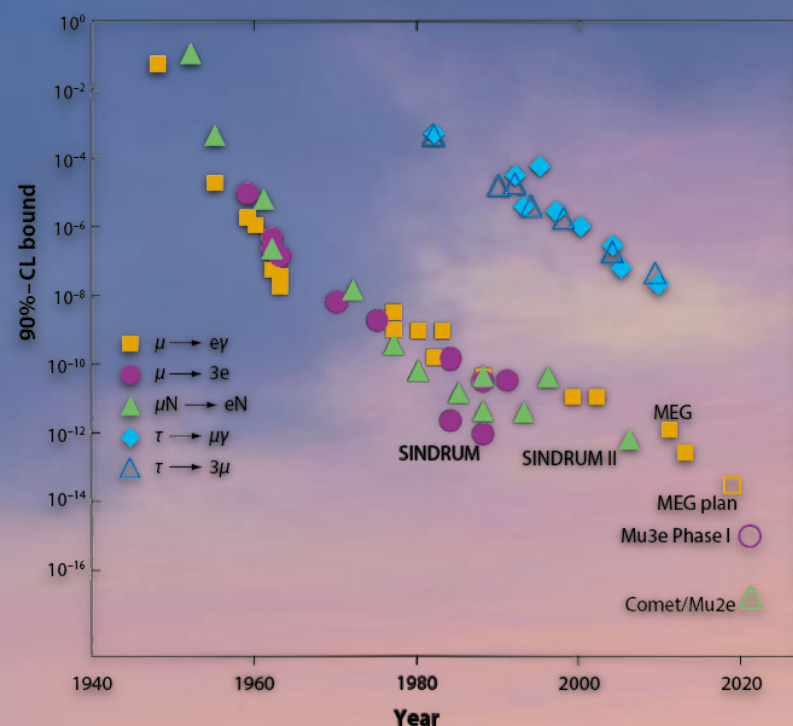


CLFV2026

5th International Conference on Charged Lepton Flavor Violation

Sapienza Università di Roma, June 17-19, 2026



Conference Summary

Hajime Nishiguchi,



KEK / J-PARC



CLFV2026

 60 Participants

 27 Oral Contributions, 16 Posters

The Landscape of CLFV2026

 7 Sessions : Theoretical perspectives (3 talks), CLFV with muons (4), CLFV without muons (5), EDM and muon $g-2$ (4), Other experiments (2), Future Facilities and Experiments (6) and Dark Matter Searches (3)

— Session 1 —

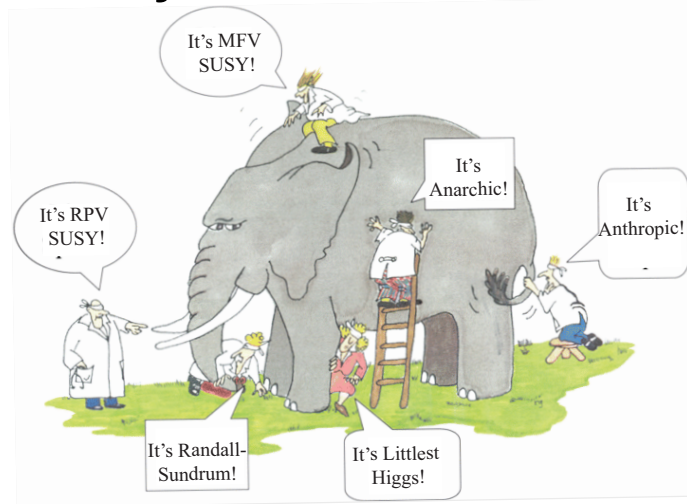
Theoretical Perspectives

- 🔊 Theory Overview
- 🔊 Grobal cLFV constraints
- 🔊 New exotic muon decays



What kind of BSM Physics?

- You don't *directly* access the new particle in a low-energy CLFV process.
- Must draw inferences.
- Need multiple measurements in different channels and correlations between them to understand the underlying new physics.
- Closely related to other important questions:
 - Neutrino mass generation
 - Baryogenesis
 - Flavor puzzle
 - Dark matter
 - $g-2$, EDM,

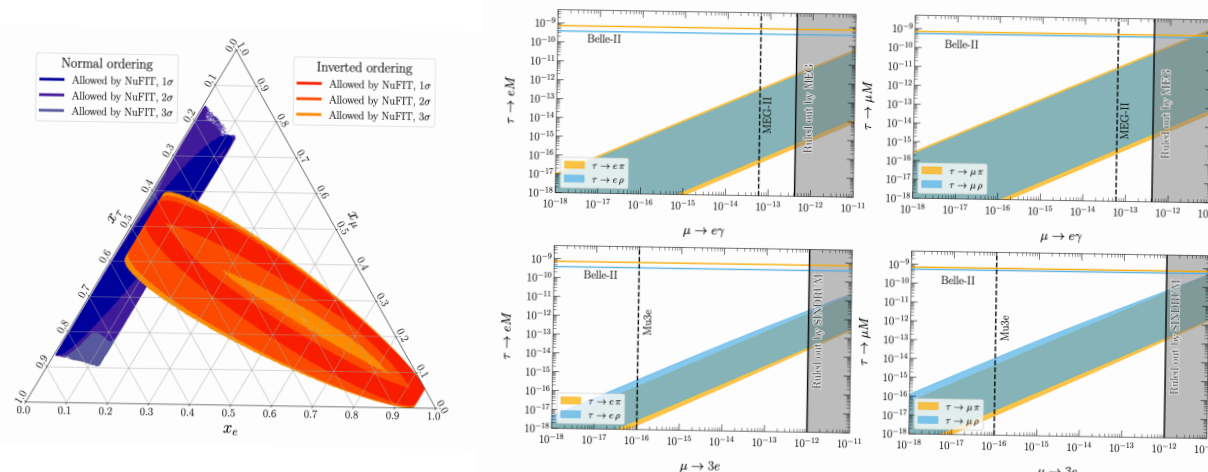


R. Bernstein, PASCOS 2016

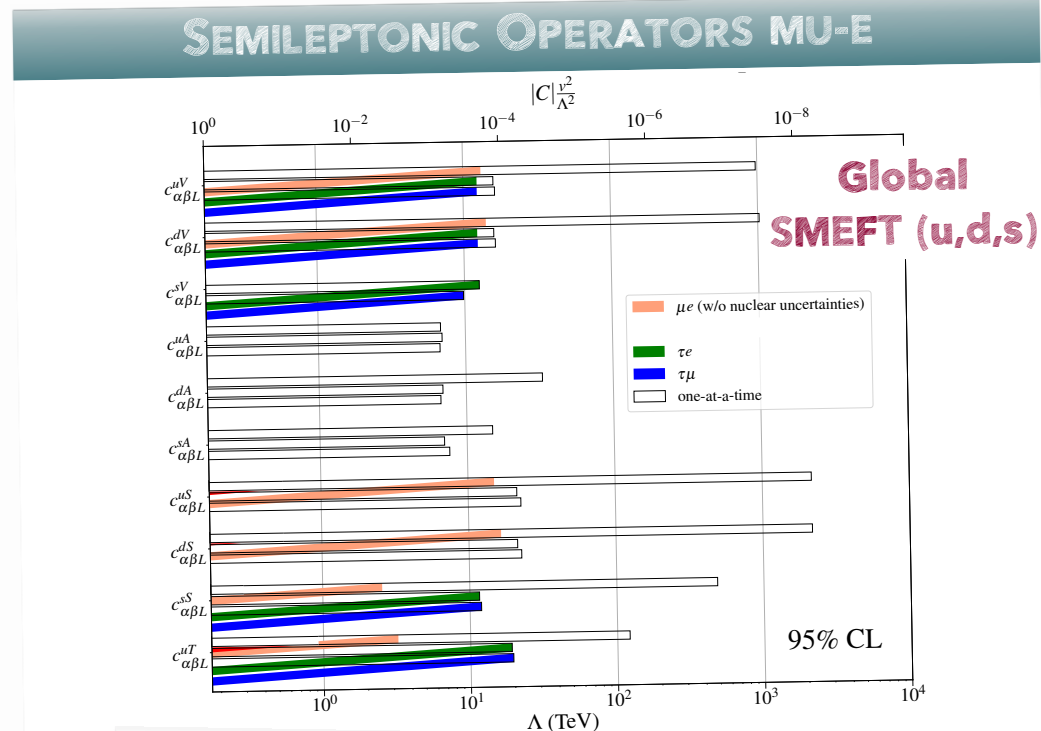
Discovery is not the end of the story

- Many possible BSM origins
- Channel correlations are crucial
- Complementarity is essential

Correlations between CLFV Rates



Urquía-Calderón, Ruchayskiy, 2511.20320

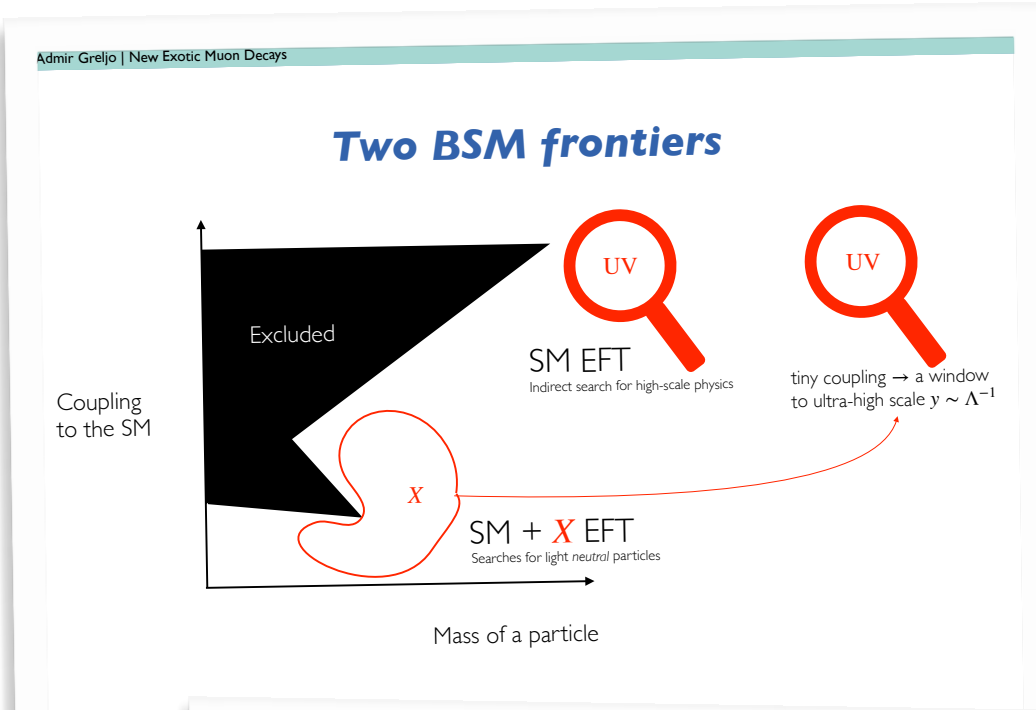


One-at-a-time limits are not the whole story

- Strong correlations among operators
- Flat directions still survive
- More observables are needed

SUMMARY

- Very strong cLFV bounds when consider each operator at a time
— bounds ($\mu \rightarrow e$) $\gg$ bounds ($\tau \rightarrow \ell$)—
- Global picture changes things for semileptonic operators:
 - ◆ Flat directions in $\tau\ell$ sectors for A, S, P
— only the simplest SMEFT(u,d) fully constrained—
 - ◆ Strong impact in the μe sector
— bounds ($\mu \rightarrow e$) $\sim$ bounds ($\tau \rightarrow \ell$)—
- Nuclear uncertainties have a key role
— bounds ($\mu \rightarrow e$) $\ll$ bounds ($\tau \rightarrow \ell$)—
- More observables are need to globally constrain the full parameter space
— neutrino oscillation for $\mu - e$ —



Exotic signatures are a new frontier

- Light particles can evade SMEFT expectations
- Higher-multiplicity decays remain unexplored
- Exotic channels may compete with golden modes

Admir Greljo | New Exotic Muon Decays

Signature-driven approach

AG, Palavric, Tunja, Zupan; 2510.08674

$e \backslash \gamma$	0	1	2	3	4
1	e	$e\gamma$	$e2\gamma$	$e3\gamma$	$e4\gamma$
3	$3e$	$3e\gamma$	$3e2\gamma$	$3e3\gamma$	...
5	$5e$	$5e\gamma$	$5e2\gamma$	...	
7	$7e$	$7e\gamma$	...		
9	$9e$	...			

- Missing energy?
- Prompted/displaced?

Several higher-multiplicity decays are unexplored: MEG II, Mu3e?

Q: Are there consistent BSM where higher-multiplicity compete with (or dominate over) the lower-multiplicity?

