Light flavour physics
Muon and Kaon decays

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Non-Collider Physics
Mainz, April 2017

JG|U

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

Flavour-changing neutral currents as probes for new physics

- NA62 measures $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

  (Standard model at ~ 10^{-10})

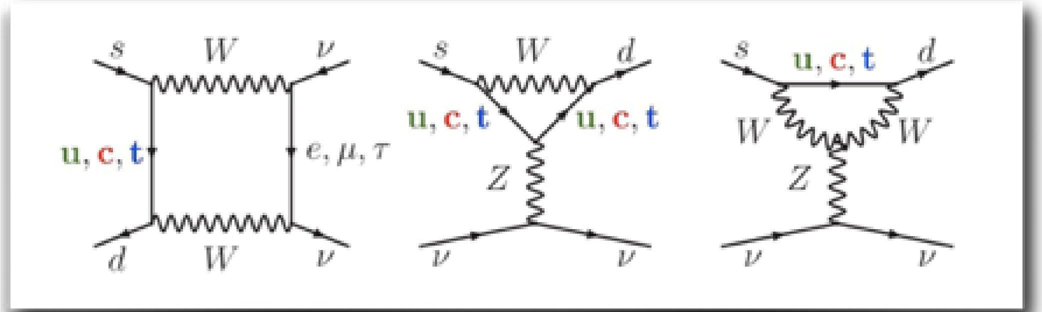
- Mu3e searches $\mu^+ \rightarrow e^+ e^- e^+$

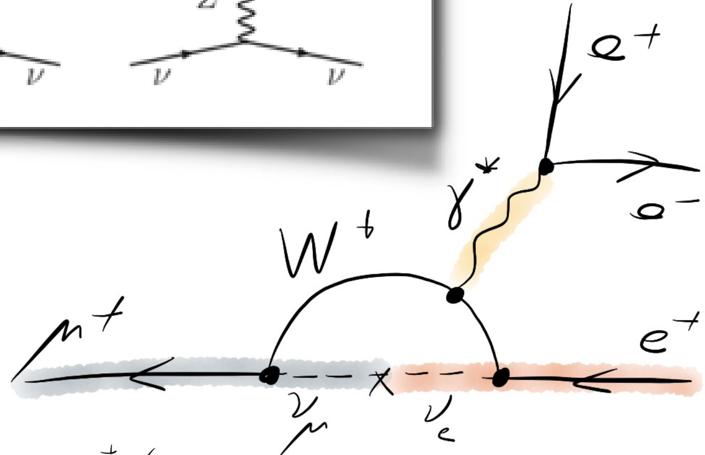
  (Standard model at ~ 10^{-54})

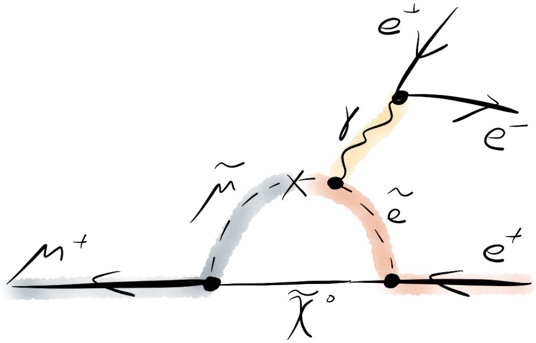
- Both extremely sensitive for new physics out to very large mass scales

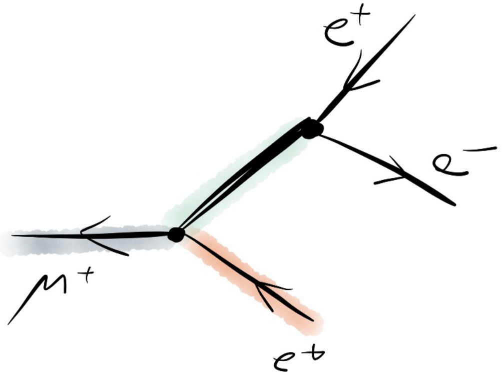
- Or very weakly coupled MeVish new particles

- Complementary to collider searches









Kaon decays in NA62 and beyond

Thanks to R. Wanke for all the input

NA62 at the CERN SPS

Measurement of:

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

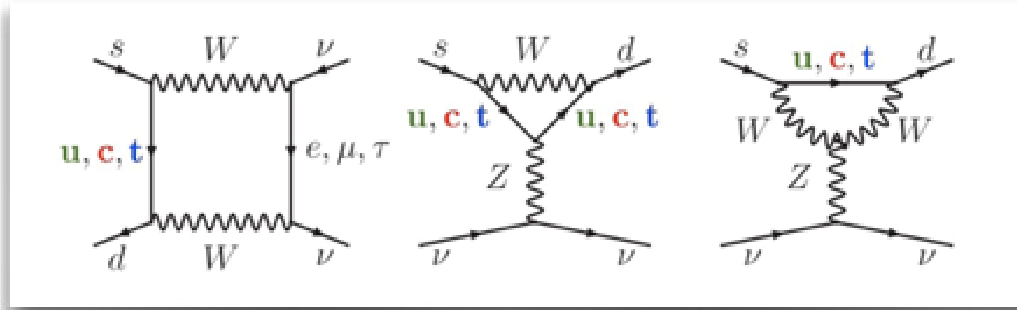
- Golden channel for physics beyond SM
- Standard model ($V_{ts}\ V^*_{td}$):

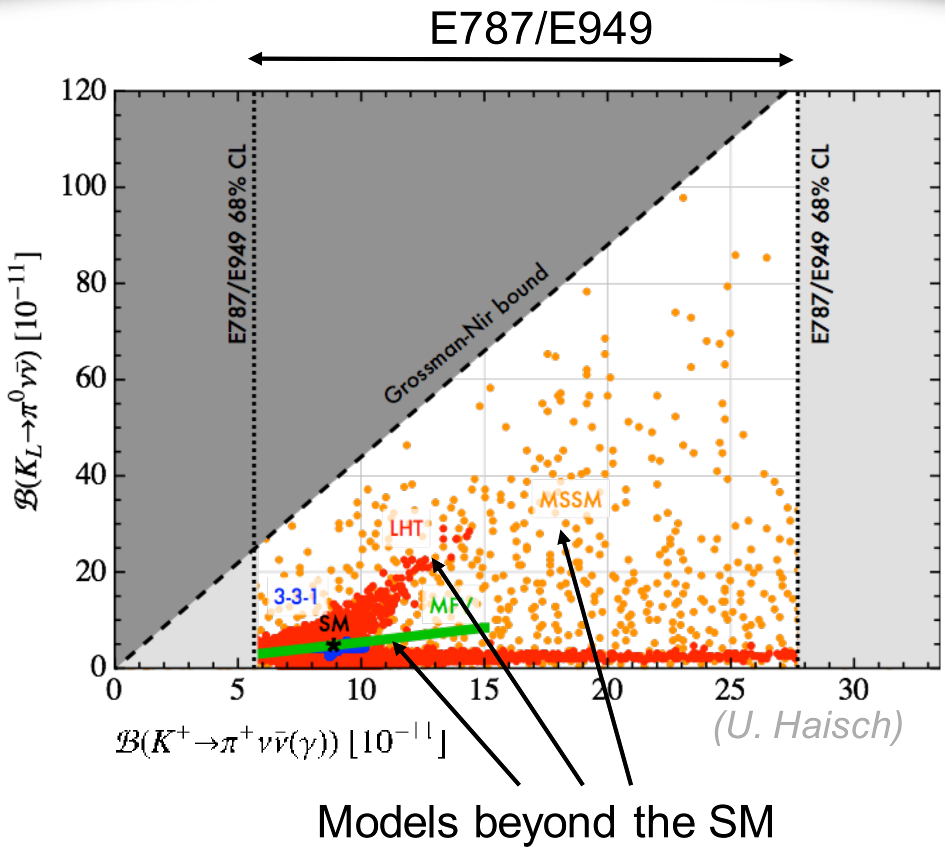
  $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 8 \cdot 10^{-11}$

- Previous measurement (E787/E949, 2008)

  $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17 \pm 11) \cdot 10^{-11}$

- Complementary: KOTO (JPARC): $K_L \rightarrow \pi^0 \nu \bar{\nu}$

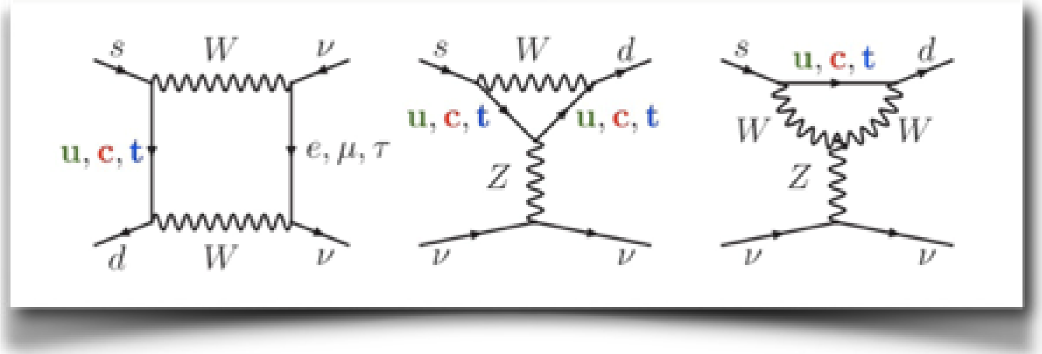


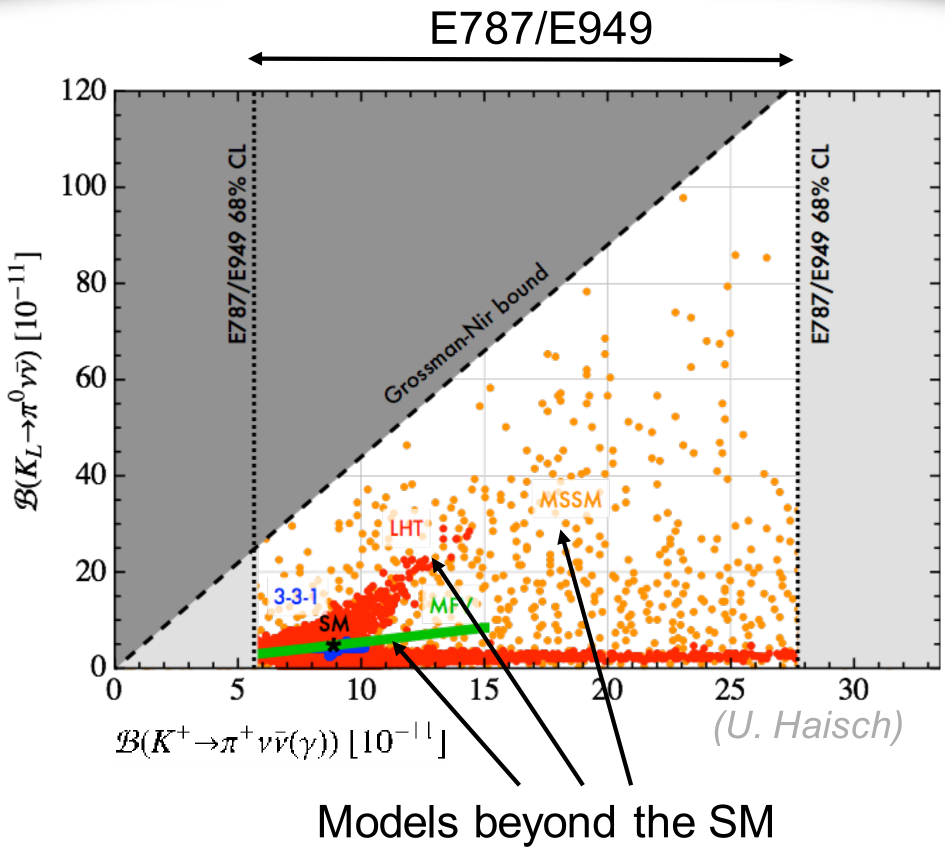


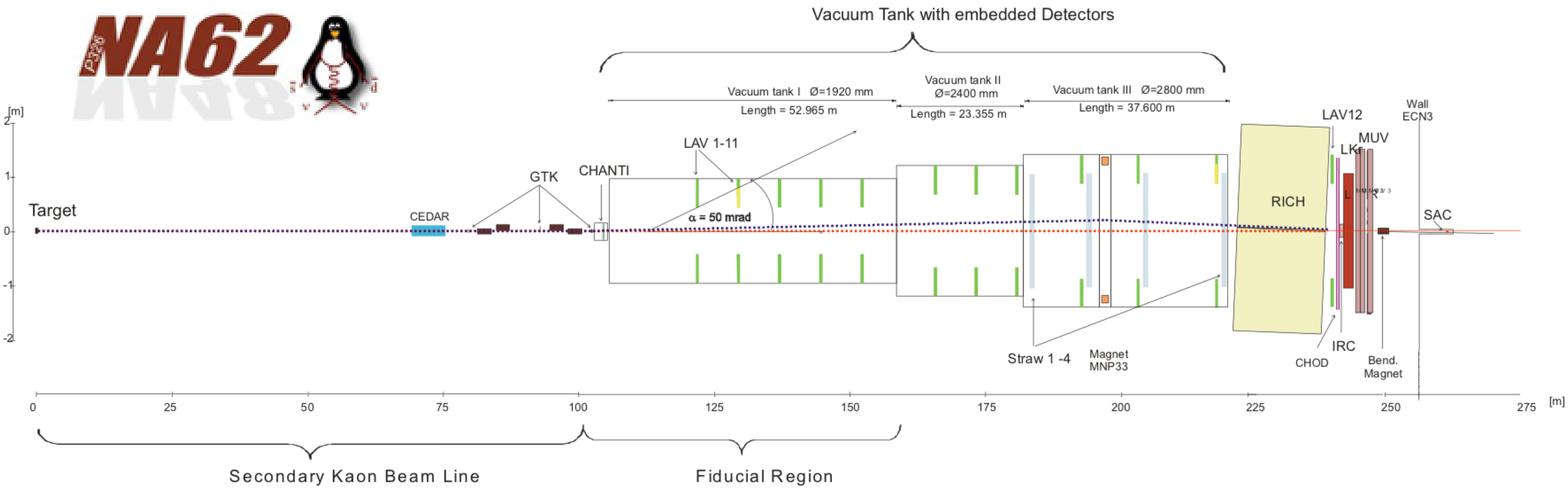
NA62 at the CERN SPS

Measurement of: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- Aim for ~100 decays
- Signal/Background 5-10
- Fixed-target experiment at the SPS
- ~ 10^{13} kaon decays/year in fiducial volume
- Three years of data taking 2016-2018





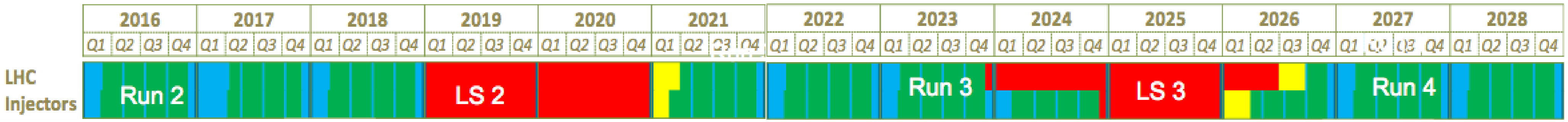


29 institutes from 13 countries

German contribution,
Mainz: V. Büscher, R. Wanke

- Hadron calorimeter/muon veto system
- Hodoscope for charged particles
- L1/L2 PC farm
- Data analysis

