Karlsruhe Institute of Technology

Institute of Experimental Particle Physics

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

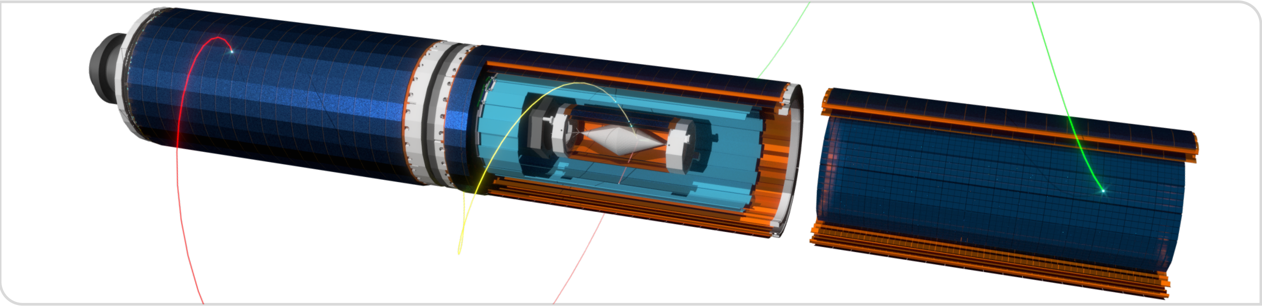
Baden-Württemberg

MINISTERIUM FÜR WISSENSCHAFT, FORSCHUNG UND KUNST

The Flavour of Leptons

Taking a Glimpse at BSM Physics with Lepton Flavour Violation

Ann-Kathrin Perrevoort | September 19, 2022



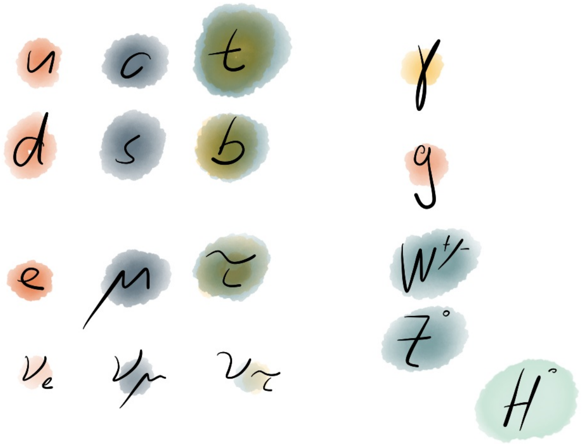
Overview

1. Lepton Flavour Violation as a sign of physics beyond the Standard Model

2. Search for $Z \to e\tau$ and $Z \to \mu\tau$ with ATLAS

3. Searches for Lepton Flavour Violation with the Mu3e Experiment

Standard Model of Particle Physics
and beyond



Standard Model of Particle Physics
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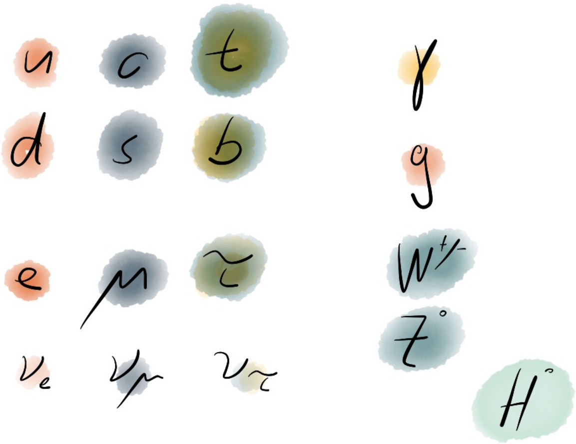
Standard Model (SM) of Particle Physics describes all known particles and their interactions



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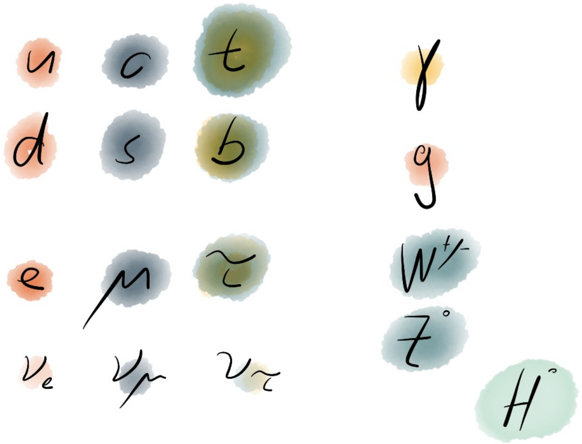


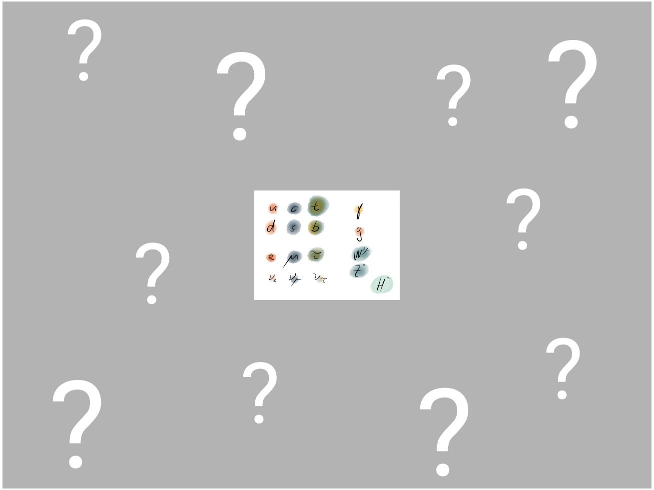
Standard Model of Particle Physics

and beyond

Standard Model (SM) of Particle Physics describes all known particles and their interactions

but it is incomplete

- gravity not included
- no explanation for dark matter/dark energy (covers only 5% of all matter and energy in the Universe)
- no sufficient CPV for baryon-asymmetry
- ...



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There is a plethora of models beyond the SM (BSM)

but only a few observational hints

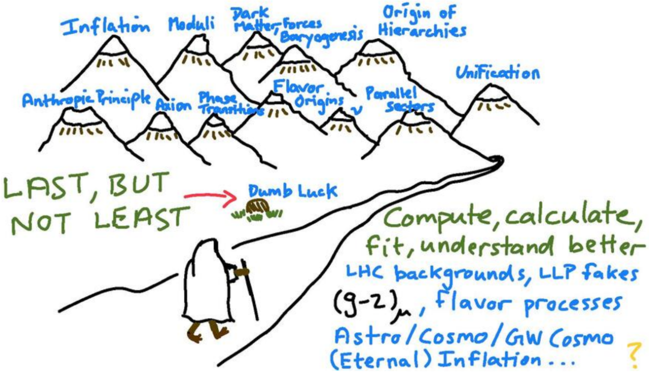

Figure taken from R. Sundrum, Snowmass Theory Frontier 2022

Standard Model of Particle Physics
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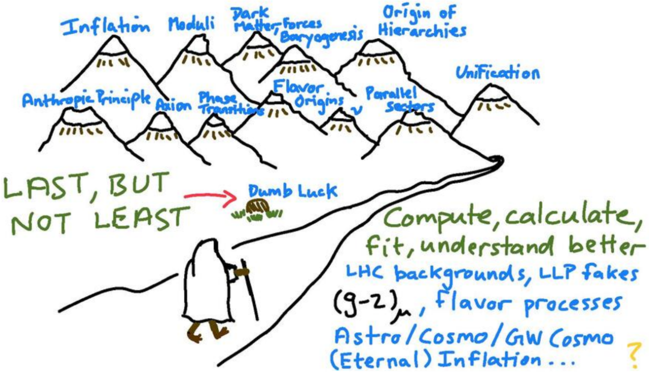
- neutrino oscillations and neutrino mass
- anomalous magnetic moment of the muon $(g-2)_\mu$
- flavour anomalies, esp. $b \to s\ell\ell$, $b \to c\ell\nu$
- potentially a few more: Cabibbo angle, high-mass Drell-Yan, X17, …



