The Mu3e Experiment

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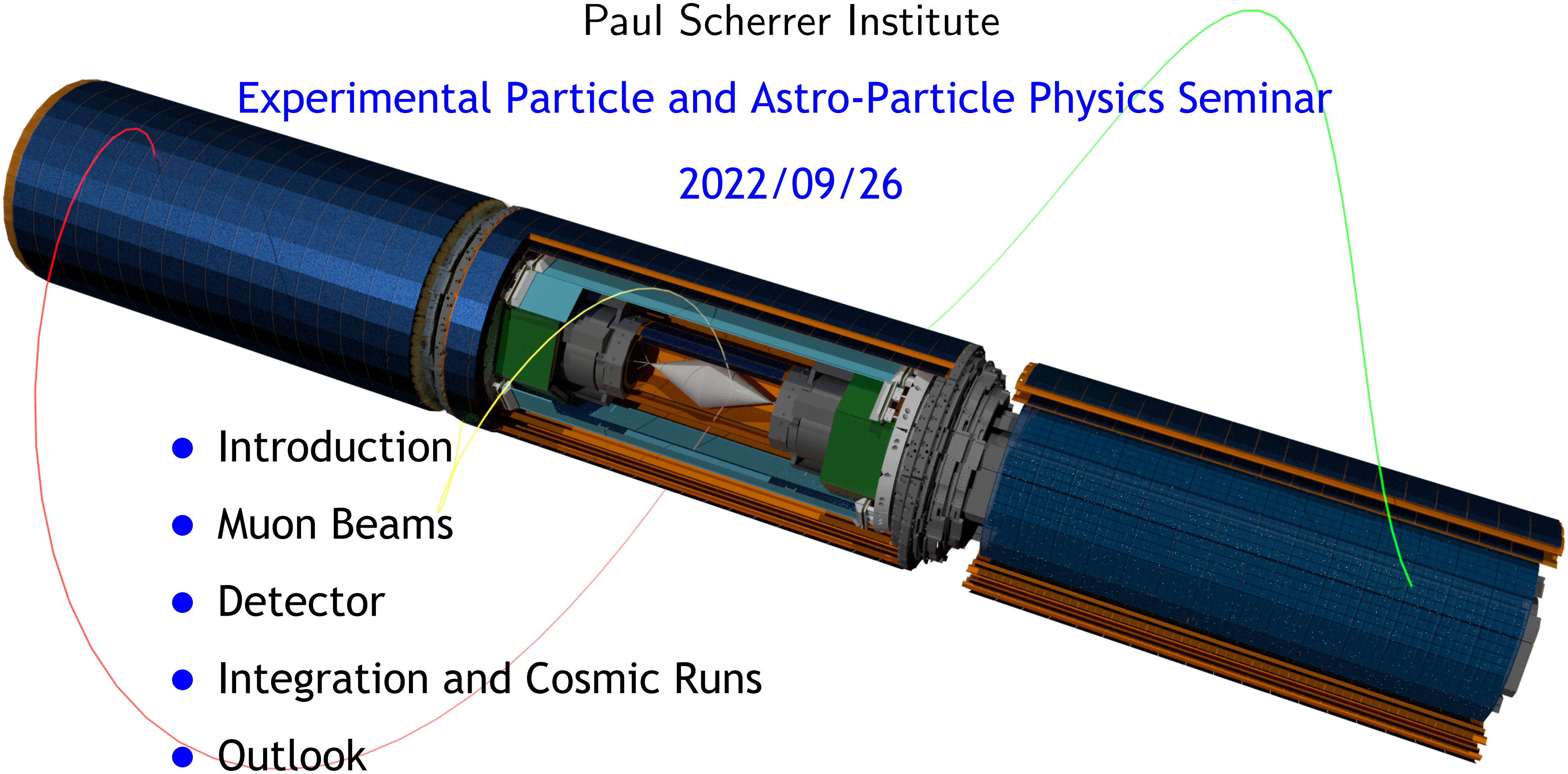
Paul Scherrer Institute

Experimental Particle and Astro-Particle Physics Seminar

2022/09/26



- Introduction
- Muon Beams
- Detector
- Integration and Cosmic Runs
- Outlook

(Mu3e $\equiv \mu^+ \rightarrow e^+e^-e^+$)

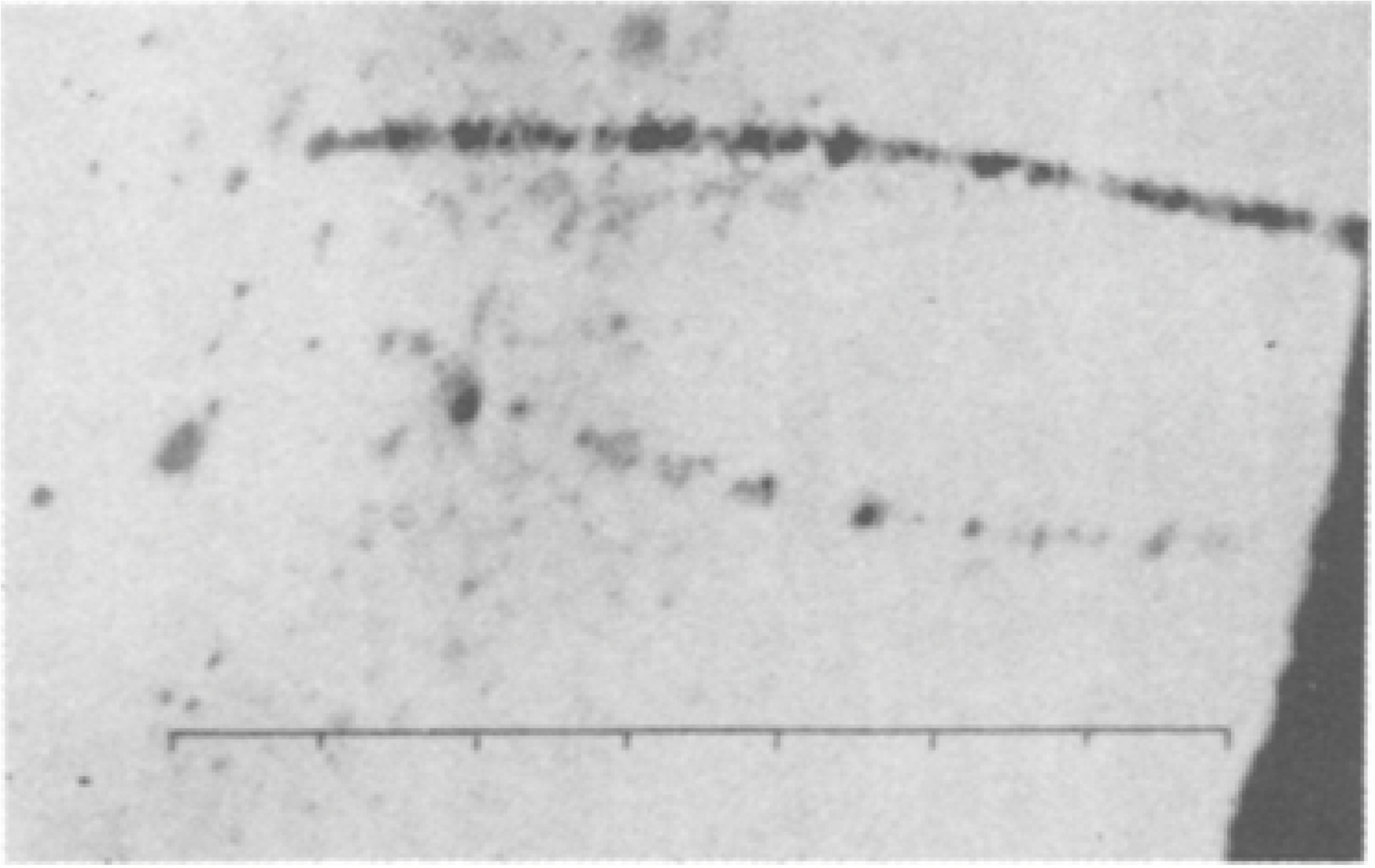


Fig. 5.

Doppelspur als Resultat einer vermutlichen Kernexplosion. 7-fache Vergrößerung. Untere Spur = Elektron von 37 000 000 V. Natur der oberen positiven Korpuskel nicht sicher bekannt.

(first - unidentified - muon track image in Wilson cloud chamber) P. Kunze, Z Phys 83,1 (1933)

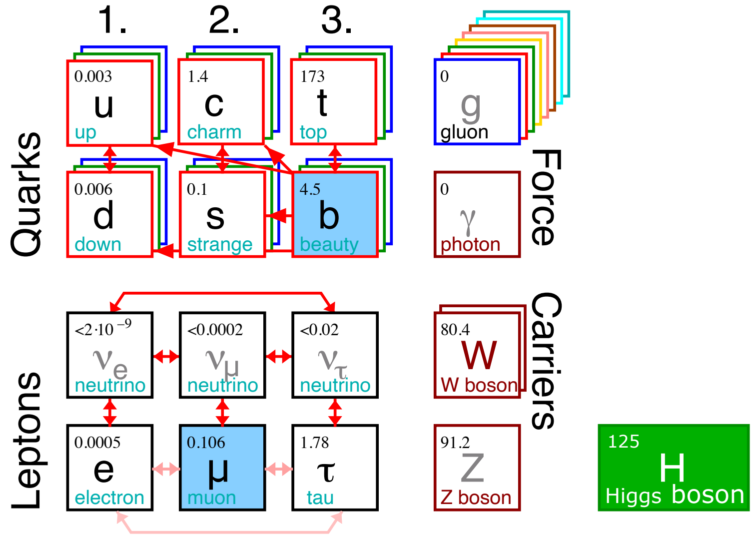
Flavor Physics

- The Standard Model of particle physics is given by
  - Lagrangian and its symmetries $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ → 'Gauge physics'
  - Pattern for spontaneous symmetry breaking → 'Higgs physics'
  - Elementary particles → 'Flavor physics'

- Flavor physics of leptons and quarks
  - 1937 discovery of muon lepton (Anderson, Neddermeyer . . .)
    - 1956 discovery of (electron anti-) neutrino (Cowan, Reines)
    - 1975 discovery of tau lepton (Perl)
  - 1947 discovery of 'strangeness' (Rochester, Butler . . . Pais)
    strong production, weak decays (interpretation in hindsight)

  → more than one generation

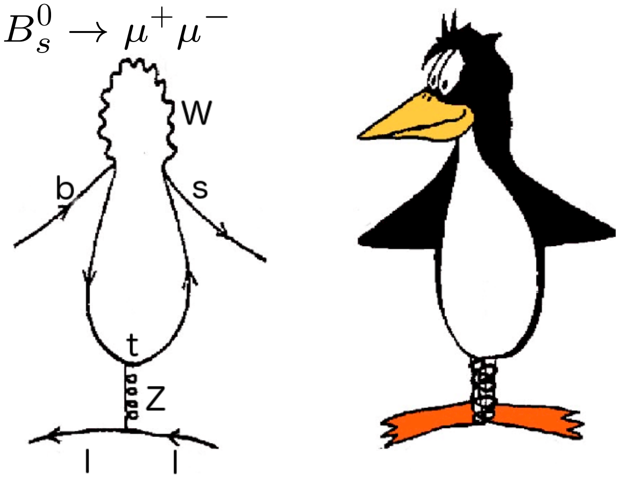
- Immediate questions
  - why? ('who ordered that?', I. Rabi)
  - interactions between generations?
    decays
    oscillations
  - implications?



Charged lepton flavor violation (CLFV)

$b \to s\mu\mu$

$B_s^0 \to \mu^+\mu^-$

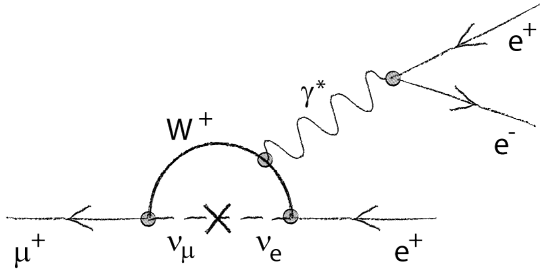


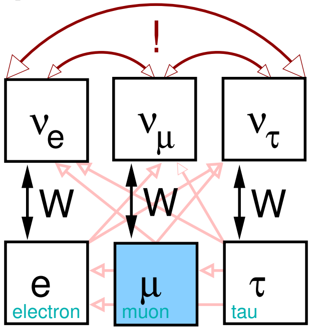
- Flavor changing neutral currents (FCNC)
  - ▷ forbidden in SM at tree level

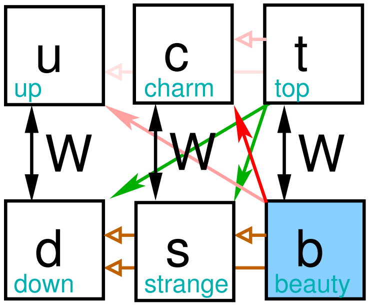
    allowed in charged current loop effects
  - ▷ 'effective' FCNC well established in SM (and ?)

    e.g. Penguin decays

    oscillations of neutral mesons and neutrinos
- But not at all for charged leptons!
  - ▷ CLFV = charged lepton decay violating lepton-flavor number







NO CLFV decay observed, ever!

???

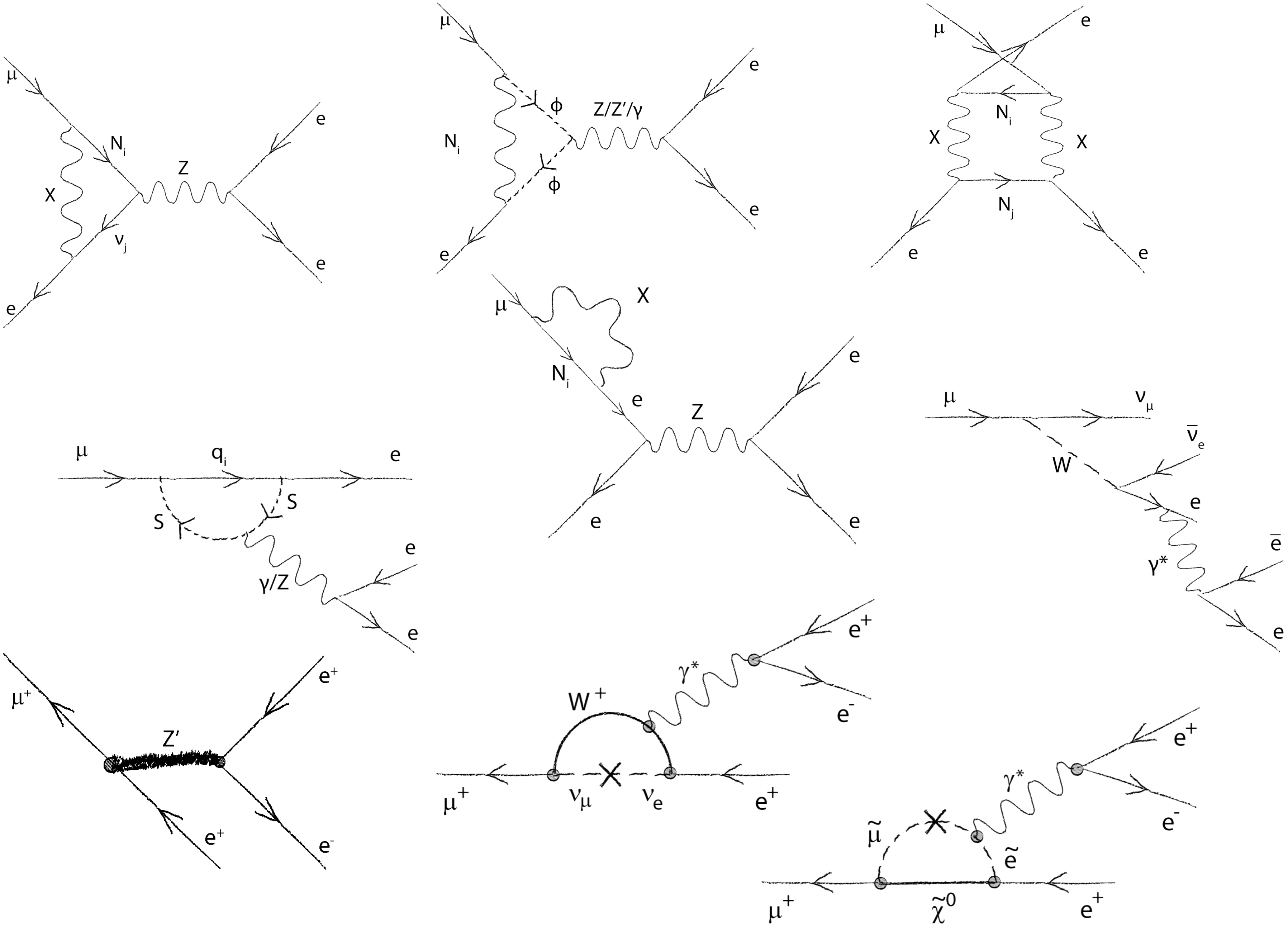
- Why?? SM can do this (as for quarks)?!
  - ▷ Yes! But $m_\nu \ll m_W$

$$\boxed{\mathcal{B}_{SM}(\mu^+ \to e^+e^-e^+) \quad \approx \quad 10^{-55}}$$

- 'New' physics?
  - ▷ sure, anything can be made to work

Note: In SM with massless neutrinos, individual lepton-flavor numbers are conserved (such a basis can be chosen)

For example . . .


