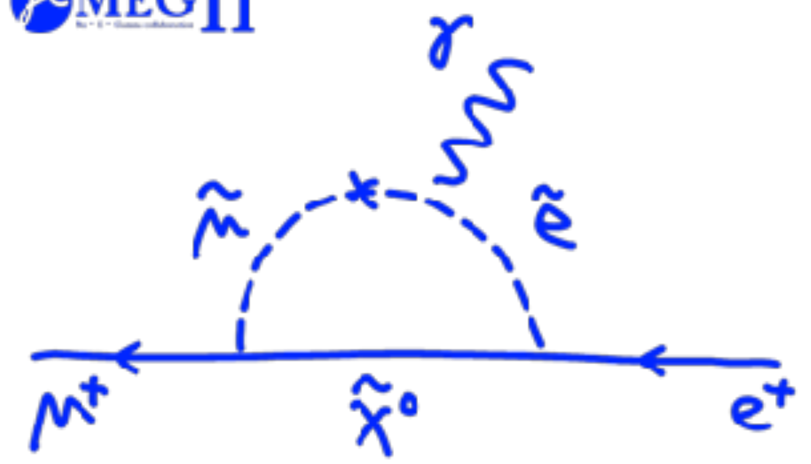
レプトンフレーバーを破るミュー粒子稀崩壊探索実験MEG II 最初の結果

東京大学　素粒子物理国際研究センター

岩本敏幸　他MEG II コラボレーション



2023年9月18日

日本物理学会2023年第78回年次大会 東北大学

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にむけて

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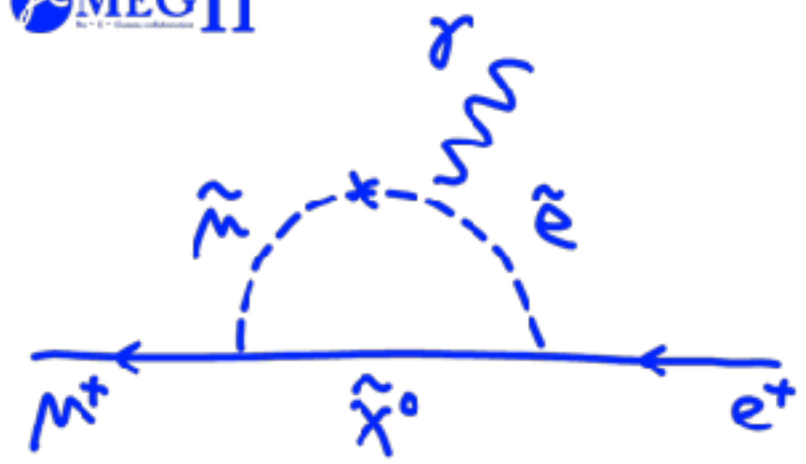
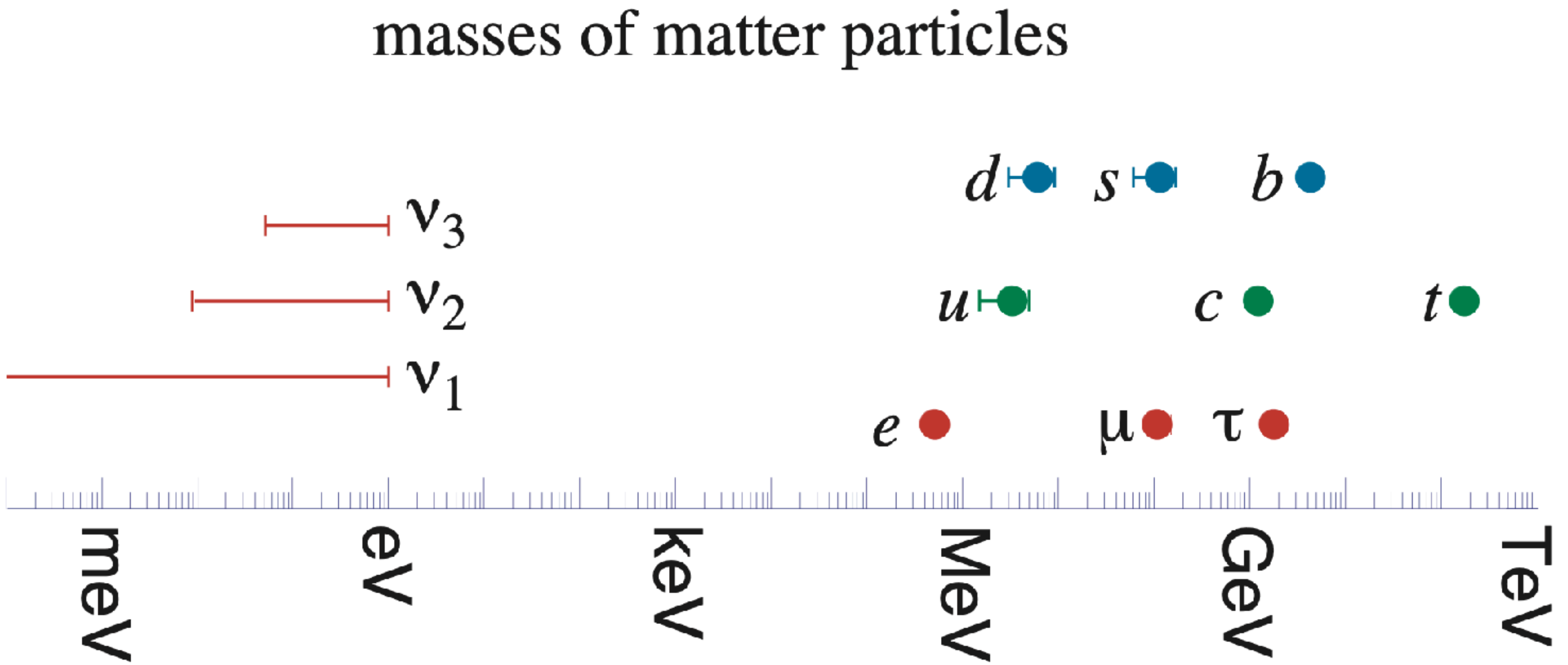


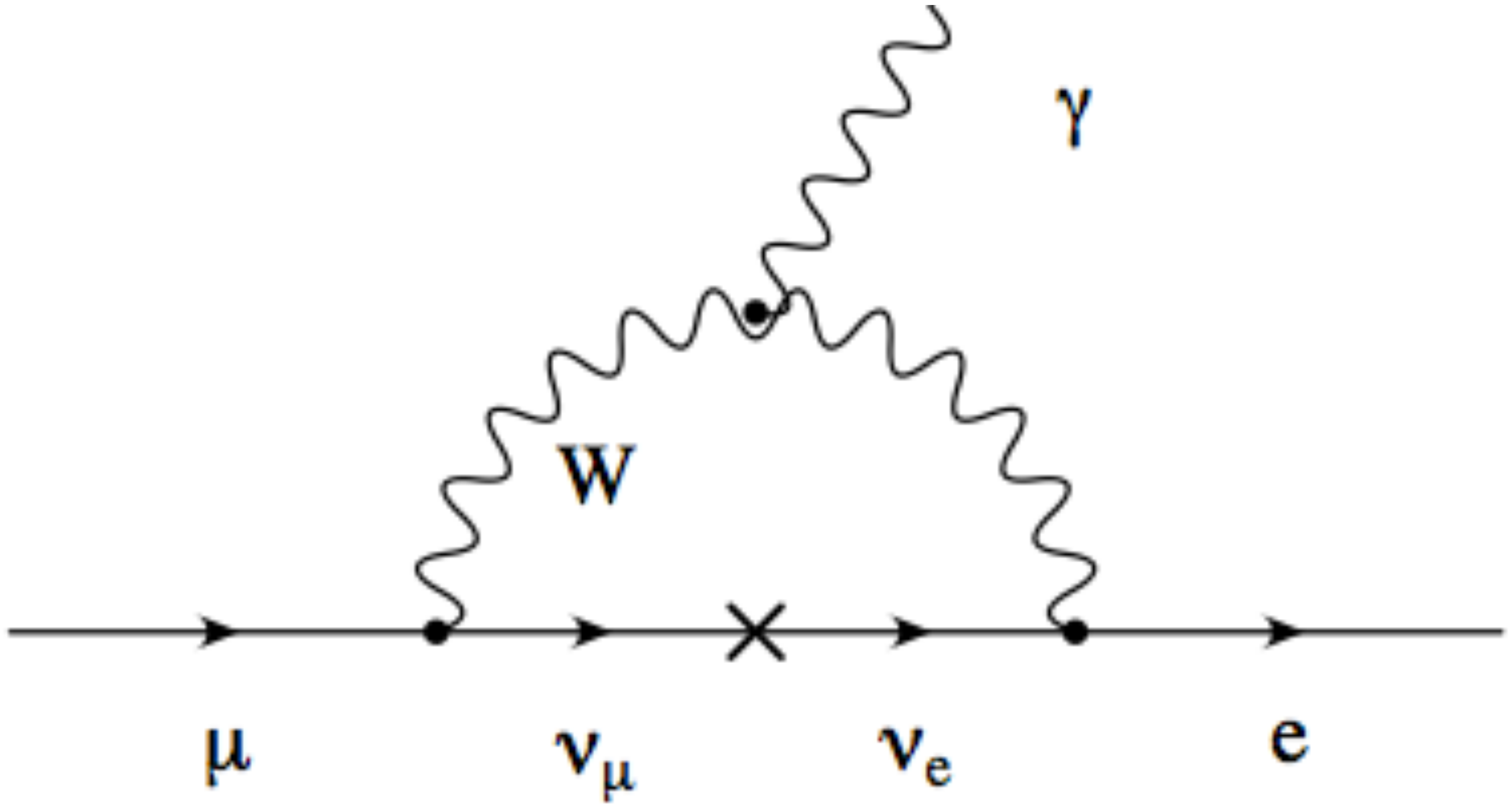
Charged lepton flavor violation

- There are three generations (flavors), but the reason remains a mystery
- Flavor transition in Quark and in neutrino has played a decisive role in the development of particle physics
- No observation yet for the charged lepton flavor transition



arXiv:1205.2671

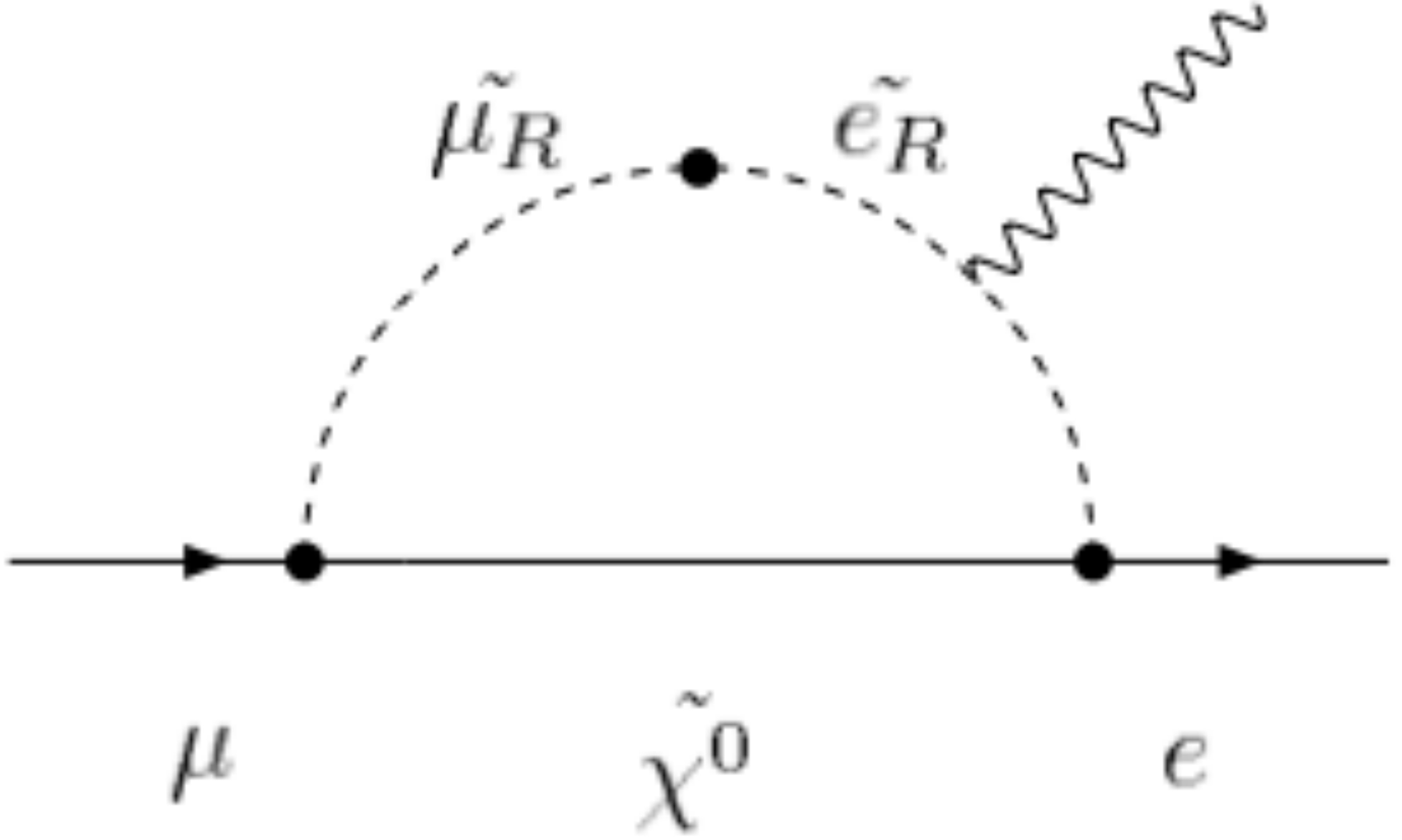
Standard model (with ν mass) vs New physics



$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi}\left|\sum_{k=1,3}\frac{U_{\mu k}U^*_{ek}m^2_{\nu_k}}{M^2_W}\right|^2$$

$$\sim 10^{-54}$$

Neutrino is too light

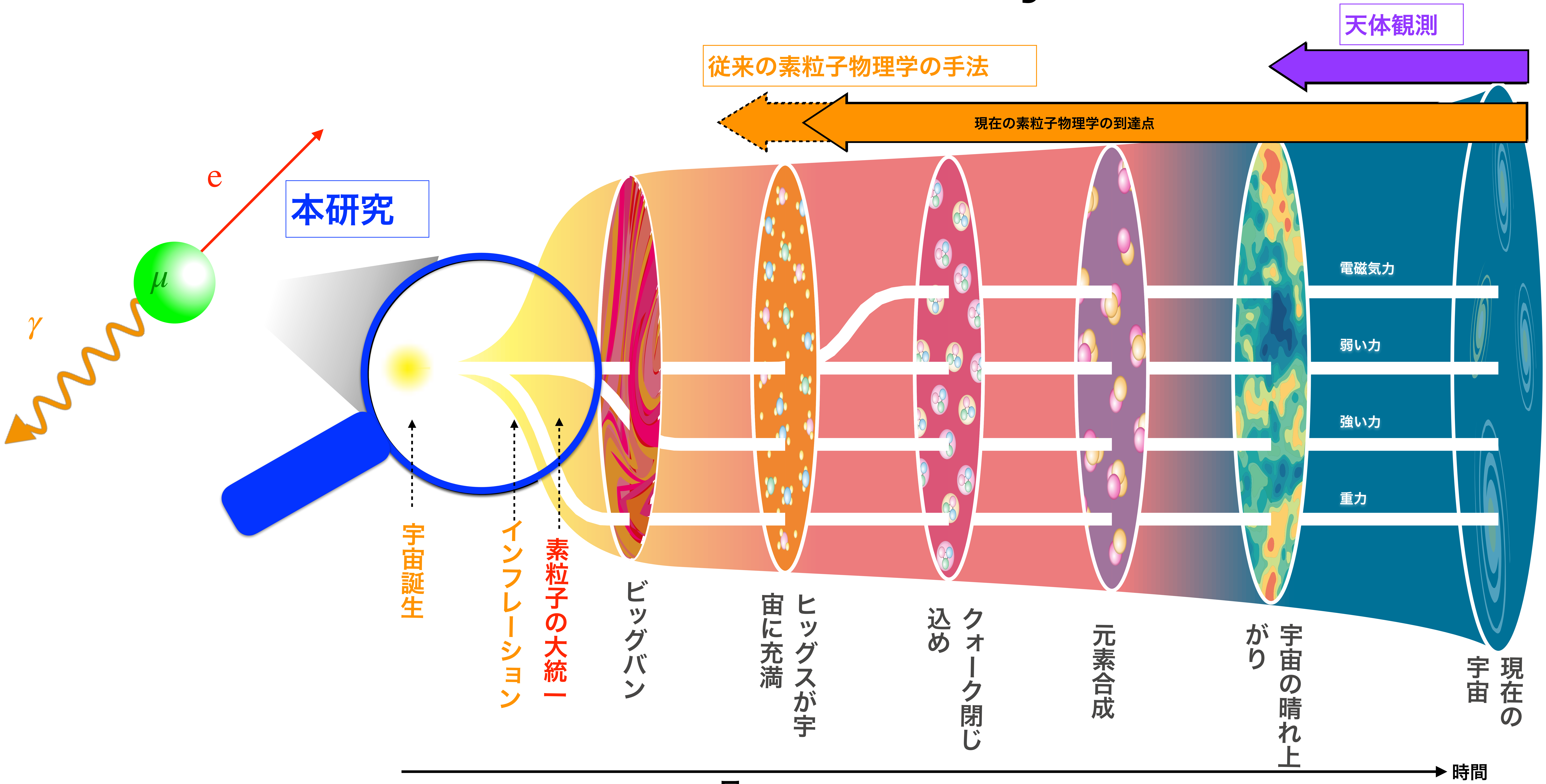


New particles from SUSY in the loop can enhance the branching ratio

SUSY-GUT / SUSY-seesaw

Evidence of $\mu^+ \to e^+\gamma$ = Evidence of new physics

Grand unification and early Universe

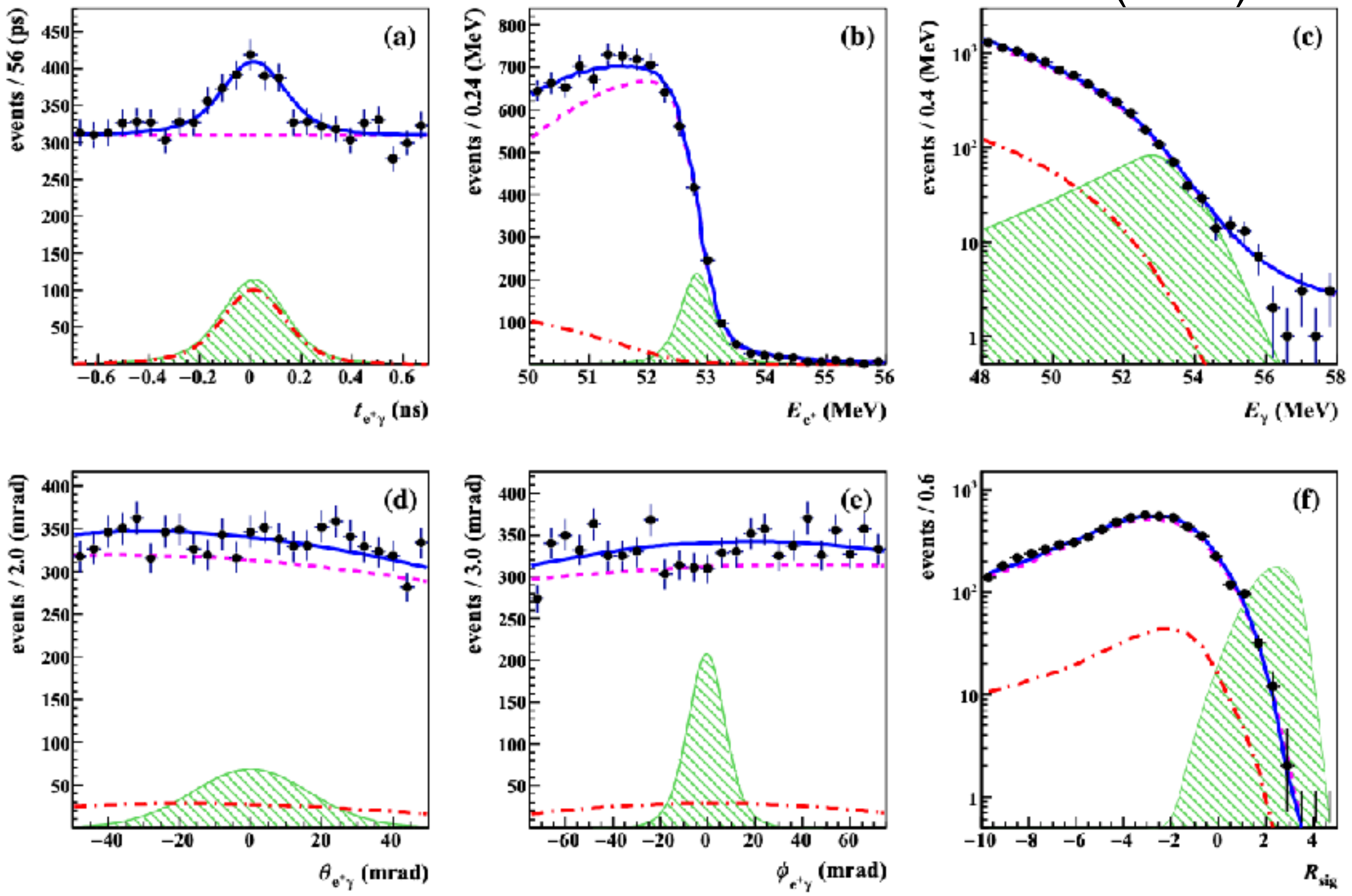


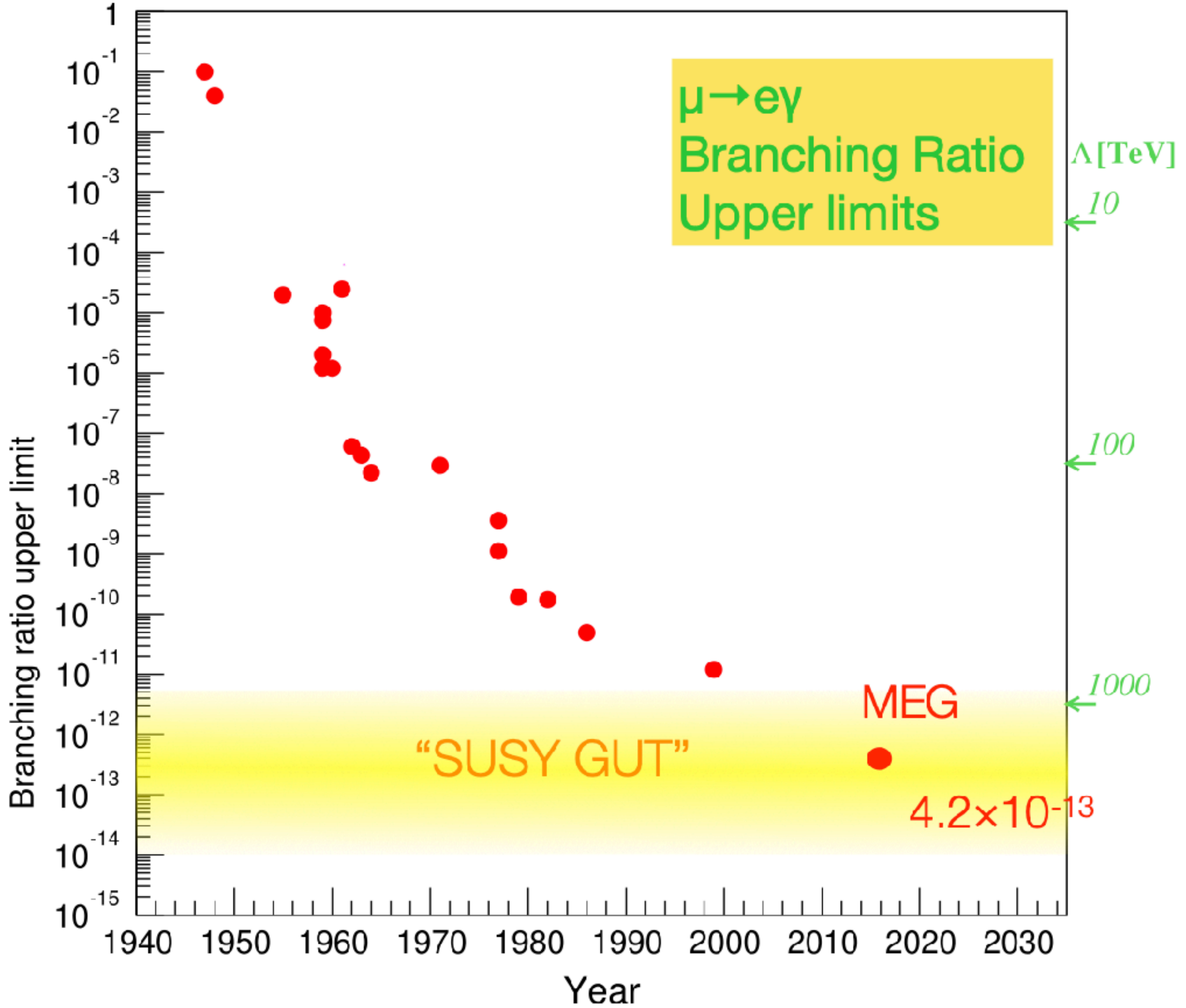
Current best limit for $\mu \to e\gamma$

MEG experiment final result in 2016

- 7.5×10^{14} stopped μ on target
- Br($\mu \to e\gamma$) $< 4.2 \times 10^{-13}$ @90%CL
  - Sensitivity : 5.3×10^{-13}
- Sensitivity is limited by detector resolutions

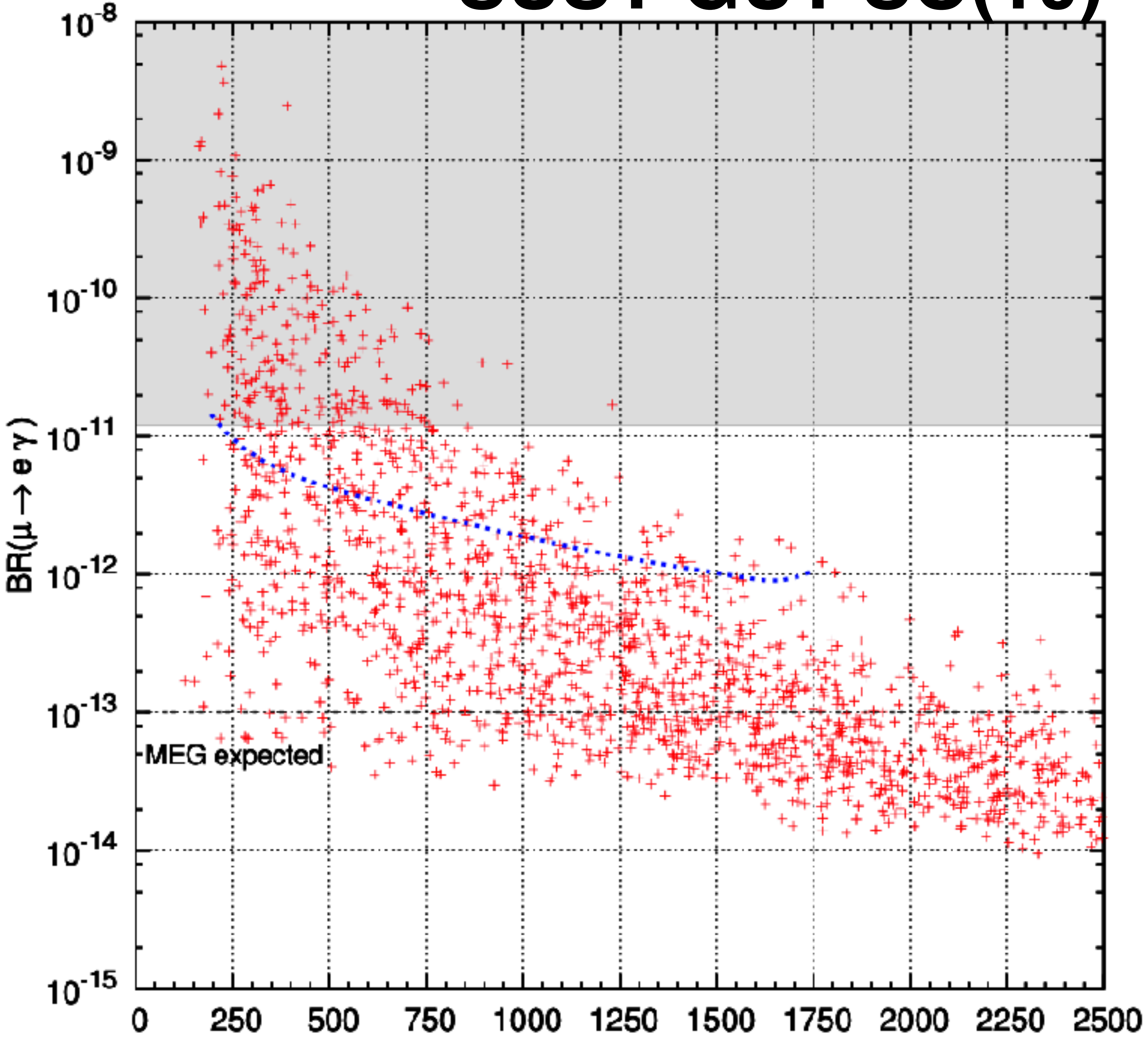
EPJC 76(2016)434





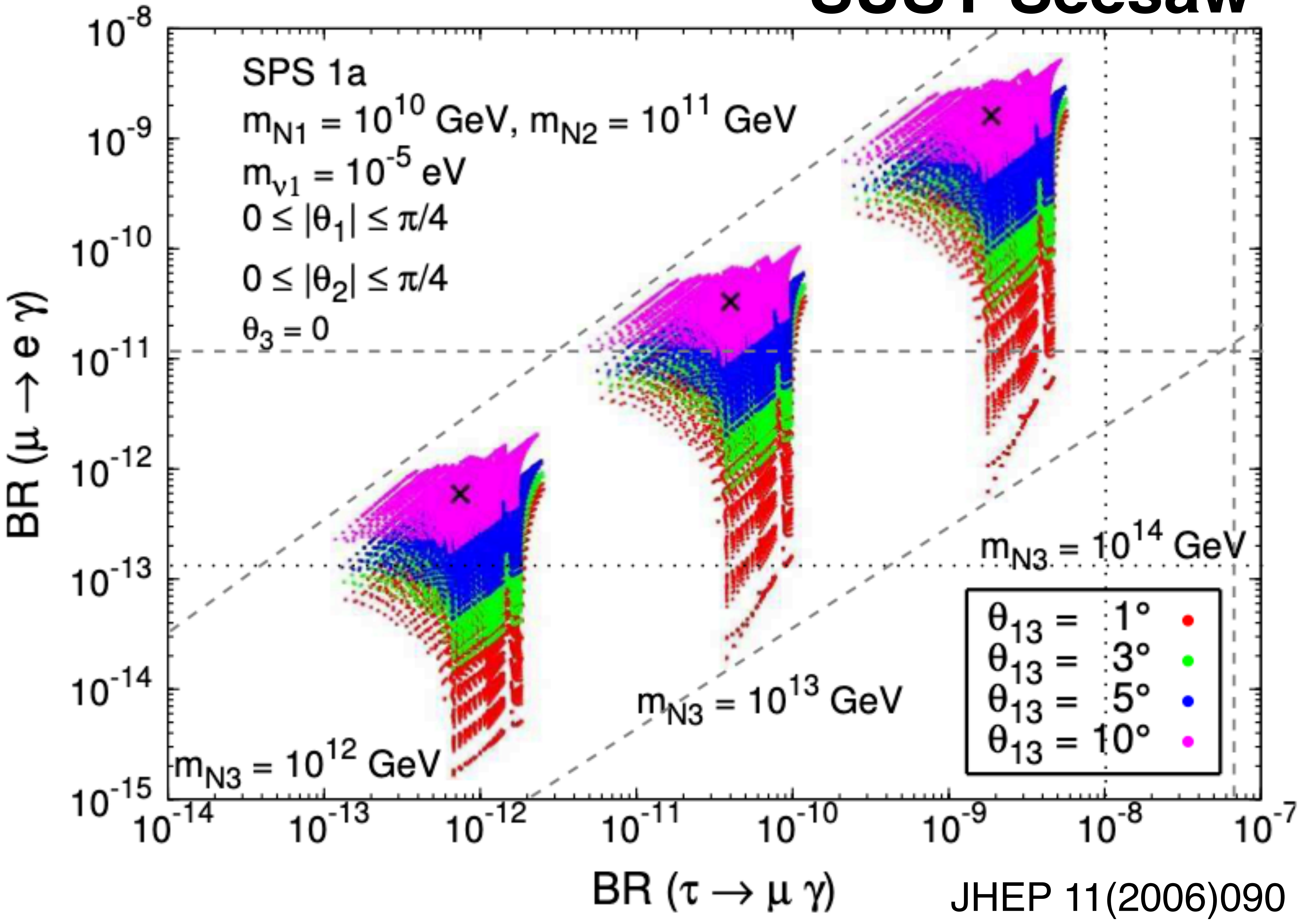
μ→eγ expectation from new physics

SUSY-GUT SO(10)



