Searching for flavour violation in the charged lepton sector with the COMET experiment at J-PARC

C Cârloganu, LPC/IN2P3/CNRS

Fermion mixings in the SM

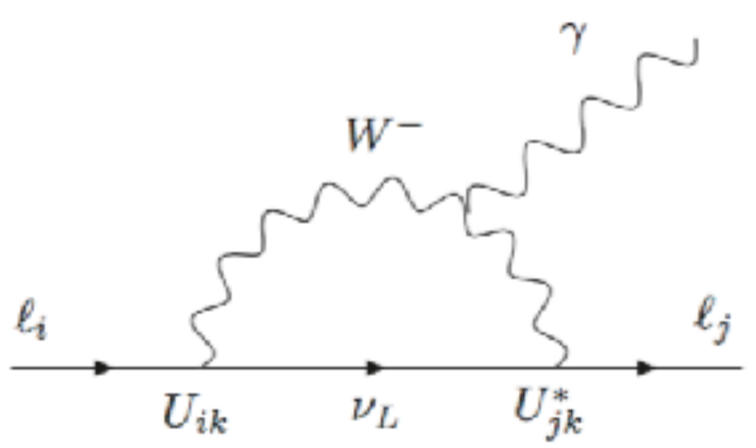
Quark sector:

- Flavour violated by charged current interactions $V_{ij}^{CKM} W^{\pm} \bar{q}_i q_j$
- Observed in oscillation/decay processes

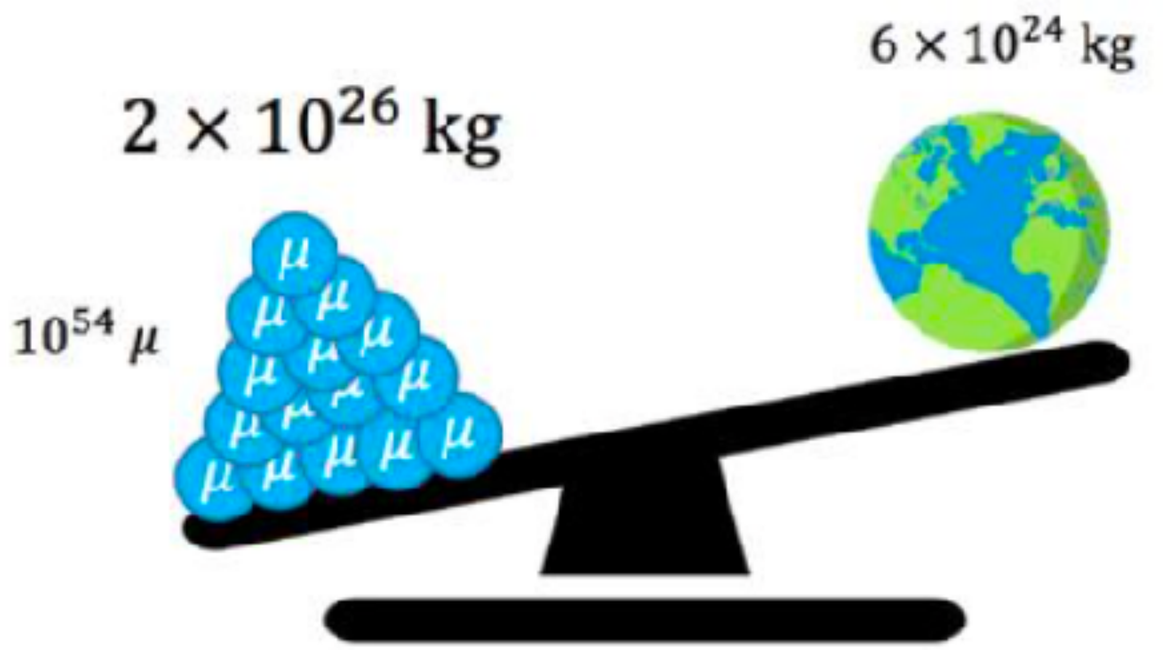
$$K^0 - \bar{K}^0,\ b \to s\gamma,\ D^+ \to \pi^+\mu^+\mu^-\ (c\bar{d} \to u\bar{d})$$

Lepton sector:

- Massive, oscillating neutrinos → flavour violation $U_{PMNS} W^{\pm} \bar{l} \nu$



$$\mathrm{BR}(\mu \to e\gamma) \propto \left| \sum U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \sim 10^{-54}$$



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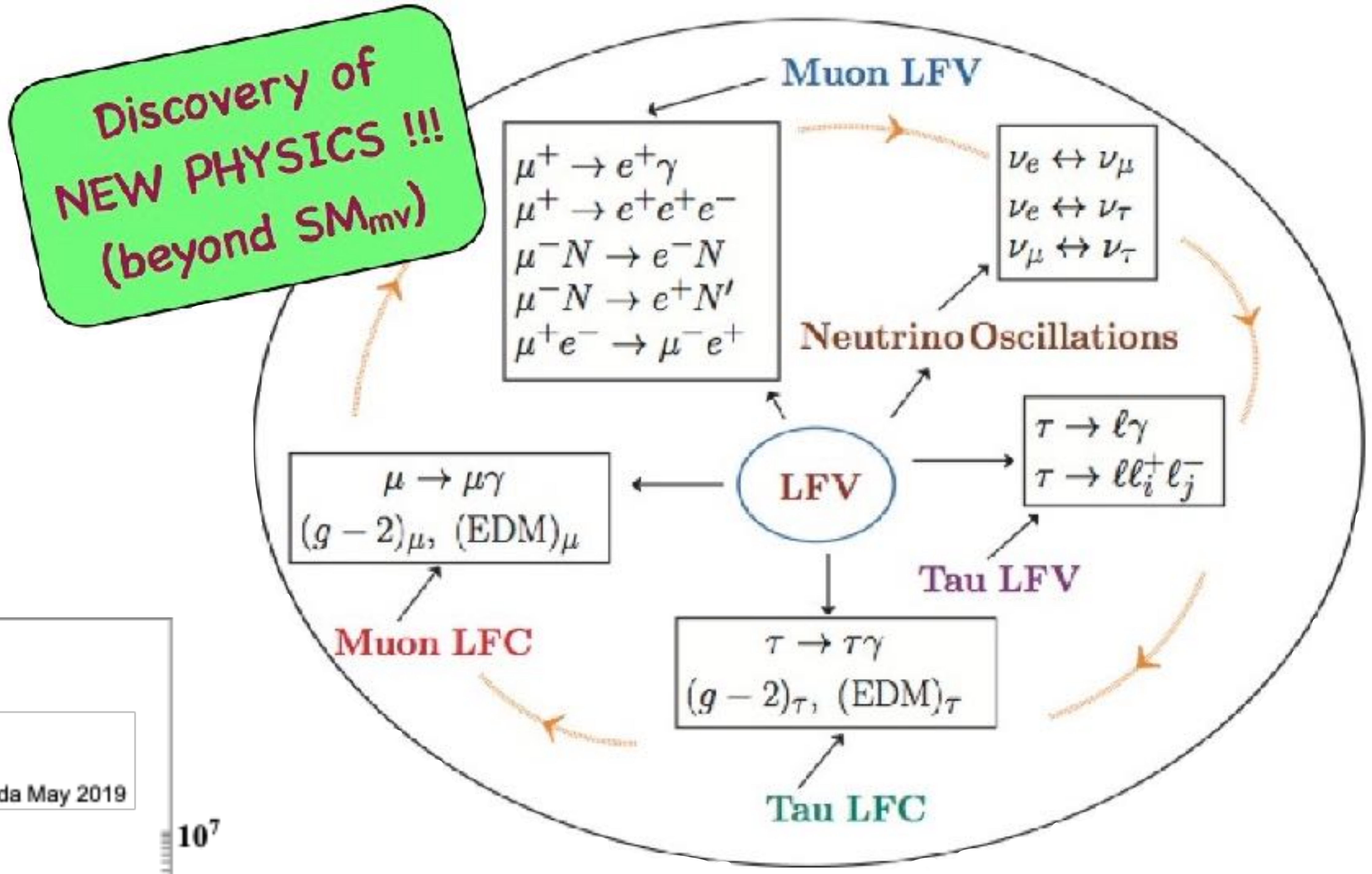
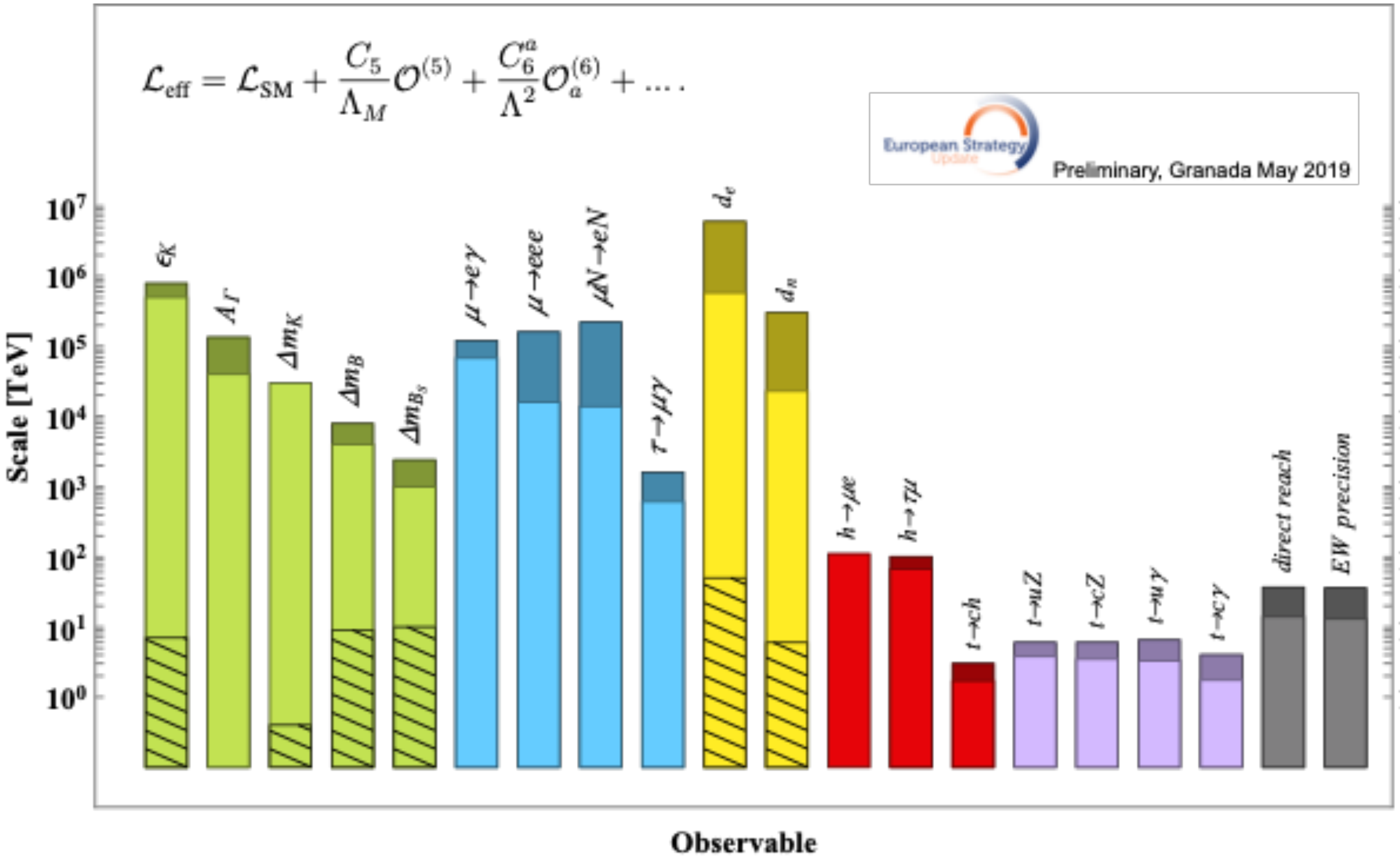
if cLFV observed ⇒ New Physics in the lepton sector beyond minimally extended SM

Sensitivity of leptonic observables to New Physics

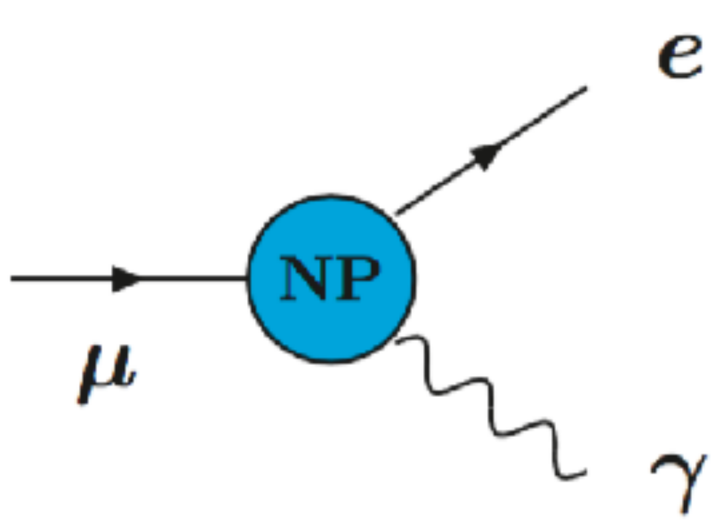




$\tau \to e\gamma$	$<3.3 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	superKEKB
$\tau \to eee$	$<2.7 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	superKEKB
$\tau \to \mu\gamma$	$<4.4 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	superKEKB
$\tau \to \mu\mu\mu$	$<2.1 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	superKEKB/LHCb

cLFV in muon channels

μ → e γ

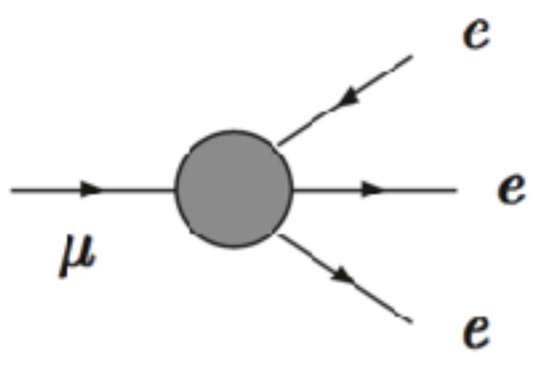


Coincident, back-to-back e^+ - γ

$E_e = E_\gamma = m_\mu/2$ (~ 52.8 MeV)

Collaboration	year	BR(μ → eγ) 90% C.L.
LAMPF/MEGA	1999	1.2×10^{-11}
PSI/MEG	2011	2.8×10^{-11}
PSI/MEG	**2016**	$\mathbf{4.2 \times 10^{-13}}$
PSI MEG II		4×10^{-14}

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



Σ E =m; $\Sigma \vec{P}$ =0

vertex; coincidence

Collaboration	year	BR(μ → eee) 90% C.L.
LAMPF/Crystal Box	1988	3.5×10^{-11}
PSI/SINDRUM	**1988**	$\mathbf{1.0 \times 10^{-12}}$
JINR	1991	3.6×10^{-11}
PSI/PSI/Mu3e		10^{-15} - 10^{-16}

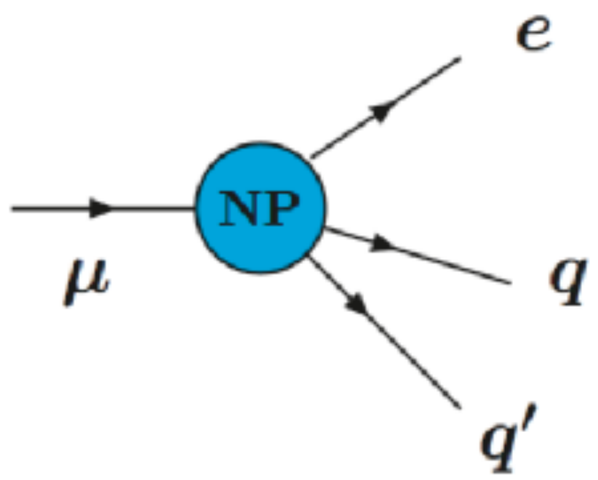
μ^-+ (A,Z) → e^-+ (A,Z)

E(Al, Pb, Ti) ≈100 MeV

single electron;

well defined energy

well defined time



CR(μ − e, N) bo		
4.3×10^{-12}		
4.6×10^{-11}		
7×10^{-13}	**Au**	2006

Experiment (material)	future sensitivity	year
Mu2e (Al)	$\mathbf{3 \times 10^{-17}}$	~ 20xx
COMET (Al) - Phase I (II)	10^{-15} (10^{-17})	~ 20yy(zz)
PRISM/PRIME (Ti)	$\mathbf{10^{-18}}$	
DeeMe (SiC)	10^{-14}	

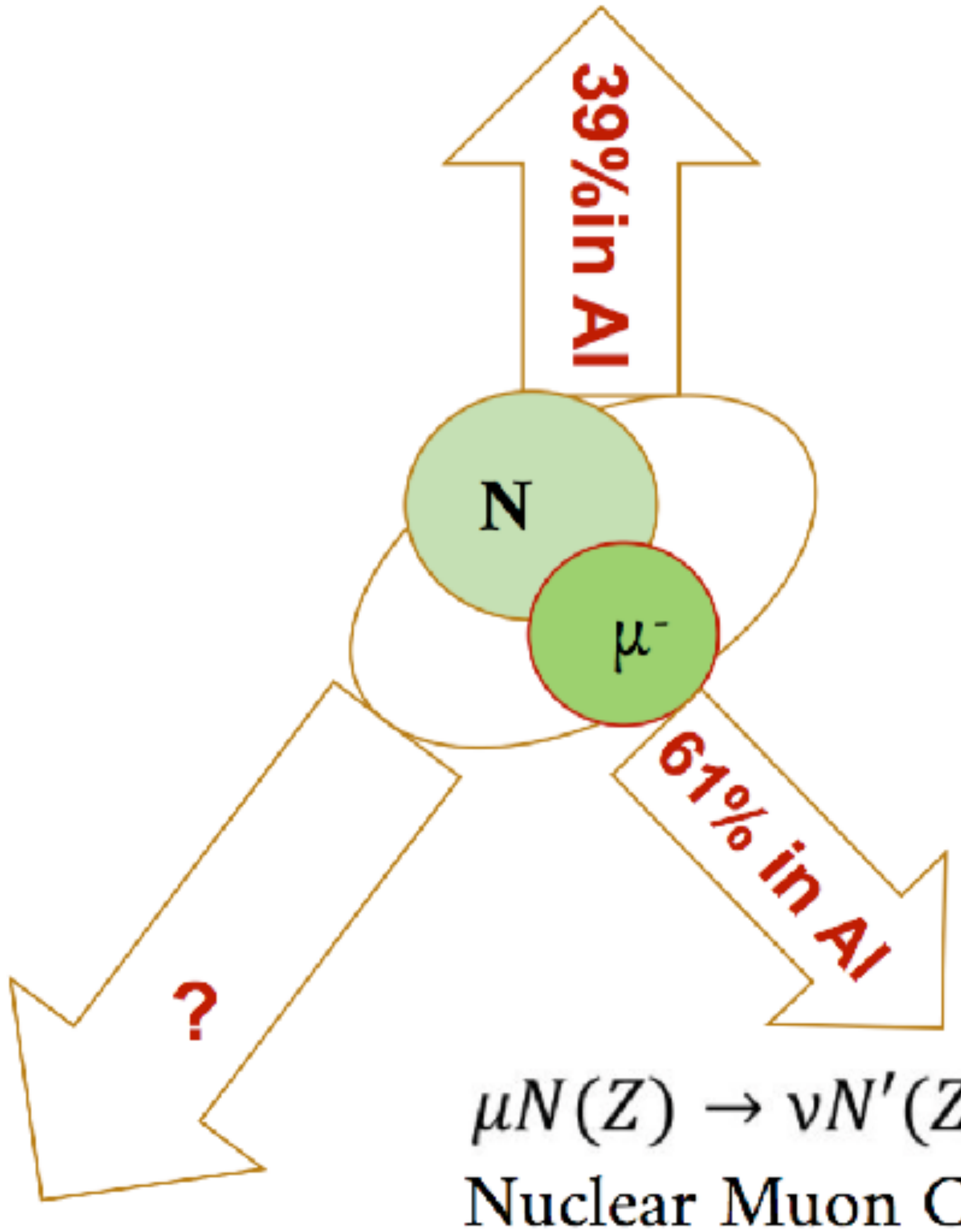
Muonic atoms

μ^- stopped in a target → 1s bound state

+

muonic X-Rays

Decay In Orbit $\mu N \rightarrow e\nu\bar{\nu}N$



$\mu N(Z) \rightarrow \nu N'(Z-1)$

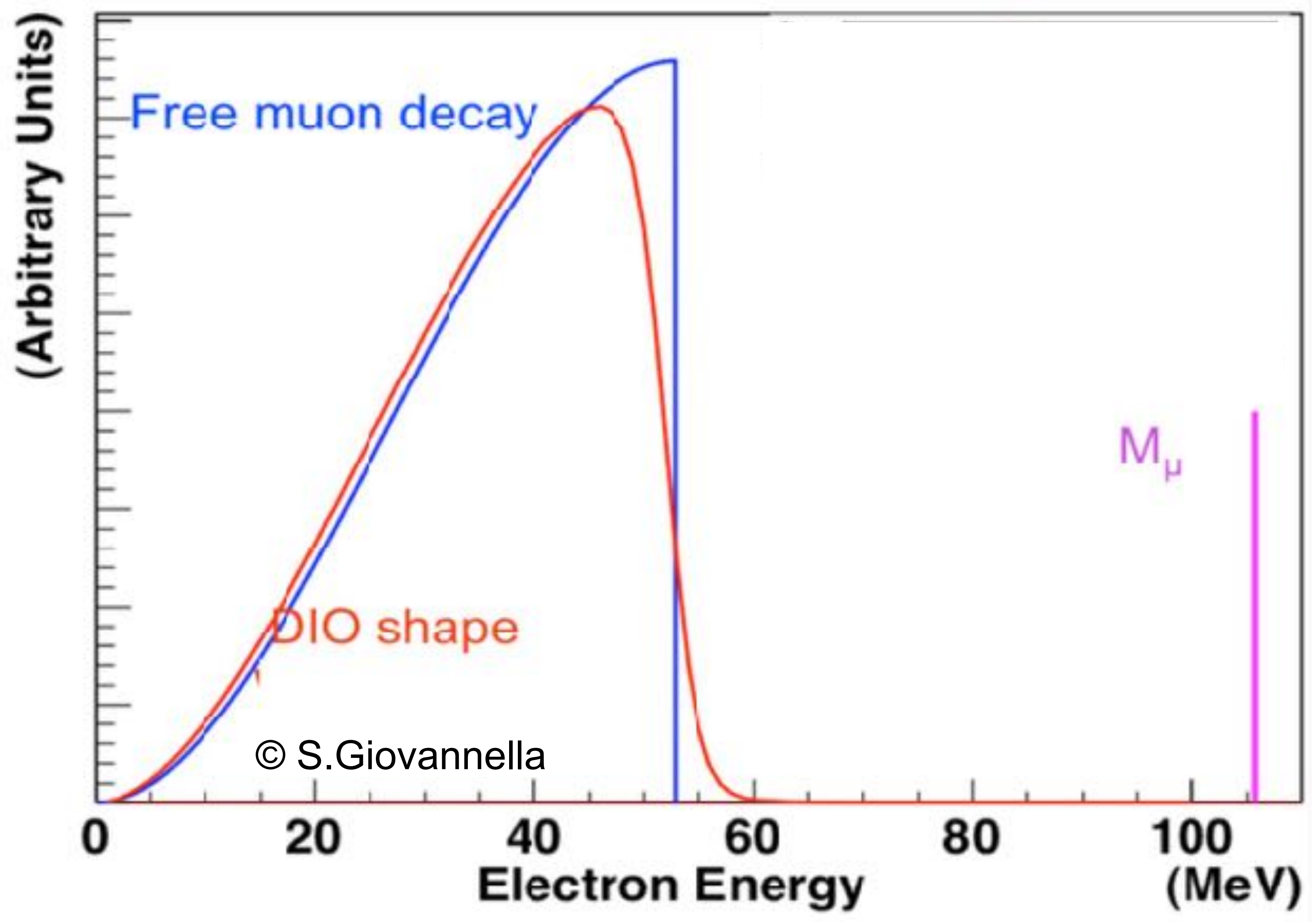
Nuclear Muon Capture

⇩

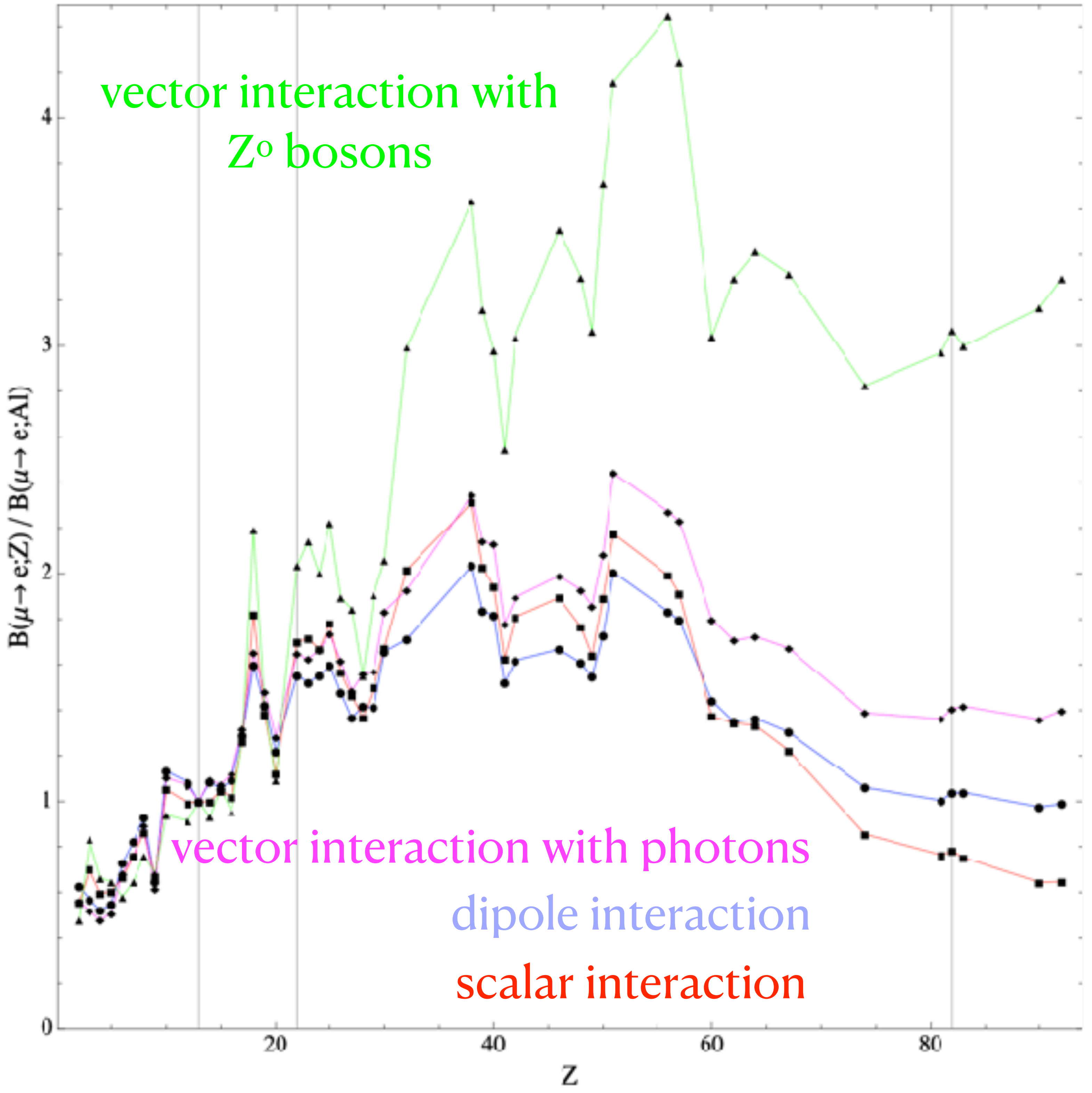
low energyneutrons, protons,γ's

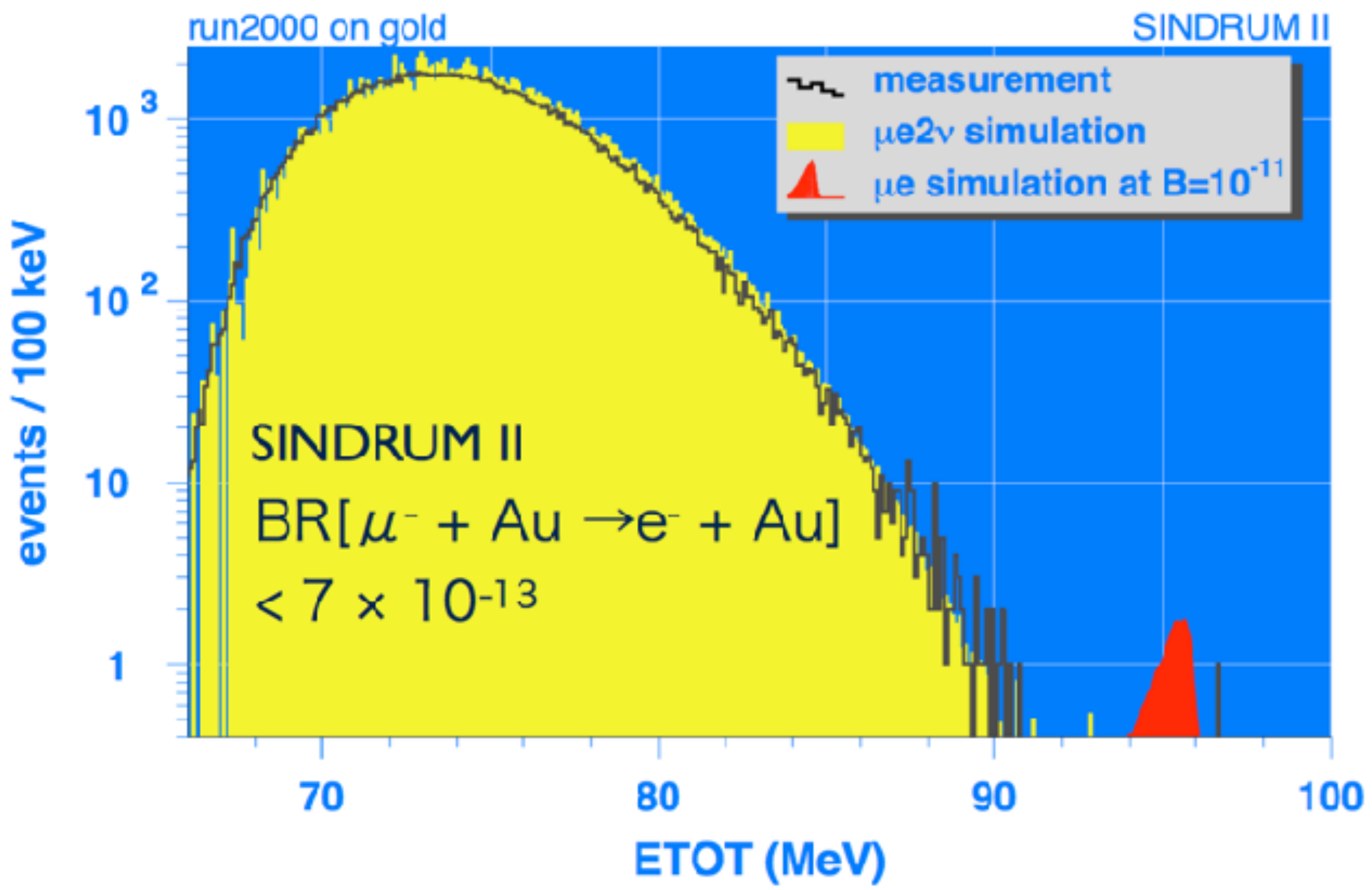
⇩

noise in the detector



V Cirigliano, R Kitano, Y Okada, P Tuzon, Phys.Rev., D80, 013002 (2009)

