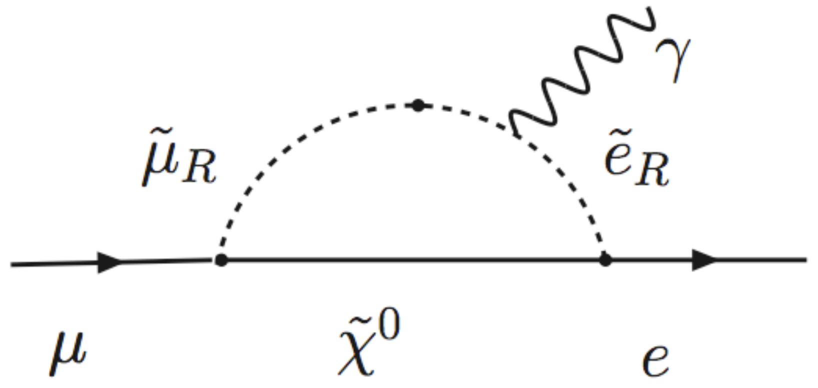
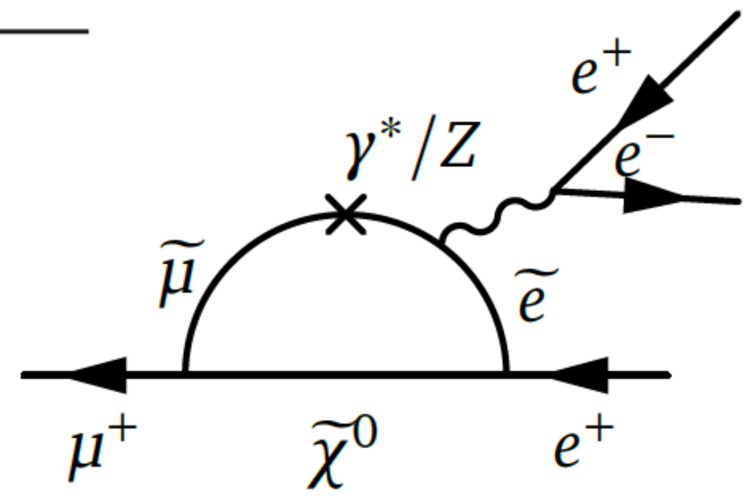
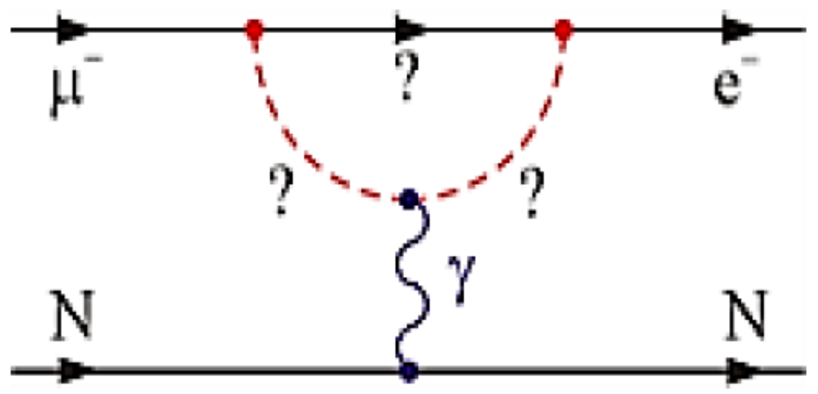
Charged Lepton flavour violation searches at PSI

Angela Papa
Paul Scherrer Institute and University of Pisa/INFN
FCCP 2022, 24th September Capri (Italy)







Content

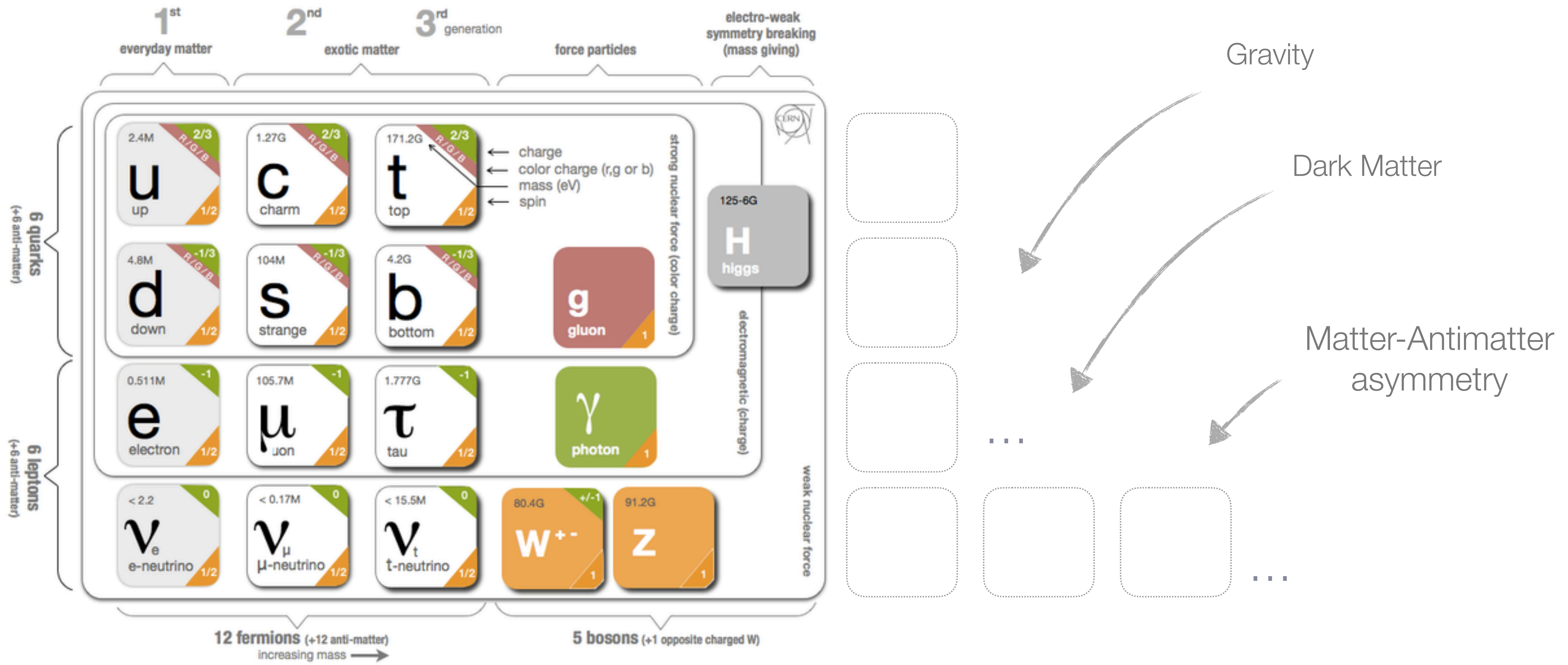
- Muon physics cases
- Muon beams
- Muon experiments

Content

- **Muon physics cases**
- Muon beams
- Muon experiments

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



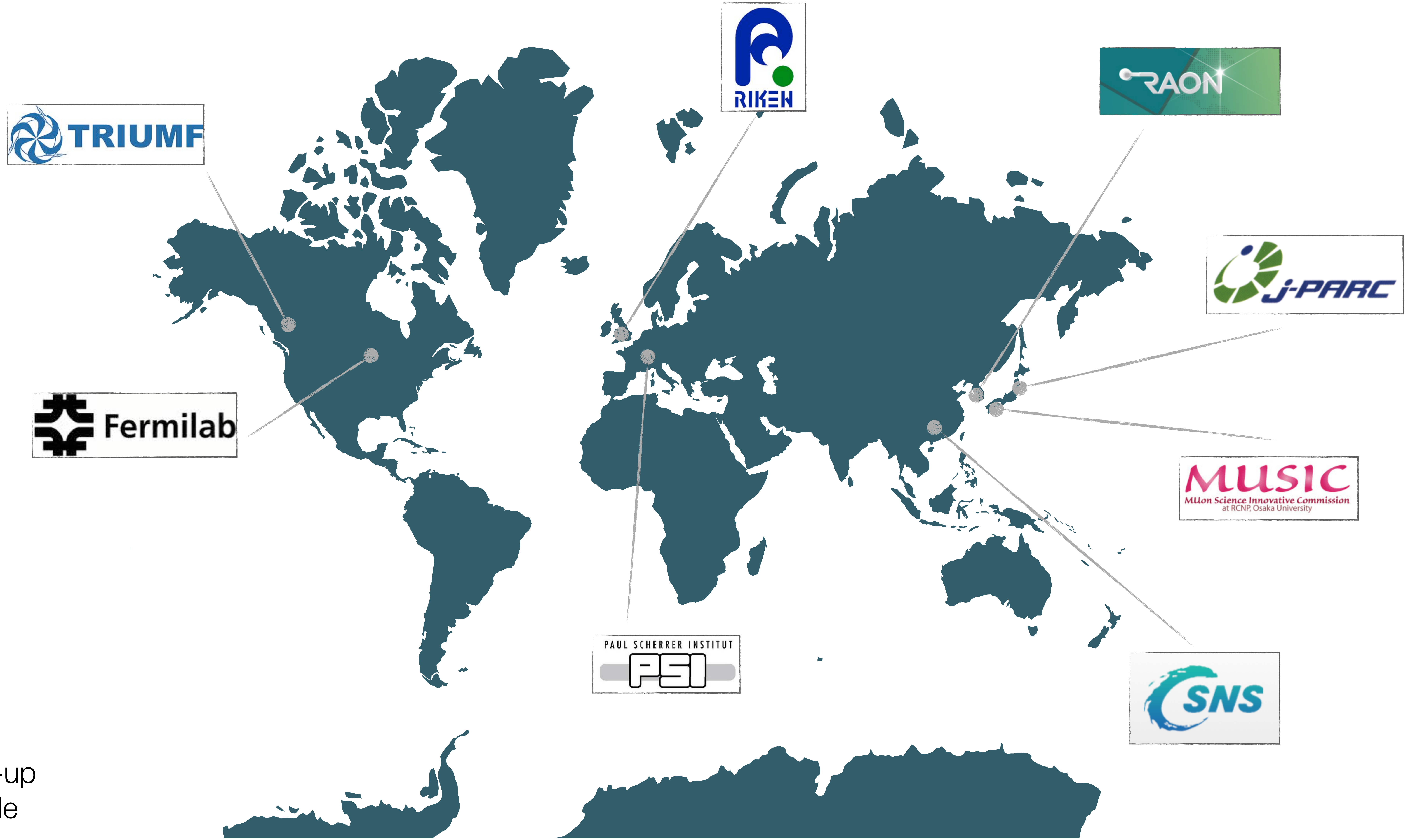
Focus here on:
- muon cLFV

- 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**

Content

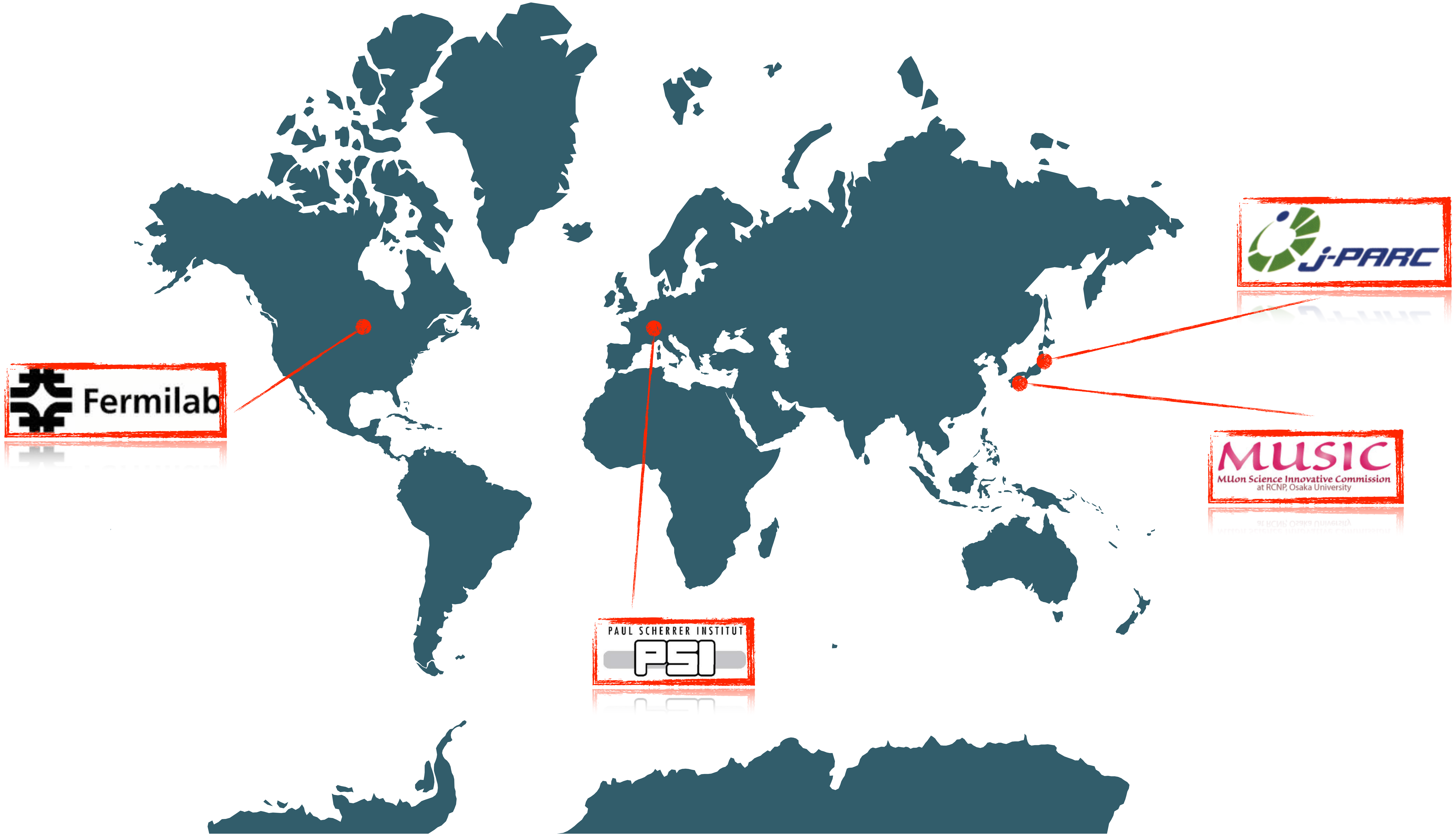
- Muon physics cases
- **Muon beams**
- Muon experiments

Muon beams worldwide



Note: See the back-up for a summary table

Muon beams worldwide associated to "present" experiments

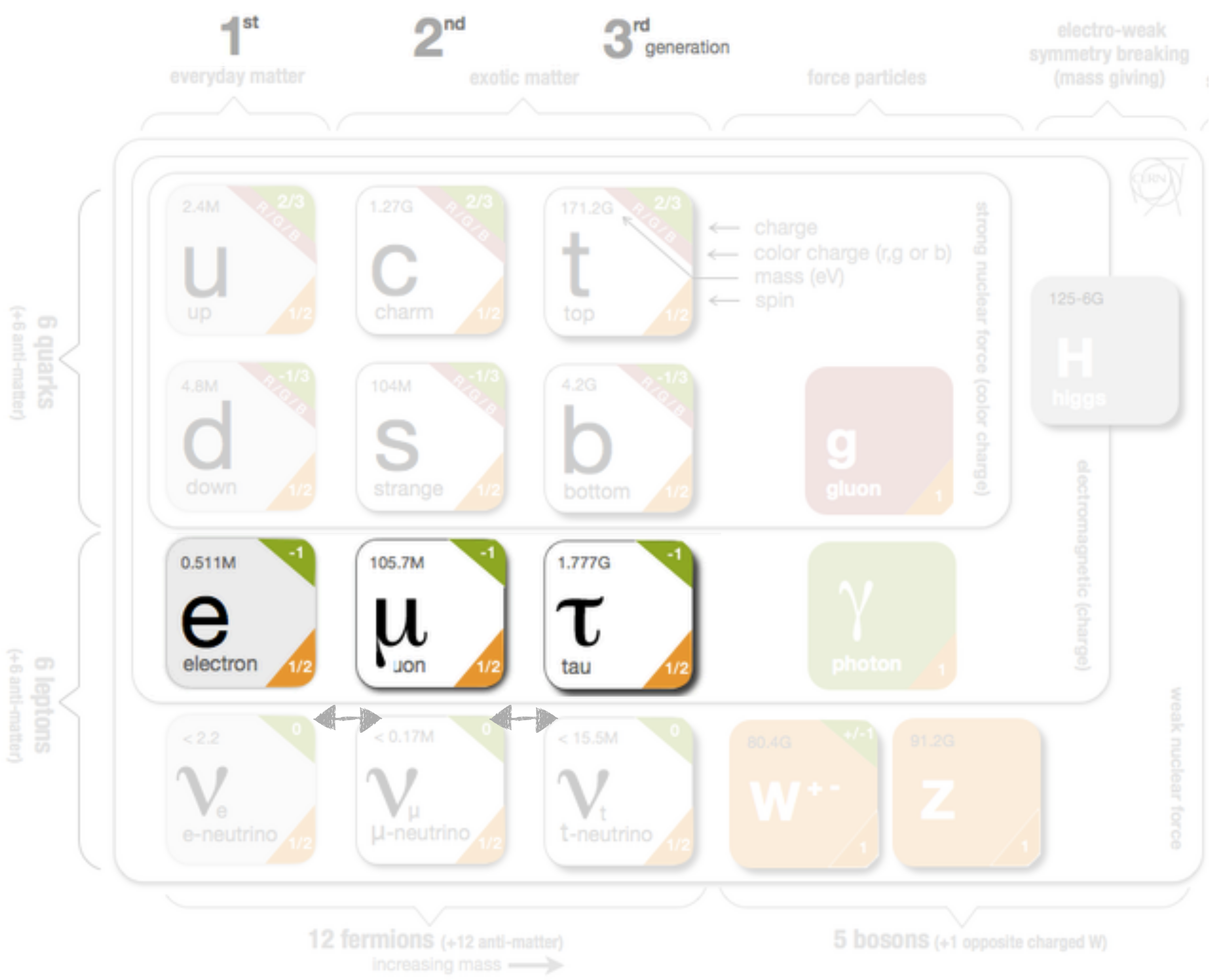


Content

- Muon physics cases
- Muon beams
- **Muon (present) experiments at PSI**
    - **cLFV searches: MEGII and Mu3e**

Charged lepton flavour violation search: Motivation

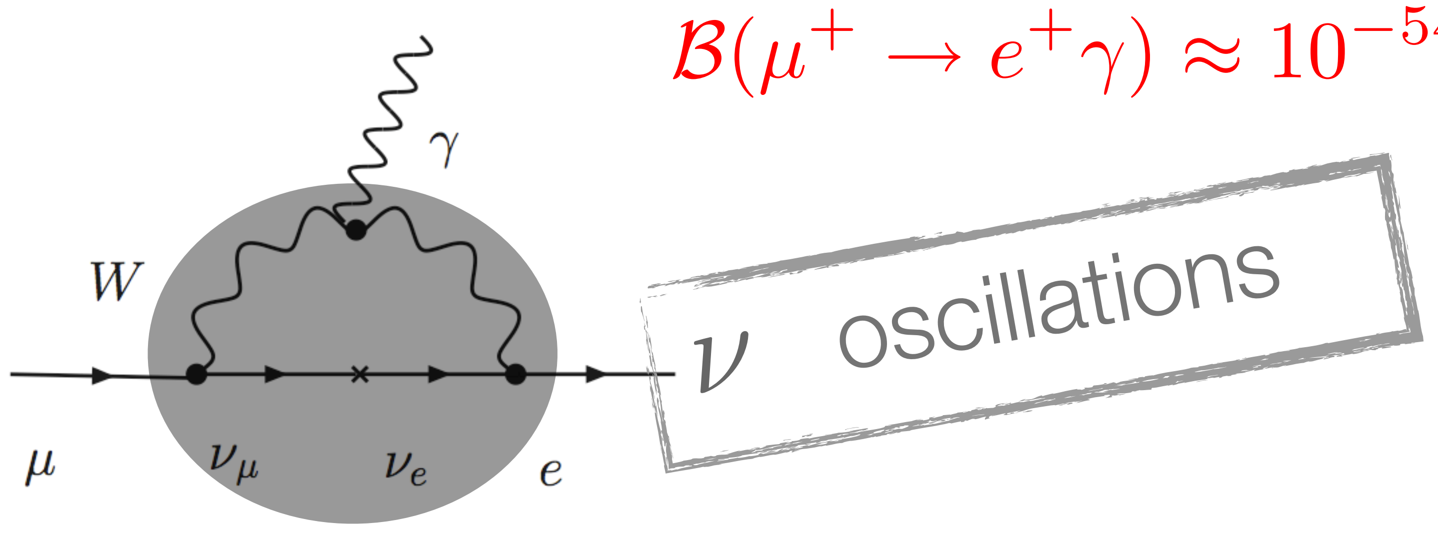
- **Neutrino oscillations**: Evidence of physics Behind Standard Model (BSM). **Neutral lepton flavour violation**
- **Charged lepton flavour violation: NOT** yet observed
- An experimental **evidence** of cLFV at the current sensitivities will be a **clear signature of New Physics**



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

SM with massive neutrinos (Dirac)

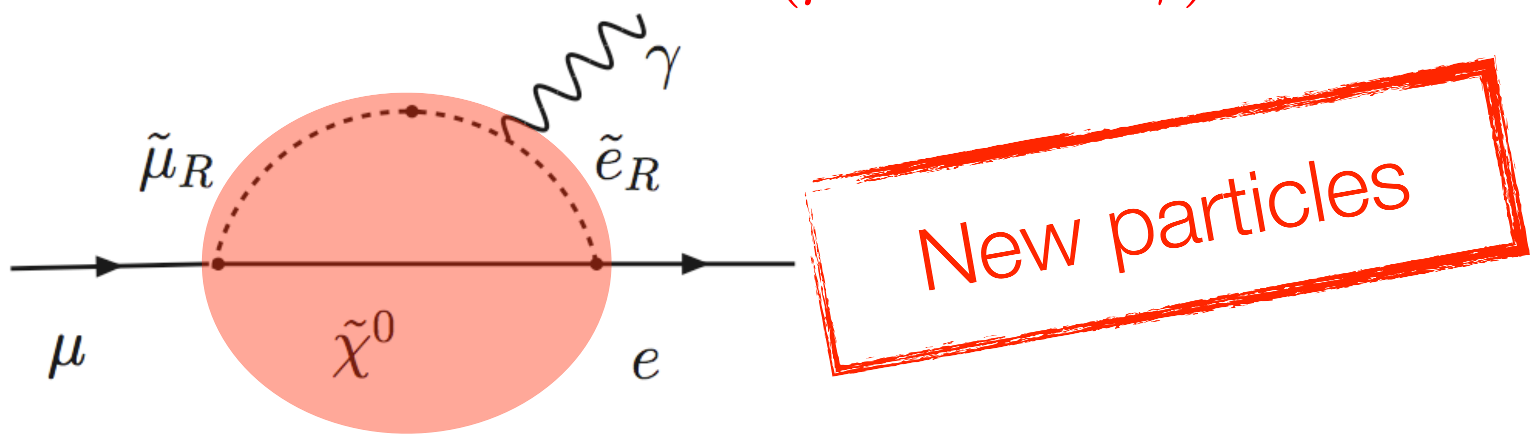
$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$



too small to access experimentally

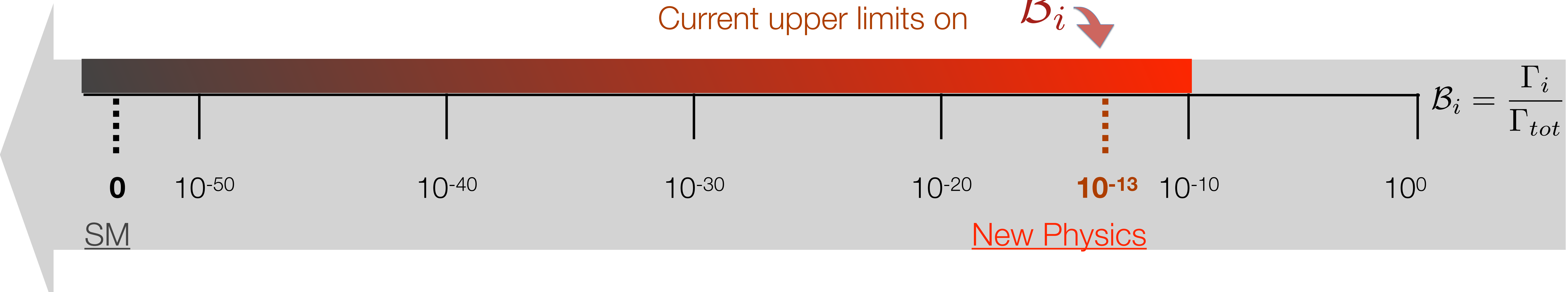
BSM

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



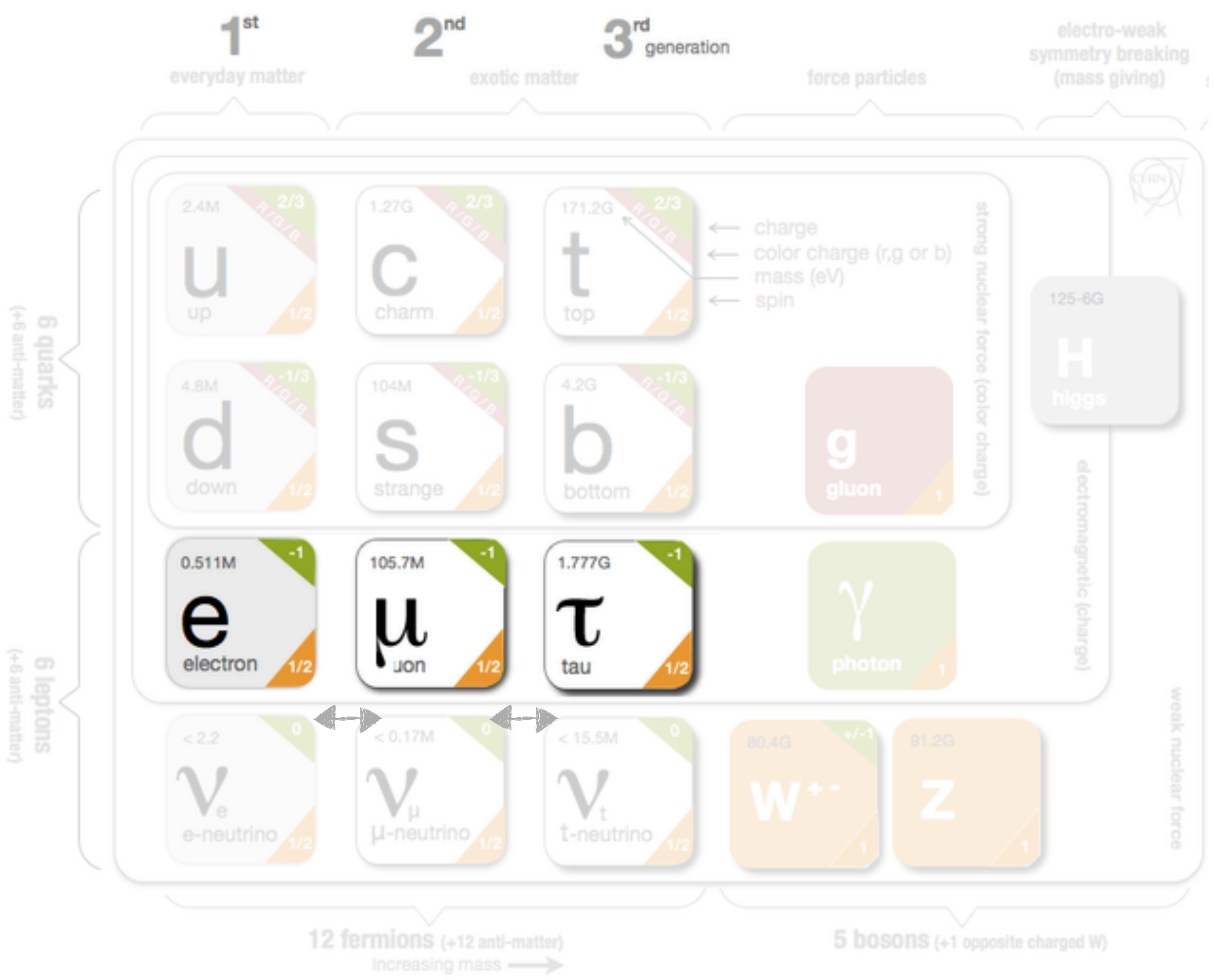
an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)

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



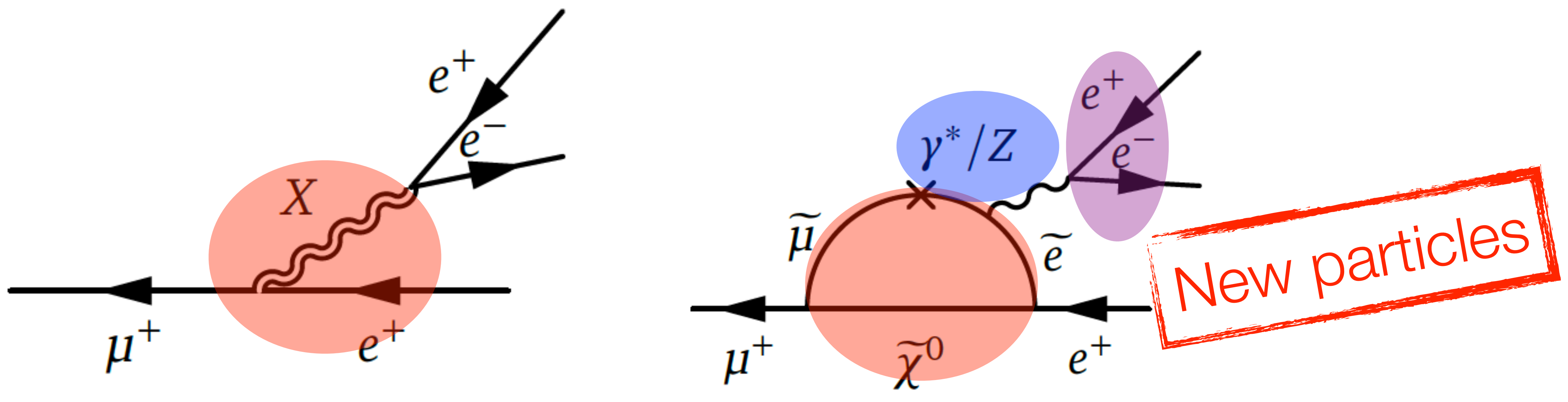
Charged lepton flavour violation search: Motivation

- **Neutrino oscillations**: Evidence of physics Behind Standard Model (BSM). **Neutral lepton flavour violation**
- **Charged lepton flavour violation: NOT** yet observed
- An experimental **evidence** of cLFV at the current sensitivities will be a **clear signature of New Physics**

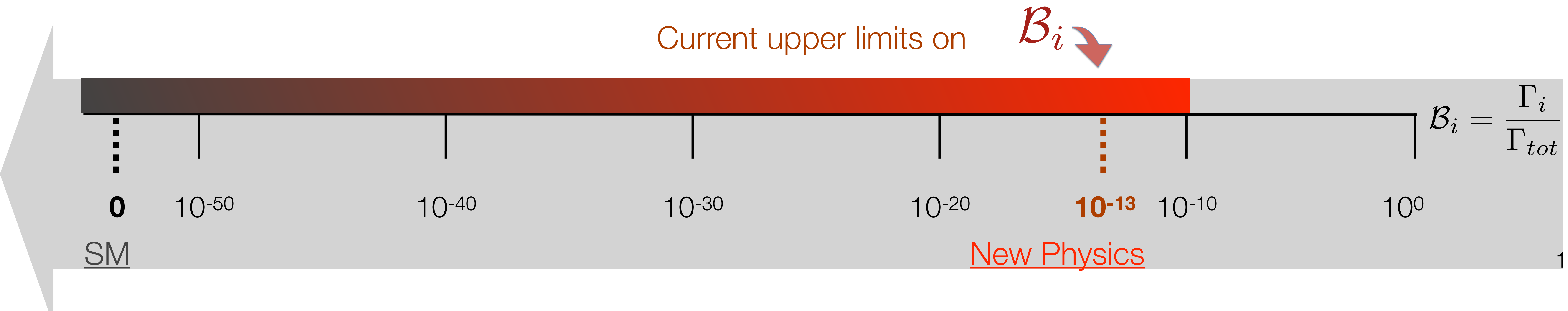


$\Delta N_i \neq 0$ with i = 1,2,3

BSM

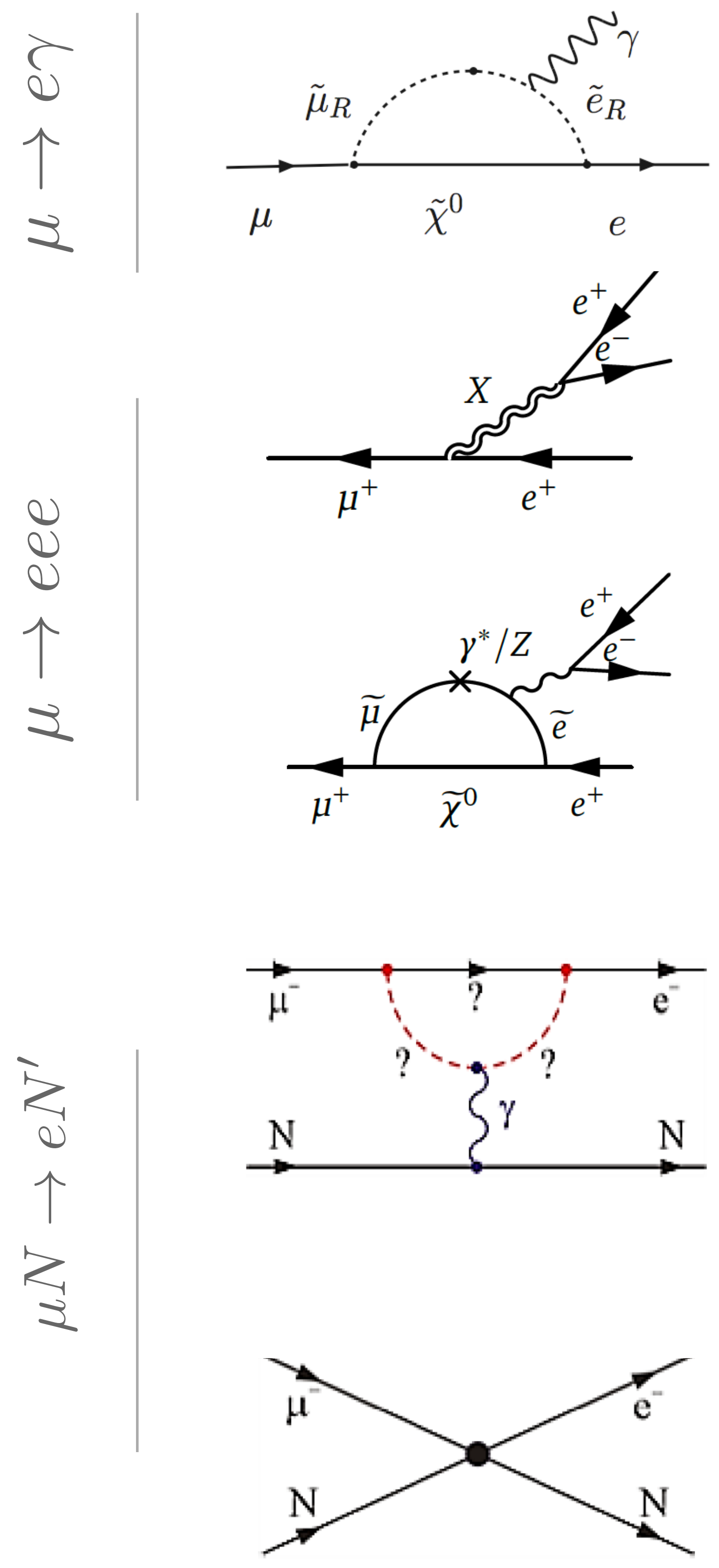


$\mu^+ \to e^+e^+e^-$ $\mu^+ \to e^+e^+e^-$

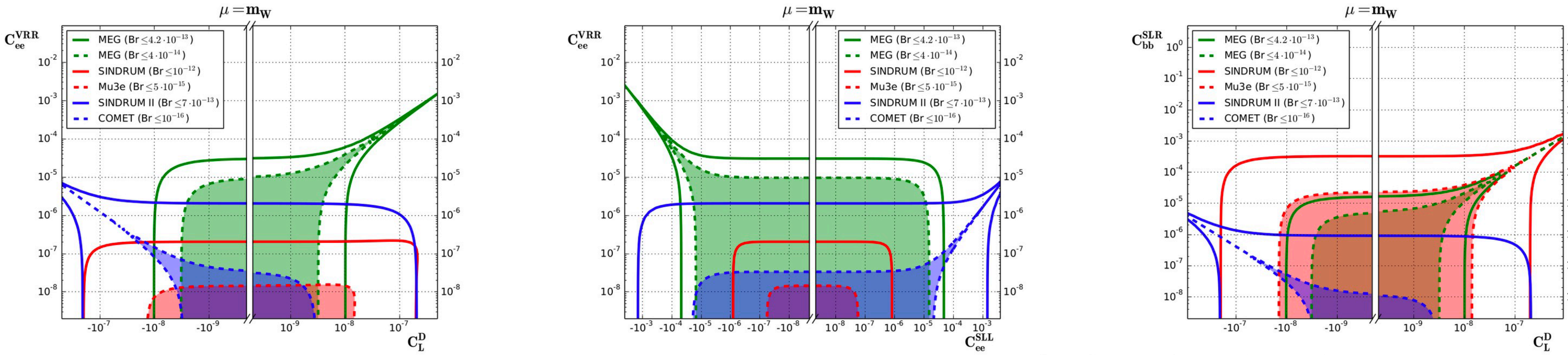


CLFV searches with muons: Status and prospects

- In the near future impressive sensitivities via the so called “golden” muon channels
- **Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV**



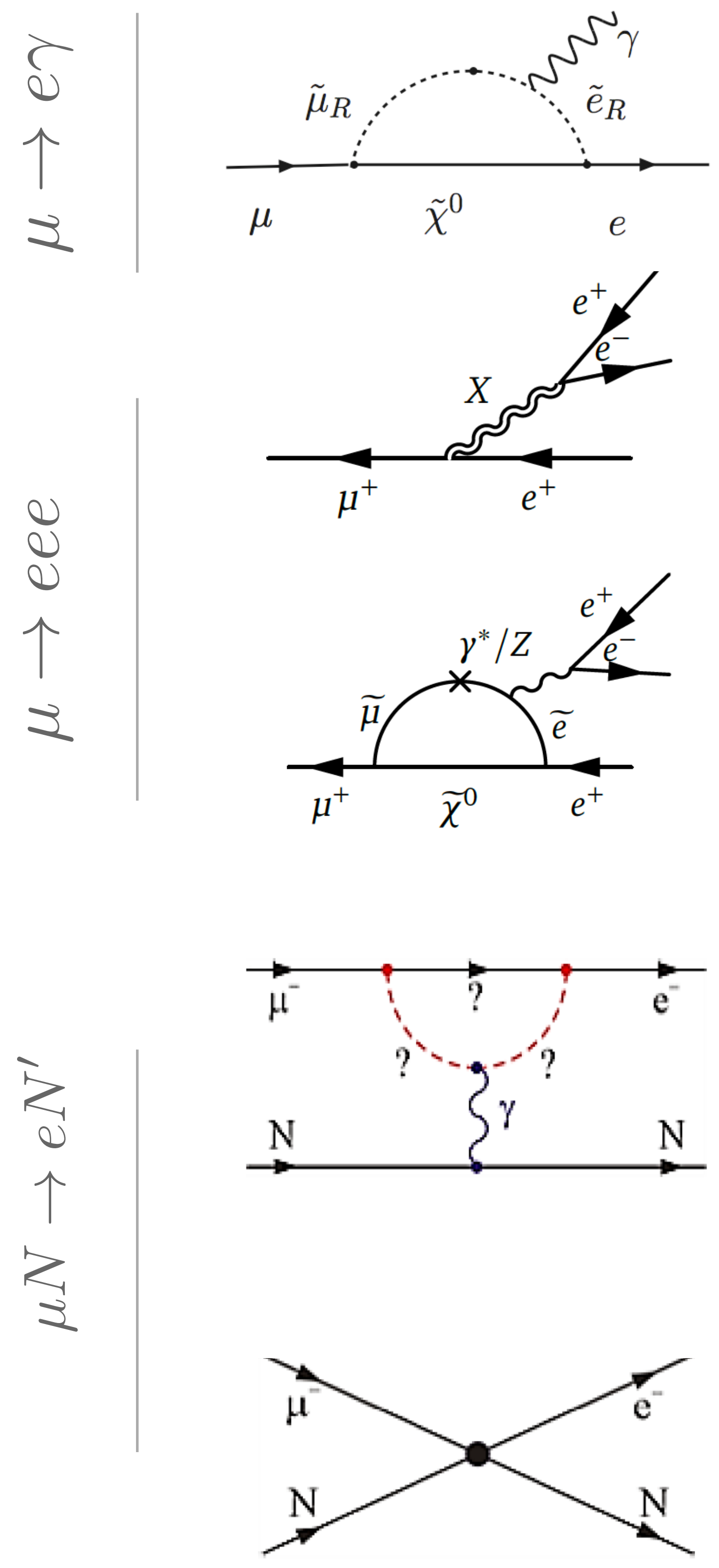
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum \mathcal{O}_5 + \frac{1}{\Lambda^2}\sum \mathcal{O}_6$$

