Mu3e-Experiment

- the Intensity Frontier

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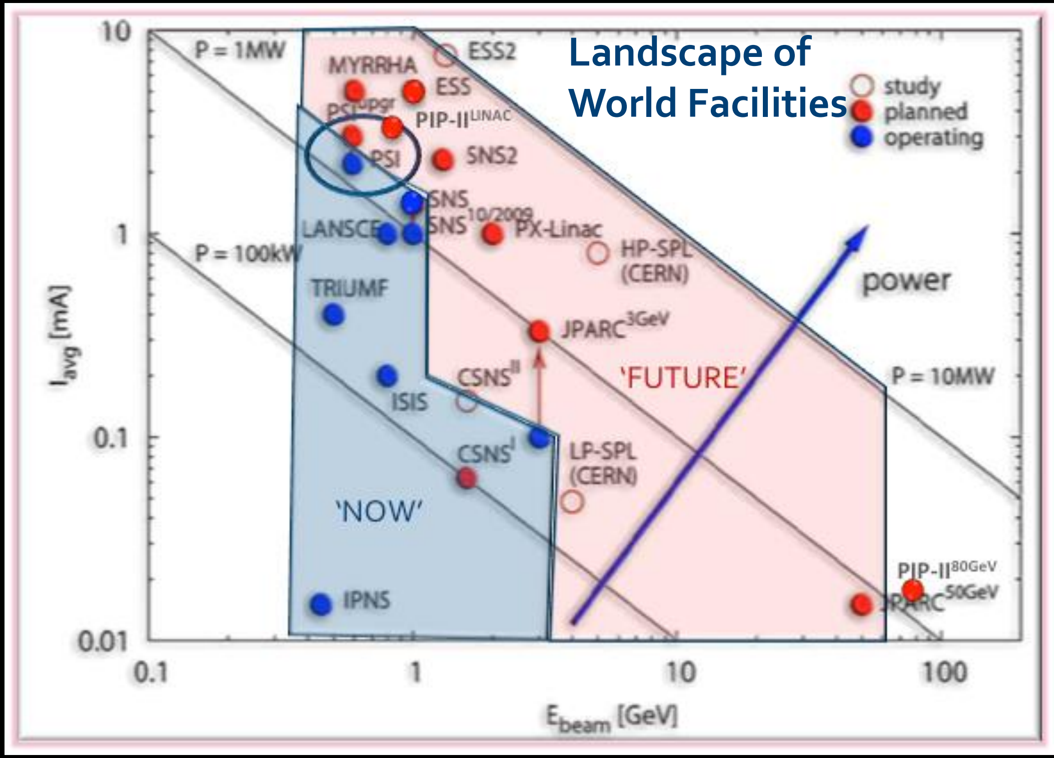
- On behalf of the Mu3e Collaboration

PSI a Benchmark for the High-Intensity Precision Frontier

The unique "**HIPA**" high-intensity proton accelerator **complex** at PSI - **runs at the "Intensity Frontier"**



Routine 1.3 MW Beam Power

so enables

- the **World'd highest intensity DC Surface Muon Beams** > $10^8 \mu^+ s^{-1}$
- Optimal machine duty-cycle for coincidence experiments (100% macro duty-cycle)

Can explore the Predicted realm of 'New Physics' through precision experiments, allowing insight into mediating particle mass scales far beyond the reach of the 'High-Energy Frontier Machines'

.... **Λ > 1000 TeV**

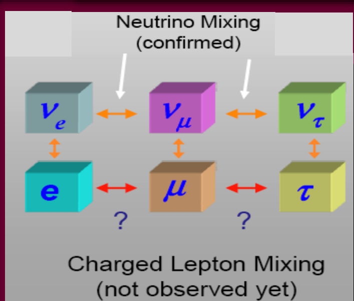
Intensity Frontier – Muons & cLF-Physics

Fundamental Questions still Remain Unanswered!!!

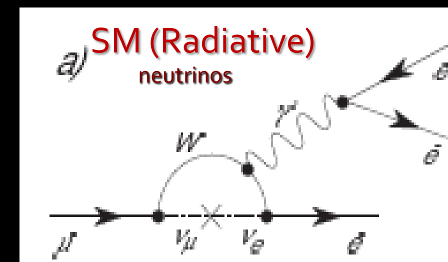
To unravel the puzzle of *FLAVOUR MIXING* & *CP-VIOLATION*
& the connection between the 3 generations of Fermions
in the *quark & lepton sectors*

e.g. Possible Mu3e couplings

LF violated in the neutral sector

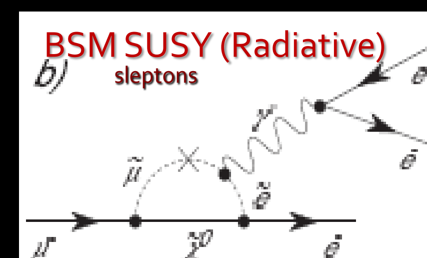


one needs the complementarity of
the ***High-energy*** & ***High-intensity*** Frontiers
LHC, PSI-HIPA, Super-KEKB, FNAL, J-PARC



Muons seem to provide the most sensitive limits
(copious source, small mass, long life)

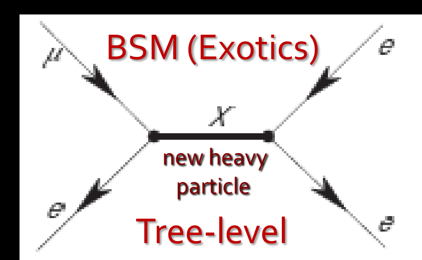
Dipole photonic Loops



"GOLDEN CHANNELS"
in the Charged Lepton Sector:

$\mu \to e\gamma$ **$\mu N \to eN$** **$\mu \to 3e$**

All 3 channels are needed since
subject to same as well as different couplings



e.g. $\mu \to 3e$ (similar $\mu N \to eN$, $\mu \to e\gamma$ but $\mu \to e\gamma$ no 4-fermion)

Current cLFV-Experimental Limits

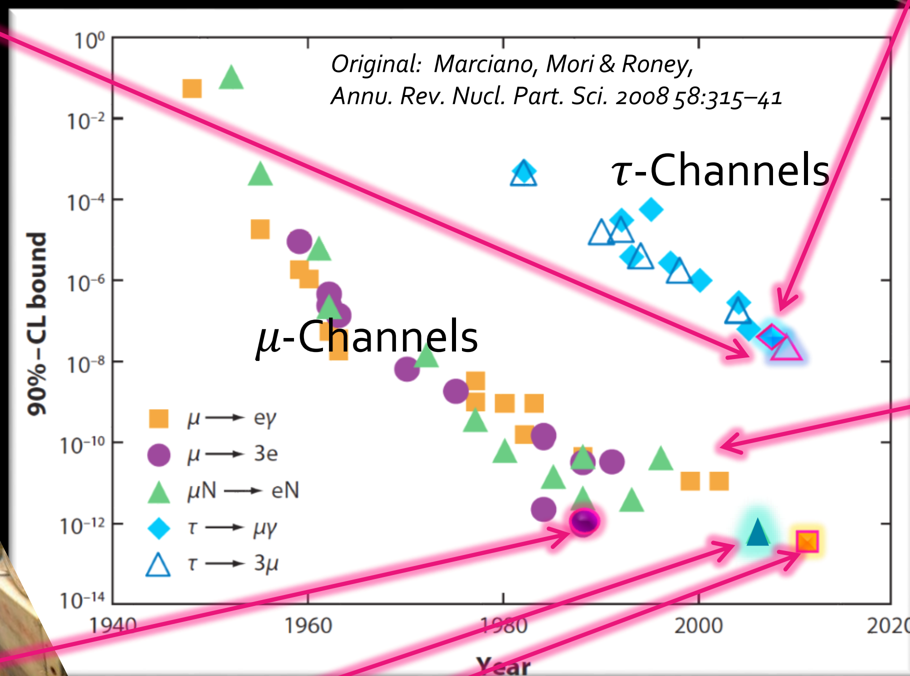
Belle
(KEKB)
$\tau \rightarrow 3\mu$ (3e)
$< 2.1\cdot10^{-8}$ ($2.7\cdot10^{-8}$)

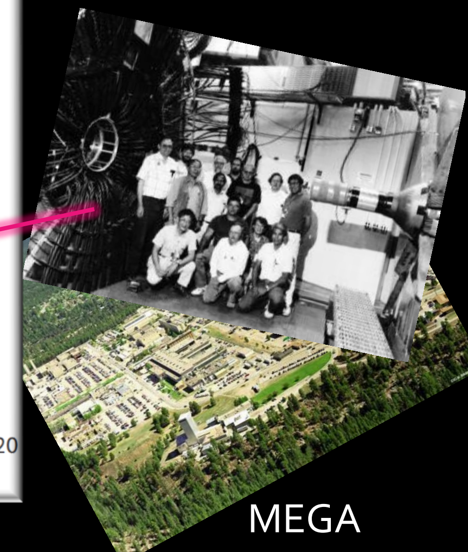
BaBar
(SLAC)
$\tau \rightarrow \mu\gamma$ (eγ)
$< 4.4\cdot10^{-8}$
($3.3\cdot10^{-8}$)

