Overview of worldwide efforts in the search for charged lepton flavour violation with muons

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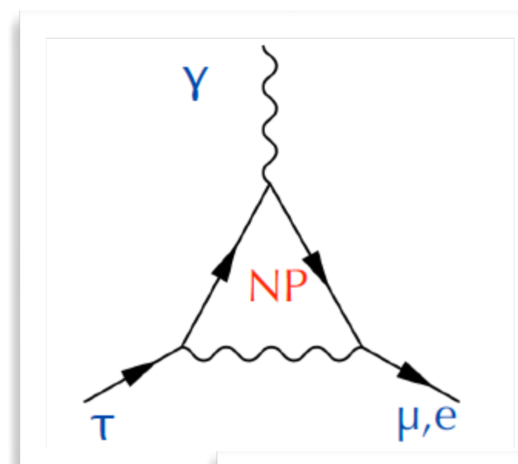
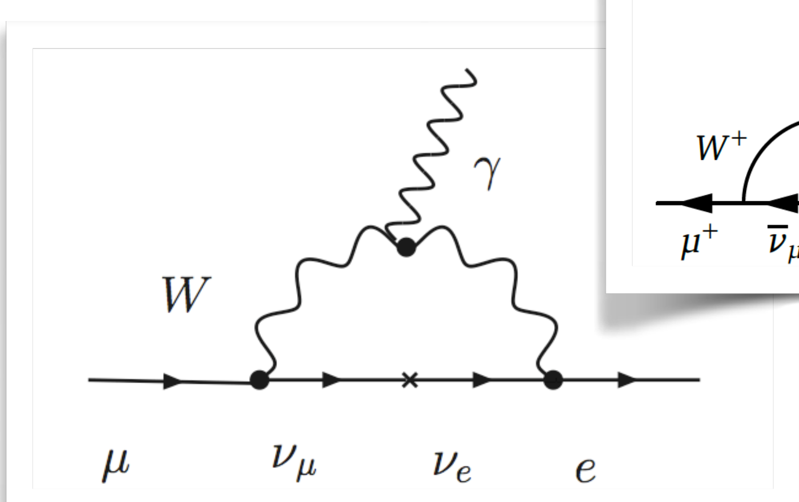
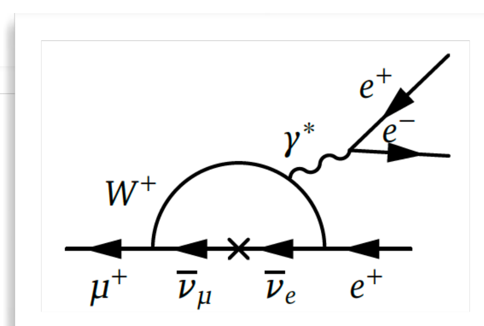
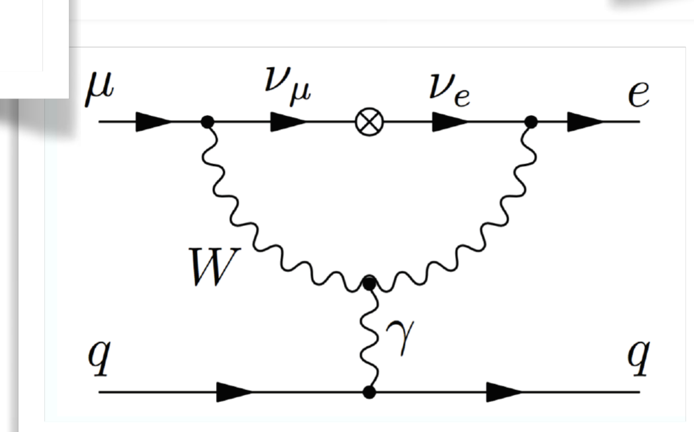
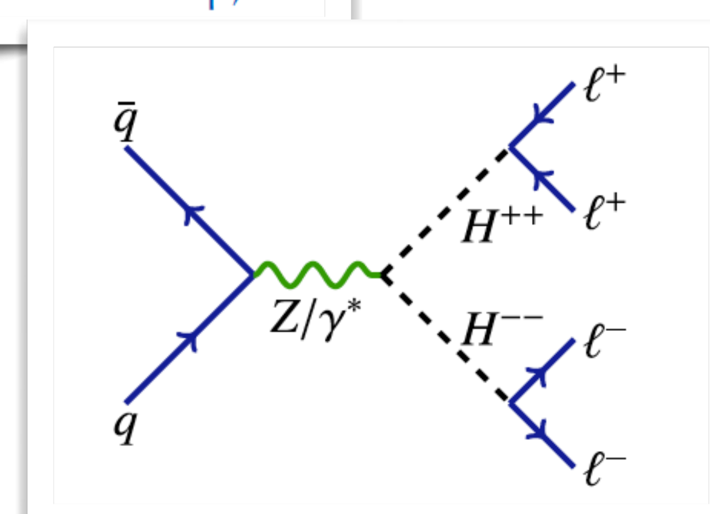
University of Pisa/INFN (Italy) and Paul Scherrer Institute (Switzerland)
UniZH - July 4th, 2022 LF(U)V workshop









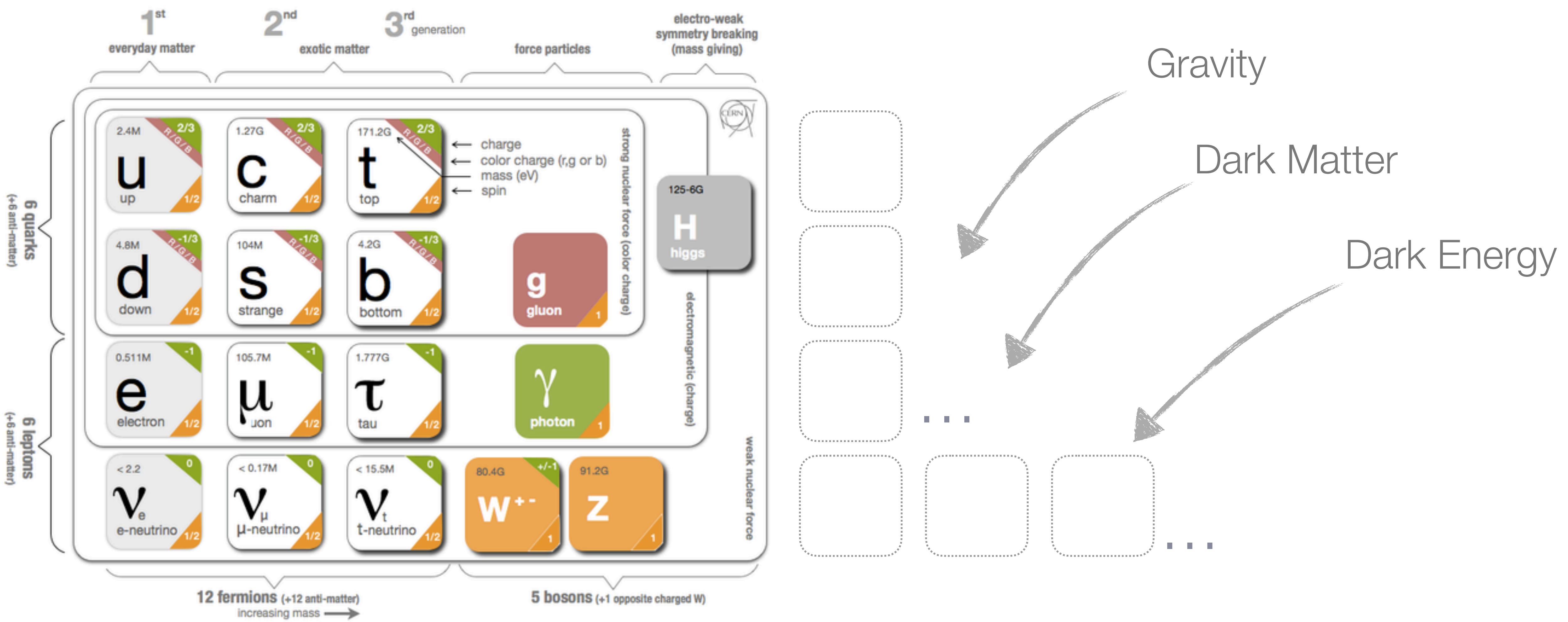


Content

- Introduction: charged lepton flavour violation with muons. The physics cases
- The Most Intense DC and Pulsed Muon beams in the World:
  Present and future prospects
- Overview of current experimental activities based on DC and Pulsed Low Energy muon beams

The role of the low energy precision physics

- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory



- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale

The role of the low energy precision physics

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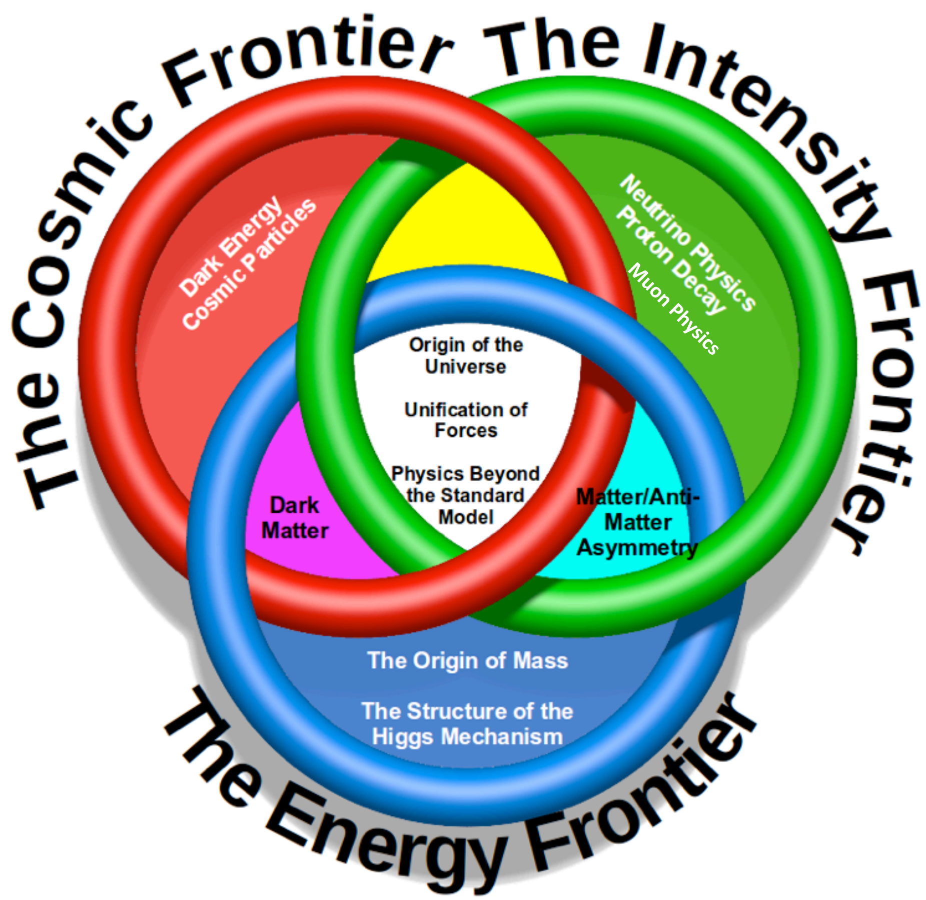
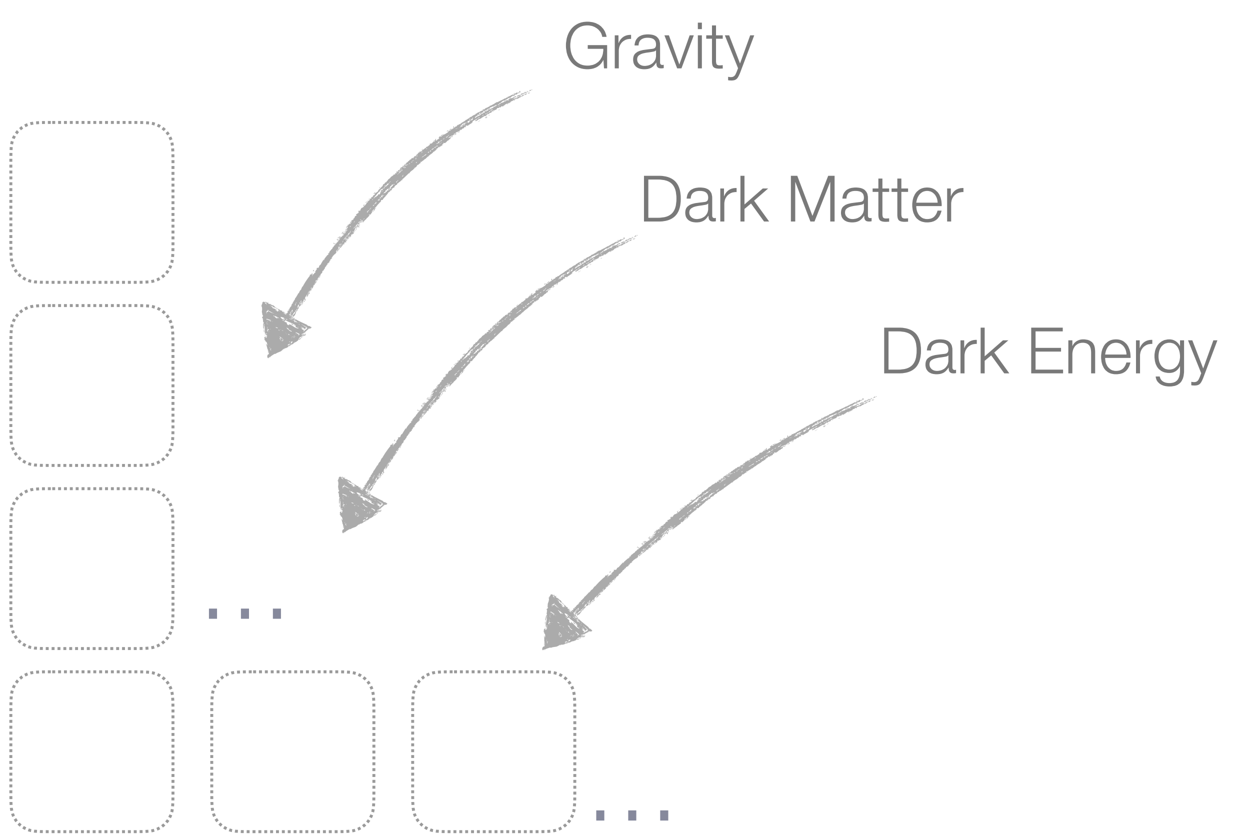




- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale

The role of the low energy precision physics

- Two main strategies to unveil new physics
  - Indirect searches
  - Precision tests

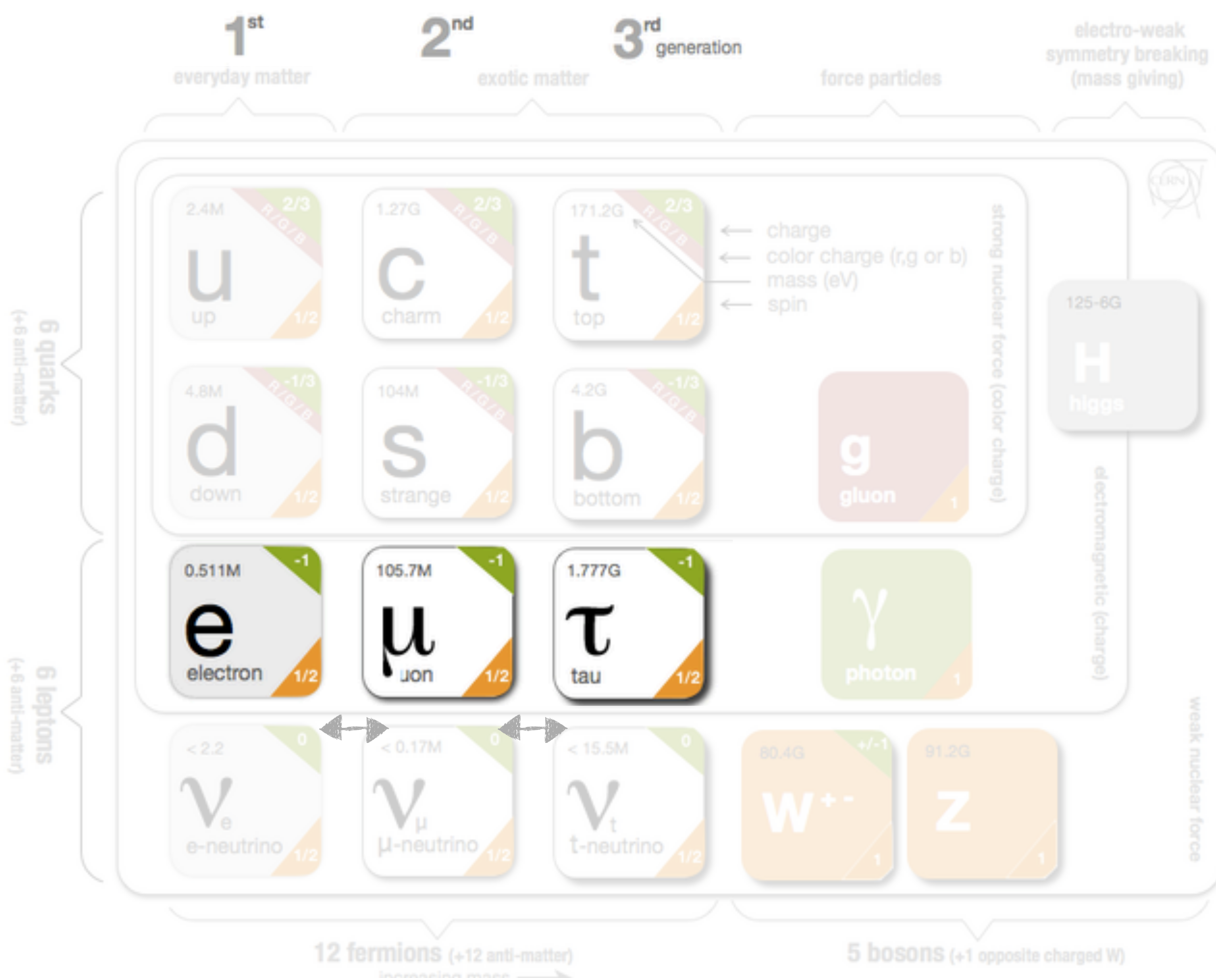
The role of the low energy precision physics

- Two main strategies to unveil new physics
  - **Indirect searches**
  - Precision tests

Charged lepton flavour violation

- Neutrino oscillations: Evidence of physics Behind Standard Model (BSM)

  Neutral lepton flavour violation



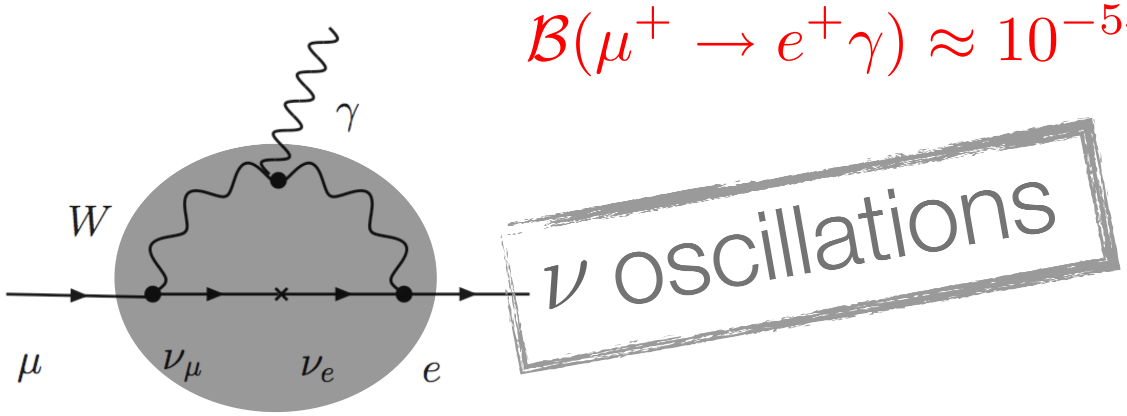
$$\Delta N_i \neq 0$$ with i = 1,2,3

- Charged lepton flavour violation: NOT yet observed

Charged lepton flavour violation search: Motivation

SM with massive neutrinos (Dirac)

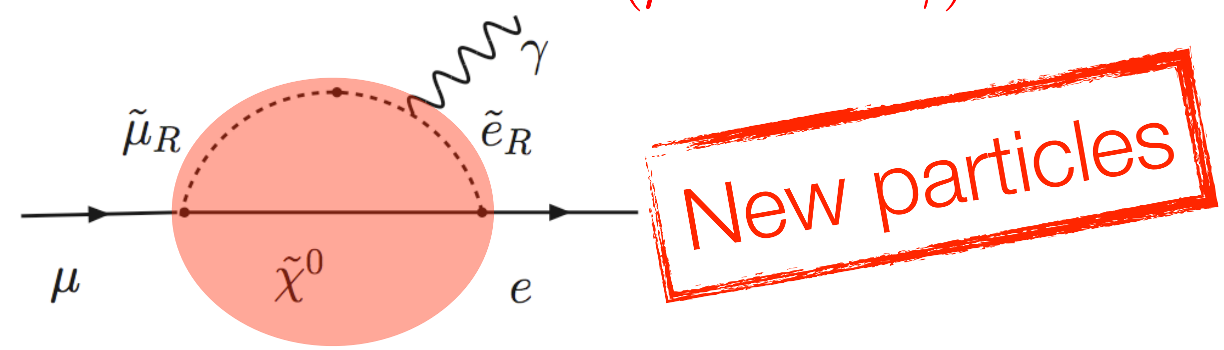
$$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$$



too small to access experimentally

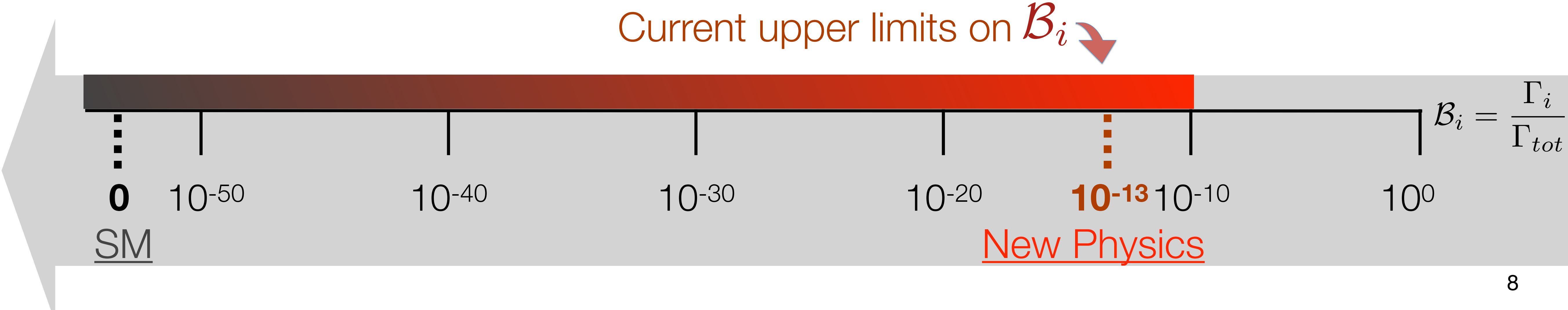
BSM

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

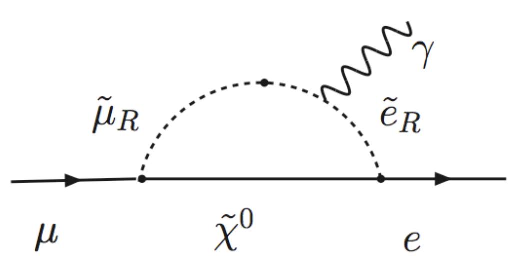


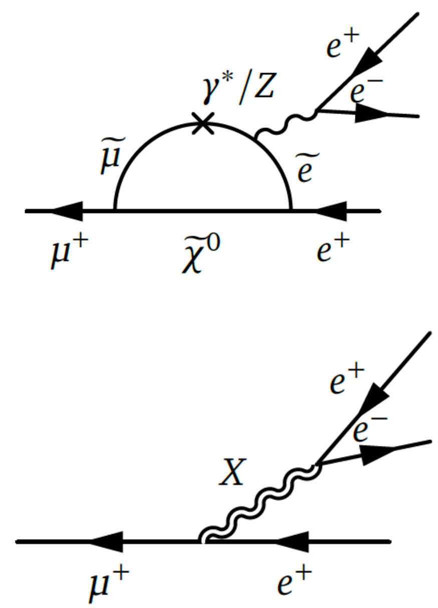
an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)

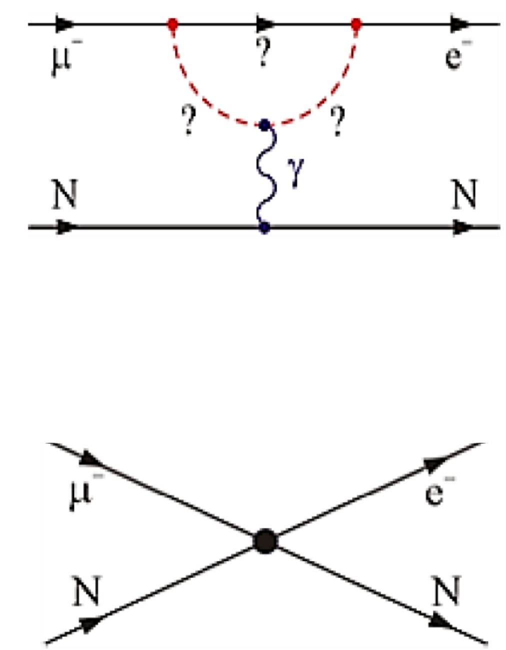
Current upper limits on $\mathcal{B}_i$

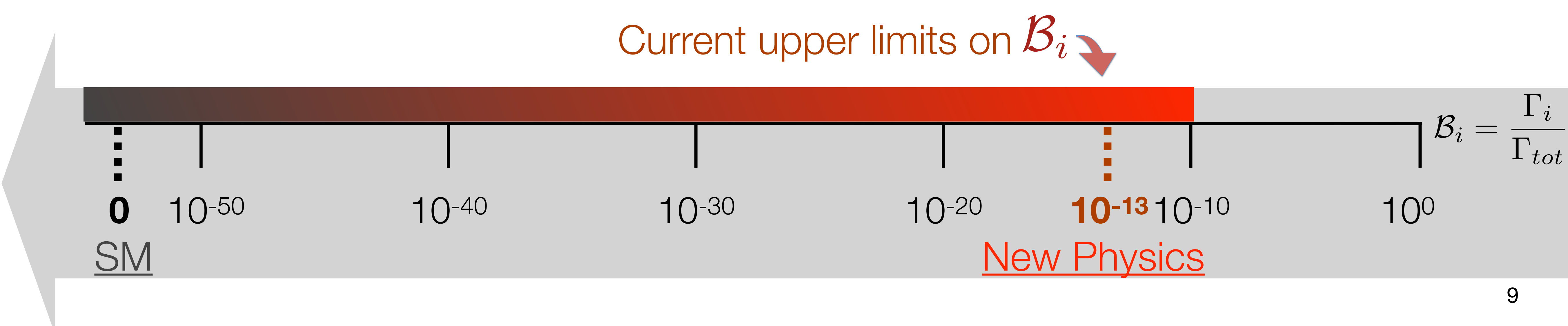


Muon golden channels



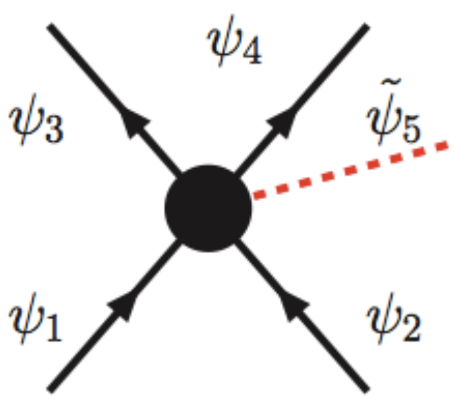






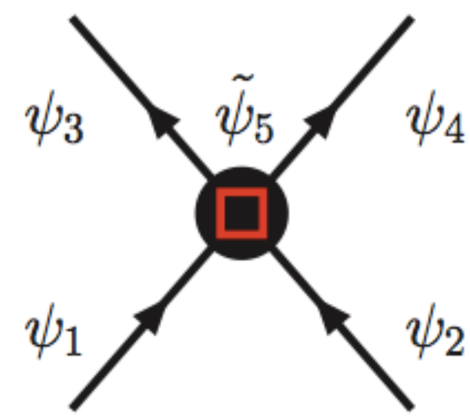
Complementary to “Energy Frontier”

Energy frontier



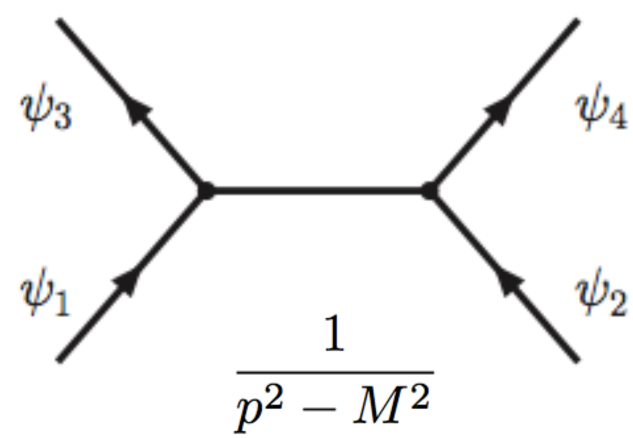
Real BSM particles

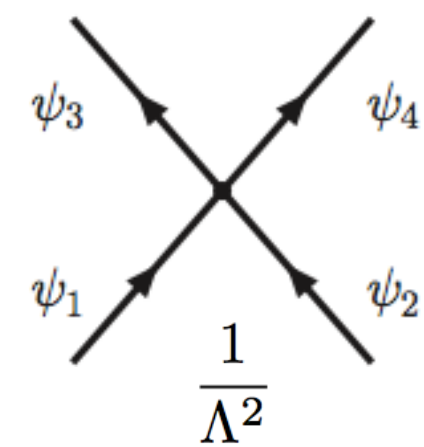
Precision and intensity frontier



Virtual BSM particles

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





Unveil new physics

Probe energy scale otherwise unreachable

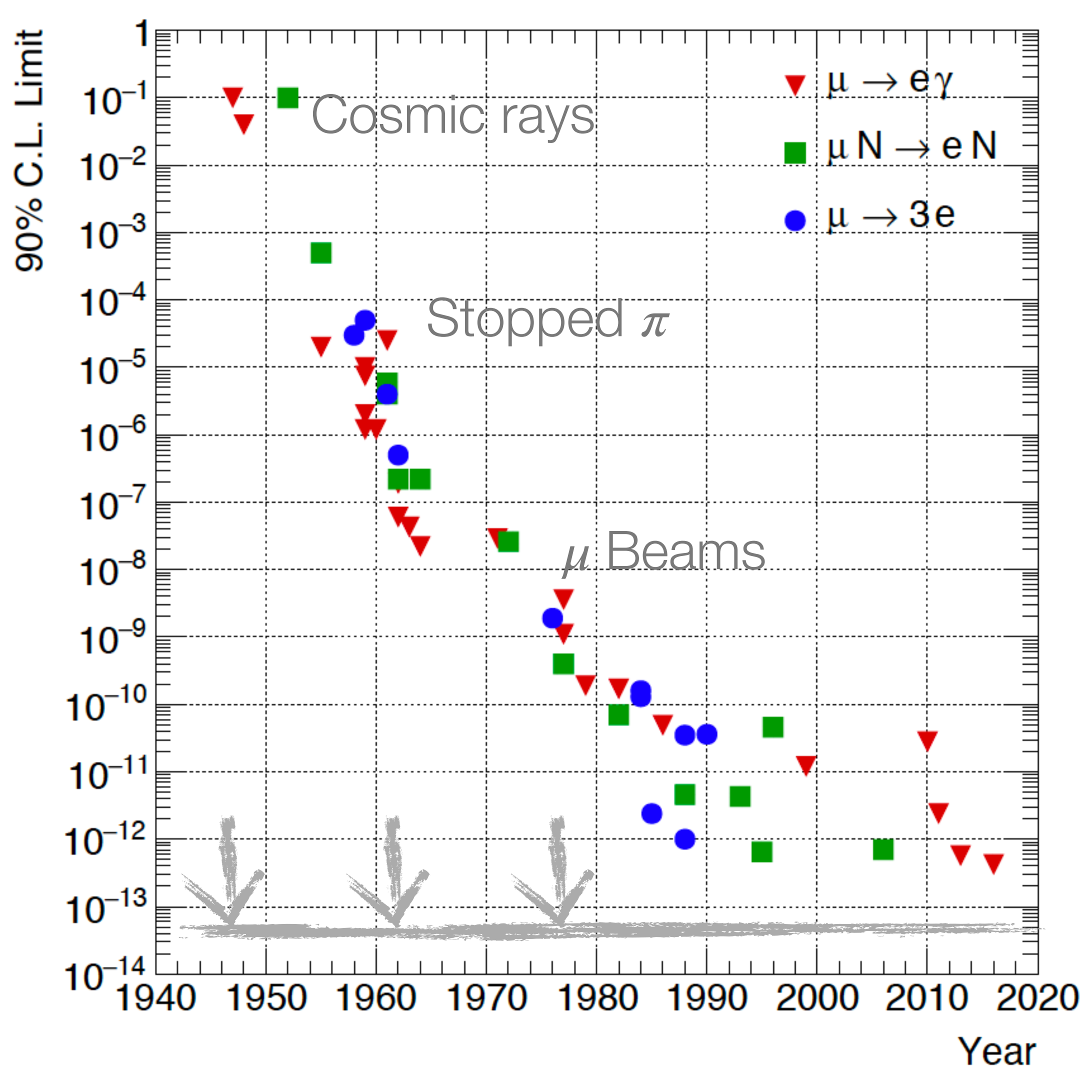
E > 1000 TeV

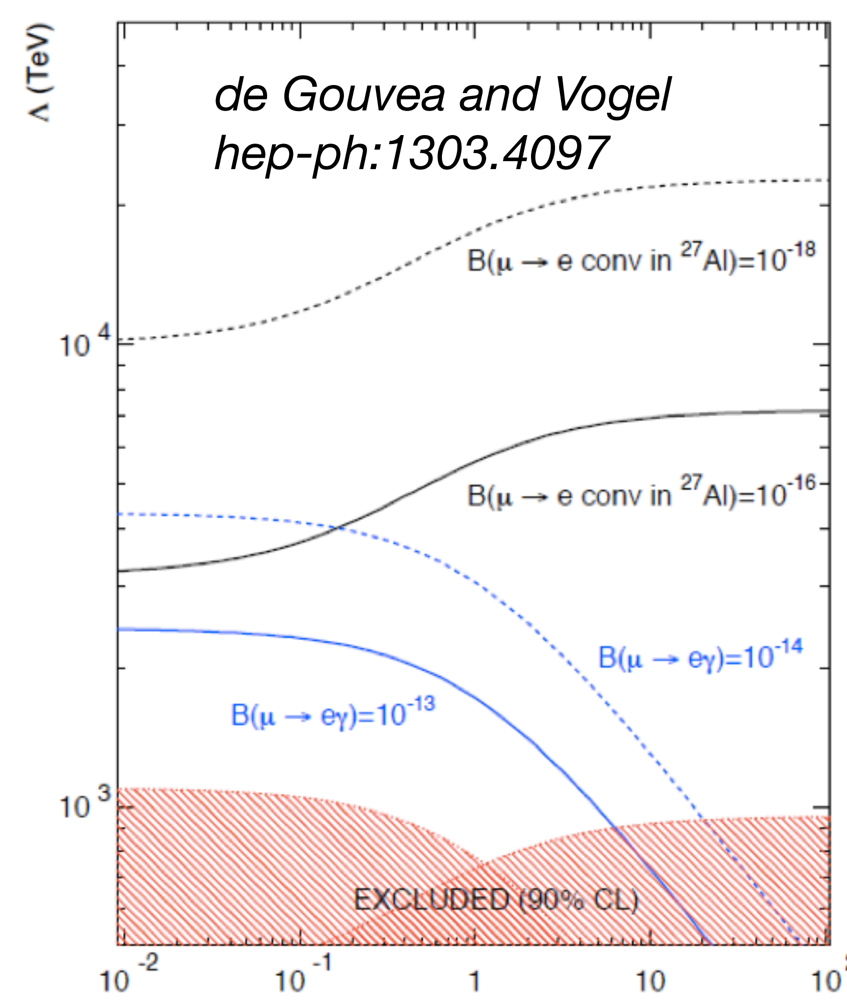
cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities:

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2 x 10^{-13}	~ 6 x 10^{-14}
$\mu \to eee$	1.0 x 10^{-12}	~1.0 x 10^{-16}
$\mu N \to eN'$	7.0 x 10^{-13}	few x 10^{-17}

- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV





Beam features vs experiment requirements

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

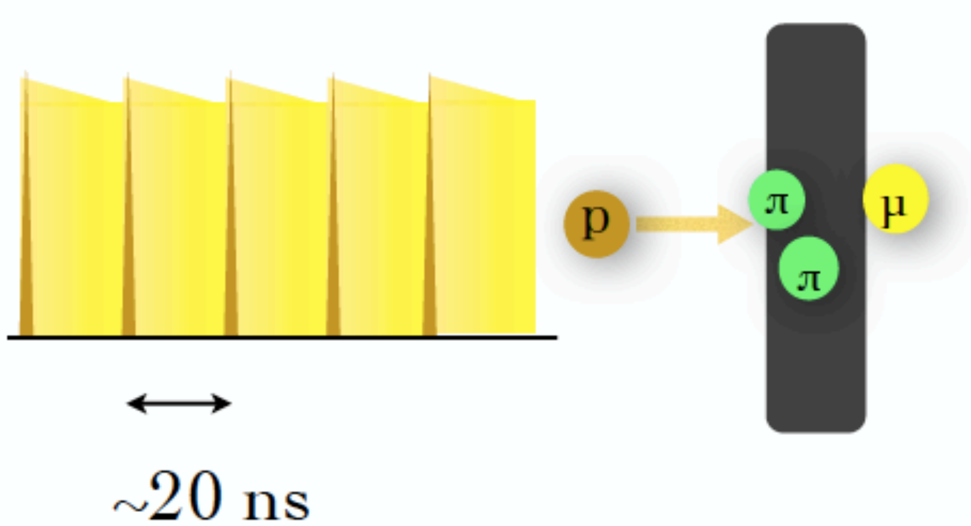
DC or Pulsed?

