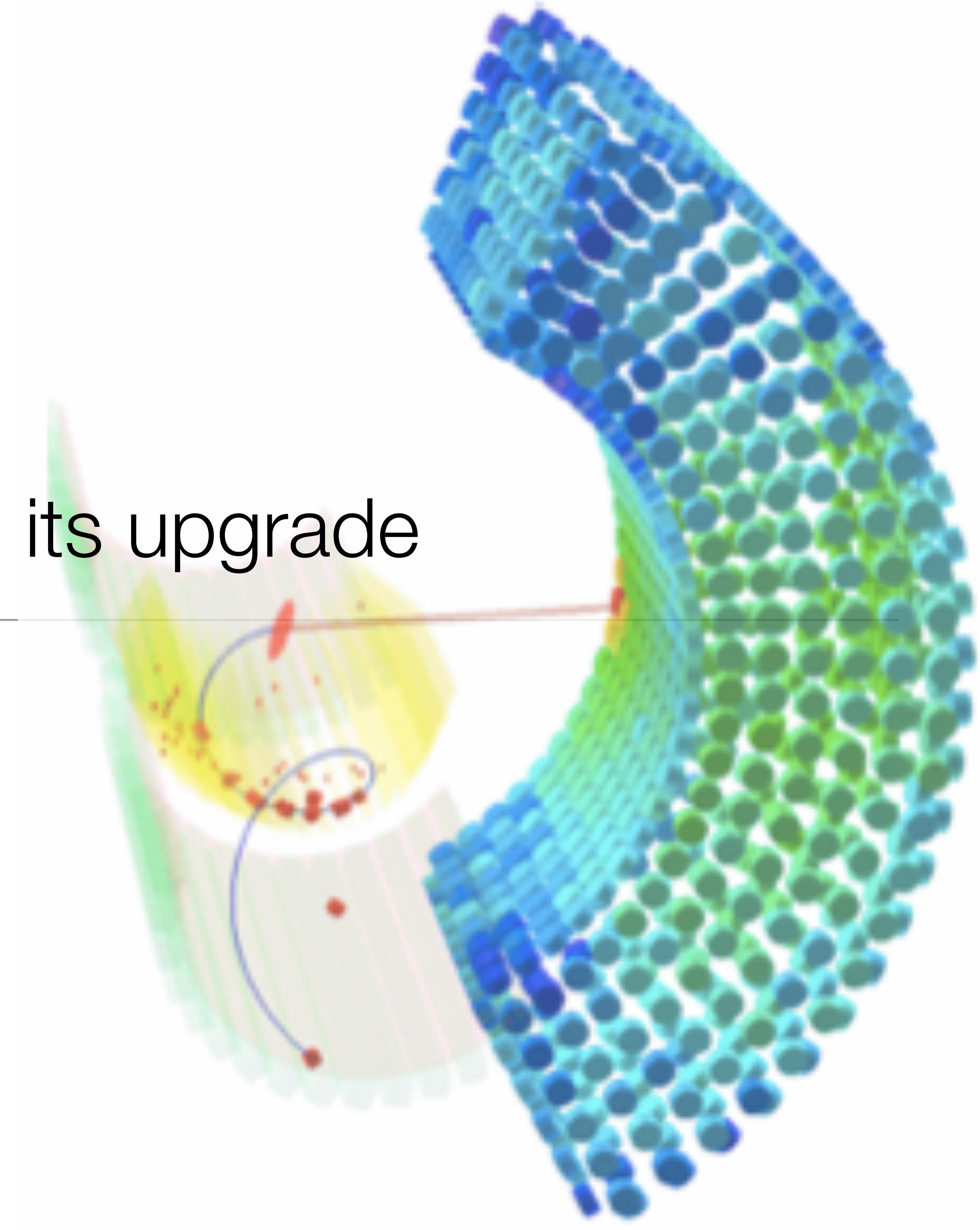
The MEG experiment and its upgrade

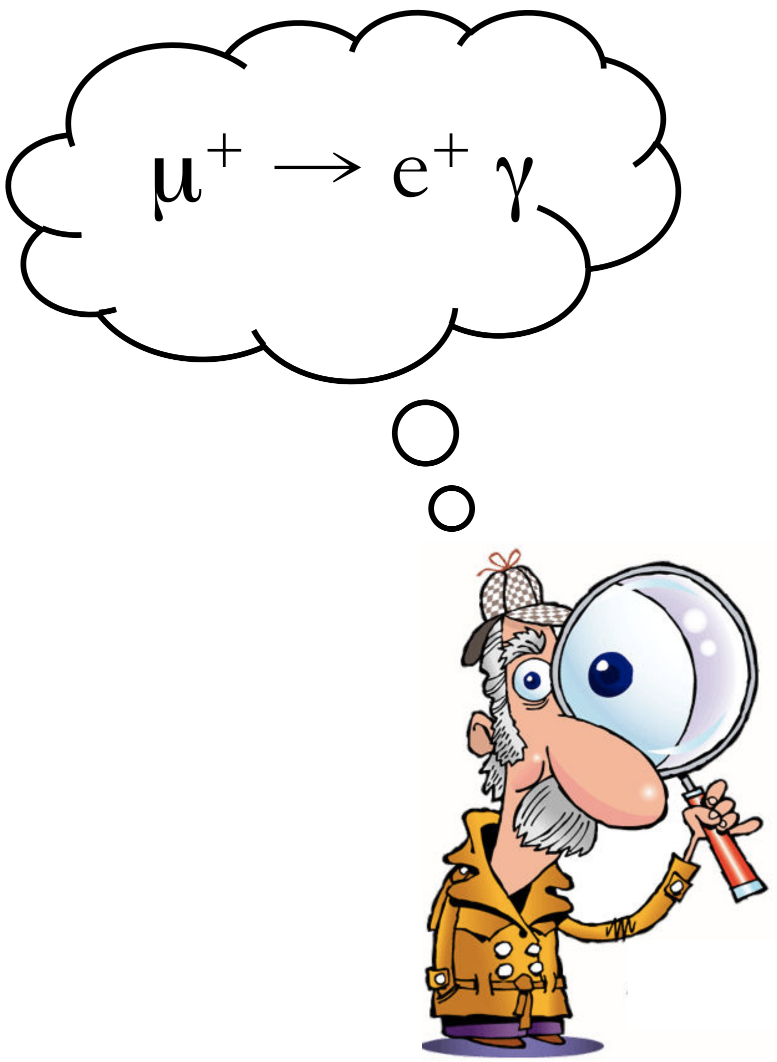


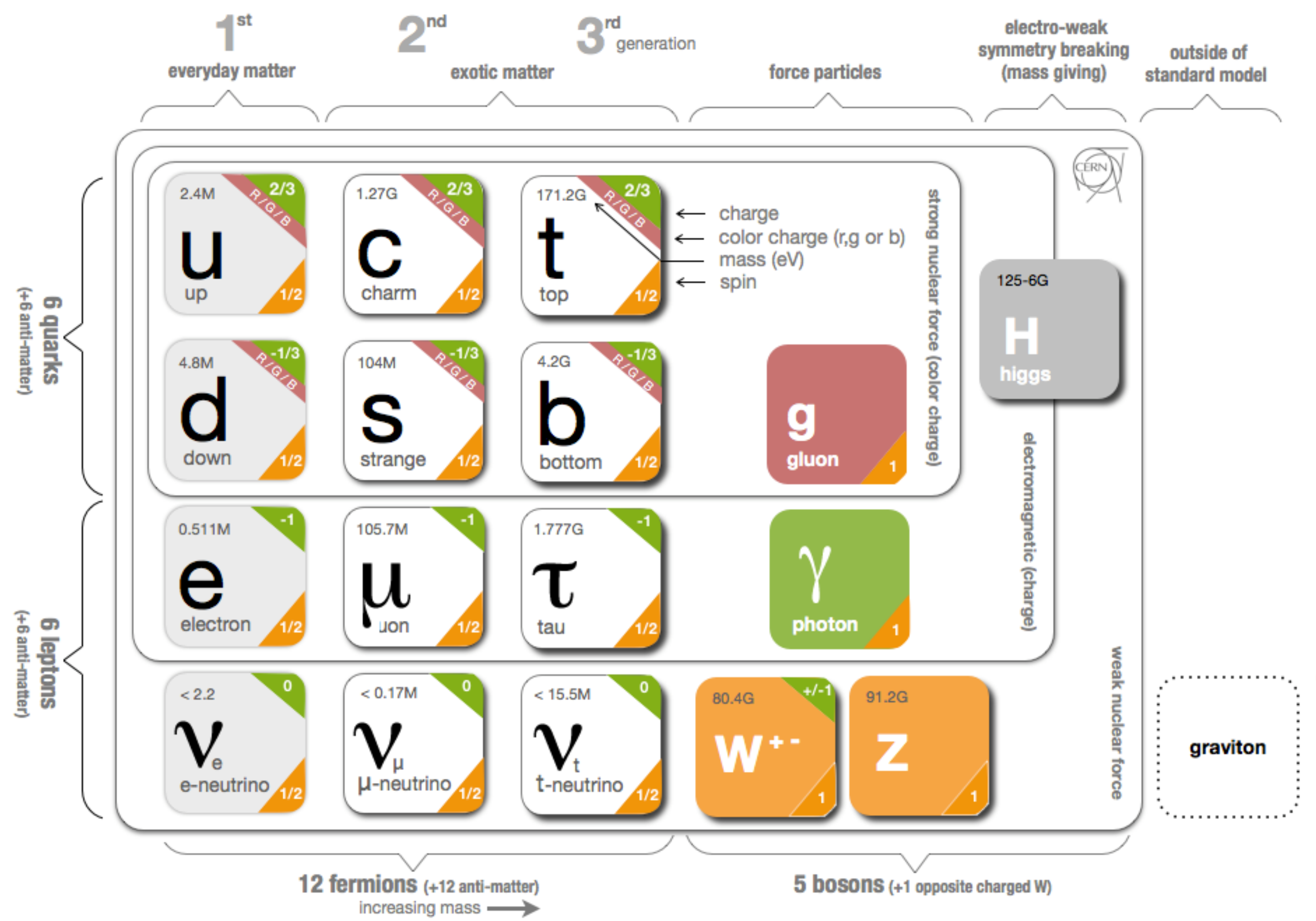
Angela Papa
Paul Scherrer Institute
on behalf of the MEG collaboration

Clermont-Fd, 24th October 2014

The physics connected to the MEG experiment

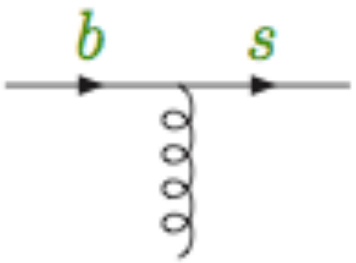
- The MEG experiment search for $\mu^+ \rightarrow e^+ \gamma$ decay, which violetes the conservation of the lepton number in the charged lepton sector (cLFV)





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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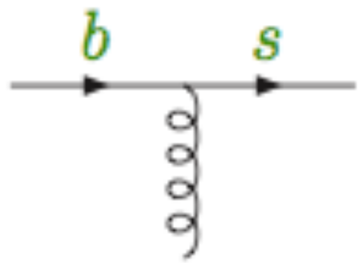
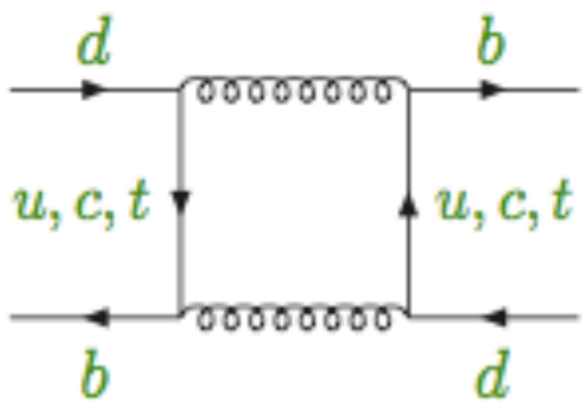
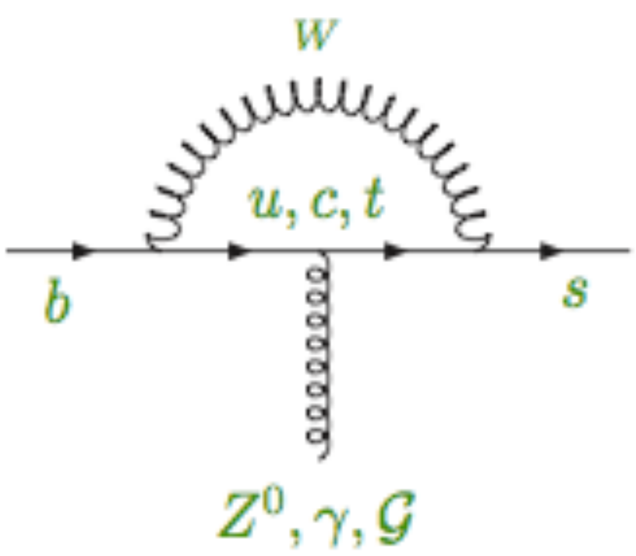


- At the quantum level (quantum loops)
  - in the quark sector, FCNC are induced by charged current loop effects, due to mixing among fermion generations
    - e.g. $K_L^0 \to \mu\mu$ in the quark section





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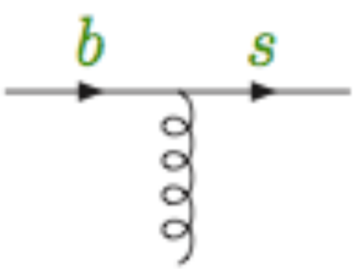

- At the quantum level (quantum loops)
  - in the quark sector, FCNC are induced by charged current loop effects, due to mixing among fermion generations
    - e.g. $K_L^0 \rightarrow \mu\mu$ in the quark section
  - what about lepton sector ?

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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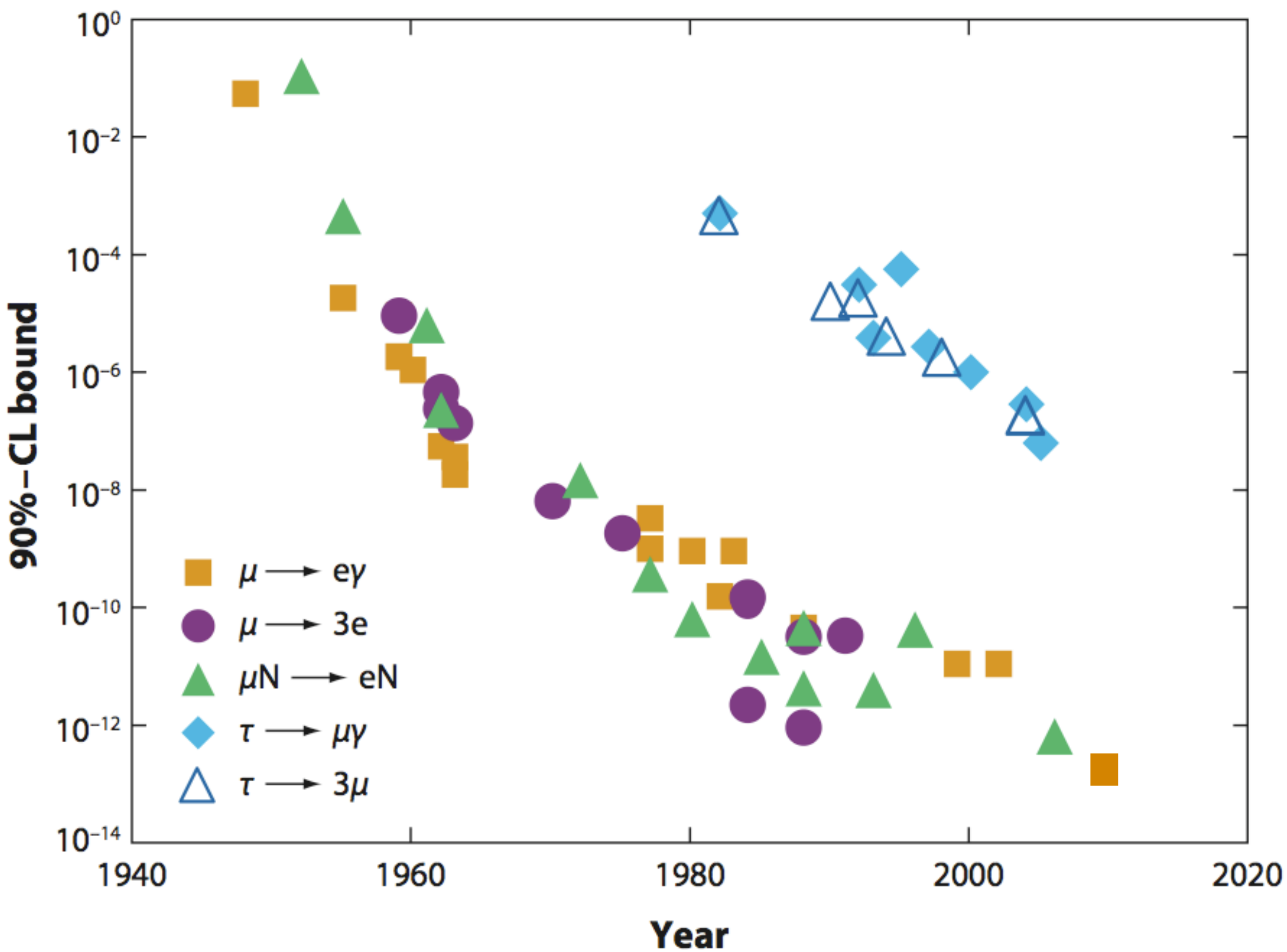

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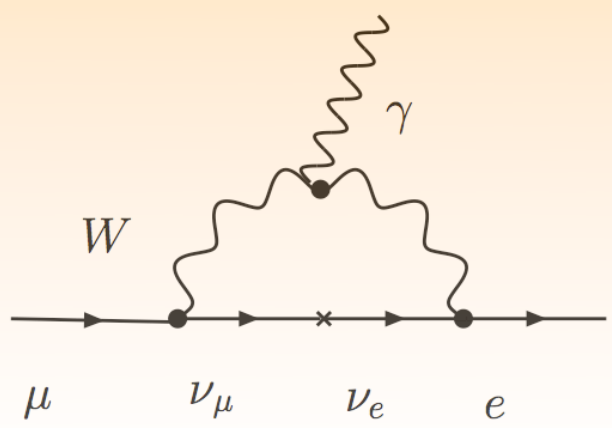
The $\mu^+ \rightarrow e^+ \gamma$ decay as an example

- Taking into account of neutrino oscillations



SM with massive neutrinos (Dirac)

