Muon cLFV search in Europe: the $\mu^+ \to e^+ \gamma$ and the $\mu^+ \to e^+ e^+ e^-$ decays

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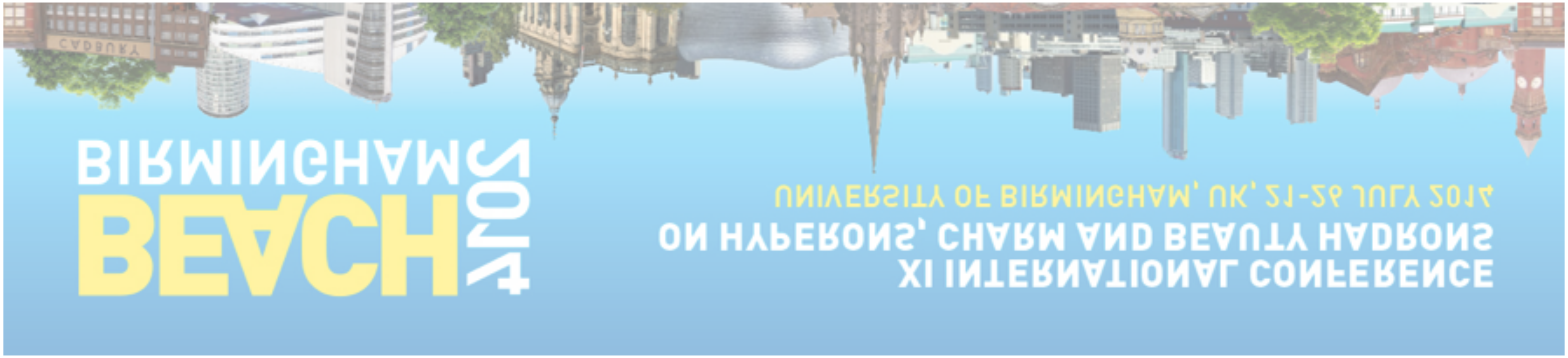
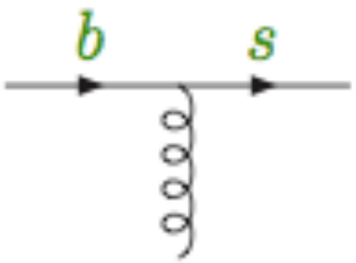
Angela Papa
Paul Scherrer Institute
on behalf of the MEG and the Mu3e collaboration



Flavour Changing Neutral Currents (FCNC)

- At the tree level
  - flavour is violated in Charged Current interactions (mediated by $W^{\pm}$)
  - flavour is conserved in all Neutral Current interactions (mediated by g, Z^0 and γ)

  the are no vertices of the type i.e.:



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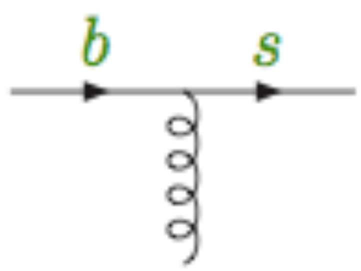

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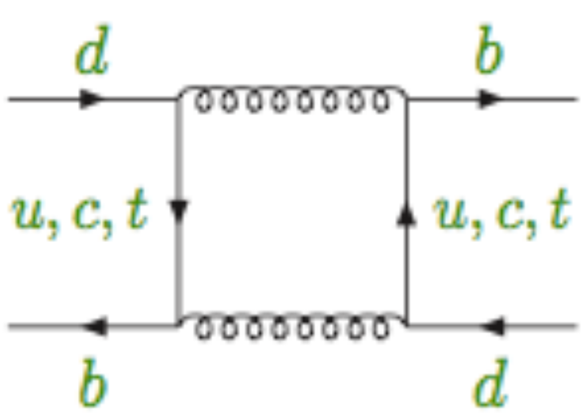
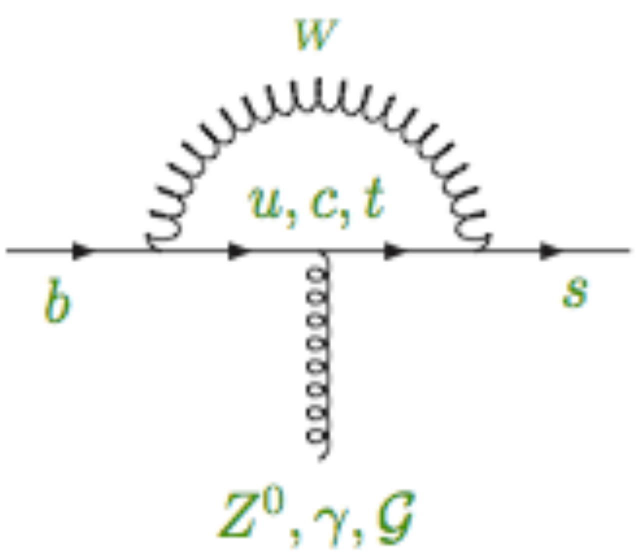
  - FCNC are induced by charged current loop effects, due to mixing among fermion generations
    - e.g. $K_L^0 \rightarrow \mu\mu$ in the quark section





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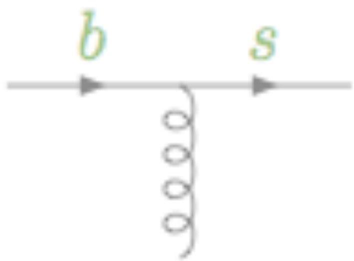

- At the quantum level (quantum loops)
  - FCNC are induced by charged current loop effects, due to mixing among fermion generations
    - e.g. $K_L^0 \rightarrow \mu\mu$ in the quark section
    - what about lepton section ?

Lepton Flavour Violation of Charged Leptons (cLFV)

- Lepton flavour is preserved into the SM (“accidental” symmetry)
  - not related to the theory gauge
  - naturally violated in SM extentions

LFV of neutral leptons confirmed
-neutrino oscillations-

LFV of charged leptons not yet observed

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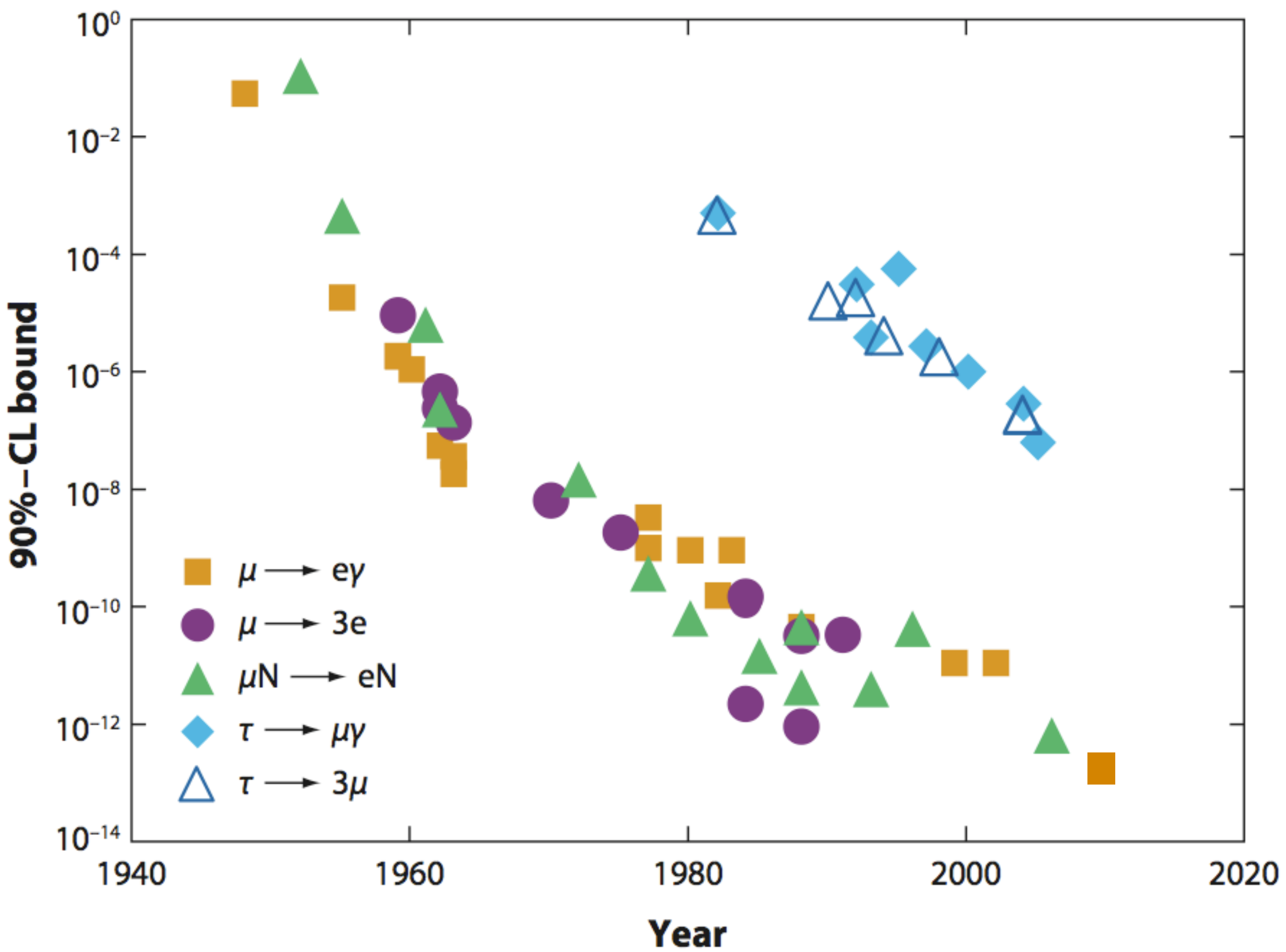

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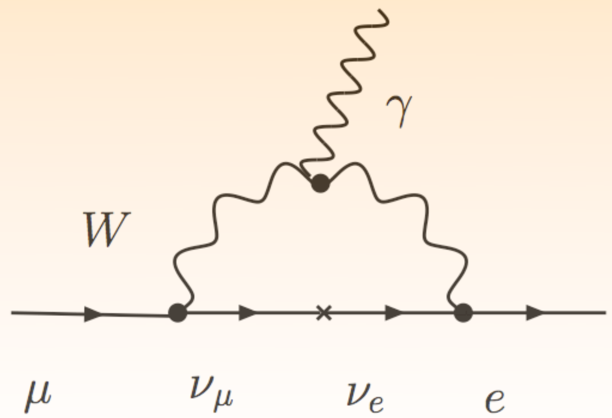
The $\mu^+ \to e^+ \gamma$ decay as an example

- Taking into account of neutrino oscillations



SM with massive neutrinos (Dirac)

$$\Gamma(\mu \to e\gamma) = \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{\alpha}{2\pi} \sin^2 2\theta \, sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

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

too small to access experimentally

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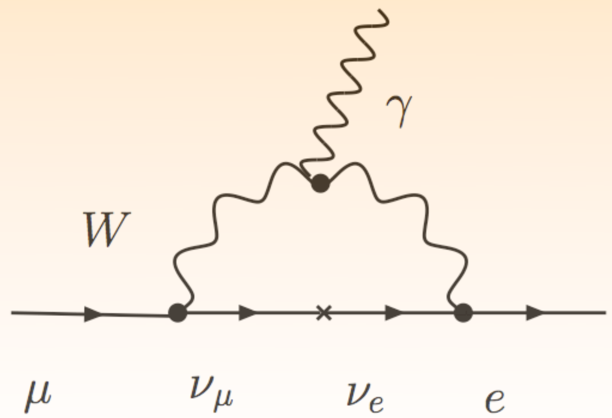

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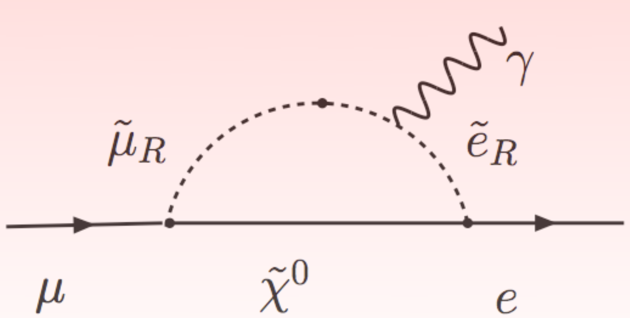
- BSM theories such as SU(5) SUSY-GUT and SO(10) SUSY-GUT models predict measureble LFV decay BR



SU(5) SUSY-GUT or SO(10) SUSY-GUT

$$\Gamma(l_1 \rightarrow l_2\gamma) = \frac{\alpha G_F^2 m_{l_1}^5}{2048\pi^4}(|D_R|^2 + |D_L|^2)$$

$$D_R = D_L \approx \frac{1}{G_F \Lambda^2}$$

$$10^{-14} < B(\mu^+ \rightarrow e^+\gamma) < 10^{-11}$$

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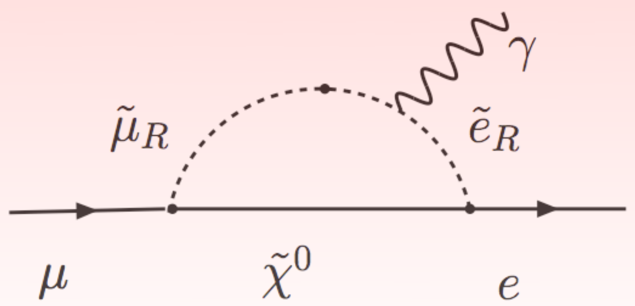

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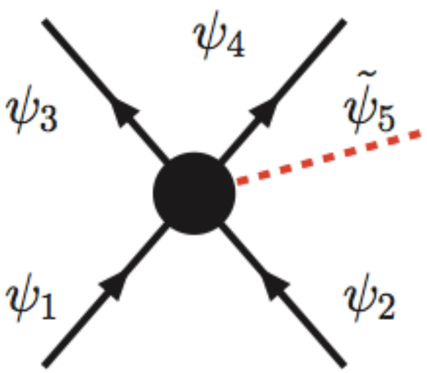
Null result will turn out in a precise test of established model and will ruled out speculative ones

cLFV signature will be a clear evidence of New Physics

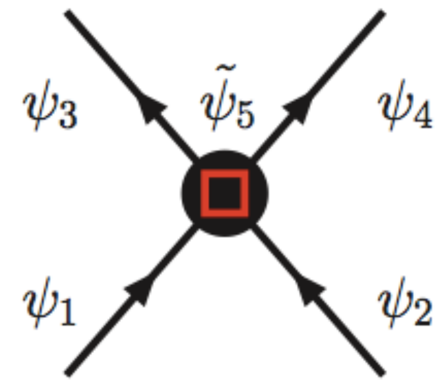
The role of low energy physics in the LHC era

Rare decay searches as a complementary way to unveil BSM physics and explore much higher energy scale w.r.t. what can be done at the high-energy frontiers

- Direct/indirect production of BSM particles



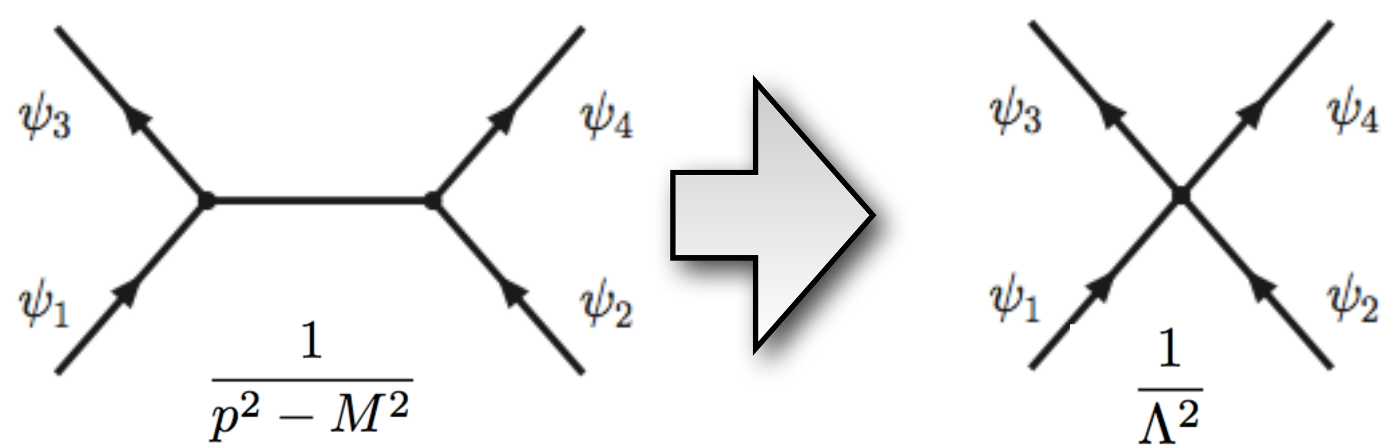
- Real BSM particles produced in the final state
- Energy frontier (LHC)



