東京大学
素粒子物理国際研究センター
International Center for Elementary Particle Physics
The University of Tokyo

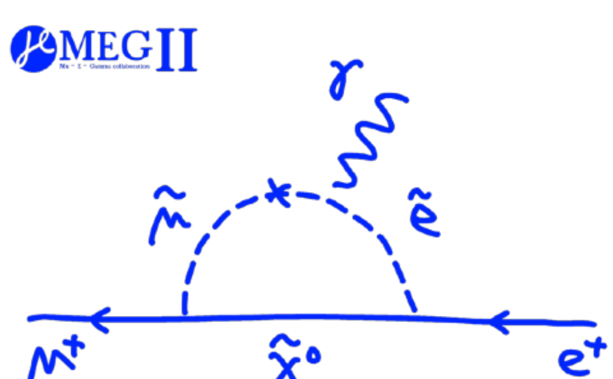
Status of MEG II and Mu3e at PSI

Toshiyuki Iwamoto
ICEPP, the University of Tokyo

8 June 2020

Conference on Flavour Physics and CP violation (FPCP) 2020

JSPS Core-to-Core Program



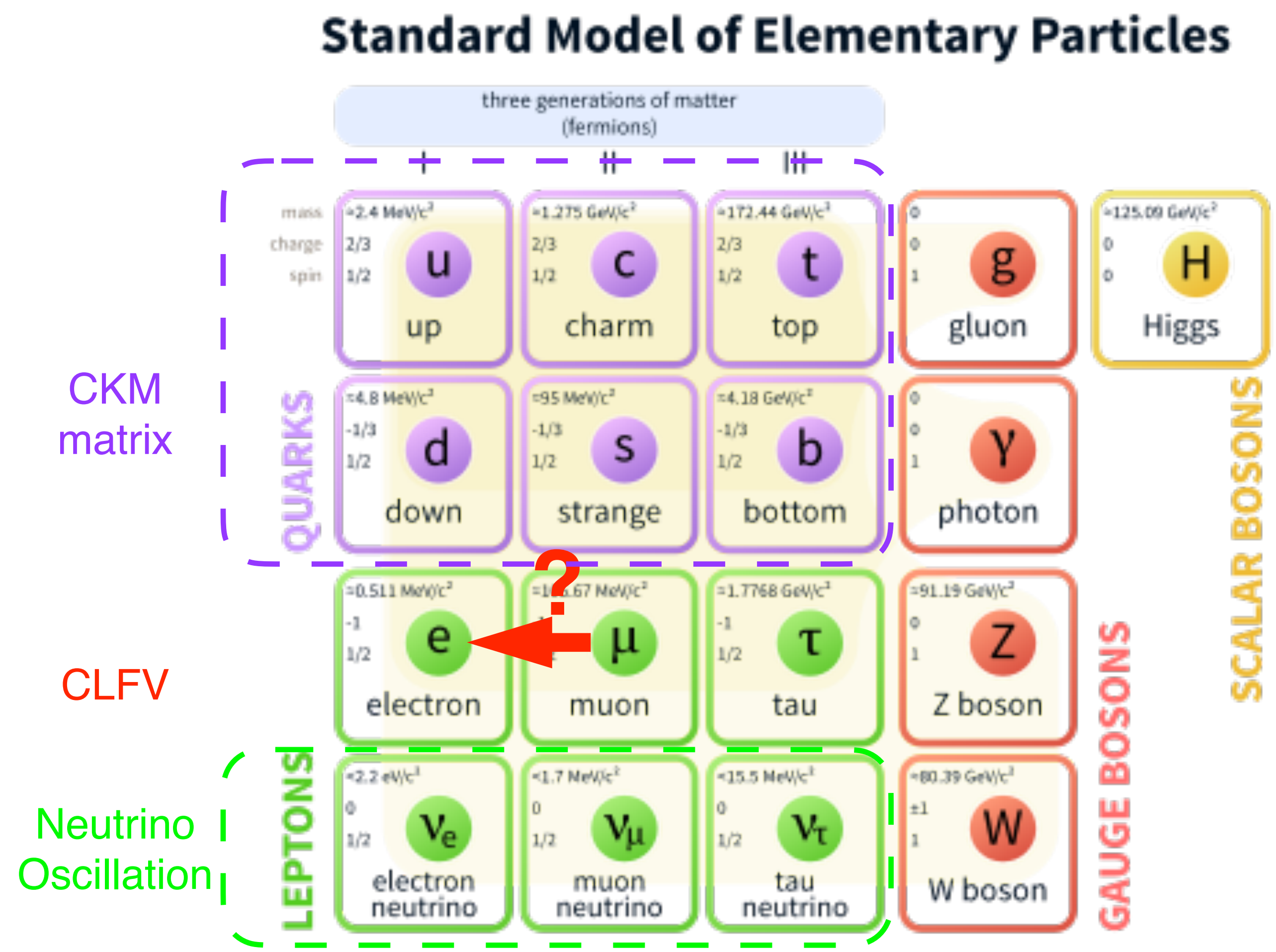
Mu3e

Introduction

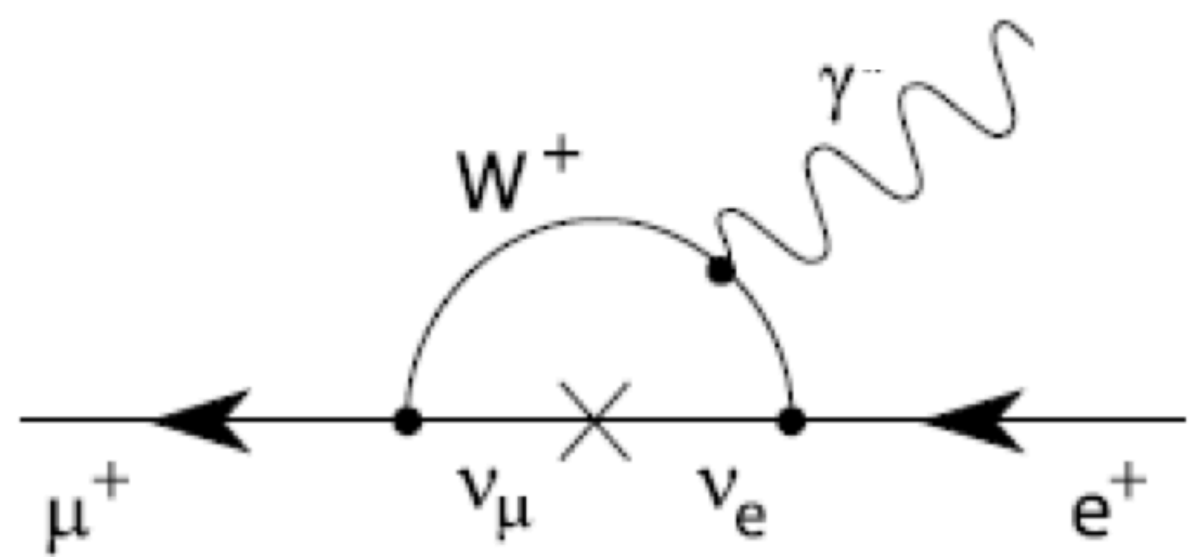
- Charged Lepton Flavor Violation (CLFV)
  - FV happens in quarks (CKM matrix) and neutral lepton (neutrino oscillation)
  - Why has charged lepton flavor violation never been observed yet?
- $\mu \rightarrow e\gamma$
  - Long search history since the muon has been discovered.
  - In Standard model + neutrino oscillation, CLFV can occur, but tiny,

    $Br(\mu \rightarrow e\gamma) \sim 10^{-54}$

  - An observation of CLFV is evidence of new physics.



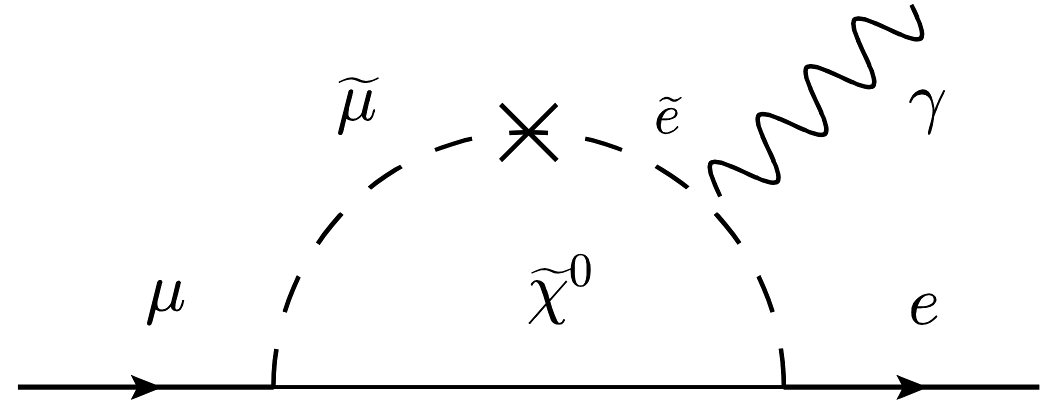
From Wikipedia

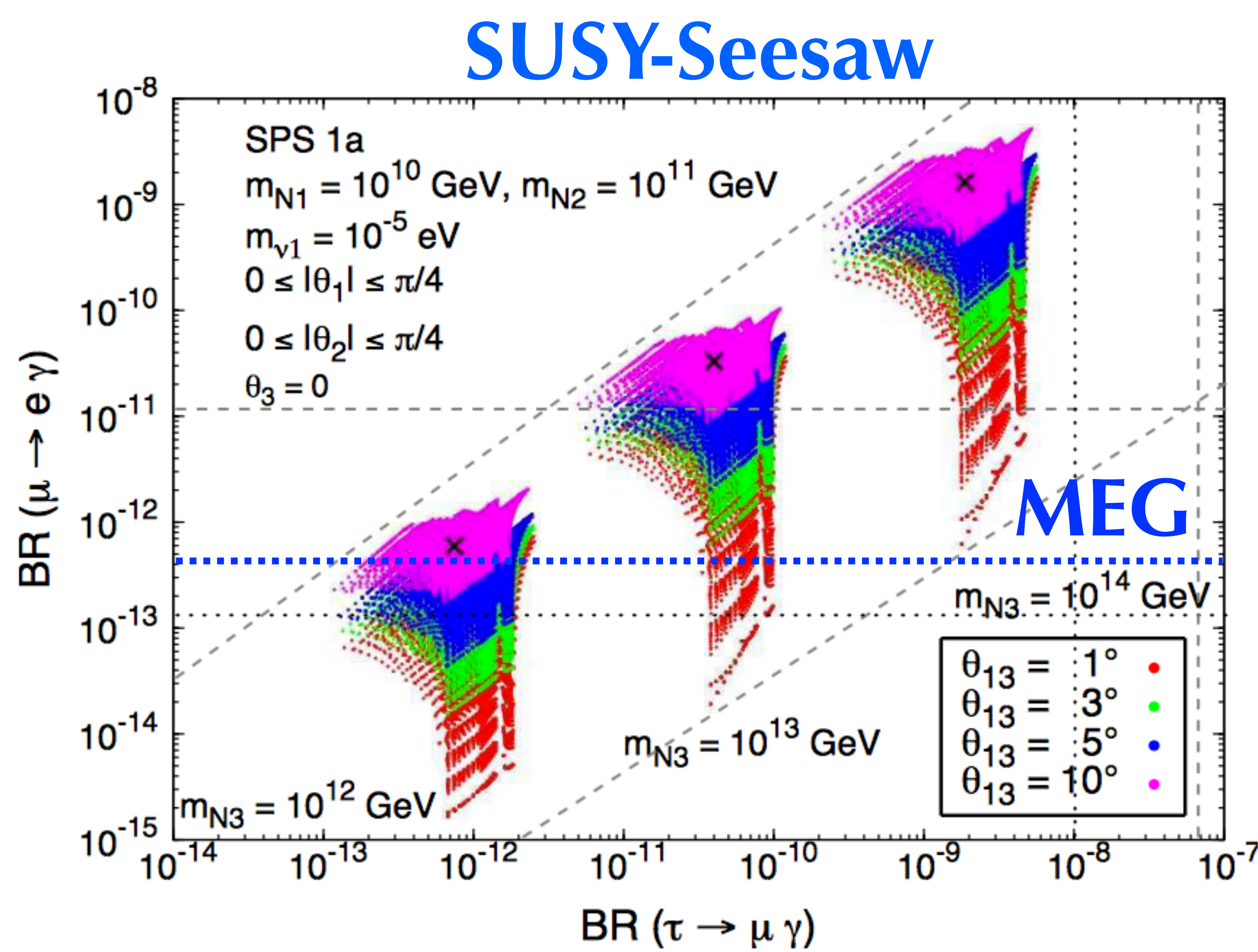


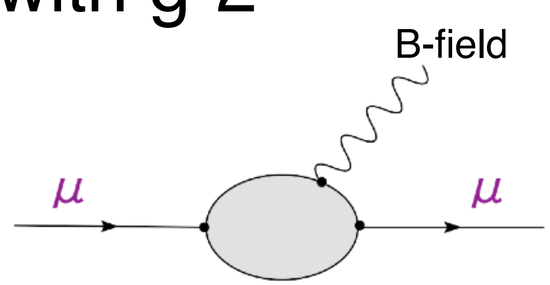
Charged Lepton Flavor Violation

- Why is CLFV interesting?
  - CLFV processes can be enhanced by new physics through new particles in loop
  - CLFV appears naturally in many NP theories such as SUSY-GUT, SUSY-seesaw etc.
  - The experimental sensitivity already reaches the theory prediction region, and there is a real chance for discovery!
- CLFV modes
  - μ→eγ, μ→3e, μN→eN, τ→3μ, τ→μγ, …
  - After discovery, correlations among other results will be necessary to determine the underlying new physics
  - These modes are complementary
- Strong correlation with g-2

theory :Dominik Stoeckinger
exp : Esra Barlas Yucel





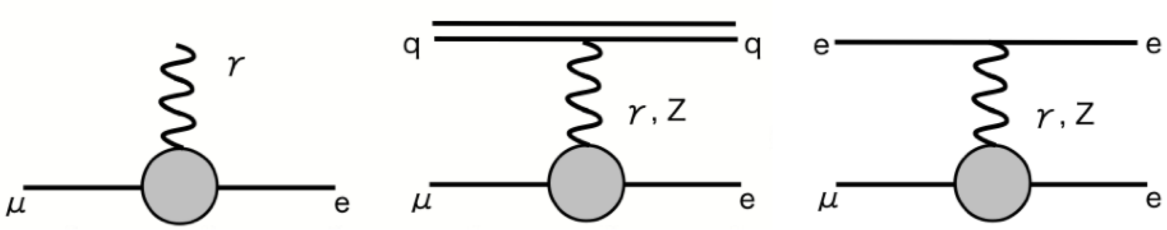


S. Antusch et al, JHEP 0611:090(2006)

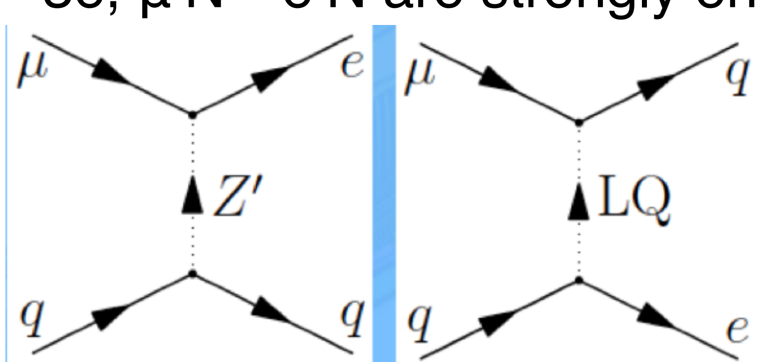
CLFV muon and tau searches

	Upper limit	Experiment (year)	Prospect	Experiment
μ→eγ	4.2 x 10^{-13}	MEG (2016)	6 x 10^{-14}	MEG II
μ→3e	1.0 x 10^{-12}	SINDRUM (1988)	~ 10^{-15} - 10^{-16}	Mu3e phase I - II
μ-e conversion	7 x 10^{-13}	SINDRUM II (2006)	~10^{-17}	DeeMe, COMET, Mu2e
τ→μγ	4.4 x 10^{-8}	BaBar (2010)	10^{-9} - 10^{-10}	Belle II
τ→3μ	2.1 x 10^{-8}	Belle (2010)	10^{-9} - 10^{-10}	Belle II

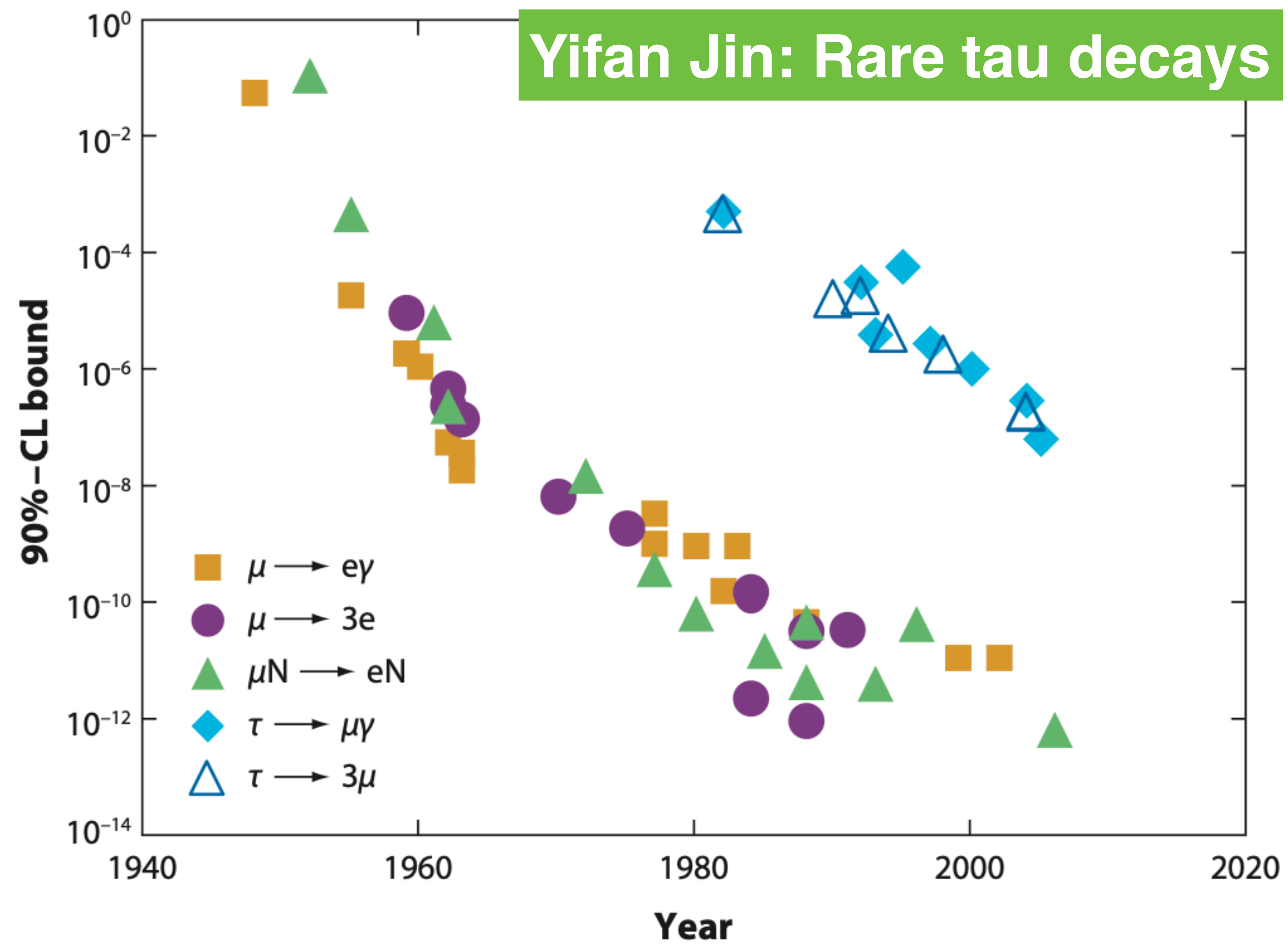
- If electromagnetic transitions
  - Dipole dominant (SUSY etc.)
  - Br(μ→eγ) : Br(μ→3e) : R(μ-Al→e-Al)
    = 1 : 1/390 : 1/170



- If tree terms
  - μ→3e, μ-N→e-N are strongly enhanced
  -



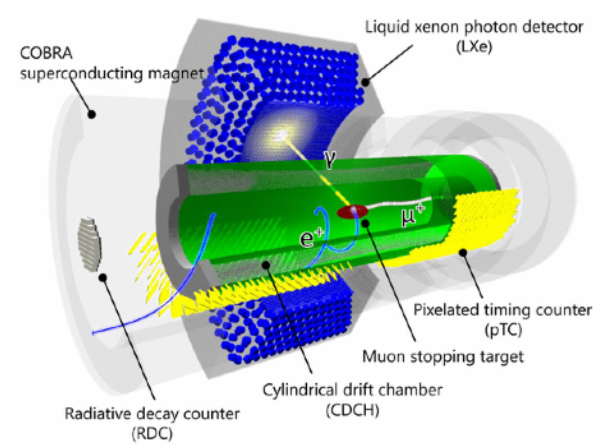
Yifan Jin: Rare tau decays



cLFV experiments in the world

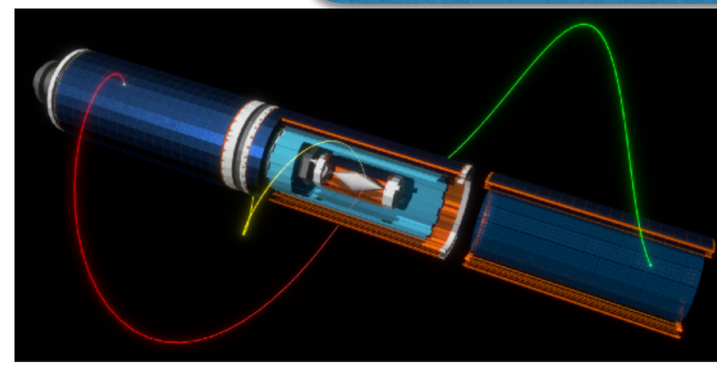
MEG II

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



Mu3e

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



Coincidence measurement:
DC beam needed to minimize backgrounds from accidental coincidences

