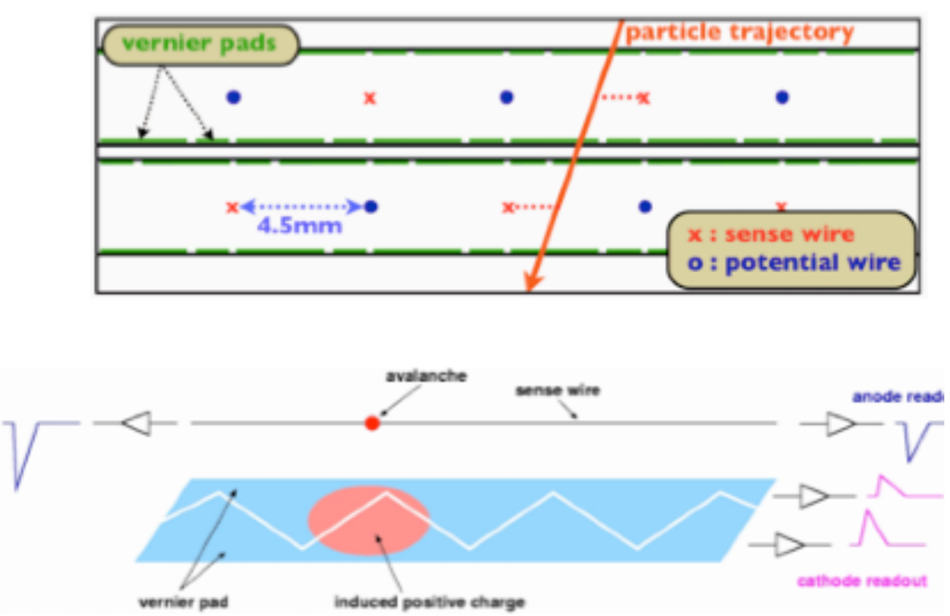
Positron Tracker

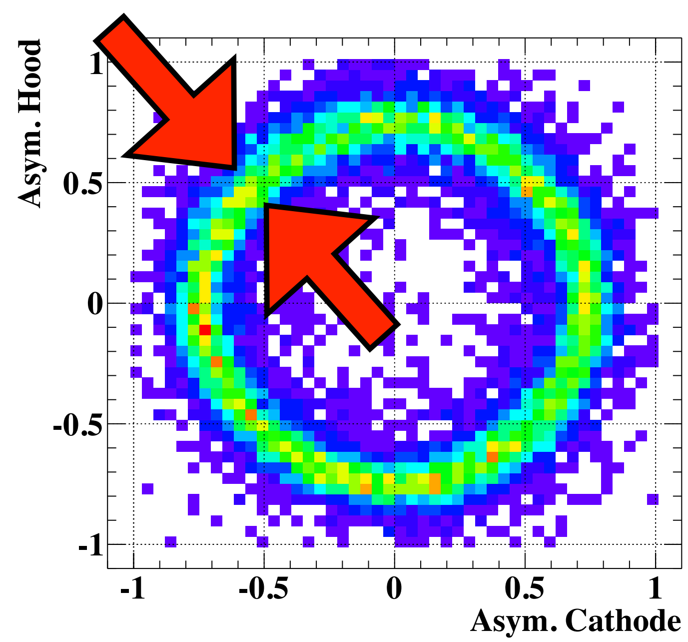


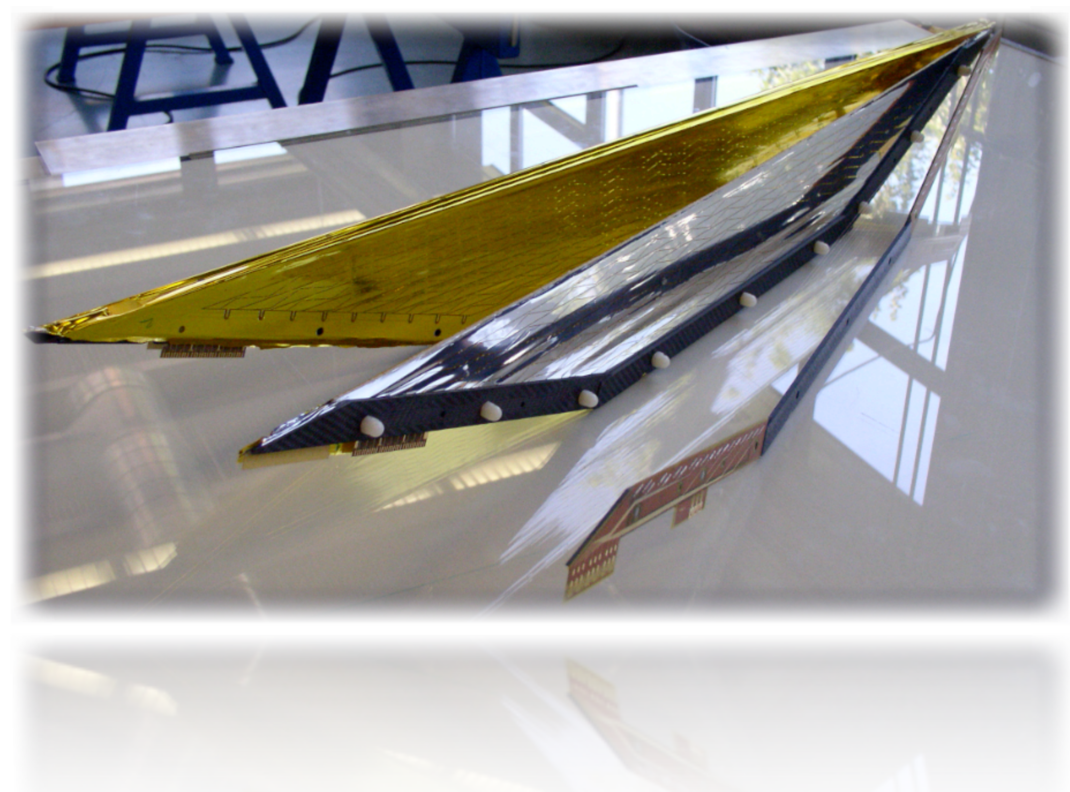
- 16 chambers radially aligned with 10° intervals
- 2 staggered arrays of drift cells
- 1 signal wire and 2 x 2 vernier cathode strips made of 15 μm kapton foils and 0.45 μm aluminum strips
- Chamber gas: He-C_2H_6 mixture
- Within one period, fine structure given by the Vernier circle

σ_R ~ 300 μm transverse coordinate (t drift)

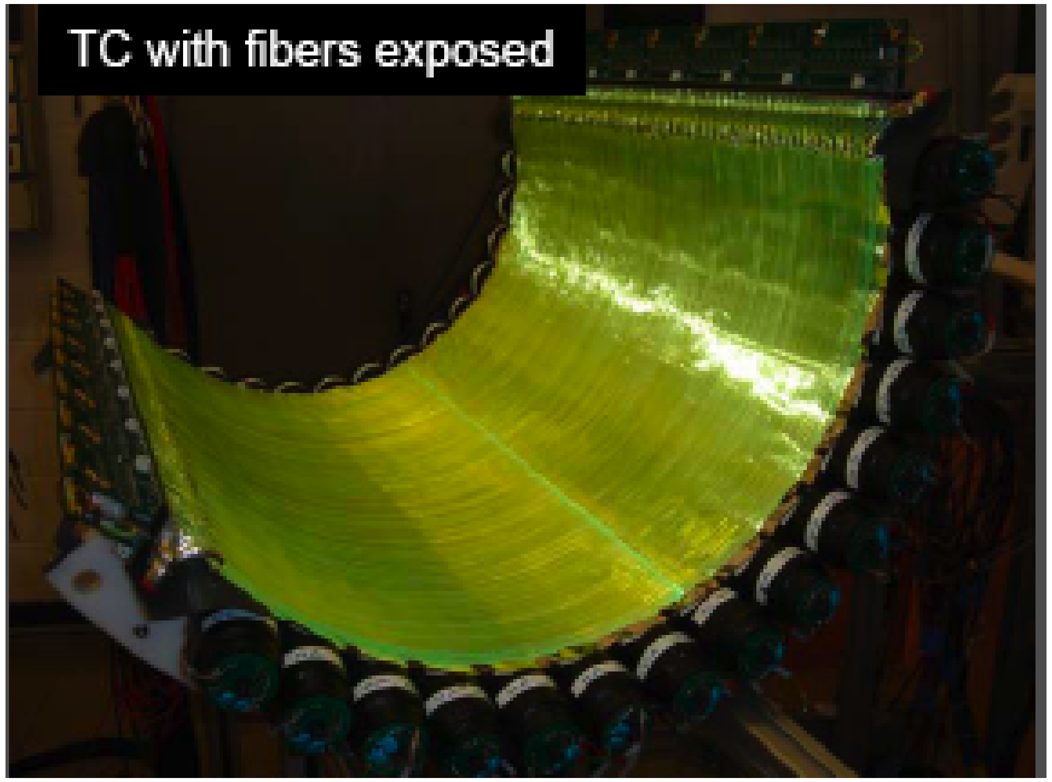
σ_z ~ 700 μm longitudinal coordinate (Vernier)