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

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

too small to access experimentally

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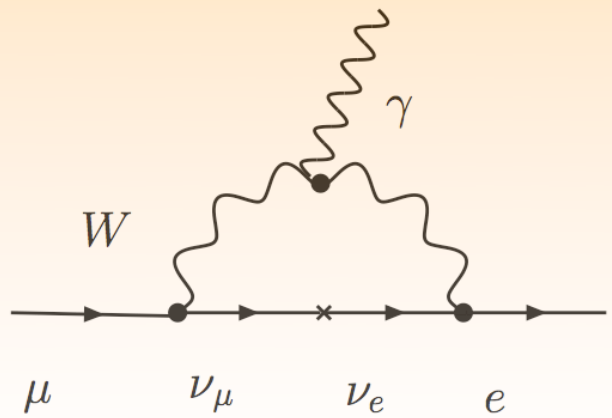

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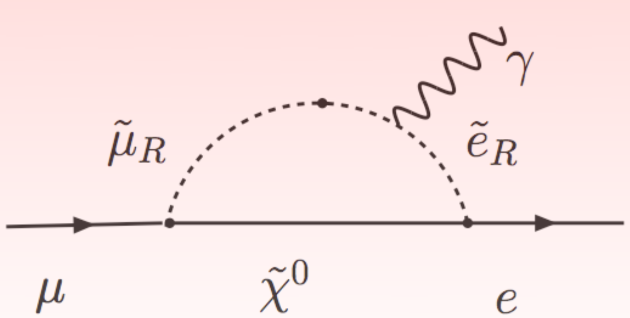
- SM well tested and successfull model, low-energy effective theory of a yet-more-fundamental one
- BSM theories such as SU(5) SUSY-GUT and SO(10) SUSY-GUT models predict measureble LFV decay BR



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

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

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

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

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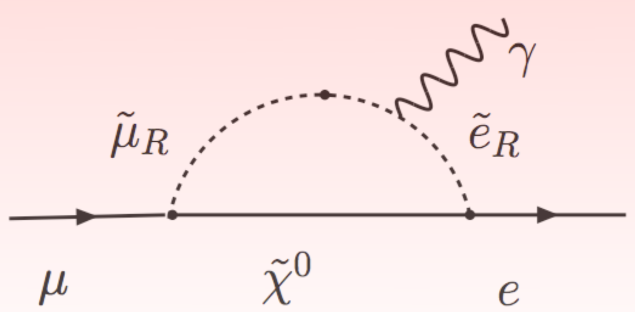

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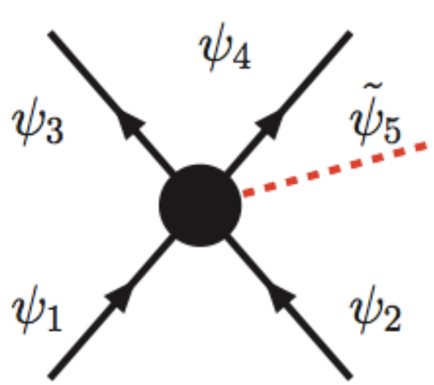
Null result will turn out in a precise test of established model and will ruled out speculative ones

<u>cLFV signature will be a clear evidence of New Physics</u>

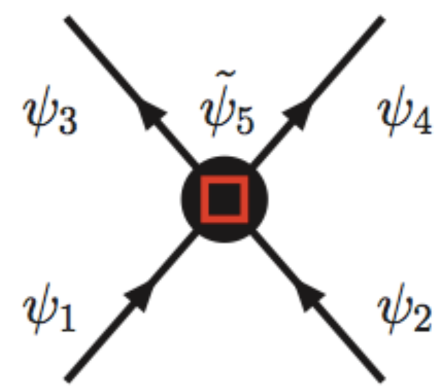
The role of low energy physics in the LHC era

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)



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- Precision and intensity frontier

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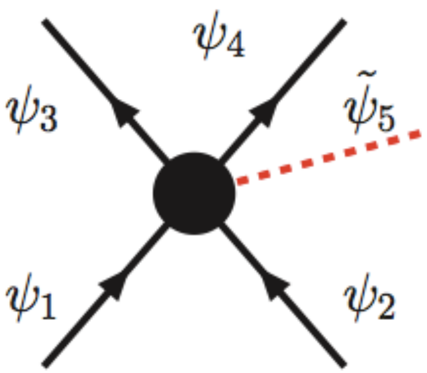

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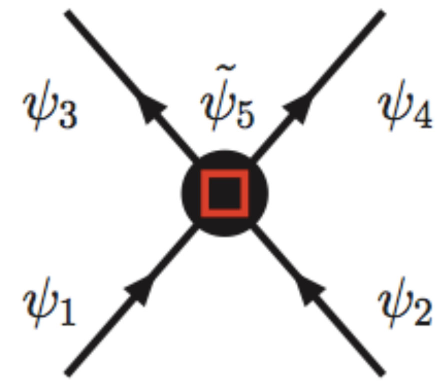
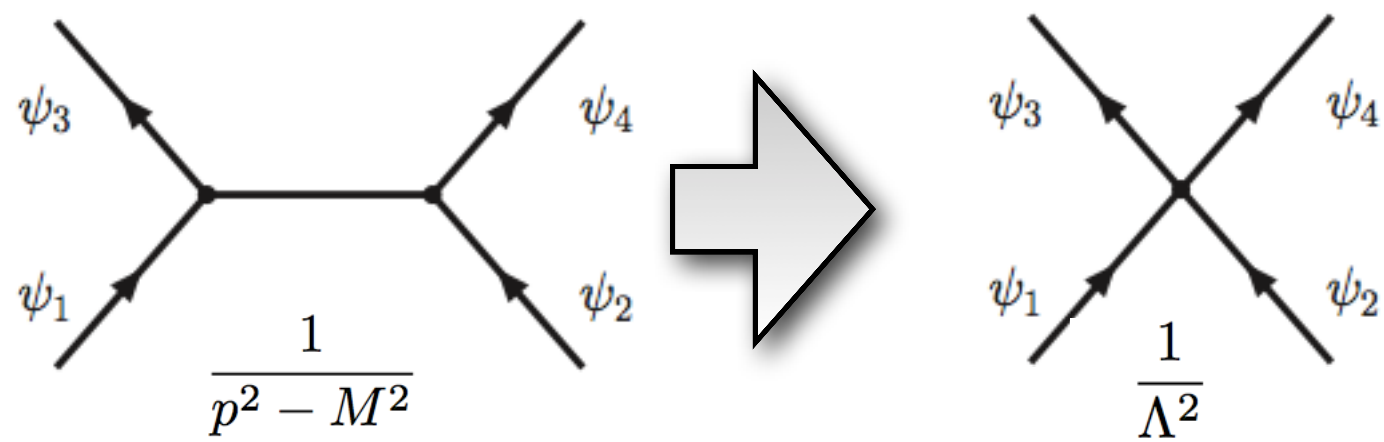


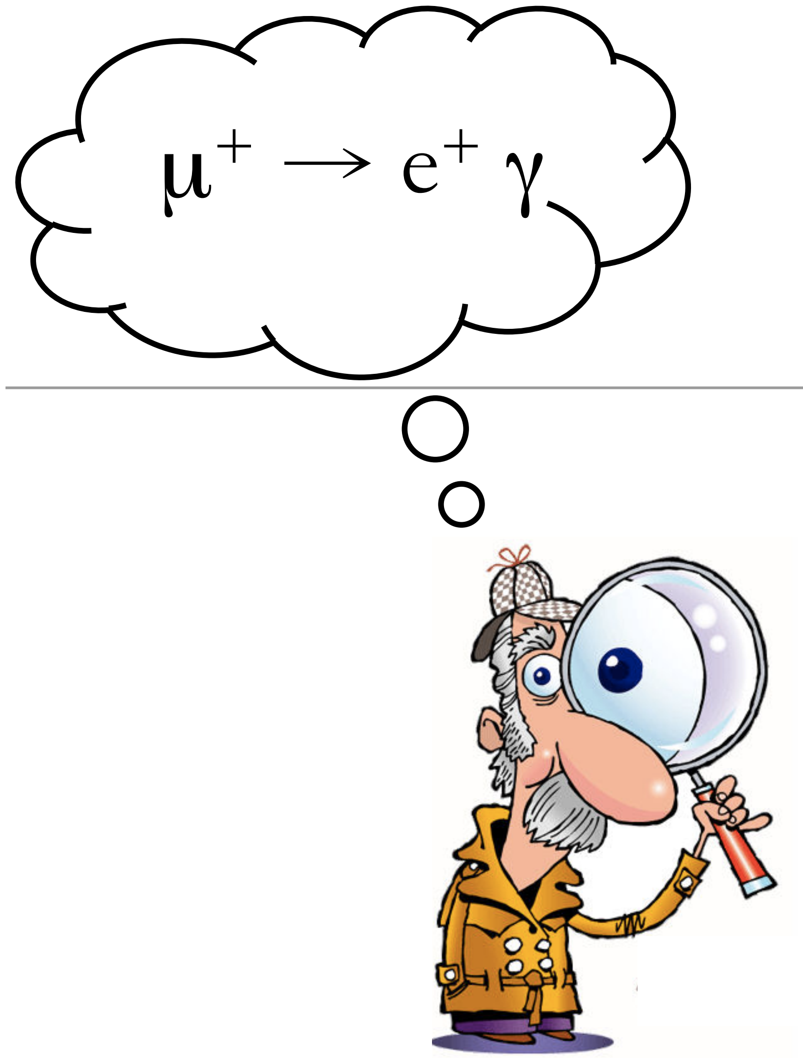
- Virtual BSM particles produced in loops
- Precision and intensity frontier

- Effective field theory approach

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

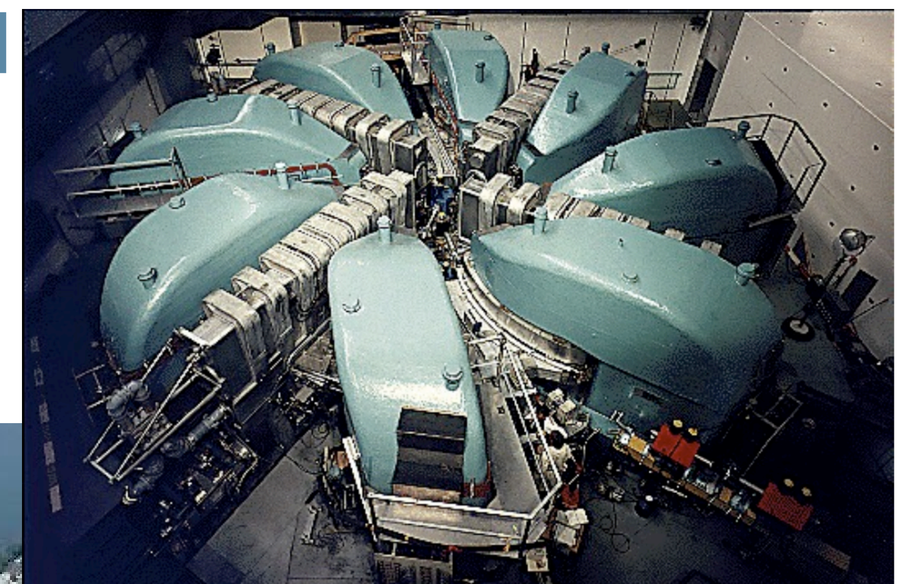


- L_{eff} is in terms of inverse powers of heavy scale



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**

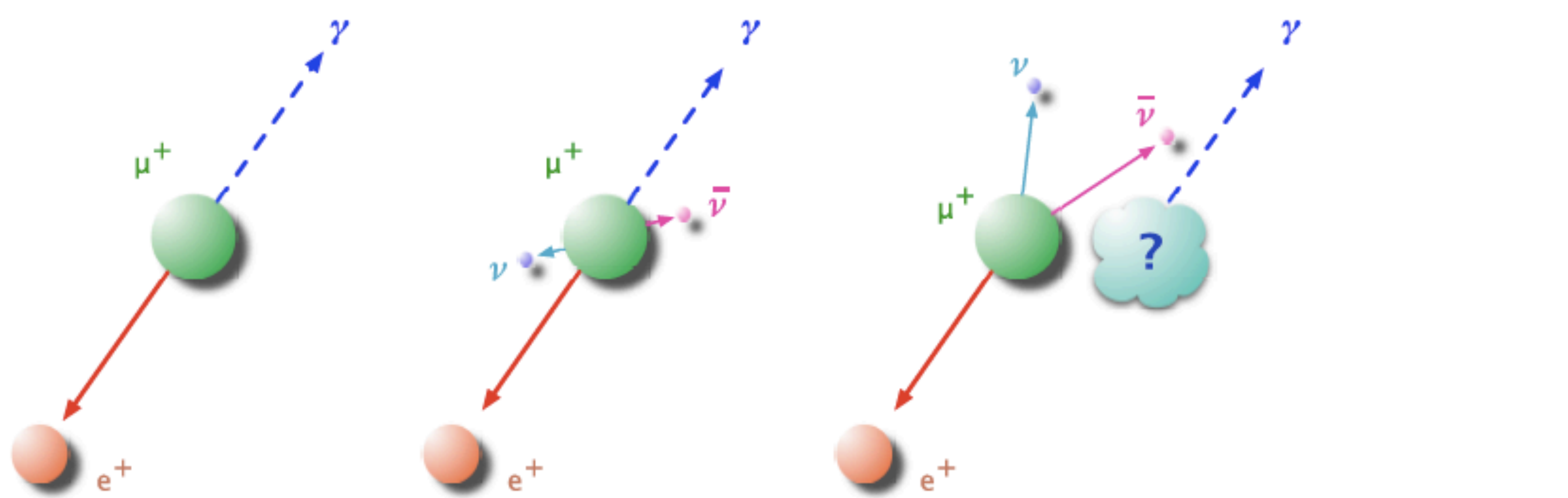
The MEG experiment

- 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)
- **Five observables** $(E_g, E_e, t_{eg}, \vartheta_{eg}, \phi_{eg})$ **to characterize** $\mu^+ \longrightarrow e^+ \gamma$ **events**

signal
BR ~ 10^{-13}

RMD background
BR ~ 10^{-15}

Accidental background
BR ~ 10^{-14}



The MEG experimental set-up

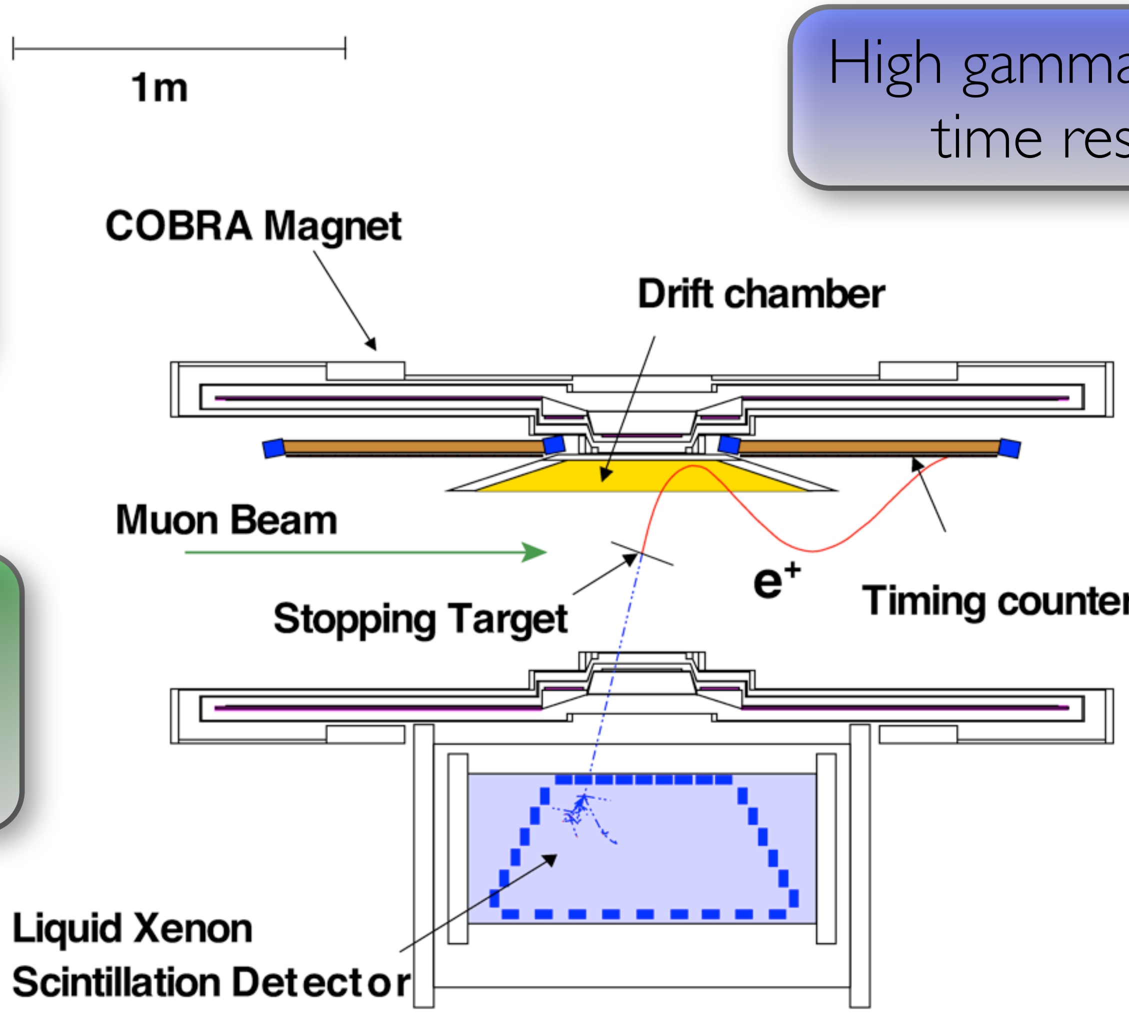
- The MEG experiment aims to search for $\mu^+ \to e^+ \gamma$ with a sensitivity of ~10^{-13} (best upper limit $BR(\mu^+ \to e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)

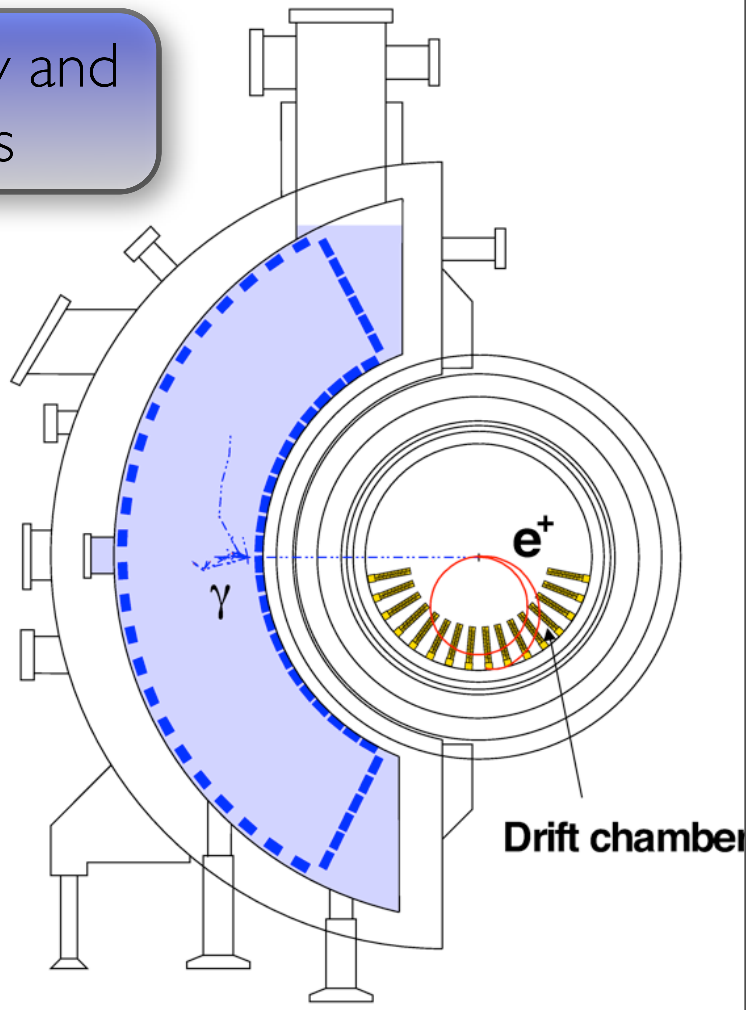
The world most intense dc muon beam at PSI