MEG (PSI)
$\mu \rightarrow e\gamma$
$< 5.7\cdot10^{-13}$

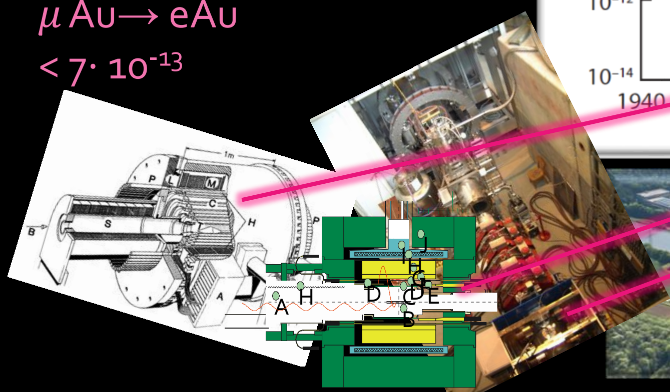
SINDRUM (PSI)
$\mu \rightarrow 3e$
$< 1.0\cdot10^{-12}$

SINDRUM II (PSI)
μ Au $\rightarrow$ eAu
$< 7\cdot10^{-13}$

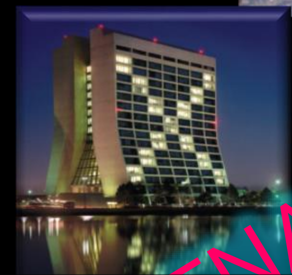




MEGA
(LAMPF)
$\mu \rightarrow e\gamma$
$< 1.2\cdot10^{-11}$



Next Generation Facilities & cLFV Experiments



FUTURE cLFV Experiment Landscape

$\mu \to e\gamma$: MEG II (PSI) ~ $5\cdot10^{-14}$ - O($10^{8}\mu^{+}$/s) DC

$\mu \to 3e$: Mu3e (PSI) ~ 10^{-16} – Ph.I O($10^{8}\mu^{+}$/s), Ph.II O($10^{9}\mu^{+}$/s) DC

MuSIC (Osaka) ~ 10^{-14} - O($10^{8}\mu^{+}$/s) DC

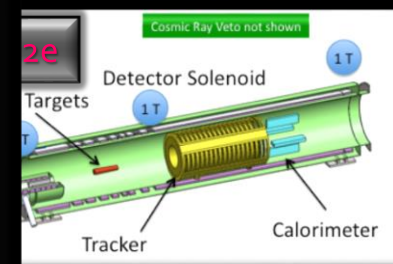
$\mu N \to eN$: DeeMee (J-PARC) 10^{-14} - O($10^{10}\mu^{-}$/s) pulsed

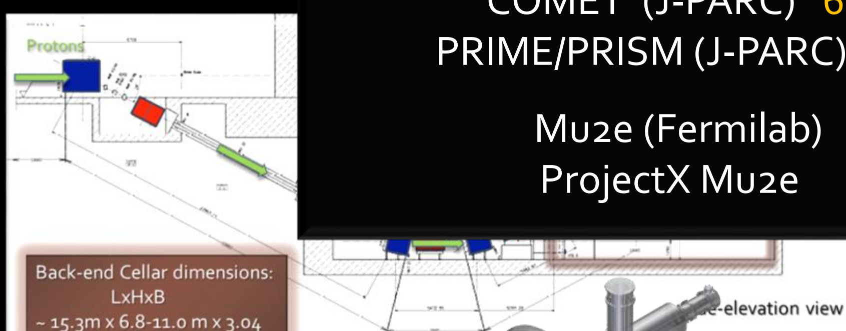
COMET (J-PARC) $6\cdot10^{-17}$ - O($10^{11}\mu^{-}$/s) pulsed

PRIME/PRISM (J-PARC) $< 10^{-18}$ - O($10^{11-12}\mu^{-}$/s) pulsed

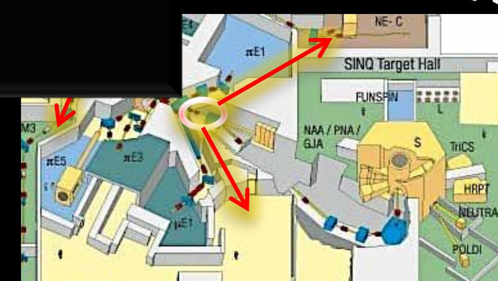
Mu2e (Fermilab) $6\cdot10^{-17}$ - O($10^{10}\mu^{-}$/s) pulsed

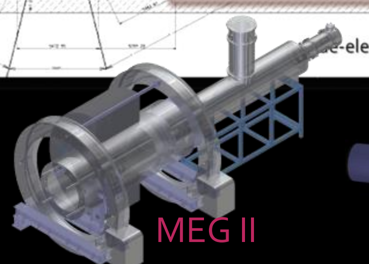
ProjectX Mu2e $< 10^{-18}$ - O($10^{12}\mu^{-}$/s) pulsed

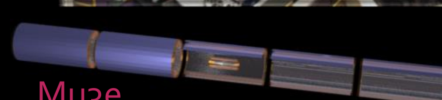




HiMB@EH







Mu3e Experiment at PSI

Search for the cLFV decay $\mu^+ \rightarrow e^+e^+e^-$

University of Heidelberg
PI

University of Genève
DPNC

University of Heidelberg
KIP

University of Zürich
PI

Mu3e Collaboration

ETH Zürich
IPP

KIT Karlsruhe
IPE

Paul Scherrer Institut PSI
LTP

University of Mainz
INP

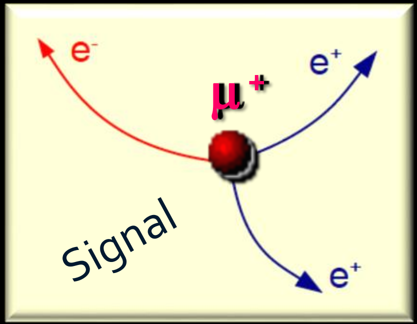
Experimental Challenge

- *Observe more than 10^{16} Muon decays*
- *Handle GHz muon rates*
- *Suppress backgrounds by > 16 orders of magnitude*
- *Have sufficient signal sensitivity & rejection power to achieve $\mathcal{O}(10^{-16})$ measurement*

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

3 charged Particles: $2e^+$ & e^-

(i) coincident in time ***(measure time t_{eee})***
(ii) Coplanar + same vertex
(iii) ΣEnergy = M_μ ***(measure E_e)***
(iv) $\Sigma\, p_i = 0$ ***(measure P_e)***
(v) Track curvature in Bfield



Good Energy & Momentum Resolution

"Physics" Background

Radiative muon decay RMD with Internal or External Conversion

$B(\mu^+ \rightarrow e^+ e^+ e^- \nu\nu) = 3.4 \cdot 10^{-5}$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu e^+ e^-$$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$$

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

Pion Decays: negligible

$$\pi^+ \rightarrow e^+ \nu_e e^+ e^-$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu \gamma$$

"Combinatorial" Background

A) e^+ Michel decays + Fake e^-

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \; + e^-$$

Fake e^- : γ-conversion, Bhabha scattering mis-reconstruction

B) RMD (IC) + Michel (Fake e^+)

$$\mu^+ \rightarrow (e^+) \nu_e \bar{\nu}_\mu e^+ e^-$$

+ *Michel*

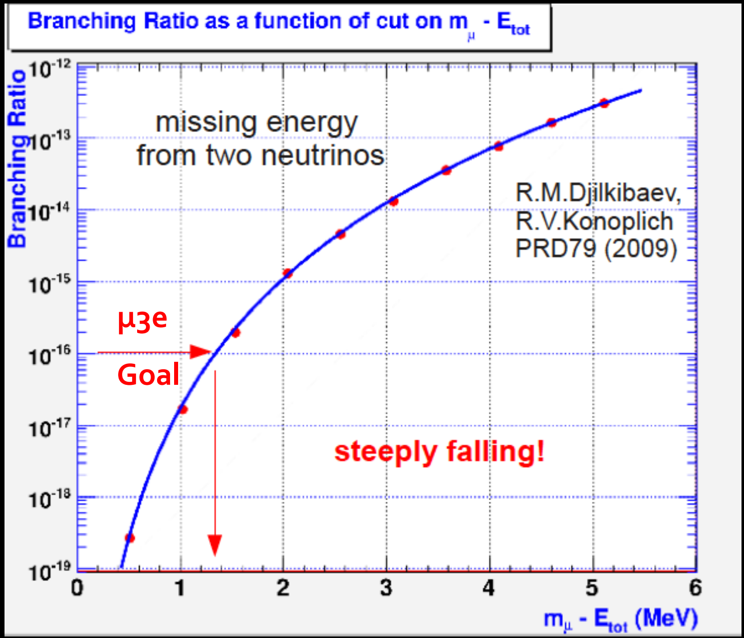
Precise Vertexing, Timing & P-resolution