Time scale



$K^+ \to \pi^+ \nu \bar{\nu}$	Broad physics program	KLEVER

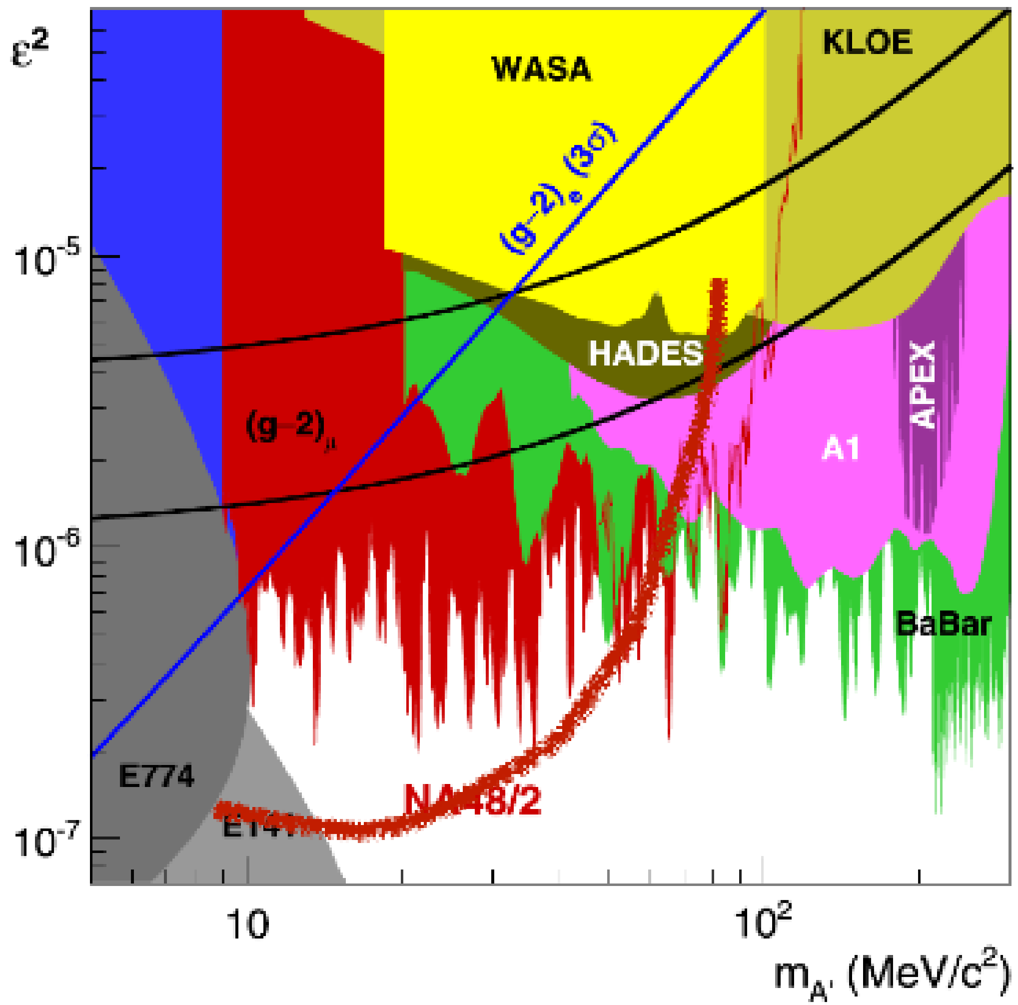
- 2016: Sensitivity for 1 SM event (result in summer)
- 2017/18: 10% measurement of $K^+ \to \pi^+ \nu \bar{\nu}$
- As much other physics as trigger allows

- Lepton Flavour Violation/ Lepton Number Violation
- Rare π^0 decays
- Heavy neutrinos, "hidden sector" particles

- Measurement of $K_L \to \pi^0 \nu \bar{\nu}$

Example: Dark Photon in π^0 decay

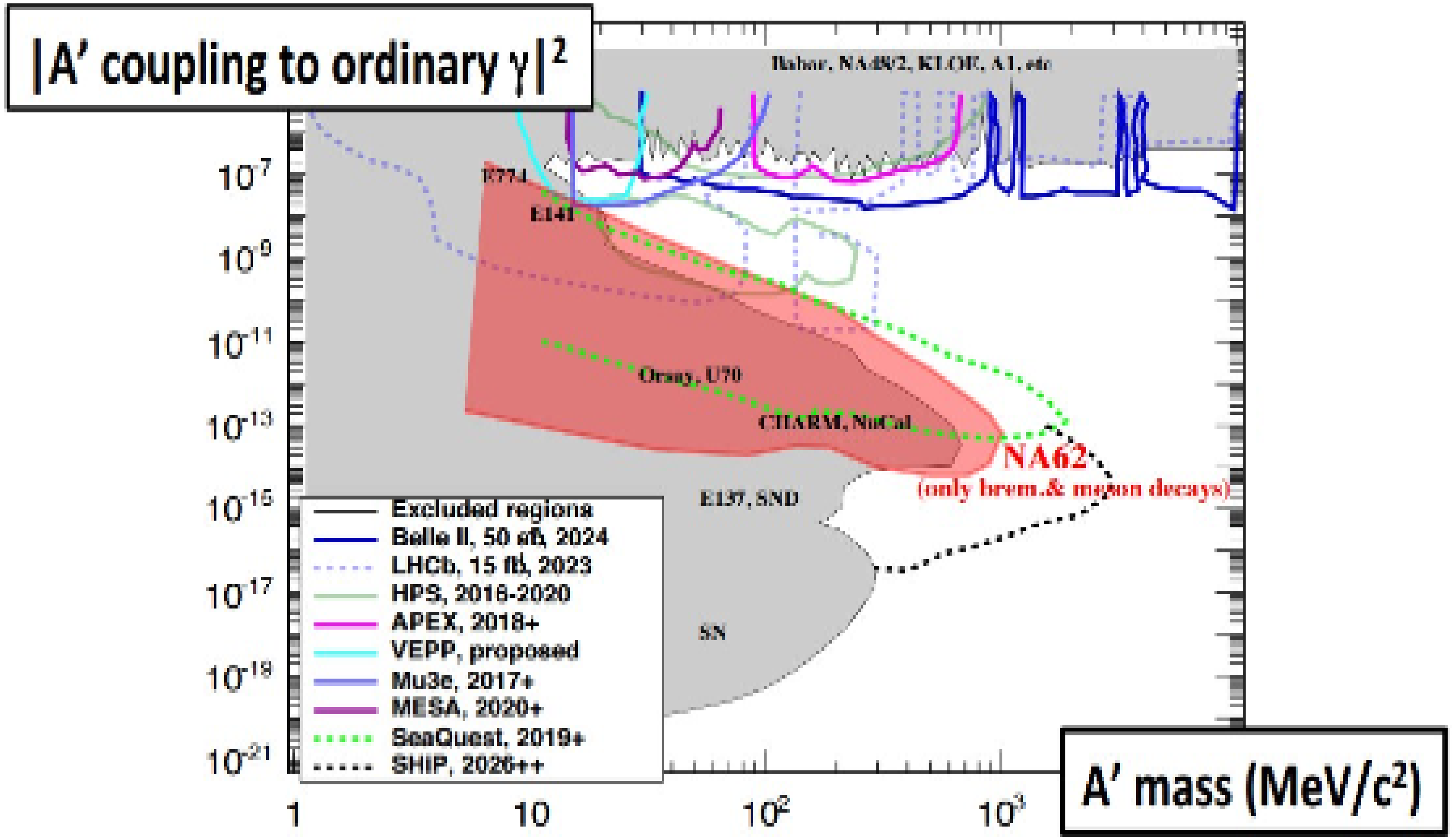
- Search for $\pi^0 \rightarrow A' \gamma$ with $A' \rightarrow e^+e^-$
- Expect 10^8 $\pi^0 \rightarrow \gamma\, e^+e^-$ decays a year
- m_{ee} resolution ~ 1 MeV
- Sensitive to $m_{A'} < 100$ MeV at $\varepsilon \approx 10^{-3}$



NA62 in beam dump mode

- Close collimators
- Search for long-lived neutral particles:

Dark photon:
$A' \rightarrow e^+e^-$ and $\mu^+\mu^-$

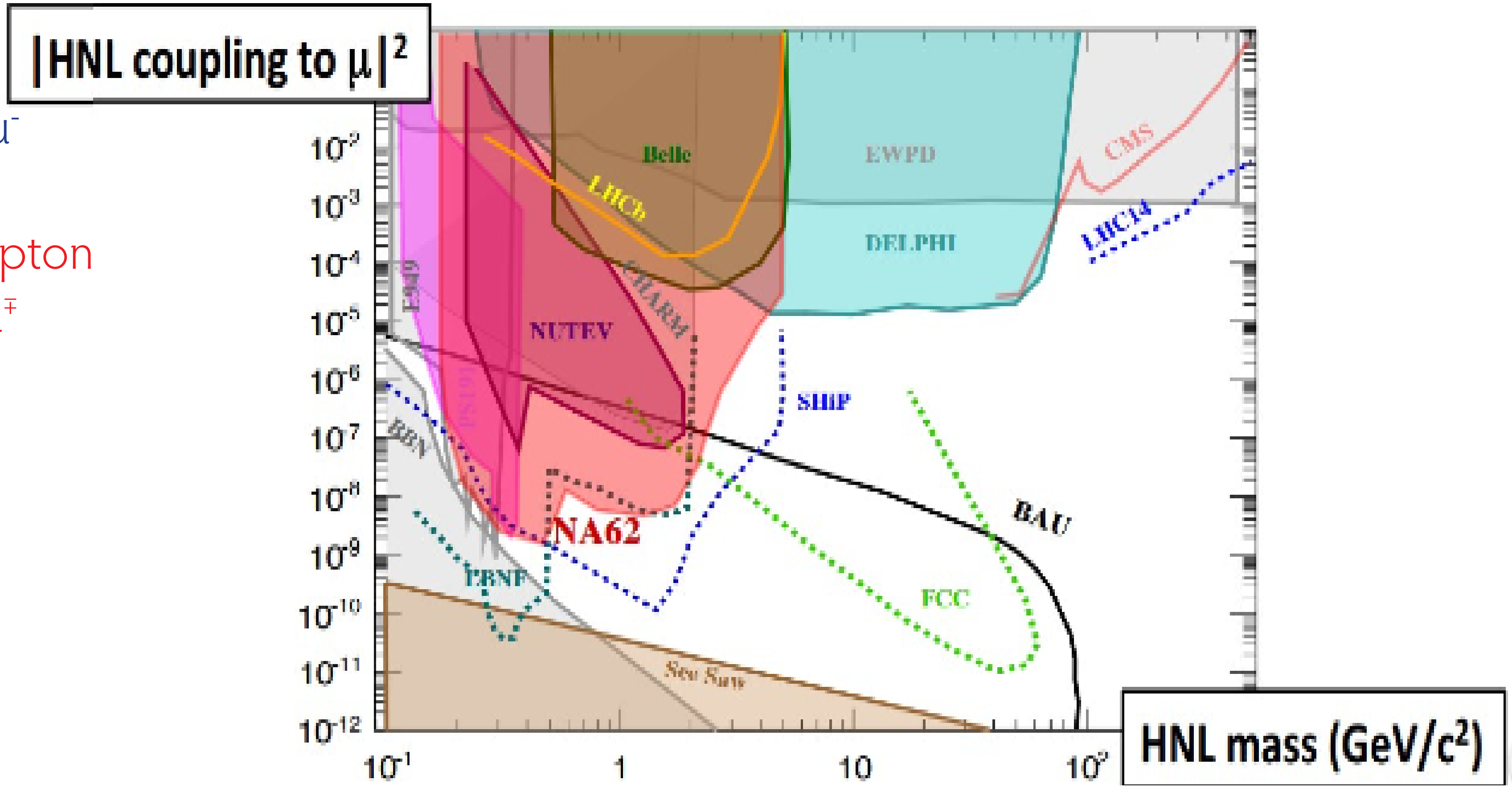


NA62 in beam dump mode

- Close collimators
- Search for long-lived neutral particles:

Dark photon
$A' \rightarrow e^+e^-$ and $\mu^+\mu^-$

Heavy neutral lepton
$HNL \rightarrow \pi^\pm e^\mp / \pi^\pm \mu^\mp$



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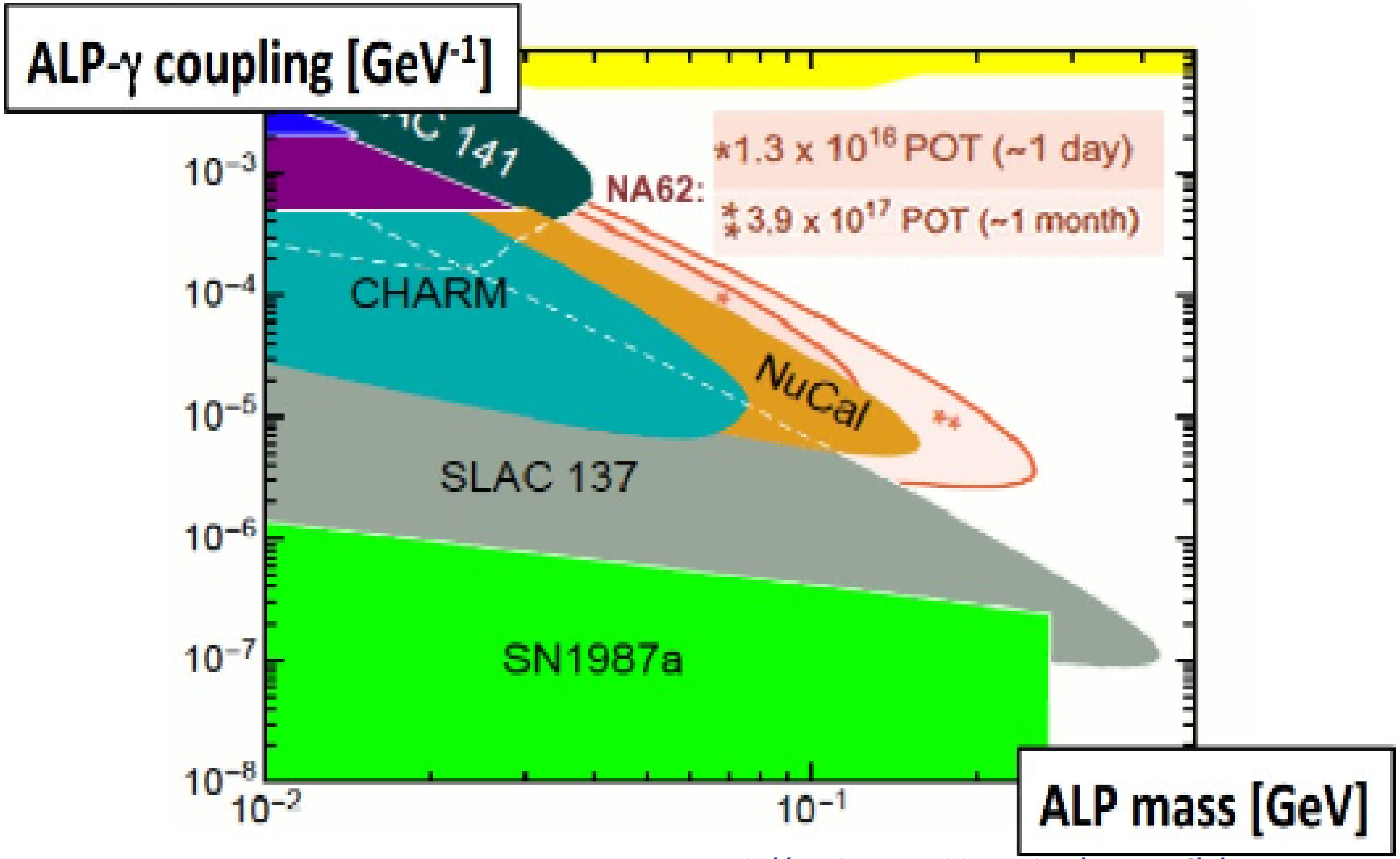
Dark photon
$A' \rightarrow e^+e^-$ and $\mu^+\mu^-$

Heavy neutral lepton
$HNL \rightarrow \pi^\pm e^\mp / \pi^\pm \mu^\mp$

Axion-like particles
$ALP \rightarrow \gamma\gamma$



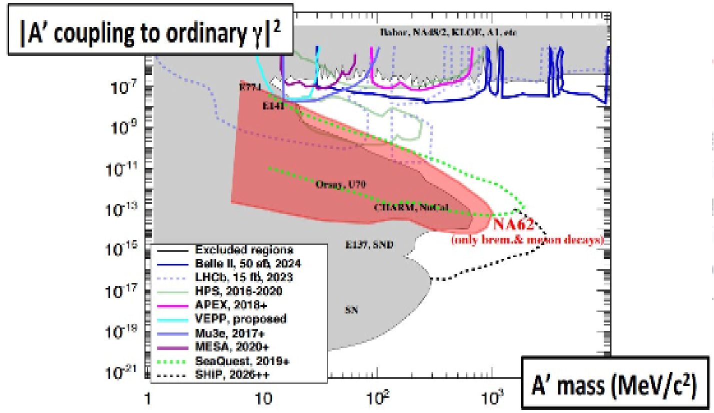
NA62 in beam dump mode

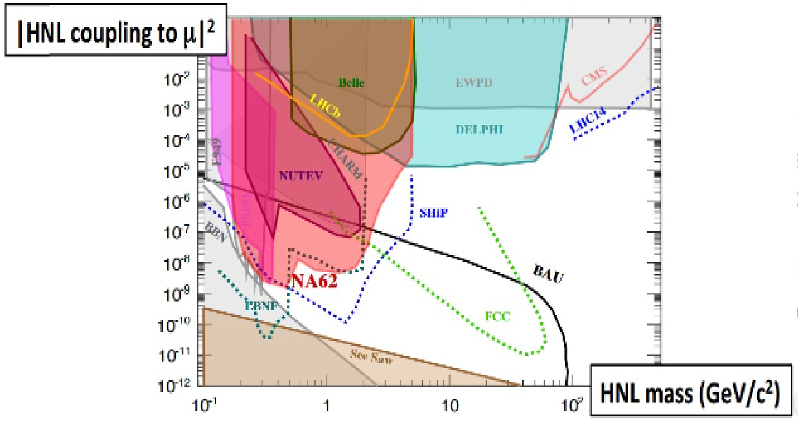
- Close collimators
- Search for long-lived neutral particles
- Similar to SHiP, 5 years earlier