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- Theory Outlook -

The story is richer than it seems

- Many possible BSM origins remain viable
- Interpretation requires complementary probes
- New signatures may lie beyond traditional searches

— Session 2 —

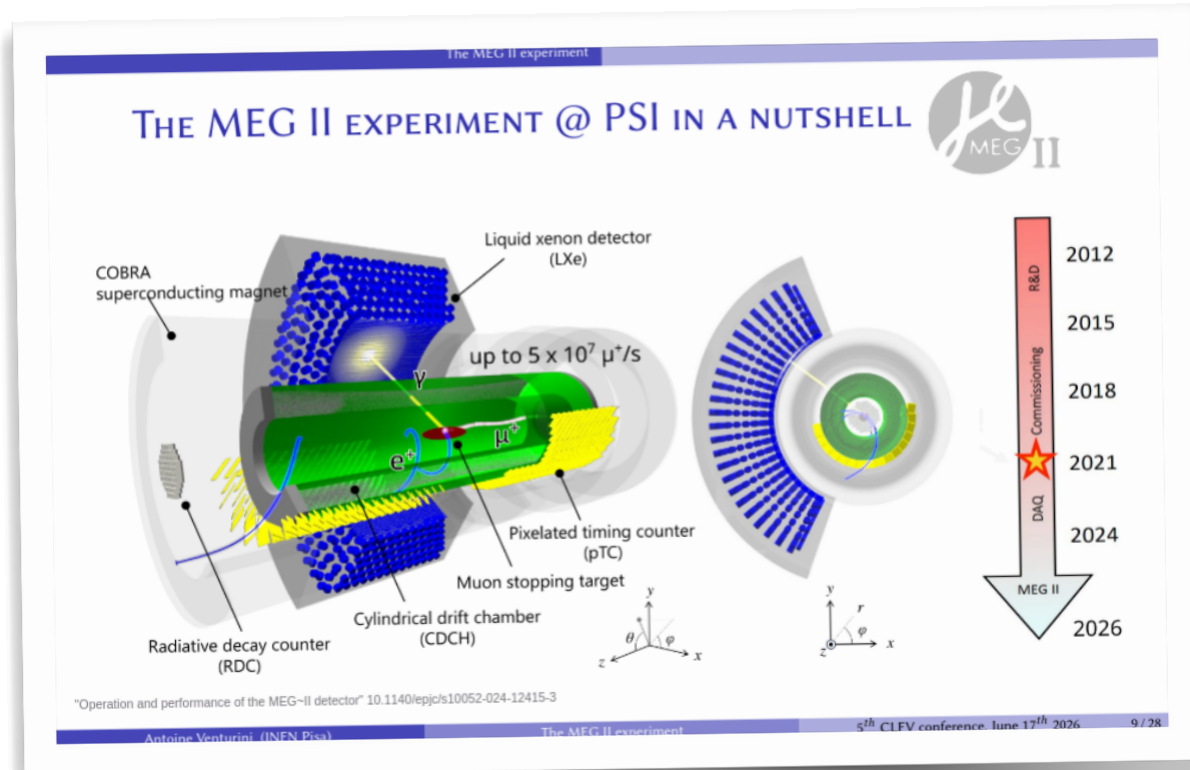
CLFV with muons

- Status of the MEG II
- Status of the Mu3e
- Status of the Mu2e
- Status of the COMET



Status of the MEG II Experiment

A. Venturini

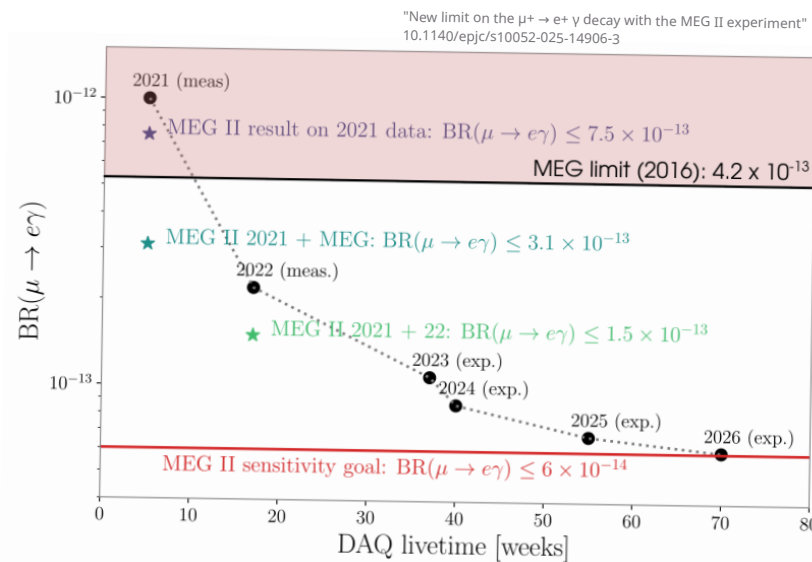


MEG II is delivering physics

- Detector performance is well established
- Data taking and analysis are progressing steadily
- Final sensitivity is within reach

MEG II: PRESENT STATUS AND FUTURE

- ▶ **Most stringent limit on this decay**
 $BR(\mu^+ \rightarrow e^+ \gamma) \leq 1.5 \times 10^{-13}$
- ▶ Result published in 2025
- ▶ **Working on the analysis of 2023 and 2024 dataset** and a lot more data to be analyzed and collected
- ▶ MEG II final goal sensitivity within reach:
 $BR(\mu^+ \rightarrow e^+ \gamma) \leq 6 \times 10^{-14}$



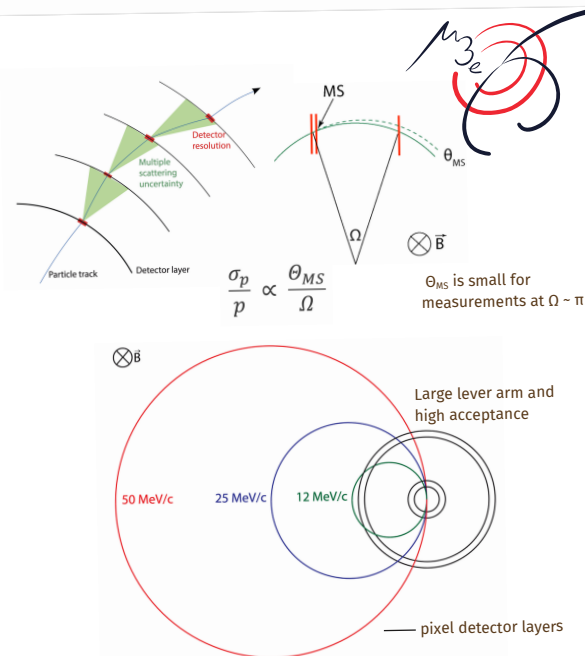
Status of the Mu3e Experiment

T. Kar

Mu3e Tracking Concept

Need very good momentum and vertex resolution

- Tracking in a homogeneous B-field of 1 T
- High granularity pixel ($80 \times 80 \mu\text{m}^2$) tracker: 3D space point
- Tracking in a multiple scattering dominated environment
 - Ultra-thin pixel tracker with only four layers
 - Gaseous helium environment
- Optimise for precision and acceptance (momentum)



17.06.2026, CLFV2026

Tamasi Kar, PI Heidelberg

Page 10

Mu3e is moving beyond commissioning

- Innovative detector concept has been validated
- Detector performance is under control
- Physics data taking is the next step

Vertex Detector Performance

Hit Maps of Layer 1 and Layer 2 of the vertex detector

- All 108 (50 μm) Mupix11 chips installed
 - 4 chips: mechanical damage before installation
 - 12 chips: unstable
 - 10 chips: lost before/during the operation
 - A few others: link instabilities or inefficient



Many lessons learned!



17.06.2026, CLFV2026

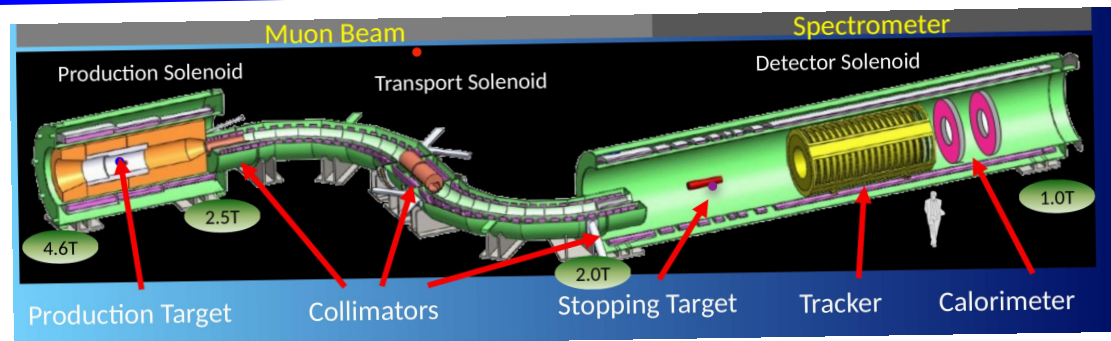
Tamasi Kar, PI Heidelberg

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Status of the Mu2e Experiment

Y. Oksuzian

Mu2e Apparatus



► Interactive 3D Animation of the Mu2e Apparatus

- Every 1695 ns, 8 GeV protons hit production target to produce π^- ; π^-/μ^- reflected toward transport solenoid
- Transport Solenoid (TS) delivers π^-/μ^- to Detector Solenoid, and TS selects momentum & charge, avoids direct line of sight
- Muons stop on Al Stopping Target; $>30,000 \mu^-$ stop every $1.7 \mu\text{s}$
- Conversion electron momentum, energy and timing measured in tracker and calorimeter

U.S. Department of Energy
Argonne National Laboratory is a U.S. Department of Energy Laboratory managed by UChicago Argonne, LLC

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Argonne

The Mu2e apparatus is coming together

- Major detector systems are taking shape
- The final solenoid is nearing completion
- A 3-month beamtime is planned for 2027

Detector Solenoid Progress (at the Vendor)

- DS is the largest of the three Mu2e solenoids; houses the stopping target, tracker and calorimeter, and bends conversion-electron trajectories for the momentum measurement
- **Fabrication essentially complete**; cryogenic (N_2/He) lines passed final leak test
- Remaining: end-gusset weld (after leak-tight declaration) → cold test at 4 K → **ship Jul 2026** (if all OK)



Chimney complete; solenoid ends dry-fit



4x welding setup (Apr 2026), at the vendor

U.S. Department of Energy
Argonne National Laboratory is a U.S. Department of Energy Laboratory managed by UChicago Argonne, LLC

18/37

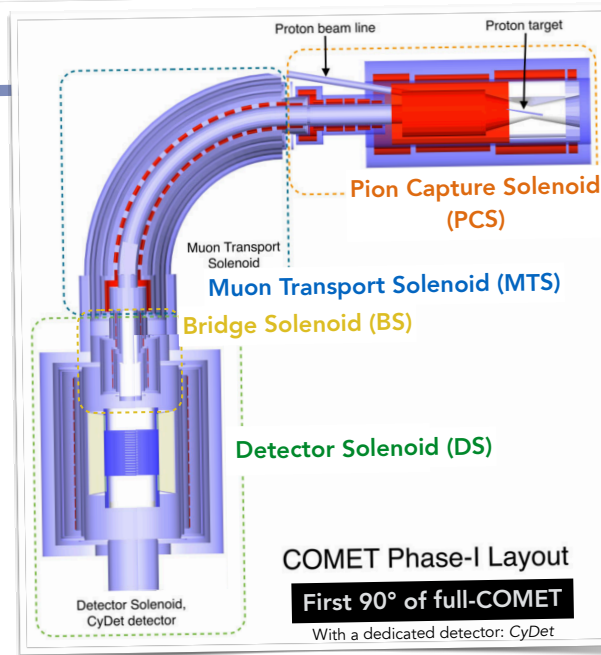
Argonne

Status of the COMET Experiment

R. Nagai

COMET Phase-I

- Physics search with $SES \sim 10^{-15}$ with a **dedicated** detector
- Furthermore,
 - Measure muon beam characteristics to reduce beam-related syst. uncertainties
 - Validate detector performances for Phase-II
- B-fields from the solenoids are partially overlapped
→ integrated field control is one of the keys



Ryo Nagai (UOsaka)

CLFV 2026 @ Rome

17 June 2026

5

COMET is preparing for a controlled start

- Beam performance is being validated
- Detector systems are coming together
- Integrated commissioning is coming into view

Installation of DS

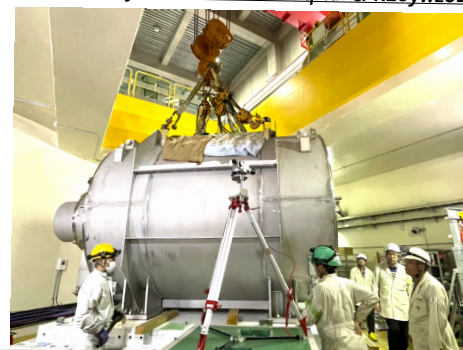
- Installation in the COMET Hall was completed in Nov. 2025
- Ready for the (integrated) B-field measurement and the detector installation!



