university of groningen / faculty of science and engineering

Experimental Lepton Flavour Physics

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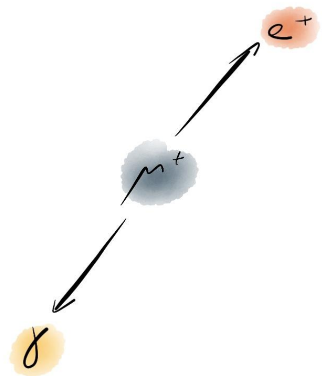
HEP Herbstschule
Bad Honnef, Sept. 2025

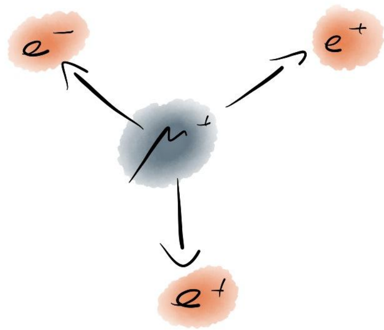
Experimental Lepton Flavour Physics

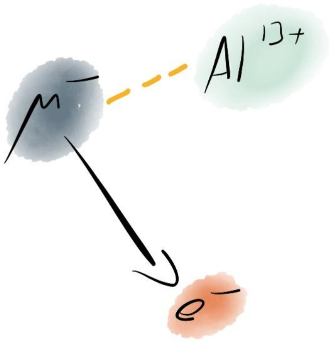
~~Neutrino Experiments~~ Muon cLFV Experiments

Lecture 3

cLFV with Muons: Golden Channels







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

› Monoenergetic e^+ and γ, back-to-back

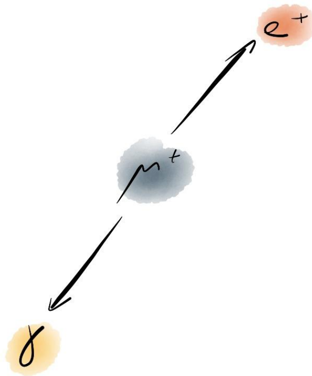
› Background from accidental combinations

› Continuous beam

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

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

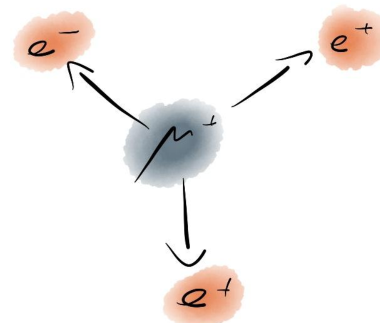
cLFV with Muons: Golden Channels



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

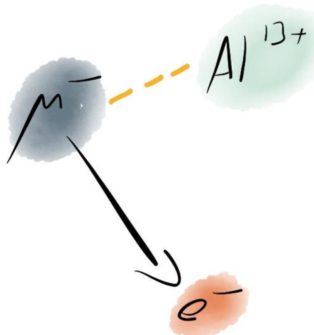
- Continuous high-rate μ^+ beam
- Experiment with high resolution in
  - γ energy
  - e^+ momentum
  - Relative timing $e^+ \gamma$
  - Opening angle $e^+ \gamma$

MEG / MEG II @ PSI



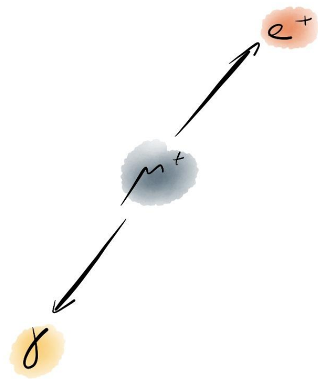
$\mu^+ \rightarrow e^+ e^- e^+$

- Invariant mass of $e^+ e^- e^+ = m_\mu$
- $\boldsymbol{\sum p_e = 0}$
- Background from $\mu^+ \rightarrow e^+ e^- e^+ \nu \bar{\nu}$ and accidental combinations
- Continuous beam



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

cLFV with Muons: Golden Channels



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- Continuous high-rate μ^+ beam
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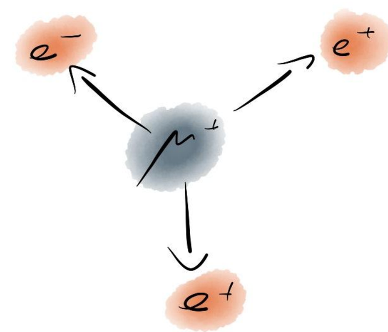
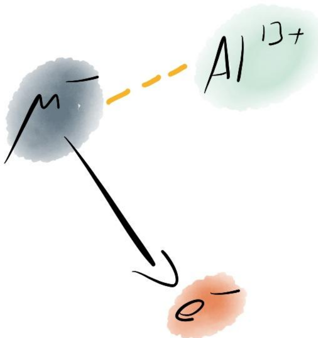


$\mu^+ \to e^+ e^- e^+$

- Continuous high-rate μ^+ beam
- Experiment with high resolution in
  - $e^{+/-}$ momentum
  - $e^+e^-e^+$ vertex position $\Rightarrow$ minimize material
  - Relative timing $e^+e^-e^+$