Experimental Optimization

1) $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu e^+ e^-$

To cope with the "**physics background**"! need precise momentum measurement & excellent energy resolution for missing energy ΣE_ν

To reach $\mathcal{B}(\mu \rightarrow 3e) \leq 10^{-16}$ *need* σ_E < 1 MeV

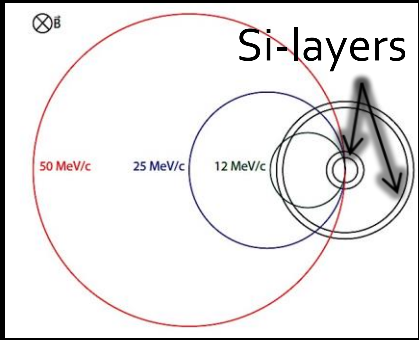


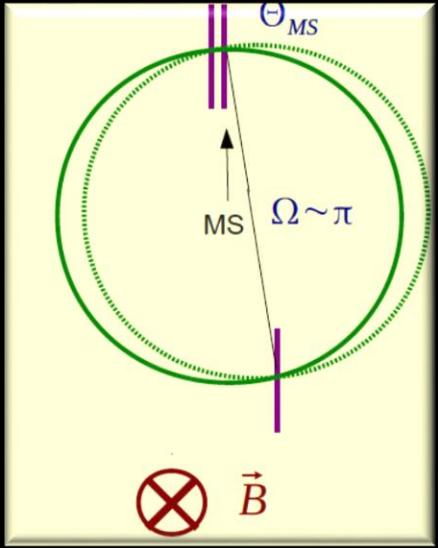
2)

High-rate, high-precision tracking in **1 T Bfield Use ⇨ Si**

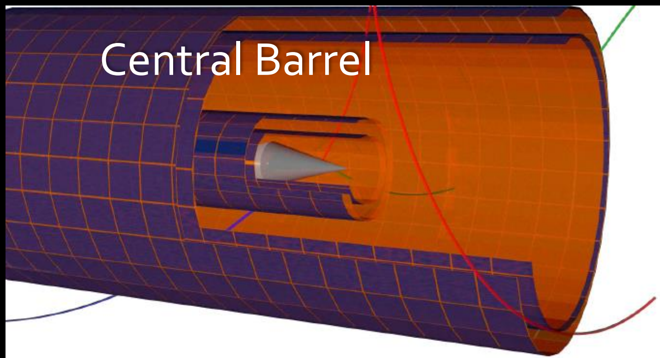
- Granularity of tracker is high then momentum resolution σ_p/p dominated by Multiple Scattering
  $\sigma_p/p \propto \sqrt{N_{LAYERS}}$ use FEW but THIN Layers!
- Good momentum resolution - NEED
  - large lever-arm -> large r-detector BUT loose low-p tracks
  - best precision as with 180° spectrometer

Solution small r-detector⇨ Re-curl stations for re-curling tracks





The Staged Approach



Phase IA: Sensitivity reach ***O(10^{-14})***
Muon rate ***O(10^{7})Hz ,***

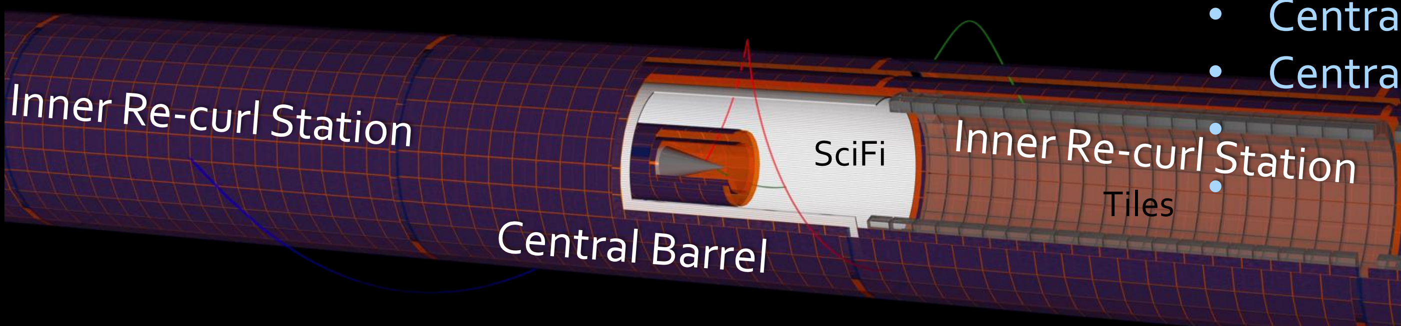
2017

- Central (inner + outer) Si-layers ONLY

Phase IB: Sensitivity reach ***O(10^{-15})***
Muon rate ***O(10^{8})Hz ,***

2018+

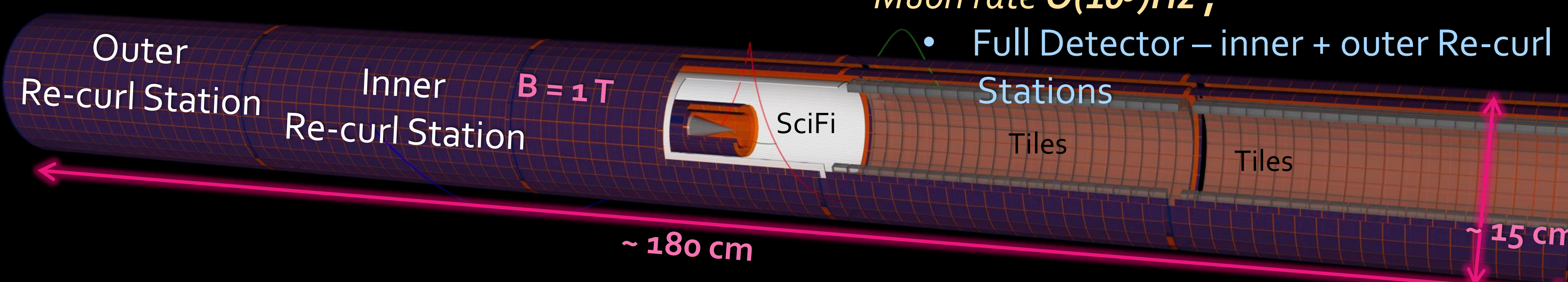
- Central (inner + outer) Si-layers
- Central SciFi tracker
- Re-curl Si-layers
- Re-curl Sci.-Tile layer