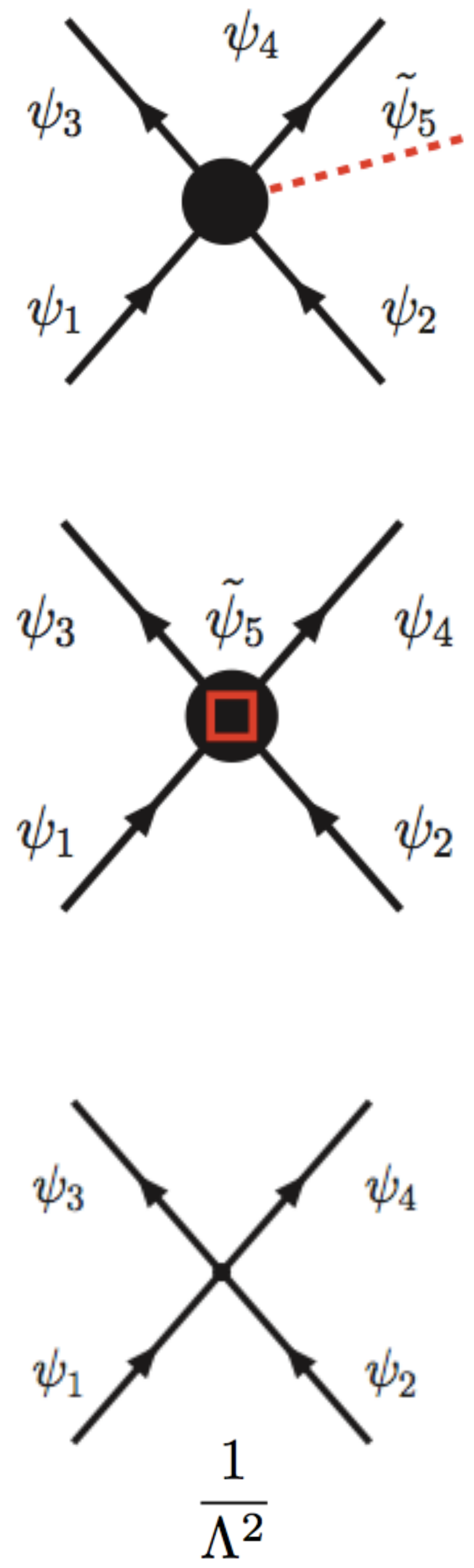


Crivellin, Davidson, Pruna, Signer, JHEP 05 117 (2017)

CLFV searches with muons: Status and prospects

- In the near future impressive sensitivities via the so called “golden” muon channels
- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV
- **Probing energy scale otherwise unreachable at the energy frontiers**





Energy frontier

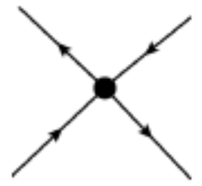
Precision and intensity frontier

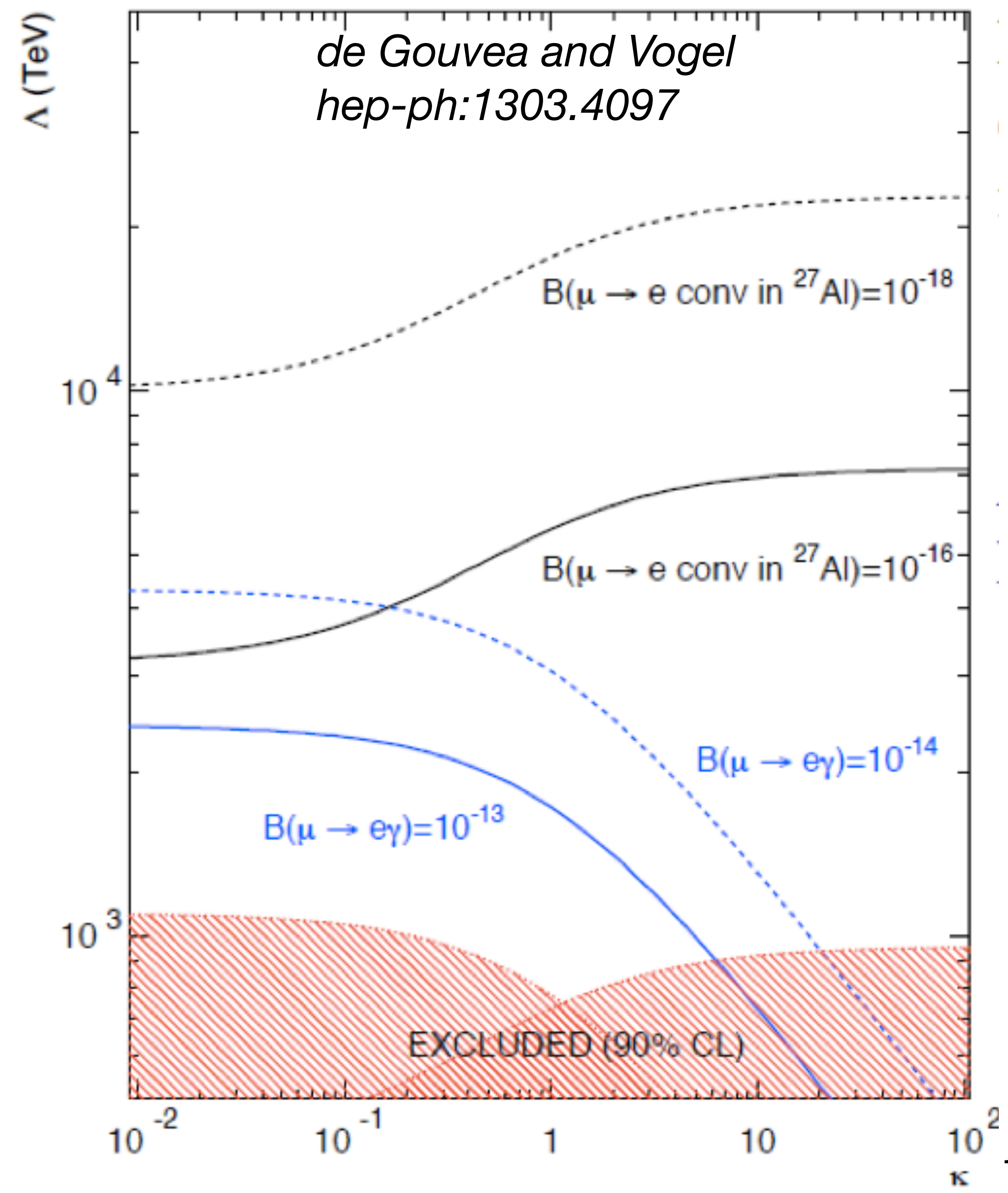
Probe energy scale otherwise unreachable

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

E > 1000 TeV

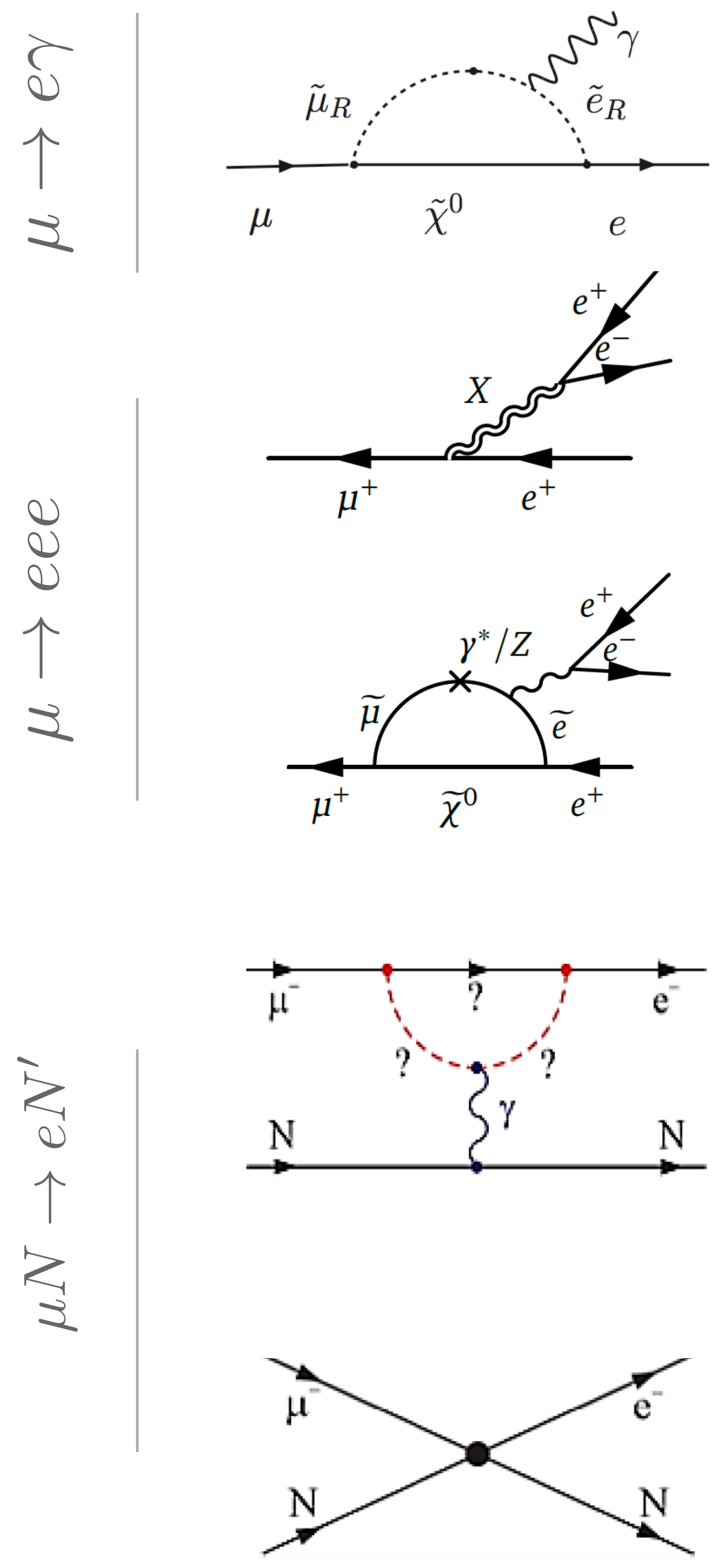
Model independent lagrangian

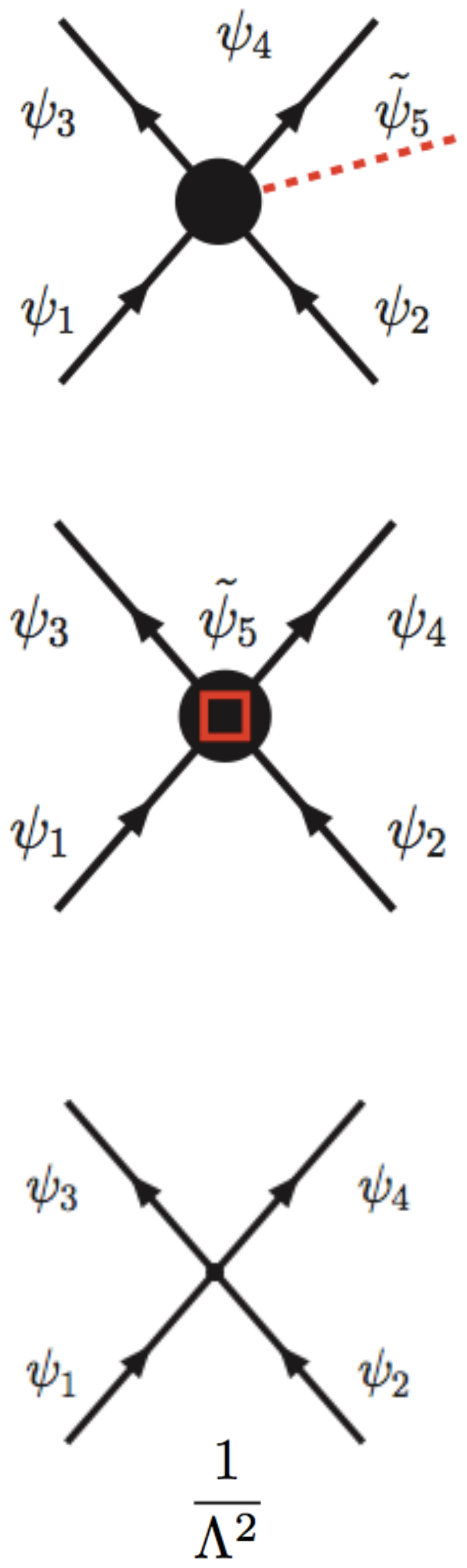
$\frac{m_\mu}{(\kappa+1)\Lambda^2} \times$  +	$\frac{\kappa}{(\kappa+1)\Lambda^2} \times$ 
dipole term	contact term
$\mu \to e\gamma$	
$\mu \to eee$	
$\mu N \to eN$	



CLFV searches with muons: Status and prospects

- In the near future impressive sensitivities via the so called "golden" muon channels
- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV
- Probing energy scale otherwise unreachable at the energy frontiers
- **Note: τ ideal probe for NP w. r. t. μ (Smaller GIM suppression, stronger coupling, many decays). μ most sensitive probe due to huge statistics (= muon campus)**





Energy frontier

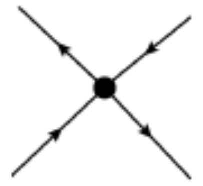
Precision and intensity frontier

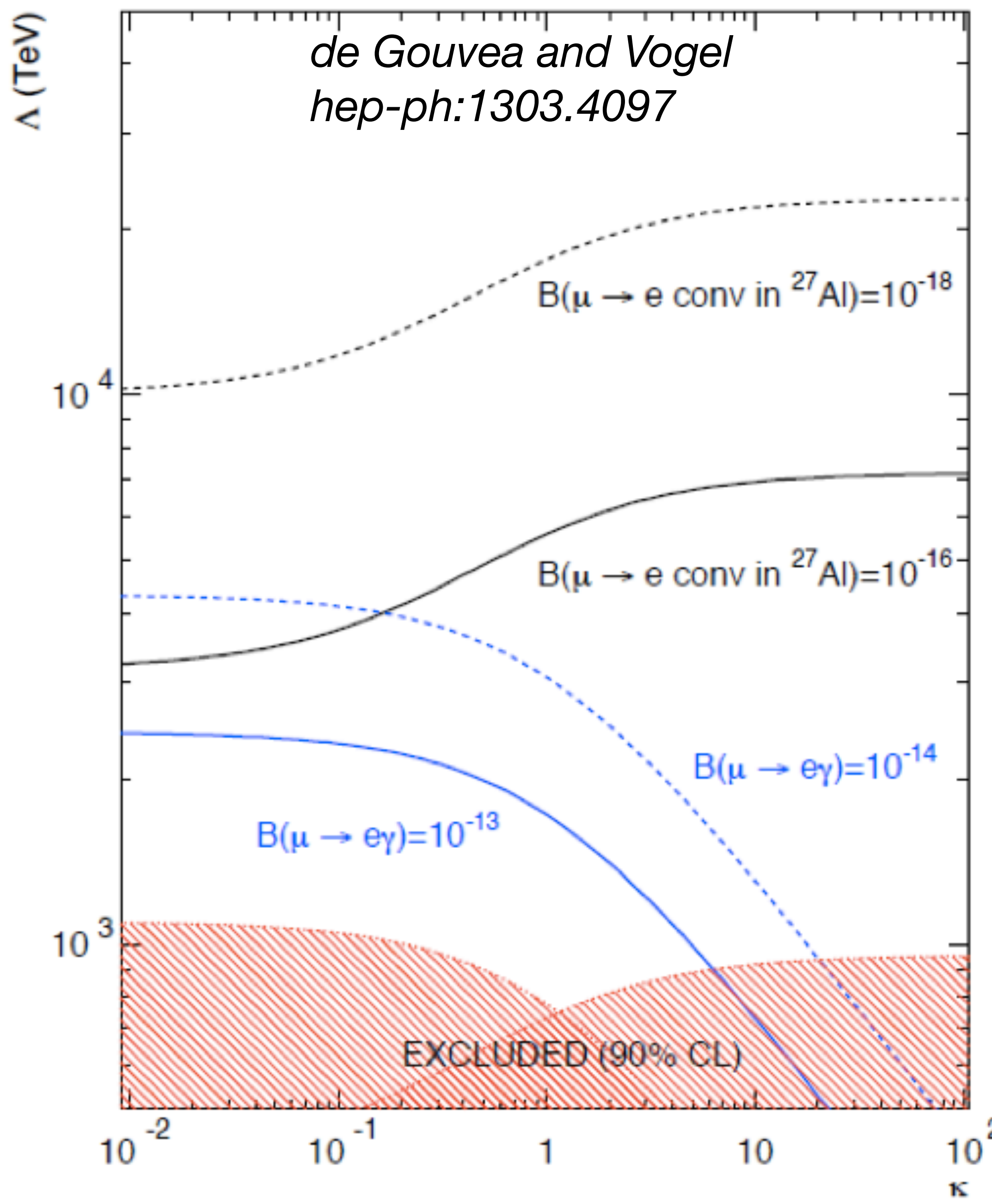
Probe energy scale otherwise unreachable

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

E > 1000 TeV

Model independent lagrangian

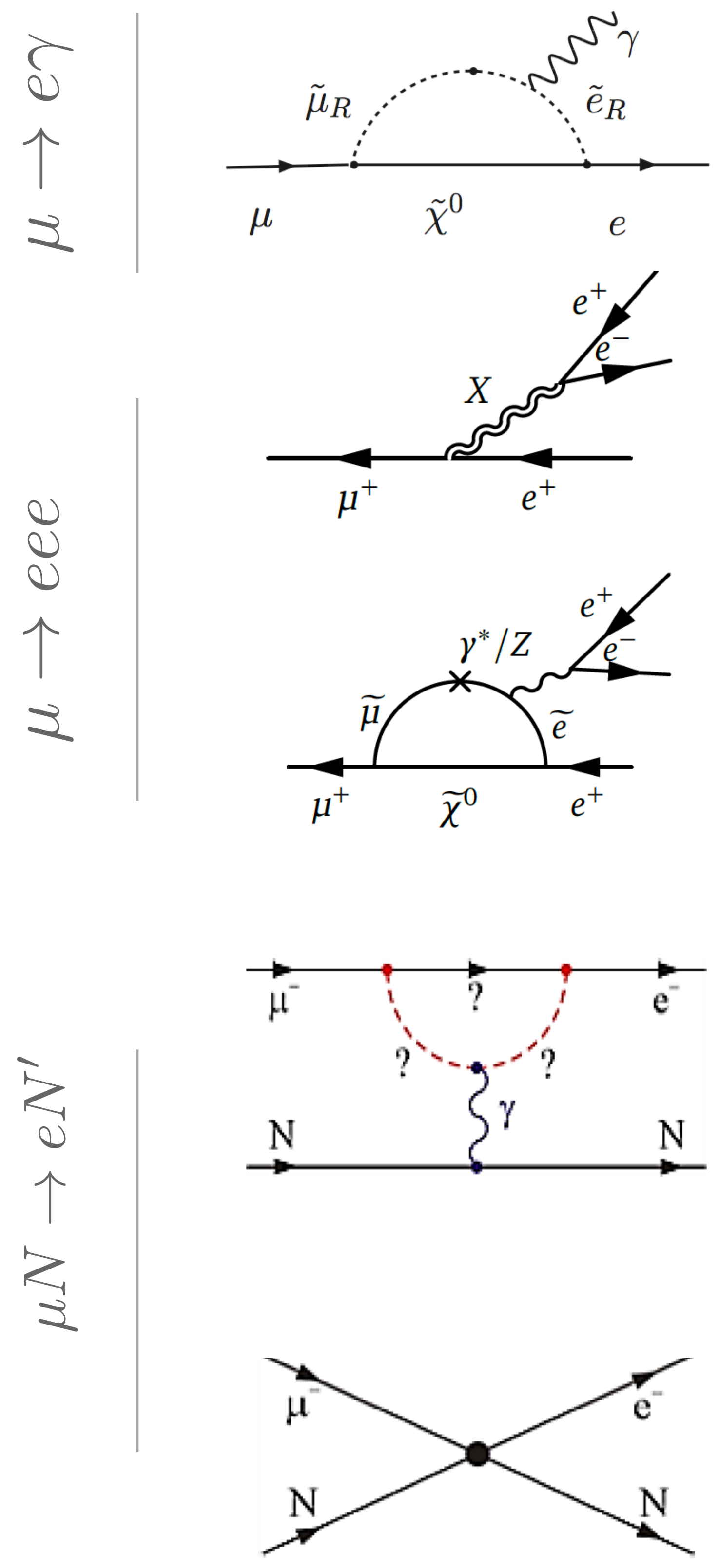
$\frac{m_\mu}{(\kappa+1)\Lambda^2} \times$  dipole term	$+ \frac{\kappa}{(\kappa+1)\Lambda^2} \times$  contact term
$\mu \to e\gamma$	
$\mu \to eee$	
$\mu N \to eN$	

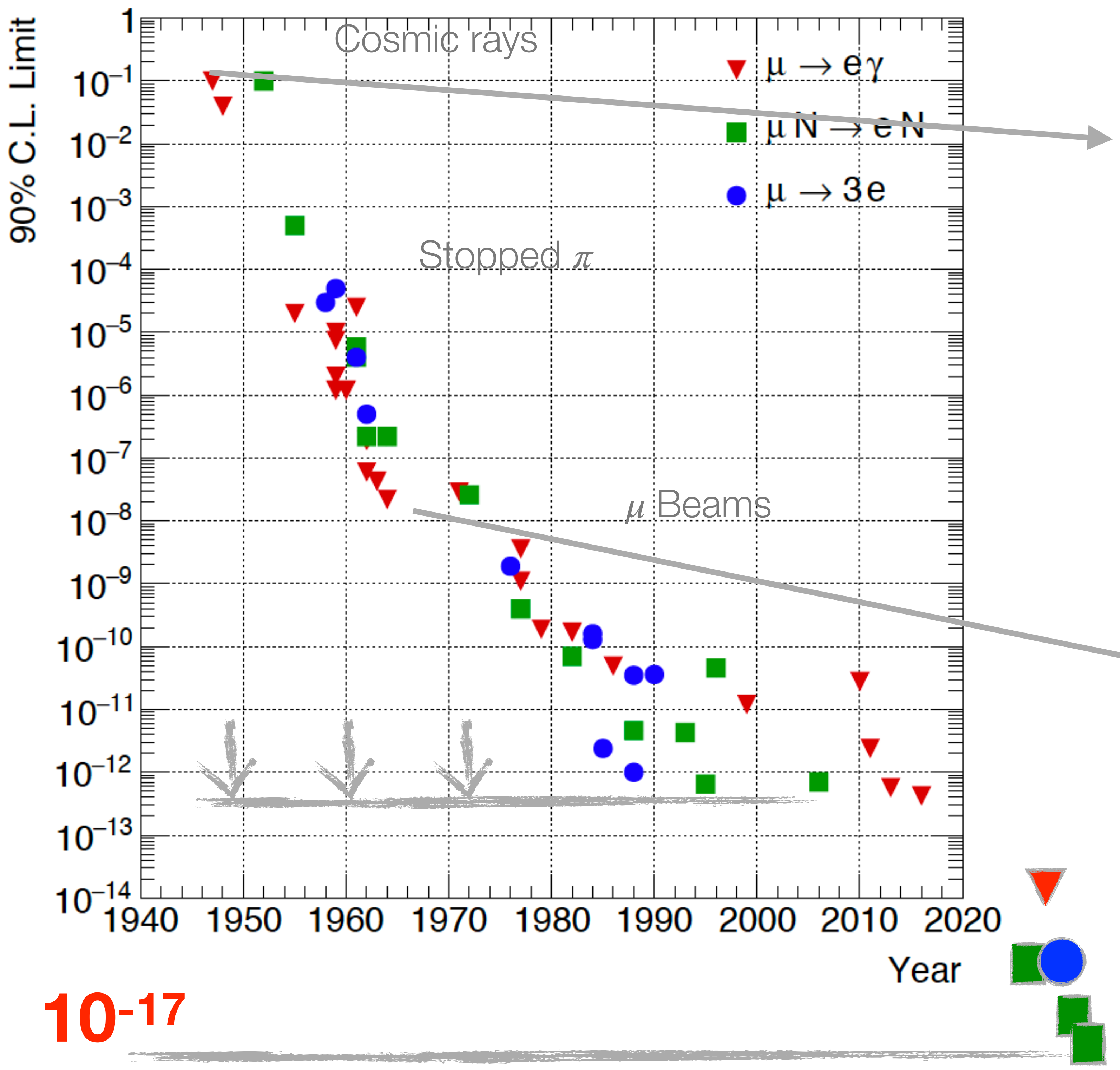


CLFV searches with muons: Status and prospects

- In the near future impressive sensitivities via the so called “golden” muon channels

	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}





$\mu \neq e^*$

$\nu_\mu \neq \nu_e$

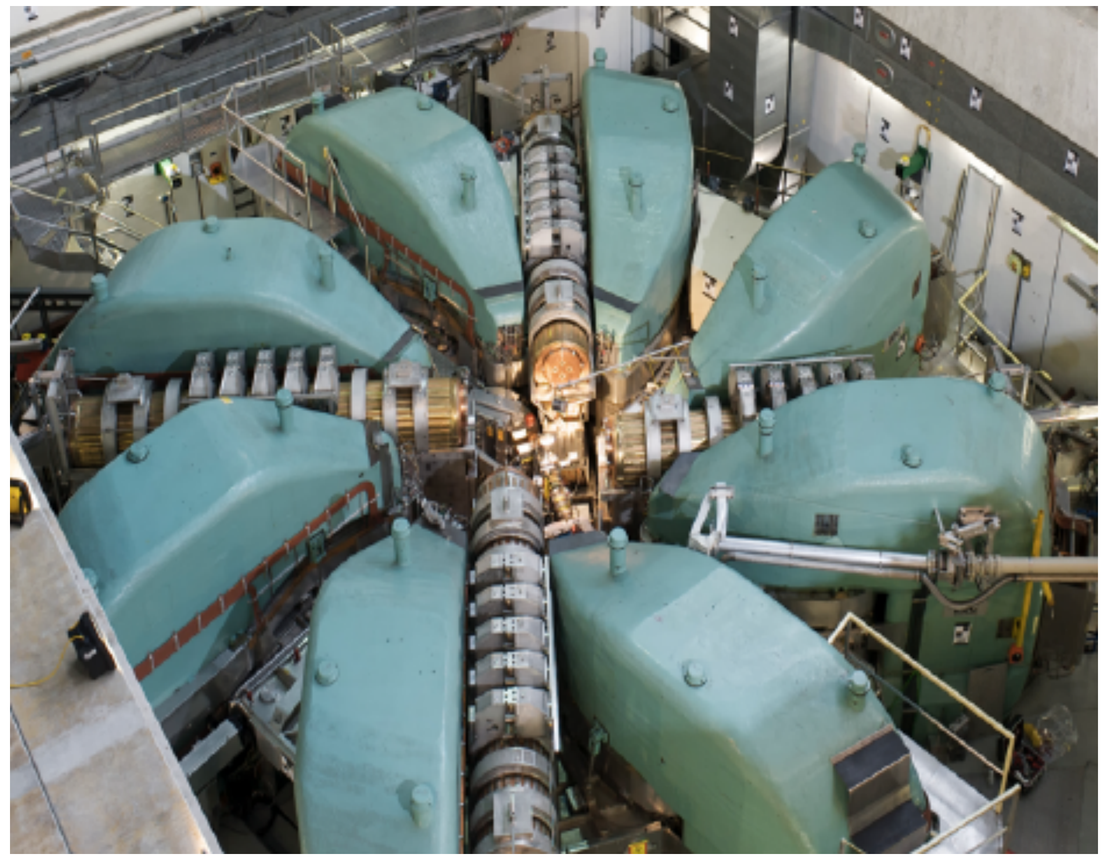
1947:
Pontecorvo and
Hincks

1962:
Lederman, Schwartz, and Steinberger
1988 Nobel

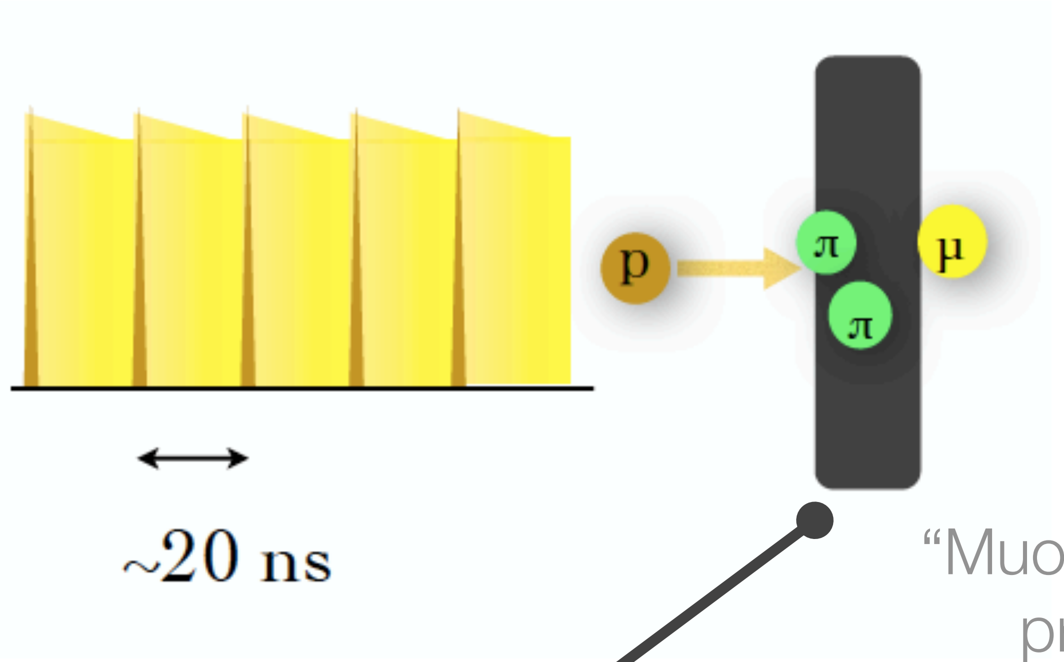
In the near future O(5-10) years:
Impressive sensitivity

PSI’s muon beams

- PSI delivers the most intense continuous (DC) low momentum (surface) muon beam in the world up to few x 10^8 mu/s (28 MeV/c, polarised beam (**Intensity Frontiers**)

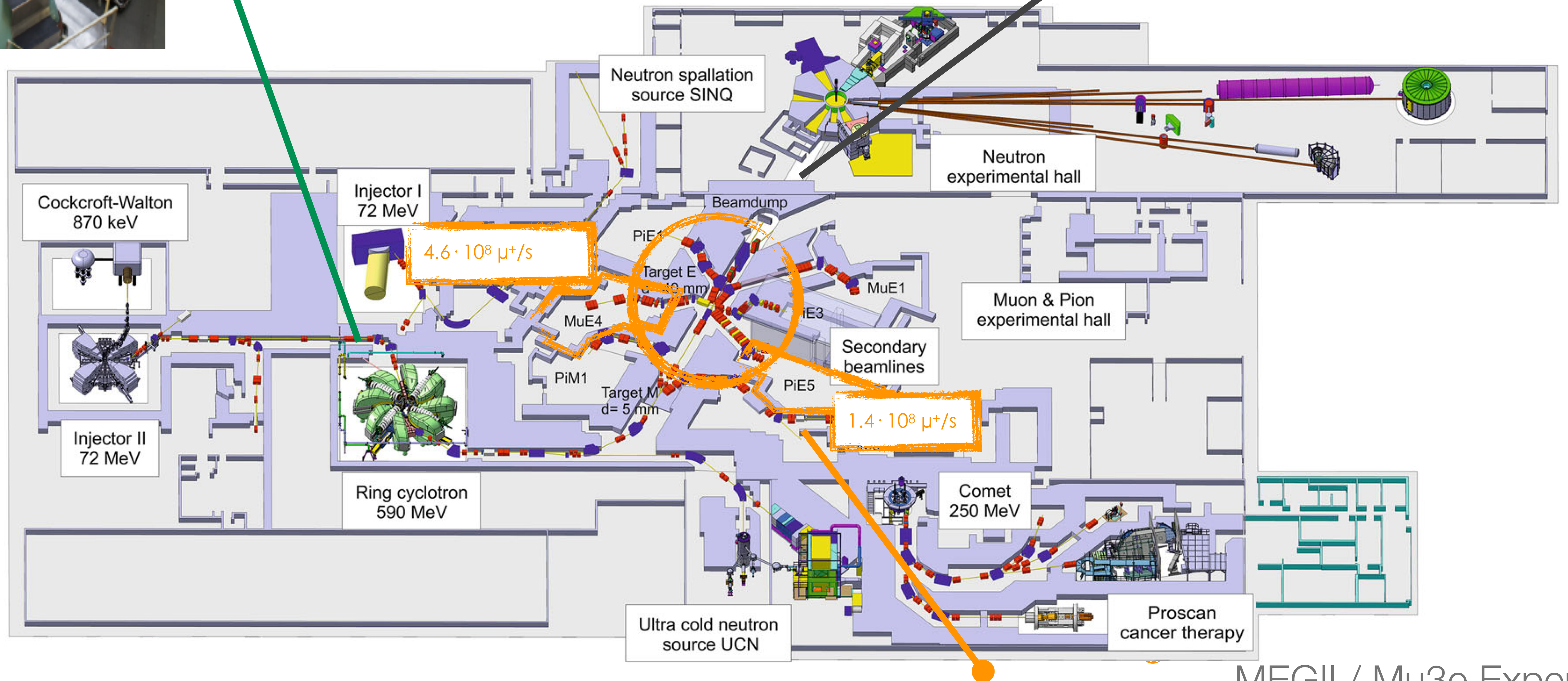


590 MeV proton
ring cyclotron
1.4 MW



Proton RF ~ 50 MHz
“DC” muon beam

“Muon” Target “E”
production

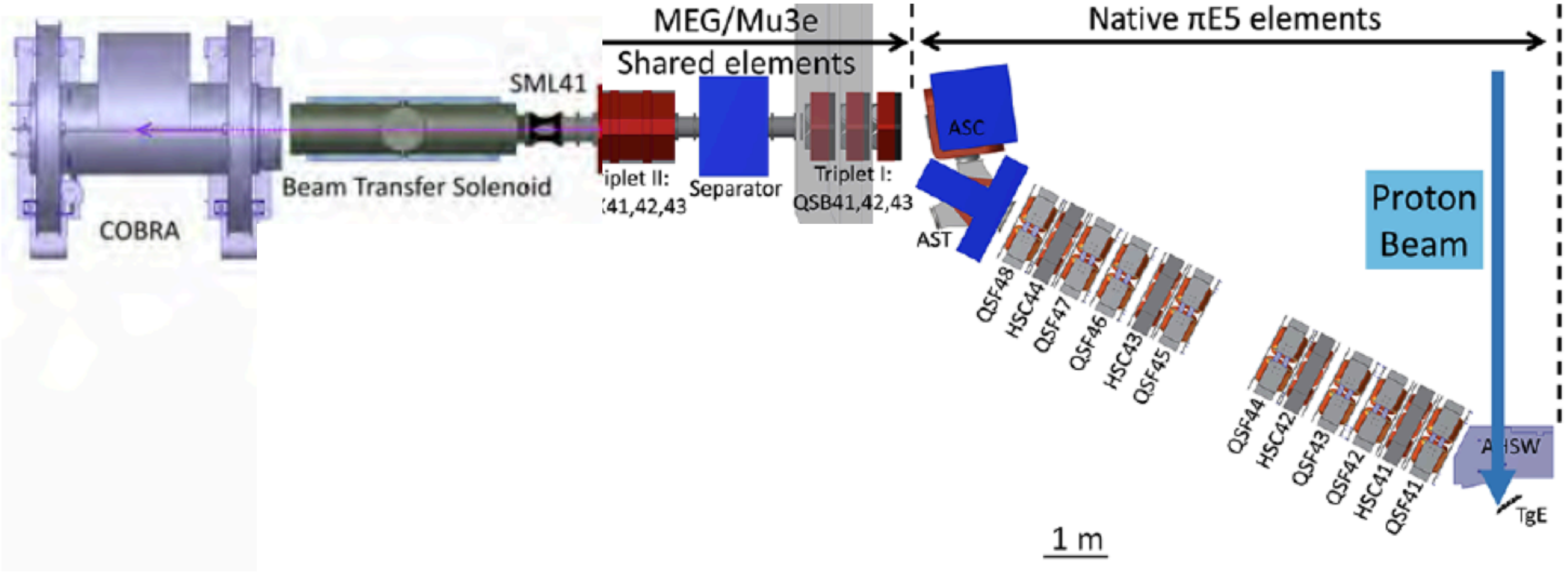


MEGII / Mu3e Experimental area

The MEGII and Mu3e beam lines

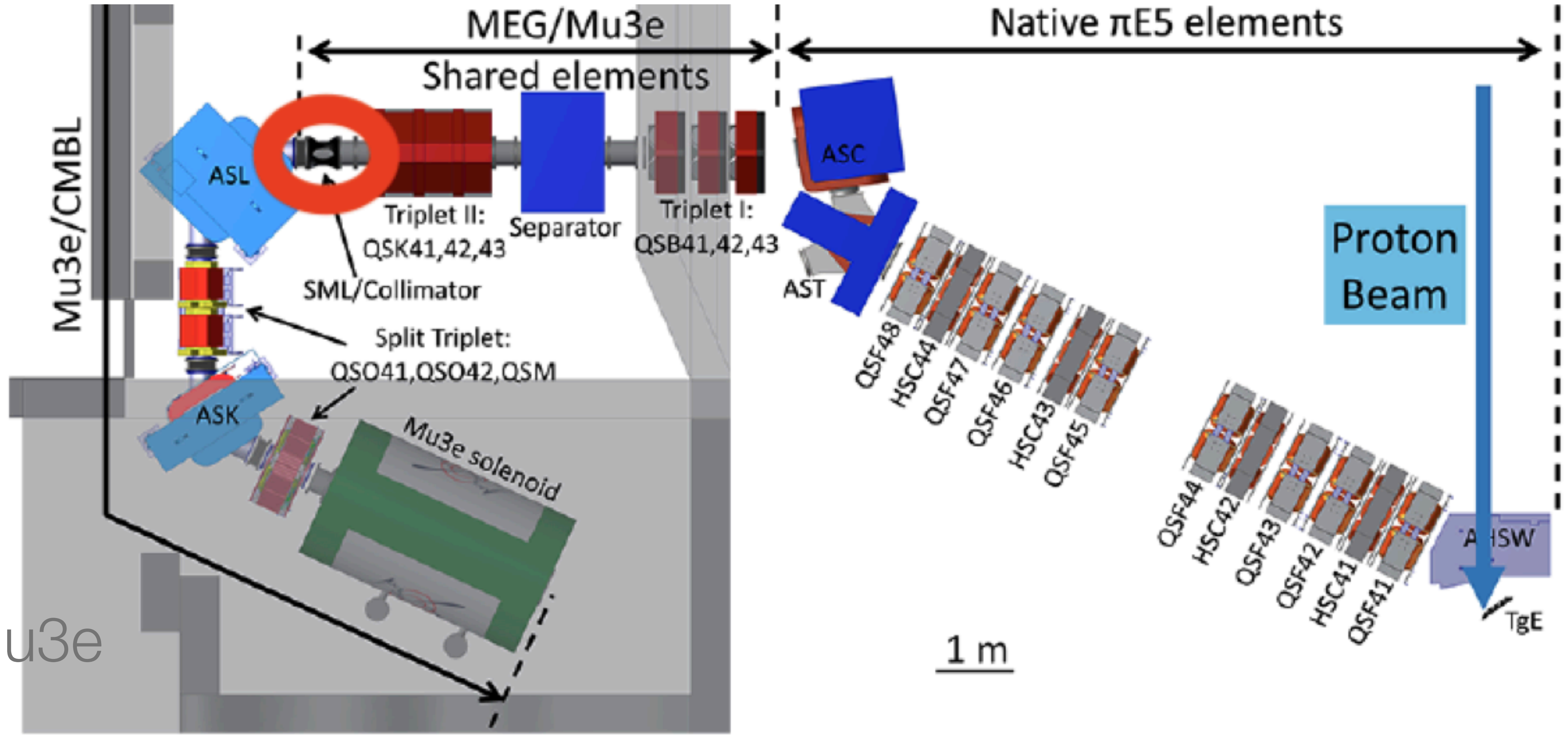
- MEGII and Mu3e (phase I) similar beam requirements:
  - **Intensity O(10^8 muon/s), low momentum p = 28 MeV/c**
  - **Small straggling and good identification of the decay region**
- MEG II beam settings released since 2019. More then 10^8 mu/s can be transport into Cobra (up to 1.6e8@2.2 mA during 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 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)

