# The COMET experiment at J-PARC and Lepton Flavor Violating ALPs

Thomas Bouillaud
*on behalf of the COMET collaboration.*

The Axion Quest 2024 @ Quy Nhon

**August 5, 2024**

# COherent Muon to Electron Transition (COMET)

Search for the Charged Lepton Flavor Violating (CLFV) $\mu - e$ conversion

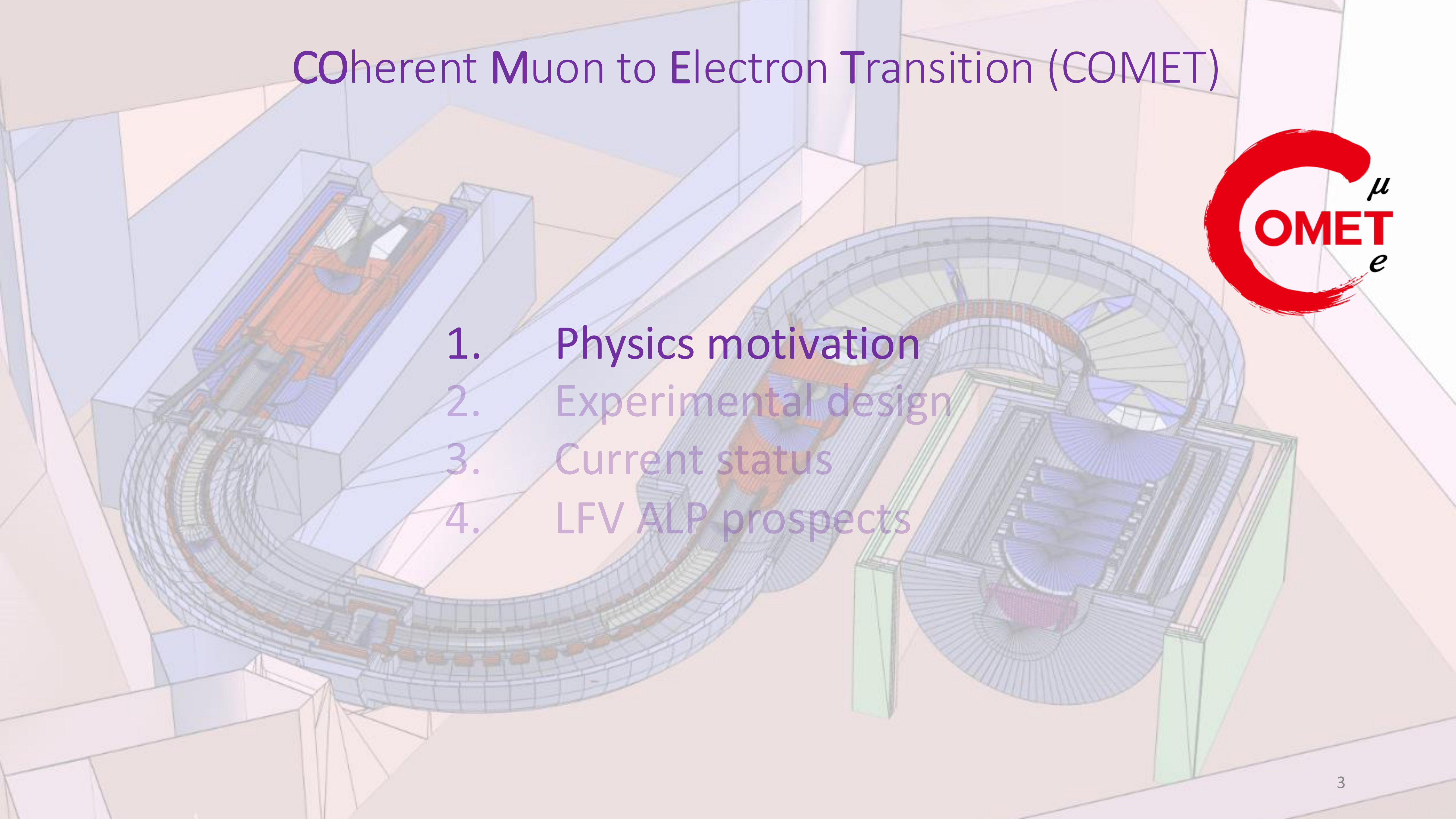
$$\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$$ in Aluminum

$(L_\mu, L_e) = (1,0)$ $(L_\mu, L_e) = (0,1)$

**Outline**

1. Physics motivation
2. Experimental design
3. Current status
4. LFV ALP prospects

# COherent Muon to Electron Transition (COMET)



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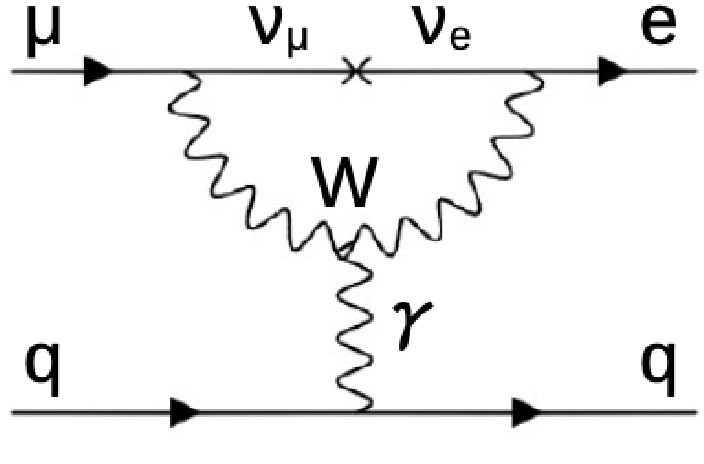
# A New Physics probe with low SM background

## Standard Model $\mu$ decay

Neutrino oscillation indicate LFV and non-zero neutrino masses. What about Charged LFV?
→ Very suppressed due to small neutrino masses

$$\mathcal{B}(\mu \to e\gamma) \propto \left| \sum_i (U_{\mathrm{PMNS}})^*_{\mu i} (U_{\mathrm{PMNS}})_{ei} \frac{M^2_{\nu i}}{M^2_W} \right|^2$$

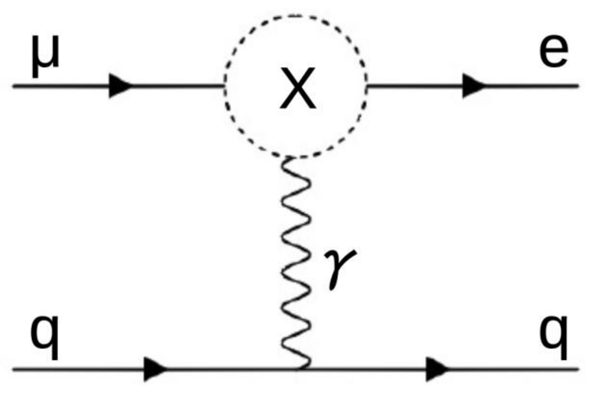
$$\approx \mathcal{O}(10^{-54})$$



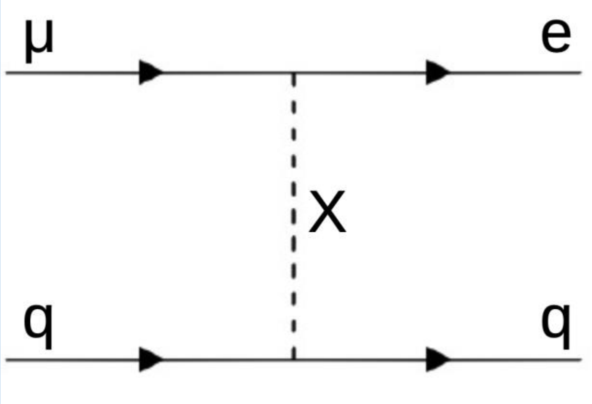

## BSM $\mu - e$

Two contributions from New Physics models:

1. **Photonic** (dipole contribution)

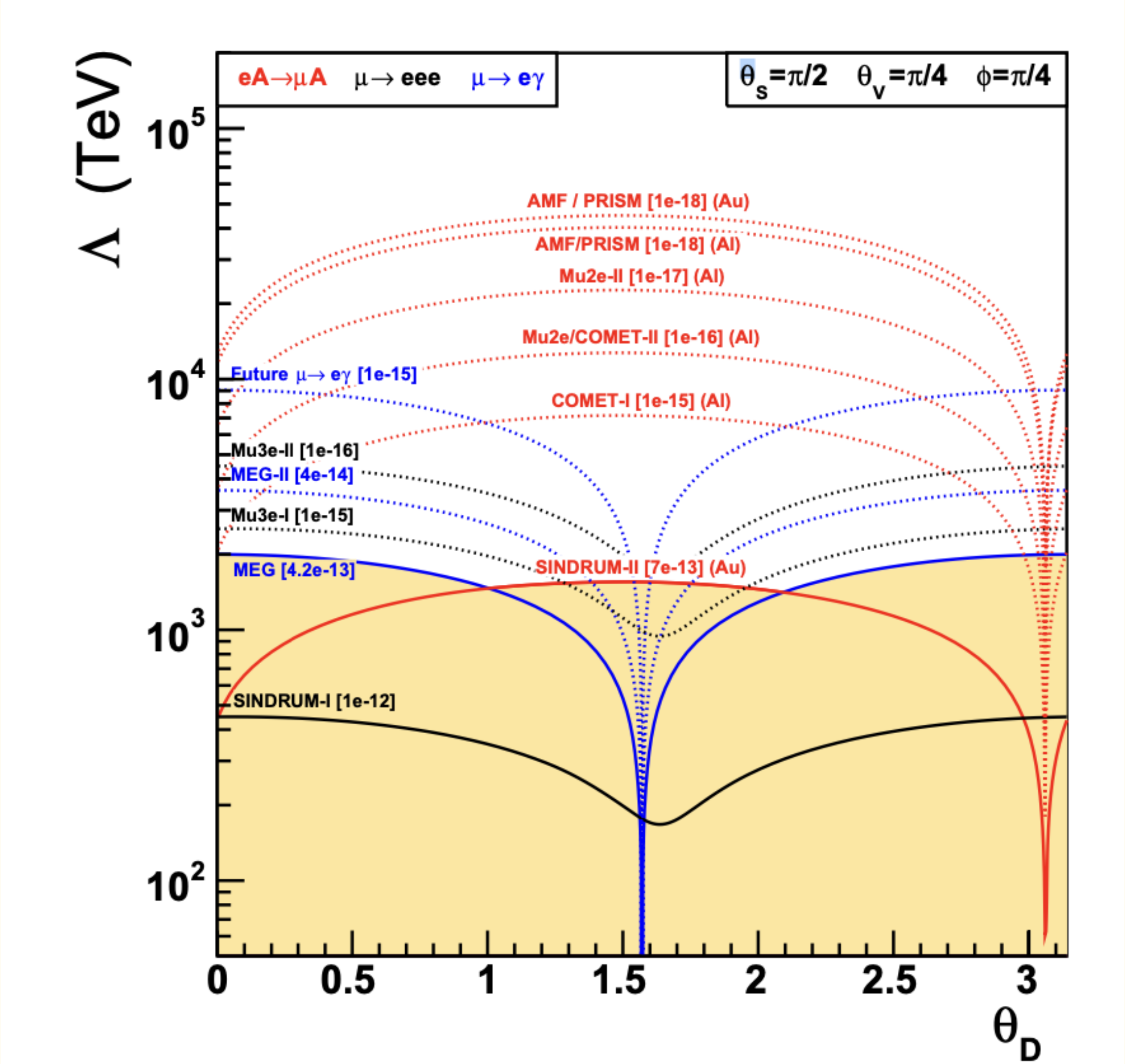



2. **Non-photonic** (four-fermion contact interaction)



# A New Physics probe with low SM background

Davidson et al., 2022




← Maximal **Photonic contribution** Minimal →

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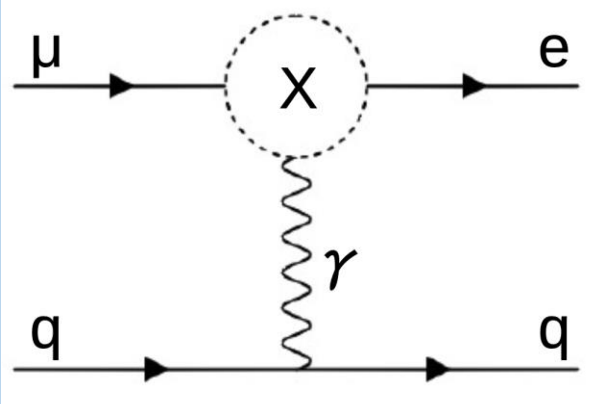


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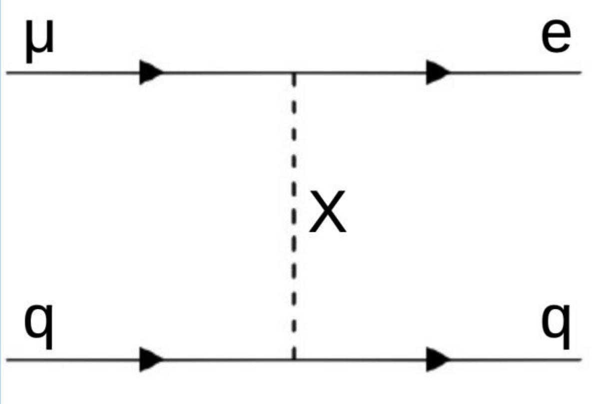

