The $\mu^+ \rightarrow e^+\gamma$ decay search with the full dataset of the MEG experiment and status of the MEG II experiment

Angela Papa, PSI
on behalf of the MEG collaboration
Thursday, 20th October 2016
Paul Scherrer Institute

Physics of fundamental Symmetries and Interactions - PSI2016

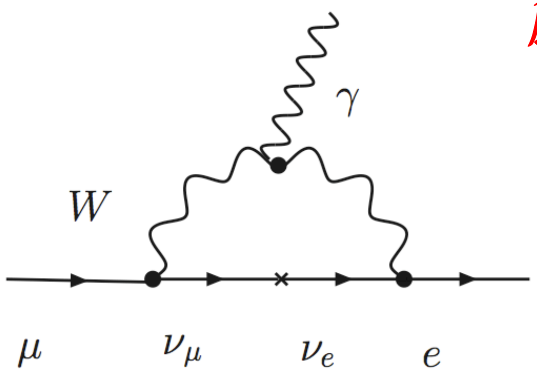
Topics

- Charged lepton flavour violation (cLFV) searches: the motivations
- The $\mu^+ \to e^+ \gamma$ decay seach with the MEG experiment
    - the data sample and the analysis
    - the final result
- Status of the MEG II experiment

cLFV: A clear signature of New Physics

SM with massive neutrinos (Dirac)

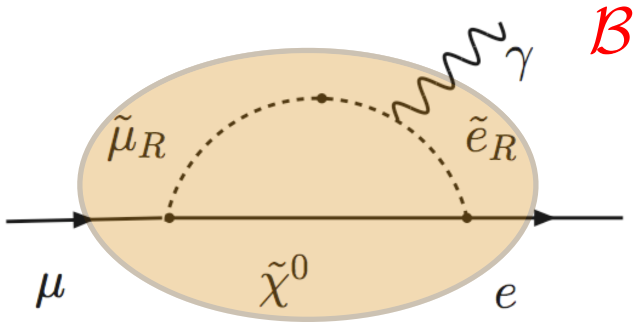
$$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$$



too small to access experimentally

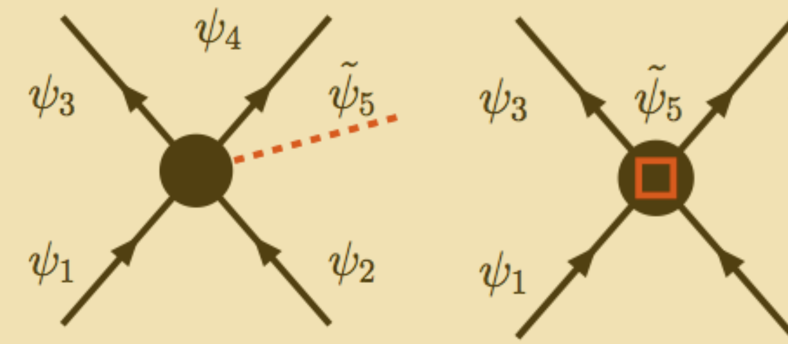
i.e. SU(5) SUSY-GUT or SO(10) SUSY-GUT

$$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$$



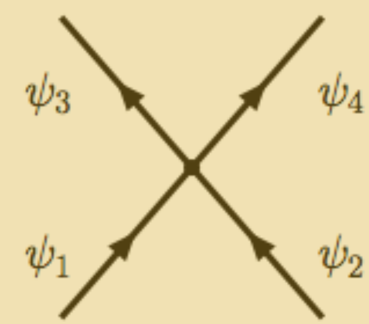
an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)

to unveil behind SM physics
via virtual particles



to probe otherwise
unreachable and unexploited
new physics energy scale

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$



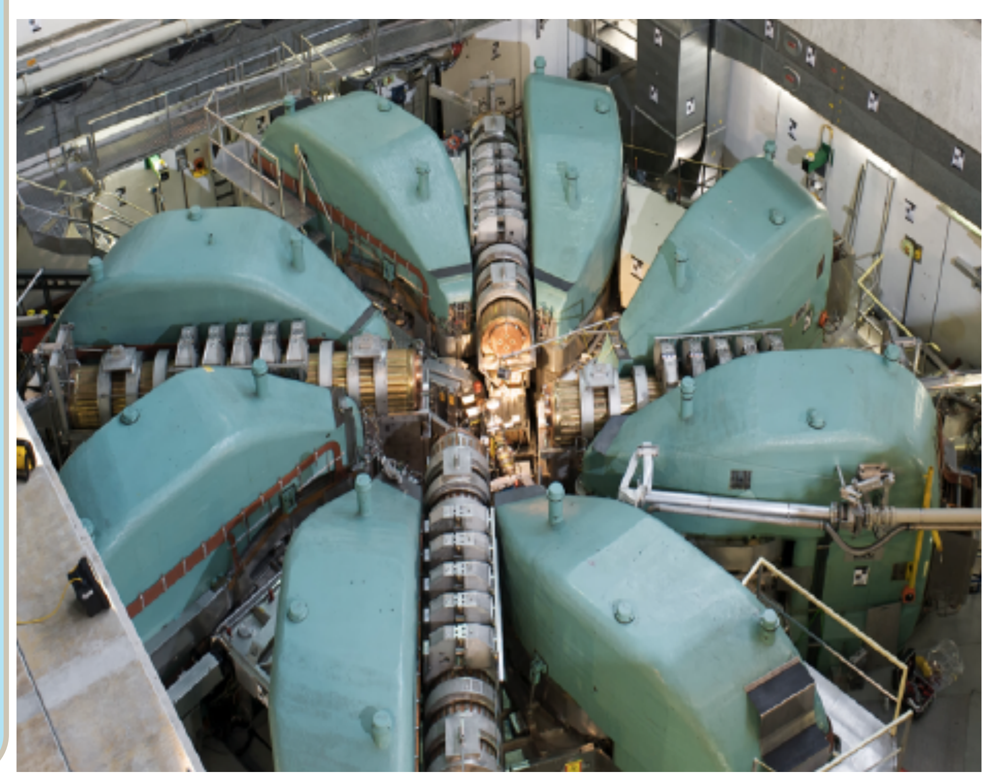
$$\frac{1}{\Lambda^2}$$

cLFV with muons

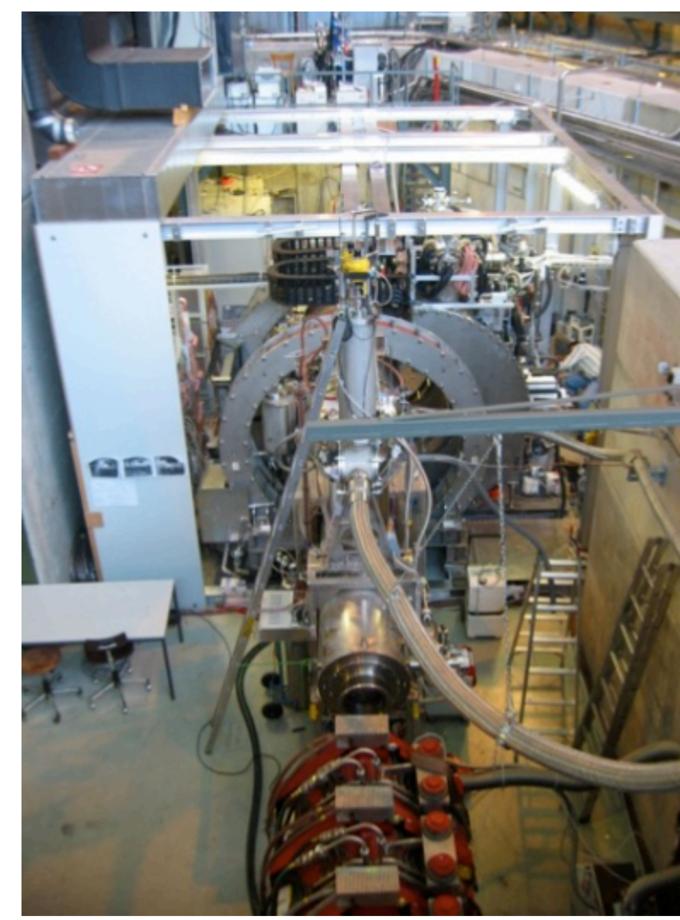
- τ ideal probe for NP w. r. t. μ
  - Smaller GIM suppression
  - Stronger coupling
  - Many decays
- μ most sensitive probe
  - Huge statistics

- MEG/MEG II beam requirements:
  - Intensity O(10^8 muon/s), low momentum p = 29 MeV/c
  - Small straggling and good identification of the decay region

590 MeV proton ring cyclotron
1.4 MW



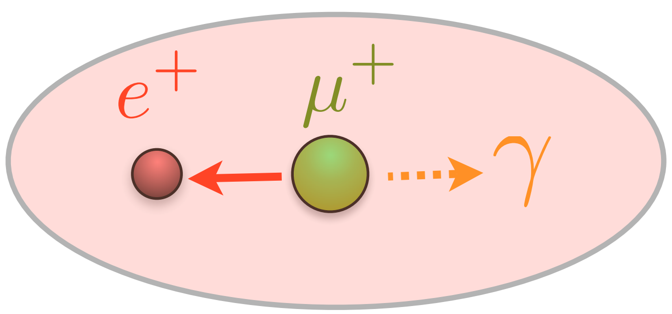
MEG/MEGII Beam Line

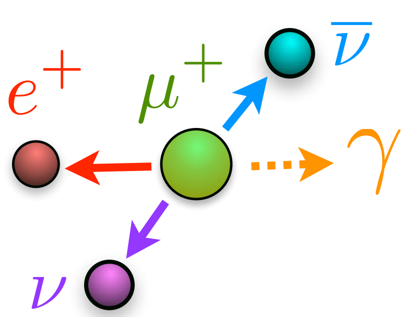


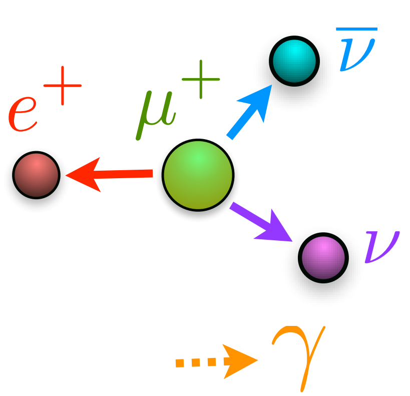
A. Baldini et al. (MEG Collaboration),
Eur. Phys. J. **C73** (2013) 2365

The MEG experiment

- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 10^{-13}$ (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$ events



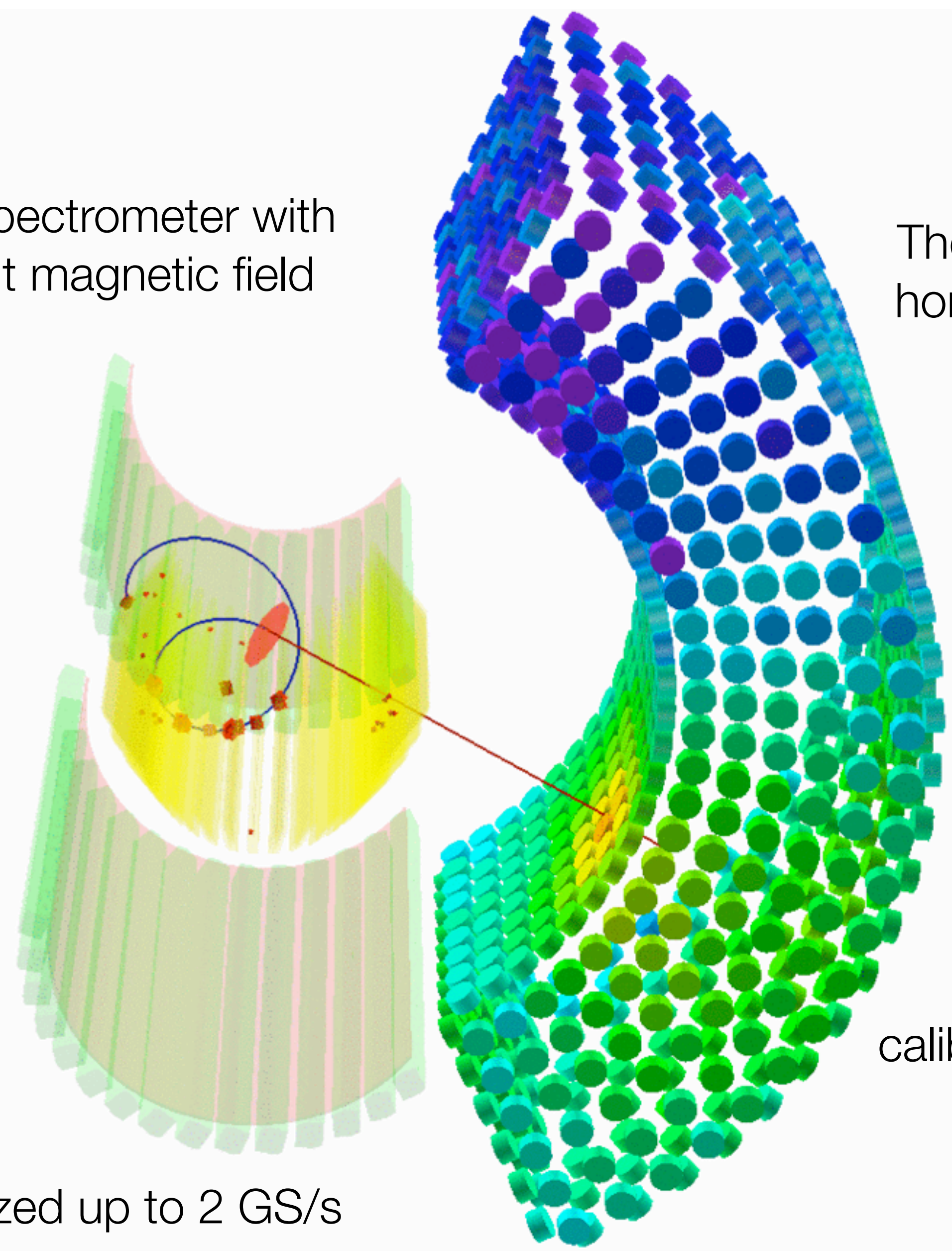




The first spectrometer with
a gradient magnetic field

The largest (900 L)
homogeneous LXe
calorimeter

The most intense DC
μ beam



Complementary
calibration and monitoring
methods

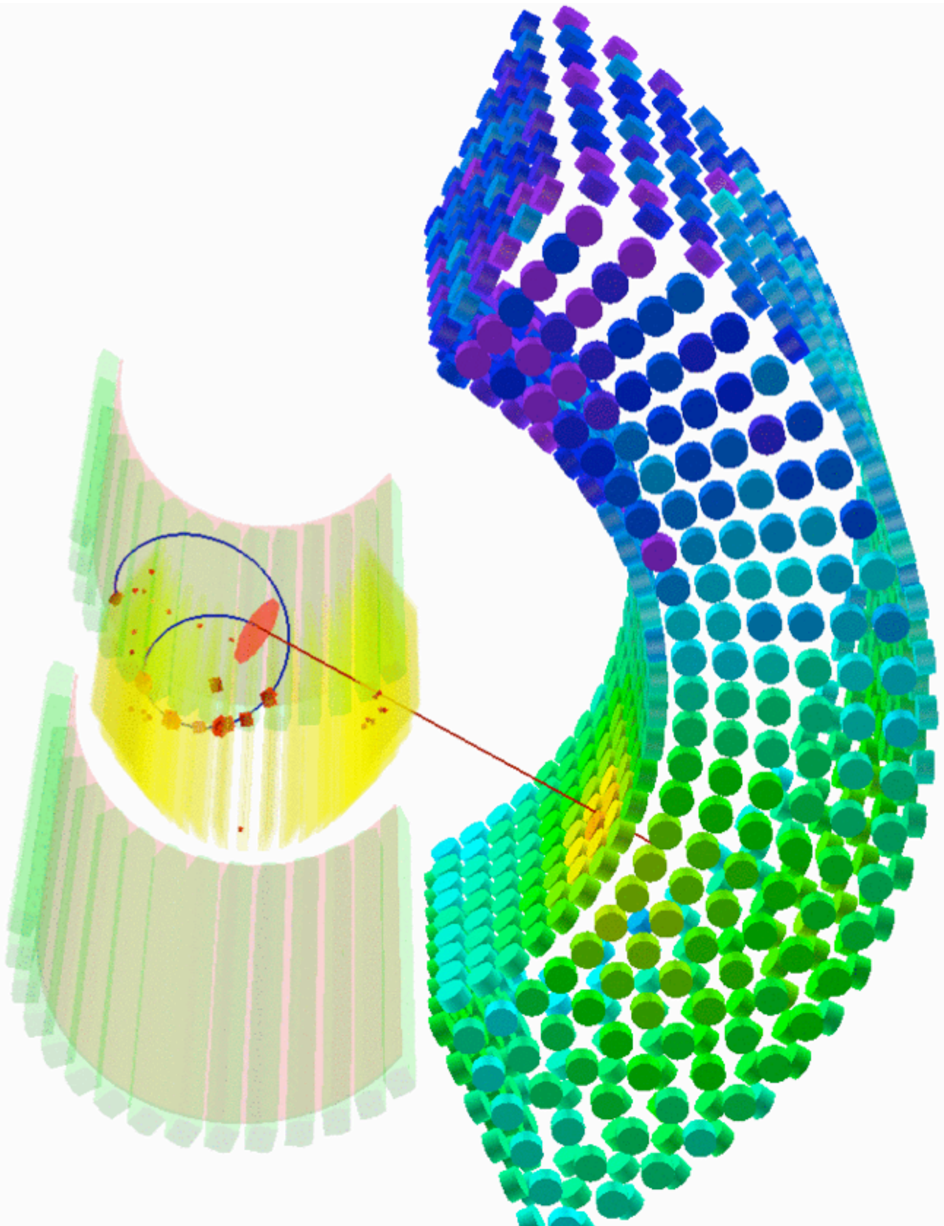
All signals digitized up to 2 GS/s

A. Baldini et al. (MEG Collaboration), Eur. Phys. J. **C73** (2013) 2365

The MEG experiment

- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 10^{-13}$ (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$ events

	Resolutions (σ)
Gamma Energy (%)	1.7(depth>2cm), 2.4
Gamma Timing (ps)	67
Gamma Position (mm)	5(u,v), 6(w)
Gamma Efficiency (%)	63
Positron Momentum (keV)	305 (core = 85%)
Positron Timing (ps)	108
Positron Angles (mrad)	7.5 (Φ), 10.6 (θ)
Positron Efficiency (%)	40
Gamma-Positron Timing (ps)	127
Muon decay point (mm)	1.9 (z), 1.3 (y)