- Virtual BSM particles produced in loops
- Precision and intensity frontier

- Effective field theory approach

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



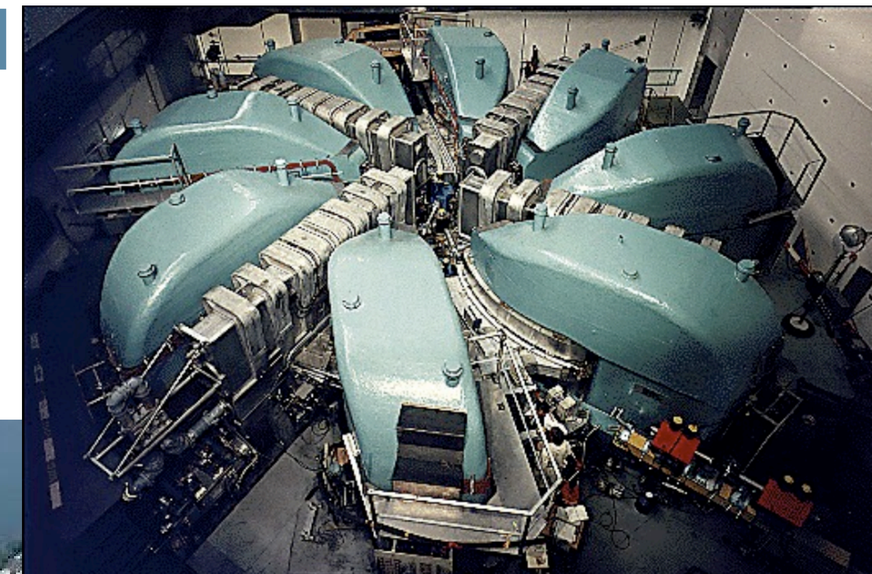
- L_{eff} is in terms of inverse powers of heavy scale

$$\mu^+ \rightarrow e^+ \gamma$$

$$\mu^+ \rightarrow e^+ e^+ e^-$$

Favorite place: the Paul Scherrer Institute

1.2 MW PROTON CYCLOTRON



- The most intense continuous positive (surface)muon beam at low momentum (28 MeV/c)
  - **up to few x 10^8 muon/s**

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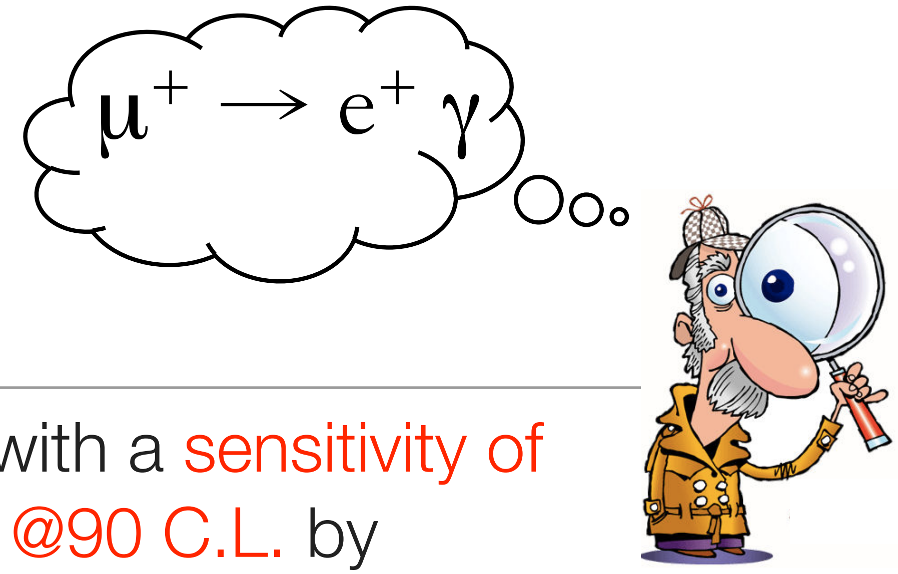
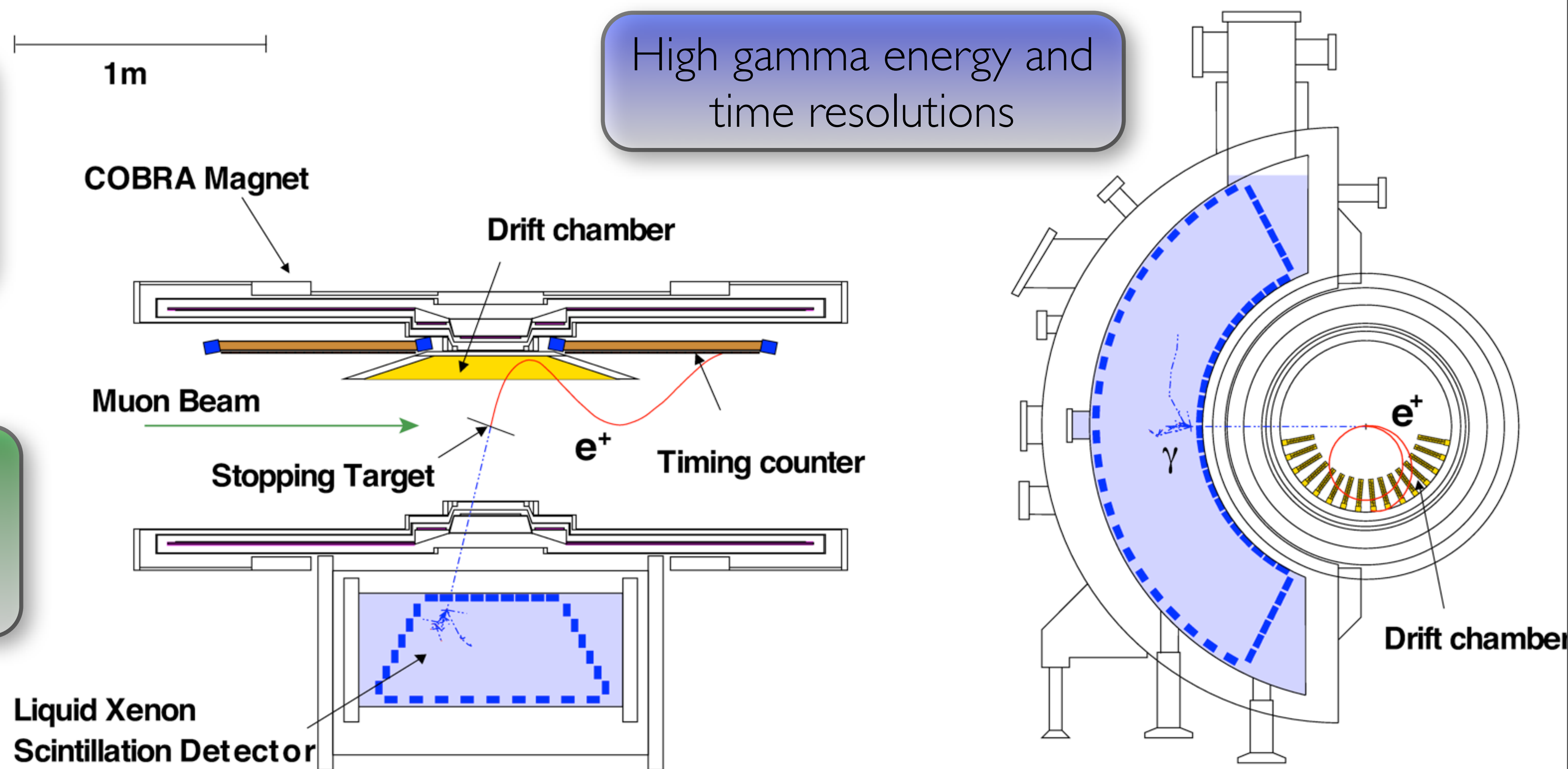


The MEG experimental set-up

- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 10^{-13}$ (best upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)

The world most intense dc muon beam at PSI

I = 3x 10^7 muon/s



High gamma energy and time resolutions

Very precise positron momentum and time resolutions

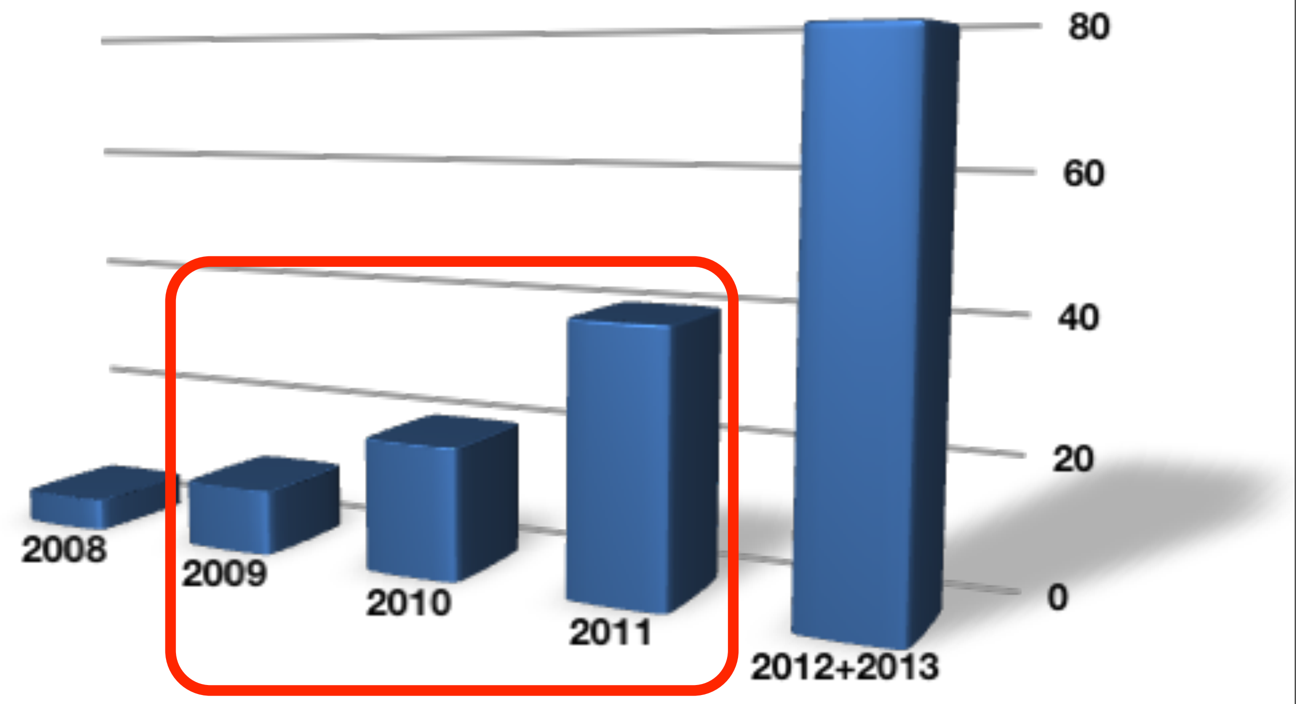
High efficiency event selection and frequency signal digitization

Complementary calibration and monitoring methods

Detector performance and Data sample

Analyzed/ published

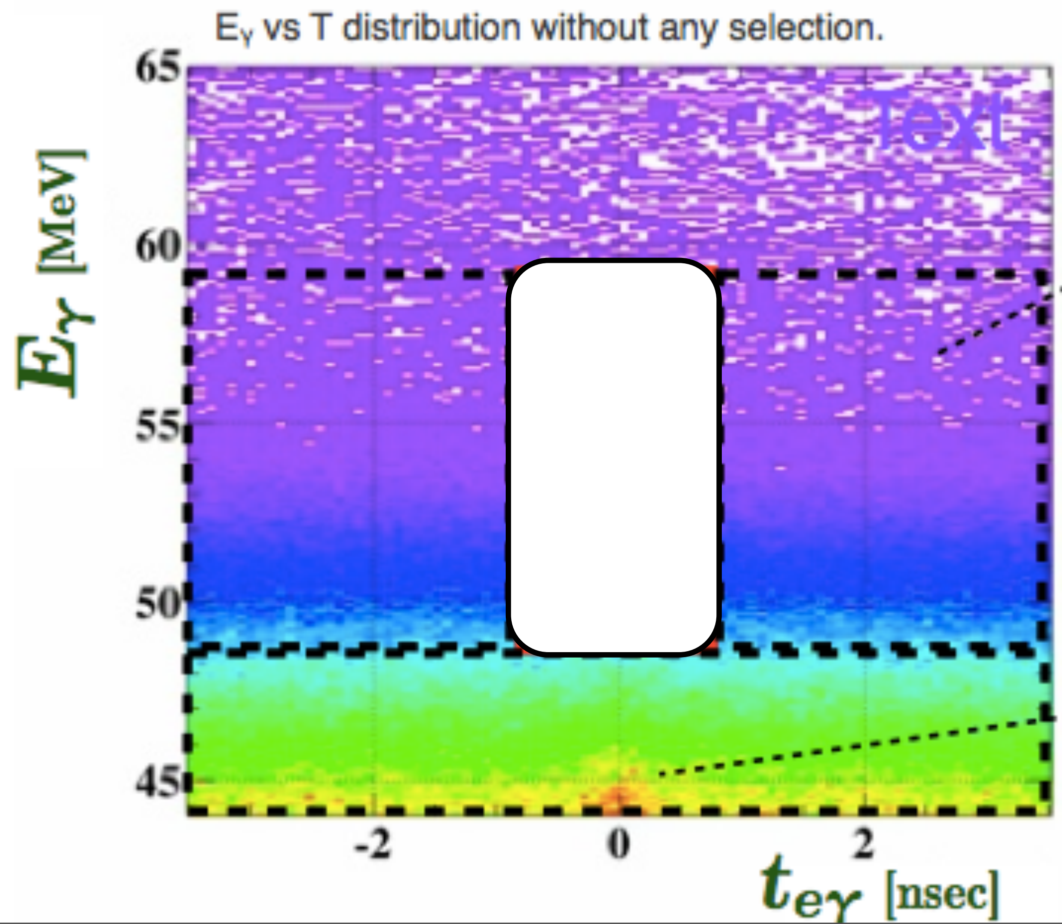
	Resolutions (σ)
Gamma Energy (%)	1.7(depth>2cm), 2.4
Gamma Timing (psec)	67
Gamma Position (mm)	5(u,v), 6(w)
Gamma Efficiency (%)	63
Positron Momentum (KeV)	305 (core = 85%)
Positron Timing (psec)	108
Positron Angles (mrad)	7.5 (Φ), 10.6 (θ)
Positron Efficiency (%)	40
Gamma-Positron Timing (psec)	127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

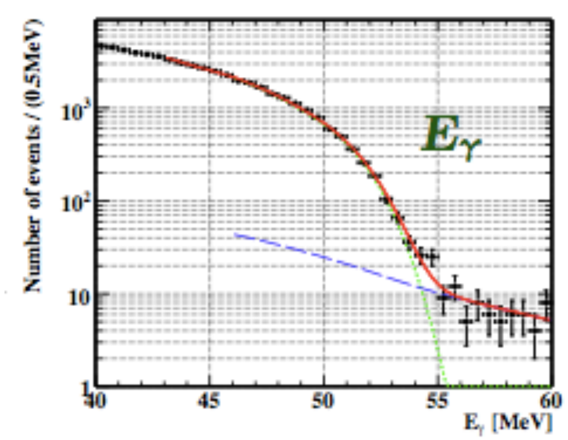


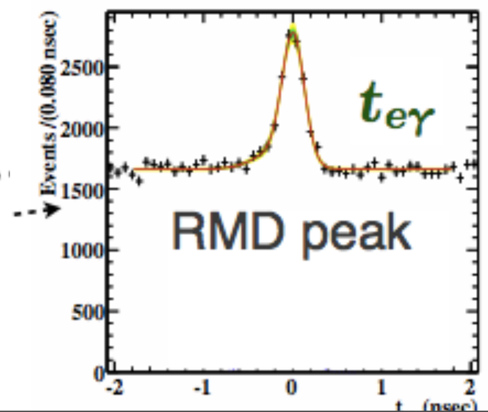
	μ stopped	sensitivity
2009+10	1.75×10^{14}	1.3×10^{-12}
2011	1.85×10^{14}	1.1×10^{-12}
2009+10+11	3.60×10^{14}	7.7×10^{-13}

Physics Analysis Overview and Event Selection

- Five observables **(E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg})** to characterize $\mu \rightarrow e\gamma$ events
- Event selection: Trigger selection (E_g > 45 MeV , $|\Delta t_{eg}|$< 10 ns, $|\Delta\phi|$ < 7.5^0) + at least 1 reconstructed track
- Blind Analysis (Sideband, Blind box)
- Maximum likelihood to extract N_{sig}
- CL frequentistic approch







Phy. Rev. Lett. 110, 201801 (2013)