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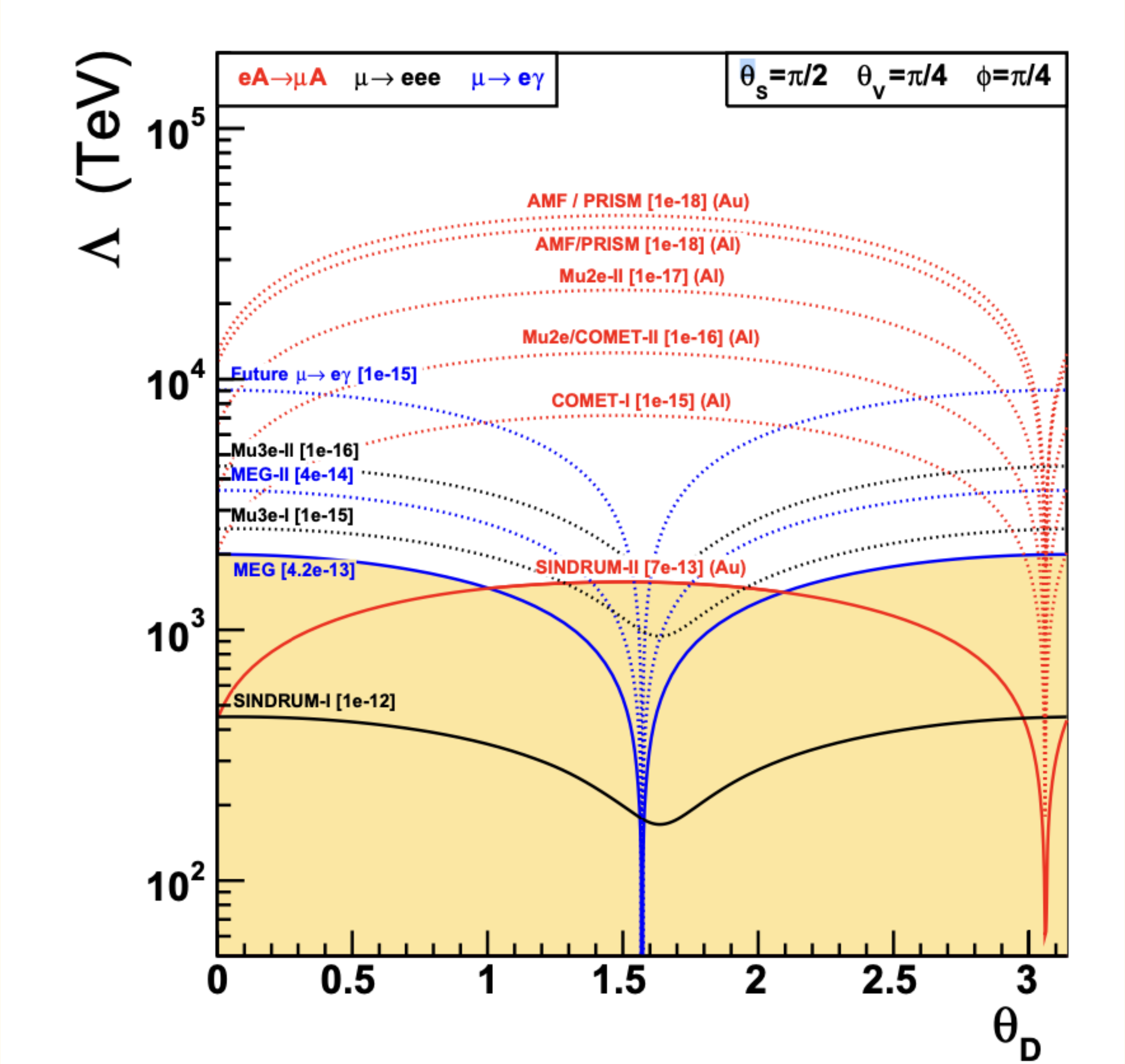
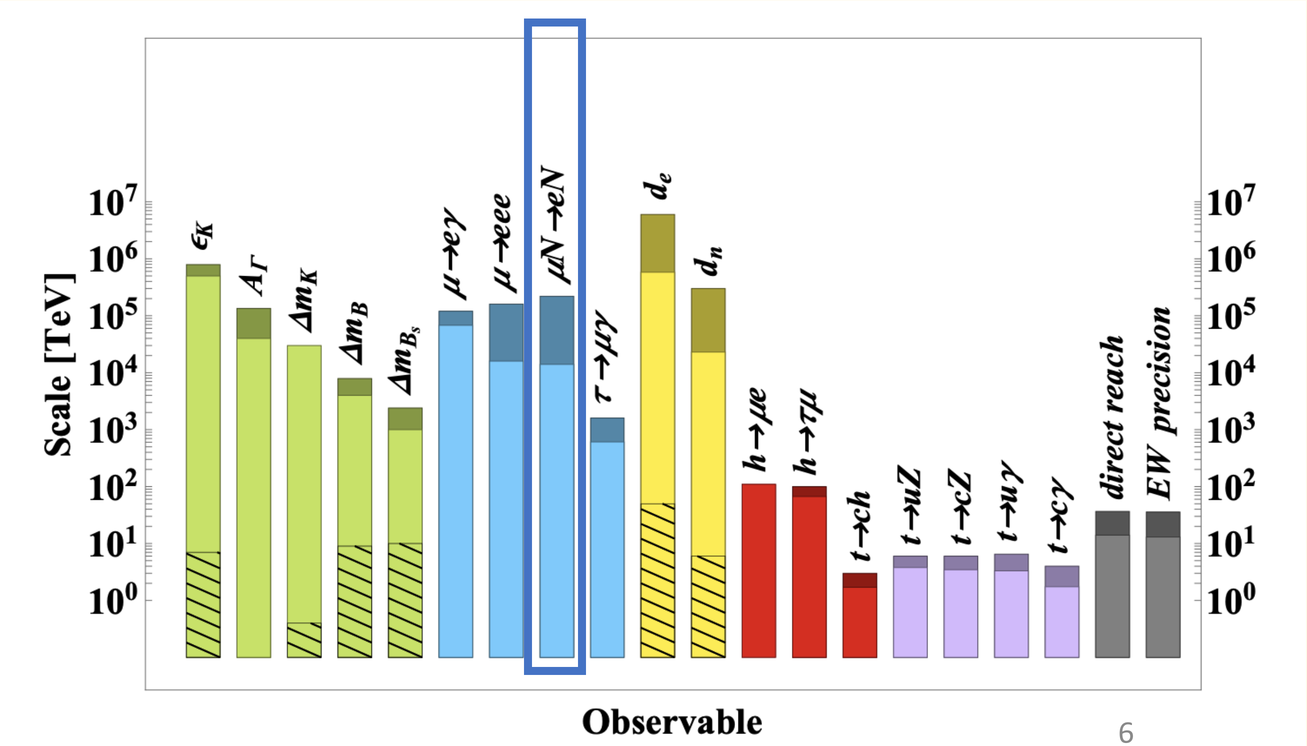



← Maximal **Photonic contribution** Minimal →

$$CR(\mu^- + N \to e^- + N) = \frac{\Gamma(\mu^- + N \to e^- + N)}{\Gamma(\mu^- + N \to \text{all})}$$

COMET sensitivity goal $\mathcal{O}(10^{-17})$ probes NP at $\Lambda > 10^4$ TeV



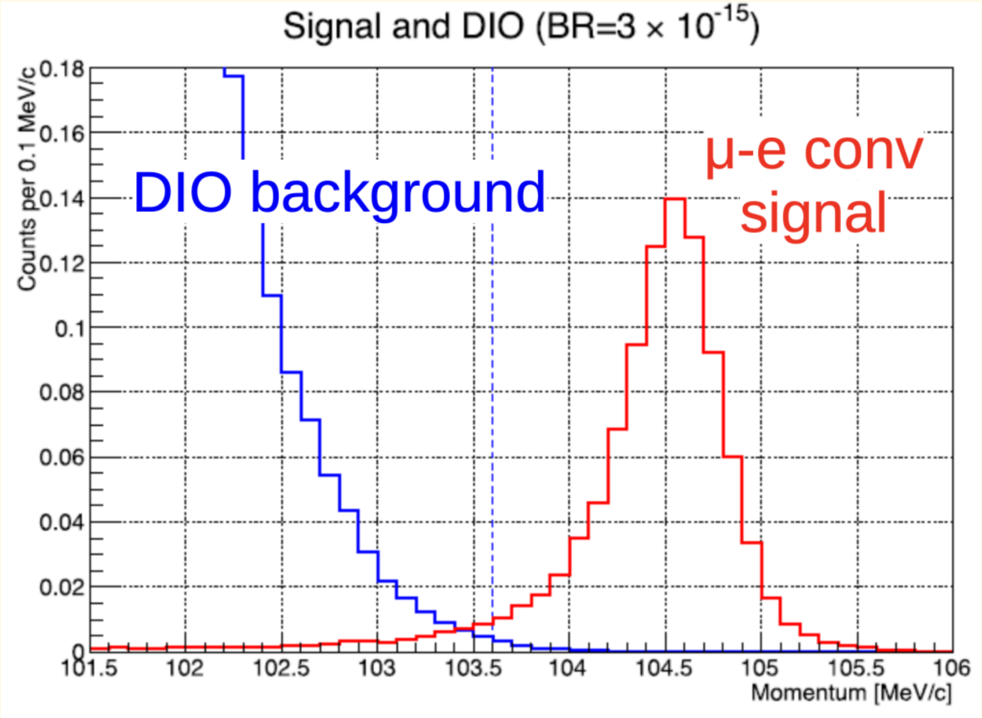

European Strategy Update, 2019

# $\mu - e$ signal and background

$\mu - e$ conversion signal is a mono-energetic electron of about the muon mass:

$$E_e = m_\mu - B_\mu - E_{\text{recoil}} \approx 105\ \text{MeV}$$

→ Well above the energy spectrum of Muon Decay In Orbit (DIO)




## Three sources of background:

1. **Intrinsic physics:**
   Muon DIO $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
   Muon Radiative Nuclear Capture
   $\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1) + \gamma$
2. **Beam-related:**
   Muons, pions, Radiative Pion Capture, …
3. **External:**
   Mainly cosmic ray muons

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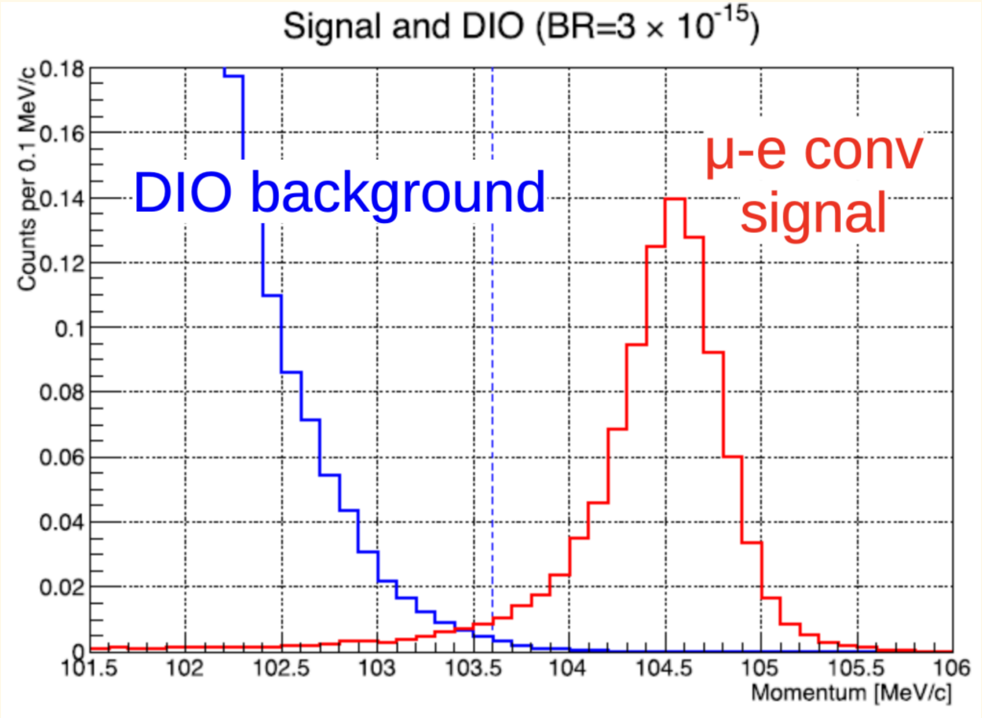


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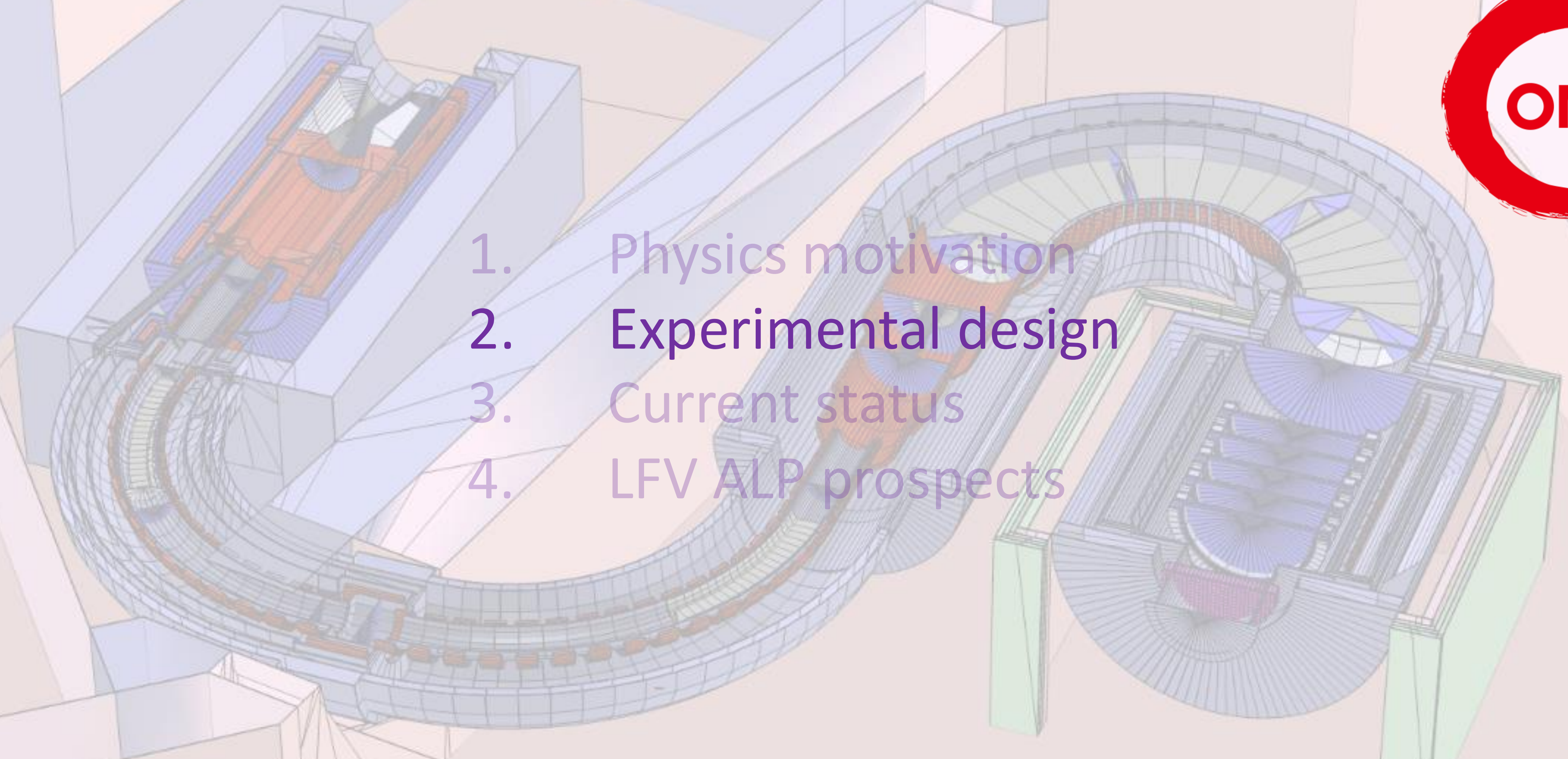
**→ High energy resolution detectors**

