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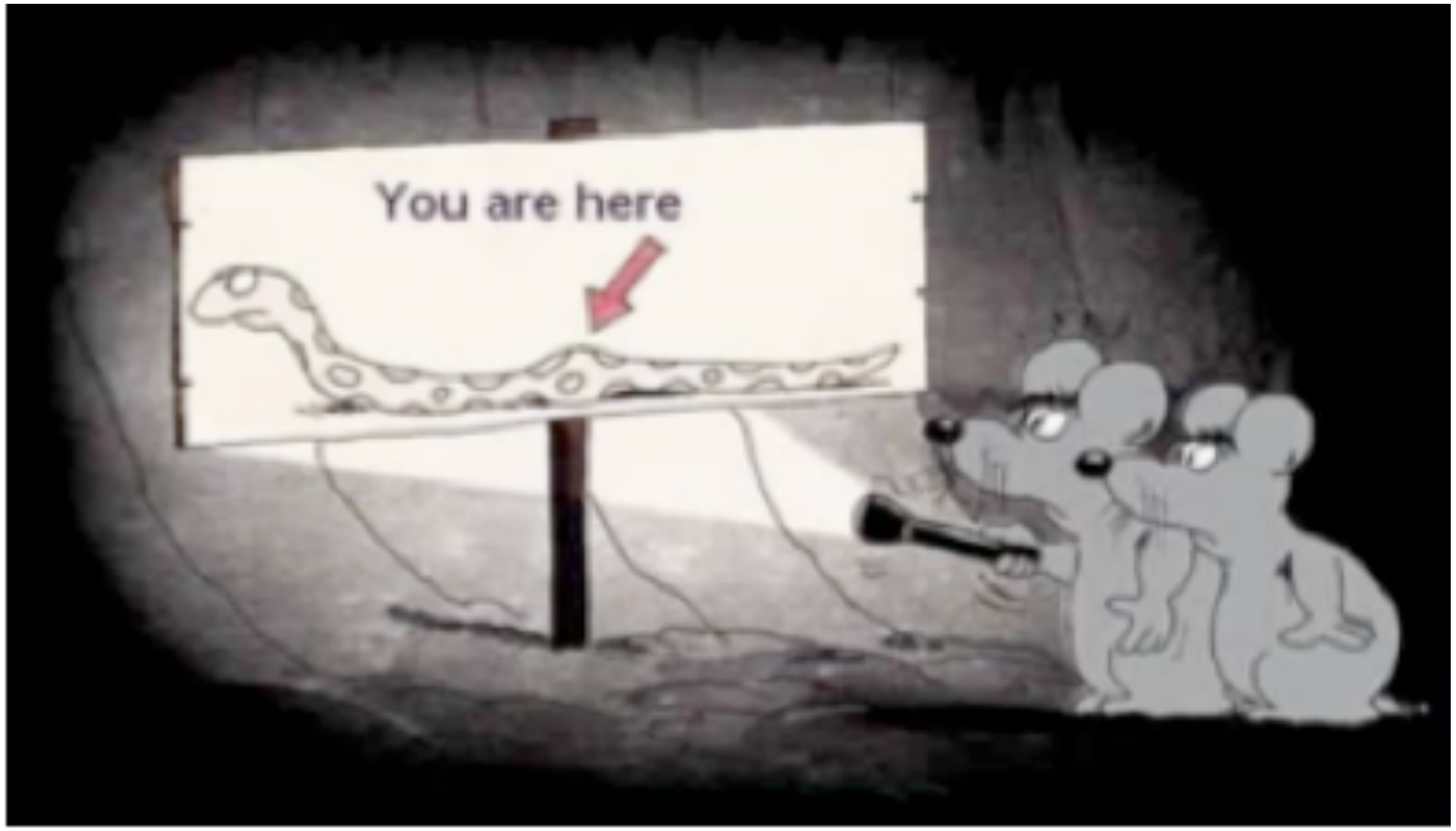
on behalf of the MEG Collaboration

New limit on LFV searches from the MEG experiment

Friday, 27th January 2012
Queen Mary University of London
London, England

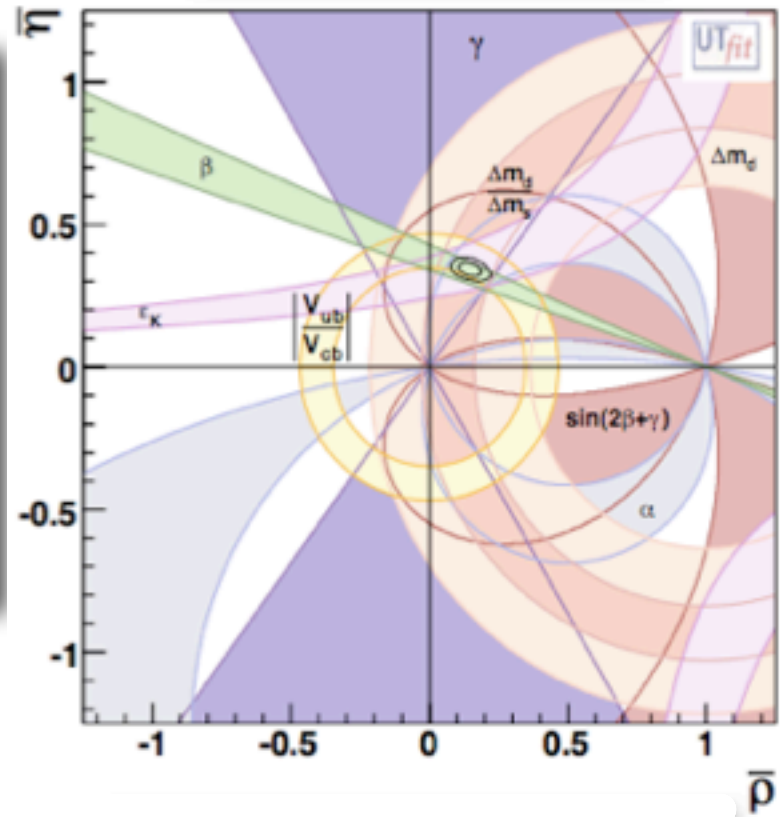
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Where we are

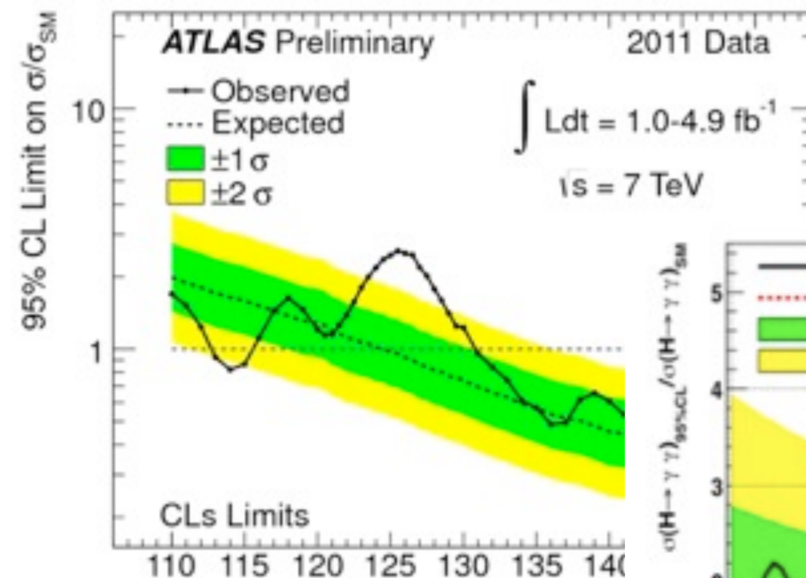


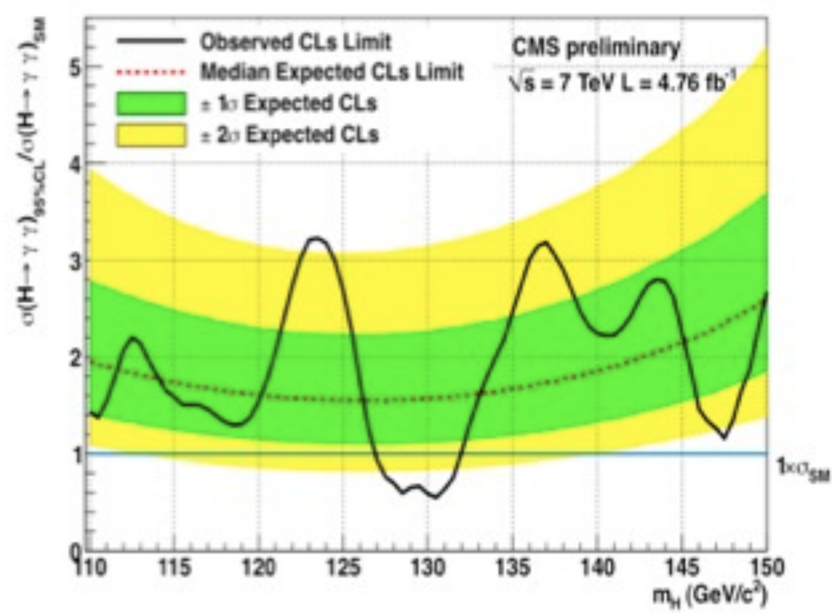
SM success (& failure)

Flavour sector



Electroweak sector





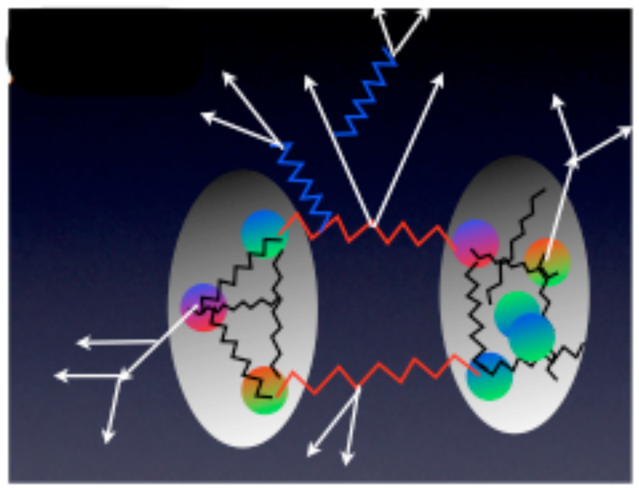
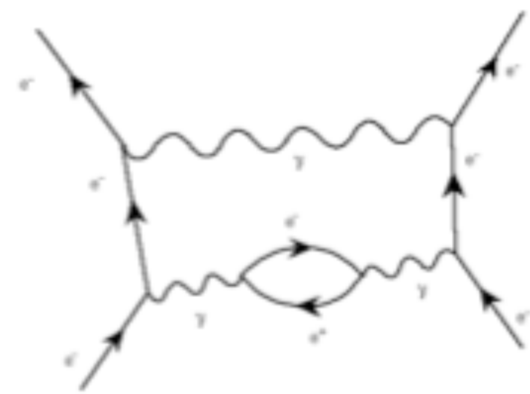
LHC "indications" of Higgs seems A LOT a SM Higgs.....

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

- Nonetheless, we know it is not the ultimate theory. Some of the reasons:
  - Neutrino oscillations
  - Dark Matter/Energy
  - 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)	Through the flavour sector (LFV,CPV, FCNC, ν mixing, EDM)
	
The High Energy Frontier	The High Intensity Frontier
New particles produced increasing c.m. energy	Virtual processes indirectly test the NP energy scale (sometimes further than LHC reach)

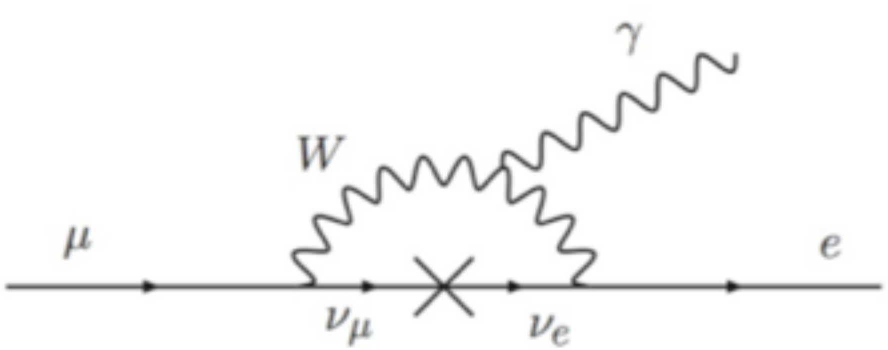
Full complementarity between the two approaches

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

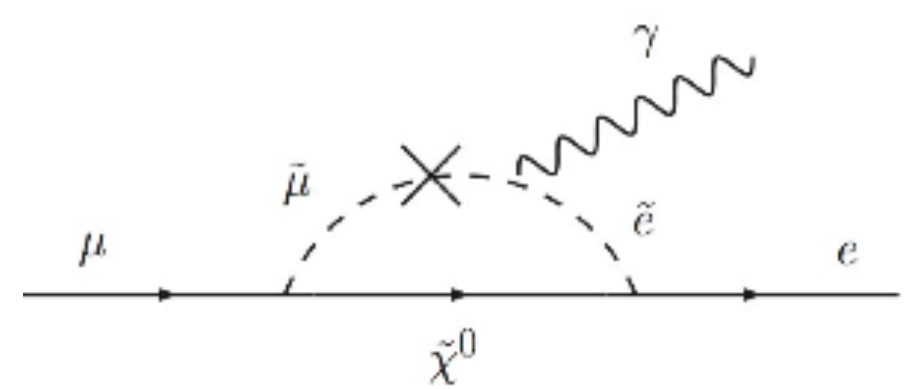
> Observation of μ → e γ would be an unambiguous evidence of NP beyond SM

- 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



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

BR (μ → e γ) ~ 10^{-54}

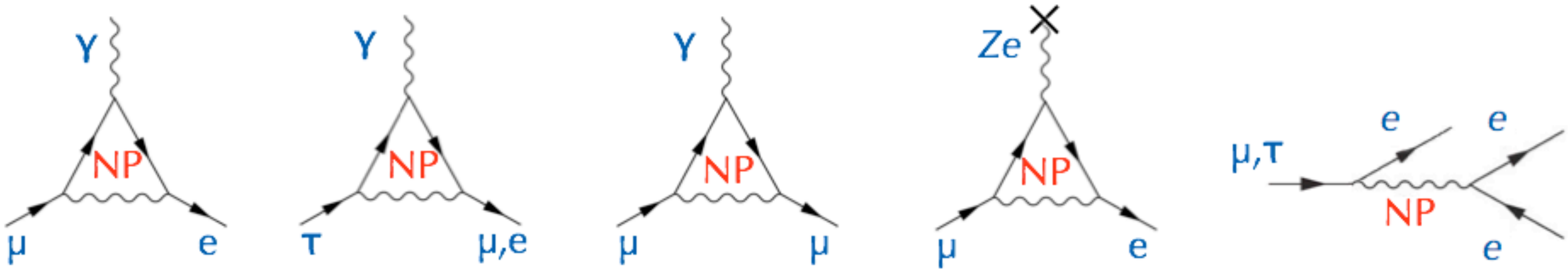


$$BR(\ell_i \to \ell_j\gamma) \propto \delta_{ij}^2 \tan^2\beta$$

BR (μ → e γ) ~ 10^{-13} - 10^{-14}

Charged LFV processes

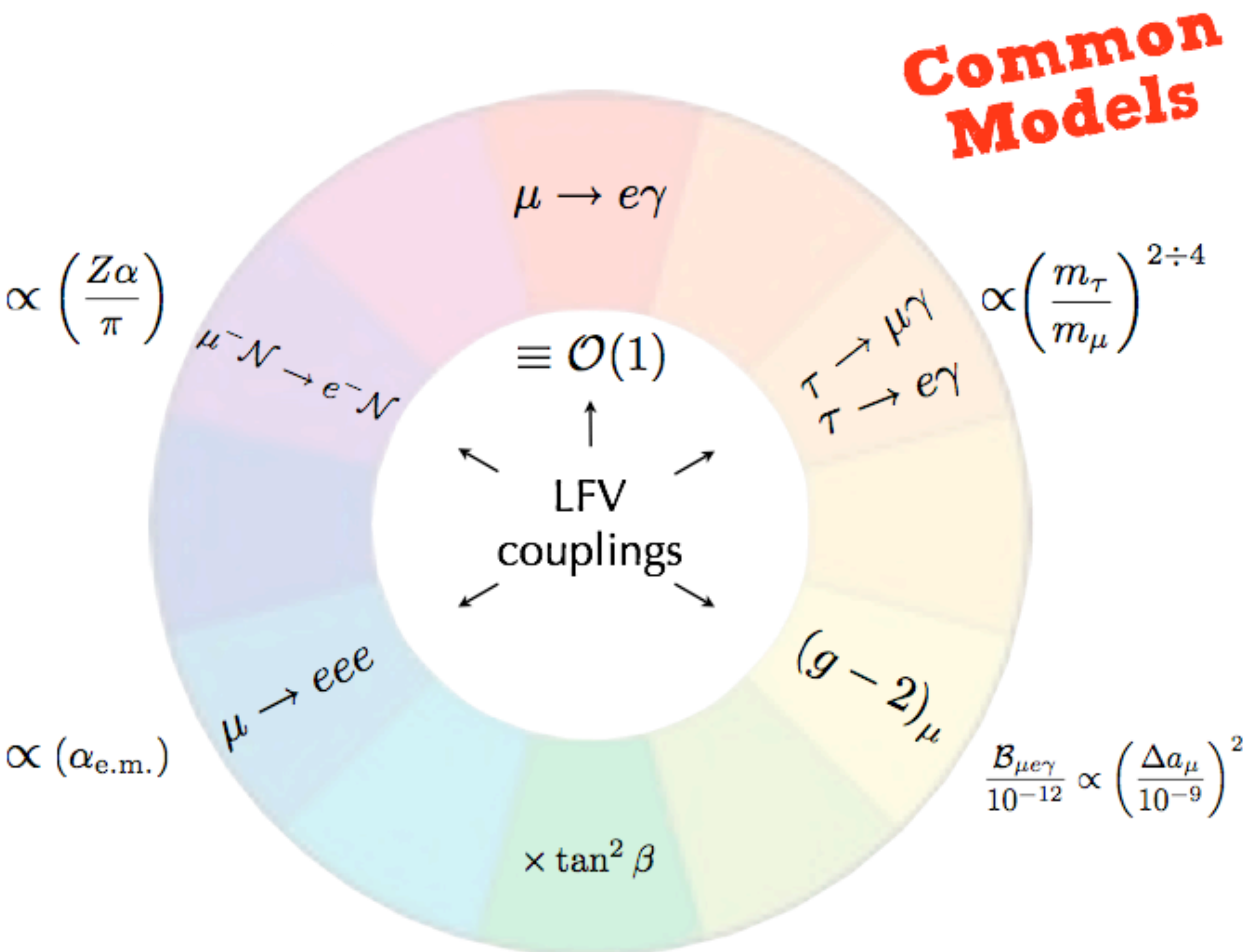
A new lepton-lepton coupling $y_{ij}\bar{\ell}_i F^{\mu\nu}\ell_j\sigma_{\mu\nu}$



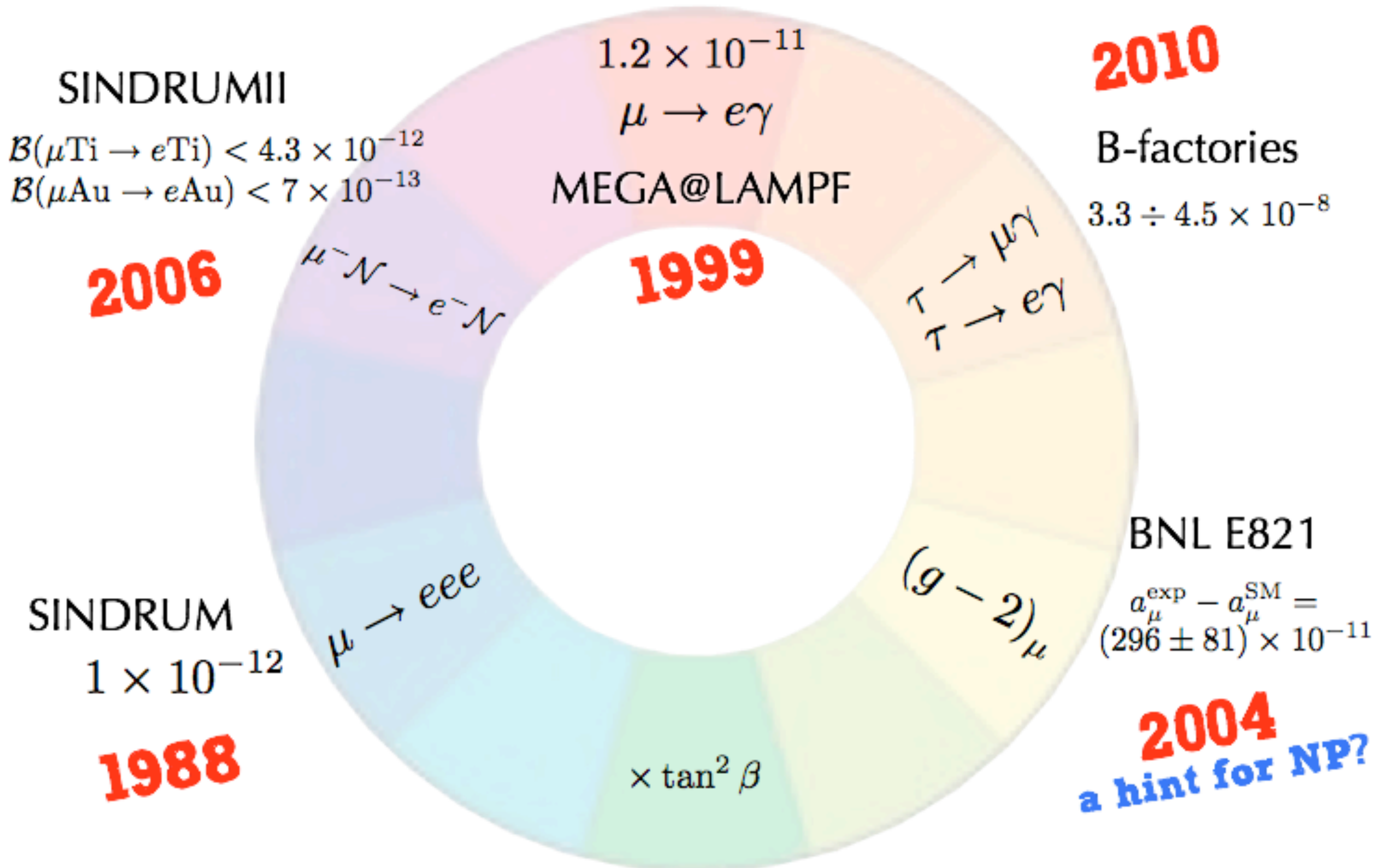
$\mu \to e\gamma$	$\tau \to \mu\gamma$ $\tau \to e\gamma$	$(g-2)_\mu$	$\mu^- N \to e^- N$	$\mu \to eee$