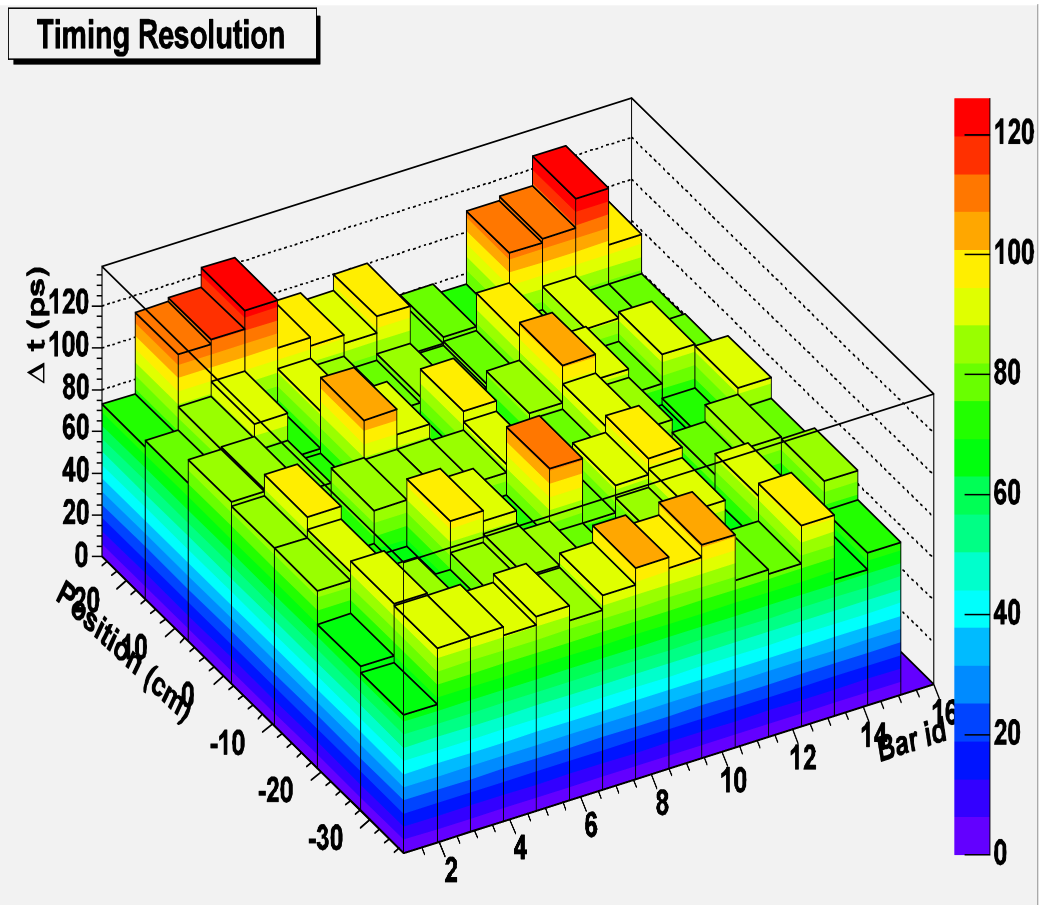




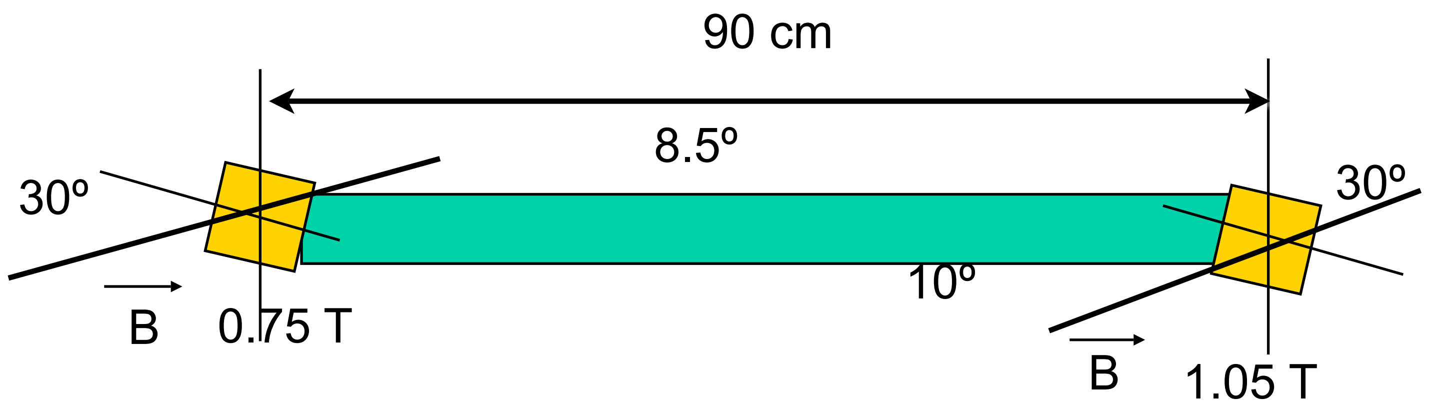


Timing Counter





- Two layers of scintillators:
  - Outer layer, read out by PMTs: timing measurement
  - Inner layer, read out with APDs at 90°: z-trigger
- Resolution σ_{time}~ 40 psec (100 ps FWHM)