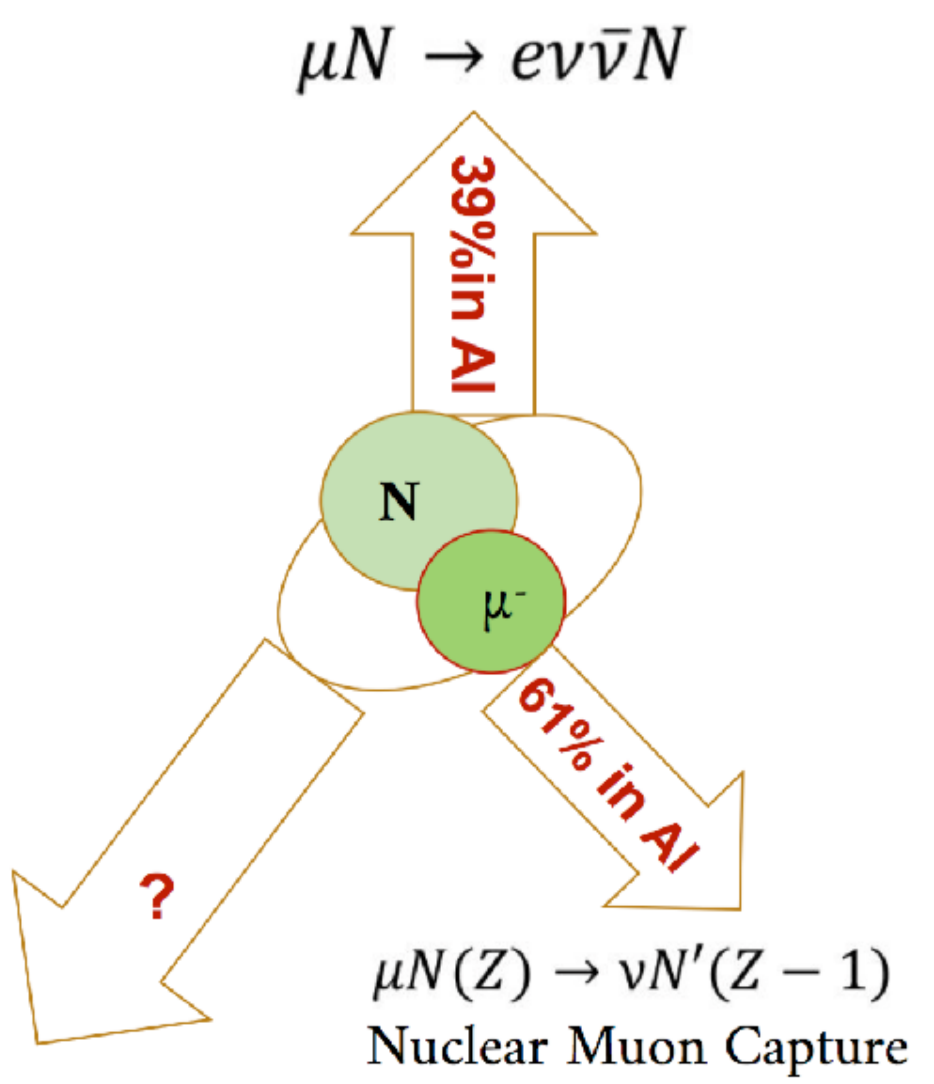


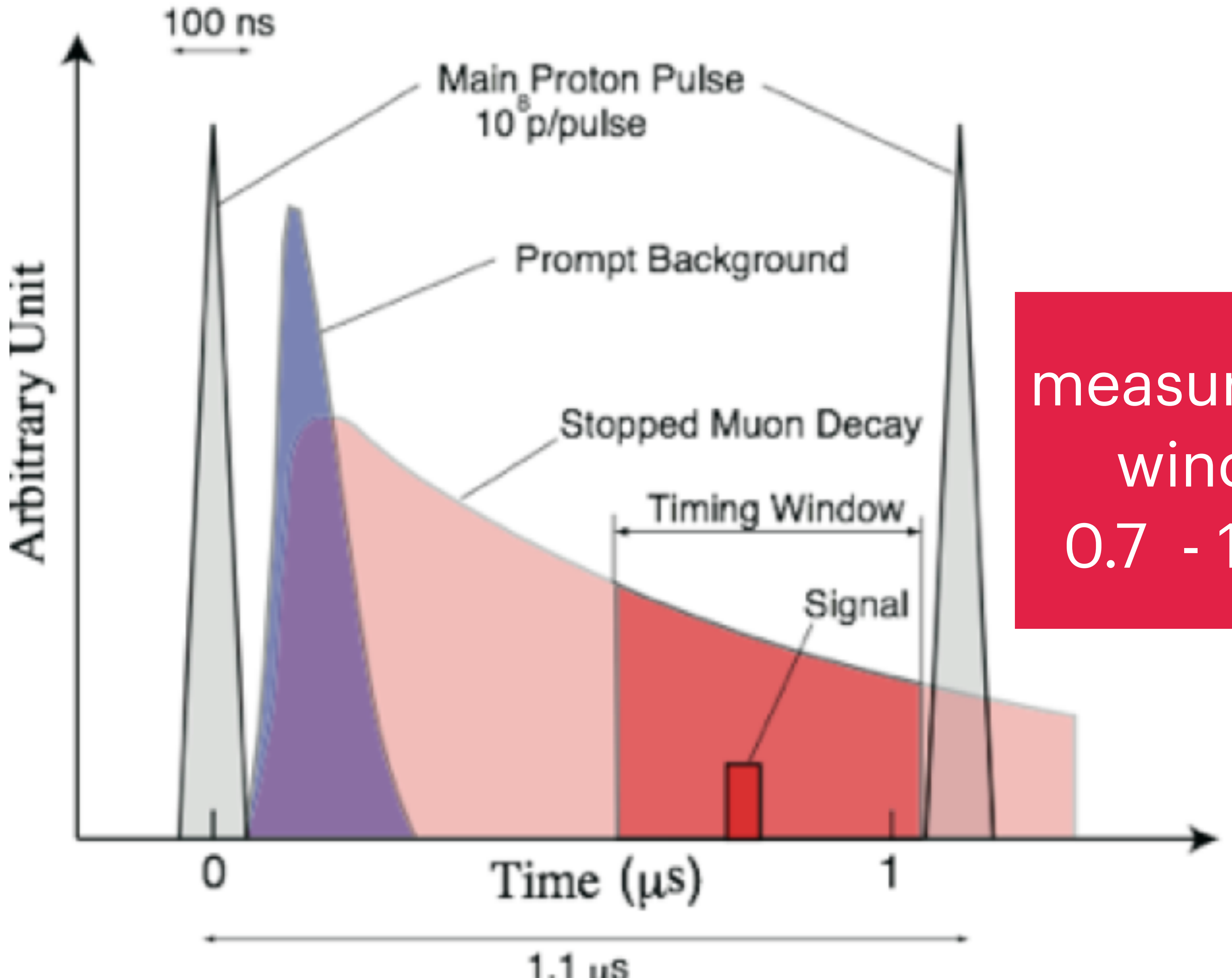


Required momentum resolution : better than 200 keV/c

μ − e conversion in muonic atoms :: experimental concept

Decay In Orbit

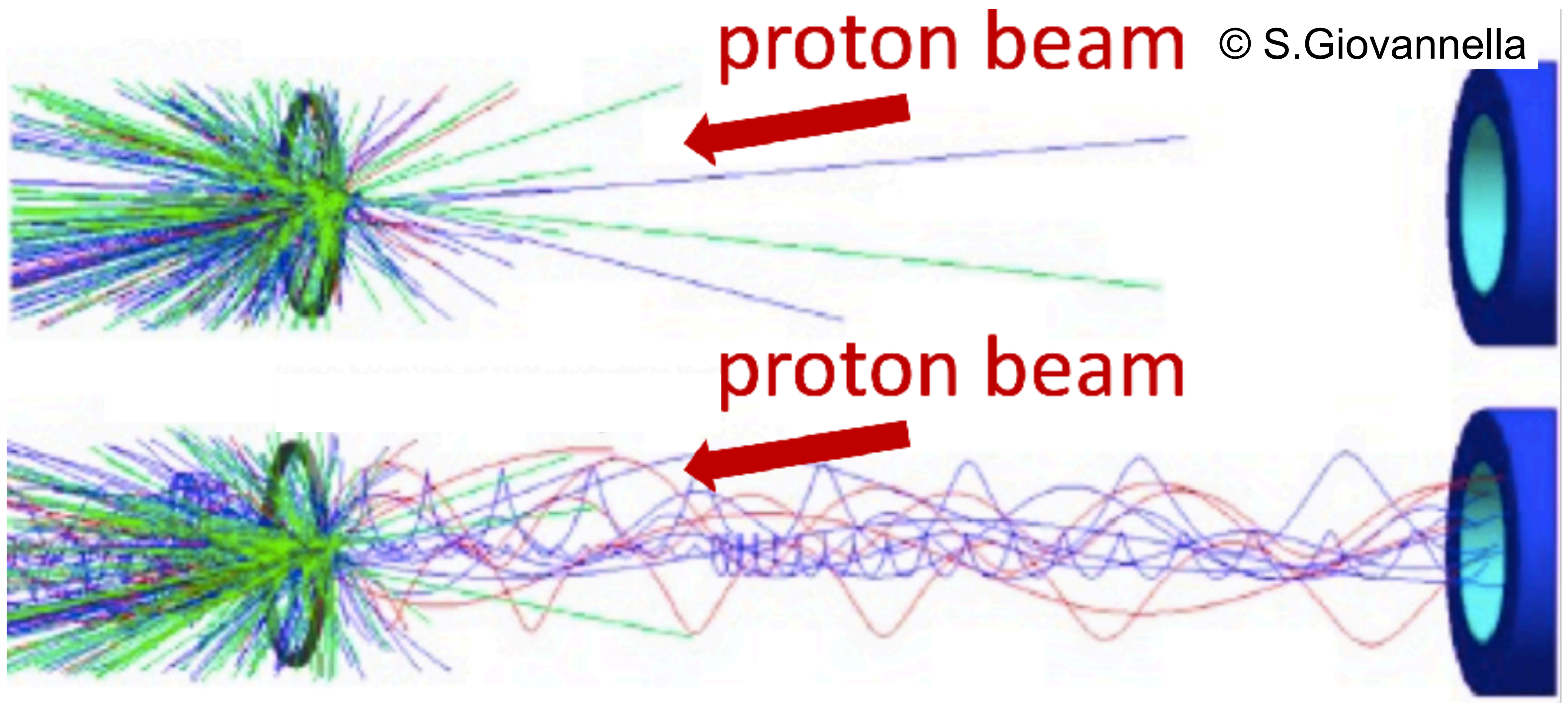




measurement window 0.7 - 1.17 μs

Soft pions confined with solenoidal B field

Strong gradient to increase the yield through magnetic reflection



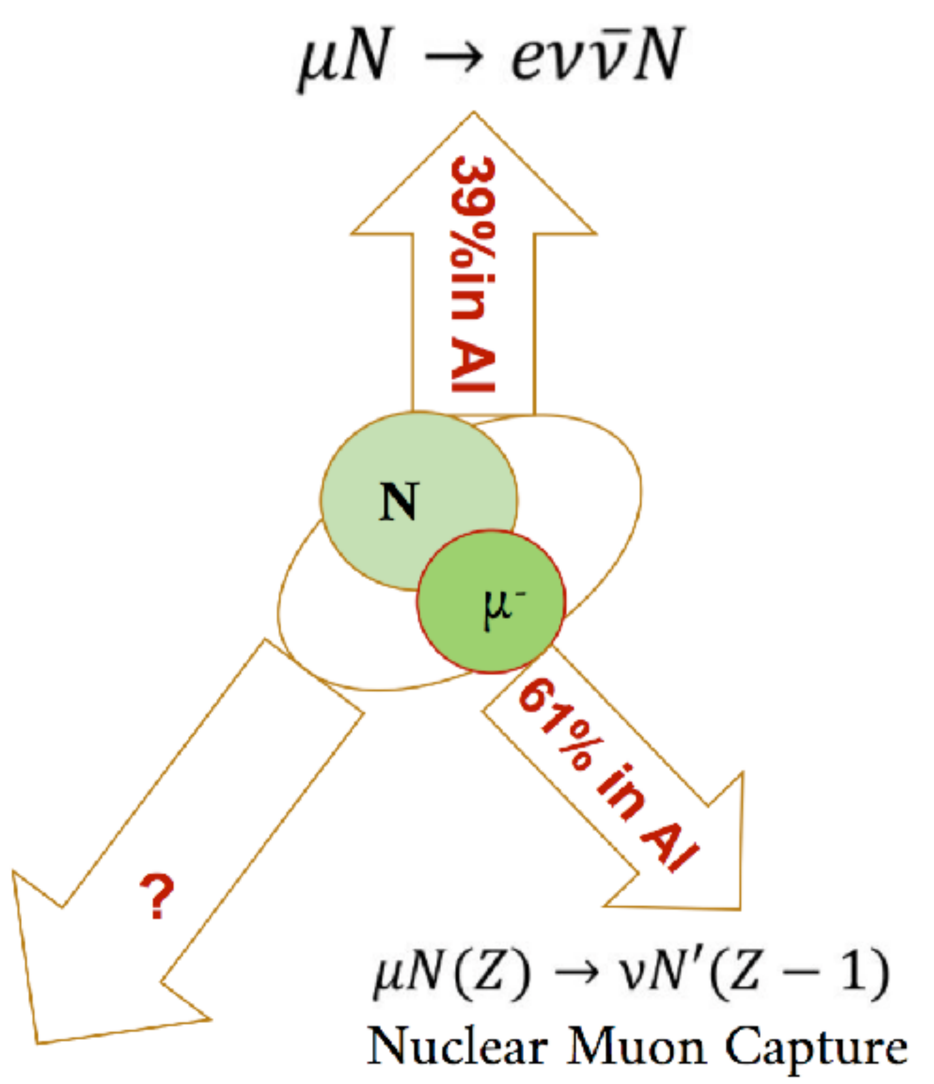
Delayed DAQ gate to suppress prompt backgrounds

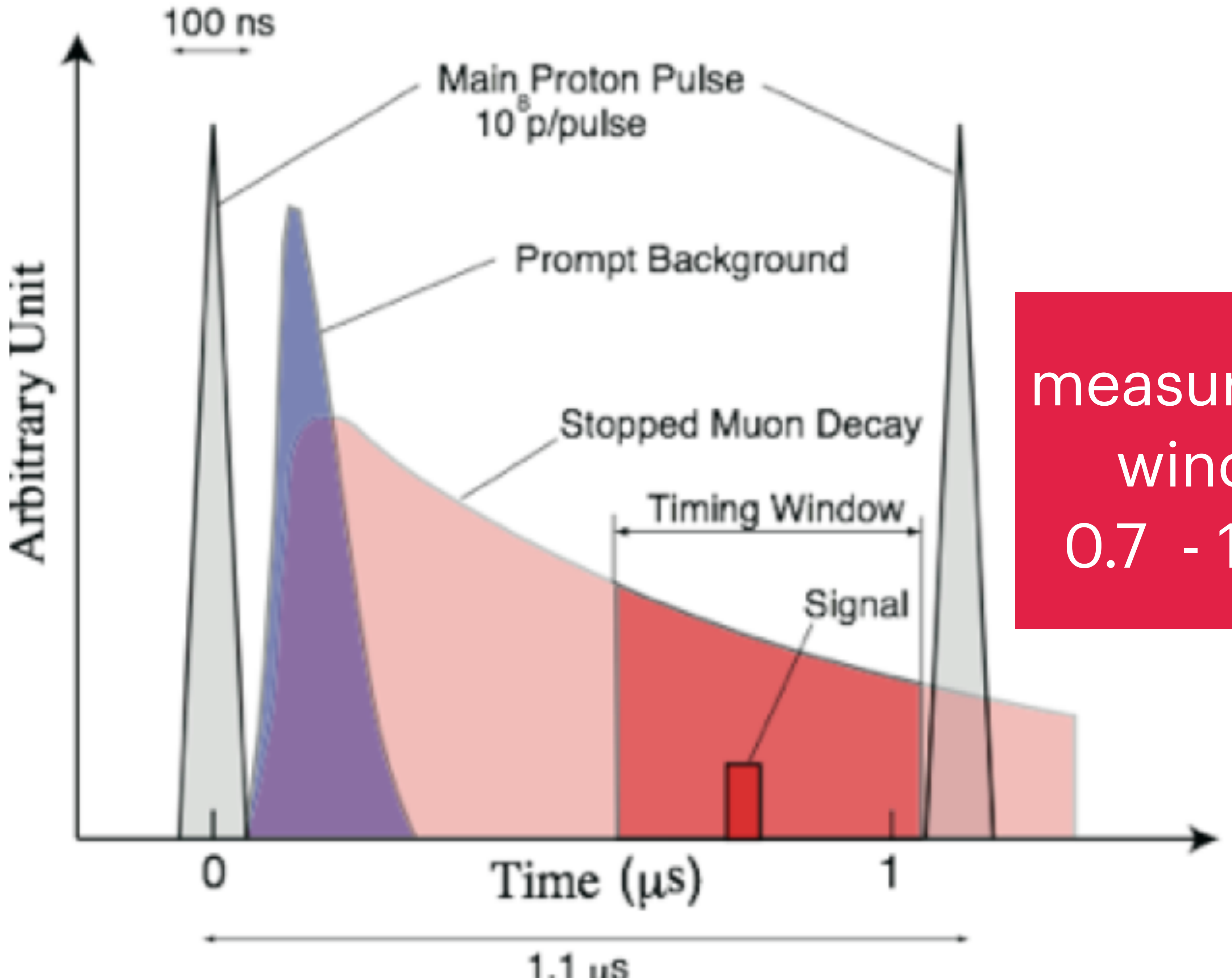
Narrow proton pulses

O(10^{10}) out-of-time protons suppression

Material target	Atomic number (Z)	Muonium lifetime (ns)
Aluminum	13	864
Titanium	22	330
Lead	82	74

Decay In Orbit



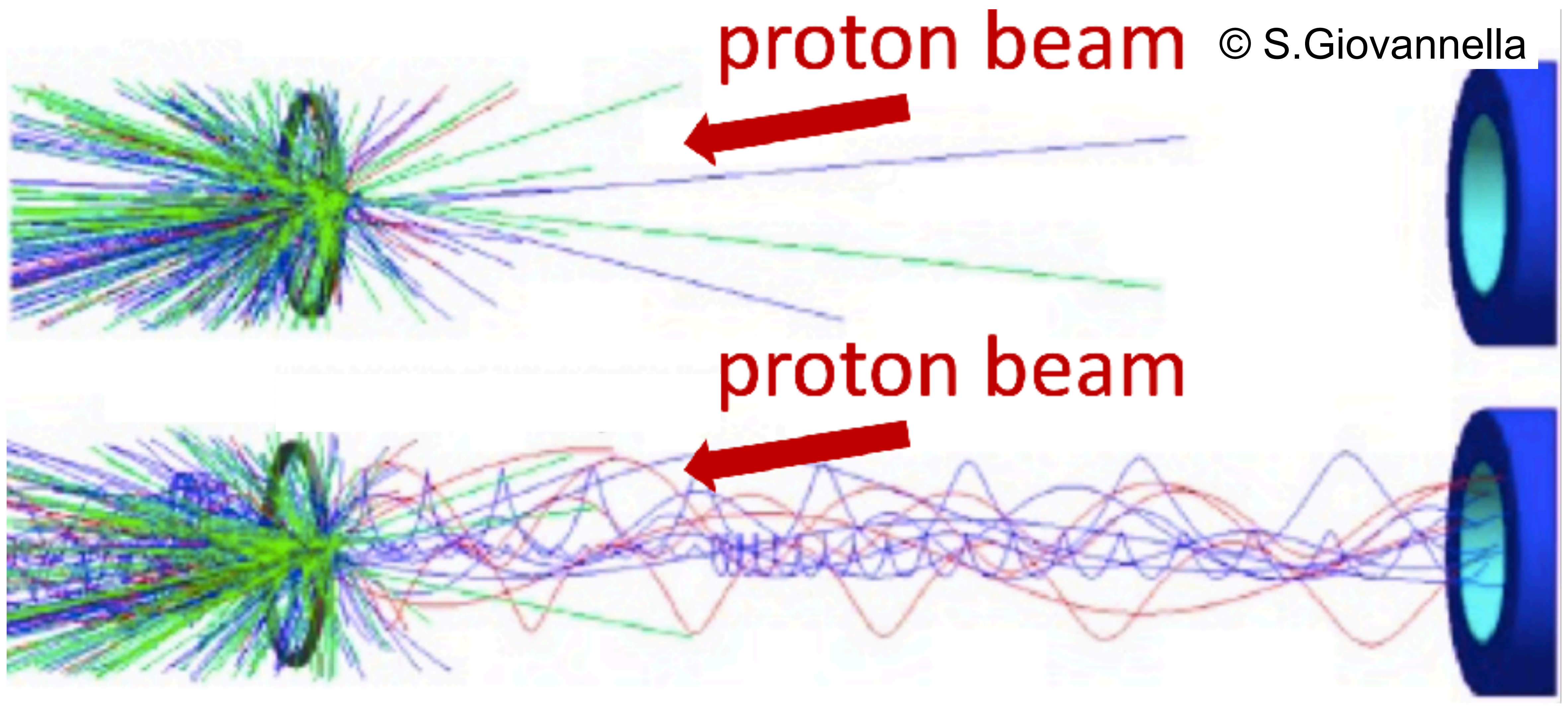


measurement window 0.7 - 1.17 μs

© Lobashev and Djilkibaev, MELC experiment [Sov.J.Nucl.Phys. 49, 384 (1989)]

Soft pions confined with solenoidal B field

Strong gradient to increase the yield through magnetic reflection



Delayed DAQ gate to suppress prompt backgrounds

Narrow proton pulses

O(10^{10}) out-of-time protons suppression

Atmospheric muons can fake signal events

⇒ proportional to the running time

⇒ higher beam intensity is preferrable

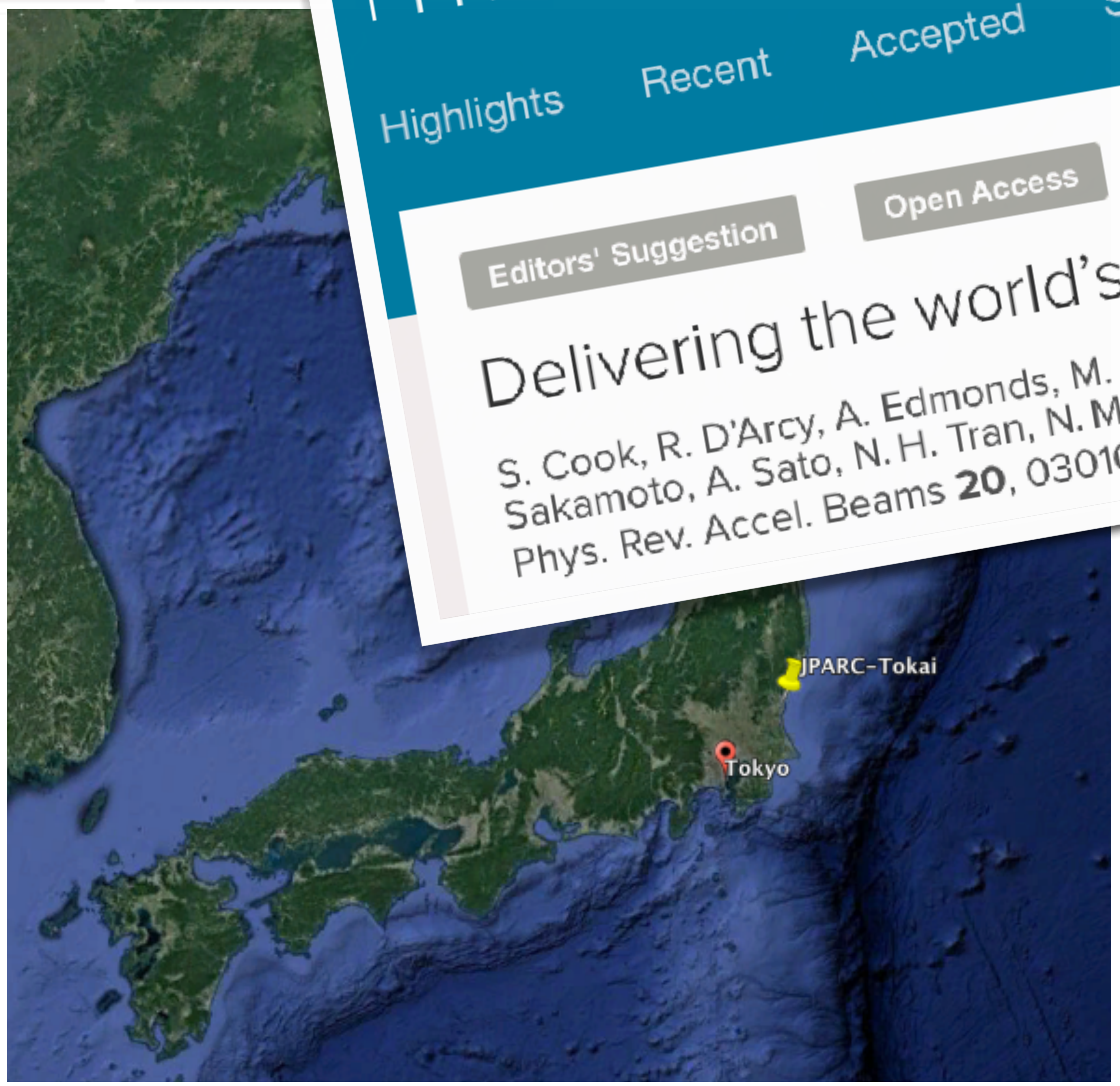
Improve by a factor 10^4 the present limit $R_{\mu e} < 7\ 10^{-13}$

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

This requires:
- **10^{18} stopped muons**
- high background suppression (**$N_{bckg} \ll 0.5$**)

COMET @ JParc Facility (KEK / JAEA)

43 institutes, 18 countries



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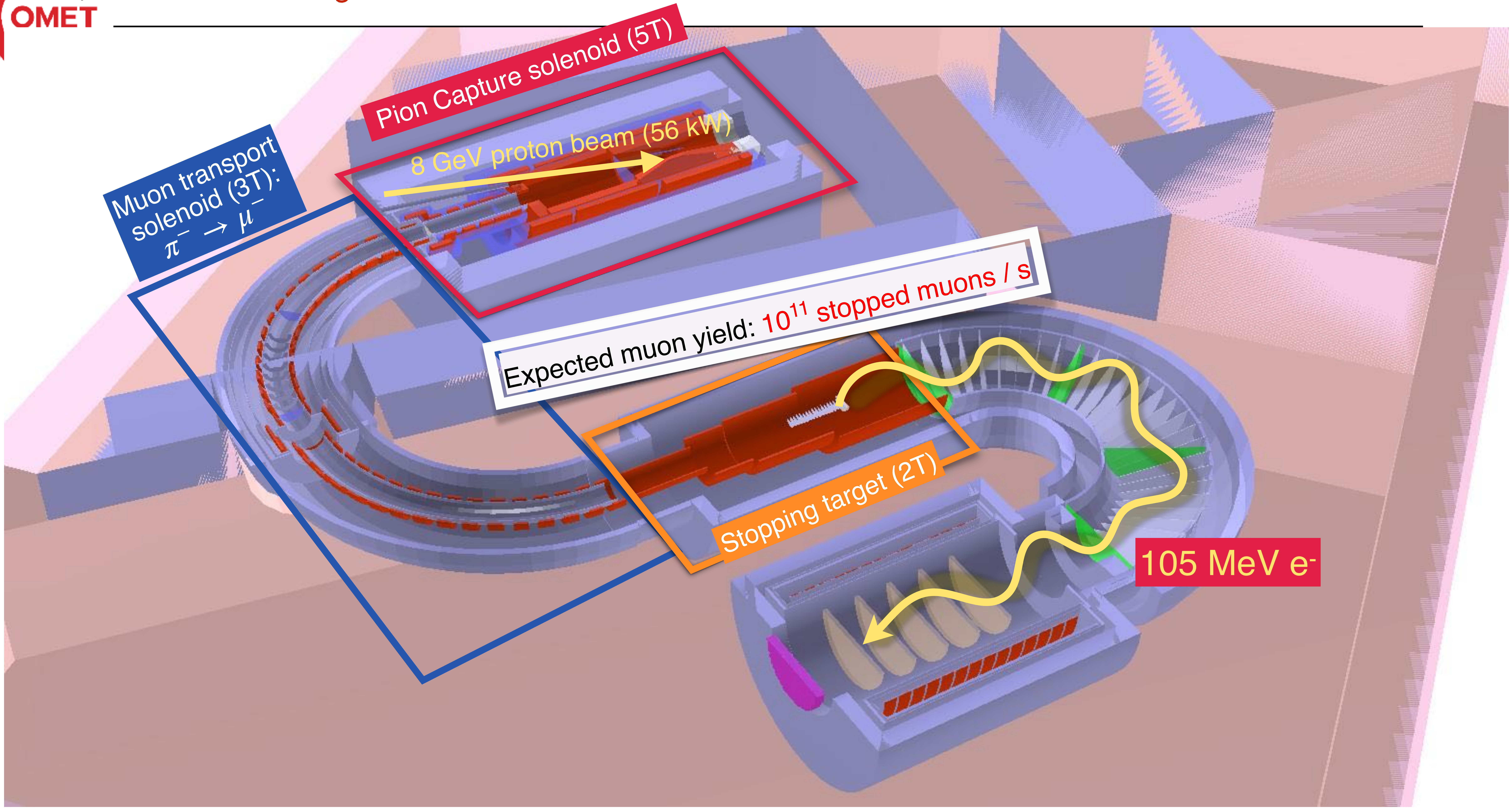
Delivering the world's most intense muon beam

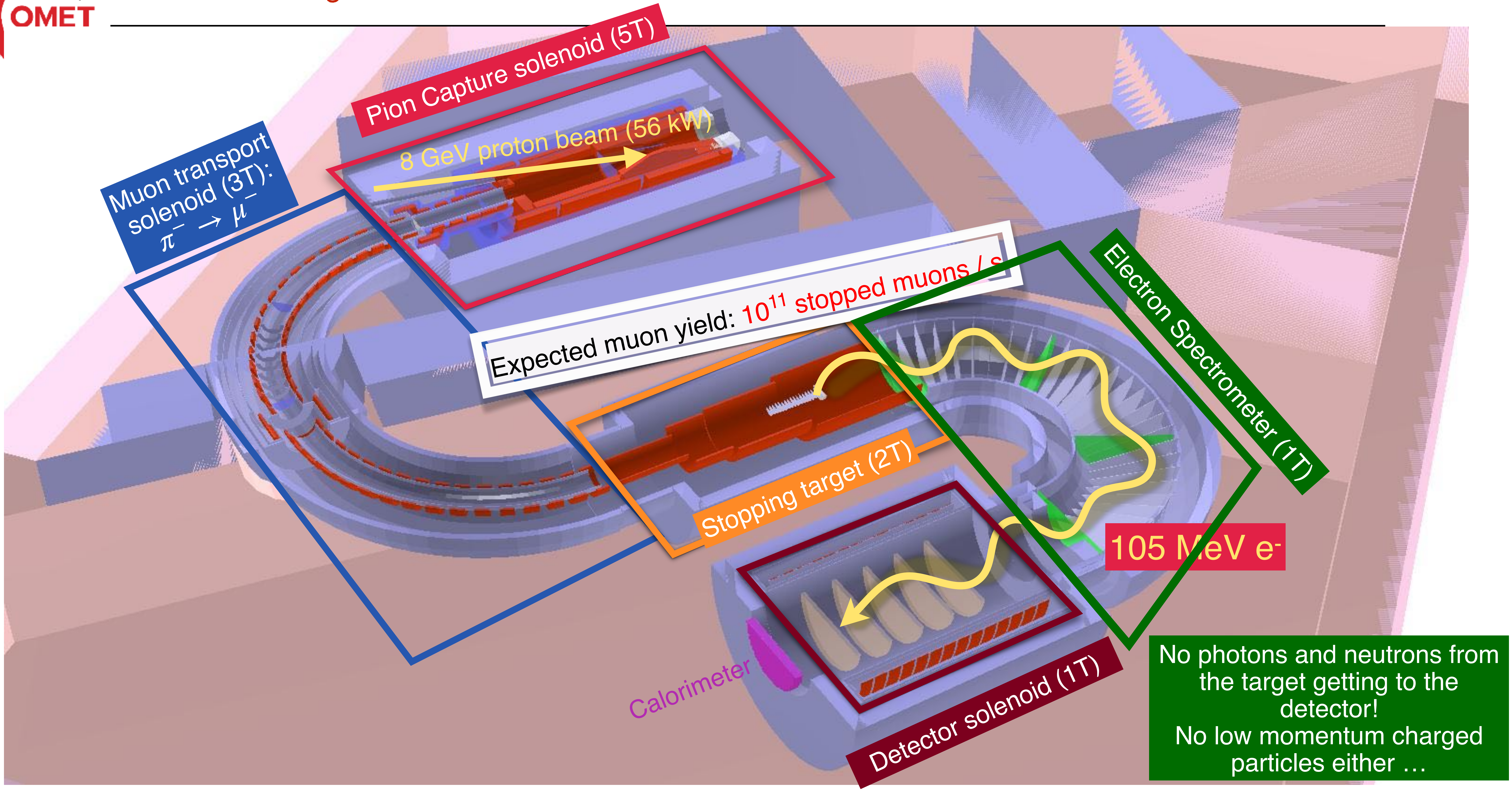
S. Cook, R. D'Arcy, A. Edmonds, M. Fukuda, K. Hatanaka, Y. Hino, Y. Kuno, M. Lancaster, Y. Mori, T. Ogitsu, H. Sakamoto, A. Sato, N. H. Tran, N. M. Truong, M. Wing, A. Yamamoto, and M. Yoshida