<https://youtu.be/y7w5exfLMx4?si=9qHu7cPR23yww6BK>



Ryo Nagai



- CLFV with muons -

**A new era of muon CLFV searches
is beginning**

- MEG II is delivering physics
- Mu3e, Mu2e, and COMET are advancing rapidly
- Multiple complementary searches will operate this decade

— Session 3 —

CLFV without muons

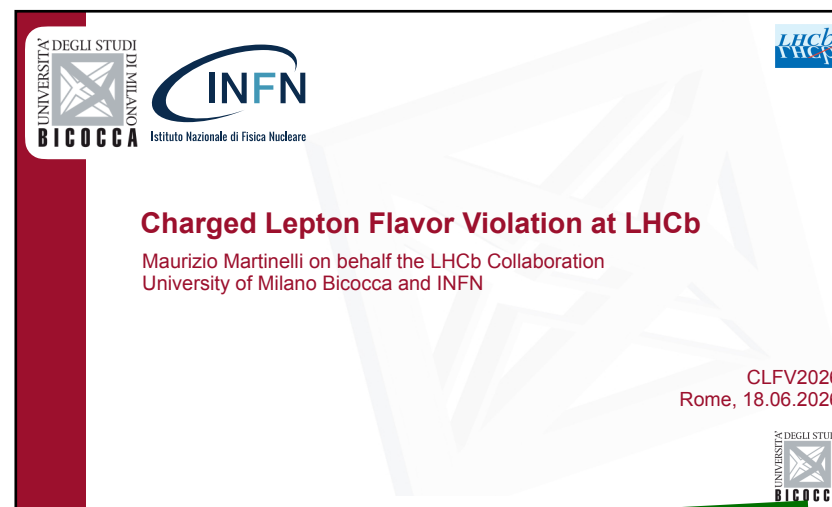
- CLFV at ATLAS/CMS
- CLFV at LHCb
- CLFV at Belle II
- CLFV at BES-3
- CLFV at IceCube



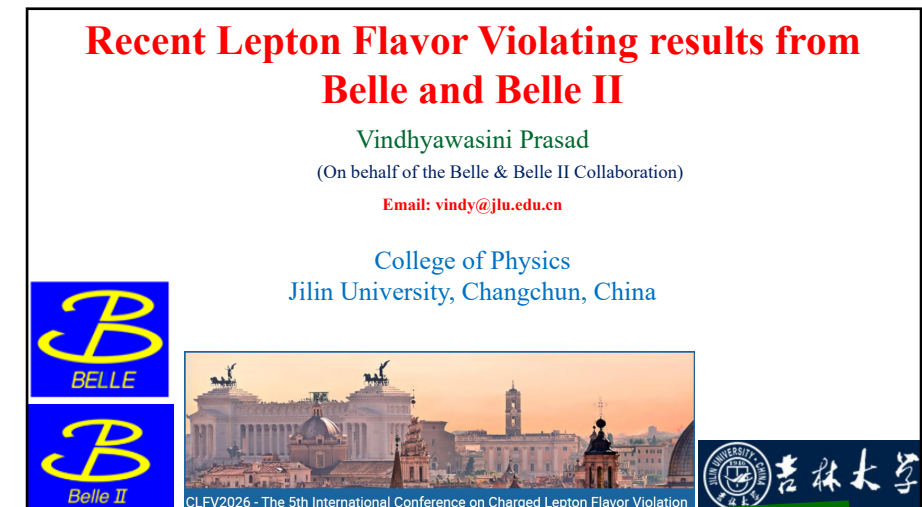
- CLFV without muons - CLFV is being explored across many frontiers



Energy Frontier



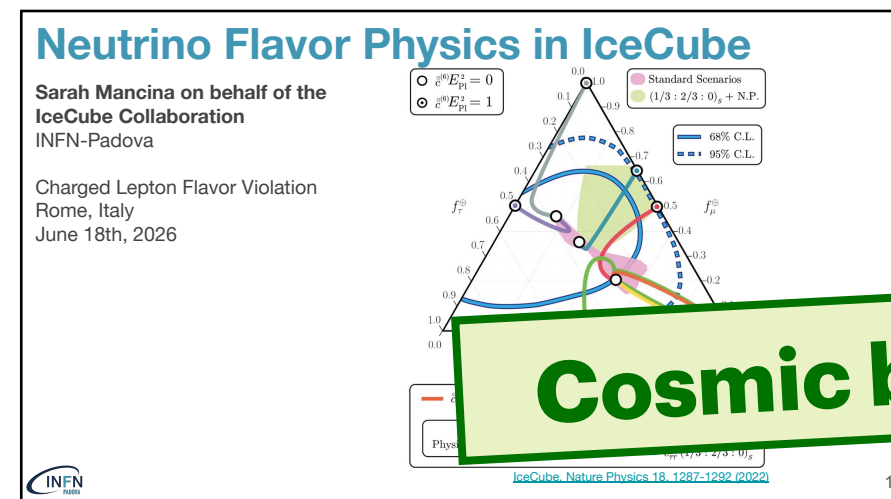
Heavy Flavour



Tau Factory



Threshold Machine



Cosmic baseline

CLFV searches at ATLAS/CMS

P. Verwilligen

ATLAS & CMS Operations & Data-Taking

■ LHC Operations

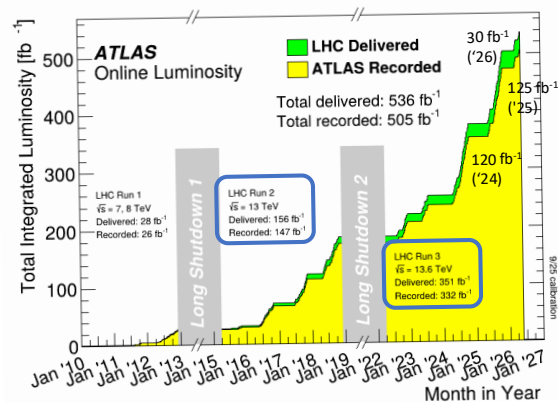
- 12 years of pp collisions (2010 – 2026)
- Record performance in the last 3 years (2024-26)
- LHC Phase-1 concluded - ready to move to Phase-2

■ ATLAS & CMS

- Operating at 2x design luminosity $\mathcal{L}$ - PU 64
- Overall recording 95% of delivered lumi $\mathcal{L}$
- 120 fb⁻¹ ('24) + 125 fb⁻¹ ('25) + 30 fb⁻¹ ('26)

■ Physics Analyses

- Full Run-2 (~140 fb⁻¹)
- Early Run-3 (~70 fb⁻¹)
- Full Run-3 (~320 fb⁻¹)



Piet Verwilligen

CLFV searches in ATLAS & CMS – CLFV Roma 2026

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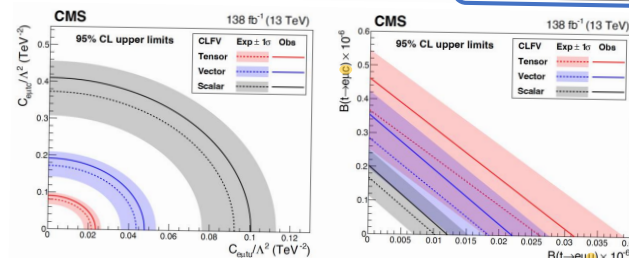
LHC provides an energy-frontier view of CLFV

- Huge datasets enable rare top and tau searches
- Top decays directly probe heavy-flavor CLFV
- $\tau \rightarrow 3\mu$ remains a powerful benchmark channel

CLFV search in $\mu e t q$ vertex

- No excess observed
 - Limits on Wilson Coefficients converted to limits on Branching Ratio
- Most stringent limits on $\mathcal{B}(t \rightarrow e\mu q)$ today
 - $\mathcal{B}(t \rightarrow e\mu q) < 0.4 \cdot 10^{-6} - 1.0 \cdot 10^{-8}$ - $\mathcal{O}(10)$ improvement

CLFV coupling	Lorentz structure	$C_{eqtq}/\Lambda^2 (\text{TeV}^{-2})$		$\mathcal{B}(t \rightarrow e\mu q) \times 10^{-6}$	
		Exp. (68% CL range)	Obs.	Exp. (68% CL range)	Obs.
$e\mu u$	Tensor	0.022 (0.018–0.026)	0.024	0.027 (0.018–0.040)	0.032
	Vector	0.044 (0.036–0.054)	0.048	0.019 (0.013–0.028)	0.022
	Scalar	0.093 (0.077–0.114)	0.101	0.010 (0.007–0.016)	0.012
$e\mu c$	Tensor	0.084 (0.069–0.102)	0.094	0.396 (0.272–0.585)	0.498
	Vector	0.175 (0.145–0.214)	0.196	0.296 (0.203–0.440)	0.369
	Scalar	0.385 (0.318–0.471)	0.424	0.178 (0.122–0.266)	0.216



Piet Verwilligen

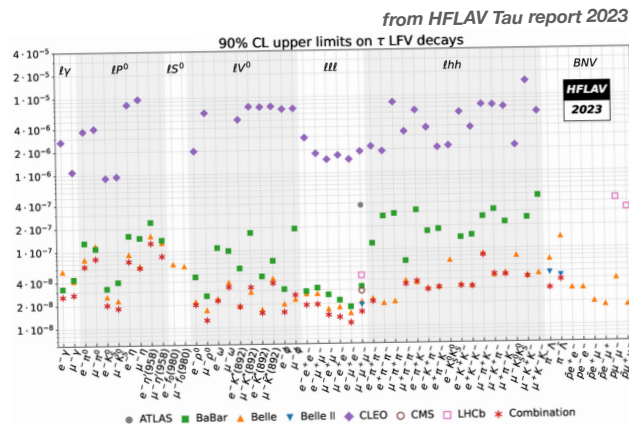
CLFV searches in ATLAS & CMS – CLFV Roma 2026

p. 11

CLFV in τ decays

Several Opportunities

- Many decay modes
- Different experiments
- LHCb well placed thanks to
 - Excellent PID and tracking
 - Large τ production through heavy flavor decays
- Unfortunately, large *charm* decays background limits LHCb sensitivity to many modes



Searches for CLFV: $\tau \rightarrow \mu^+ \mu^- \mu^+$

Maurizio Martinelli - cLFV @ LHCb | 18.06.2026

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LHCb exploits heavy-flavor production for CLFV searches

- Large τ samples arise from heavy-flavor decays
- Excellent vertexing and PID enable challenging searches
- Sophisticated analysis techniques suppress large backgrounds

LHCb Analysis Strategy

Data

- Run2 (2016-2018 - 5.4/fb)

Search

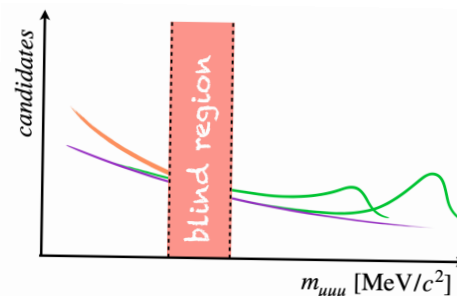
- Performed in $|m(\mu^+ \mu^- \mu^+) - m_\tau| < 20 \text{ MeV}/c^2$

Main Backgrounds

- Random combinations of μ (combinatorial)
- Misidentified hadrons (e.g. $D_{(s)}^- \rightarrow \pi^- \pi^+ \pi^-$ decays)
- Real 3μ final states from $D_s^- \rightarrow \eta(\mu^- \mu^+ \gamma) \mu^- \nu_\mu$ decays

Signal Extraction

- Background suppression through muon identification and kinematic selection
- Signal/Background separation via two multivariate classifiers
- Fit on categories for signal yield estimate and normalised to $D_s^- \rightarrow \phi(\mu^- \mu^+) \pi^-$ for upper limit estimate



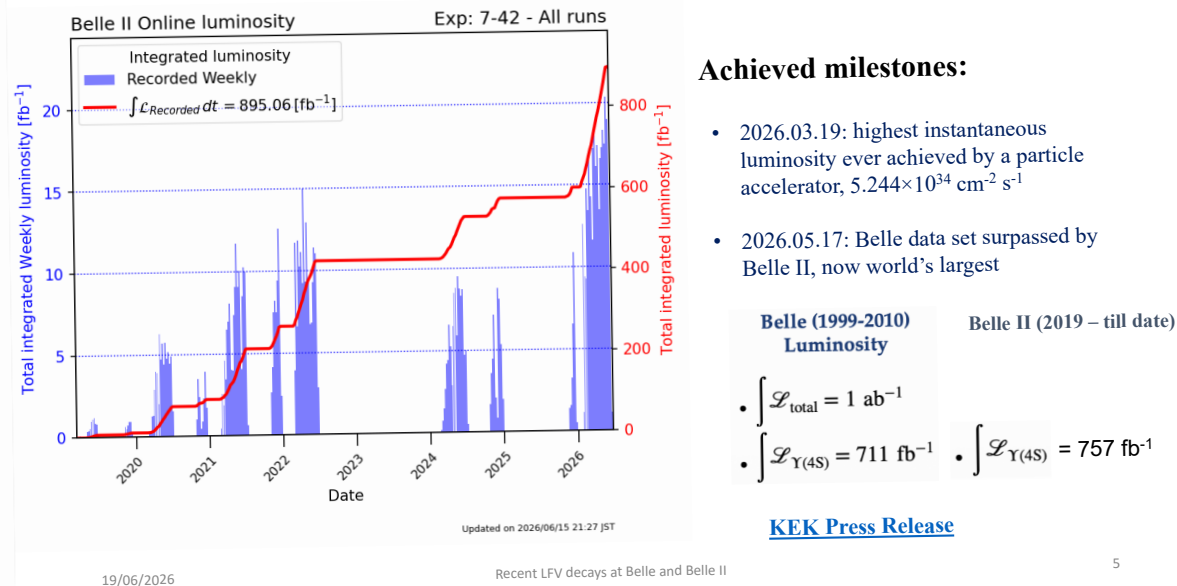
Searches for CLFV: $\tau \rightarrow \mu^+ \mu^- \mu^+$