BKG $\propto$ (Rate)^2

PSI

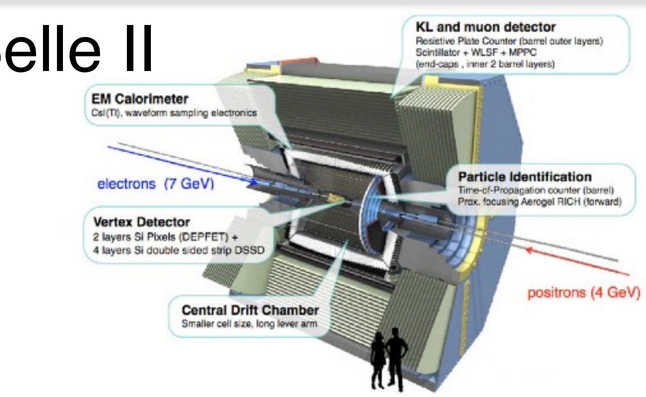
CERN

LHCb/ATLAS/CMS

$\tau \rightarrow 3\mu$, $\tau \rightarrow \mu\gamma$

KEK

Belle II

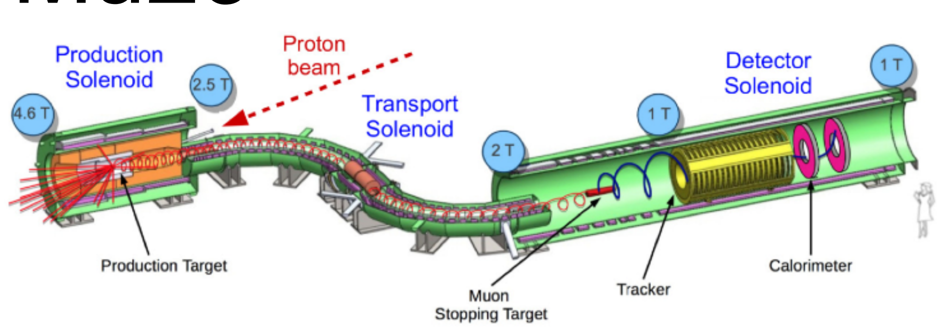


Fermilab

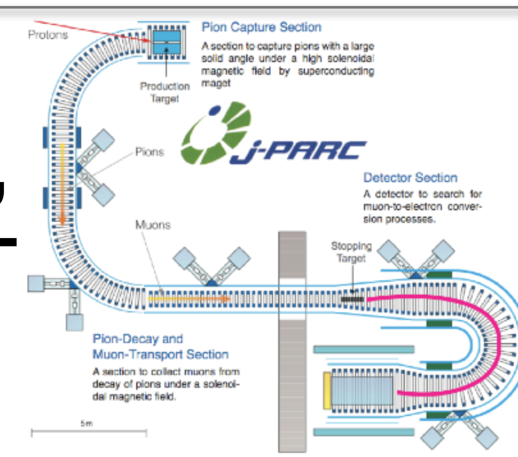
$\mu^- N \rightarrow e^- N$

J-PARC

Mu2e



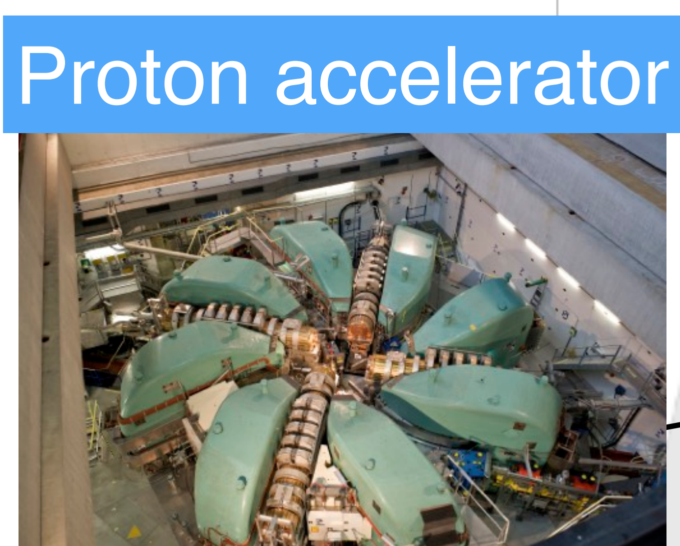
DeeMe,
COMET

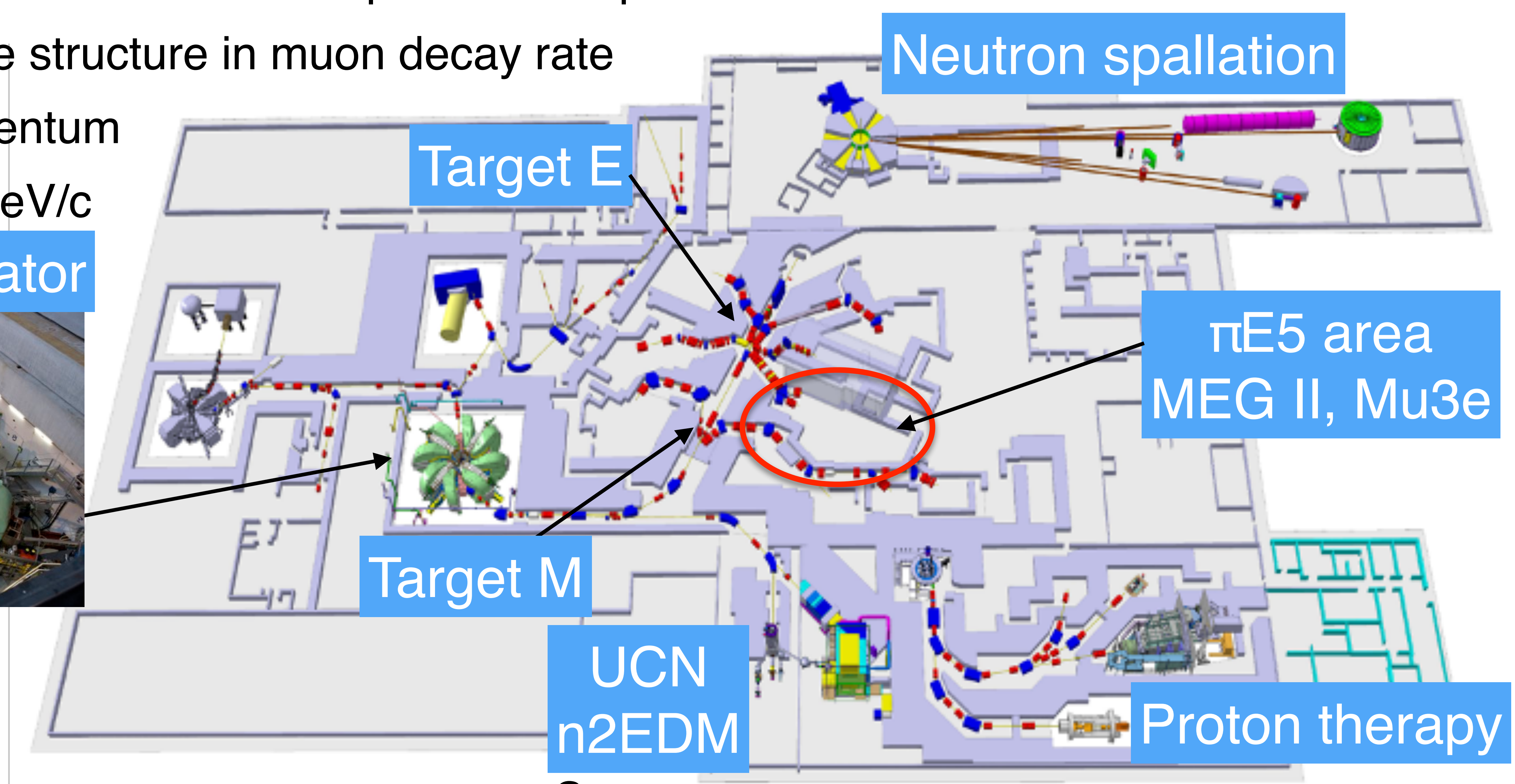


Single e^- measurement:
pulsed beam needed
Many pion-induced backgrounds after proton pulse
wait it out with 26 ns lifetime

PSI DC muon beam

- Paul Scherrer Institute in Switzerland
  - 590 MeV 2.4mA proton ring cyclotron
  - Only one accelerator in the world to produce DC muon beam > 10^8 μ/s
  - 50 MHz rf time structure << μ lifetime ~2μs
    - No time structure in muon decay rate
  - Low momentum
    - ~ 29 MeV/c

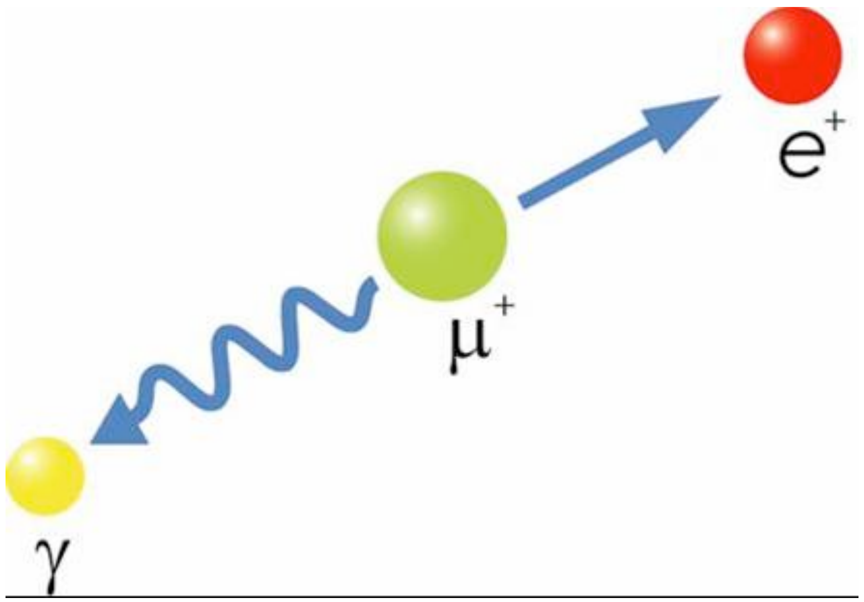




MEG II experiment

μ→eγ signal and background

Signal

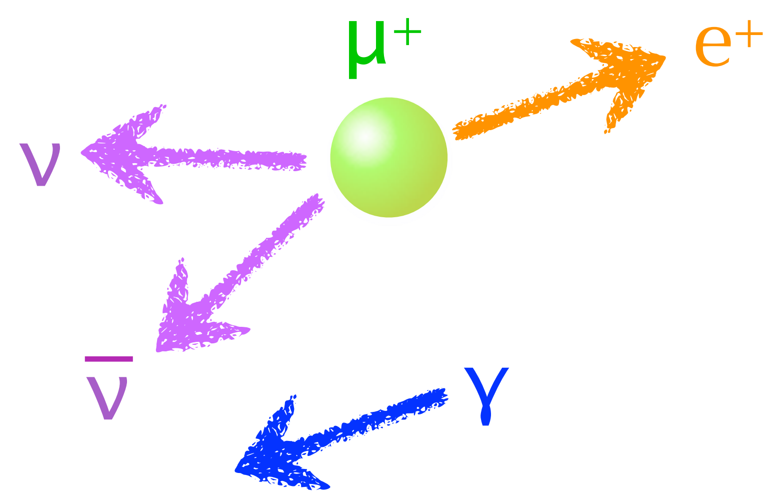


$E_\gamma, E_e \simeq 52.8\text{MeV}$
$\Theta_{e\gamma}=180°$, $T_\gamma=T_e$

Background

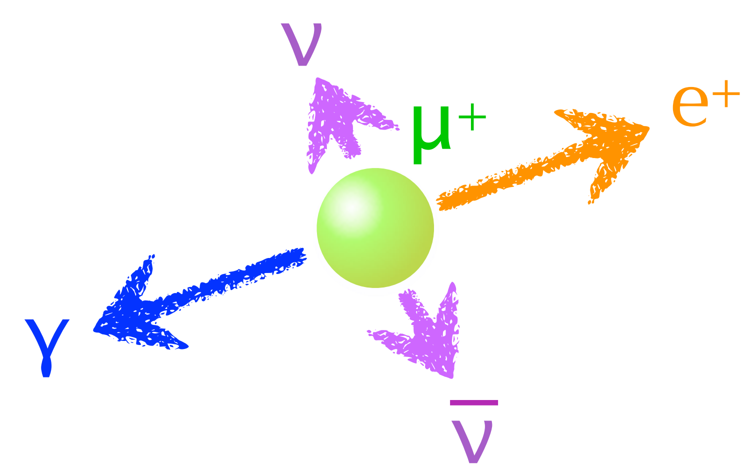
Accidental

Dominant BG



Michel e^+ + random γ from RMD/Annihilation in flight (AIF)

Radiative Muon Decay

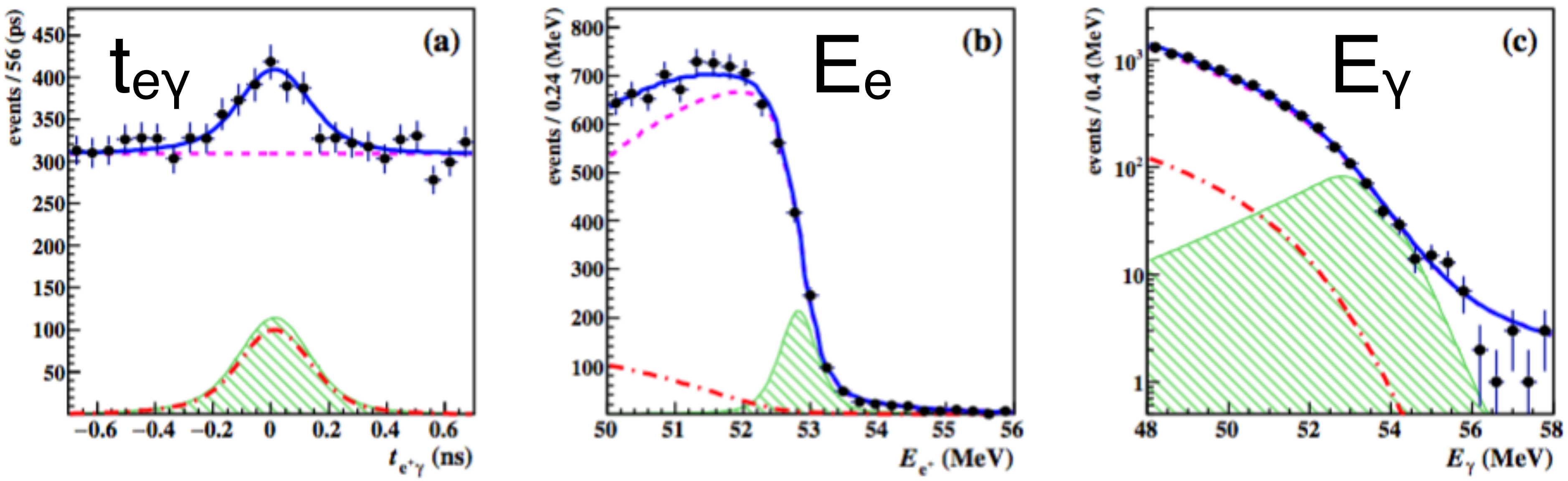


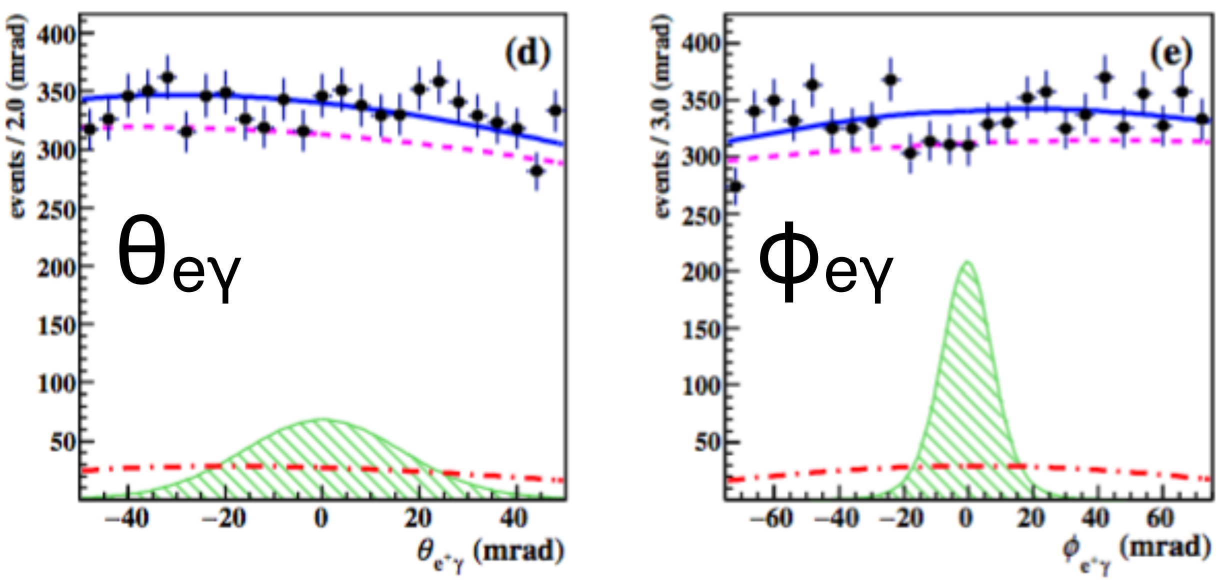
e^+-γ timing coincident

$$N_{acc} \propto (R_\mu)^2 \times (\Delta E_\gamma)^2 \times \Delta E_e \times (\Delta\Theta_{e\gamma})^2 \times \Delta t_{e\gamma} \times T$$

- Lower instantaneous muon beam rate (DC muon beam)
- Better detector resolutions

Example of event distribution MEG analysis





- Used five observables $E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}$
- Maximum likelihood analysis
  - Accidental PDF (dominant)
  - Radiative Muon Decay PDF
  - Signal PDF
  - Sum of all PDFs

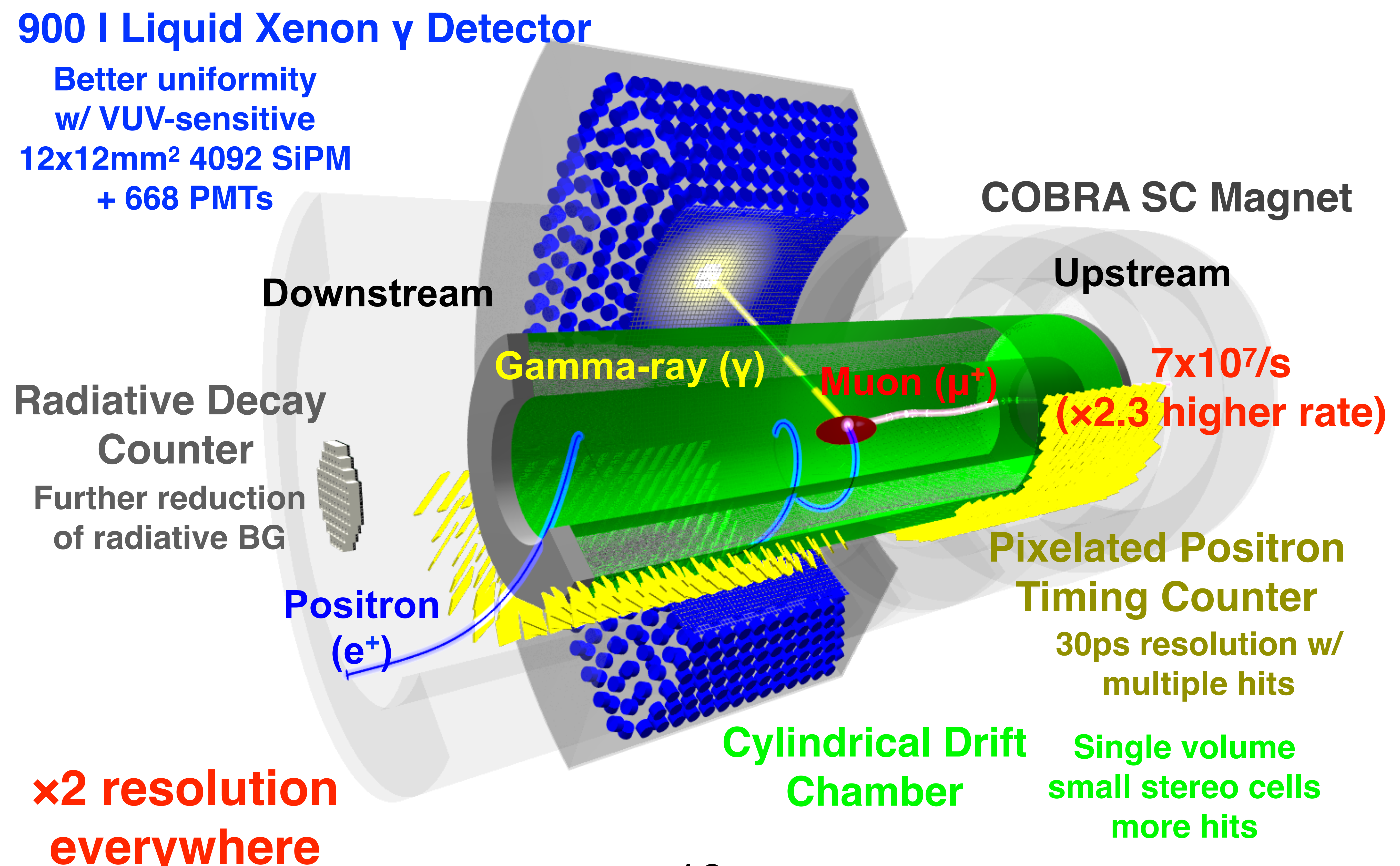
- $N_{ACC} = 7684 \pm 103$
- $N_{RMD} = 663 \pm 59$
- Signal PDF enhanced

- Full dataset : 7.5×10^{14} μ^+ stopped on the target
- **$Br(\mu^+ \rightarrow e^+\gamma) <$ 4.2×10^{-13} @ 90% C.L.**

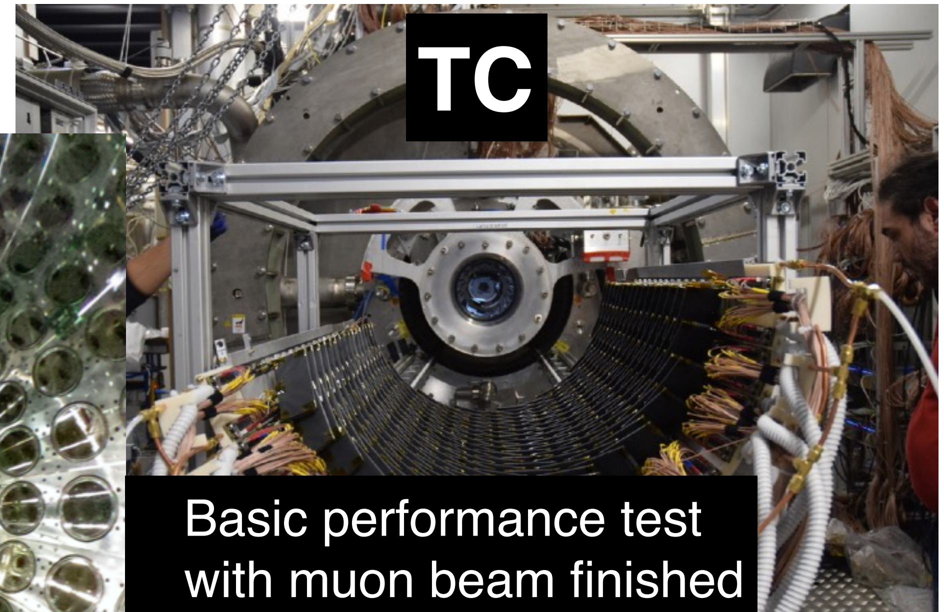
$$N_{acc} \propto (R_\mu)^2 \times (\Delta E_\gamma)^2 \times \Delta E_e \times (\Delta\Theta_{e\gamma})^2 \times \Delta t_{e\gamma} \times T$$

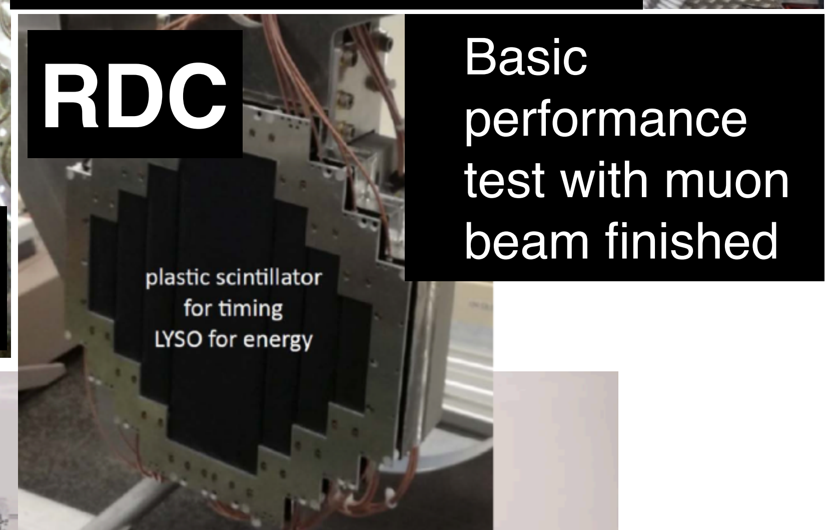
- Lower instantaneous muon beam rate (DC muon beam)
- Better detector resolutions