μ
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Handles on CLFV

2208.00020
PPNP,71,75

- ‘Golden’ (muon) modes
  - ▷ $\mu^+ \to e^+\gamma$

    established $\mu^+ \neq e^{+*}$

    hints towards ν_μ
  - ▷ $\mu^+ \to e^+e^-e^+$

    more observables (3-body decay)
  - ▷ $\mu^-N \to e^-N$

    no ‘accidental’ background

$\Rightarrow$ Connections between modes

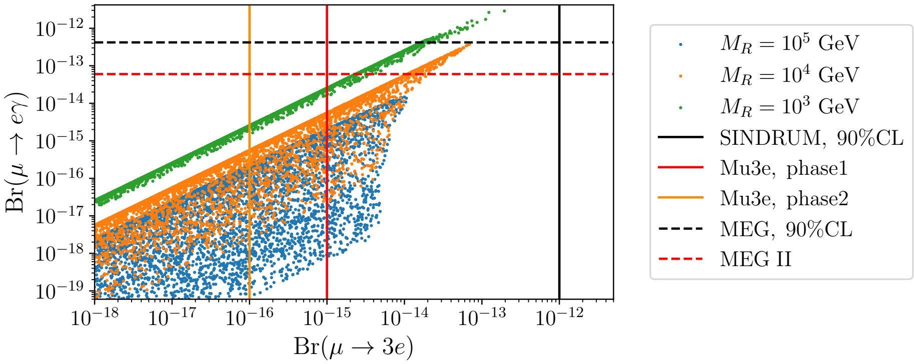
model-dependent

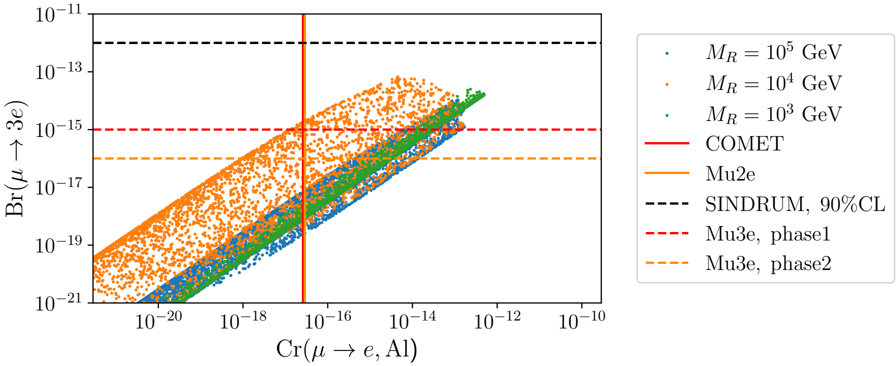
(Symmetry Protected Type-I Seesaw)

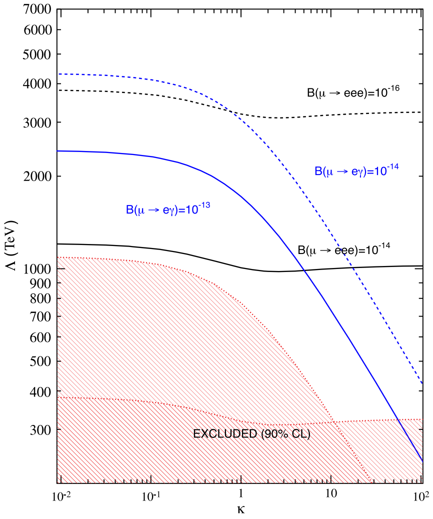
effective Lagrangians

(mass scale Λ and operator strength ratio κ)

- ‘Other’ (?) modes
  - ▷ Rare meson decays, $e.g.$, $K^0_L \to \mu^\pm e^\mp$, $B^0 \to e^\pm\mu^\mp$
  - ▷ Rare Z decays, $e.g.$, $Z \to e^\pm\mu^\mp$
  - ▷ Muonium anti-muonium oscillations





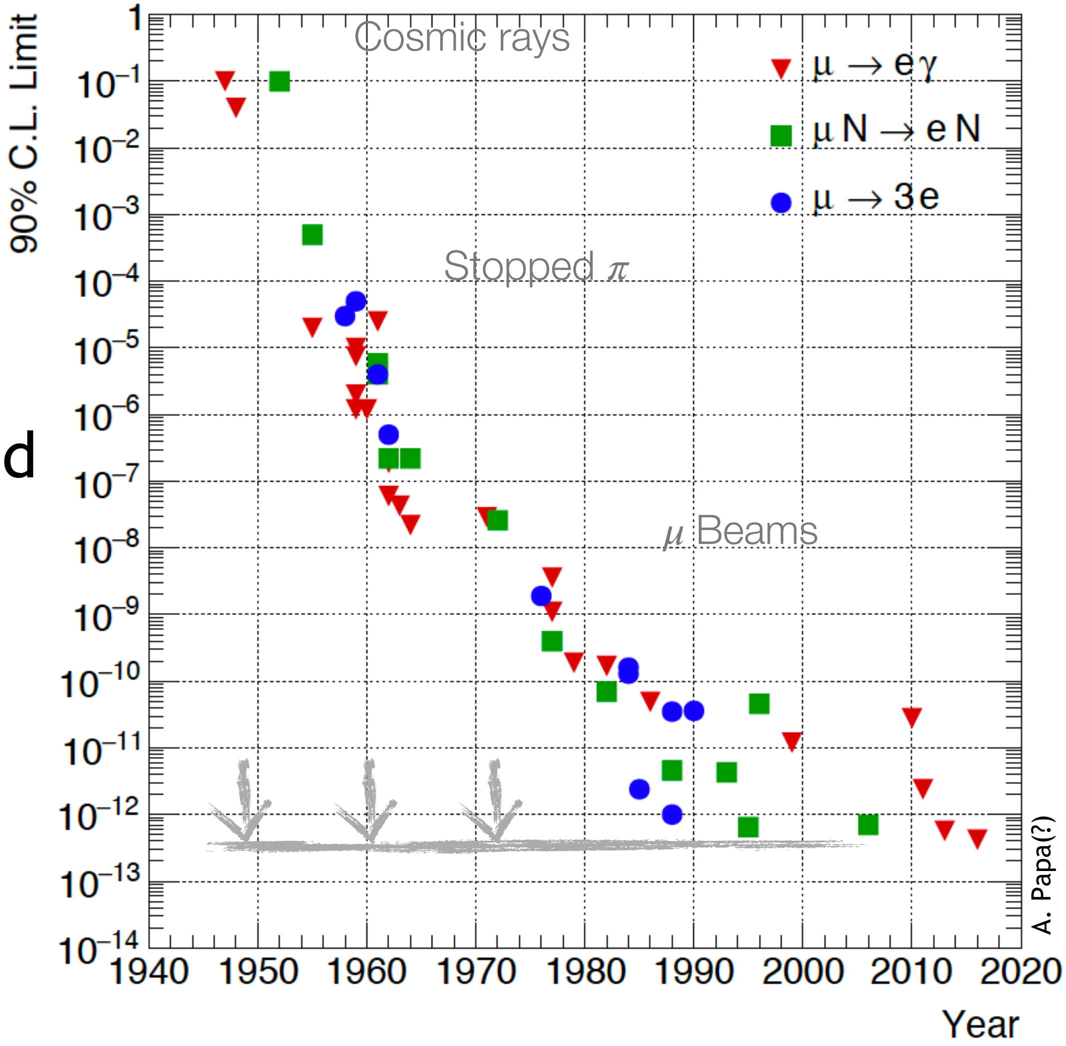


CLFV in muon decays

- Why muon decays?
  - ▷ muons available at very high-rate beam facilities
  - ▷ relatively clean experimental environments
  - ▷ calculable
- Progress technology driven
  - ▷ cosmic muons
  - ▷ stopped pions
  - ▷ muon beams

$\Rightarrow$ Worldwide effort to go beyond

$\rightarrow$ with all 3 modes!

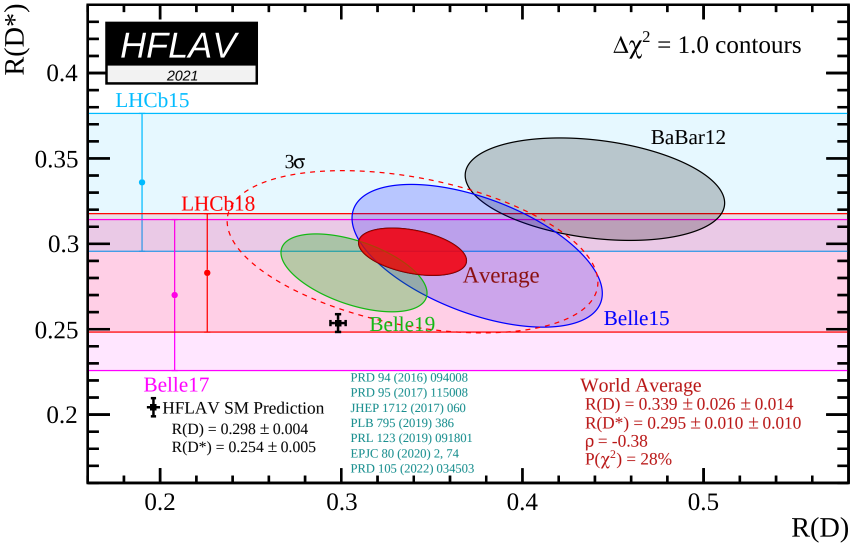


Note: also searches for CLFV in τ decays, e.g. Belle(-2), and other experiments

Not (quite) the same: LFUV

HFLAV 2021
N Phys, 18, 277 (2022)

- Lepton flavor universality violation. Hot since 2012, 'B-anomalies'
- Comparison of semileptonic $B \to D^*$ decays with τ and $\ell = e/\mu$



$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$$

(convergence towards the SM :-)

3.3σ

- $B \to K^{(*)}\mu^+\mu^-$ vs. $B \to K^{(*)}e^+e^-$

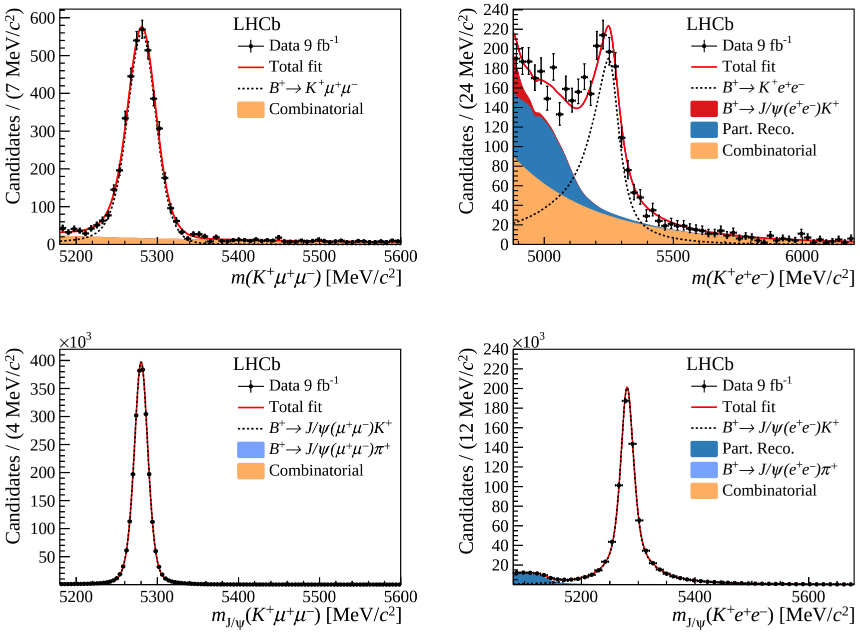
dilepton inv. mass (squared) $1.1 < q^2 < 6$ GeV^2

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to J/\psi\,\mu^+\mu^-)} \Big/ \frac{\mathcal{B}(B \to Ke^+e^-)}{\mathcal{B}(B \to J/\psi\,e^+e^-)}$$

$$= 0.846 \,{}^{+0.042}_{-0.039}\text{(stat)}\,{}^{+0.013}_{-0.012}\text{(syst)}$$

3.1σ

($exactly$ the same central value as in previous iteration)



My expectation: CLFV quest will survive B-anomalies excitement

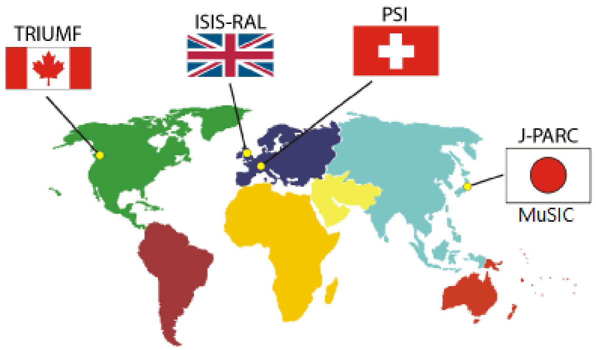
Muon beams

Muon beams? Muon beams!

- Many communities interested in muons
  - ▷ particle physicists
  - ▷ condensed matter, . . .

⇒ Very large number of facilities

→ fast and efficient accelerator R&D



- Beam structure
  - ▷ pulsed beams

    non-coincidence/delayed signatures

    p synchrotons (J-PARC, FNAL, RAL)