- cLFV processes are a wide field of research
    - LFV decays
    - Muon to electron conversion in matter
    - Anomalous magnetic moment

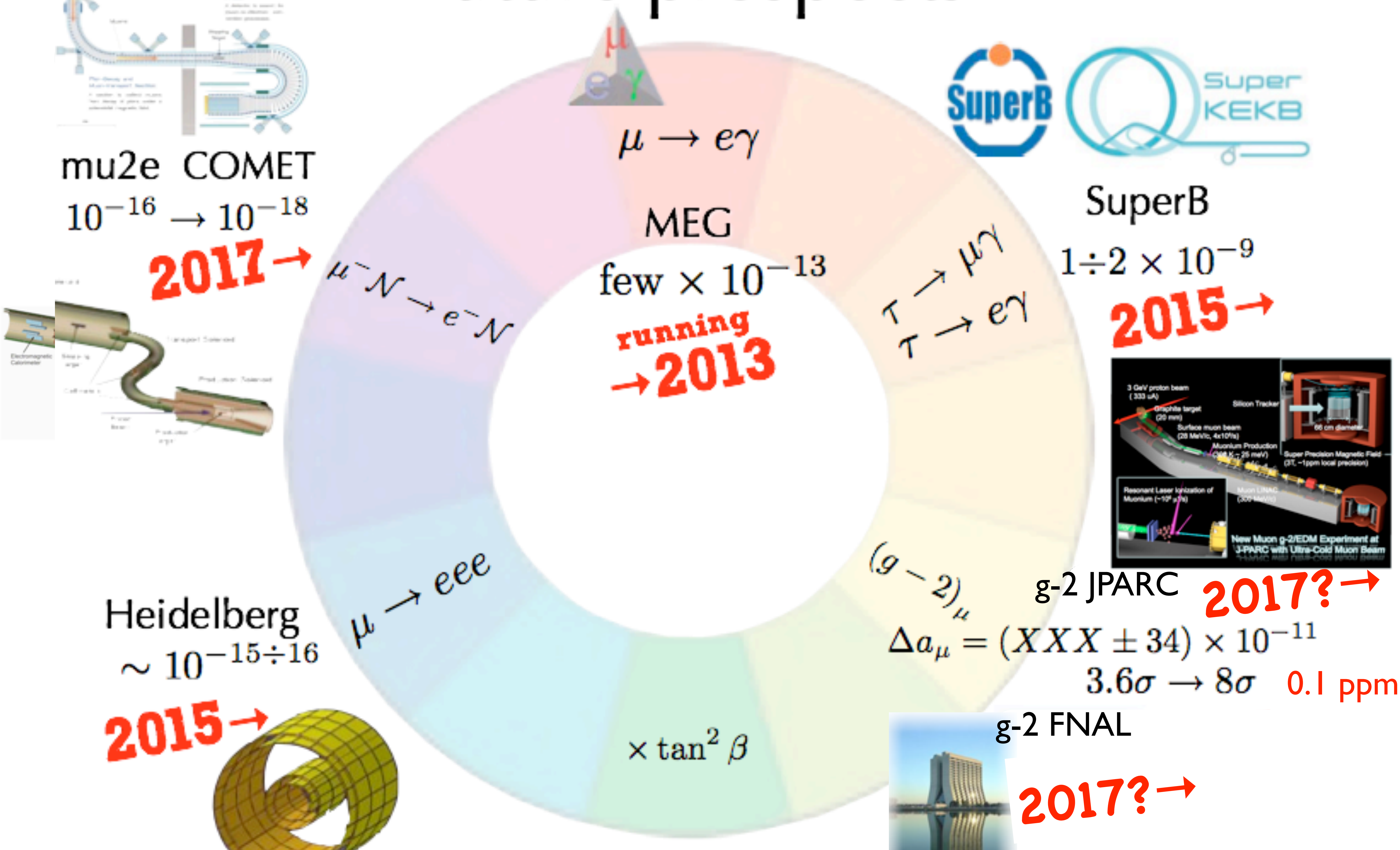
The cLFV wheel



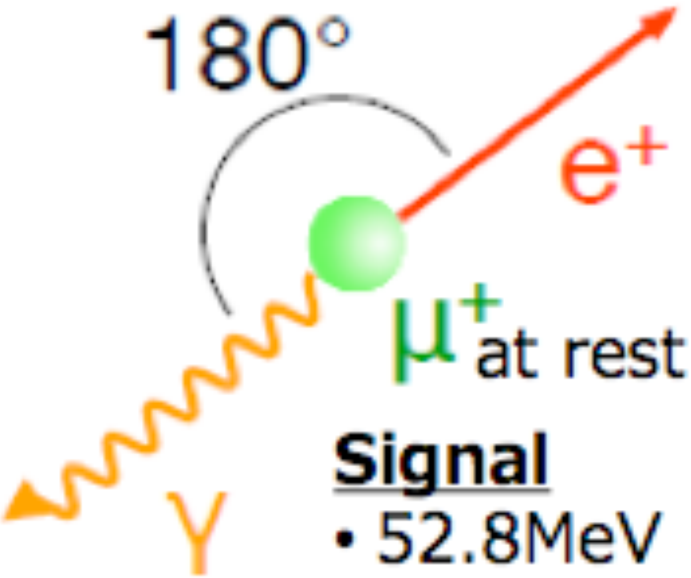
Present Limits



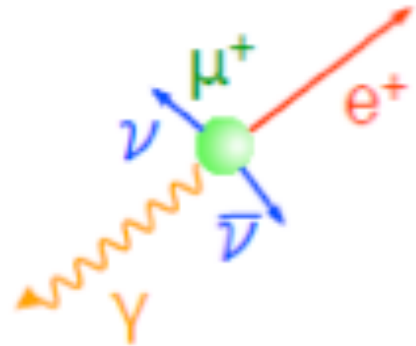
Future Prospects



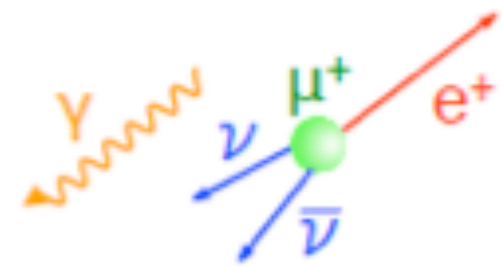
μ→eγ :experimental signature



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

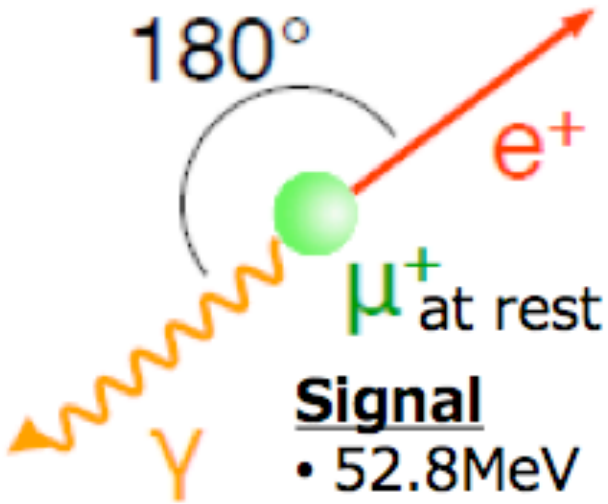


Physics BG
(radiative muon decay)
- <52.8MeV
- Any angle
- Time coincidence

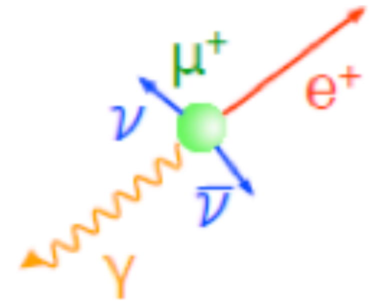


Accidental BG
- <52.8MeV
- Any angle
- Random

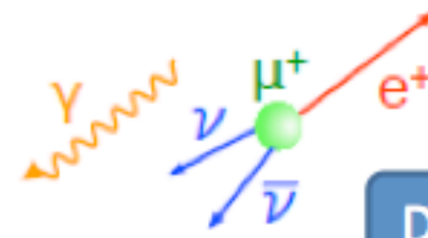
$\mu \rightarrow e\gamma$:experimental challenge!!



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



Physics BG RMD
(radiative muon decay)
- <52.8MeV
- Any angle
- Time coincidence

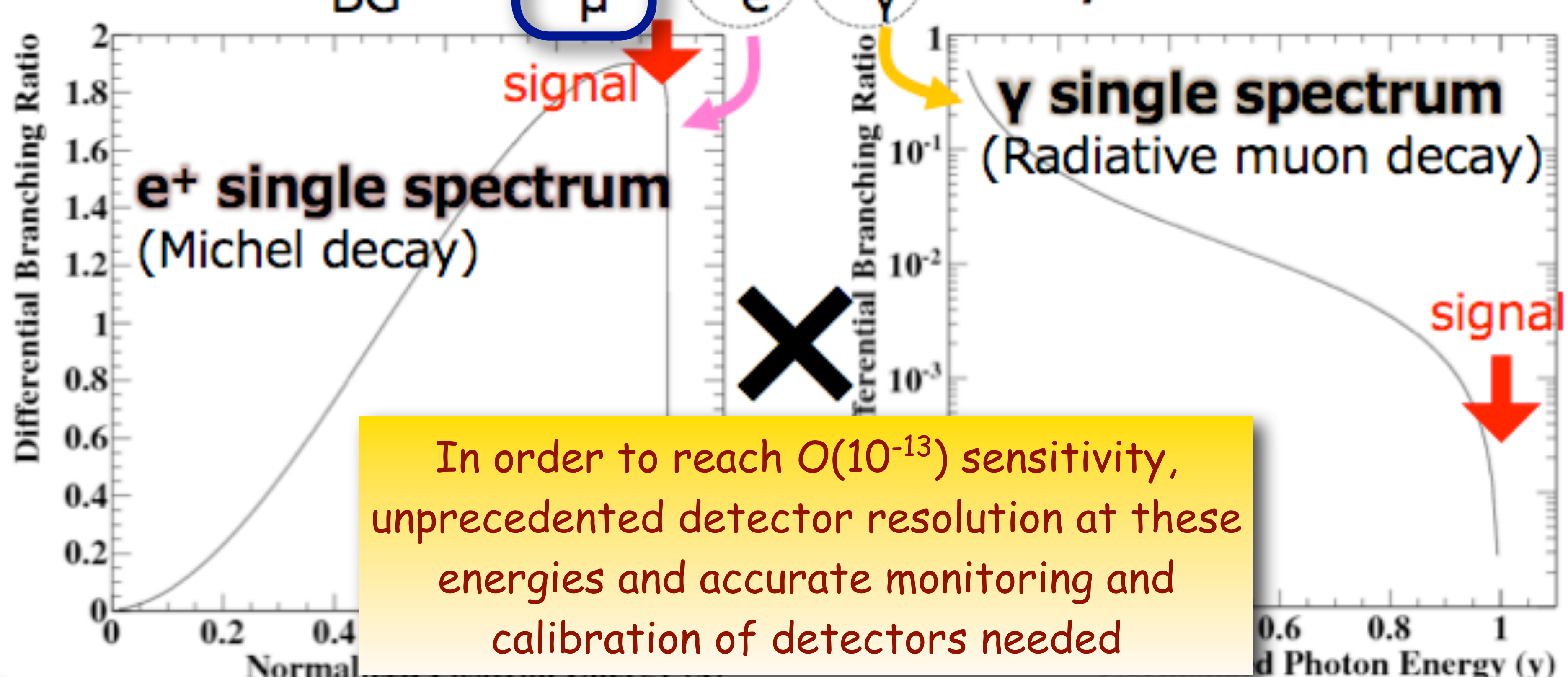


Accidental BG
- <52.8MeV
- Any angle
- Random

Dominant

Accidental background is determined by the experimental resolutions

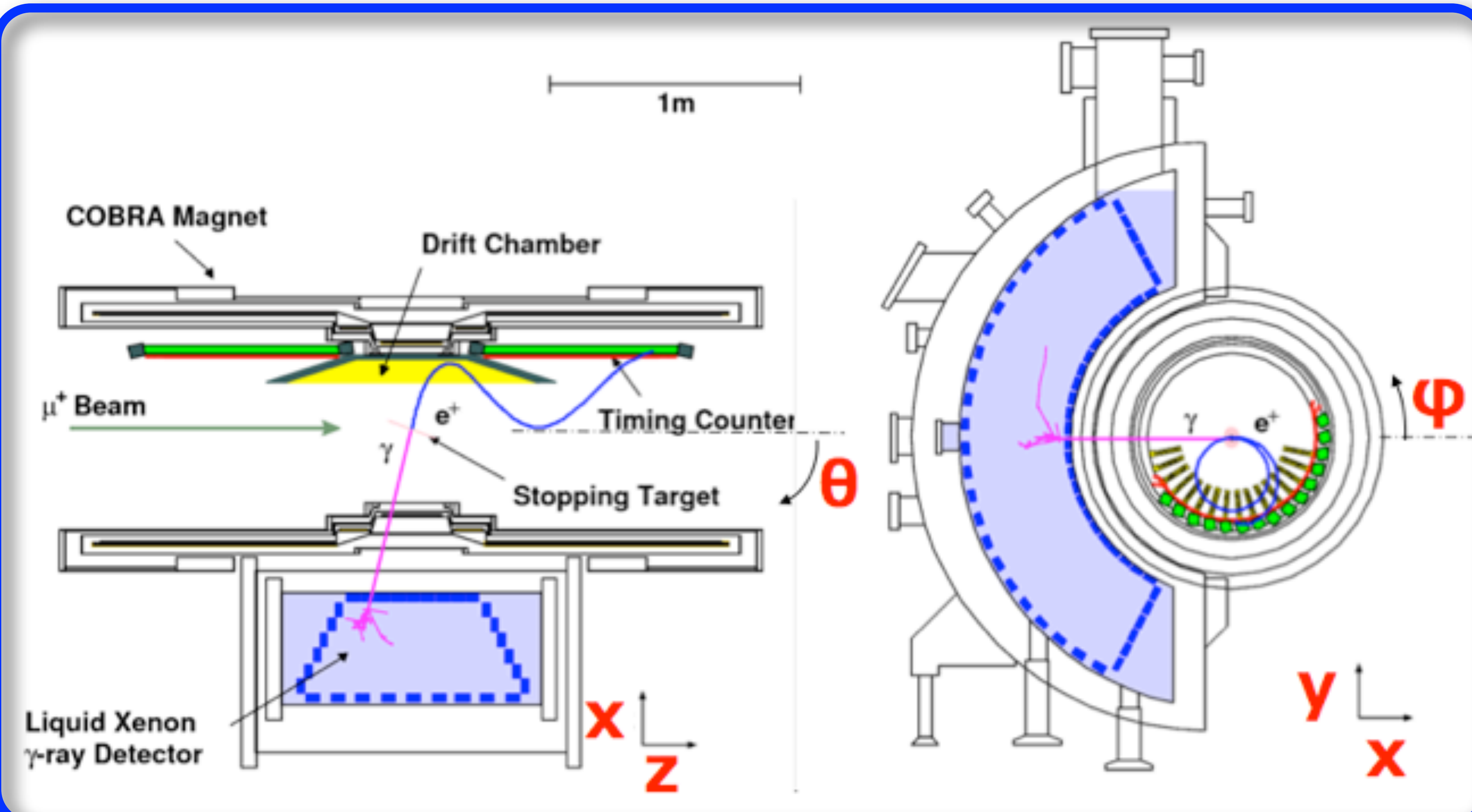
$$R_{BG} \propto R_\mu^2 \cdot f_e \cdot f_\gamma \cdot \delta\omega/4\pi \cdot \delta t$$



In order to reach O(10^{-13}) sensitivity, unprecedented detector resolution at these energies and accurate monitoring and calibration of detectors needed

MEG in a nutshell

- Most intense DC muon beam of 3 x 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
- ~10^7 fully efficient trigger bkg suppression



~ 60 collaborators

INFN Genova
INFN Lecce
INFN Pavia
INFN Pisa
INFN Roma

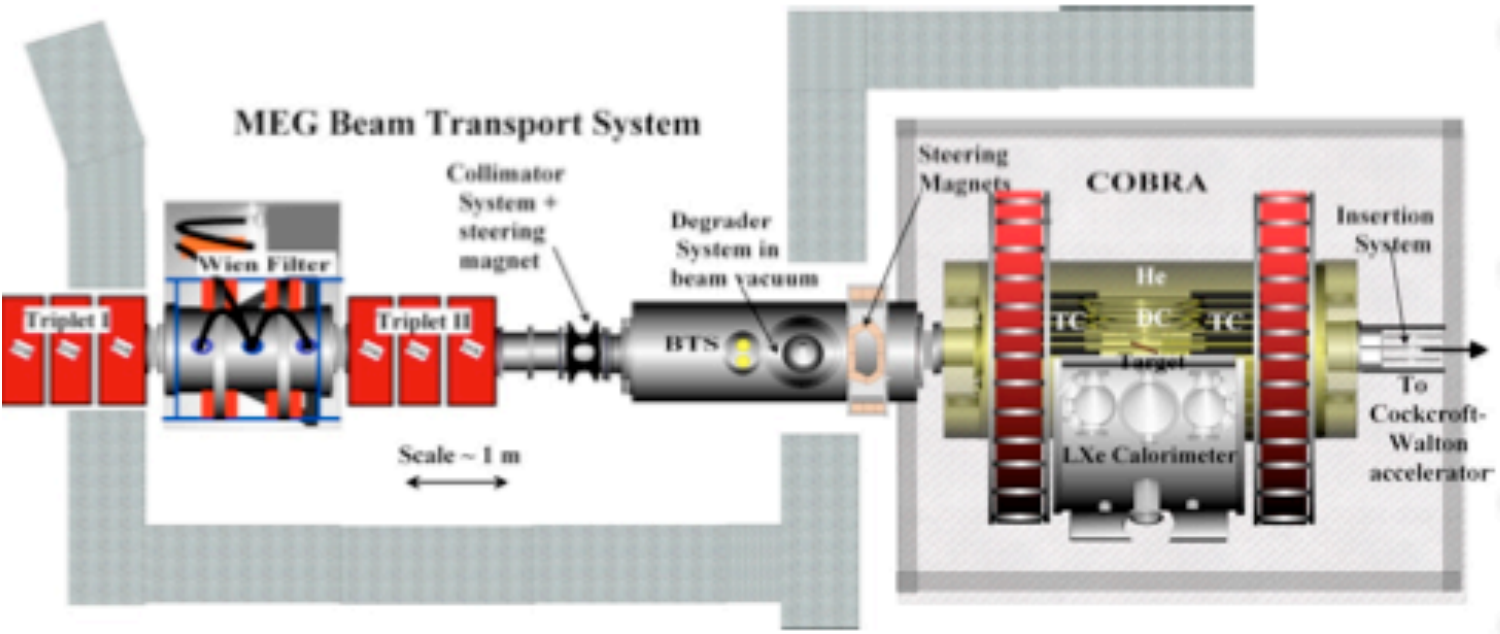
KEK
Tokyo Univ.
Waseda Univ.