Summary of Results

(**) 90% C.L. upper limit averaged over pseudo-experiments based on null-signal hypothesis with expected rates of RMD and BG

	Best fit	**Upper Limit (90% C.L.)**	**Sensitivity ****
2009+10	0.09×10^{-12}	1.3×10^{-12}	1.3×10^{-12}
2011	-0.35×10^{-12}	6.7×10^{-13}	1.1×10^{-12}
2009+10+11	-0.06×10^{-12}	5.7×10^{-13}	7.7×10^{-13}

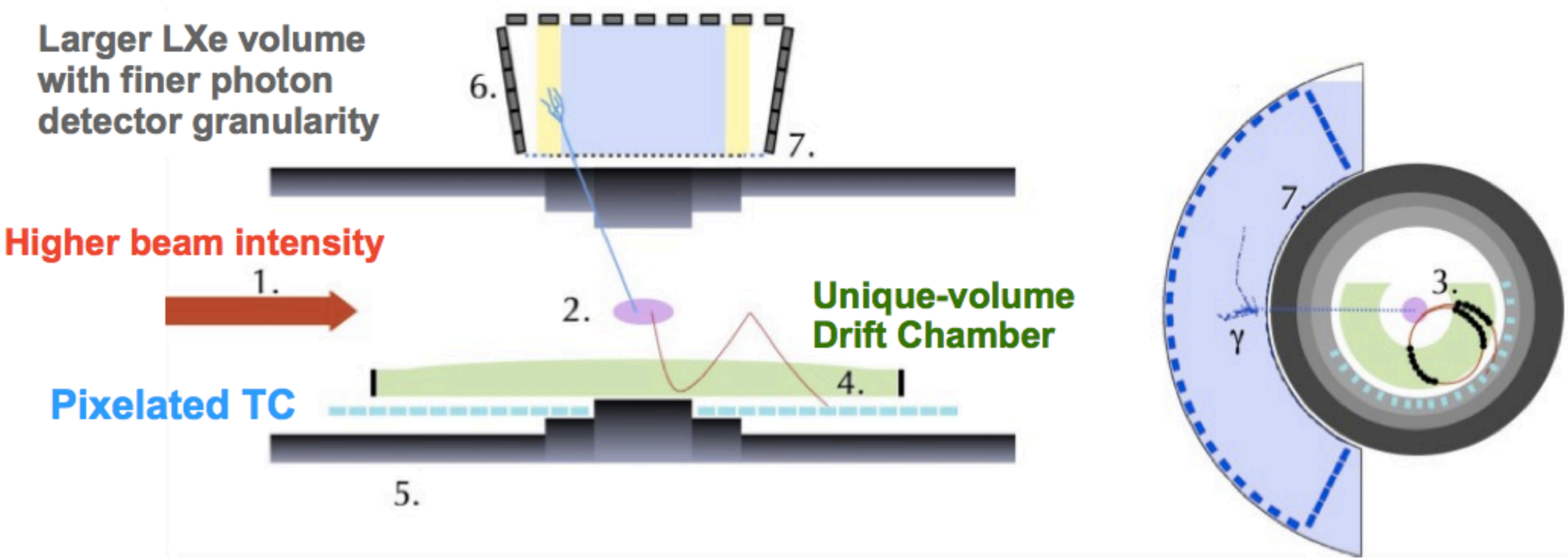
$B(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13}$ (all combined data) *

x4 more stringent than the previous upper limit
($B(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12}$ -MEG 2009-10)

x20 more stringent than the MEGA experiment result
($B(\mu^+ \rightarrow e^+ \gamma) < 1.2 \times 10^{-11}$ -MEGA 2001)

Future Prospects: MEGII

- An upgrade of MEG, aiming at a sensitivity improvement of one order of magnitude (**down to 5 x 10^{-14}**) approved by PSI and funding agencies is ongoing



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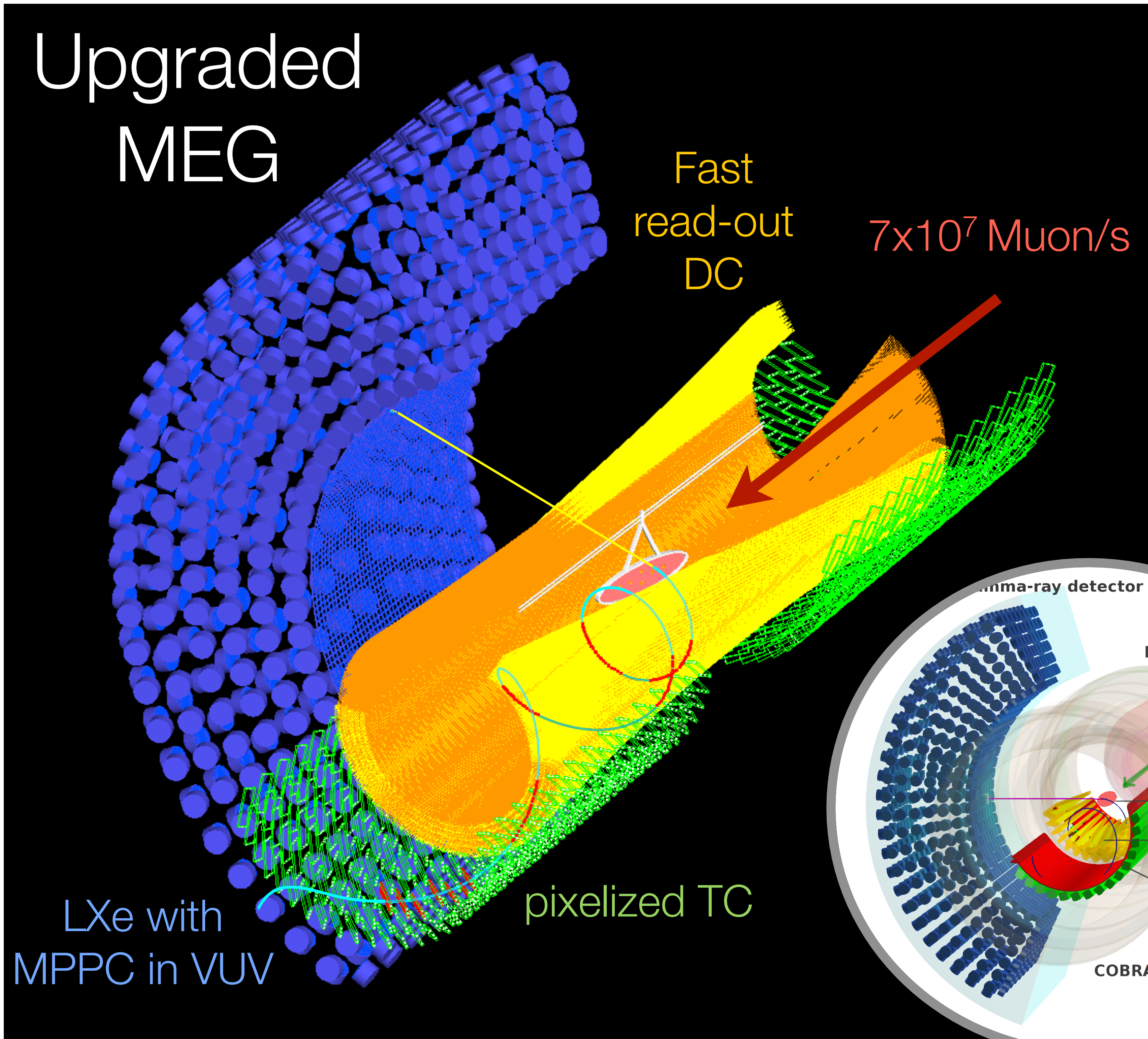


Kept the key elements of MEG

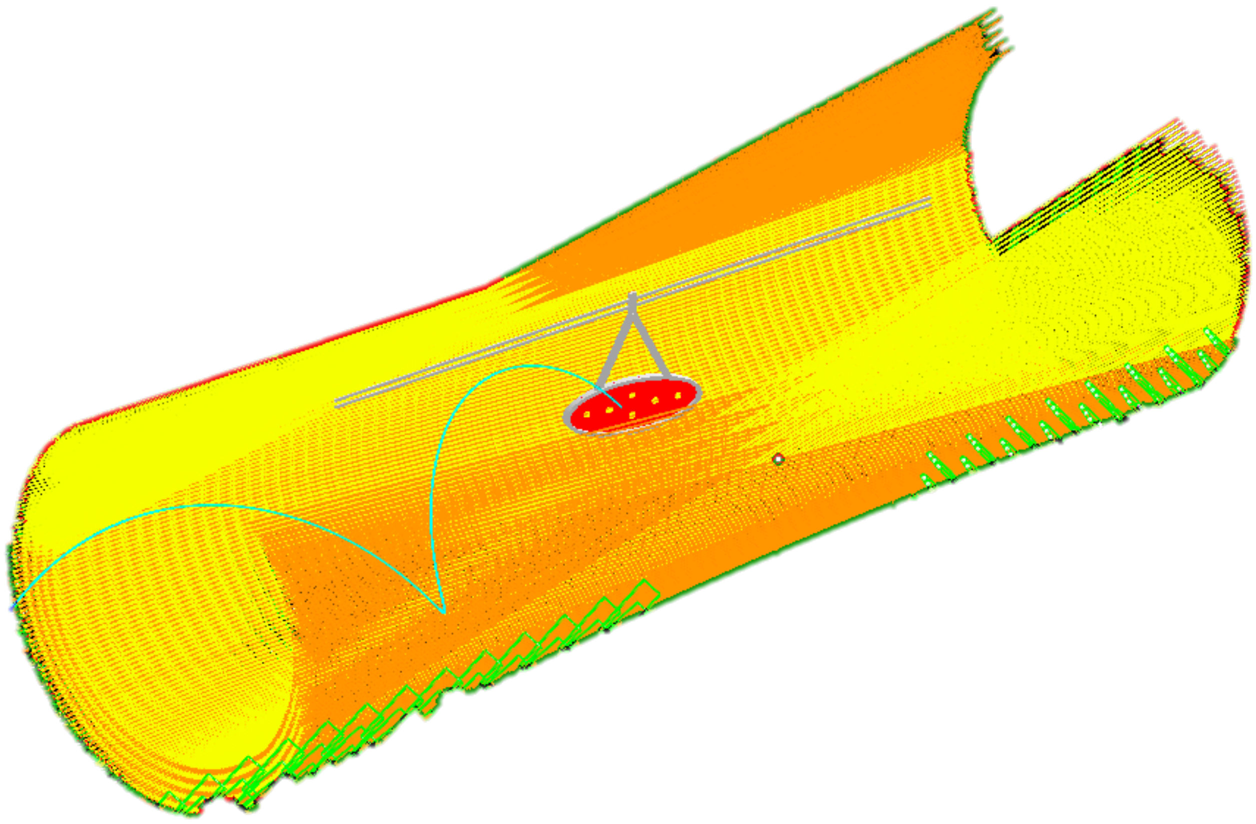
1. World's most intense DC muon beam @ PSI
2. Innovative LXe γ-ray detector
3. Gradient B-field e^+-spectrometer
4. Thousends virtual oscilloscopes (DAQ)
5. Sophisticated calibration methods

MEG Now

MEGII: just few numbers

High granularity
Less material
High Trasparency DC
towards the TC counter

$\sigma(E_e)$ [keV] ~ 150 (325);
$\sigma(\theta_e,\Phi_e)$ [mrad] ~ 5 (7-11);
ε(det) [%] ~ 80 (40);



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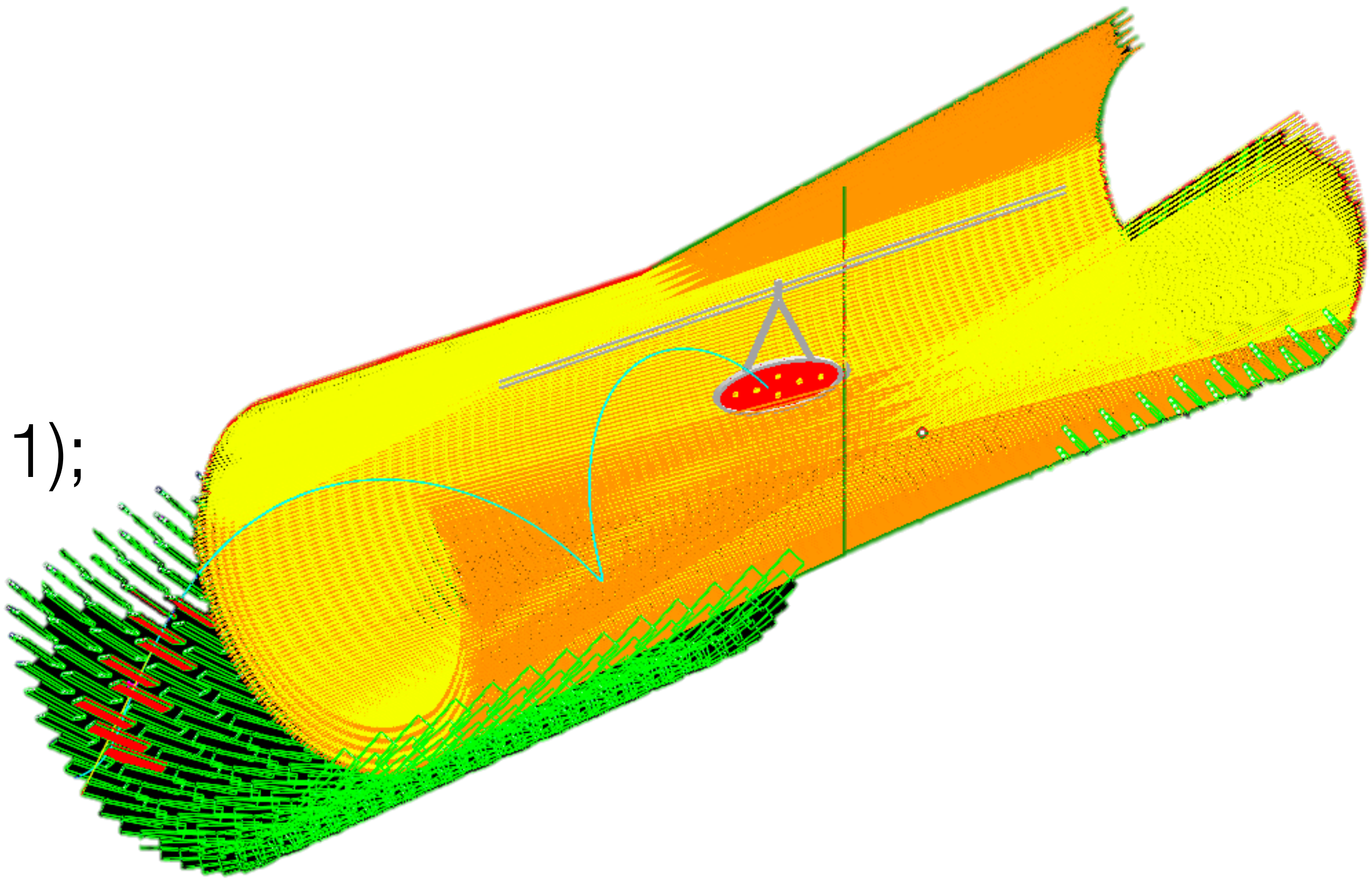

