How to build a high-rate precision particle physics experiment

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JG|U

Emmy Noether-Programm

Deutsche Forschungsgemeinschaft

DFG

Overview

Why high rate experiments?

- Testing the standard model at the intensity frontier

From idea to experiment:

- The design process

Challenge:

- Tracking at high rates

Case studies:

- Charged lepton flavour violation experiments

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From idea to experiment:

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Challenge:

- High speed data acquisition

Case studies:

- Charged lepton flavour violation experiments


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But:

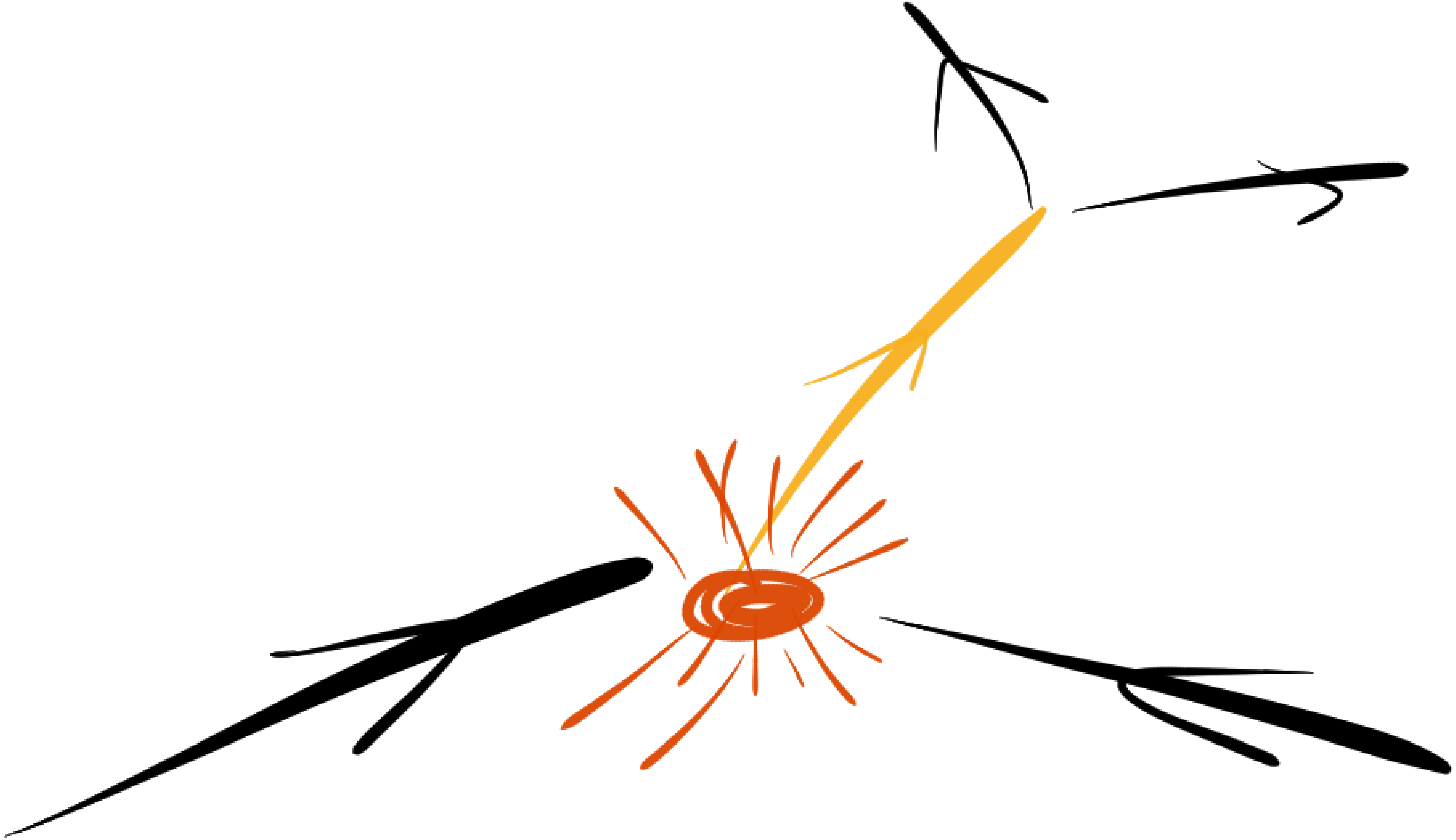
- Gravity
- Dark matter
- Dark energy
- Matter-/antimatter asymmetry
- Neutrino masses

- Hierarchy problem (naturalness)
- Grand unification
- Strong CP problem

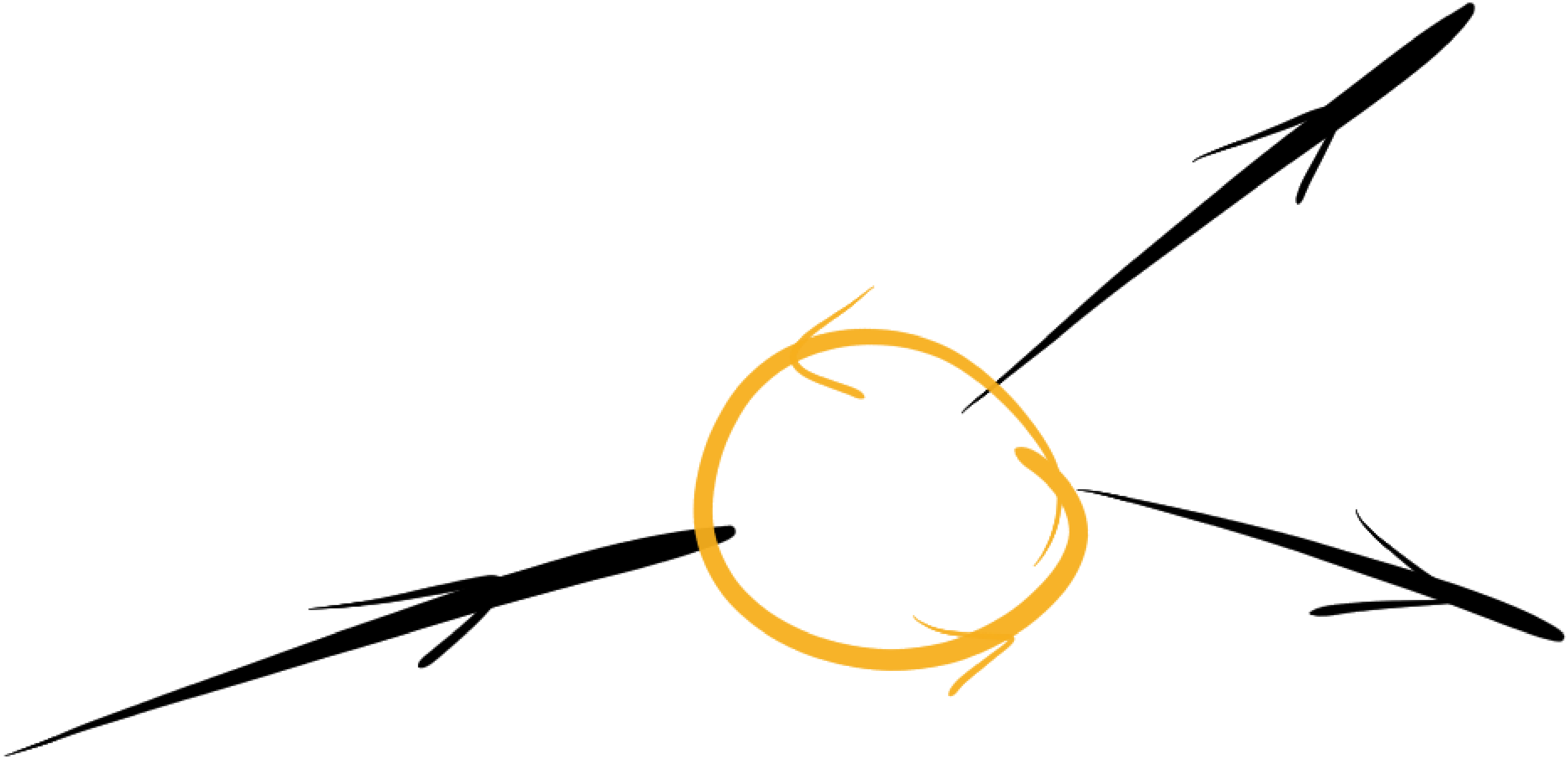
So there must be something else...

...but where?

Produce at high energies?



Observe in loops



“Intensity frontier”

Searching for very rare processes needs:

- High intensity
- Low background, high sensitivity

Example: Muons - how to get high intensity

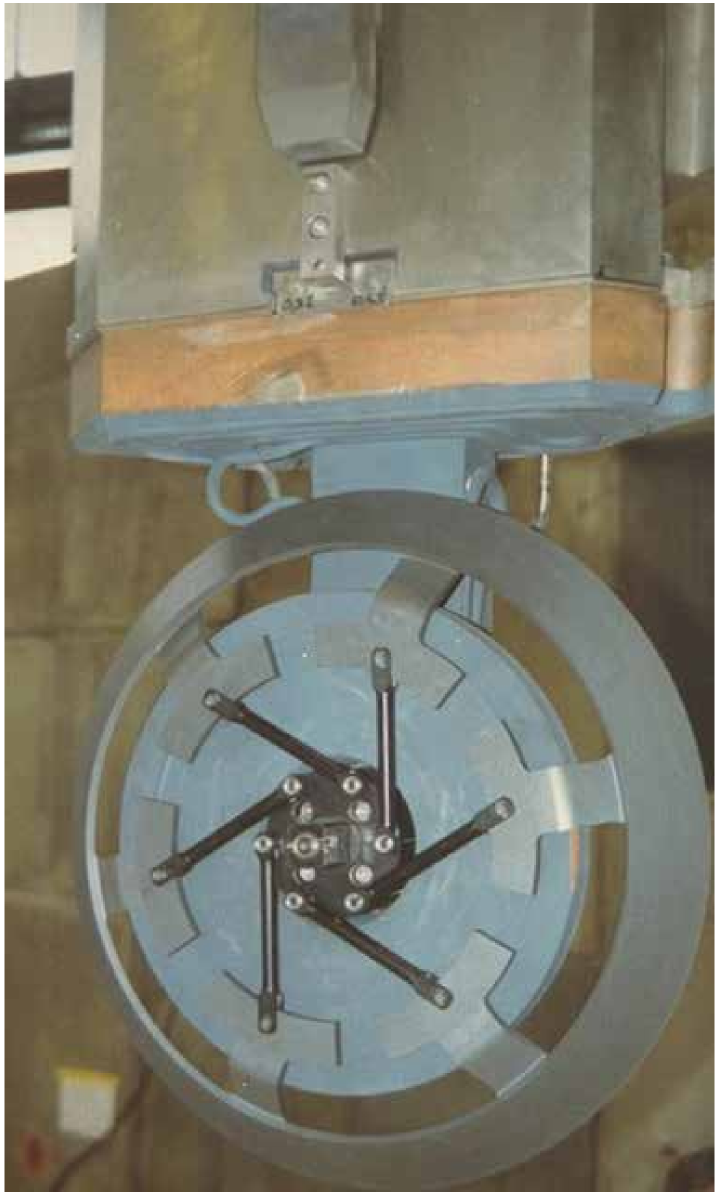
Paul Scherrer Institute in Villigen, Switzerland

Example: Muons - how to get high intensity

Paul Scherrer Institute in Villigen, Switzerland

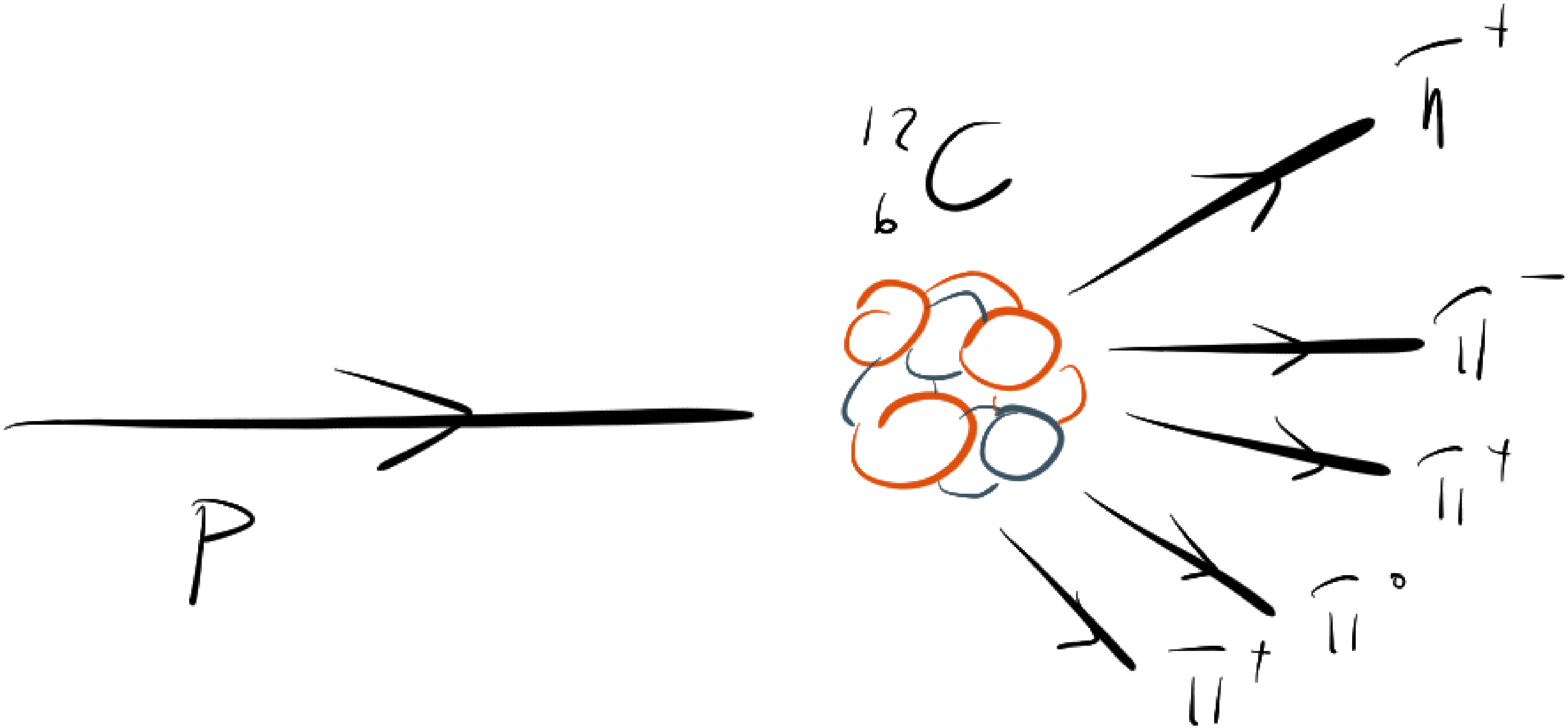
World's most intensive proton beam
2.2 mA at 590 MeV: 1.3 MW of beam power

Example: Muons - how to get high intensity

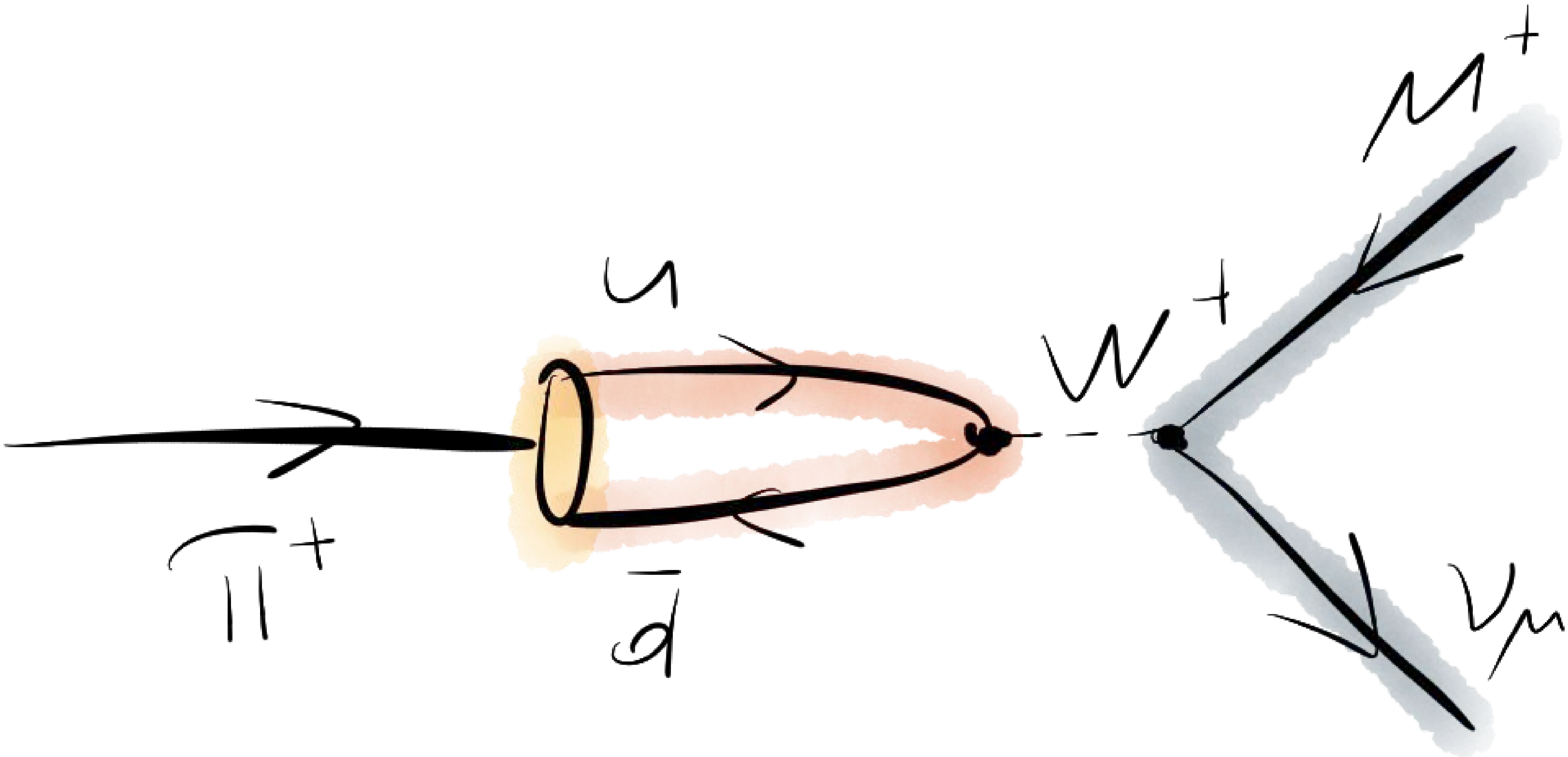


- Rotating carbon wheel as target
- Hit with proton beam

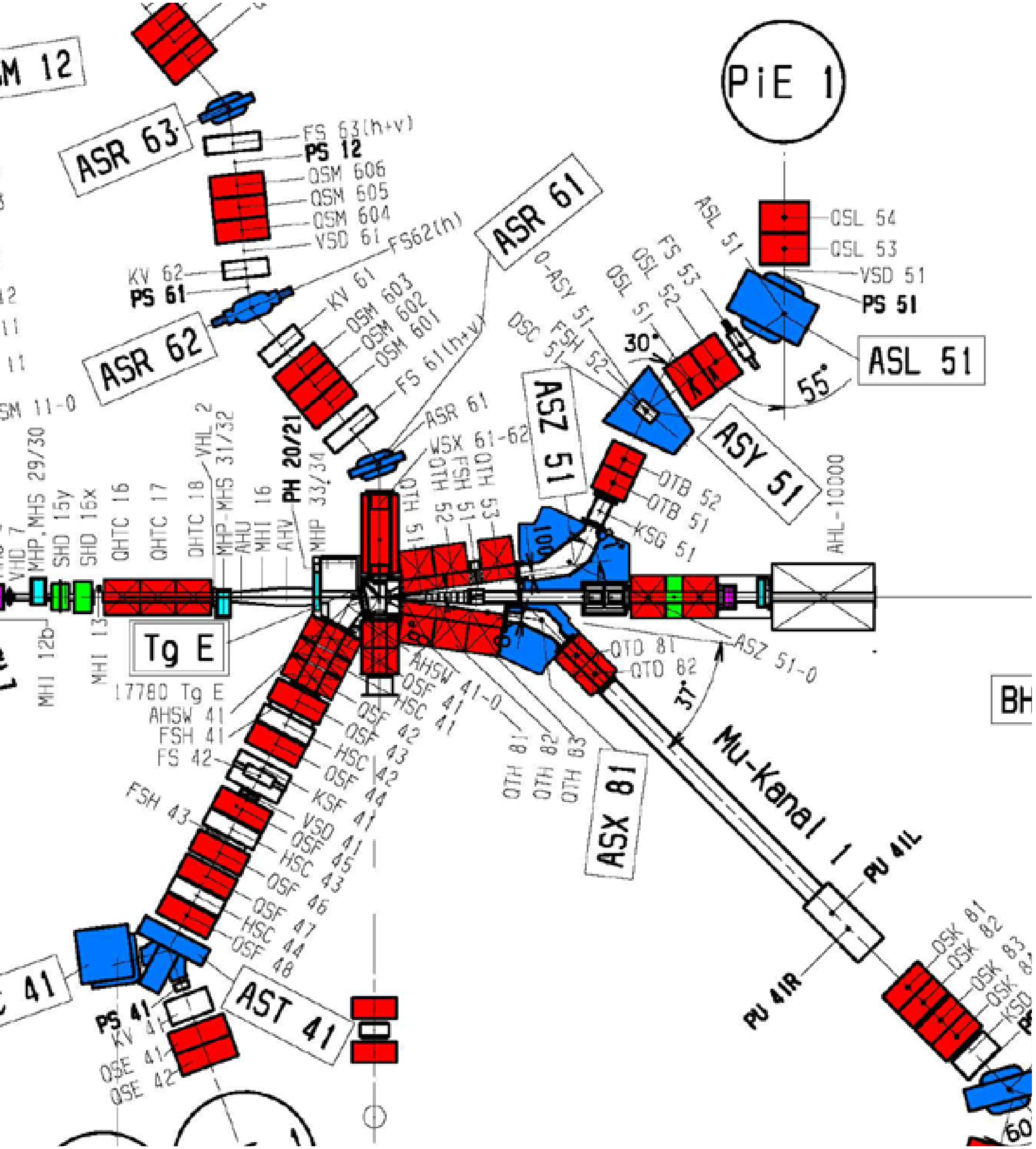
Pion production



Pion decay



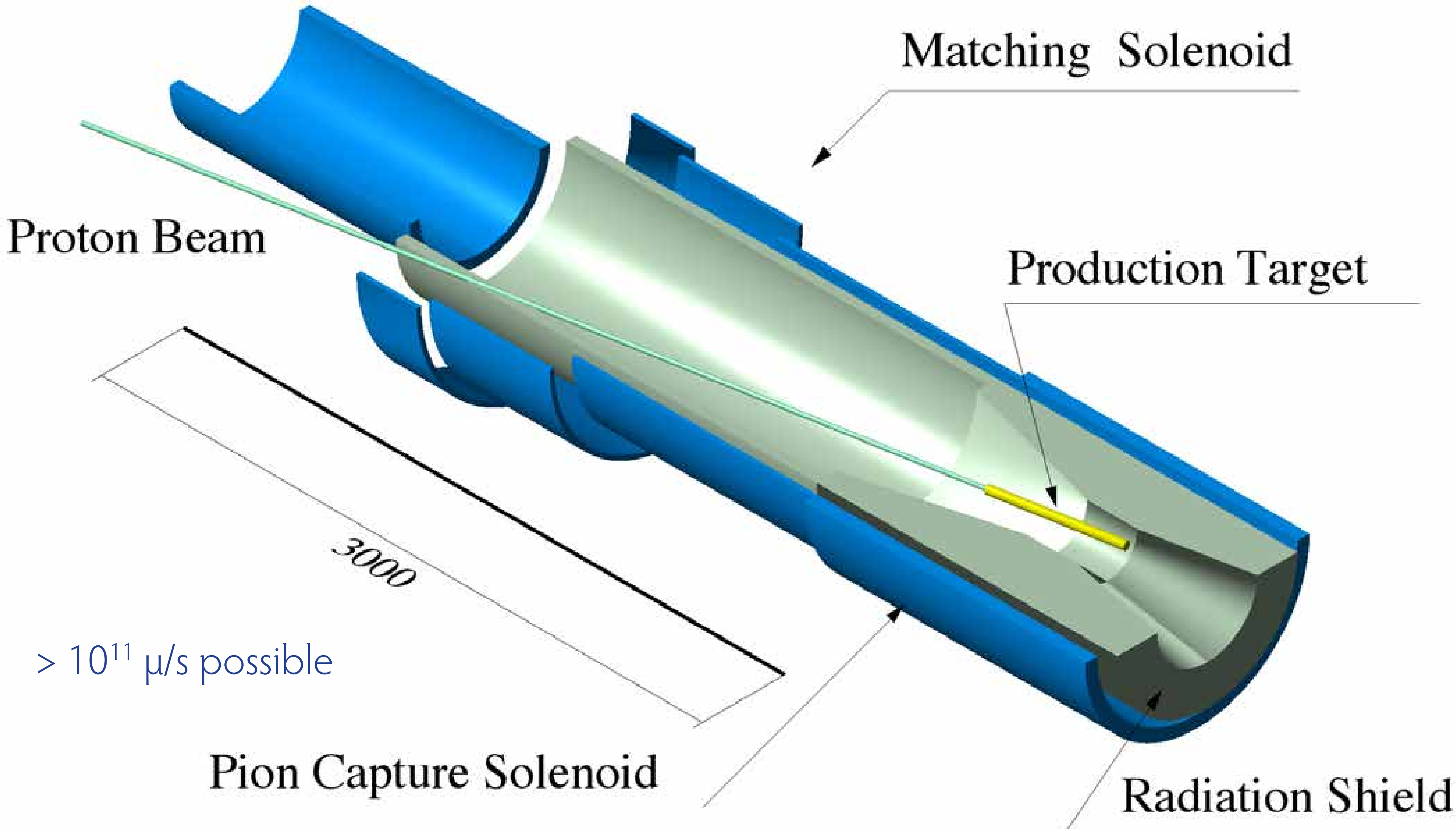
Muon beamlines



- Target serves many beamlines
- Usable intensity ~ 10^8 μ/s

How to get higher intensities?