JHEP 0912(2009)057

SUSY-Seesaw

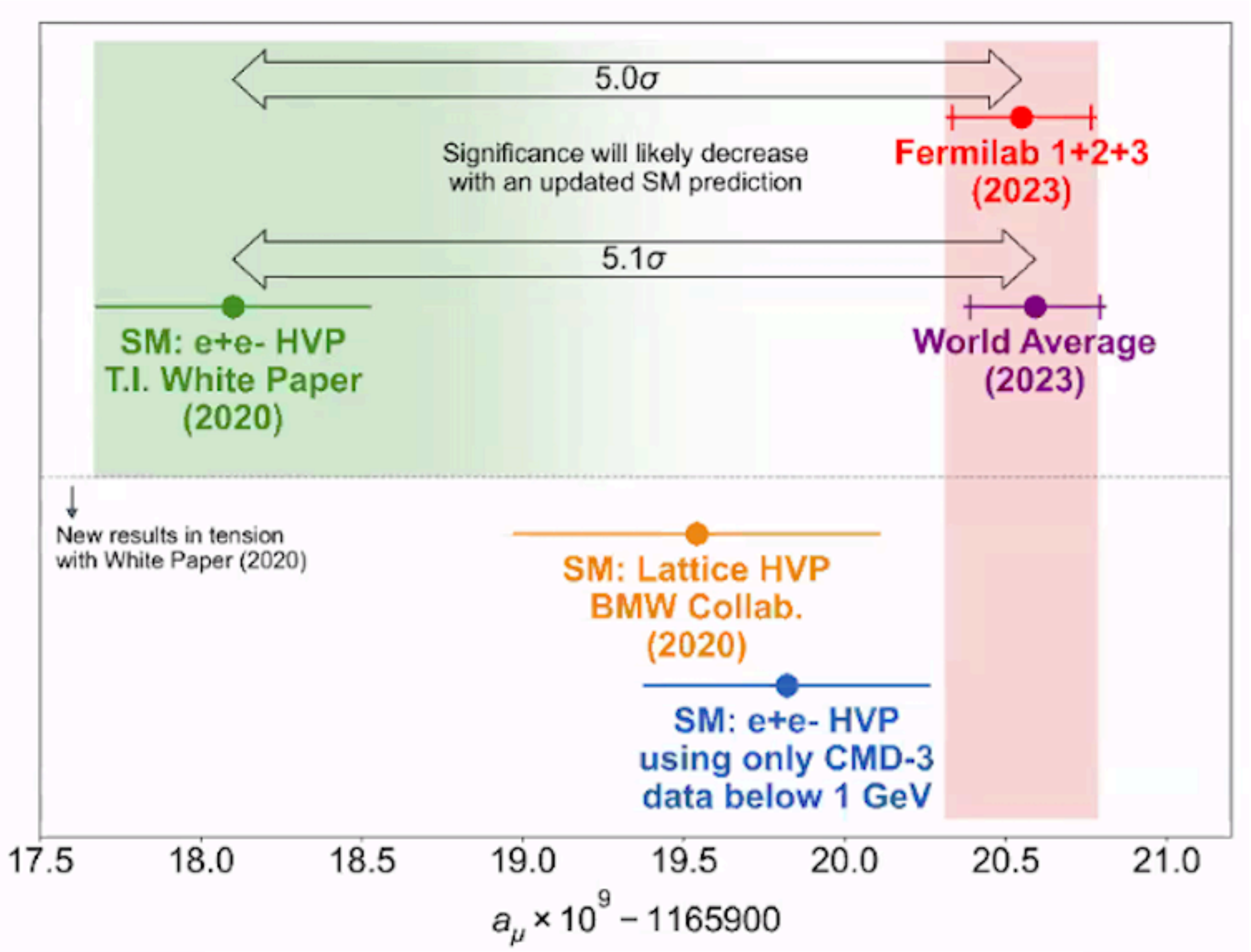


JHEP 11(2006)090

Real chance for discovery

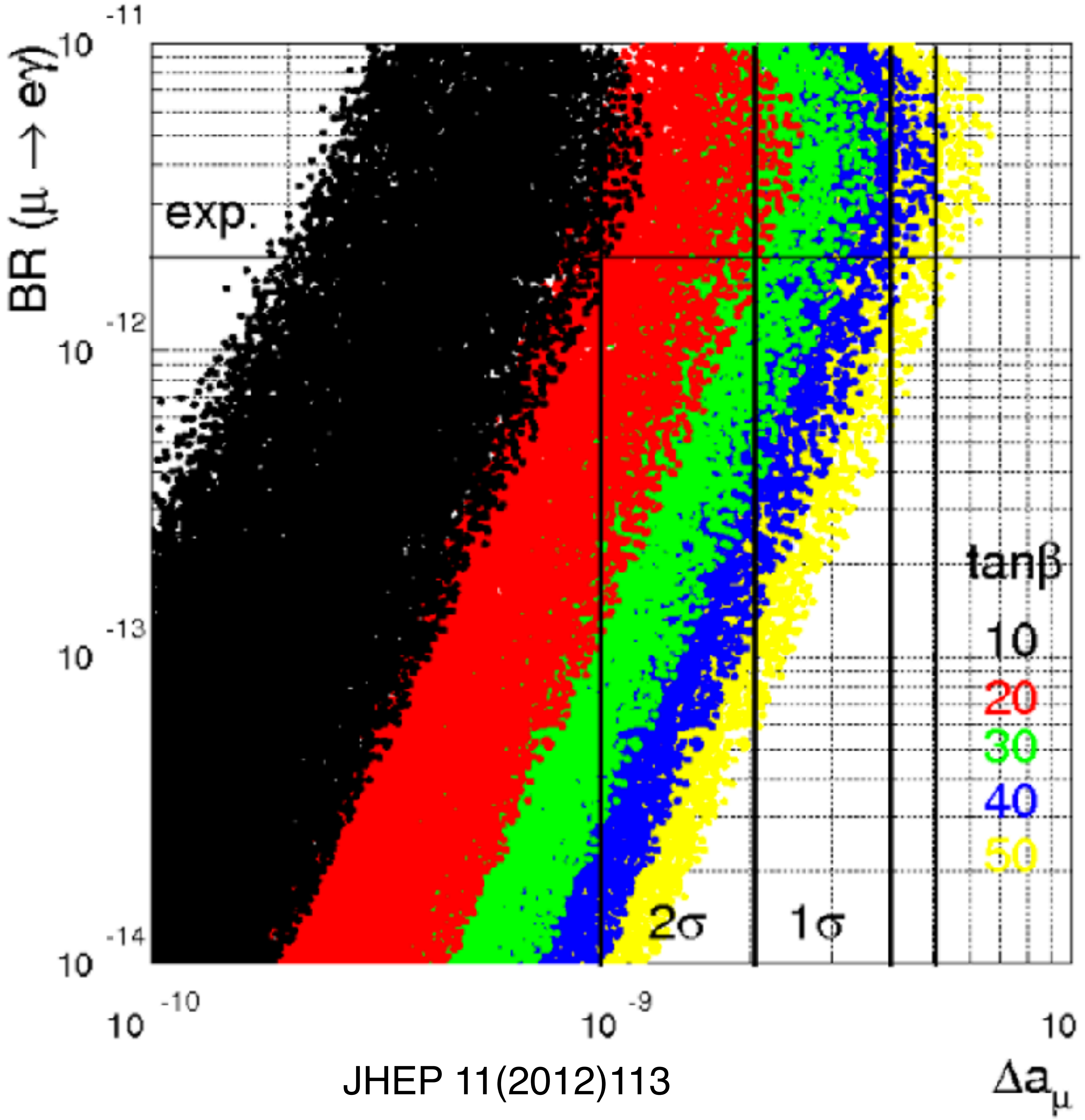
Already some regions from theoretical expectation excluded

CLFV with other indications



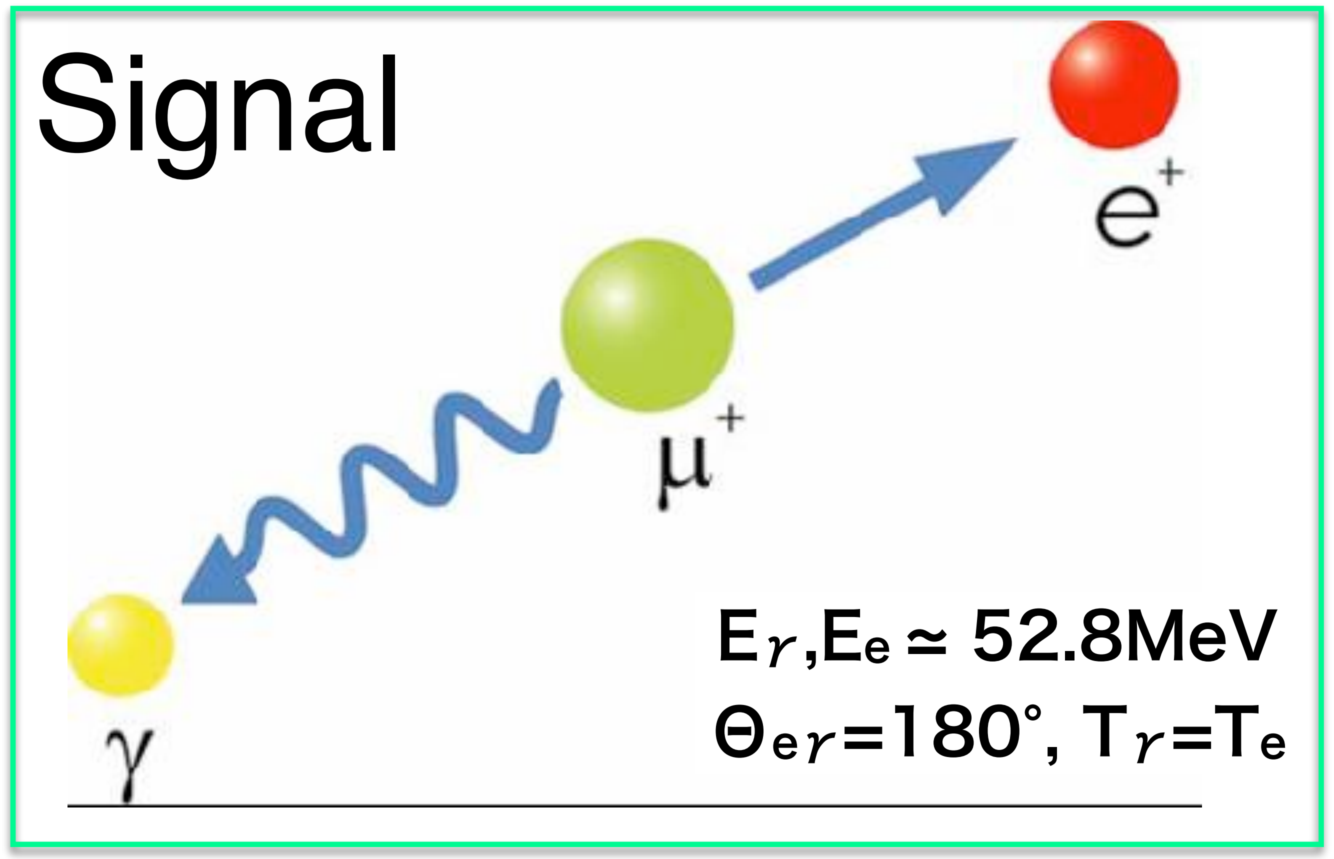
Disclaimer from A. Keshavarzi's Lattice 2023 talk:

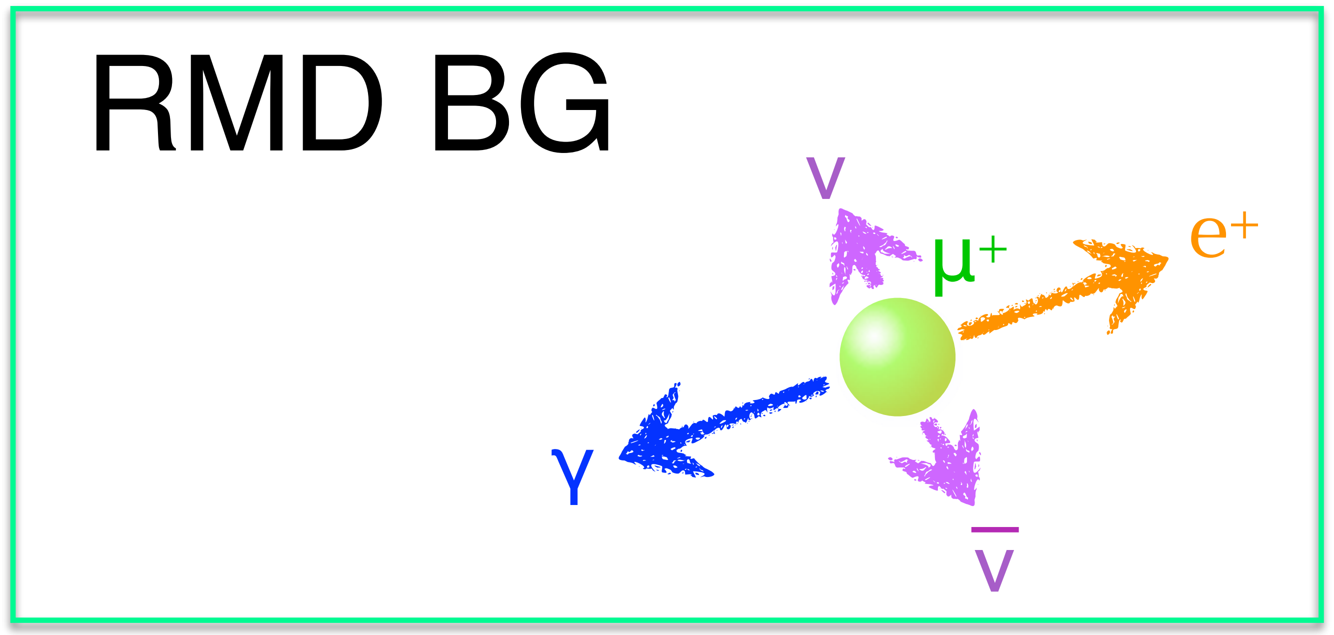
IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → <u>should not be taken as final!</u>

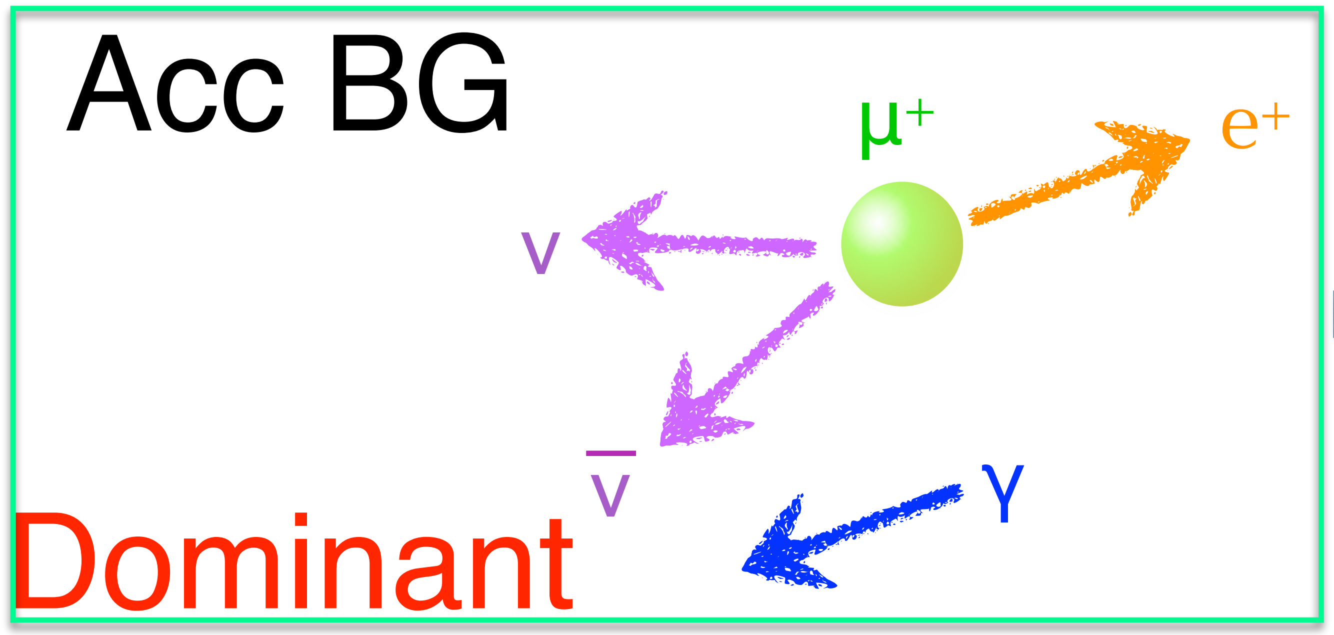


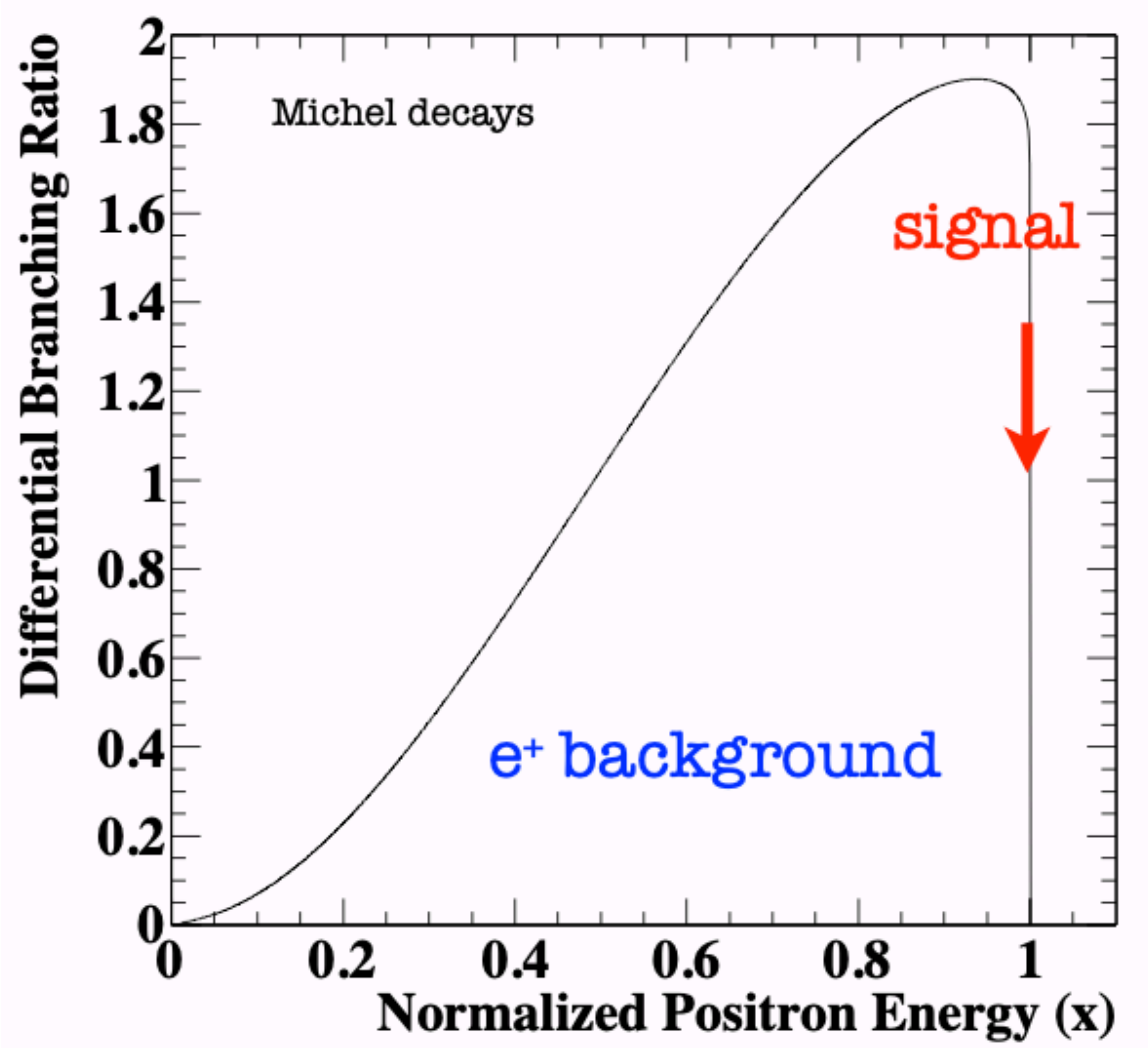
JHEP 11(2012)113

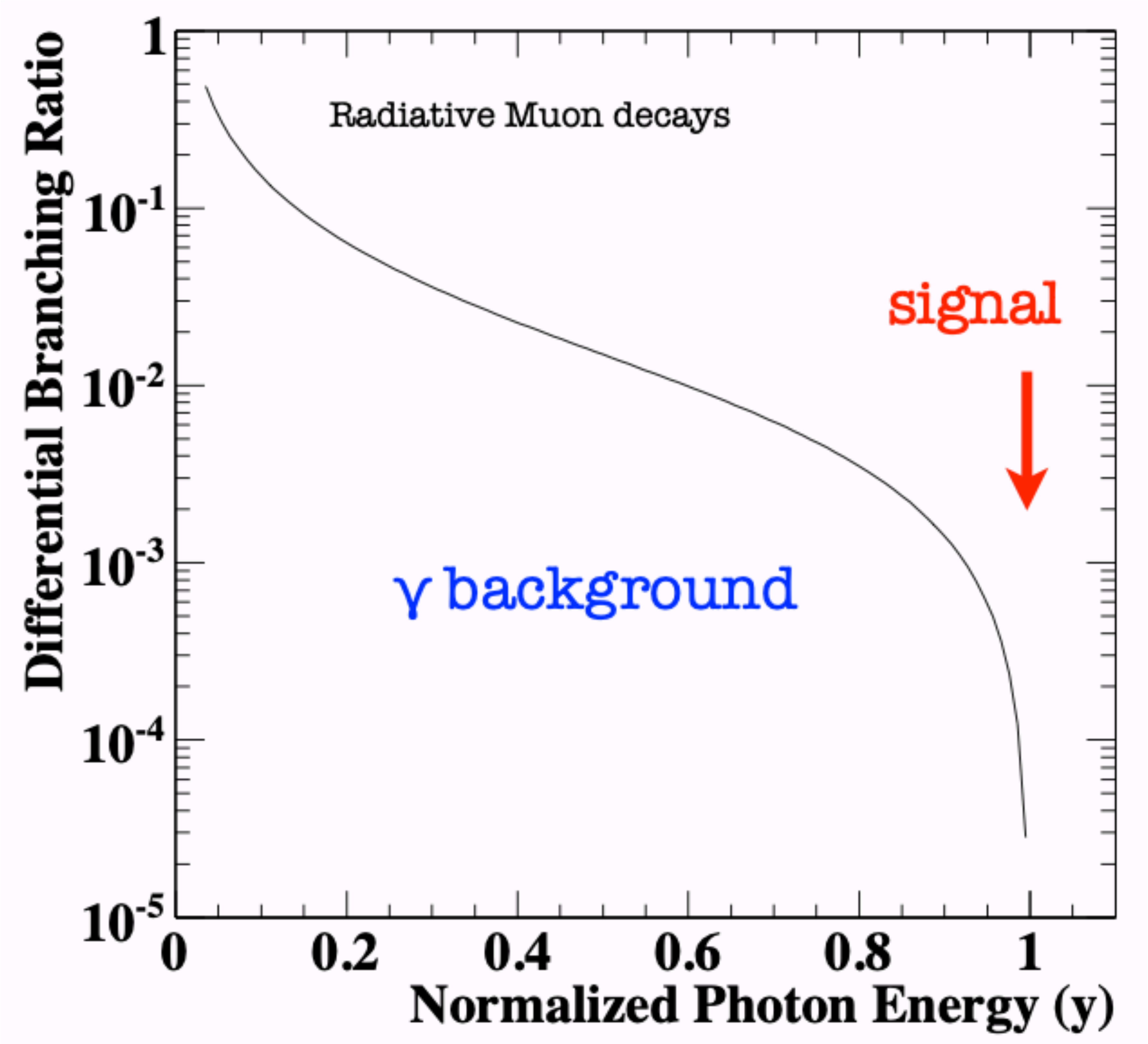
$\mu^+ \rightarrow e^+\gamma$ signal and backgrounds











$N_{Sig} \propto R_\mu \times T \times Br(\mu \rightarrow e\gamma) \times \varepsilon$