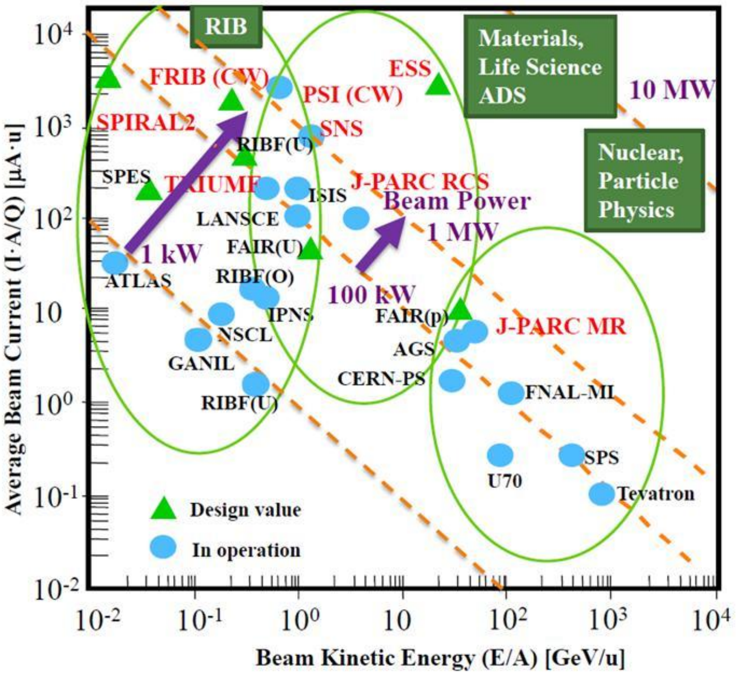
    storage ring

    up to $10^{11}\mu^+/$s
  - ▷ DC for coincidence signatures

    p cyclotrons, PSI, TRIUMF, MuSIC

    smaller rates

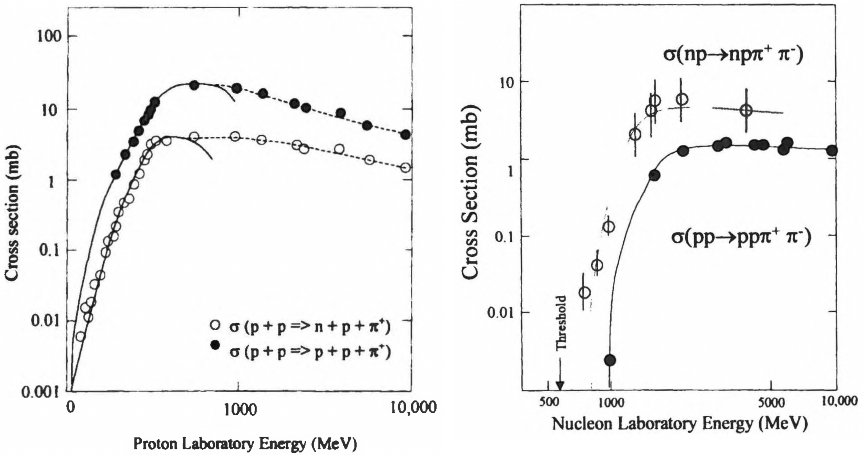
    up to $10^8 - 10^{10}\mu^+/$s



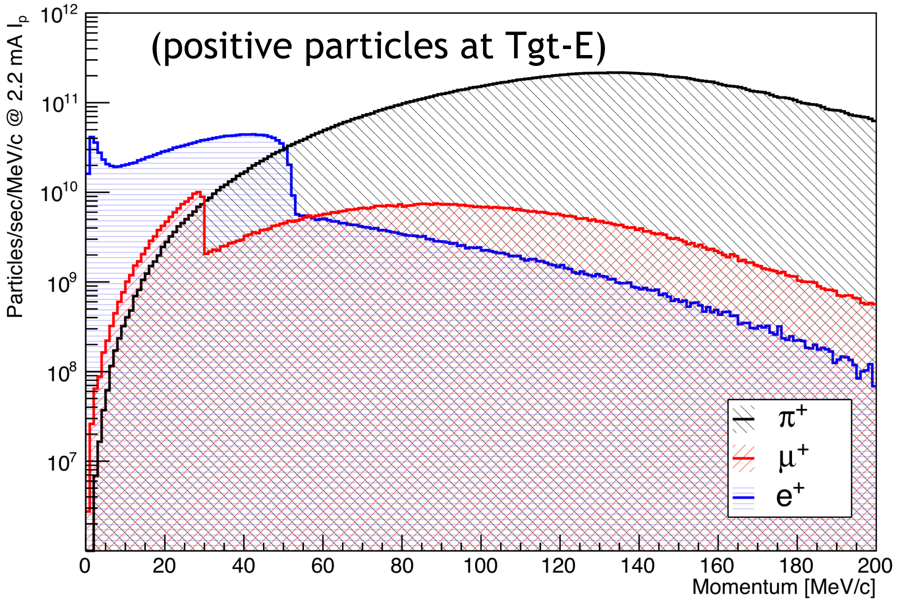
Muon production I

Eaton, Kilcoyne (1997)
Thesis Z. Hodge (2018)

- Proton-nucleon interactions
  - $pN \to pN\pi$, $\pi \in \{\pi^+, \pi^-, \pi^0\}$
  - $E_p > 280\,$MeV: single pion production
  - $E_p > 600\,$MeV: double pion production
  - In 'backward' production
    $N(\pi^+)/N(\pi^-) \approx 4/1$



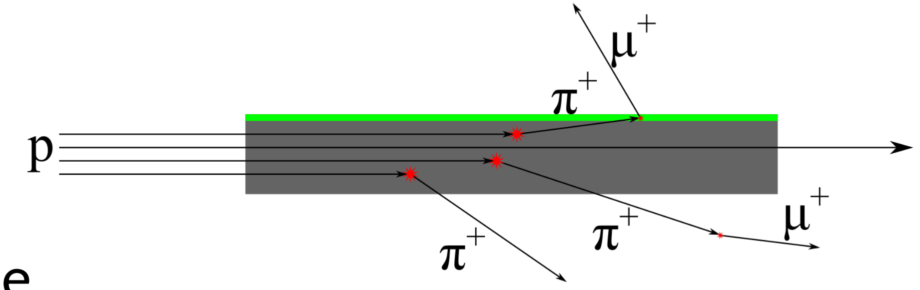
- Pions decay (to muons)
  - $\tau_\pi = 26\,$ns, $c\tau = 7.8\,$m



- Muon production
  - cloud (decay) muons $p_\mu > 30\,$MeV
  - surface muons $p_\mu \approx 29.79\,$MeV
  - sub-surface muons $p_\mu < 26\,$MeV
- Positron contamination
  - from μ^+ decays ($\tau_\mu = 2.197\,\mu$s, $c\tau = 658.6\,$m)
    'Michel decays'
  - from π^0 decays (photon conversion or Dalitz decays)

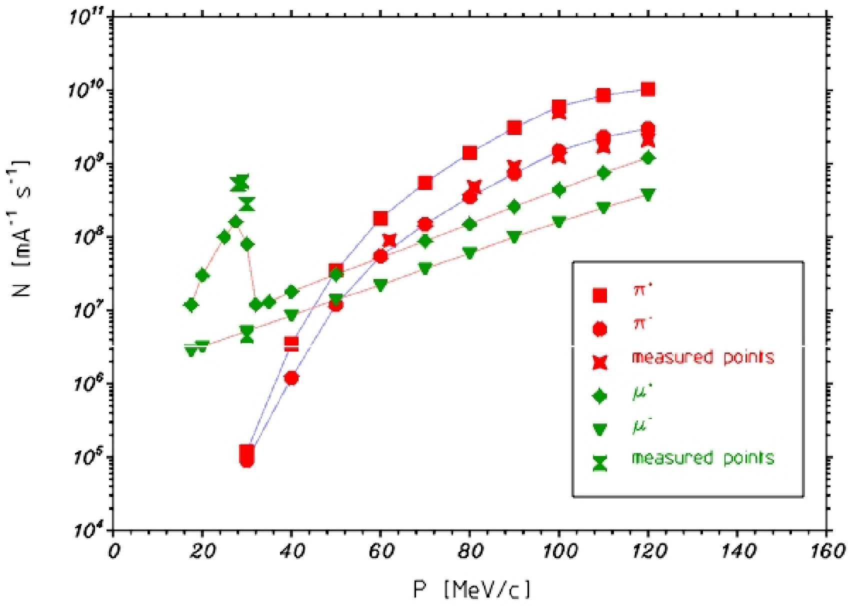
Muon Production II

- Cloud muons
  - ▷ pion decay in flight, close to production target (spread out)
  - ▷ wide momentum range possible
  - ▷ both charges



- Surface muons
  - ▷ π^+ stop and decay close to surface
  - ▷ small source $\to$ precise beam optics
  - ▷ only positive muons (π^- form pionic atoms, undergo nuclear capture)
- Decay of positive pions at rest
  - ▷ With $\vec{p}_{\pi^+} = 0, m_{\nu_\mu} = 0, \vec{p}_{\nu_\mu} = -\vec{p}_{\mu^+}$

$$
\begin{aligned}
m_{\pi^+} &= \sqrt{\vec{p}^2_{\mu^+} + m^2_{\mu^+}} + \sqrt{\vec{p}^2_{\nu_\mu} + m^2_{\nu_\mu}} \\
\to |\vec{p}_{\mu^+}| &= \frac{m^2_{\pi^+} - m^2_{\mu^+}}{2m_{\pi^+}} \\
|\vec{p}_{\mu^+}| &= 29.79\,\text{MeV}
\end{aligned}
$$



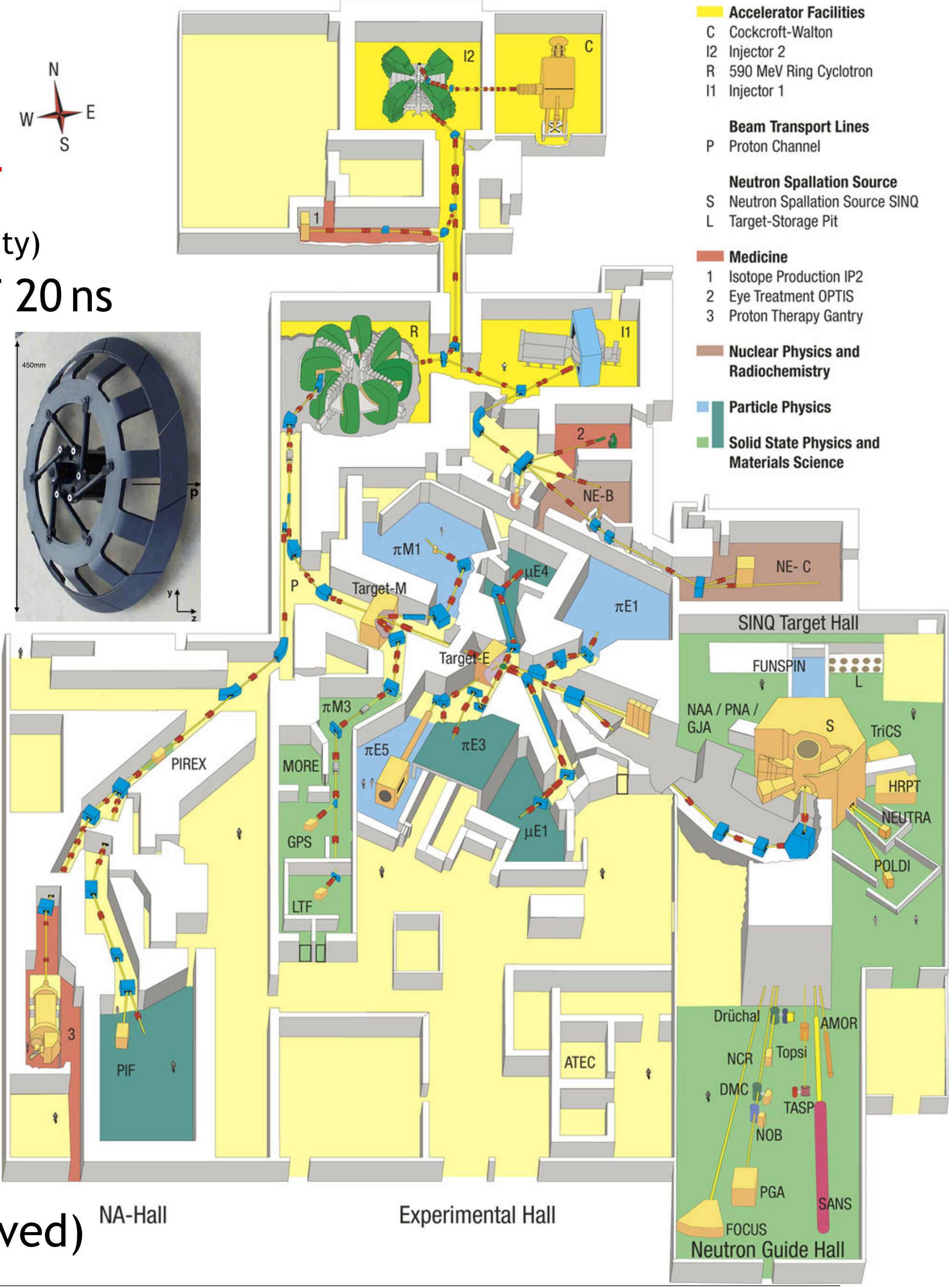
PSI π/μ beams

- **HIPA** (High-intensity proton accelerator facility)
  - time structure of cyclotron RF 20 ns
  - Power

$$\begin{aligned} P &= U \times I \\ &= 590\,\text{MeV} \times 2.2\,\text{mA} \\ &= 1.3\text{MW} \end{aligned}$$

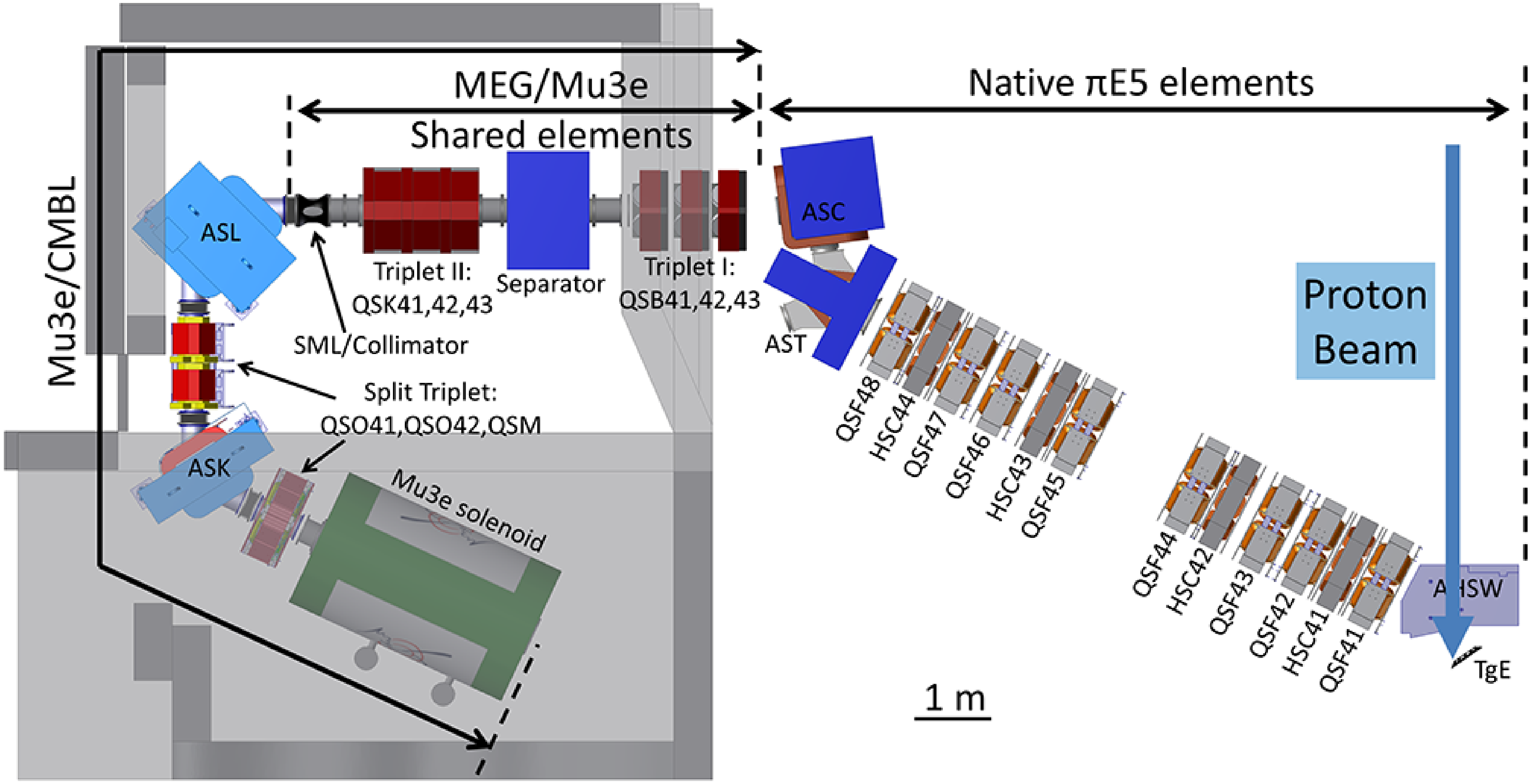
  - two targets
    - M ('mince') 5 mm
    - E ('epaisse') 40 mm

- πE5 beamline
  - particle physics
    - SINDRUM, SINDRUM II
    - MEG, MEG-2
    - Mu3e
- Beamlines for Mu3e
  - CMBL for phase-1
  - HiMB for phase-2 (to be approved)



