

LEVERHULME TRUST \_\_\_\_\_



# MEG-2, Mu3e, Mu2e charged Lepton Flavor Violation experiments

Fedor Ignatov

Particle Physics Annual Meeting Liverpool, 23 May 2025

### charged Lepton Flavour Violation search

- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale
- Charged lepton favour violation: NOT yet observed
- An experimental evidence of cLFV at the current sensitivities will be a clear signature of New Physics

#### SM with massive neutrinos (Dirac)

 $B(\mu \rightarrow e\gamma / eee) \sim 10^{-54}$ 

 $B(\mu \rightarrow e\gamma / eee) \sim 10^{-13} - 10^{-18}$ 

BSM



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v oscillations

W

μ

Vu

### 80 year of cLFV

L.Calibbi and G.Signorelli, Riv.Nuovo Cim. 41 (2018) 2, 71-174



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# Muon intensity/precision frontier facilities



# Paul Scherrer Institute (PSI) experiments



# **MEGII** experiment



#### Ke detector

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

CDCH

I GE AL

pTC

1 71-191

LXe inside

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WaveDREAM

rough

waveform digitizer

RD

# Tracking in DCH of MEGII

Liverpool responsibility:

tracks pattern recognition algorithms

<u>MEG DCH Operation under high hit rate</u> Hit rate up to 1.2 MHz per cell at 5×10<sup>7</sup> s<sup>-1</sup> beam rate: 25% cell occupancy in 250ns.

Higher occupancy than in Alice TPC or Belle2 CDC MEGII CDCH 9 layers vs 159 rows 56 layers MEG2 Track Finding is harder

Needs stereo view + 4D reconstruction (stereo DCH + t0 for each track)

PR based on conventional Kalman filter track following method

ML: Transformer + GNN as additional prefilter are under development by collaboration



### **MEGII** experiment



# MEGII result 2021+2022 runs



### X17 boson search

#### Search for the X17 particle in <sup>7</sup>Li(p,e<sup>+</sup>e<sup>-</sup>)<sup>8</sup>Be processes with the MEG II detector

![](_page_10_Figure_2.jpeg)

<sup>7</sup>Li $(p, e^+e^-)^8$ Be studied at  $E_p = 450, 650, 800, 1100 \text{ keV}$ 

 $e_{+}/e_{-}$  energy sum and angular correlation  $\Theta$ 

 Internal Pair Conversion (IPC) distribution shows excess at
 *Θ*~140° at several beam energies

decay of a light particle

best fit  $m_X = 16.95 \text{ MeV/c}^2$  $BR(X) = 6 \times 10^{-6}$ 

#### MEGII unblinded analysis at 13 November 2024

No significant signal observed ATOMKI result was excluded at 94%

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MEGII dedicated X17 runs using CW proton beam

![](_page_10_Figure_12.jpeg)

# Mu3e Experiment (PSI)

### Liverpool Mu3e experiment team

Staff members:

- Joost Vossebeld (head of the Mu3e group, Pixel Detector coordinator)
- Helen Hayward
- Nikos Rompotis
- Paolo Beltrame (Data & MC Manager)
- Mark Wang
- Matthew Brown (technician)

#### PhD students:

- Charles Kinsman (year 3)
- Jak Woodford (started Oct 2024)

#### Master and BSc students:

- Dan King (Mphys)
- Ting Chan (BSc)

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Kameron Vickers (BSc)

**Official Collaboration roles in red** 

![](_page_11_Picture_17.jpeg)

Thanks to Mu3e team for providing the slides

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https://www.psi.ch/en/mu3e

### Mu3e Detector

![](_page_12_Figure_1.jpeg)

### **Detector construction status**

#### 12.05.2025 • PSI Lab News

#### Mu3e craned into the magnet for June test run

The Mu3e detector was craned from the staging area to the piE5 beam area, where it plan to take beam with final detector elements from all three subdetectors in June.

Mu3e Vertex Detector : The first HVMAPS tracking detector with MuPix11 on beam this June

![](_page_13_Picture_5.jpeg)

Next year Vertex, SciFiber ~ half of Outer Pixel Tracker, SciTile modules

![](_page_13_Figure_7.jpeg)

![](_page_13_Picture_8.jpeg)

# **Pixel Activities at Liverpool**

![](_page_14_Picture_1.jpeg)

84 pixel 86 pixel 86 pixel

![](_page_14_Picture_3.jpeg)

MuPIX: High Voltage Monolithic Active Sensors, pixels and the detector electror integrated into the same chip

Liverpool is responsible for the MuPix11 Quality Test of the External Layers (together with the Oxford University)

All individual MuPix sensors to be qualified before ladder construction (gluing)  $\Rightarrow \sim 10000$  sensors to be tested

• One complete set up for the QC

• Probe Station from *SemiProbe Incorporated* 

PC with Intel® Arria10 FPGAs board
Front-End Board and probe card from the Mu3e collaboration