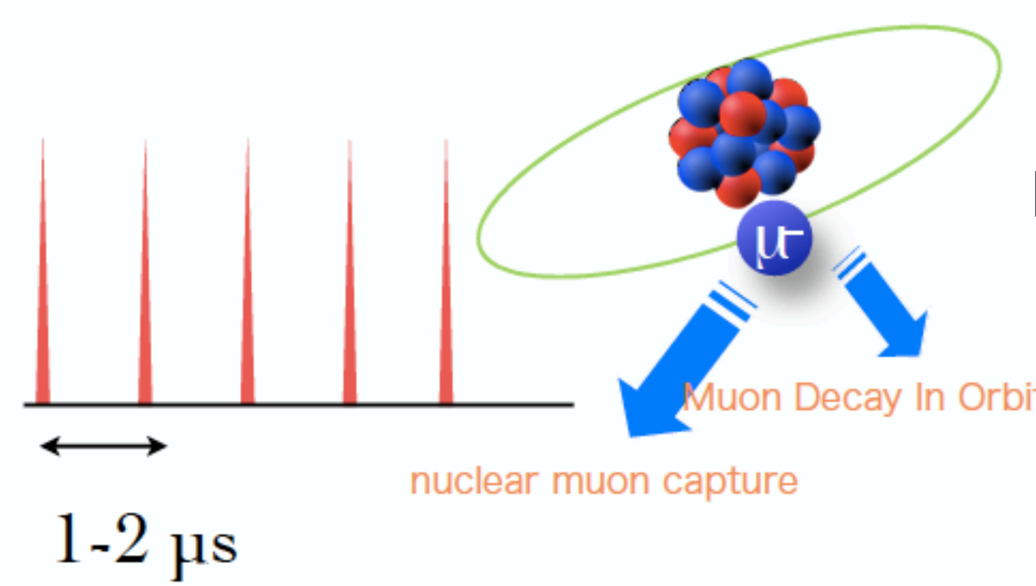
I_{beam} ~ 10^8 - 10^{10} μ/s

I_{beam} ~ 10^{11} μ/s

- DC beam for coincidence experiments
  - $\mu \rightarrow e \gamma$, $\mu \rightarrow e\,e\,e$
- Pulse beam for non-coincidence experiments
  - μ-e conversion

@ PSI





@ JPARC, FERMILAB

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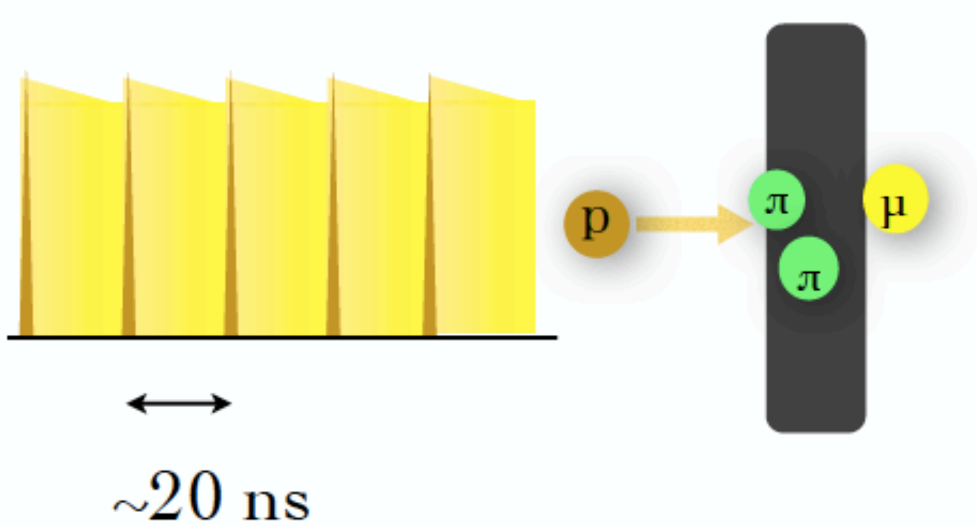

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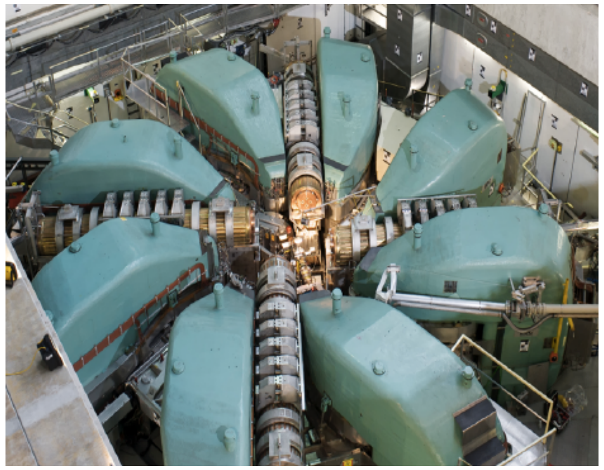
The world's most intense continuous muon beam

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

- PSI delivers the most intense continuous low momentum muon beam in the world (**Intensity Frontiers**)
- MEG/MEG II/Mu3e beam requirements:
  - Intensity O(10^8 muon/s), low momentum p = 29 MeV/c
  - Small straggling and good identification of the decay

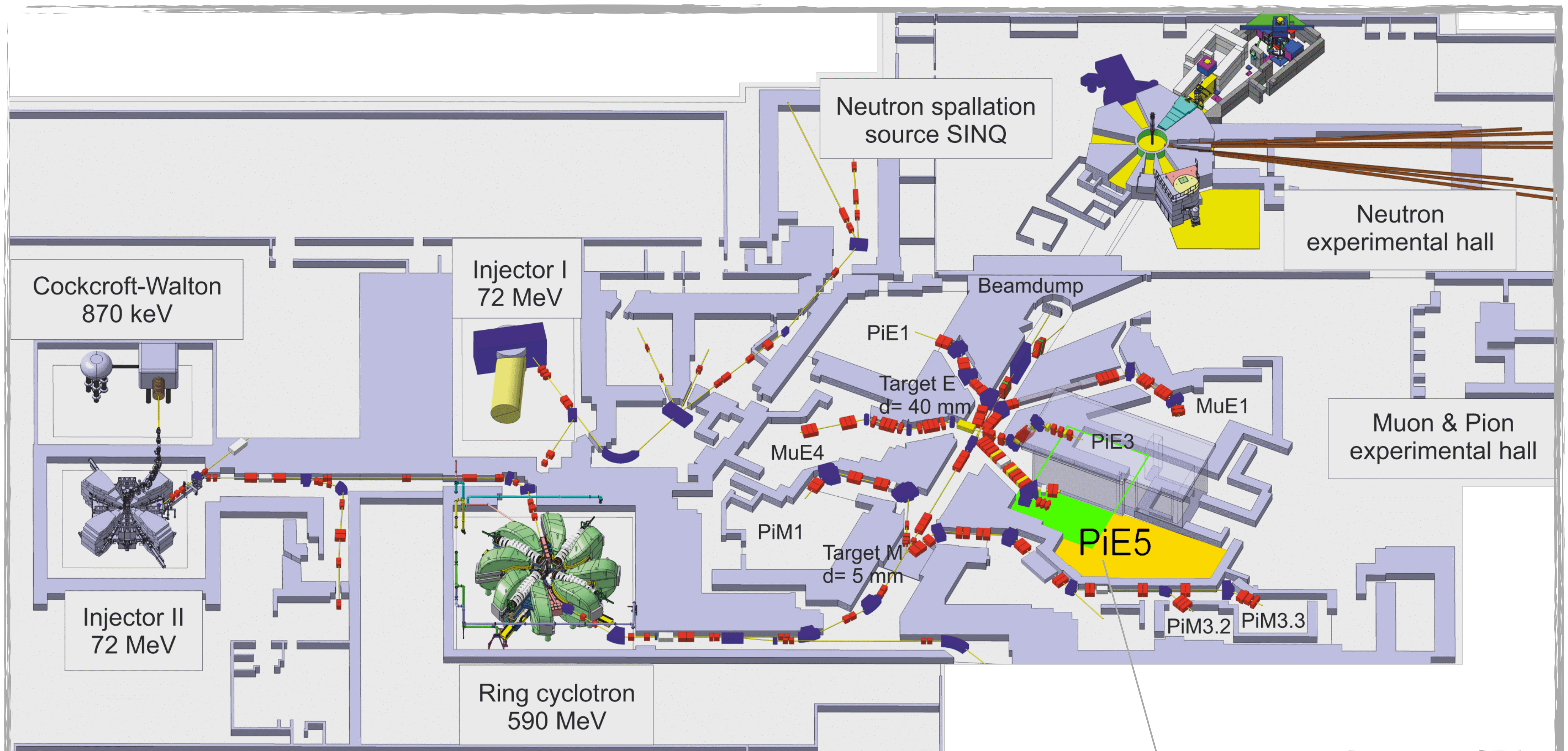


590 MeV proton
ring cyclotron
1.4 MW

PSI landscape

The world’s most intense continuous muon beam

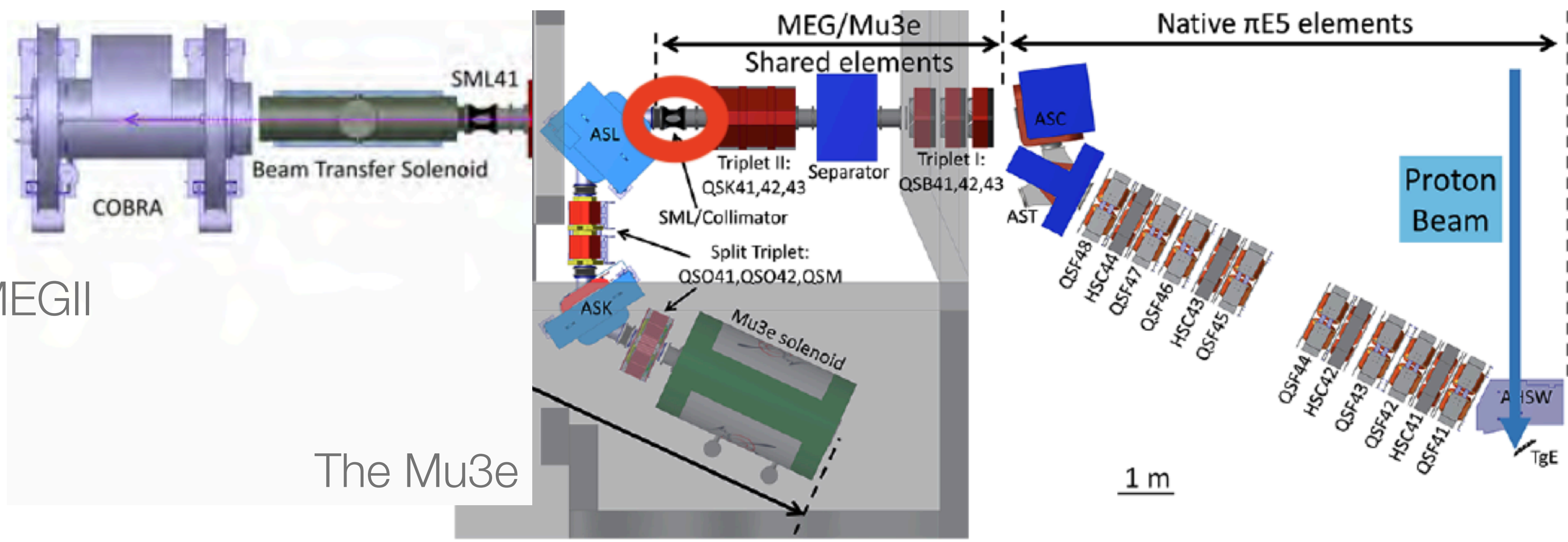
- PSI High Intensity Proton Accelerator experimental areas



MEGII / Mu3e Experimental area

The MEGII and Mu3e beam lines

- MEGII and Mu3e (phase I) similar beam requirements:
  - **Intensity O(10^8 muon/s), low momentum p = 28 MeV/c**
  - **Small straggling and good identification of the decay region**
- MEG II beam settings released since 2019. More then 10^8 mu/s can be transport into Cobra (up to 1.6e8@2.2 mA during the 2022 beam time)
- A dedicated compact muon beam line (CMBL) sharing a large fraction of the native piE5&MEG elements will serve Mu3e
  - Proof-of-Principle: Delivered 8 x 10^7 muon/s during 2016 test beam (up to 1e8@2.4 mA during the 2022 beam time with the full assembled Mu3e beam line)



The MEGII

The Mu3e

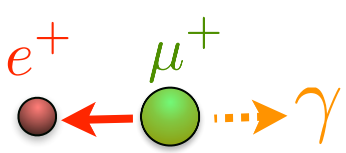
MEG: Experimental setup and result

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

A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434

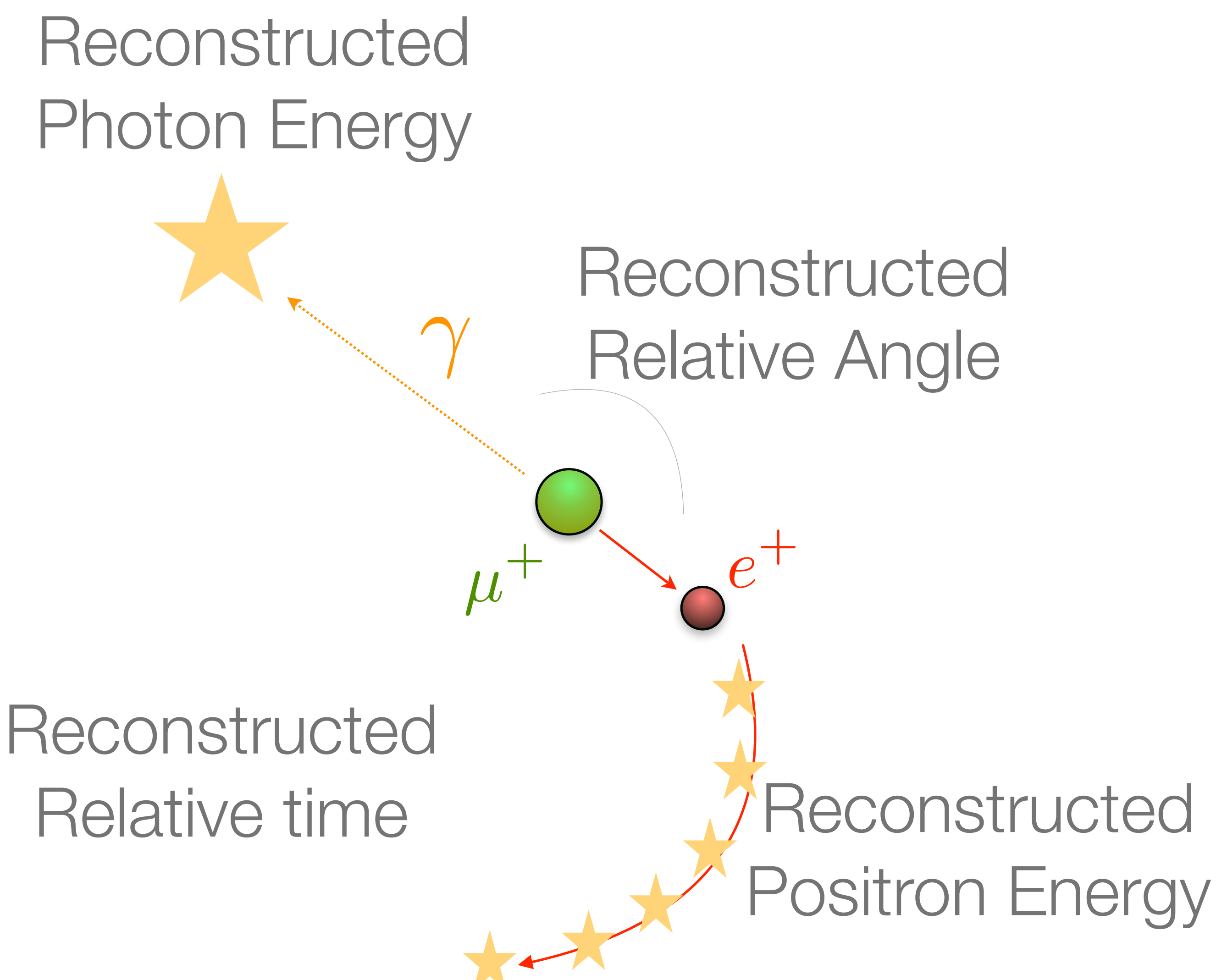
- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 10^{-13}$ (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow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

Signature

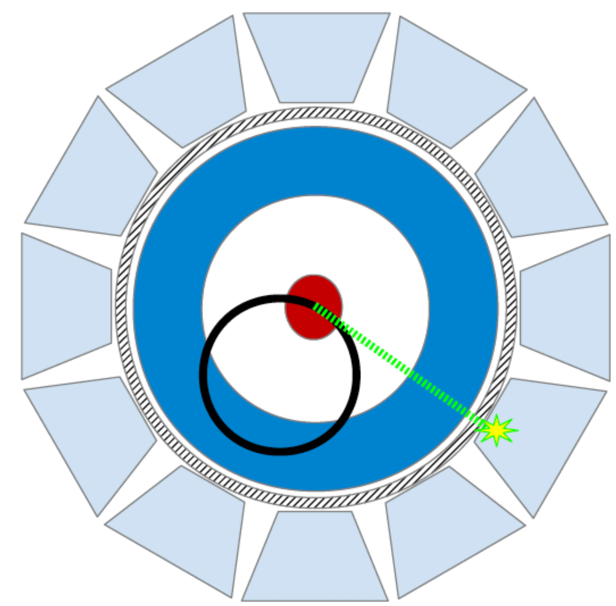


Signature

- **Five** observables **(E_γ, E_e, $\Delta t_{e\gamma}$, $\theta_{e\gamma}$, $\varphi_{e\gamma}$)** to identify a $\mu \rightarrow e\gamma$ event and reject background events

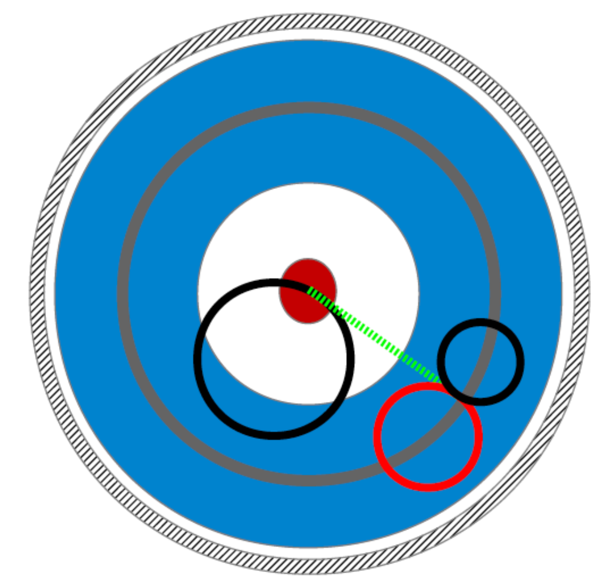


Calorimeter



Improved calorimeter
Increased angular
acceptance

Photon conversion



Improved photon
energy reconstruction
Improved photon
direction
reconstruction

Vertex decay
reconstruction

MEG:
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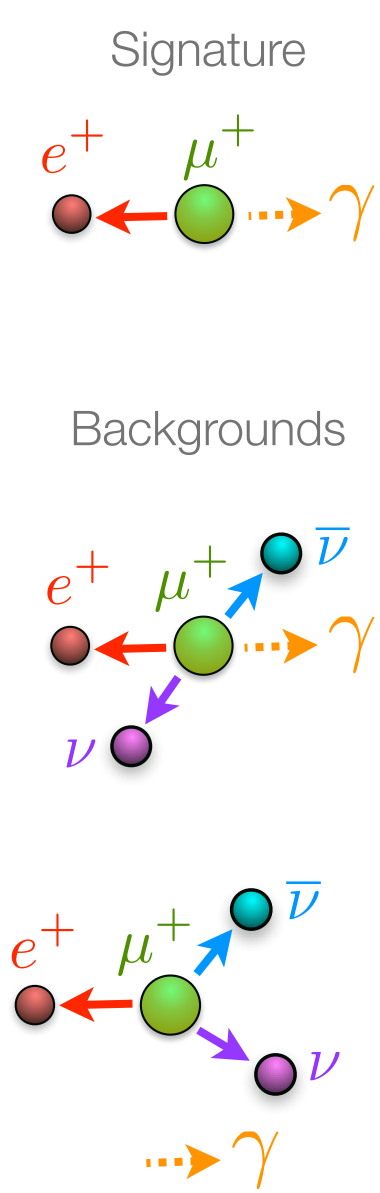
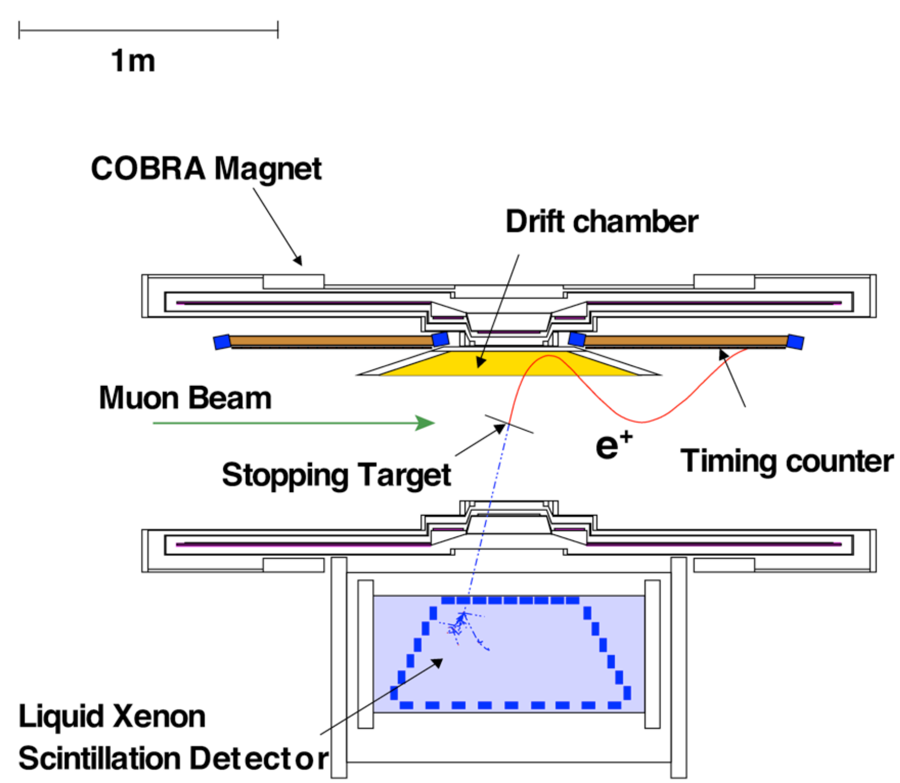
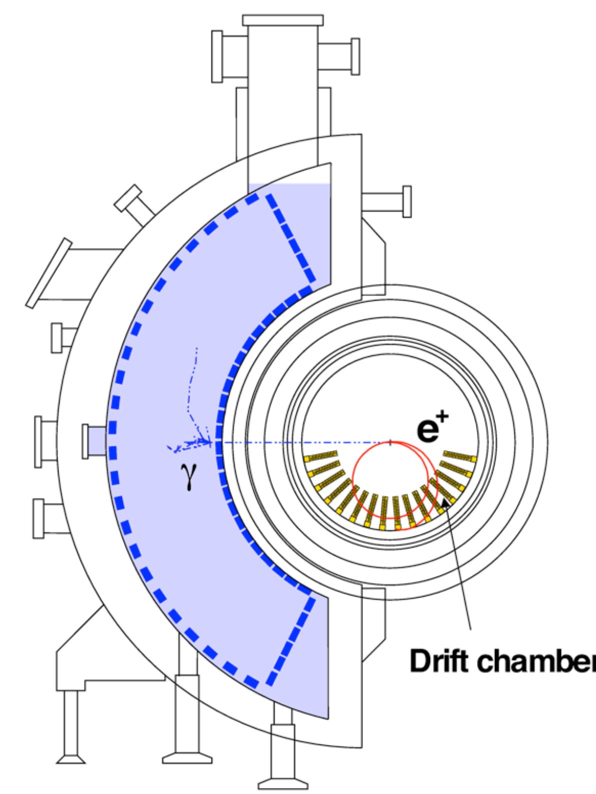




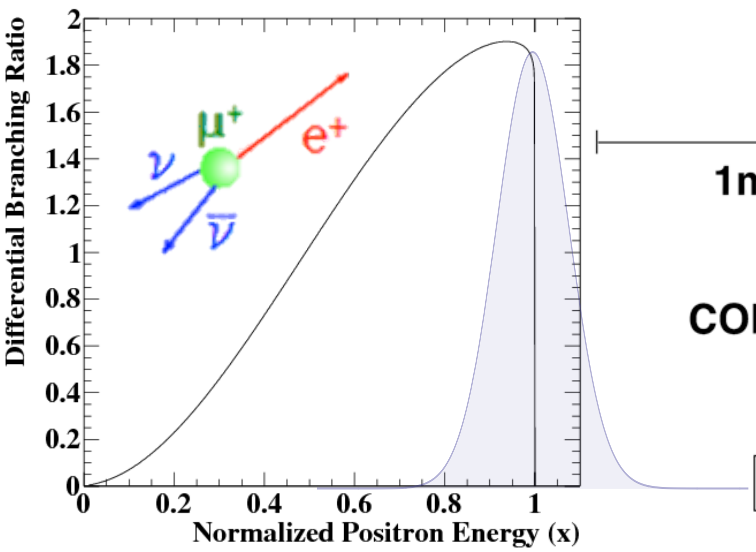


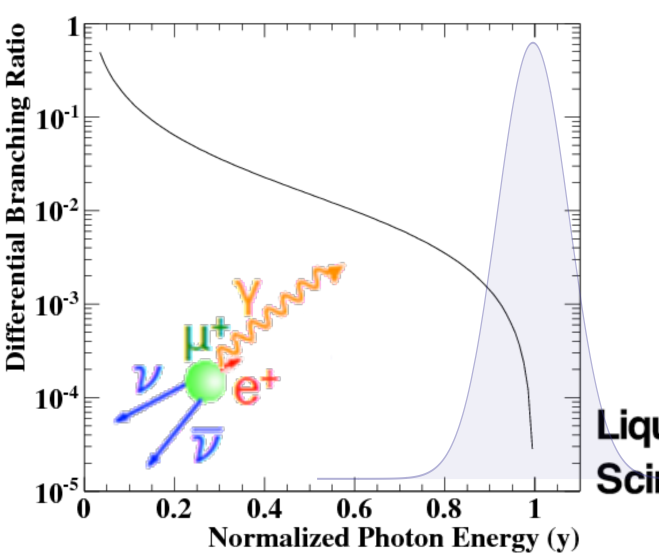
Full data sample: 2009-2013
Best fitted branching ratio at 90% C.L.:

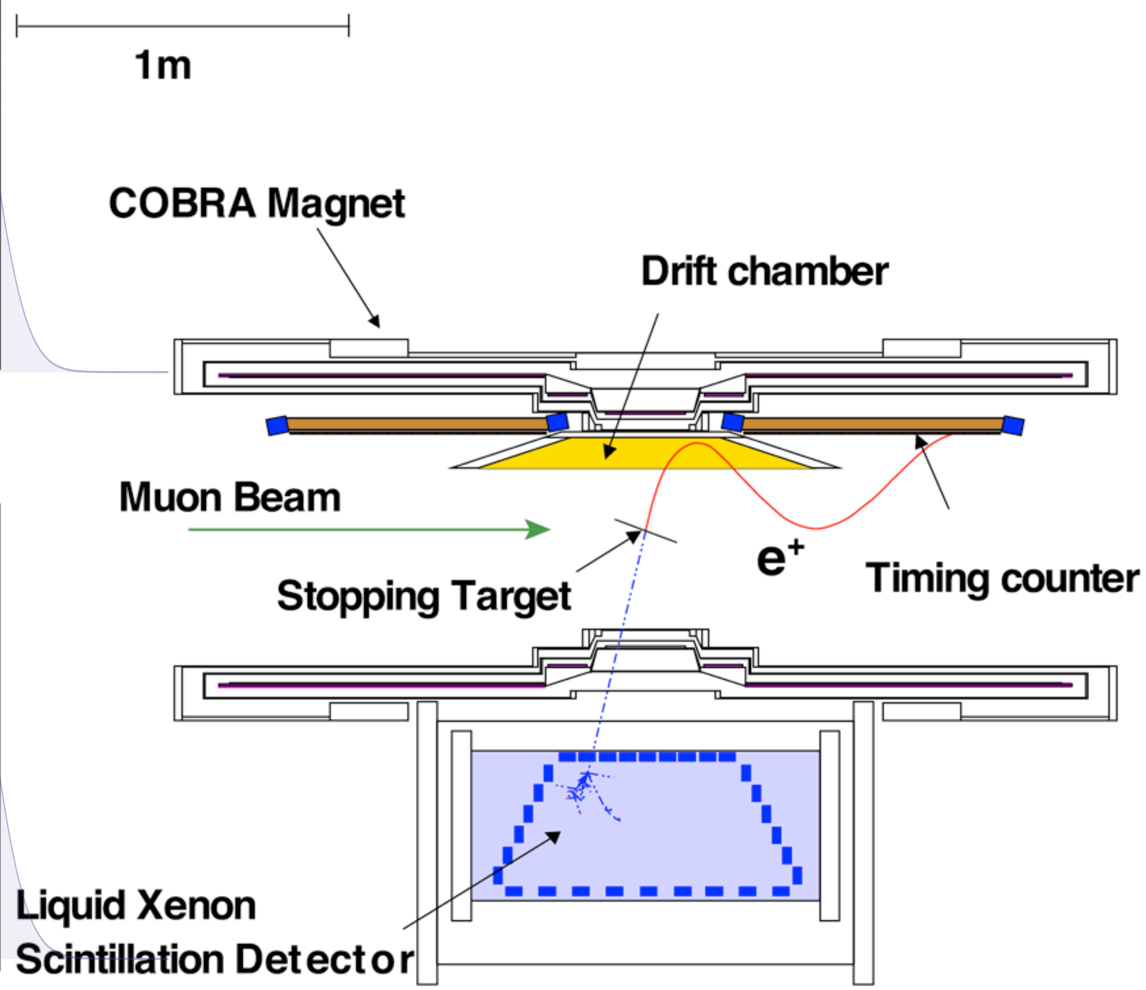
$$\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

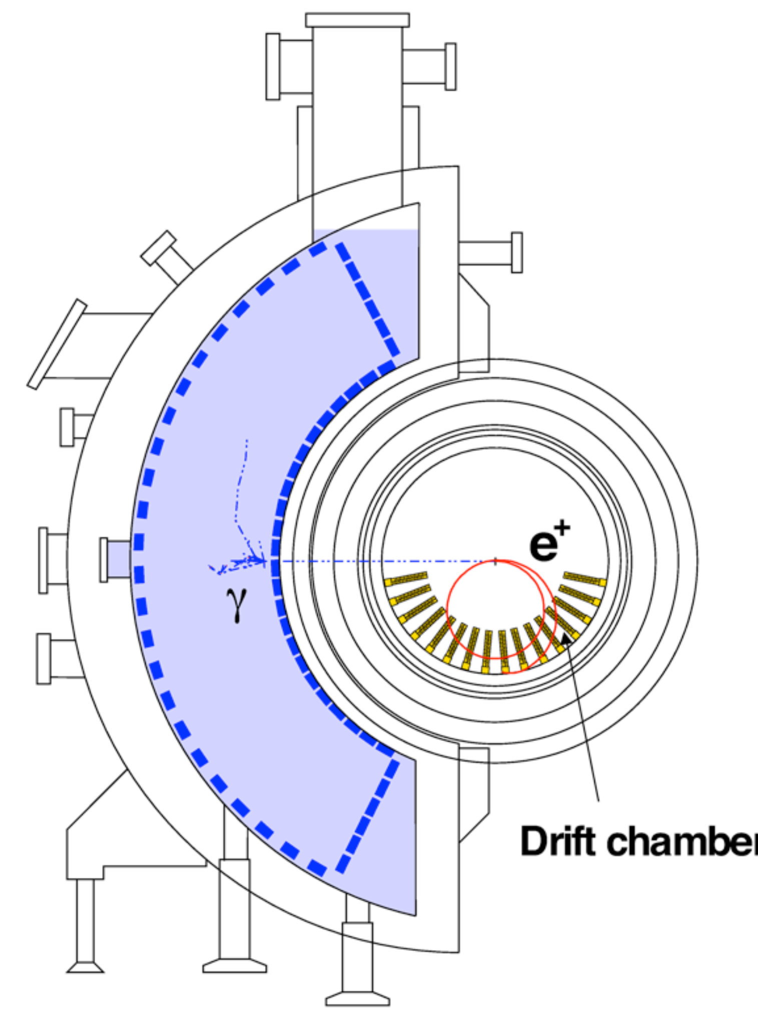
MEG: The key elements

1. The world's intense low momentum muon beam stopped in a thin and slanted target
2. The gradient field e^+-spectrometer
3. The innovative Liquid Xenon calorimeter
4. The full waveform based DAQ (digitization up to 1.6 GSample/s)
5. Complementary calibration and monitoring methods

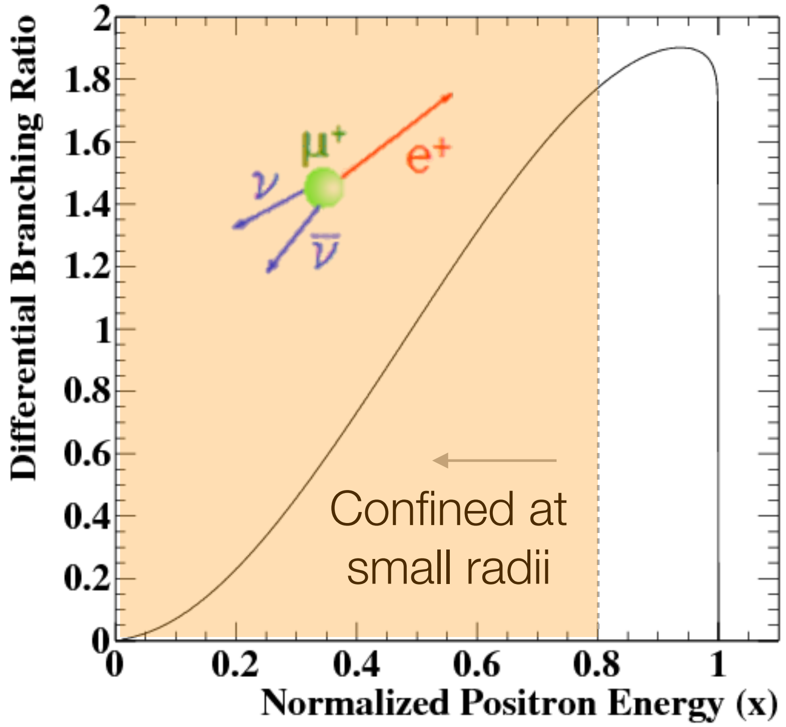




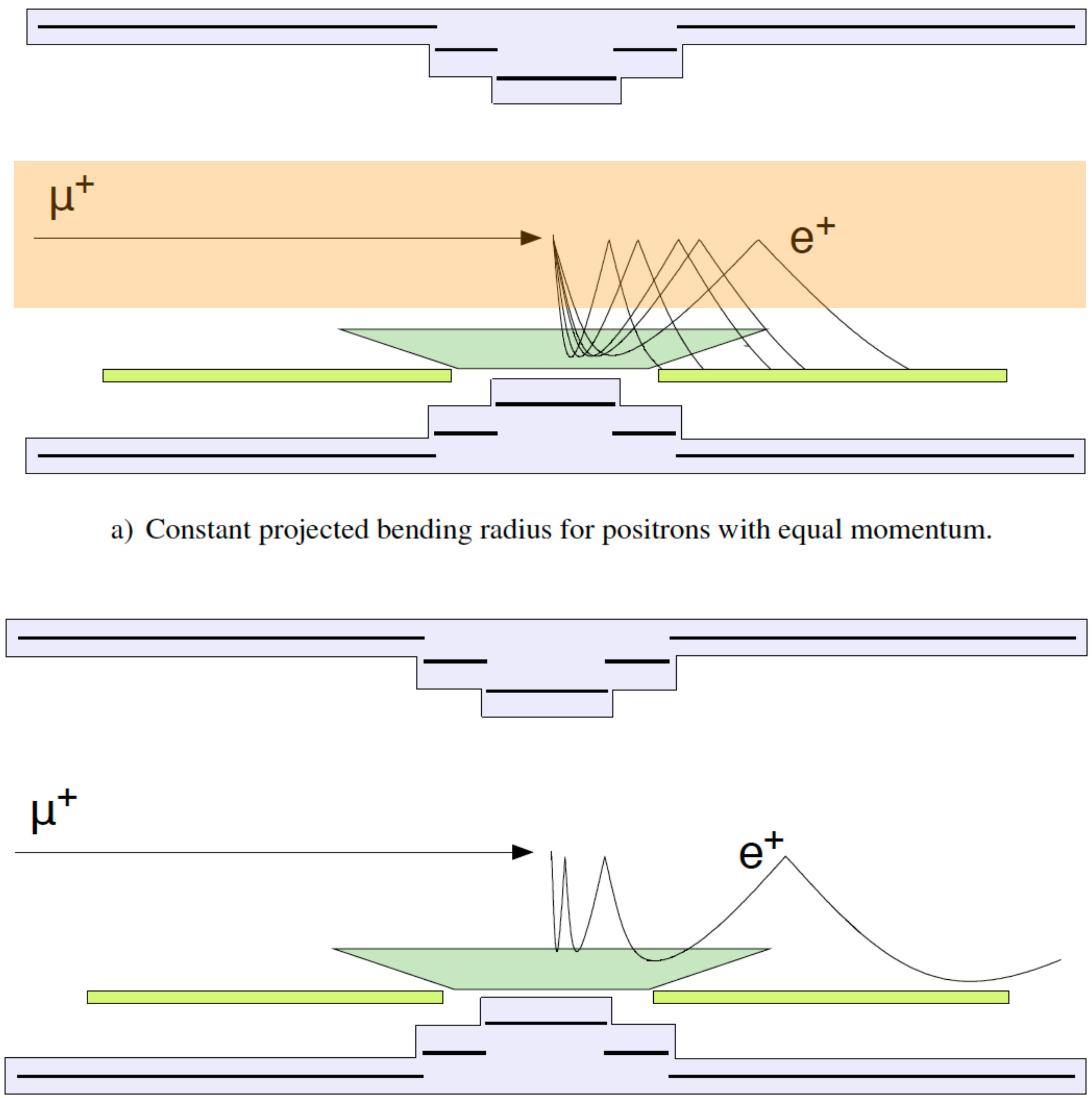




MEG: The spectrometer



- Low momentum positrons swept away without hitting the chambers
- Projected radius independent of the emission angle
- Very low material budget (~ 2 10^{-3} X_0)
- High momentum resolution (σ_p ~ 315 keV/c), angular resolutions (σ_ϕ ~ 7.5 mrad , σ_θ ~ 10.6 mrad) and timing resolution (σ_t ~ 100 ps) never reached up to now with a single detector at 52.8 MeV!

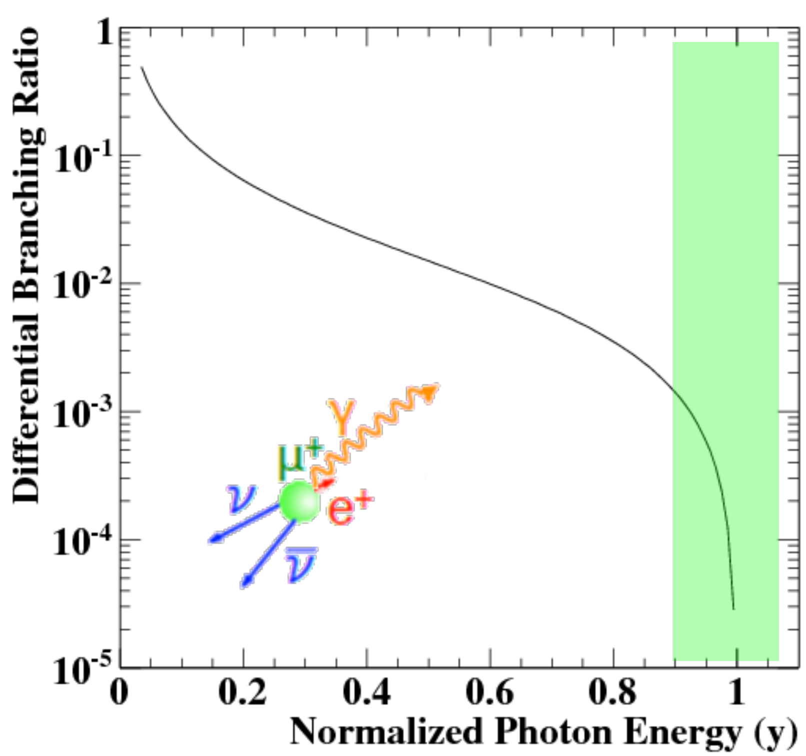


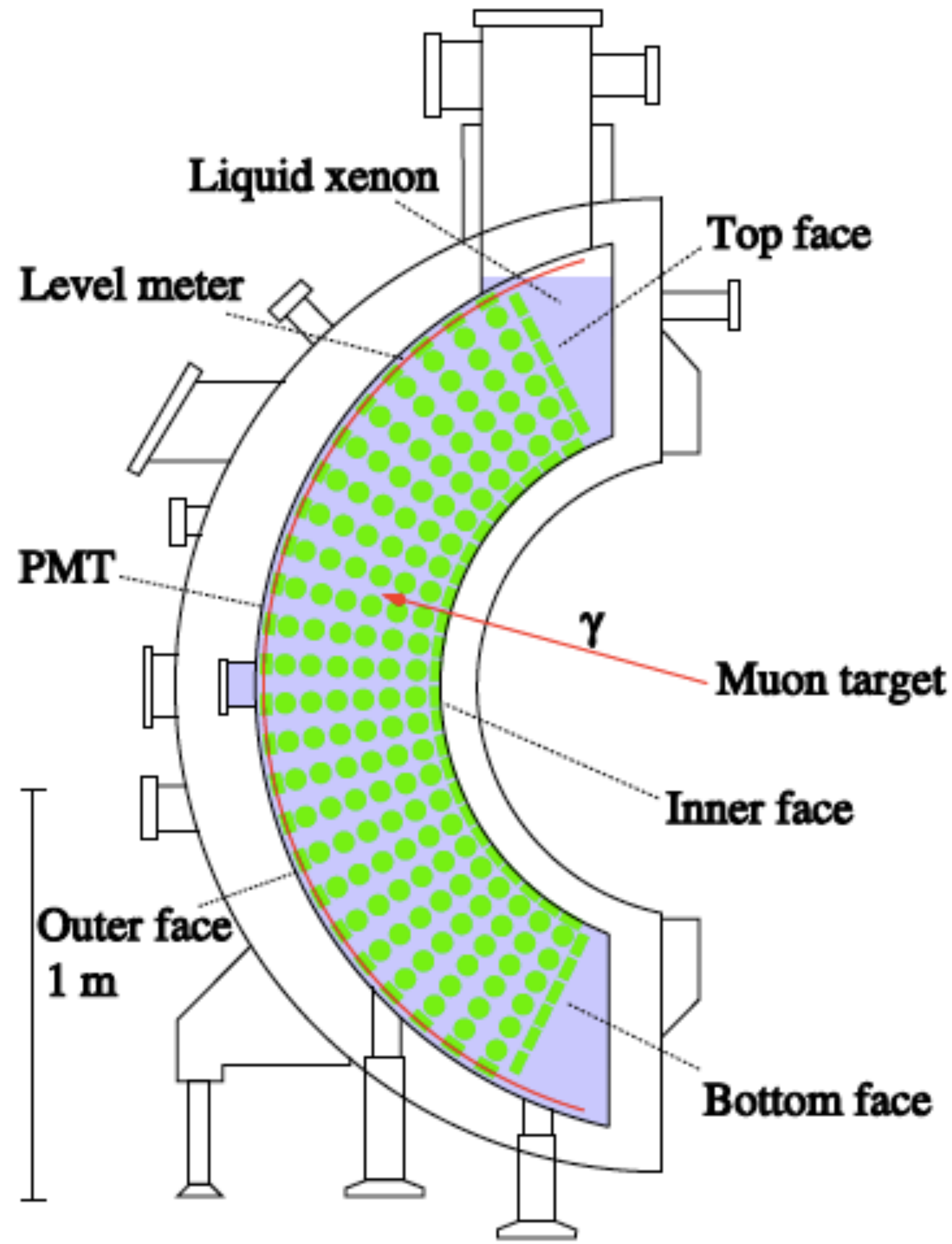
a) Constant projected bending radius for positrons with equal momentum.

b) Quick sweep-out of particles with $\cos\theta_{e^+} \approx 0$.

MEG: The LXe calorimeter

- High detection efficiency (High Z/ Low X_0)
- High energy, timing and position resolutions (High LY, Fast time constants, High density, High photosensor coverage)
- Purity < 1 ppm and stable conditions over the time
- Particle ID
- Energy (σ_E /E <2.5%) and timing resolutions(σ_t < 70 ps) never reached up to now with a single detector at 52.8 MeV!