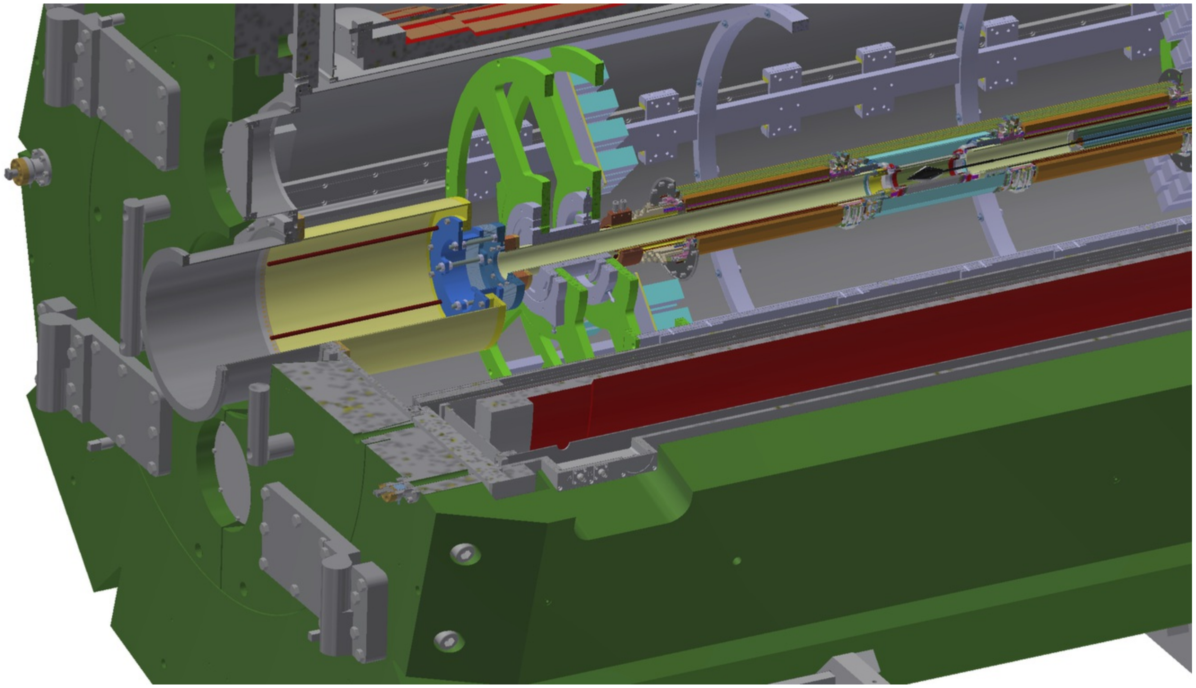
Compact muon beamline in πE5

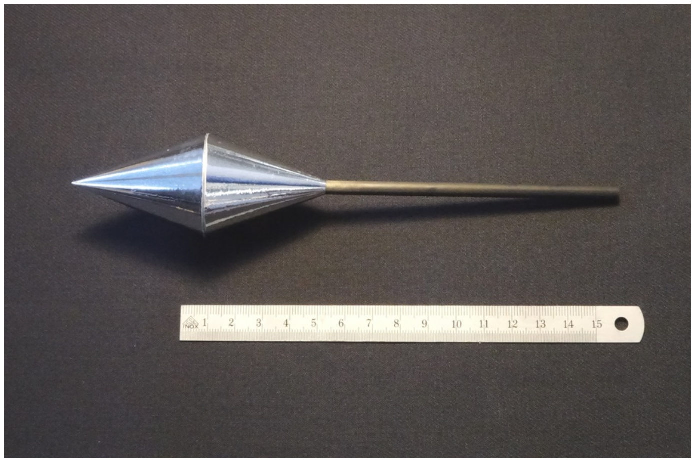
- Beam tuning 2022
  - ▷ measured rate inside Mu3e solenoid: $7.5 \times 10^7 \mu^+/$ s (at $I_p = 2.4$ mA)
  - ▷ limitations by end windows under investigation
  - → already close to phase-1 rate assumptions in TDR

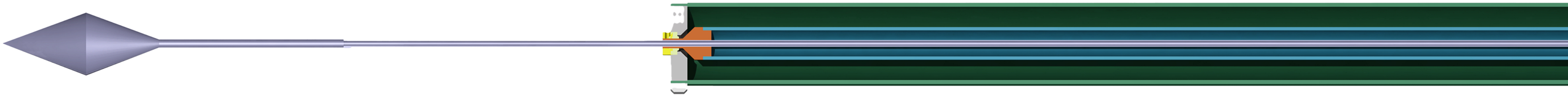


The end of the muon beam

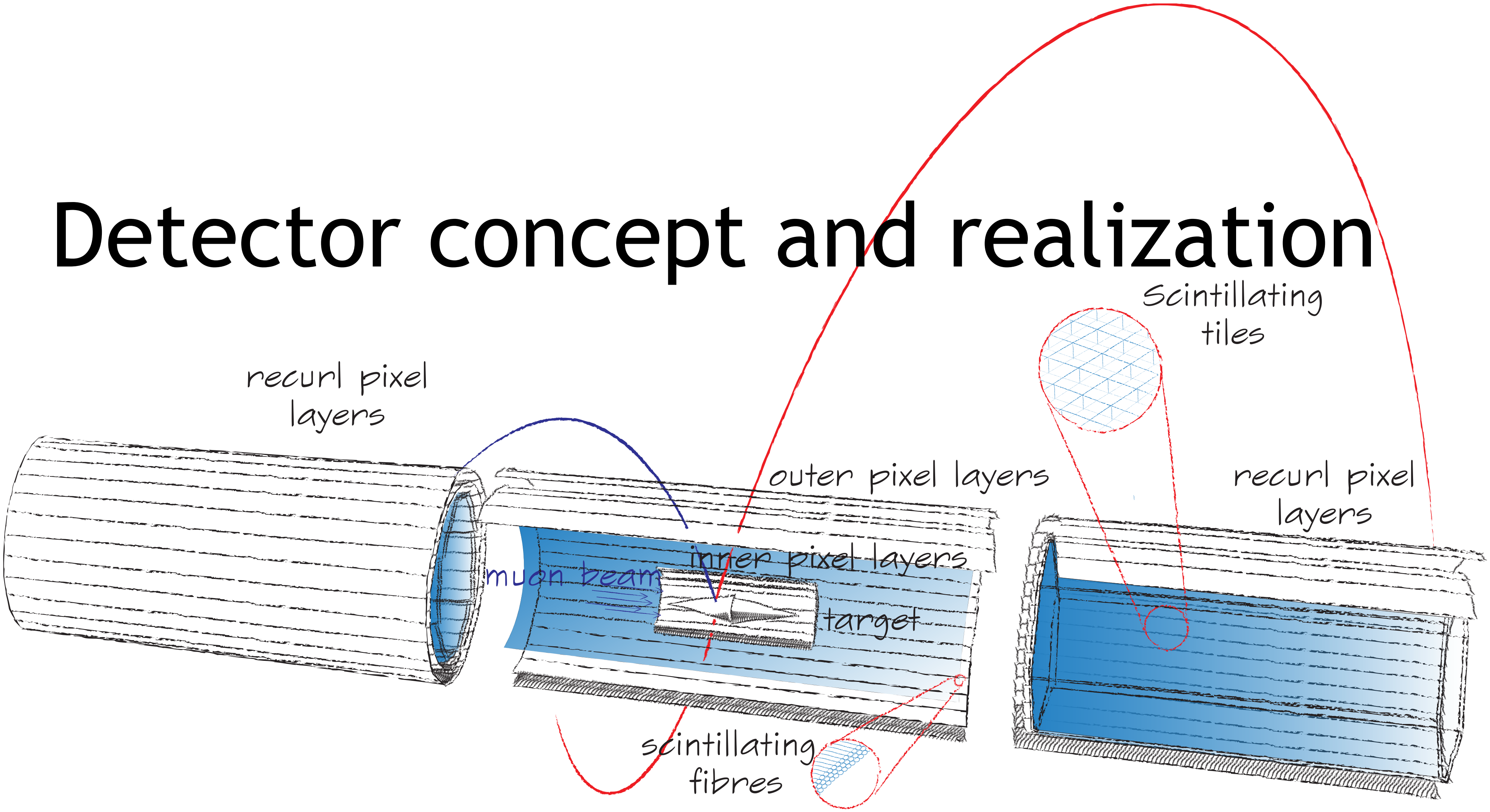
- Solenoidal magnet
  - ▷ $d = 1\,m$, $\ell = 2.7\,$m, $B = 1\,$T, $w = 31\,$t (cf. CMS: 14000 t)
- Hollow double cone mylar target
  - ▷ $100\,\mu$m thickness







Detector concept and realization

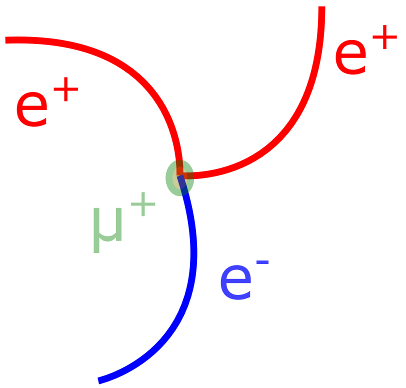


Very large number of positive stopped muons

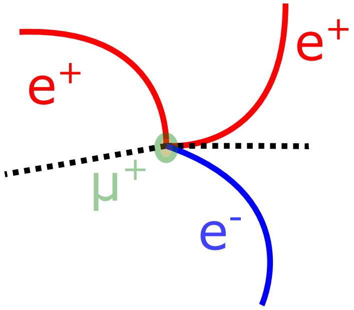
- sensitivity to very small branching fractions
- negative muons interact with nuclei (different physics)
- stopped to build detector around it $\rightarrow$ range $\sim p^{3.5}$ $\rightarrow$ minimize straggling

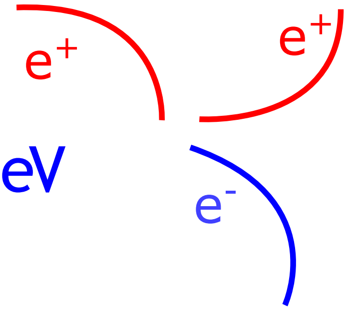
Mu3e Signal and Background

- $\mu^+ \to e^+e^-e^+$ signal decay requirements
  - ▷ large acceptance (3 tracks)
  - ▷ charge identification (e^+,e^-)
  - ▷ excellent vertexing (singular decay point)
  - ▷ excellent timing (singular decay time)
  - ▷ excellent momentum resolution (invariant mass)
  - → ultra-low material thickness



- Background sources
  - ▷ Internal conversion $\mu^+ \to e^+\bar{\nu}_\mu\nu_e\gamma^*(e^+e^-)$
    - missing momentum/energy from 2 neutrinos
  - ▷ Accidental background
    - e^+ from μ^+ ‘Michel’ decays (many)
    - e^- from Bhabha scattering ($e^+e^- \to e^+e^-$)
    - e^+e^- from internal conversion
    - e^- from Compton scattering ($\gamma e^- \to \gamma e^-$)

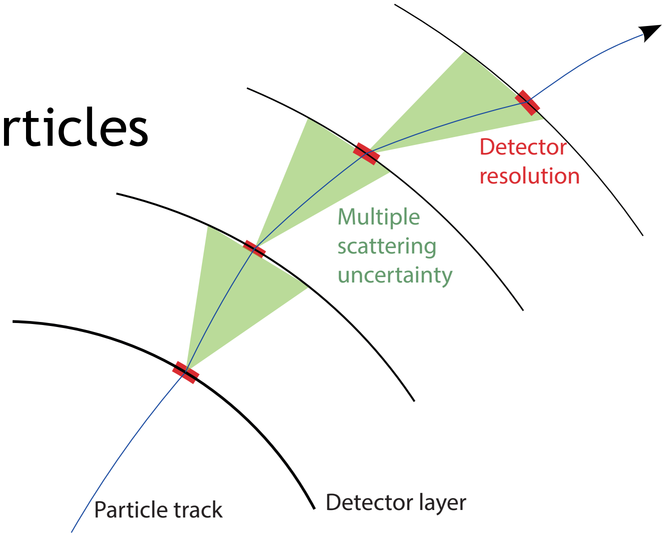




- Maximum final state track momentum 53 MeV
  - → multiple scattering regime

Mu3e Tracking Concept

- Multiple scattering regime
  - ▷ minimize material traversed by charged particles
  - ▷ pixel size not limiting factor

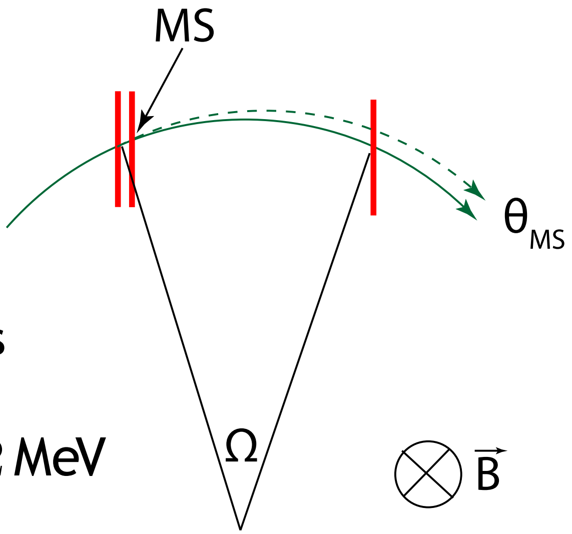


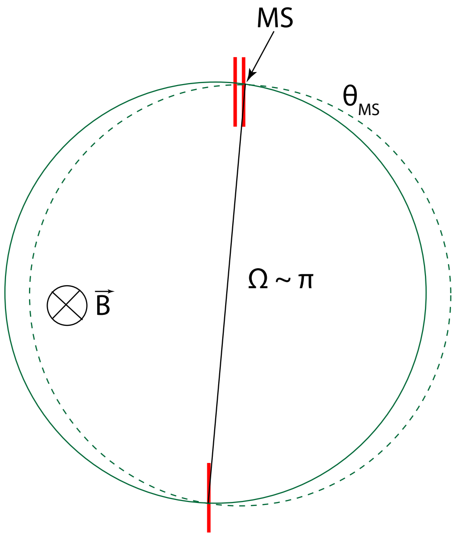
- Optimize places of hit measurements
  - ▷ minimum number of pixel layers
  - ▷ With $B = 1\,\mathrm{T}$ field and track curvature Ω

$$\boxed{\frac{\sigma_p}{p} \sim \frac{\theta_{\mathrm{ms}}}{\Omega}}$$

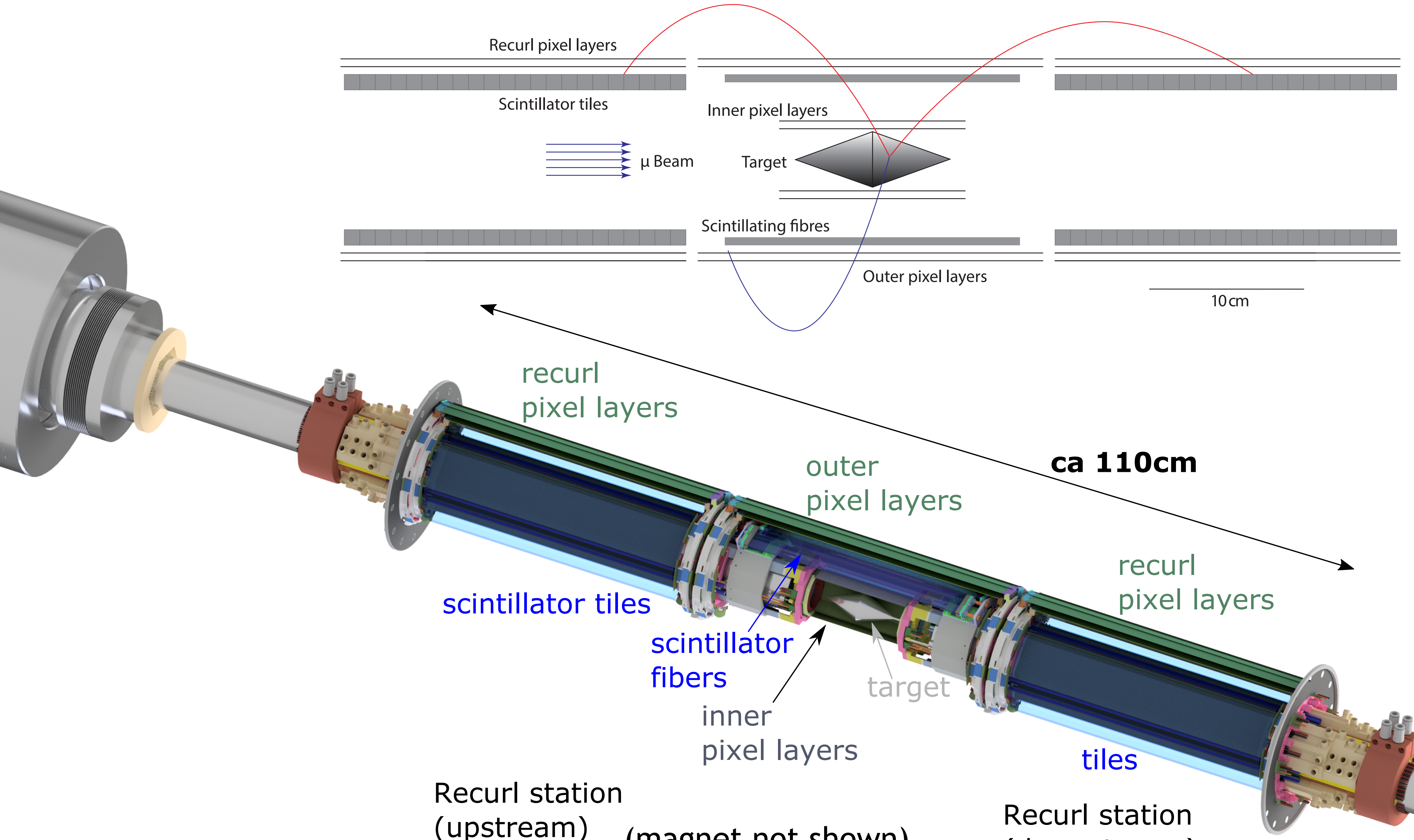
→ large lever arm
  - large radii
  - measure curling tracks ($p < 53\,\mathrm{MeV}$)