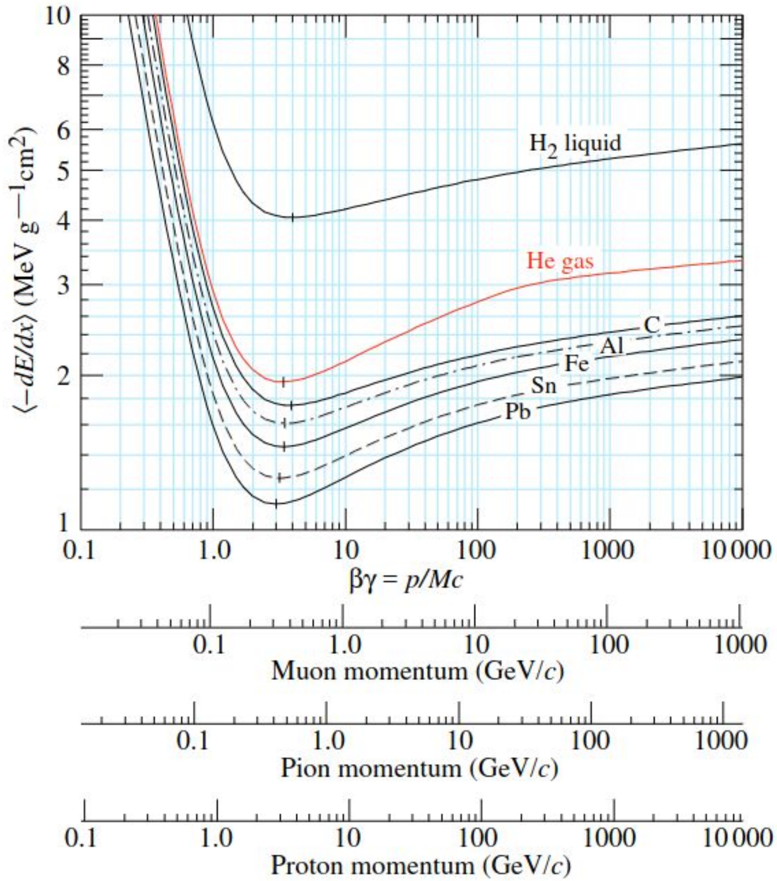
Mu3e @ PSI



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

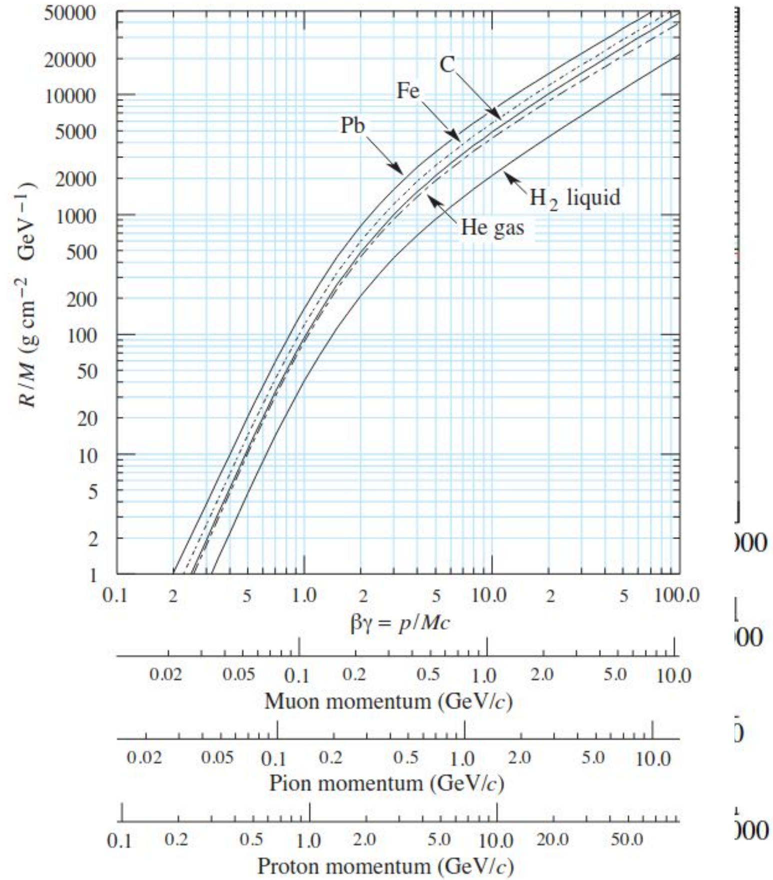
Muons at Low Momentum

- **High-momentum muons** ($\mathcal{O}$(p) = 1GeV-10GeV) are minimum-ionizing particles (**MIP**)
  - **Pass through** large amounts of **material**



Muons at Low Momentum

- **High-momentum muons** ($\mathcal{O}$(p) = 1GeV-10GeV) are minimum-ionizing particles (**MIP**)
  - **Pass through** large amounts of **material**
- **Low-momentum muons** ($\mathcal{O}$(p) = 1MeV-10MeV) have **high dE/dx**
  - Can be easily **stopped** in thin **material** layers



Why Muon Decays at Rest?

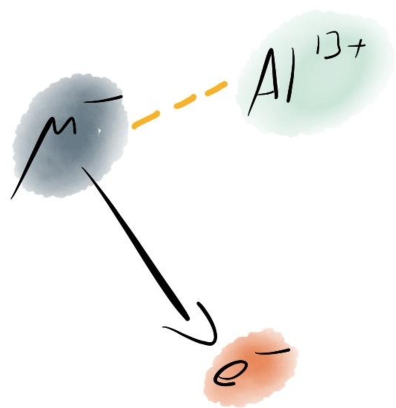
Muon decay at rest

- **Every muon** arriving at the experiment **decays in the experiment**
  - High rate
  - Decay vertex in center
- **Lab frame is rest frame**
  - Easier kinematics
  - Tracks spread isotropically over full detector volume
- **Additional background** from interaction with material?
  - At most electrons and photons
  - No problem is lower p than signal electrons

Muon decays in flight

- **Most muons fly through** the experiment
  - Lower rate
  - Muon dump
  - Decay vertex somewhere
- Decay products are **boosted**
  - Transformation to rest frame
  - Vertexing more difficult
  - Higher track density per volume

$\mu^-N \rightarrow e^-N$ with Mu2e and COMET

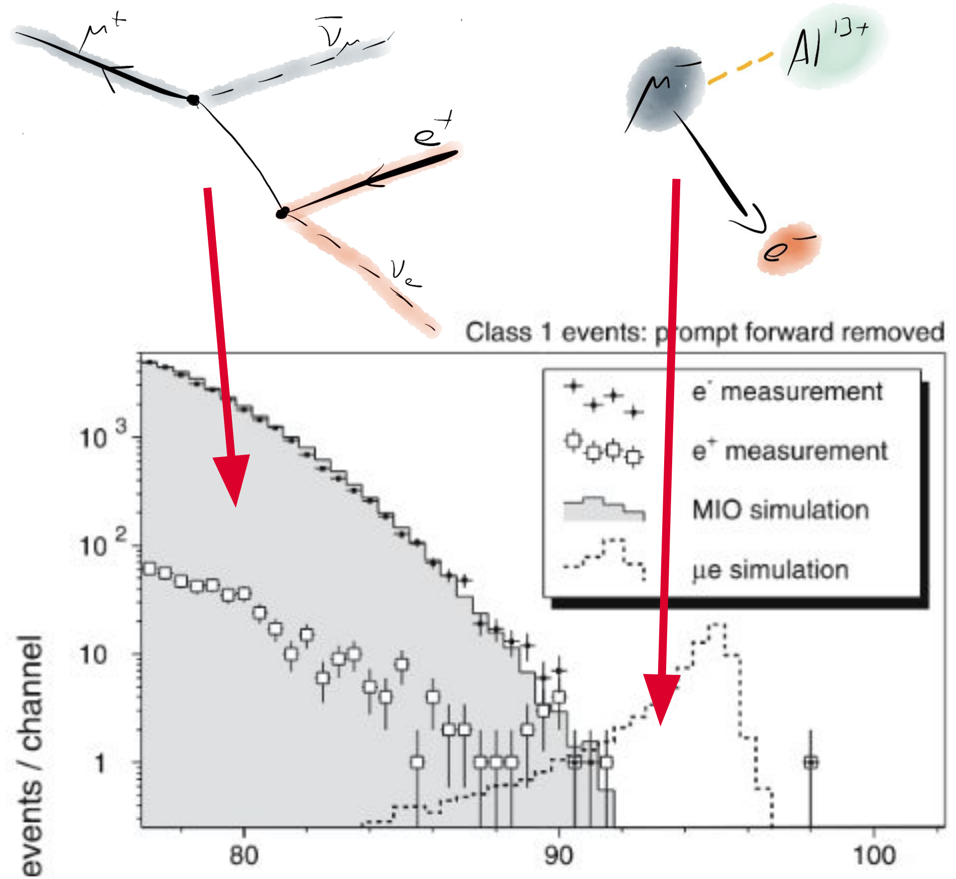


$\mu^- N \to e^- N$ Conversion

- Conversion of $\mu \to e$ within muonic atom: **$\mu^- N \to e^- N$**

- Signal
  - Mono-energetic e^- ~ 105 MeV for N=Al

- Background
  - Muon decay in orbit $\mu^- N \to e^- \nu \bar{\nu} N$
  - Neutrinos invisible
  - Beam-related backgrounds ex. muon decays in-flight, antiprotons, pions
  - Cosmics