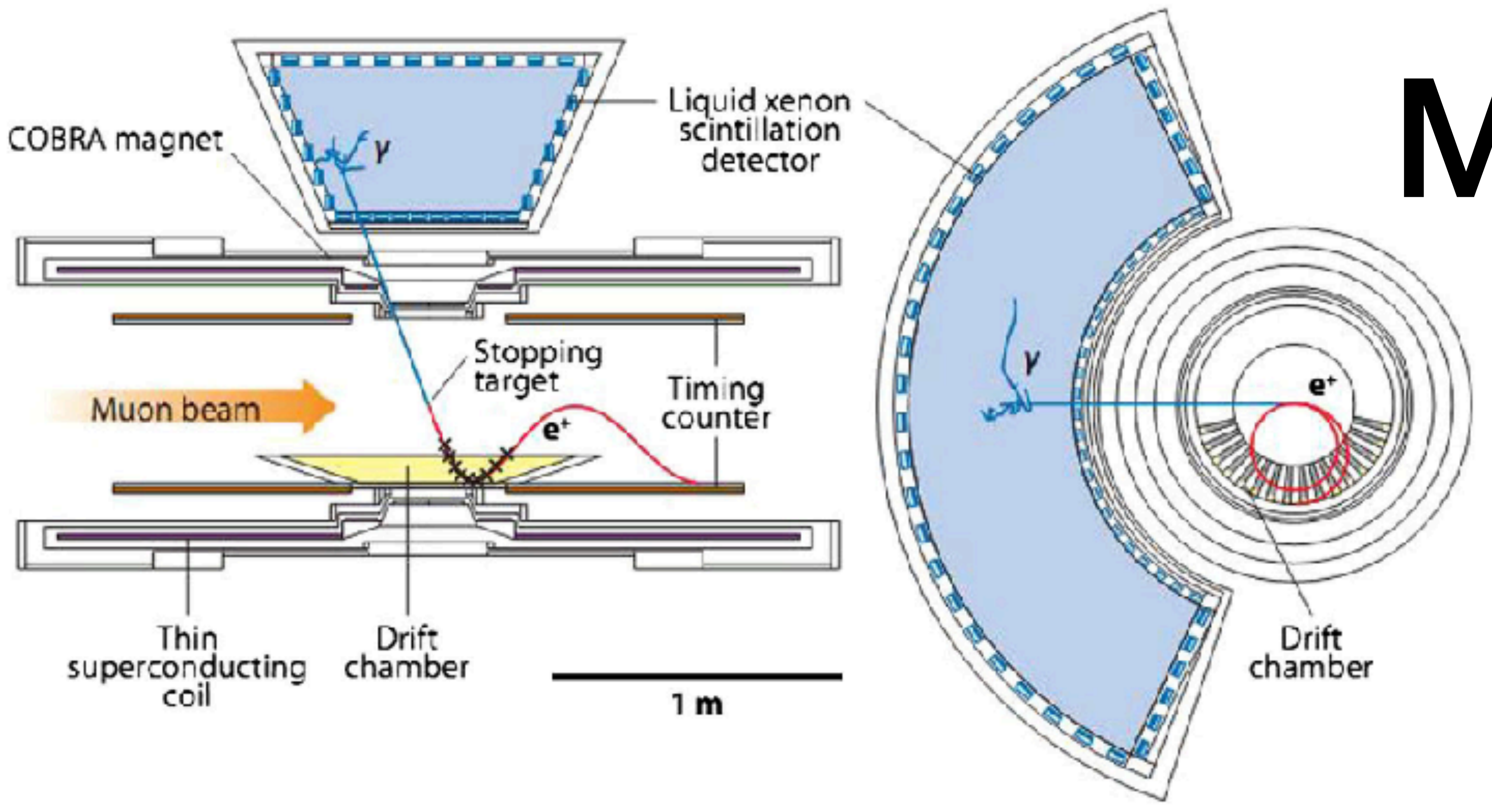
Efficiency crucial for statistics

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

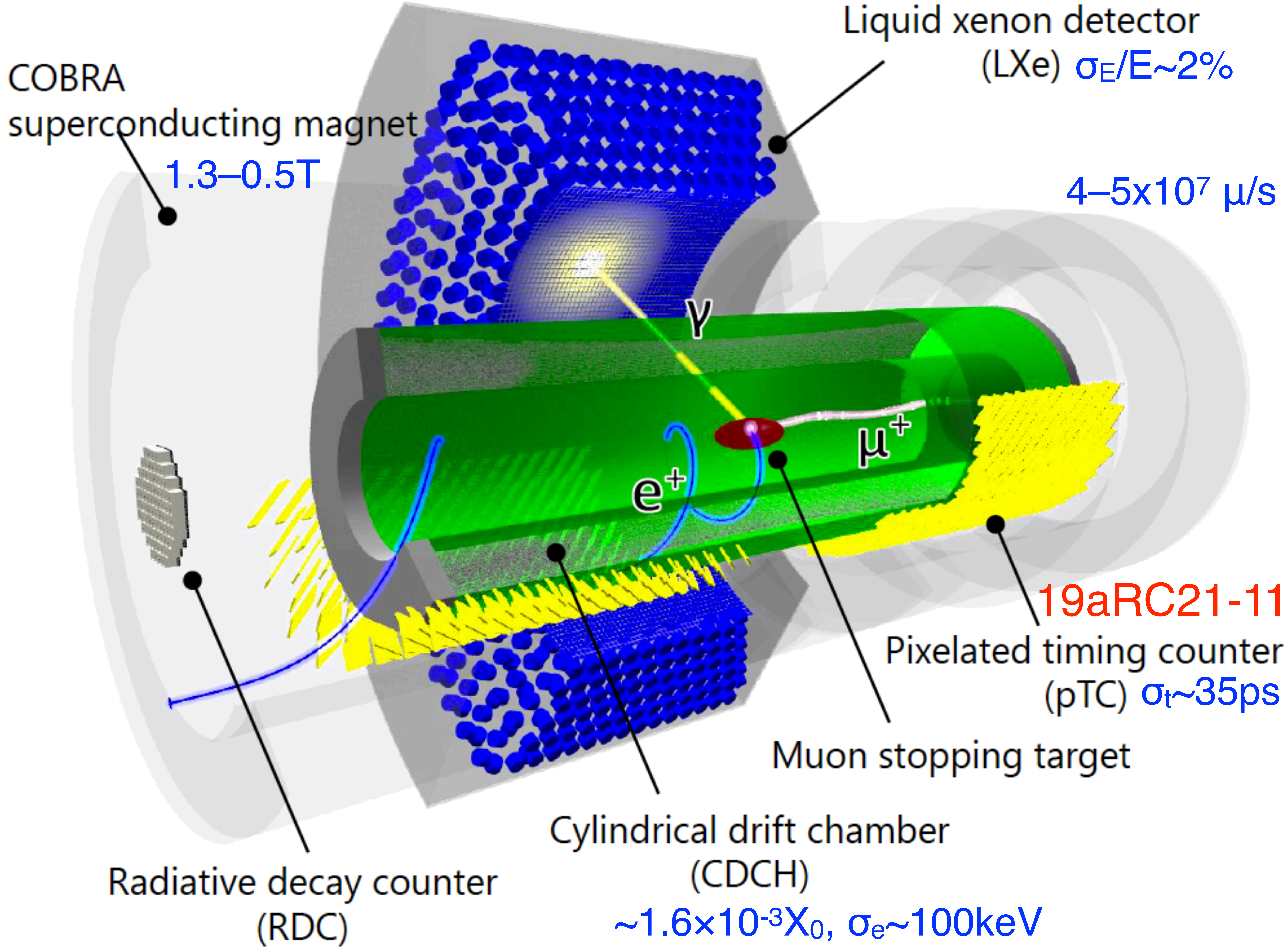
Beam rate — Resolutions — Elapsed time

Good resolution crucial to lower the accidental background (N_{BG})

MEG → MEG II



Geometrical acceptance 11%



Resolution improvement

- Cylindrical drift chamber (E_e, $\theta_{e\gamma}$, $\phi_{e\gamma}$)
- pixelated timing counter ($T_{e\gamma}$)
- Liquid xenon detector (E_γ, $\theta_{e\gamma}$, $\phi_{e\gamma}$)

Large statistics

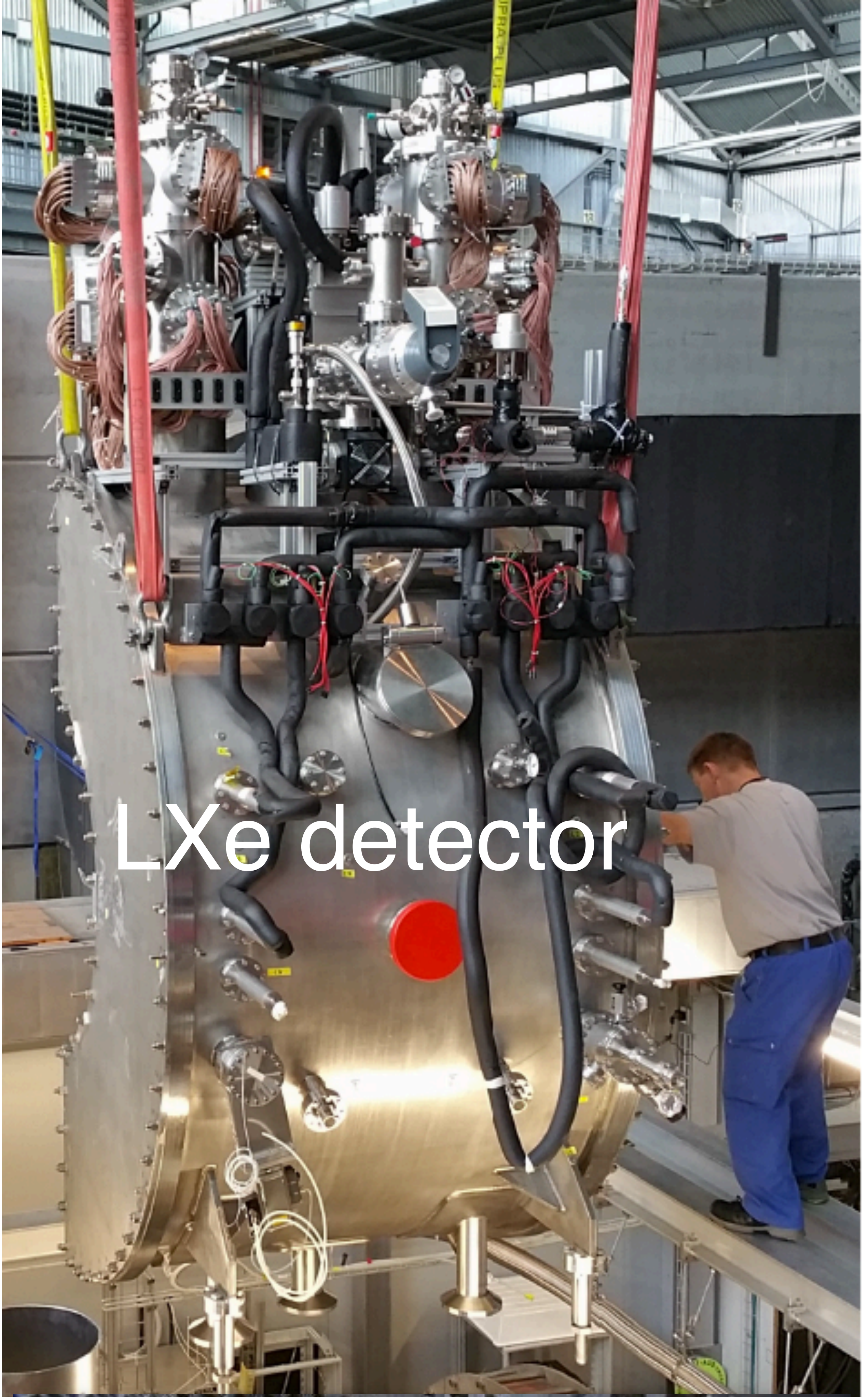
- Higher detection efficiency (ε_e)
- Proton cyclotron at Paul Scherrer Institute in Switzerland ($R_\mu \sim 4$–5×10^7 μ/s)

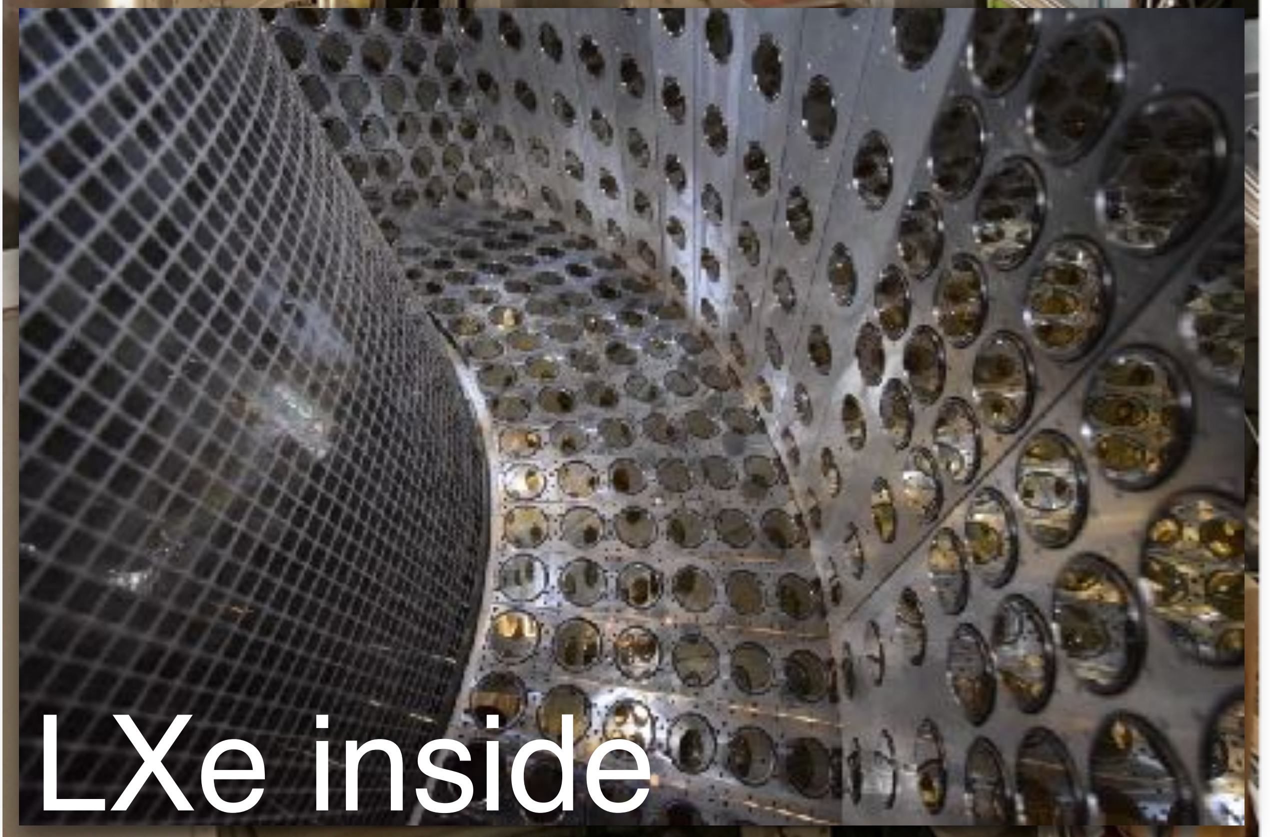
RMD Background tagging (RDC)

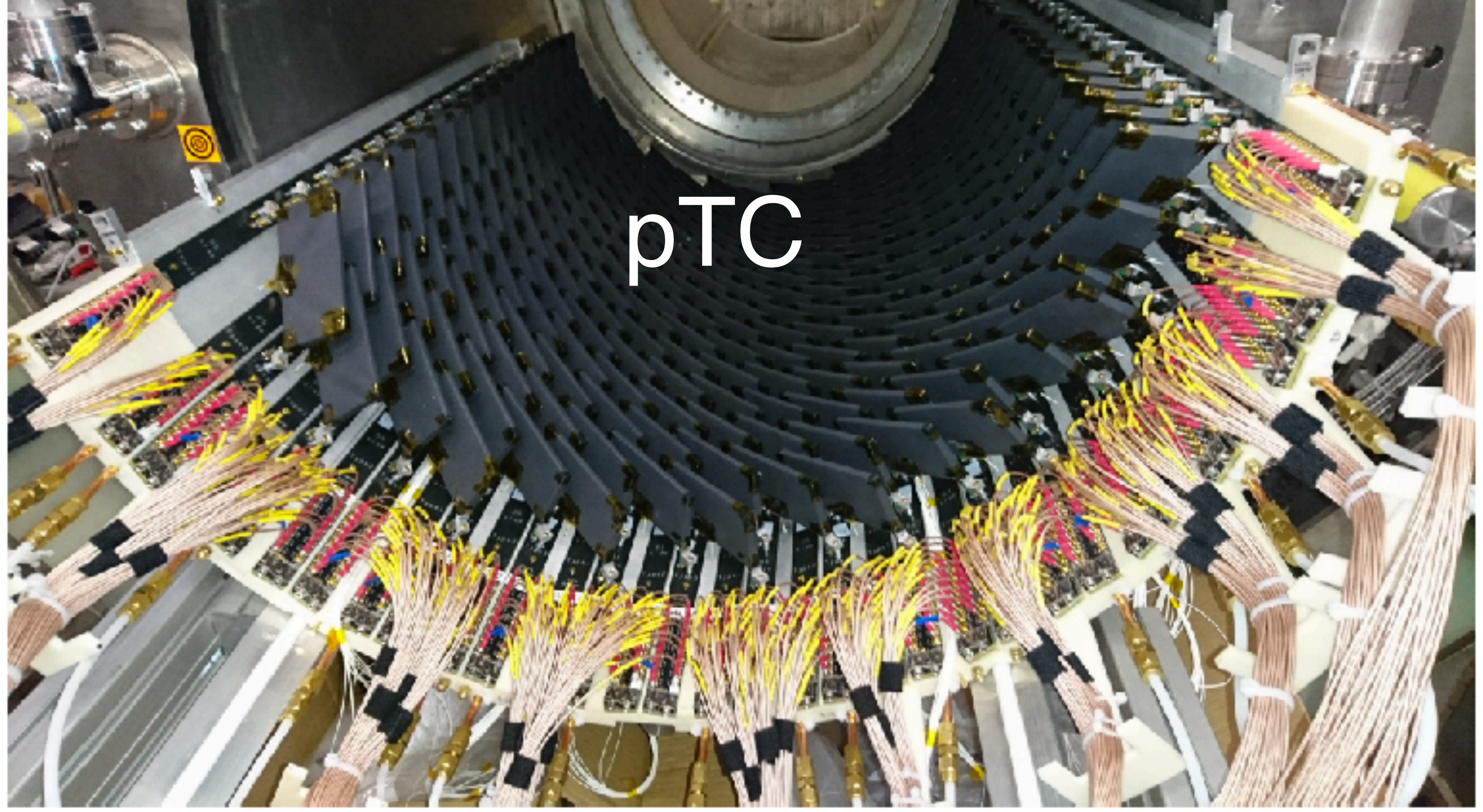
Target sensitivity : 6×10^{-14} (90%C.L.)

18pRA34-7,8

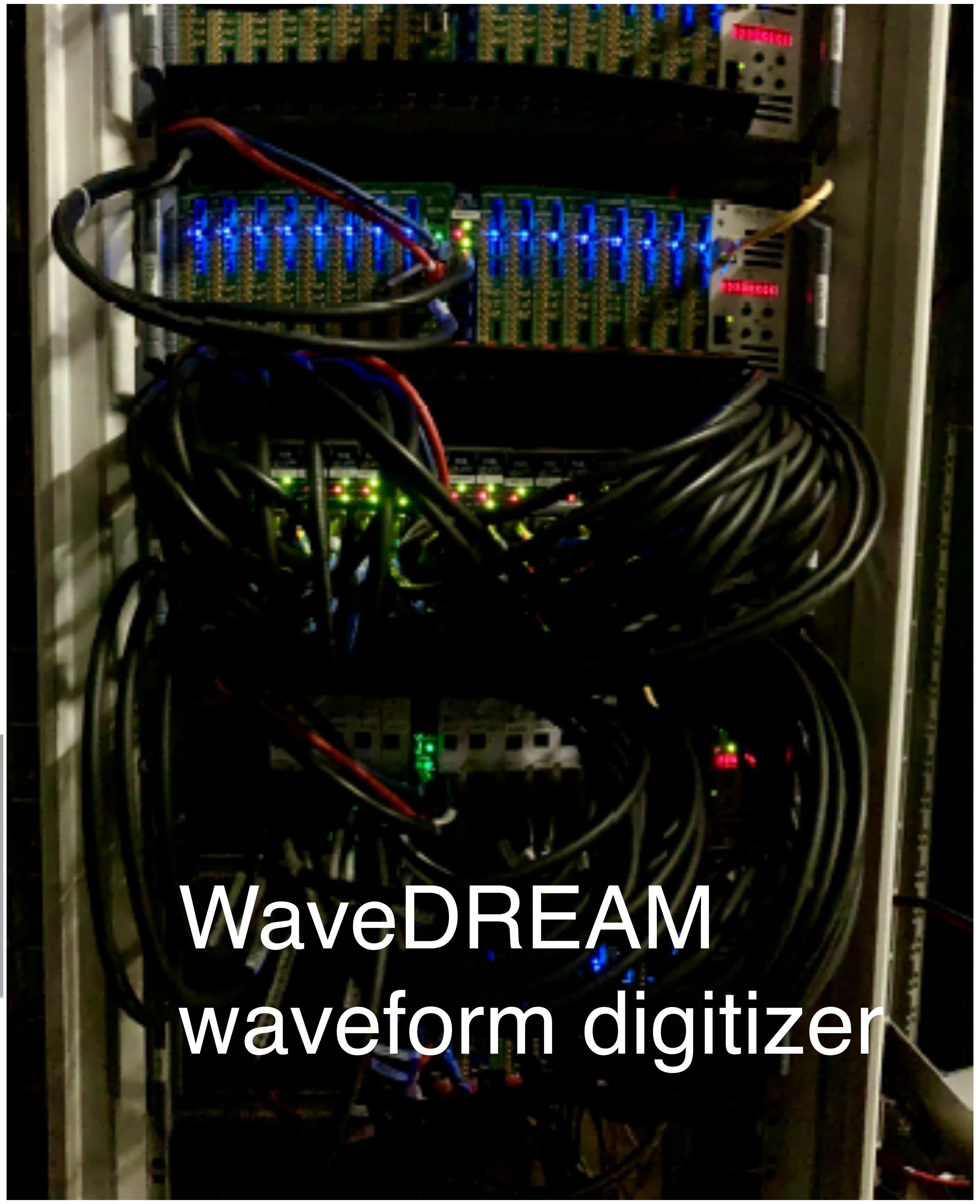
EPJC 78(2018)380

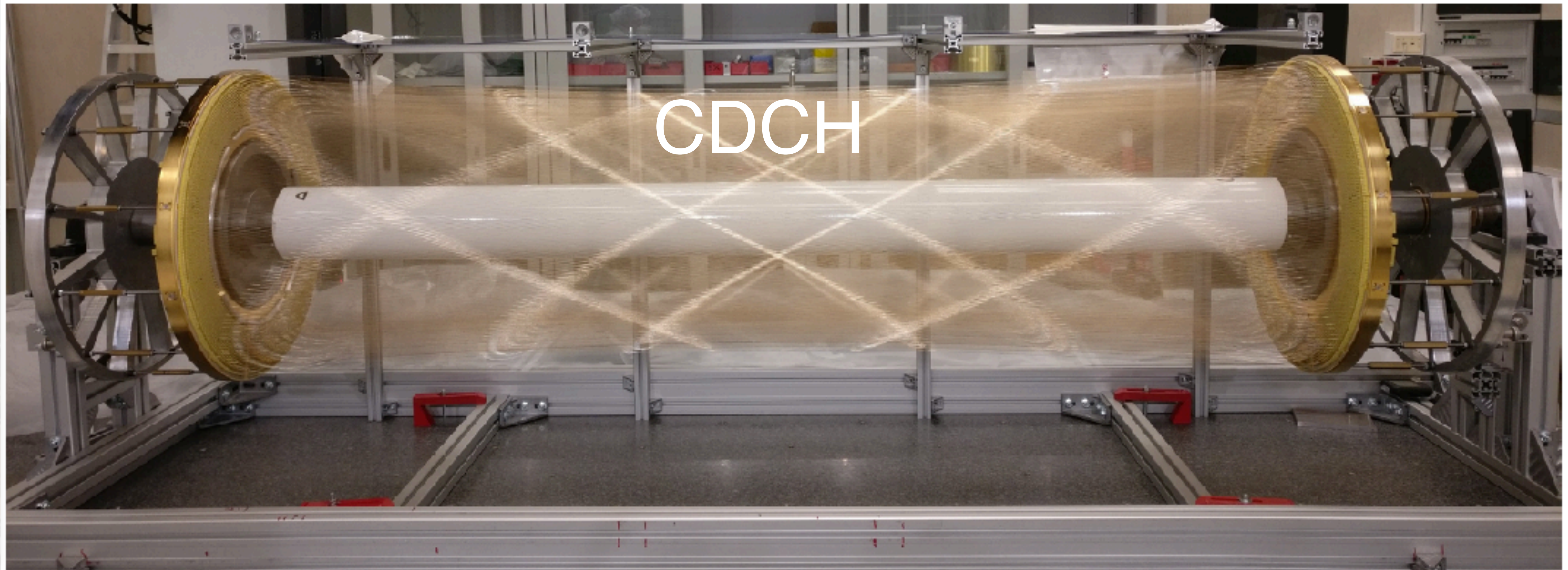


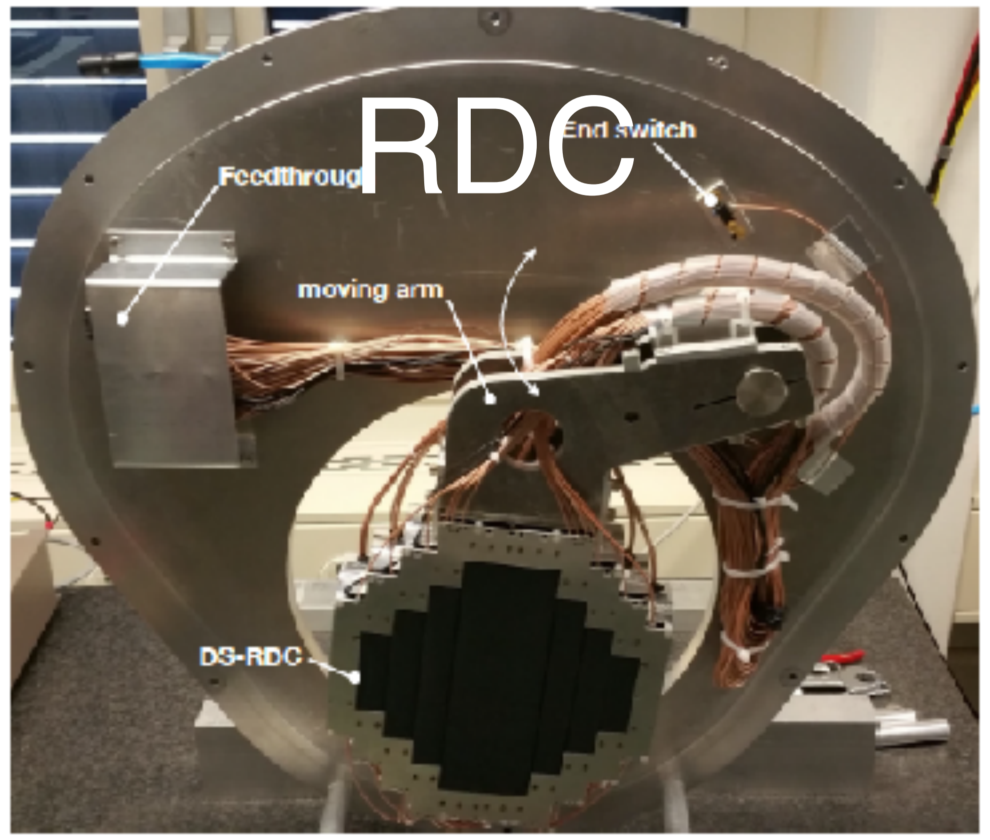




MEG II proposal 2013
Detector R&D 2012-2015
Construction in 2015-2020
Commissioning and physics run 2021-







Detector performance before physics run

	P_e	θ_e	E_γ	x_γ	$T_{e\gamma}$	ε_e	ε_γ
MEG	380keV/c	9.4mrad	2.4%/1.7%	5mm	122ps	30%	63%
MEG II proposal	130keV/c	5.3mrad	1.1%/1.0%	2.4mm	84ps	70%	69%
MEG II updated (2021)	100keV/c	6.7mrad	1.7%/1.7%	2.4mm	70ps	65%	69%

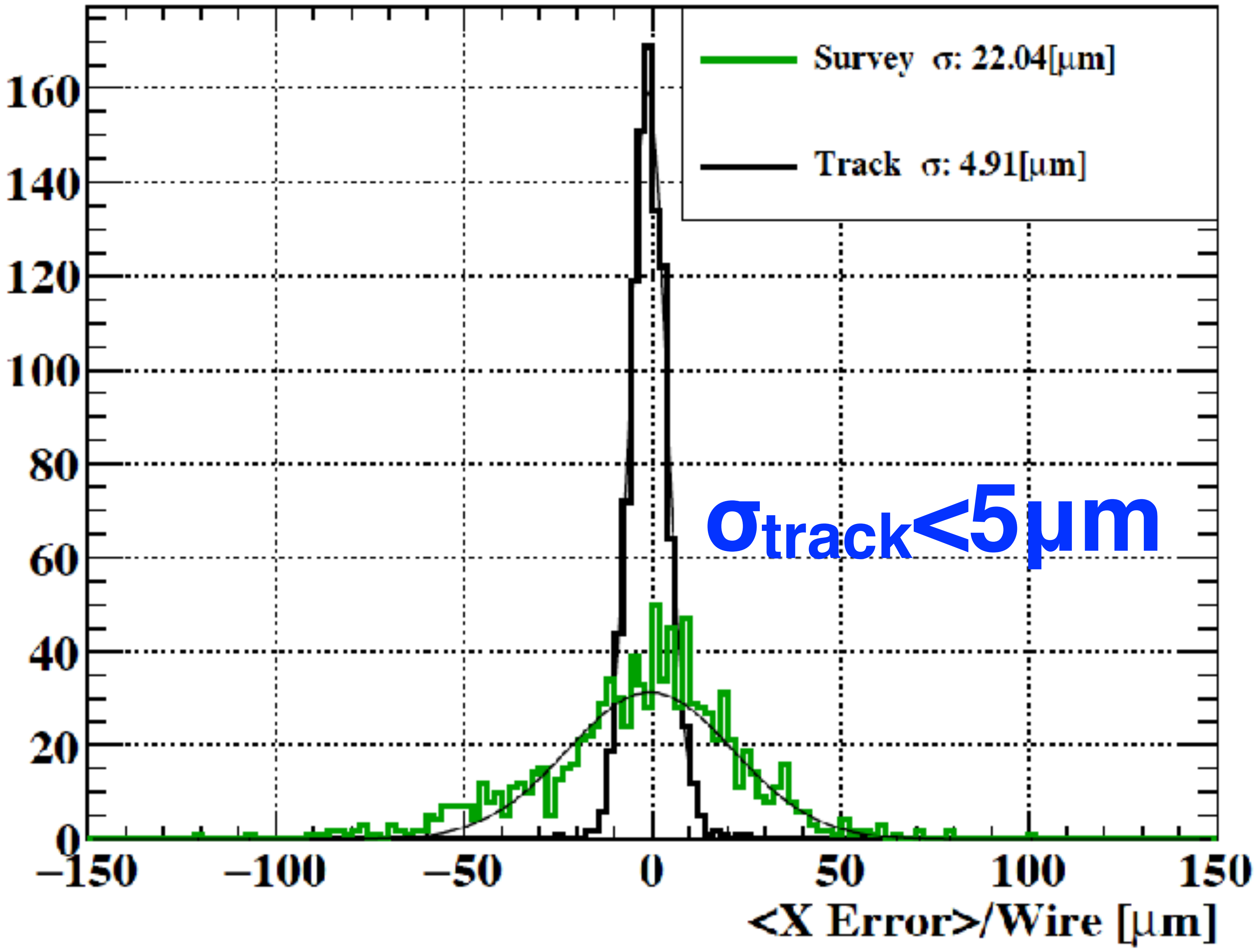
Symmetry 2021, 13(9), 1591

- The performance was estimated before starting the physics run in 2021.
- The detector performance is carefully investigated with the calibration data and physics data during the physics run period to be used for the $\mu \to e\gamma$ search

