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High Energy Research Organization (KEK), Japan  
on behalf of the MEG Collaboration

# New limit on LFV searches from the MEG experiment

Thursday, 17<sup>th</sup> November 2011  
Laboratoire de l'Accélérateur Linéaire  
Centre Scientifique d'Orsay  
Orsay Cedex, France





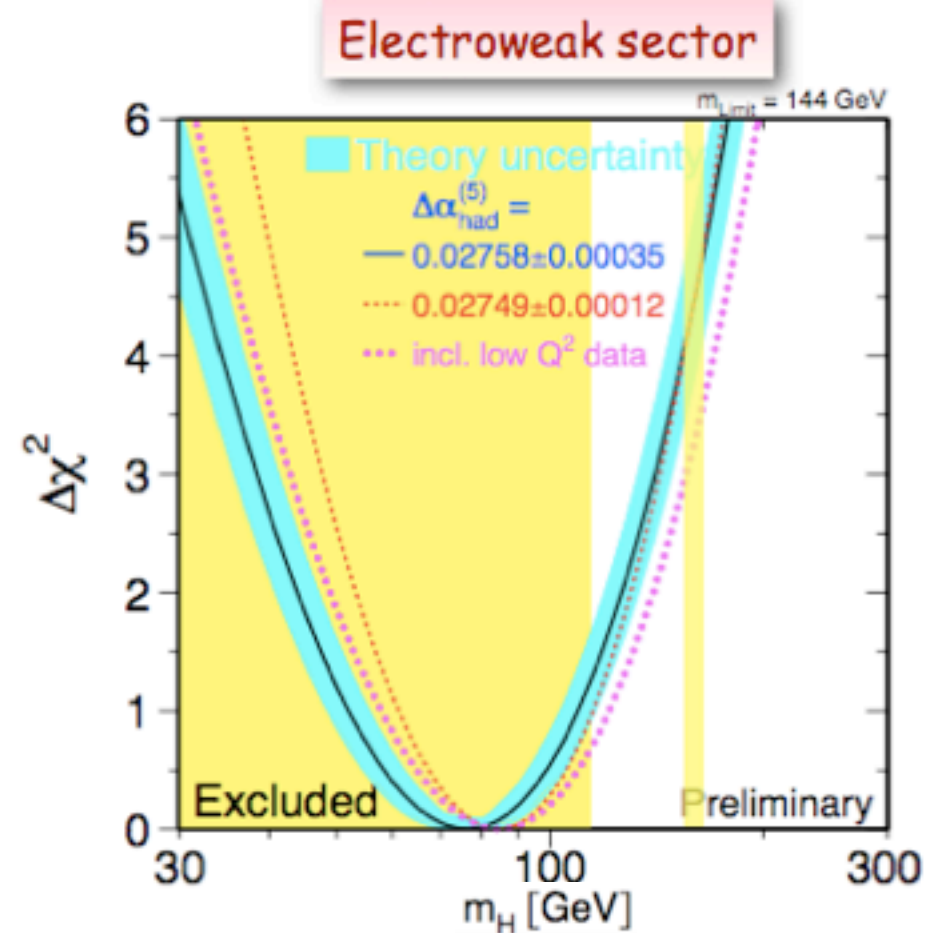
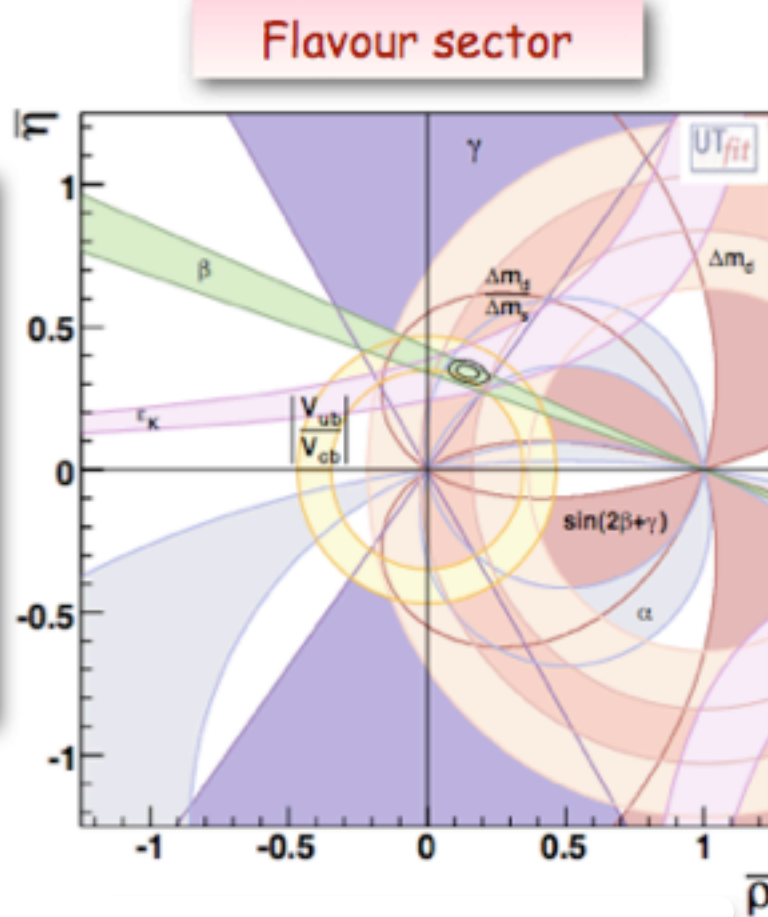


# Where we are



# SM success (& failure)

No significant deviation:  
NP should appear as a correction to the SM picture



Nonetheless, we know it is not the ultimate theory. Some reasons:

- Neutrino oscillations
- Dark Matter/Energy
- No Higgs (..yet)
- No quantitative way to account for matter/antimatter asymmetry in universe
- Hierarchy, unification, flavour problems
- .....

Everybody is eager for New Physics !!

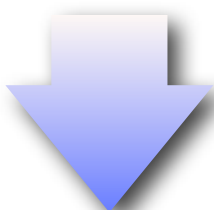
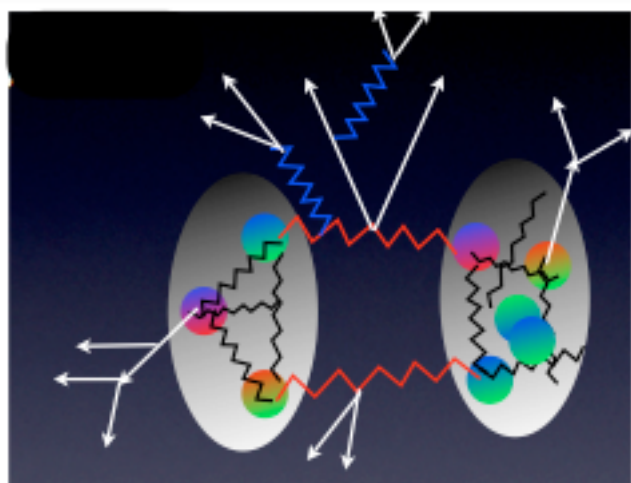
I'm not a theorist..  
not here to cover why we  
need to go beyond SM :)



# Going beyond the SM



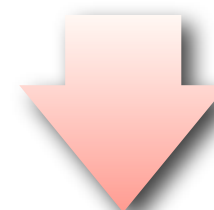
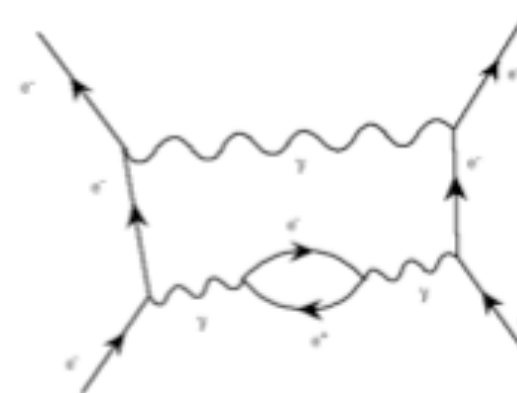
Through the gauge sector  
(Higgs, EWSB)



The High Energy Frontier

New particles produced increasing  
c.m. energy

Through the flavour sector  
(LFV, CPV, FCNC,  $\nu$  mixing, EDM)



The High Intensity Frontier

Virtual processes indirectly test the NP energy  
scale (sometime further than LHC reach)

Full complementarity between the two approaches



# Why Lepton Flavour Violation

Lepton Flavour Conservation is an accidental symmetry of SM:

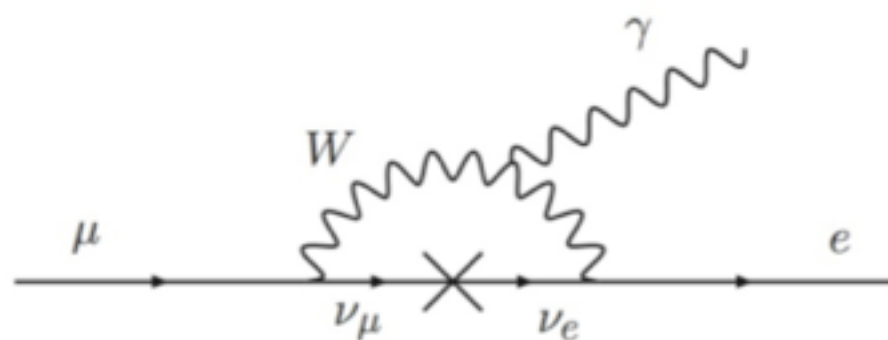
- Not related to the gauge structure of the theory
- Naturally violated in SM extensions

Observation of  $\mu \rightarrow e \gamma$  would be an unambiguous evidence of NP beyond SM

LFV already observed in the neutral sector: neutrino oscillations

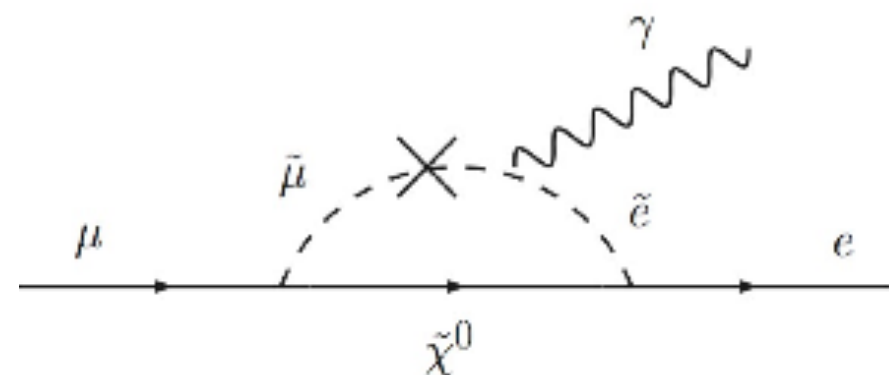
LFV in charged sector could be mediated by

- neutrino oscillation in SM extensions with massive neutrinos
- off-diagonal terms in the slepton mass matrix (through RG evolution) in SUSY



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

$$\text{BR}(\mu \rightarrow e \gamma) \sim 10^{-54}$$



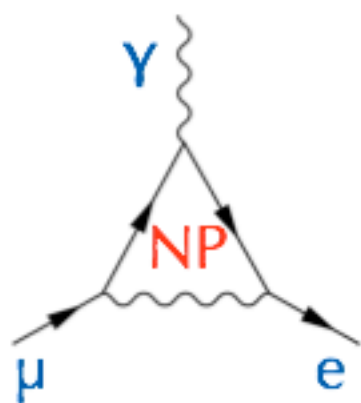
$$\text{BR}(\ell_i \rightarrow \ell_j \gamma) \propto \delta_{ij}^2 \tan^2 \beta$$

$$\text{BR}(\mu \rightarrow e \gamma) \sim 10^{-13} - 10^{-14}$$

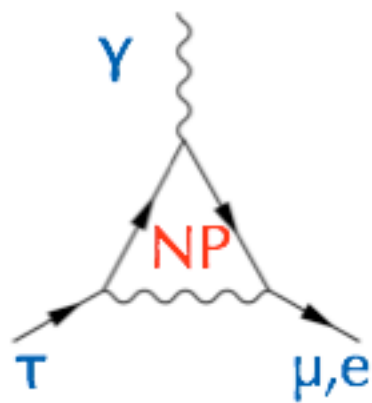
# Charged LFV processes

A new lepton-lepton coupling

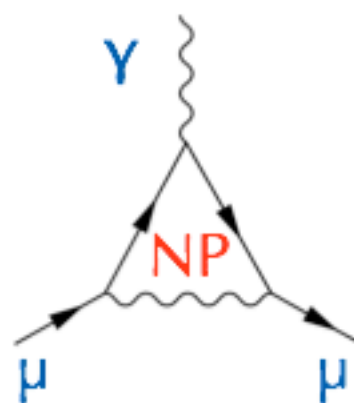
$$y_{ij} \bar{\ell}_i F^{\mu\nu} \ell_j \sigma_{\mu\nu}$$



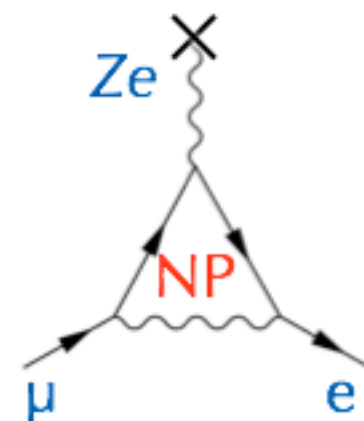
$$\mu \rightarrow e \gamma$$



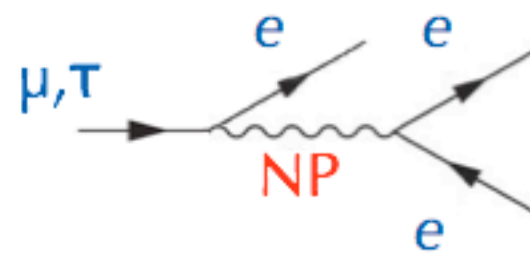
$$\begin{aligned} \tau &\rightarrow \mu \gamma \\ \tau &\rightarrow e \gamma \end{aligned}$$



$$(g - 2)_\mu$$



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



$$\mu \rightarrow eee$$

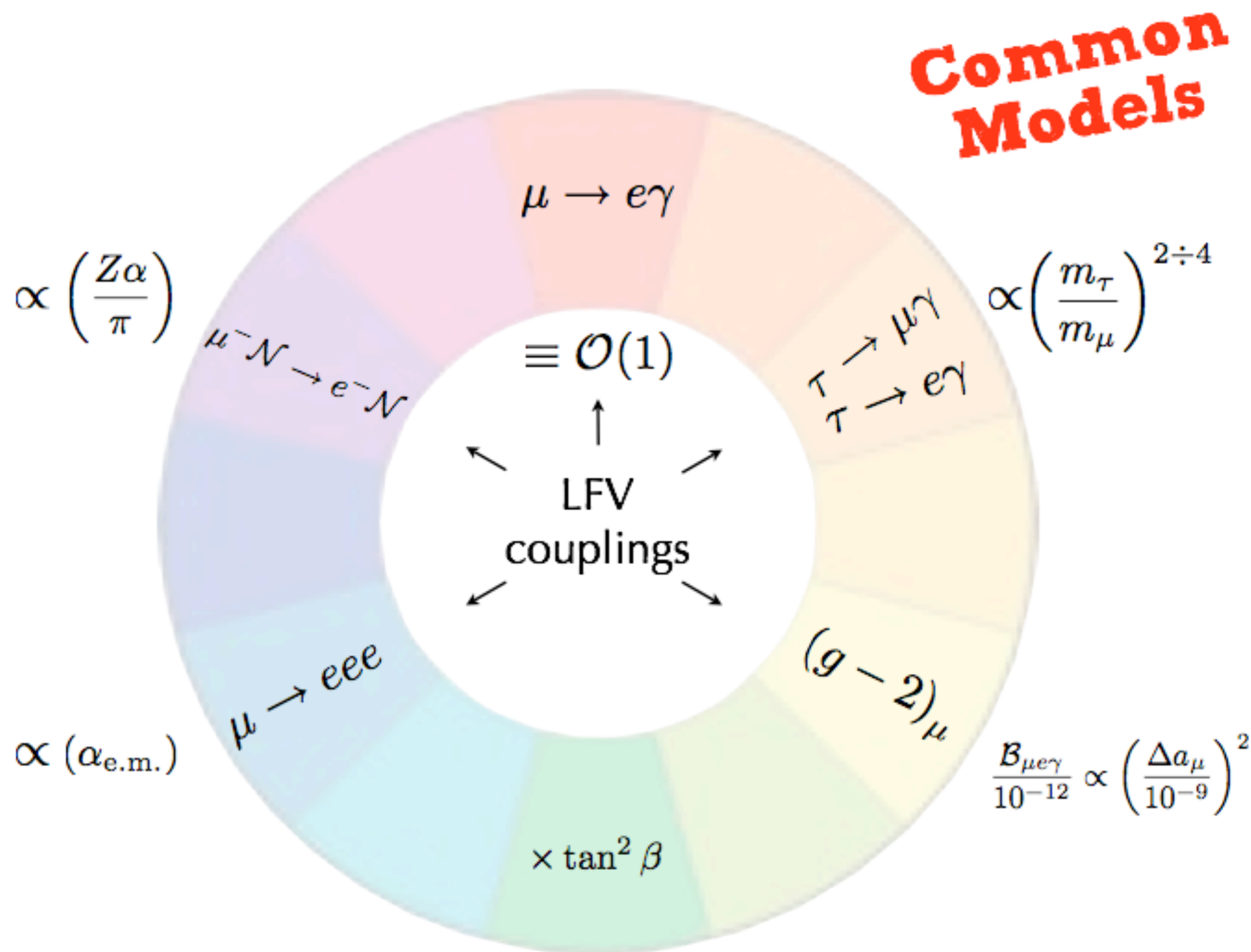
cLFV processes are a wide field of research

- LFV decays
- Muon to electron conversion in matter
- Anomalous magnetic moment



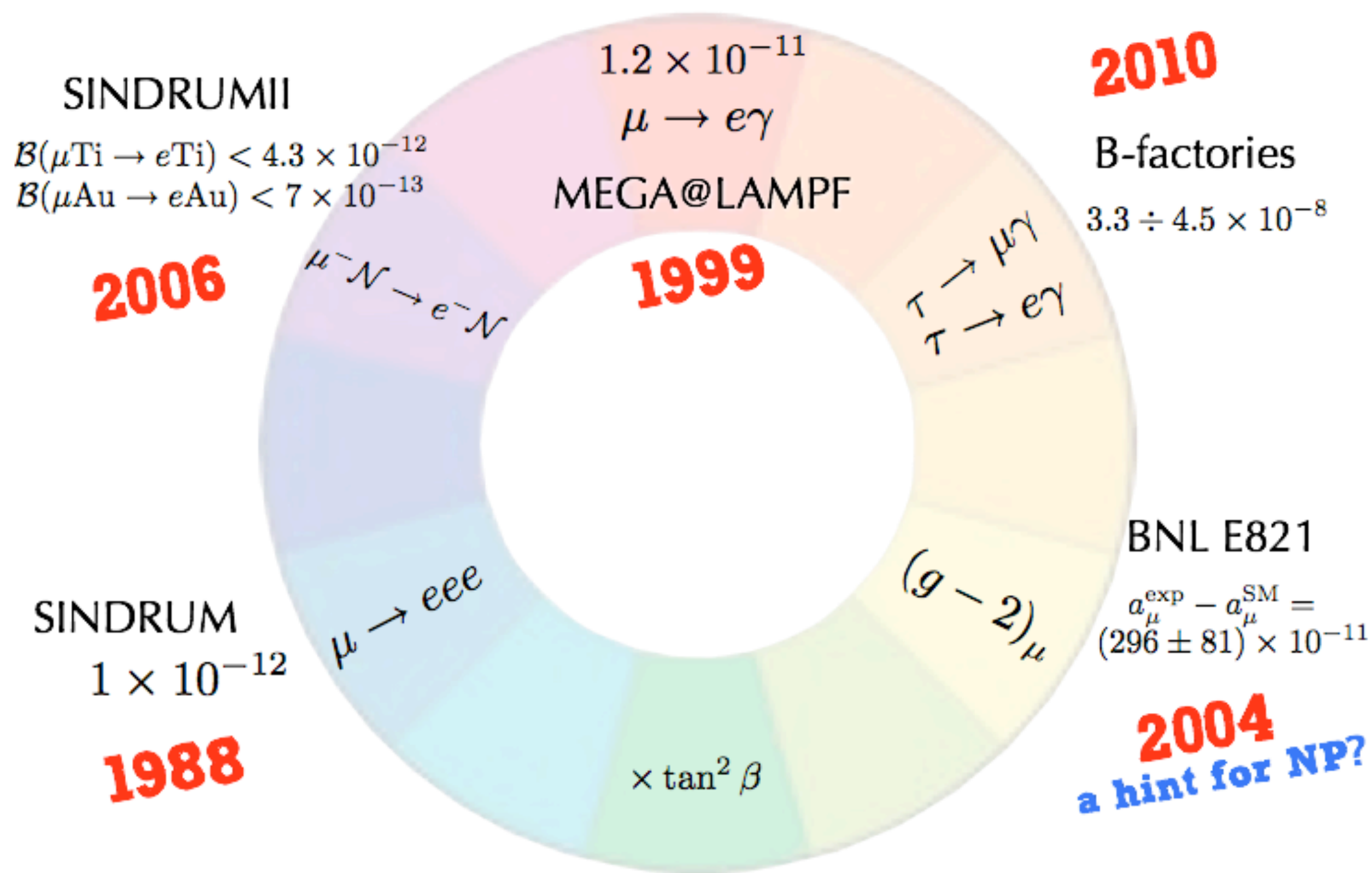


# The cLFV wheel



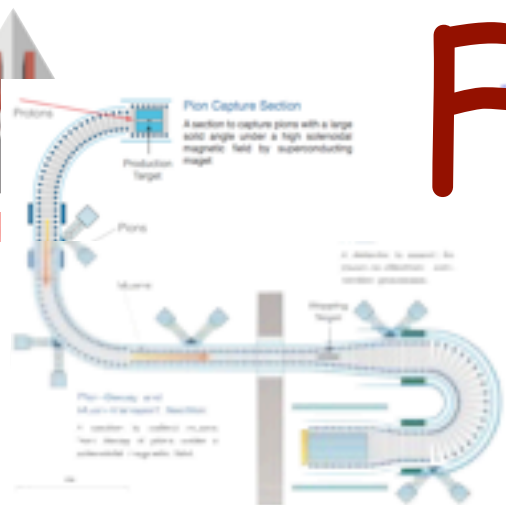


# Present Limits



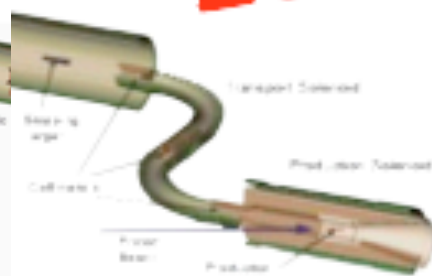


# Future Prospects



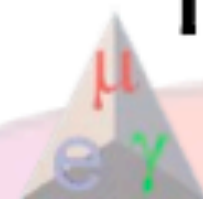
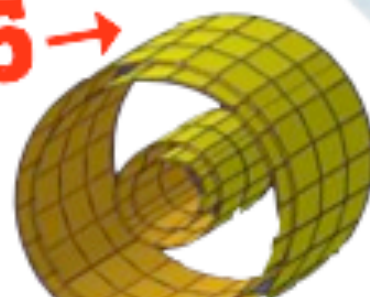
mu2e COMET  
 $10^{-16} \rightarrow 10^{-18}$