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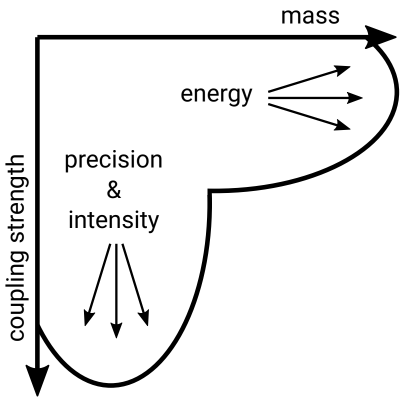
How to Discover BSM Physics?
in the Laboratory

Energy frontier

- direct production of ‘new’, heavy particles
- needs higher and higher collision energy

Intensity / precision frontier

- indirect search
- ‘new’ particles in loop and box diagrams
- heavy and/or weakly coupled
- deviations from SM predictions
- processes forbidden in the SM



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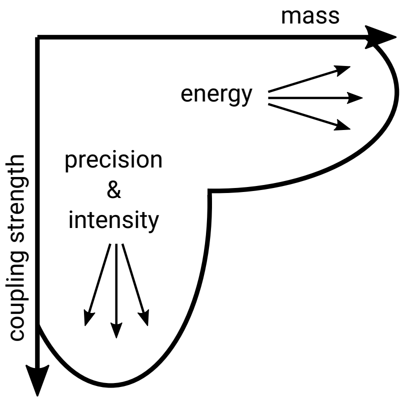
- Lepton Flavour Violation (LFV)



Lepton Flavour Violation
as a sign for Physics Beyond the SM

- Lepton flavour is accidental symmetry of the SM

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Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

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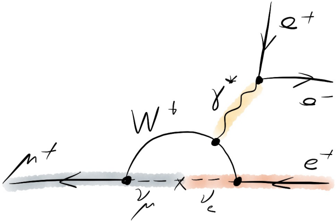
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

- Lepton flavour violation (LFV) in the charged lepton sector not (yet?) observed
- cLFV is heavily suppressed in the νSM:

$$\mathscr{B}_{\mu\to eee} \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \quad \rightarrow \quad \mathscr{B}_{\mu\to eee} < 10^{-54}$$



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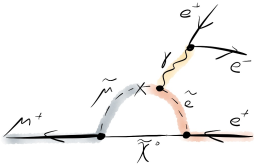
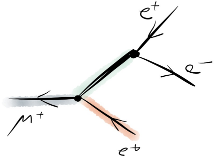
- Observation would be an unambiguous sign of physics beyond the SM





Lepton Flavour Violation in Z Decays
Search for $Z \to \ell\tau$ in ATLAS

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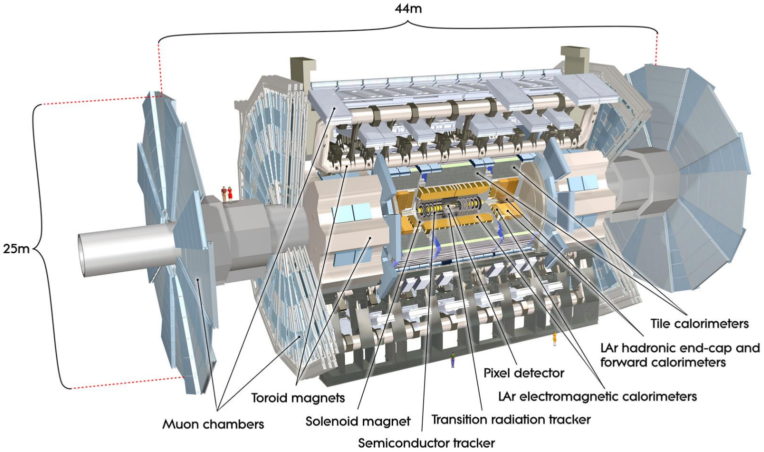
Search for the LFV decay $Z \to \ell\tau$
($\ell = e$ or μ)

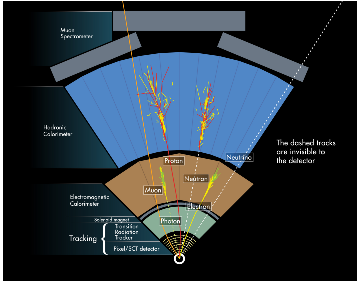
- ATLAS experiment at the Large Hadron Collider (LHC)
- pp collisions at $\sqrt{s}$ =13 TeV
- Run 2 (2015-2018): 139 fb^{-1} of data recorded

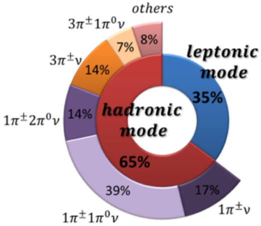
$\hat{=}$ 8 billion Z decays



Search for the LFV Decay $Z \to \ell\tau$ in ATLAS
Objects Reconstruction

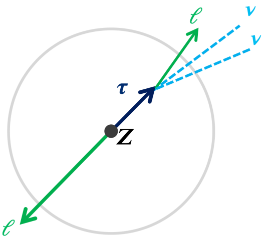
- Electrons, muons and jets reconstructed from tracks and energy deposits in calorimeters
- Analysis uses two tau decay modes
  - $Z \to \ell\tau \to \ell\tau_{\text{had-vis}}\nu$
    $\tau_{\text{had-vis}}$ reconstructed from hadronic decay products: 1 or 3 associated charged particle tracks
  - $Z \to \ell\tau \to \ell\ell'\nu\bar{\nu}$
    τ_{lep} have no dedicated reconstruction $\Rightarrow$ light leptons
    Used for the first time in a ATLAS Z-LFV search
- Neutrinos not directly detected: missing transverse momentum $E_{\text{T}}^{\text{miss}}$



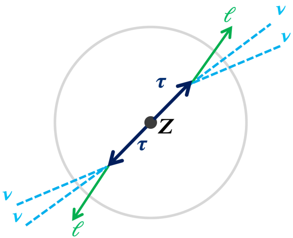


Search for the LFV Decay $Z \to \ell\tau$ in ATLAS
Signal and Backgrounds

Signal $Z \to \ell\tau$



Background

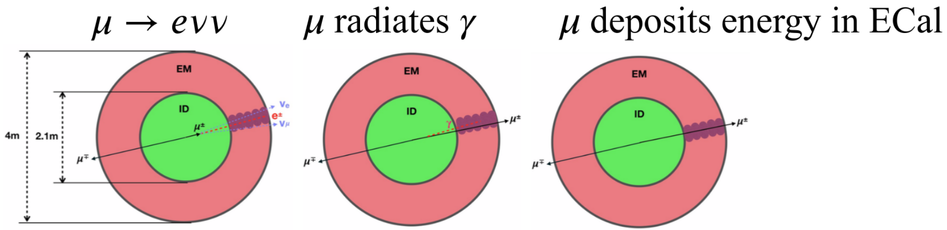


- Opposite-sign, back-to-back $\ell\tau$ (or $\ell\ell'$) pair
- τ_{lep} channel
  - only uses $e^{\pm}\mu^{\mp}$ ($Z \to \ell\ell$ background)
  - leading-p_{T} ℓ_1 from Z, subleading-p_{T} ℓ_2 from τ
- Neutrinos ($E_{(\text{T})}^{\text{miss}}$) collinear with τ