Phys. Rev. Accel. Beams **20**, 030101 – Published 15 March 2017

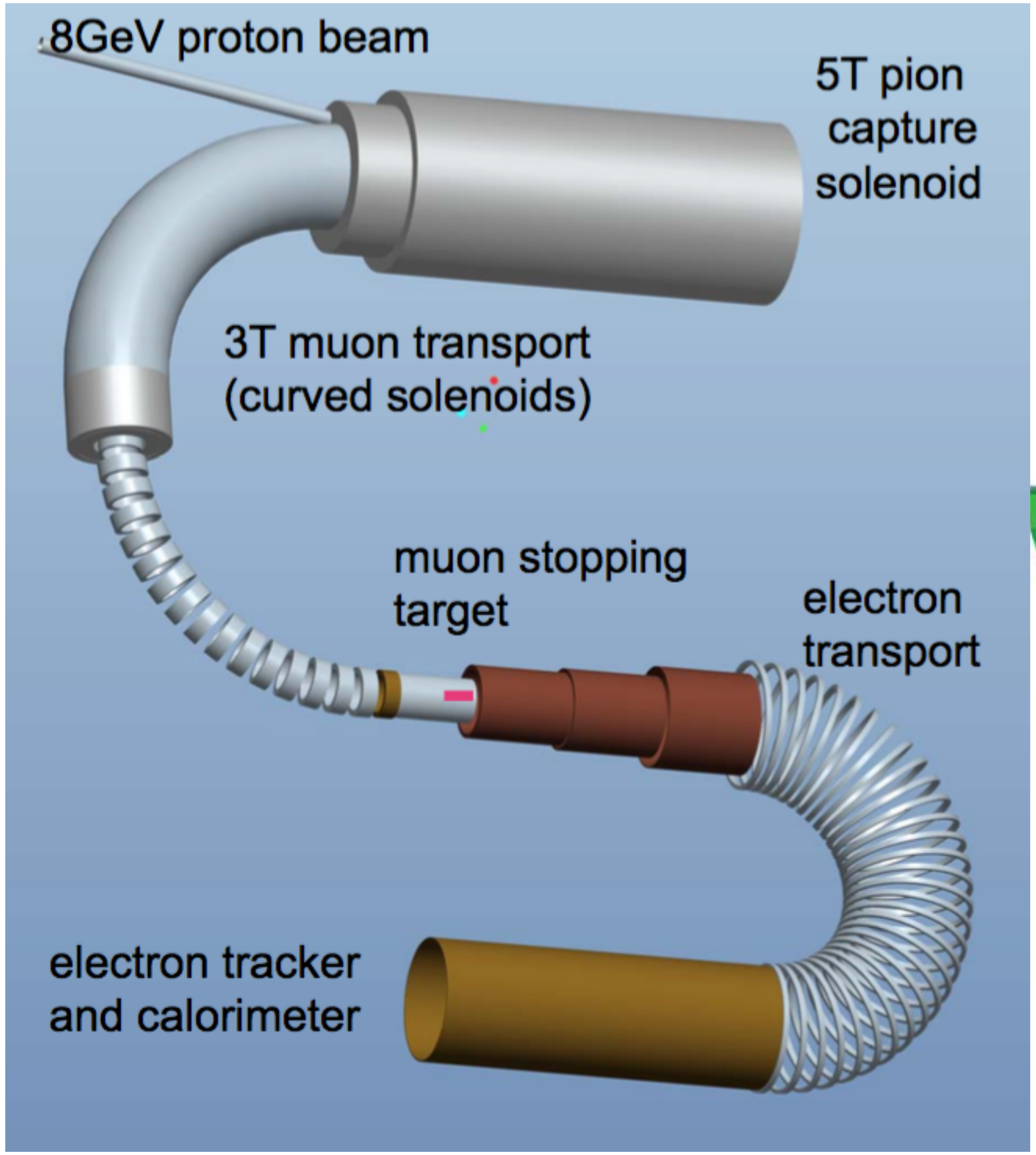
COMET design

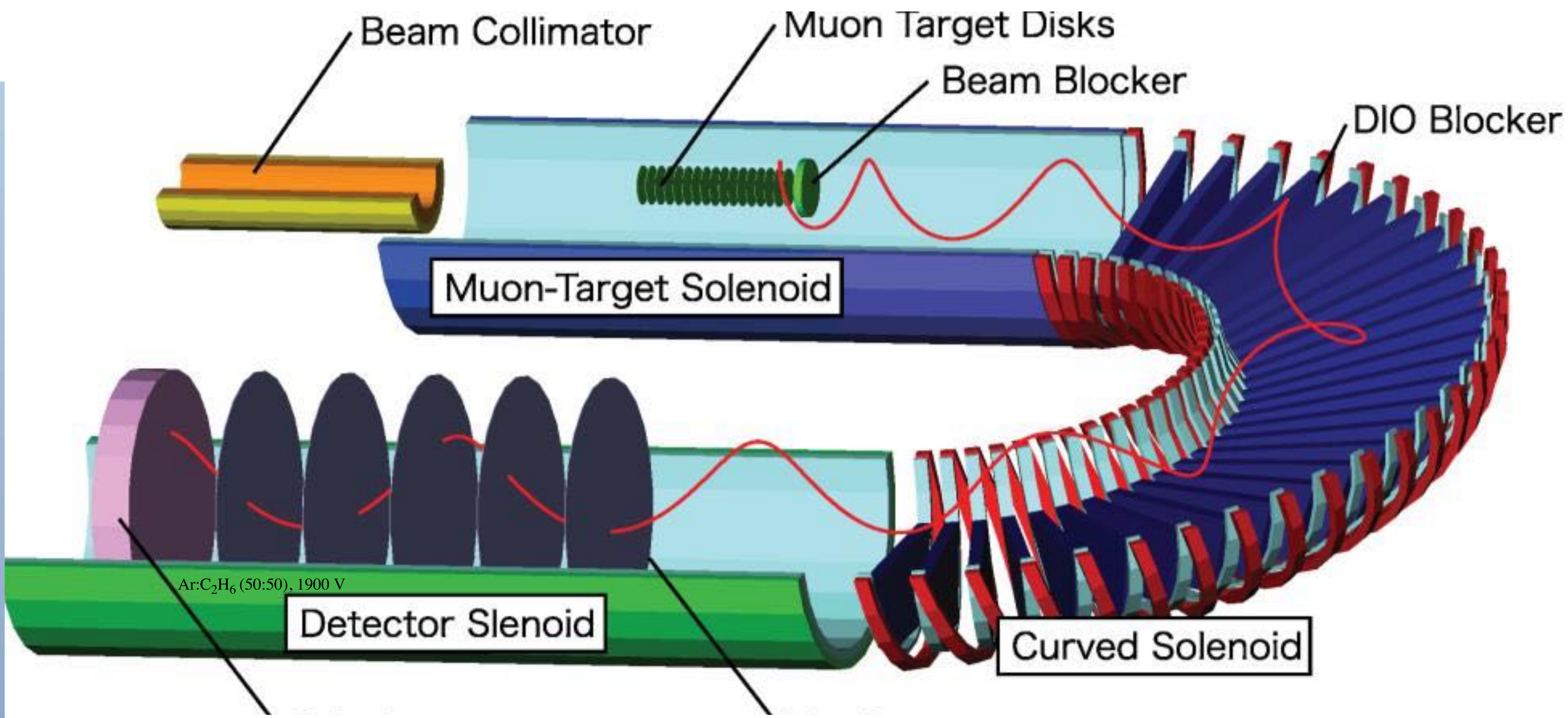


COMET design



COMET design :: detection section





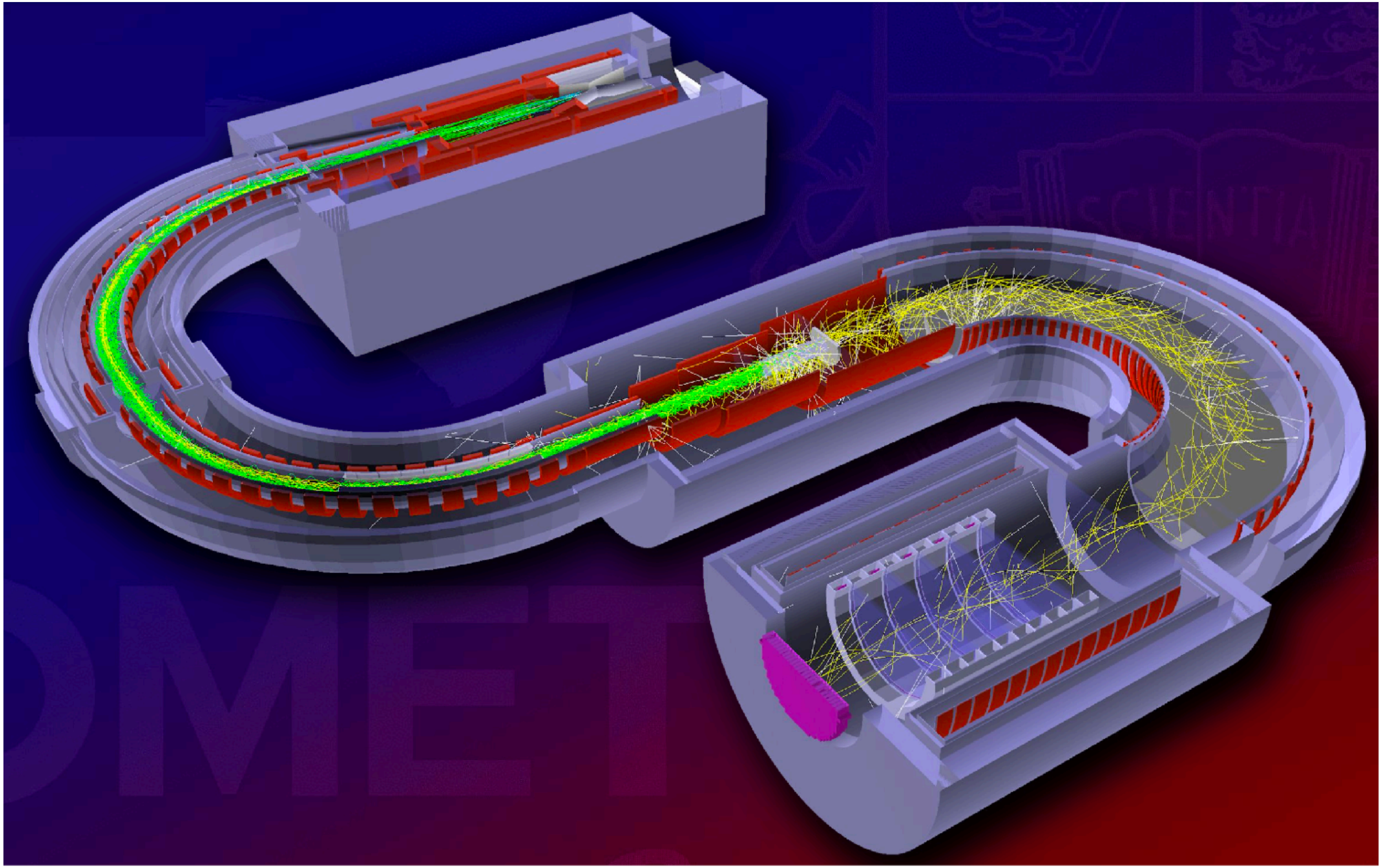
Electromagnetic calorimeter

- trigger & timing: response time faster than 100 ns
- electron energy : $\Delta E/E < 5\%$ (@105 MeV)
- cluster position: σ_x<1 cm
- 50 cm of radius
- made of 1920 LYSO crystals $2\times2\times12$ cm^3 (10.5 X_0)
- read out by APDs (operates @ 1 T)

Straw tubes tracker

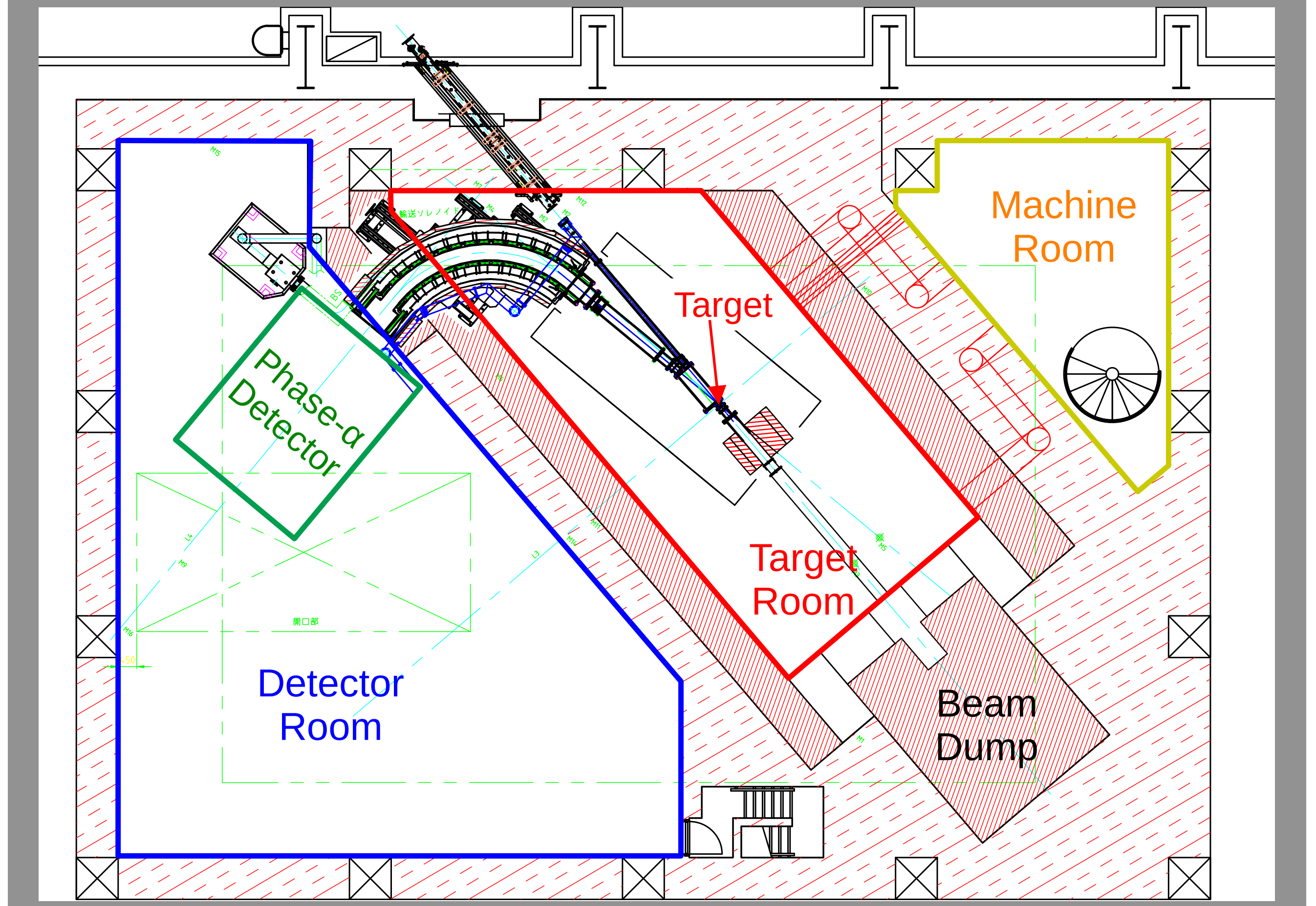
- operates in vacuum @ 1T
- Δp = 150~200 keV/c (@105 MeV/c)
- 12 μm thick, 5 mm diameter for Phase-II
- at least five stations

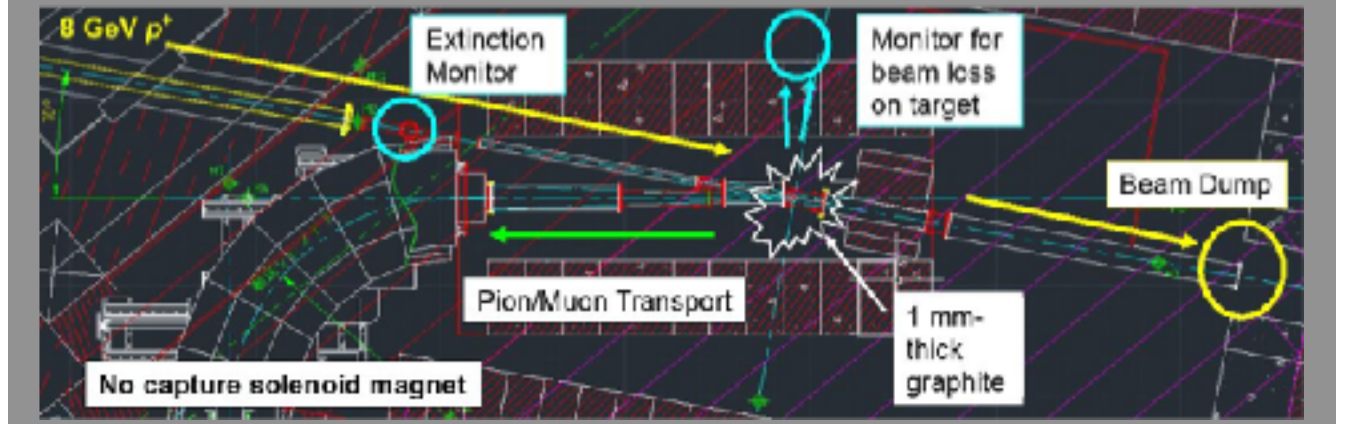
A simulated COMET event



COMET , a 2(,5) -stage experiment

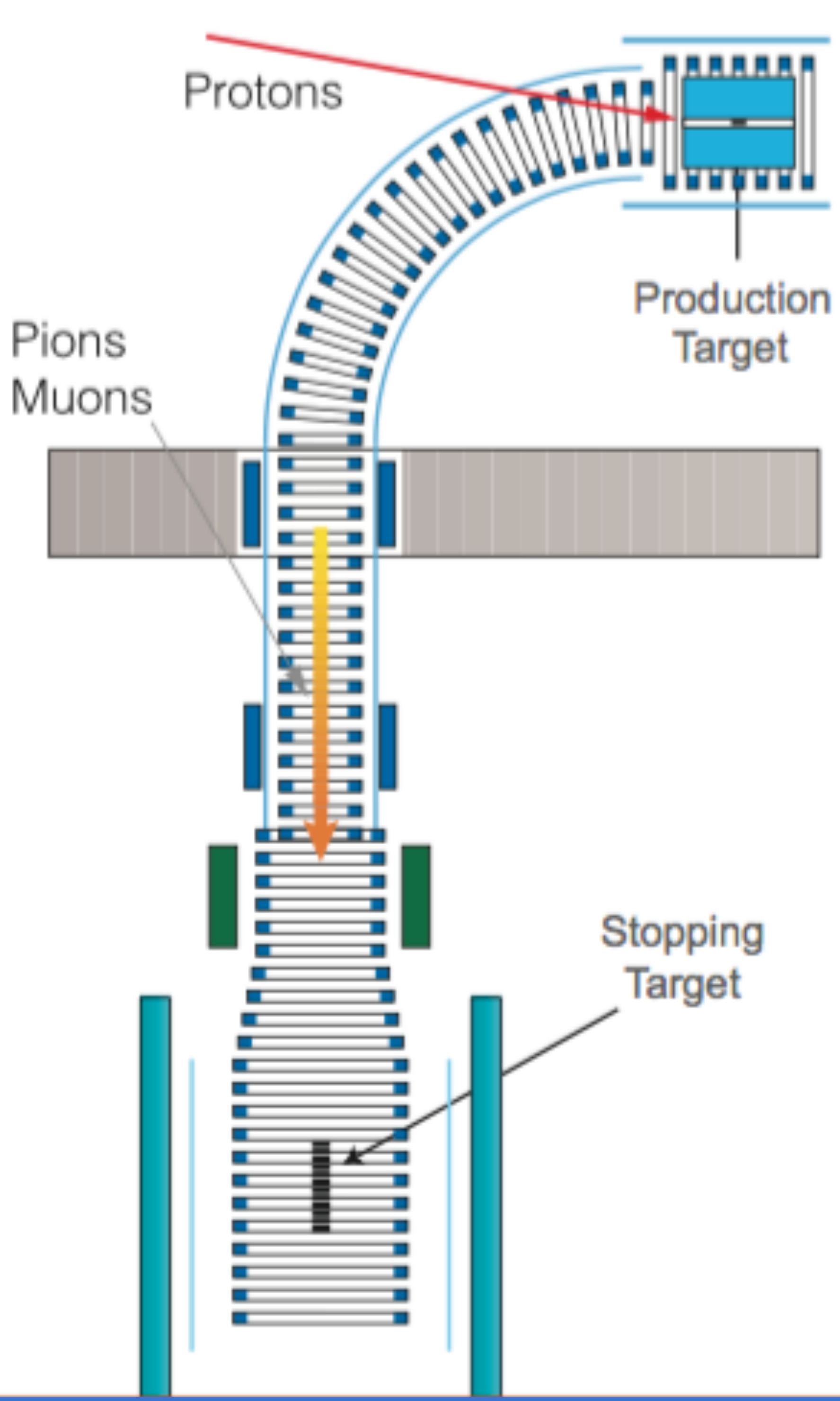
Phase α 2022





- Low intensity run (260 W) without Pion Capture Solenoid
- Thin graphite p-target
- Proton beam diagnostic detectors
- Secondary particle detectors

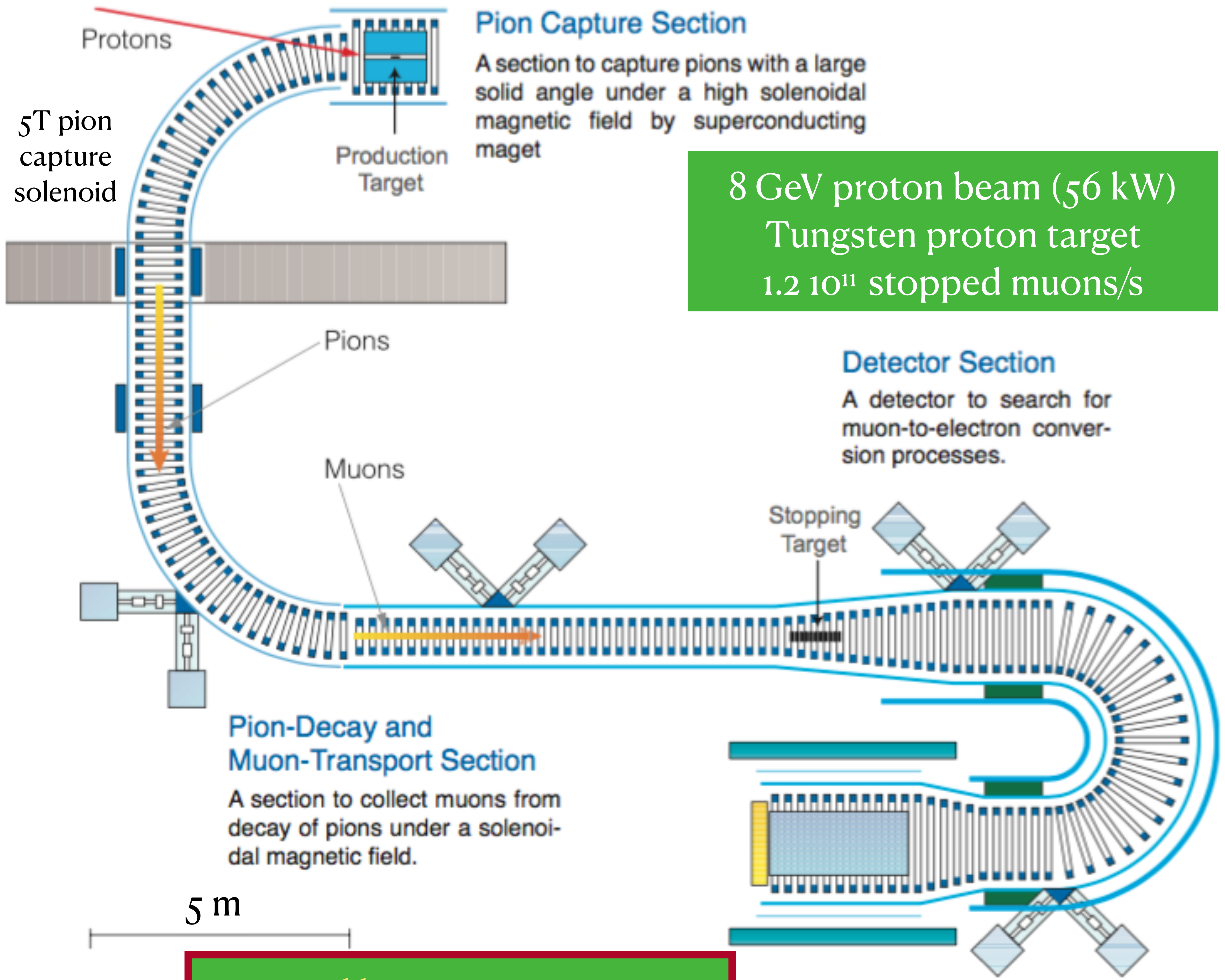
Phase I



8 GeV proton beam (3.2 kW)
Graphite proton target
1.2 10^9 stopped muons/s

Expected limit : 7 10^{-15} @ 90% CL
Total background: 0.01 events
Running time: 0.4 yrs (1.2 10^7 s)

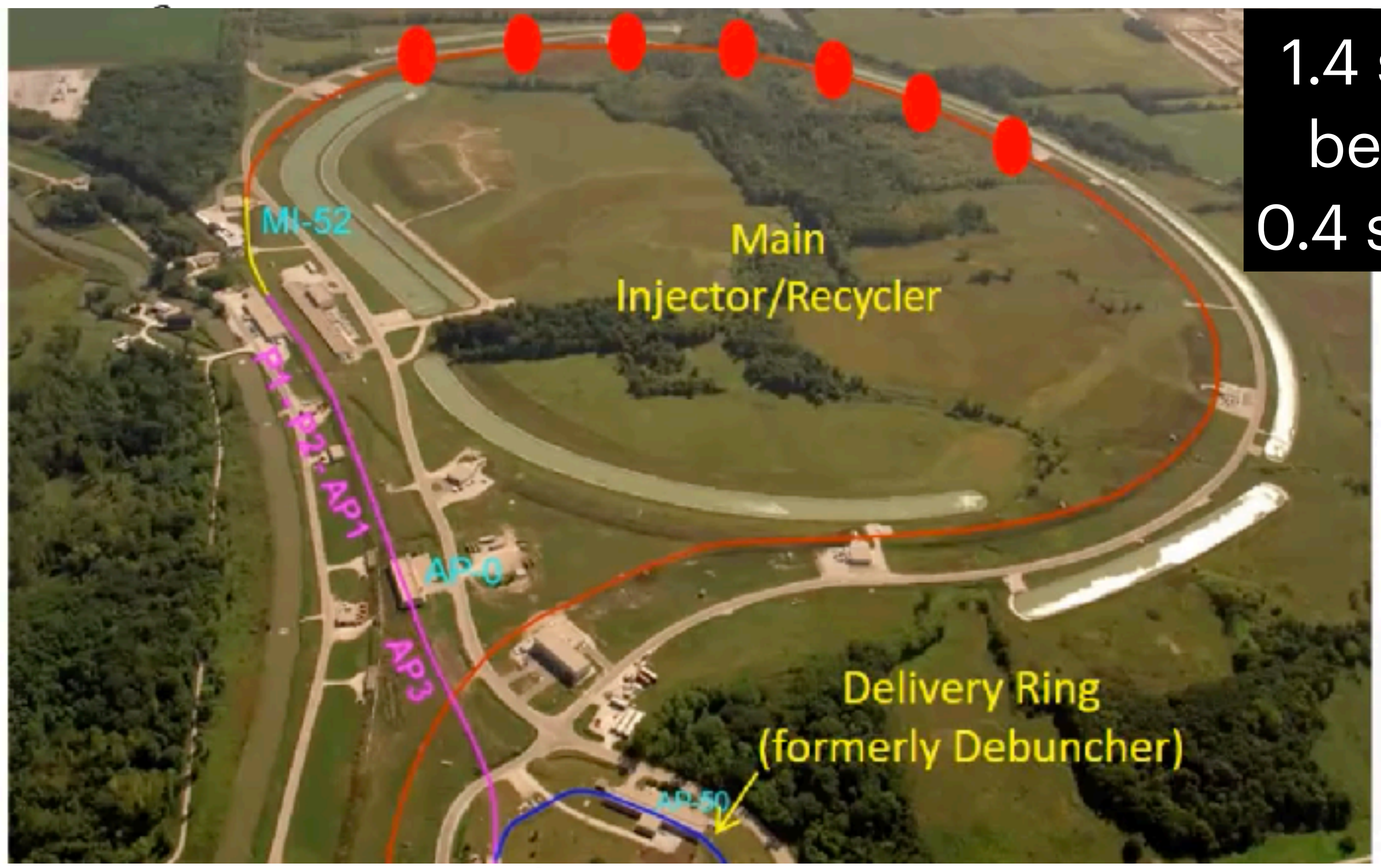
Phase II



8 GeV proton beam (56 kW)
Tungsten proton target
1.2 10^{11} stopped muons/s

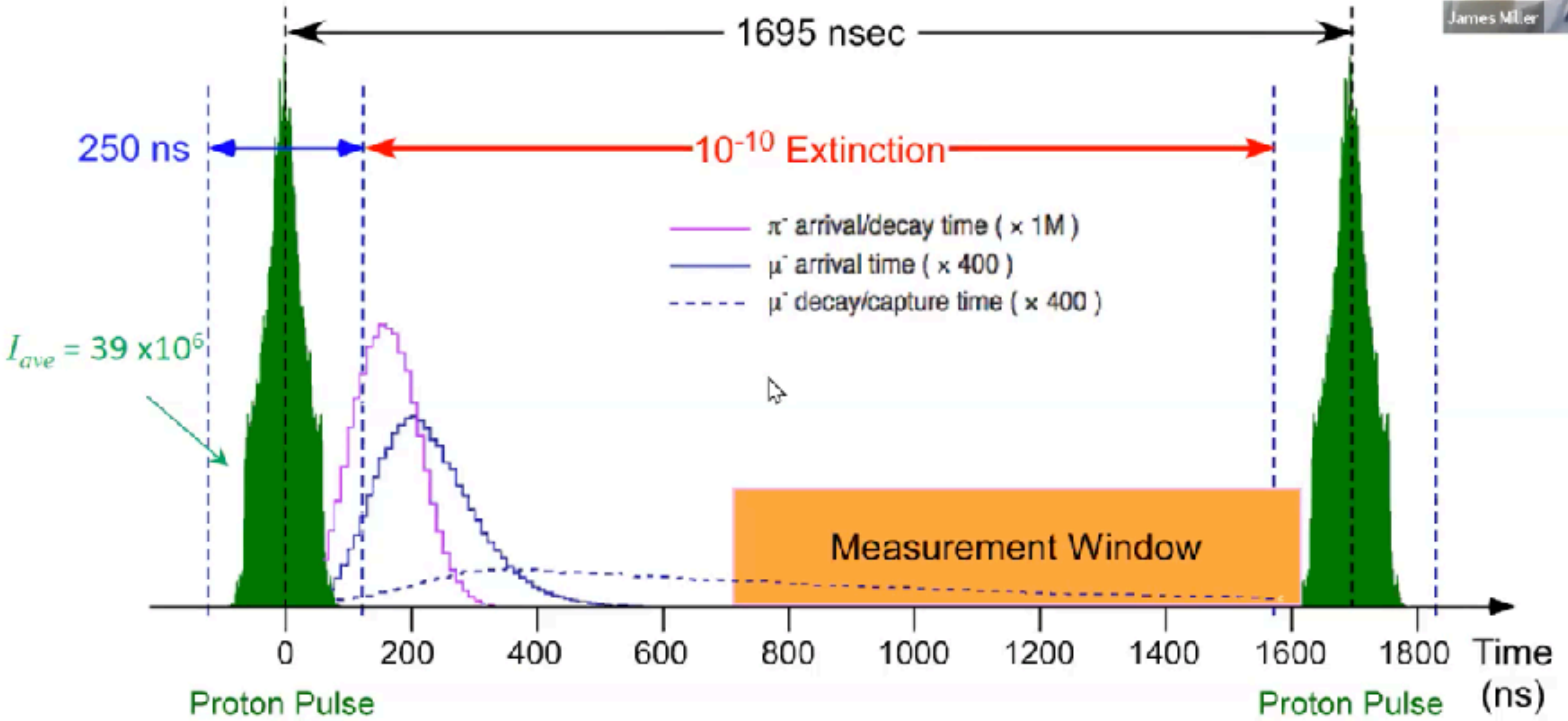
Expected limit : 7 10^{-17} @ 90% CL
Total background: 0.32 events
Running time: 1 yr (2 10^7 s)