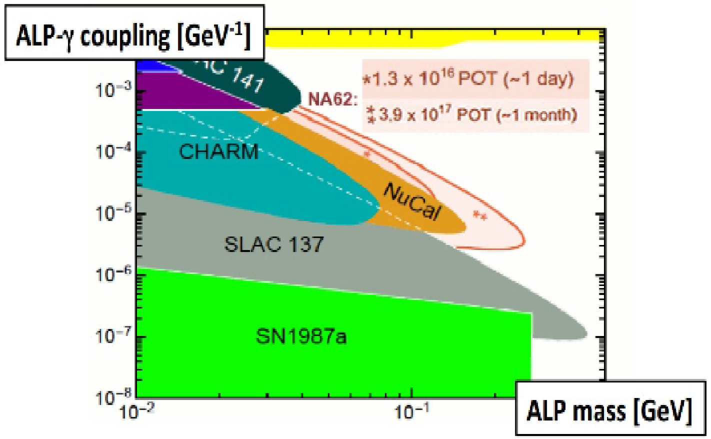
- Changes to detector:

  Veto-detector to suppress particles upstream of decay region
  (Interest of Italian and Russian groups)

  Preshower detector for photon direction:
  m_X in $X \rightarrow \gamma\,\gamma$
  (Interest of Mainz, synergy with SHiP)



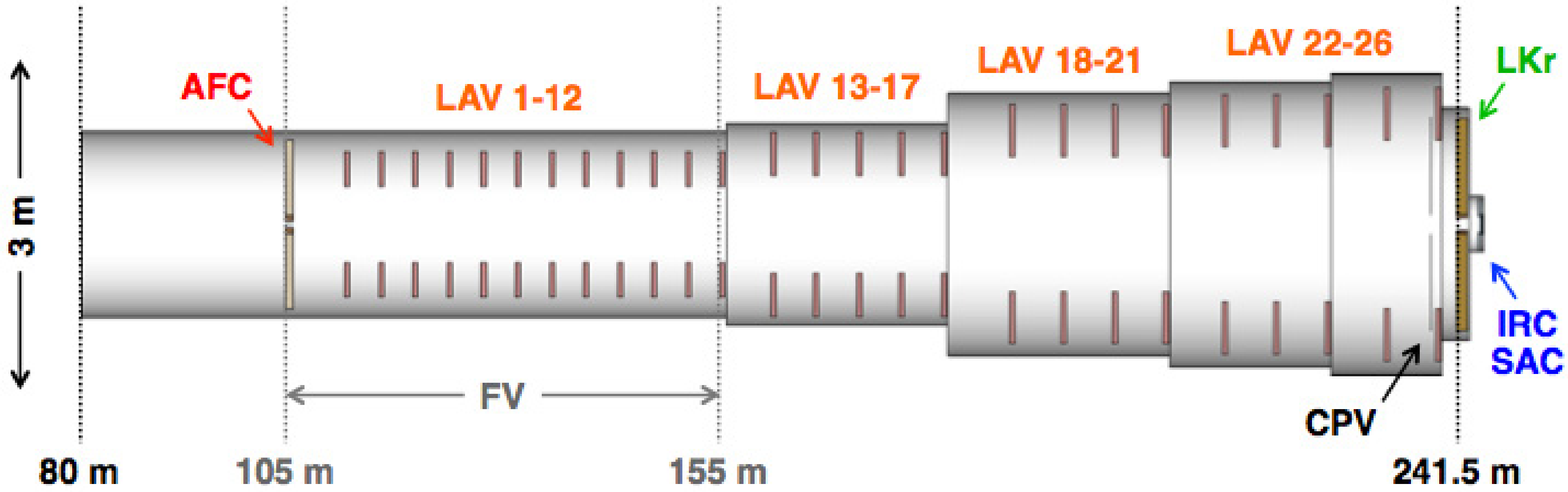




KLEVER

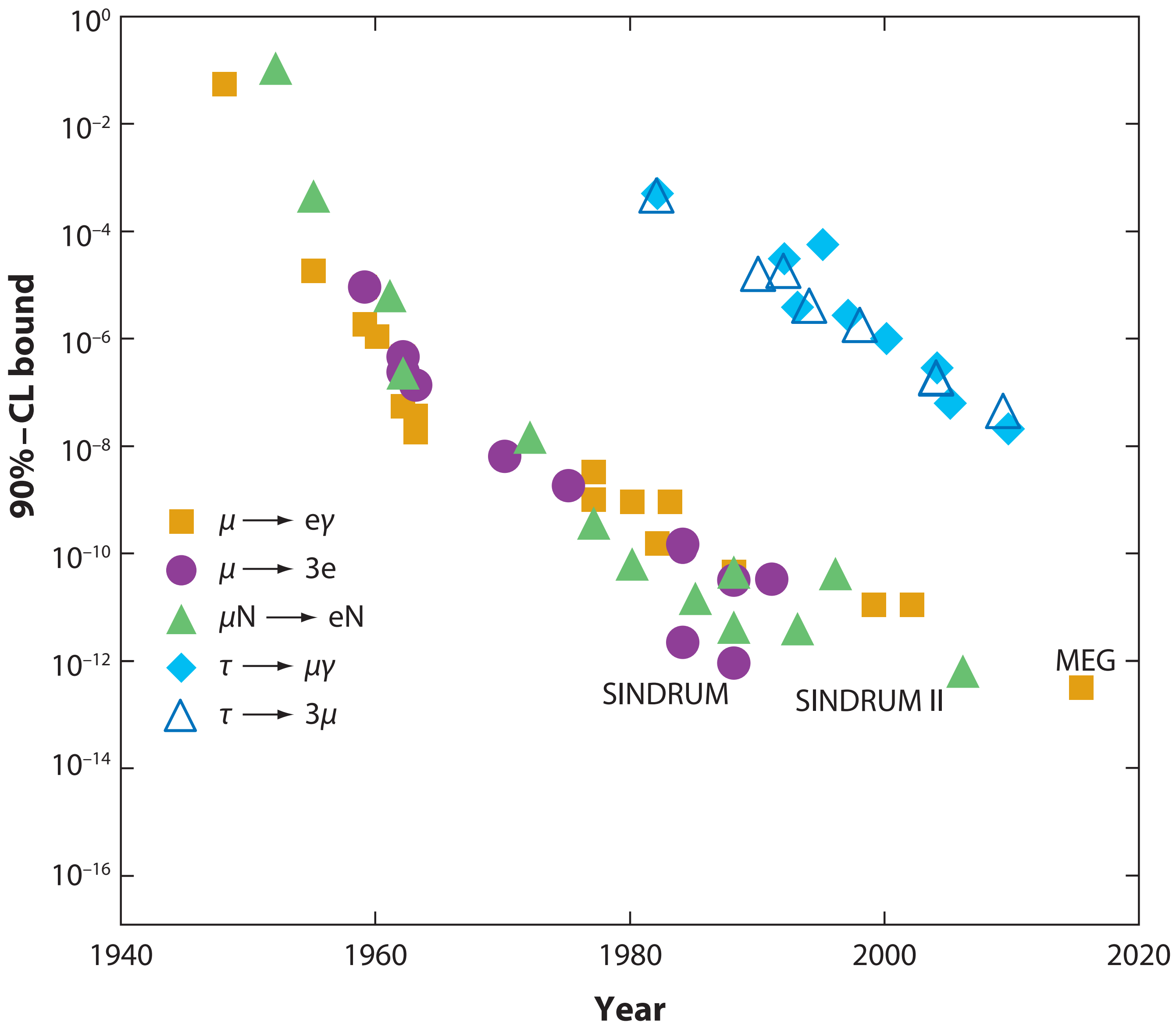
- Measure ~ 100 $K_L \rightarrow \pi^0 \nu \bar{\nu}$ events
- Signal/Background ~ 1
- Almost completely new experiment:
  Reuse calorimeter, but new veto system

- Proposal well-founded
  feasibility and financing need to be demonstrated



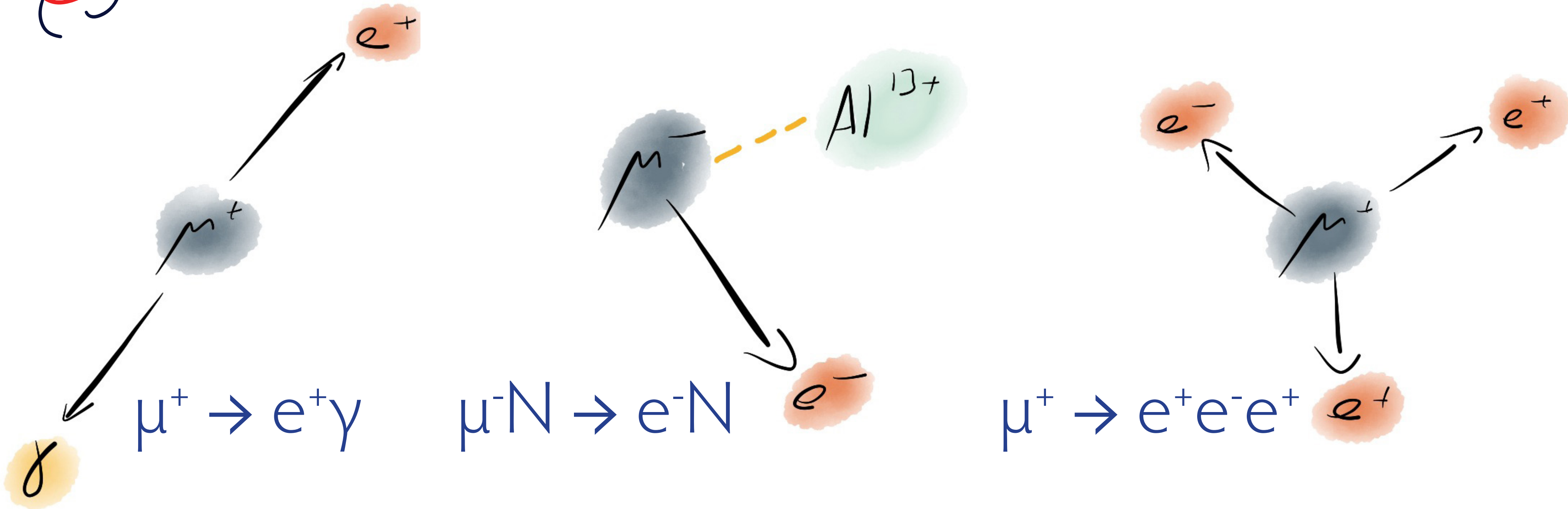
Searching for Lepton Flavour Violation with Mu3e

History of Lepton Flavour Violation searches



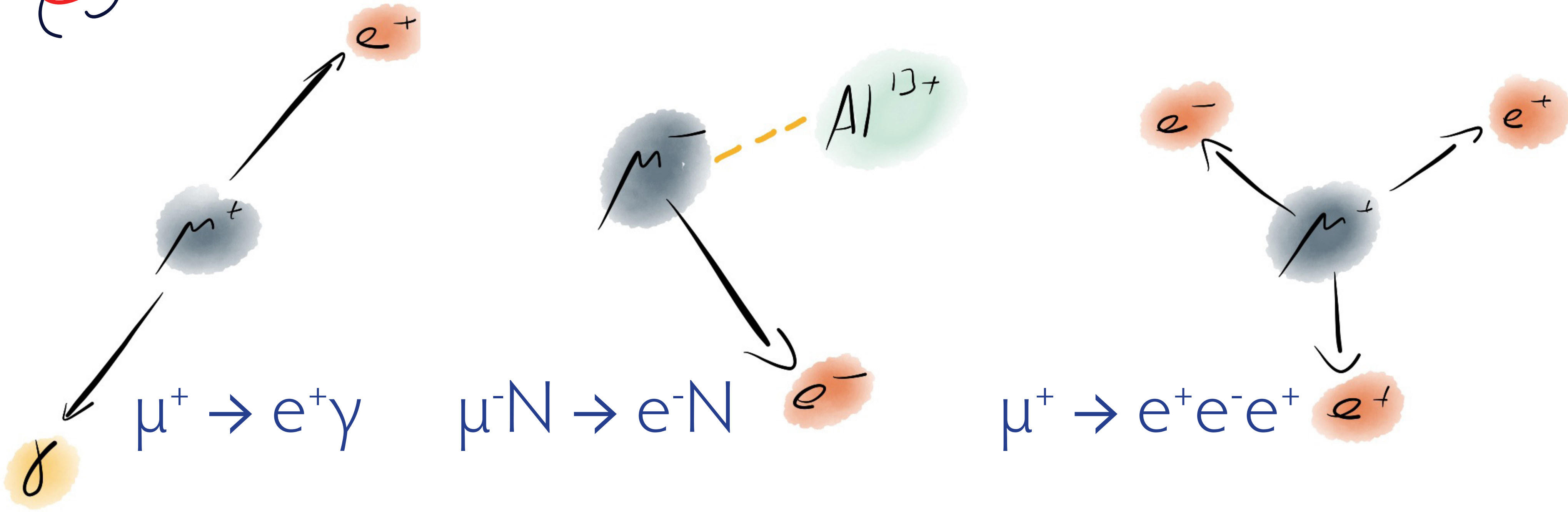
(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

LFV Muon Decays: Experimental Situation



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

LFV Muon Decays: Experimental Situation



MEG (PSI)

$B(\mu^+ \to e^+\gamma) < 4.2 \cdot 10^{-13}$

(2016)

SINDRUM II (PSI)

$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$

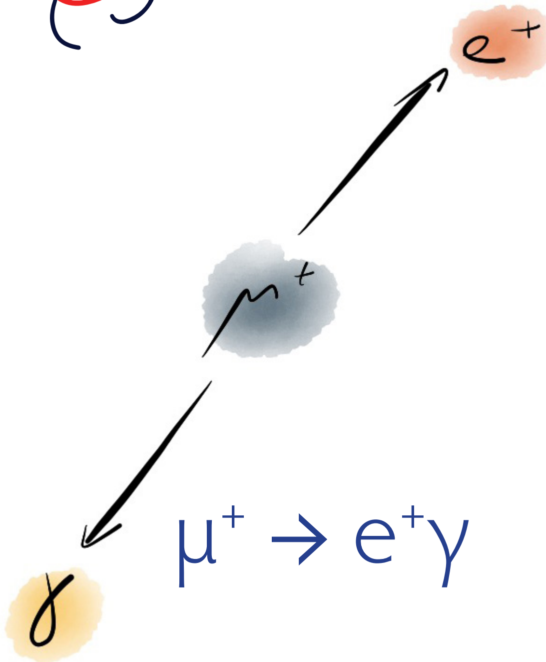
(2006)

SINDRUM (PSI)

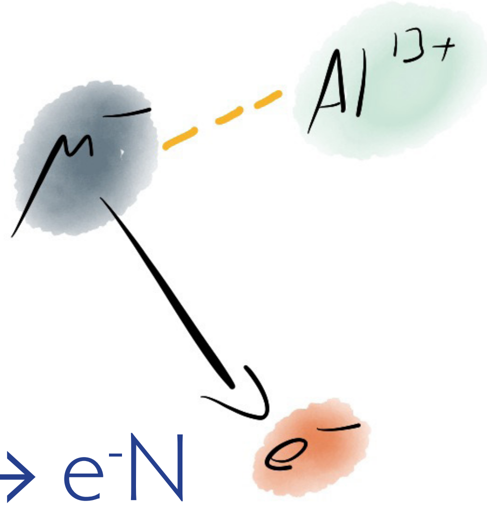
$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$

(1988)

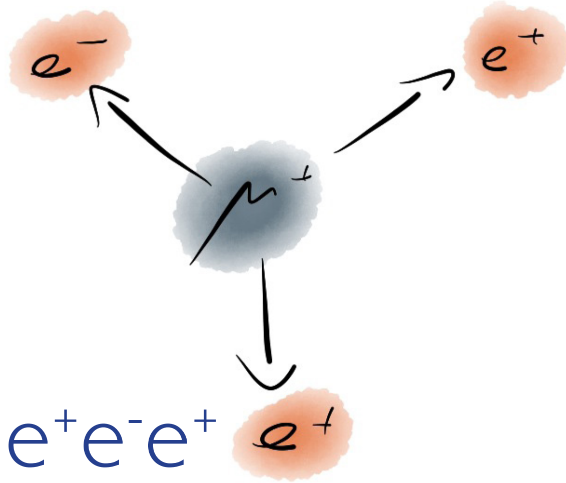
LFV Muon Decays: Experimental Situation



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



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



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

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$B(\mu^+ \rightarrow e^+\gamma) < 4.2 \cdot 10^{-13}$