3×10^7 μ^+/s

Analysis status

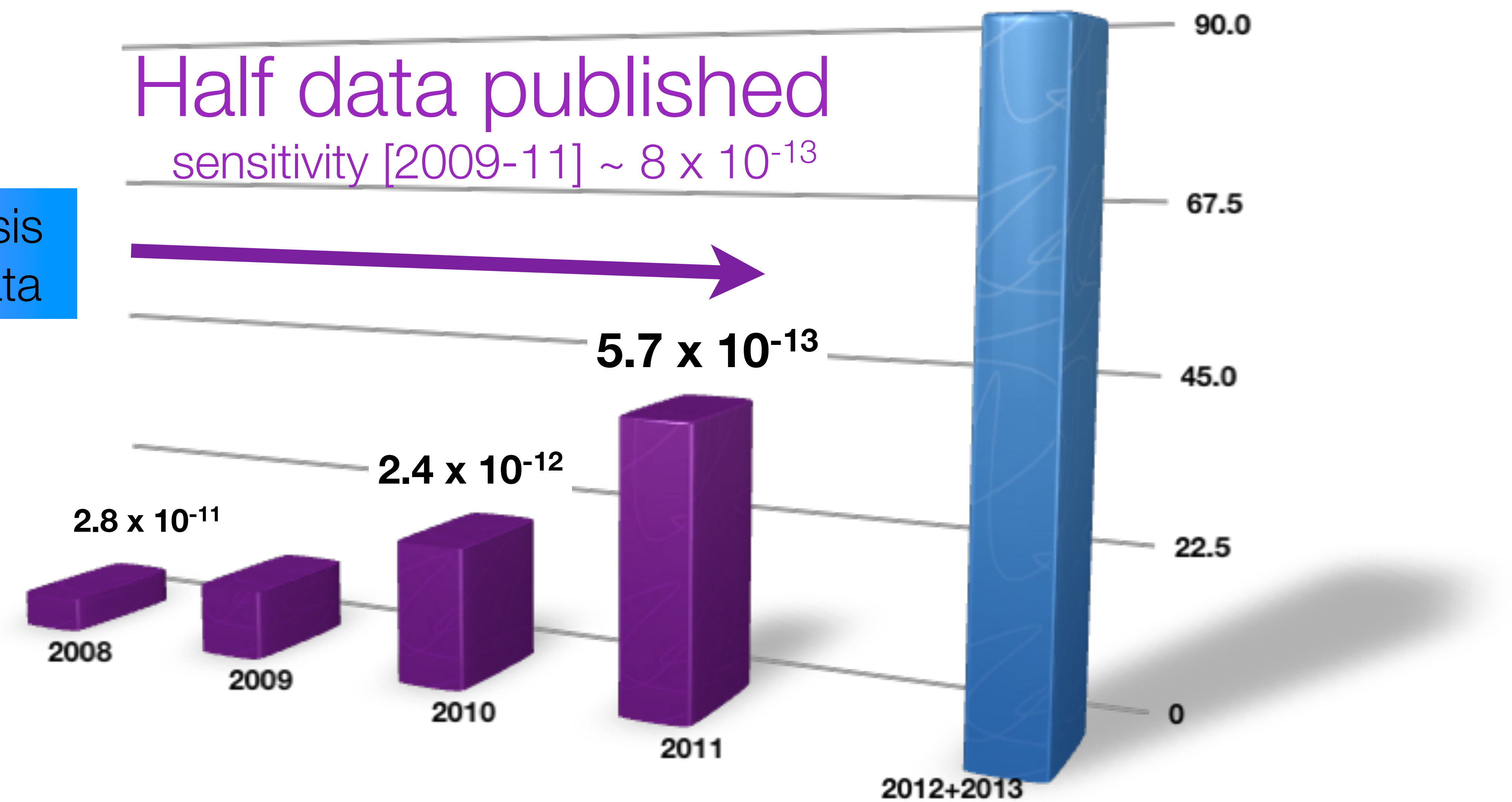
Unblinded Dec. 2015

sensitivity [2009-13] ~ 5 x 10^{-13}

Half data published

sensitivity [2009-11] ~ 8 x 10^{-13}

Improved analysis applied to all data



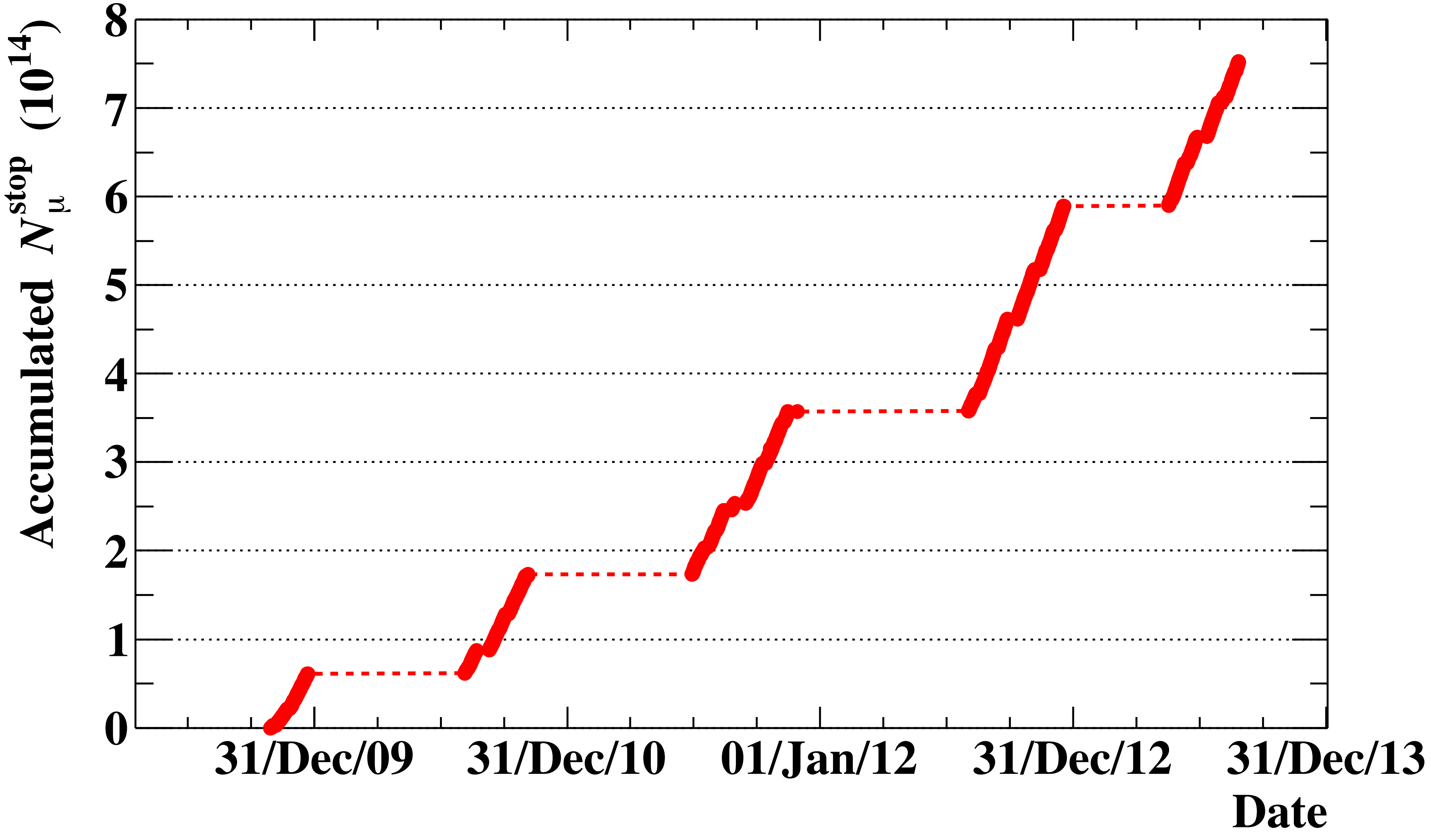
Previous upper limit before MEG

$\mathcal{B}(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$

@ 90% C.L. by the MEGA experiment

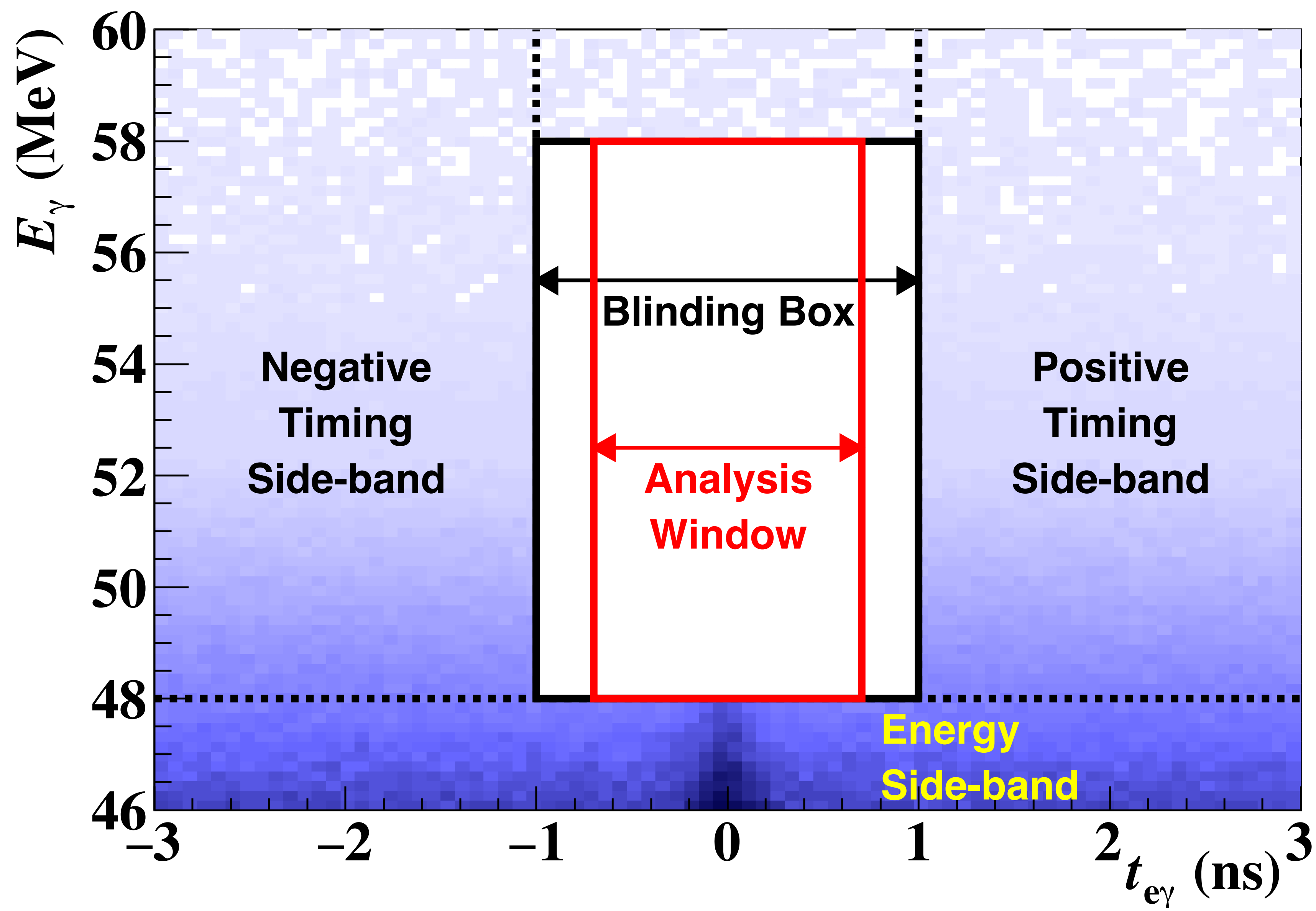
Full data sample

- the accumulated number of stopped muons on target as a function of the time
  - 7.5 x 10^{14} (2009-2013 data sample)



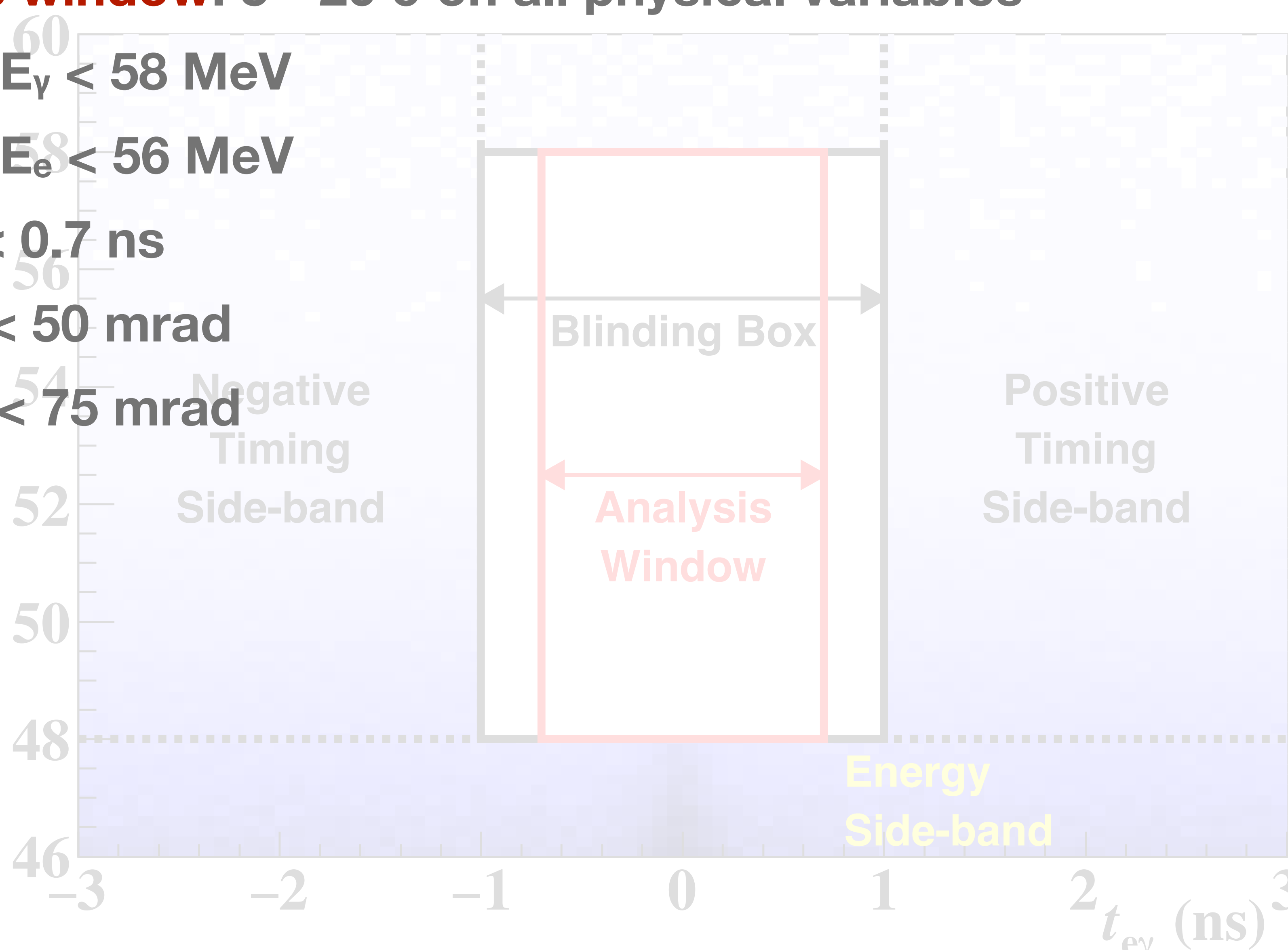
Analysis strategy

- based on a **blind** and likelihood analysis
  - to prevent any bias in the evaluation of the expected background in the signal region



Analysis strategy

- based on a **blind** and likelihood analysis
  - to prevent any bias in the evaluation of the expected background in the signal region
  - **analysis window: 5 - 20 σ on all physical variables**
    - **$48 < E_\gamma < 58$ MeV**
    - **$50 < E_e < 56$ MeV**
    - **$|t_{e\gamma}| < 0.7$ ns**
    - **$|\theta_{e\gamma}| < 50$ mrad**
    - **$|\phi_{e\gamma}| < 75$ mrad**



Analysis strategy

- based on blind and **likelihood** analysis
  - to avoid boundary effects at the borders of the analysis region
  - to improve the sensitivity distinguishing between signal, RMD and accidental bkg

$$\mathcal{L}(N_{sig}, N_{RMD}, N_{ACC}, \mathbf{t}) =$$

$$\frac{e^{-N}}{N_{obs}!} C(N_{RMD}, N_{ACC}, \mathbf{t}) \times$$

$$\prod_{i=1}^{N_{obs}} (N_{sig} S(\mathbf{x}_i, \mathbf{t}) + N_{RMD} R(\mathbf{x}_i) + N_{ACC} A(\mathbf{x_i}))$$

where:

$\mathbf{x_i} = \{E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}\}$ $\quad \mathbf{t} = \{t_{pos}, t_{nopla}\}$ $\quad N = N_{sig} + N_{RMD} + N_{ACC}$

Analysis strategy

- based on blind and **likelihood** analysis
  - to avoid boundary effects at the borders of the analysis region
  - to improve the sensitivity distinguishing between signal, RMD and accidental bkg

"the" variable **nuisance parameters**

nuisance parameter constraints

$$\mathcal{L}(N_{sig}, N_{RMD}, N_{ACC}, \mathbf{t}) = \frac{e^{-N}}{N_{obs}!} C(N_{RMD}, N_{ACC}, \mathbf{t}) \times$$

$$\prod_{i=1}^{N_{obs}} (N_{sig} S(\mathbf{x}_i, \mathbf{t}) + N_{RMD} R(\mathbf{x}_i) + N_{ACC} A(\mathbf{x_i}))$$

event-by-event PDFs for signal, RMD and accidental bkg

where:

$\mathbf{x_i} = \{E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}\}$ $\mathbf{t} = \{t_{pos}, t_{nopla}\}$ $N = N_{sig} + N_{RMD} + N_{ACC}$

Normalization

- How to convert the number of observed events into a branching ratio

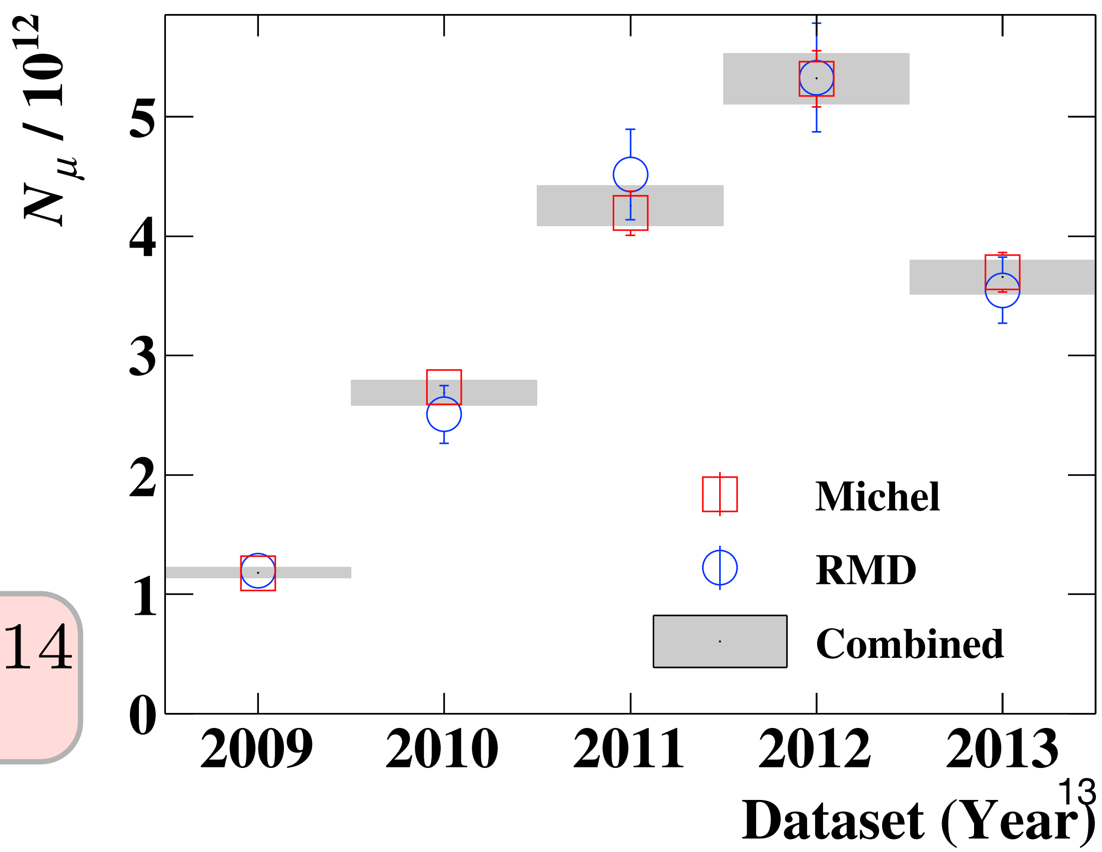
$$N_{sig} = N_{\mu} \times \mathcal{B}(\mu \to e\gamma) \times \langle A \times \epsilon \rangle_{e\gamma}$$
$$\equiv k \times \mathcal{B}(\mu \to e\gamma)$$

Inverse of the Single Event Sensitivity

- two **independent** ways: **Michel (M)** and **RMD** counting

N_{μ} from Michel + RMD: **3.5%** uncertainty on the full dataset

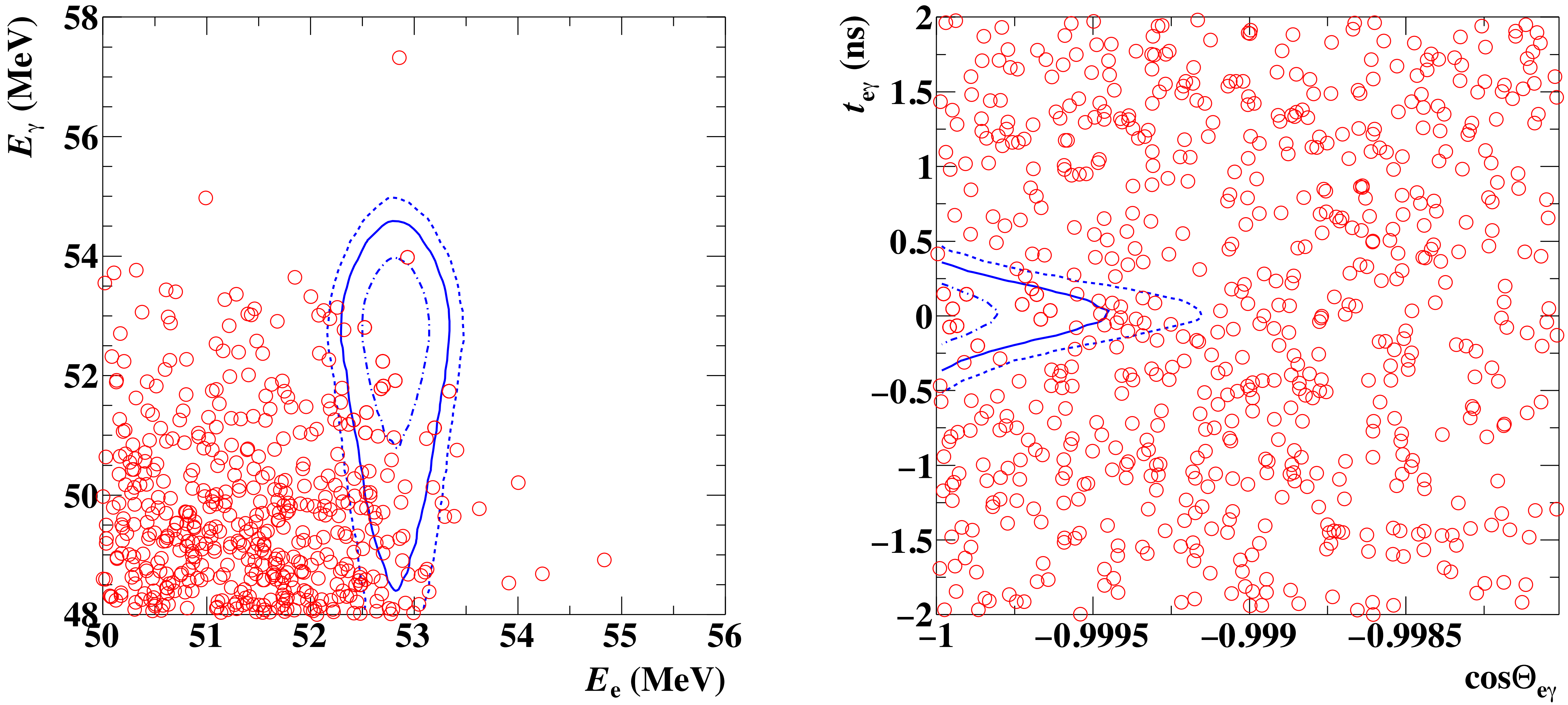
$$N_{sig} = N_{M,RMD} \times \frac{\mathcal{B}(\mu \to e\gamma)}{\mathcal{B}_{M,RMD}} \times \frac{\langle A \times \epsilon \rangle_{e\gamma}}{\langle A \times \epsilon \rangle_{M,RMD}}$$



$$\boxed{SES \equiv k^{-1} = (5.84 \pm 0.21) \times 10^{-14}}$$

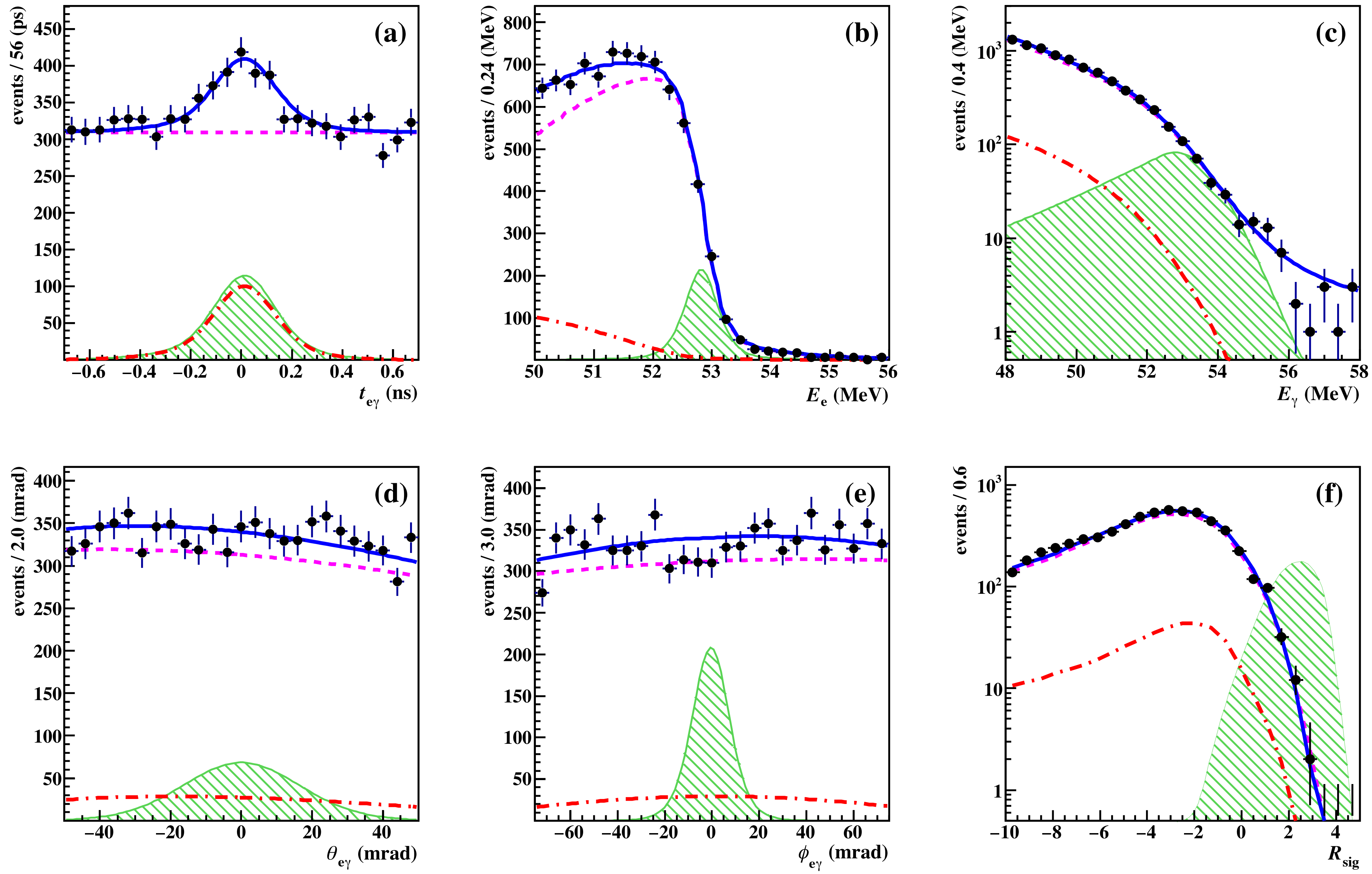
Event distributions

- 8344 events in the blinding box: **No signal excess observed**
- the signal PDF contours (1σ, 1.64σ and 2σ) are also shown



Best fitted likelihood function projections

- to the five observables and to R_{sig} : $R_{sig} = log_{10}\left(\frac{S\mathbf{x_i}}{f_R R(\mathbf{x_i}) + f_A A(\mathbf{x_i})}\right)$



Legend:

black dots: data
blue: best fit
magenta: ACC bkg
red: RMD
green: signal x 100 U.L.