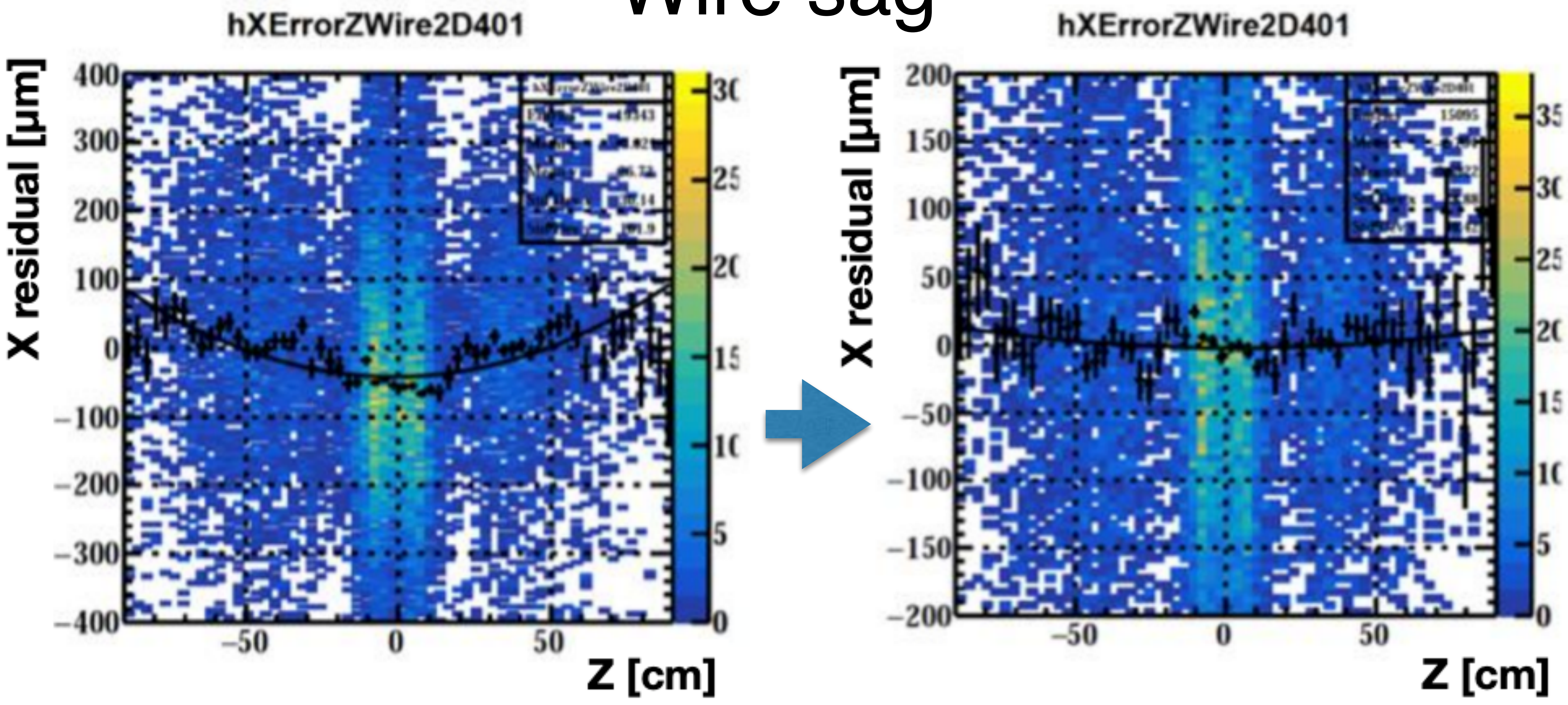
Analysis Highlights

Alignment of CDCH

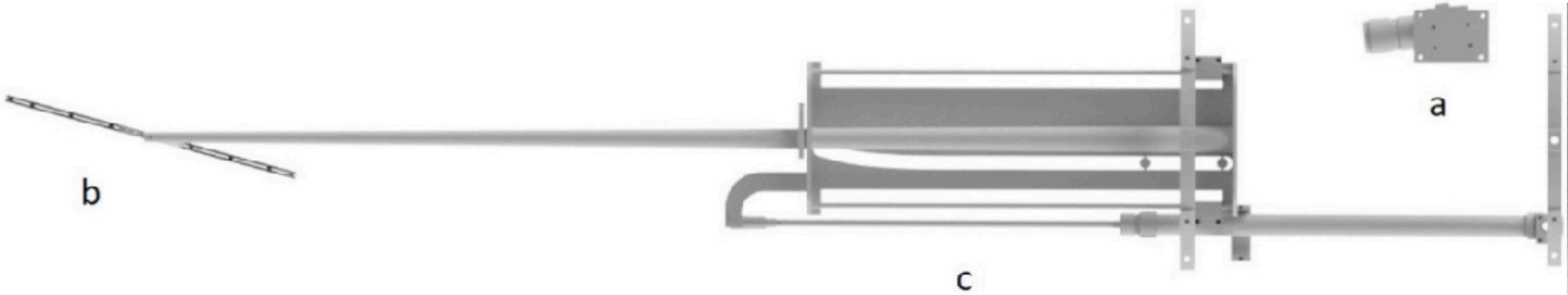
- Alignment becomes important once resolutions are improved
  - CDCH wire alignment (position, inclination, sag)
  - Michel positron tracks for an iterative adjustment



Wire sag

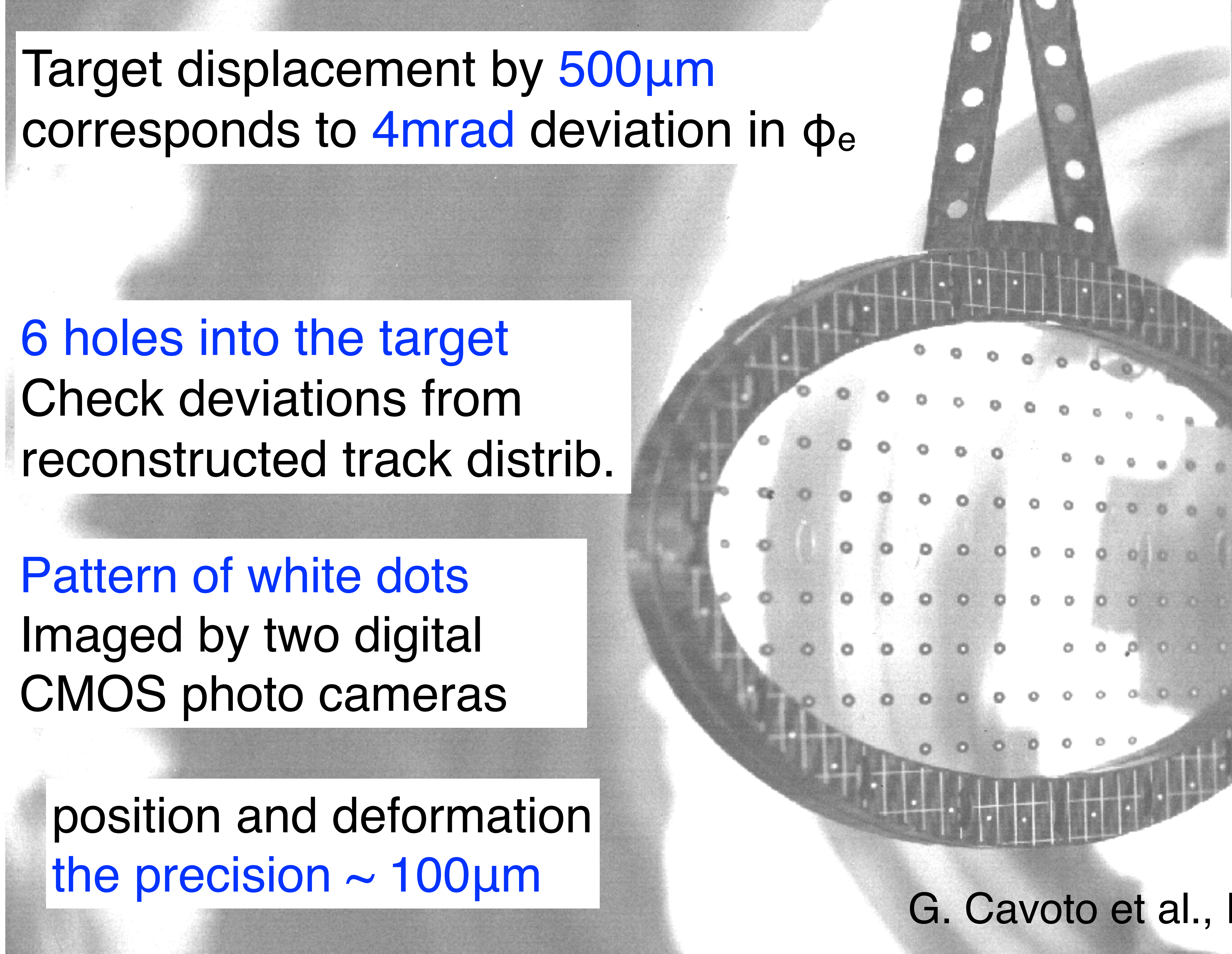


Alignment of target



Largest Systematic uncertainty in MEG

Sensitivity of 13% degraded by target position and planarity

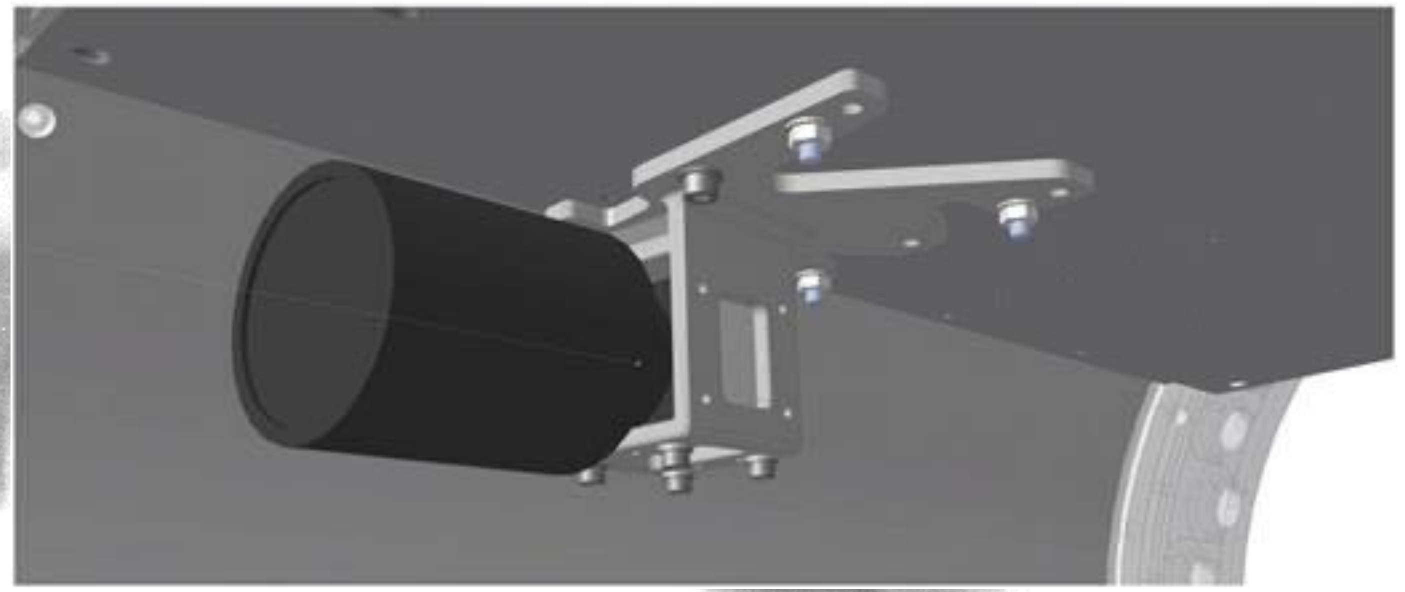


Target displacement by 500µm corresponds to 4mrad deviation in ϕ_e

6 holes into the target
Check deviations from reconstructed track distrib.

Pattern of white dots
Imaged by two digital CMOS photo cameras

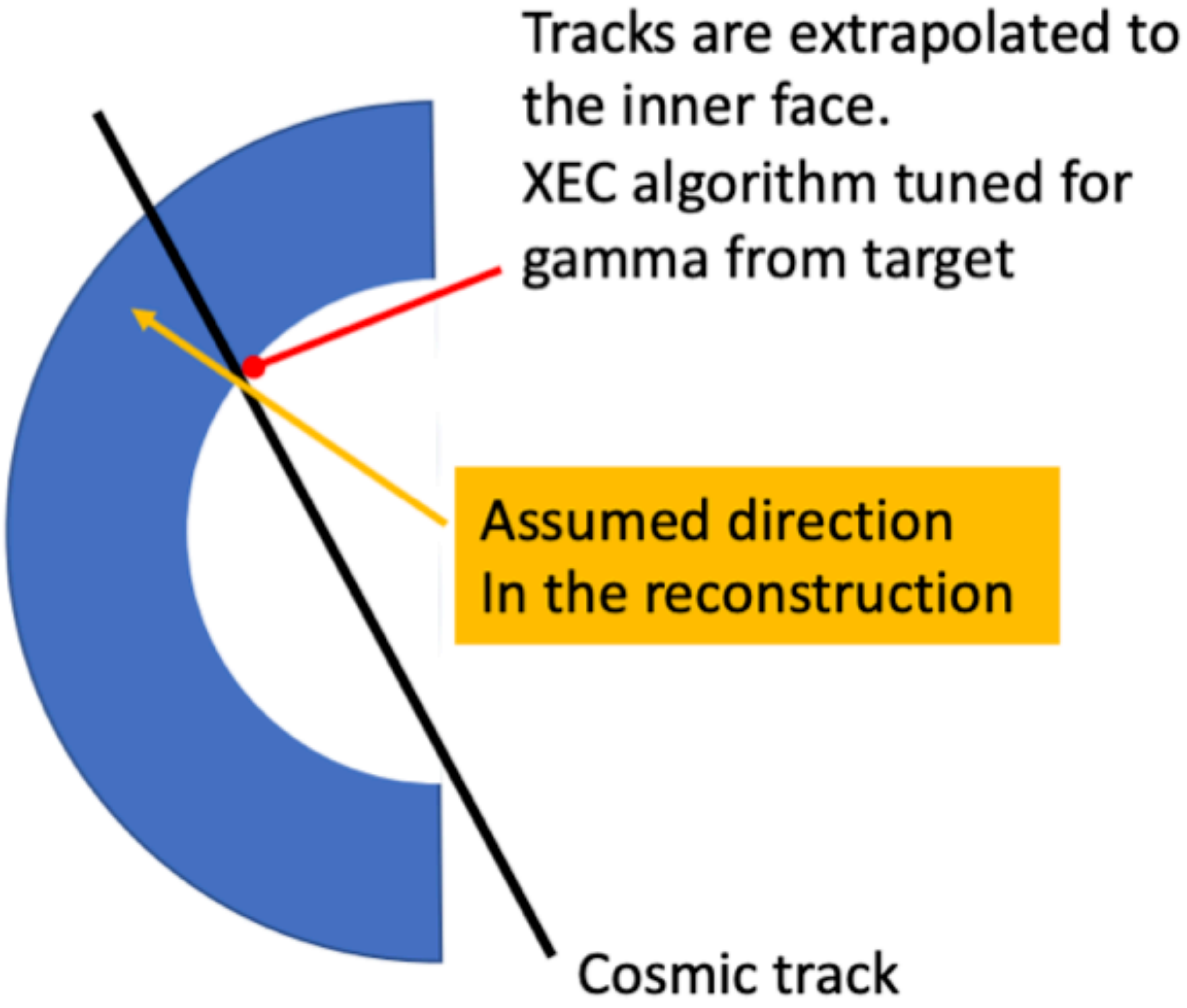
position and deformation
the precision ~ 100µm



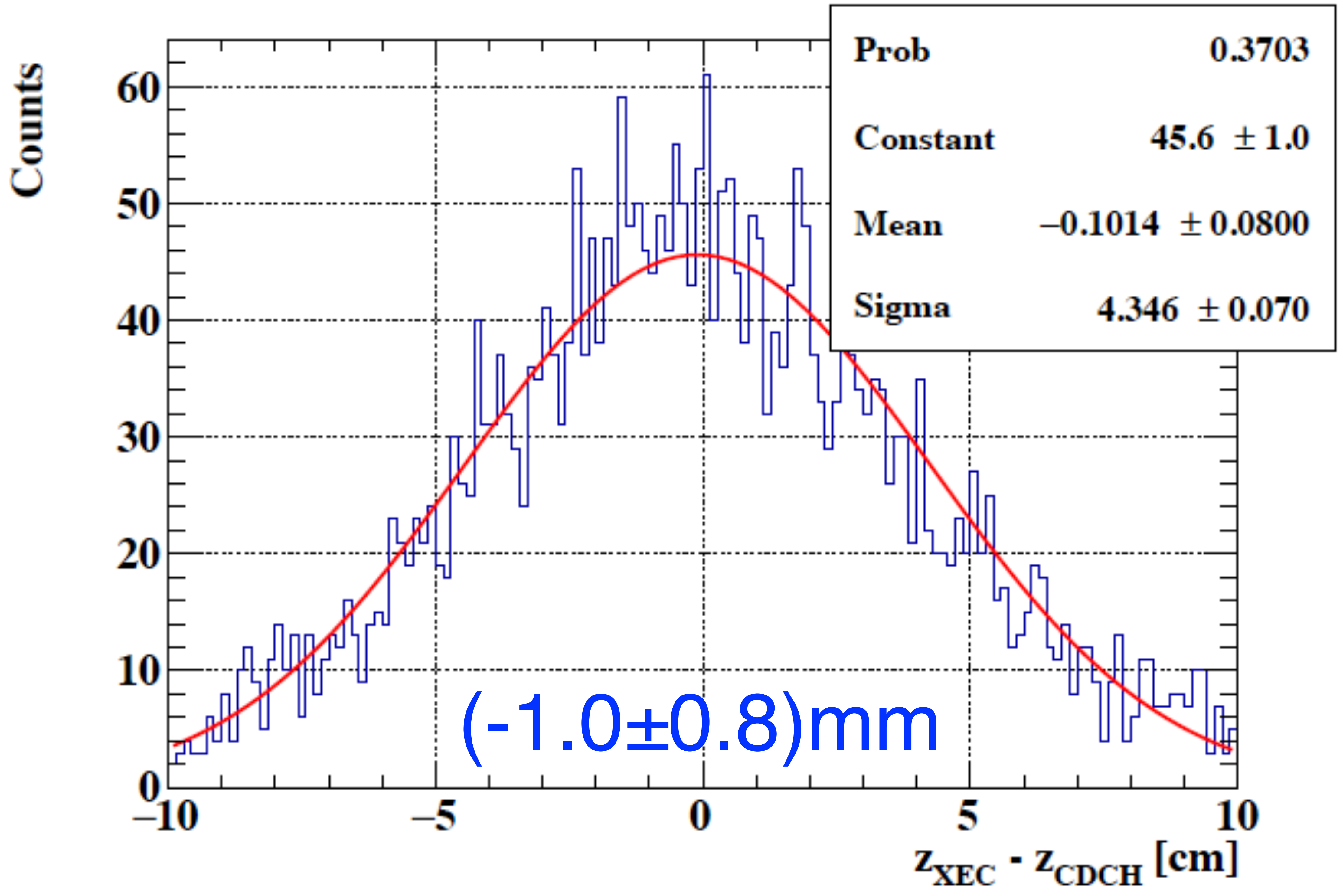
L 270mm, H 66mm
Scinti. material
Thickness 174±20 µm
Angle 75° to z

G. Cavoto et al., Rev. Sci. Instrum. 92(2021) 4, 043707

Alignment between LXe and CDCH

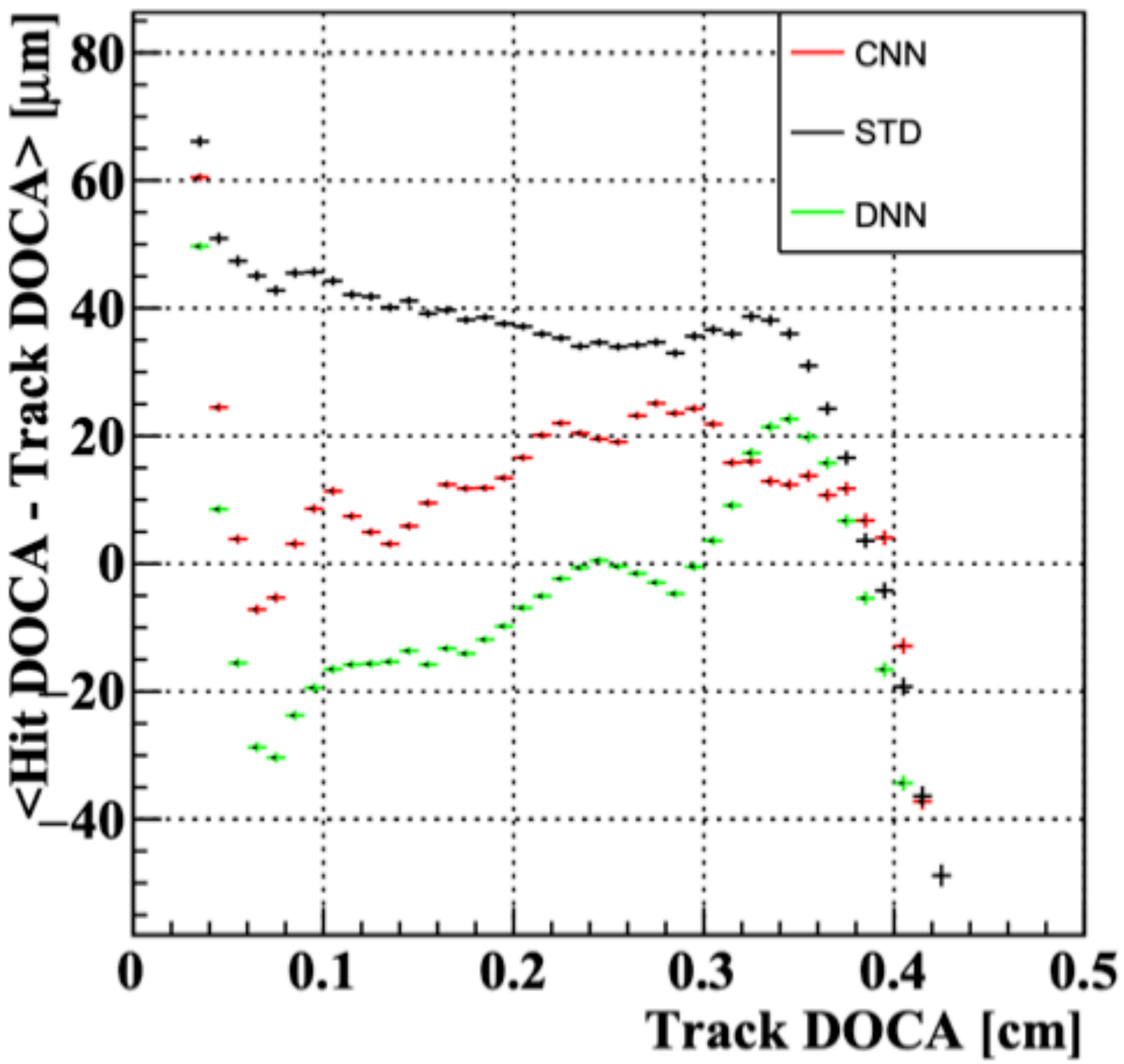


- No calibration source to check the LXe and CDCH alignment
- Extremely important to directly check the relative alignment
- Cosmic rays are used



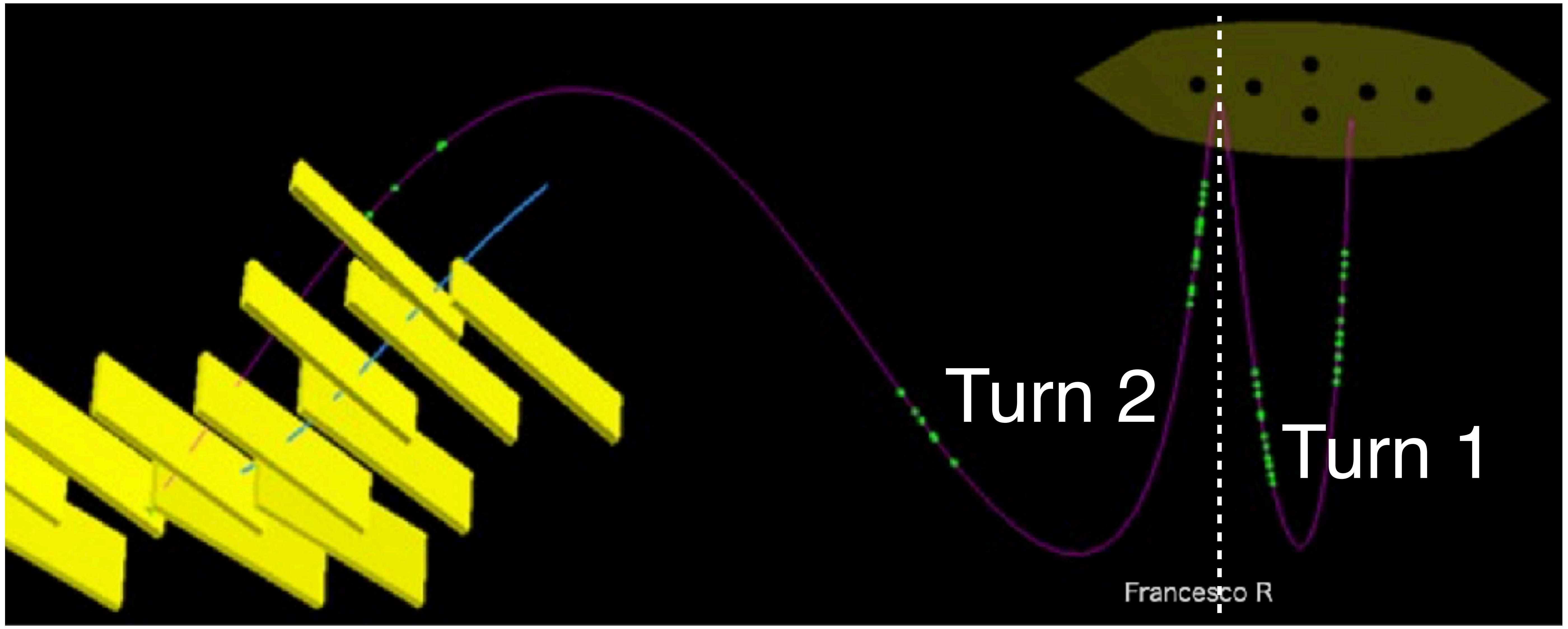
New algorithms

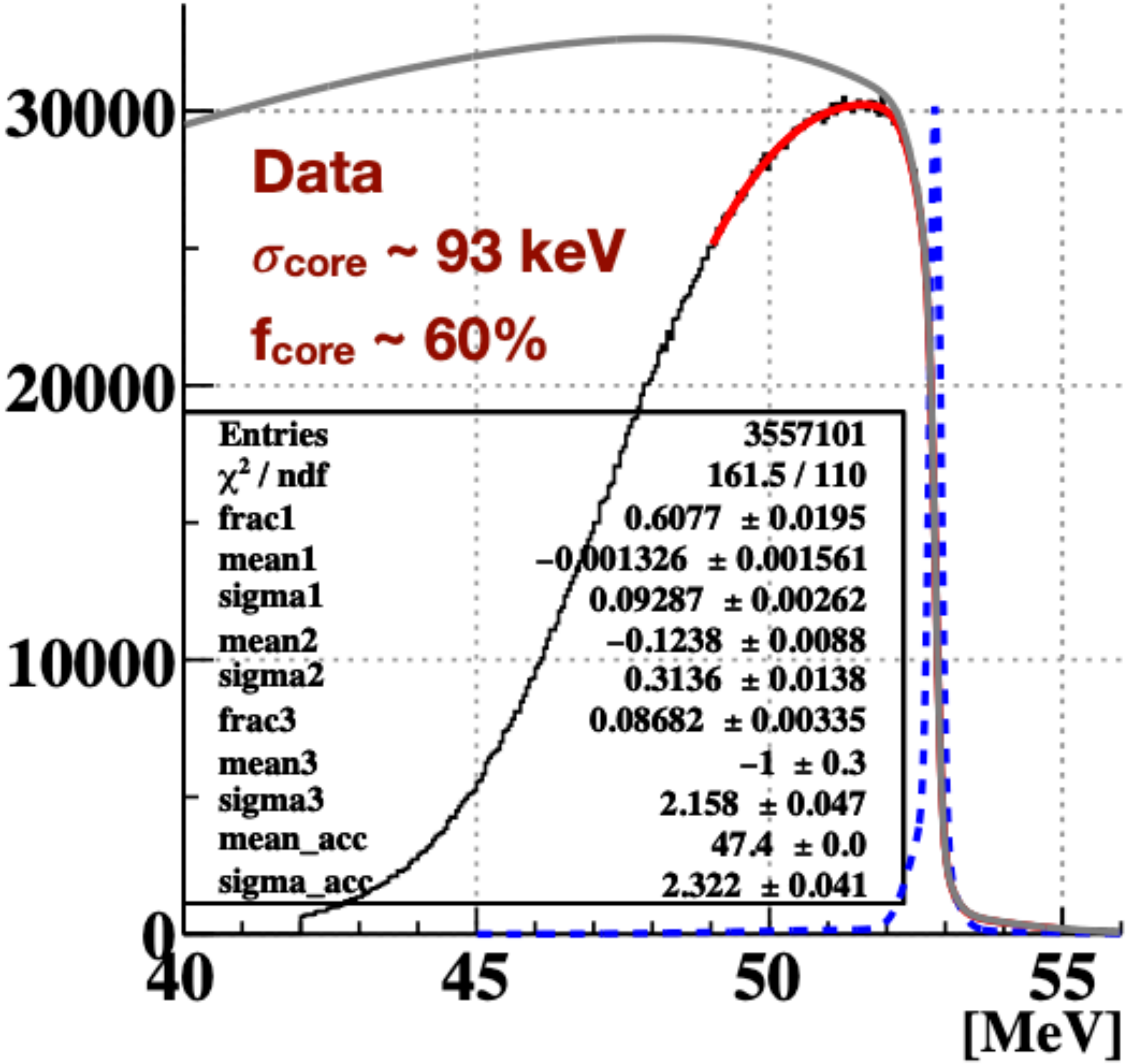
- Standard CDCH hit reconstruction
  - with the time of the first electrons reaching wires
  - large bias when the track passes close to the wire by statistical fluctuations of the primary ionization
- Innovative machine-learning approach
  - extracting an unbiased CDCH hit position
  - CDCH waveforms input into a neural network
  - output of distance of closest approach (DOCA) of the track
  - All ionization clusters are used
- Strong reduction of the hit reconstruction biases and significant improvement of the single-hit resolution observed
  - σ_{DOCA} = 150 – 160 μm (improved by 5%)