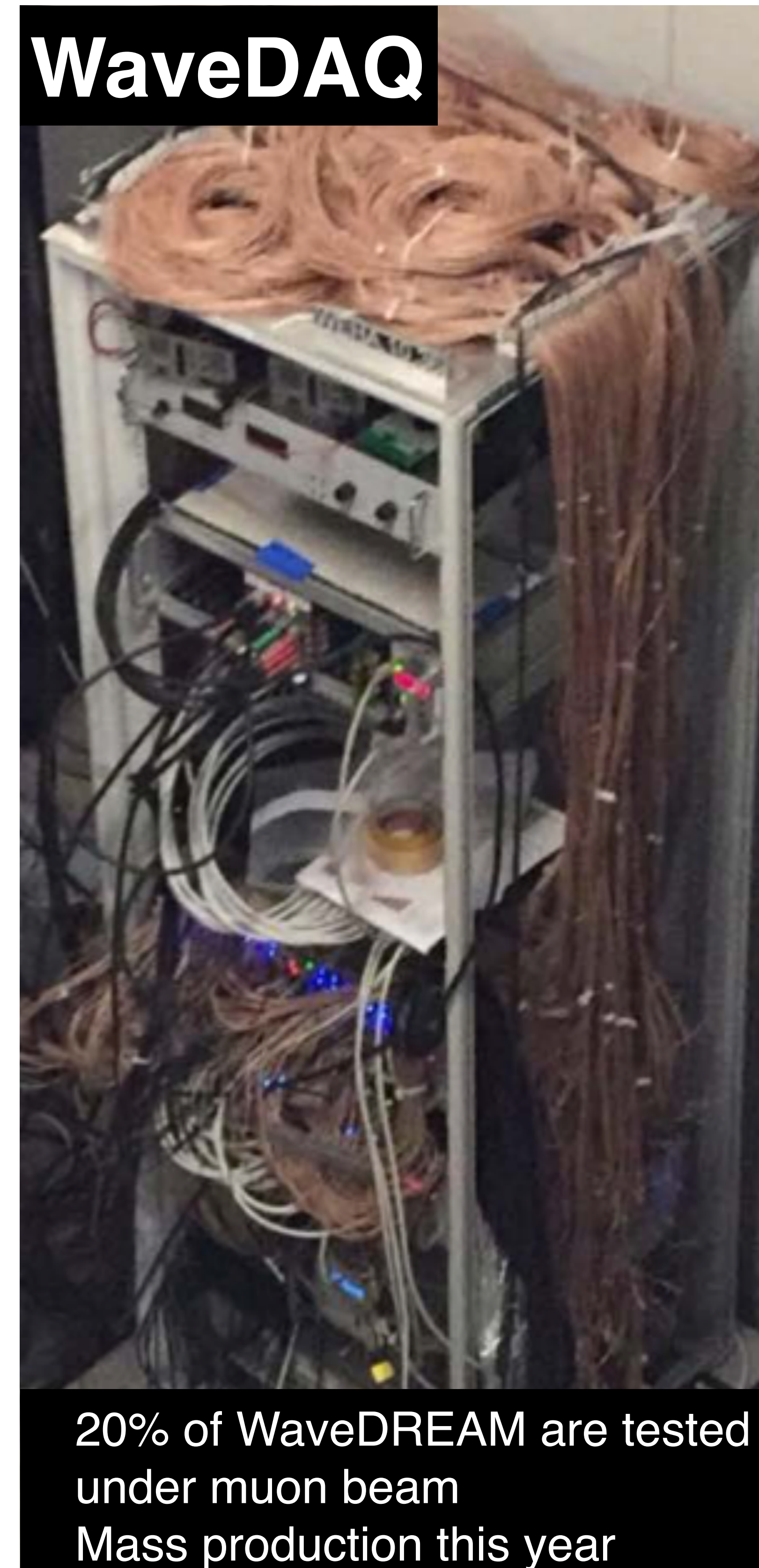
MEG II Experiment



MEG II Status

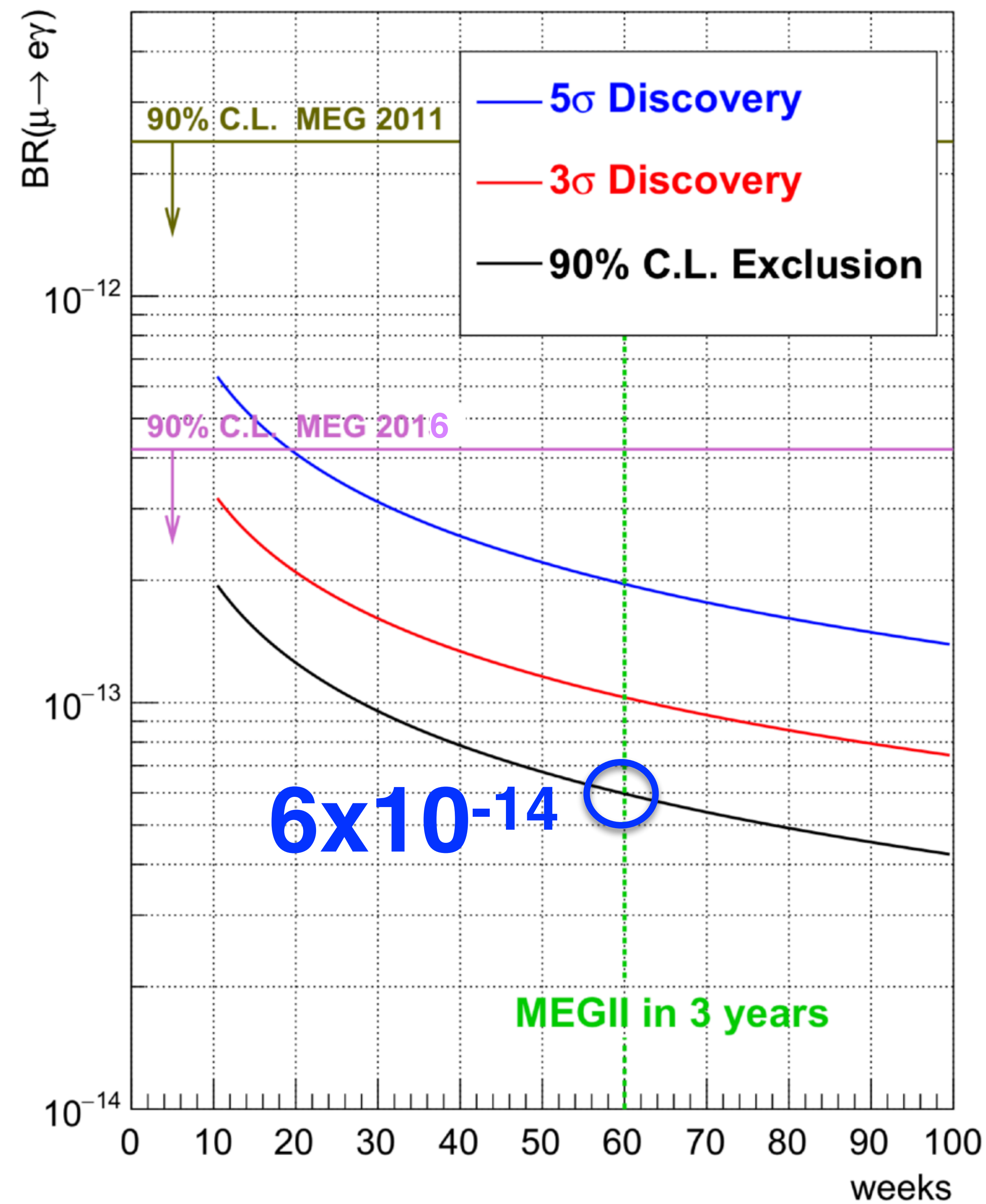






Sensitivity

Resolution	MEG	MEG II
E_{e+} (keV)	380	130
θ_{e+} (mrad)	9.4	5.3
ϕ_{e+} (mrad)	8.7	3.7
z_{e+}/y_{e+} (mm) core	2.4/1.2	1.6/0.7
E_γ(%) (w>2cm/<2cm)	1.7/2.4	1.0/1.1
u_γ, v_γ, w_γ (mm)	5/5/6	2.6/2.2/5
$t_{e\gamma}$ (ps)	122	84
Efficiency (%)		
Trigger	99	99
γ	63	69
e^+ (tracking × matching)	30	70

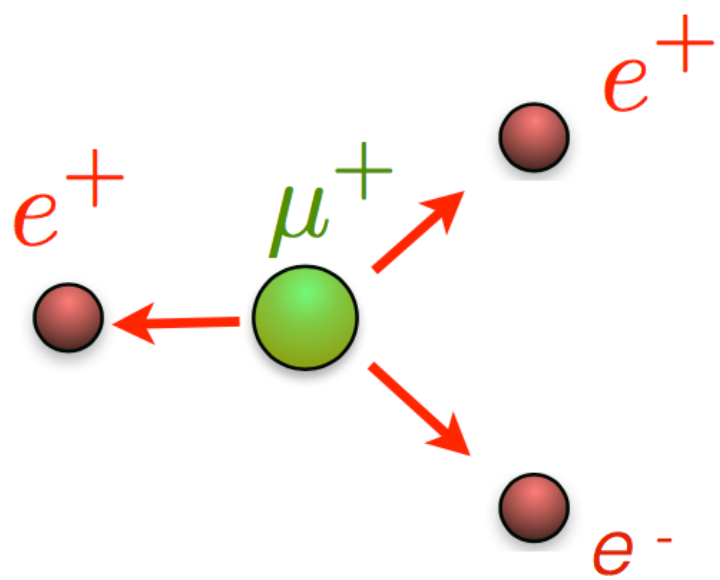


- Data for a few months exceed the current limit, and reach 6×10^{-14} in three years
- Engineering run followed by physics run from 2021

Mu3e experiment

$\mu^+ \rightarrow e^+e^+e^-$ signal and background

Signal

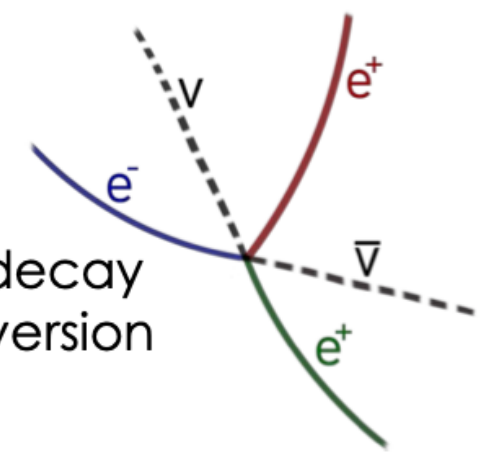


$\Sigma p_e = 0$
$\Sigma E_e = m_\mu$
Common vertex
Coincident

Background

Radiative SM decay
+ photon conversion

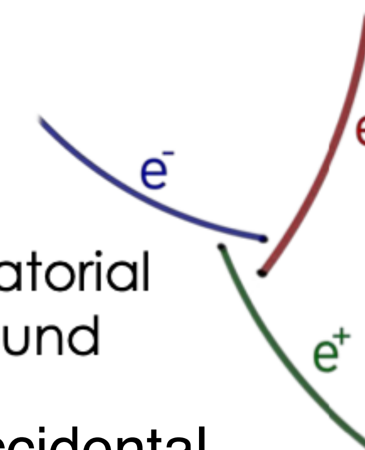
$\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$



$\Sigma p_e \neq 0$
$\Sigma E_e \neq m_\mu$
Common vertex
Coincident

Combinatorial
background

Accidental



$\Sigma p_e \neq 0$
$\Sigma E_e \neq m_\mu$
No common vertex
Not coincident

Mu3e

Superconducting solenoid Magnet

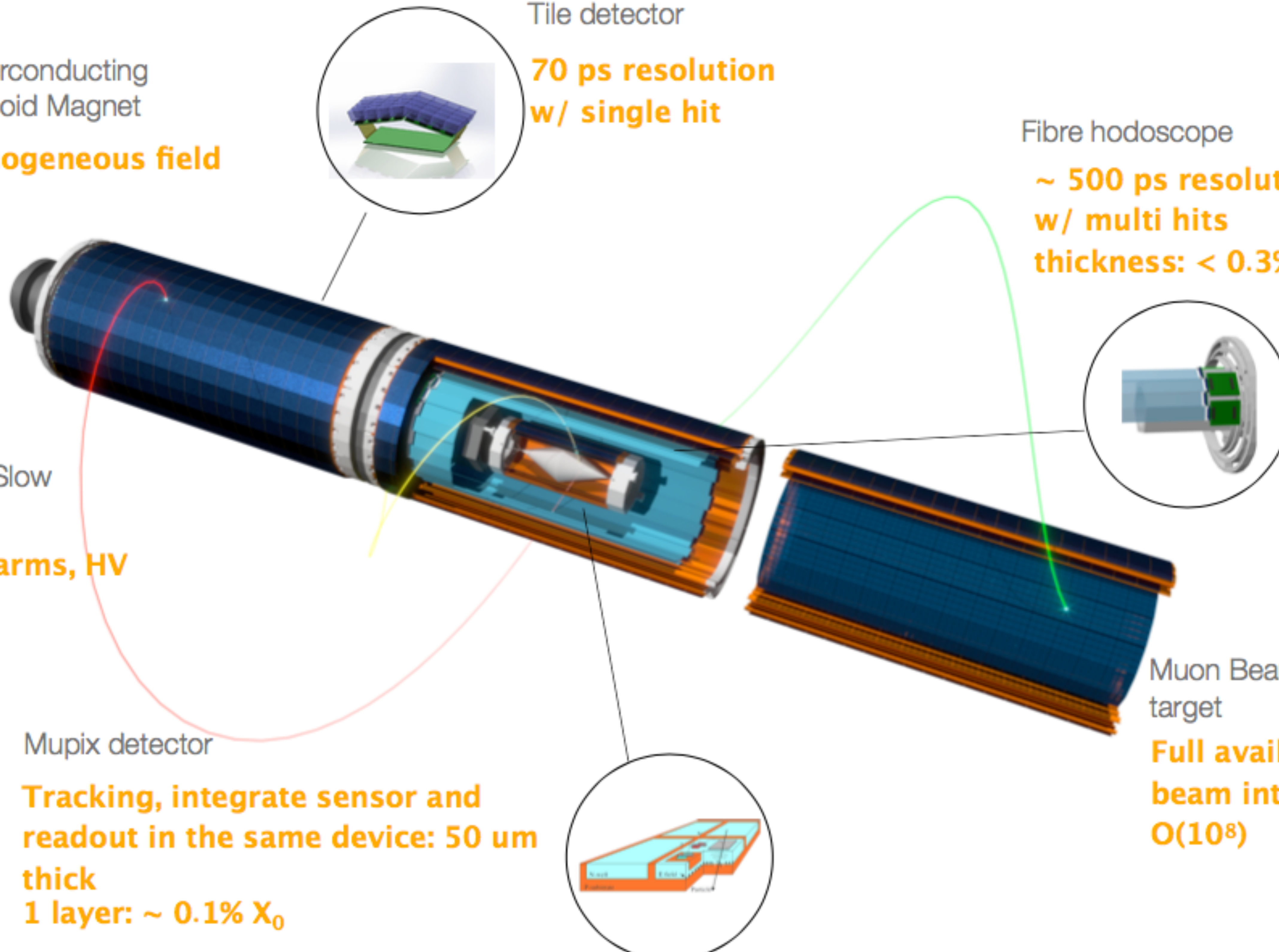
Homogeneous field 1T

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.

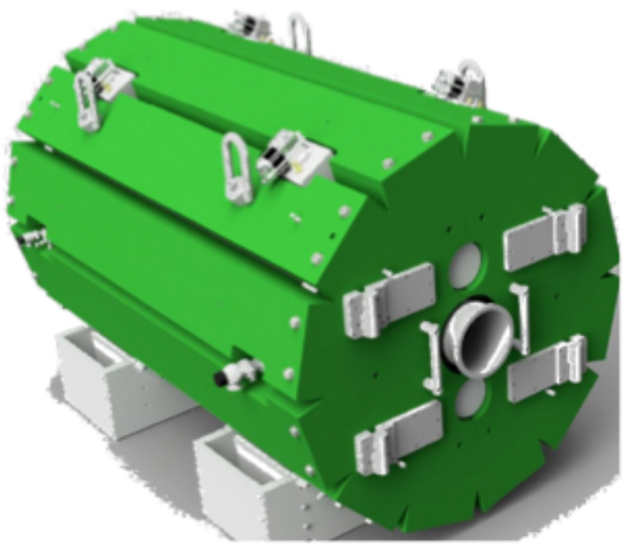
Muon Beam and target

Full available beam intensity $O(10^8)$

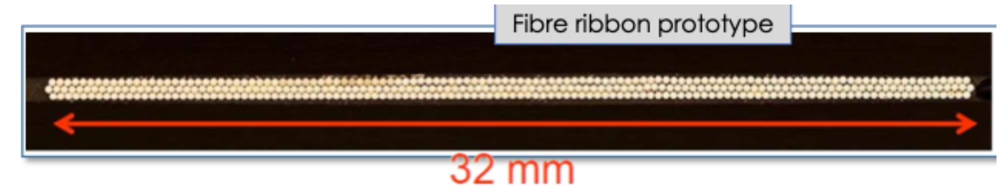
Mupix detector

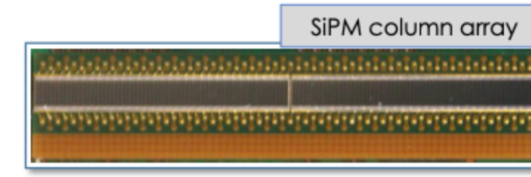
Tracking, integrate sensor and readout in the same device: 50 um thick
1 layer: ~ 0.1% X_0

Mu3e current status

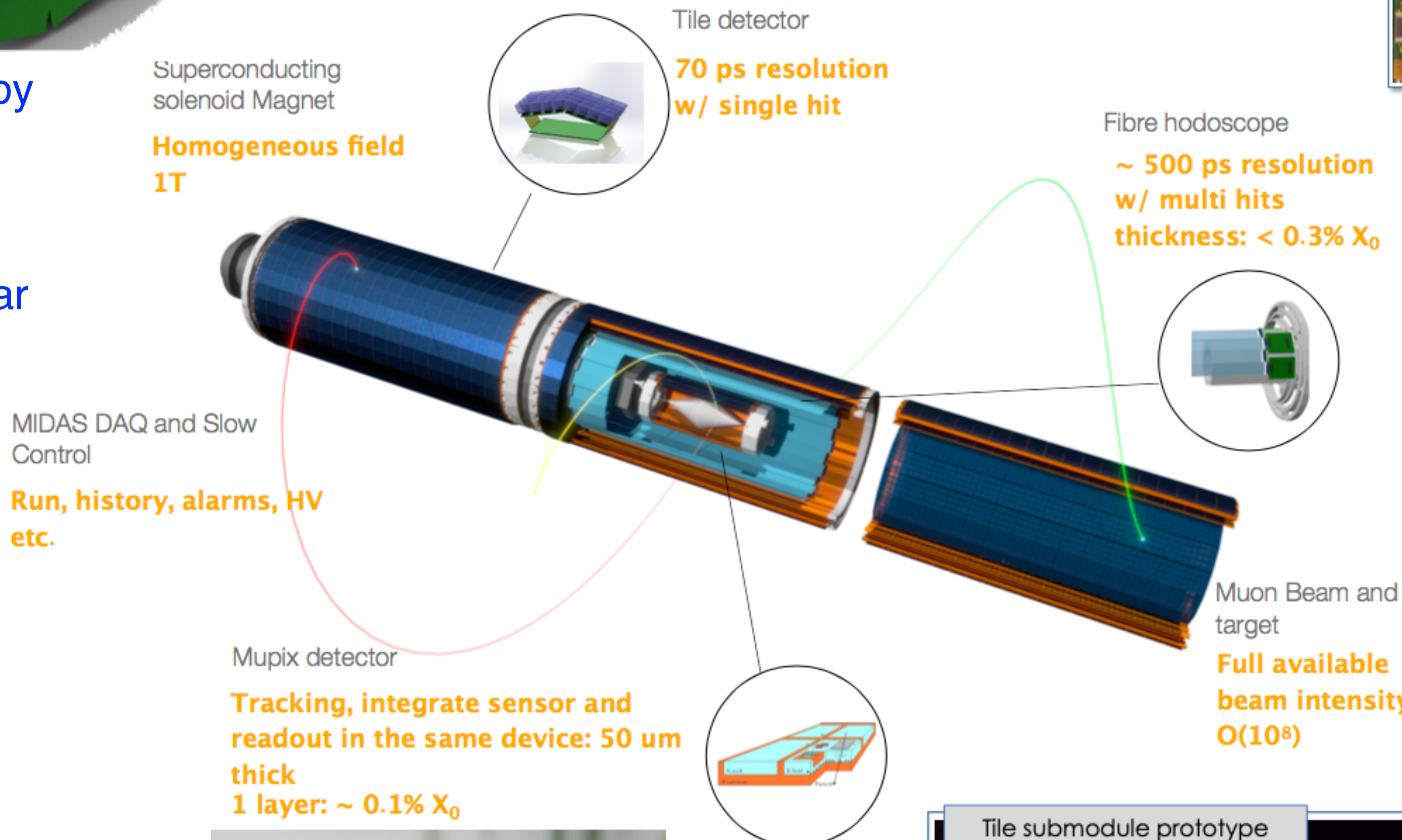


Being produced by Cryogenic Ltd.
Homogeneous magnetic field
Available this year



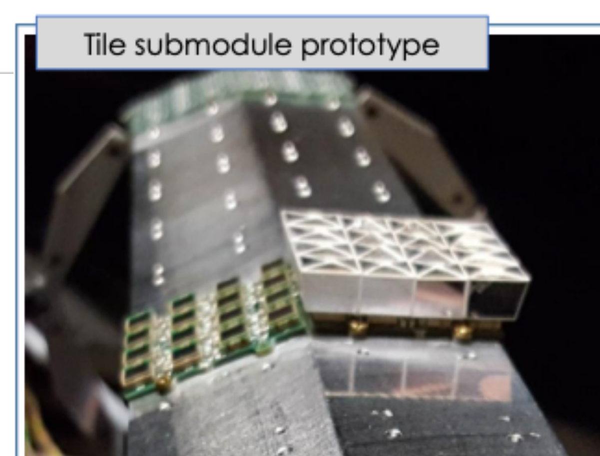


Prototype test successfully done
Fullfils Mu3e requirements (time resolution < 500 ps)