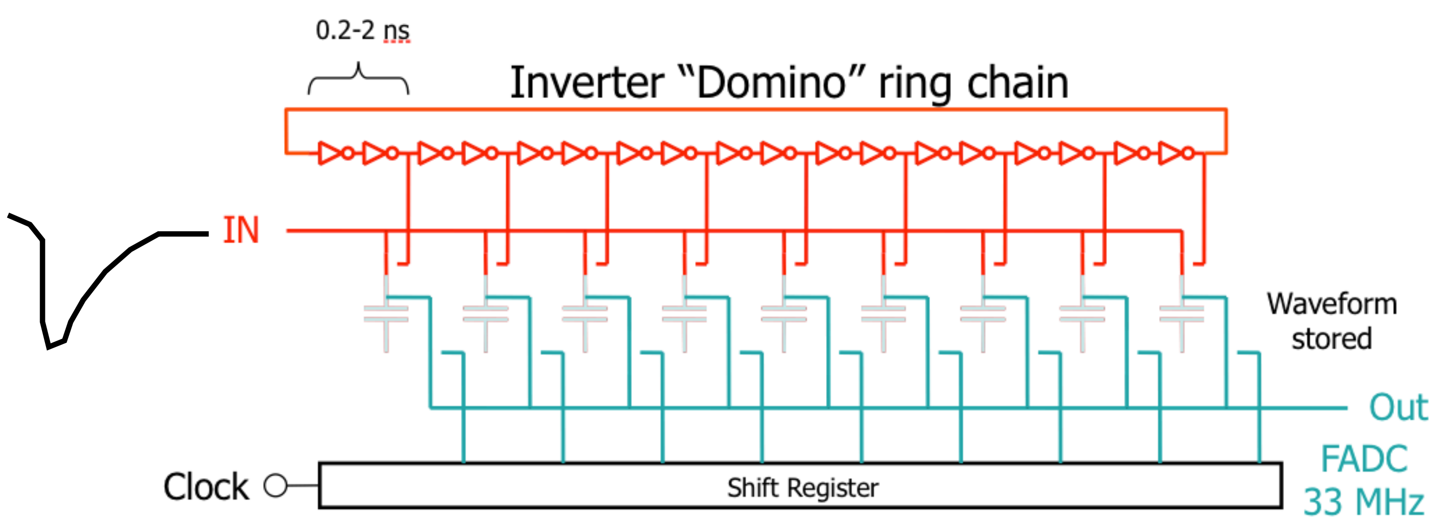


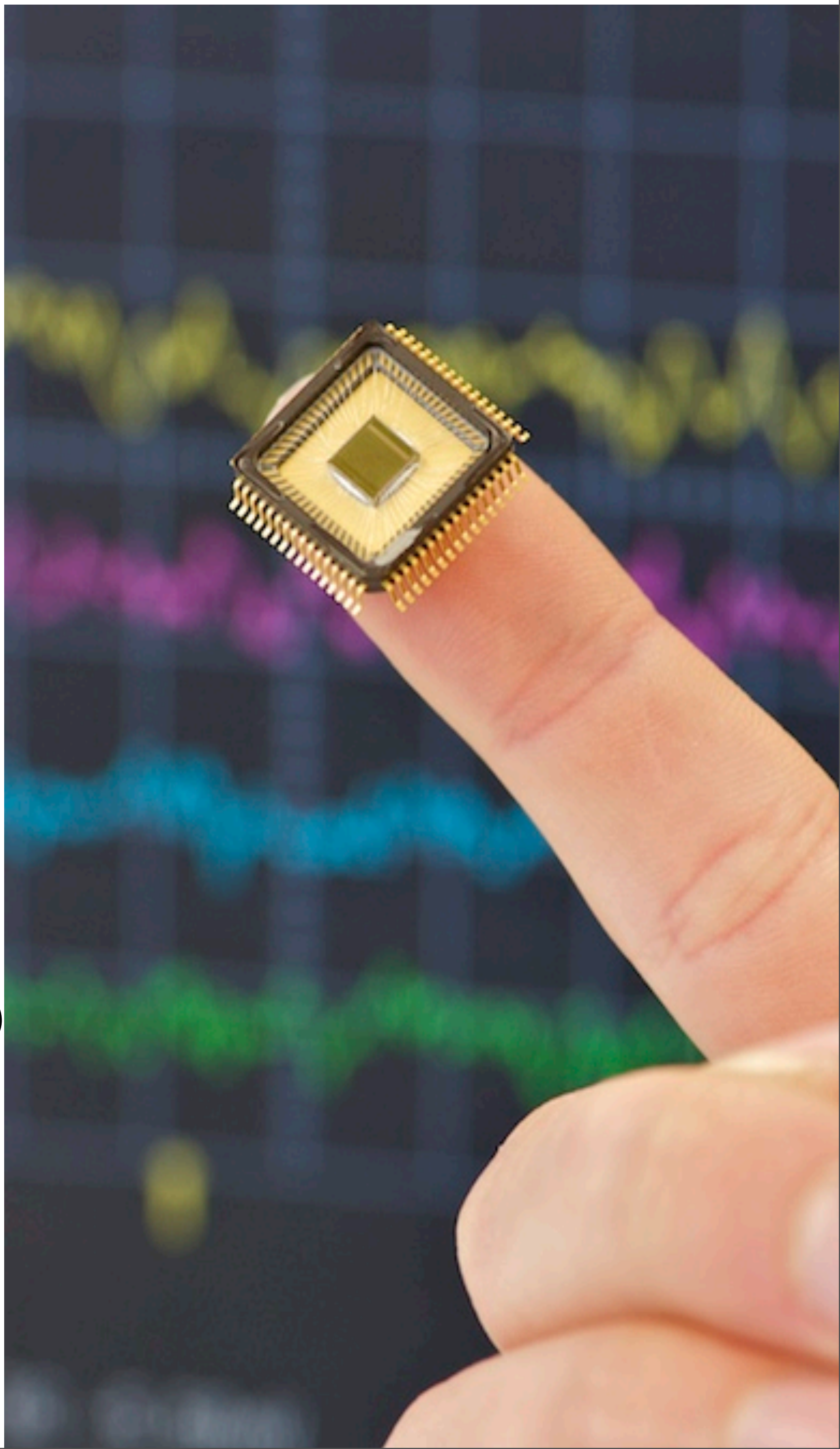
Exp. application (*)	Counter size (cm) (T x W x L)	Scintillator	PMT	λ_{att} (cm)	σ_t(meas)	σ_t(exp)
G.D.Agostini	3x 15 x 100	NE114	XP2020	200	120	60
T. Tanimori	3 x 20 x 150	SCSN38	R1332	180	140	110
T. Sugitate	4 x 3.5 x 100	SCSN23	R1828	200	50	53
R.T. Gile	5 x 10 x 280	BC408	XP2020	270	110	137
TOPAZ	4.2 x 13 x 400	BC412	R1828	300	210	240
R. Stroynowski	2 x 3 x 300	SCSN38	XP2020	180	180	420
Belle	4 x 6 x 255	BC408	R6680	250	90	143
MEG	**4 x 4 x 90**	**BC404**	**R5924**	**270**	**38**	

