CHARGED LEPTON FLAVOR EXPERIMENTAL OVERVIEW

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THE UNIVERSITY OF TOKYO

WHAT IS FLAVOR?

- A "***heavy electron***" (i.e. muon) never decayed radiatively into an electron although such a decay does not violate any conservation law.

$$\mu \to e\gamma$$

  - New quantum numbers, "**Flavors,**" were introduced to explain it.

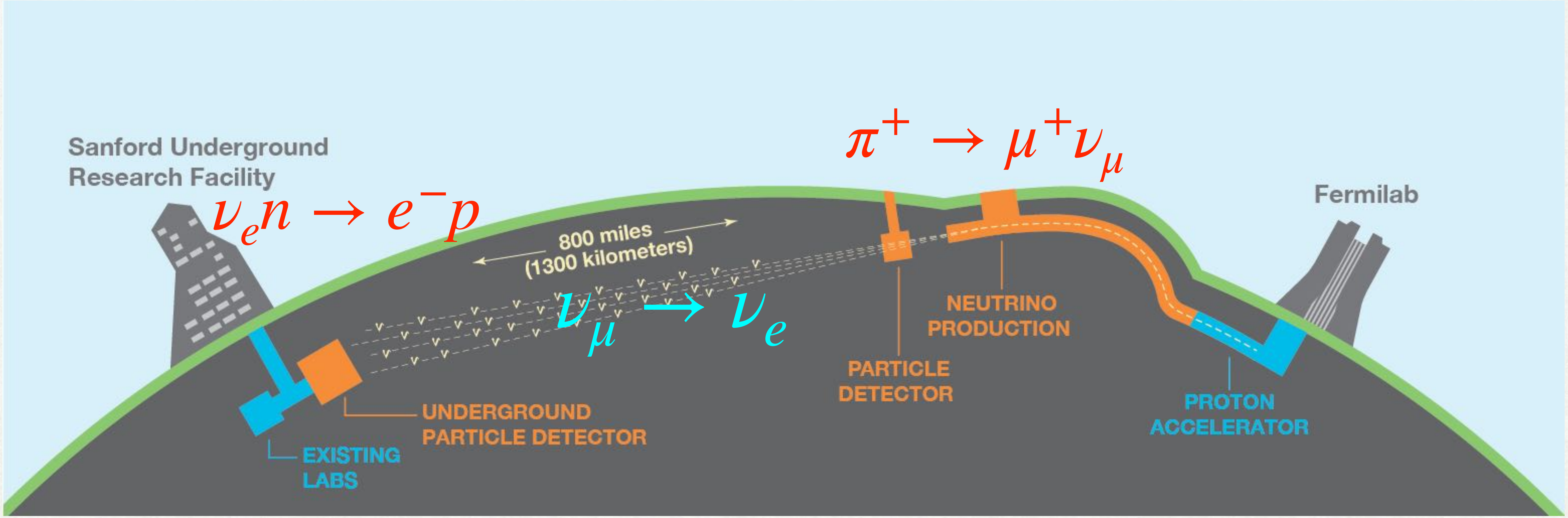
- ***Quarks*** seem to approximately conserve flavors.

  - FCNC decays such as $b \to s\gamma$ occur only at 10^{-5} level.

- ***Neutrinos*** oscillate and have no respect for Flavors!

- What about ***Charged Leptons***?

NEUTRINO OSCILLATIONS

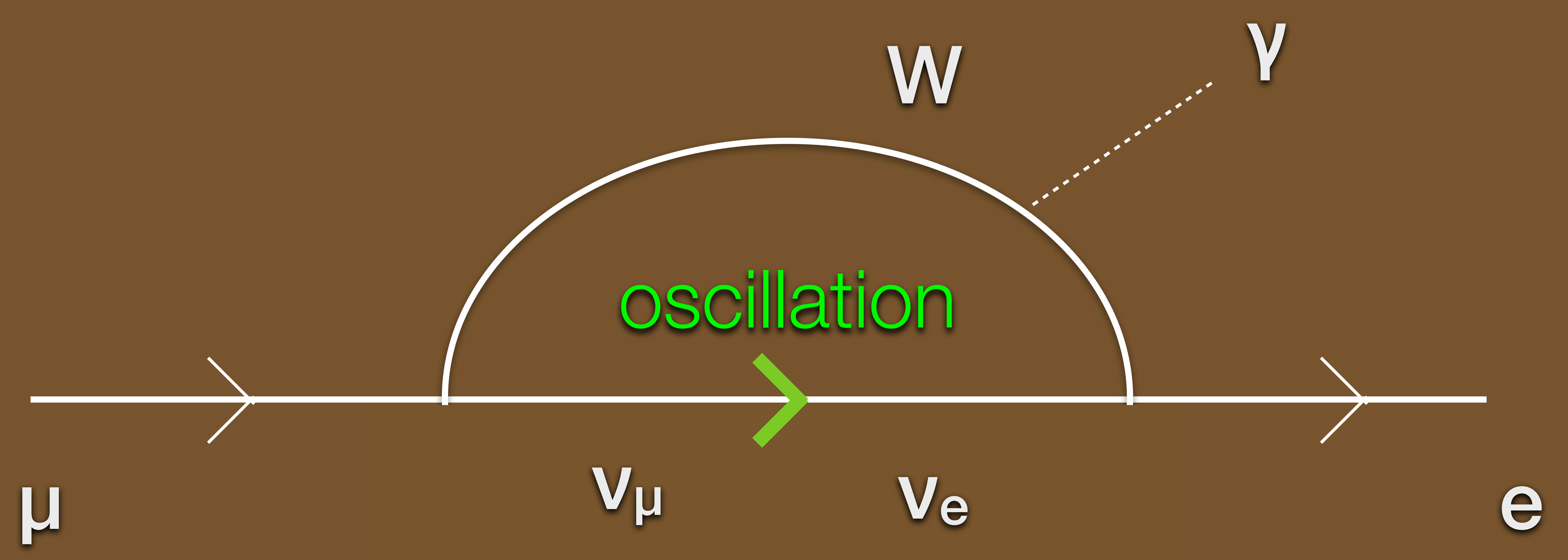


- We don't really measure neutrinos in these measurements!

$$\pi^+ n \to \mu^+ e^- p$$

CHARGED LEPTON FLAVOR VIOLATION (CLFV)!

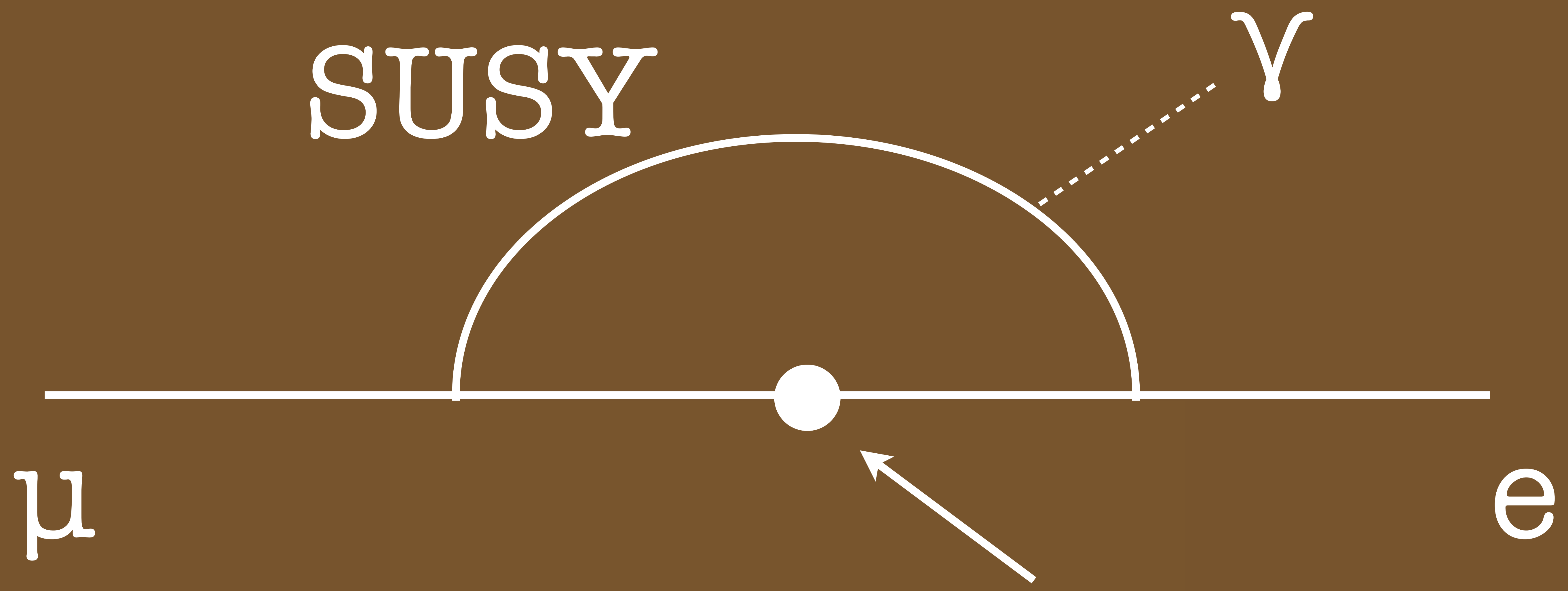
CHARGED LEPTONS SHOULD MIX!



$$\frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}\left(\frac{m^2_{\nu_i}}{M^2_W}\right)U_{ei}\right|^2 \leq 10^{-50}$$

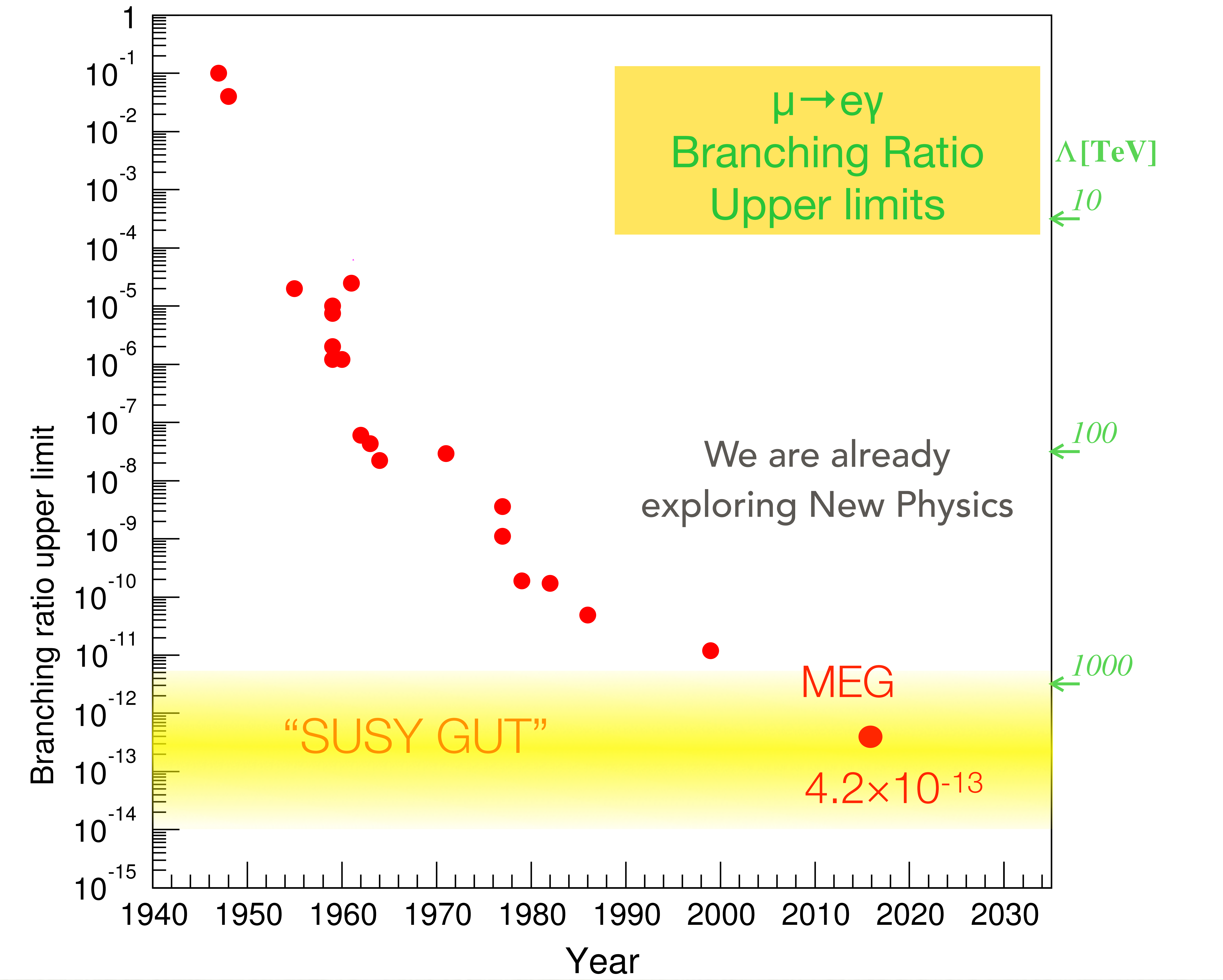
No, the neutrinos are just too light…

TEV SCALE NEW PHYSICS HELP THEM MIX !



$$\left|\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{M^2_{SUSY}}\right| \sim 10^{-12}$$

Induced via RGE
down from GUT/seesaw
even if no mixing



μ→eγ
Branching Ratio
Upper limits
Λ[TeV]
10
100
1000
We are already
exploring New Physics
MEG
"SUSY GUT"
4.2×10-13
Branching ratio upper limit
Year
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10-14
10-15
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030

WHERE TO LOOK FOR CLFV?

Check many interesting talks in the parallel sessions

MUON DECAYS & CONVERSIONS

K. Ieki (MEG/MEG II)

H. Nishiguchi (COMET)

M. Aoki (DeeMe)

M. Yucel (Mu2e)

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K. Inami, D. Sahoo (Belle/Belle II)

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NEW LIGHT PARTICLES

$Z' \to \mathrm{inv}$ $\mathrm{ALP} \to \gamma\gamma$ $\tau \to \ell\alpha$

E. Graziani, F Tenchini (Belle II)

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$H \to \tau\ell$ H. Borecka-Bielska (ATLAS)

NEW HEAVY PARTICLES

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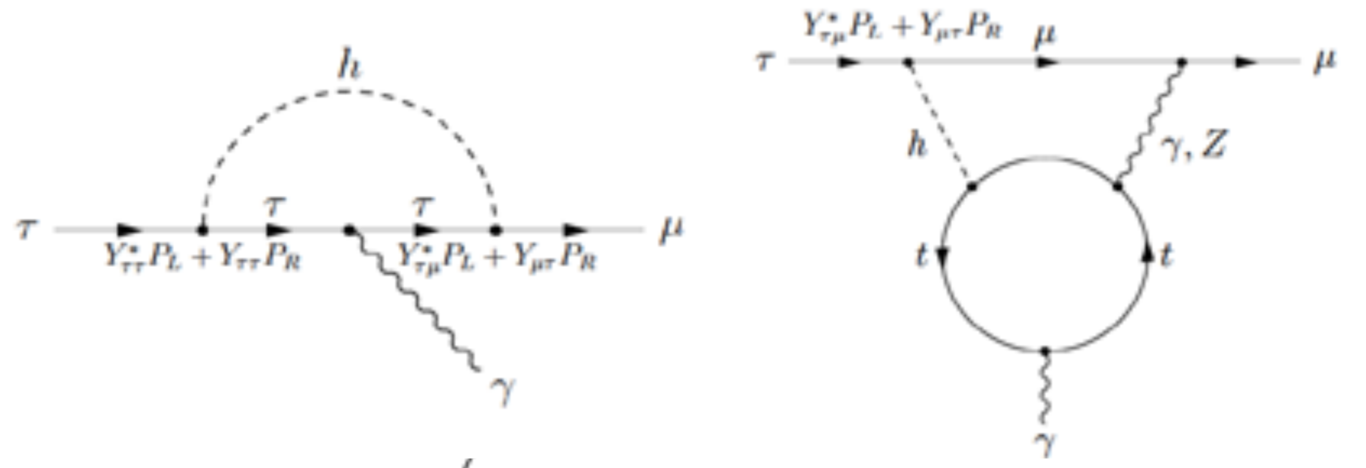
LFV HIGGS COUPLINGS

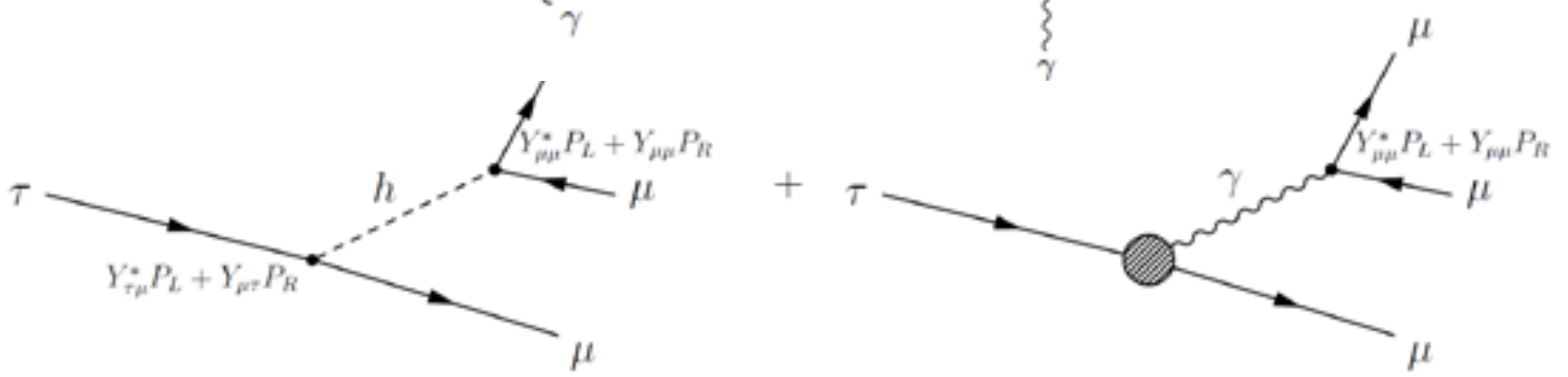
$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c..$$

CLFV Higgs decay $\sqrt{|Y_{\ell\tau}|^2+|Y_{\tau\ell}|^2} = \frac{8\pi\Gamma_H(SM)}{m_H}\frac{BR(H\to\ell\tau)}{1-BR(H\to\ell\tau)}$

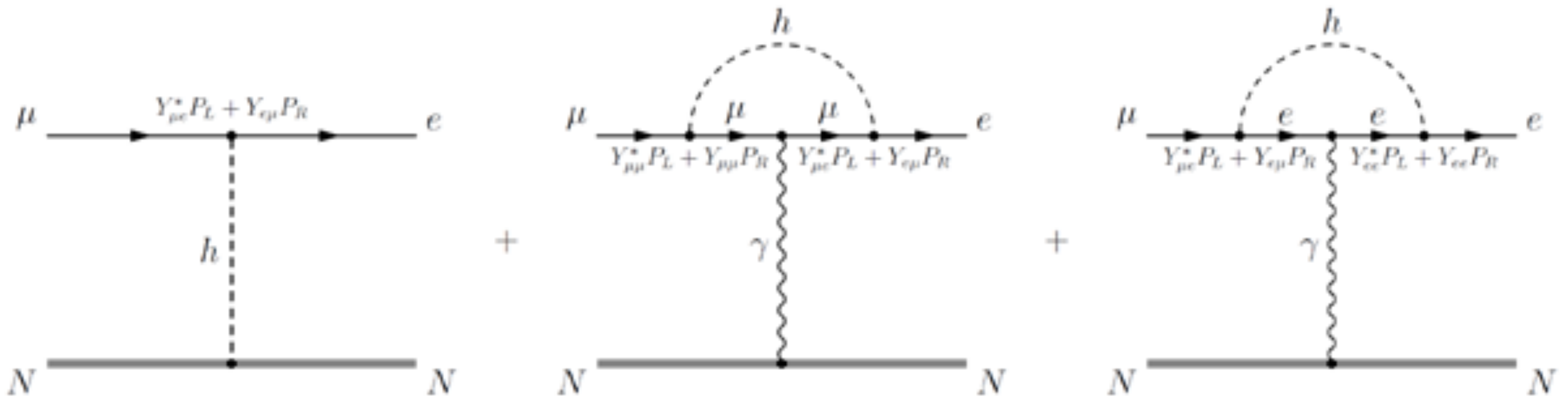
$\tau\to\mu\gamma\ (\mu\to e\gamma)$



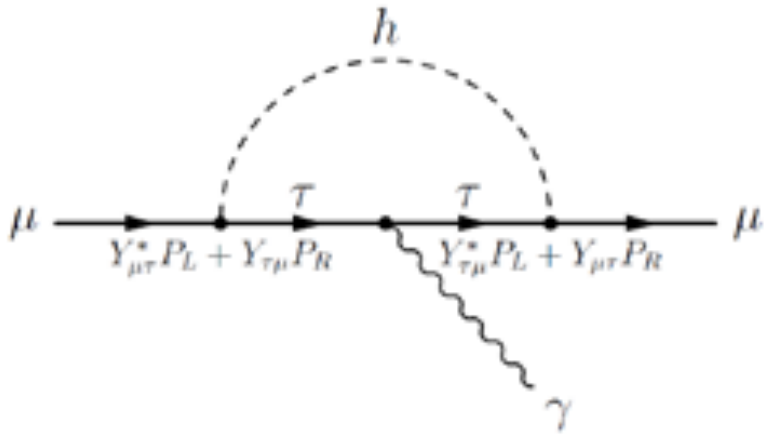
$\tau\to l'll\ (\mu\to eee)$



$\mu N\to eN$



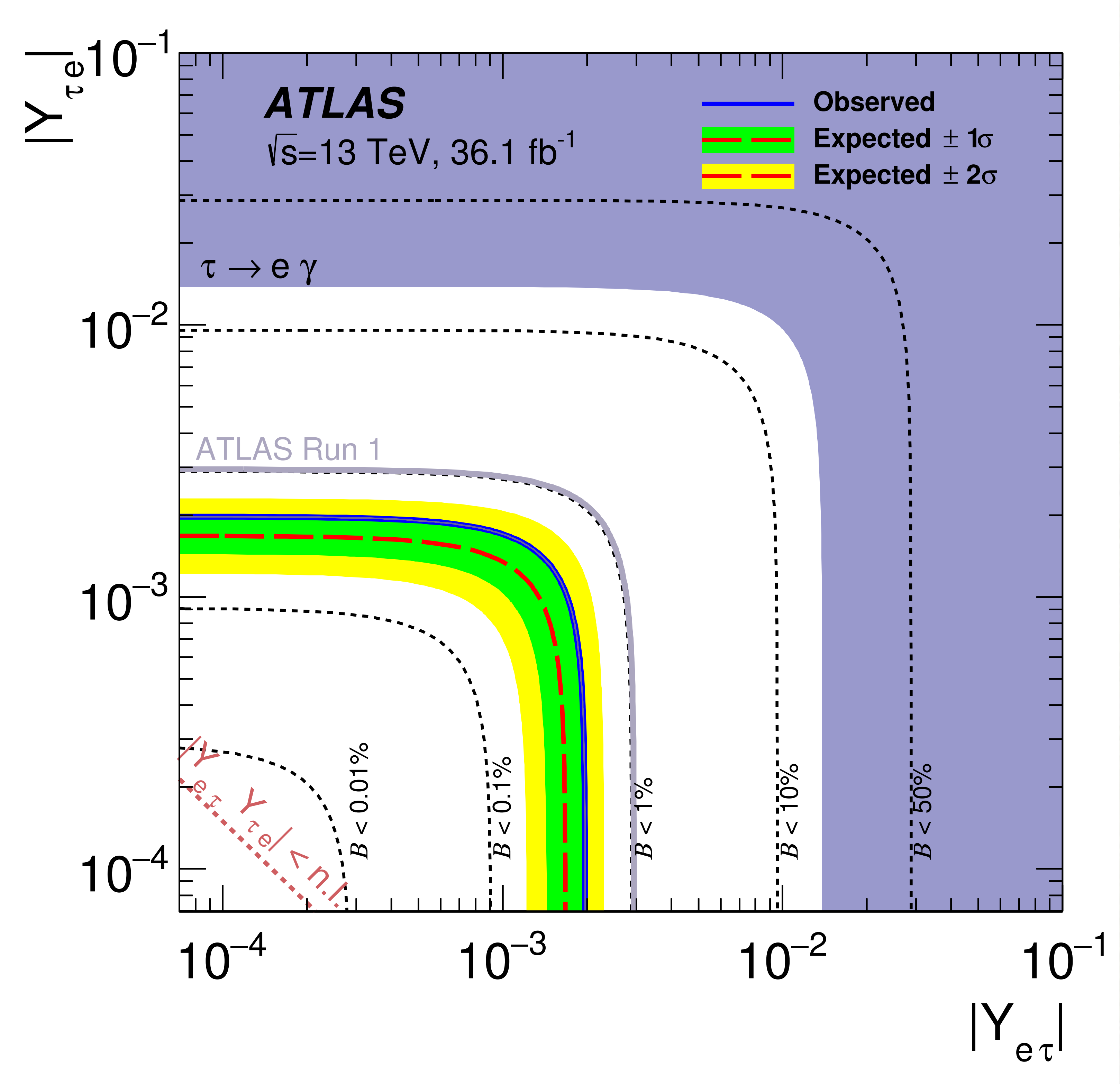
g-2

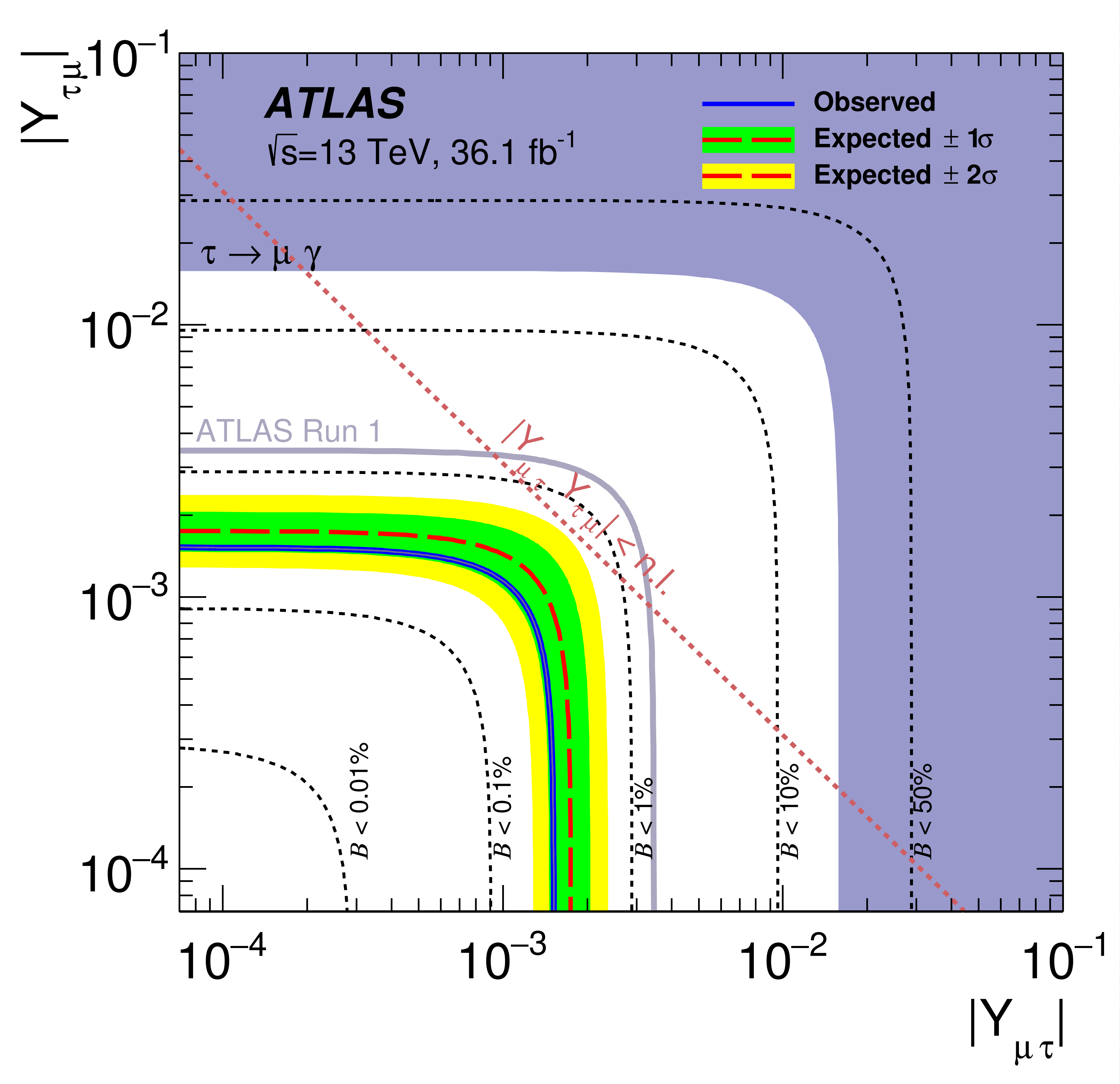


- Various LFV processes are connected through common fundamental LFV couplings.
- LFV Higgs couplings are also probed by muon & tau LFV processes.
- LHC experiments have higher sensitivities for LFV Higgs couplings involving tau.
- complementarity

Upper limits on the absolute values of $Y_{\ell\tau}$ couplings

$$|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2 = \frac{8\pi}{m_H}\frac{\mathcal{B}(H\to\ell\tau)}{1-\mathcal{B}(H\to\ell\tau)}\Gamma_H$$





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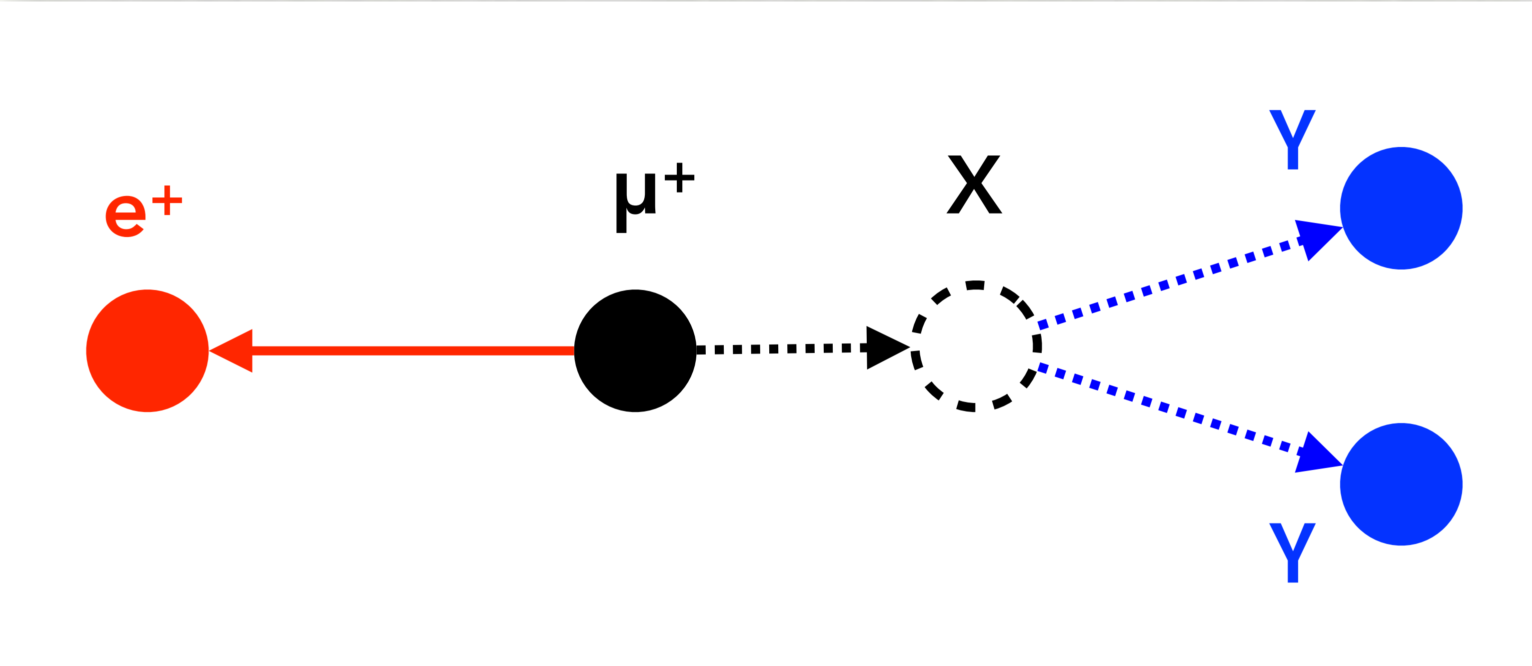
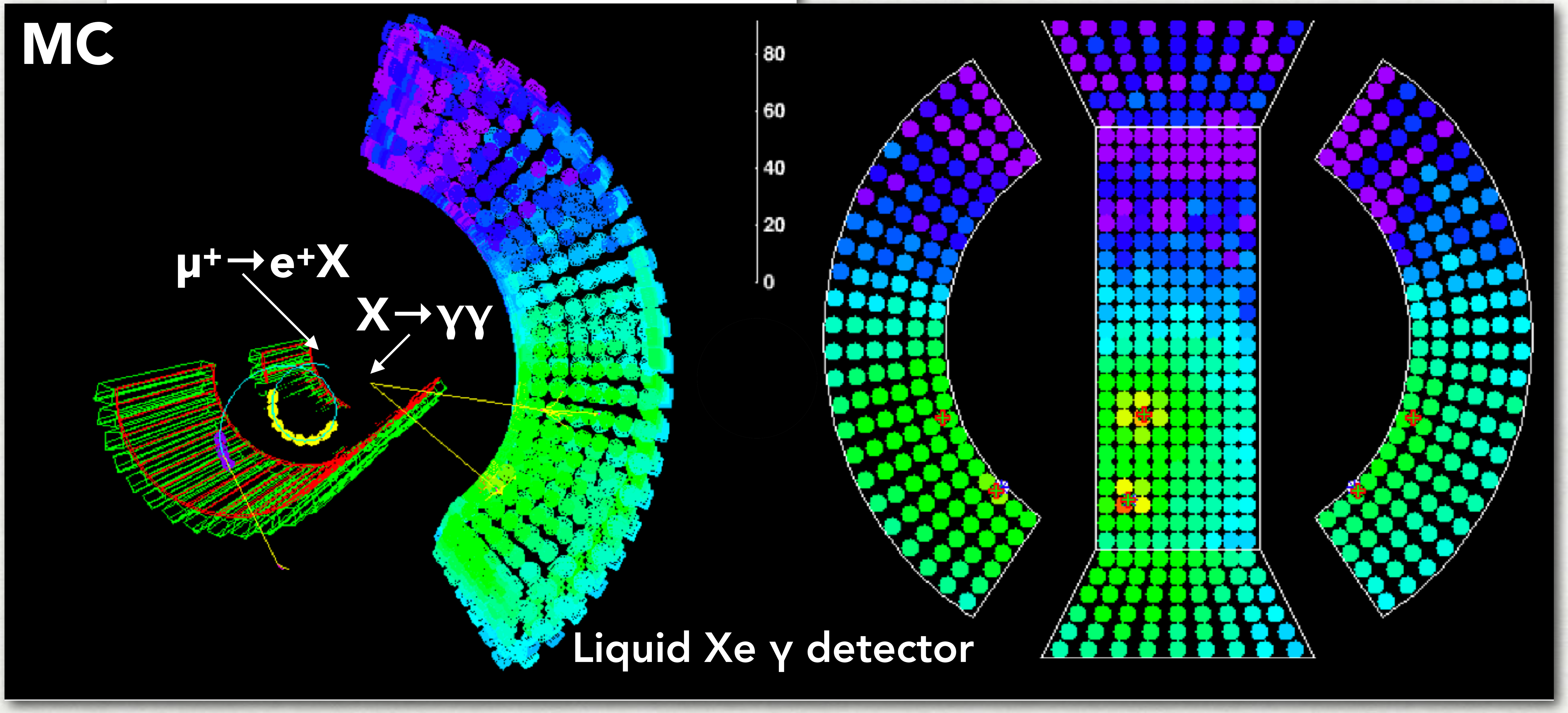