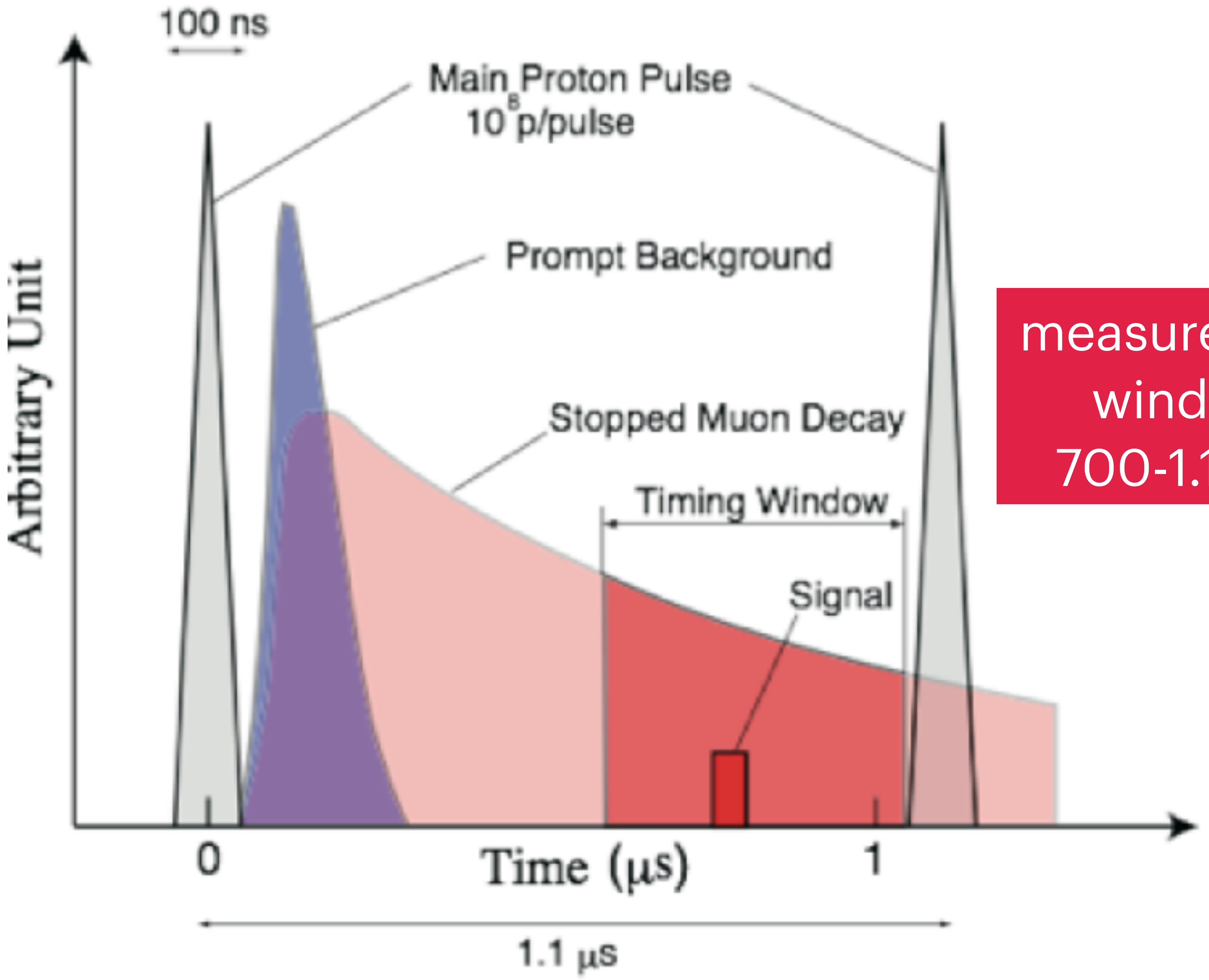
JParc



1.4 s long MI cycles, beam on on Mu2e: 0.4 s→ 8 kW on target

Pulsed Proton Beam



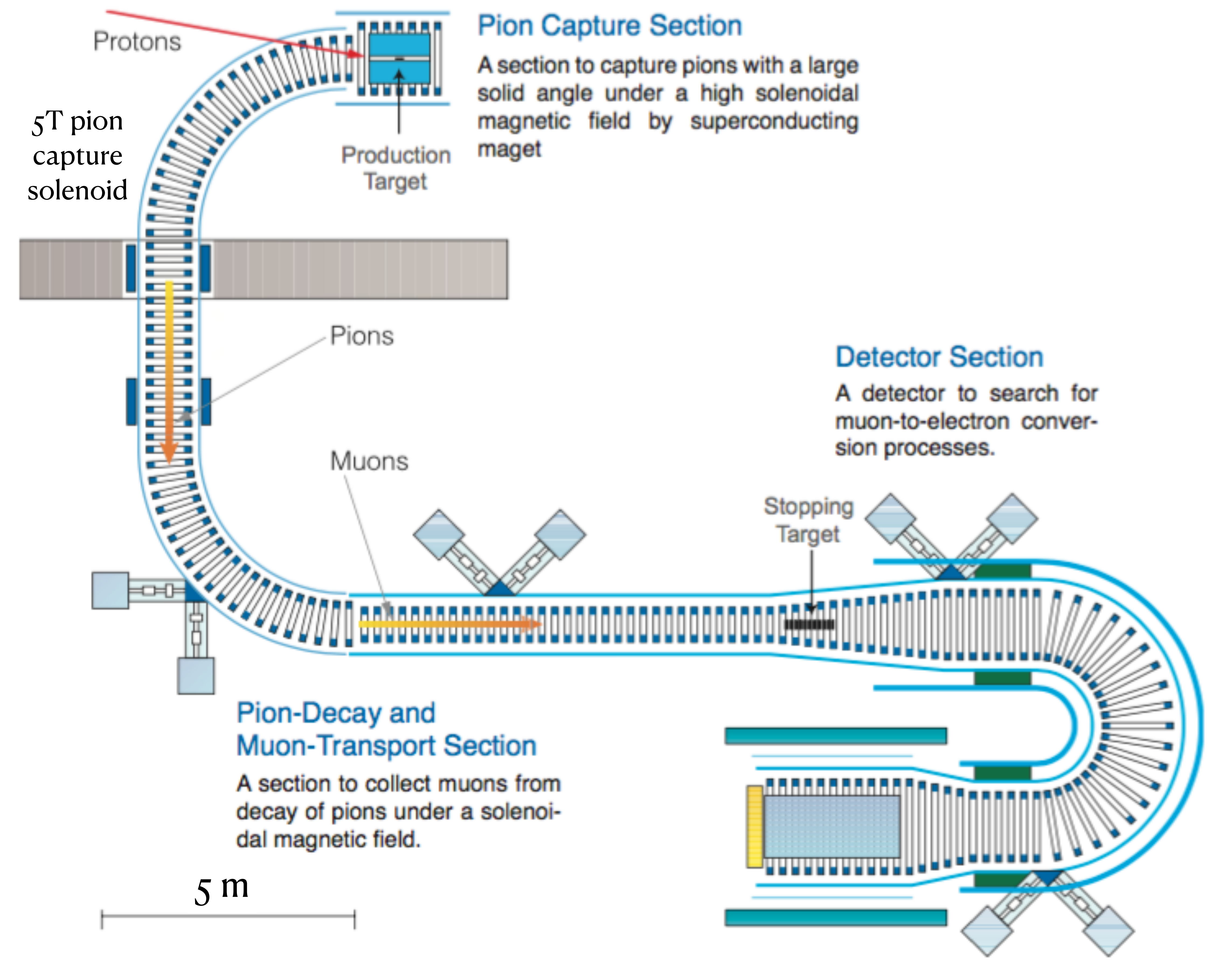


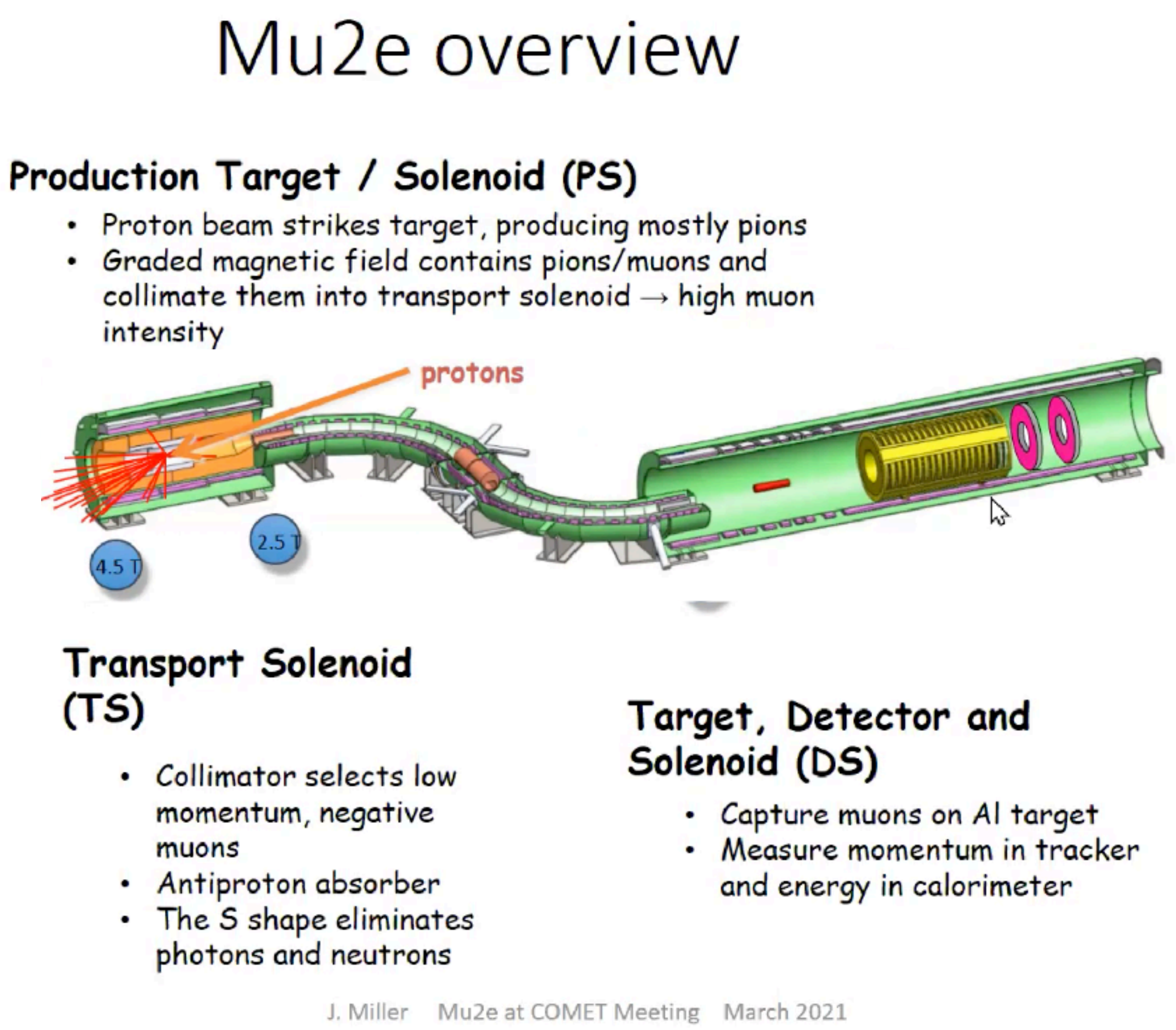
measurement window 700-1.17 μs

- The proton beam on target consists of a train of ~25,000 narrow pulses separated by 1.695 μsec

8 GeV proton beam (56 kW)
Tungsten proton target
1.2 10¹¹ stopped muons/s

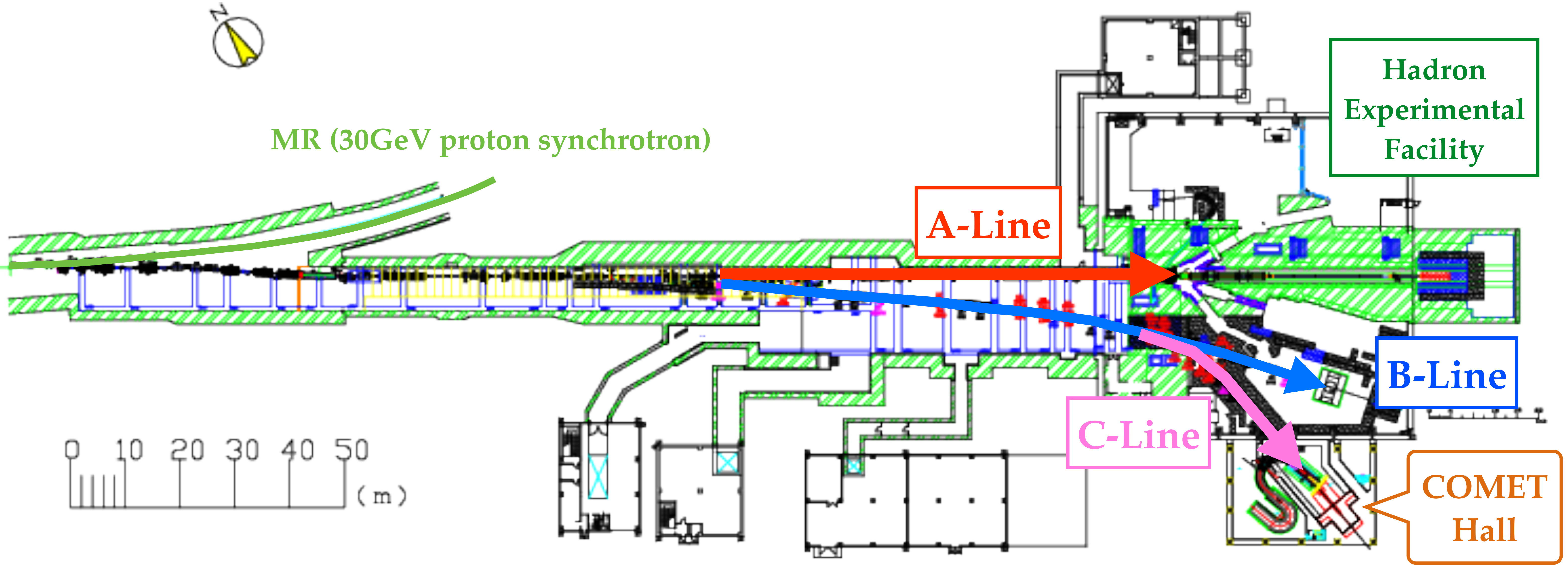
Expected limit : 7 10⁻¹⁷ @ 90% CL
Total background: 0.32 events
Running time: 1 yr (2 10⁷ s)





COMET Status :: Facility Construction

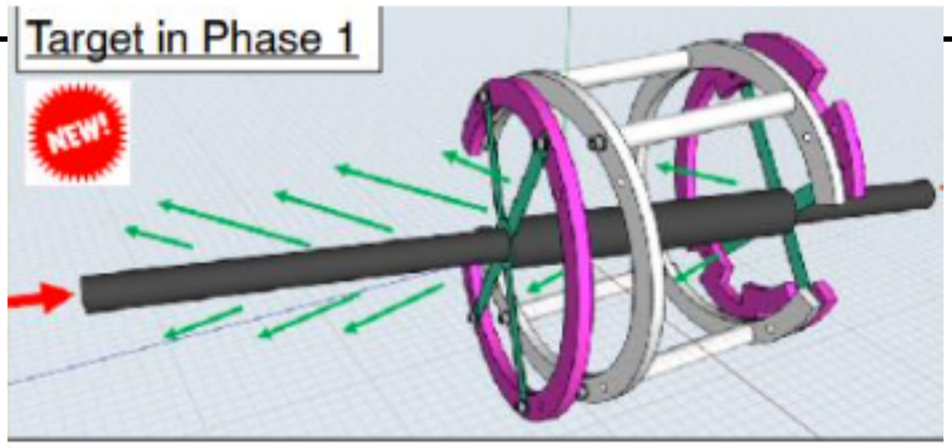
Upstream of the proton C-line completed in 2021



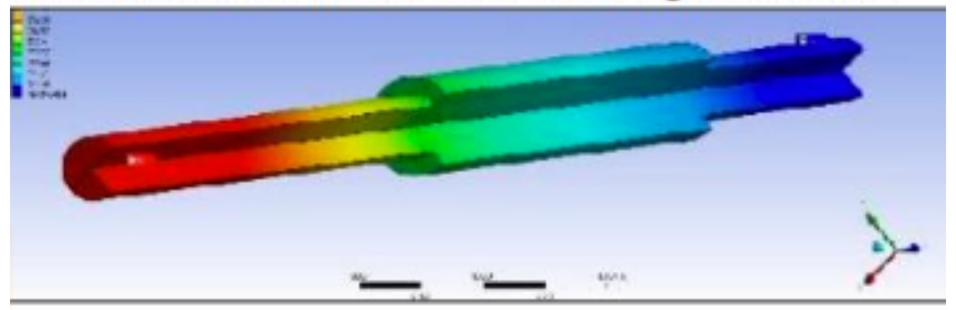
Shutdown of J-PARC MR until middle of 2022 for PS upgrade for MW beam

COMET beamline construction to be completed during shutdown

Phase-I Graphite target design done

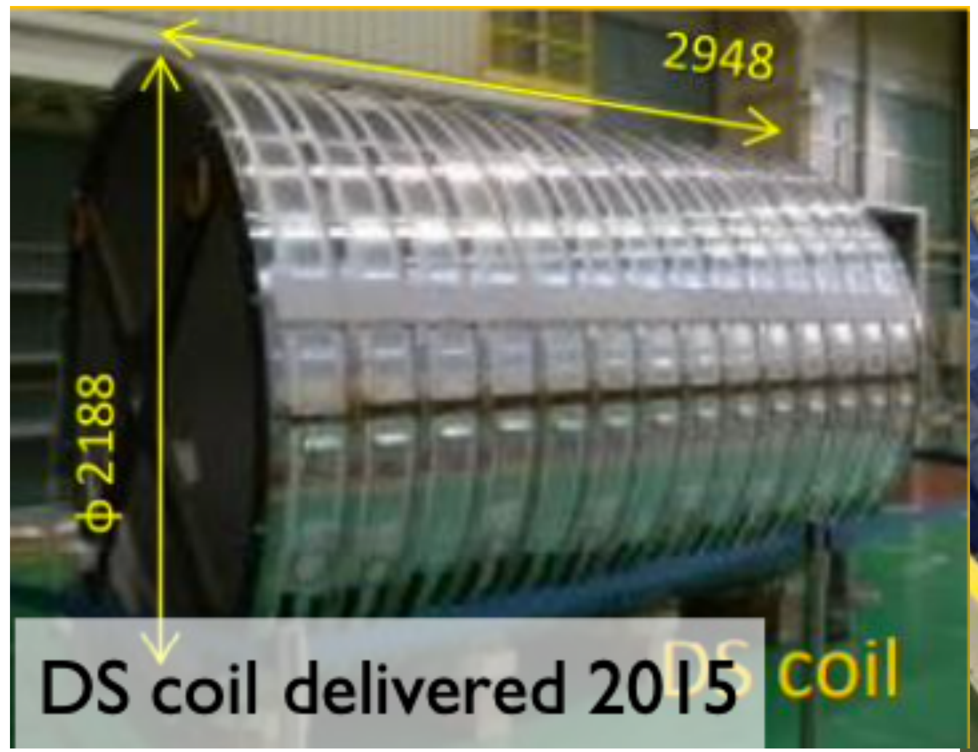


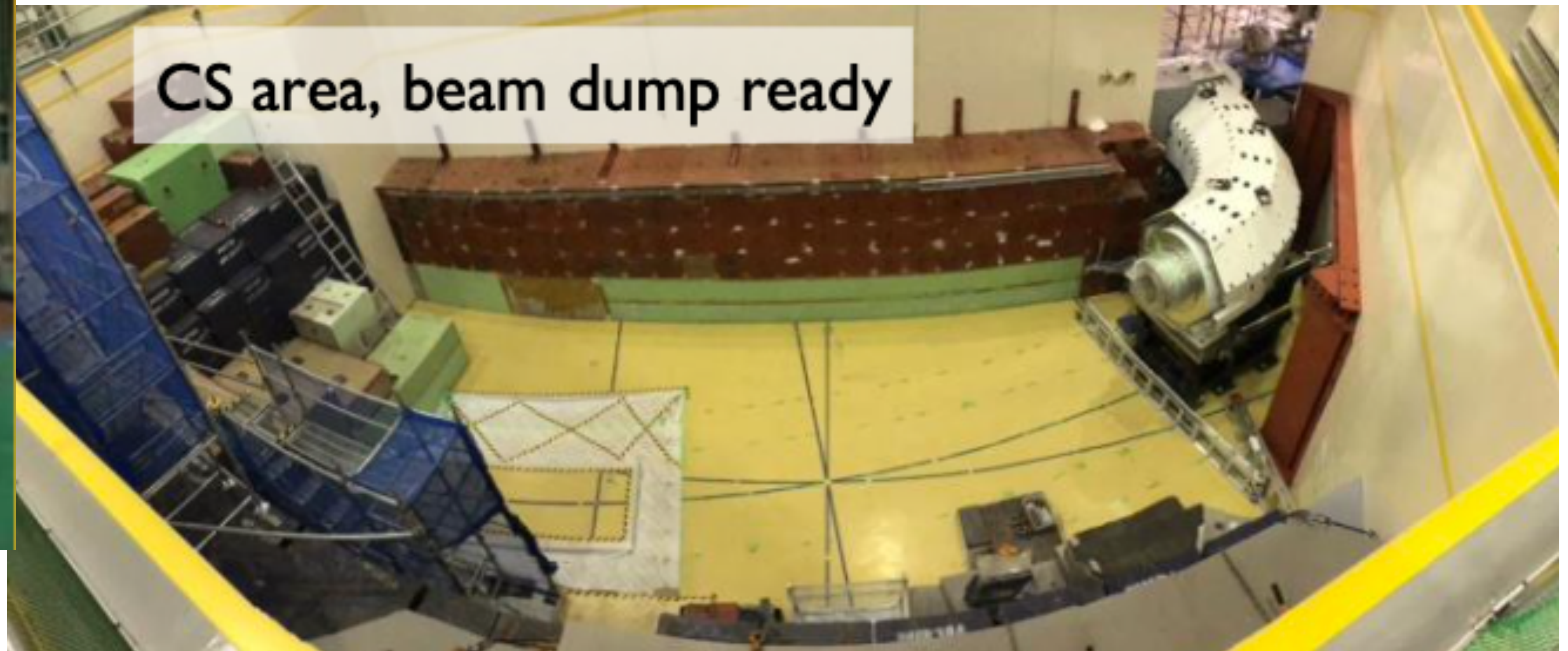
Graphite
Diameter: 26 mm and 40 mm, Length: 700 mm



FEM simulation is completed. Max. temp. 245 degC.

Pion capture solenoids (CS and TS cold mass) to be delivered in summer 2023. Cryostats under construction.





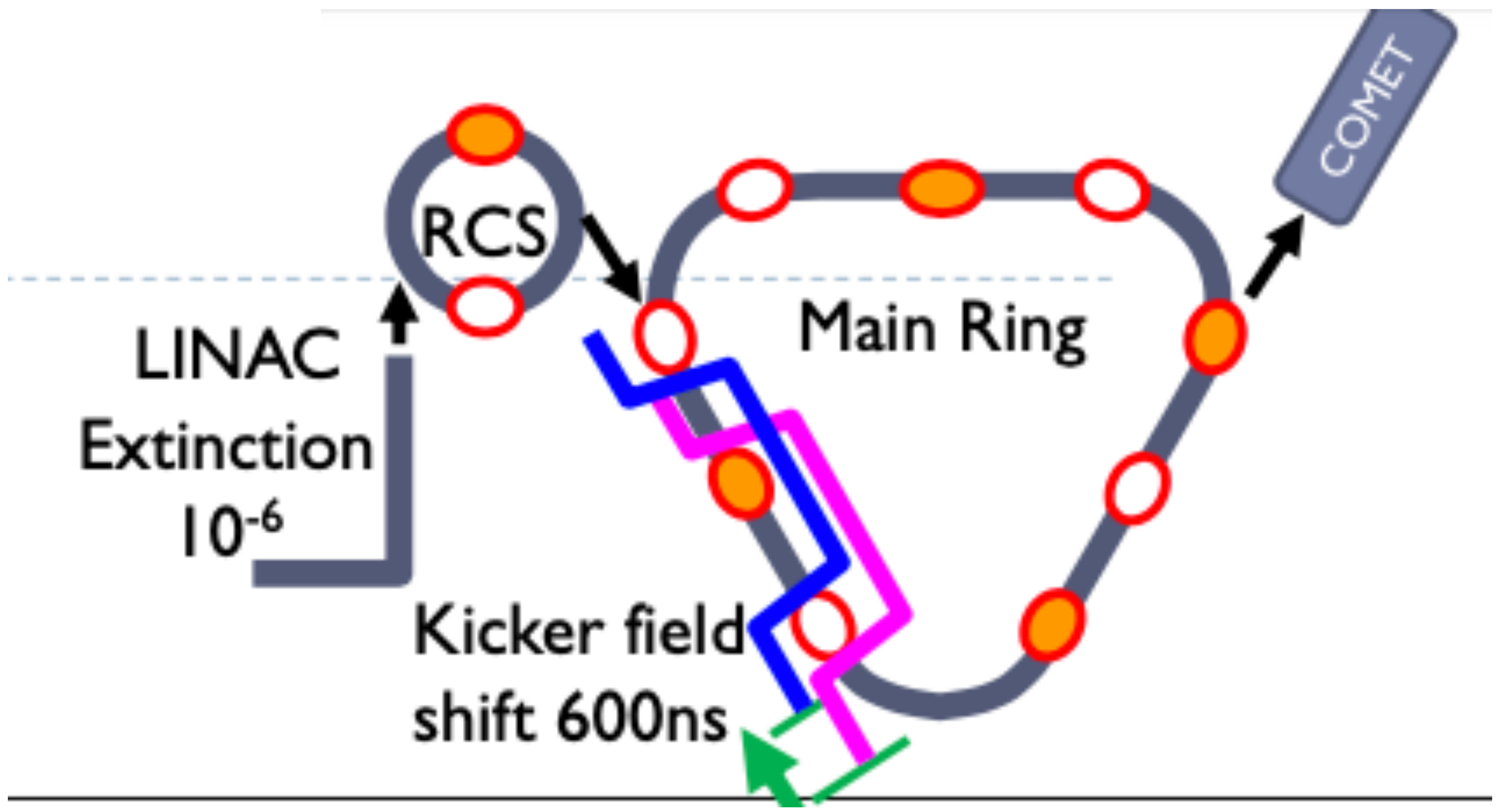
Pulsed beam to reduce the electron and pion beam background

Tiny leakage of protons in between consecutive pulses can cause a background through Beam Pion Capture process:

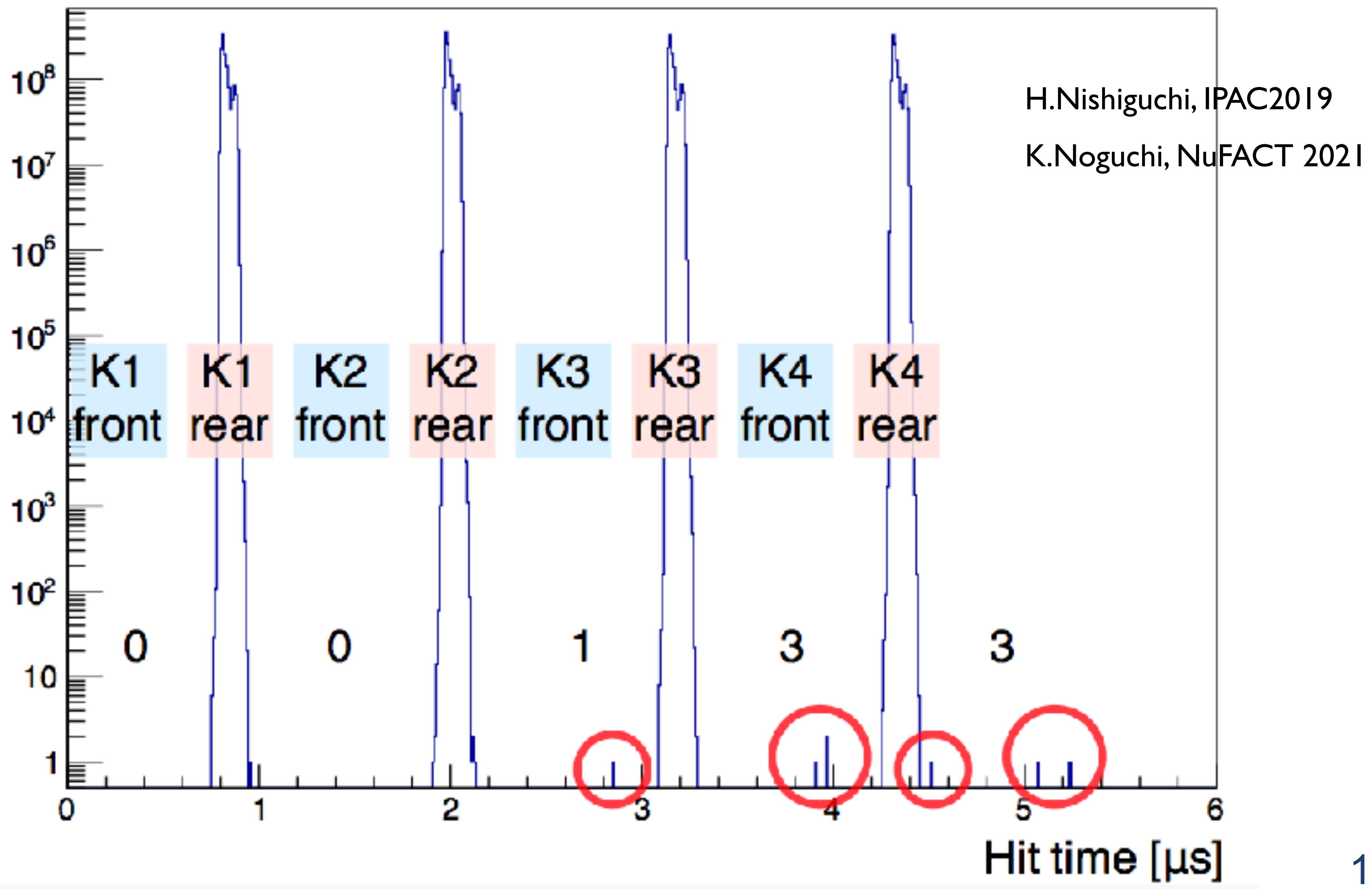
$\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$
$\gamma \rightarrow e^+ e^-$

Requirement:

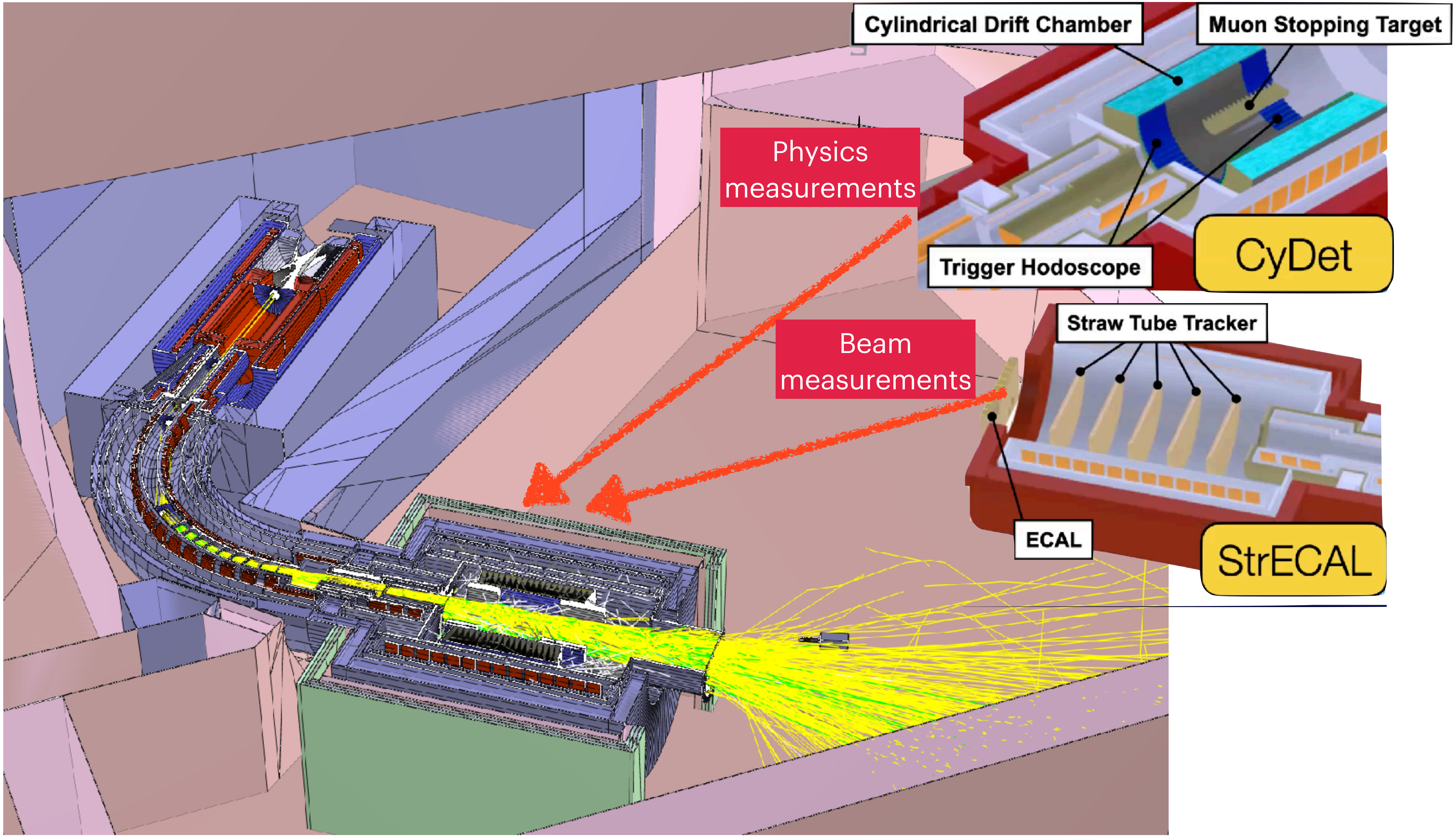
extinction better than 10^{-10} to reach design sensitivity $O(10^{-17})$



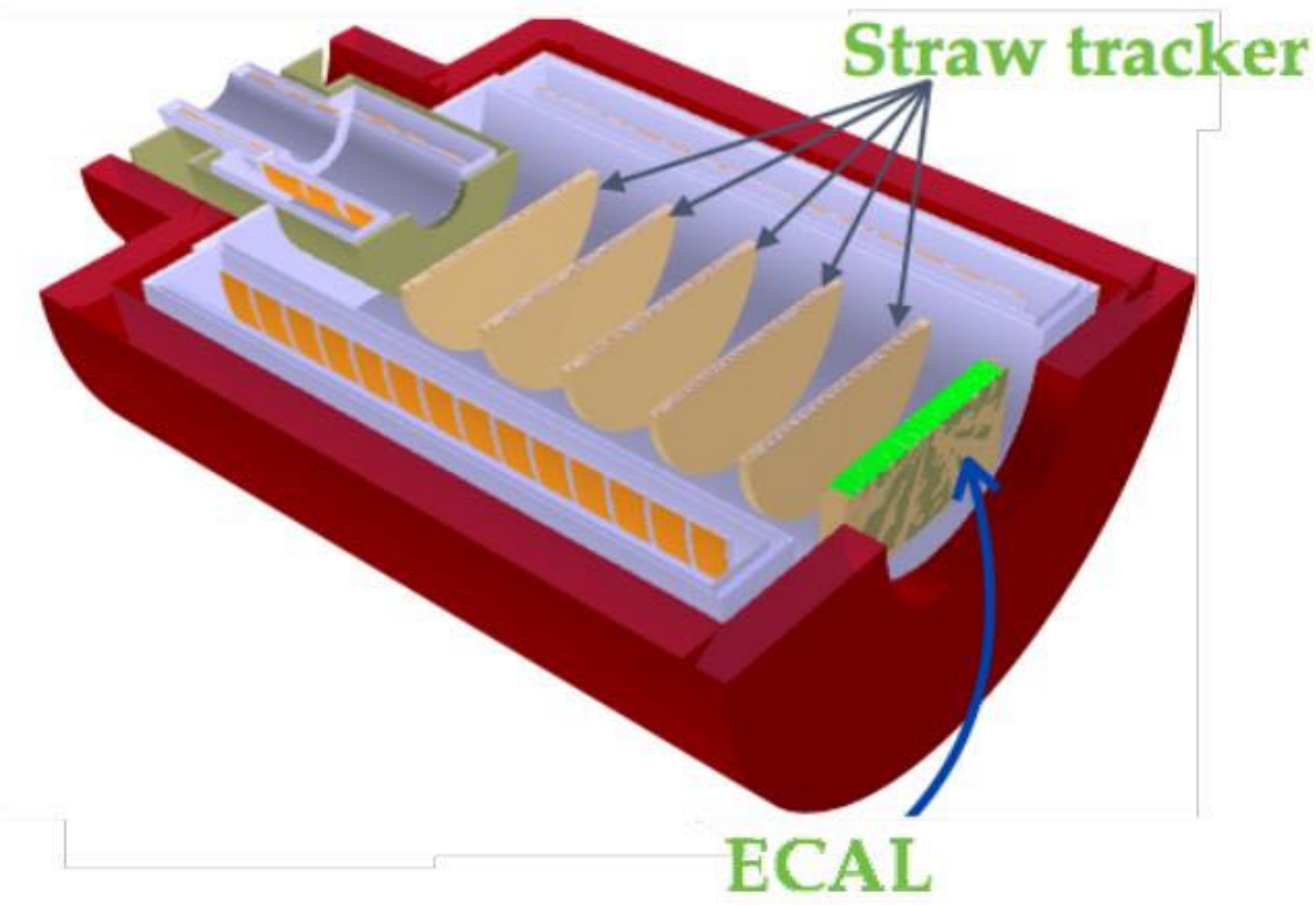
Measurement in Hadron hall 9.3×10^{-11} Extinction achieved (Preliminary)