**→ Pulsed-beam with good extinction**
**→ Curved solenoid**

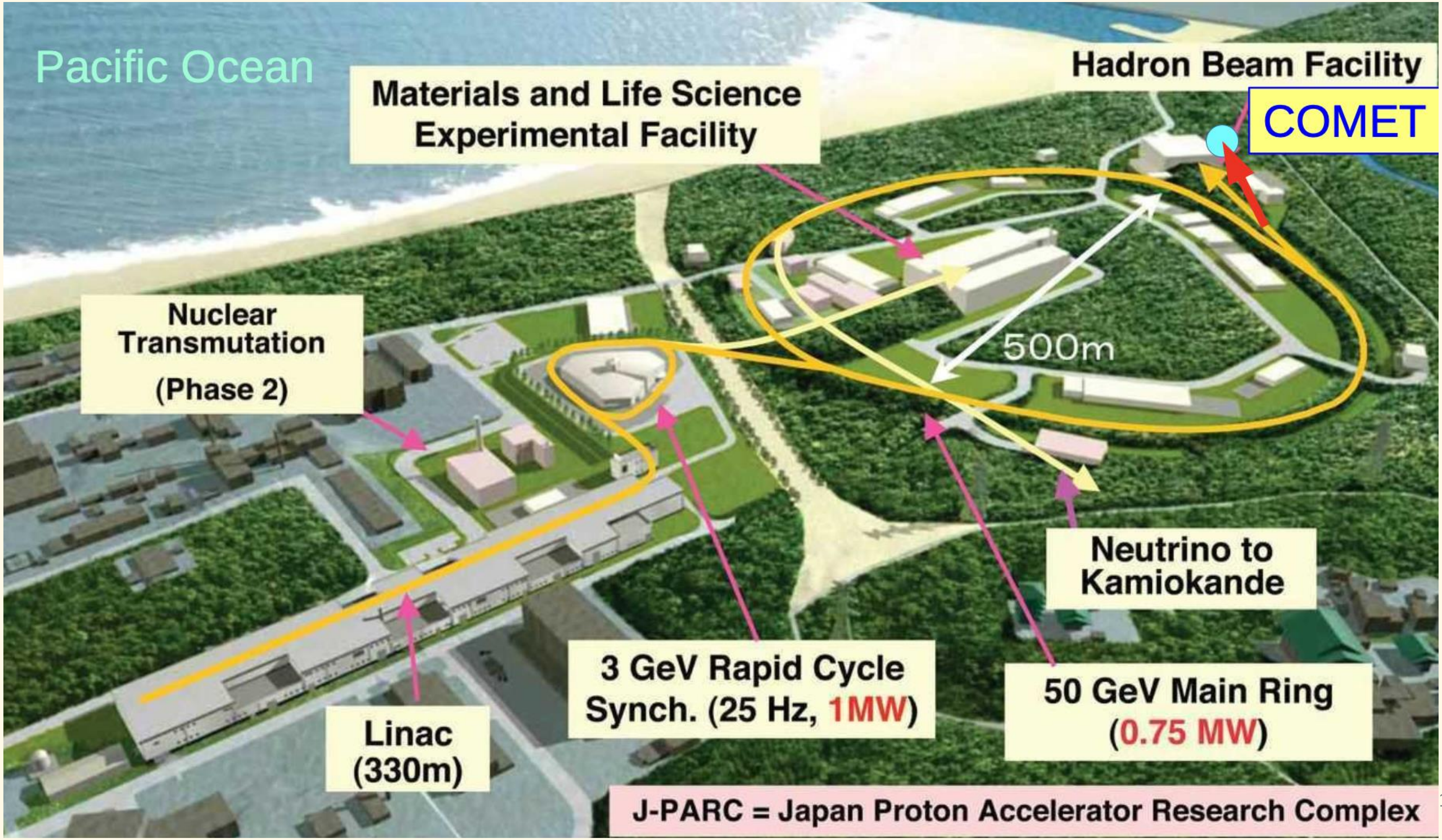
**→Cosmic ray veto**

# COherent Muon to Electron Transition (COMET)



1. Physics motivation
2. **Experimental design**
3. Current status
4. LFV ALP prospects

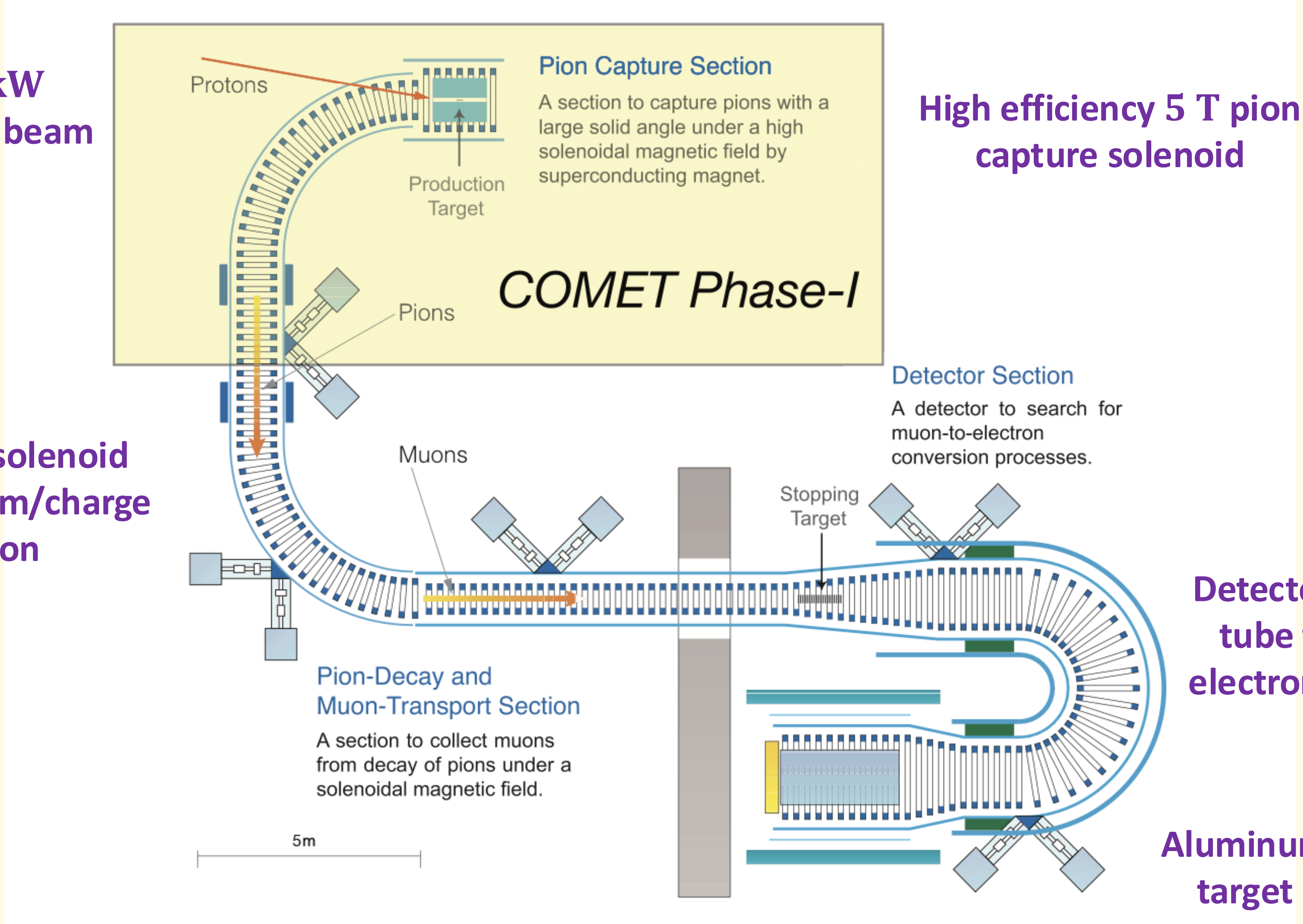
# COMET @ J-PARC, Tokai, Japan



# COMET design concept

**8 GeV, 56kW pulsed proton beam**

**3 T curved solenoid for momentum/charge selection**



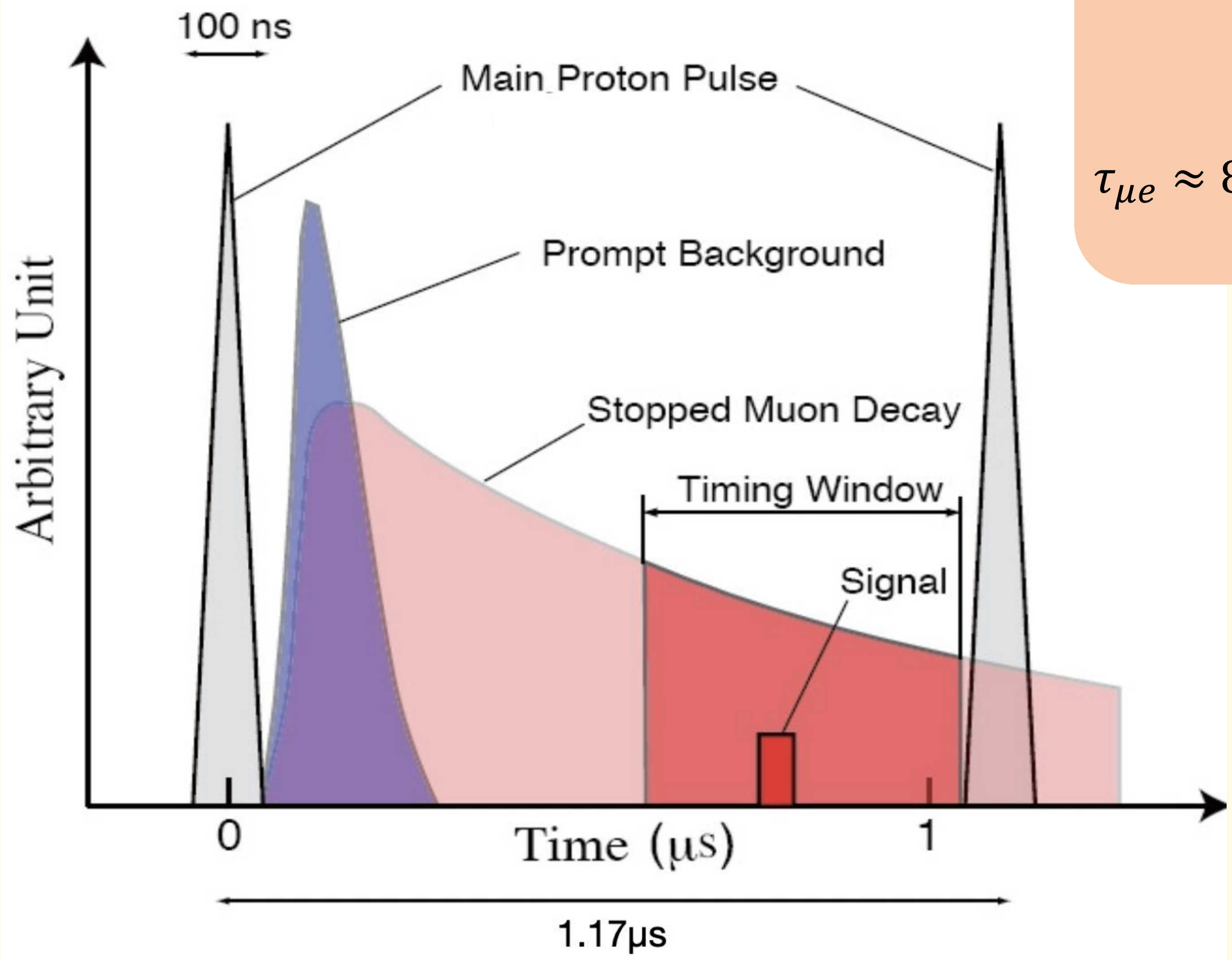

**High efficiency 5 T pion capture solenoid**

**Detector with straw tube tracker and electron calorimeter**

**Aluminum target**

# COMET's muon beam

$10^{12}$ protons/pulse




Pulsed-beam constrained by muonic atom lifetime:

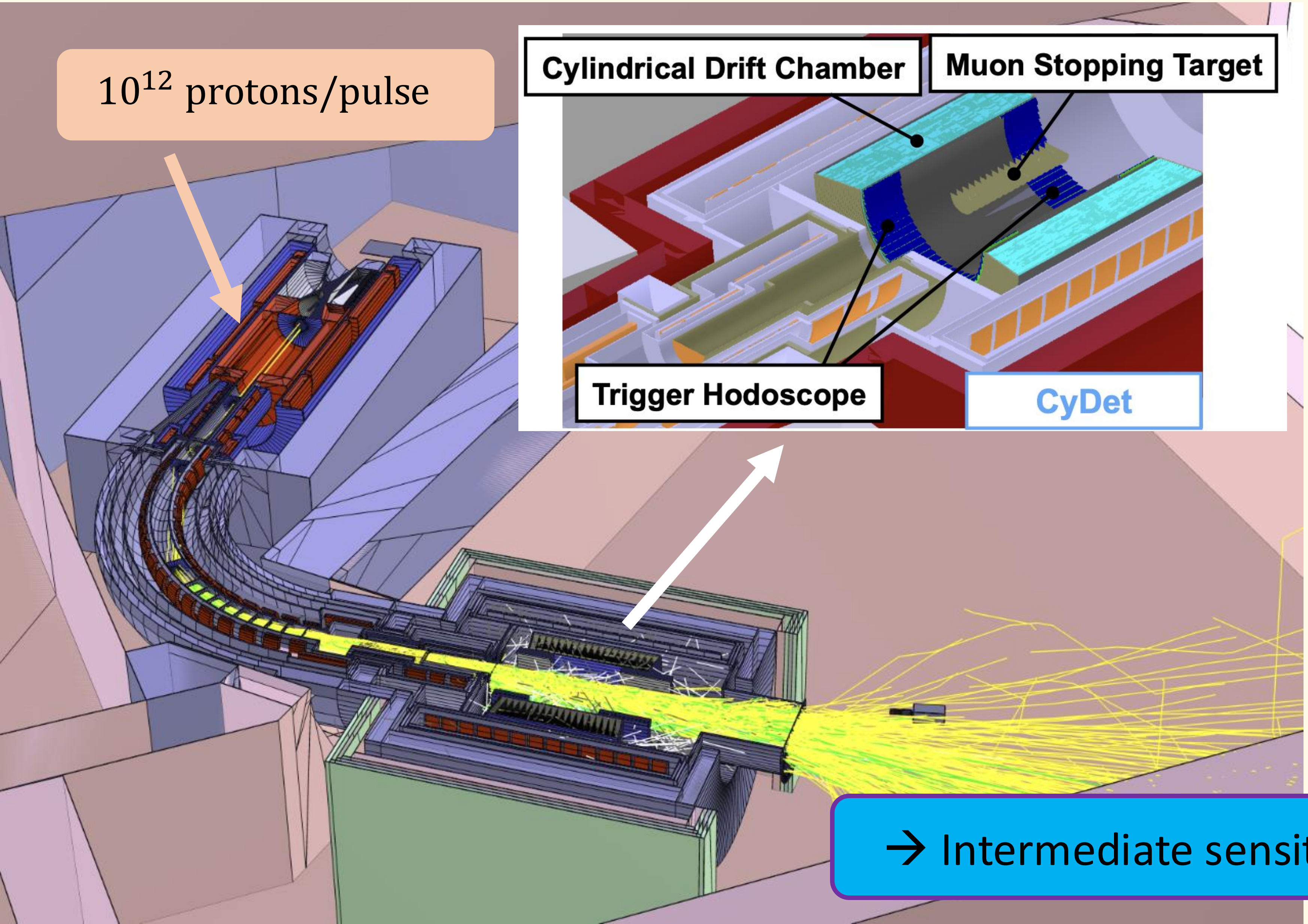
$\tau_{\mu e} \approx 864$ ns $<$ pulse spacing $>$ pulse duration

$$\text{Extinction Factor} \equiv \frac{N_{\text{leaked protons}}}{N_{\text{pulsed protons}}}$$

**Goal: reach a proton extinction factor $\approx 10^{-10}$**

# A 2-phase approach: **Phase-I**

**Physics run**

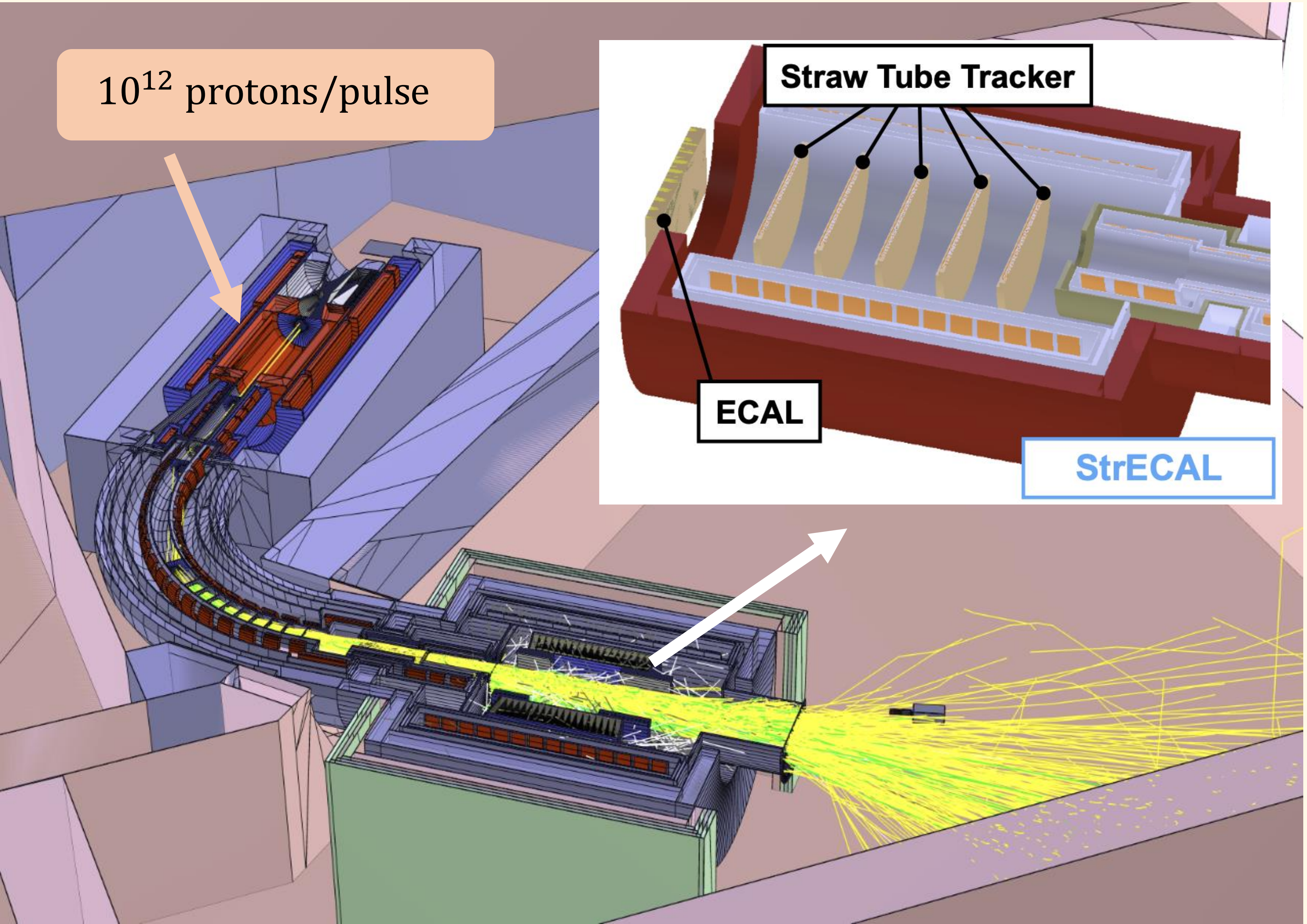



Particles emitted from the **aluminum muon stopping target** are momentum/charge selected by the $1$ T **detector solenoid**, and enter **CyDet:**

- **Cylindrical Drift Chamber (CDC):**
  Provides high resolution $p$ measurement
- **Cylindrical Trigger Hodoscopes (CTH):**
  Gives primary trigger on a 4-fold coincidence of scintillators

→ Intermediate sensitivity $\mathcal{O}(10^{-15})$

# A 2-phase approach: **Phase-I**



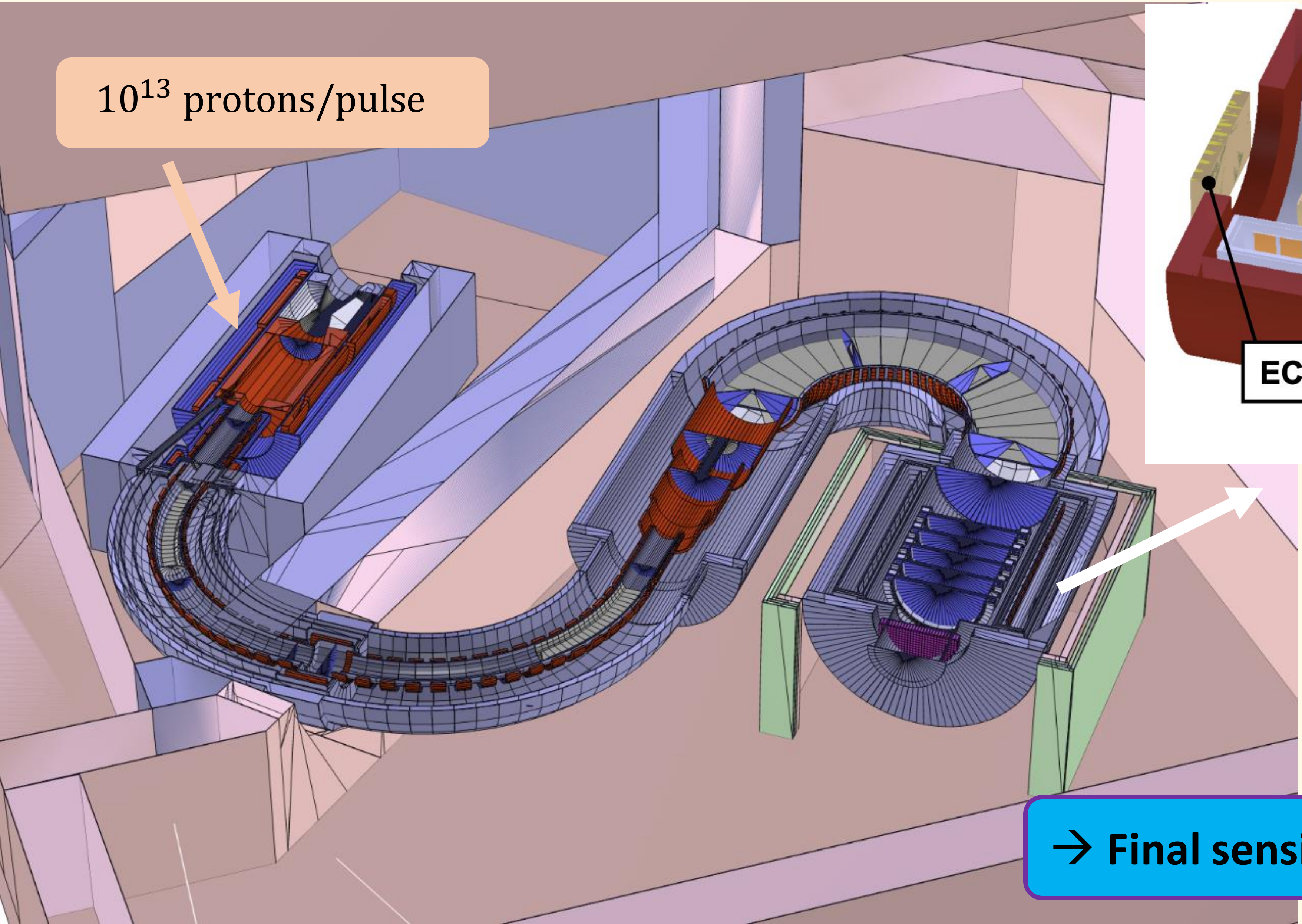

## Beam study run

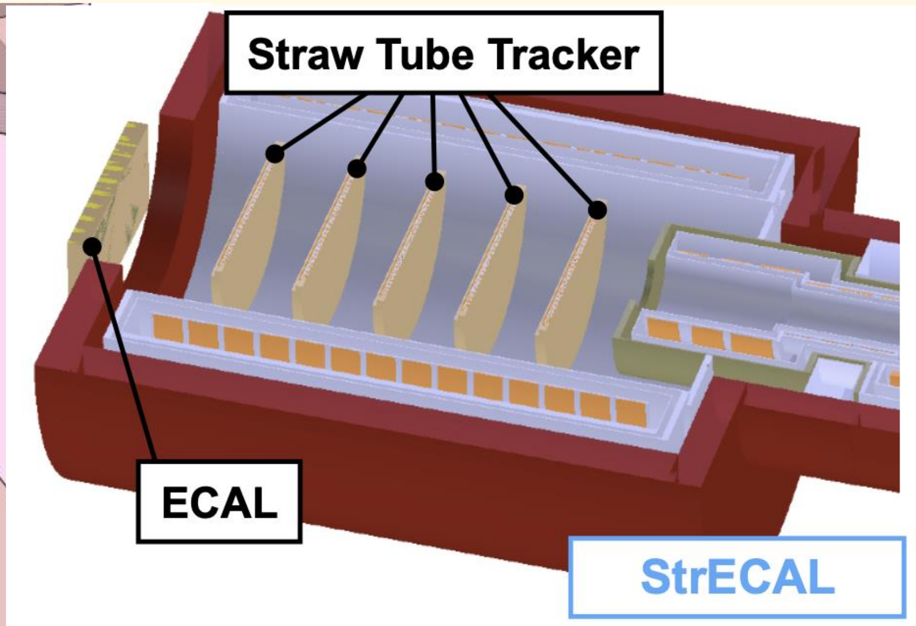
**Goal:** Measure the beam background in preparation for Phase-II using **StrECAL**

- **Straw tube tracker:** Each plane provides $x, y$ position for $p$ measurement
- **Electron calorimeter:** Measures hit position and allows PID by $E/p$