- MEG searched for LFV muon decay mediated by a new light particle decaying into two gammas.



arXiv:2005.00339, submitted to EPJC

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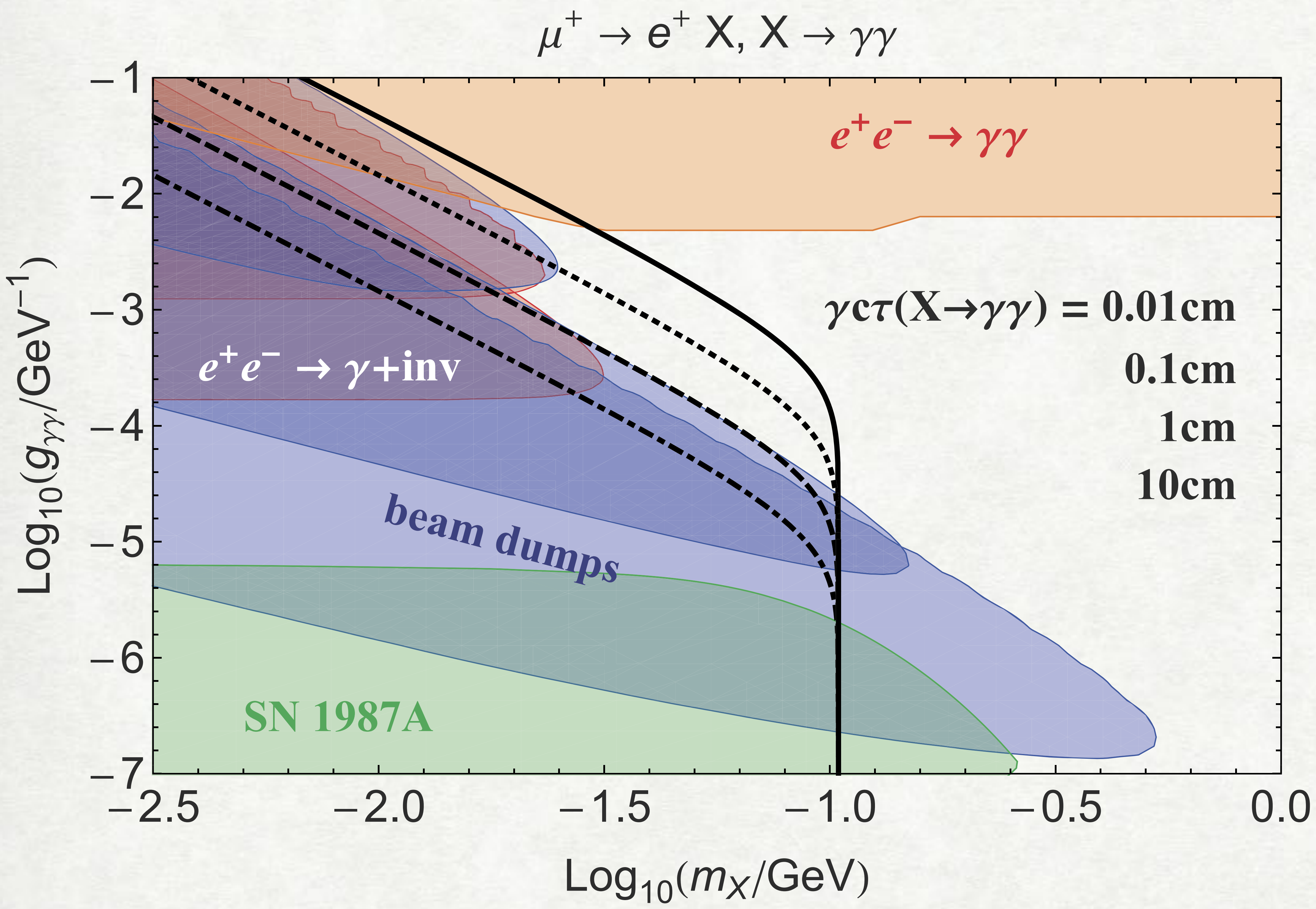
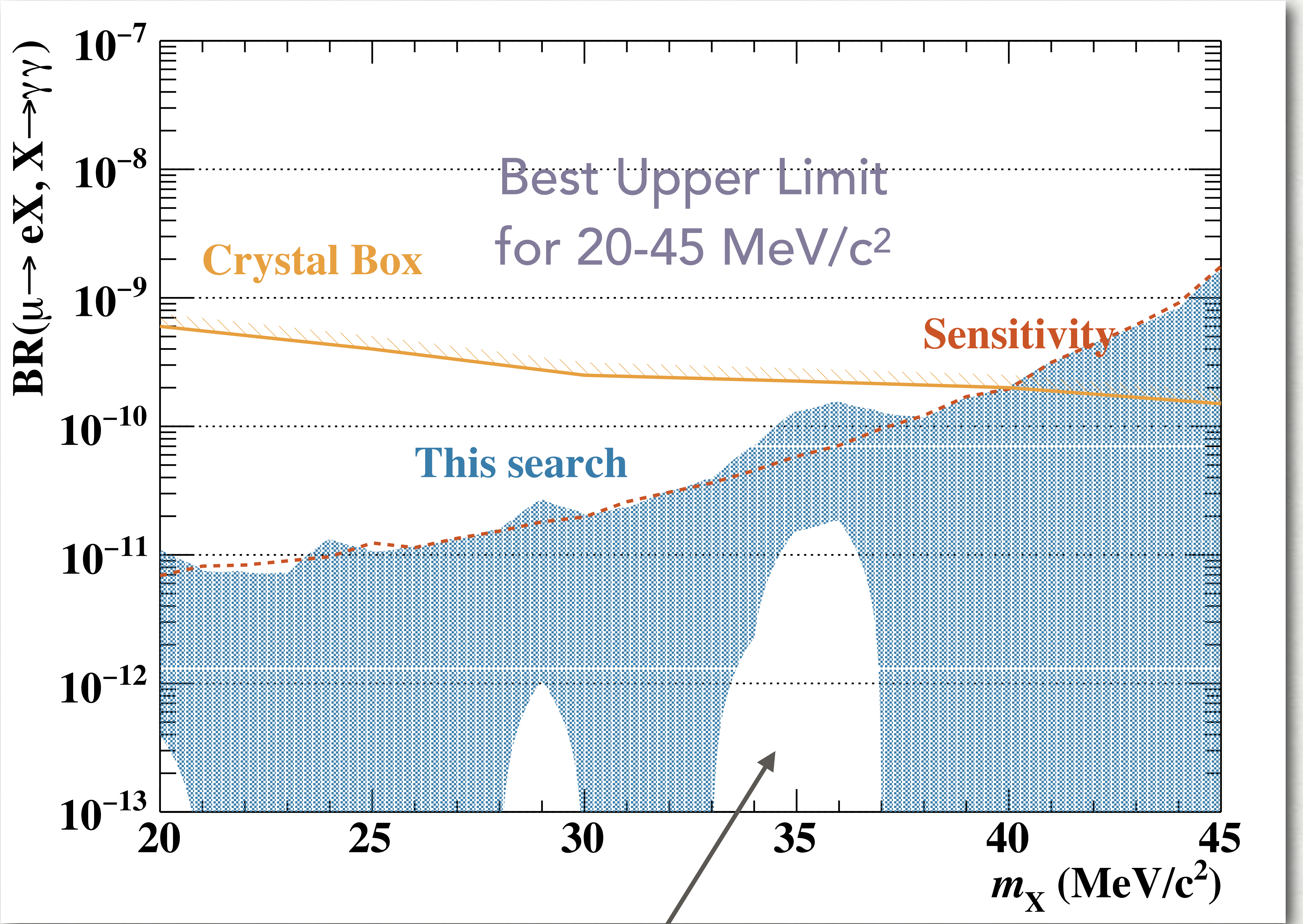


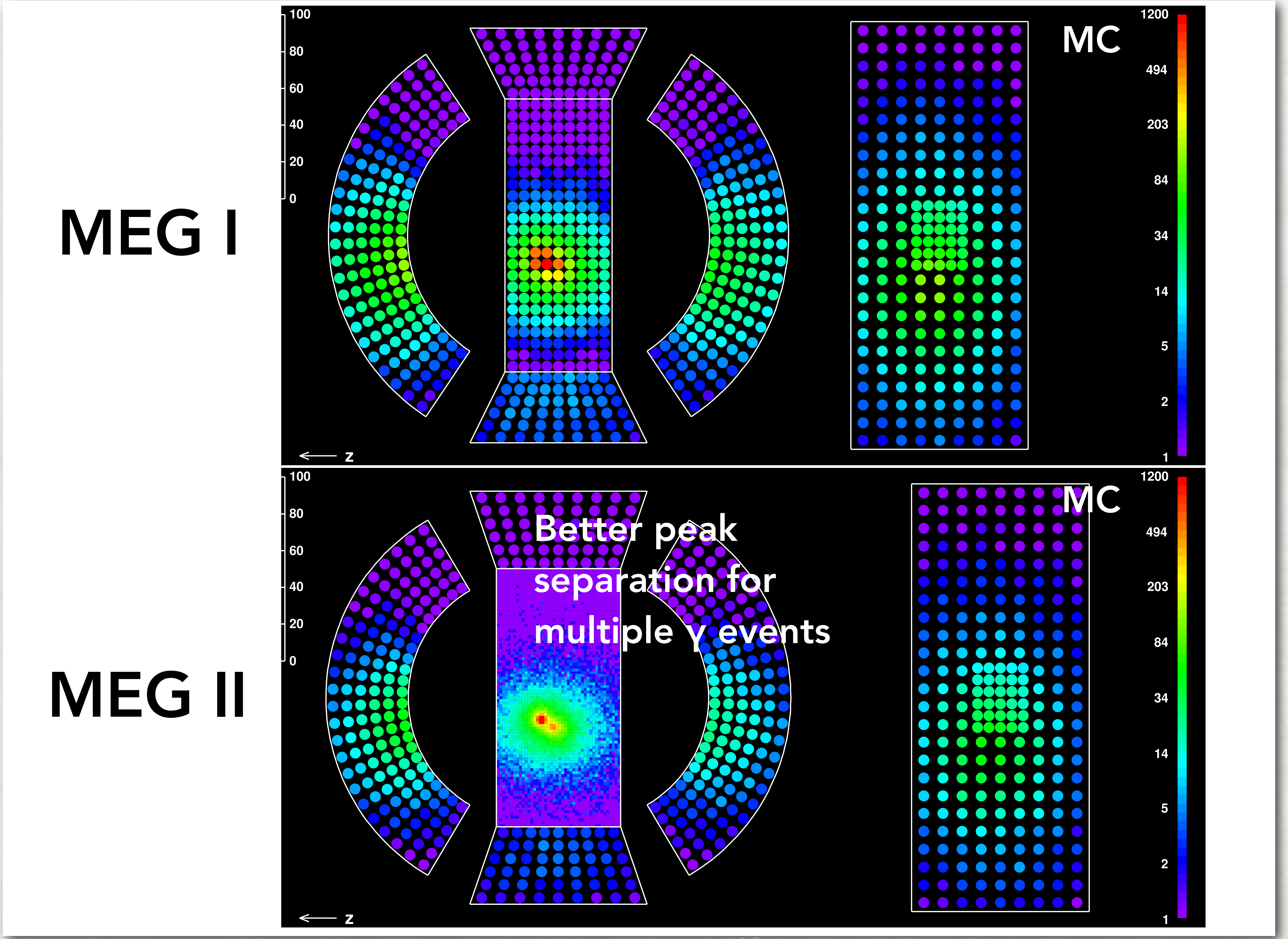
J. Heeck, W. Rodejohann, PLB 776 (2018) 385

- The whole MEG data used



2.2σ local, 1.3σ w/look-elsewhere

MUCH BETTER SENSITIVITY EXPECTED FOR MEG II



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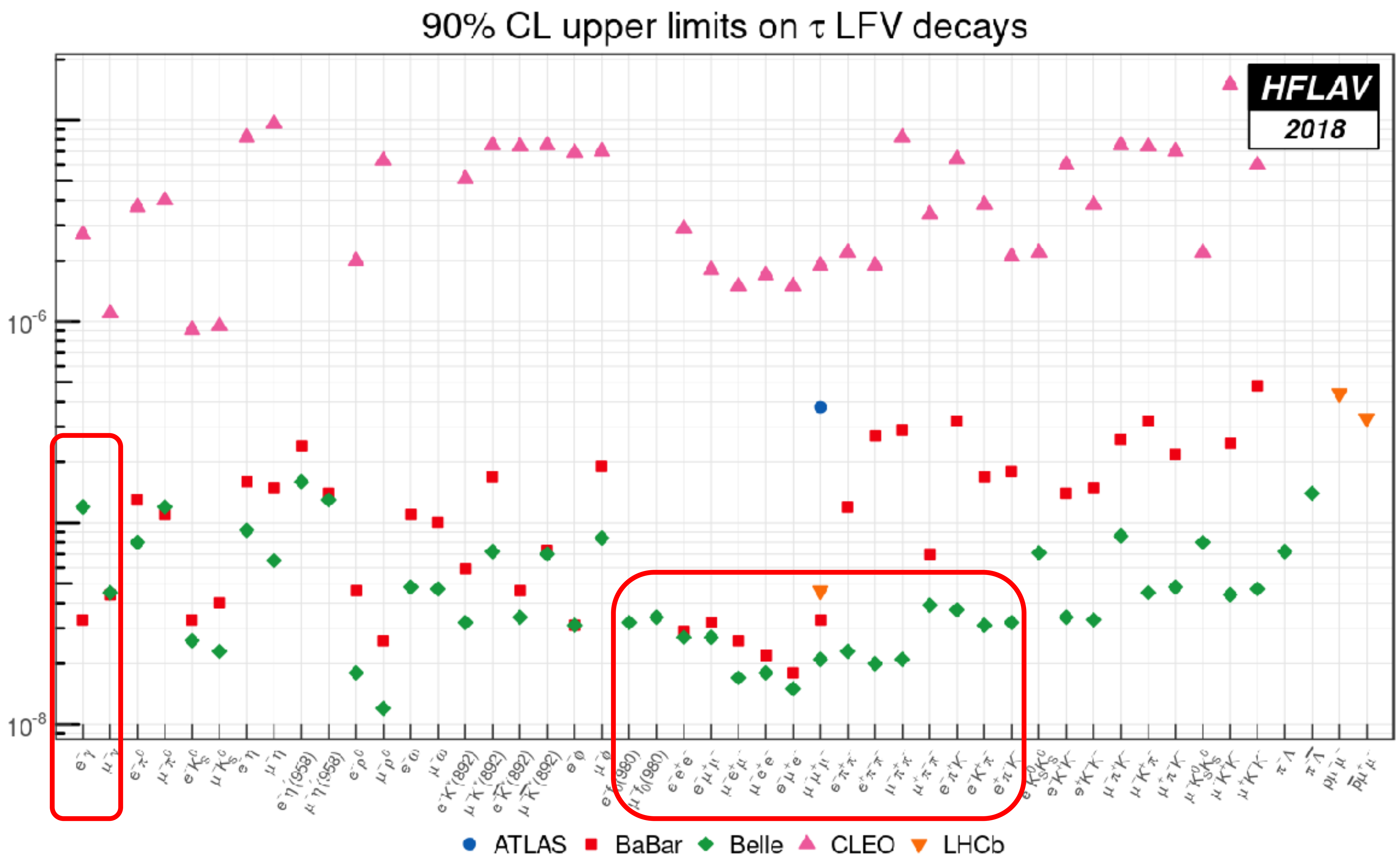
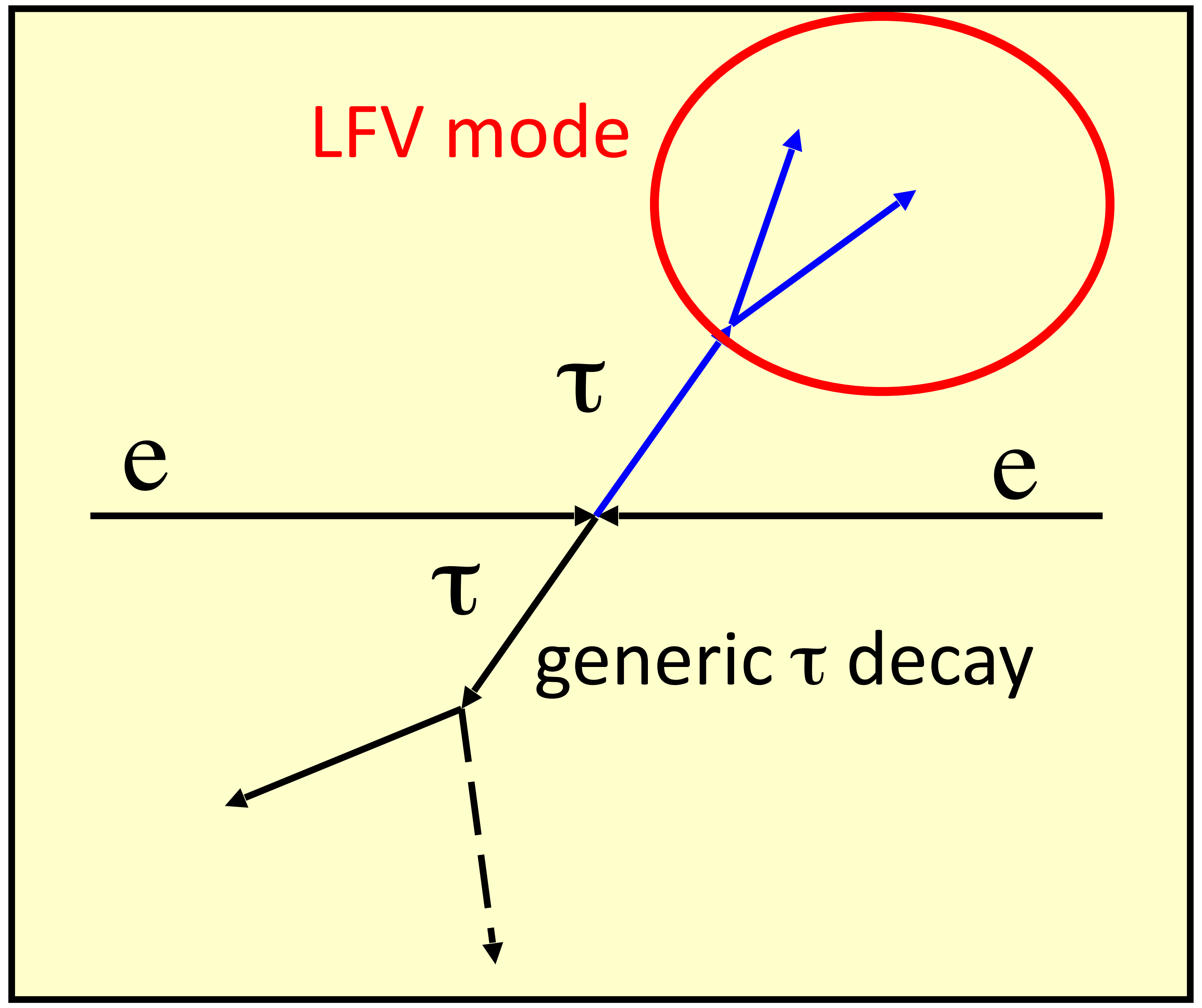
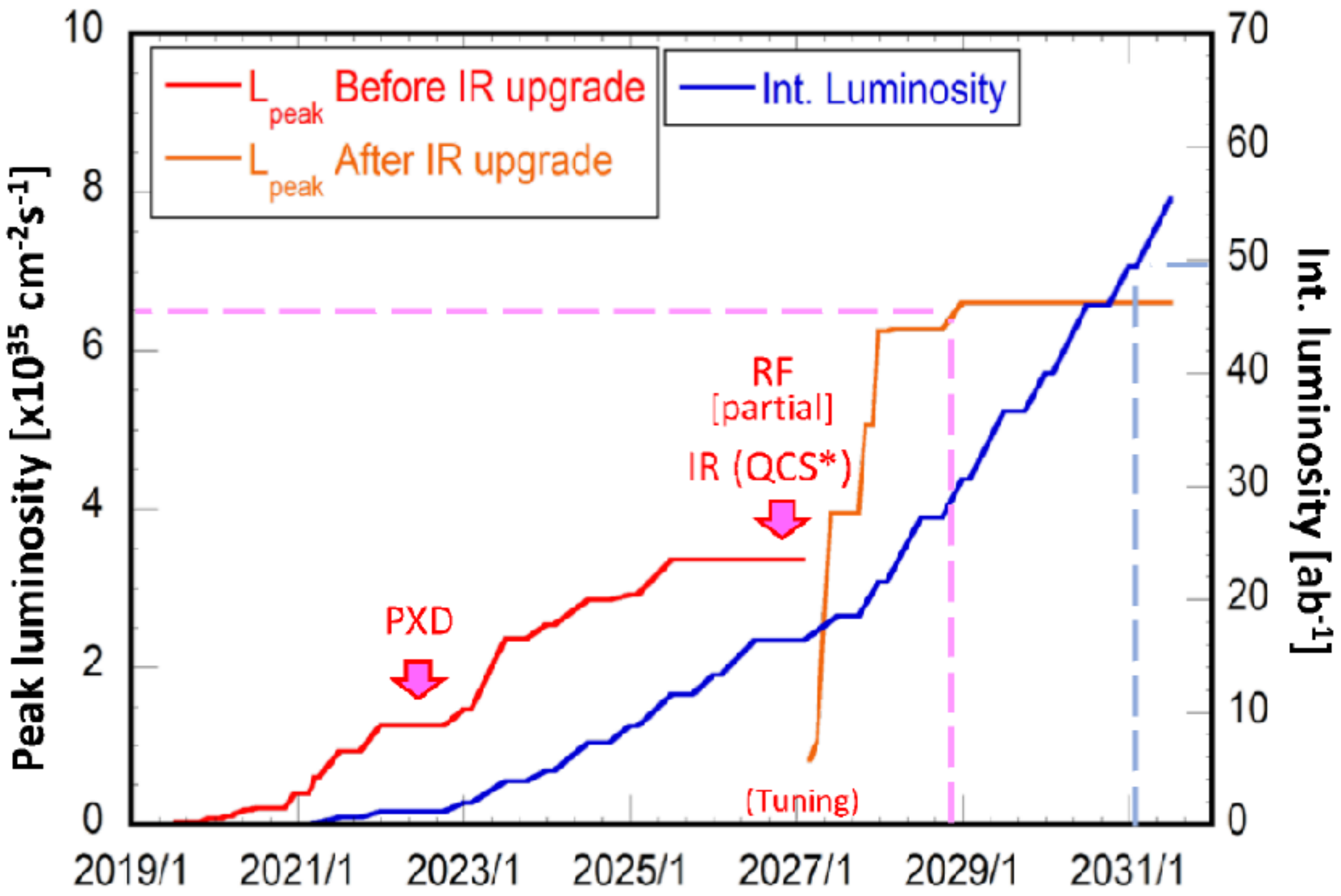
Upper limits on LFV τ decays

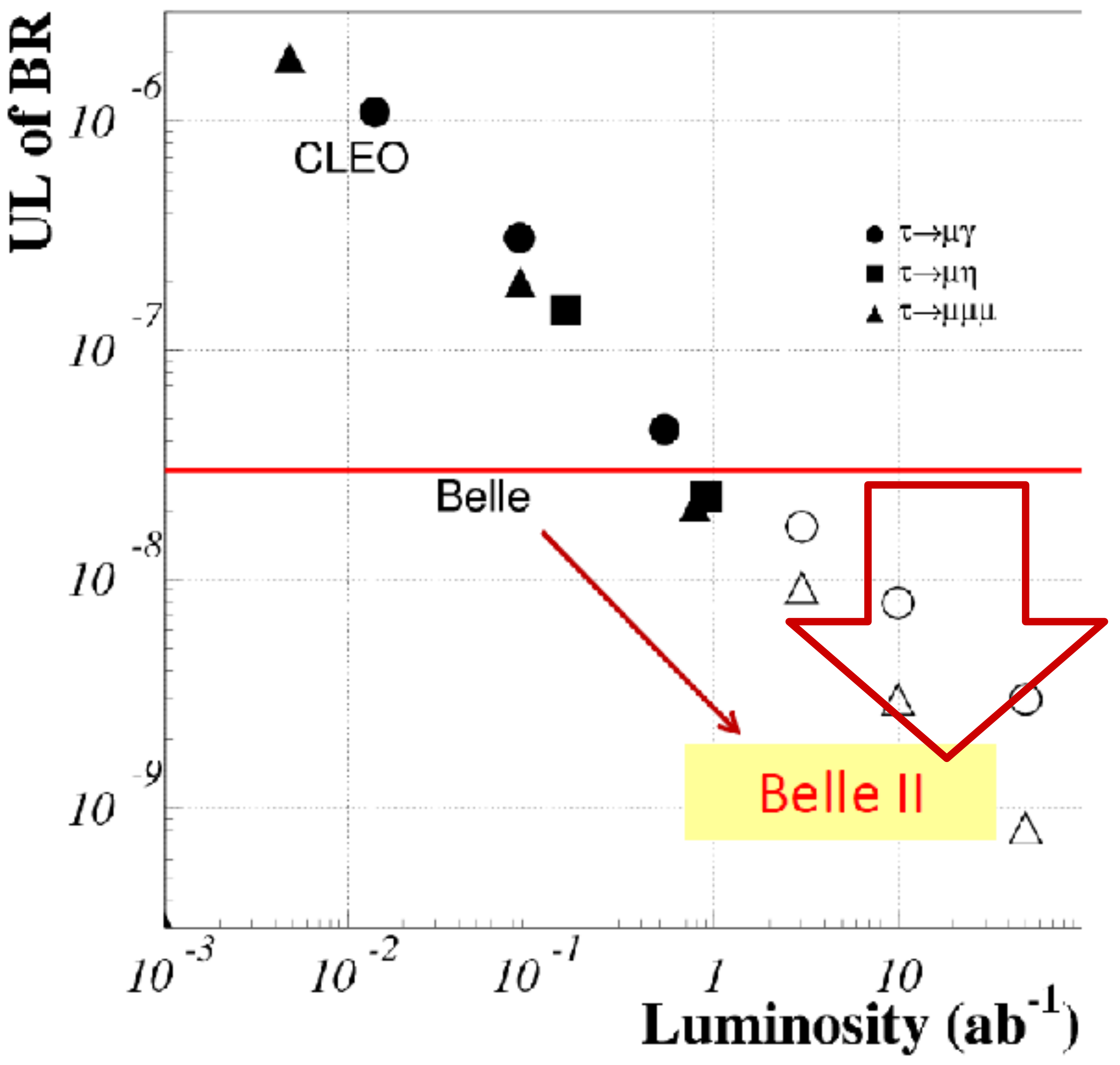




- Belle, Babar reached O(10^{-8}) branching ratio, LHCb improving the result
- τ→3 leptons, l+mesons (to charged particles) show better sensitivity because of less background, compared to τ→l γ.