I = 3x 10^7 muon/s

Very precise positron momentum and time resolutions

High gamma energy and time resolutions





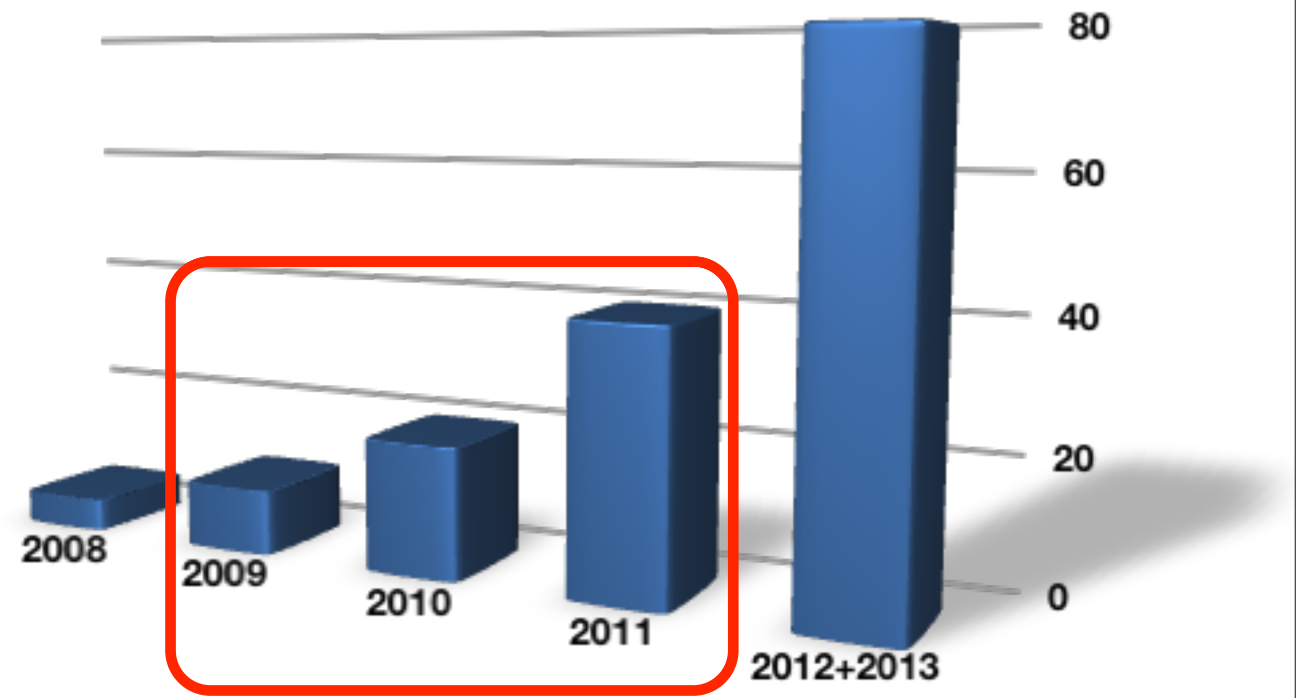
High efficiency event selection and frequency signal digitization

Complementary calibration and monitoring methods

Detector performance and Data sample

Analyzed/ published

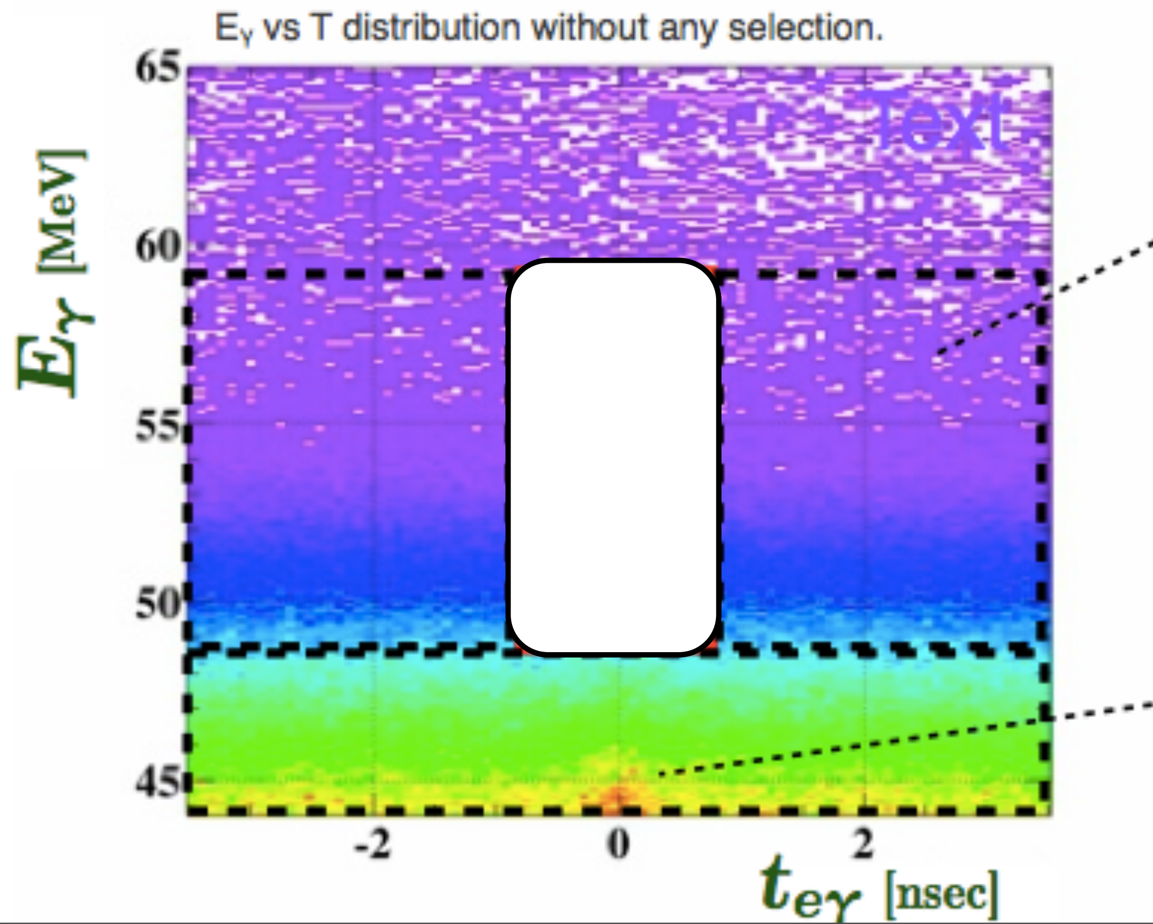
	Resolutions (σ)
Gamma Energy (%)	1.7(depth>2cm), 2.4
Gamma Timing (psec)	67
Gamma Position (mm)	5(u,v), 6(w)
Gamma Efficiency (%)	63
Positron Momentum (KeV)	305 (core = 85%)
Positron Timing (psec)	108
Positron Angles (mrad)	7.5 (Φ), 10.6 (θ)
Positron Efficiency (%)	40
Gamma-Positron Timing (psec)	127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

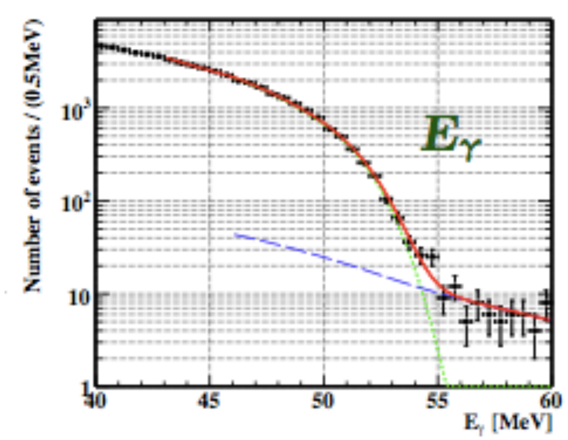


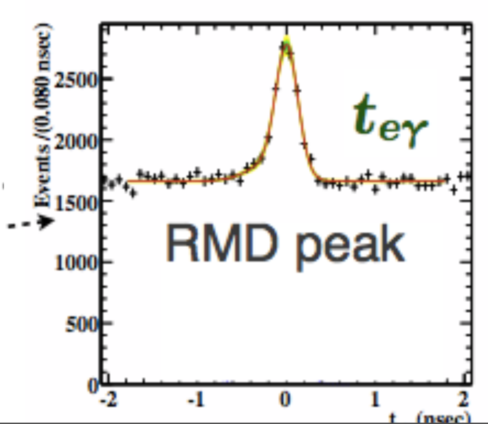
	μ stopped	sensitivity
2009+10	1.75×10^{14}	1.3×10^{-12}
2011	1.85×10^{14}	1.1×10^{-12}
2009+10+11	3.60×10^{14}	7.7×10^{-13}

Physics Analysis Overview and Event Selection

- Five observables **(E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg})** to characterize $\mu \to e\gamma$ 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) *

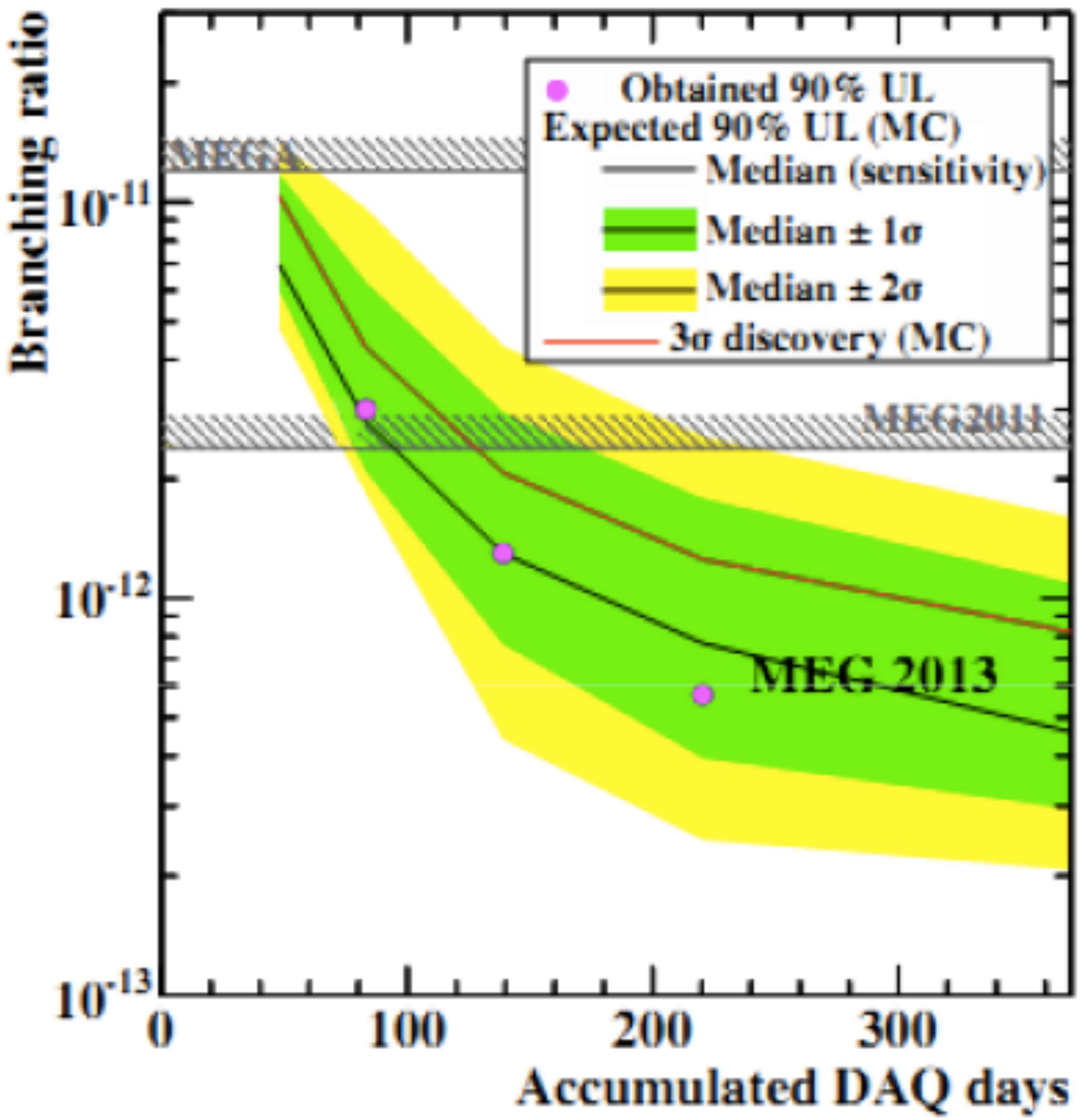
x4 more stringent than the previous upper limit

($B(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12}$ -MEG 2009-10)

x20 more stringent than the MEGA experiment result

($B(\mu^+ \rightarrow e^+ \gamma) < 1.2 \times 10^{-11}$ -MEGA 2001)

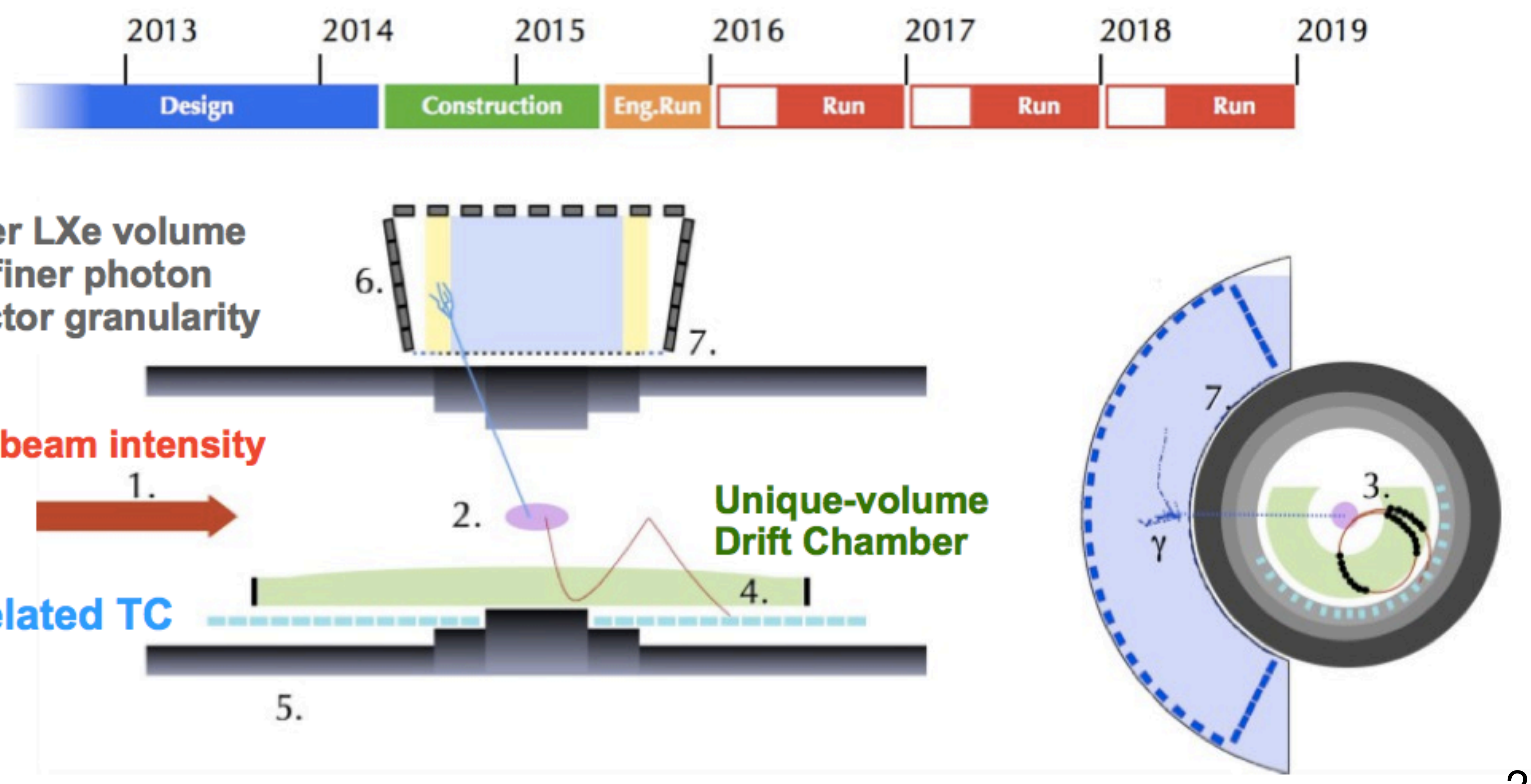
Where we are



Branching ratio
10^{-11}
10^{-12}
10^{-13}
0
100
200
300
Accumulated DAQ days
Obtained 90% UL
Expected 90% UL (MC)
Median (sensitivity)
Median ± 1σ
Median ± 2σ
3σ discovery (MC)
MEGA
MEG2011
MEG 2013