Maurizio Martinelli - cLFV @ LHCb | 18.06.2026

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Recorded integrated luminosity



Belle II is becoming the τ -LFV frontier

- Belle II now exceeds the Belle dataset
- Multiple τ -LFV channels are entering the precision era
- Sensitivity is expected to improve rapidly with luminosity



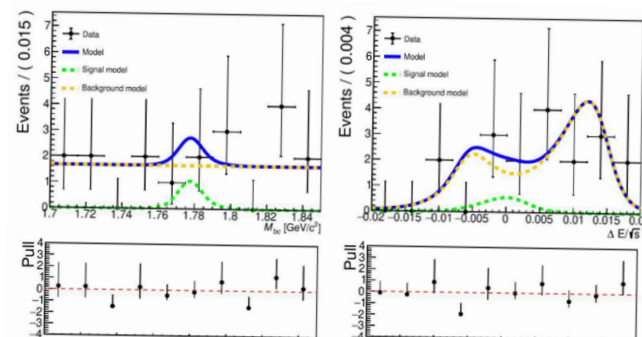
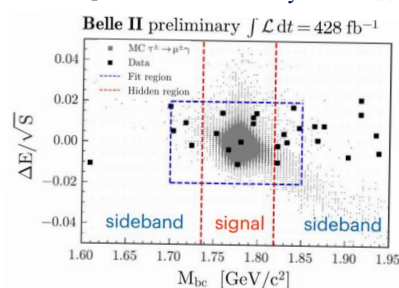
Search for LFV $\tau^- \rightarrow \mu^- \gamma$

- Extract signal from unbinned ML 2D fit
 - 15.7 ± 3.4 background events expected, 18 events observed
- Fit result for signal is consistent with zero
 - Set 90% CL upper limit:

$$B(\tau \rightarrow \mu \gamma)^{\text{exp}} < 5.8 \times 10^{-8}$$

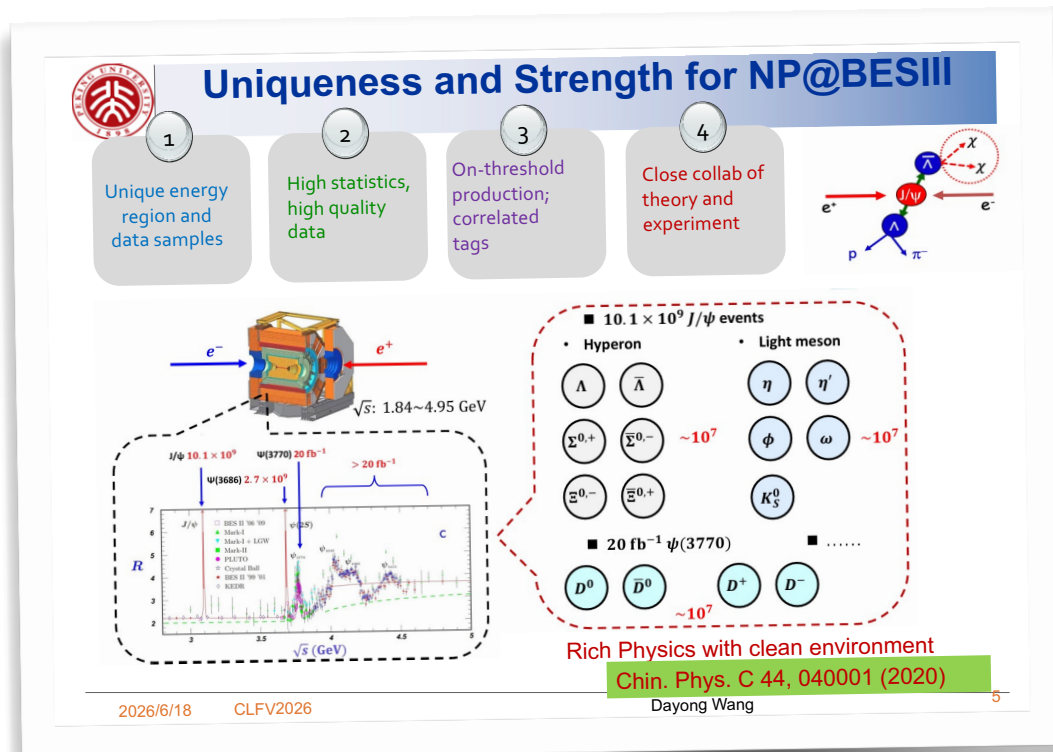
$$B(\tau \rightarrow \mu \gamma)^{\text{obs}} < 9.5 \times 10^{-8}$$

- Belle II measurement is statistically limited
 - higher efficiency and lower background rate than Belle
 - expect better sensitivity with 1 ab^{-1}



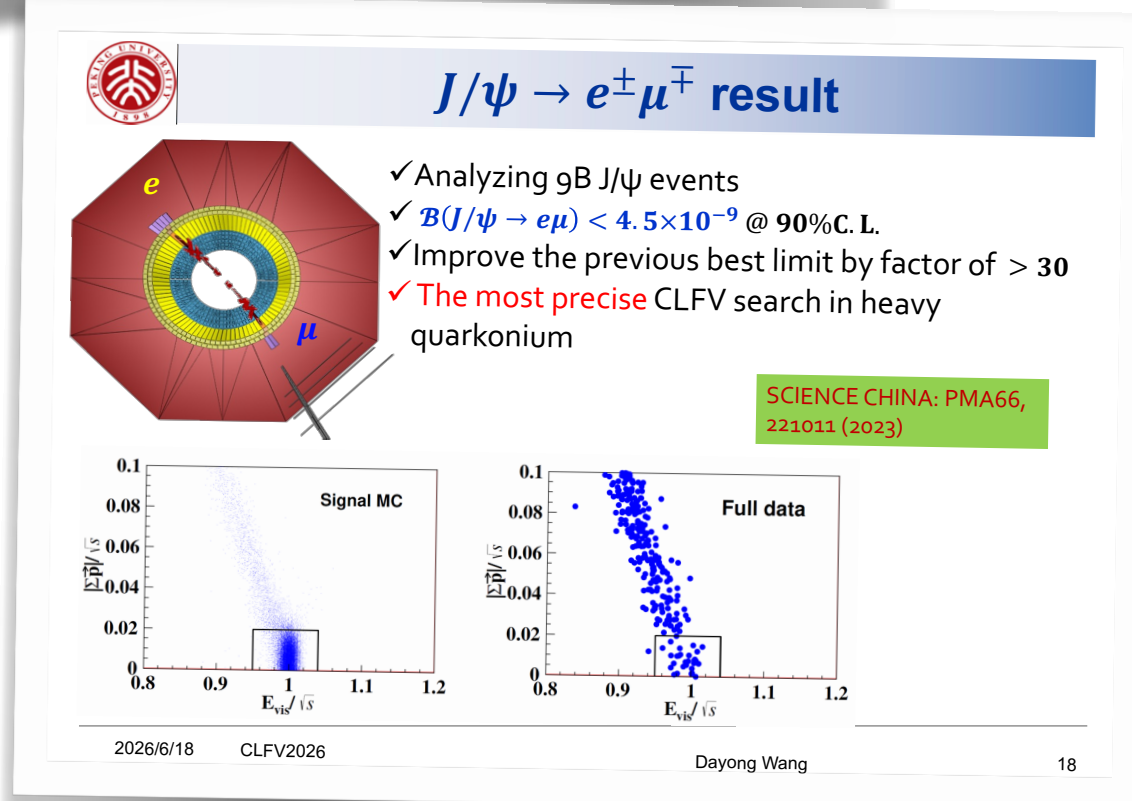
Recent LFV decays at Belle and Belle II

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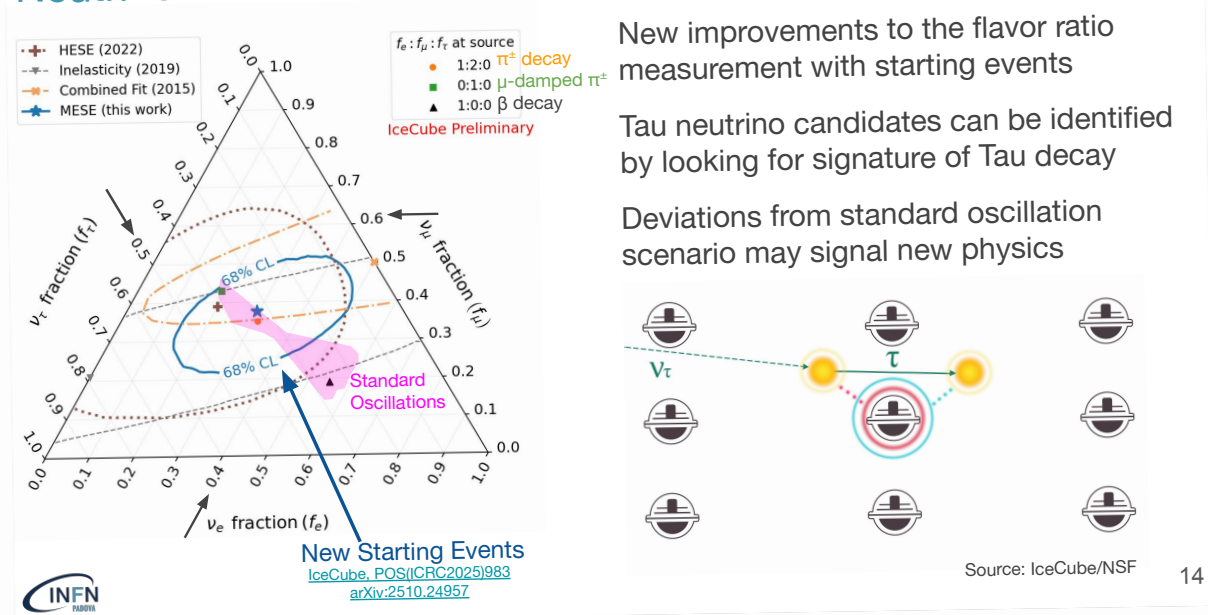


BES-III explores CLFV at the threshold frontier

- Threshold production provides uniquely clean environments
- Huge charmonium datasets enable rare CLFV searches
- BESIII accesses channels unavailable elsewhere