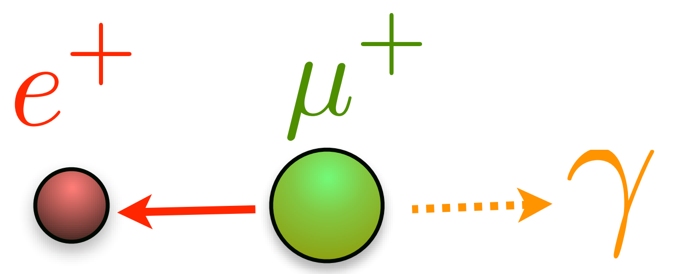


The Mu3e

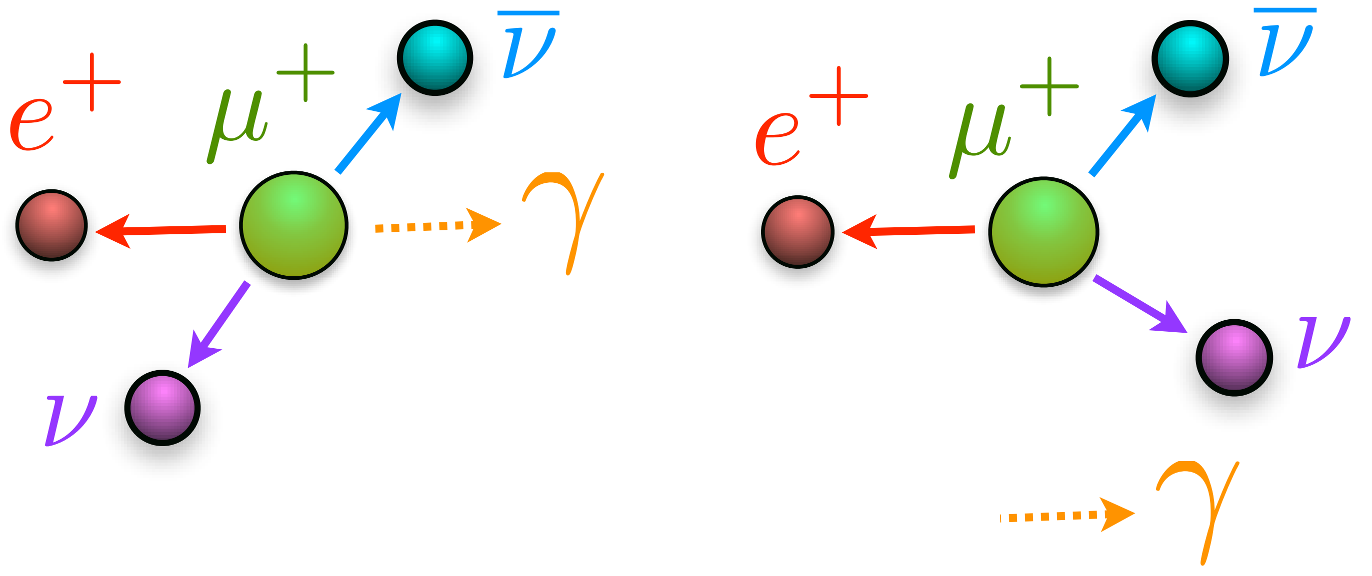
The MEGII experiment at PSI

- Best upper limit on the BR ($\mu^+ \rightarrow e^+ \gamma$) set by the MEG experiment (**$4.2\ 10^{-13}$** @90% C.L.)
- Searching for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~ **$6\ 10^{-14}$**
- Five observables **(E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg})** to identify $\mu^+ \rightarrow e^+ \gamma$ events

Signature



Backgrounds



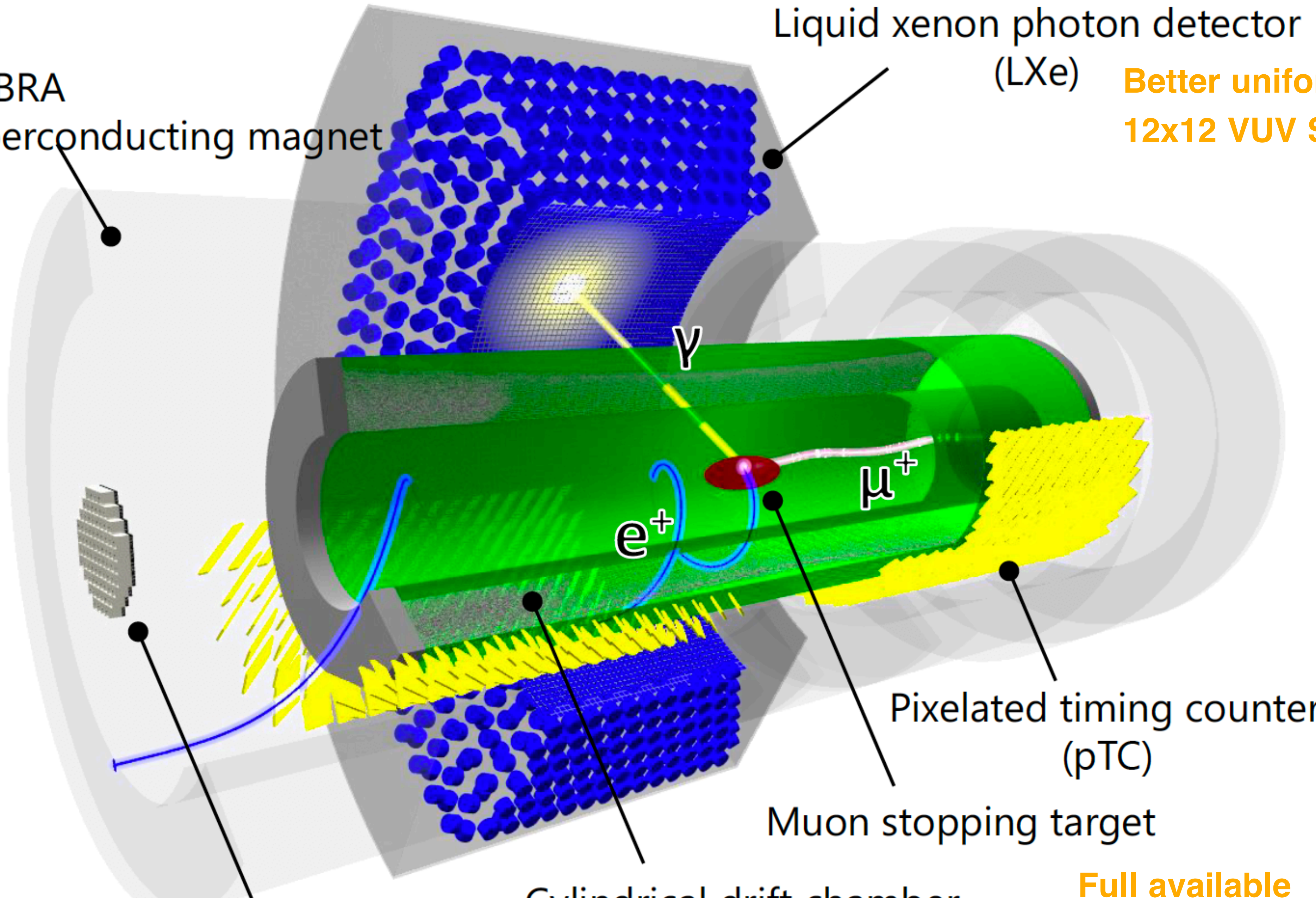
New electronics: Wavedream

~9000 channels at 5GSPS

x2 Resolution everywhere

Updated and new Calibration methods

Quasi mono-chromatic positron beam



Better uniformity w/ 12x12 VUV SiPM

x2 Beam Intensity

35 ps resolution w/ multiple hits

Full available stopped beam intensity 7×10^7

Single volume $He:iC_4H_{10}$

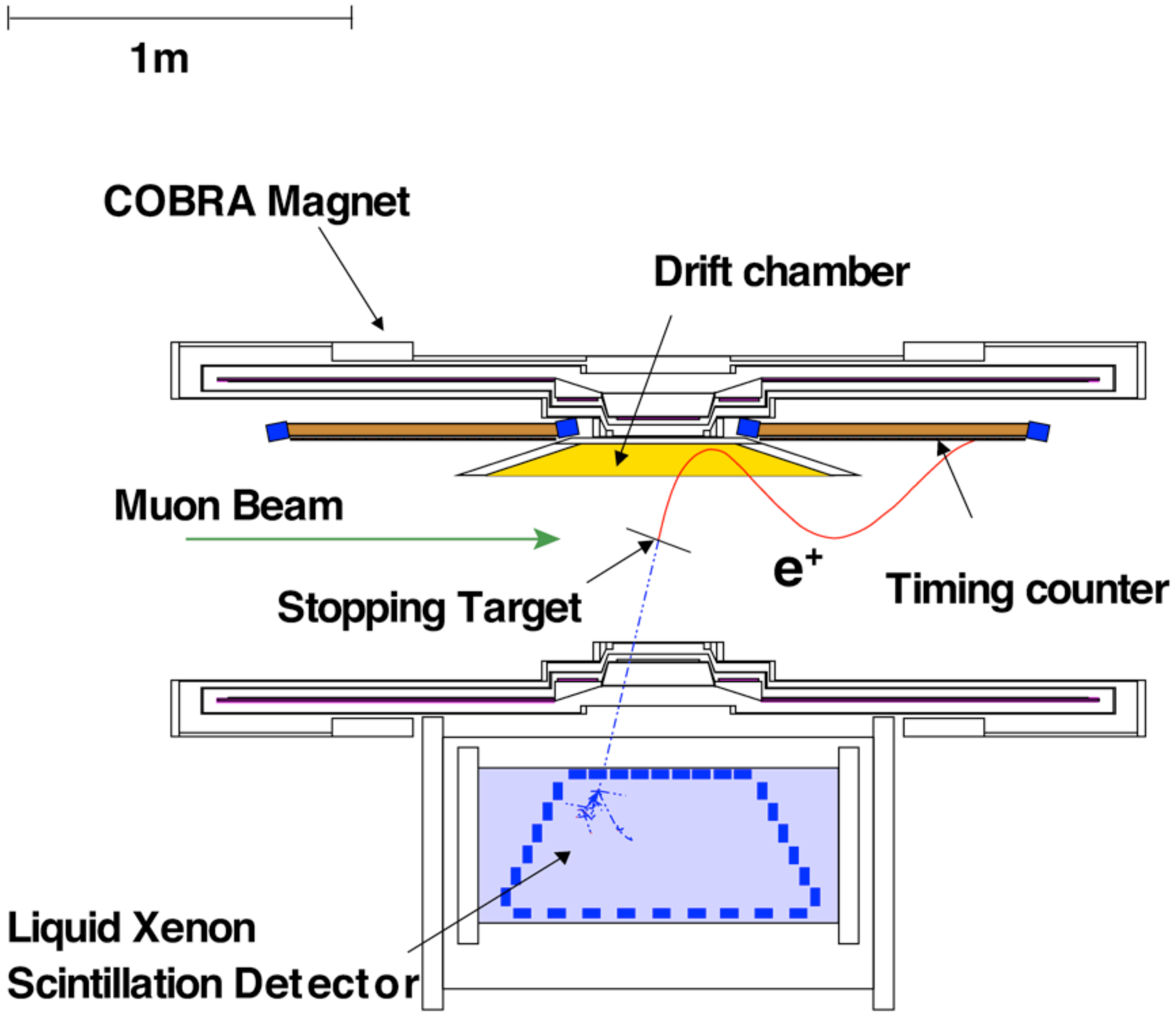
Background rejection

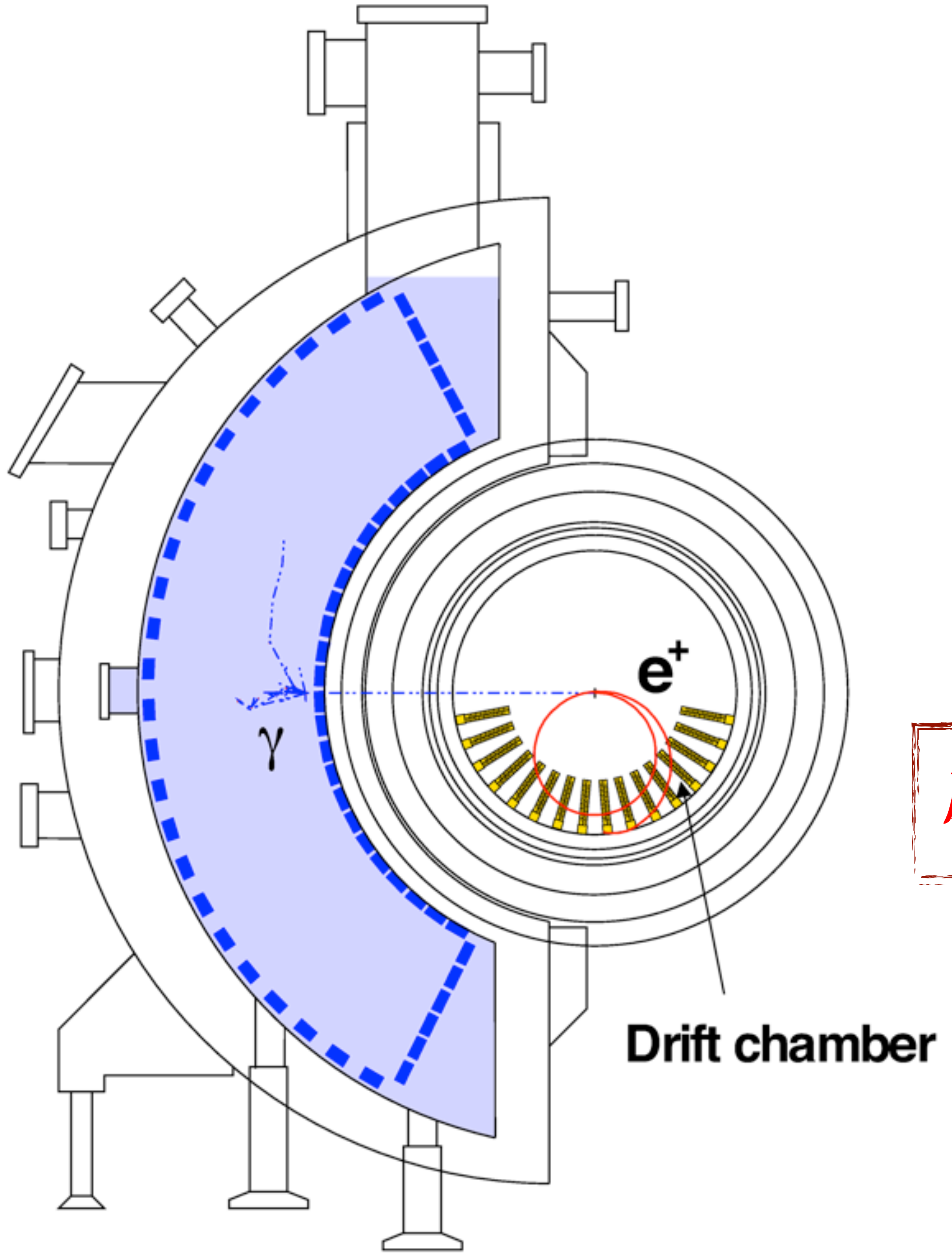
A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C73 (2013) 2365

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

A step back: The MEG experiment

- The MEG experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~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



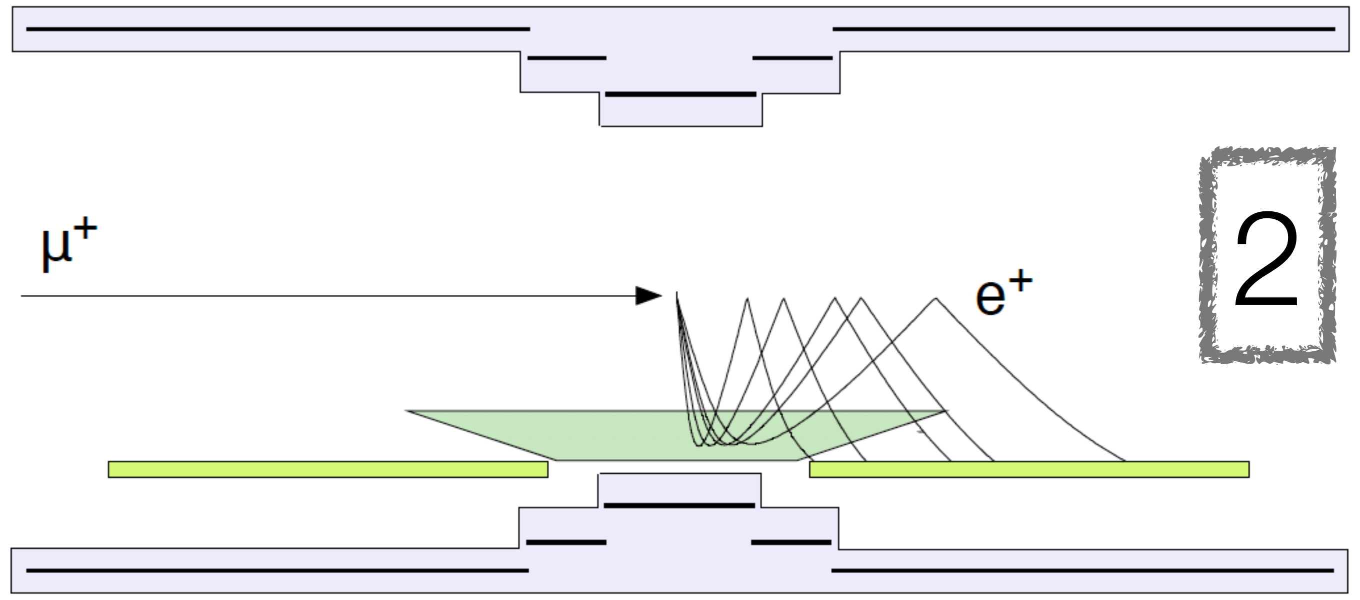


Full data sample:
2009-2013
Best fitted branching ratio
at 90% C.L.:

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

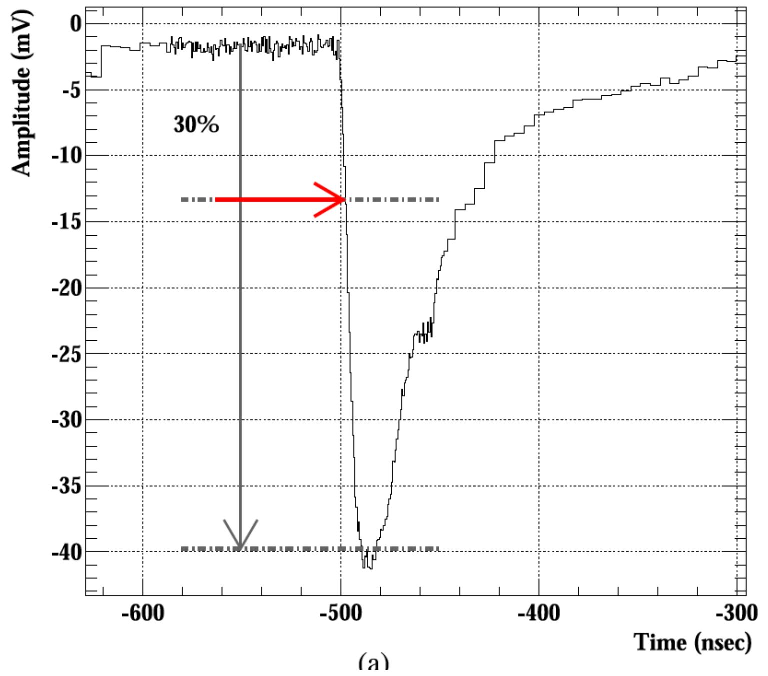
MEG: The key elements

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

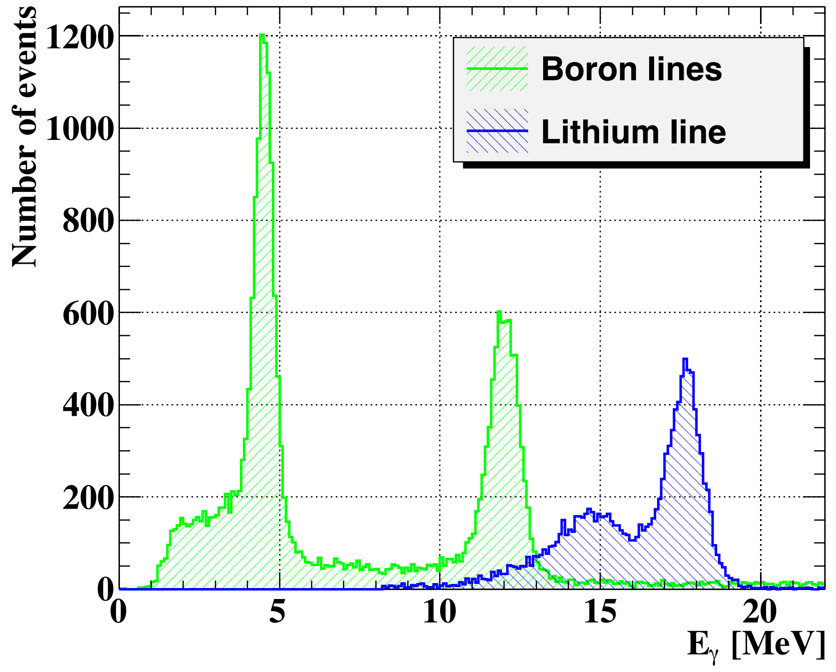


a) Constant projected bending radius for positrons with equal momentum.

2

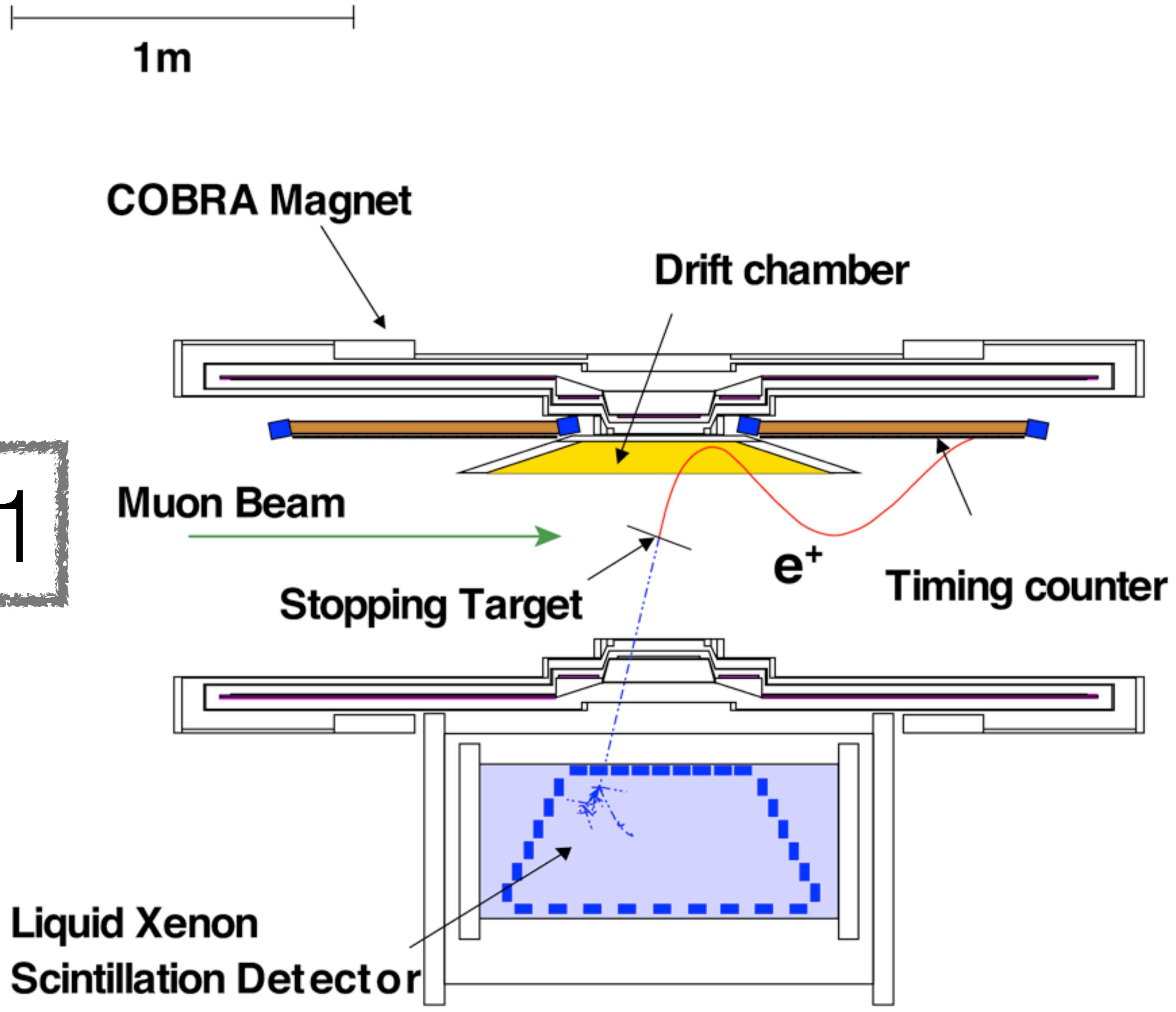


4

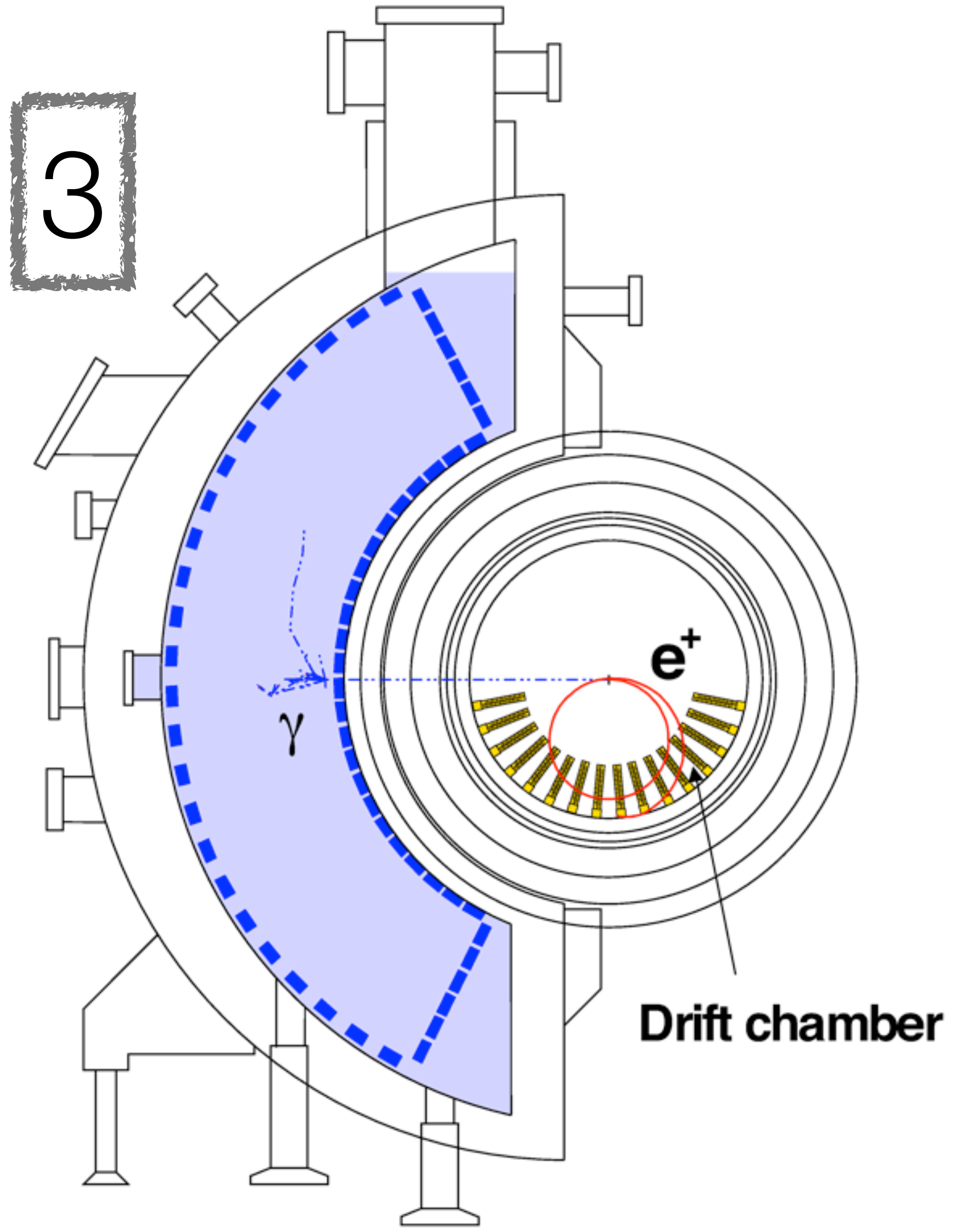


5

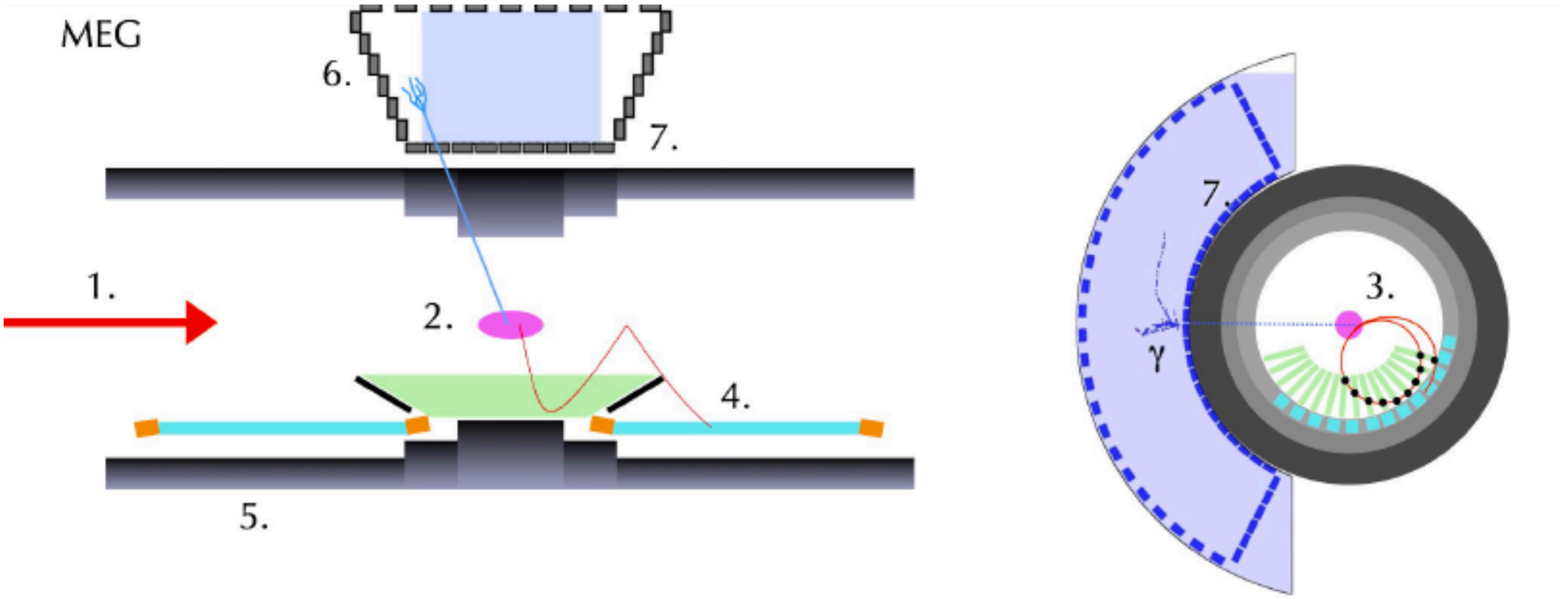
1



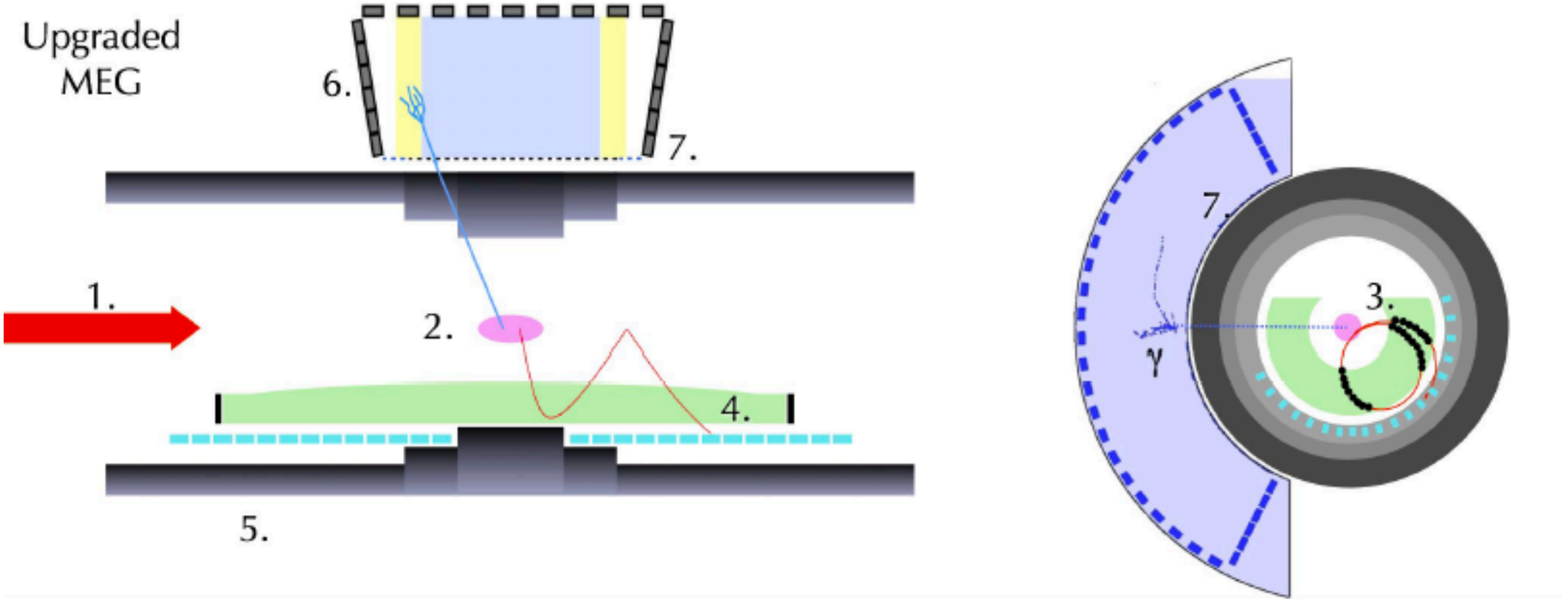
3



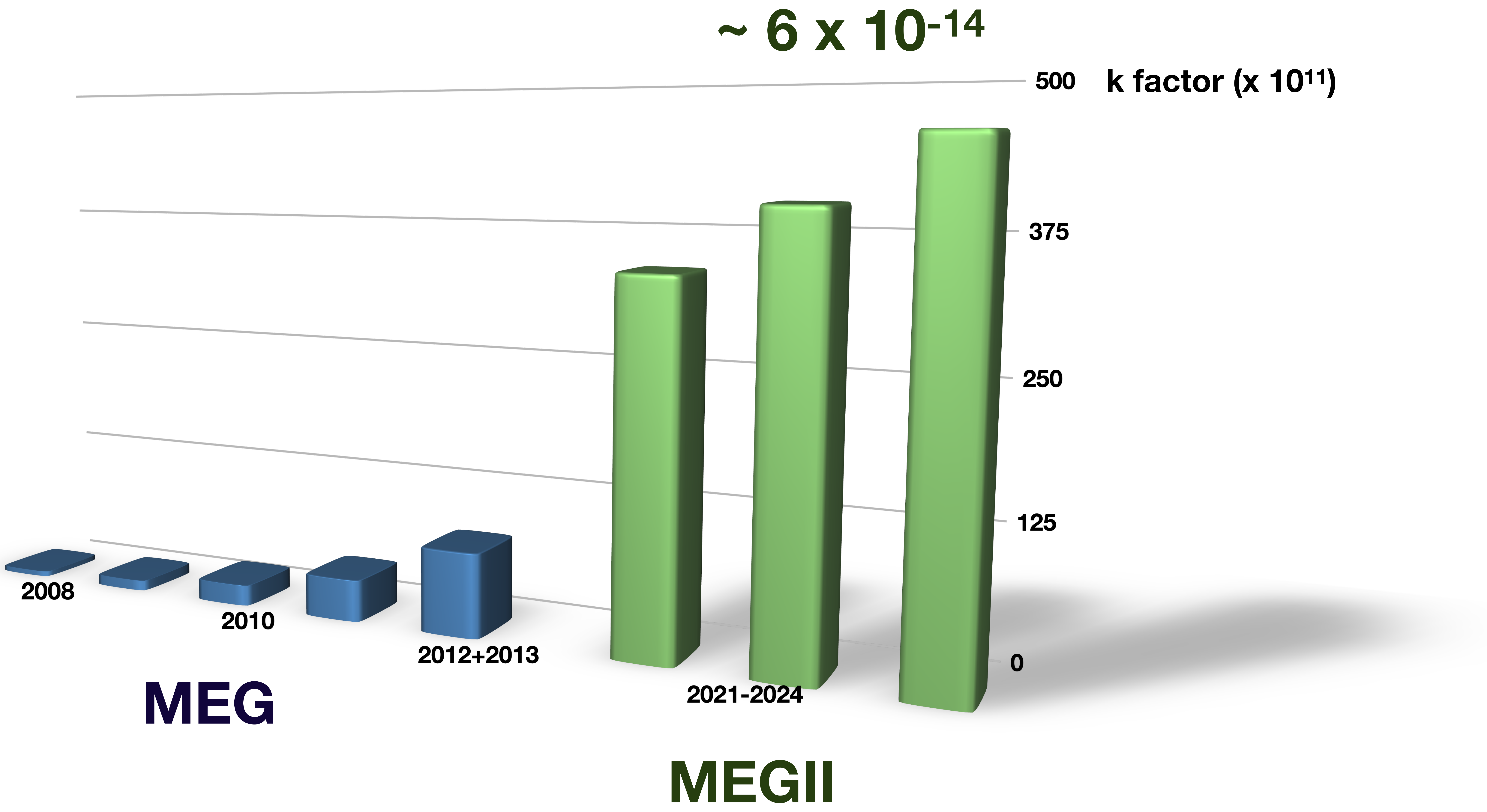
The MEG experiment vs the MEGII experiment



The MEG experiment vs the MEGII experiment



Where we will be

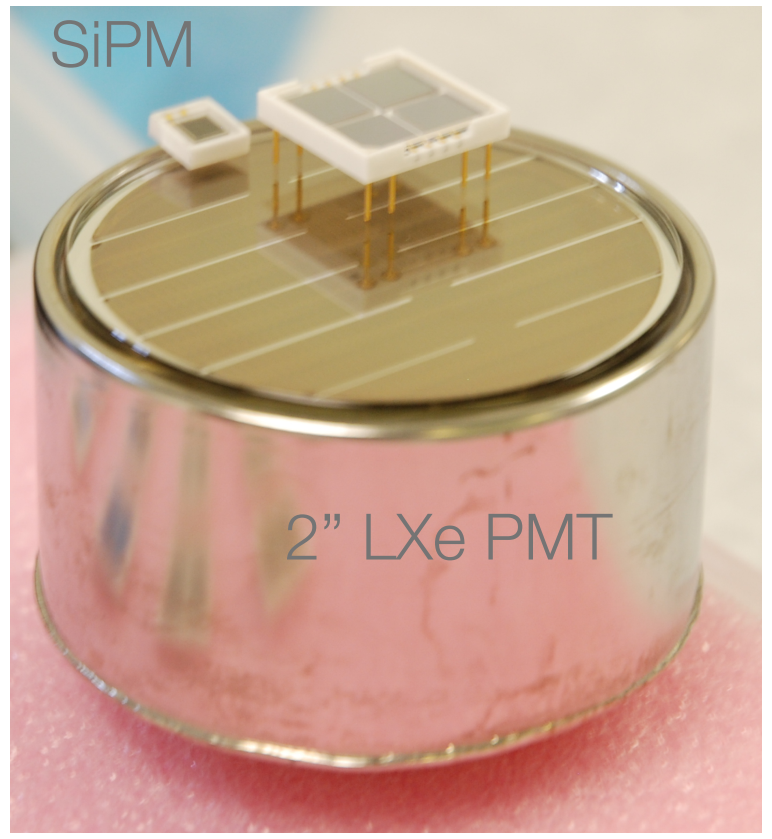


MEGII: The upgraded LXe calorimeter

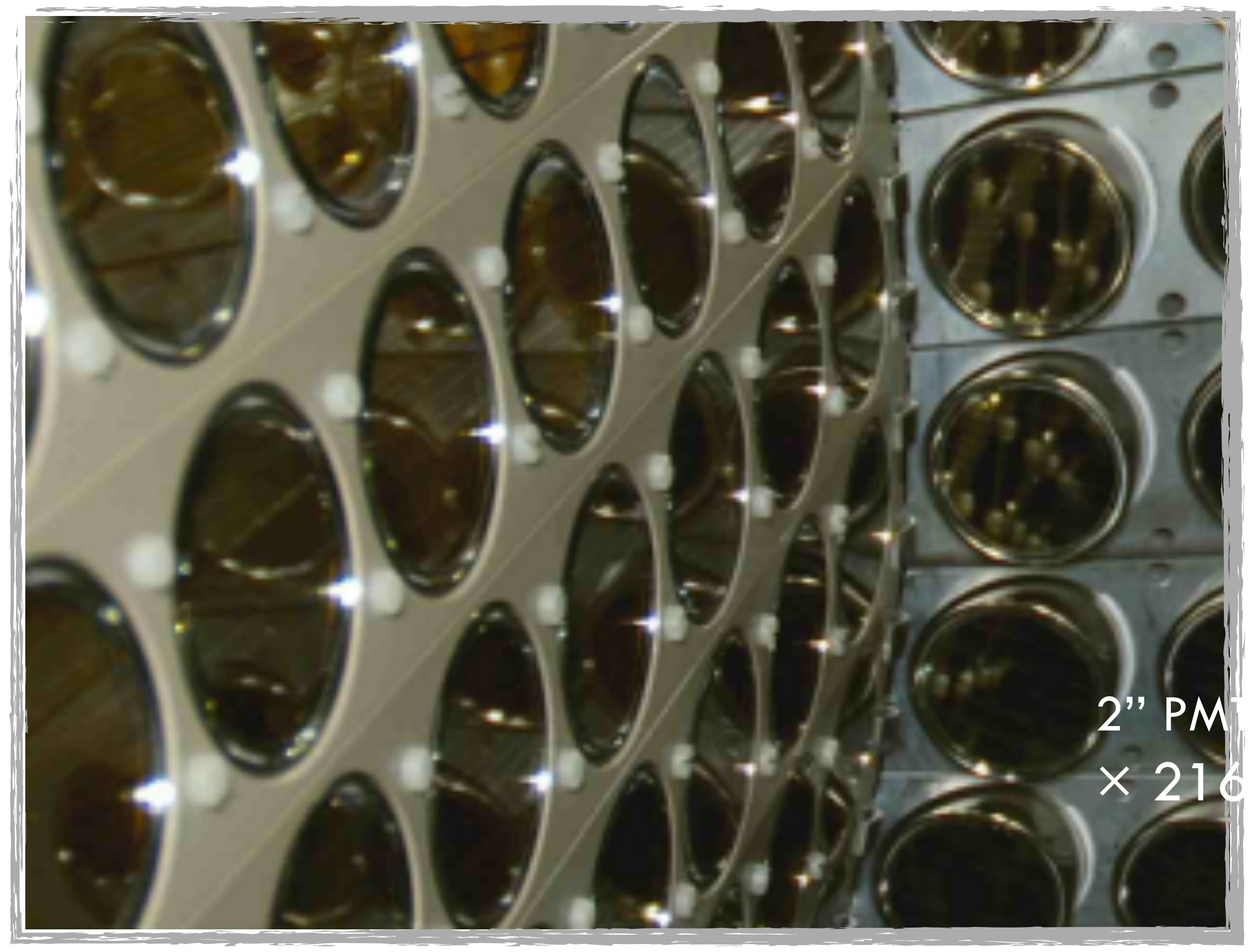
- Increased uniformity/resolutions
- Increased pile-up rejection capability
- Increased acceptance and detection efficiency