Higher intensities - target in magnet



> 10^{11} μ/s possible

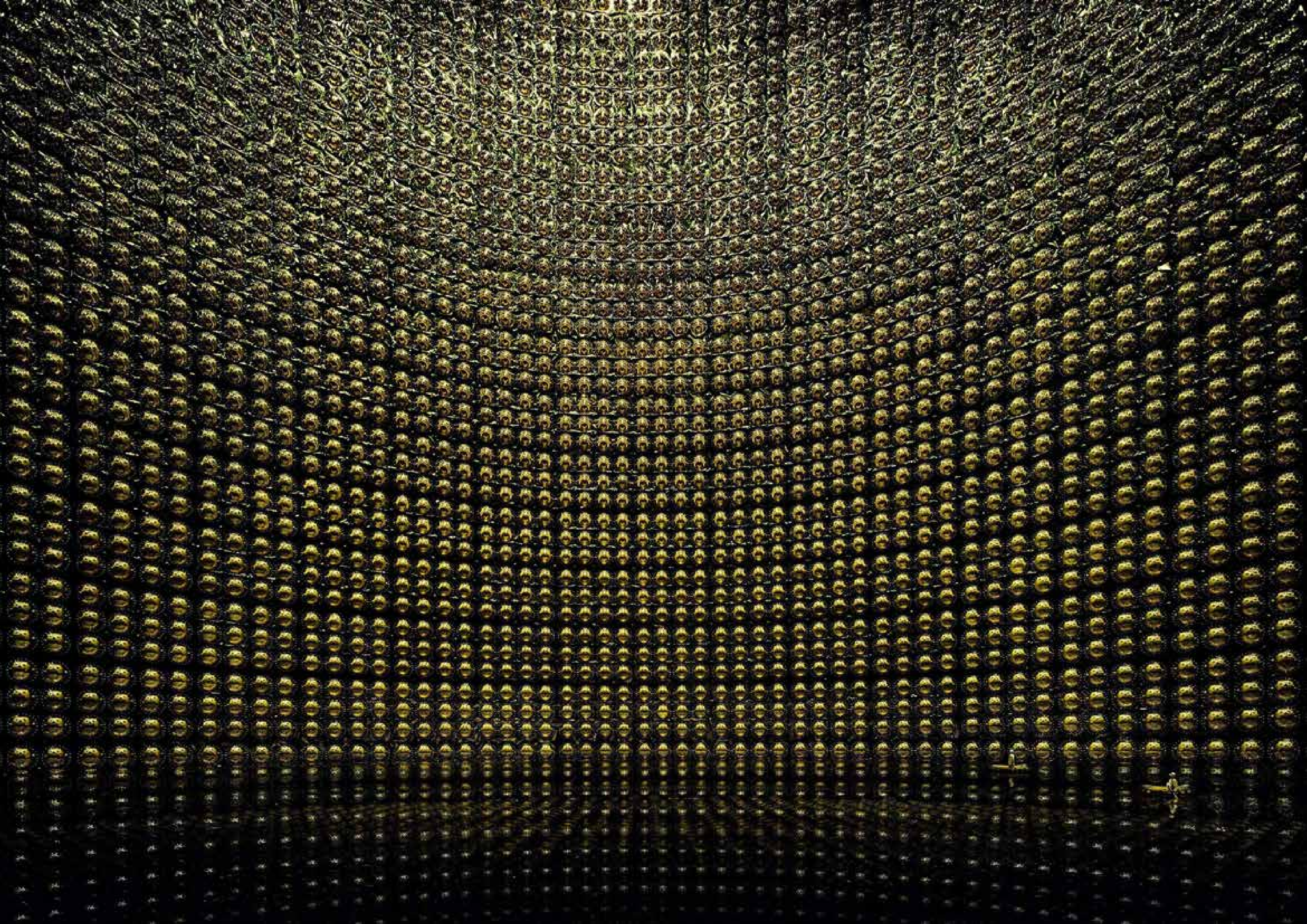
Gradient field: magnetic bottle
Capture most pions produced in target

Shielding of superconducting magnet very challenging

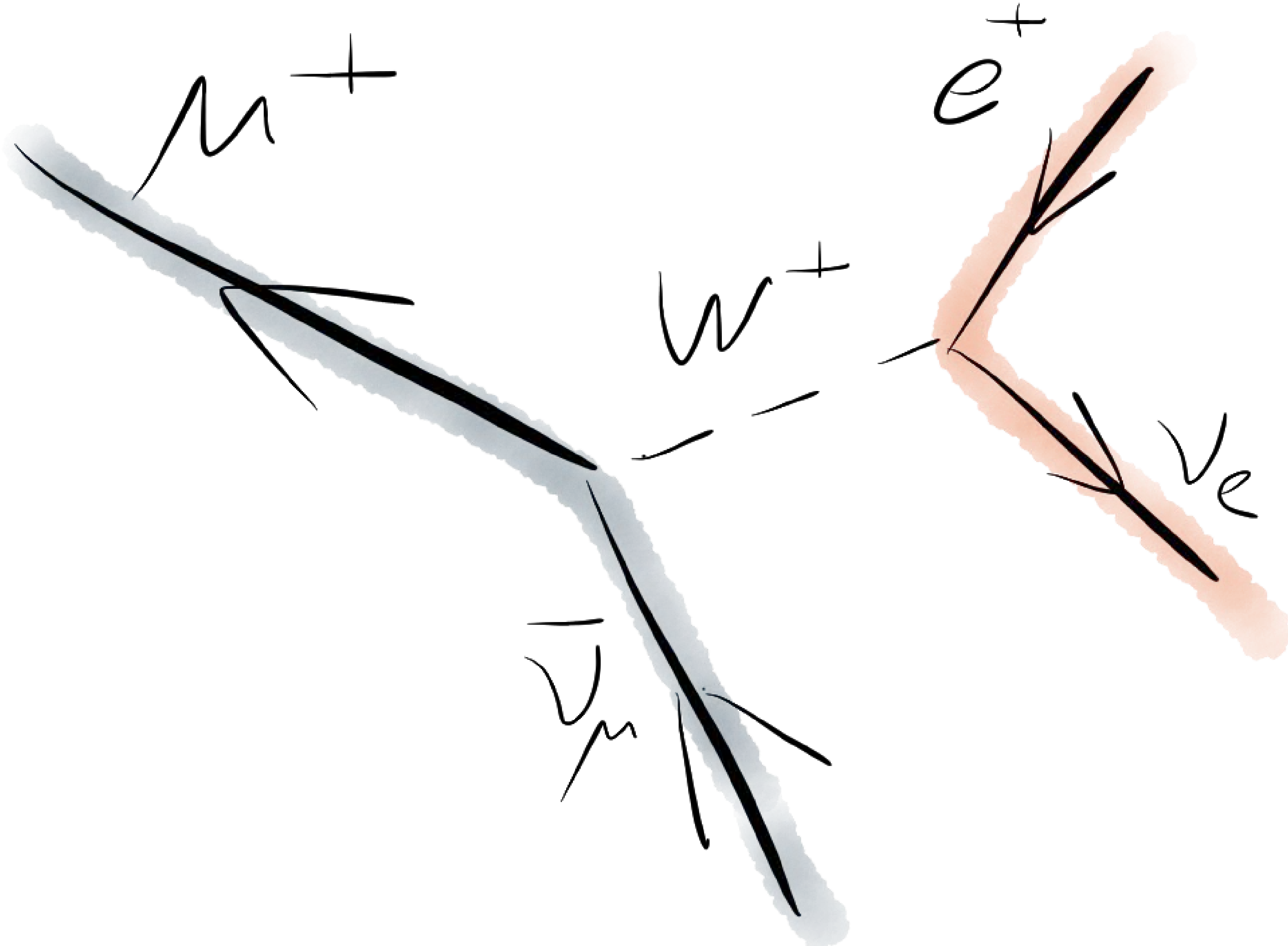
High intensity means many particles
and
lots of opportunities to do something beyond the standard model

Long lifetime!

Stable particles - protons



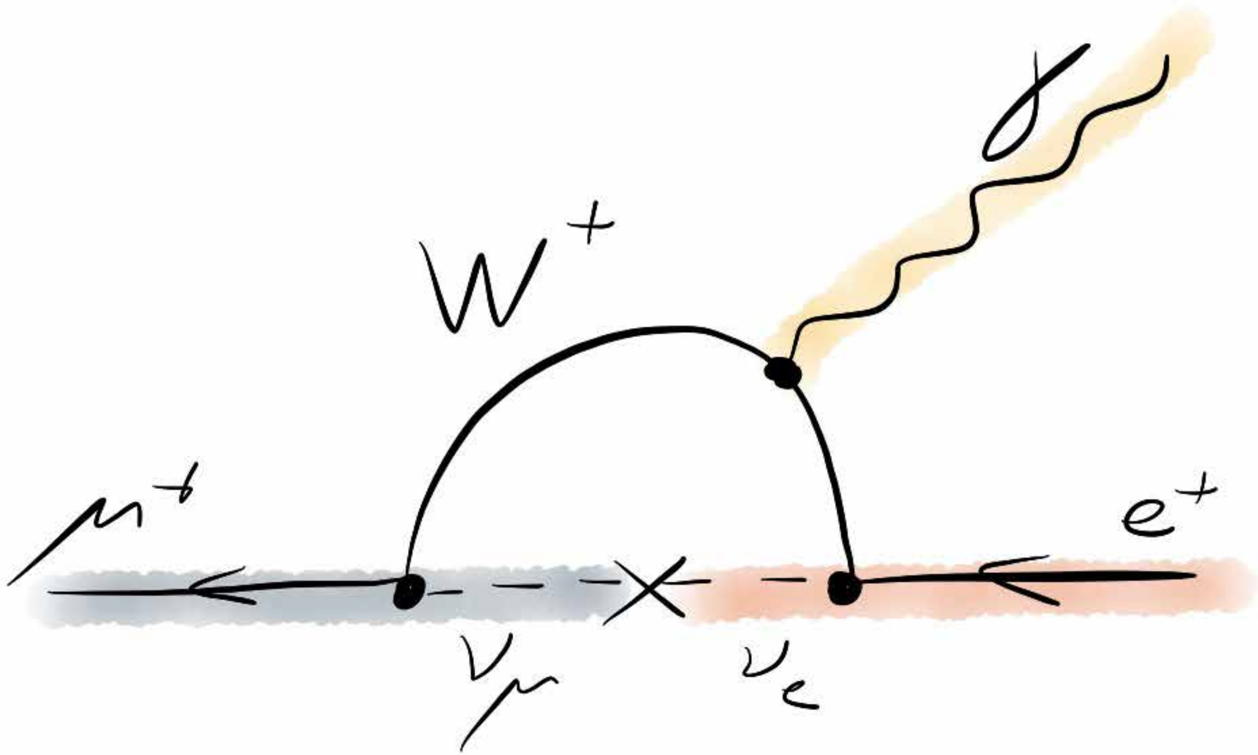
Weak decays



Study deviations from predicted decay distributions

or

search for suppressed/forbidden decays

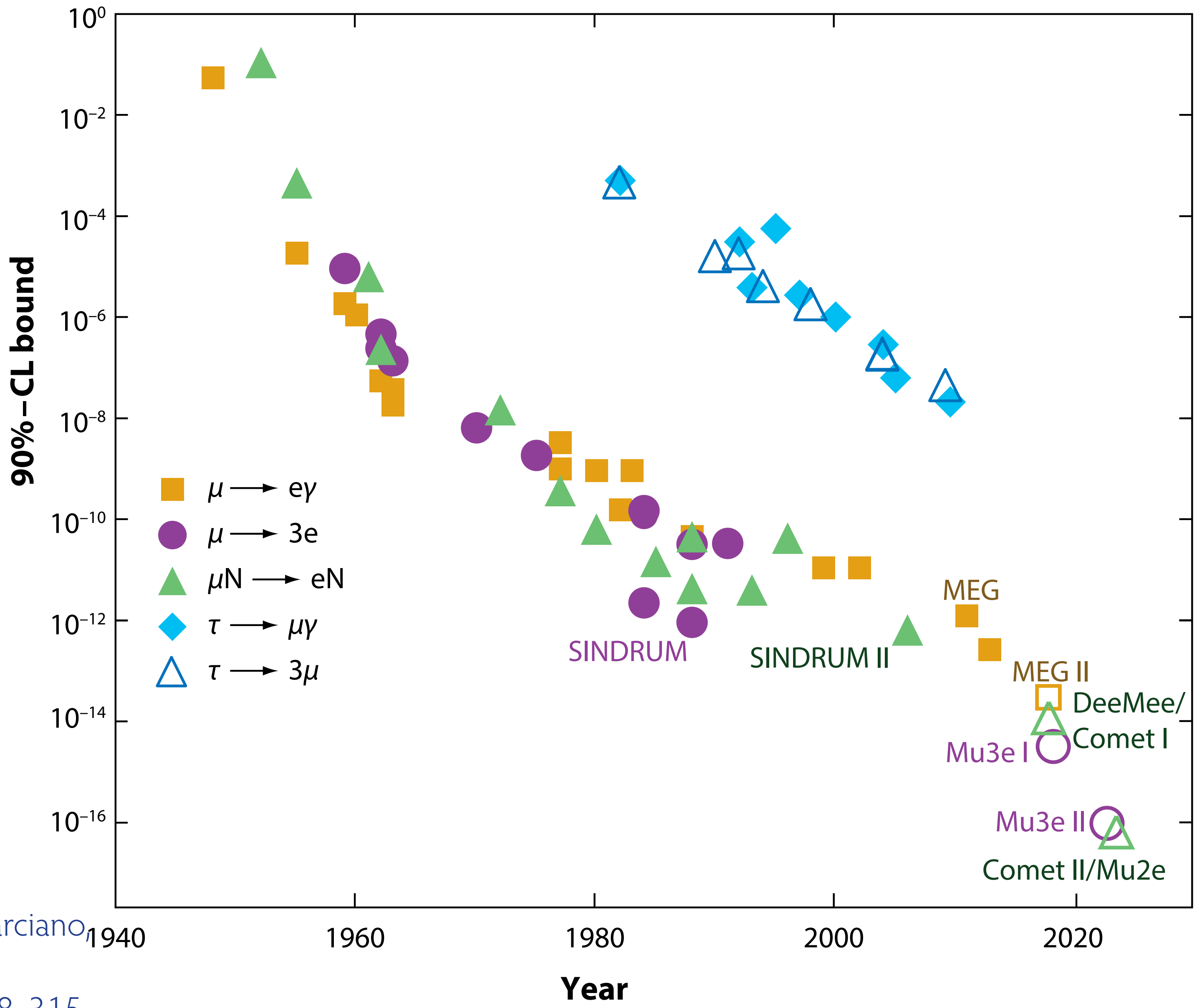


Standard Model branching fractions of

10^{-50ish}

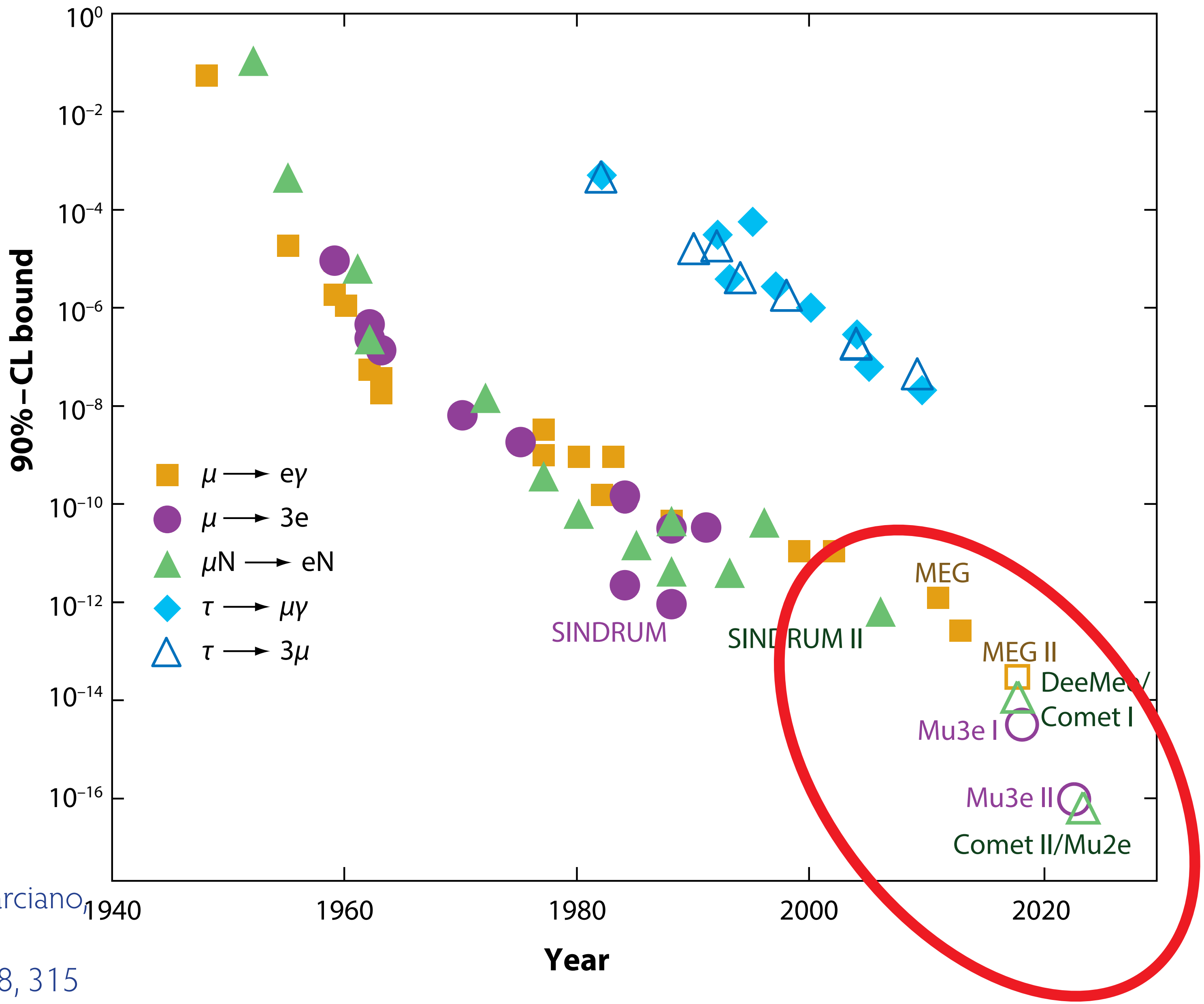
Only limited by number of muons
and background suppression

History of LFV experiments



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

History of LFV experiments



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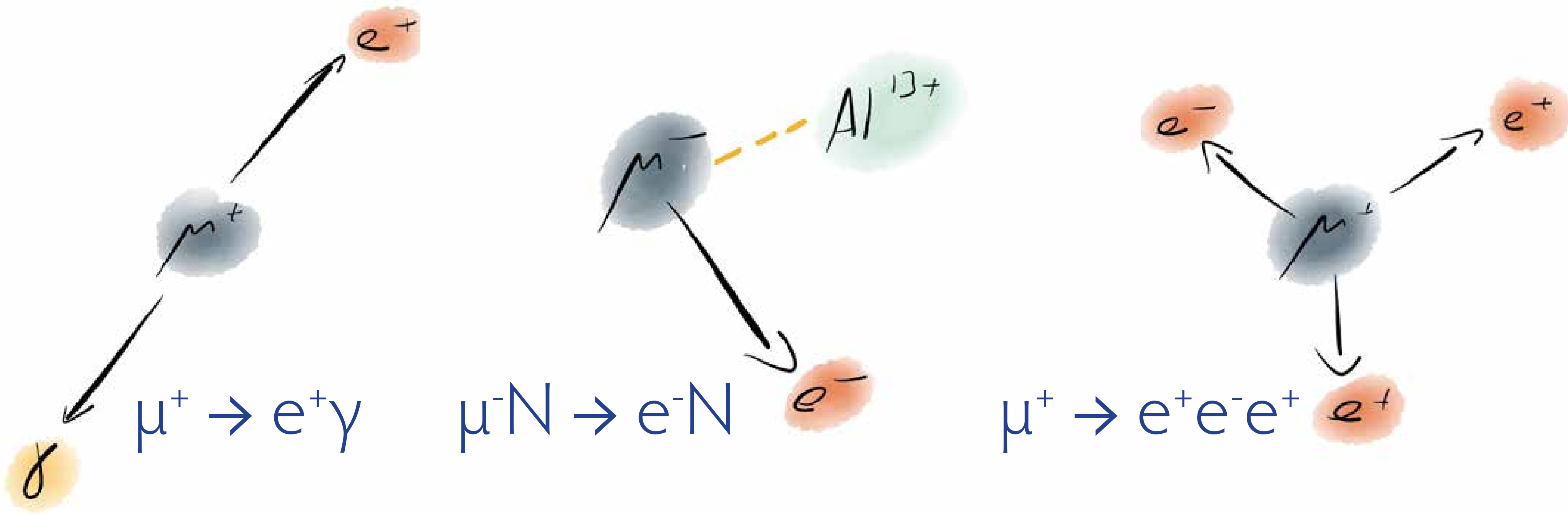
LFV Muon Decays: Experimental Situation



MEG (PSI)	SINDRUM II (PSI)	SINDRUM (PSI)
$B(\mu^+ \to e^+\gamma) < 5.7 \cdot 10^{-13}$	$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$	$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$
(2013)	(2006)	(1988)
	relative to nuclear capture	

A new experiment:

The design process

What questions to ask?

Design process - Constraints

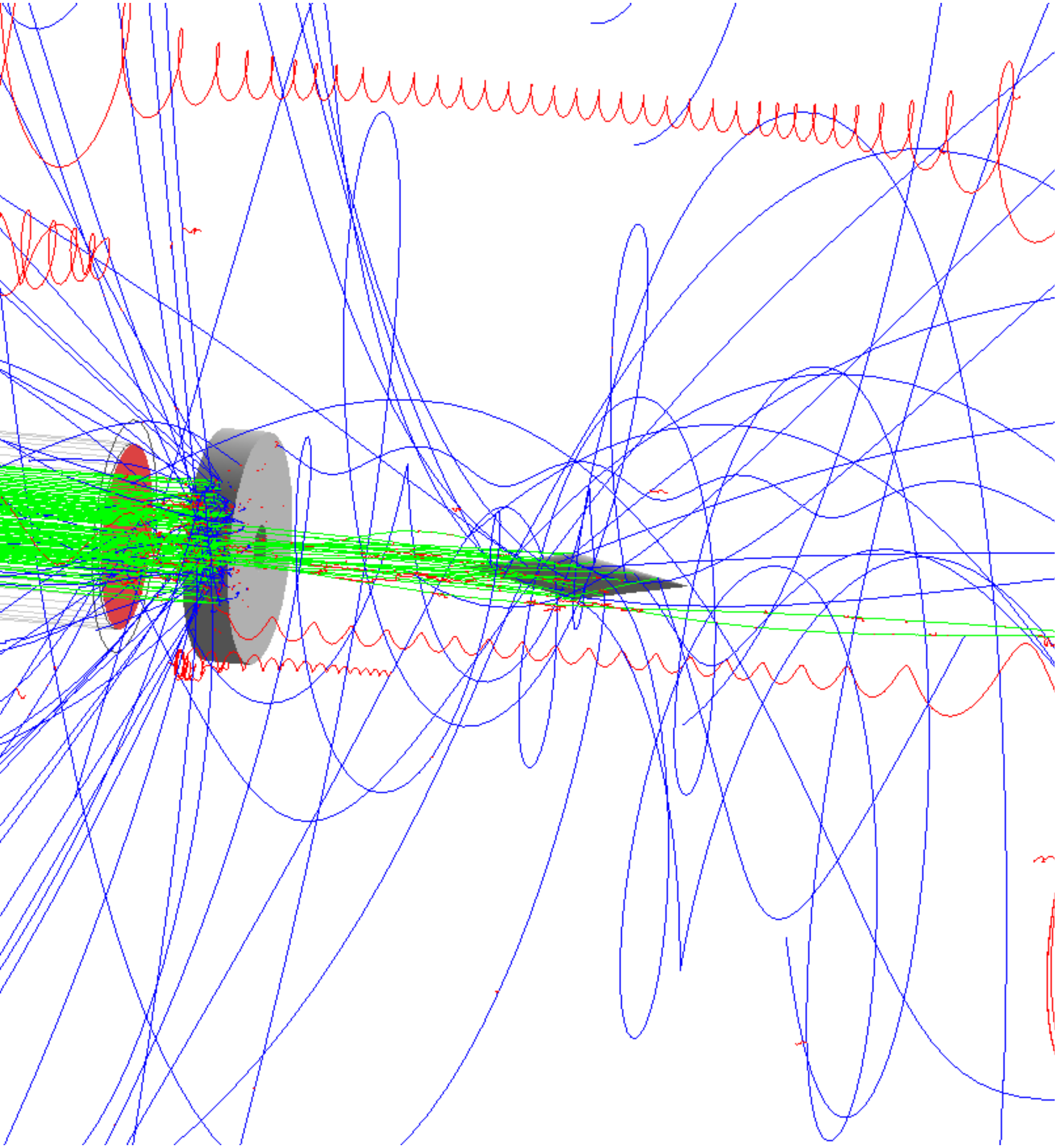
- Physics performance
- Detector capabilities
- Physical constraints: Supports, cables etc.

Design process - Constraints

- Physics performance
- Detector capabilities
- Physical constraints: Supports, cables etc.

- Cost!