**2017** →



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

**2015** →



$\mu \rightarrow e \gamma$

MEG

few  $\times 10^{-13}$

**running**  
**→ 2013**

$\mu^- N \rightarrow e^- N$

$\mu \rightarrow e e e$

$\times \tan^2 \beta$

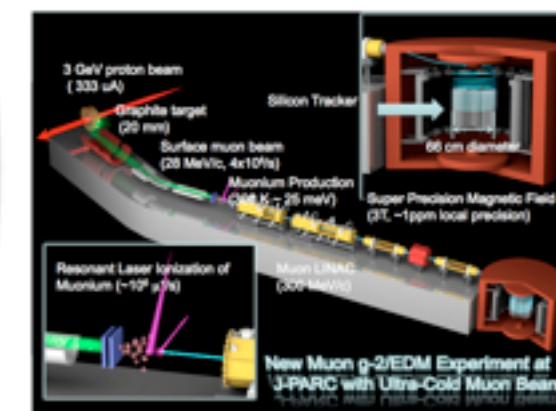


SuperB

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

**2015** →

$\tau \rightarrow \mu \gamma$   
 $\tau \rightarrow e \gamma$



g-2 JPARC

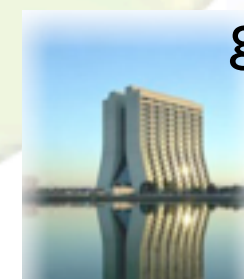
**2017?** →

$(g-2)_\mu$   
 $\Delta a_\mu = (XXX \pm 34) \times 10^{-11}$   
 $3.6\sigma \rightarrow 8\sigma$

**0.1 ppm**

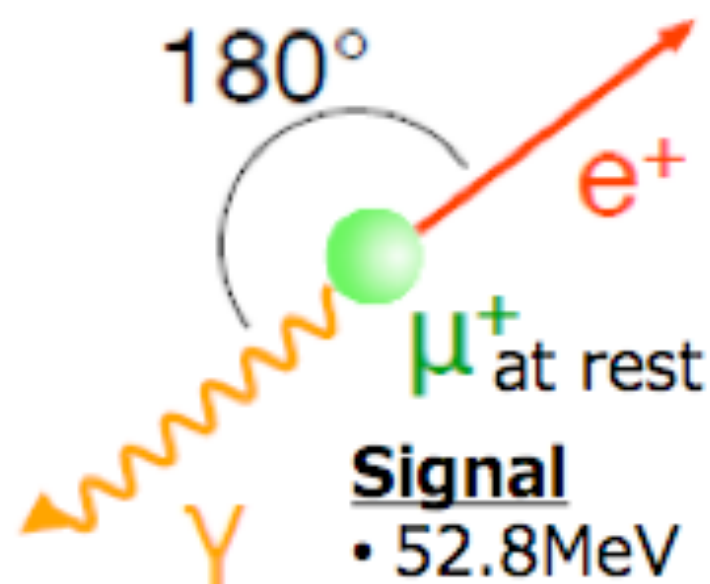
g-2 FNAL

**2017?** →



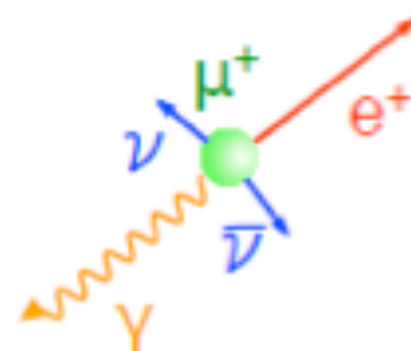


# $\mu \rightarrow e \gamma$ : experimental signature



## **Signal**

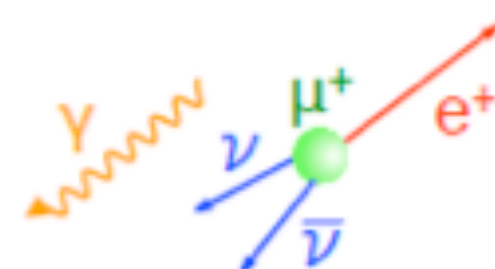
- 52.8 MeV
- Back-to-back
- Time coincidence



## **Physics BG**

(radiative muon decay)

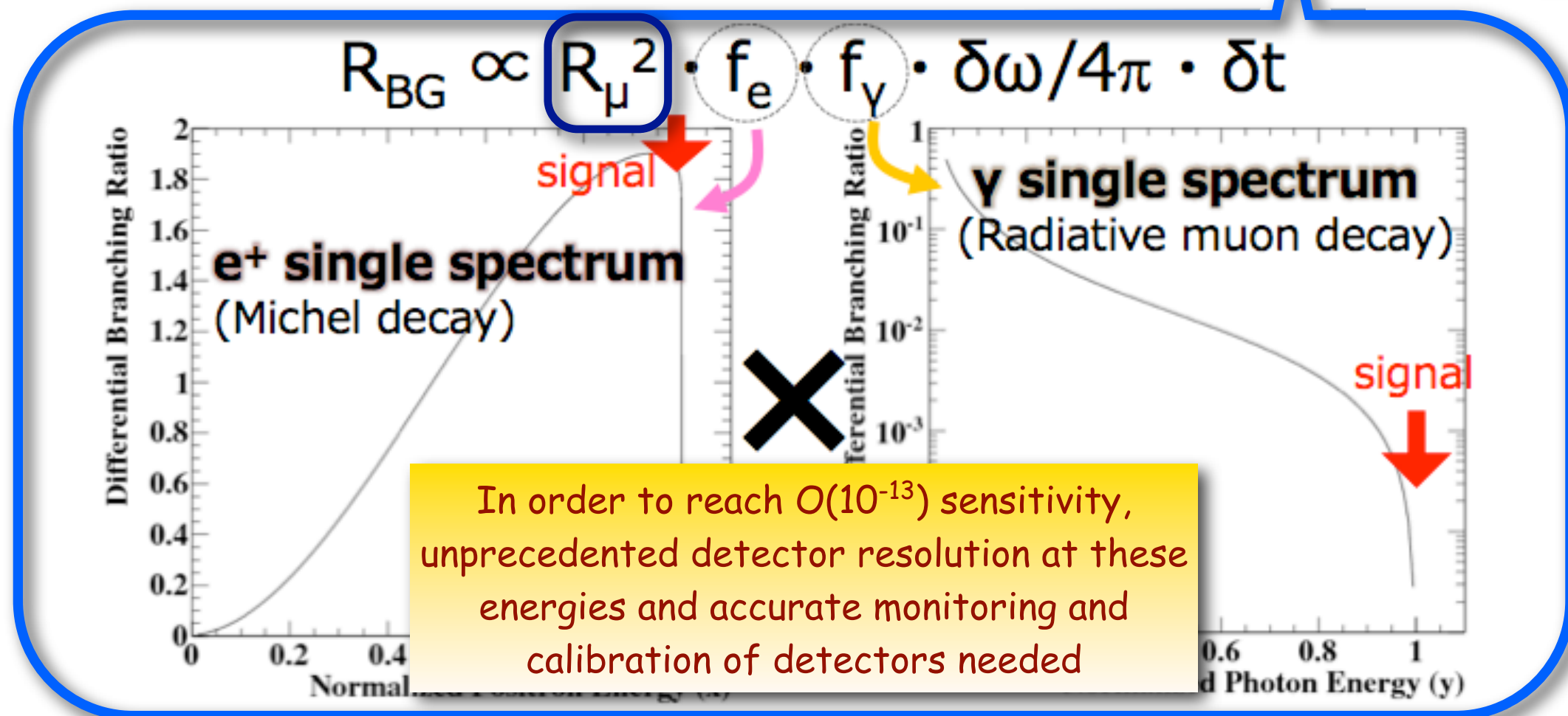
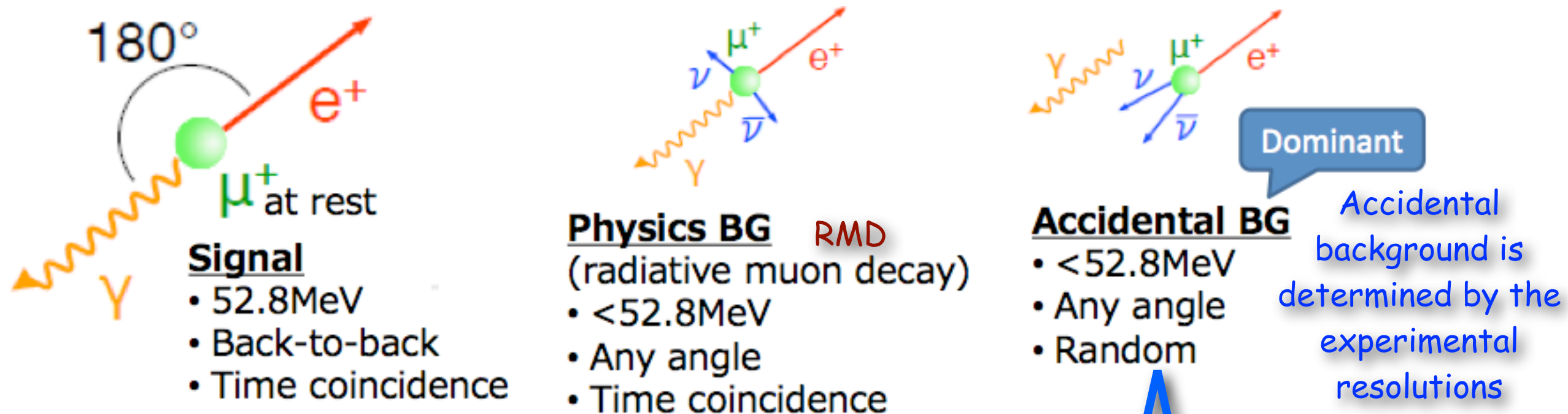
- < 52.8 MeV
- Any angle
- Time coincidence



## **Accidental BG**

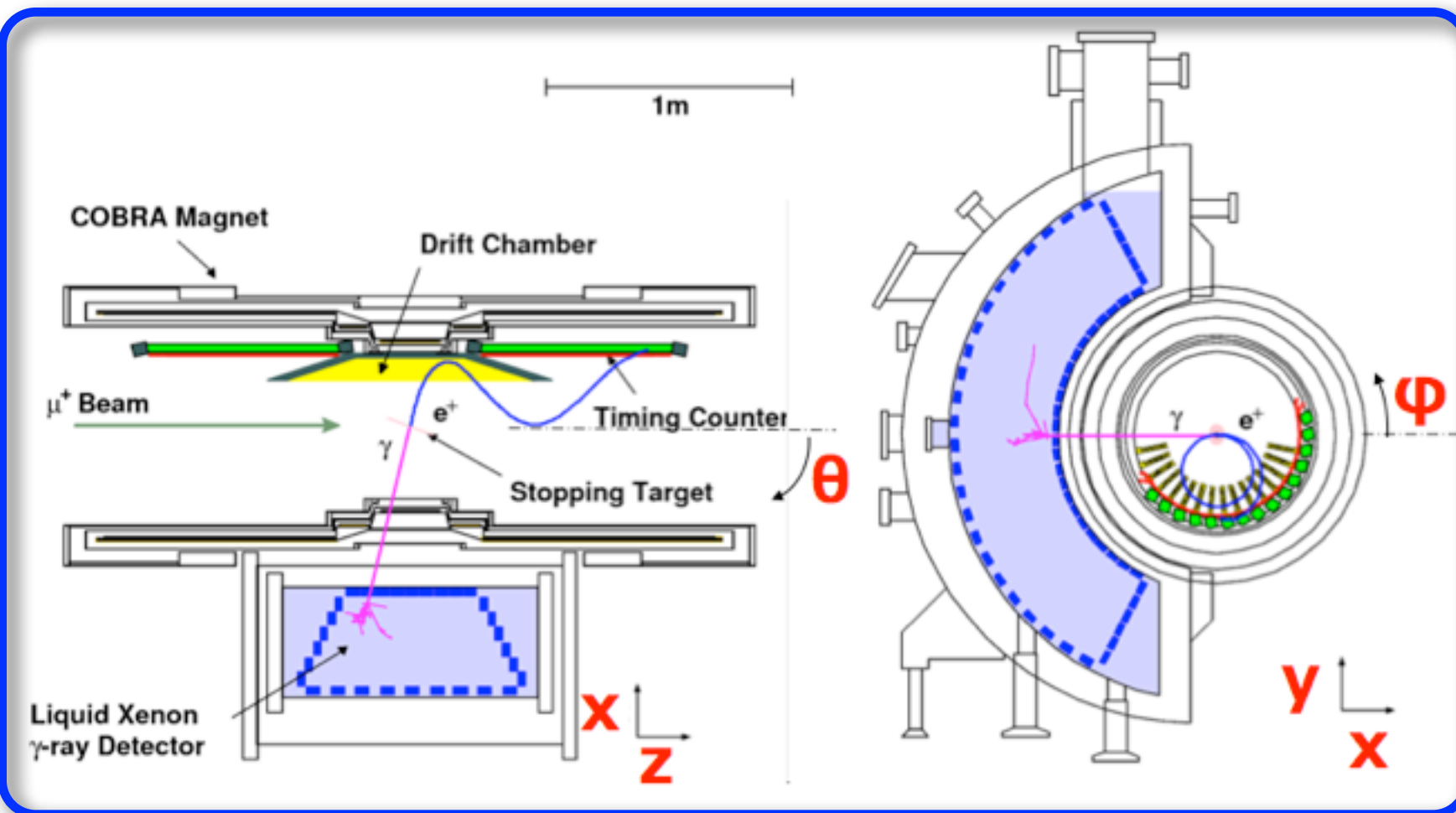
- < 52.8 MeV
- Any angle
- Random







# MEG in a nutshell



- Most intense DC muon beam of  $3 \times 10^7$  muon/s at PSI
- Quasi-solenoidal spectrometer & low mass drift chamber for  $e^+$  kinematic measurement
- Scintillator bars and fibers for  $e^+$  timing
- Liquid Xenon calorimeter for photon detection
- $\sim 10^7$  fully efficient trigger bkg suppression

~ 60 collaborators



INFN Genova  
INFN Lecce  
INFN Pavia  
INFN Pisa  
INFN Roma



KEK  
Tokyo Univ.  
Waseda Univ.



UC Irvine



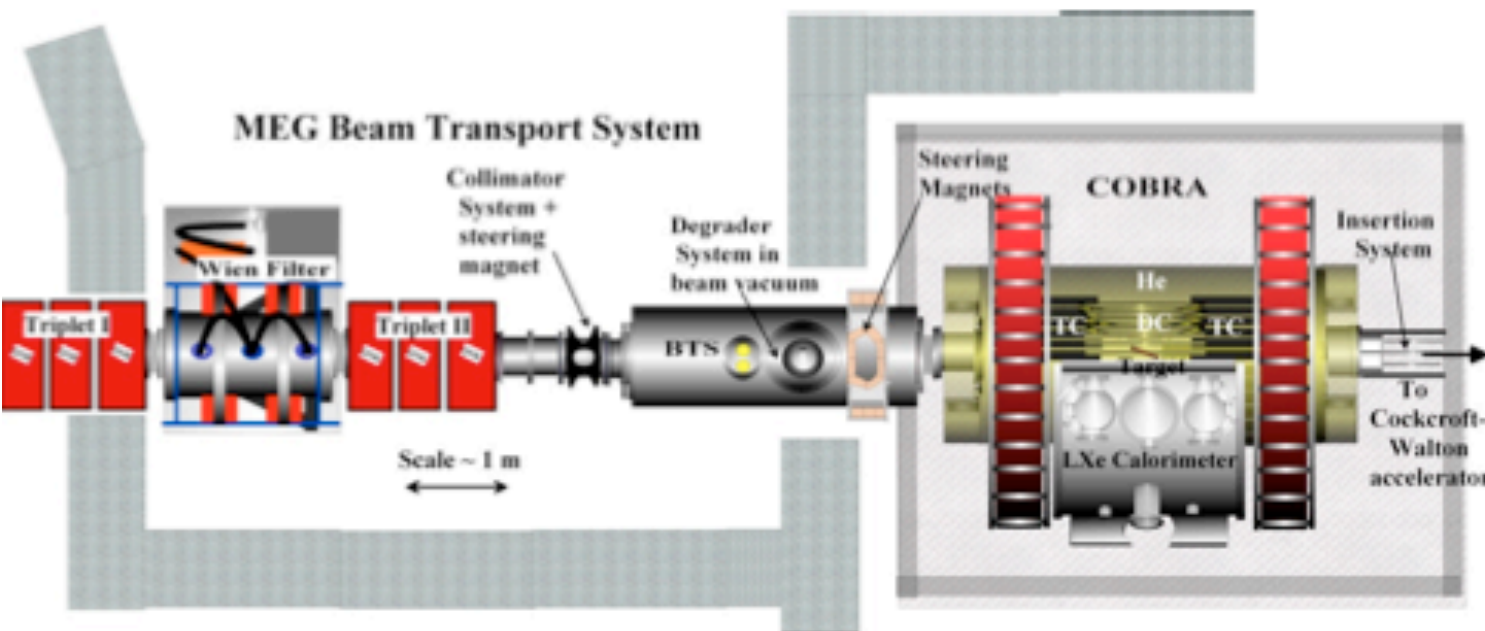
PSI



BINP - Novosibirsk  
JINR - Dubna



# The PSI $\pi E5$ beam & target



Most intense proton DC beam in the world : 2 mA @ 1.3 MW

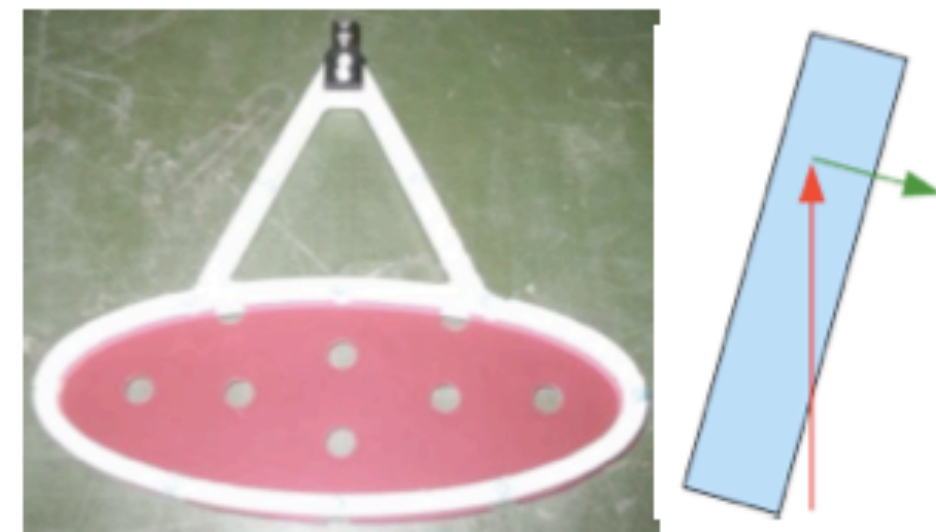
28 MeV/c "surface muons" from decay of  $\pi$  at rest

Wien filter for  $e/\mu$  separation

Solenoid to couple beam with the COBRA magnetic field

Need enough material for stopping muons but low bremsstrahlung for signal positron:

- degrader 200/300  $\mu\text{m}$  + target 205  $\mu\text{m}$
- 20.5° angle between beam and target
- material with high radiation length  $X_0$  ( $\text{CH}_2$ )





# Liquid Xenon $\gamma$ detector



First ton-scale ( $\sim 900$  L) LXe calorimeter in use in the world

## Pros

- High light yield ( $\sim 75\%$  NaI)
- Fast response ( $\tau_{\text{decay}} = 45$  ns)
- High stopping power ( $X_0 = 2.8$  cm)
- No self absorption
- Uniform, no segmentation, no aging