(2016)

upgrading

SINDRUM II (PSI)

$B(\mu^- Au \rightarrow e^- Au) < 7 \cdot 10^{-13}$

(2006)

Mu2e/Comet

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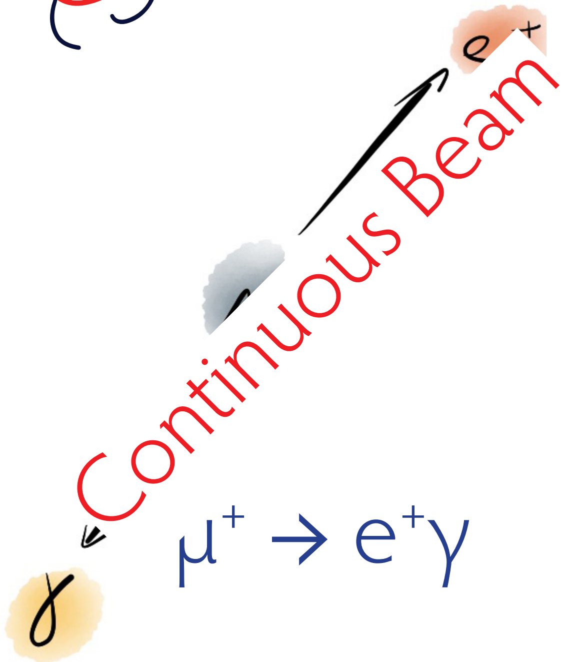
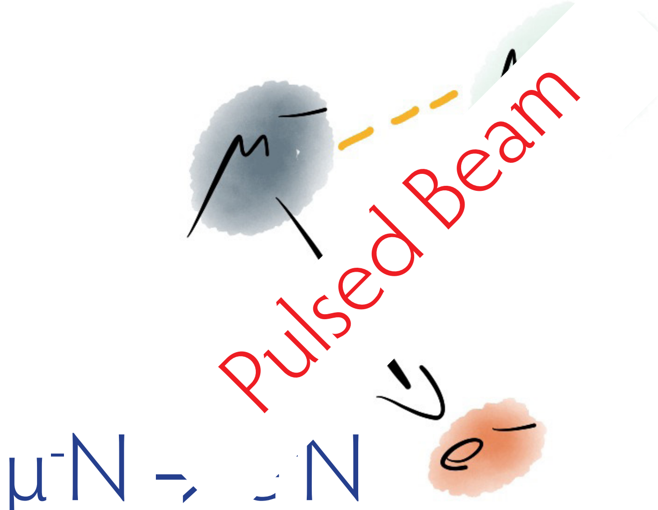
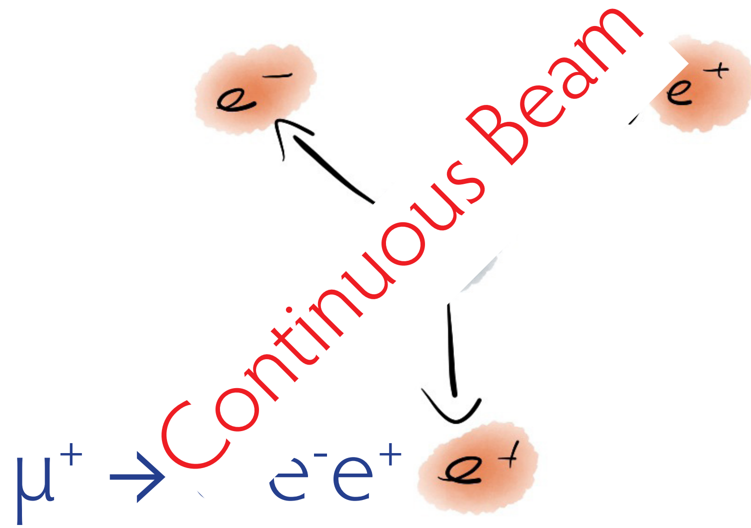
(1988)

Mu3e

LFV Muon Decays: Experimental Situation



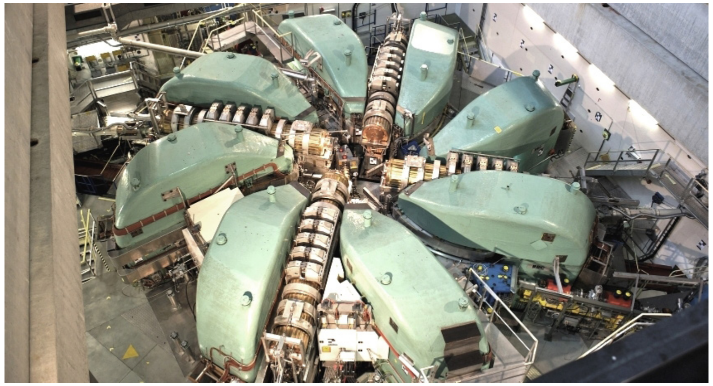




MEG (PSI)	SINDRUM II (PSI)	SINDRUM (PSI)
$B(\mu^+ \to e^+\gamma) < 4.2 \cdot 10^{-13}$	$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$	$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$
(2016)	(2006)	(1988)
upgrading	Mu2e/Comet	Mu3e

Low Energy Muon Beams

PSI



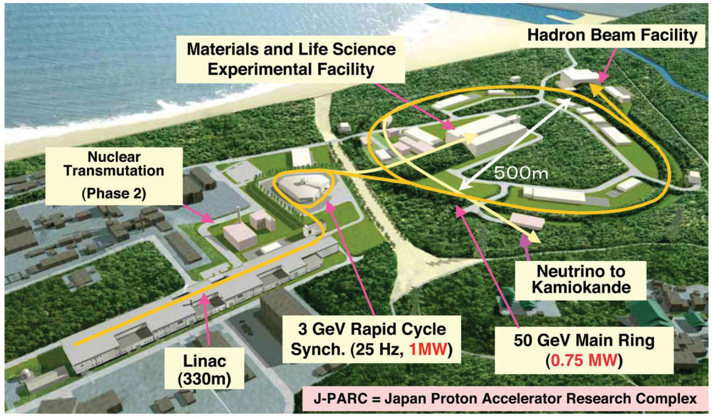
World's most intensive proton beam

2.2 mA at 590 MeV: 1.3 MW of beam power

10^8 μ/s available
Study for 10^{10} μ/s

Continuous beam

JPARC



10^{11} μ/s from 8 GeV/c protons

pulsed

Fermilab

Re-use part of the Tevatron infrastructure

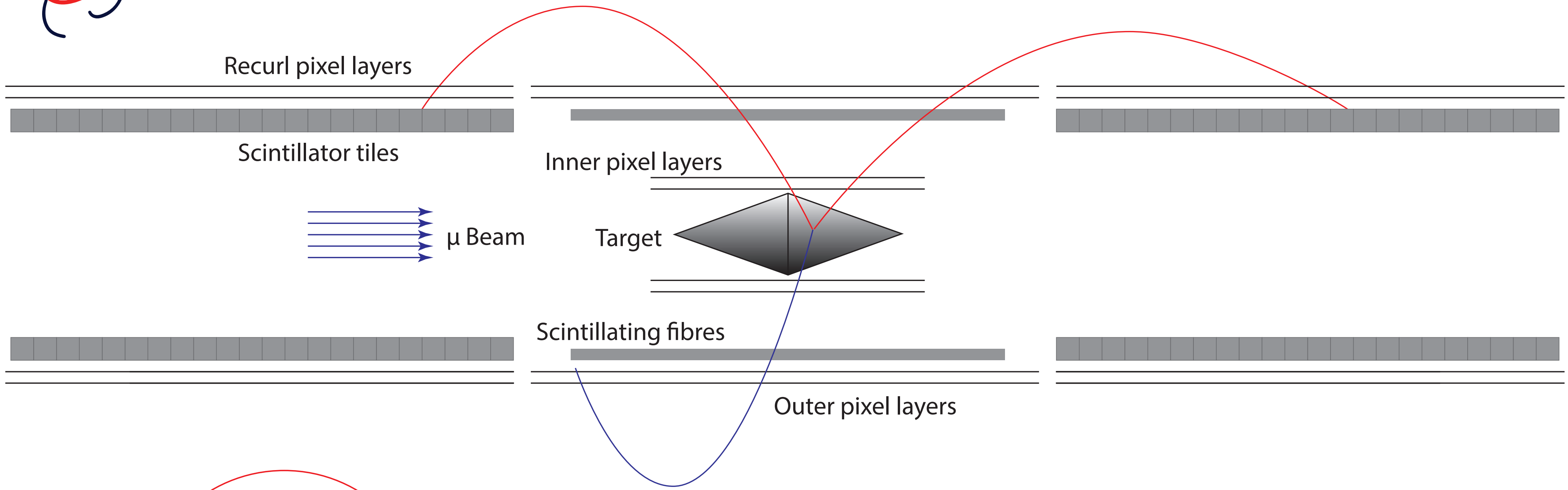
Proton pulses every 1700 ns
> 10^{10} μ/s

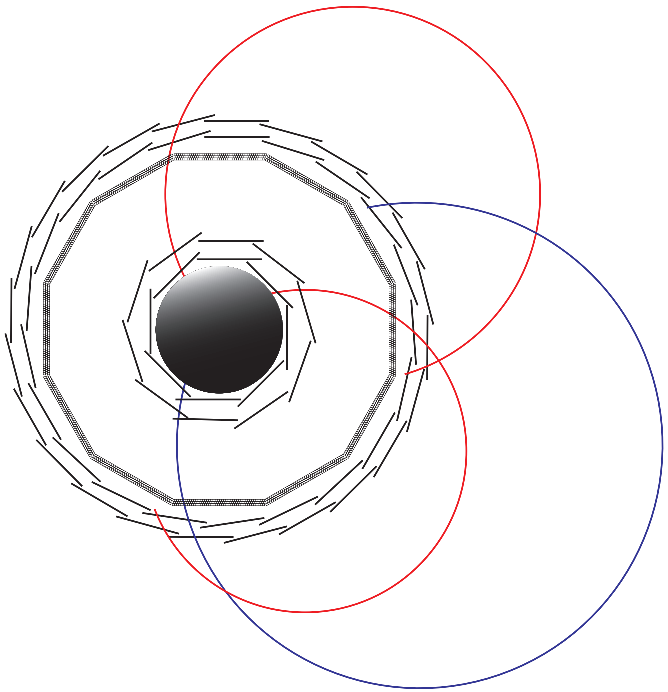
Proton Improvement Plan-II: another 2 orders of magnitude

The Mu3e Collaboration

- DPNC, Geneva University
- Physics Institute, Heidelberg University
- KIP, Heidelberg University
- IPE, Karlsruhe Institute of Technology
- Institute of Nuclear Physics, JGU Mainz
- Paul Scherrer Institute
- Physics Institute, Zürich University
- Institute for Particle Physics, ETH Zürich
- UK institutes in the process of joining

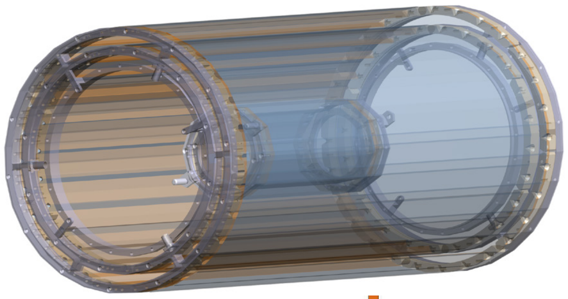
The Mu3e Detector

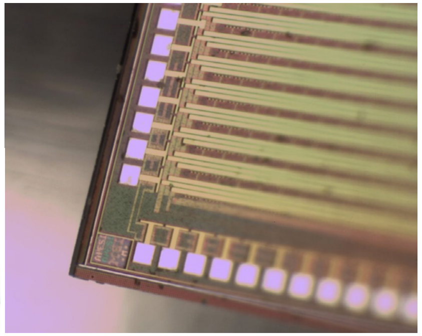


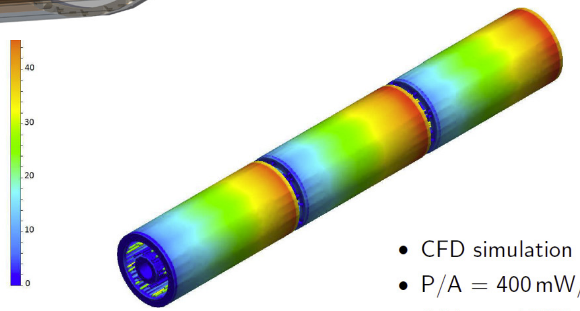


- HV-MAPS pixel detector: Heidelberg (Schöning), Karlsruhe (Perić) + UK
- Tile detector: Heidelberg (Schultz-Coulon)
- Fibre detector: PSI, ETHZ, Geneva
- DAQ, filter farm, reconstruction: Mainz (Berger)
- Beam and infrastructure: PSI

Mu3e highlights

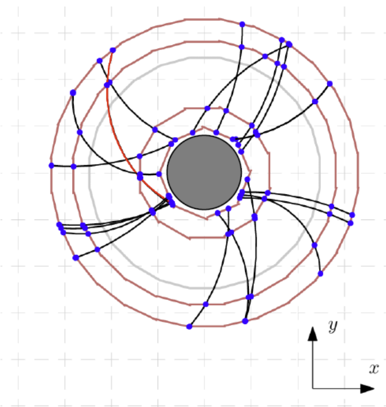


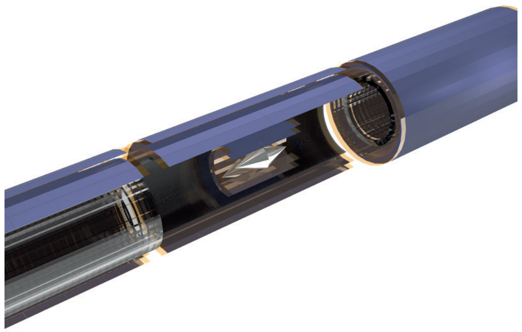




- CFD simulation
- P/A = 400 mW/cm^2
- $\Delta T_{max} < 50°C$

Technical design of the Phase I
Mu3e Experiment

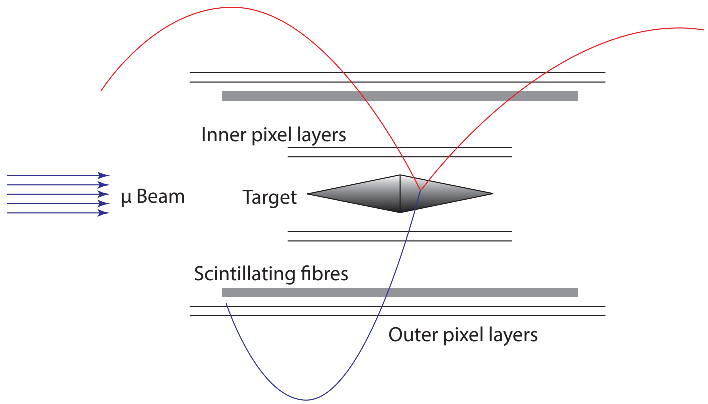




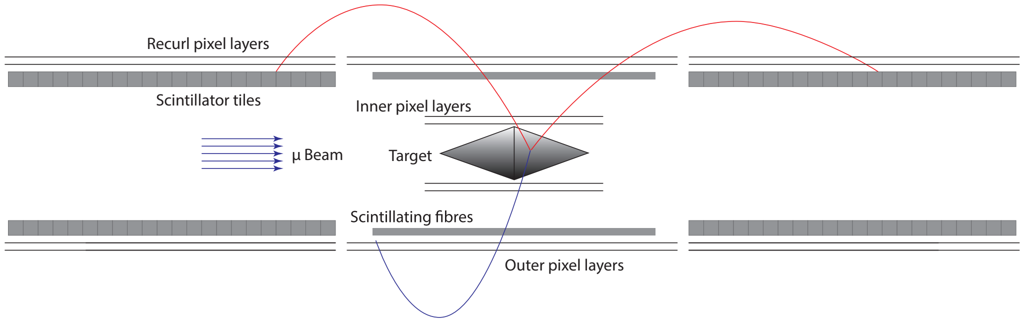
- First large-scale use of HV-MAPS detectors
- Pixel layers just 0.1% X_0 thick
- Innovative gaseous Helium cooling
- New track fit, reconstructing all 10^8 tracks/s on just 12 GPU computers
- Technical design report presented to PSI last December

Mu3e timeline

- 2019: Magnet delivery, engineering run



- 2020+: Phase I data taking
  (existing beamline)
  SES: $2 \cdot 10^{-15}$ after three years