Best existing TC

Readout electronics

every channel is connected to a GHz WFD



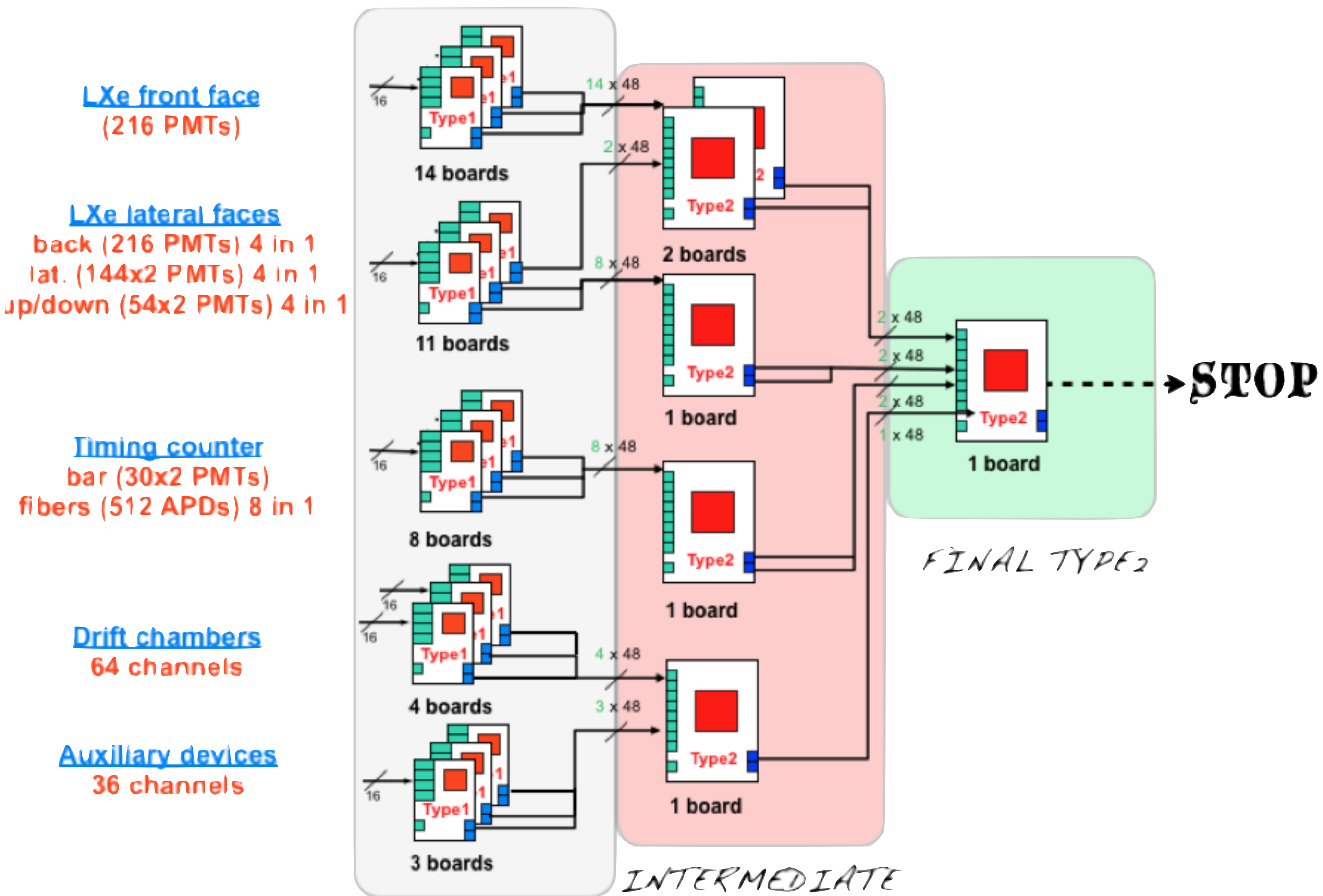


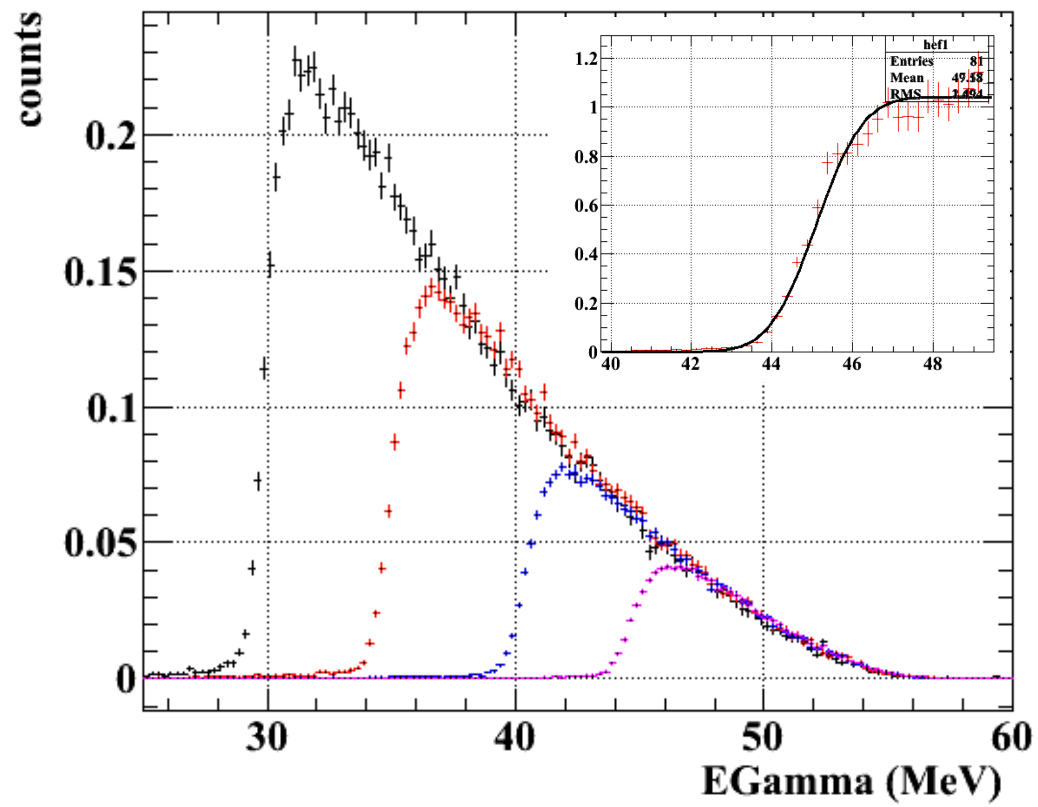
DRS chip (Domino Ring Sampler)

- Custom sampling chip designed at PSI (bw of 950 MHz)
- 0.2→5GHz sampling. →40 ps timing resolution
- Sampling depth 1024 bins for 9 channels/chip
- Full waveform is a handle to do pile-up rejection

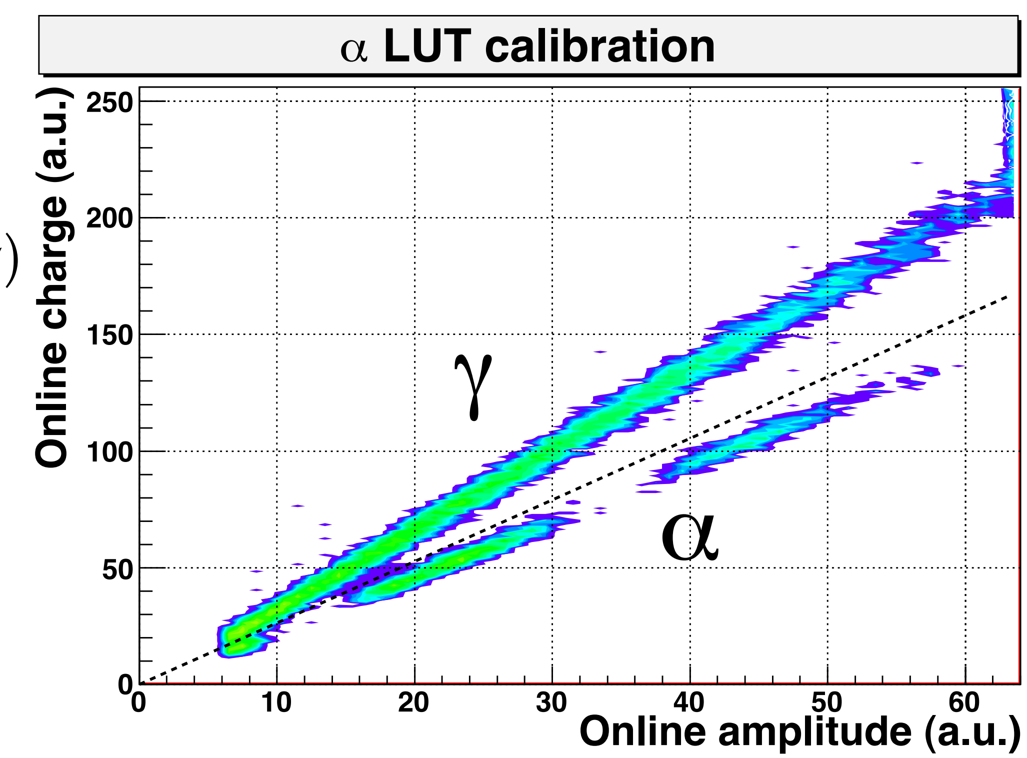
Trigger

- 100 MHz waveform digitizer on VME boards
  - perform online pedestal subtraction