Tools - Detector Simulation



Build the detector in your computer

- Simulate interactions of particles with matter using the Geant4 software package
- Develop reconstruction and analysis software
- Check detector performance against goals
- Iterate

Tools - Prototypes

Build (small) parts of the detector and test

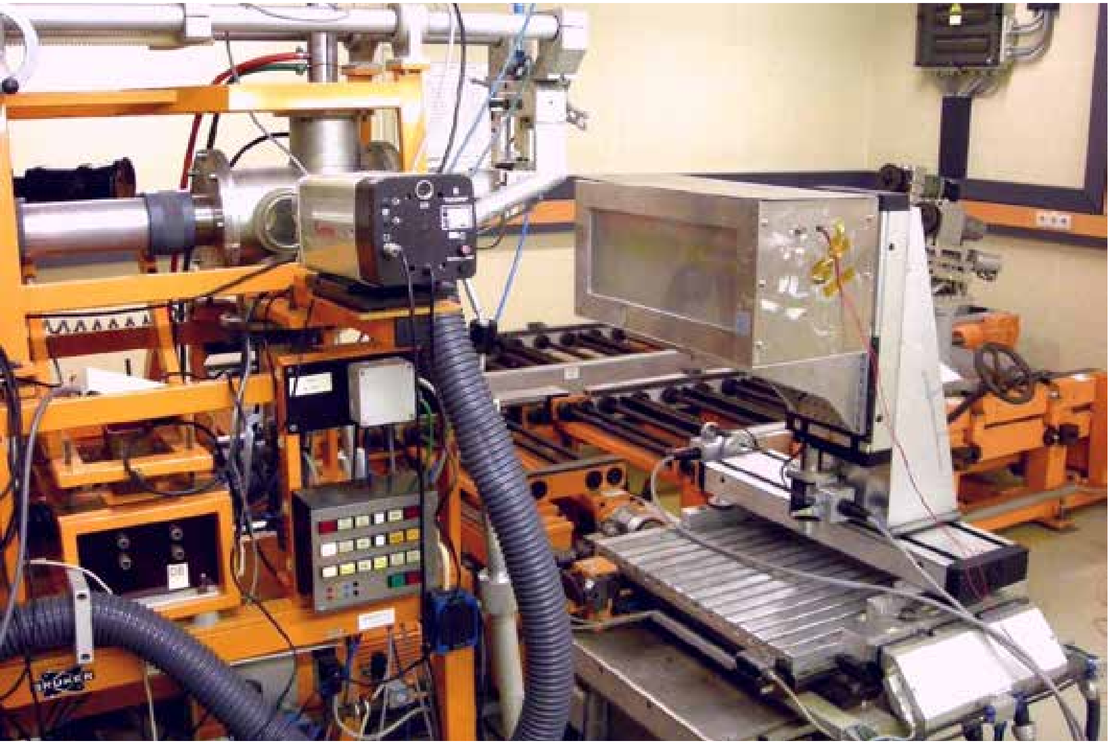
- Mechanics

Tools - Prototypes

Build (small) parts of the detector and test

- Mechanics
- Thermal properties

Tools - Prototypes



Build (small) parts of the detector and test

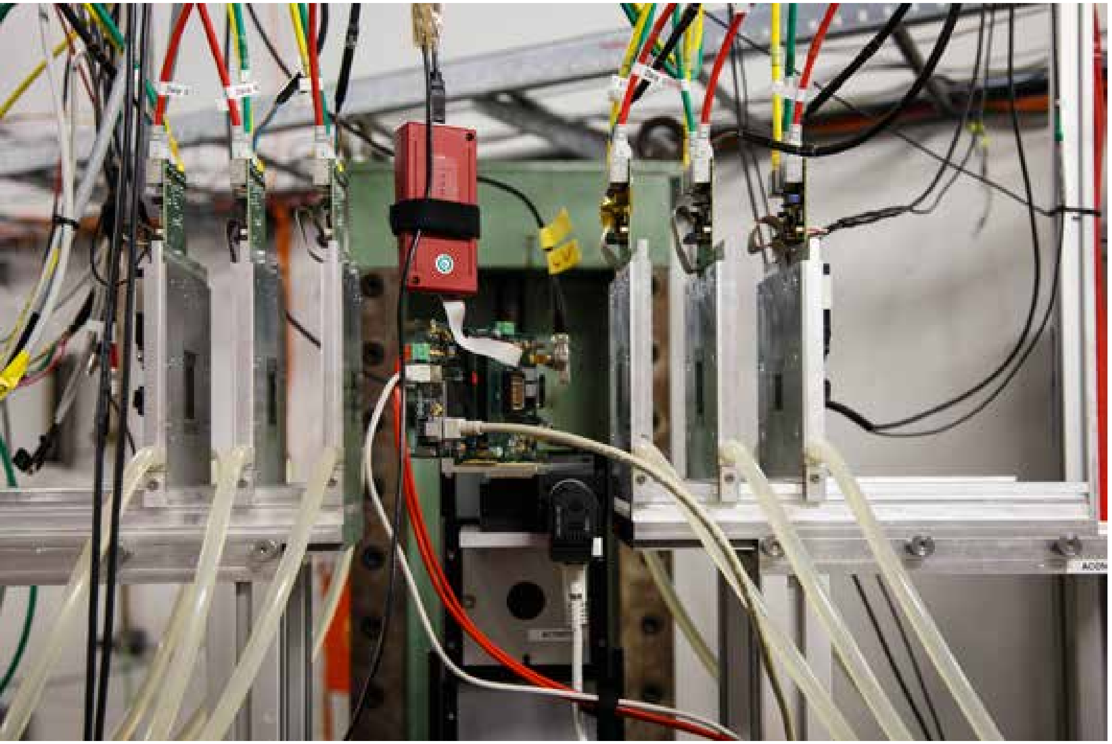
- Mechanics
- Thermal properties
- Radiation hardness

Tools - Prototypes

Build (small) parts of the detector and test

- Mechanics
- Thermal properties
- Radiation hardness
- Particle detection (sources or beam)

Tools - Prototypes



Build (small) parts of the detector and test

- Mechanics
- Thermal properties
- Radiation hardness
- Particle detection (sources or beam)
- etc.

Find collaborators...

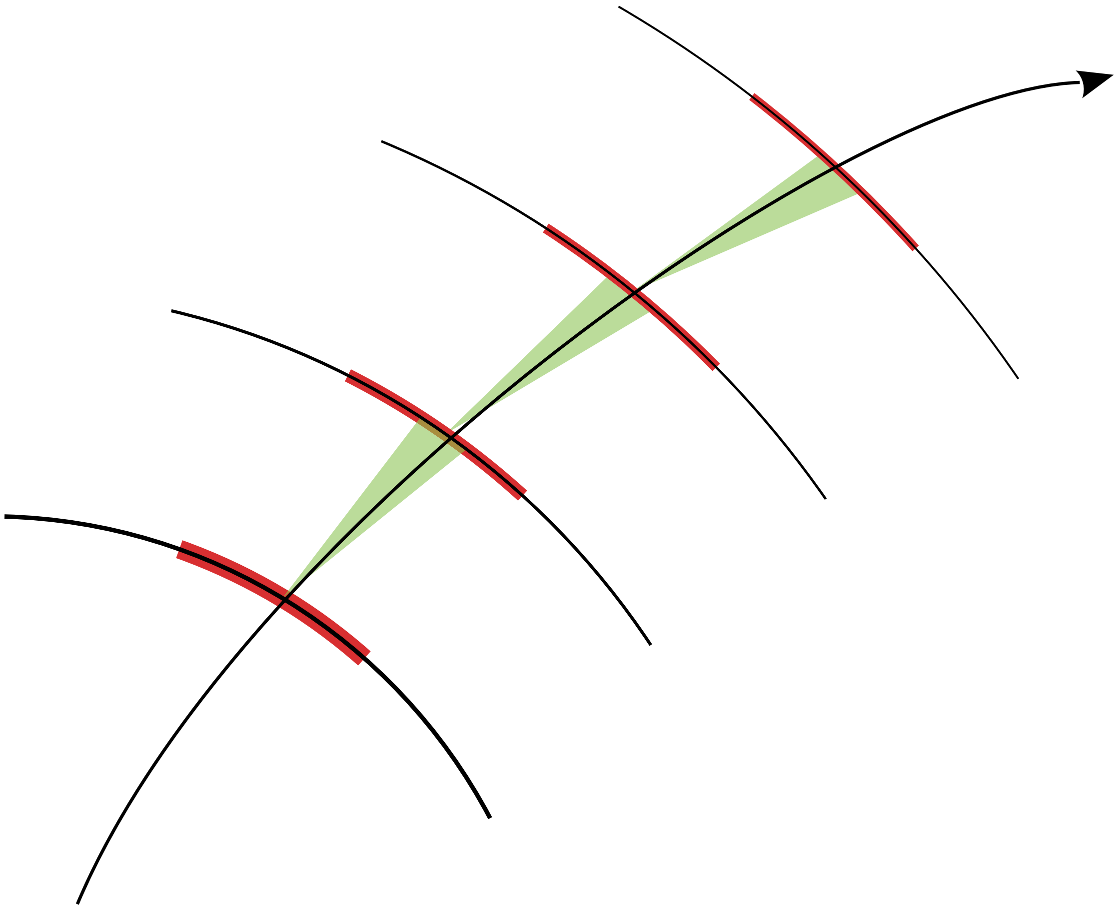
Find money...

Obtain beam time...

Case study:

Particle tracking in high rate environments

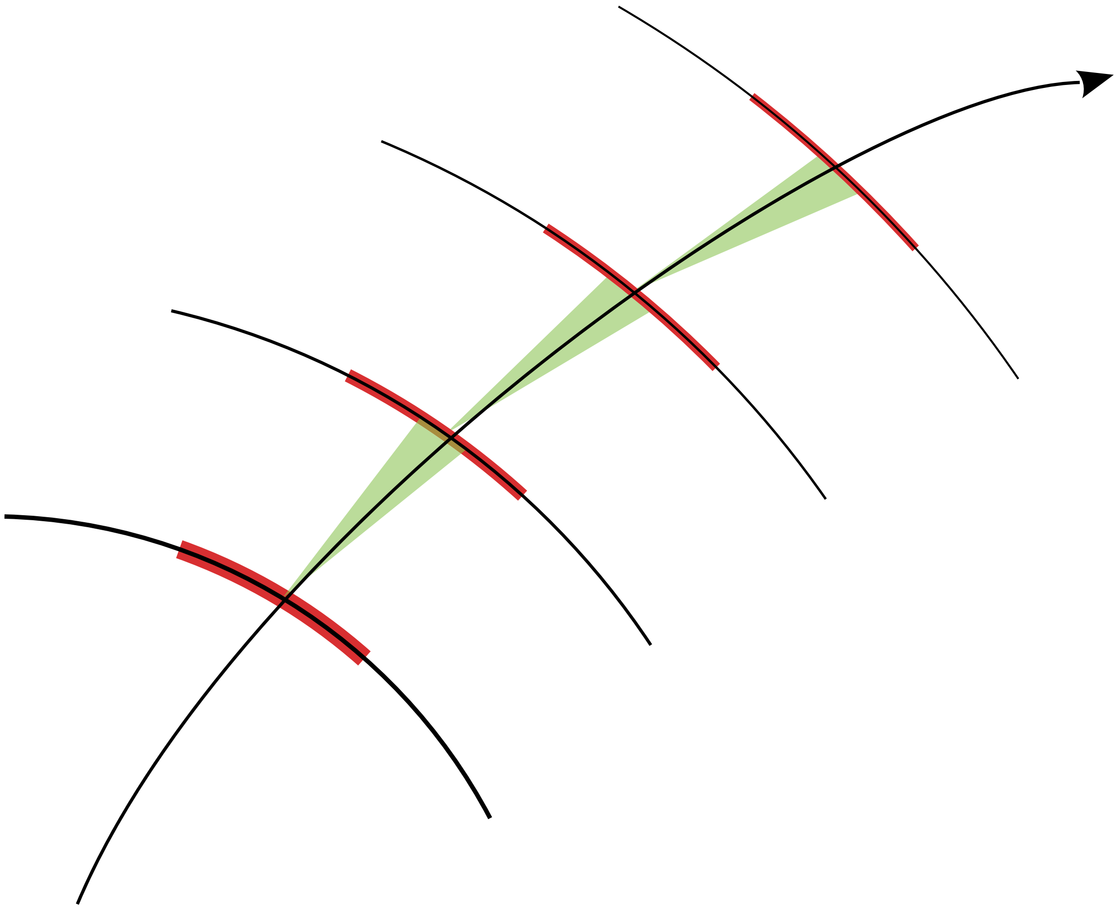
Why tracking?



Reconstructing paths of charged particles allows for:

- Particle counting
- Momentum measurement (with a magnetic field)
- Some timing measurements
- Reconstruction of a common point of origin (vertexing)

Tracking resolution

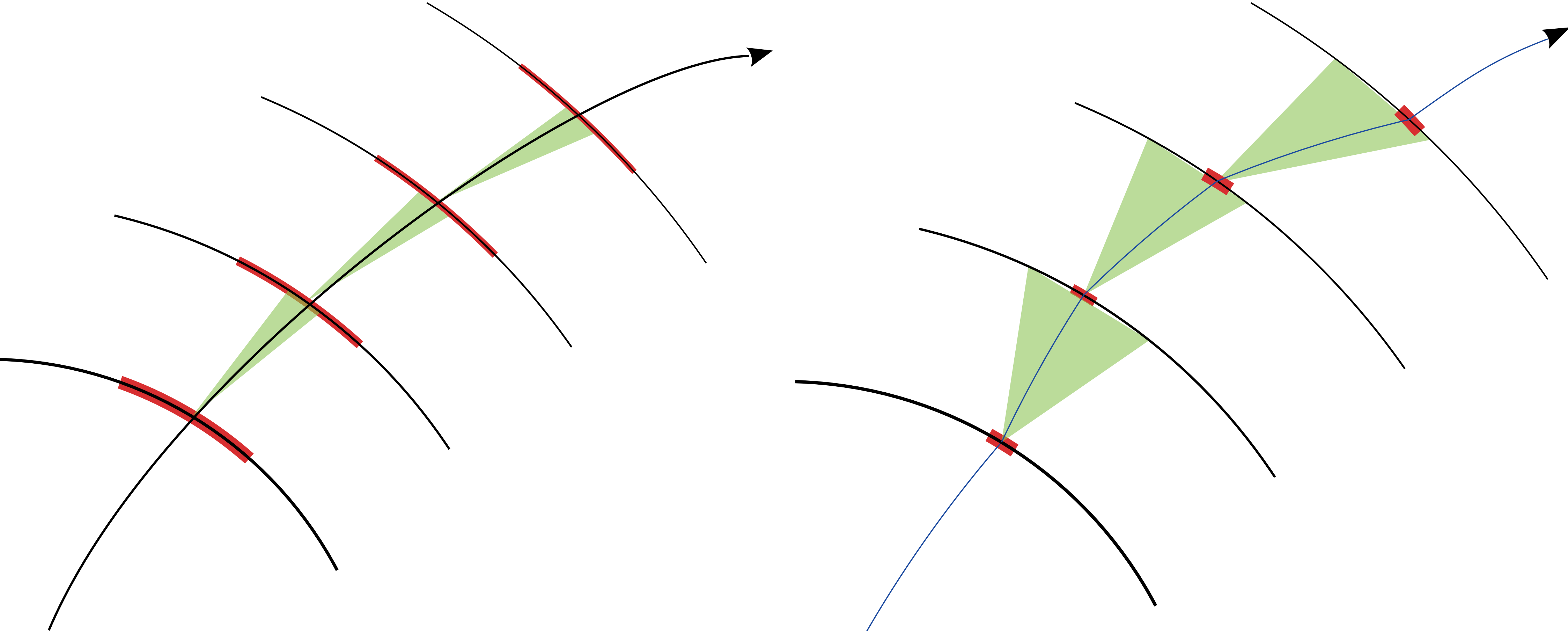


Usually physics goal requires a certain momentum resolution

Momentum resolution is determined by

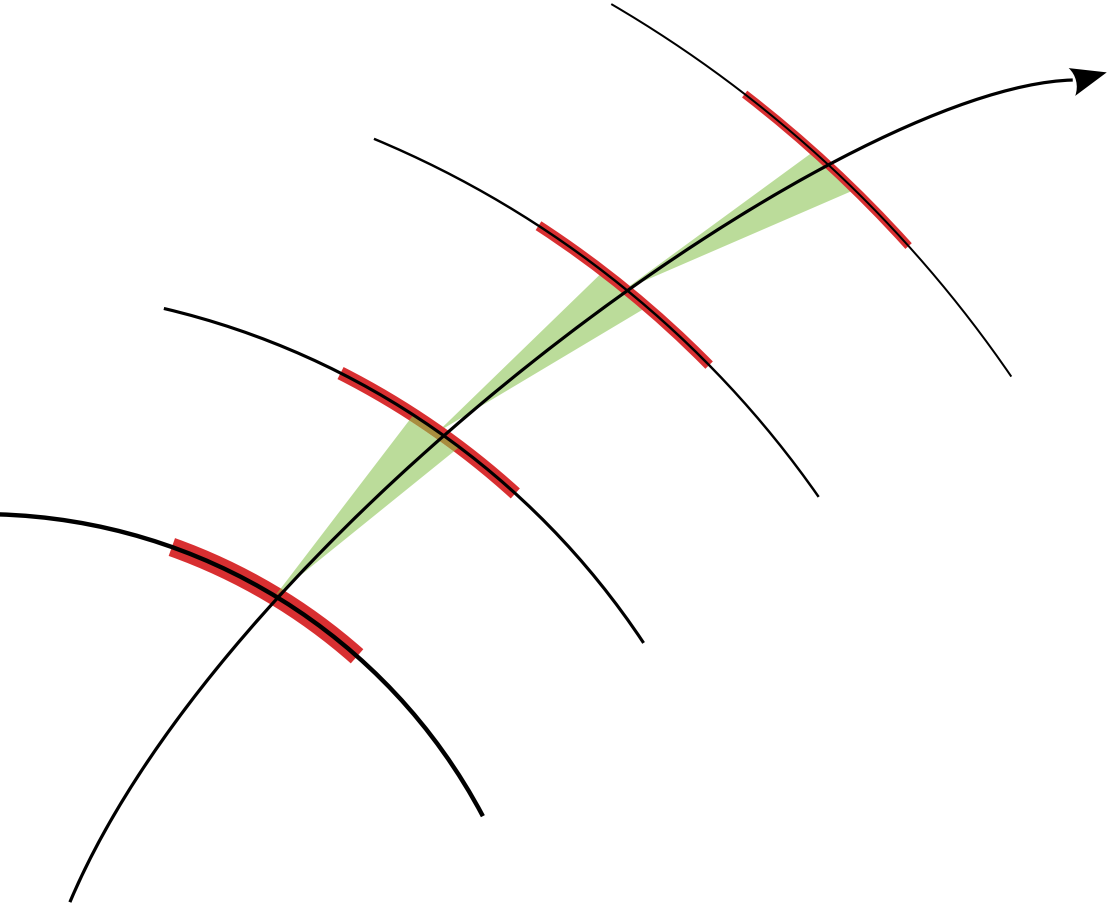
- Single point resolution of detector
- Deflection of particle in detector (Multiple coulomb scattering)
- Number and arrangement of detectors

Two regimes: Resolution & Scattering



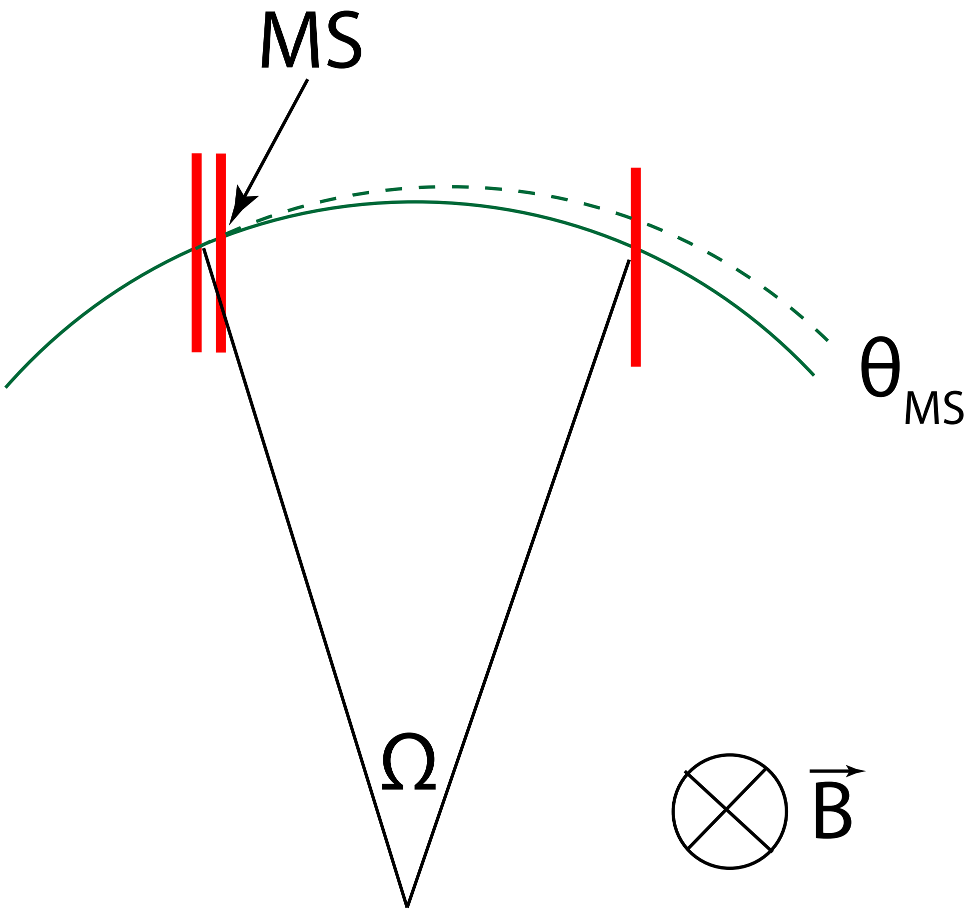
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

Resolution regime



- Add more layers
- Constrained by cost and space (inside a magnet)

Scattering regime

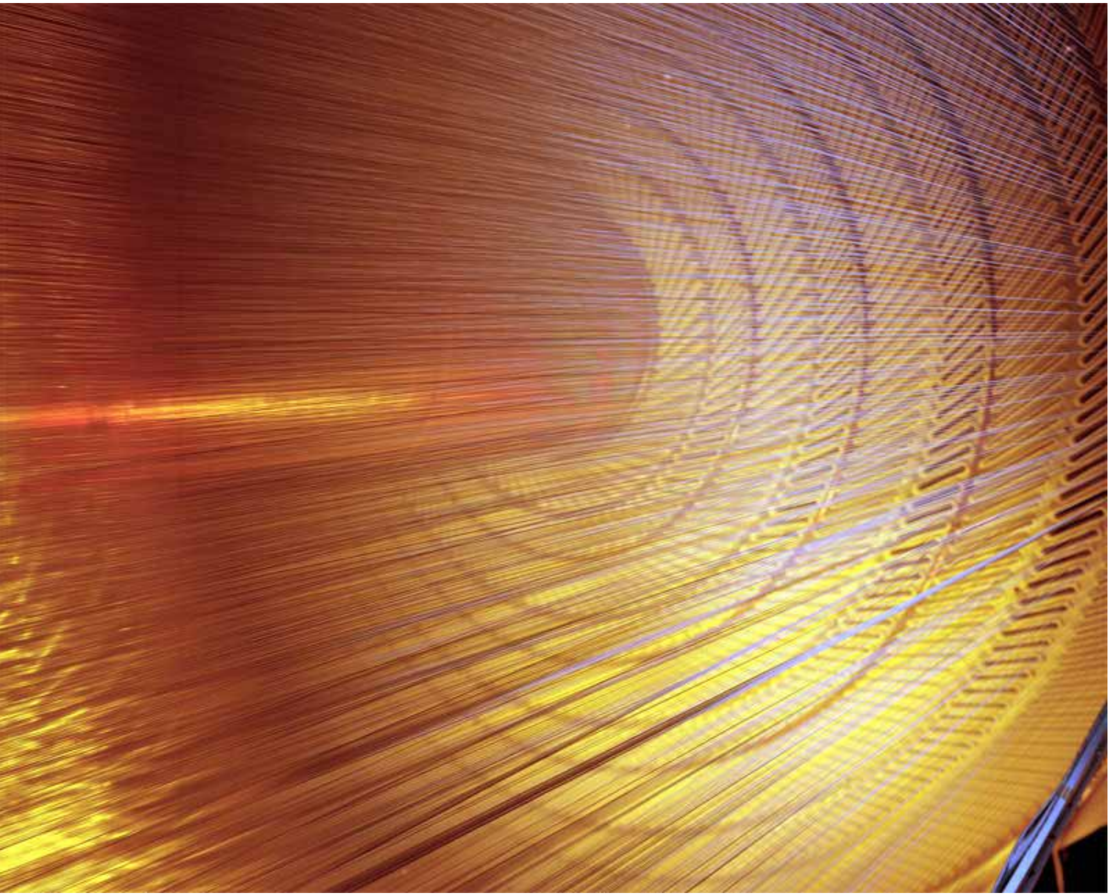


- Momentum resolution to first order:

$$\sigma_P/P \sim \theta_{MS}/\Omega$$

- Precision requires large lever arm (large bending angle Ω) and low multiple scattering θ_{MS}
- Constrained by space and material required for detection

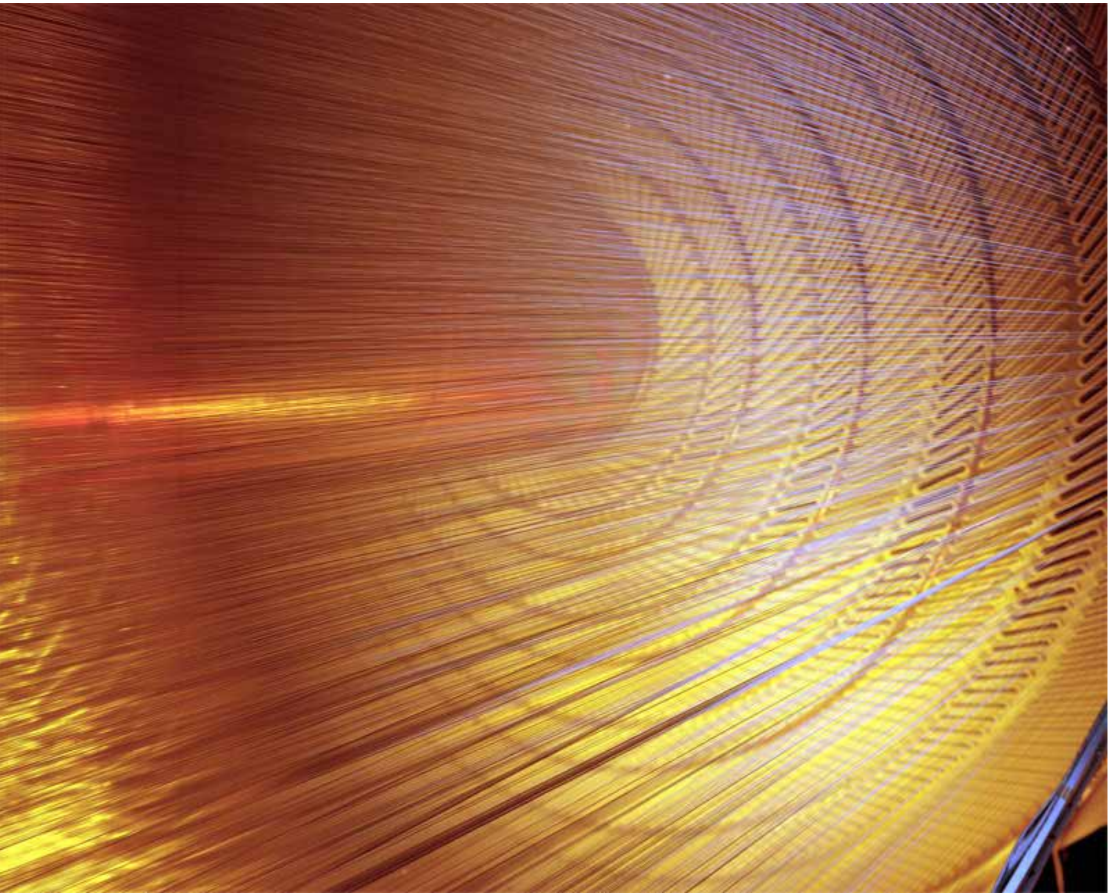
Thin detectors: Gas



- Particles ionize gas
- Strong electrical field between wires collects charges
- Amplification in near-field of wire