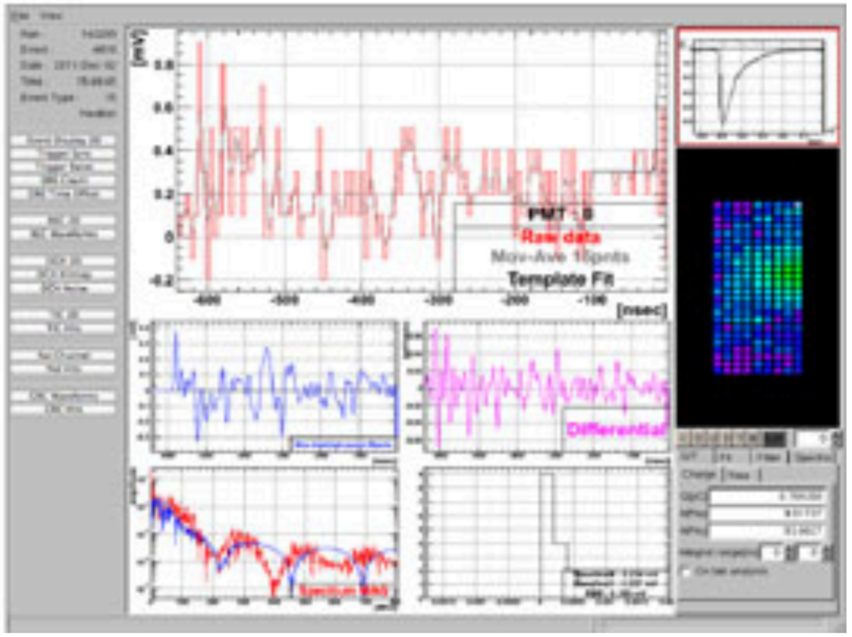


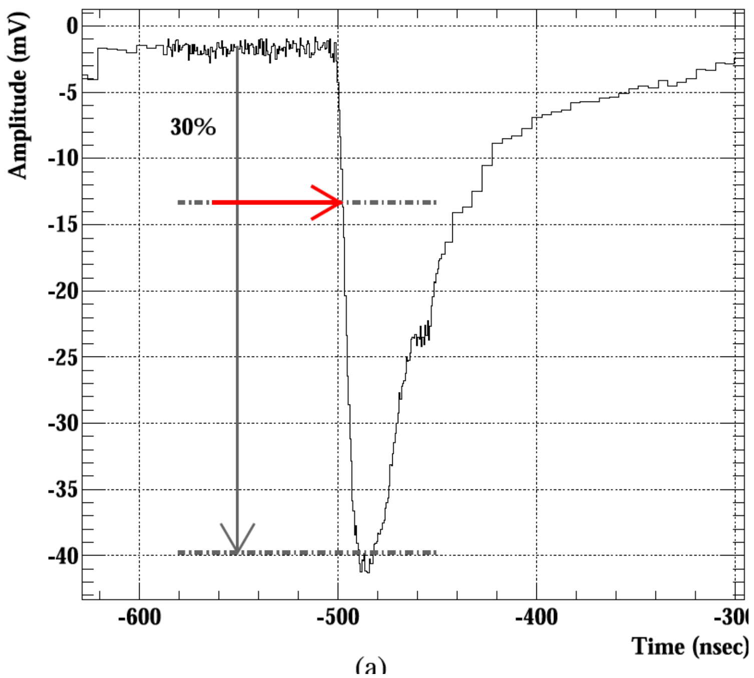


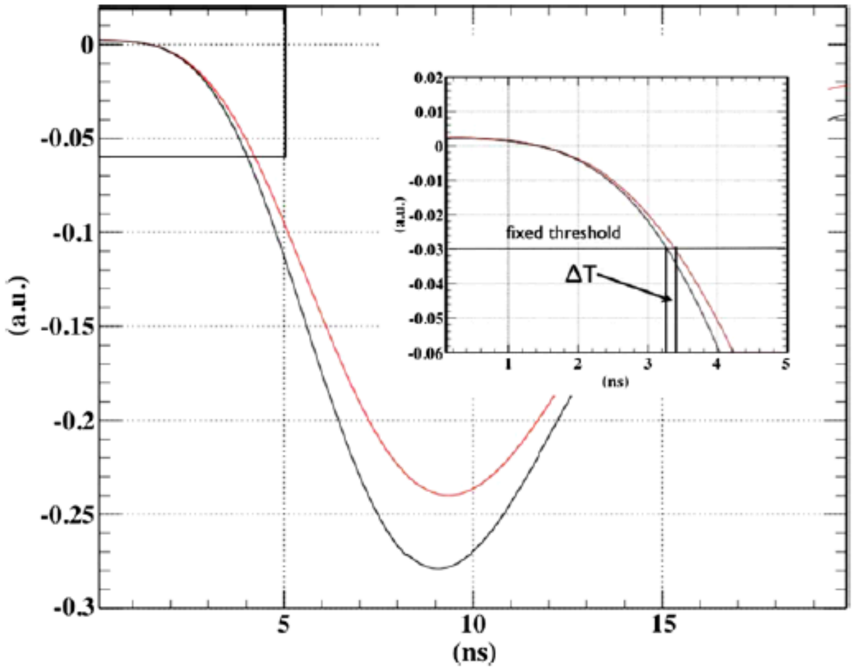
- Volume: 0.9 m^3 LXe
- 846 PMTs immersed in LXe
- thin entrance wall (honeycombe structure)
- Photocathodic coverage 40%
- Solid angle coverage 10%of 4π
- X_0 = 2.77 cm
- density = 2.95 g/cm^3
- n = 1.65
- Z = 54
- R_M = 4.1 cm
- LY = 40000 ph/MeV
- Time constants = 4, 22 and 45 ns
- Particle Identification

MEG: The Data Acquisition (DAQ)

- Flexible and efficient trigger system, to select the candidate events, using fast detectors only
  - FADC digitization at 100 MHz
  - online selection algorithms implemented into FPGAs
- Domino Ring Sampler (DRS) chip for excellent pile-up rejection and timing resolutions with a full waveform digitization (> 100 MHz)
  - all 1000 PMTs signals (LXe and TC) digitize at 1.6 GSample/s
  - all 3000 DC channels (anodes and cathodes) digitize at 800 MSample/s



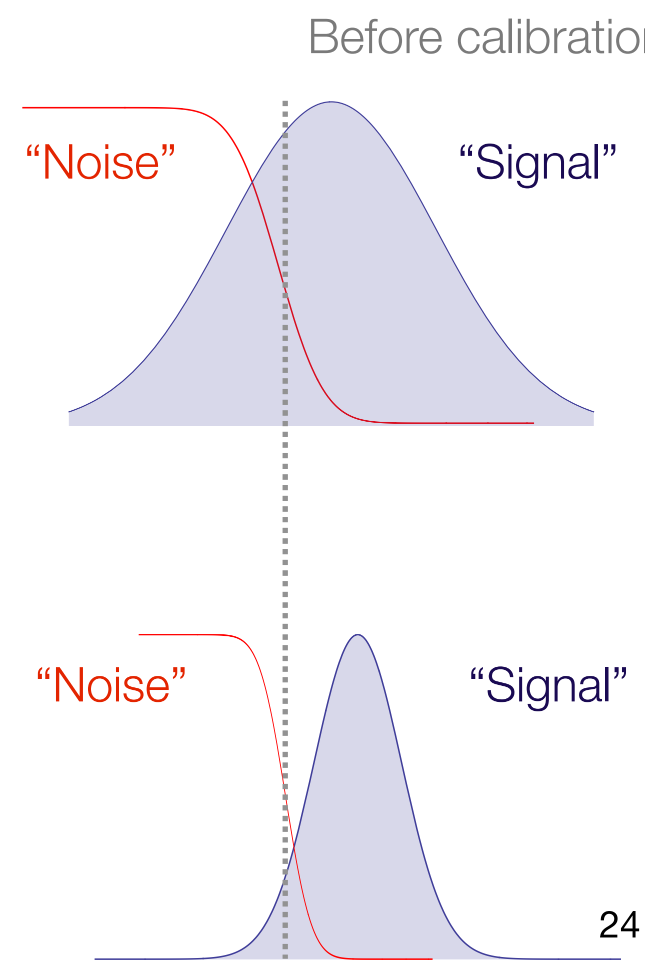


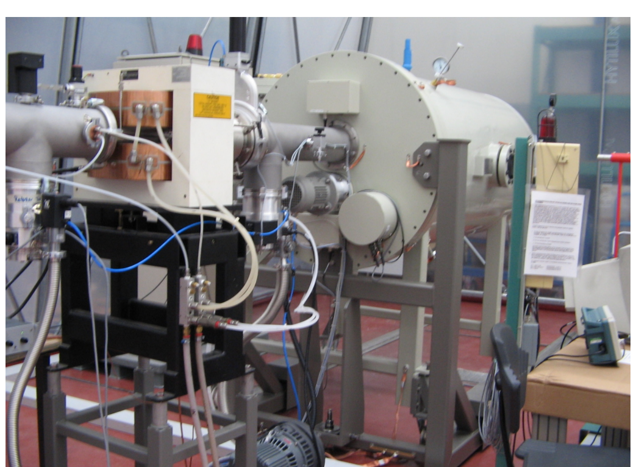


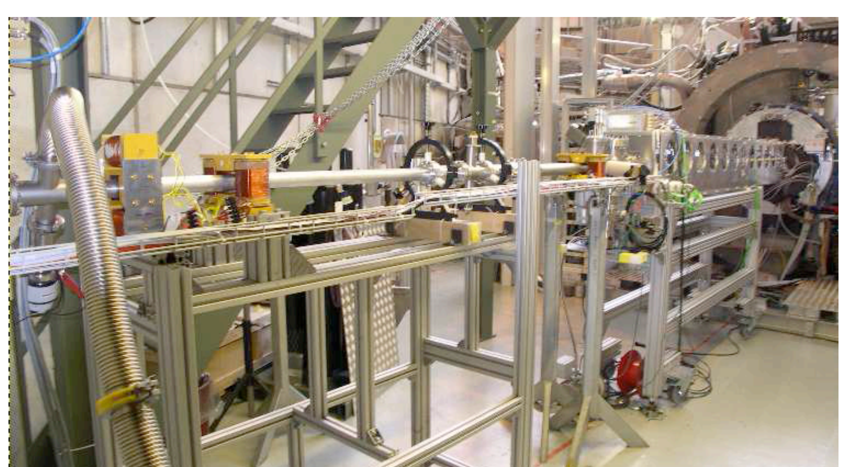
MEG: The calibration methods

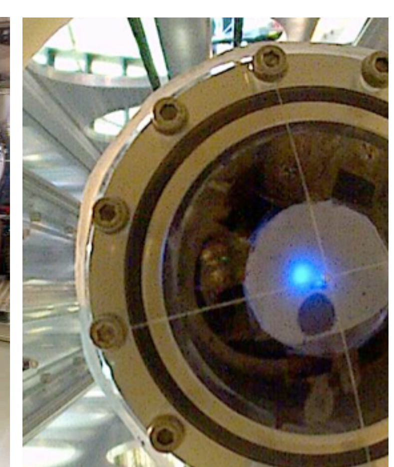
- Multiple calibration and monitoring methods: detector resolution and stability are the key points in the search for rare events over the background

Process		Energy (MeV)	Frequency
CEX reaction	$p(\pi^-, \pi^0)n, \pi^0 \rightarrow \gamma\gamma$	55, 83	annually
C-W accelerator	$^7Li(p, \gamma_{17.6})^8Be$	17.6	weekly
	$^{11}B(p, \gamma_{11.6})^{12}C$	4.4&11.6	weekly
Neutron Generator	$^{58}Ni(n, \gamma_9)^{59}Ni$	9	daily
Mott Positrons	$p(e^+, e^+)p$	53	annually









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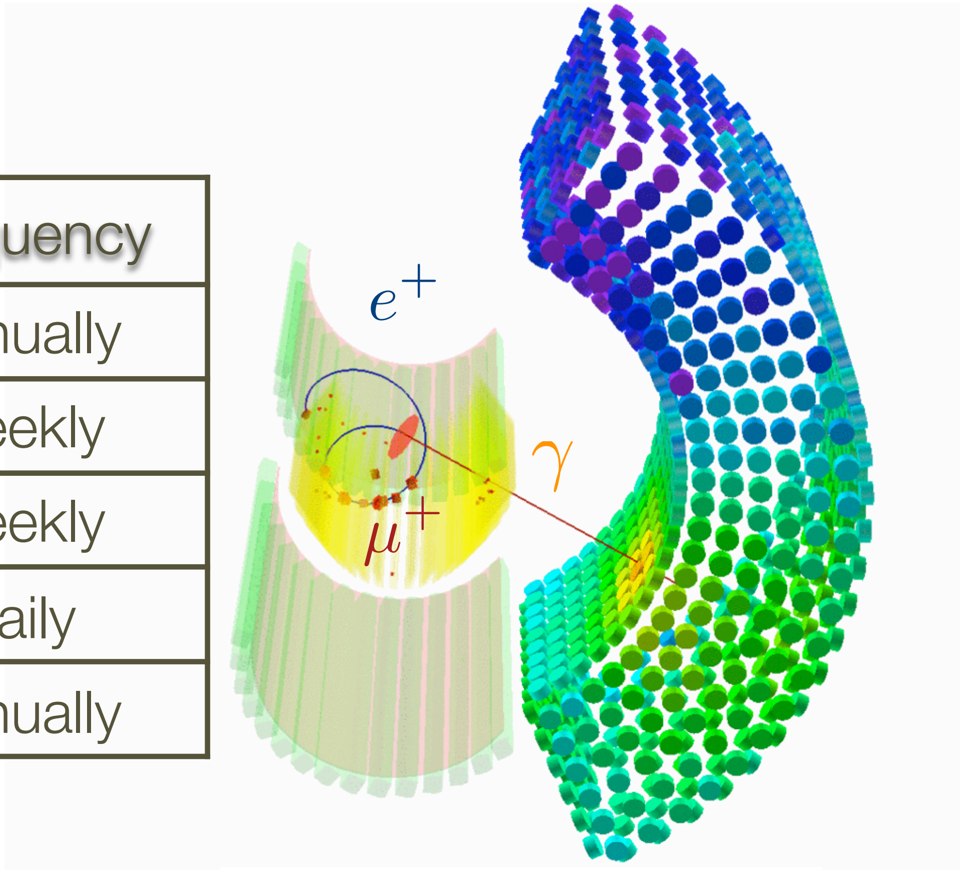
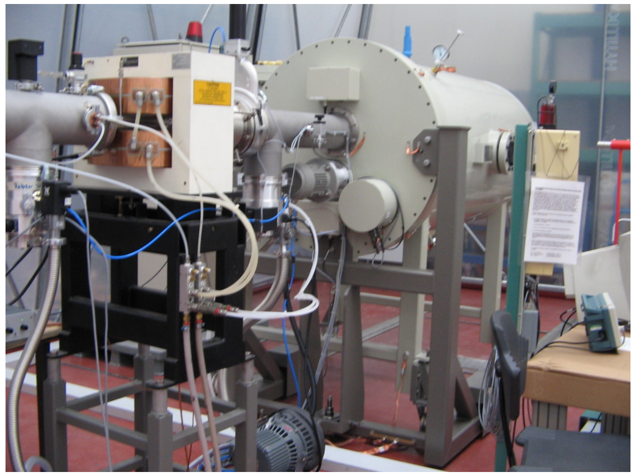
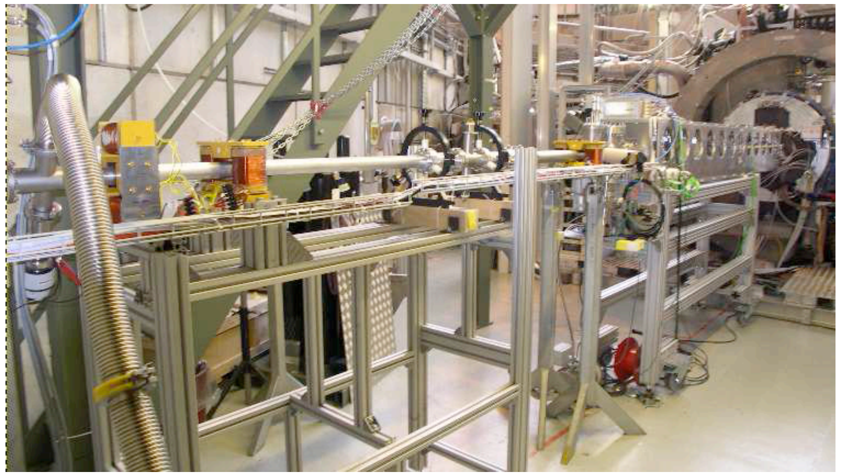
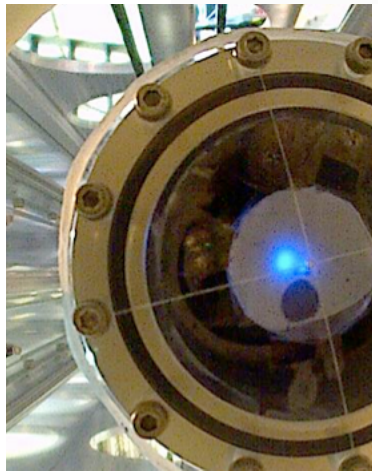
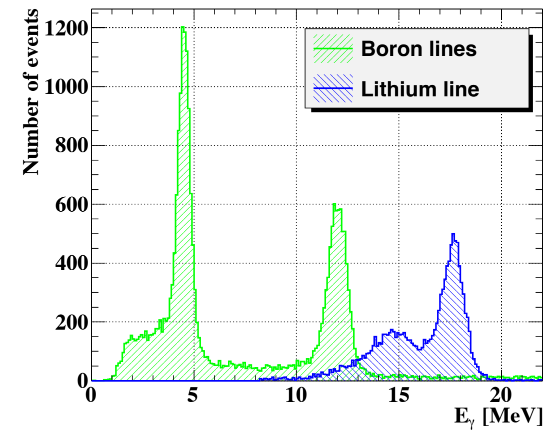
C-W accelerator	${}^{7}Li(p, \gamma_{17.6}){}^{8}Be$	17.6	weekly
	${}^{11}B(p, \gamma_{11.6}){}^{12}C$	4.4&11.6	weekly
Neutron Generator	${}^{58}Ni(n, \gamma_9){}^{59}Ni$	9	daily
Mott Positrons	$p(e^+, e^+)p$	53	annually











How the sensitivity can be pushed down?

- More sensitive to the signal...

high statistics

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

Beam rate

Acquisition time

Geometrical acceptance

Detector efficiency

Selection efficiency

- More effective on rejecting the background...

high resolutions

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

Positron Energy resolution

Gamma Energy resolution

Relative timing resolution

Relative angular resolution

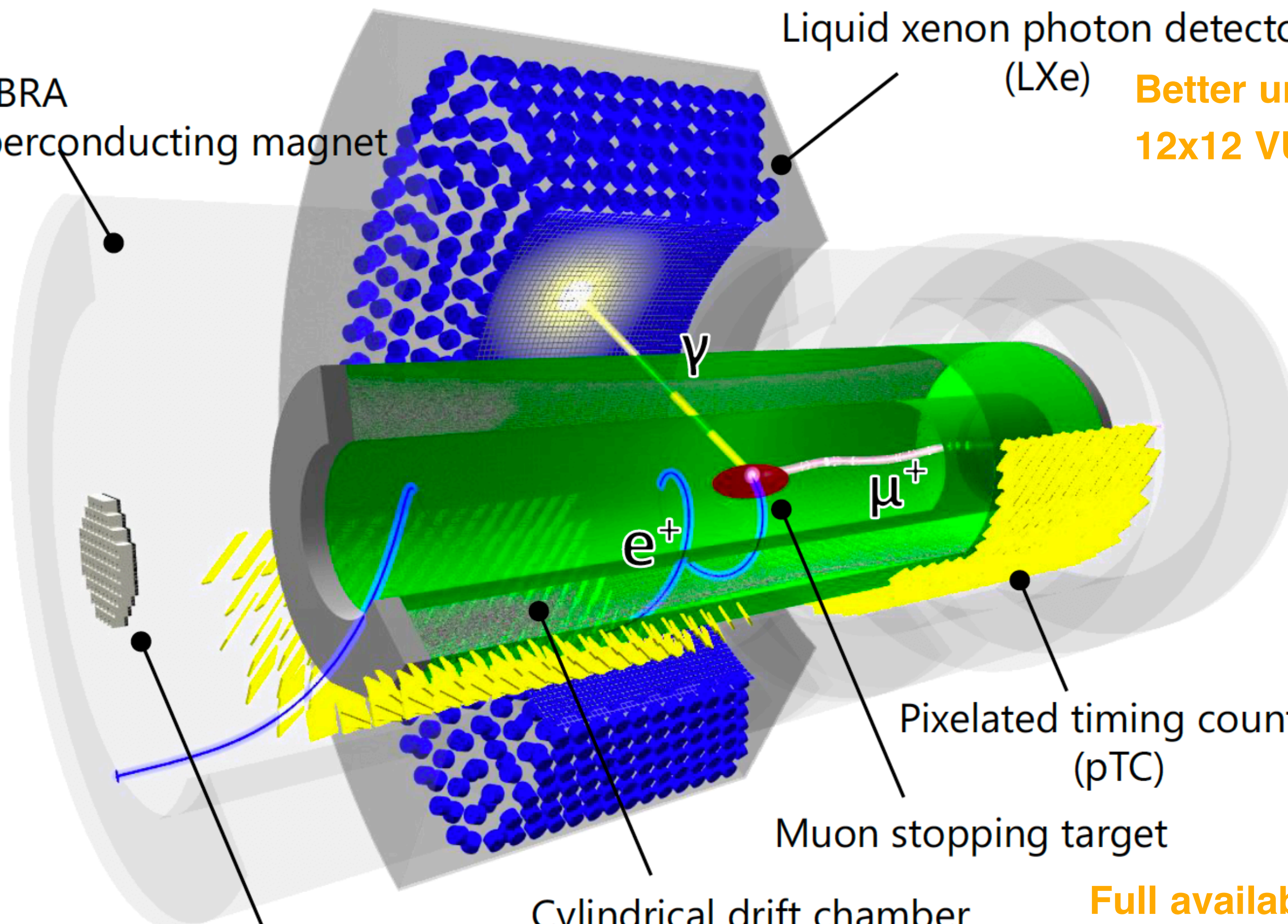
A.M. Baldini et al. (MEGII collab.)
Eur. Phys. J. 78 (2018) 380

The MEGII experiment

New electronics:
Wavedream

~9000 channels at 5GSPS

x2 Resolution everywhere



Better uniformity w/ 12x12 VUV SiPM

x2 Beam Intensity

35 ps resolution w/ multiple hits

Updated and new Calibration methods

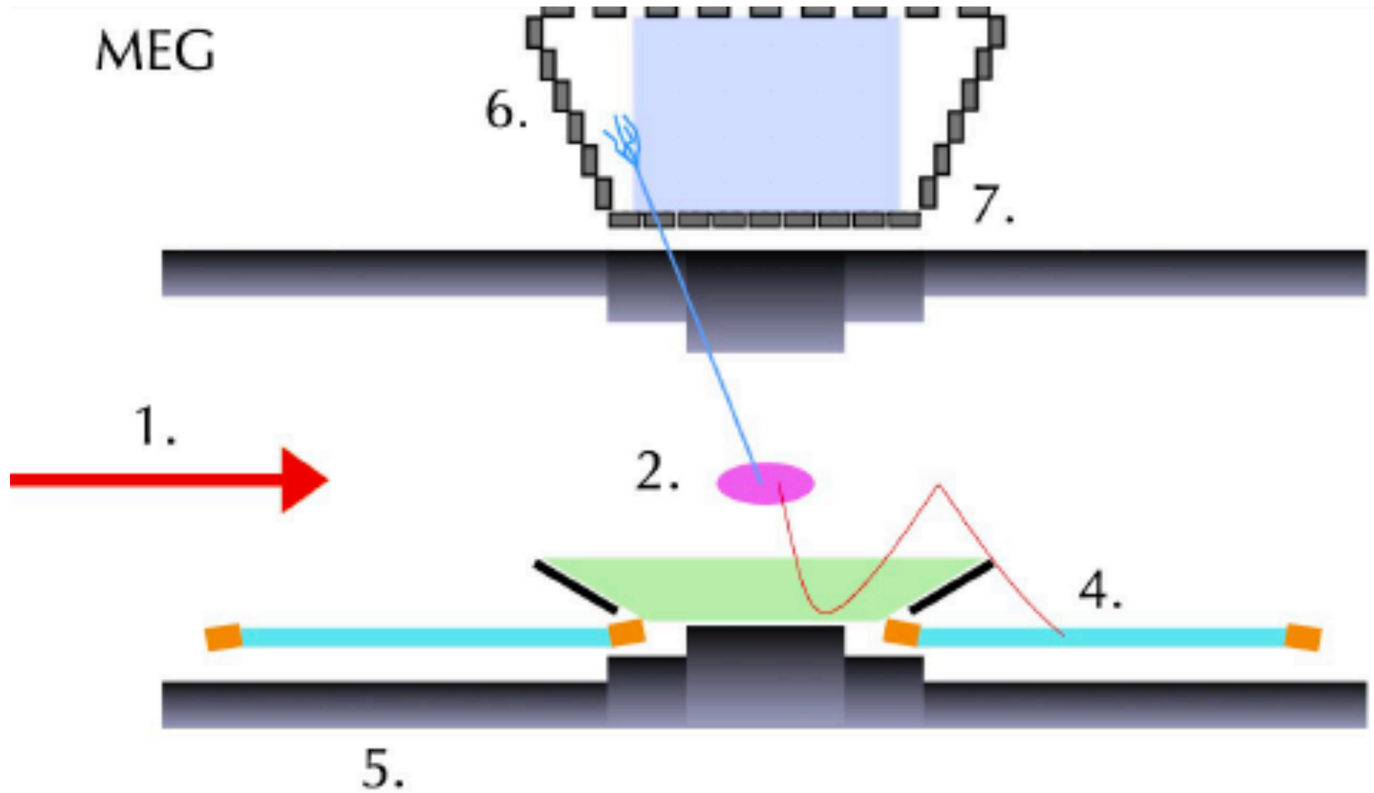
Quasi mono-chromatic positron beam

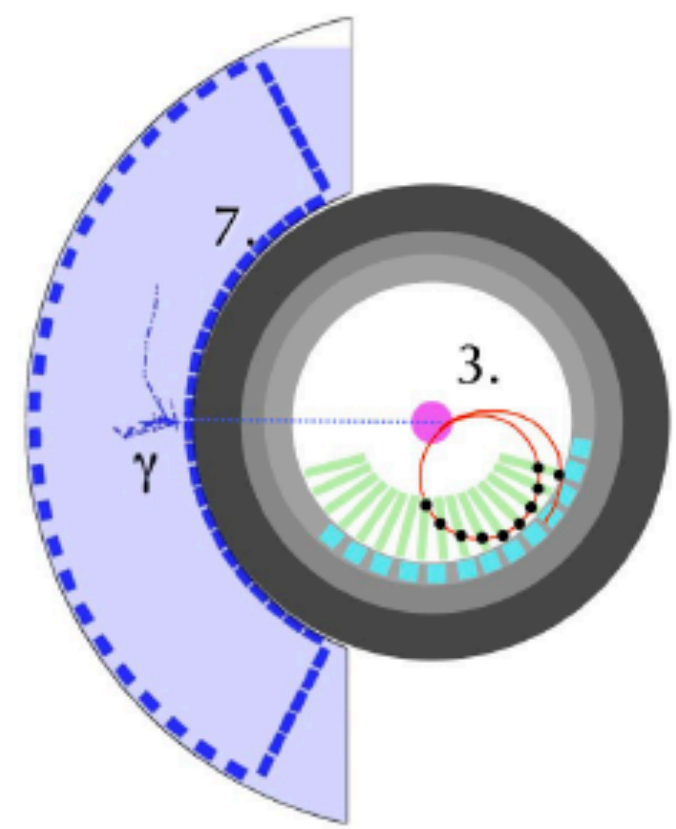
Background rejection

Single volume $He:iC_4H_{10}$

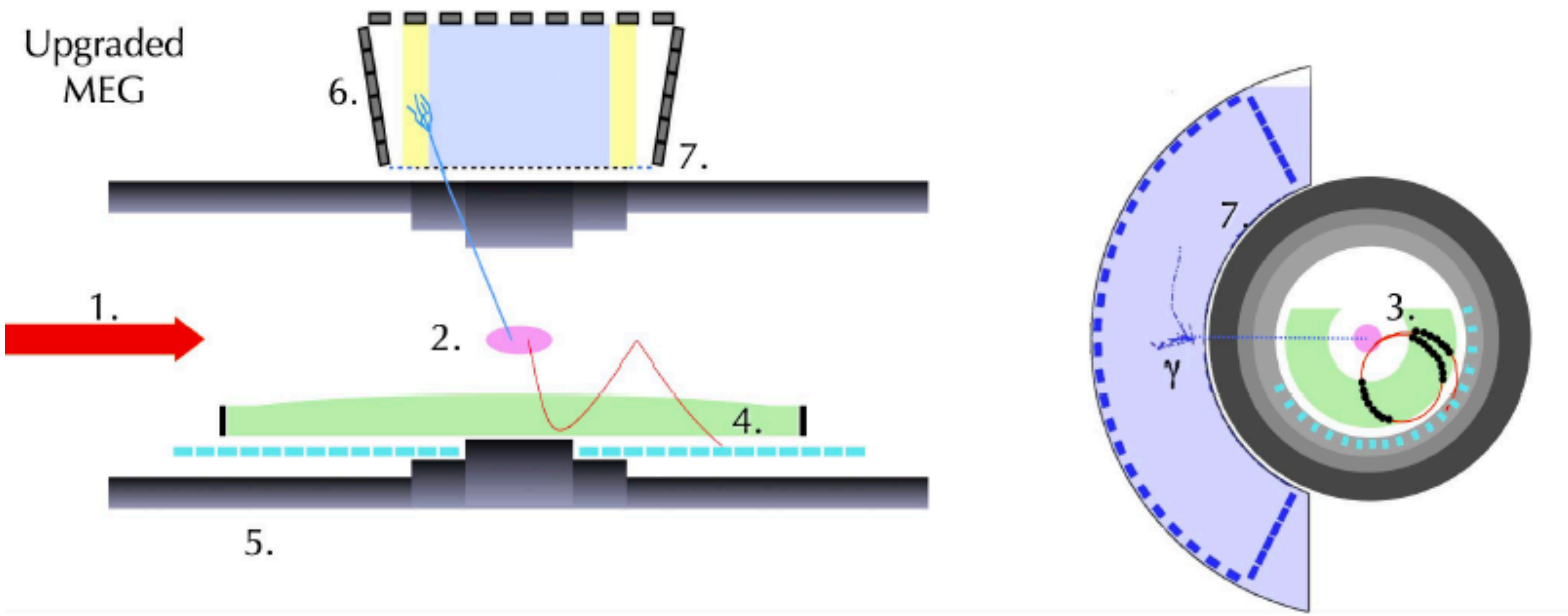
Full available stopped beam intensity 7×10^7

The MEG experiment vs the MEGII experiment

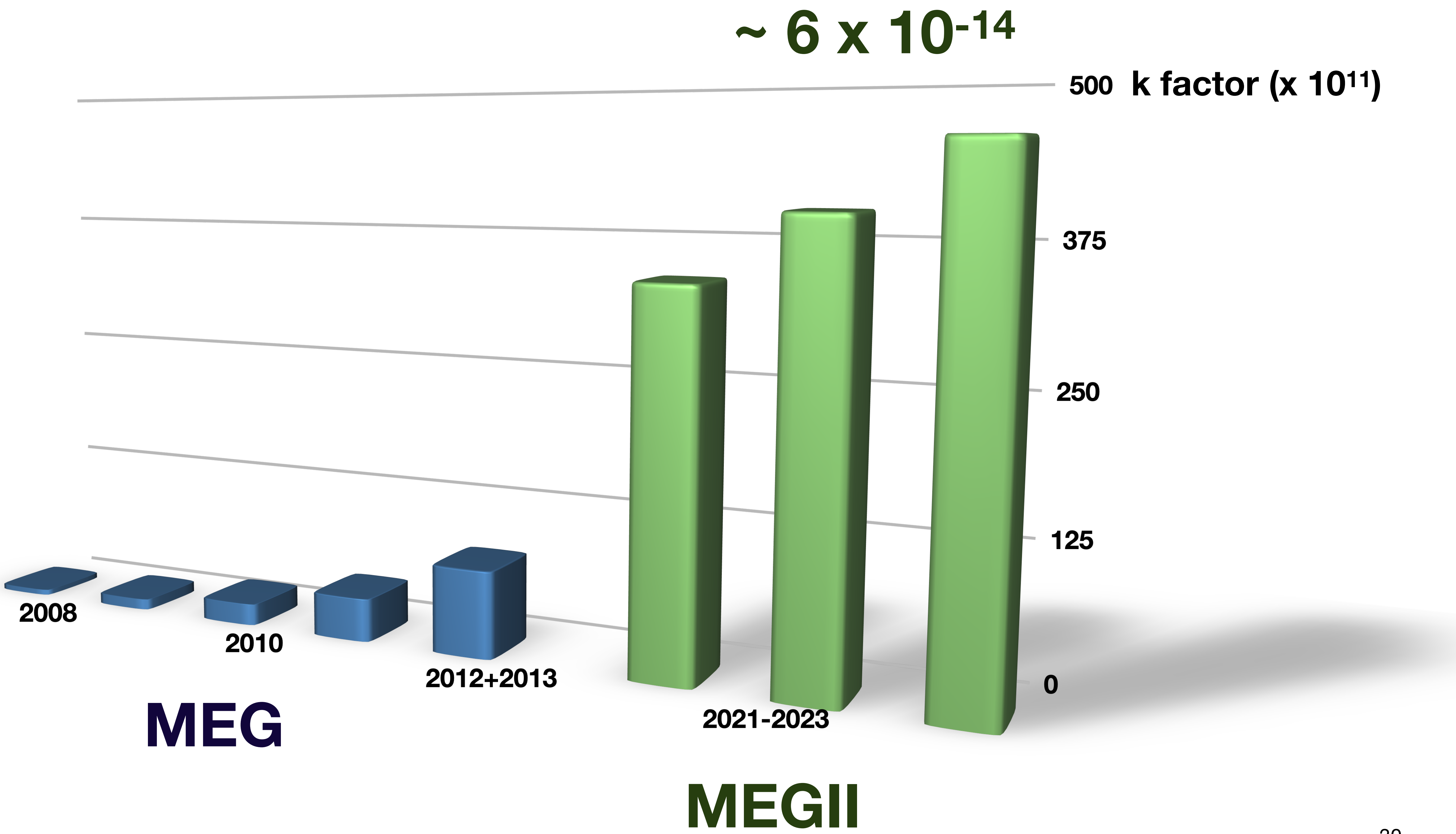




The MEG experiment vs the MEGII experiment



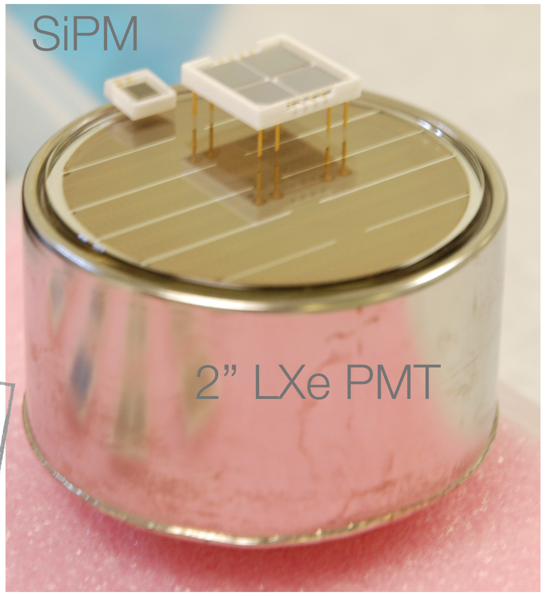
Where we will be



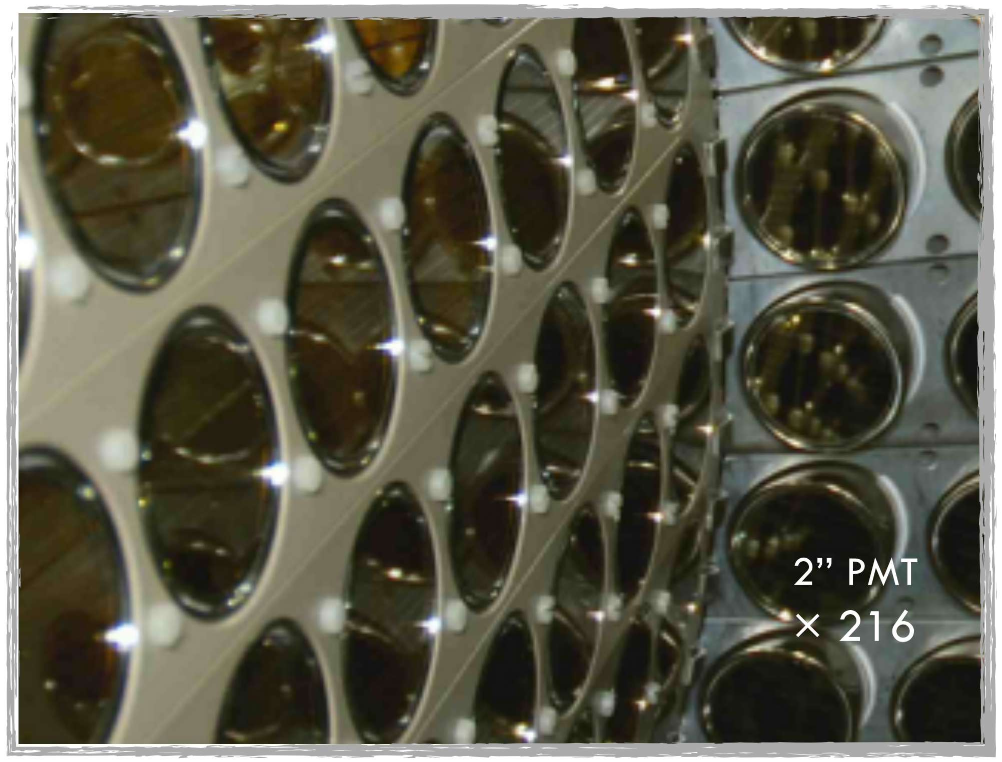
MEGII: The upgraded LXe calorimeter

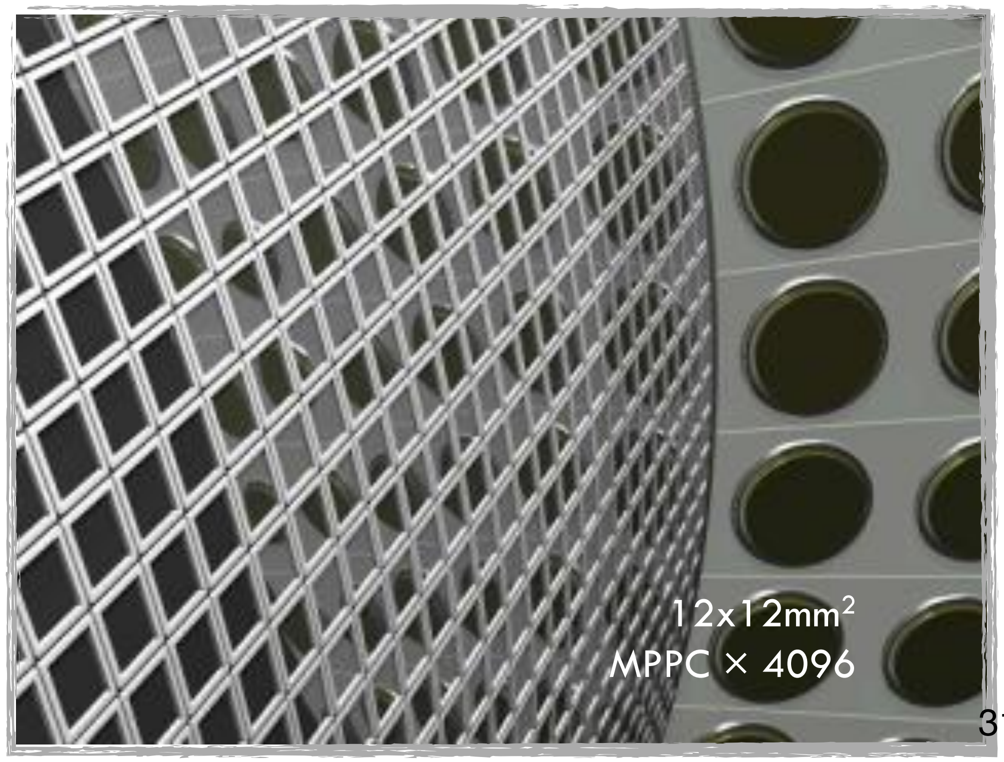
- Increased uniformity/resolutions
- Increased pile-up rejection capability
- Increased acceptance and detection efficiency
- Detector performance in final conditions: analysis ongoing

New



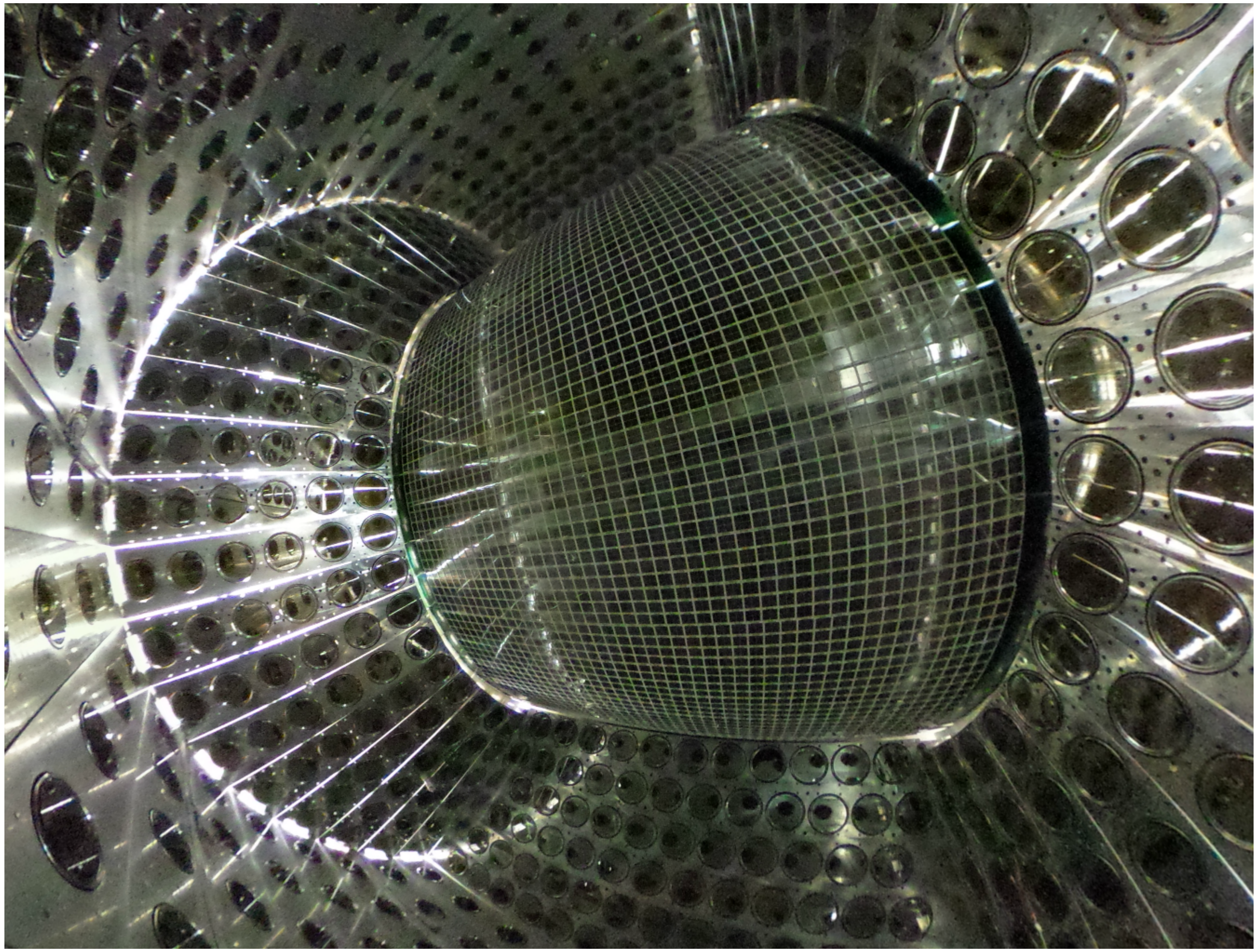
	MEG	MEGII
u [mm]	5	2.4
v [mm]	5	2.2
w [mm]	6	3.1
E [w<2cm]	2.4%	1.1%
E [w>2cm]	1.7%	1.0%
t [ps]	67	60



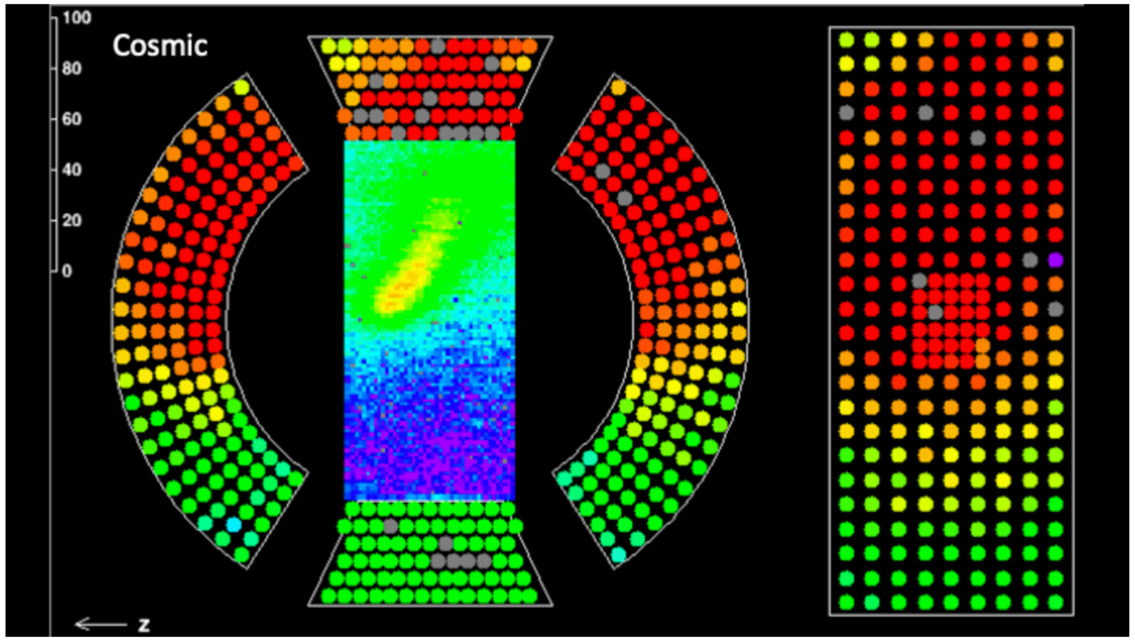


MEGII: The upgraded LXe calorimeter

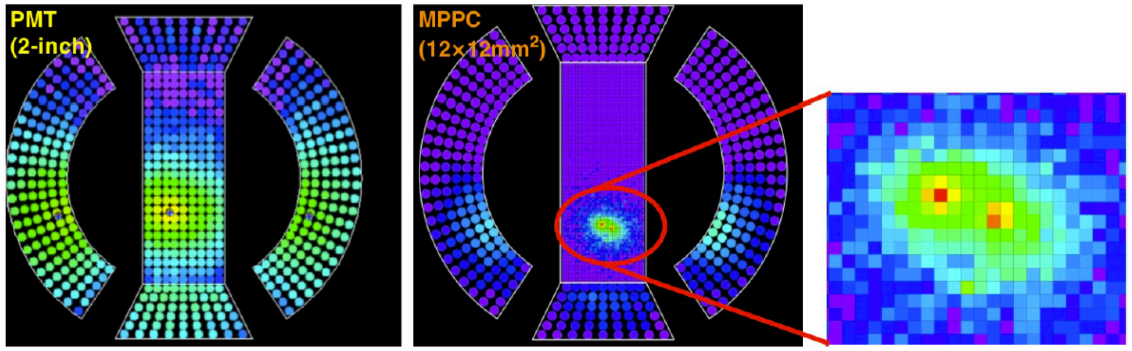
Detector commissioning:



Data

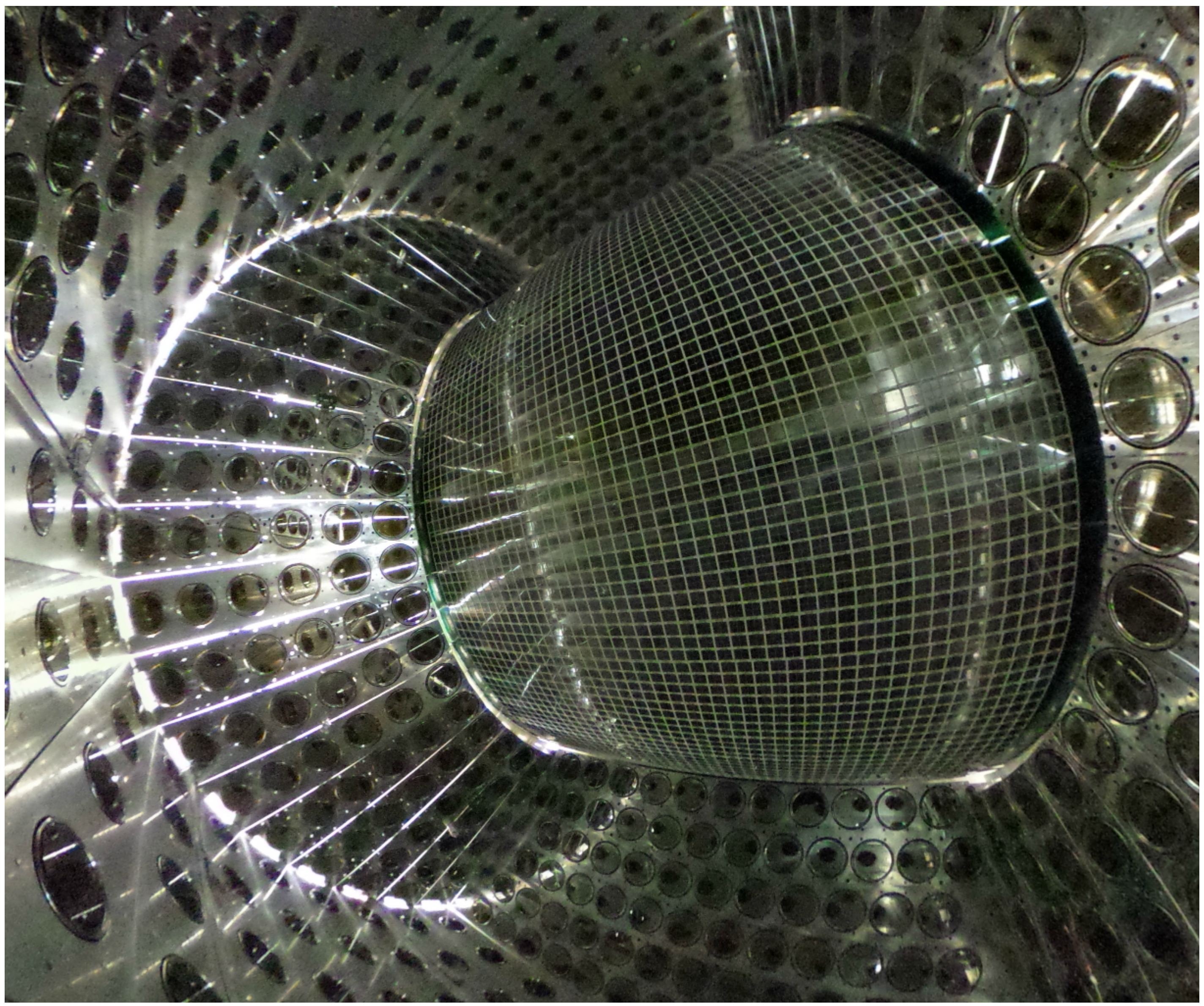


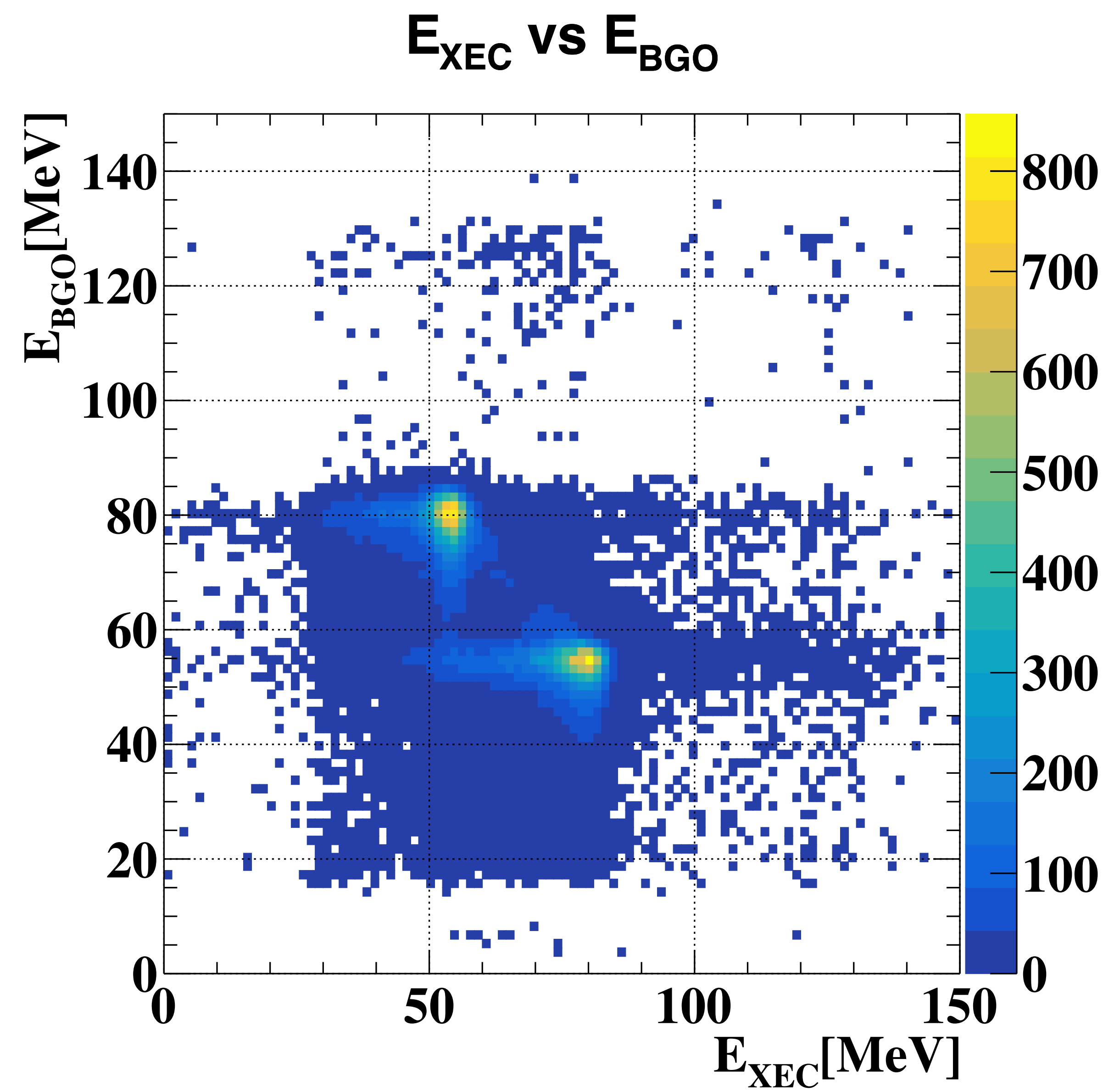
MC simulation



MEGII: The upgraded LXe calorimeter

Data from the **first** Physics Run2021



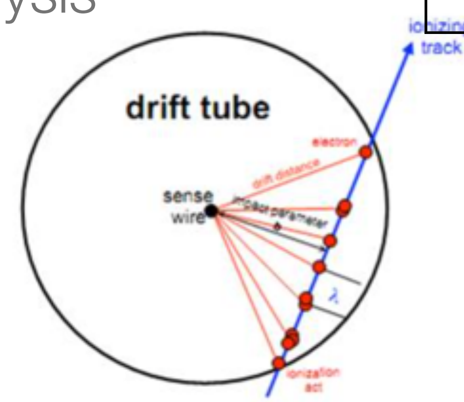


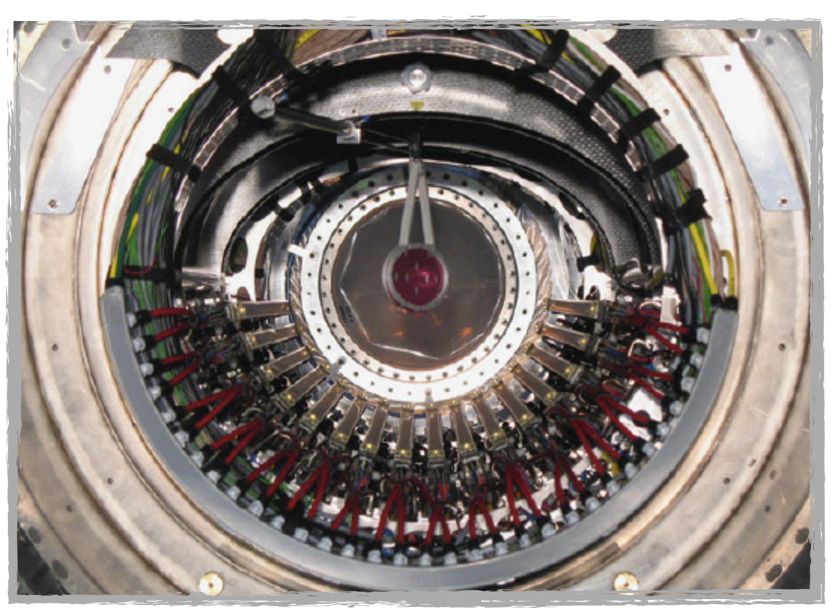
MEGII: The new single volume chamber

- Improved hit resolution: σ_r ~< 120 um (210 um)
- High granularity/Increased number of hits per track/ cluster timing technique
- Less material (helium: isobutane = 90:10, $1.6 \times 10^{-3}\ X_0$)
- High transparency towards the TC
- Detector performance in final conditions: analysis ongoing

	MEG	MEGII
p [keV]	306	90
θ [mrad]	9.4	6.3
ϕ [mrad]	8.7	5.0
ϵ [%]*	40	70

(*) It includes also the matching with the Timing Counter





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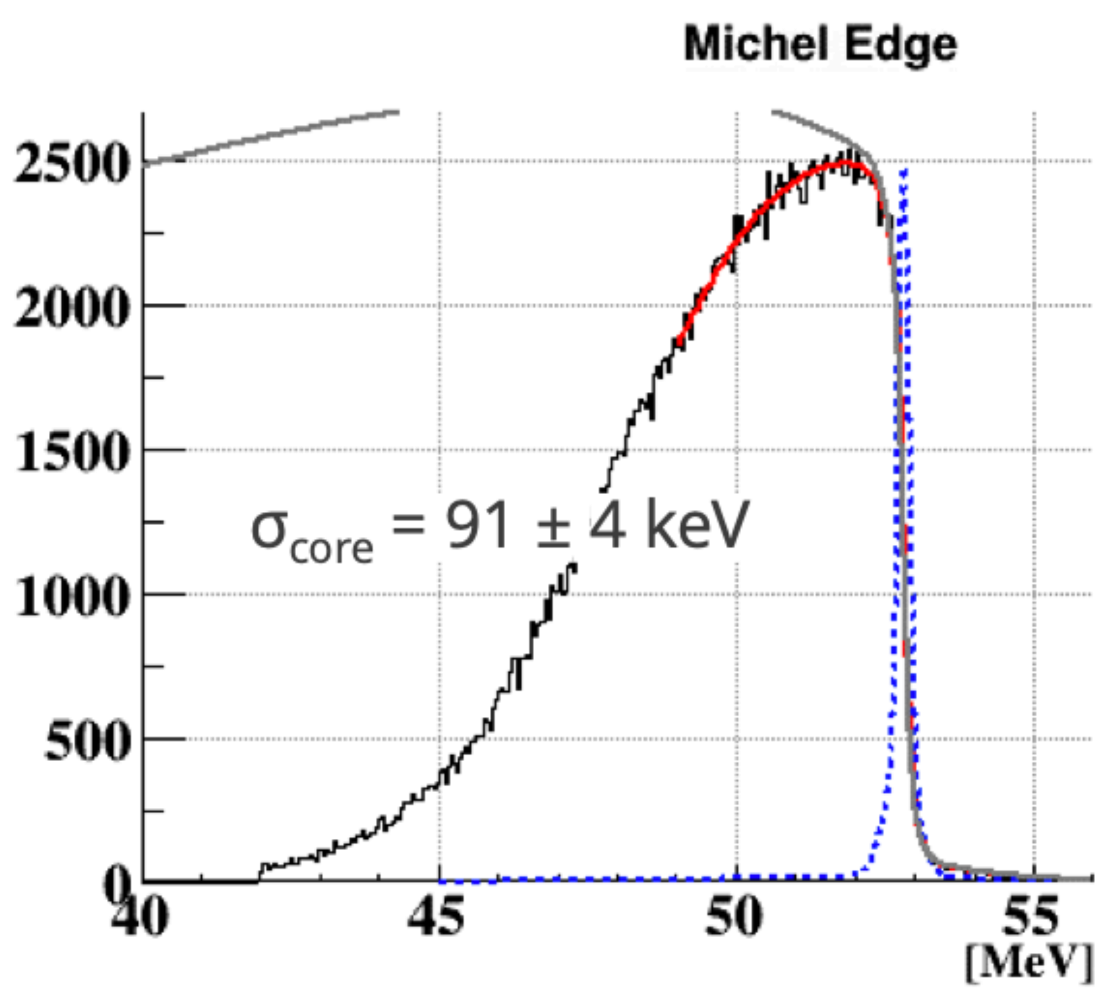

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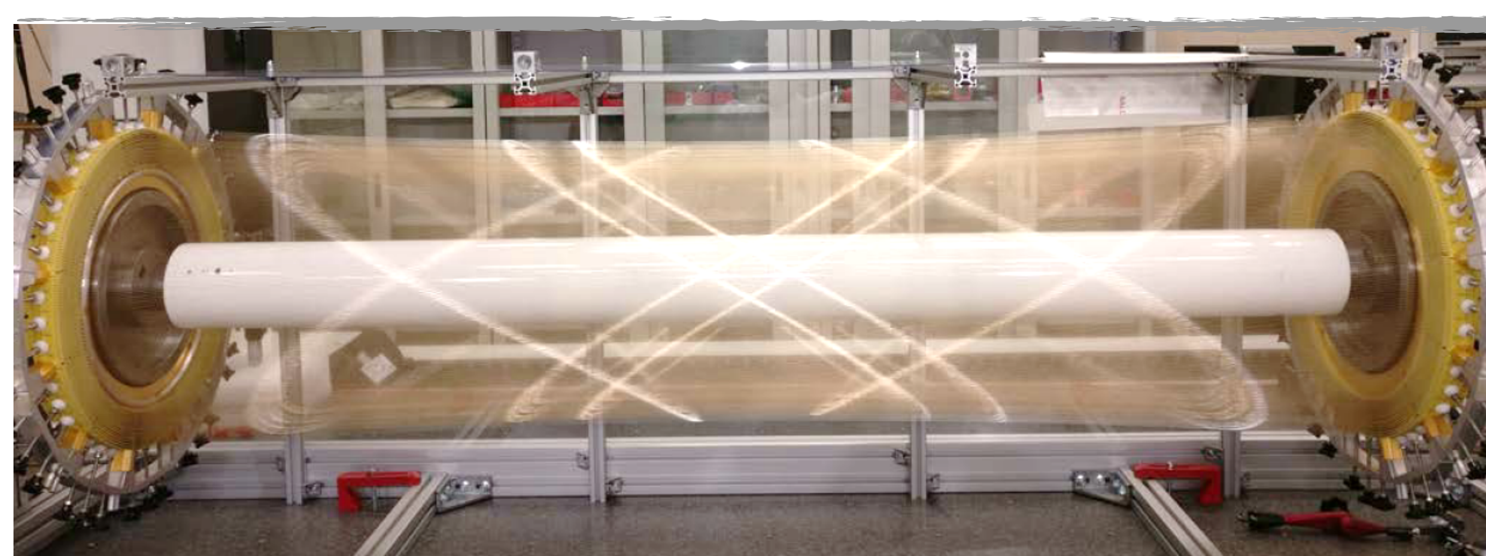
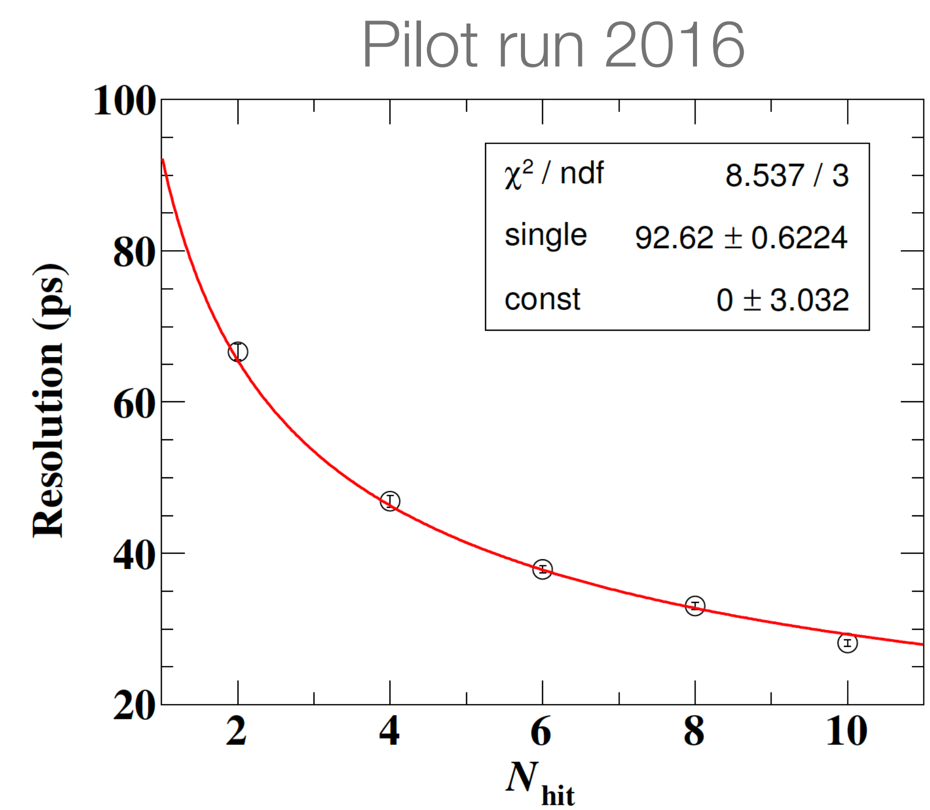
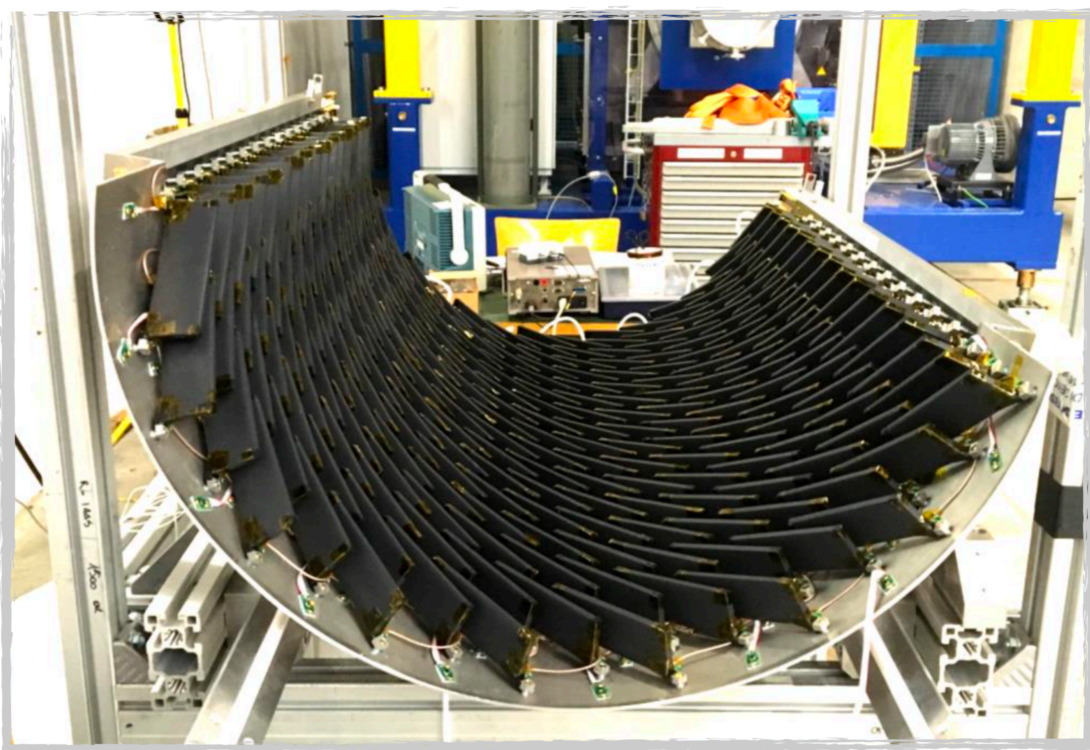


MEGII: the pixelized Timing Counter

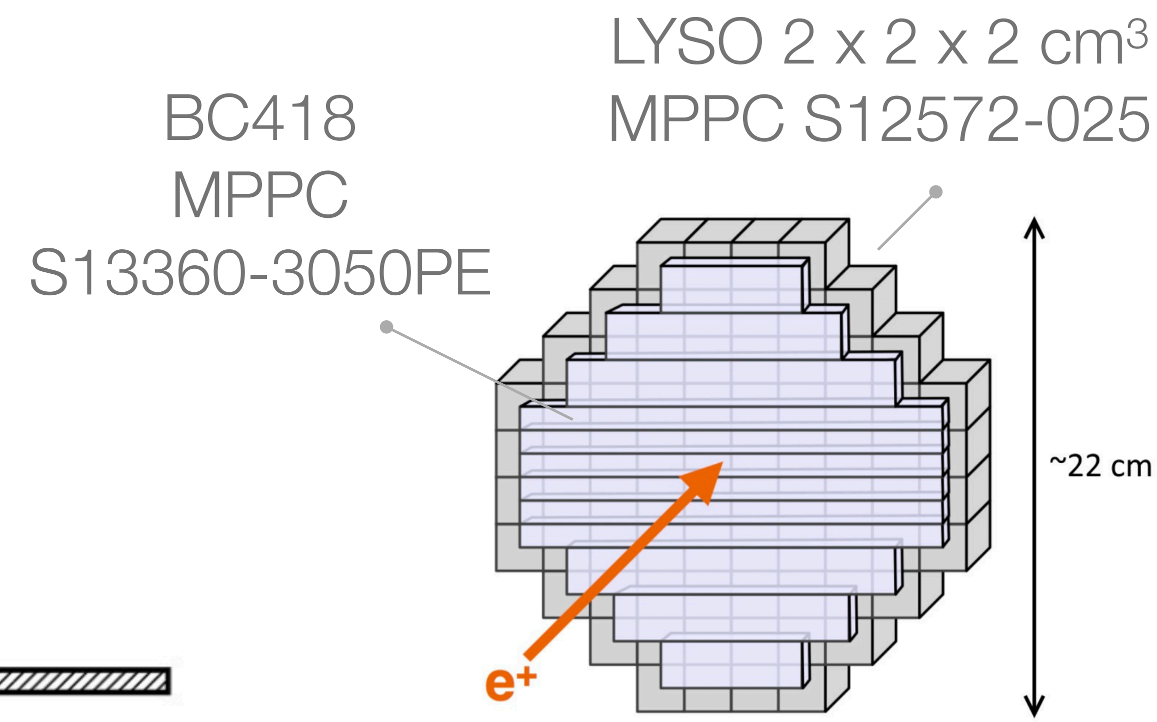
- Higher granularity: 2 x 256 of BC422 scintillator plates (120 x 40 (or 50) x 5 mm³) readout by AdvanSiD SiPM ASD-NUM3S-P-50-High-Gain
- Improved timing resolution: from 70 ps to 35 ps (multi-hits)
- Less multiple scattering and pile-up
- Assembly: Completed
- Expected detector performances confirmed with data during pre-eng. 2016 and 2017

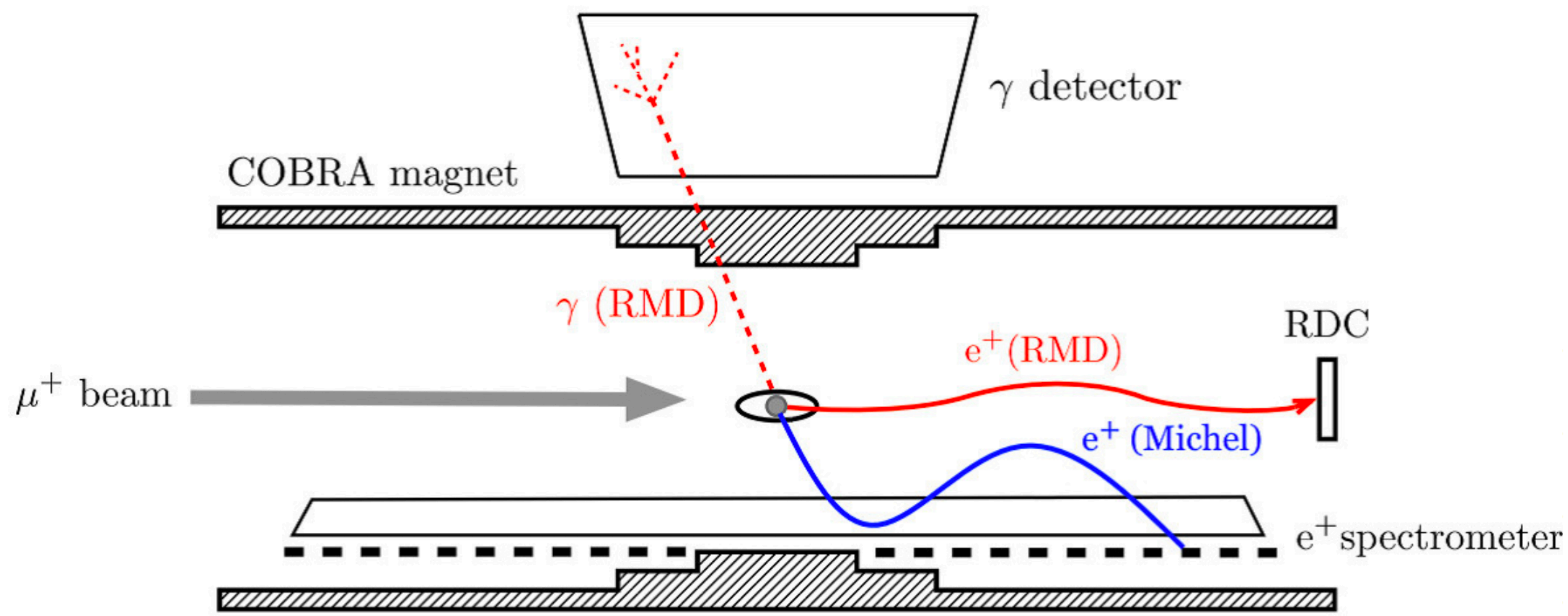


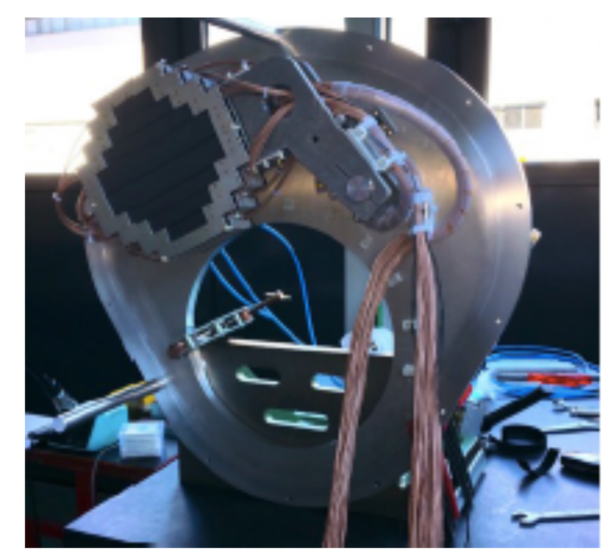


MEGII: The Radiative Decay Counter

- Added a new auxiliary detector for background rejection purpose. Impact into the experiment: Improved sensitivity by 20%
- Commissioning during the 2016 pre-engineering run
- Status: Ready for MEGII !





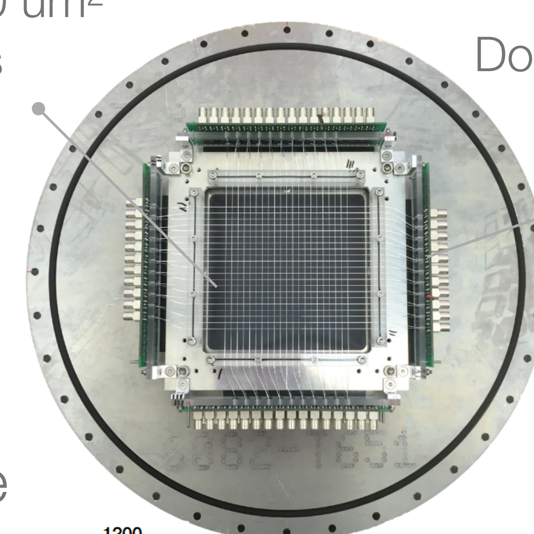


MEGII: new calibration methods and upgrades

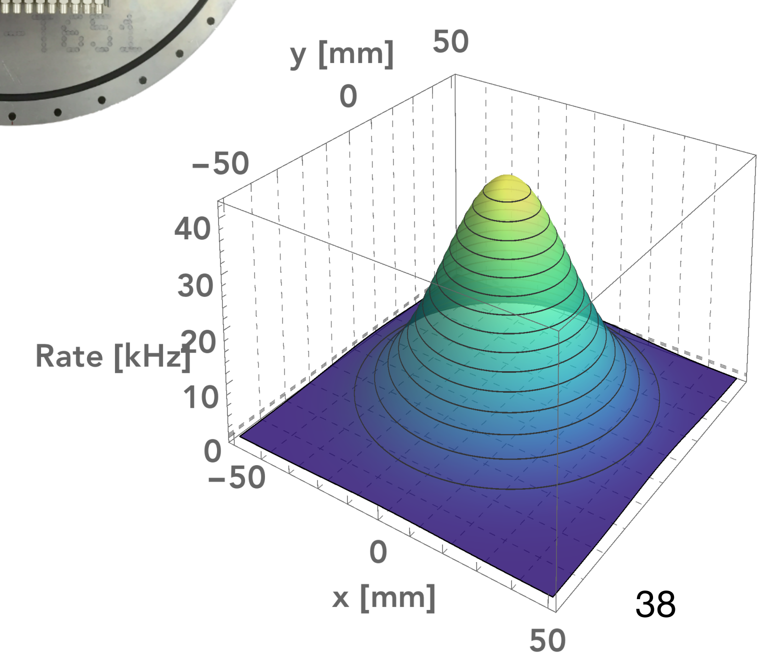
- CEX reaction: $p(\pi^-, \pi^0)n$, $\pi^0 \rightarrow \gamma\gamma$
- 1MV Cockcroft-Walton accelerator
- Pulsed D-D Neutron generator
- NEW: Mott scattered positron beam to fully exploit the new spectrometer
- NEW: SciFi beam monitoring. Not invasive, ID particle identification, vacuum compatible, working in magnetic field, online beam monitor (beam rate and profile)
- NEW: Luminophore (CsI(Tl) on Lavsan/Mylar equivalent) to measure the beam properties at the Cobra center
- NEW: LXe X-ray survey
- NEW: Laser system for the pTC

MC BCF12 250 x 250 um^2 scintillating fibers

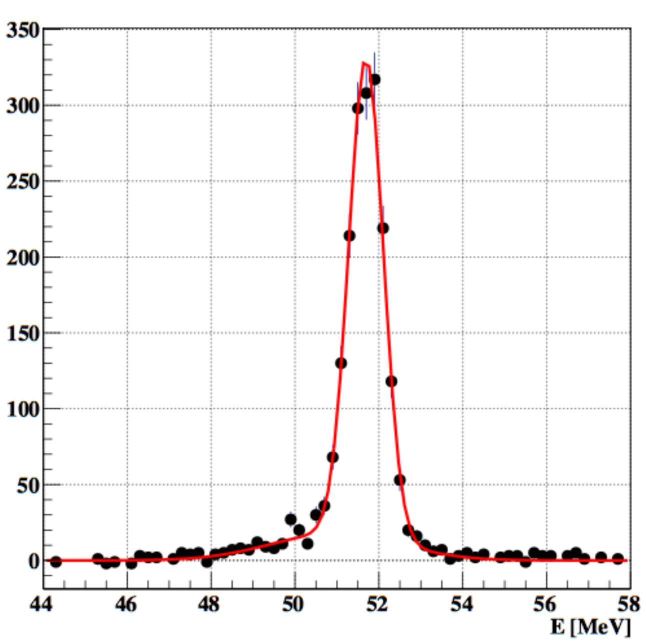
Double readout: MPPC S13360-3050C



SciFi

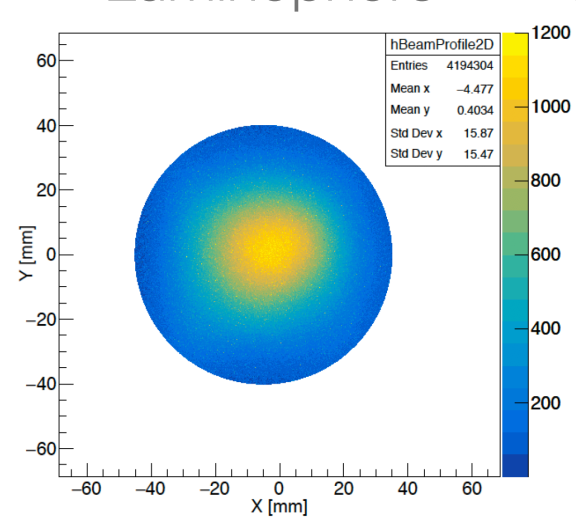


Monochromatic e-line



pTC's laser

Luminophore



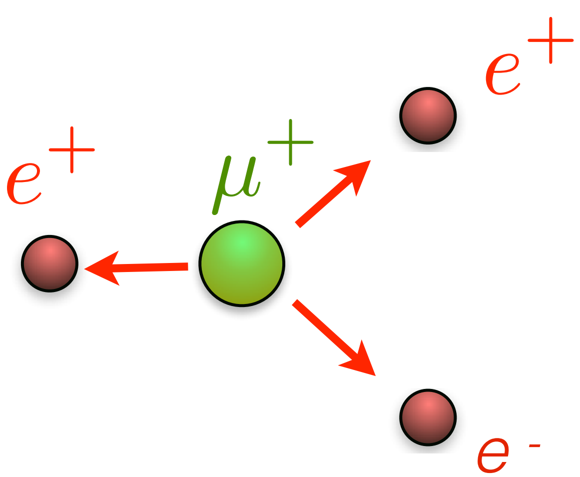
MEGII: The new electronic - DAQ and Trigger

- DAQ and Trigger
  - ~9000 channels (5 GSPS)
  - Bias voltage, preamplifiers and shaping included for SiPMs
- Run 2021: Electronics fully installed and tested with all sub-detectors and calibration tools
- Run 2021: All calibration and physics trigger configurations released

Mu3e: The $\mu^+ \to e^+e^+e^-$ search

- The Mu3e experiment aims to search for $\mu^+ \to e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit BR($\mu^+ \to e^+ e^+ e^-$) ≤ 1 x 10^{-12} @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \to eee$ events

Signature

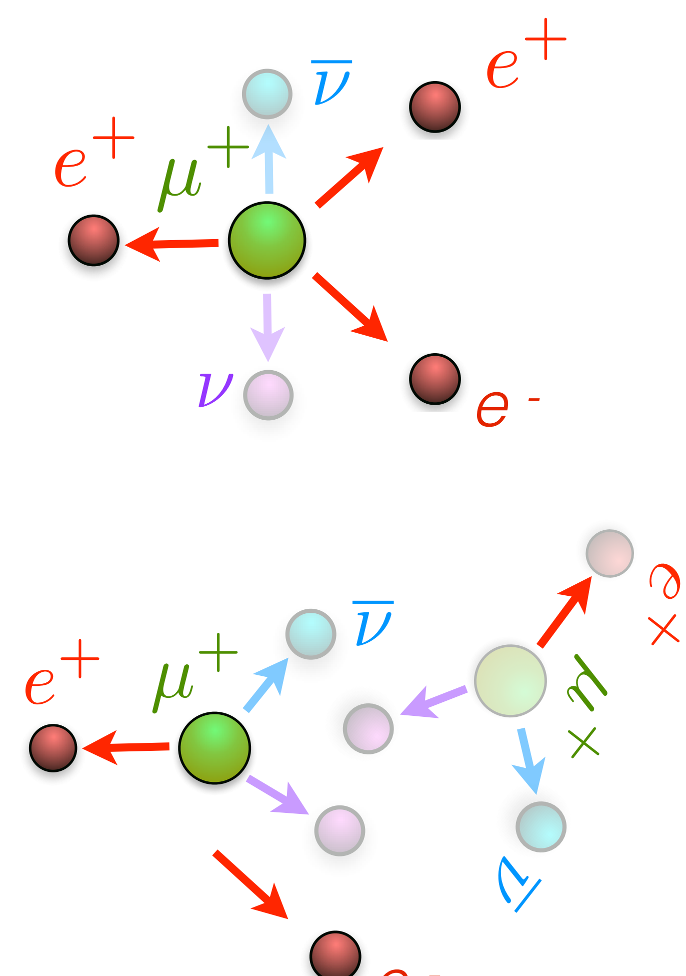


$$\Delta t_{eee} = 0$$

$$\Sigma \overline{p}_e = 0$$

$$\Sigma E_e = m_\mu$$

Background



The Mu3e experiment: Schematic 3D

Superconducting solenoid Magnet

Homogeneous field

1T

Tile detector

70 ps resolution

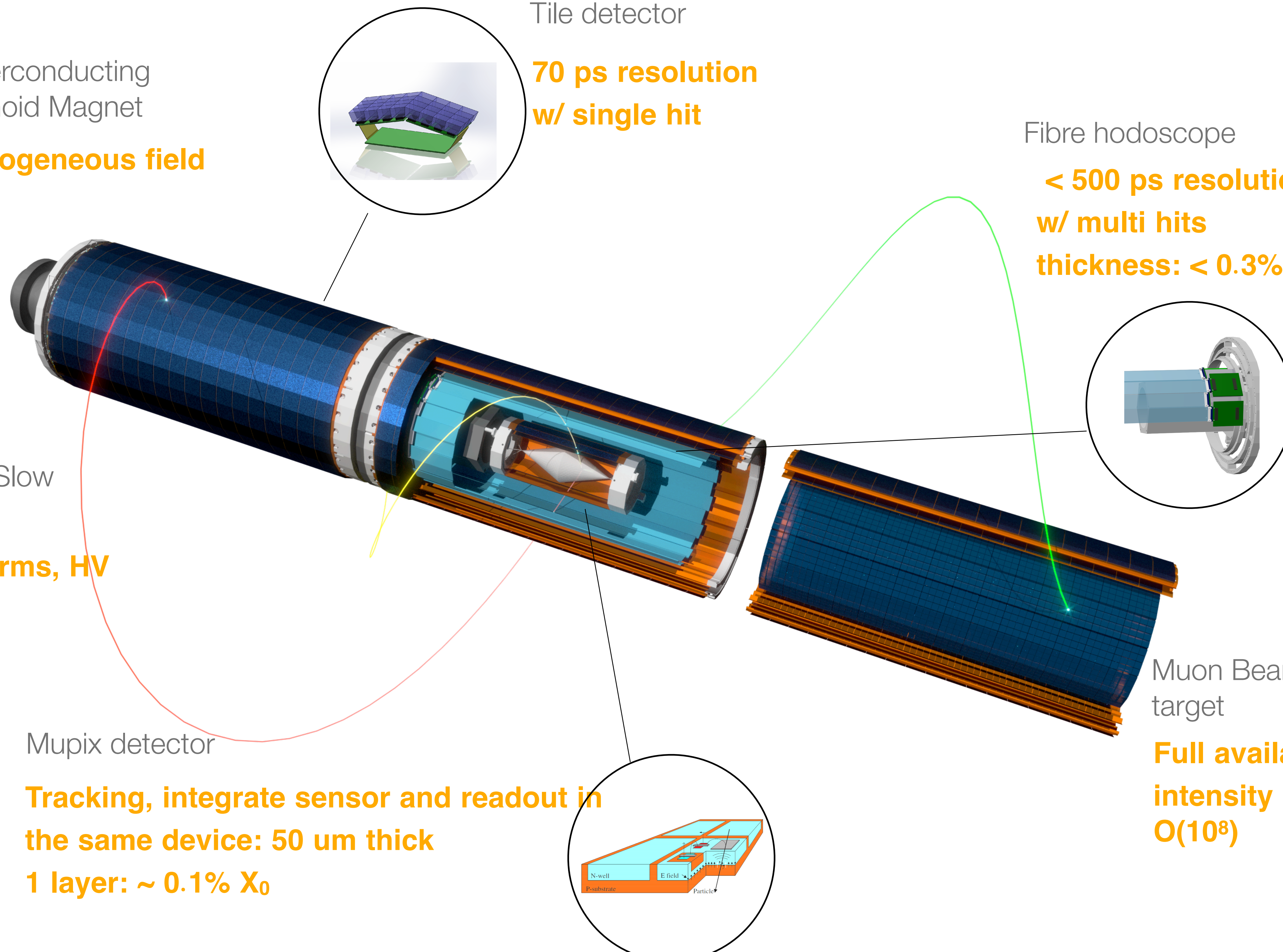
w/ single hit

Fibre hodoscope

< 500 ps resolution

w/ multi hits

thickness: < 0.3% X_0



MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

Muon Beam and target

Full available beam intensity

$O(10^8)$

Mupix detector

Tracking, integrate sensor and readout in the same device: 50 um thick

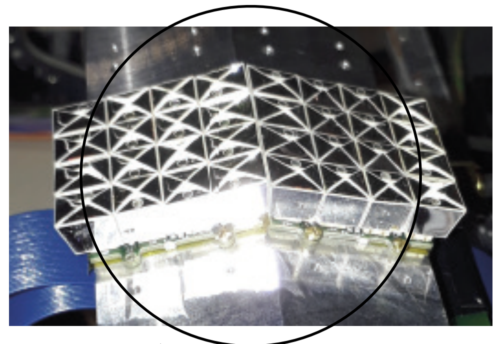
1 layer: ~ 0.1% X_0

The Mu3e experiment: R&D completed. Prototyping phase

Superconducting solenoid Magnet

Homogeneous field

1T



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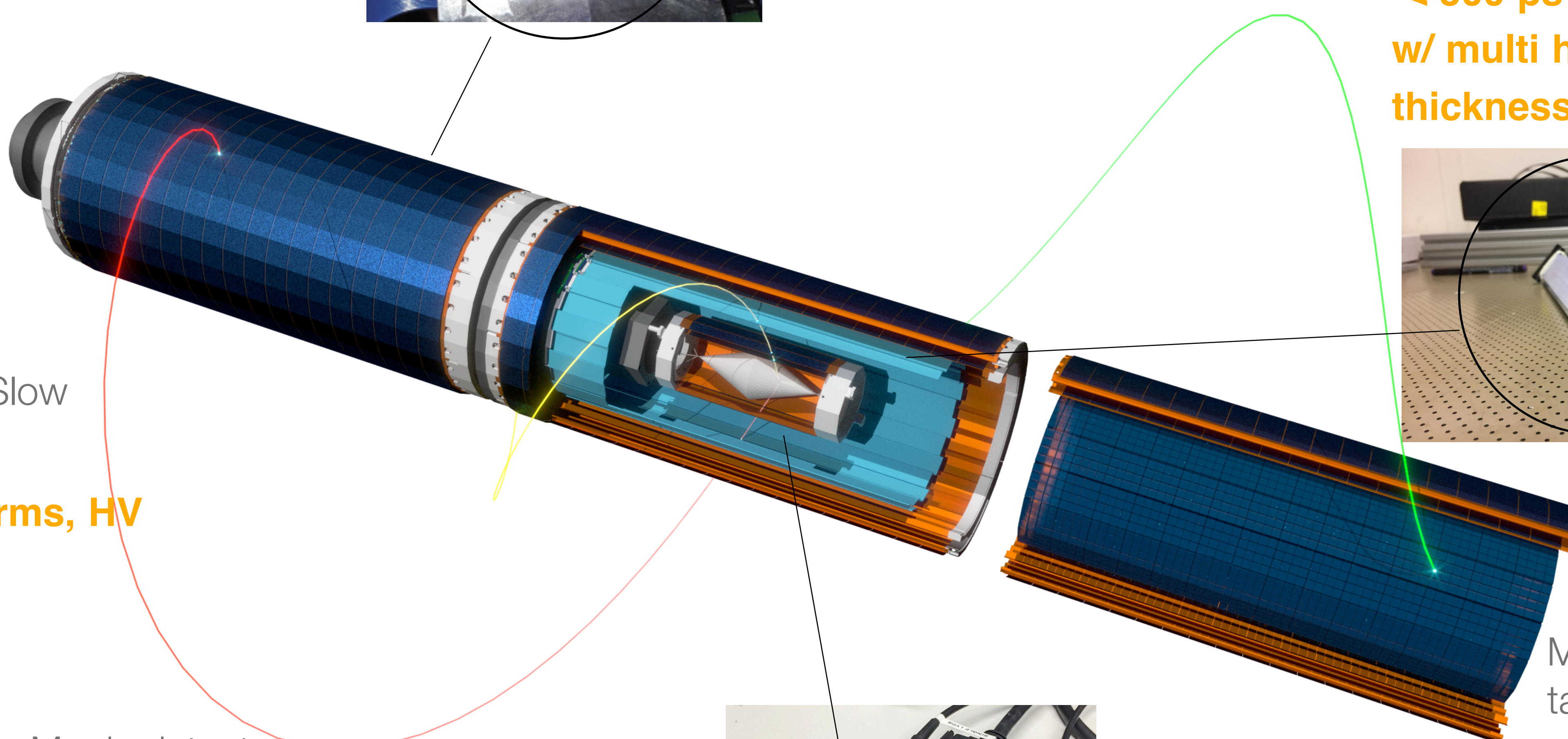