## Challenges

- Vacuum ultra violet (178 nm)
- Low temperature (165 K)
- Need high purity

Measure photon energy and time and position of conversion inside the LXe

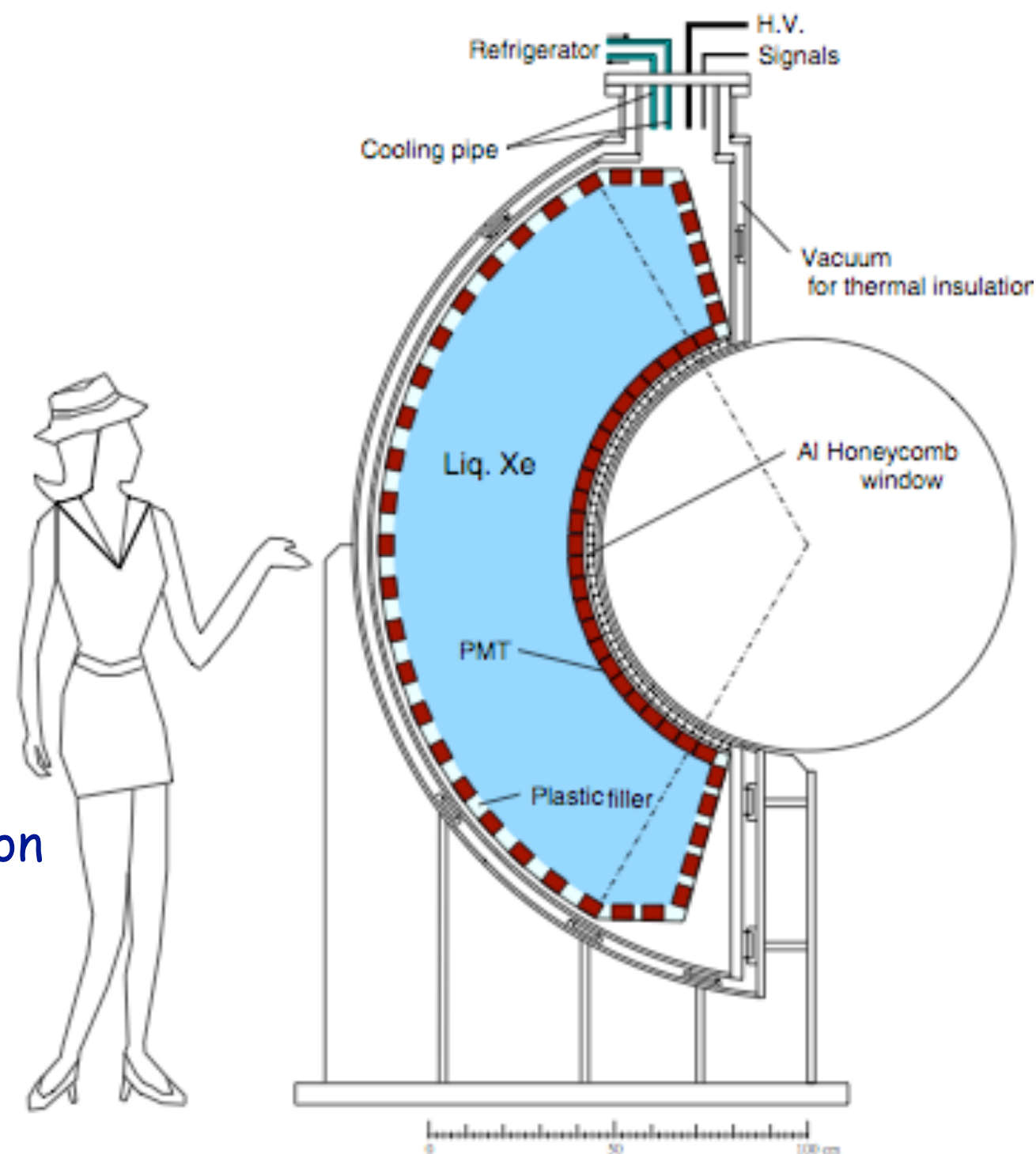
- $\sigma_E/E < 2\%$  @ 52.8 MeV
- $\sigma_t = 67$  ps
- $\sigma_x = 5\text{-}6$  mm

proposal

1.2 %

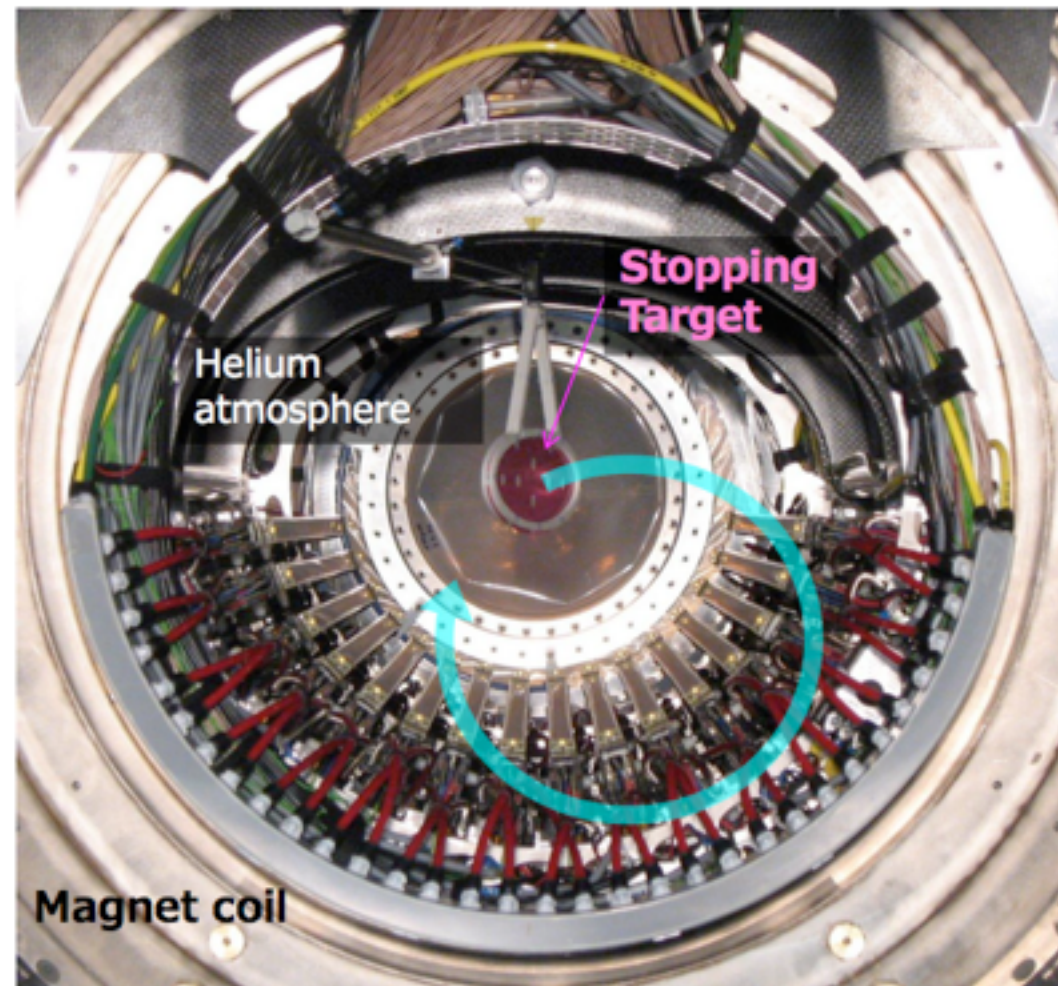
43 ps

3.8-5.1 mm





# The Spectrometer



Experimental requirements:

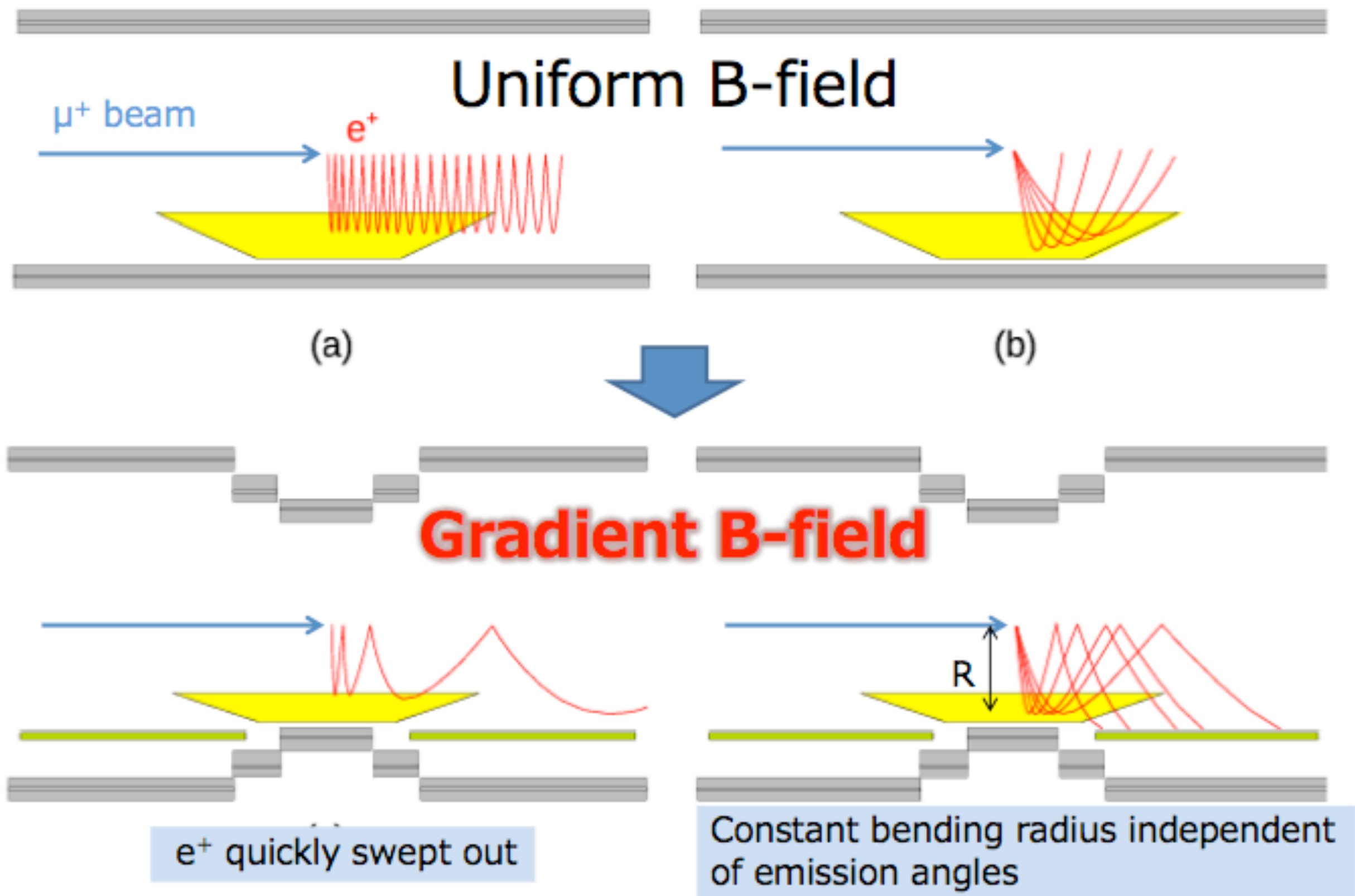
Very good momentum and angular resolution ( $\sim 200$  KeV @ 52.8 MeV and  $\sim 5$  mrad)

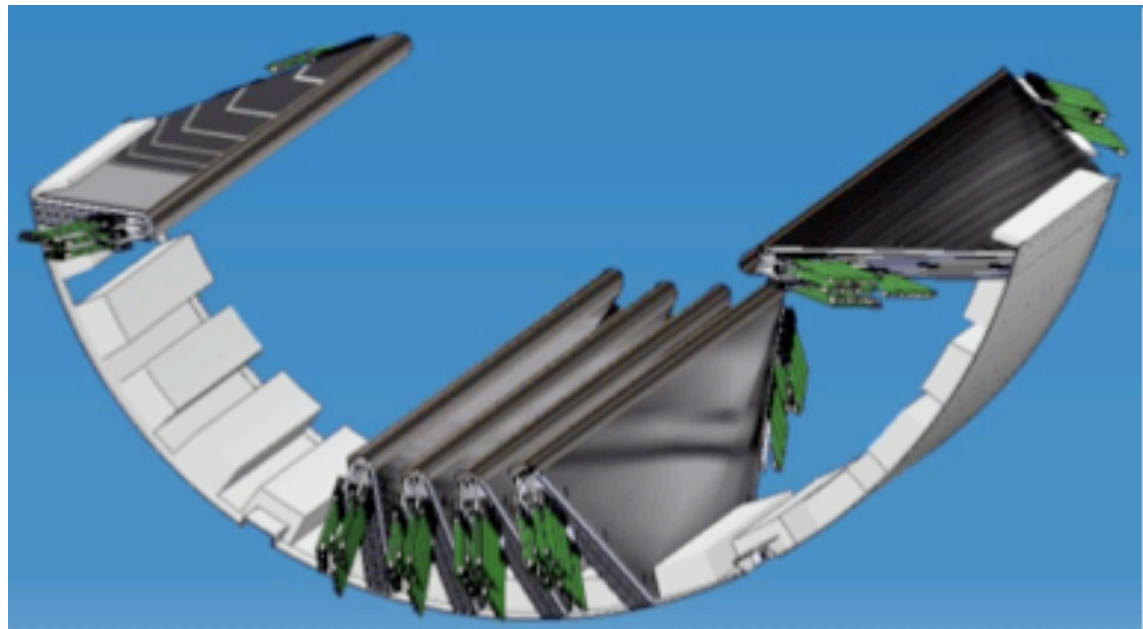
Low pile-up for efficient background rejection



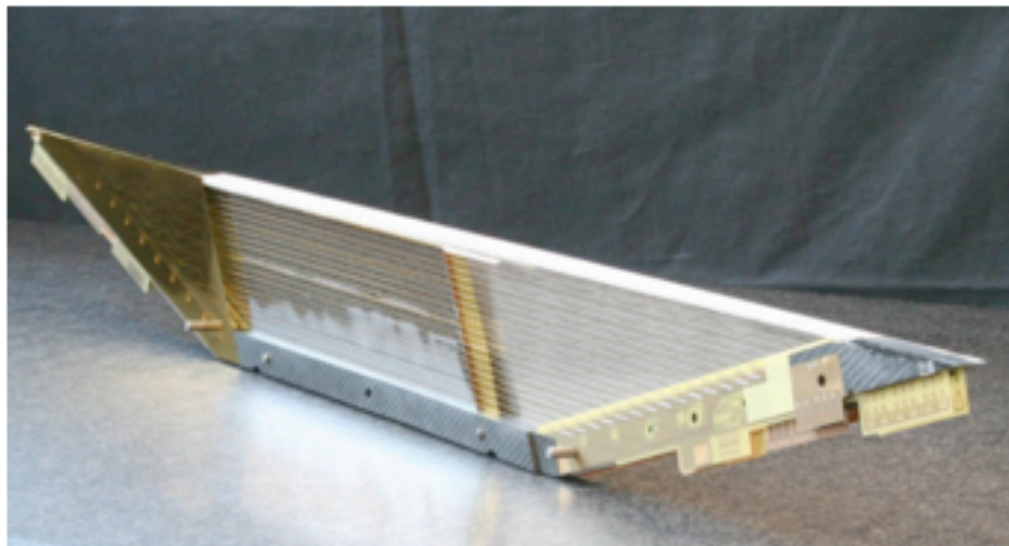
Low mass drift chambers in graded magnetic field (COBRA)



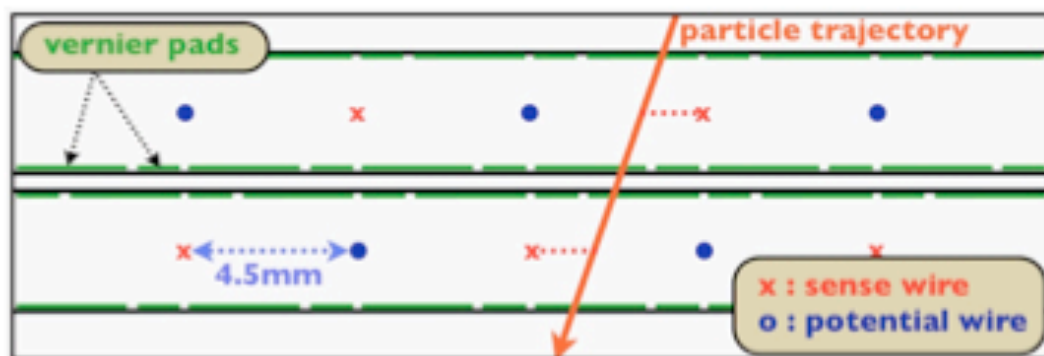




- 16 chamber sectors, 2 planes each
- Staggered array of drift cells
- Helium:Ethane 50/50 mixture
- Ultra low mass chamber to suppress MS that limits momentum and angular resolutions



- 12.5  $\mu\text{m}$  cathode foils with Vernier pattern for Z hit position
- $\sim 0.2\%$   $X_0$  along  $e^+$  trajectory
- Reconstruct  $e^+$  momentum vector at target with Kalman filter technique



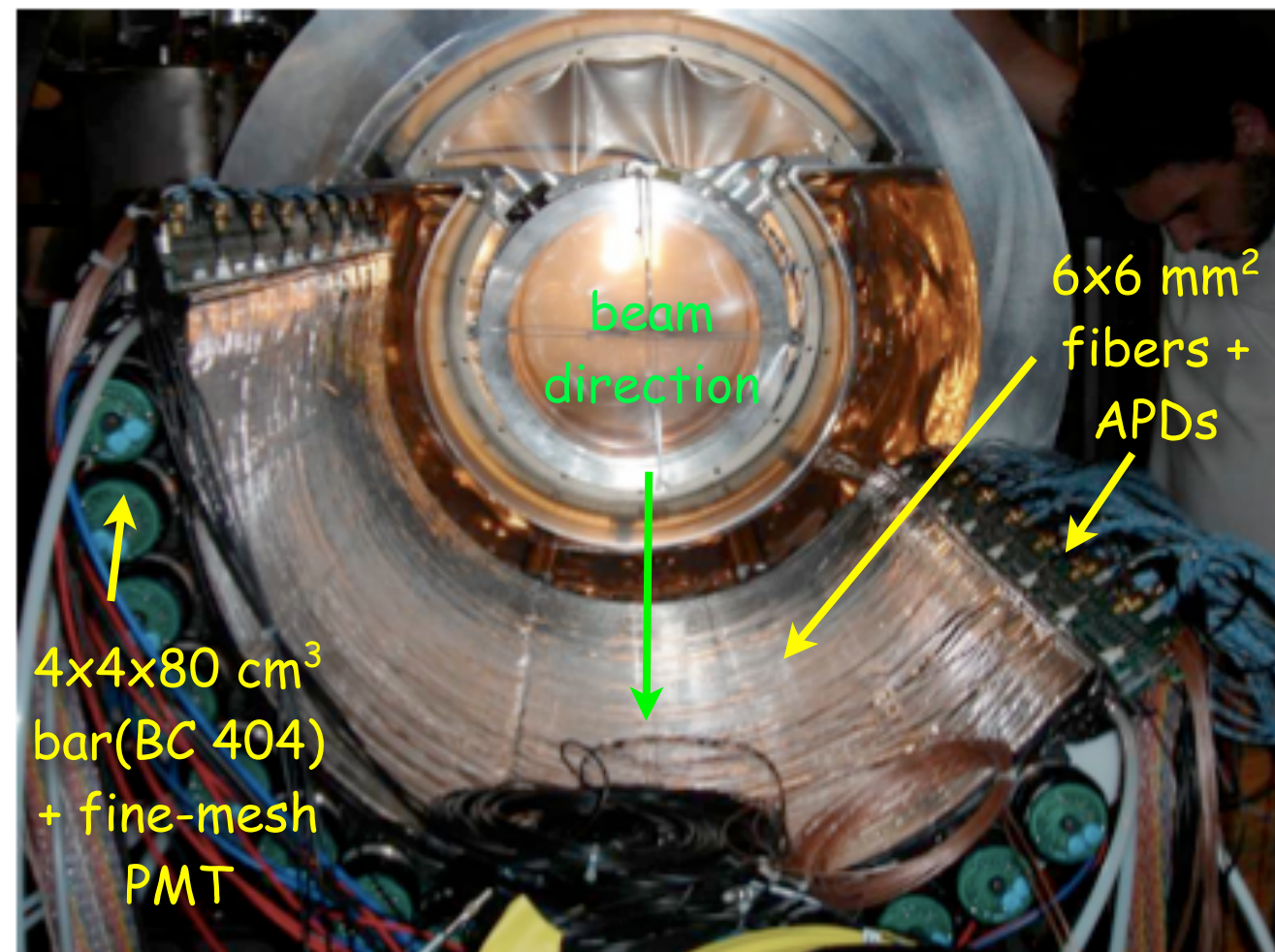
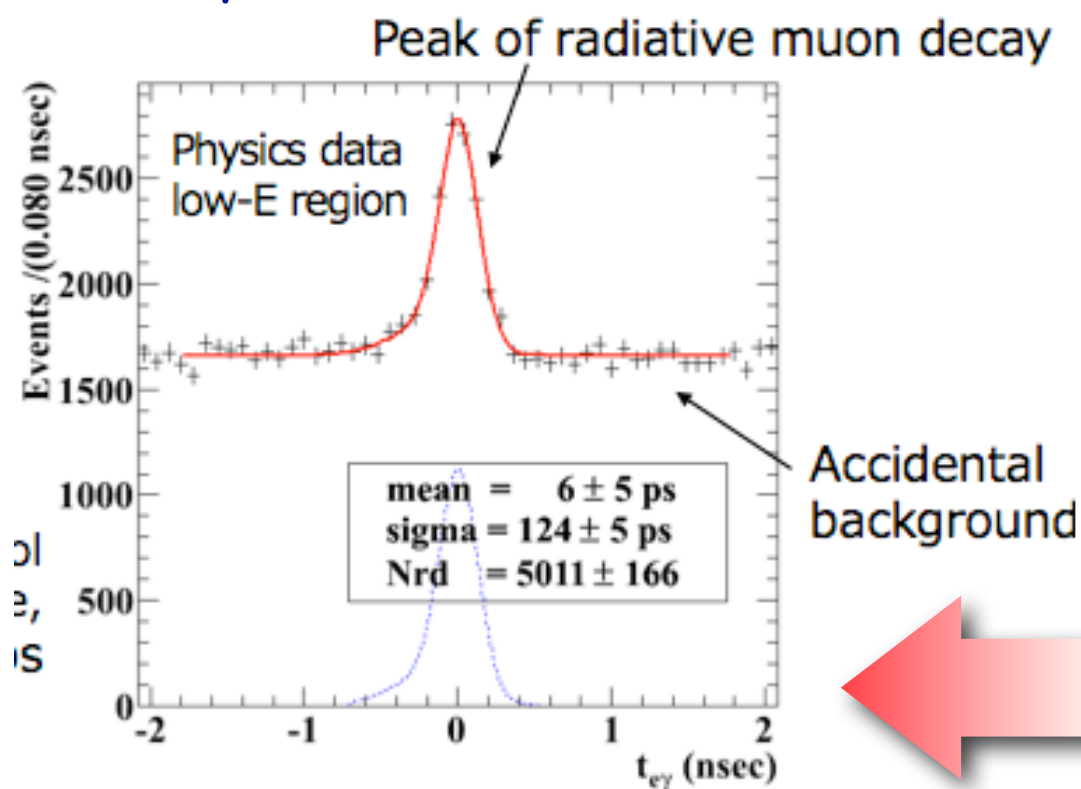
- |                                      |                   |
|--------------------------------------|-------------------|
| $\sigma_E/E \sim 0.6\%$              | proposal<br>0.3 % |
| $\sigma_\theta \sim 10 \text{ mrad}$ | 5 mrad            |
| $\sigma_\phi \sim 7 \text{ mrad}$    | 5 mrad            |





# Time Measurement

- Positron time measured by timing counter:  
2 sections (upstream & downstream) of 15 bars each read by fine mesh PMTs
- Further z impact position measurement with scintillating fibers read by APDs
- Crucial for positron time measurement:  
intrinsic time resolution: current  $\sim 70$  ps/  
goal  $\sim 50$  ps



Muon decay time:

TC hit time +  $e^+$  flight length from DC

LXe hit time +  $\gamma$  flight length

$$t_{e\gamma} = t_{e^+} - t_{\gamma}$$

$\sigma_{t_{e\gamma}} = 122$  ps from RMD





# Trigger & DAQ



## DAQ

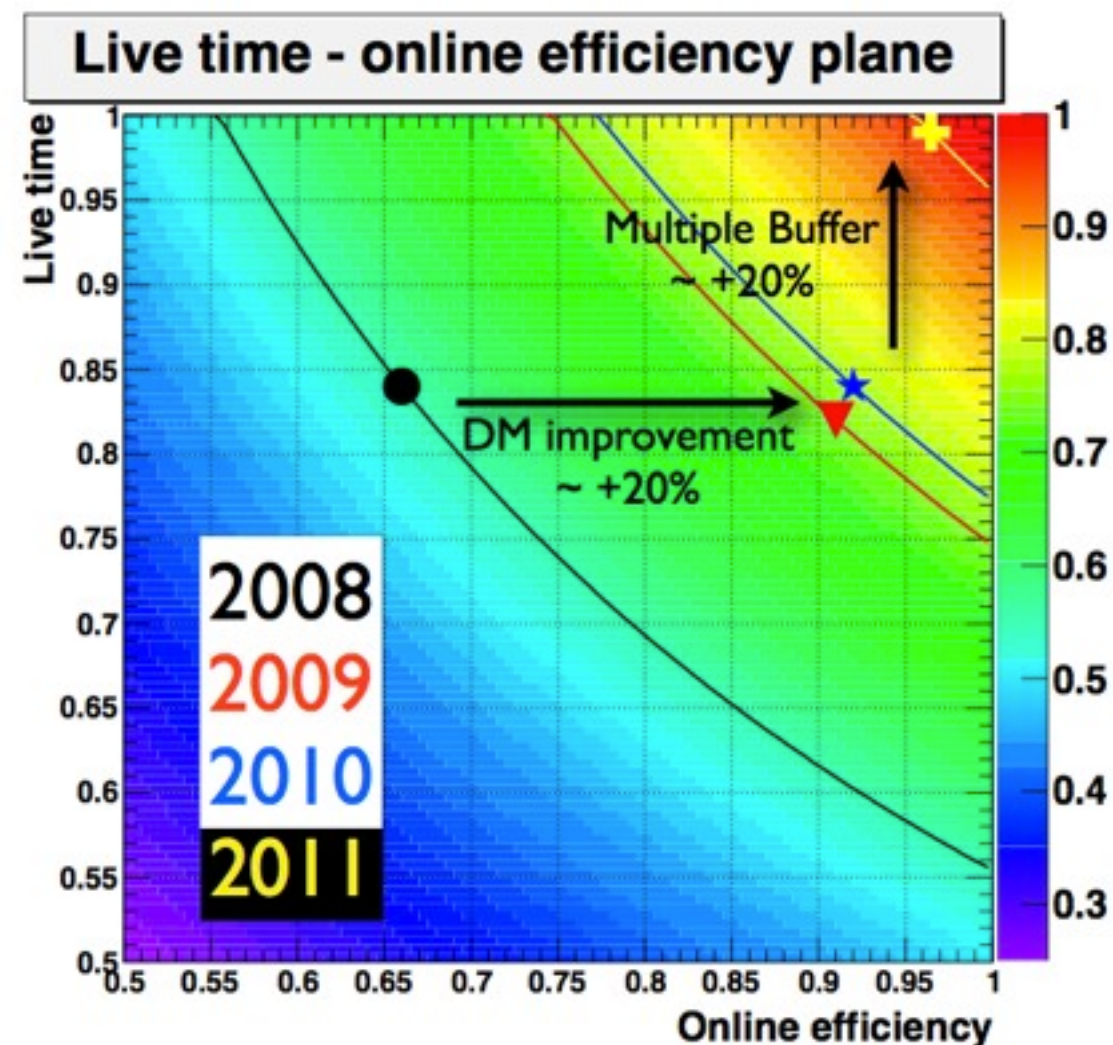
- Custom WF digitizer DRS chip design at PSI
- Sampling speed [800 MHz, 5 GHz]
- Bandwidth 1 GHz
- inter-chip synchronization < 30 ps

## Trigger experimental requirements

- $O(10^7)$  background suppression
- > 95 % efficiency on signal
- Maximum latency ~ 450 ns
- Flexibility for physics analysis as well as calibrations

## MEG choices

- 100 MHz digital conversion of input signals
- Selection algorithms on FPGAs
- Use of fast detector, LXe and TC:
  - $E_\gamma > 45 \text{ MeV} \rightarrow \text{rate } 2 \times 10^3 \text{ Hz}$
  - $\Delta t$  between LXe and TC  $\rightarrow \text{rate } 100 \text{ Hz}$
  - Collinearity based on LUT tables  $\rightarrow 10 \text{ Hz}$



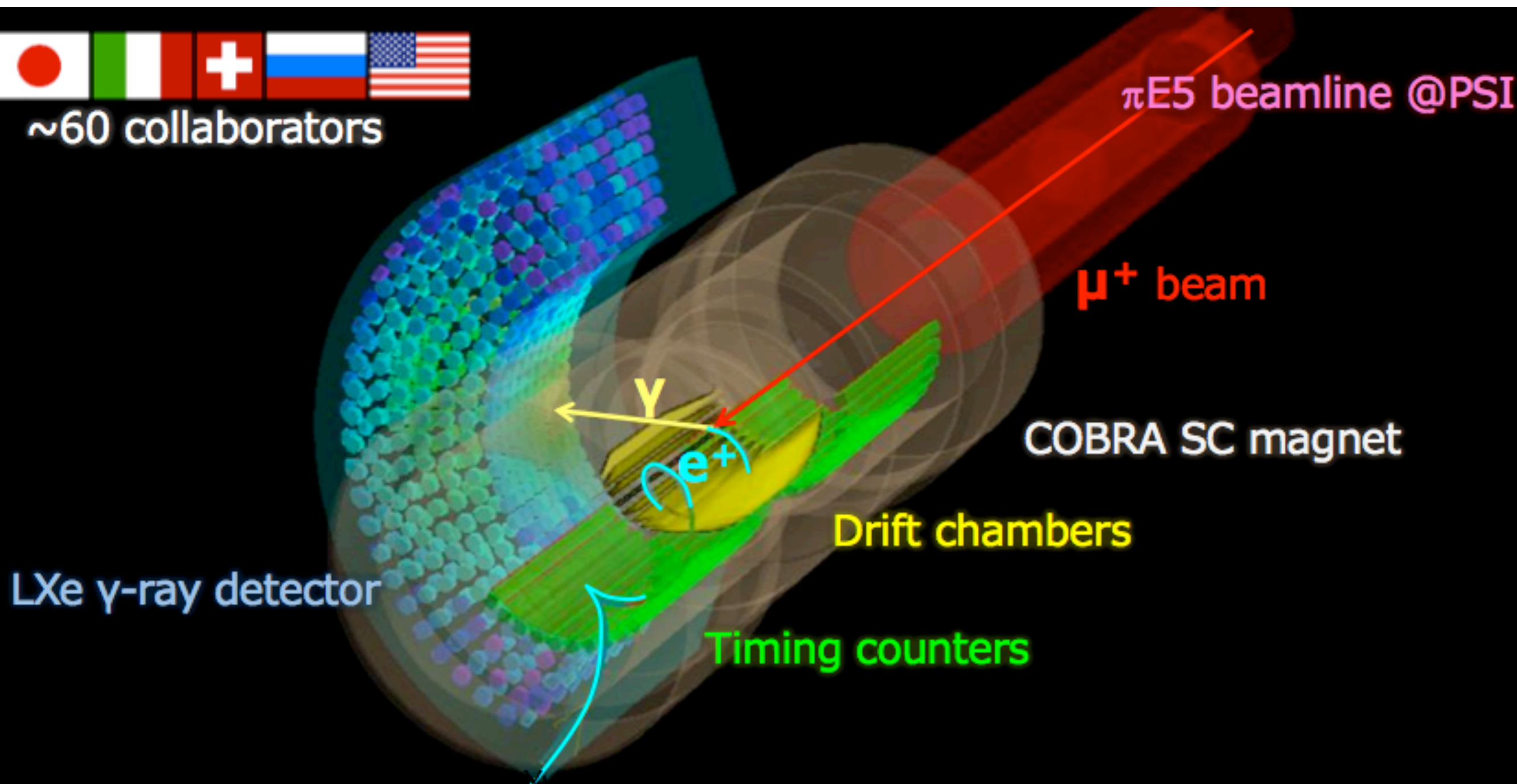
Trigger improvements through time thanks to improved online resolutions (DM improvement) and multiple buffer readout implementation (MB)



# MEG picture



~60 collaborators

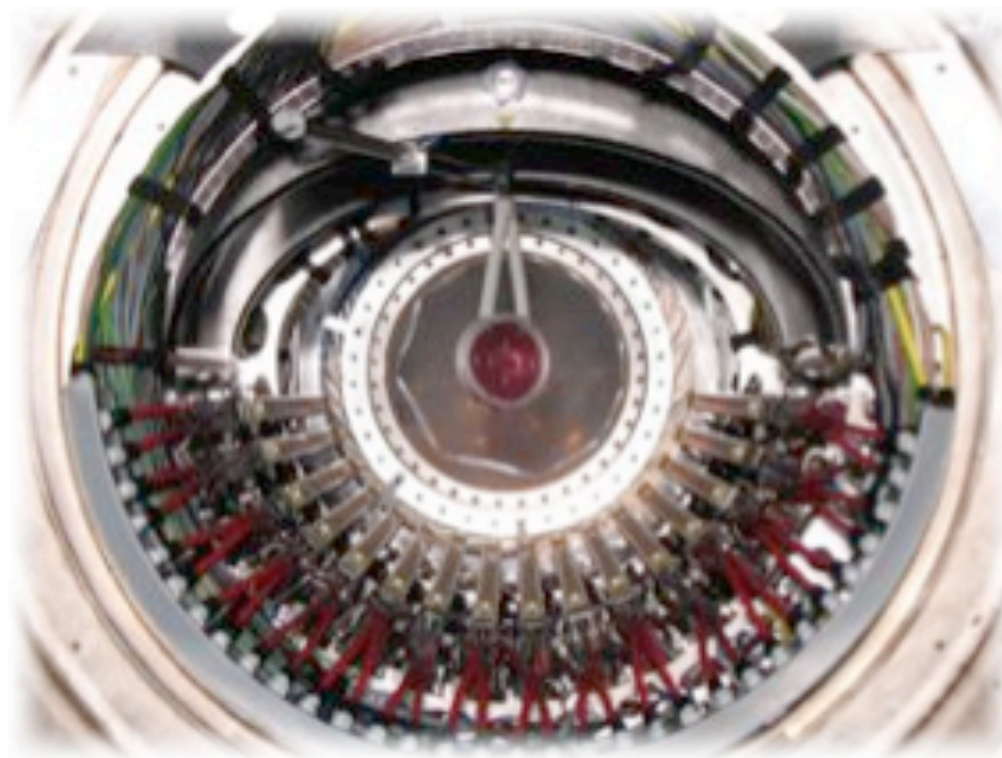




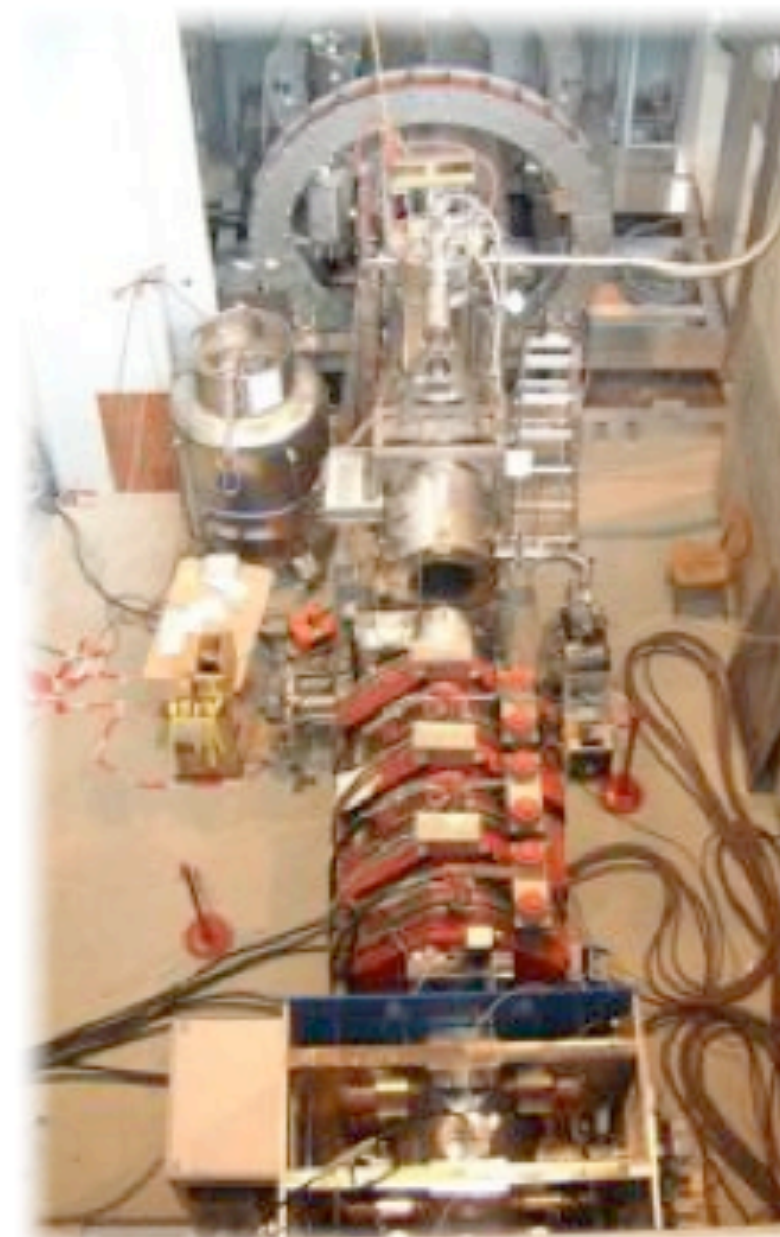
LXe detector



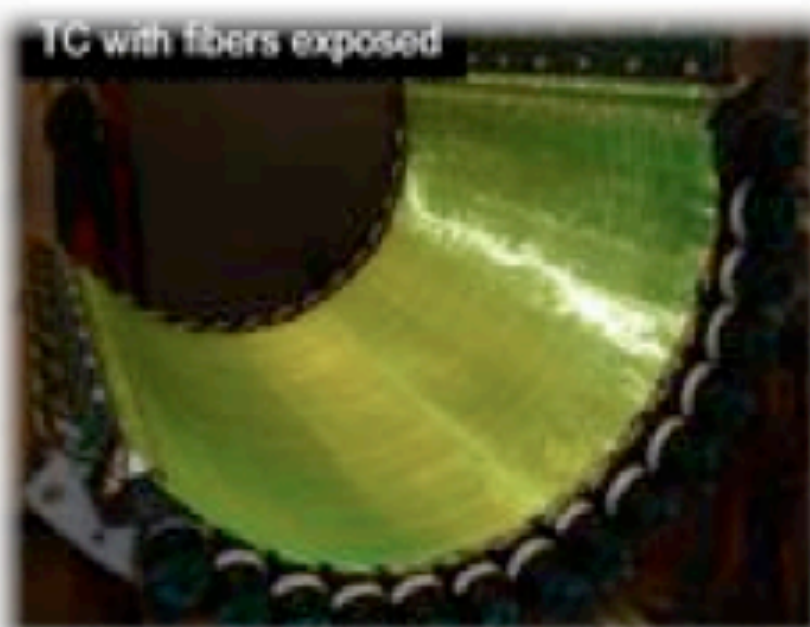
DC system



Beam Line



TC with fibers exposed





**LED**  
PMT gain

**$\alpha$  source**  
PMT QE  
Absorption length

**Ni  $\gamma$  generator**  
9 MeV  $\gamma$ -line  
beam on/off calib.

**CEX**  
 $\gamma$ -resolutions:  
- energy  
- time  
- impact point

LH<sub>2</sub> target

**XENON CALIBRATION**

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

$t_{ey}$

**CW p-accel**  
Light Yield  
LXe-TC t-calib

## TRACKER CALIBRATION

**Cosmic Ray**

- DC alignment
- TC uniformity
- LXe monitoring

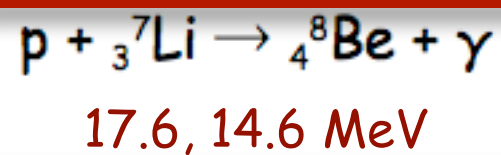
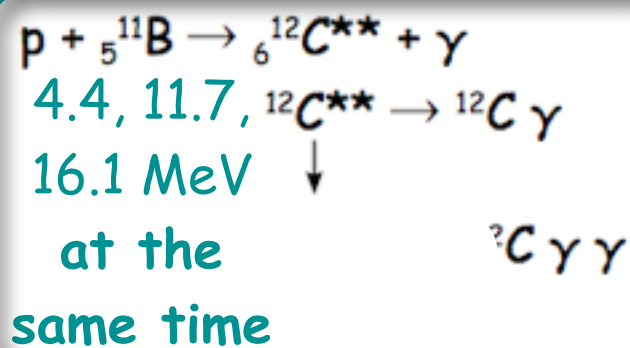
**$e^+$  Mott-scatter**

- Monochromatic, tunable momentum beam

**Michel decays**

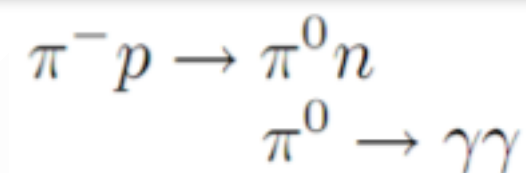
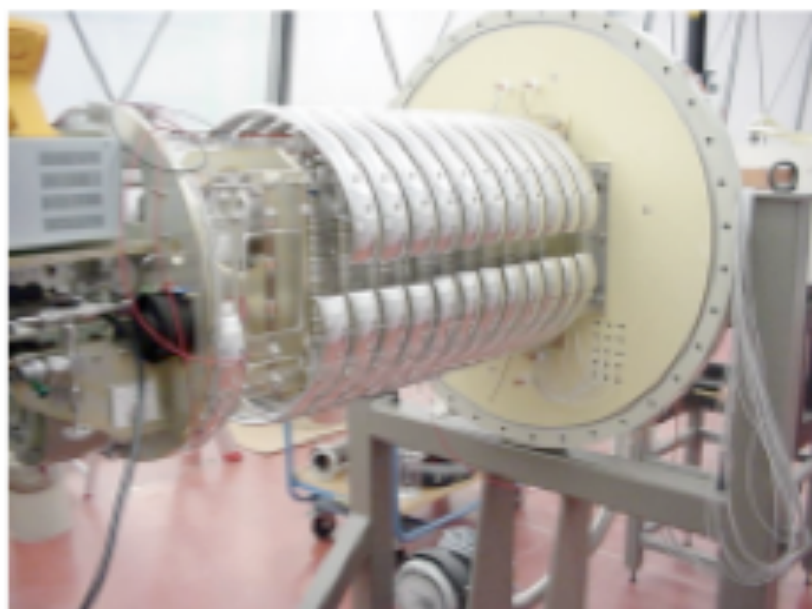
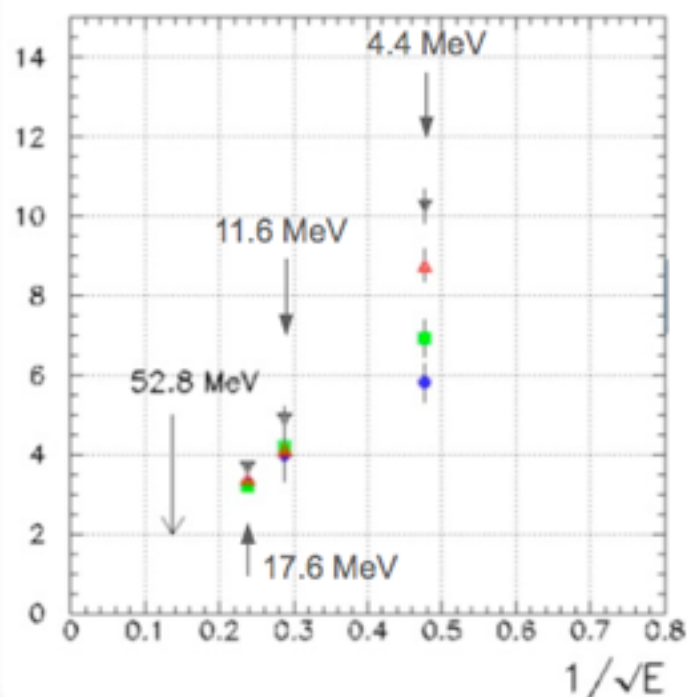
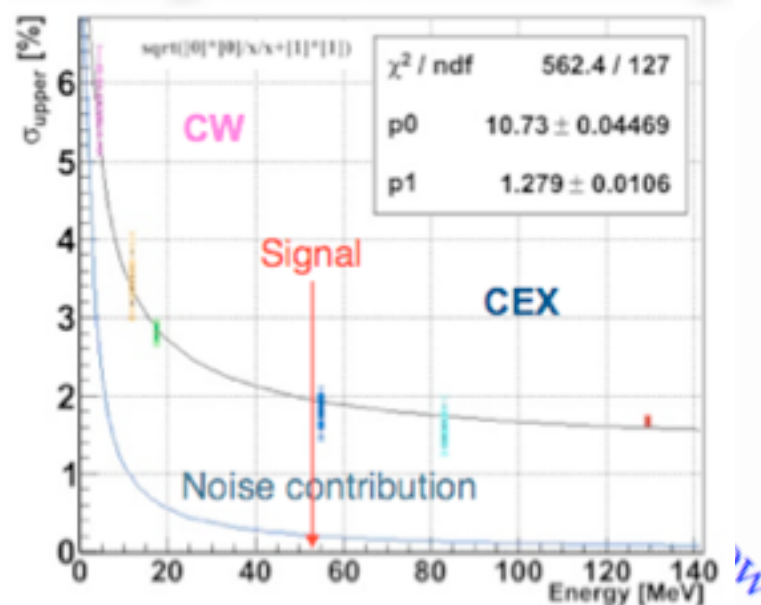
- $\mu \rightarrow e \nu \bar{\nu}$  for momentum energy scale