- Position resolutions of ~150 μm per point with very little material

Thin detectors: Gas



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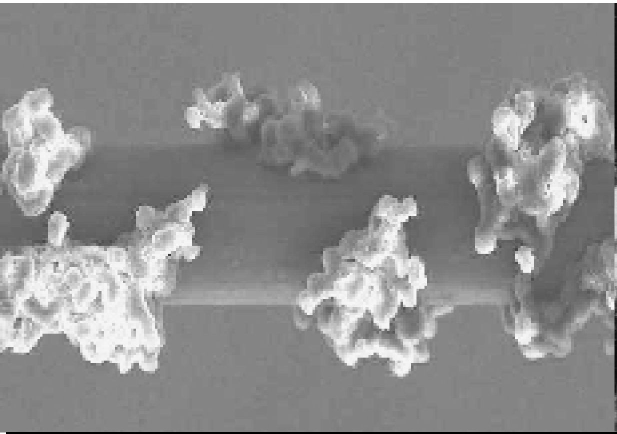
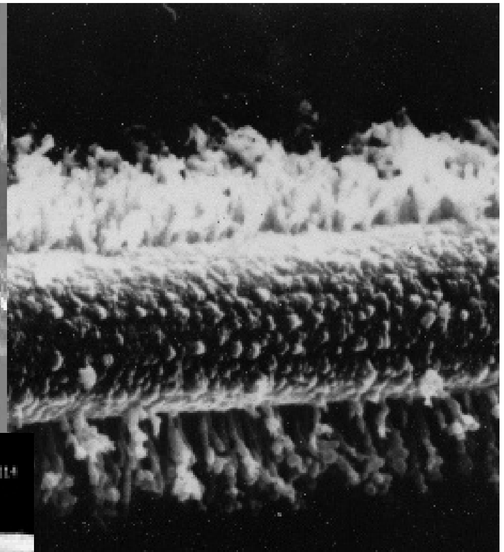
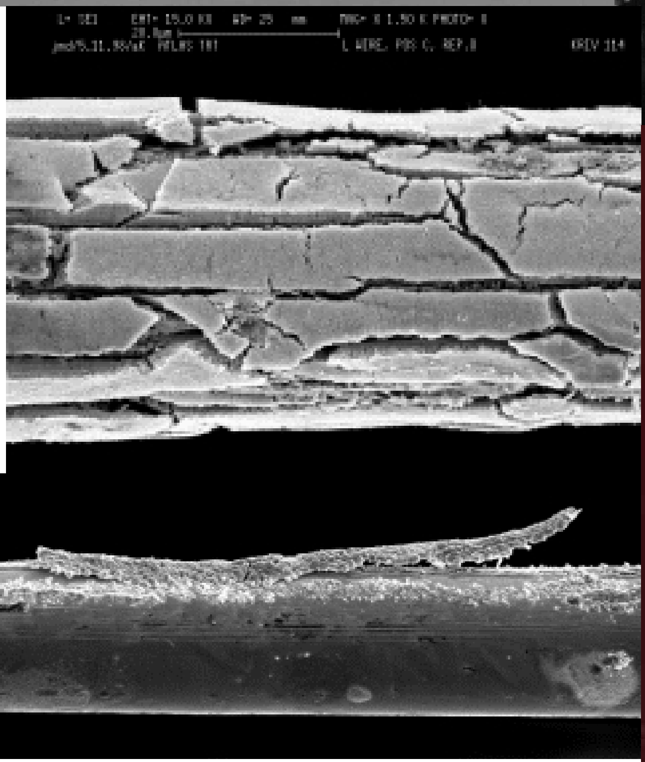
- Ions drift much longer - space charge - worse resolution and efficiency

Thin detectors: Gas



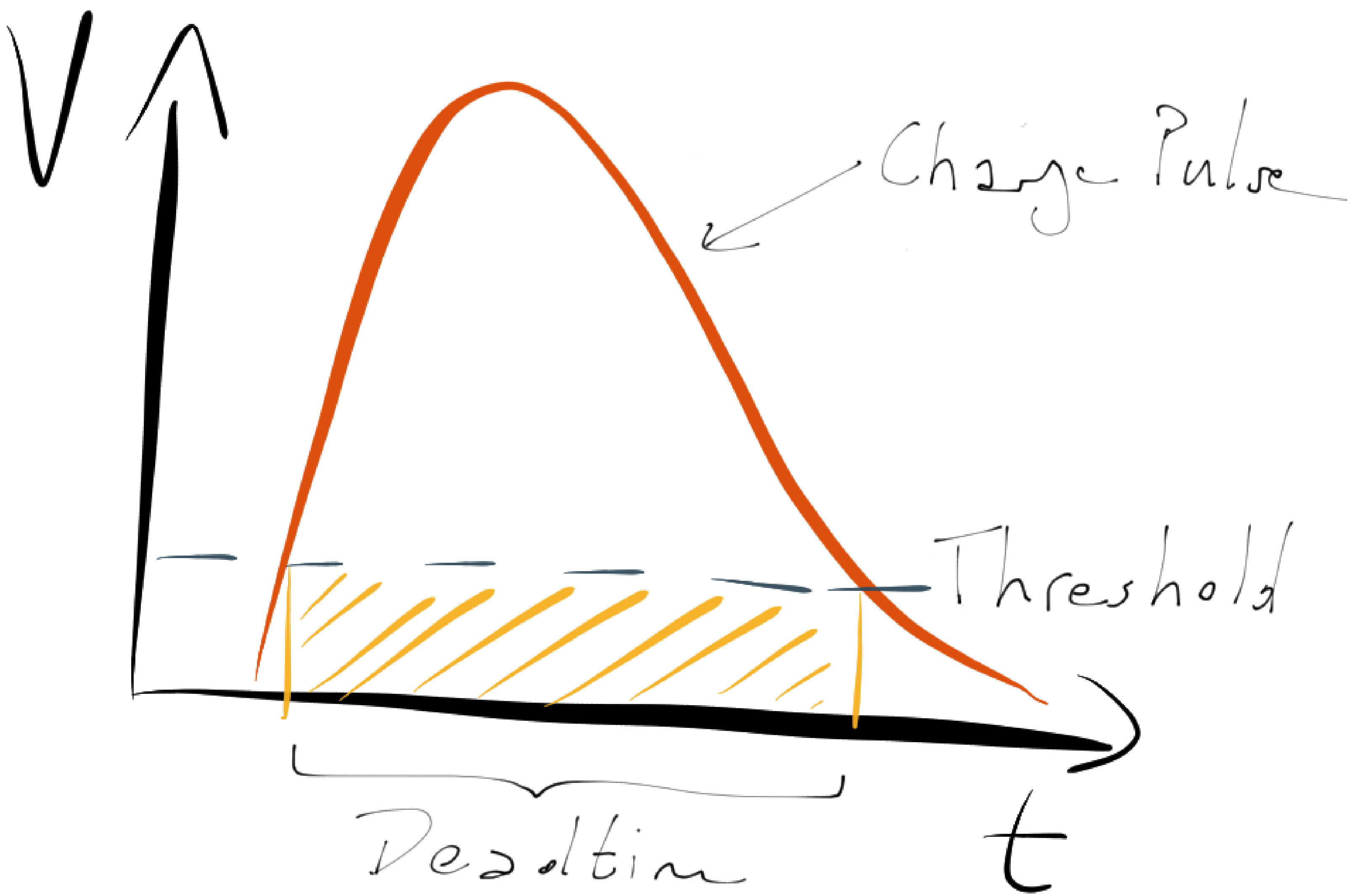




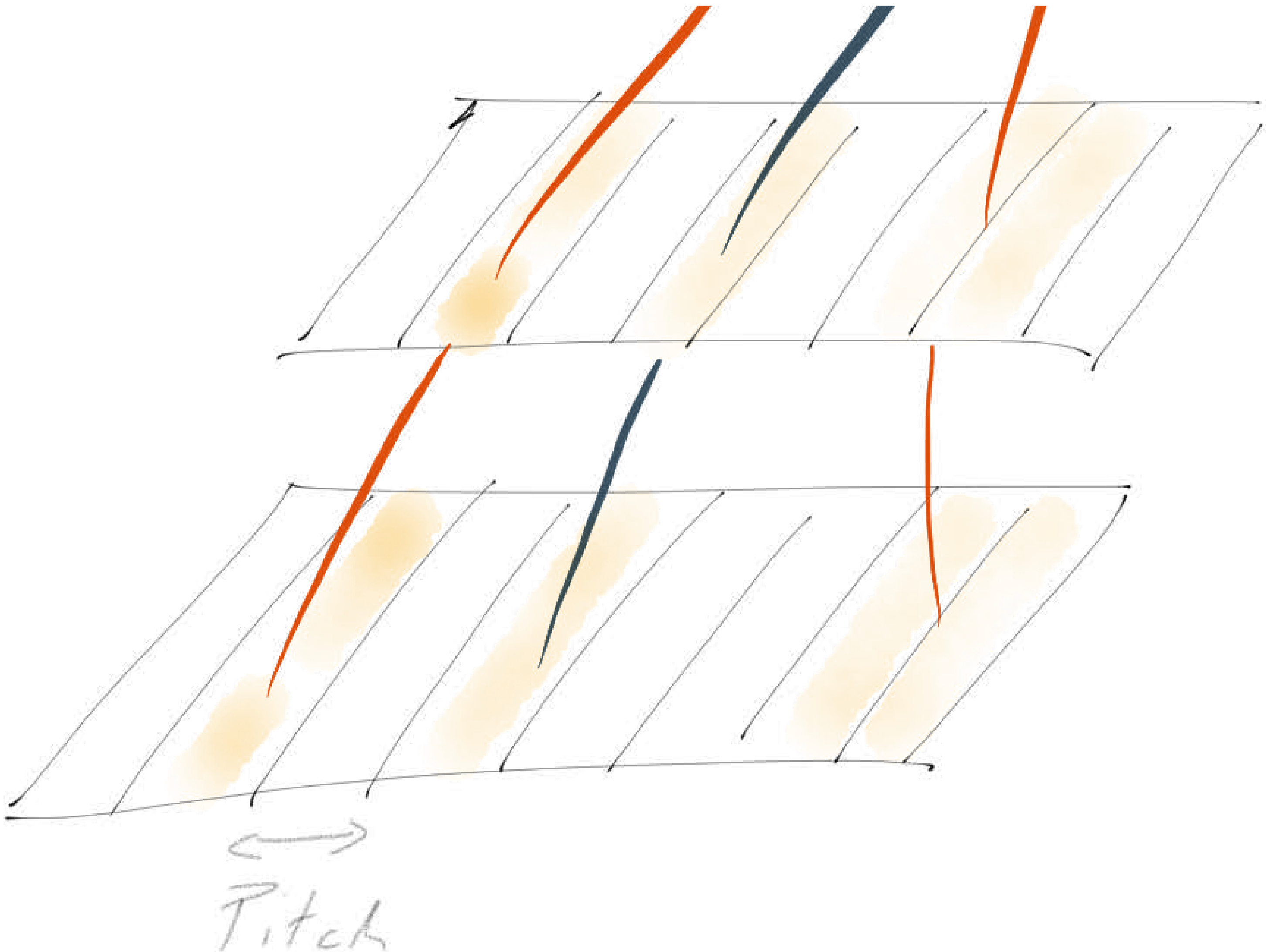
- Particles ionize gas
- Strong electrical field between wires collects charges
- Amplification in near-field of wire
- Position resolutions of ~150 µm per point with very little material
- Ions drift much longer - space charge - worse resolution and efficiency
- Gas chemistry in near field - aging

Tracking detectors and high rates

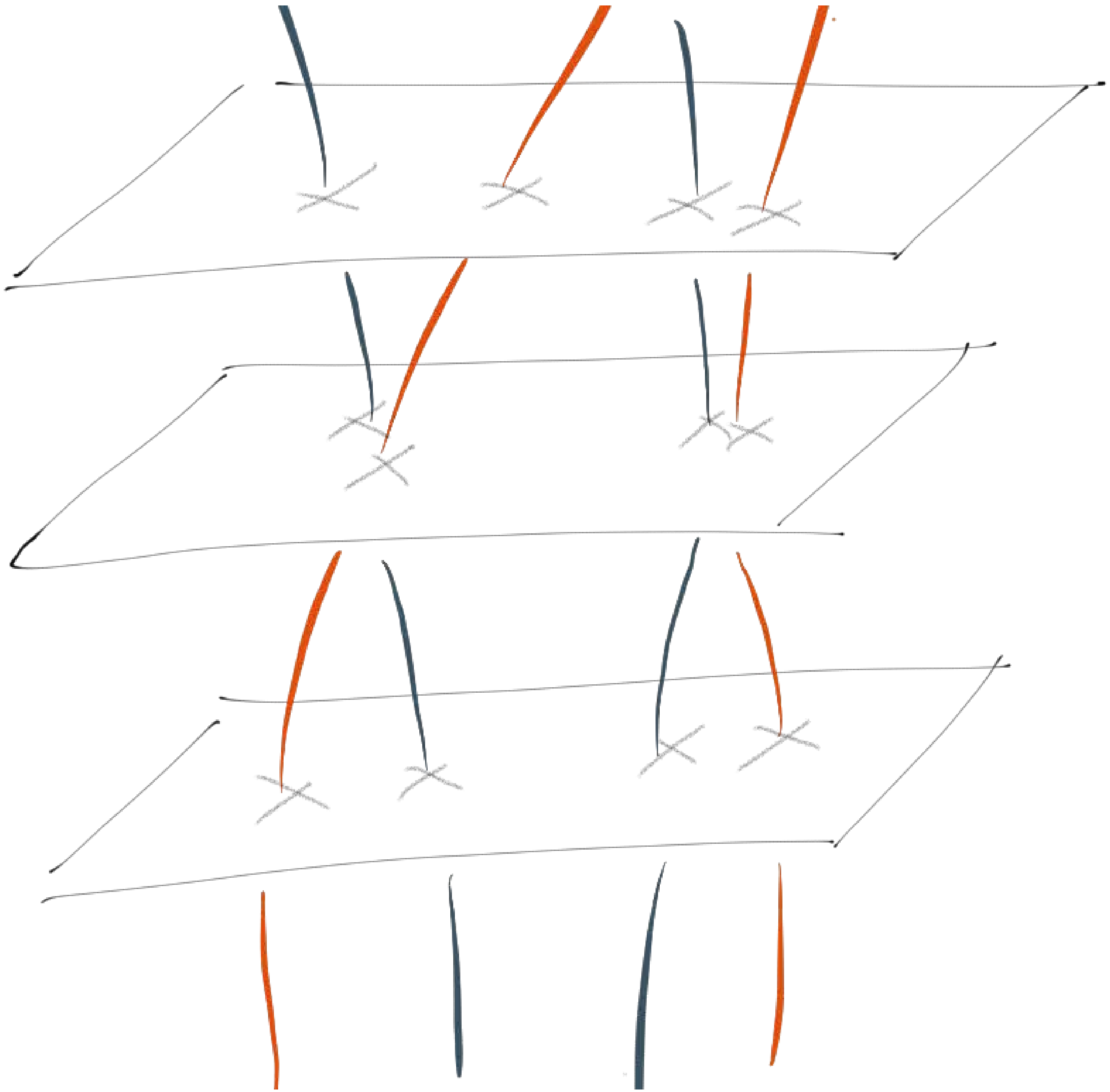
Deadtime



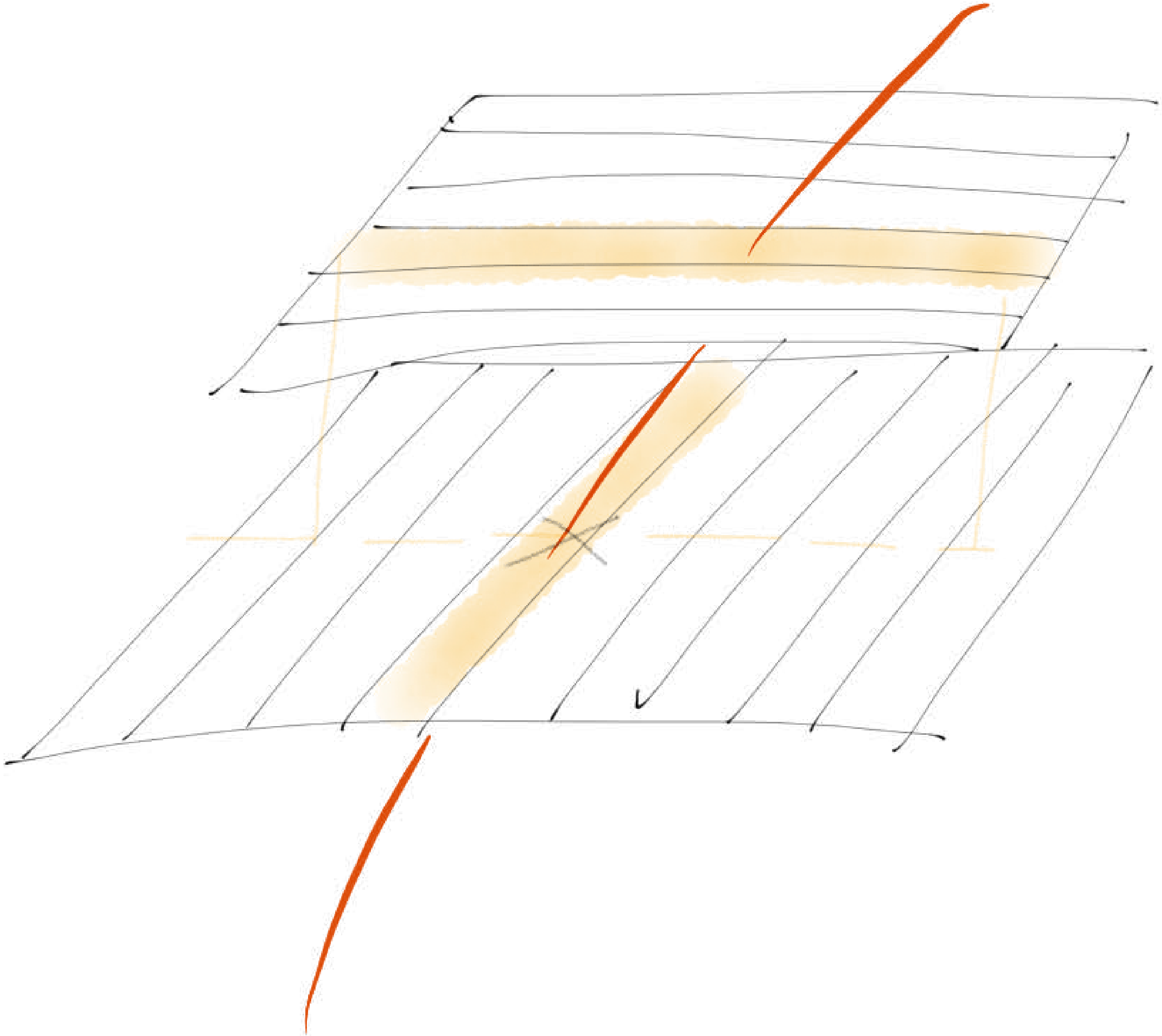
Granularity



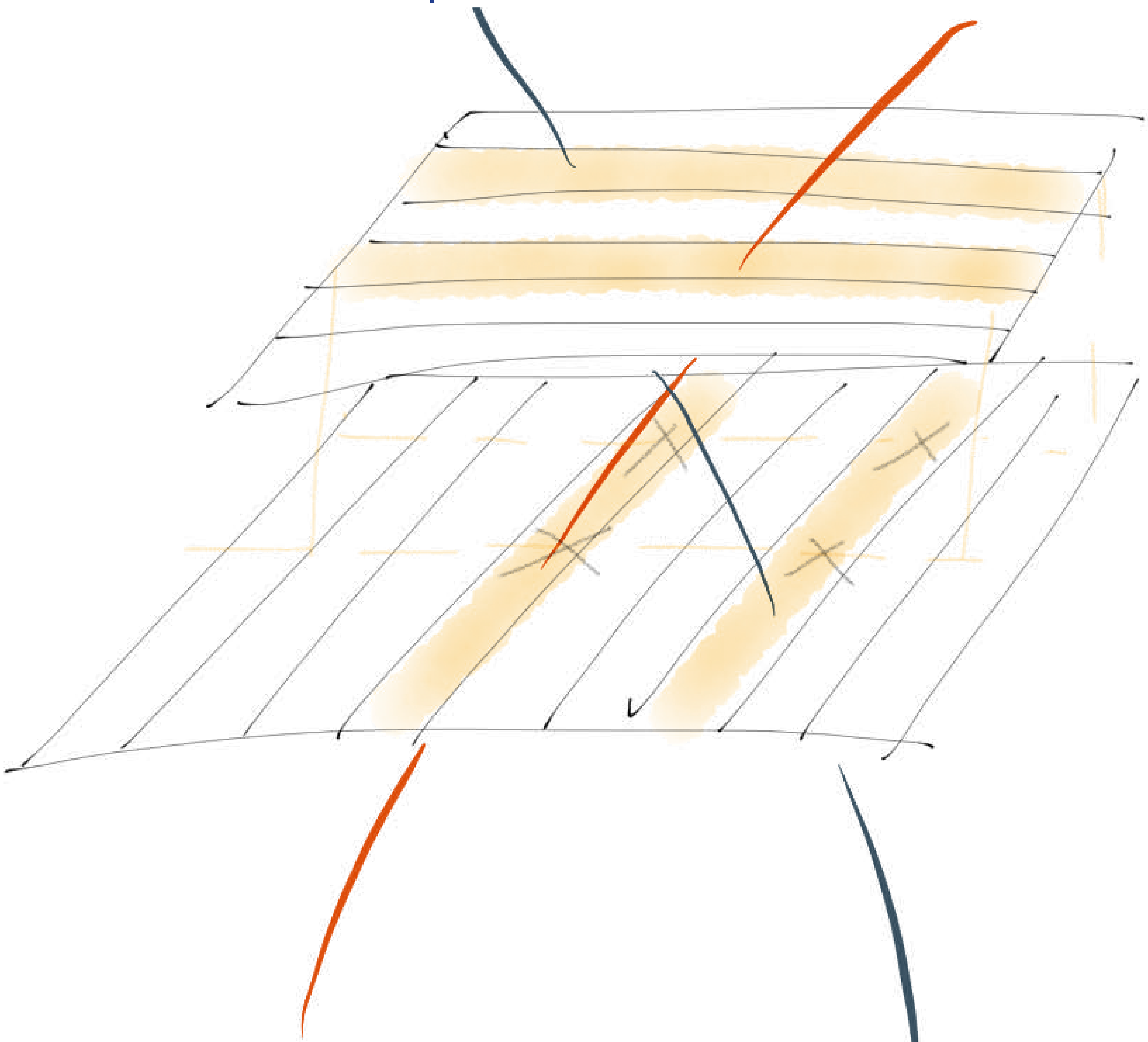
Confusion



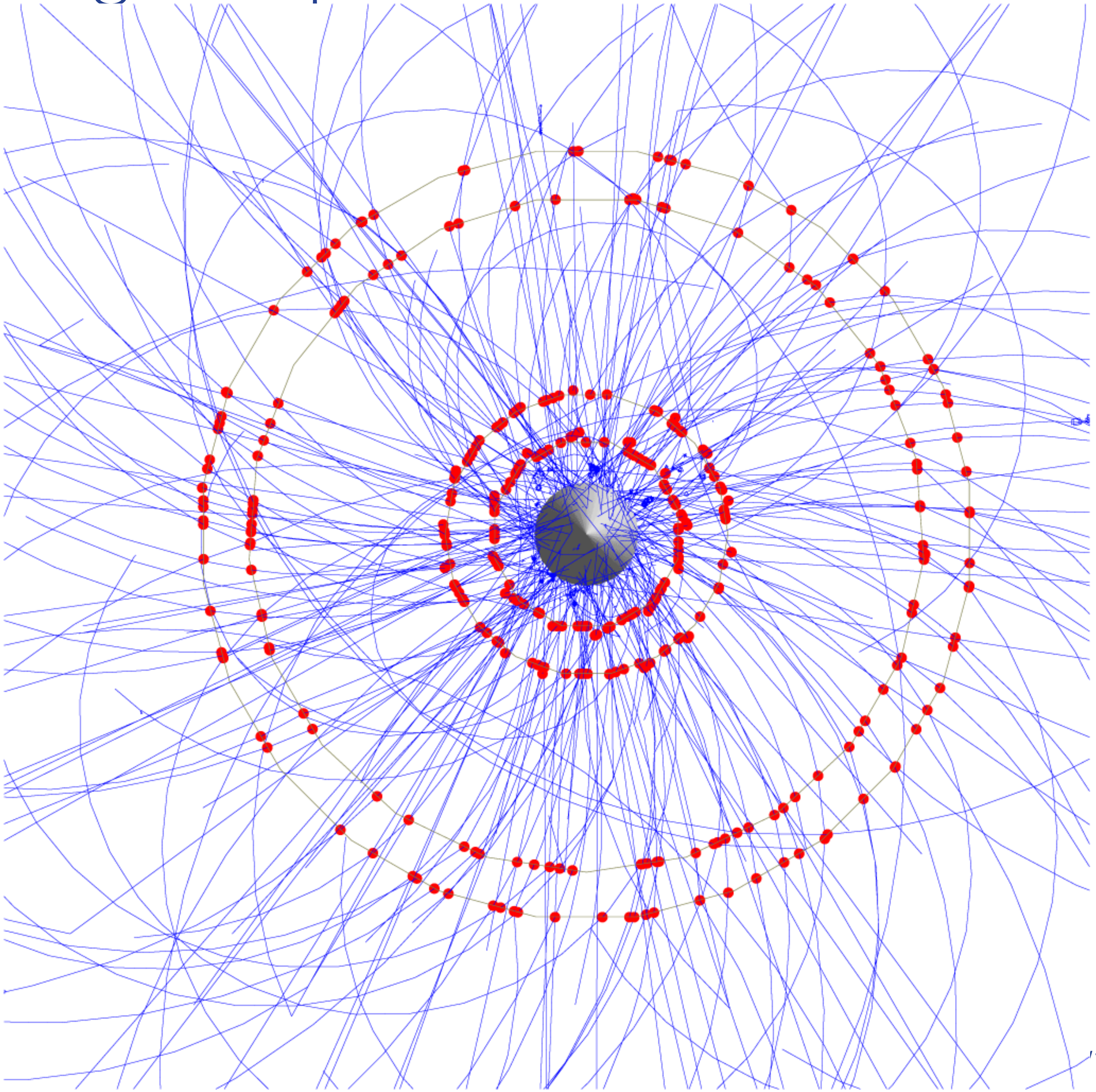
Stereo



Stereo - reconstruction problem



Pattern recognition problem



Demands for detectors

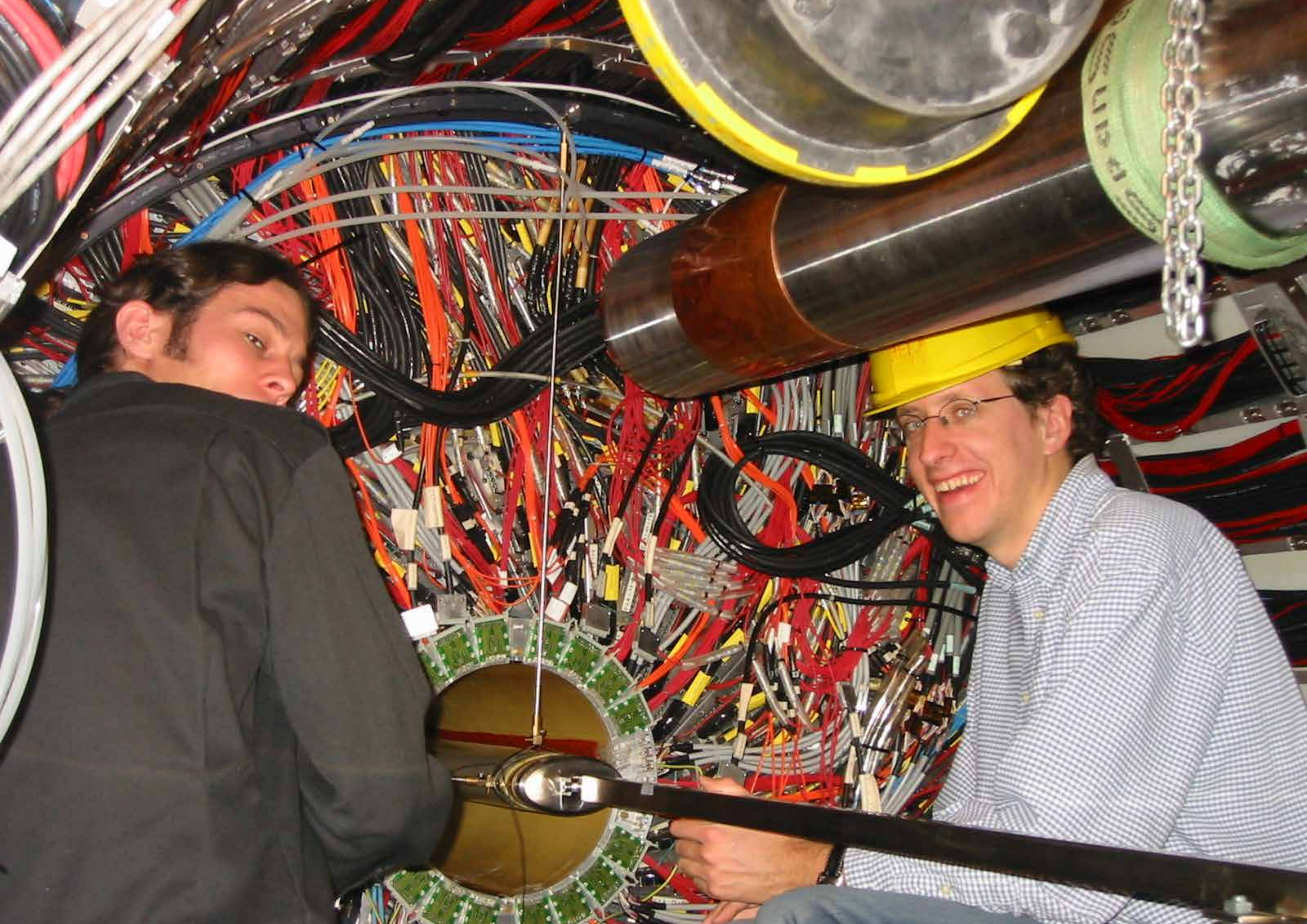
- High resolution
- Low mass
- High granularity
- If possible 3D
- Good timing