COMET Phase I



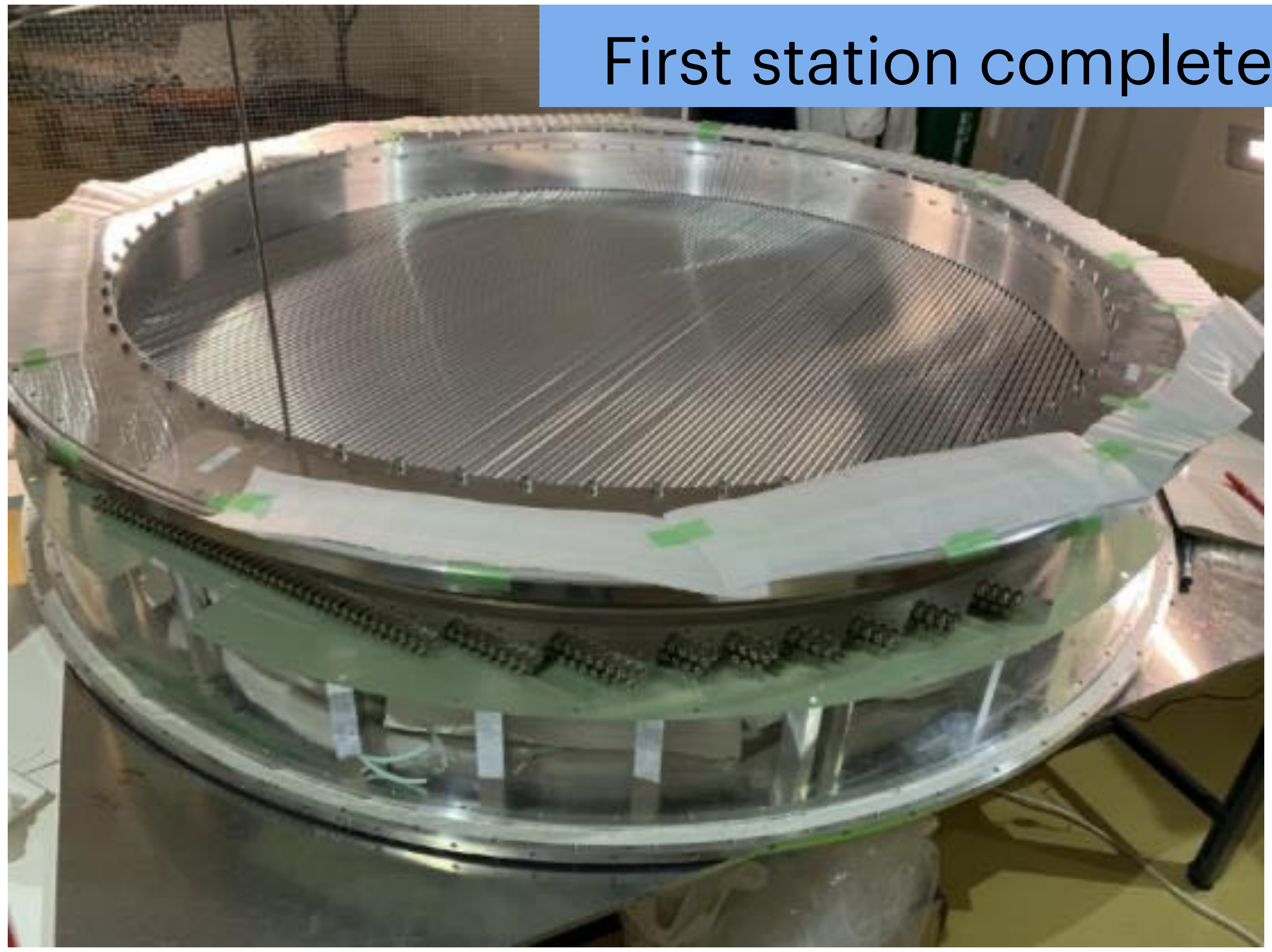
COMET Status :: StrawECAL (Staw tracker + ECAL)

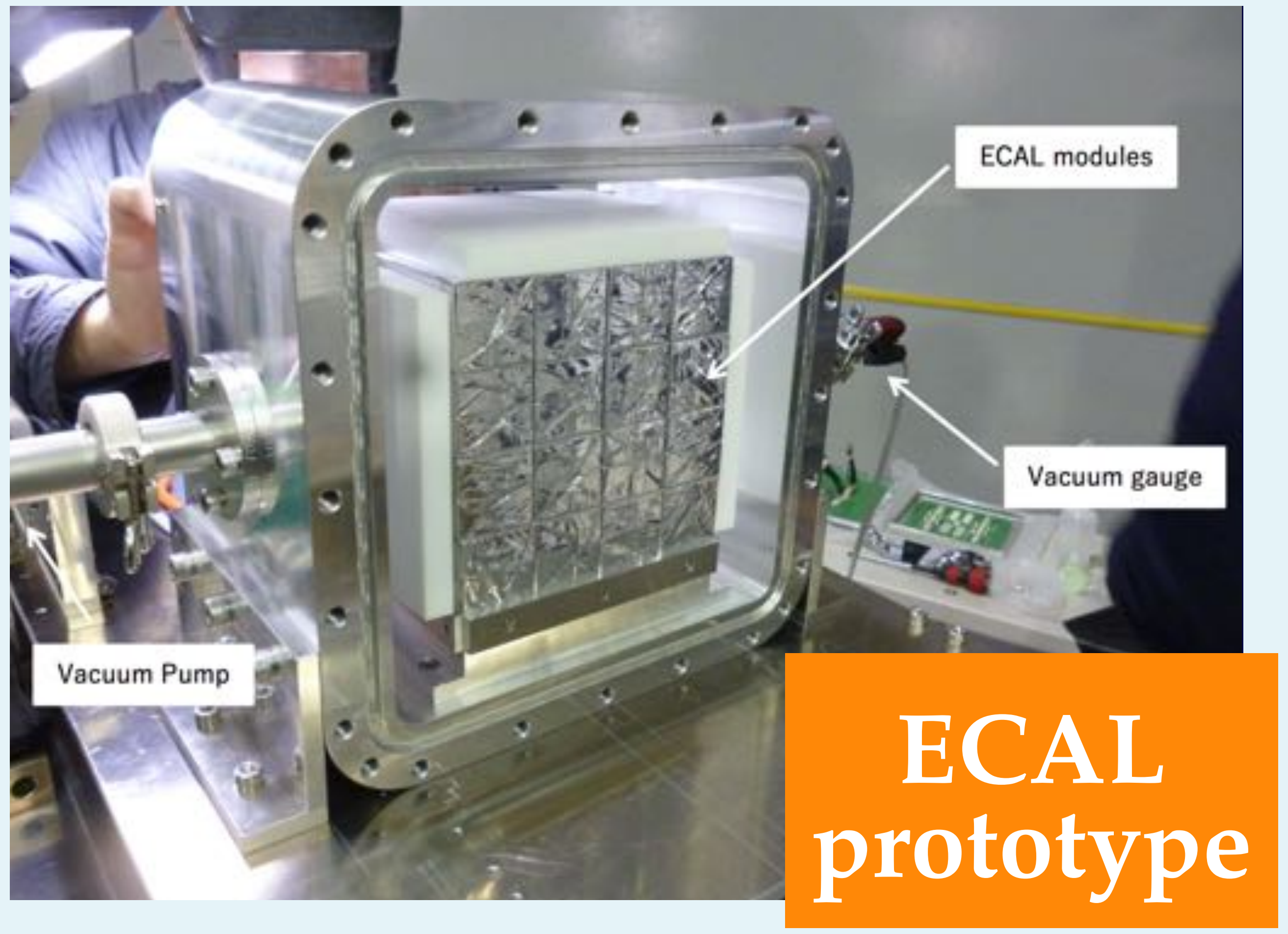


5 stations of straw detectors+ ~2000 LYSO-cells calorimeter

Hajime Nishiguchi
NuFact2021

First station completed !





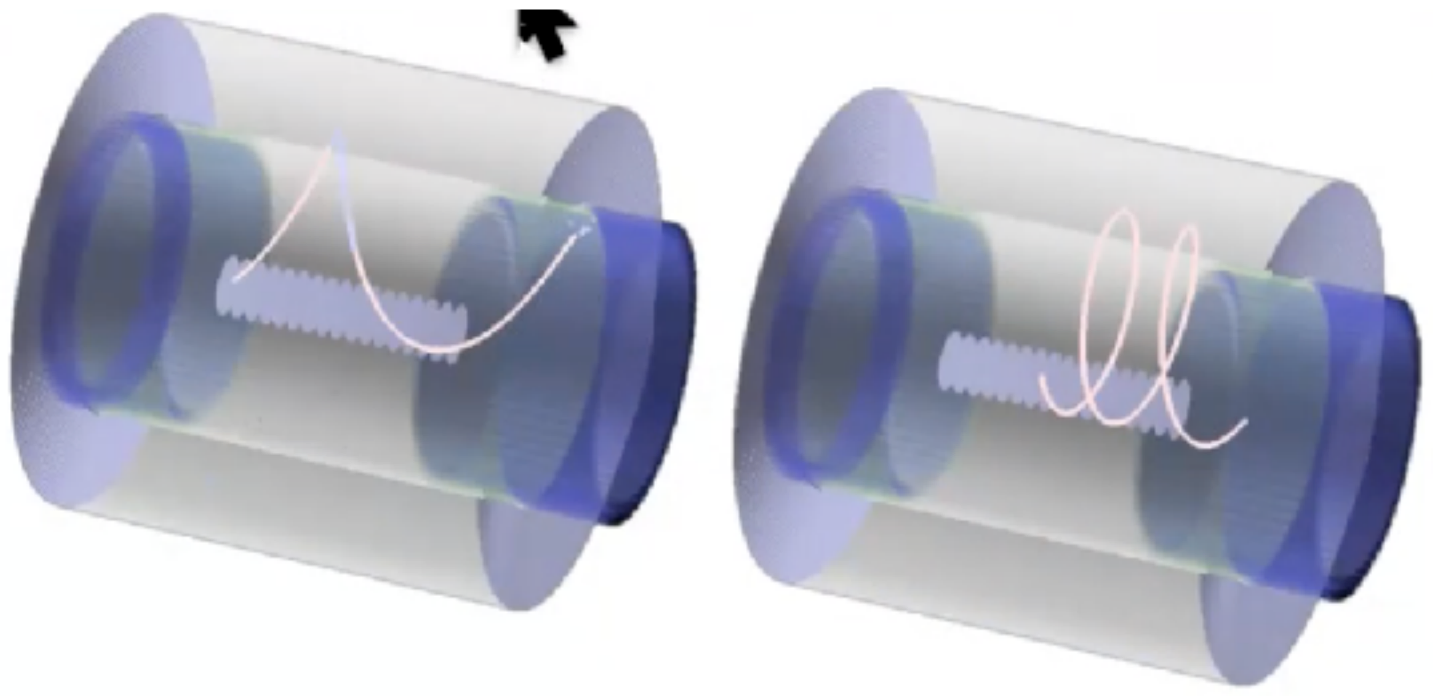
ECAL prototype

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

Beam test with prototype achieved 150um spatial resolution, <200keV/c momentum resolution feasible

COMET Phase-I :: Cylindrical Drift Chamber

- 20 concentric sense layers
- mechanical design based on Belle II CDC
- all stereo layers ± 70 mrad (alternate)
- Helium based gas (He:iC4H10=90:10) to minimise multiple scattering
- large inner bore (~500 mm) to avoid beam flash and DIO



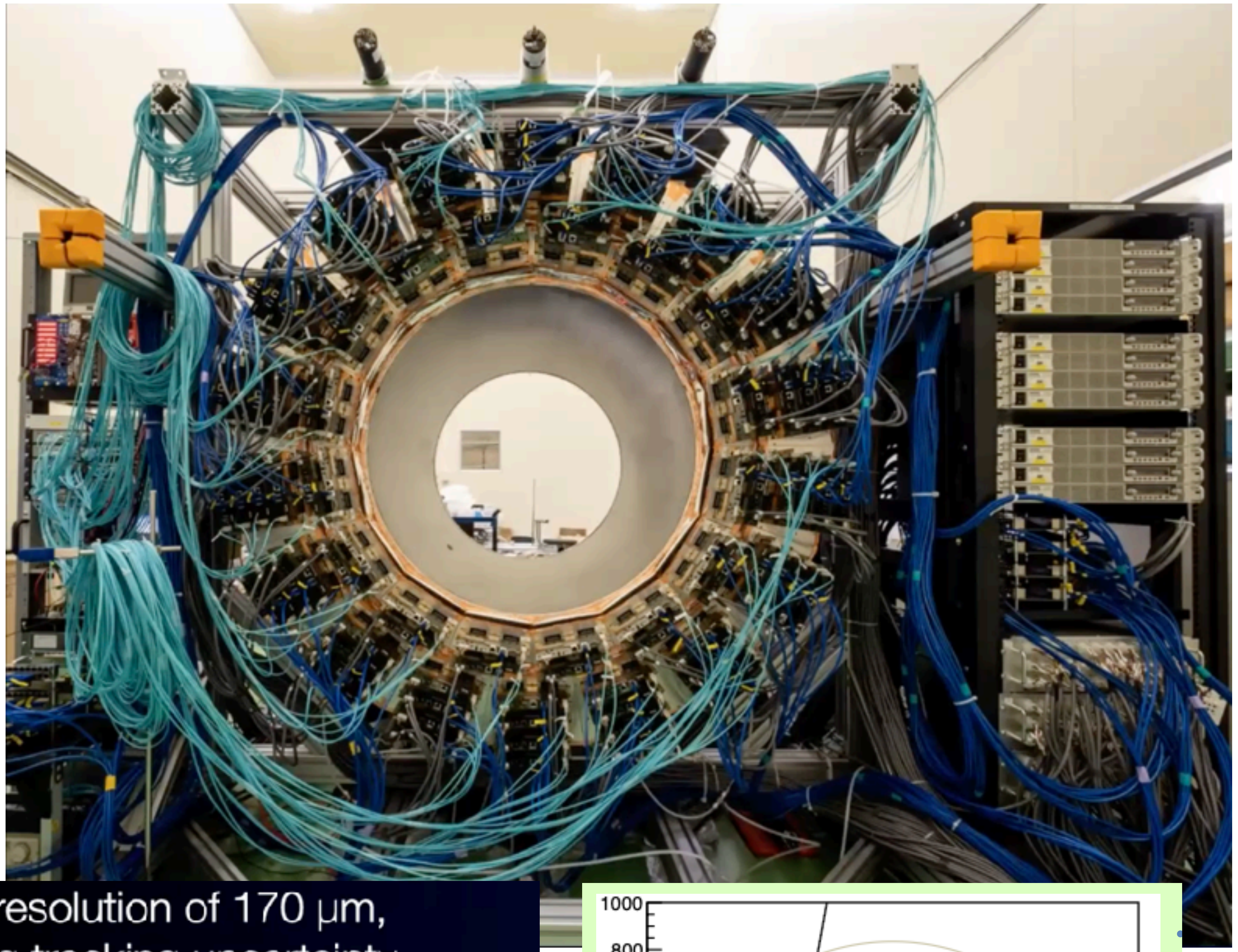
- CDC fully read out since 2019
- Currently at KEK being commissioned with cosmic rays

- signal tracks (~100 MeV/c) contained inside the CDC for better signal resolution
- triggered events : 60% single turn tracks & 40% multiple turn tracks

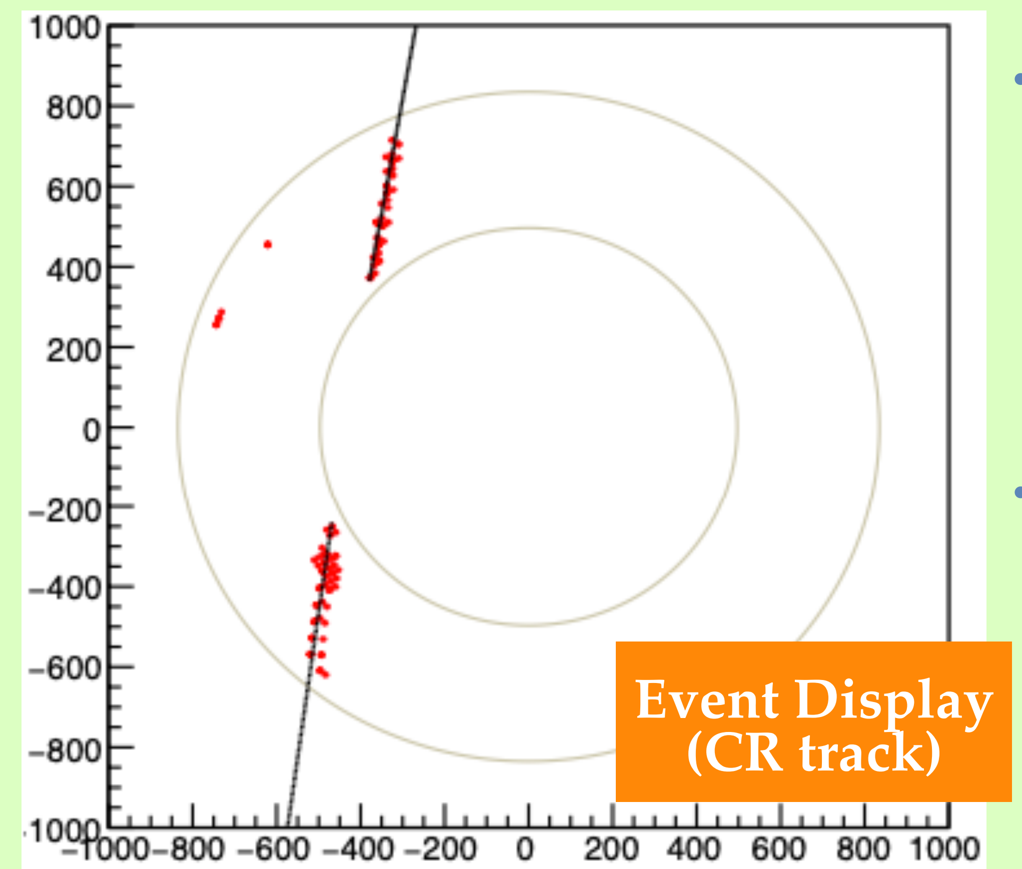
Momentum resolution: better than 200 keV/c @ 105 MeV/c

HV=1850 V
He /i-C4H10 90/10
100 cc/min

Test of a small prototype of the COMET cylindrical drift chamber
Nucl. Inst. Meth A 1015 (2021) 165756.

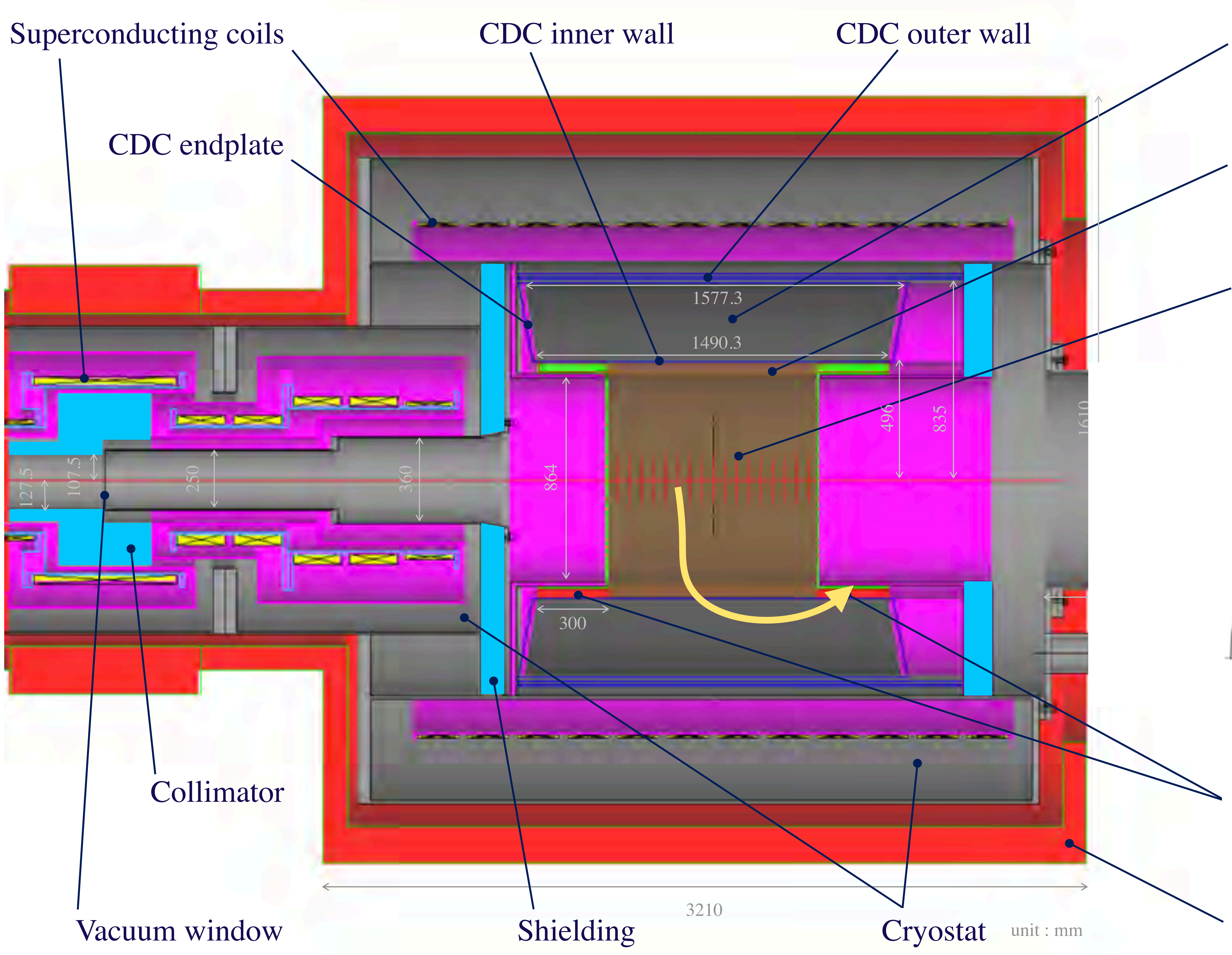


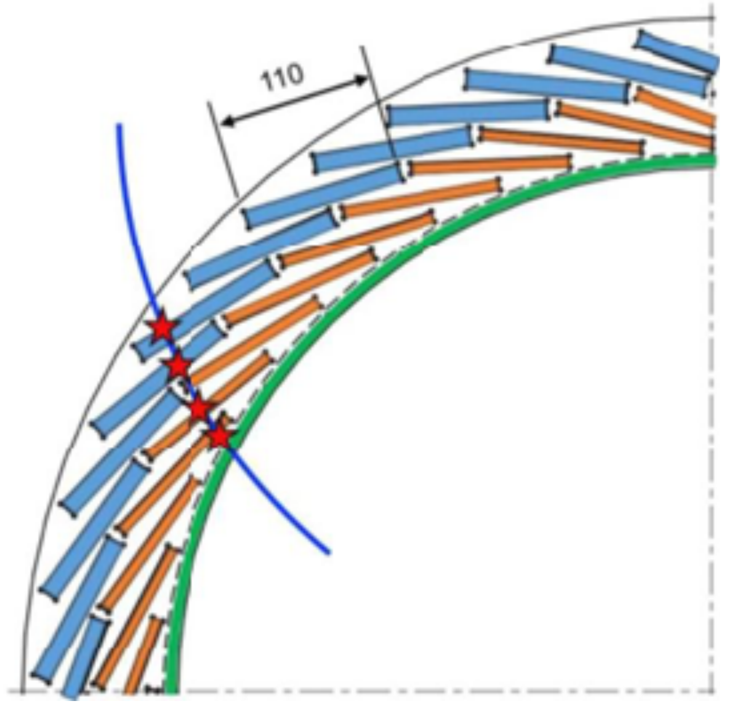
- Spatial resolution of 170 μm, including tracking uncertainty, achieved.
- Hit efficiency of 98% achieved
- Significant noise reduction achieved
- Detail study of detector response
  - space-charge effects
  - crosstalks
- Water cooling testing of the CDC readout underway

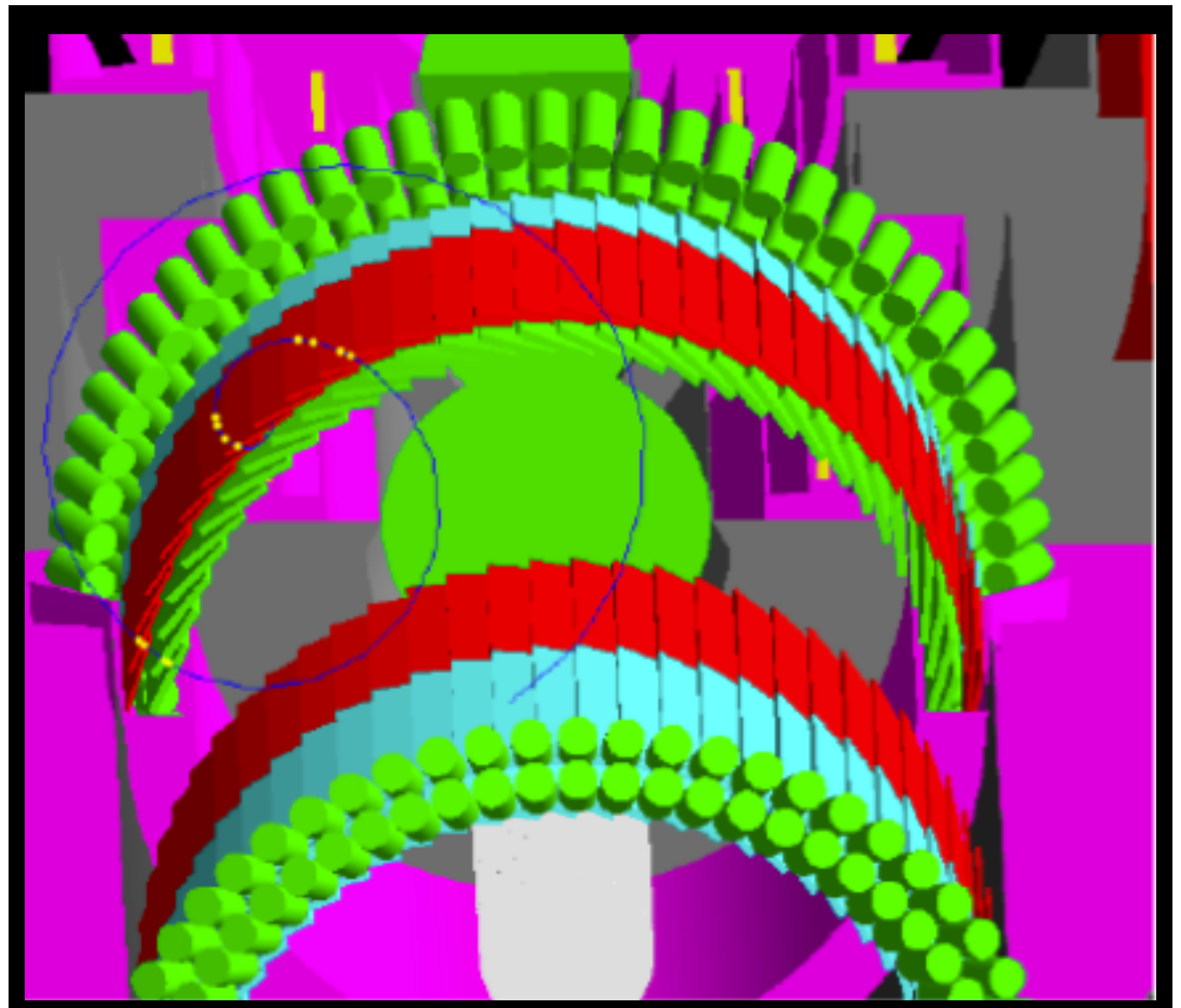


Event Display (CR track)

COMET Phase-I :: Electron Detectors (CyDet)



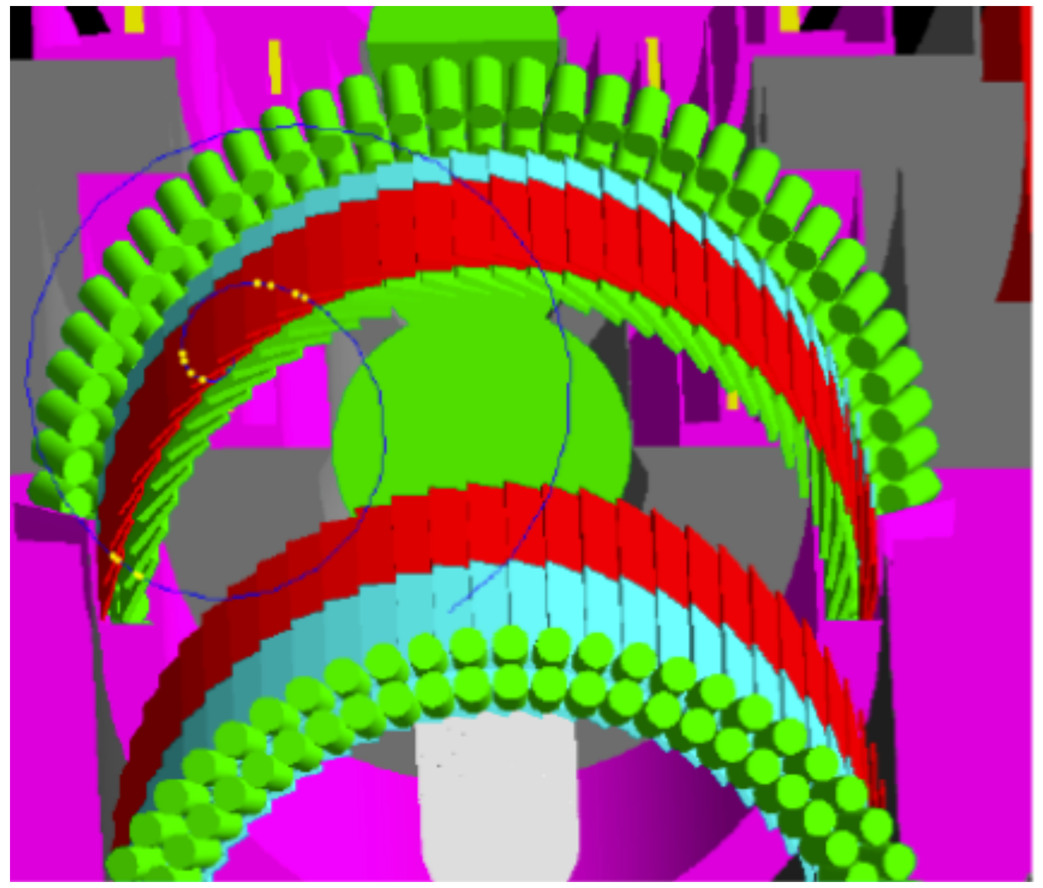




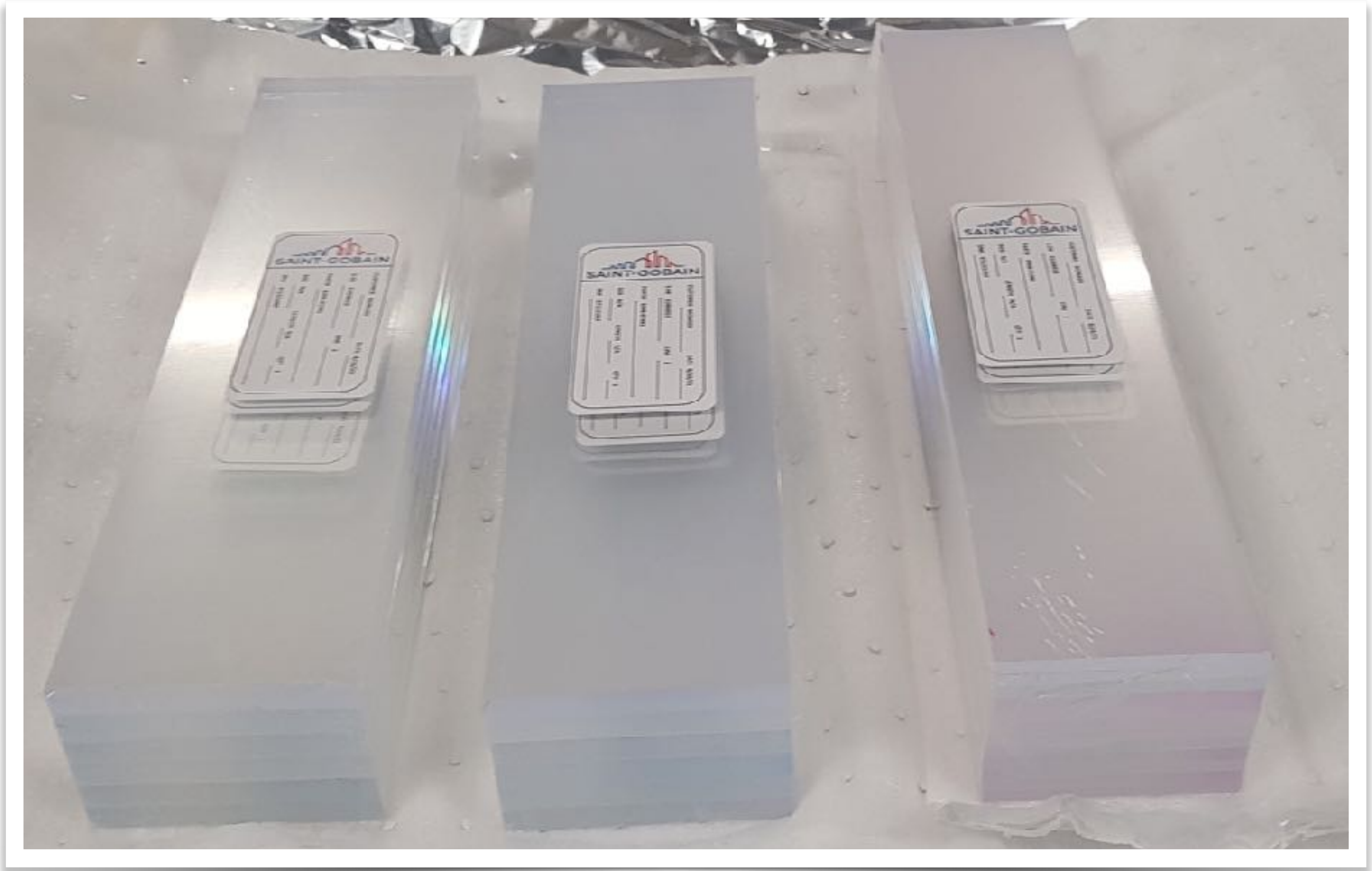
2-rings of ultra fast scintillators (64 segments, 33/36 x 1 x 1 cm3) read by optical fibres and SiPMs