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



Current detector: MEG

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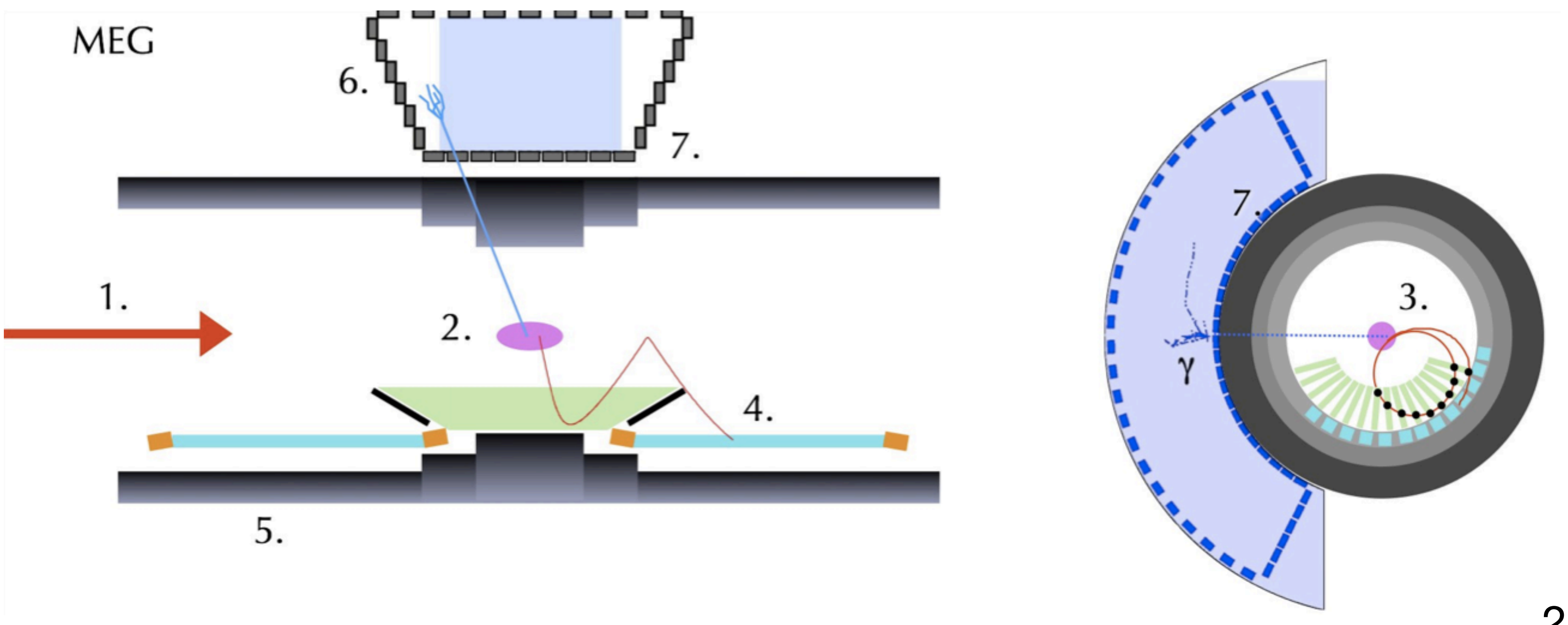

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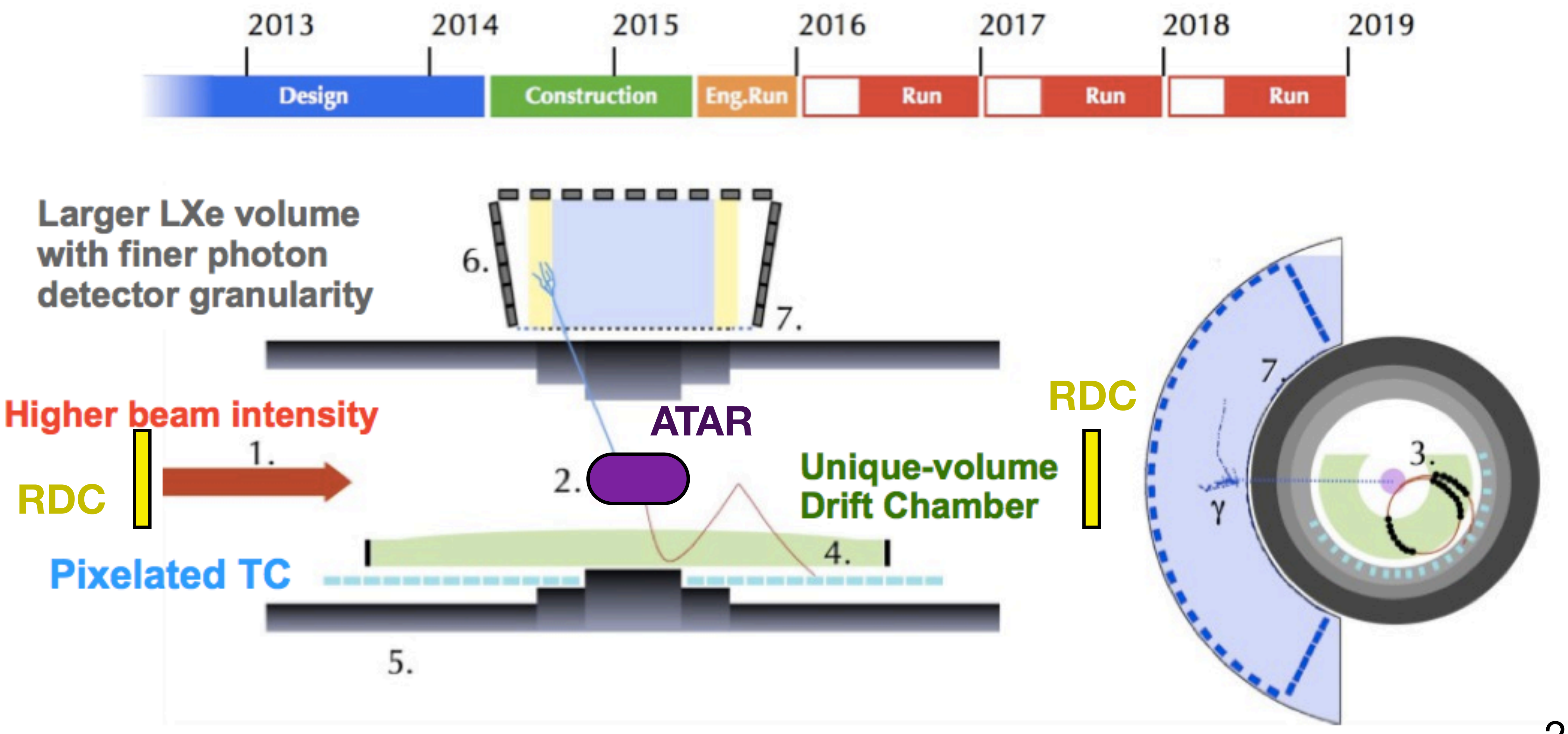

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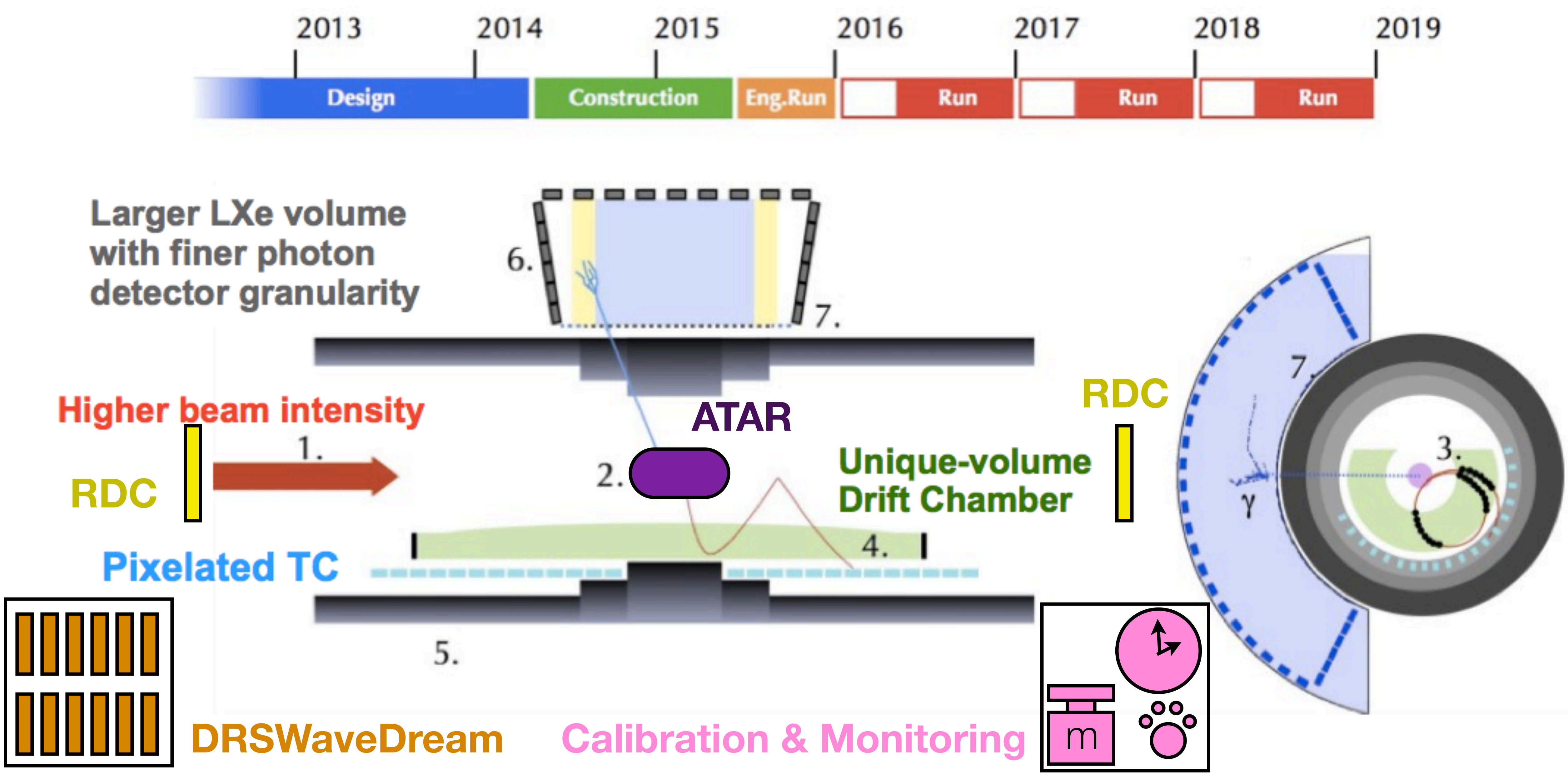

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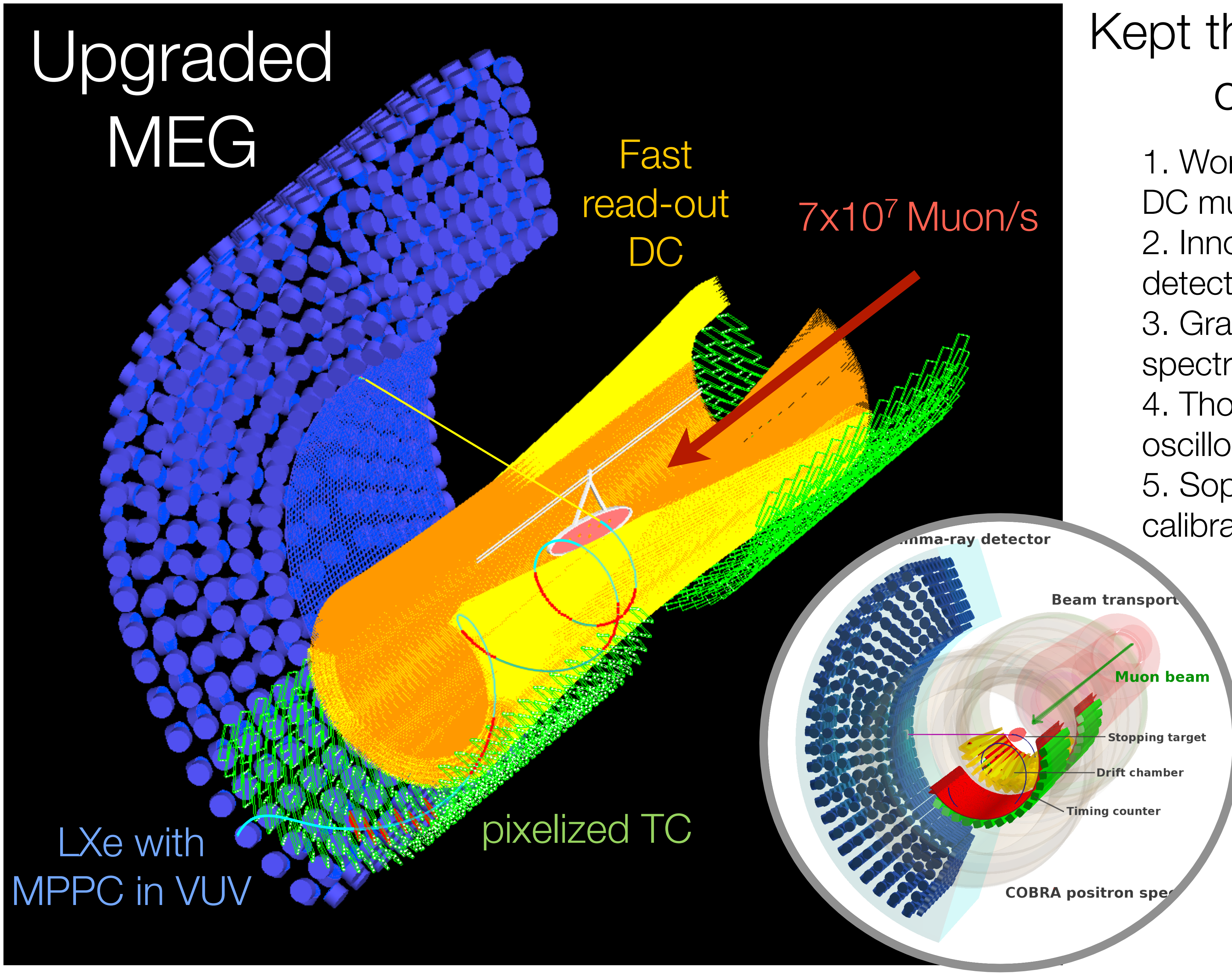

Kept the key elements of MEG

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

Future Prospects: MEGII

- The most intense continuous positive (surface)muon (7×10^7 p/s) beam at low momentum (28 MeV/c)
  - high sensitivity in a relative short time (few years)
  - accidental background undercontrol ($B_{acc} \sim R$)
  - low straggling and good identification of the decay region
  - muons stopped in a thin target (current CH_2 thickness: 204 um)

Kept the key elements of MEG

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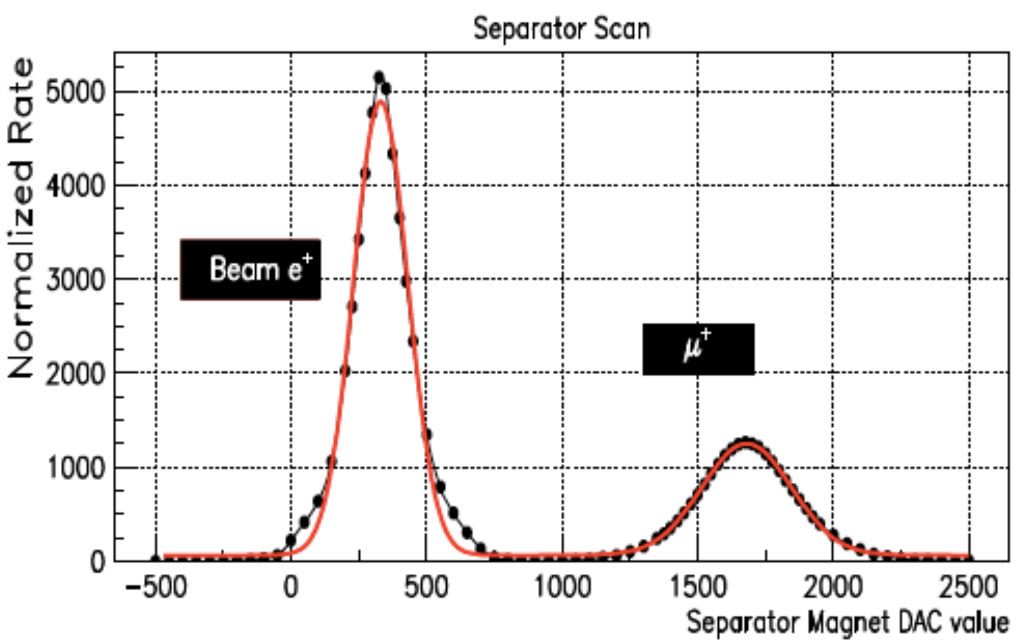

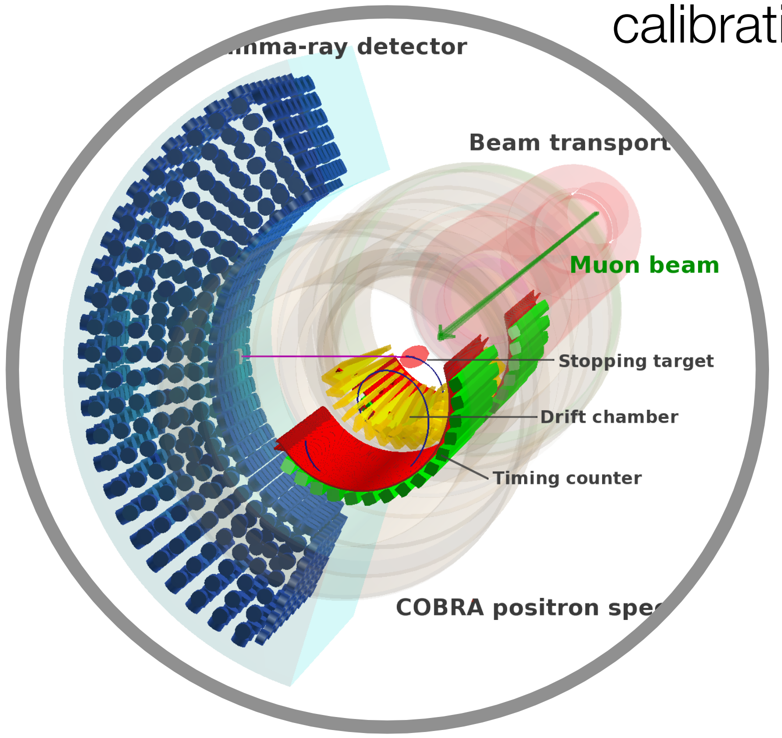

MEG Now

Future Prospects: MEGII

- A large homogeneous calorimeter using only scintillation light
  - very good resolutions for photon energy, direction and time measurements