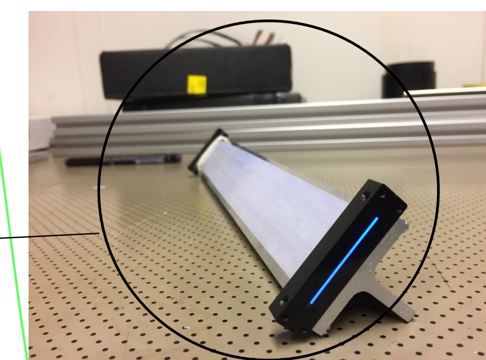

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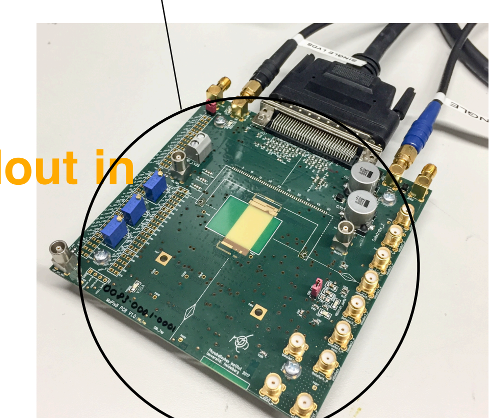
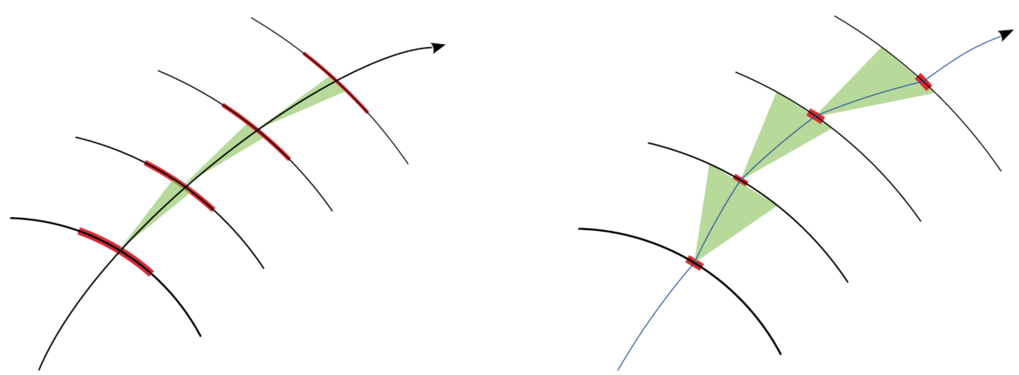


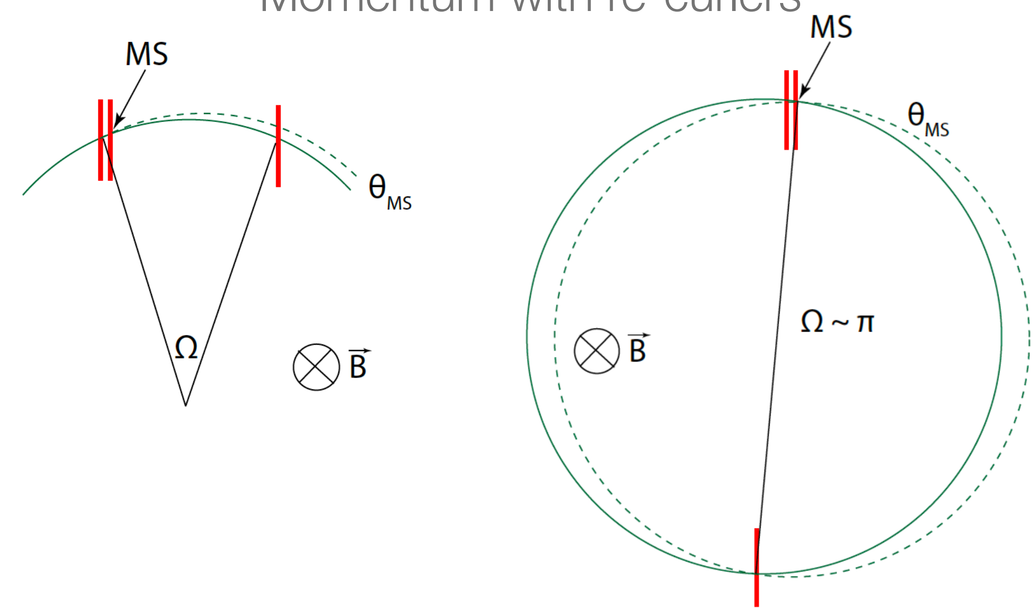
The pixel tracker: The principle

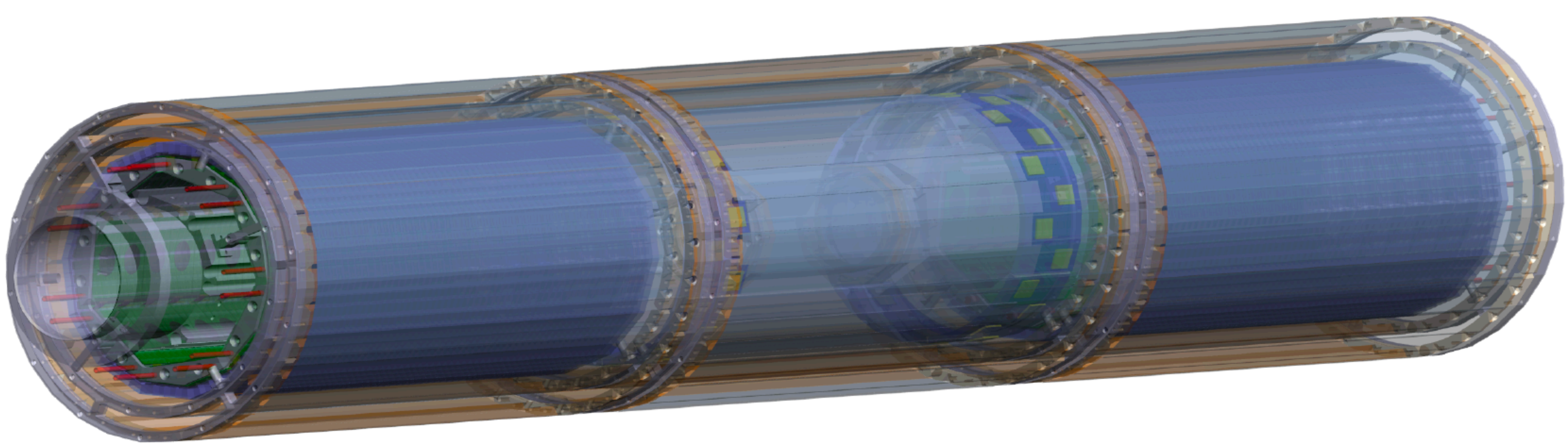
- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime

Tracking in the spacial and scattering dominated regime



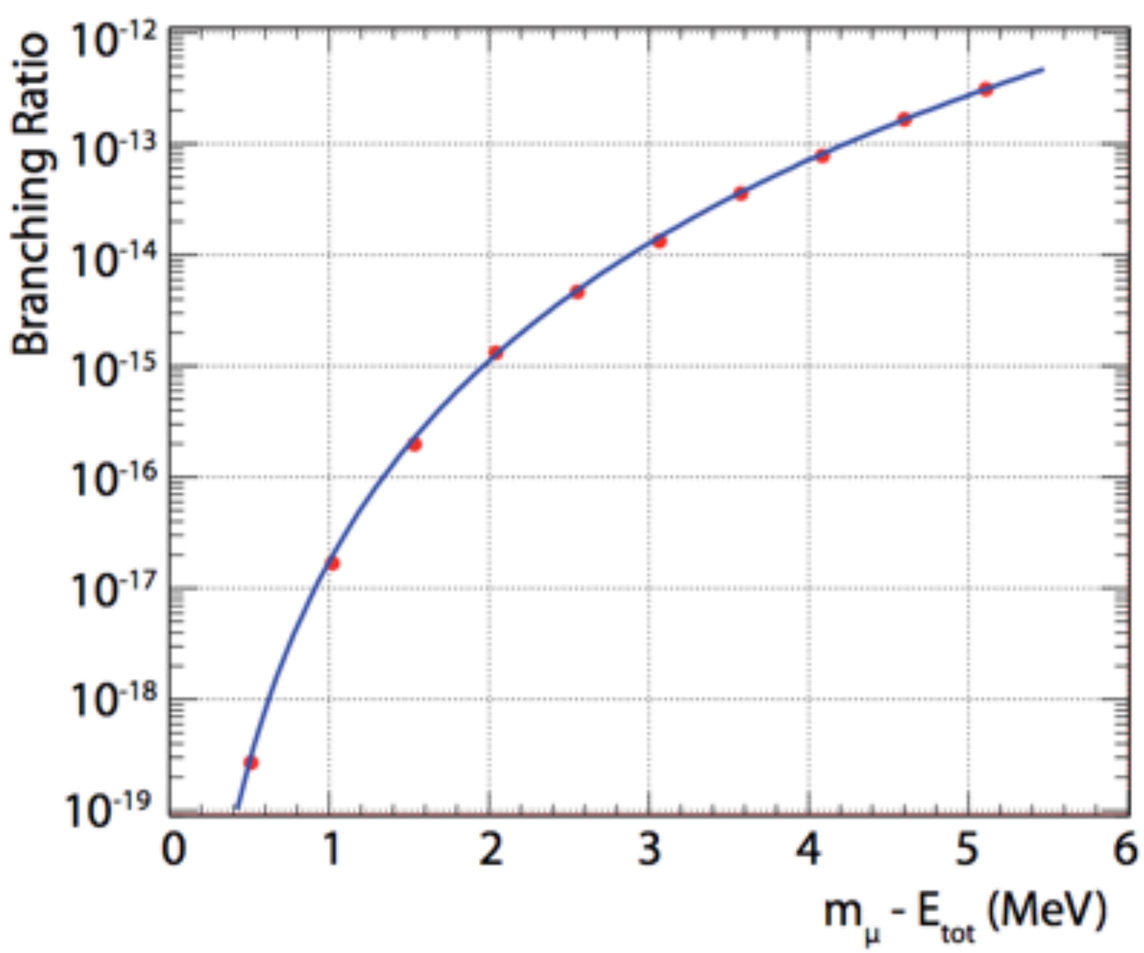
Momentum with re-curlers

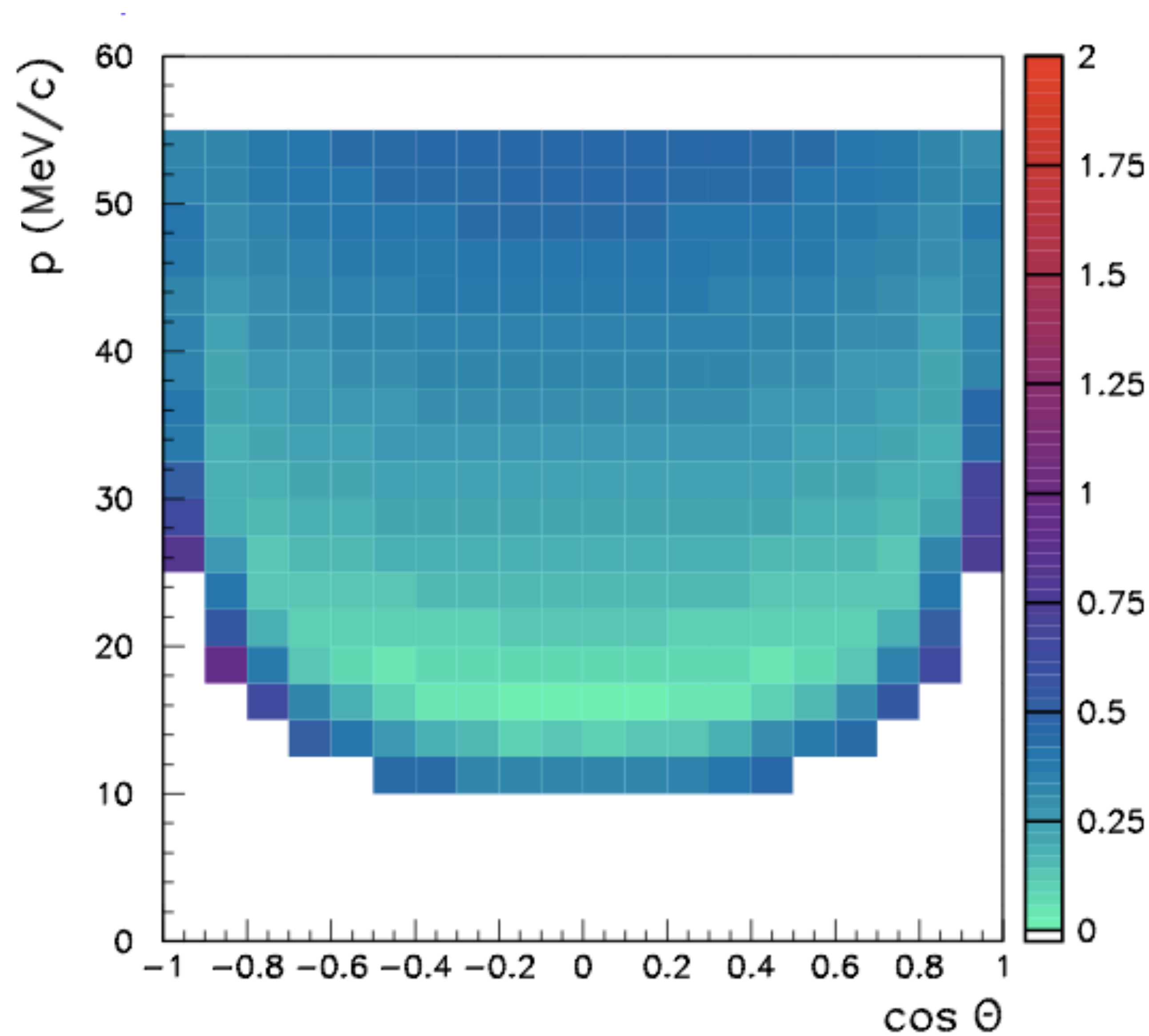




The pixel tracker: The performances

- Momentum resolution: < 0.5 MeV/c over a large phase space
- Geometrical acceptance: ~ 70%
- X/X_0 per layer: ~ 0.011%
- Vertex resolution: < 200 μm





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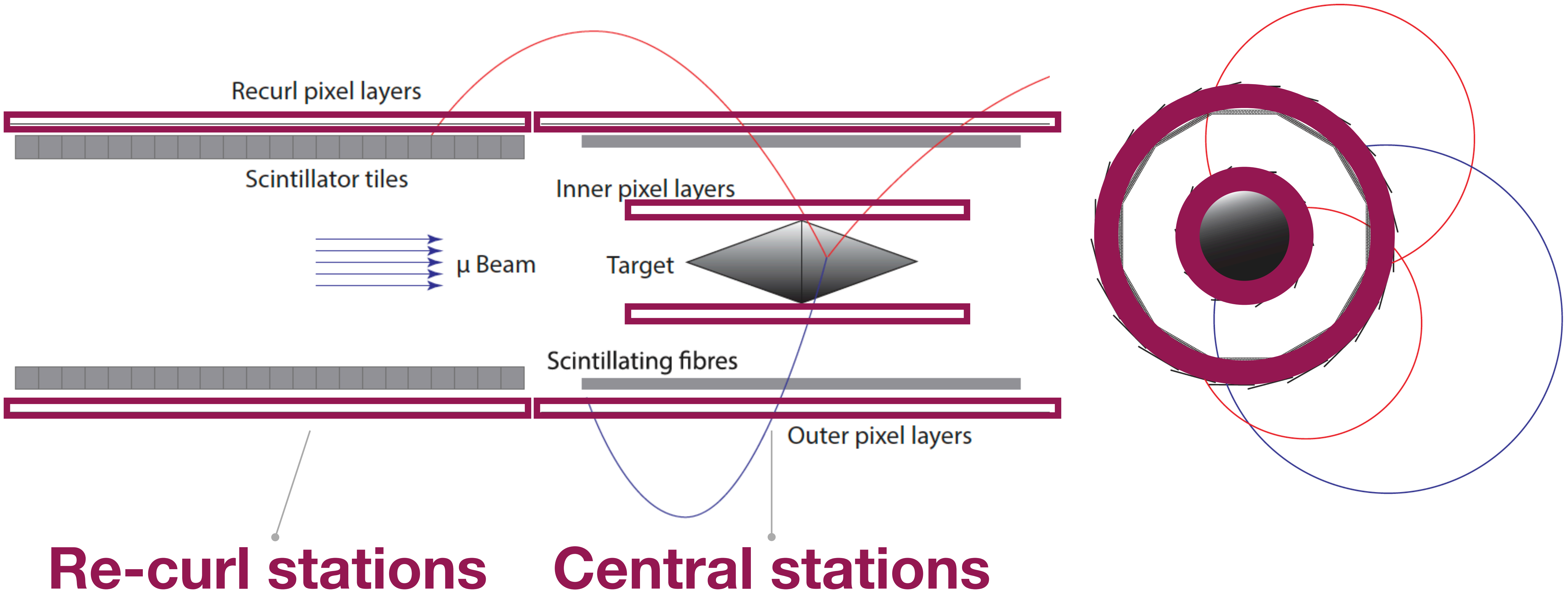
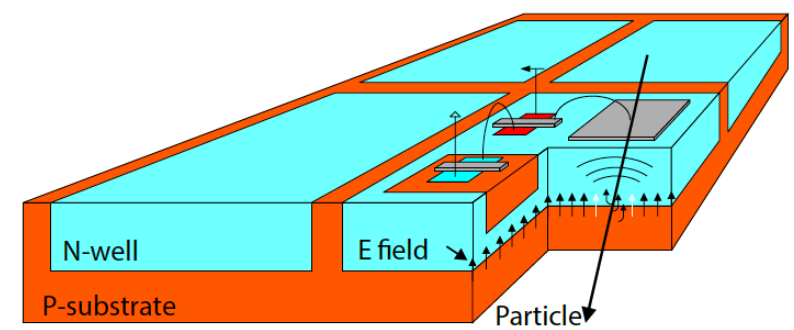


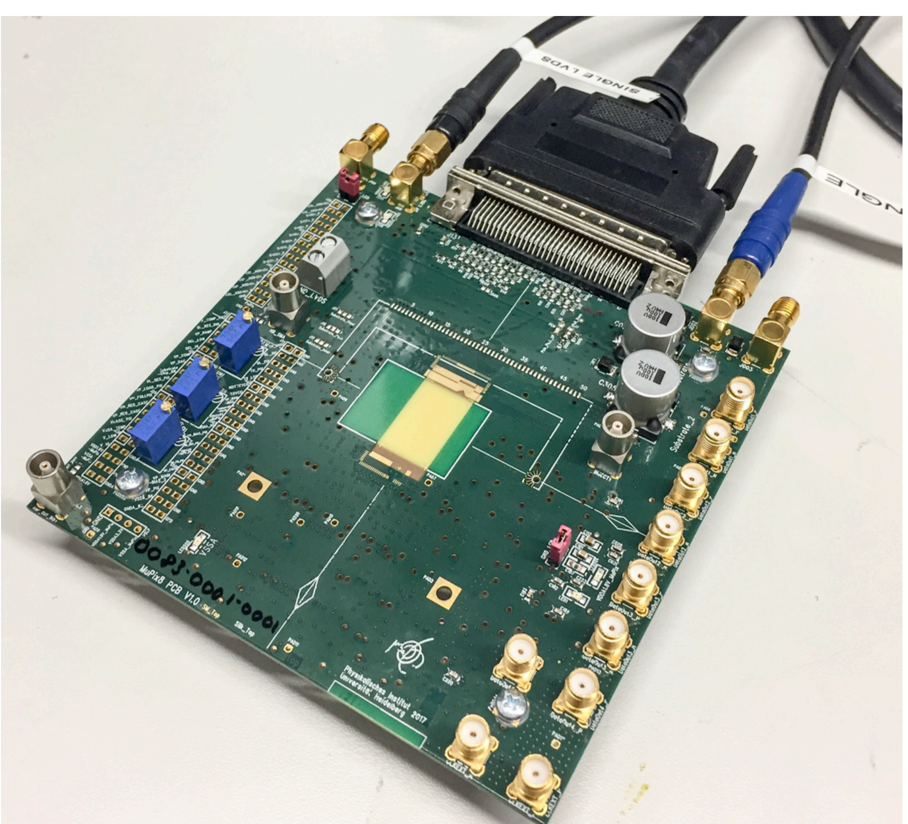
The pixel tracker: The MuPix detector

- Based on HV- MAP: Pixel dimension: 80 x 80 μm^2 , Thickness: 50 μm , Time resolution: < 20 ns, Active area chip: 20 x 20 mm^2 , Efficiency: > 99 %, Power consumption : < 350 mW/cm^2
- MuPix 7: The first small-scale prototype which includes all Mu3e functionalities
- MuPix 8, the first large area prototype: from O(10) mm^2 to 160 mm^2 : Ready and extensively tested!
- MuPix 9, small test chip for: Slow Control, voltage regulators and other test circuits. 2019 year test beam campaign
- MuPix 10, towards the final version: 380 mm^2

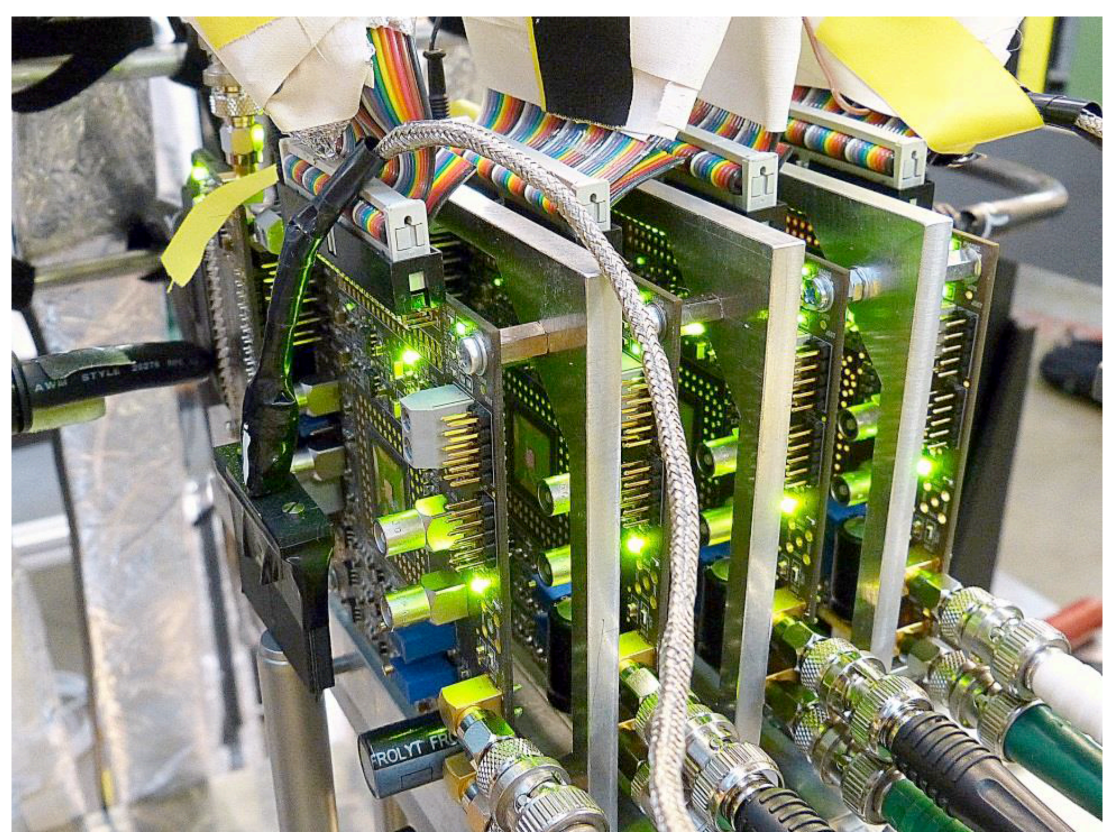
Ivan Peric, Nucl.Instrum.Meth. A582 (2007) 876-885



MuPix8



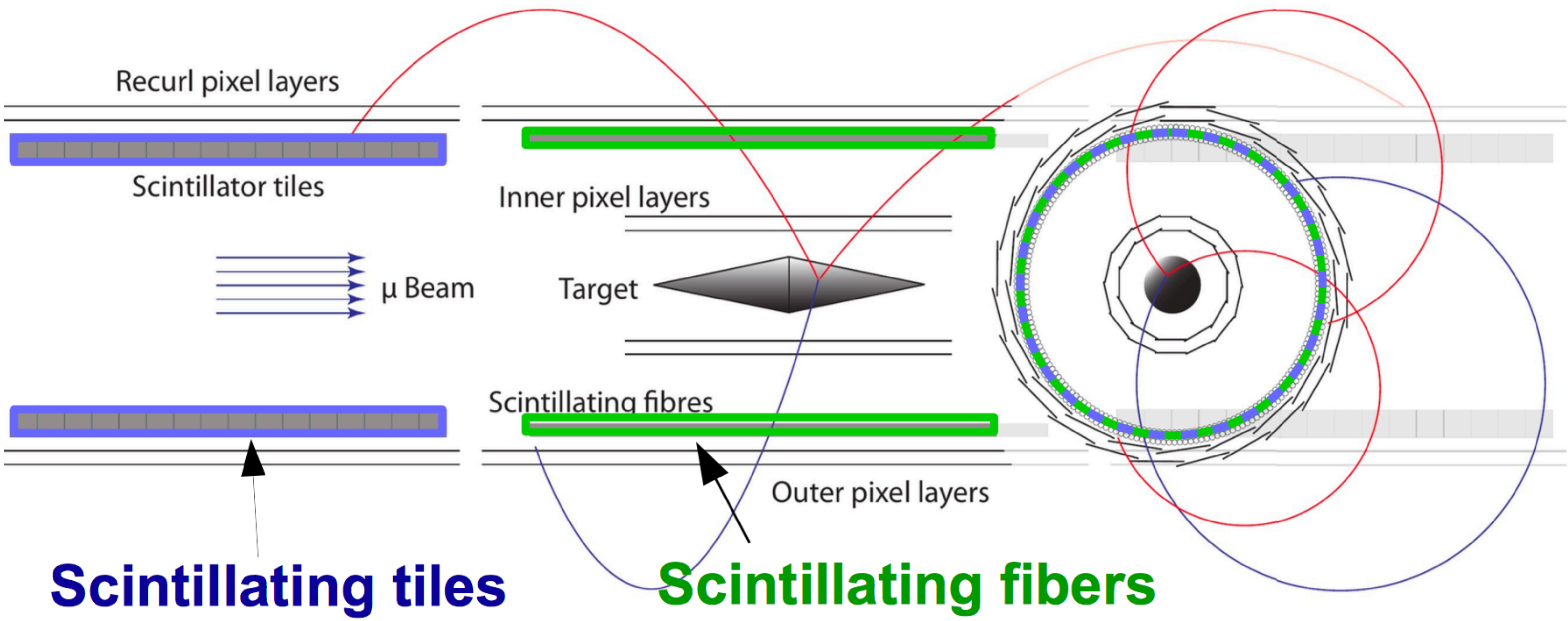
Mupix 7 telescope



Prototype	Active Area [mm^2]
MuPix1	1.77
MuPix2	1.77
MuPix3	9.42
MuPix4	9.42
MuPix6	10.55
MuPix7	10.55

The timing detectors: Fibers and tiles

- Precise timing measurement: Critical to reduce the accidental BGs
  - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
  - Scintillating tiles O(100 ps), full detection efficiency (>99%)



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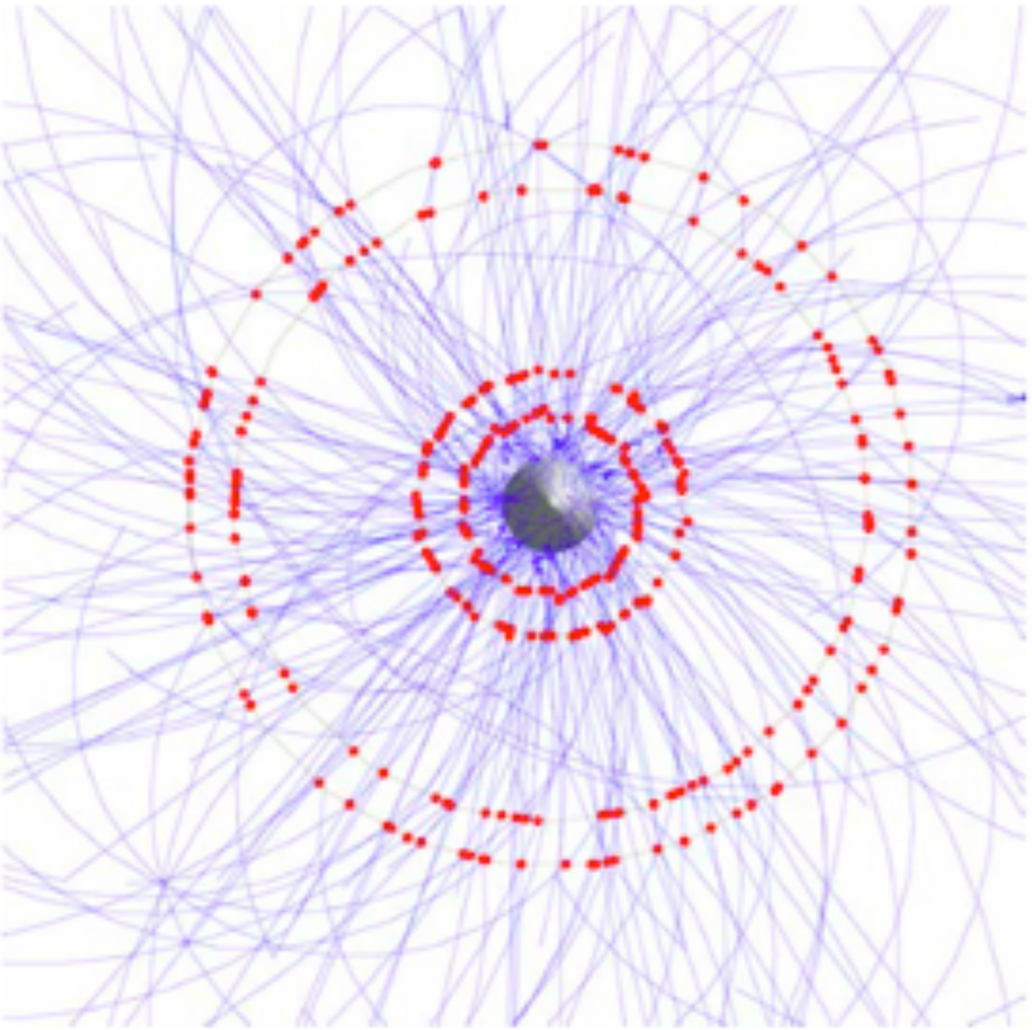
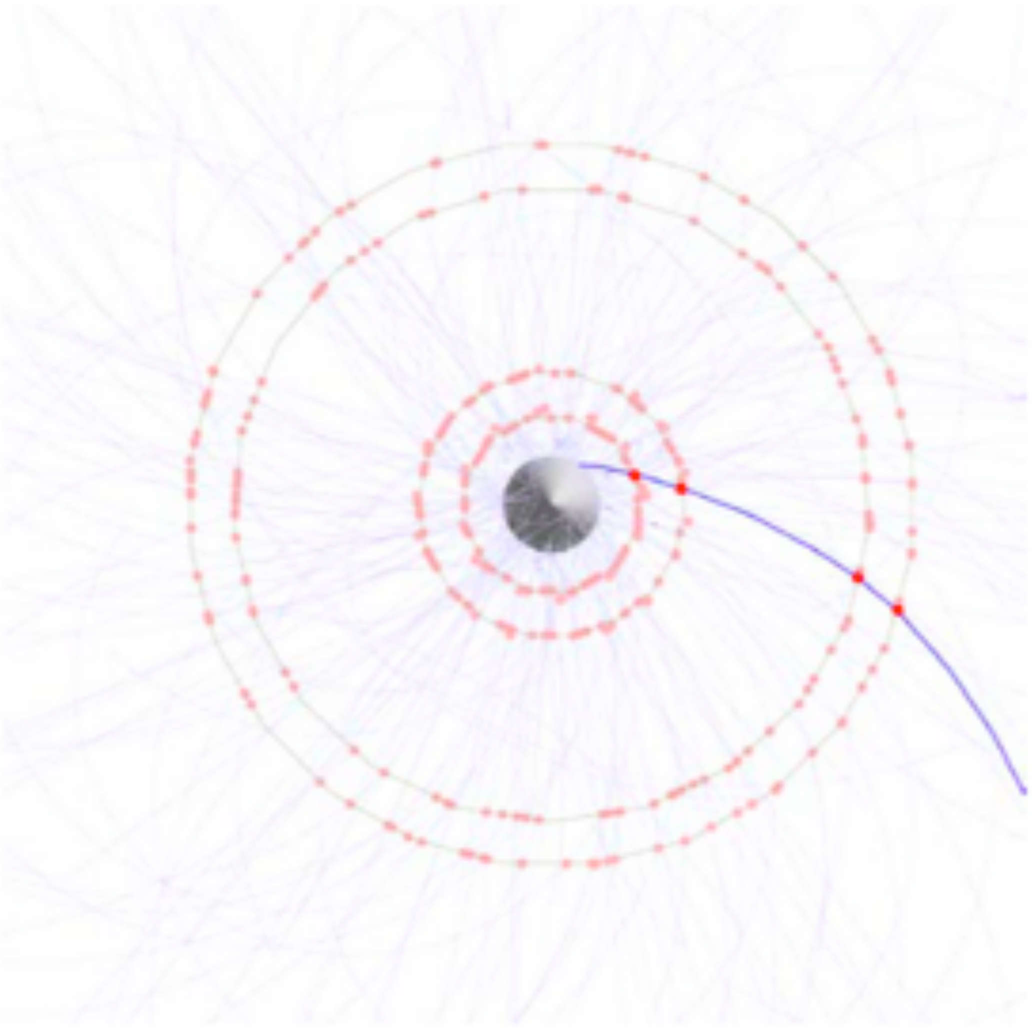


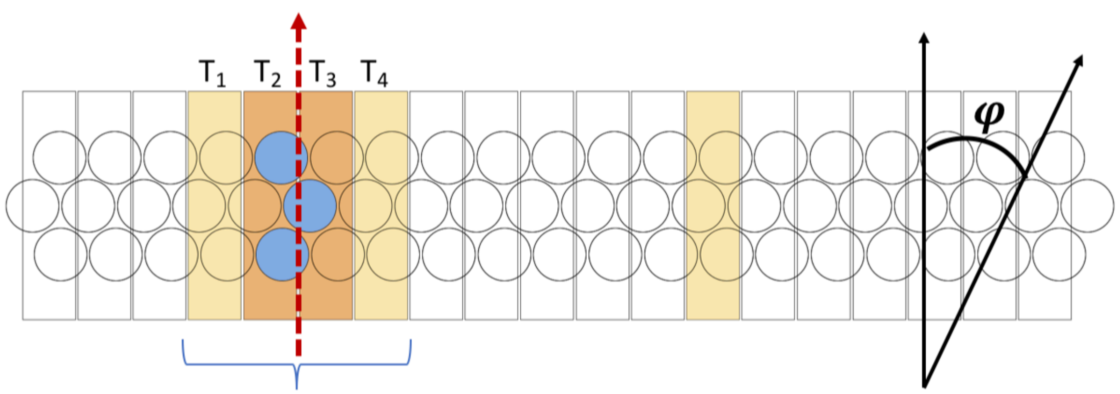
Pixels: O(50 ns)



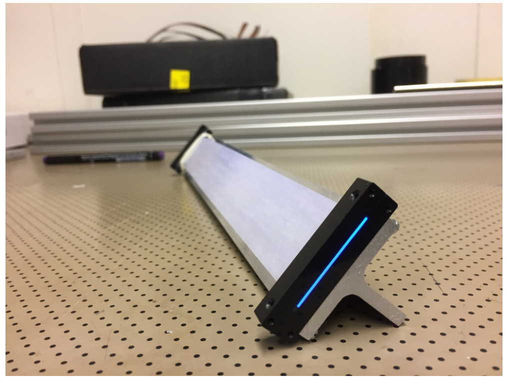
Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

SciFi prototypes: Results

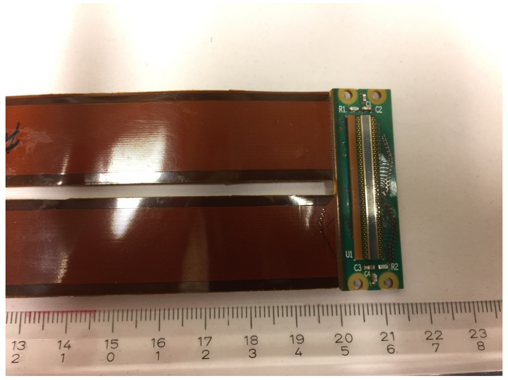
- Studied a variety of fibres (SCSF 78 MJ, clear; SCSF 78 MJ, with 20% TiO2; NOL 11, clear; NOL 11, with 20% TiO2; SCSF 81 MJ, with 20% TiO2; BCF12 clear; BCF12, with 100 nm Al deposit)
- Confirmed full detection efficiency (> 96 % @ 0.5 thr in Nphe) and timing performances for multi-layer configurations (square and round fibres) with several prototypes: individual and array readout with standalone and prototyping (STiC) DAQ

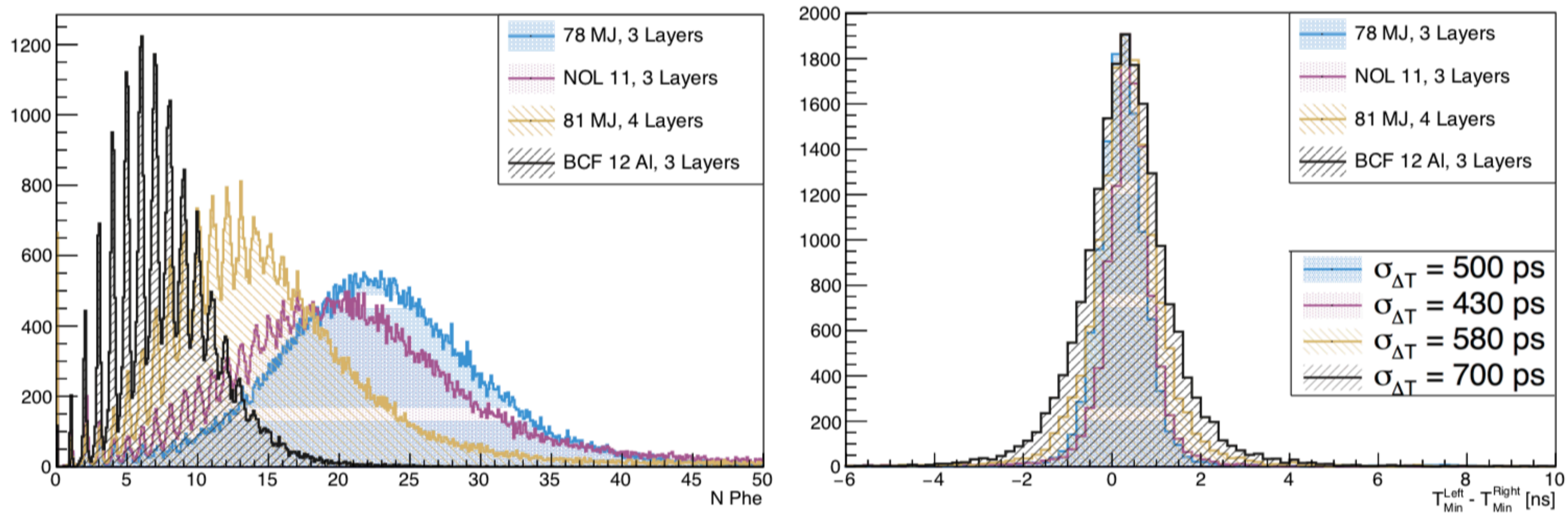


Fibre ribbons:



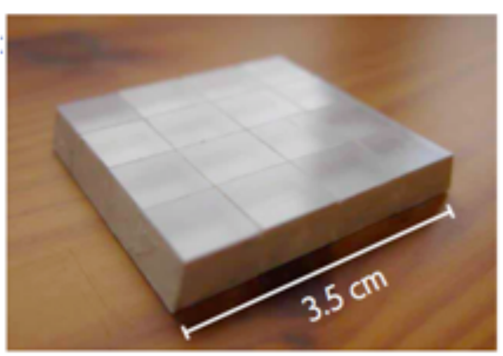
SiPM Array:
Hamamatsu S13552-HQR

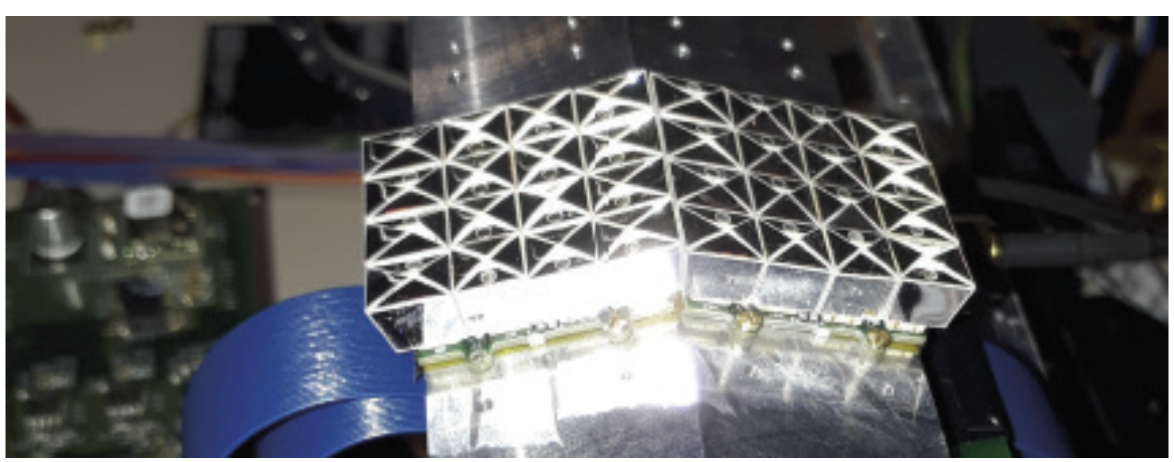


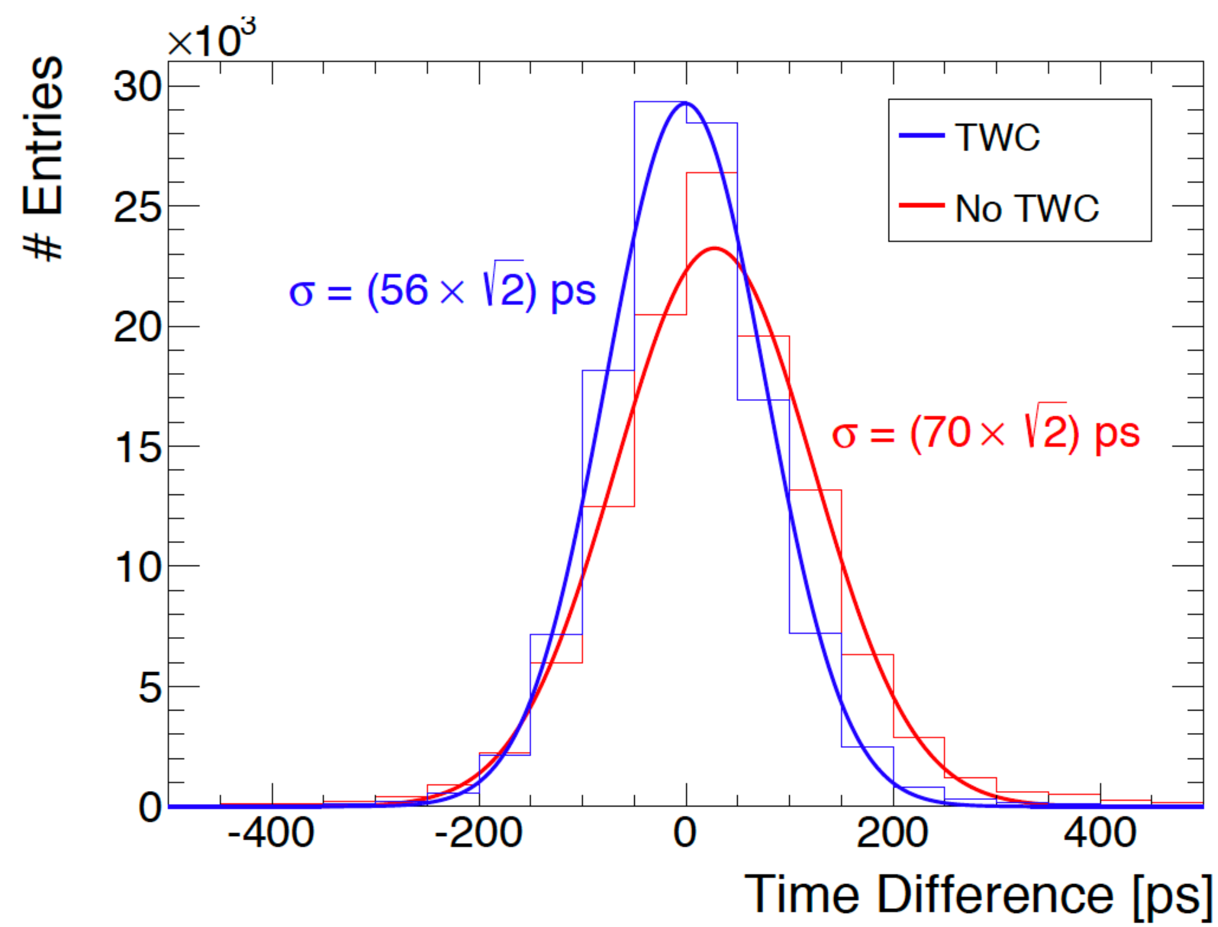


Tile Prototype: Results

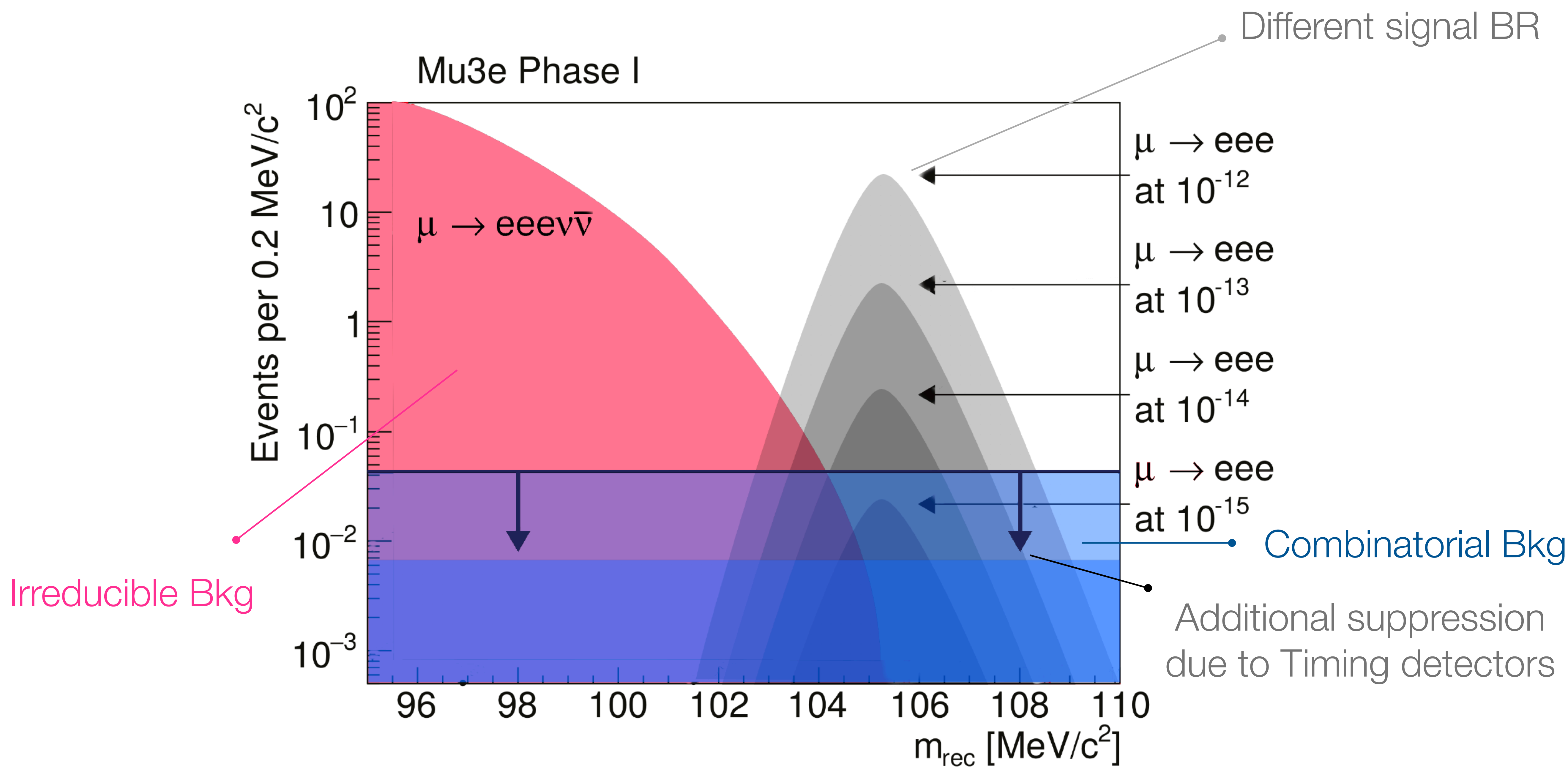
- Mu3e requirements fulfilled: Full detection efficiency (> 99 %) and timing resolution O (60) ps
- 4 x 4 channel BC408
- 7. 5 x 8. 5 x 5. 0 mm^3
- Hamamatsu S10362-33-050C (3 x 3 mm^2)
- readout with STiC2



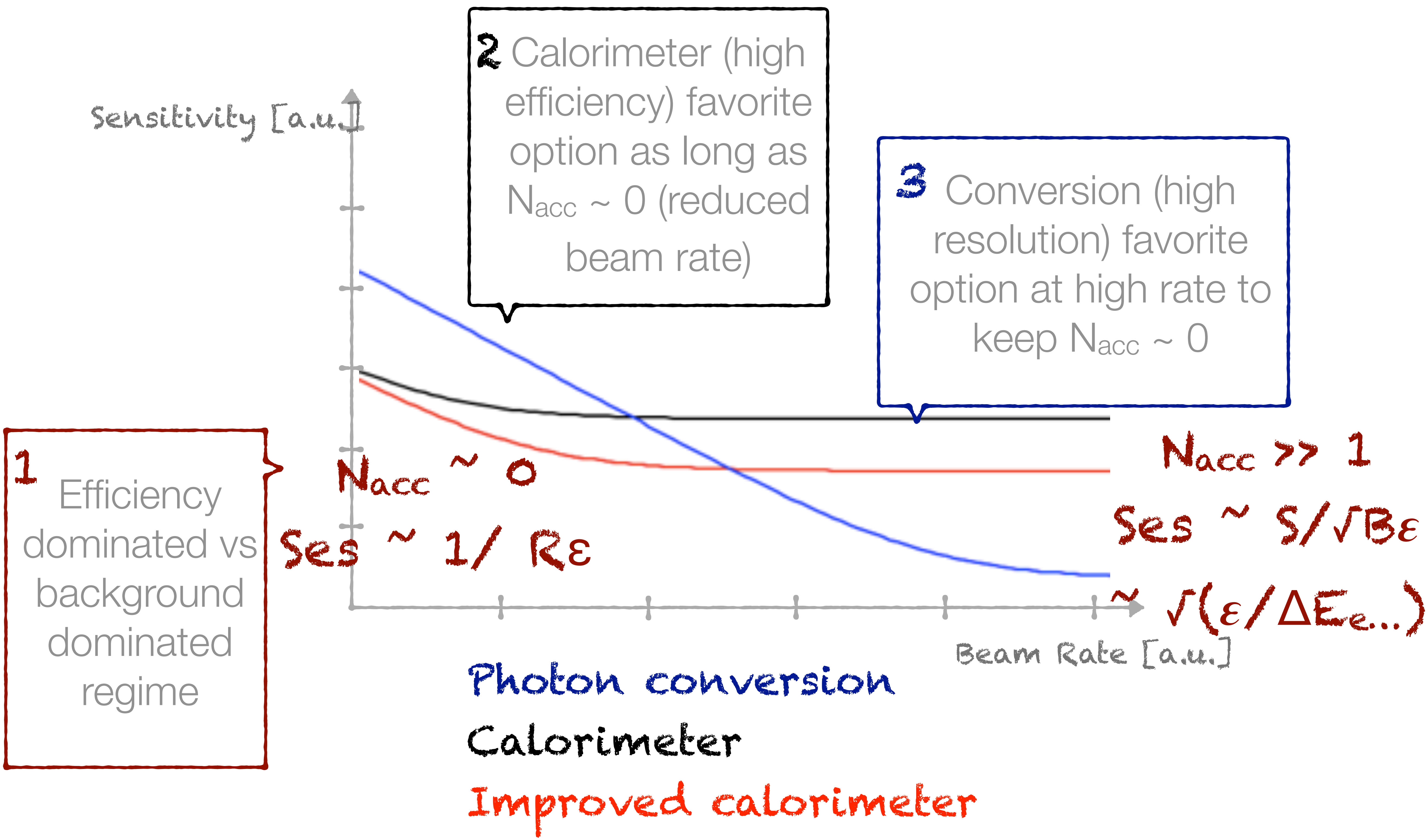




Mu3e Phase I sensitivity

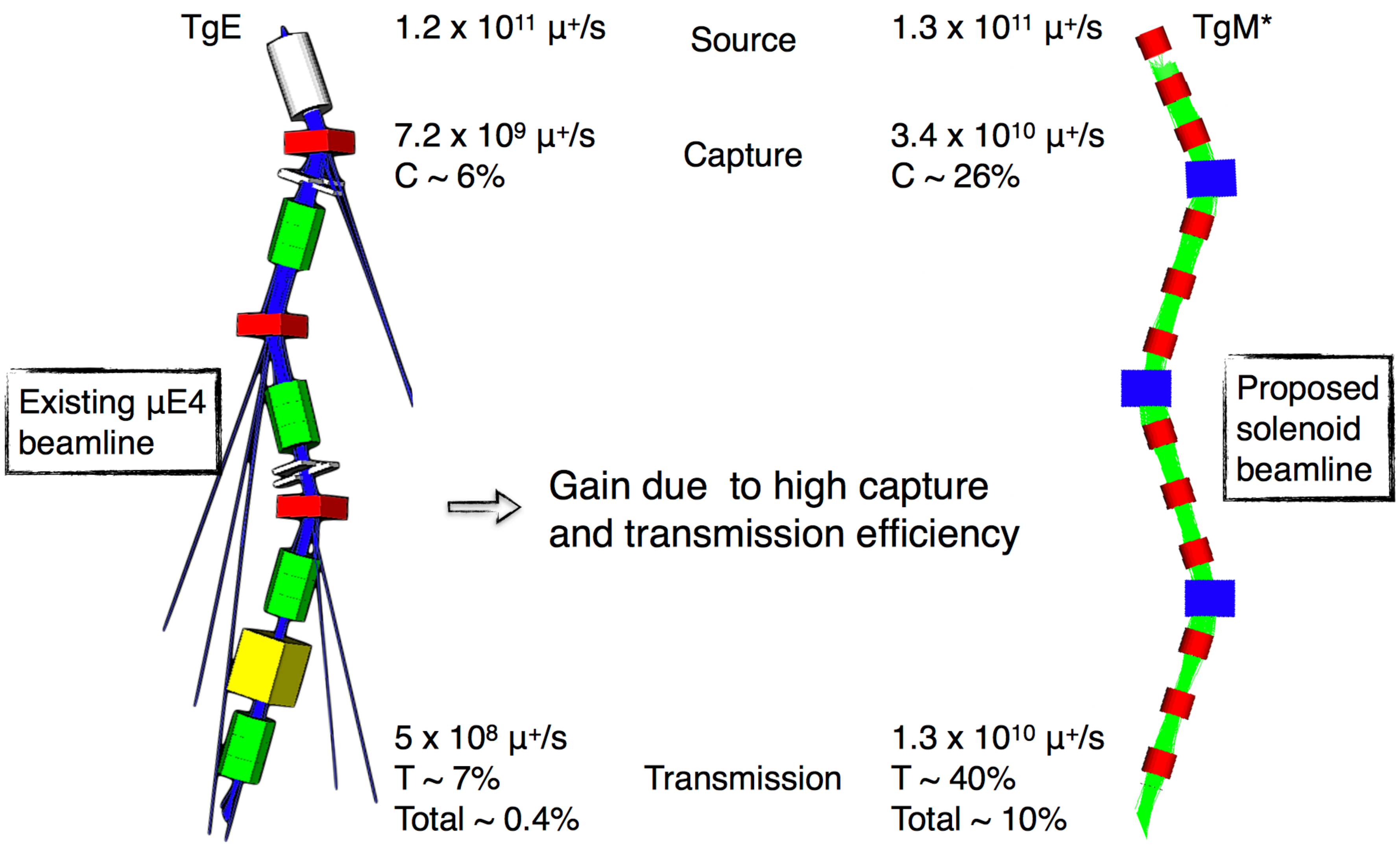


Experimental sensitivity as a function of beam rate for few experimental approaches



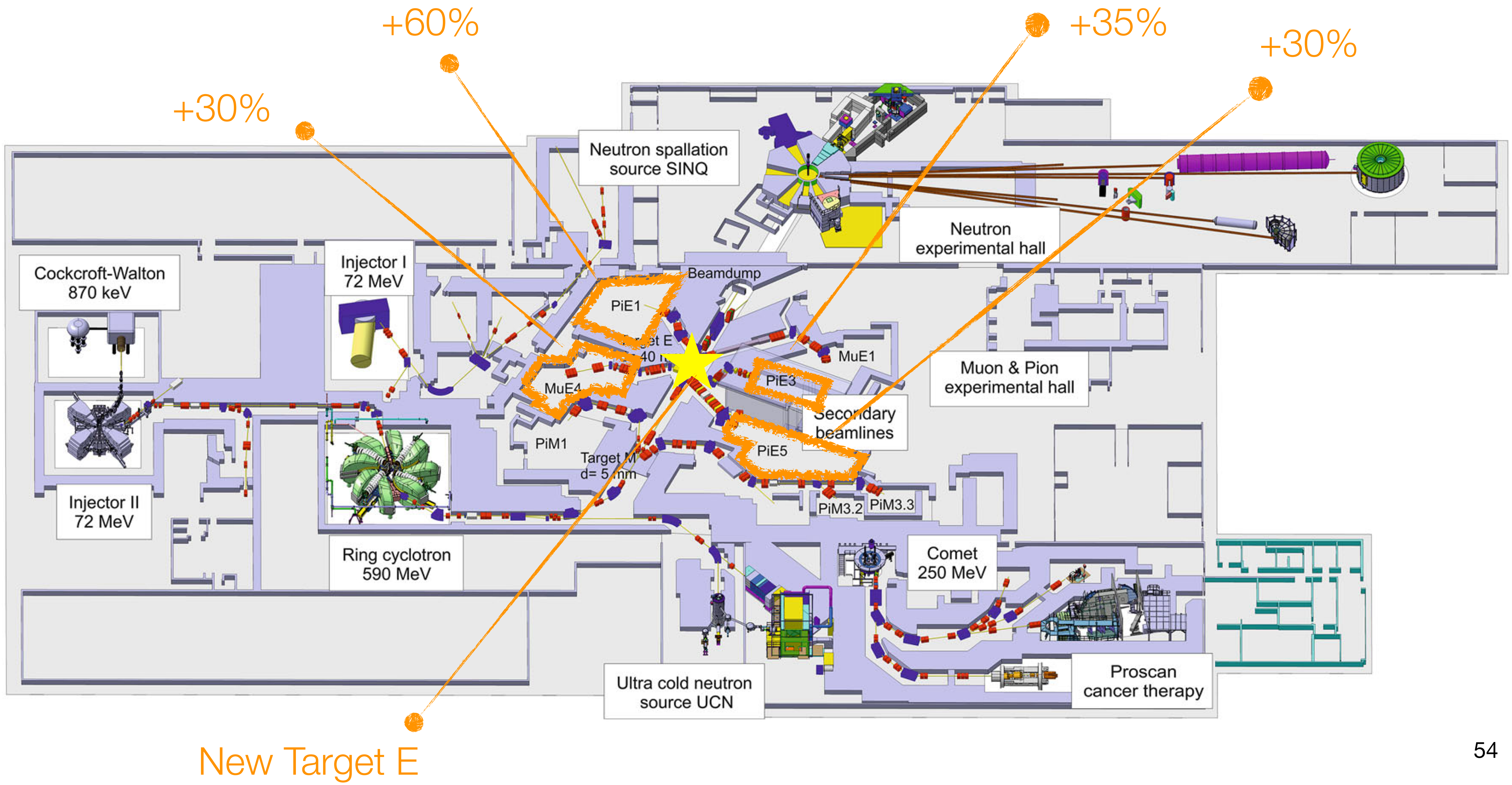
DC muon beams. Future prospects: HiMB

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Time schedule: **O(2027)**
- **Key elements: Slanted Target and optimised beam line** (higher capture efficiency and large space acceptance transport channel)



Slanted target: First test on 2019 and since then in operation

- Expect ~30-60 % enhancement
- Measurements successfully done in different experimental areas in fall 2019
- **Increased muon yield CONFIRMED!**
- To be seen: **impact of higher thermal stress on long term stability of target wheel**



Beam features vs experiment requirements

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

DC or Pulsed?

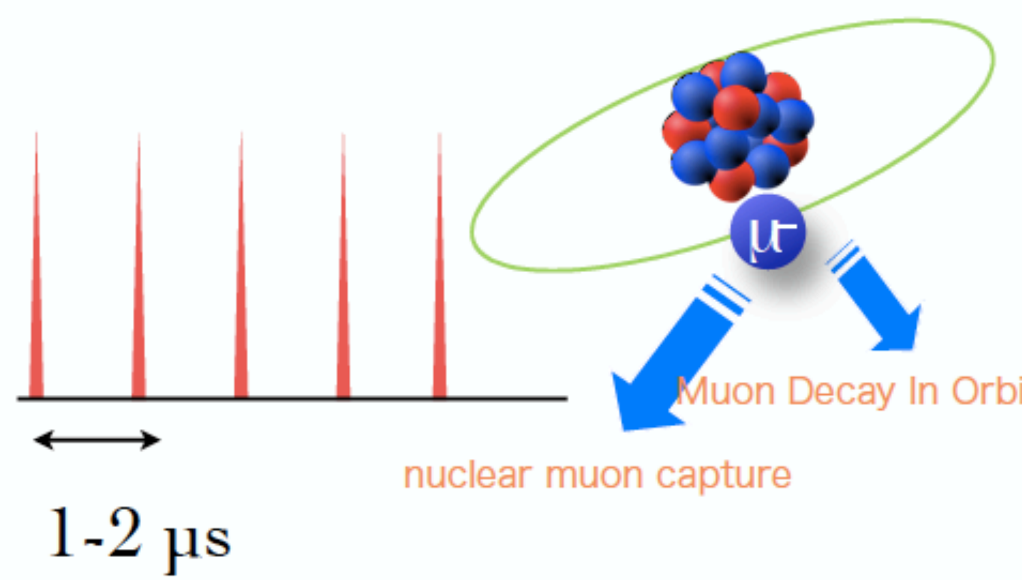
I_{beam} ~ 10^8 - 10^{10} μ/s

- DC beam for coincidence experiments
  - $\mu \to e \gamma$, $\mu \to e\ e\ e$

@ PSI

I_{beam} ~ 10^{11} μ/s

- Pulse beam for non-coincidence experiments
  - μ-e conversion



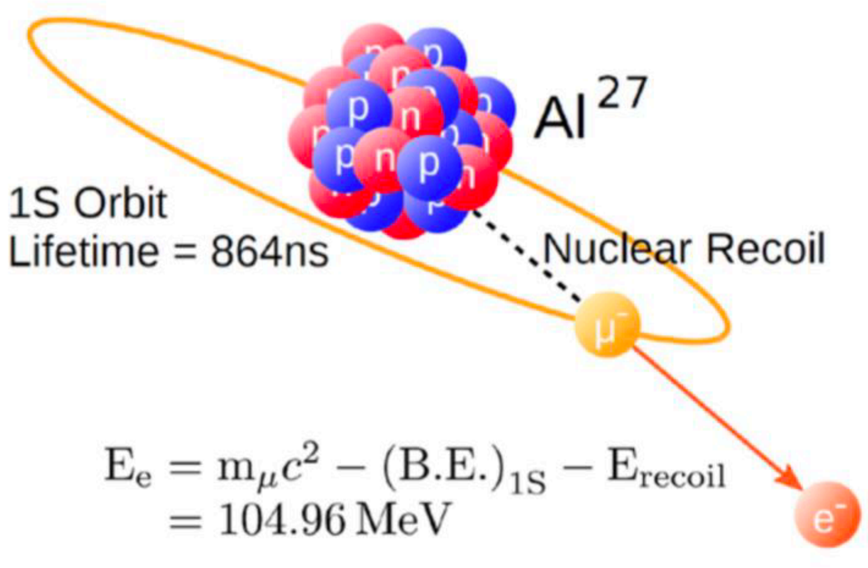
@ JPARC, FERMILAB

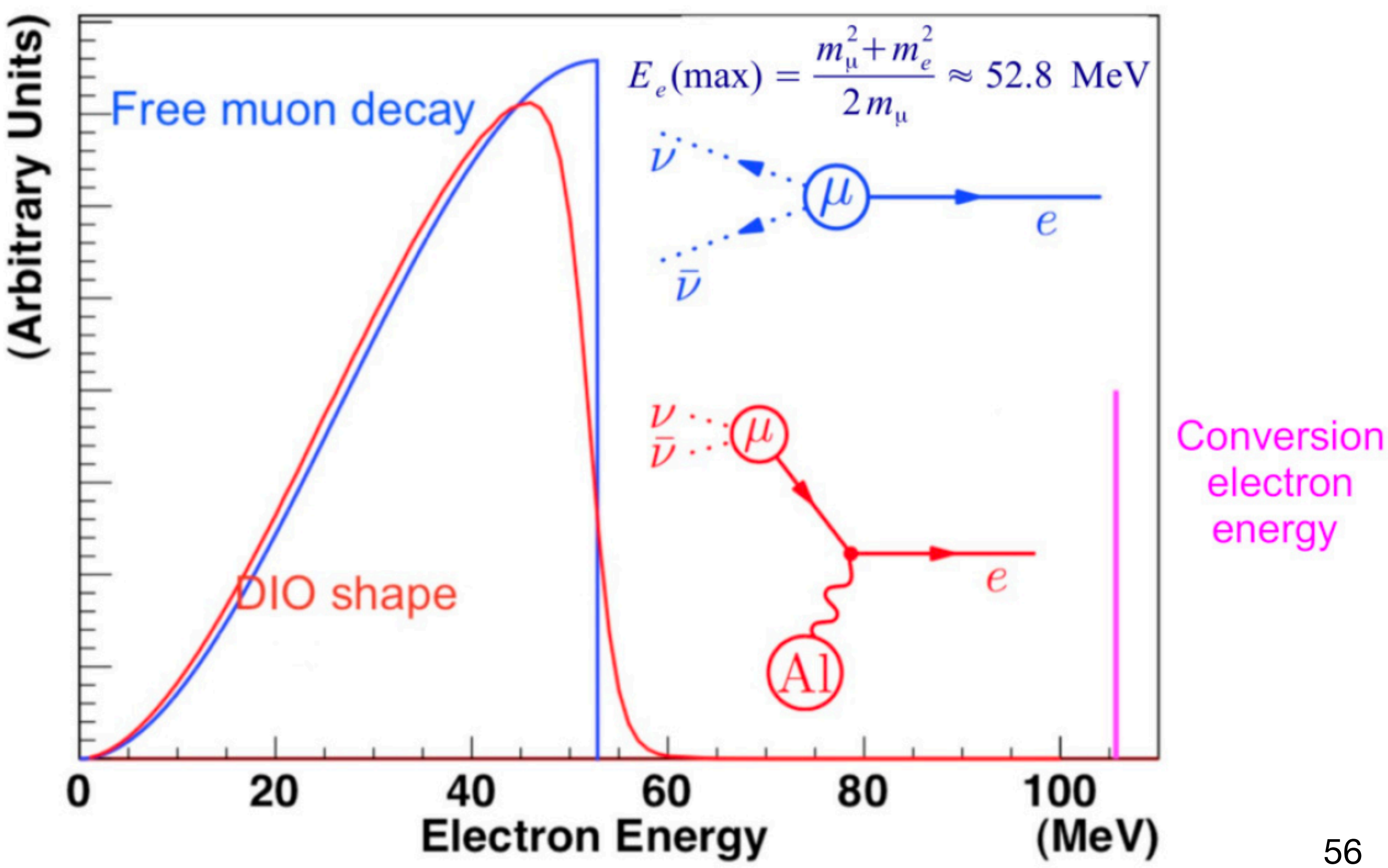
μ^- N → e^- N experiments

- Signal of mu-e conversion is single mono-energetic electron

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

- Background: Any event at the endpoint energy can mimic the signal





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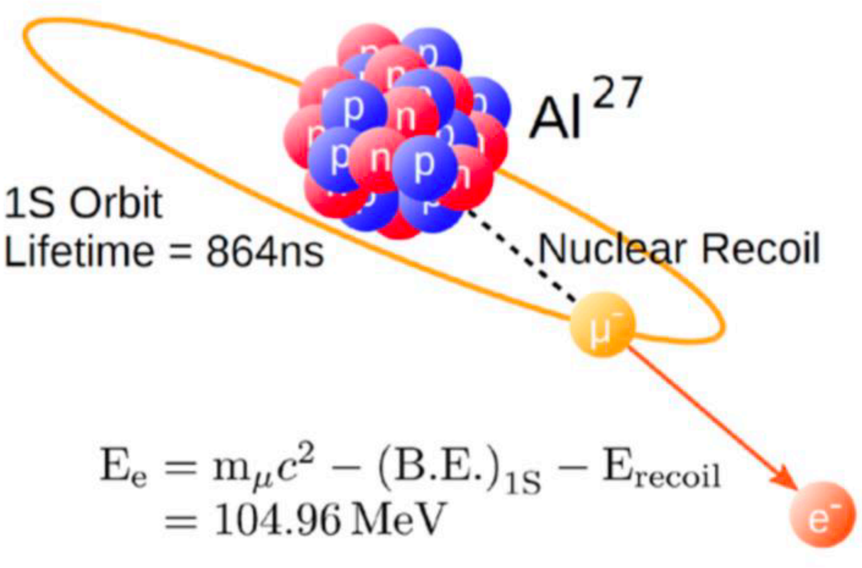
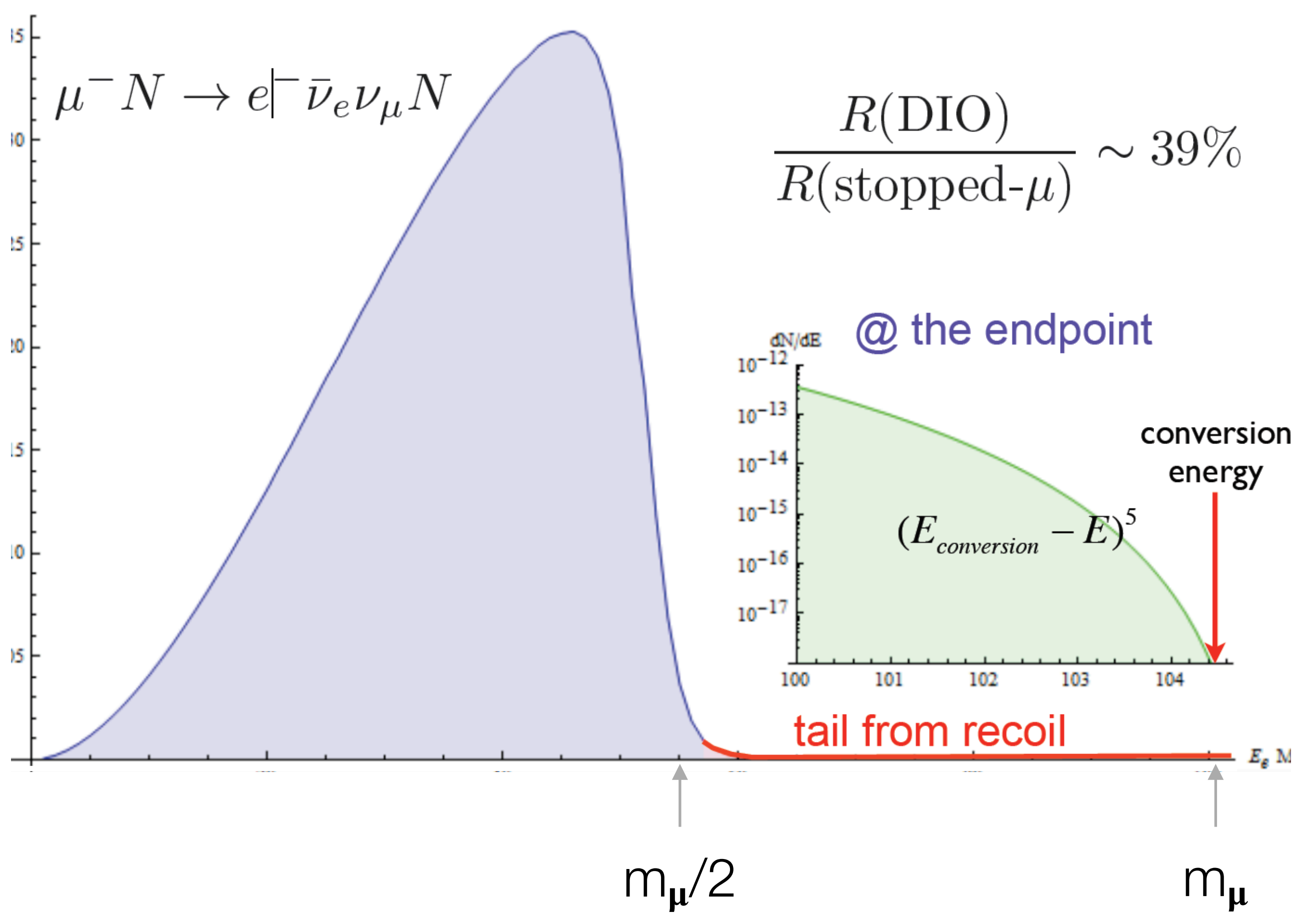


$$\mathrm{E_e} = \mathrm{m}_\mu c^2 - (\mathrm{B.E.})_{1S} - \mathrm{E_{recoil}}$$
$$= 104.96\,\mathrm{MeV}$$

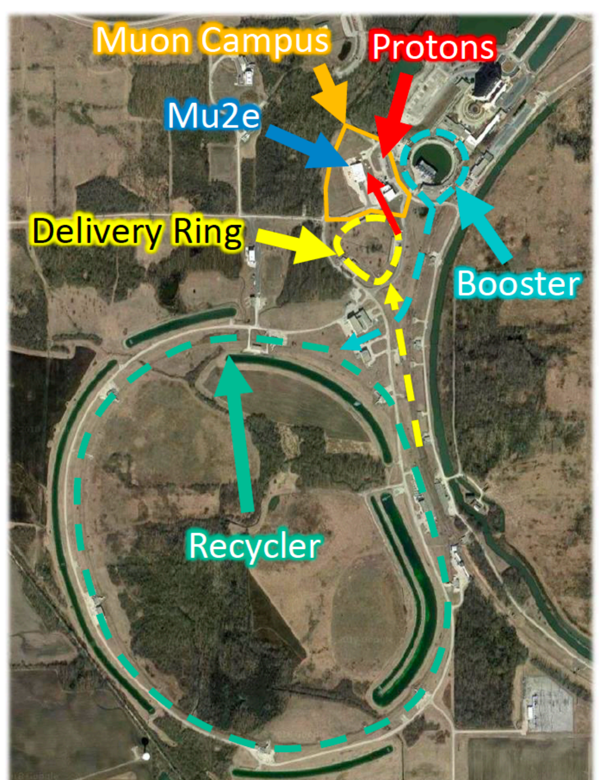


$\mu^- N \rightarrow e^- N$ experiments

- Signal of mu-e conversion is single mono-energetic electron
- Stop a lot of muons! $O(10^{18})$

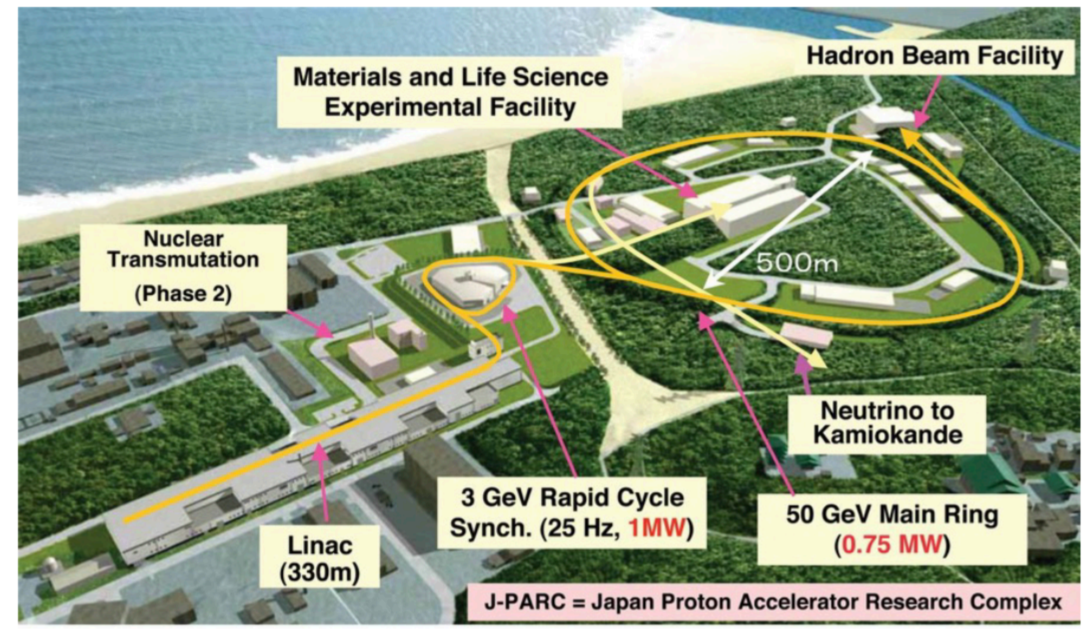
The two giants campus delivering astonishing intese pulsed muon beams

Fermilab

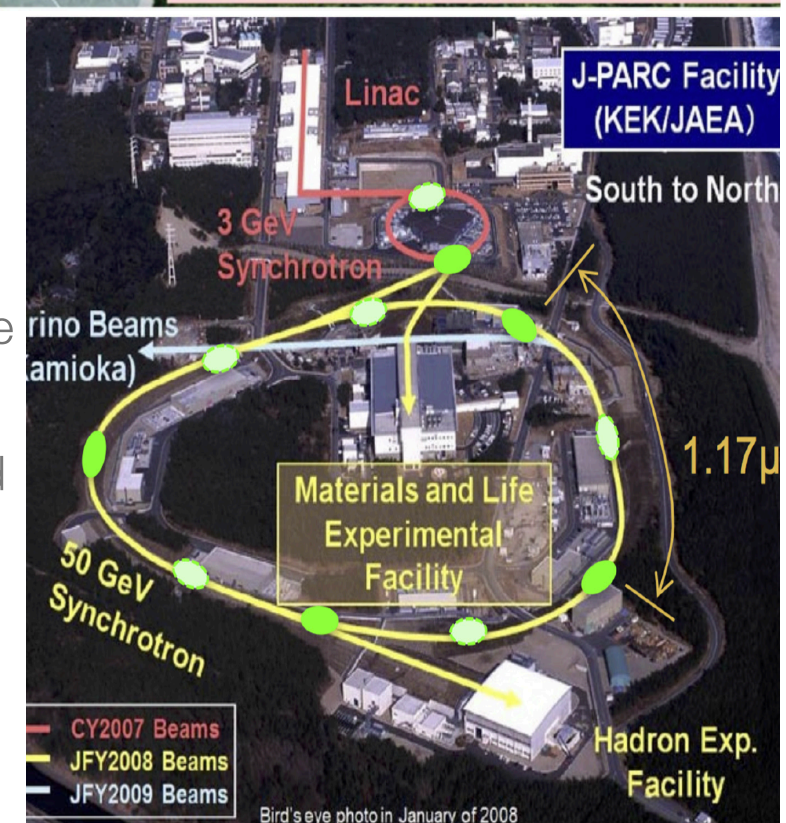


- **Booster** provides 8 GeV protons to the **Recycler**
- **Recycler** stacks protons into 4 bunches
- **Delivery Ring** takes 1 out of every 4 bunches from the **Recycler**
- **Mu2e** slow extracts **protons** every 1695 ns

JPARC

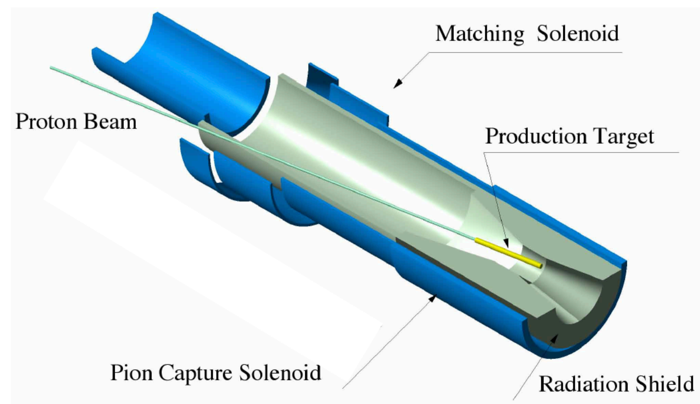


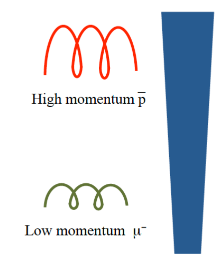
- **Bunched** 8 GeV protons extracted from the Main Ring and delivered to the pion target production inside a capture solenoid
- **Muons** are charge and momentum selected using curved superconducting solenoids



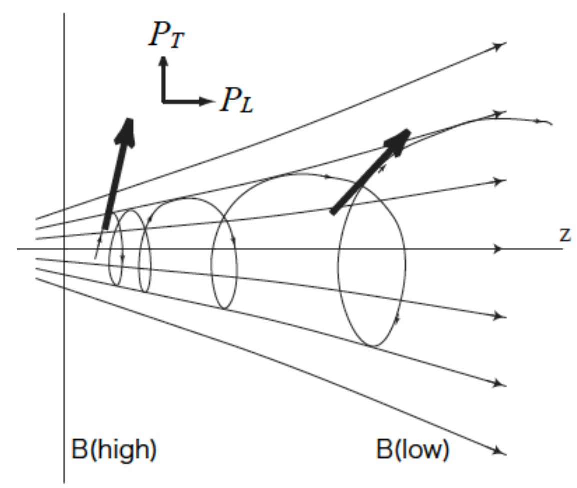
More and selected pulsed muons in three steps

- 1. Pion production in magnetic field

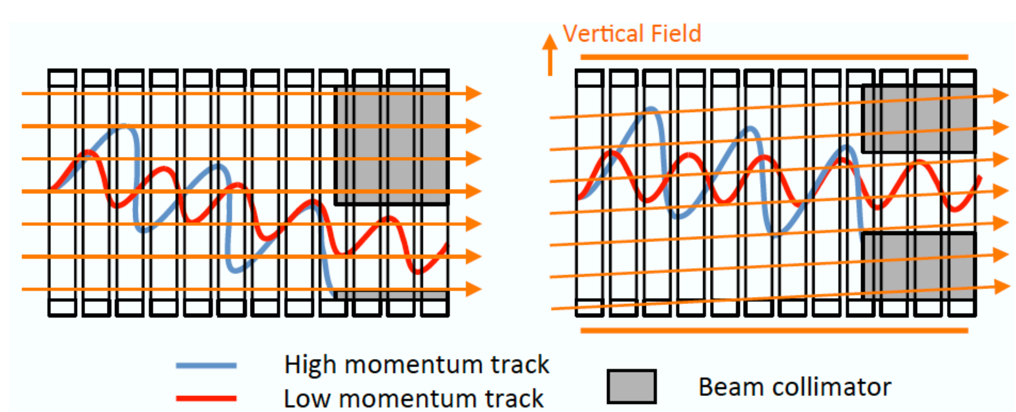




- 2. Pion/muon collection using gradient magnetic filed

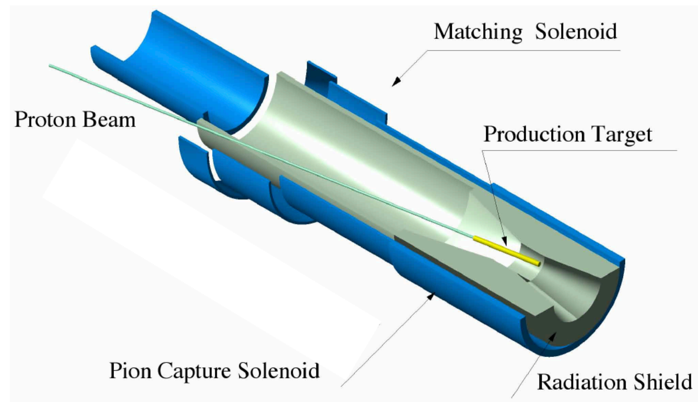


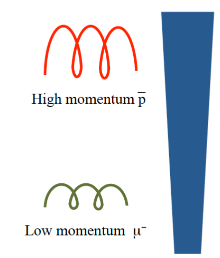
- 3. Beam transport with curved solenoid magnets

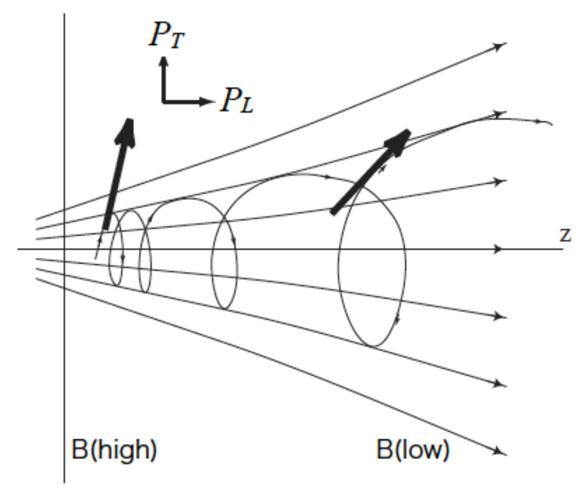


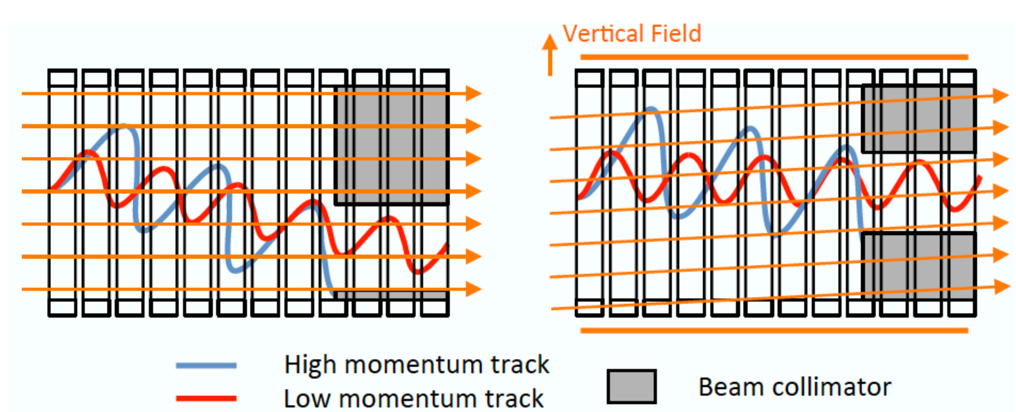
More and selected pulsed muons in three steps