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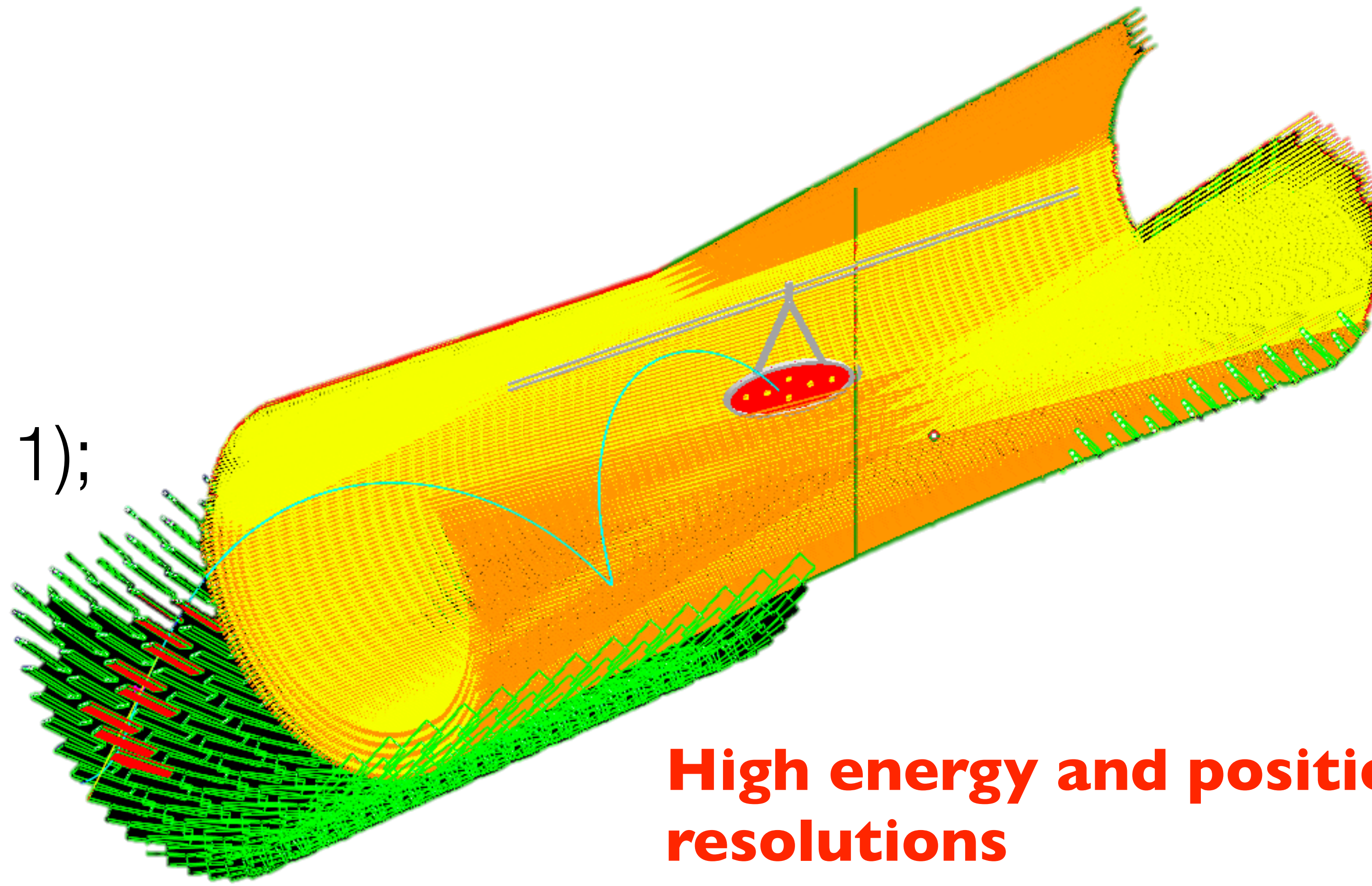
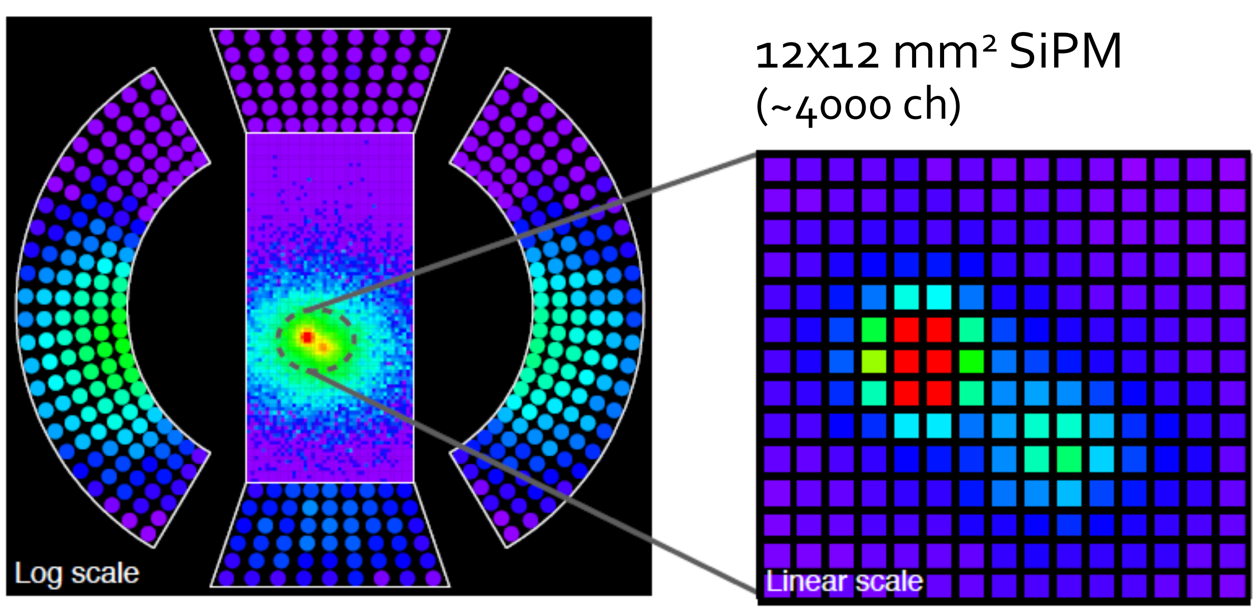


High energy and position resolutions
High pile-up rejction capability
High acceptance and detection efficiency



$\sigma(E_\gamma)/E_\gamma$ [%] ~ 1.3 (w<2cm) (2.6); ~ 1.0 (w>2cm) (1.7)
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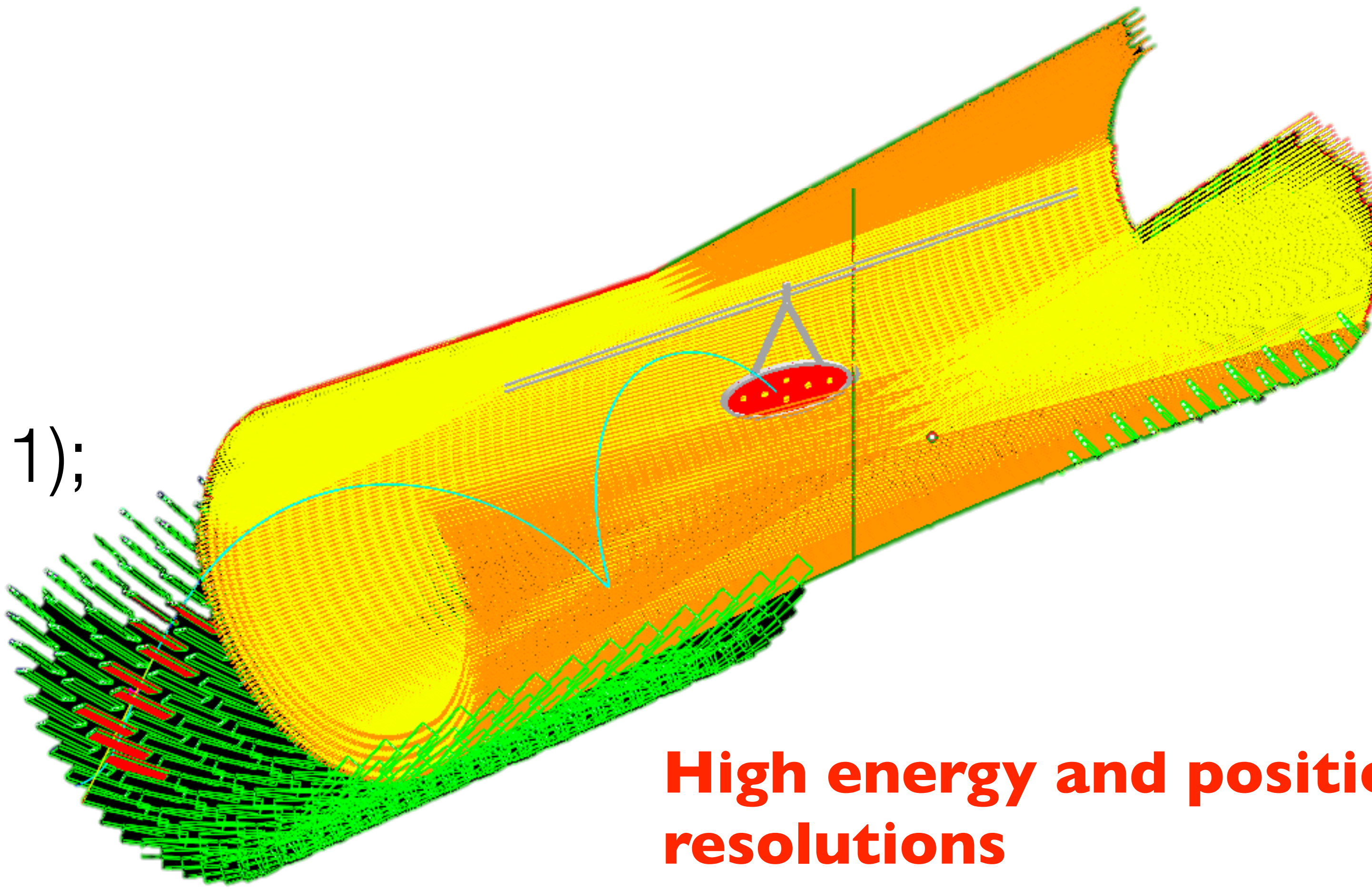

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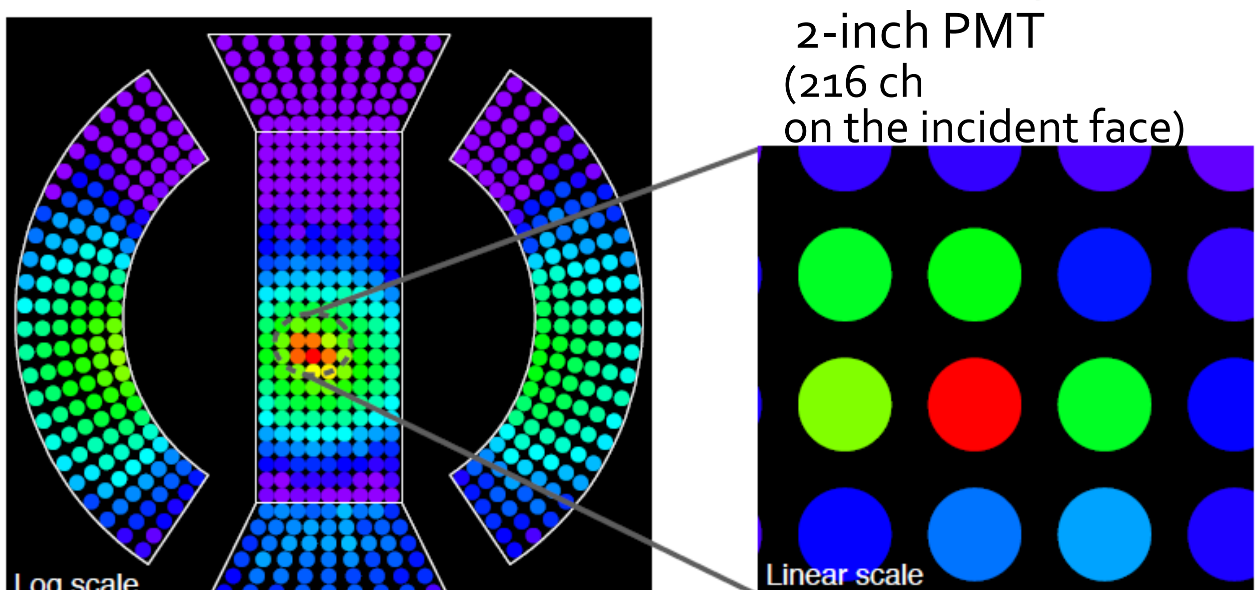

2-inch PMT
(216 ch
on the incident face)

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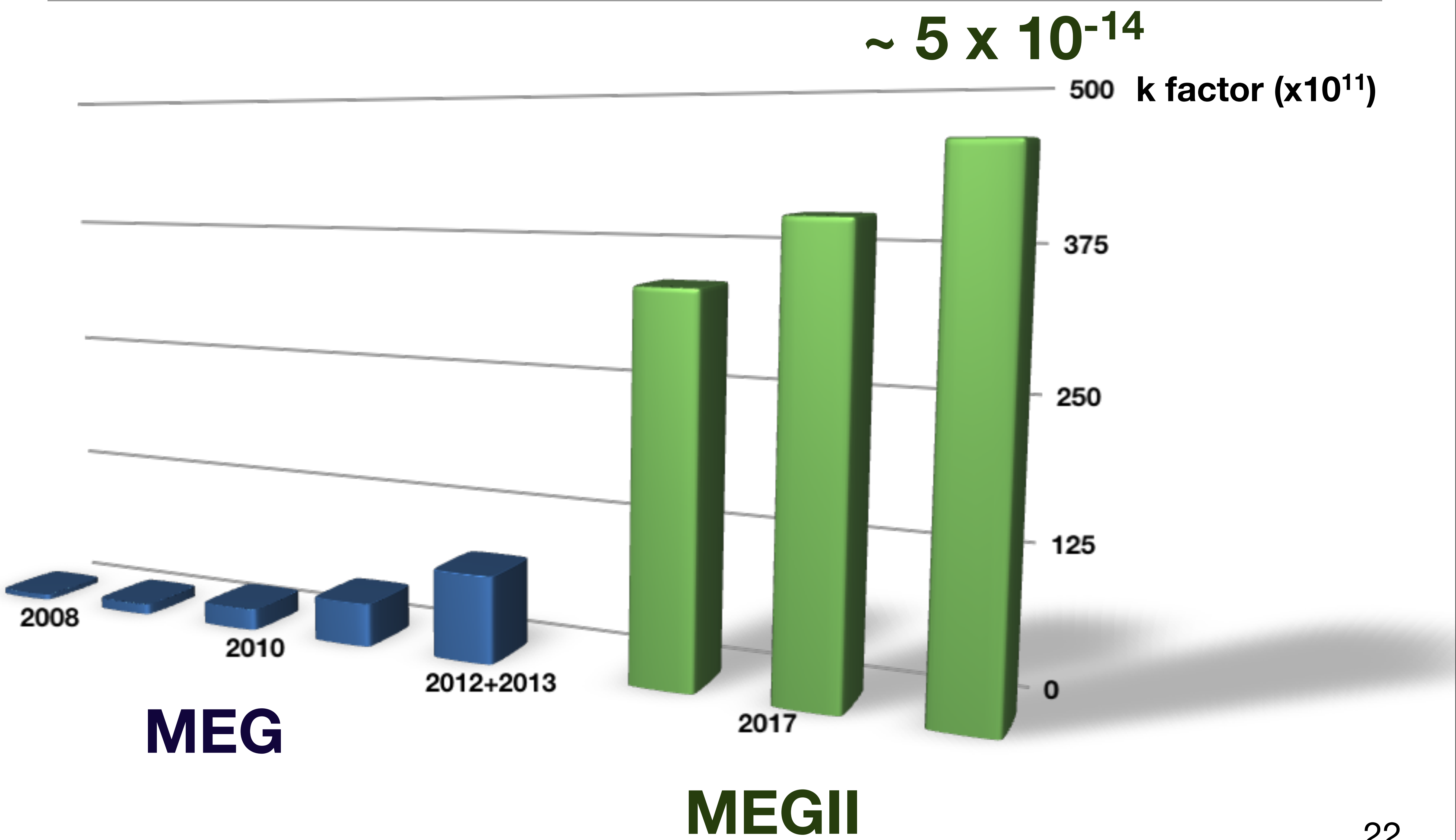
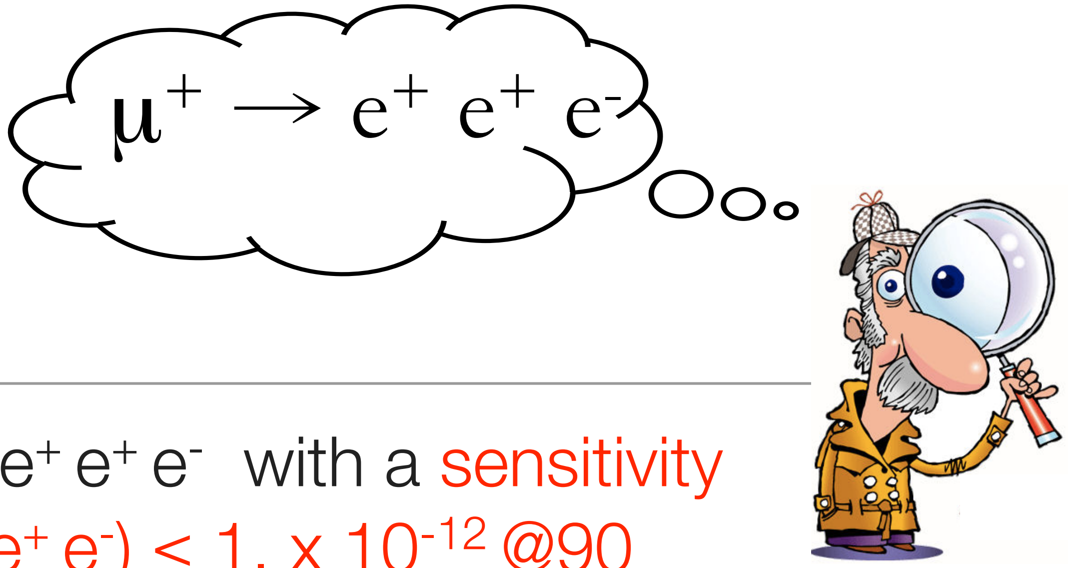
Where we will be