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    ex. muon decays in-flight, antiprotons, pions
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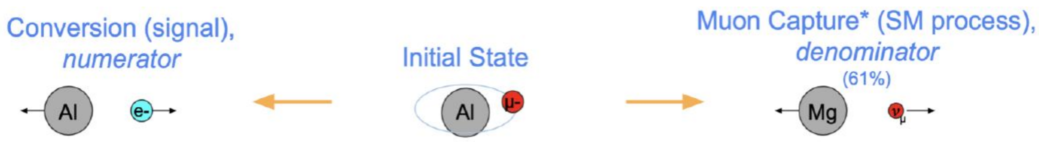
- It's not a decay, it's a conversion
  ⇒ Conversion rate

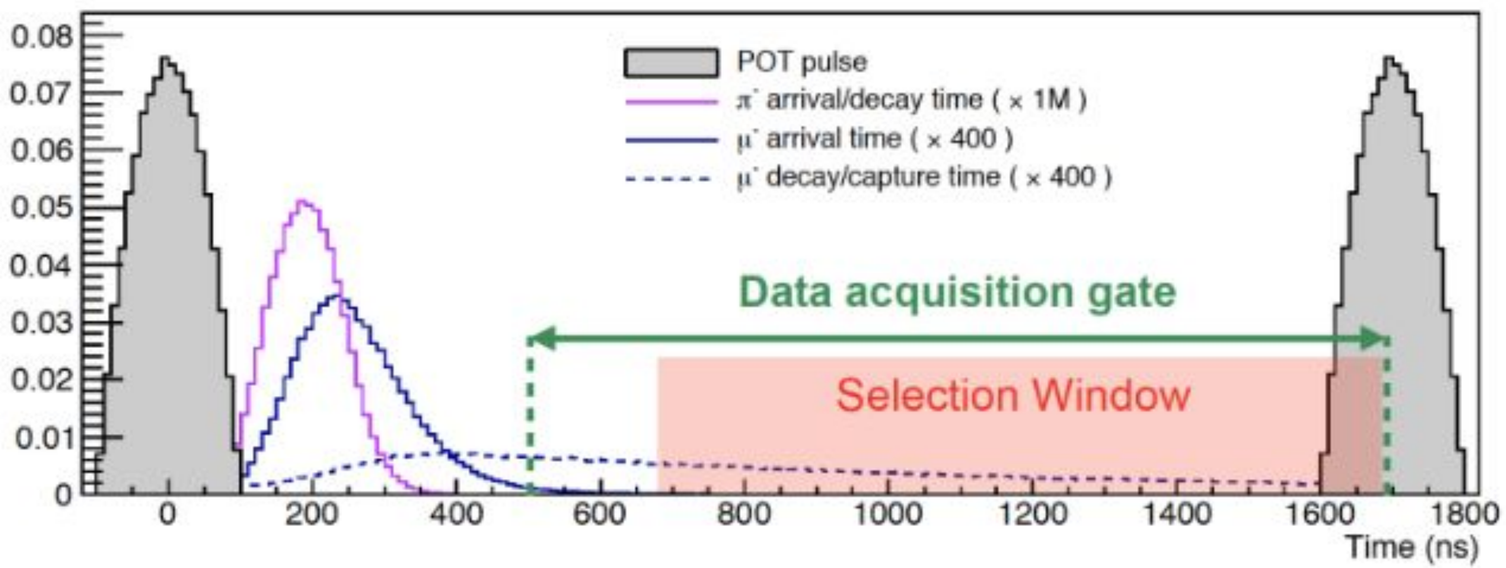
$$\mathcal{R}_{\mu e} = \frac{\Gamma(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al})}{\Gamma(\mu^- + \mathrm{Al} \to \nu_\mu + \mathrm{Mg})}$$



- Current limit:
  $\mathfrak{R}(\mu \mathrm{Au} \to e \mathrm{Au}) < 7 \times 10^{-13}$ at 90% CL
  SINDRUM II @PSI (2006)

$\mu^-N \rightarrow e^-N$ Conversion: Pulsed Beam

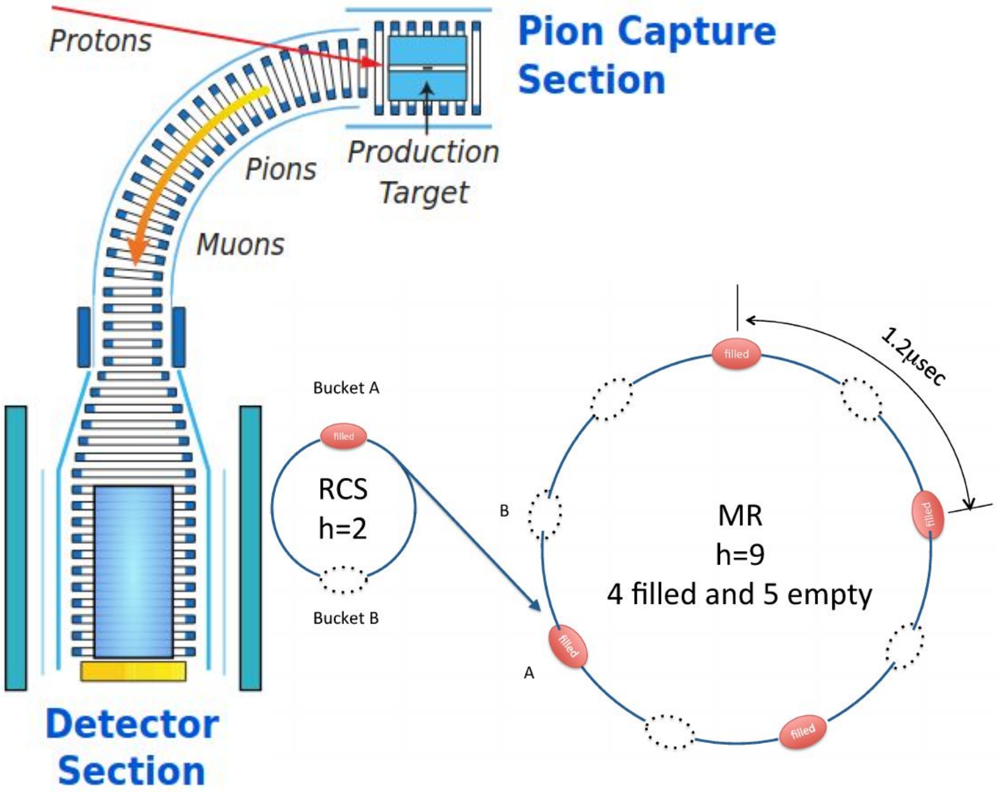
- With **beam-related backgrounds**, need an experiment with
  - **Pulsed** muon beam
  - **Muonic atom** μ^-N with **long lifetime**, ex. T(μAl) = 864 ns



$\mu^- N \to e^- N$: COMET Experiment

COMET at J-Parc: **μ^-Al →e^-Al**
COherent Muon to Electron Transition

- **Pion** production:
  Intense **proton** beam **pulse** on **production target**: **p→π**