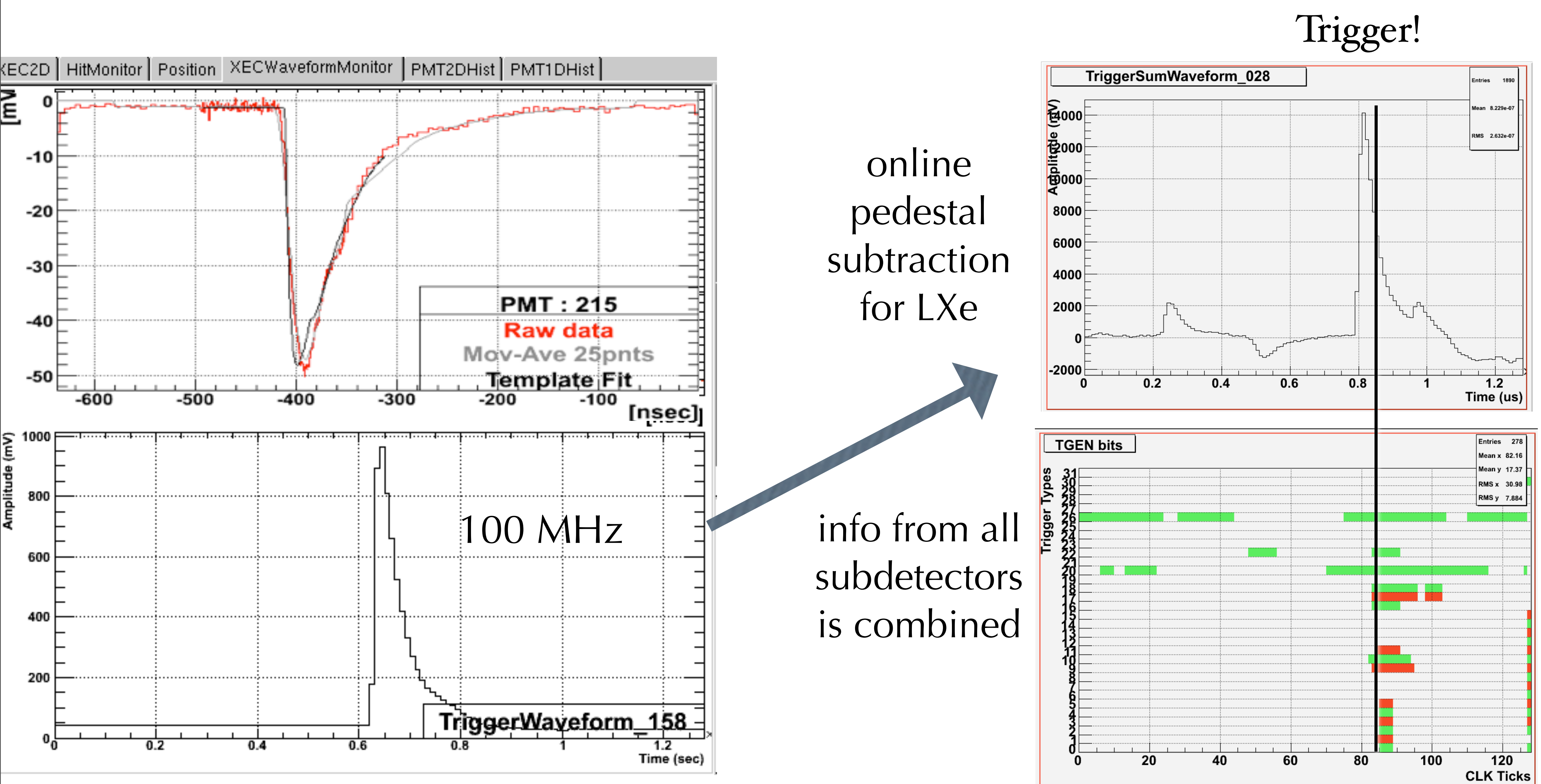


- Built on a FADC-FPGA architecture (500 ns latency)
  - γ energy, $e^+\gamma$ coincidence, $e^+\gamma$ collinearity
  - 2.5% resolution at the E_γ = 45 MeV threshold
  - Fully efficient on the signal region
- Complex algorithms implemented
  - online α/γ discrimination