UC Irvine

PSI

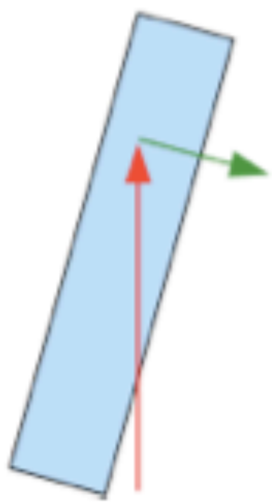
BINP - Novosibirsk
JINR - Dubna

The PSI πE5 beam & target



- Most intense proton DC beam in the world : 2 mA @ 1.3 MW
- 28 MeV/c "surface muons" from decay of π at rest
- Wien filter for e/μ separation
- Solenoid to couple beam with the COBRA magnetic field

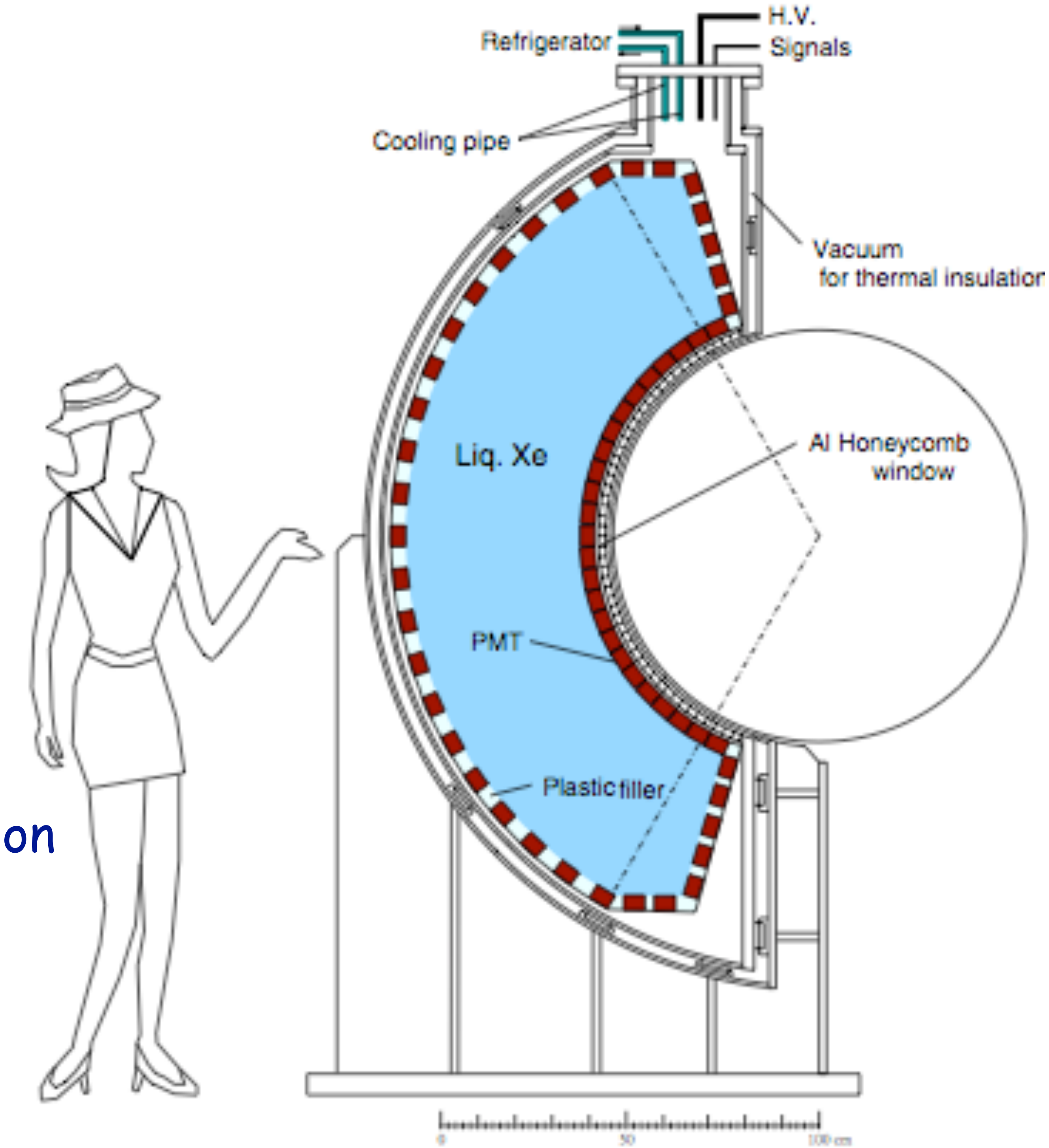
- Need enough material for stopping muons but low bremsstrahlung for signal positron:
  - degrader 200/300 μm + target 205 μm
  - 20.5° angle between beam and target
  - material with high radiation length X_0 (CH_2)



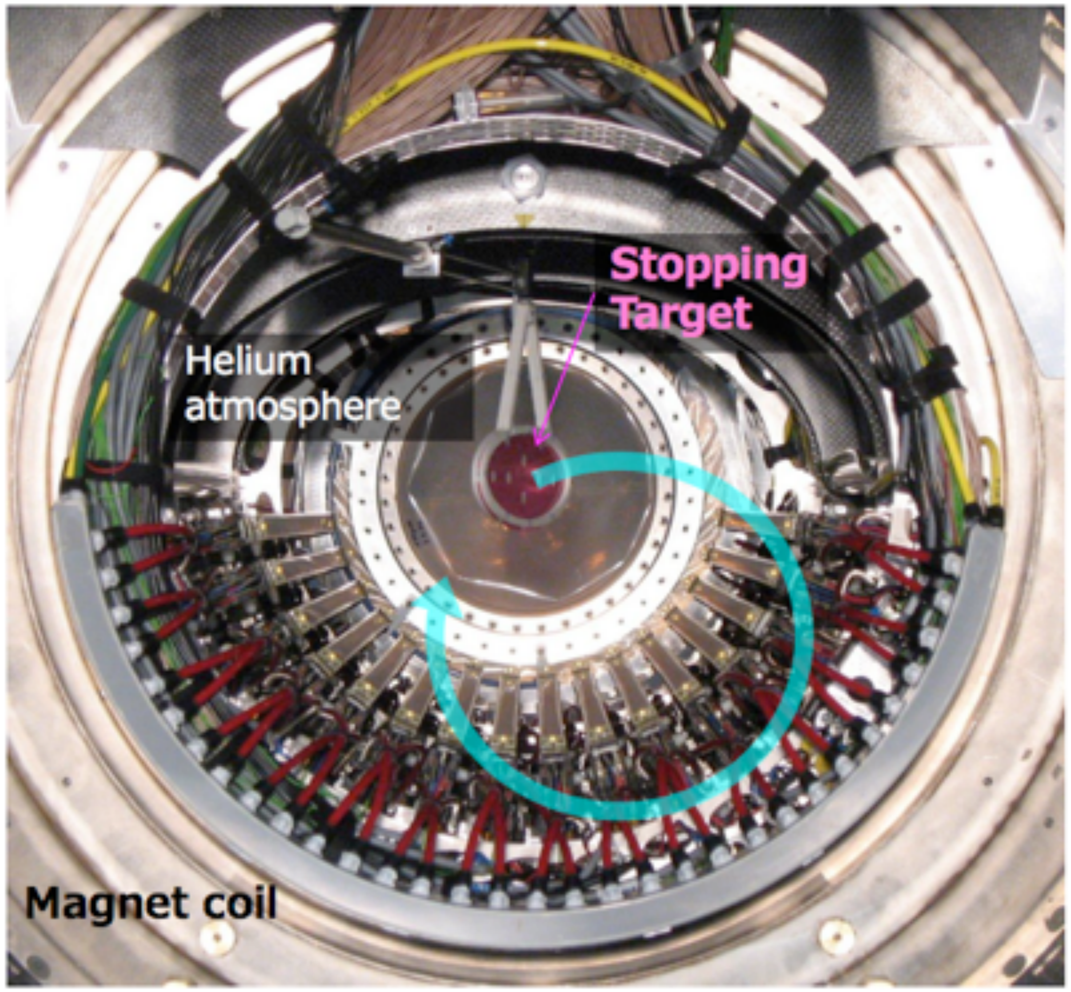
Liquid Xenon γ detector

- First ton-scale (~ 900 L) LXe calorimeter in use in the world
- Pros
  - High light yield (~ 75% NaI)
  - Fast response (τ_{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

	proposal
σ_E/E < 2 % @ 52.8 MeV	1.2 %
σ_t = 67 ps	43 ps
σ_x = 5-6 mm	3.8-5.1 mm



The Spectrometer



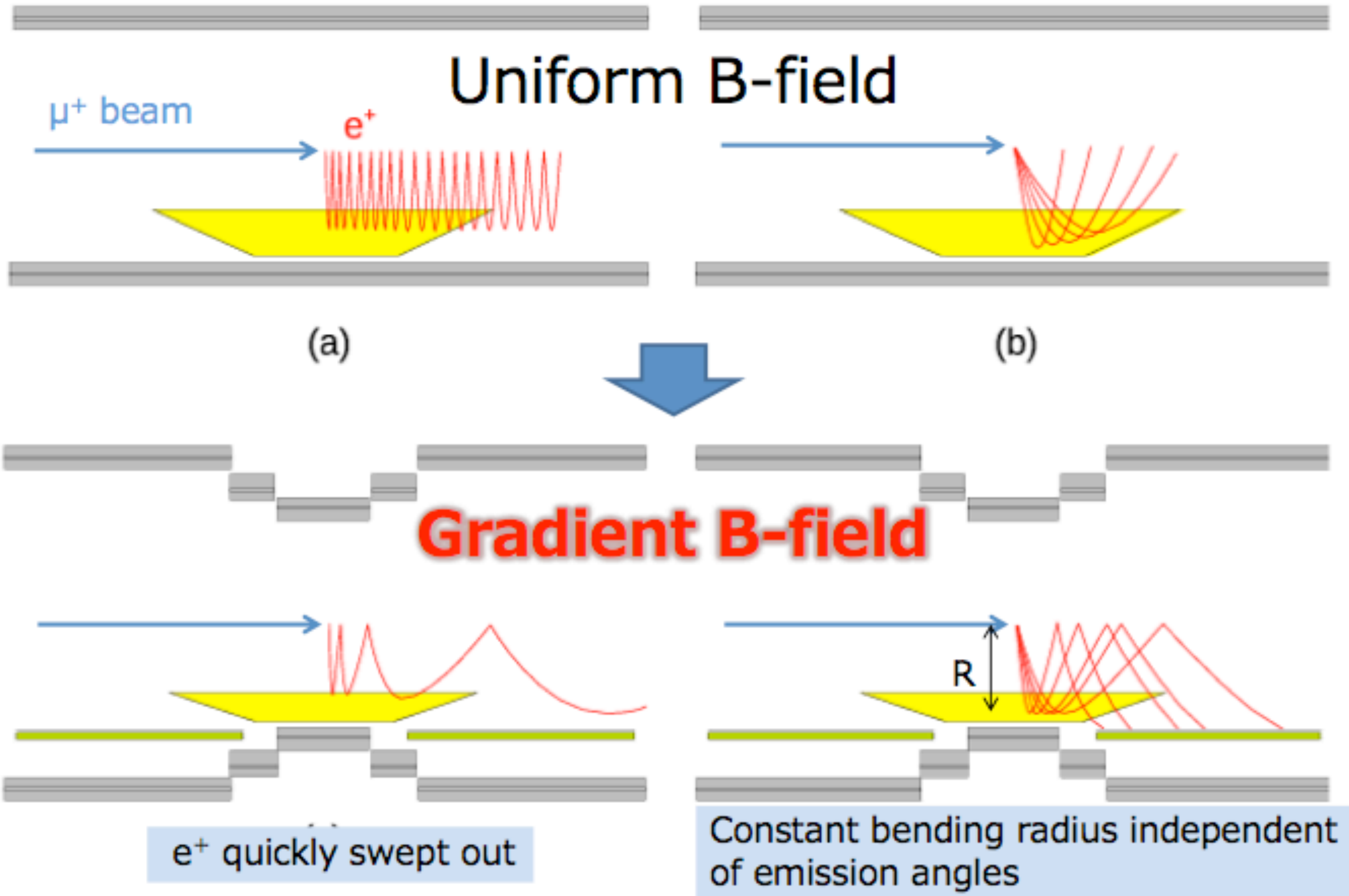
Experimental requirements:

Very good momentum and angular resolution (~ 200 KeV @ 52.8 MeV and ~ 5 mrad)

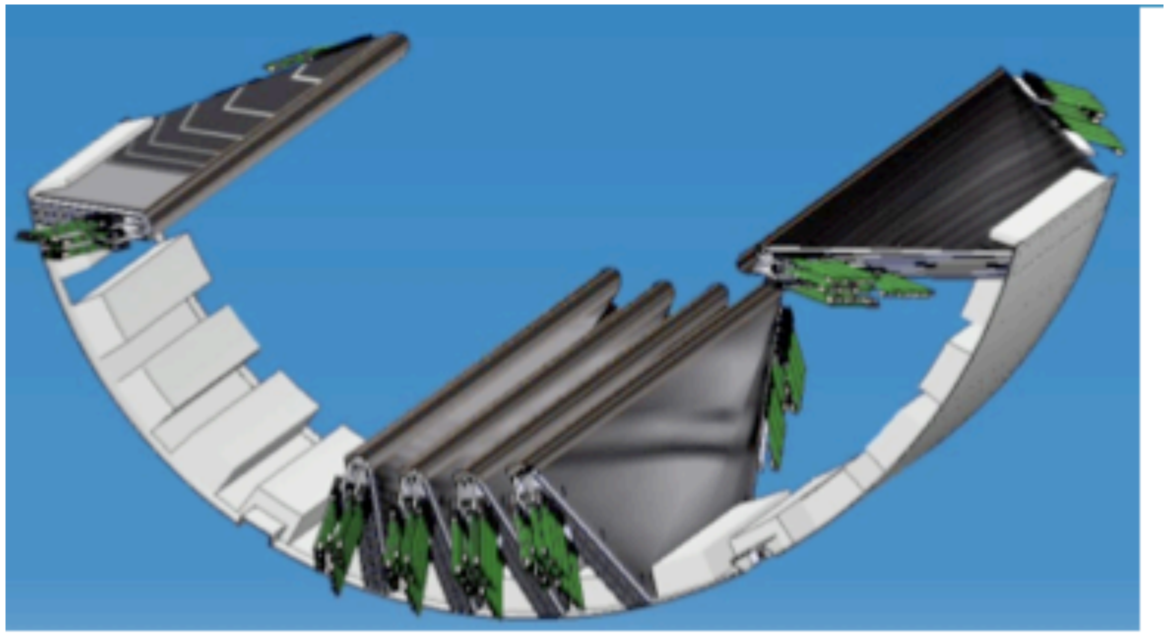
Low pile-up for efficient background rejection

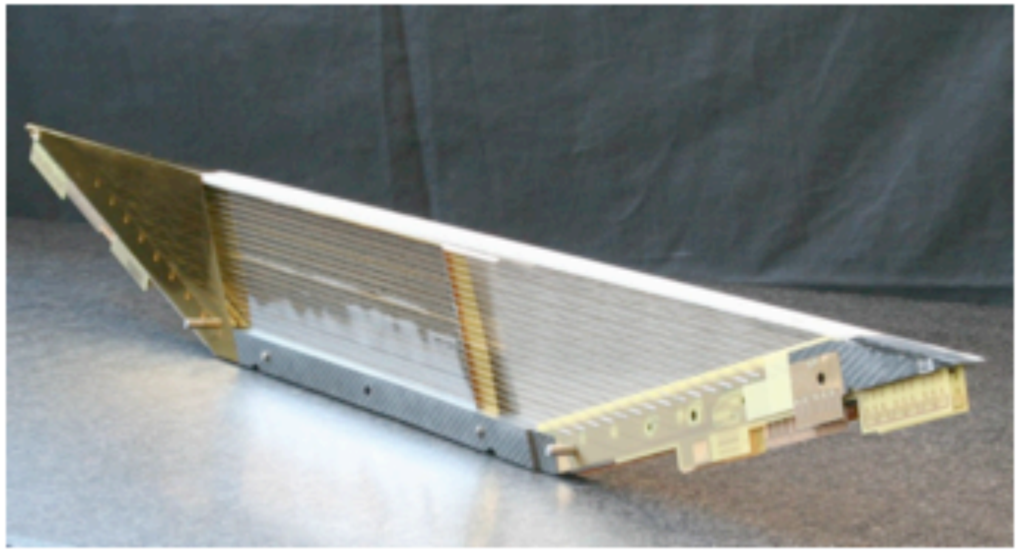
Low mass drift chambers in graded magnetic field (COBRA)

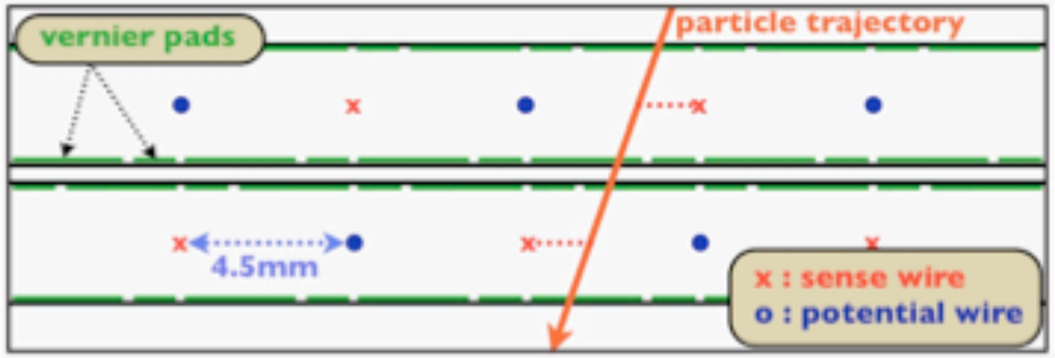
COnstant Bending RAdius Magnet



Drift Chambers





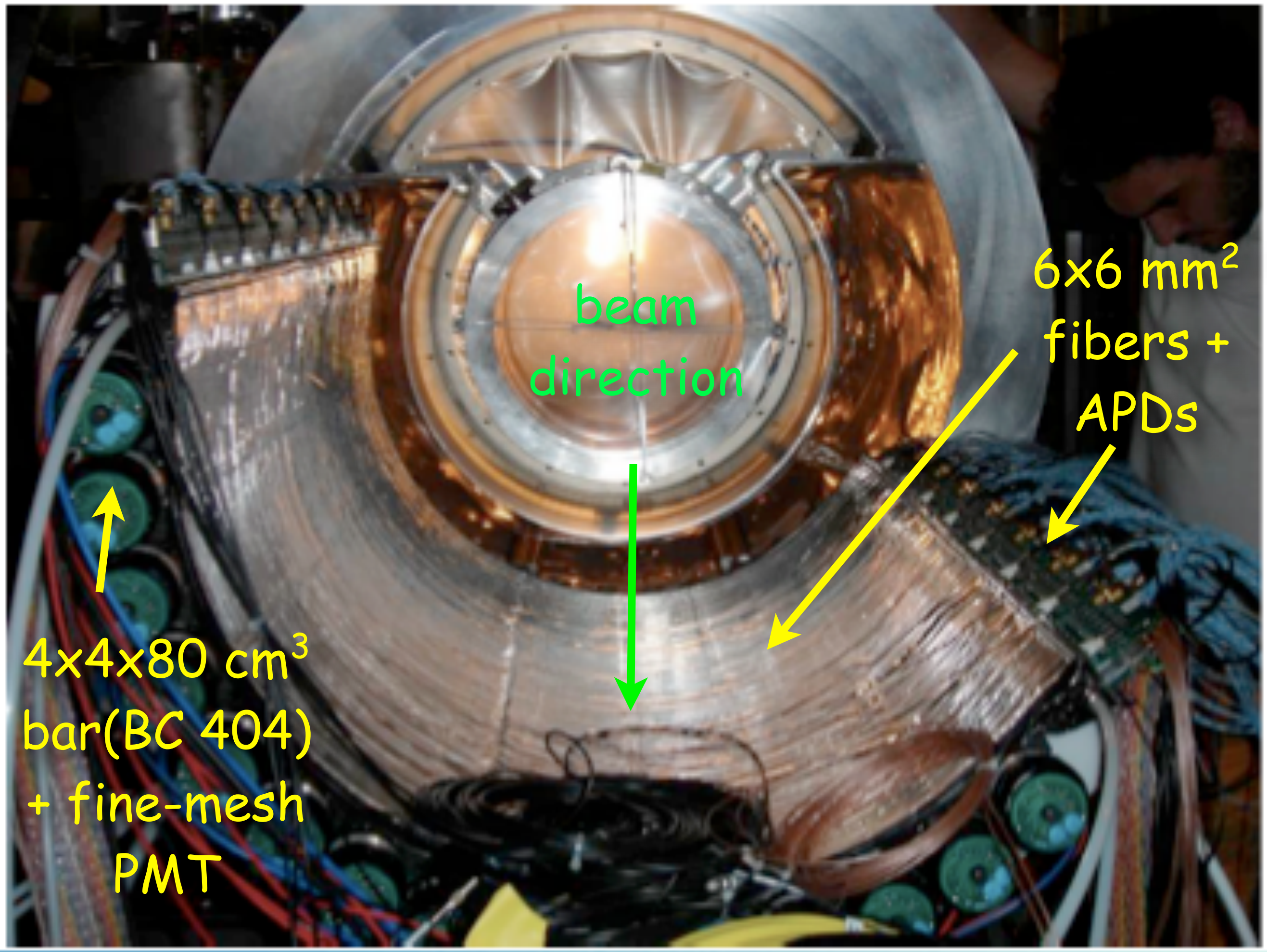


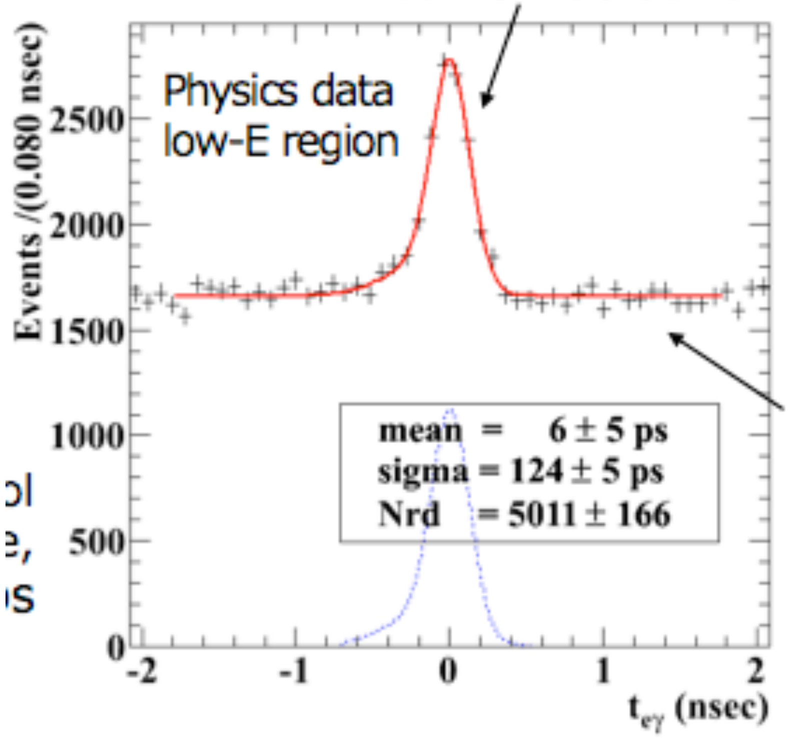
- 16 chamber sectors, 2 planes each
- Staggered array of drift cells
- Helium:Ethane 50/50 mixture
- Ultra low mass chamber to suppress MS that limits momentum and angular resolutions
  - 12.5 μm cathode foils with Vernier patter for Z hit position
  - ~ 0.2 % X_0 along e^+ trajectory
- Reconstruct e^+ momentum vector at target with Kalman filter technique

	proposal
σ_E/E ~ 0.6 %	0.3 %
σ_θ ~ 10 mrad	5 mrad
σ_φ ~ 7 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 ~ 70 ps/ goal ~ 50 ps