Phase II: Sensitivity reach ***O(10^{-16})***
Muon rate ***O(10^{9})Hz ,***

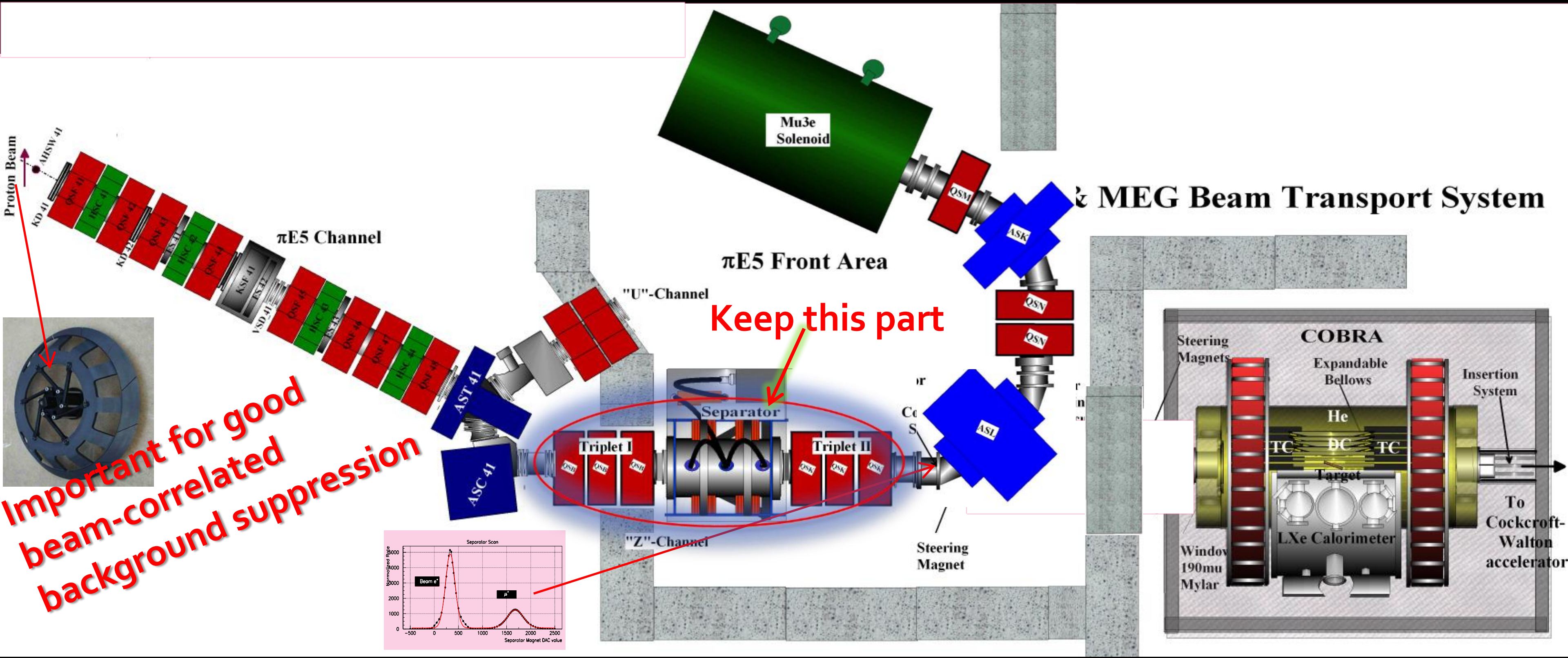
> 2020…

- Full Detector – inner + outer Re-curl Stations

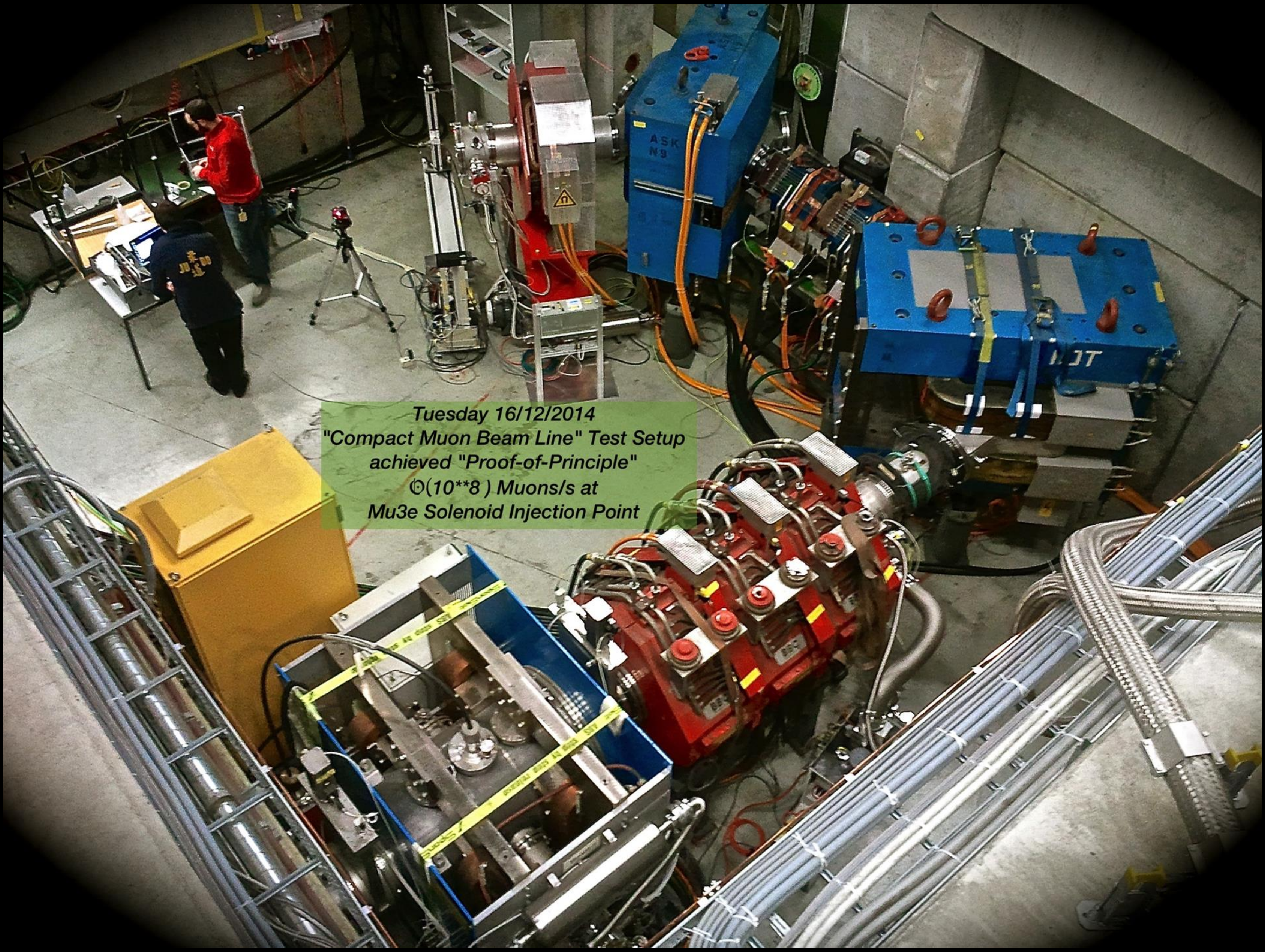


Intensity Frontier "Compact Muon Beam Line" CMBL

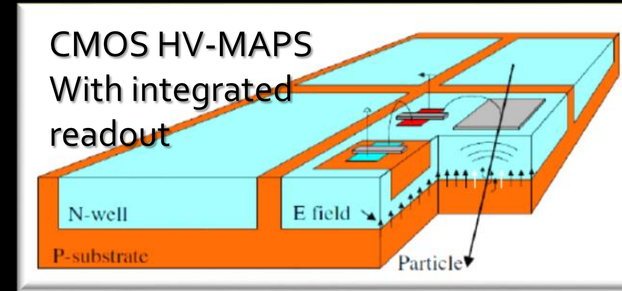
- Both Experiments **"MEG II"** & **"Mu3e Phase I"** will run at the highest rates ➔need to share one of the most intense muon beams in the world! ➔ PiE5
- Mu3e has similar beam requirements to MEG II O(10^8) μ^+/s , 28 MeV/c - **ONLY πE5 possible!!!**
- **Solution ➔ Mu3e "Compact Muon Beam Line"** Ultra-compact beam line - Allowing both experiments to **CO-EXIST** with minimal switch-over & without compromising the physics goals
- **Split-triplet optics** for compactness



The Mu3e CMBL Test Setup



On Route to the Silicon Trackers



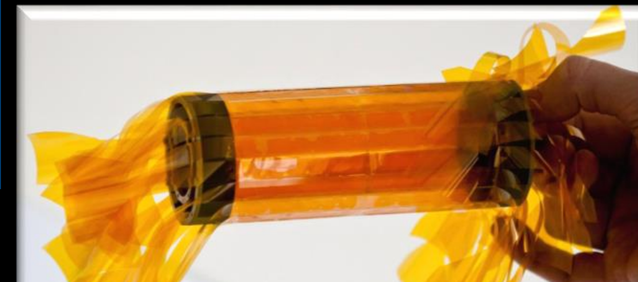
Used in central Barrel Region & Re-curl Station

Main Function

- Rate Capability
- Momentum Resolution
- Vertexing

Requirements

- Minimal material budget
- High granularity



Inner double-layer Support structure
25 µm + 25 µm Kapton flex-print mock-up

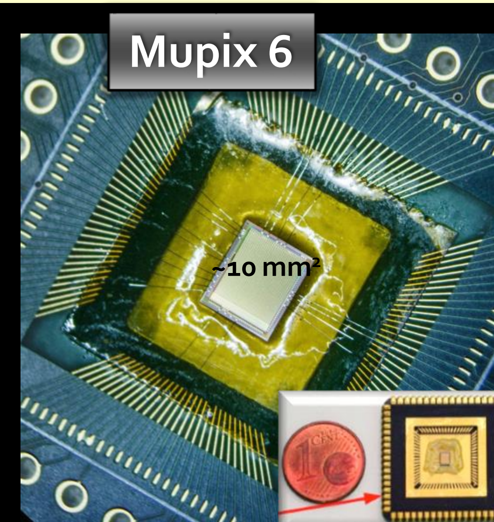
I.Peric, P. Fischer et al., NIM A 582 (2007) 876 (ZITI Mannheim, Uni Heidelberg)

Technology used

HV-MAPS – "High Voltage Monolithic Active Pixel Sensors"

- **HV-CMOS technology** reverse bias ~60V
- Fast Charge collection via drift **< 1 ns (9 µm depletion-layer)**
- **Thinning to < 50 µm** possible **< 1 ‰ X_0 per layer**
- **Integrated read-out electronics** in n-well
  -> Preamp, discriminator, Timestamp, address, zero-suppression
- **Triggerless fast readout** (time-frames 50 ns – 20MHz)
- Total **275 M channels**
- **<20 ns time resolution, vertex resolution ~ 200 µm**