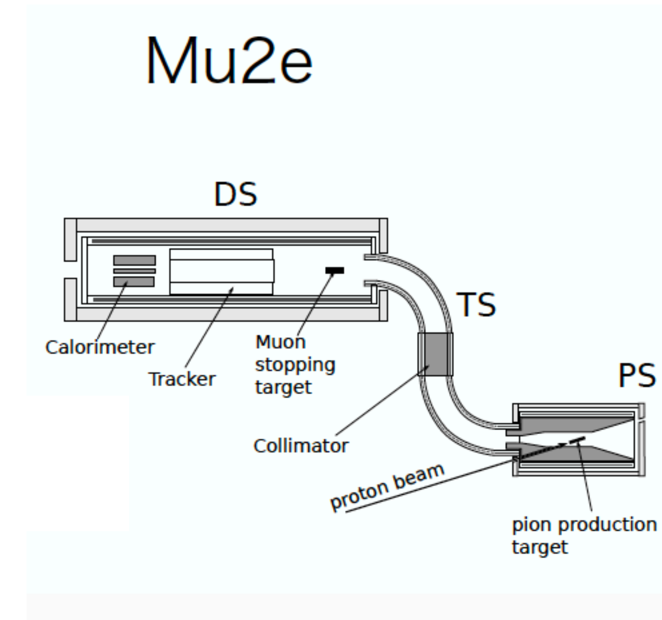
- 1. Pion production in magnetic field
- 2. Pion/muon collection using gradient magnetic filed
- 3. Beam transport with curved solenoid magnets

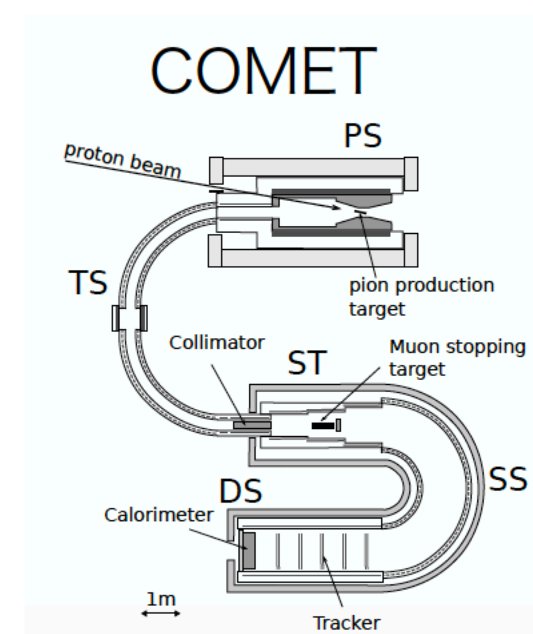






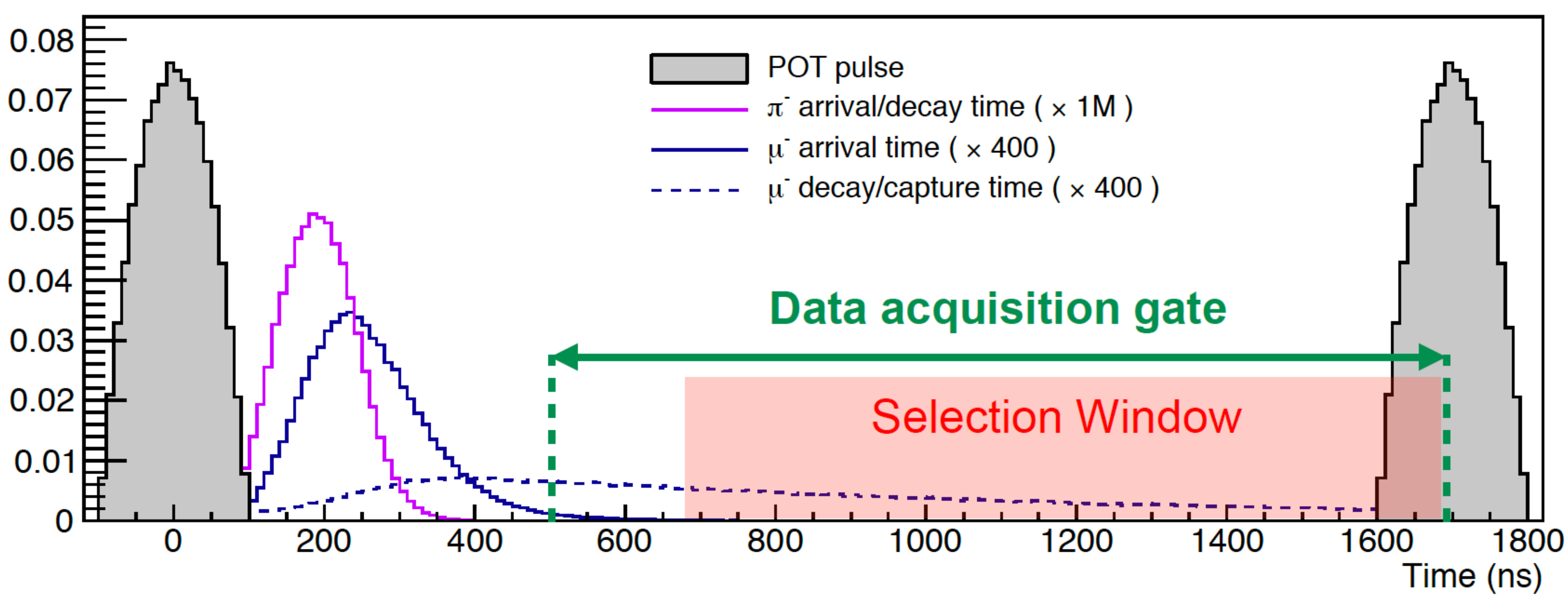






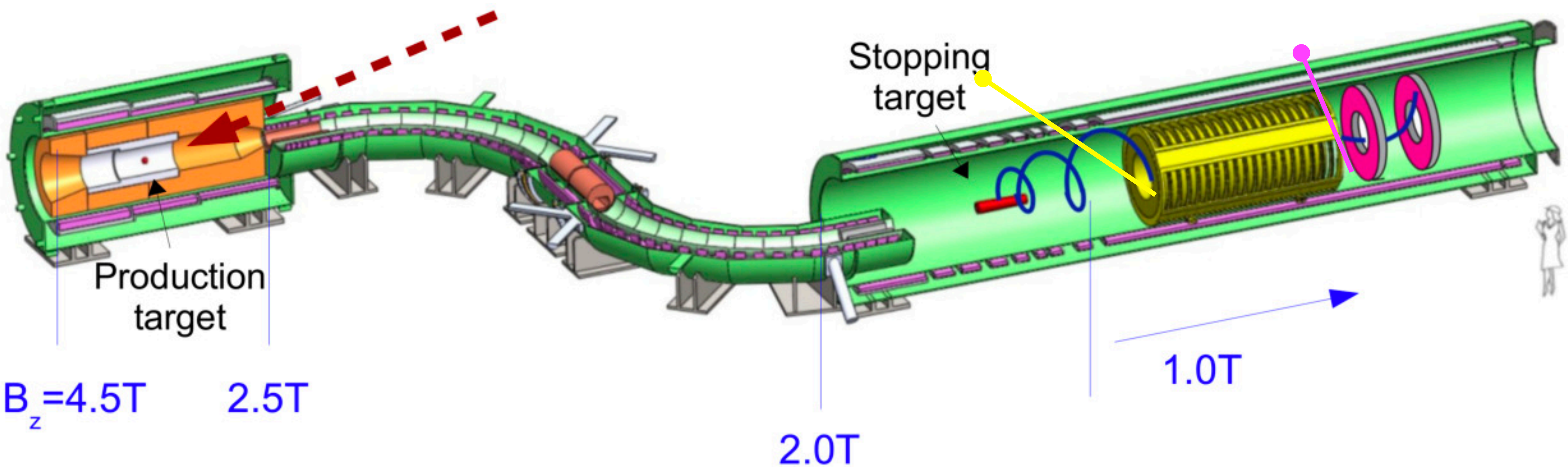
μ^- N → e^- N experiments

- Signal of mu-e conversion is single mono-energetic electron
- Stop a lot of muons! O(10^{18})
- Backgrounds:
  - Beam related, Muon Decay in orbit, Cosmic rays
- Use timing to reject beam backgrounds (extinction factor 10^{-10})
  - Pulsed proton beam 1.7 μs between pulses
  - Pions decay with 26 ns lifetime
  - Muons capture on Aluminum target with 864 ns lifetime
- Good energy resolution and Particle ID to defeat muon decay in orbit
- Veto Counters to tag Cosmic Rays



The Mu2e experiment

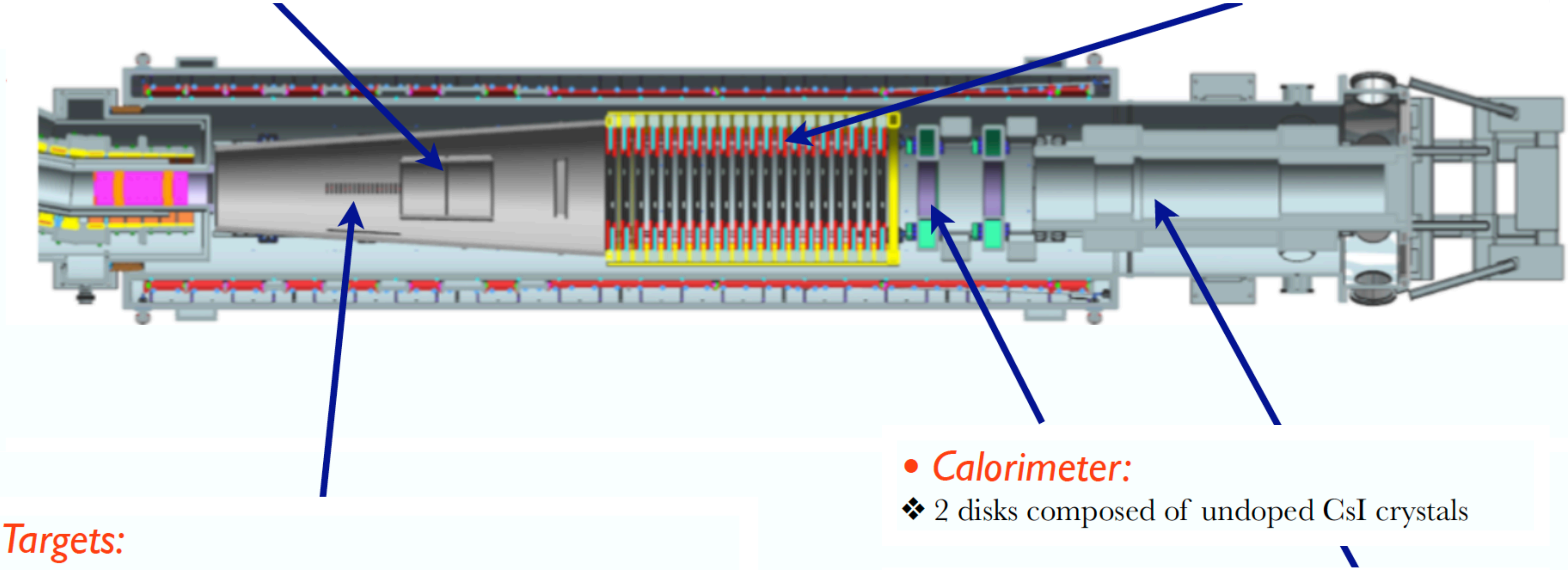
- Three superconducting solenoids: Production, Transport and Detector solenoids
- Muons stop in thin aluminum foils
- High precision straw tracker for momentum measurement
- Electromagnetic calorimeter for PID
- Scintillators for the Veto



The Mu2e experiment

• *Proton absorber:*
❖ made of high-density polyethylene
❖ designed in order to reduce proton flux on the tracker and minimize energy loss

• *Tracker:*
❖ ~20k straw tubes arranged in planes on stations, the tracker has 18 stations
❖ Expected momentum resolution < 200 keV/c



• *Targets:*
❖ 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

• *Calorimeter:*
❖ 2 disks composed of undoped CsI crystals

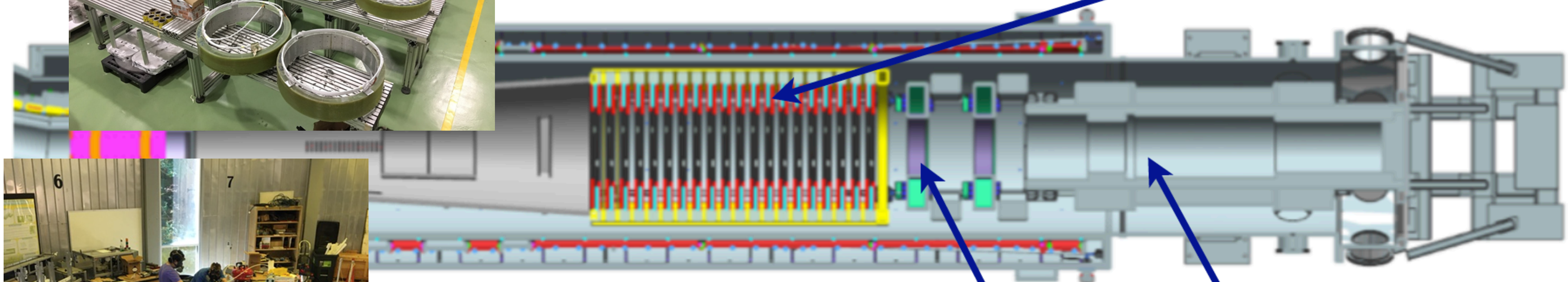
• *Muon beam stop:*
❖ made of several cylinders of different materials: stainless steel and polyethylene

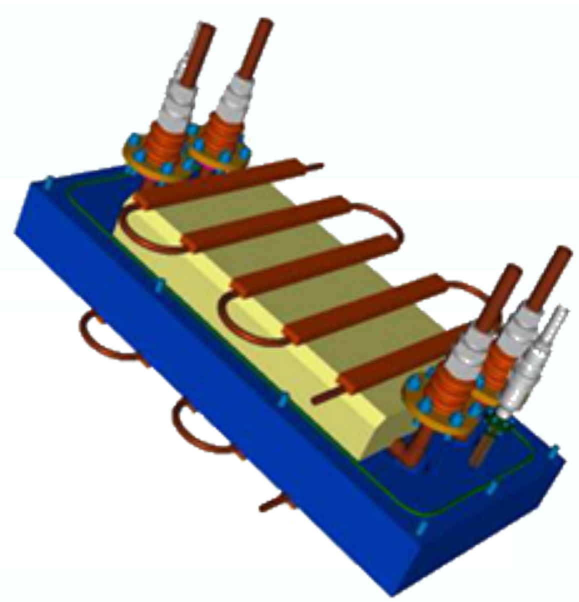
The Mu2e experiment: Status

- 2021: Detector and Beam-line commissioning; 2022-2024: Data taking

- *Tracker:*

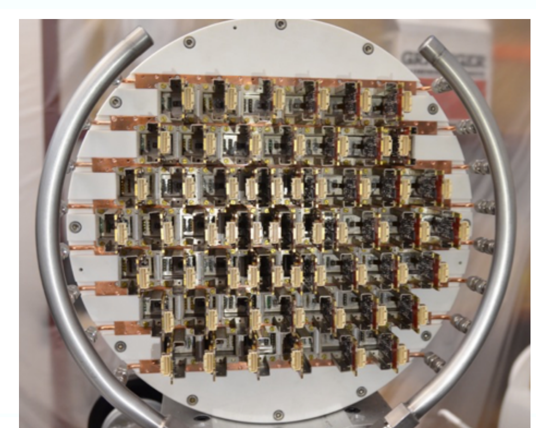
- *Beamline and solenoids*



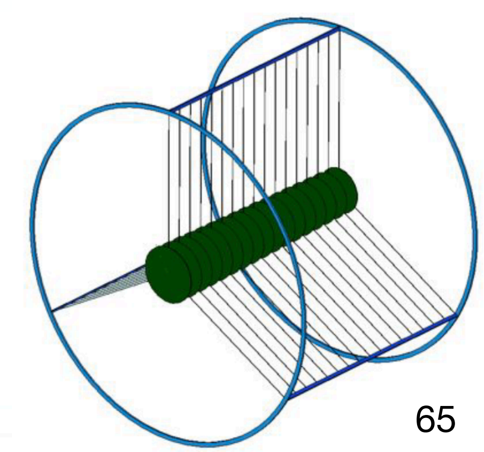


- *Cosmic Ray Veto*

- *Calorimeter:*



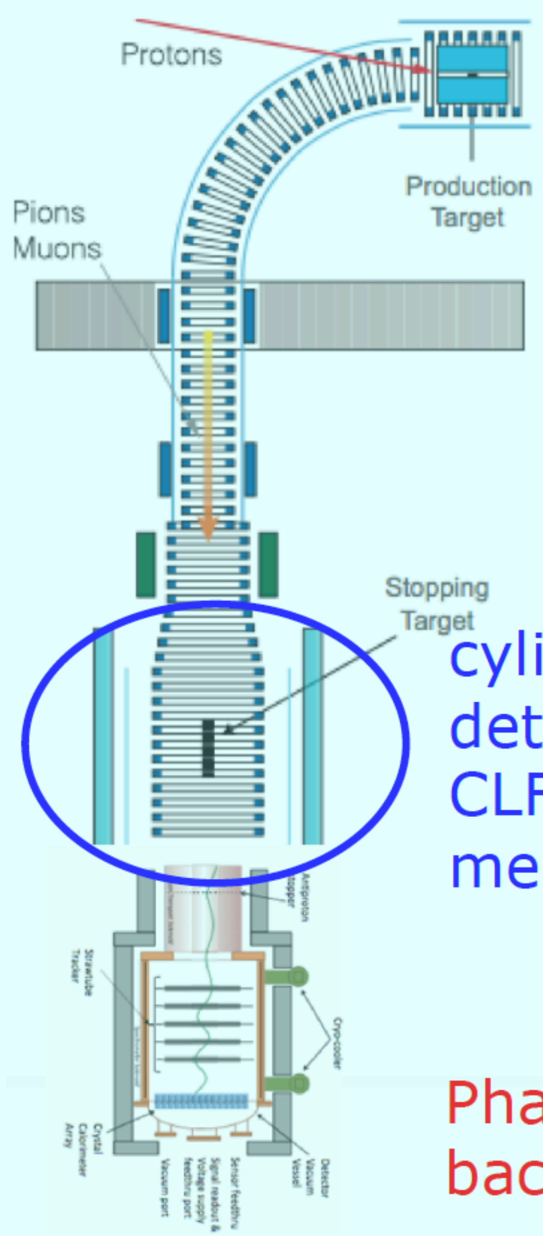
- *Muon beam stop:*



The COMET experiment

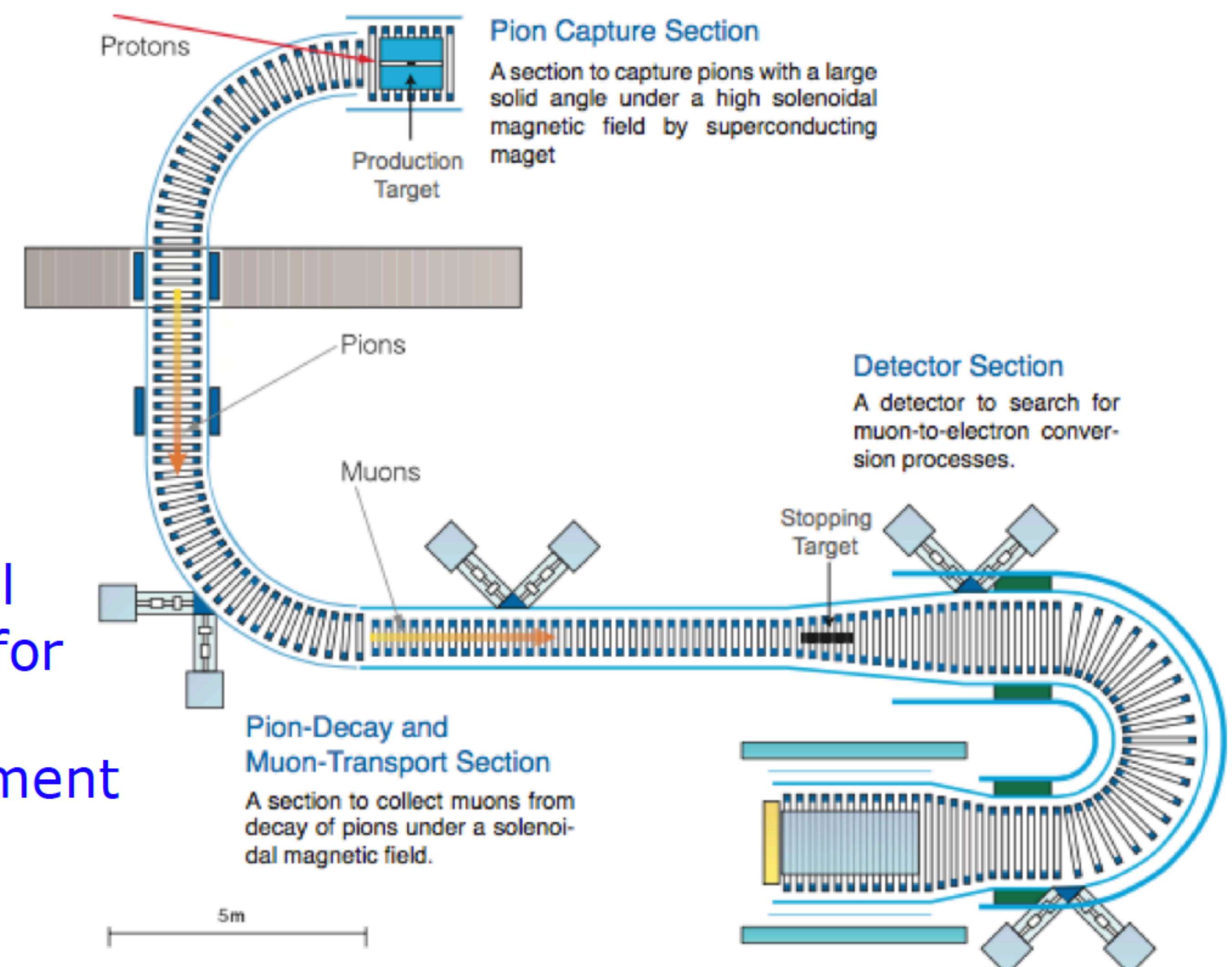
- Stage phase approach: Phase I and Phase II

COMET phase I



cylindrical detector for CLFV measurement

COMET phase II

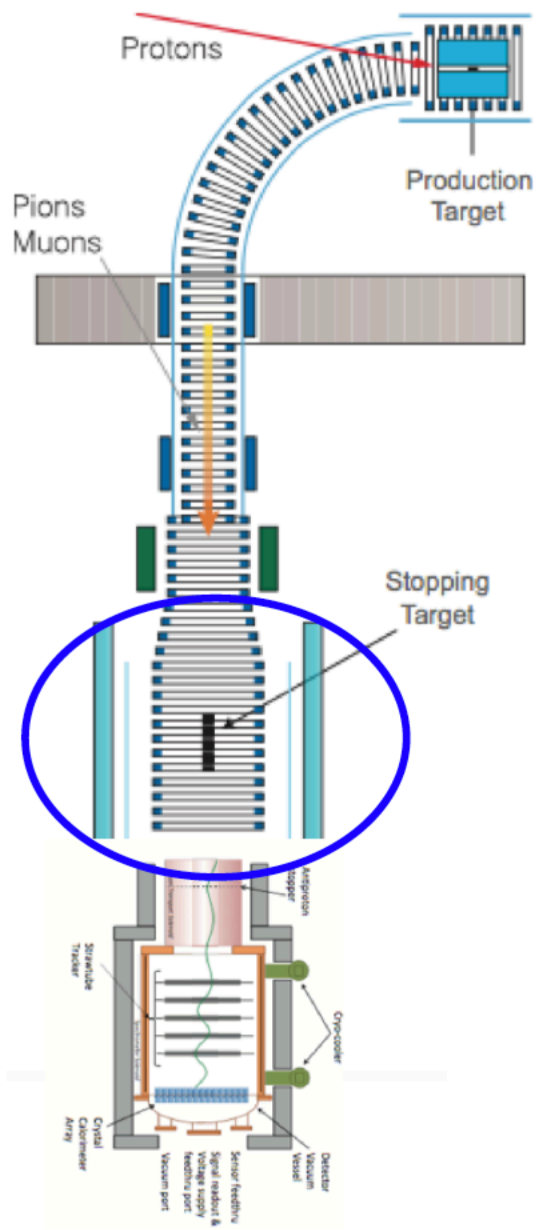


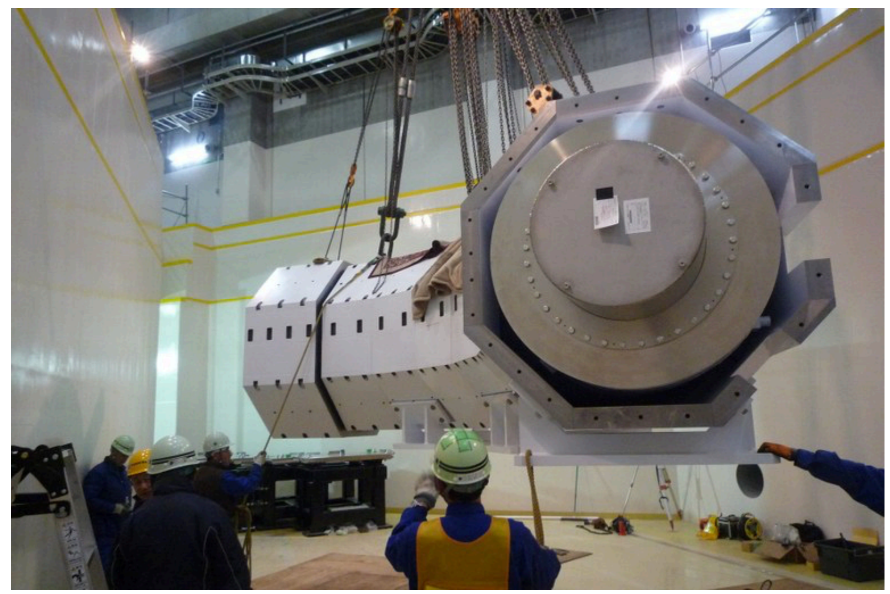
Phase-II prototype for background characterisation

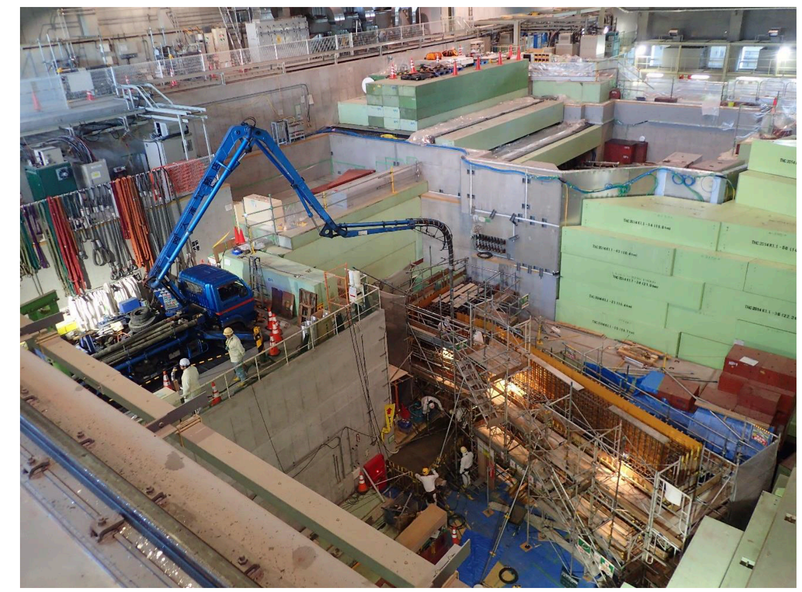
The COMET experiment: Status

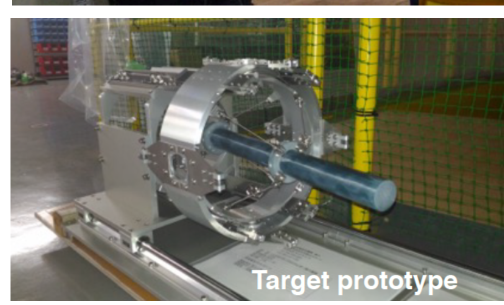
- Stage phase approach: ultimate sensitivity with phase II [Data taking in: 2021/2022]

COMET phase I

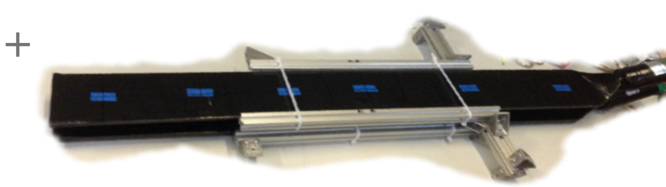




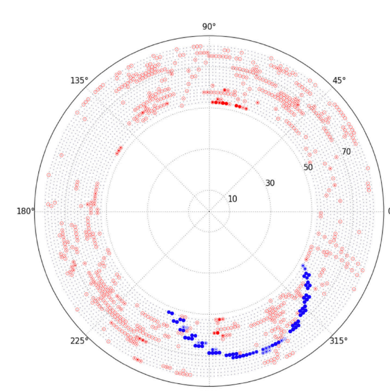


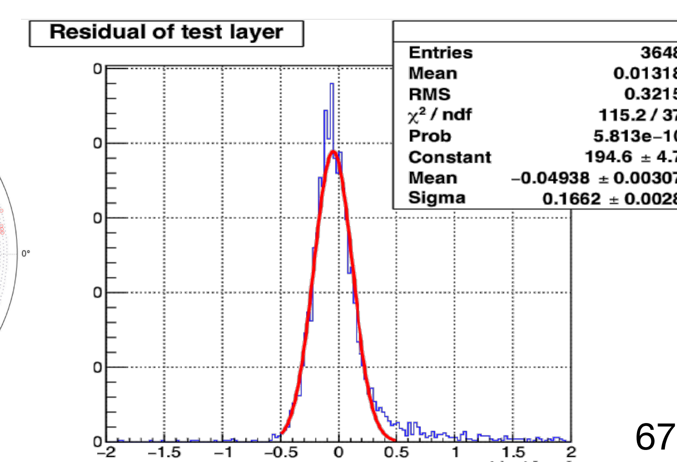


Trigger scintillators + Cerenkov detector



Trigger/DAQ/Analysis: in very good shape



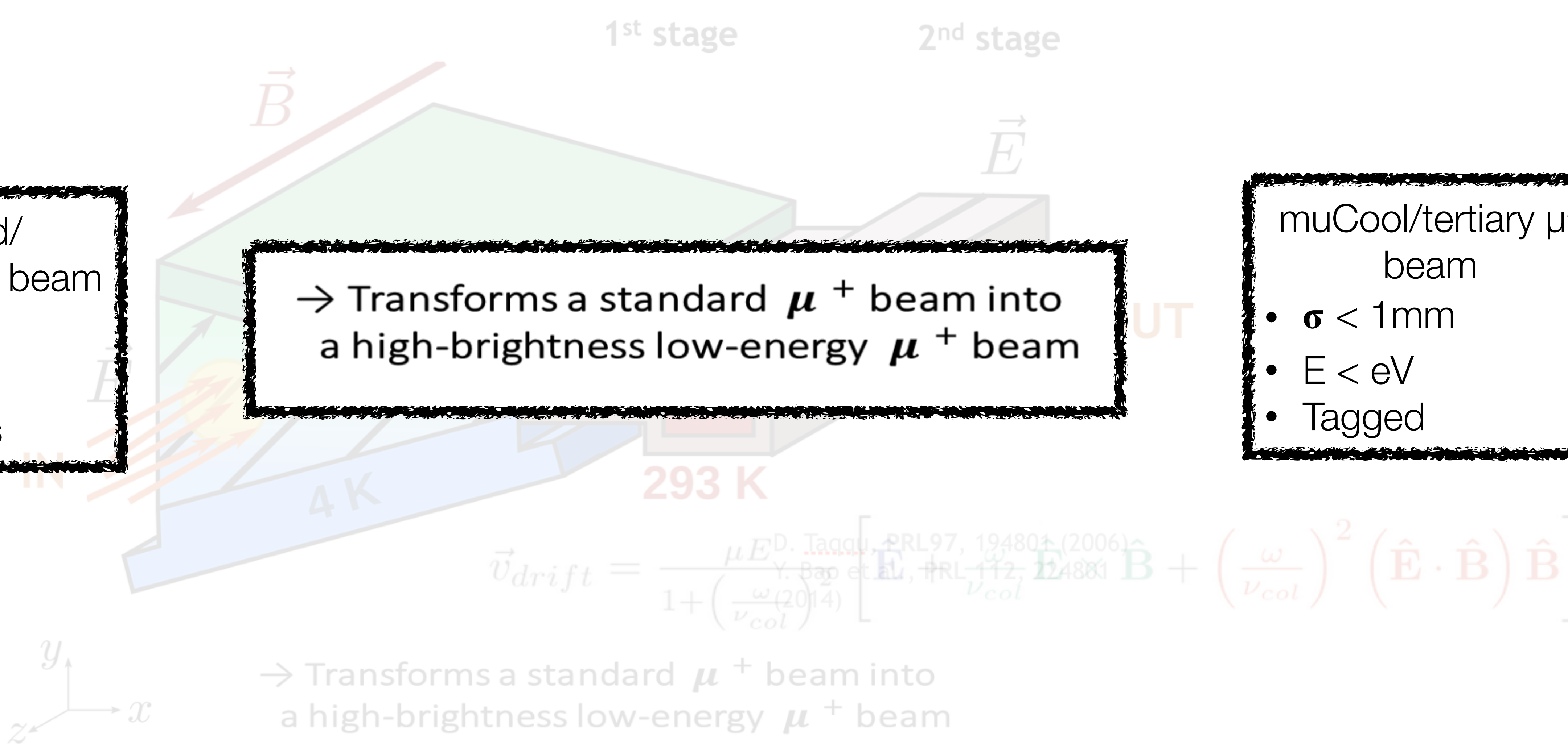


D. Taqqu, PRL 97 (2006) 194801
Y. Bao et al., PRL 112 (2014) 224801

The muCool project at PSI

- Aim: High-brightness low energy muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^{10}** with an efficiency of **10^{-3}**

for:
μSR (solid state physics)
muonium (spectroscopy, gravitational interaction...)
muon experiments (μEDM, g-2…)



Standard/ secondary μ+ beam
- σ = 10 mm
- E = 4 MeV
- Continuous

→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

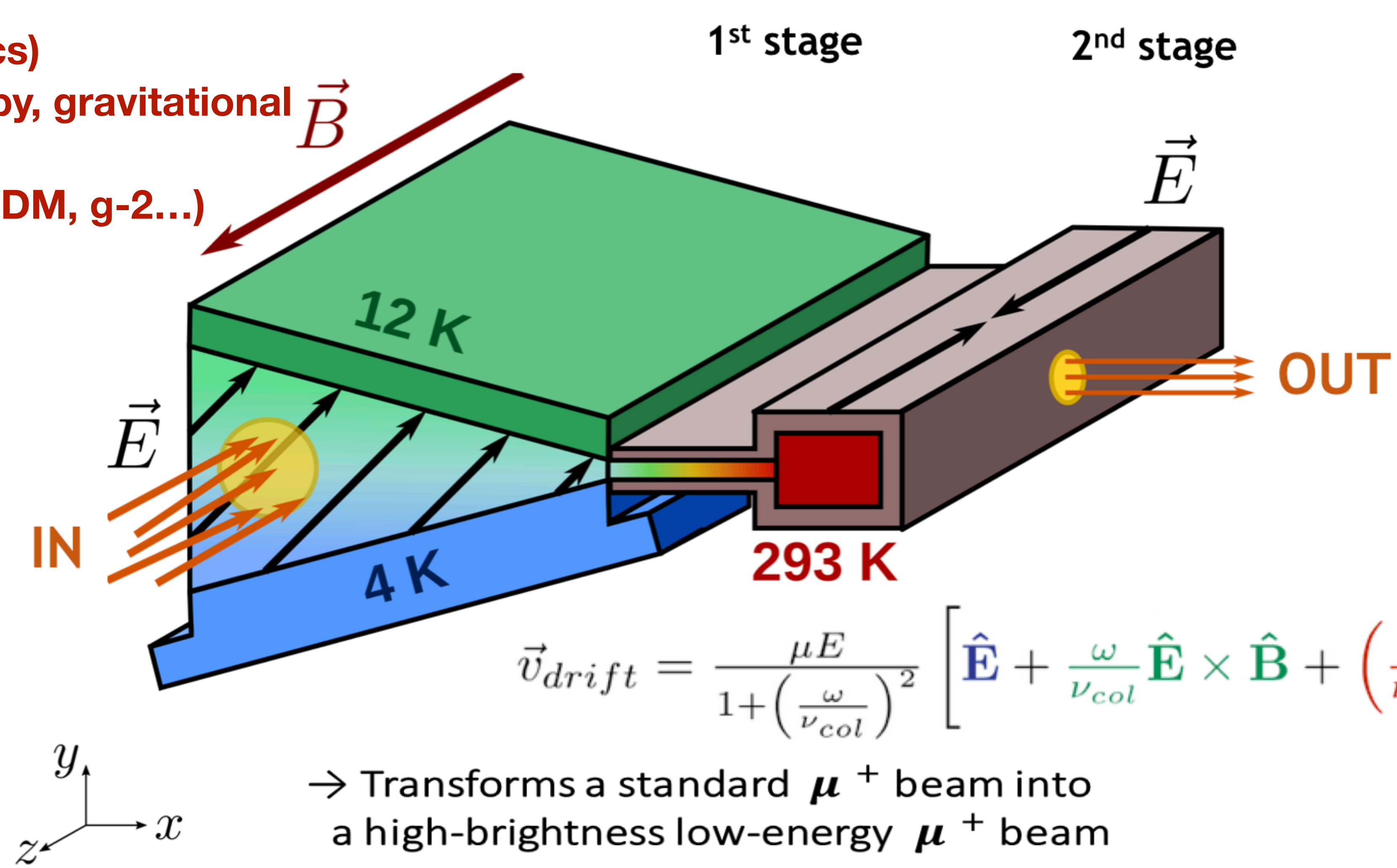
muCool/tertiary μ+ beam
- σ < 1mm
- E < eV
- Tagged

D. Taqqu, PRL 97 (2006) 194801
Y. Bao et al., PRL 112 (2014) 224801
I. Belosevic et al., EPJ C 79 (2019) 430

The muCool project at PSI

- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor $\mathbf{10^{10}}$ with an efficiency of $\mathbf{10^{-3}}$
- Longitudinal and transverse compression (1st stage + 2nd stage): experimentally proved
- **Next Step**: Extraction into vacuum

μSR (solid state physics)
muonium (spectroscopy, gravitational interaction…)
muon experiments (μEDM, g-2…)

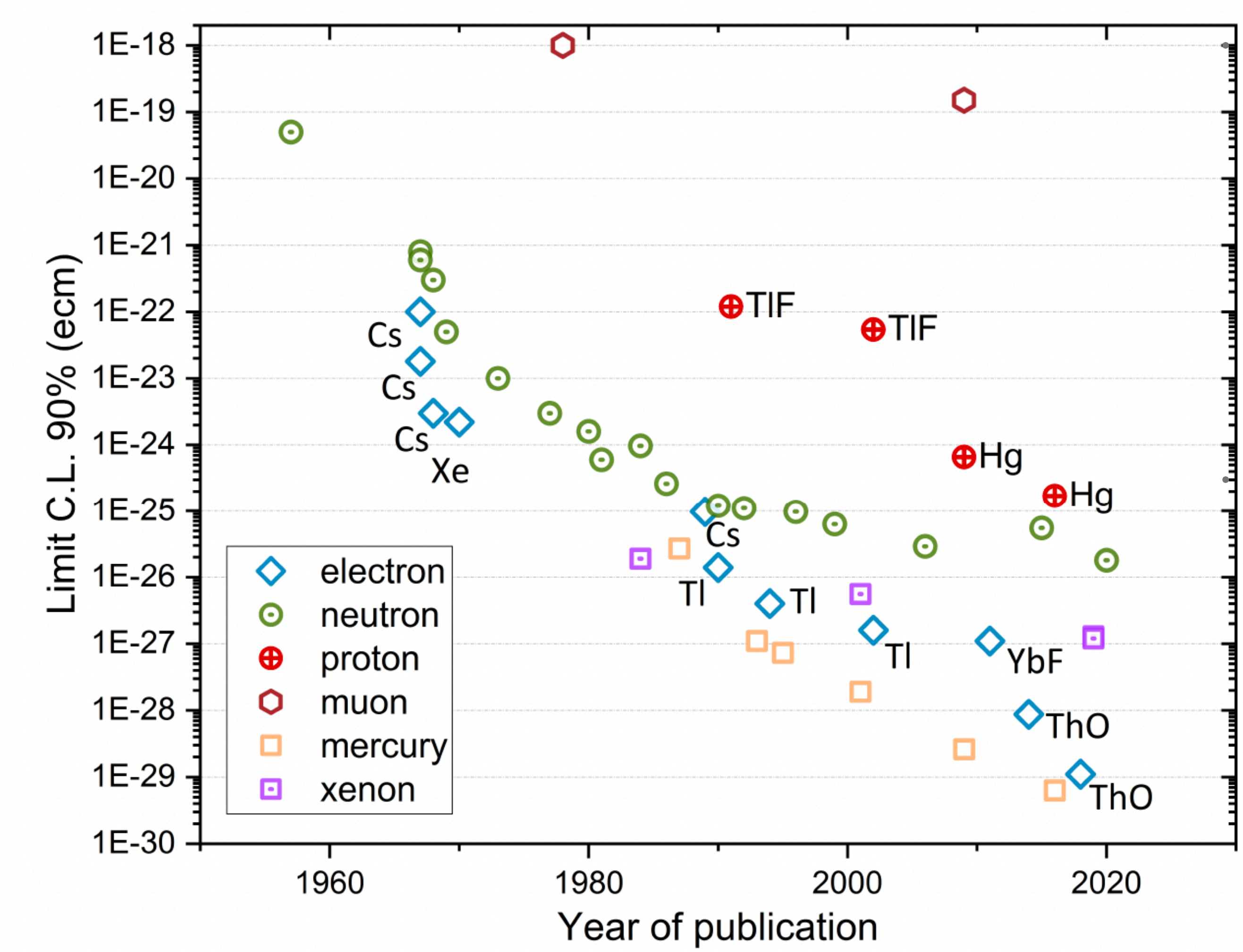


$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

muEDM at PSI

- FNAL/JPARC g-2 experiments aims at d_μ ~ **O(10^{-21}) $e$cm**
- **Dedicated muEDM search at PSI in stages. Precursors: $d_\mu < 3\times10^{-21}$ $e$cm. Final: $d_\mu < 6\times10^{-23}$ $e$cm**



- Electric dipole moments (EDMs) of fundamental particles are intimately connected to the violation of time invariance and the combined symmetry of charge and parity