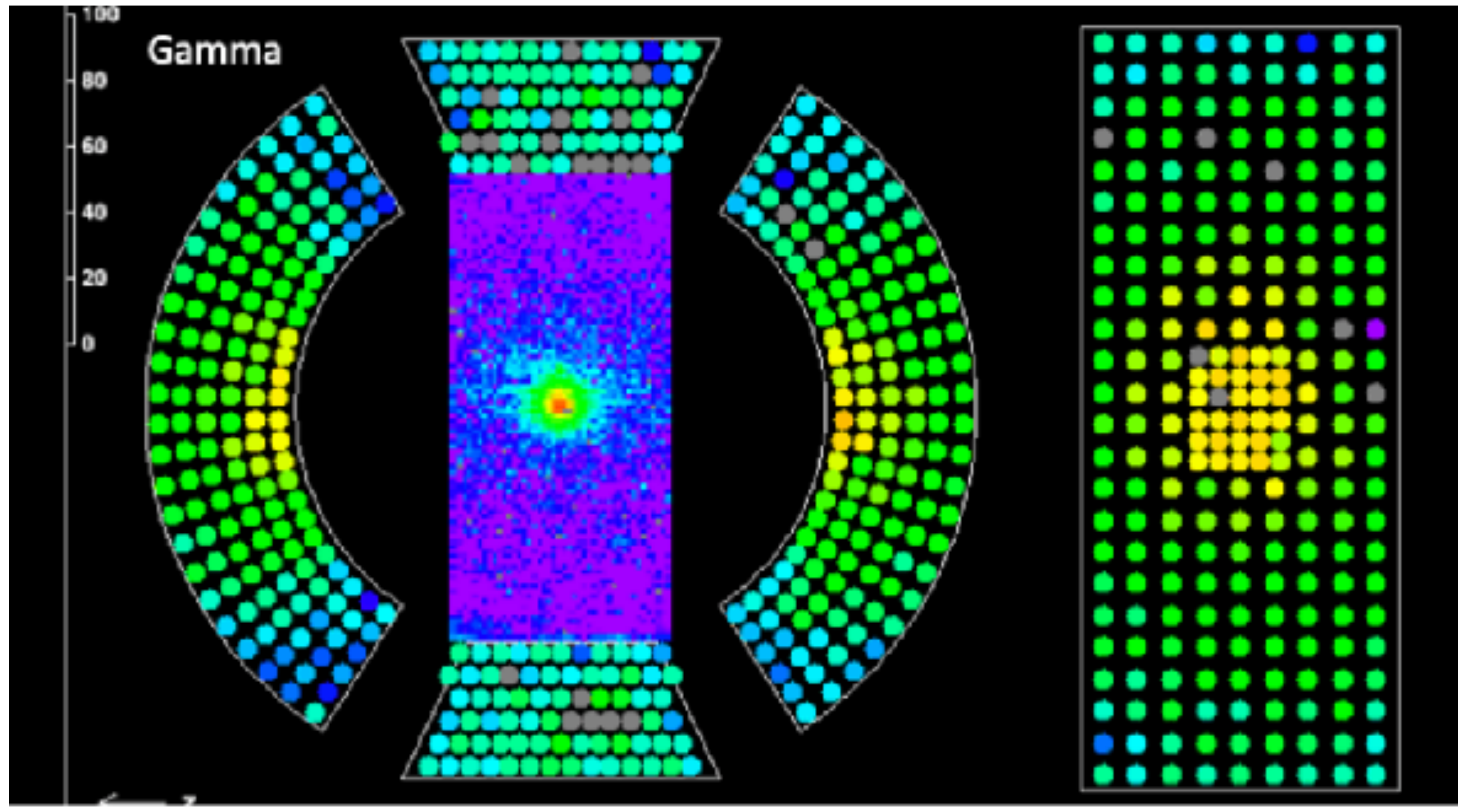


Performance evaluation for CDCH

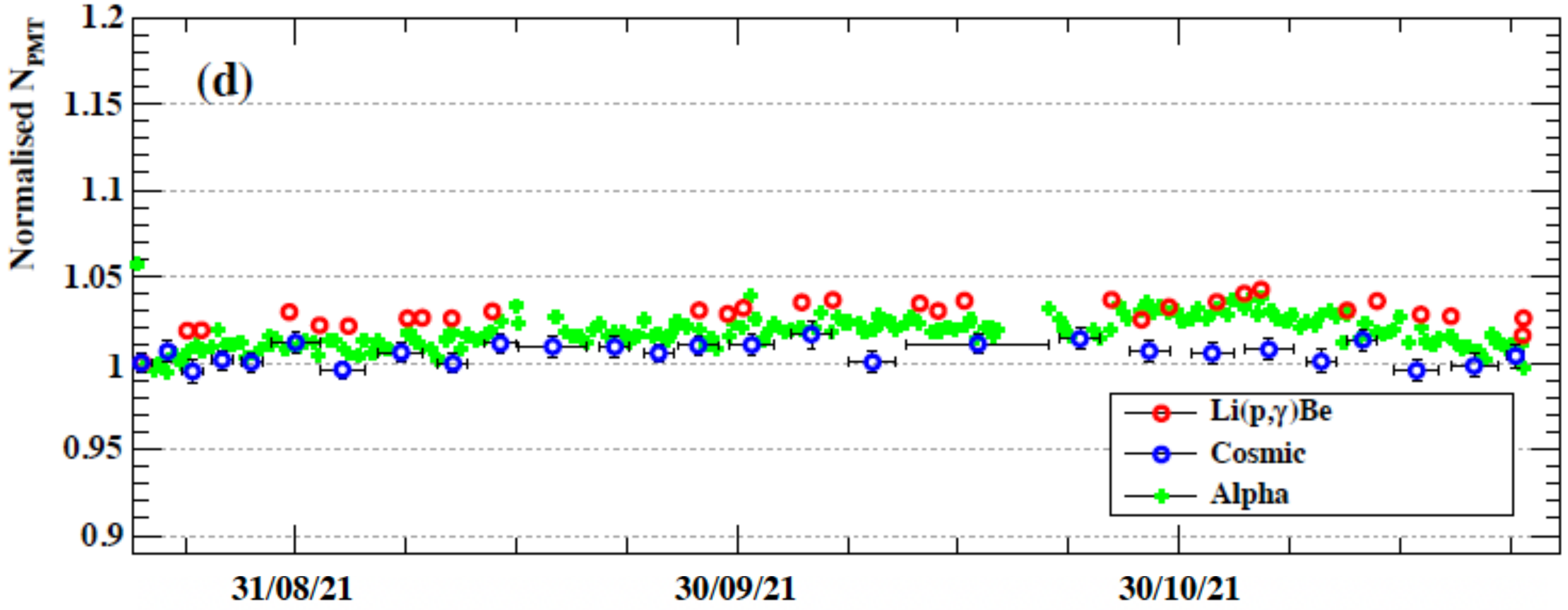
- Effect of the alignment on kinematic variable resolutions are evaluated by double-turn method







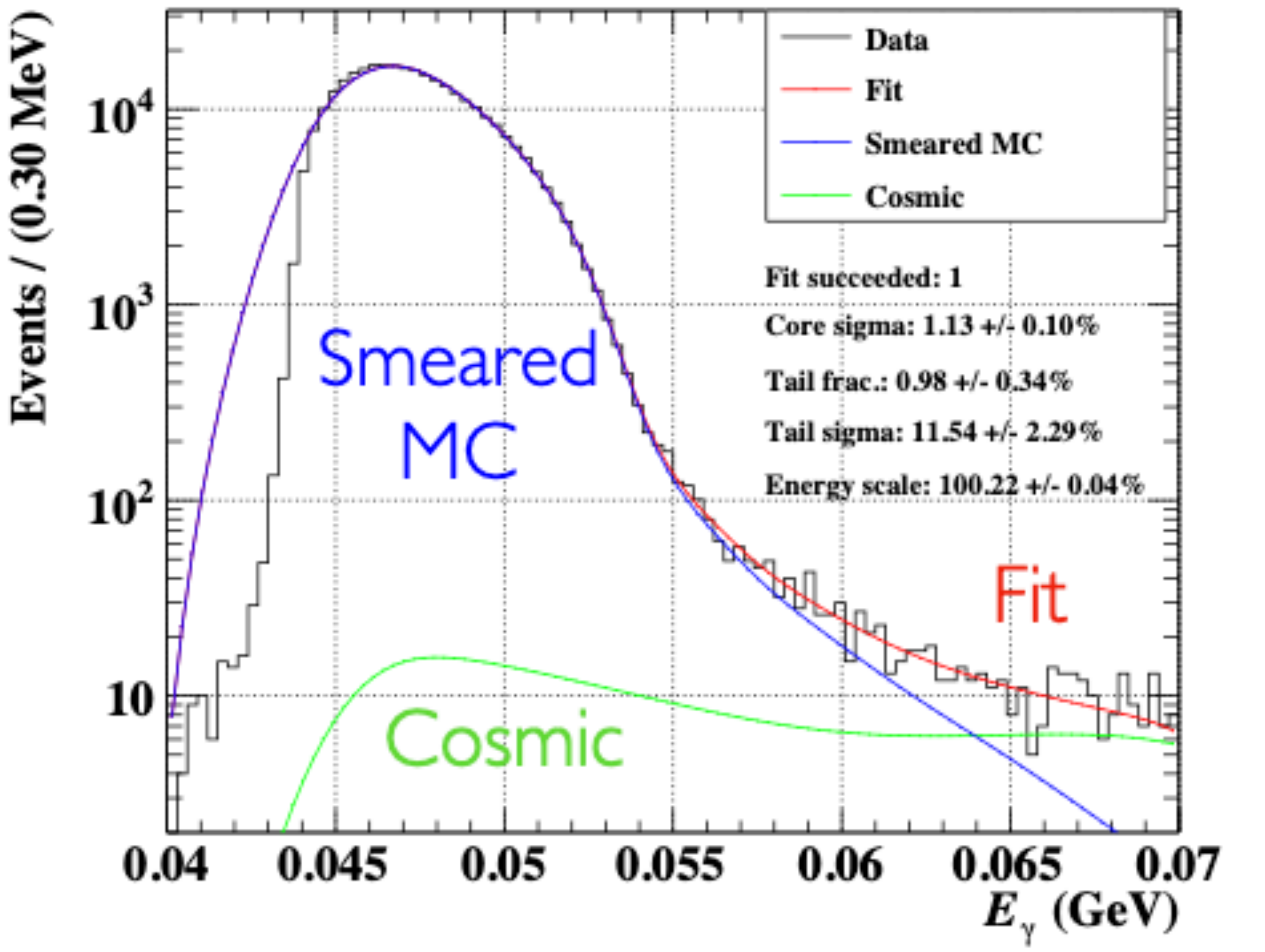
LXe reconstruction



- Calibration, monitoring, and performance evaluation
  - LED, α, cosmic, Li(p,17.6MeV γ)Be, 55MeV γ from π^0, BG spectrum
  - LXe light yield, PMT gain and MPPC PDE decrease, energy non-uniformity, time dependence

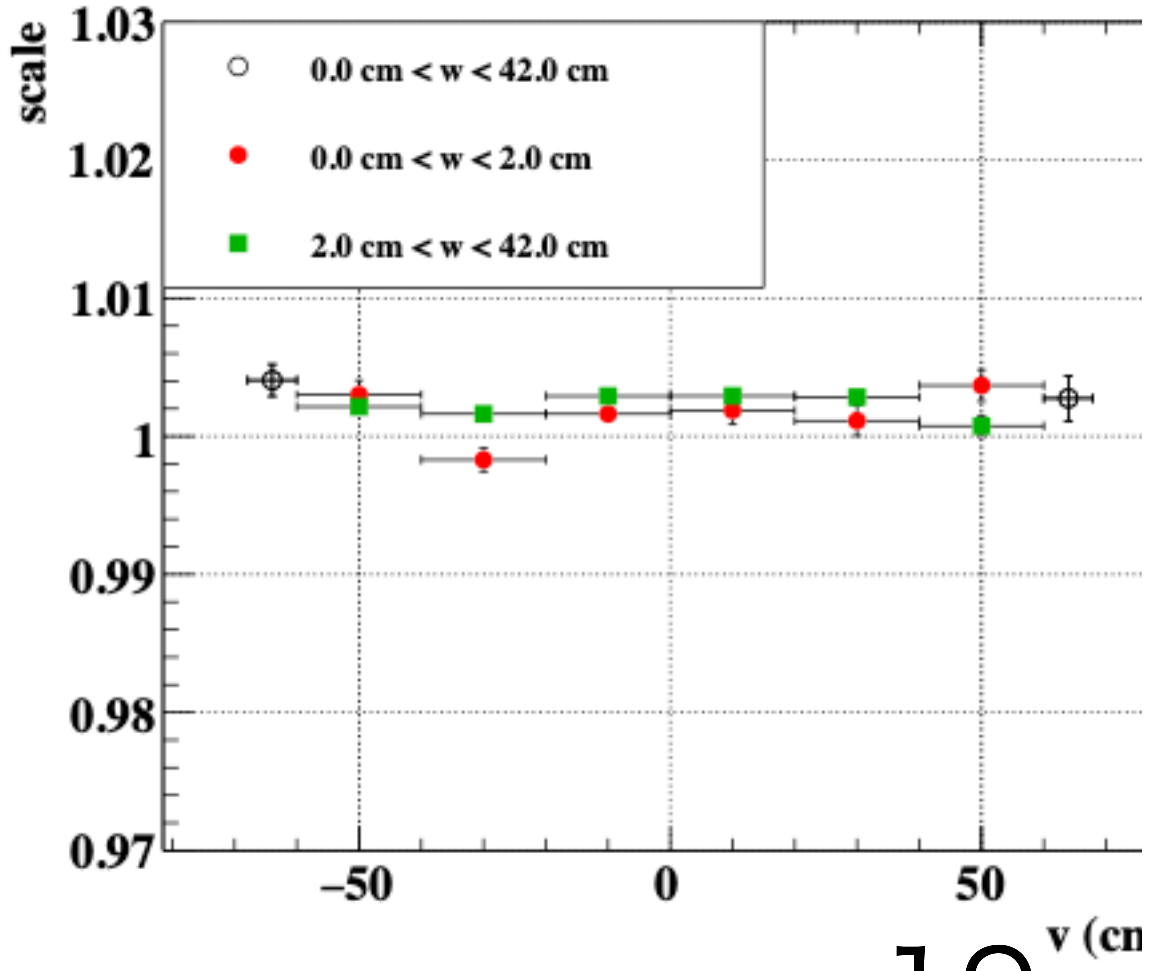
- E_γ scale non-uniformity observed with different energy
  - Uniformity correction by combined data. E_γ scale uncertainty ~ 0.4%

BG γ spectrum

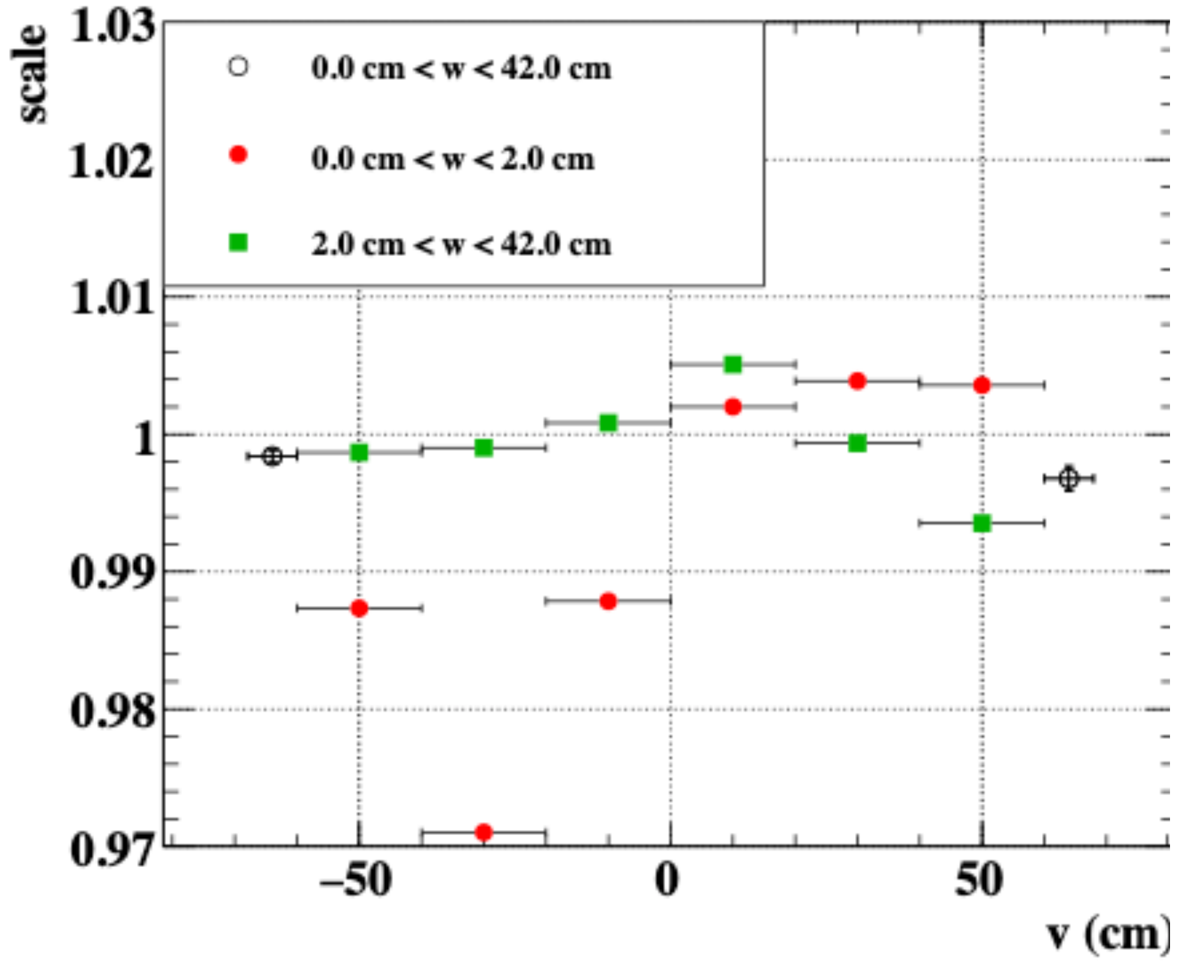


Energy scale: a fit parameter

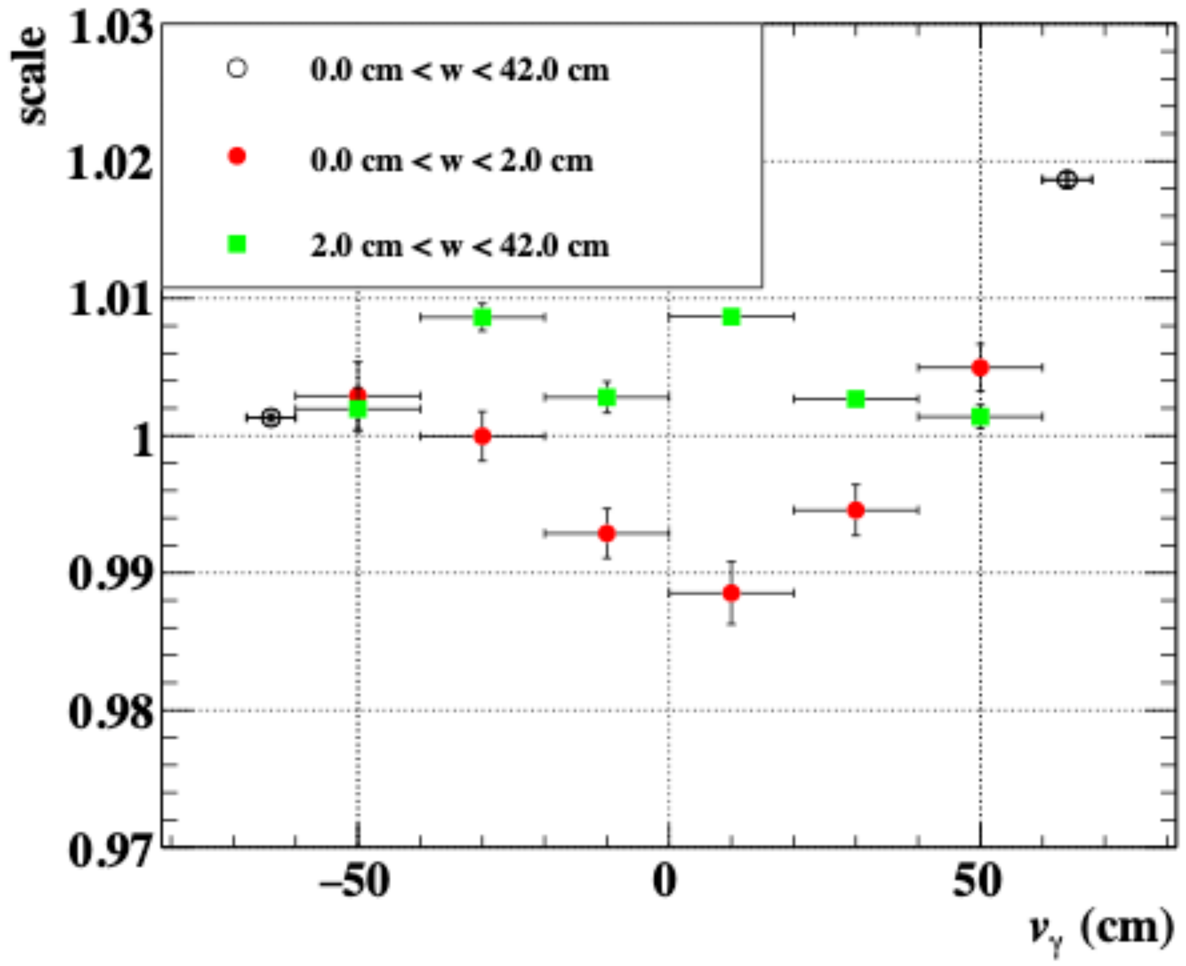
55 MeV γ



17.6 MeV γ

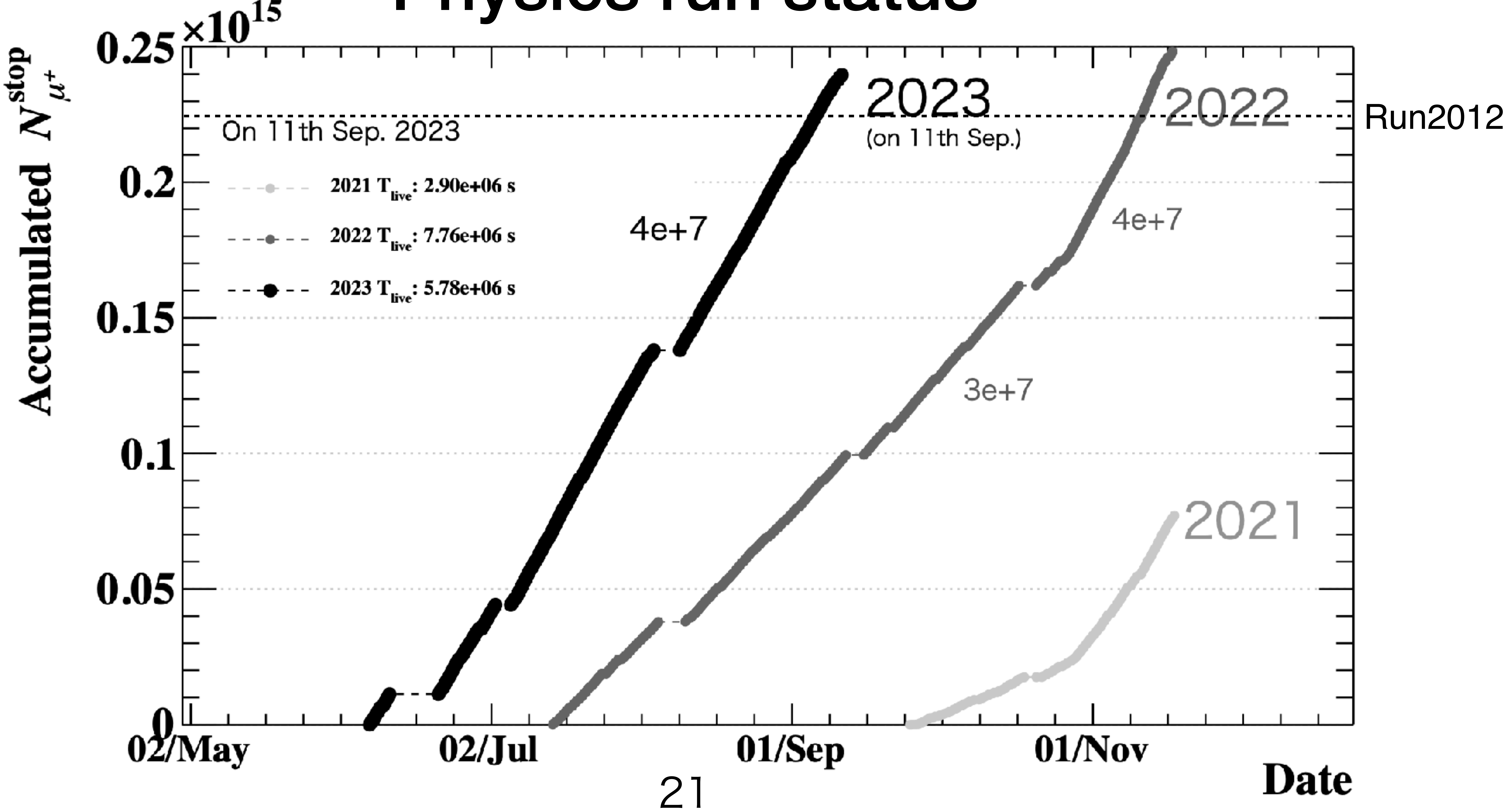


BG γ (<52.8 MeV)



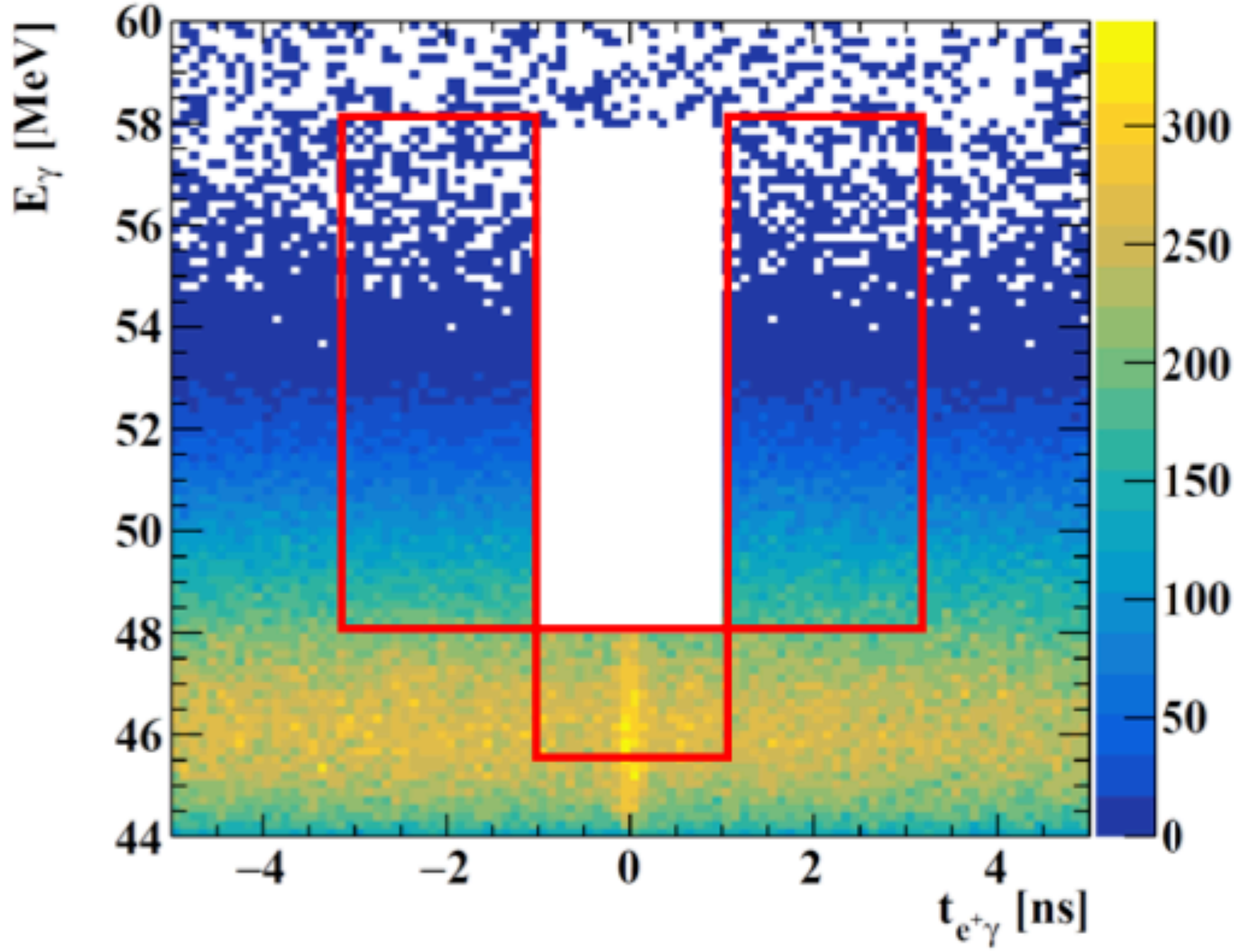
$\mu^+ \to e^+\gamma$ search

Physics run status



Method of $\mu \to e\gamma$ search

- Blind analysis
  - Time coincidence within 1ns, 48MeV<Eγ<58MeV
- Likelihood analysis to estimate N_{sig}
  - Confidence interval from Feldman-Cousins method
- Sideband to extract PDFs, analysis check