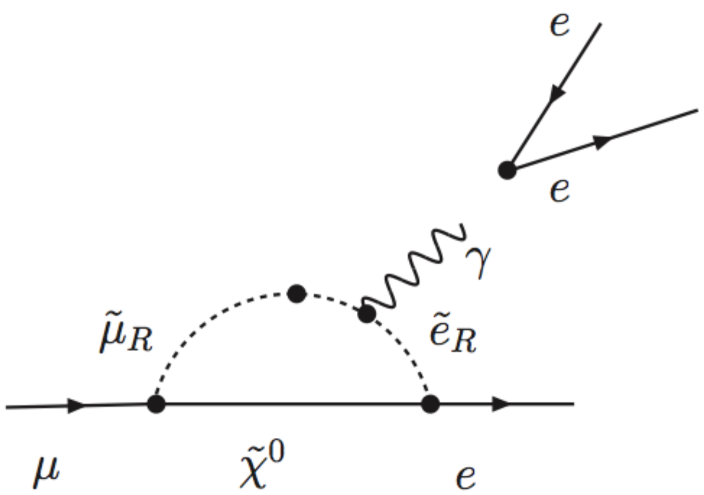


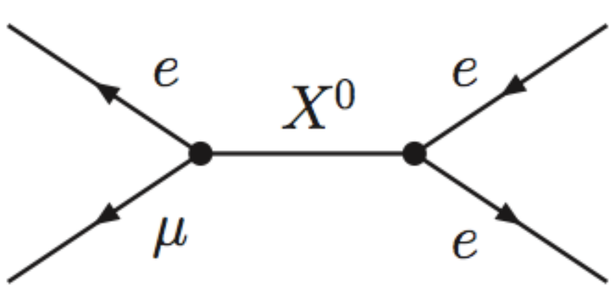


The Mu3e experiment

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of ~10^{-16} (current best upper limit $BR(\mu^+ \rightarrow e^+ e^+ e^-) \leq 1. \times 10^{-12}$ @90 C.L. by the SINDRUM experiment)

$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(k+1)\Lambda^2}\overline{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2}\overline{\mu}_R \gamma_\mu e_L \overline{f} \gamma^\mu f$$





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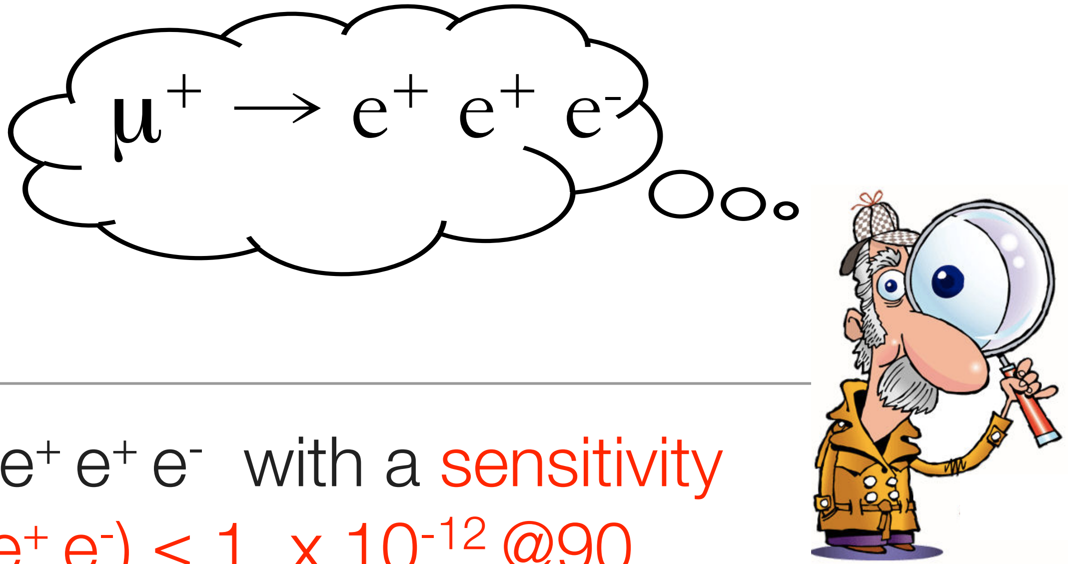

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Case 1: dominant dipole coupling ($k \rightarrow 0$)

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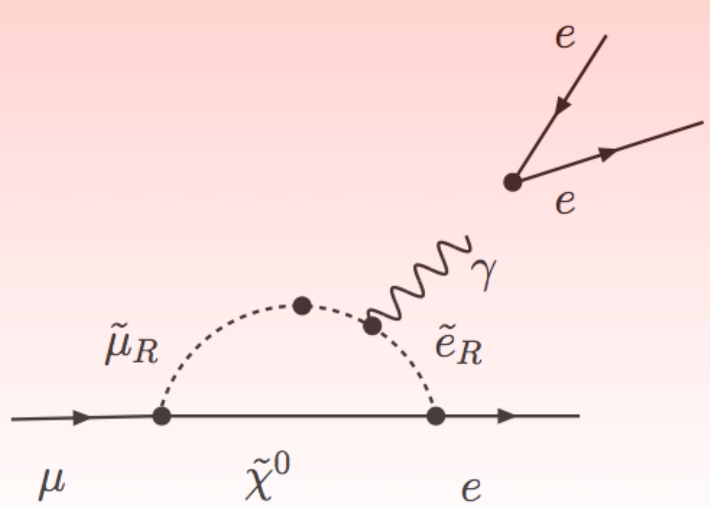
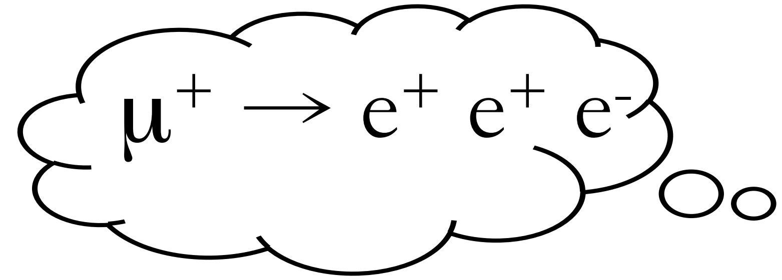


$$\frac{BR(\mu^+ \rightarrow e^+ e^+ e^-)}{BR(\mu^+ \rightarrow e^+ \gamma)} \sim 0.006$$

$\mu^+ \rightarrow e^+ \gamma$ most sensistive channel!



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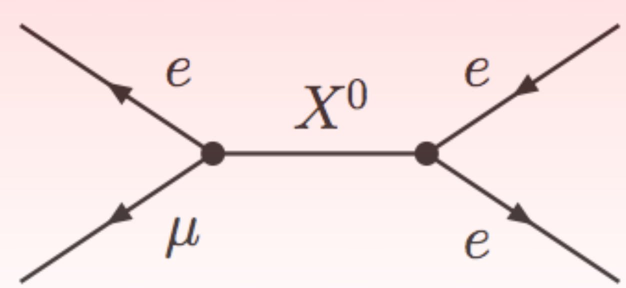
Case 2: tree level interaction (k > 10)

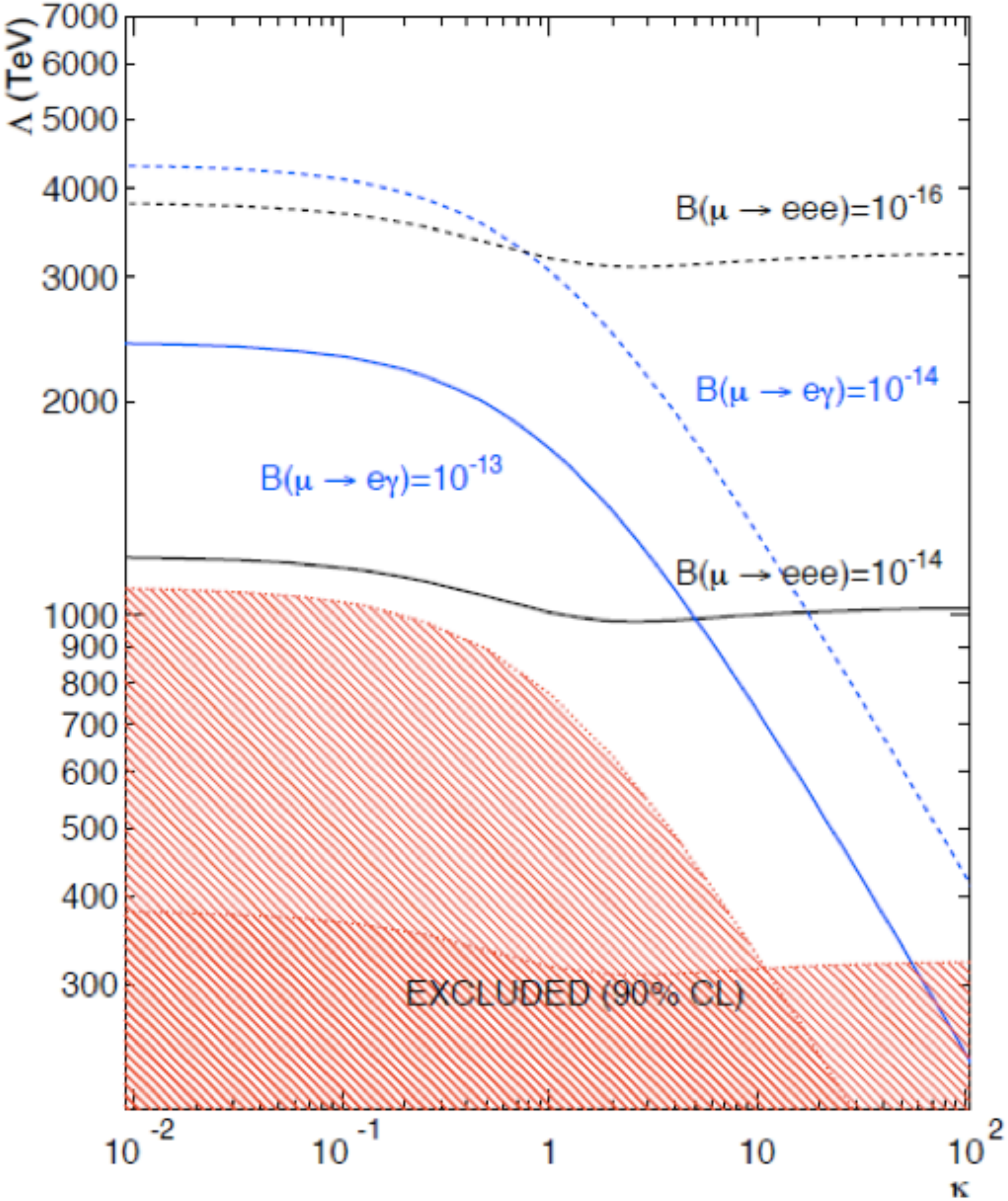
$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(k+1)\Lambda^2} \overline{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2} \overline{\mu}_R \gamma_\mu e_L \overline{f} \gamma^\mu f$$

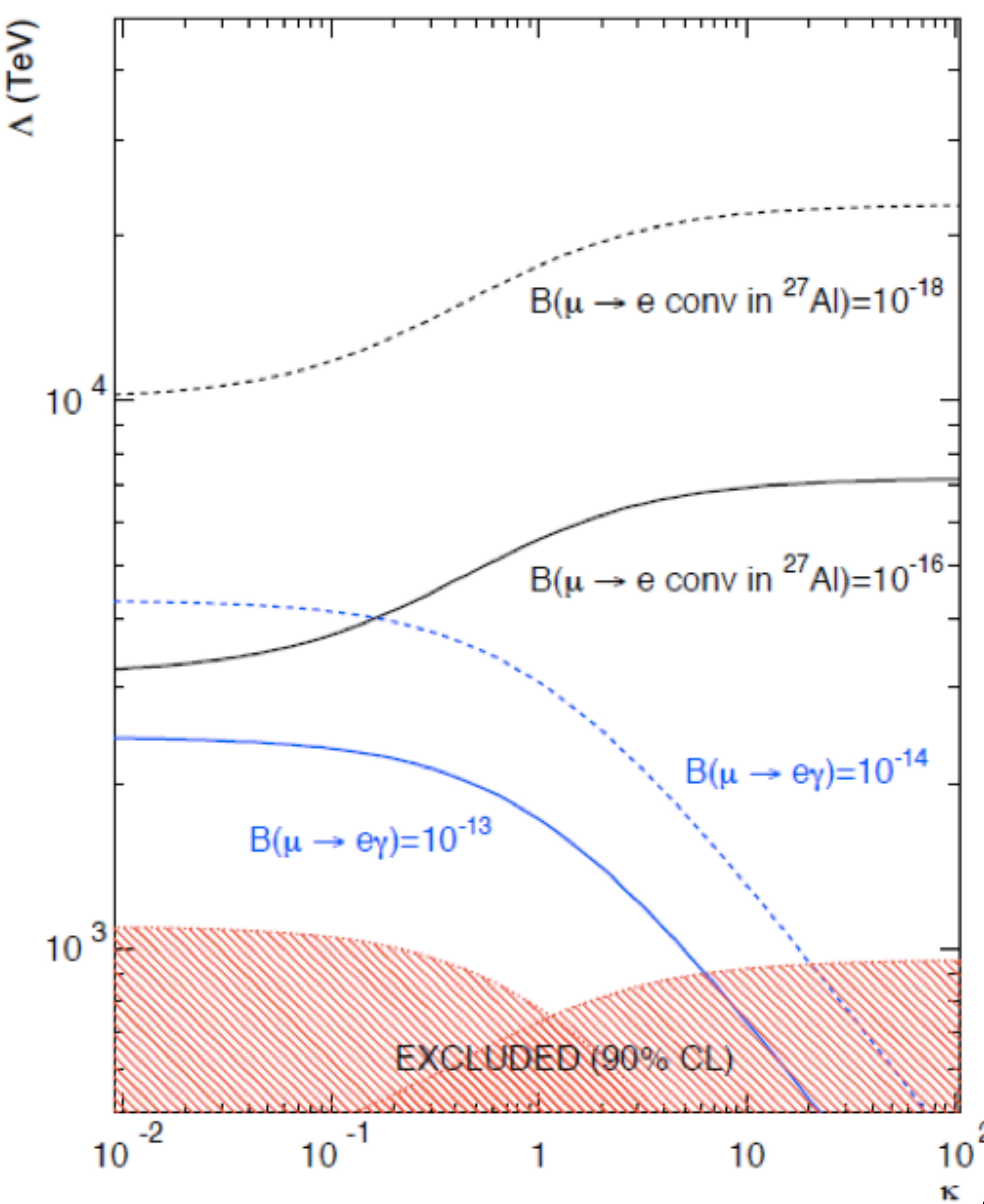
$$\frac{BR(\mu^+ \rightarrow e^+ e^+ e^-)}{BR(\mu^+ \rightarrow e^+ \gamma)} >> 1$$

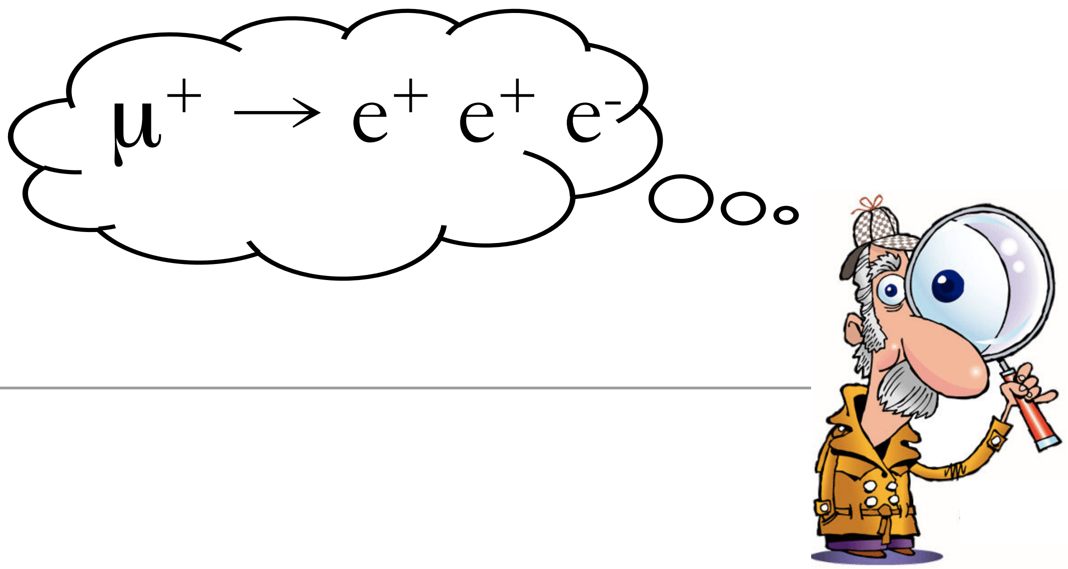


tree level interaction accessible only via $\mu^+ \rightarrow e^+ e^+ e^-$!