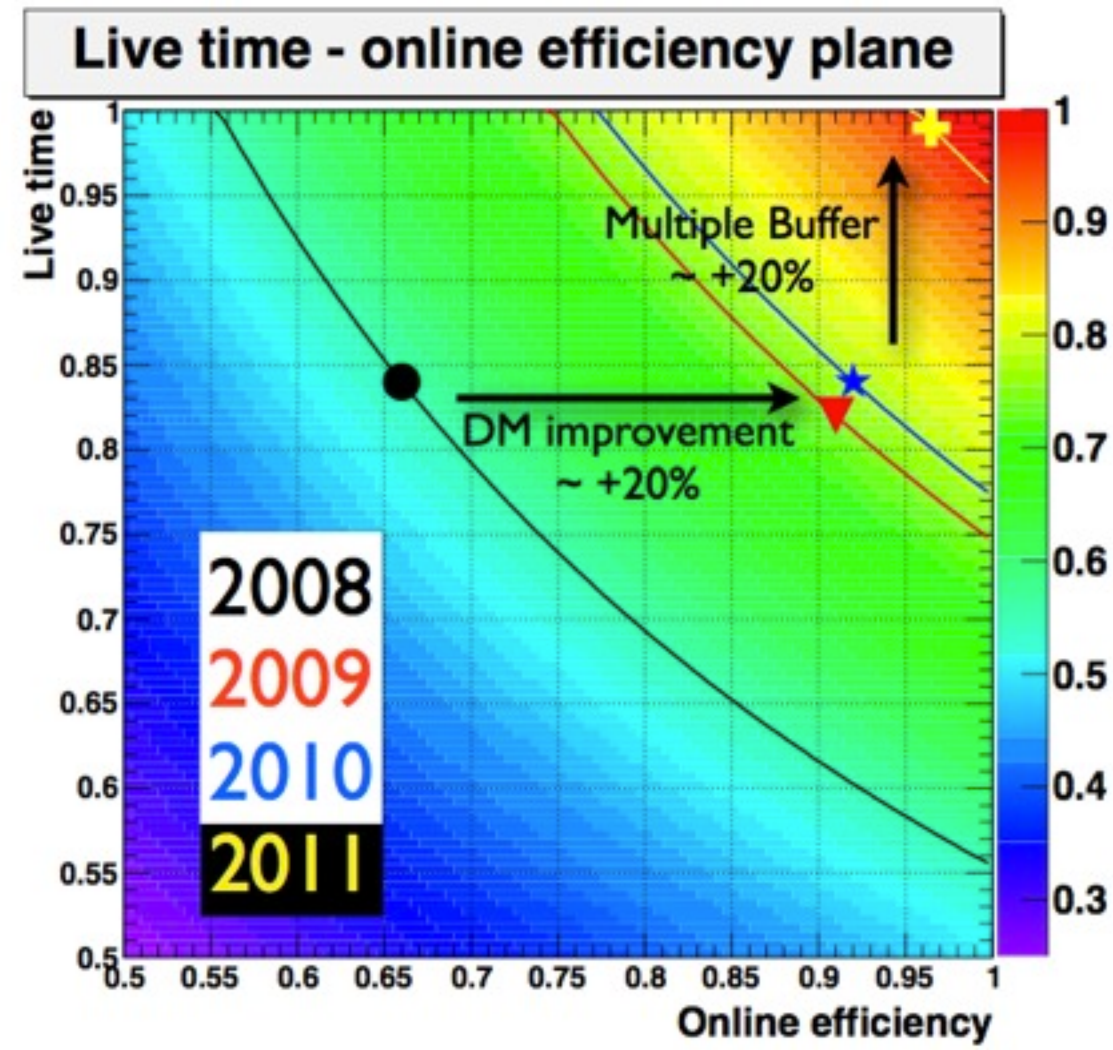




- Muon decay time:
  - TC hit time + e^+ flight length from DC
  - LXe hit time + γ flight lenght
  - $t_{e\gamma} = t_{e+} - t_\gamma$
- $\sigma_{te\gamma}$ = 122 ps from RMD

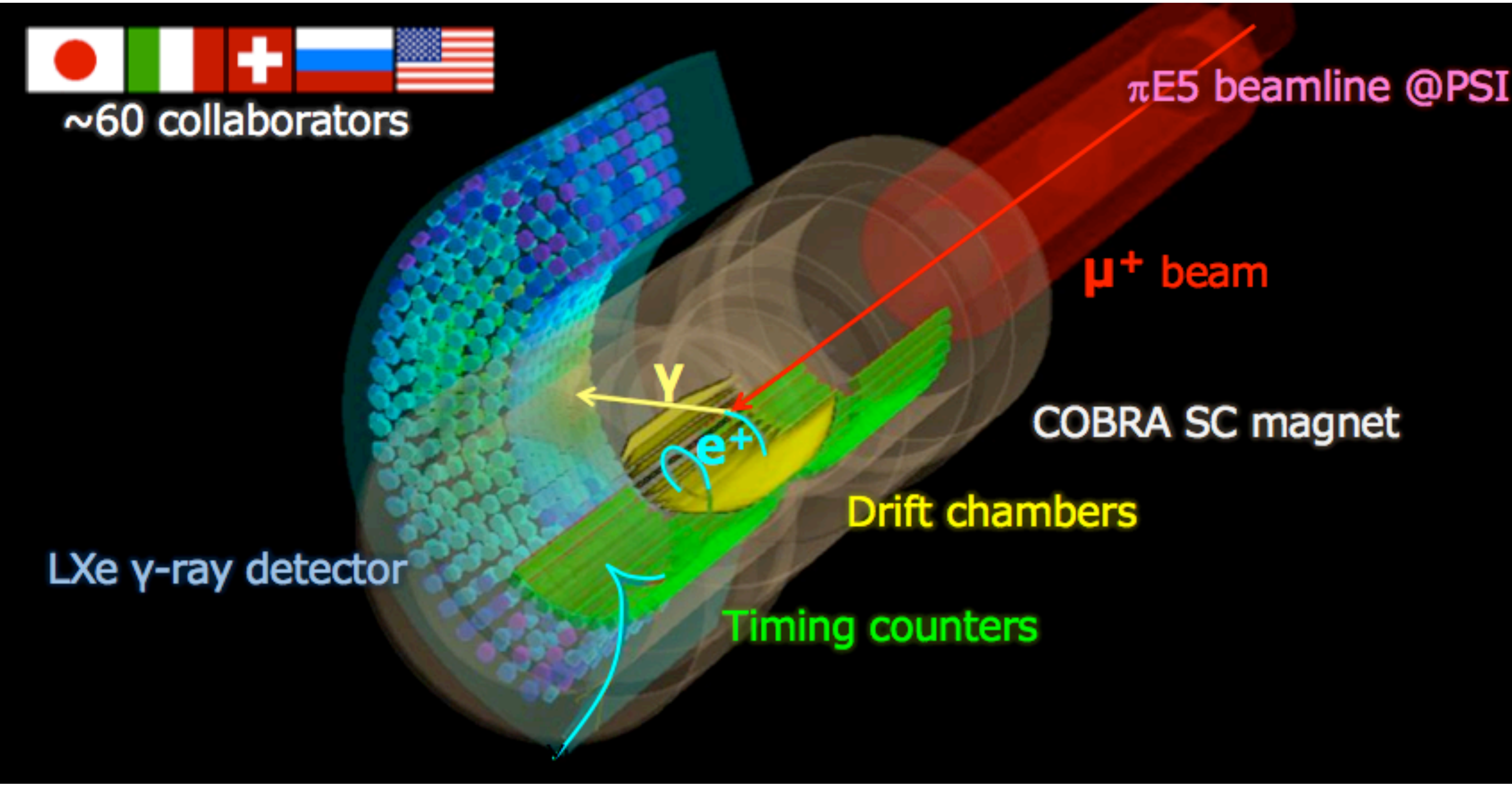
Trigger & DAQ

- 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_γ > 45 MeV ---> rate 2 x 10^3 Hz
    - Δt between LXe and TC --> rate 100 Hz
    - Collinearity based on LUT tables --> 10 Hz



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

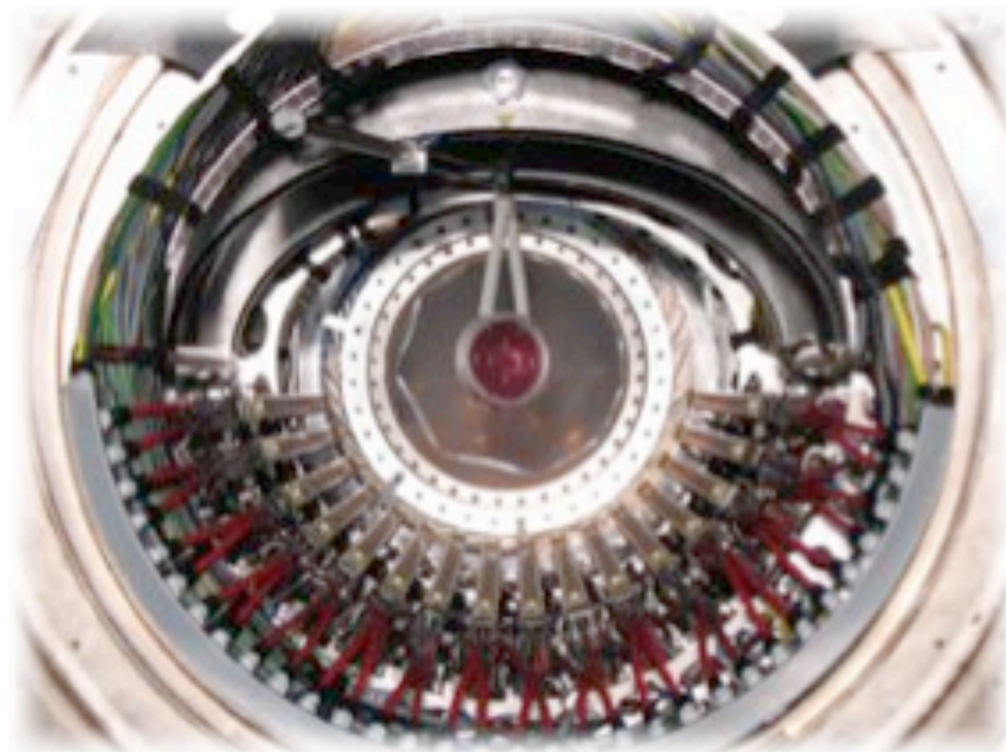
MEG picture


~60 collaborators
πE5 beamline @PSI
μ+ beam
γ
e+
COBRA SC magnet
Drift chambers
LXe γ-ray detector
Timing counters

Detector Pictures

LXe detector

DC system

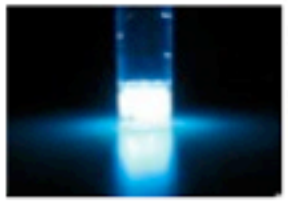


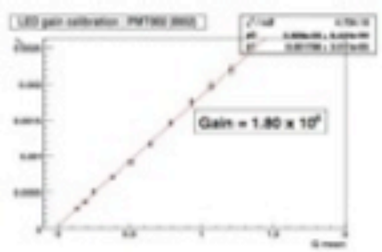
Beam Line

Calibrations

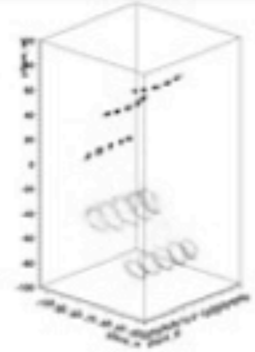
XENON CALIBRATION

LED
PMT gain

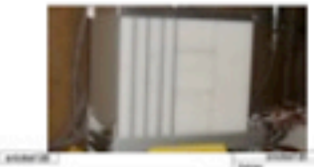


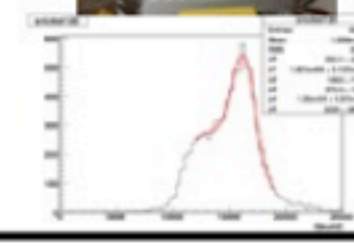


α source
PMT QE
Absorption length

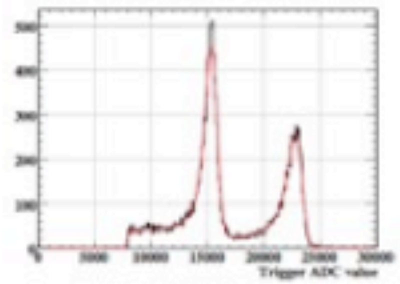


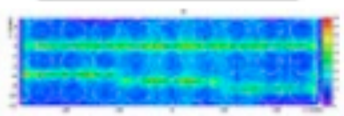
Ni γ generator
9 MeV γ-line
beam on/off calib.

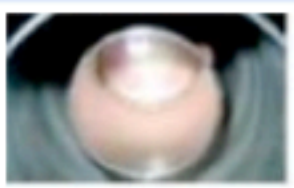




CEX
γ-resolutions:
- energy
- time
- impact point

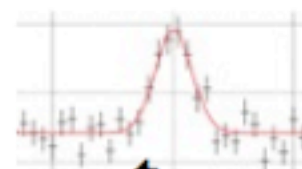






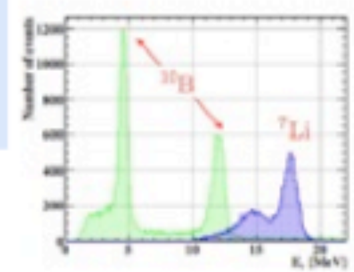
LH_2 target

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

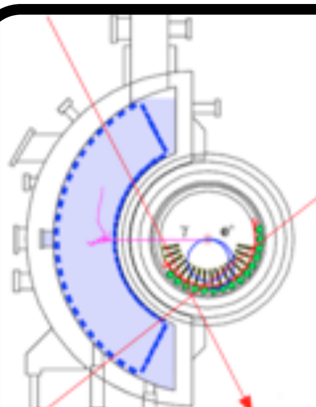


$t_{e\gamma}$

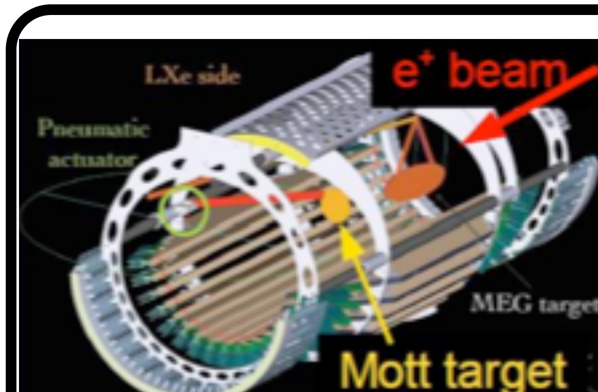
CW p-accel
Light Yield
LXe-TC t-calib



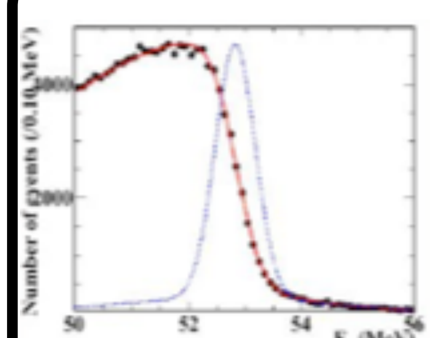
TRACKER CALIBRATION



Cosmic Ray
- DC alignment
-TC uniformity
-LXe monitoring



e^+ Mott-scatter
- Monochromatic, tunable momentum bean



Michel decays
- $\mu \rightarrow e \nu\nu$ for momentum energy scale

CW and CEX calibrations

$p + {}_5^{11}B \rightarrow {}_6^{12}C^{**} + \gamma$

4.4, 11.7, $^{12}C^{**} \rightarrow {}^{12}C\,\gamma$

16.1 MeV $\downarrow$

at the $\quad$ $^{12}C\,\gamma\,\gamma$

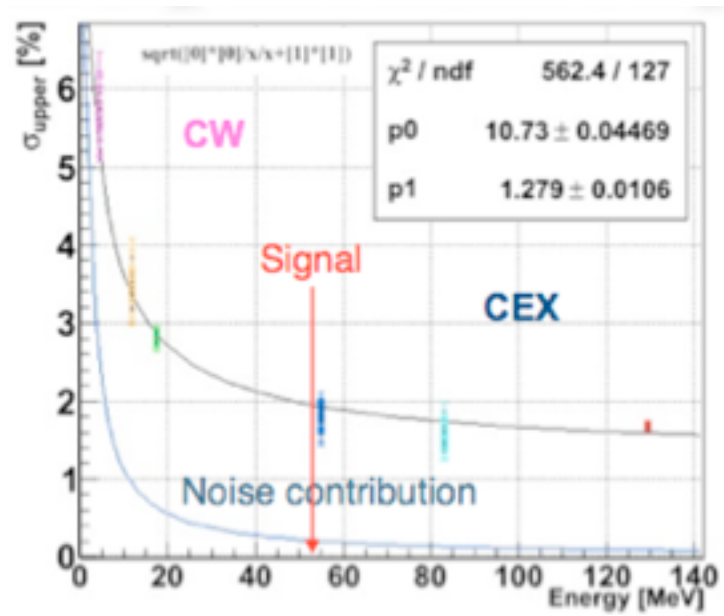
same time

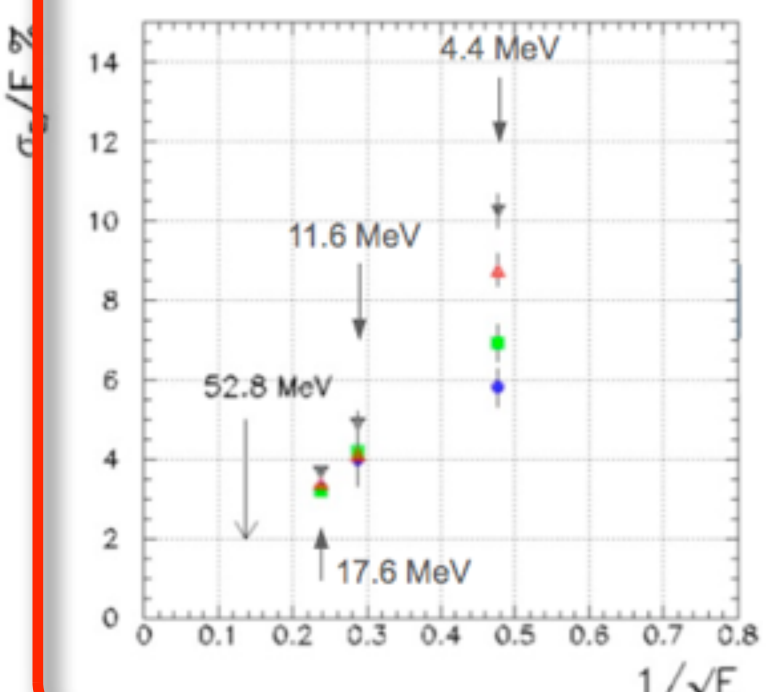
$p + {}_3^7Li \rightarrow {}_4^8Be + \gamma$