![](_page_14_Figure_10.jpeg)

Layer

![](_page_14_Picture_12.jpeg)

# Physics, Performance & Software

### Alternative track reconstruction

![](_page_15_Figure_2.jpeg)

# Momentum resolution of tracks with missing hits

![](_page_15_Figure_4.jpeg)

### GPU-based reconstruction performance

#### Jak Woodford

Track reconstruction on GPU compared with the offline implementation of the algorithm

![](_page_15_Figure_8.jpeg)

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### Physics, Performance & Software

### Data quality check tool

Liverpool is responsible in developing and maintaining a tool that compares MC and data samples to a reference to identify differences from version to version

N Rompotis, P Beltrame, Ting Chan (BSc student)

Novel track finding algorithms

Graph Neural Nets

![](_page_16_Figure_6.jpeg)

Dan King (MPhys student), N Rompotis

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![](_page_16_Figure_8.jpeg)

#### Cellular automaton-based track finding

![](_page_16_Figure_10.jpeg)

#### Mark Wang

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# FermiLab muon camp

![](_page_17_Picture_1.jpeg)

# Mu2e experiment (Fermilab)

#### https://mu2e.fnal.gov/

### Liverpool Mu2e team

#### Staff members

- Themis Bowcock
- Joe Price (STM operations, Tracking)
- Laura Harkness-Brennan
- Dan Judson

#### **PDRAs**

New position available

#### PhD students

Sean Isaac (Starting Oct 2025)

![](_page_18_Picture_12.jpeg)

Thanks to Joe Price for providing the slides for Mu2e

### Mu2e general

Search for  $\mu$  e conversion in the field of a nucleus

![](_page_19_Figure_2.jpeg)

Signal: a mono-energetic electron **Requirements:** 

- High intensity (stop 10<sup>18</sup>) muons
- << 1 background event</li>

![](_page_19_Figure_6.jpeg)

First Cosmic data in hall for all detectors expected 2025

First physics Mu2e Run I in **2027**! (to improve the last Sindrum II sensitivity by a factor **10**<sup>3</sup>)

Further Mu2e Run II after PIP-II installation shut down ~2029 (to achieve the final 10<sup>4</sup> improvement goal) 20 **HEP annual**, Liverpool

### **Mu2e – System highlights**

3 Solenoids - Production (PS), Transport (Tsu, TSd), Detector (DS)

- TS fully tested and installed
- PS assembly completed, leak testing installation imminent
- DS leak testing thermal shields, installation late summer 2025

![](_page_20_Picture_5.jpeg)

![](_page_20_Picture_6.jpeg)

![](_page_20_Picture_7.jpeg)

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### **Mu2e – Detector status**

Detectors being installed in Mu2e hall

- STM (HPGe and LaBr) installation complete
- Cosmic Ray Veto (CRV) installation complete
- Calorimeter installing into hall as we speak!
- Tracker: not installed...

...All 20,736 straws and 216 panels produced, all 36 planes assembled. QC and Leak testing ongoing

installation this fall (autumn)

![](_page_21_Picture_8.jpeg)

![](_page_21_Picture_9.jpeg)

### **Stopping Target Monitor**

- Stopping Target Monitor (STM) provided by Liverpool
- STM determines the overall rate for normalisation (N<sub>captures</sub>)
- Count characteristic γ- and x-rays
- UK leads the Stopping Target Monitor (STM) detector group
- Org. chart roles in operations and commissioning of STM
- STM at Fermilab 
   <sup>©</sup> ready for integration with other detectors and main DAQ
- Shipped "spare" to FNAL early 2025

![](_page_22_Picture_8.jpeg)

![](_page_22_Picture_9.jpeg)

![](_page_22_Figure_10.jpeg)

![](_page_22_Figure_11.jpeg)

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# Outline

Exciting time for charge Lepton Flavour Violating processes search!

MEGII final result in 3-4 years

Mu3e will go to test run at beamline for the first time in few weeks

Mu2e / COMET are in the final stage of assembly in ~ 2 years start collecting data

Liverpool participates in most muon experiments

cLFV limits reduction by 3-4 orders of mangnitude is on the way!

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# Backup

# MEG2 CDCH

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![](_page_25_Picture_1.jpeg)

![](_page_25_Figure_2.jpeg)

Dimensions: Long-narrow shape with large stereo angles Small cell size (6.6-9 mm)

US endplate

200

hi Entries Mean x Mean y Std Dev x Std Dev y

# MEG2 Tracking

- 1. Hit detection from the waveform data
- 2. Track finding

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3. Operation under high hit rate

![](_page_26_Figure_4.jpeg)

![](_page_26_Figure_5.jpeg)

# MEGII X17 search

Best fit on X17 signal is 0 events with an expectation on of 100 events

![](_page_27_Figure_2.jpeg)

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![](_page_28_Picture_0.jpeg)

#### Latest Mu2e collaboration meeting photo (February 2024)

![](_page_28_Picture_2.jpeg)

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