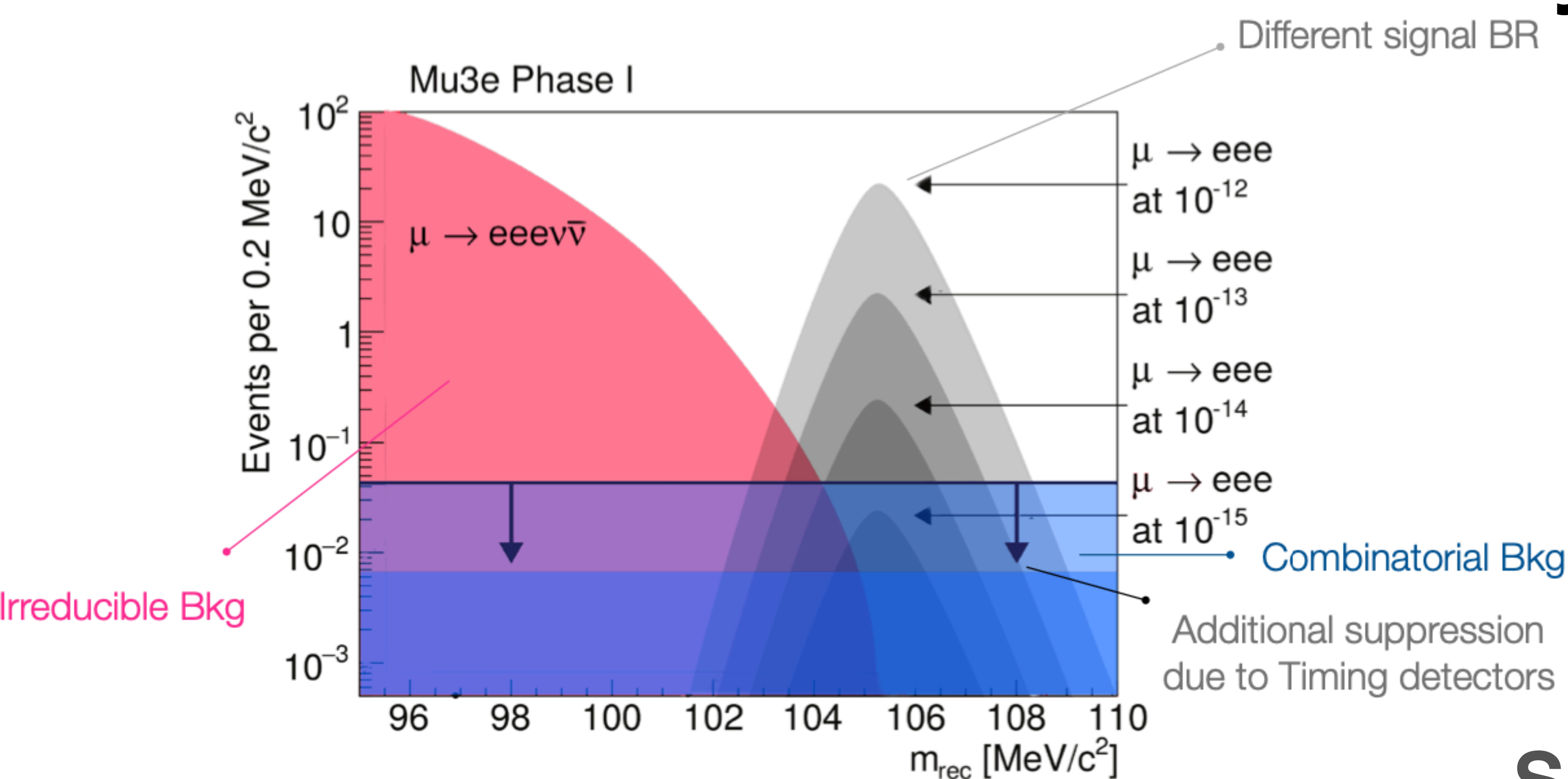
Prototype (MuPix 8) test successfully done
Fullfils Mu3e requirements
Last prototype (MuPix 10) will be tested soon

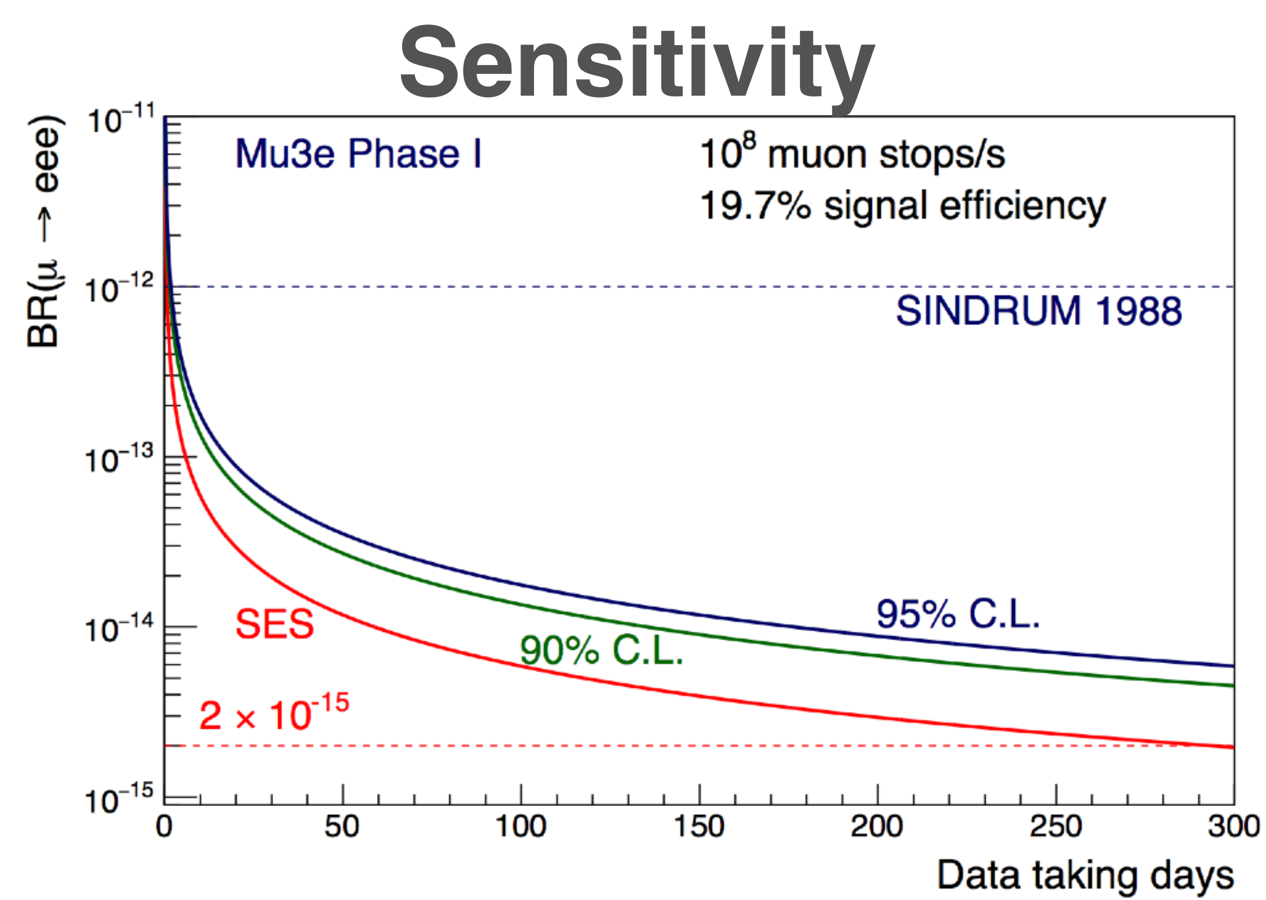
MuPix 8 beam telescope



Prototype test successfully done
Fullfils Mu3e requirements (time resolution < 100 ps)
Test beam: 45 ps

Mu3e Sensitivity





- Data for a month exceed the current limit by a factor of 10, and reach $< 1\times10^{-14}$ in 200 days
- Engineering run followed by physics run from 2021/2022

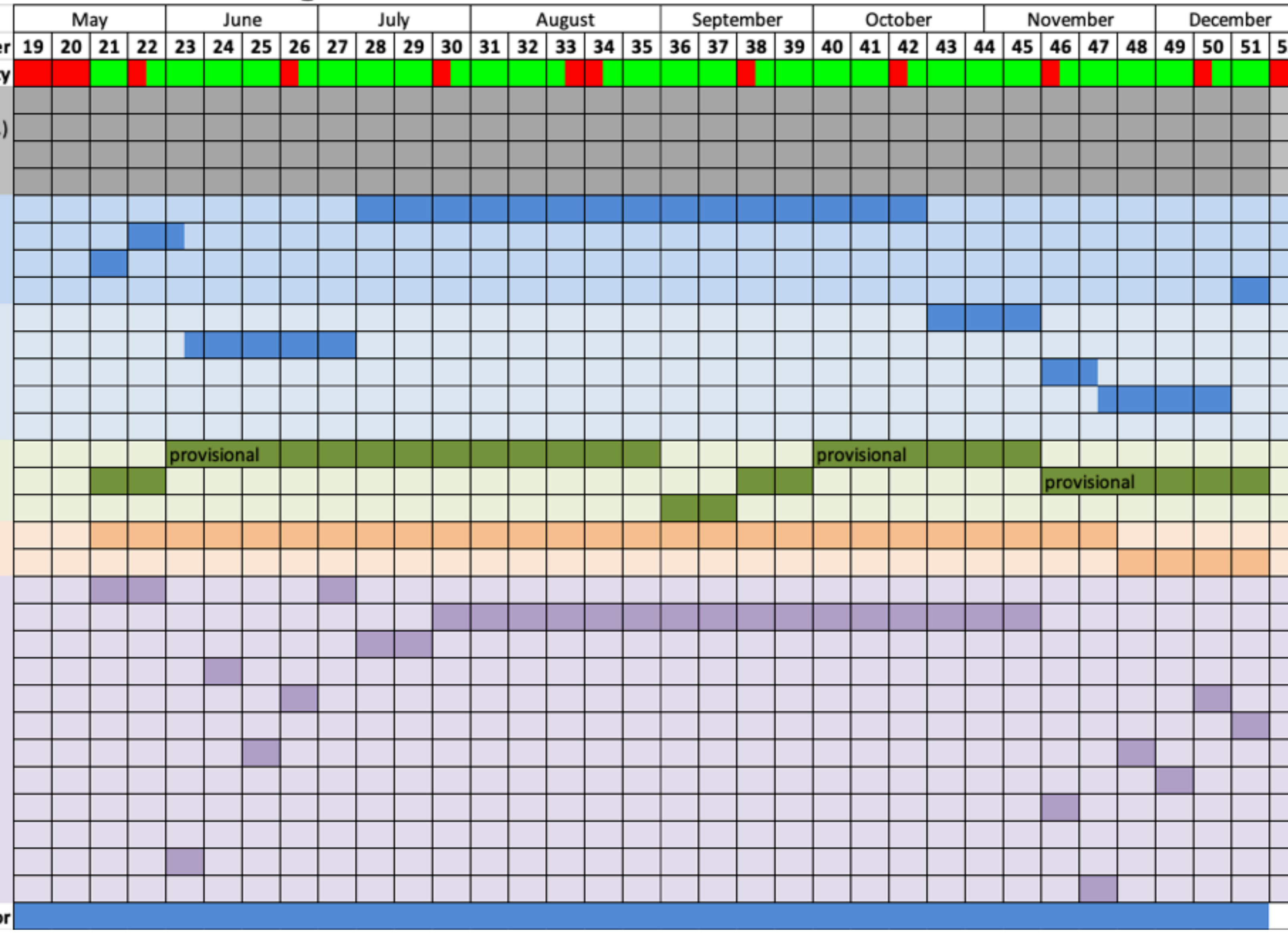
PSI beam time

PSI 590 MeV Program 2020

Last update: Jan 29th, 2020, S. Ritt <stefan.ritt@psi.ch>

http://www.psi.ch/ltp/FacilitiesEN/schedule_2020.pdf

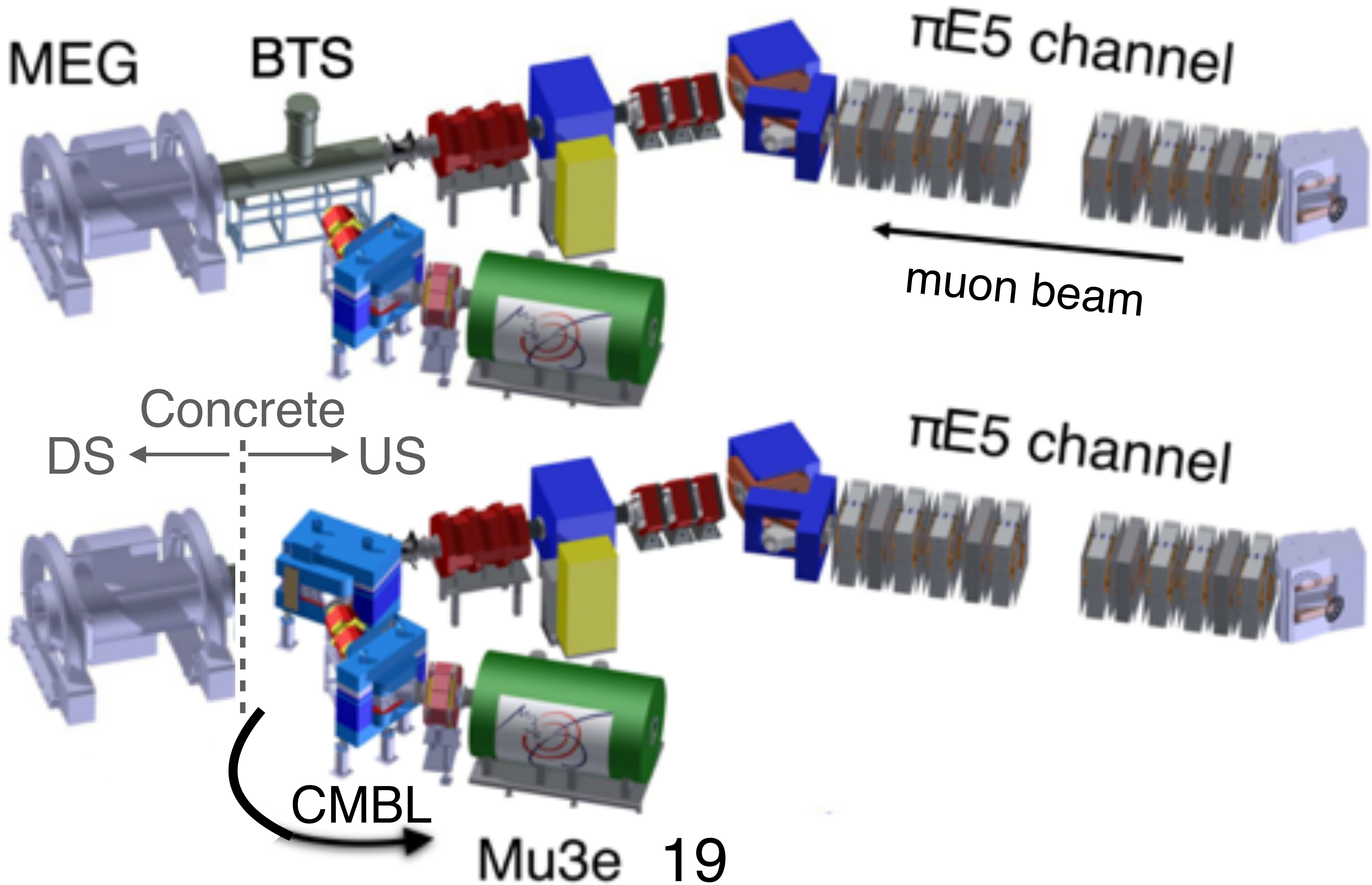
		PSP	PSI Contact	Availability
PiM3	MuSR (GPS&LTF)		Amato	Amato (coord.)
PiE3	MuSR high field		Scheuermann	Scheuermann (coord.)
MuE1	MuSR (GPD)		Amato	Amato (coord.)
MuE4	MuSR (LEM)		Prokscha	Prokscha (coord.)
PiE1-1	MuSR (Dolly)		Amato	Amato (coord.)
	PSEC-Micromegas		Antognini	Sohl
	RPC counters		Antognini	Bencivenni
	MuEDM		Schmidt-Wellenburg	Schmidt-Wellenburg
PiE1-2	R-20-01.1	5203.85800.012	Knecht	Zinatulina
	R-08-01.3 Musun	5203.32030.004	Knecht	Kravchenko
	MIXE		Amato	Amato/Knecht
	Muonium		Knecht	Soter
	uRWELL		Knecht	Poli Lener
PiE5	R-99-05.2 MEG	5203.32030.001	Ritt	Mori
	R-12-03.1 Mu3E	5203.32030.002	Ritt	Schoening
	Praktikum	5203.85800.012	Meier	Grab
UCN	R-05-03.1 n2EDM		Schmidt-Wellenburg	Schmidt-Wellenburg
	Mirror-Neutron		Schmidt-Wellenburg	Ayres
PiM1	R-12-03.1 Mu3E	5203.32030.002	Ritt	Schoening
	R-12-01.2 MUSE	5203.32030.006	Reggiani/Ritt	Gilman
	Praktikum	5203.85800.012	Meier	Steinkamp
	CMS Diamond Detectors	5203.85800.012	Meier	Hits
	PIMice	5203.85800.012	Reggiani	Desorgher
	HVMAPS	5203.85800.012	Meier	Fritsch
	RADEM (PIF)	5203.85800.012	Hajdas	Hajdas
	TIMESPOT	5203.85800.012	Papa	Cardini
	COMET/NA62	5203.85800.012	Papa	Nishiguchi
	TOTEM	5203.85800.012	Papa	Garcia
	RadMap	5203.85800.012	Meier	Losekamm
	PAD-Micromegas	5203.85800.012	Meier	Camerlingo
				Spin-rotator



- MEG II and Mu3e both request beam time in 2020 to πE5 beam line. Beam time is provisionally assigned by PSI review committee.
- The schedule is fully delayed by COVID-19. We will try to start the experiment in September.

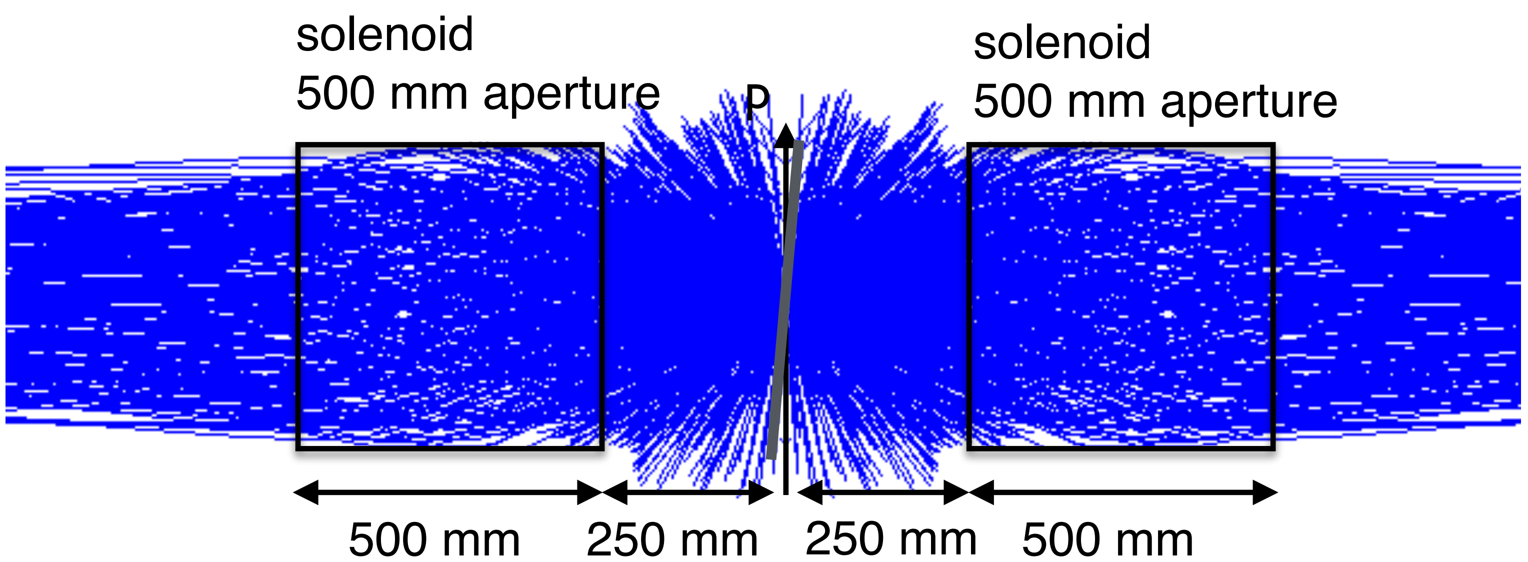
Conflict at πE5 in PSI?