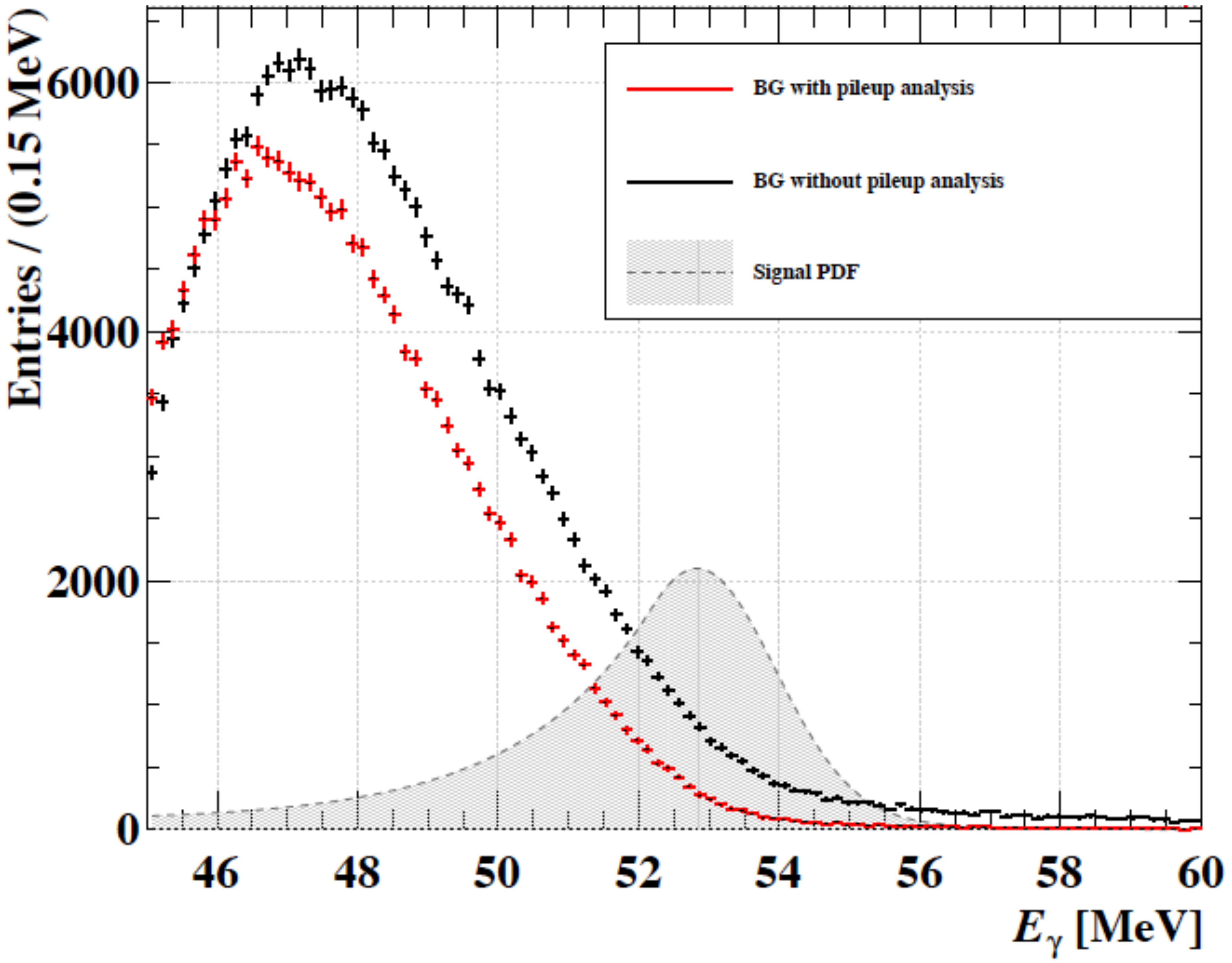


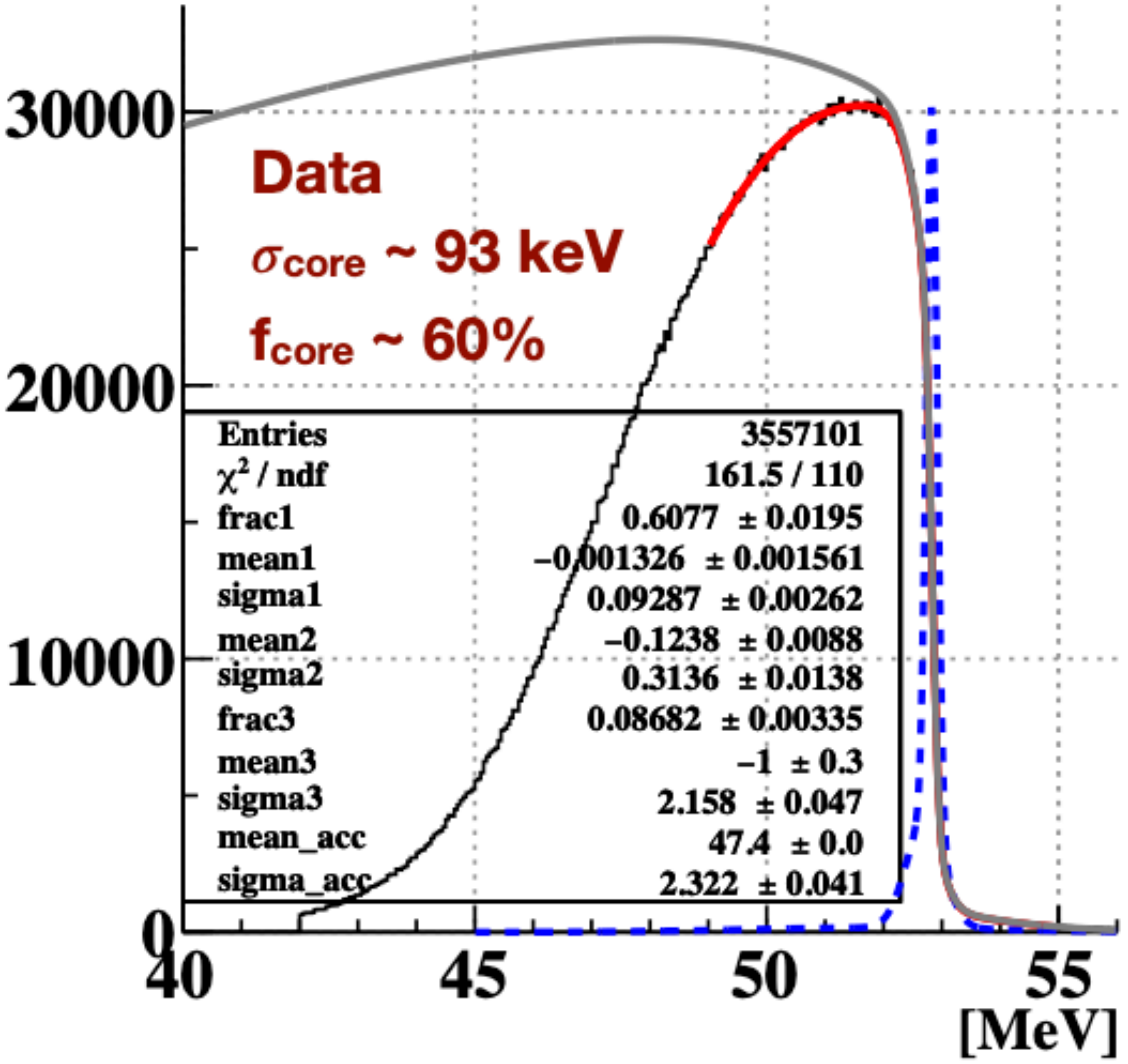
$$\mathcal{L}(N_{\rm sig}, N_{\rm RMD}, N_{\rm ACC}) := \frac{e^{-(N_{\rm sig}+N_{\rm RMD}+N_{\rm ACC})}}{N_{\rm obs}!} e^{-\frac{(N_{\rm RMD}-\langle N_{\rm RMD}\rangle)^2}{2\sigma^2_{\rm RMD}}} e^{-\frac{(N_{\rm ACC}-\langle N_{\rm ACC}\rangle)^2}{2\sigma^2_{\rm ACC}}}$$

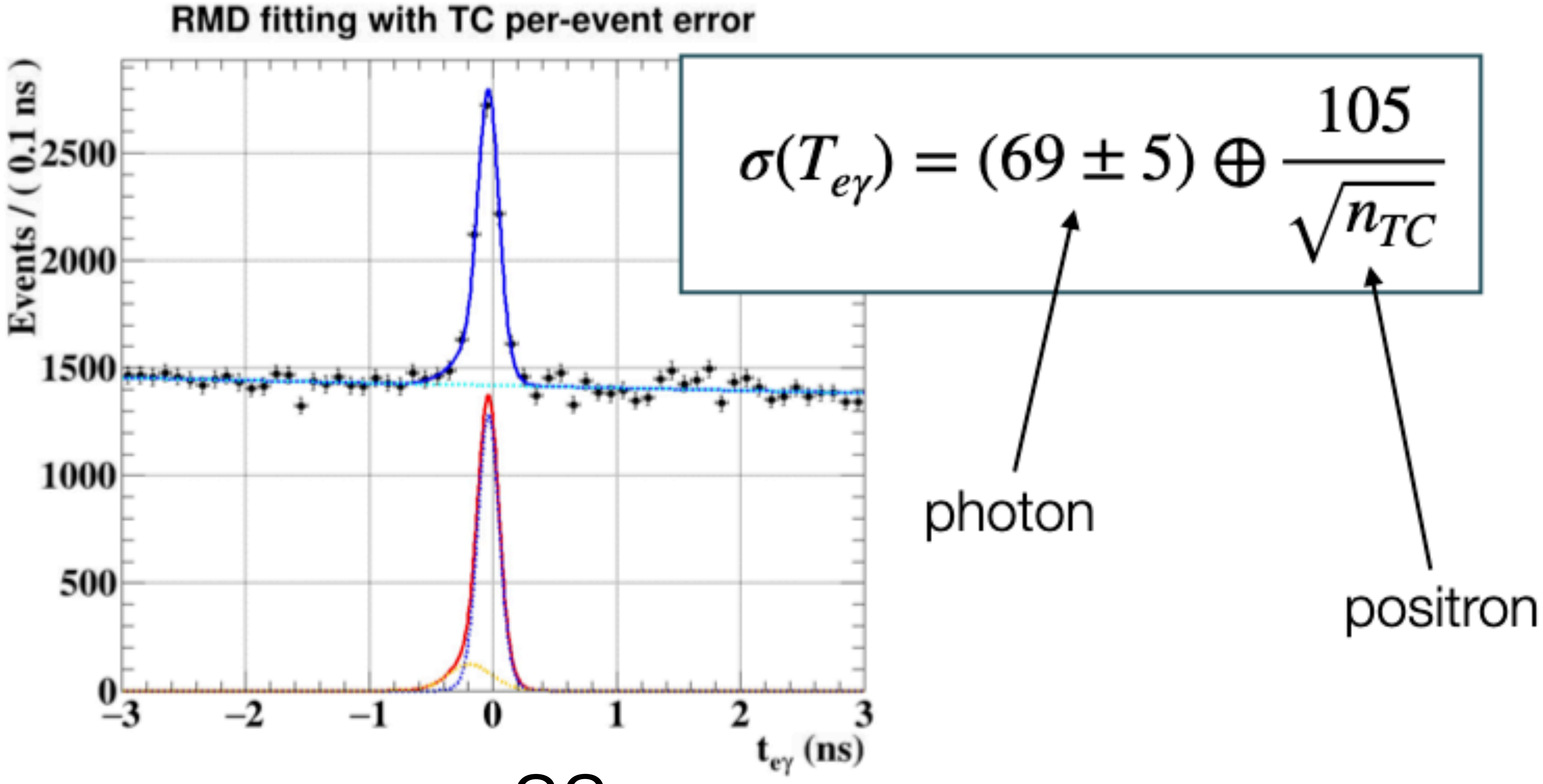
$$\times \prod_{i=1}^{N_{\rm obs}} (N_{\rm sig}S(\vec{x}_i) + N_{\rm RMD}R(\vec{x}_i) + N_{\rm ACC}A(\vec{x}_i)),$$

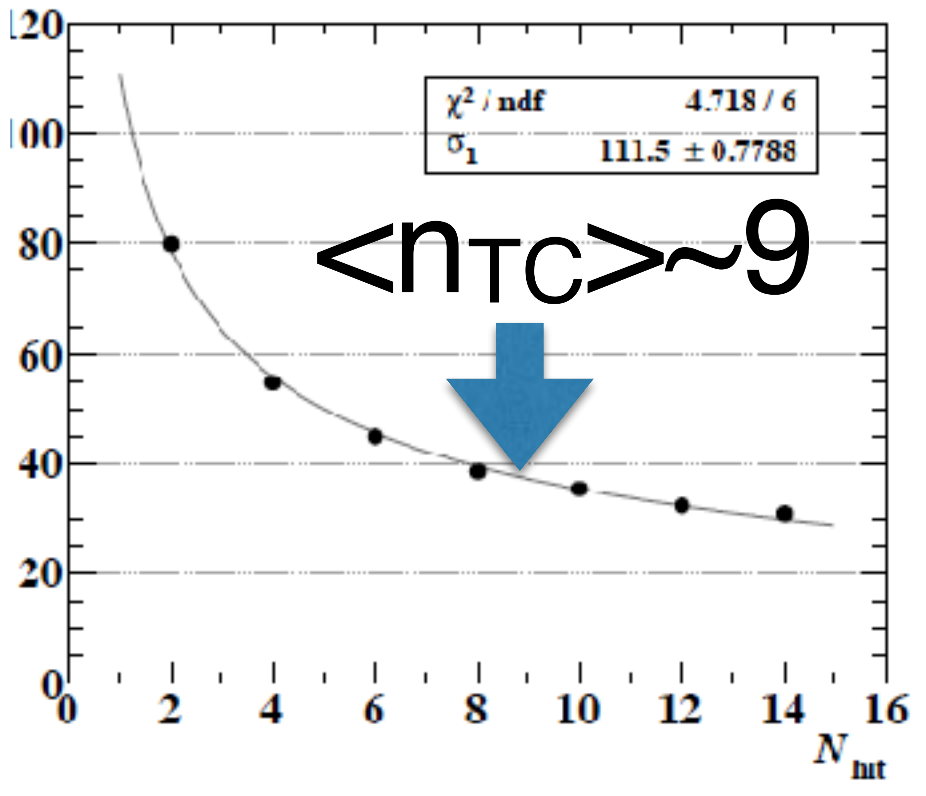
Extraction of PDFs

- Signal and RMD PDFs from resolution measurements
- Accidental BKG PDFs from sidebands (fully data-driven)









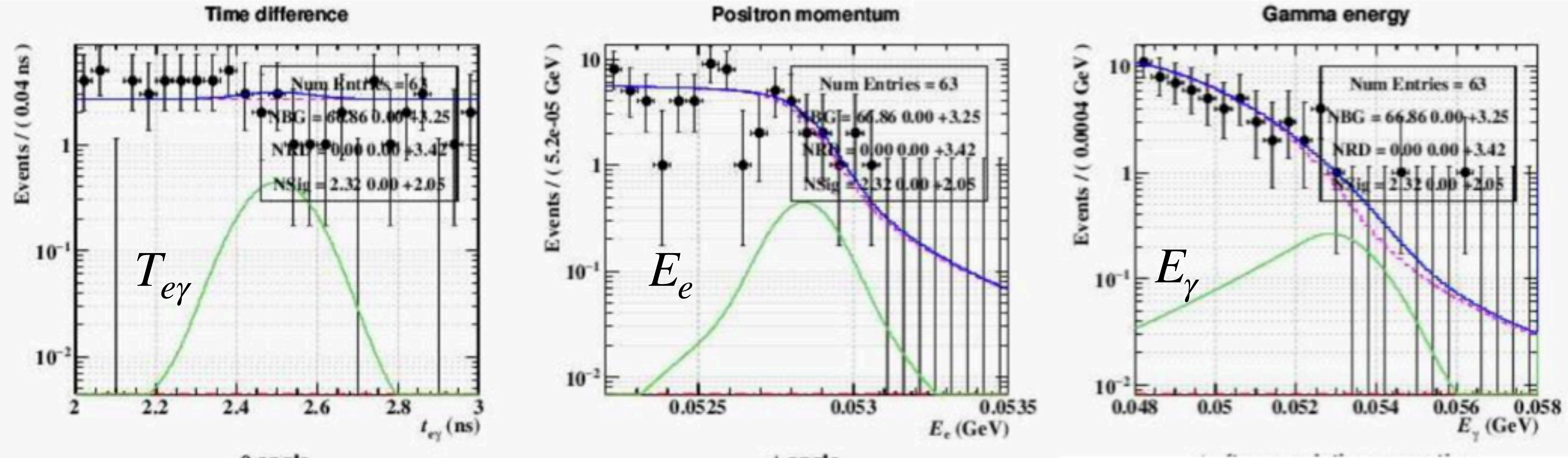
Performance summary

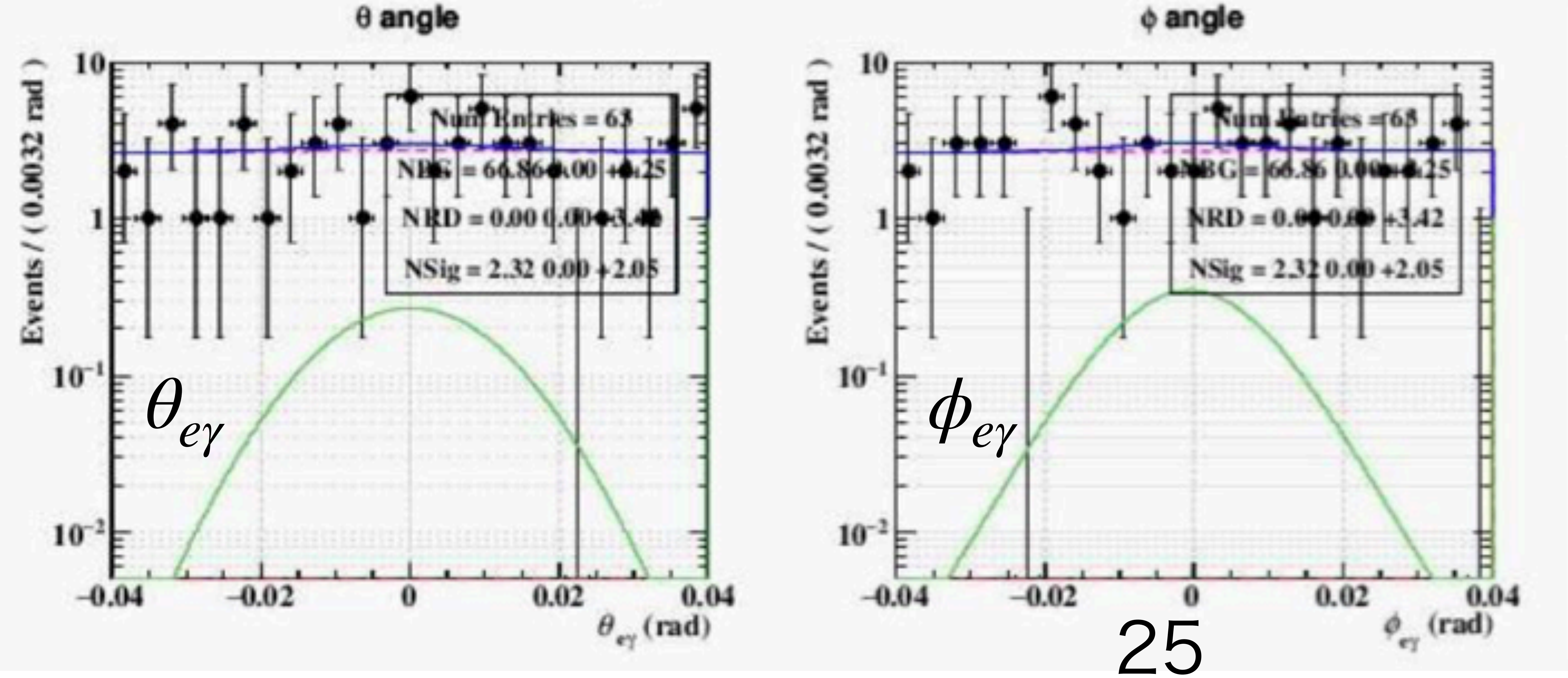
	P_e	θ_e	E_γ	x_γ	$T_{e\gamma}$	ε_e	ε_γ
MEG	380keV/c	9.4mrad	2.4%/1.7%	5mm	122ps	30%	63%
MEG II proposal	130keV/c	5.3mrad	1.1%/1.0%	2.4mm	84ps	70%	69%
MEG II updated (2021)	100keV/c	6.7mrad	1.7%/1.7%	2.4mm	70ps	65%	69%
MEG II current	89keV/c	7.1mrad	2.0%/1.8%	2.5mm	78ps	65%	63%

- 2021 data analysis will be done with the performance shown in this table

A paper dedicated to the operation and the performance of the MEG II detector will be published soon.

Sideband fit result





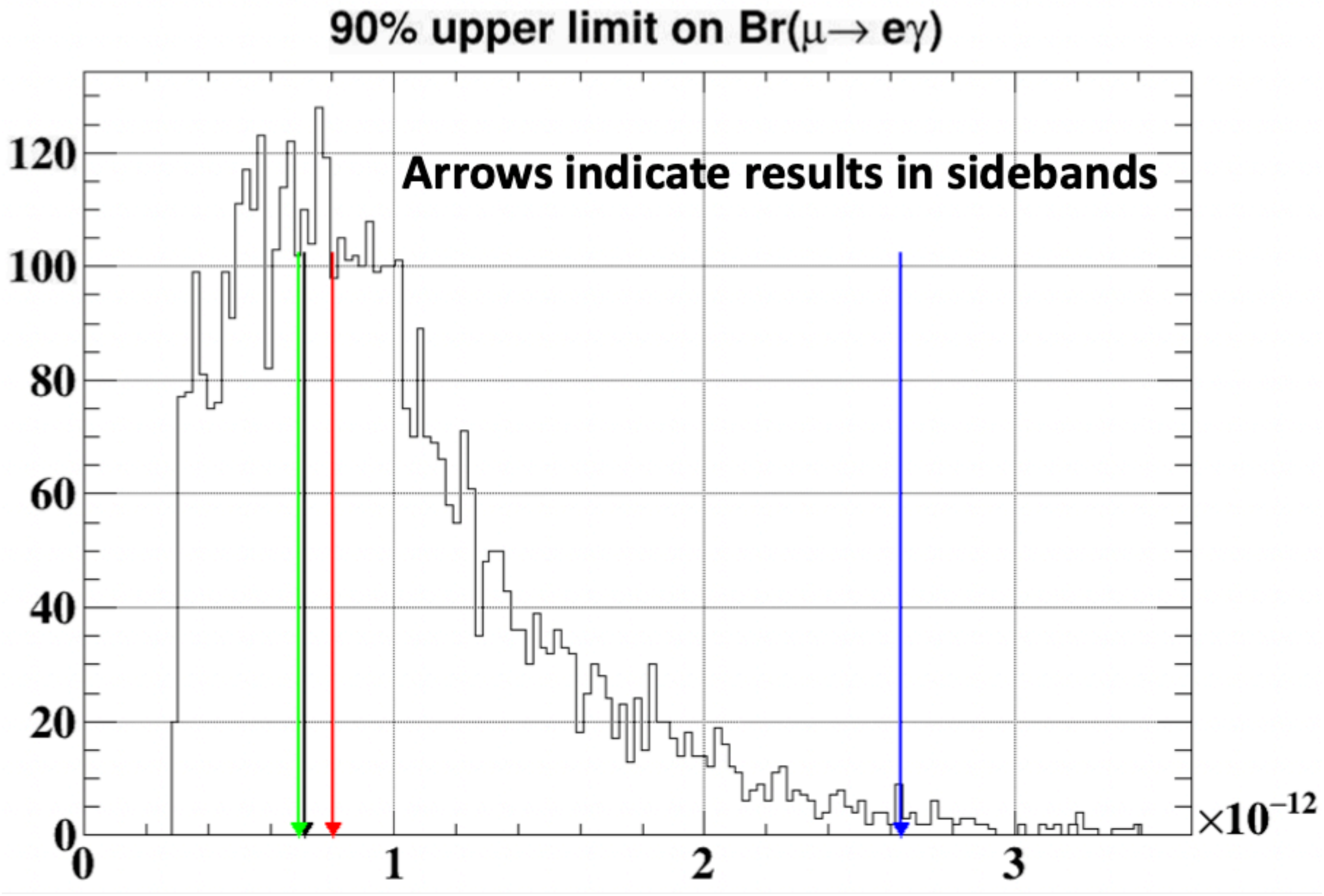
- Four time sideband regions are fitted
  - This one : 2–3ns

Event distribution in sideband example

- 5 high rank events in signal likelihood ratio S(x)/B(x)

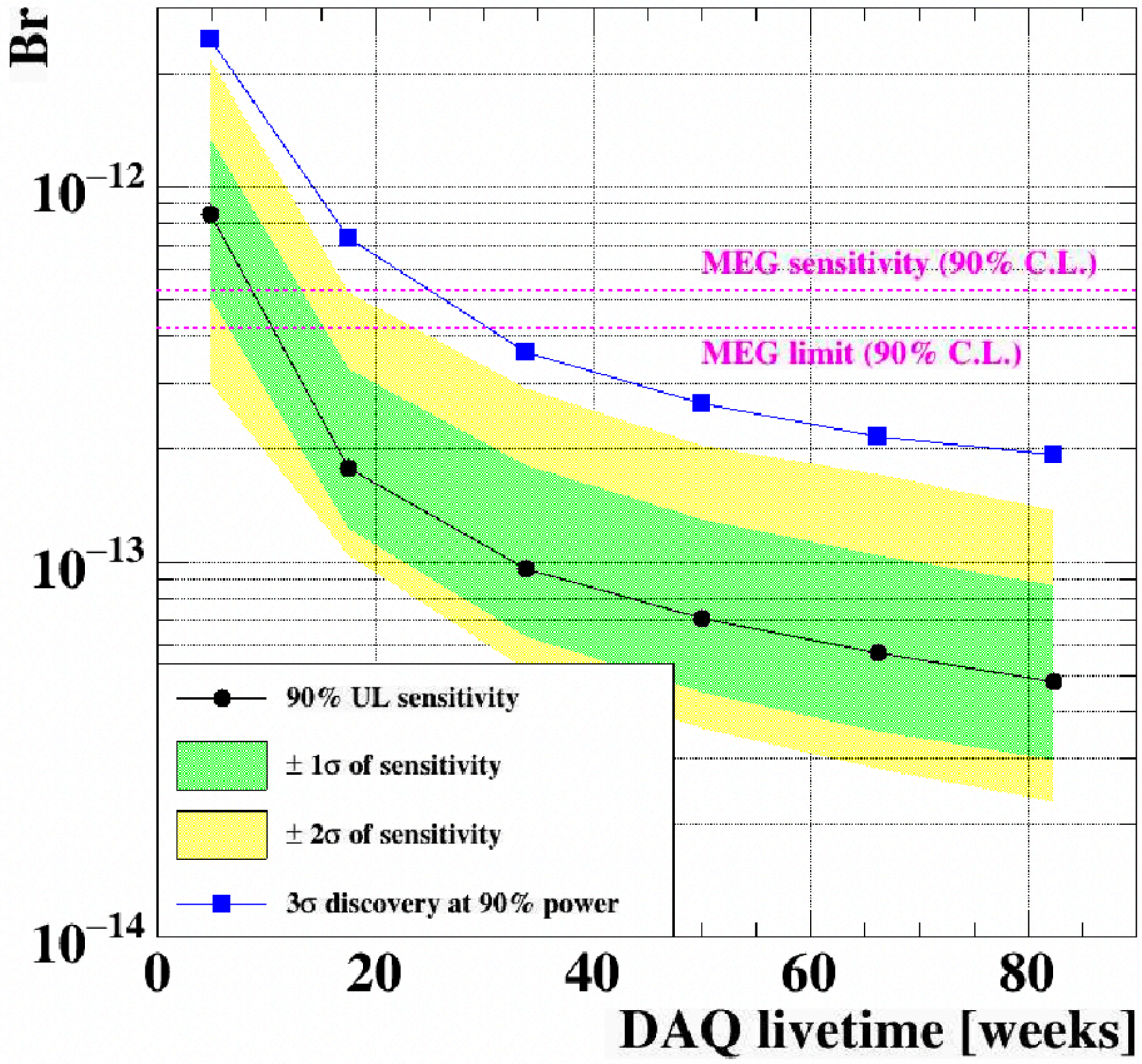
2021 Data Sensitivity

- Branching ratio
  - Br = N_{sig}/N_{μ}
    - N_{μ}: the number of effectively measured muon decays
- N_{μ} in 2021
  - Michel positron counting method
    - $(2.55\pm0.13)\times10^{12}$
  - RMD counting method
    - $(3.1\pm0.3)\times10^{12}$
  - Combined : $(2.64\pm0.12)\times10^{12}$
- Sensitivity of 2021 data
  - Median 90% C.L. upper limit for BG-only hypothesis
  - **8.8×10^{-13}**
  - Systematics : 3–4% contribution
- Result will be published in a PSI Special Seminar on 20th October 2023. Stay tuned.