▷ $B = 1\,\mathrm{T} \rightarrow p_{T\mathrm{min}} \approx 12\,\mathrm{MeV}$





Mu3e Detector Overview



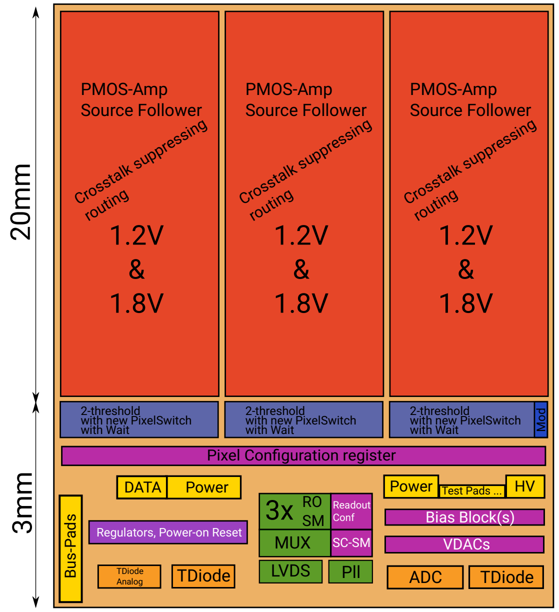
Recurl station
(upstream)

(magnet not shown)

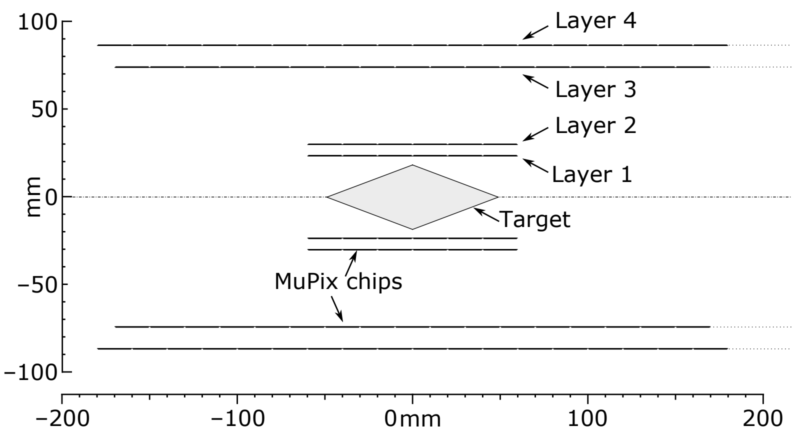
Recurl station
(downstream)

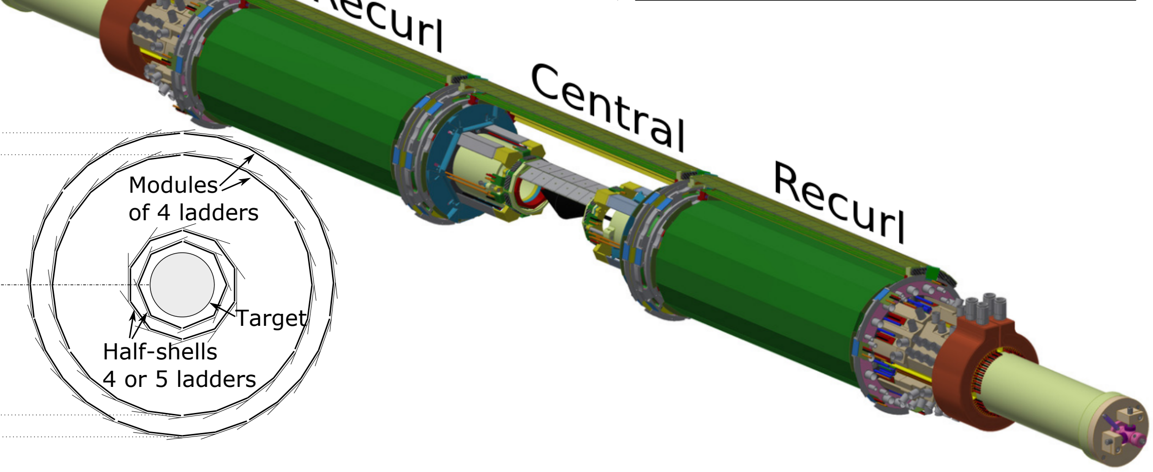
Pixel Chip and Tracker

- Ultra-thin light-weight tracker with custom HV-MAPS MuPix
  - ▷ high-voltage monolithic active pixel sensors
  - ▷ thinnable to $50\,\mu$m
  - ▷ $2\,$cm $\times$ $2\,$cm large sensor
  - ▷ 256×250 pixels ($80\,\mu$m $\times$ $80\,\mu$m) $\rightarrow$ 64000 pixels
  - ▷ sensor and readout in one chip (‘monolithic’)



- Tracker with
  - ▷ 2 vertex and 3×2 outer layers
  - ▷ 2844 MuPix chips $\rightarrow$ 182 MPix
  - ▷ gaseous He cooling
  - $\rightarrow$ ca $0.1\% X_0$/layer

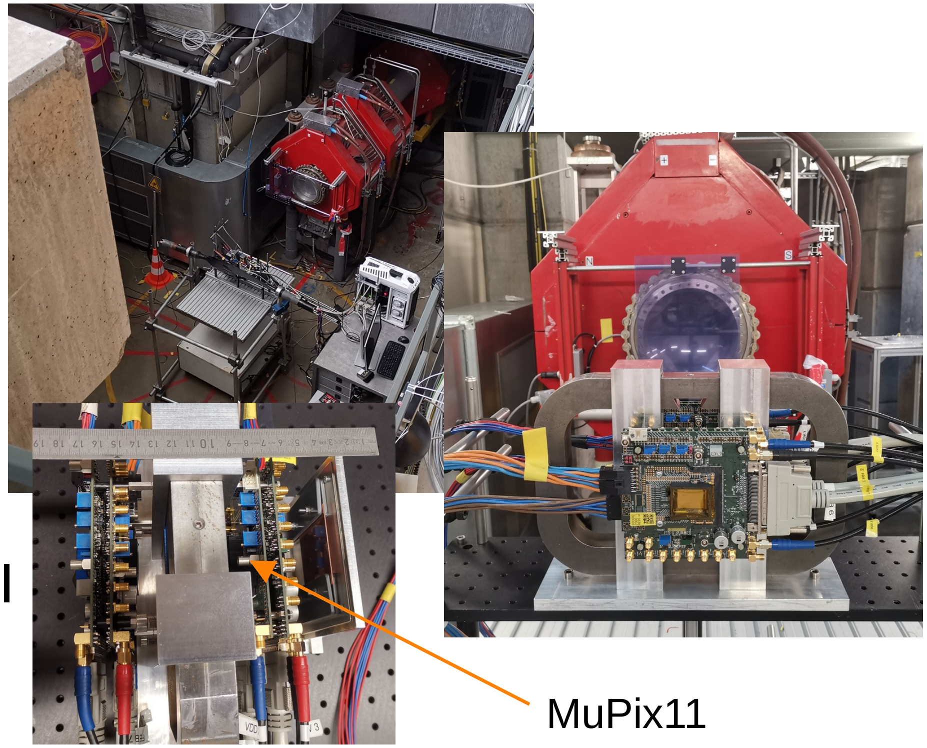




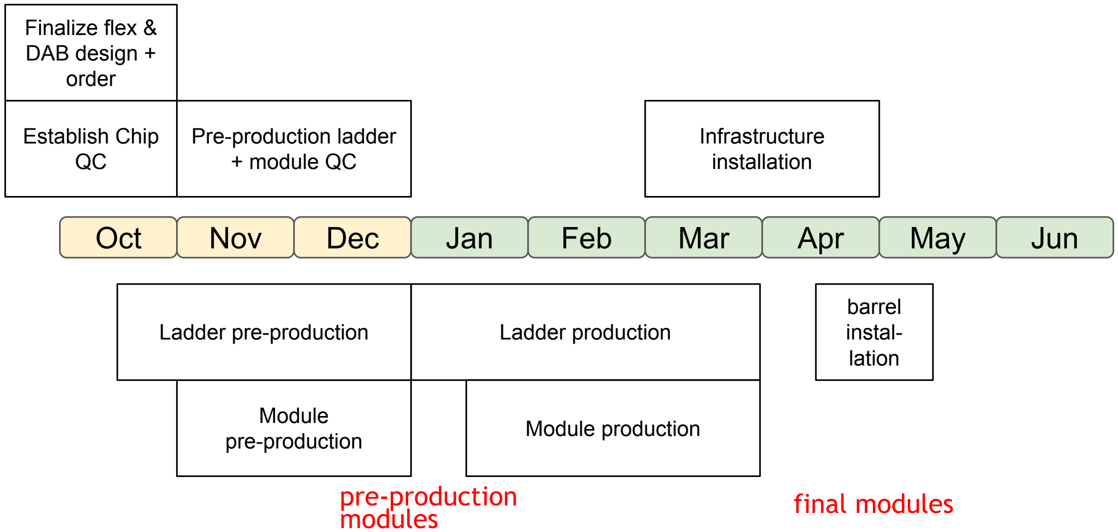
MuPix11 and (vertex) tracker assembly

- 'Final' MuPix version
  - ▷ fixes for
    - configuration (register resets)
    - r/o speed limitations
    - severe voltage drops
  - ▷ Jan 2022: Submission to TSI
  - ▷ Aug 2022: Received in Heidelberg
    50 μm, 100 μm, unthinned
  - ▷ Aug 2022: Testbeams (350 MeV) at PSI

⇒ Initial results look very good
  - ▷ all previous issues fixed



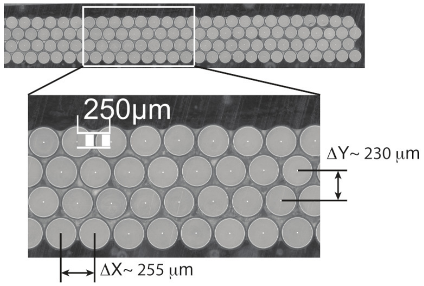
- Vertex tracker assembly
  - ▷ ladder
  - ▷ module ('half-shell')
  - ▷ detector
  - → much of it at PSI

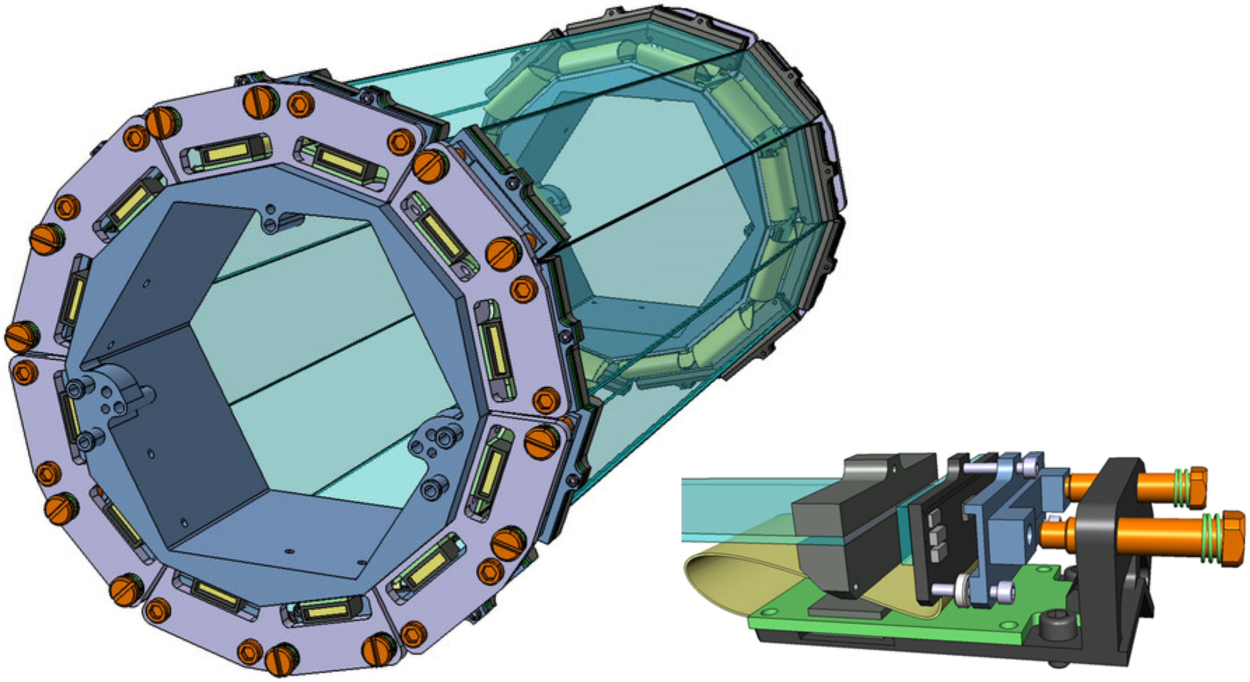


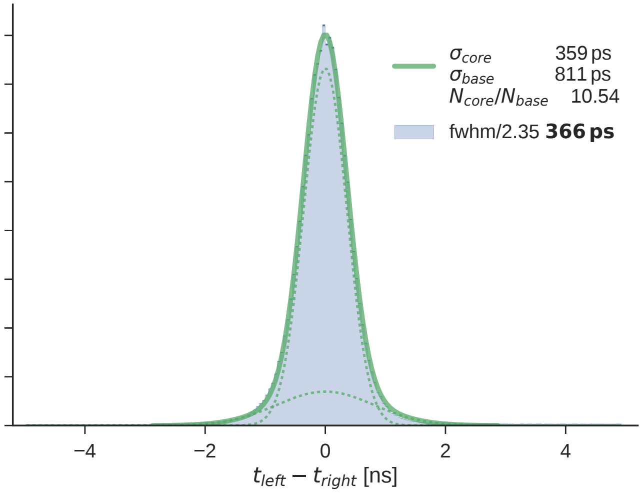
Scintillating Fiber Detector

- 12 ribbons with three(!) layers of fibers
  - fibers with $d = 250\,\mu$m, $\ell = 300\,$mm, $< 0.2\% X_0$
  - 128 fibers/layer, 2 ribbons/module (Kuraray double-clad SCSF-78MJ)
- Readout with custom MuTRIG