N_{RDM} = 663 +- 59

N_{ACC} = 7684 +- 103

A. Baldini et al. (MEG Collaboration), Eur. Phys. J. **C76** (2016) 434

Result

March 8th 2016

- Confidence interval calculated with Feldman & Cousin approach with profile likelihood ratio ordering
- profile likelihood ratios as a function of the BR: all consistent with a null-signal hypothesis

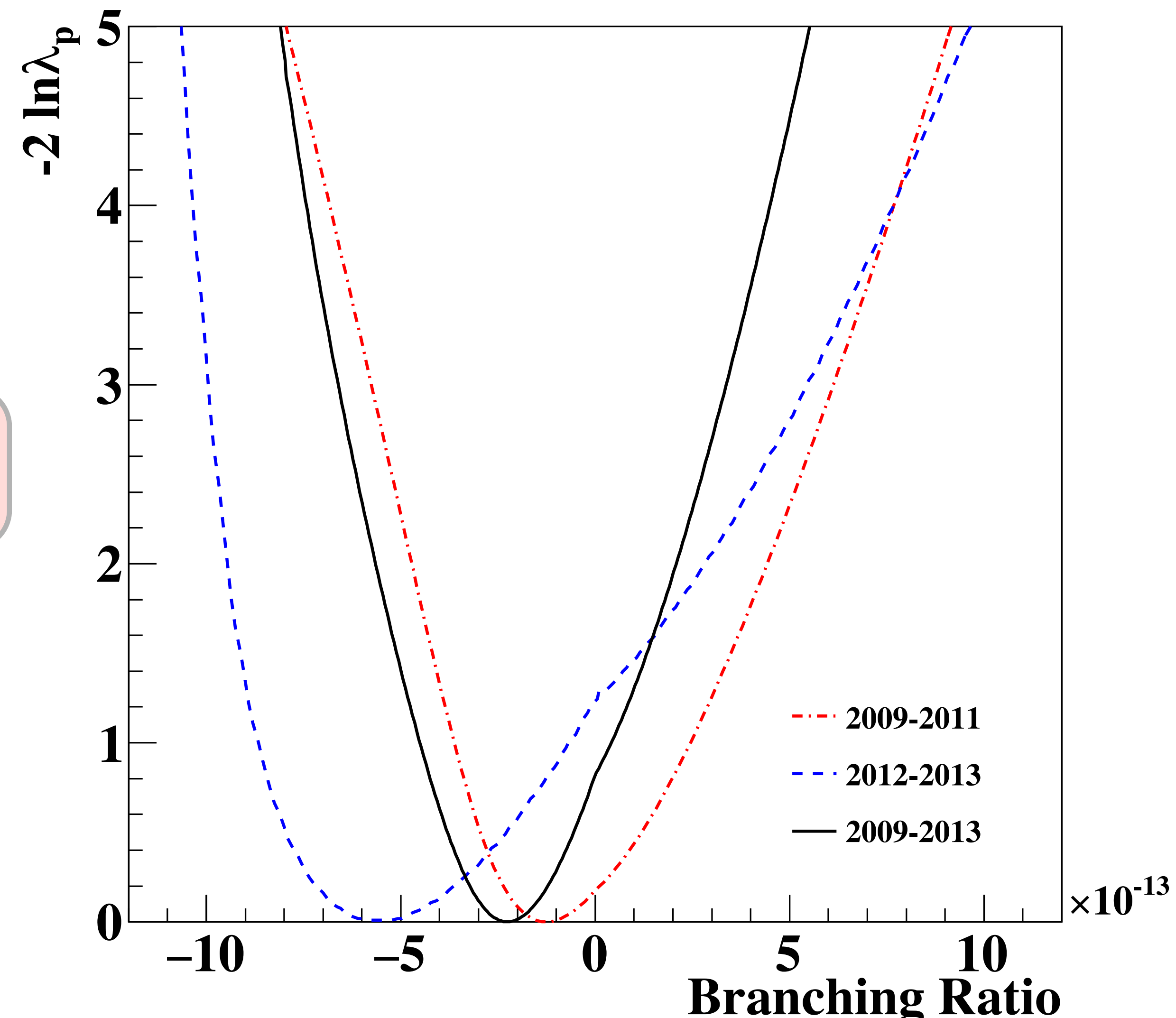
Full data sample:
2009-2013
Best fitted branching ratio at
90% C.L.*:

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

(*) from MEGA to MEG:

improvement by a factor ~ ***30***

Systematic uncertainties:
Target “alignment”: 5%
Other sources: < 1%



How the sensitivy can be pushed down?

- More sensitive to the signal...

high statistics

$$\mathrm{SES} = \frac{1}{\boxed{R} \times T \times A_g \times \boldsymbol{\varepsilon}(e^+) \times \boldsymbol{\varepsilon}\,(\mathrm{gamma}) \times \boldsymbol{\varepsilon}(\mathrm{TRG}) \times \boldsymbol{\varepsilon}(\mathrm{sel})}$$

Beam rate
Acquisition time
Geometrical acceptance
Detector efficiency
Selection efficiency

- More effective on rejecting the background...

high resolutions

$$B_{acc} \sim R \times \boxed{\Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta \Theta_{egamma})^2}$$

Positron Energy resolution
Gamma Energy resolution
Relative timing resolution
Relative angular resolution

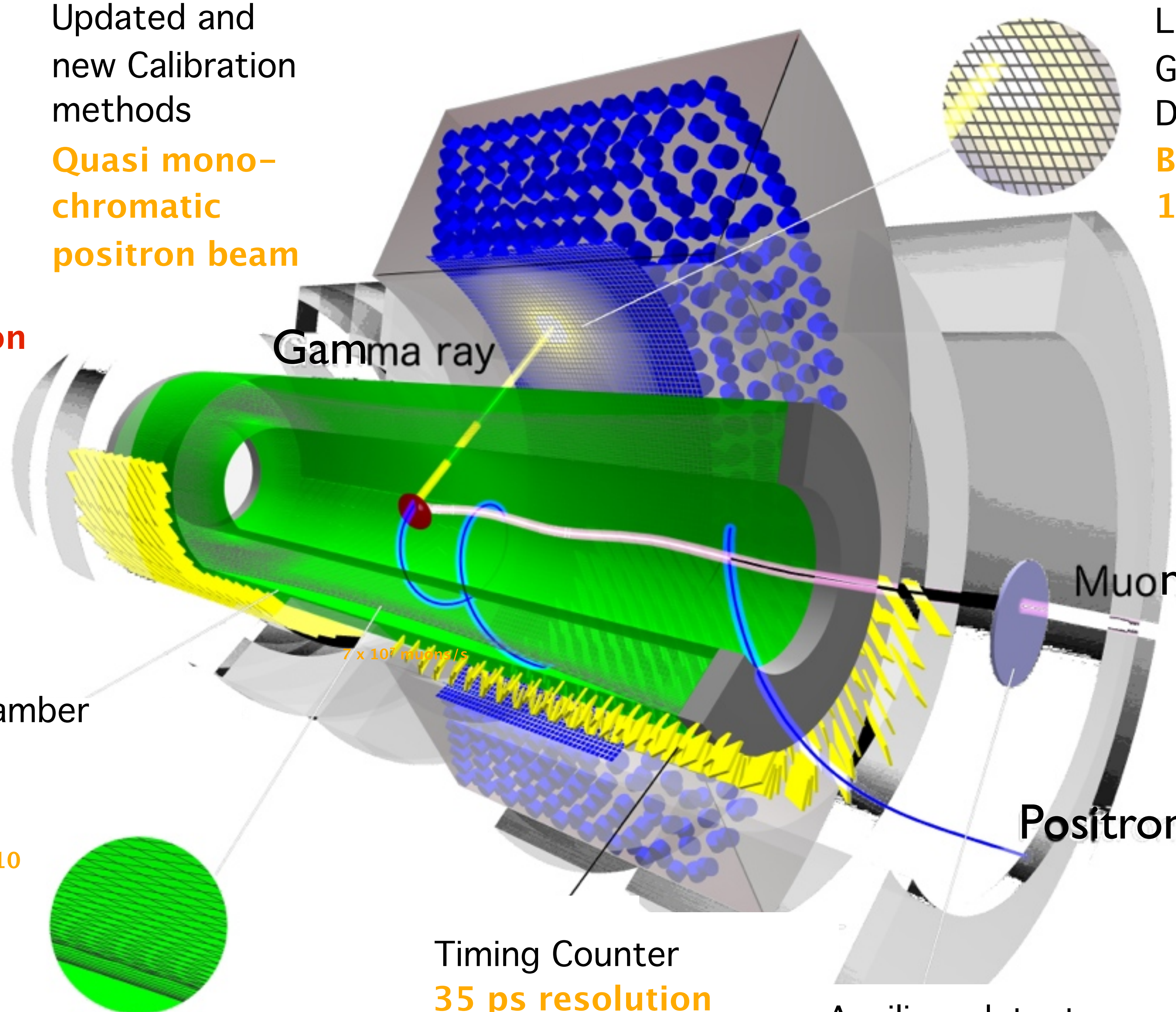
MEGII: $\mu^+ \rightarrow e^+\gamma$ decay search

Wavedream
~9000 channels at 5GSPS

Updated and new Calibration methods
Quasi mono-chromatic positron beam

Liquid Xenon Gamma-ray Detector
Better uniformity w/ 12x12 VUV SiPM

x2 resolution everywhere



Cobra magnet
Gradient B field up to 1.3 T

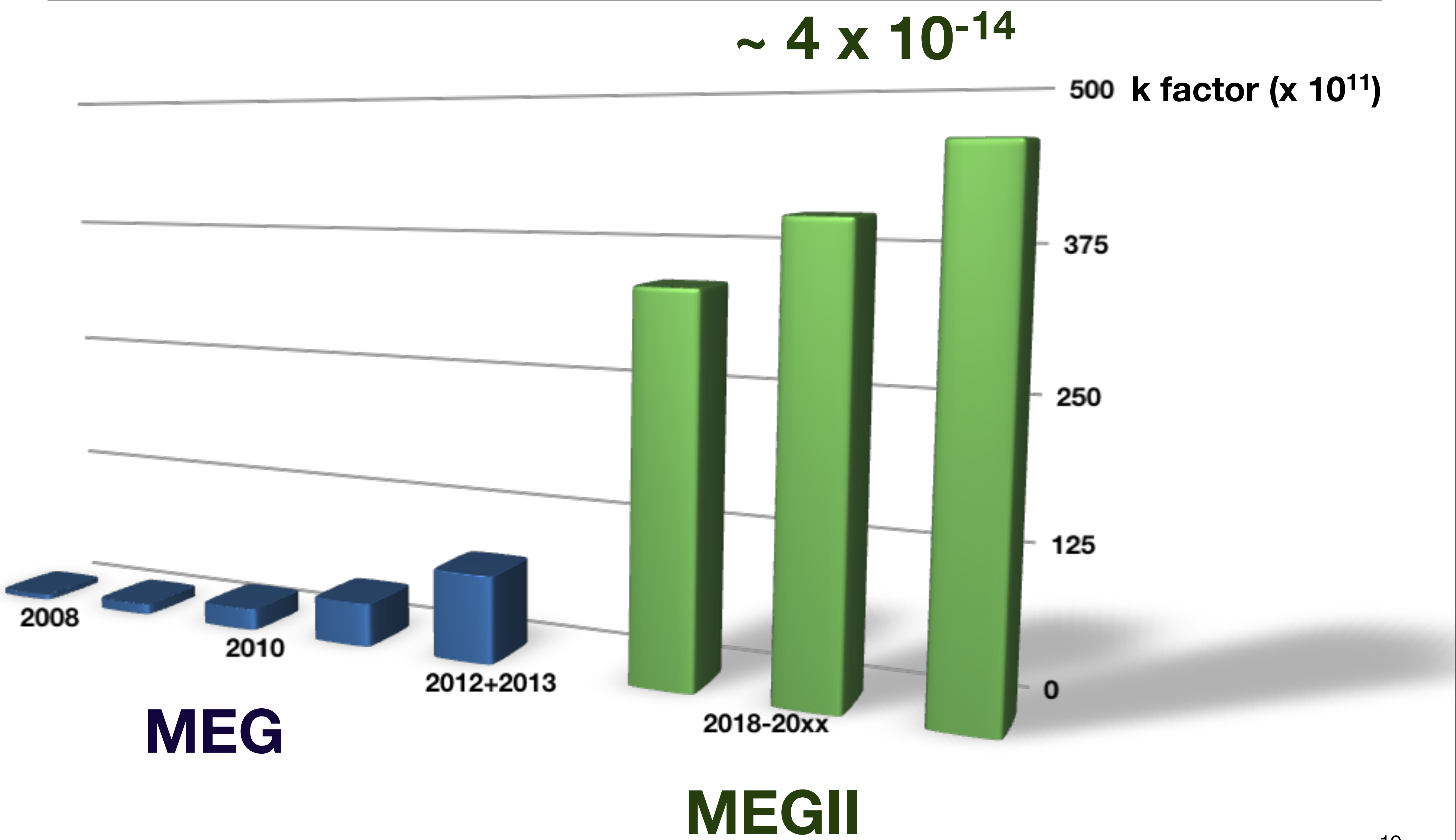
Muon Beam and target
Full available stopped beam intensity 7×10^7

Drift Chamber
Single volume $He:iC_4H_{10}$

Timing Counter
35 ps resolution w/ multiple hits

Auxiliary detectors
Background rejection

Where we will be



2013	2014	2015-6	2017	+ 3 years of run
Design	Construction	PreEng Run	Eng. Run	

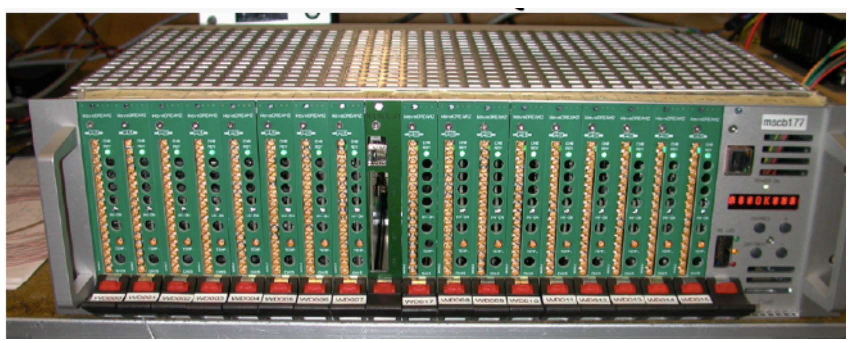
MEGII Status

Sensitivity [2017-20] ~ 4 x 10^{-14}

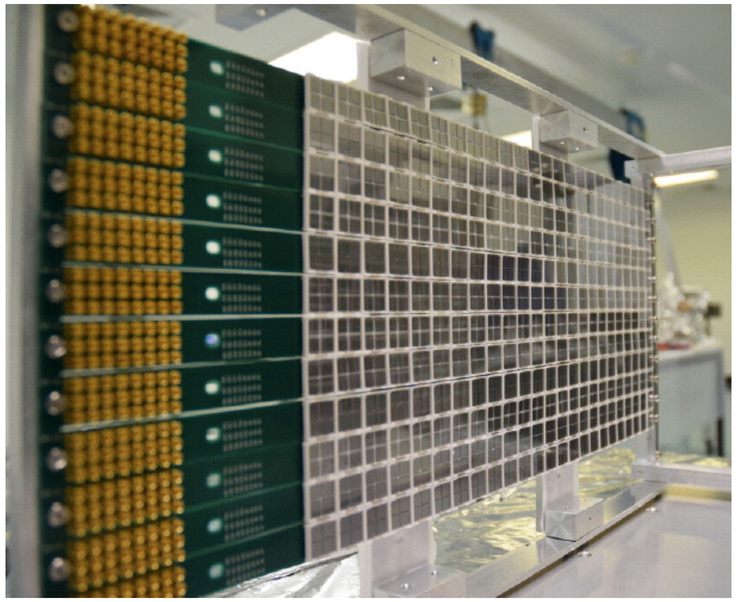
- a real "upgrade": kept the skeletron of the experiment/key ideas and refurbished beam line and all subdetectors

Optimum beam and calibrations

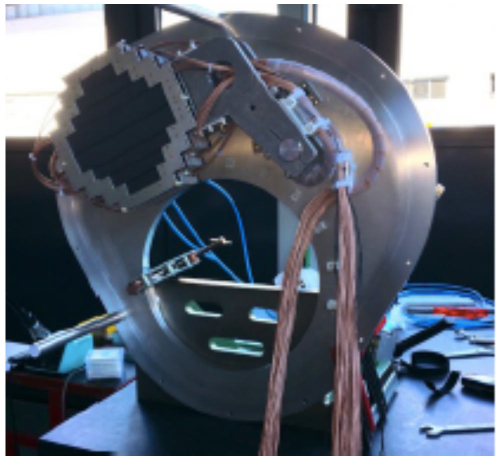
new DAQ + TRG (up to **5 Gsample/s**)



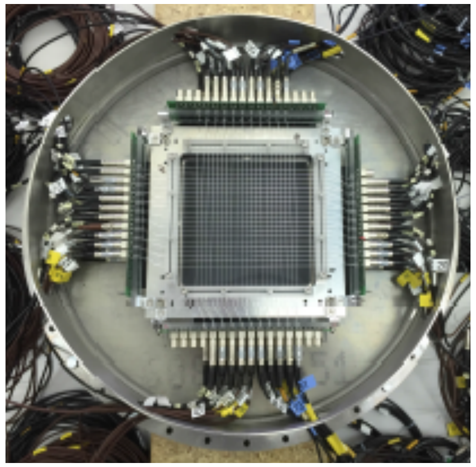
new MPPC in the **VUV**



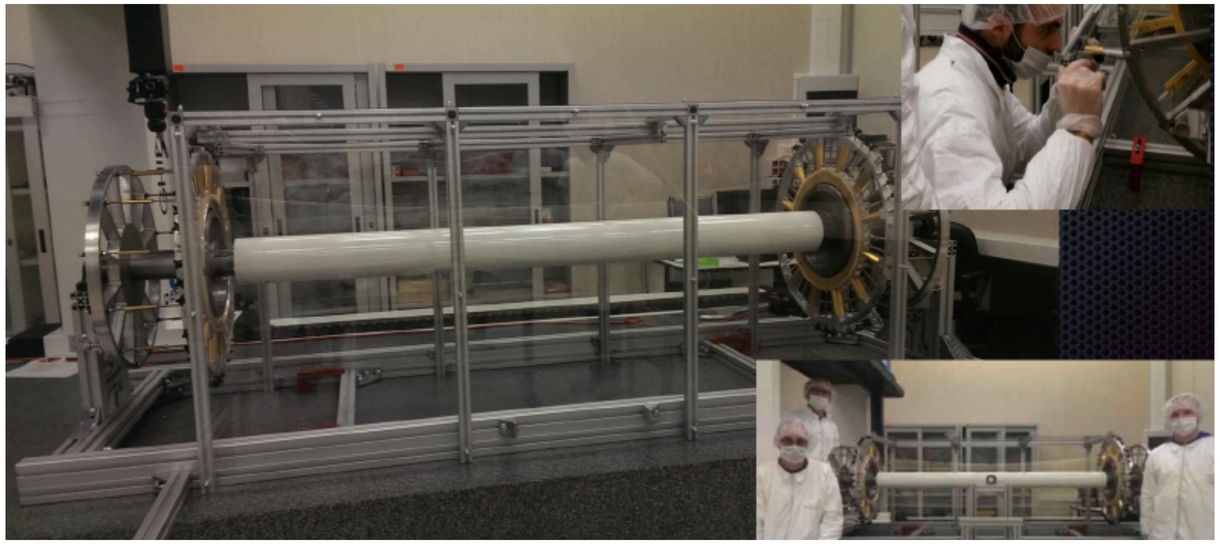
new AUX detector (**<< BKG**)



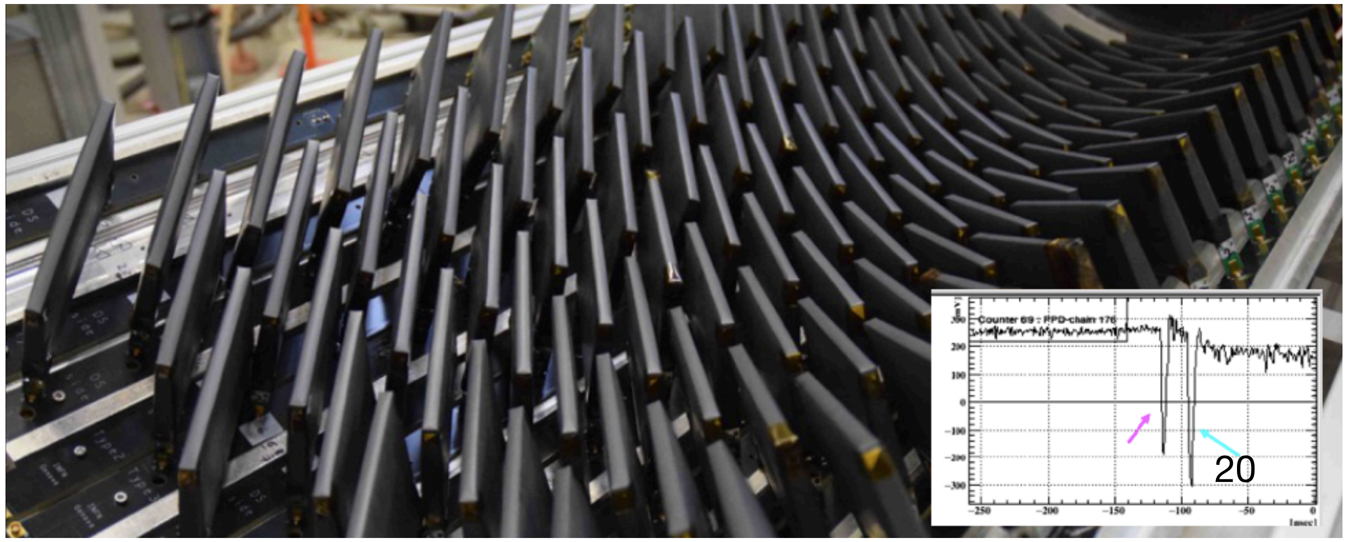
new Beam detector (**Online profile and rate**)



new DCH (**stereo**)



new TC (**multi-hits**)



Dedicated Posters at PSI2016

MEG II experiment: Upgraded Liquid Xe Detector with SiPM readout, Kei IEKI
VUV-sensitive MPPCs for liquid xenon detector in MEG II experiment, Shinjii OGAWA
Performance of MEG II Positron Timing Counter Based on Commissioning Run Result, Miki NISHIMURA
Thin scintillating fibers coupled to SiPMs for fast beam monitoring and timing purposes, Giada RUTAR
Radiative Decay Counter for Ultimate Sensitivity of MEG II Experiment, Ryoto IWAI
Muon Beam Monitoring Using Luminophore Foils at PSI, Zachary HODGE
A Scintillation Stopping Target for the MEG II Experiment, Felix BERG
The calibration and monitoring methods for the MEG experiment and its upgrade, Angela PAPA

Conclusions and Outlook (1)

- a high-precision search for the lepton flavour violating muon decay $\mu^+ \to e^+ \gamma$ has been performed with the MEG experiment

- data have been acquired in the 2009-2013 years for a total stopped muons on the target of **7.5×10^{14}**

- based on the full dataset a **sensitivity of 5.3×10^{-13}** has been achieved

- a new upper limit for the branching ratio of *$B(\mu^+ \to e^+ \gamma) < 4.2 \times 10^{-13}$ at 90% C.L.* has been established (a factor 30 improvement with respect to the previous MEGA experiment and also the strongest bound on any forbidden decay particle)

- **an upgrade of the apparatus is ongoing (MEGII) aiming at a sensitivity down to 4×10^{-14}**

Conclusions and Outlook (2)

- Different channels are sensitive in a different ways to the various lagrangian terms: a complementary study is mandatory for discovering first and understanding later the physics which governs such a processes

- Experiments searching for **$\mu^+ \to e^+ e^+ e^-$, $\mu^- N \to e^- N$ are in preparation aiming at astonishing SES**

- **cLFV remains one of the most exiting place where to search for new physics**

Thank you for your attention!