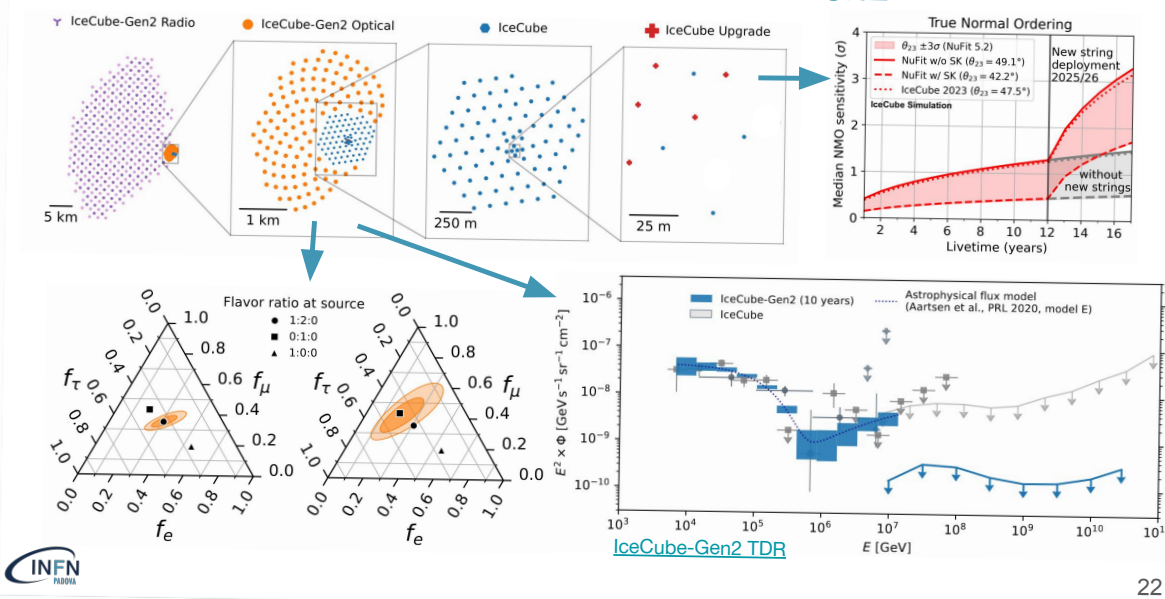
Neutrino flavor ratio measurements



IceCube uses cosmic neutrinos to probe flavor physics

- Flavor ratios test neutrino propagation over cosmic baselines

The next generation of IceCube: IceCube-Gen2



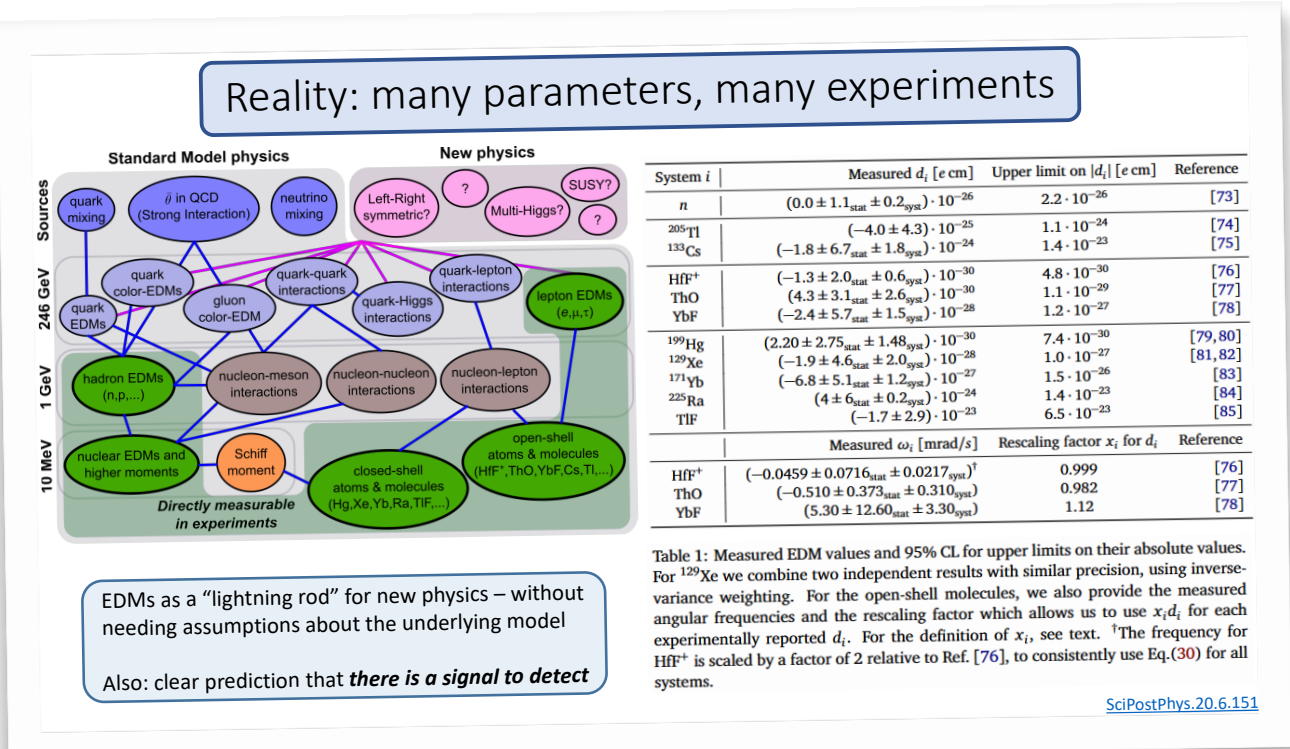
- Tau-neutrino identification strengthens sensitivity to new physics
- IceCube-Gen2 will extend the reach of flavor studies

— Session 4 —

EDM and Muon g-2

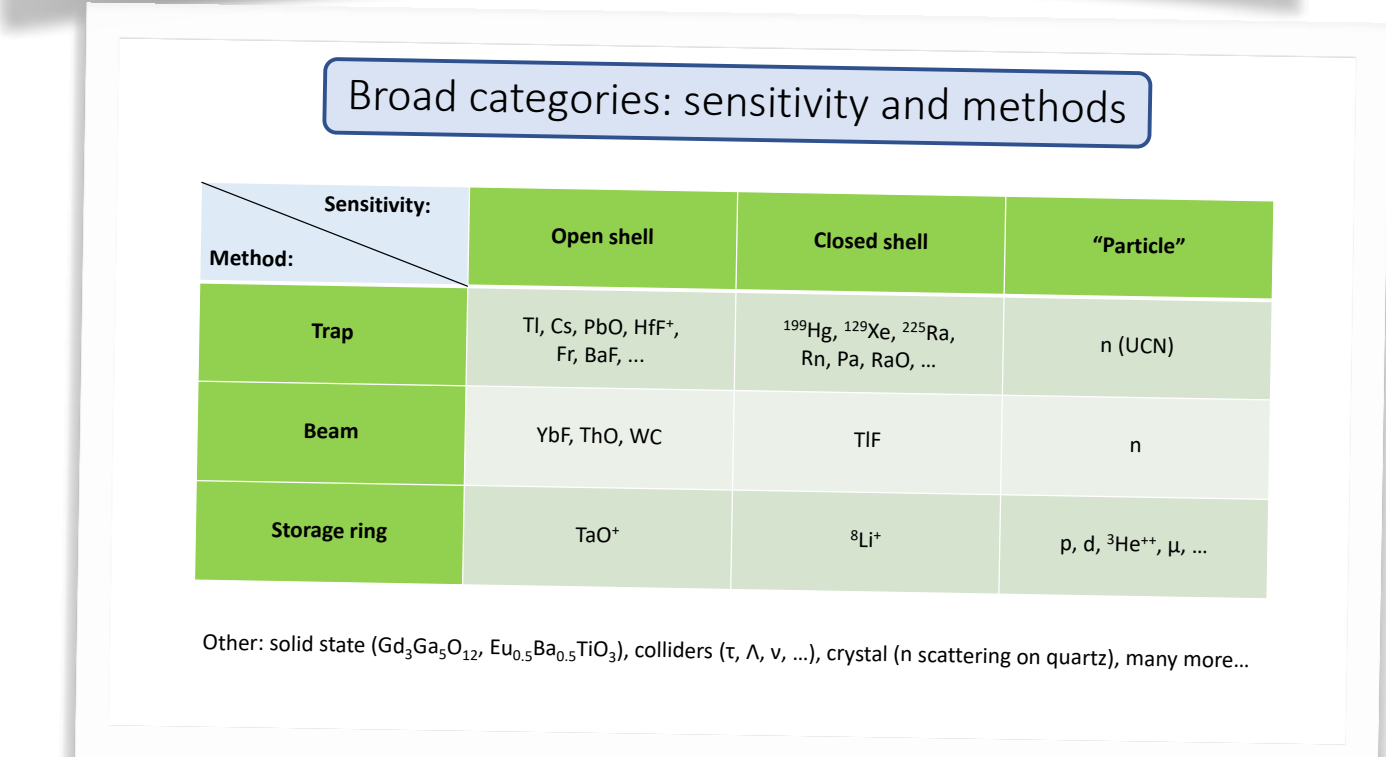
- Present/Future EDM
- Theoretical Perspective
- Results from FNAL g-2
- Status of J-PARC g-2





EDMs require many experiments and one global interpretation

- Different systems probe different CP-violating operators
- Complementarity is essential for interpretation
- Sensitivity continues to improve across many fronts



Electric Dipole Moments: Theoretical Perspective

M. Pospelov

Purcell and Ramsey (1949) (“How do we know that strong interactions conserve parity?” $\rightarrow |d_n| < 3 \times 10^{-18} \text{ ecm.}$)

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d \mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

$d \neq 0$ means that both P and T are broken. If CPT holds then CP is broken as well.

CPT is based on locality, Lorentz invariance and spin-statistics = very safe assumption.

search for EDM = search for CP violation, if CPT holds

Relativistic generalization

$$H_{\text{T,P-odd}} = -d \mathbf{E} \cdot \frac{\mathbf{S}}{S} \rightarrow \mathcal{L}_{\text{CP-odd}} = -d \frac{i}{2} \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi F_{\mu\nu},$$

corresponds to dimension five effective operator and naively suggests $1/M_{\text{new physics}}$ scaling. Due to $SU(2) \times U(1)$ invariance, however, it scales as m_f/M^2 .

Current limits translate to multi-TeV sensitivity to M.

4

New indirect constraints on muon EDM

- Owing to the fact that the electric field inside a large nucleus is not that small $eE \sim Z \alpha R_N^{-1} \sim 30 \text{ MeV}$ compared to m_μ , effects formally suppressed by higher power of m_μ win over three-loop electron EDM.

- **New results:**

Hg EDM experiment: $S_{199\text{Hg}}/e \simeq (d_\mu/e) \times 4.9 \times 10^{-7} \text{ fm}^2$, $|d_\mu| < 6.4 \times 10^{-20} \text{ e cm}$

ThO EDM experiment: $d_e^{\text{equiv}} \simeq 5.8 \times 10^{-10} d_\mu \Rightarrow |d_\mu| < 1.9 \times 10^{-20} \text{ e cm.}$

New limit from Boulder HfF: $\sim 9 \times 10^{-21}$

- Factor of 20 improvement over the BNL constraint, $|d_\mu| < 1.8 \times 10^{-19} \text{ e cm}$,
- New benchmark for the muon beam EDM experiments.

NB: 3-loop contributions calculated by Grozin et al. has been revised

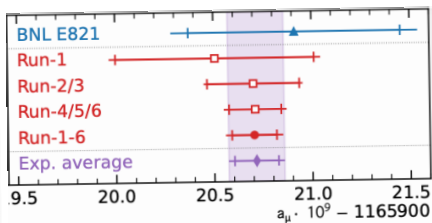
- Tau EDM is constrained by three-loop induced d_e .

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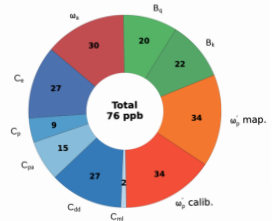
EDMs remain one of the most powerful probes of new physics

- No signal at the LHC increases the importance of indirect probes
- EDMs can probe CP-violating physics far beyond collider reach
- New indirect limits extend EDM sensitivity to heavy particles

The final Muon g-2 result



- New result from Run-4/5/6 data **reduced uncertainty by 1.8 times** over Run-1/2/3
- **Syst. Uncertainties:** Contribute roughly equally to total error



- **New FNAL $g - 2$ result for Run-4/5/6 in excellent agreement with Run-1/2/3**
 - **FNAL Runs 1-6 combination results:**
- $$a_\mu = 116592070.5(14.8) \times 10^{-11} \text{ (127 ppb)}$$
- **Combined FNAL and BNL results is the most precise measurement of a_μ :**

$$a_\mu = 116592070.5(14.8) \times 10^{-11} \text{ (127 ppb)}$$

$$a_{\mu}^{exp} = 116592071.5(14.5) \times 10^{-11} \text{ (124 ppb)}$$

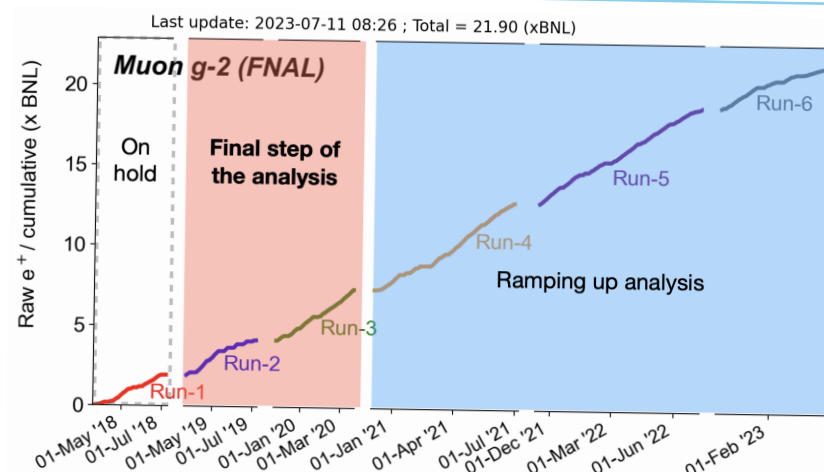
Run-4/5/6		
Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	...	114
ω_a^m (systematic)	...	30
C_e Electric Field	347	27
C_p Pitch	175	9
C_p Phase Acceptance	-33	15
C_{dd} Differential Decay	26	27
C_{ml} Muon Loss	0	2
$(\omega_p \times M)$ (mapping, tracking)	...	34
$(\omega_p \times M)$ (calibration)	...	34
B_k Transient Kicker	-37	22
B_q Transient ESQ	-21	20
μ_p / μ_B	...	4
m_μ / m_e	...	22
Total systematic for $\mathcal{R}_\mu$	...	76
Total for a_μ	572	139

A. Driutti (University & INFN Pisa)

CLFV2026 - June 18, 2026

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FNAL Muon EDM Analysis Plan



- **Run-1:** Analysis on hold due to faulty quad resistors;
- **Run-2/3:** blinded tracker analysis nearly completing (in collaboration review stage), results is expected for this year!
- **Run-4/5/6:** analysis started: final tracker + calo based analysis!