$\Rightarrow$ Time resolution $\approx 400\,$ps



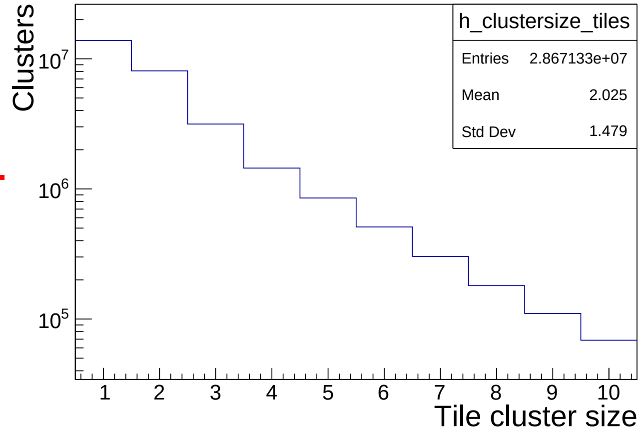


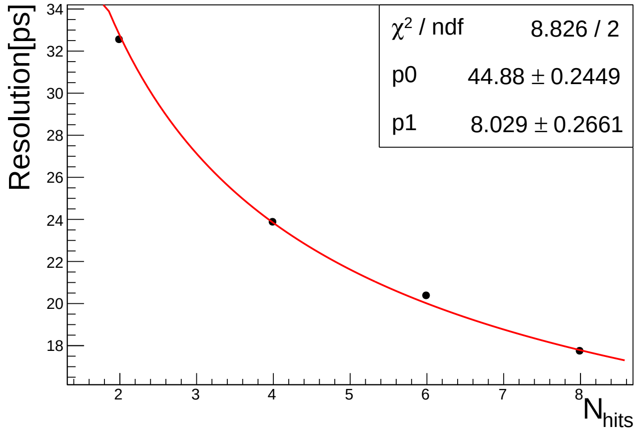


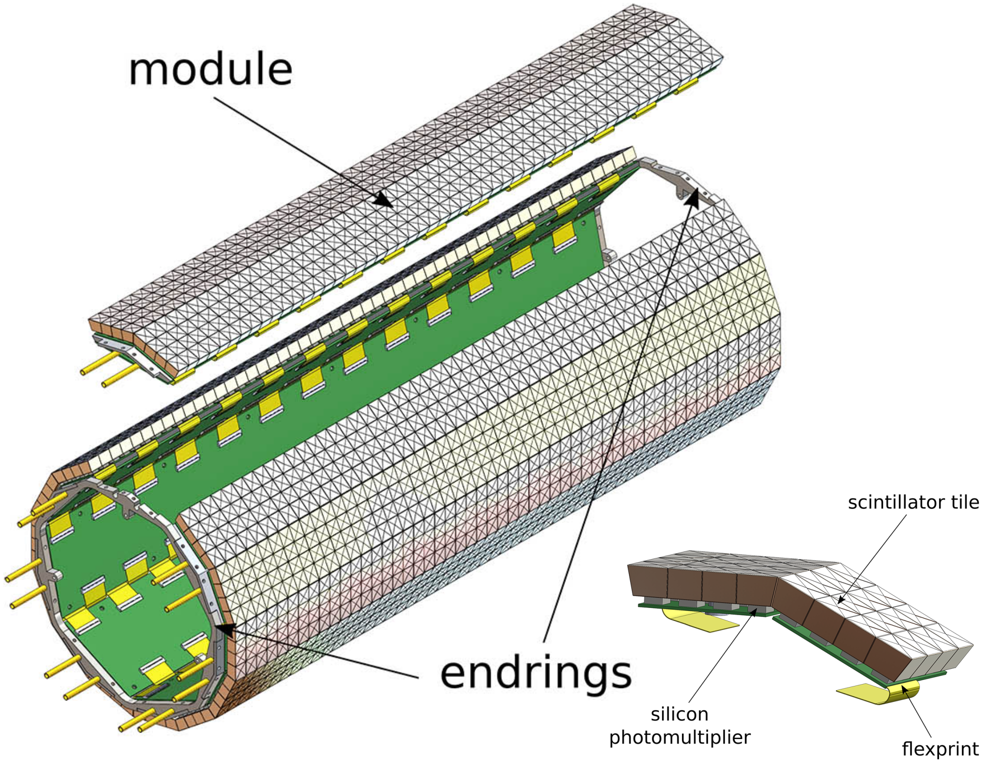
Scintillating Tile Detector

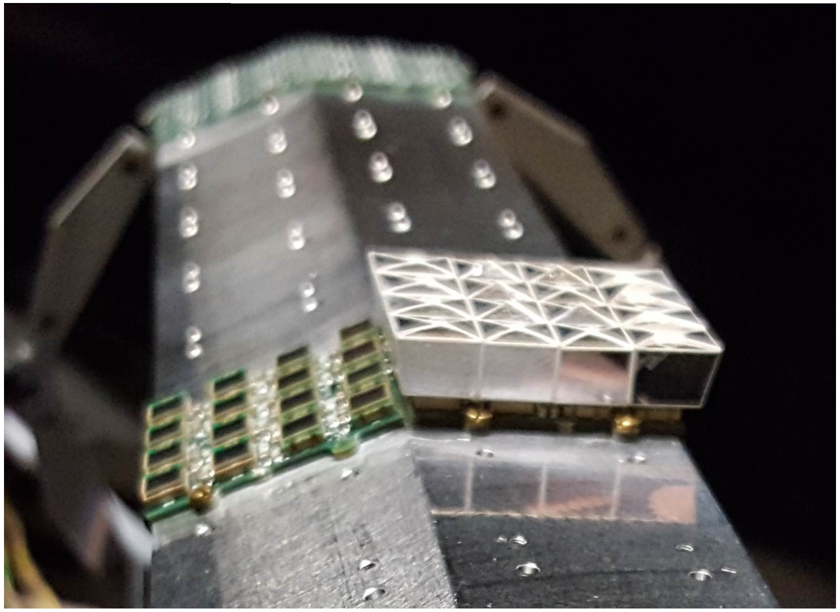
- 2 recurl stations ($\ell = 34.2\,\mathrm{cm}$)
  - ▷ 14 modules with 52×8 tiles
  - ▷ each tile with SiPM
  - ▷ SiPM readout with MuTRIG

$\Rightarrow$ Time resolution $\approx 30\,\mathrm{ps}$ (expected)





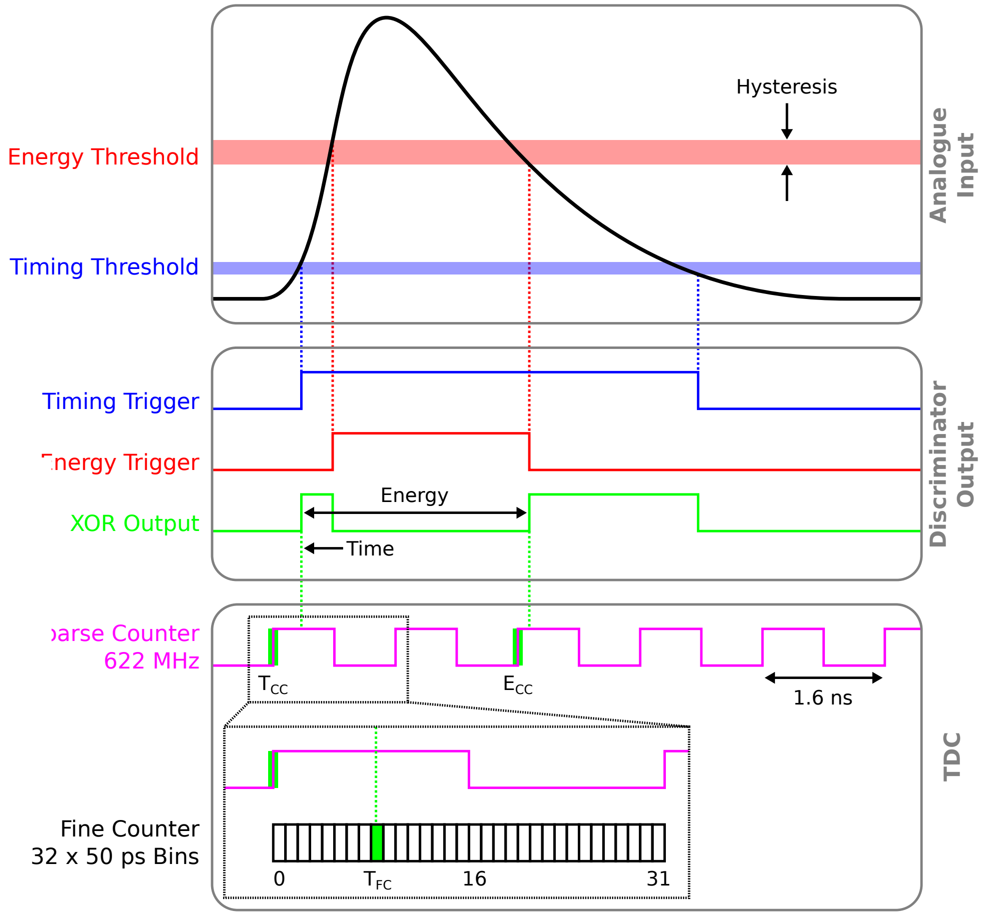


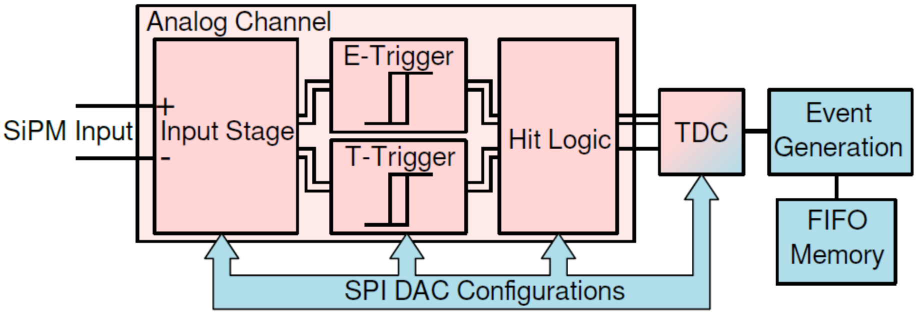


MuTrig

- MuTRIG = Muon Timing Resolver Including Gigabit-link
  - no relation to ‘trigger’!
  - based on STiCv3.1 chip (KIP, Heidelberg), with much improved r/o speed
  - MuTRIG3 under validation

- Characteristics
  - 32 channel SiPM r/o
  - single 1.15 Gb/sec data link
  - differential analog front-end
  - 50 ps binning TDC
  - 30 ns recovery time after hit (per channel)





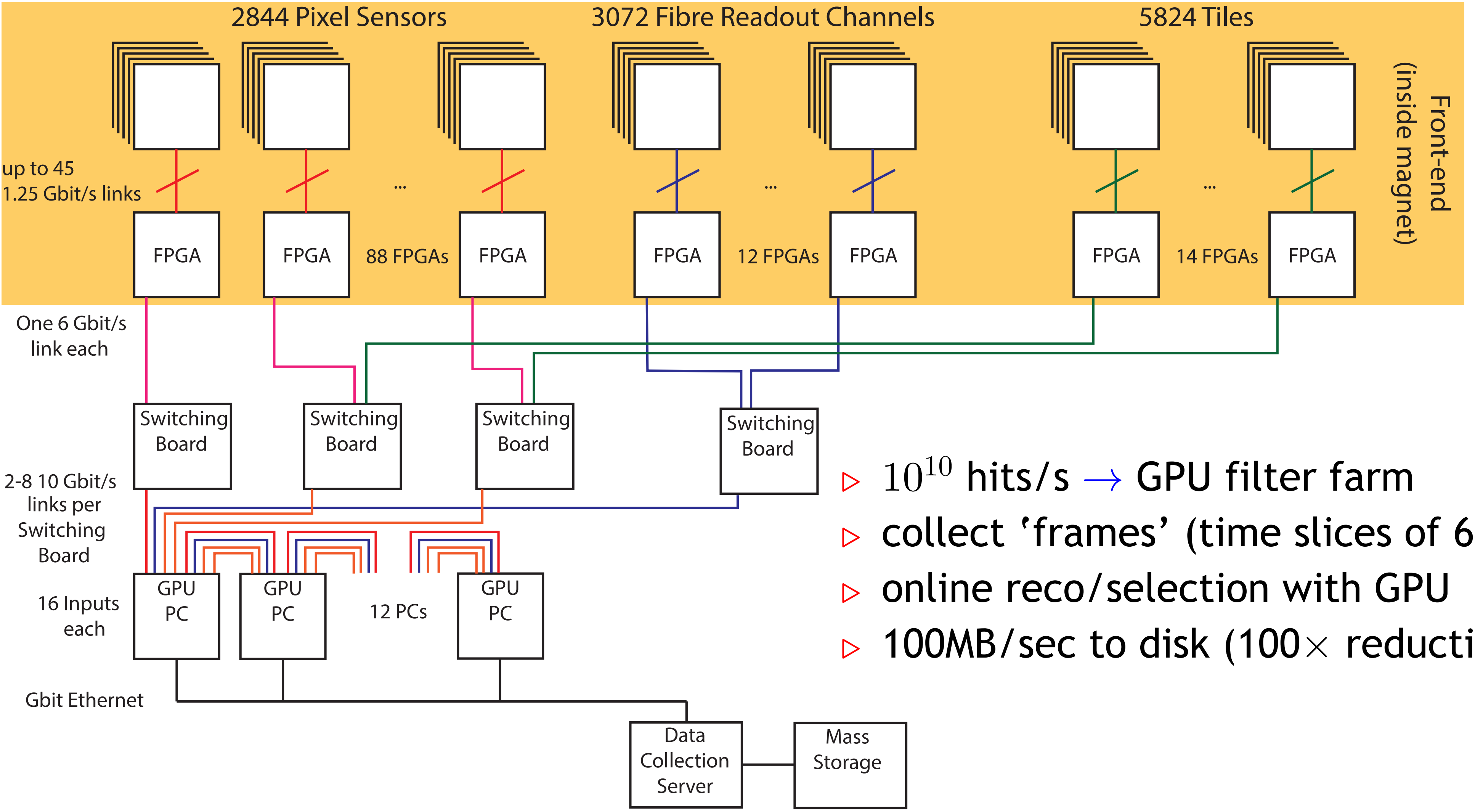
Trigger

nothing

(would have to trigger on complete signal topology, vertex'ed three-prong with mass requirements)

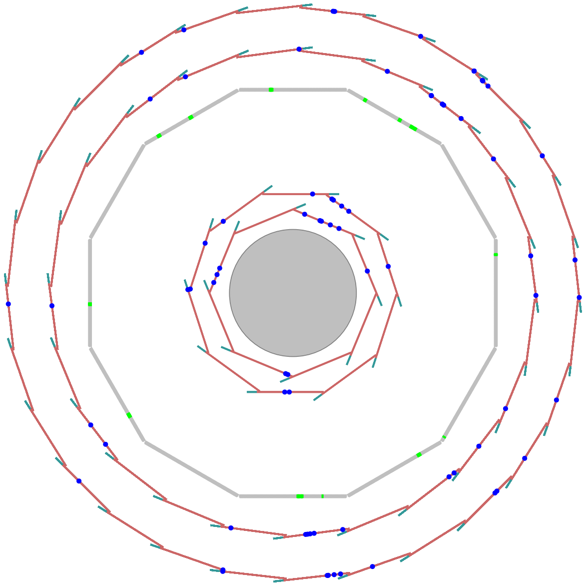
Data Acquisition

- Mu3e is a triggerless detector
  - ▷ ASICS send continuous stream of zero-suppressed data to DAQ



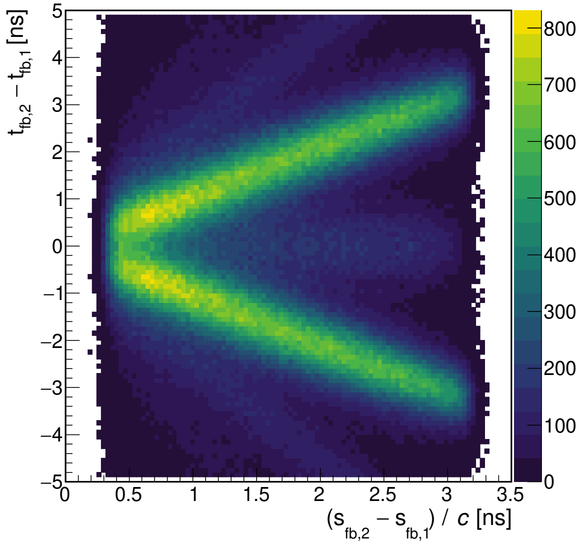
- ▷ 10^{10} hits/s → GPU filter farm
- ▷ collect ‘frames’ (time slices of 64 ns)
- ▷ online reco/selection with GPU
- ▷ 100MB/sec to disk (100× reduction)