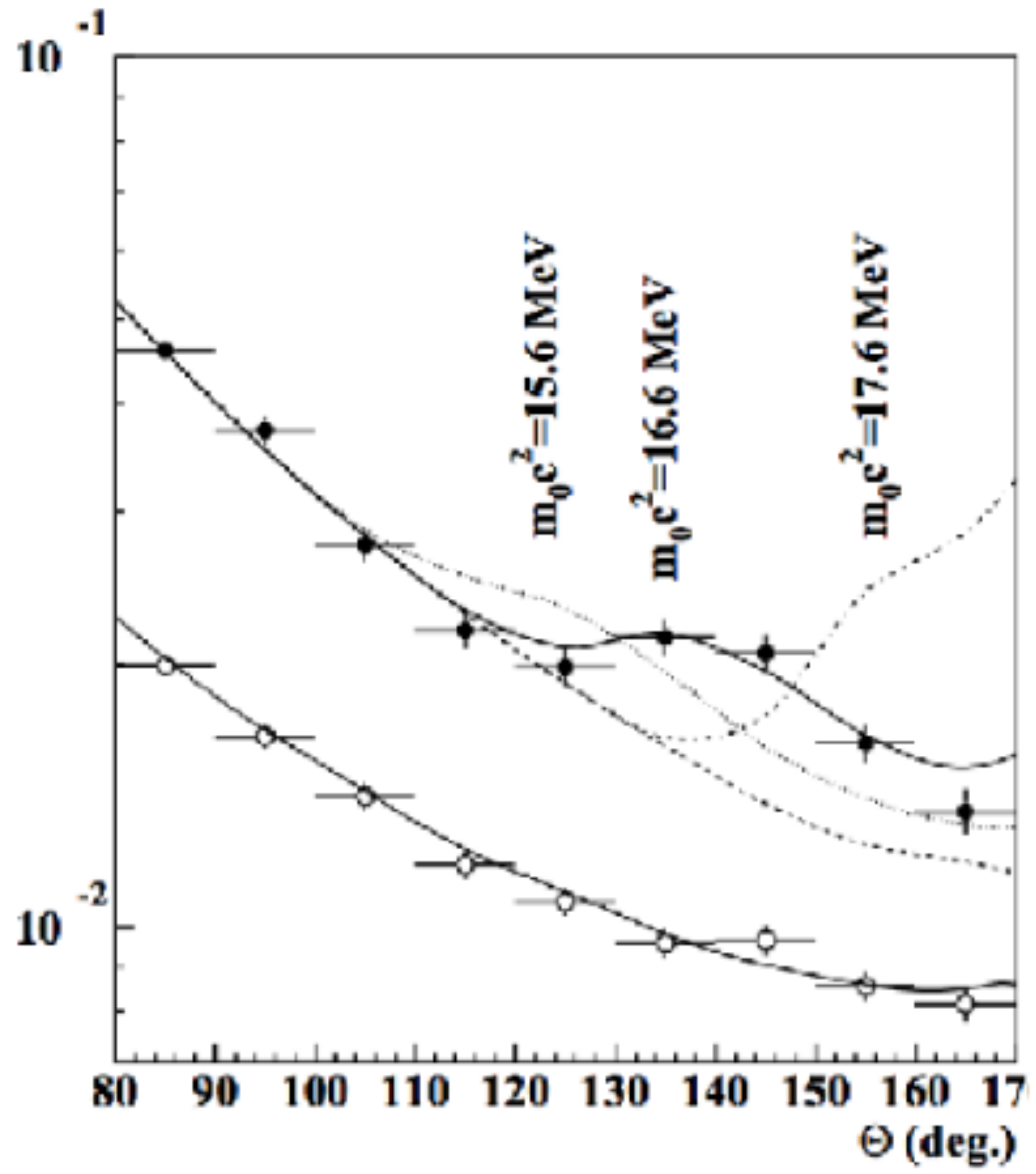
MEG II prospects

- MEG II experiment will accumulate the physics data several years at least until 2027
  - The PSI accelerator beam line has an upgrade plan (HiMB) to have the beam intensity of 10^{10} μ/s starting from 2027
  - The PiE5 beamline will be shared with Mu3e experiment
- The sensitivity of the MEG II experiment will reach Br(μ→eγ) ~(5–6)×10^{-14} @90%C.L. by then
- In parallel, 2022 analysis is ongoing. The results will be published next year which will have better sensitivity than MEG

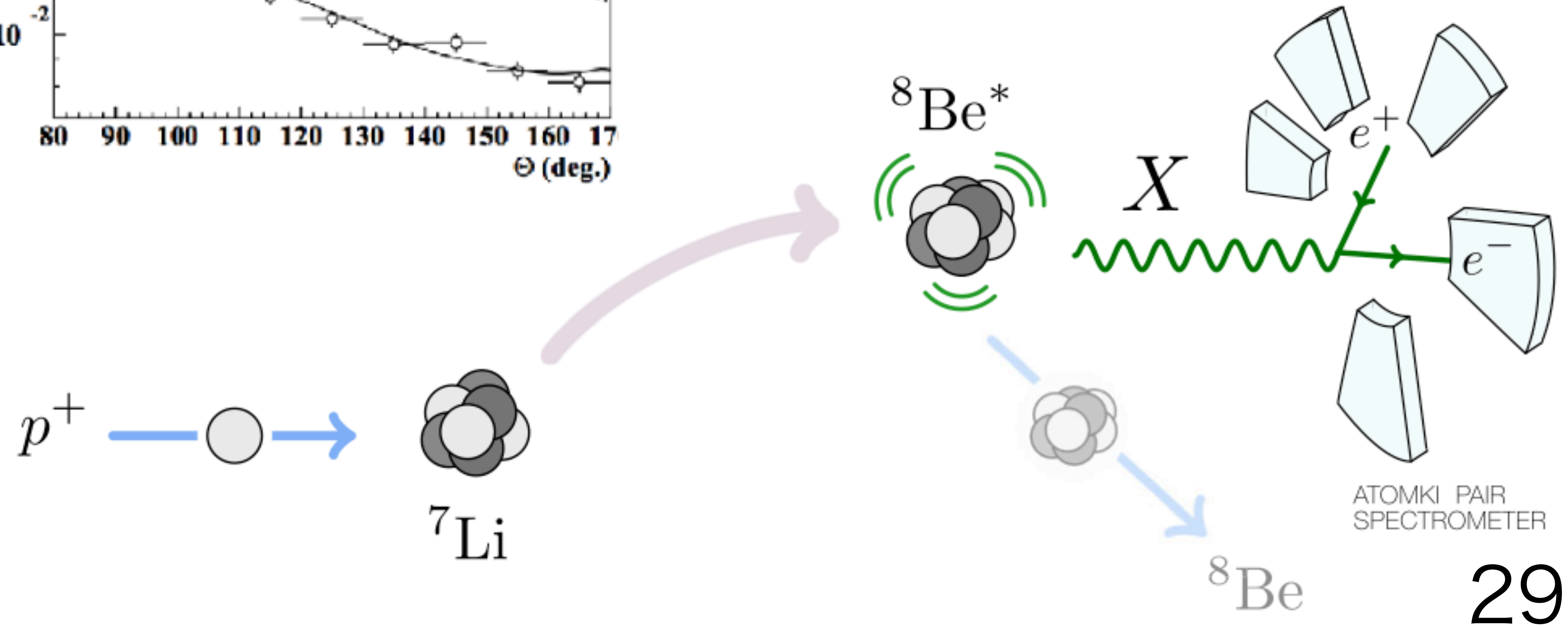


Beryllium anomaly

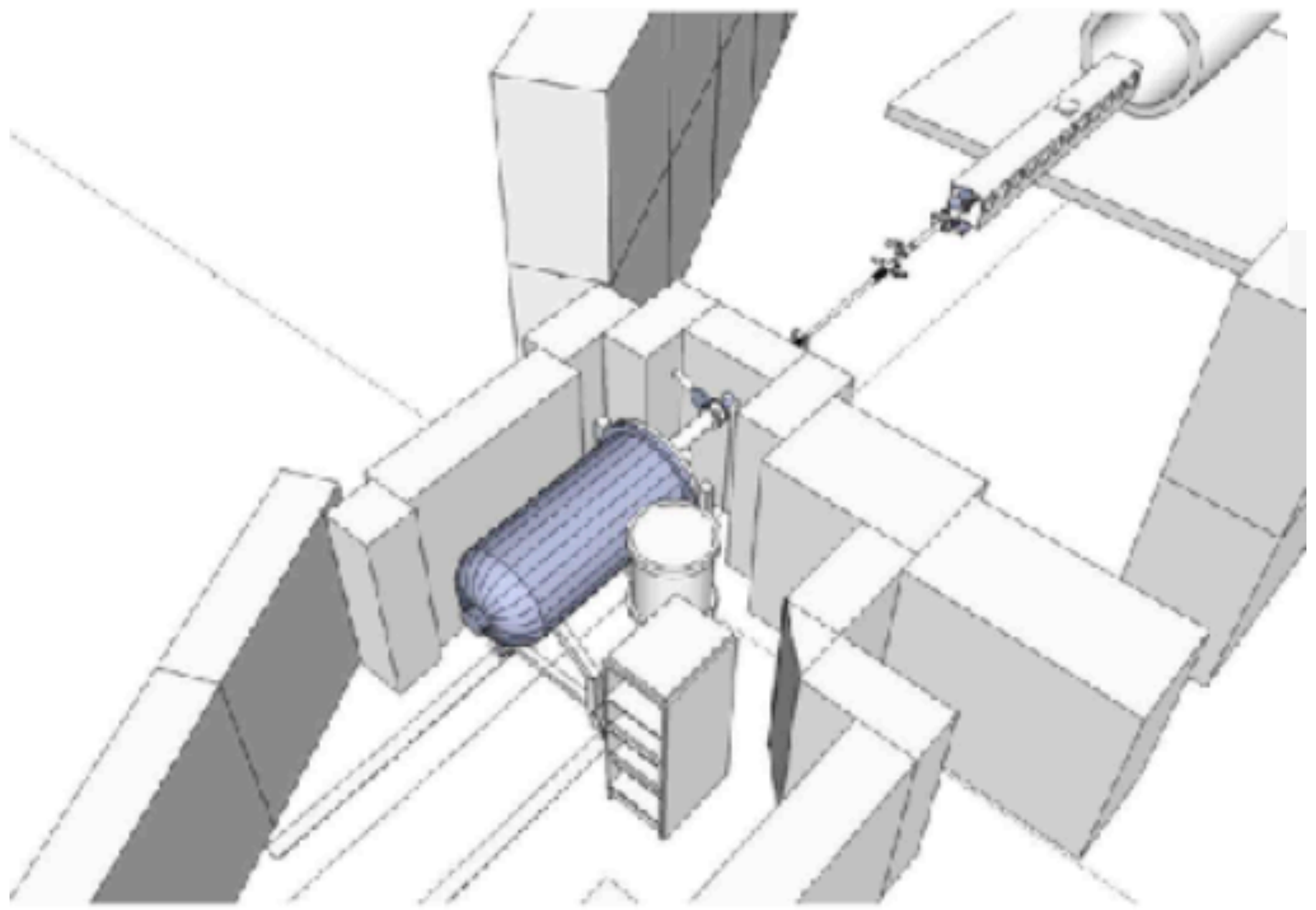
- Hint for a neutral, 17MeV boson: X17 (ATOMKI collaboration)

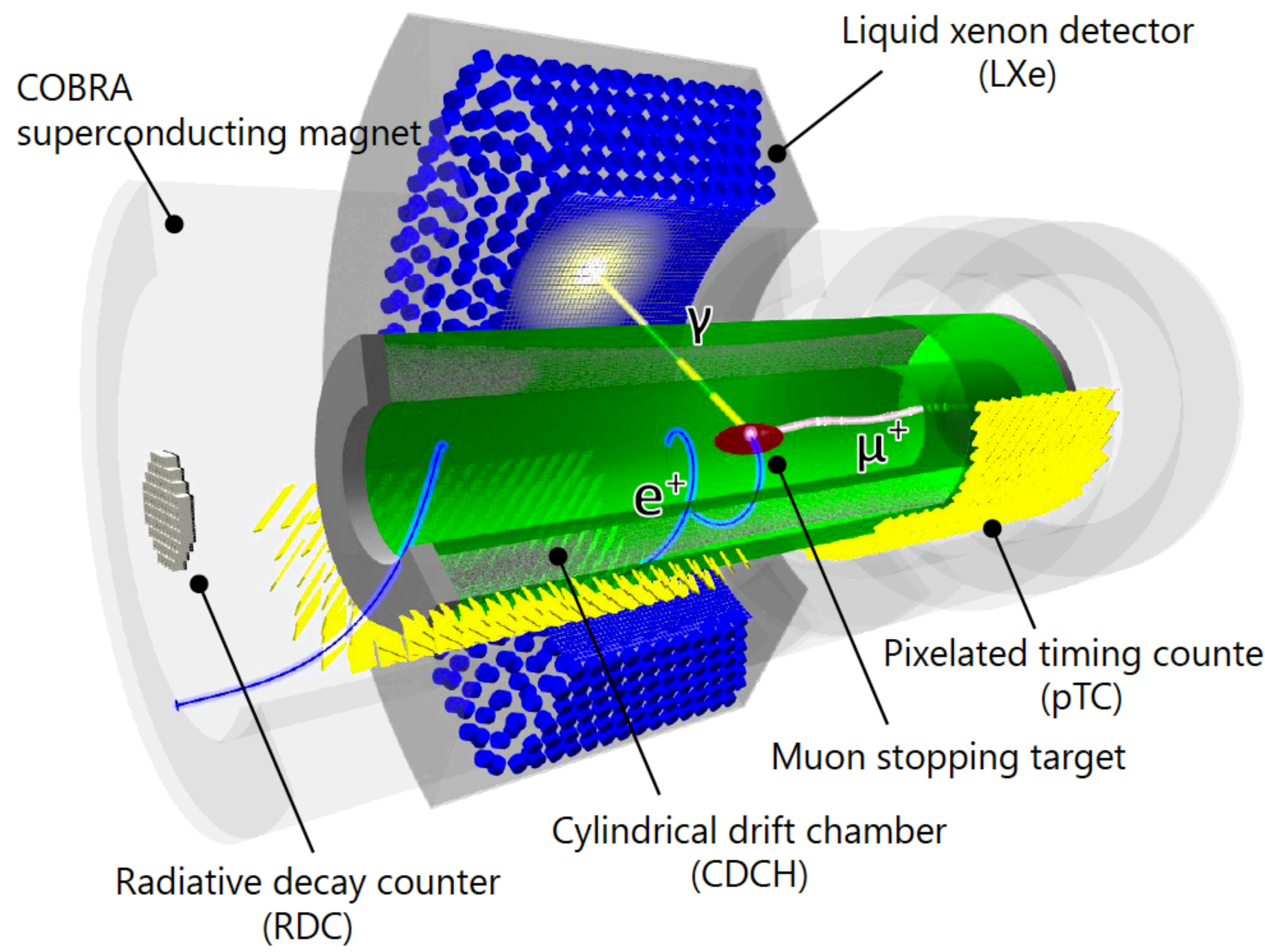


- Observed in $^7Li(p, e^+e^-)^8Be$ reaction
- Excess consistent with light boson mass = 16.95 MeV/c^2
- Branching ratio (X17/γ) = 6×10^{-6}

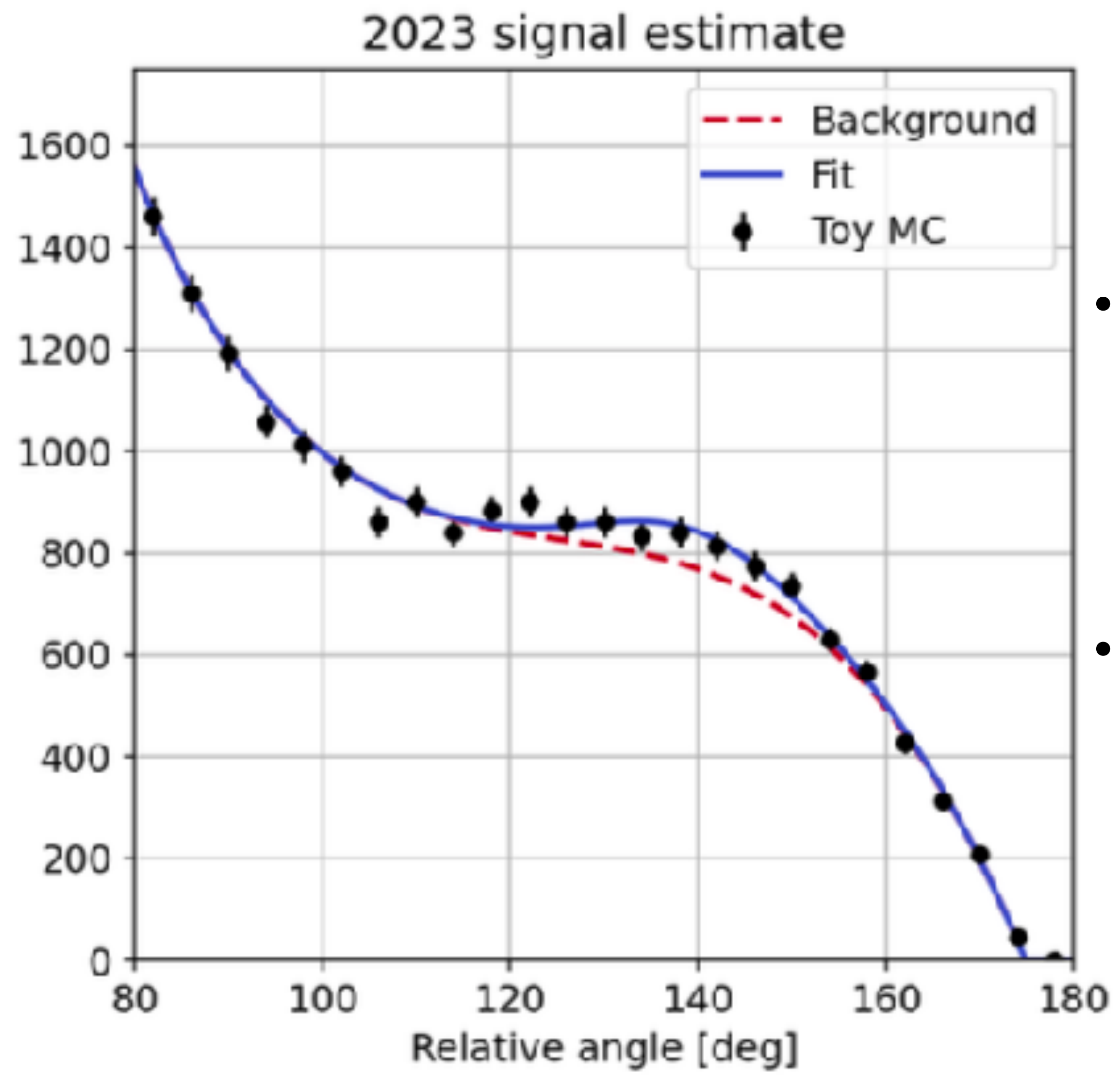


The MEG II CW accelerator and its beamline





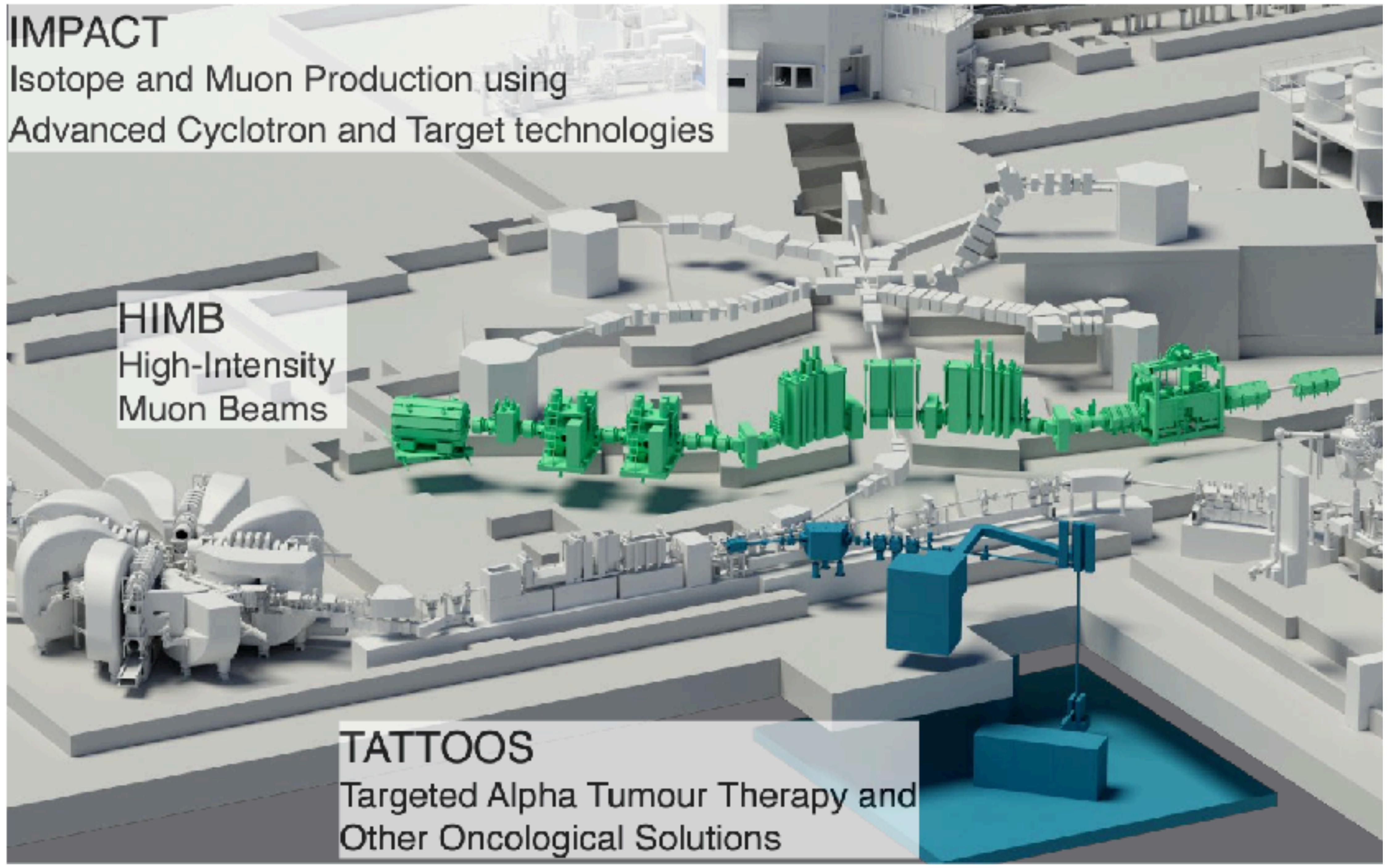
- MEG II has a dedicated CW accelerator for 17.6MeV γ for LXe calibration purpose
- This can be used for X17-boson searches



- Data were taken in 2023 during PSI accelerator shutdown period
- Results will be published soon

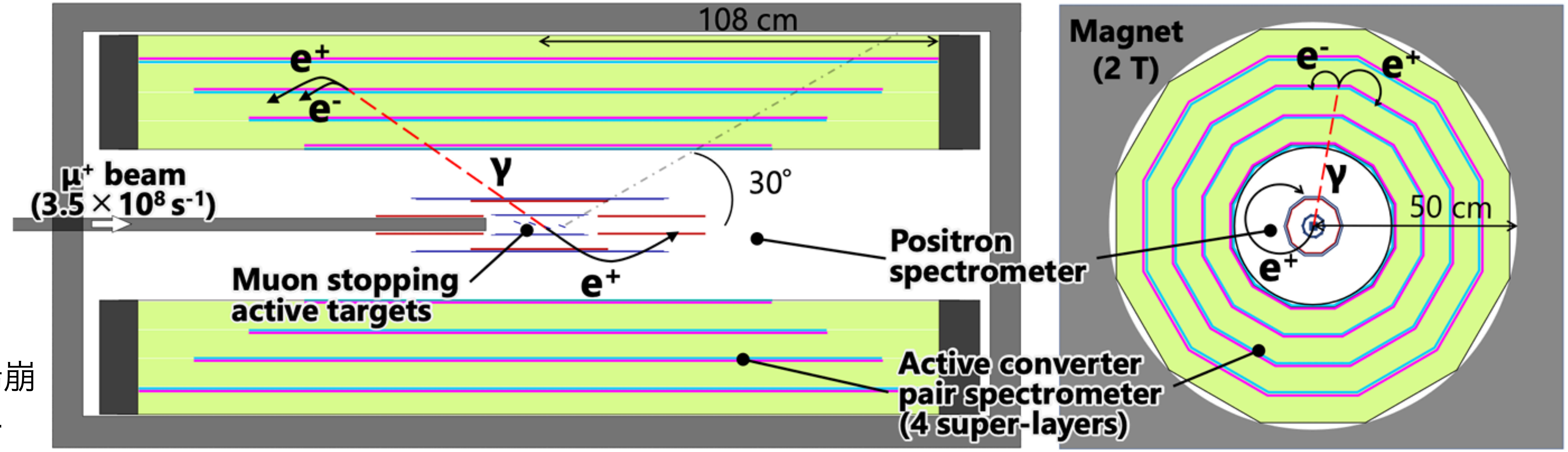
Future prospects (1)

- New experiment for $\mu \to e\gamma$ search
  - HiMB project at PSI (~$10^{10}\mu/s$) (2027 – 2028)
  - High resolution, high rate capability for the detectors
- Photon pair spectrometer with active converter
  - Better resolutions, angle measurements
- Silicon positron spectrometer similar with Mu3e
- Separate active targets



16pRA81-12

- Target sensitivity
  Br($\mu \to e\gamma$) ~
  $\mathcal{O}(10^{-15})$

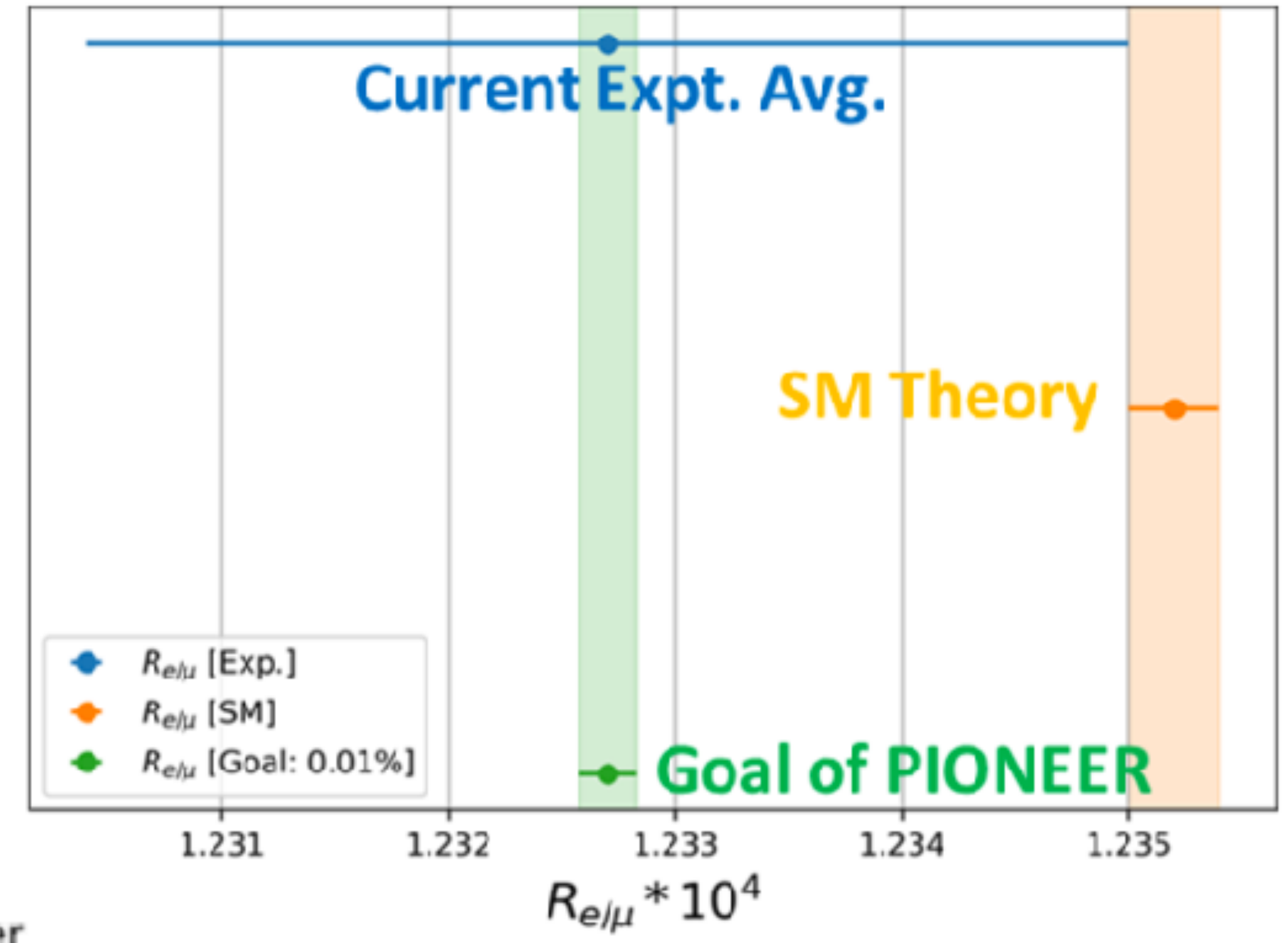


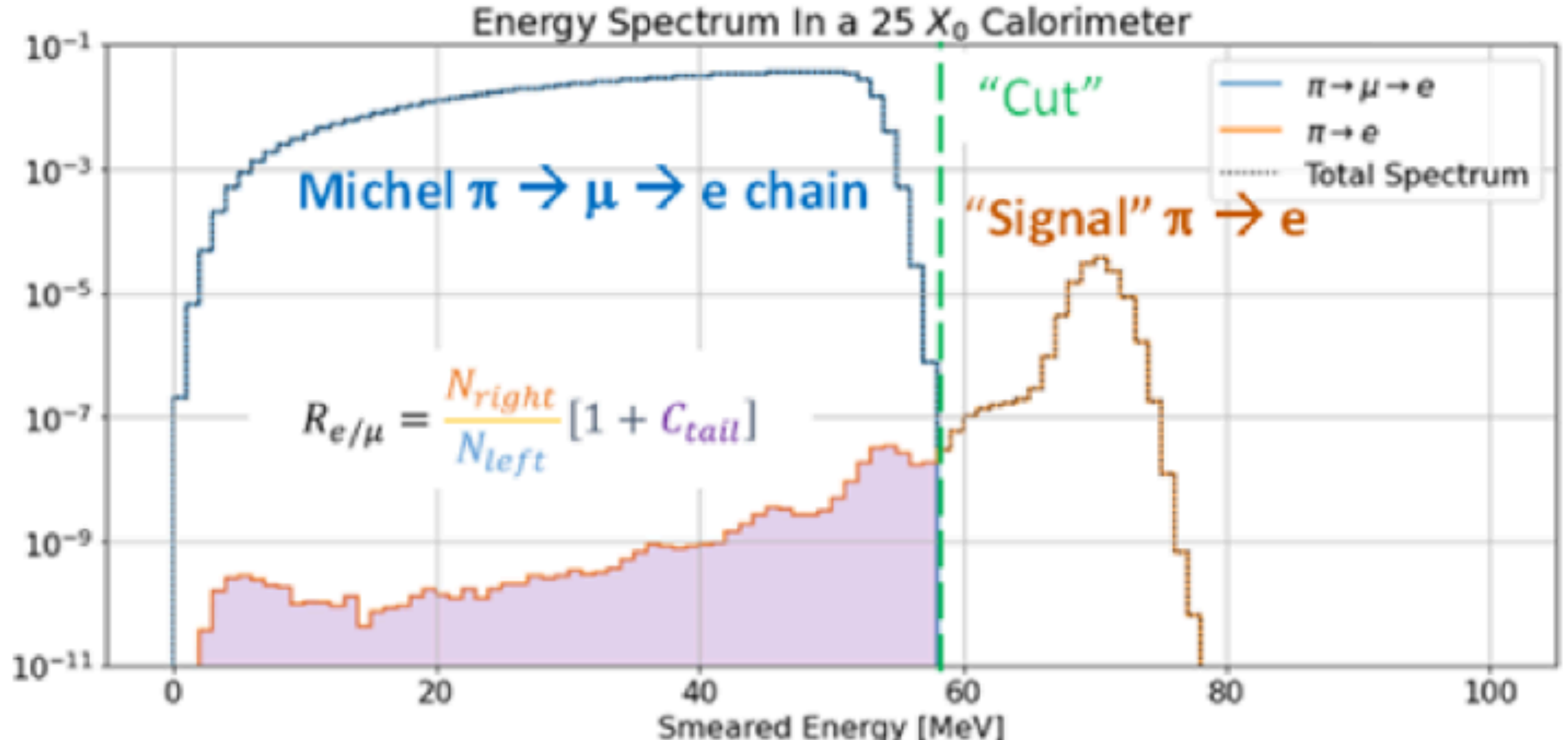
基盤S (代表 大谷航)
世界最高感度のミュー粒子稀崩
壊探索で迫る素粒子の大統一