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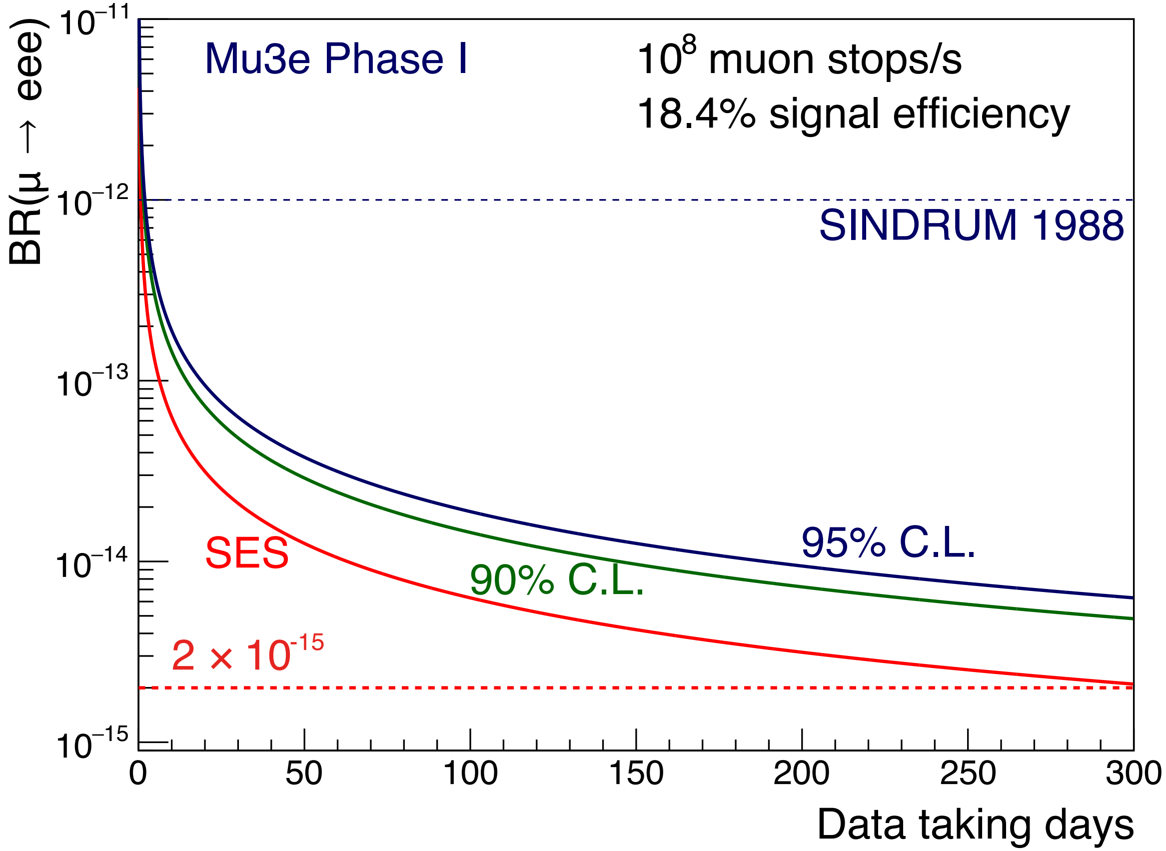
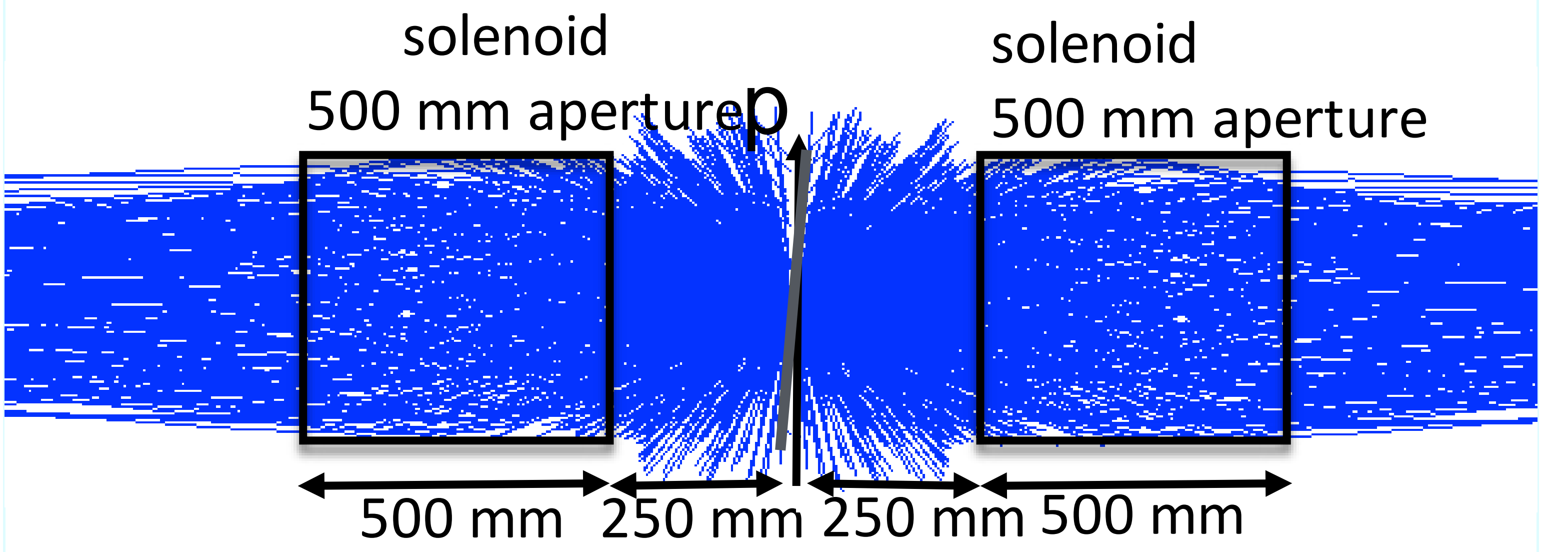


High intensity Muon Beamline HiMB

Ongoing study at PSI

- Should provide at least 10^{10} µ/s
- Mu3e as first user
- Second beamline for µSR (solid state physics)
- Requires significant investment at PSI
- PSI managment/ Swiss government decision



Mu3e timeline

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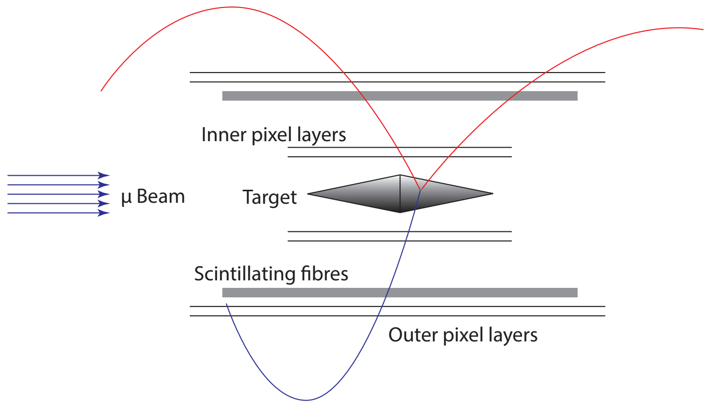

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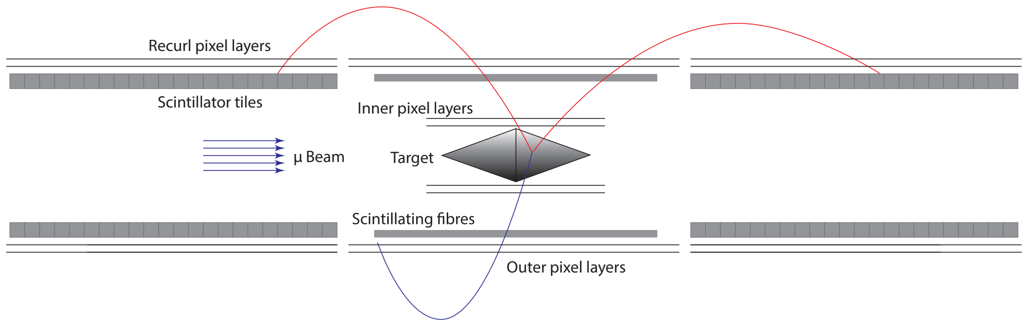
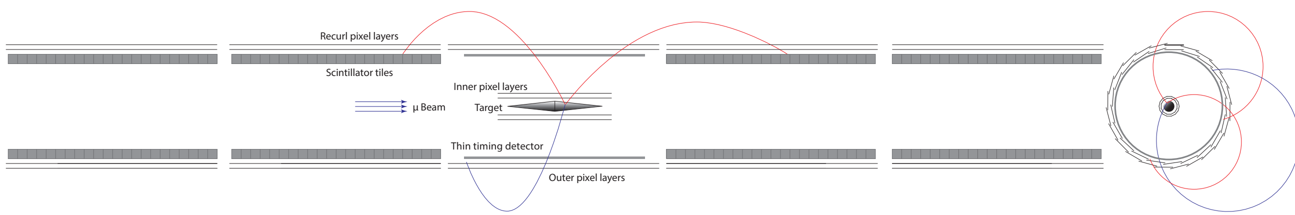


- 2023++: New beamline, phase II data taking
  SES: $1 \cdot 10^{-16}$ after three years



Mu3e beyond μ → eee

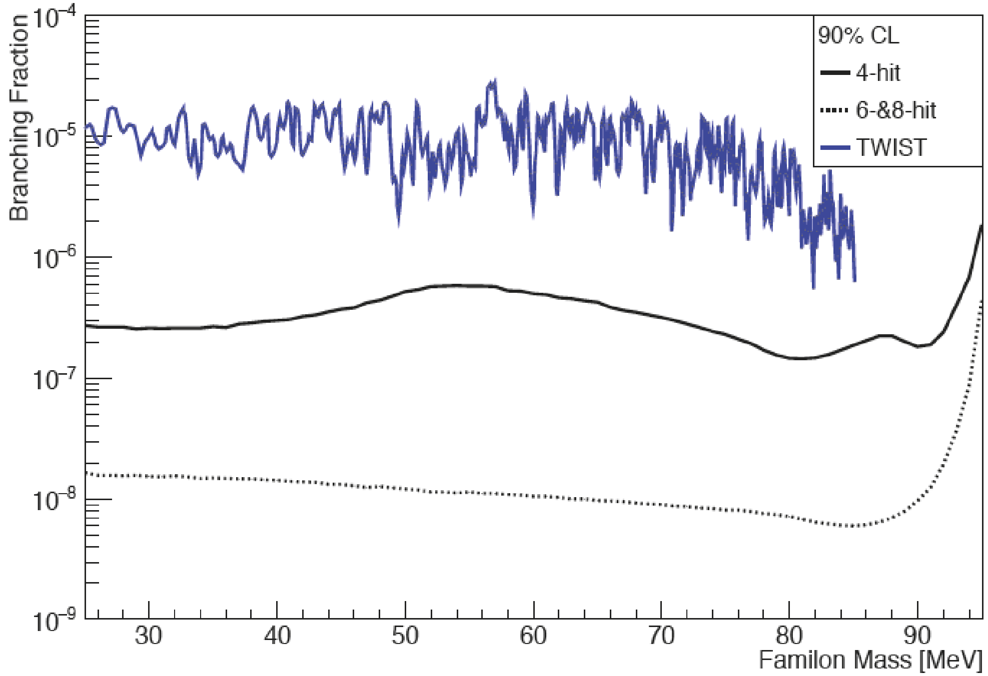
In parallel
(partially requires filter farm extensions):

- μ → e X
  X e.g. a Familon
- μ → e A' $\nu\bar{\nu}$ with A' → e^+e^-
  A' a dark photon
- μ → eeeee
  Familon induced, better with lower field

With detector modifications:

- μ → e γ with photon conversion
  SES estimated at roughly 10^{-14}
- Muonium-Antimuonium oscillations

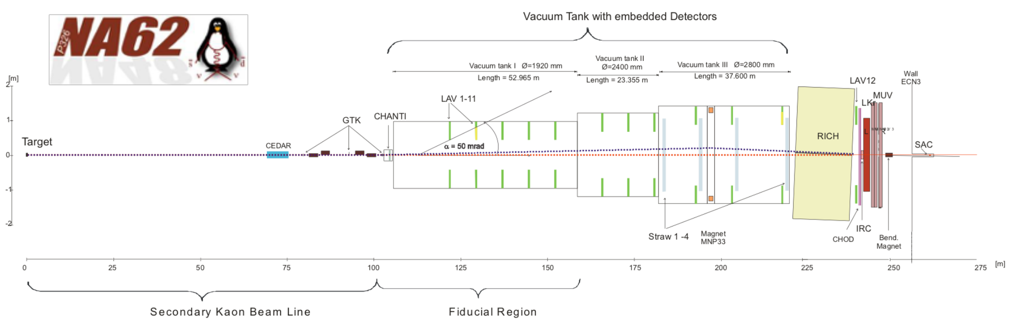
Sensitivity to $\mu \to eX$ for $1 \cdot 10^{15}$ muon stops



Summary

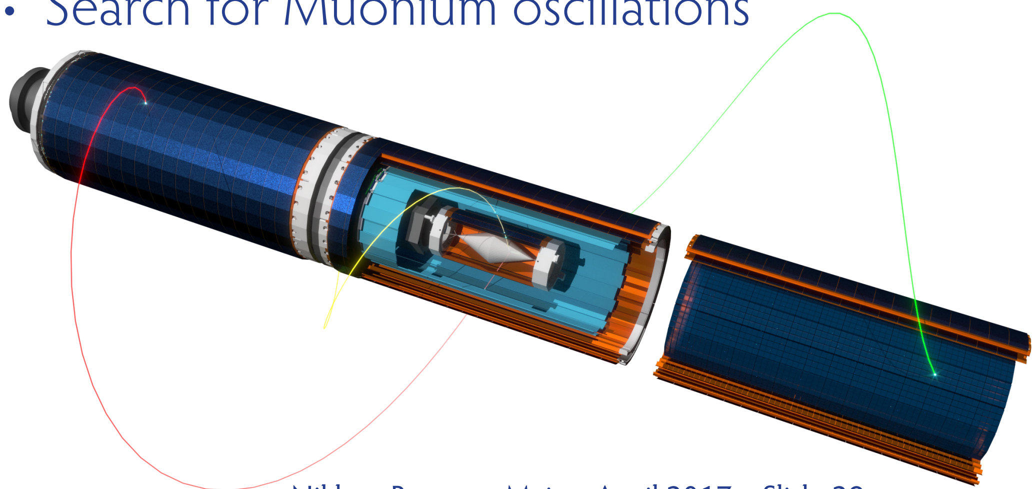
NA62 has an exciting program beyond $K^+ \rightarrow \pi^+\nu\bar{\nu}$

- Rare and forbidden decays
- Beam dump mode: Mini-SHiP
- $K_L \rightarrow \pi^0\nu\bar{\nu}$ with KLEVER



Mu3e searches for $\mu \rightarrow eee$

- Phase I to start 2019
- Phase II requires high-intensity beamline at PSI
- Other rare and forbidden μ decays in parallel
- Possible $\mu \rightarrow e\gamma$ extension
- Search for Muonium oscillations



Backup

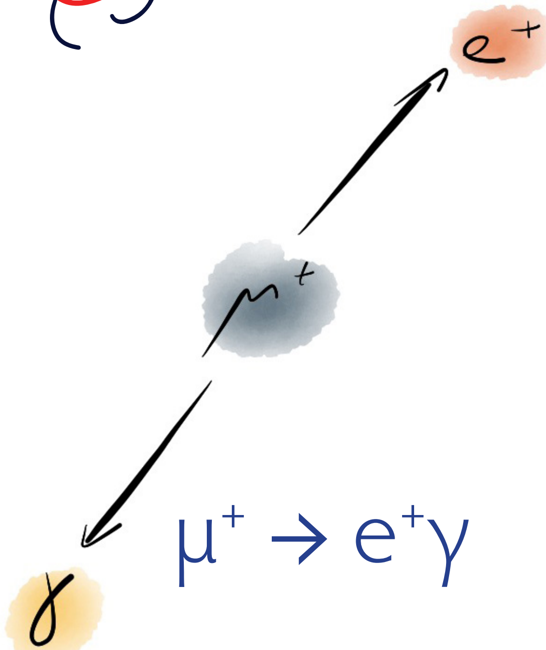
LFV, LNV decays with NA62

Channel	Violation	90% CL Limit	Experiment	NA62 Reach
$K^+ \to \pi^+ \mu^+ e^-$	LFV	$< 1.3 \times 10^{-11}$	E865	$\sim 10^{-12}$
$K^+ \to \pi^+ \mu^- e^+$	LFV	$< 5.2 \times 10^{-10}$	E865	$\sim 10^{-12}$
$K^+ \to \pi^- \mu^+ e^+$	LFV, LNV	$< 5.0 \times 10^{-10}$	E865	$\sim 10^{-12}$
$K^+ \to \pi^- e^+ e^+$	LNV	$< 6.4 \times 10^{-10}$	E865	$\sim 2 \times 10^{-12}$
$K^+ \to \pi^- \mu^+ \mu^+$	LNV	$< 1.1 \times 10^{-9}$	NA48/2	$\lesssim 10^{-12}$
$K^+ \to \mu^- \nu e^+ e^+$	LNV	$< 2.0 \times 10^{-8}$	Geneva/Saclay	$\sim 5 \times 10^{-12}$
$\pi^0 \to \mu^- e^+$	LFV	$< 3.4 \times 10^{-9}$	KTeV	$\lesssim 10^{-10}$
$\pi^0 \to \mu^+ e^-$	LFV	$< 3.8 \times 10^{-10}$	KTeV	$\lesssim 10^{-10}$
$\pi^0 \to \mu^- \nu e^+ e^+$	LFV	$< 1.6 \times 10^{-6}$	JINR-Spec	$\lesssim 10^{-10}$