- from our latest MEG/MEGII collaboration meeting in Tokyo...

cLFV search landscape

Rough estimate of numbers of researchers, in total ~ 850 (with some overlap)

Muons ~ 250

- MEG, PSI
- MEGII, PSI
- Mu3e, PSI
- DeeMee, J-PARC
- MuSiC, Osaka
- Mu2e, FNAL
- COMET, J-PARC
- PROJECT X, FNAL
- PRIME, J-PARC

Taus ~ 250

- BABAR, PEPII
- BELLE/BELLE II, KEKB/SuperKEKB
- LHCb, CERN
- BESIII, Beijing

Kaons ~ 100

- NA48,CERN
- NA62,CERN
- KOTO, J-PARC

cLFV @ LHC ~ 250

- ATLAS,CERN
- CMS,CERN

cLFV best upper limits

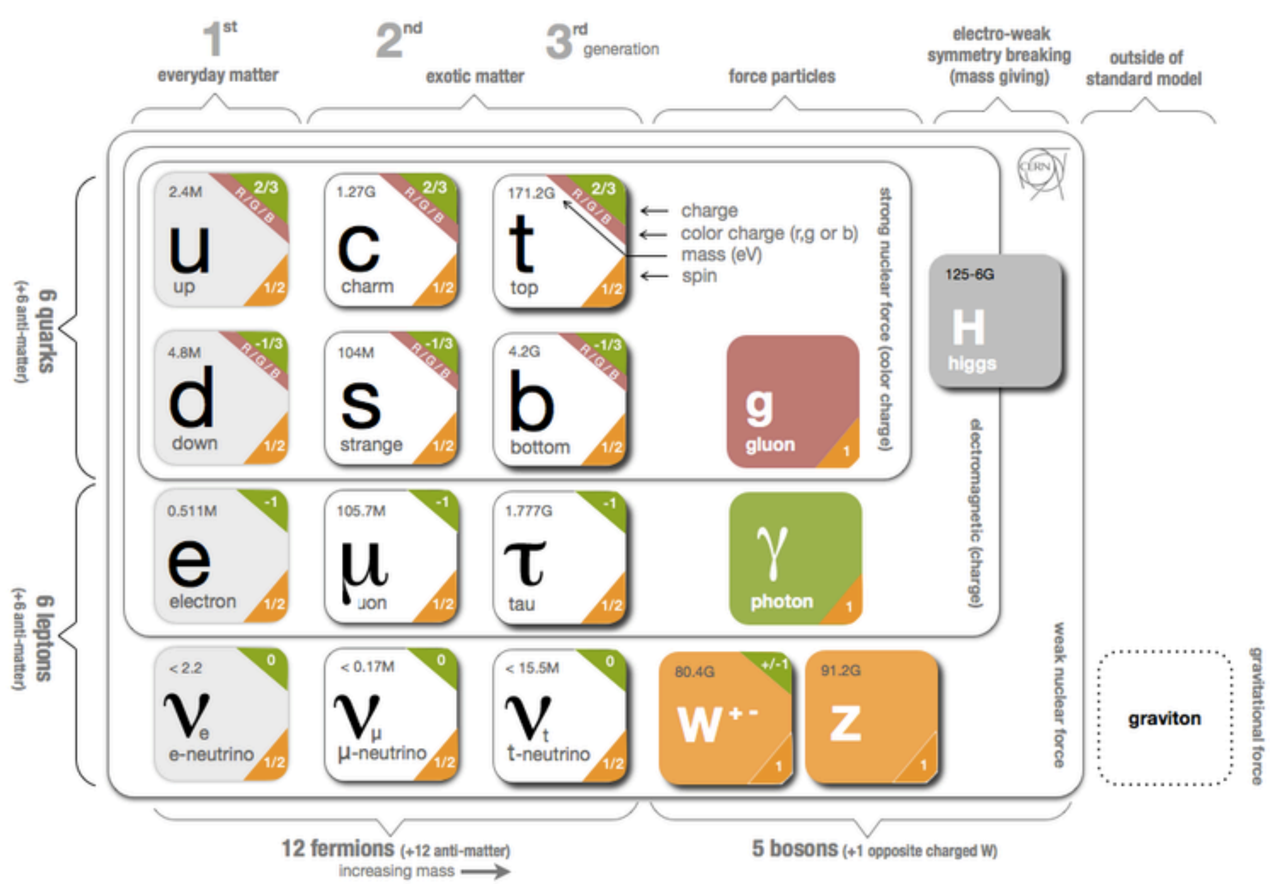
Process	Upper limit	Reference	Comment
$\mu^+ \to e^+ \gamma$	4.2×10^{-13}	arXiV:1605.05081	MEG
$\mu^+ \to e^+ e^+ e^-$	1.0×10^{-12}	Nucl. Phy. B299 (1988) 1	SINDRUM
$\mu^- N \to e^- N$	7.0×10^{-13}	Eur. Phy. J. c 47 (2006) 337	SINDRUM II
$\tau \to e \gamma$	3.3×10^{-8}	PRL 104 (2010) 021802	Babar
$\tau \to \mu \gamma$	4.4×10^{-8}	PRL 104 (2010) 021802	Babar
$\tau^- \to e^- e^+ e^-$	2.7×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$\tau^- \to \mu^- \mu^+ \mu^-$	2.1×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$\tau^- \to \mu^+ e^- e^-$	1.5×10^{-8}	Phy. Let. B 687 (2010) 139	Belle
$Z^0 \to \mu e$	7.5×10^{-8}	Phy. Rev. D 90 (2014) 072010	Atlas ($\mu \to 3e : 10^{-12}$)
$Z^0 \to \mu e$	7.3×10^{-8}	CMS PAS EXO-13-005	CMS
$H \to \tau \mu$	1.85×10^{-2}	JHEP 11 (2015) 211	Atlas (*)
$H \to \tau \mu$	1.51×10^{-2}	Phy. Let. B 749 (2015) 337	CMS
$K_L \to \mu e$	4.7×10^{-12}	PRL 81 (1998) 5734	BNL

* $B(H \to \mu e) < O(10^{-8})$ from $\mu \to e \gamma$

Backup

The role of the low energy precision physics

The Standard Model of particle physics is a great triumph of modern physics



but unable to answer:
- dark matter
- dark energy
- gravity
- extremely small CP phase
- flavour and origin of CP violation
- why three families
- ...

- **Searches for rare/forbidden decays**
- Symmetry tests
- Precision measurements

very sensitive tools for
- unveiling new physics
- probing high energy scale

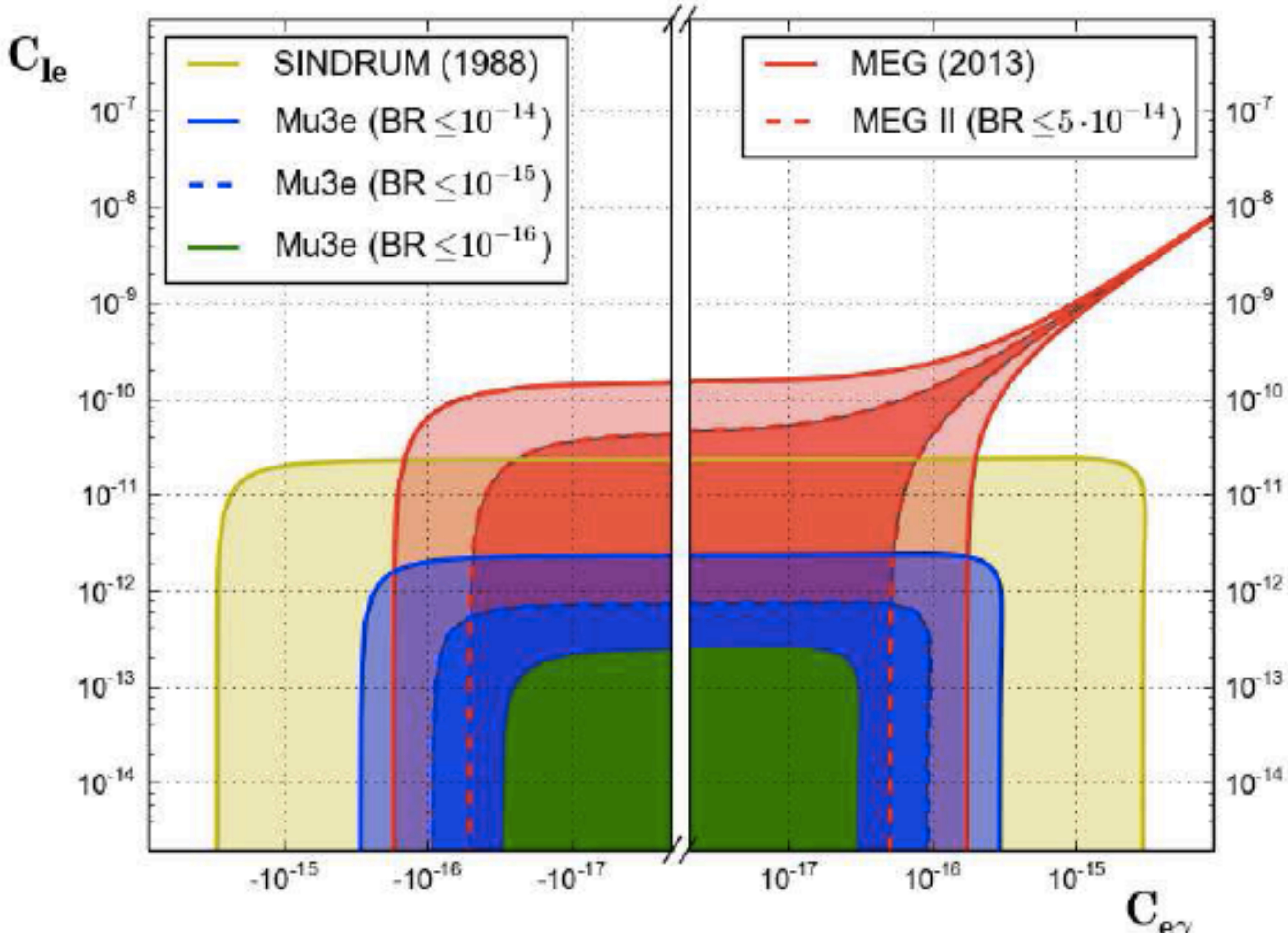
...is to contribute to a deeper understanding of the nature

cLFV: Effective lagrangian approach

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

- effective lagrangian approach
  - a framework to combine constrains from low-energy (i.e. μ-> eγ) experiments with LFV searches at higher energies (Z bosons or H -> τμ)
  - complementarity among LFV channels

$[\mathbf{C}] = \mathbf{GeV}^{-2}$

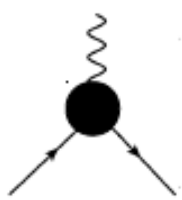
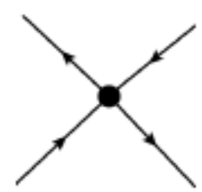


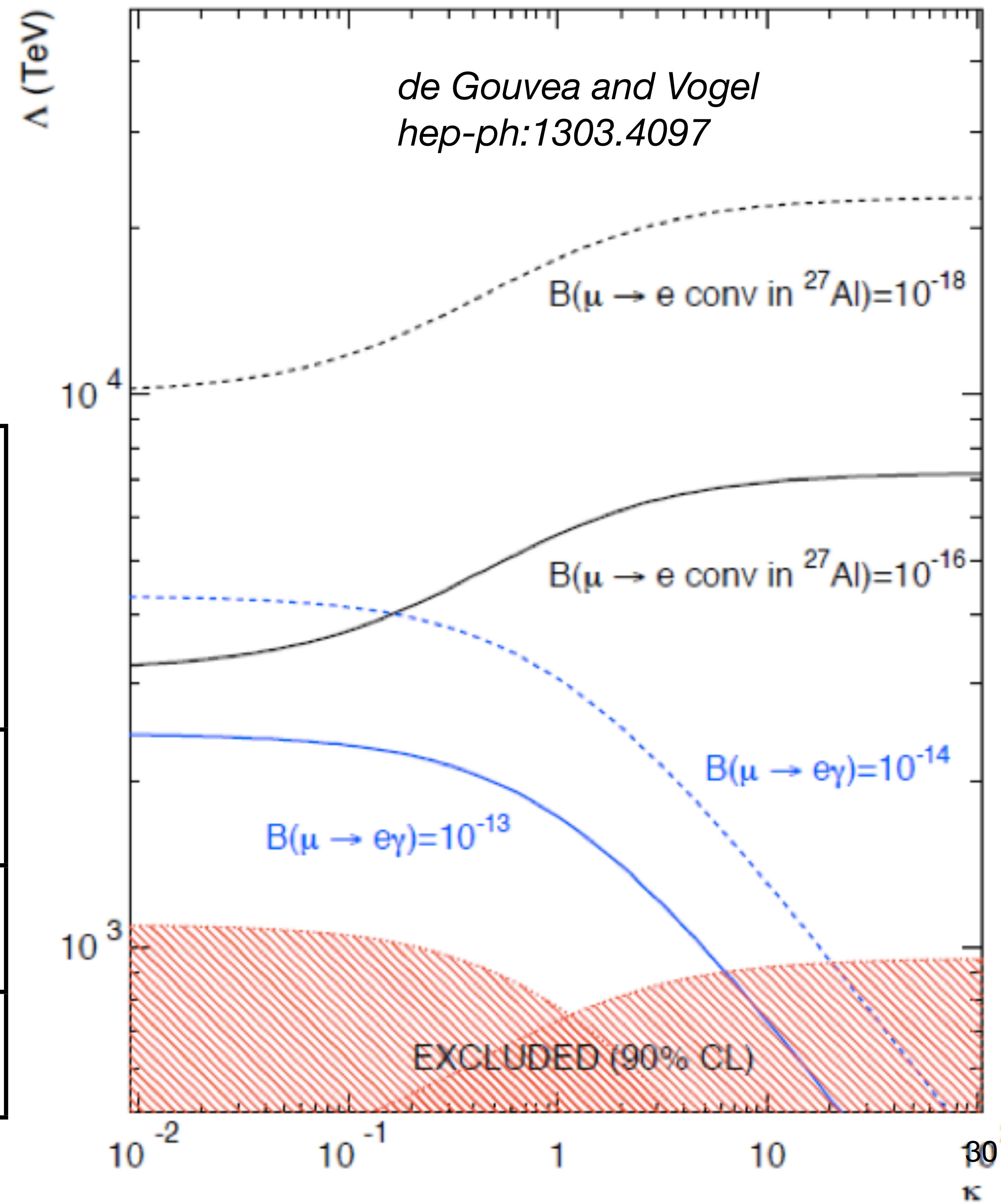
ref.: G.M. Pruna and A. Signer arXiv:1511.04421v1
G.M. Pruna and A. Signer JHEP 10 (2014) 014

cLFV: “Effective” lagrangian with the k-parameter

- Due to the **extremely-low** accessible **branching ratios**, muon cLFV can strongly **constrain** new physics models and scales

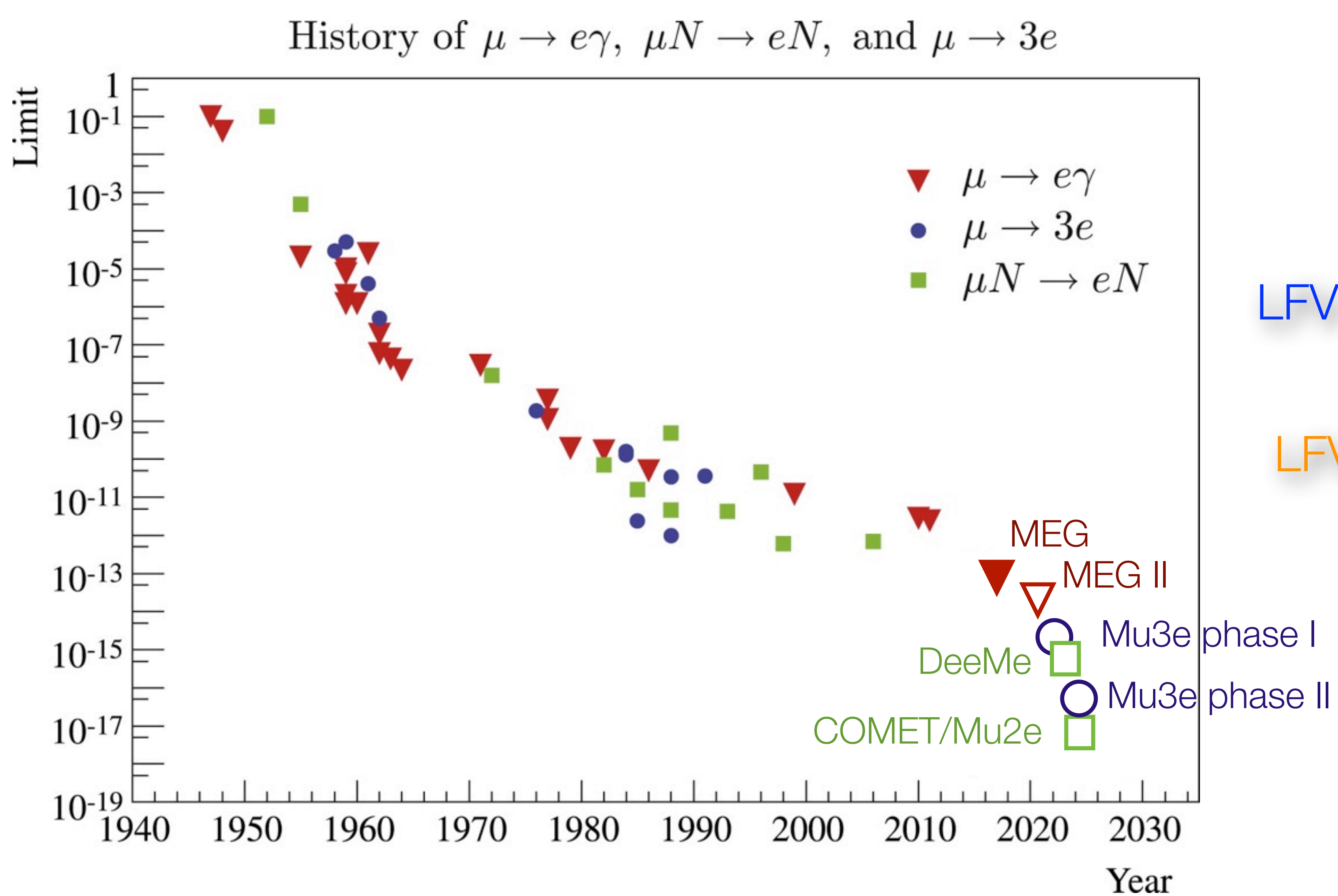
Model independent lagrangian

dipole term	contact term
$\frac{m_\mu}{(\kappa+1)\Lambda^2} \times$ 	$+ \frac{\kappa}{(\kappa+1)\Lambda^2} \times$ 
$\mu \to e\gamma$	
$\mu \to eee$	
$\mu N \to eN$	



cLFV searches with muons: status and future prospects

- Lepton flavour is preserved in the Standard Model (SM) ("accidental symmetry")
  - not related to the theory gauge
  - naturally violated in SM extensions



LFV of neutral leptons confirmed -neutrino oscillations-

LFV of charged leptons not yet observed

Beam features vs experiment requirements

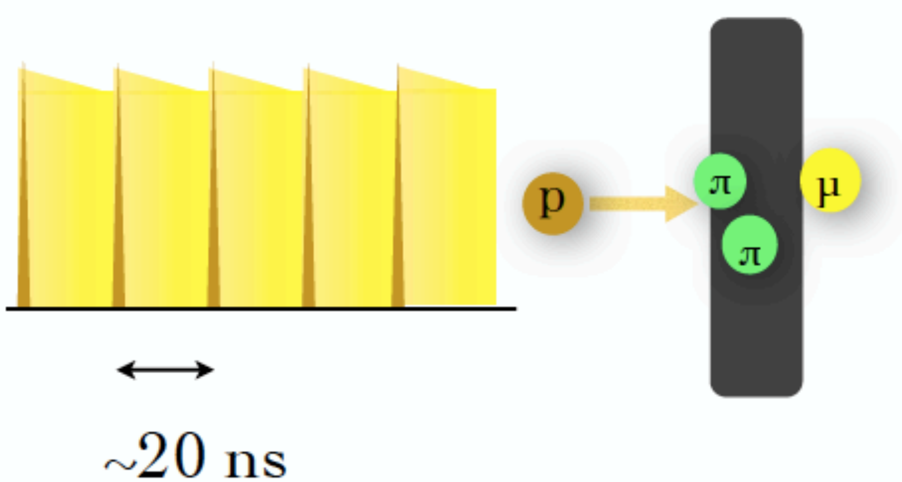
- Dedicated beam lines for high precision/sensitive SM test/BSM probe at the world's high beam intensities

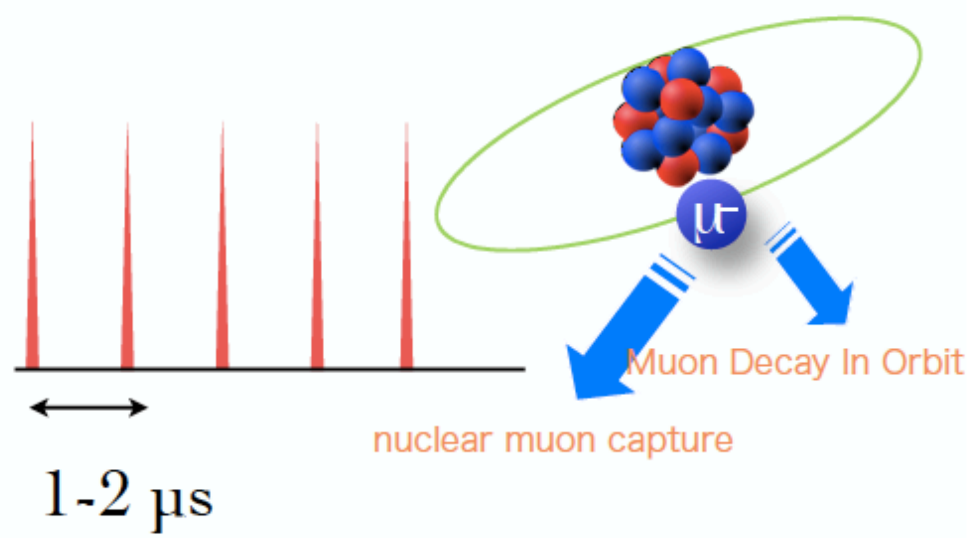
DC or Pulse?