Future prospects at Belle II





- Will collect 50ab^{-1} data by ~2031, with upgrading detector and accelerator
- B(τ→μμμ)~O(10^{-10}) at ~50ab^{-1}
- Background suppression is key issue.
  - Understanding of background (beam BG, fake PID etc.)
    - → Improvement of reconstruction algorisms
  - Intelligent event selection by machine learning technique

~5X10^{10} TAU PAIRS

SEARCHES FOR $\tau \to 3\mu$ AT HADRON COLLIDER

	Published result	Channel	Dataset	HL-LHC projection
LHCb	4.6×10^{-8}	HF	3 fb^{-1} 7or 8 TeV	
ATLAS	38×10^{-8}	W	20 fb^{-1} 8 TeV	a few 10^{-9}
CMS	8.0×10^{-8}	W+HF	33 fb^{-1} 13 TeV	a few 10^{-9}

- HL-LHC will collect 6×10^{14} tau leptons
- Needs a breakthrough in analysis techniques to compete

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MUON LFV PROCESSES

$\mu^- N \to e^- N$

- signal: monochromatic ~104MeV electron
- BG: beam-related prompt
- pulsed muon beam
- "extinction" of ~10^{-10}
- low mass tracker

$\mu^+ \to e^+ \gamma$

- signal: 2-body kinematics
- BG: accidental
- DC muon beam
- low mass tracker
- excellent gamma-ray measurement

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

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π capture and
π, μ transport by solenoids

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"COBRA" spectrometer
LXe photon detector

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

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pixel tracker
based on HV-MAPS

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INNOVATIVE EXPERIMENTAL TECHNIQUES ARE DRIVING FORCE

Live Event Window

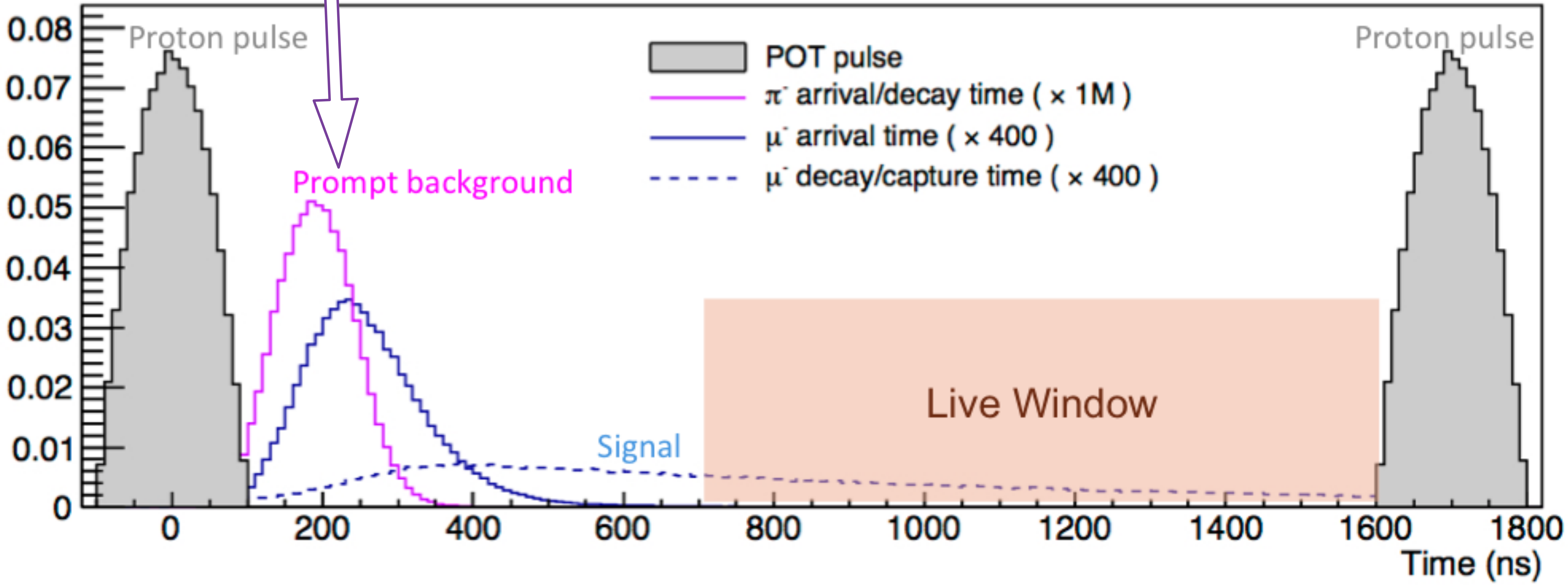
Background suppression: Radiative Pion Capture + other beam related bg

RPC : $\pi^- + N \to \gamma + N'$

$\gamma \to e^- + e^+$

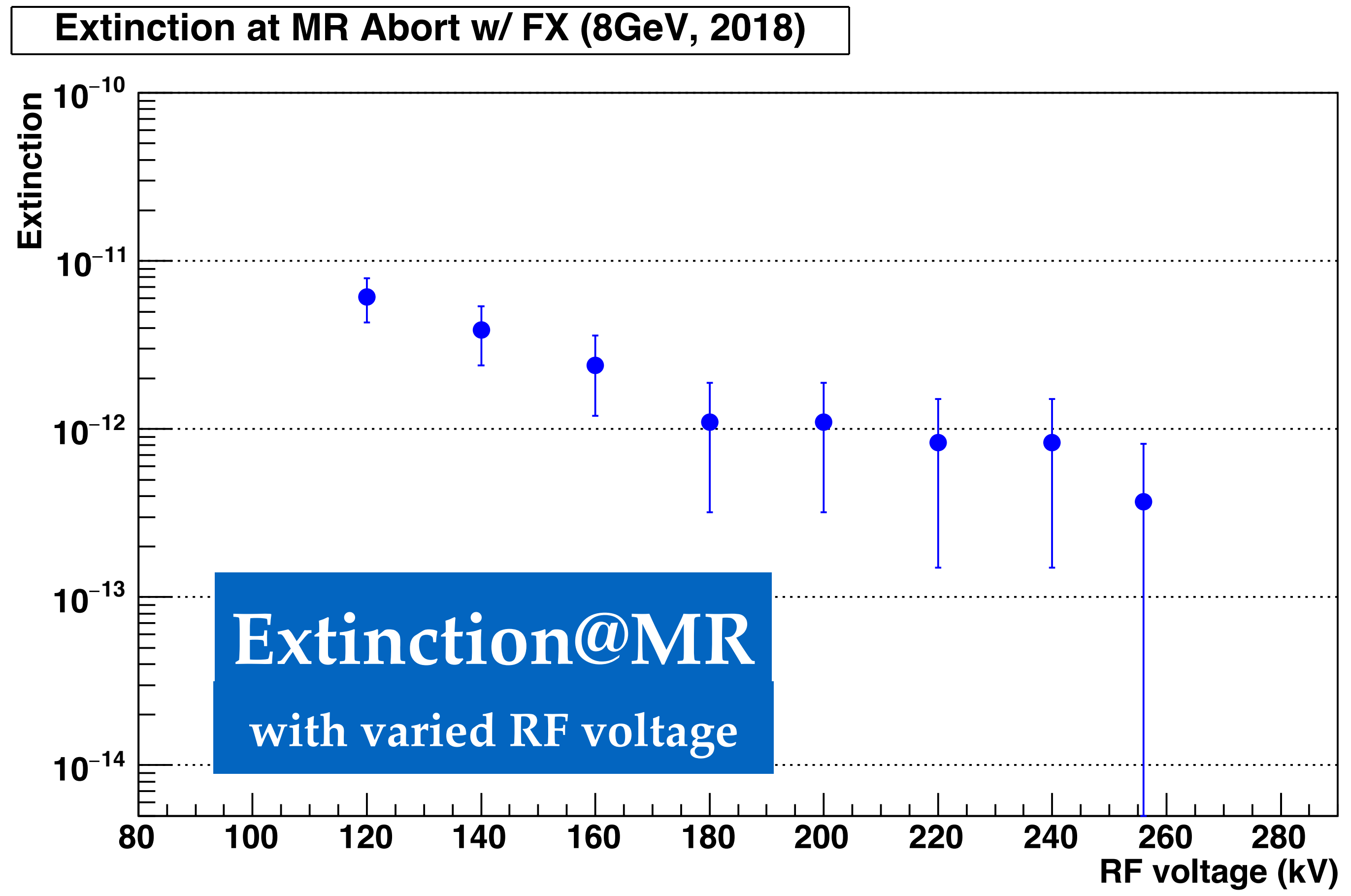
e^- **with enough momentum can fake conversion events**

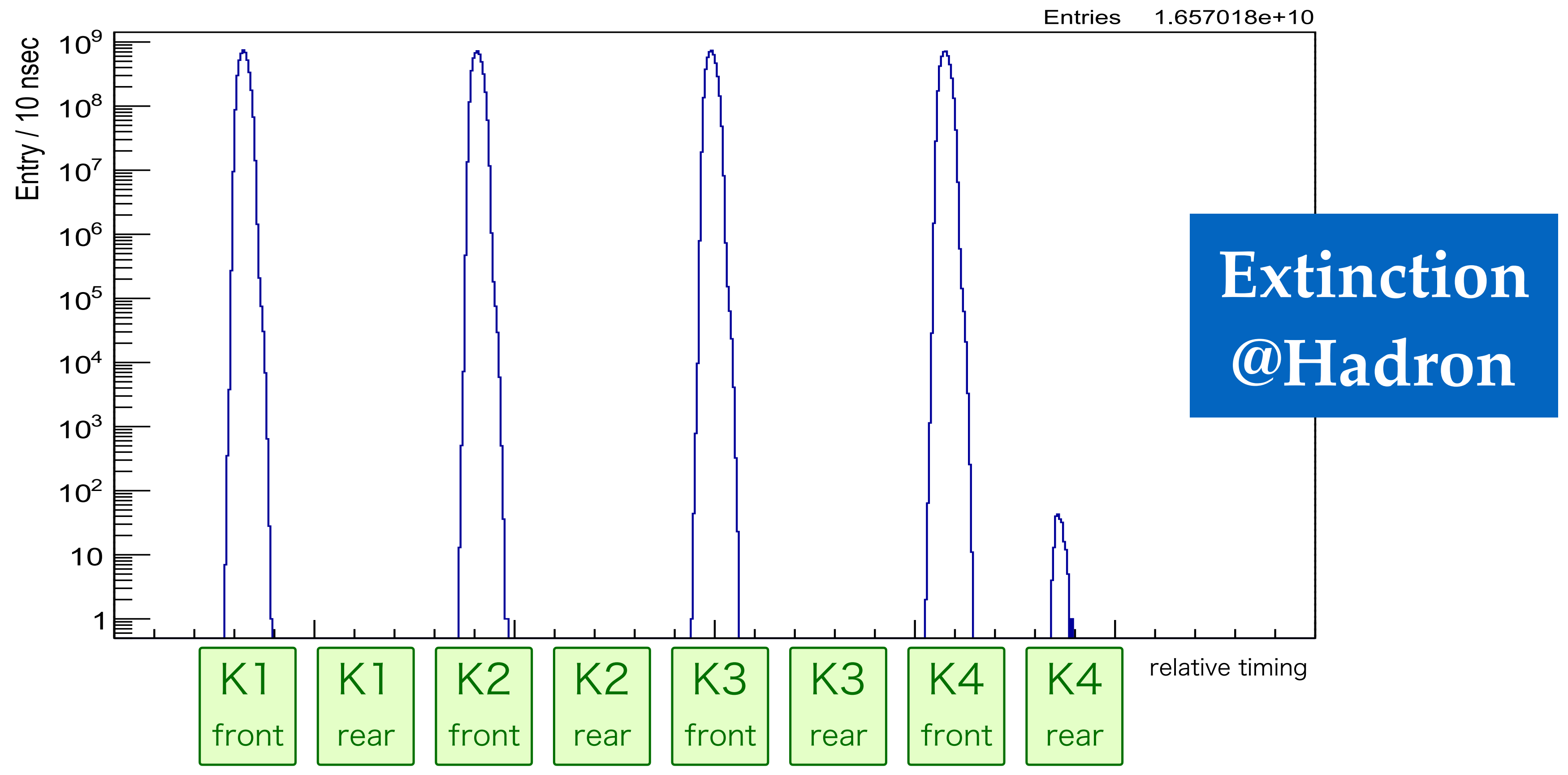
- 8 GeV pulsed proton beam @ 1695 ns intervals.
- We wait 700 ns before taking C.E data to avoid most of the **prompt** background
  - Muonic atom lifetime = 864 ns.
- Out of time protons/ beam < 10^{-10}



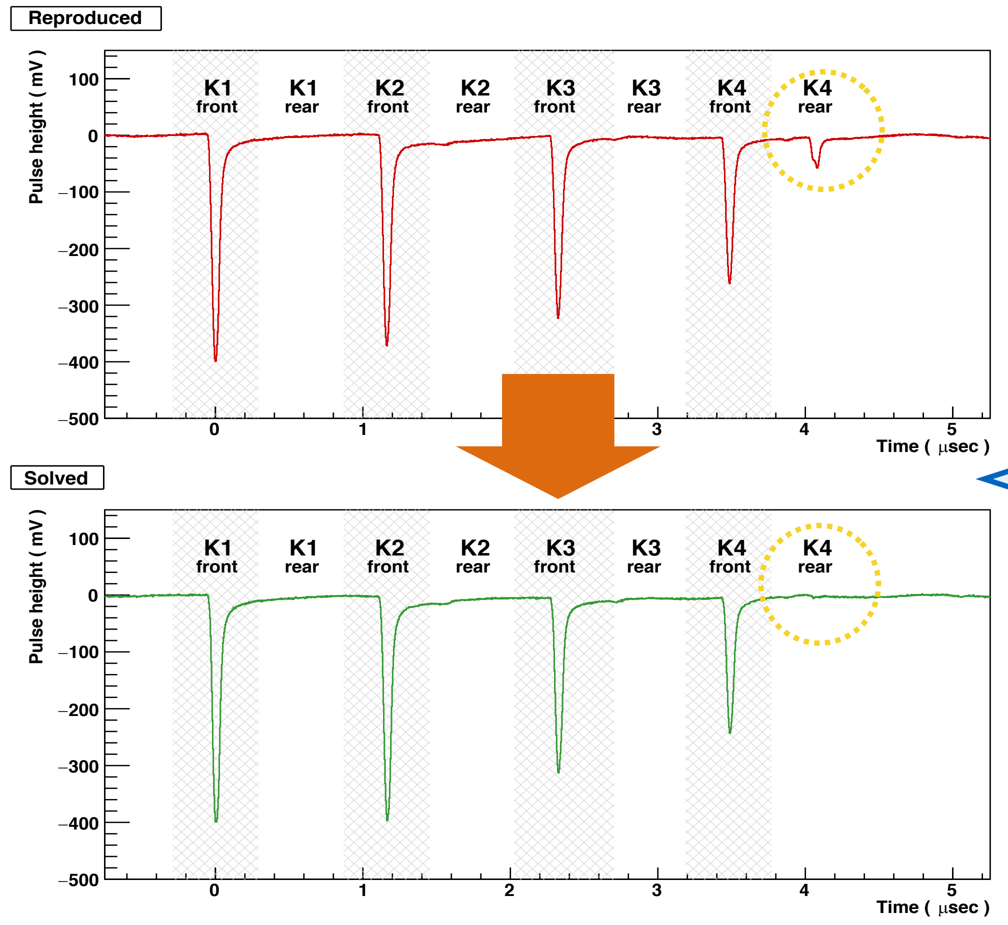
Current Status (2) — Accelerator Development —

- **Dedicated 8 GeV Operation Test was conducted in Jan-Feb 2018.**
  - Operation chain; injection / acceleration / extraction, successfully established.
  - Good bunched slow extraction efficiency of 97% , achieved





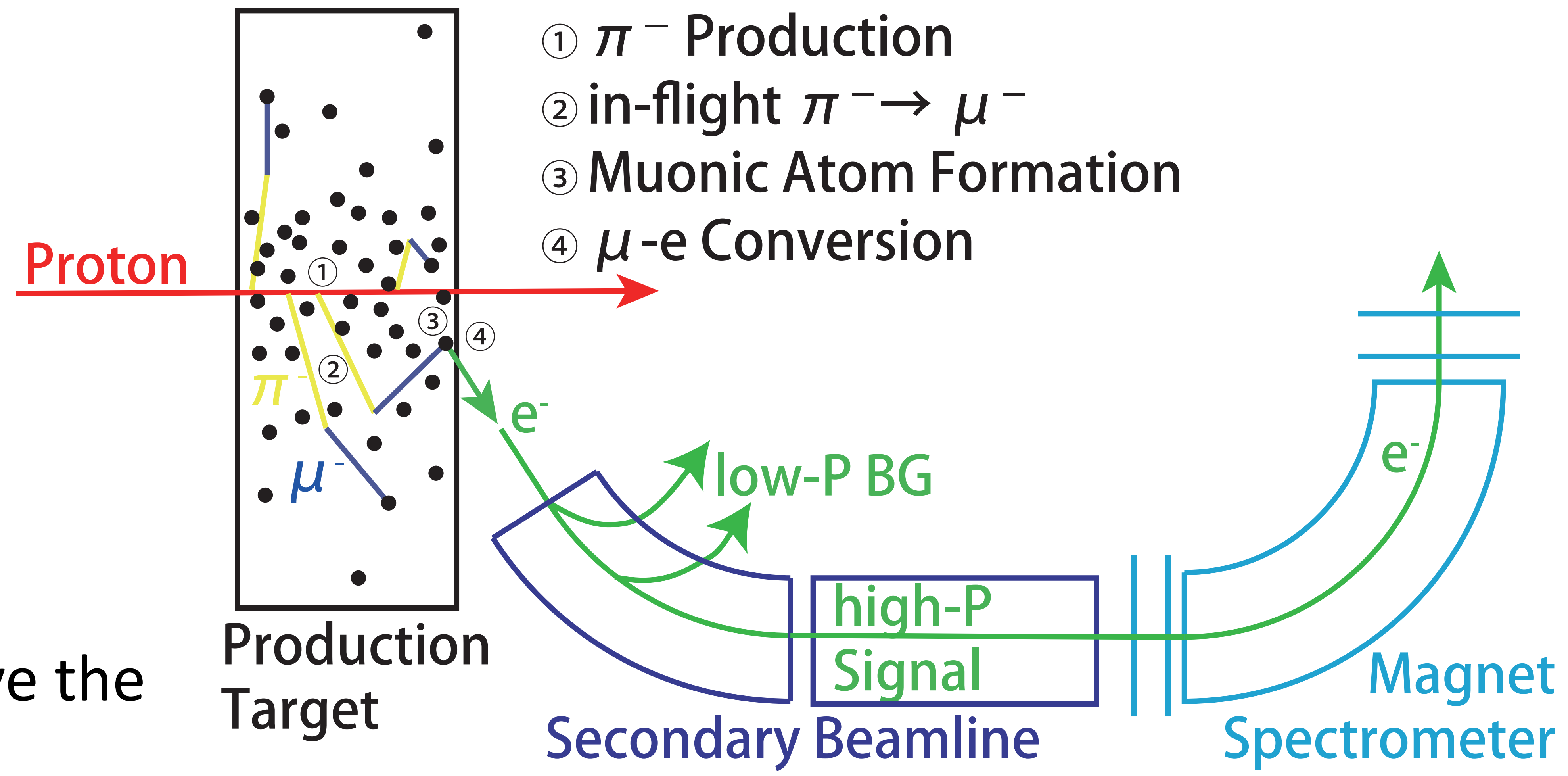
- **Extinction development** was also successfully conducted at Main Ring Proton Synchrotron and Secondary Beam Line in Hadron Experimental Facility.
- **Excellent extinction ($O(10^{-12})$-$O(10^{-11})$)** in MR was confirmed. But, Small leaks observed in secondary beam (equivalent to $1\text{x}10^{-10}$ extinction)

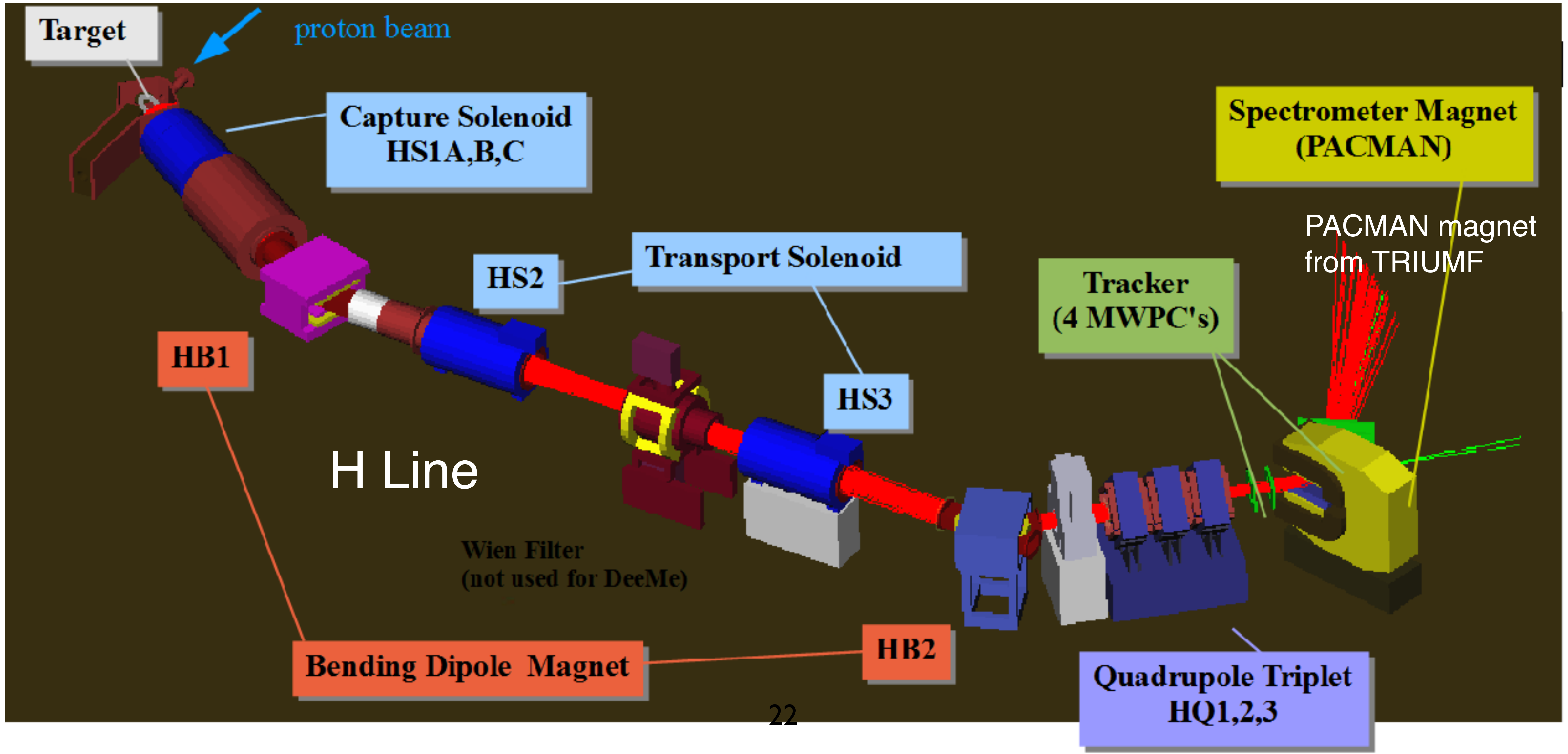


Solution for this small leakage was found, and verified in MR.
Next test, under preparation.
Proposal for next test, submitted.

DeeMe Project

- KEK/IMSS J-PARC S1A type Project
  - SES: **1×10^{-13} (Graphite, 2×10^{7}sec)**
    - 2×10^{-14}(SiC)、5×10^{-15}(8×10^{7}sec)
- Proposed to KEK/IMSS in 2010
- Stage-2 Approved w/Graphite
- Grant-in-Aid for detector construction
  - **completed**
- **Large-acceptance H-Line is essential** to achieve the physics goal: @ D-Line, it will be x10 worse.





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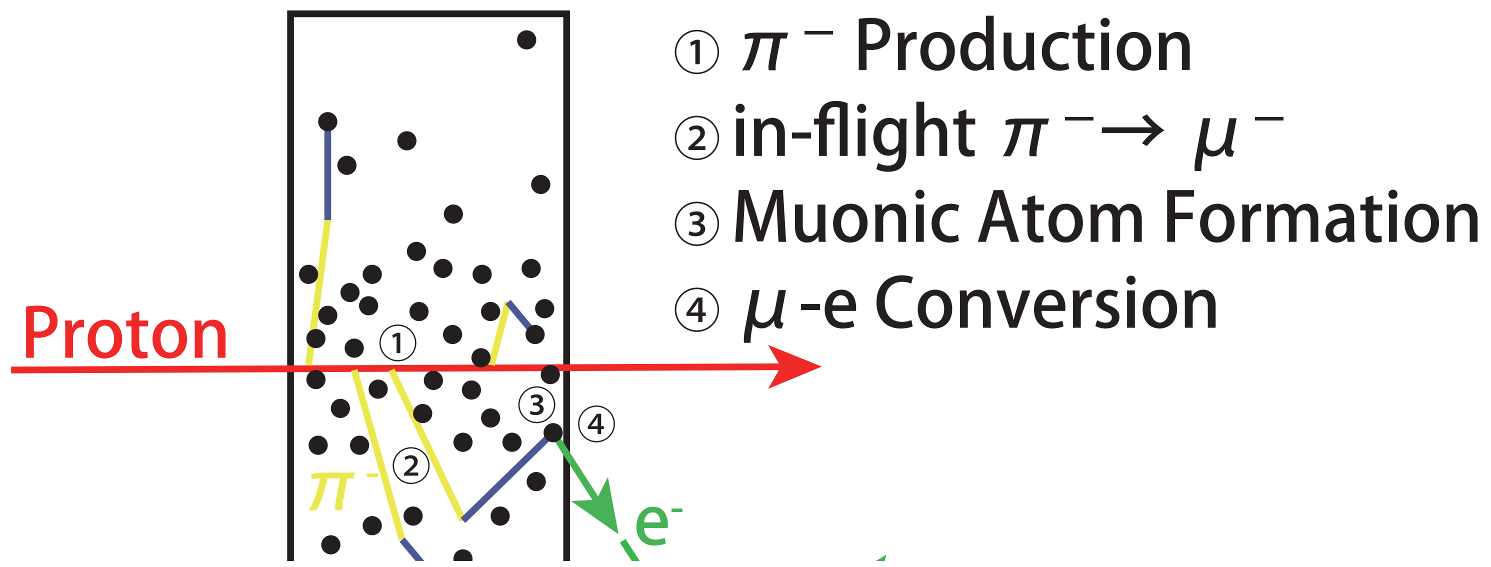
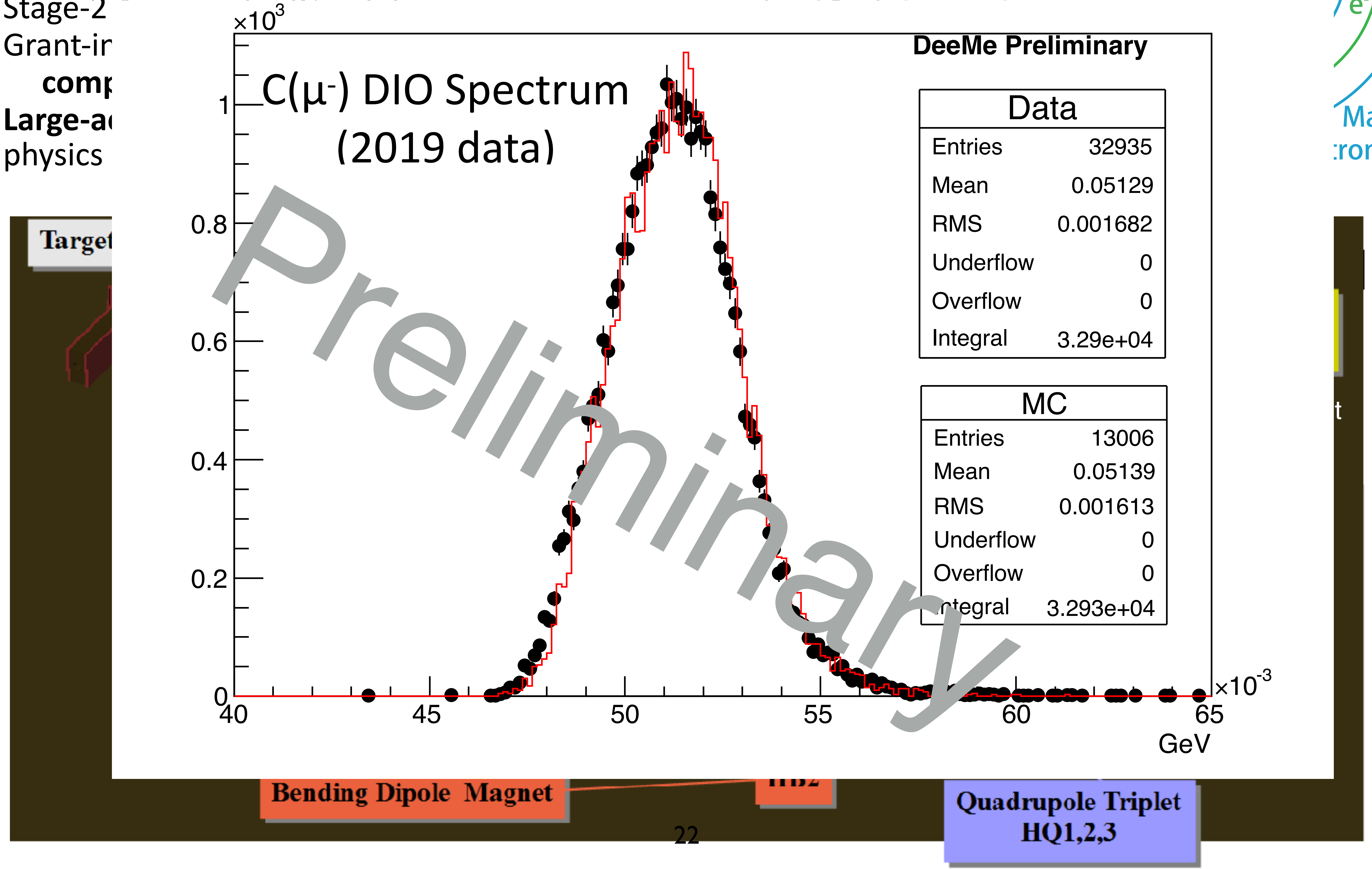
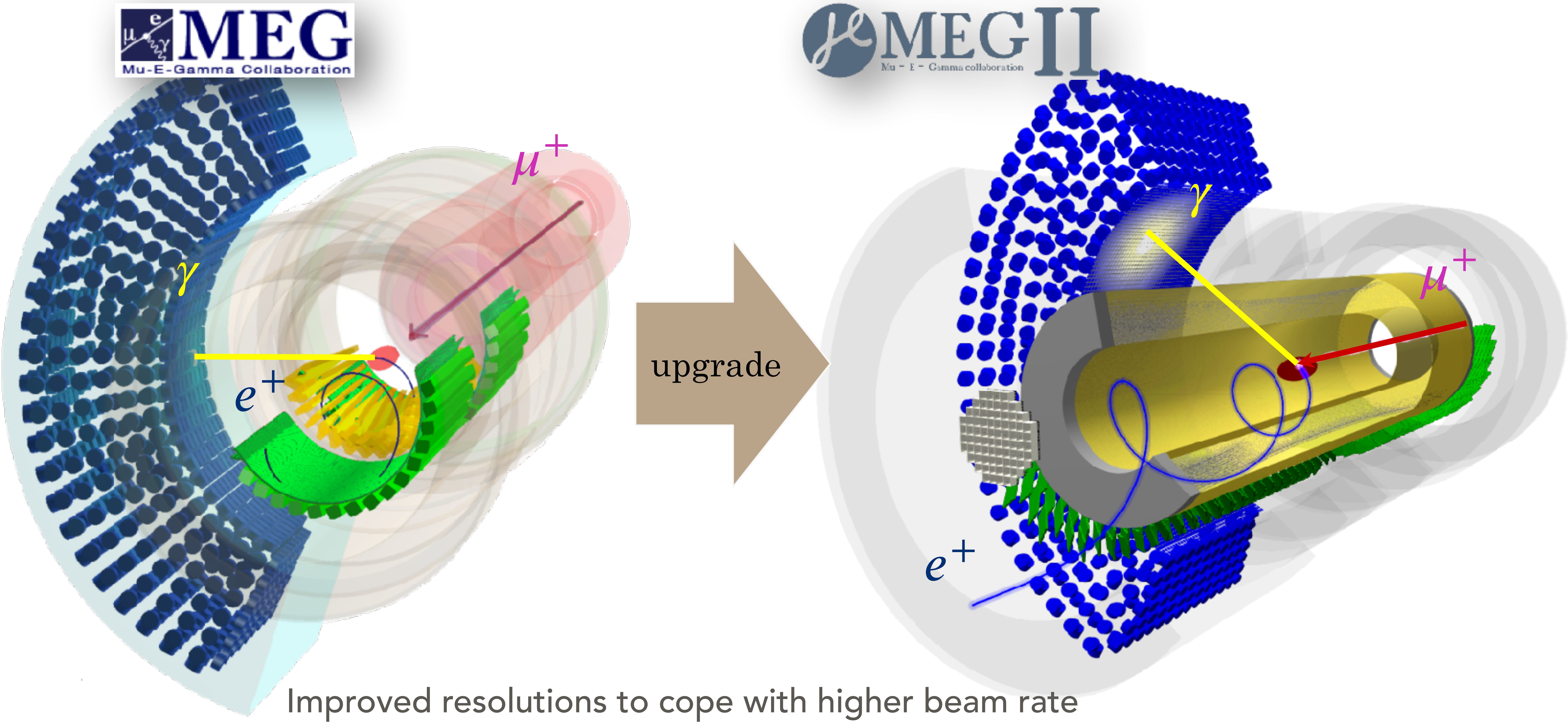
- Grant-ir...
  - **comp...**
- **Large-a...** physics





Detector upgrades from MEG

MEG DNA is gradient magnetic field & 2.7ton liquid xenon photon detector



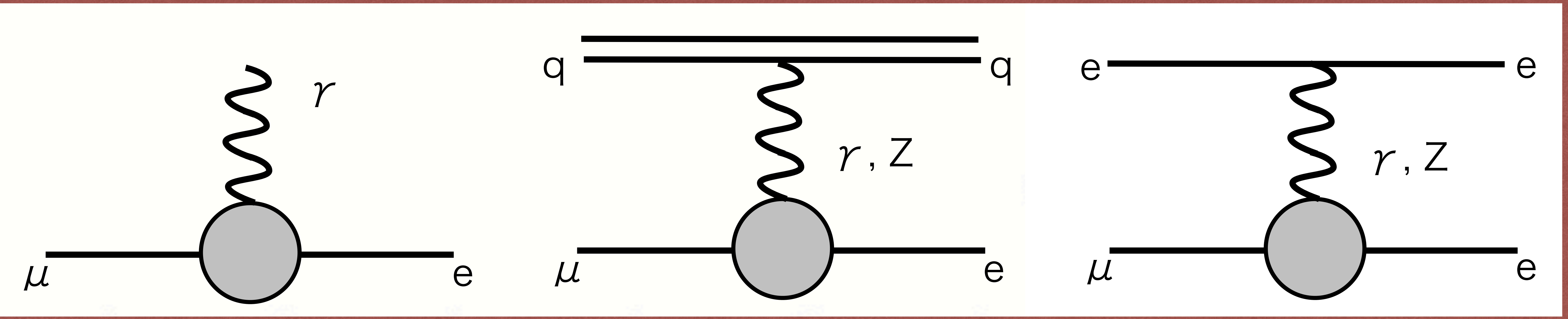
Improved resolutions to cope with higher beam rate

MUON CLFV SENSITIVITY COMPARISONS

$\mu \to e\gamma$ $\mu N \to eN$ $\mu \to 3e$

"dipole" dominant

(SUSY etc)