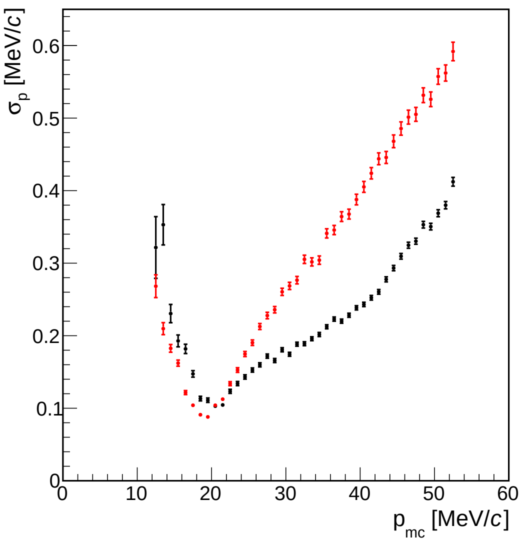
Reconstruction

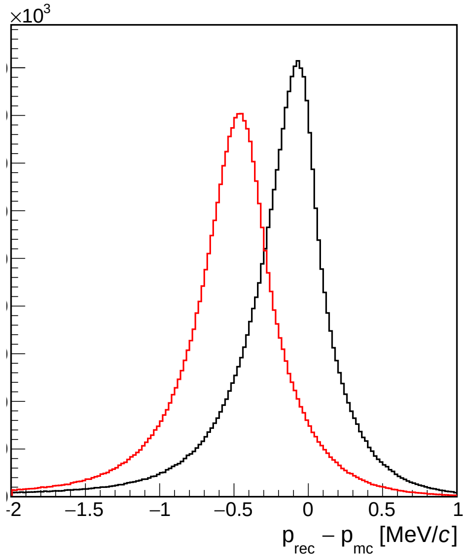


- Tracking
  - ▷ triplet extended to short tracks (S4)

    triplet fake rate 100%, S4 fake rate 1%
    - S4 efficiency $\approx 95\%$
  - ▷ short tracks extended to long tracks (S6, S8)
    - S6,8 efficiency $\approx 80\%$
- Timing
  - ▷ extrapolated tracks $\rightarrow$ hit
  - $\rightarrow$ flight direction (charge)



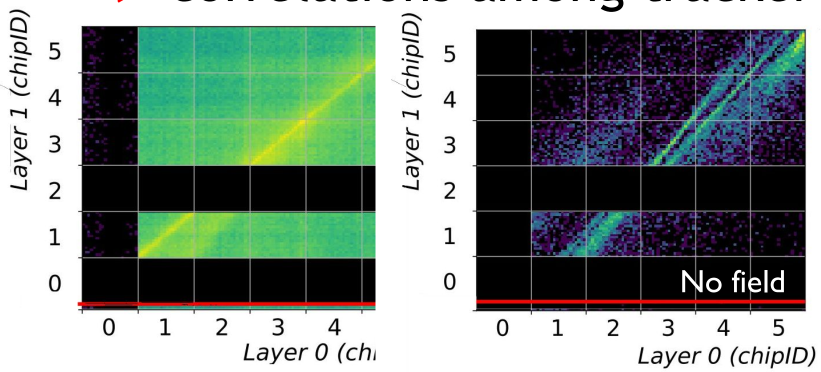


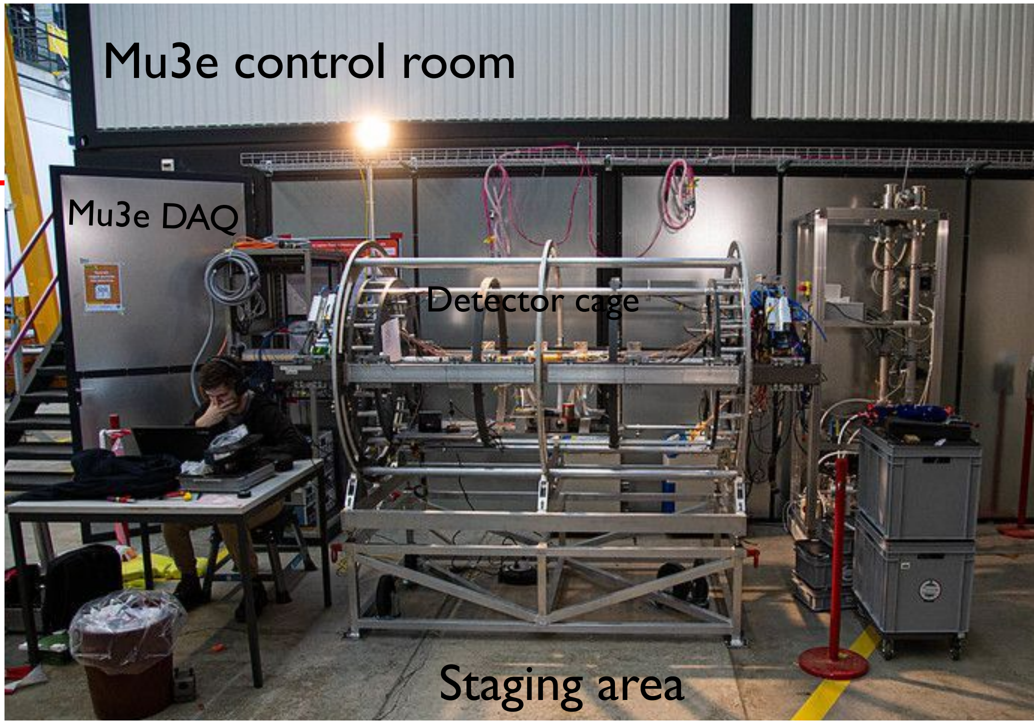


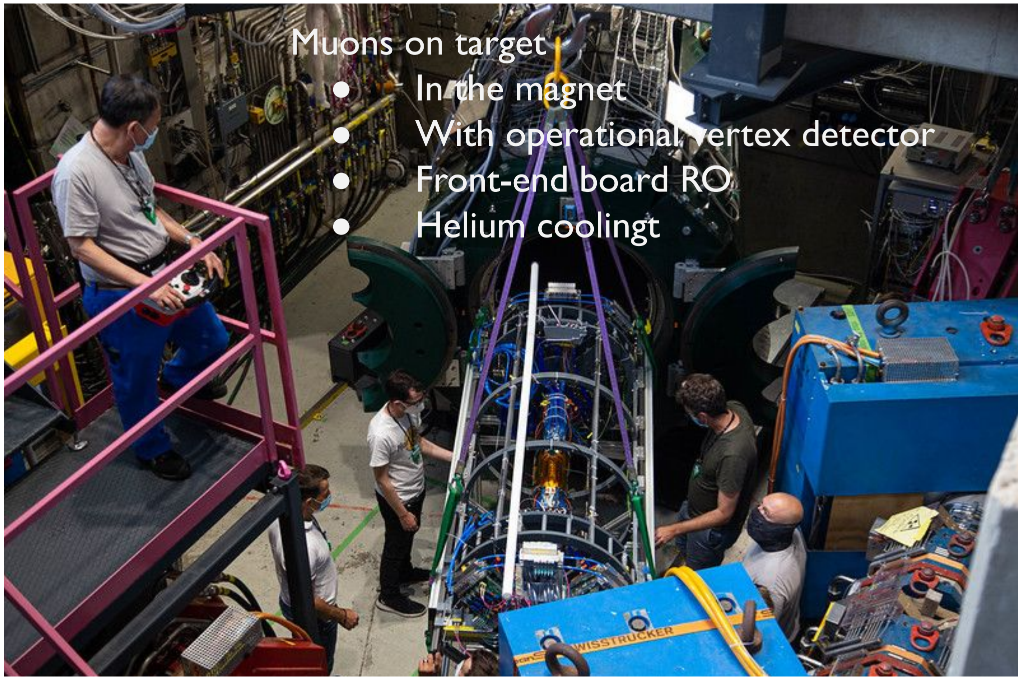
Integration and Cosmic Runs

Integration Run 2021

- Detector setup
  - ▷ 2-layer vertex detector prototype
    - MuPix10
    - PCB instead of HDI
  - ▷ 2 scintillator fiber ribbons
  - ▷ magnet
- Services
  - ▷ He cooling
  - ▷ Cage
  - ▷ πE5 beam
- ‘Results’
  - ▷ correlations among tracker layers





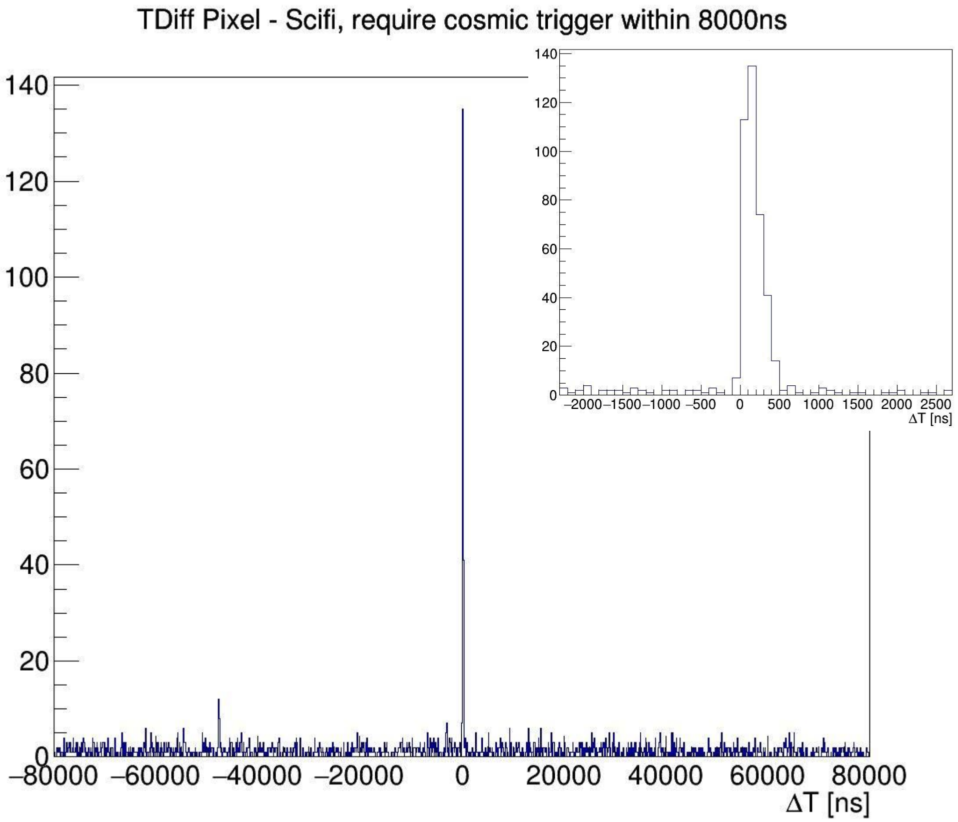

Muons on target

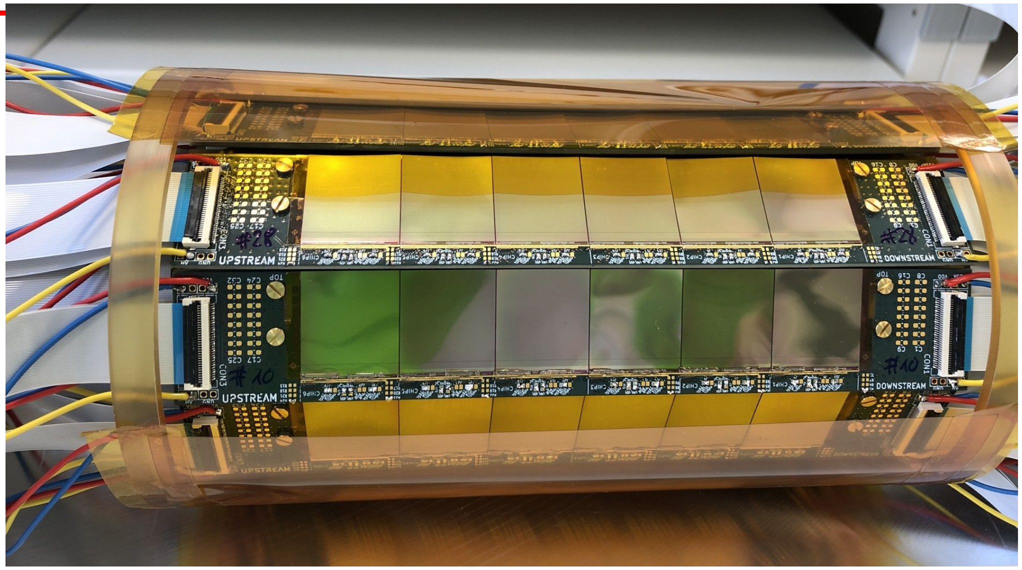
- In the magnet
- With operational vertex detector
- Front-end board RO
- Helium coolingt

Cosmic Run 2022

- Detector setup similar to 2021
  - no magnet
  - 1 scintillator fiber ribbon
- ‘Results’

<u>Pixel-SciFi coincidences</u>



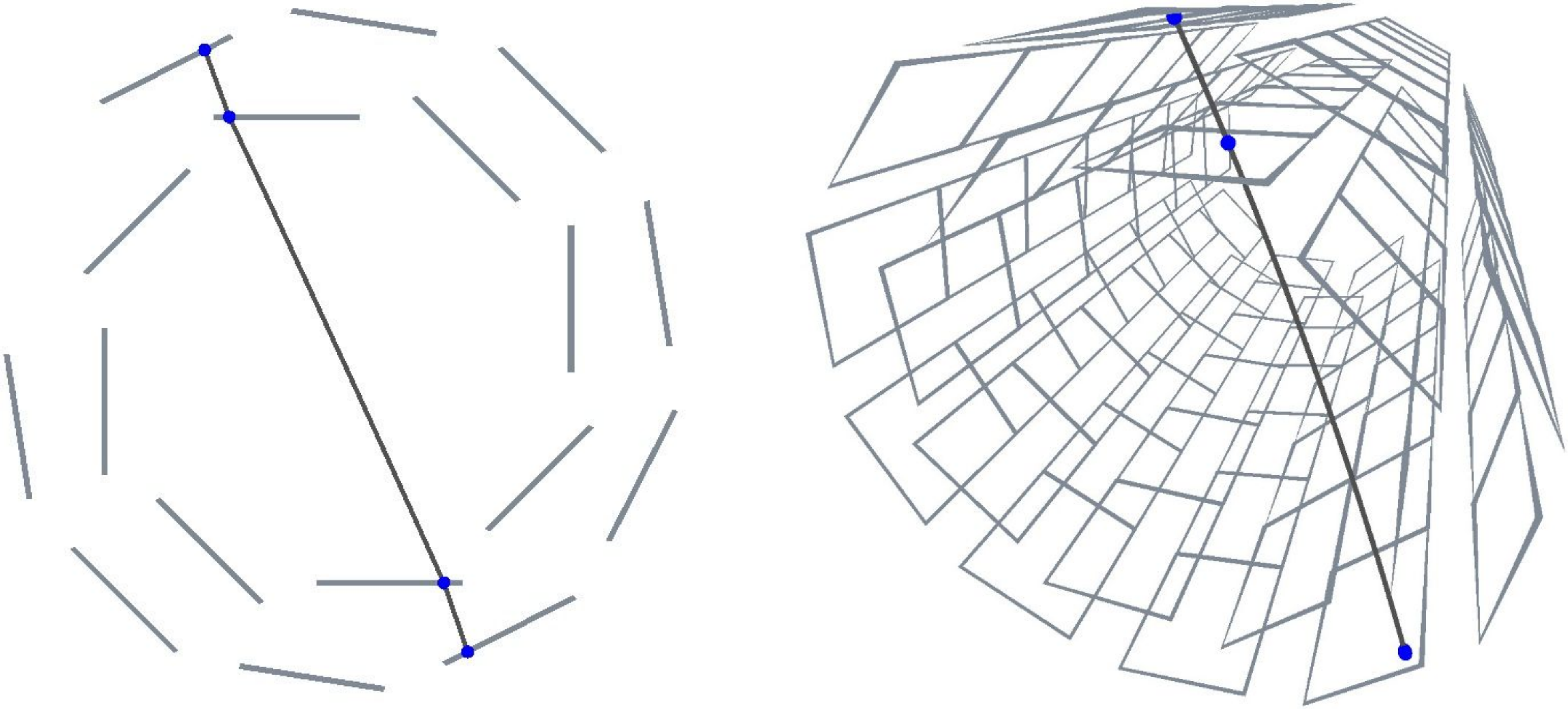


6 MuPiX chip L1 ladders

Scintillator paddles for diagnostics with cosmic muons

Cosmic track :-)