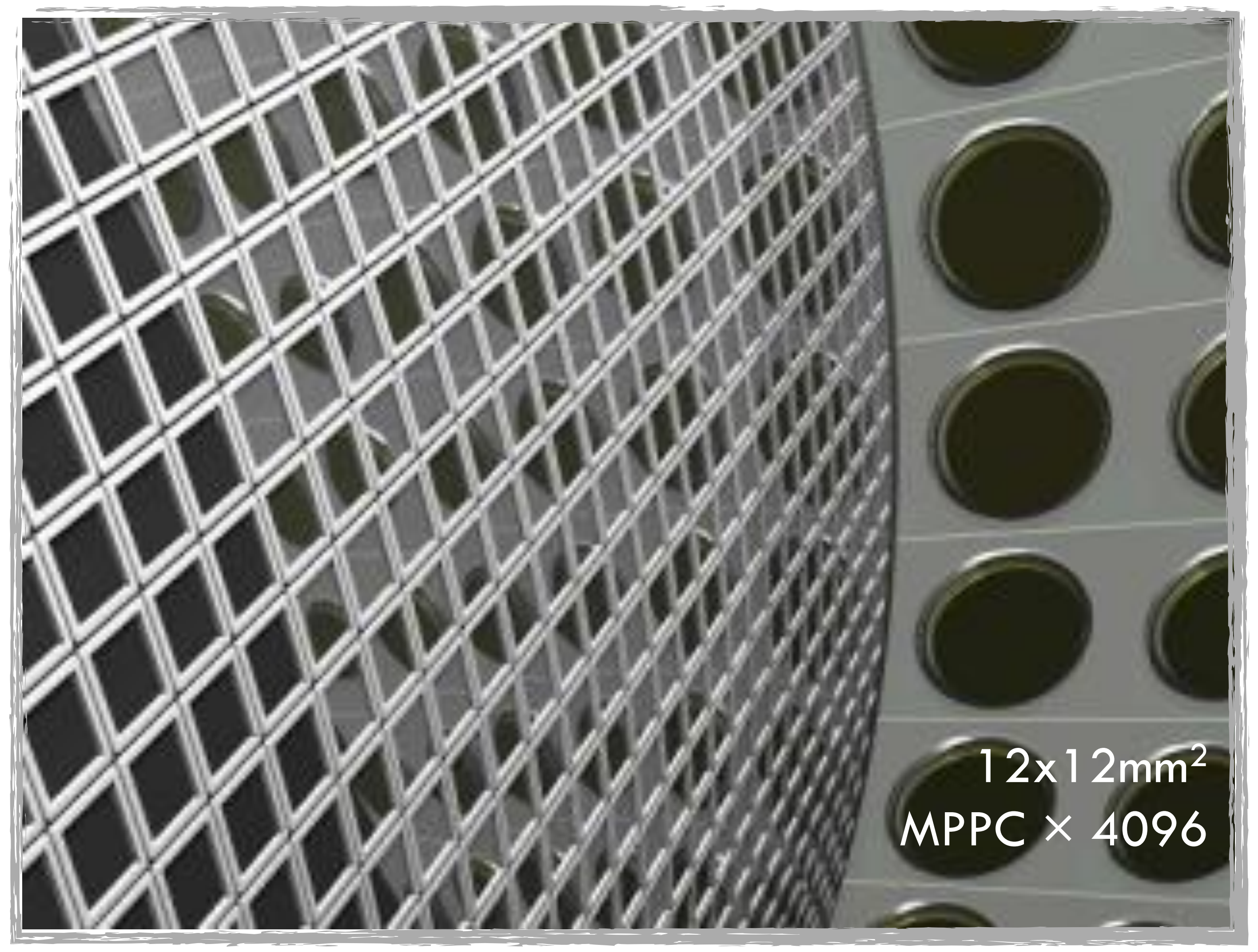
normal

new 12x12 mm^2 LXe SiPM

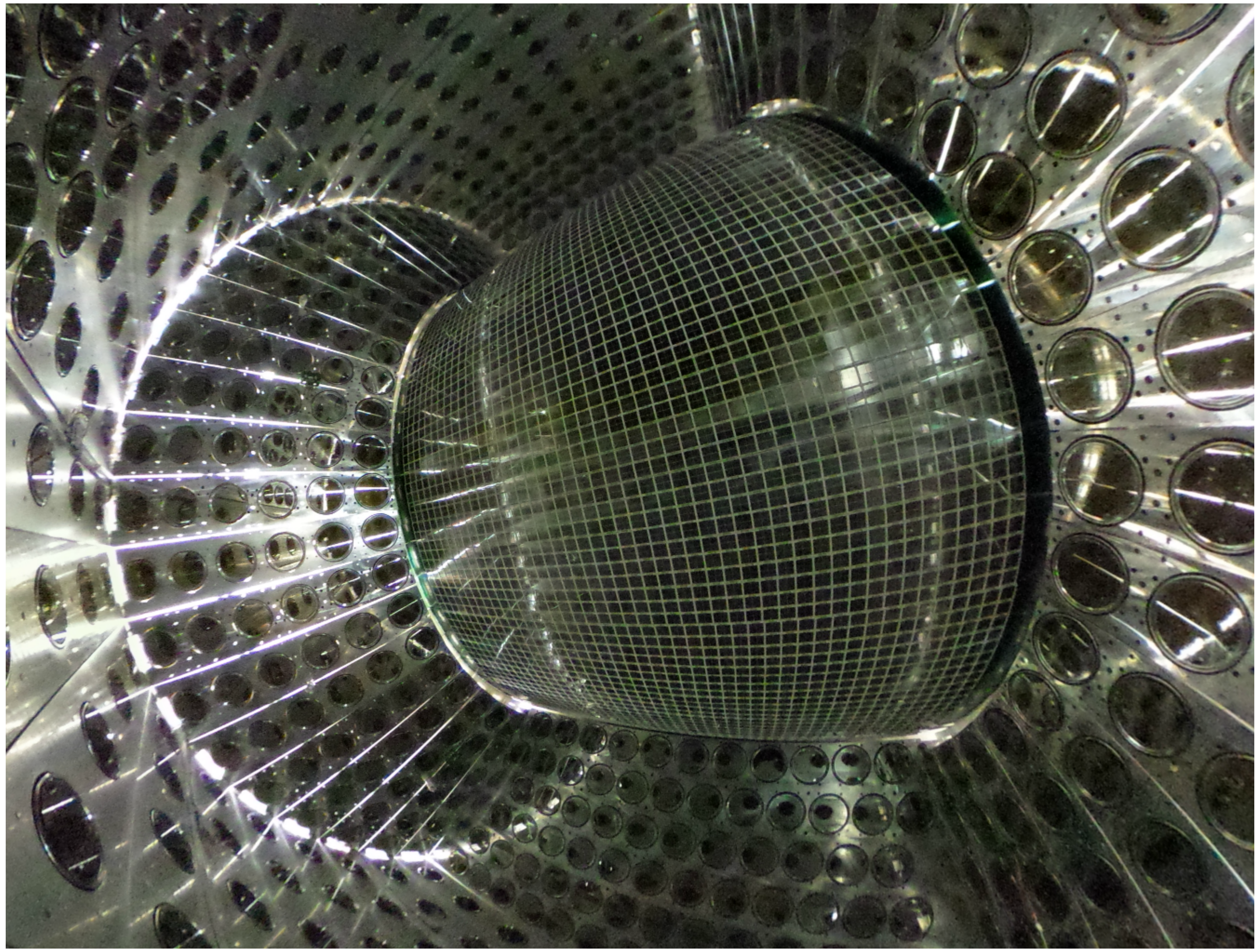


	MEG	MEGII
u [mm]	5	2.4
v [mm]	5	2.2
w [mm]	6	3.1
E [w<2cm]	2.4%	1.1%
E [w>2cm] (w<2cm)m)	1.7%	1.0%
t [ps]	67	60

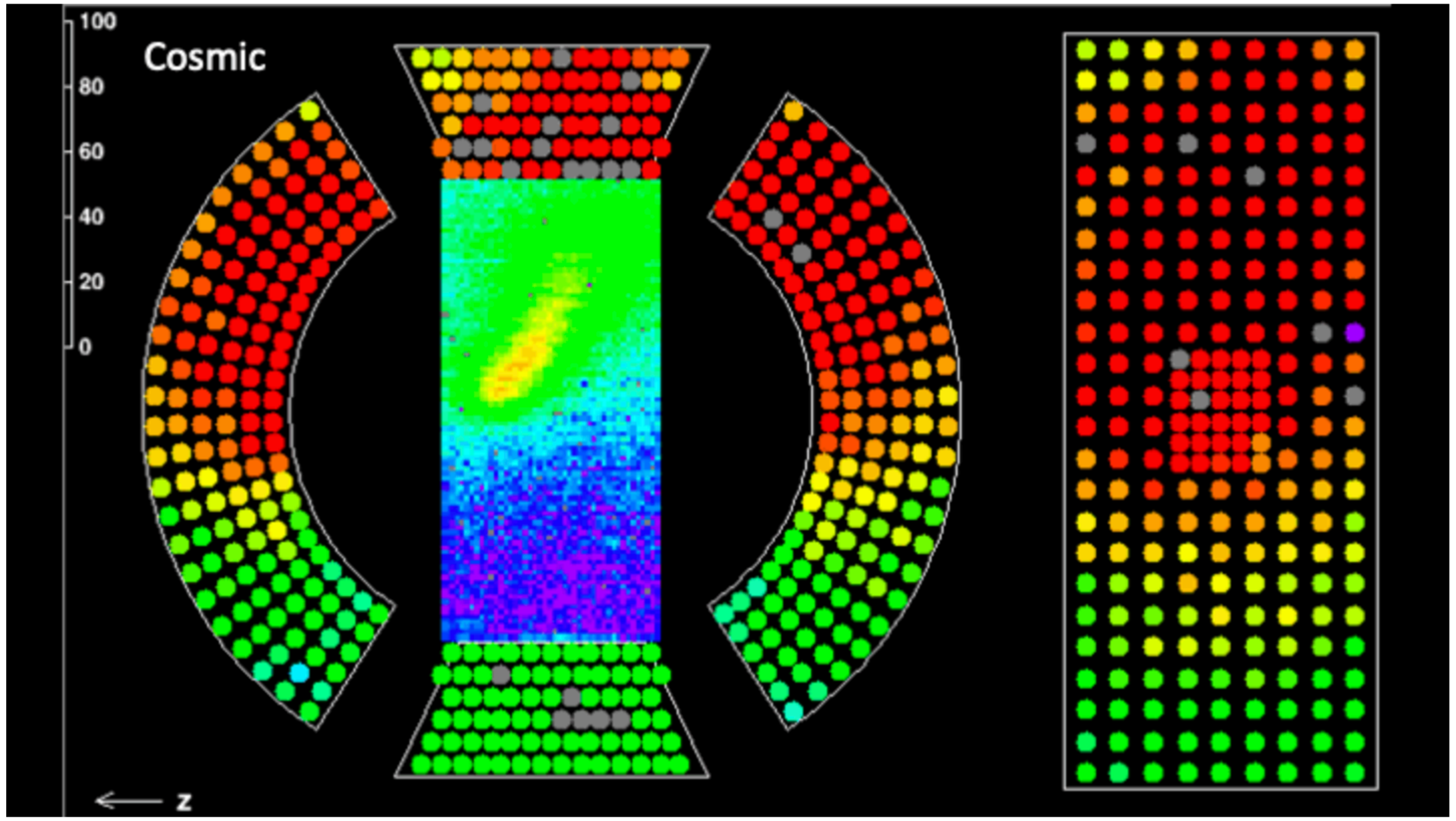


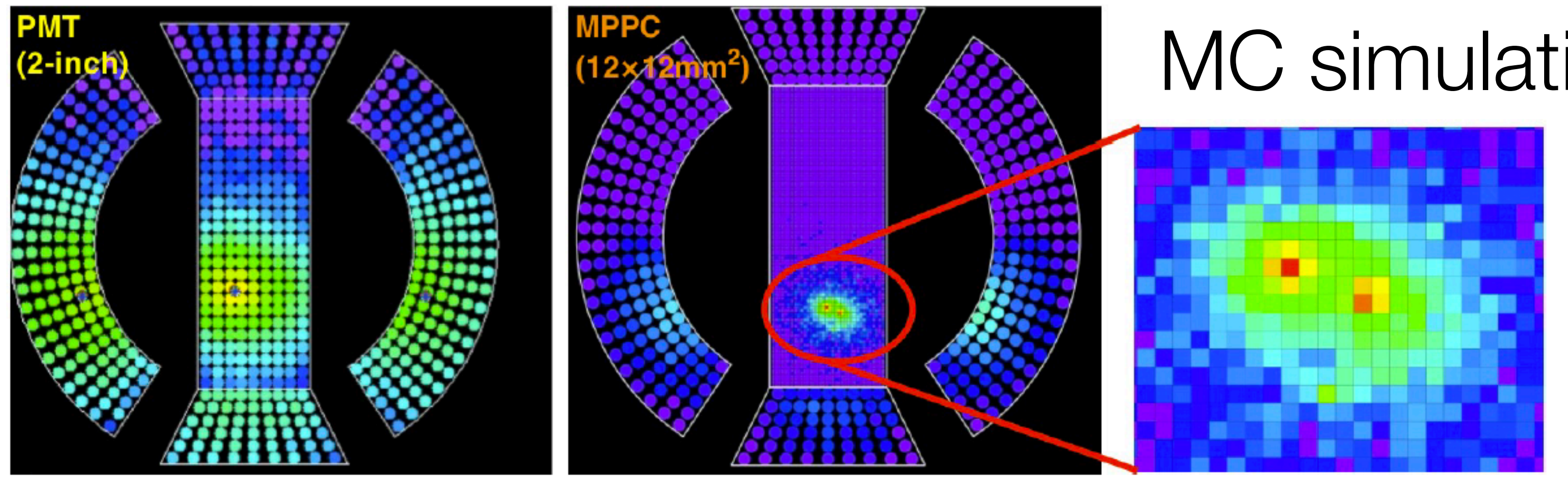


MEGII: The upgraded LXe calorimeter



Data





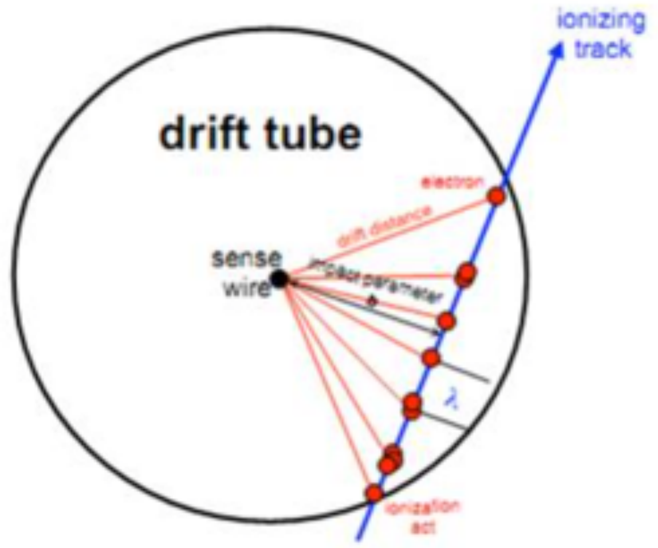
MC simulation

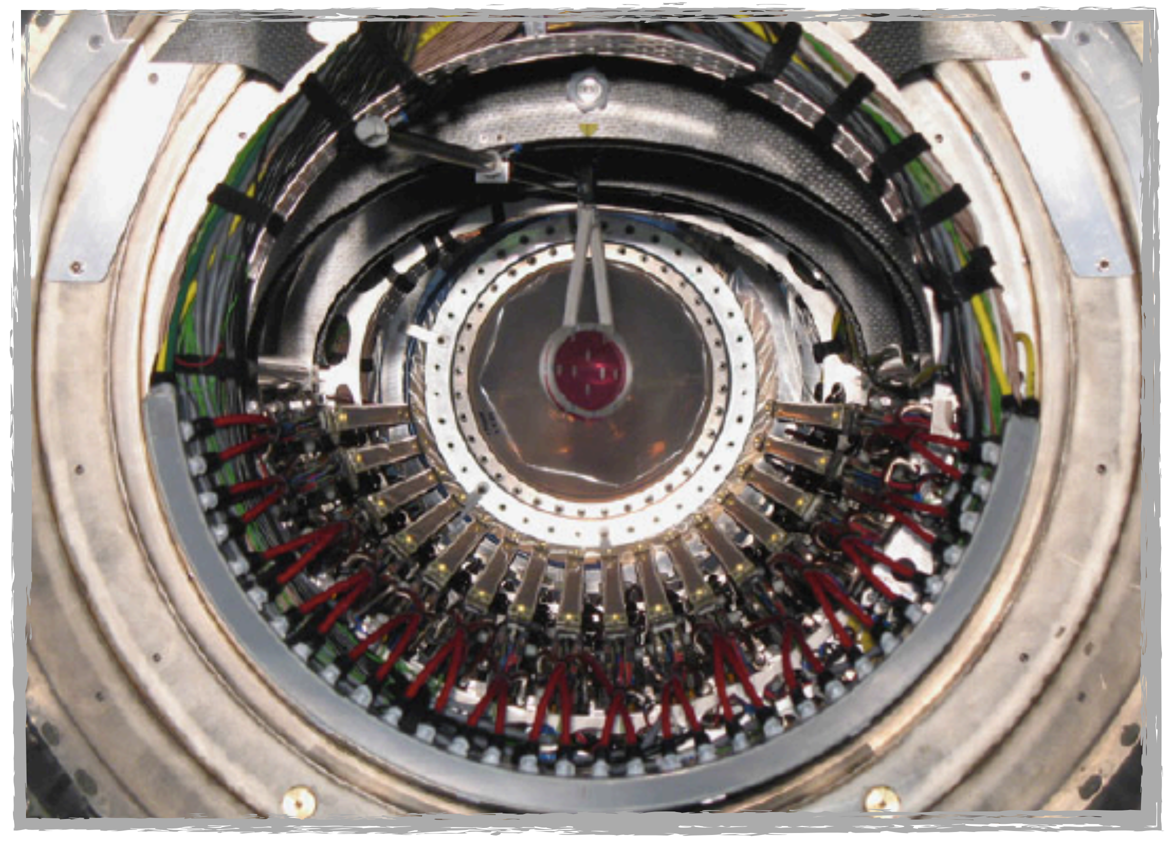
MEGII: The new single volume chamber

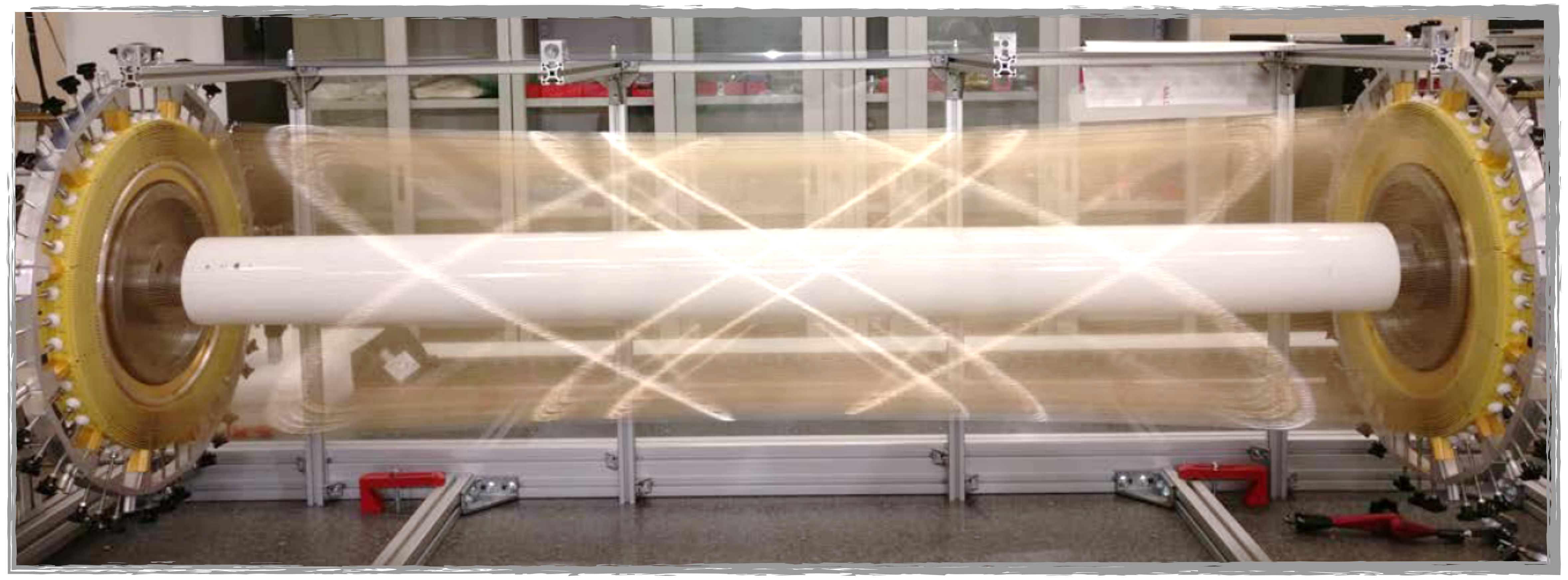
- Improved hit resolution: σ_r ~< 120 um (210 um)
- High granularity/Increased number of hits per track/ cluster timing technique
- Less material (helium: isobutane = 90:10, $1.6 \times 10^{-3}\ X_0$)
- High transparency towards the TC
- Detector performance in final conditions: analysis ongoing

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

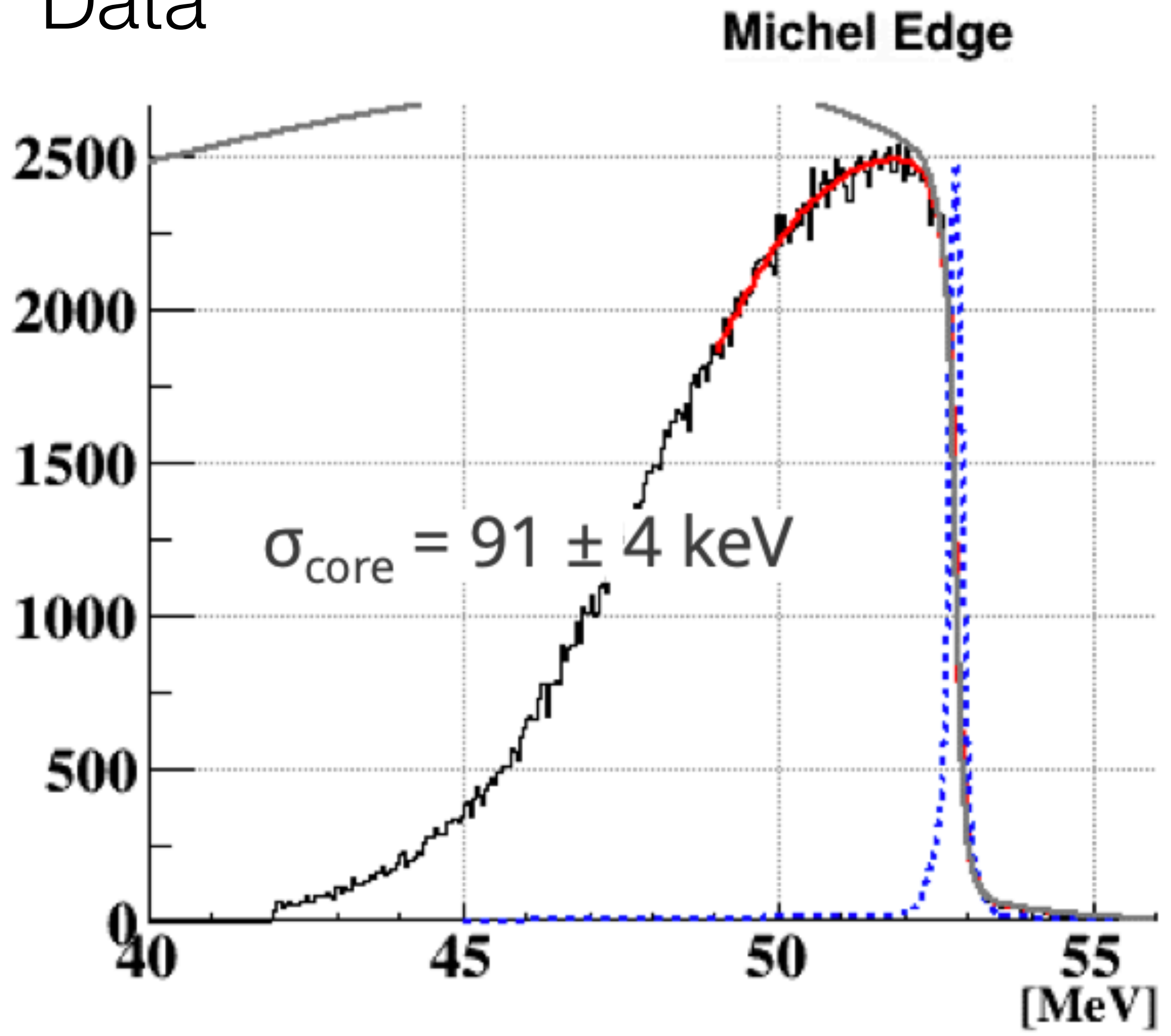
(*) It includes also the matching with the Timing Counter





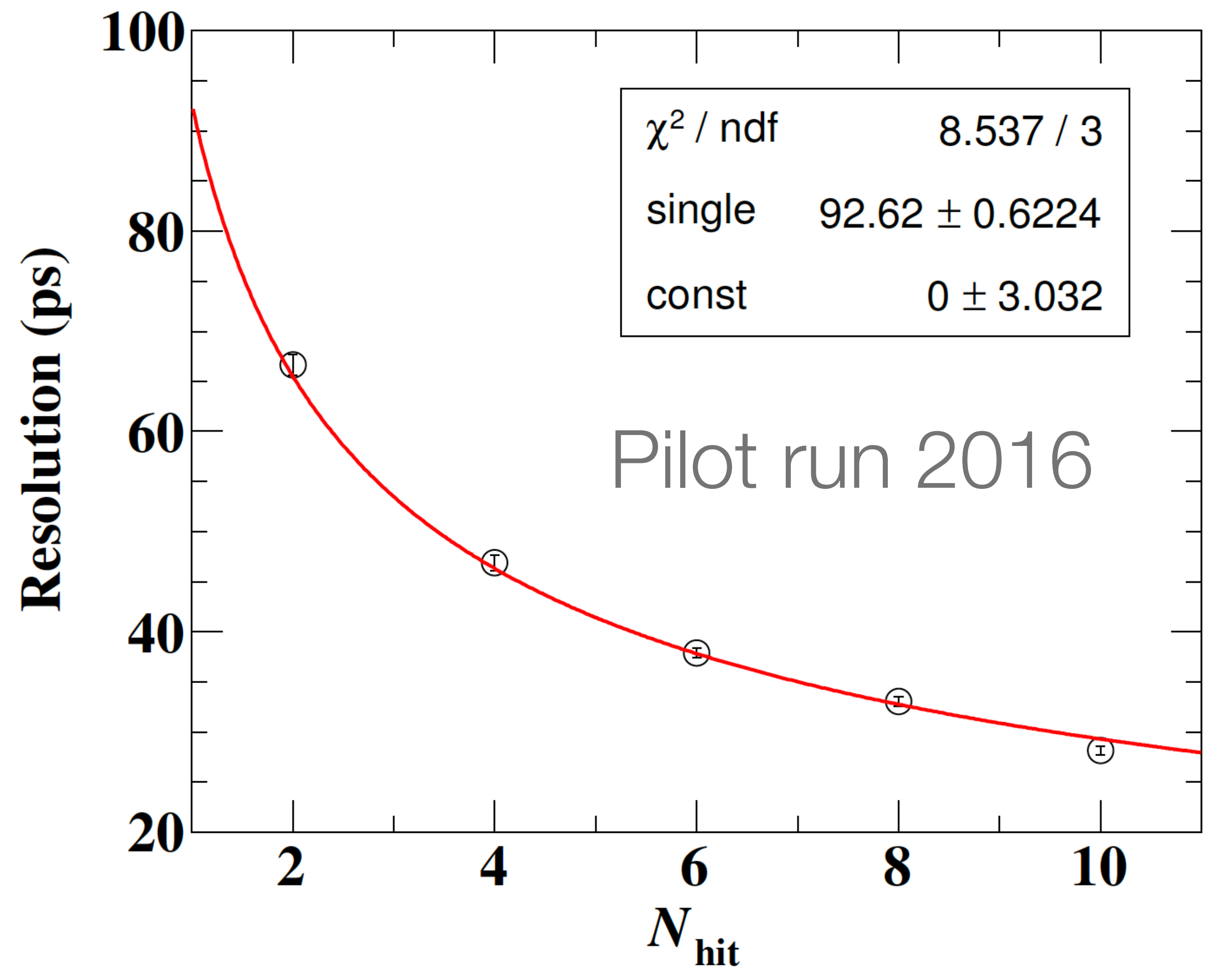


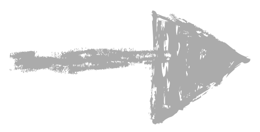
Data

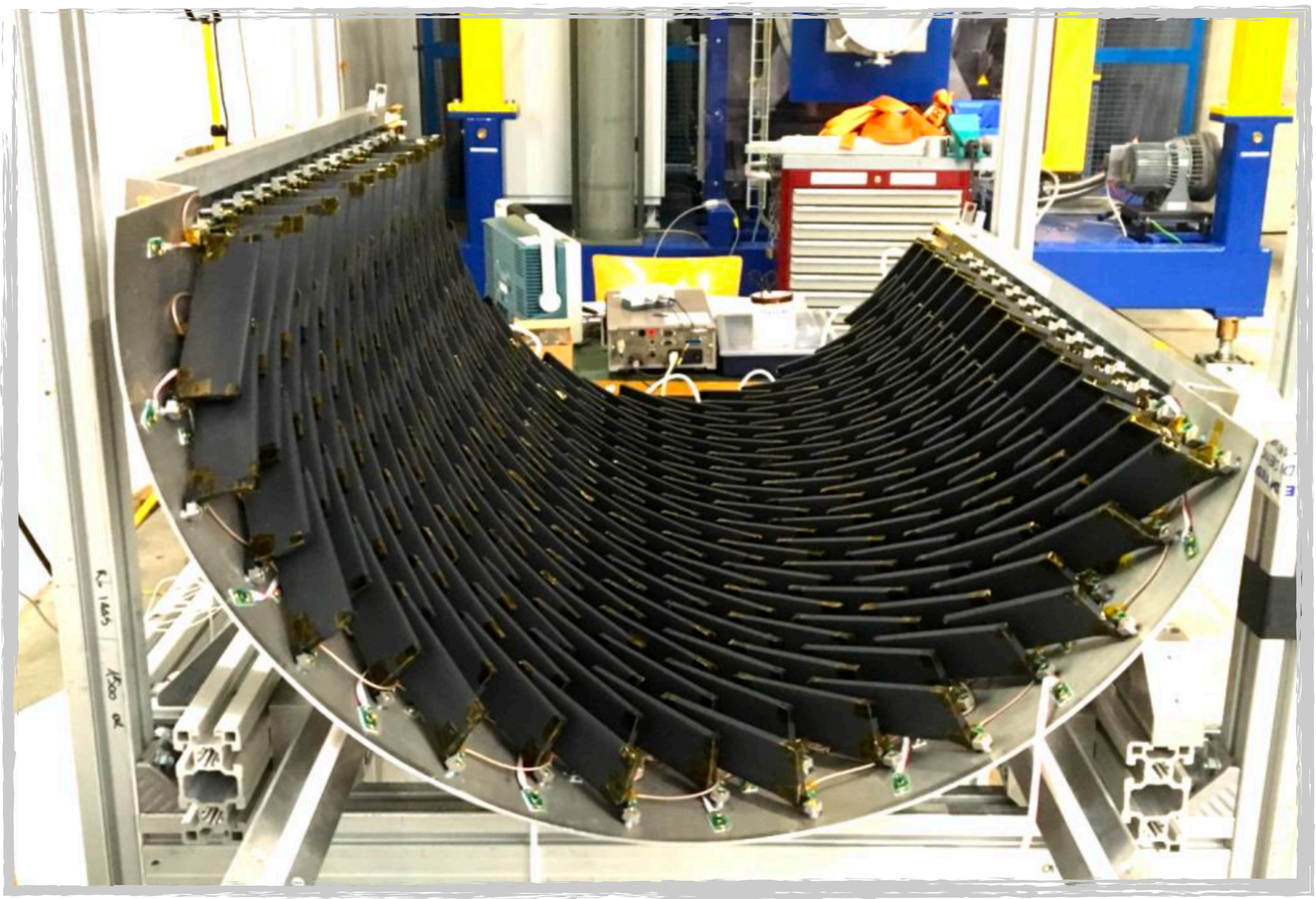


MEGII: the pixelized Timing Counter

- Higher granularity: 2 x 256 of BC422 scintillator plates (120 x 40 (or 50) x 5 mm^3) 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

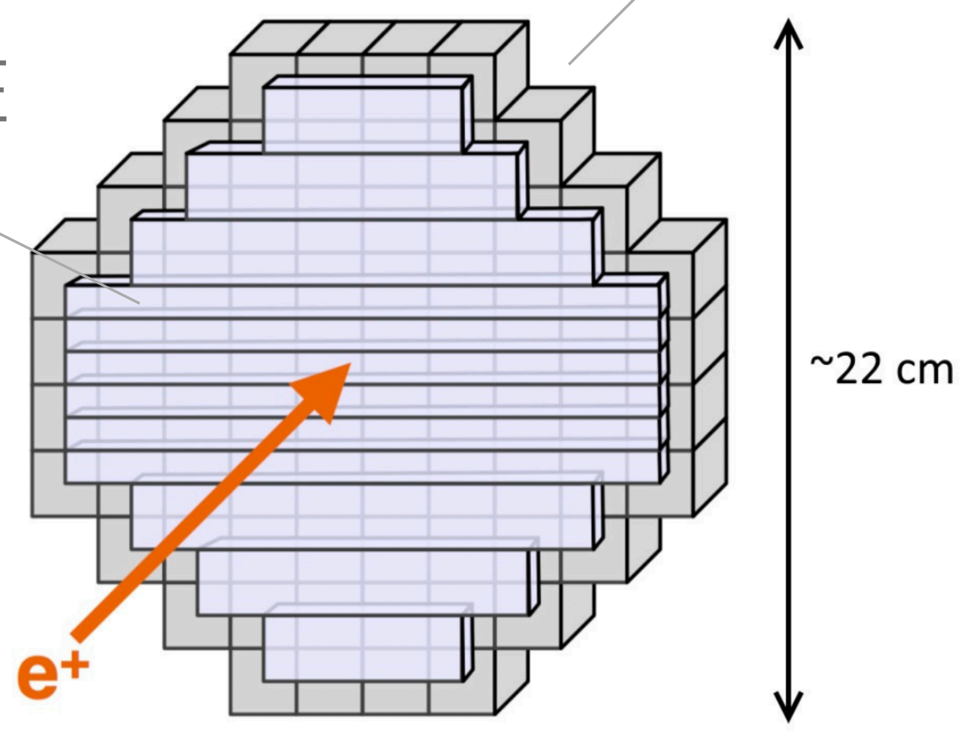


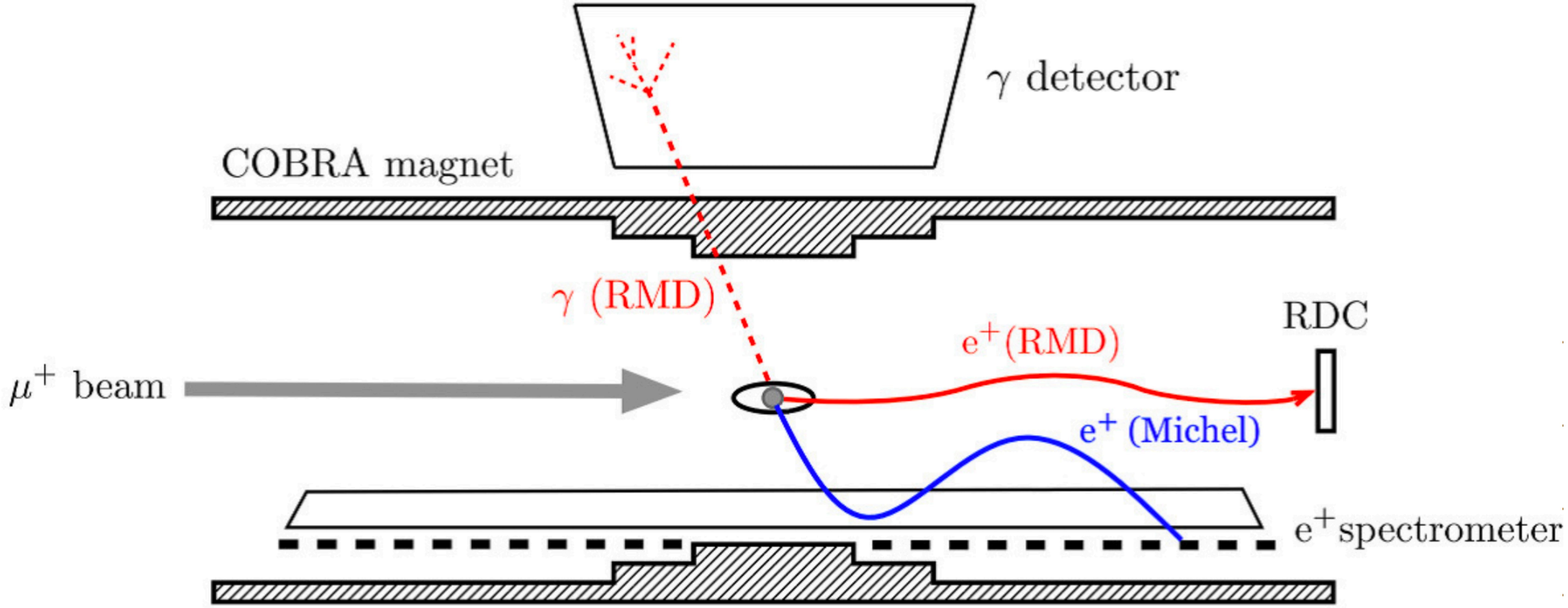


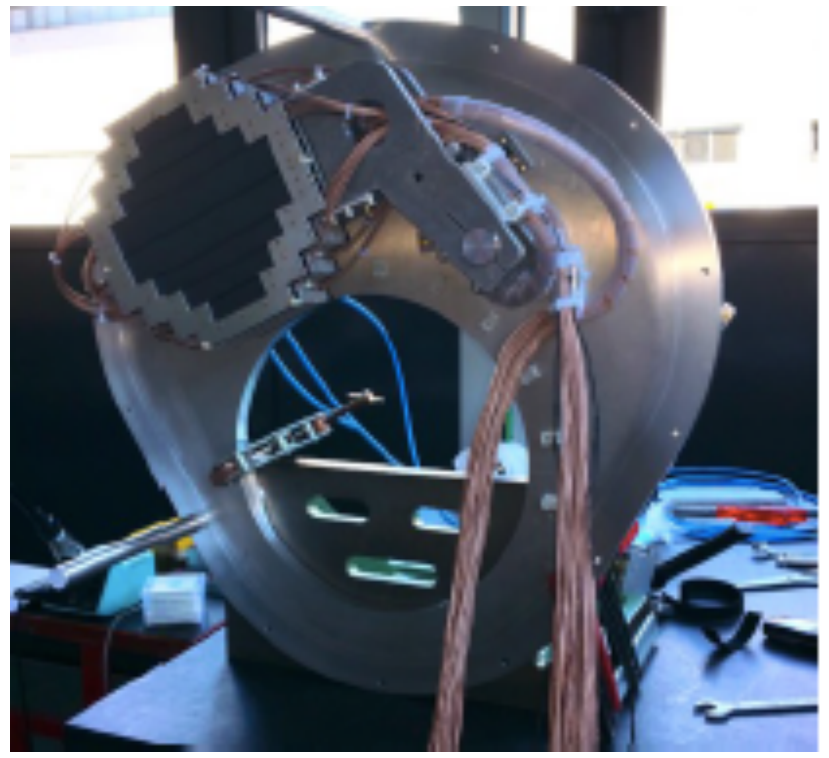


MEGII: The Radiative Decay Counter

- 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 !