1 : 1/390 : 1/170

BR = 2×10^{-14} : 5×10^{-17} : 1×10^{-16}

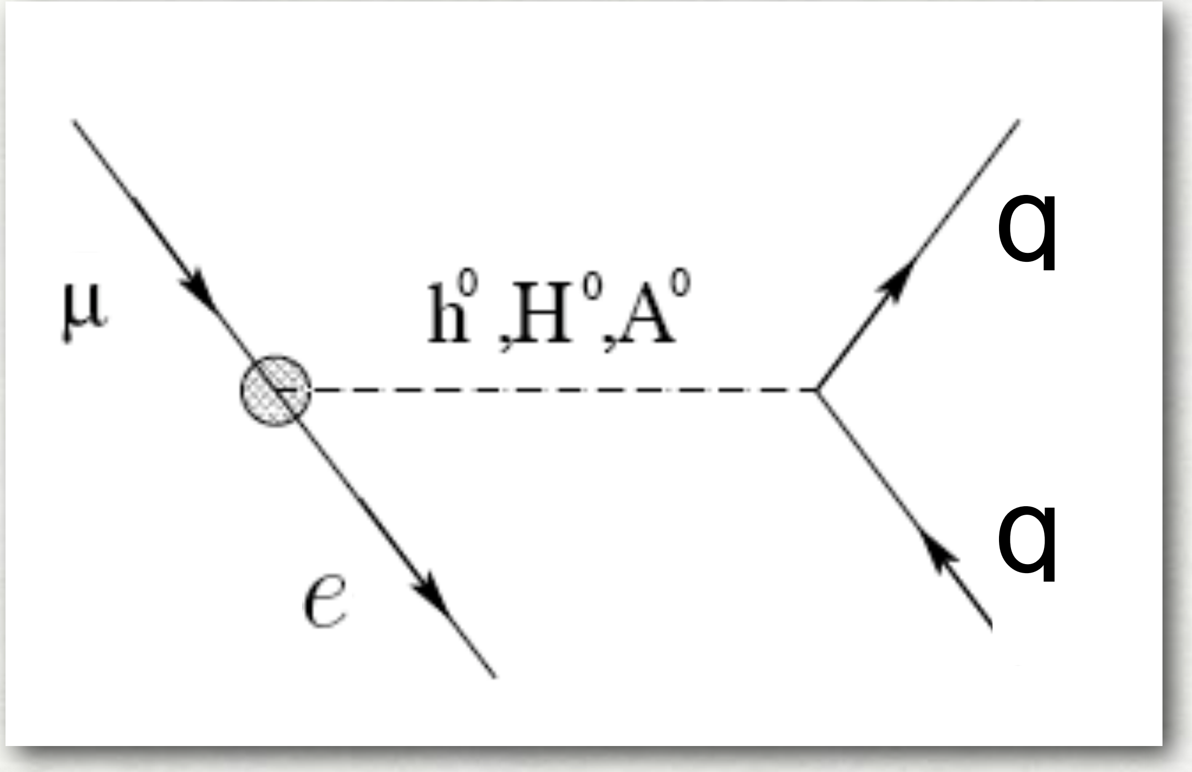
for Al target

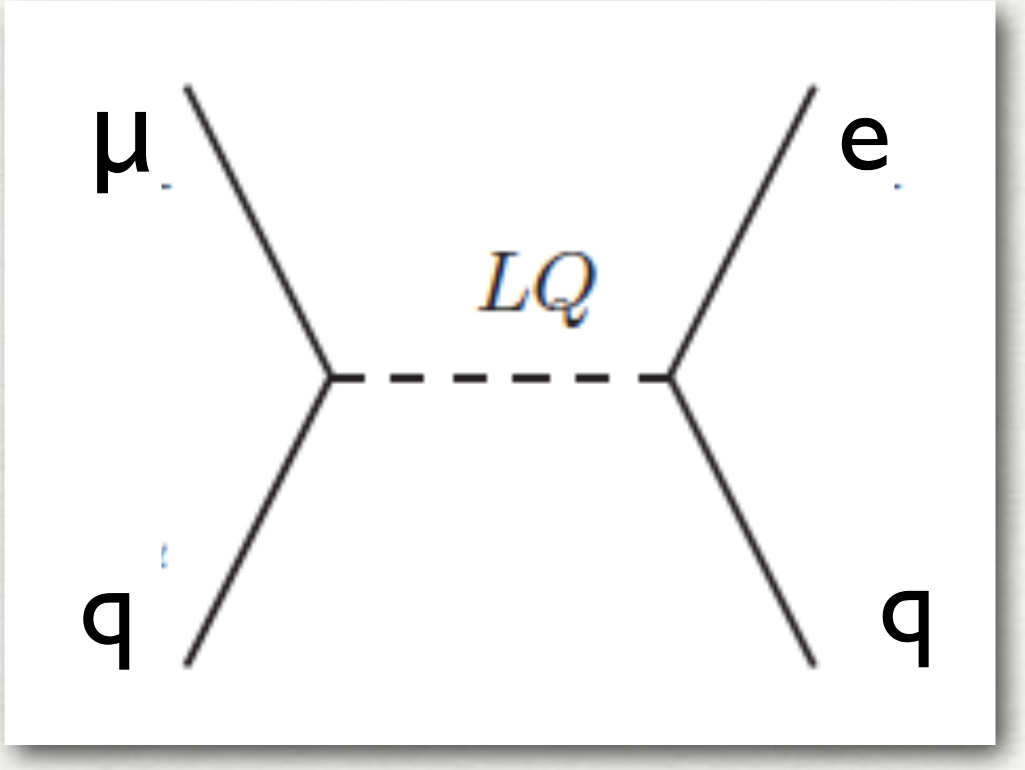
NON-DIPOLE CONTRIBUTIONS FROM NEW PHYSICS

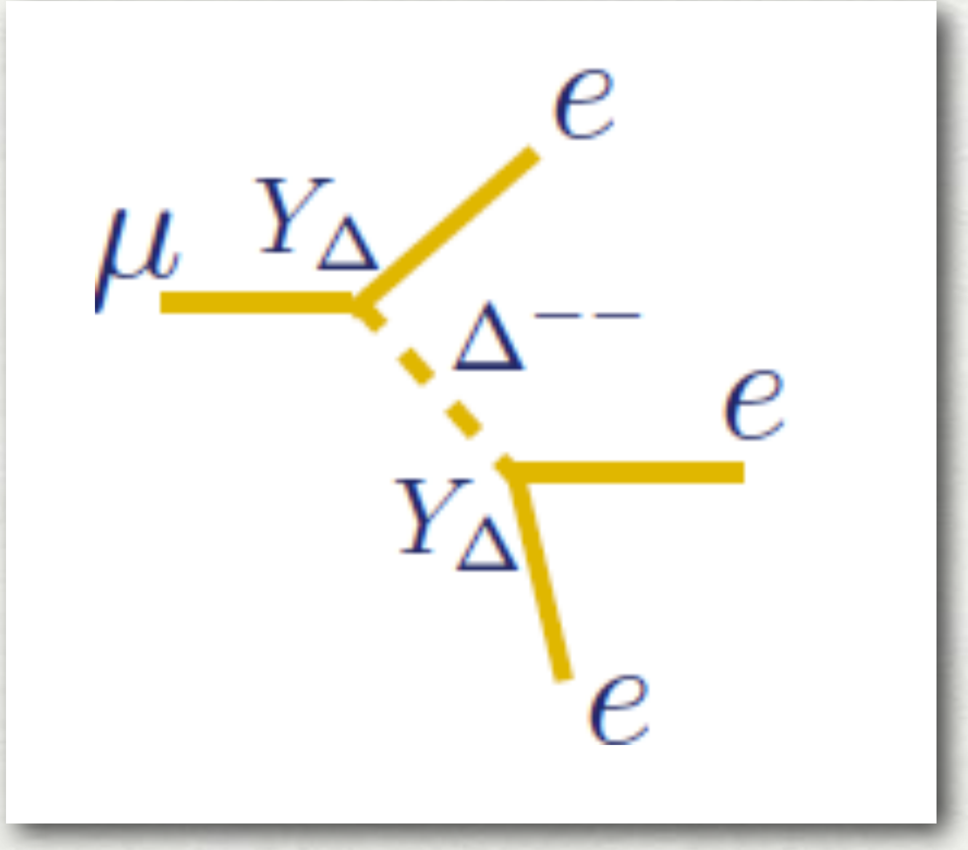
- $\mu N \to eN$ and $\mu \to 3e$ can have large contributions from other operators.

- To disentangle the secrets of New Physics, all the three muon CLFV processes should be pursued together.

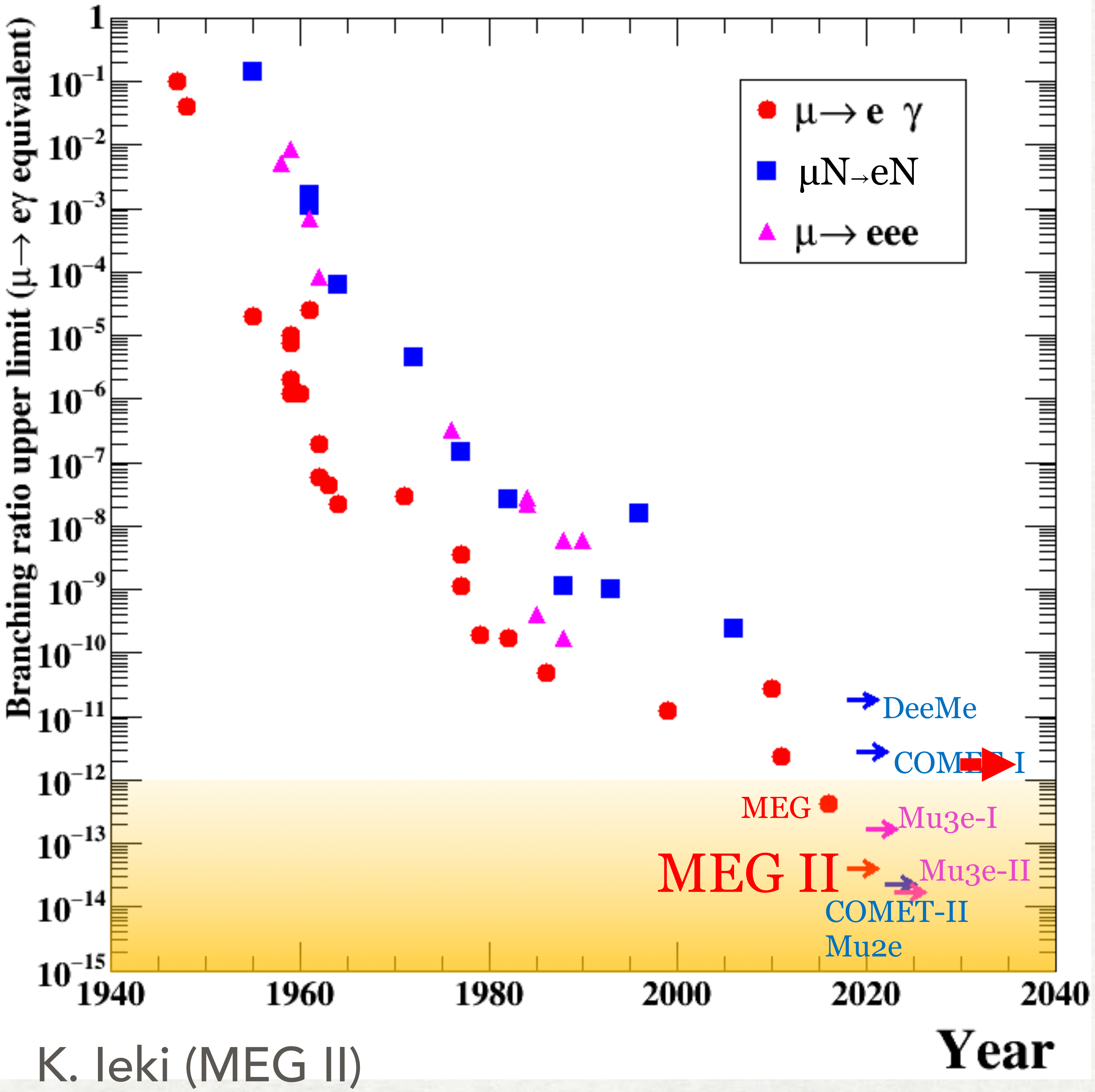
- Angular distributions of $\mu \to e\gamma$ and $\mu \to 3e$, and atom-dependence of $\mu N \to eN$ can be decisive after discoveries.







“$\mu \to e\gamma$ EQUIVALENT” DIPOLE LFV SENSITIVITY

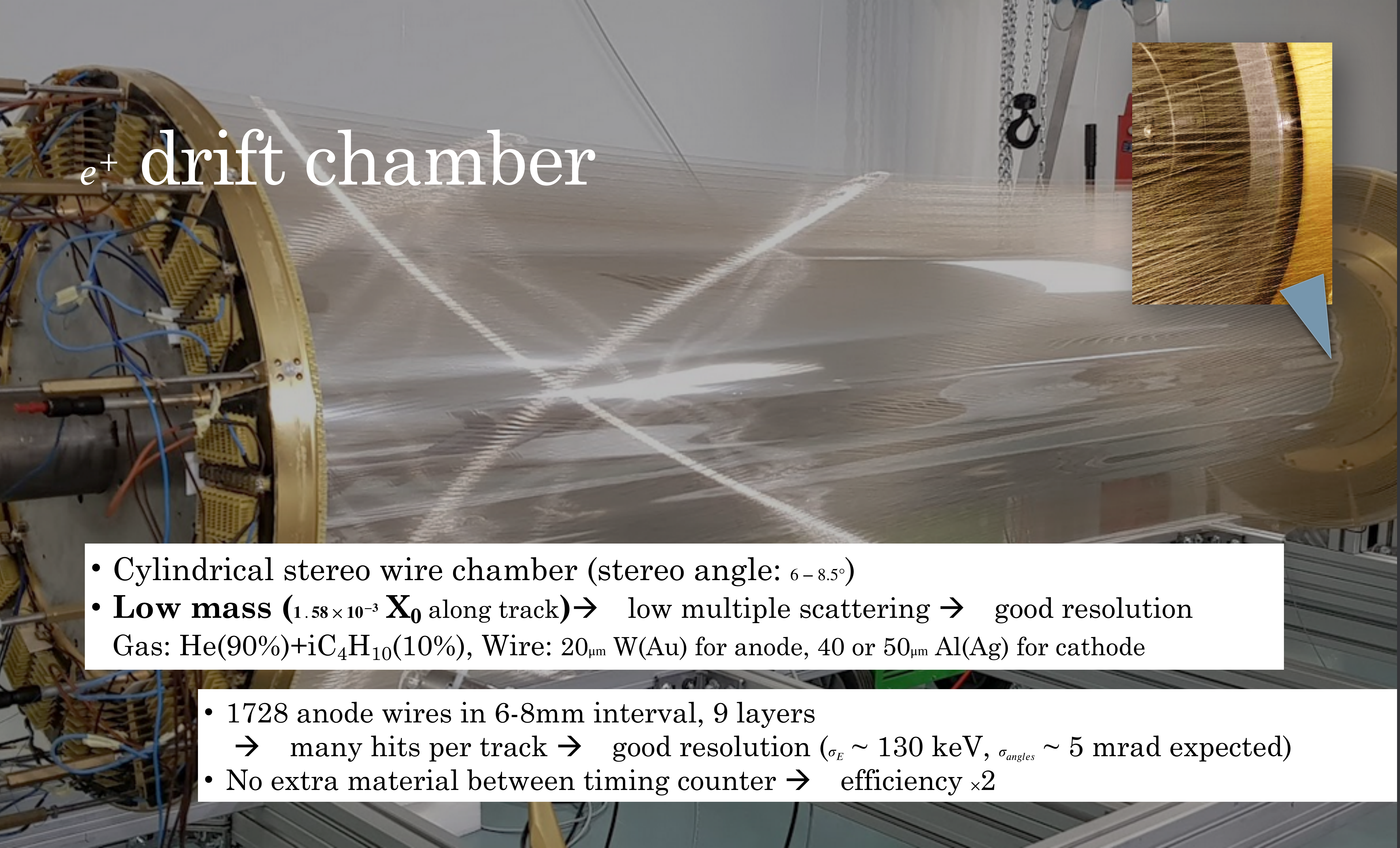


K. Ieki (MEG II)

- Final sensitivity goals are very similar within a factor 2-3
- Further upgrades being planned

MEG II

e^+ drift chamber



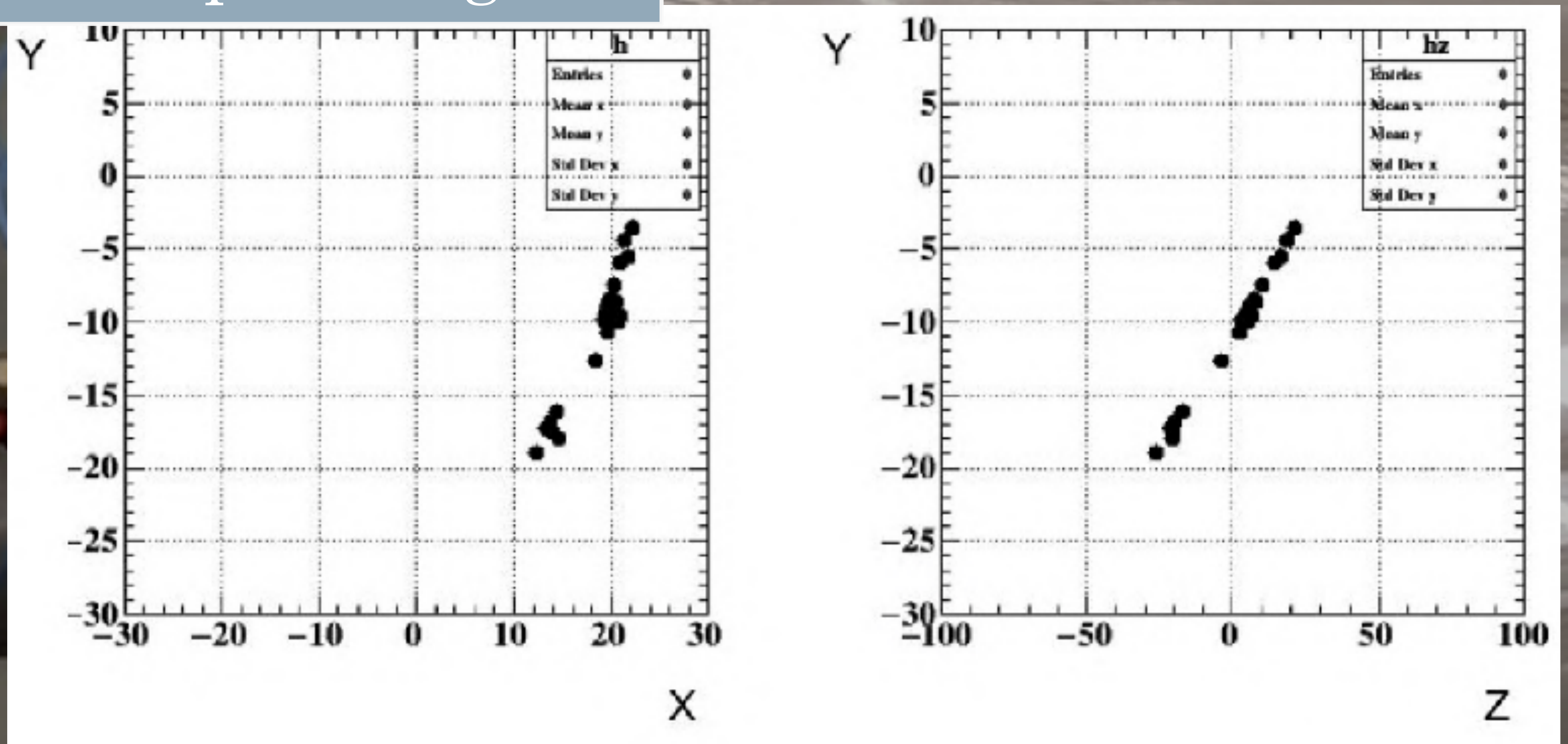
e^+ drift chamber

- Cylindrical stereo wire chamber (stereo angle: $6-8.5°$)
- **Low mass (1.58×10^{-3} X_0 along track)** → low multiple scattering → good resolution
  Gas: He(90%)+iC_4H_{10}(10%), Wire: 20µm W(Au) for anode, 40 or 50µm Al(Ag) for cathode

- 1728 anode wires in 6-8mm interval, 9 layers
  → many hits per track → good resolution (σ_E ~ 130 keV, σ_{angles} ~ 5 mrad expected)
- No extra material between timing counter → efficiency ×2

e^+ drift chamber

Example of signal



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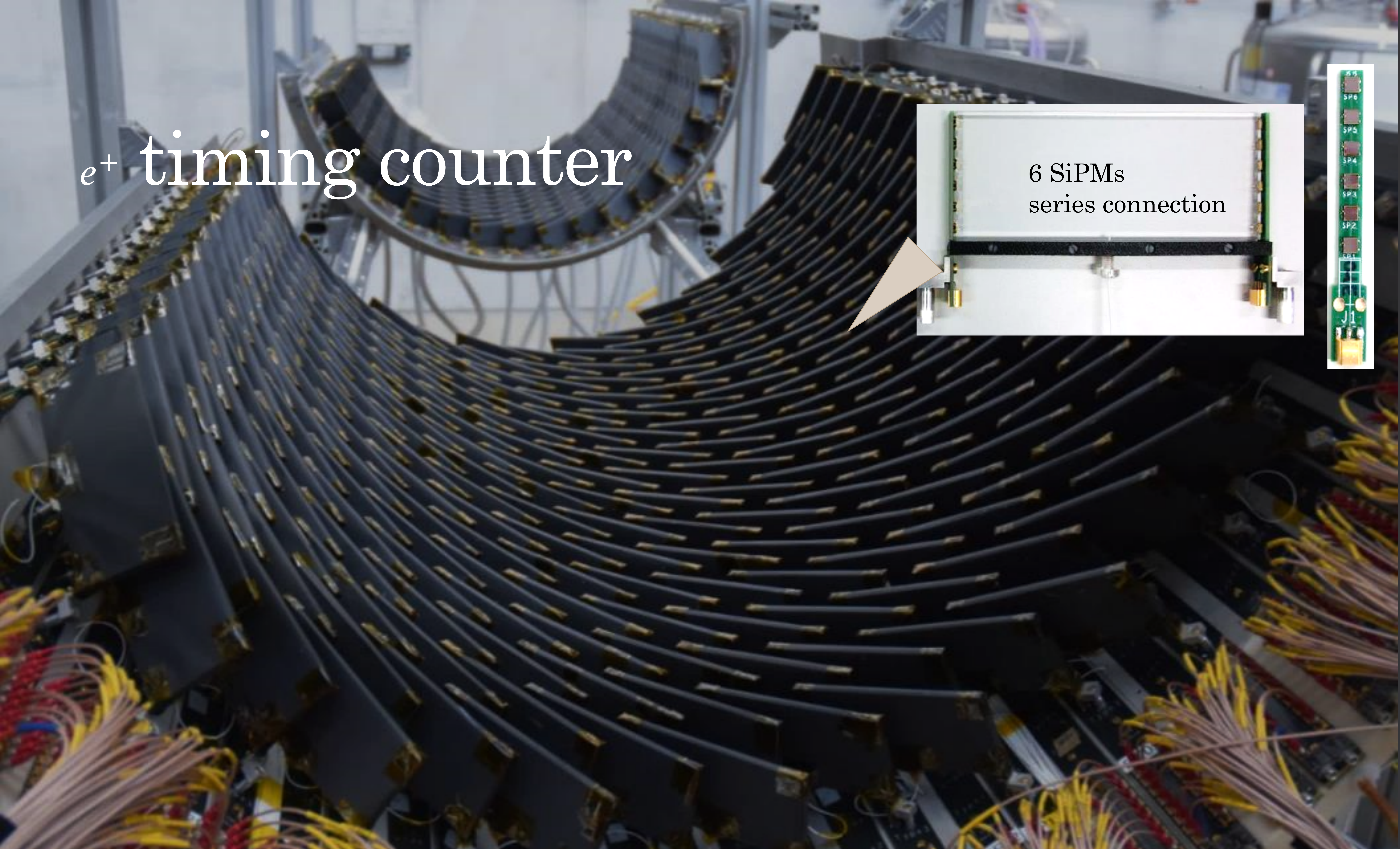
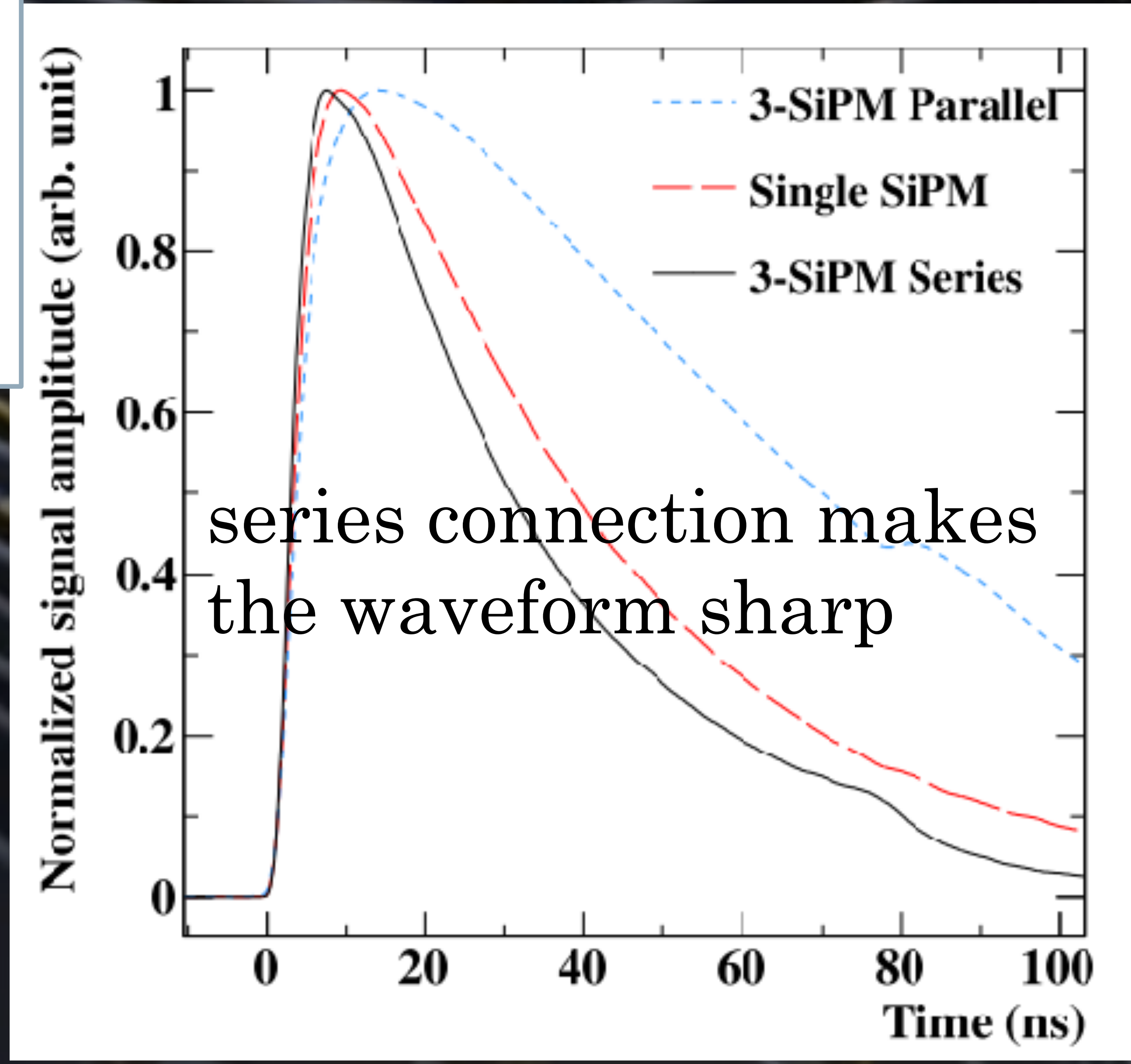
e^+ timing counter

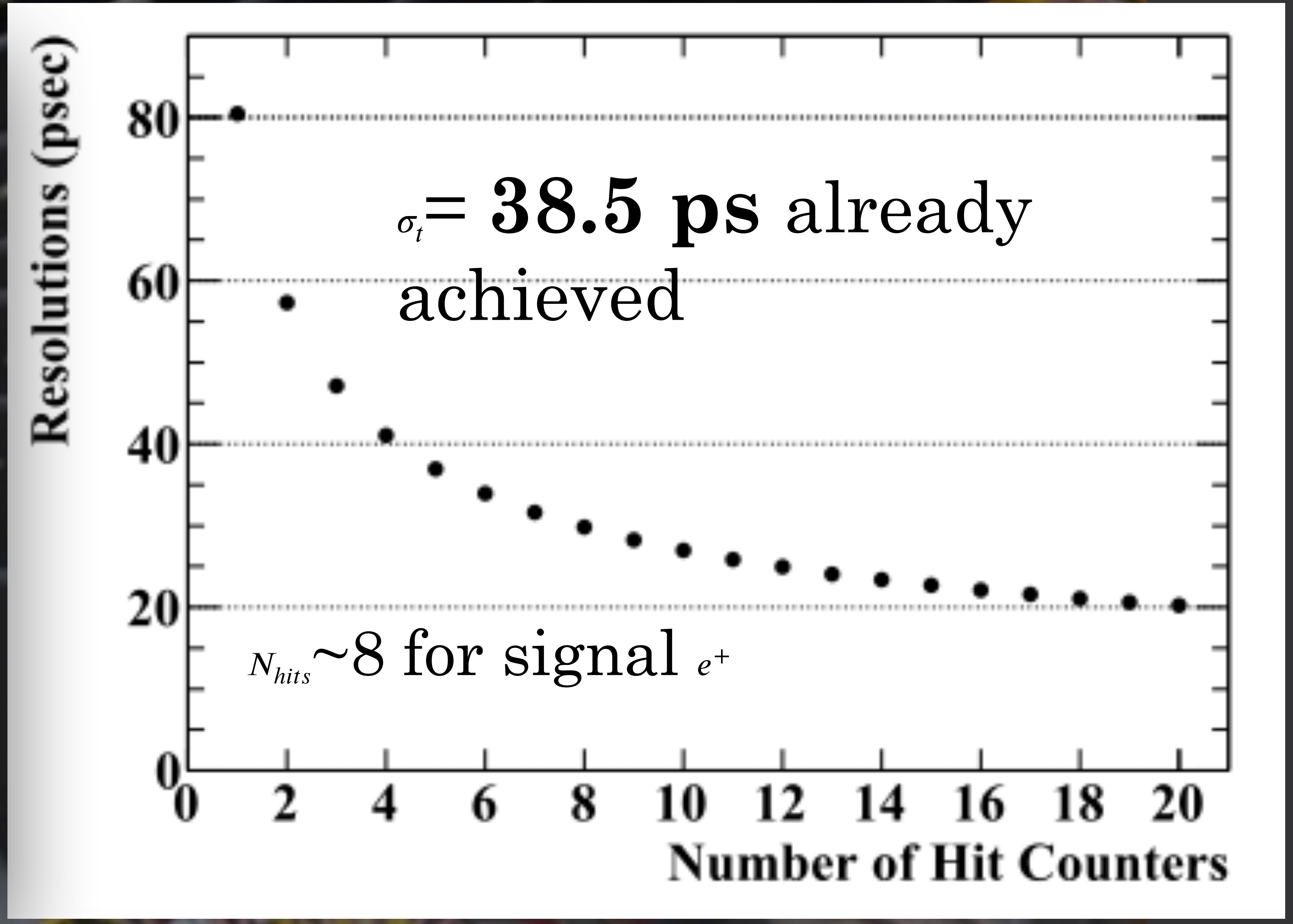


e^+ timing counter

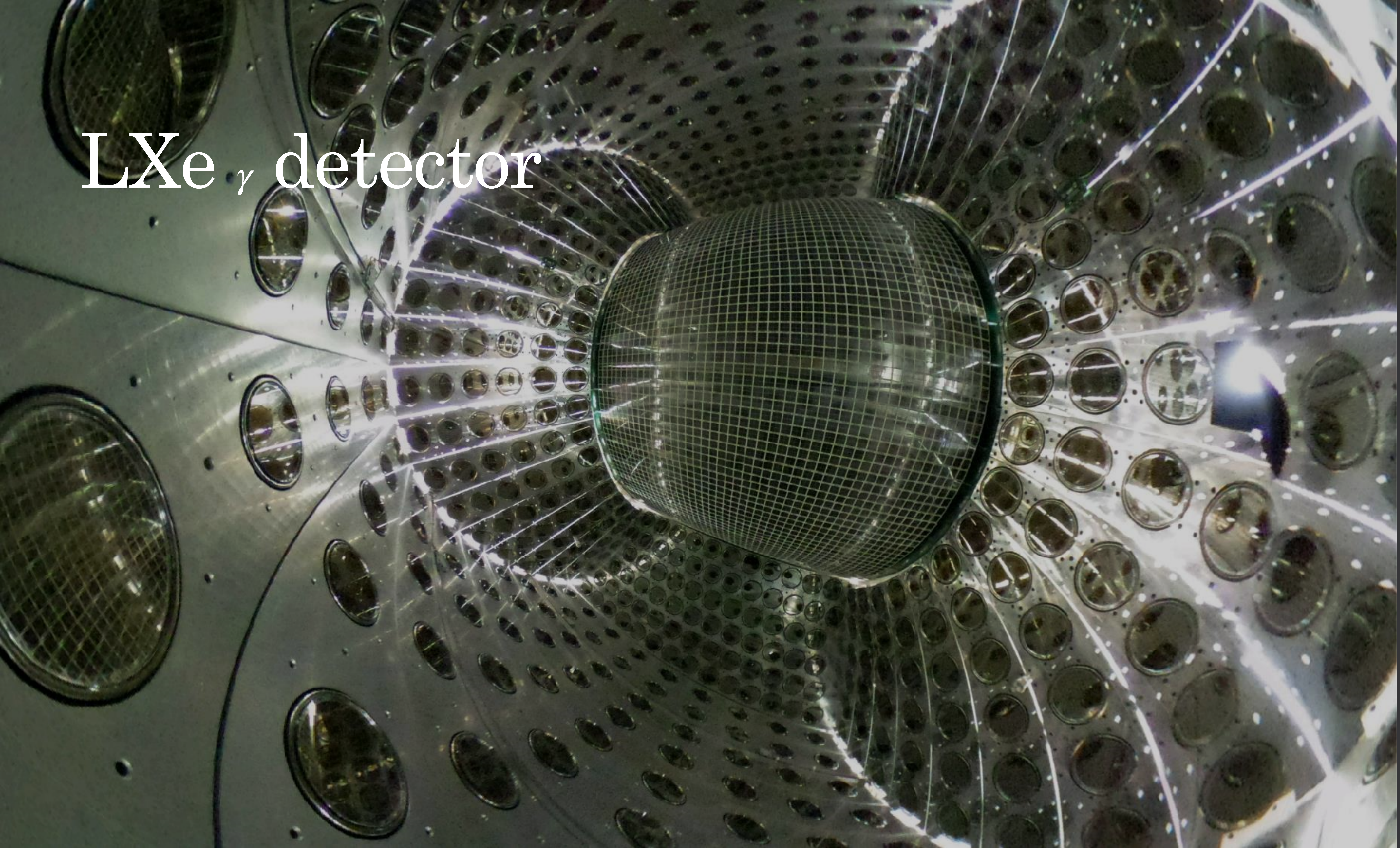
- Fast plastic scintillator + SiPM
- **Increased segmentation**
  → many hits per track
    → good resolution

To improve time resolution:
- Use many SiPMs → high light yield
- Connect them in series
  → less readout ch, short risetime