A. Driutti (University & INFN Pisa)

CLFV2026 - June 18, 2026

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The legacy of muon g-2 extends beyond a_μ

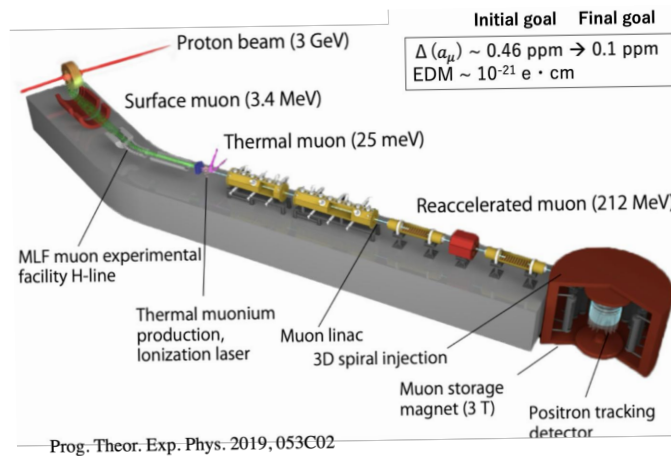
- The final FNAL result reaches 124 ppb precision
- Comparison with theory remains a central challenge
- The dataset enables EDM, CPT/LV, and dark matter searches

Status of muon g-2/EDM Exp at J-PARC L. Cotrozzi

E34 experiment at J-PARC

New features w.r.t. previous $g - 2$ experiments with «conventional» muon beams:

- **Low emittance** muon beam (1/1000)
- Muon acceleration to 212 MeV
- No strong focusing
- 3D spiral injection:
 - Spiral compressed by radial fields
 - Good injection efficiency (x10)
- Compact storage ring (1/20)
- Tracking detector
- Excellent sensitivity to muon EDM: about 100 times better than the previous limit (BNL)



L. COTROZZI – CLFV2026 CONFERENCE – 18/06/2026

5

J-PARC is building an independent path to muon precision physics

- Ultra-cold muons enable a fundamentally different approach
- A compact storage ring replaces electric focusing
- The design offers independent sensitivity to both $g-2$ and EDM

Towards a higher sensitivity

G. Venanzoni, PoS (EPS-HEP2025) 427 (2026)

	BNL E821	Fermilab E989	J-PARC E34
Muon momentum	3.09 GeV/c	3.09 GeV/c	300 MeV/c
Lorentz factor γ	29.3	29.3	~ 3
Muon lifetime in ring	64.4 μ s	64.4 μ s	6.6 μ s
Beam polarization P	$\sim 100\%$	97%	50%
Typical asymmetry A	0.40	0.40	0.40
Storage magnetic field B	1.45 T	1.45 T	3.0 T
Focusing method	Electrostatic	Electrostatic	Very weak magnetic
Ring diameter	14 m	14 m	0.66 m
Storage radius	711 cm	711 cm	33.3 cm
Cyclotron period	149 ns	149.1 ns	7.4 ns
Spin precession period T_{g-2}	4.37 μ s	4.40 μ s	2.11 μ s
Spin precession frequency ω_a	1.43 MHz	1.43 MHz	2.96 MHz
Detected positrons e^+	8.5×10^9	1.43×10^{11}	5.7×10^{11} (proj.)
Statistical goal (stat.)	460 ppb	100 ppb	450 ppb
Systematic goal (syst.)	280 ppb	80 ppb	< 70 ppb
Events in final fit N	5×10^9	1.5×10^{11}	5.7×10^{11}
EDM sensitivity (stat.)	0.2×10^{-19} e·cm	$O(10^{-21})$ e·cm	1.5×10^{-21} e·cm
EDM sensitivity (syst.)	0.9×10^{-19} e·cm	$O(10^{-21})$ e·cm	3.6×10^{-22} e·cm

Factors in $\frac{\delta\omega_a}{\omega_a}|_{stat}$:

$$\frac{1}{\omega_a \gamma \mu \tau P} \sqrt{\frac{2}{NA^2}}$$

From FNAL to J-PARC design:

- $\sqrt{N}$ increases 1.94x
- ω_a increases 2.06x
- P decreases 1.94x
- γ decreases 9.77x

L. COTROZZI – CLFV2026 CONFERENCE – 18/06/2026

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- EDM and muon $g-2$ -

Precision probes gain power through complementarity

- Different observables probe different new-physics effects
- Theory and experiment together shape the interpretation
- Independent approaches strengthen future discoveries

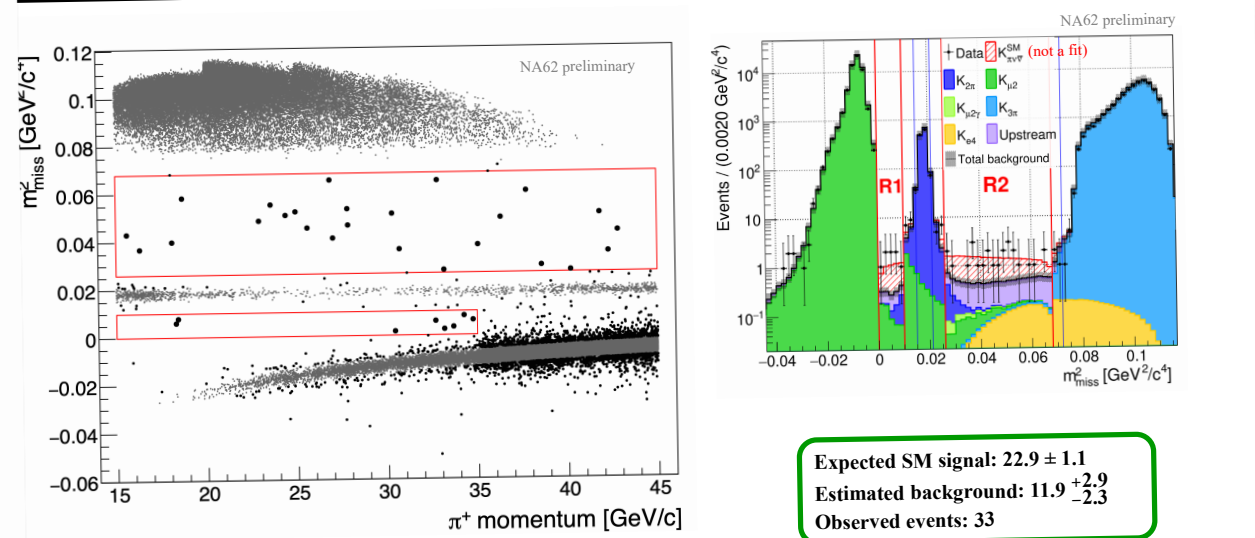
— Session 5 —

Other Experiments

- 📍 NA62
- 📍 PIONEER



Opening the box: 2023-2024 data



18/06/2026 M. Mirra

Recent results from NA62 experiment at CERN 14/25

NA62 is entering the precision era of rare kaon physics

- Rare kaon decays probe physics beyond the TeV scale
- NA62 now reaches $>5\sigma$ sensitivity to $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- The next dataset will further sharpen the picture

Summary and outlook

Using the 2016–2024 dataset, NA62 measured $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with a precision of about 20%.

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{2016-2024}^{NA62} = (9.6^{+1.9}_{-1.8}) \times 10^{-11}$$

The smallest decay BR measured with a 5σ significance. The ultimate goal is to reach a precision of approximately 15%.

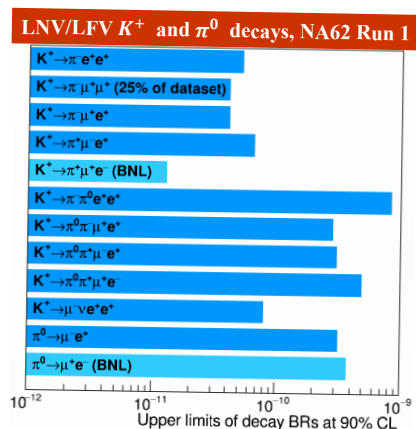
World's leading sensitivity to most LFV/LNV K^+ decays:

Run 1 results summary:

- ✓ LFV/LNV programme completed; best limits set for 10 decay modes.
- ✓ Sensitivity is not limited by backgrounds.

Prospects with Run 2 dataset:

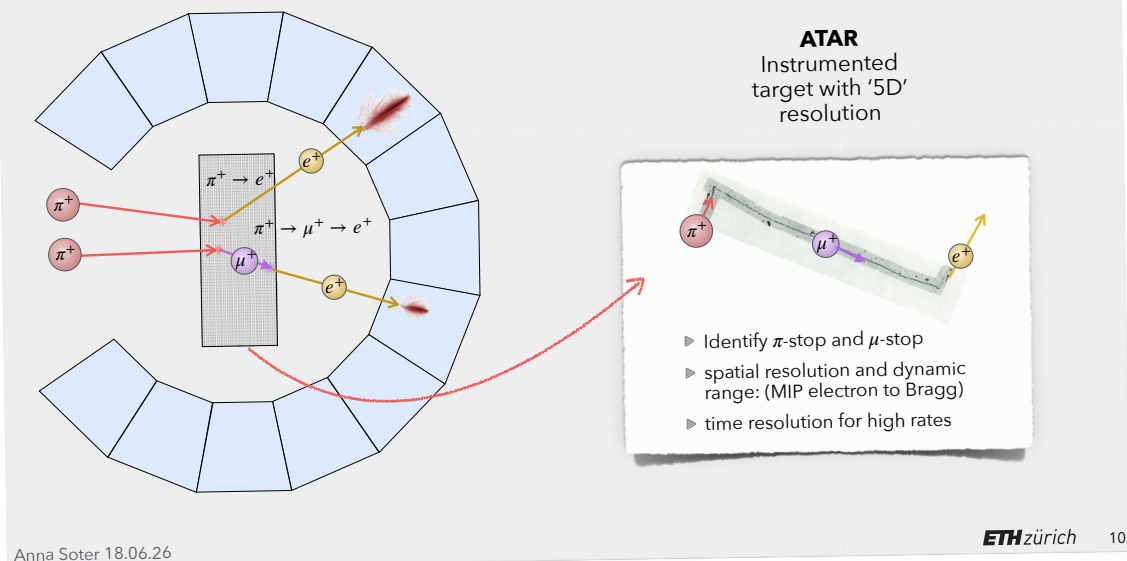
- ✓ Di-lepton trigger upgrades including LKr clustering at L0, improved L1-STRAW reconstruction
- ✓ Di-lepton datasets equivalent to $O(10^{13})$ kaon decays are collected
- ✓ Expect an order of magnitude improvement in sensitivity



18/06/2026 M. Mirra

Recent results from NA62 experiment at CERN 25/25

Main detectors for PIONEER Phase I.



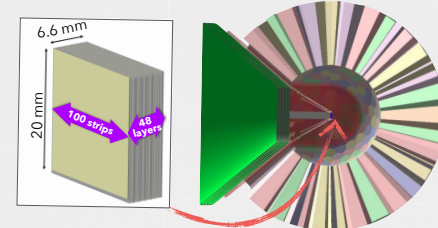
PIONEER is building a new generation of pion precision experiments

- Dedicated detectors for pion decays
- ATAR is the heart of the experiment
- Precision tests of LFU and CKM unitarity

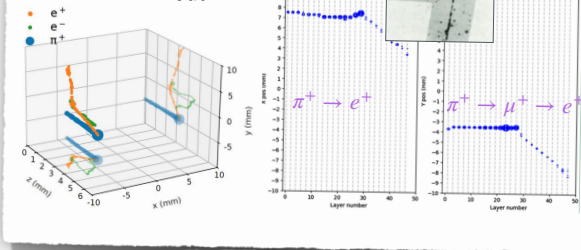
Active target (ATAR)

Fully instrumented Si strip (LGAD) layers:

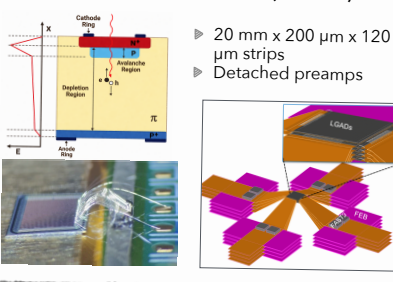
- ▶ **3D position** (x,y,z) with <200 um resolution
- ▶ **Time:** 100 ps single hit resolution (few ~ns pulse pair)
- ▶ **Energy:** high dynamic range, MIPs to heavily ionizing pion



A modern 'emulsion' with fast readout



Low-gain-avalanche diodes (Ti-LGAD)



Anna Soter 18.06.26

ETH zürich 18

- NA62 & PIONEER -

Simple decays can provide powerful tests of fundamental physics

- Rare kaon decays probe extremely high energy scales
- Precision pion decays test LFU and CKM unitarity
- Meson decays remain sensitive to physics beyond the Standard Model

— Session 6 —

Future Facilities and Experiments

- FCCee
- Muon Collider
- HiMB
- Future muegama
- Upgrades at FNAL
- KOTO-II



Tau Physics at FCC

FCC-ee will produce largest $e^+e^- \rightarrow \tau^+\tau^-$ sample ever

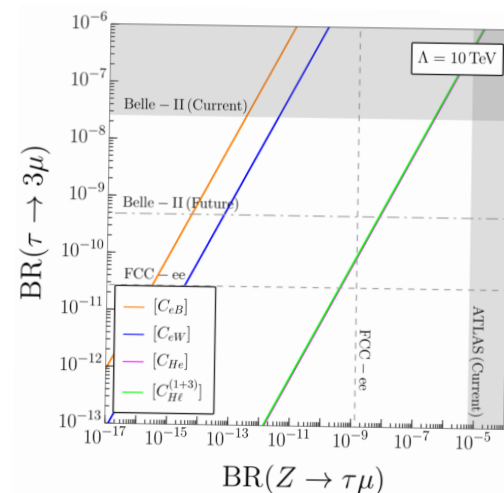
facility	Z [million]	$\tau^+\tau^-$ [million]	$\tau^+\tau^-$ relative sample size	
LEP	25	0.84		
BABAR	-	$0.5 \cdot 10^3$		
Belle	-	$1.0 \cdot 10^3$		
Belle II	-	$45 \cdot 10^3$		
STCF at 4.26 GeV, 10 years	-	$35 \cdot 10^3$		
CEPC	$4 \cdot 10^6$	$135 \cdot 10^3$	$1.6 \cdot 10^5 \times \text{LEP}$	$3.0 \times \text{Belle II}$
FCC-ee	$6 \cdot 10^6$	$200 \cdot 10^3$	$2.4 \cdot 10^5 \times \text{LEP}$	$4.5 \times \text{Belle II}$

FCC-ee experimental conditions much better for Tau Physics than at B-factories energies

- ▶ better momentum resolution and vertexing because less multiple scattering with higher track momenta
- ▶ better higher momentum muon id (much lower pion-to-muon misidentification)
- ▶ much better $\tau^+\tau^-$ separation from $q\bar{q}$ background because of higher $q\bar{q}$ multiplicity at Z peak
- ▶ LHC produces more tau leptons, but with much less favourable experimental conditions

[Lusiani @ Tau 2025]

LFV in Z-boson Couplings



[Allwicher, Bartocci, Cornella, Leal, Paradisi, Scantamburlo, Sumensari, to appear.]