Kept the key elements of MEG

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2. **Innovative LXe γ-ray detector**
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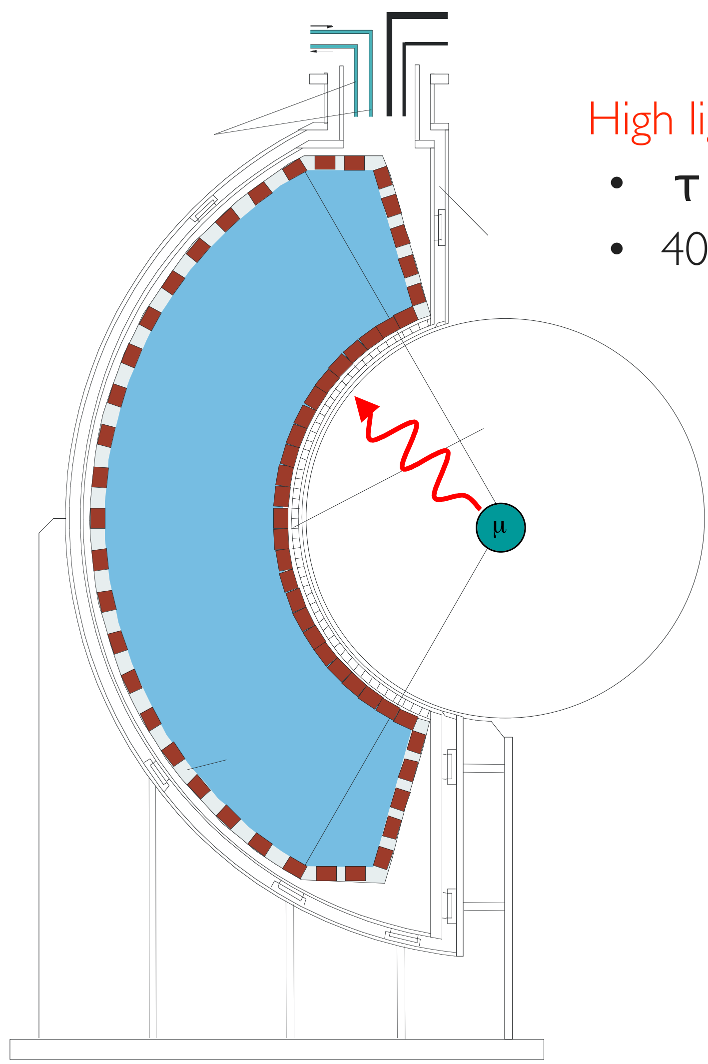
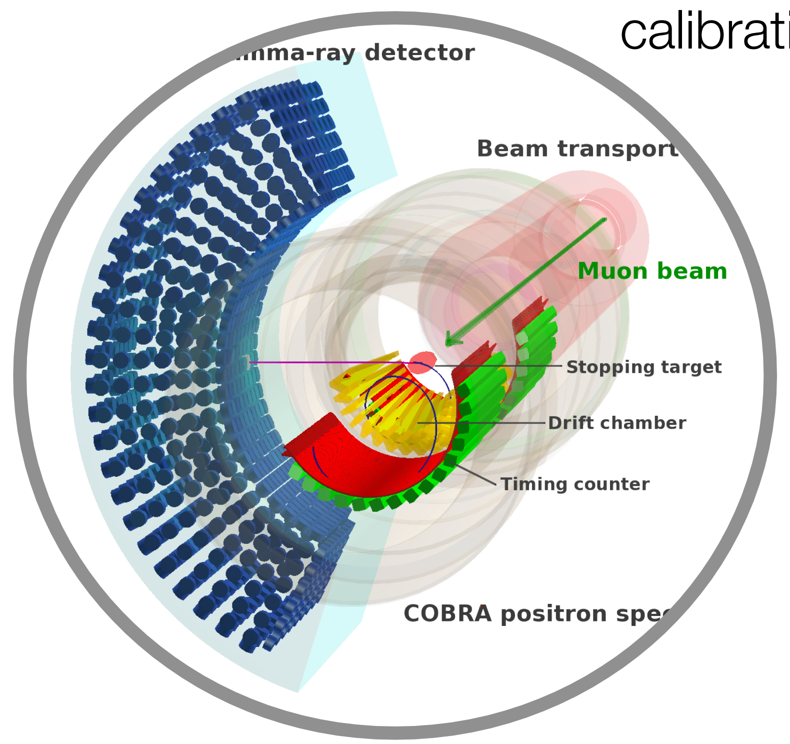


Rapid and
High light yield scintillator

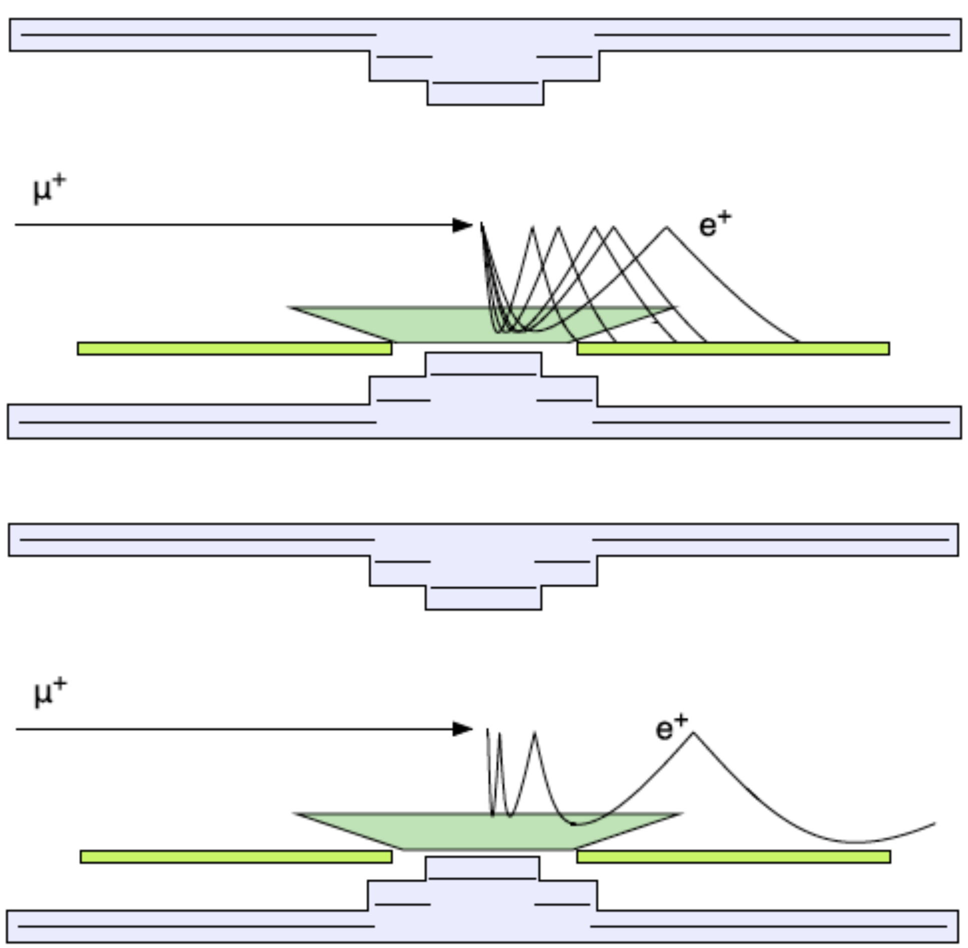
- τ = 4, 22 and 45 ns
- 40000 ph/MeV



MEG Now

Future Prospects: MEGII

- Gradient B-field
  - constant projected radius
  - low momentum e^+ swept away



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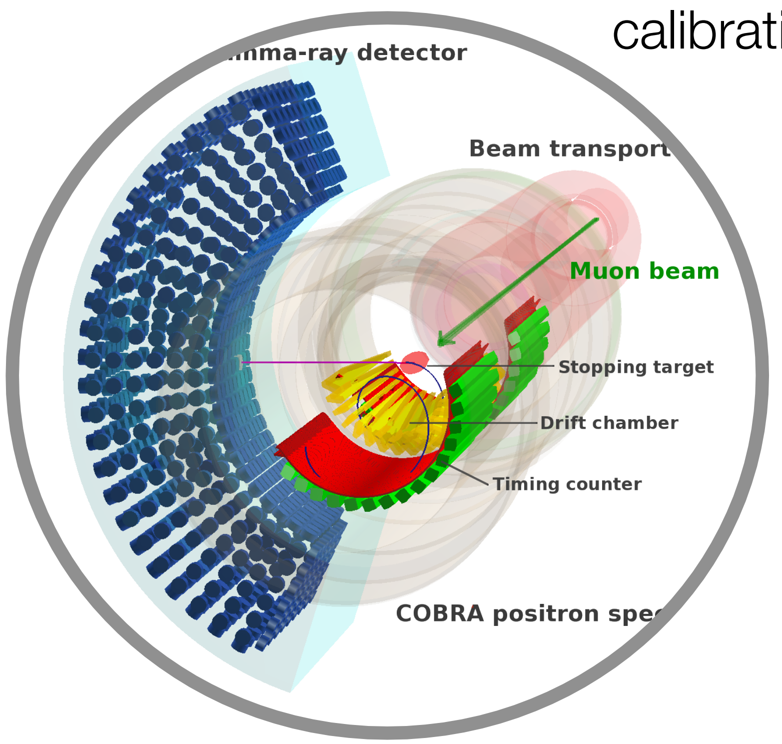
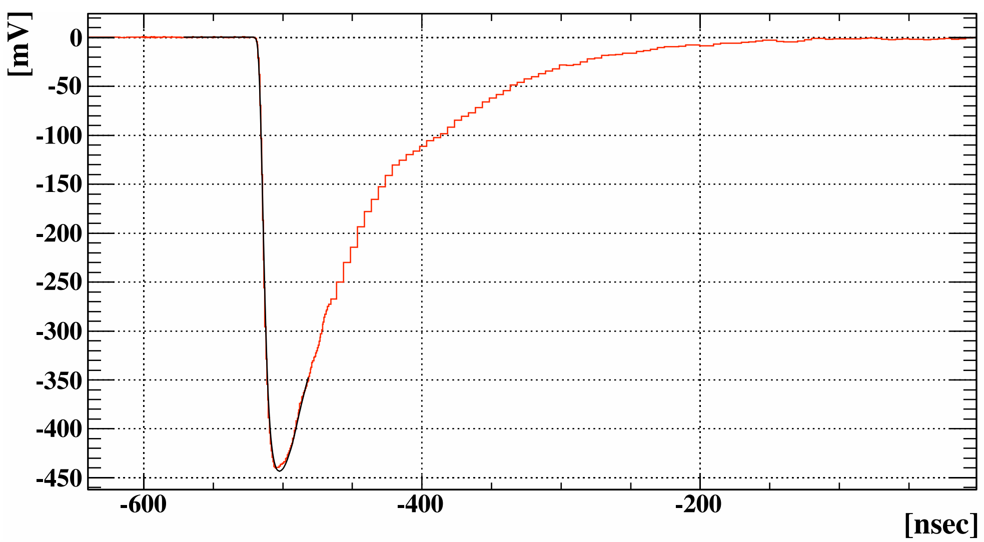


MEG Now

Future Prospects: MEGII

- DAQ based on the Domino Ring Sampler (DRS) chip
  - full waveform digitization up to 5 Gsample/s



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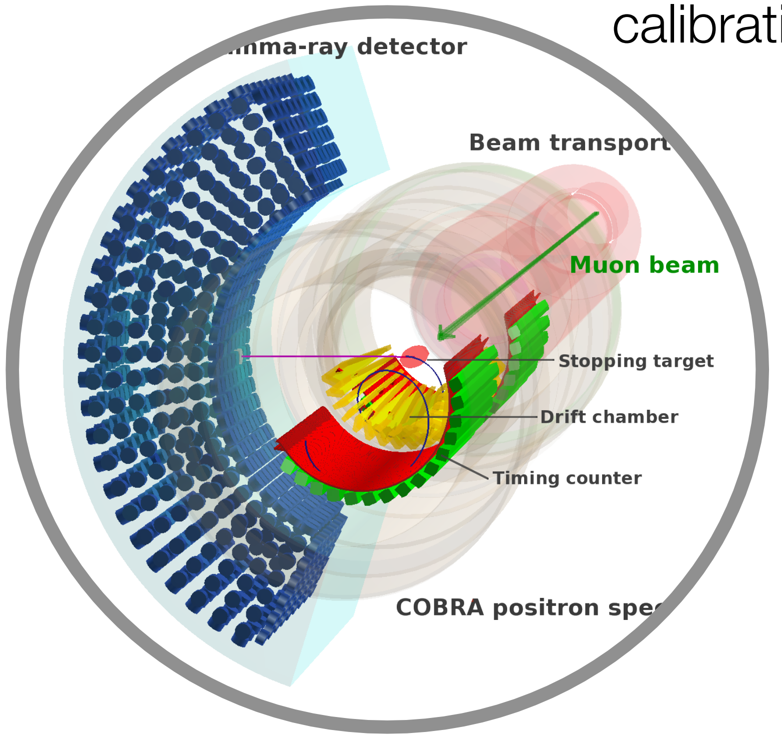
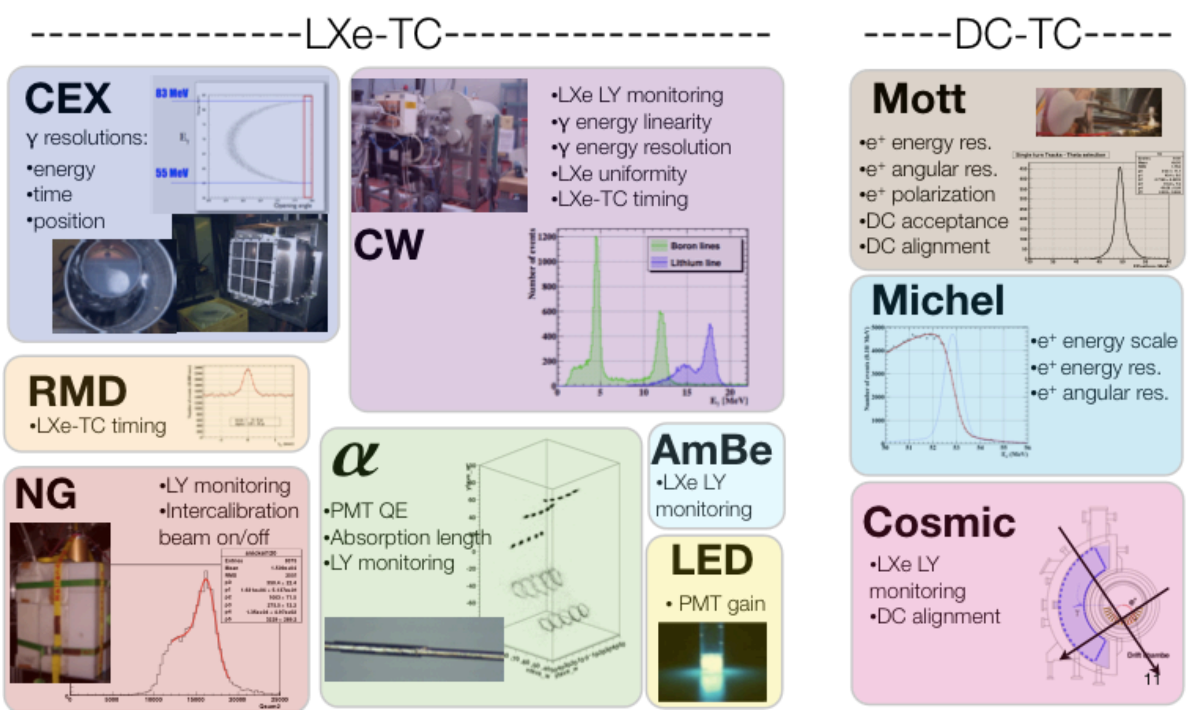


MEG Now

Future Prospects: MEGII

- Complementary calibration and monitoring methods
  - to reach and maintain the required detector performances over the time



Kept the key elements of MEG

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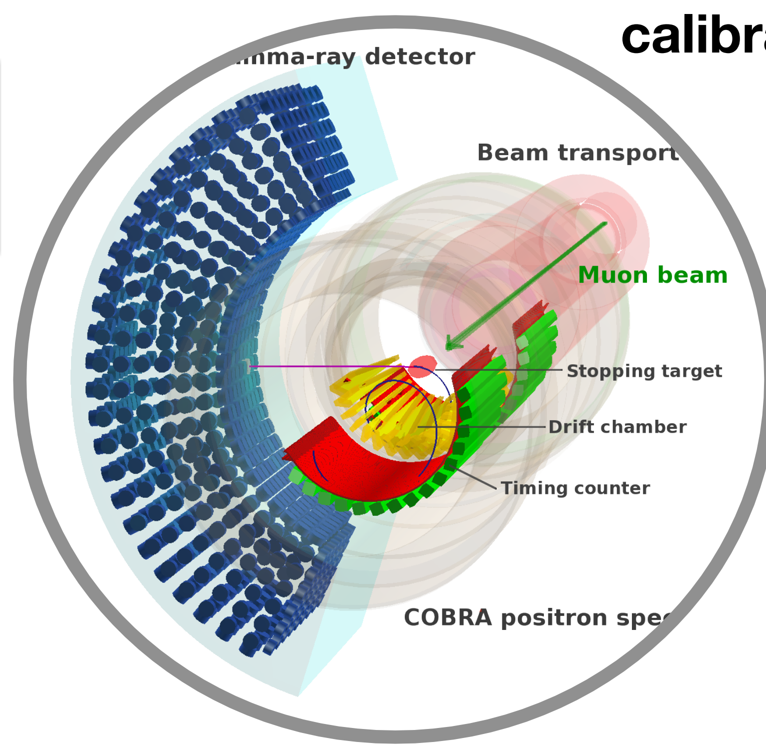
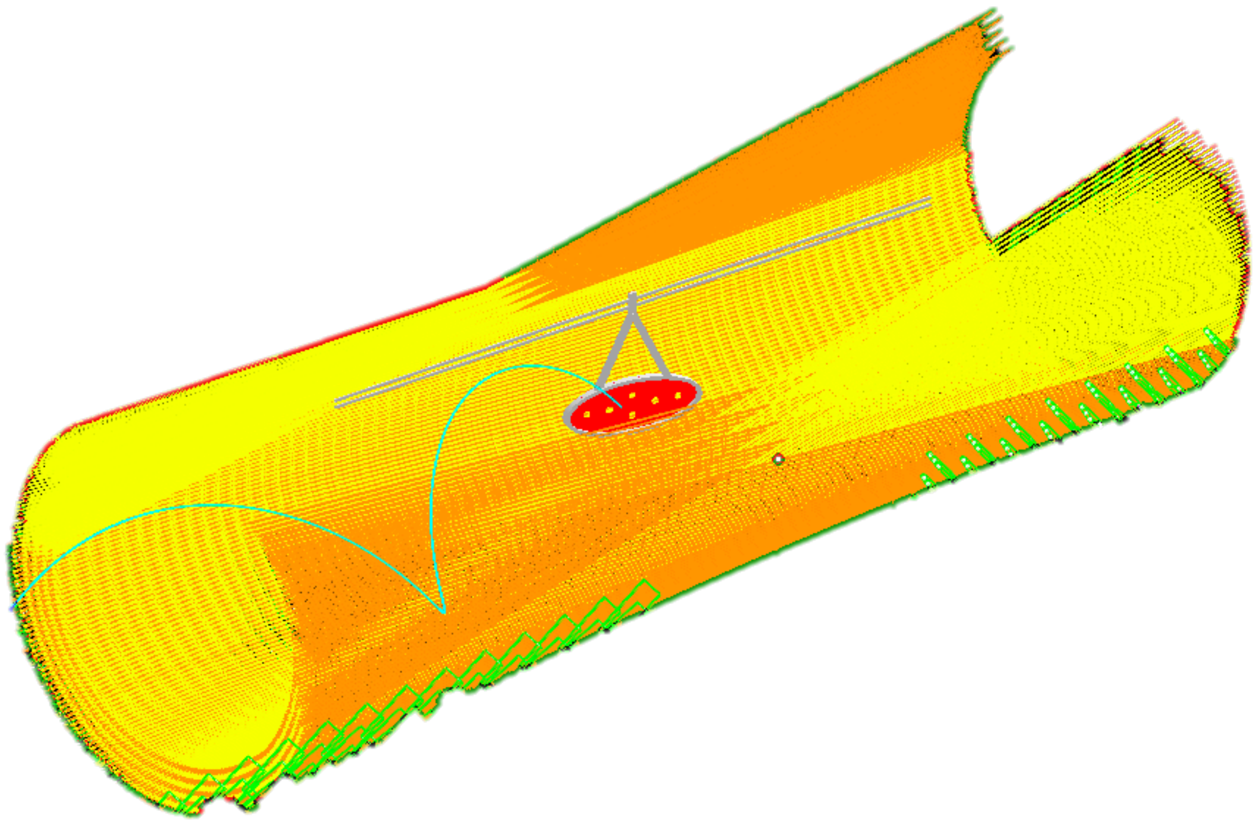