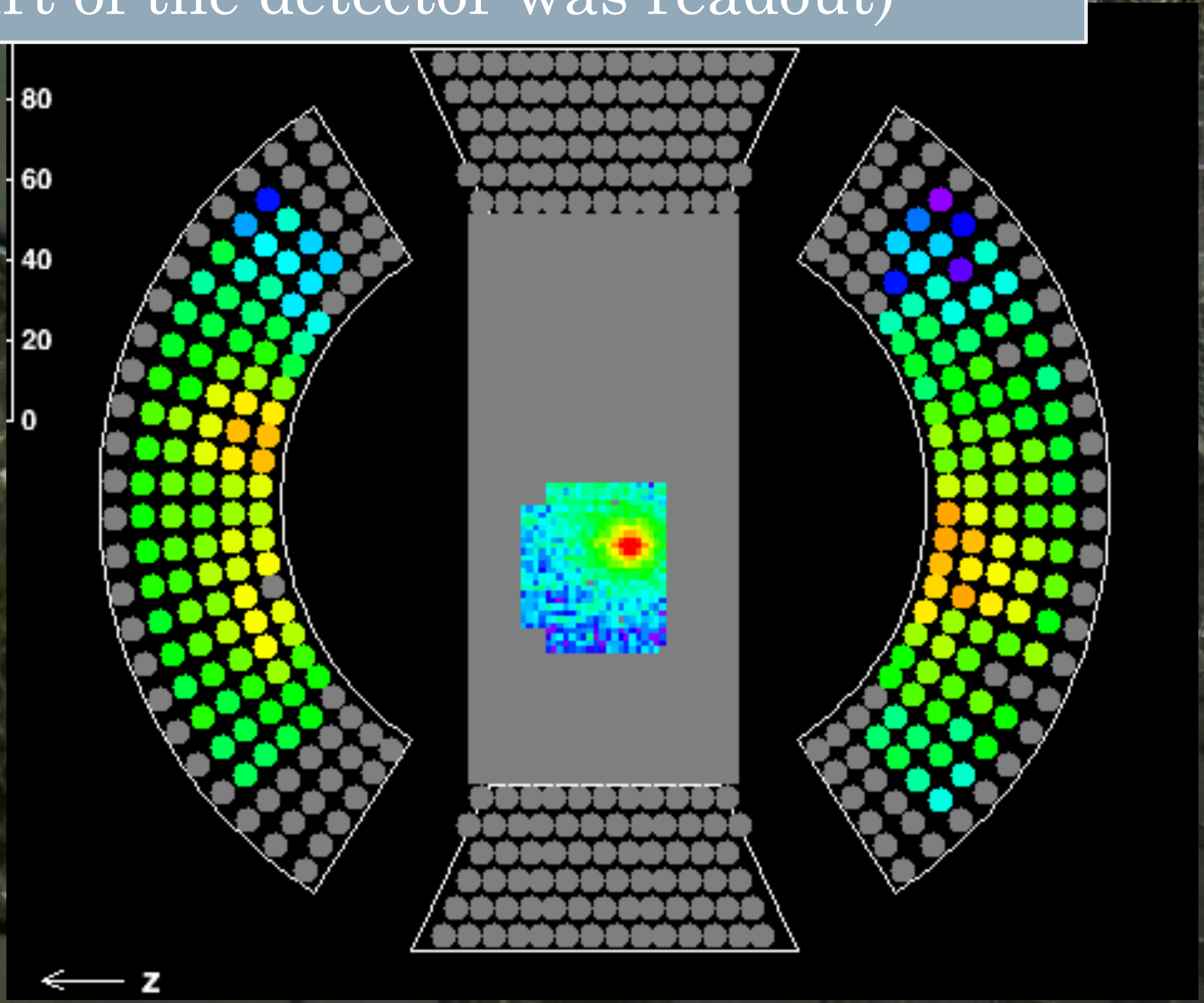


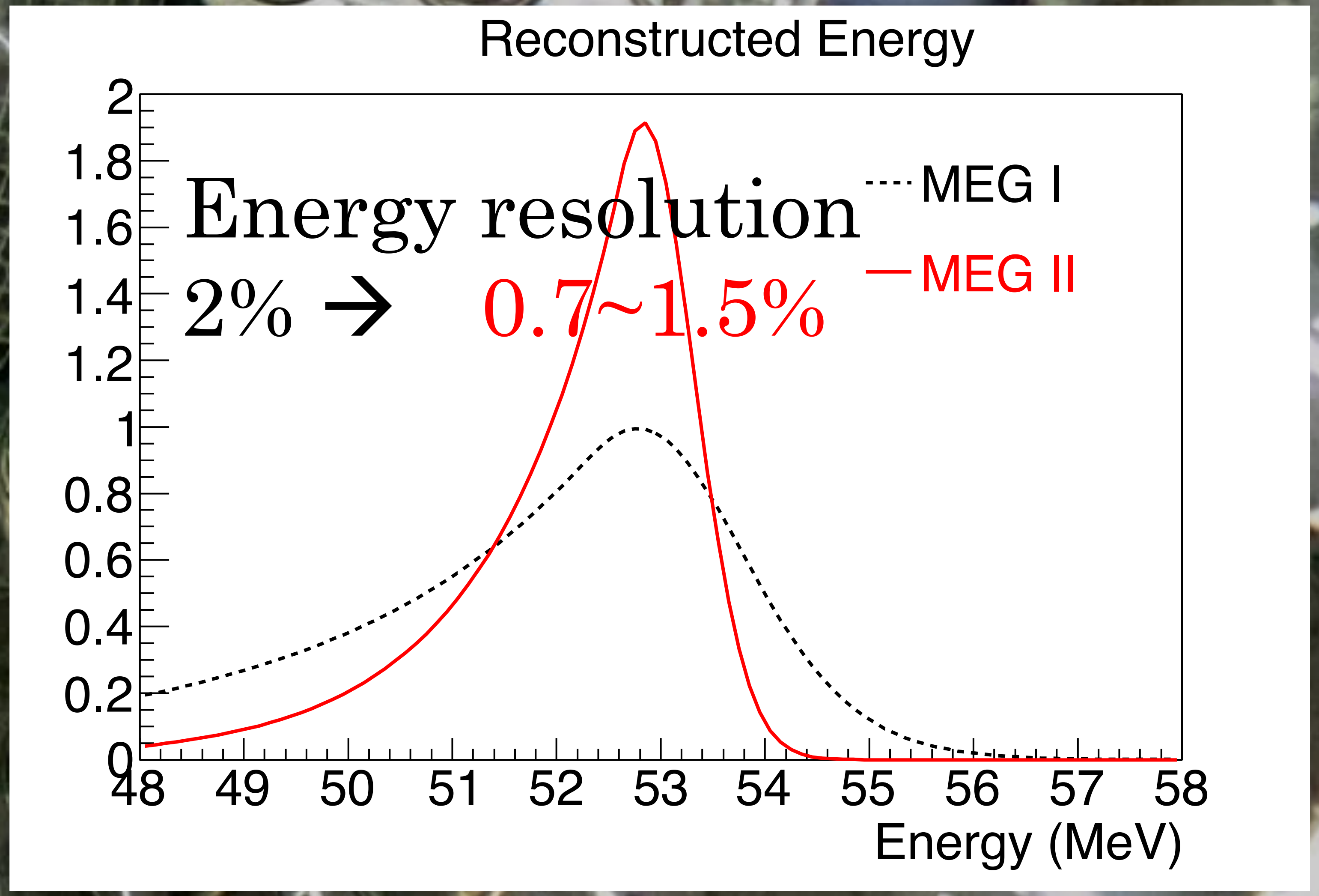
LXe γ detector



LXe γ detector

Example of γ BG event in μ beam run
(part of the detector was readout)



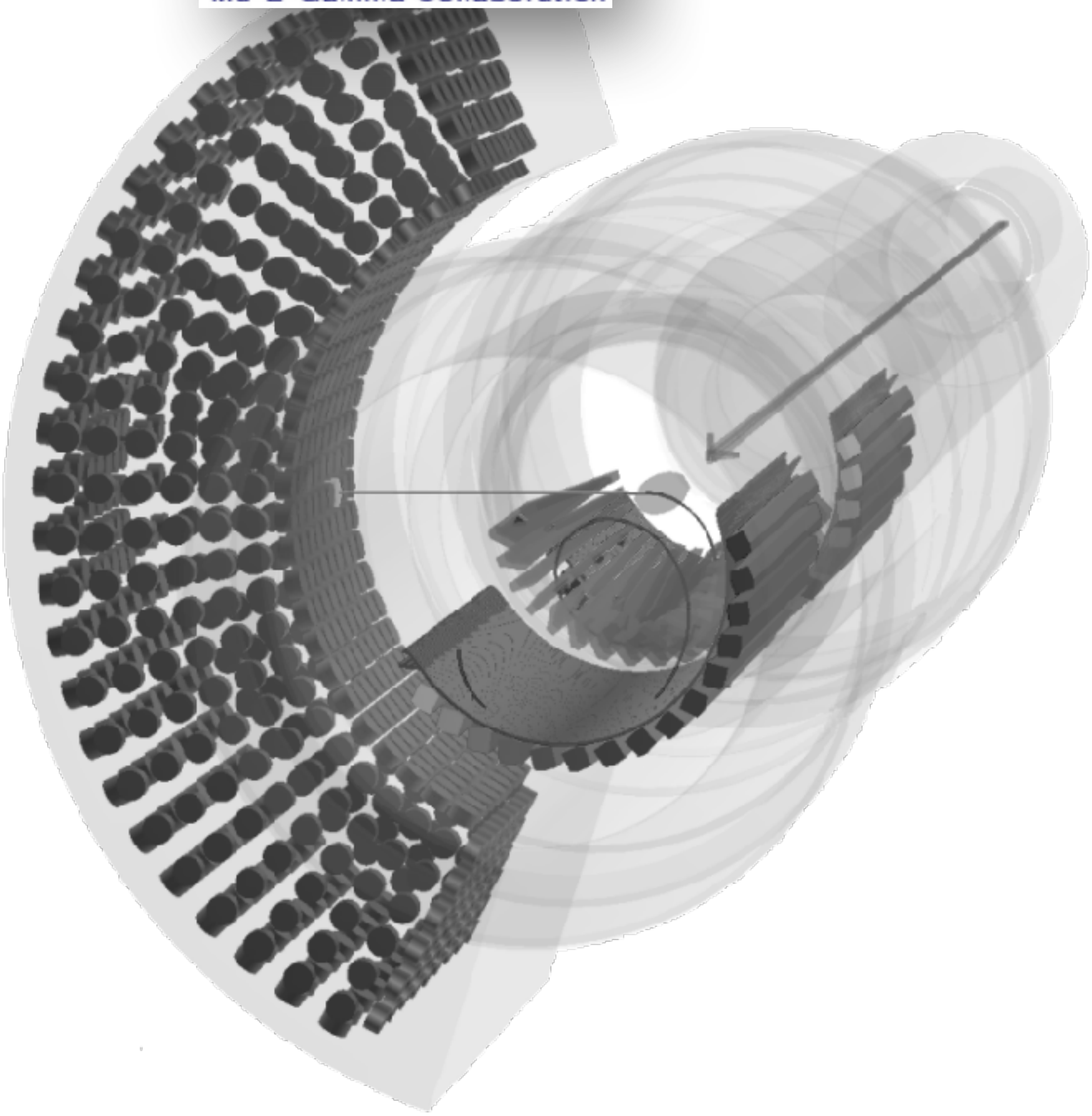


Uniformity of sensor coverage and granularity improved!

→ Energy and position resolution improves by factor of 2 in MC

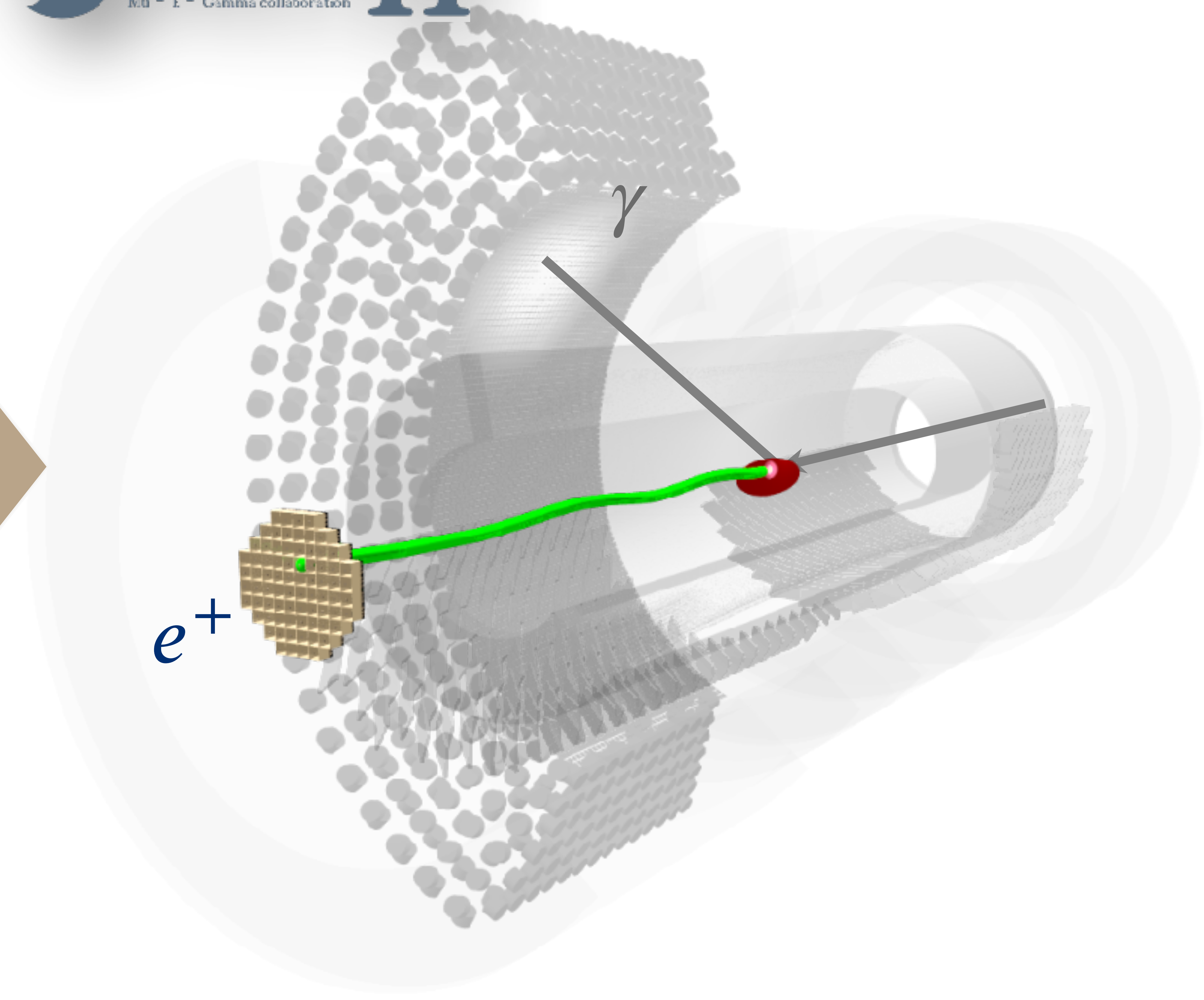
BG tagging detector

MEG
Mu-E-Gamma Collaboration

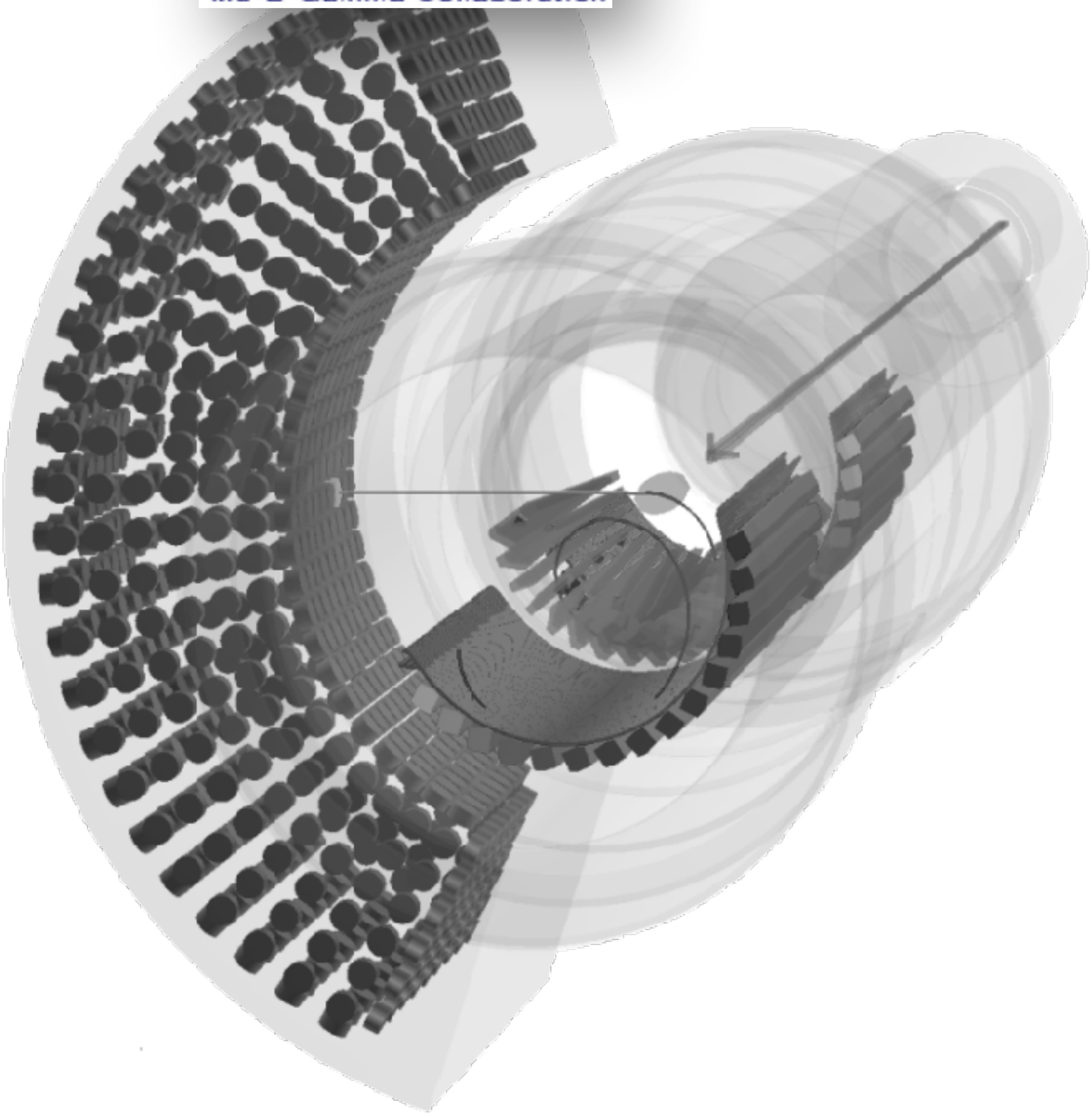


upgrade

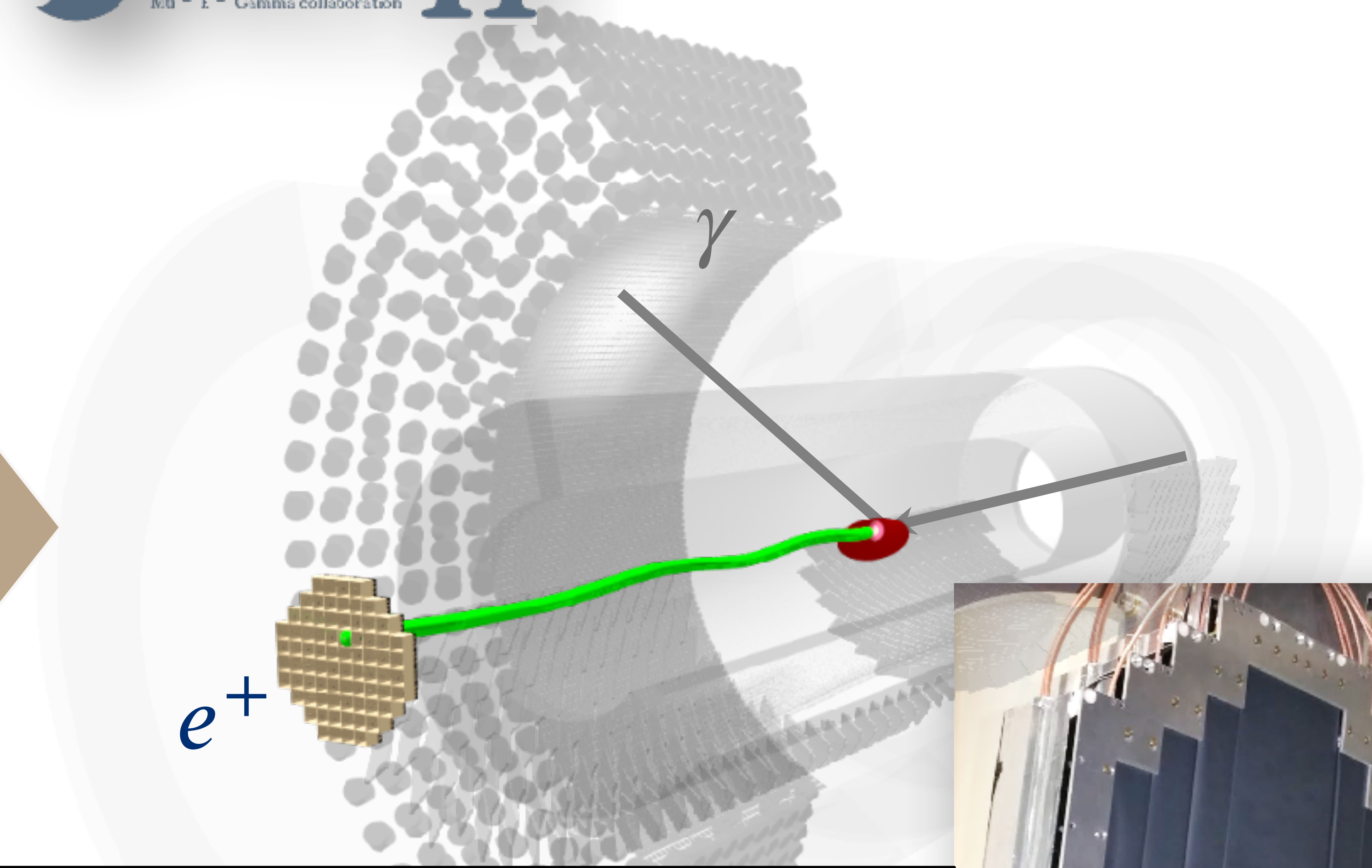
MEG II
Mu - E - Gamma collaboration



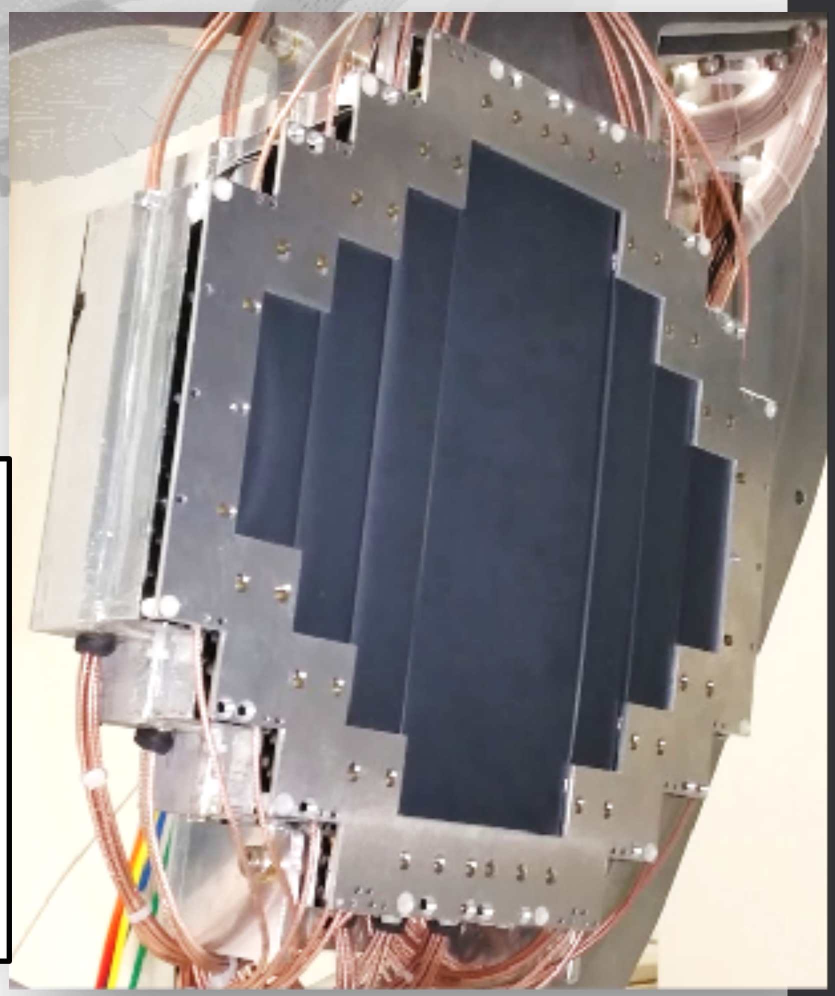
BG tagging detector



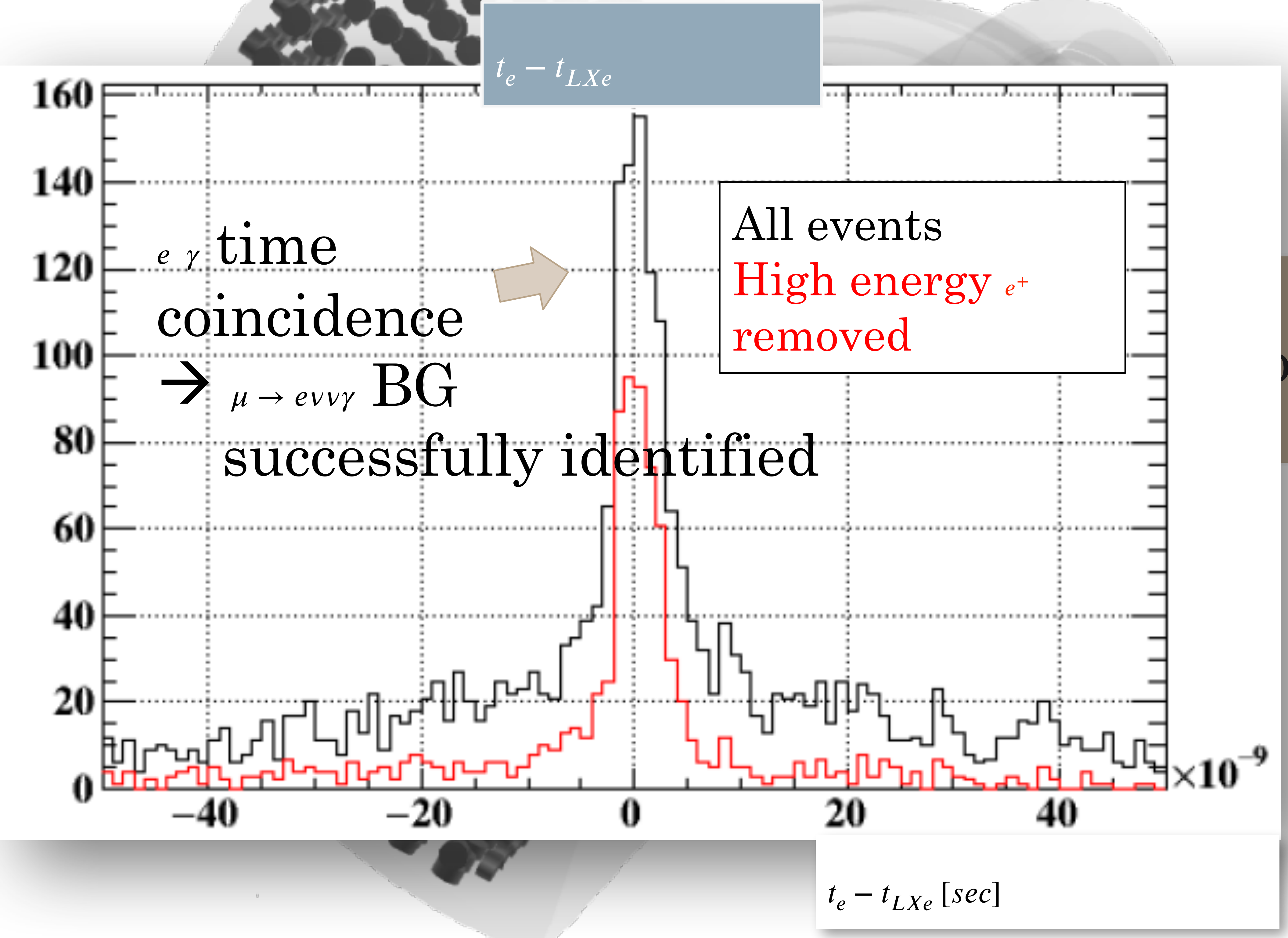
upgrade



- New detector for tagging BG γ
- Detects low energy e^+ from $\mu \to e\nu\nu\gamma$
- Plastic scintillator (timing) + LYSO crystals (energy) + SiPMs



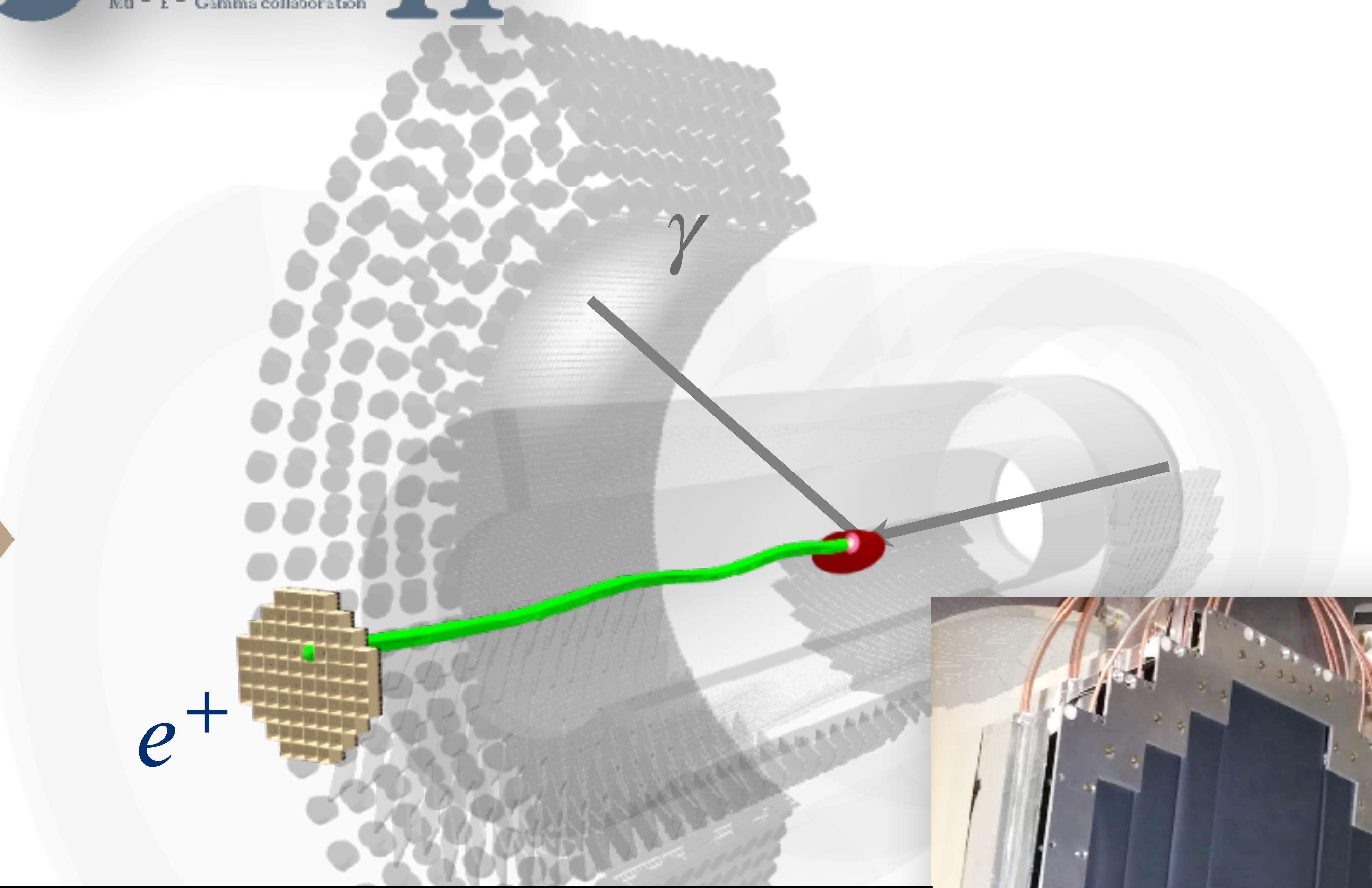
BG tagging detector

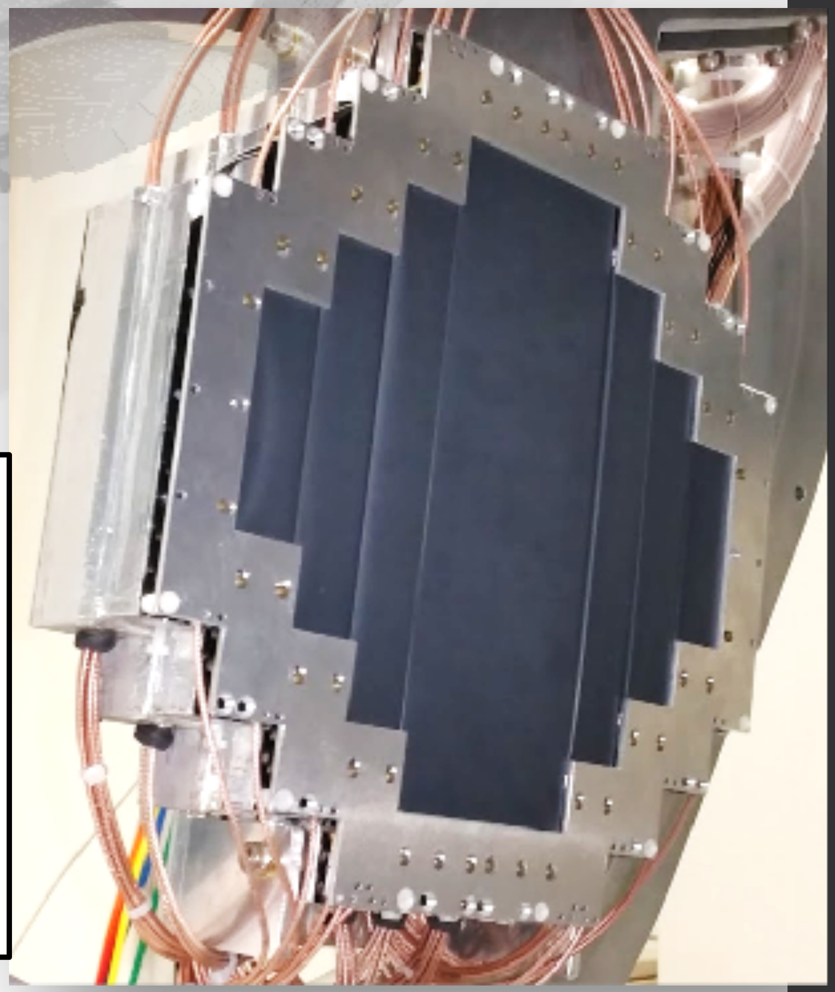


$e\gamma$ time coincidence

→ $\mu \to e\nu\nu\gamma$ BG successfully identified

pgrade





- New detector for tagging BG γ
- Detects low energy e^+ from $\mu \to e\nu\nu\gamma$
- Plastic scintillator (timing) + LYSO crystals (energy) + SiPMs

Status in 2020

- Overall status
  - **Detector construction is finished, commissioning is ongoing.**
  - Timing counter and BG tag detector are ready for physics run.