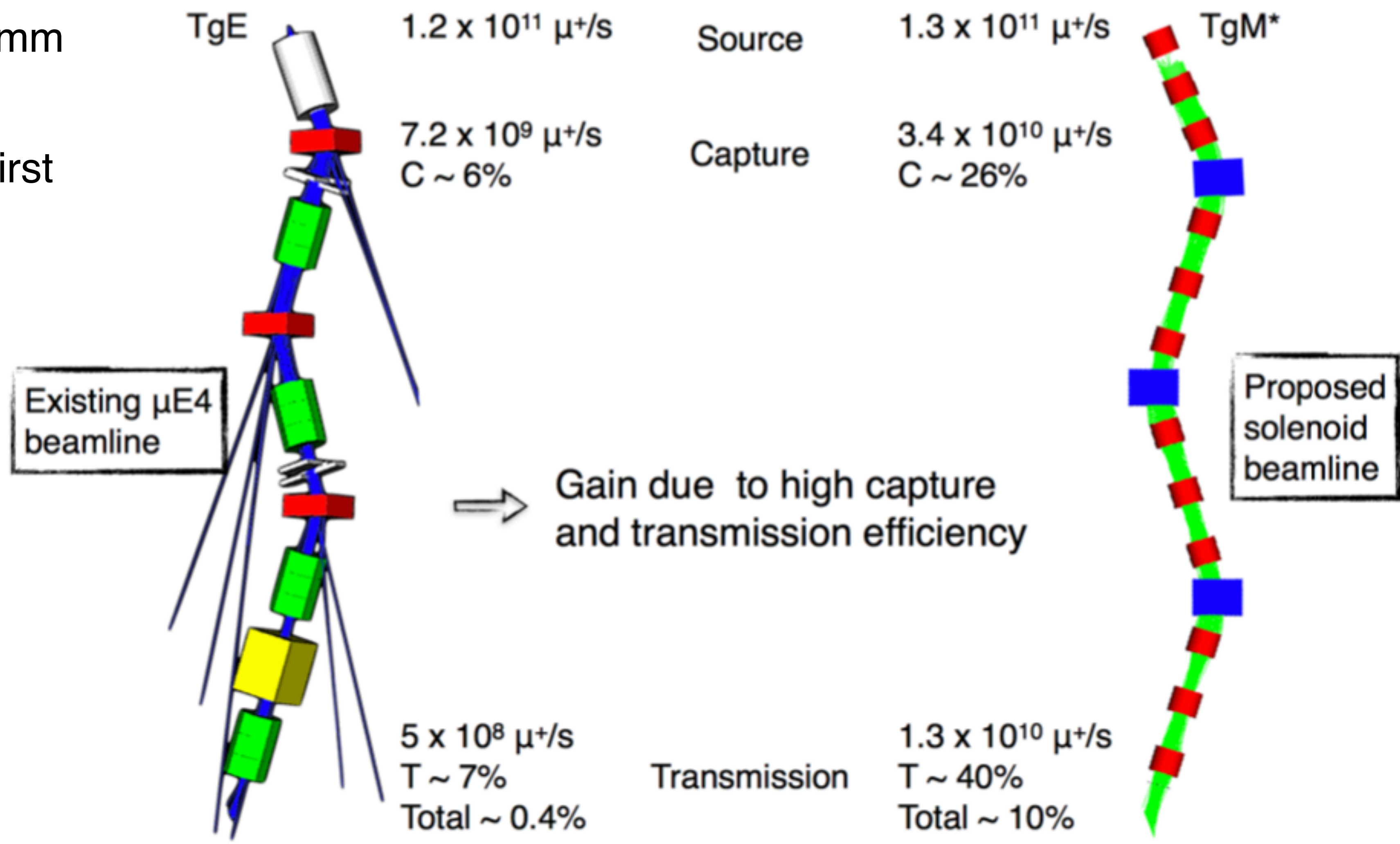
- MEG II and Mu3e will share πE5 beam line in PSI
- MEG II detector can be there even in Mu3e beam time thanks to the compact muon beam line for Mu3e (only upstream side)



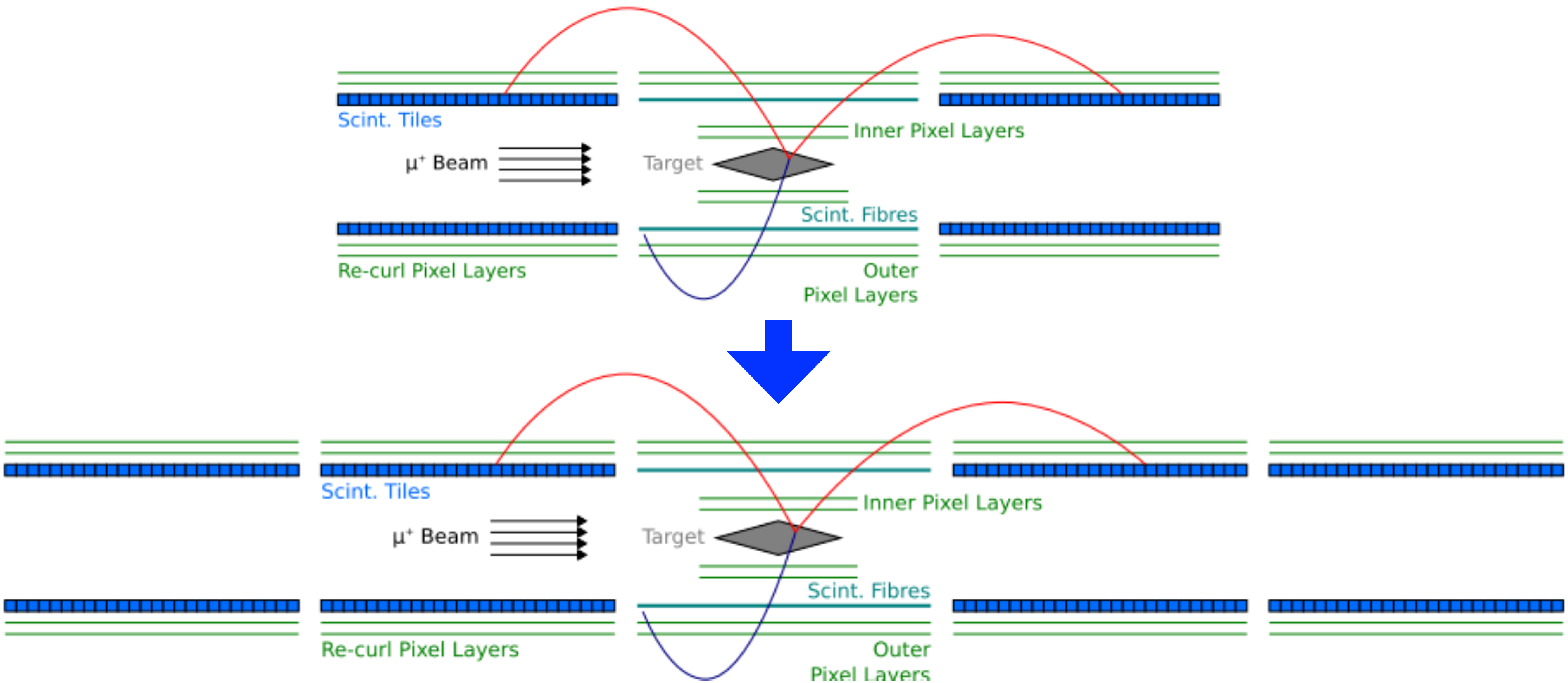
CLFV prospects with DC muon beam

- High intensity Muon Beamline (HiMB project)
  - Upgrade plan at PSI
    - Time schedule : O(2025)
  - New 20mm effective length 5° slanted target
    - 1.3×10^{11} μ^+/s
  - Capture solenoid (0.35T) at d = 250mm
    - 3.4×10^{10} μ/s
  - Solenoidal beam line can transmit (first version of beam optics)
    - 1.3×10^{10} μ/s
- Feasibility test of slant target at target E performed in 2019
  - Successful
- Many applications
  - Mu3e phase II (MEG III?)
  - μSR
  - Muonium study





Mu3e phase II



Sensitivity ~ 10^{-16}

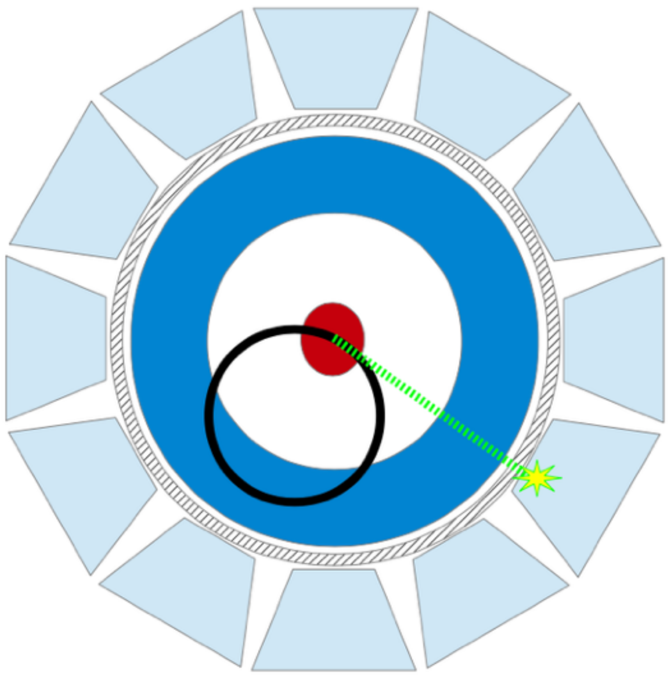
Increase muon stopping rate to $2 \cdot 10^9$ μ/s

Additional recurl stations increase acceptance for recurler

Smaller beam profile ⇒ smaller target radius

Next generation of μ→eγ searches: photon

Calorimeter



- high efficiency
- good resolution

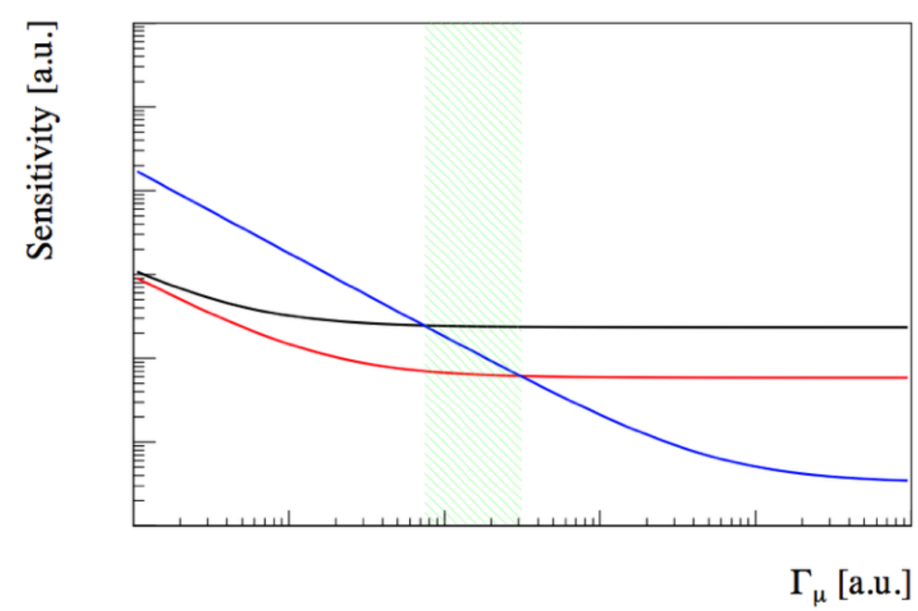
Requirements:
- high light yield
- fast response

Sensitivity trend vs beam intensity

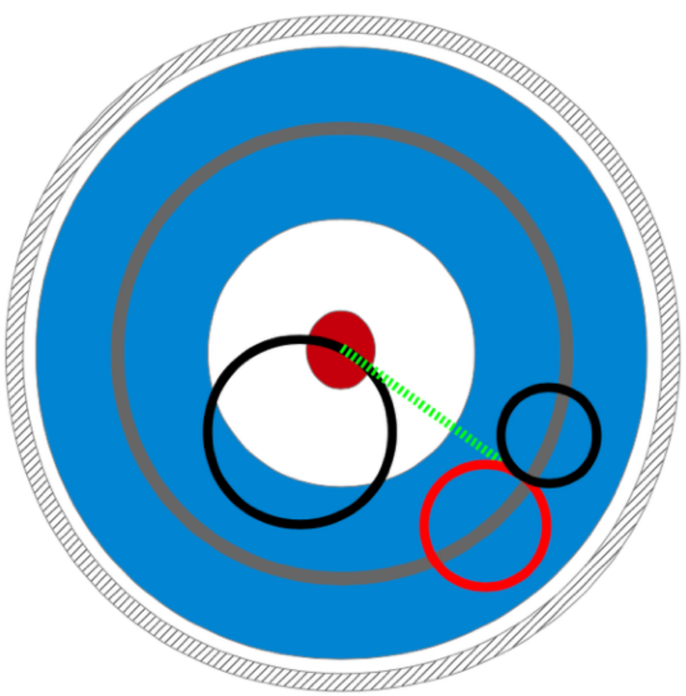
blue = pair conversion design

black = calorimeter design

red = calorimeter design with x2 resolution



Photon conversion



- low efficiency (%)
- extreme resolution
- photon direction

Requirements:
- optimization of converter thickness
(efficiency vs pair energy and angle resolution)

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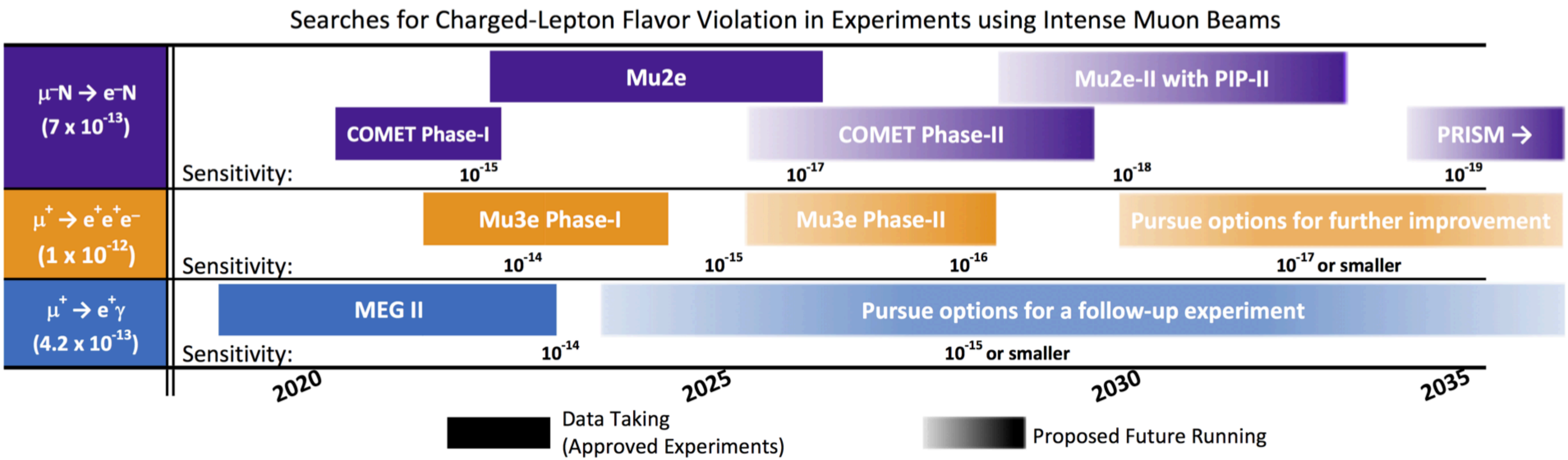
CLFV Prospects

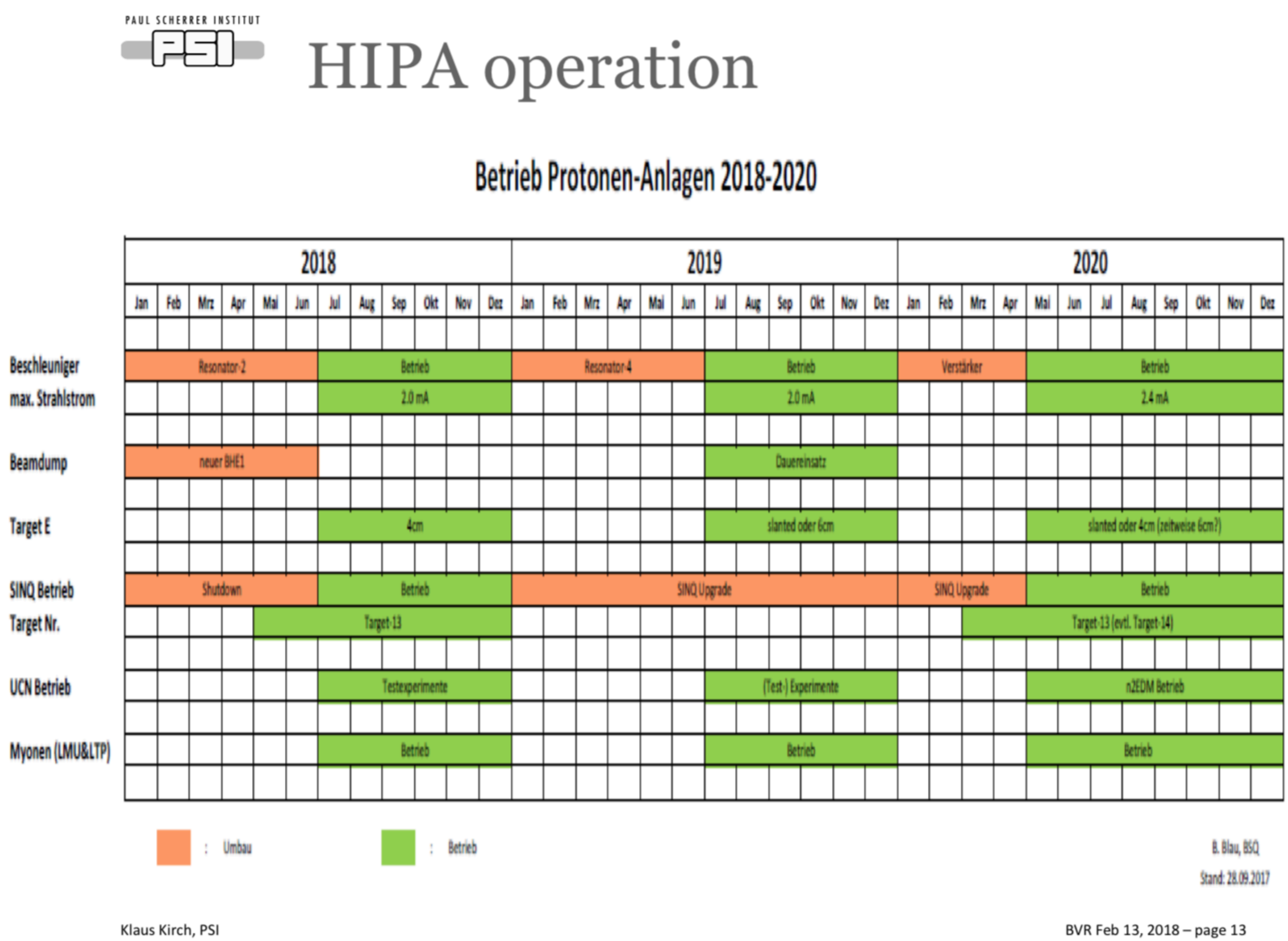
- CLFV is also discussed in the 2020 update of European strategy for Particle Physics



Summary

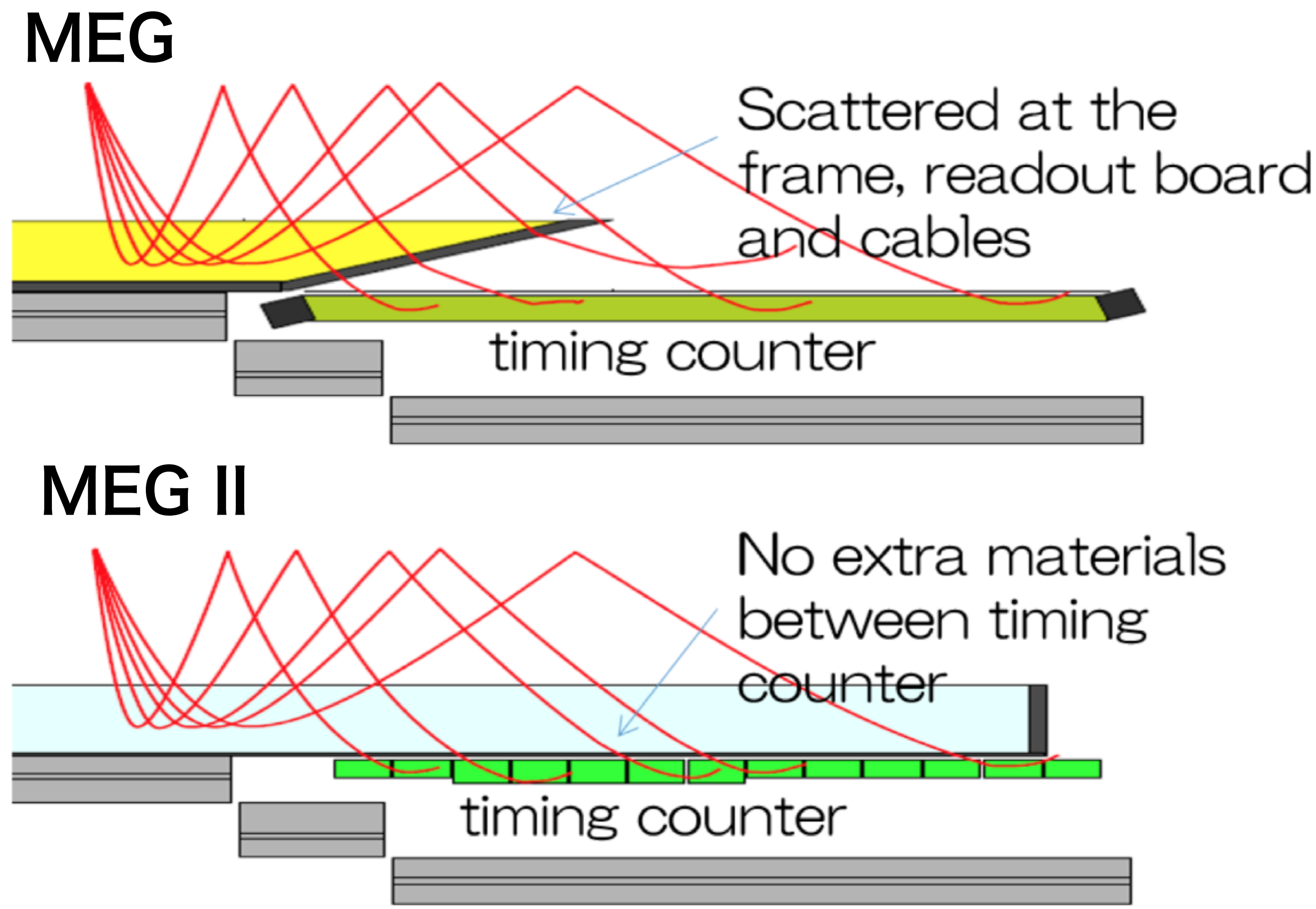
- Experiments to search for charged lepton flavor violation are sensitive to new physics beyond the SM such as SUSY-GUT, SUSY-seesaw etc.
- Global efforts are dedicated to this field with different methods to pin down the physics behind.
- World most intense DC muon beam is available at PSI in Switzerland, and two experiments (MEG II and Mu3e) will be started rather soon. So, stay tuned.
- PSI has an upgrade plan for the intense muon beam line (HiMB). New ideas for the next generation of these experiments are welcome.