Mupix 6



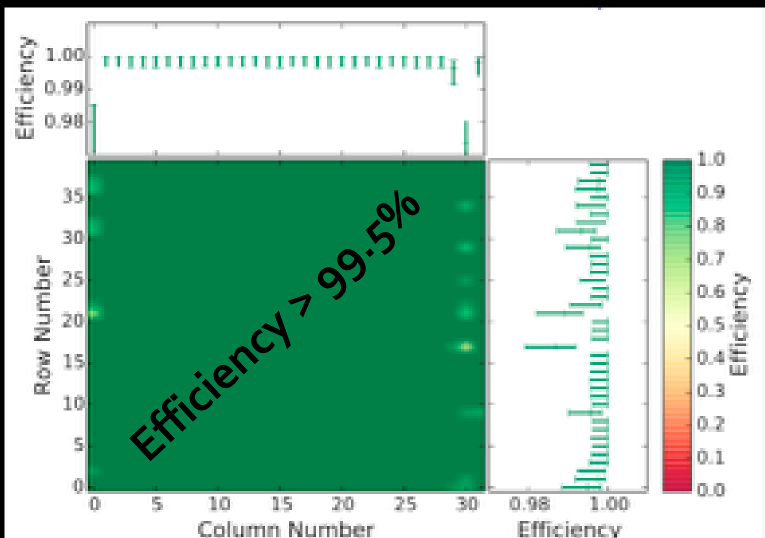
5 Generations of Mupix Chip -> current Mupix 7 has ALL featues implemented

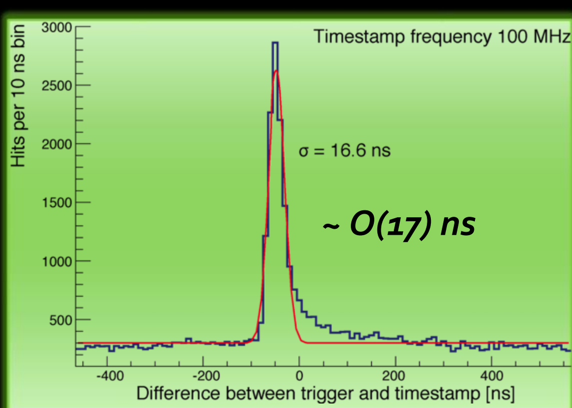
Thinned Mupix Telescope Performance

Mupix 4: DESY – beam test 5 GeV e^-

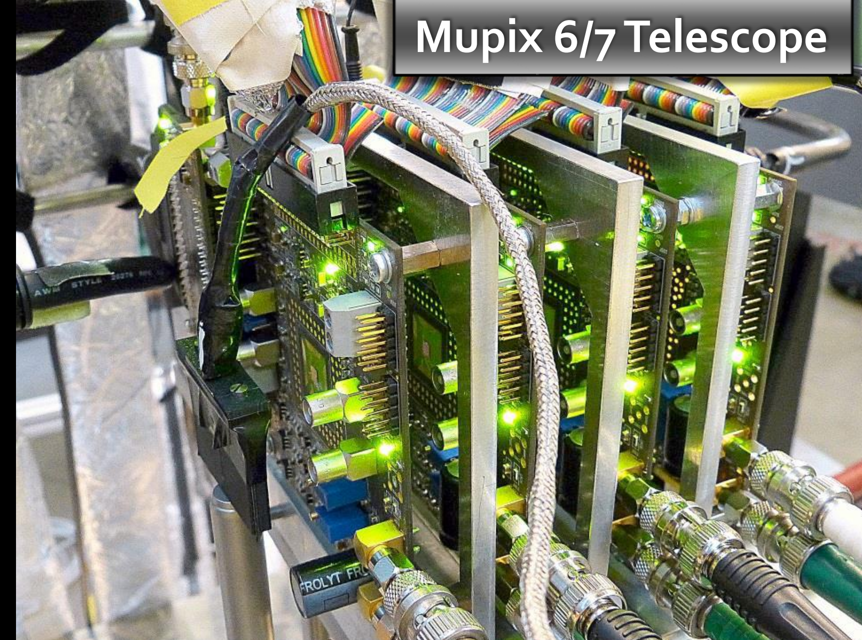
> 1MHz hit rate

Efficiency

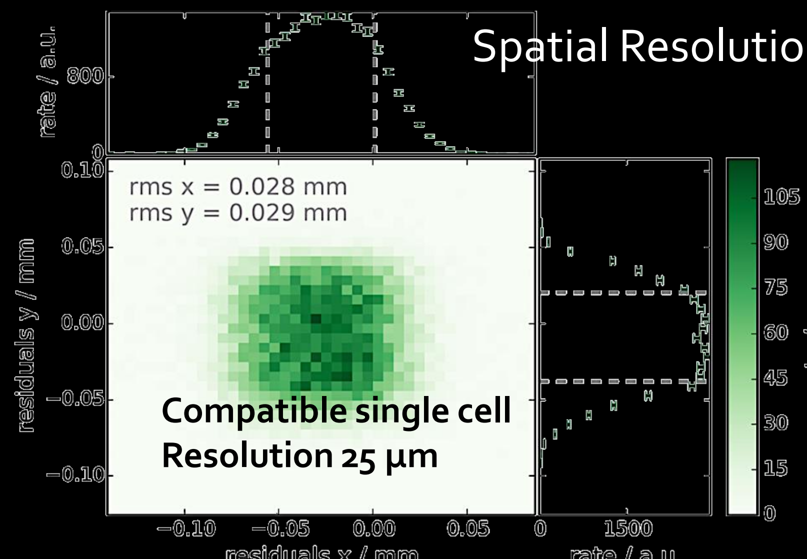




Timing Resolution



Spatial Resolution



Next – Scale-up Mupix 7 Size -> (2x1) cm²

Timing Detectors: SciFi Tracker

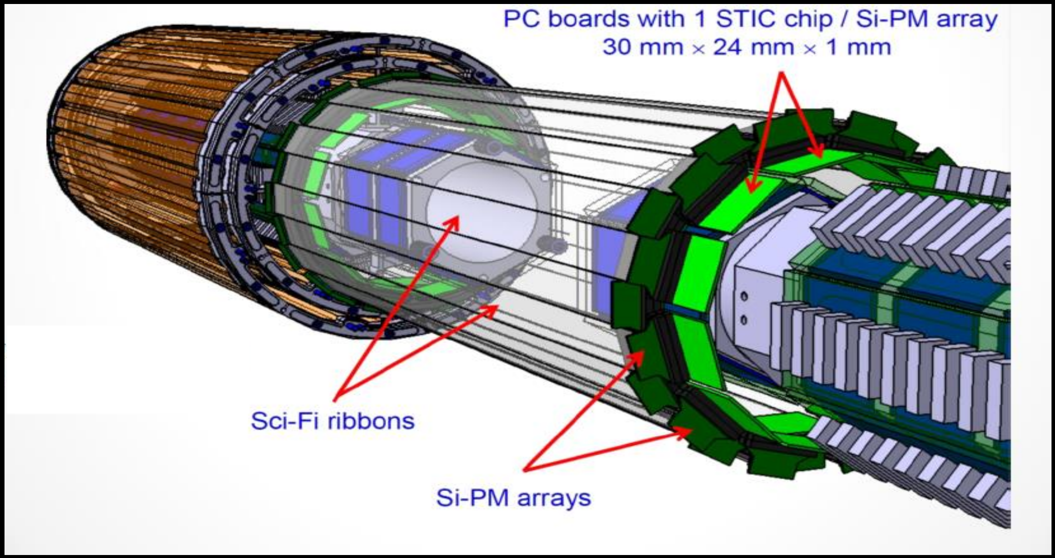
Used in central Barrel Region

Main Function

- Good Timing
- Reduce Accidentals

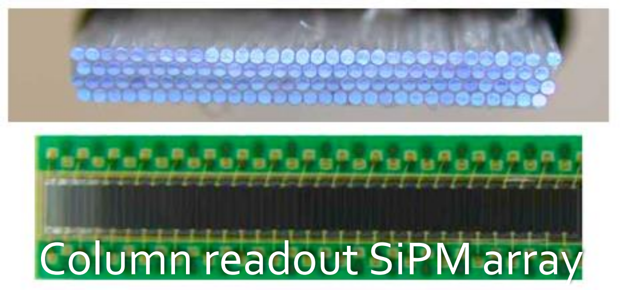
Requirements

- Minimal material budget
- High granularity
- Fast with $\sigma_T < 1$ns



Baseline Design

4500 Fibres in **3 layers a 1500/layer**
Fibres Kuraray-> **250 µm dia. Double-clad**, TiO_2 or Al coating
24 Ribbons : 16 mm wide, ~ 300 mm long