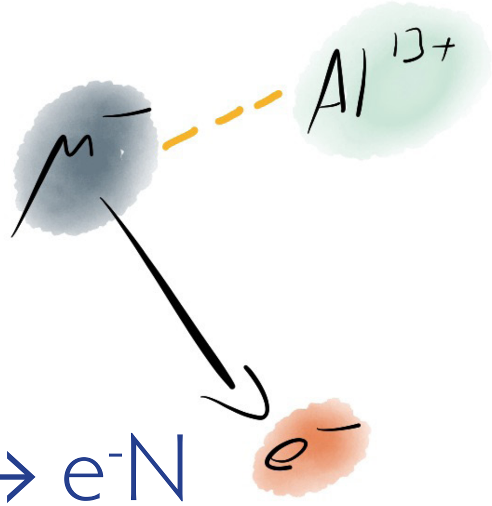
Non LFV/LNV decays with NA62

Channel	Motivation	90% CL Limit	Experiment
$K^+ \to \pi^+ X^0$	new particle	$< 5.9 \times 10^{-11}$ (m_X=0)	E787, E949
$K^+ \to \pi^+ \chi\, \chi$	new particles	——	E949
$K^+ \to \pi^+ \pi^+ e^- \nu$	$\Delta S \neq \Delta Q$	$< 1.2 \times 10^{-8}$	Geneva/Saclay
$K^+ \to \pi^+ \pi^+ \mu^- \nu$	$\Delta S \neq \Delta Q$	$< 3.0 \times 10^{-6}$	Geneva/Saclay
$\pi^0 \to e^+ e^- (\gamma)$	dark photon	——	——
$\pi^0 \to e^+ e^- e^+ e^-$	T violation	$C = -0.77 \pm 0.53$	Samios *et al.*
$\pi^0 \to \gamma\,\gamma\,\gamma$	C violation	$< 3.1 \times 10^{-8}$	Crystal Box
$\pi^0 \to \gamma\,\gamma\,\gamma\,\gamma$	light scalar	$< 2 \quad \times 10^{-8}$	Crystal Box
$\pi^0 \to \nu\,\bar{\nu}$	RH neutrino	$< 2.7 \times 10^{-7}$	E949

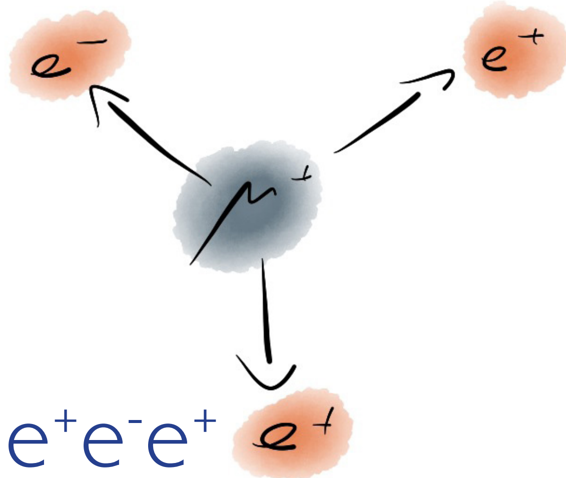
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

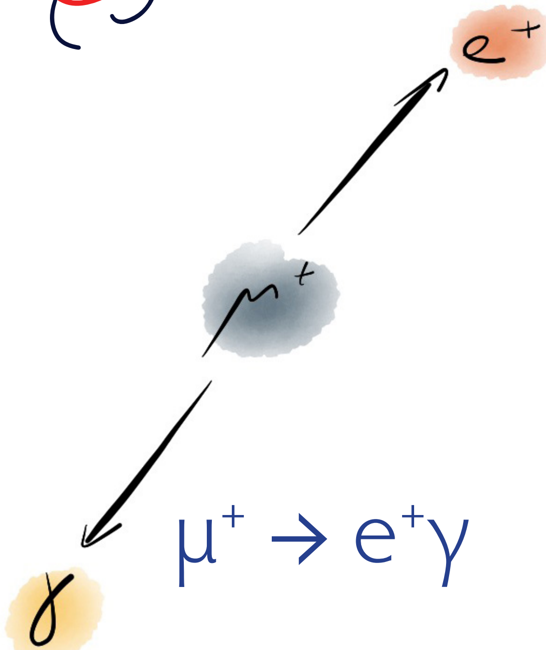
Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

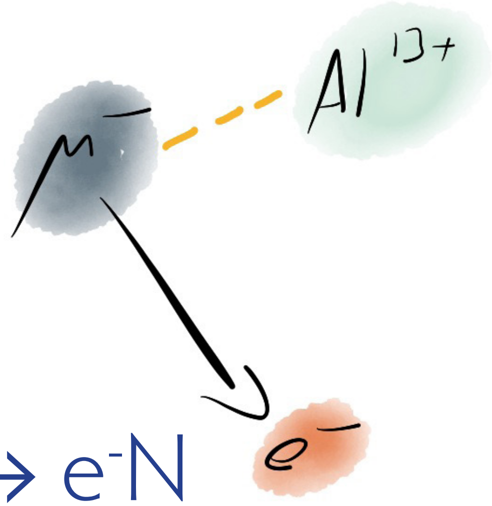
Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma p_i = 0$

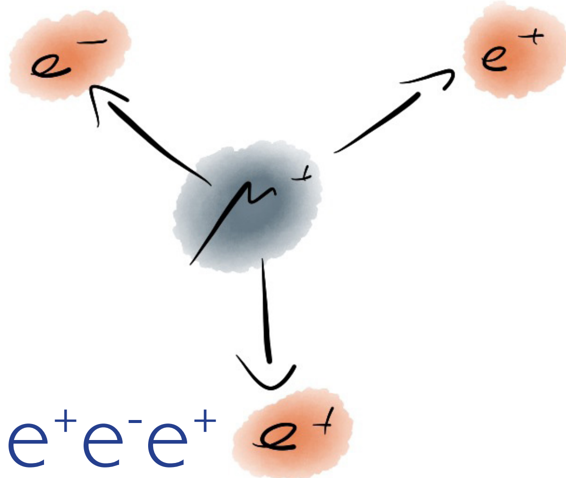
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Background

- Accidental background

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Background

- Decay in orbit
- Antiprotons, pions, cosmics

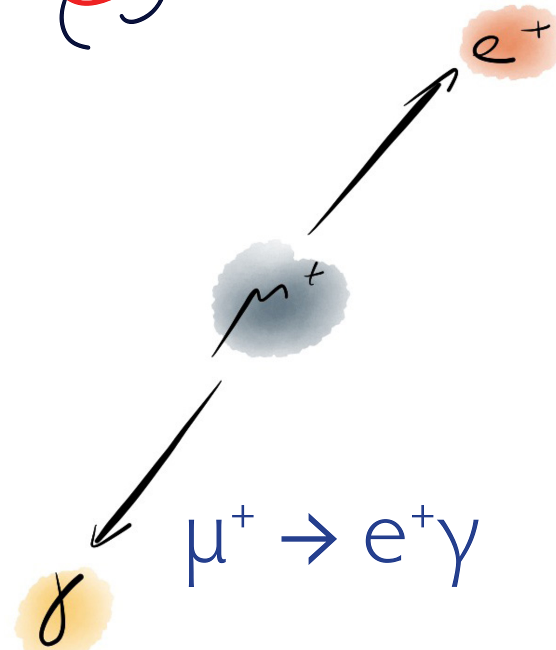
Kinematics

- 3-body decay
- Invariant mass constraint
- $\Sigma p_i = 0$

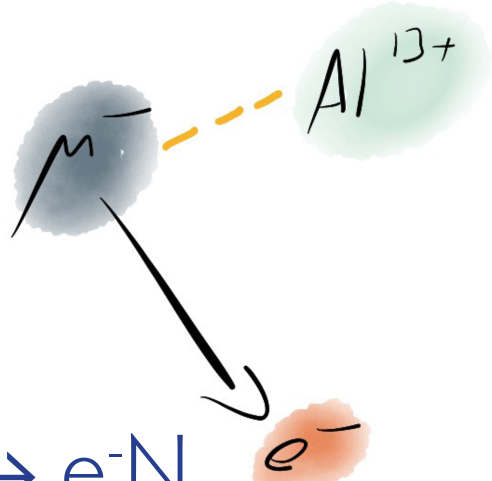
Background

- Radiative decay
- Accidental background

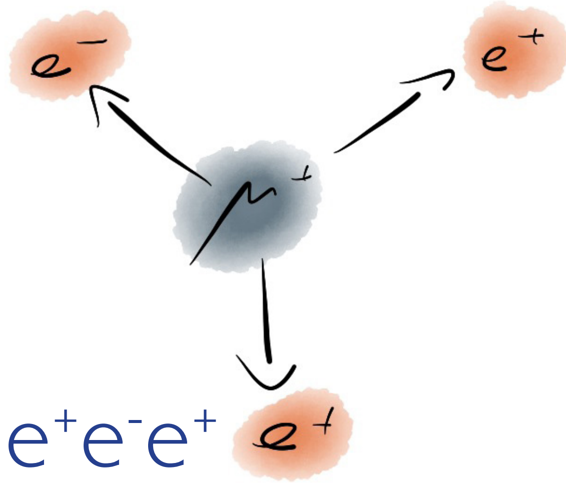
LFV Muon Decays: Experimental signatures



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



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



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

Kinematics

- 2-body decay
- Monoenerge
- Back-to-b

Backgro

- A al background

Continuous Beam

Kinematics

- Quasi 2-body d
- Monoenerge
- Single p etected

Backgro

- D orbit
- A protons, pions

Pulsed Beam

Kinematics

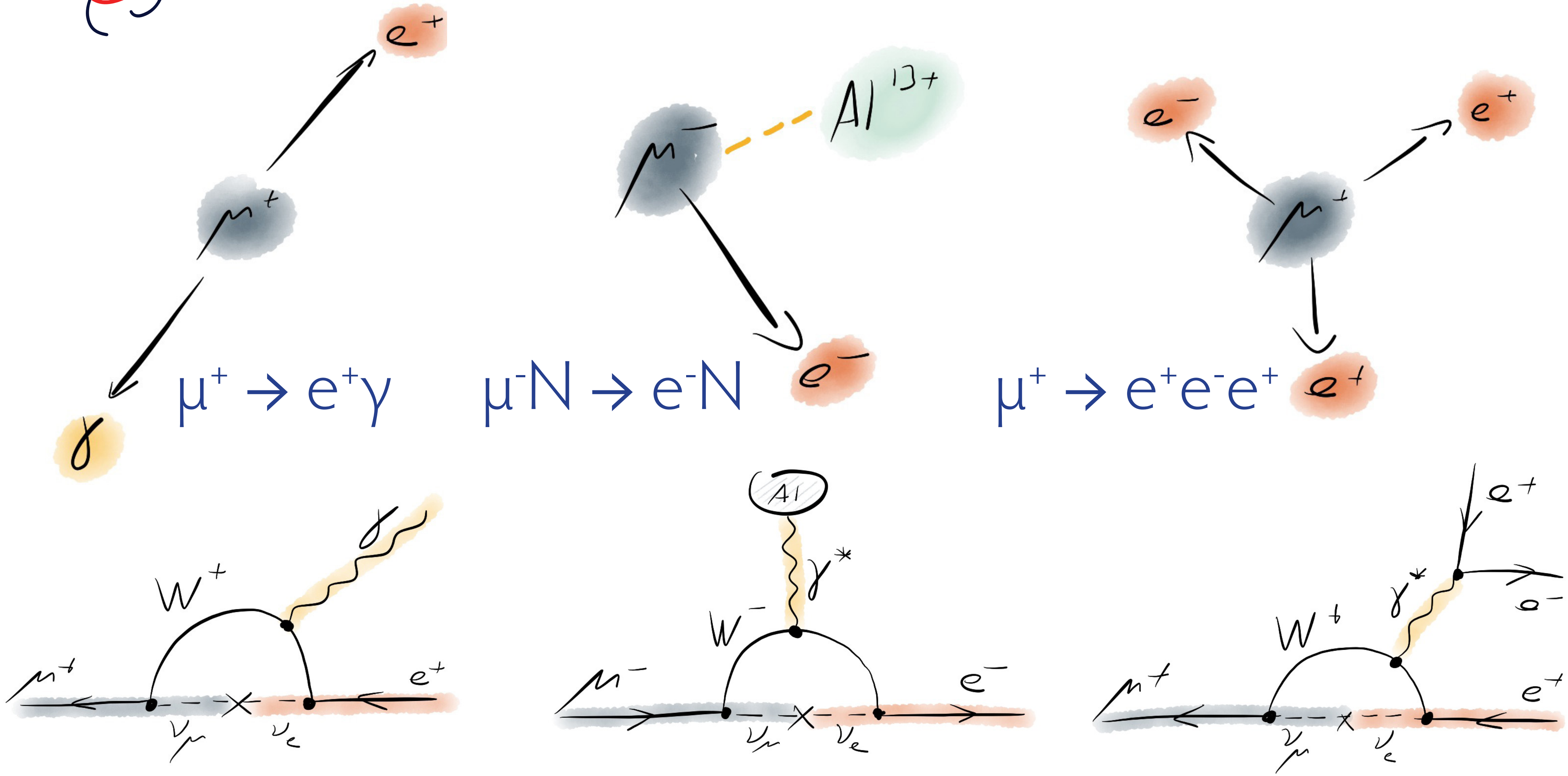
- 3-body decay
- Invariant mas aint
- $\Sigma p_i = 0$

Backgro

- R decay
- Ac ental background

Continuous Beam

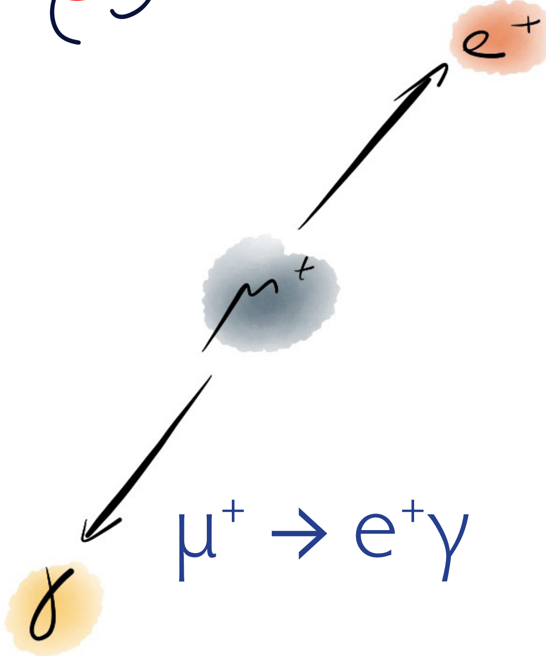
LFV Muon Decays: Standard Model



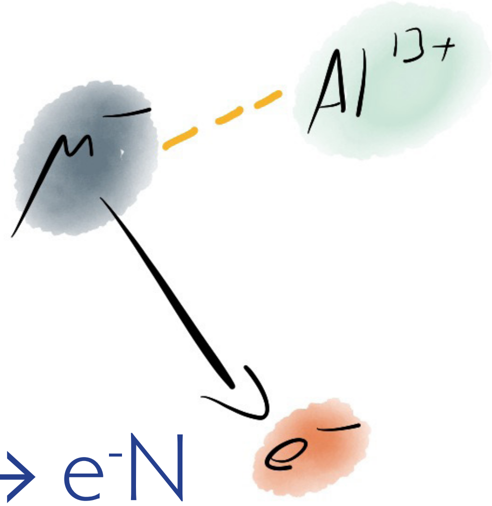
$\mu^+ \rightarrow e^+\gamma$ $\mu^-N \rightarrow e^-N$ $\mu^+ \rightarrow e^+e^-e^+$