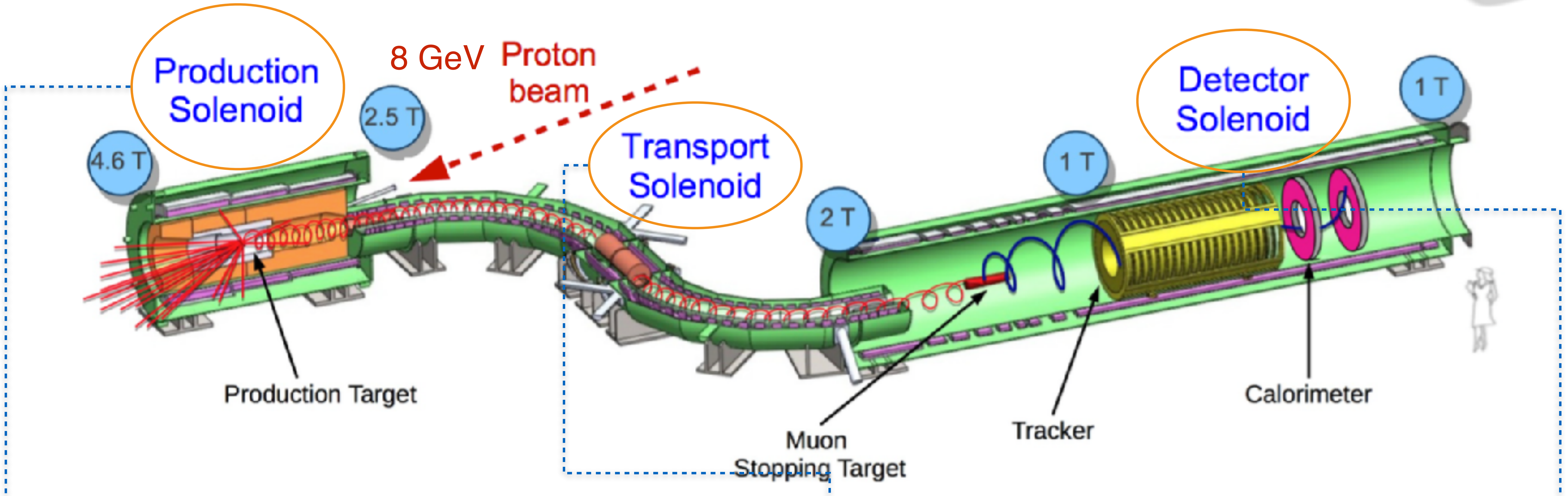
- Commissioning of drift chamber and LXe detector is ongoing
  - For drift chamber, we successfully removed broken/potentially bad wires (due to corrosion).
    Anomalous current was observed → under investigation
  - In LXe detector, photon detection efficiency of SiPMs is found to be reduced (~0.08% per 1-hour beam) likely due to surface damage by VUV photons. Annealing (heating) was found to be effective to recover it.

- **Pilot run in the end of 2020**
  - Establish stable operation of drift chamber
  - LXe detector resolution measurement with ~55 MeV γ from $\pi^0 \to 2\gamma$ from π^- beam ($\pi^- p \to \pi^0 n$)

MU2E

Solenoids

NbTi Superconducting Magnets

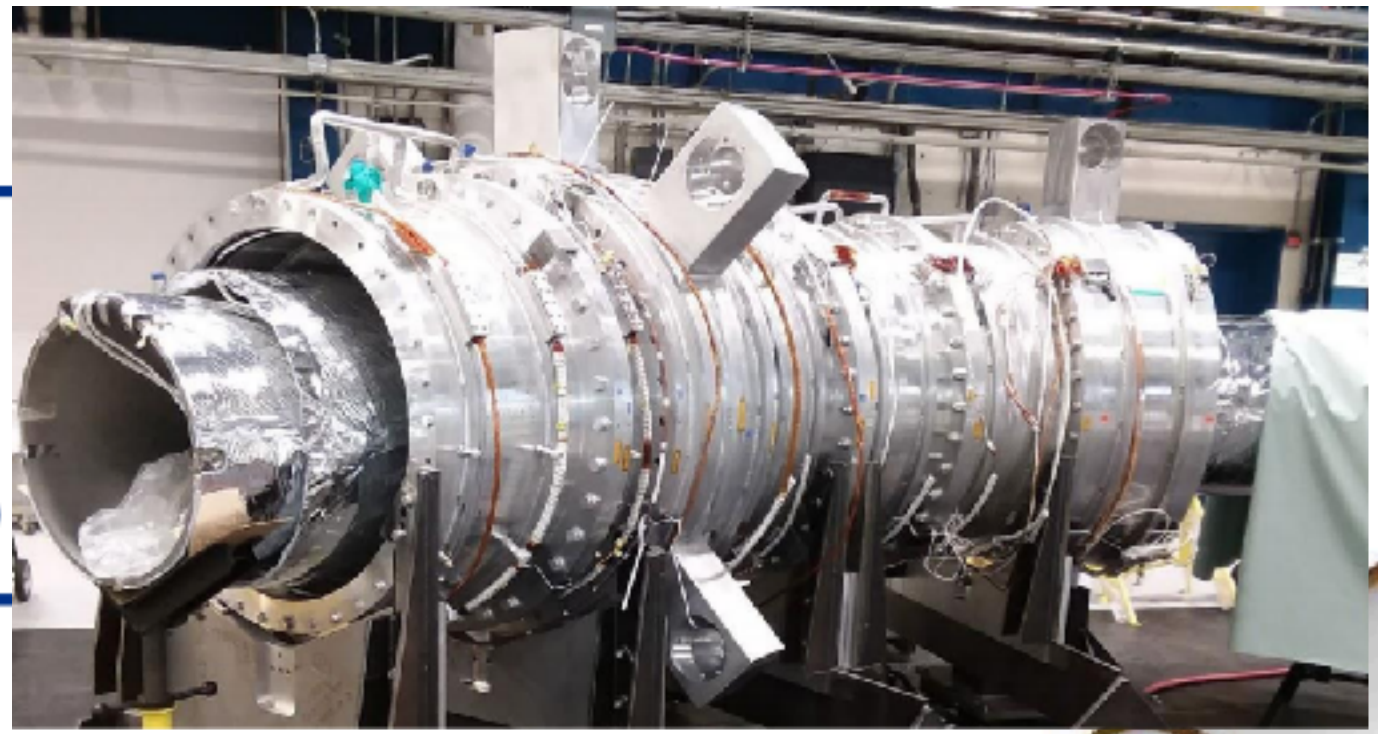


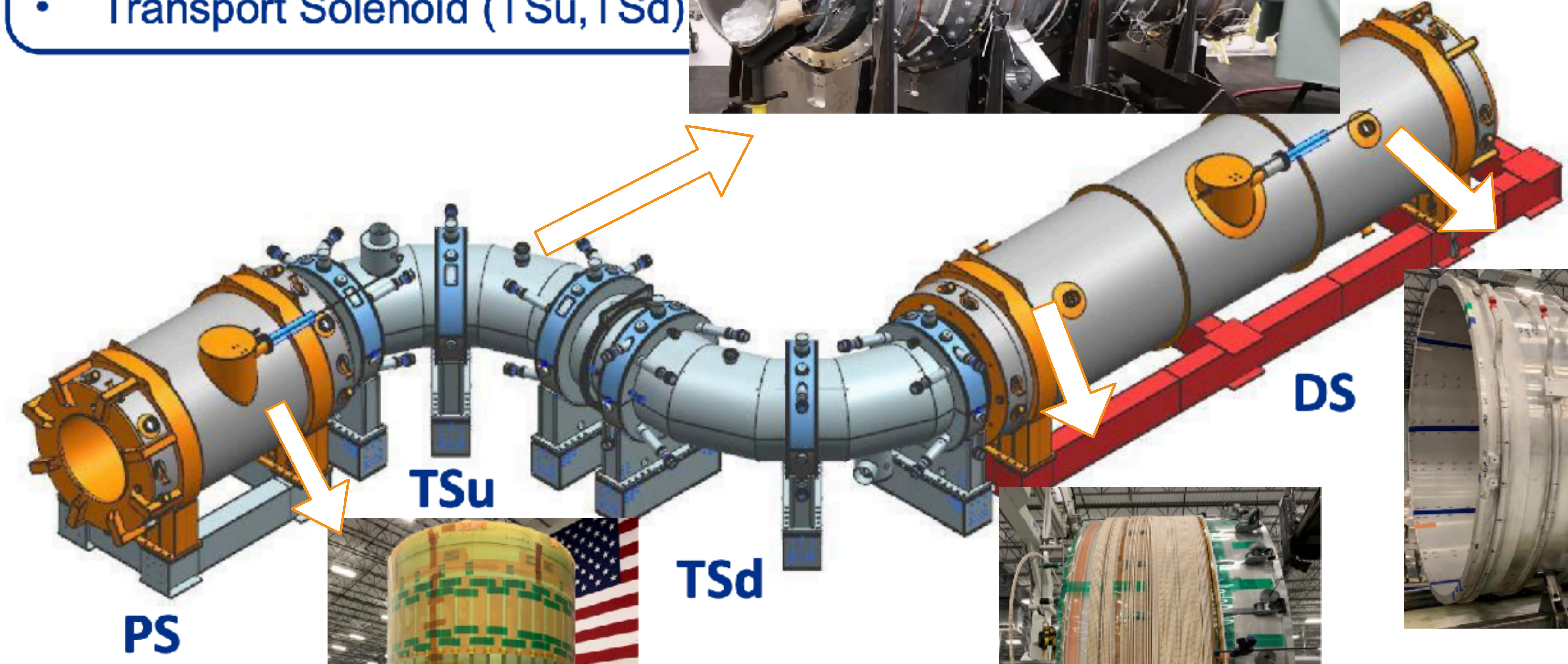
- Direct low momentum pions/muons to transport solenoid.
- S-shaped geometry with collimators select low momentum and negatively charged particles.
- Houses muon stopping target, tracker & calorimeter.

Solenoids - progress

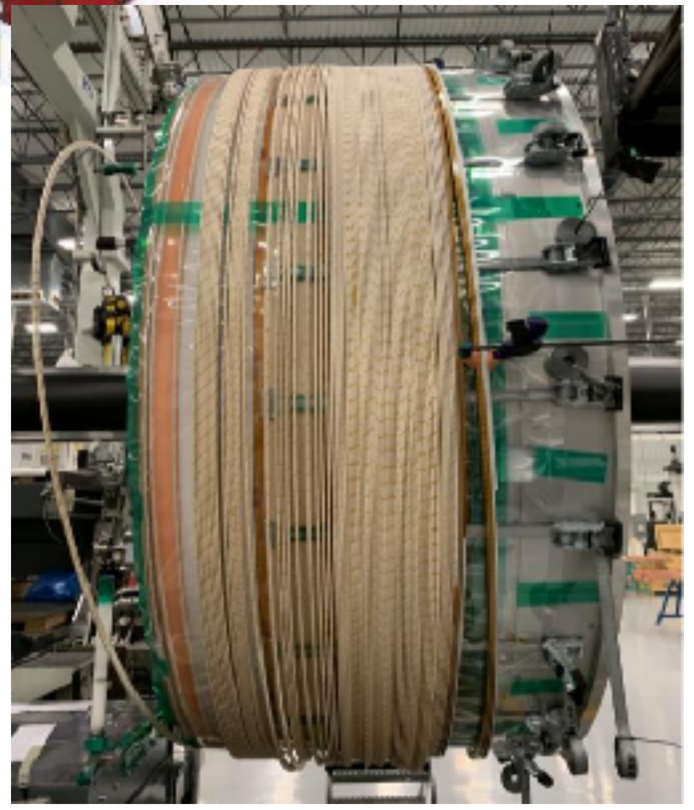
- Production Solenoid (PS)
- Detector Solenoid (DS)
- Transport Solenoid (TSu,TSd)

Fully tested





Post VPI

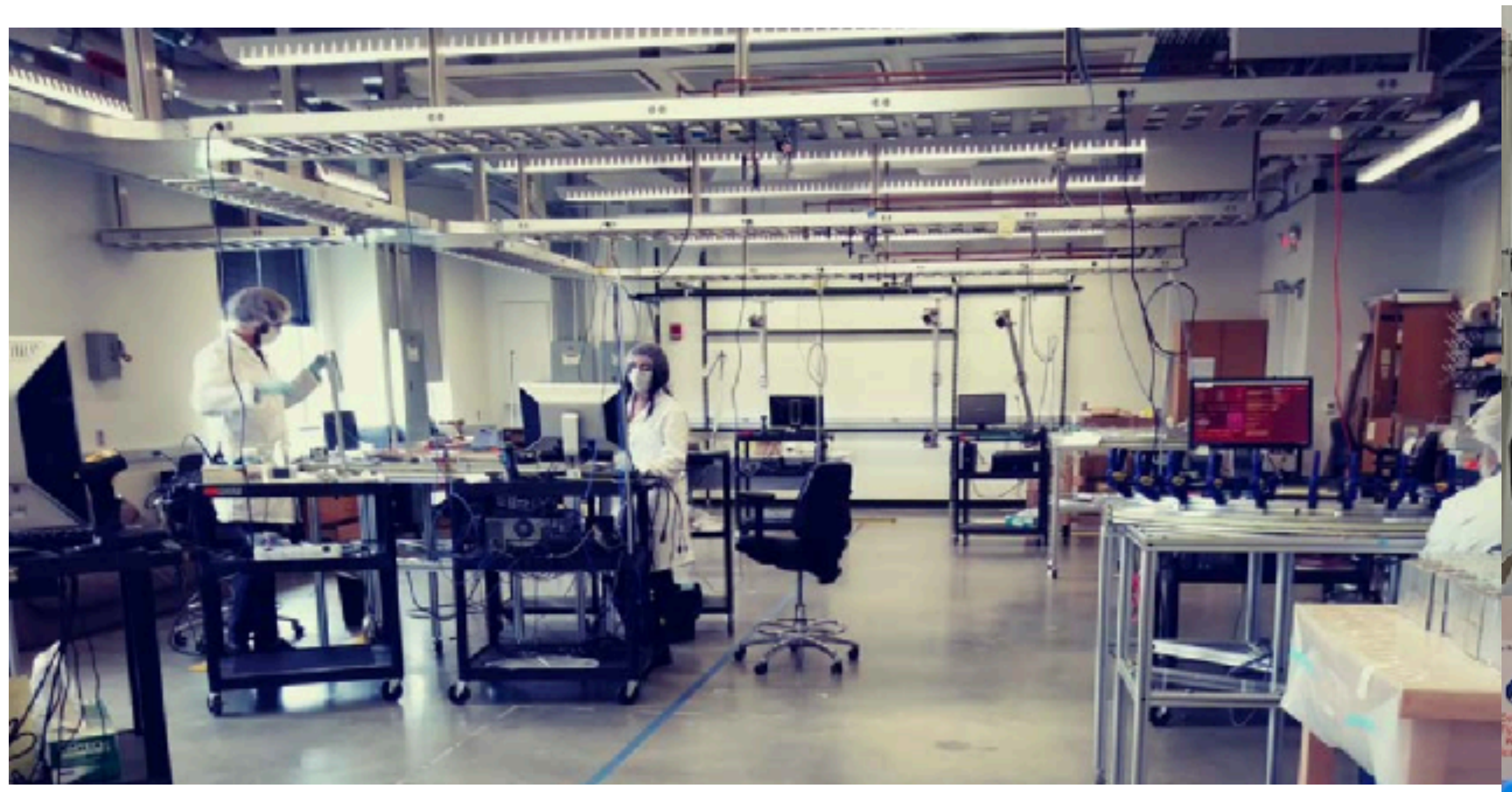


Winding complete

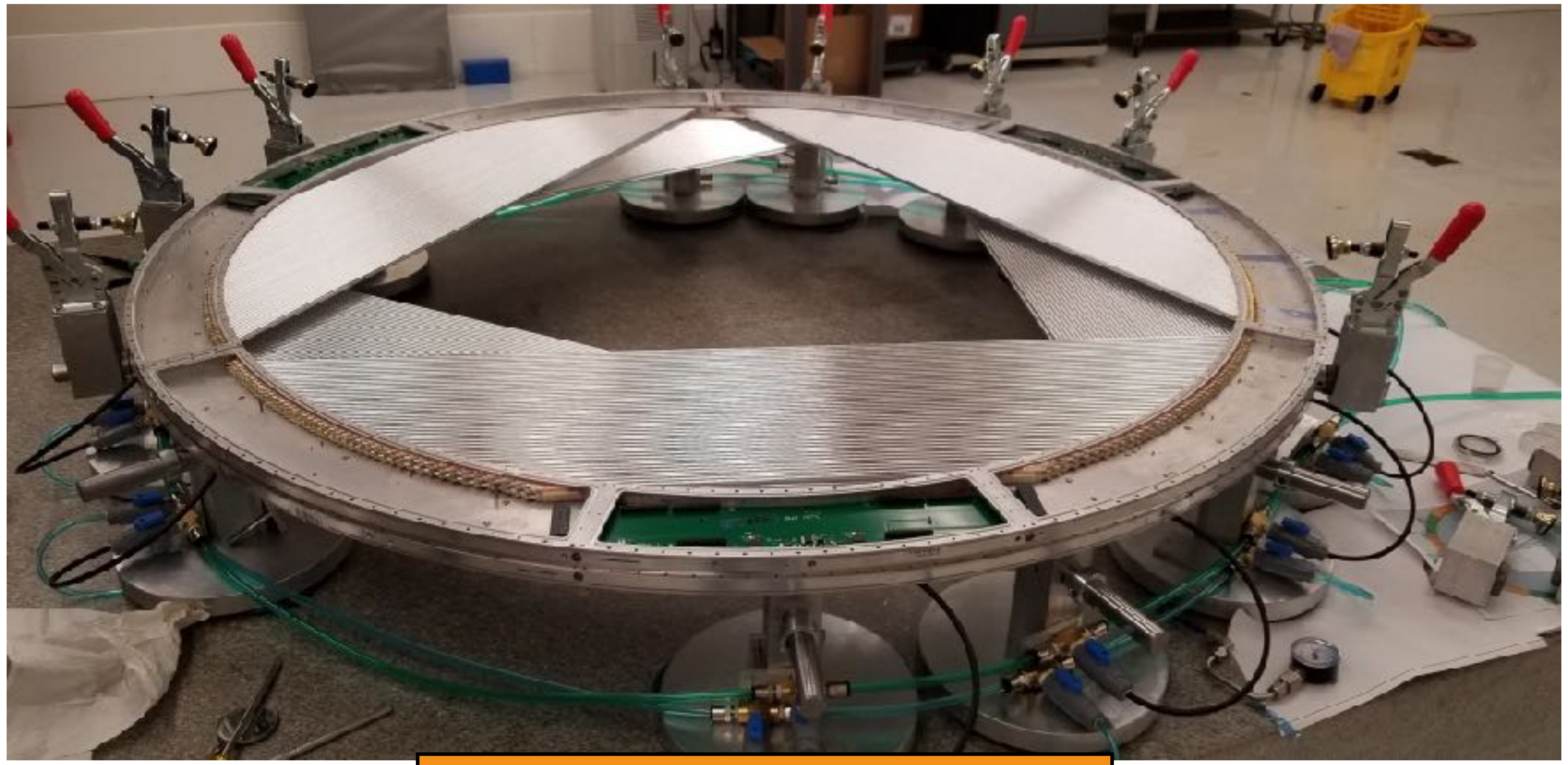
In construction

Tracker - progress

- Panels are produced in Uni. of Minnesota.
- 40/216 tracker panels are produced.



- Dry fit of first tracker plane - Feb-20
- Vertical slice test(a test of <u>complete tracker plane</u> with <u>production electronics</u>) of the first plane is planned for Sept-20.

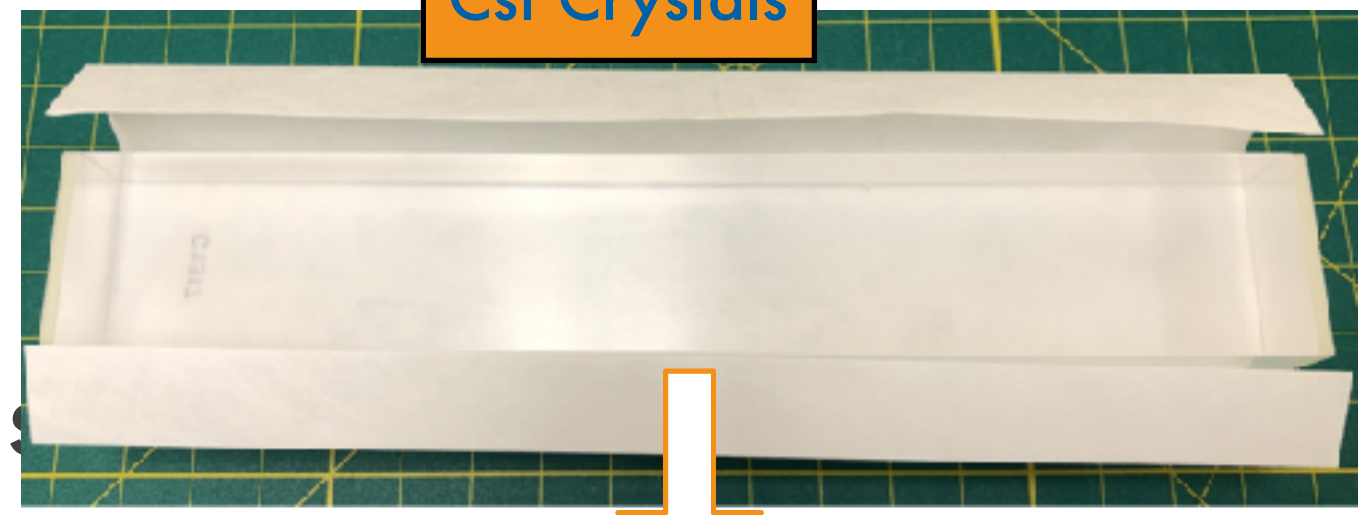


First tracker plane - dry fit

Calorimeter - progress

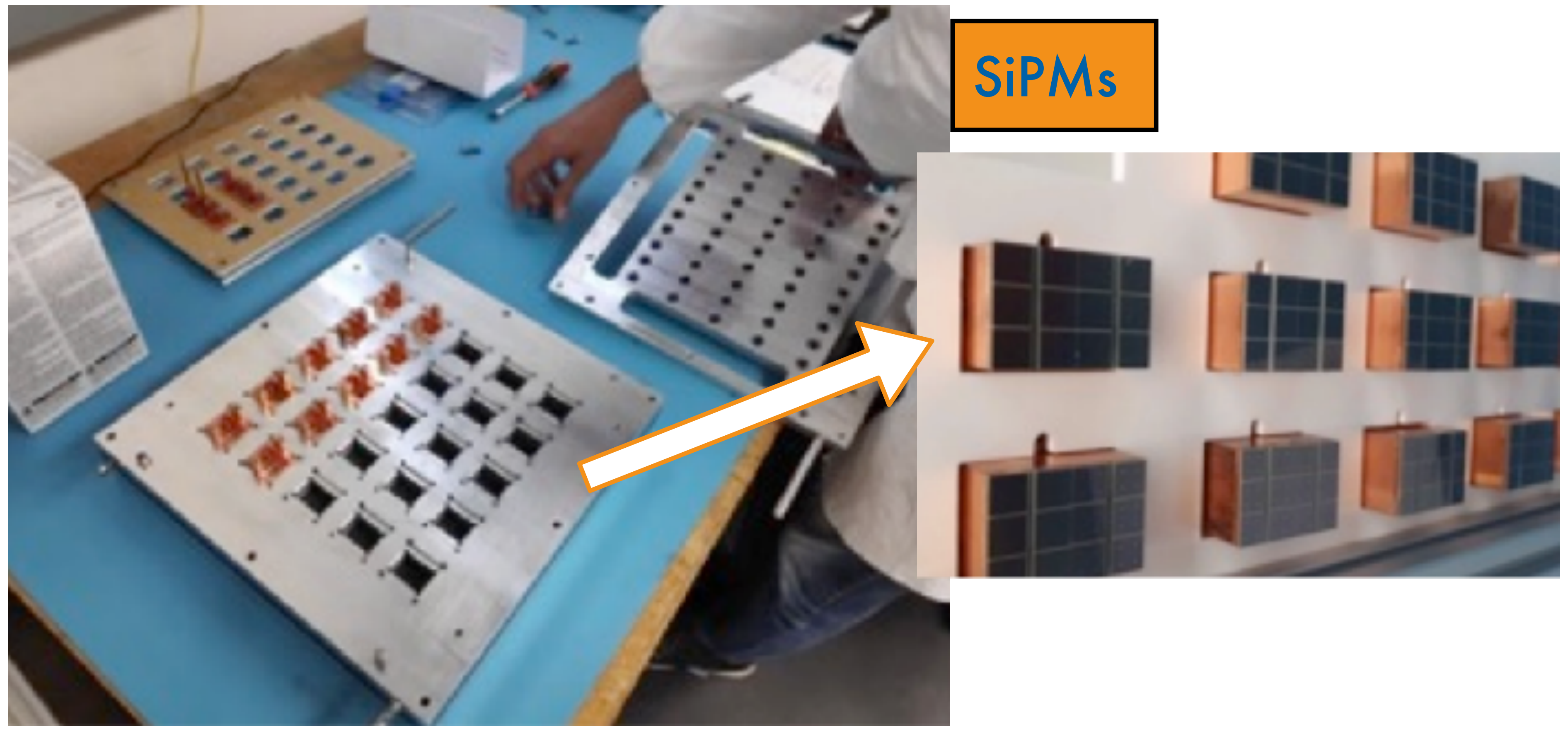
- Plan to finish production of CsI crystals in August.
- Crystals are produced at SICCAS and sent to be tested at Caltech.
- Electronics will be tested at DUBNA and then shipped to FNAL.
- 3950 SiPMs are completed and accepted with 1.2% rejection rate.

CsI Crystals



No.	L.Y. (mean) (P.E. / MeV)	LRU (%)	Reso. (%)	F/T (%)
C1316	116.84 115.26	5.15 **1.06**	16.29 16.60	86.08 86.06
C1317	122.79 125.43	**1.91** 5.10	16.04 15.70	86.39 86.54
C1318	112.67 114.63	**2.21** 8.92	16.61 16.85	86.21 86.27
C1319	133.56 135.54	**1.74** 2.63	15.43 15.54	87.35 87.33
C1320	121.69 121.73	**2.13** 6.81	16.77 15.91	85.82 85.87
C1321	139.46 139.58	**1.20** 4.28	15.64 14.81	86.48 86.50
C1322	122.35 124.06	**1.10** 2.83	16.04 15.85	86.41 86.44
C1323	124.18 123.22	5.33 **2.51**	16.15 16.20	85.03 85.00

No.	L.Y. (mean) (P.E. / MeV)	LRU (%)	Reso. (%)	F/T (%)
C1324	126.82 125.54	5.60 **2.74**	15.88 16.00	88.25 85.98
C1325	125.89 127.55	**3.75** 6.58	16.05 16.37	90.57 90.66
C1326	147.12 147.89	**2.18** 9.07	15.25 15.48	88.64 88.63
C1327	129.14 130.05	**1.30** 11.39	15.72 15.65	86.32 86.30
C1328	146.63 149.19	**3.43** 7.64	14.93 15.37	87.38 87.35
C1329	143.79 146.60	**4.14** 8.12	15.75 15.47	89.51 89.48
C1330	147.23 147.90	**1.95** 4.20	15.25 15.25	88.16 88.11



SiPMs

Mechanical production is ongoing

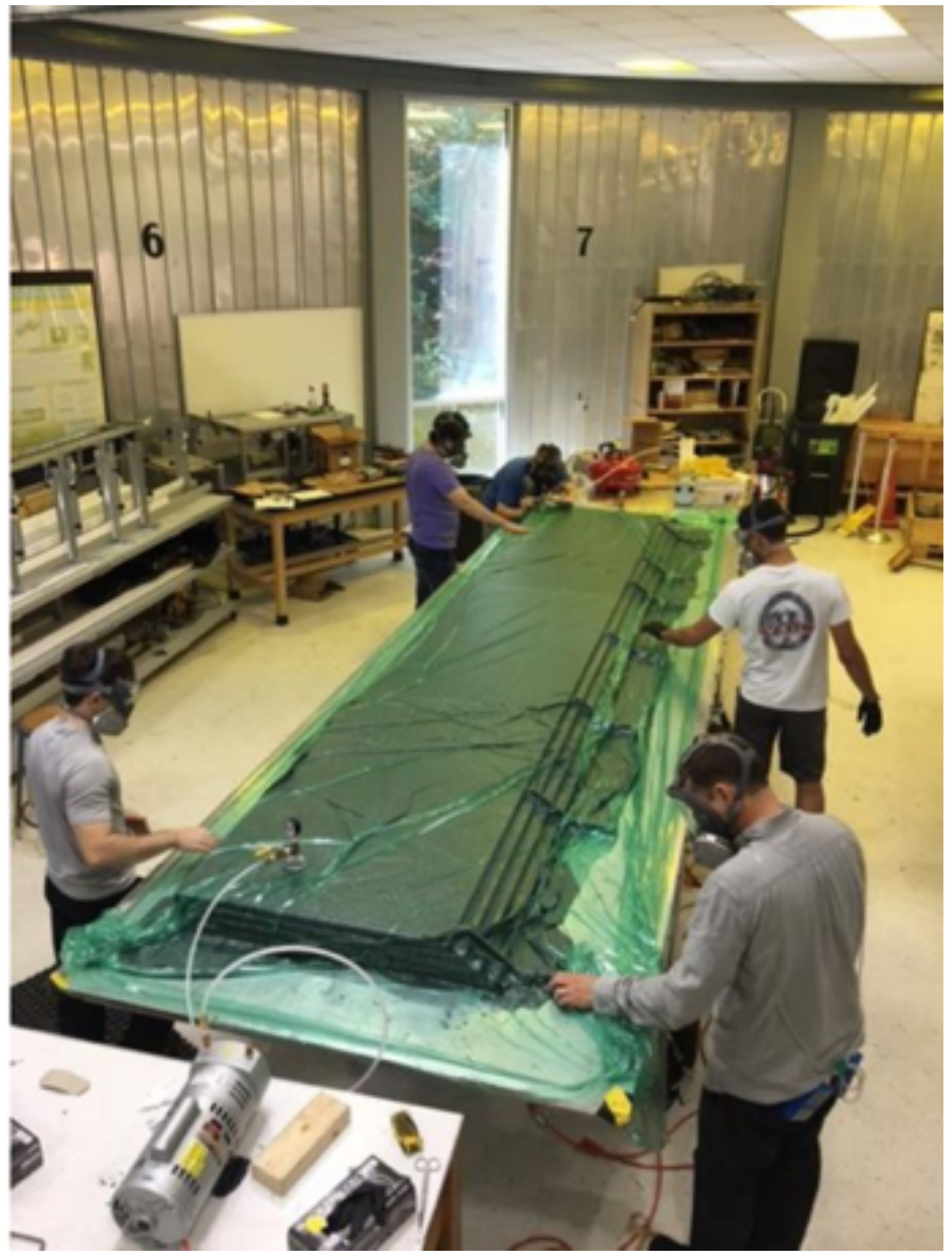
Fermilab

CRV - progress

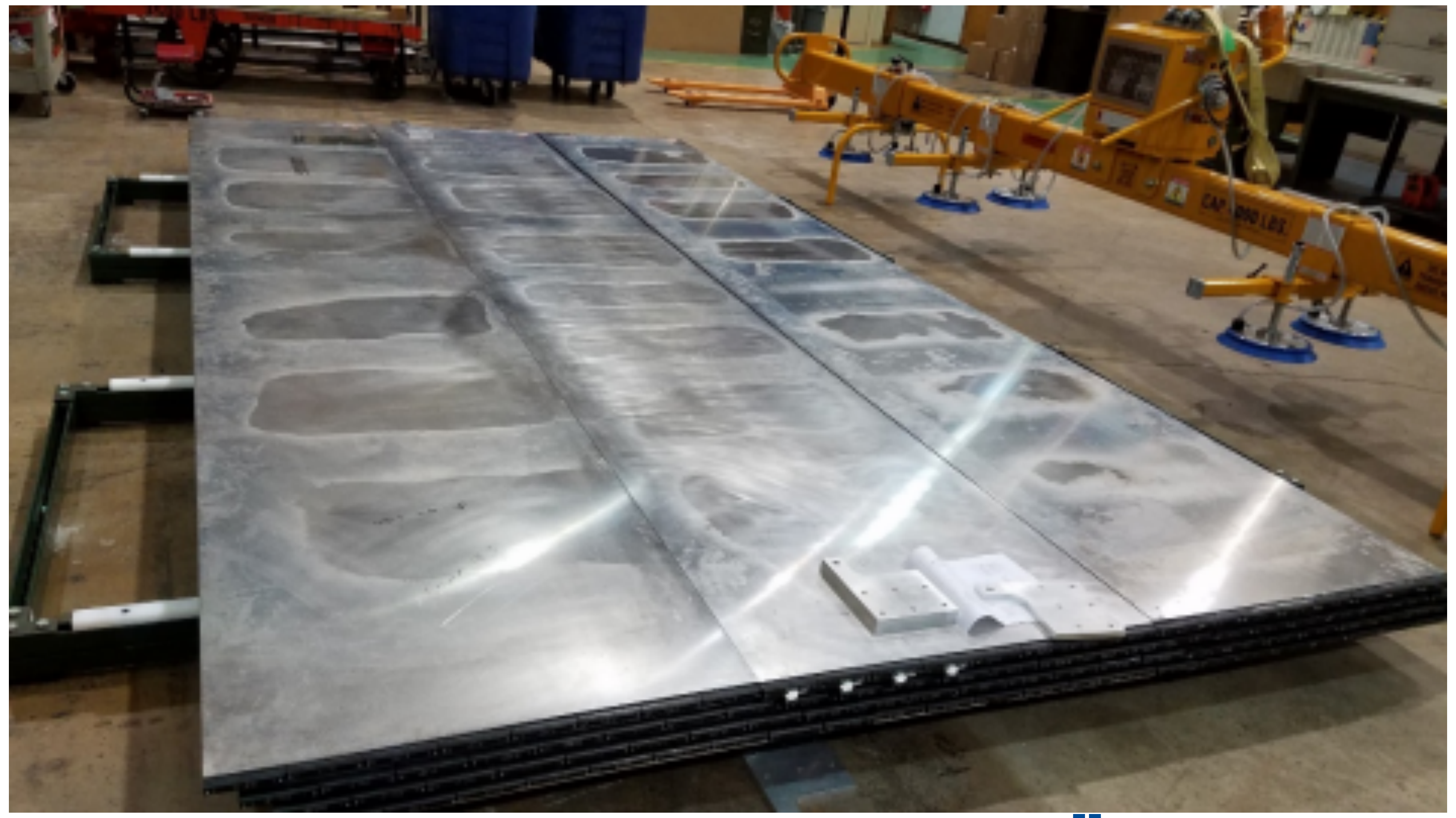
- 80% SiPMs tested, 99% yield.
- 1560/2688 di-counters(58%) produced.
- 20/83 production modules(24%) are completed.