# A 2-phase approach: **Phase-II**

$10^{13}$ protons/pulse






- More intense beam
- Full S-shape solenoid
- **StreCal** as end-detector

**→ Final sensitivity** $\mathcal{O}(10^{-17})$

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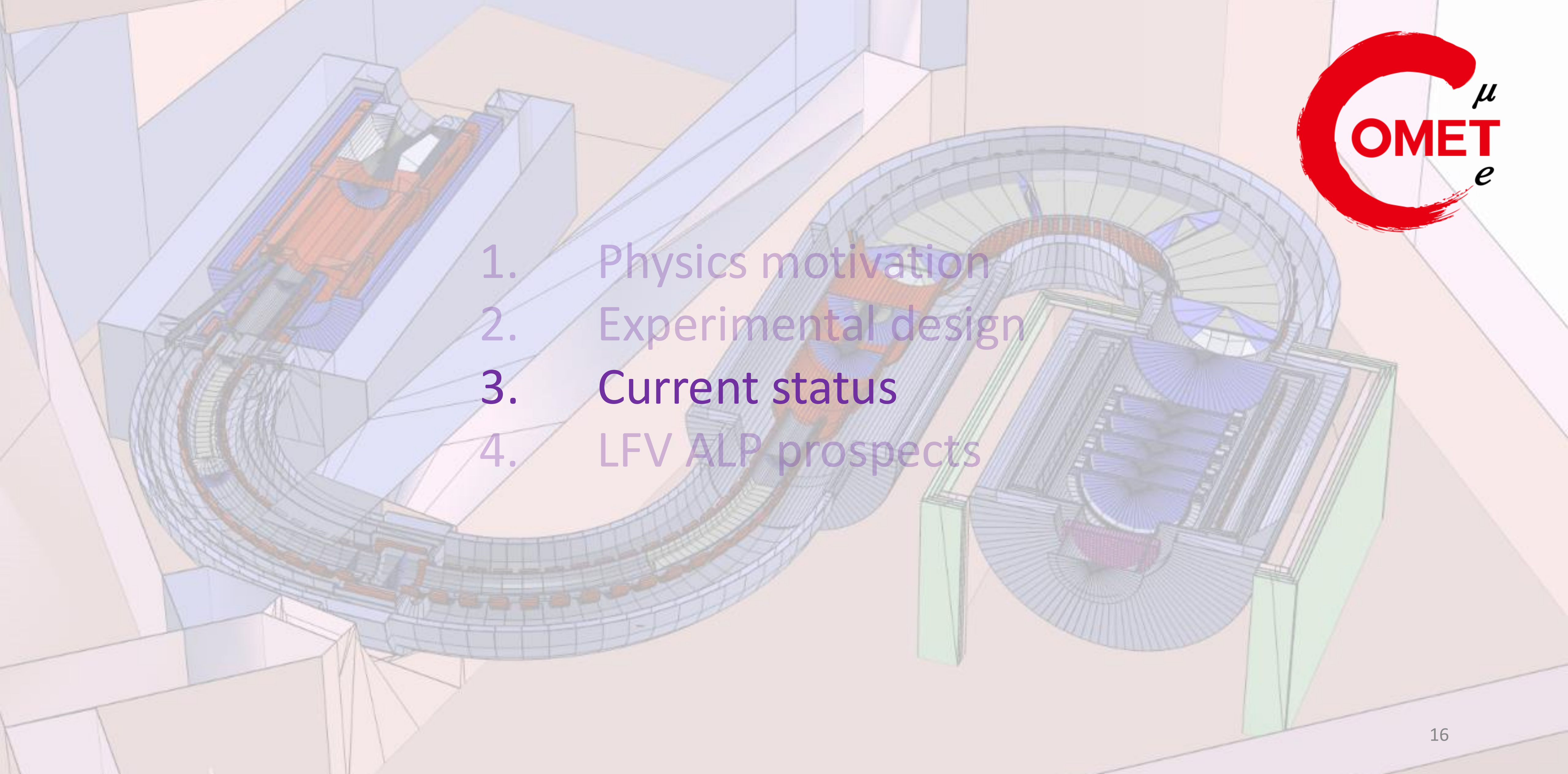

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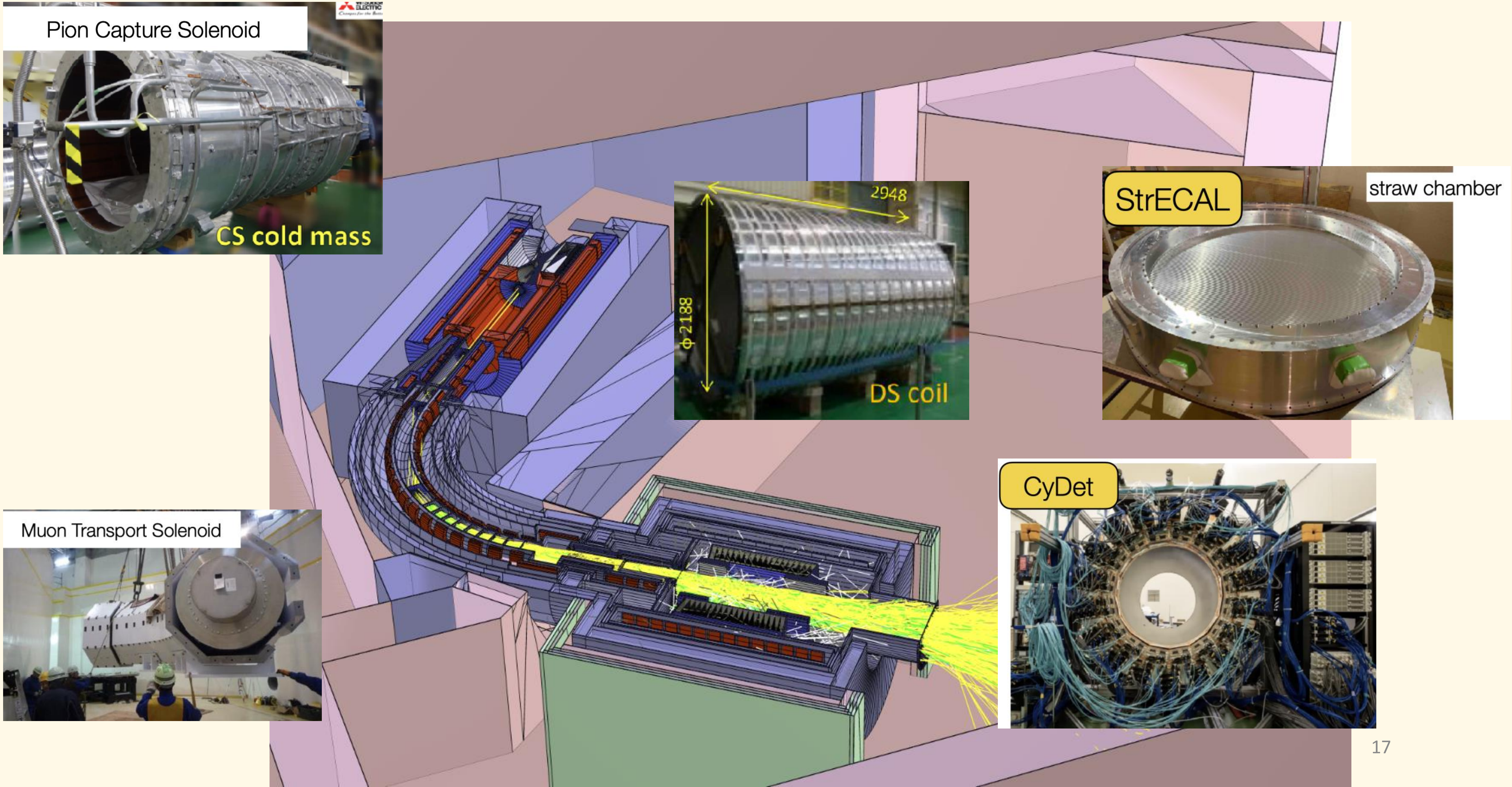
# Current status: towards Phase-I



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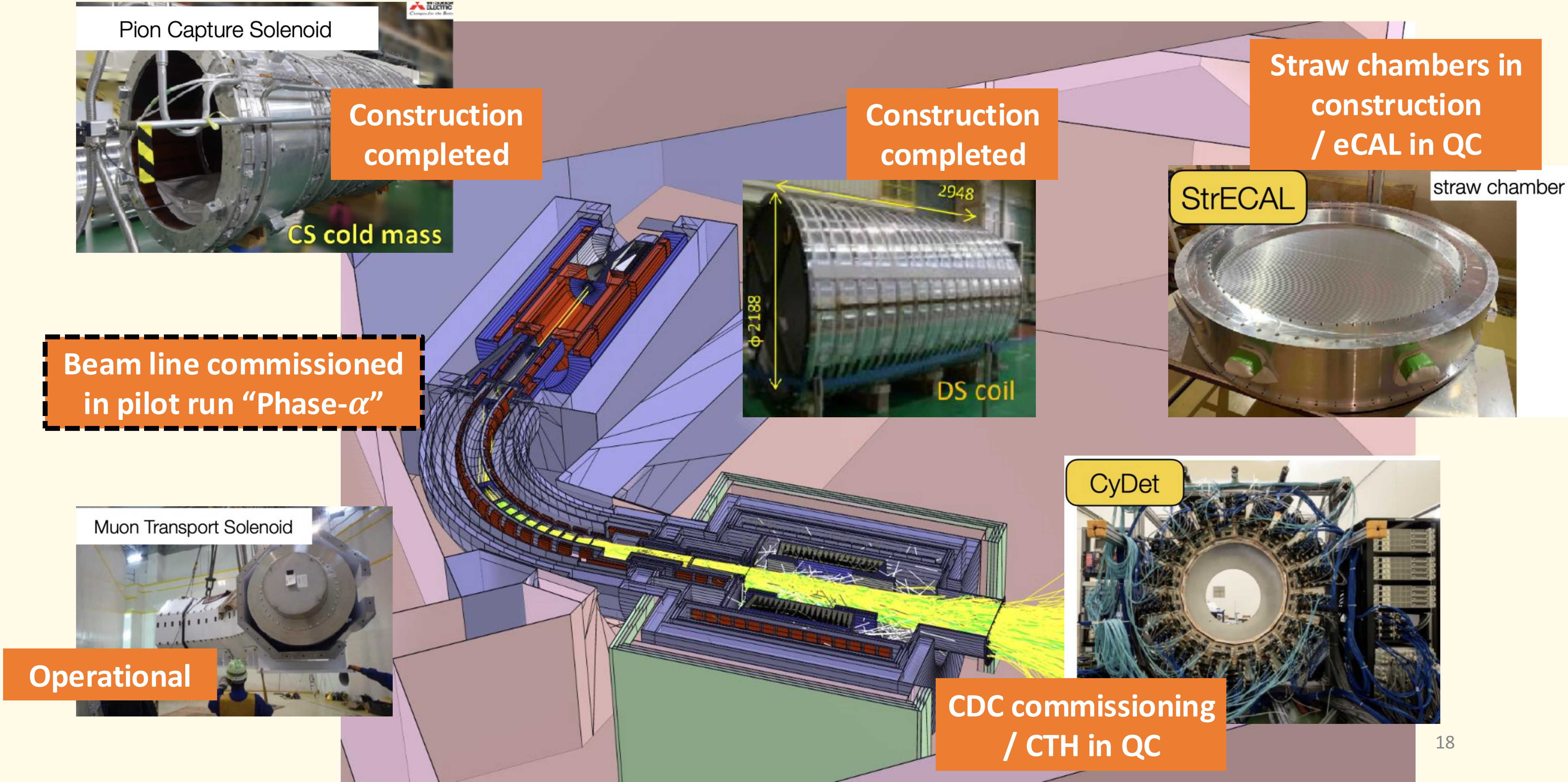
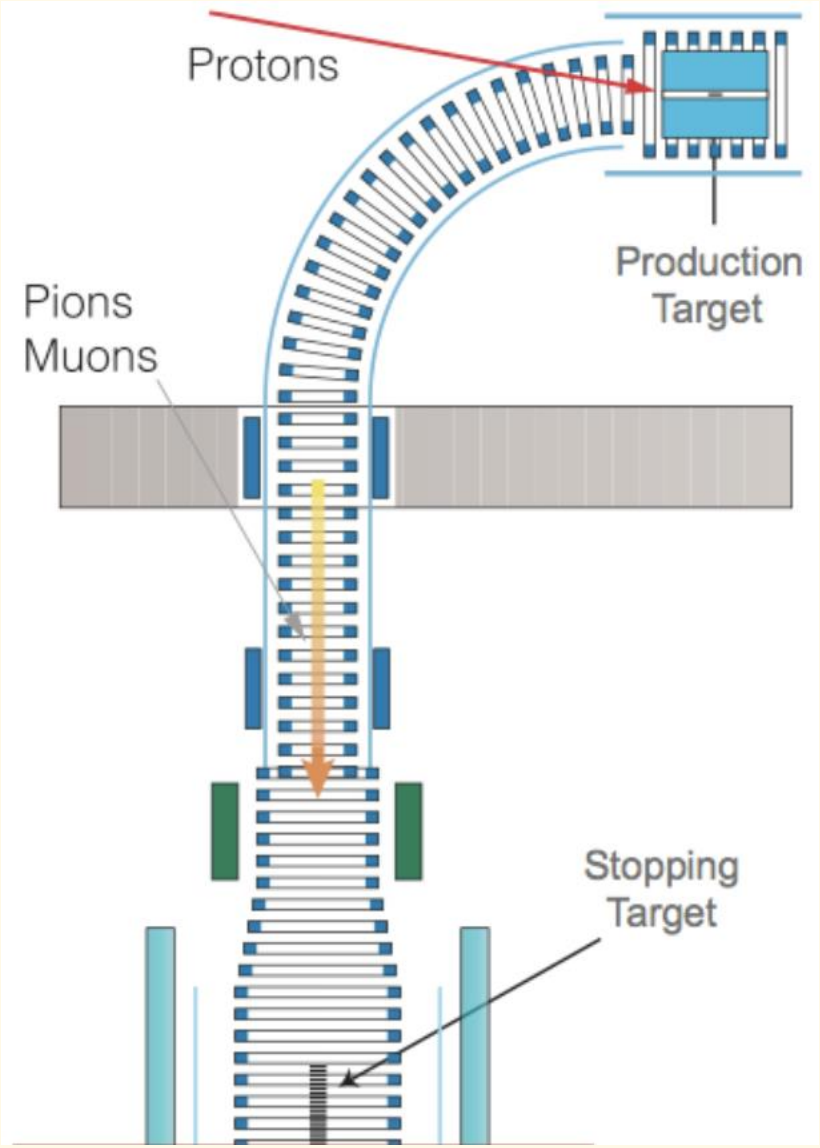