Performance

Eff. Thickness 700 µm **< 2 ‰ X_o**
Timing resolution $\sigma_t < 500$ ps

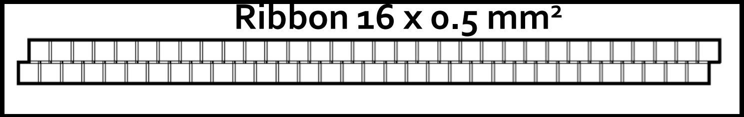
Readout

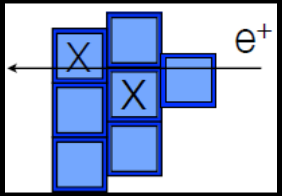
SiPMs (both ends) via
64-ch LHCb-type SiPM column readout
or custom single-fibre readout
STiC/MuSTiC – custom ASIC developed
KIP Heidelberg

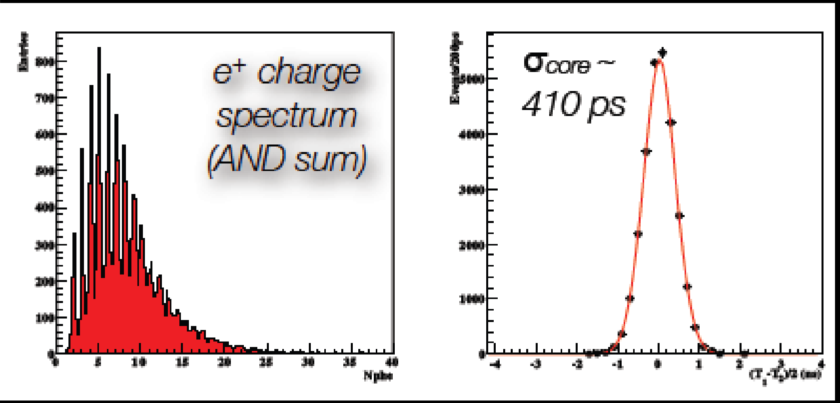
SCiFi -continued

Alternative Design: 250 μm Square Fibres

Fibres in **2-3 staggered layers a 1500/layer**
Fibres Saint-Gobain-> **250 μm Square Double-clad**, Al coating







Test Performance mips

Mean timing resolution σ_t ~ 410 ps
Efficiency (double layer) > 99%
Optical x-talk < 1%

Timing Detector – Tile Detector

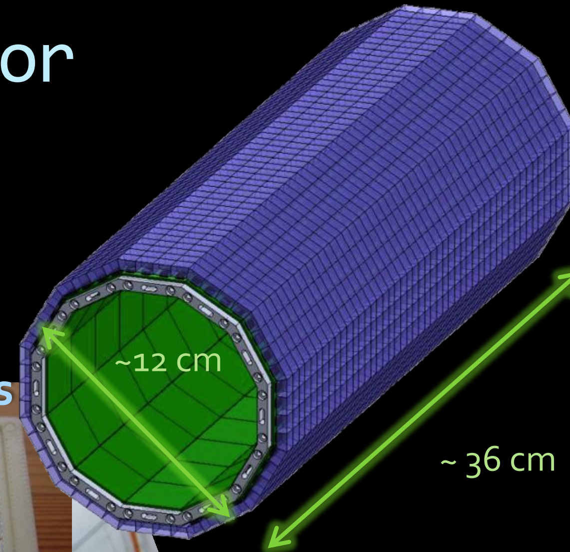
Used in Re-curl Stations

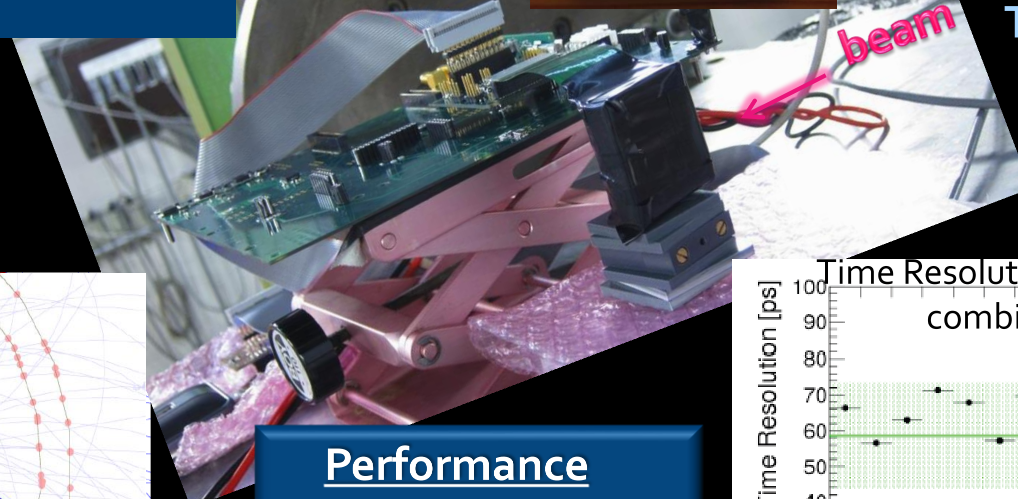
Main Function

- Excellent Timing
- Reduce Accidentals

Requirements

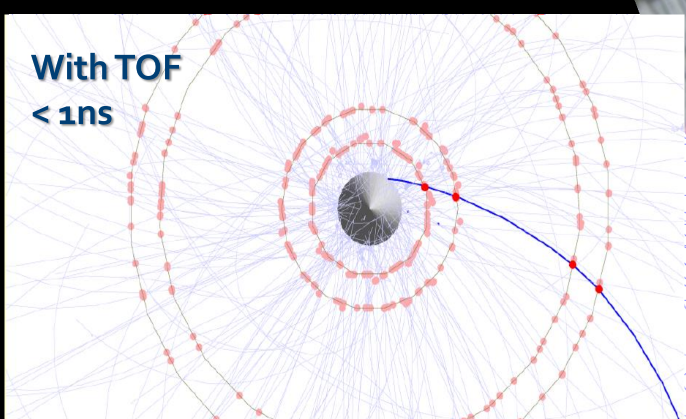
- High granularity 3360 chs/ module
- High resolution σ_T < 100 ps
- Max. efficiency