Vertical modules

CRV module vacuum bagged

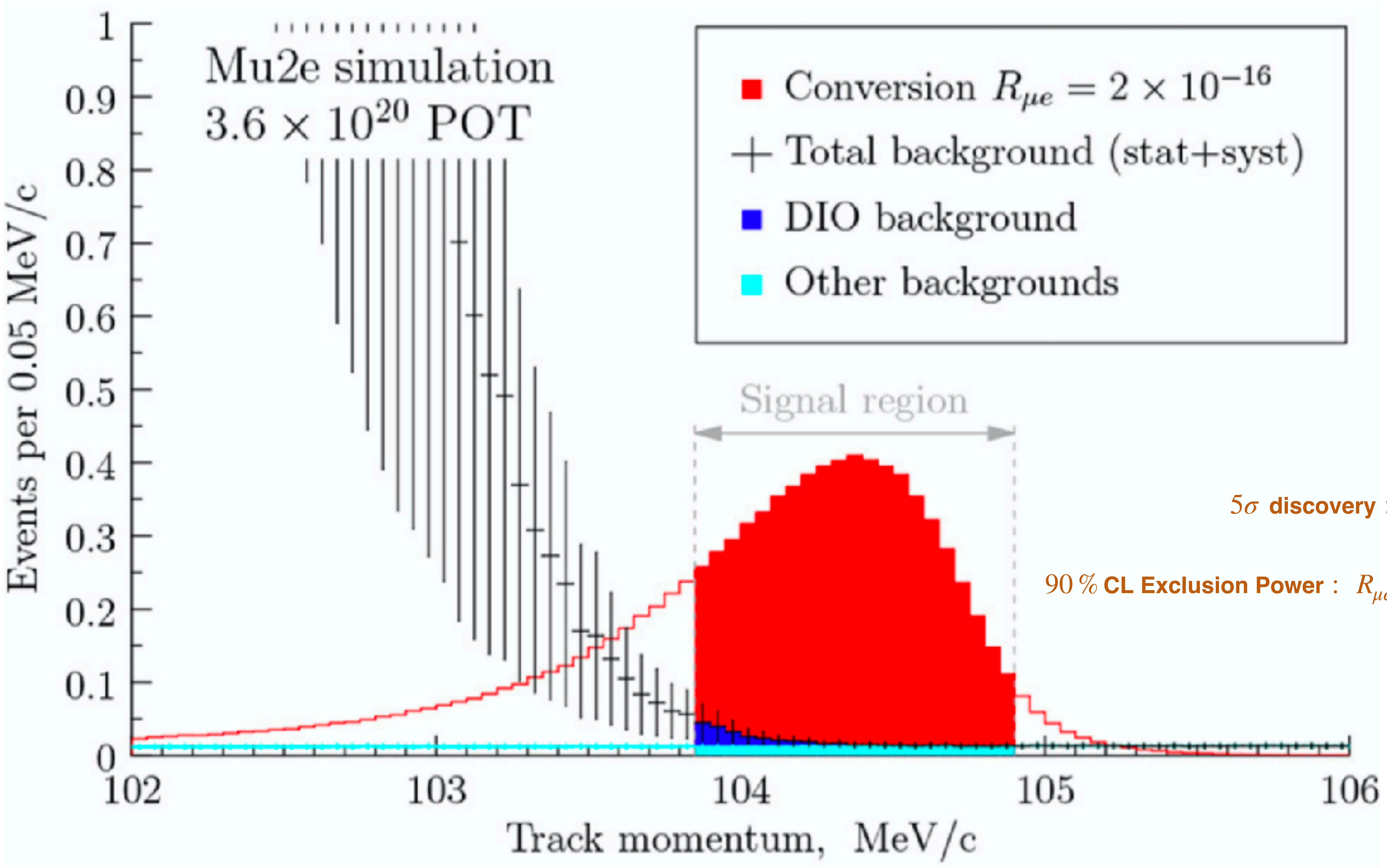


Side modules



Fermilab

Sensitivity



5σ **discovery** : $R_{\mu e} \geq 2 \times 10^{-16}$

$90\,\%$ **CL Exclusion Power** : $R_{\mu e} \geq 8 \times 10^{-17}$

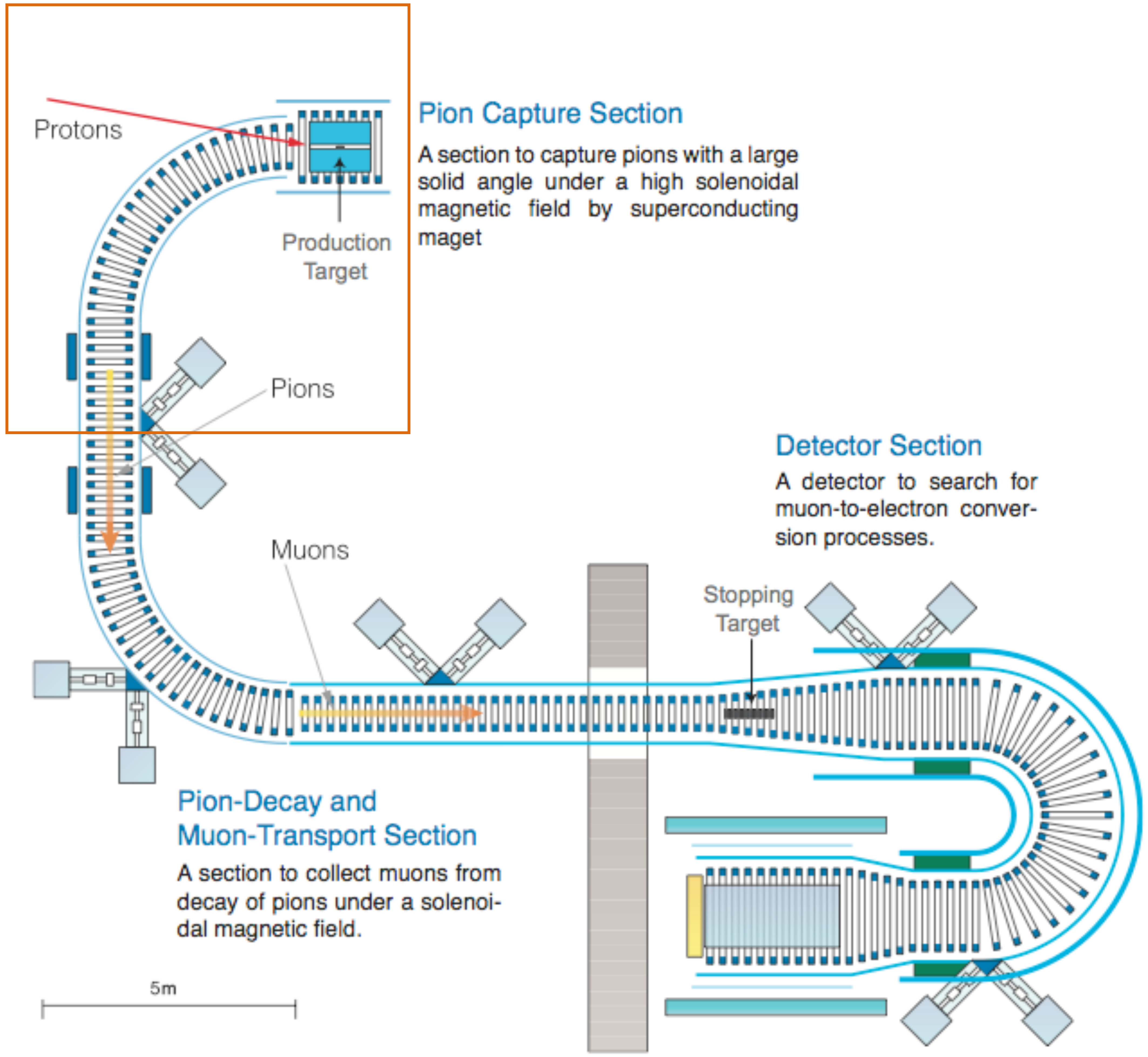
7 conversion electrons are needed for 5σ

Summary

- Mu2e will improve current limit on conversion rate by 10^4 @ $R_{\mu e} = 3 \times 10^{-17}$.
- Will probe mass scales up to 10^4 TeV.
- Current schedule;
  - Installation and commissioning starting in 2021
  - Start physics data taking in 2024.
  - $\times 1000$ improvement over current limit by 2025
  - LBNF/PIP-II shutdown.
  - $\times 10000$ improvement over current limit by the end of the decade.
- Next 2-3 years will see a big effort on building and commissioning the detector.

COMET

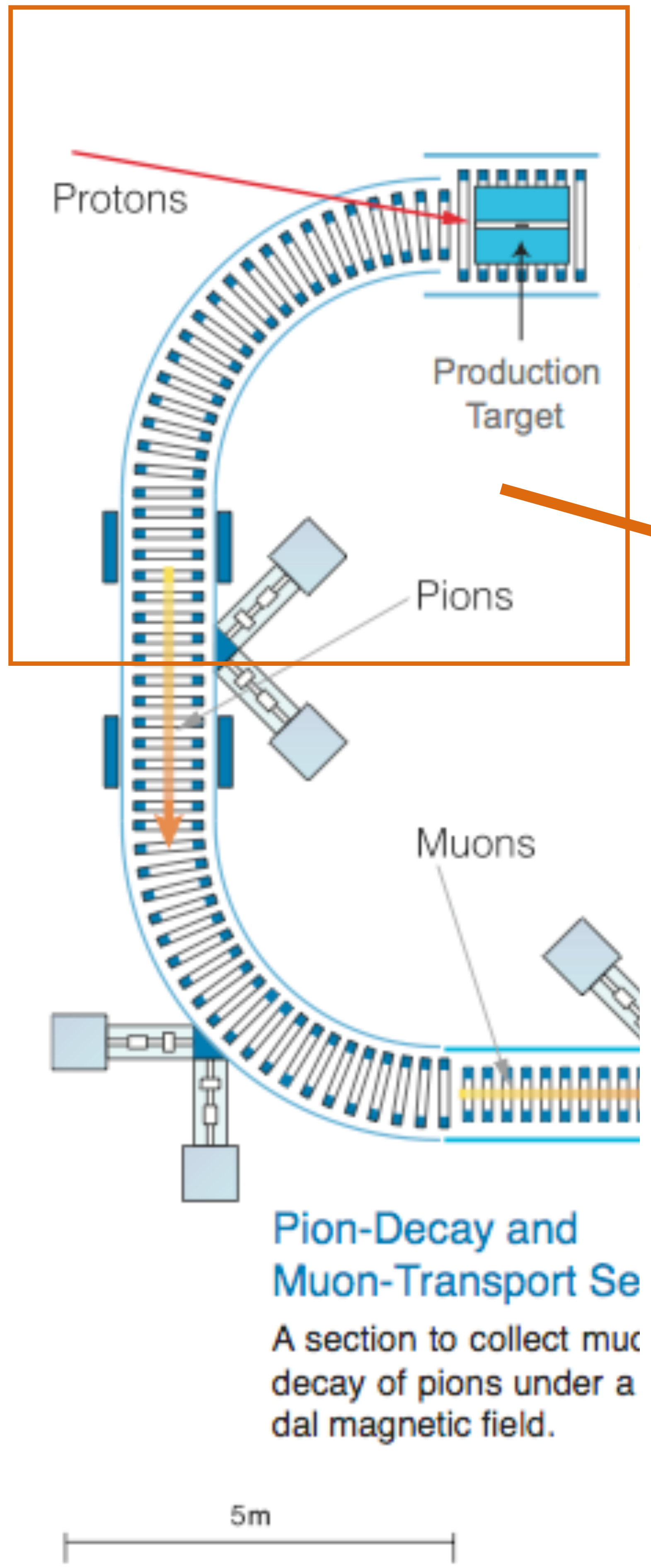
Two-Staged Approach

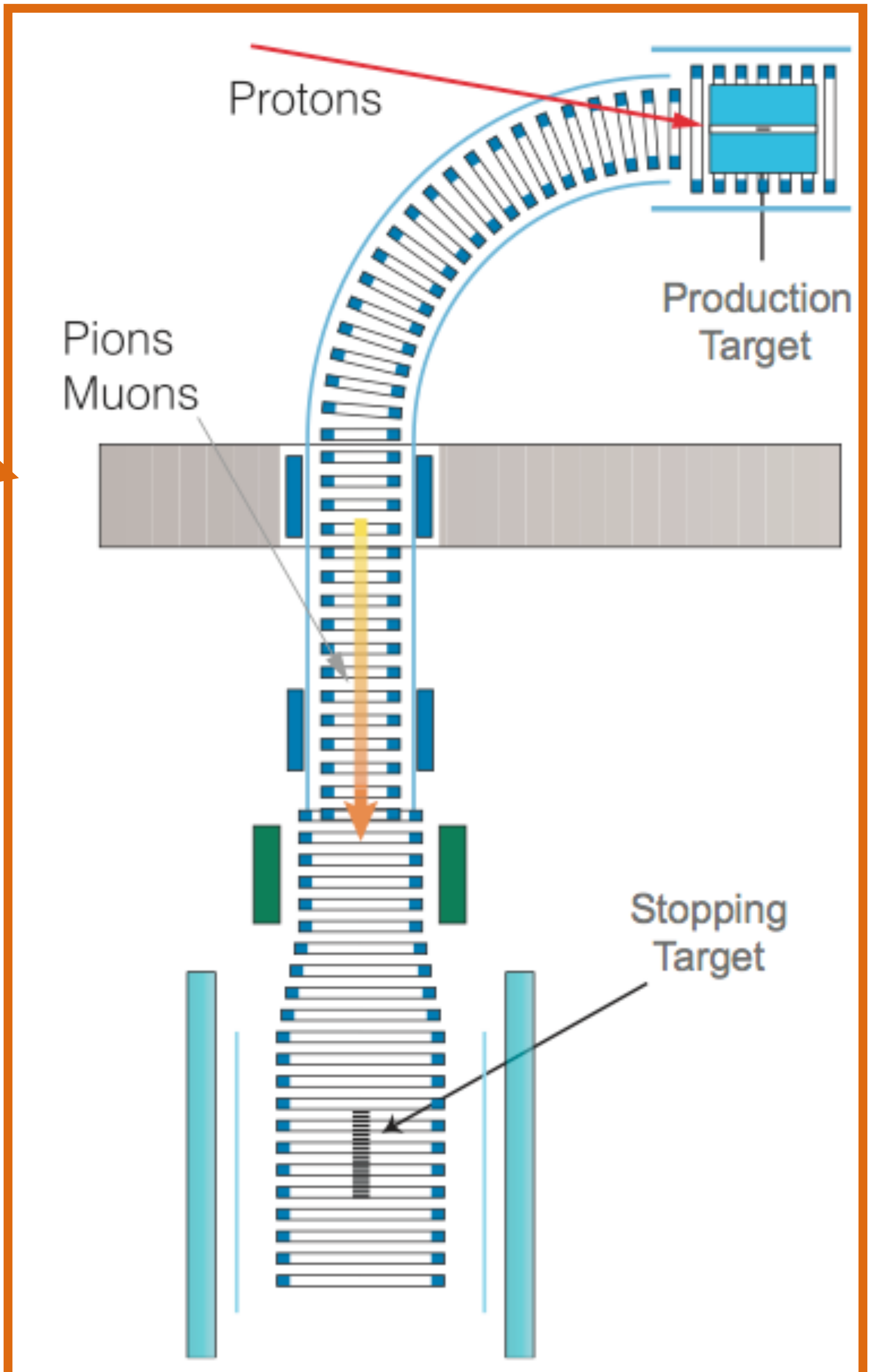


- **COMET Phase-I**
  - Construct up to first 90° bend and place detector.
  - Perform direct beam measurement
    - No backward σ_π data so far
    - No real BG data so far
  - Perform μ-e Search with an intermediate sensitivity ($O(10^{-15})$)

- **COMET Phase-II**
  - Complete all transport
  - Perform μ-e Search with a full sensitivity ($O(10^{-17})$)

Two-Staged Approach





【 COMET Phase-I 】

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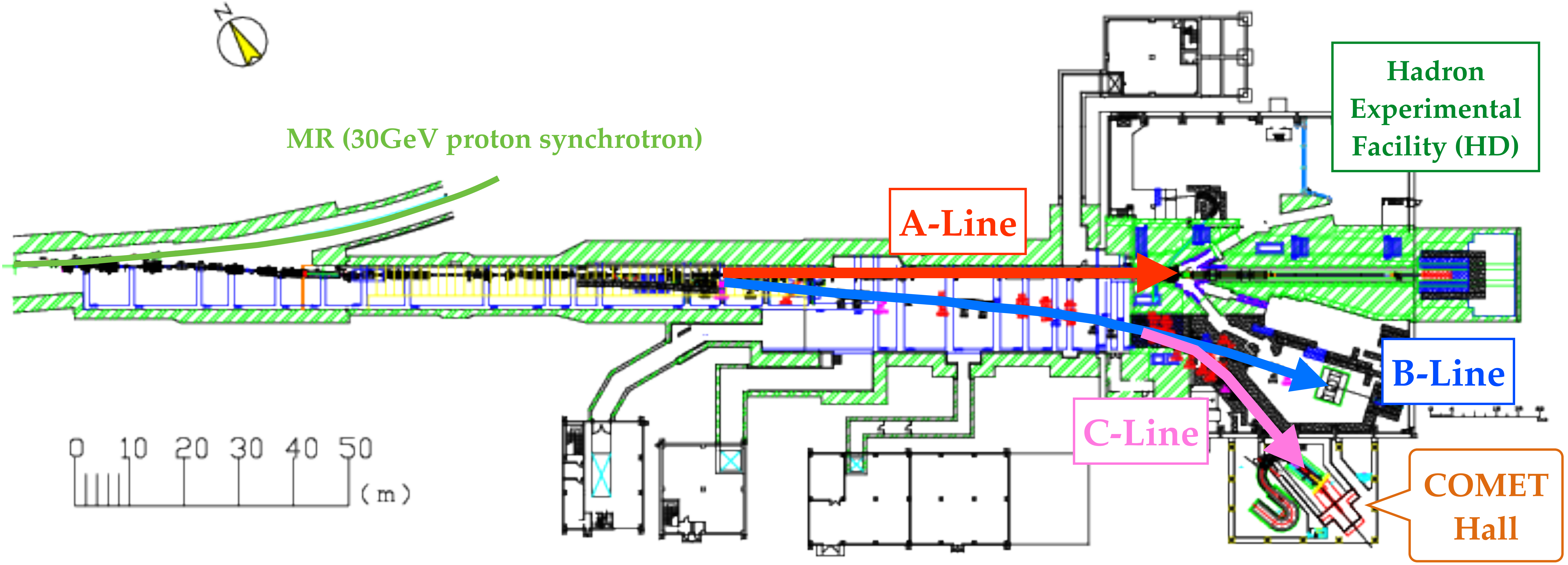
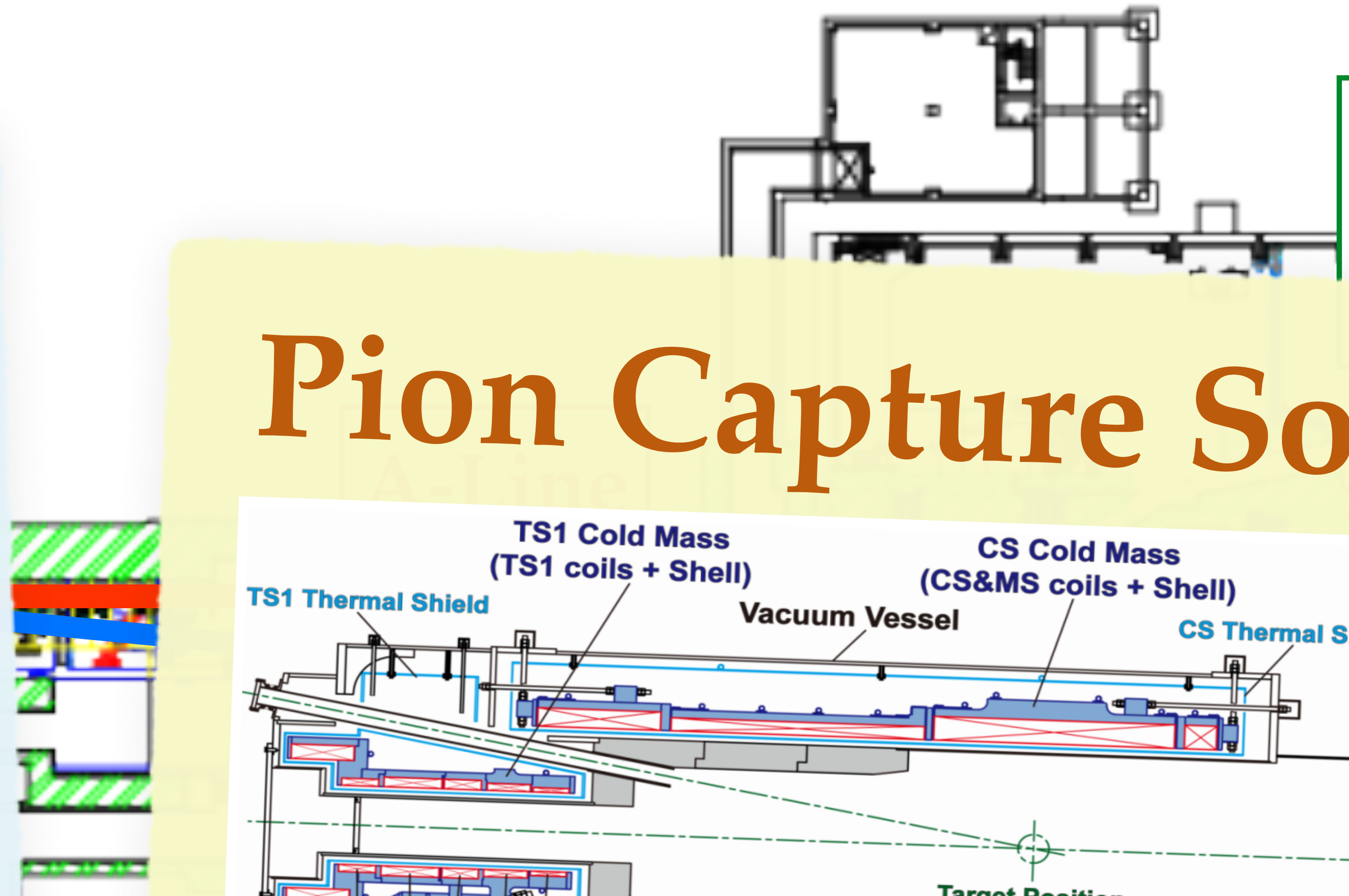
- **COMET Phase-II**
  - Complete all transport
  - Perform μ-e Search with a full sensitivity ($O(10^{-17})$)

Current Status (1) — Facility Construction —

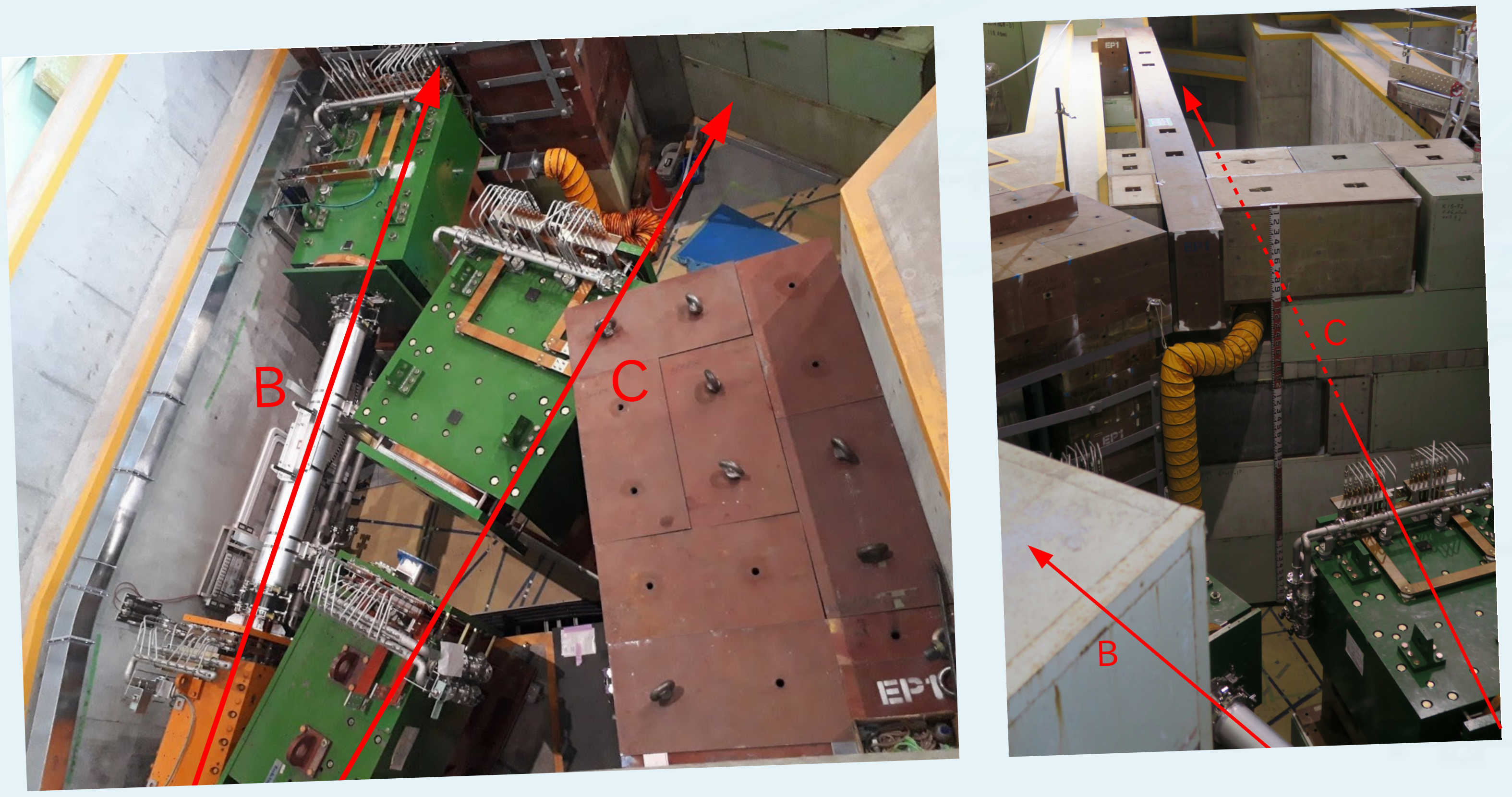


- Dedicated proton beam line is under construction.
  - Three proton beam lines in Hadron Experimental Facility. **A-Line** is primary and in-operation. **B-Line** just completed and started operation in June 2020. C-Line, dedicated for COMET, is under construction and expected to be completed in 2021.
- Inside COMET hall, pion/muon transport system is under construction.
  - Transport solenoid is already completed. Other components, pion capture solenoid, detector solenoid *etc*., are under construction.

Current Status (1) — Facility Construction —

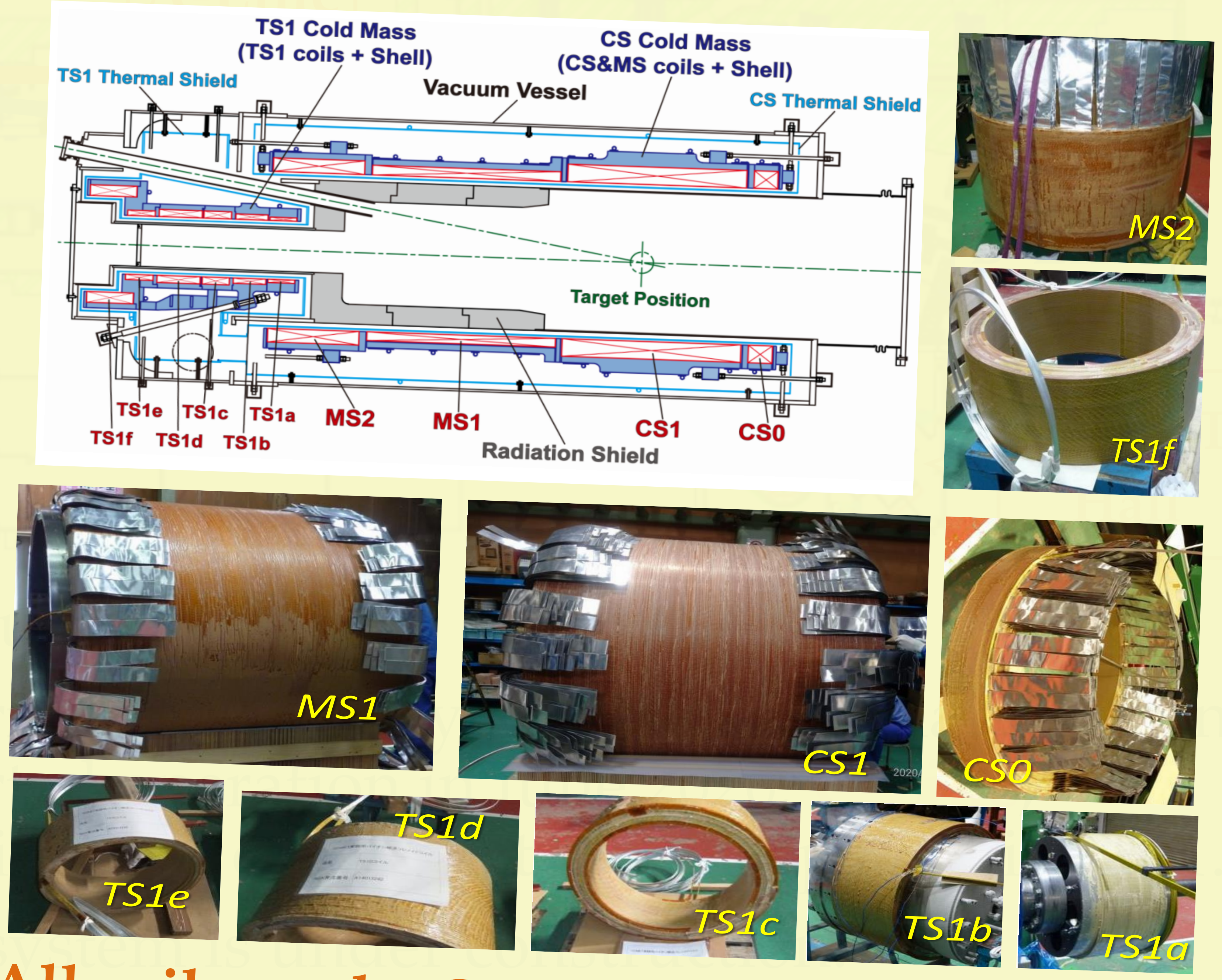


Proton Beam Line



B-Line, completed and in-operation.
C-Line, under construction and will be completed in 2021. First beam will be delivered to COMET hall in 2022.