Message: LFV tau decays are more powerful than Z decays at FCC-ee!

95% C.L.	Current (Belle, LHC)	Future (Belle II, HL-LHC)	FCC-ee
$\tau \rightarrow \mu\gamma$	4.2×10^{-8}	5×10^{-9}	1.2×10^{-9}
$\tau \rightarrow \mu\mu\mu$	1.9×10^{-8}	3×10^{-10}	2.0×10^{-11}
$Z \rightarrow \mu\tau$	6.5×10^{-6}	—	10^{-9}
$h \rightarrow \mu\tau$	1.5×10^{-3}	4×10^{-4}	8.1×10^{-5}

[FCC-ee projections by Lusiani et al.]

Large statistics expected at FCC-ee:
 ♦ $\sim 10^{12}$ Z bosons
 ♦ $\sim 10^{11}$ τ pairs

FCC-ee could become a powerful laboratory for τ flavor physics

- Enormous samples of Z bosons and τ leptons
- Sensitivity to multiple LFV channels
- τ decays may outperform Z-decay searches

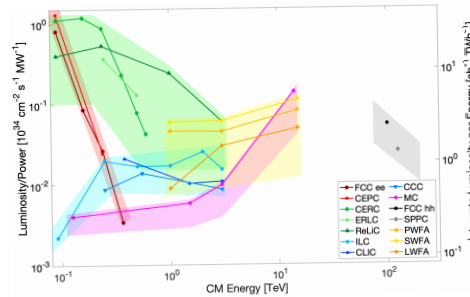
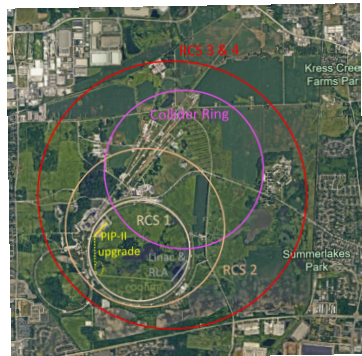
CLFV at a High Energy Muon Collider S. Homiller

A High-Energy Muon Collider

Recent growing interest in the possibility of a *high-energy* (~ 10 TeV) muon collider to succeed the LHC

$$P_{\text{sync}}^{\text{loss}} \sim \left(\frac{E}{m}\right)^4 \frac{1}{R^2}$$

Heavier leptons offer a route past the “precision” vs. “power” tradeoff



Lots of challenges, but a phase change for the size & scaling for the Energy Frontier, so worth taking seriously!

Info, resources at muoncollider.us, muoncollider.web.cern.ch/



Samuel Homiller — shomiller@pitt.edu

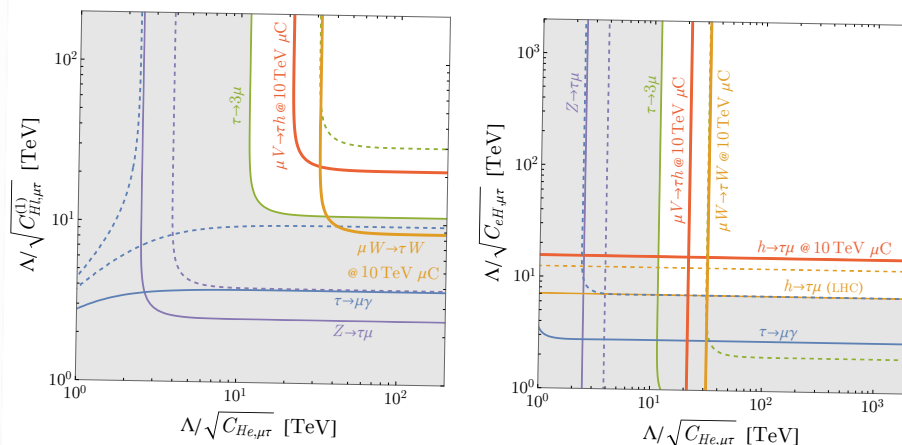
CLFV at a High-Energy Muon Collider 14

Muon colliders could bring CLFV to the energy frontier

- Multi-TeV muon collisions become possible
- CLFV can be probed through multiple processes
- Different channels help reveal the nature of LFV

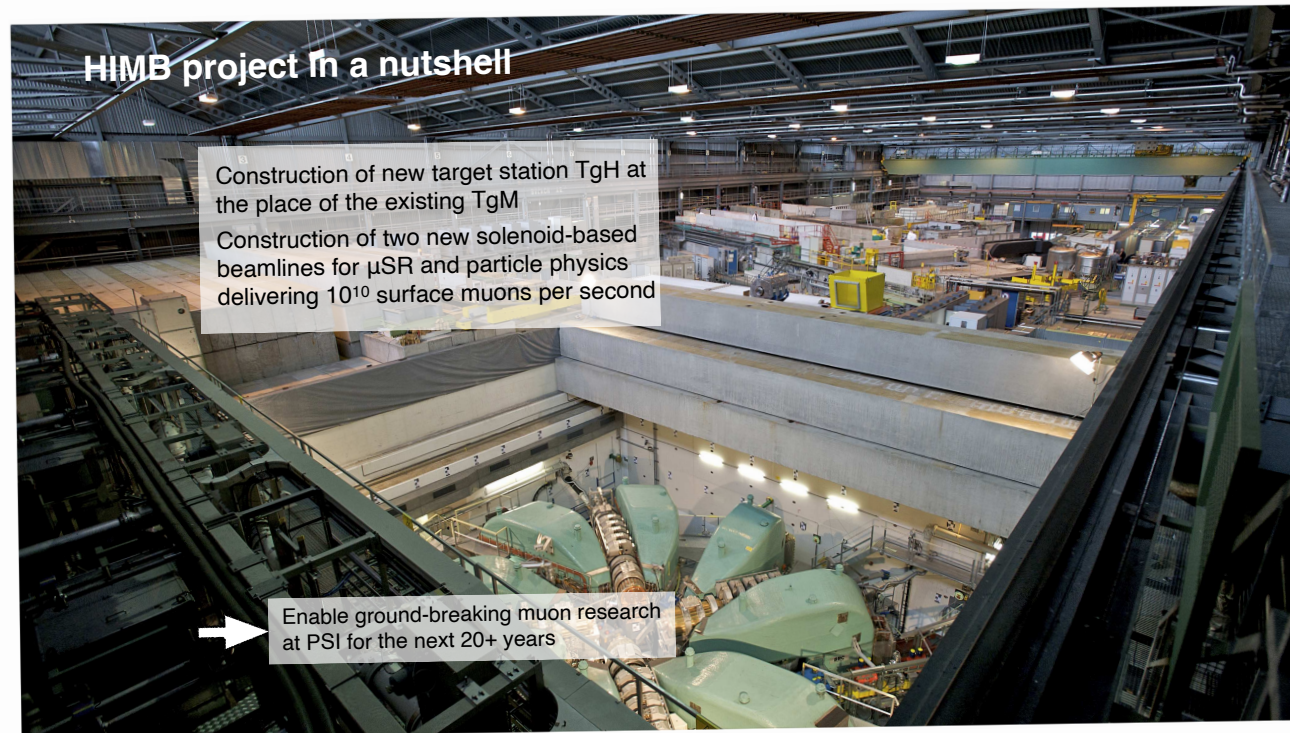
Comparison to Low-Energy Probes

Multiple, different processes $\Rightarrow$ characterization of LFV interactions



Samuel Homiller — shomiller@pitt.edu

CLFV at a High-Energy Muon Collider 27



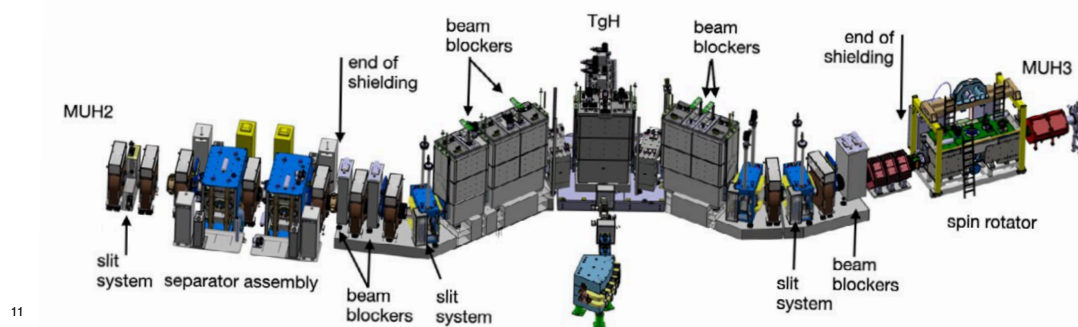
HiMB is building the next intensity frontier for muon science

- 100× higher muon rates are targeted
- New beamlines and infrastructure are taking shape
- A broad future muon program becomes possible

Layout MUH2 and MUH3

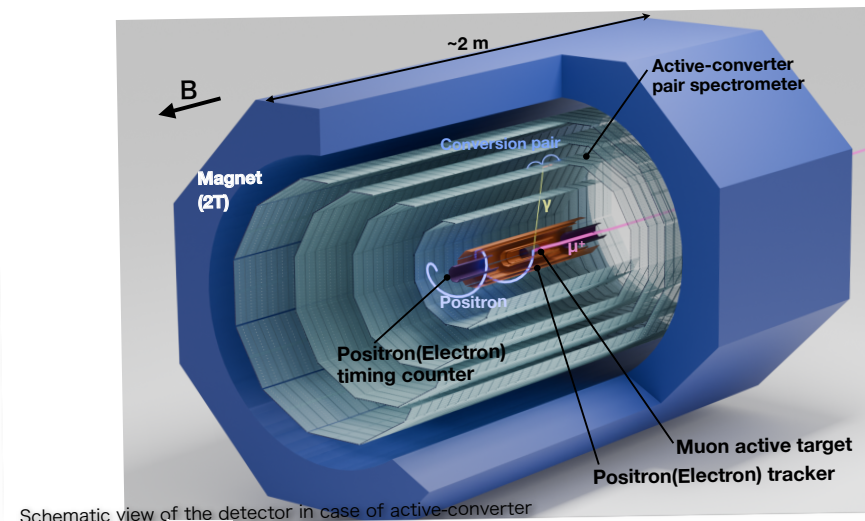


Two specialized capture solenoids at 250 mm to the slanted target. Beamlines at 90 degrees to proton beam consisting of large 500 mm aperture dipoles and solenoids. MUH2 for particle physics. MUH3 for μ SR coupling into the “existing” beamline. Layout frozen with vast majority of components final and ordered or under construction or ready for construction.



Detector concept

- Detector concept for the future $\mu \rightarrow e \gamma$ search
 - **Gamma** : Active-converter pair spectrometer or Calorimeter
 - **Positron** : Spectrometer using Si tracker + Timing counter (Scintillator+SiPM)
 - Active muon target for more precise angle information of positron

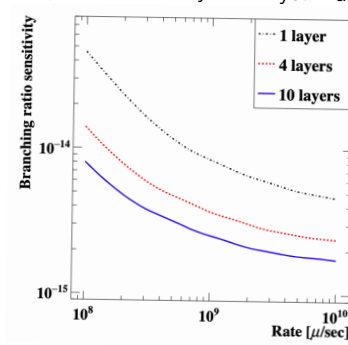


Sensitivity estimation

- Sensitivity is estimated based on simulation
 - Photon detection efficiency for single layer is ~3.3%
 - $\rightarrow$ Sensitivities are estimated with three scenarios of the number of layers
 - For positron side, not a precise estimates
 - Based on studies so far and the experiences from MEG II
- **Sensitivity $(2-3) \times 10^{-15}$ reachable with multi-conversion layers at $10^9 \mu/\text{sec}$**

Target performances	
	Resolutions/efficiencies
Photon energy	200 keV
Photon position	200 μm
Photon timing	30 ps
Photon angle	150 mrad
Photon detection efficiency (4 layers)	10 %
Positron energy	100 keV
Positron angle	6 mrad
Positron timing	30 ps
Positron detection efficiency	70 %
Geometrical acceptance	85 % (36 %)

Projected sensitivity with 3-year run



The next generation of $\mu \rightarrow e \gamma$ search is taking shape

- New detector concepts are being designed
- HiMB opens opportunities for higher muon rates
- Sensitivity beyond MEG II is within reach

Advanced Muon Facility (AMF)

- A single facility capable of simultaneous μ^+ and μ^- production, storage, and delivery to experiments
 - >10x MEG-II(I)
 - >10x Mu3e
 - >10(0)x Mu2e(-II)
 - Various stopping targets?
 - Muonium-antimuonium oscill.
 - Others? (muSR?)