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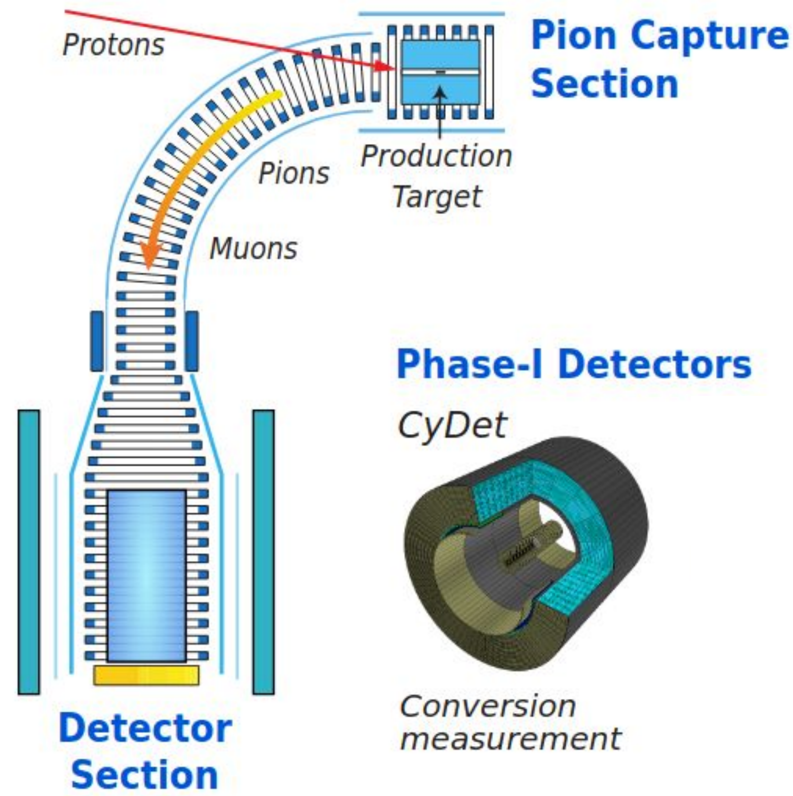
COMET at J-Parc: **$\mu^- Al \to e^- Al$**
COherent Muon to Electron Transition

- Muon production:
  Intense proton beam pulse on production target: $p \to \pi$
- Decay **$\pi \to \mu$** within 90° transport solenoid (no 'line-of-sight')
- Formation of **muonic atoms**:
  Stopping muons on stopping target



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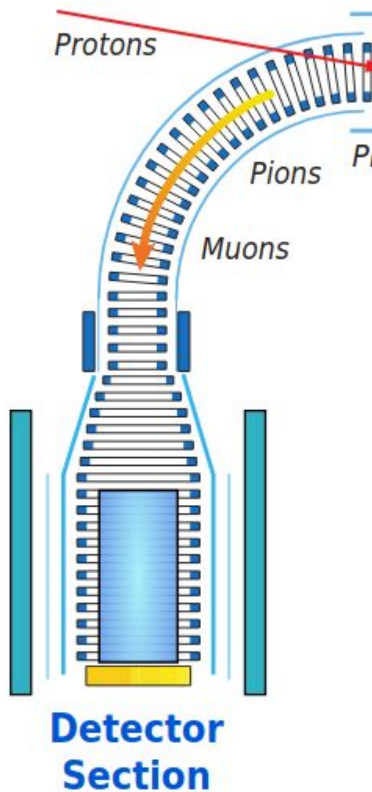
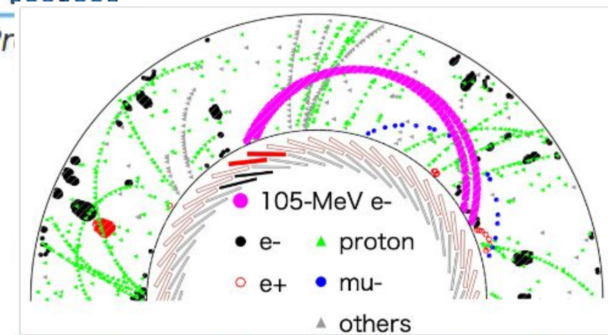
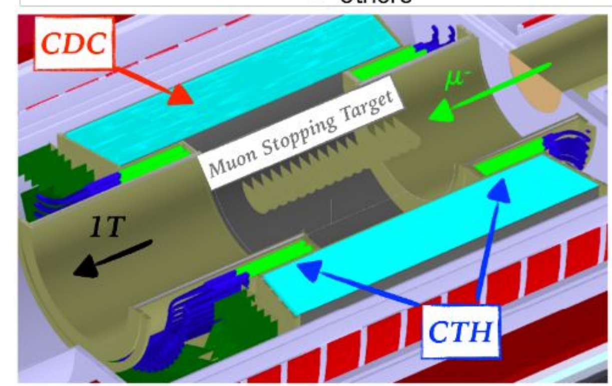
COherent Muon to Electron Transition

- Muon production:
  Intense proton beam pulse on production target: $p \rightarrow \pi$
- Decay $\pi \rightarrow \mu$ within 90° transport solenoid (no 'line-of-sight')
- Formation of muonic atoms:
  Stopping muons on stopping target
- **Wait** for the conversion
- **Measure** conversion electron
  - CyDet: drift chamber + scintillators



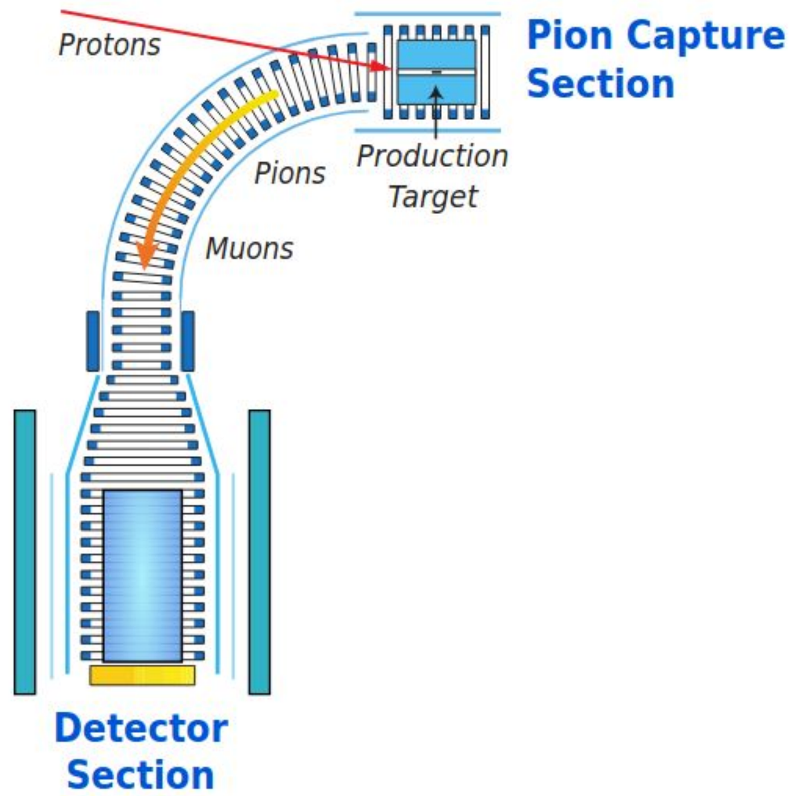




$\mu^- N \rightarrow e^- N$: COMET Experiment

COMET (J-Parc): **$\mu^- Al \rightarrow e^- Al$**

- **Phase I**
  - 90° transport solenoid between production and stopping target
  - CyDet detector surrounding stopping target
  - Sensitive to **$\mathcal{R}(\mu Au \rightarrow e Au) \sim 10^{-15}$**