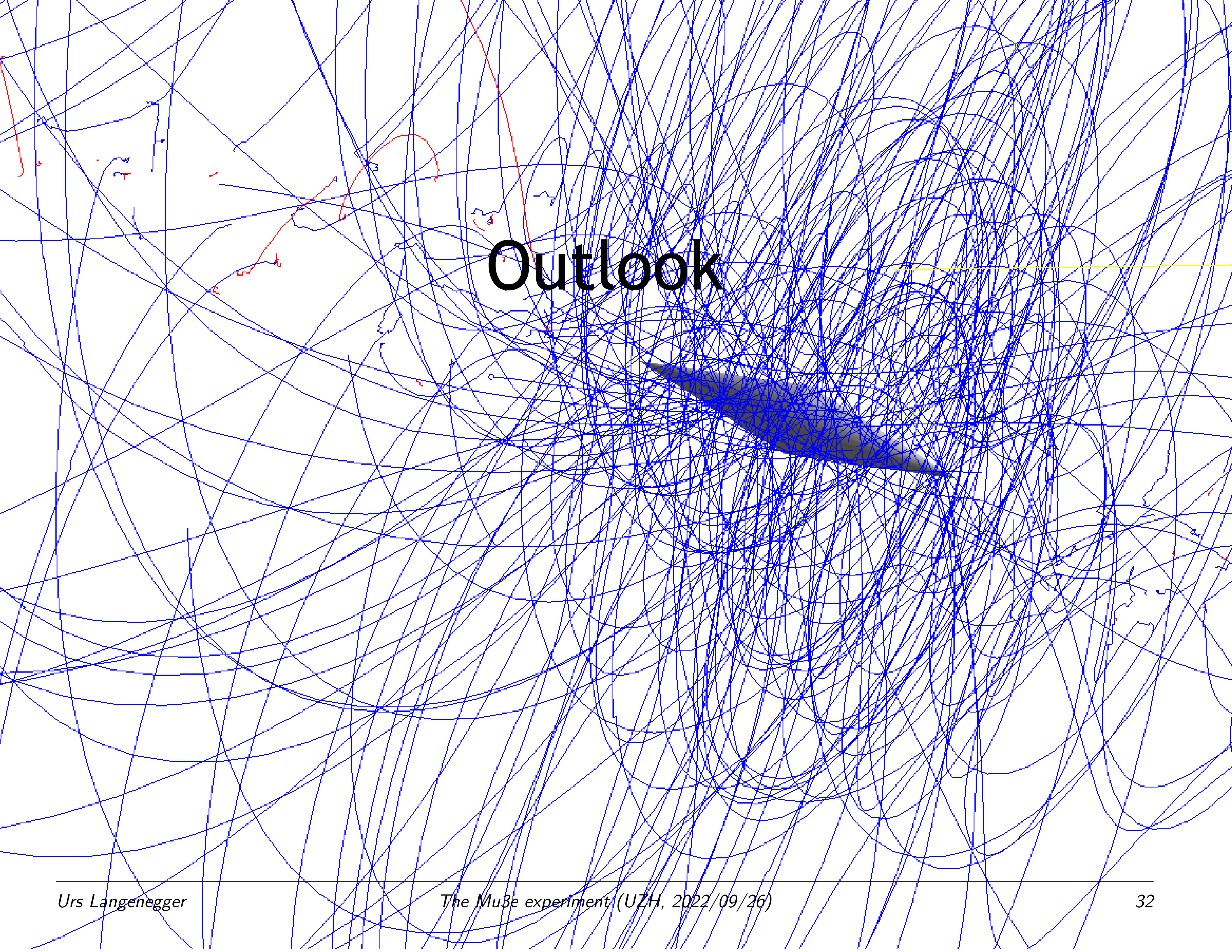
- Quasi-online event display



⇒ Online and offline software (mostly) working!

 ▷ next challenge: calibrations and alignment

Outlook



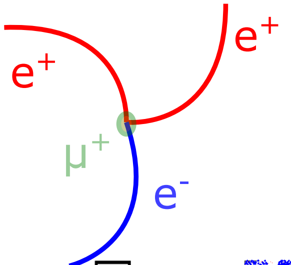
Analysis

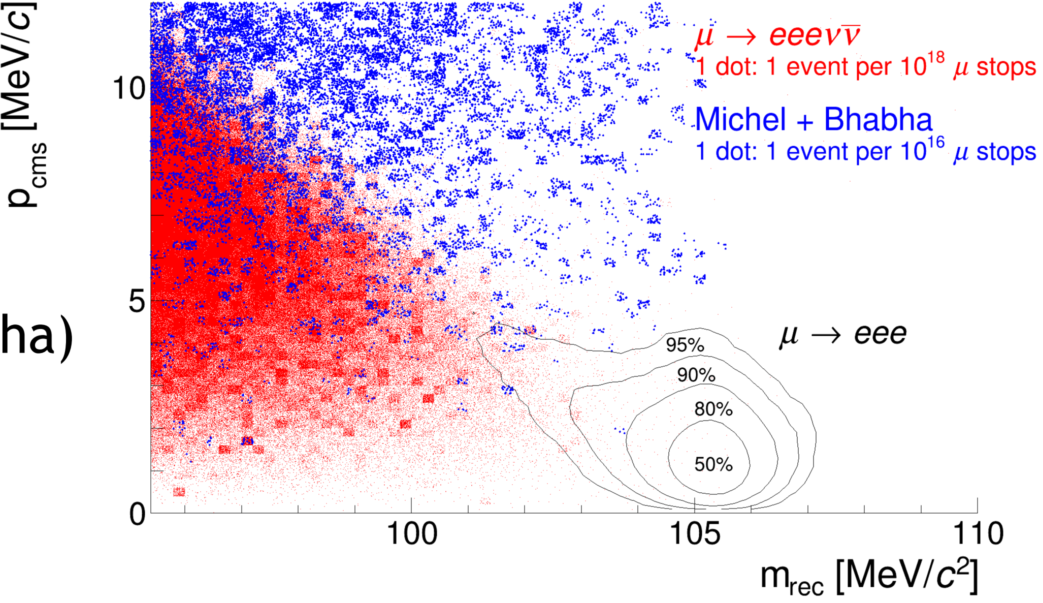
- Signal selection handles
  - ▷ one μ^+ decay

    charge correlation $e^+e^-e^+$

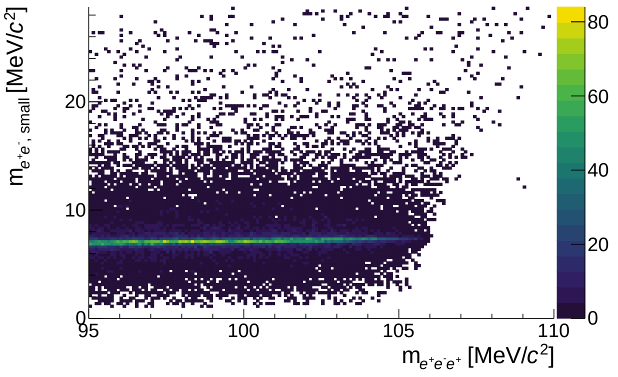
    $m(e^+e^-e^+) \approx m_\mu^+$

    good vertex on target surface
  - ▷ decay at rest $|\Sigma_i \vec{p}_i| < 4$ MeV





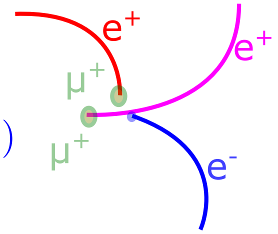
- Background rejection
  - ▷ $m_{e^+e^-,\text{low}} \notin [5,10]$ MeV ($\rightarrow$ Bhabha)

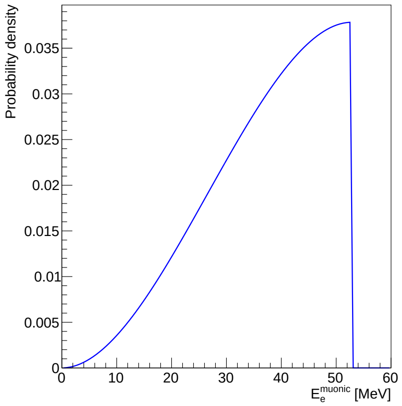


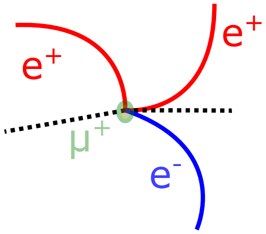
$$p_{\text{ini}}^{e^+} + p_{\text{ini}}^{e^-} = p_{\text{fin}}^{e^+} + p_{\text{fin}}^{e^-} \quad (p_0 \equiv \langle|\vec{p}|\rangle)$$

$$\rightarrow m_{\text{fin}}^2 \approx 2\, p_{\text{ini}}^{e^+}\, p_{\text{ini}}^{e^-} = 2\,(p_0, \vec{p}_0)\,(m_e, 0)$$

$$\rightarrow m_{\text{fin}} = \sqrt{2 m_e p_0} \approx 7\,\text{MeV}$$







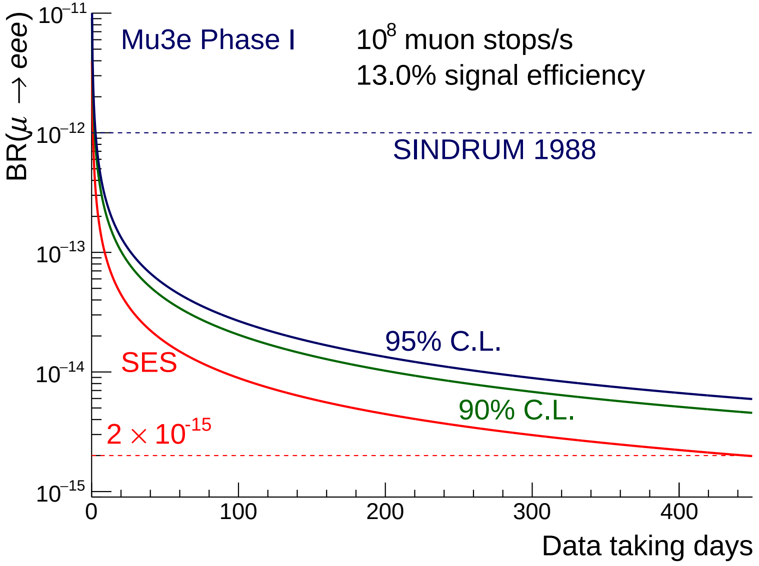
Sensitivity Expectations

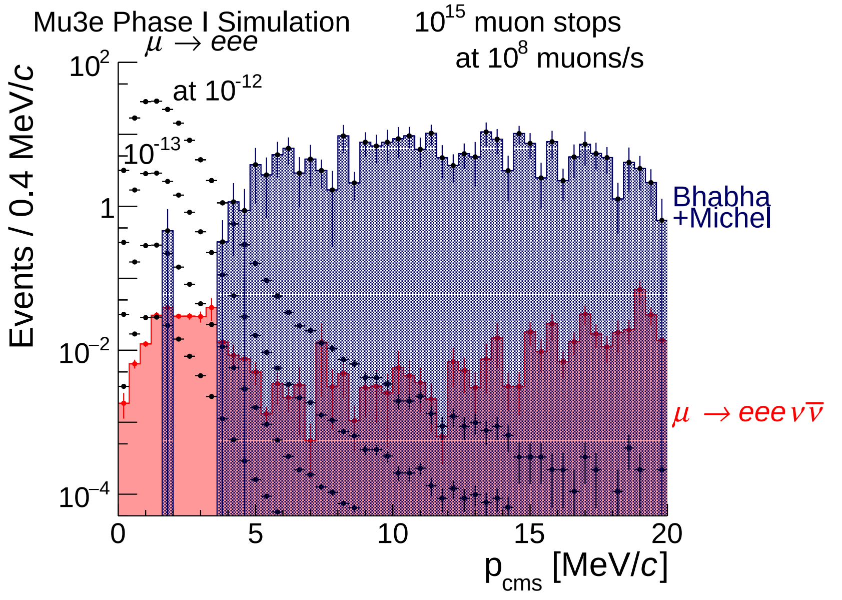
- ‘Without background’
  - ▷ single event sensitivity

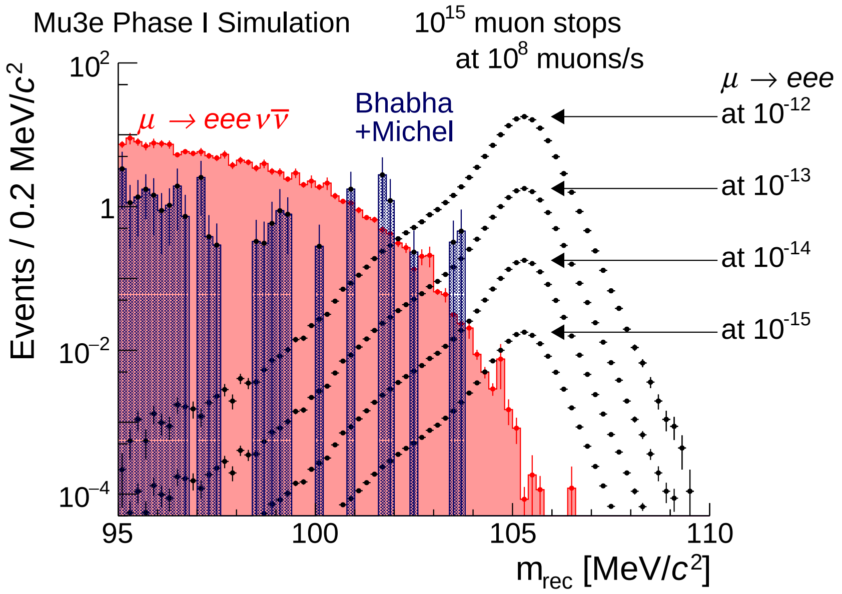
$$\boxed{\text{SES} \equiv \frac{1}{\varepsilon \times R \times t}}$$

with rate R and measurement time t,
$i.e.\ N_{\text{tot}} = R \times t$

  - ▷ For Mu3e
    - $R \approx 10^8 \mu^+ / \text{s}$
    - efficiency $\varepsilon \sim \varepsilon^3_{\text{track}}$

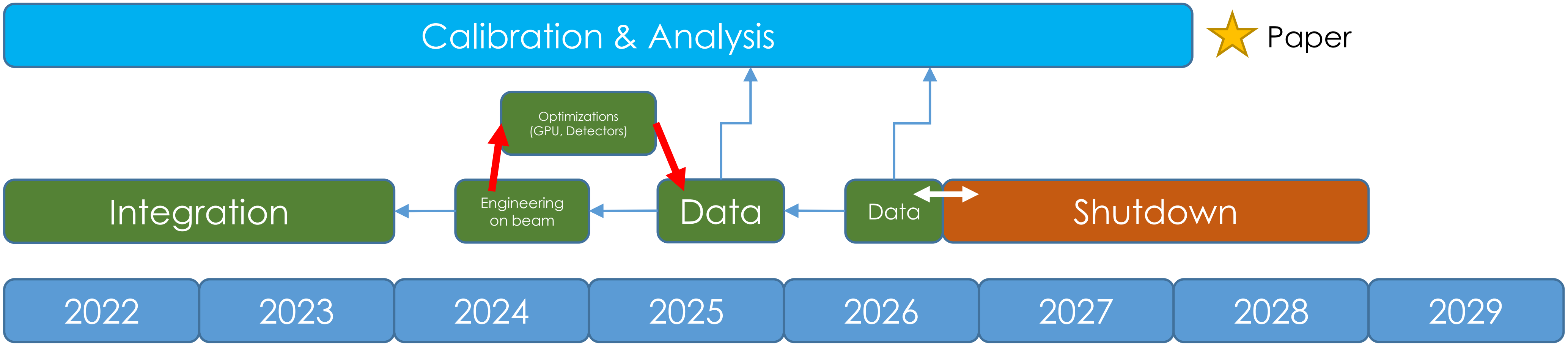






Planning the Future for Phase-1 Mu3e

- Goal: final full detectors by the end of 2023
  - pixel
    - Alu-Kapton flex (HDI)
    - MuPix11
  - timing detectors
    - MuTRIG3
    - r/o modules
  - services
    - DC-DC modules
    - He cooling $2\,\mathrm{g/s} \rightarrow 50\,\mathrm{g/s}$
    - Water cooling for electronics $< 0°C$



$\Rightarrow$ Build detector in staging area 2022/2023
Detector commissioning in 2024, physics run in 2025 (/2026)

Conclusions

- Mu3e is a (b)leading-edge experiment to search for $\mu^+ \to e^+e^-e^+$
  - PSI is the best place to do this with high-rate DC muon beams
- Extended detector development over the past decade
  - HVMAPS MuPix pixel chip with
    $0.1 X_0$/layer
  - MuTRIG SiPM r/o chip
    1.15 Gb/sec data link
    ≈ 30 ps time resolution
- Detector integration started with ‘vertical slices’
  - Cosmic run 2021
  - Integration run 2022
- Detector construction
  - to be finished end of 2023
- Data taking
  - commissioning in 2024
  - physics running in 2025/2026