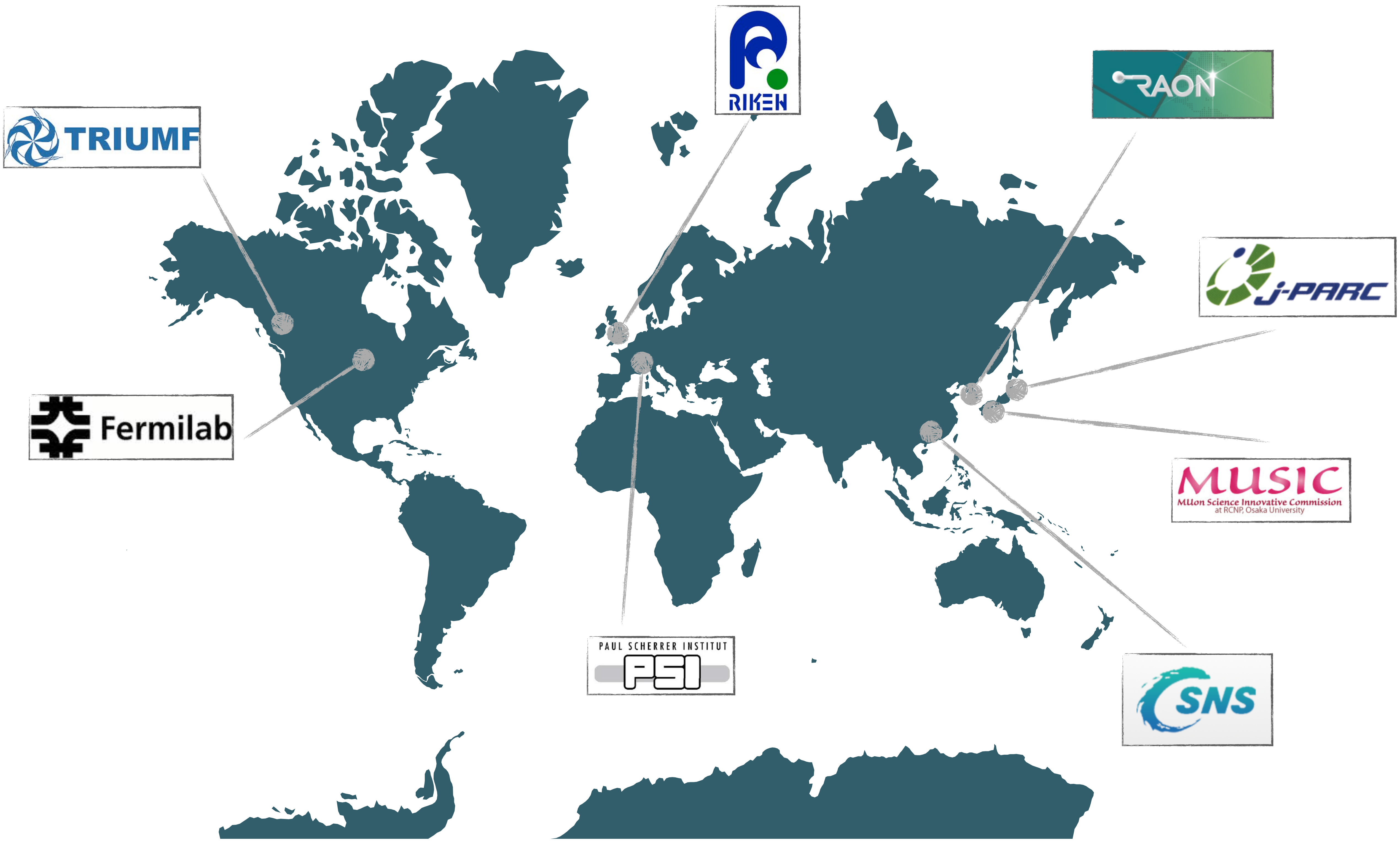
Impressive limits on the electron EDM deduced from measurements using atoms or molecules, e.g., thorium oxide molecules $d_e e < 1.1\times10^{-29-2}$ $e$cm (CL 90%) lead to $d_\mu e$ $<2.3\times10^{-27-}$– $e$cm (CL 90%), which is many orders of magnitude better than the direct limit d_μ

- m_μ/m_e naive rescaling assumes minimal flavor violation (MFV), that is a model dependent assumption

The **muon plays an exceedingly prominent role in unveiling path towards BSM**. All substantial evidence found in laboratory experiments for a departure from SM physics involves the muon

- g-2 experiment at FNAL ($a = (g-2)/2$ —> 4.2σ)
- LFU in B-meson decays (3.1σ, more than 5σ evidence when combining all LFU observable in B-meson decays)
- deficit in the 1st-row unitarity of the CKM matrix may be interpreted as LFU violation (about 4σ)

DC and Pulsed muon beams - present and future



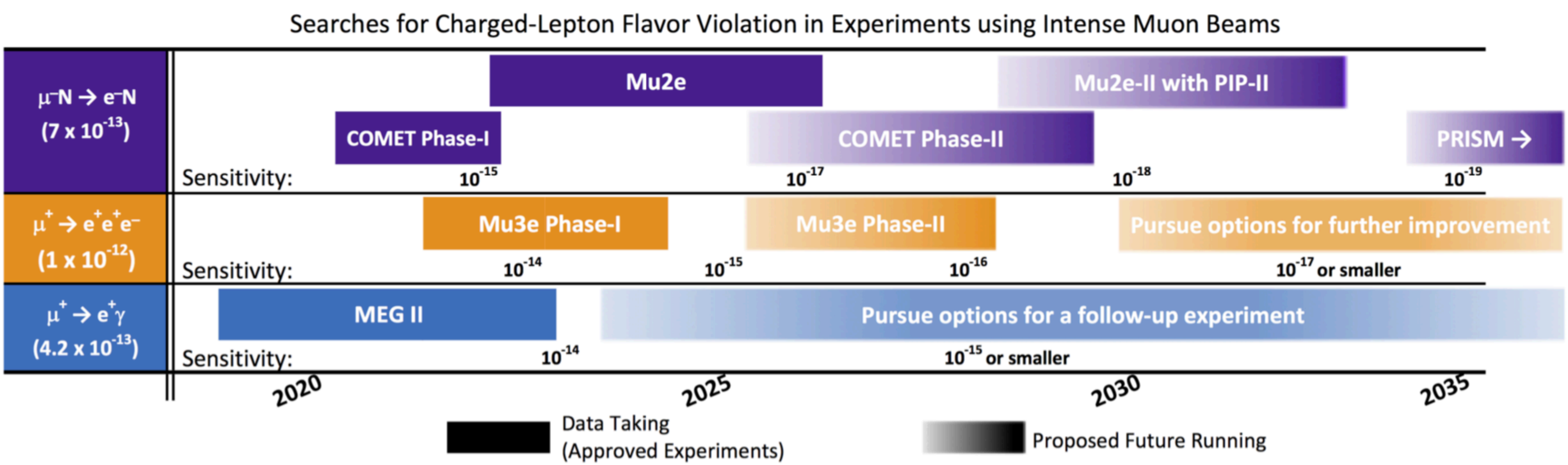
L. Calibbi and G. Signorelli, il Nuovo Cimento **41** (2018) 71

DC and Pulsed muon beams - present and future

Laboratory	Beam Line	DC rate (μ/sec)	Pulsed rate (μ/sec)
PSI (CH) (590 MeV, 1.3 MW)	$\mu E4, \pi E5$ HiMB at EH	$2 \div 4 \times 10^8$ (μ^+) $\mathcal{O}(10^{10})$ (μ^+) (>2018)	
J-PARC (Japan) (3 GeV, 210 kW) (8 GeV, 56 kW)	MUSE D-Line MUSE U-Line COMET		$3 \times 10^7(\mu^+)$ $6.4 \times 10^7(\mu^+)$ $1 \times 10^{11}(\mu^-)$(2020)
FNAL (USA) (8 GeV, 25 kW)	Mu2e		$5 \times 10^{10}(\mu^-)$(2020)
TRIUMF (Canada) (500 MeV, 75 kW)	M13, M15, M20	$1.8 \div 2 \times 10^6(\mu^+)$	
RAL-ISIS (UK) (800 MeV, 160 kW)	EC/RIKEN-RAL		$7 \times 10^4(\mu^-)$ $6 \times 10^5(\mu^+)$
KEK (Tsukuba, Japan) (500 MeV, 25 kW)	Dai Omega		$4 \times 10^5(\mu^+)$(2020)
RCNP (Osaka, Japan) (400 MeV, 400 W)	MuSIC	$10^4(\mu^-) \div 10^5(\mu^+)$ $10^7(\mu^-) \div 10^8(\mu^+)$(>2018)	
JINR (Dubna, Russia) (660 MeV, 1.6 kW)	Phasotron	$10^5(\mu^+)$	
RISP (Korea) (600 MeV, 0.6 MW)	RAON	$2 \times 10^8(\mu^+)$(>2020)	
CSNS (China) (1.6 6eV, 4 kW)	HEPEA	$1 \times 10^8(\mu^+)$(>2020)	

Outlooks

- Astonishing sensitivities in muon cLFV channels are foreseen for the incoming future
- **cLFV remains one of the most exciting place where to search for new physics**
- Submitted inputs to the European Strategy Committee



Thanks for your attention!

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

Kaons ~ 100

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

cLFV @ LHC ~ 250

- ATLAS,CERN
- CMS,CERN
- LHCb, CERN

J/ψ @ BEPCII ~ 100

- BESIII, Beijing

Back-up

EDM: From the “frequency” approach to the frozen-spin technique

$$\vec{\omega} = \frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{q}{m}\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)$$

ω_a ω_e

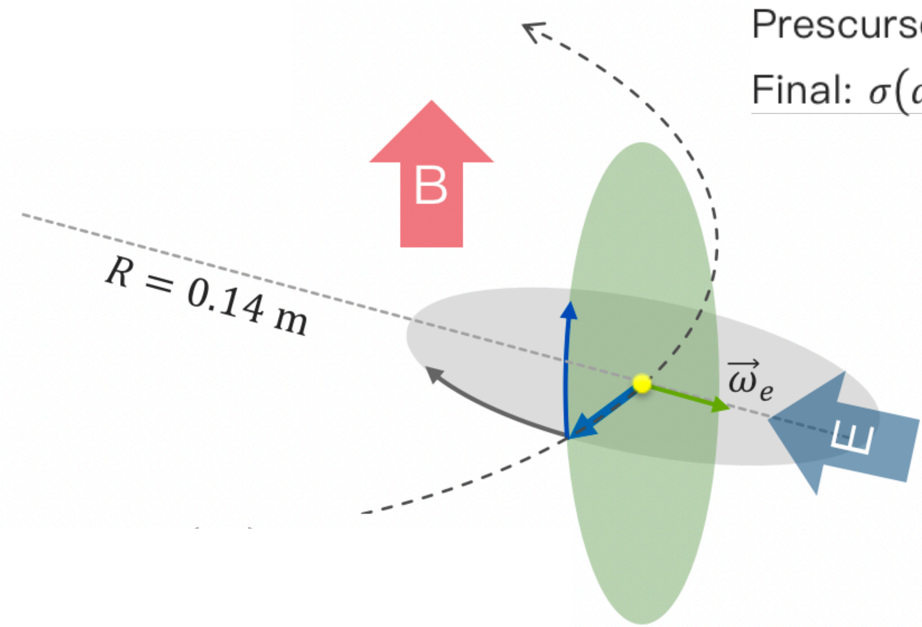
- The frozen-spin technique uses an Electric field perpendicular to the moving particle and magnetic field, fulfilling the condition:

$$a\vec{B} = \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}_f}{c}$$

- Without EDM, $\omega = 0$, the spin follows the momentum vector as for an ideal Dirac spin-1/2 particle, while with an EDM it will result in a precession of the spin with ω_e || E
- The sensitivity to a muon EDM is given by the asymmetry up/down of the positron from the muon decay

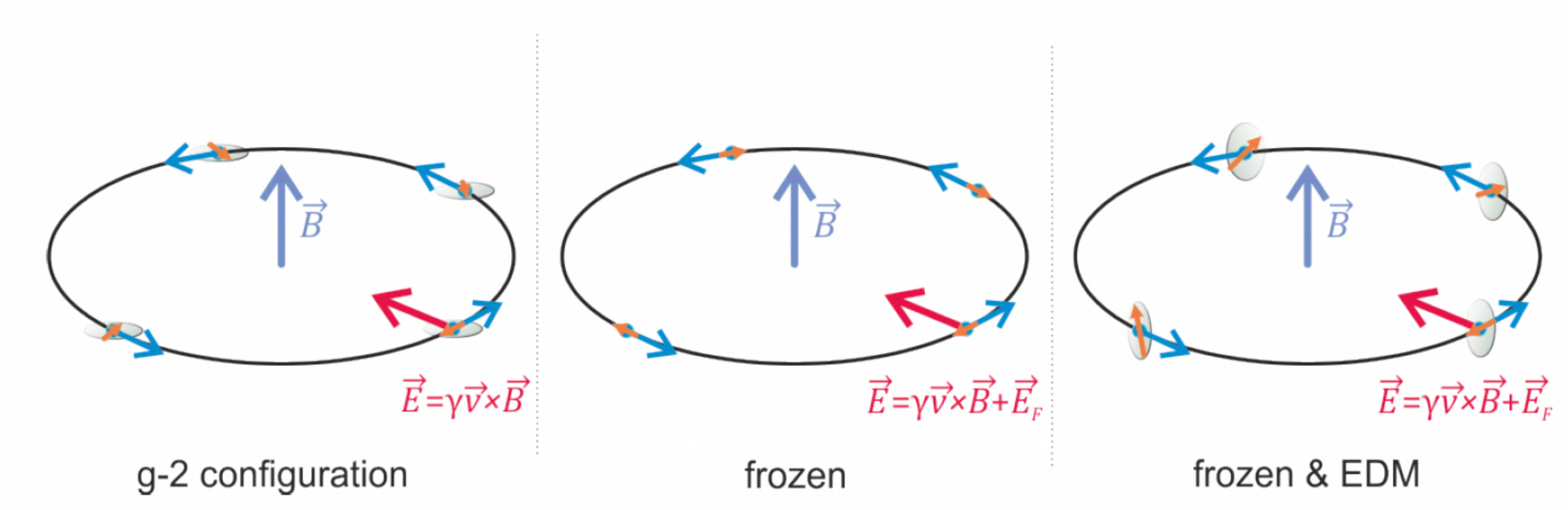
Prescursor: $\sigma(d_\mu) < 3 \cdot 10^{-21} e\text{cm}$

Final: $\sigma(d_\mu) < 6 \cdot 10^{-23} e\text{cm}$

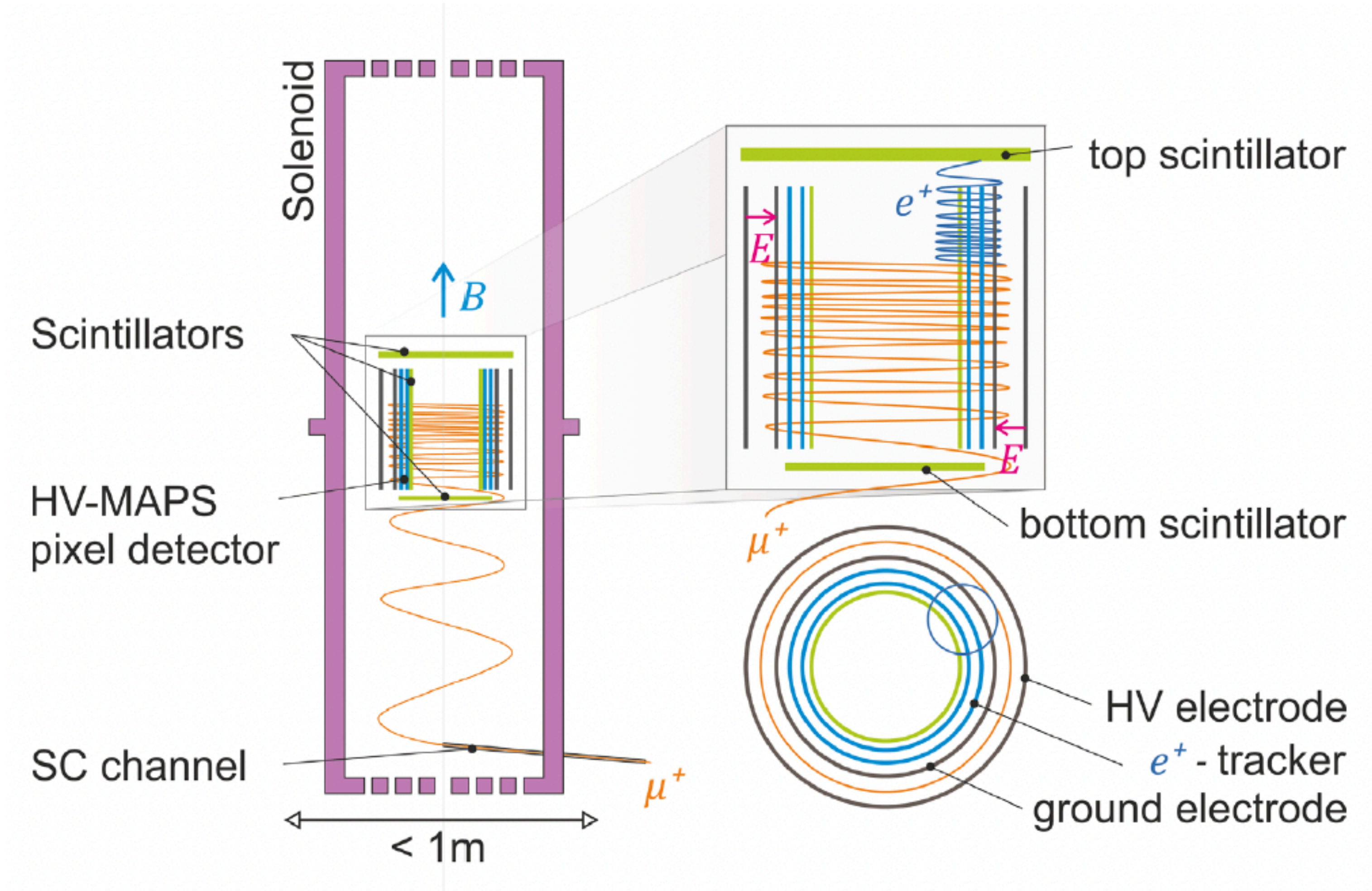


EDM: From the "frequency" approach to the frozen-spin technique

- Putting everything together, here a summary:



muEDM final at PSI: Frozen spin and longitudinal injection



p=125 MeV/c [muE1]

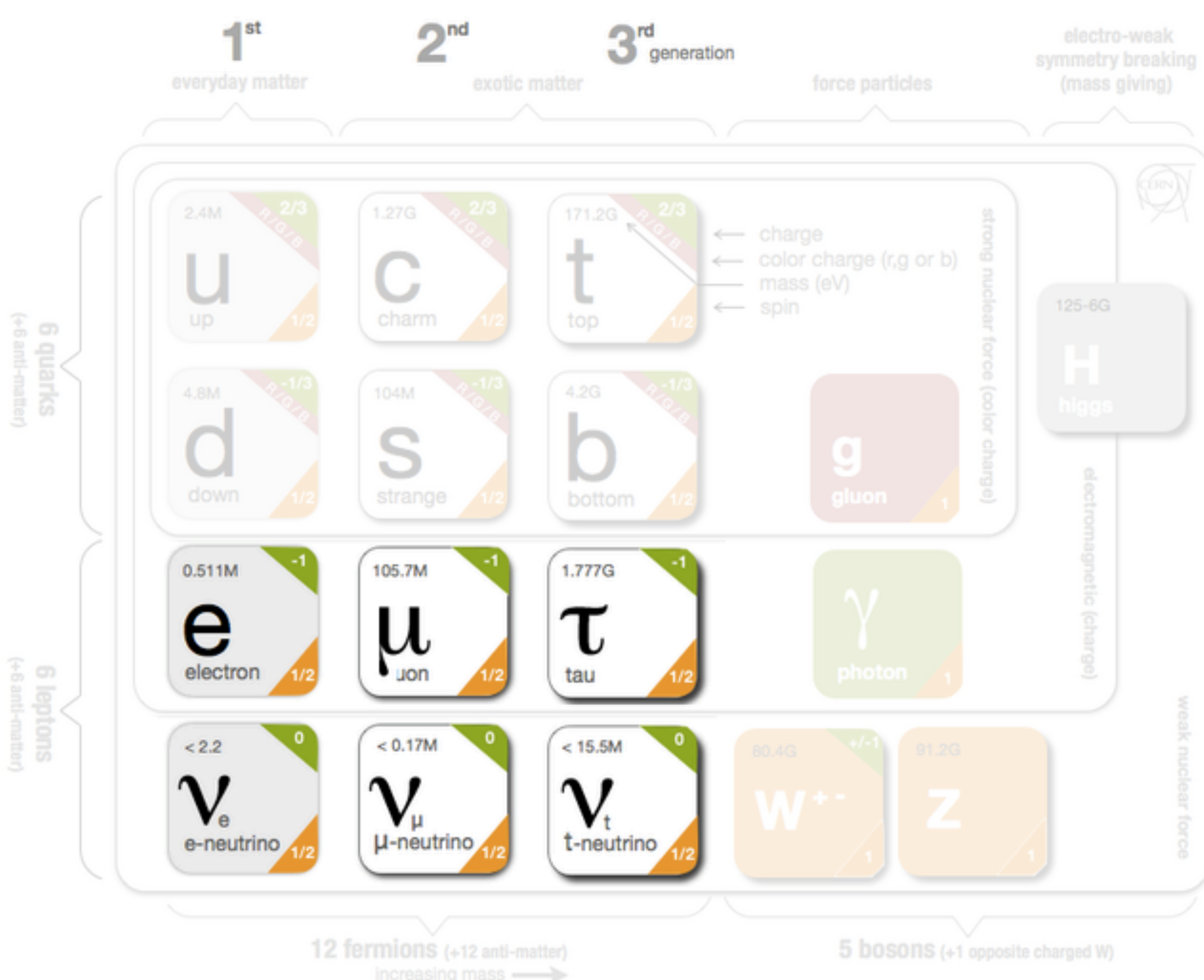
- μ^+ from Pion–decay → high polarization $p \approx 95\%$
- Injection through superconducting channel
- Fast scintillator triggers pulse
- Magnetic pulse stops longitudinal motion of μ^+
- Weakly focusing field for storage
- Thin electrodes provide electric field for frozen spin
- Pixelated detectors for e^+– tracking

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
$Z \to \mu e$	7.5×10^{-7}	Phy. Rev. D 90 (2014) 072010	Atlas
$Z \to \mu e$	7.3×10^{-7}	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 $\mu \to e \gamma$

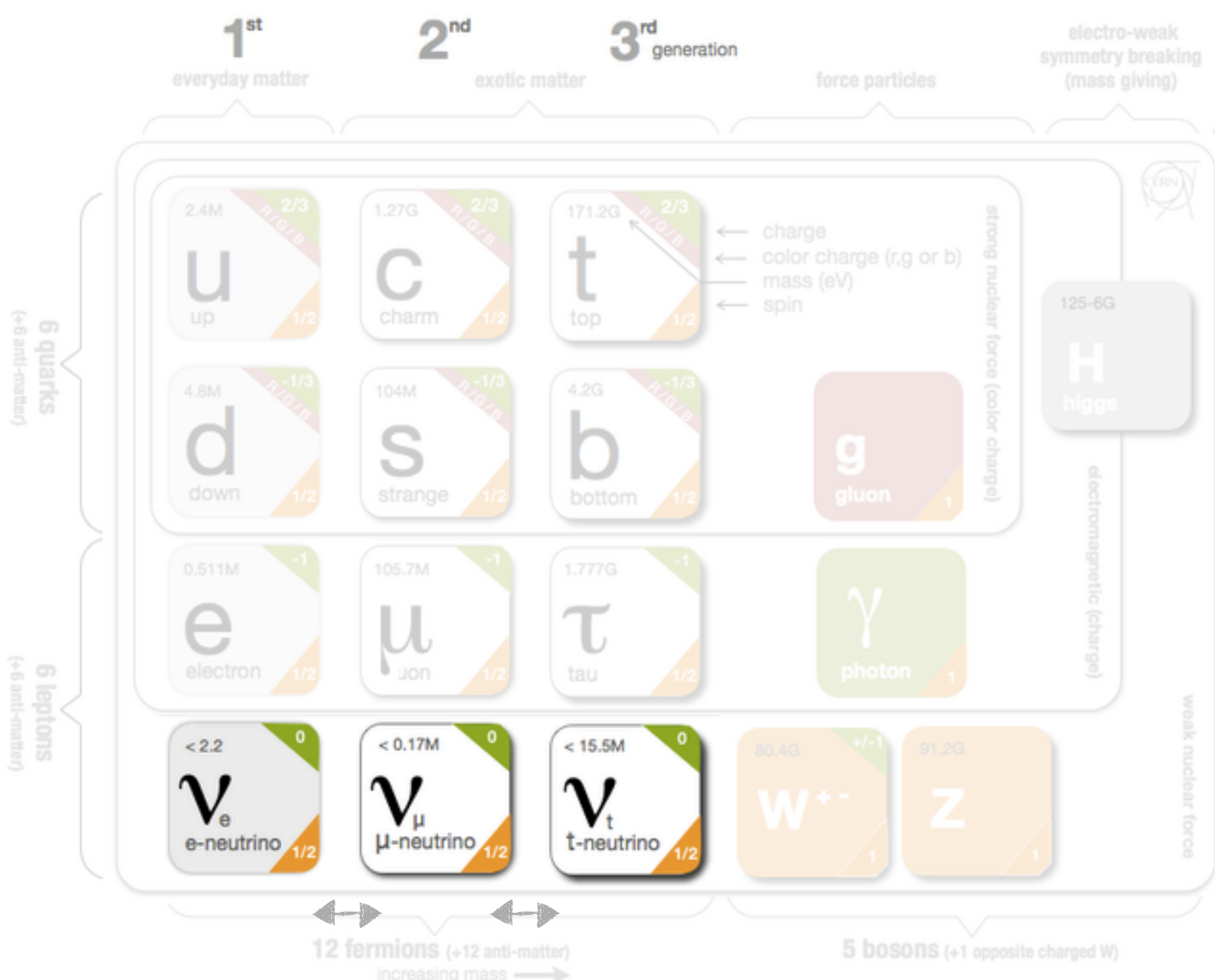
Charged lepton flavour violation



Charged lepton flavour violation

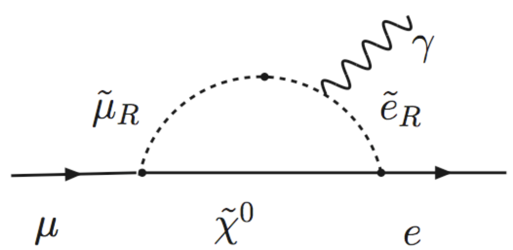
- Neutrino oscillations: Evidence of physics Behind Standard Model (BSM)

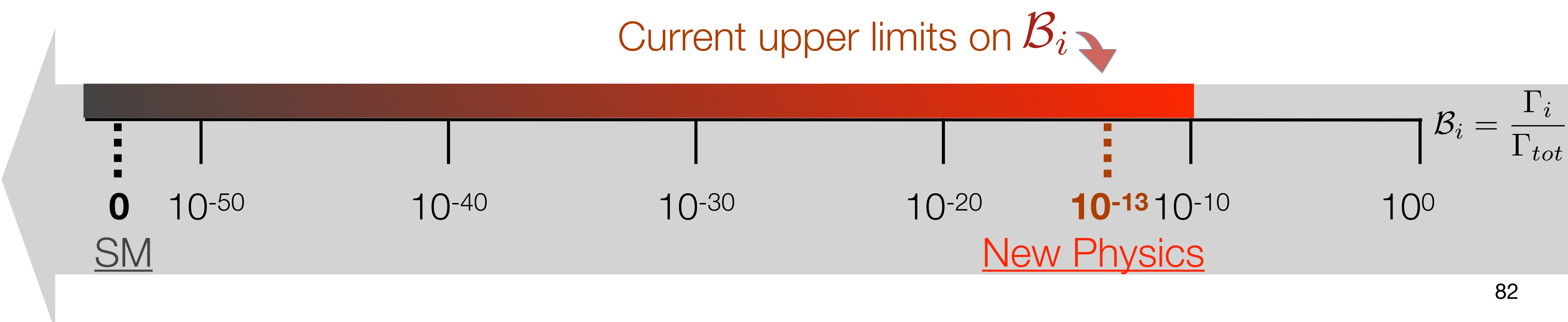
  Neutral lepton flavour violation



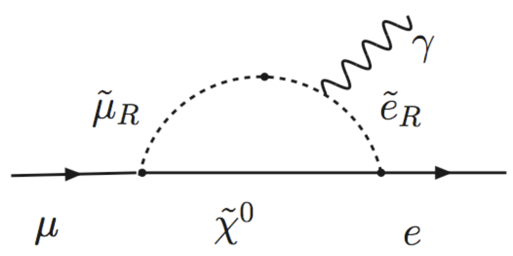
$\Delta N_i \neq 0$ with i = 1,2,3

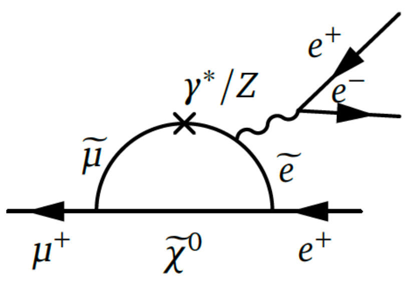
Muon golden channels

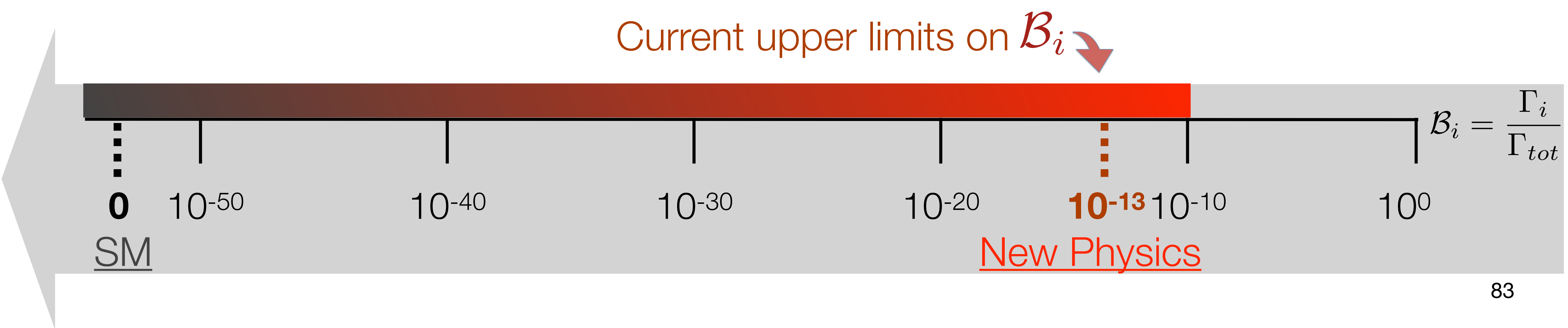




Muon golden channels







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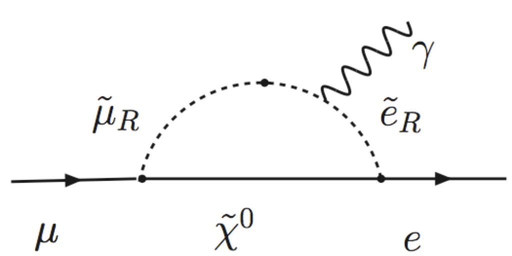
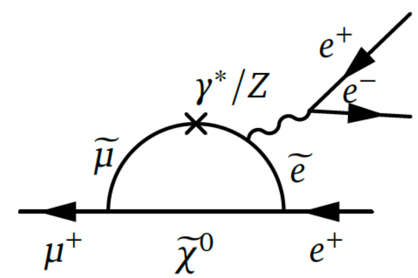
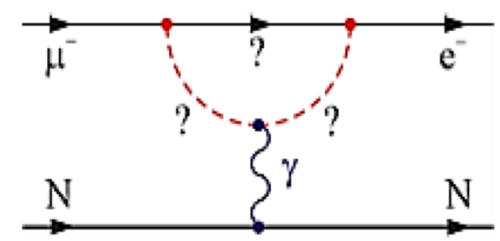
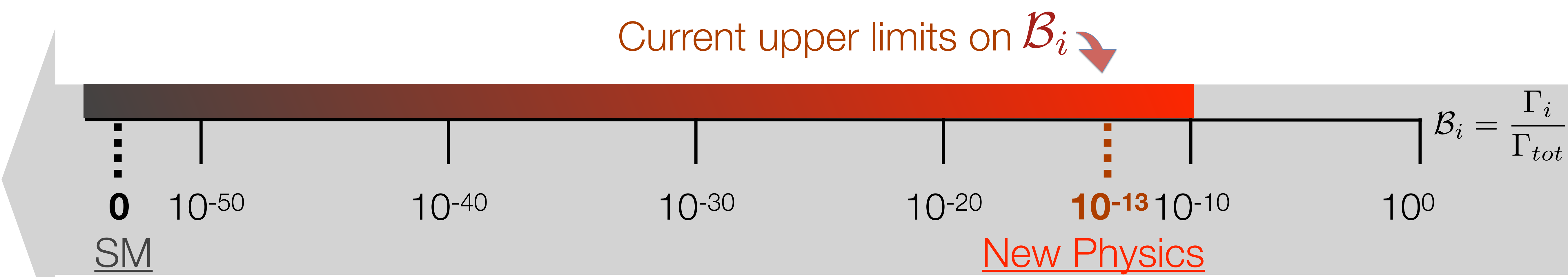






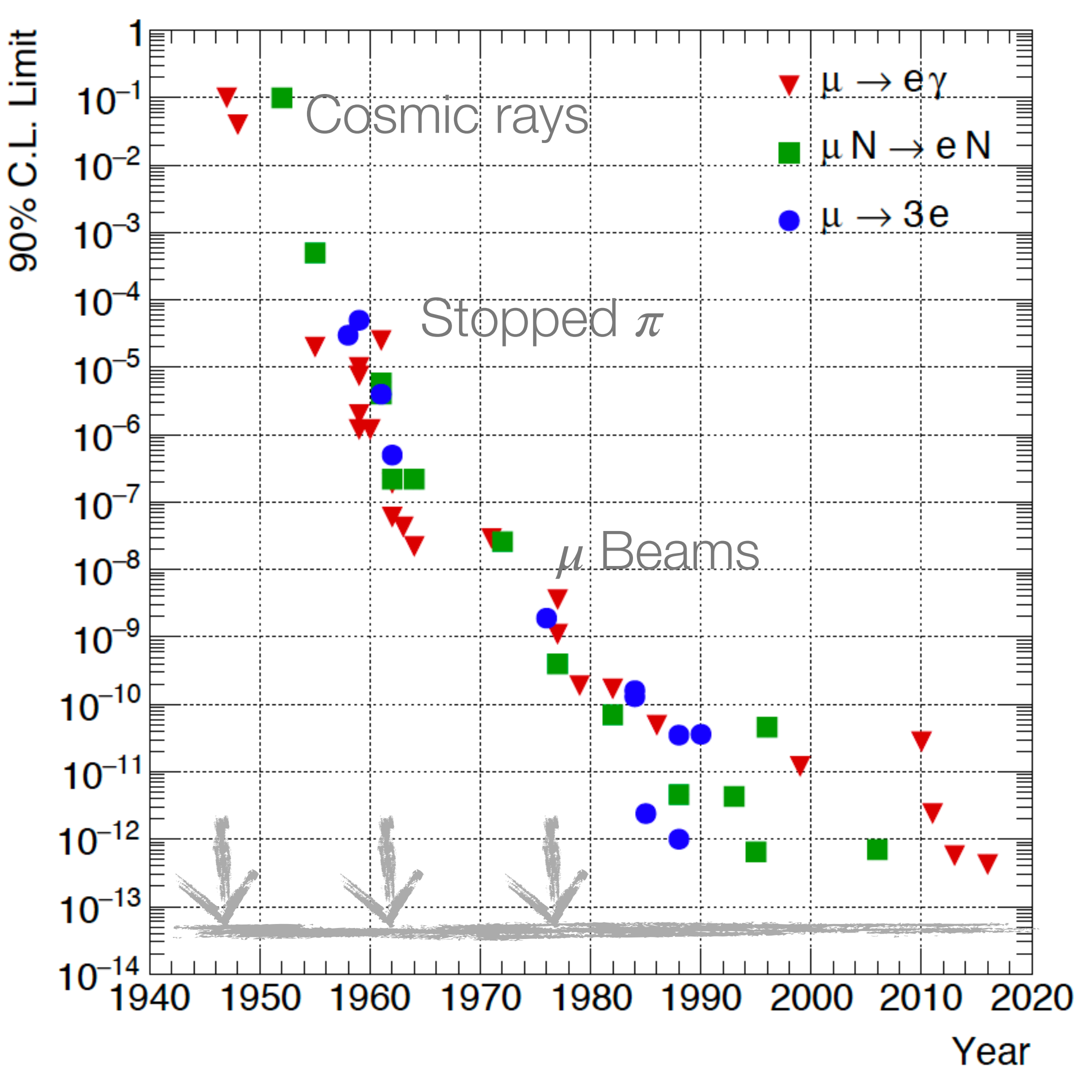


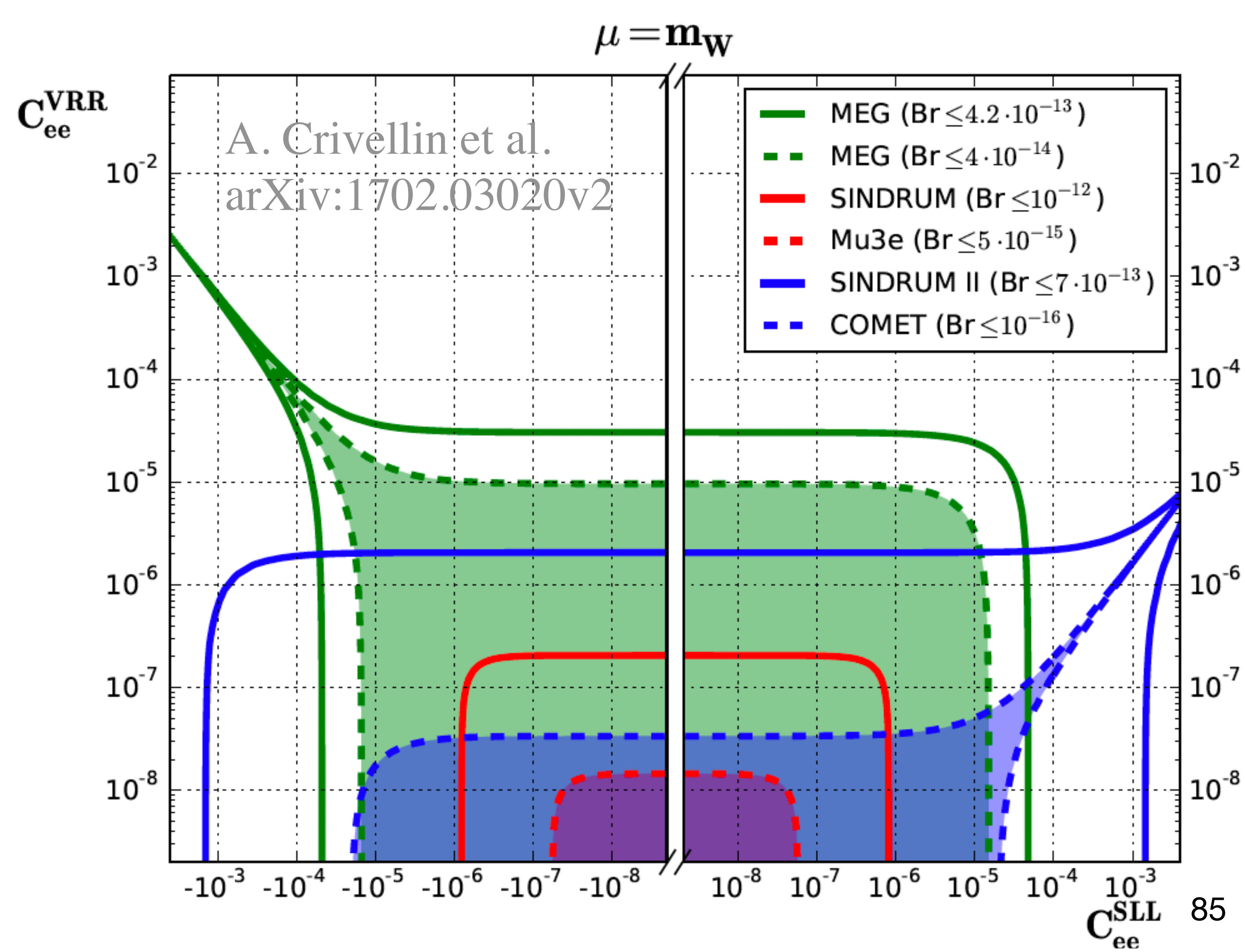
cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities:

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2 x 10^{-13}	~ 6 x 10^{-14}
$\mu \to eee$	1.0 x 10^{-12}	~1.0 x 10^{-16}
$\mu N \to eN'$	7.0 x 10^{-13}	few x 10^{-17}

- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV

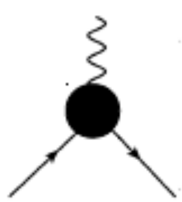
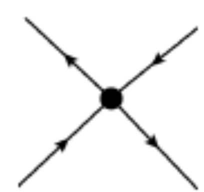


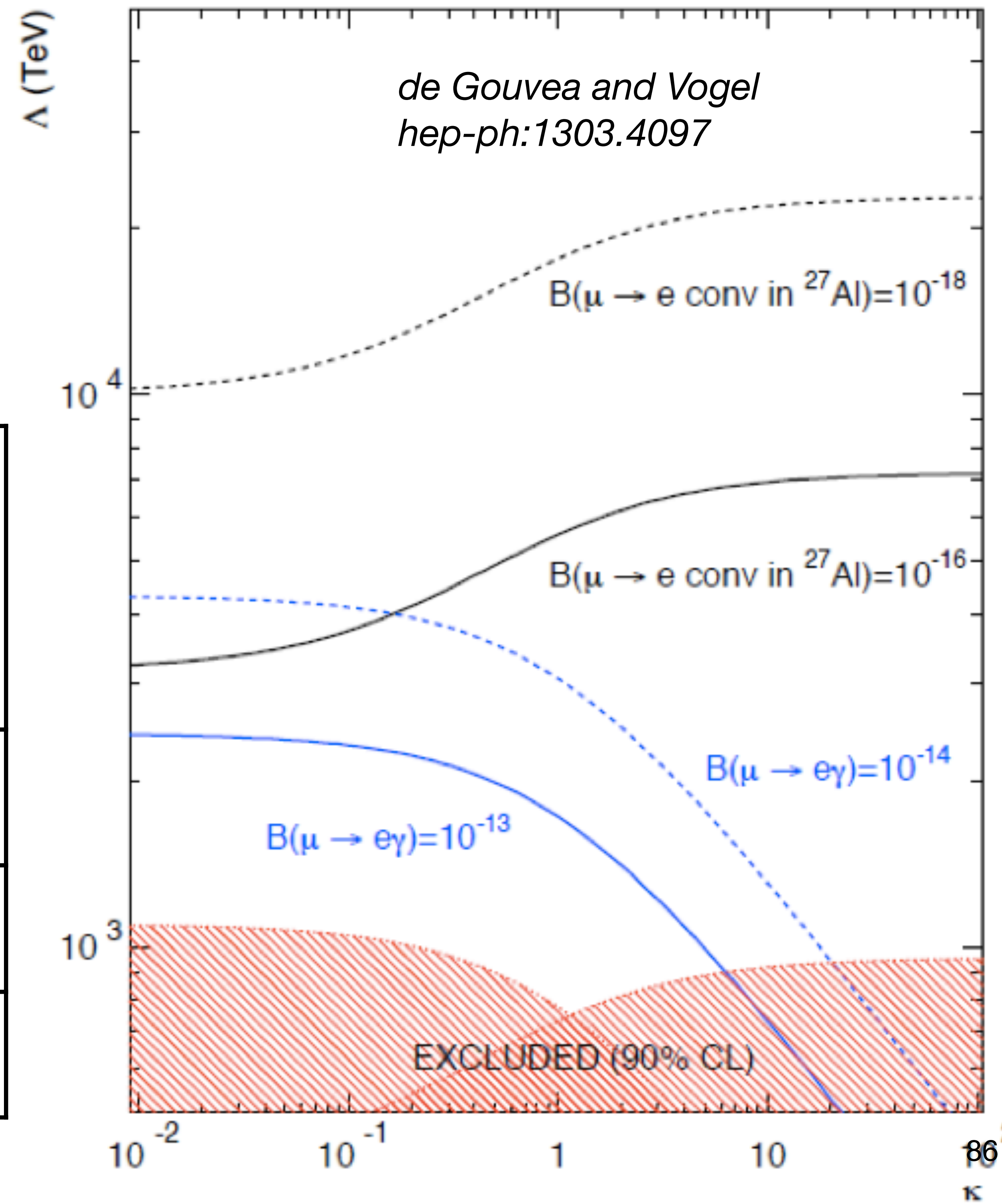


cLFV: “Effective” lagrangian with the k-parameter

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

Model independent lagrangian

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



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