Branching ratios suppressed by $\propto \frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$

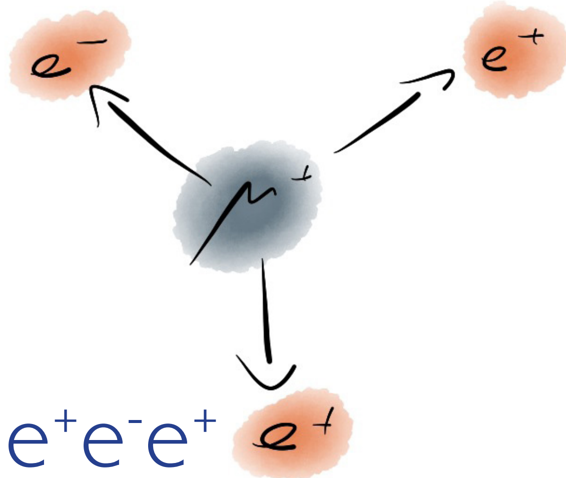
LFV Muon Decays: Susy Loops



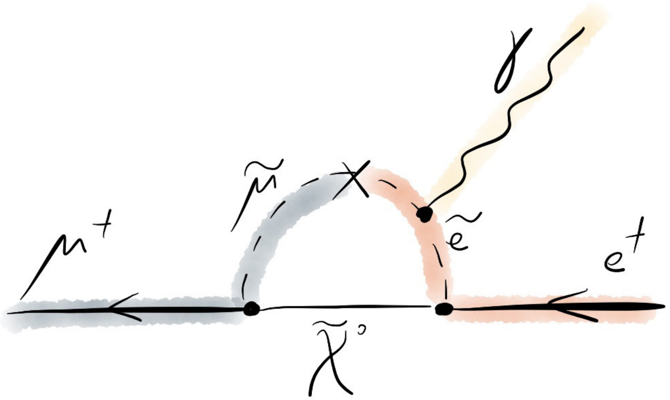
$\mu^+ \to e^+\gamma$

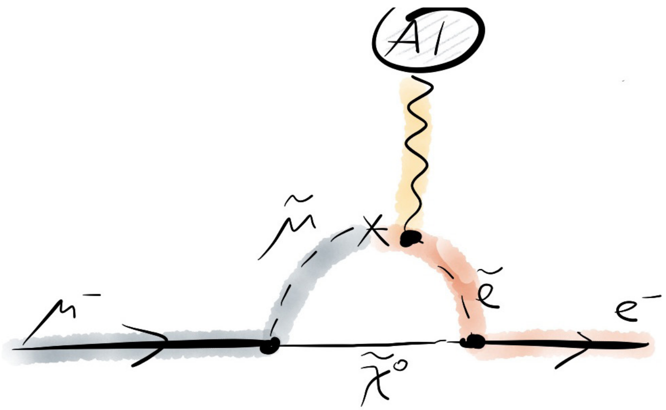


$\mu^- N \to e^- N$

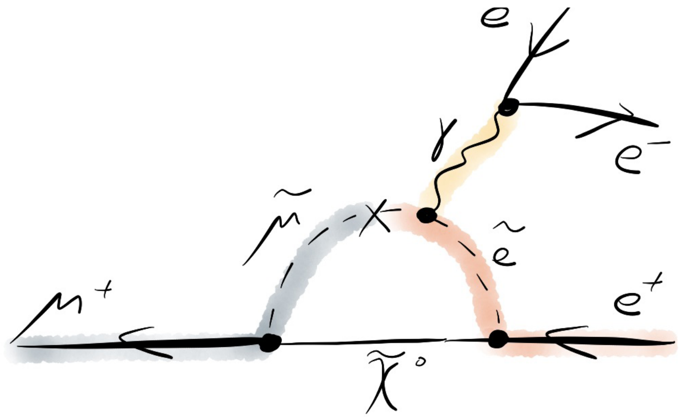


$\mu^+ \to e^+e^-e^+$



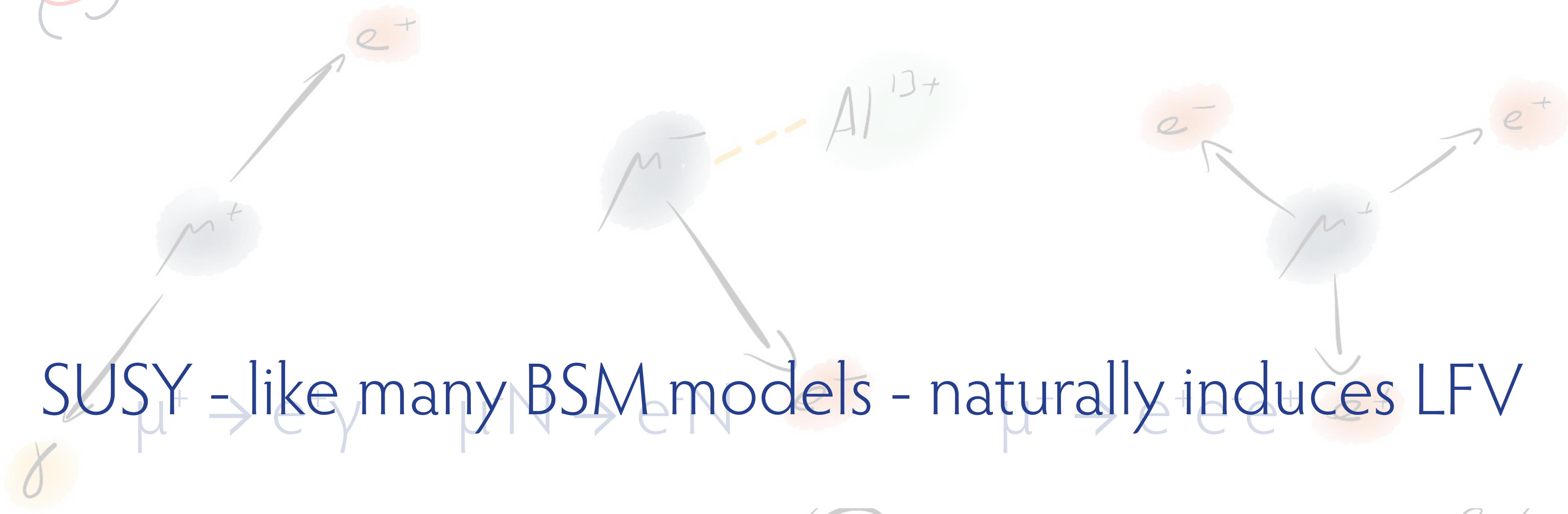


Coherent conversion in nucleus field for $Q^2(\gamma) \sim 0$



Suppressed by extra vertex w.r.t. $\mu \to e\gamma$

LFV Muon Decays: Susy Loops



SUSY - like many BSM models - naturally induces LFV

Coherent conversion in nucleus field for $Q^2(\gamma) \sim 0$

Suppressed by extra vertex w.r.t. $\mu \rightarrow e\gamma$

LFV Muon Decays: Susy Loops

SUSY - like many BSM models - naturally induces LFV

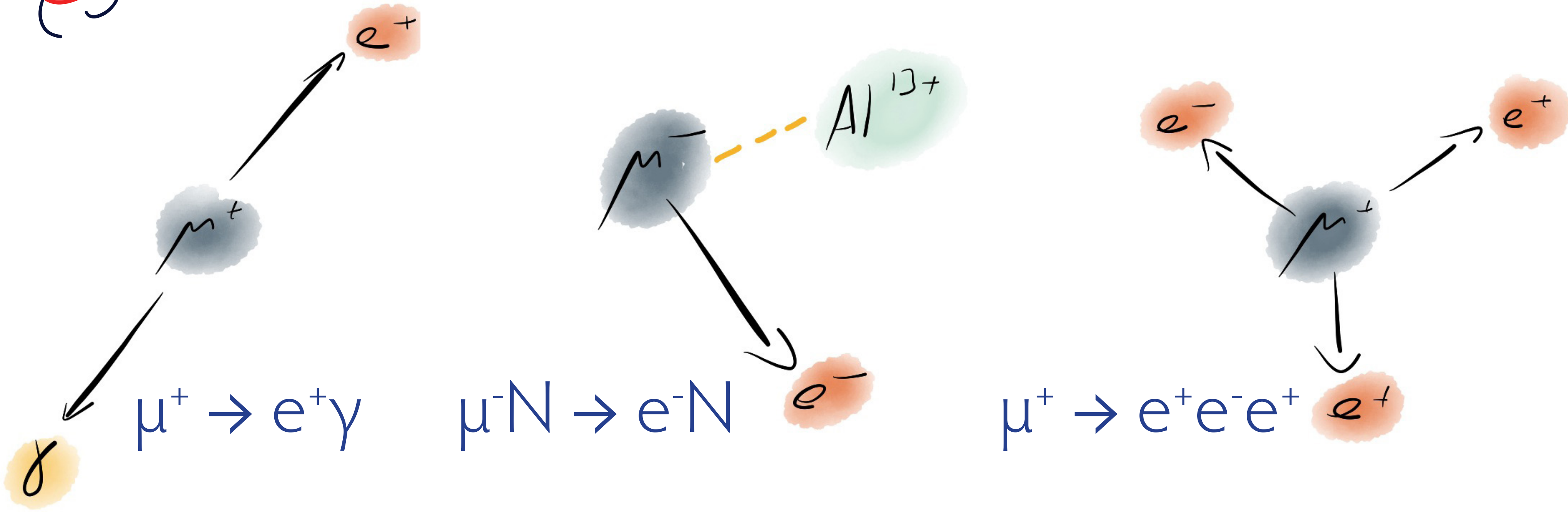
LFV in $\mu^+ \rightarrow e^+\gamma$ implies LFV also in $\mu^-N \rightarrow e^-N$ and $\mu^+ \rightarrow e^+e^-e^+$

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

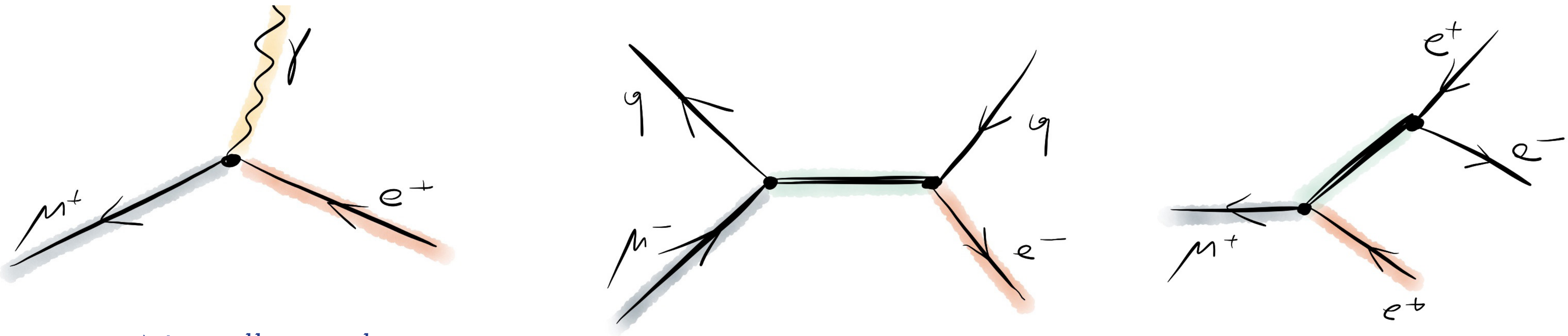
Coherent conversion in nucleus field for $Q^2(\gamma) \sim 0$

Suppressed by extra vertex w.r.t. $\mu \rightarrow e\gamma$

LFV Muon Decays: Tree diagrams



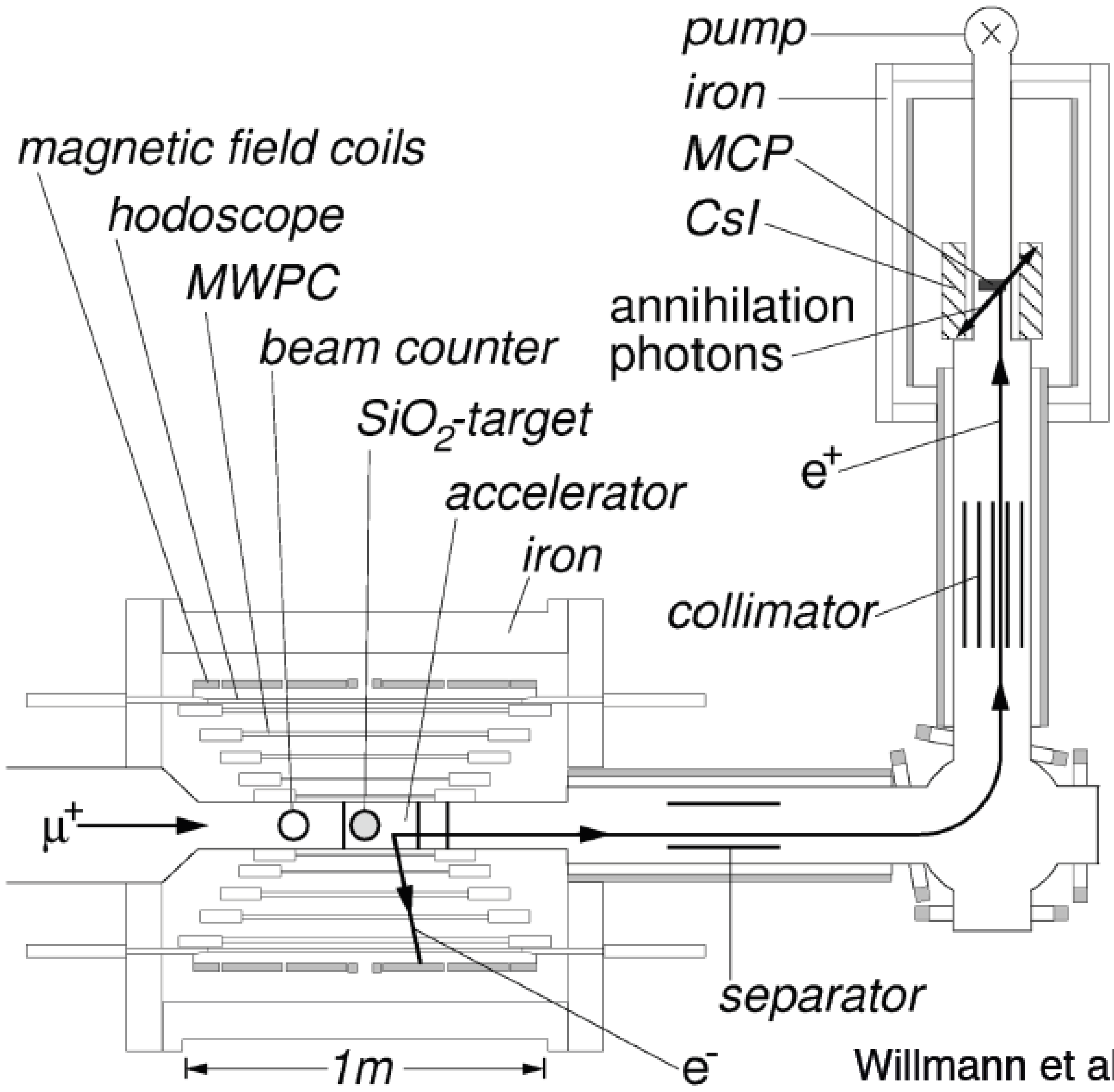
$\mu^+ \rightarrow e^+\gamma$ $\mu^-N \rightarrow e^-N$ $\mu^+ \rightarrow e^+e^-e^+$



Not allowed | e.g. Leptoquarks | e.g. extra Z', LFV Higgs etc.