6/19/2026

CLFV 2026 --- M. T. Hedges

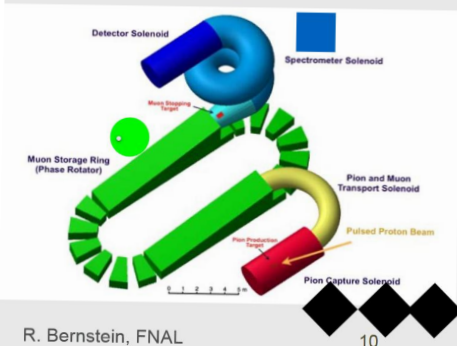
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Fermilab is looking beyond Mu2e-II toward future muon facilities

- Mu2e-II studies are progressing
- Advanced muon facilities are being explored
- High-power targetry is becoming a key challenge

Not a groundbreaking revelation... One Concept for $\mu^- N \rightarrow e^- N$

- FFA (PRISM) is essentially a muon storage ring
- Wait out π decays in the beam, produce a pure, cold muon beam



skier's guide

- hard but not new
- really hard but not new
- ◆ really hard AND new

Future CLFV facilities will be driven by advances in high-power targetry!

R. Bernstein, FNAL

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Future Muon Program

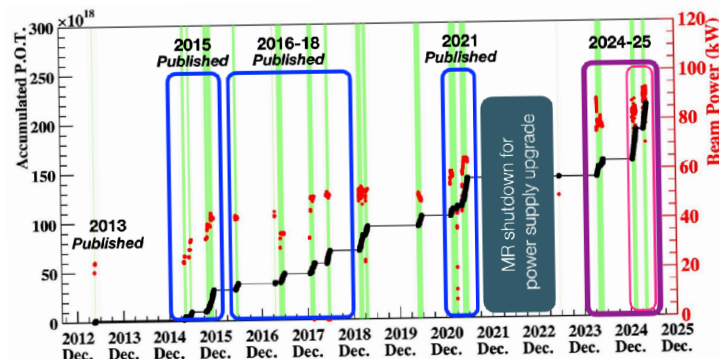
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The KOTO-II Experiment

S. Martellotti

Ongoing 2024-2025 data analysis

Beam power gradually increased: 64 kW(2021) → 80 kW(2024) → 92 kW (2025) → 100 kW (exp. 2026)



KOTO upgrades after 2021

- UCV with thinner scintillating fibers (0.5 mm → 0.2 mm):
Halo neutron reduced by 30%
- Additional magnet before the decay volume:
 $K^\pm$ reduced by a factor > 15
- Deep learning cut in Csl calo:
6 times higher rejection power against halo $K_L \rightarrow 2\gamma$
- DAQ improvements
New GPU trigger with more rate capability

CLFV2026 - Silvia Martellotti

12/24

KOTO-II is preparing to enter a new era of rare kaon physics

- KOTO continues to improve its sensitivity
- KOTO-II is moving from concept to reality
- Precision studies of rare kaon decays are coming into view

Hadron Facility Extension and KOTO II

Design work has begun for a new experiment aimed at achieving the required sensitivity.
The J-PARC E107 experiment has received scientific approval, with realization targeted for 2030

KOTO II needs significant modification with a large-scale budget

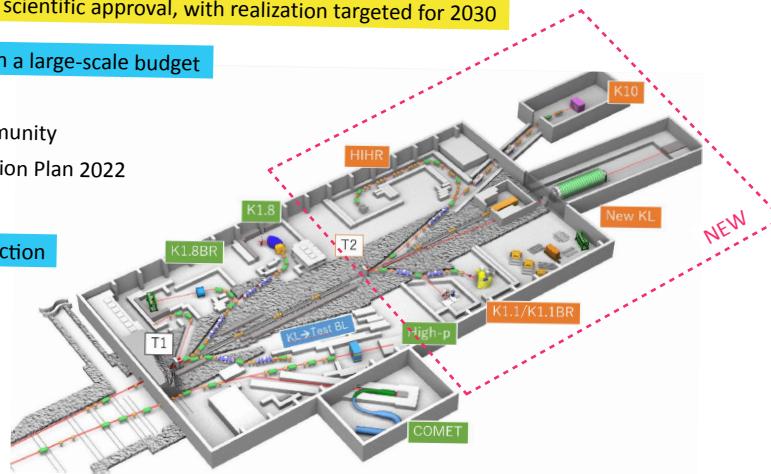
Extension of the experimental facility

- joint project with nuclear physics community
- supported by KEK Project Implementation Plan 2022

Construction of a new detector

Collaboration formed, working groups in action

- 69 members
- 26 institutions for 10 countries



CLFV2026 - Silvia Martellotti

15/24

- Futures Facilities / Projects -

New frontiers are emerging across energy, intensity, and precision

- Future facilities are pushing multiple frontiers
- New experiments are already being planned
- The next generation is beginning to take shape

— Session 7 —

Dark Matter Searches

- LF Dark Matter
- Muonium Oscillations
- Ultralight DM



Fun Session !

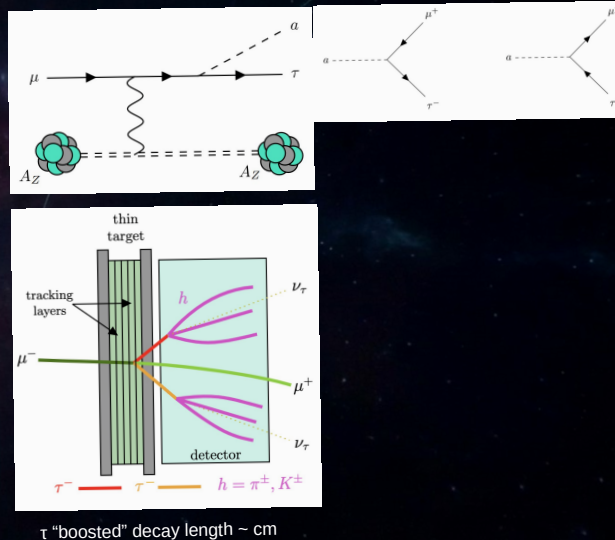
Dark Matter Searches

- LF Dark Matter
- Muonium Oscillations
- Ultralight DM



The LFV “Smoking Gun” – muon charge flip

- A visibly decaying LFV ALP ($a \rightarrow \mu^\pm \tau^\mp$) yields a muon charge flip.
- **Example:** Incident $\mu^- \rightarrow$ Final state $\mu^+ \tau^- \tau^-$
- **Challenge:** Requires active target to reconstruct tau leptons & see no large hadronic activity
- **Advantage:** If done so, SM backgrounds are virtually zero!



Dark matter may reveal itself through flavor

- LFV dark matter creates unique signatures
- Muon beams provide clean discovery channels
- Neutron stars probe flavor-changing interactions

Neutron stars as the ultimate LFV DM (e- μ) laboratory

Inelastic capture mechanism

Up-scattering:
 $\chi_e \rightarrow \chi_\mu$
(Powered by gravitational boost)

Down-scattering:
 $\chi_\mu \rightarrow \chi_e$
(Off stable muon population)

Extreme Stellar Parameters

- **Central Density:**
 $\rho_c \sim 1.185 \times 10^{15} \text{ g/cm}^3$
- **Fermi Sea Chemical Potential:** $\mu \sim 250 \text{ MeV}$
- **Result:** Highly efficient capture of LFV Dark Matter, permanently trapping it within the star's gravitational well.

Theory and Experiment of Muonium Oscillations: MACEing Our Way Forward

A. Petrov

Muonium oscillations: just like $K^0 \bar{K}^0$ mixing, but simpler!

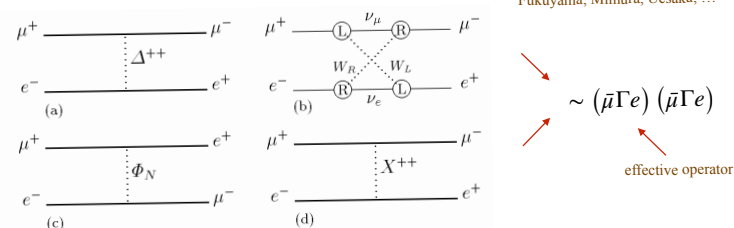
★ Lepton-flavor violating interactions can change $M_\mu \rightarrow \bar{M}_\mu$

Pontecorvo (1957)
Feinberg, Weinberg (1961)

• Such transition amplitudes are tiny in the Standard Model

– ... but there are plenty of New Physics models where it can happen

Clark, Love; Cvetič et al,
Li, Schmidt; Endo, Iguro, Kitahara;
Fukuyama, Mimura, Uesaka; ...



– theory: compute transition amplitudes for ALL New Physics models!

– experiment: produce M_μ but look for the decay products of $\bar{M}_\mu$

Alexey A Petrov (USC)

18

CLFV 2026, 17-19 June, 2026

Muonium offers a unique window on charged lepton flavor violation

- Muonium enables searches beyond traditional CLFV channels

- Oscillations probe new flavor-violating interactions
- Future measurements could provide complementary discoveries

Bound states: muonium

- Muonium: a bound state of μ^+ and e^-
 - $(\mu^+ \mu^-)$ bound state is *true muonium*

- Muonium lifetime $\tau_{M_\mu} = 2.2 \mu s$

- main decay mode: $M_\mu \rightarrow e^+ e^- \bar{\nu}_\mu \nu_e$

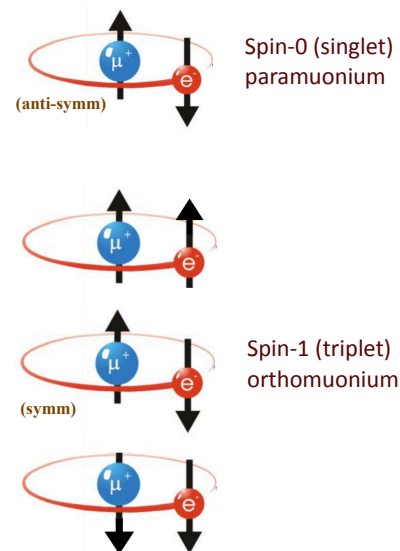
- annihilation: $M_\mu \rightarrow \bar{\nu}_\mu \nu_e$

- Muonium's been around since 1960's

- used in chemistry

- QED bound state physics, etc.

- New Physics searches: decays, oscillations



Hughes (1960)

The masses of singlet and triplet are almost the same!

Alexey A Petrov (USC)

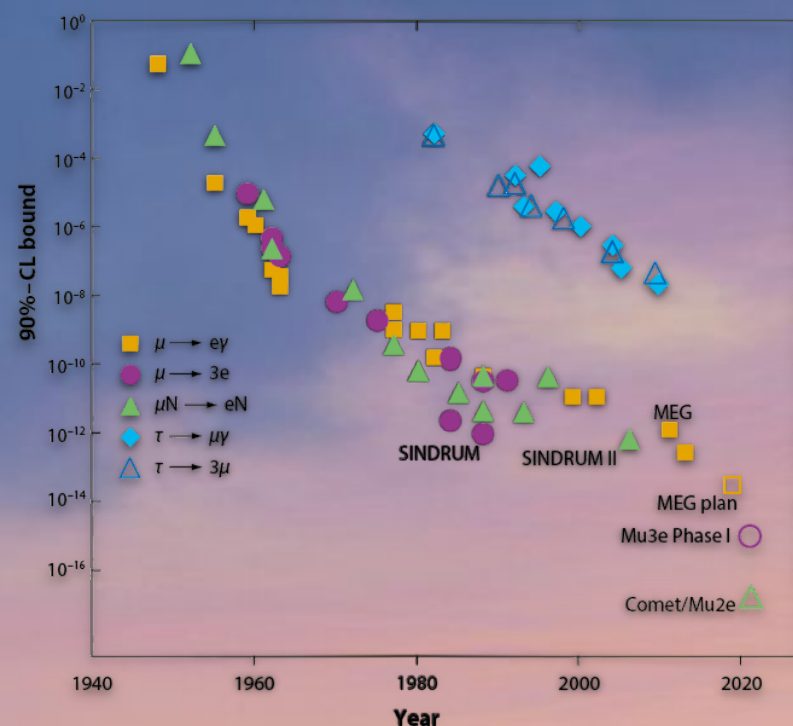
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CLFV 2026, 17-19 June, 2026

CLFV2026

5th International Conference on Charged Lepton Flavor Violation

Sapienza Università di Roma, June 17-19, 2026



Conference Summary

— Overall Summary —

The field is moving from “vision” to “realization”

- CLFV searches are becoming reality
- New facilities and experiments are taking shape
- Complementary probes strengthen the path to discovery

CLFV2023 @ Heidelberg

Promising ideas
Ambitious projects
Future experiments



CLFV2026 @ Rome

Data & Commissioning
Steady Construction
Approved projects



Lastly...

Grazie per aver
organizzato un incontro
così meraviglioso.

Local Organizing Committee

Gianluca Cavoto (Sapienza Università di Roma)
Maria Cristina D'Amato (INFN Frascati, Secretariat)
Simona Giovannella (INFN Frascati, co-chair)
Stefano Miscetti (INFN Frascati)
Federico Mescia (INFN Frascati)
Francesco Renga (INFN Roma, co-chair)
Cecilia Voena (Sapienza Università di Roma)

Looking forward to seeing you at the next CLFV !!