$I_{beam} \sim 10^9 - 10^{10}$ μ/s

$I_{beam} \sim 10^{11}$ μ/s

- DC beam for coincidence experiments
  - $\mu \to e \gamma$, $\mu \to e\ e\ e$
  - $I_{beam} \sim 10^8$ μ/s
- Pulse beam for non-coincidence experiments
  - μ-e conversion





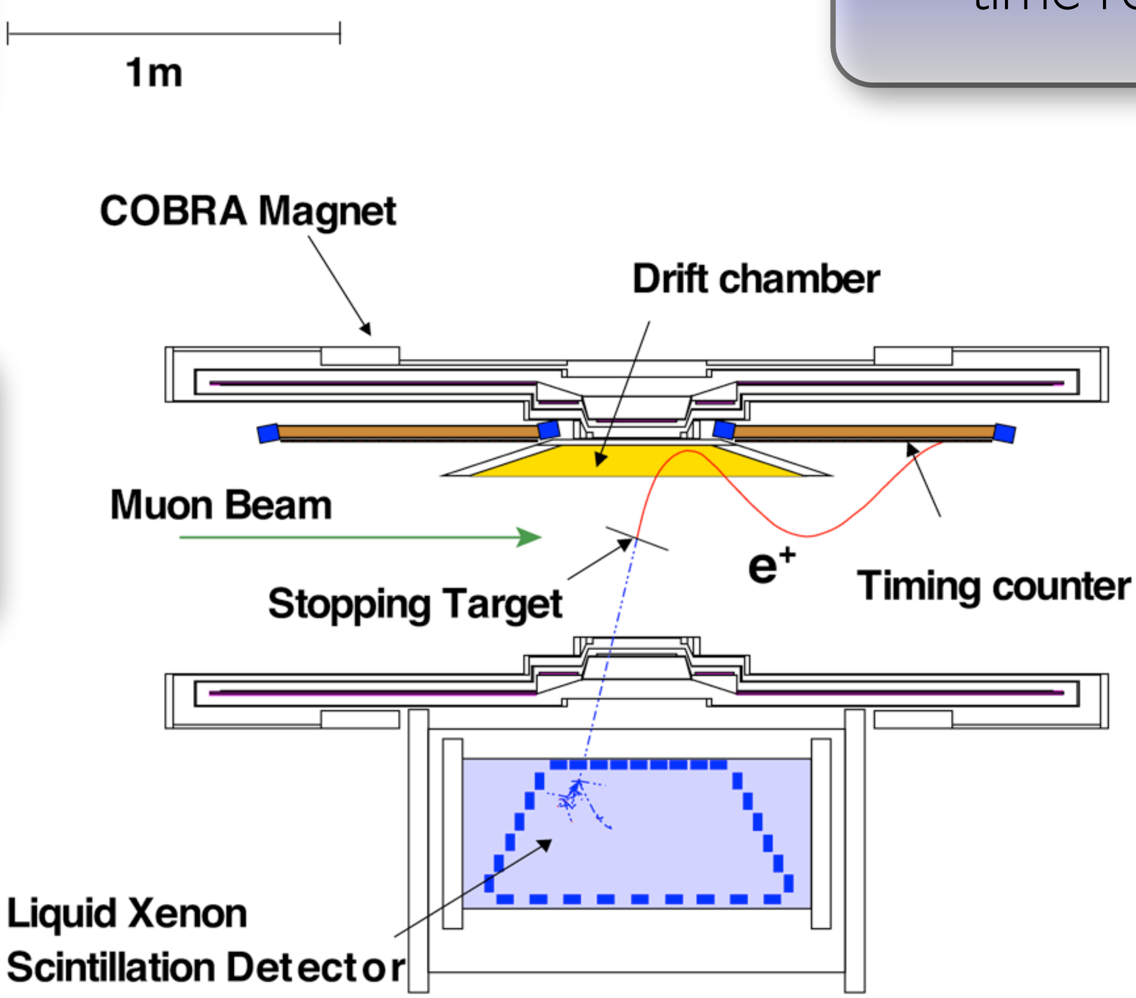
A. Baldini et al. (MEG Collaboration), Eur. Phys. J. ***C73*** *(2013) 2365*

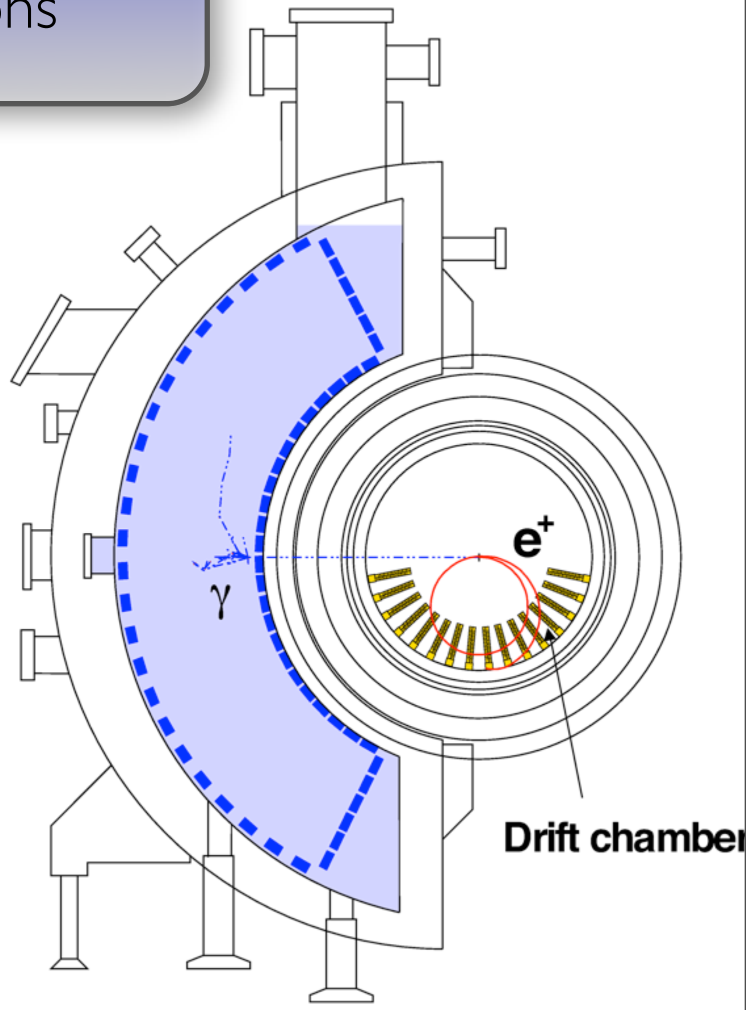
Experimental set-up

The most intense DC muon beam

Positron Very precise momentum and time resolutions

Gamma High energy and time resolutions





High efficiency event selection and frequency signal digitization

Complementary calibration and monitoring methods

Detector performance

The most intense DC muon beam

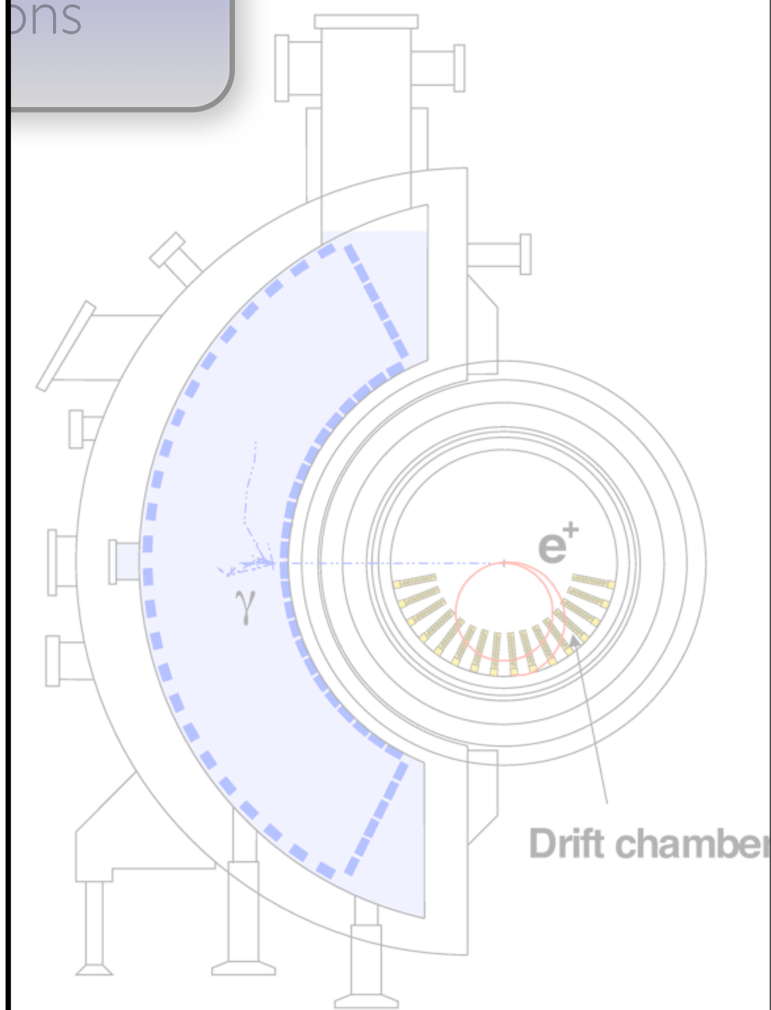
Positron Very precise momentum and time resolutions

High efficiency and frequency

rgy and ons

Liqu Scin

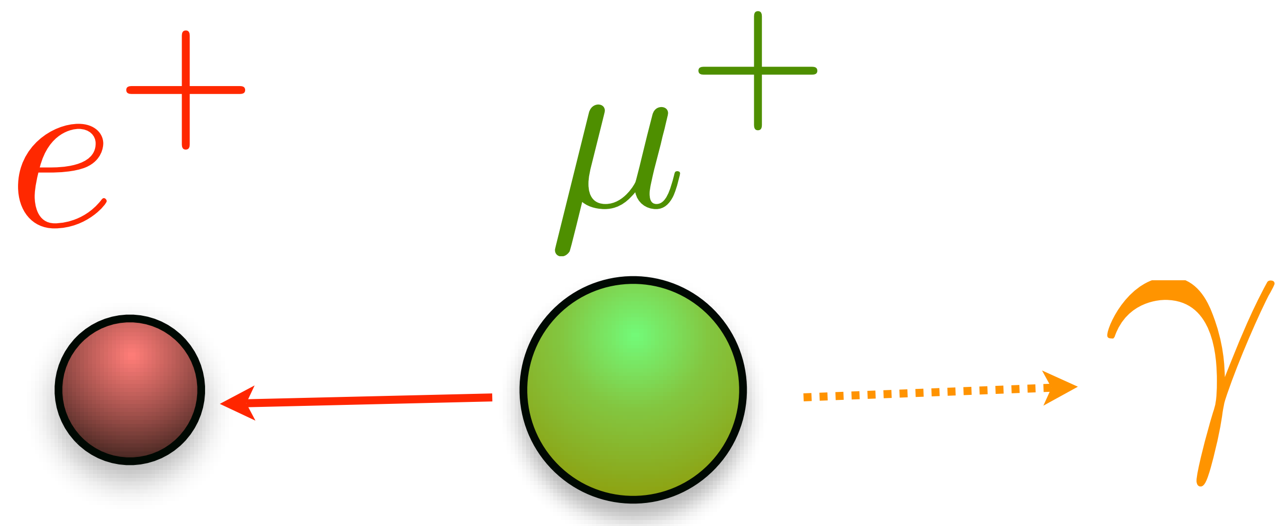
	Resolutions (σ)
Gamma Energy (%)	1.7(depth>2cm), 2.4
Gamma Timing (psec)	67
Gamma Position (mm)	5(u,v), 6(w)
Gamma Efficiency (%)	63
Positron Momentum (KeV)	305 (core = 85%)
Positron Timing (psec)	108
Positron Angles (mrad)	7.5 (Φ), 10.6 (θ)
Positron Efficiency (%)	40
Gamma-Positron Timing (psec)	127
Muon decay point (mm)	1.9 (z), 1.3 (y)



ementary calibration and onitoring methods

$\mu^+ \to e^+\gamma$ ID

- via five kinematical variables:
    - E_γ
    - E_e
    - $t_{e\gamma}$
    - $\theta_{e\gamma}$
    - $\phi_{e\gamma}$



$\mu \to e\gamma$ signature (muons at rest)

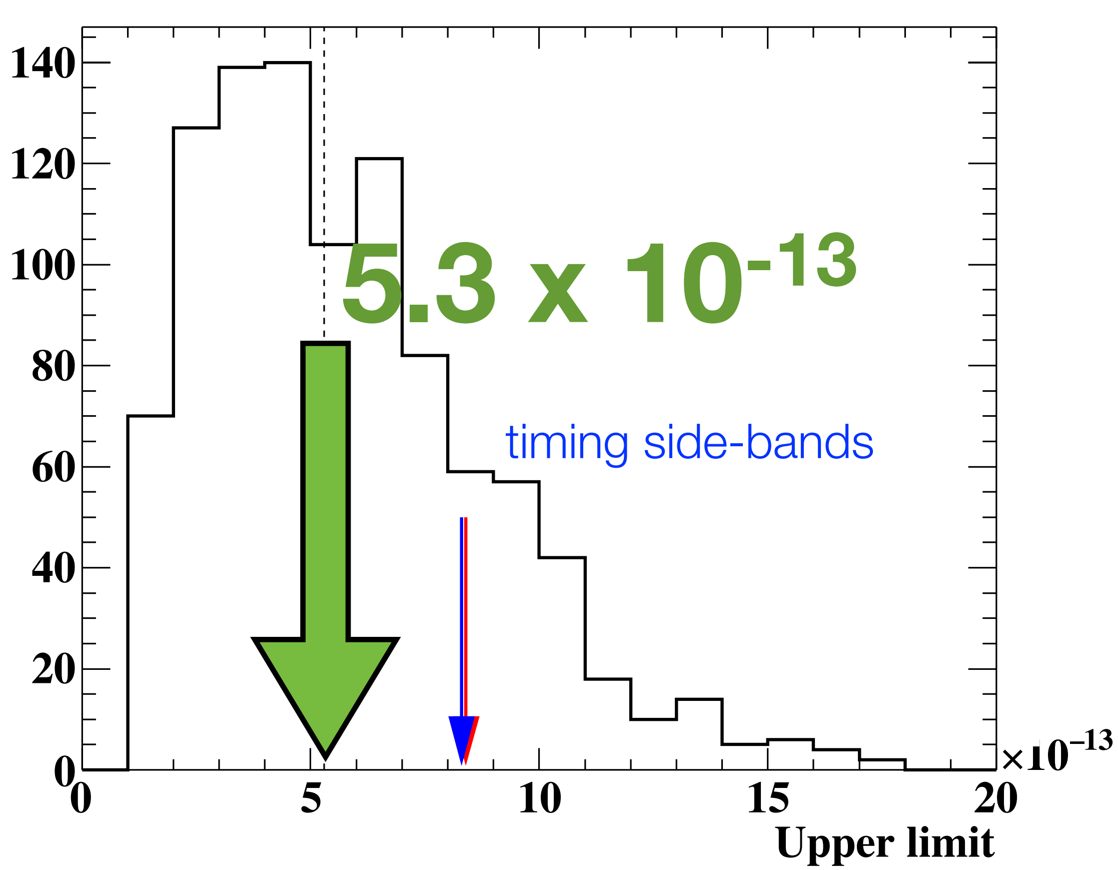
$$E_\gamma = E_e = m_\mu/2$$

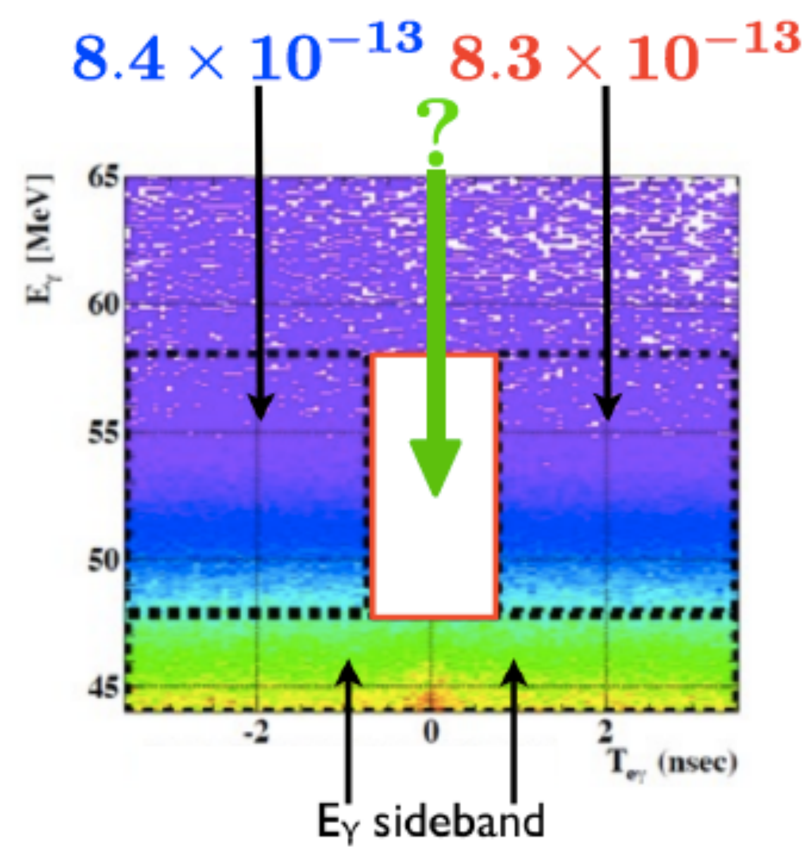
$$\Delta t_{e\gamma} = 0$$

$$\Delta\Theta_{e\gamma} = 0$$

Sensitivity and checks

- Is evaluated by taking the **median** average of the distribution of the branching ratio upper limit at 90% C.L. for **pseudo experiments** with **null signal** hypothesis
  - RMD and accidental bkg included as estimated from side-bands
  - systematics uncertanties taken into account
- As a **check**, the analysis has also been tested in fictitious analysis windows in the **timing side-bands** centred at $t_{e\gamma}$ = +- 2 ns





Event selection

trigger

$E_g > 40$ MeV & $|\Delta t_{eg}| < 10$ ns & $|\Delta\varphi| < 7.5^0$

pre-selected events

Al least 1 reconstructed track on DCHs

short relative time between LXe-TC

(~16% of the original sample)

side-bands

to optimise the algorithms

to study the backgrounds

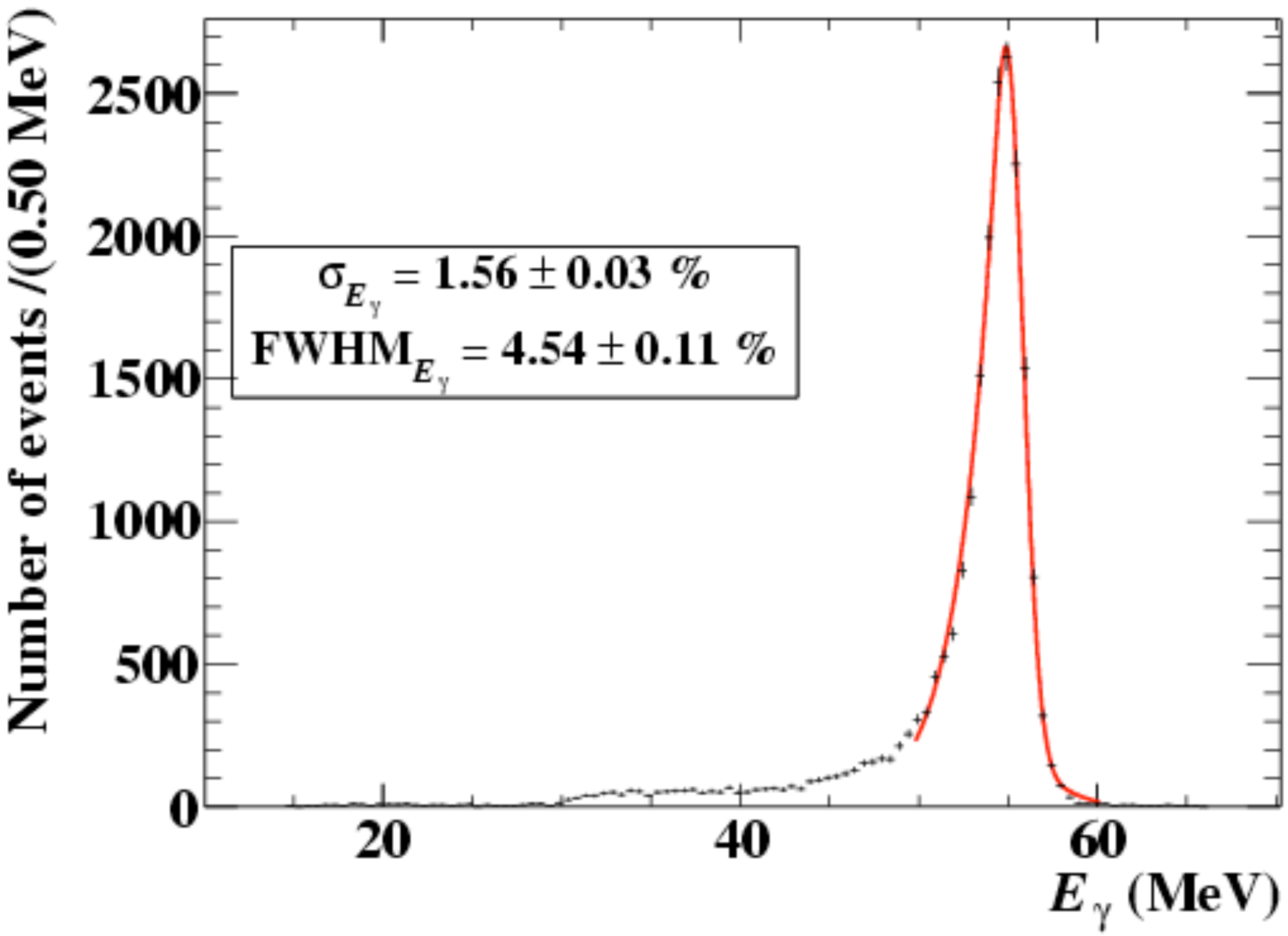
to evaluate the sensitivity

blinding box

hidden events

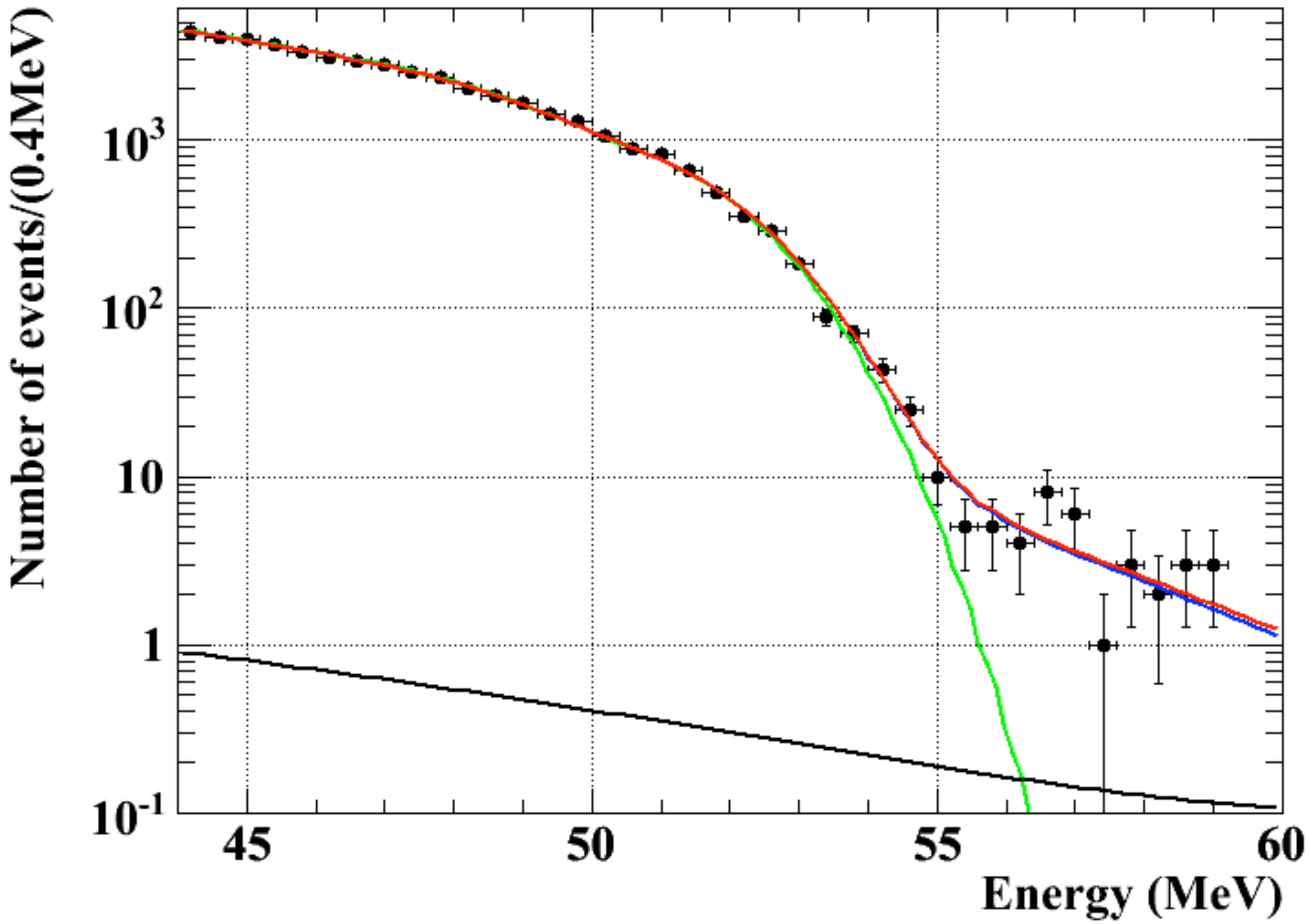
Detector response function

- e.g. of gamma-ray from the CEX reaction in the LXe calorimeter at 55 MeV



Background study: accidental bkg

- e.g. gamma-ray background spectrum in the LXe calorimeter



Legend:

black dots: data

black dots: CR

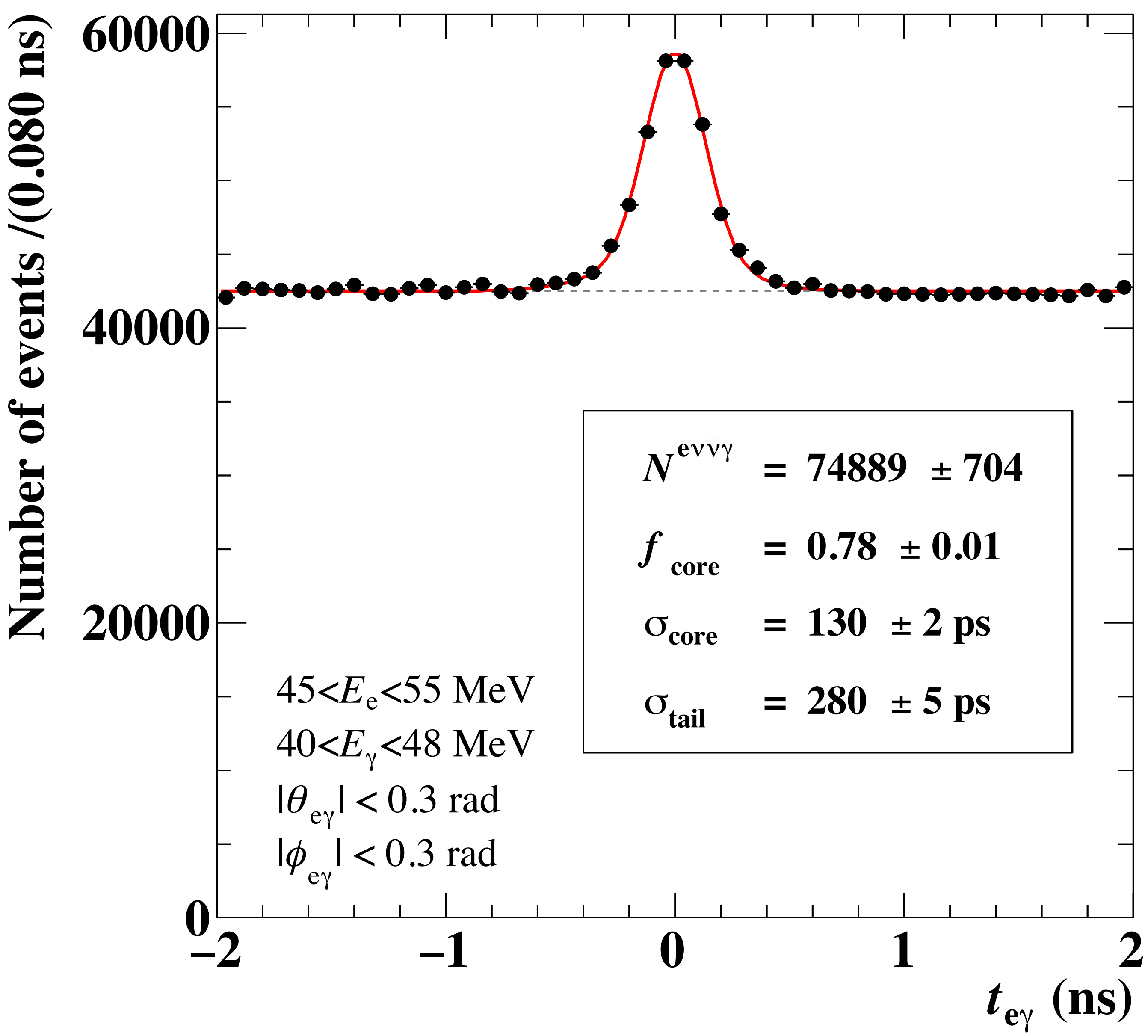
green: RMD + AIF

blue: RMD + AIF + pile up

red: all bkg

Background study: RMD

- $t_{e\gamma}$ distribution in the energy-side band



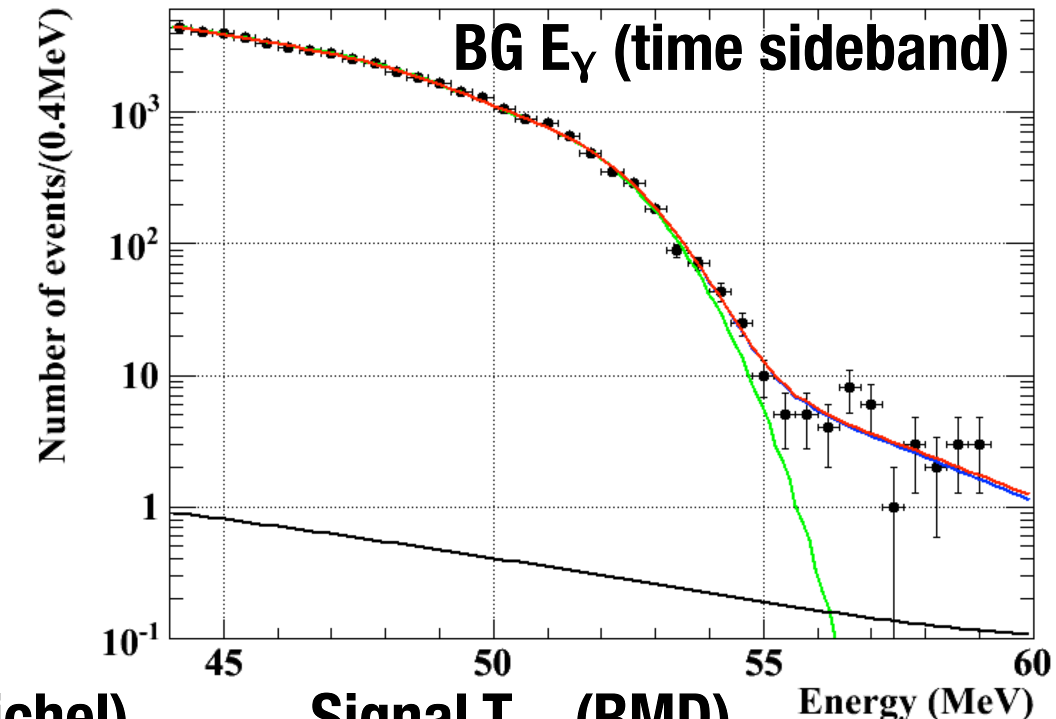
Probability Density Functions

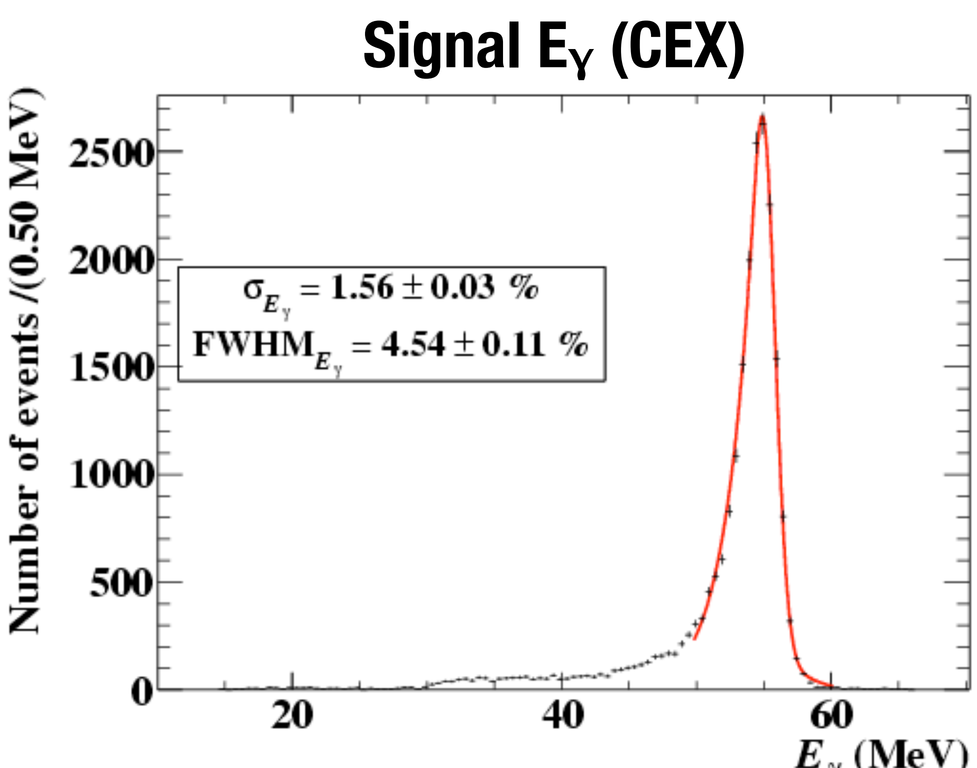
- **Probability density functions (PDF)** for likelihood function are mostly extracted from **data**

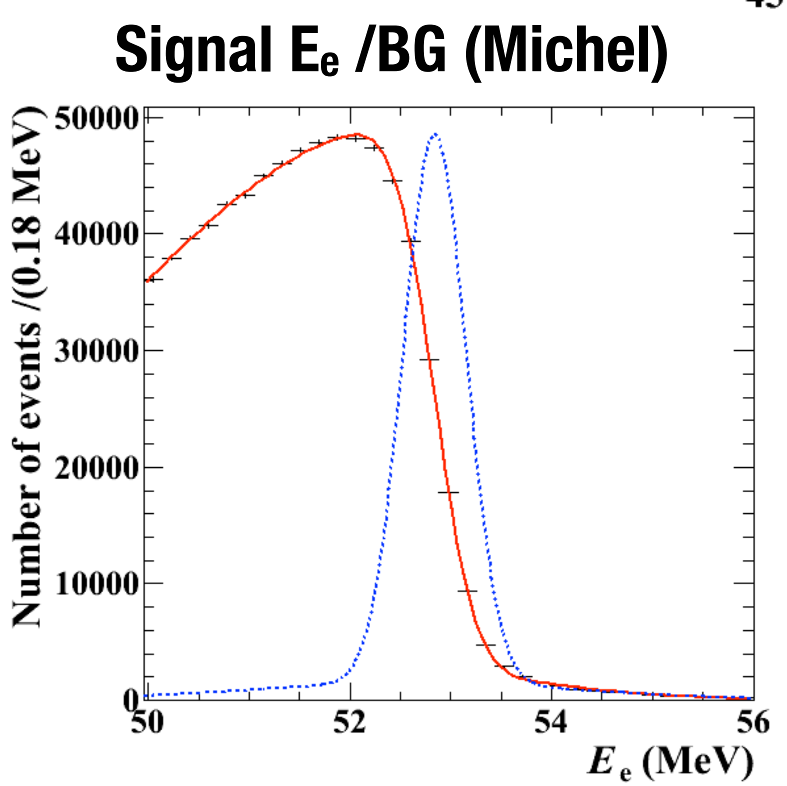
The signal PDF *S* is the product of the PDFs for Ee, θeγ, Φeγ,Teγ which are correlated variables, and the Eγ PDF

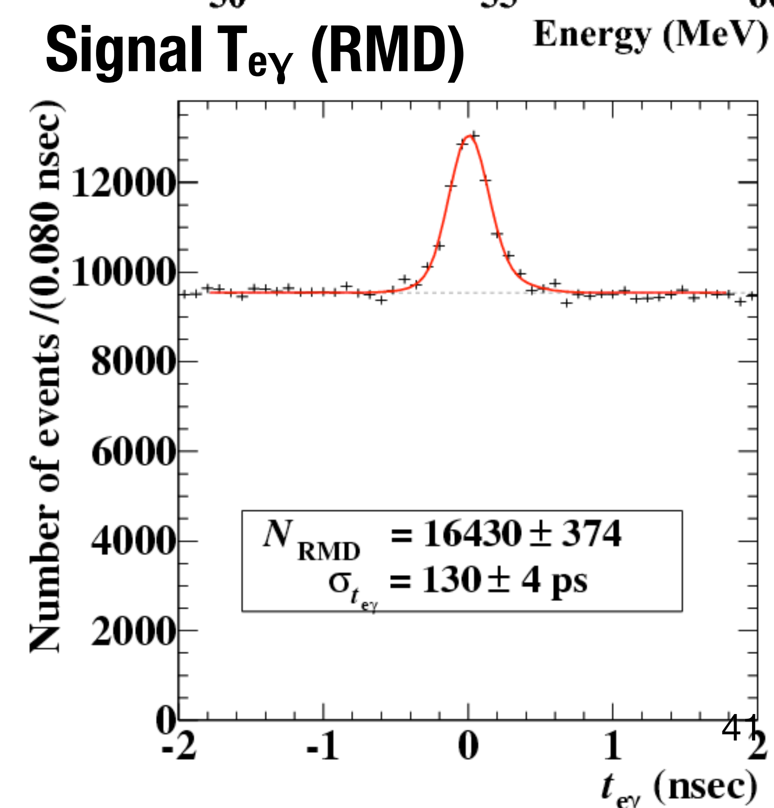
The RMD PDF *R* is the product of the same Teγ PDF as that of the signal and the PDF of the other four correlated observables, which is formed by folding the theoretical spectrum with the detector response functions

The BG PDF *B* is the product of the five PDFs, each of which is defined by the single background spectrum, precisely measured in the sidebands



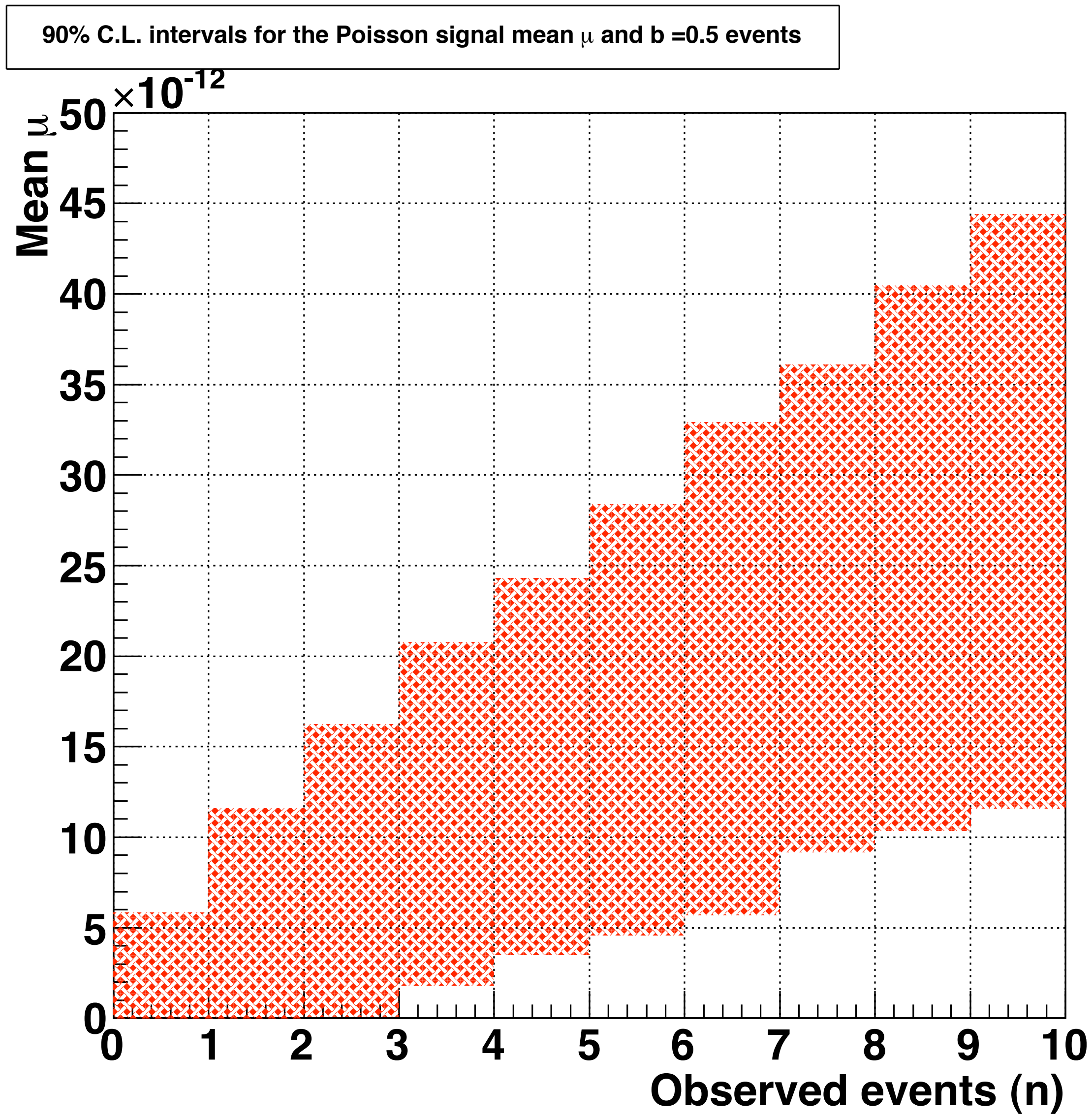






Confidence interval

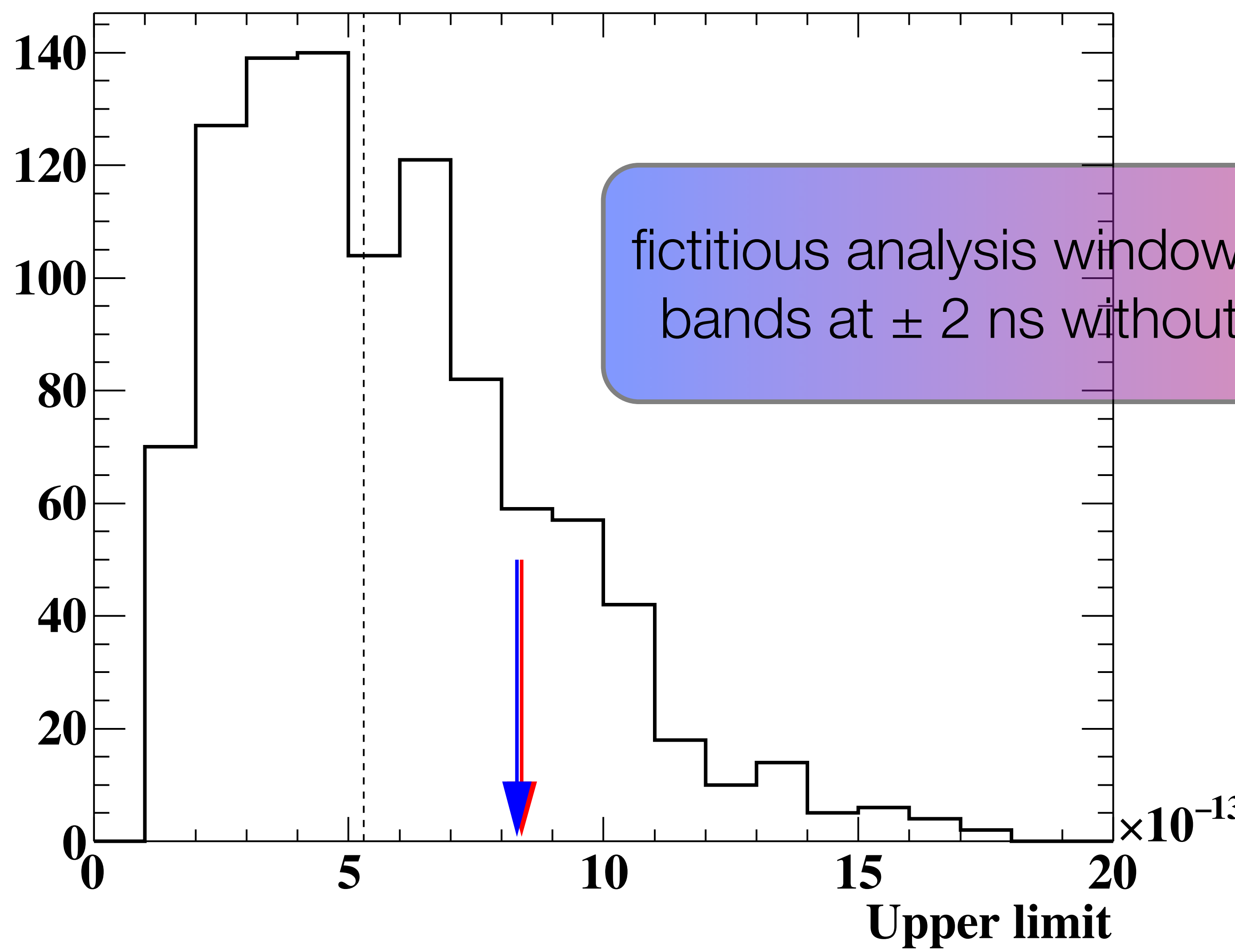
- Feldman&Cousins prescription
  - e.g. : the construction proceeds by finding the acceptance region for all values of μ, for the given value of b (= 0.5)



$$P(n|\mu) = (\mu + b)^n \frac{e^{-(\mu+b)}}{n!}$$

Sensitivity

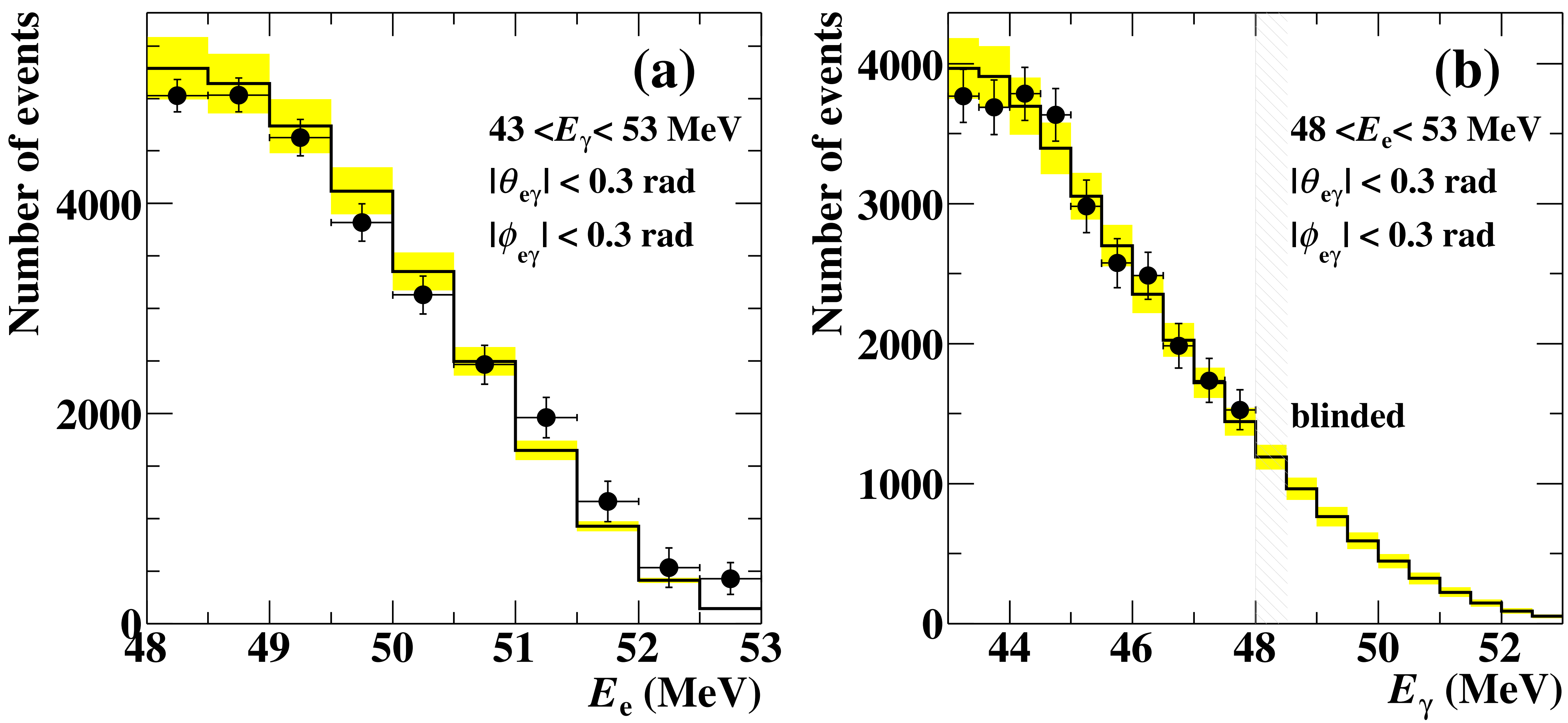
- is evaluated by taking the median average of the distribution of the branching ratio upper limit at 90% C.L. for pseudo experiments with null signal hypothesis
  - RMD and accidental bkg included as estimated from side-bands
  - systematics uncertainties taken into account



fictitious analysis window in the timing side-bands at ± 2 ns without RMD constraints