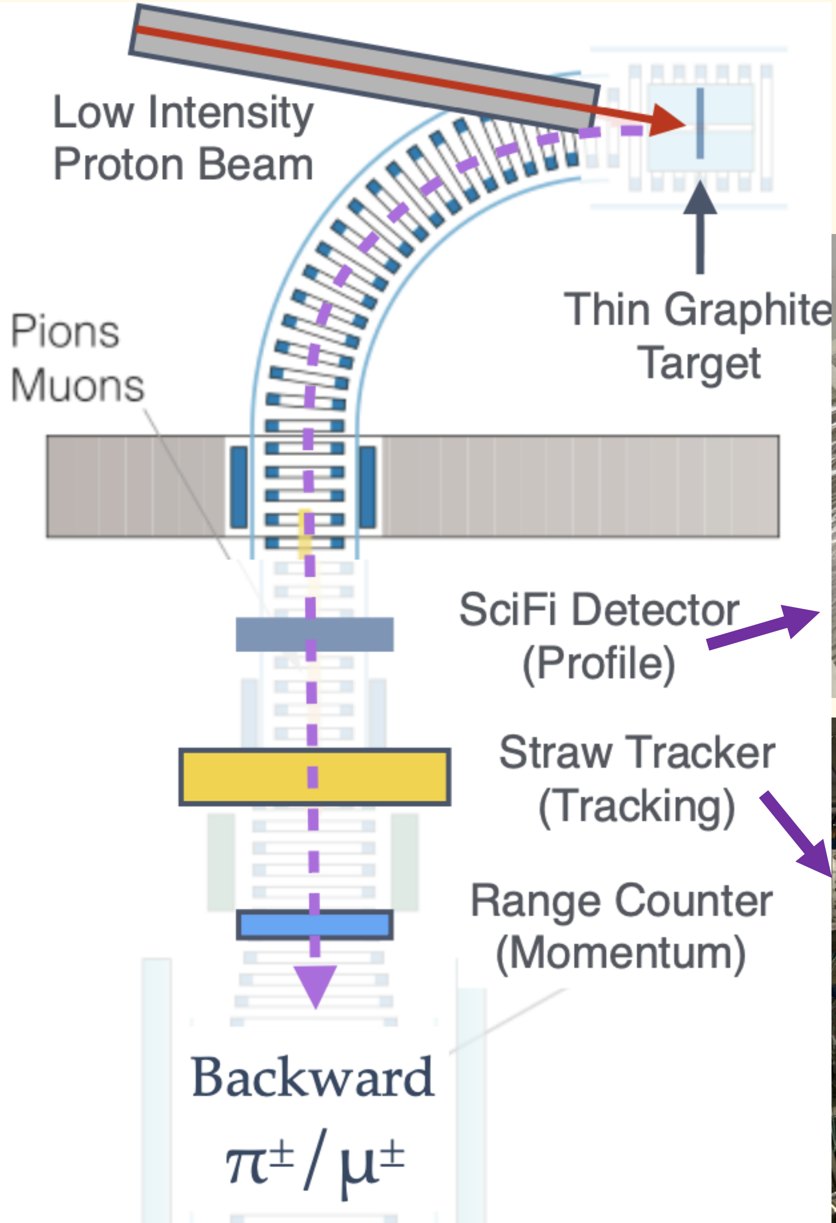
# Current status: beam study with Phase-$\alpha$



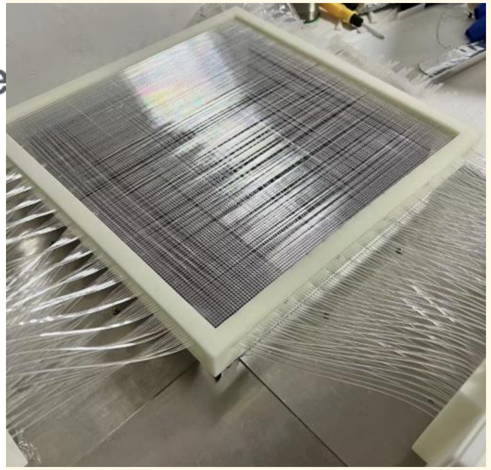

Pion Capture
Solenoid (PCS)

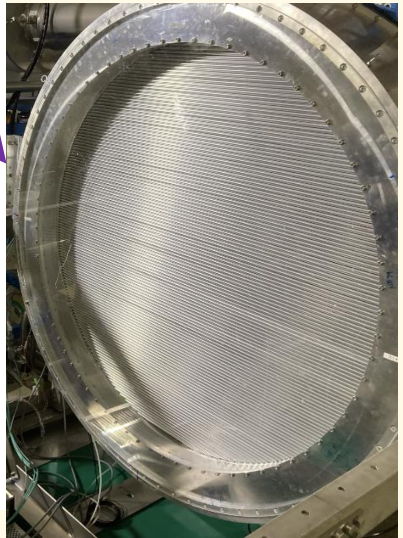
Phase-I setup

# Current status: beam study with Phase-$\alpha$



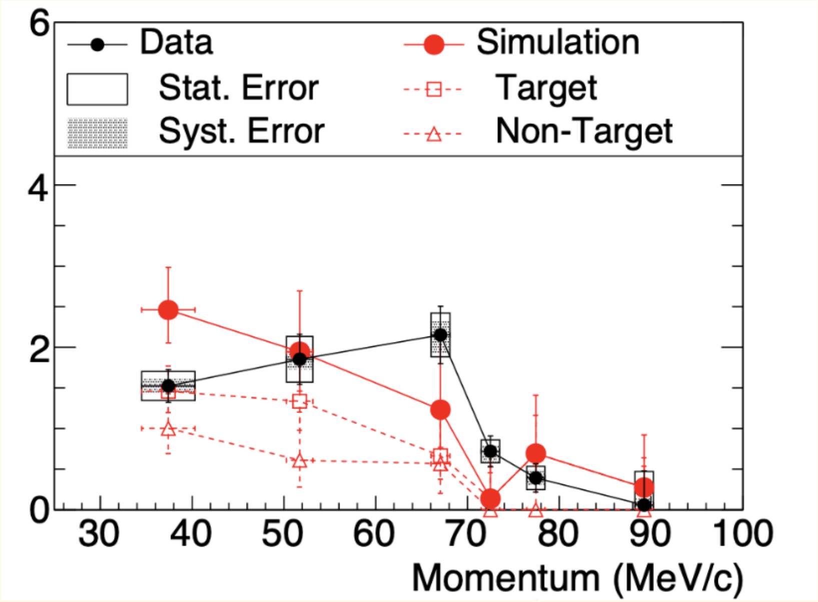

**Phase-$\alpha$ setup**





→ Used a low-intensity proton beam w/o Pion Capture Solenoid to study the muon beamline

$N_{\mu}^{stop}$ /$10^{12}$POT




→ Muon beam consistent with simulations

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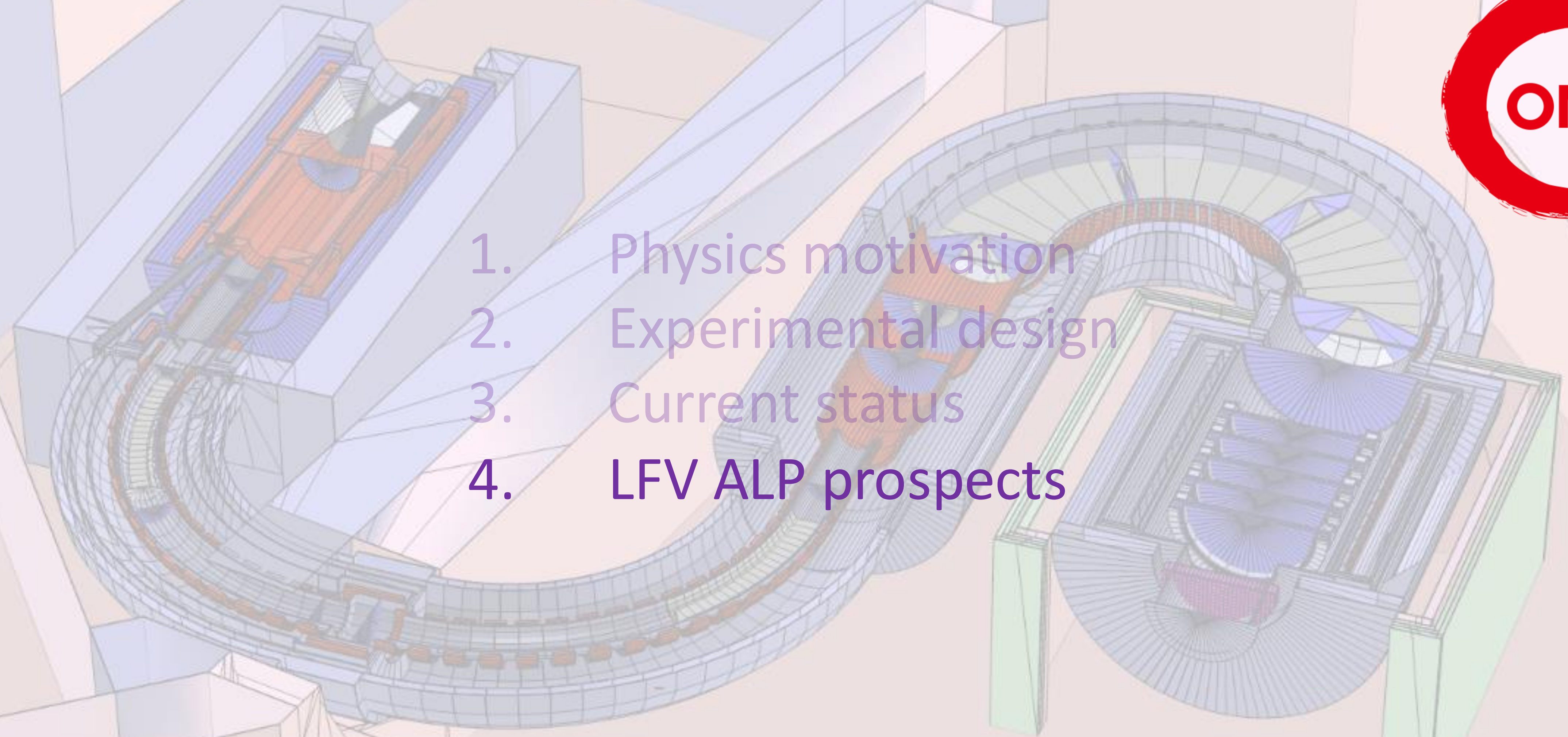

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# ALP searches in COMET

**LVF ALP:** $m_a < m_\ell$

Light and invisible particle with flavor violating coupling to leptons:

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a} \left( C_{ij}^V \bar{\ell}_i \gamma_\mu \ell_j + C_{ij}^A \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right)$$

induces 2-body LFV leptonic decays

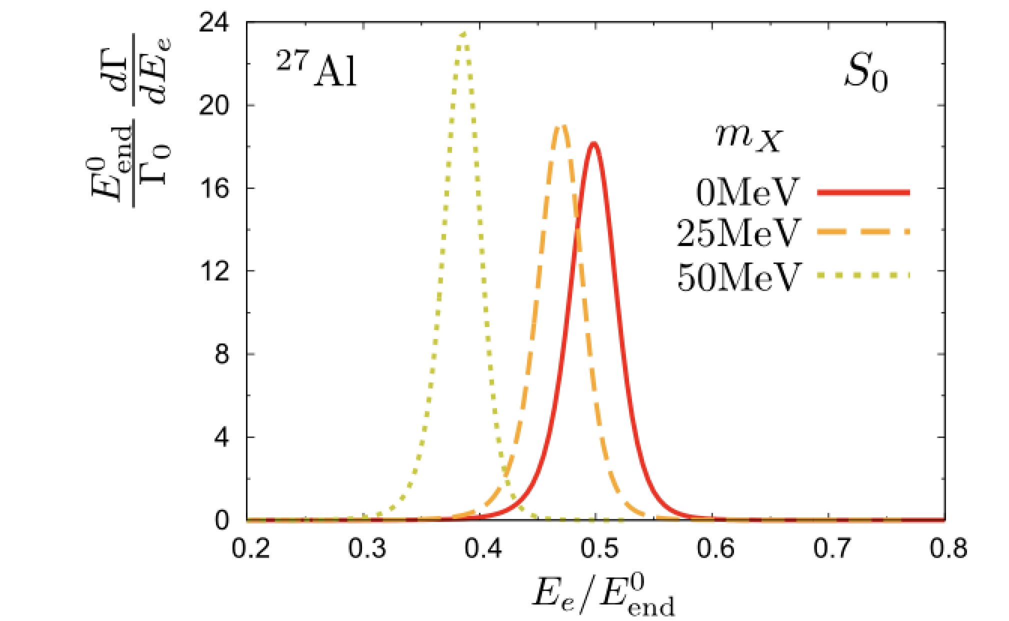
$$\Gamma(\ell_i \to \ell_j a) = \frac{1}{16\pi} \frac{m_{\ell_i}^3}{F_{ij}^2} \left(1 - \frac{m_a^2}{m_{\ell_i}^2}\right)^2 \propto \frac{1}{f_a^2}$$

$$F_{ij} \equiv \frac{2 f_a}{\sqrt{|C_{ij}^V|^2 + |C_{ij}^A|^2}}$$

Calibbi et al. (2021)

Possible search in COMET, however the narrow signal region around mono-energetic electron meant to avoid DIO background also avoids ALP signal…

Uesaka (2020)




COMET signal region around $m_\mu$

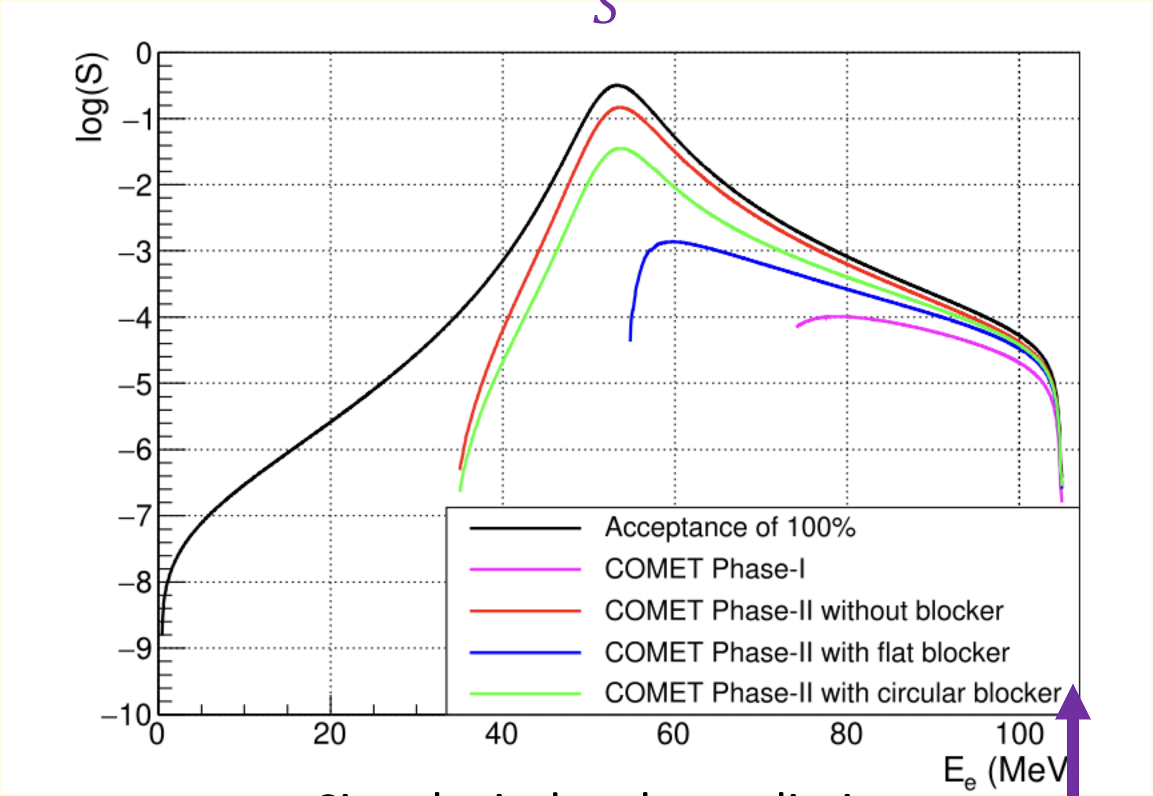
Energy spectrum of the emitted electron peaks at $m_\mu/2$ for $m_a \to 0$