MEG Now

MEGII: the new spectrometer

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);



MEGII: just few numbers

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Less material
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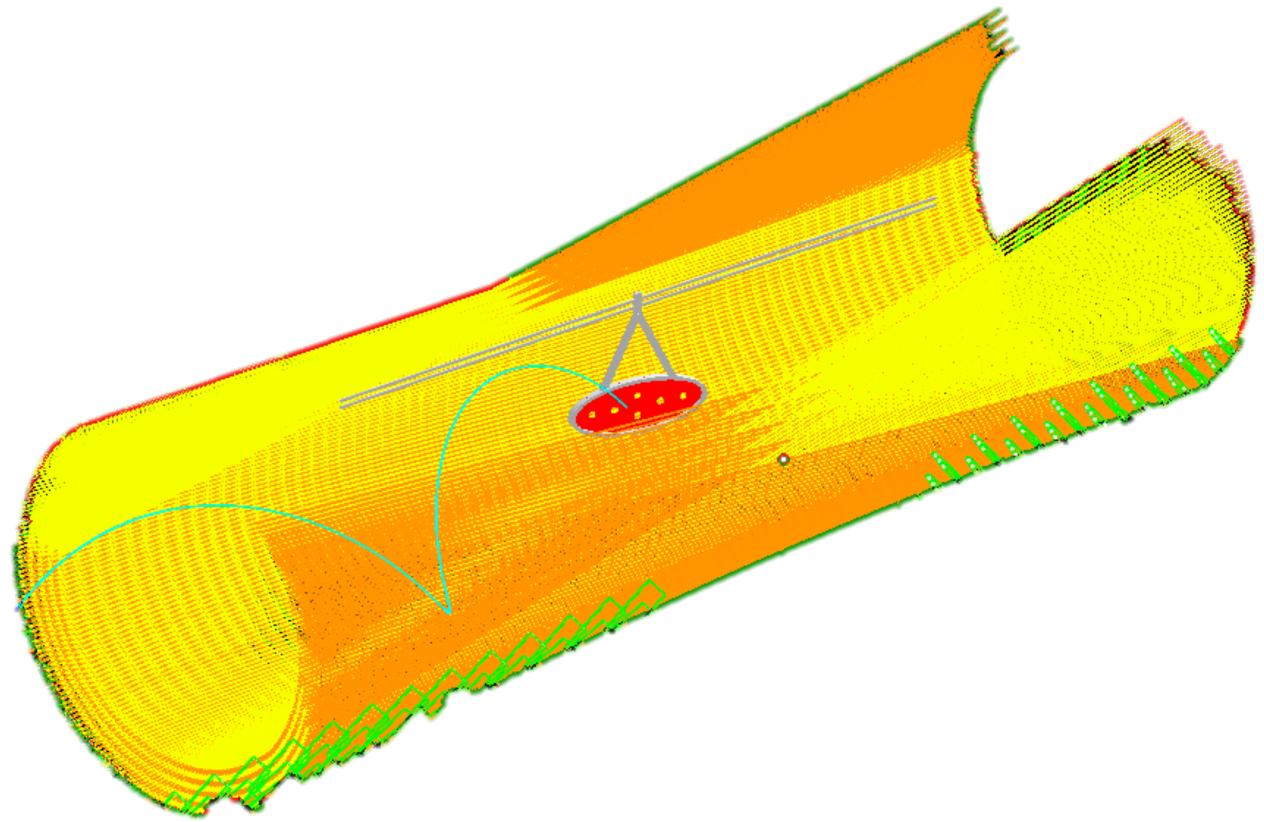

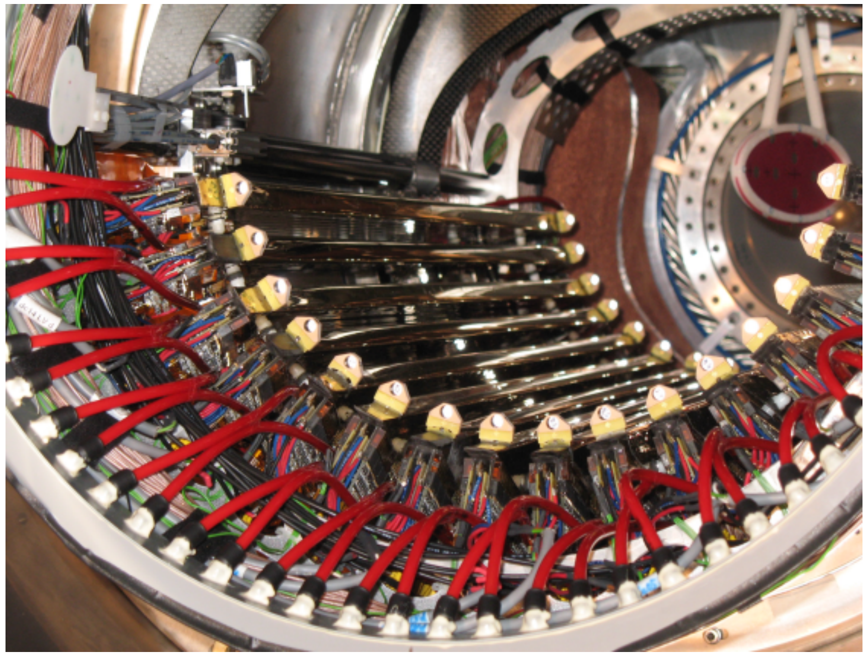

Current DCH

MEGII: just few numbers

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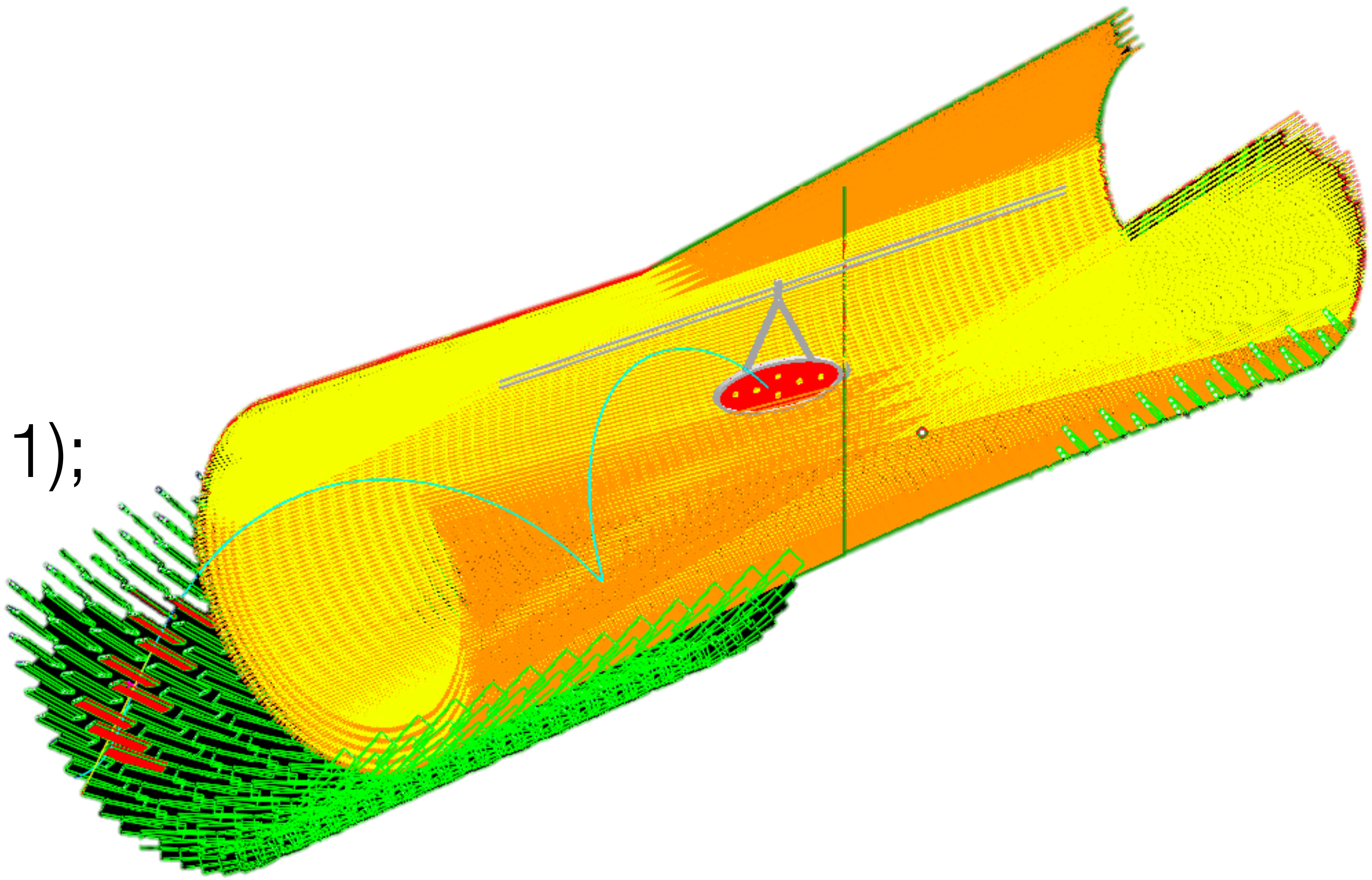
Less material
High Trasparency DC
towards the TC counter

$\sigma(E_e)$ [keV] ~ 150 (325);
$\sigma(\theta_e,\Phi_e)$ [mrad] ~ 5 (7-11);
$\sigma(t_e)$ [ps] ~ 30 (70);



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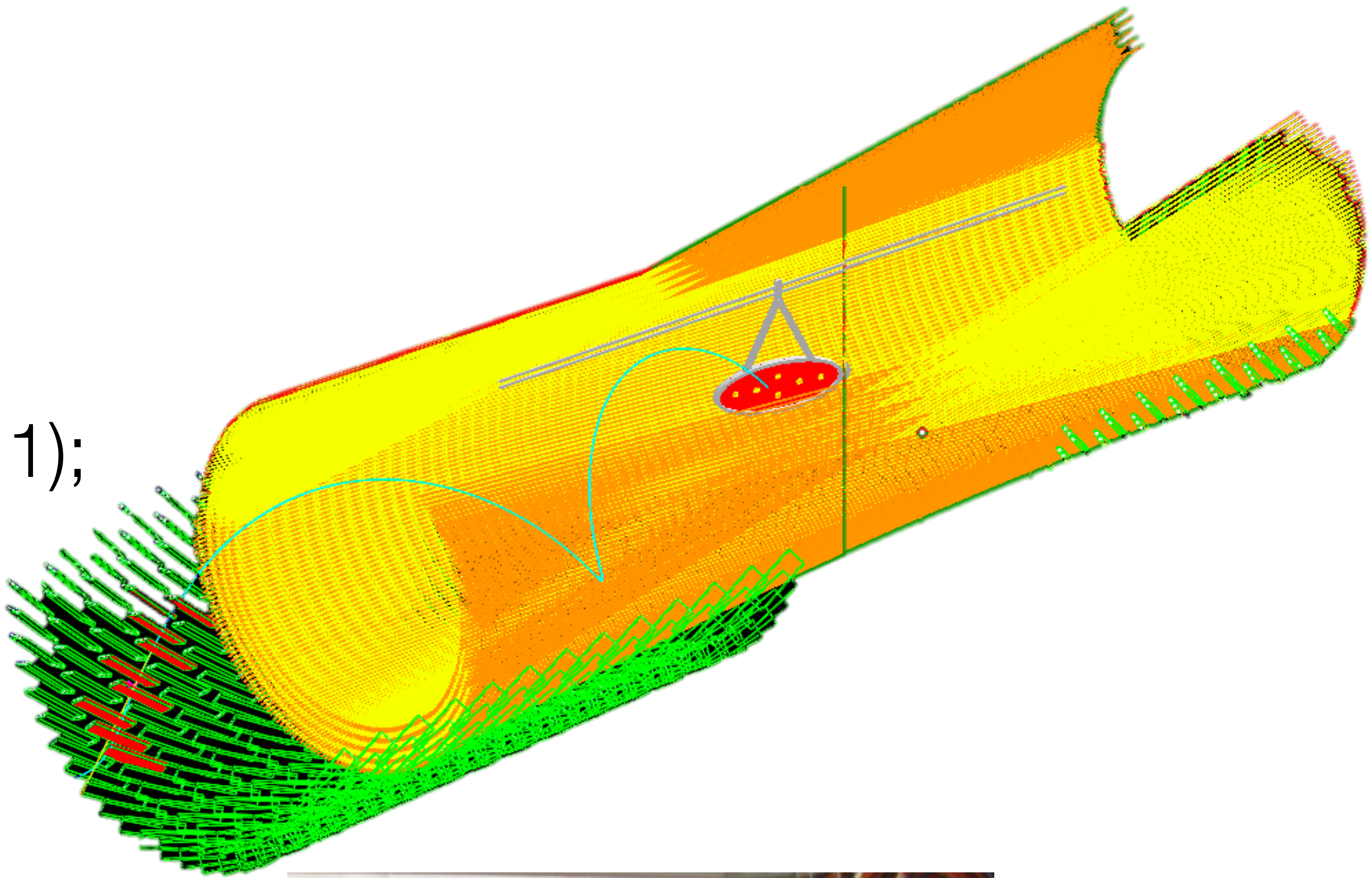
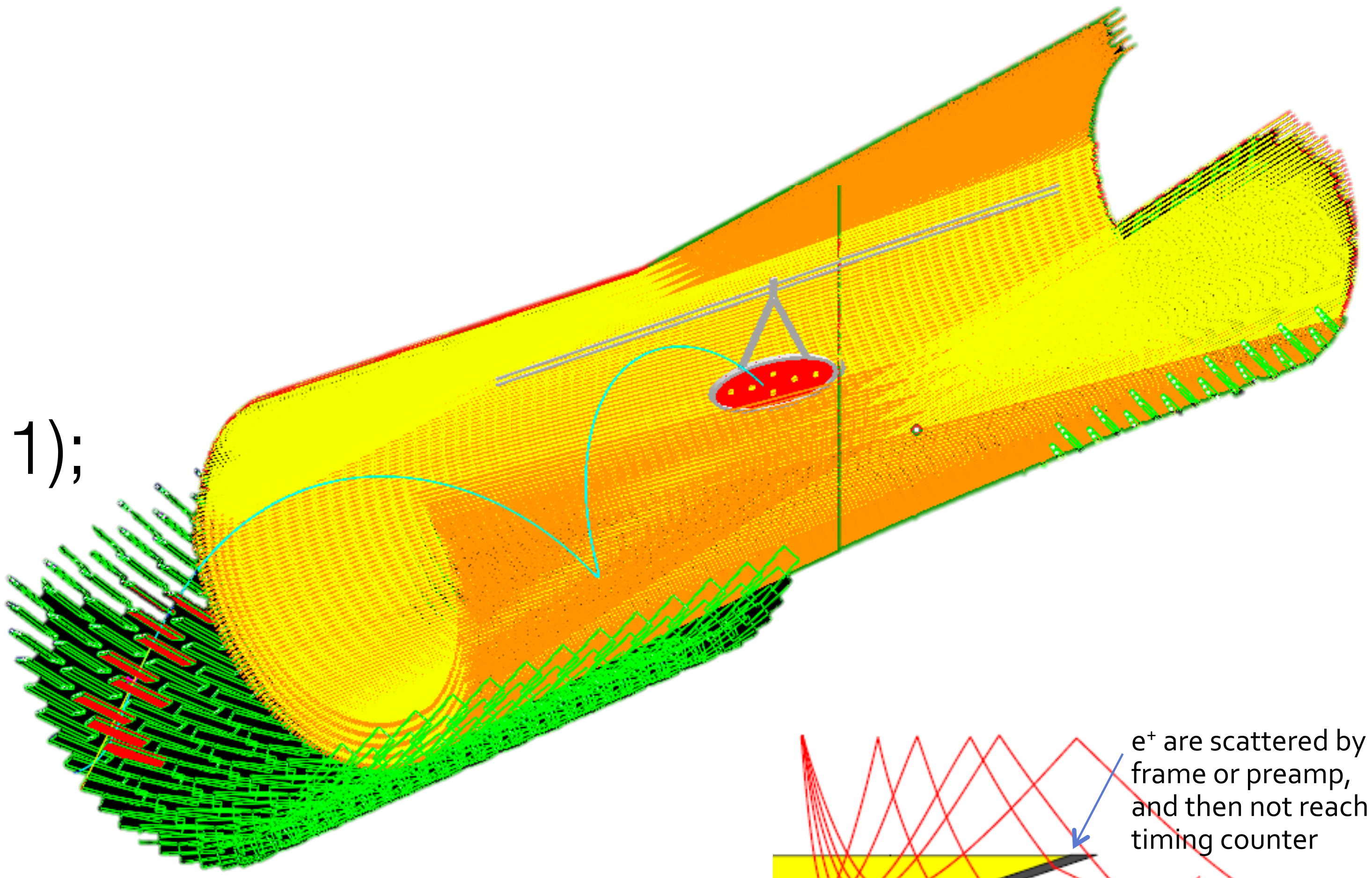