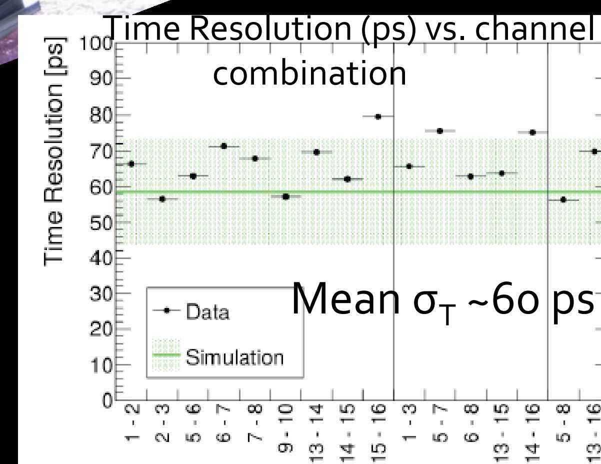
Test Beam DESY

The Timing Asset



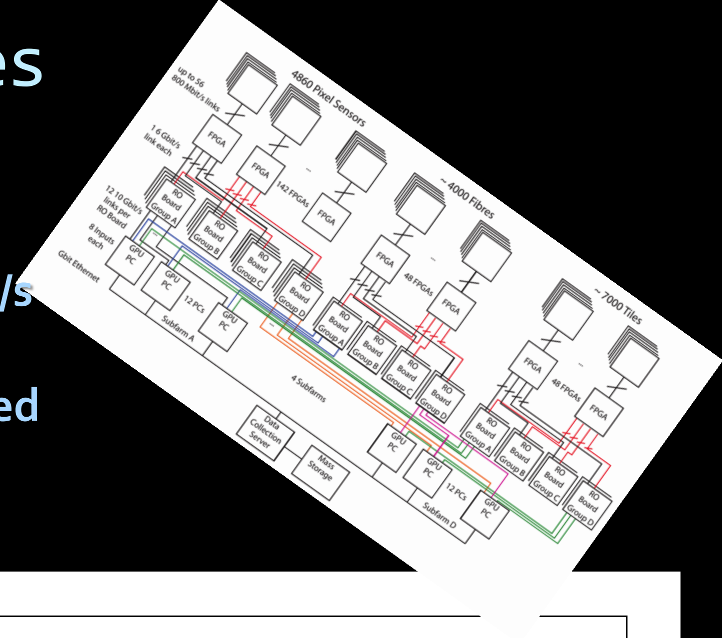
Performance

Time resol. ~ 60 ps
Efficiency > 99%
Pileup (phase I) < 1%

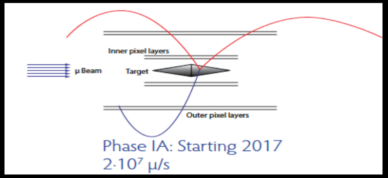


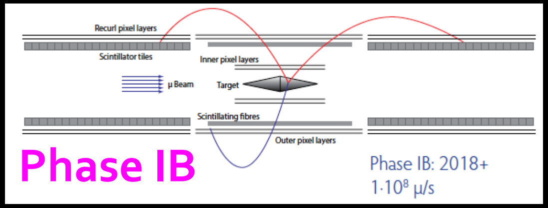
Expectation – Sensitivities

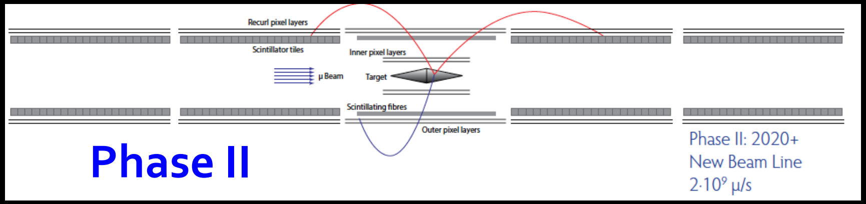
- Fully digitized, zero-suppressed channel readout
  ~ 275 M chs
- No trigger continuous FE read-out (time slices) **~1Tbit/s**
- ~50 PCs & GPUs (on-line Filter Farm)
- On-line track reconstruction **10^9 3D track fits/s achieved**
- Data reduction factor **1000 ⇒ on tape 100Mbyte/s**

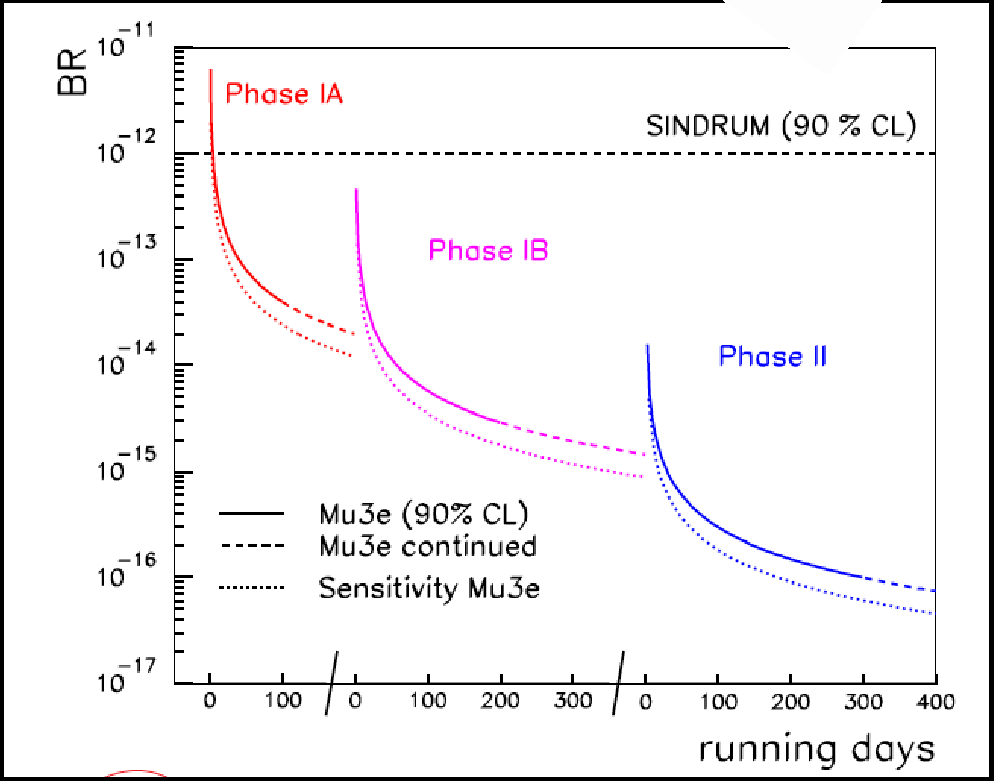


Phase IA





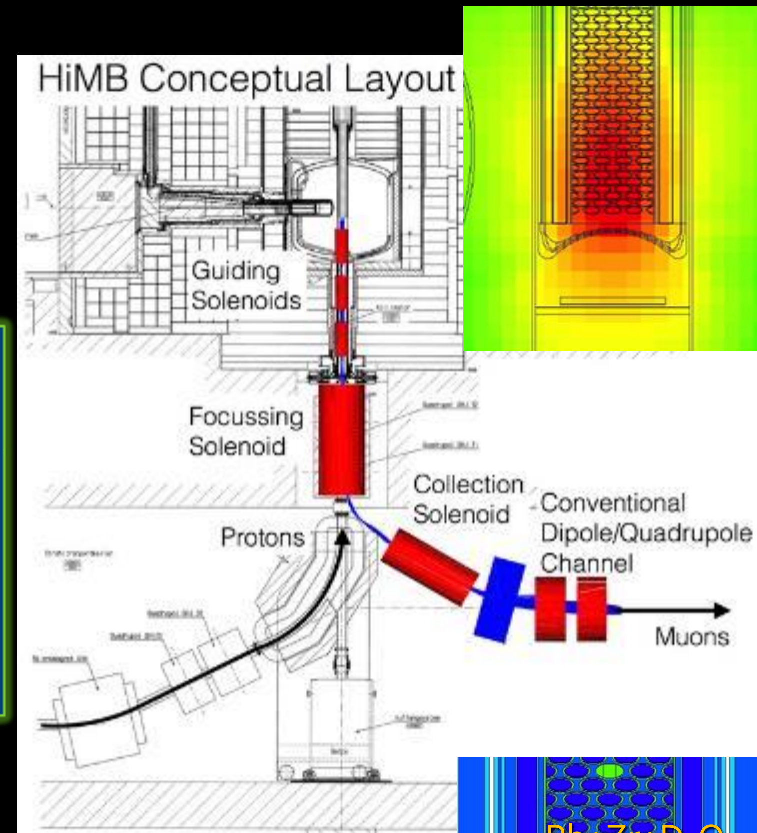




Phase II – continuing @ the Intensity Frontier

GHz Muon beam required for next generation
LFV-experiments at PSI such as Mu3e Phase II…

A **2-year Feasibility Study** started end 2013 known as the **HiMB-Project** to look into the possibilities of a new "**H**igh-**i**ntensity **M**uon **B**eam" at PSI

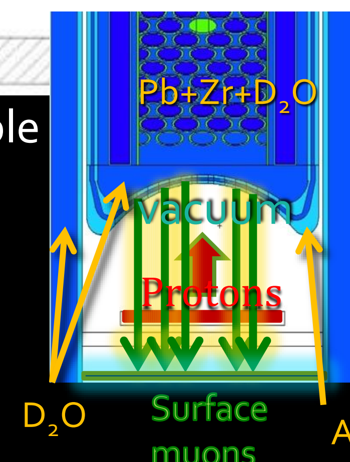


➔ **Based on a Novel Idea**

Use window of the SINQ spallation neutron target as a Source of surface muons – extracting them in the opposite direction down the proton beam line into a cellar region just below the spallation source, using solenoidal channel.

HiMB Project mid-term Findings

- Harsh environment -> Severe restrictions on magnet technologies possible
- Only radiation-hard coils possible
- Main restriction from small beam-pipe aperture dia = 220 mm
- Only feasible if can lift restriction on beam-pipe ➔ need to modify SINQ moderator tank -> Not Possible **NOW HiMB@EH**