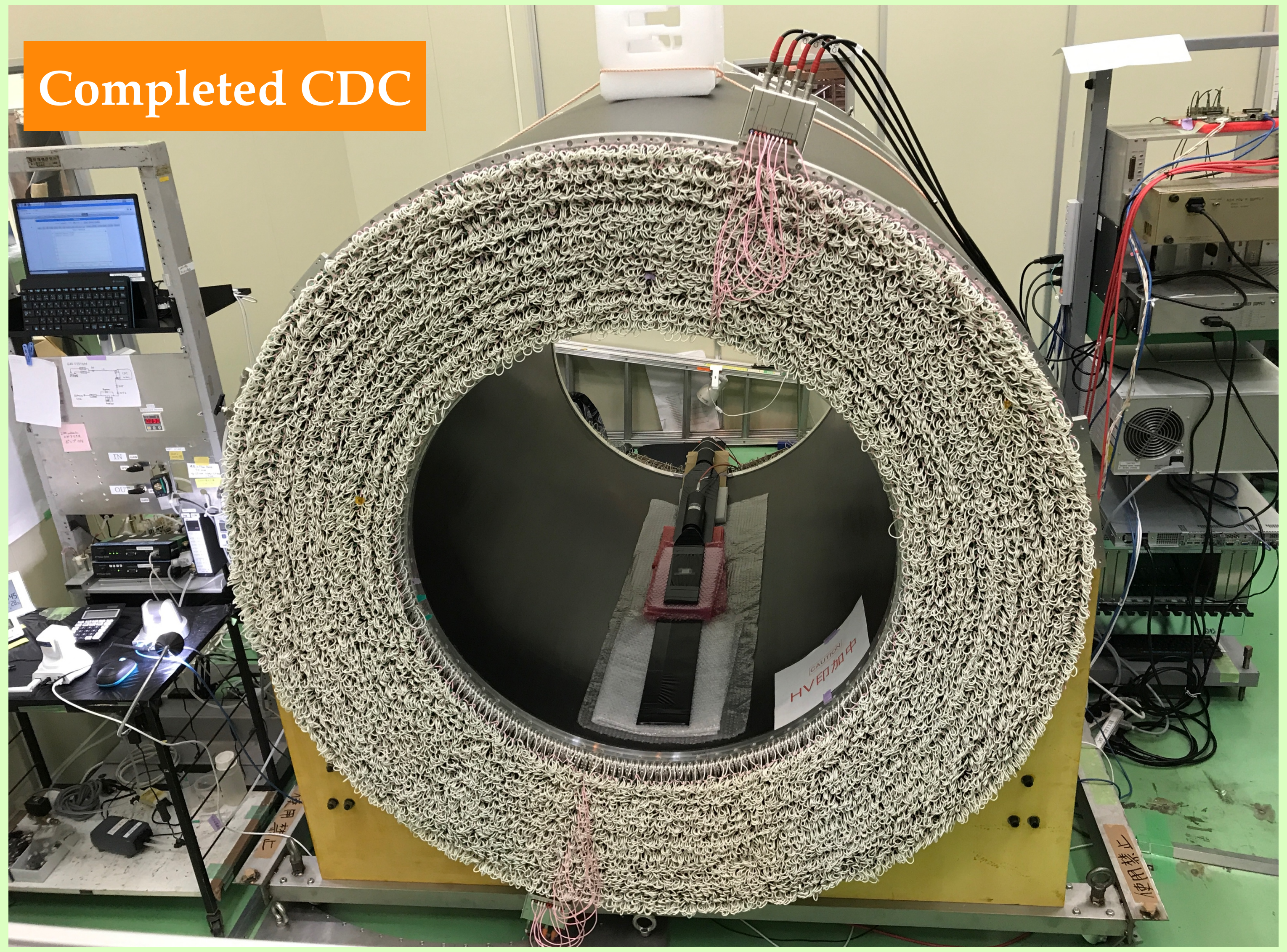
Pion Capture Solenoid

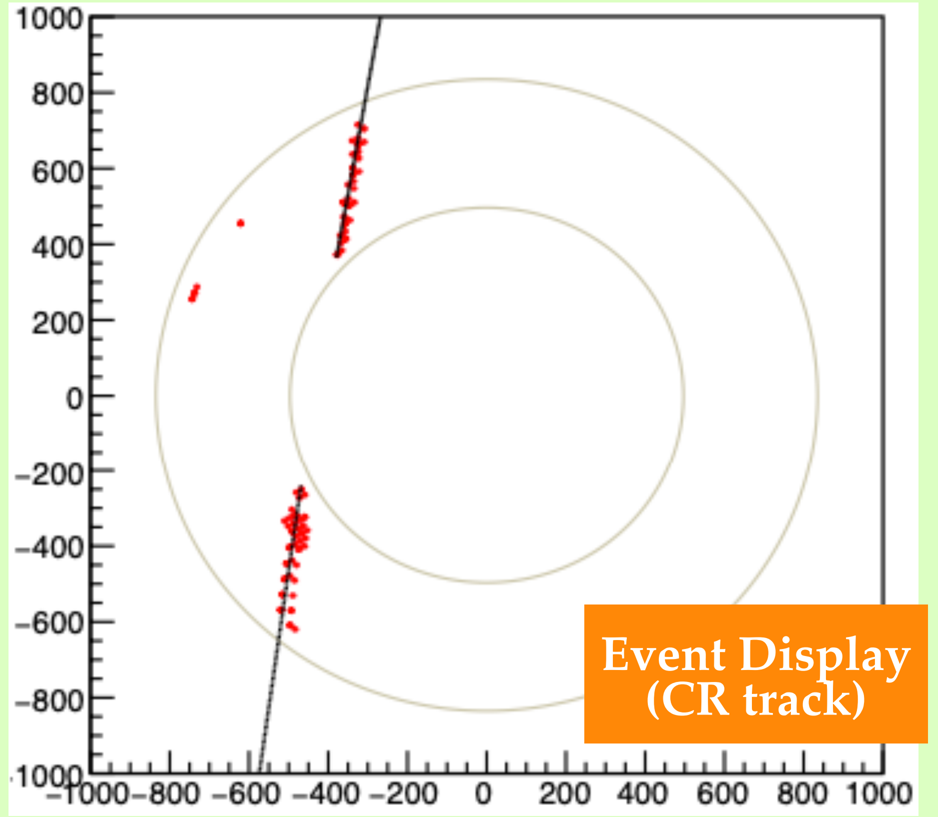


All coils ready. Construction for all parts started. Will be completed in 2022.

Current Status (3) — Detector Construction —

CyDet (for μ-e conv. search)

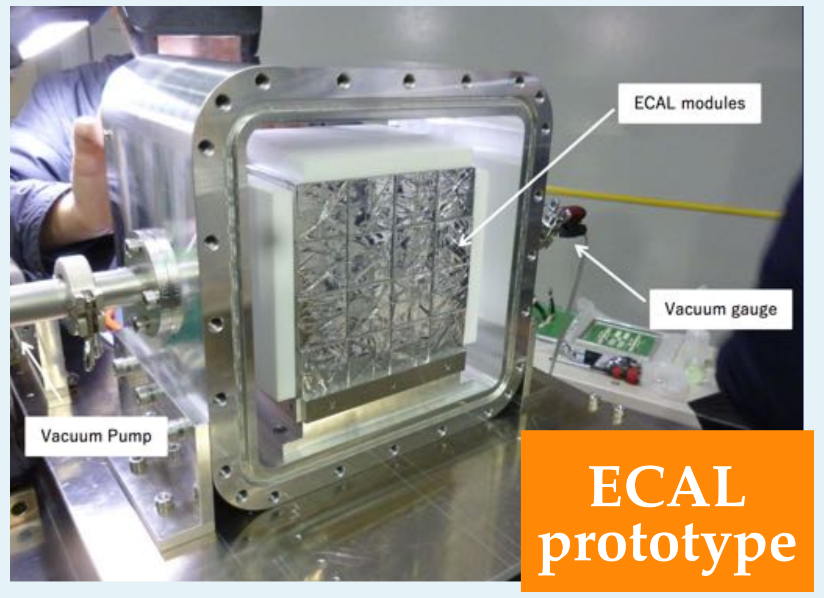




- CDC, completed and under commissioning with cosmic-ray.
- Trigger hodoscope is under development.

StrECAL (for beam measurement)

- Straw 1st station is under construction, will be completed soon.
- Five stations will be constructed in total.



- ECAL prototype successfully completed.
- Detector assembly will start soon.

Schedule

- Construction on all items are ongoing at a fast pace.
  - Facility;
    - Proton beam line. C-Line construction started and will be completed in 2021. First beam is expected in 2022.
    - Transport line (π/μ). Transport solenoid, completed. Pion capture will be completed in 2022. All parts will be ready in early 2023.
  - Detector;
    - CyDet. CDC, completed and under commissioning. Trigger hodoscope construction will follow.
    - StrECAL. Straw tracker, 1st station is under construction, and all five stations will be completed by 2022. ECAL, detector assembly will start soon and will be completed by 2022.
  - Accelerator;
    - Dedicated 8 GeV operation test was conducted in 2018. Good extinction was confirmed. Next test is under preparation.
- As soon as C-Line and radiation shield will be completed (expected in 2022), proton beam commissioning will start. It will be followed by the engineering and physics runs of COMET Phase-I.

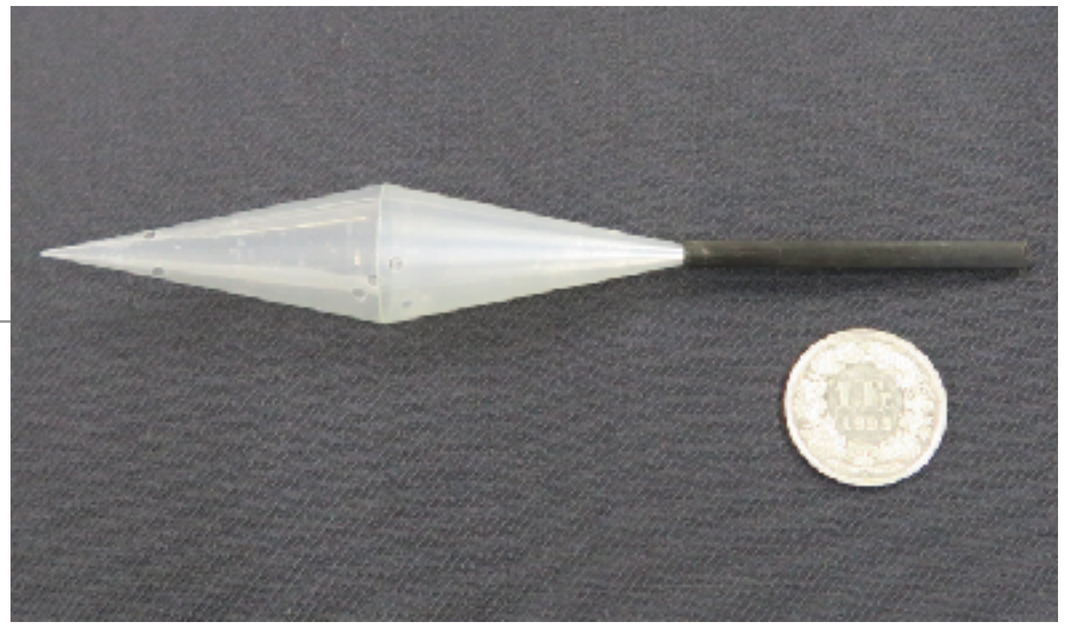
Summary of COMET Phase-I & Phase-II

	COMET-Phase-I	COMET-Phase-II
experiment starts (*)	in ~2023	Ready in 3 years after Phase-I completion
beam power	3.2kW (8GeV, 400nA)	56kW (8GeV, 7μA)
running time	150 days	2.0 x 10^7 (sec)
# of protons	3.0 x 10^(19)	8.5 x 10^(20)
# of muon stops	1.5 x 10^(16)	2.0 x 10^(18)
muon rate	5.8 x 10^9	1.0 x 10^(11)
# of muon stops / proton	0.00052	0.00052
# of BG	0.02	0.3
S.E.S.	3.1 x 10^(-15)	2.6 x 10^(-17)
U.L. (90%CL.)	7.0 x 10^(-15)	6.0 x 10^(-17)

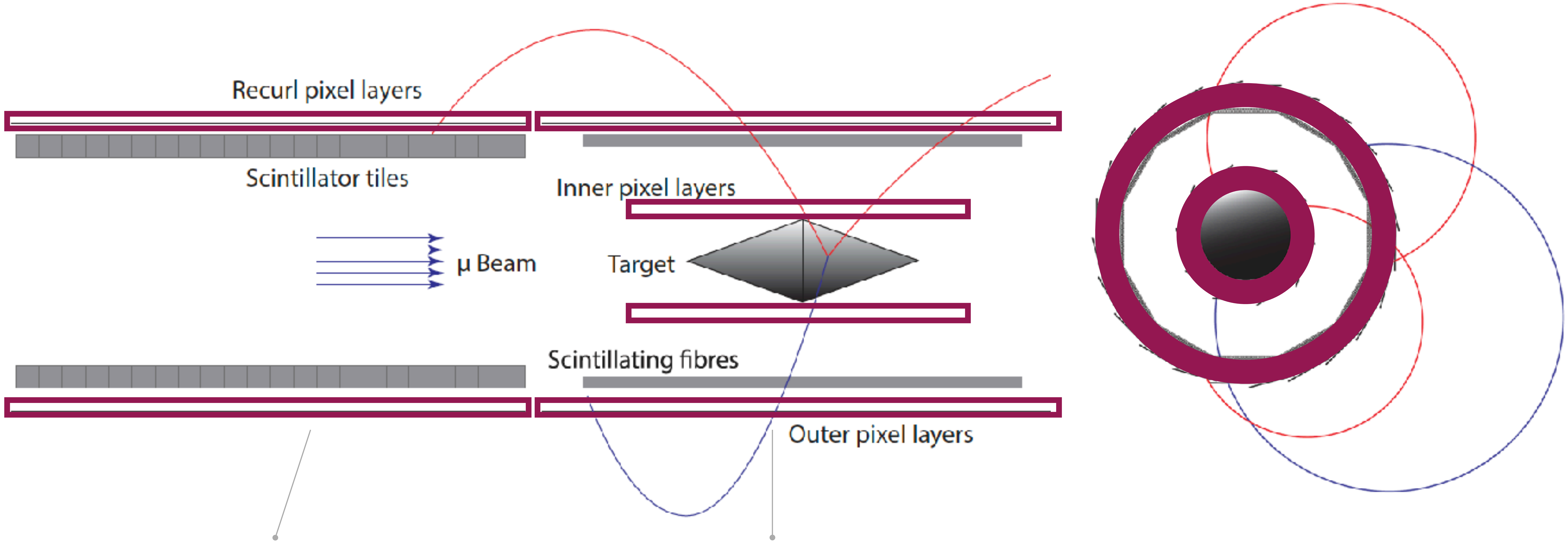
* including the engineering run

MU3E

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%



Re-curl stations **Central stations**

Most recent News

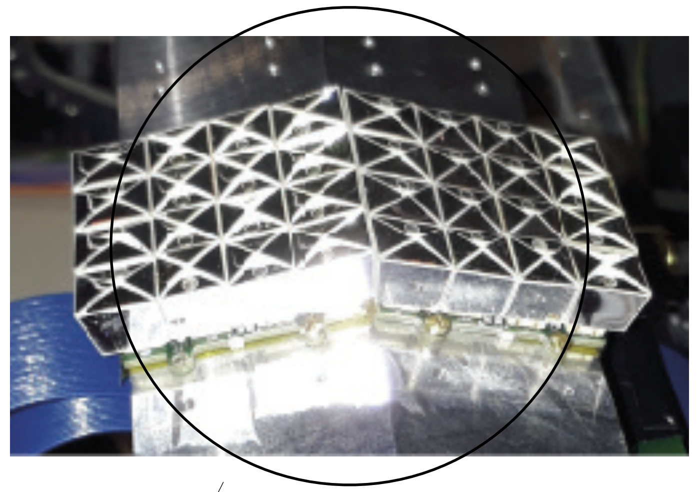
- Magnet from Cryogenic just arrived at PSI: The construction phase of the experiment has started!
- Field Intensity: 1T; Field description: dB/B ≤ 10^{-4}; Field stability: dB/B(100 d) ≤ 10^{-4}

The Mu3e experiment: R&D completed. Construction phase

News: Detector slice test beam foreseen at the end of the year at PSI

Superconducting solenoid Magnet

Homogeneous field 1T

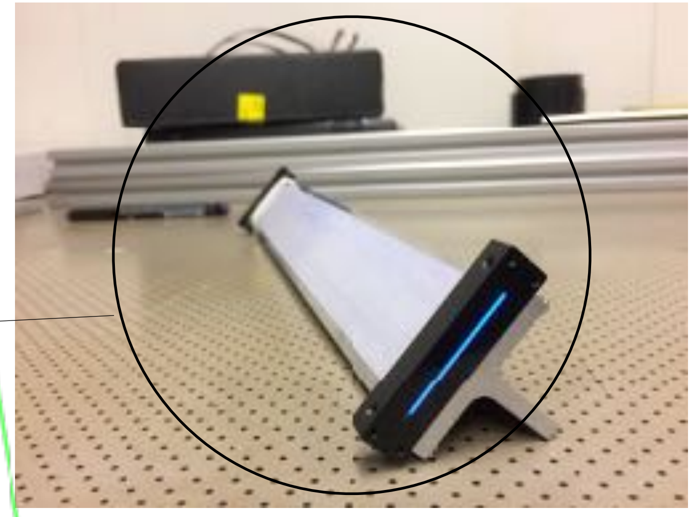


Tile detector

70 ps resolution w/ single hit

Fibre hodoscope

< 500 ps resolution w/ multi hits thickness: < 0.3% X_0



MIDAS DAQ and Slow Control

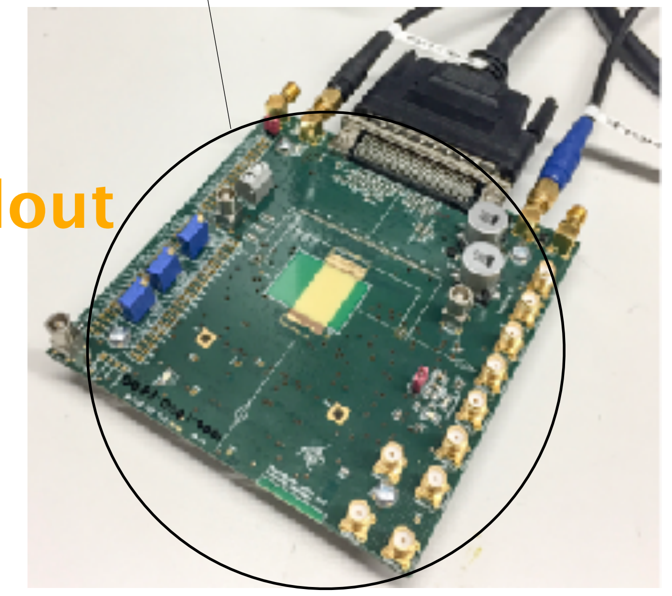
Run, history, alarms, HV etc.

Muon Beam and target

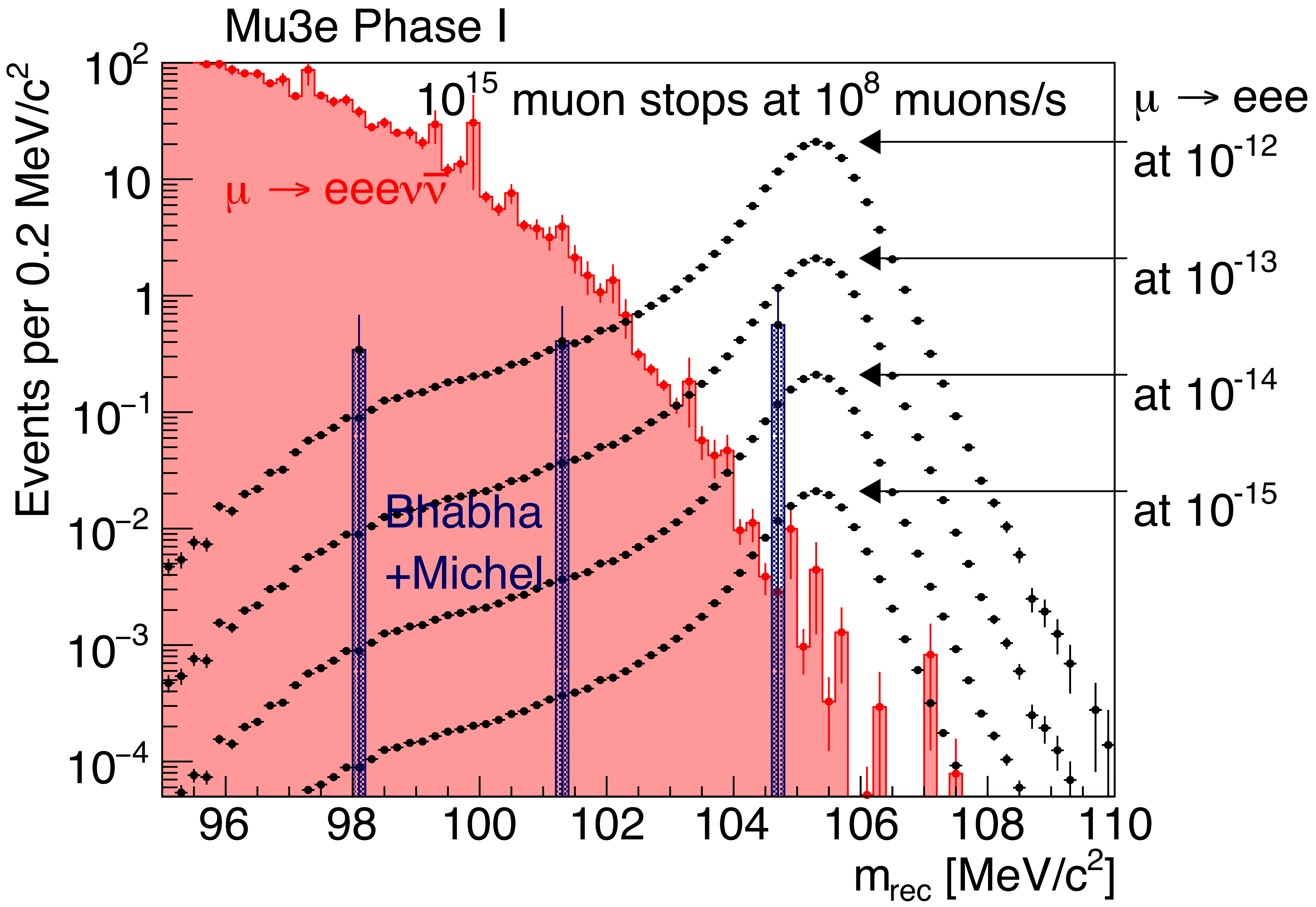
Full available beam intensity O(10^8)

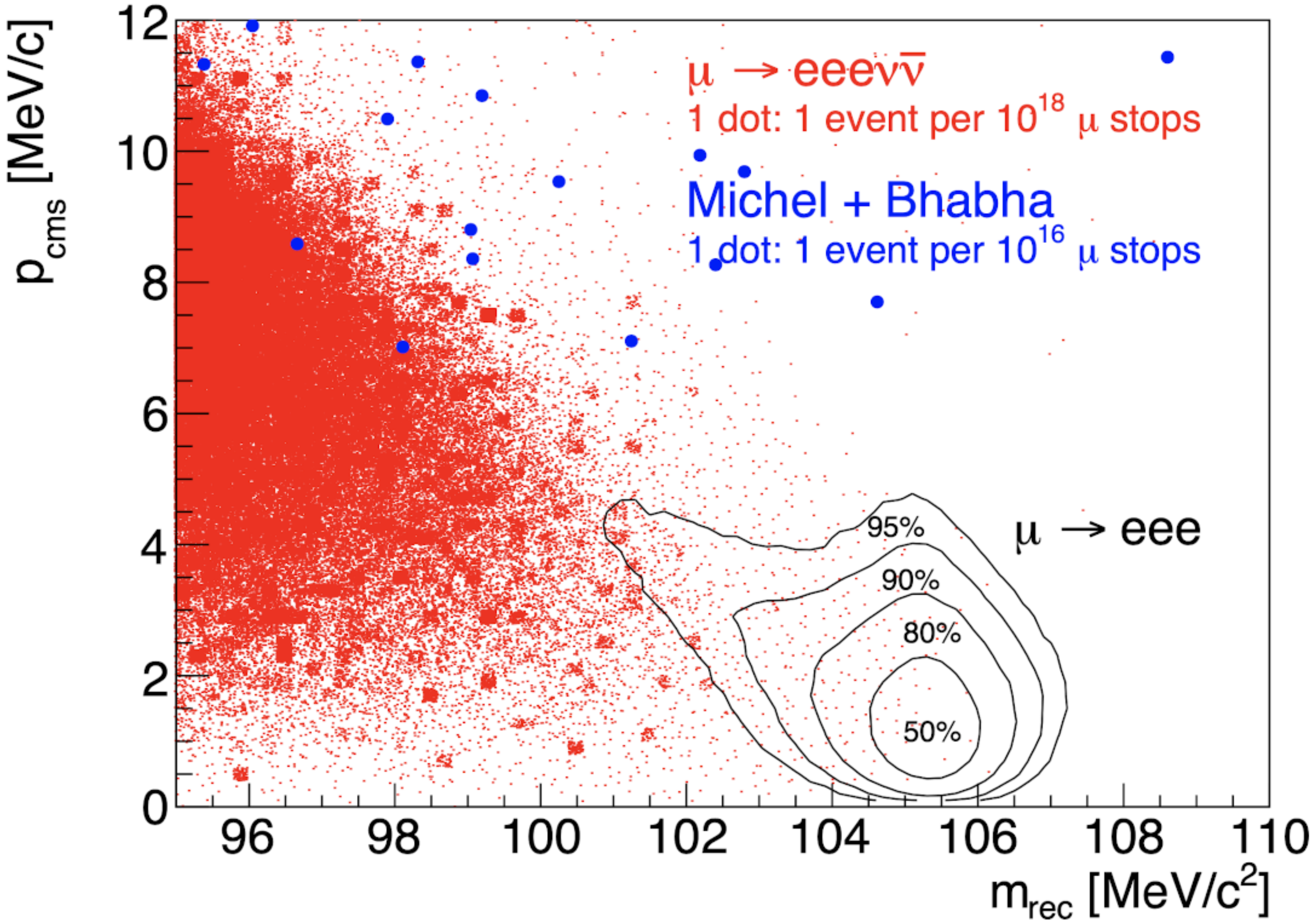
Mupix detector

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



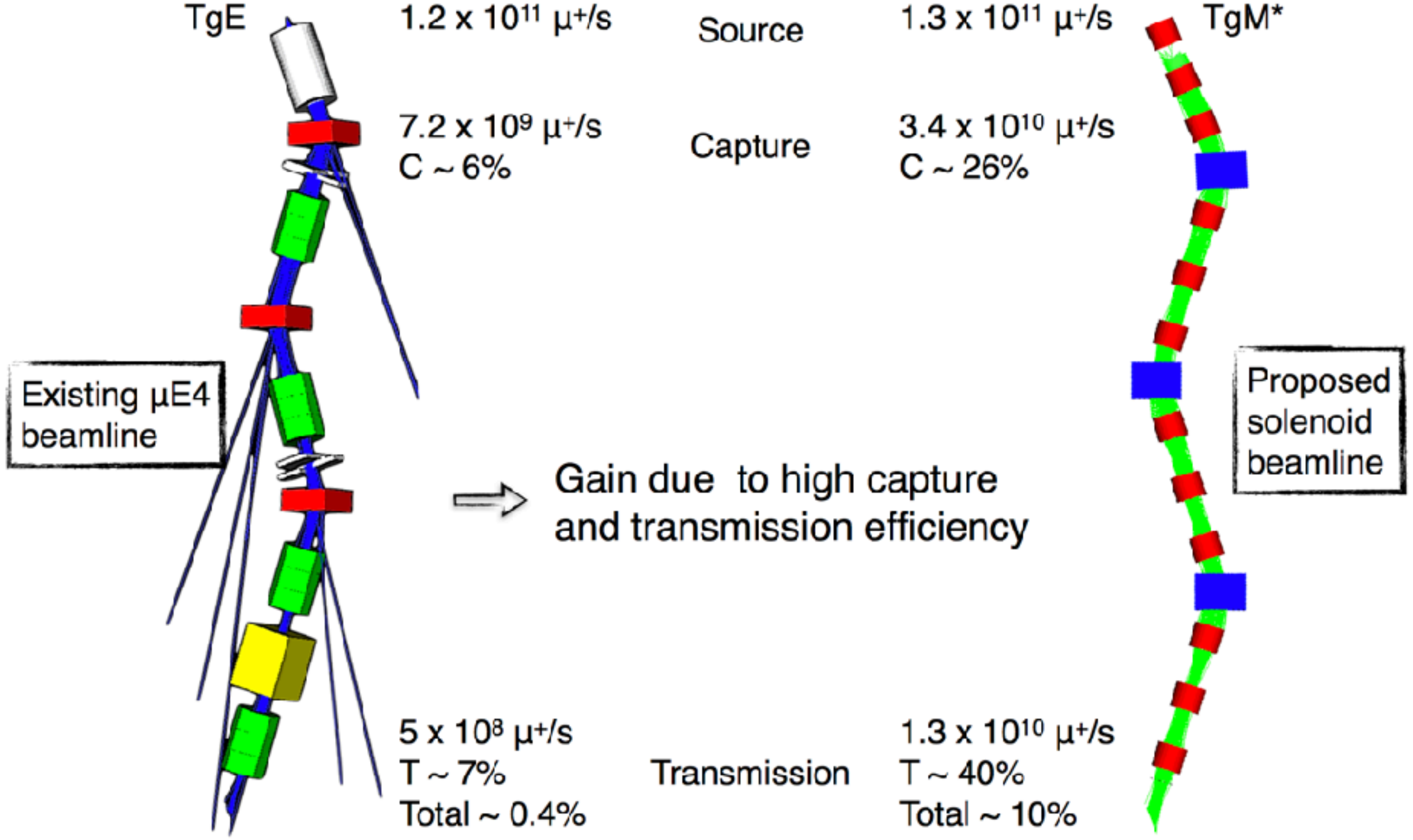
How we detect $\mu^+ \to e^+ e^- e^+$





The High intensity Muon Beam (HiMB) project at PSI

- Beam line optimisation
  - **Increased capture and transmission**



- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Strategy:
  - Target optimization
  - Beam line optimization
- Time schedule: **O(2025)**

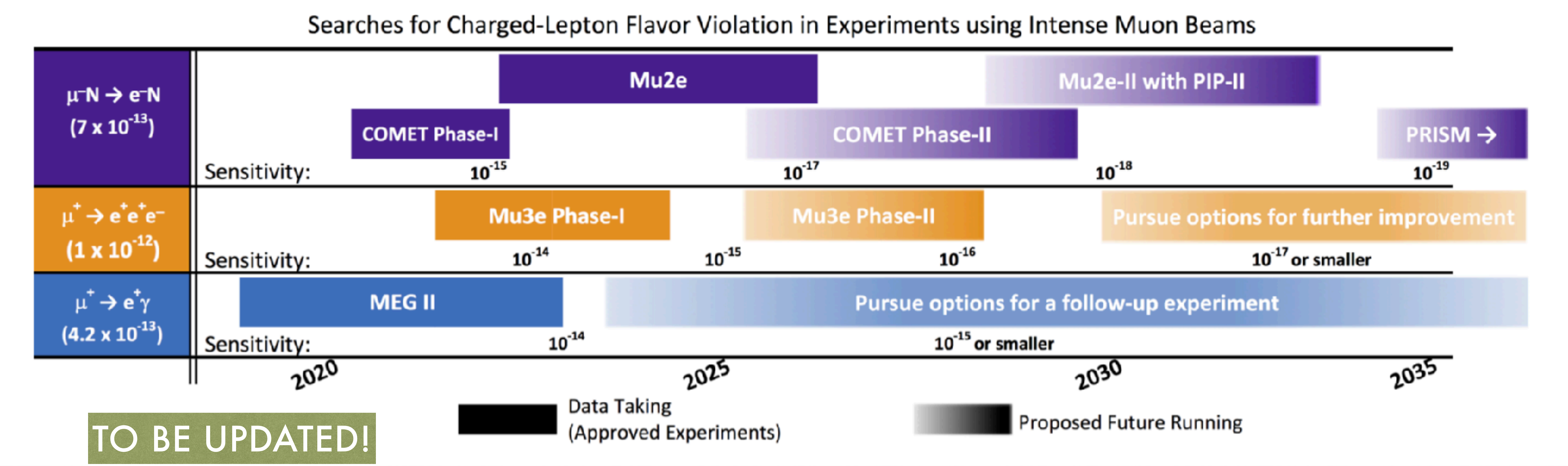
MU3E NEEDS HIMB

$\mu \to e\gamma$ EXPERIMENT BEYOND MEG II?

- Put into perspective the beam line optimisation the equivalent beam power would be of the order of **several tens of MW**

CONCLUSION

- We will see the most exciting decade to come for CLFV searches.



Submission for European Strategy Update, arXiv:1812.0654