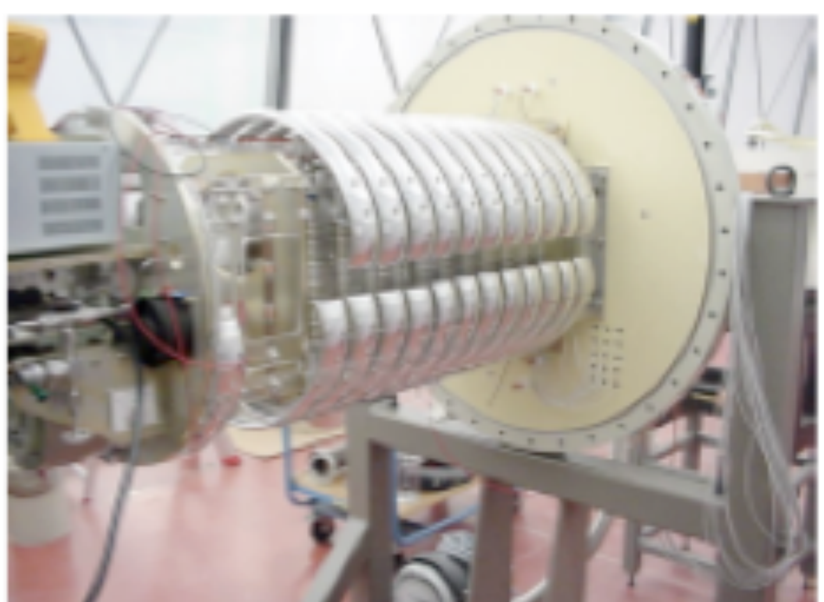
17.6, 14.6 MeV

Target of $Li_2B_4O_7$ allows both calibrations at same time

Cockcroft-Walton accelerator

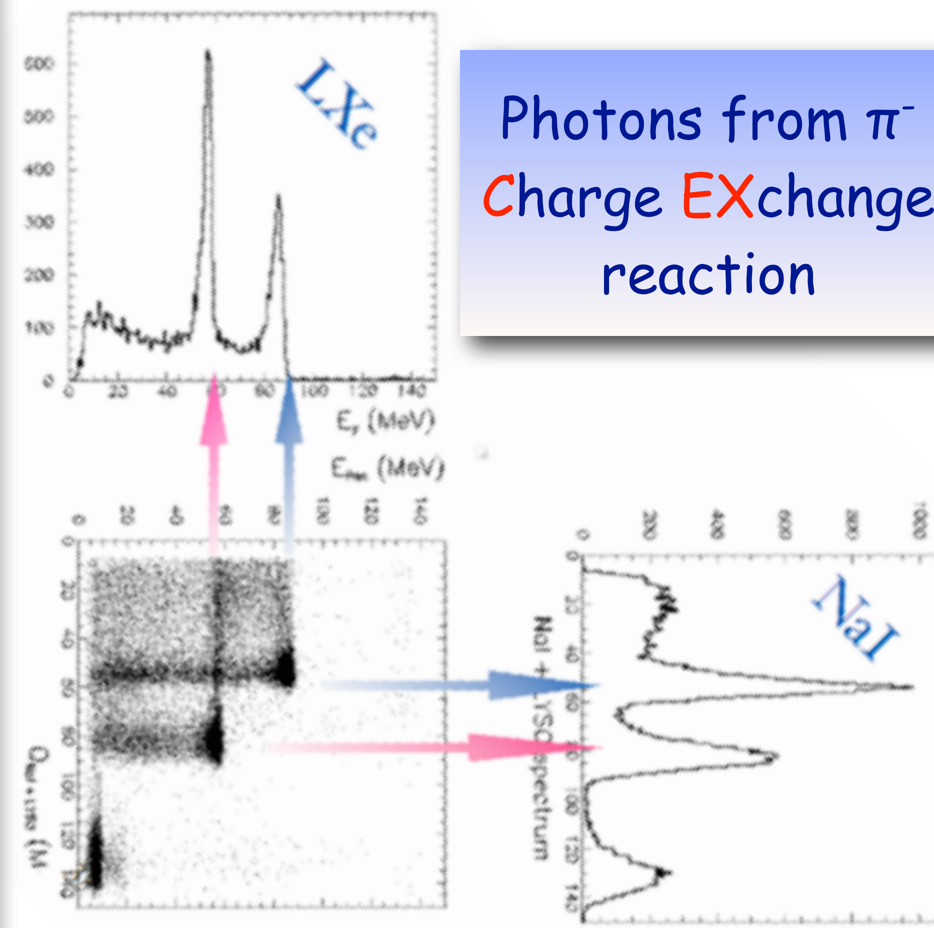




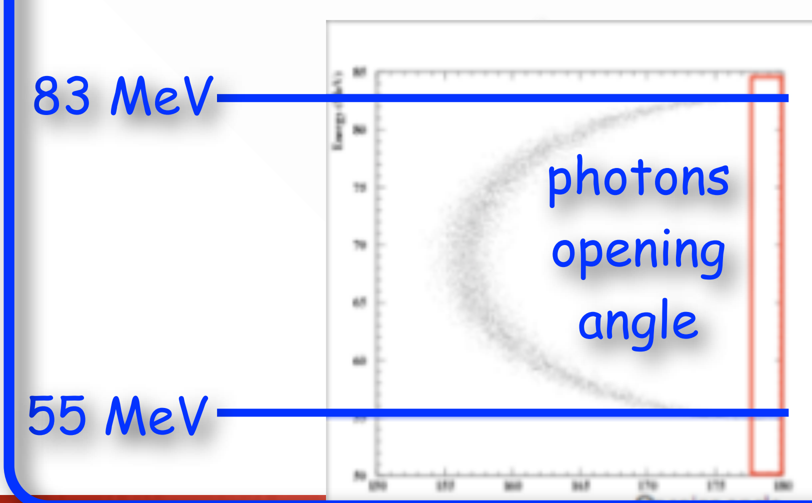


$\pi^- p \rightarrow \pi^0 n$

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

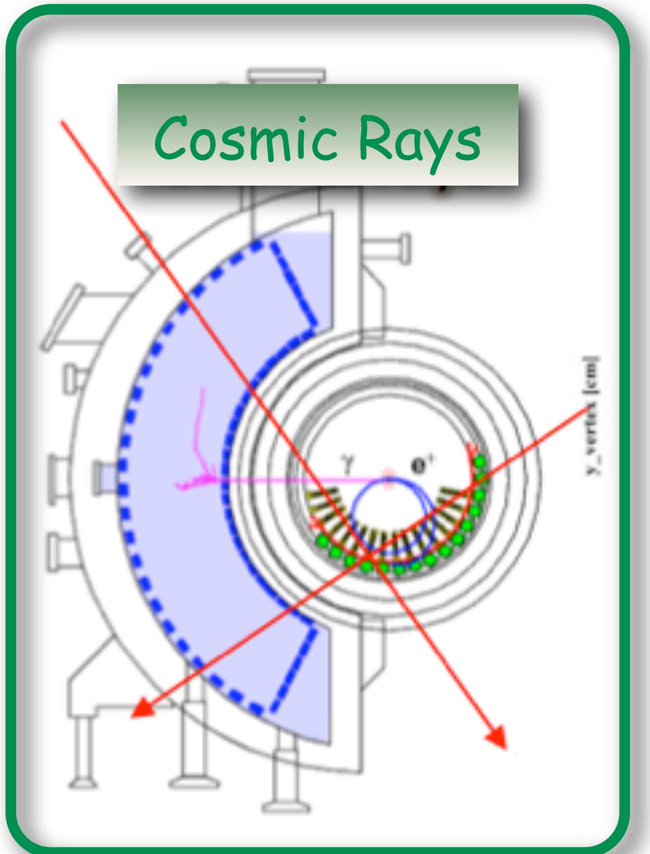


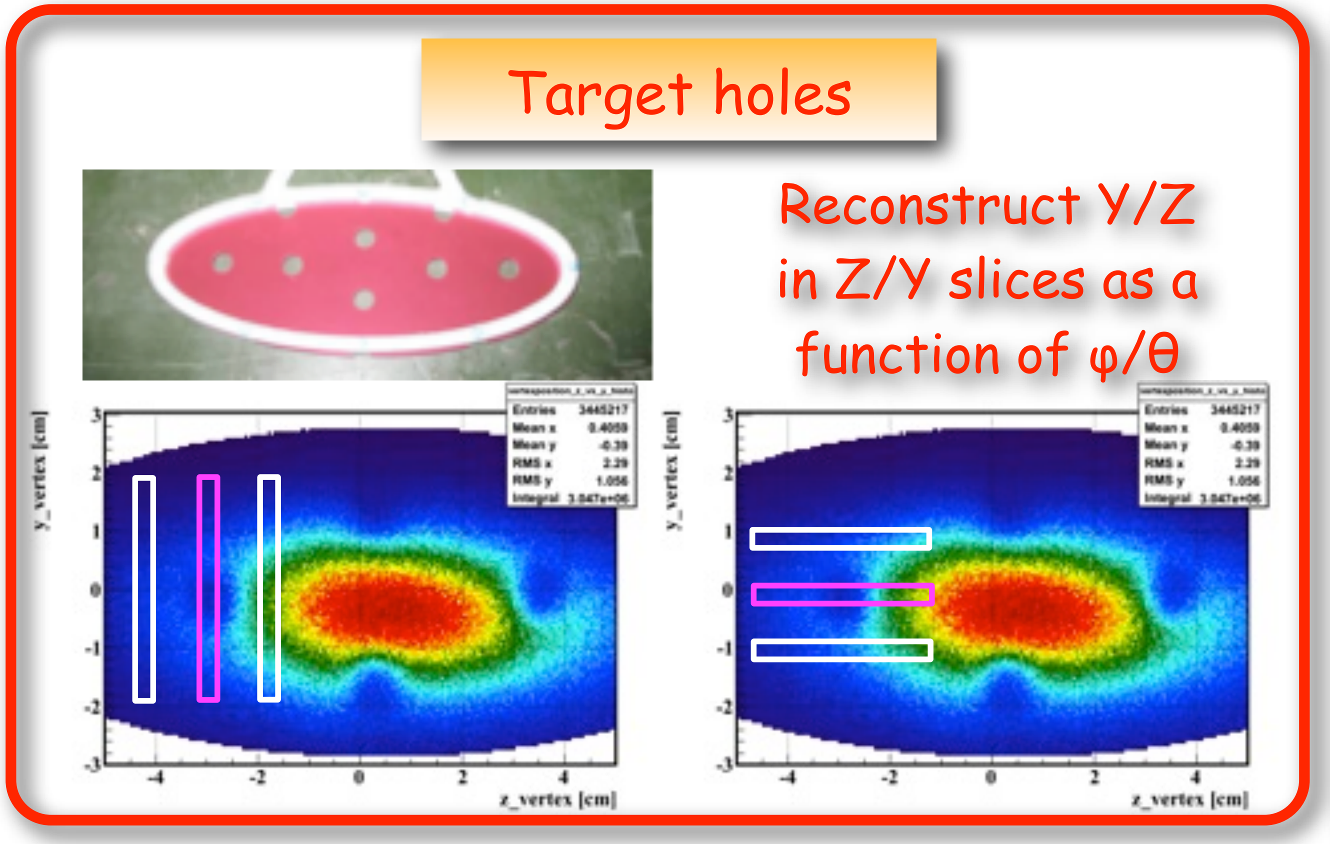
Photons from π^- Charge EXchange reaction

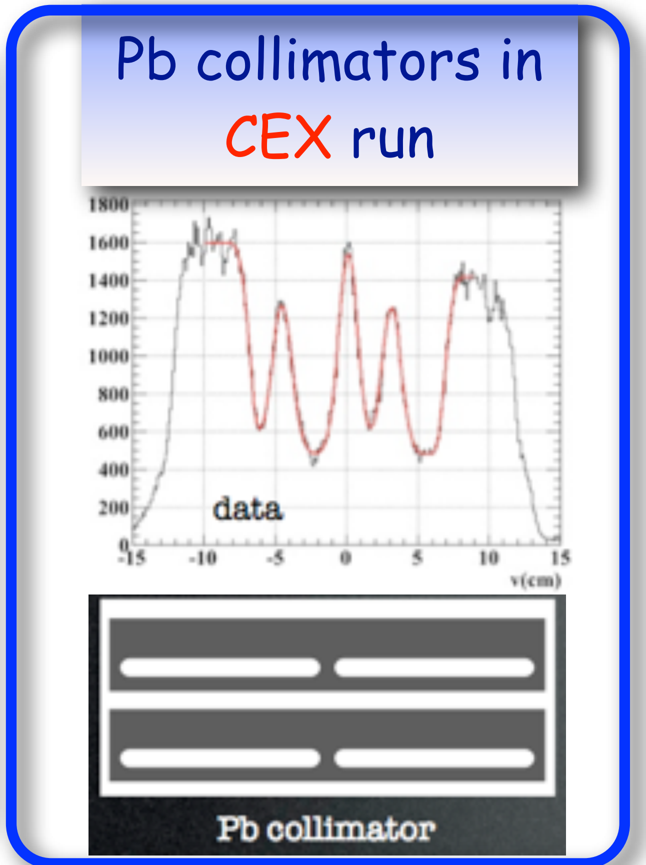


Alignment

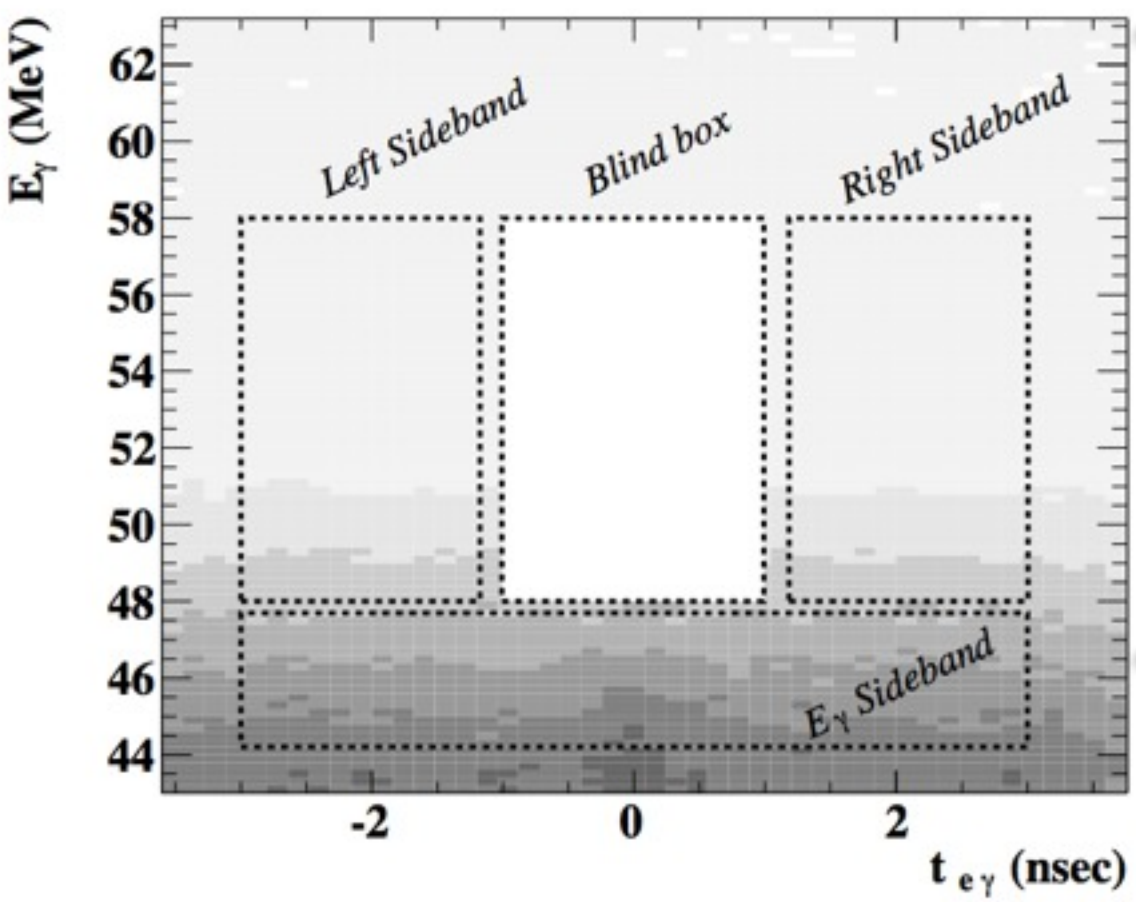
- Good alignment is crucial to reduce systematics on relative photon-positron angle
  - No back to back source for calibration
  - Nonetheless, we improved alignment inside and among detectors
    - DC - B field - target - LXe
- Tools:
  - Optical surveys
  - DC: Millipede (a la CMS) with cosmic rays + Michel e^+
  - Target holes
  - LXe: Pb collimators
  - B field: resolutions and correlations







Analysis Technique

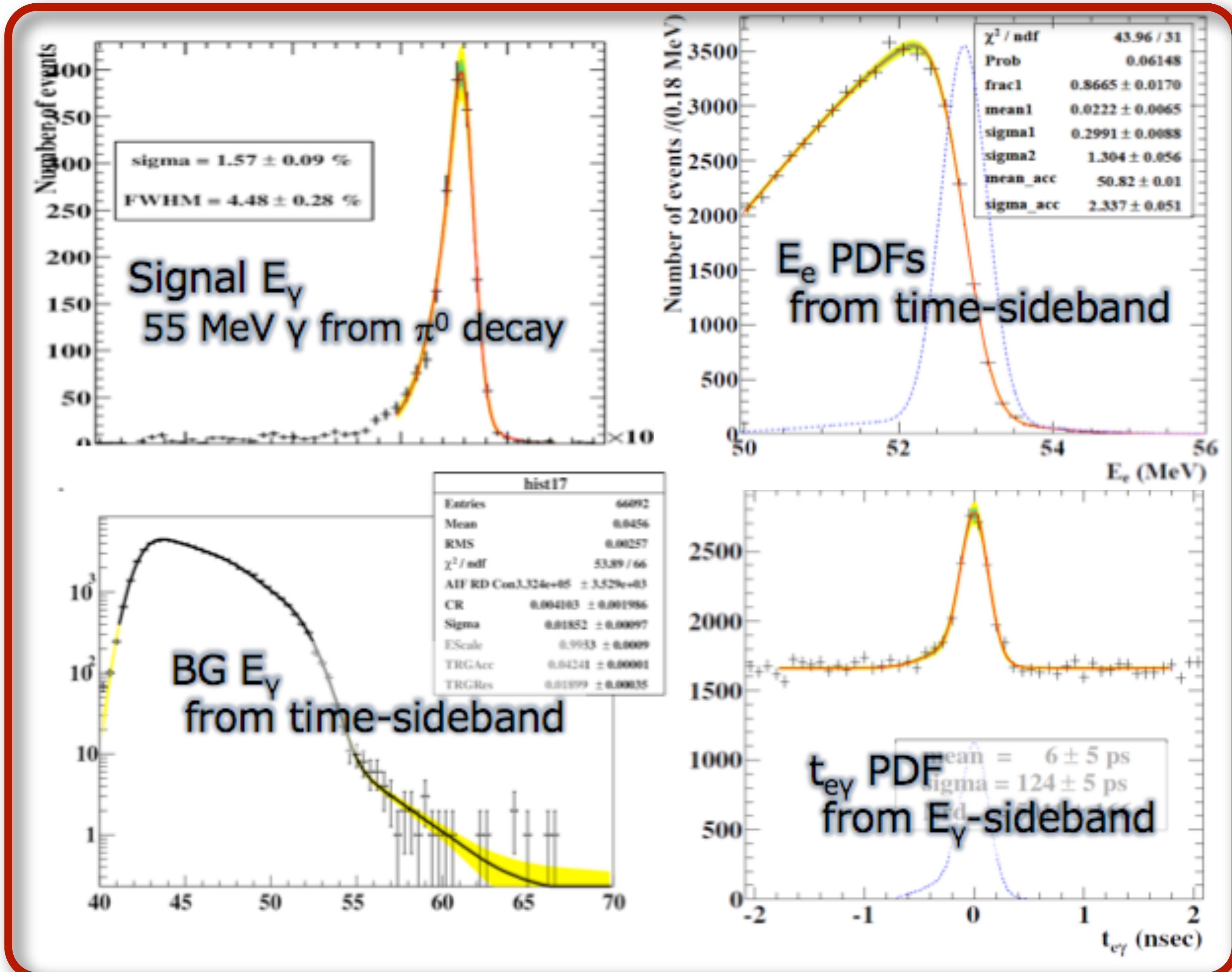


- Blind analysis technique adopted:
  - Events inside a signal region of E_γ and $t_{e\gamma}$ not used for analysis development
  - Background characterization from sidebands:
    - accidental bkg from off-time sidebands,
    - RMD from low energy E_γ sideband
- Extended unbinned ML fit of N_{sig}, N_{RMD} and N_{bkg}
  - Observables E_γ, E_e, $t_{e\gamma}$, $\theta_{e\gamma}$, $\varphi_{e\gamma}$,

- Number of muons stopped on target: 1.7×10^{14} (6.5×10^{13} (2009) + 1.1×10^{14} (2010))
  - Count unbiased Michel sample in physics data simultaneously with the signal
    - Count RMD sample in E_γ sideband (independent sample) for consistency check
  - Independent of instantaneous beam rate and insensitive to acceptance and efficiency

$$\mathrm{BR}(\mu^+ \to e^+\gamma) = \frac{N_{\mathrm{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f^E_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{\mathrm{trig}}_{e\nu\bar{\nu}}}{\epsilon^{\mathrm{trig}}_{e\gamma}} \times \frac{A^{\mathrm{TC}}_{e\nu\bar{\nu}}}{A^{\mathrm{TC}}_{e\gamma}} \times \frac{\epsilon^{\mathrm{DCH}}_{e\nu\bar{\nu}}}{\epsilon^{\mathrm{DCH}}_{e\gamma}} \times \frac{1}{A^{\mathrm{g}}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}},$$