- $Z \to \tau\tau$ decays
- Decays of $t\bar{t}$, two gauge bosons, ...
- $W(\to \ell\nu) +$ jets events:
  jet$\to \tau_{\text{had-vis}}$ or jet$\to \ell$ fakes
- $Z \to \mu\mu$ with $\mu \to e$ fakes in τ_{lep} channel

Search for the LFV Decay $Z \to \ell\tau$ in ATLAS

Background: $\mu \to e$ Fakes in τ_{lep} Channel



- $Z \to \mu\mu$ decays with $\mu \to e$ mis-identification look signal-like
- Suppression by cut on $p_{\text{T}}^{\text{trk}}(e)/p_{\text{T}}^{\text{cluster}}(e)$

Search for the LFV Decay $Z \to \ell\tau$ in ATLAS

Fakes Estimate using the Fake Factor Method

- Fakes from jet$\to \tau_{\text{had-vis}}$ or jet$\to \ell$ misidentification estimated in data-driven Fake Factor (FF) Method

  PRD 98(2018)092010

- Count events passing or failing a certain reconstruction quality in the signal (SR) and fake enriched regions (FR)
- τ_{lep} channel
  - Estimate fakes for subleading-p_{T} ℓ_2
  - Pass or fail isolation criterium of ℓ_2
  - FR like SR but with same-sign $e\mu$
  - FFs binned in $p_{\text{T}}(\mu)$ vs $p_{\text{T}}(e)$ vs $|\eta(e)|$
- τ_{had} channel
  - Estimate fakes for $\tau_{\text{had-vis}}$
  - Pass or fail identification criterium
  - FRs for W+jets, multi-jet, Z+jets, $t\bar{t}$
  - FFs binned in $p_{\text{T}}(\tau_{\text{had-vis}})$

	FR	SR
pass ID	N_{FR}^{pass} /	N_{SR}^{fakes}
	=F	xF
fail ID	N_{FR}^{fail}	N_{SR}^{fail}

Search for the LFV Decay $Z \to \ell\tau$ in ATLAS

Signal-Background Discrimination: Neural Net

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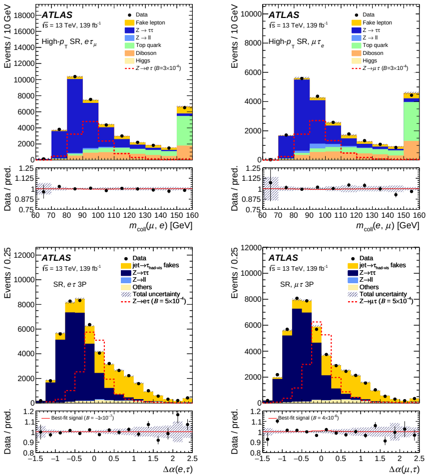
- Binary neural net (NN) classifiers to discriminate signal and background
- Exploit all correlations of the $\ell - \tau - E_{\mathrm{T}}^{\mathrm{miss}}$ system
- Low-level inputs: four-momenta of ℓ and $\tau_{\text{had-vis}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$, boosted and rotated to remove known symmetries
- High-level inputs: m_{inv}, m_{coll}, $\Delta\alpha$
- Each input variable is standardized: $\hat{x} = \frac{x - \bar{x}}{\sigma_x}$
- Individual NNs trained to discriminate against dominant backgrounds
  - τ_{lep} channel: $Z \to \tau\tau$, di-boson, $t\bar{t}$ + single-t
  - τ_{had} channel: W+jets, $Z \to \tau\tau$, $Z \to \ell\ell$
- Combined to a single score $\Rightarrow$ fitted distribution



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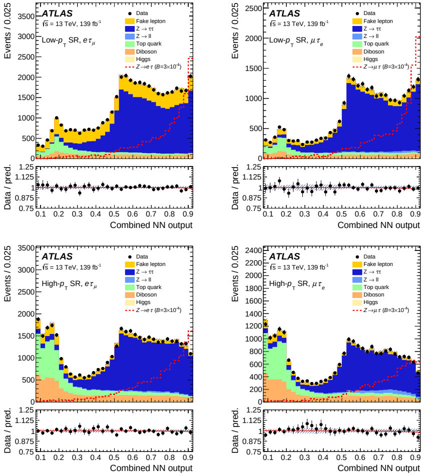

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Signal-Background Discrimination: Neural Net

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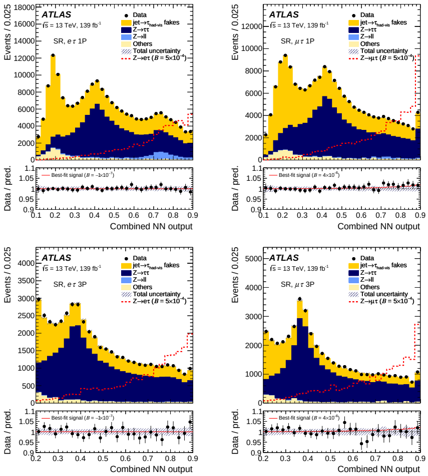

Search for the LFV Decay $Z \to \ell\tau$ in ATLAS

- Fitted NN distribution in each SR in both channels
- Parameter-of-interest: signal strength modifier ($\propto \mathcal{B}(Z \to \ell\tau)$)
- Combination of full Run 2 τ_{lep} and τ_{had} channels + full Run 1 $Z \to \mu\tau_{\text{had}}$ analysis

Final state, polarization assumption	Obs. (exp.) UL on $\mathcal{B}(Z \to \ell\tau)$ at 95% C.L. [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarized τ	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\text{had}}$ Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{\text{had}}$ Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
$\ell\tau_{\text{lep}}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\text{lep}}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\text{lep}}$ Run 2, right-handed τ	8.4 (11)	9.8 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)
OPAL at LEP, unpolarized τ [1]	9.8	17
DELPHI at LEP, unpolarized τ [2]	22	12

- No statistically significant deviation from the SM prediction observed
- Superseding LEP limits on $Z \to \ell\tau$ by factor of 2, for the 1st time at the LHC
- Still statistically limited

Nat.Phys. 17 (2021) 819–825
PRL 127 (2022) 271801

[1] Zeit.Phys.C 67(1995)555-563
[2] Zeit.Phys.C 73(1997)243-251

Lepton Flavour Violation

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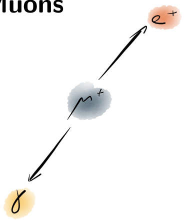
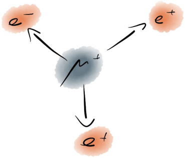
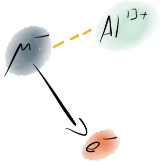
$\Rightarrow$ Muon decays