cLFV search: complementry approch



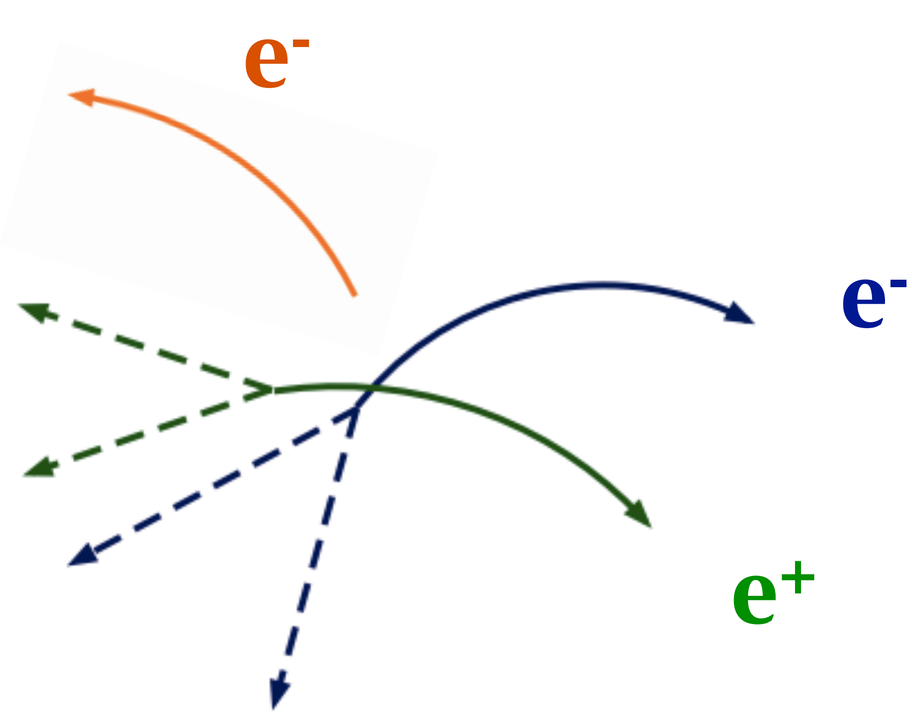


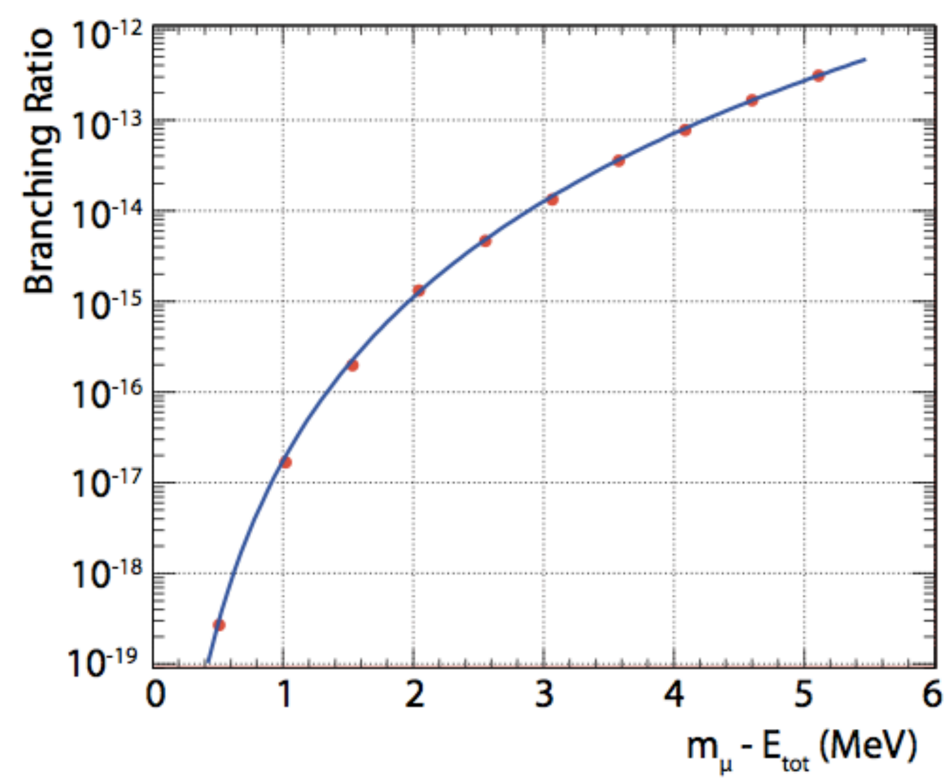


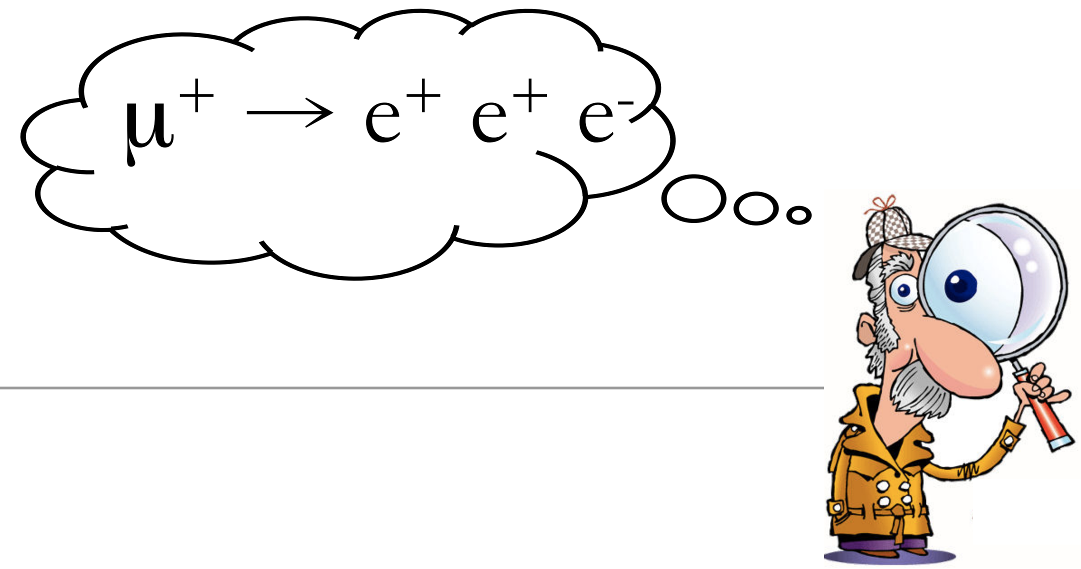
The Mu3e experiment

- The $\mu^+ \rightarrow e^+ e^+ e^-$ signature
  - 3 charged particle in the final state
  - no neutral particle in the fonal state allows for higher detector performances

- The $\mu^+ \rightarrow e^+ e^+ e^-$ main backgrounds
  - $\mu^+ \rightarrow e^+ e^+ e^- \nu \nu$
  - combinatorial $\mu^+ \rightarrow e^+ \nu \nu$, $\mu^+ \rightarrow e^+ \nu \nu$, $e^+ e^-$

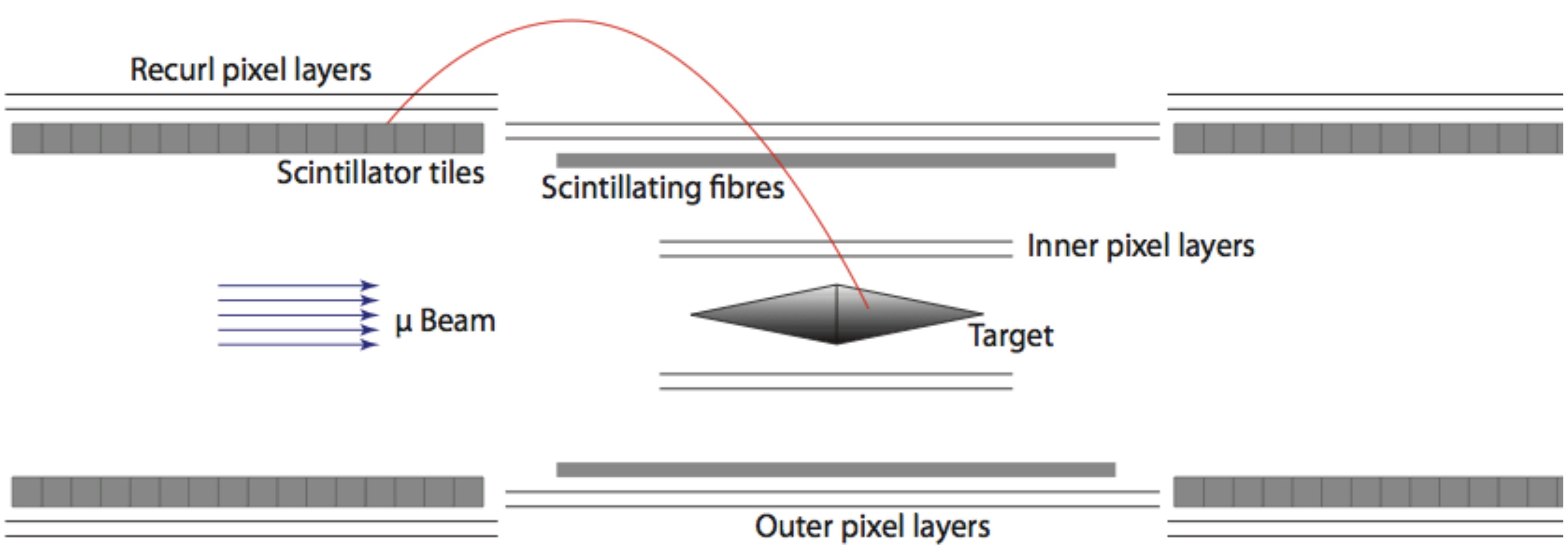


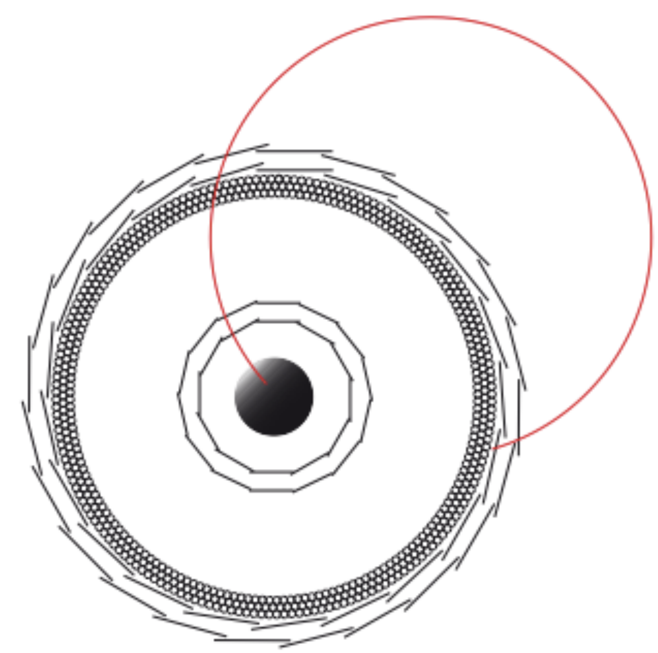


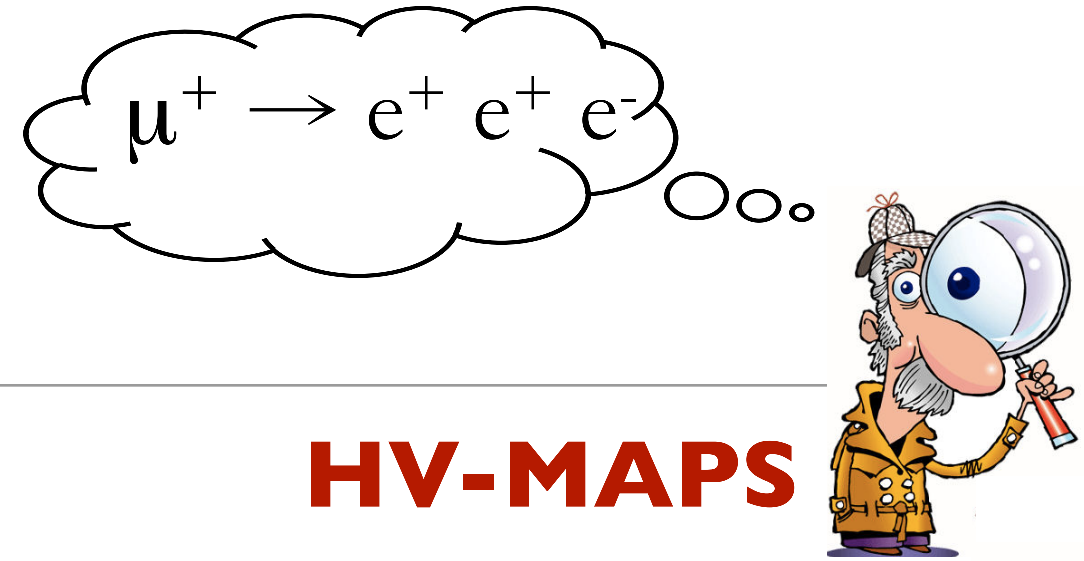


The Mu3e experiment

- High intensity beam (up to 10^9 muon/s !)
- Excellent momentun resolution
- Good vertex resolution
- Good timing resolution
- Low material badget



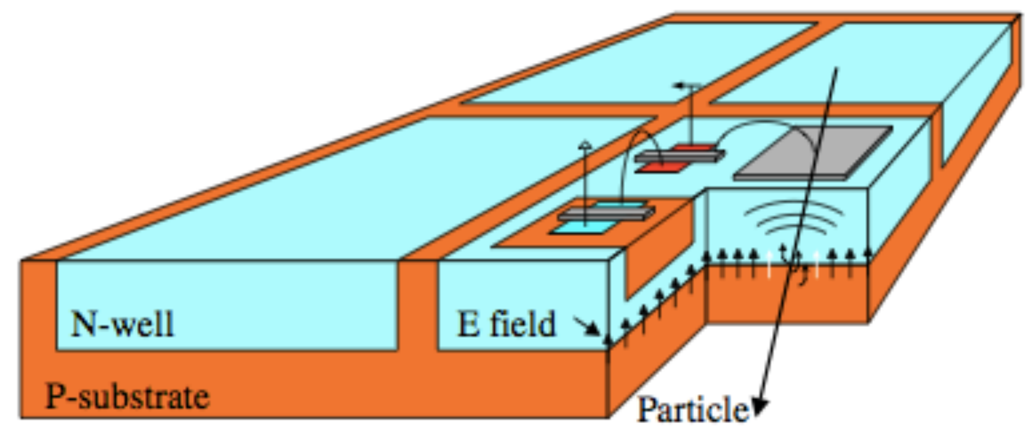


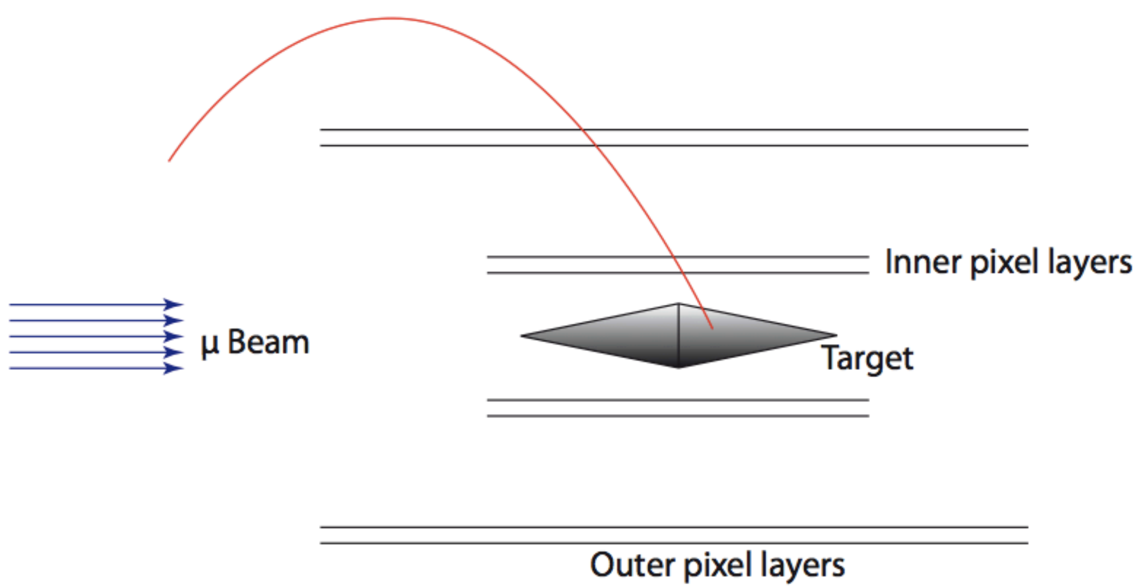


The Mu3e experiment

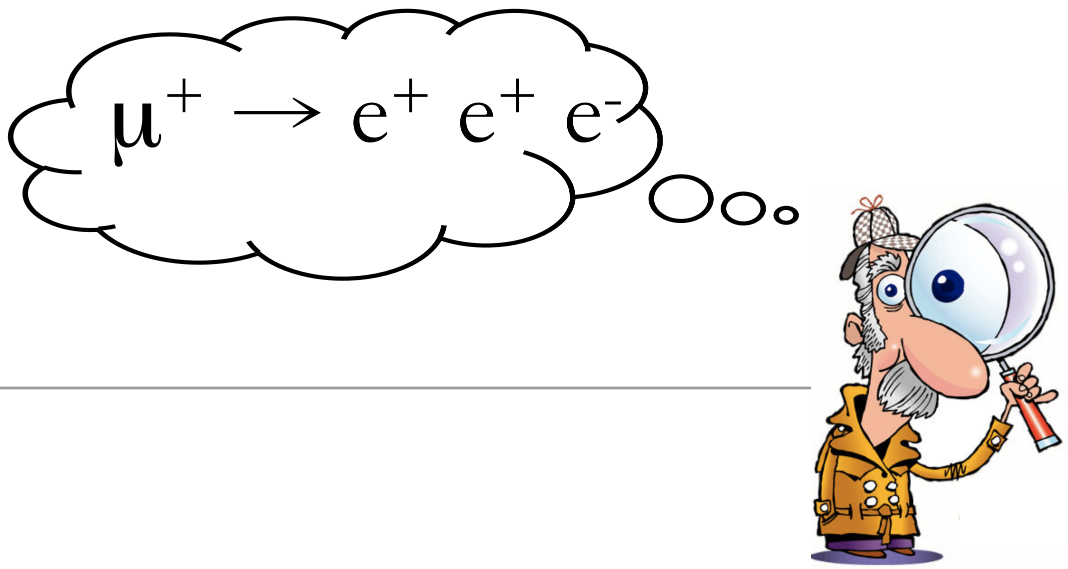
HV-MAPS

- Pixel dimension: 80 x 80 um^2
- Thinning to 50 um
- The sensor and read-out are integrated on the same device