Background study: RMD

- projected distribution of RMD events in the energy side-band with the expectations
- rate and shape consistent with SM calculation

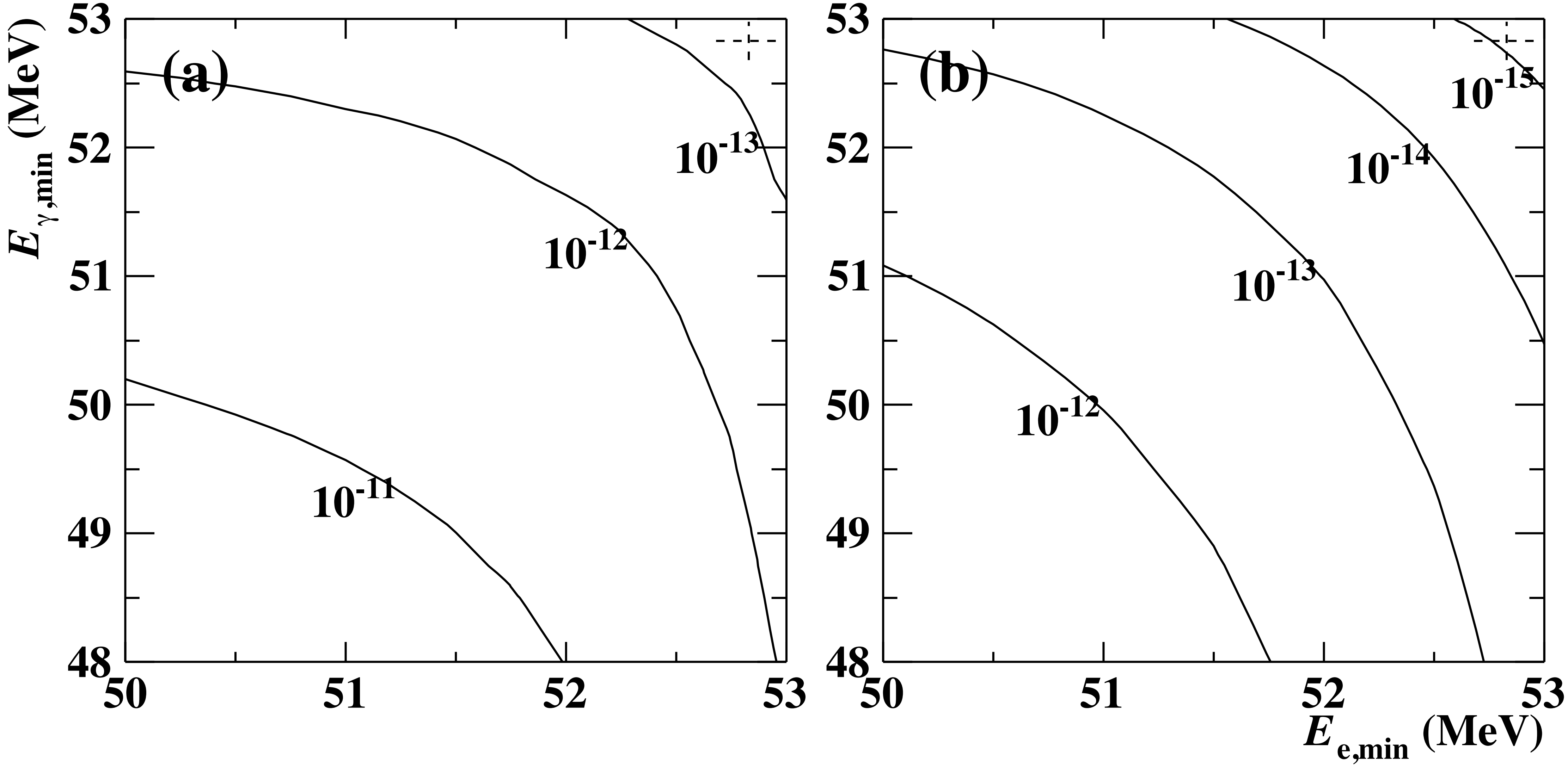


LXe-spectrometer alignment

- optical survey
- physics processes to cross-check δz "only"
  - positron AIF: $\delta z \sim 2.1$ mm
  - CR without Cobra magnetic field: $\delta z \sim 1.8$ mm
    - $\delta z \sim 2.0 \pm 0.4$ mm (corresponding to $\theta_{e\gamma} \sim 0.85$ mrad)
  - δz is used as an estimate of the systematic uncertainty of the survey
  - survey results used for the alignment

RMD and ACC bkg

- effective branching ratios into the shown kinematic window with **$|t_{e\gamma}| < 0.24$ ns and $\cos\Theta_{e\gamma} < -0.9996$**



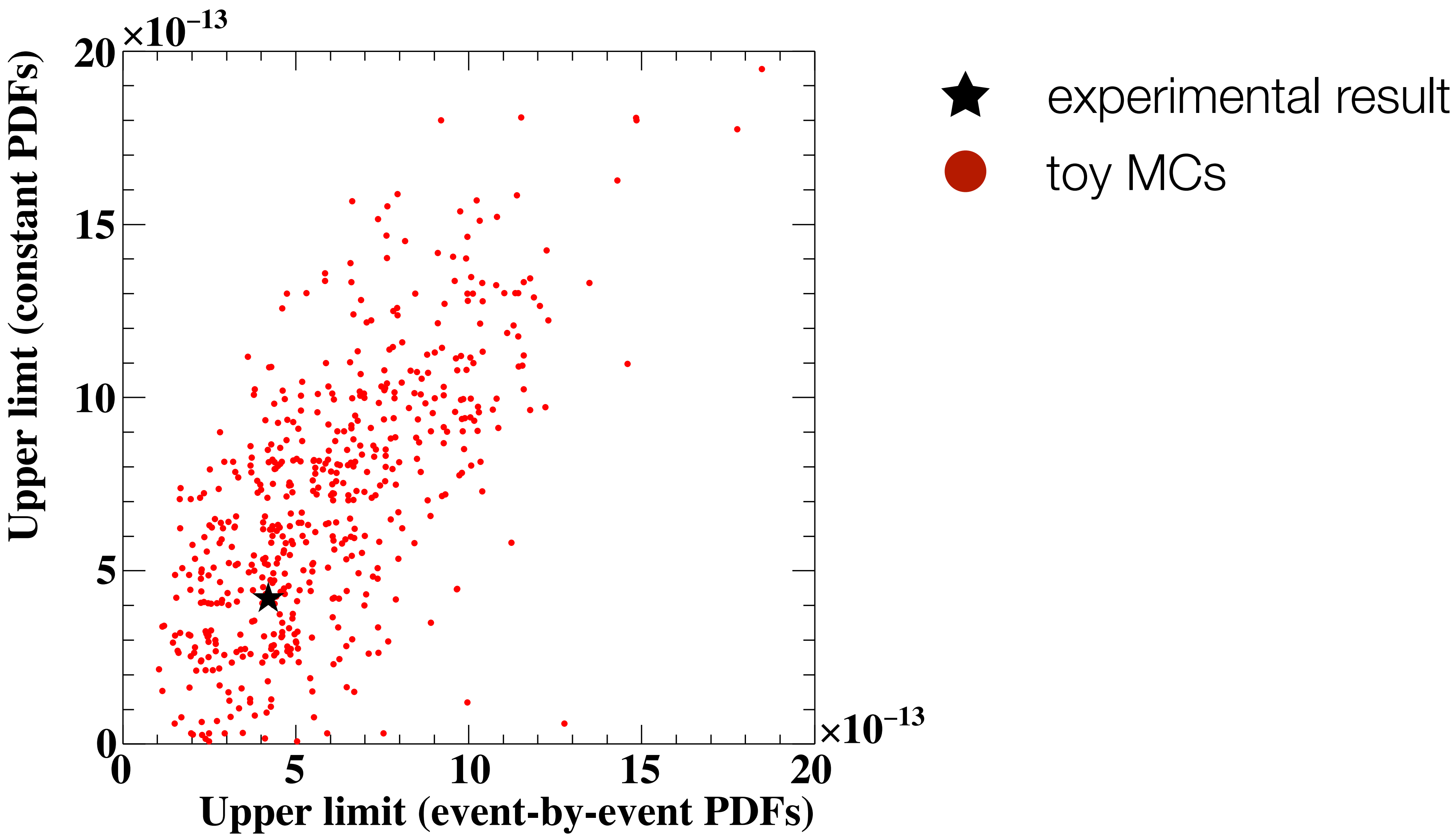
Sanity checks

- e.g. maximum likelihood analysis fit performed also with constant PDFs (default event-by-event PDFs)
- results in close agreement

analysis	event-by-event PDFs	constant PDFs
$\mathcal{B}_{fit} \times 10^{13}$	- 2.3	- 2.5
$\mathcal{B}_{90} \times 10^{13}$	4.2	4.3

Sanity checks

- e.g. maximum likelihood analysis fit performed also with constant PDFs (default event-by-event PDFs)
- consistency also with a set of pseudo-experiments: event-by-event PDFs on average 20% better sensitivity

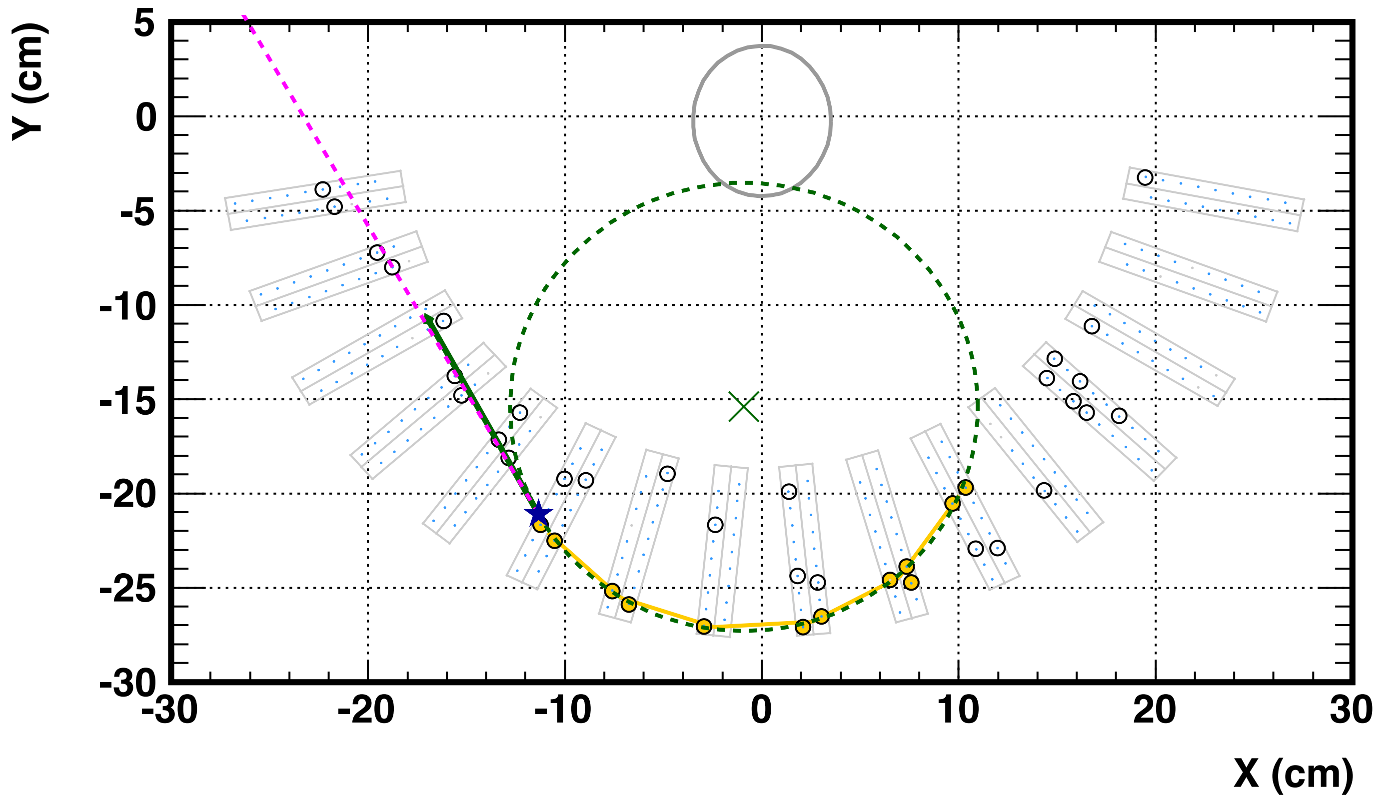


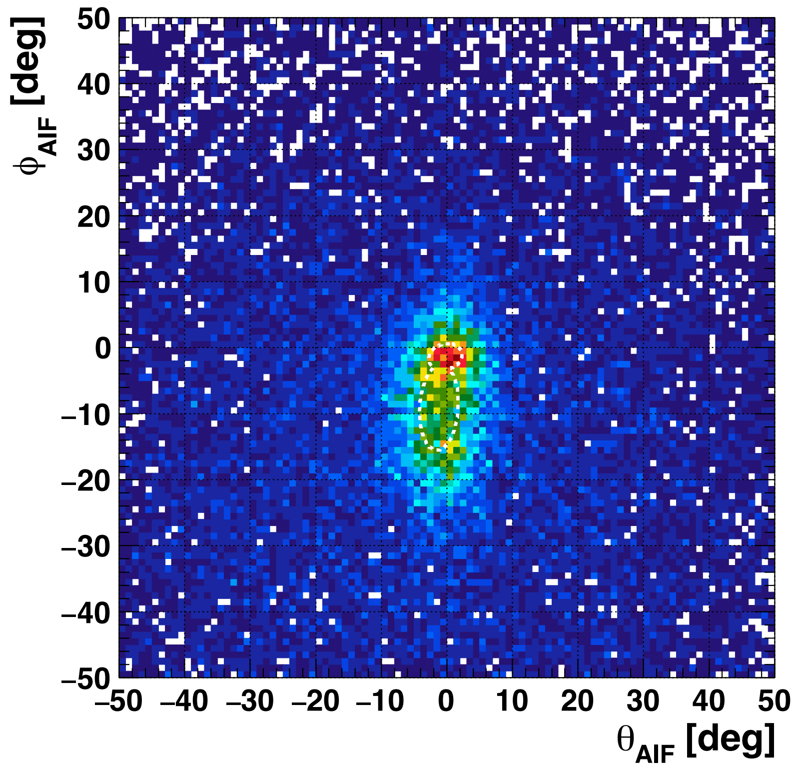
Discussion

- improvements and issues in the $\mu^+ \to e^+ \gamma$ analysis
  - analysis of the annihilation-of-flight (AIF) gamma rays
  - recovery of the missing first turns
  - alignment of the muon stopping target

Annihilation-In-Flight (AIF) rejection

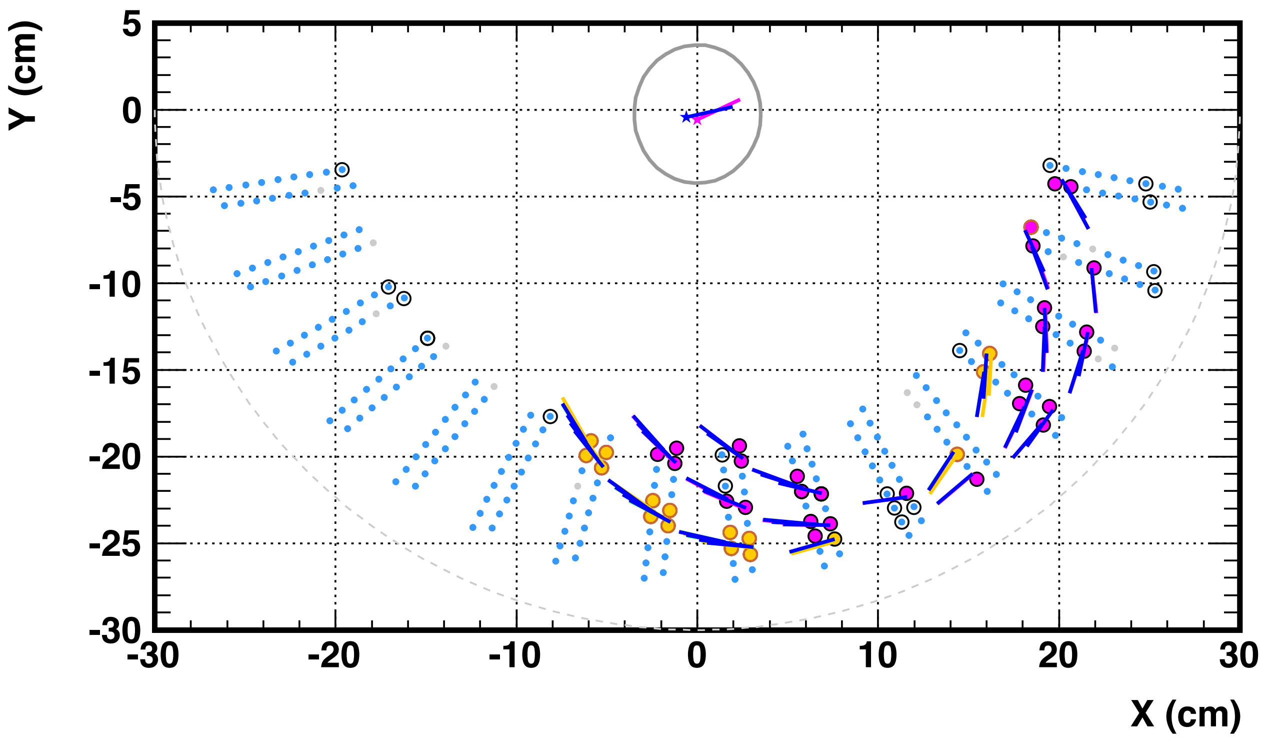
- gamma-rays from positrons annihilation inside DCH identified and rejected
- overall background rejection ~1.9%
    - signal inefficiency ~ 1.1%

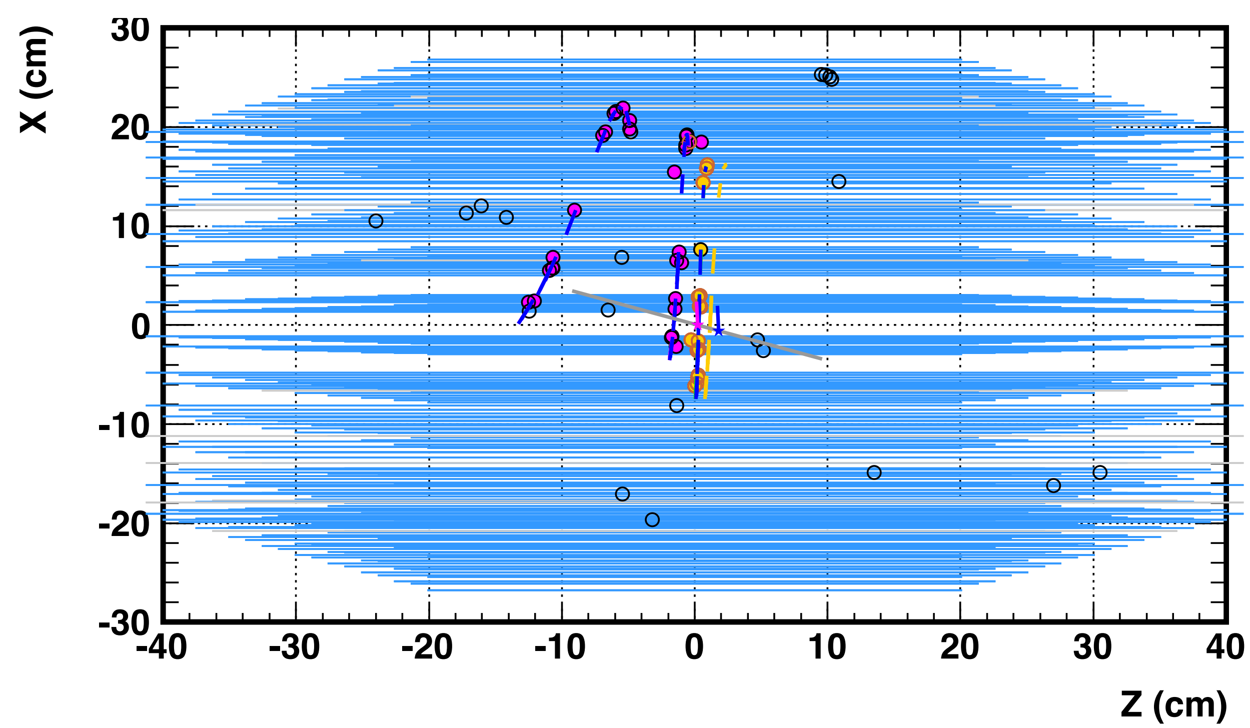




Missing first turn

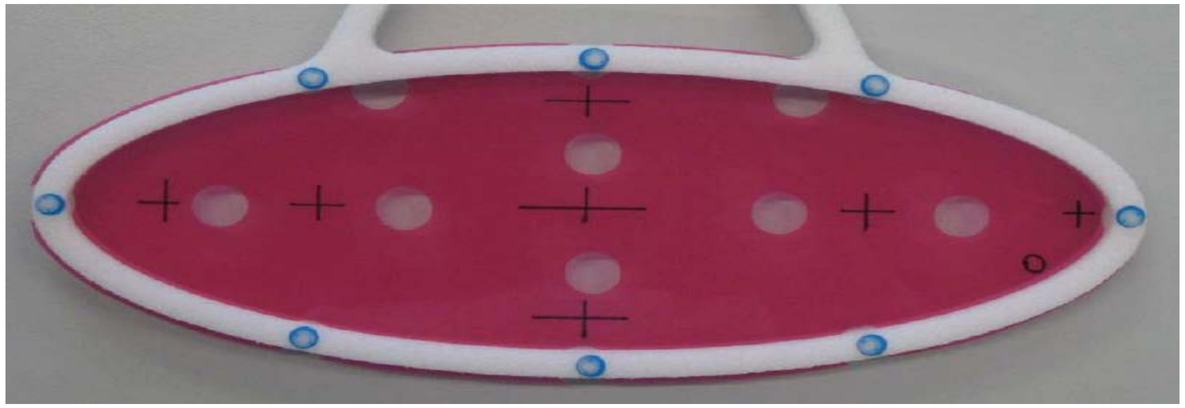
- implies an incorrect assignment of positron angular variables and momentum, as well as inappropriate muon decay point and time
- recovery algorithm implemented
  - **signal efficiency improved by ~ 4%**