# CW and CEX calibrations

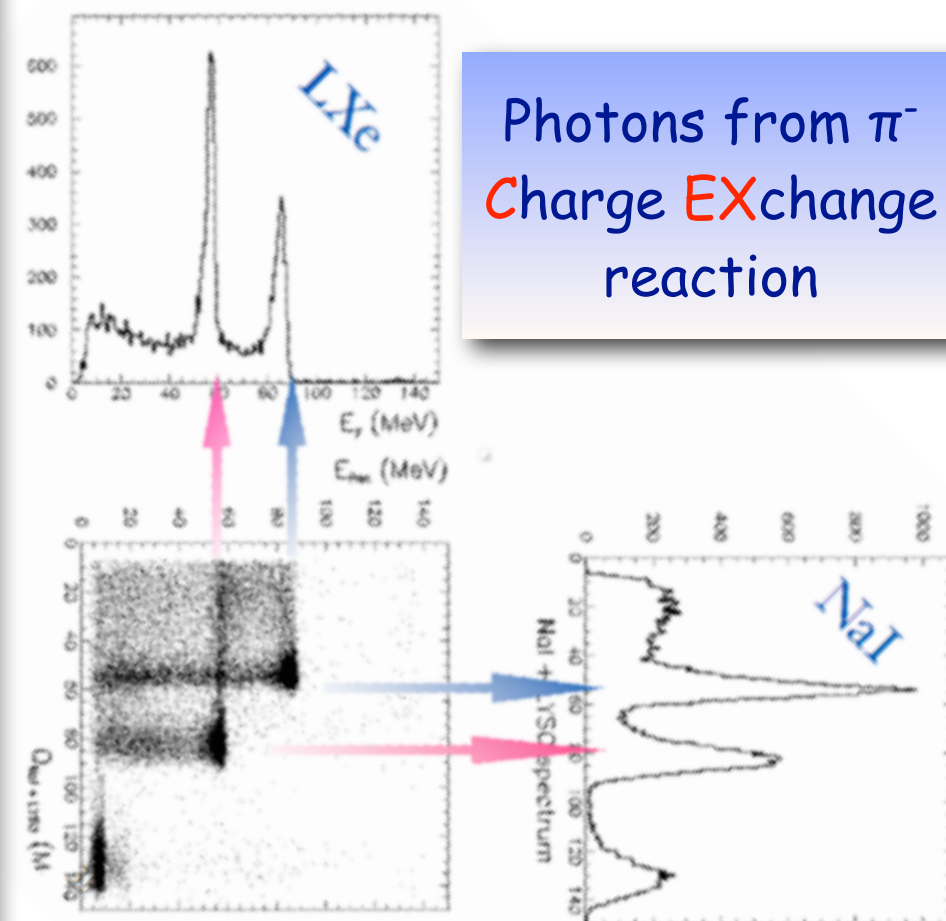


Target of  $\text{Li}_2\text{B}_4\text{O}_7$  allows both  
calibrations at same time

Cockcroft-Walton  
accelerator



Photons from  $\pi^-$   
Charge EXchange  
reaction



83 MeV

55 MeV

photons  
opening  
angle



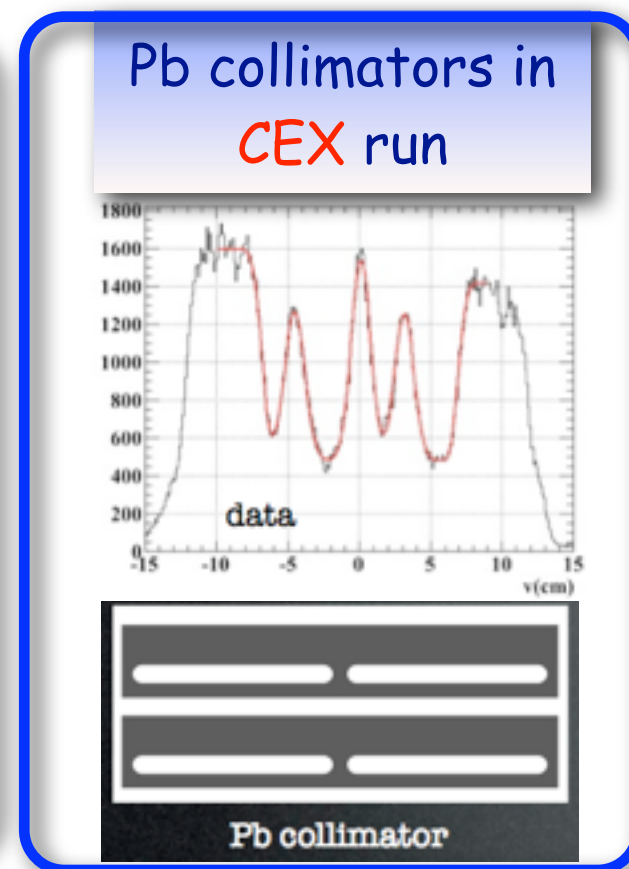
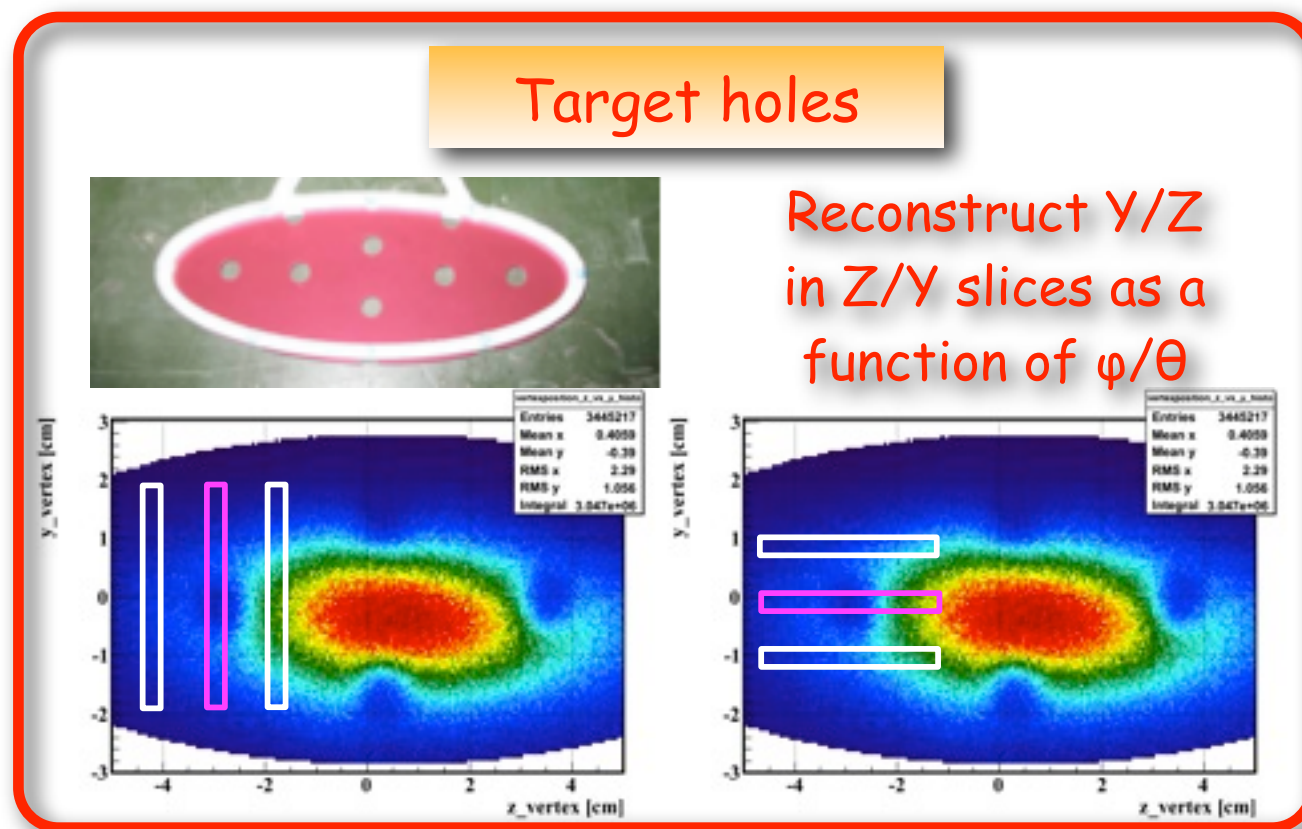
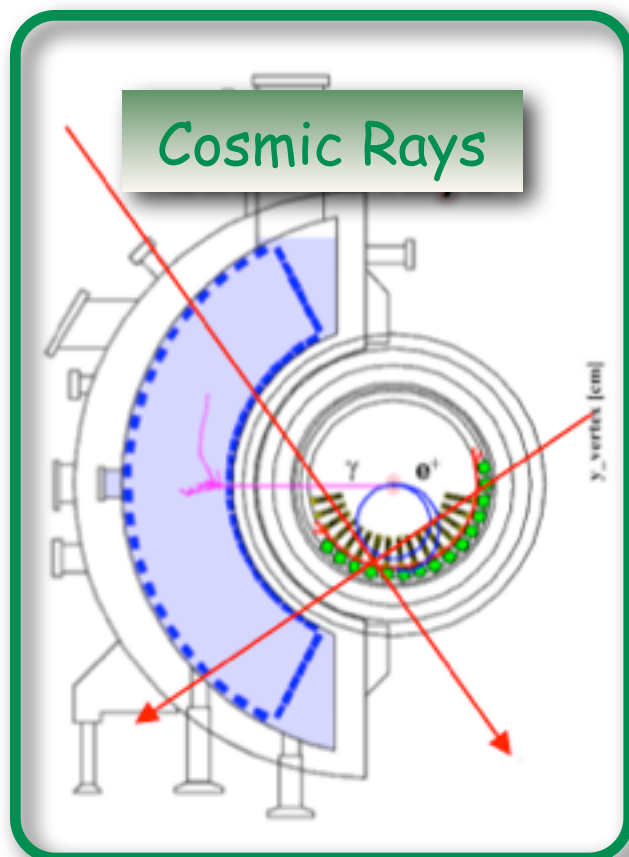


# Alignment

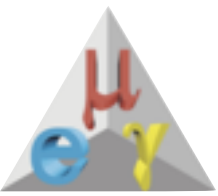


- Good alignment is crucial to reduce systematics on relative photon-positron angle
  - No back to back source for calibration
  - Nonetheless, we improved alignment inside and among detectors
    - DC - B field - target - LXe

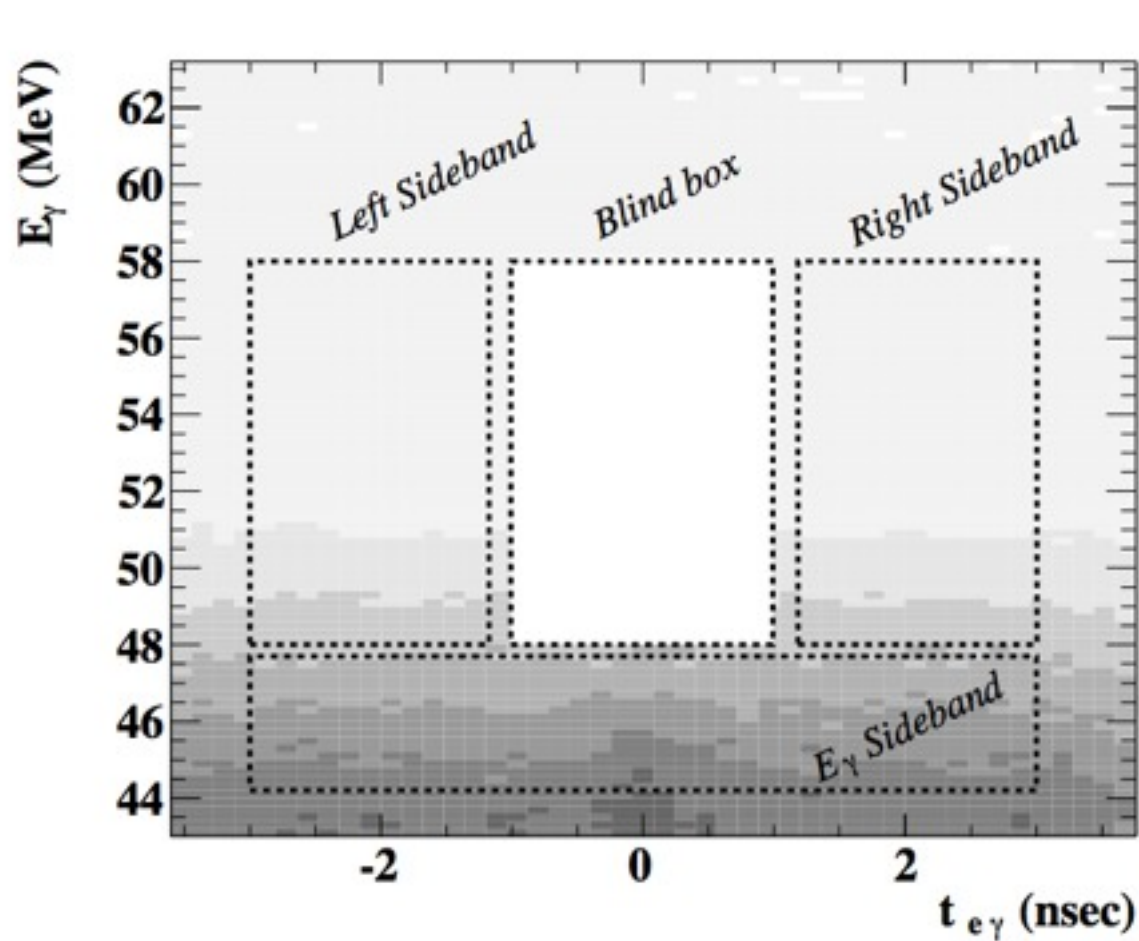
- Tools:
  - Optical surveys
  - DC: Millipede (a la CMS) with cosmic rays + Michel  $e^+$
  - Target holes
  - LXe: Pb collimators
  - B field: resolutions and correlations







# Analysis Technique



Blind analysis technique adopted:

Events inside a signal region of  $E_\gamma$  and  $t_{e\gamma}$  not used for analysis development

Background characterization from sidebands:

accidental bkg from off-time sidebands,

RMD from low energy  $E_\gamma$  sideband

Extended unbinned ML fit of  $N_{\text{sig}}$ ,  $N_{\text{RMD}}$  and  $N_{\text{bkg}}$

Observables  $E_\gamma$ ,  $E_e$ ,  $t_{e\gamma}$ ,  $\theta_{e\gamma}$ ,  $\phi_{e\gamma}$ ,

Number of muons stopped on target:  $1.7 \times 10^{14}$  ( $6.5 \times 10^{13}$  (2009) +  $1.1 \times 10^{14}$  (2010))

Count unbiased Michel sample in physics data simultaneously with the signal

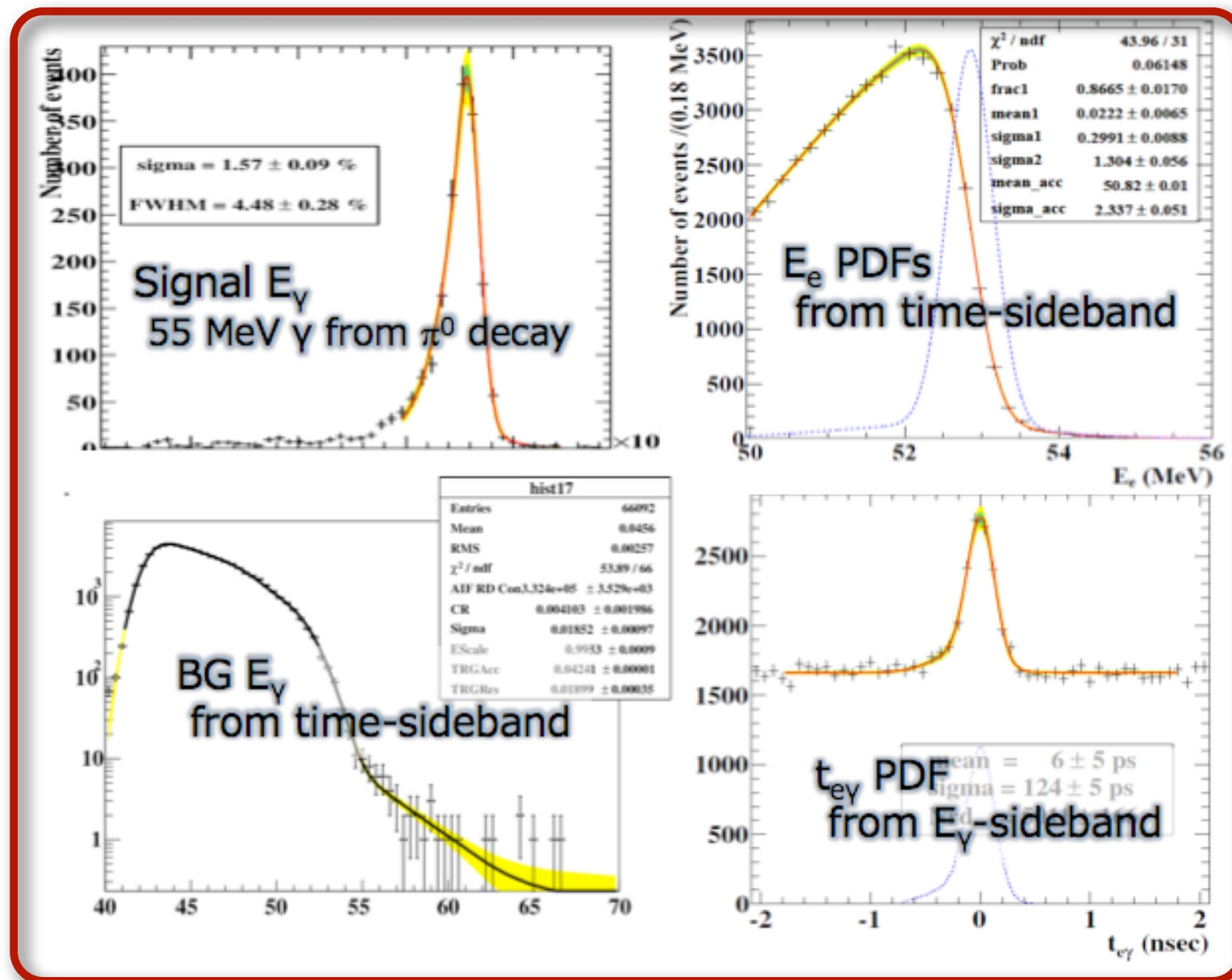
Count RMD sample in  $E_\gamma$  sideband (independent sample) for consistency check

Independent of instantaneous beam rate and insensitive to acceptance and efficiency

$$\text{BR}(\mu^+ \rightarrow e^+ \gamma) = \frac{N_{\text{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f_{e\nu\bar{\nu}}^E}{P} \times \frac{\epsilon_{e\nu\bar{\nu}}^{\text{trig}}}{\epsilon_{e\gamma}^{\text{trig}}} \times \frac{A_{e\nu\bar{\nu}}^{\text{TC}}}{A_{e\gamma}^{\text{TC}}} \times \frac{\epsilon_{e\nu\bar{\nu}}^{\text{DCH}}}{\epsilon_{e\gamma}^{\text{DCH}}} \times \frac{1}{A_{e\gamma}^g} \times \frac{1}{\epsilon_{e\gamma}},$$



# PDFs



- Signal  $E_e$  PDF from fit to Michel edge data
- Signal angle PDFs measured on data from tracks which make two turns inside the spectrometer
- Background angle PDFs measured on time sideband
- RMD PDFs from theoretical distributions convoluted with measured resolutions

Fit variables:  $E_\gamma$ ,  $E_e$ ,  $t_{e\gamma}$ ,  $\theta_{e\gamma}$ ,  $\varphi_{e\gamma}$



# Signal Positron PDFs & Correlations

Signal positron PDFs are evaluated from tracks which make **2 turns** inside the spectrometer, treating each turn as an **independent pseudo track**

Since all positrons must come from the target ( $\sim 200 \mu\text{m}$  thick, fairly considered bidimensional in our analysis), this constraint removes one degree of freedom from the problem, introducing **correlations among all positrons track parameters and resolutions**

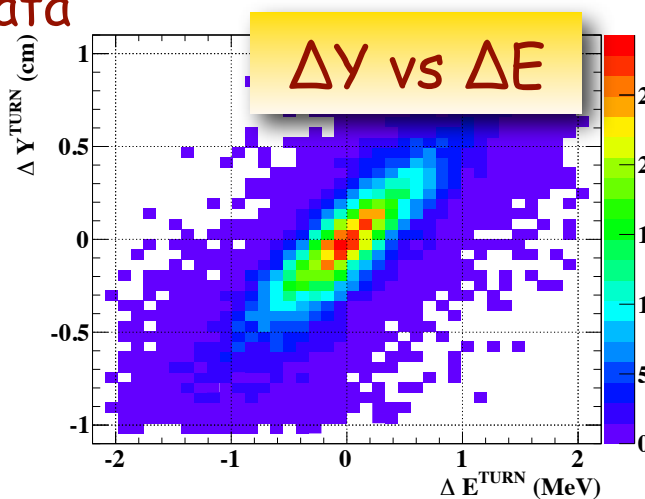
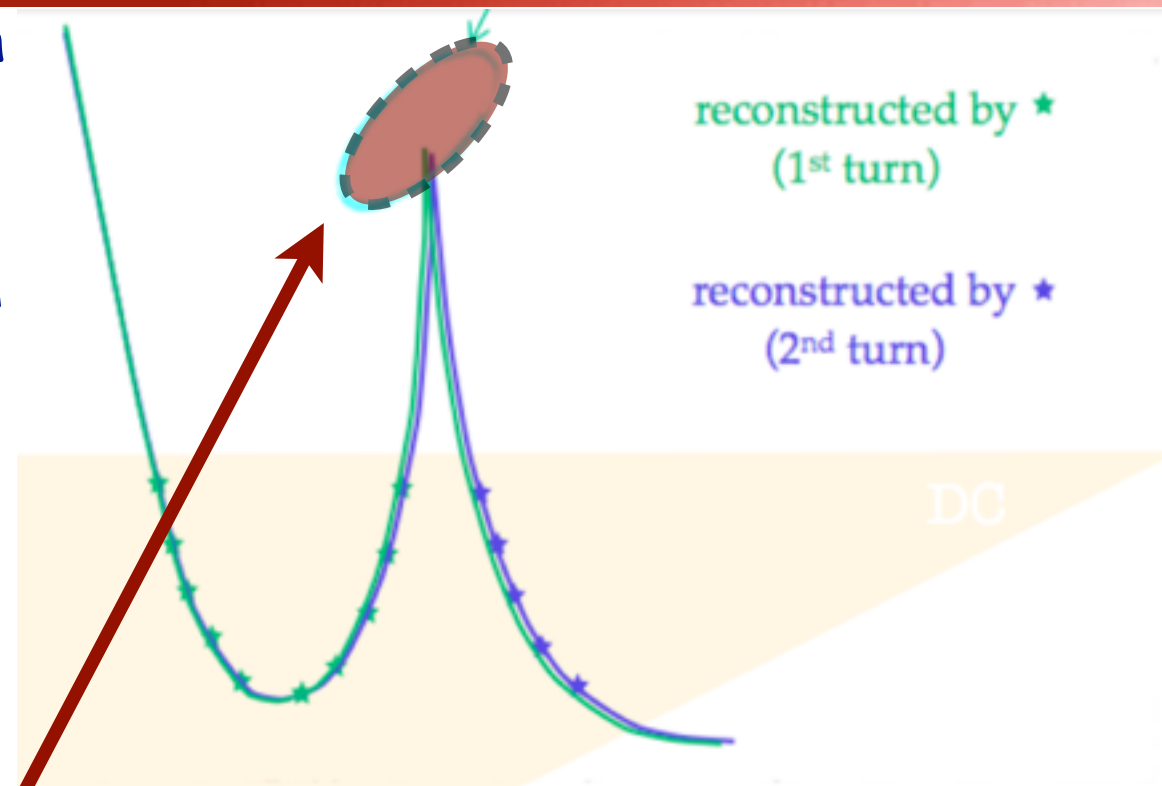
This geometrical effect **worsen resolutions**, which can nevertheless be partially **recovered** taking correlations into account in the likelihood analysis