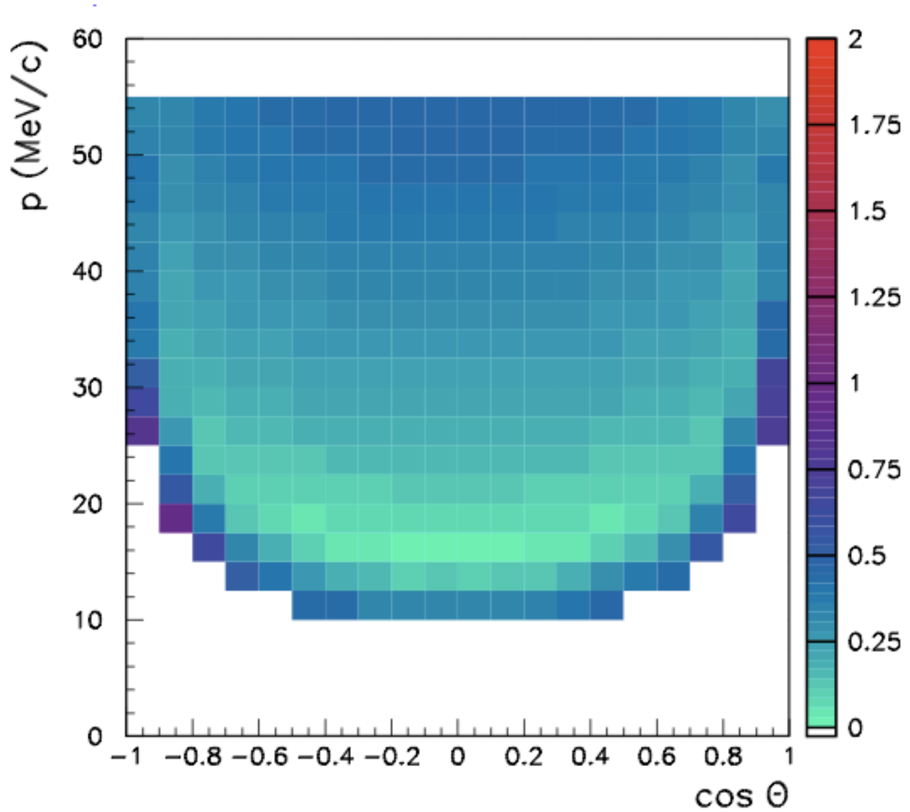


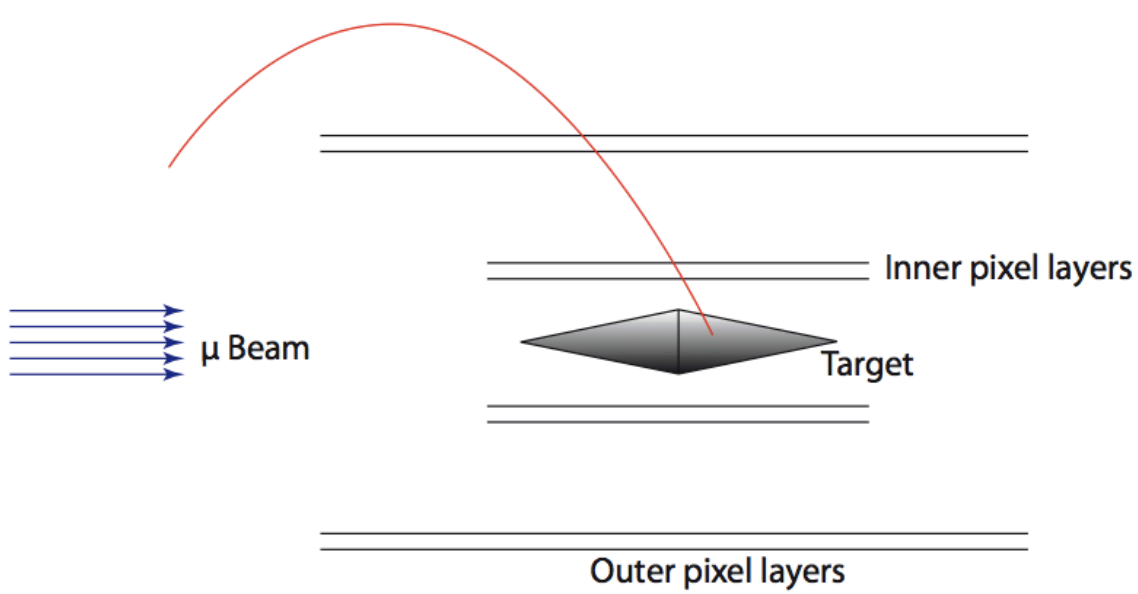


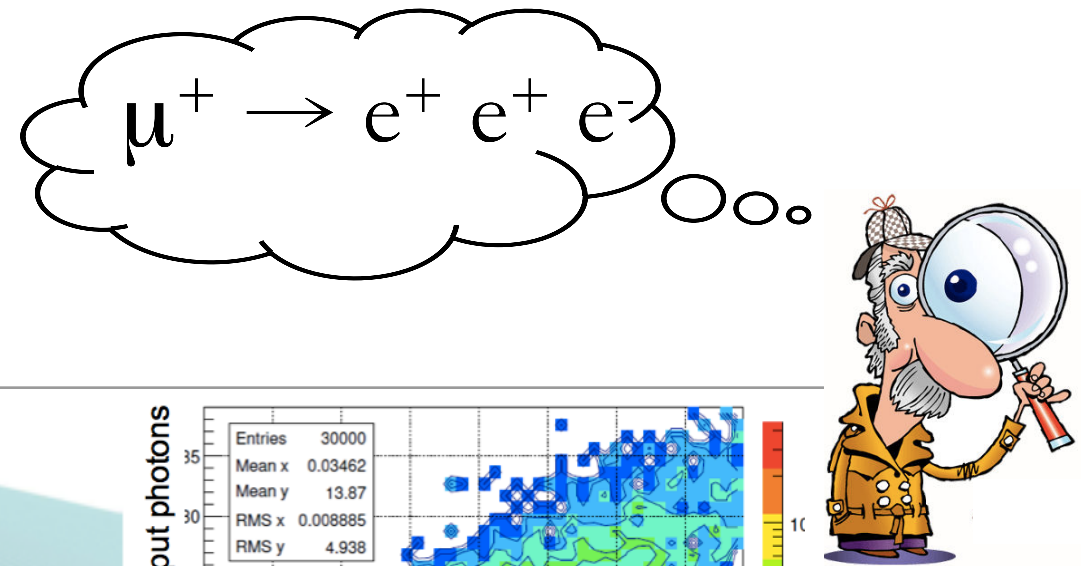
The Mu3e experiment



- Pixel dimension: 80 x 80 um^2
- Thinning to 50 um
- The sensor and read-out are integrated on the same device
- Momentum resolution < 0.5 MeV/c over a large phase space
- Vertex resolution < 200 um