2-rings of Cherenkov counters (acrylic plastic, 300x90x10 mm3) to be added in a second step

Four-hold coincidence provides trigger and PID

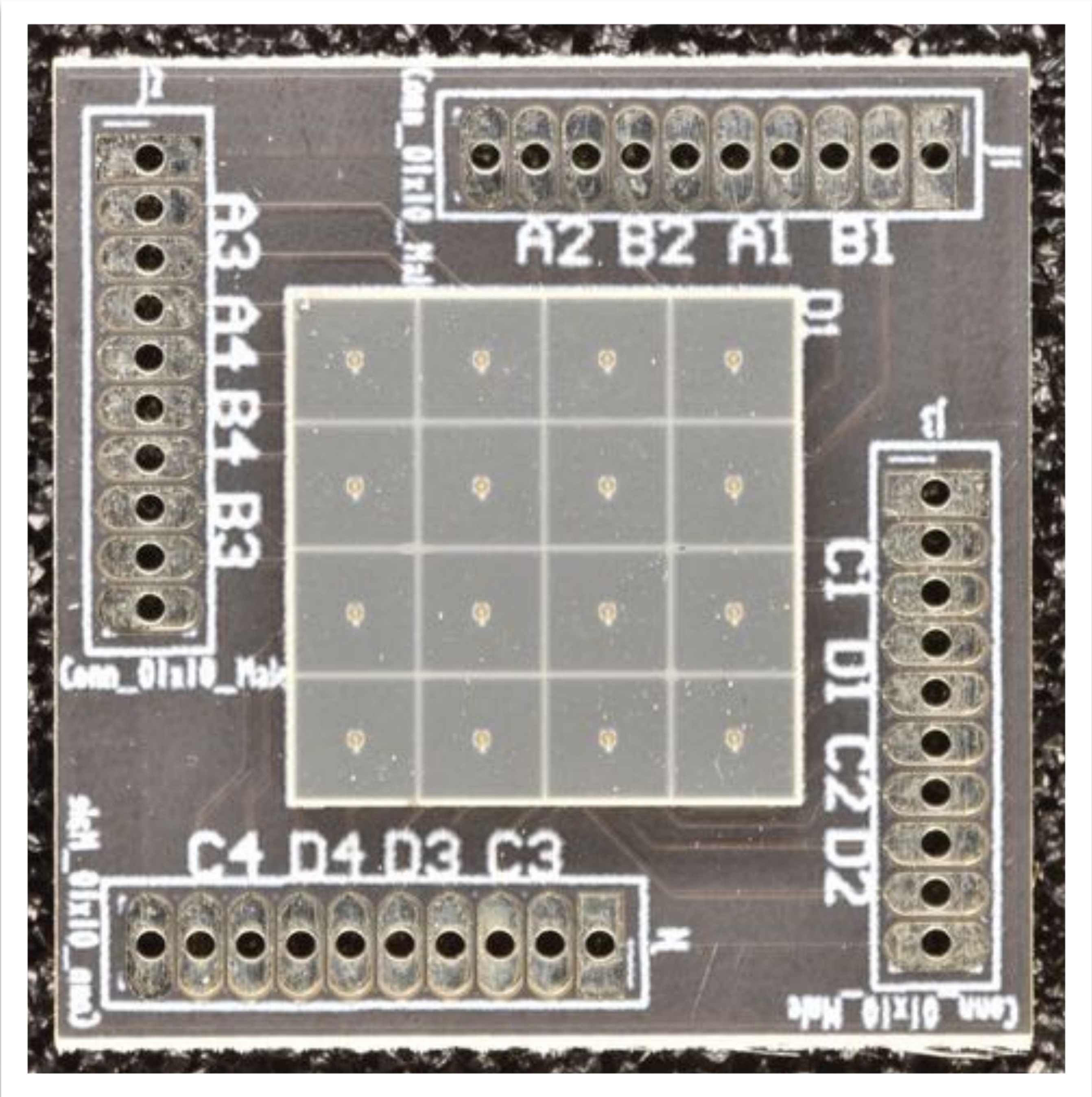


plastic counters (BC-408 from Saint-Gobain).



Only
trigger for COMET Phase-I

MPPC assembled on PCB

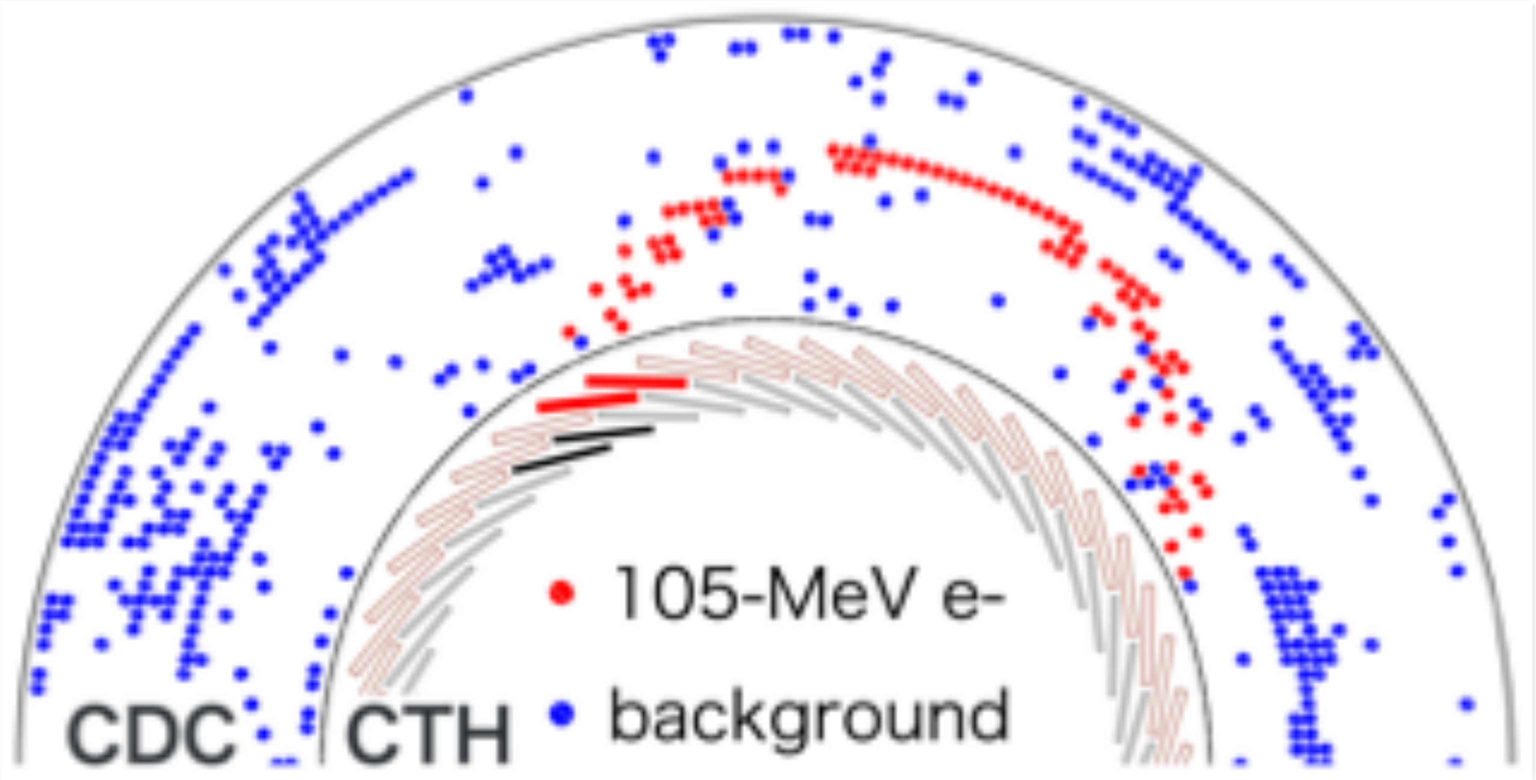


Hit selection using Gradient Boosting Decision Trees (GBDT)

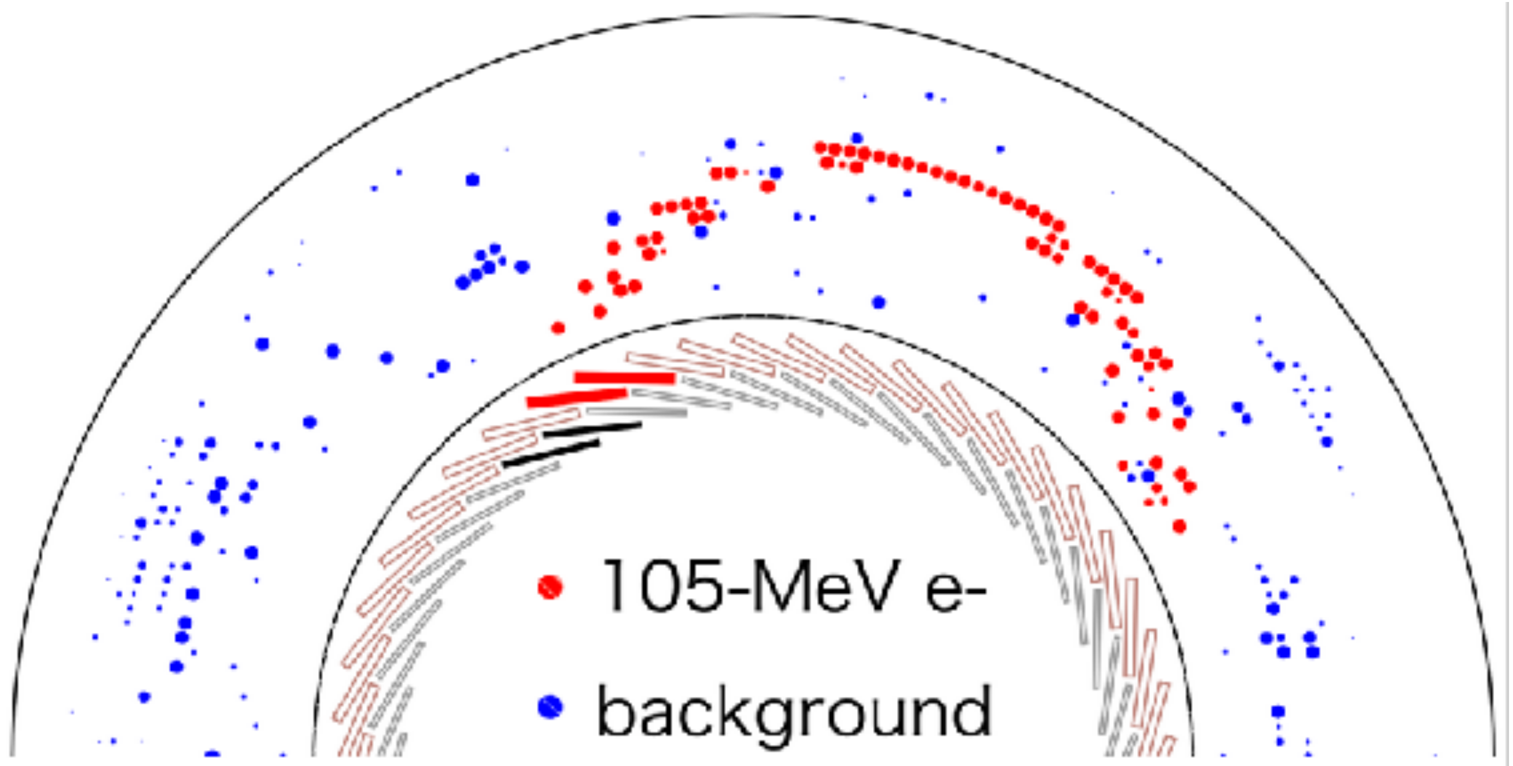
Classify hits using their local neighbours, charge and layer information

Lookup table stored in a FPGA on the trigger board COTTRI.

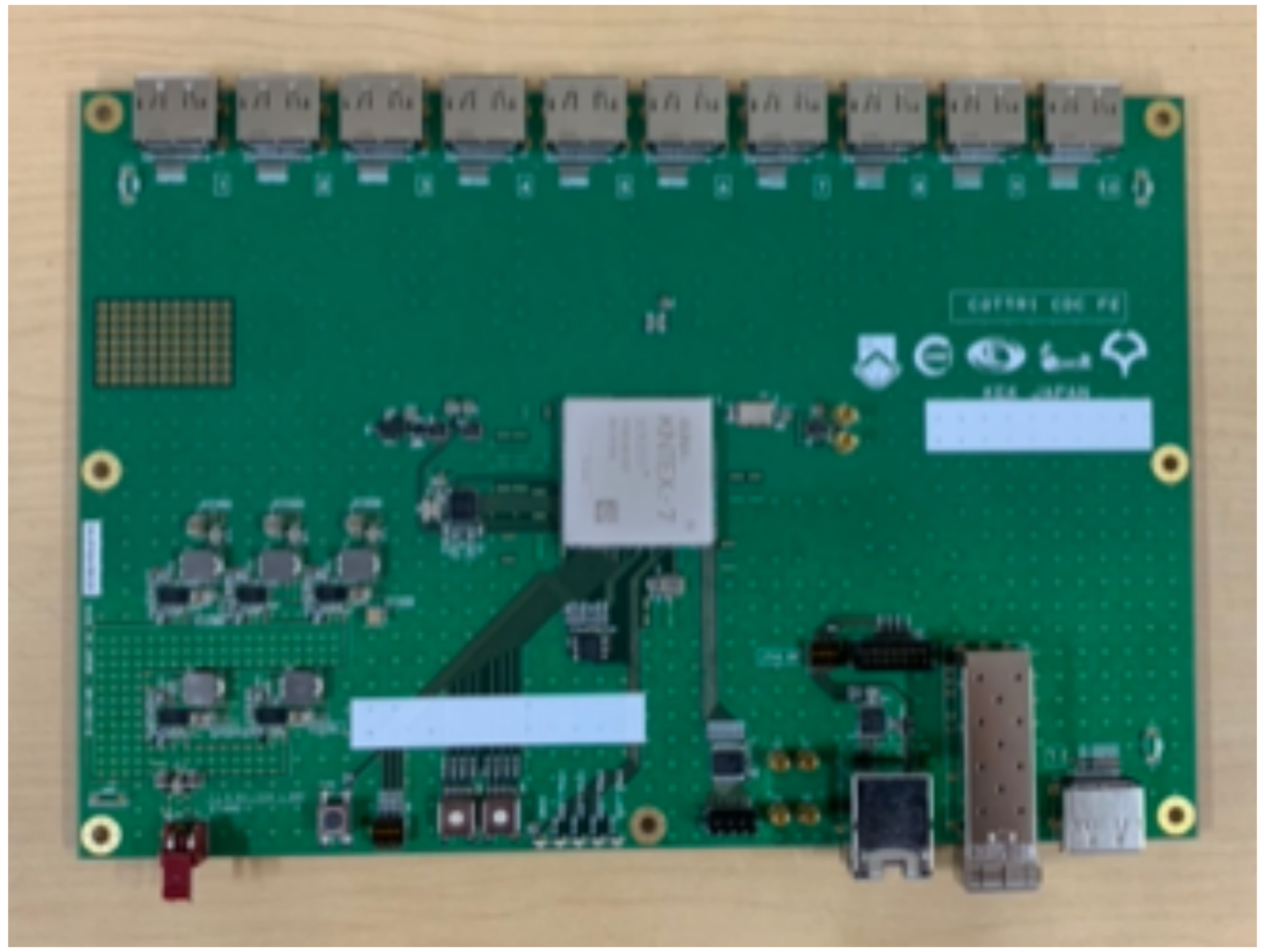
Trigger rate is reduced from 91 kHz to 13 kHz for 96% efficiency and 3.2μs latency



before GBDT



after GBDT

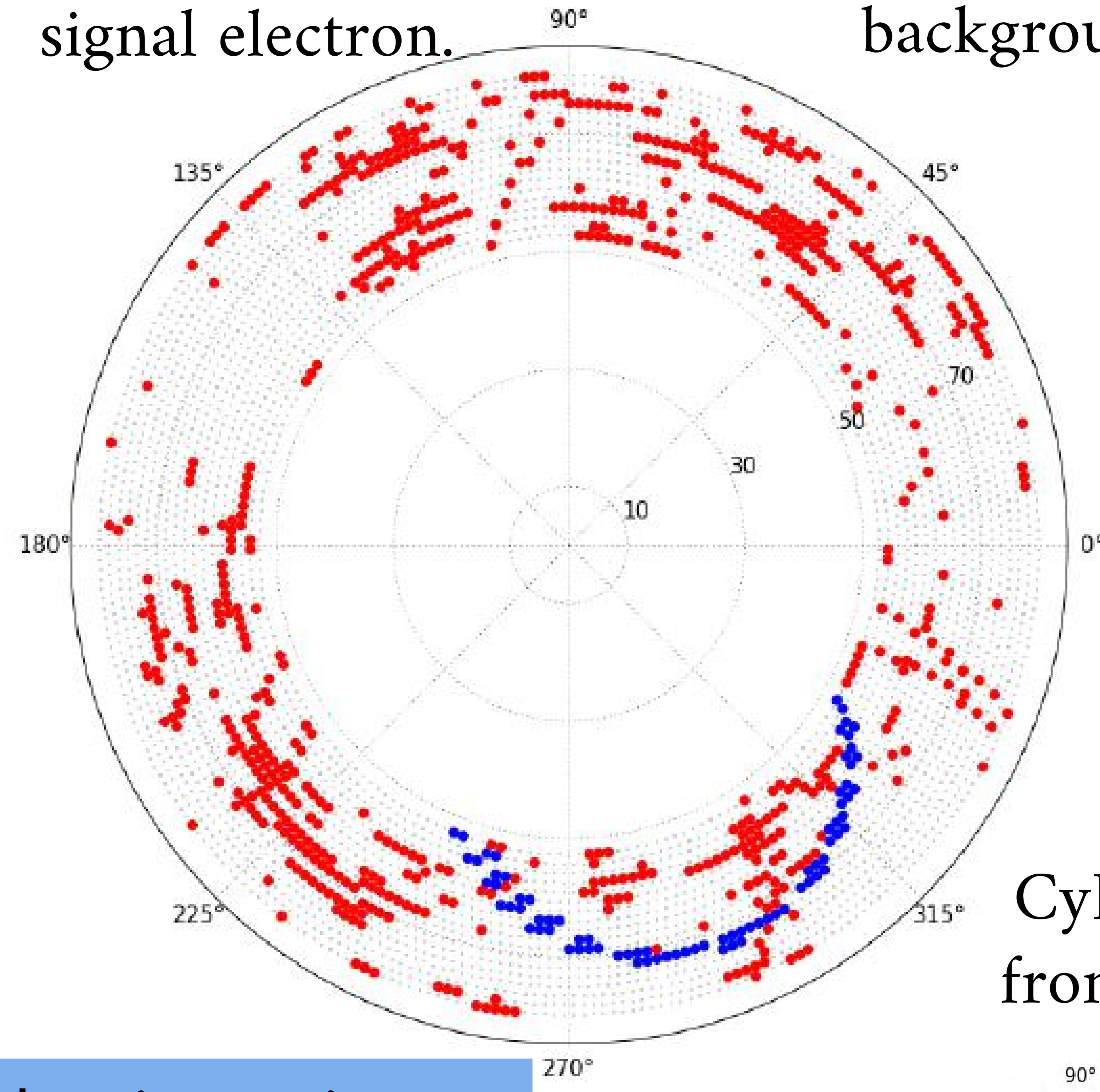


COTRI Trigger Board

- Y. Nakazawa, PhD thesis, Osaka University 2020
- Y. Nakazawa et al. IEEE NS, 2021

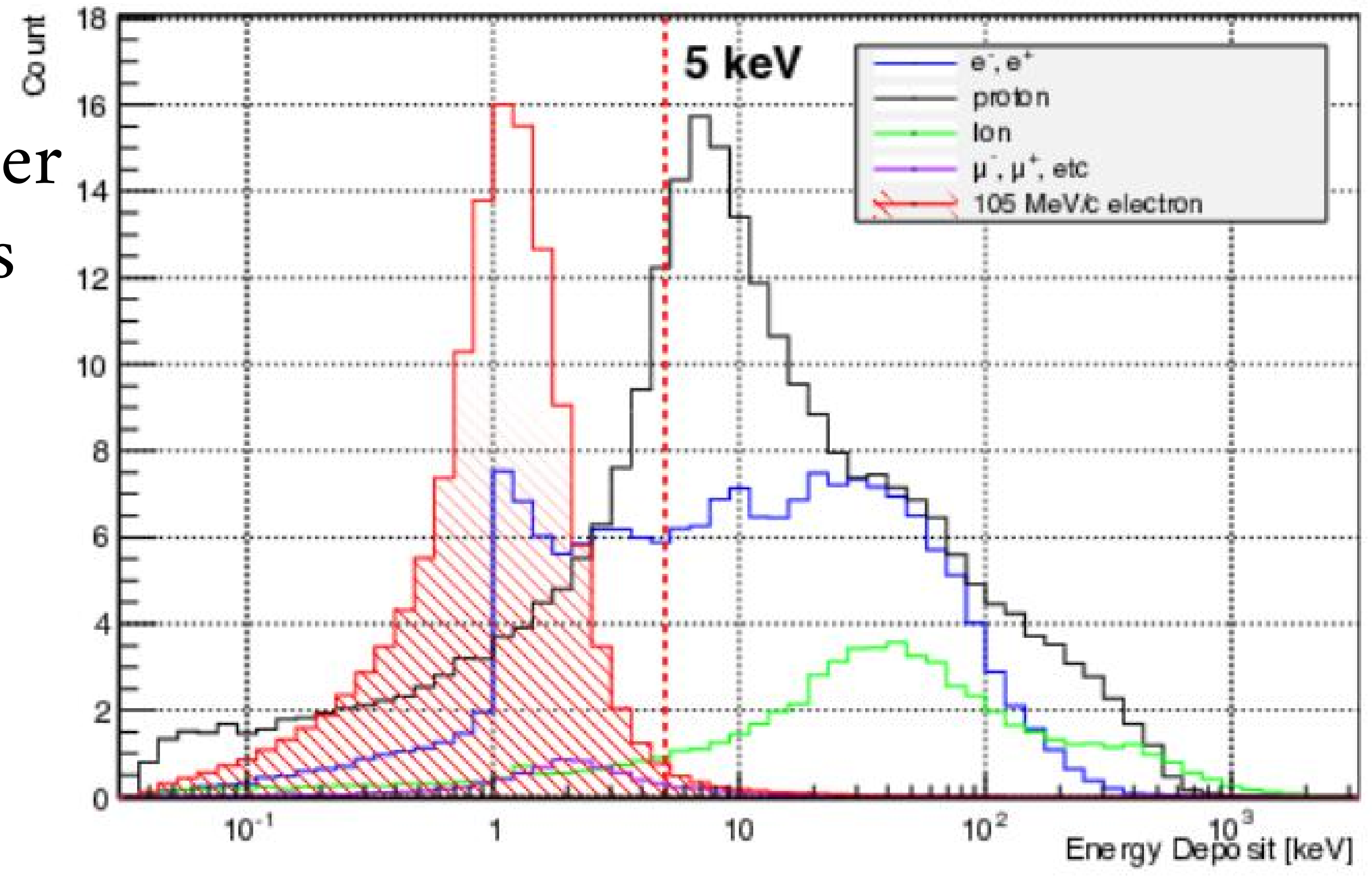
Blue hits correspond to the signal electron.

Red points are hits caused from background processes



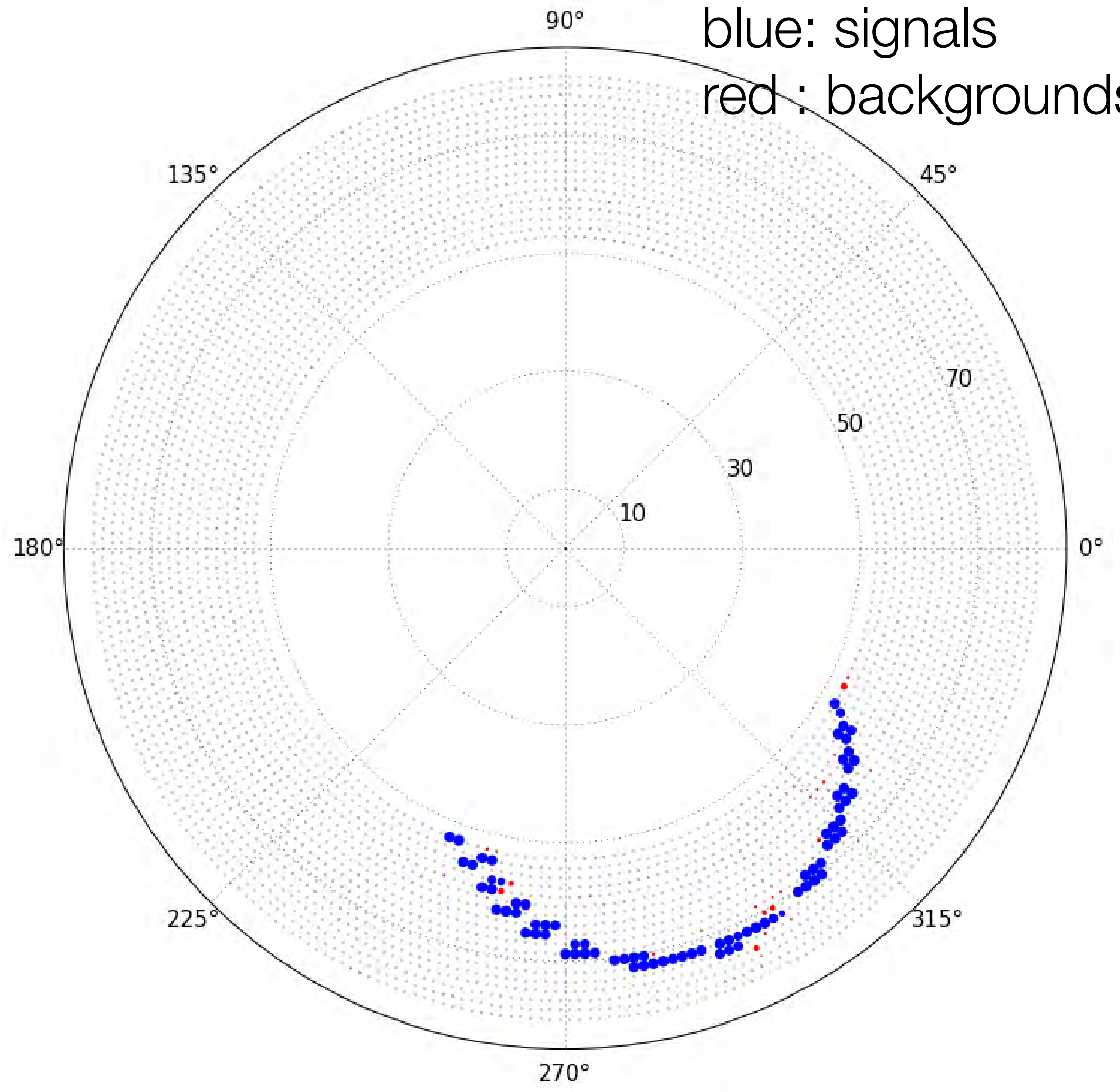
Most background hits are rejected based on timing, charge.

Total energy deposits per cell for signal electrons and noise hits



CyDet event. This is a projected view from the central plane of the detector

Hit selection using Gradient Boosted Decision Trees (GBDT) and Hough Transform



blue: signals
red : backgrounds

95% background rejection for 99% hit efficiency

$$BR(\mu^- + Al \rightarrow e^- + Al) = 3.1\times10^{-15}$$

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Antiproton-induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

Summary of the estimated background events for a single-event sensitivity of 3×10^{-15}

Backgrounds and Sensitivity - for ultimate goal of x10000 SINDRUM

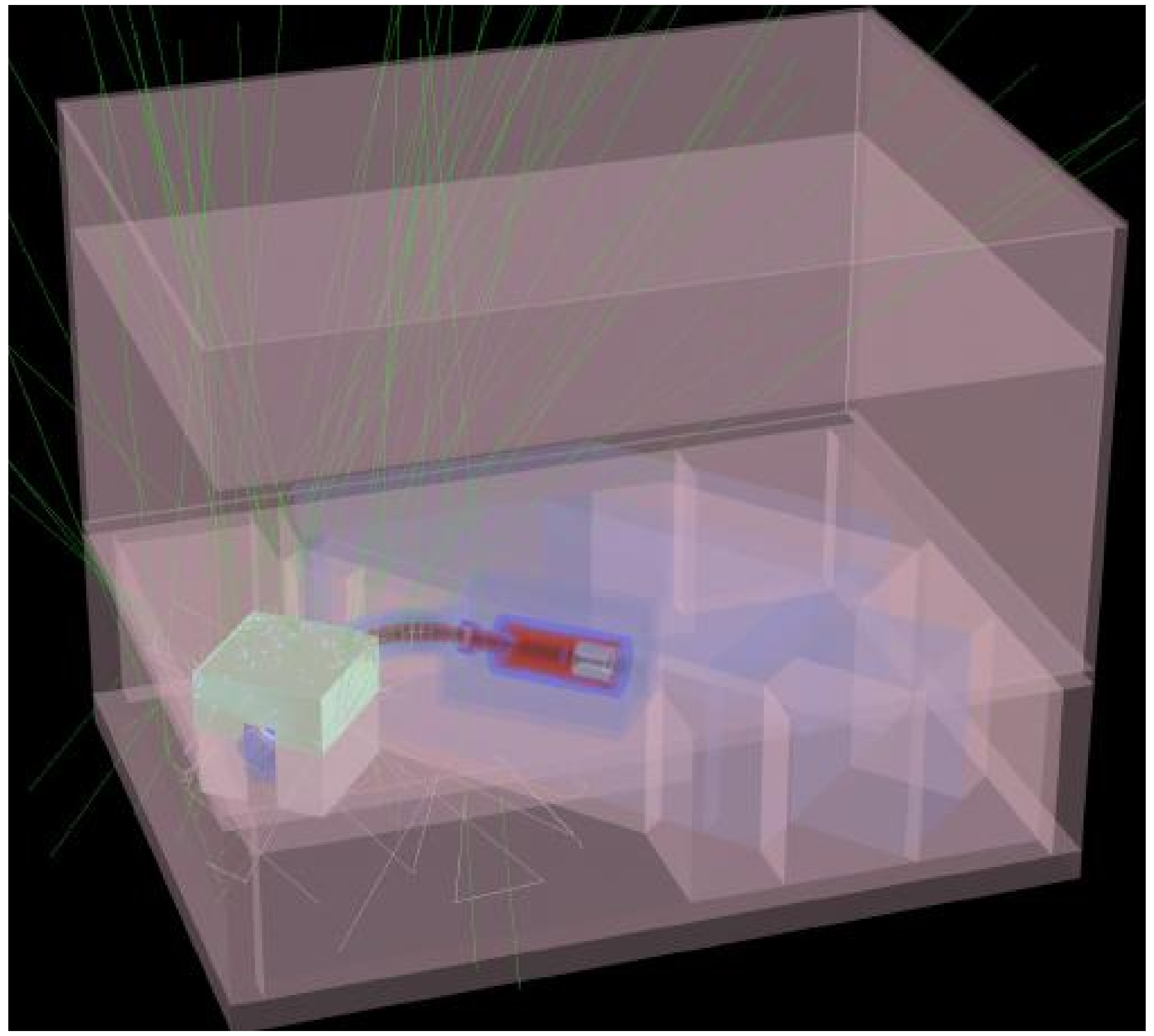
With statistics of 3.6×10^{20} POT

Process	Expected event yield
Cosmic ray muons	0.21 ± 0.06
DIO	0.14 ± 0.11
Antiprotons	0.04 ± 0.02
Pion capture	0.021 ± 0.002
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total background	0.41 ± 0.13(stat+syst)

5σ discoverable: median $R_{\mu e} = 2 \times 10^{-16}$ SES 3×10^{-17}

For no conversion 90% CL upper limit $R_{\mu e} < 8 \times 10^{-17}$

Atmospheric muons = main background ?
Cover as hermetically as possible the detectors with very high efficiency veto counters (CRV)
The short data acquisition foreseen for COMET helps, **BUT** ...