Lepton Flavour Violation

with Muons







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

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

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

- Invariant mass of $e^+e^-e^+ = m_\mu$
- $\sum \vec{p}_e = \vec{0}$
- Continuous beam
- Background from $\mu \to ee e\nu\nu$ and accidental combinations

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

- Monoenergetic e^-
- Pulsed beam
- Background from decay in orbit, antiprotons, pions, cosmics

Lepton Flavour Violation
with Muons

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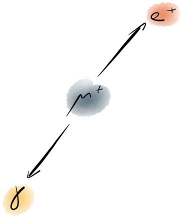
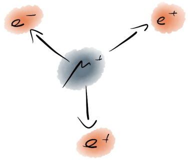
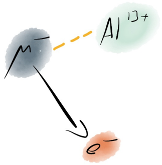






$\mu^+ \to e^+\gamma$

- Current limit:
  MEG (PSI, 2016):
  $\mathscr{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$
- MEG II is running:
  goal $\mathscr{B}(\mu \to e\gamma) < 6 \times 10^{-14}$

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

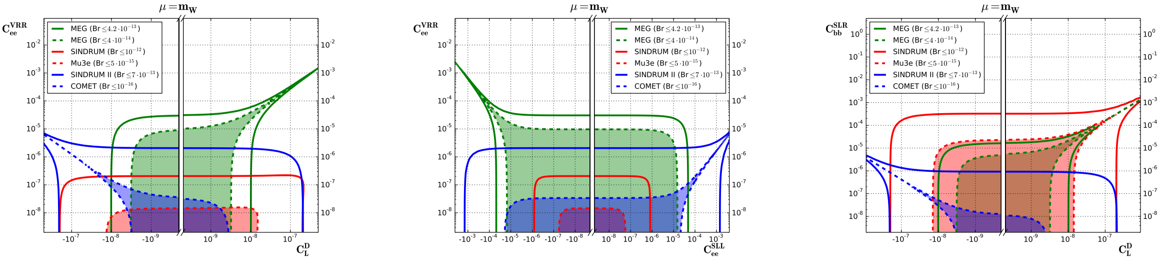
- Current limit:
  SINDRUM (PSI, 1988):
  $\mathscr{B}(\mu \to eee) < 1.0 \times 10^{-12}$
- Future: Mu3e (PSI)

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

- Current limit:
  SINDRUM II (PSI, 2006):
  $\mathscr{R}(\mu\mathrm{Au} \to e\mathrm{Au}) < 7 \times 10^{-13}$
- Future: Mu2e (Fermilab),
  DeeMe and COMET (J-PARC)
  goal 2×10^{-13} to 7×10^{-15}
  + upgrades

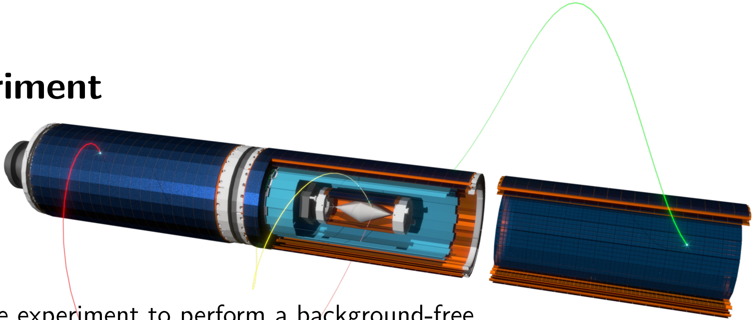
Lepton Flavour Violation
with Muons

- Classical muon LFV searches: $\mu \to e\gamma$, $\mu \to eee$, $\mu N \to eN$
- Each channel has specific strengths and weaknesses
- Comparison by means of effective field theories: $\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda}\sum \mathscr{O}_{\text{5-dim}} + \frac{1}{\Lambda^2}\sum \mathscr{O}_{\text{6-dim}} + \dots$
- Pin down type of BSM interaction by combination of the searches



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

Mu3e Experiment



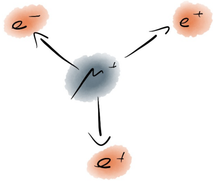
- Mu3e is a future experiment to perform a background-free search for the cLFV decay $\mu^+ \to e^+ e^- e^+$
- Under construction at Paul Scherrer Institute (PSI) in CH
- Aiming for a sensitivity in $\mathscr{B}$ of

$$\text{a few } 10^{-15} \text{ in phase I}$$
$$10^{-16} \text{ in phase II}$$

- Challenges
  - Background suppression & high muon decay rates

Mu3e Experiment

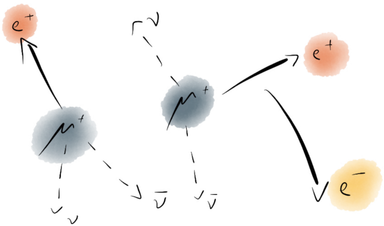
Signal and Background



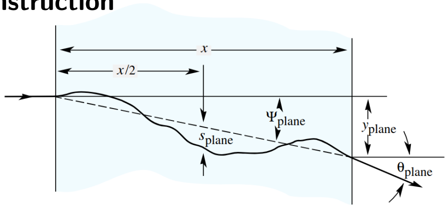
- Signal $\mu^+ \to e^+ e^- e^+$
- Same vertex, coincident
- Decay at rest
  - $\sum P_e = (m_\mu, 0, 0, 0)$
  - $\mathcal{O}(\vec{p}_e) = 10\,\mathrm{MeV}$

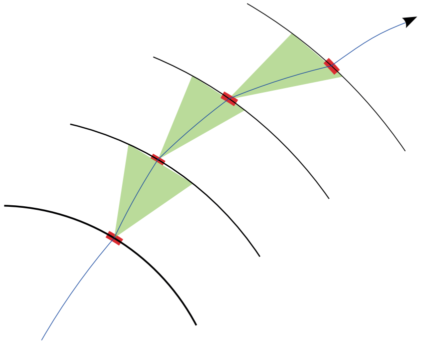
- Accidental combinations of e^+ from $\mu \to e\nu\nu$ with e^- or e^+e^- from Bhabha scattering, photon conversion, mis-reconstruction
- Need good timing and vertexing, low material

- Background from rare decay: $\mathscr{B}(\mu \to ee e\nu\nu) = 3.4 \times 10^{-6}$
- Missing momentum due to neutrinos
- Need excellent momentum resolution



Mu3e Experiment
Track Reconstruction





- Low energy e^+/e^- affected by multiple Coulomb scattering
  - Energy loss and deflection
- Momentum resolution is dominated by scattering not pixel size

$$\frac{\sigma_p}{p} \propto \frac{\theta_{\mathrm{MS}}}{\Omega}$$

- 'Recover' momentum resolution
  - Consider scattering in track reconstruction
  - Low material
  - Optimized geometry, i.e. large lever arm Ω

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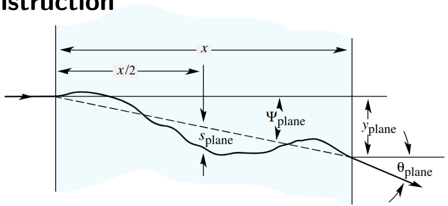