Solid state detectors

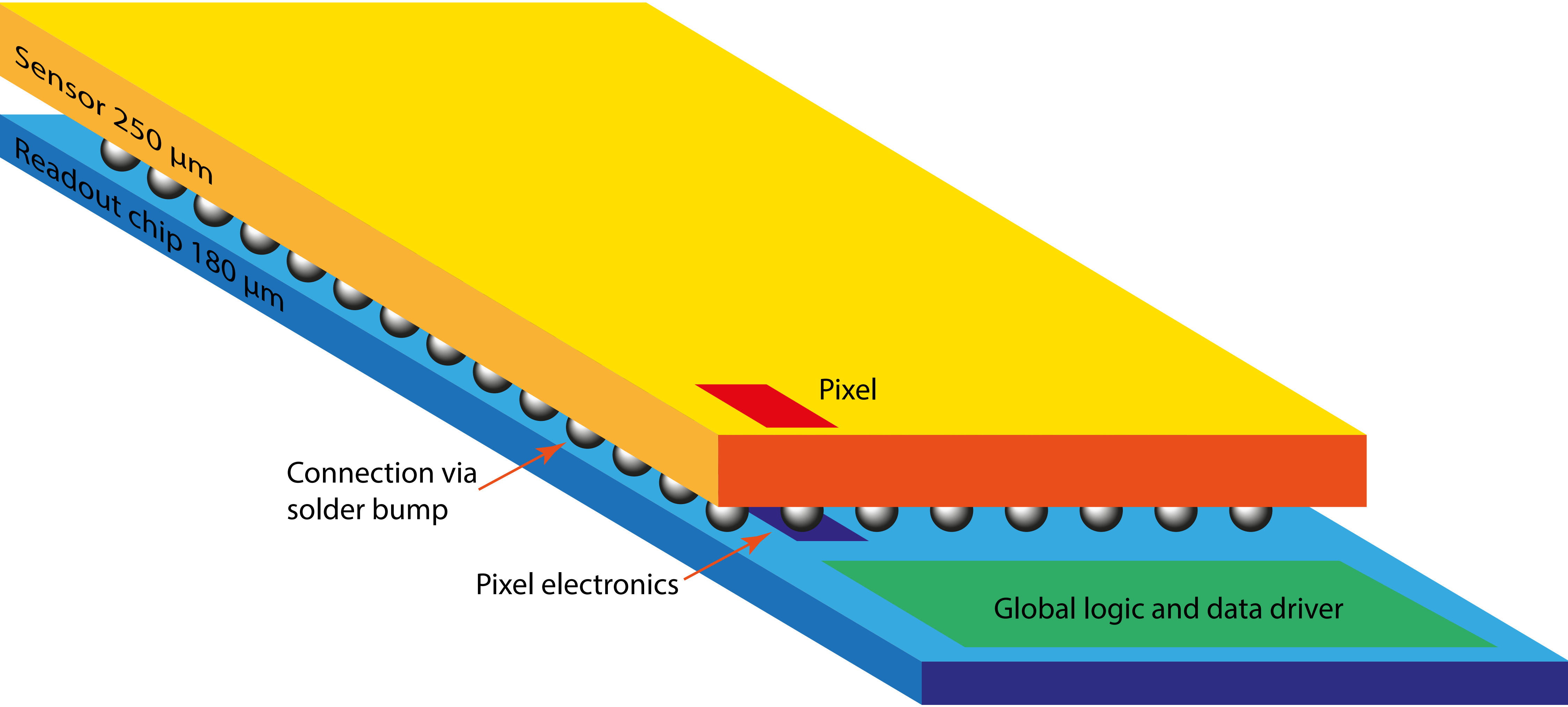
- Reversely biased diode in semiconductor as detection element (typically few 100 V)
- Some amplifier
- Some digitization scheme

Silicon Strips

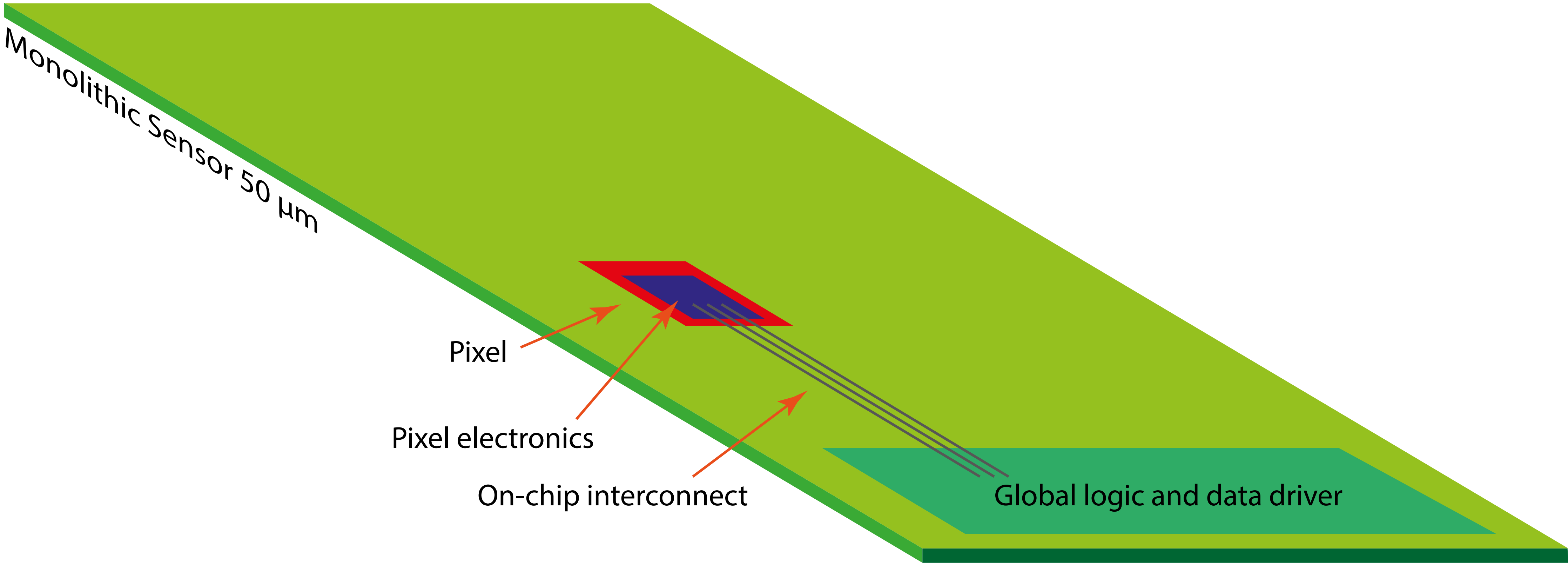
Silicon Strips



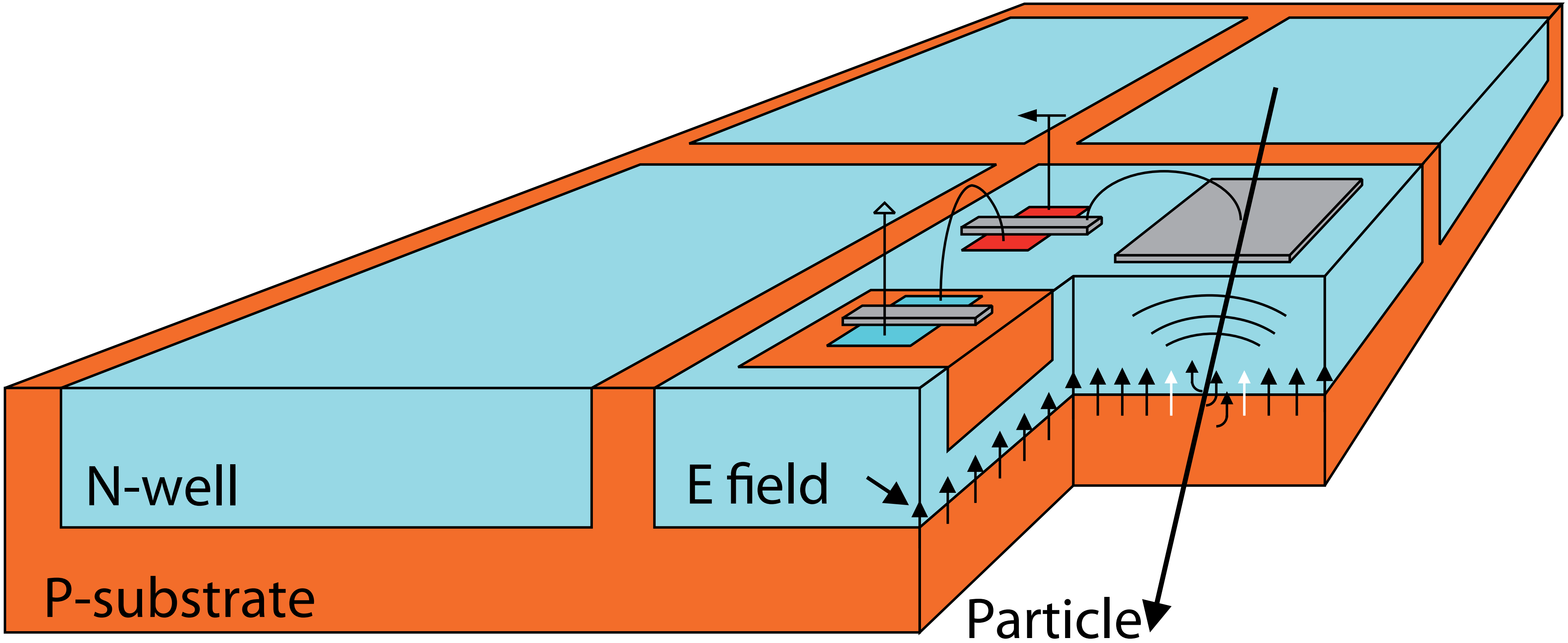
Silicon Pixels



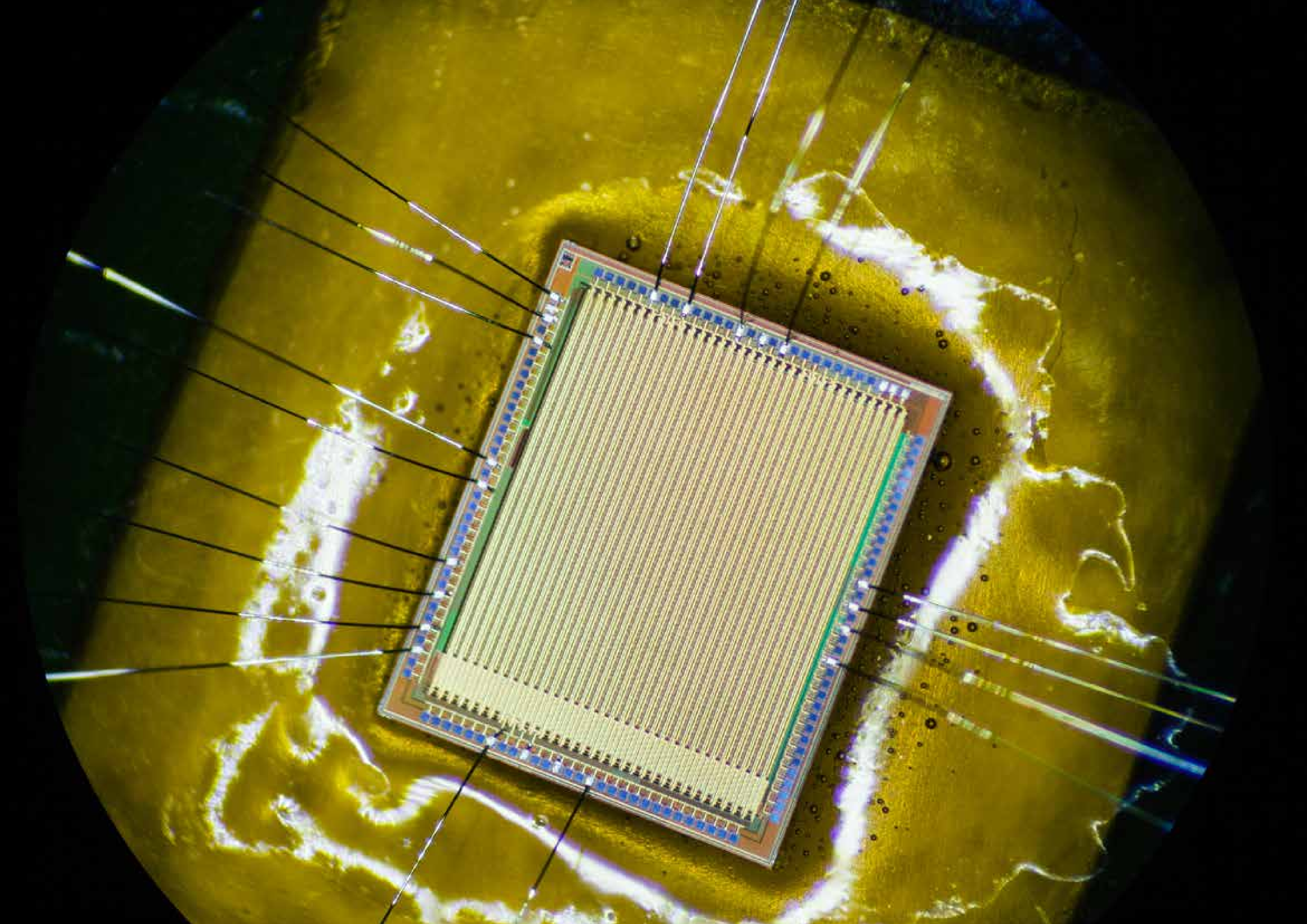
Monolithic Pixel sensors

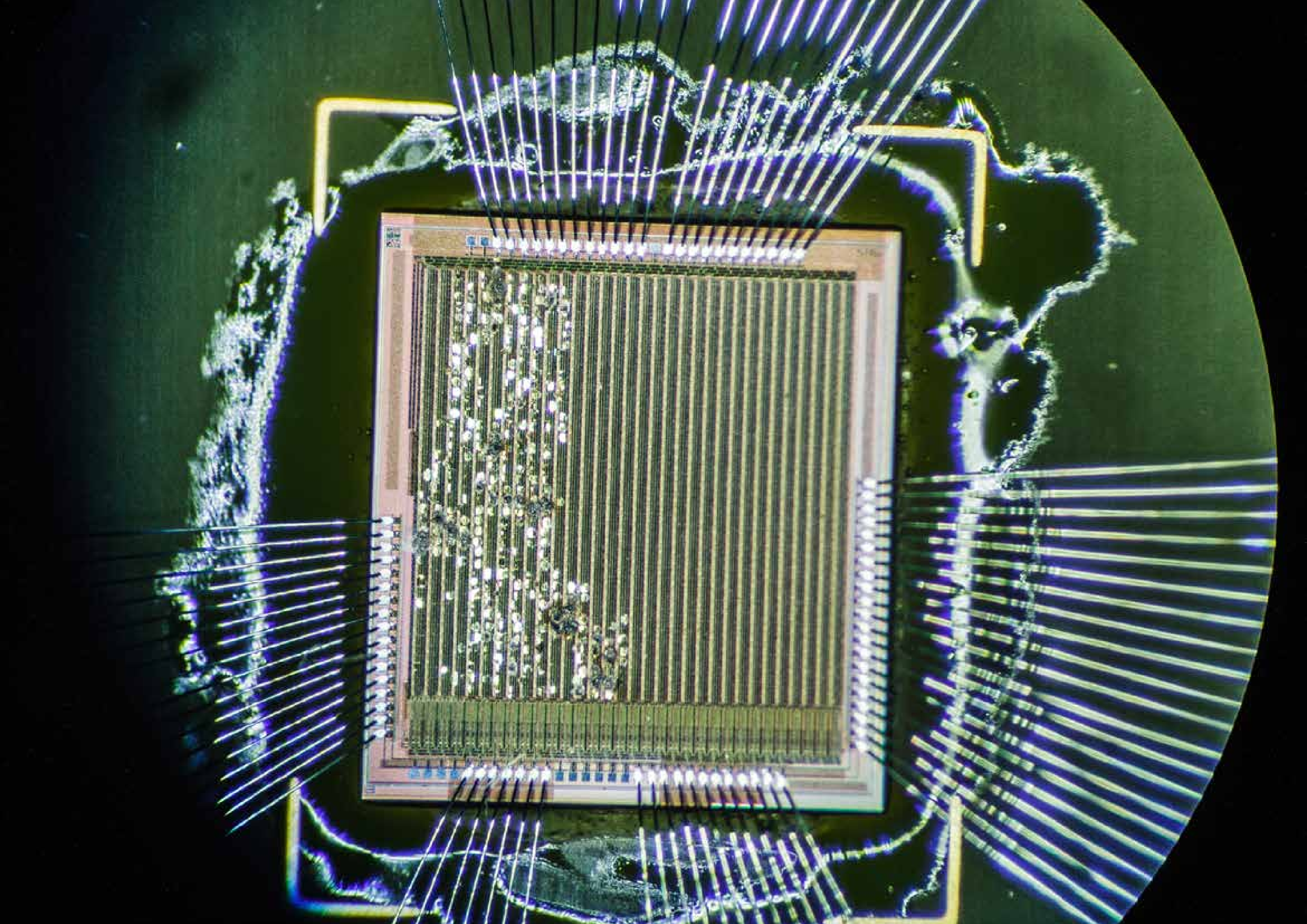


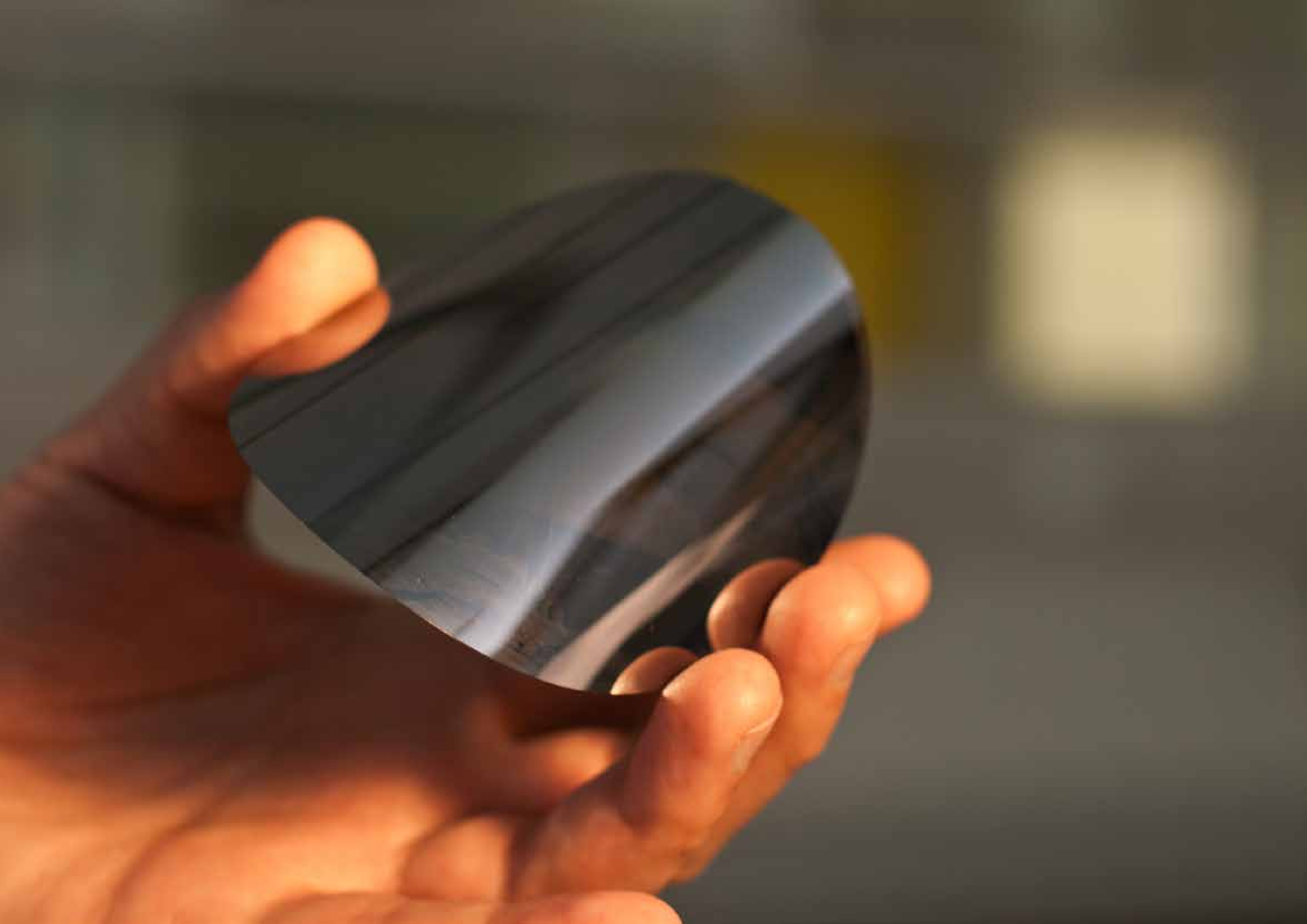
Fast and thin sensors: HV-MAPS



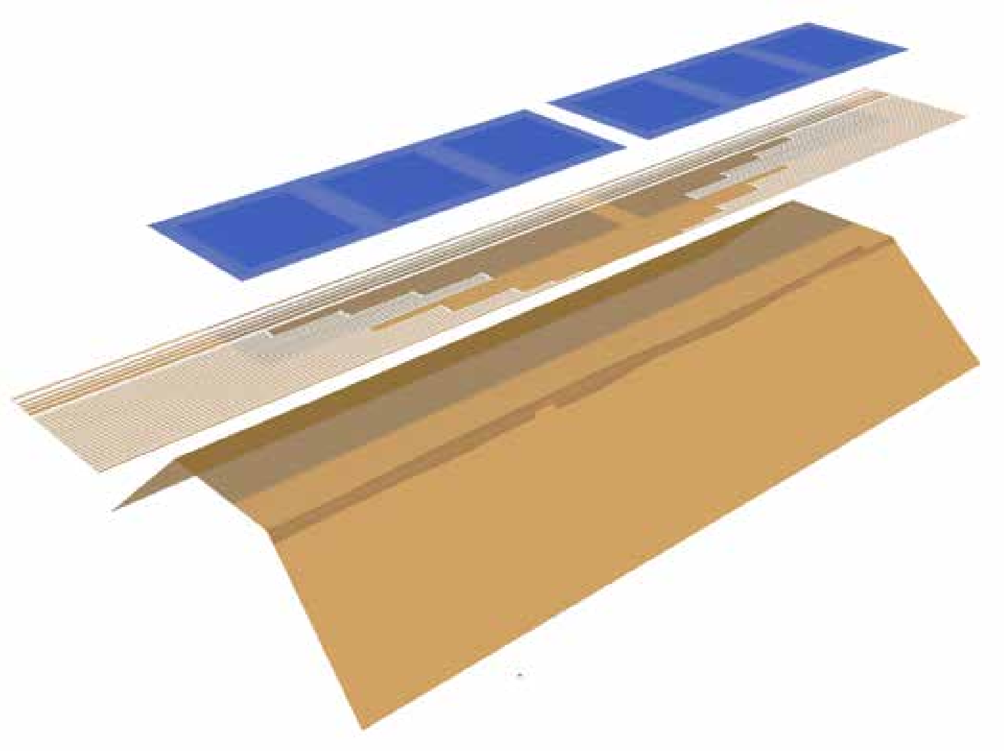
- (I.Perić, P. Fischer et al., NIM A 582 (2007) 876)







Mechanics



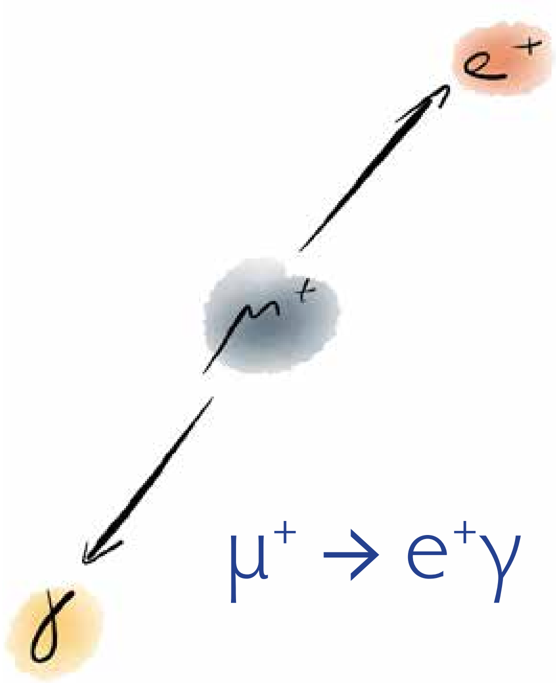
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer

“Classic” technology and incremental upgrade

Searching for $\mu \rightarrow e\gamma$ with

MEG

MEG Signal and background

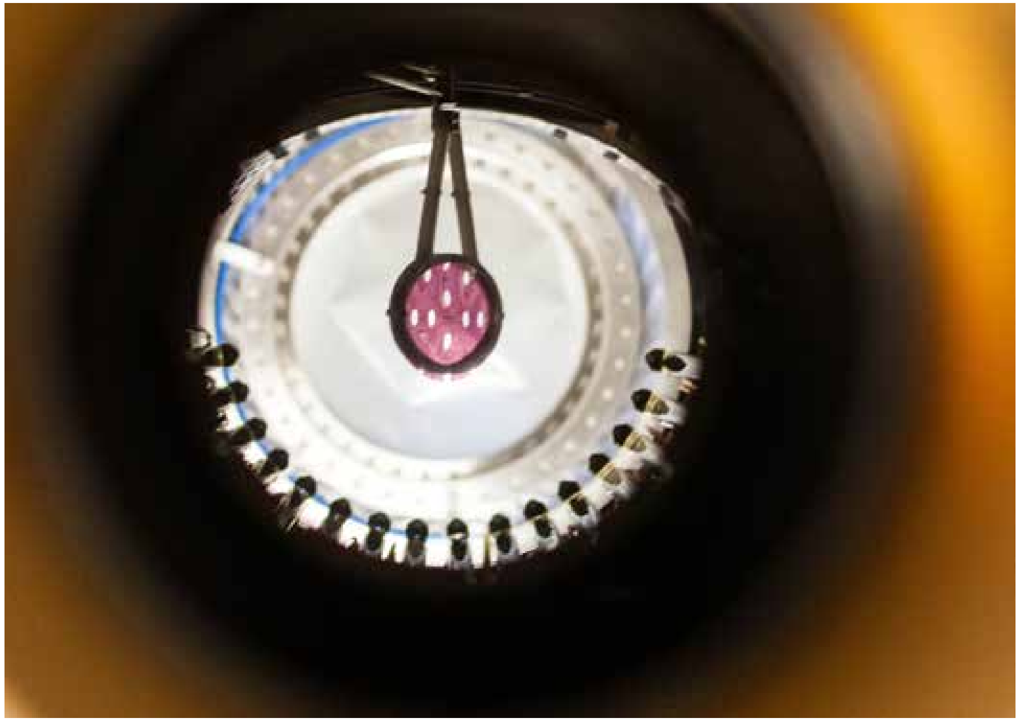


$\mu^+ \rightarrow e^+\gamma$

Kinematics

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

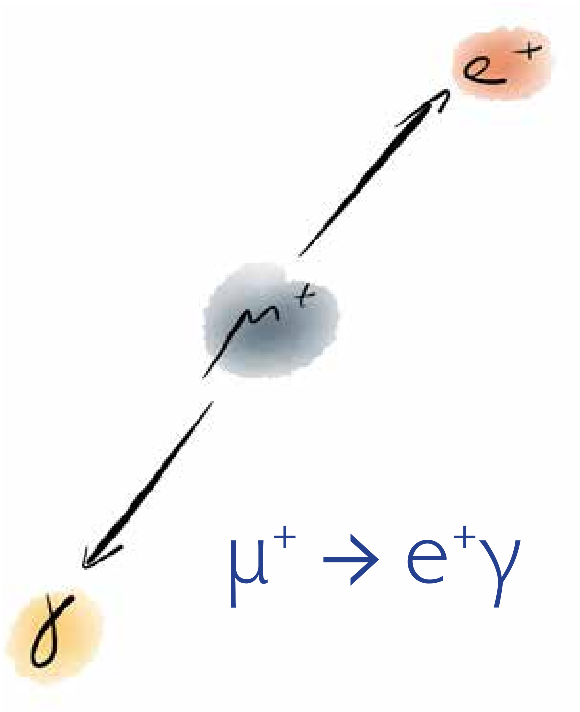
Rates and accidentals



- Muon lifetime 2.2 μs
- Single muon in target experiments limited to < 450'000 μ/s
- Corresponds to few 10^{12} μ decays a year

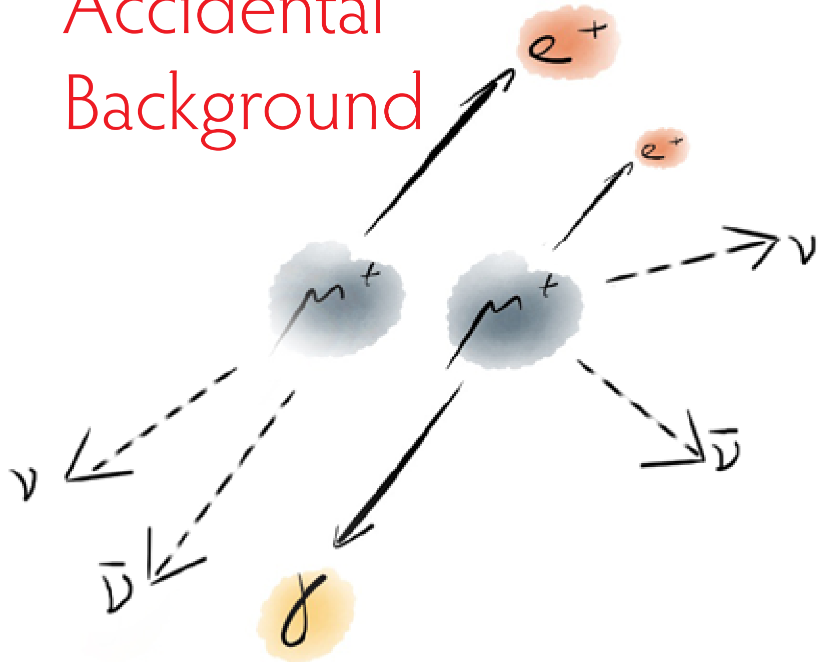
- New experiments operate at 10^{7}++ μ/s
- Many muons on target at any time
- Accidental background

MEG Signal and background



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

Accidental Background

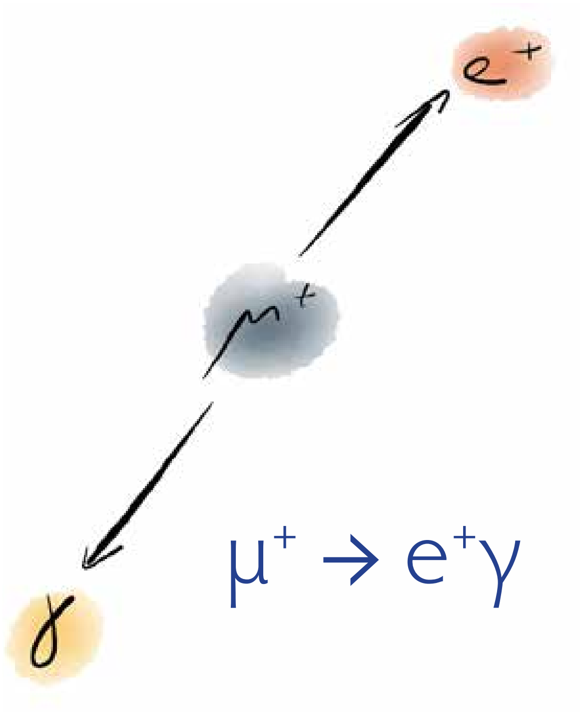


Kinematics

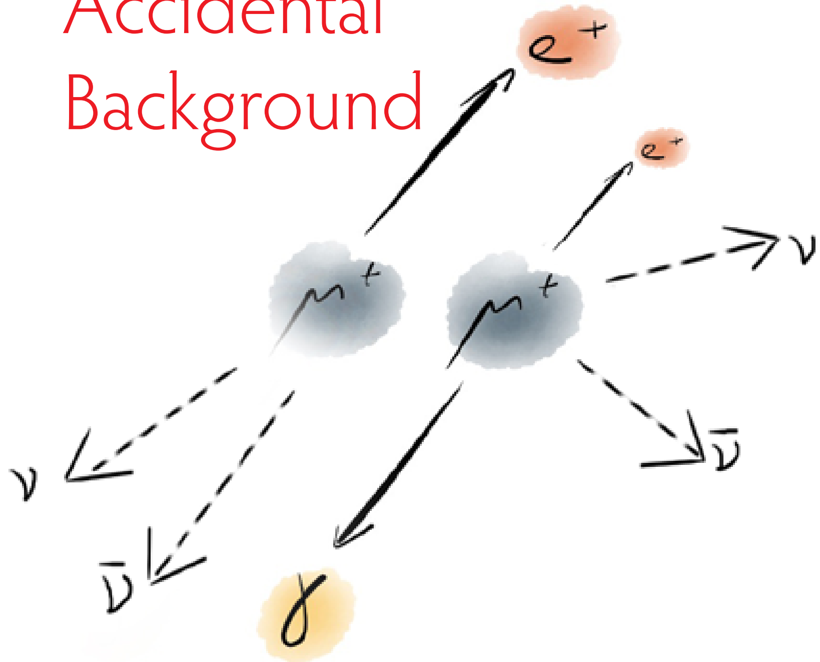
- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

- Not exactly in time
- Not exactly same vertex
- e^+, γ energies somewhat off
- Not exactly back-to-back

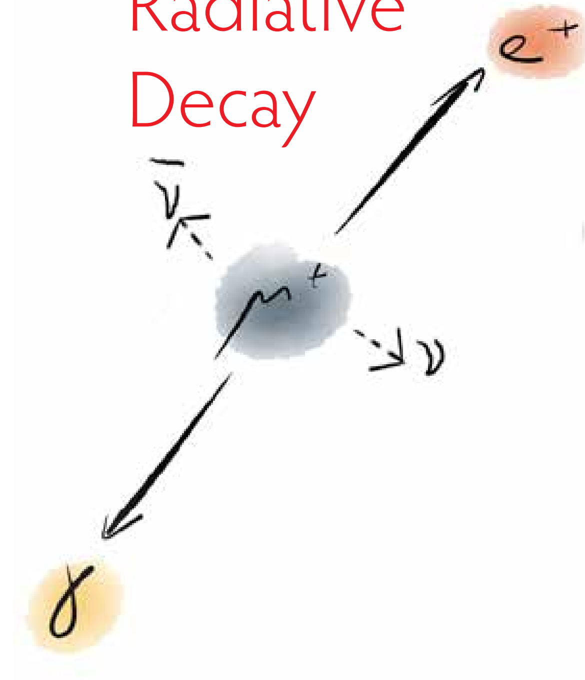
MEG Signal and background



Accidental Background



Radiative Decay



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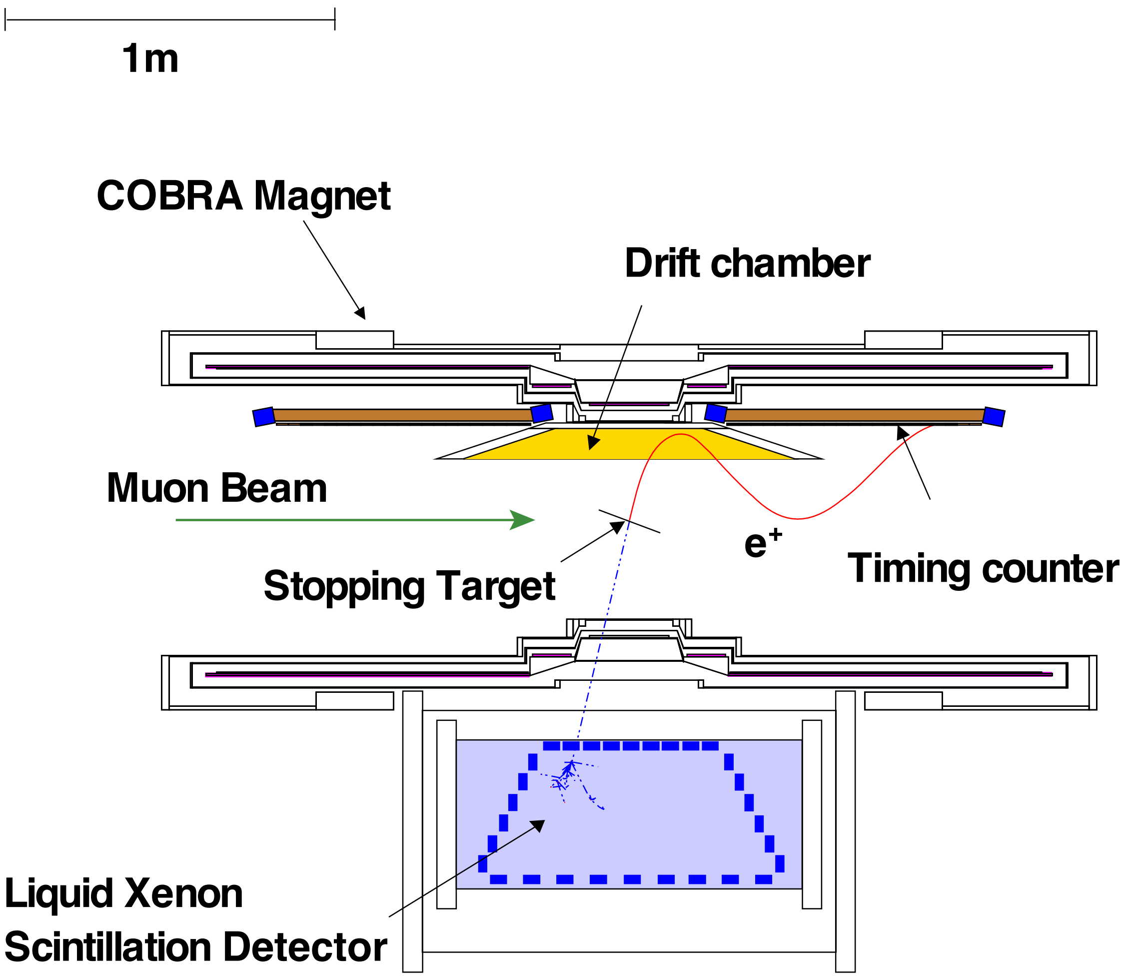
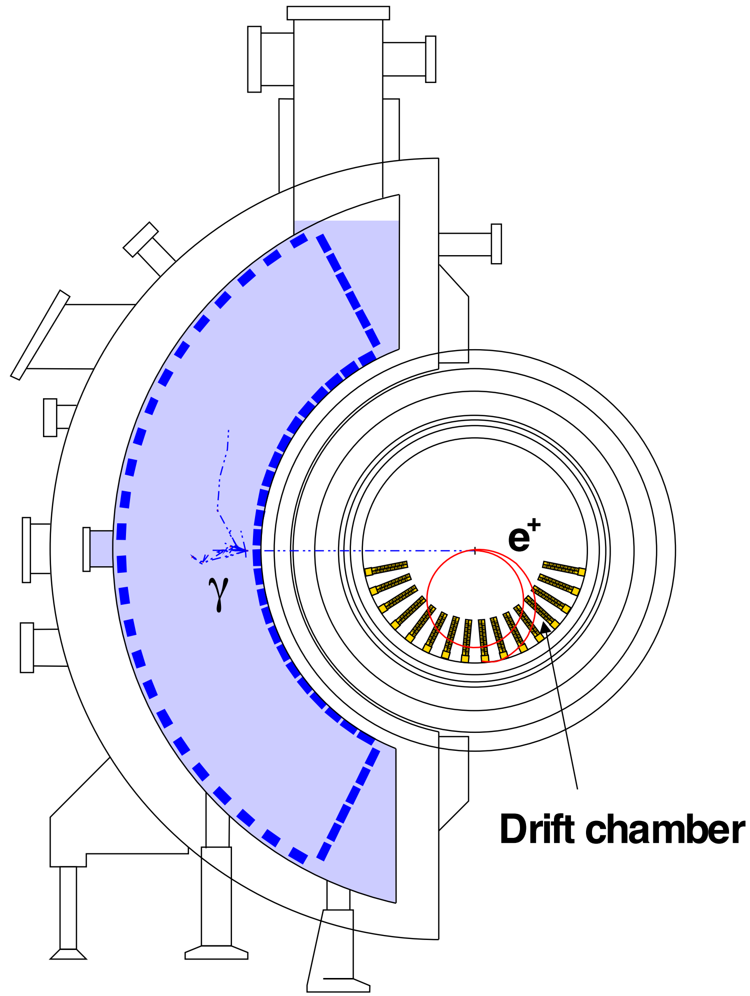
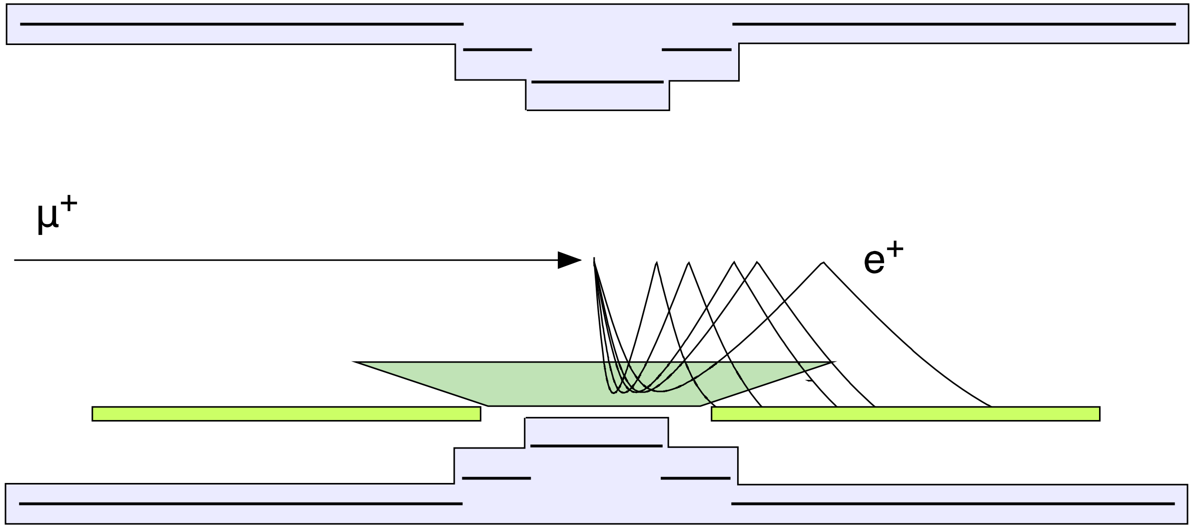
The MEG Detector



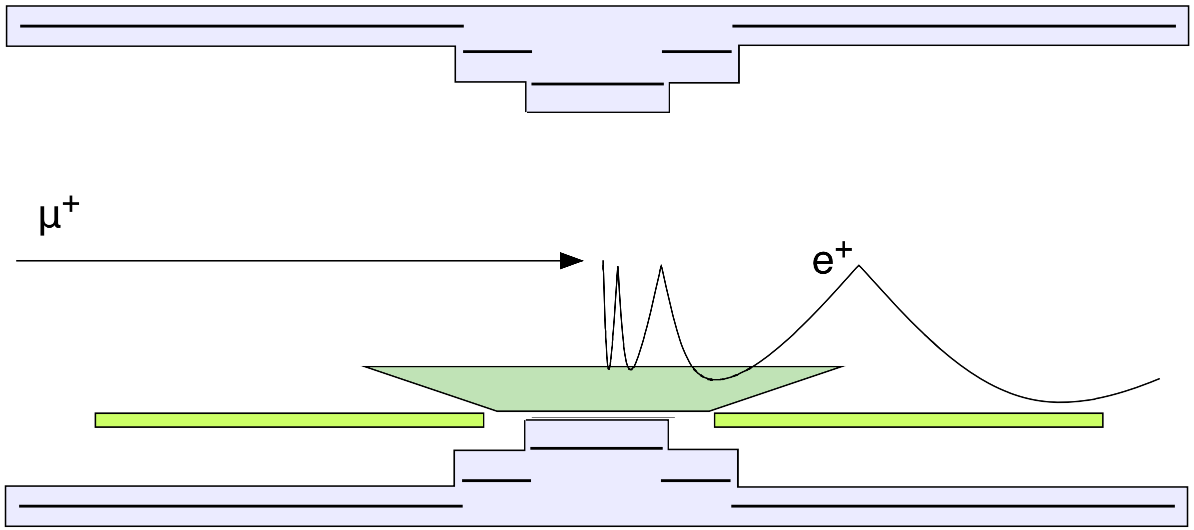


J. Adam et al. EPJ C 73, 2365 (2013)

COBRA Magnet

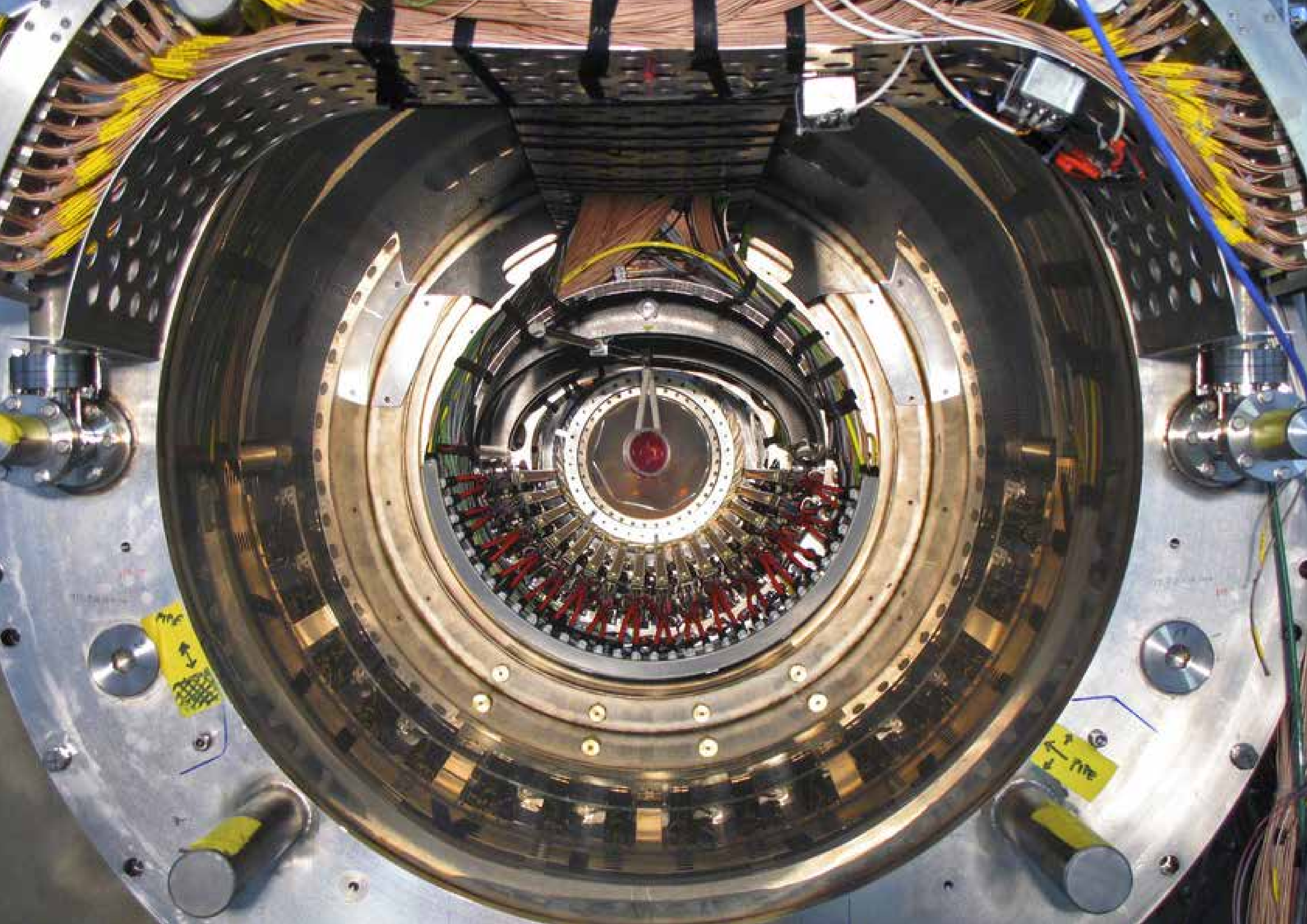


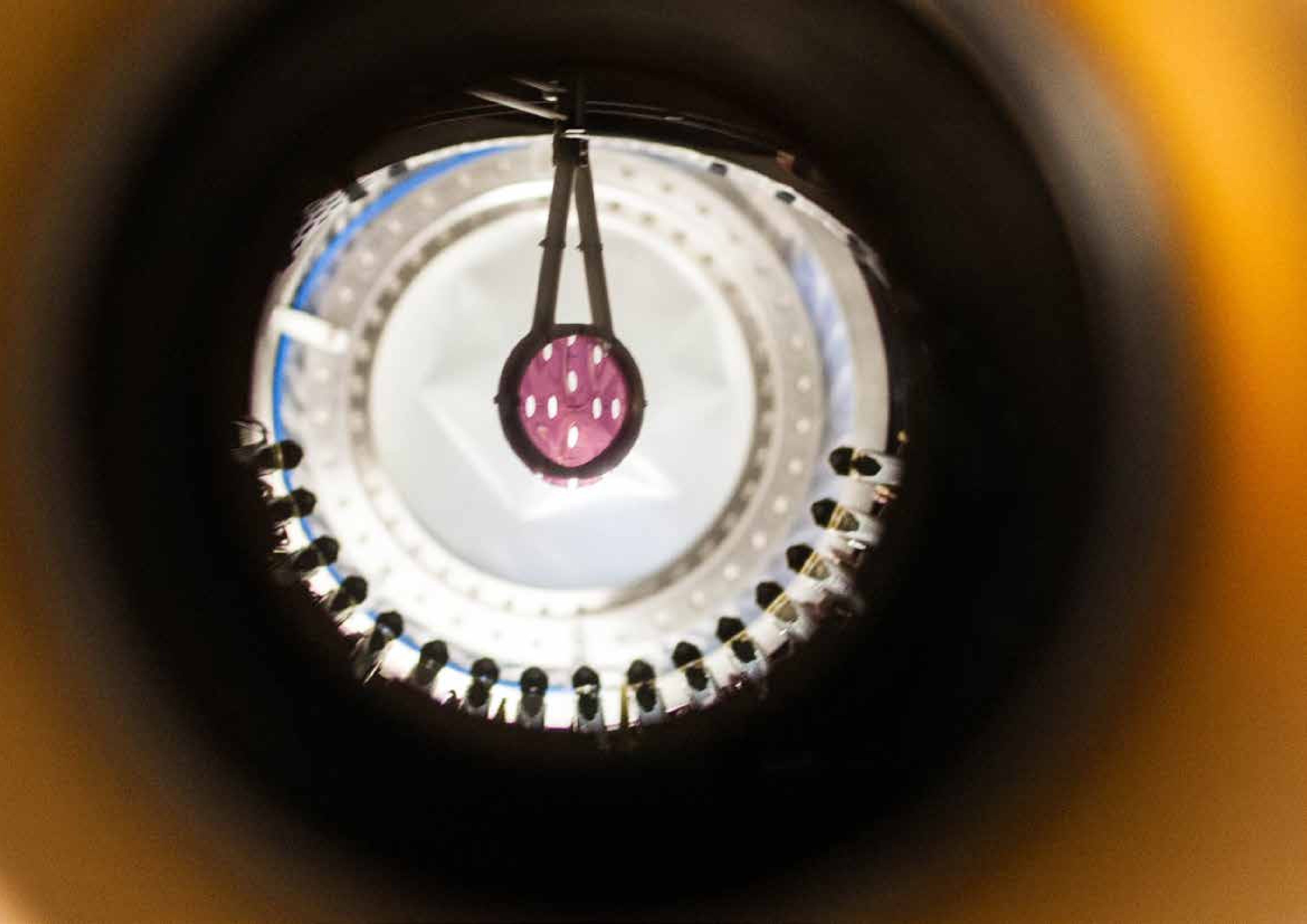
Gradient field gives constant bending radius independent of angle