The (rare) muons and muon-induced electrons w/o CRV veto might undergo high angle scattering before penetrating in the detection volume → they might come from (almost) everywhere

Impossible to simulate this background with high accuracy with direct MC (Geant 4) , but feasible with a backward MC

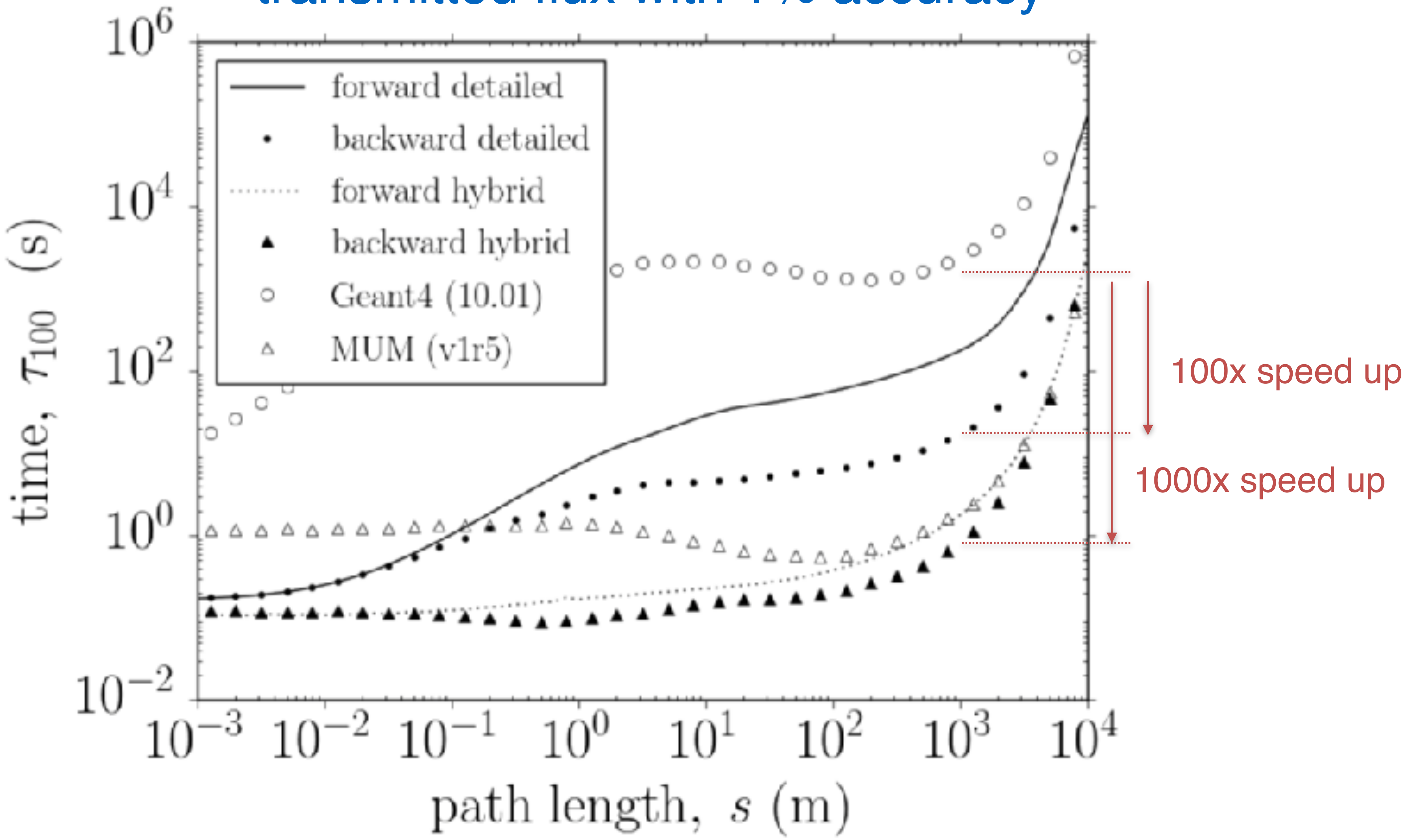
Non analog simulation using Importance Sampling and Backward Monte Carlo

- Run a standard SimG4 simulation with primary muons generated close to (and illuminating) the CYDET
- Select candidate events using COMET signal selection criteria
- Backward propagate the selected primary muons up in the atmosphere using the detailed geometry of the COMET experimental hall implemented in Geant 4 and the neighboring topographical data

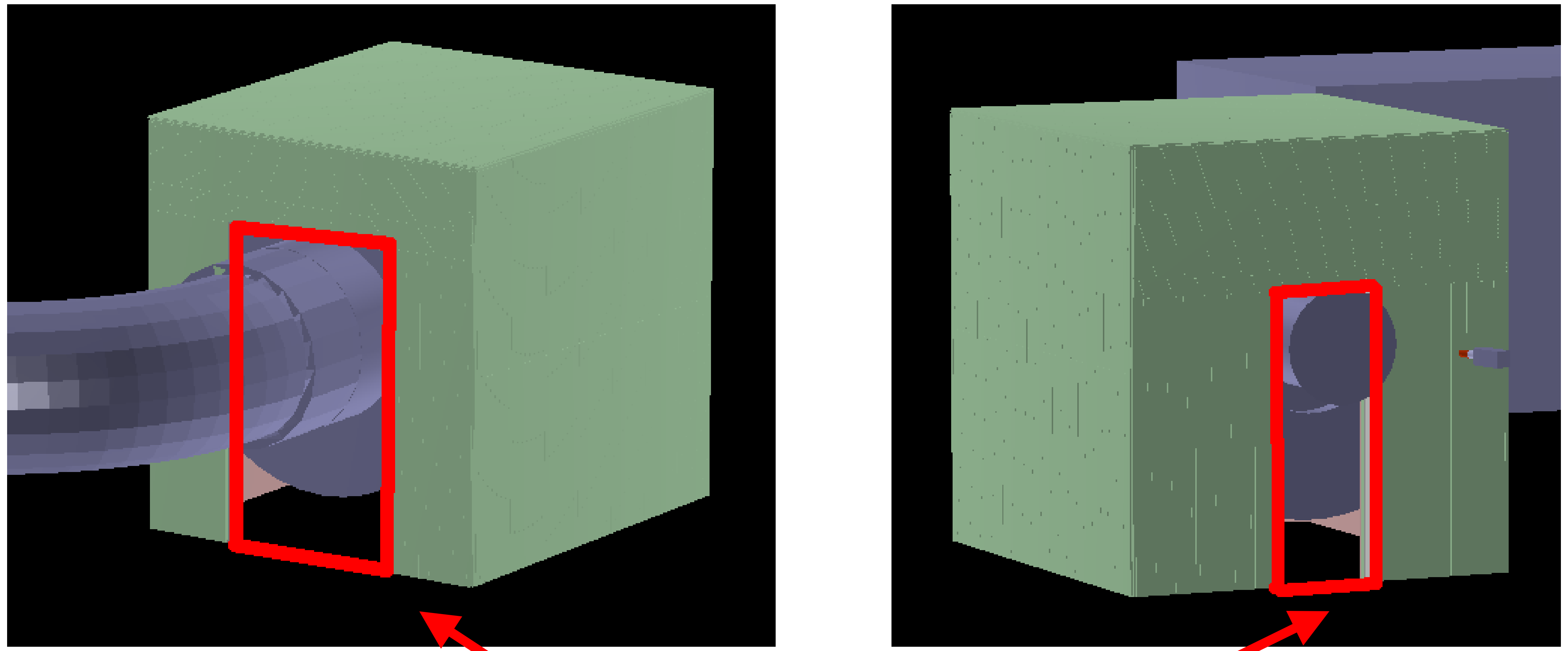
The corresponding MC rate (in Hz) is given by the ratio of the flux to the bias generation PDF

V. Niess *et al*, CPC 2018, 229, pg 54

CPU time needed to simulate the transmitted flux with 1% accuracy



Simulation Scheme for Atmospheric Muons



generation surfaces

October 2019

... we estimate a total number ... eaking events” for the 146 live days of COMET ...

VERY PRELIMINARY

memento: TDR COMET : < 0.01

Evolution of the CRV geometry in 2020 to limit the atmospheric muon background :

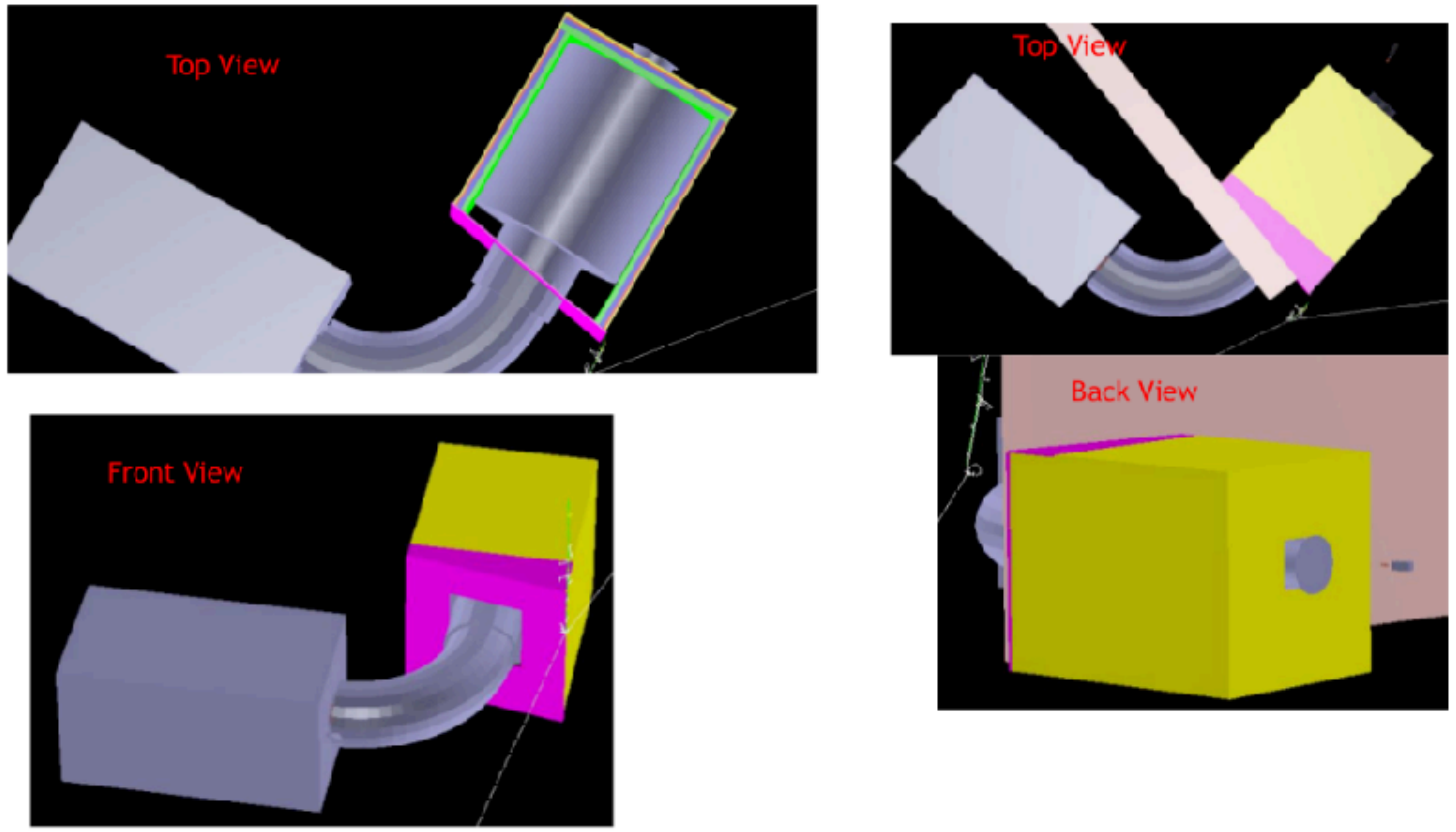
- beam openings reduced by half with respect to the TDR
- hybrid CRV with GRPCs in high radiation areas

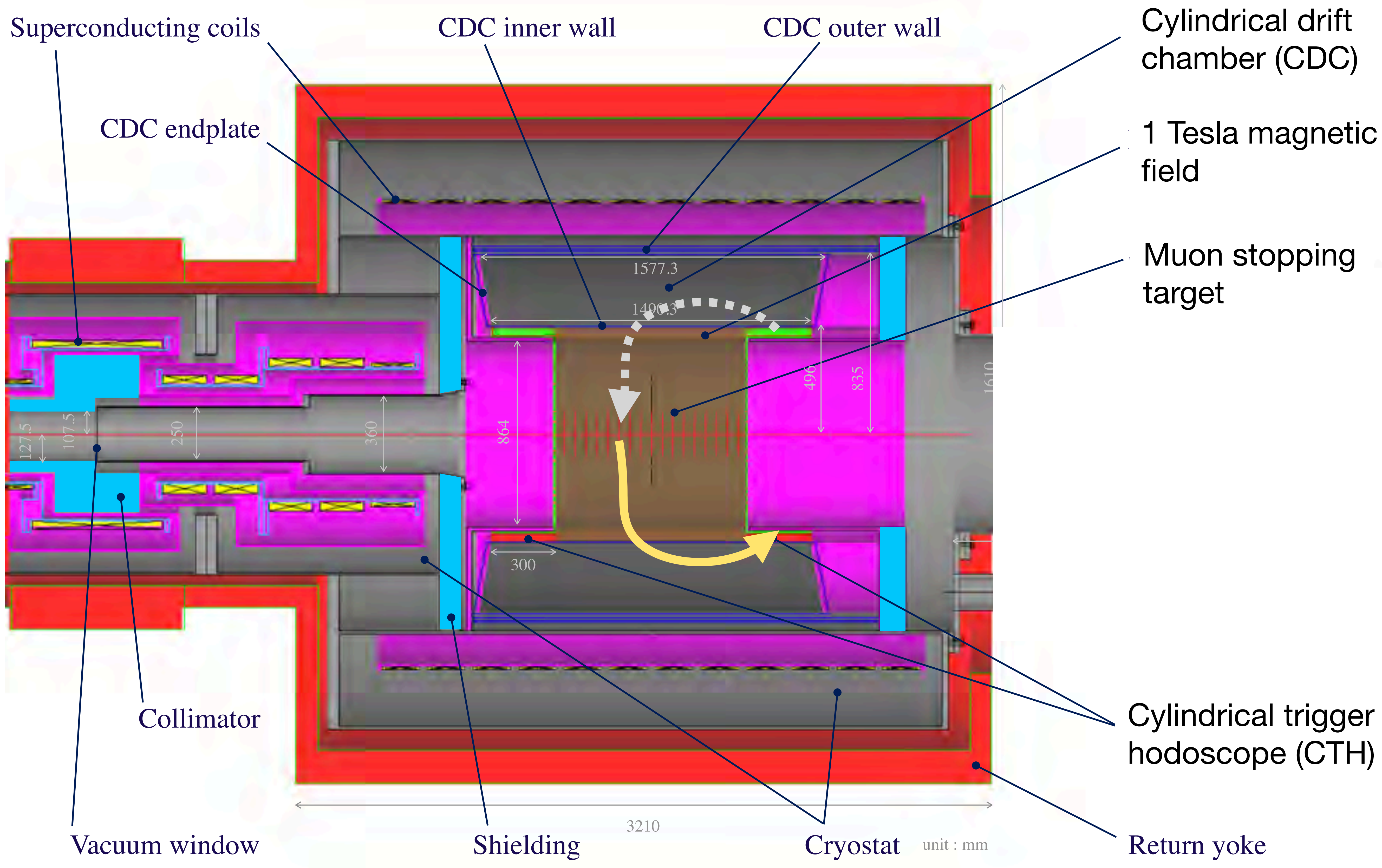
main background

CRV tracks	e^-	e^+	μ^-	μ^+
0	?	?	0.001 ± 0.001	**2.4 ± 0.9**
1	172 ± 56	8.3 ± 4.1	17.3 ± 11.0	165 ± 43
> 1	121 ± 38	17.4 ± 6.8	< 0.001	< 0.001

Table 2: Number of candidate tracks in the signal momentum window with or without coincident track(s) in the CRV for an effective livetime of 17.5 days.

can be vetoed by the CRV





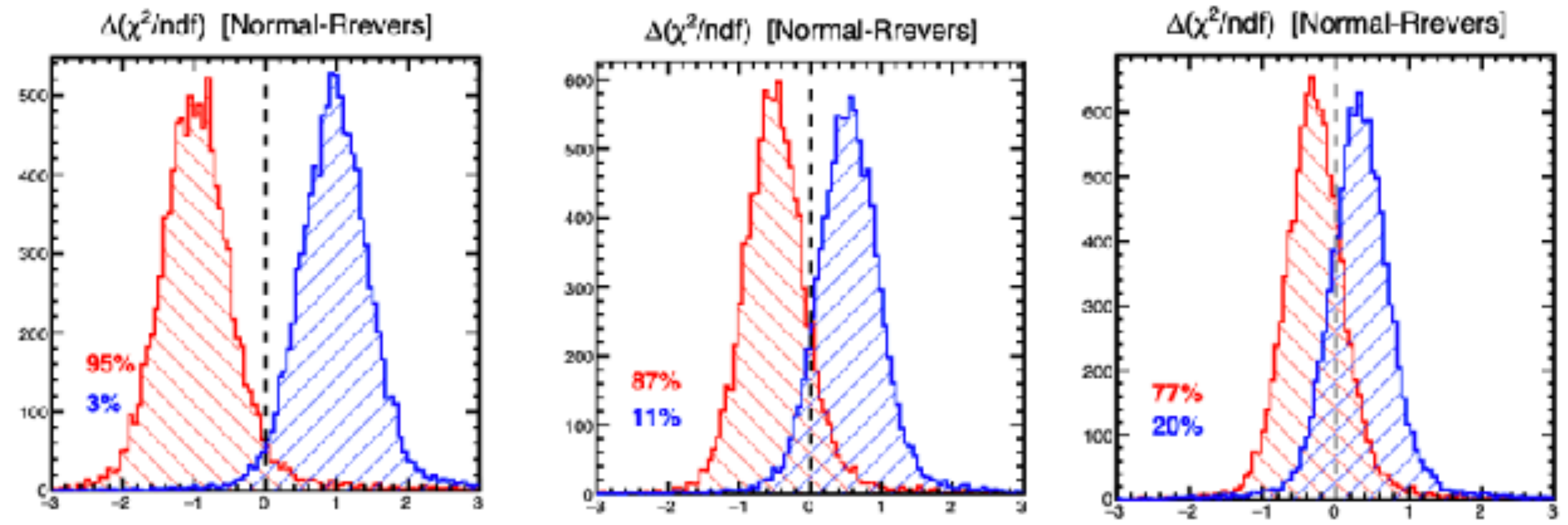
	μ-e Conv. Signal	Sneaking cosmic BG
Particle	e^-	μ^+
Speed β	1	0.7
Track direction	Target → CDC → CTH (Normal)	CTH → CDC → Traget (Reverse)

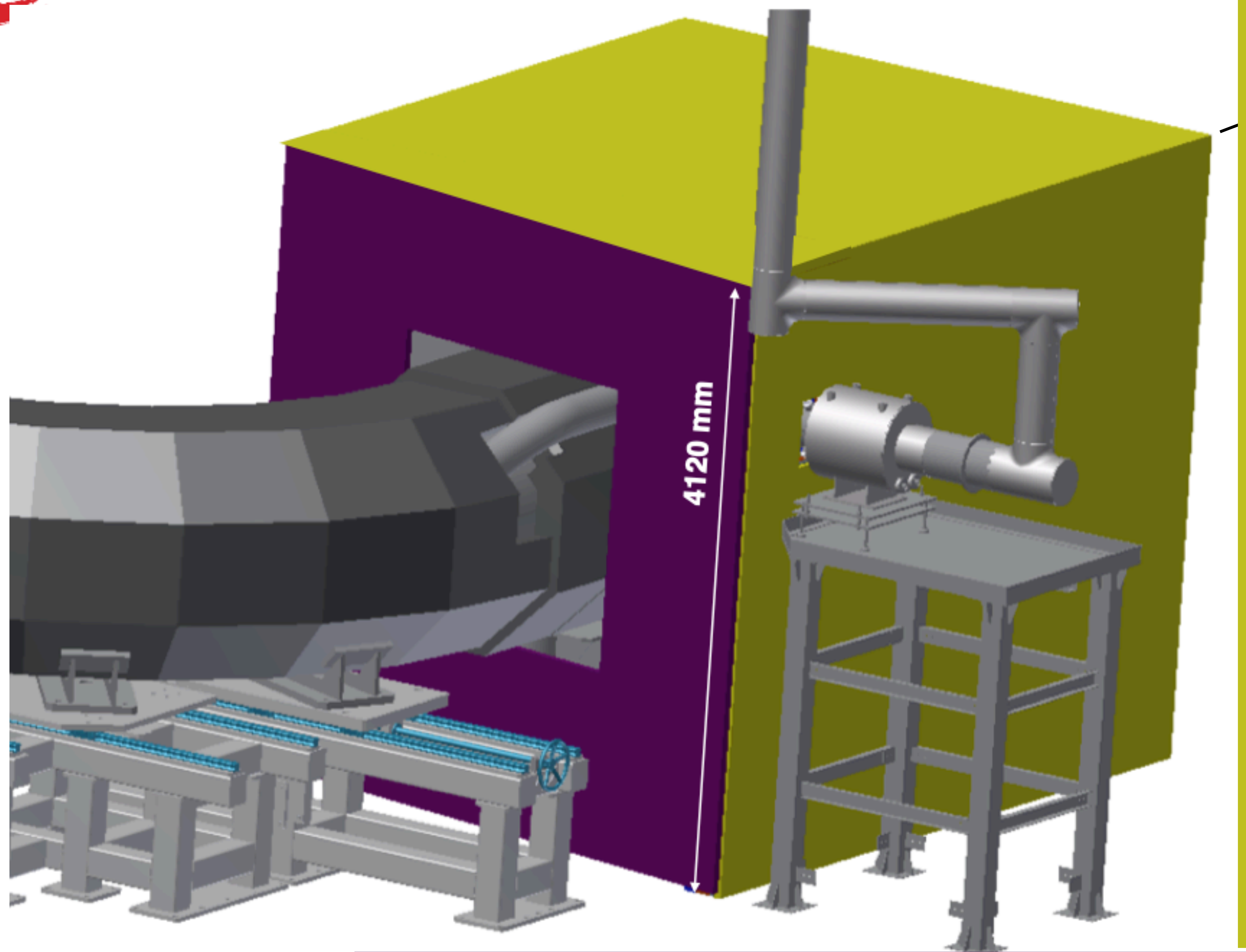
for 105 MeV/c

- multiple-turns track, direction identified from momentum attenuation in-between turns
- single turn tracks:
  - t0 used for correcting the CDC drift time is estimated from the TOF between CTH and each CDC hit.
  - miscorrection of 9.7 ns for reverse μ^+ tracks

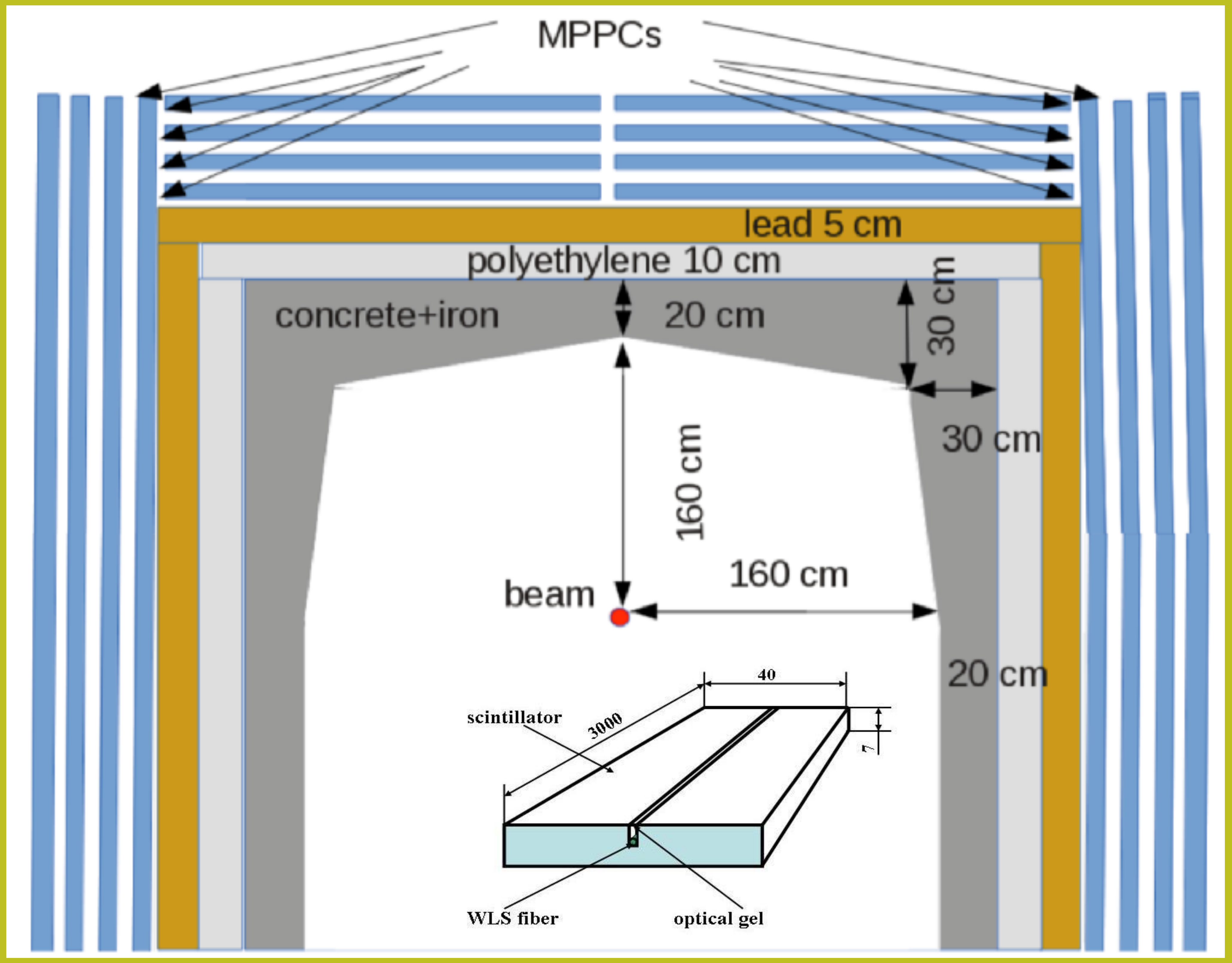
$\Delta(\chi^2/ndf) < 0$

Spatial Resolution	100 μm	150 μm	200 μm
Signal Retention (e^-)	95%	87%	77%
Contamination (μ^+)	3%	11%	20%





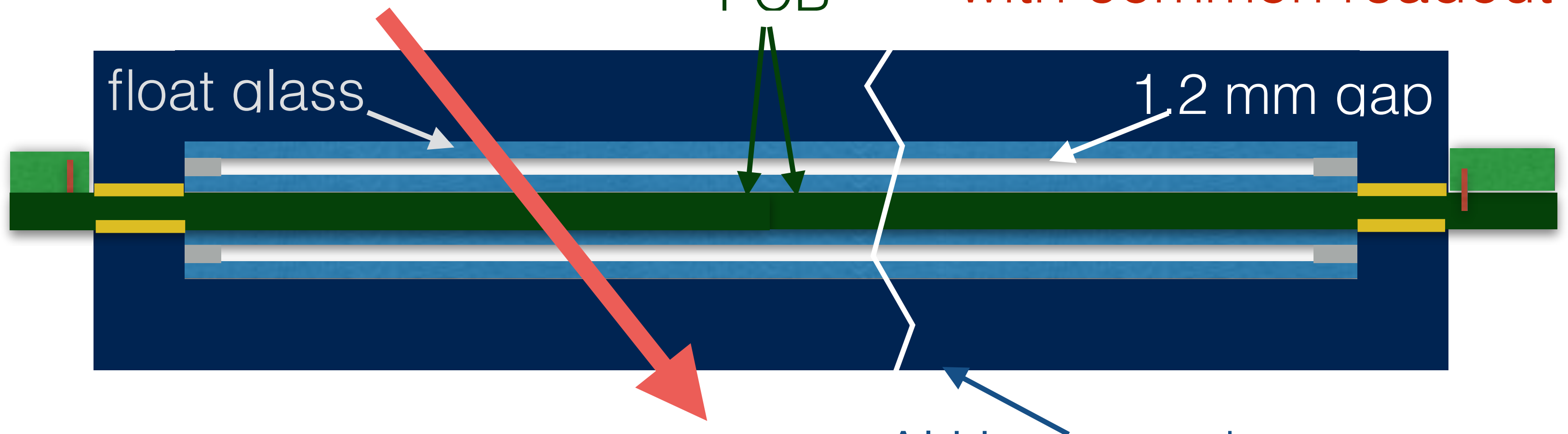
Scintillators CRV



GRPC CRV

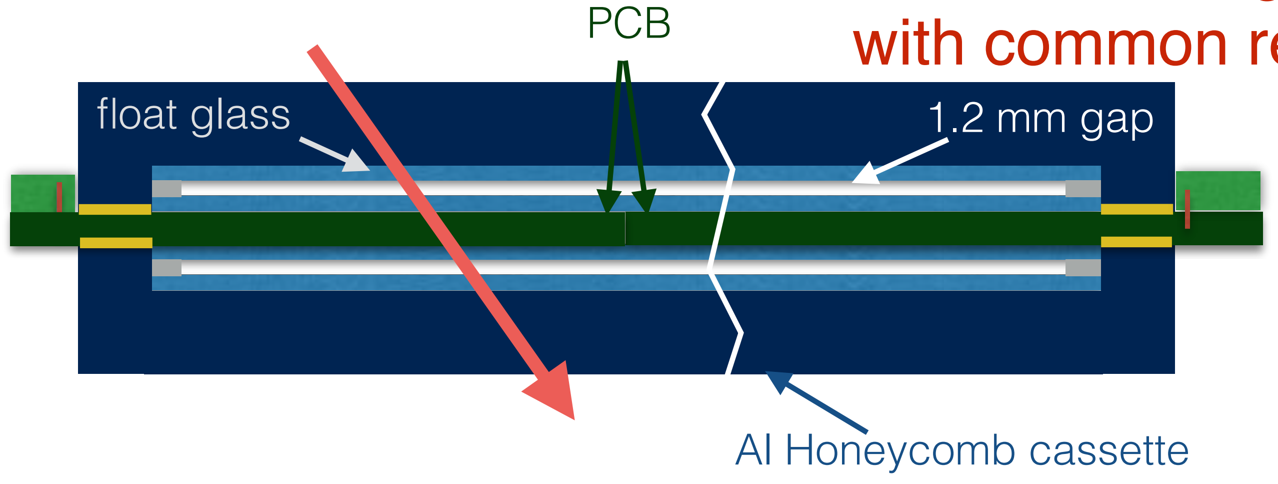
A tracker module: 7 detector modules (baseline)

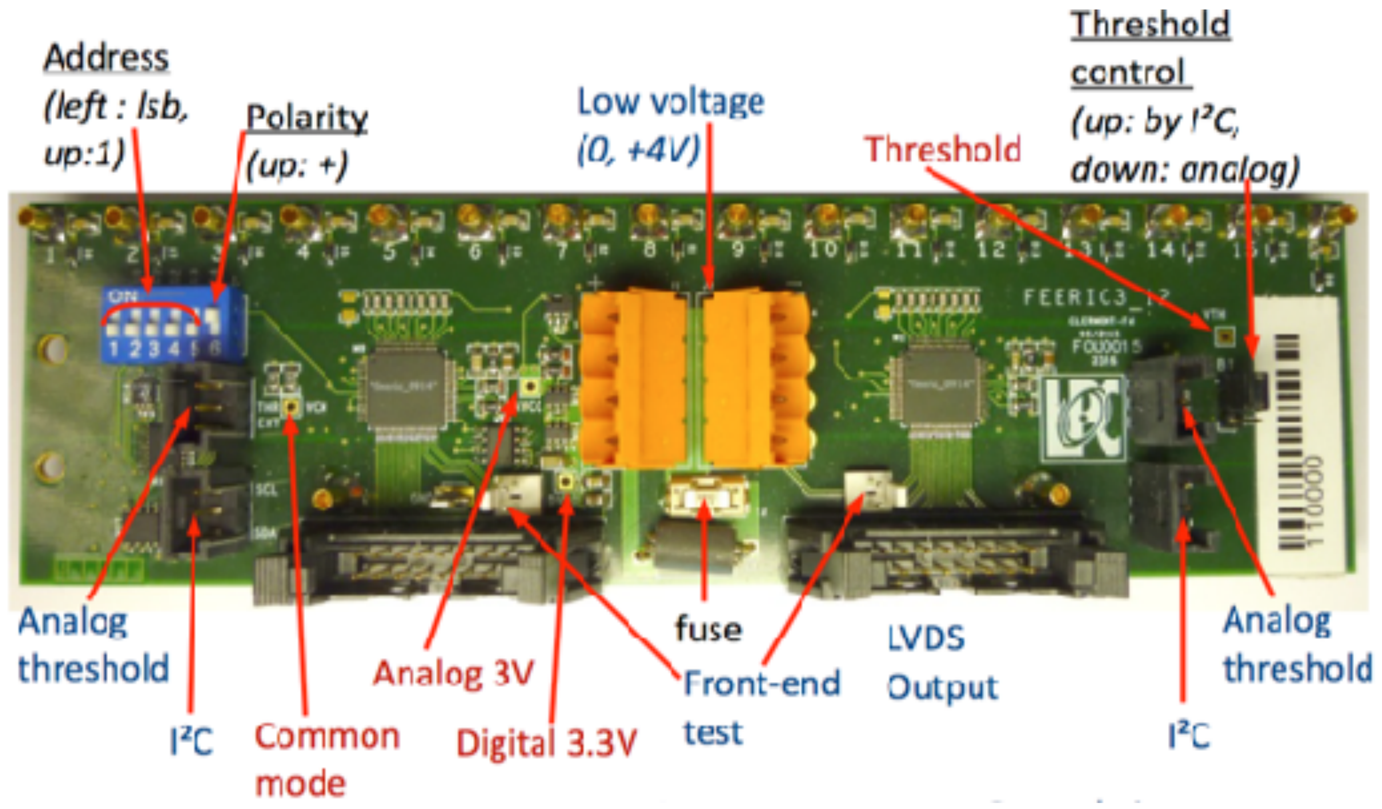
a module (1900x600 mm2):
two single-gap GRPCs
with common readout