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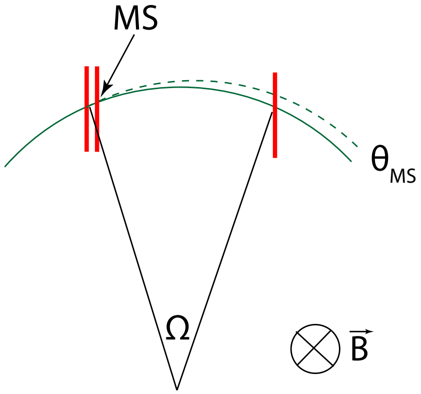

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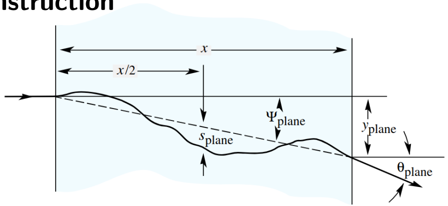

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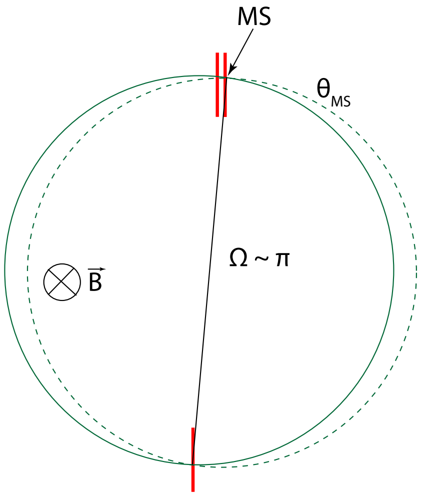
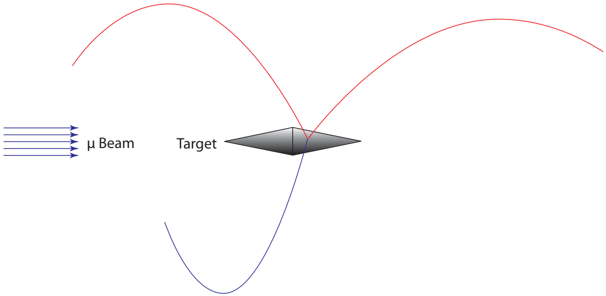


Mu3e Experiment
Experimental Concept

- Muons stopped on target
  $\rightarrow$ decay at rest

Mu3e Experiment
Experimental Concept



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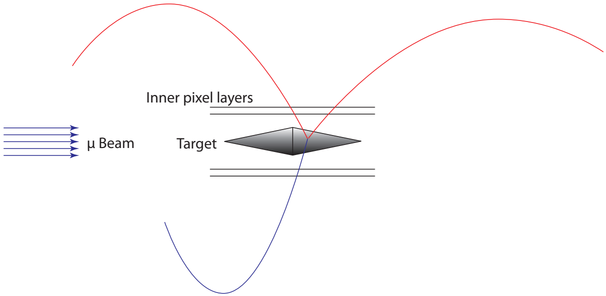

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- 4 layers of ultra-thin silicon pixel sensors

Mu3e Experiment
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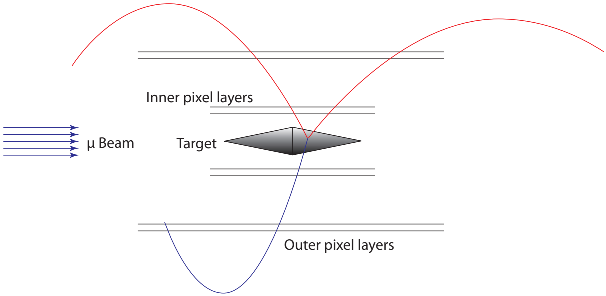

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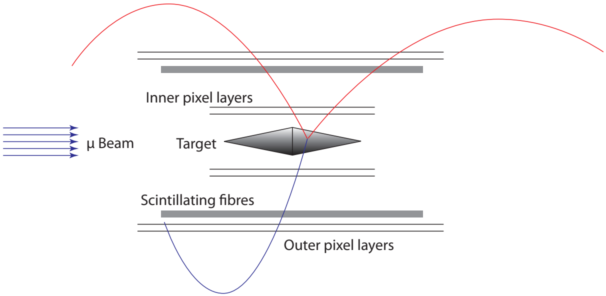

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- Track e^+/e^- trajectories in 1 T solenoidal field
- 4 layers of ultra-thin silicon pixel sensors
- Timing with scintillating fibres

Mu3e Experiment
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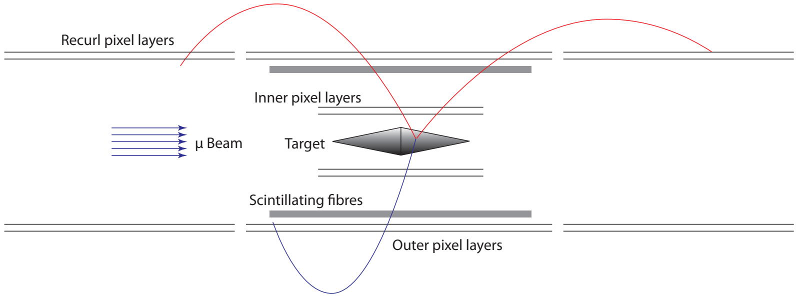

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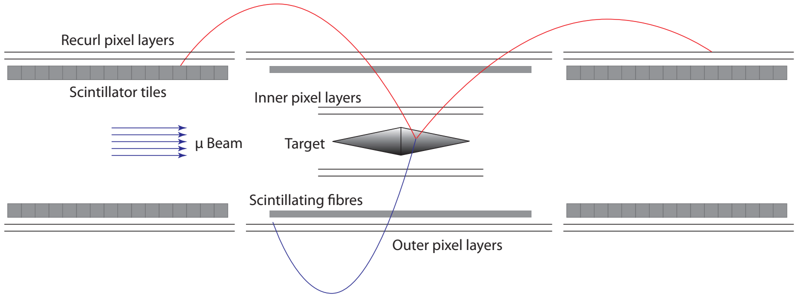
- Recurl-stations with pixel sensors

Mu3e Experiment
Experimental Concept



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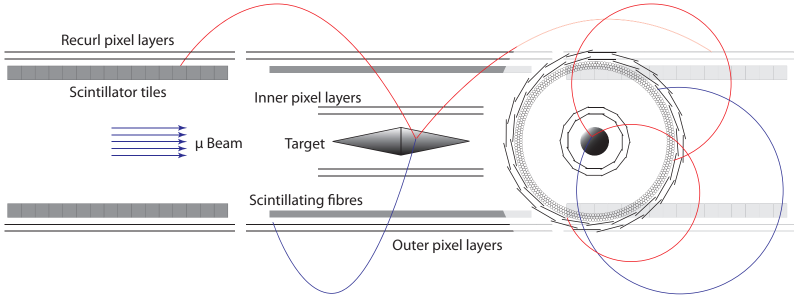
Mu3e Experiment

Experimental Concept



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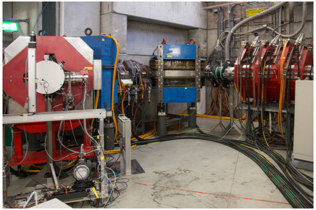
- Track e^+/e^- trajectories in 1 T solenoidal field
- 4 layers of ultra-thin silicon pixel sensors
- Timing with scintillating fibres
- Recurl-stations with pixel sensors and scintillating tiles
- Cooling with gaseous Helium
- 120 cm long, 18 cm diameter