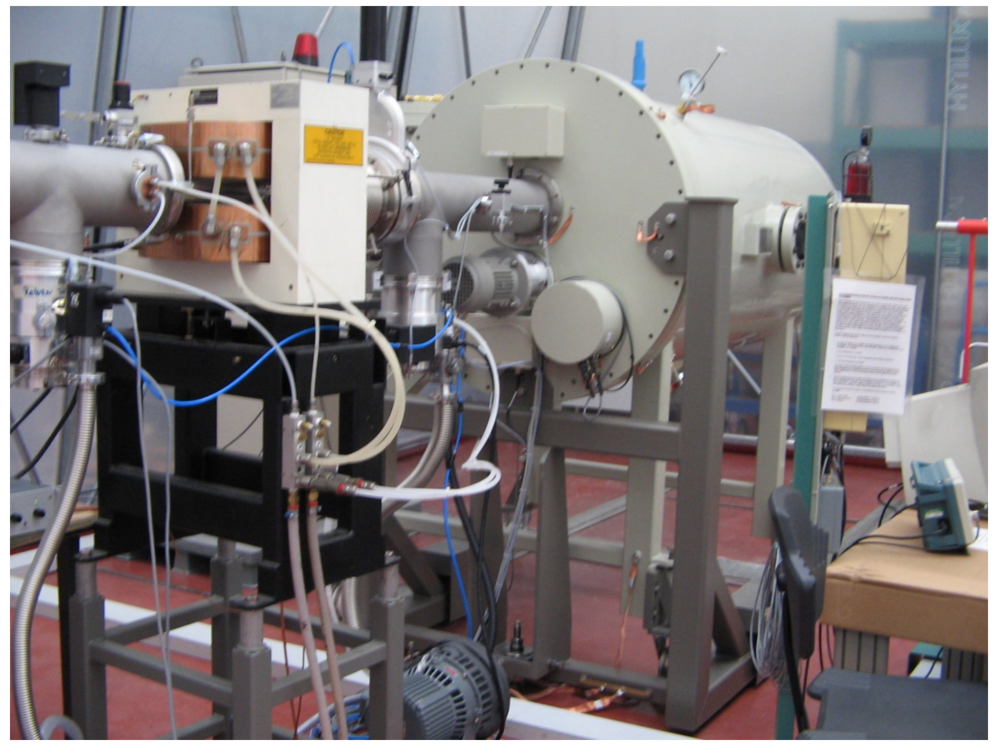


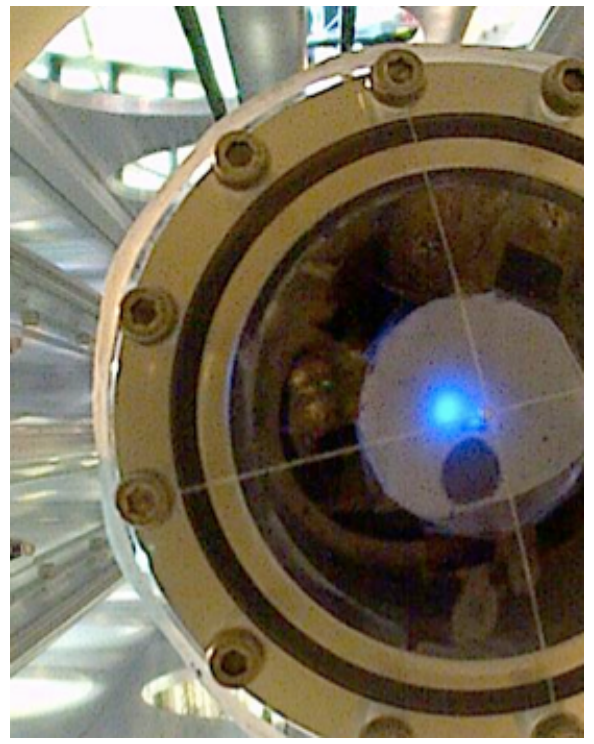


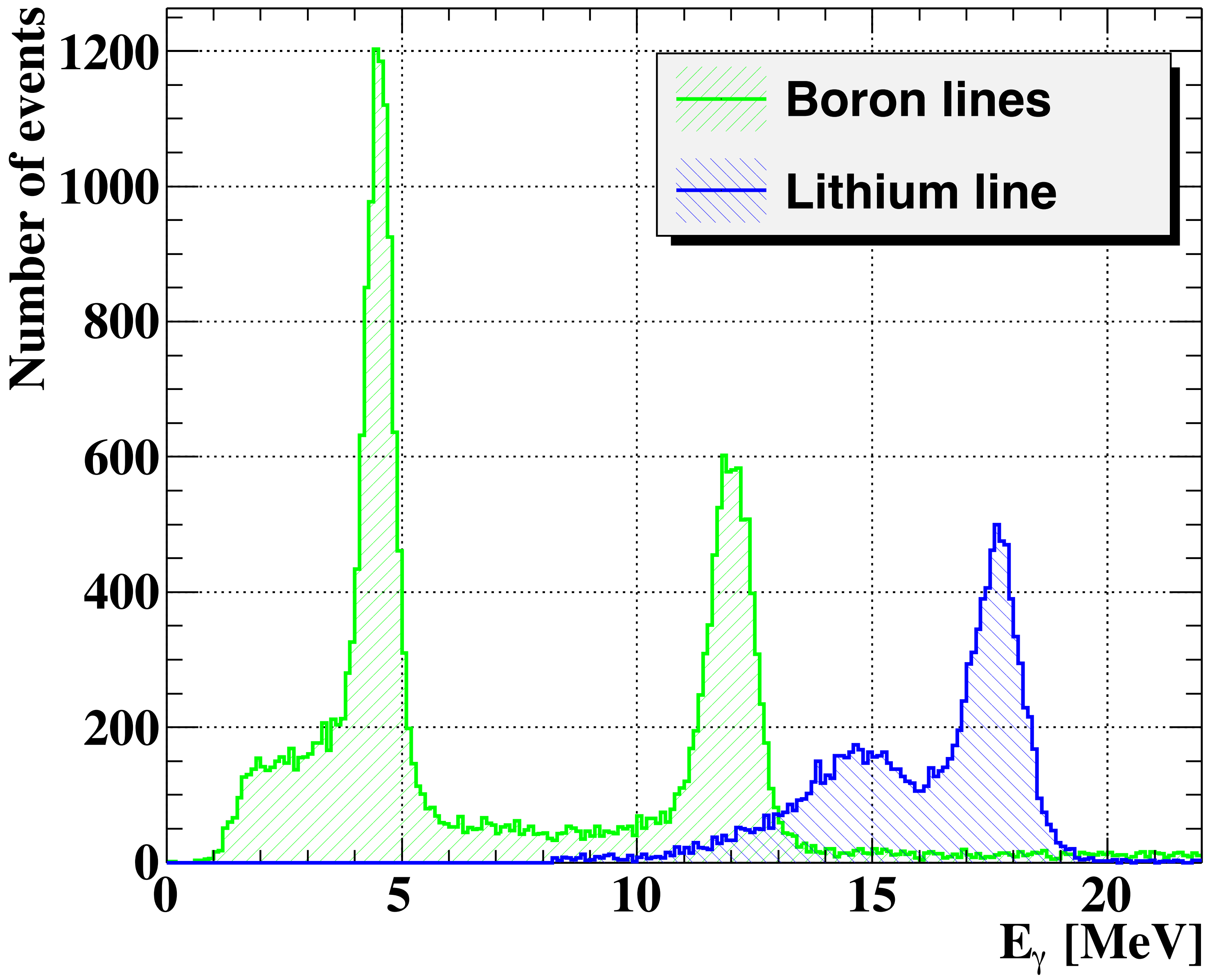
MEG: The calibration methods

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



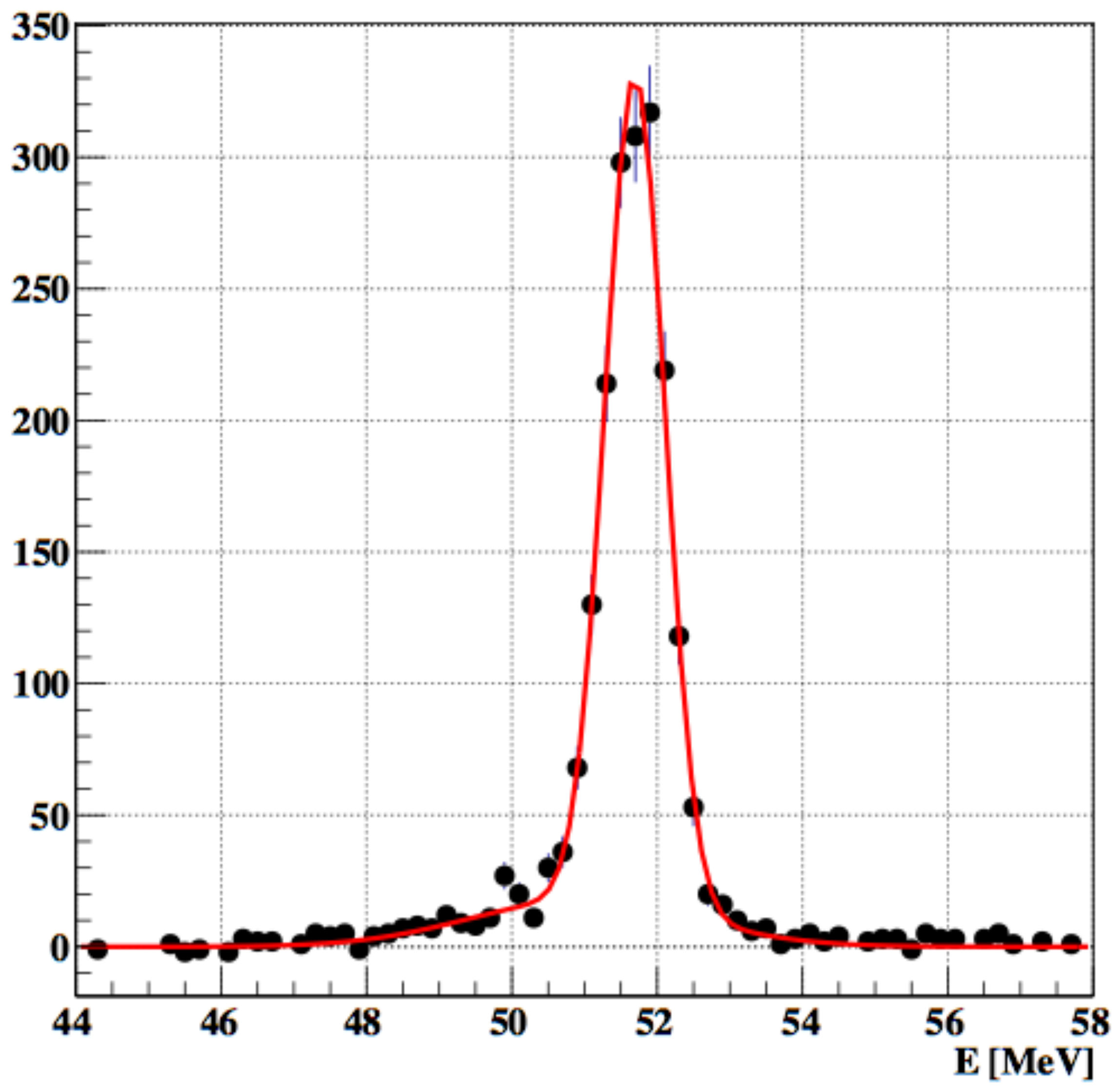




MEGII: new calibration methods and upgrades

- CEX reaction: $p(\pi^-,\pi^0)n$, $\pi^0 \to \gamma\gamma$
- 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

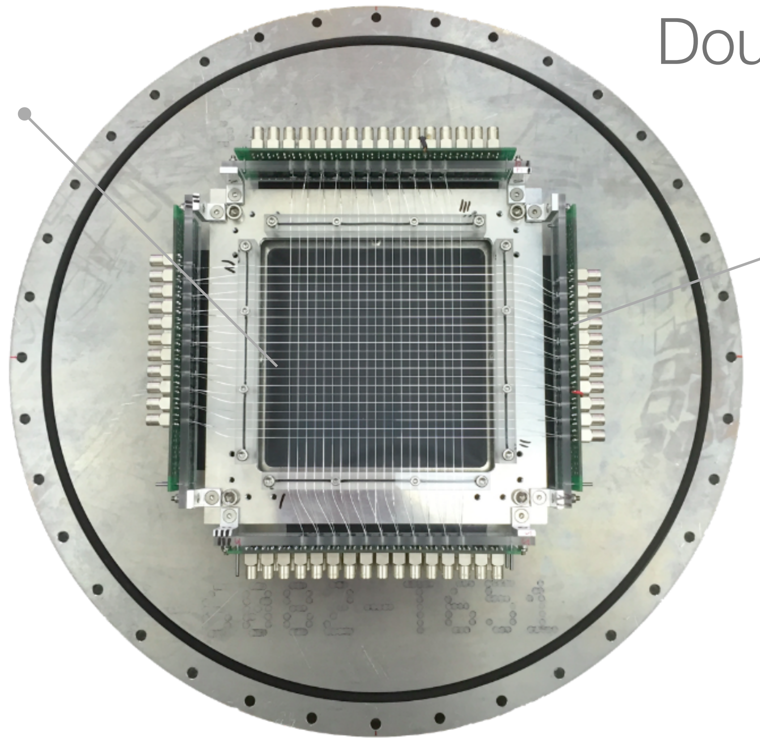
Monochromatic e-line



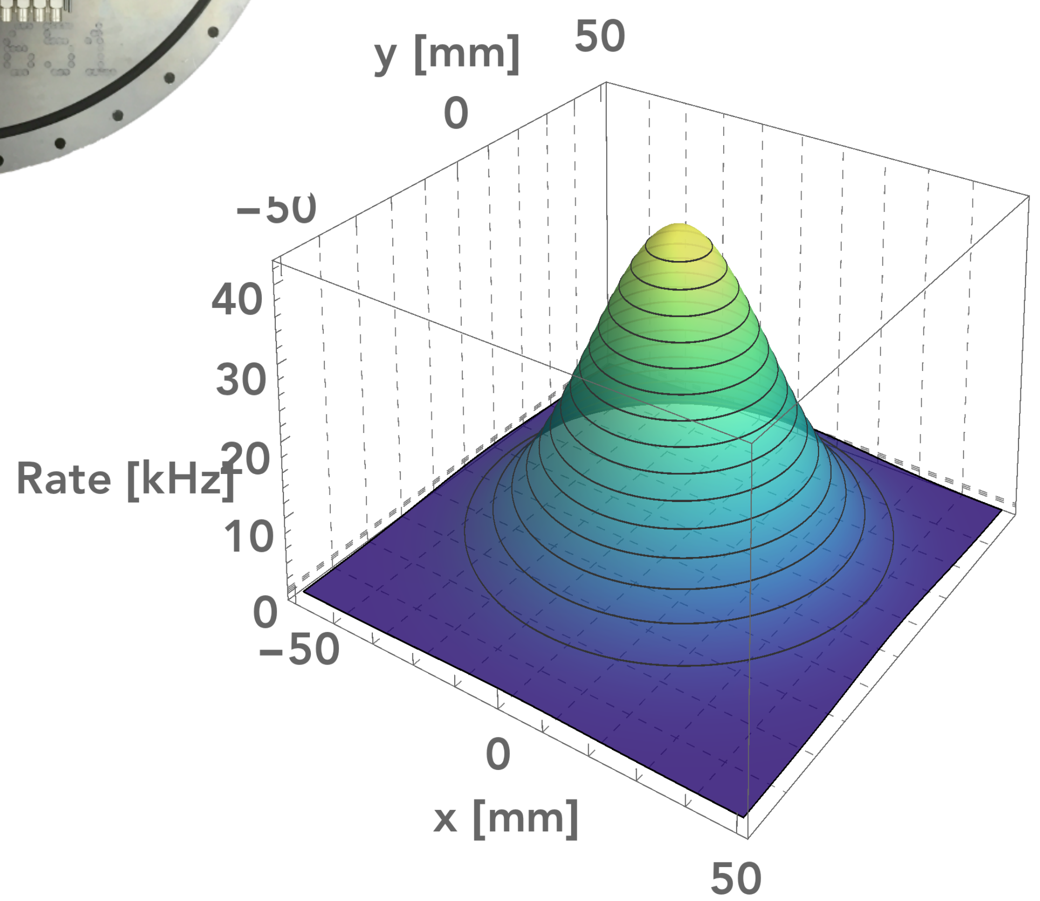
pTC's laser

MC BCF12 250 x 250 um^2 scintillating fibers

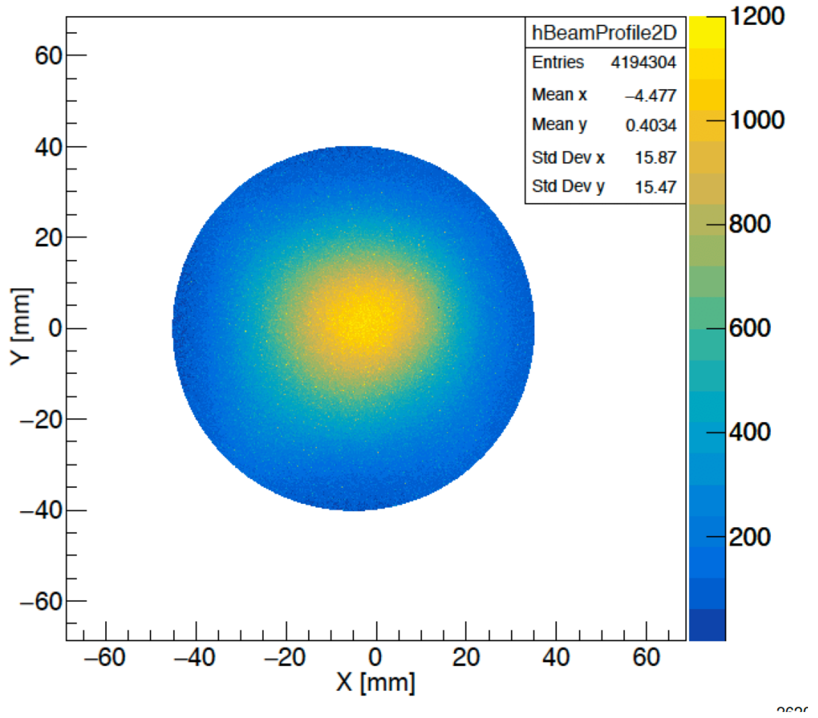
Double readout: MPPC S13360-3050C



SciFi



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

Latest news and currents status

Key points:

- **Run2021 very successful**
- Electronics fully installed and tested with all sub-detectors and calibration tools
- All calibration and physics trigger configurations released
- Assessed performances of each sub-detectors in the final MEG II conditions
- Collected data at different beam intensities
- Dedicated RMD at reduced beam intensity as proof-of-principle of the experiment quality
- **Physics run started at the end of September 2021**
- …with the COVID19 outbreak ongoing

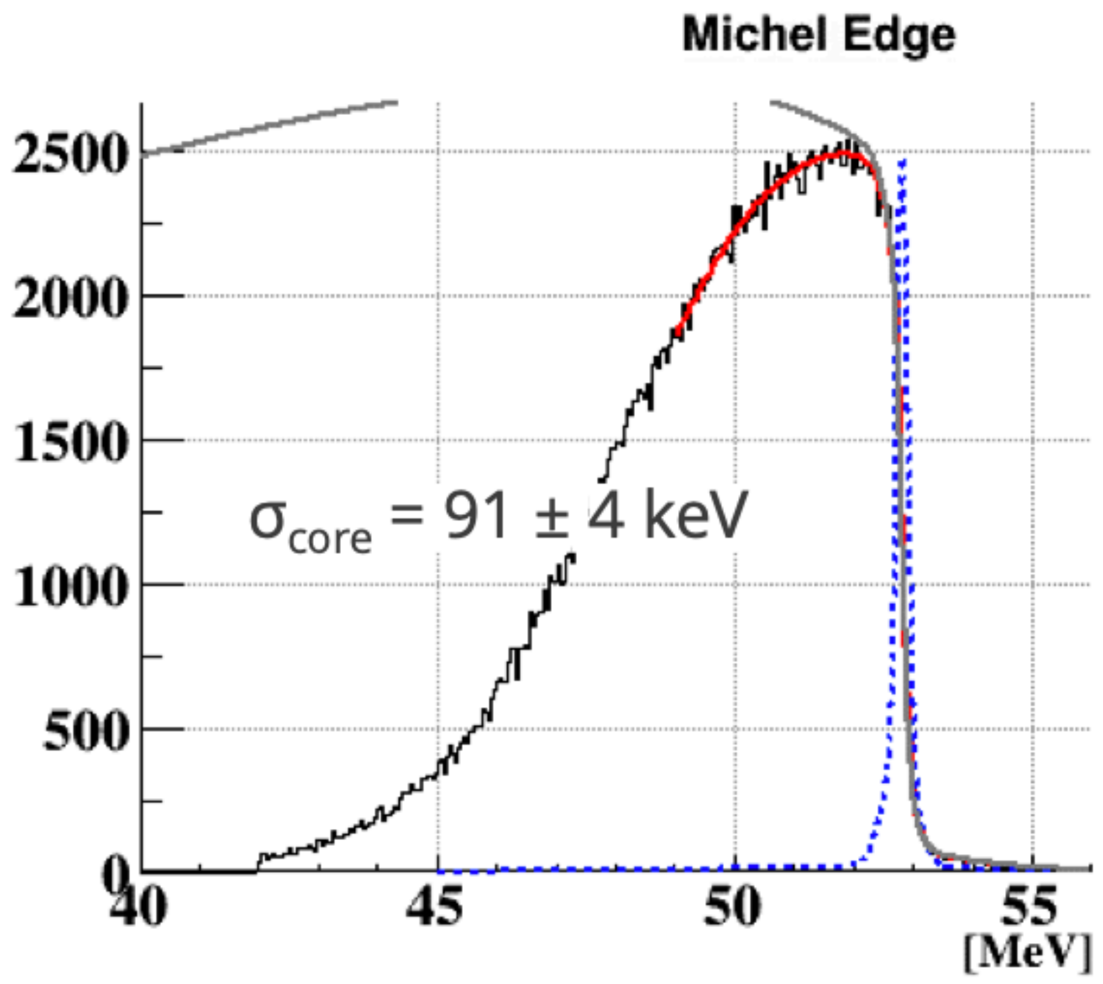
Current status:

- **MEGII beam time 2022 started (June 7th)**
- **MEGII physics run 2022 with shifts started (July 6th)**

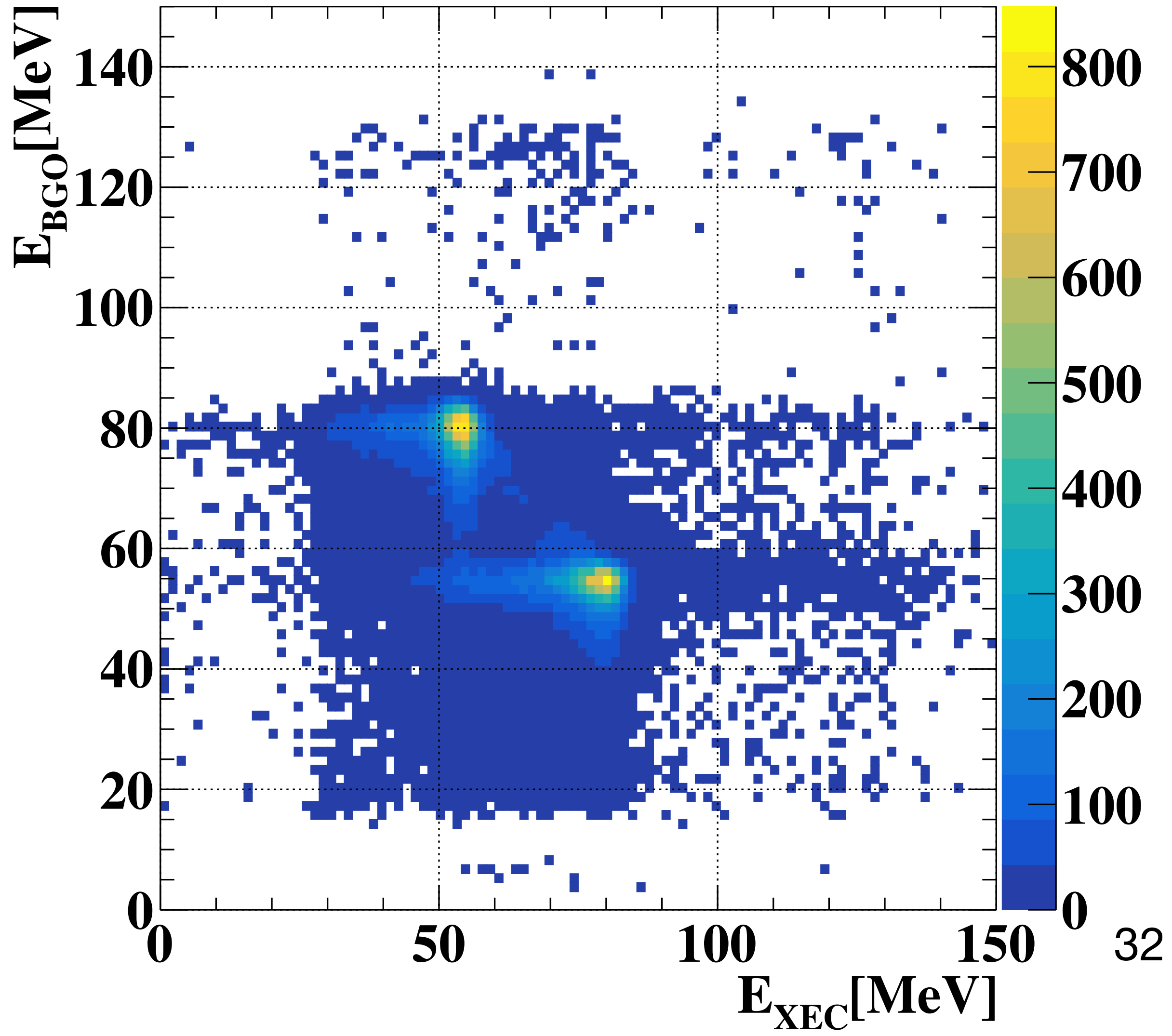
Outlook:

- MEG sensitivity expected to be **surpassed by the Run 2022**

MEGII **fully** installed!



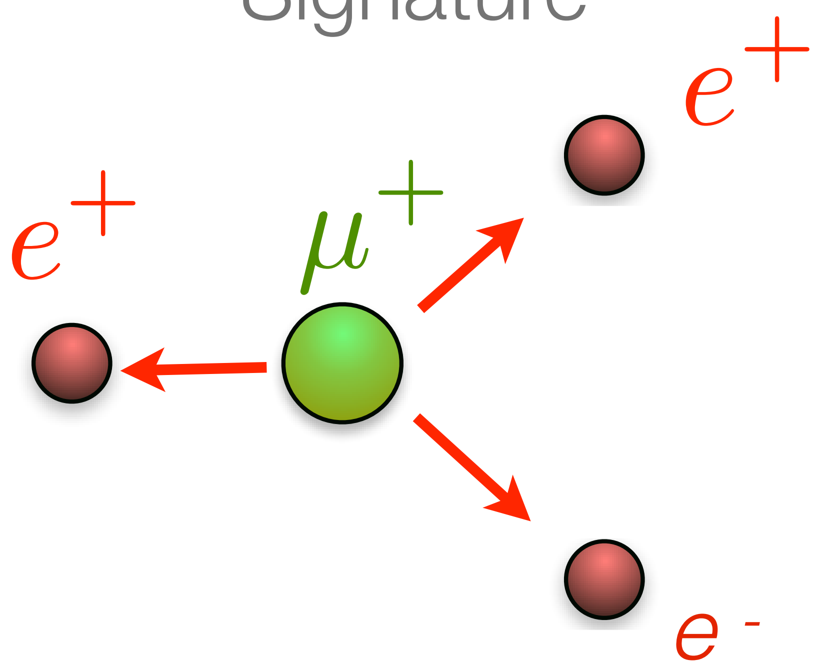
Data from the **first** Physics Run2021



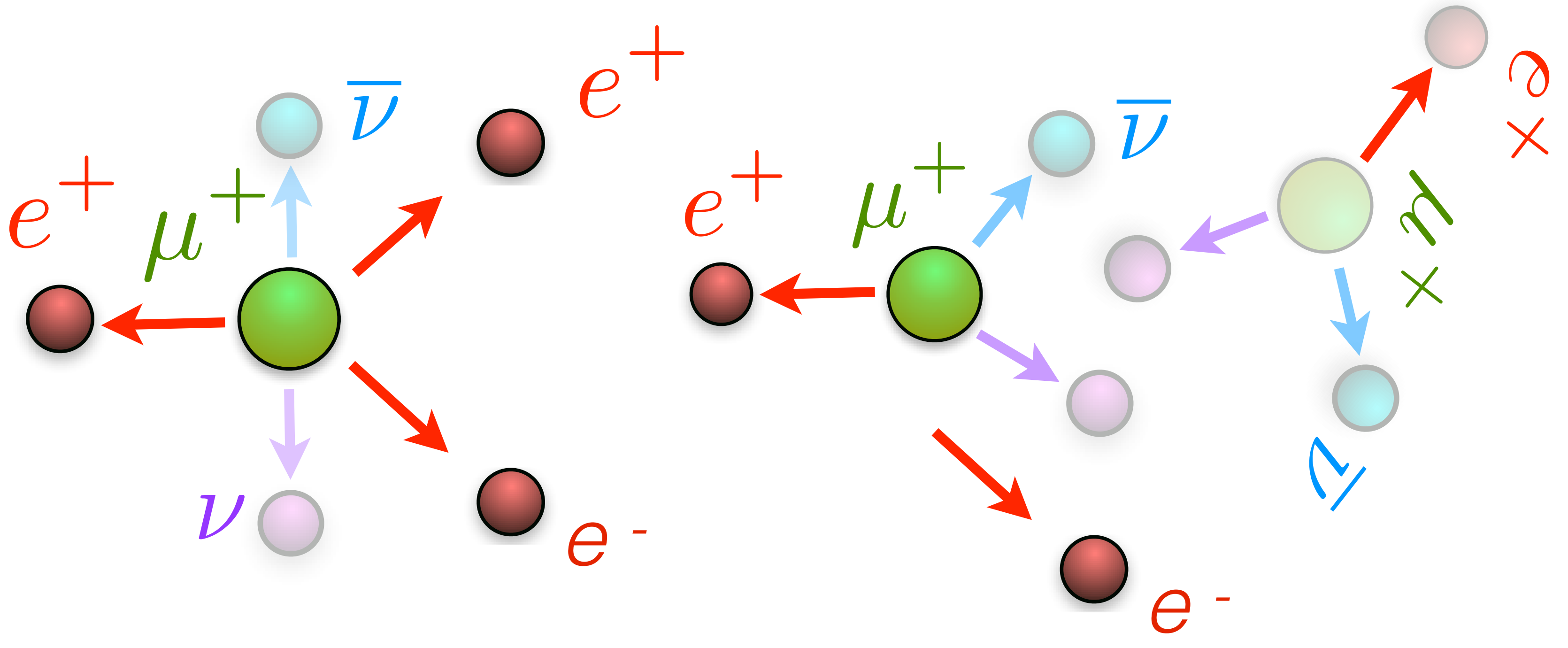
The Mu3e experiment at PSI

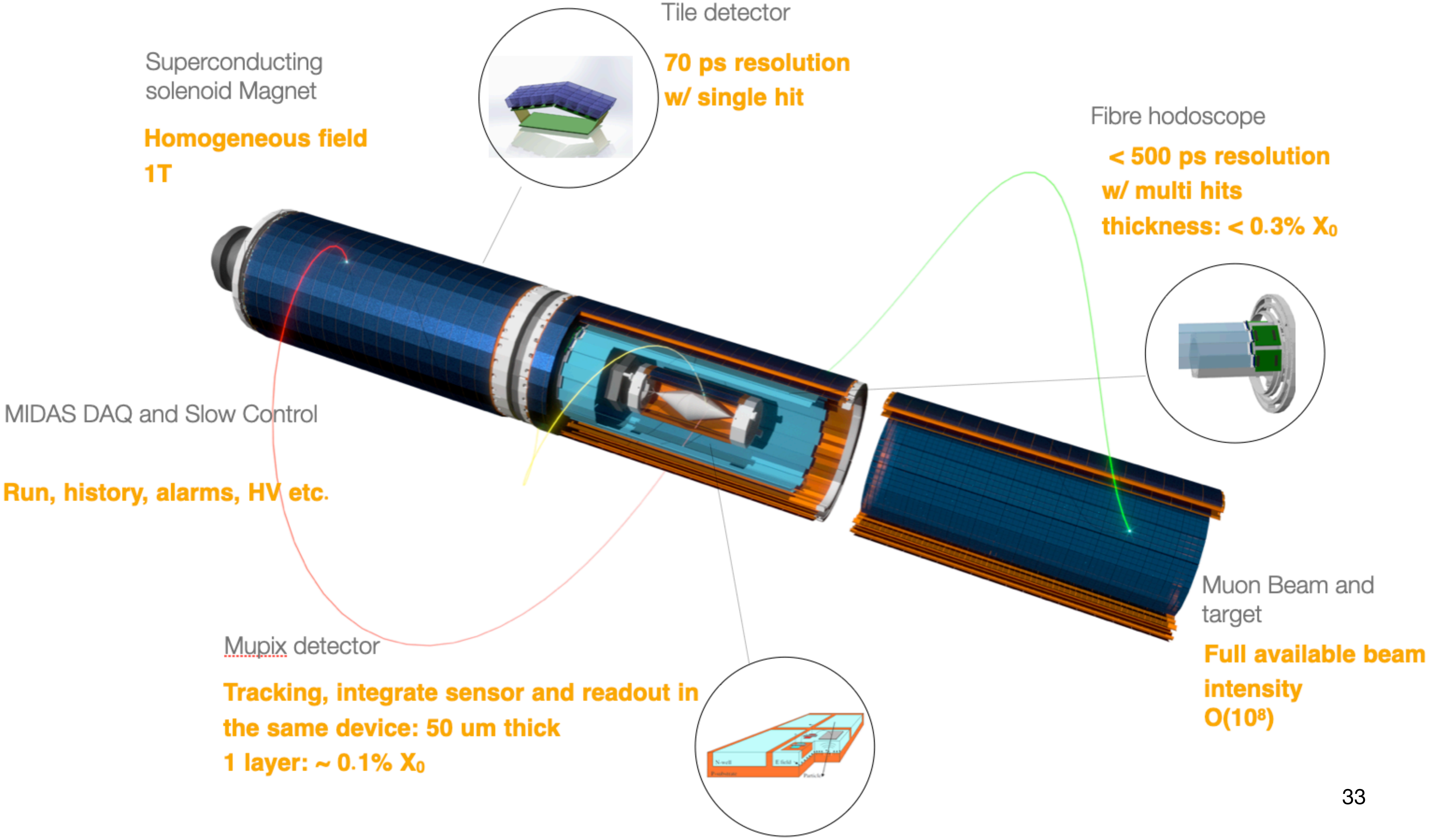
- The Mu3e experiment aims to search for $\mu^+ \to e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit BR($\mu^+ \to e^+ e^+ e^-$) ≤ 1 x 10^{-12} @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \to eee$ events

Signature



Backgrounds

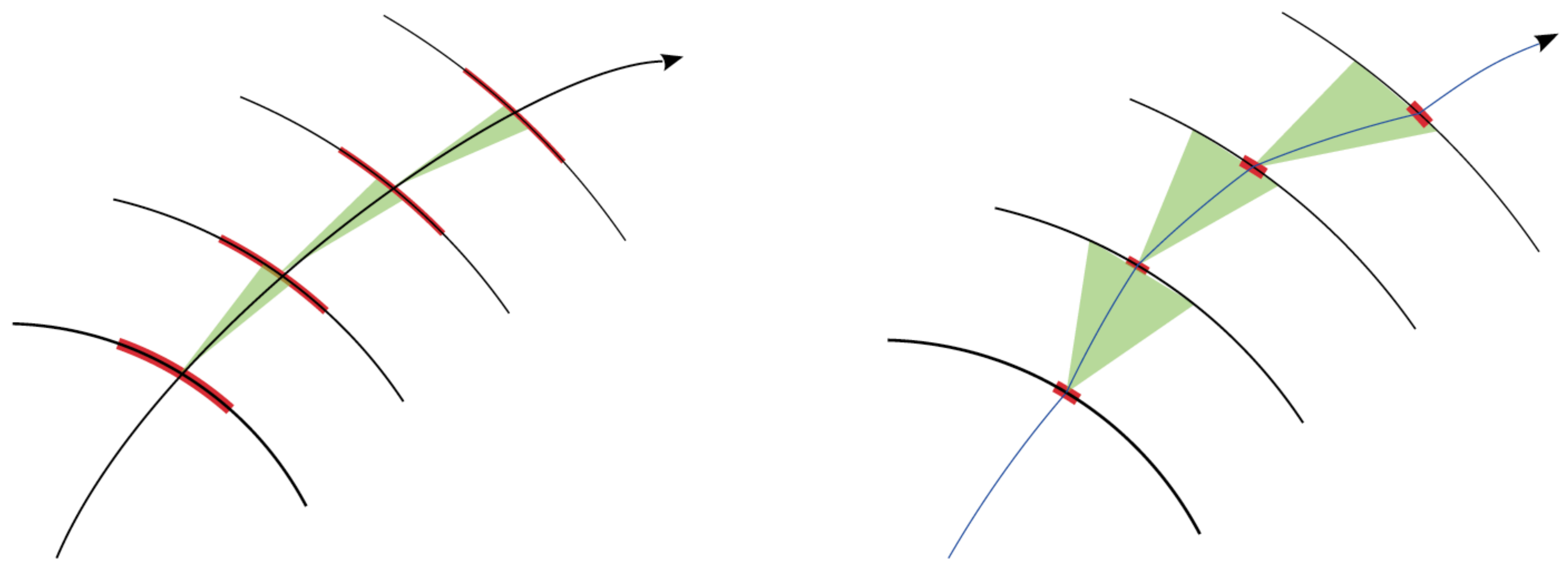




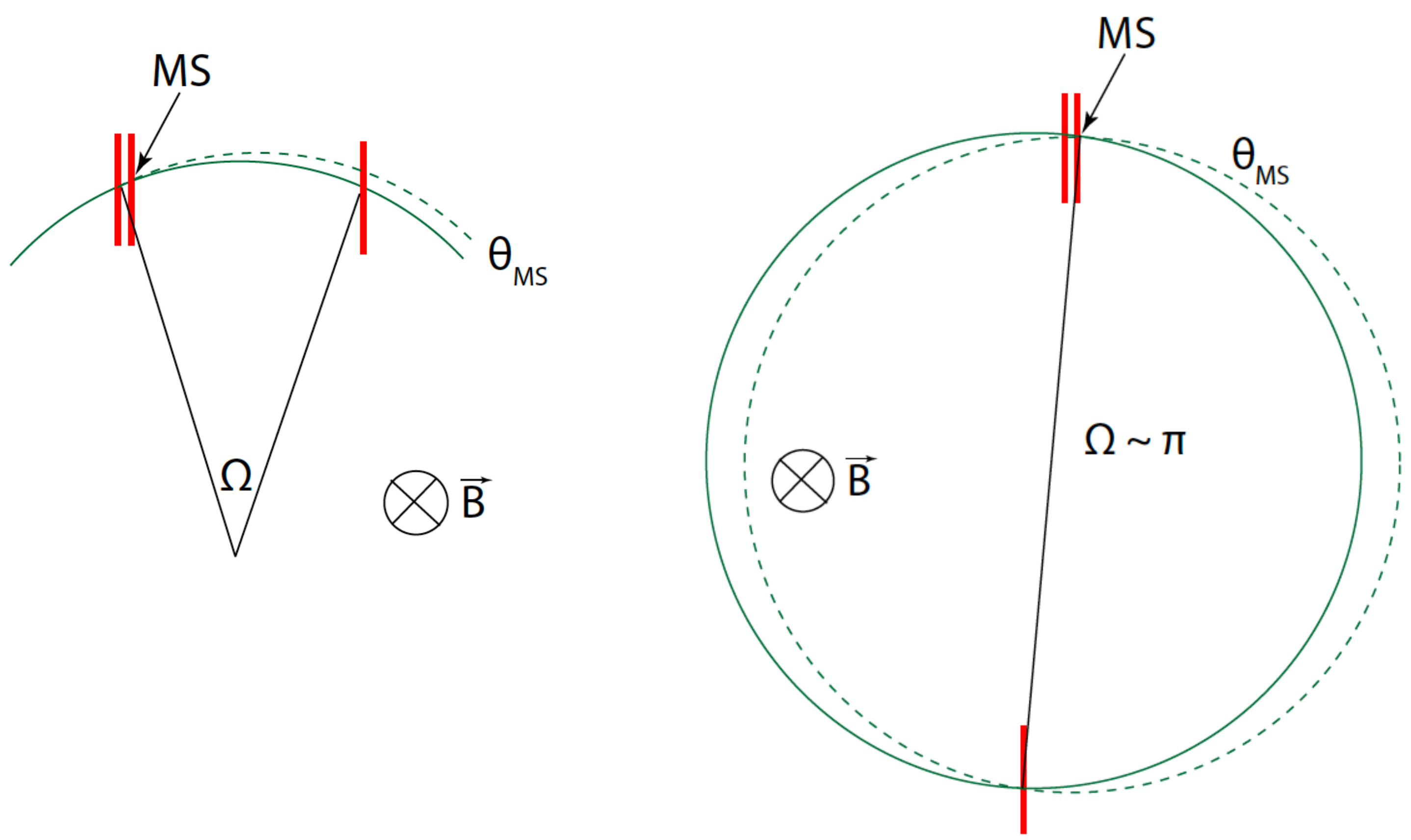
The pixel tracker: The principle

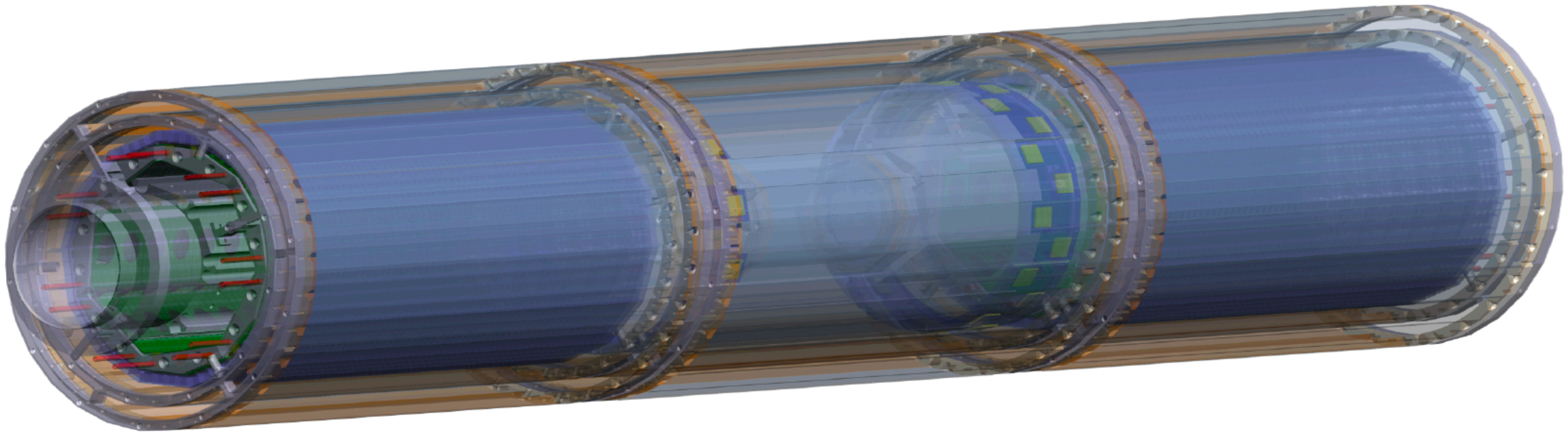
- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime

Tracking in the spacial and scattering dominated regime



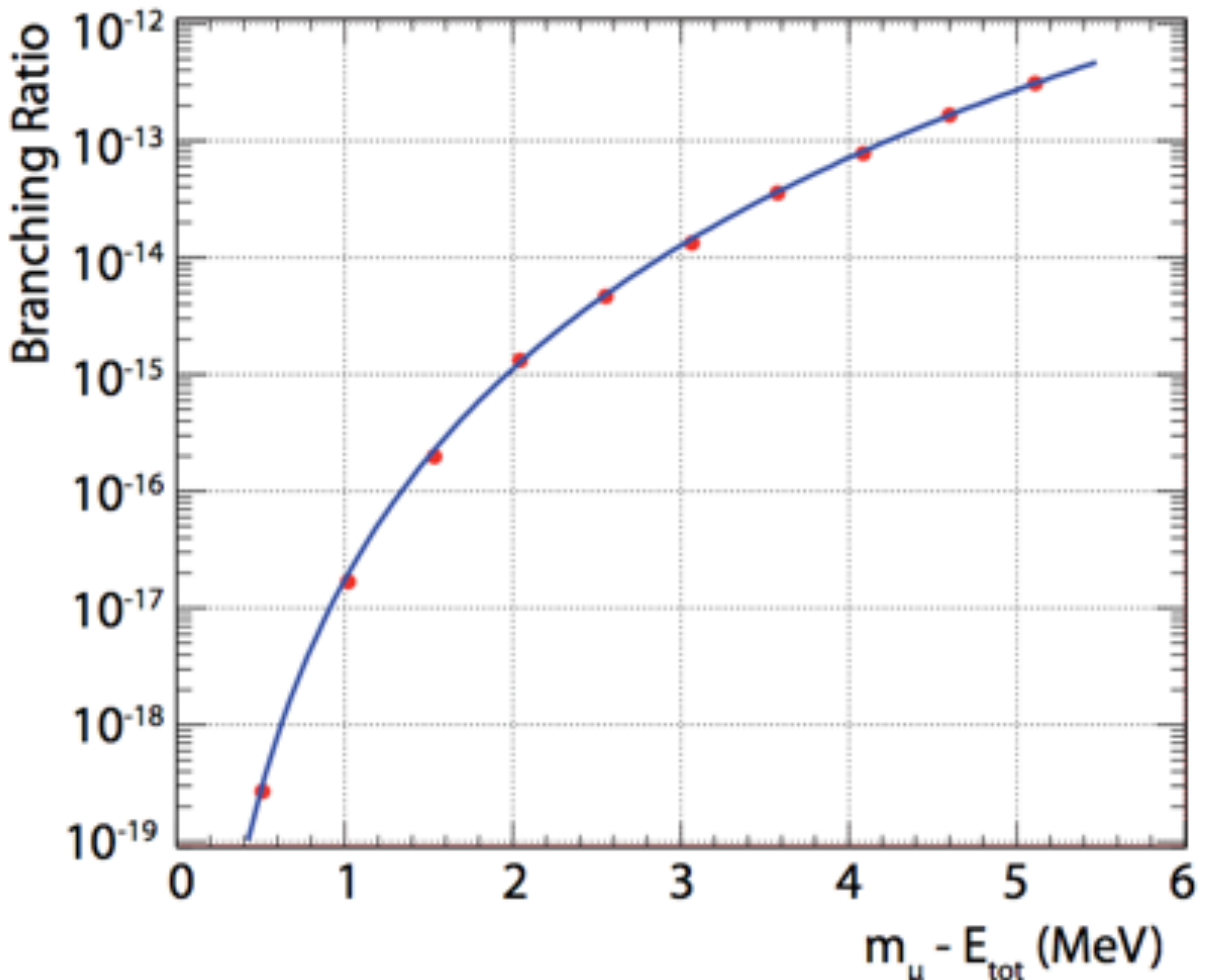
Momentum with re-curlers

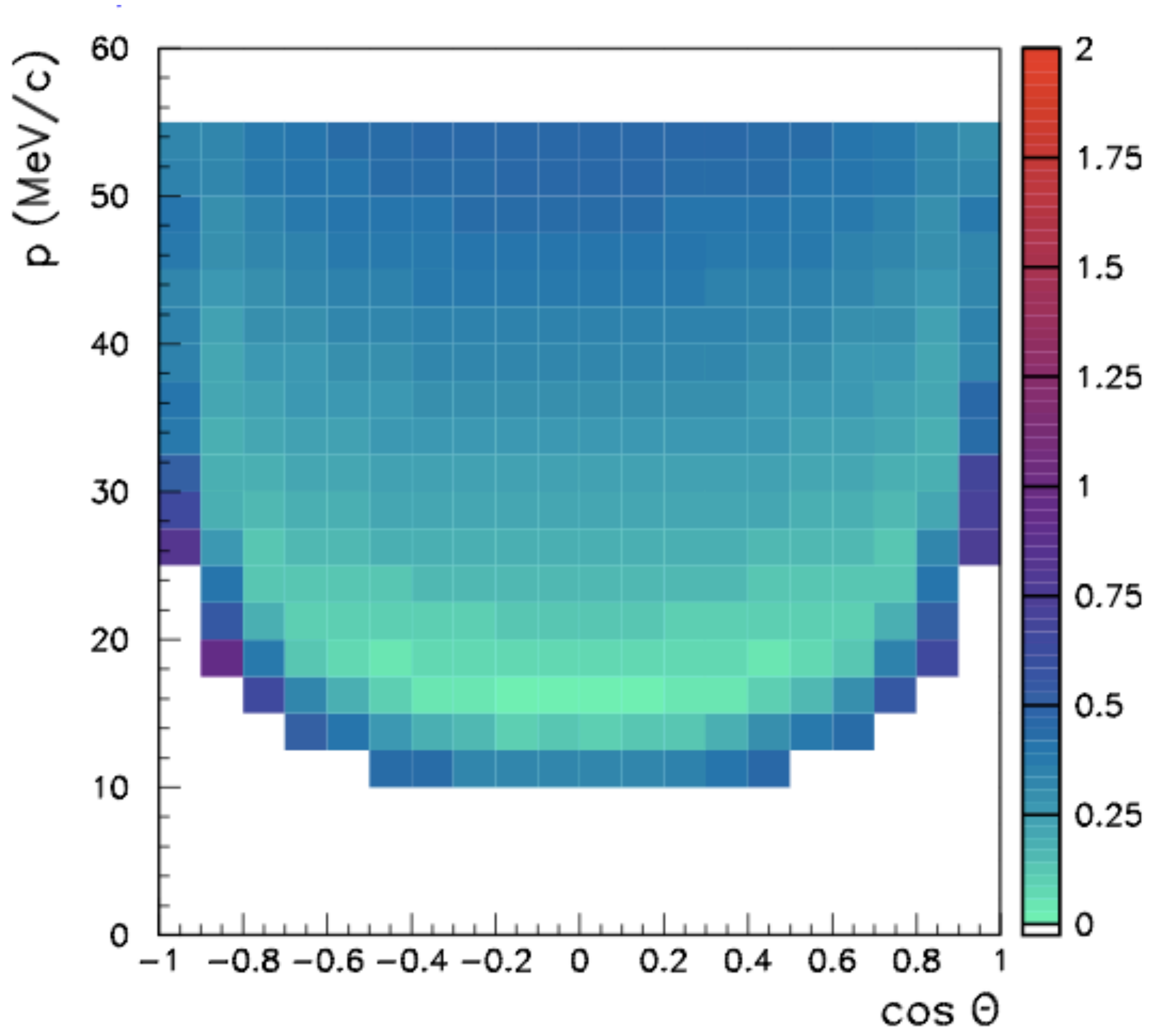




The pixel tracker: The performances

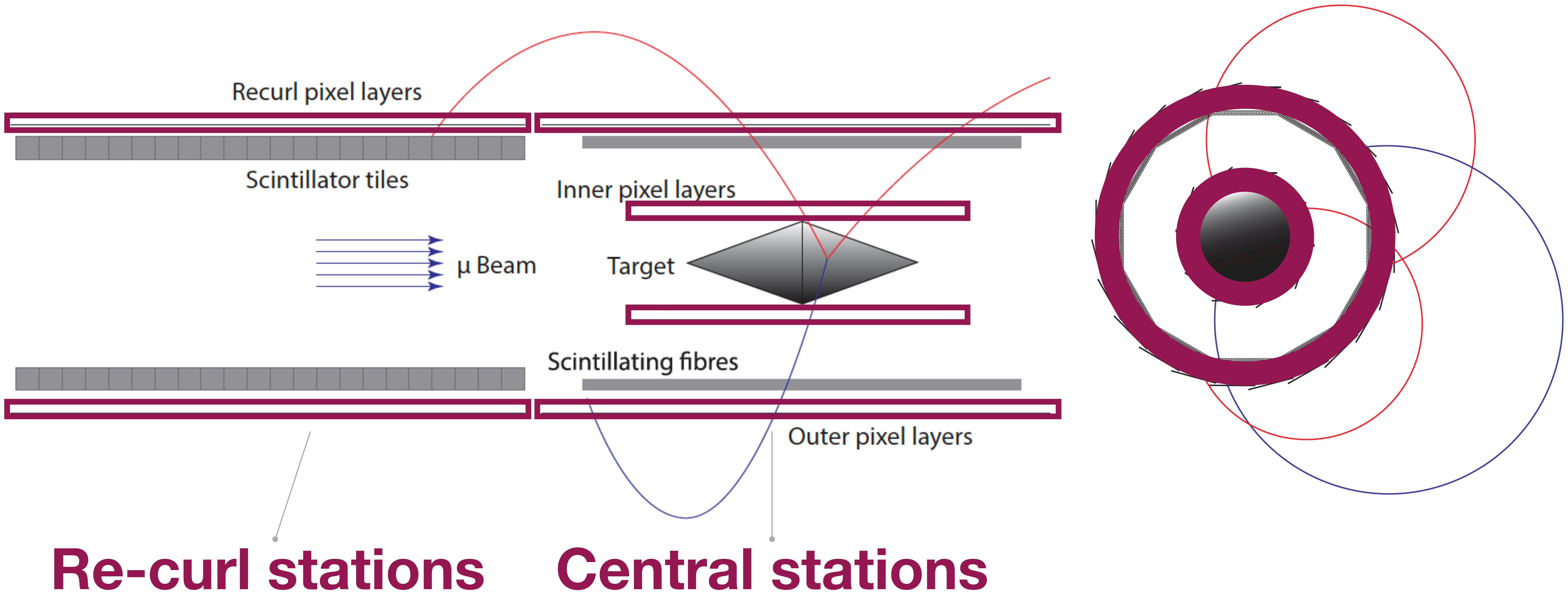
- Momentum resolution: < 0.5 MeV/c over a large phase space
- Geometrical acceptance: ~ 70%
- X/X_0 per layer: ~ 0.011%
- Vertex resolution: < 200 μm





The pixel tracker: Overview

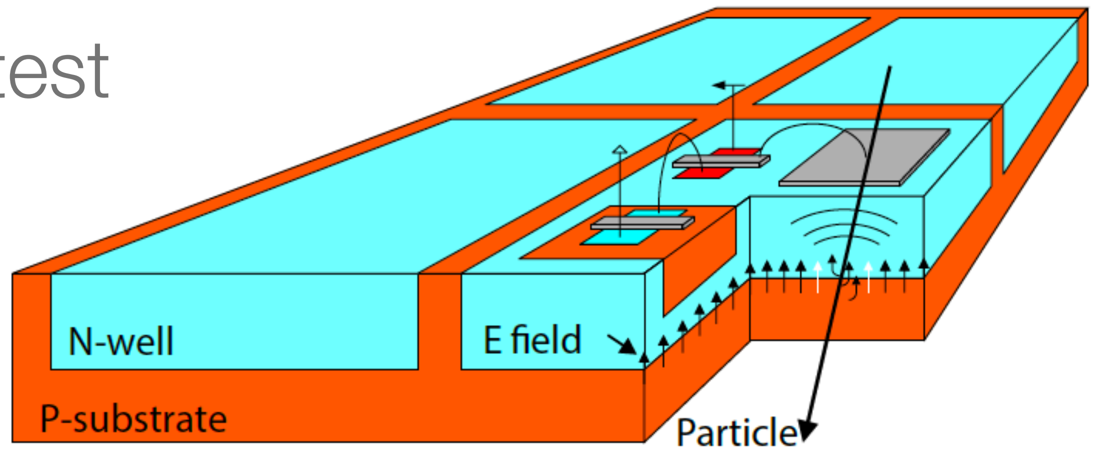
- Central tracker: Four layers; Re-curl tracker: Two layers
- Minimum material budget: Tracking in the scattering dominated regime
- Momentum resolution: < 0.5 MeV/c over a large phase space; Geometrical acceptance: ~ 70%; X/X_0 per layer: ~ 0.011%



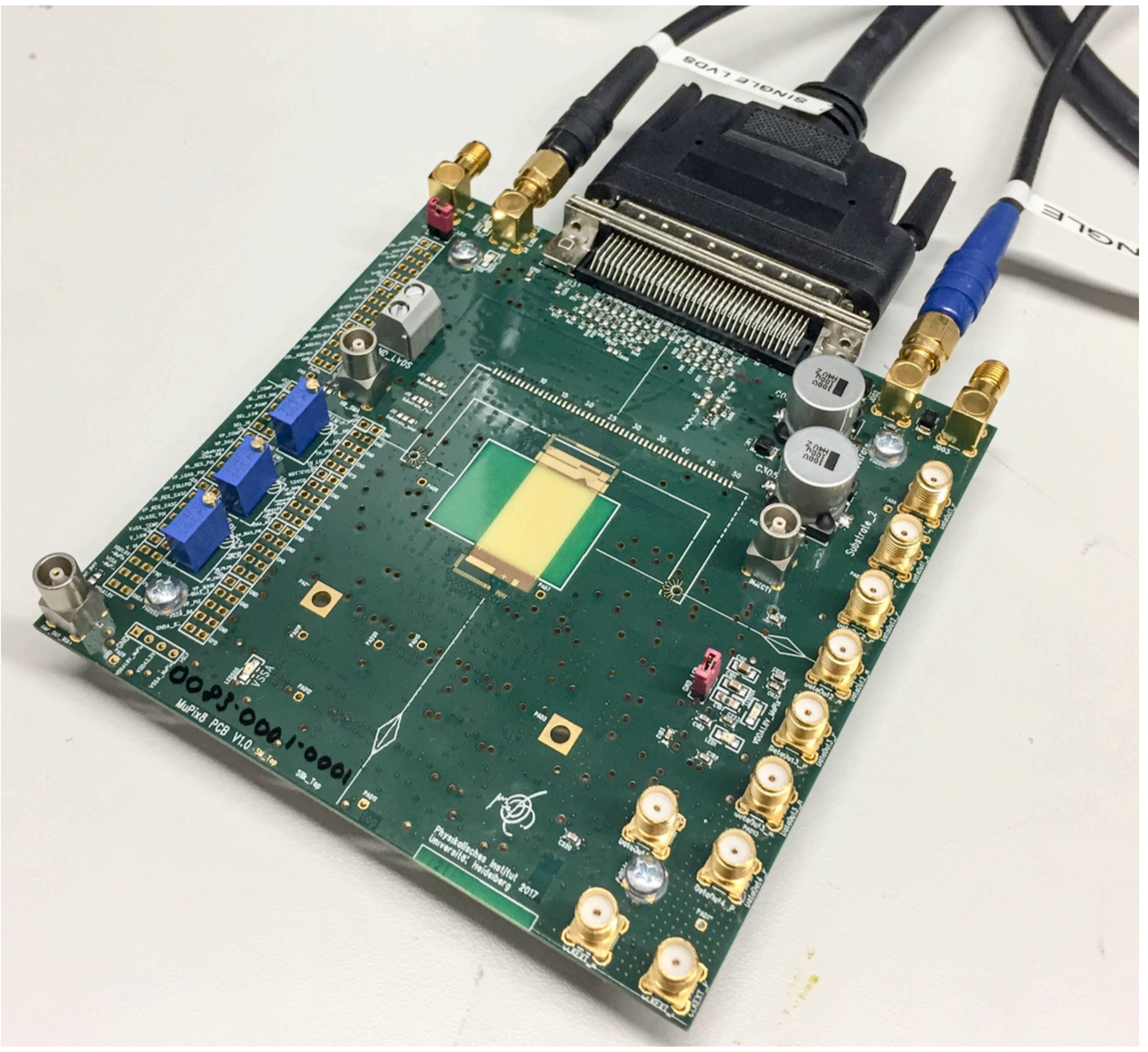
The pixel tracker: The MuPix detector

- 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

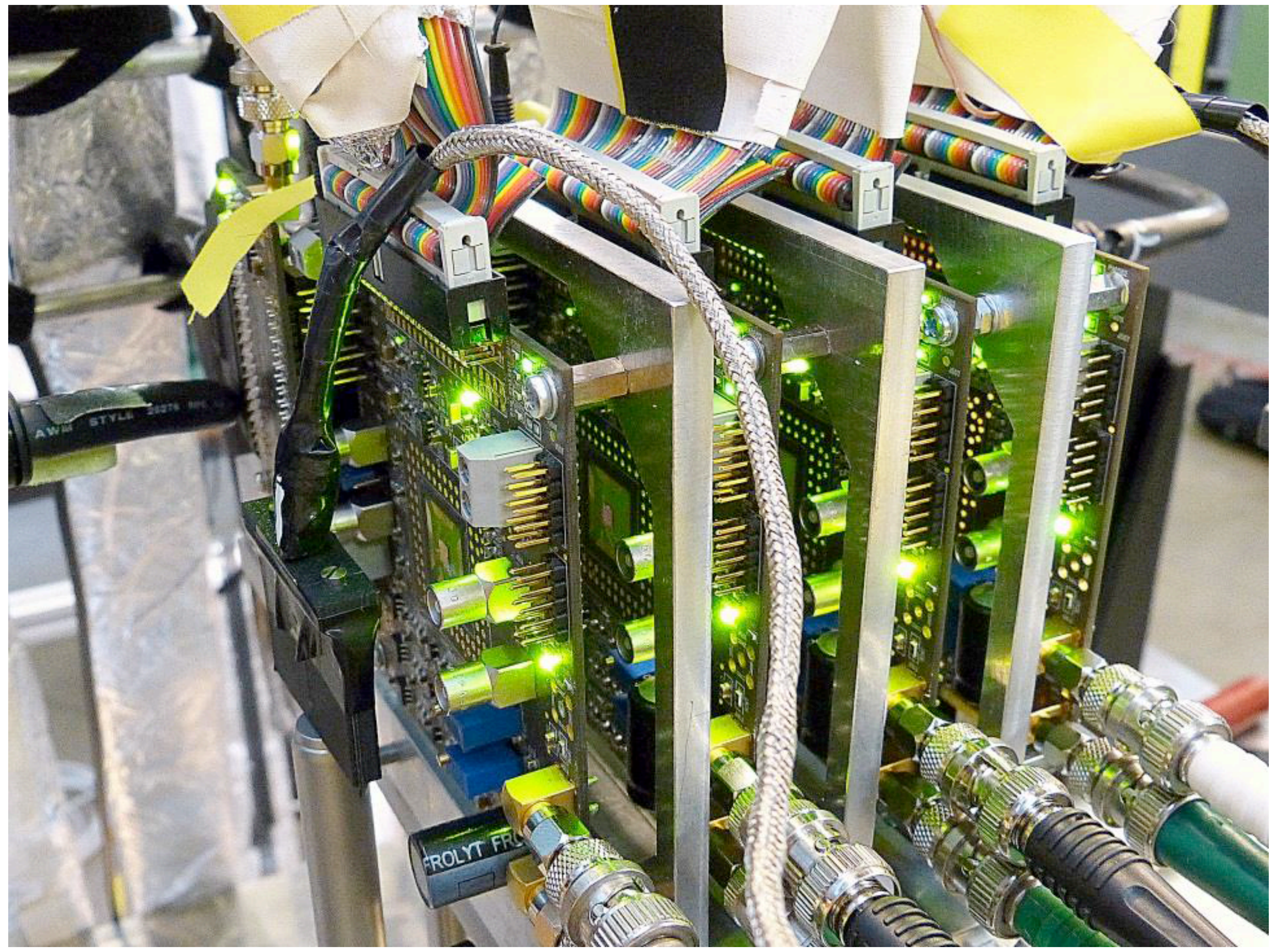
Ivan Peric, Nucl.Instrum.Meth. A582 (2007) 876-885



MuPix8



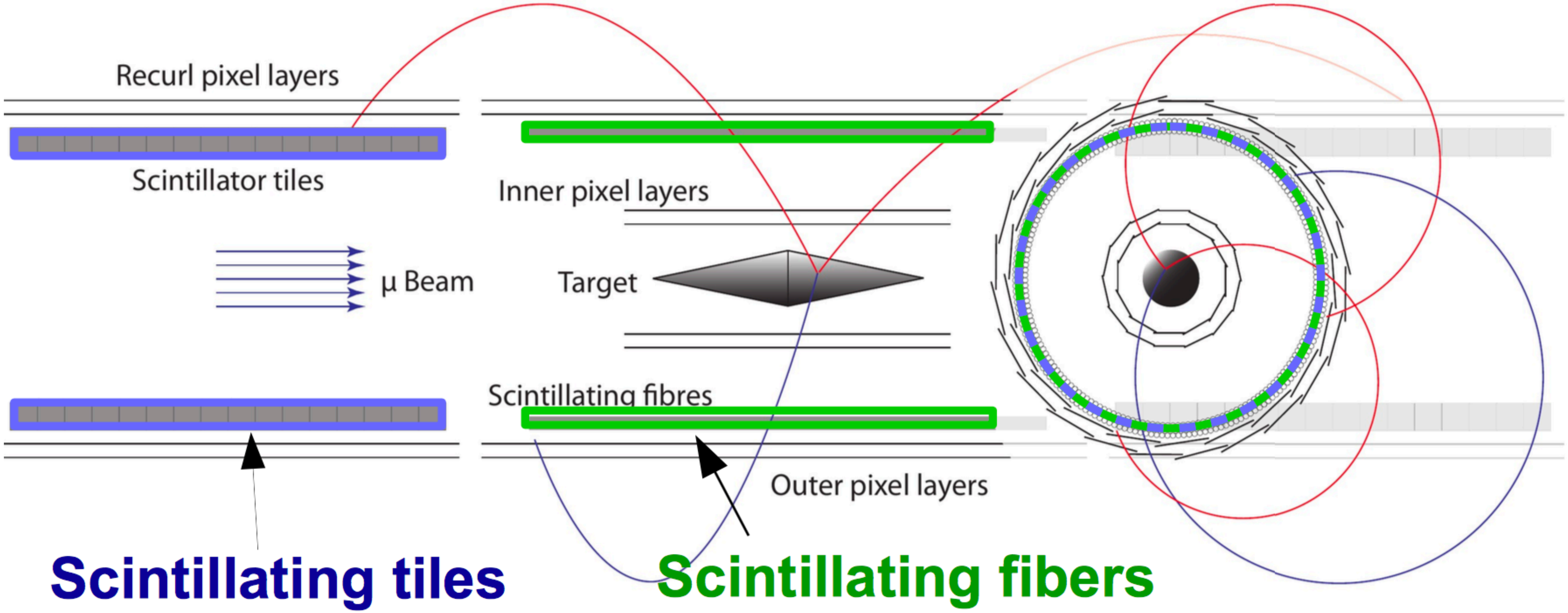
Mupix 7 telescope



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

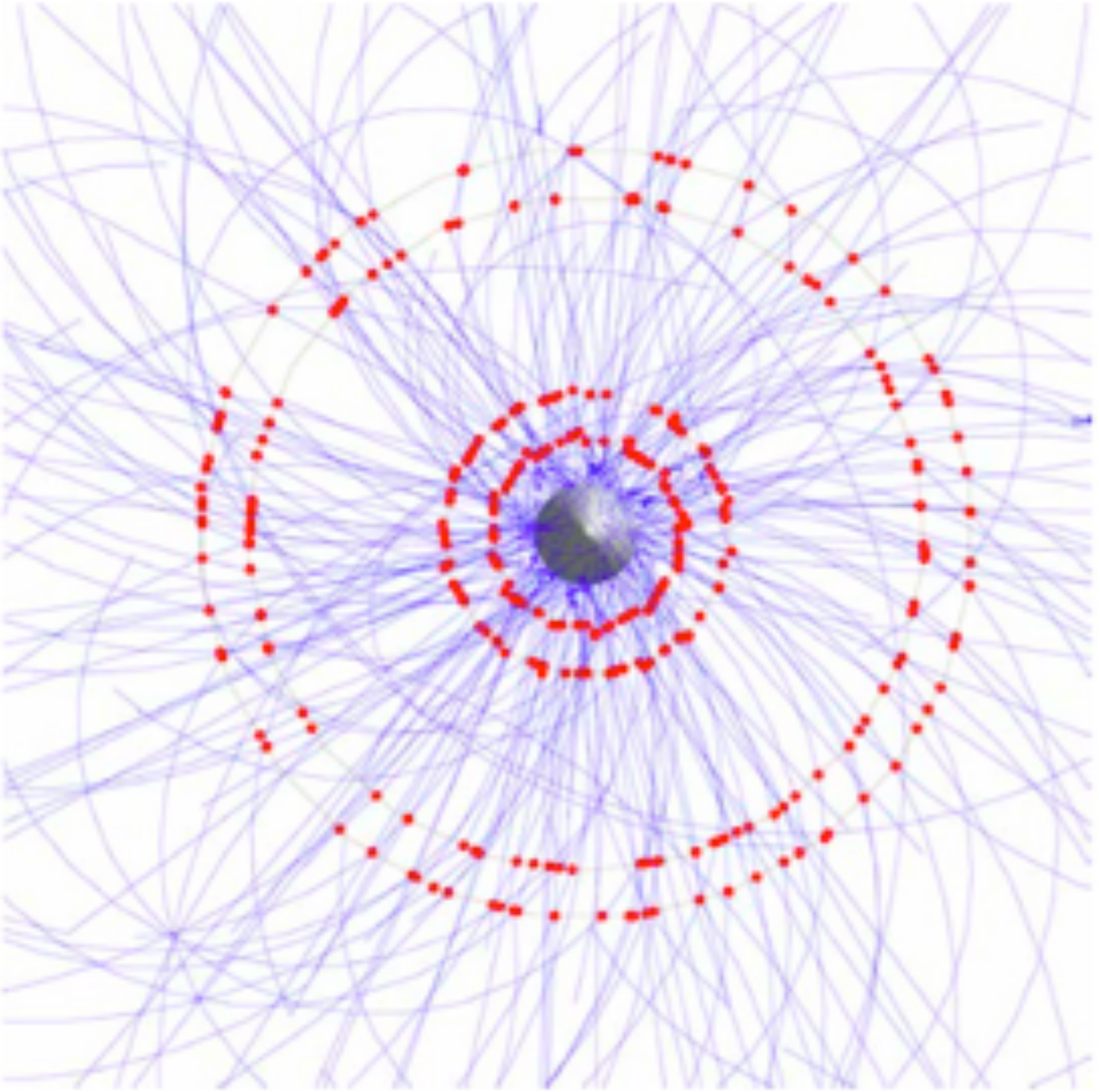
The timing detectors: Fibers and tiles

- 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%)

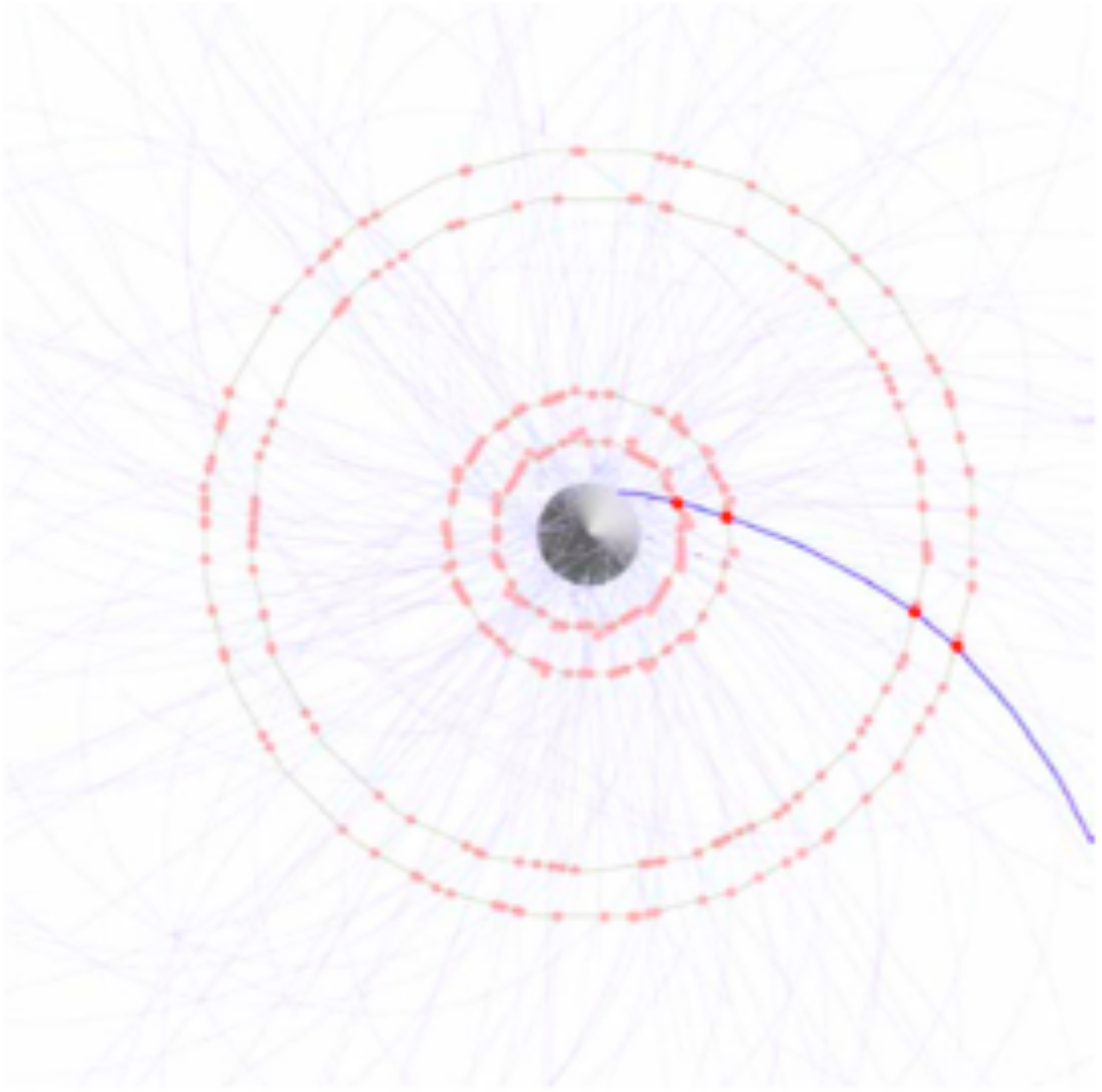


The timing detectors: Fibers and tiles

- 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%)



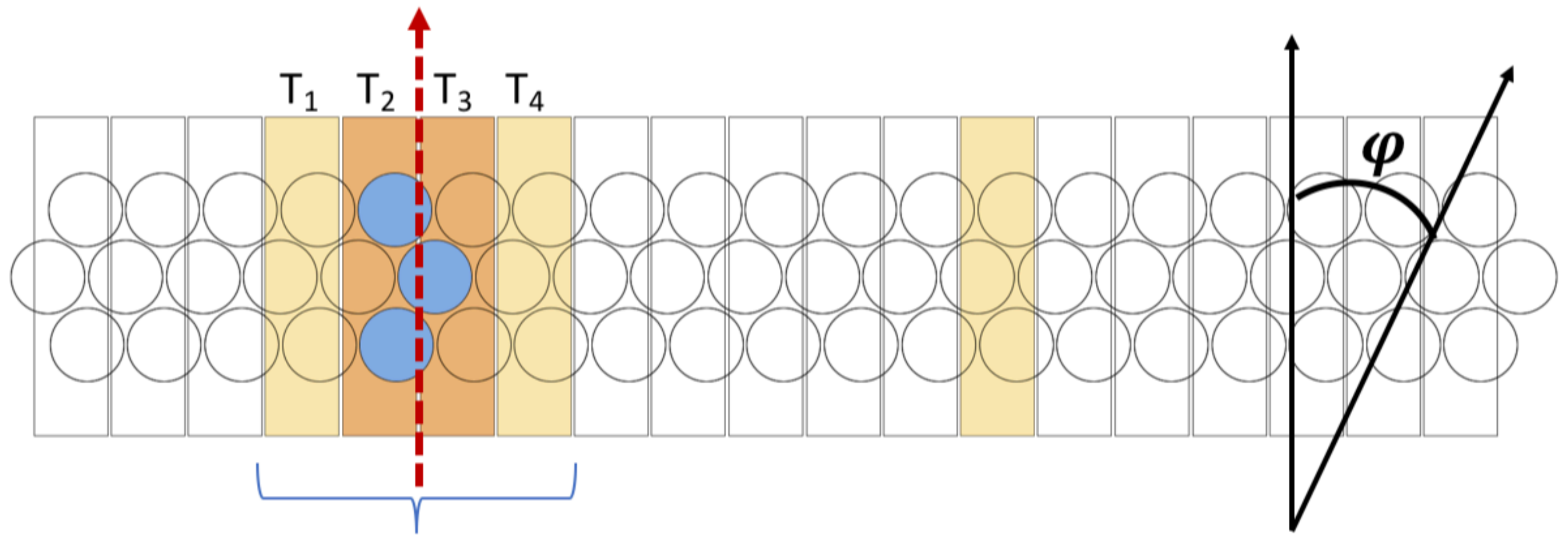
Pixels: O(50 ns)



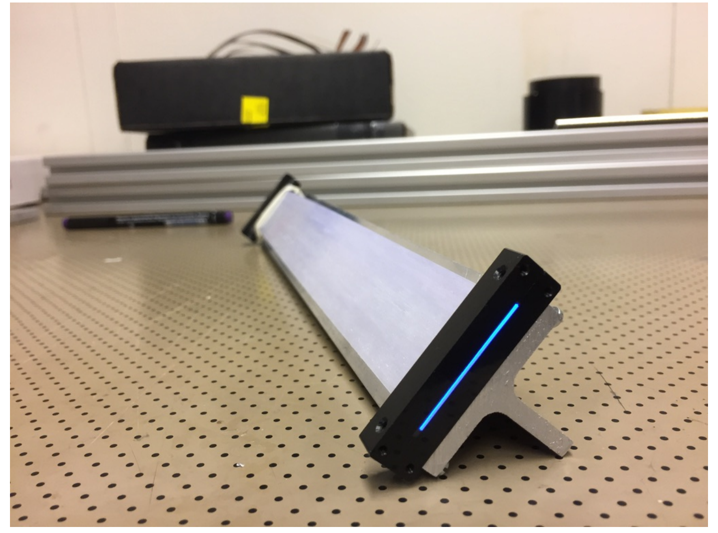
Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

SciFi prototypes: Results

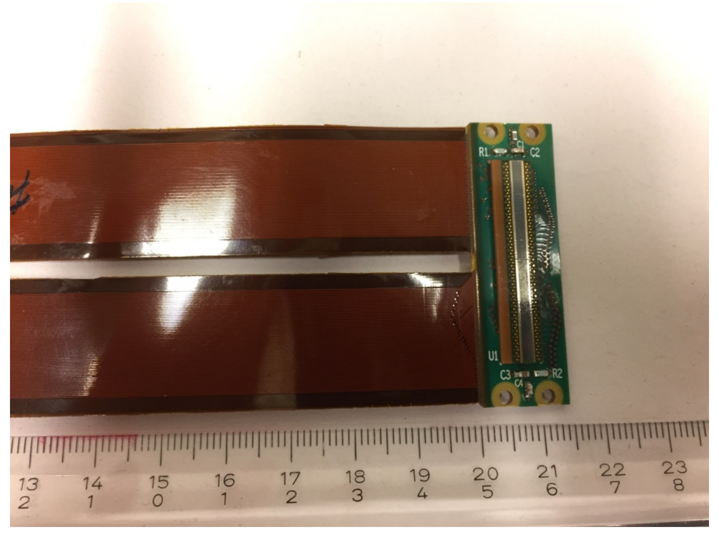
- Studied a variety of fibres (SCSF 78 MJ, clear; SCSF 78 MJ, with 20% TiO2; NOL 11, clear; NOL 11, with 20% TiO2; SCSF 81 MJ, with 20% TiO2; BCF12 clear; BCF12, with 100 nm Al deposit)
- Confirmed full detection efficiency (> 96 % @ 0.5 thr in Nphe) and timing performances for multi-layer configurations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