Future prospects (2)

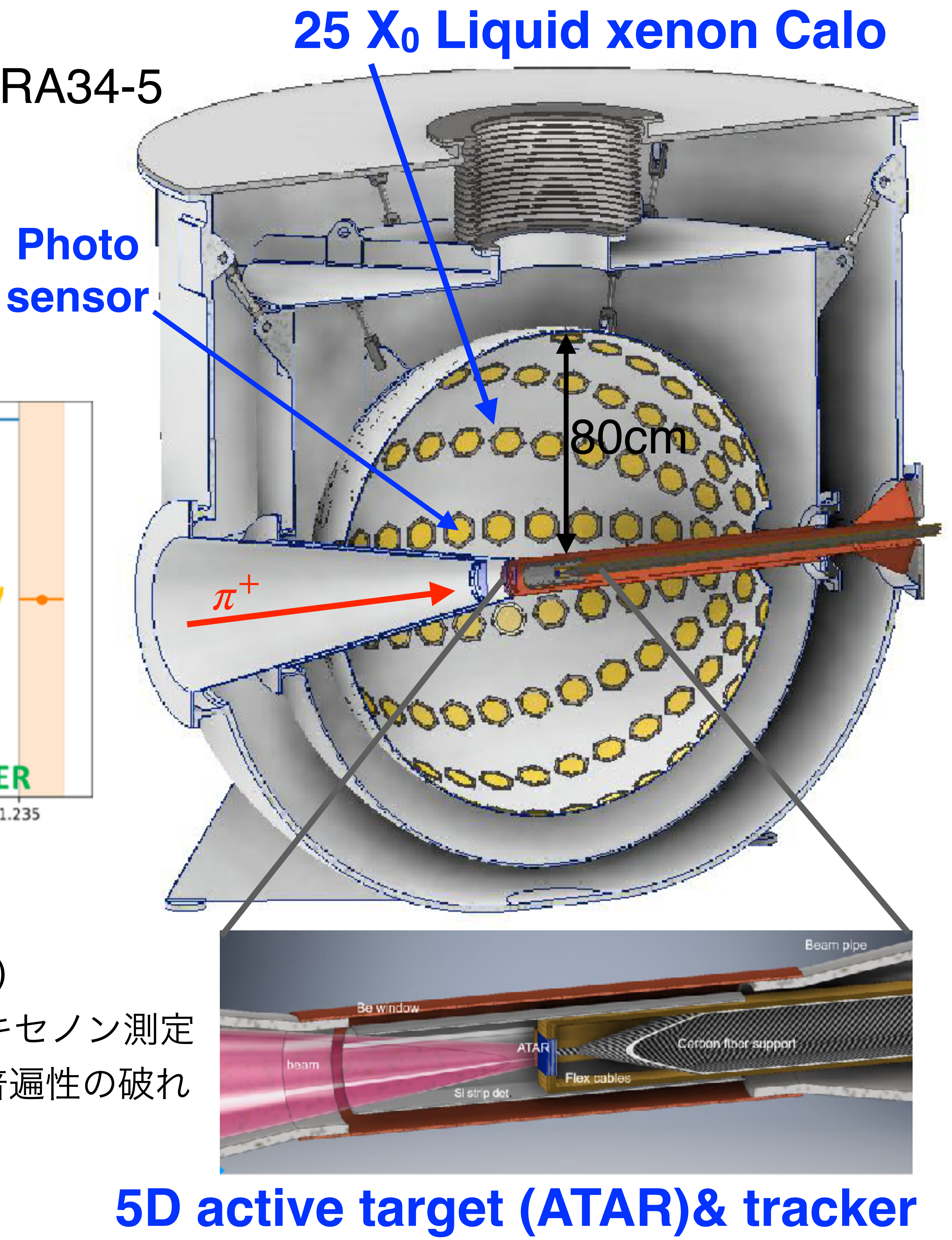
16pRA34-5

- PIONEER experiment
  - to explore the lepton universality violation & CKM unitarity with rare pion decays
  - $$R_{e/\mu} = \frac{\pi \to e\nu}{\pi \to \mu\nu}$$
  - Fast, uniform LXe calorimetry with excellent energy resolution <1.5% to suppress low energy tail
  - Mature LXe technology by MEG





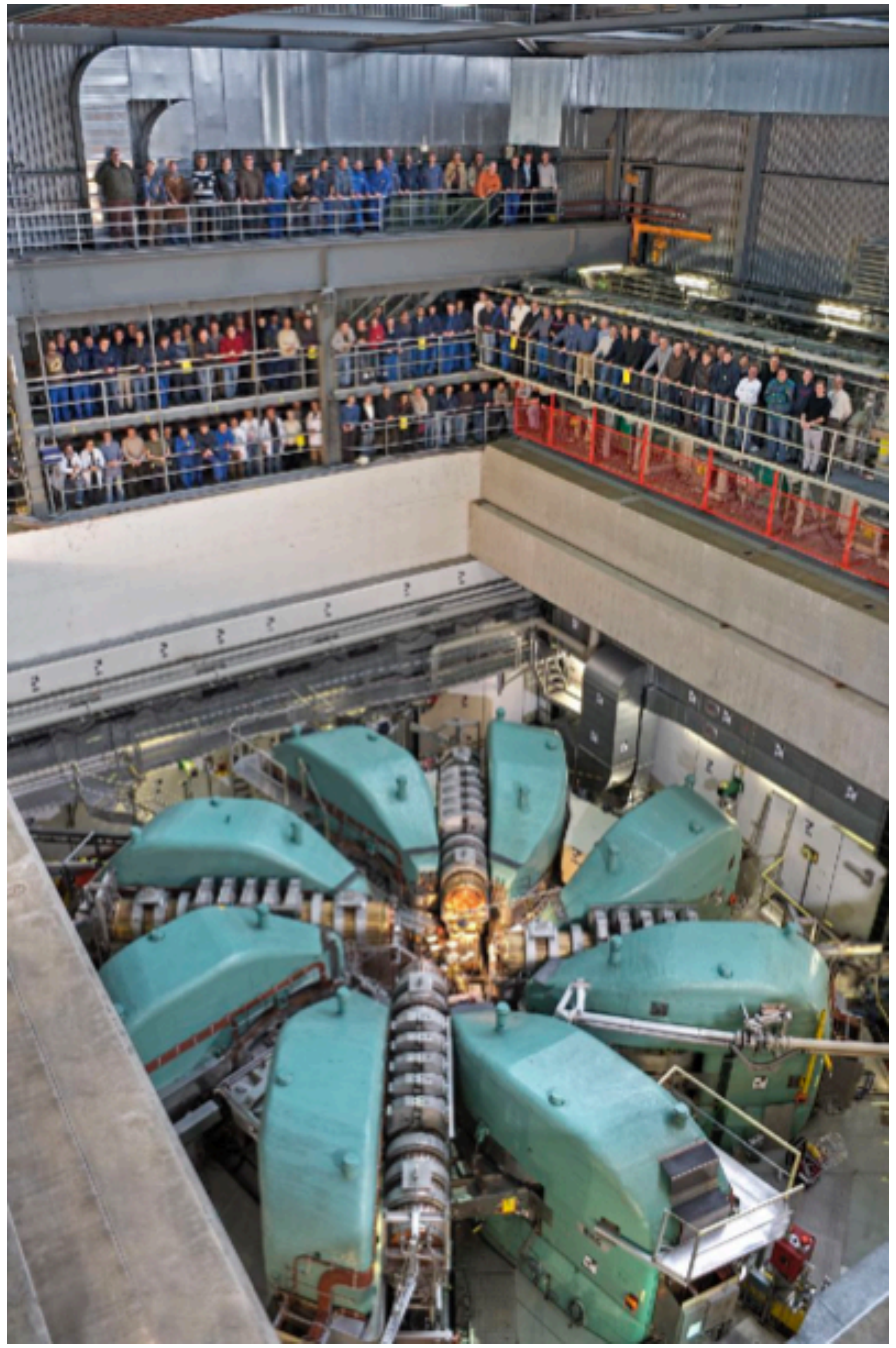
基盤A (代表 森俊則)
高分解能大型液体キセノン測定器によるレプトン普遍性の破れの精密検証

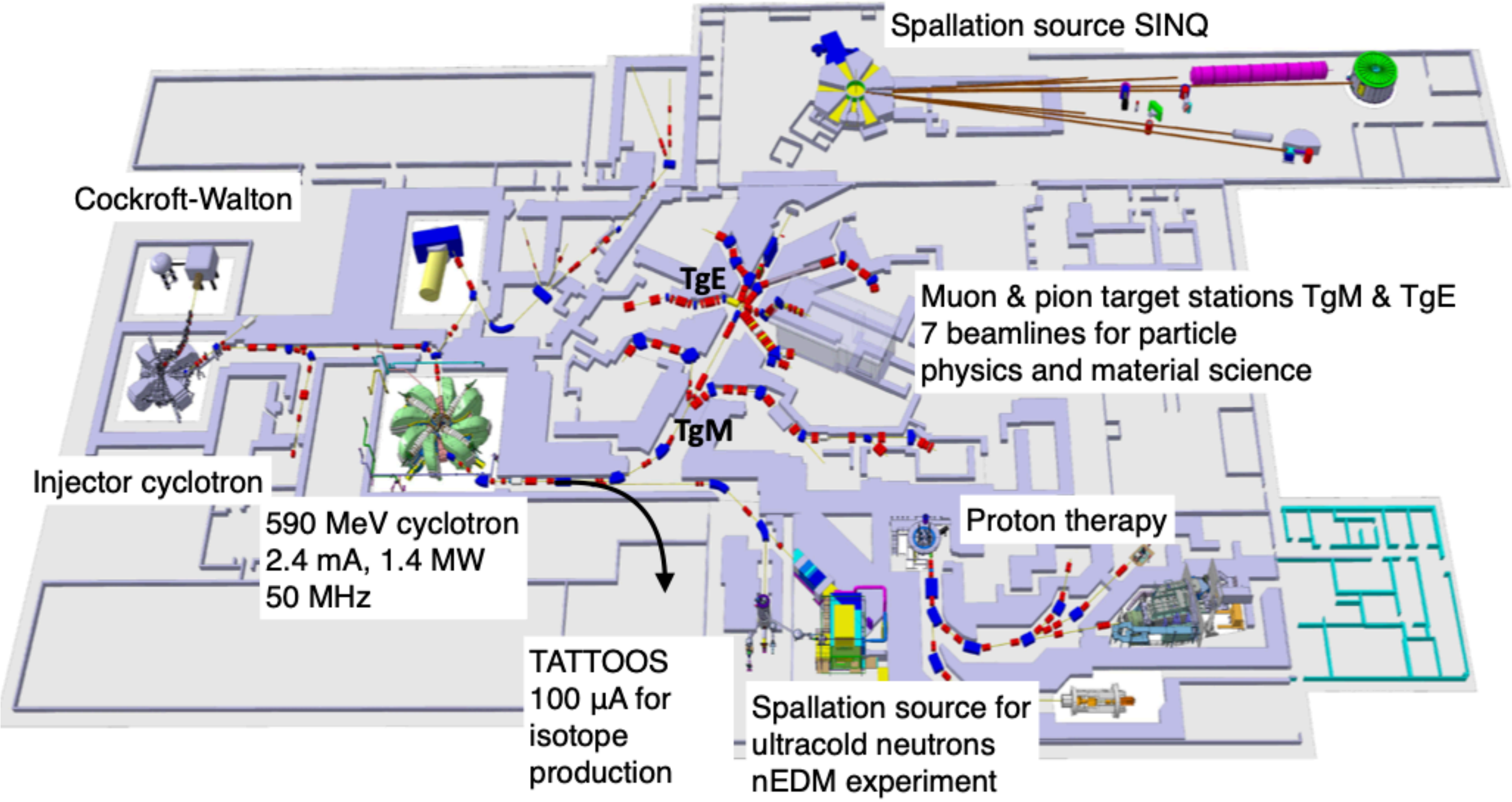


Conclusion

- The MEG II experiment has started physics run in 2021, and the results based on 2021 data with the sensitivity of 8.8×10^{-13} will be published soon.
- The sensitivity of 2022 data will be $\sim2\times10^{-13}$ well beyond the MEG experiment, and the publication for the 2022 data is aimed at next year.
- Our target sensitivity (6×10^{-14}) will be reached in several years.

PSI accelerator

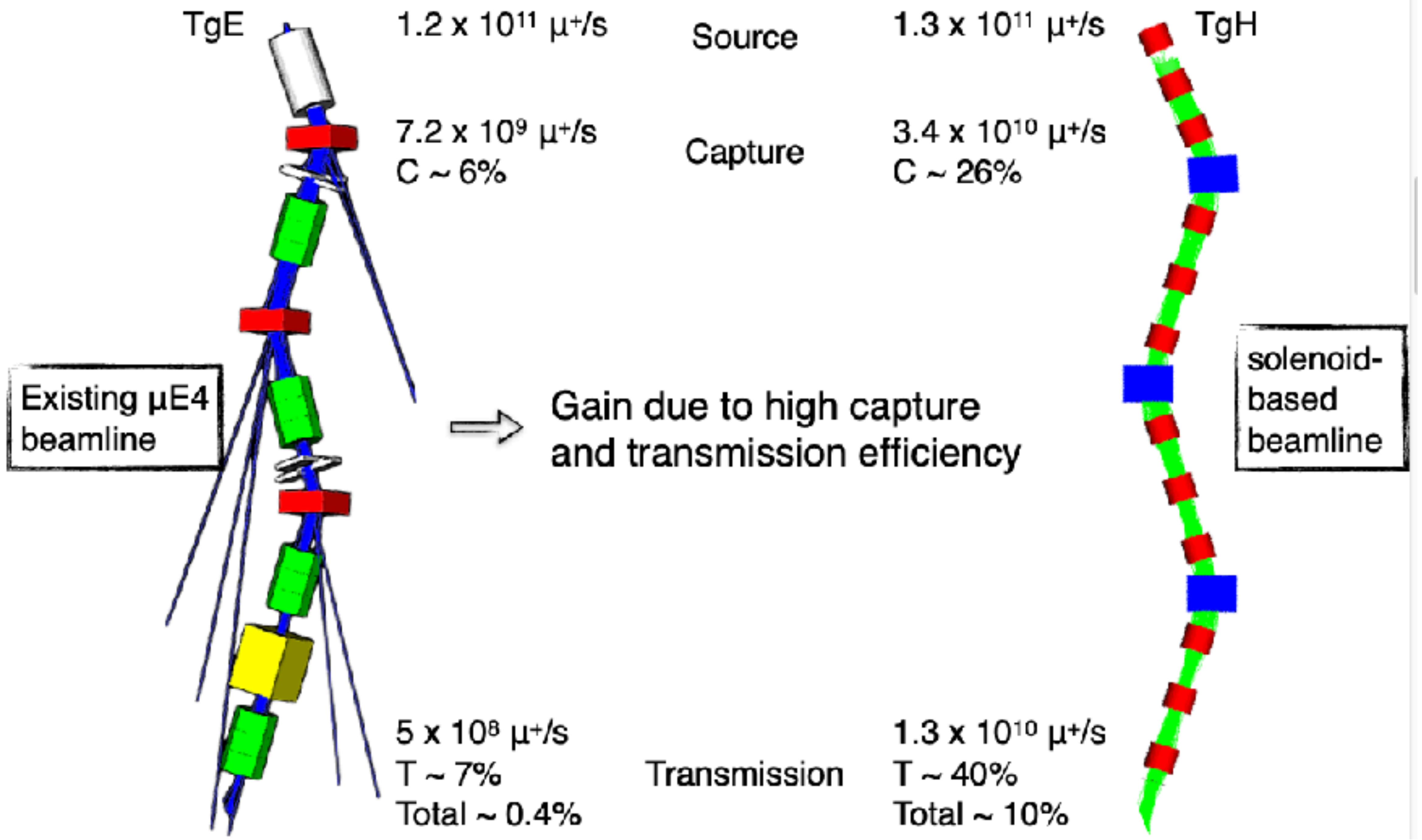


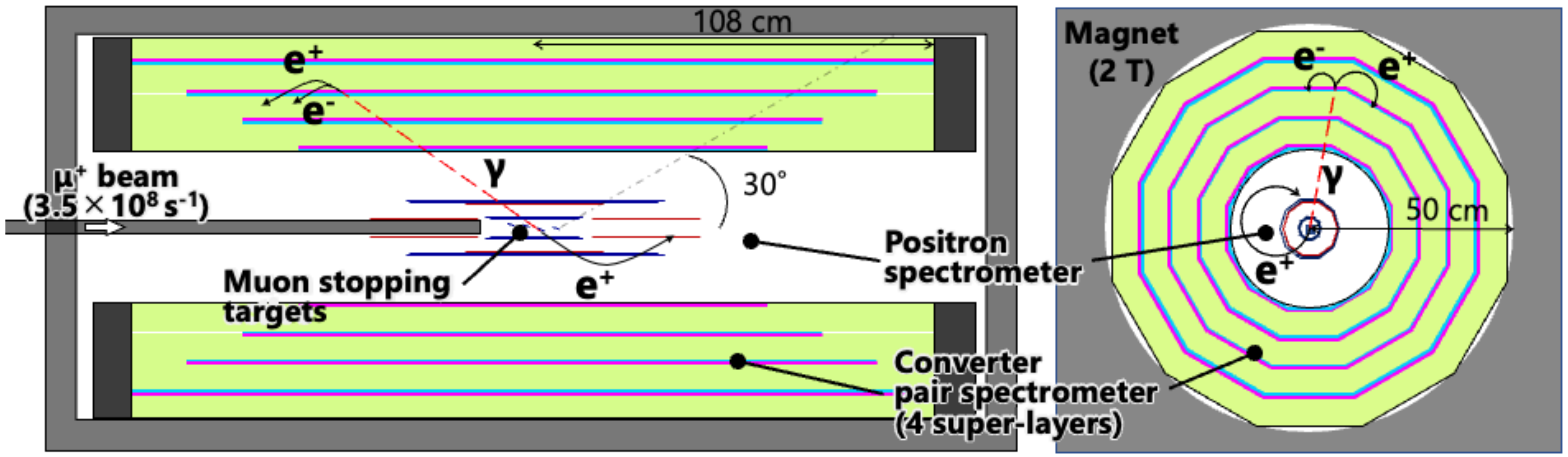


- CHRISP - Swiss Research InfraStructure for Particle physics at Paul Scherrer Institute in Switzerland
- World most intense DC muon beam available : > $10^8 \mu^+/s$
- High precision particle physics experiments complementary to the experiments at the highest energies at CERN's LHC
- There is an upgrade project, HIMB (High Intensity Muon Beam) project, 10^{10} μ/s
  - Science case workshop 6-9 April 2021
  - Conceptual Design Report by end 2021
  - Implementation during 2027/2028 during 16-months HIPA shutdown

After MEG II

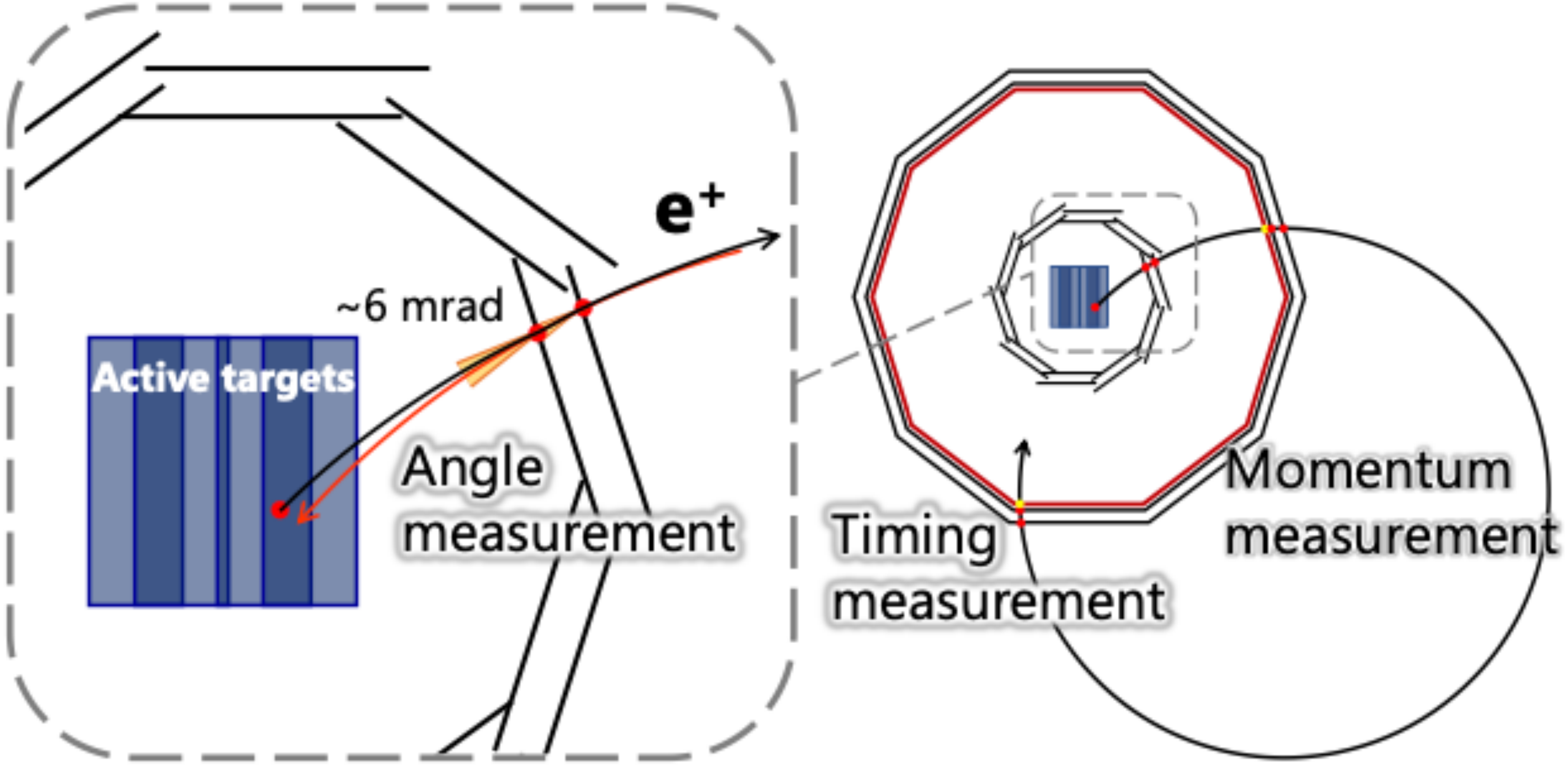
- High Intensity Muon Beam project (HiMB) at PSI
  - 10^{10} μ^+/s (100× improvement)
  - CDR by end of 2021
  - Implementation during 2027/2028
  - Science Case workshop 6-9 April 2021
- Future μ→eγ experiment for CLFV
  - Goal: Br(μ→eγ) ~10^{-15}
  - Discover new physics and precision measurements
  - Detector R&D to make maximum use of HiMB
  - Resolution improvements
    - Calorimeter → converter + pair spectrometer
  - High rate tolerance
    - Drift chamber → Silicon detector
- Possible to measure μ→eee at the same time

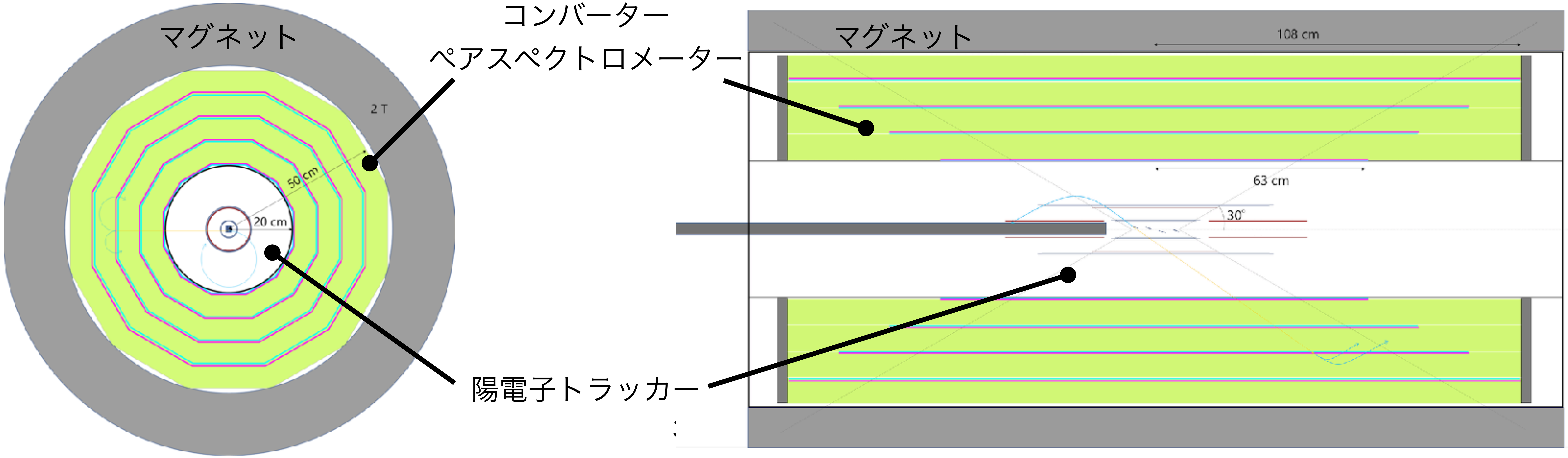


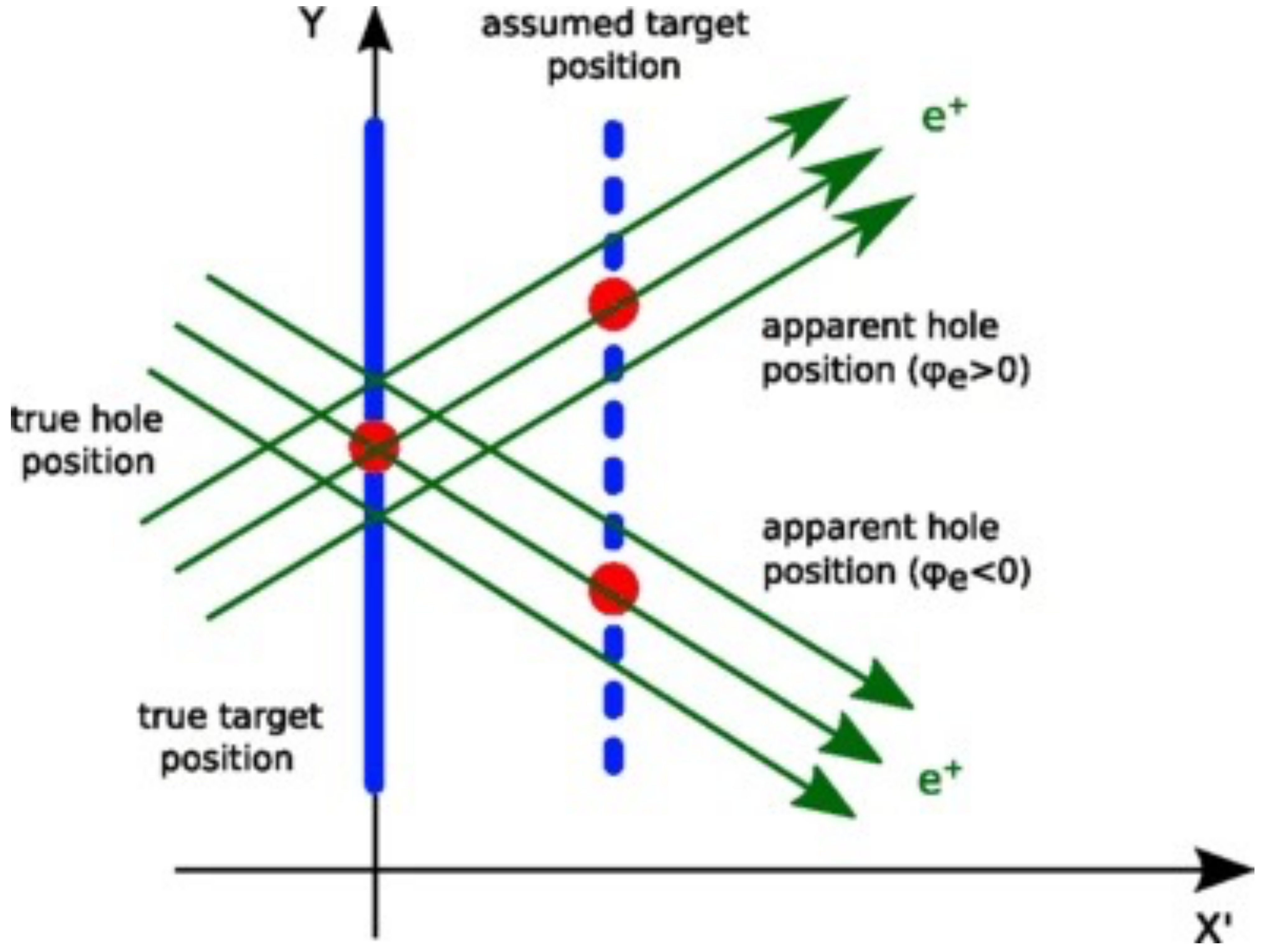


Future μ→eγ

- Positron spectrometer
  - HV-MAPS + scintillator or mRPC
  - Resolutions
    - energy 0.3%(150keV)・time 30ps・angle 6mrad・detection efficiency 70%
- Gamma converter + pair spectrometer
  - Resolutions
    - energy 0.4% (200keV)・time 30ps・position 0.2mm・angle 50mrad・detection eff. 60%






Y
assumed target position
e+
apparent hole position (φe>0)
true hole position
apparent hole position (φe<0)
true target position
e+
X'