Mu3e Experiment
Muon Beam

- PSI is home of world's most intense continuous muon beam
- Cyclotron produces 2.2 mA proton beam with 590 MeV
- Production of pions and muons on Carbon target
- Continuous, sub-surface μ^+ with 28 MeV

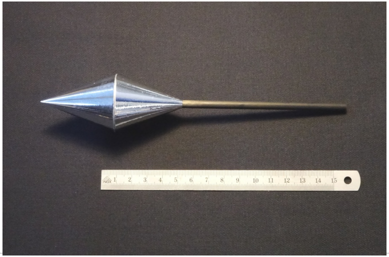
10^8 μ/s at Compact Muon Beamline (CMB)

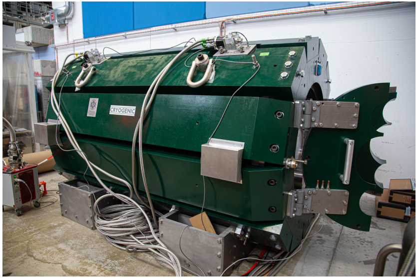
10^{10} μ/s with the future High Intensity Muon Beams (HIMB) project (2029+)



Mu3e Experiment
Stopping Target and Magnet

- Distribute muon stops over large surface
- Reduce material traversed by decay products
- Hollow, double-cone target made from Mylar
- 100 mm long, 38 mm diameter, 70 µm/80 µm thick
- Stopping rate of 95.5 %

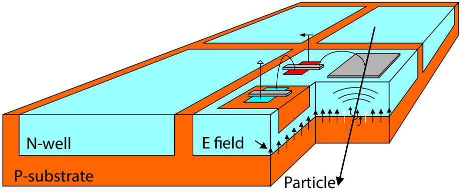


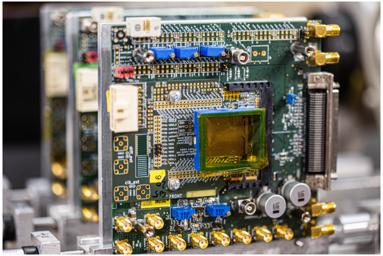


- Solenoid magnet with 1.0 T nominal field (range 0.5 T to 2.7 T)
- Warm bore: $L = 2.7\,\mathrm{m}$, $\varnothing = 1.0\,\mathrm{m}$
- Homogeneous magnetic field: $\frac{\Delta B}{B} < 10^{-3}$

Mu3e Experiment
Pixel Detector

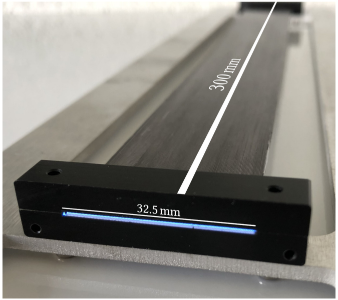
- High Voltage Monolithic Active Pixel Sensor (HV-MAPS)
- Fast charge collection in small active region
- Fully integrated digital readout
- Thinned to 50 µm
  only 1.15 ‰ of radiation length
  incl. flexprint and support
  structure
- Active sensor size 2 cm × 2 cm
  Pixel size 80 µm × 80 µm
- Currently characterising final version sensors

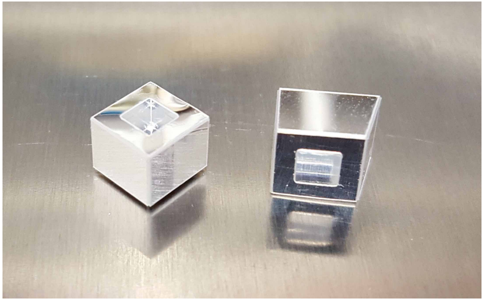




Mu3e Experiment
Scintillating Timing Detectors

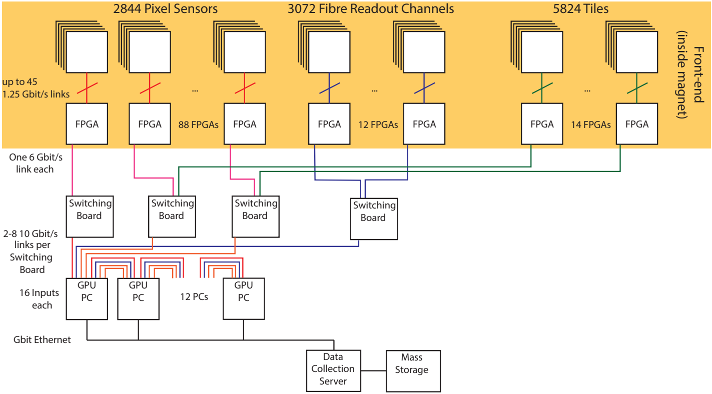
- 3 layer ribbons of 250 µm scintillating fibres in central detector, 30 cm long
- Scintillating tiles of size 6 mm × 6 mm × 5 mm in recurl stations
- Readout with SiPMs and custom MuTRiG ASIC





Mu3e Experiment
Data Acquisition

- Triggerless, continuous readout of all sub-detectors
- Filter farm sees whole detector information for a time slice
  - Track reconstruction in central detector and vertex finding on GPUs
  - Events with $\mu \rightarrow eee$ candidates are send off to mass storage
  - Data reduction by a factor of 80



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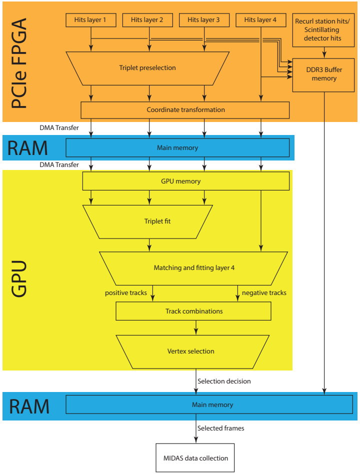
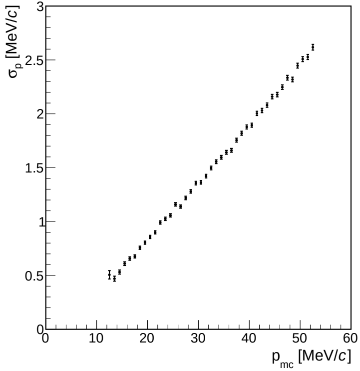
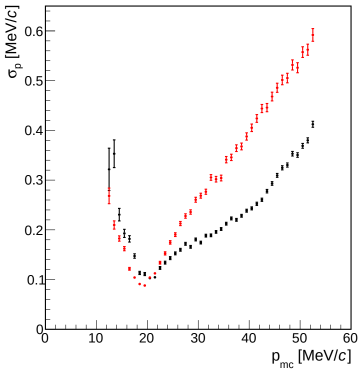


Mu3e Experiment
Sensitivity Studies

- Geant4 based detector simulation
- Reconstruction of recurling tracks pays off
- Improvement in $\frac{\sigma_p}{p}$ by up to factor 10