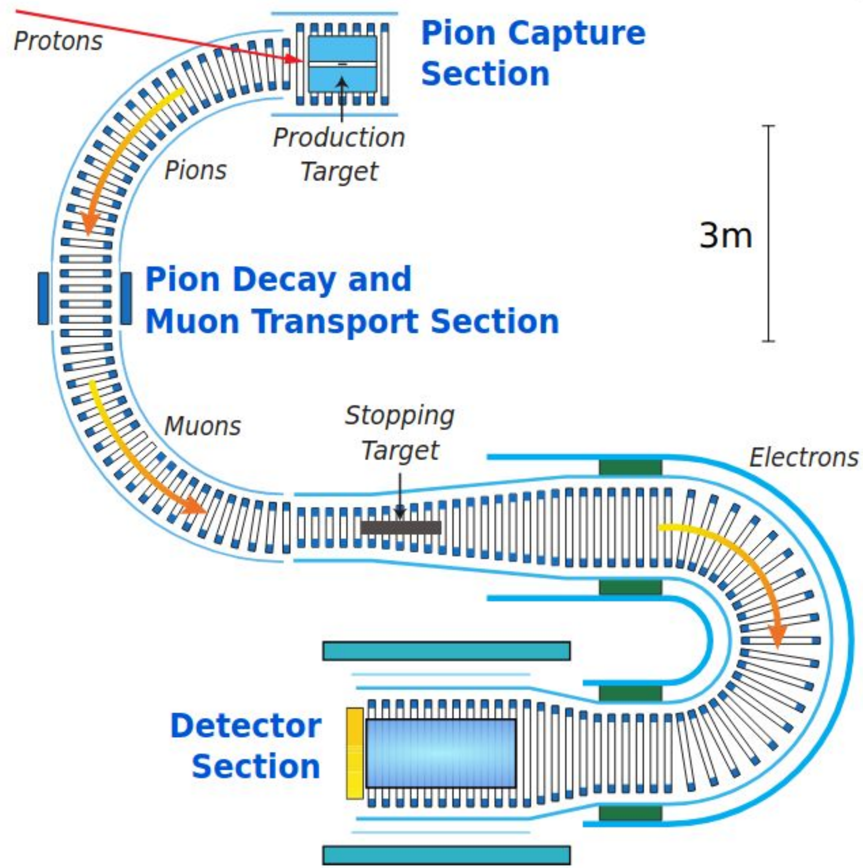


$\mu^- N \to e^- N$: COMET Experiment

COMET (J-Parc): $\mathbf{\mu^- Al \to e^- Al}$

- **Phase I**
  - 90° transport solenoid between production and stopping target
  - CyDet detector surrounding stopping target
  - Sensitive to $\boldsymbol{\mathcal{R}(\mu Au \to eAu) \sim 10^{-15}}$

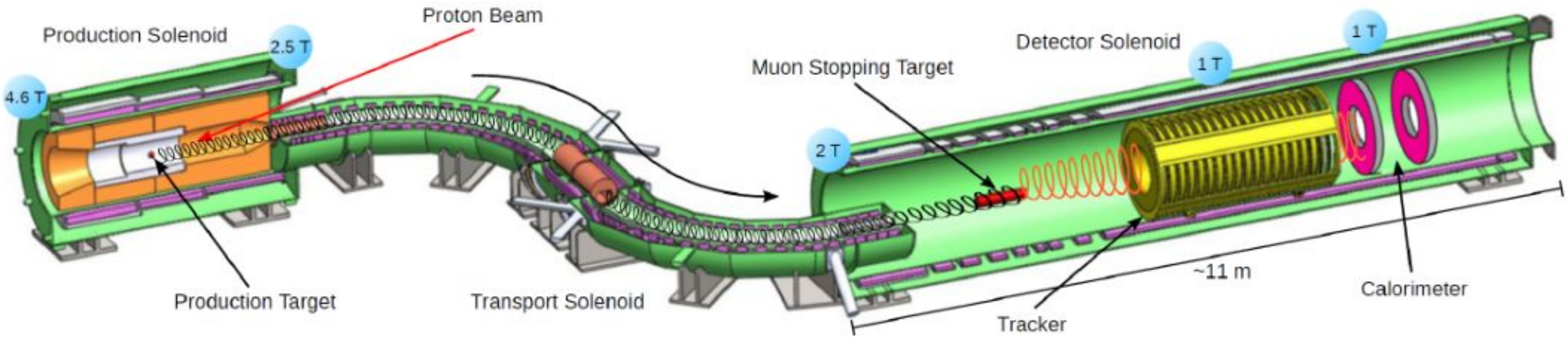
- **Phase II**
  - Increase muon production rate (x20)
  - 180° transport section
  - Separation of target and detector
  - Sensitive to $\boldsymbol{\mathcal{R}(\mu Au \to eAu) \sim 10^{-17}}$



$\mu^- N \rightarrow e^- N$: Mu2e Experiment

Mu2e (FNAL): **$\mu^- Al \rightarrow e^- Al$**

- Transport solenoid **separating production and stopping** target
- Stopping target in front of detector section (tracker + calorimeter)
- Cosmic Veto



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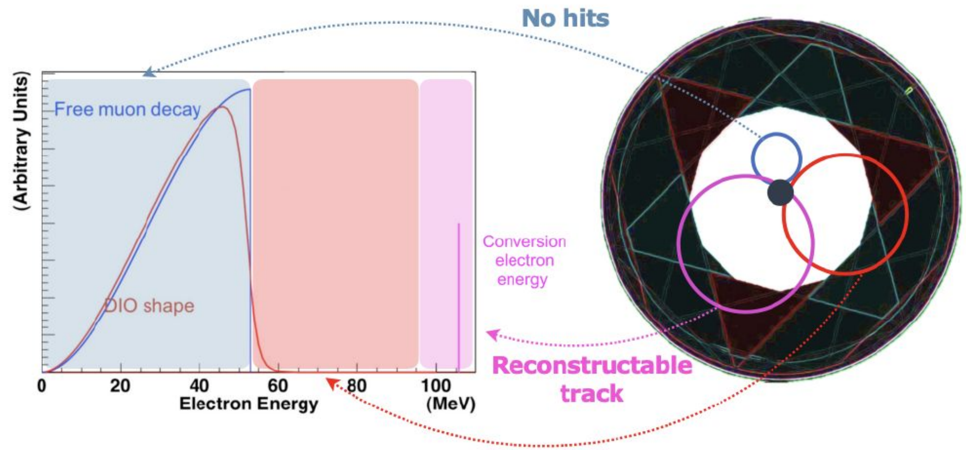