Evaluating resolution at the 2-turn track turning point on a fictitious plane with same inclination as the target allows to **extract correlations from data**

$$\delta\phi_e = -2 \tan \phi_e \frac{\delta R}{R} = -2 \tan \phi_e \frac{\delta E}{E}$$

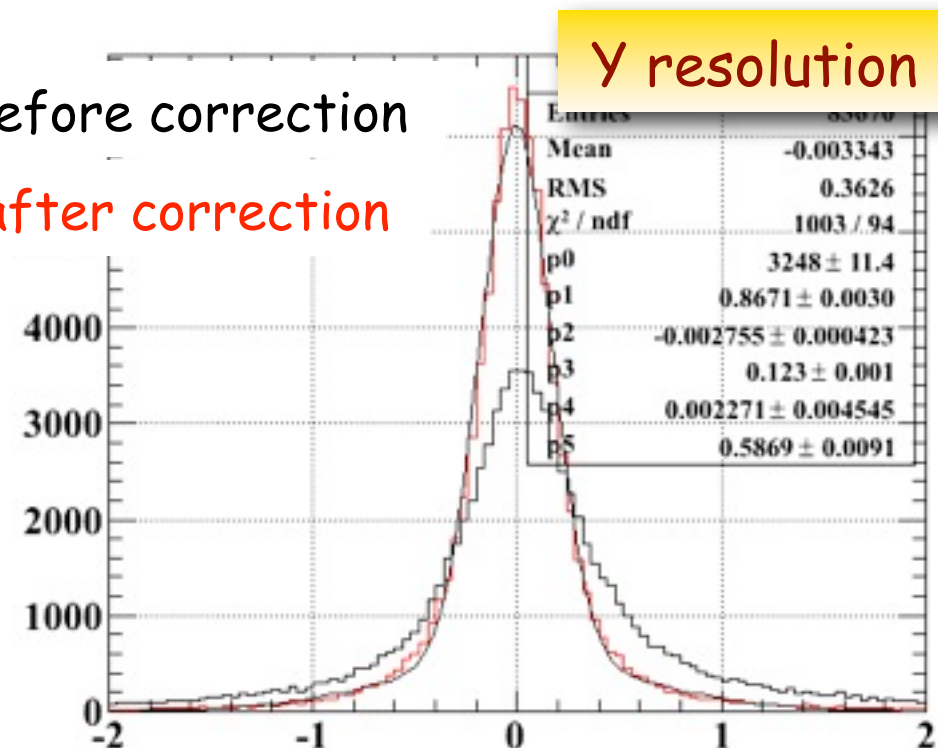
$$\delta Y = 2\delta R \cos \phi_e + R \sin \phi_e \delta\phi_e = \frac{2R}{\cos \phi_e} \frac{\delta E}{E}$$

$$\delta Z = \frac{2R}{\sin^2 \theta_e} \delta\theta_e - 2R \cot \theta_e \frac{\delta E}{E}$$



before correction

after correction



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

Slightly worse  $e^+$  tracking in 2010 due to noise problem

Photon timing improvement thanks to WF digitizer upgrade in 2010





# This result

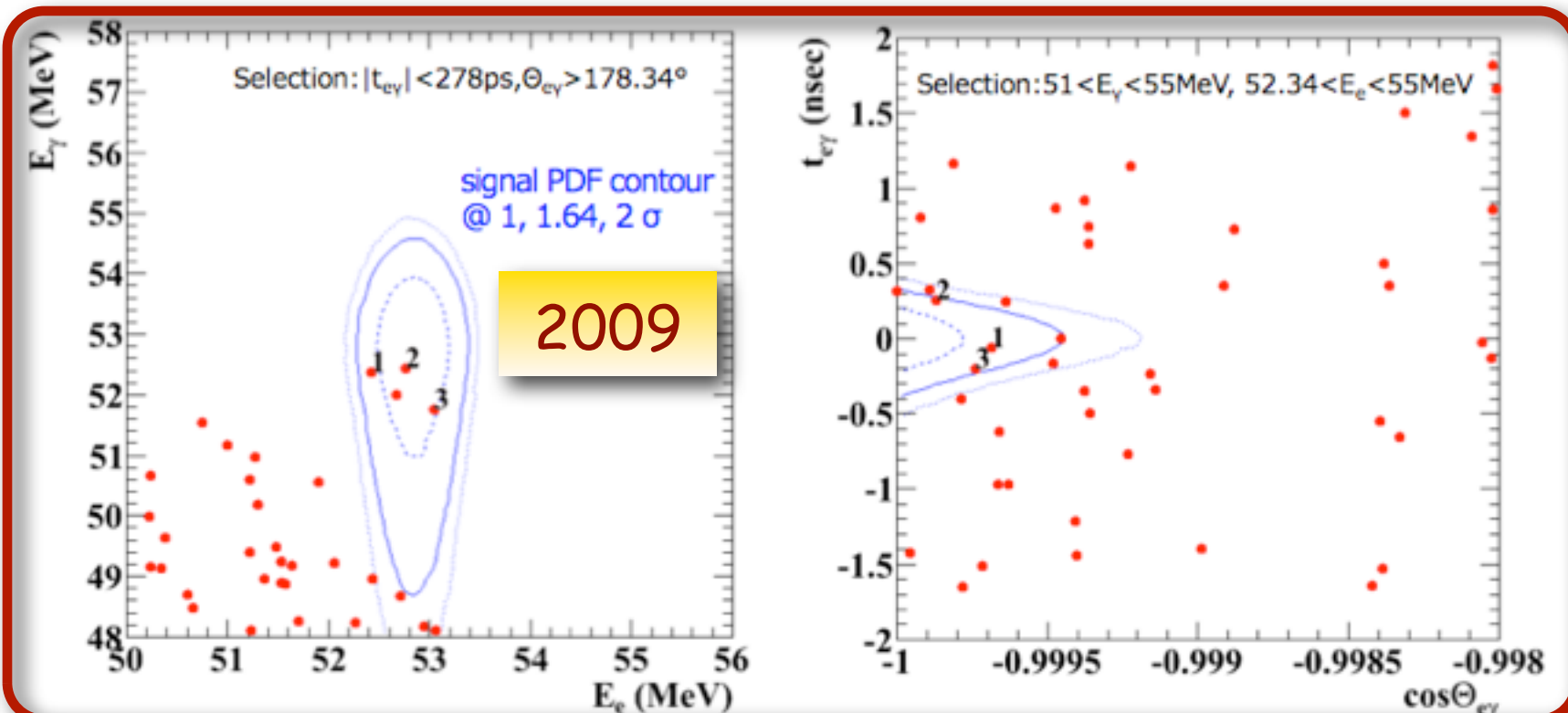
- 2009 + 2010 dataset combined analysis (2010 data  $\sim 2 \times$  2009 data)
- Improved understanding of the experiment w.r.t. ICHEP 2010:
  - Improved alignment inside and among detectors through newly developed techniques
  - Improved magnetic field map
  - Implementation of correlations at the target in likelihood analysis, strongly reducing the systematics and the effective resolutions
- Improvements in the likelihood analysis technique w.r.t. ICHEP 2010
  - $N_{\text{bkg}}$  constrained from sideband data
  - Profile-likelihood interval with Feldman-Cousins method

compare  
best UL  $12 \times 10^{-12}$

Sensitivity of combined data  $1.6 \times 10^{-12}$  @ 90% CL  
 $3.3 \times 10^{-12}$  in 2009 +  $2.2 \times 10^{-12}$  in 2010

Sensitivity  
confirmed on  
time AND  
angular  
sideband data

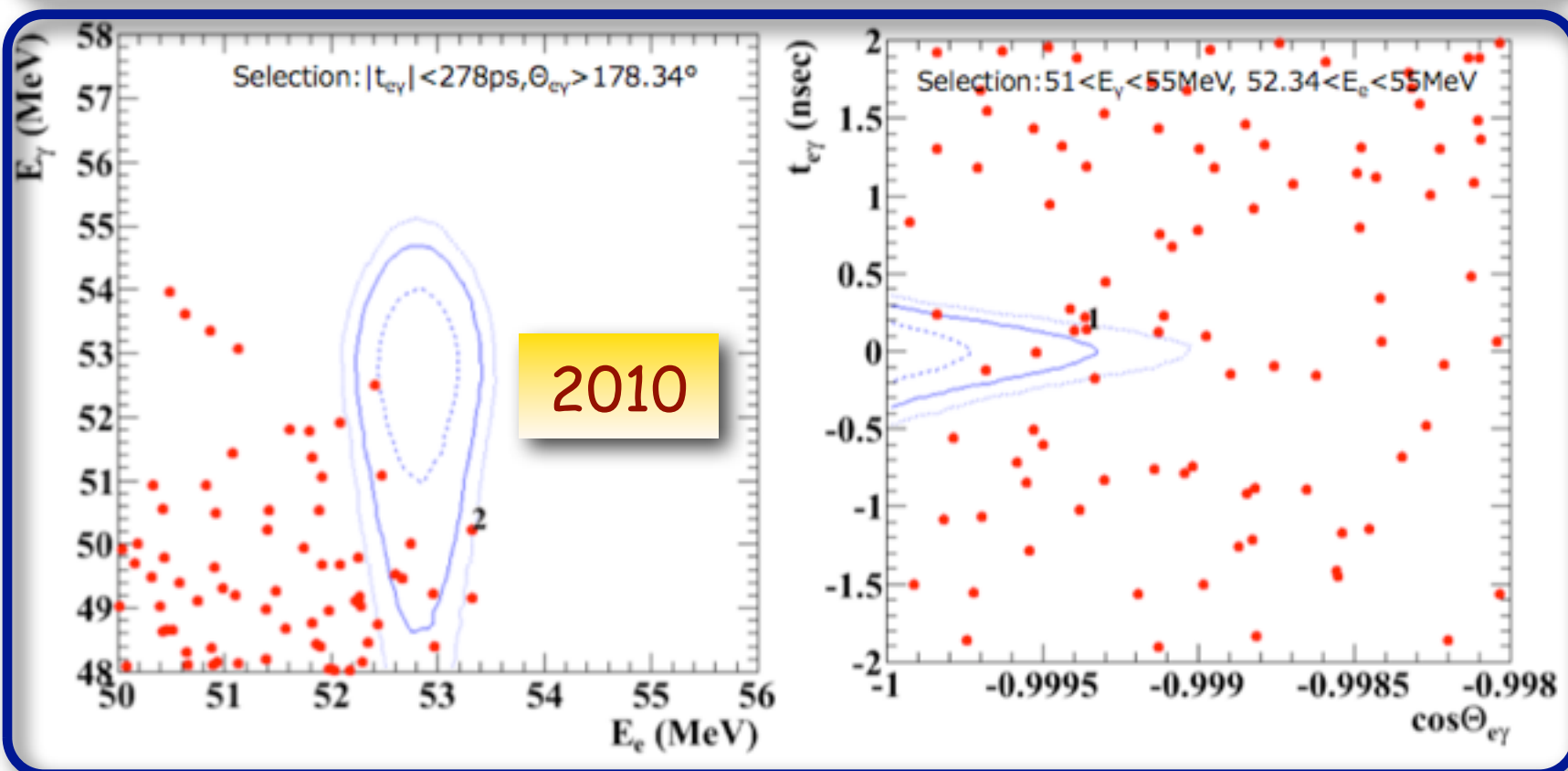
# 2009 and 2010 results



2009 data re-analyzed with improvements : best  $N_{\text{sig}}$  fit 3.4 (ICHEP '10 best  $N_{\text{sig}}$  fit 3.0) ---> **STABLE RESULT**

$1.7 \times 10^{-13} < \text{BR} < 9.6 \times 10^{-12}$  @ 90% CL

p-Value for null signal 8%



2010 data best  $N_{\text{sig}}$  fit -2.2

$\text{BR} < 1.7 \times 10^{-12}$  @ 90% CL

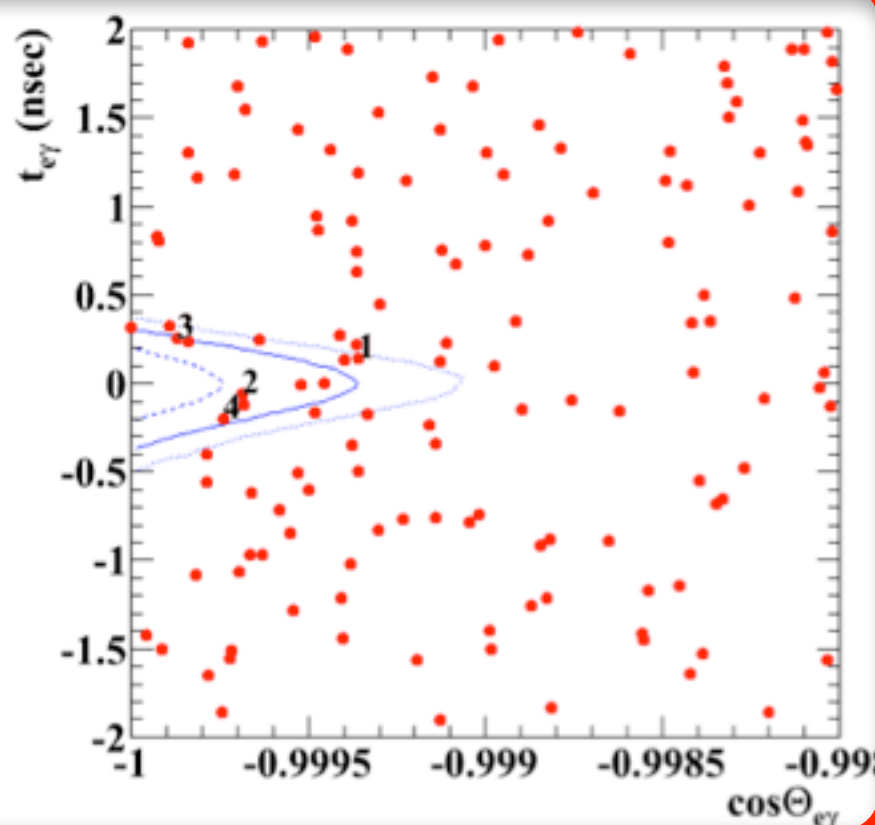
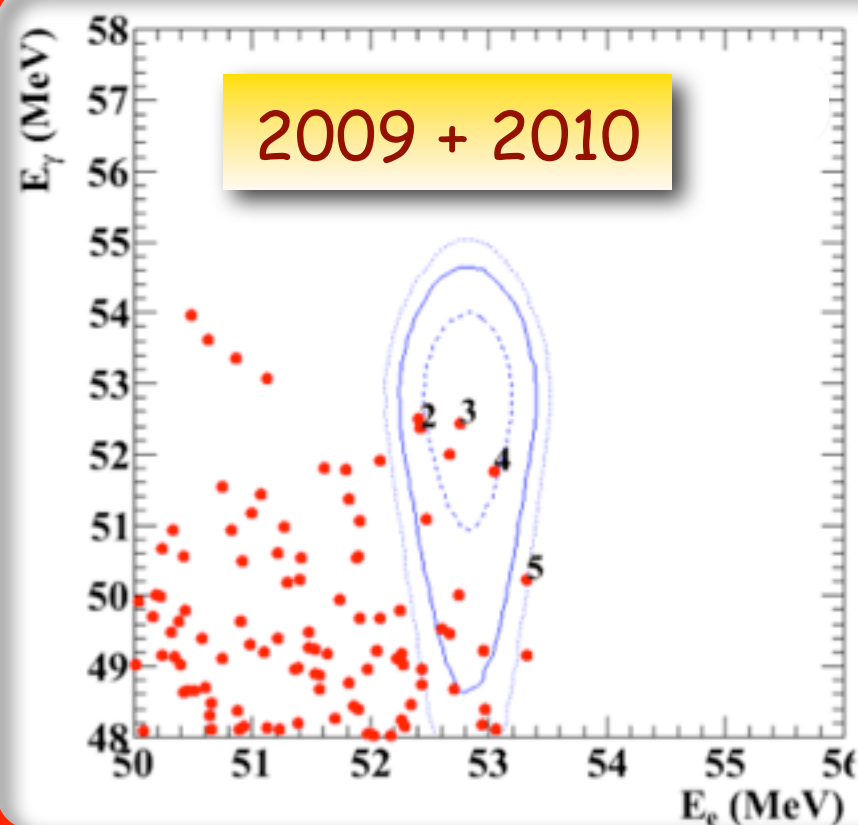
Sensitivity  $2.2 \times 10^{-12}$





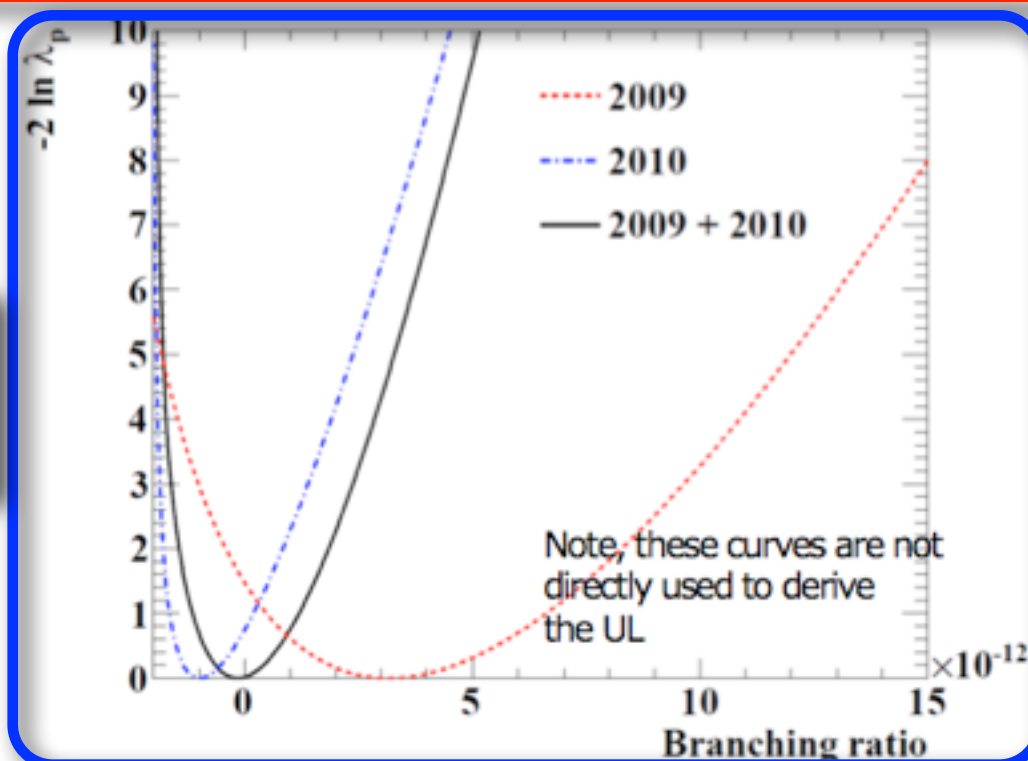
# Combined Result

2009 + 2010



	expected	best fit
$N_{\text{sig}}$		-0.5
$N_{\text{RMD}}$	$79.4 \pm 7.9$	$76 \pm 12$
$N_{\text{bkg}}$	$881.7 \pm 15.1$	$882 \pm 22$