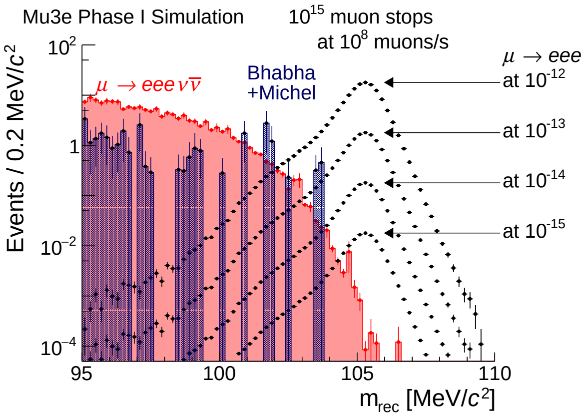
outgoing tracks only (4 hits)



recurling tracks (6 and 8 hits)

Mu3e Experiment
Sensitivity Studies

- Simulated full phase I data taking
- Sensitivities to $\mathscr{B}$ in the rage of 10^{-14} to a few 10^{-15} at 90 % CL in reach



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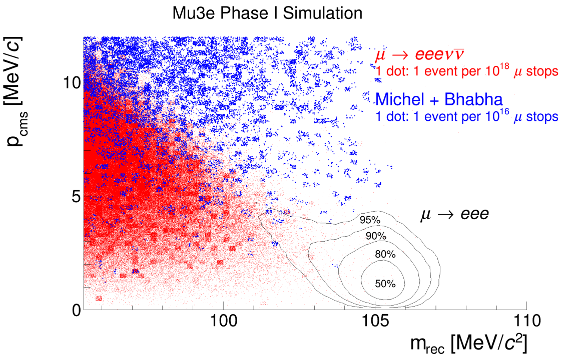

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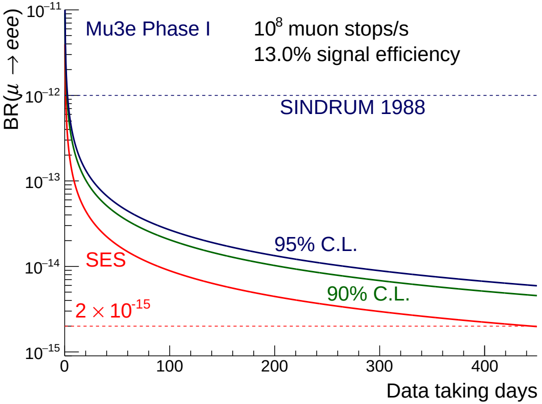
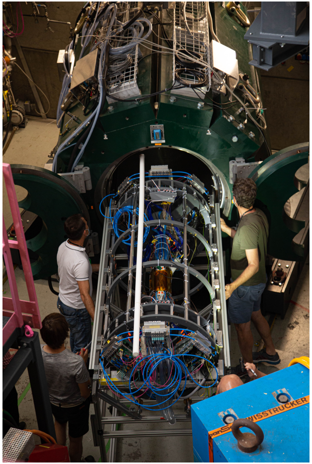
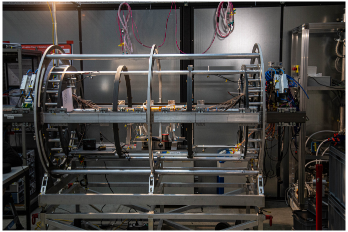


Mu3e Experiment
Status

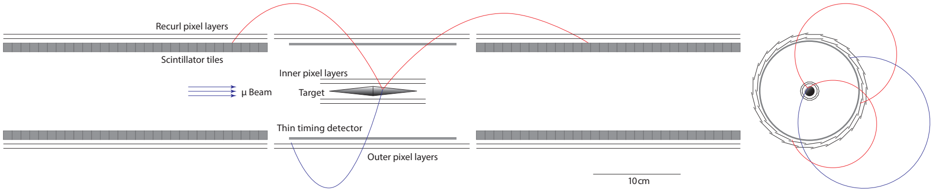
- Design of custom ASICs MuPix and MuTRiG finalized
- Integration run in 2021
- Cosmics run in 2022
- Moving into production phase
- First data expected in 2024



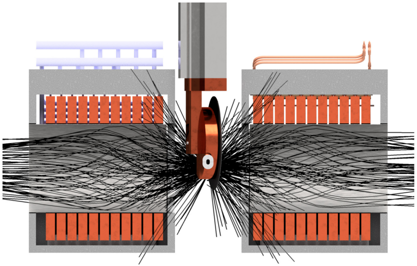


ann-kathrin.perrevoort@kit.edu | KIT - ETP

Mu3e Experiment
Phase II and HIMB



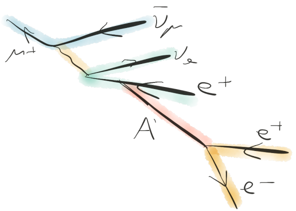
- Reach final sensitivity of 10^{-16} with upgraded phase II detector
  - Elongated recurl station
  - Target with smaller radius
  - To be operated at $2 \times 10^{9}\ \mu/\mathrm{s}$
- High-Intensity Muon Beams (HIMB) project at PSI
  - New target and new capturing solenoids
  - Muon rates of $10^{10}\ \mu/\mathrm{s}$
  - Planned to be operational in 2029

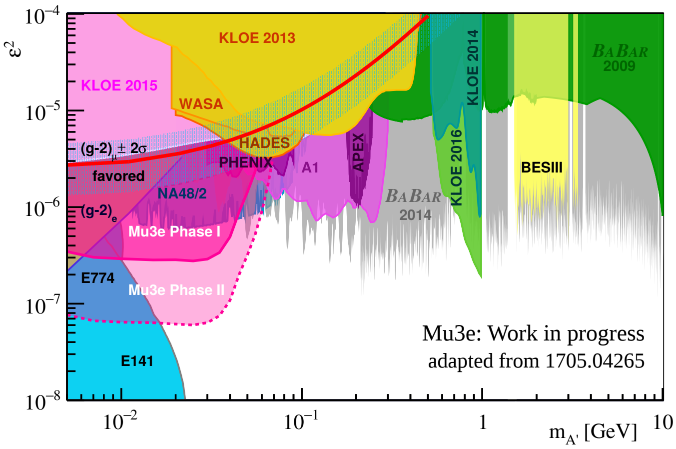


Other Exotic Physics with Mu3e

Dark Photons

- Large dataset of muon decays can be exploited in other searches
- Ex: Dark photon emitted in muon decays with prompt decay
  $\rightarrow$ Resonance in e^+e^-



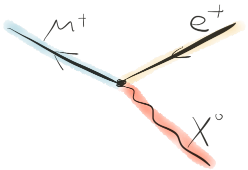


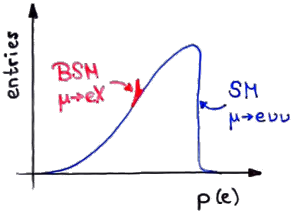
Lagrangian from Echenard, Essig, Zhong, JHEP 01 (2015) 113

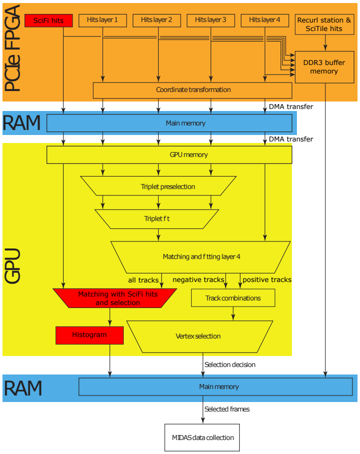
Other Exotic Physics with Mu3e

Familons

- Search for $\mu^+ \to e^+ X^0$ decays
- Ex: Familon
  (Goldstone boson from spontaneously broken flavour symmetry, Wilczek, PRL 49 (1982) 1549)