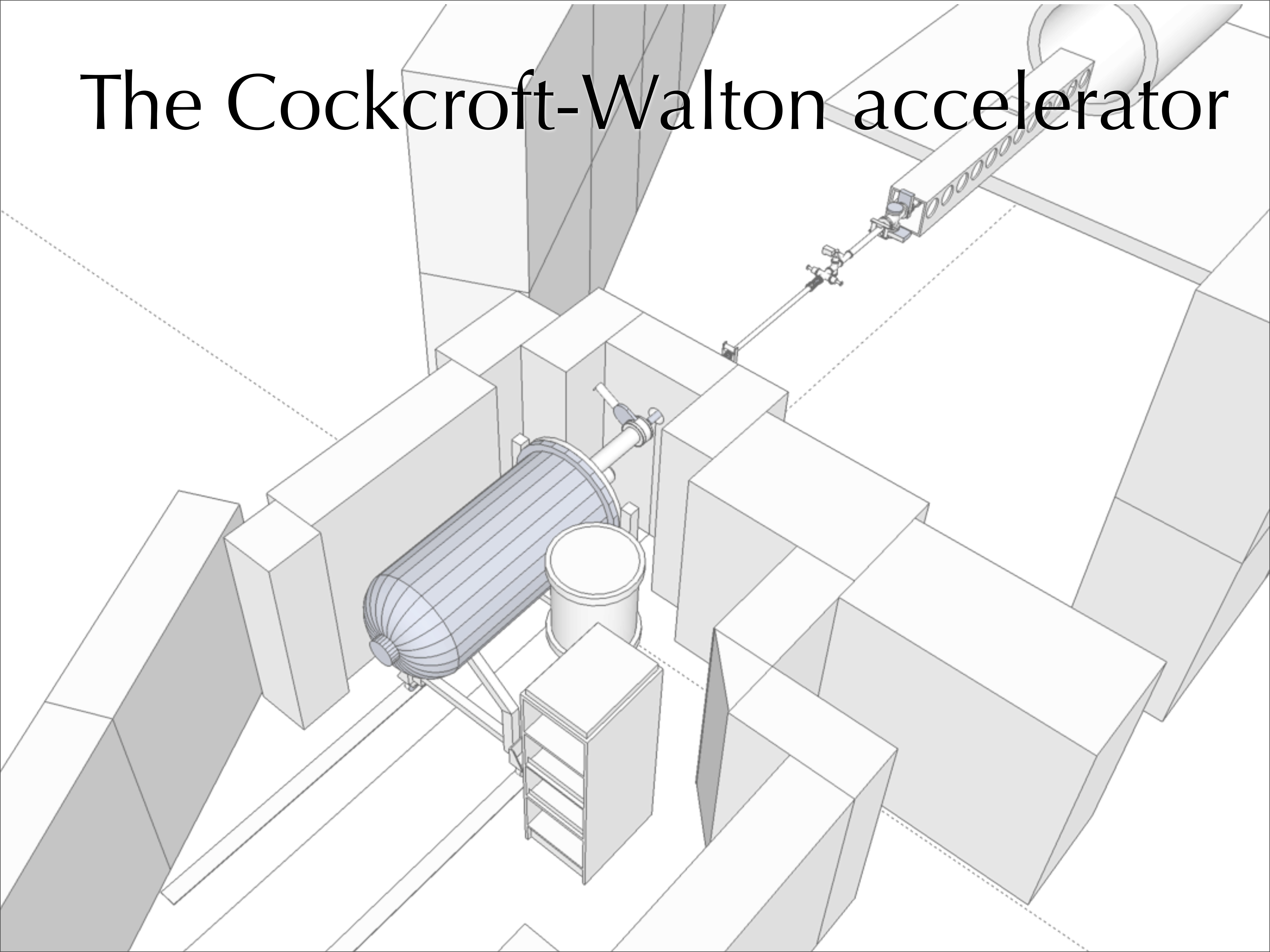


TRG + DAQ example

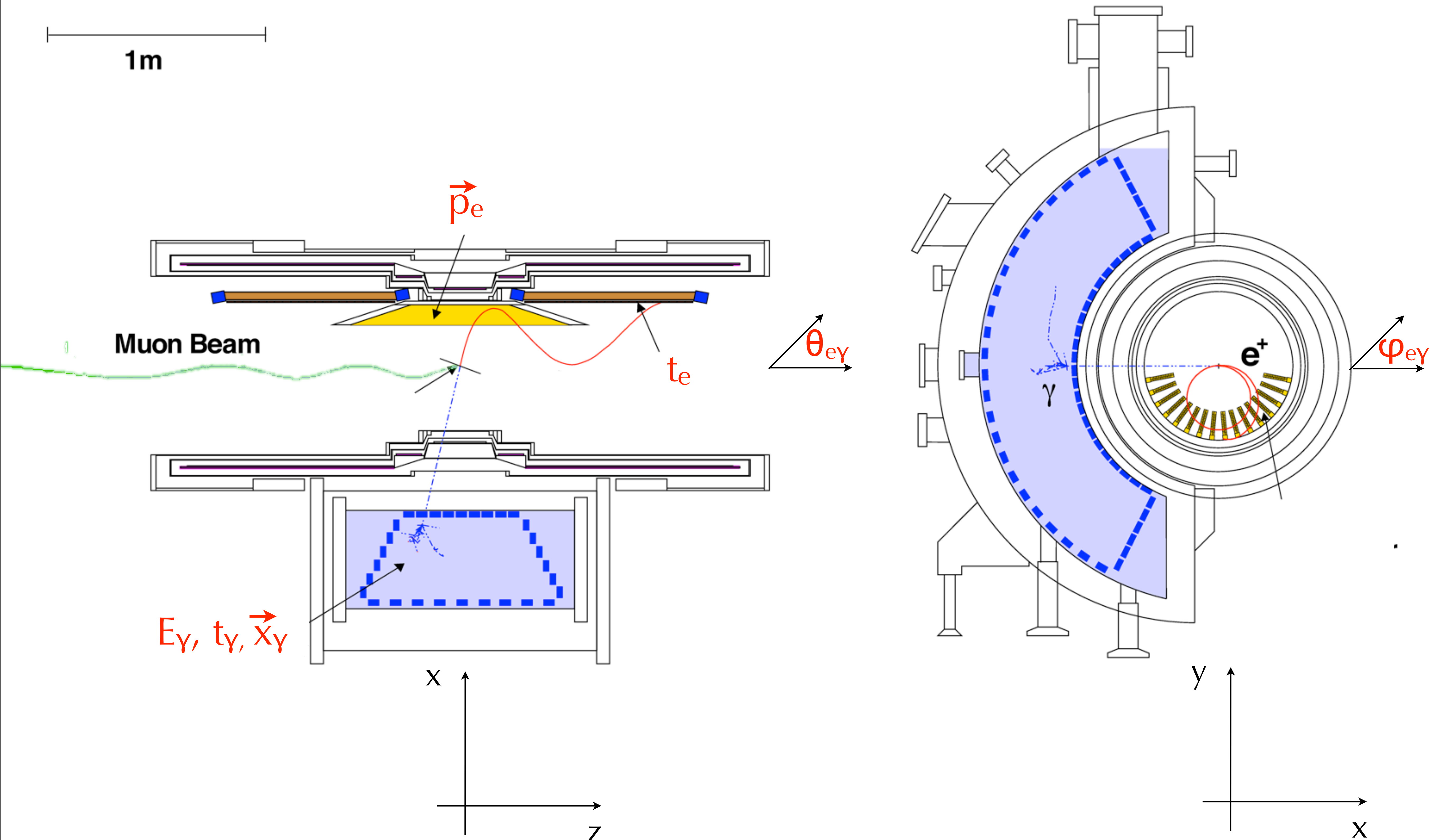
- For (almost) all channels, for each sub-detector we have two waveform digitizers with complementary characteristics



The Cockcroft-Walton accelerator



MEG scheme

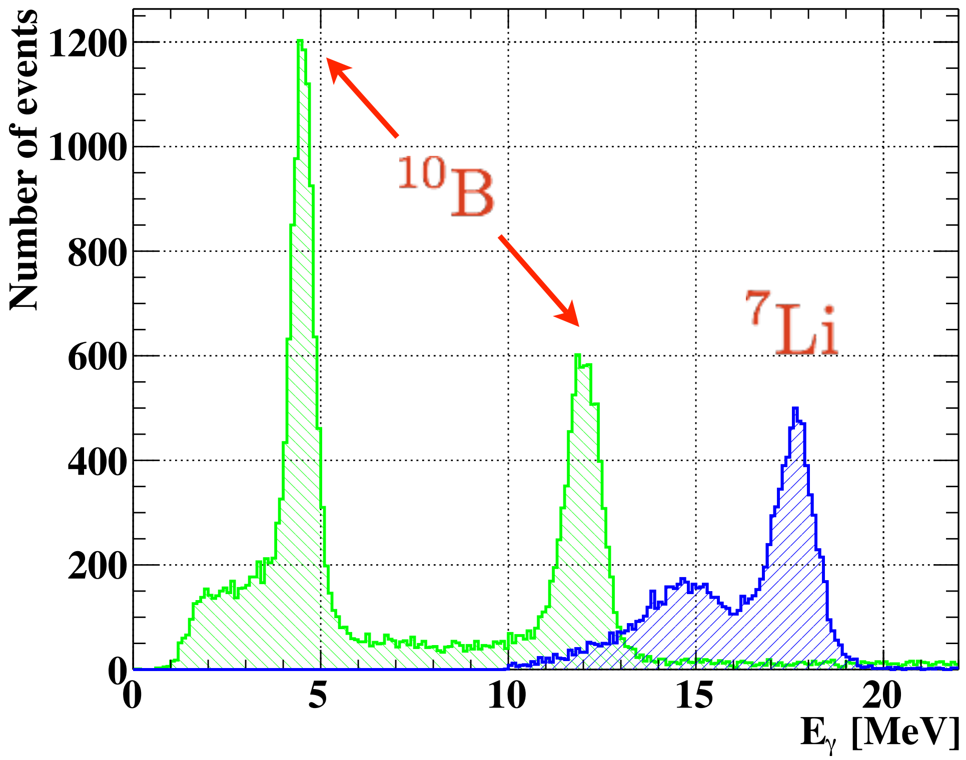


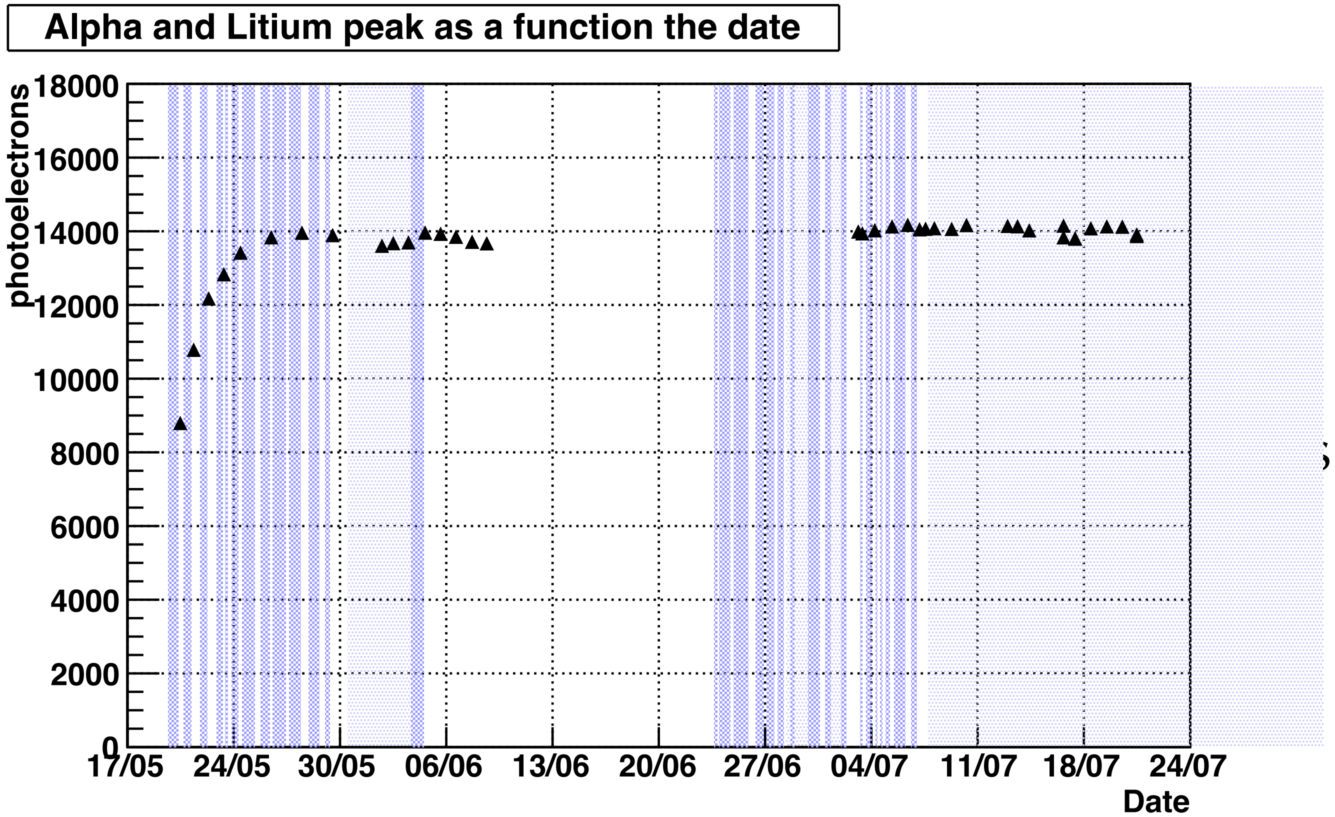
1m
Muon Beam
$\vec{p}_e$
t_e
$\theta_{e\gamma}$
E_γ, t_γ, $\vec{x}_\gamma$
x
z
e^+
γ
$\varphi_{e\gamma}$
y
x