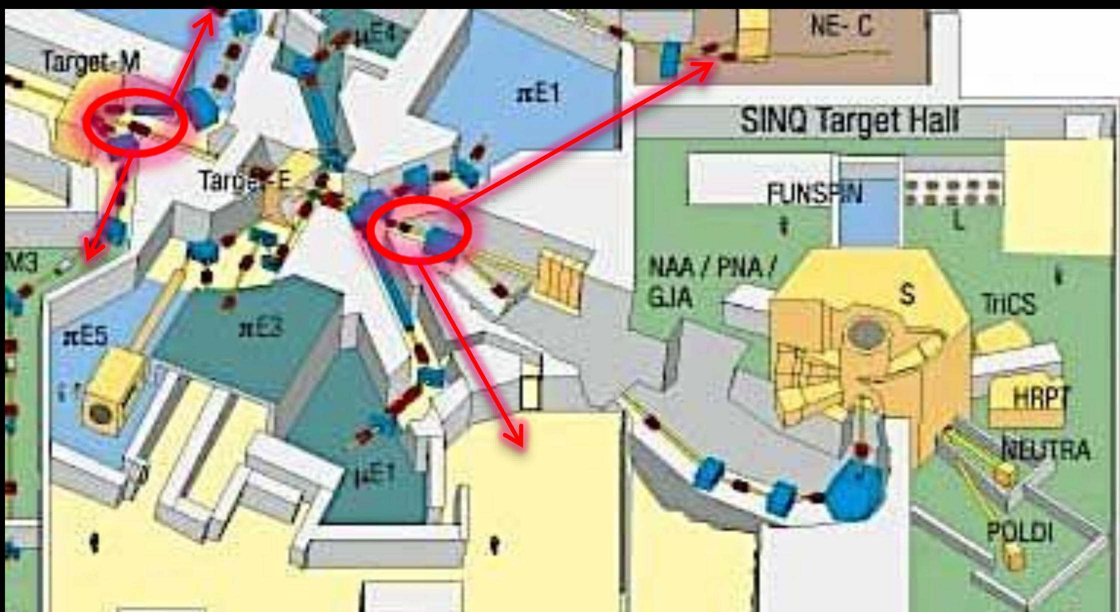


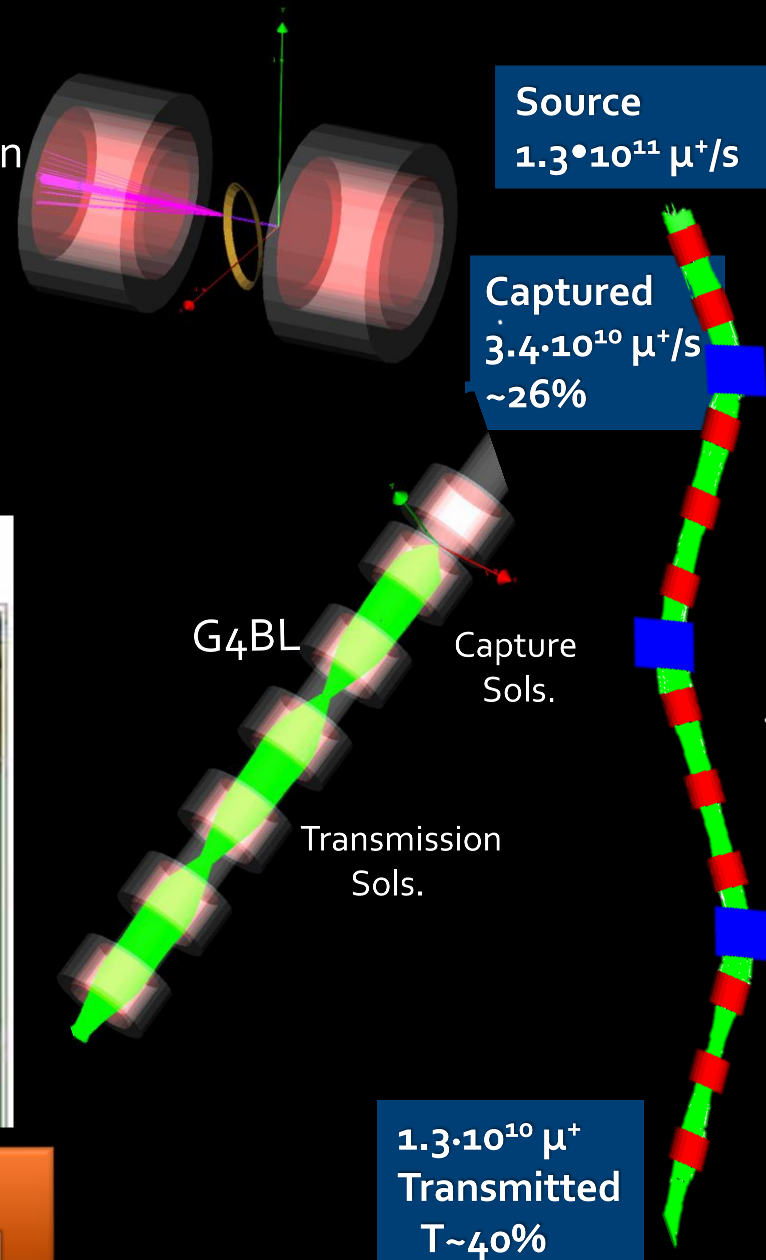
HiMB@SINQ → HiMB@EH

HiMB@EH -> Now Studying PSI Proton-hall Version
Candidate → Replace thin Target M Station at PSI

Current Basis: Split Solenoidal Channel with 20 mm C

1-side Particle Physics: High-intensity option
1-side Materials Science: High Polarization option





First Simulations Suggest
$O(10^{10})$ μ^+/s can be Transmitted
over ~ 20 m at I_p= 2.3mA

Collaboration Commitments

- Beam and Target (PSI)
- Solenoidal Magnet (PI-HD)
- Pixel Detector (PI-HD, KIT, Mainz)
- Scintillating Fibre Detector (ETHZ, PSI, UniG,UniZ)
- Scintillating Tile Detector (KIP-HD)
- Detector Readout and Filter Farm (UniM)
- Mechanics and Cooling (PSI, PI-HD)
- Experiments Infrastructure (PSI)
- Slow Control (PSI)
- Computing - under discussion!

Backup

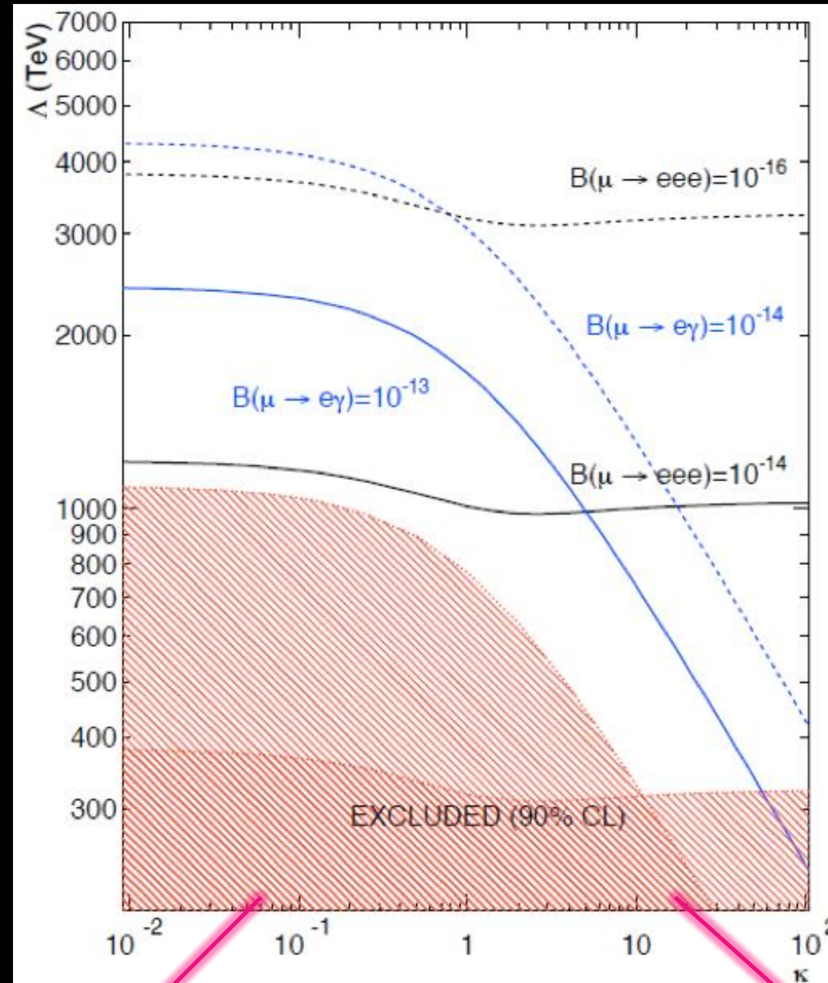
Model-independent Approach

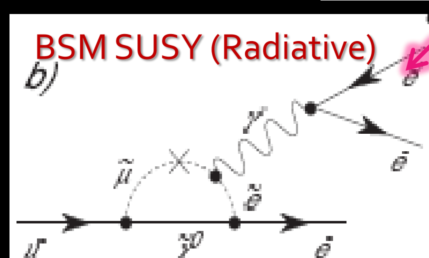
Sensitivity to new BSM mediating mass-scales Λ

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{e}\gamma^\mu e\right)$$

A. de Gouvêa
Nucl. Phys. B 188 (2009) 303-308

Λ = mediating mass scale
κ = dimensionless parameter giving relative contribution of dipole κ< 1 or 4-fermion κ>>1 contribution

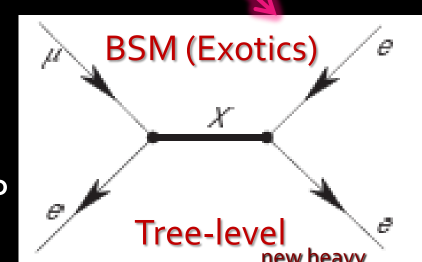




Small
κ -> 0

B(μ->eγ) dominates

Large
κ -> ∞



ONLY B(μ->eee)