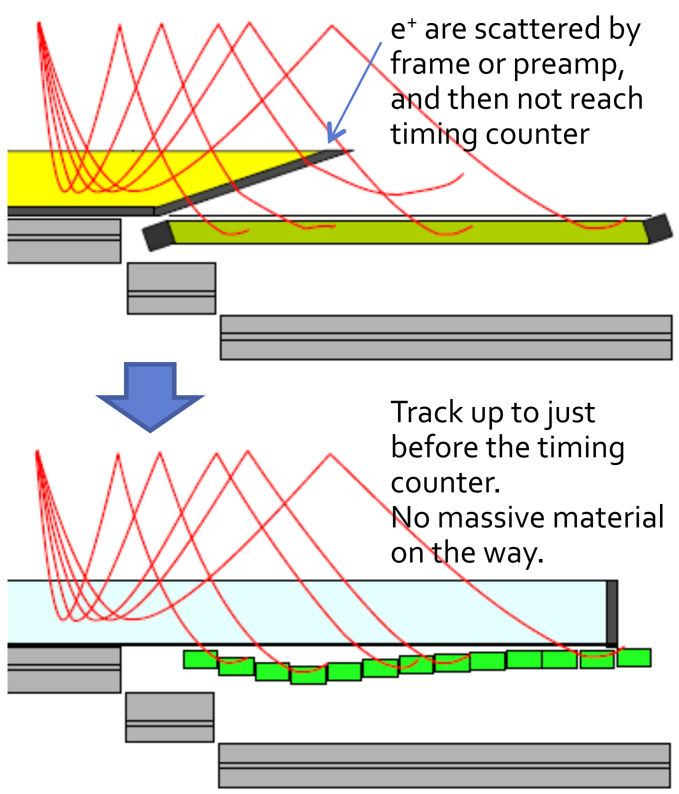
Current TC

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);
$\sigma(t_e)$ [ps] ~ 30 (70);
ε(det) [%] ~ 80 (40);

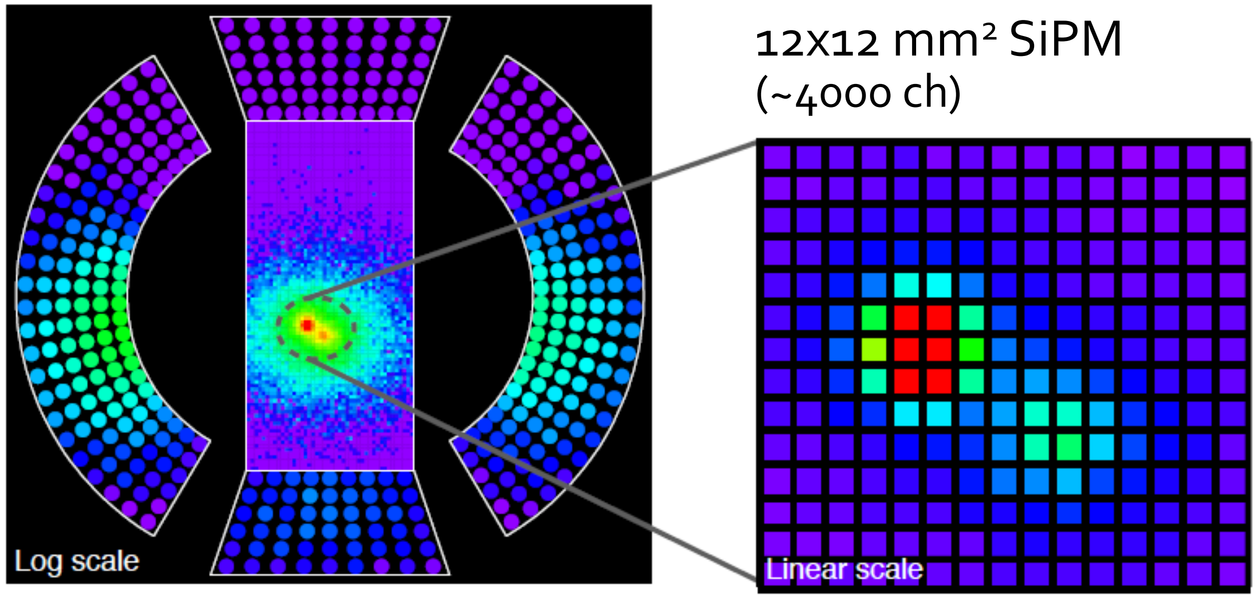




MEGII: the upgraded LXe calorimeter

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)
$\sigma(x_\gamma)$ [mm] ~ 2 (w<2cm) (5);



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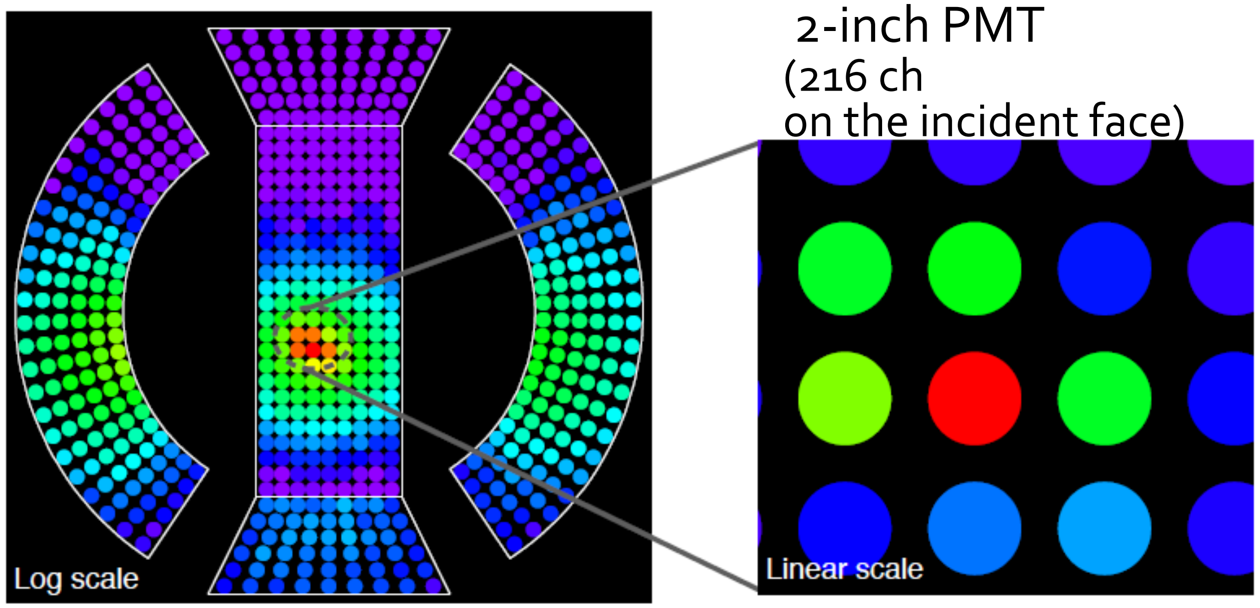
2-inch PMT
(216 ch
on the incident face)



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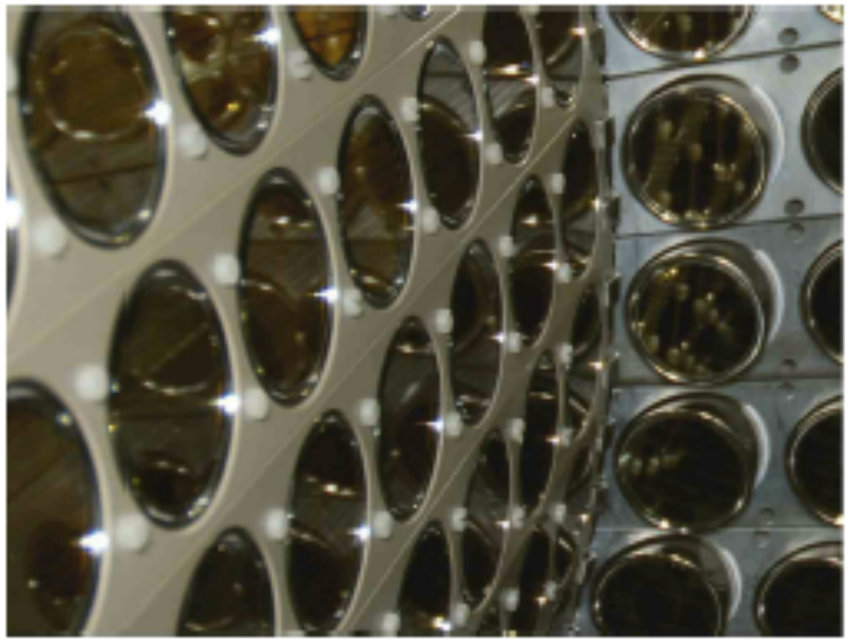
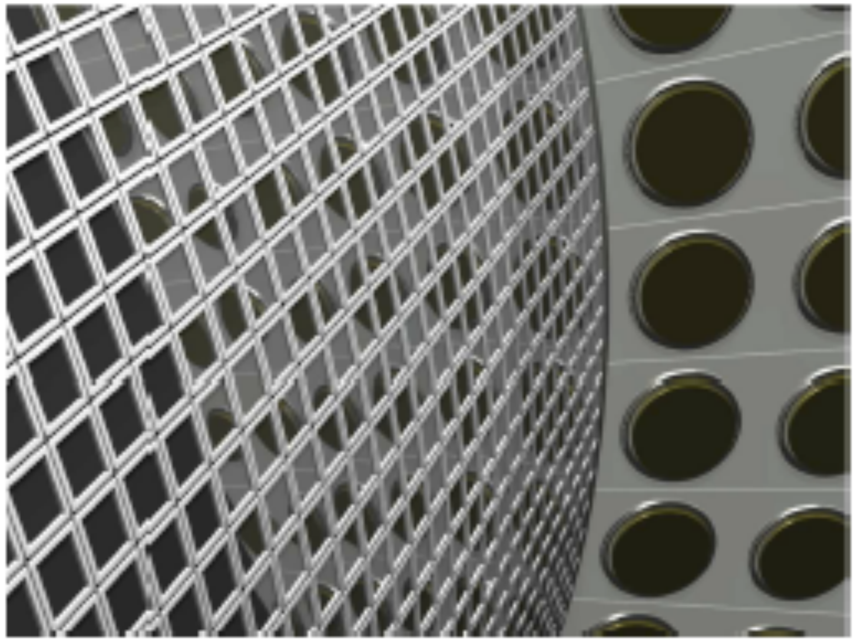
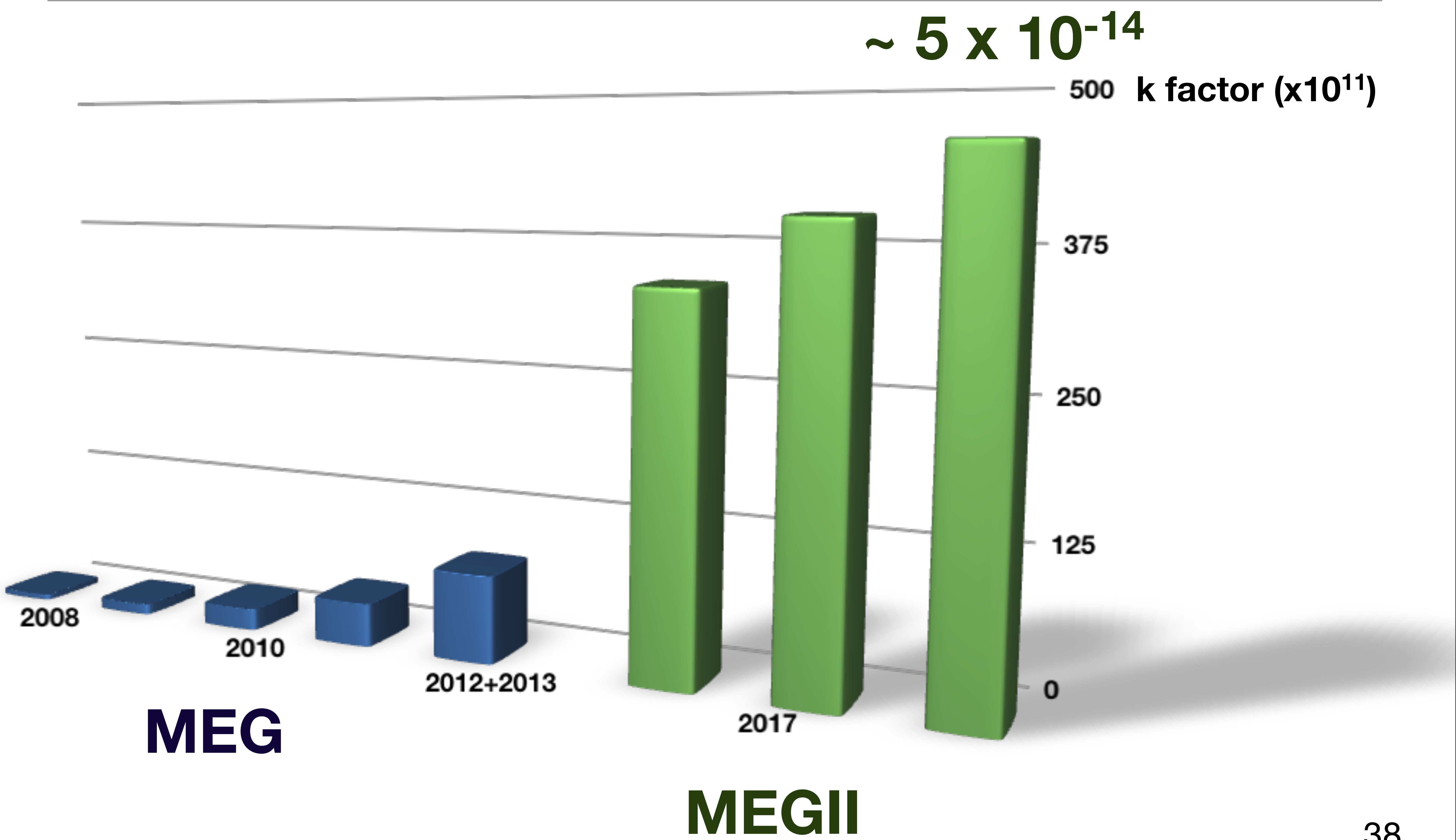
current



upgrade

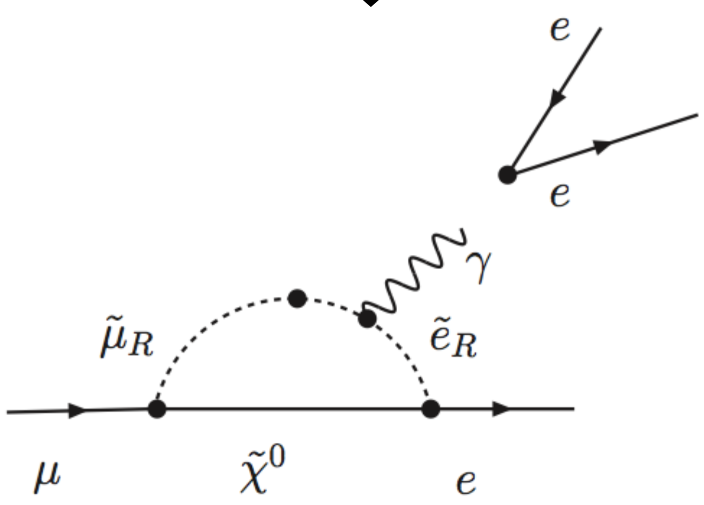


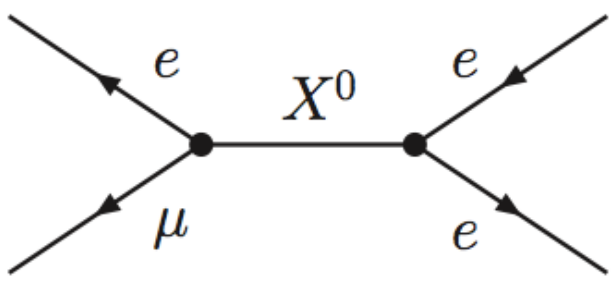
Where we will be

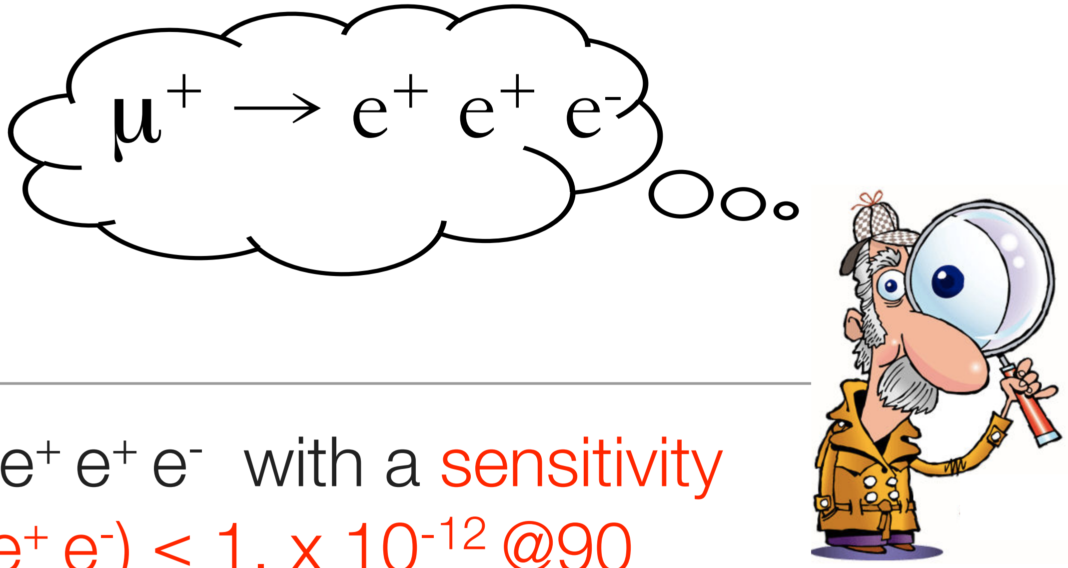


The muon's cLFV effective lagrangian

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





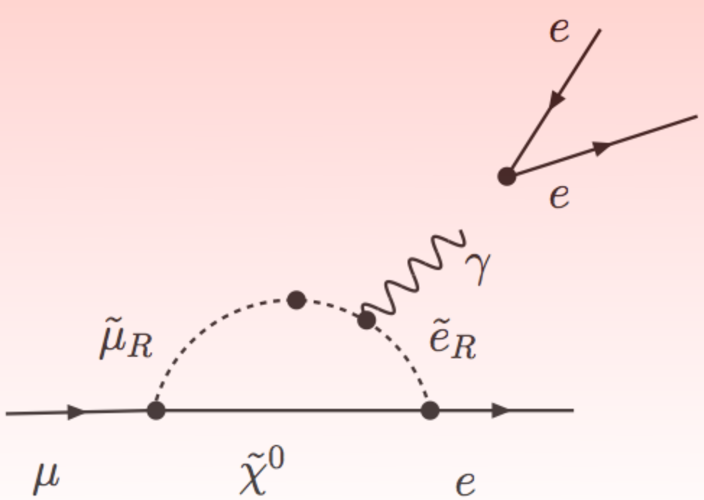


The Mu3e experiment

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

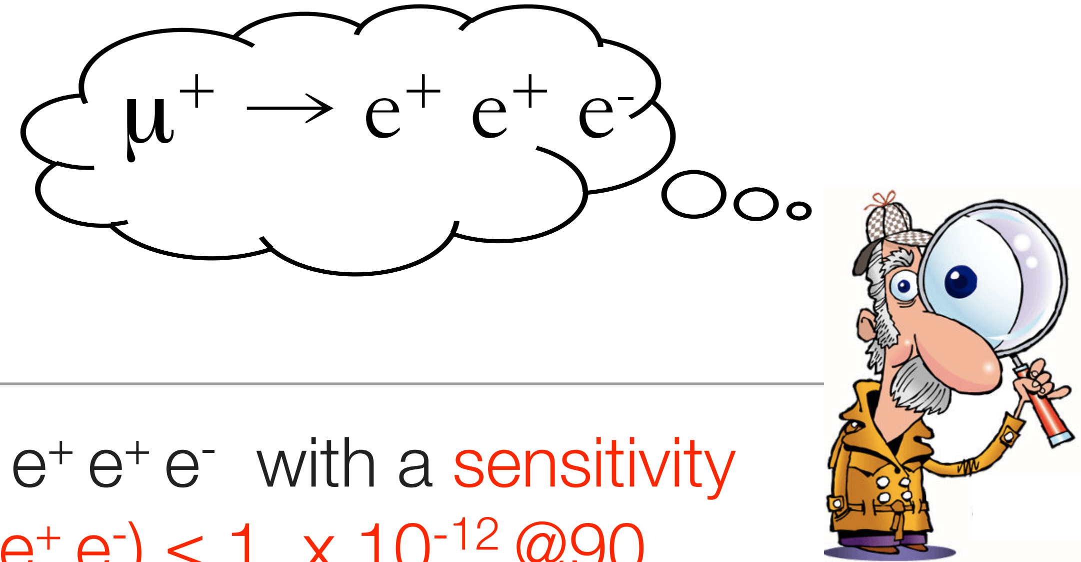
Case 1: dominant dipole coupling ($k \rightarrow 0$)