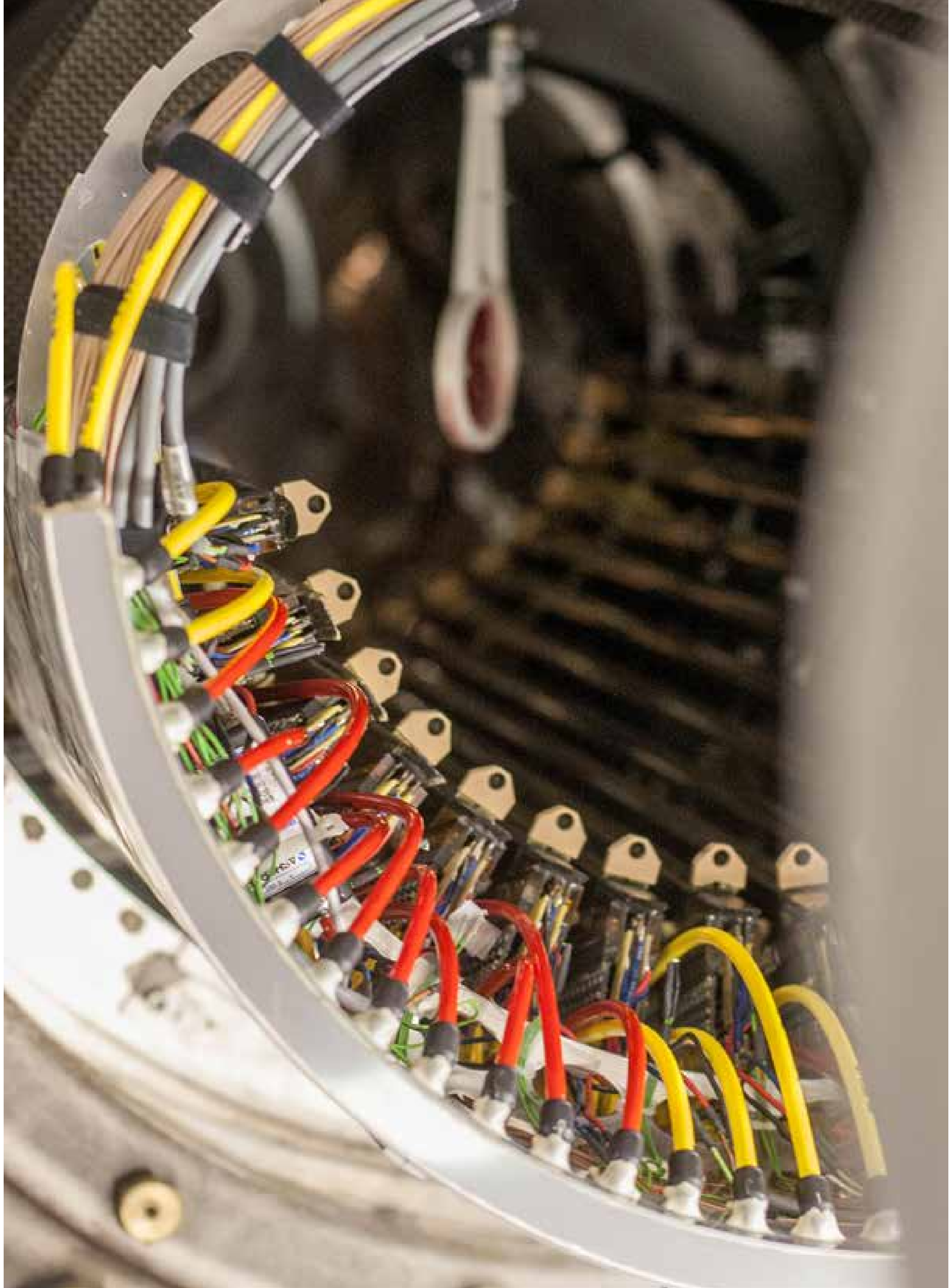


Fast sweep of curlers

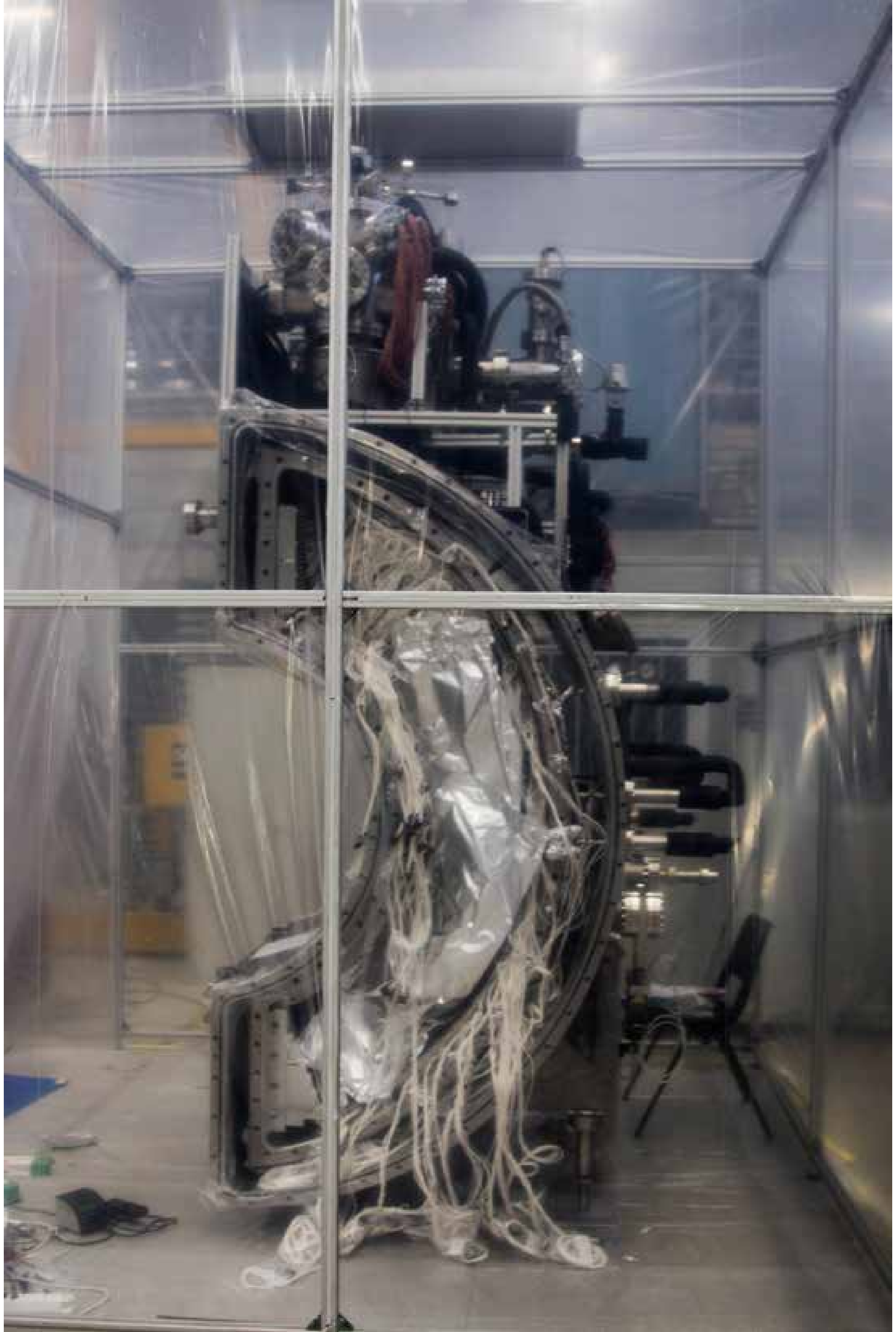
J. Adam et al. EPJ C 73, 2365 (2013)


PIPE
PIPE






1039
RA 1397
RA 1029

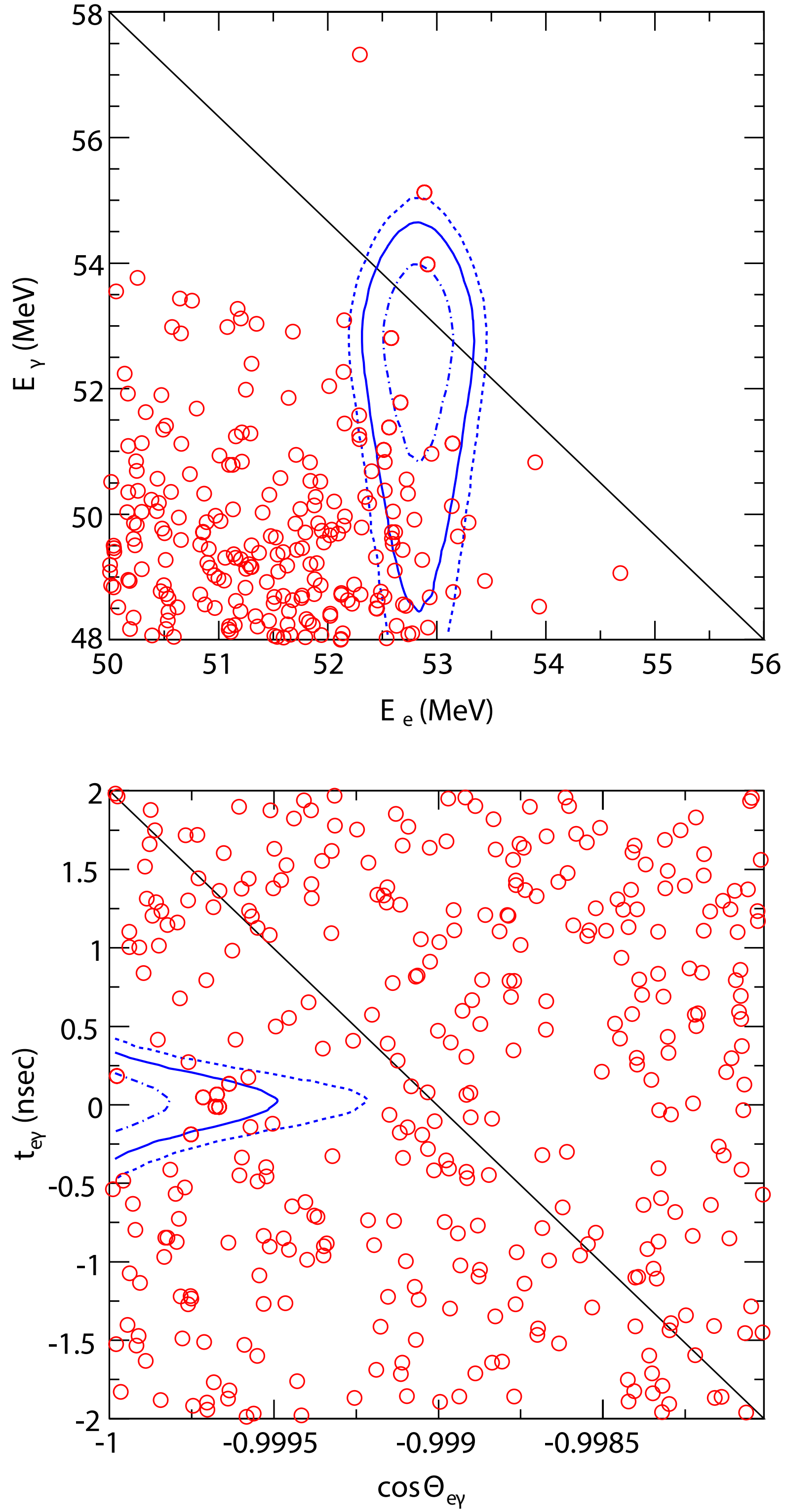


MEG Results

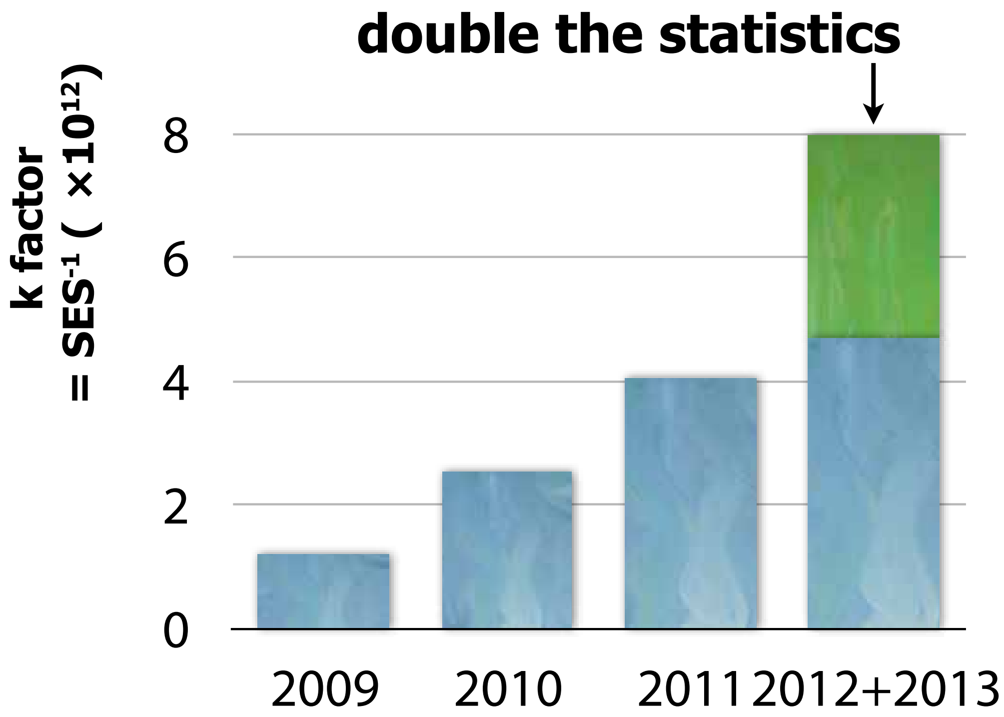
- 2009-2011 data
- Blue: Signal PDF, given by detector resolution
- No signal seen
- Upper limit at 90% CL:

$BR(\mu \to e\gamma) < 5.7 \times 10^{-13}$

J. Adam et al. PRL 110, 201801 (2013)



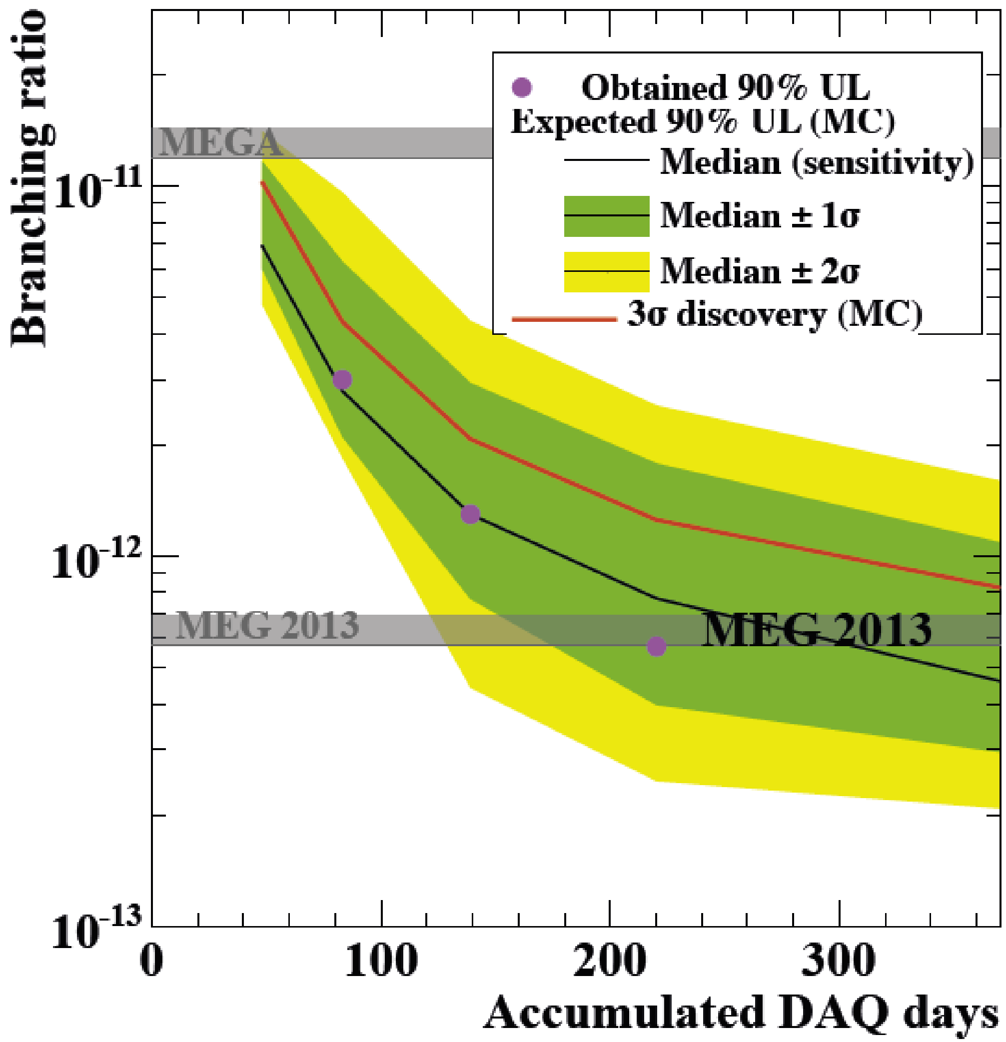
MEG - Data

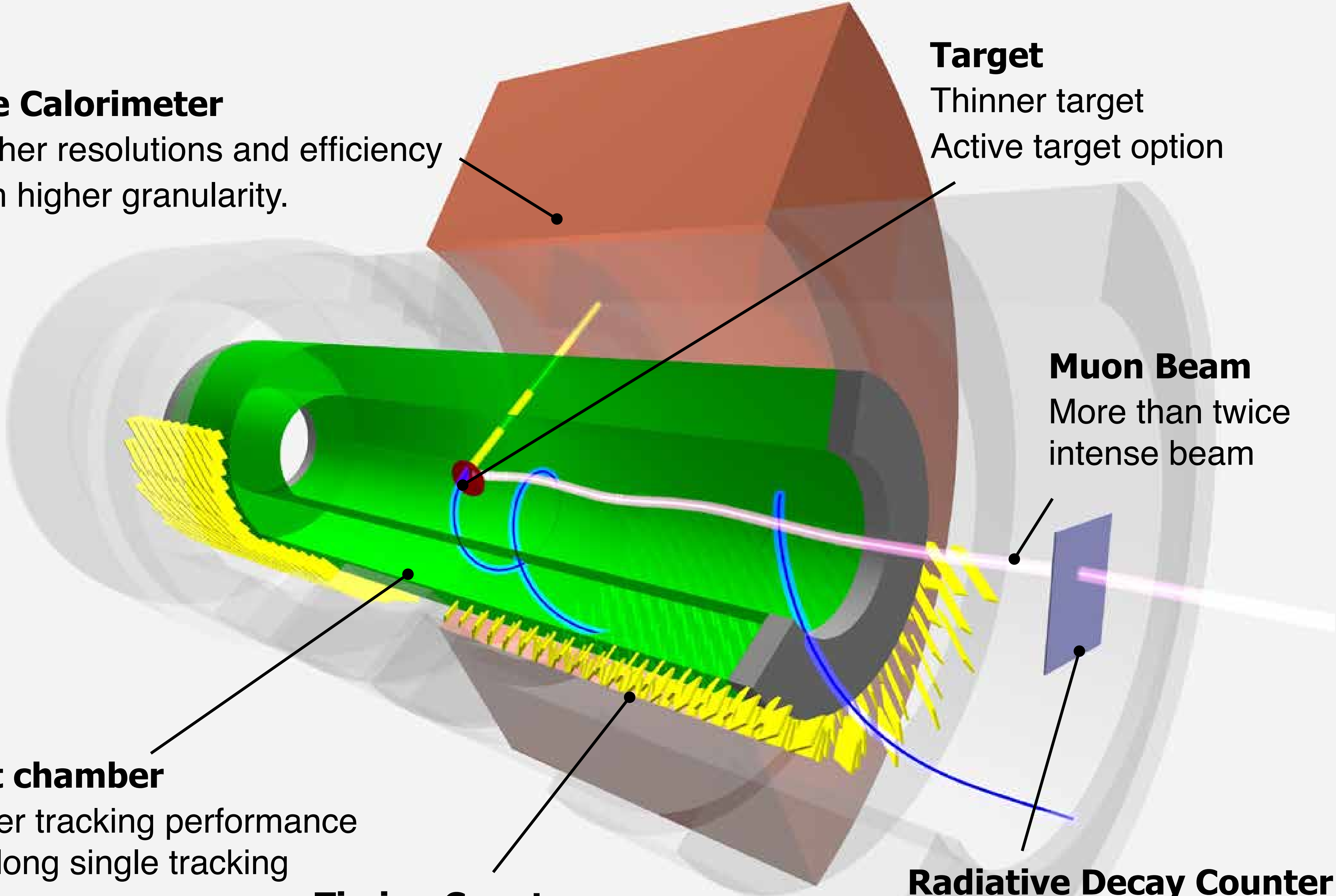


- Further improvements need detector improvements - upgrade ongoing

- 2012 & 2013 data are being analysed

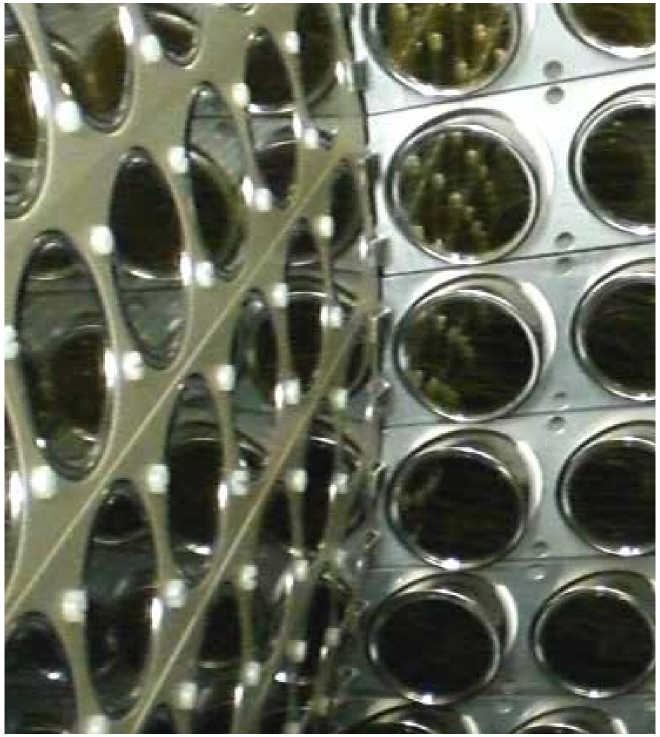
Observed limits and sensitivity

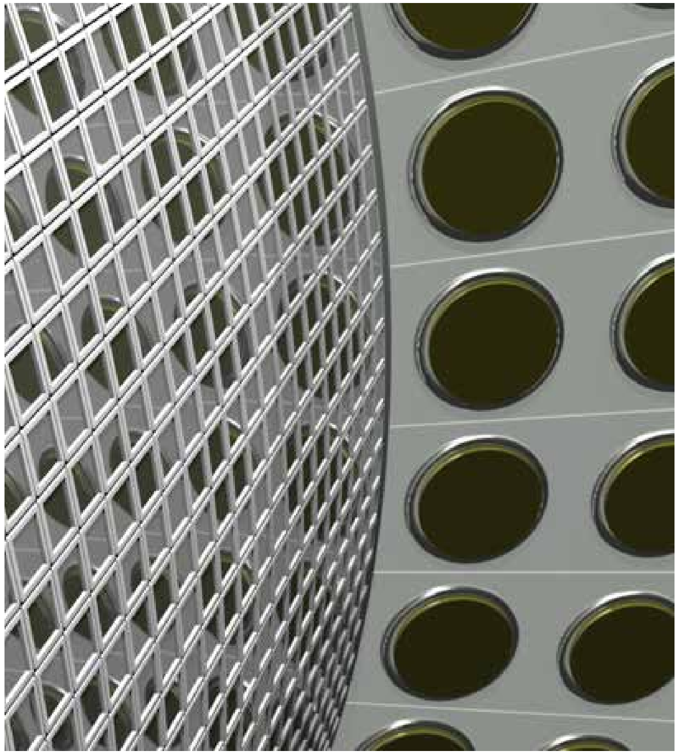



LXe Calorimeter
Higher resolutions and efficiency
with higher granularity.
Target
Thinner target
Active target option
Muon Beam
More than twice
intense beam
Drift chamber
Higher tracking performance
with long single tracking
volume
Timing Counter
Higher time resolution with
highly segmented detector
Radiative Decay Counter
Identify gammas from muon
radiative-decays
(optional)

MEG Upgrade - Calorimeter

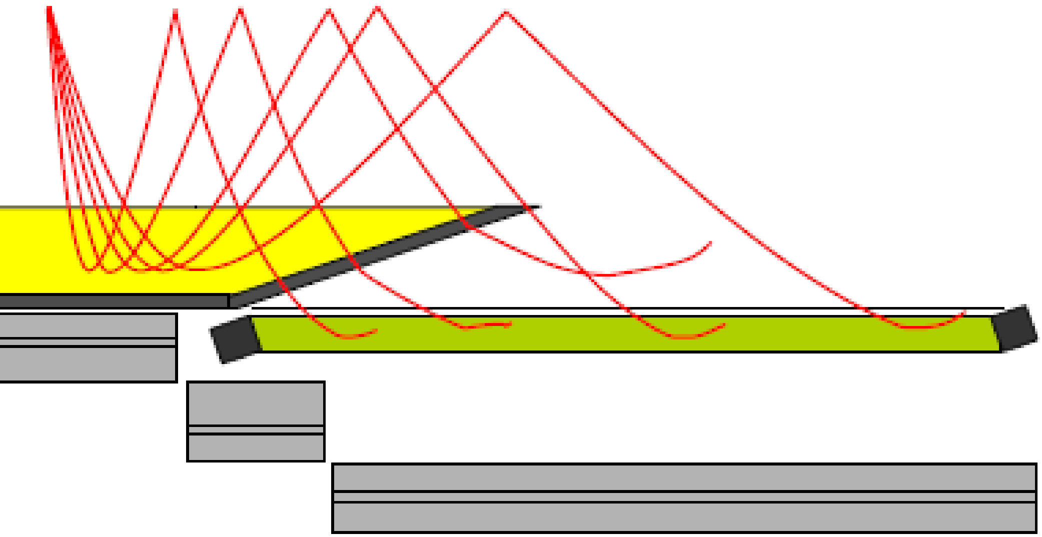
- ~4000 VUV sensitive SiliconPMs on entry face (new development with Hamamatsu)
- Better position and energy resolution
- Better efficiency