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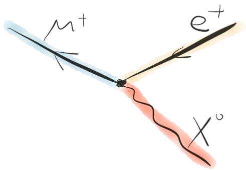

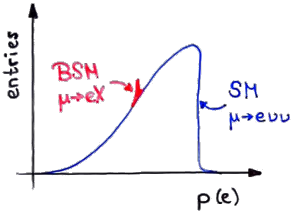

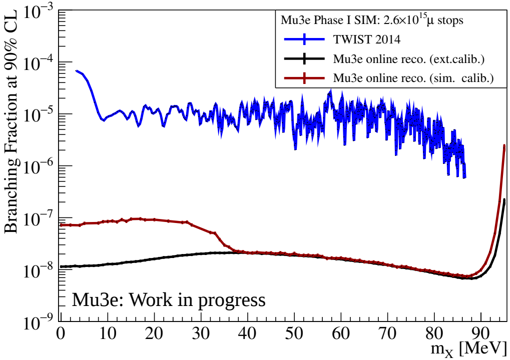

- Challenge: single-e events are not saved
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Summary

Karlsruhe Institute of Technology

- Observation of lepton flavour violation would be an unambiguous sign of BSM physics

- World's strongest exclusion limits in full Run 2 ATLAS search
  $\mathscr{B}(Z \to e\tau) < 5.0 \times 10^{-6}$ at 95% CL
  $\mathscr{B}(Z \to \mu\tau < 6.5 \times 10^{-6}$ at 95% CL

- Mu3e aims to search for the LFV decay $\mu \to eee$ with an ultimate sensitivity of 10^{-16}
- Opportunities for searches beyond $\mu \to eee$

ATLAS EXPERIMENT

τ_{had} channel

Nat.Phys. 17 (2021) 819–825

τ_{lep} and combination

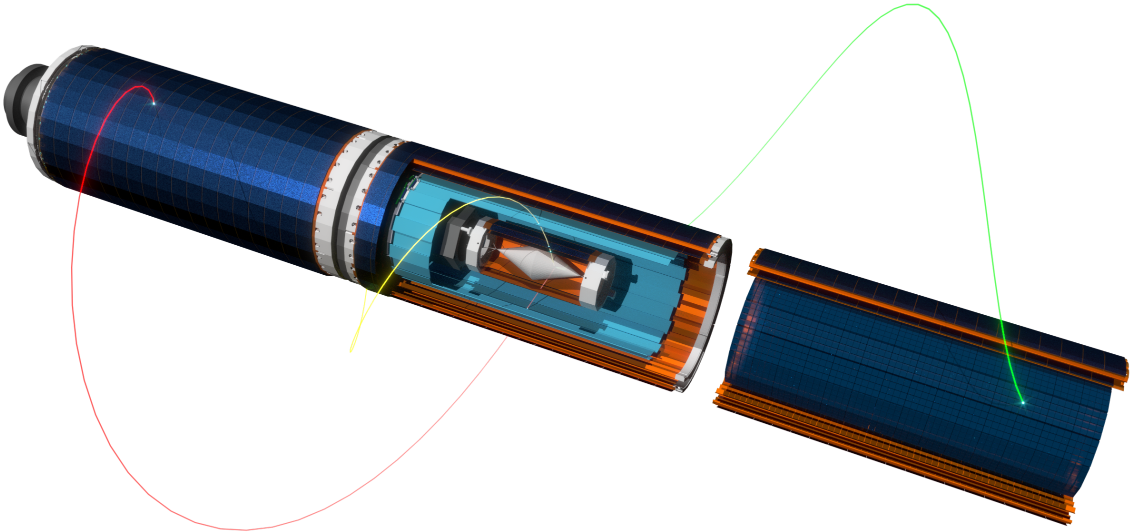
PRL 127 (2022) 271801

Mu3e TDR

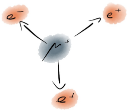
NIM A 1014 (2021) 165679

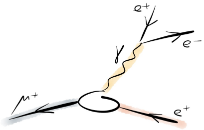
Mu3e at PSI

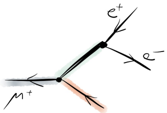
www.psi.ch/en/mu3e

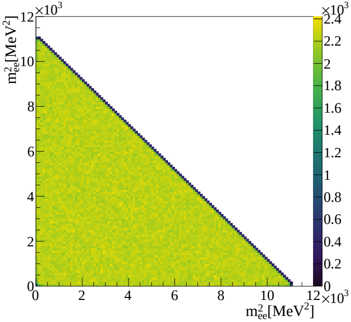


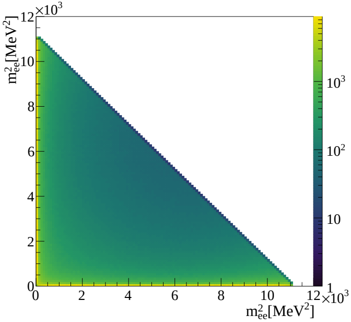
Mu3e Experiment
Signal Decay with EFTs

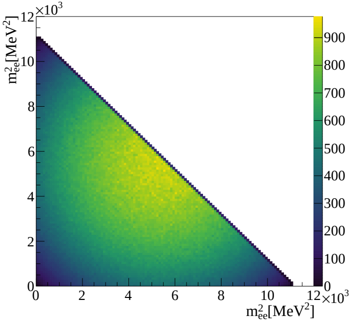










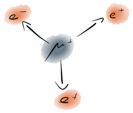


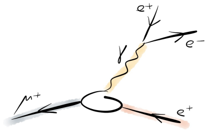
Generated

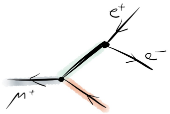
Lagrangian from Kuno, Okada, Rev.Mod.Phys. 73 (2001) 151-202

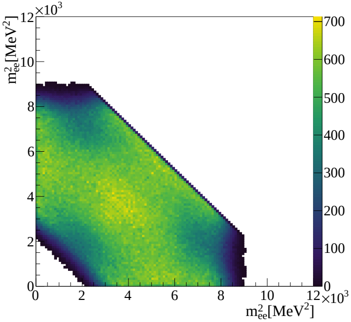
Mu3e Experiment

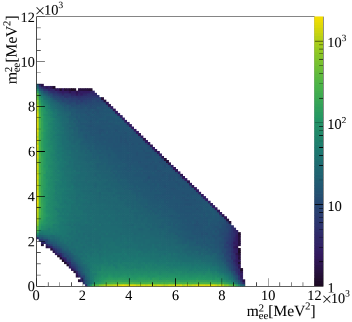
Signal Decay with EFTs

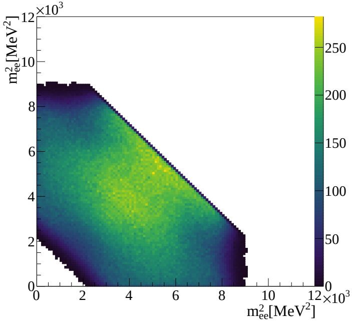












Reconstructed

Lagrangian from Kuno, Okada, Rev.Mod.Phys. 73 (2001) 151-202