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



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

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



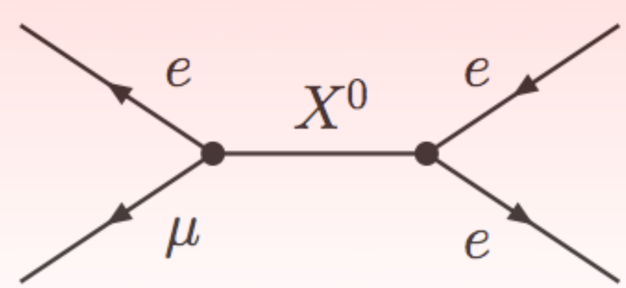
The Mu3e experiment

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

<u>Case 2</u>: tree level interaction (k > 10)

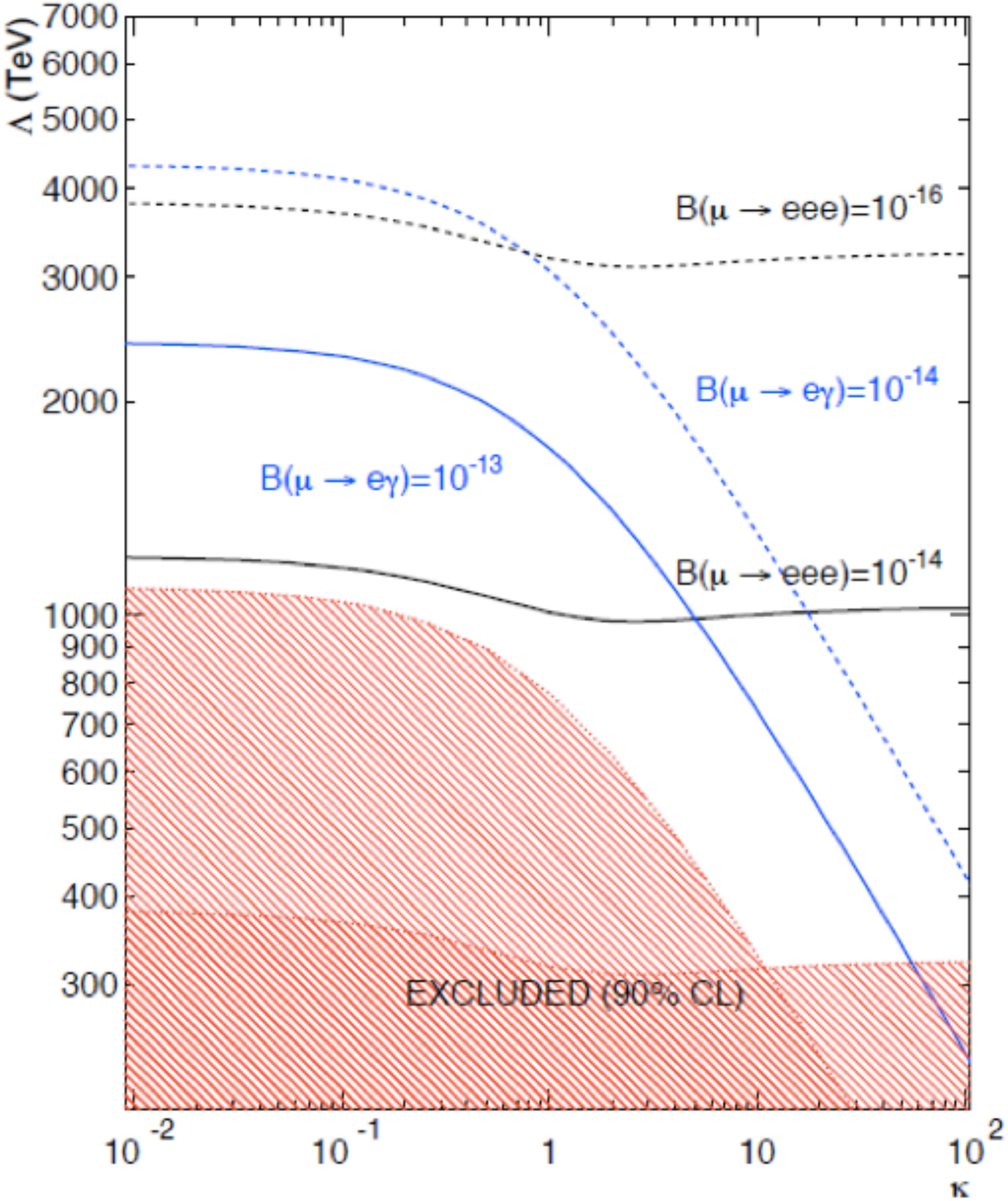
$$\mathcal{L}_{cLFV} = \frac{m_\mu}{(k+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2}\bar{\mu}_R \gamma_\mu e_L \bar{f} \gamma^\mu f$$

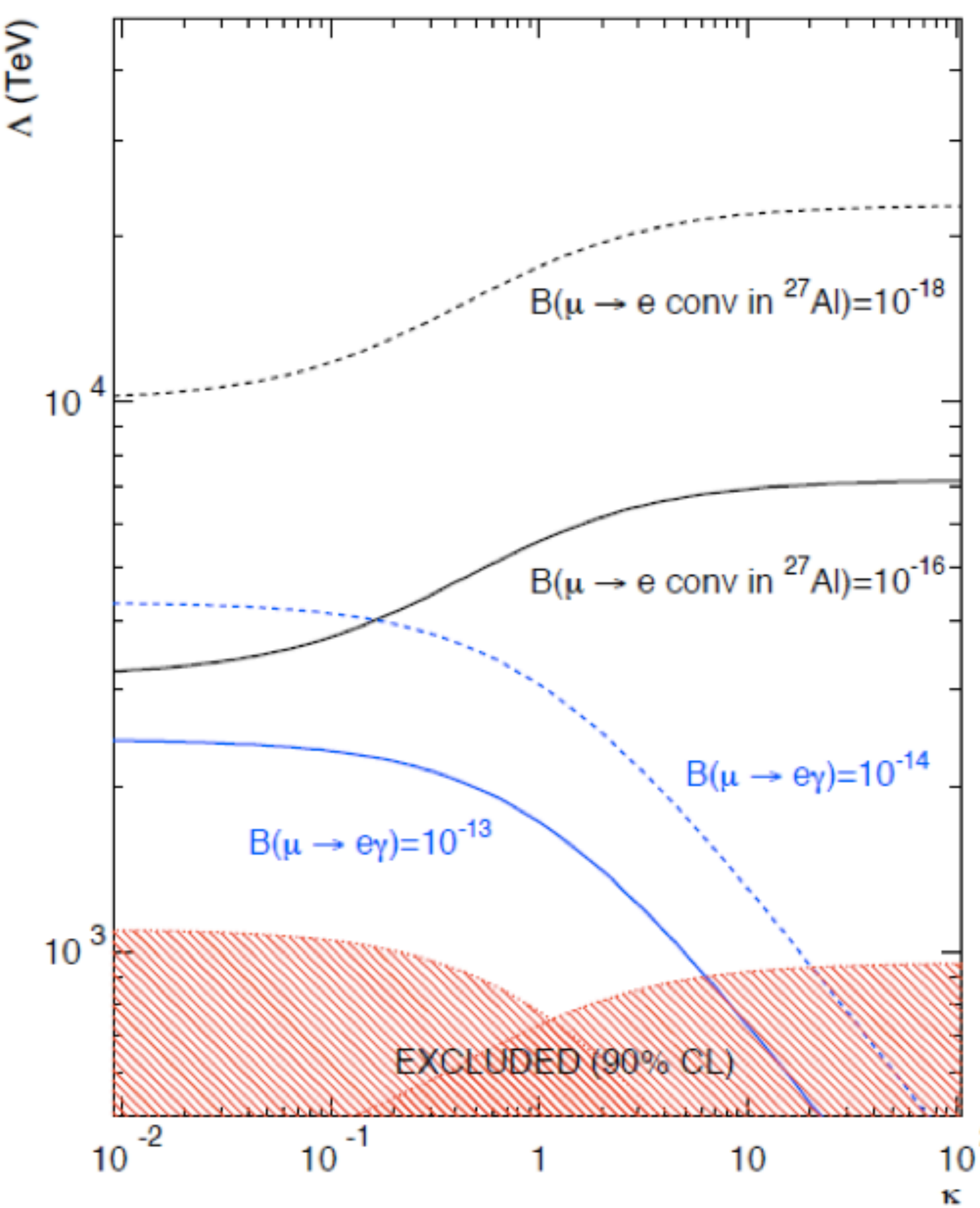
$$\frac{BR(\mu^+ \to e^+ e^+ e^-)}{BR(\mu^+ \to e^+ \gamma)} >> 1$$



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

cLFV search: complementry approch





Summary

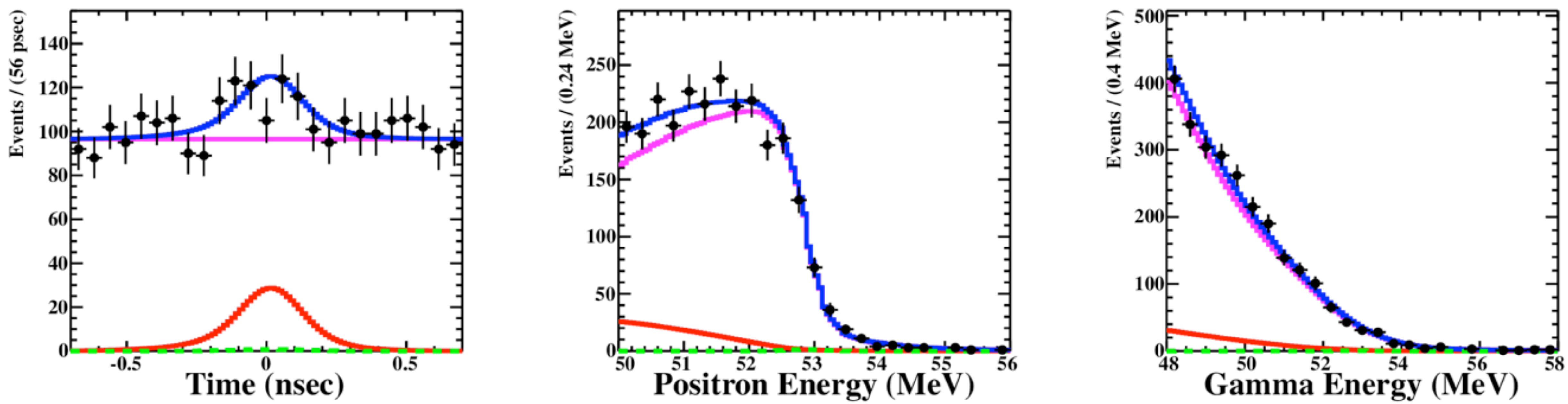
- Lepton flavour violation is presently one of the most exciting branch of particle physics

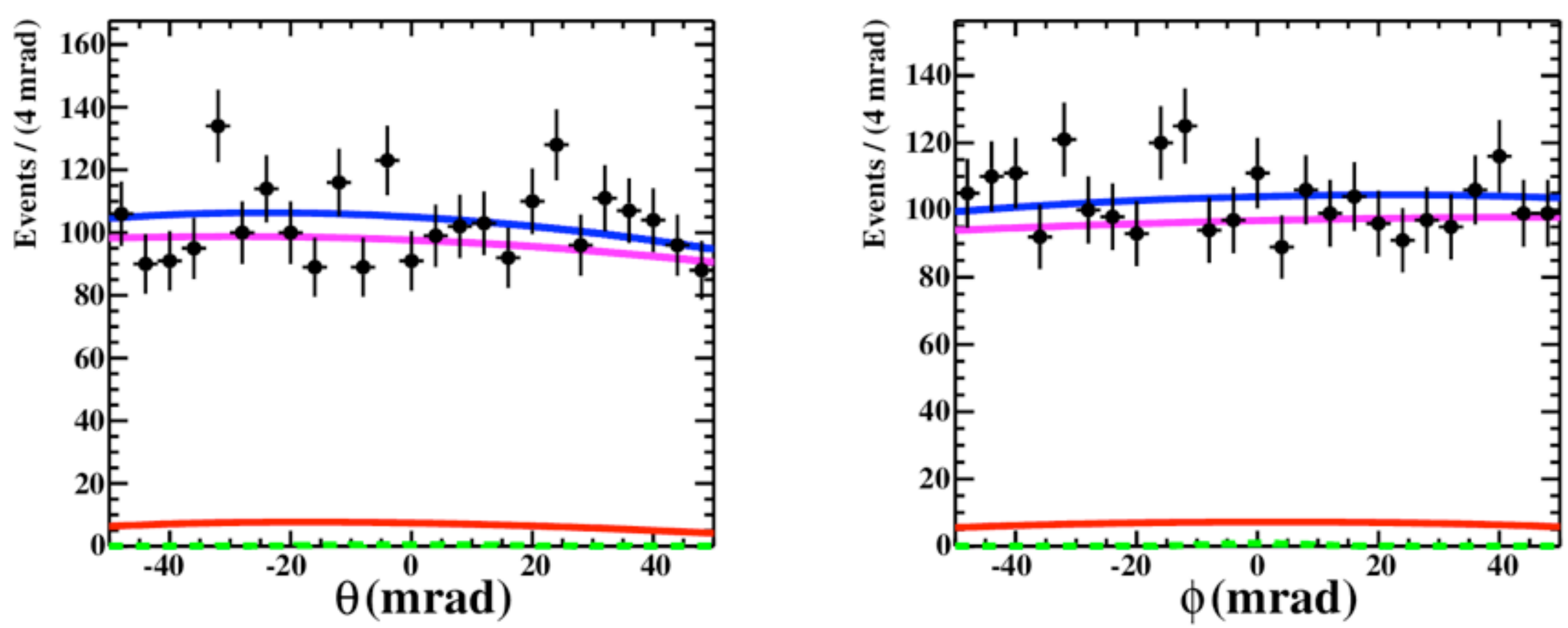
- The MEG experiment @PSI was design to reach a sensitivity of ~ few x 10^{-13} on the $\mu^+ \rightarrow e^+ \gamma$ decay. It has set the most stringent upper limit on the BR($\mu^+ \rightarrow e^+ \gamma$) < 5.7 x 10^{-13} (based on the 2009-2011 sample)

- 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}

Likelihood Fit (2009-2011)



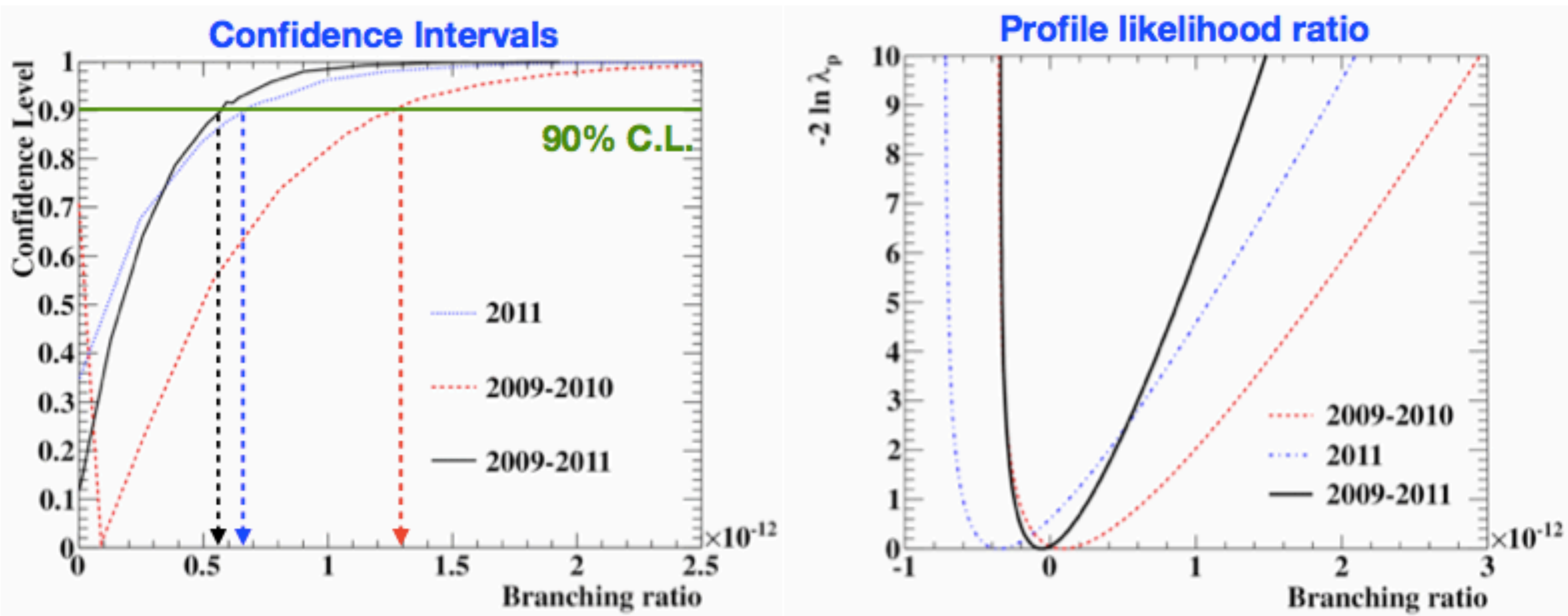


Green: Signal
Red: RMD
Purple: BCK
Blue: Total
Black: Data

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