PDFs

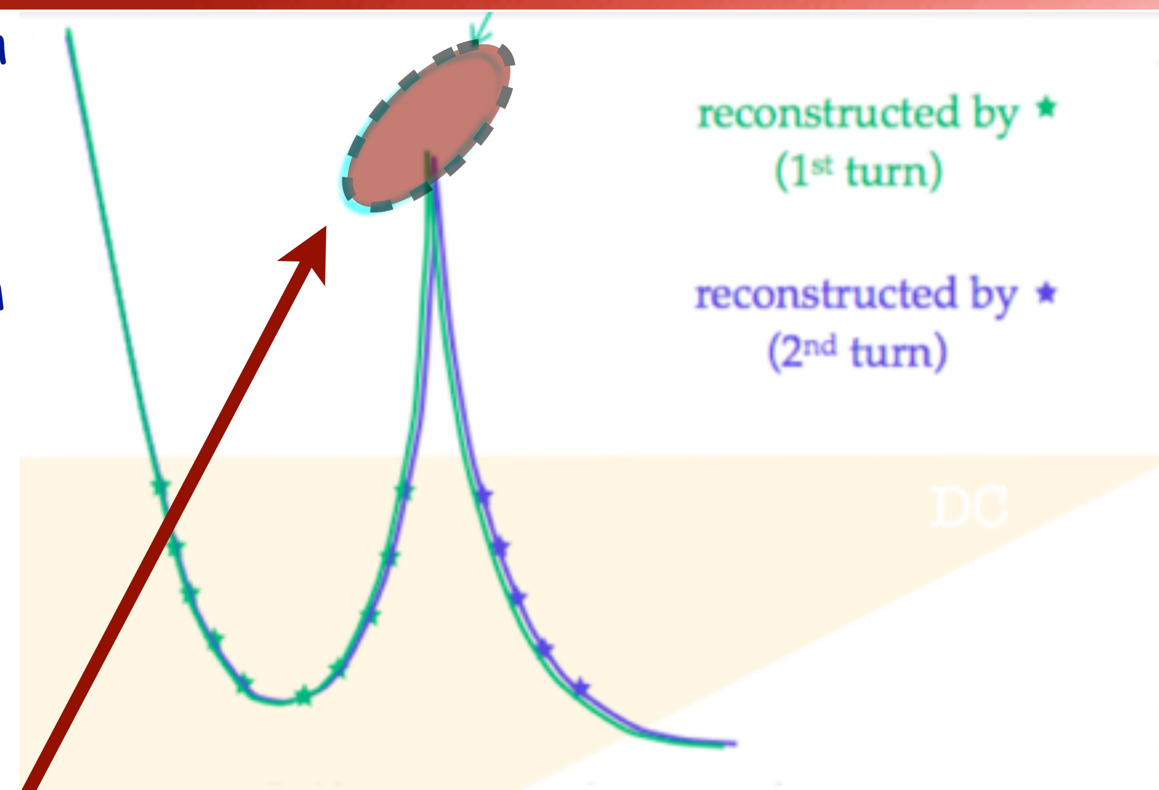


- Signal E_e PDF from fit to Michel edge data
- Signal angle PDFs measured on data from tracks which make two turns inside the spectrometer
- Background angle PDFs measured on time sideband
- RMD PDFs from theoretical distributions convoluted with measured resolutions

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

Signal Positron PDFs & Correlations

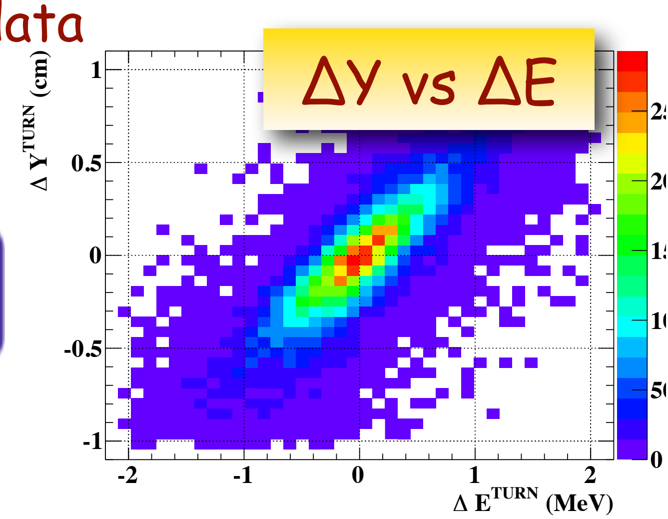
- Signal positron PDFs are evaluated from tracks which make 2 turns inside the spectrometer, treating each turn as an independent pseudo track
- Since all positrons must come from the target (~200 μm thick, fairly considered bidimensional in our analysis), this constraint removes one degree of freedom 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

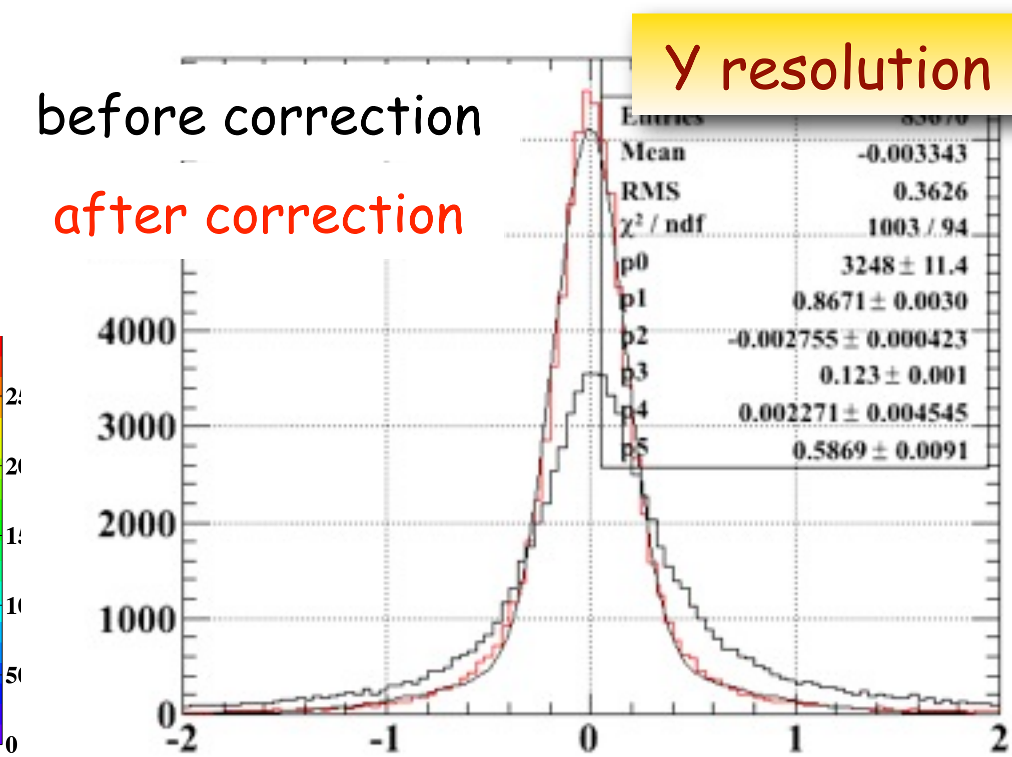


$$\delta\phi_e = -2\tan\phi_e\frac{\delta R}{R} = -2\tan\phi_e\frac{\delta E}{E}$$

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

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





Performances

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

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

Photon timing improvement thanks to WF digitizer upgrade in 2010

Phys. Rev. Lett. 107, 171801 (2011)

This result

- 2009 + 2010 dataset combined analysis (2010 data ~ 2 x 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_{bkg} constrained from sideband data
  - Profile-likelihood interval with Feldman-Cousins method

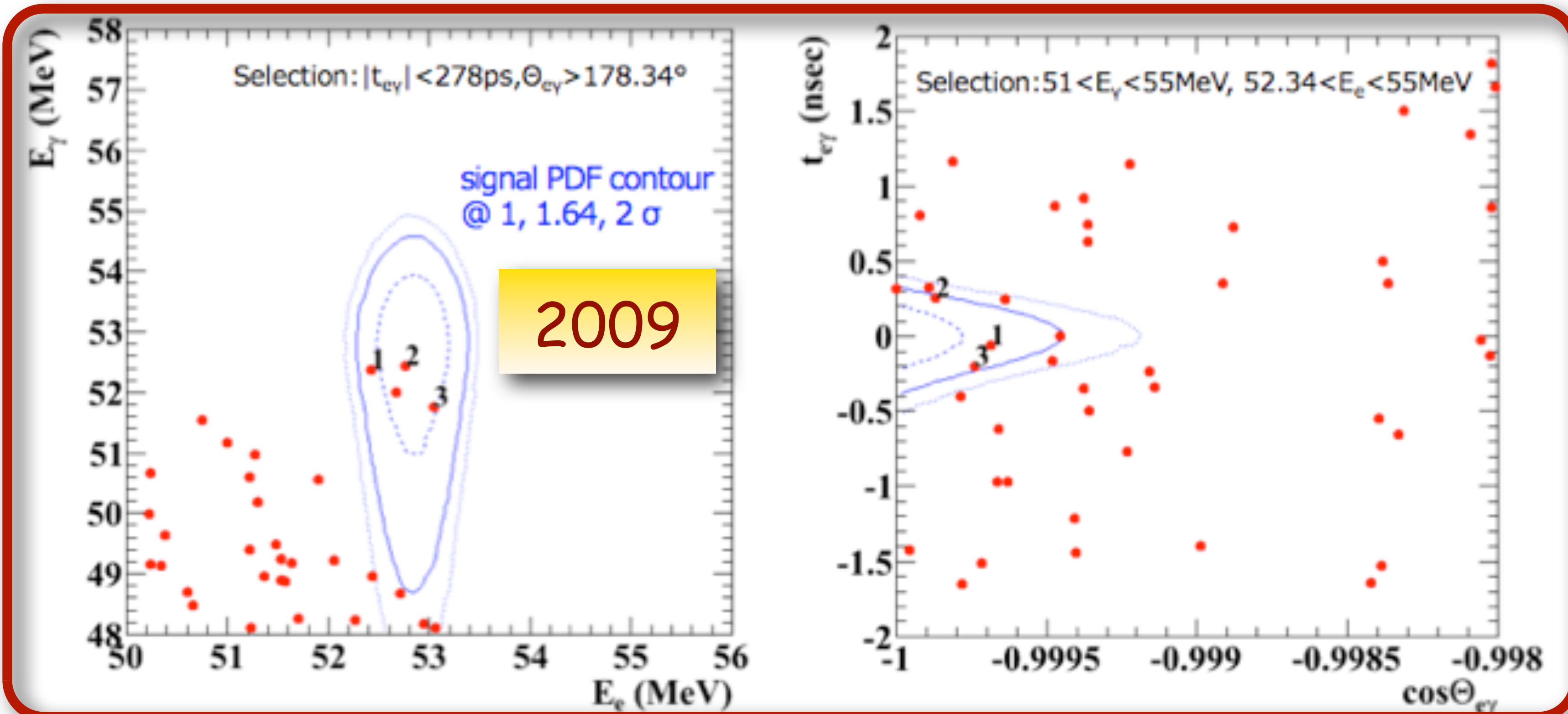
compare best UL 12×10^{-12}

Sensitivity confirmed on time AND angular sideband data

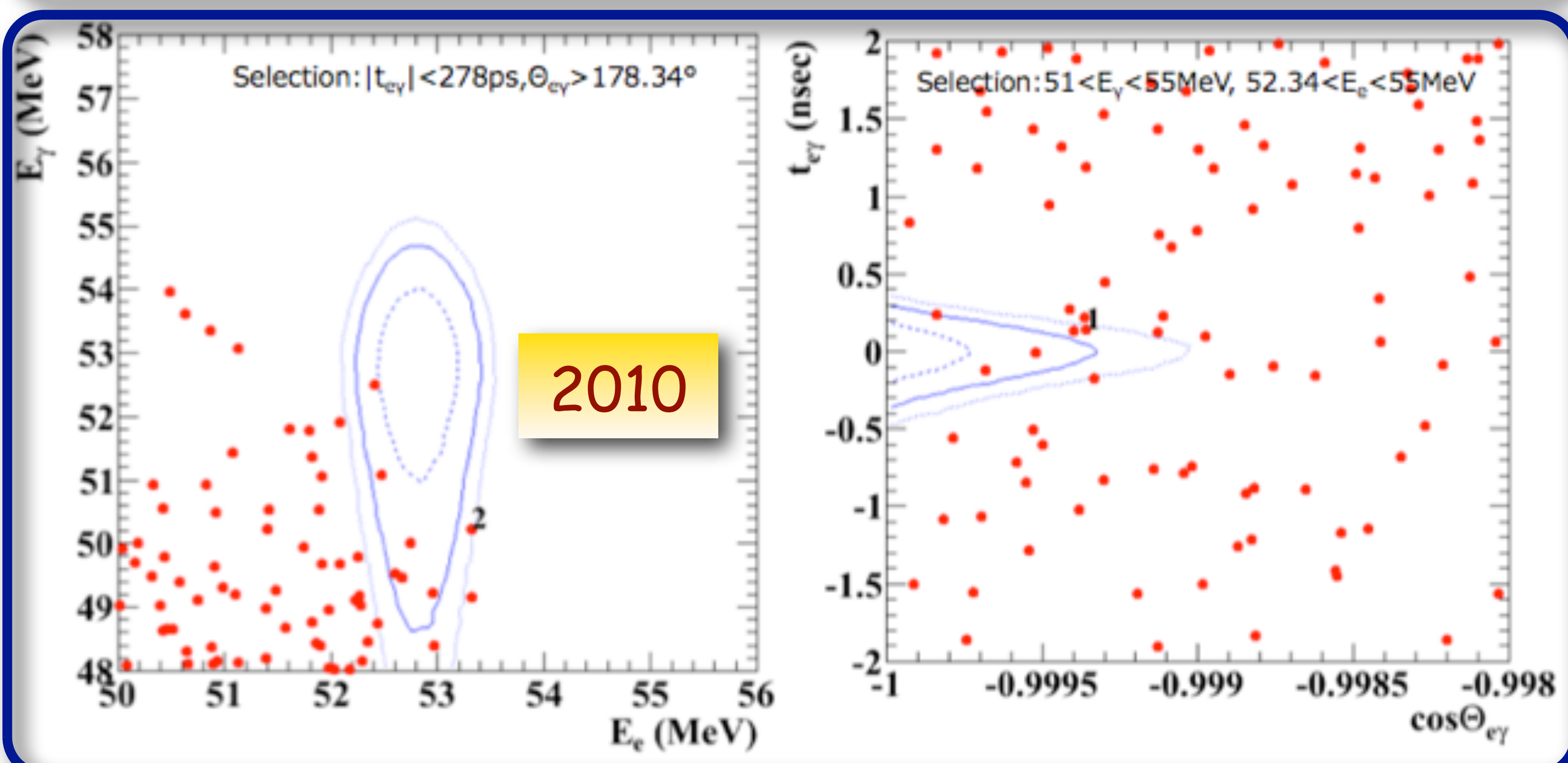
Sensitivity of combined data 1.6×10^{-12} @ 90% CL

3.3×10^{-12} in 2009 + 2.2×10^{-12} in 2010

2009 and 2010 results

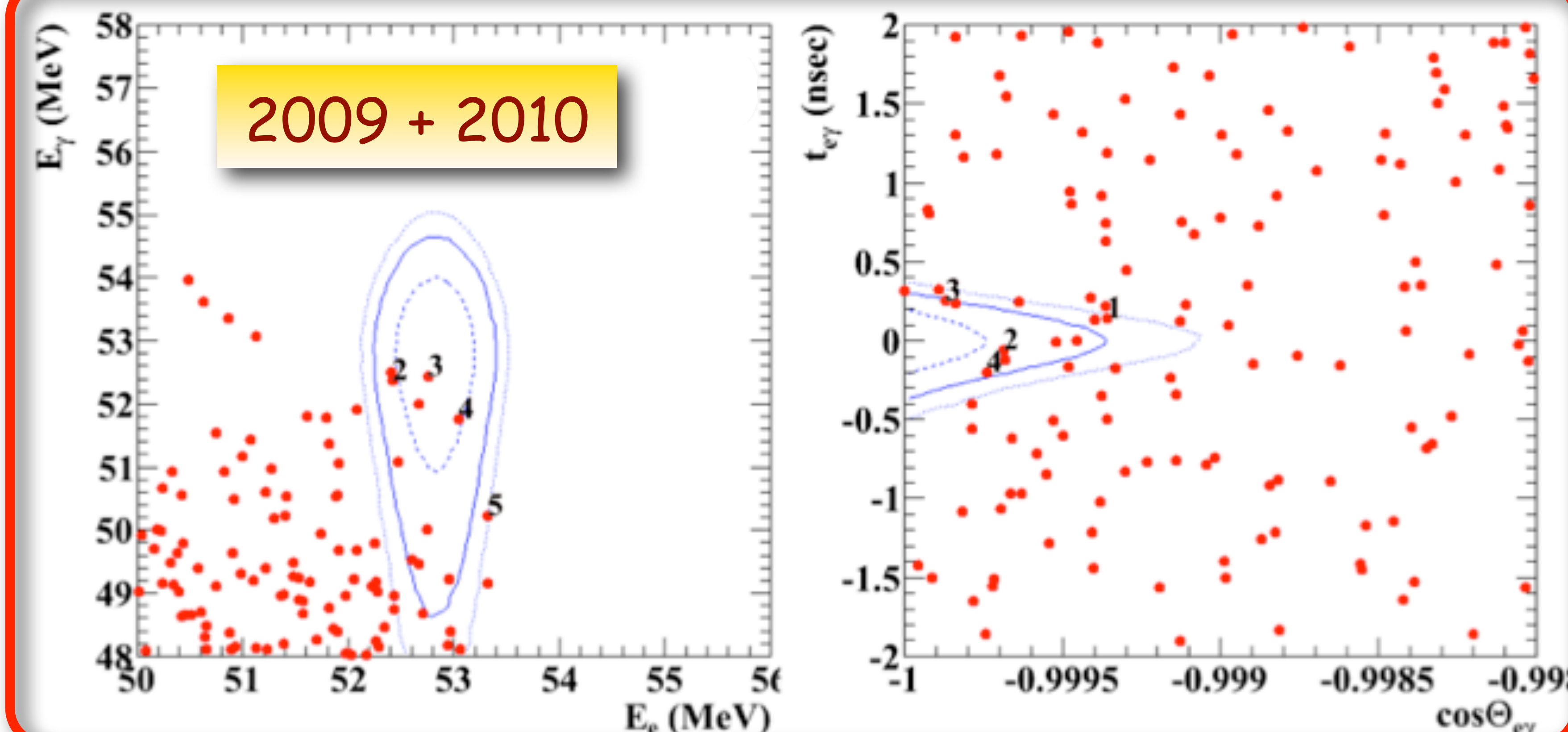


- 2009 data re-analyzed with improvements : best N_{sig} fit 3.4 (ICHEP '10 best N_{sig} fit 3.0) ---> **STABLE RESULT**
- 1.7×10^{-13} < BR < 9.6×10^{-12} @ 90% CL
- p-Value for null signal 8%



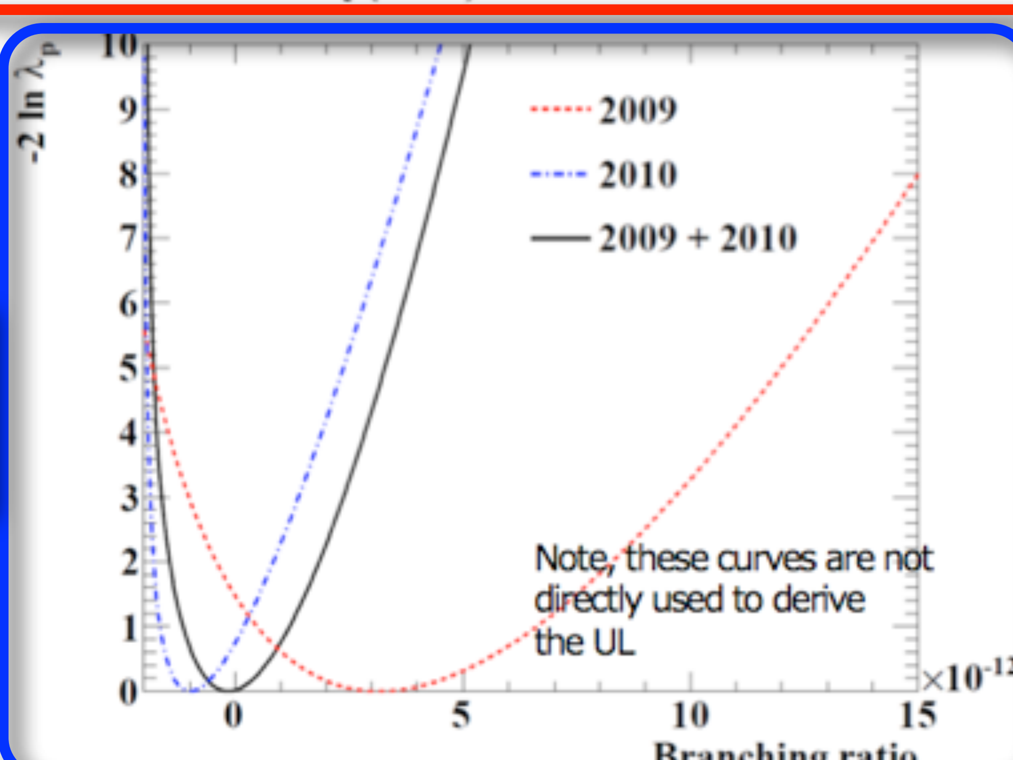
- 2010 data best N_{sig} fit -2.2
- BR < 1.7×10^{-12} @ 90% CL
- Sensitivity 2.2×10^{-12}