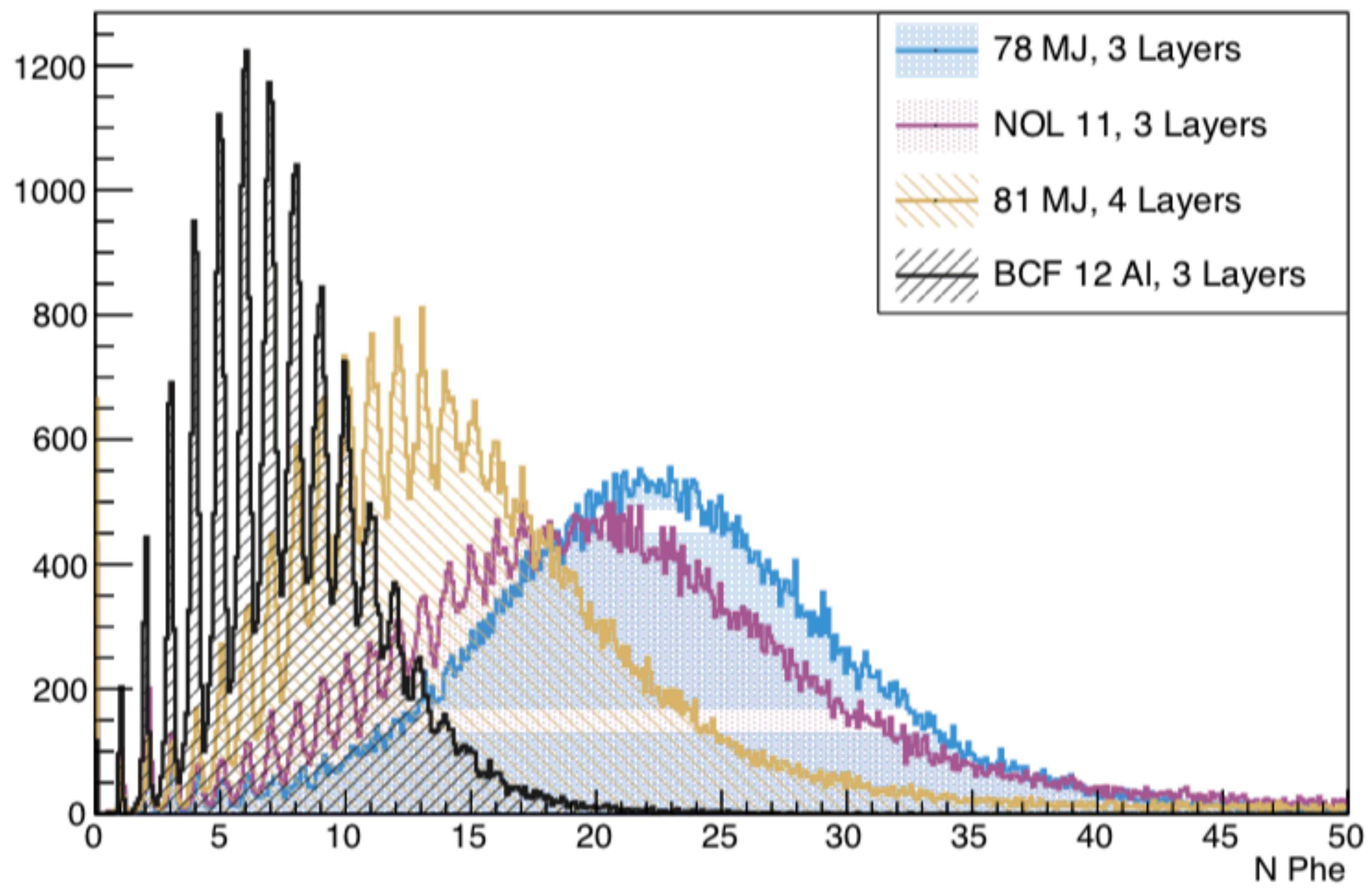


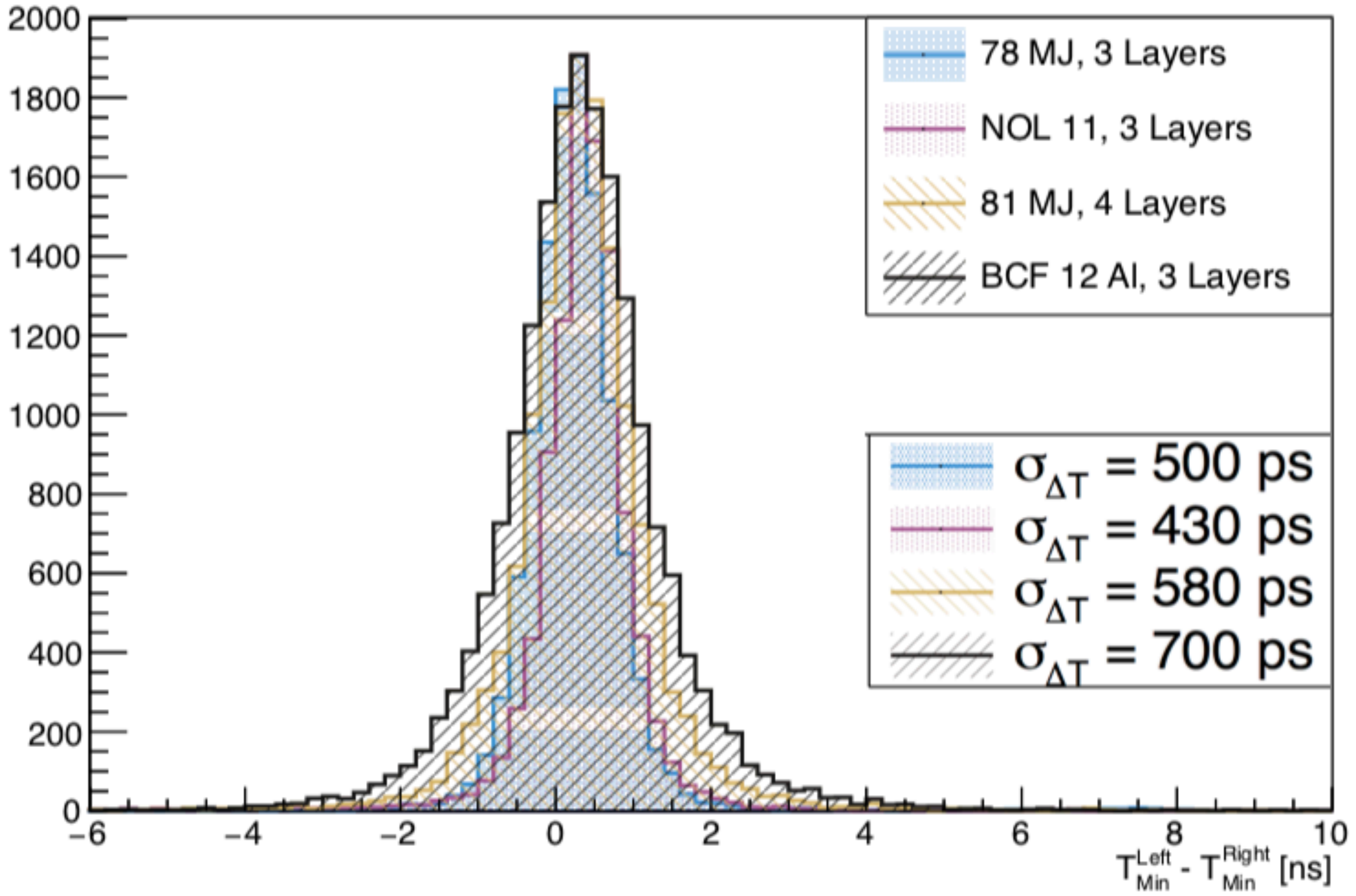
Fibre ribbons:



SiPM Array:
Hamamatsu S13552-HQR

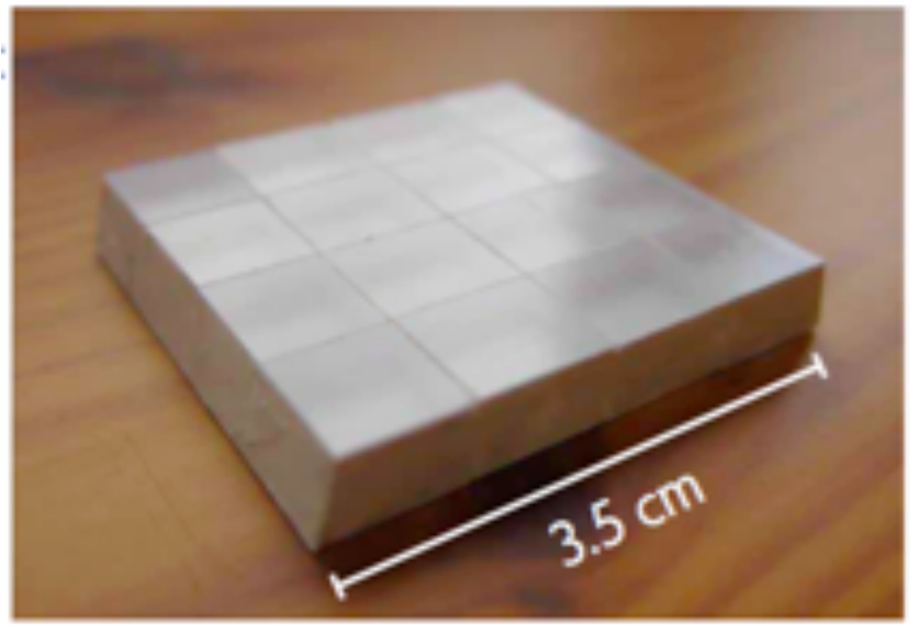


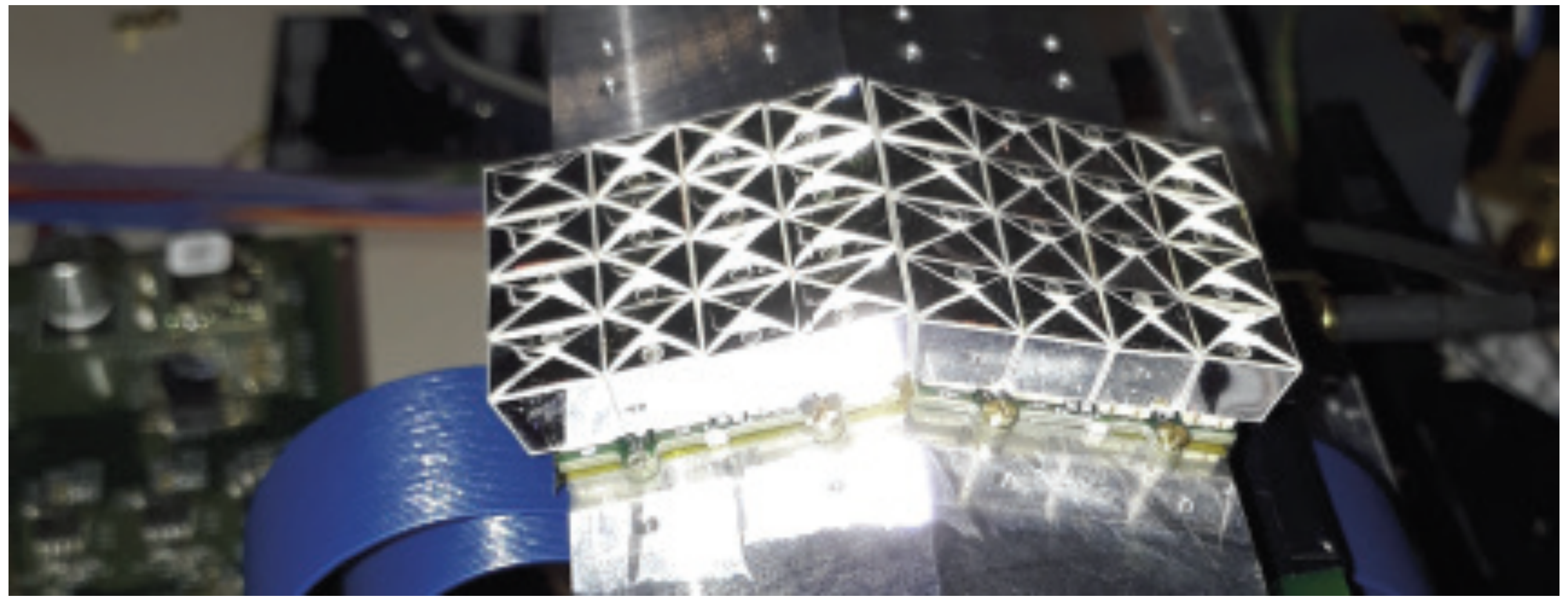


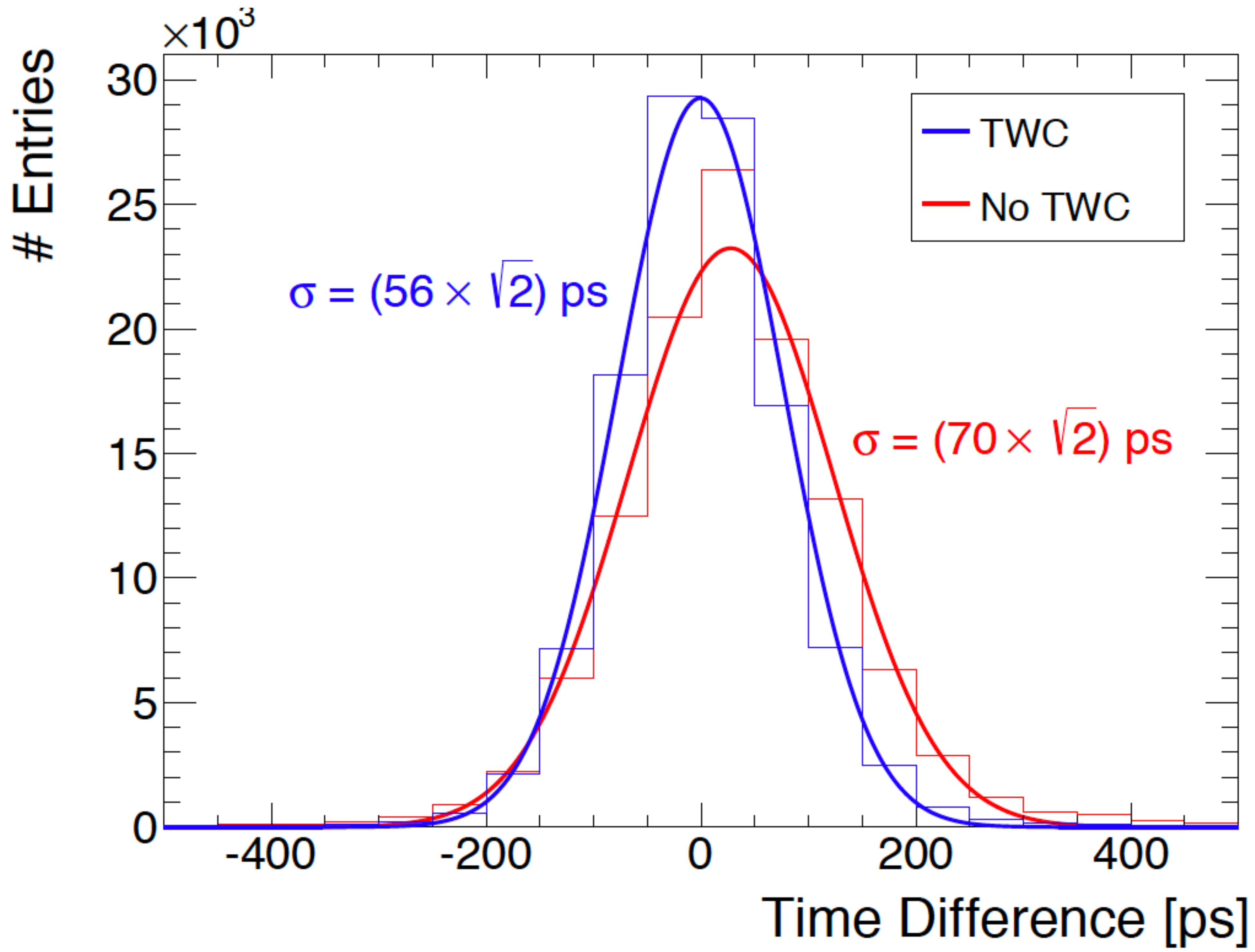


Tile Prototype: Results

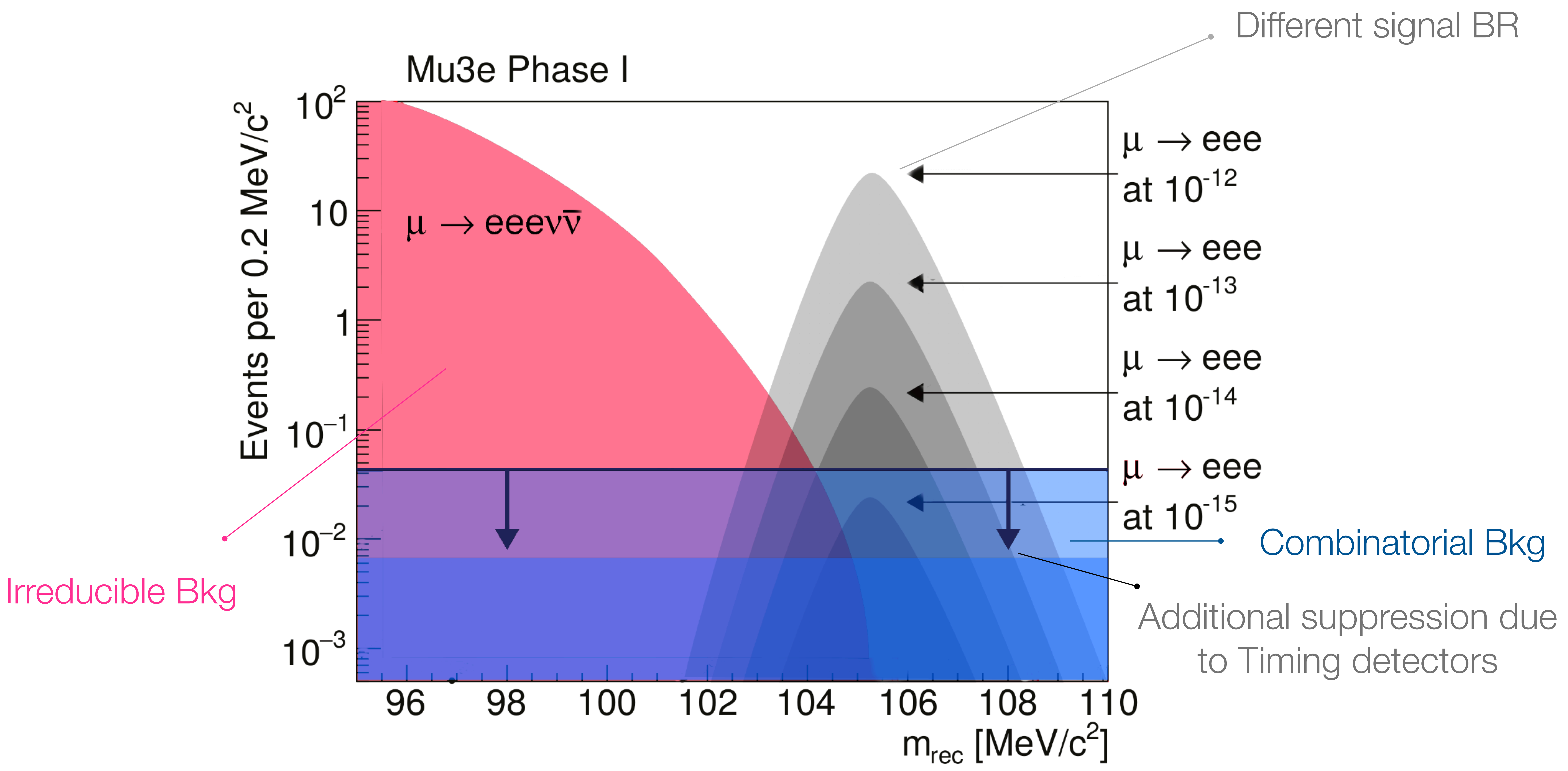
- Mu3e requirements fulfilled: Full detection efficiency (> 99 %) and timing resolution O (60) ps
- 4 x 4 channel BC408
- 7. 5 x 8. 5 x 5. 0 mm^3
- Hamamatsu S10362-33-050C (3 x 3 mm^2)
- readout with STiC2







Mu3e Phase I sensitivity



Latest news and currents status

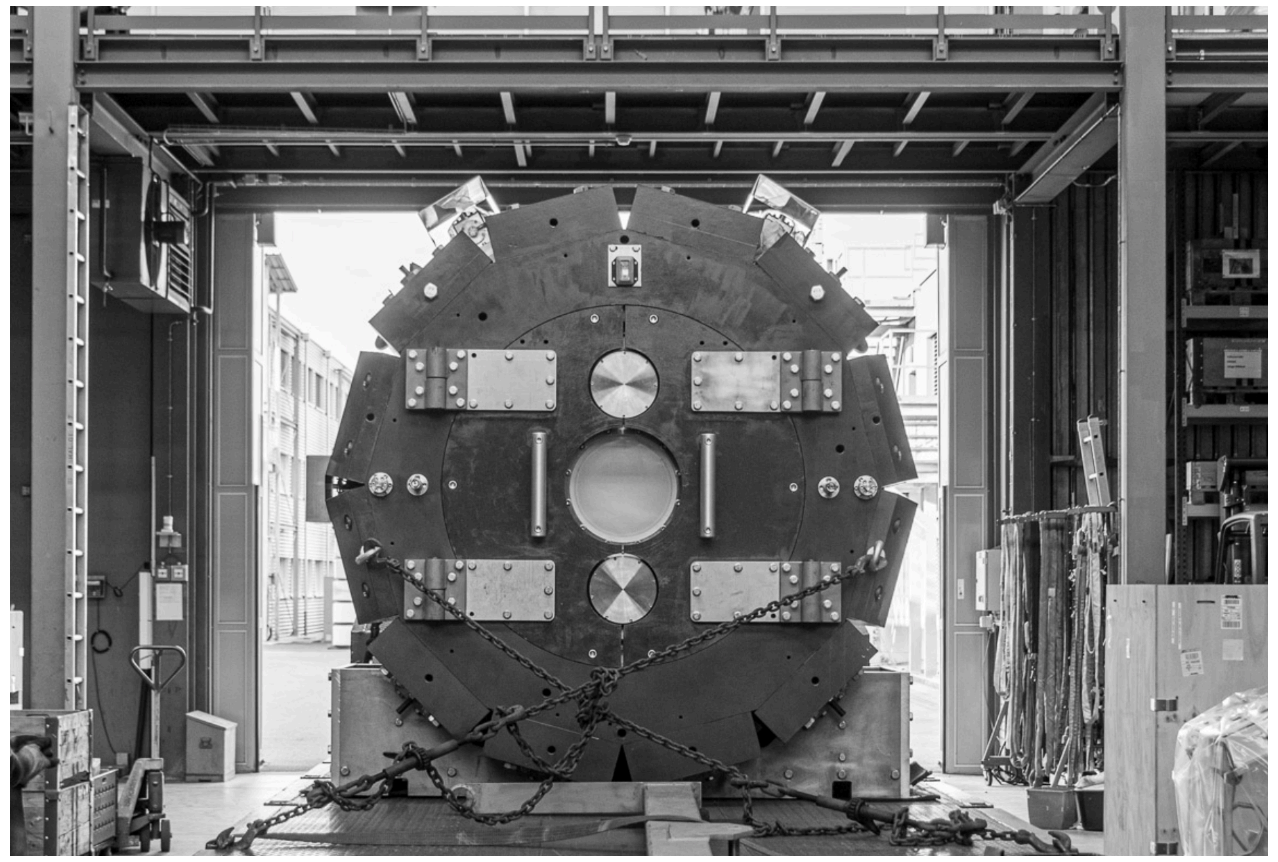
Key points:

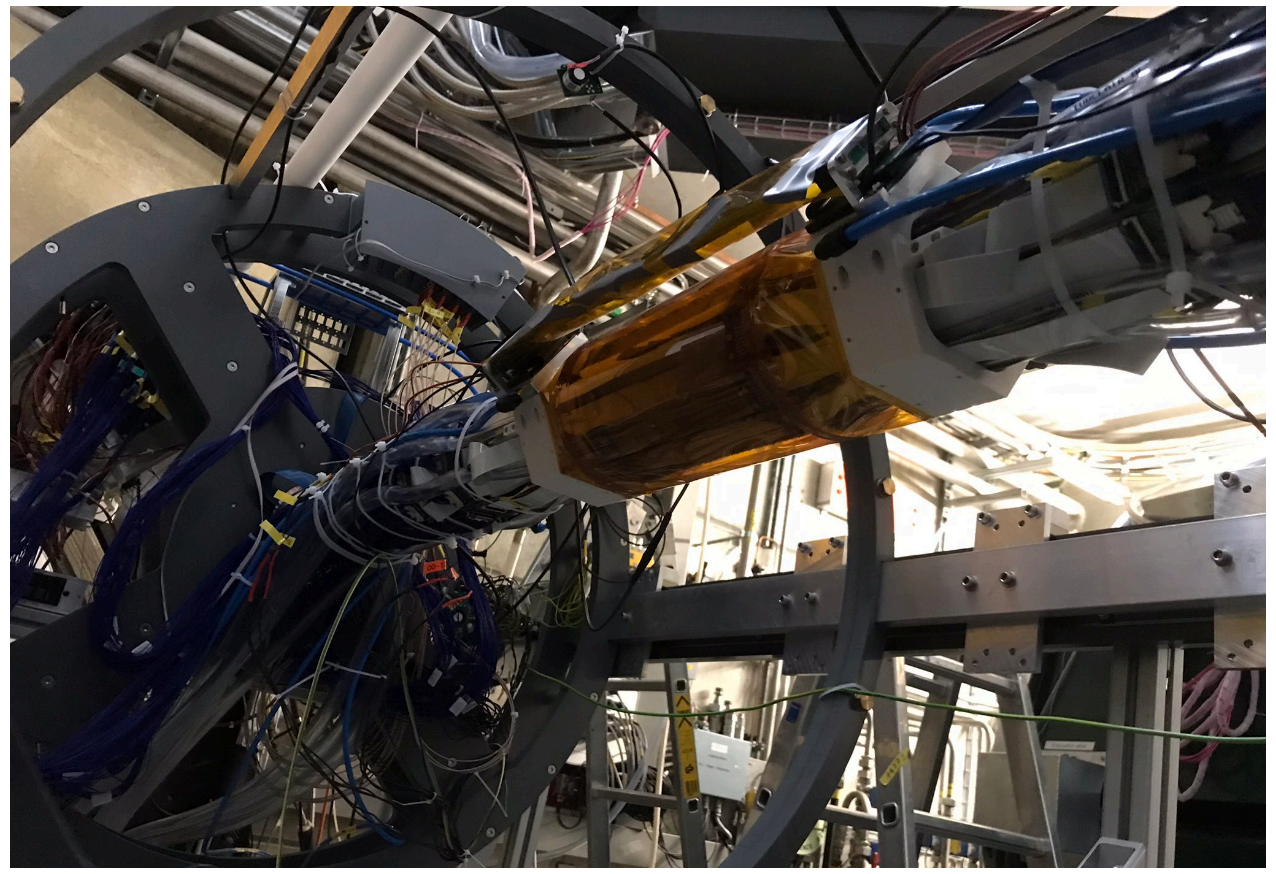
- **First integration Run 2021**
- Inner MuPix layer
- SciFi ribbons
- Sub-detector services

- **Full beam line commissioning 2022**
- Very successful: TDR promised values **matched!**
  - **2.49e10^8 mu/s @2.4 mA** (at the collimator): The highest beam rate in pie5 at the collimator
  - **1.02e10^8 mu/s @2.4 mA** (Mu3e magnet): Several beam configurations studied, some of them connected with possible Mu3e magnetic field intensity optimisation

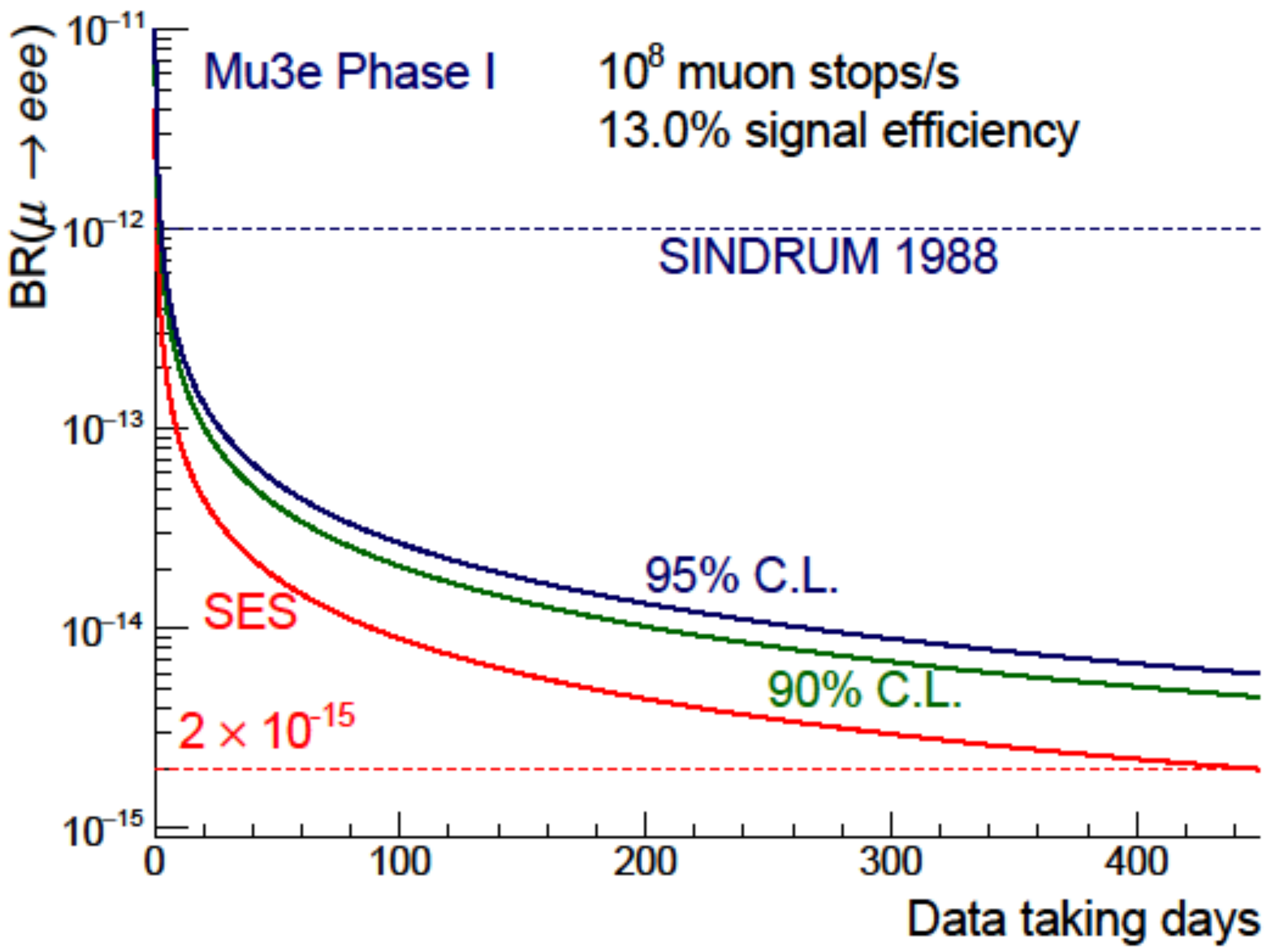
Outlook:

- Cosmic Ray Run ongoing outside the experimental area with all sub-detector services
- MuPix mass production: ongoing
- Complete integration run: 2023
- Engineering run: 2024
- First physics run: 2025

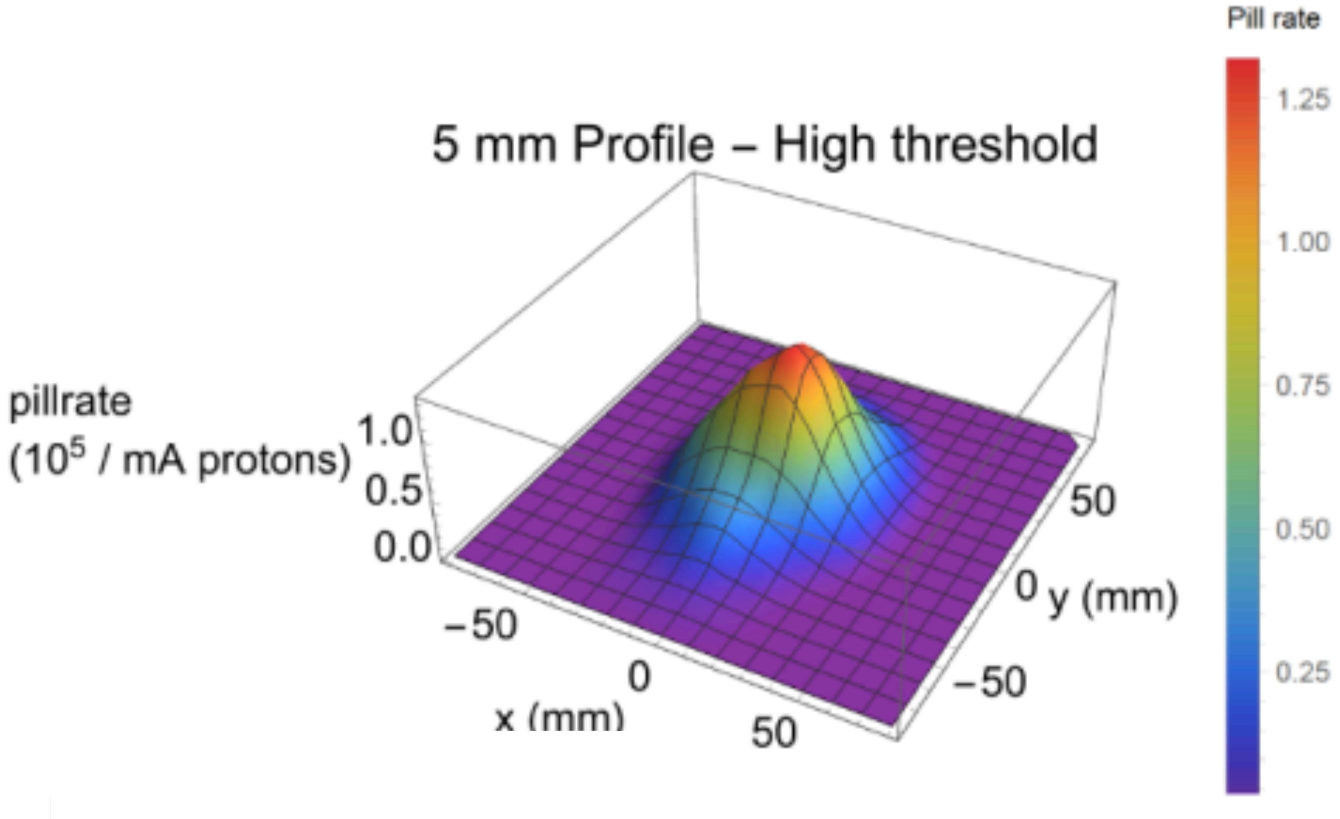




Full analysis performed on Simulated data



Beam commissioning **2022**



2.49e10^8 mu/s @2.4 mA

Summary

- Astonishing sensitivities in muon precision physics at intensity frontiers are ongoing and foreseen for the incoming future
- **Rare/forbidden decay searches and symmetry tests remain among the most exciting places where to search for new physics with strong synergy and connection with the neutrino physics program**
- Both very intense and high brightness muon beams and new detector developments are the keys for addressing this very challenging physics program

Thanks a lot for your attention !!!

Back-up

Muon beams worldwide summary

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)	

Muon beams and muon beam based experiments

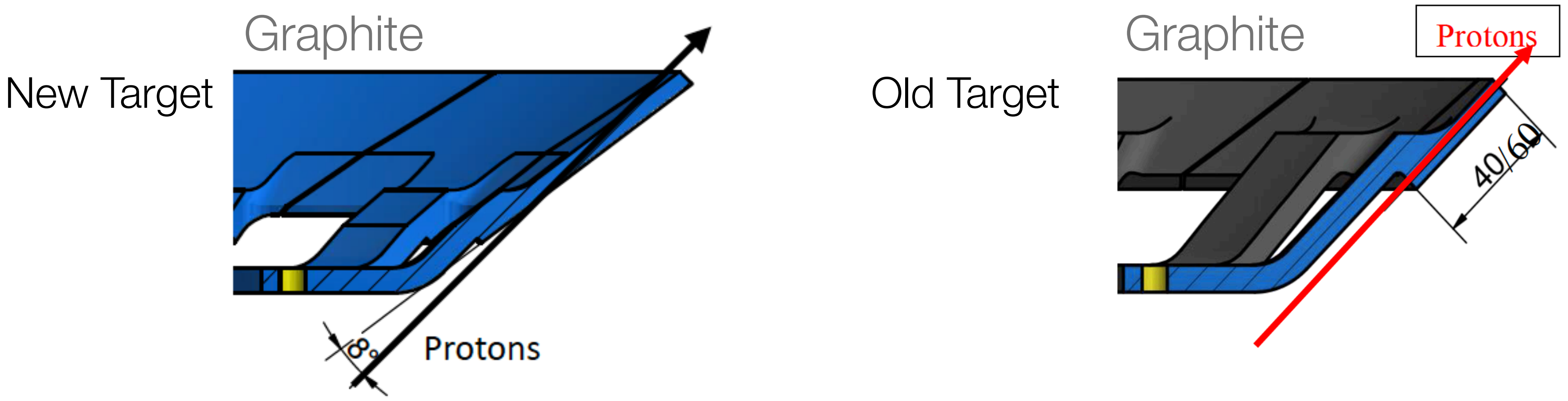
- Next generation on muon based experiments require higher muon rates
  - New opportunities for future muon (particle physics) based experiments
  - New opportunities for μSR experiments

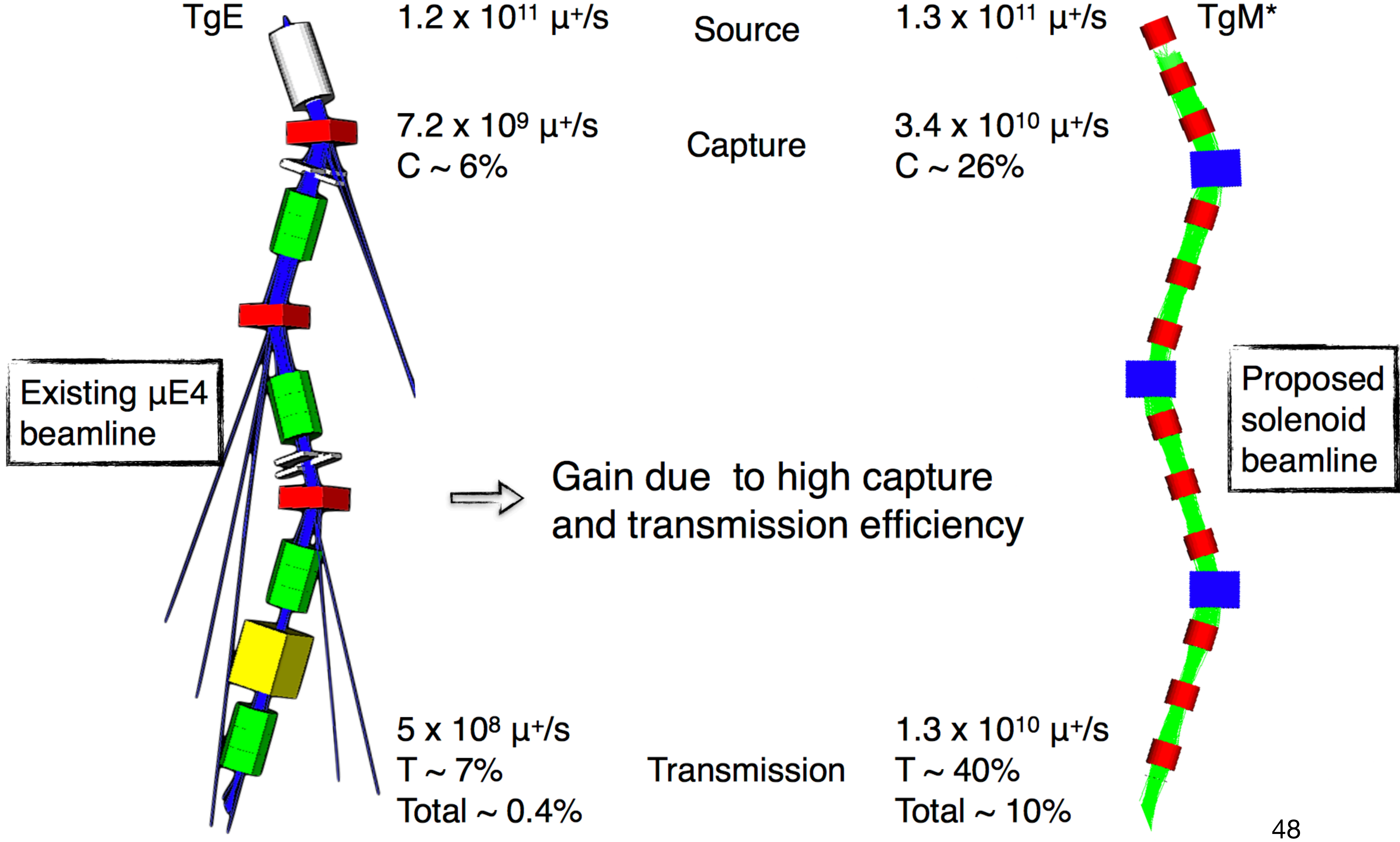
- Different experiments demand for a variety of beam characteristics:
  - DC vs pulsed
  - Momentum depends on applications: stopped beams require low momenta
  - Phase space

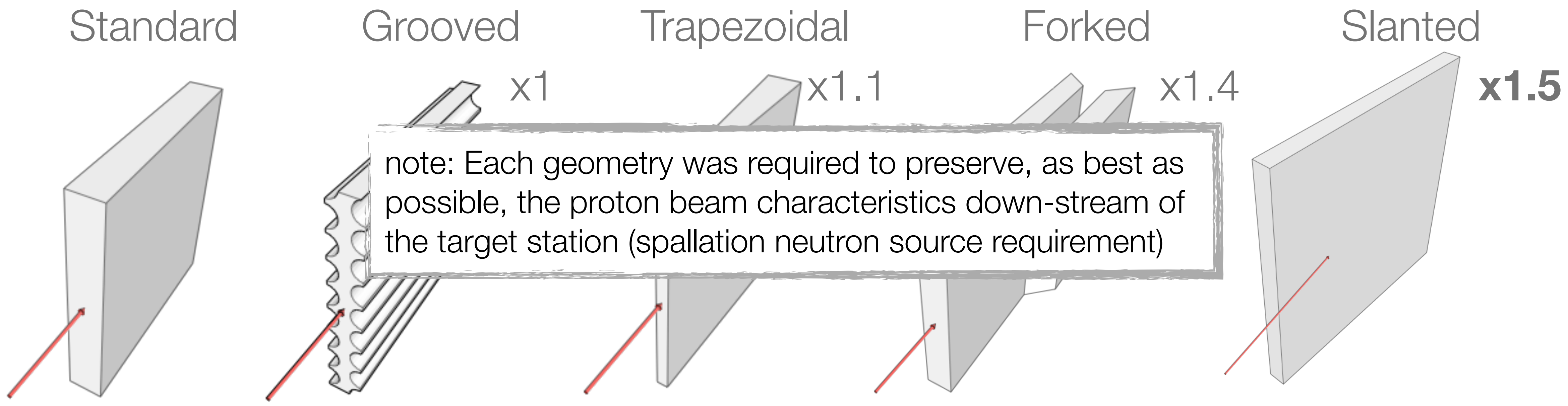
- Beam with different characteristics are/will be available worldwide