CW - daily calibration

- This calibration is performed every other day
  - Muon target moves away and a crystal target is inserted
- Hybrid target ($Li_2B_4O_7$)
  - Possibility to use the same target and select the line by changing proton energy

Reaction	Peak energy	σ peak	γ-lines
Li(p,γ)Be	440 keV	5 mb	(17.6, 14.6) MeV
B(p,γ)C	163 keV	2 10^{-1} mb	(4.4, 11.7, 16.1) MeV





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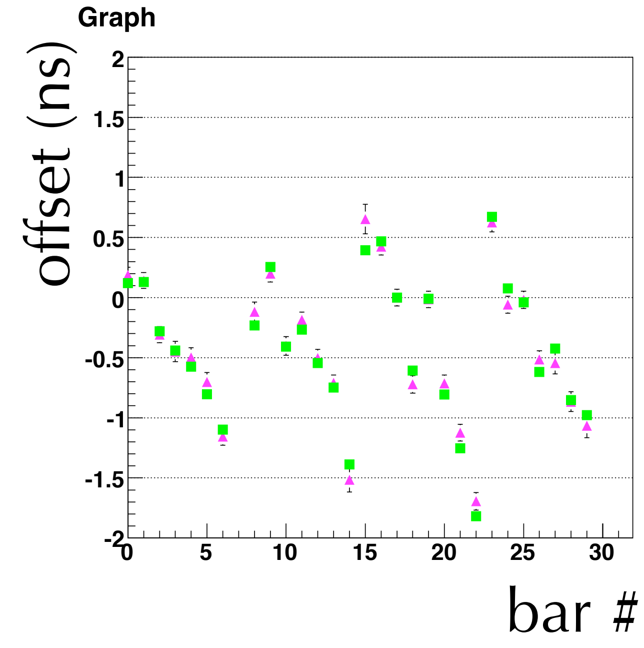

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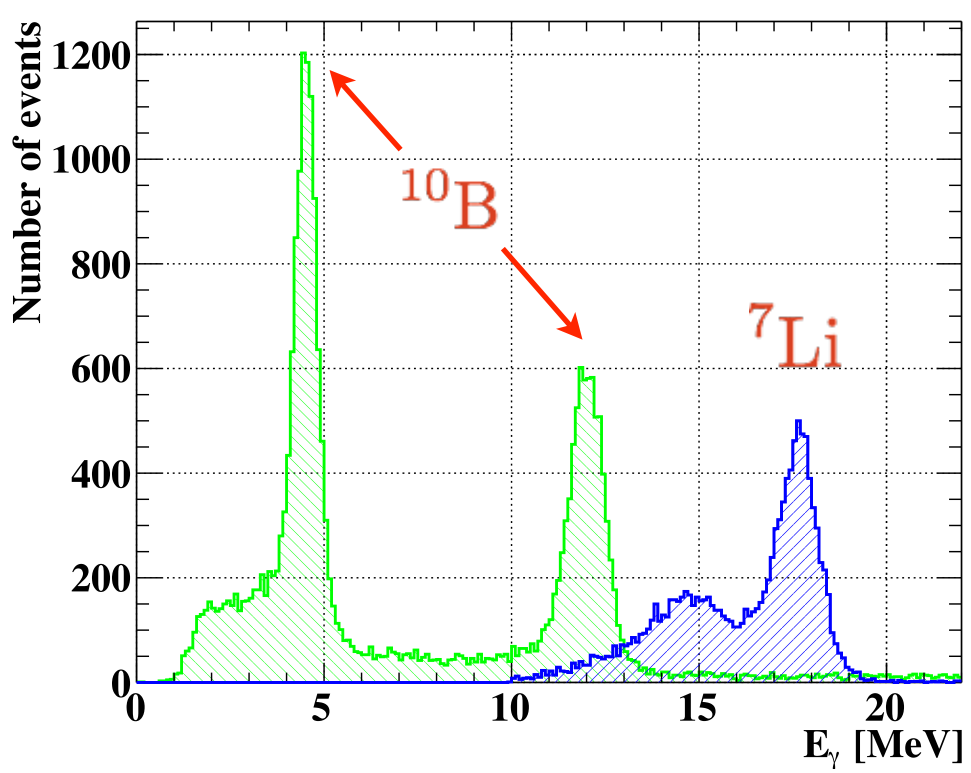