Combined Result



	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



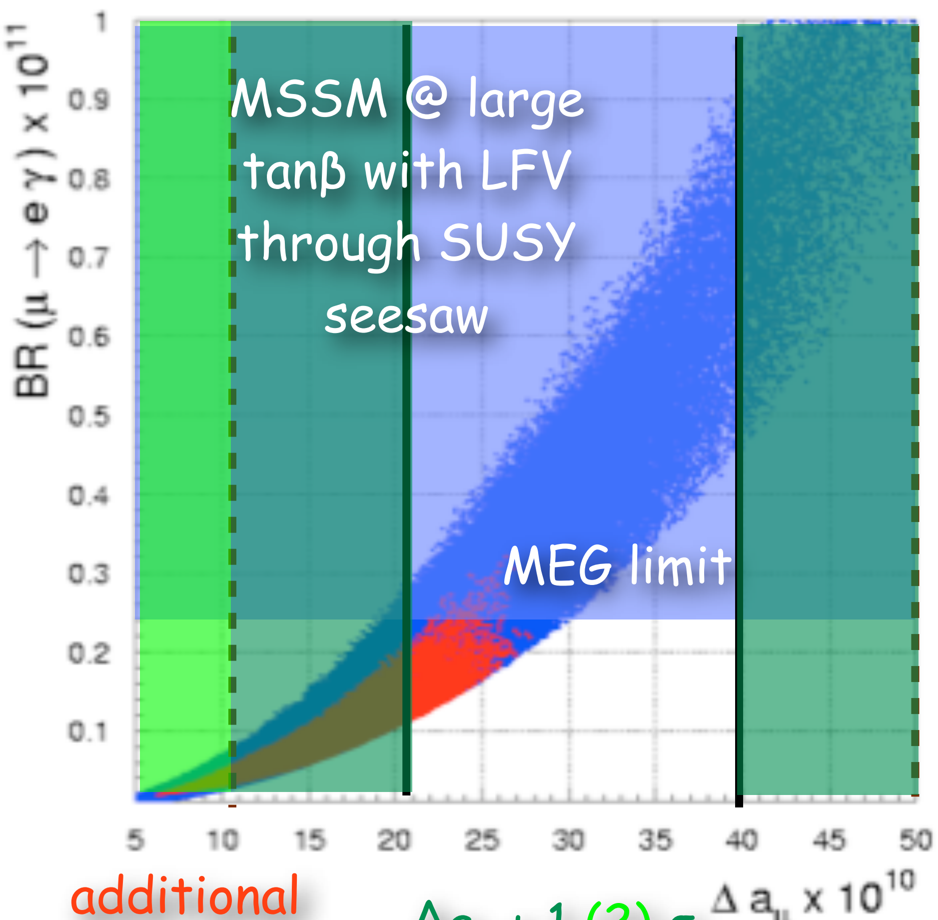
UL @ 90% CL

BR < 2.4 x 10^{-12}

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}

Implications

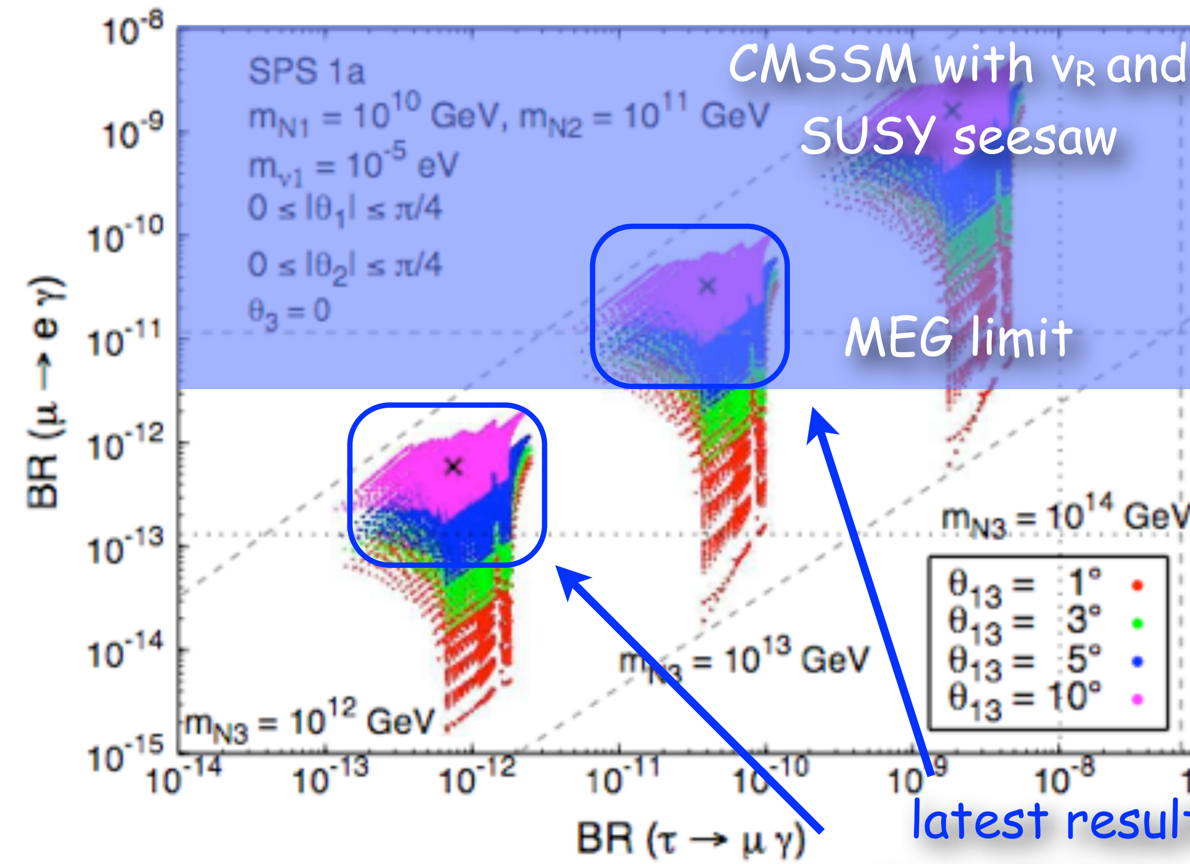
G. Isidori et al. Phys.Rev. D 75:115019, 2007



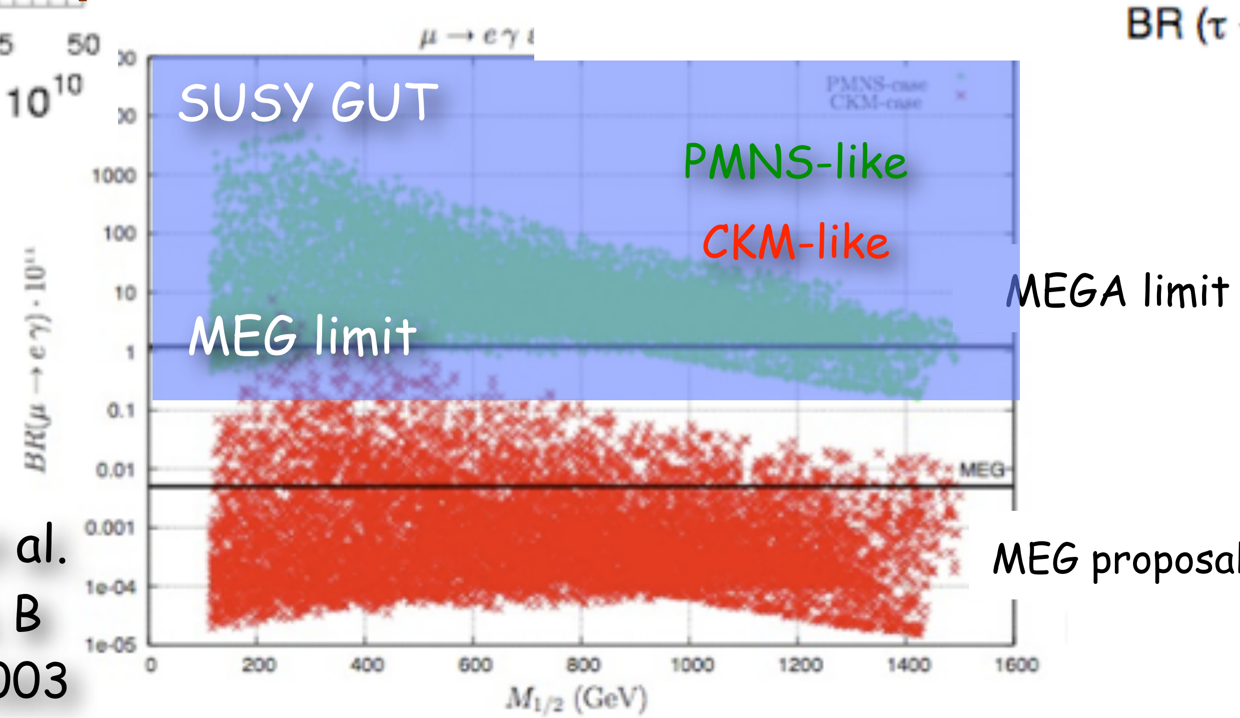
additional constraints from B physics

$\Delta a_\mu \pm 1$ (2) σ constraint

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



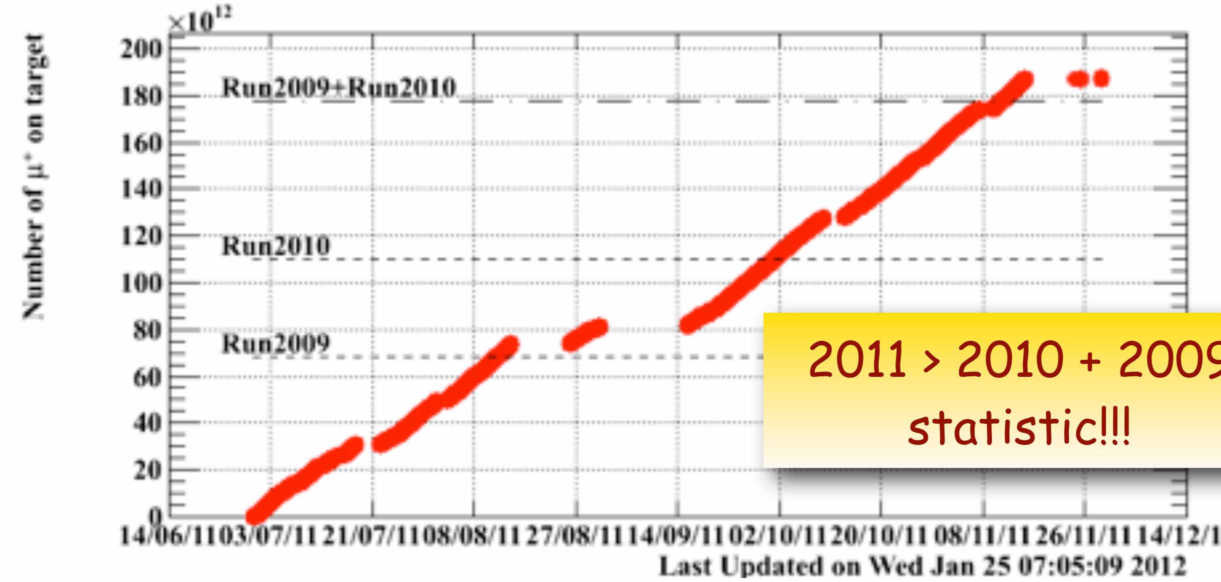
latest results from T2K/Double Chooz suggests theta13 ~ 8°



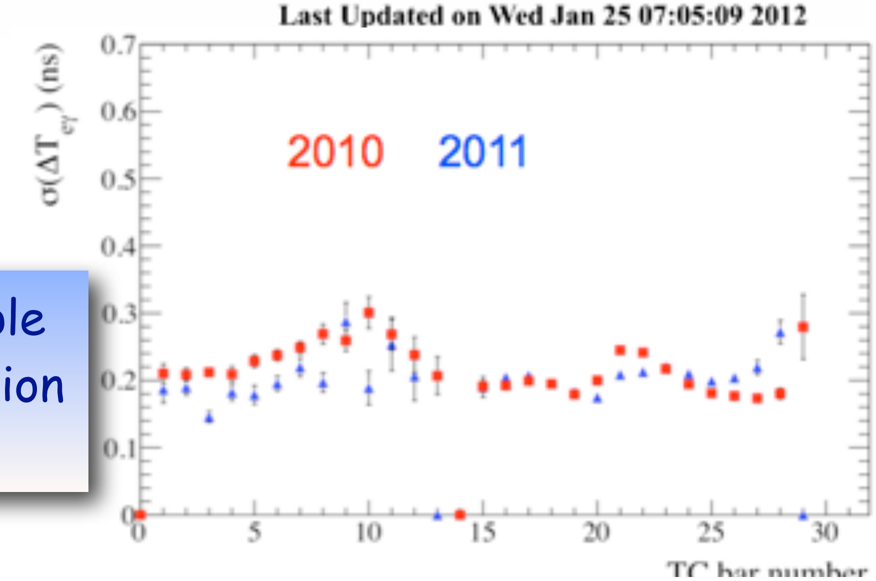
Masiero et al. Nucl.Phys. B 649:189, 2003

2011 Run

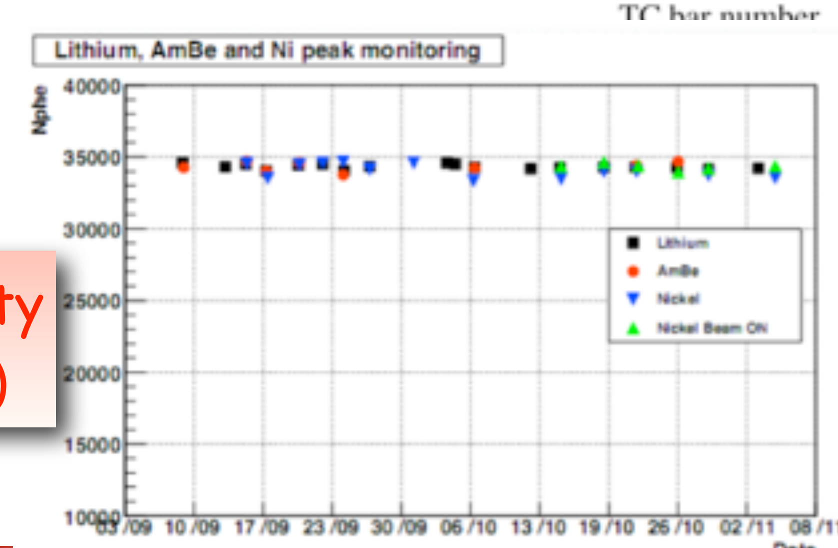
- 2011 dataset > 2009 + 2010 datasets
  - Improved DAQ & trigger efficiency up to >99% live time with >95% efficiency
  - Improved noise conditions in DC thanks to new HV power supplies
  - TC fibers APDs operational
- All positron and photon resolutions consistent with 2010 already with preliminary alignment and calibrations



2011 > 2010 + 2009 statistic!!!

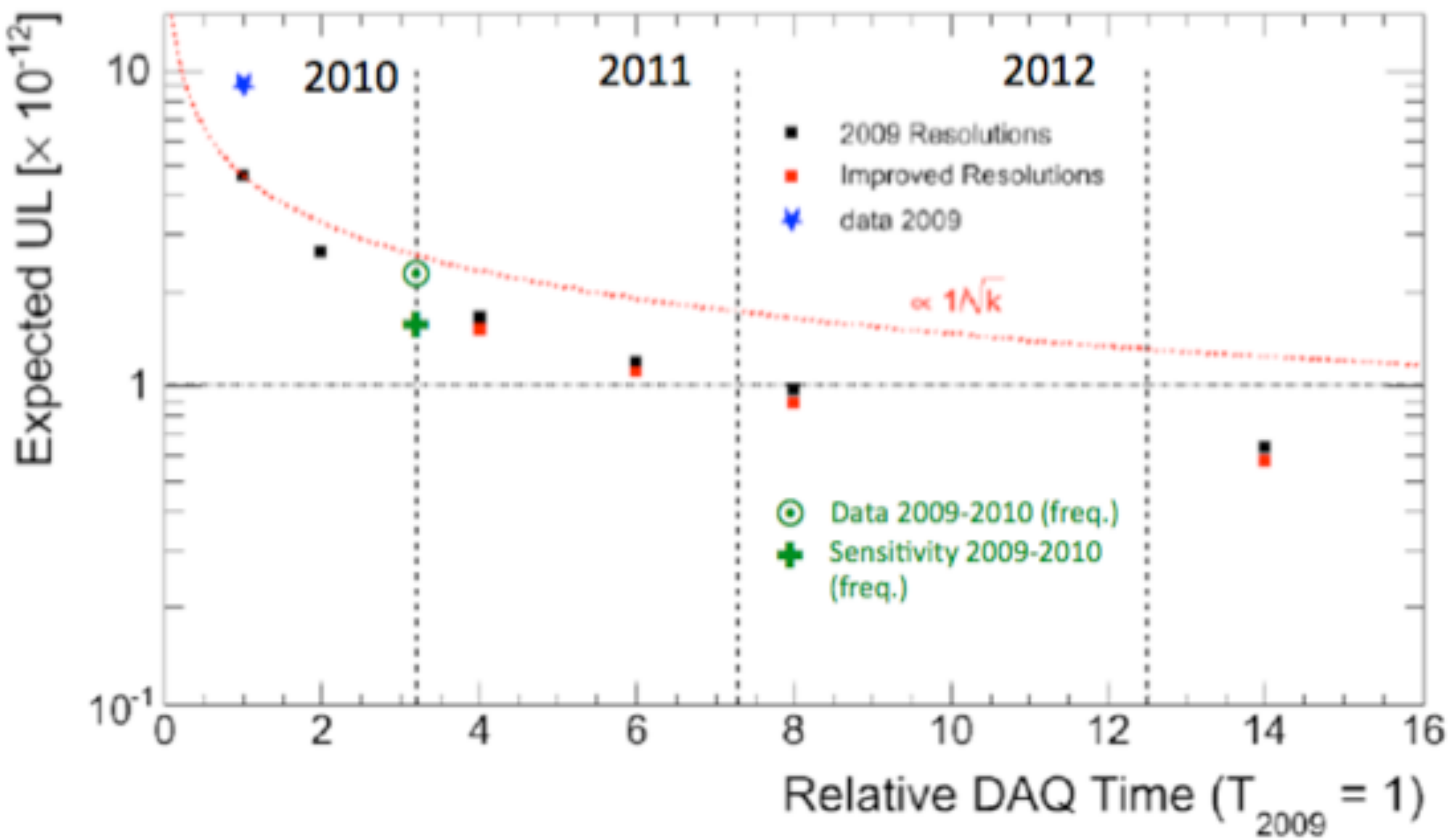


Dalitz sample time resolution for TC



Xenon stability (2009-2011)

Sensitivity prospects



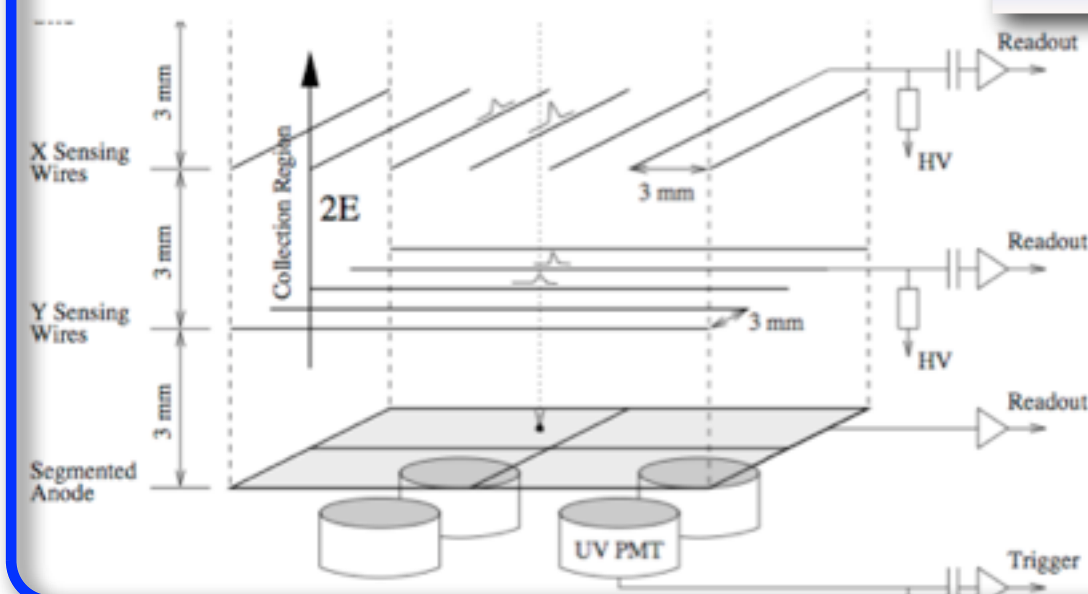
- MEG data taking will continue through 2012