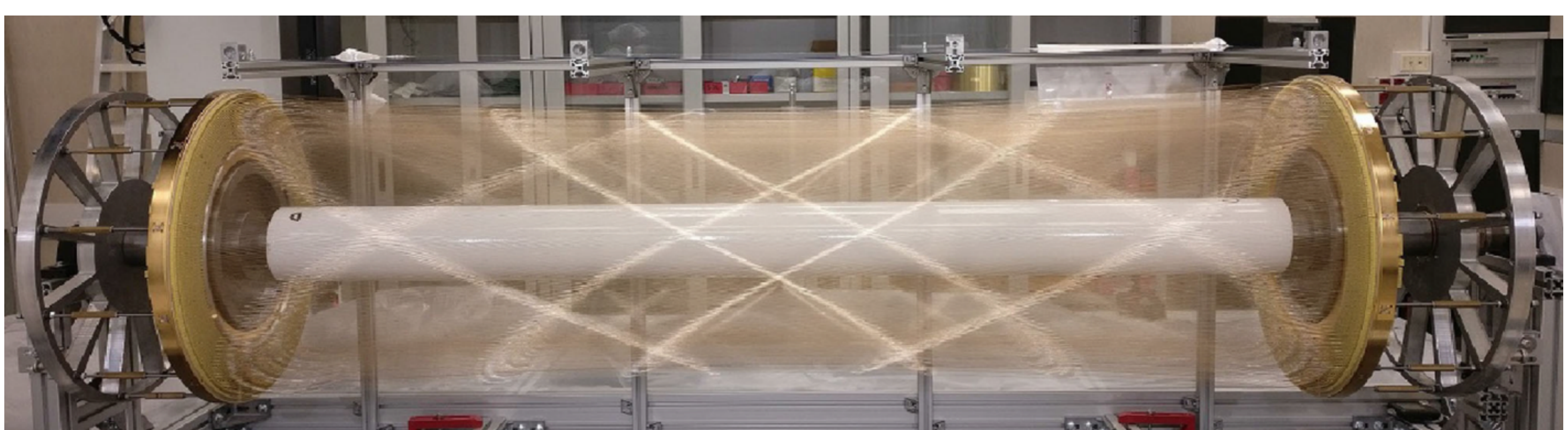
HIPA operation in 2018-2020

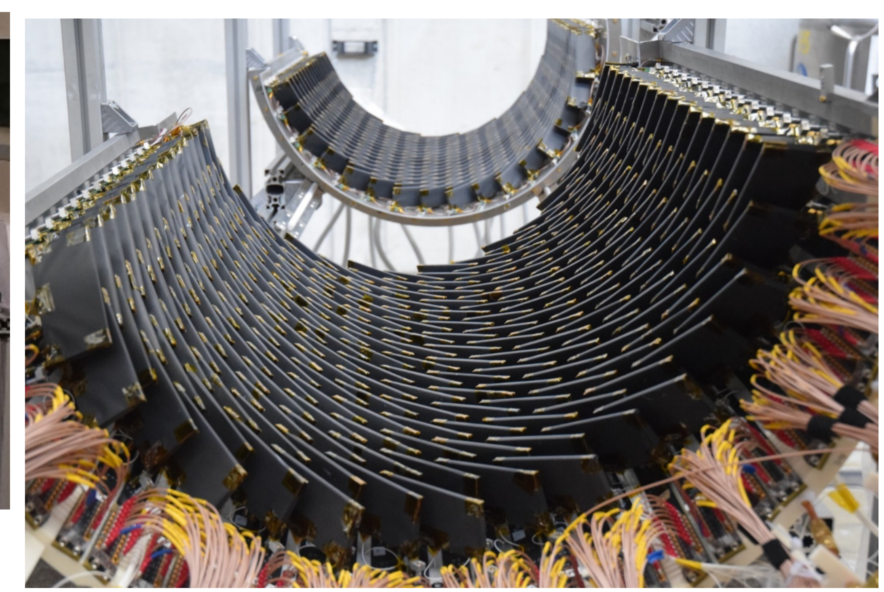


MEG II positron spectrometer

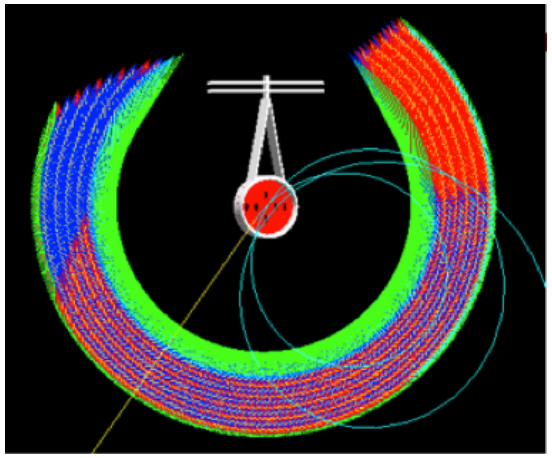
- Cylindrical Drift Chamber
  - Tracking 52.8MeV e^+ to reconstruct vertex, angle, and momentum
  - Single volume wire drift chamber with 1280 anode wires with less material
  - Higher granularity, increased number of hits per track → better angle/momentum resolution
  - High transparency towards TC → Higher positron detection efficiency
- Pixelated Timing Counter
  - Time measurement of 52.8MeV e^+
  - 15 scintillator bars → 256 scintillator plates
    - multi-counter hits → better timing resolution down to ~30ps





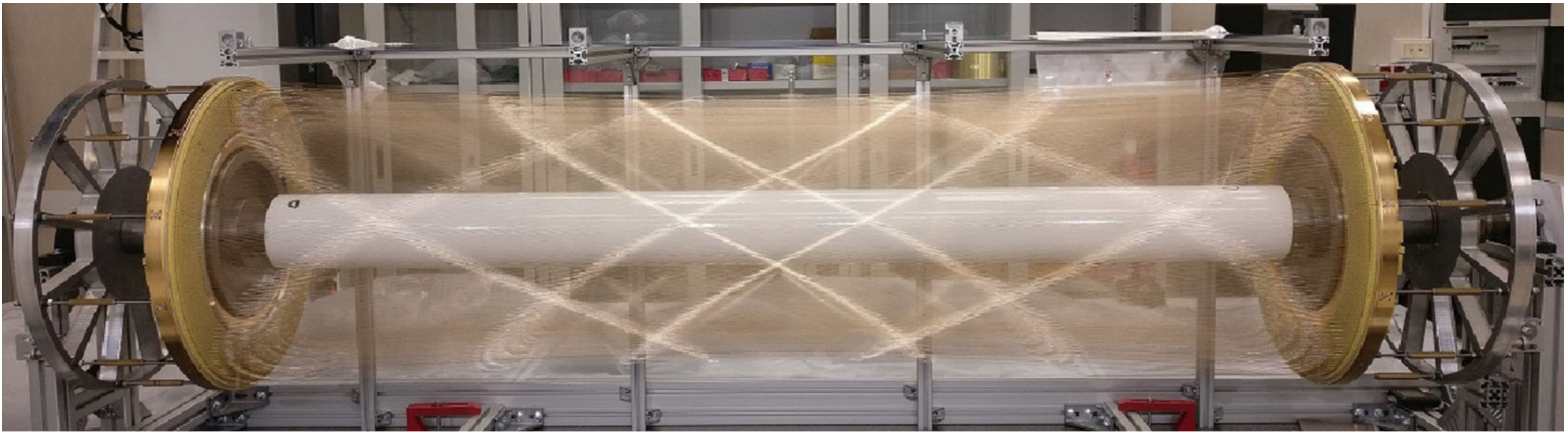


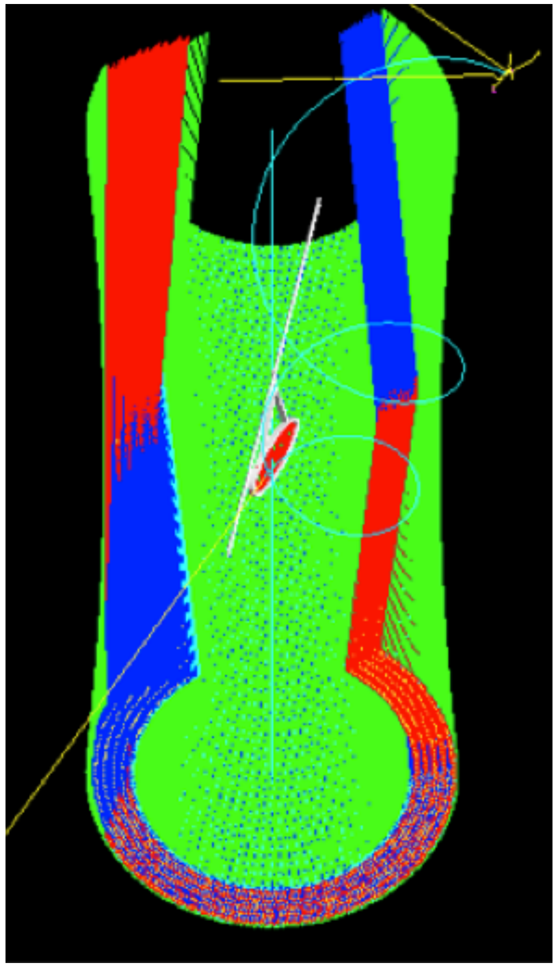
Cylindrical Drift Chamber



- Tracking 52.8MeV e^+ to reconstruct vertex, angle, and momentum
- Single volume wire drift chamber with 1280 anode wires
- Higher granularity, increased number of hits per track

MEG DCH	MEG II CDCH
16 modules	single volume
288 drift cells	1280 drift cells
40-80cm	2m long, stereo angle
$He:C_2H_6=50:50$	$He:iC_4H_{10}=85:15$

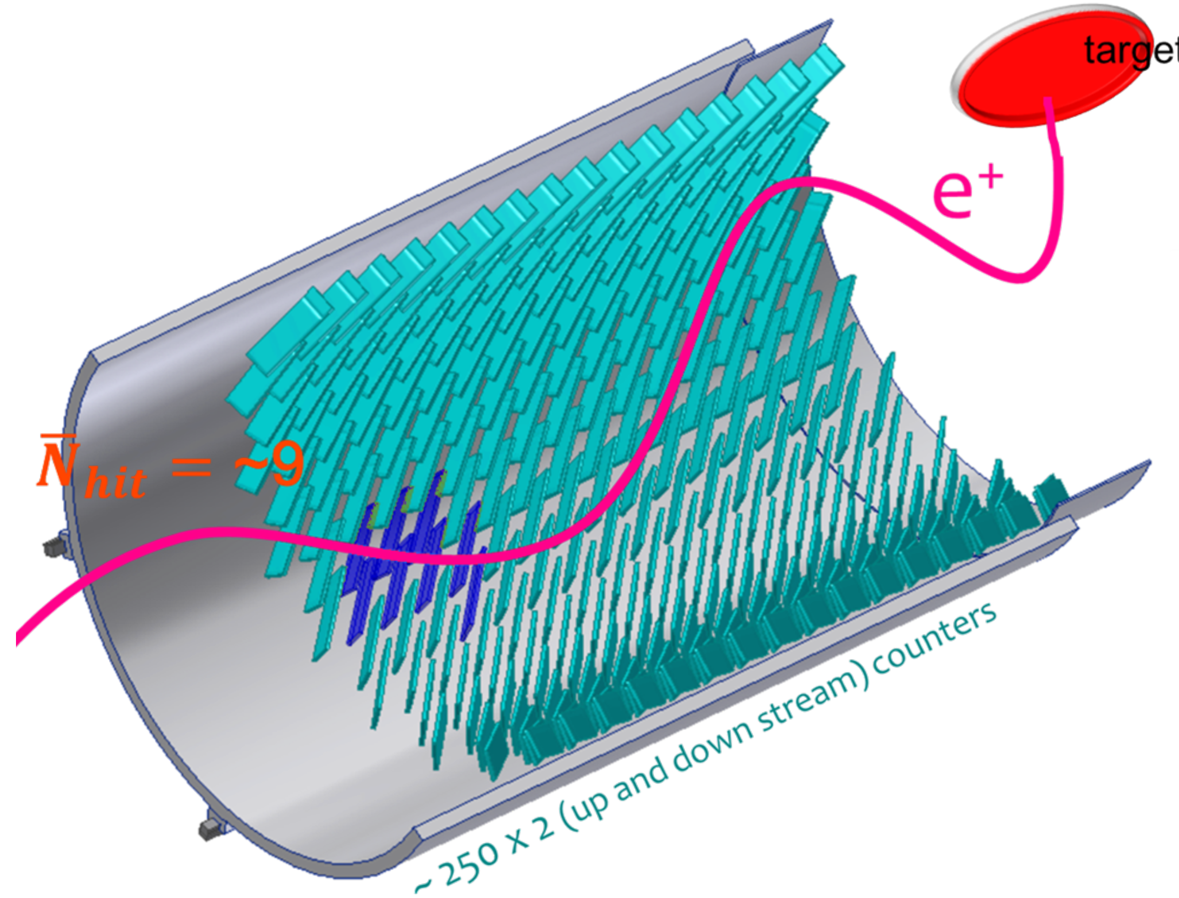


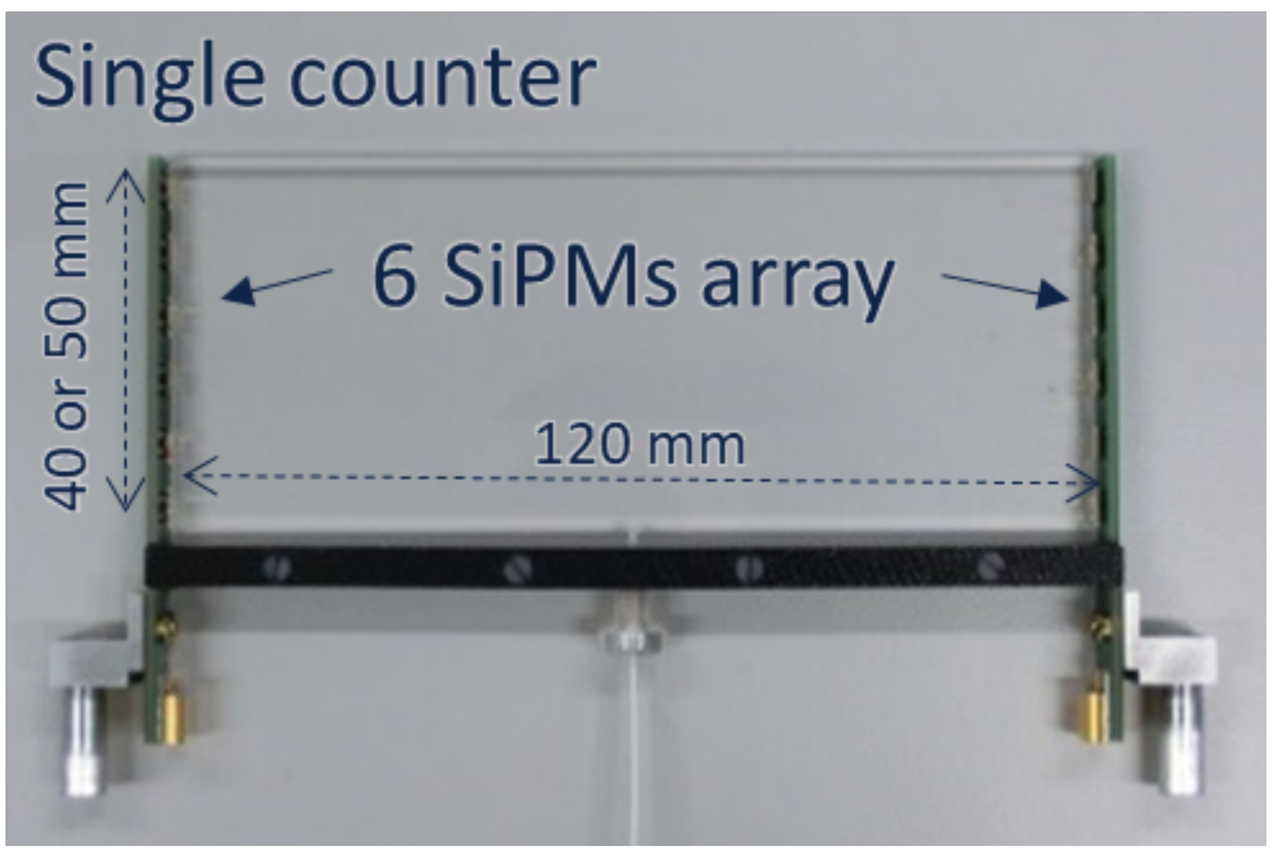


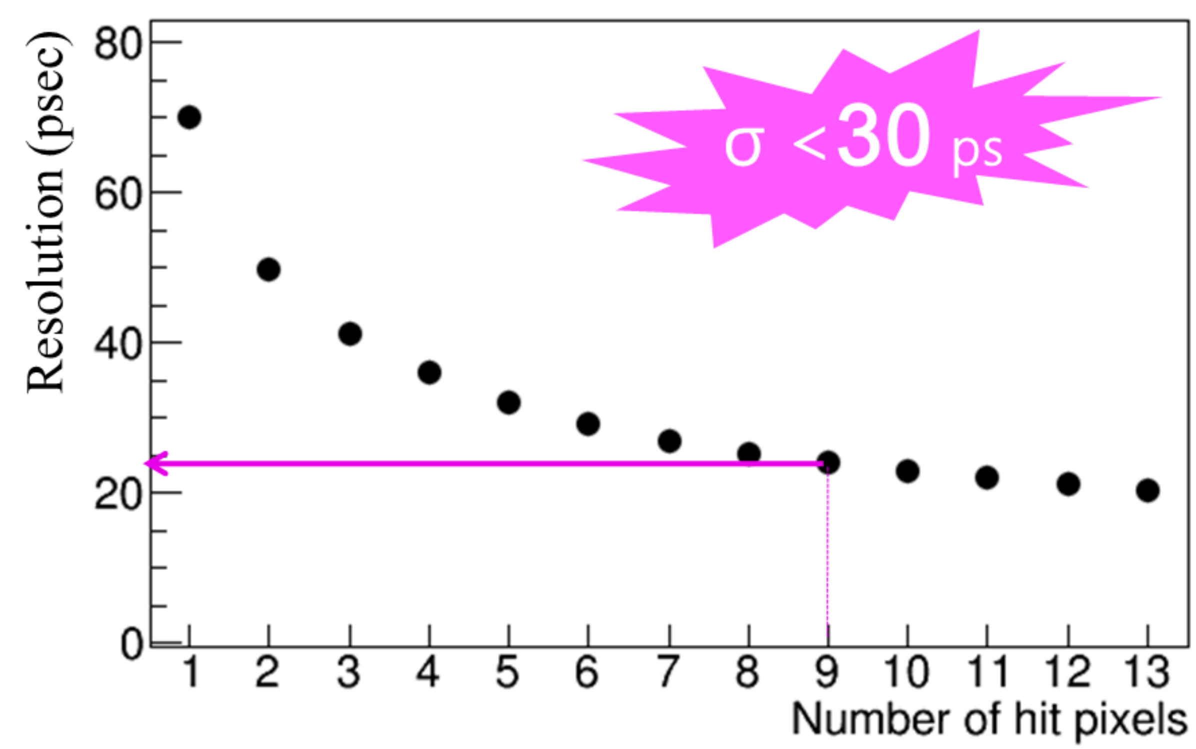
MEG II timing counter

- Time measurement of 52.8MeV e^+

MEG TC	MEG II TC
15 scintillating bars x 2	256 scintillator plates x 2
4x4x80 cm^3	12x(4or5)x0.5 cm^3
Readout by PMTs	Readout by SiPM
Single bar hit	Multiple counter hits

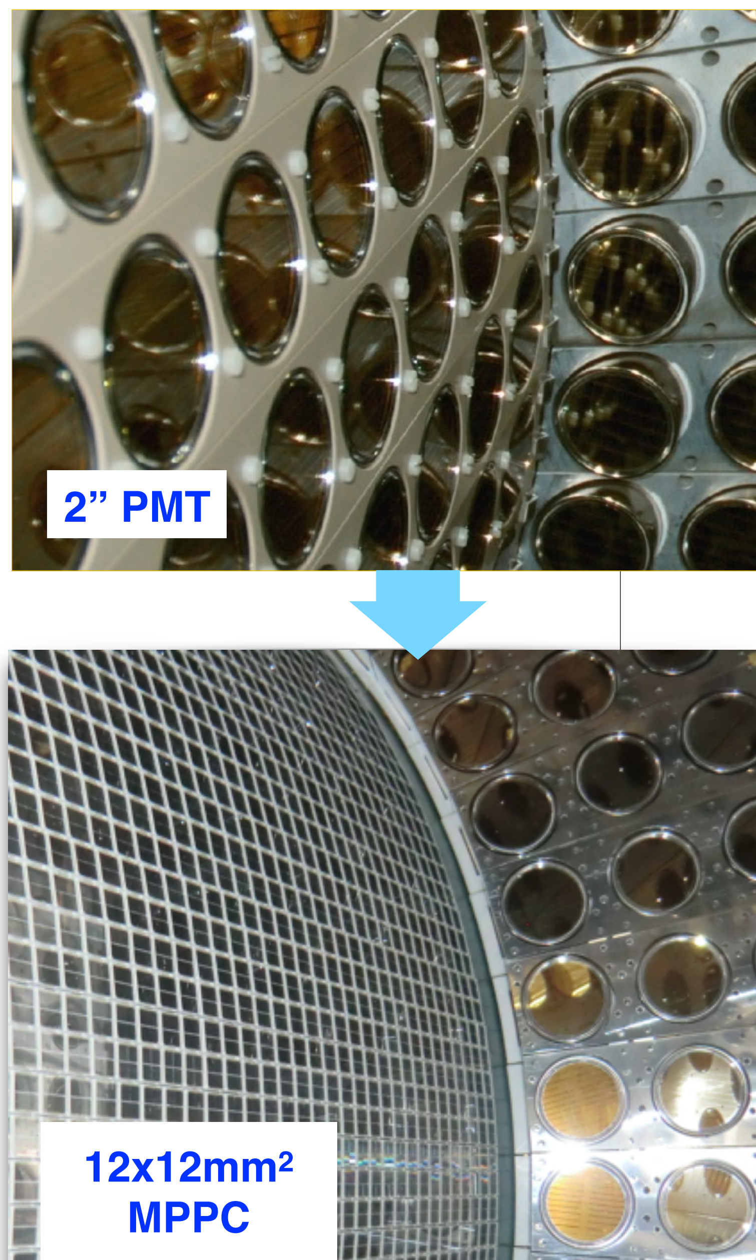


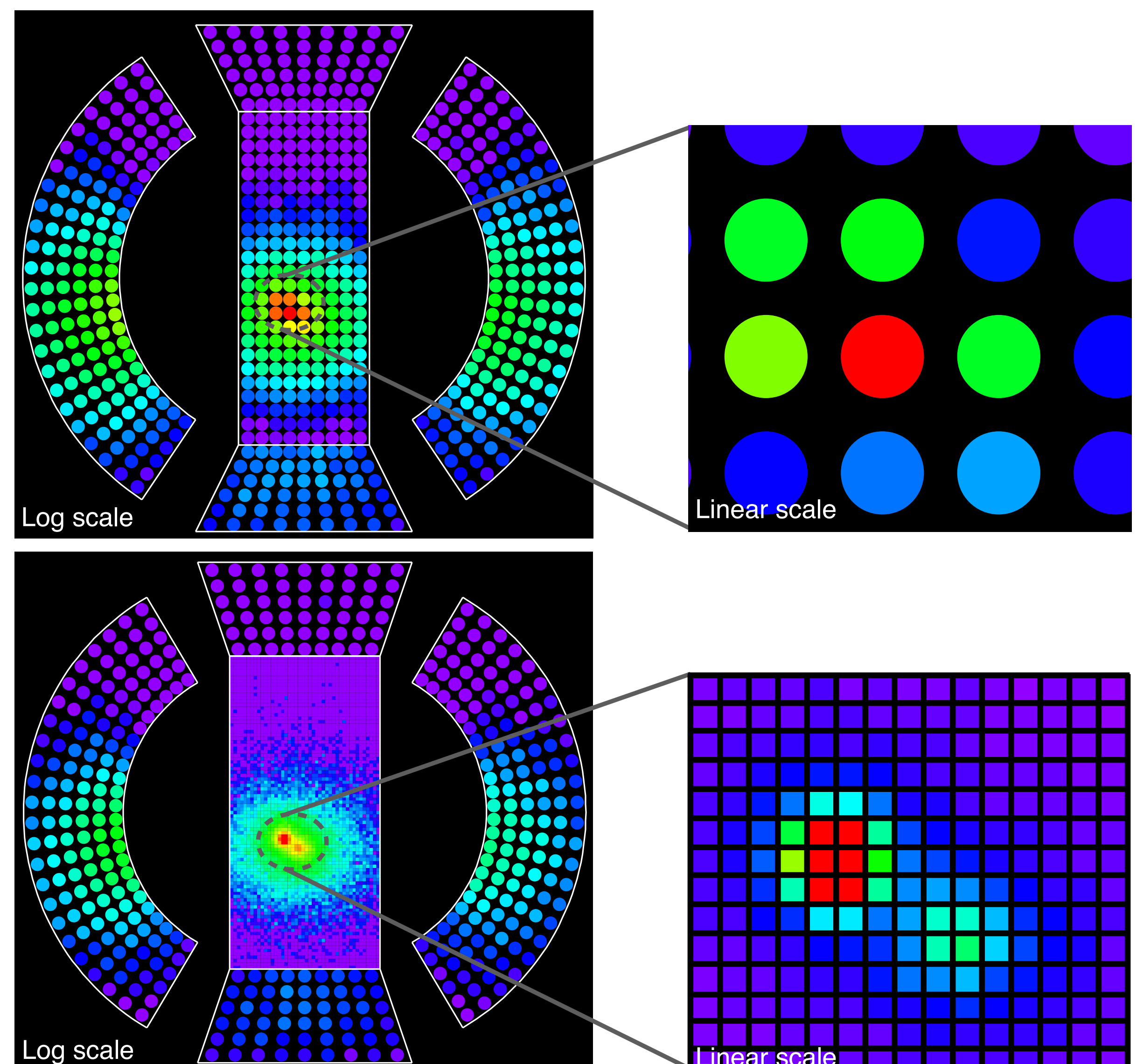




MEG II liquid xenon γ detector

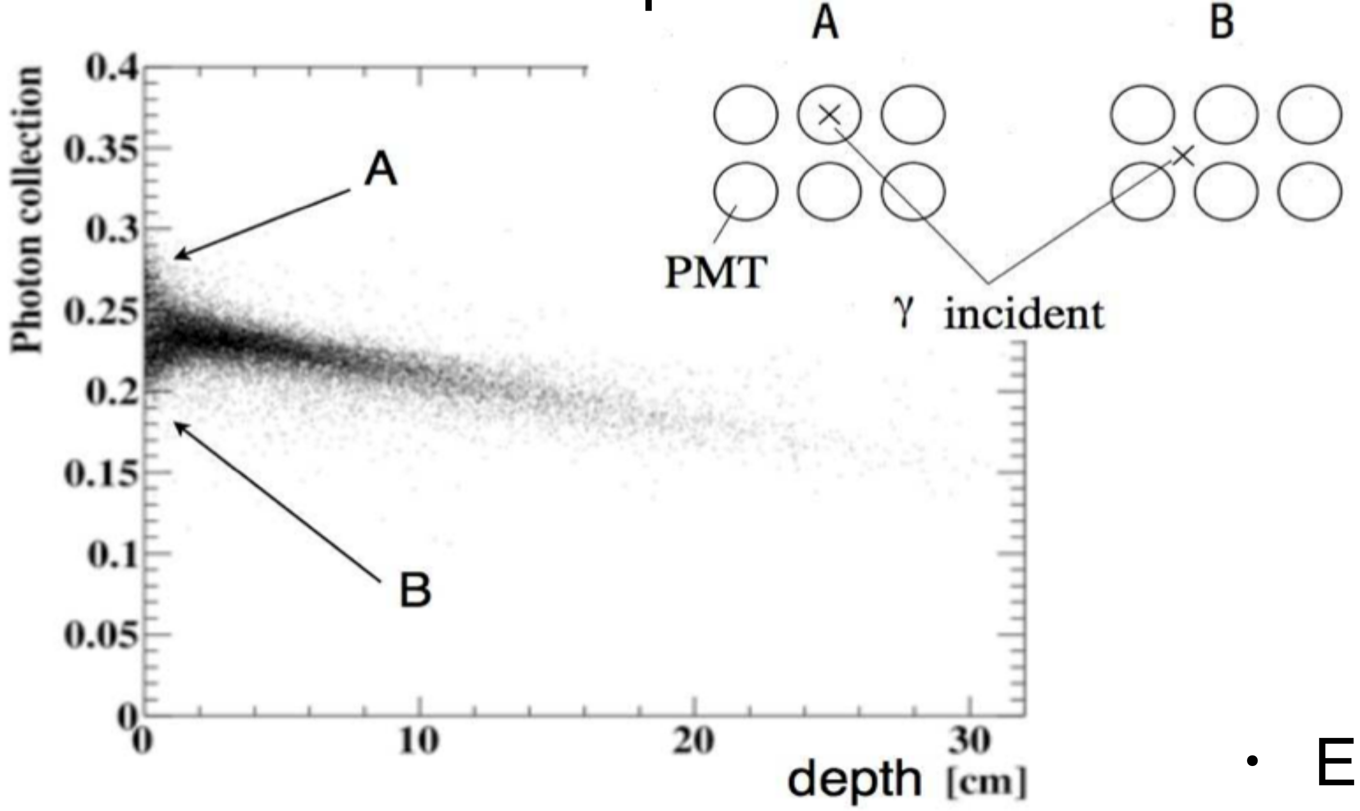
- Energy, position, time measurement of 52.8MeV γ from μ→eγ decay
- Inner 216 PMTs → 4092 MPPCs (VUV-sensitive large area MPPCs)
- Better granularity, better uniformity→Better energy, position resolution