Muonium-Antimuonium oscillations

- $\Delta L = 2$
- μ^+e^- to μ^-e^+
- Detect μ^- decay with Mu3e
- Add detector for slow positron
- Exciting progress in Japan for Mu production



Willmann et al., PRL **82**, 49 (1999)

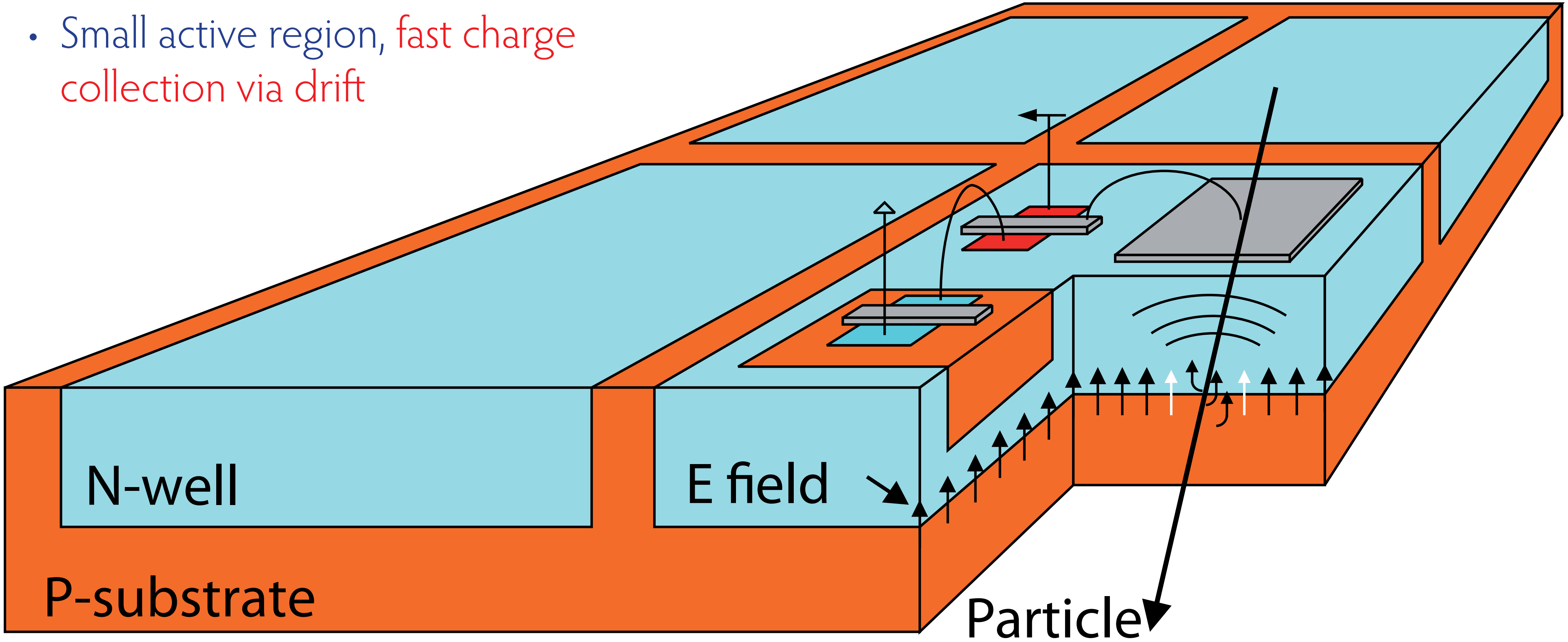
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

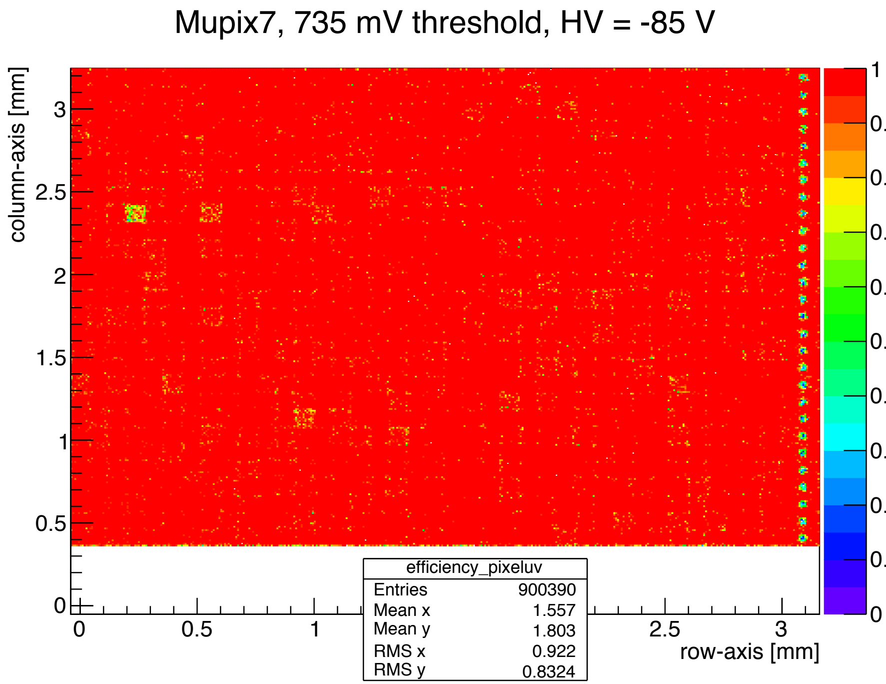
- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift

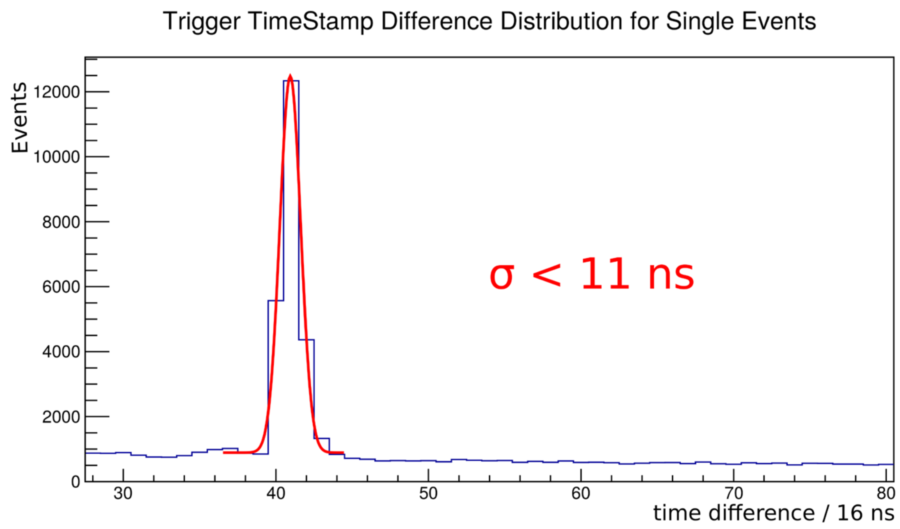
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 μm

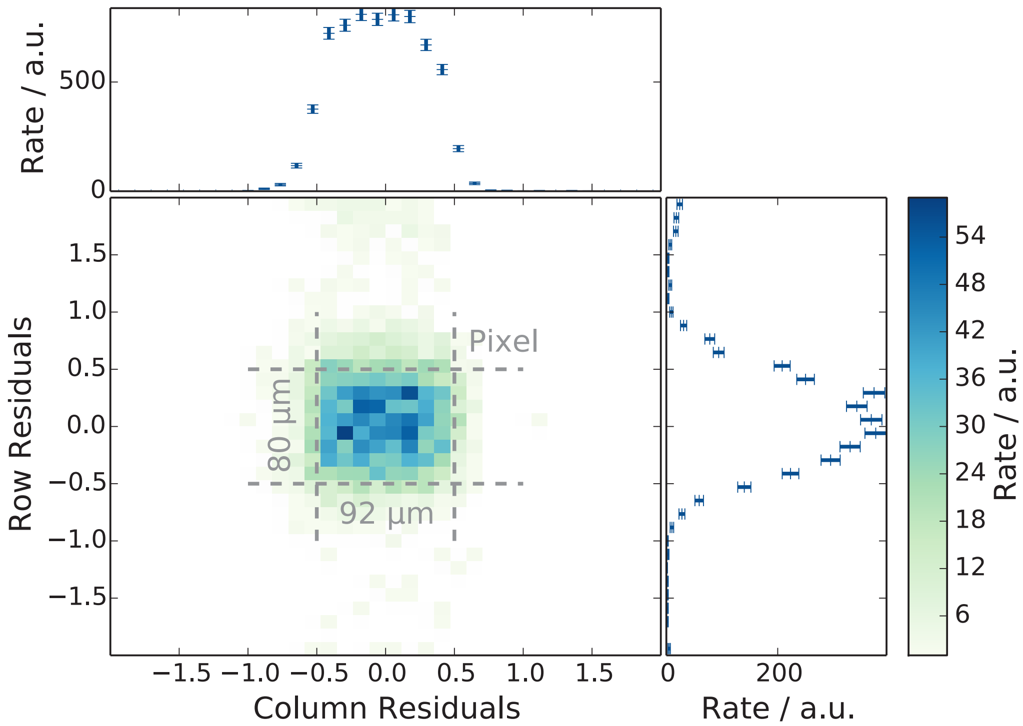
(I.Perić NIM A 582 (2007) 876)

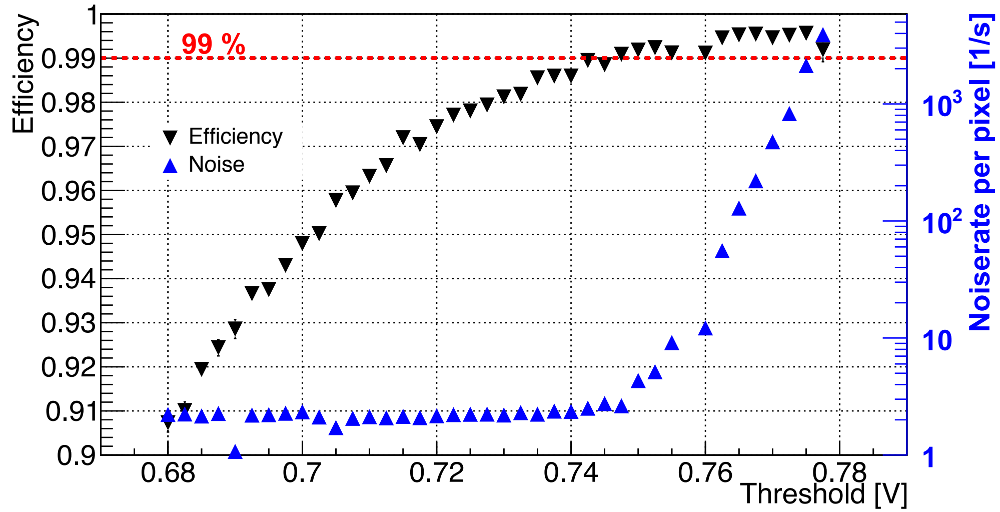


Performance



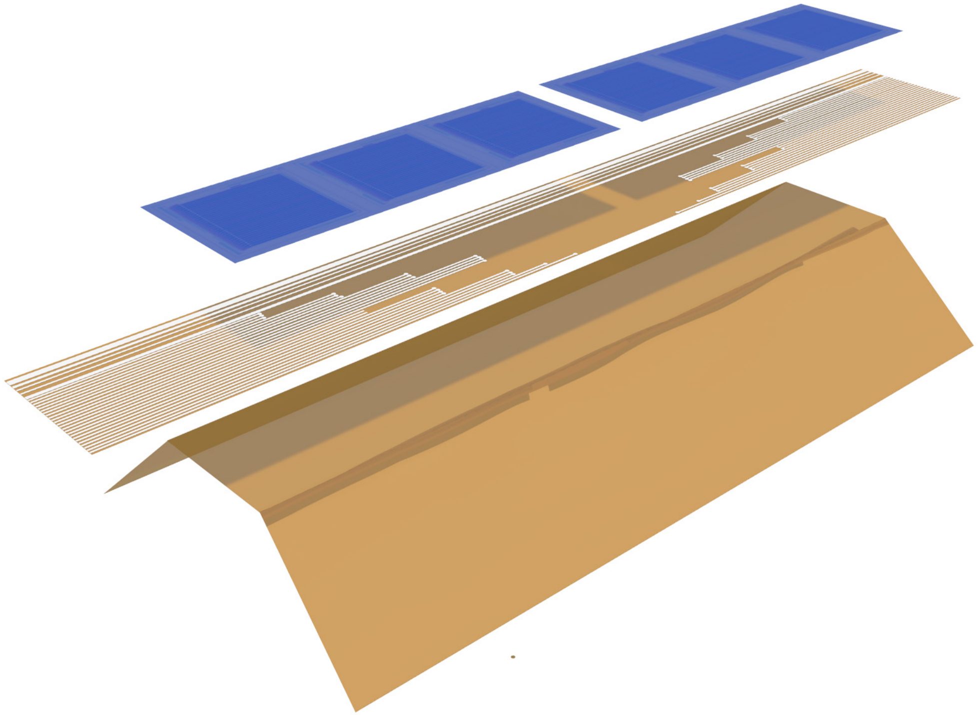






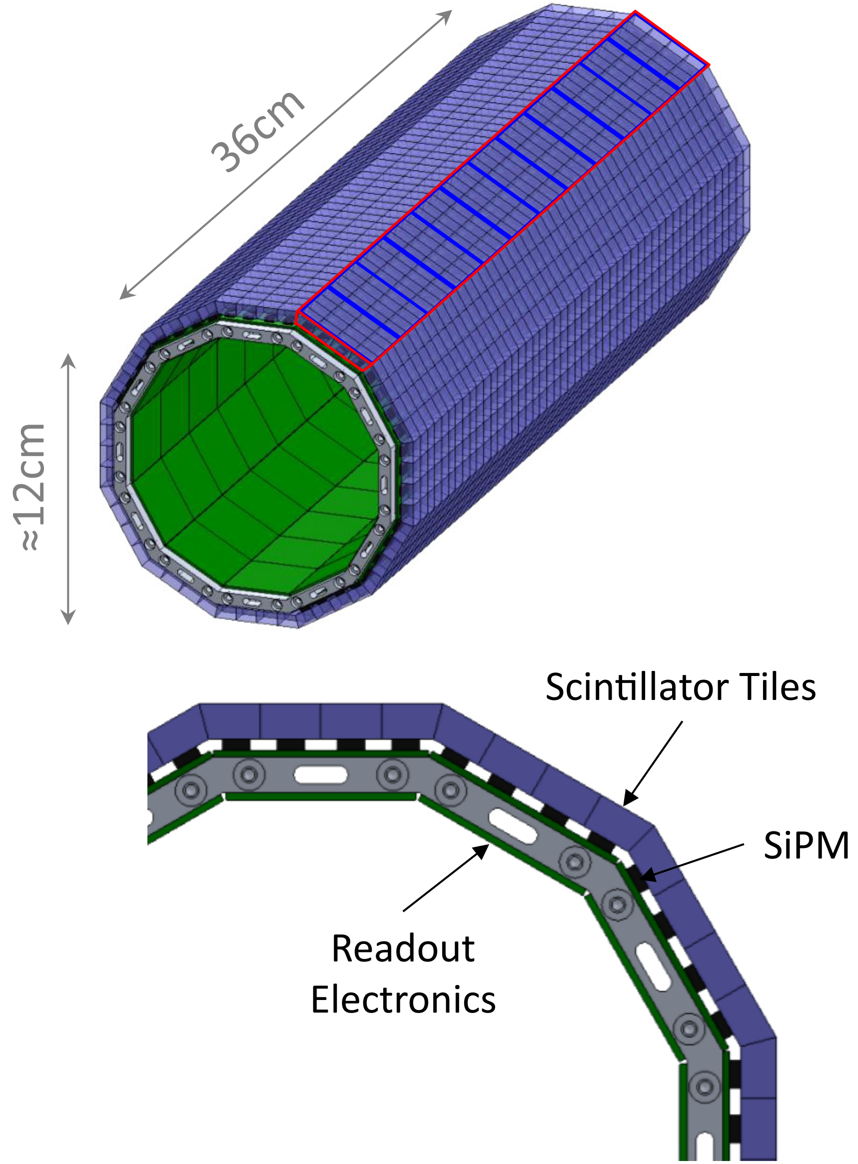
First large (2×1 cm^2) prototype arriving these days

Mechanics

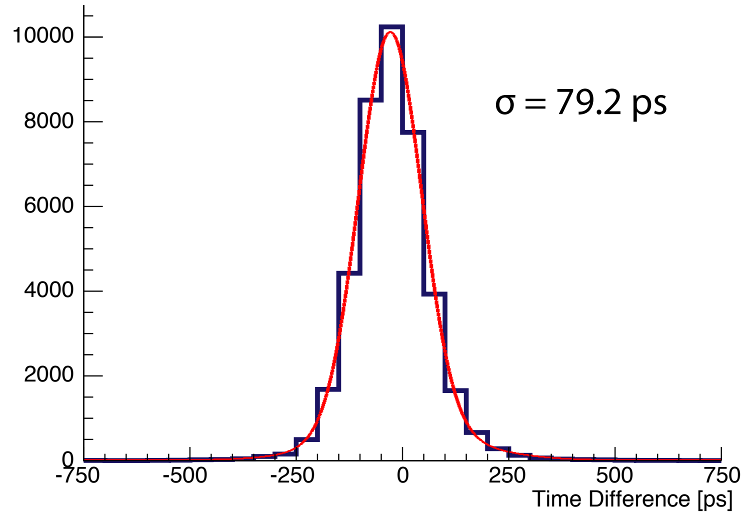


- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- About 1‰ of a radiation length per layer

Timing Detector: Scintillating tiles



- ~ 0.5 cm^3 scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)



- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution ~ 80 ps