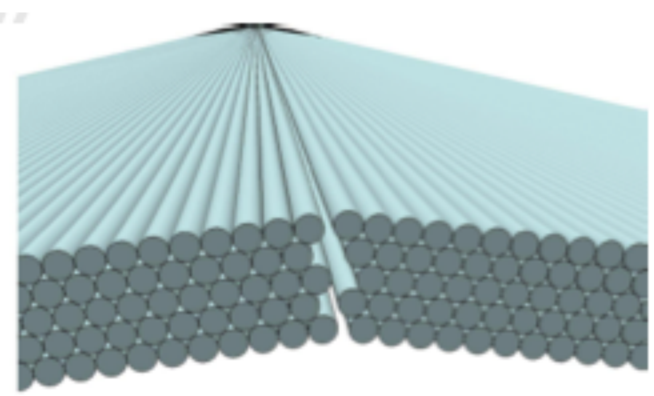


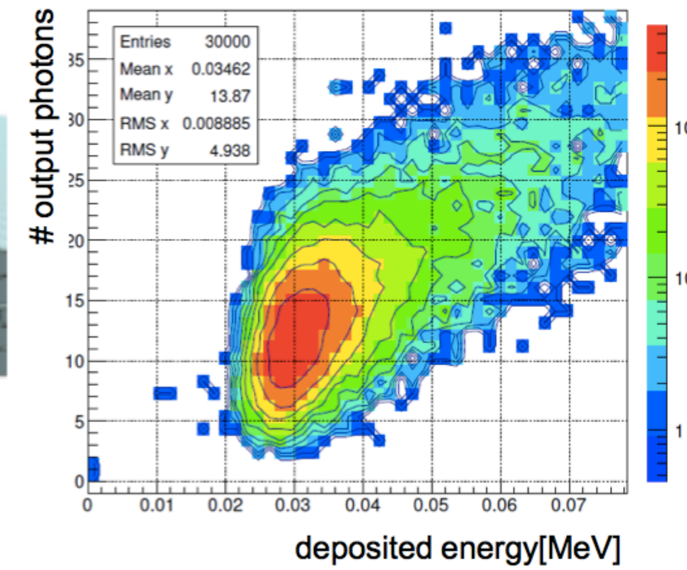


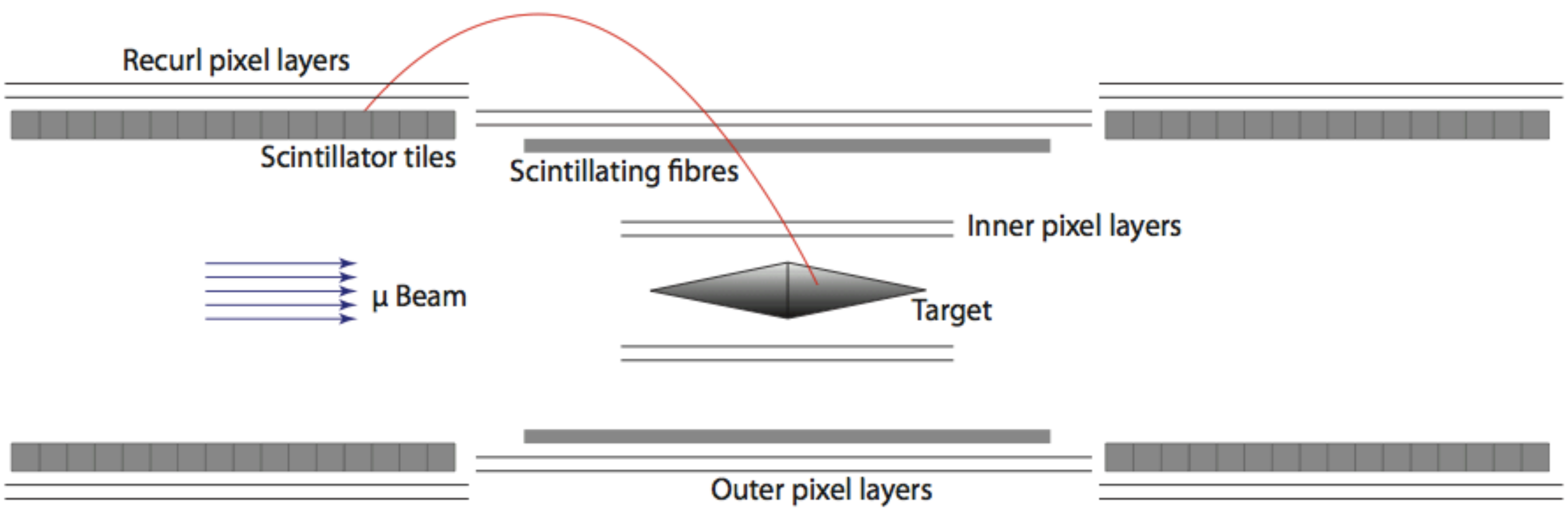


The Mu3e experiment

- Multi-layers of 250 um fiber
- Timing resolution < 1ns



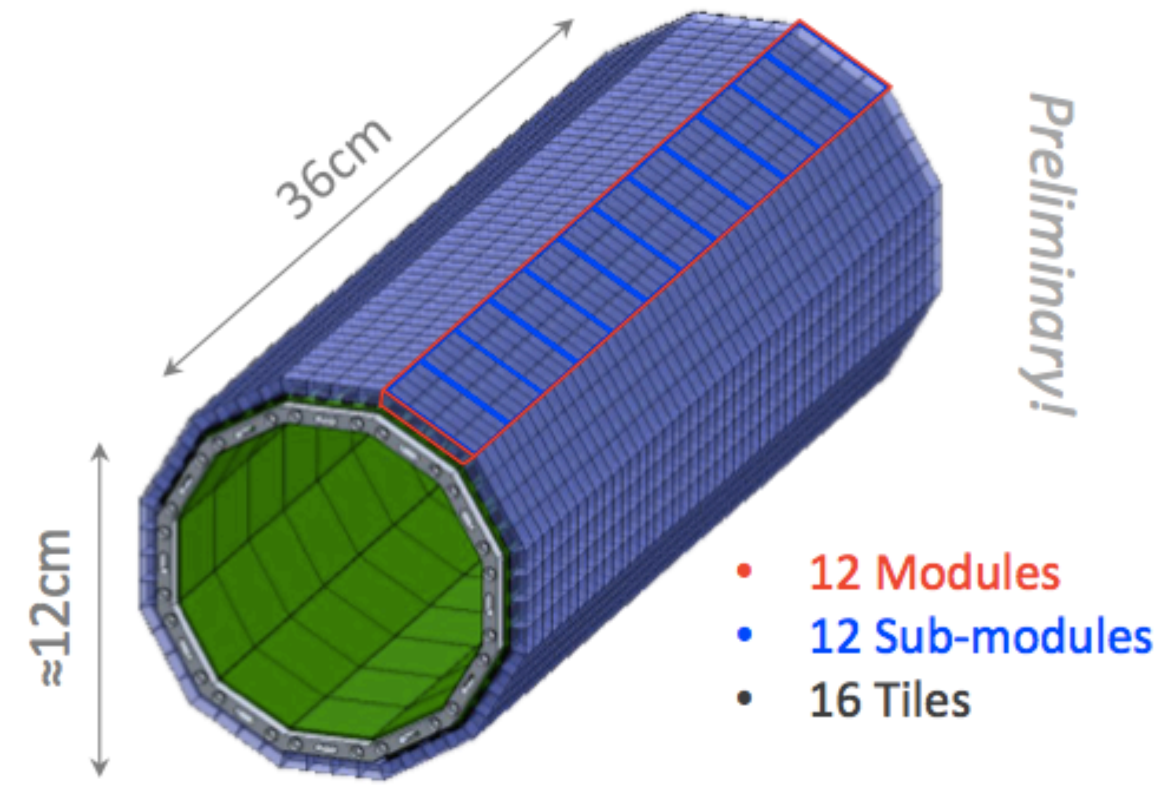


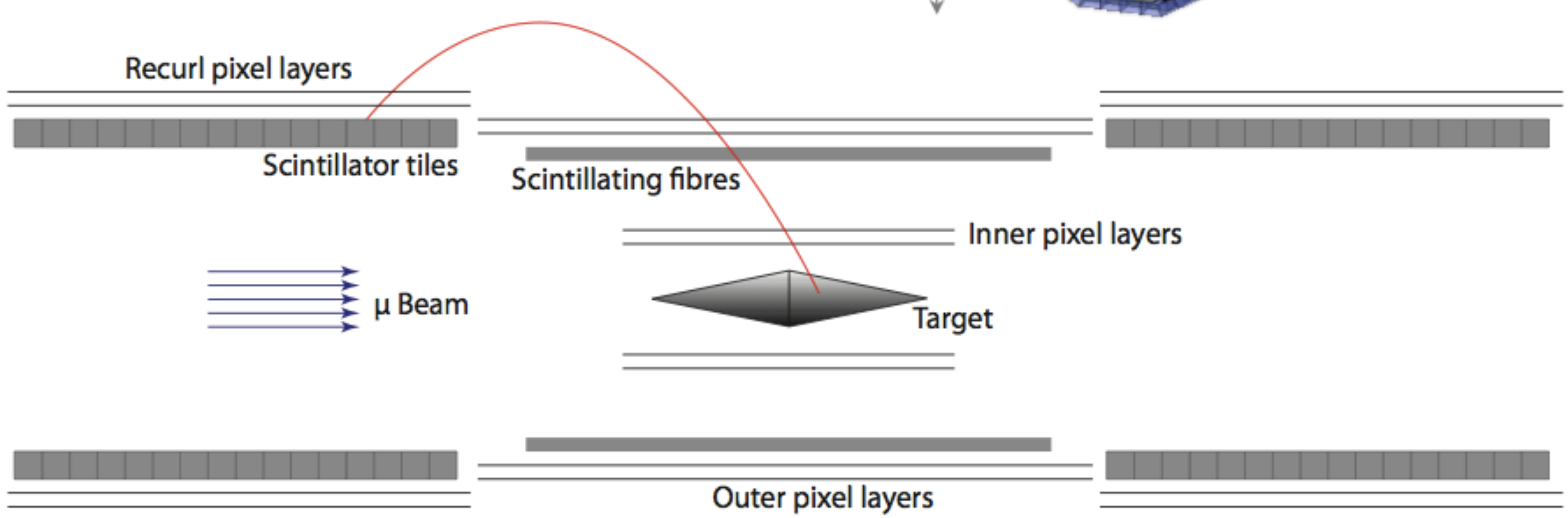


$\mu^+ \rightarrow e^+ e^+ e^-$

The Mu3e experiment

- Multi-layers of 250 um fiber
- Timing resolution < 1ns
- Tile detector
- Timing resolution < 100 ps

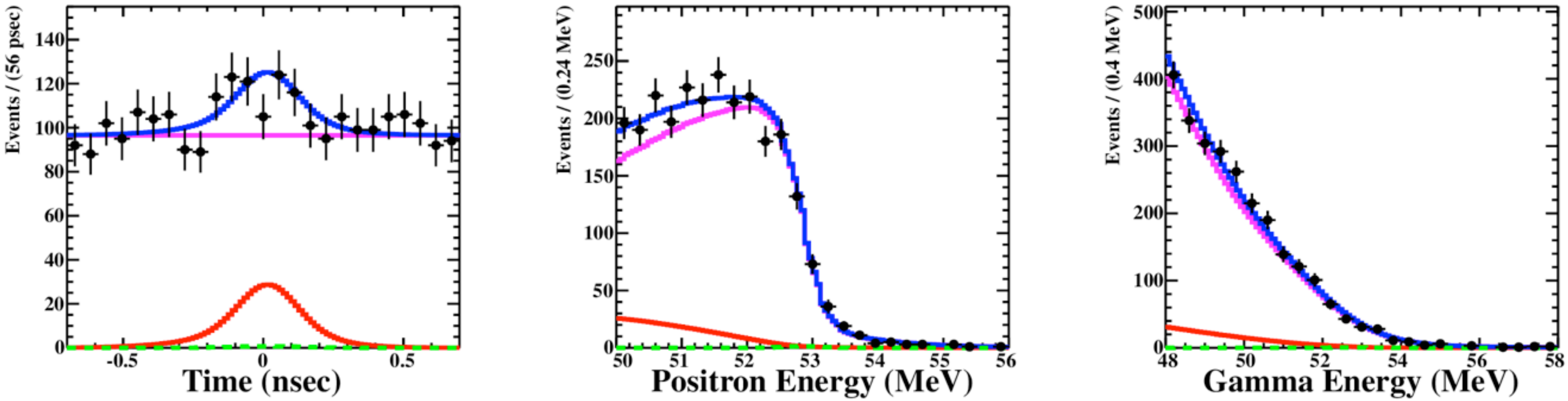


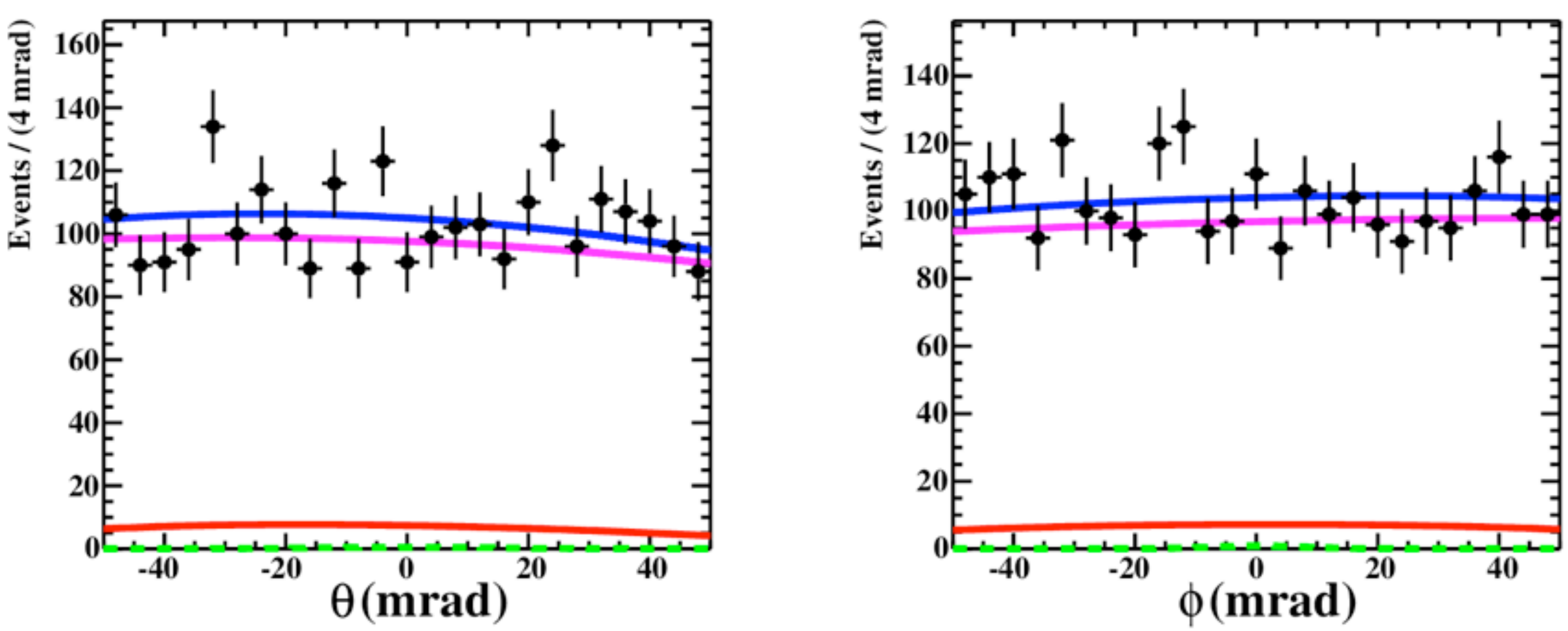


Summary

- Lepton flavour violation is presently one of the most exciting branch of particle physics
- The MEG experiment @PSI was design to reach a sensitivity of ~ few x 10^{-13} on the $\mu^+ \rightarrow e^+ \gamma$ decay. It has set the most stringent upper limit on the BR($\mu^+ \rightarrow e^+ \gamma$) < 5.7 x 10^{-13} (based on the 2009-2011 sample)
- The analysis of the full data sample is ongoing. It will be doubled including the collected statistics of the 2012-2013 sample and a new result will be delivered soon!
- An upgrade of the MEG detector started and is ongoing aiming at a sensitivity of ~ few x 10^{-14}
- The Mu3e experiment @PSI aiming at search for the $\mu^+ \rightarrow e^+ e^+ e^-$ decay with a sensitivity of ~ few x 10^{-16} started as well its preparation, complementing the muon cLVF search pursued in Europe

Likelihood Fit (2009-2011)



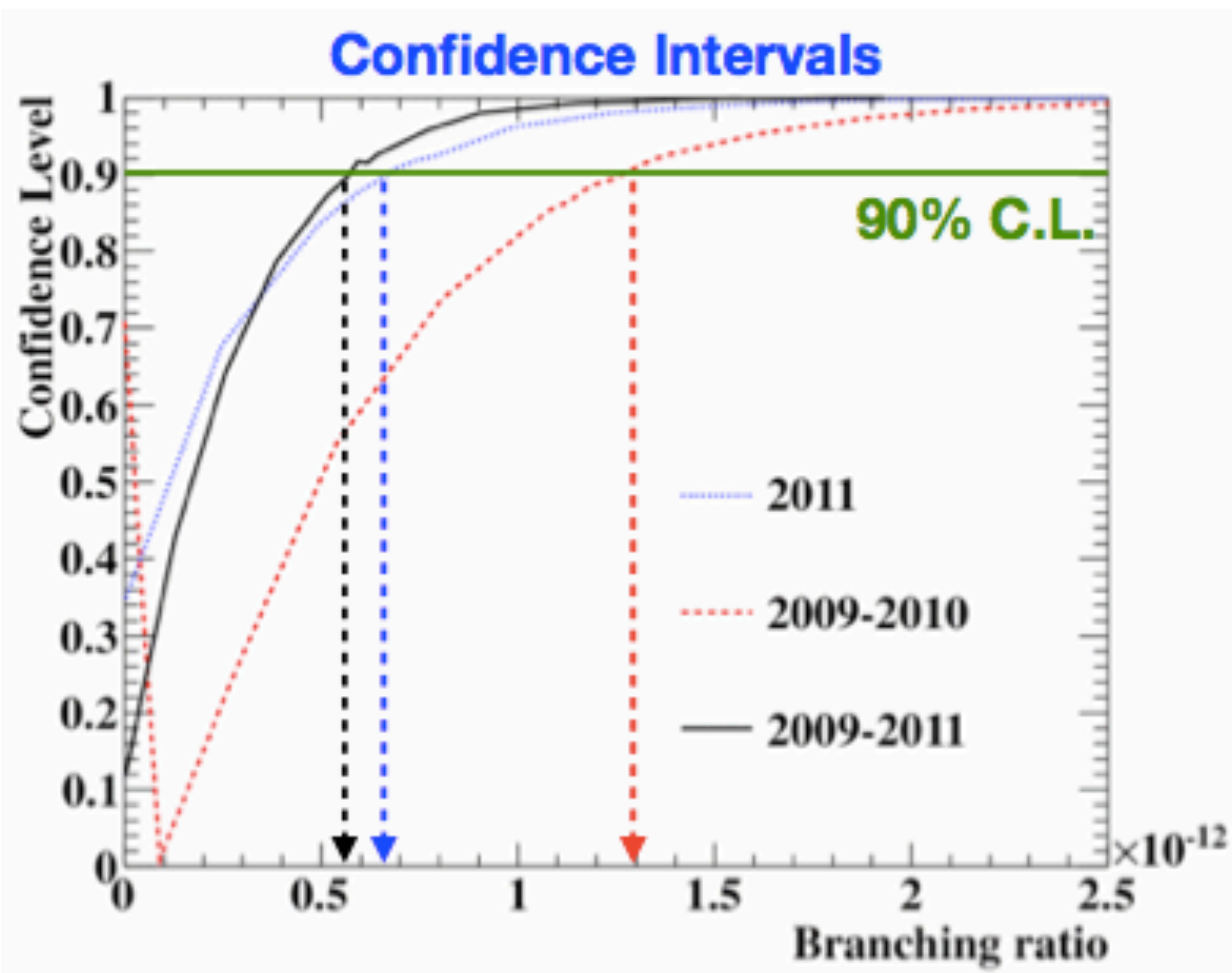


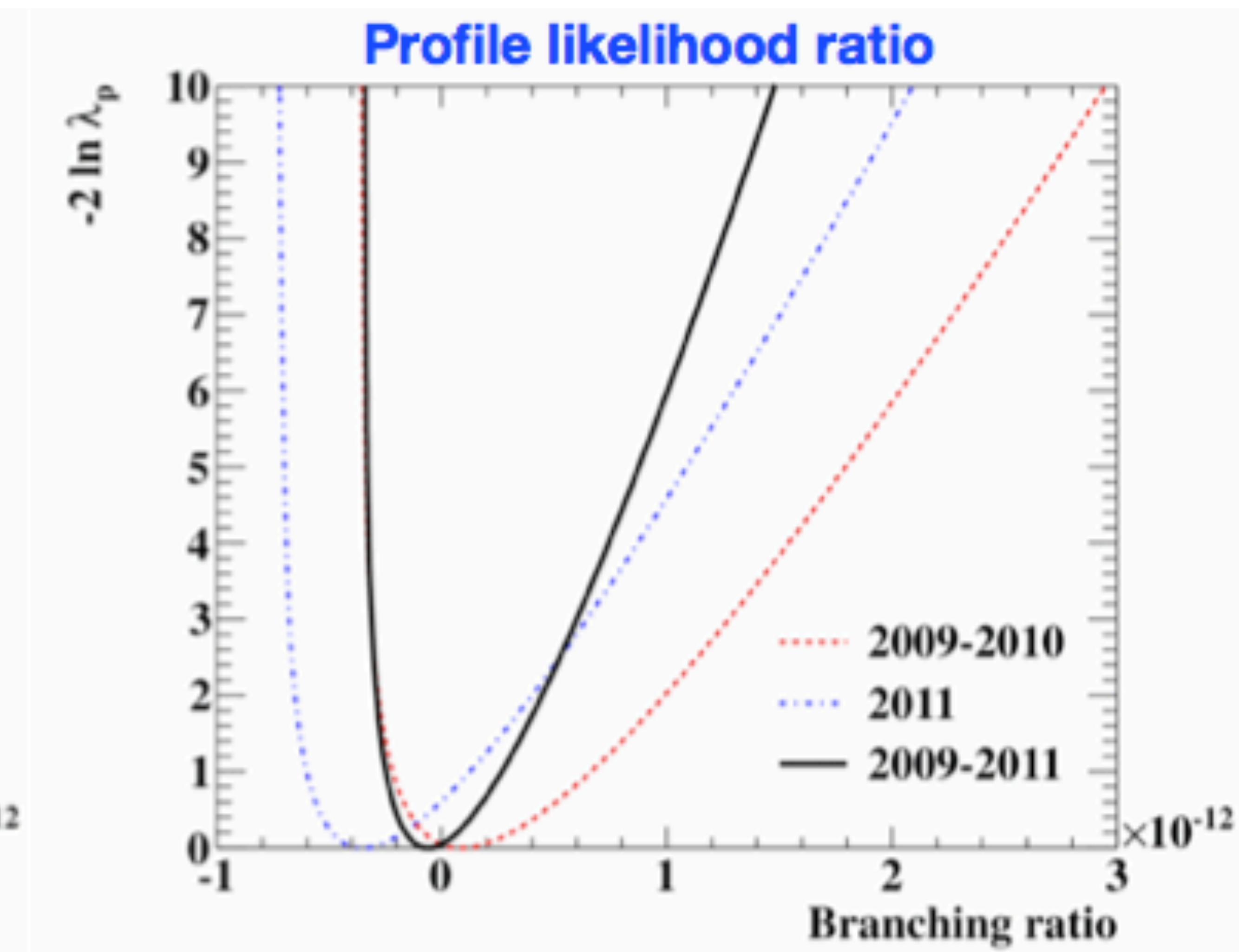
Green: Signal
Red: RMD
Purple: BCK
Blue: Total
Black: Data

NSIG = -0.4(+4.8 -1.9)
NRMD = 167.5 ± 24
NBCK = 2414 ± 37

Confidence Interval

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





Consistent with null-signal hypotesis