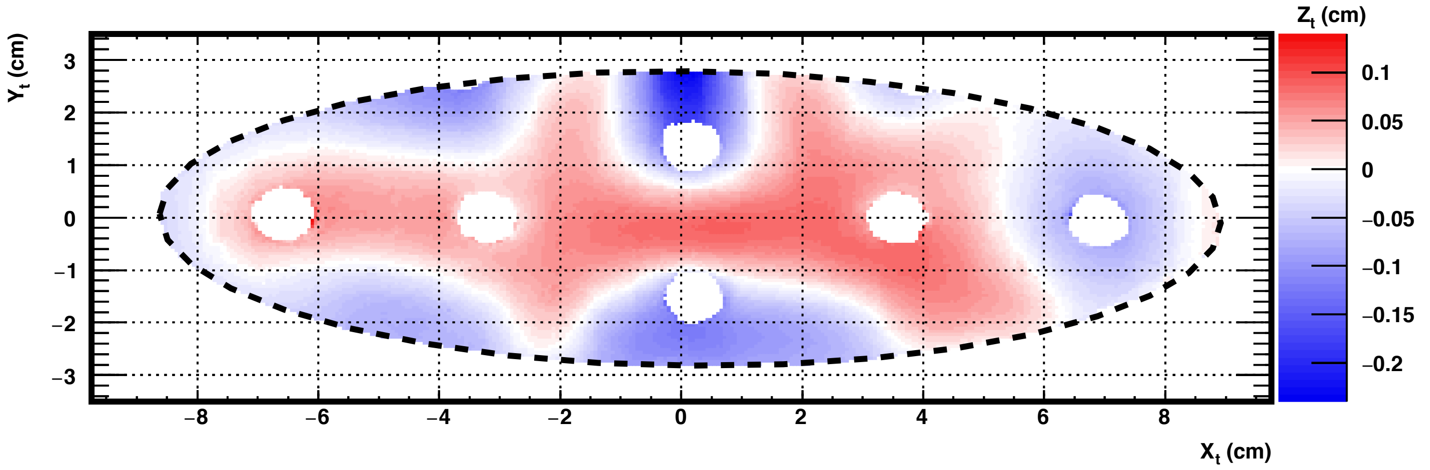


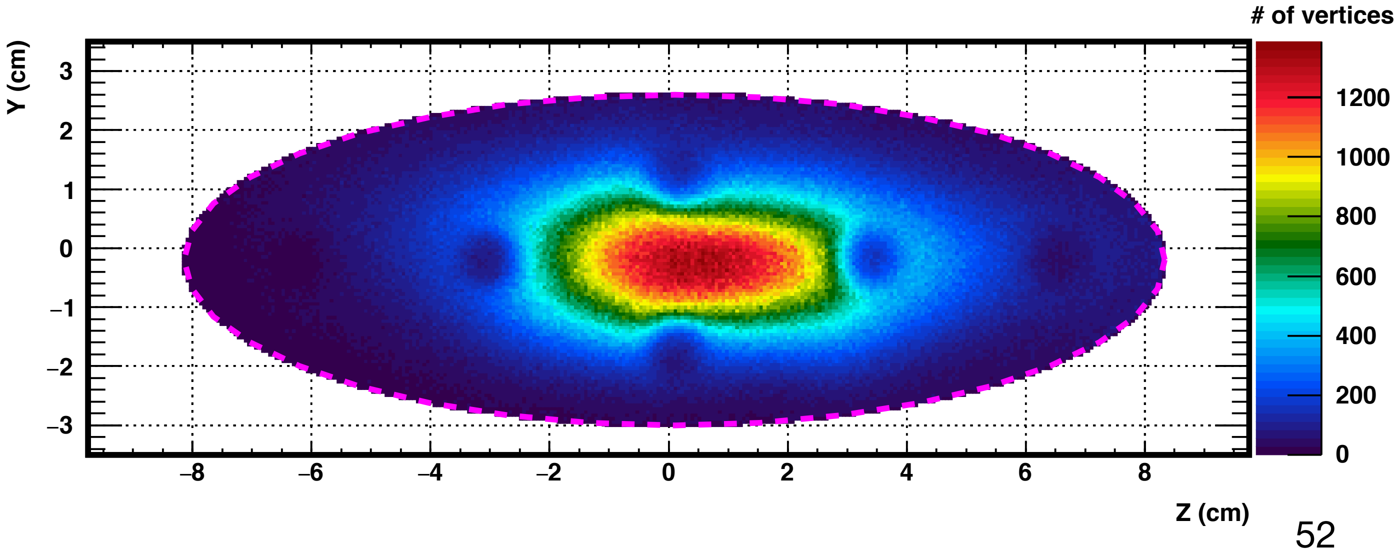


Target alignment

- target position and shape surveyed by
  - optical survey
  - “hole” reconstruction
- non-planar deformation developed during runs
- effects not negligible for the 2012-13 runs
  - 0.3 mm uncertainty along z
  - treated as nuisance parameters in the likelihood analysis
  - **~13% degradation in sensitivity**
- investigations for a “new” target underway for MEGII







Normalization

- the normalization factor N_μ is the number of muon decays effectively measured during the experiment

$$\mathcal{B}(\mu^+ \to e^+\gamma) \equiv \frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma_{total}} = \frac{N_{sig}}{N_\mu}$$

Normalization

- the normalization factor N_μ is the number of muon decays effectively measured during the experiment

$$\mathcal{B}(\mu^+ \to e^+\gamma) \equiv \frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma_{total}} = \frac{N_{sig}}{N_\mu}$$

Normalization

- the normalization factor N_μ is the number of muon decays effectively measured during the experiment

$$\mathcal{B}(\mu^+ \to e^+\gamma) \equiv \frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma_{total}} = \frac{N_{sig}}{N_\mu}$$

- two ways: **Michel** and RMD counting

$$N_\mu = \frac{N^{e\nu\overline{\nu}}}{f_E^{e\nu\overline{\nu}}} \times \frac{p^{e\nu\overline{\nu}}}{\epsilon_{trg}^{e\nu\overline{\nu}}} \times \frac{\epsilon_e^{e\gamma}}{\epsilon_e^{e\nu\overline{\nu}}} \times A_\gamma^{e\gamma} \times \epsilon_\gamma^{e\gamma} \times \epsilon_{trg}^{e\gamma} \times \epsilon_{sel}^{e\gamma}$$

N_μ with a 4.5% uncertainty on the full dataset

Normalization

- the normalization factor N_μ is the number of muon decays effectively measured during the experiment

$$\mathcal{B}(\mu^+ \to e^+\gamma) \equiv \frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma_{total}} = \frac{N_{sig}}{N_\mu}$$

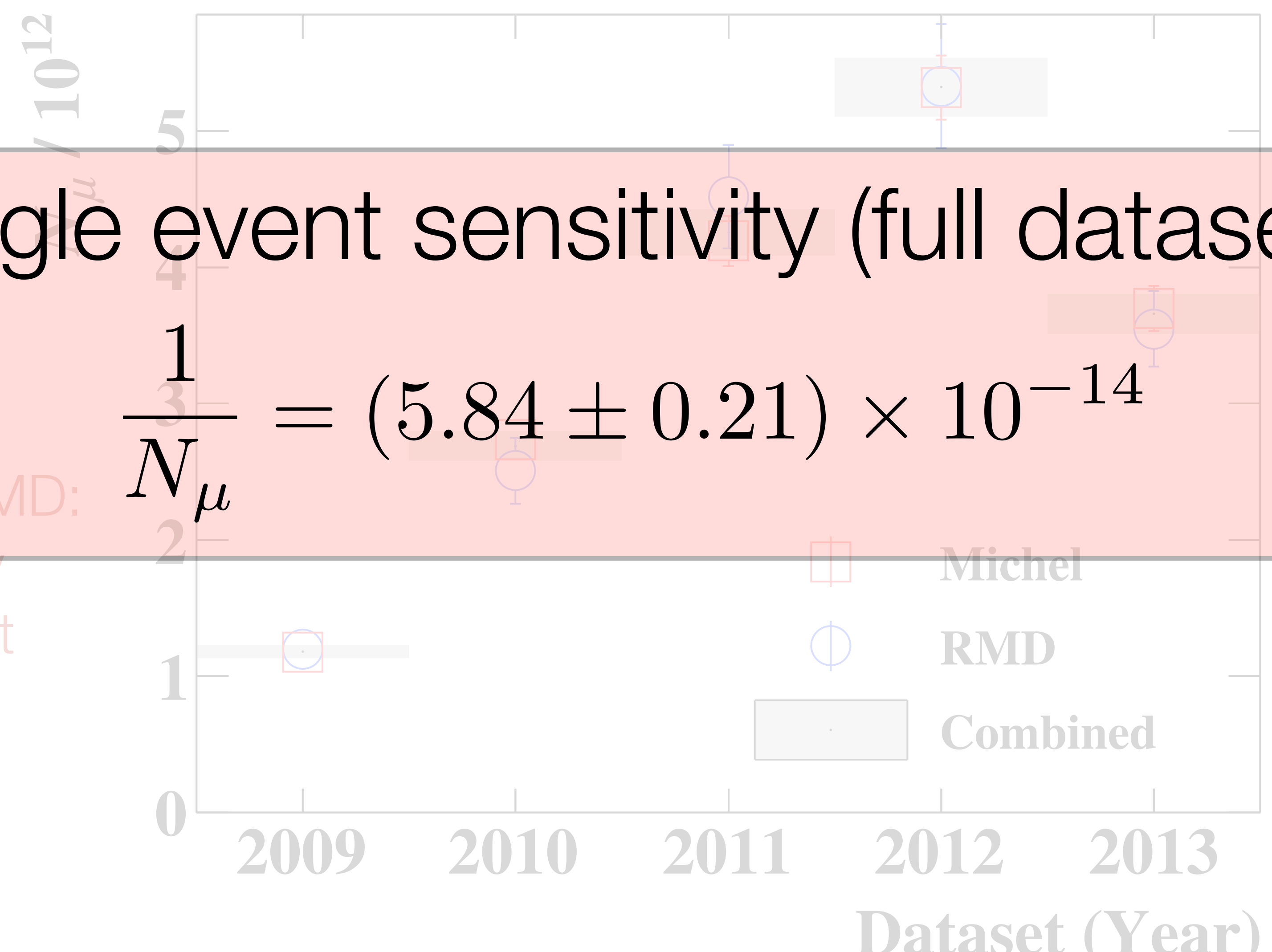
- two ways: Michel and **RMD** counting

$$N_\mu = \frac{N^{e\nu\overline{\nu}\gamma}}{\mathcal{B}^{e\nu\overline{\nu}\gamma}} \times \frac{\epsilon_e^{e\gamma}}{\epsilon_e^{e\nu\overline{\nu}\gamma}} \times \frac{\epsilon_\gamma^{e\gamma}}{\epsilon_\gamma^{e\nu\overline{\nu}\gamma}} \times \frac{\epsilon_{trg}^{e\gamma}}{\epsilon_{trg}^{e\nu\overline{\nu}\gamma}} \times \frac{\epsilon_{sel}^{e\gamma}}{\epsilon_{sel}^{e\nu\overline{\nu}\gamma}}$$

N_μ with a 5.5% uncertainty
on the full dataset

Normalization

- the normalization factor N_μ is the number of muon decays effectively measured during the experiment
- two ways: Michel and RMD counting



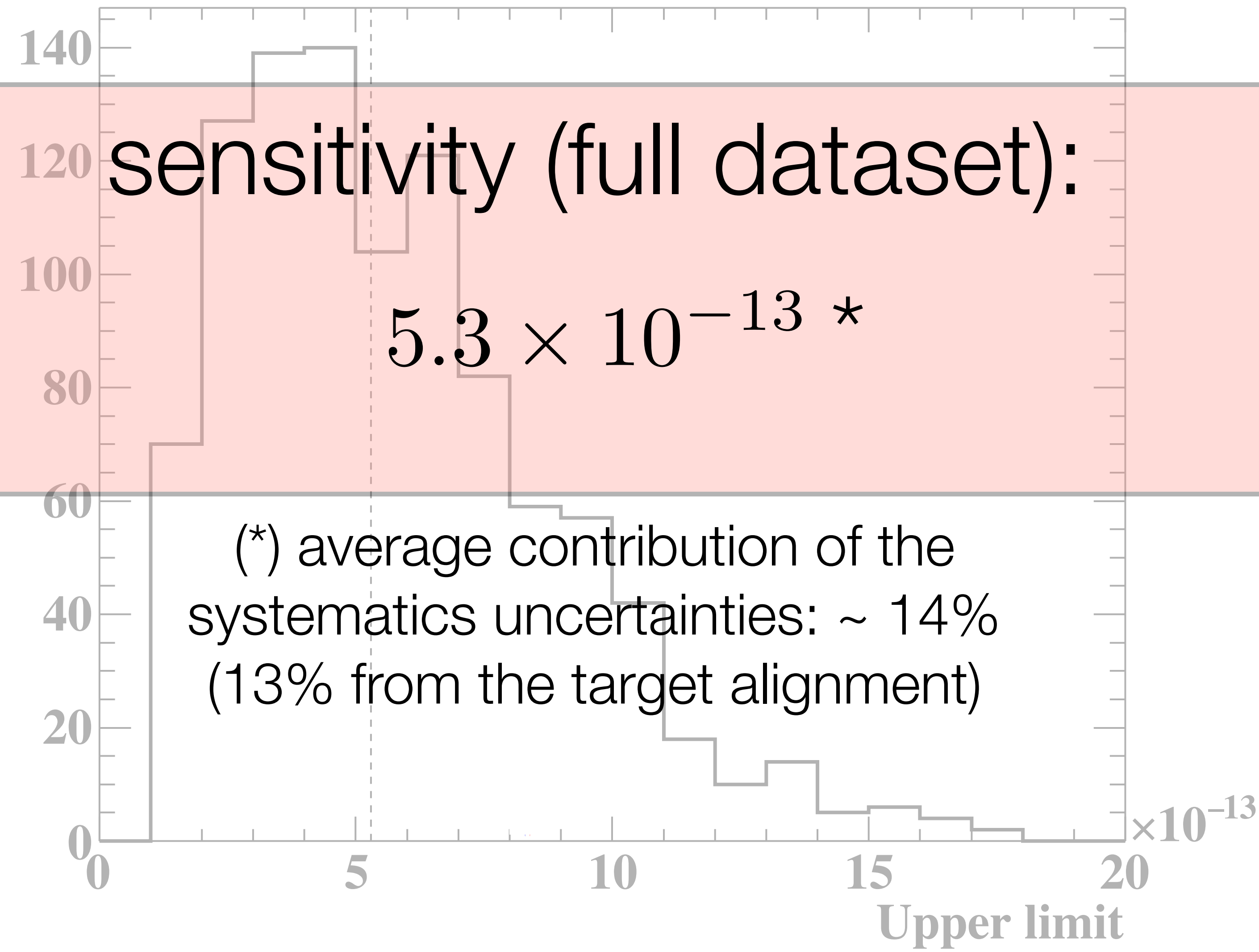
N_μ from Michel + RMD:
3.5% uncertainty
on the full dataset

single event sensitivity (full dataset):

$$\frac{1}{N_\mu} = (5.84 \pm 0.21) \times 10^{-14}$$

Sensitivity

- is evaluated by taking the median average of the distribution of the branching ratio upper limit at 90% C.L. for pseudo experiments with null signal hypothesis
  - RMD and accidental bkg included as estimated from side-bands
  - systematics uncertanties taken into account



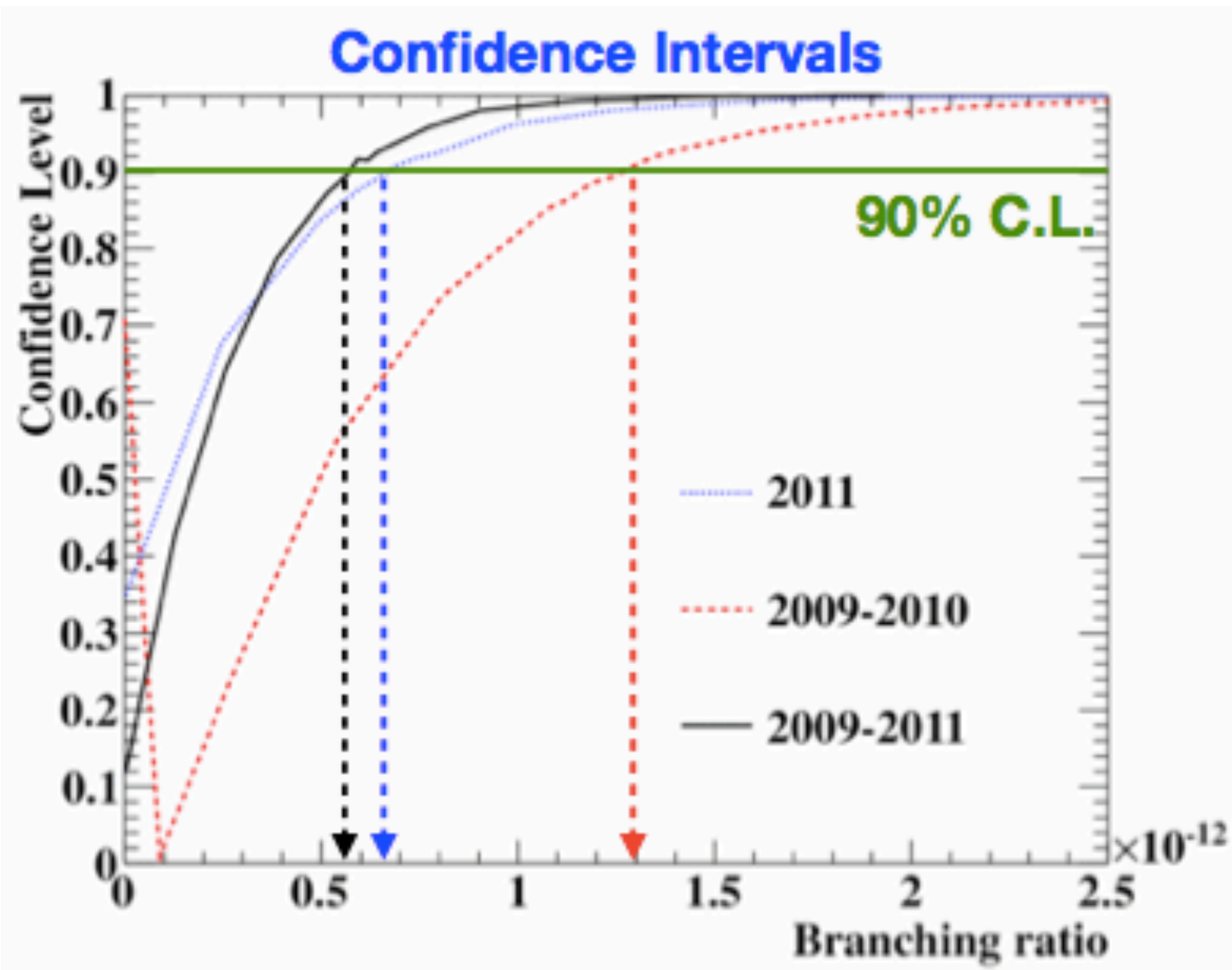
sensitivity (full dataset):

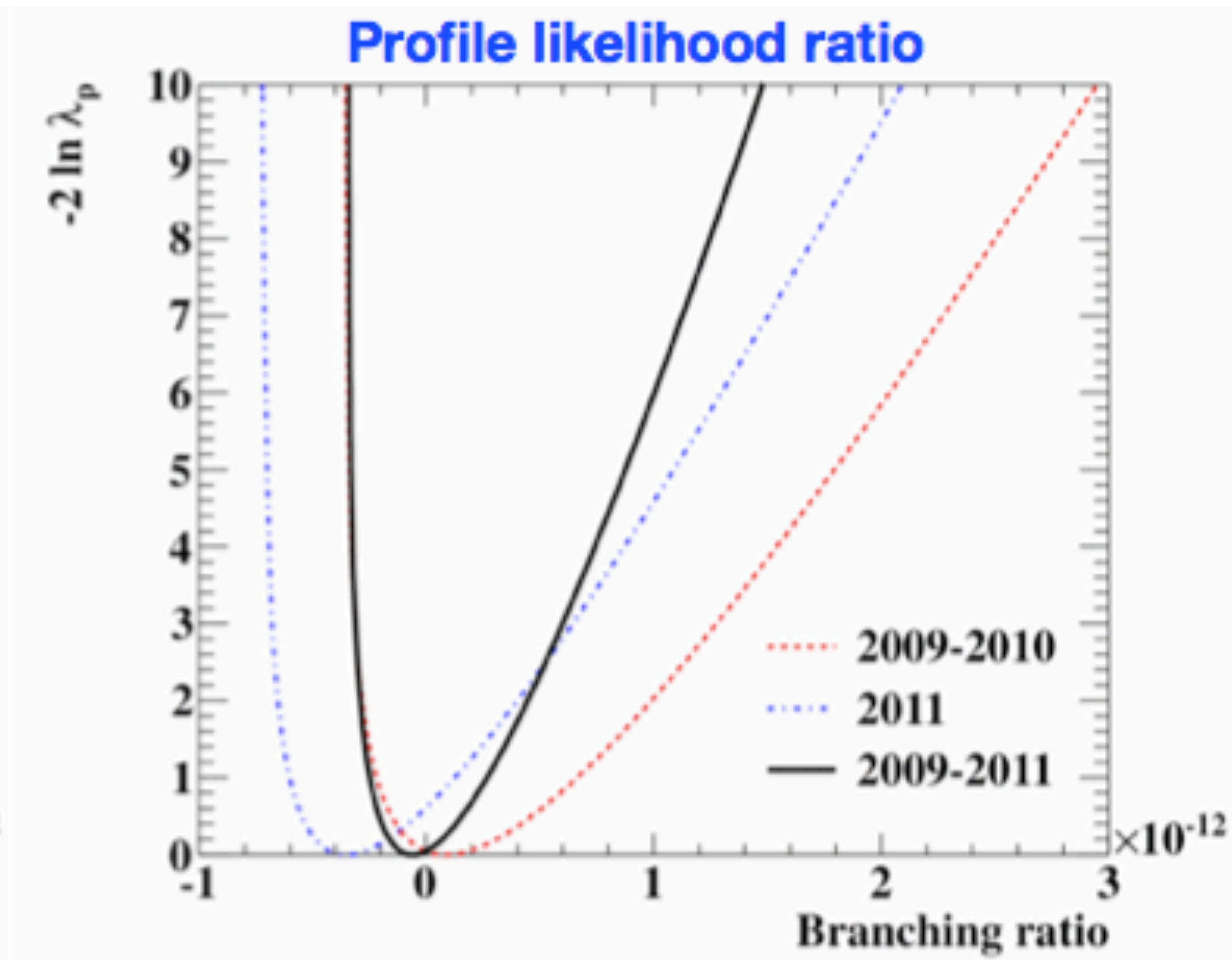
$$5.3 \times 10^{-13} \; *$$

(*) average contribution of the systematics uncertainties: ~ 14%
(13% from the target alignment)

Confidence Interval

- Confidence interval calculated with Feldman-Cousins method + profile likelihood ratio ordering





Consistent with null-signal hypotesis

Definition of the test statistics

maximise the likelihood for the spesific N_{sig}

$$\lambda_p(N_{\text{sig}}) = \begin{cases} \dfrac{\mathcal{L}(N_{\text{sig}},\hat{\hat{\boldsymbol{\theta}}}(N_{\text{sig}}))}{\mathcal{L}(0,\hat{\hat{\boldsymbol{\theta}}}(0))} & \text{if } \hat{N}_{\text{sig}} < 0 \\ \dfrac{\mathcal{L}(N_{\text{sig}},\hat{\hat{\boldsymbol{\theta}}}(N_{\text{sig}}))}{\mathcal{L}(\hat{N}_{\text{sig}},\hat{\boldsymbol{\theta}})} & \text{if } \hat{N}_{\text{sig}} \geq 0, \end{cases}$$

maximise the likelihood