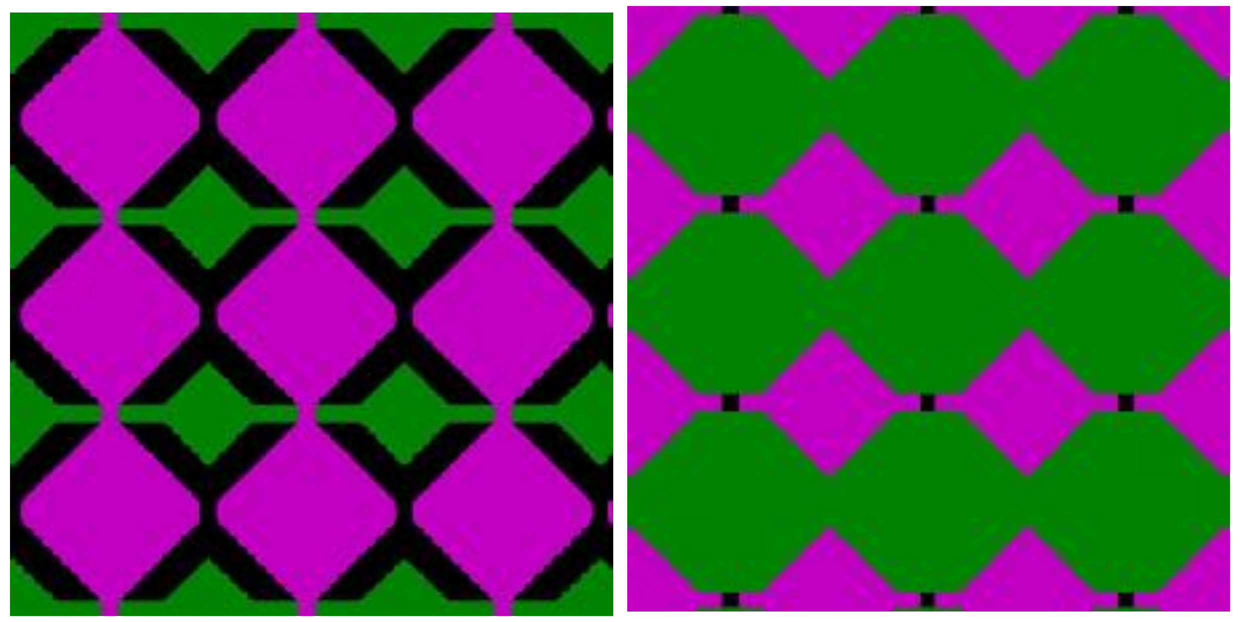


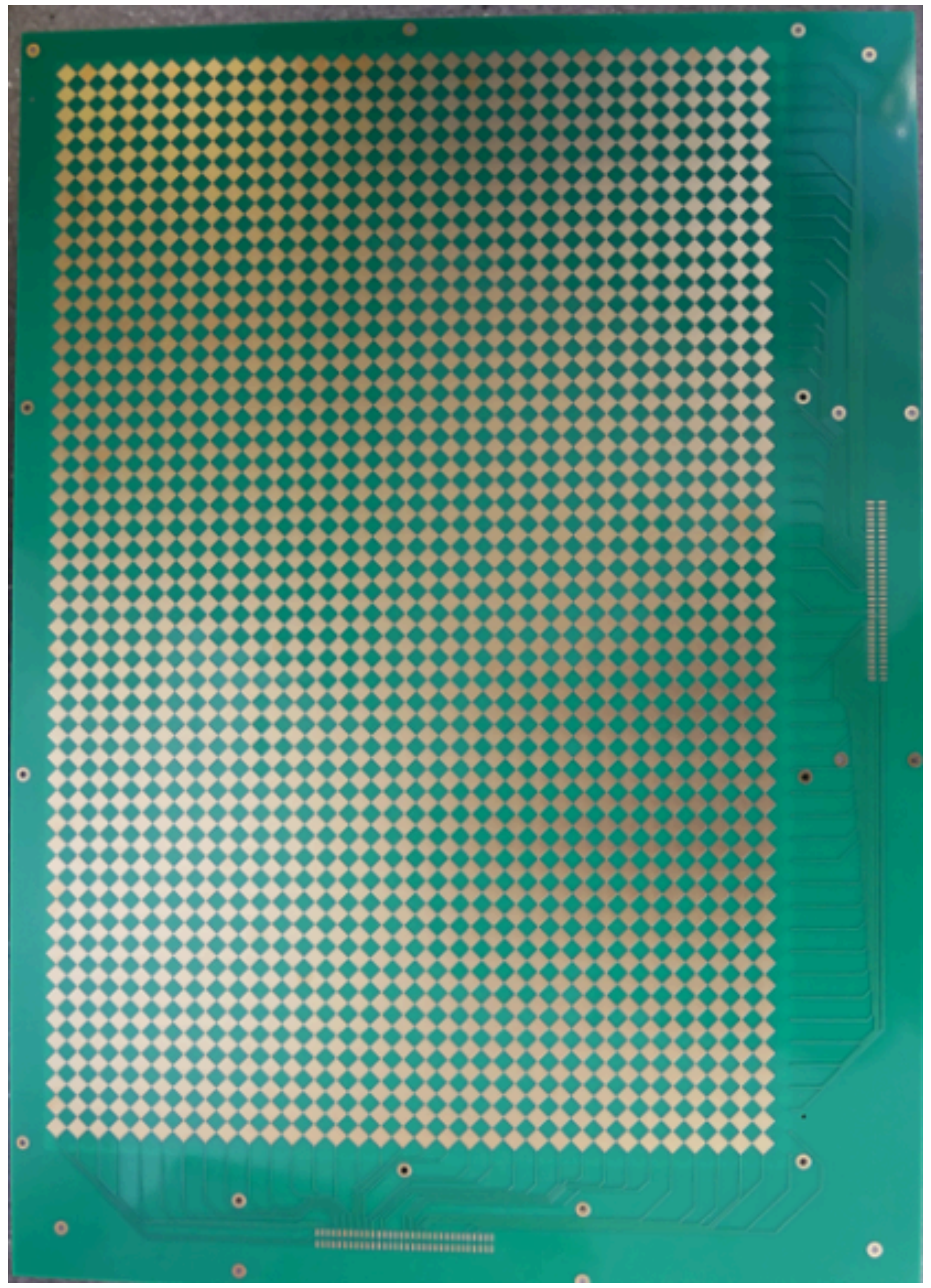
GRPCs proposal in 2019/2020

a module (1900x600 mm2):
deux GRPCs single-gap
with common readout









Segmentation and number of chambers to be defined by physics simulations & measured performance

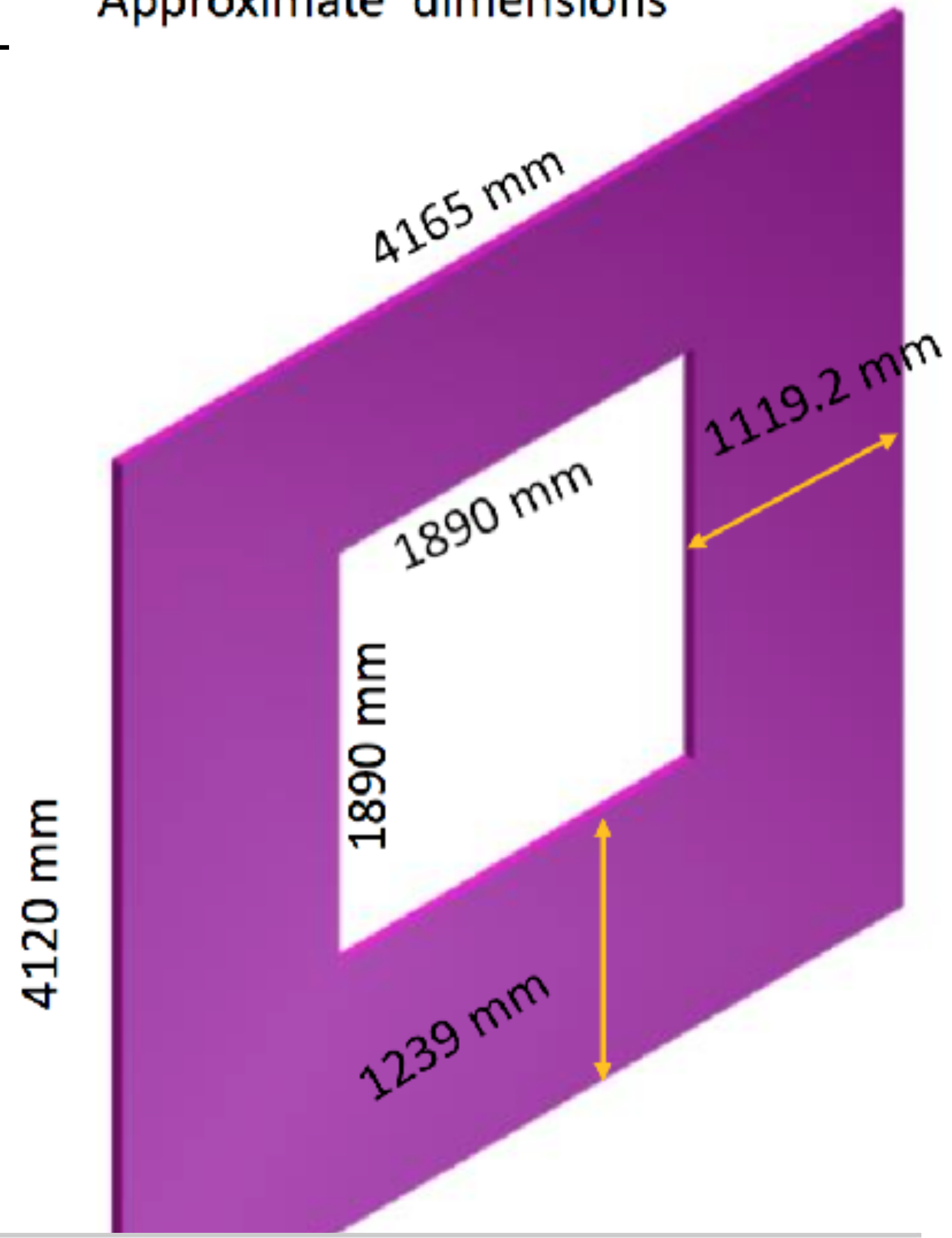
Baseline: 10 mm pitch

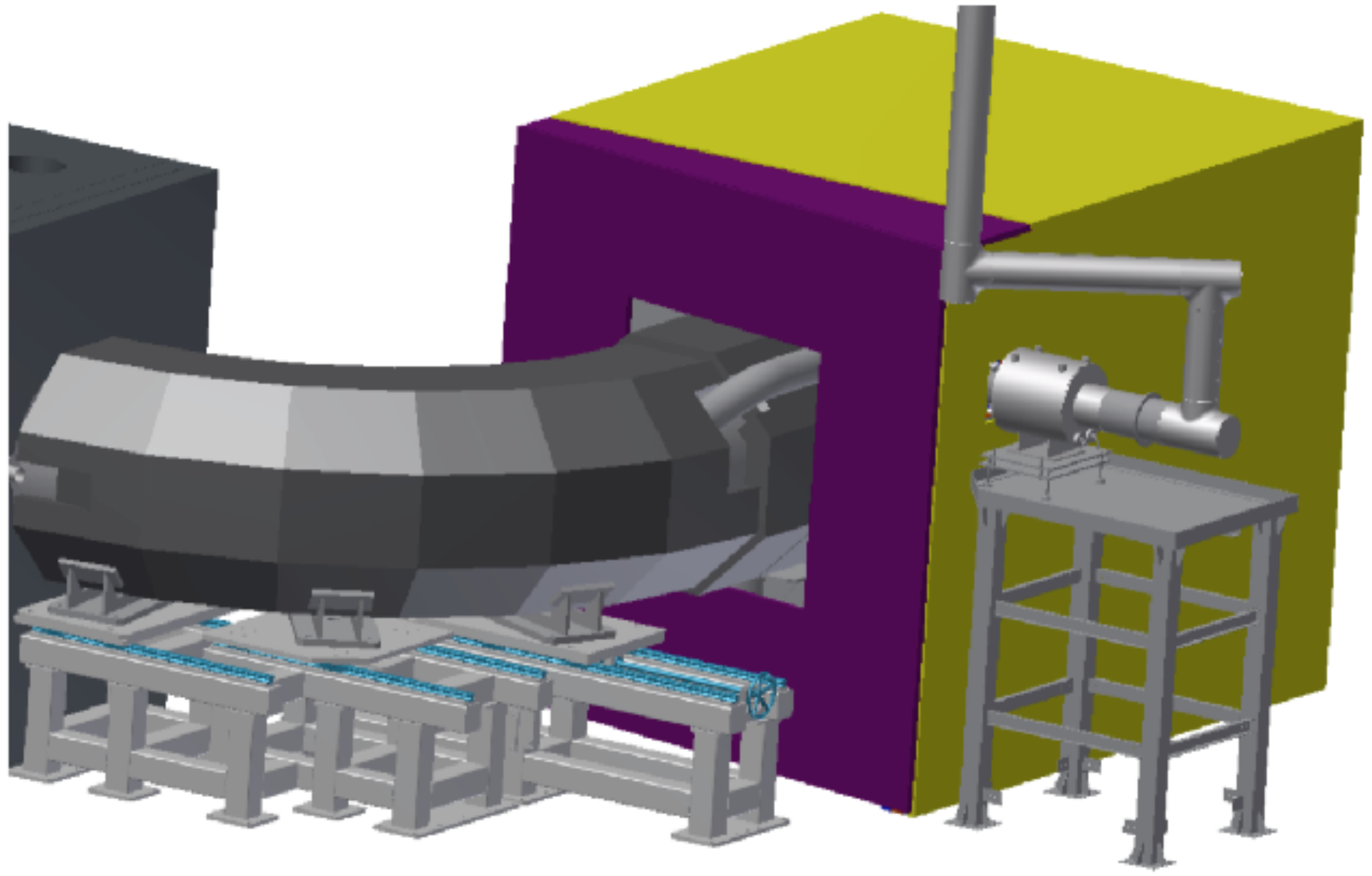
- Readout : ASICs Feeric (ALICE, ©LPC, 40 MHz)
- Front-end board: ALICE FEB(©LPC)

7 detector modules (baseline)

Small module COMET-like to validate the strip readout built in 2020 (chambers + double face PCB)

Approximate dimensions



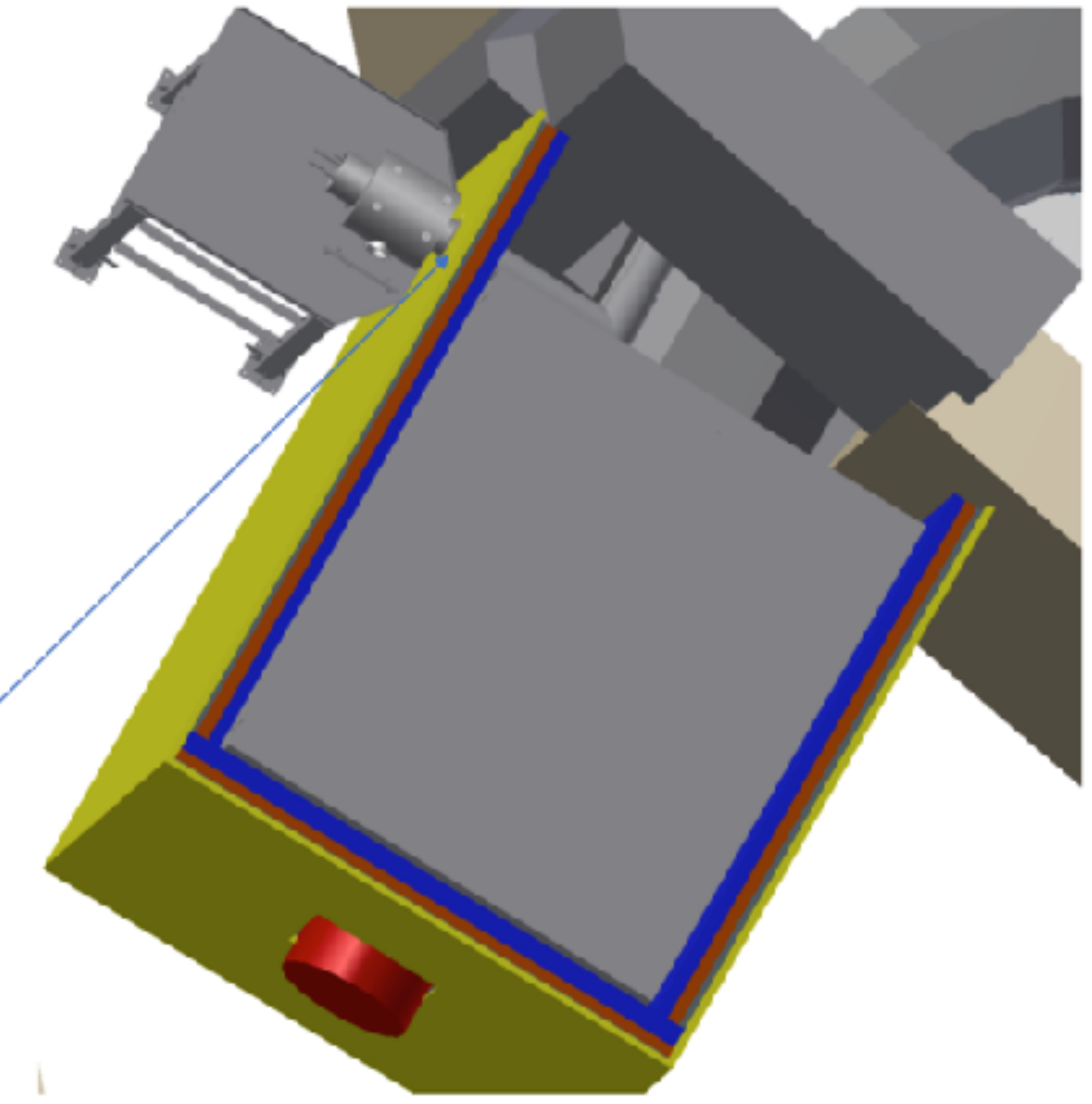


Significant COMET deadtime by CRV random coincidences (© Y. Kuno, Dec 2020)
-> use a faster electronics for CRV (~ns)

- Shielding: concrete – 10 cm, HDPE -10 cm, lead – 5 cm
- Yellow color – counters
- Grey color – lead
- Brown color – HDPE
- Blue color - concrete

Weight of left shielding

1. Concrete (density 2,407 g/cm³) = 4 548.667kg
2. HDPE (density 0.952 g/cm³) = 1 798.824kg
3. Lead (density 11,340 g/cm³) = 11 277.460kg

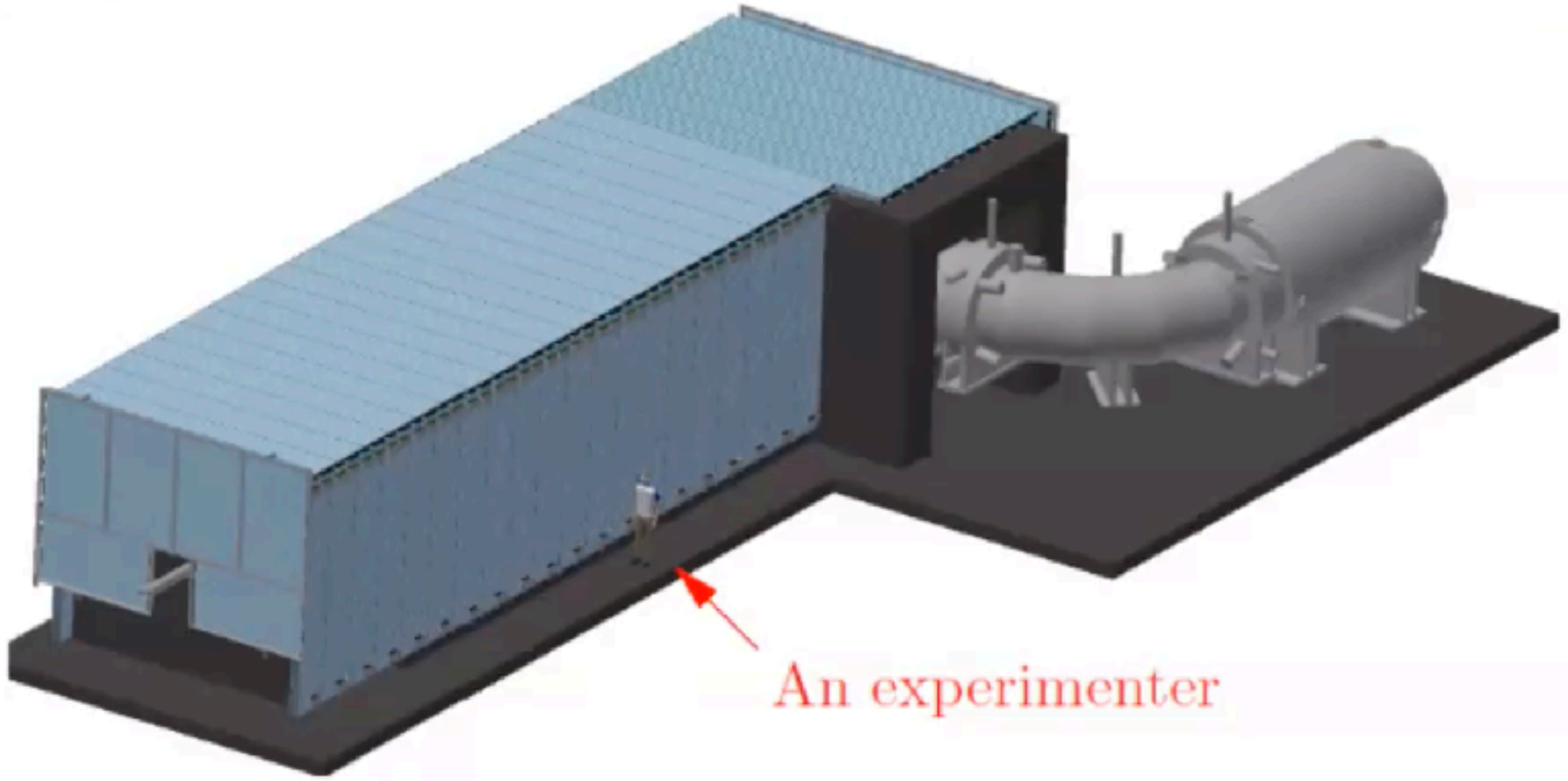


The left side CRV must have a hole !!!

Neutron&Gamma-ray fluence for 100 days at 3.2 kW operation. Update

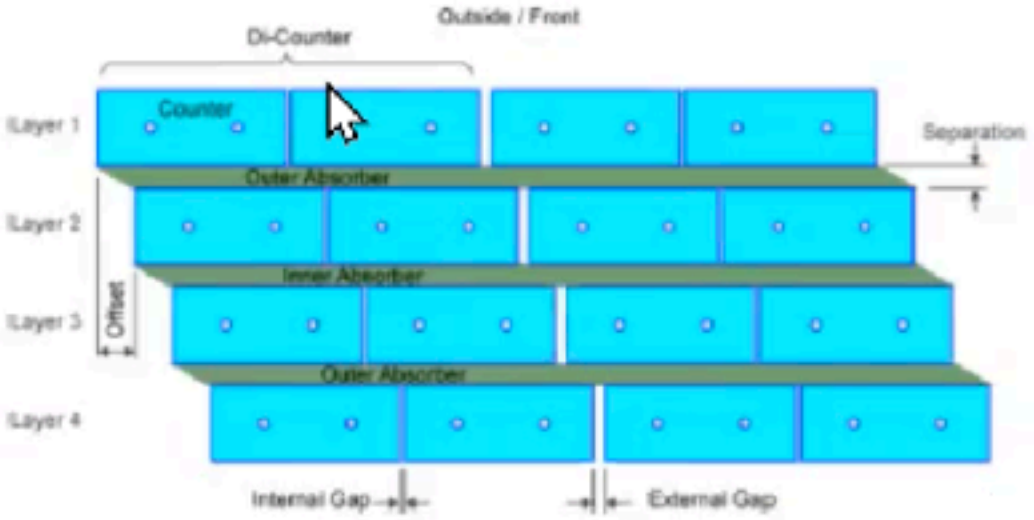
CRV	Neutron fluence for 100 days, n/cm²	1 MeV Neutron equivalent fluence for 100 days n_{1MeV}/cm^2	Gamma fluence for 100 days, γ/cm²	Gamma Dose for 100 days, Gy
	Statistics: POT 2.5E+8			
Top	φ_n=6.55 ·10⁹ n/cm²	$\varphi_{n1MeV} = 9.77\cdot10^8\ n_{1MeV}/cm^2$	$\varphi_\gamma = 1.17\cdot10^{10}\ \gamma/cm^2$	0.19 Gy
Top Trapezoid	$\varphi_n = 2.42\cdot10^{10}\ n/cm^2$	$\varphi_{n1MeV} = 1.85\cdot10^9\ n_{1MeV}/cm^2$	$\varphi_\gamma = 1.29\cdot10^{10}\ \gamma/cm^2$	0.21 Gy
Left	$\varphi_n = 7.43\cdot10^9\ n/cm^2$	$\varphi_{n1MeV} = 9.96\cdot10^8\ n_{1MeV}/cm^2$	$\varphi_\gamma = 1.11\cdot10^{10}\ \gamma/cm^2$	0.13 Gy
Right	$\varphi_n = 9.46\cdot10^9\ n/cm^2$	$\varphi_{n1MeV} = 1.16\cdot10^9\ n_{1MeV}/cm^2$	$\varphi_\gamma = 1.92\cdot10^{10}\ \gamma/cm^2$	0.17 Gy
Back	$\varphi_n = 7.6\cdot10^{10}\ n/cm^2$	$\varphi_{n1MeV} = 4.73\cdot10^{10}\ n_{1MeV}/cm^2$	$\varphi_\gamma = 3.53\cdot10^{11}\ \gamma/cm^2$	10.11 Gy
Front GRPC	$\varphi_n = 1.70\cdot10^{11}\ n/cm^2$	$\varphi_{n1MeV} = 2.36\cdot10^{10}\ n_{1MeV}/cm^2$	$\varphi_\gamma = 1.01\cdot10^{11}\ \gamma/cm^2$	2.18 Gy

Cosmic Ray Veto Detector



- Will use 4 overlapping layers of scintillator
  - Each bar is 5 x 2 x ~450 cm^3
  - 2 WLS fibers / bar
  - Read-out both ends of each fiber with SiPM
  - Have achieved $\varepsilon > 99.4\%$ (per layer) in test beam
  - Require at least 3 hits, gives 99.99% efficiency

S



Half of the scintillator modules produced so far

COMET FRANCE

Data center

Monte Carlo production
Storage
Code Management

CC-IN2P3 + IP2I

Analysis

Tracking
Simulation
Background studies

IP2I + LPNHE +
LPC Caen + LPC

CRV detector

GRPCs
Radiation tests

LPC + LPC Caen

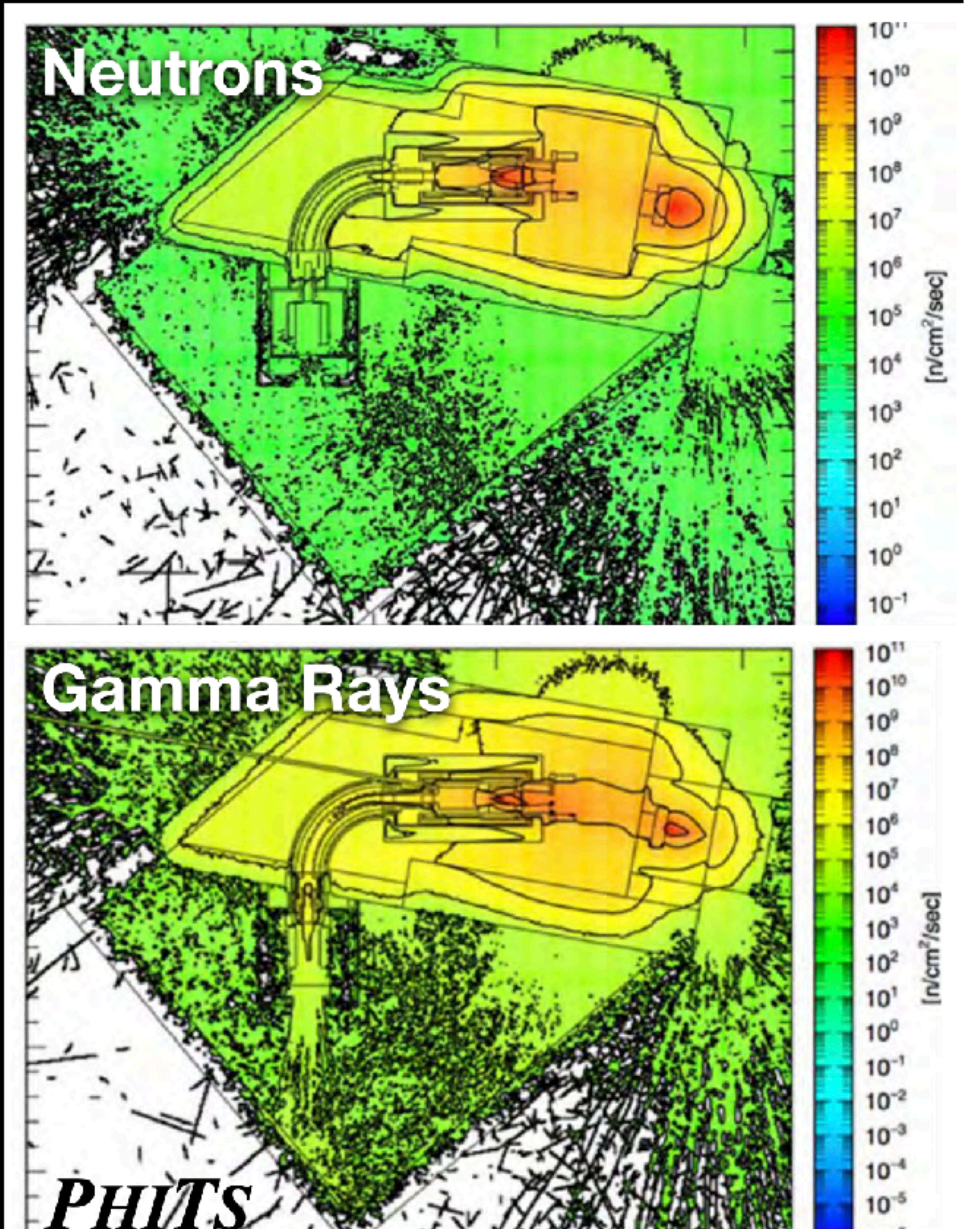
Theory

Physics of muon to electron conversion

LPC

IP2I	LEBRUN Patrice
LPC	CÂRLOGANU Cristina FAURE Geraldine NIESS Valentin TEIXERA A. M CHADEAU Nicola (PhD)
LPC-Caen	ANGELIQUE Jean-Claude BAN Gilles
LPNHE	da SILVA Wilfrid

- Radiation levels for COMET Phase-I, studied by PHITS, MARS and Geant
- In the detector regions for 150 days, including margin of safety:
  - Neutrons: 10^{12} n/cm^2
  - Gamma rays: 2 kGy
- Radiation issues
  - Electronics components
    - Regulators, optical transceiver etc.
  - FPGA
    - SEU, MBE etc.
- Irradiation tests carried out



Strong support for cLFV from the theory groups in France

Asmaa Abada (IJCLab), Sacha Davidson(LUPM), Ana M. Teixeira(LPC)

- Probe nature & properties of NP mediators
- Test SM extensions

- **Explore potential of COMET (Phase I and II)**
  - new (revisited) observables (cLFV, LNV), …
  - impact of new experimental data/facilities and future prospects

- **Several new ideas and on-going projects**
  - LNV & cLFV conversion in Nuclei
  - radiative Muonium decays
  - many-body cLFV muon decays (e.g. , ...)

- **Facility - expected to be completed in 2023:**
  - COMET Proton beam for the COMET : in 2022
  - Commissioning of proton and muon beams (COMET Phase α) : by end 2022 (JFY)
  - Pion capture system : in 2023

- **Detectors - expected for 2023:**
  - CyDet will be moved to J-PARC in 2022
  - StrCAL : by summer 2023
  - CTH : by end 2022
  - CRV : 2023.

- Start of the COMET Phase-I engineering run foreseen for end 2023 followed immediately by physics data taking.

- COMET Phase-II expected to follow shortly COMET Phase-I.

Conclusion

- COMET at J-PARC will search for neutrinoless muon to electron conversion with an expected S.E.S of 2.6×10^{-17} (4 orders of magnitude below the current limit) after 1 year of data taking using a 56 kW, 8 GeV proton beam.

- The experiment will proceed in two phases, with Phase-I (currently in preparation) expected to reach a S.E.S of 3×10^{-15} within 150 days of data taking using a less intense 8 GeV proton beam (3.2 kW).

- COMET Phase-I preparation (proton beam, experimental area and detectors construction) proceeds rapidly and on schedule despite the pandemics .

- COMET physics data expected in 2024.