Sensitivity projection in the 5×10^{-13} range

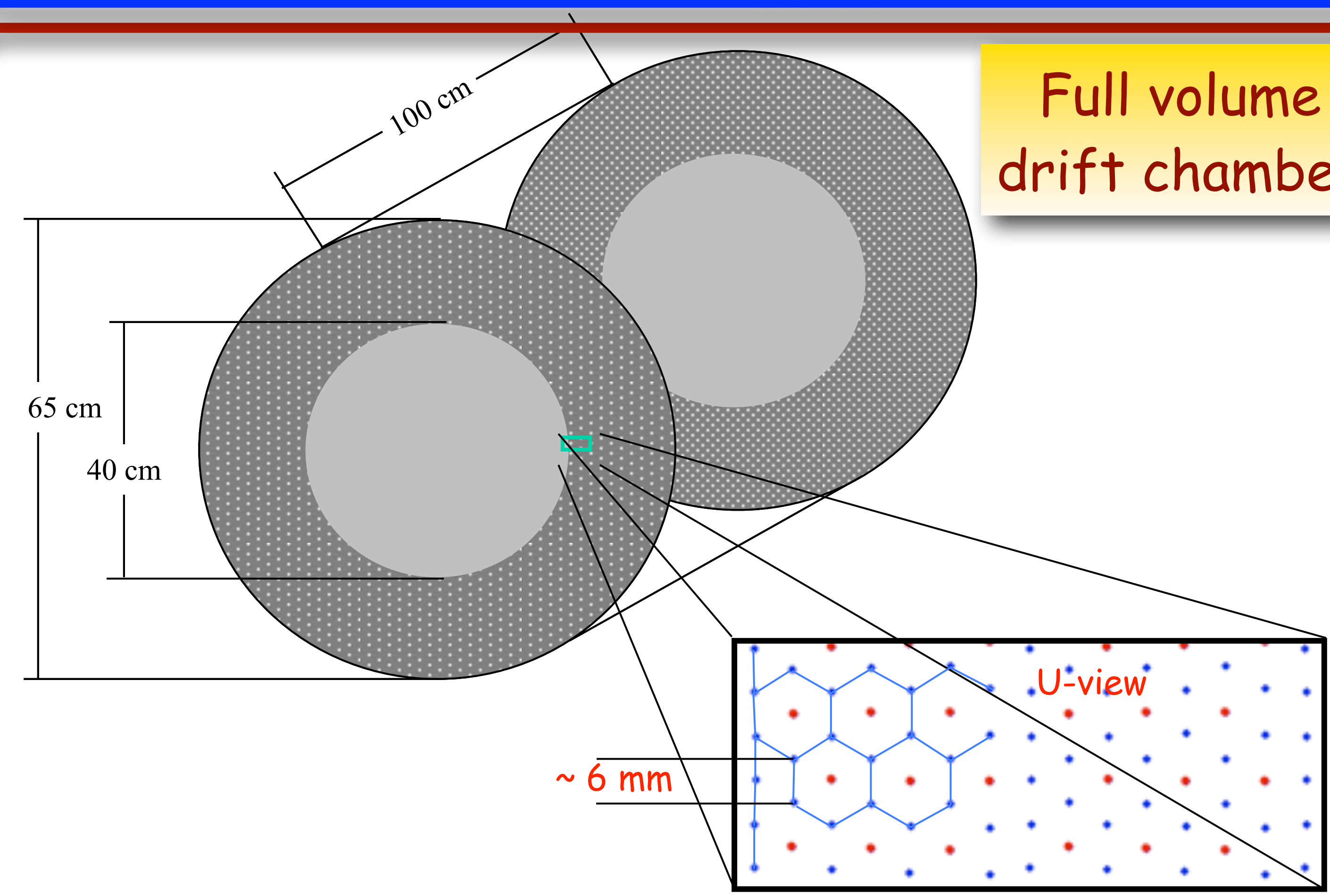
Proposals for upgrade

- 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,active target, vertex detector
  - 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

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

- MEG 2011 dataset > 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

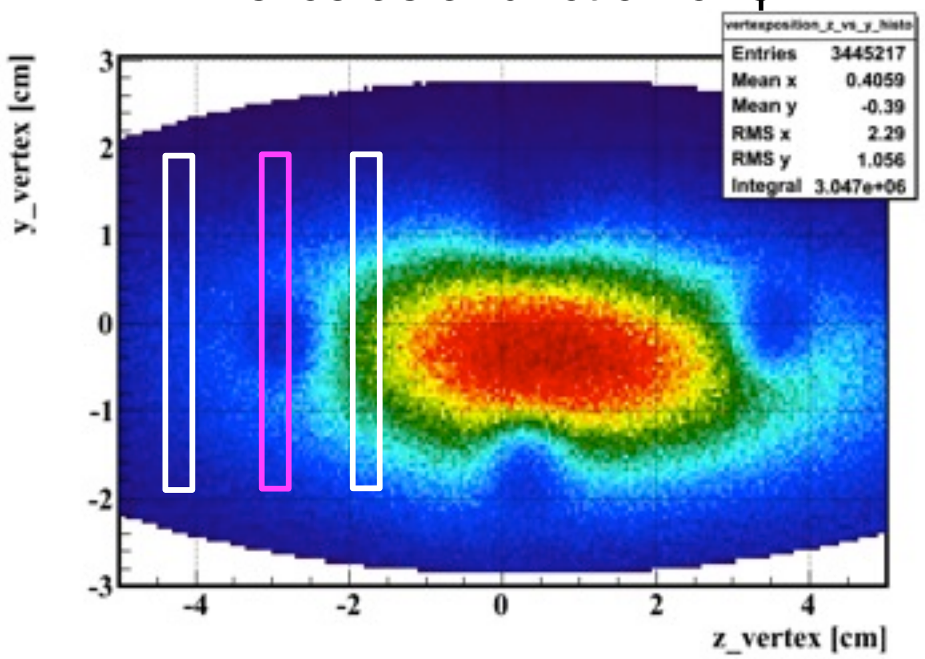

Thank you !!
MEG experiment
The MEG Collaboration

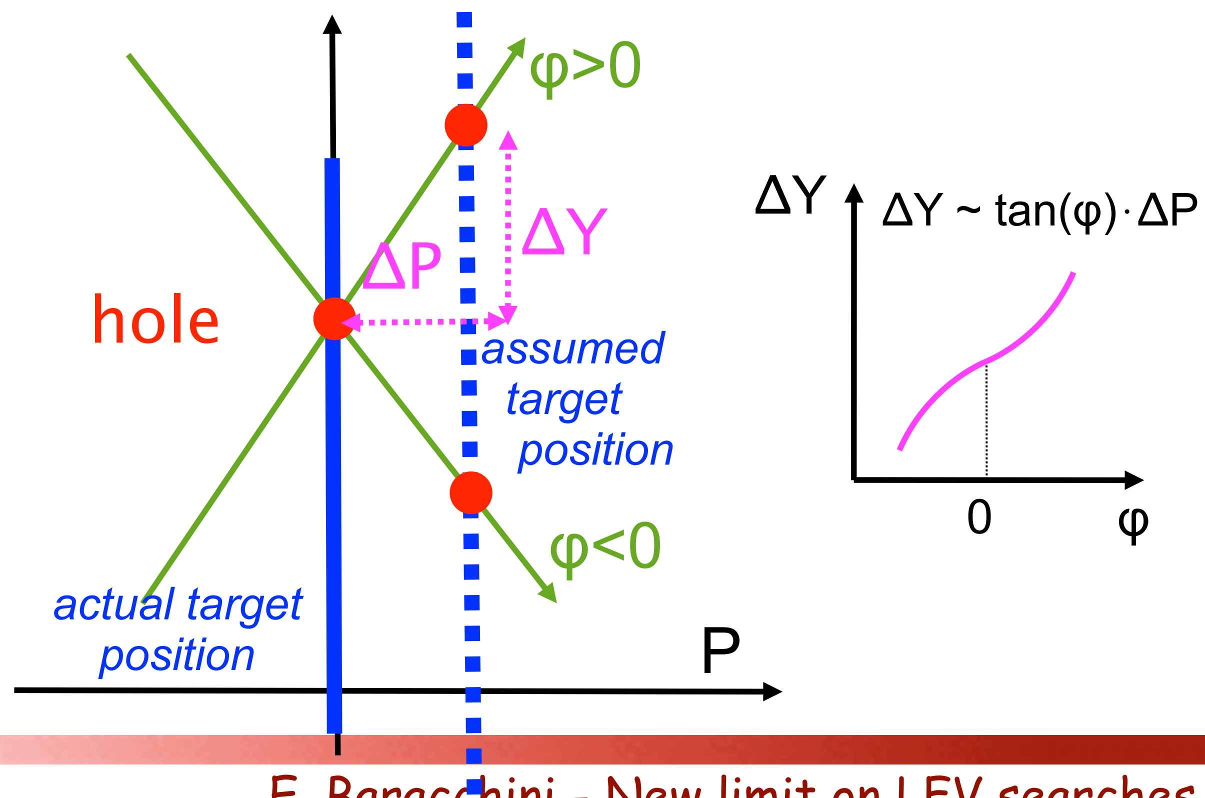
Backup slides

Target Holes

Method 1:

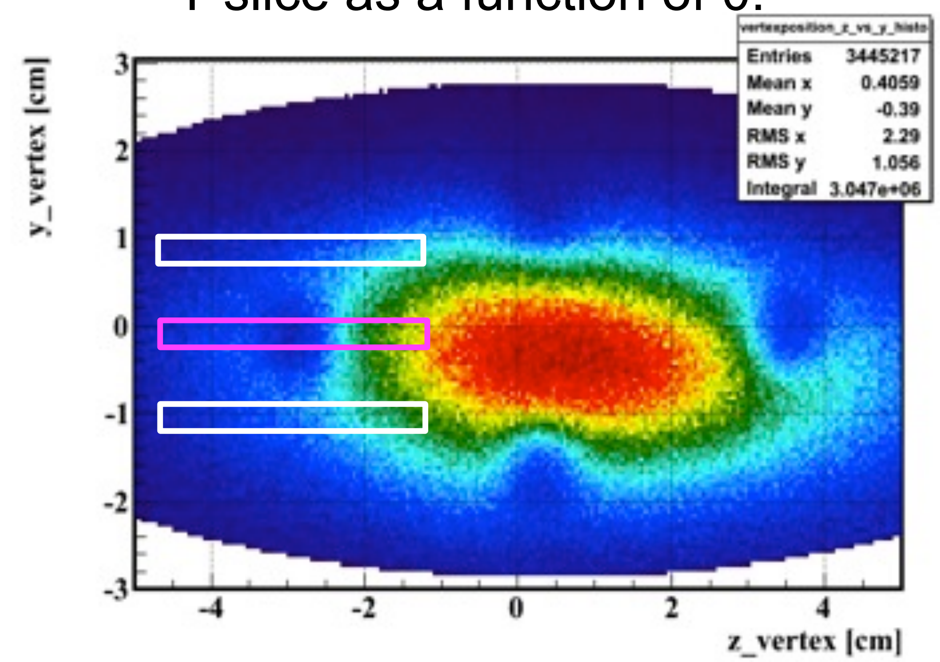
Reconstruct Y-coordinate in Z-slice as a function of φ:

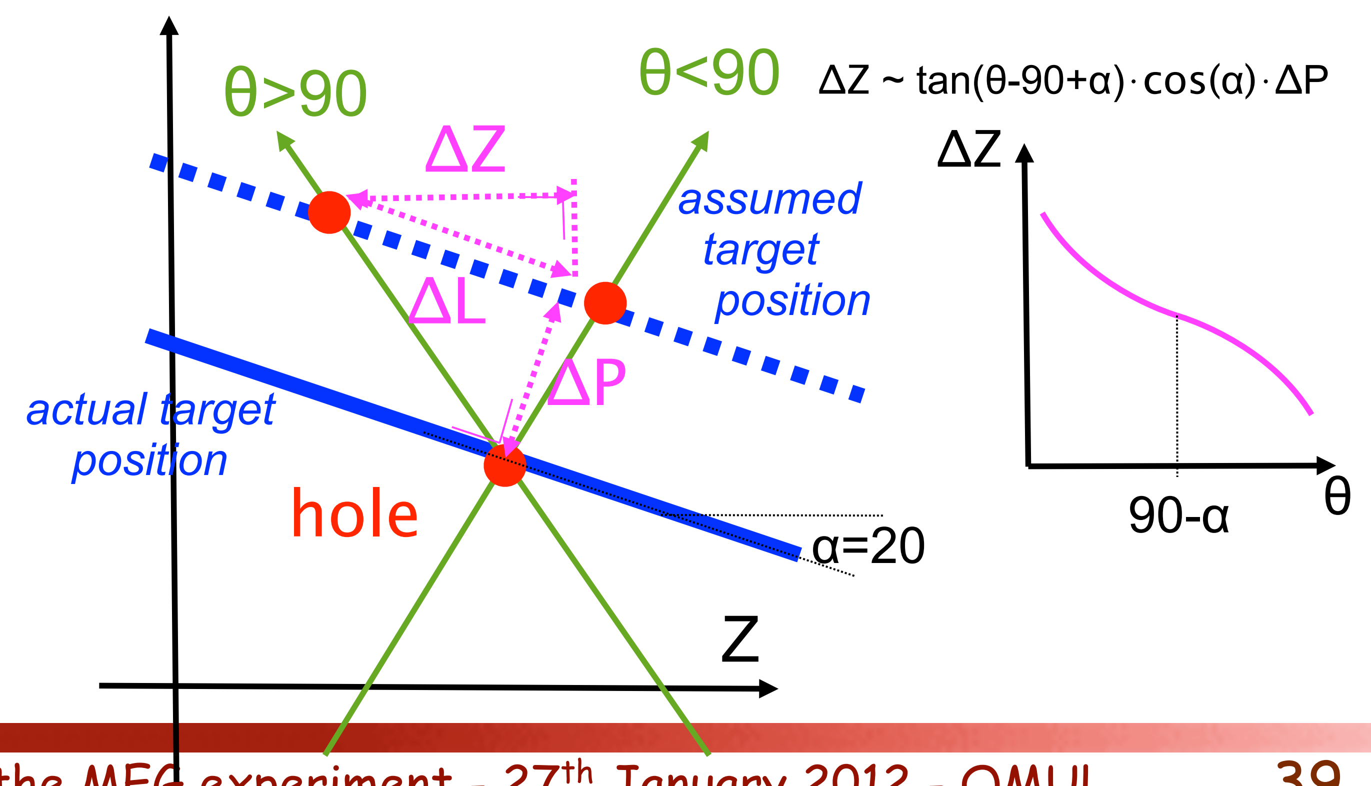




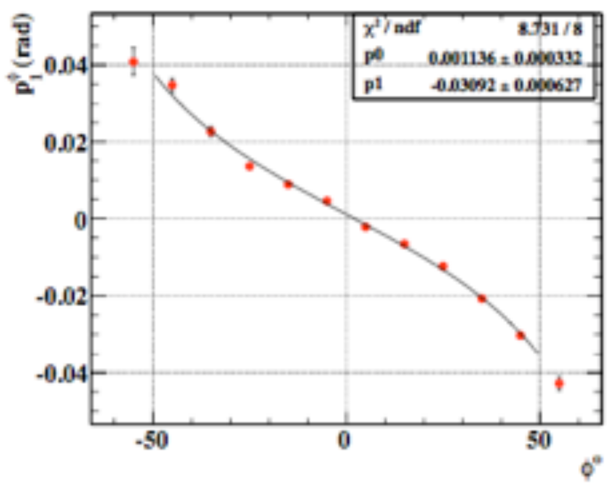
Method 2:

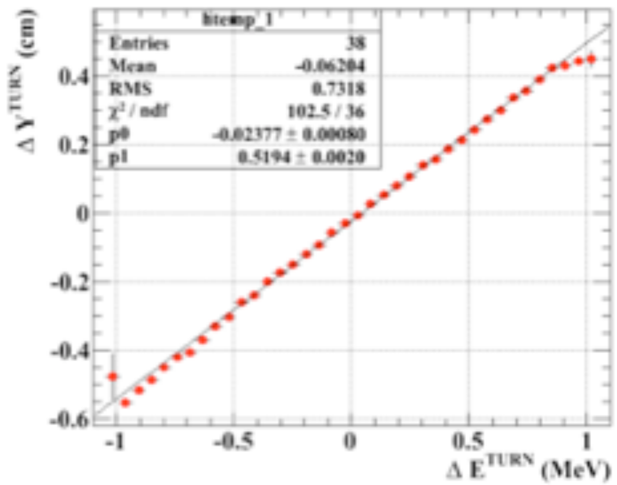
Reconstruct Z-coordinate in Y-slice as a function of θ:

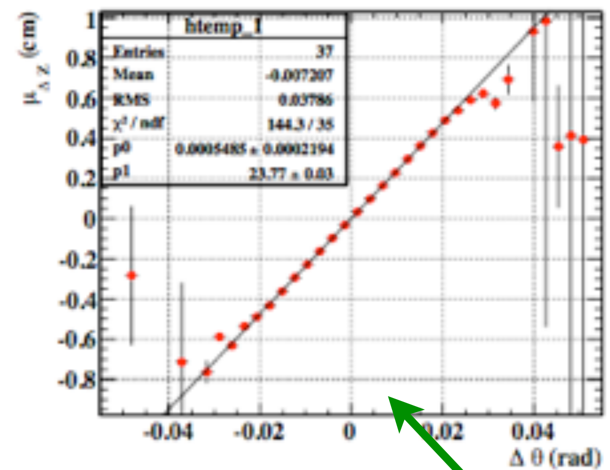


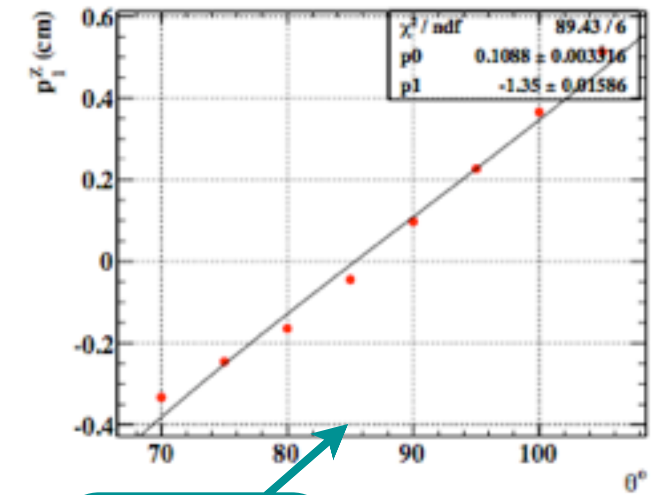


Correlations and Resolutions





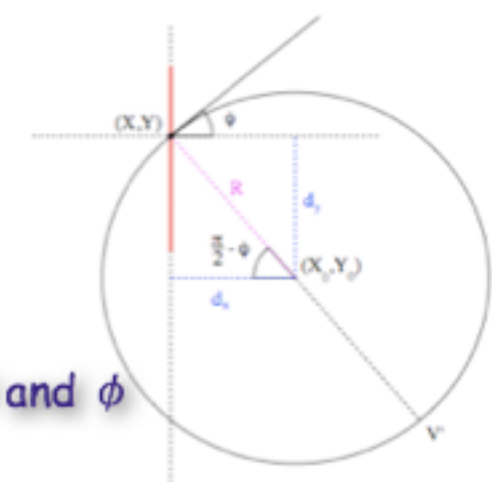


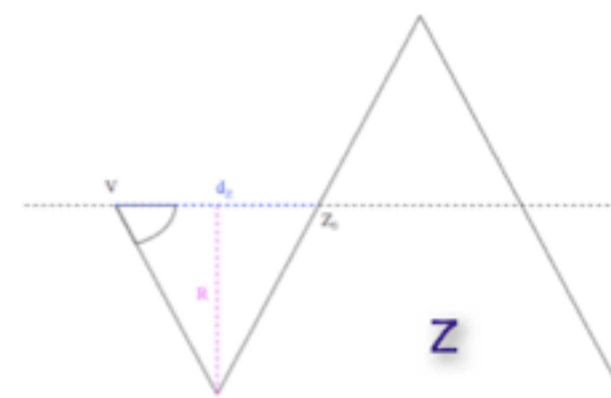


$$\delta\phi_e = -2\tan\phi_e \frac{\delta R}{R} = -2\tan\phi_e \frac{\delta E}{E}$$

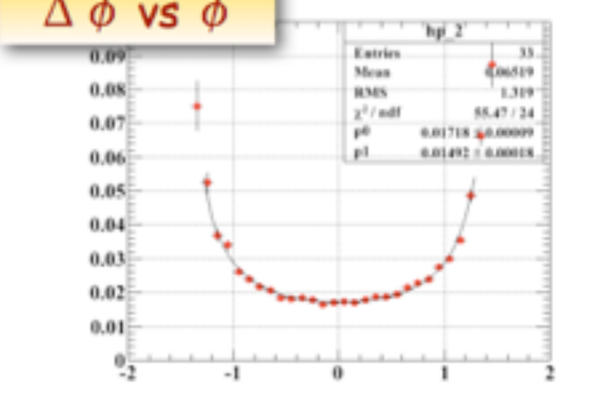
$$\delta Y = 2\delta R\cos\phi_e + R\sin\phi_e\delta\phi_e = \frac{2R}{\cos\phi_e}\frac{\delta E}{E}$$

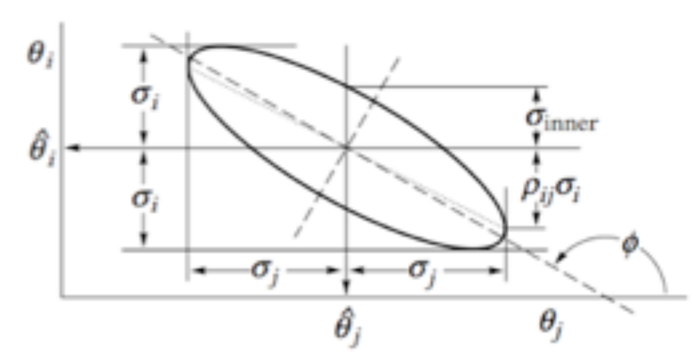
$$\delta Z = \frac{2R}{\sin^2\theta_e}\delta\theta_e - 2R\cot\theta_e\frac{\delta E}{E}$$





$\Delta\phi$ vs ϕ





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

Some more numbers :)

- Fit region

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

Sensitivity

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

2009 + 2010 combined

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

2009

	Best fit	Error (MINOS 1.645σ)
N_{sig}	+3.4	+6.6−4.4
N_{RMD}	+26.9	+4.5−4.5
N_{BG}	+273.1	+12.3−12.3

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

2010

	Best fit	Error (MINOS 1.645σ)
N_{sig}	−2.2	+5.0−1.9
N_{RMD}	+50.2	+9.2−9.2
N_{BG}	+608.5	+18.7−18.6

	Best fit	LL (90%CL)	UL (90%CL)	UL (95%CL)	CL@0
N_{sig}	−2.2	–	3.8(3.7)	5.0(N/A)	–
BR	-9.9×10^{-13}	–	1.7×10^{-12}(1.7×10^{-12})	2.3×10^{-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 in total 2% on the UL: 2.3×10^{-12} --> 2.4×10^{-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_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