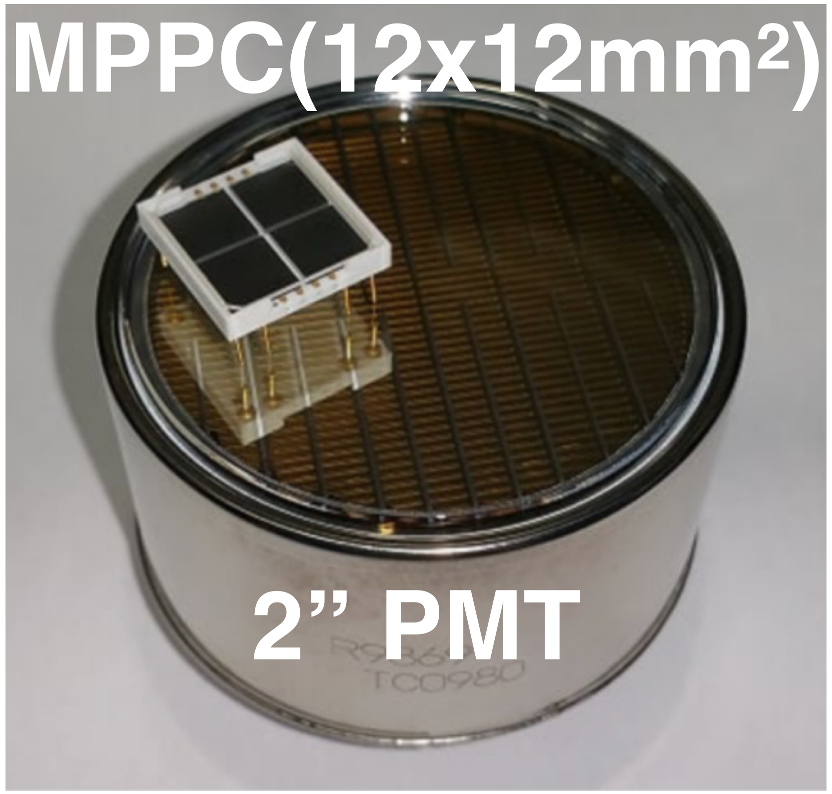




MEG II liquid xenon γ detector

of photons collected by PMTs
as a function of depth





- Energy, position, time measurement of 52.8MeV γ from μ→eγ decay

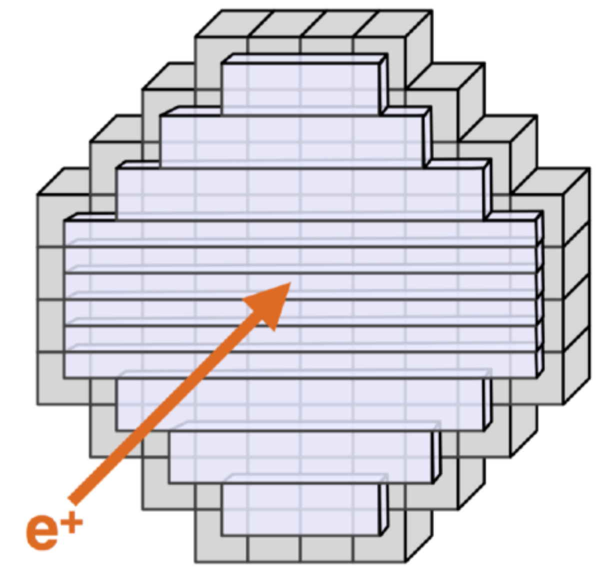
- Non uniform response for shallow events
- Replace inner PMTs with MPPCs
- Better granularity, better uniformity →Better energy, position resolution

MEG LXe	MEG II LXe
900L LXe	900L LXe
216 2"PMTs (γ entrance)	4092 12x12mm^2 MPPCs
630 PMTs (other faces)	668 PMTs

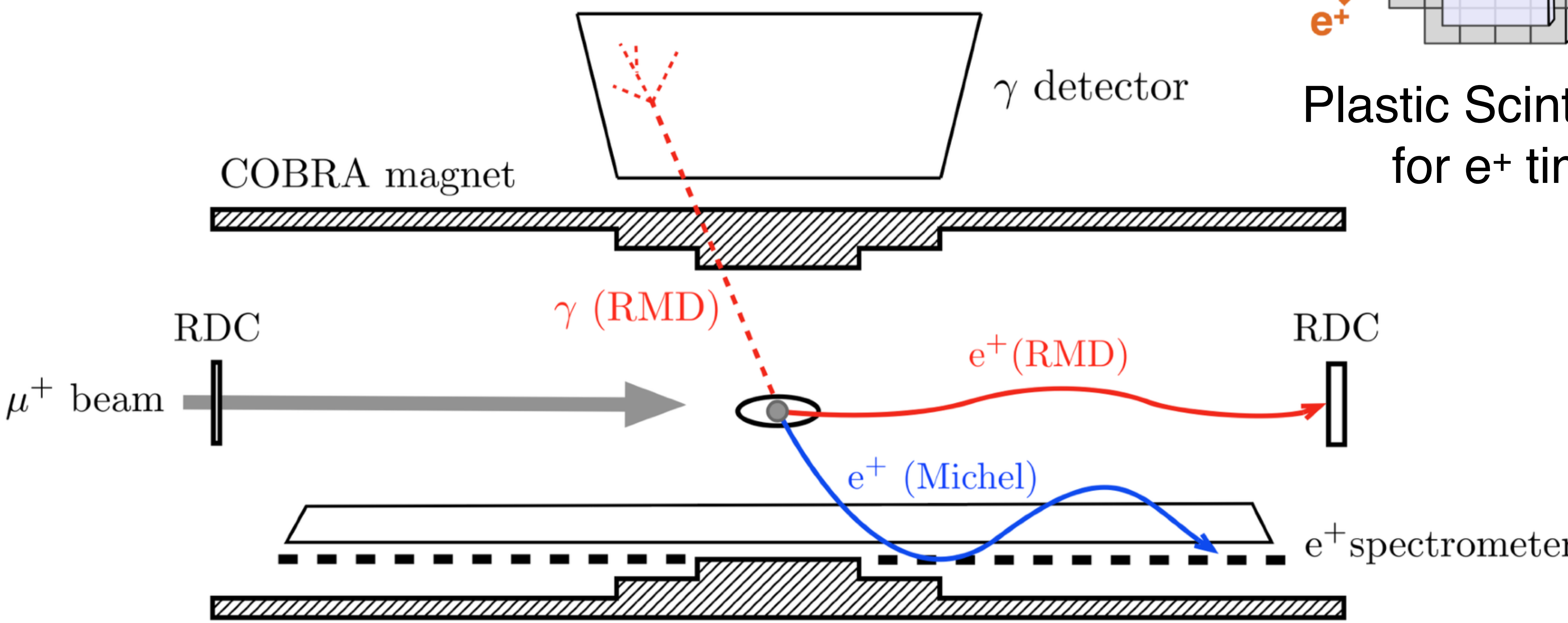
Radiative Decay Counter

- New device for MEG II
  - To tag high energy γ background from radiative muon decay by detecting low momentum e+
- Downstream detector ready, upstream detector under development
  - μ+ beam goes through US RDC

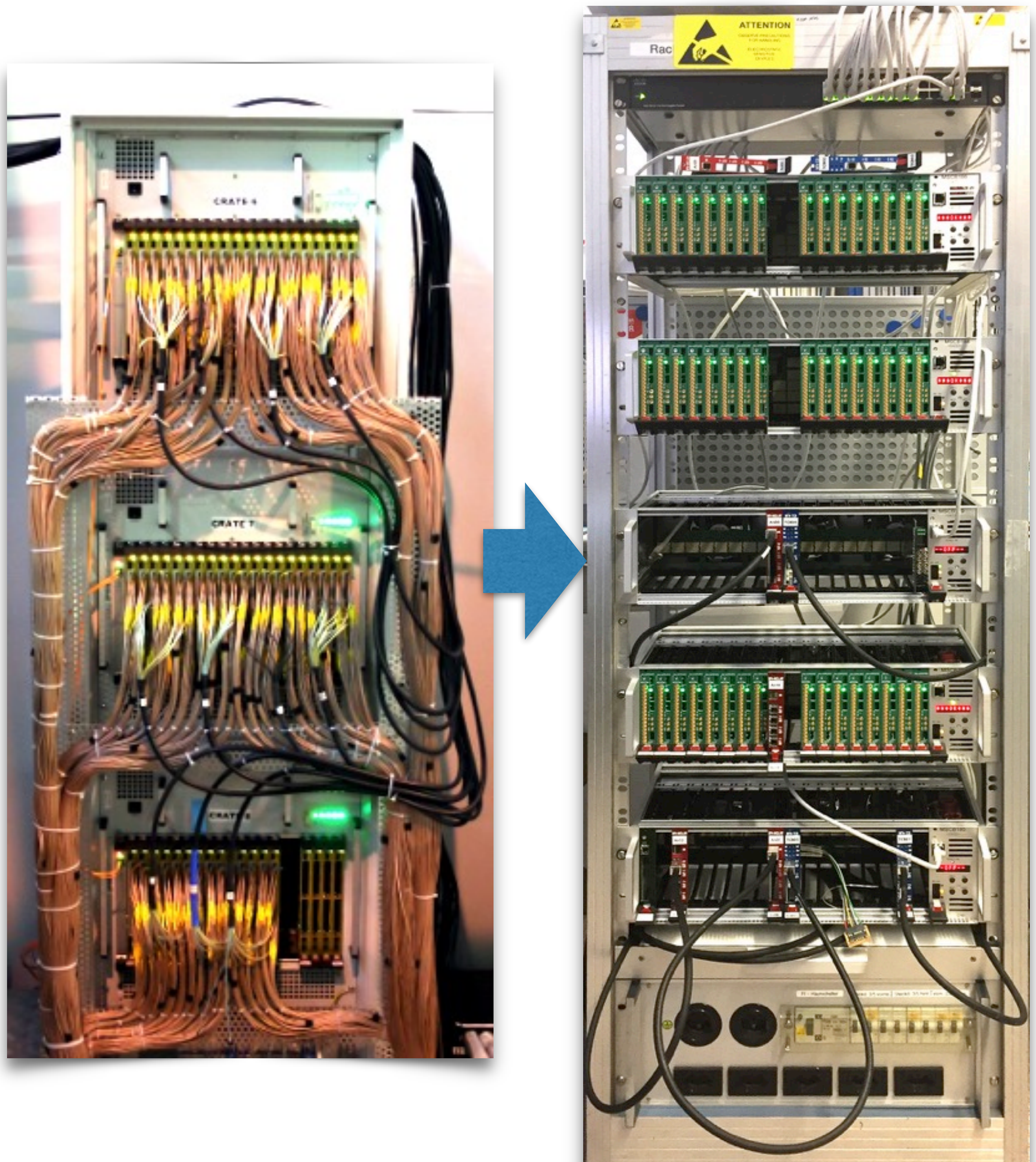
LYSO 2×2×2 cm³+SiPM for e+ energy



Plastic Scinti.+SiPM for e+ timing

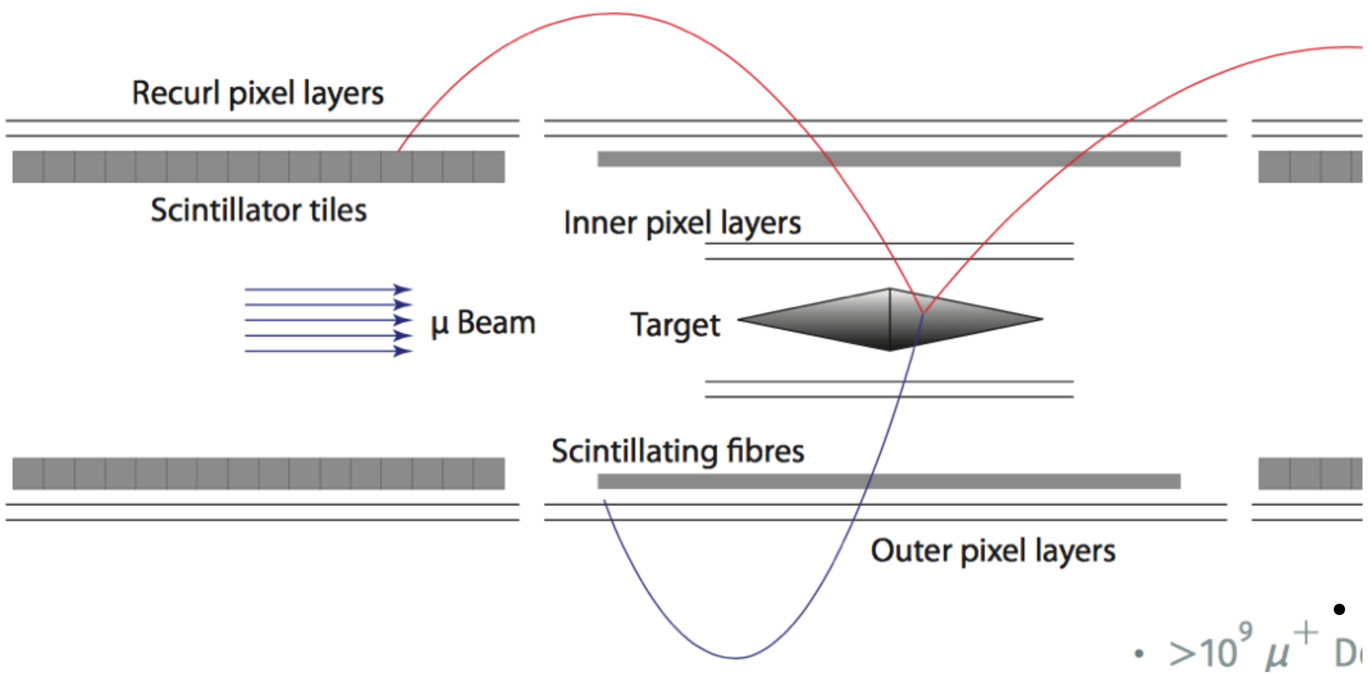


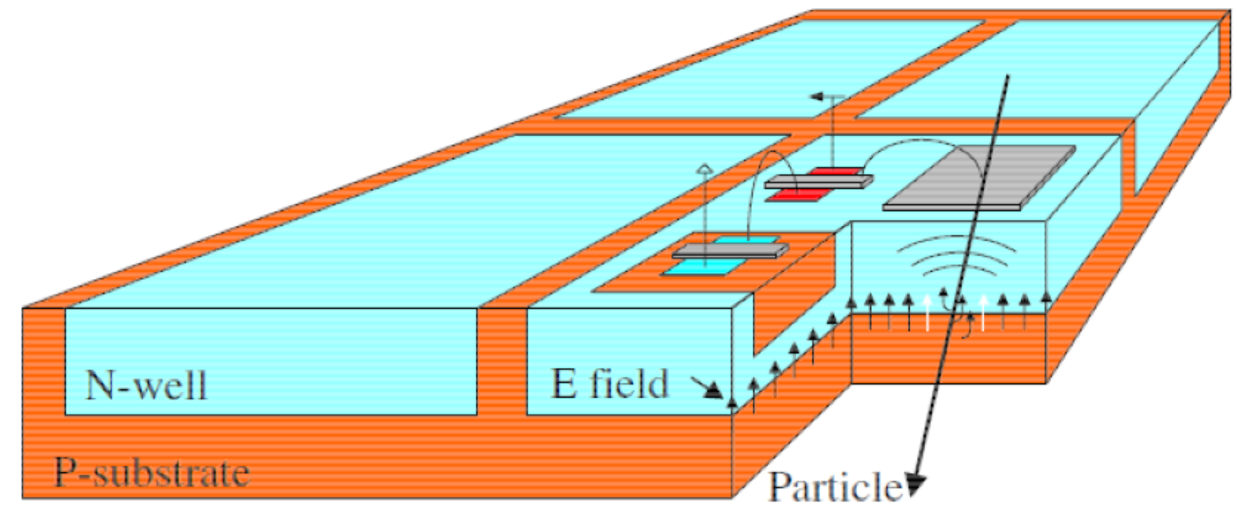
Readout Electronics



- Waveform data crucial for high rate environment
- Number of channels increased
  - For finer granularity
  - More compact boards necessary
- WaveDREAM developed by PSI
  - Waveform digitizer(DRS4) , simple trigger, amplifier and bias voltage supply (~200V) are integrated in a board, suitable for SiPM
- Online trigger important to manage high event rate and background suppression.
  - FPGA based trigger system prepared

Mu3e pixel tracker

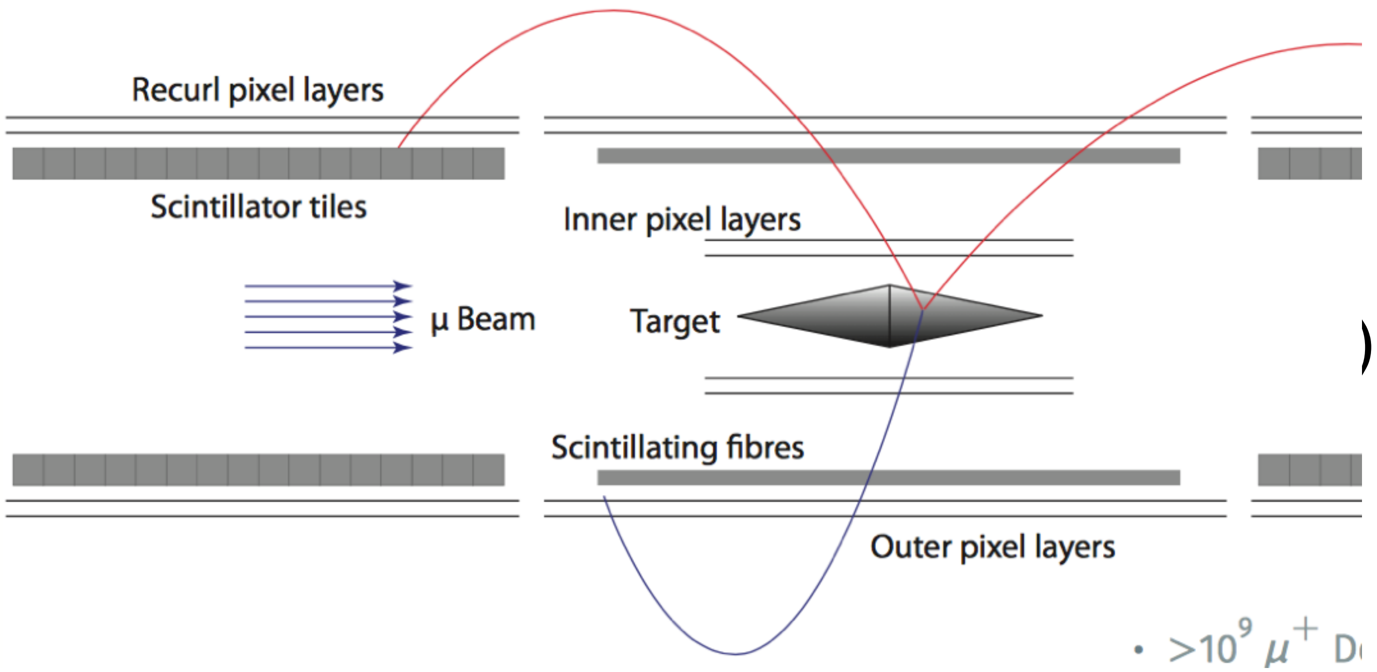


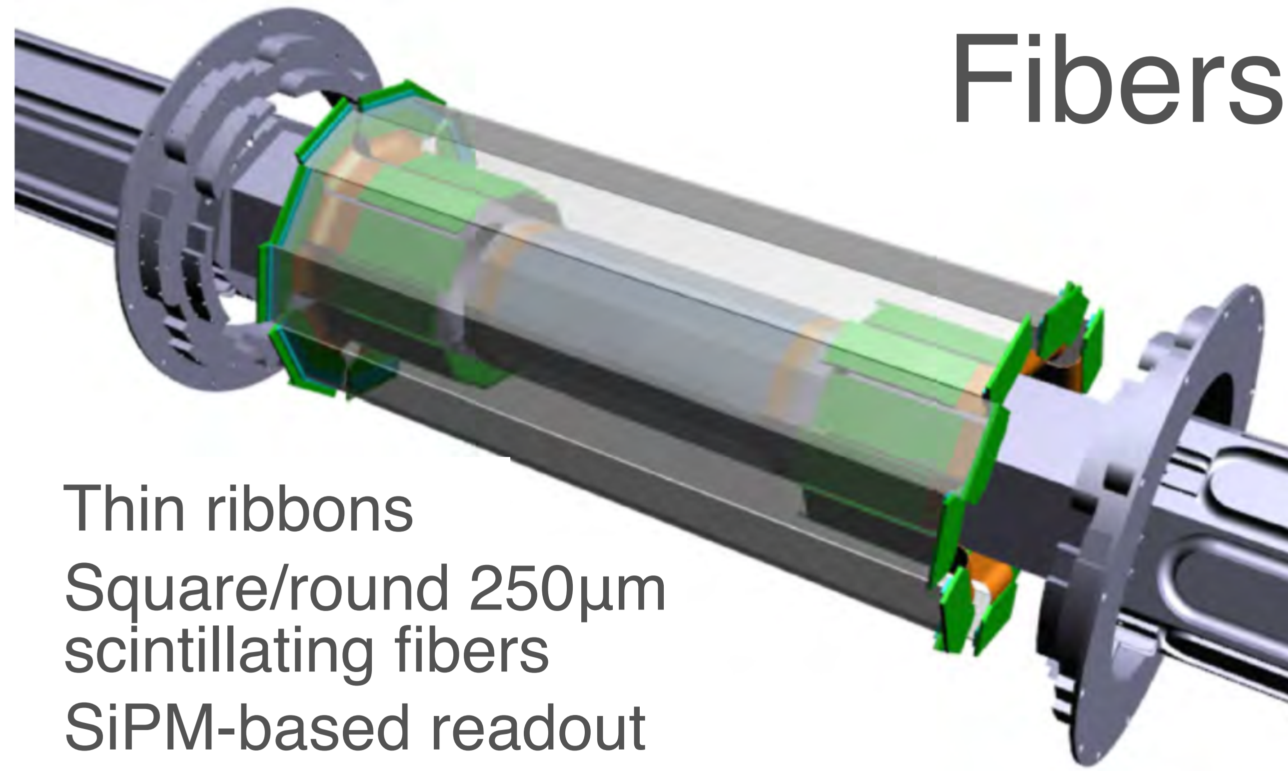


- Central tracker: Four layers
- Re-curl tracker: Two layers
- Minimum material budget: Multiple scattering dominates
- σ_p<0.5MeV/c