Profile  
Likelihood

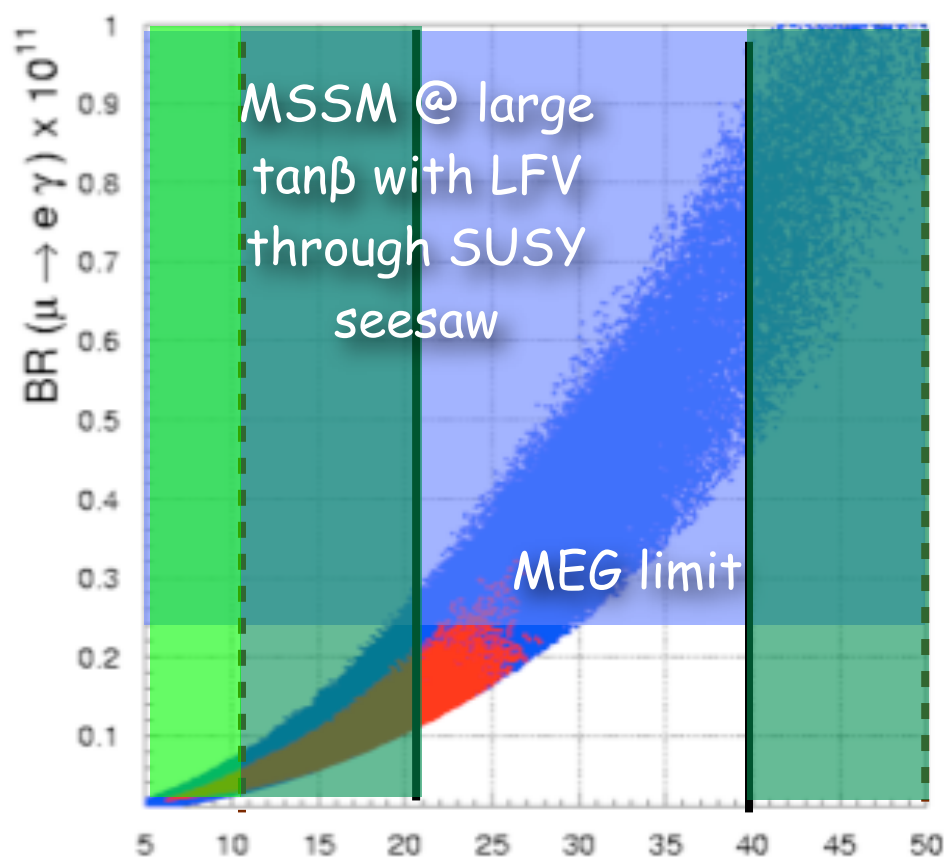


UL @ 90% CL  
 $BR < 2.4 \times 10^{-12}$

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

# Implications

G. Isidori et al. Phys.Rev. D 75:115019, 2007

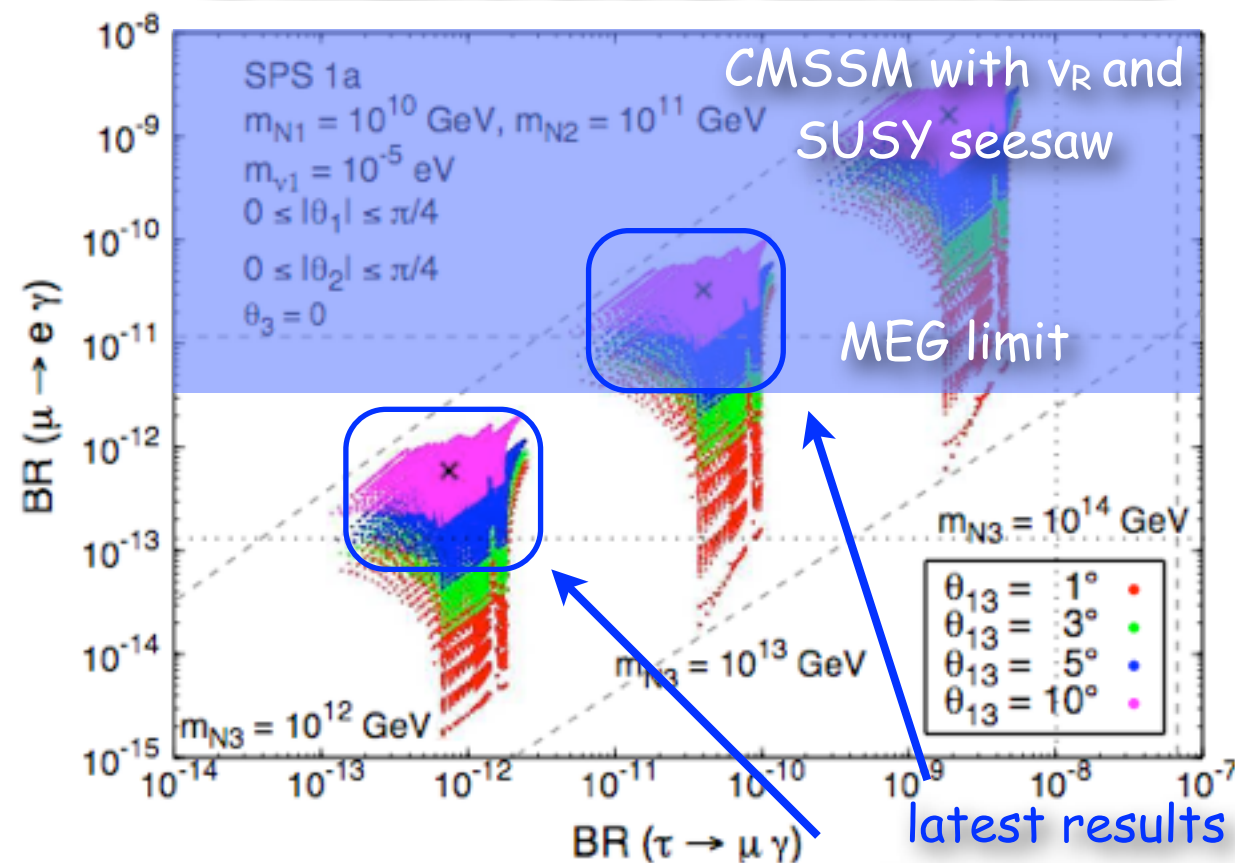


additional constraints from B physics

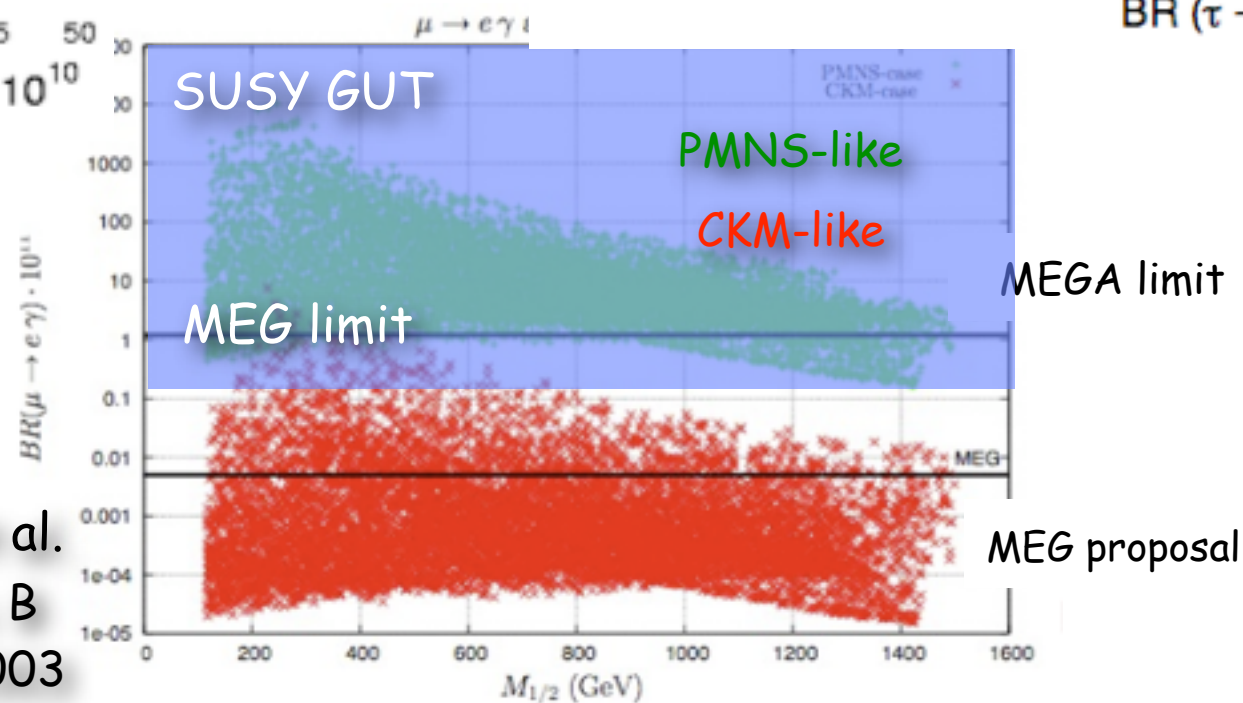
$\Delta a_\mu \pm 1$  (2)  $\sigma$  constraint

Masiero et al.  
Nucl.Phys. B  
649:189, 2003

S. Antusch et al, JHEP 0611:090 (2006)



latest results from T2K/Double Chooz suggests  $\theta_{13} \sim 8^\circ$



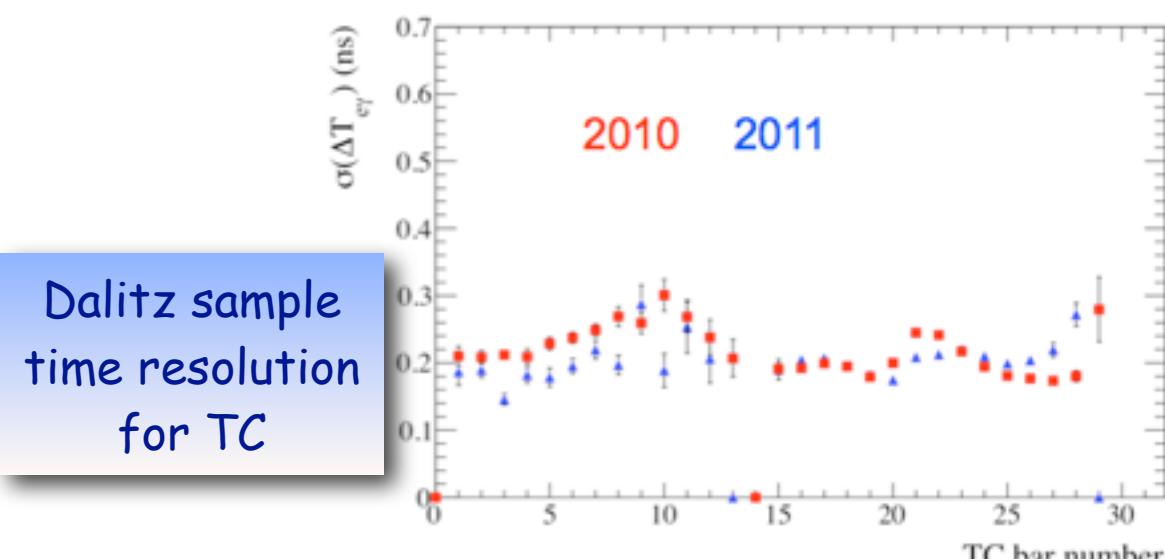
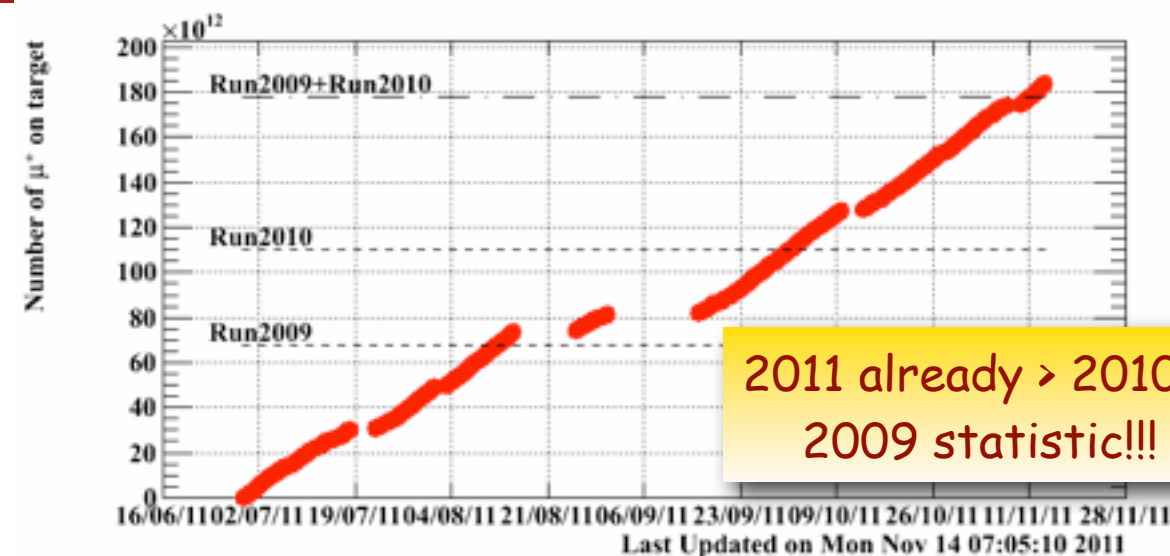




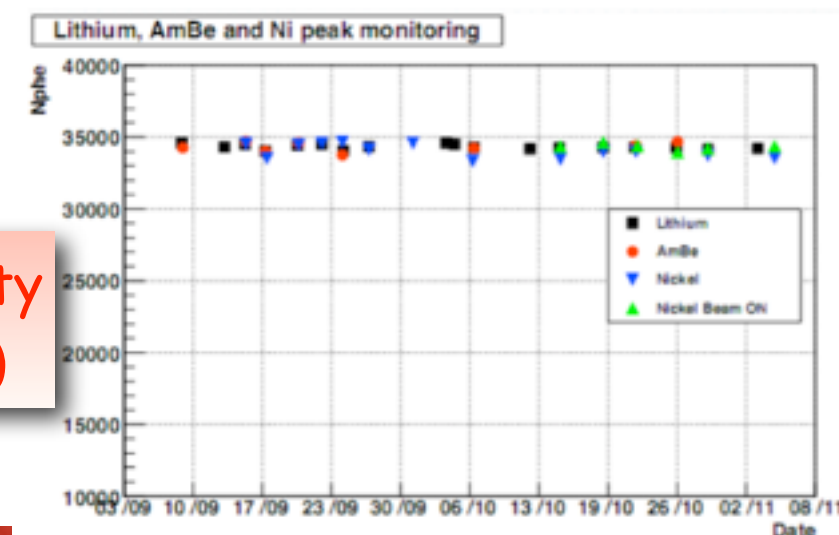
# 2011 Run



- 2011 data taking started in July
- By now, collected > 2010 + 2009 statistic
- Expected to reach ~ 2 x 2010 statistic by end of this year
- Improved DAQ & trigger efficiency up to >99% live time with >95% efficiency
- Improved noise conditions in DC thanks to new HV power supplies
- TC fibers APDs operational
- All positron and photon resolutions consistent with 2010 already with preliminary alignment and calibrations

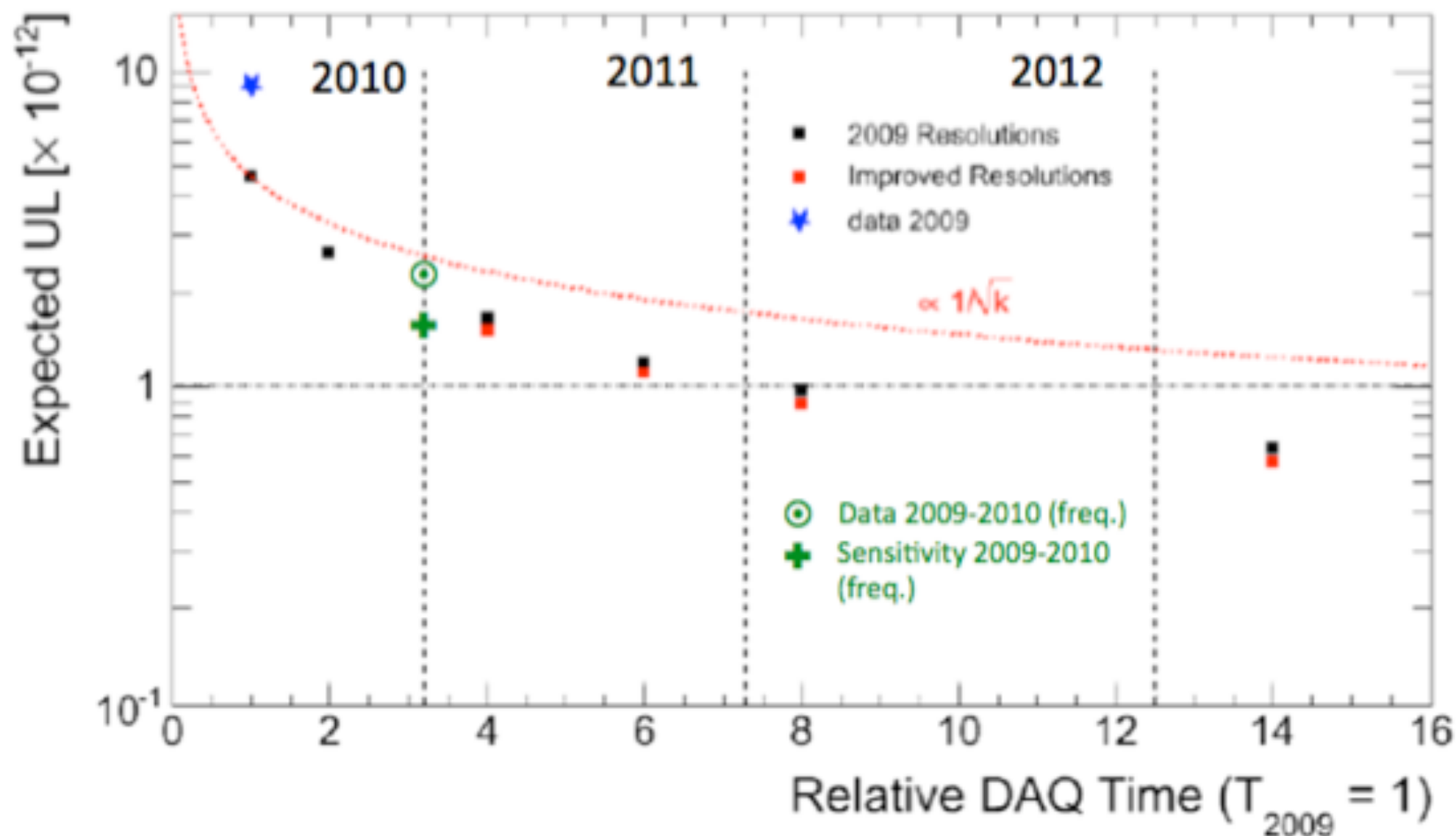


Xenon stability (2009-2011)





# Sensitivity prospects



MEG data taking will continue through 2012

Sensitivity projection in the  $5 \times 10^{-13}$  range





# Proposals for upgrade



- Several proposals for LXe and tracker short and long term upgrades

- LXe:

- Short term:** low reflectivity internal surface

- Long term:** replacement of internal window PMTs and use of charge information (italian MIUR independent R&D)

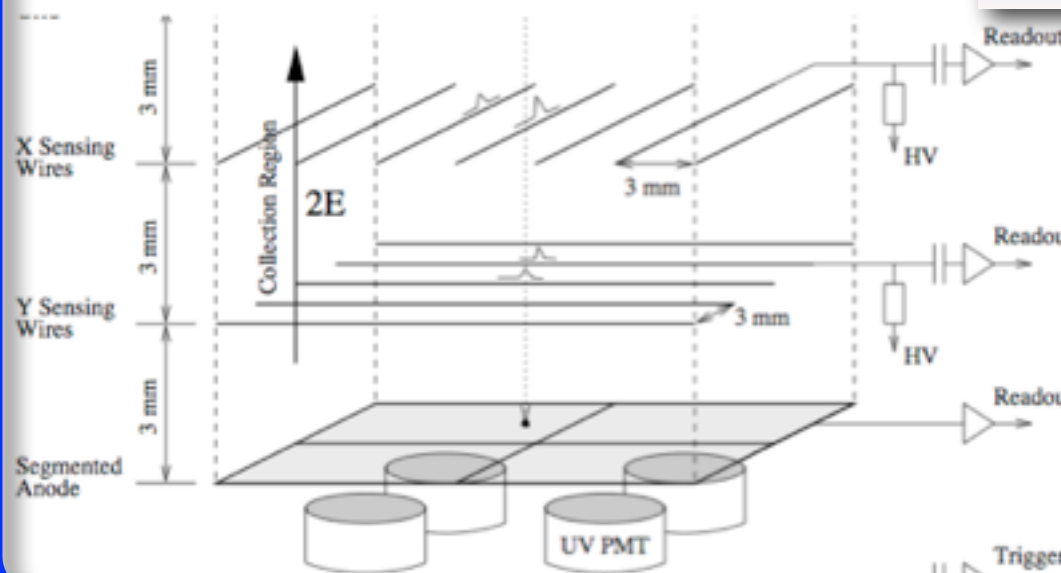
- Tracker:

- Short term:** change DC gas, target inclination and TC cables

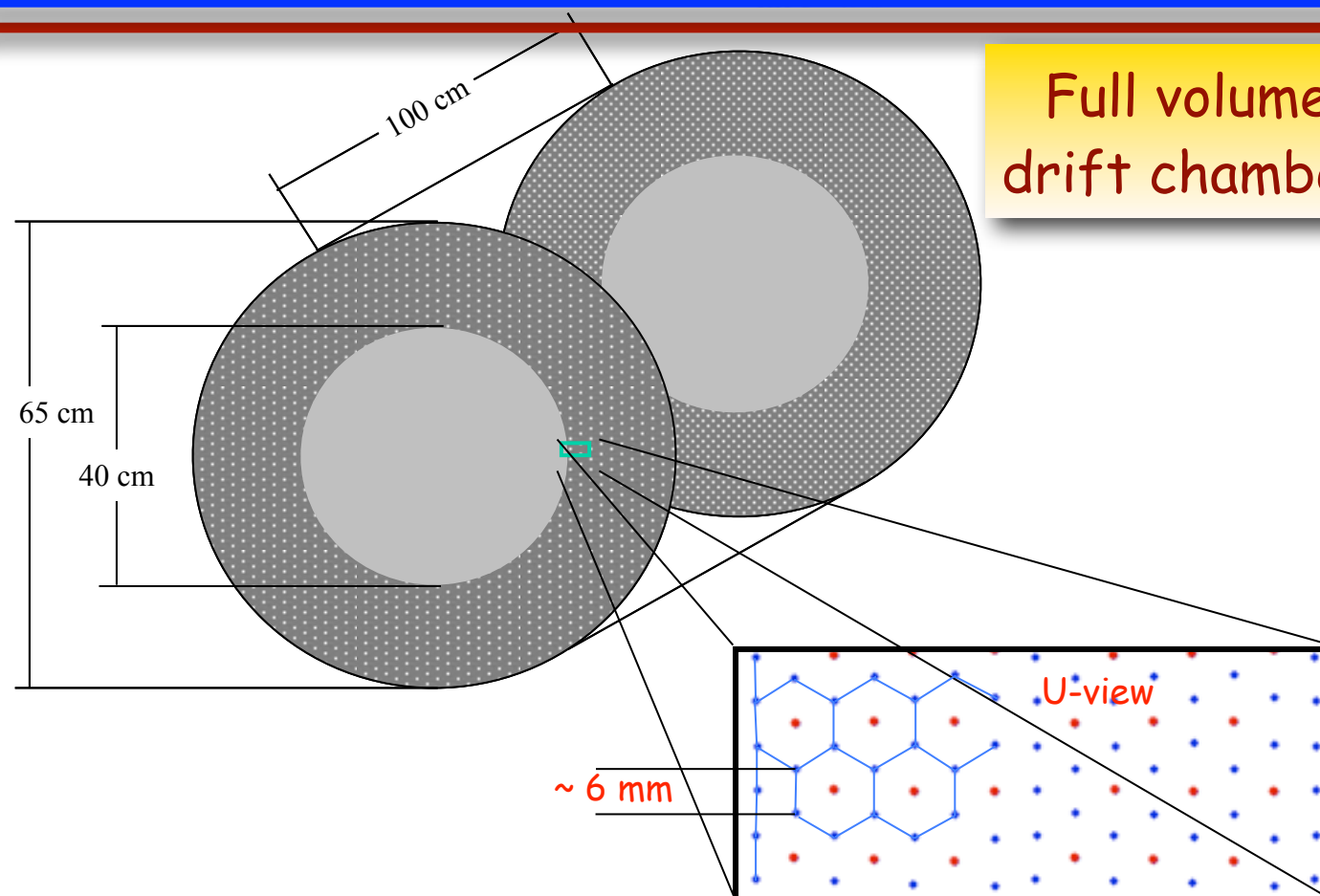
- Long term:** replace tracker, either full volume DC (capable of isolating primary ionization clusters) or set of scintillating films

- R&D now starting

## LXe charge R&D



## Full volume drift chamber




# Conclusions & Prospects


 2009 + 2010 MEG data analysis consistent with null signal

 Most stringent UL on LFV improved by a factor 5

$$\text{BR}(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12} \quad @ 90\% \text{ CL}$$

 MEG resumed data taking in July and have already accumulated > 2010 + 2009 statistic with improved trigger, DAQ and DC noise conditions

Expected sensitivity at the end of 2012: a few  $10^{13}$   
Stay tuned!! :)

 Several proposal for a short (2012-2013) and long term (2015-2016?) upgrades to further improve sensitivity



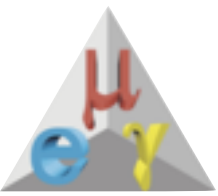


Thank you!!!