# ALP searches in COMET: with a wider signal region

**Solution (1):** widen the COMET signal region while shielding from beam-related background

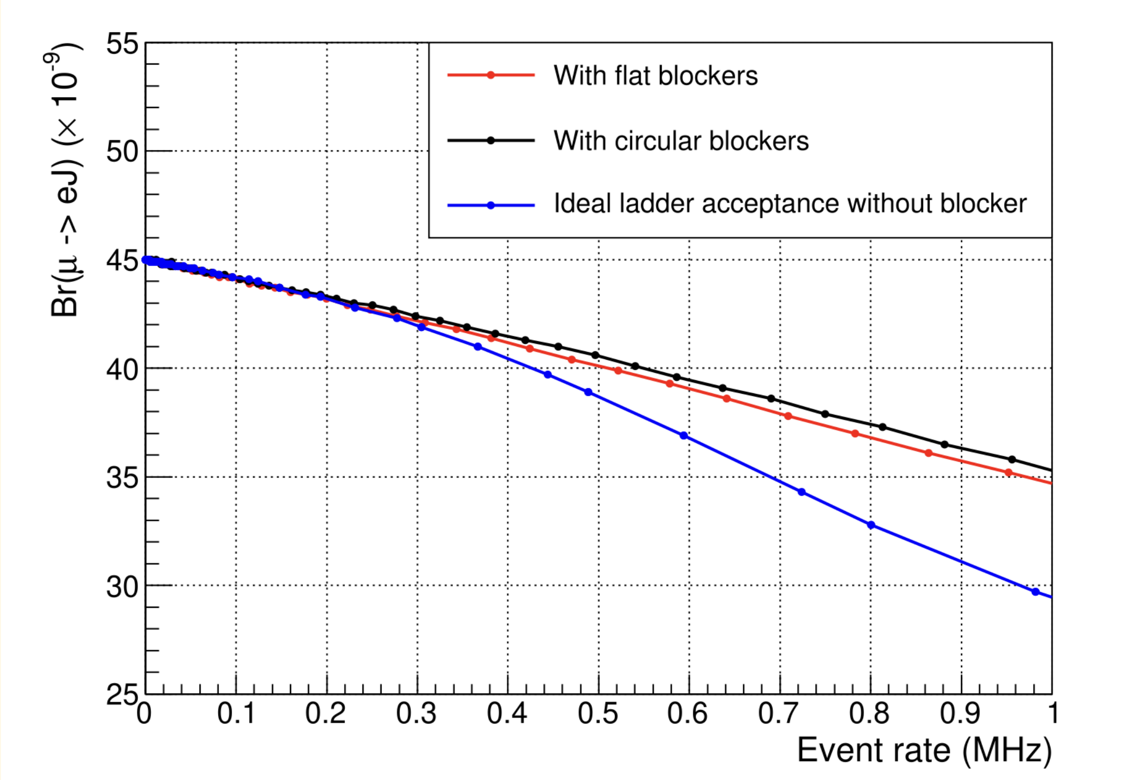
Xing et al. (2022)

Significance factor $S$ $\quad \mathcal{B}(\mu \to ea) \propto \frac{1}{S}$




Signal window lower limit

$E_{\mu\to e} = 105\text{MeV}$




$\mu$ DIO event rate

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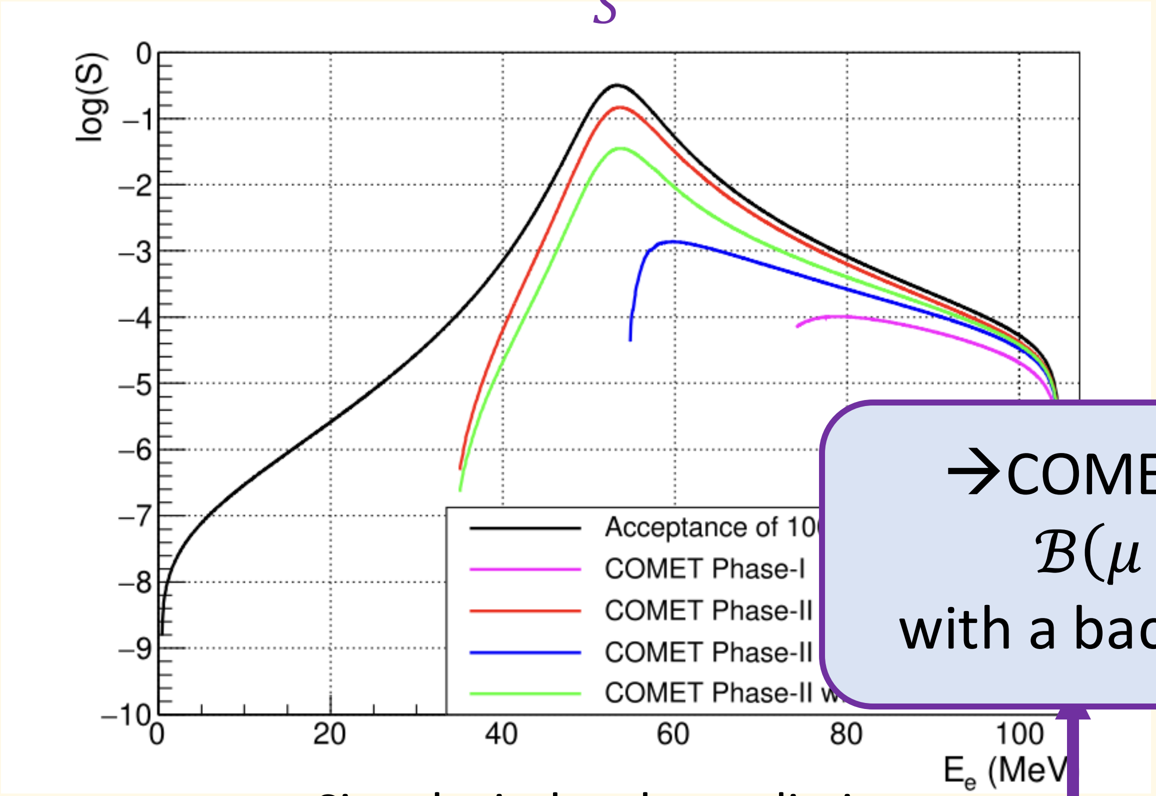


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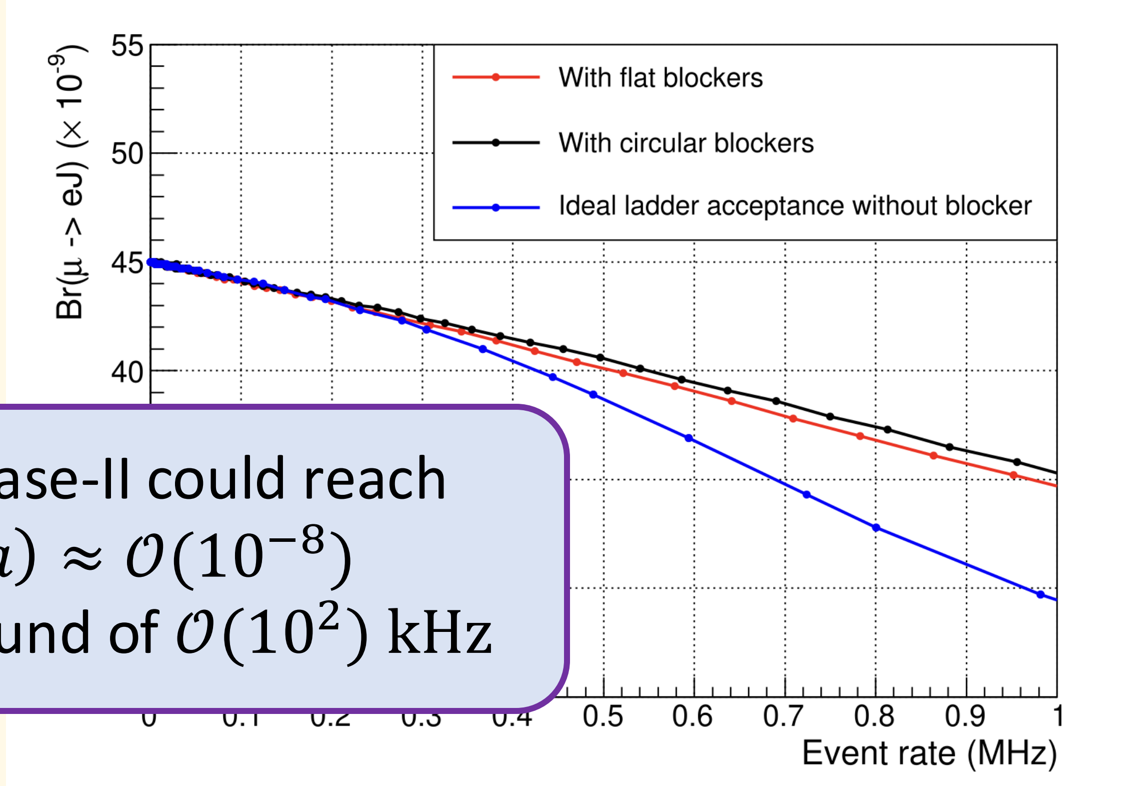



$\mu$ DIO event rate

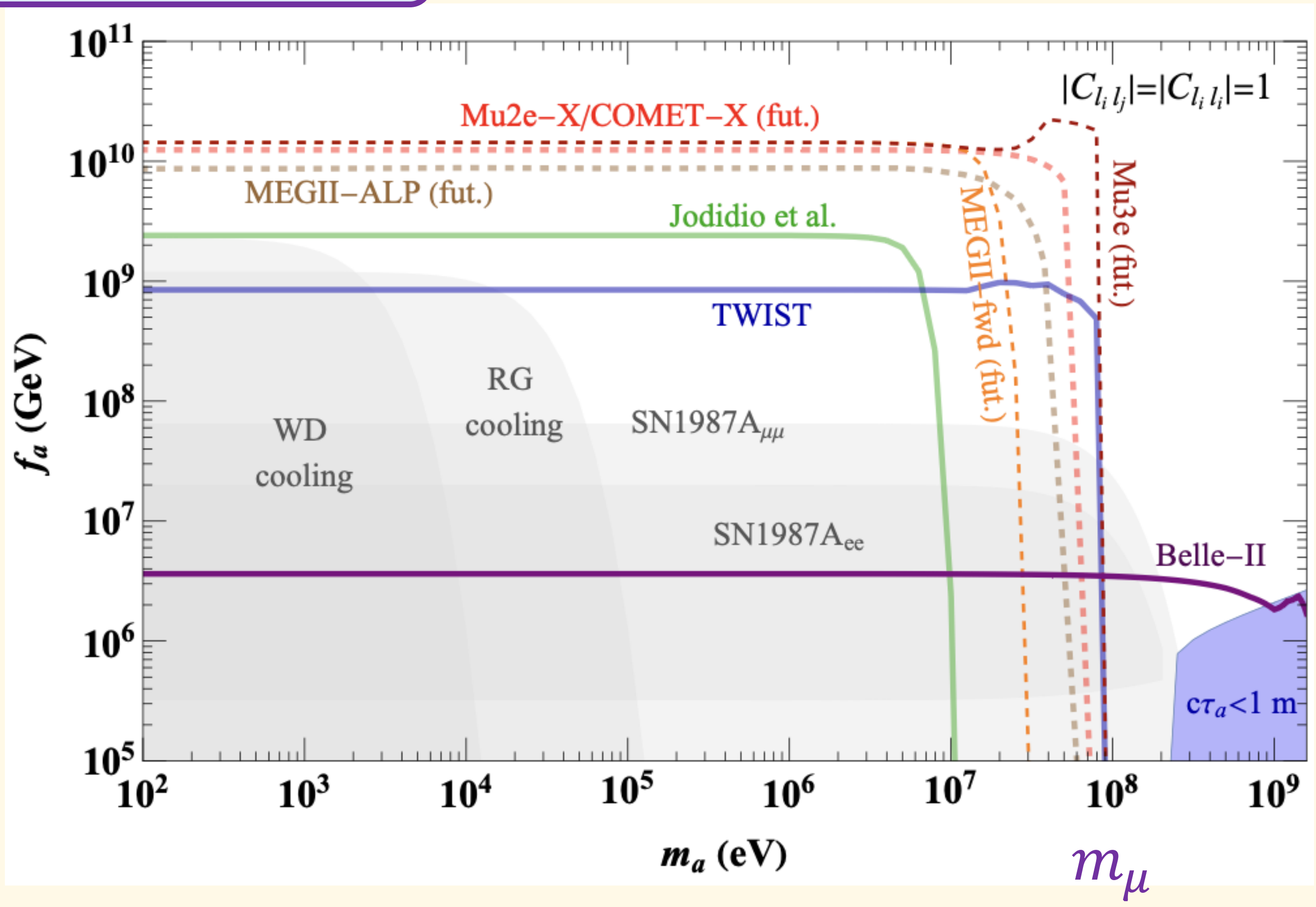
→COMET Phase-II could reach
$\mathcal{B}(\mu \to ea) \approx \mathcal{O}(10^{-8})$
with a background of $\mathcal{O}(10^2)$ kHz

# ALP searches in COMET: with a $\mu^+$ beam

**Solution (2):** use the $\mu^+$ beam of COMET detector calibration runs.

Hill et al. (2023)

- $\mu^+ \to e^+ a$
- Unlike the $\mu^-$, the $\mu^+$ will decay at rest and emit a positron with a wide energy spectrum.
- One can then search for a mono-energetic excess over the positron spectrum.