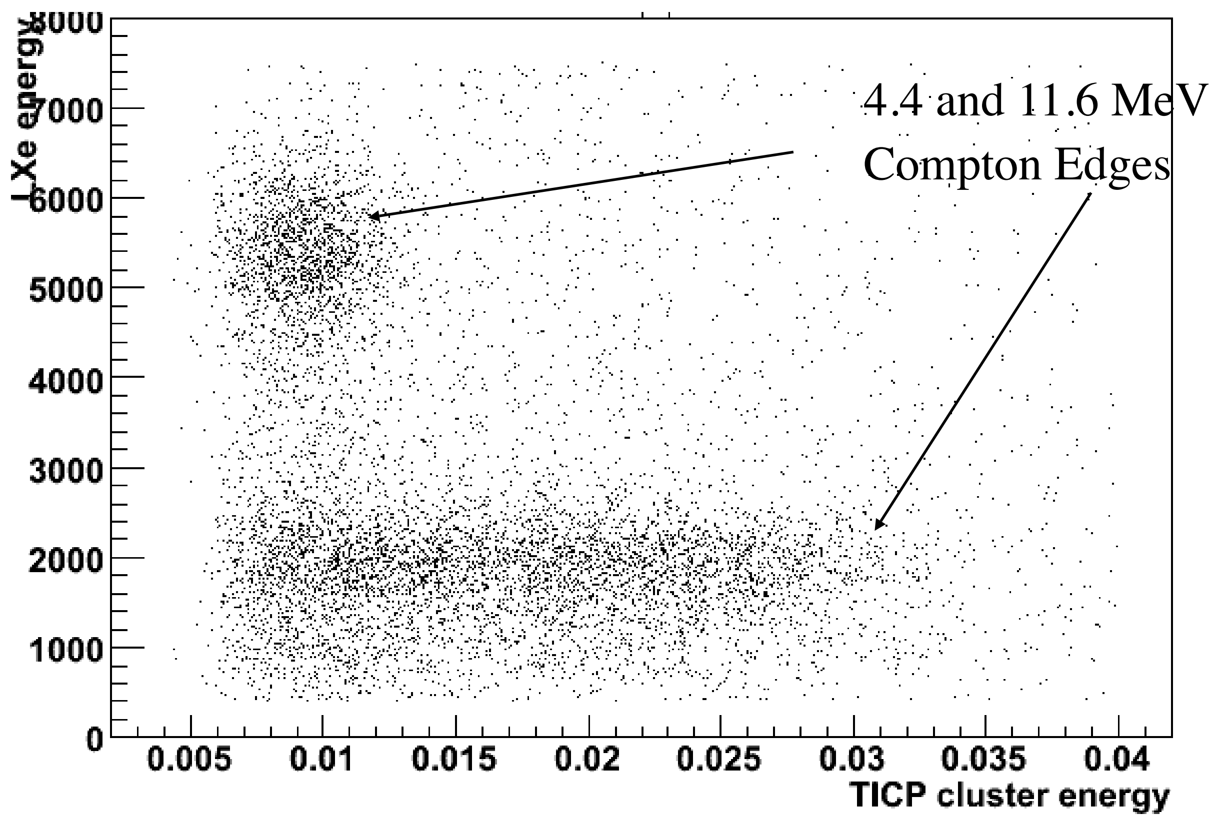

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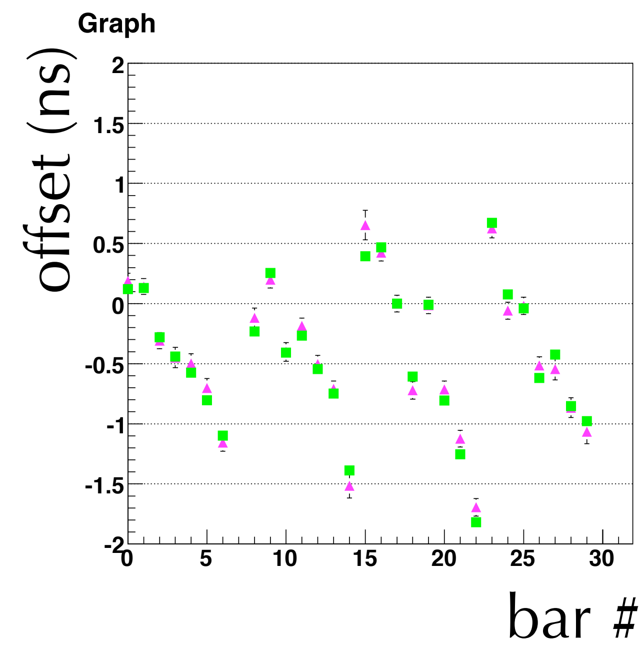

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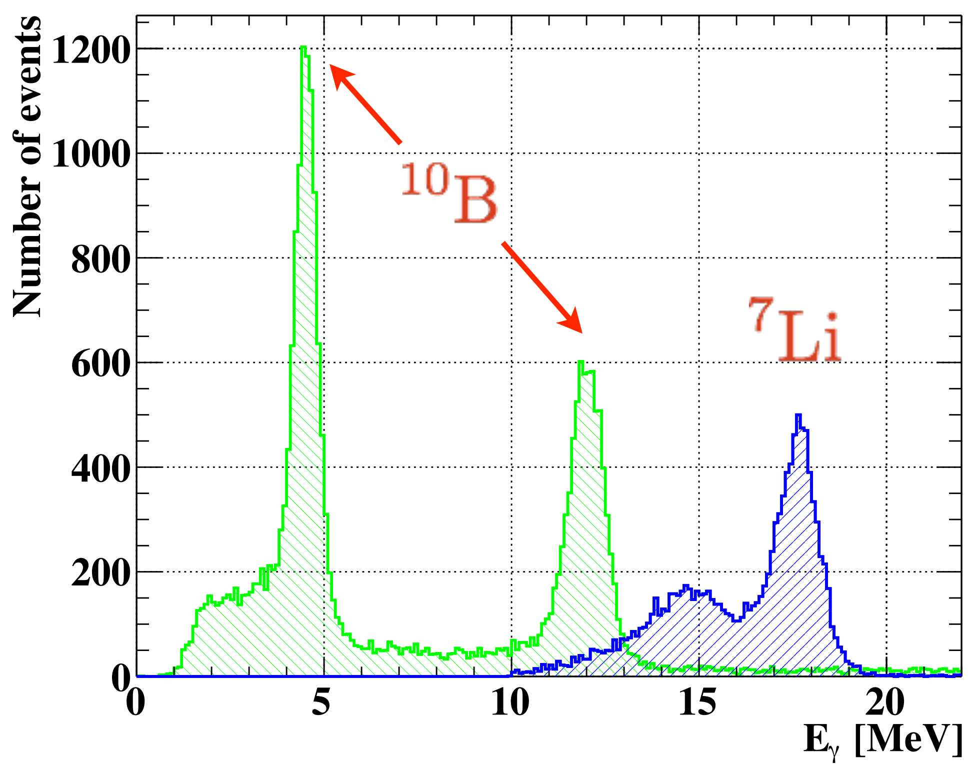

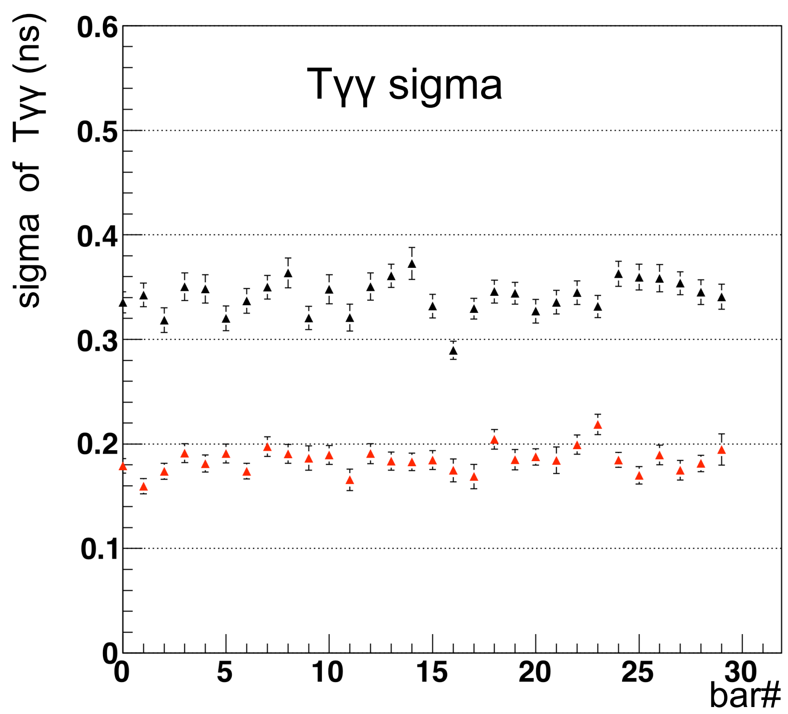

Probability Density Functions

- SIGNAL

  E_γ: from full signal MC (or from fit to endpoint)
  E_e: 3-gaussian fit on data
  $\theta_{e\gamma}$: combination of e and gamma angular resolution from data
  $t_{e\gamma}$: single gaussian from MEG trigger Radiative Decay (no cut on Eg)

- RADIATIVE

  $E_e, E_\gamma, \theta_{e\gamma}$: 3D histo PDF from toy MC that smears and weighs Kuno-Okada distribution taking into account resolution and acceptance
  $t_{e\gamma}$: single gaussian with same resolution as signal

- ACCIDENTAL

  E_γ: from fit to $t_{e\gamma}$ sideband
  E_e: from data
  $\theta_{e\gamma}$: from fit to $t_{e\gamma}$ sideband
  $t_{e\gamma}$: flat

Alternative observables definition
1) different algorithm for LXe Timing
2) Trigger LXe waveform digitizing electronics (E_γ)