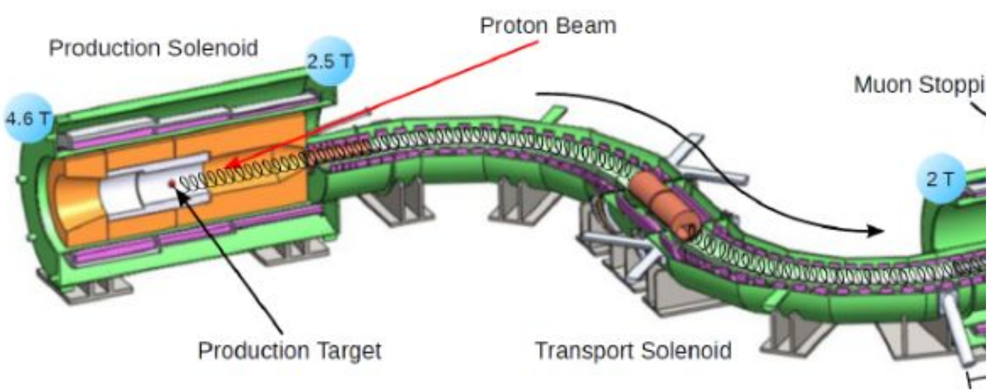

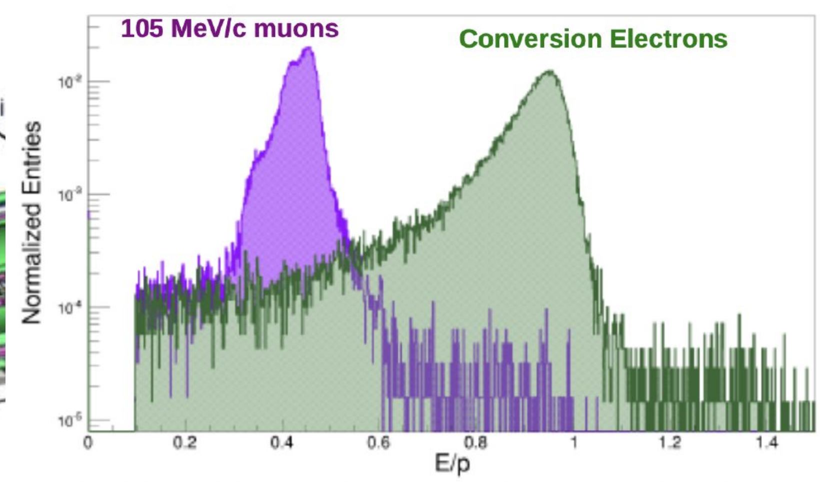

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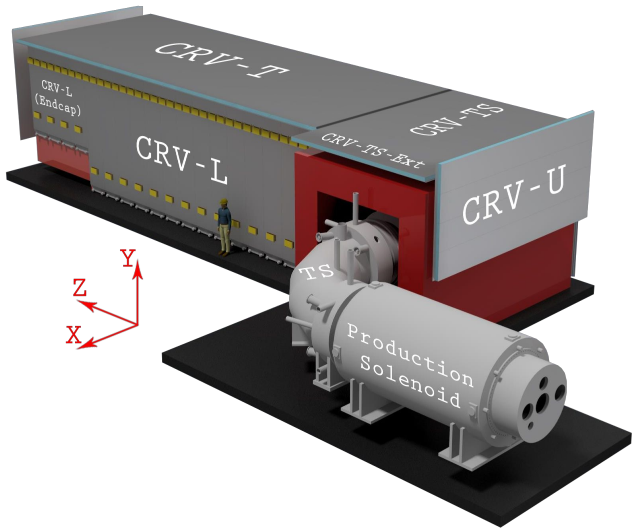

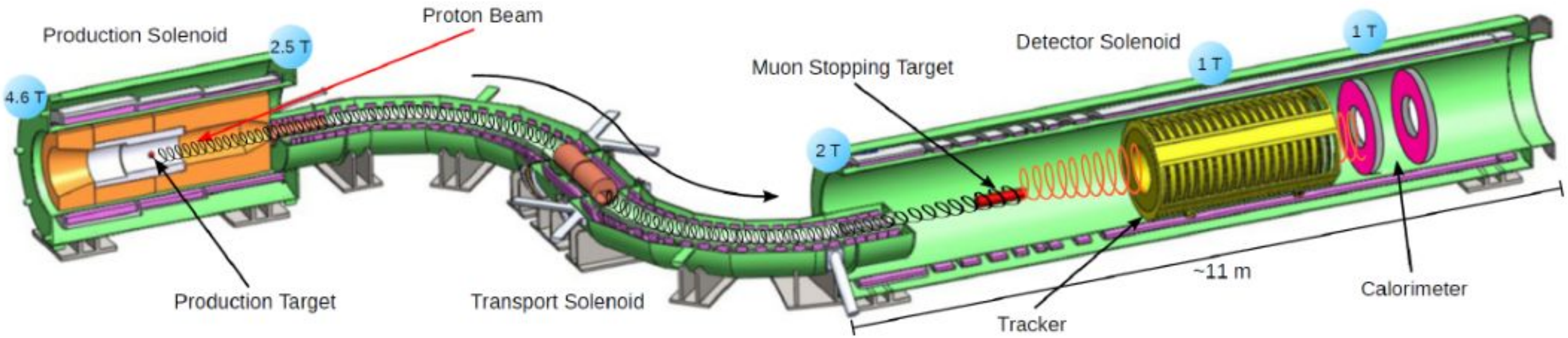

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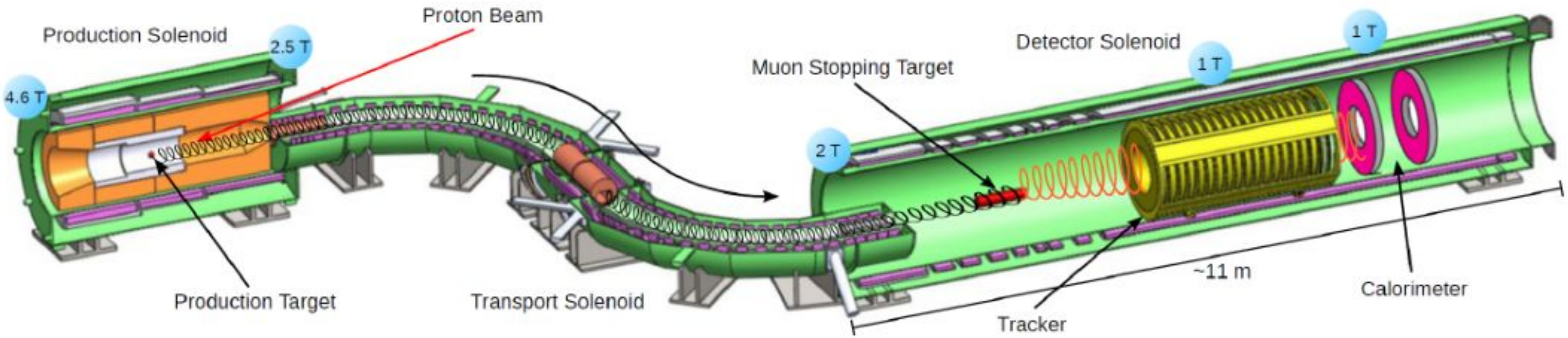
Mu2e (FNAL): **$\mu^- Al \rightarrow e^- Al$**