MEG   
experiment

The MEG Collaboration





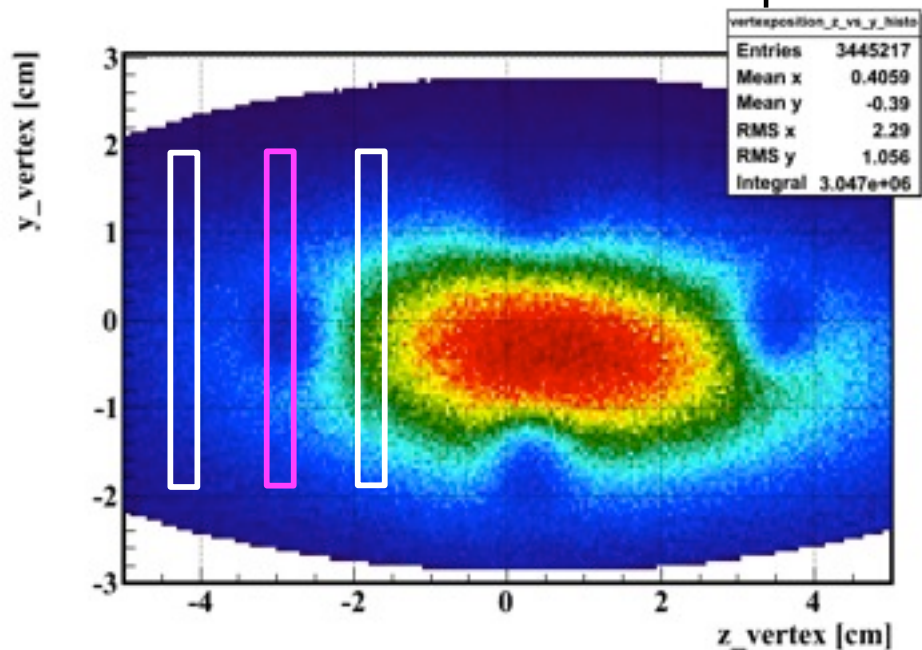
# Backup slides



# Target Holes

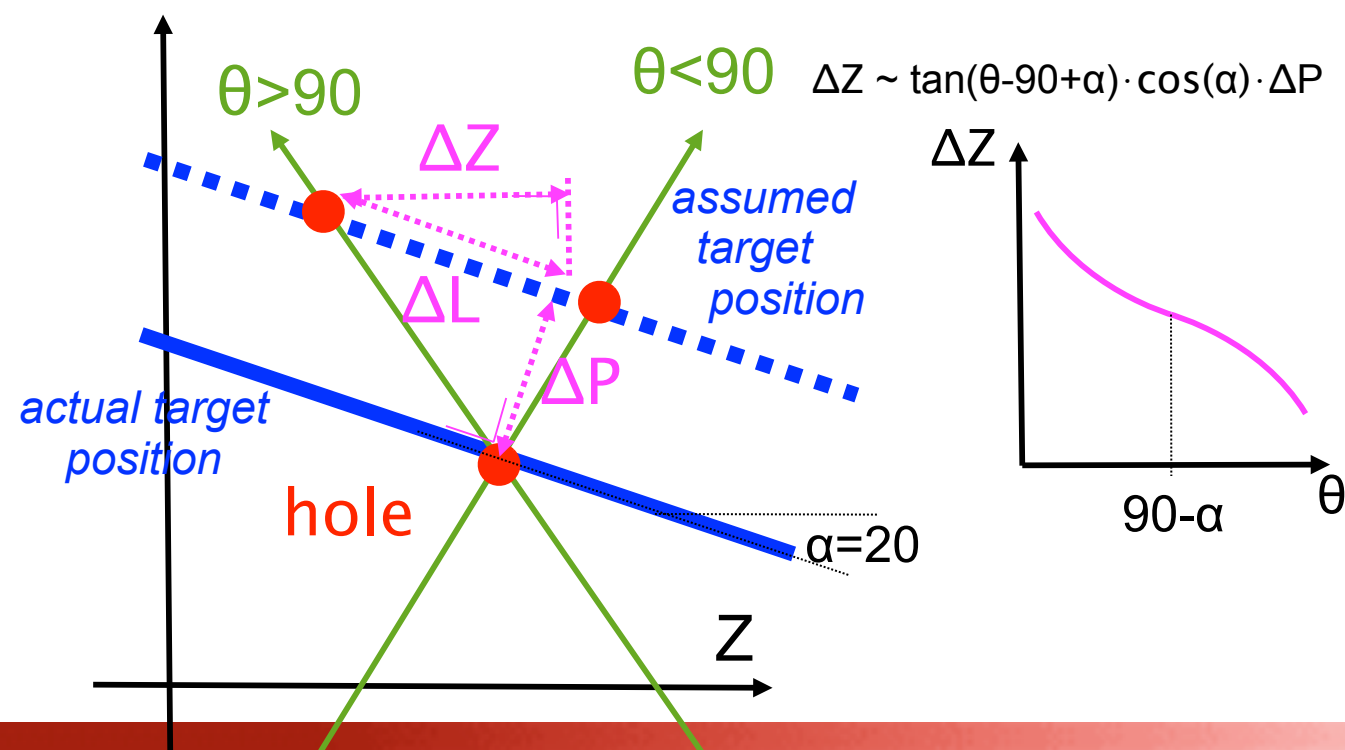
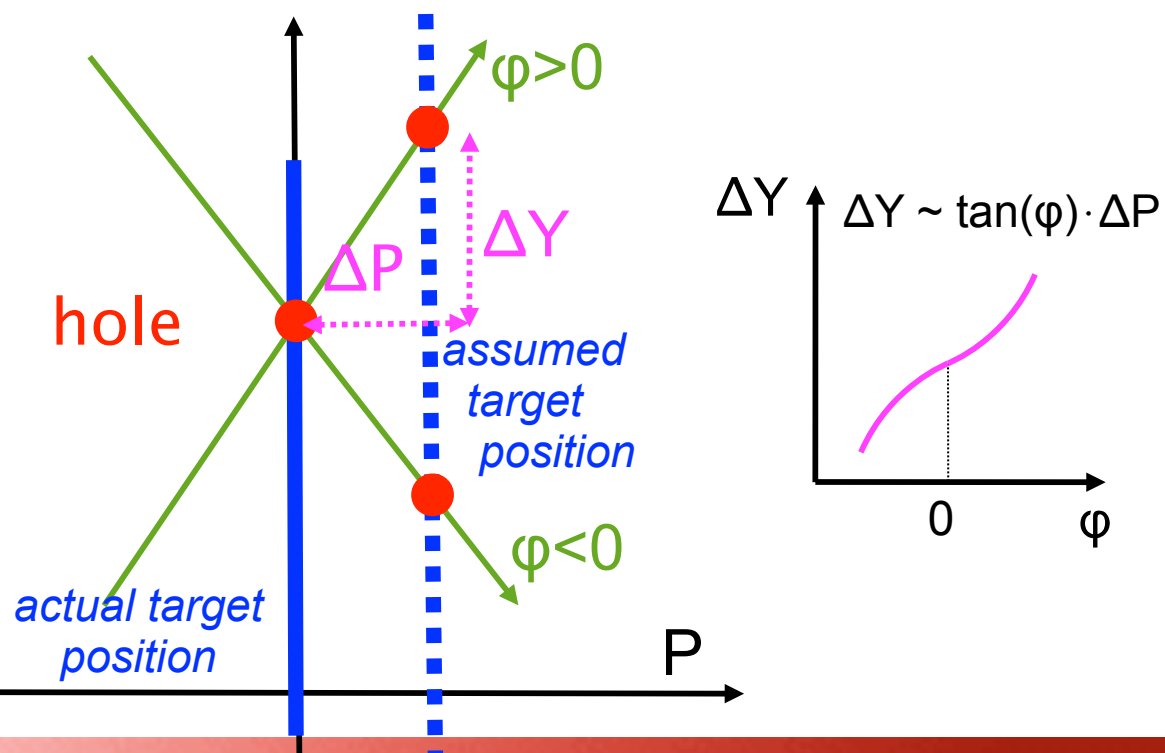
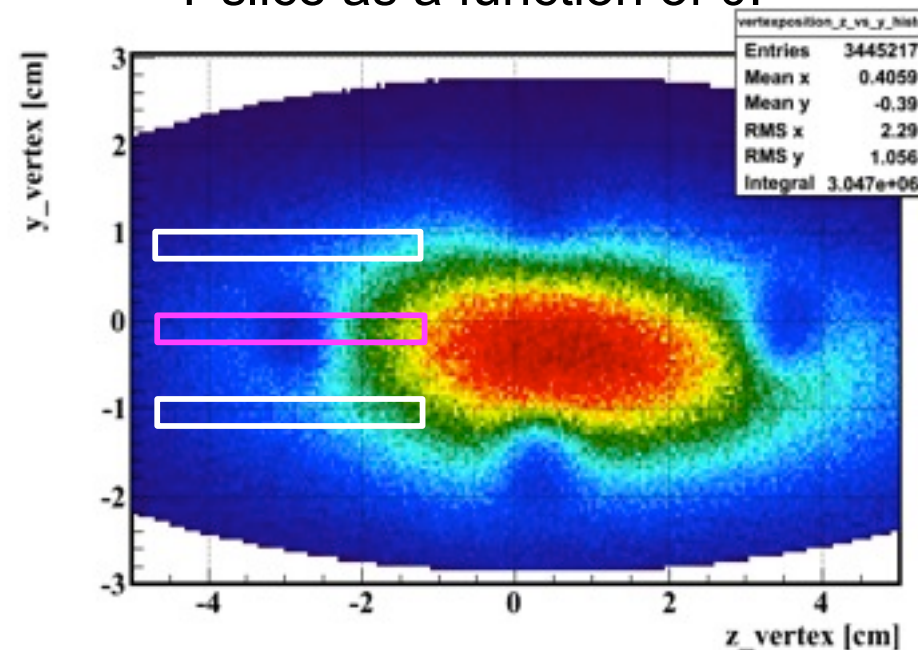
## Method 1:

Reconstruct Y-coordinate in Z-slice as a function of  $\phi$ :



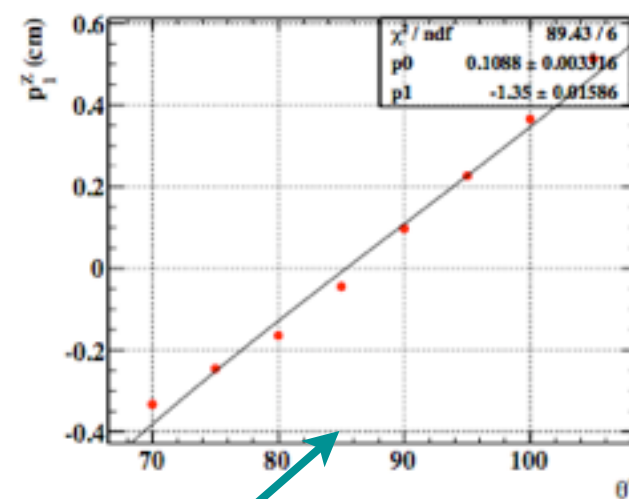
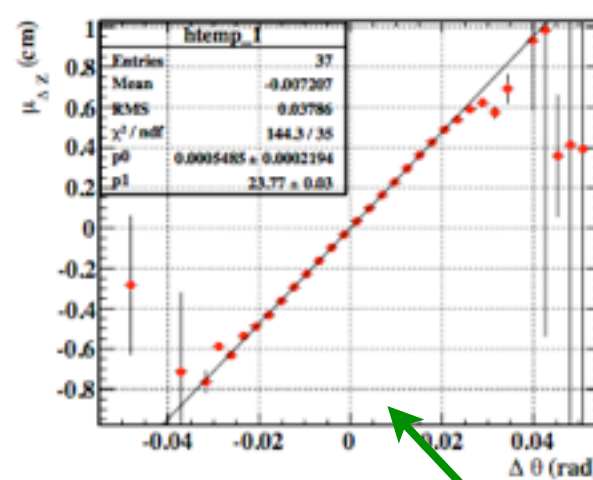
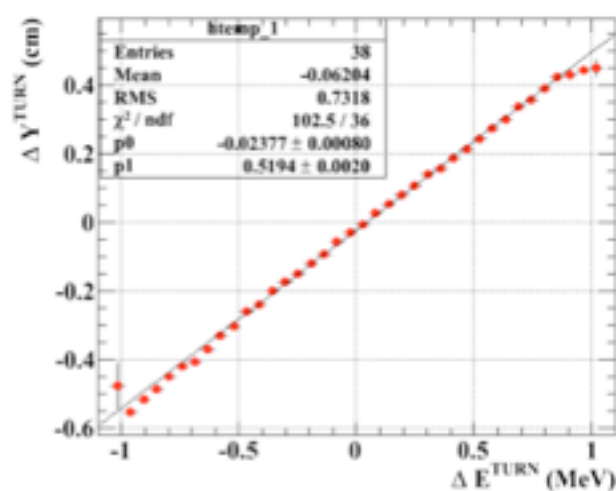
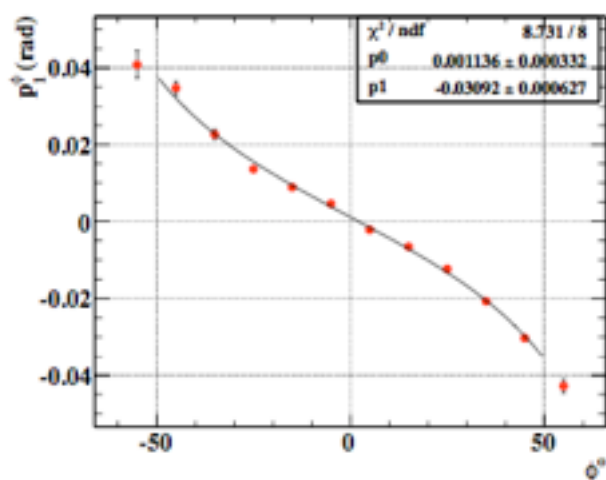
## Method 2:

Reconstruct Z-coordinate in Y-slice as a function of  $\theta$ :





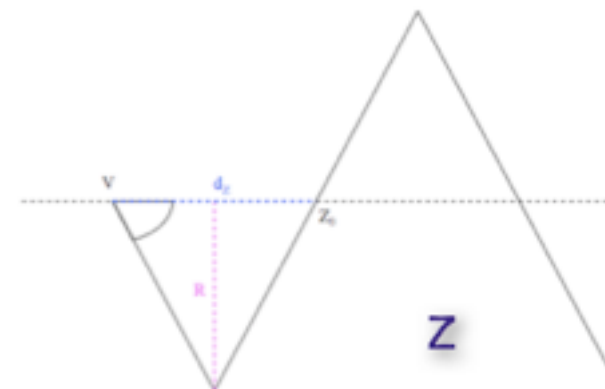
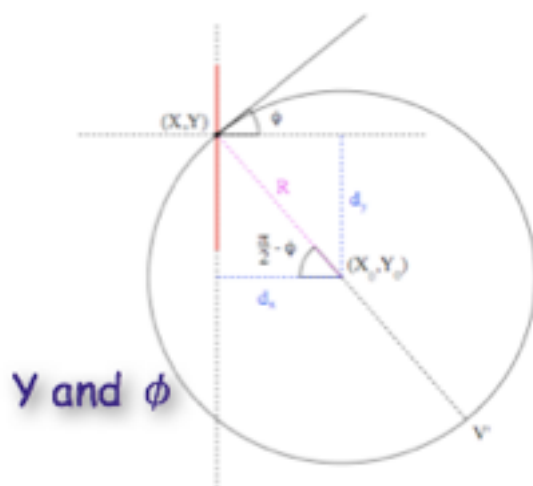
# Correlations and Resolutions



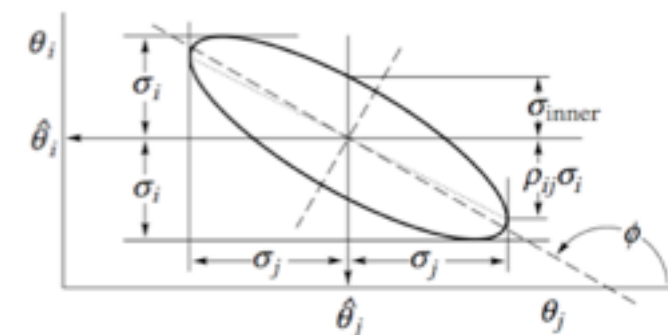
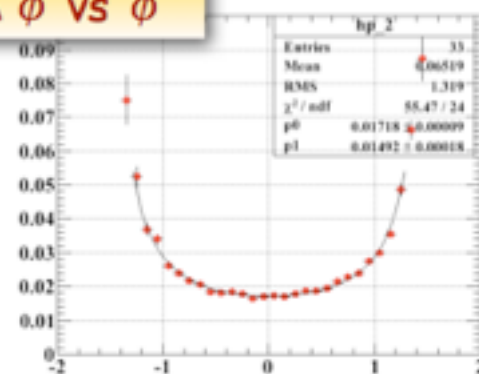
$$\delta\phi_e = -2 \tan \phi_e \frac{\delta R}{R} = -2 \tan \phi_e \frac{\delta E}{E}$$

$$\delta Y = 2\delta R \cos \phi_e + R \sin \phi_e \delta\phi_e = \frac{2R}{\cos \phi_e} \frac{\delta E}{E}$$

$$\delta Z = \frac{2R}{\sin^2 \theta_e} \delta\theta_e - 2R \cot \theta_e \frac{\delta E}{E}$$



$\Delta\phi$  vs  $\phi$



$$d\hat{\theta}_i/d\theta_j = \rho_{ij} \times \frac{\sigma_i}{\sigma_j}$$





# Some more numbers :)

## ■ Fit region

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

## Sensitivity

	2009	2010	Combined
$N_{\text{sig}}$ (median)	3.6	4.8	5.2
$BR$ (median)	$3.3 \times 10^{-12}$	$2.2 \times 10^{-12}$	$1.6 \times 10^{-12}$

## 2009 + 2010 combined

	Best fit	LL (90% CL)	UL (90% CL)	UL (95% CL)	CL@0
$N_{\text{sig}}$	-0.5	-	7.8(7.7)	9.8(N/A)	-
$BR$	$-1.5 \times 10^{-13}$	-	$2.4 \times 10^{-12}$ ( $2.3 \times 10^{-12}$ )	$2.9 \times 10^{-12}$ (N/A)	-

## 2009

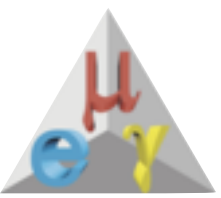
	Best fit	Error (MINOS 1.645 $\sigma$ )
$N_{\text{sig}}$	+3.4	+6.6-4.4
$N_{\text{RMD}}$	+26.9	+4.5-4.5
$N_{\text{BG}}$	+273.1	+12.3-12.3

	Best fit	LL (90%CL)	UL (90%CL)	UL (95%CL)	CL@0
$N_{\text{sig}}$	3.4	0.2(0.2)	10.4(10.1)	11.9(N/A)	0.92(0.92)
$BR$	$3.2 \times 10^{-12}$	$1.7 \times 10^{-13}$ ( $1.7 \times 10^{-13}$ )	$9.6 \times 10^{-12}$ ( $9.4 \times 10^{-12}$ )	$1.1 \times 10^{-11}$ (N/A)	0.92(0.92)

## 2010

	Best fit	Error (MINOS 1.645 $\sigma$ )
$N_{\text{sig}}$	-2.2	+5.0-1.9
$N_{\text{RMD}}$	+50.2	+9.2-9.2
$N_{\text{BG}}$	+608.5	+18.7-18.6

	Best fit	LL (90%CL)	UL (90%CL)	UL (95%CL)	CL@0
$N_{\text{sig}}$	-2.2	-	3.8(3.7)	5.0(N/A)	-
$BR$	$-9.9 \times 10^{-13}$	-	$1.7 \times 10^{-12}$ ( $1.7 \times 10^{-12}$ )	$2.3 \times 10^{-12}$ (N/A)	-



# Systematics



- Systematics effect taken into account in the calculation of confidence interval by profiling on ( $N_{RD}$ ,  $N_{BKG}$ ) and by fluctuating PDFs according to the uncertainty values
- All the results shown have systematic effects taken into account
- Size of systematic uncertainty in total 2% on the UL:  $2.3 \times 10^{-12} \rightarrow 2.4 \times 10^{-12}$
- Contribution of each item in the list was studied with toy MC experiments by comparing the results with the nominal PDFs and the one with the fluctuated ones

Relative contributions on UL

Center of $\theta_{e\gamma}$ and $\phi_{e\gamma}$	0.18
Positron correlations	0.16
Normalization	0.13
$E_\gamma$ scale	0.07
$E_e$ bias, core and tail	0.06
$t_{e\gamma}$ center	0.06
$E_\gamma$ BG shape	0.04
$E_\gamma$ signal shape	0.03
Positron angle resolutions ( $\theta_e$ , $\phi_e$ , $z_e$ , $y_e$ )	0.02
$\gamma$ angle resolution ( $u_\gamma$ , $v_\gamma$ , $w_\gamma$ )	0.02
$E_e$ BG shape	0.02
$E_e$ signal shape	0.01