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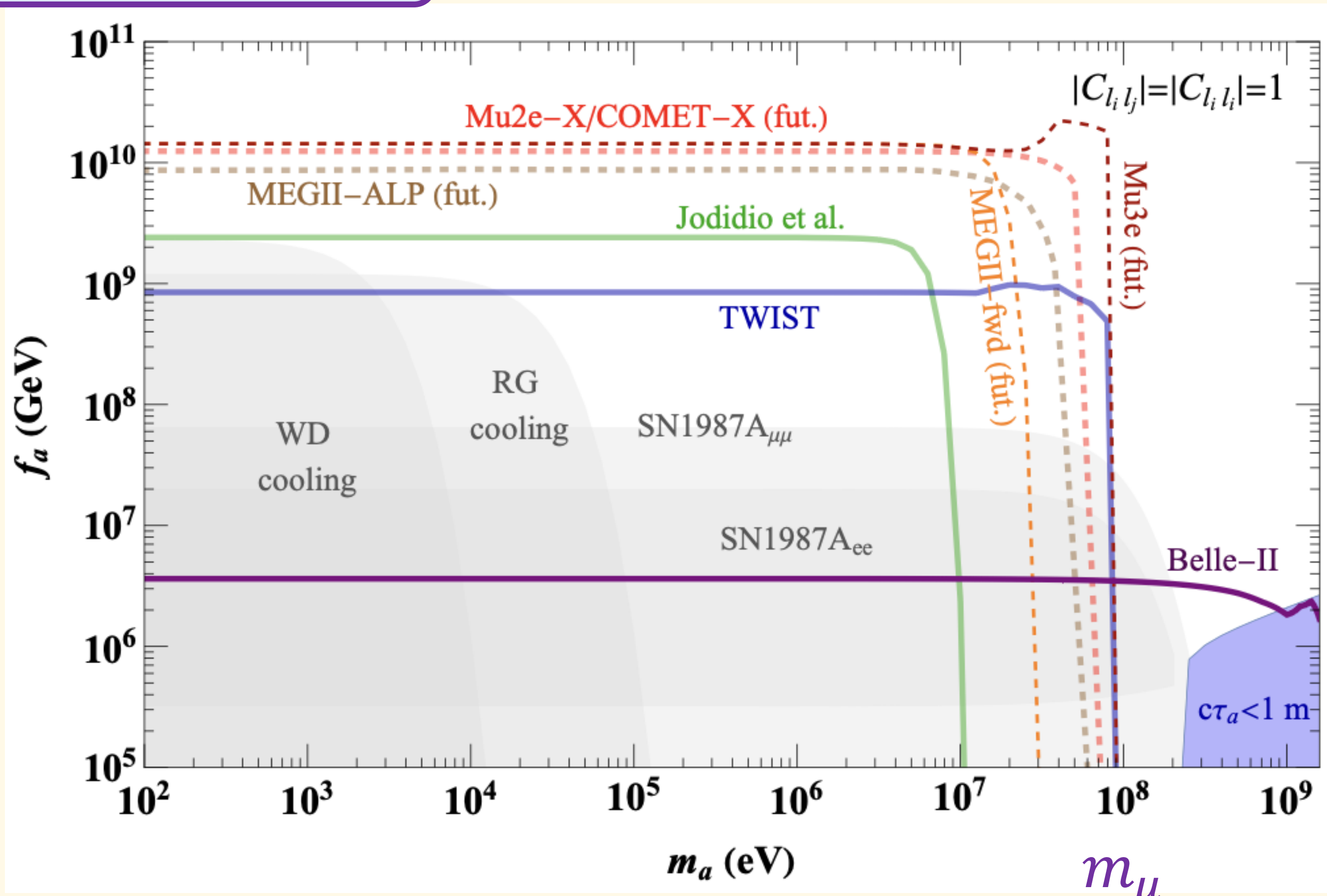
→ COMET Phase-II with $\mu^+$ could probe ALP coupling at $\Lambda = 10^{10}$ GeV




$m_\mu$

# Summary

- Neutrinoless $\mu - e$ conversion is a Charged Lepton Flavor Violating coupling with excellent New Physics sensitivity. COMET will measure the conversion ratio in Aluminum with an ultimate sensitivity of $\mathcal{O}(10^{-17})$, which probes NP at $\Lambda > 10^4$ TeV.

- A two-phase approach has been adopted:
  1. **COMET Phase-I:** partial C-shape solenoid for an intermediate sensitivity $\mathcal{O}(10^{-15})$ while also measuring beam background.
  2. **COMET Phase-II:** full S-shape solenoid for final sensitivity.

- Phase-I preparations are well underway:
  - ✓ Proton beam line and secondary muon beam successfully commissioned in **Phase-$\boldsymbol{\alpha}$**
  - ✓ Transport solenoid and pion capture solenoid constructed.
  - ✓ Development of detectors (**CyDet** and **StrECAL**) ongoing.

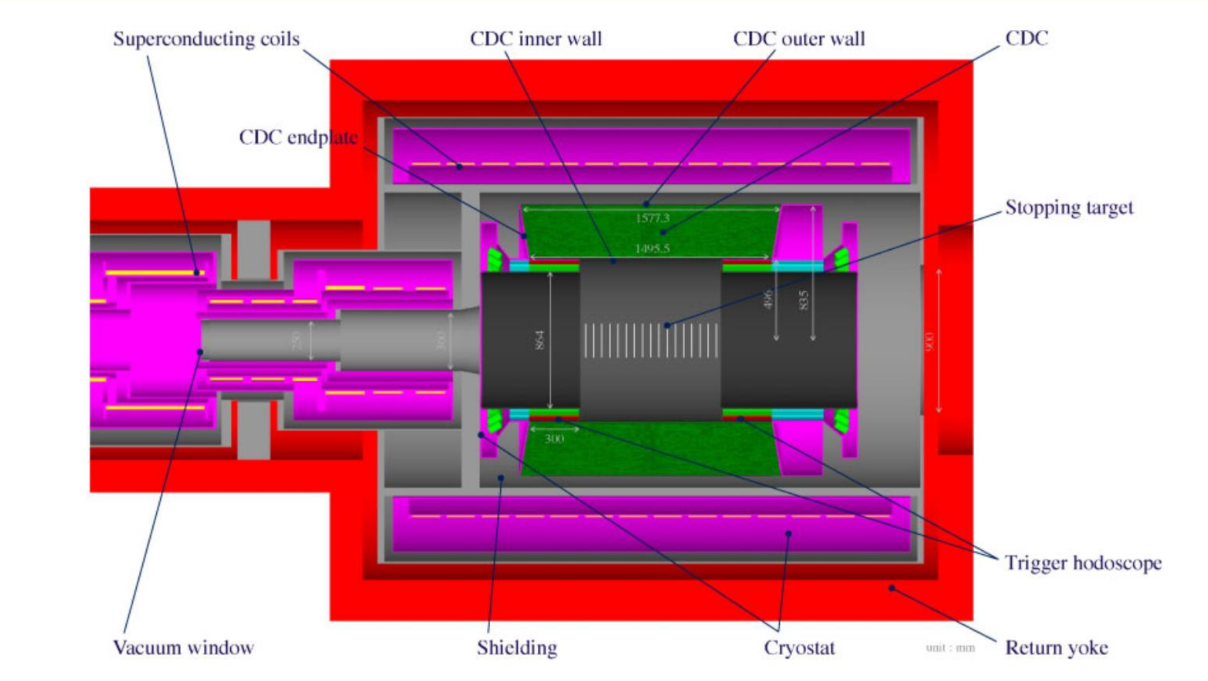
- COMET has been shown to have good potential for LFV ALP searches $\mu \rightarrow ea$, although due to the narrow COMET signal region some adjustments are required to reach competitive sensitivity.
  1. One option is to widen the energy detection region towards lower energies.
  2. Another is to use the $\mu^+$ calibration beam to probe $\mu^+ \rightarrow e^+a$.

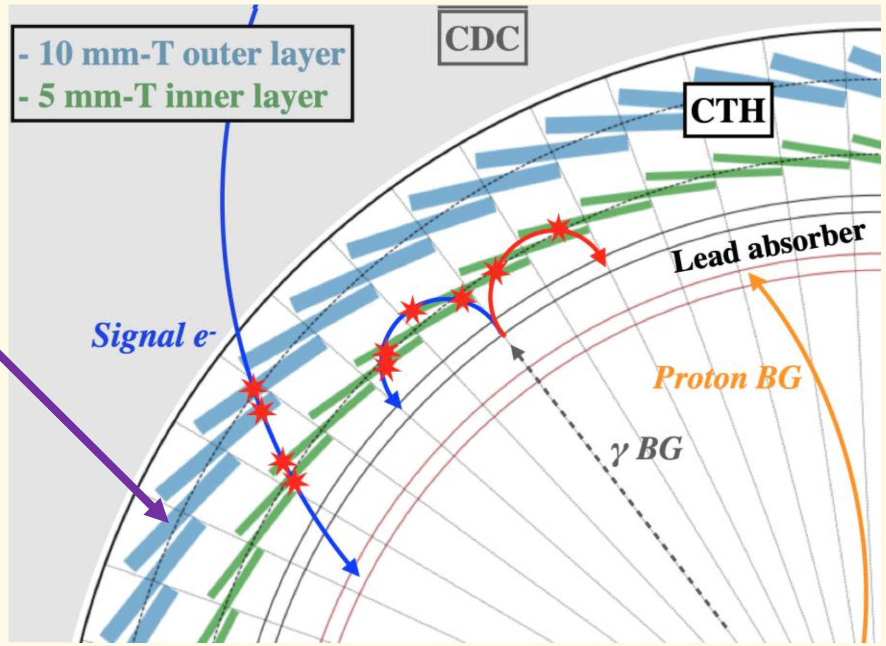
# Backup

# COMET's CTH

The Phase-I detector of COMET ("CyDET") consists of:

- **A Cylindrical Drift Chamber (CDC)** for track reconstruction
- **2 Cylindrical Trigger Hodoscopes (CTH)** (upstream / downstream)
  → Each CTH consists of 2 layers of 128 scintillator counters
  → Triggers on a 4-fold coincidence of these scintillators



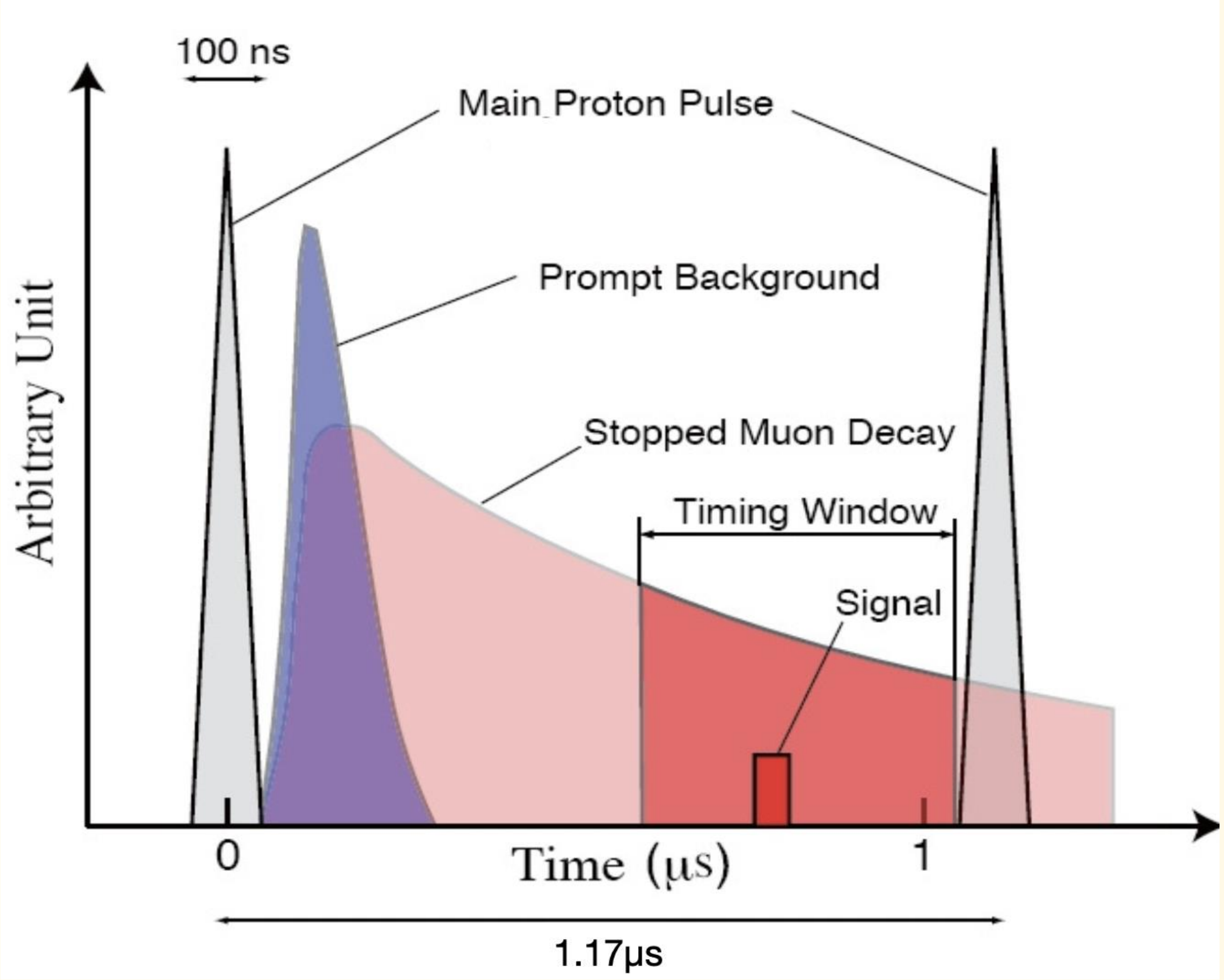




This configuration should allow to discriminate between signal electrons leaving tracks in the CDC and background from cosmic ray muons.

In order to then discriminate between Decay in Orbit (DIO) and signal $105\ \mathrm{MeV}$ electrons we require a **momentum resolution of $\mathbf{200\ keV}/\boldsymbol{c}$**

# COMET @ J-PARC, Tokai, Japan

$10^{12}$ protons/bunch




Pulsed-beam constrained by muonic atom lifetime

$864\ \text{ns}$ < pulse spacing
> pulse duration

$$\text{Extinction Factor} \equiv \frac{N_{\text{leaked protons}}}{N_{\text{pulsed protons}}}$$

**Goal:** reach a proton extinction factor $\approx 10^{-10}$

$$CR(\mu^- + N \to e^- + N) \propto \frac{1}{N_\mu^{\text{stop}} f_{\text{cap}} \mathcal{A}_{\mu\to e}}$$