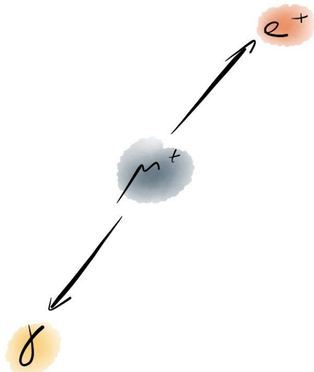
- Transport solenoid **separating production and stopping** target
- Stopping target in front of detector section (tracker + calorimeter)
- Cosmic Veto

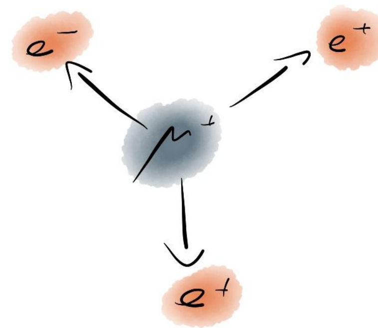
- Phase I
  - $\mathcal{R}(\mu Au \rightarrow eAu) \sim 6\times10^{-16}$ at 90% CL
- Phase II
  - 10x more protons with PIP-II
  - Detector upgrades
  - $\mathcal{R}(\mu Au \rightarrow eAu) \sim 6\times10^{-17}$ at 90% CL

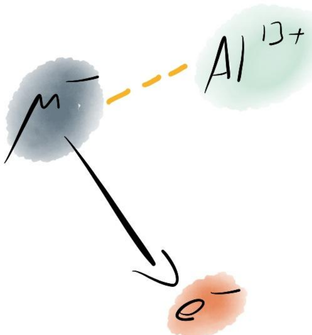


cLFV Muon Experiments Summary

cLFV with Muons: Golden Channels







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

- Monoenergetic e^+, and γ, back-to-back
- Background from accidental combinations

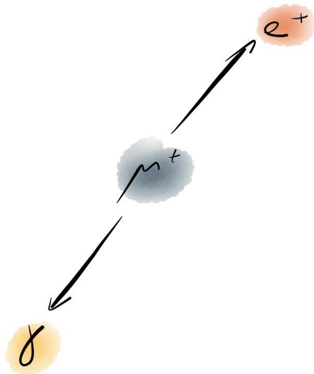
$\mu^+ \to e^+e^-e^+$

- Invariant mass of $e^+e^-e^+ = m_\mu$
- $\boldsymbol{\sum p_e = 0}$
- Background from $\mu^+ \to e^+e^-e^+\nu\bar{\nu}$ and accidental combinations

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

- Mono-energetic e^-
- Background from decay in orbit, antiprotons, pions, cosmics

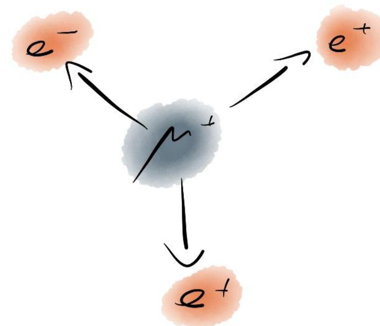
cLFV with Muons: Golden Channels



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

- Continuous high-rate μ^+ beam
- Experiment with high resolution in
  - γ energy
  - e^+ momentum
  - Relative timing $e^+ \gamma$
  - Opening angle $e^+ \gamma$

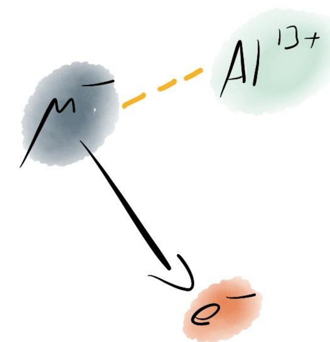
MEG / MEG II @ PSI



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

- Continuous high-rate μ^+ beam
- Experiment with high resolution in
  - $e^{+/-}$ momentum
  - $e^+e^-e^+$ vertex position $\Rightarrow$ minimize material
  - Relative timing $e^+e^-e^+$

Mu3e @ PSI

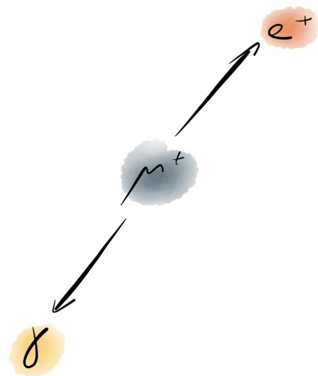


$\mu^-N \rightarrow e^-N$

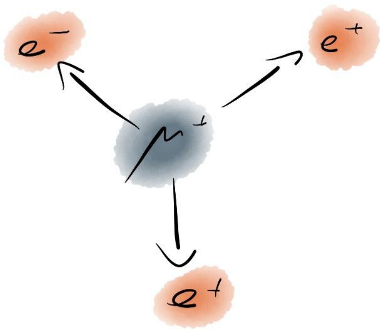
- Pulsed high-rate μ^- beam
- Experiment with high suppression of beam-related bkg
  - Long lifetime muonic atoms
  - Transport sections

COMET @ J-Parc
Mu2e @ FNAL

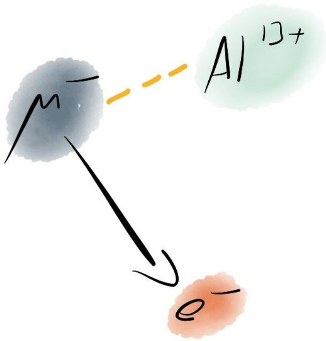
cLFV with Muons: Golden Channels



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



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



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

	$\mu^+ \rightarrow e^+\gamma$	$\mu^+ \rightarrow e^+e^-e^+$	$\mu^- N \rightarrow e^- N$
Now	$\mathcal{B}(\mu \rightarrow e\gamma) < 2.2\times10^{-13}$ at 90% CL MEG II @ PSI (2025)	$\mathcal{B}(\mu \rightarrow eee) < 1.0\times10^{-12}$ at 90% CL SINDRUM @ PSI (1988)	$\mathcal{R}(\mu Au \rightarrow eAu) < 7\times10^{-13}$ at 90% CL SINDRUMII @PSI (2006)
Future	MEG II is in operation $\mathcal{B}(\mu \rightarrow e\gamma) < 6\times10^{-14}$	Mu3e @ PSI $\mathcal{B}(\mu \rightarrow eee) < 10^{-15}$ to 10^{-16}	Mu2e @ Fermilab and COMET@J-PARC $\mathcal{R}(\mu N \rightarrow eN) < 10^{-15}$ to 10^{-17}

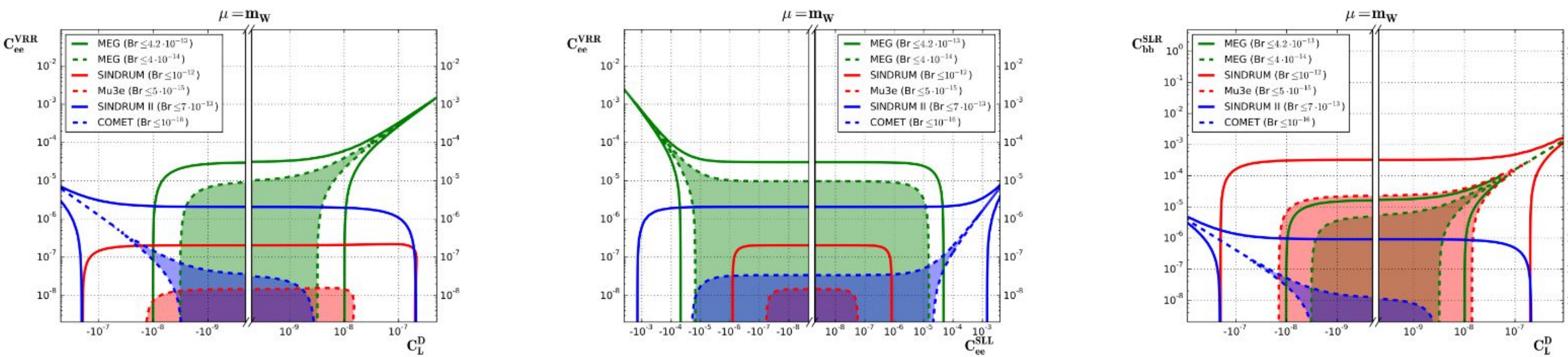
What would we learn if we see something?