- High Voltage - Monolithic Active Pixel Sensor (HV-MAPS)
- Ultra-lightweight mechanics
  - 50μm Silicon sensor
  - 25μm Kapton flexprint with Al traces
  - 25μm Kapton support frame
- Time resolution < 20ns
- Active area chip: 20x20mm^2
- Under development

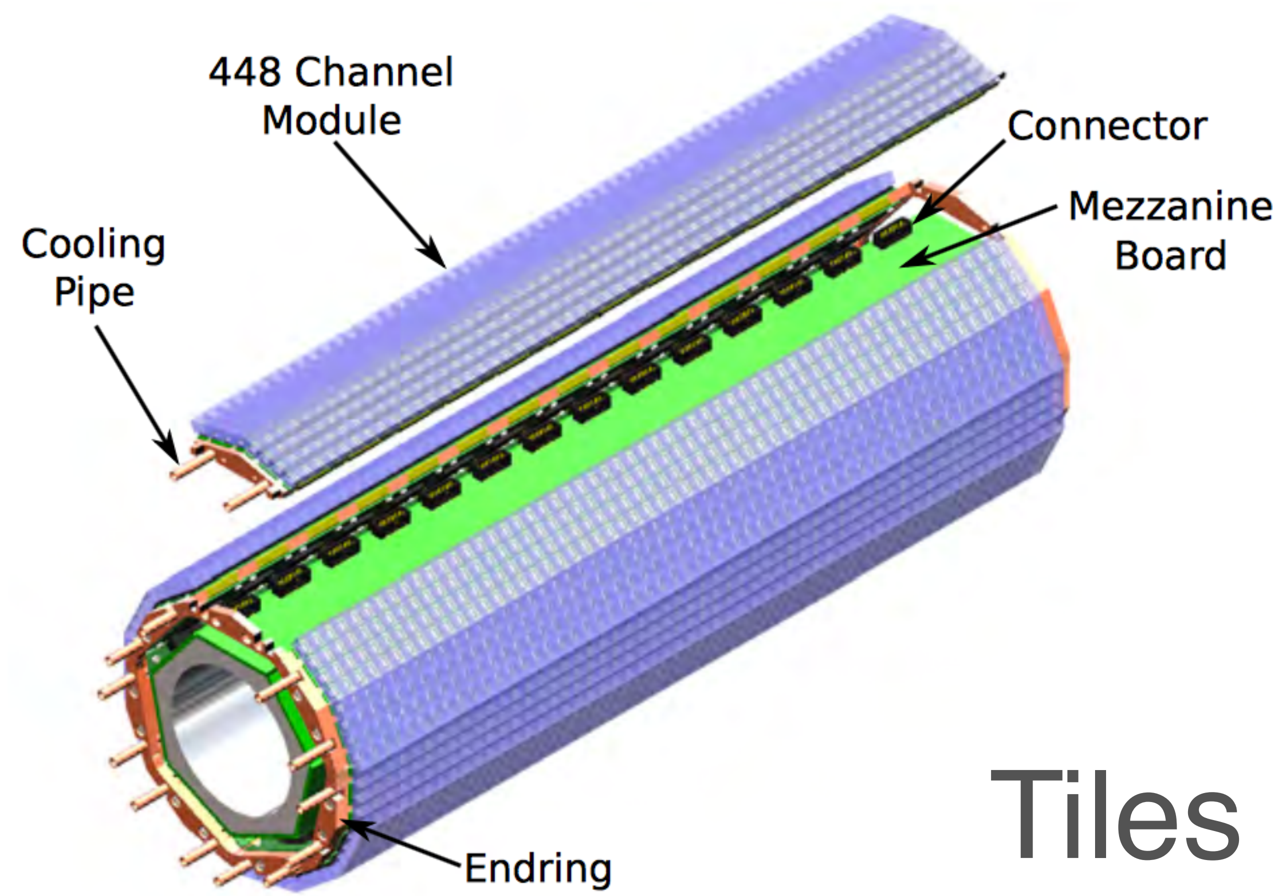
Mu3e timing detectors: Fibers and tiles





Thin ribbons
Square/round 250μm scintillating fibers
SiPM-based readout

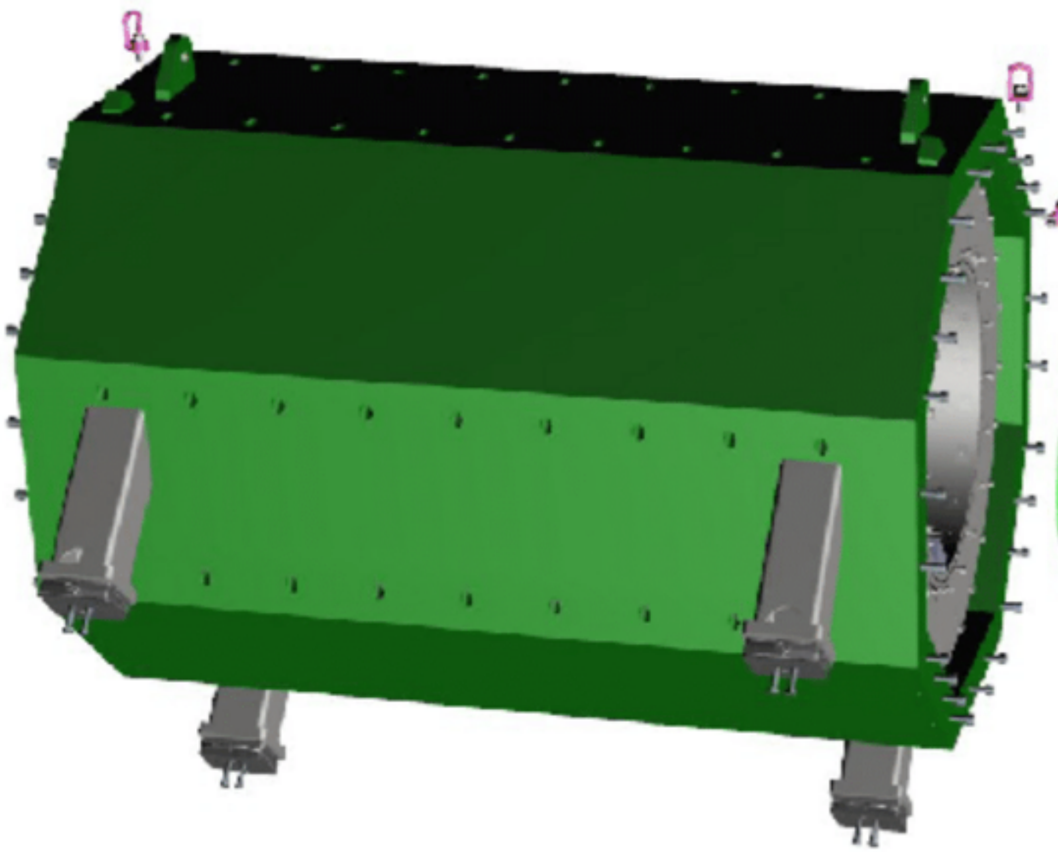
- After recurl pixel layers
- Scintillating tiles: 6.5x6.5x5.0mm^3
- SiPMs



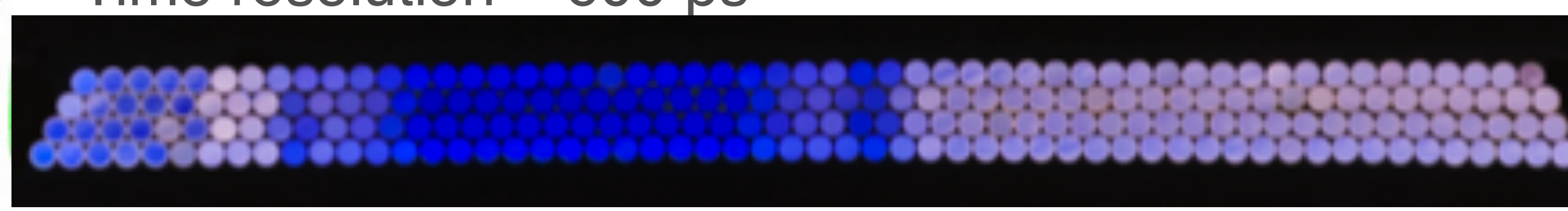
Mu3e status

Pixel tracker:
MuPix8, first full size sensor(1x2cm^2) has arrived last month

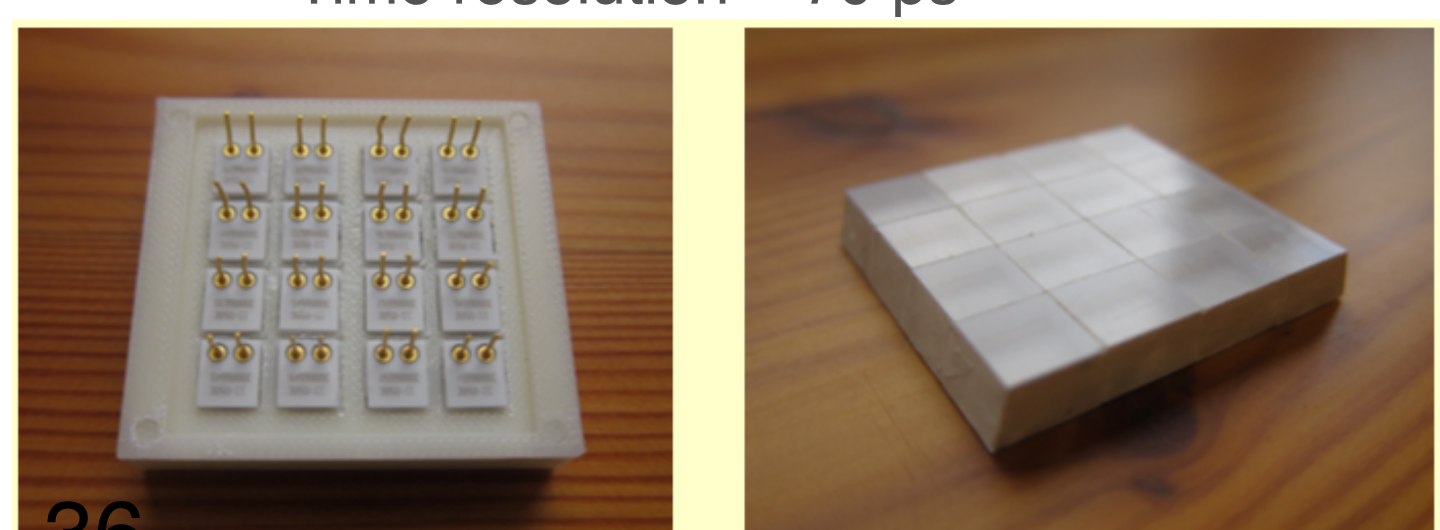
Magnet:
Delivery originally planned in 2016, but cancelled. New date in 2019



Scintillating Fibers:
Prototype of Round (Kuraray SCSF-81M), squared (Saint-Gobain BC418) are tested
Time resolution ~ 600 ps



Scintillating Tile Detector:
Promising results from 4x4 array
Time resolution ~ 70 ps



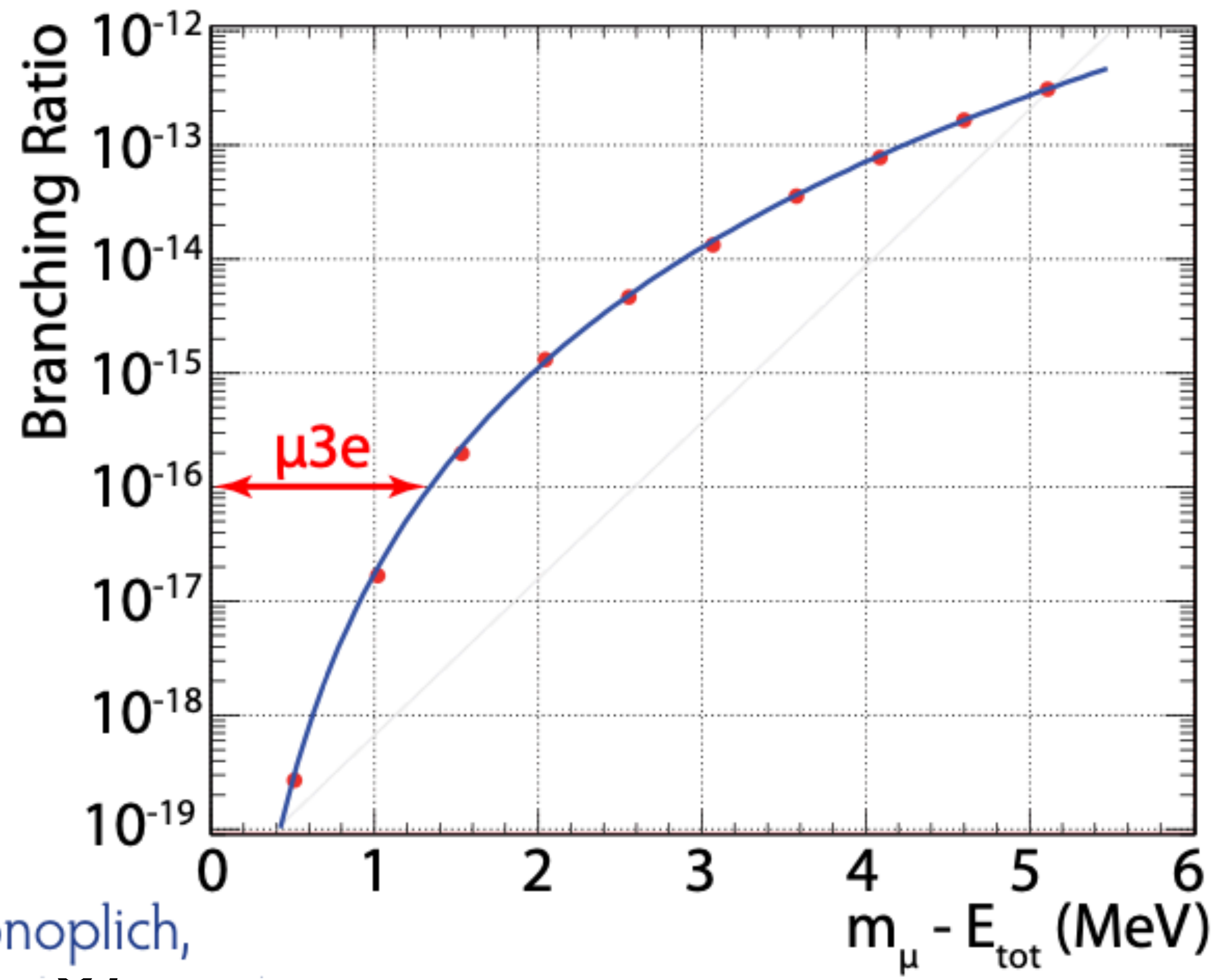
- Engineering run in 2019
- Sensitivity 2×10^{-15} in Mu3e Phase I
  10^8 μ^+/s

Internal conversion background

- Allowed radiative decay with internal conversion:

$$\mu^+ \rightarrow e^+ e^- e^+ \nu \bar{\nu}$$

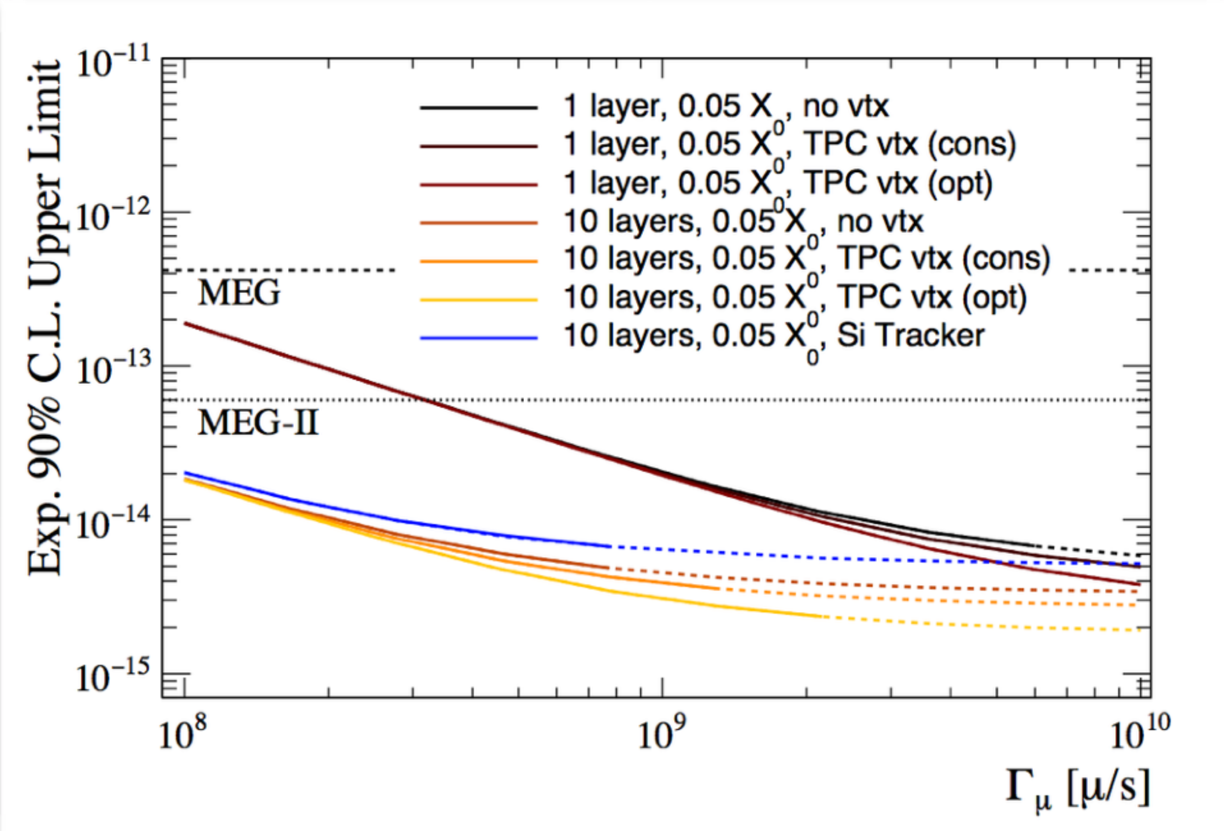
- Only distinguishing feature:
  Missing momentum carried by neutrino



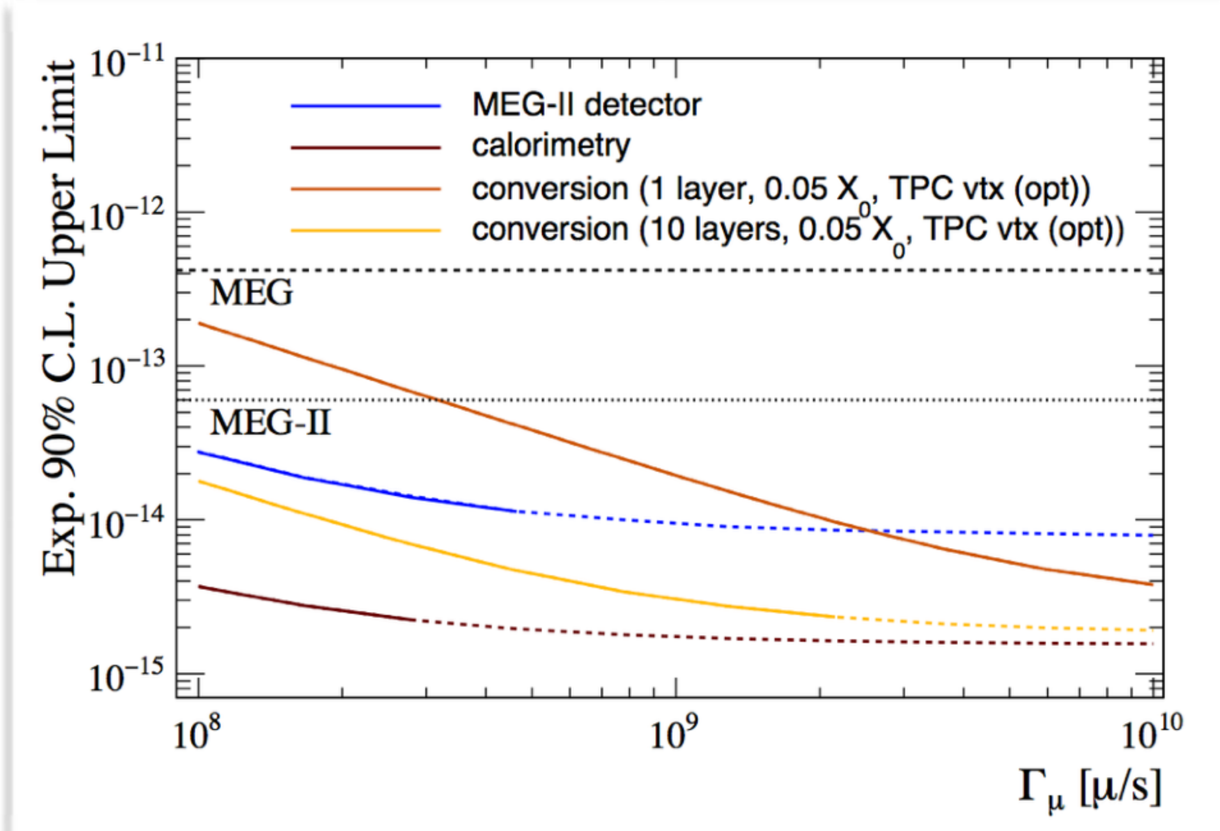
V. Konoplich,

Expected sensitivity

Photon conversion approach



Photon conversion vs calorimetric approach



A few 10^{-15} level seems to be within reach for 3 years running at 10^{8} muon/s with calorimetry or 10^{9} muons/s with photon conversion

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