The HiMB (High Intensity Muon Beam) project at PSI

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
  - Target: alternate materials (B_4C and Be_2C show 10-15% gain) and/or geometry (up to 60% of gain: Graphite **Slanted target**)
  - Beam line: high capture efficiency and large phase space acceptance transport channel
- Slanted target test (“towards the new M-target”) successfully done (2019) and installed as “default” target since 2020
  - **Increase surface muon rates for all connected beam lines (30-60% increase depending of the beamline): Confirmed**
  - **Increase safety margin for “missing” target with the proton beam: Confirmed**
  - **Slanted target final place: Current “M” target**
- PSI Long shut-down: **2017-18. HiMB from 2018**



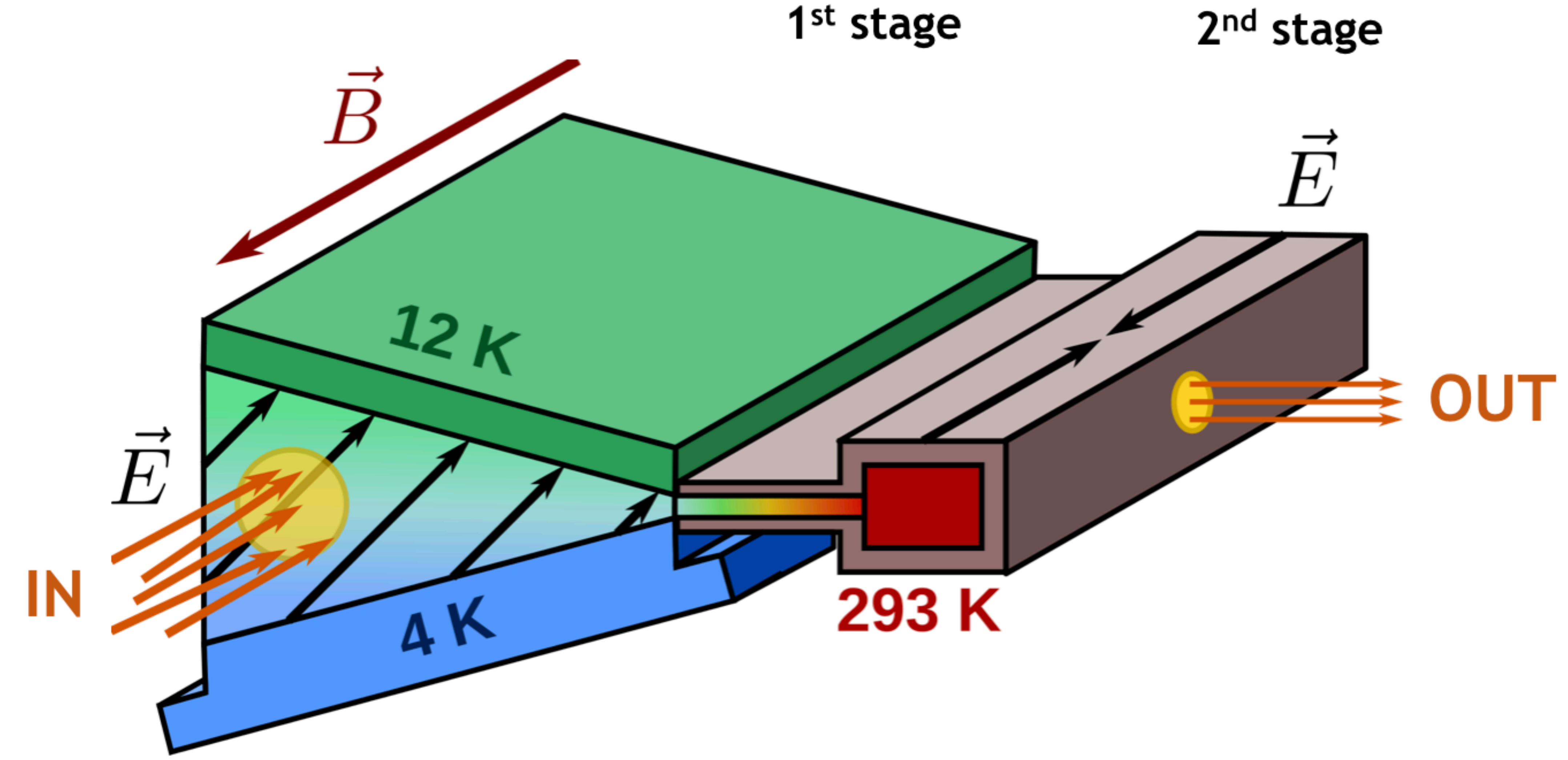




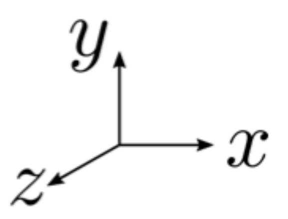
The muCool project at PSI

- 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 **10^{10}** with an efficiency of O(**10^{-4}**)

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



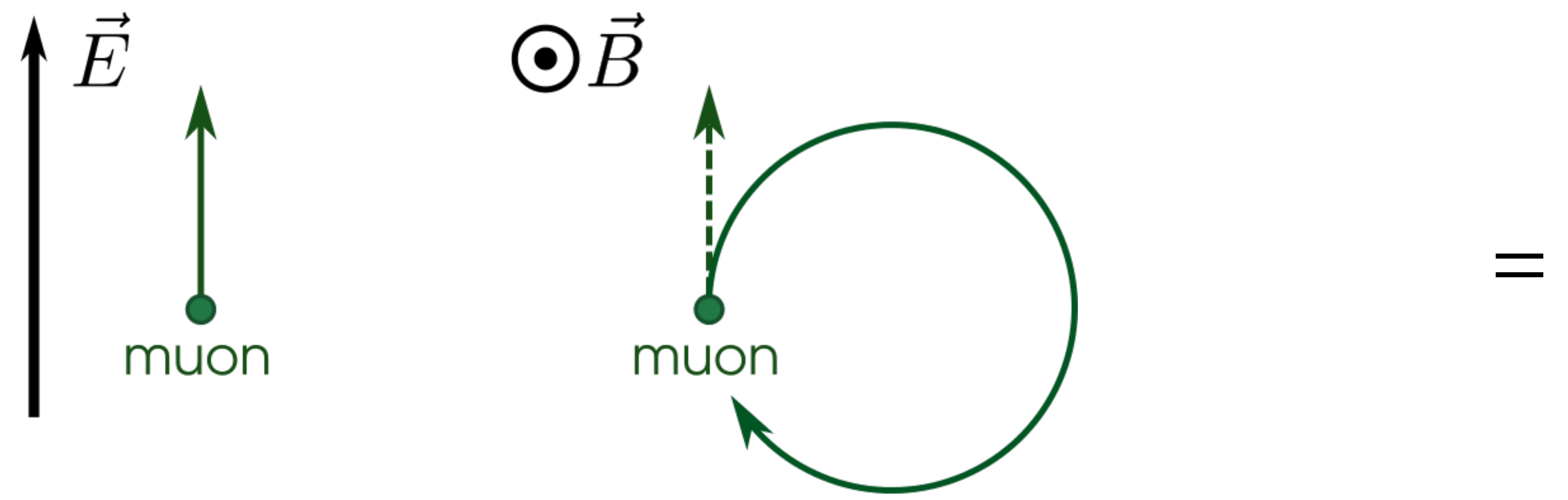
muCool/tertiary μ^+ beam
- σ < 1mm
- E < eV
- Tagged

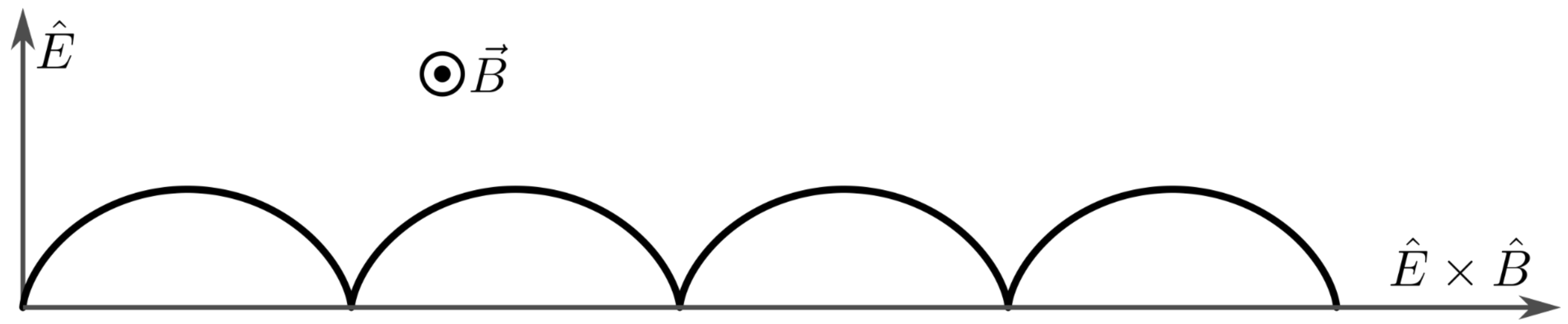


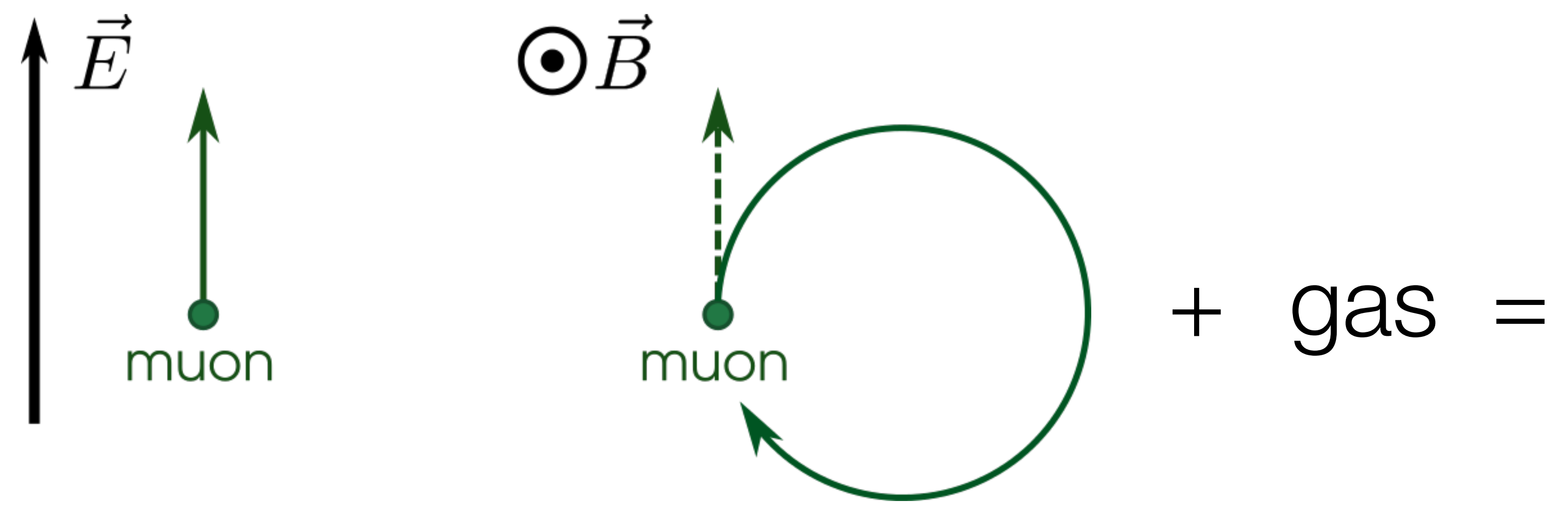
→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

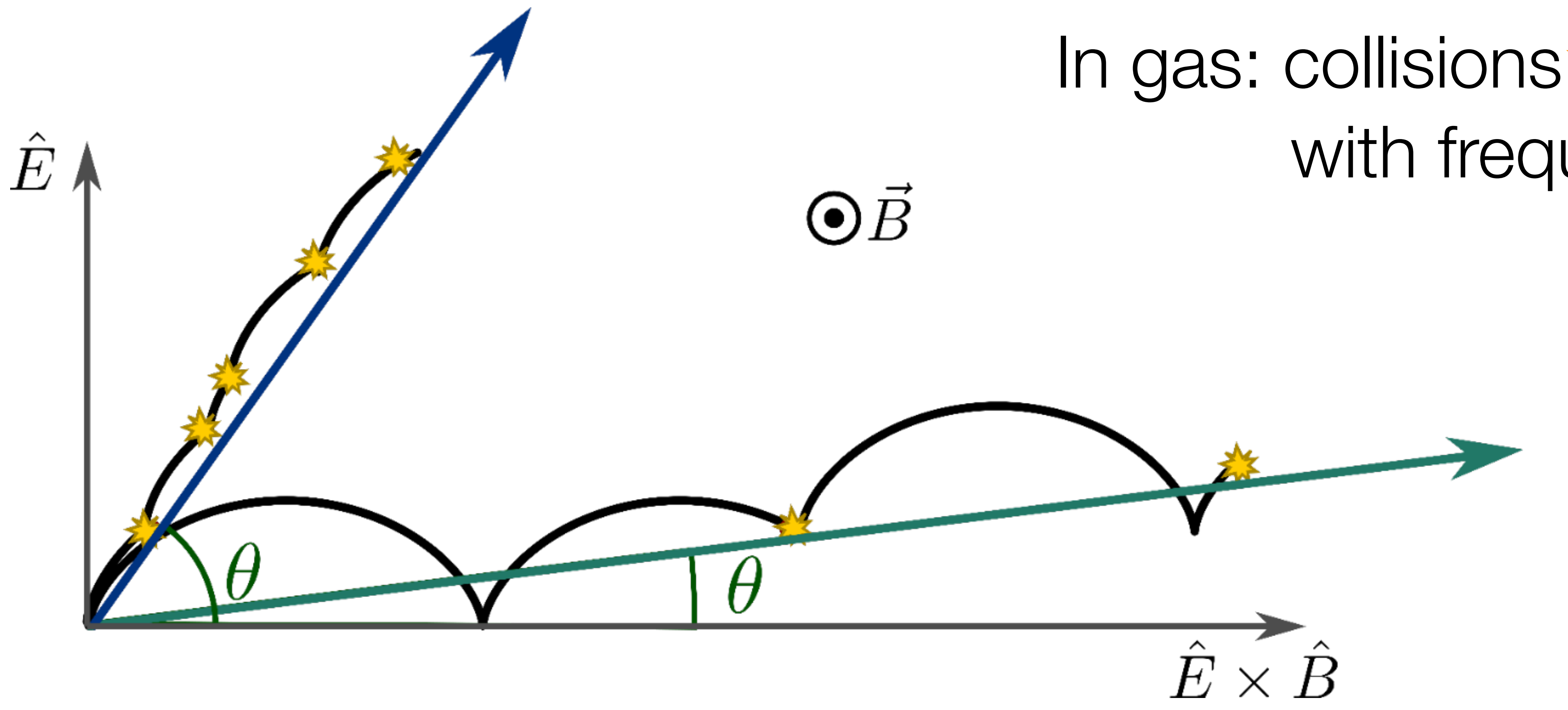
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

Trajectories in E and B field



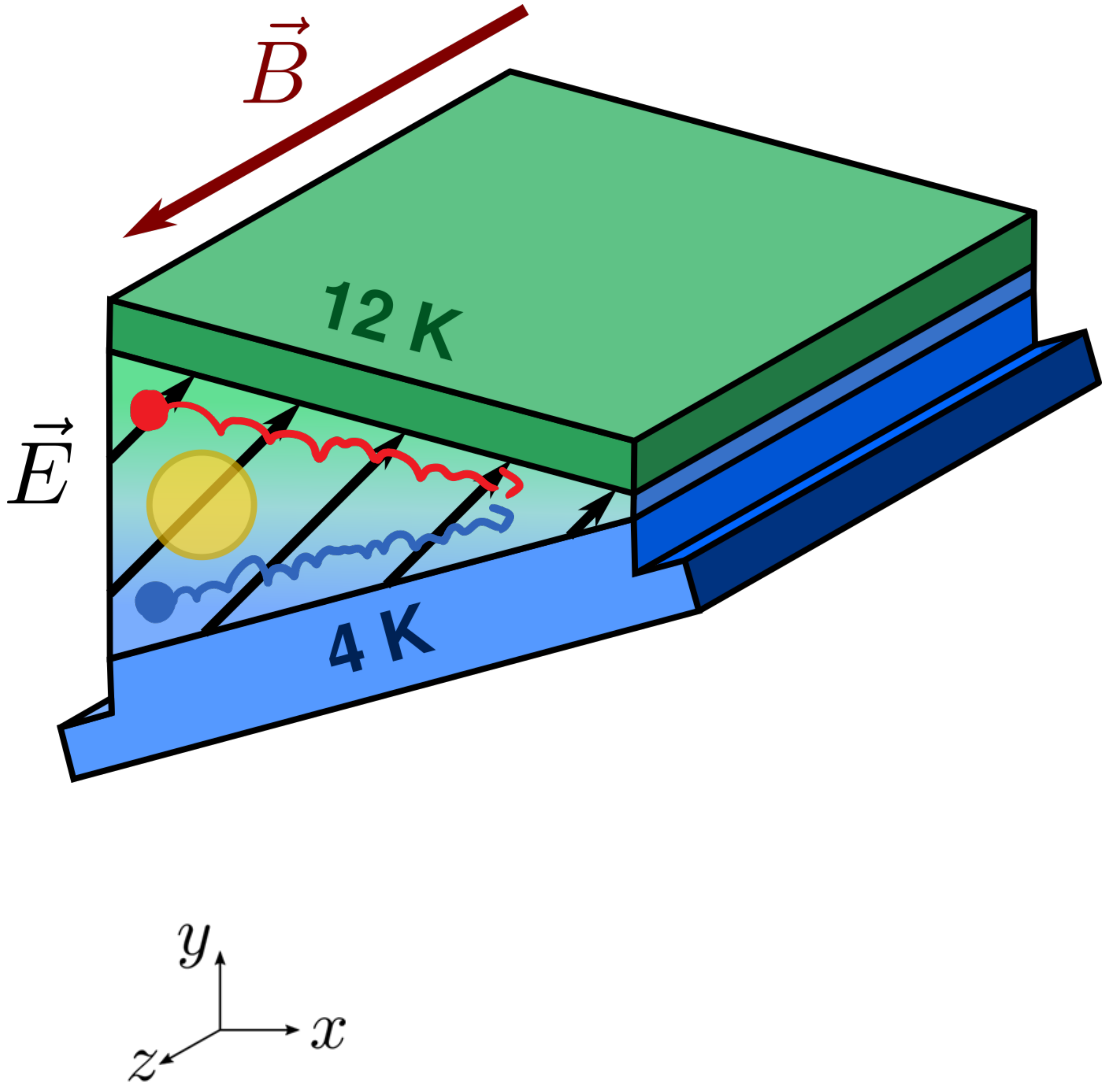


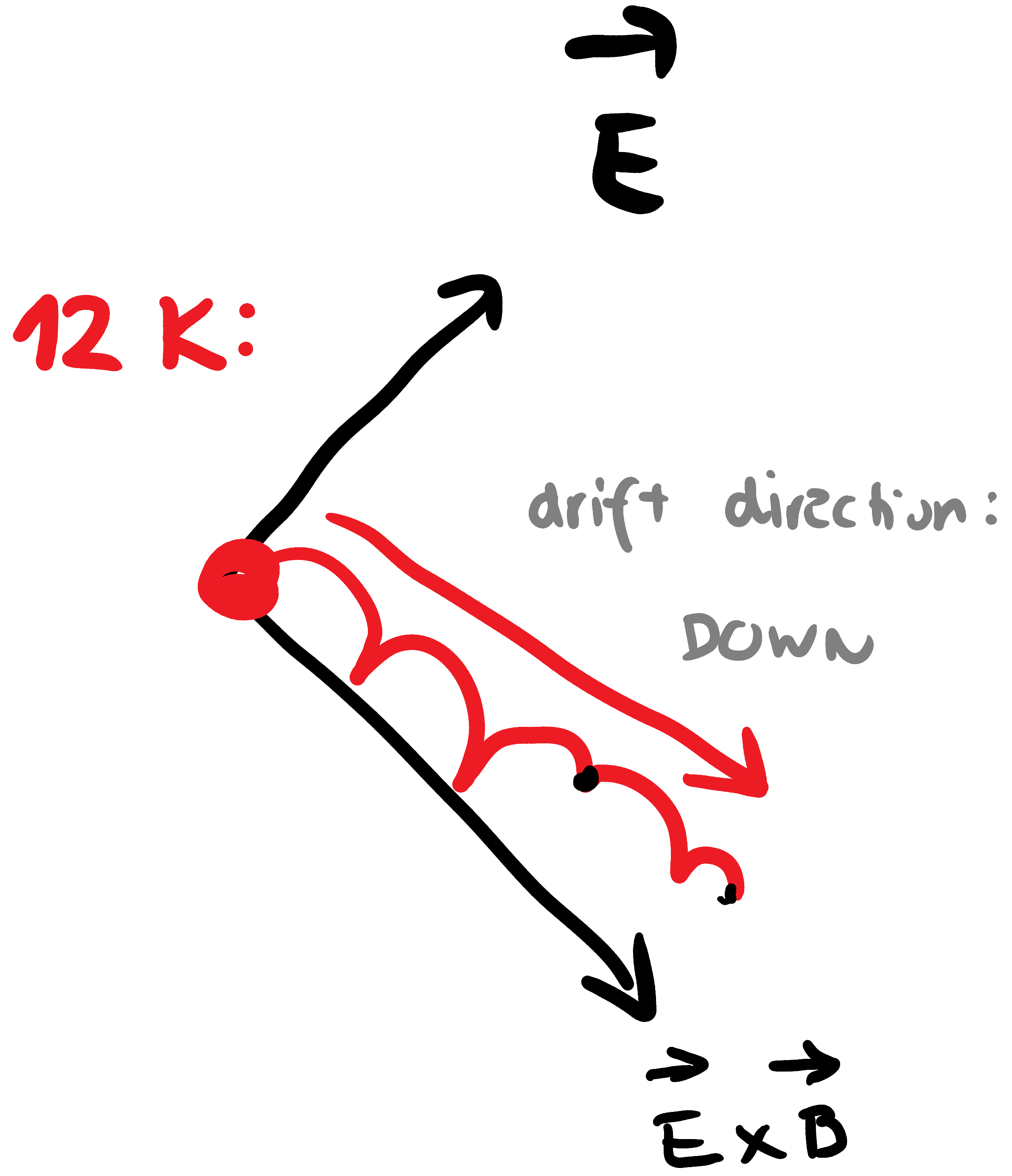


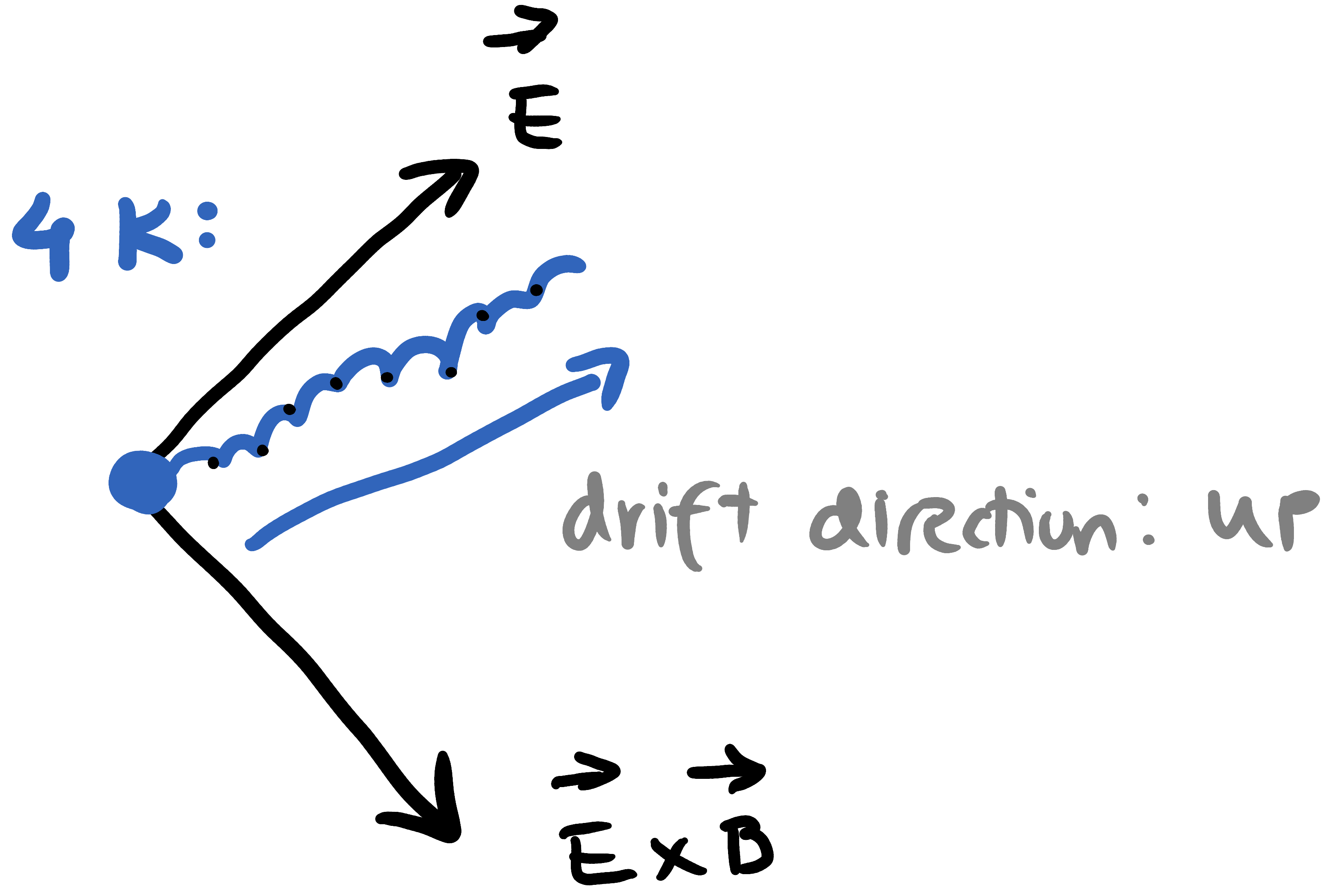


In gas: collisions ☆
with frequency f_{col}

Working principle: 1st Stage

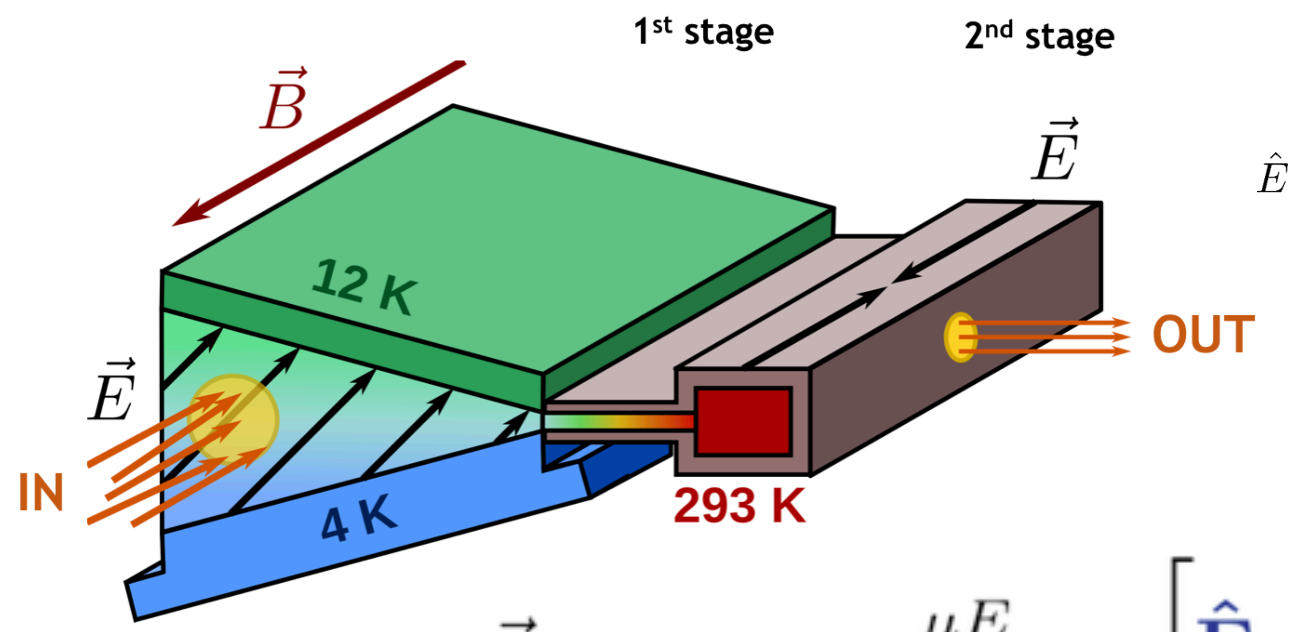


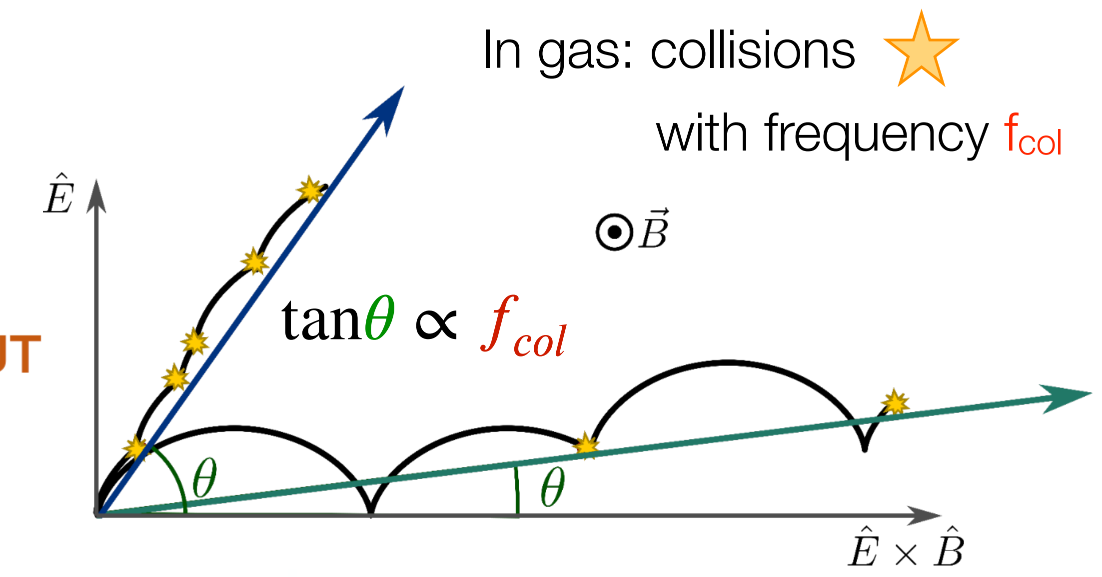




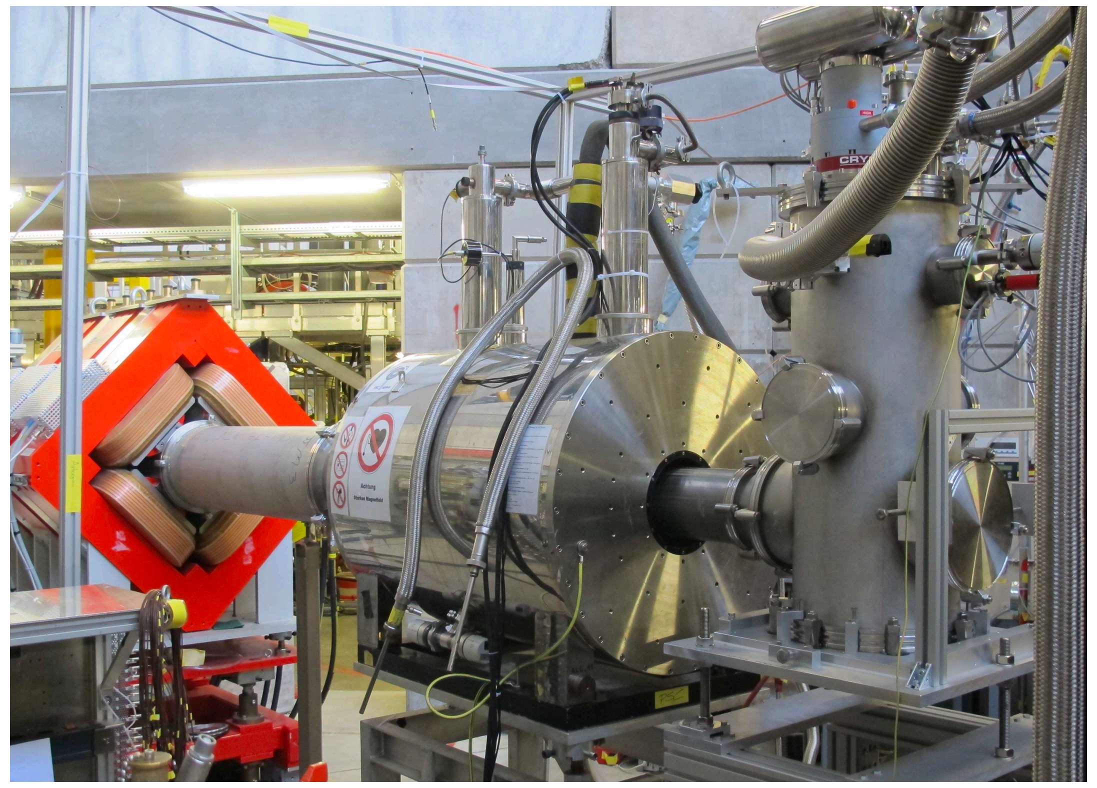
Summary: The muCool project at PSI

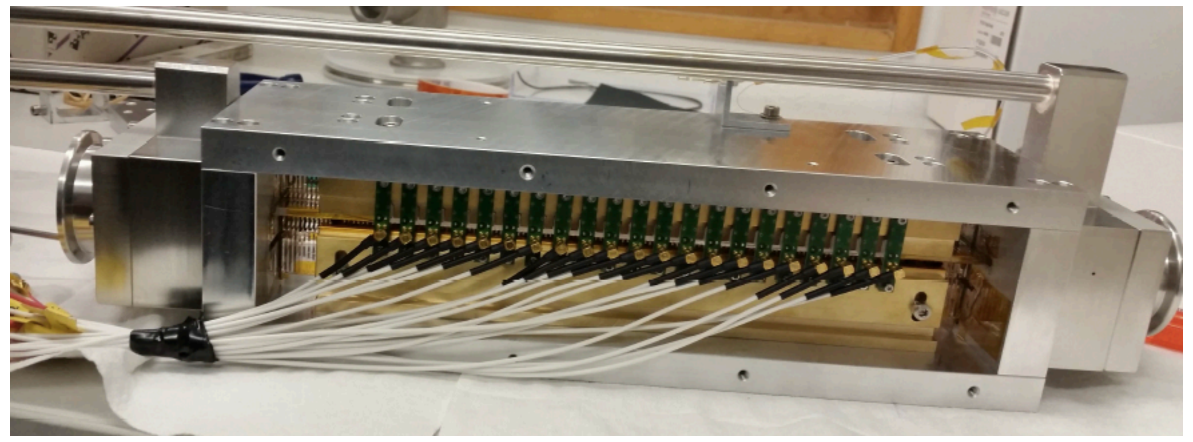
- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^{10}** with an efficiency of O(**10^{-4}**)
- Longitudinal and transverse compression (1st stage + 2nd stage): experimentally proved
- **Next Step**: Extraction into vacuum
- Current activity: abundant MC simulations in order to define the detailed experimental setup for the beam extraction in vacuum and eventually the beam re-acceleration

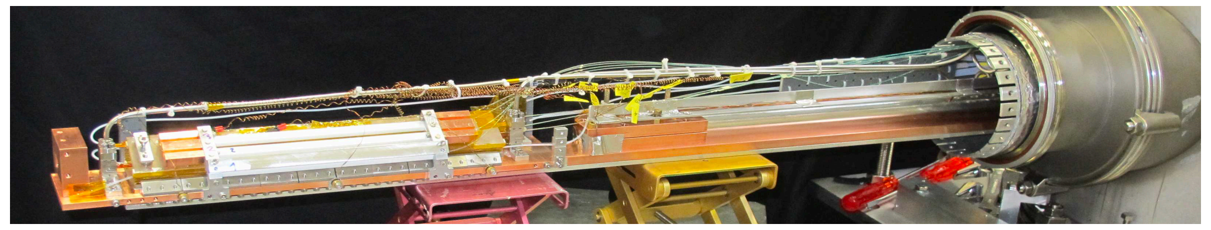




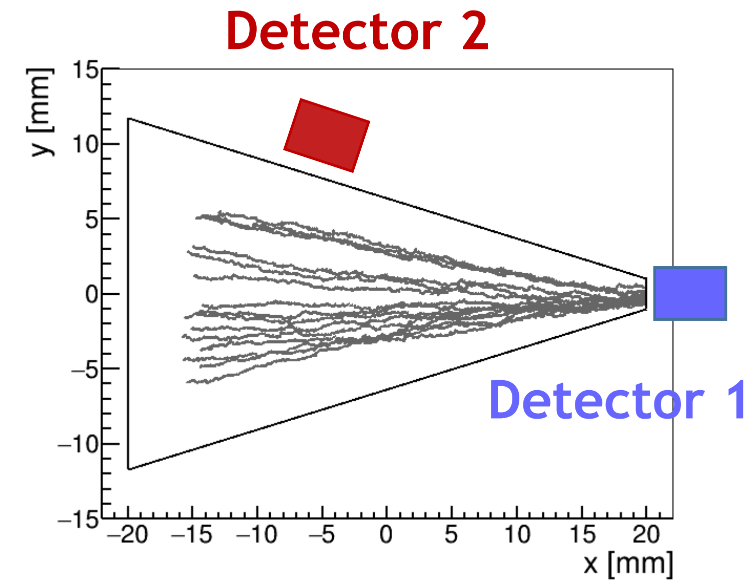
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

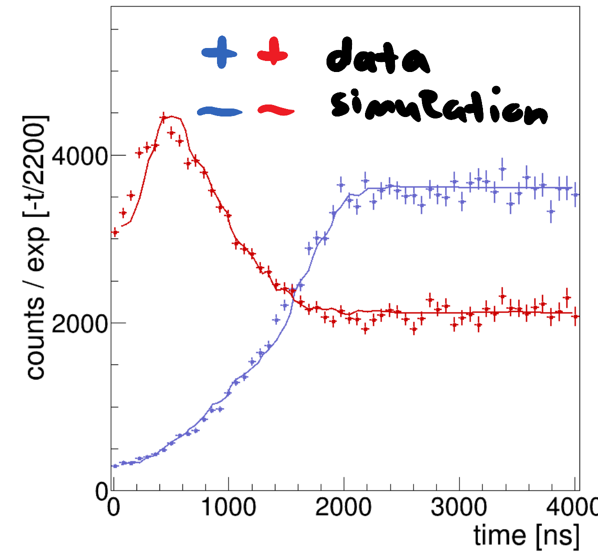




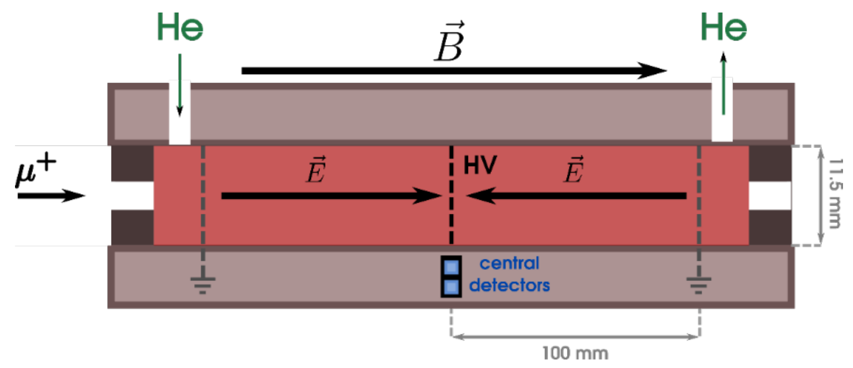


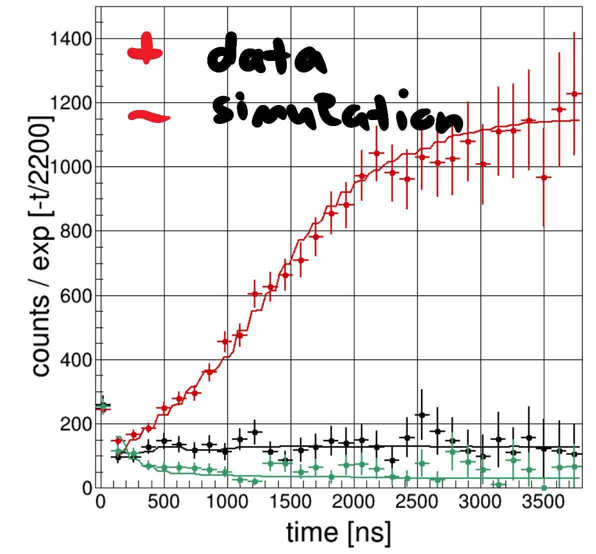
Transverse Compression





Longitudinal Compression





Longitudinal+ Transverse Compression