What if we see something?

› Each of the cLFV muon channels has specific **strengths** and **weaknesses**
Use **combination** to pin down type(s) of **BSM** interaction

› Tool of choice: **Effective field theories**

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum \mathcal{O}_{5\text{-dim}} + \frac{1}{\Lambda^2} \sum \mathcal{O}_{6\text{-dim}} + \ldots$$

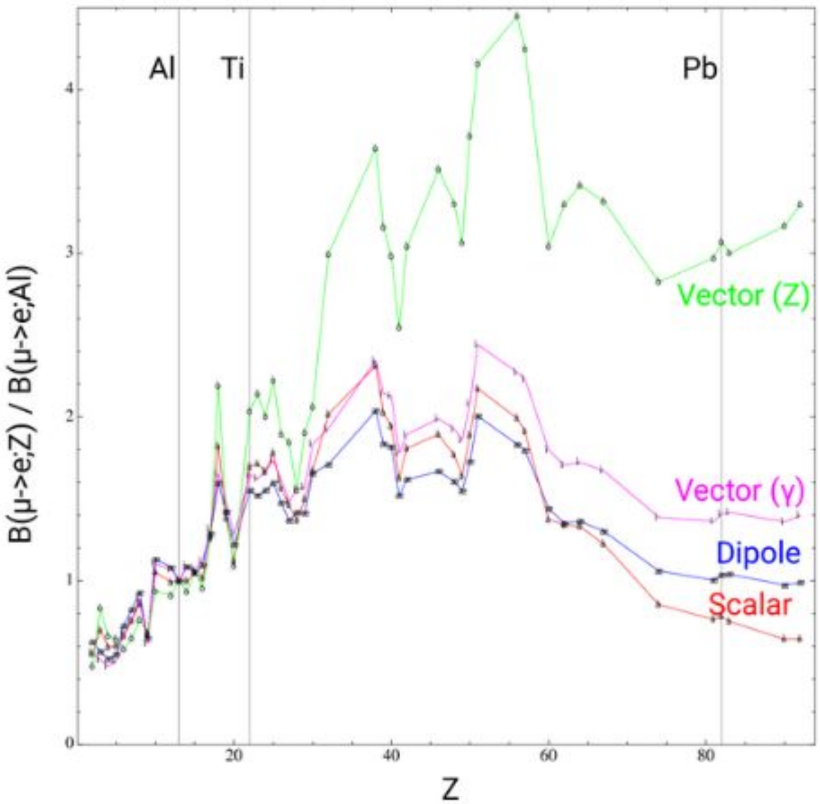


Crivellin, Davidson, Pruna, Signer, JHEP 05 117 (2017)

What if we see something?

- **μN→eN** conversion mediated via different potential **BSM interactions** shows **dependence on target material** N
- Repeat experiment with different target materials

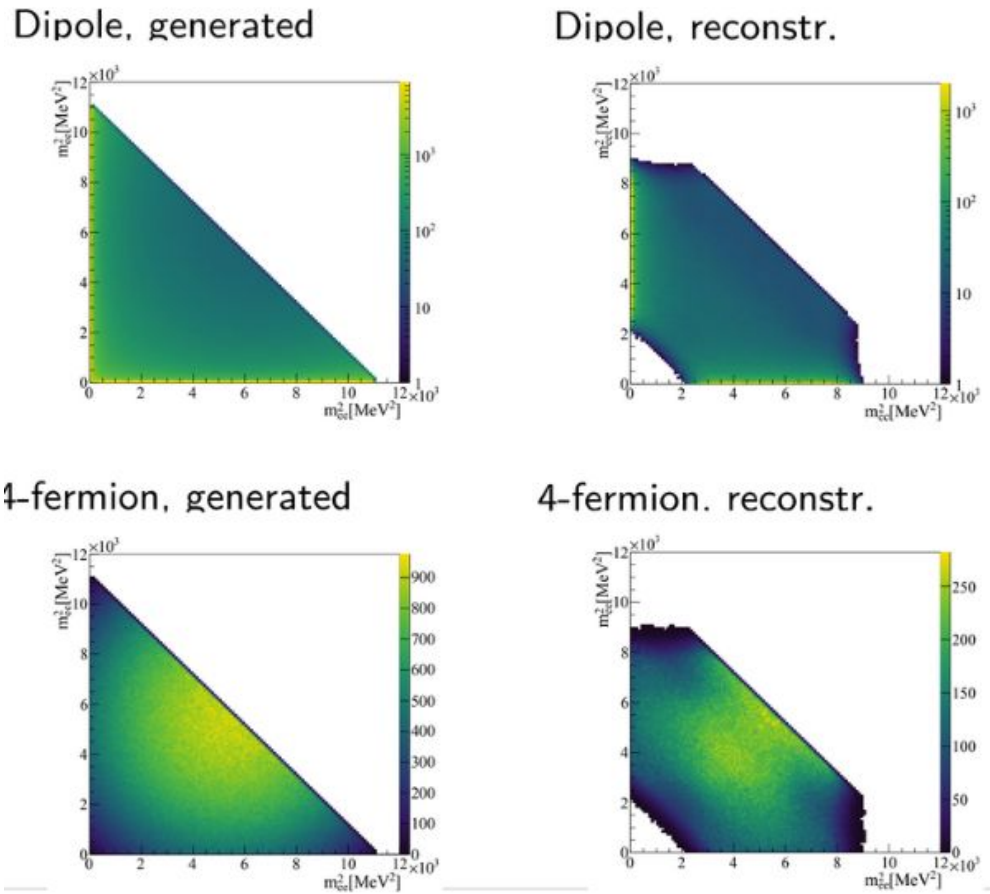
- Limited choice of target materials: Ti, V, Li (in Mu2e)
- Years of beam time per target



adapted from Cirigliano, Kitano, Okada, Tuzon, arXiv:0904.0957

What if we see something?

- Exploit the **three-body** kinematics of **μ→eee**
  - Resonance in e^+e^-/e^+e^+?
  - Asymmetry ratios
  - Dalitz plots



Summary

Summary

- High-precision searches for cLFV muon transitions
  - High-intensity muon beams
  - Dedicated experiments
  - Test BSM at high mass scales
- Highest discrimination power when all channels are combined
- Limits will improve by
  1 to 4 orders of magnitude
  within the next ~10 years

Backup


electron
e⁻
tau
τ
muon-neutrino
muon
μ
electron-neutrino
tau-neutrino

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