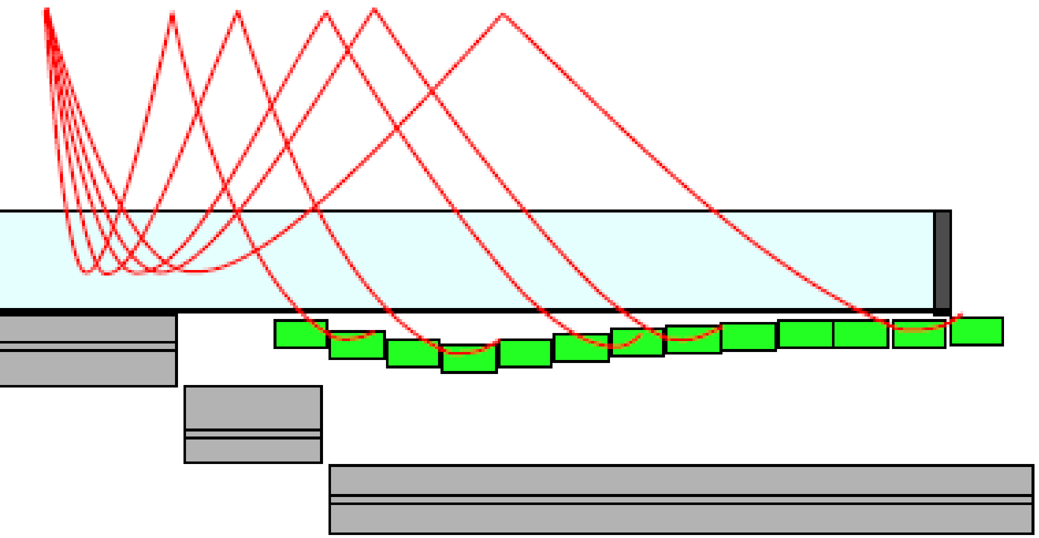


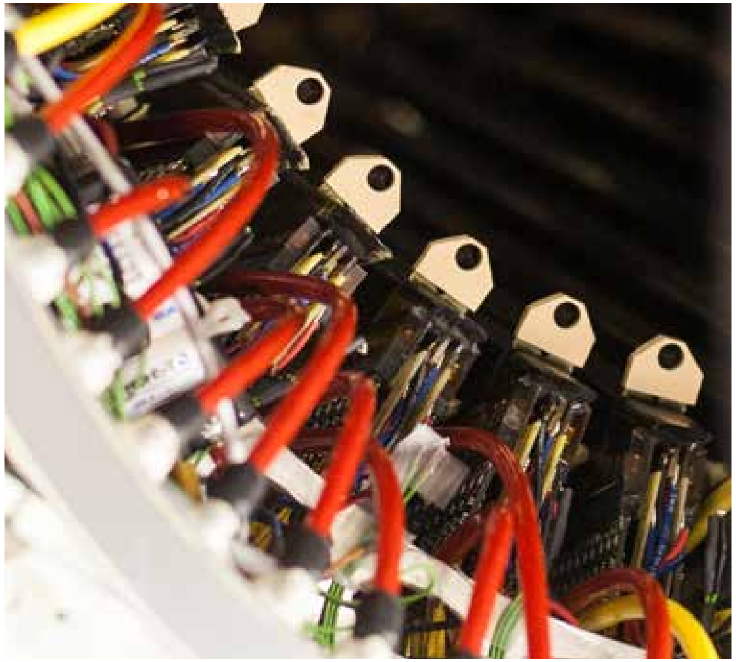


Ryu Sawada, SUSY 2014

MEG Upgrade - Drift Chamber



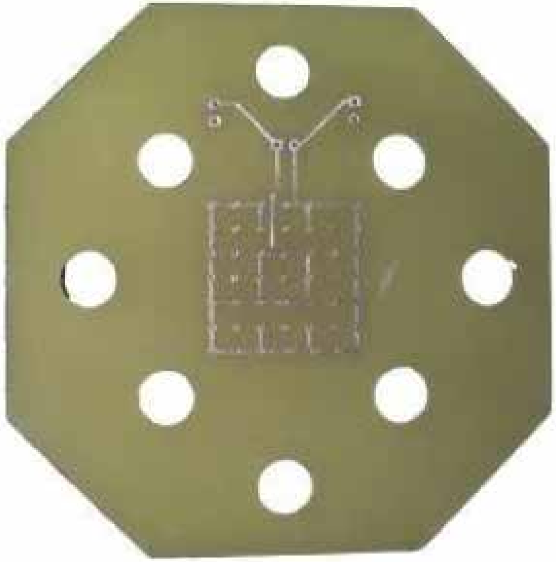


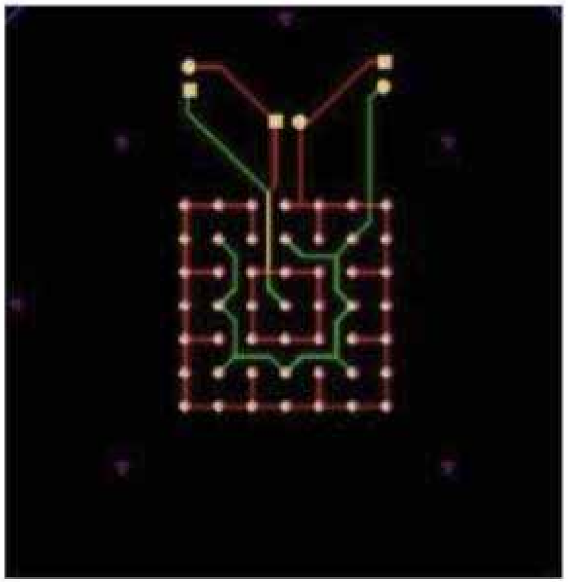


- New single volume drift chamber
- Lower Z gas mixture
- More space points per track
- Better rate capability
- Less material in front of timing counters

Ryu Sawada, SUSY 2014

MEG Upgrade - Drift Chamber Ageing





MEG Upgrade - Drift Chamber Ageing

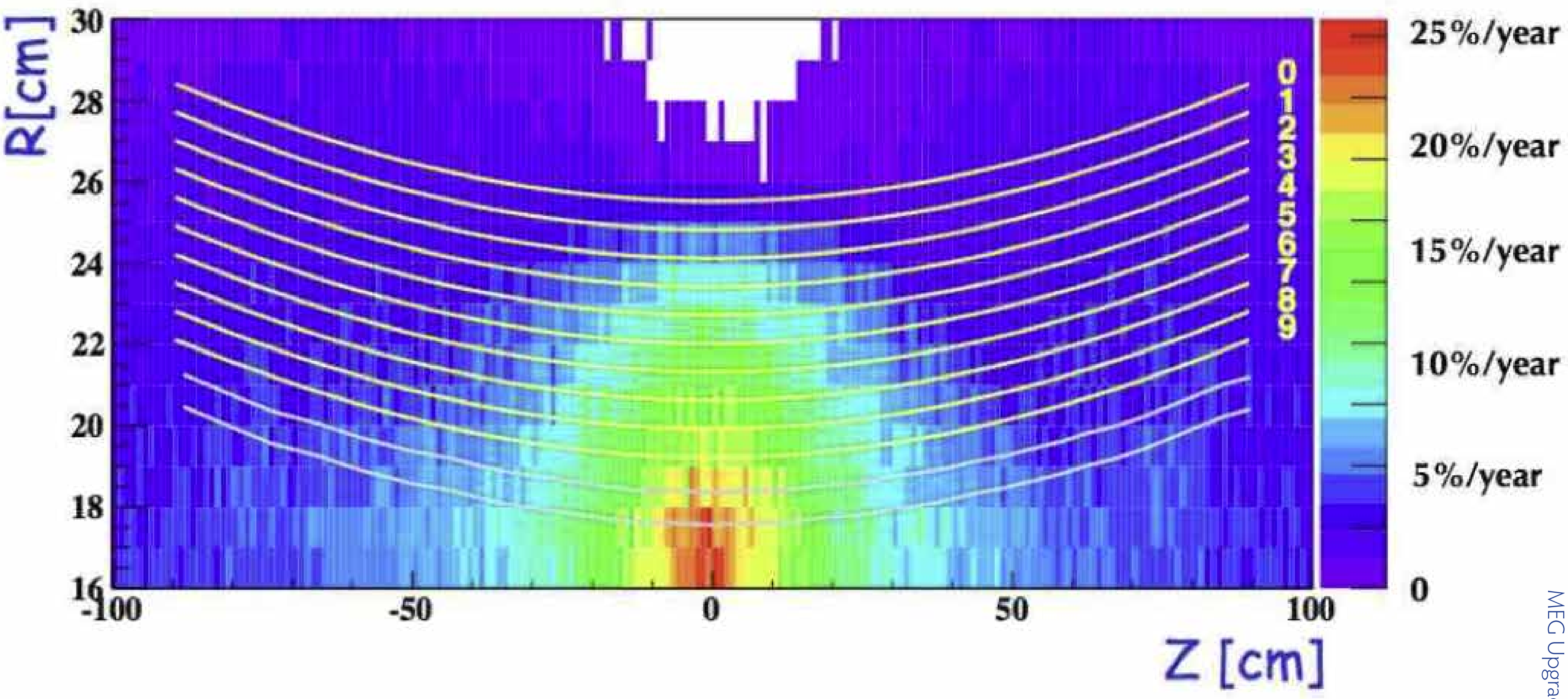
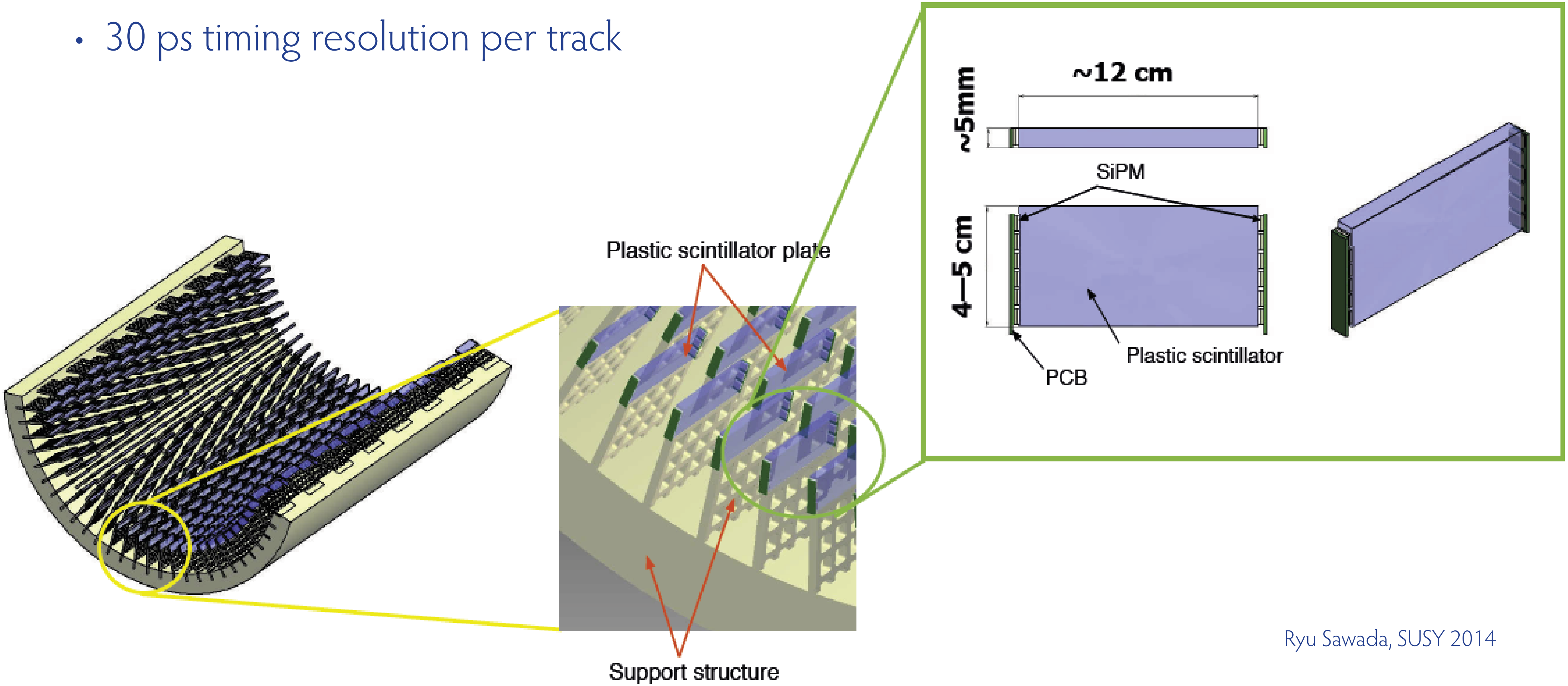


FIG. 24: Gain drop in 1-year od DAQ time at 7×10^7 μ^+/sec.

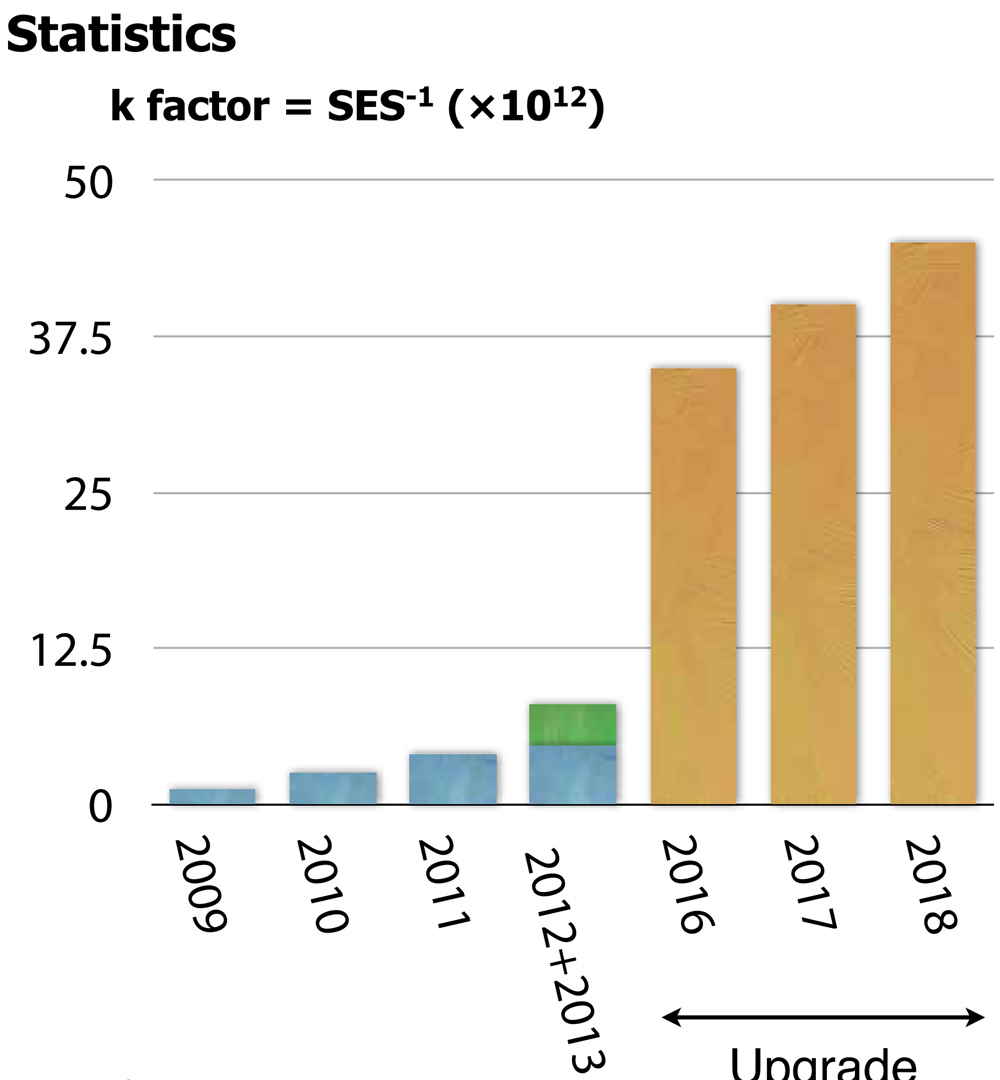
MEG Upgrade - Timing Counter

- Many small scintillators
- Read-out by SiliconPMs
- On average eight counters hit by track
- 30 ps timing resolution per track

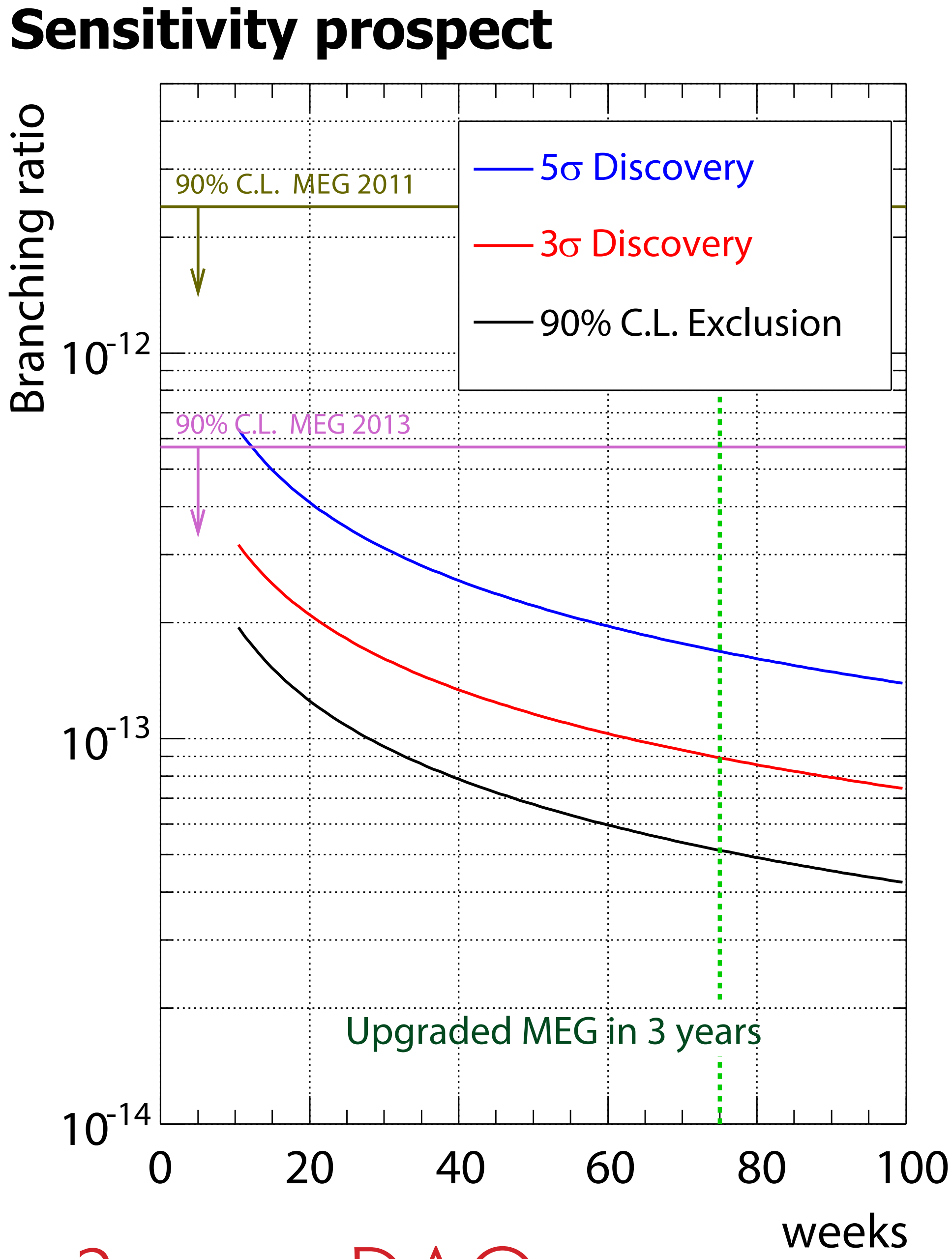


Ryu Sawada, SUSY 2014

MEG II sensitivity projection



Ryu Sawada, SUSY 2014



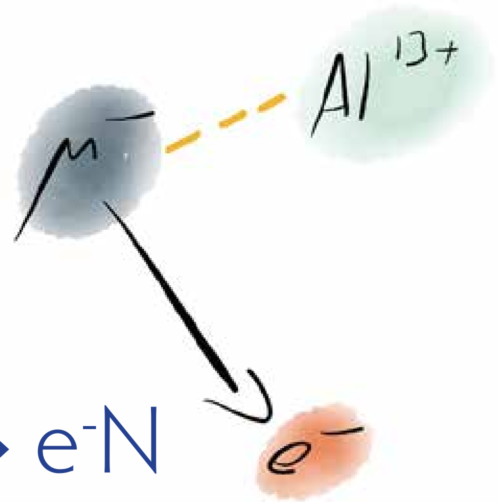
5×10^{-14} sensitivity in 3 years DAQ

High rates without seeing high rates

Searching for μ → e conversion with

Mu2e, DeeMee, COMET, PRISM

Conversion Signal and Background



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

- Single 105 MeV/c electron observed

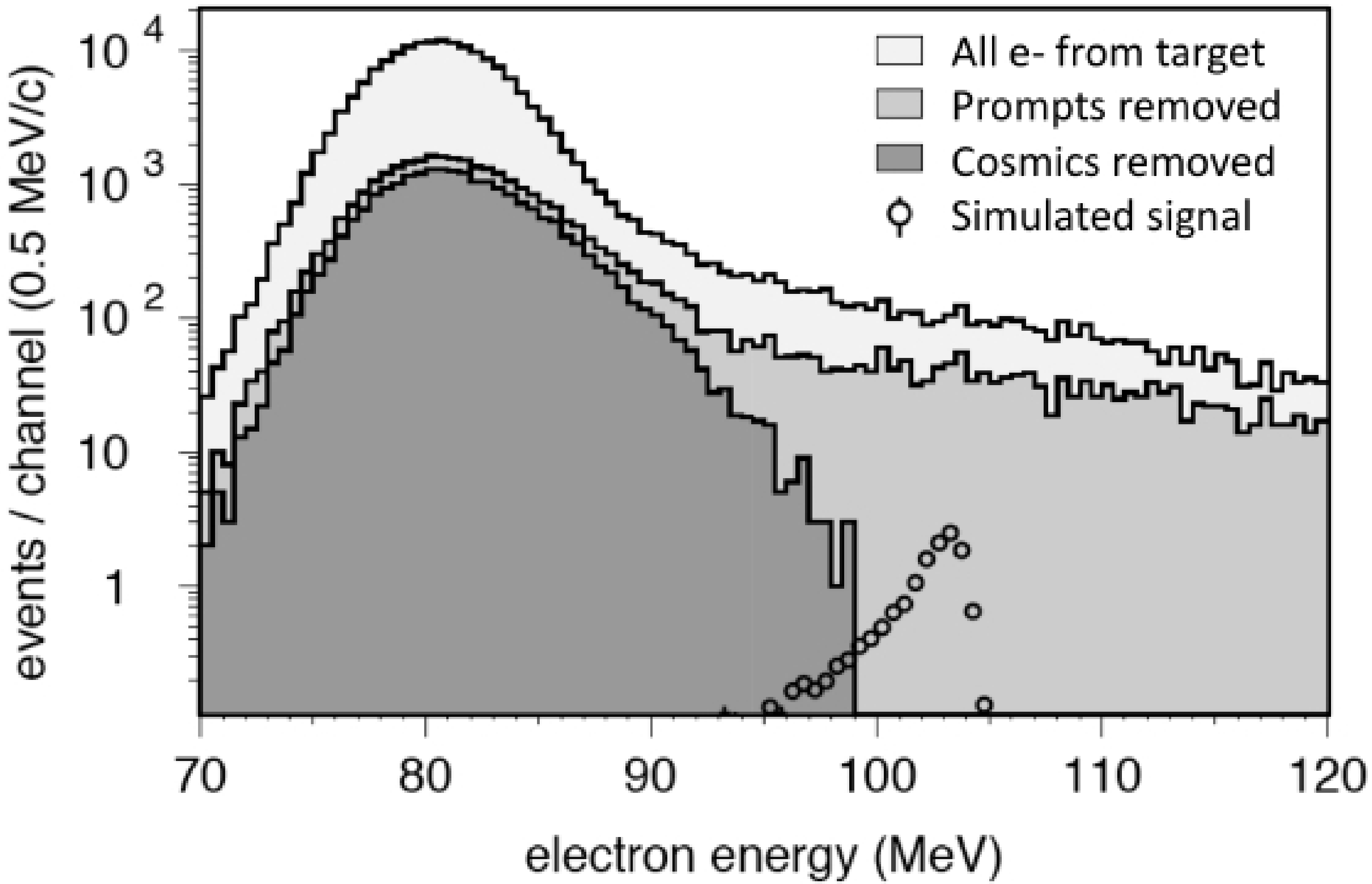
Backgrounds:

Anything that can produce a 105 MeV/c electron

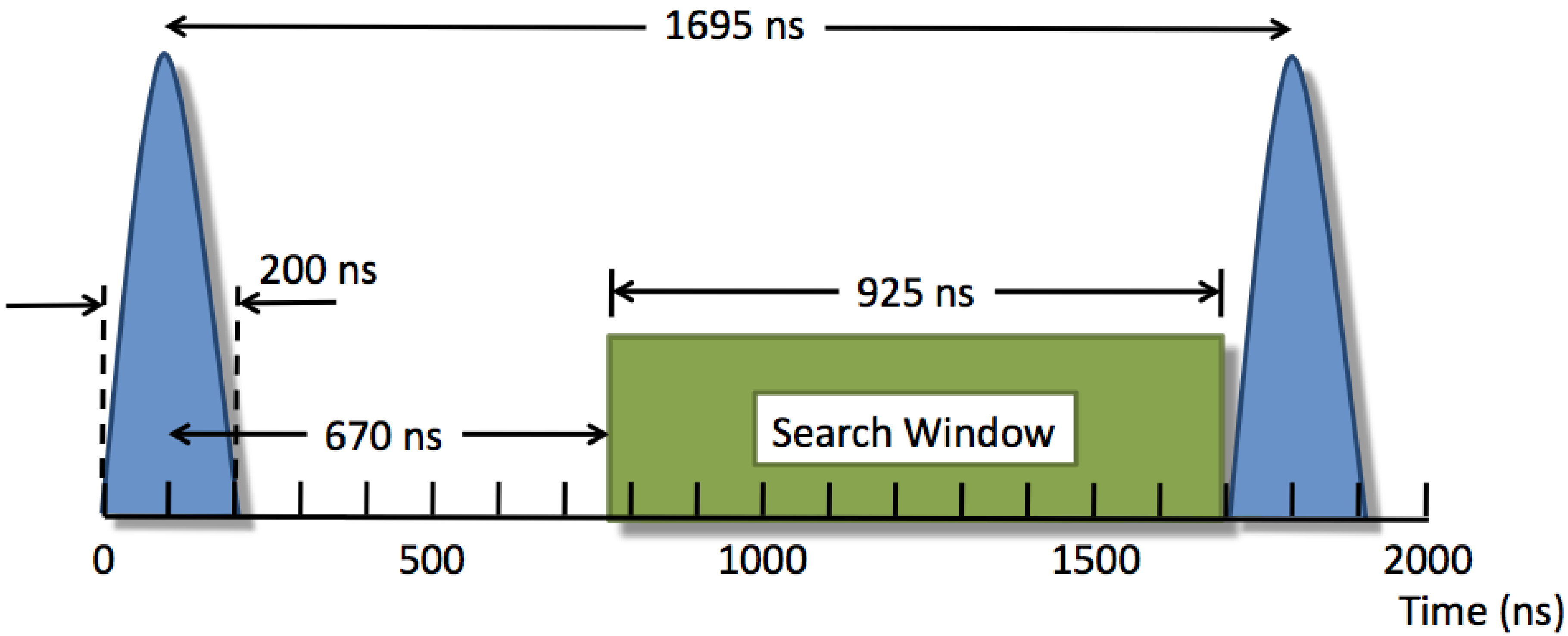
- Primary proton beam
- Decay in Orbit (DIO)
- Nuclear capture (AlCap effort at PSI)
- Cosmics

Limitations of last experiment: SINDRUM II

- Beam induced background
- Muon rates

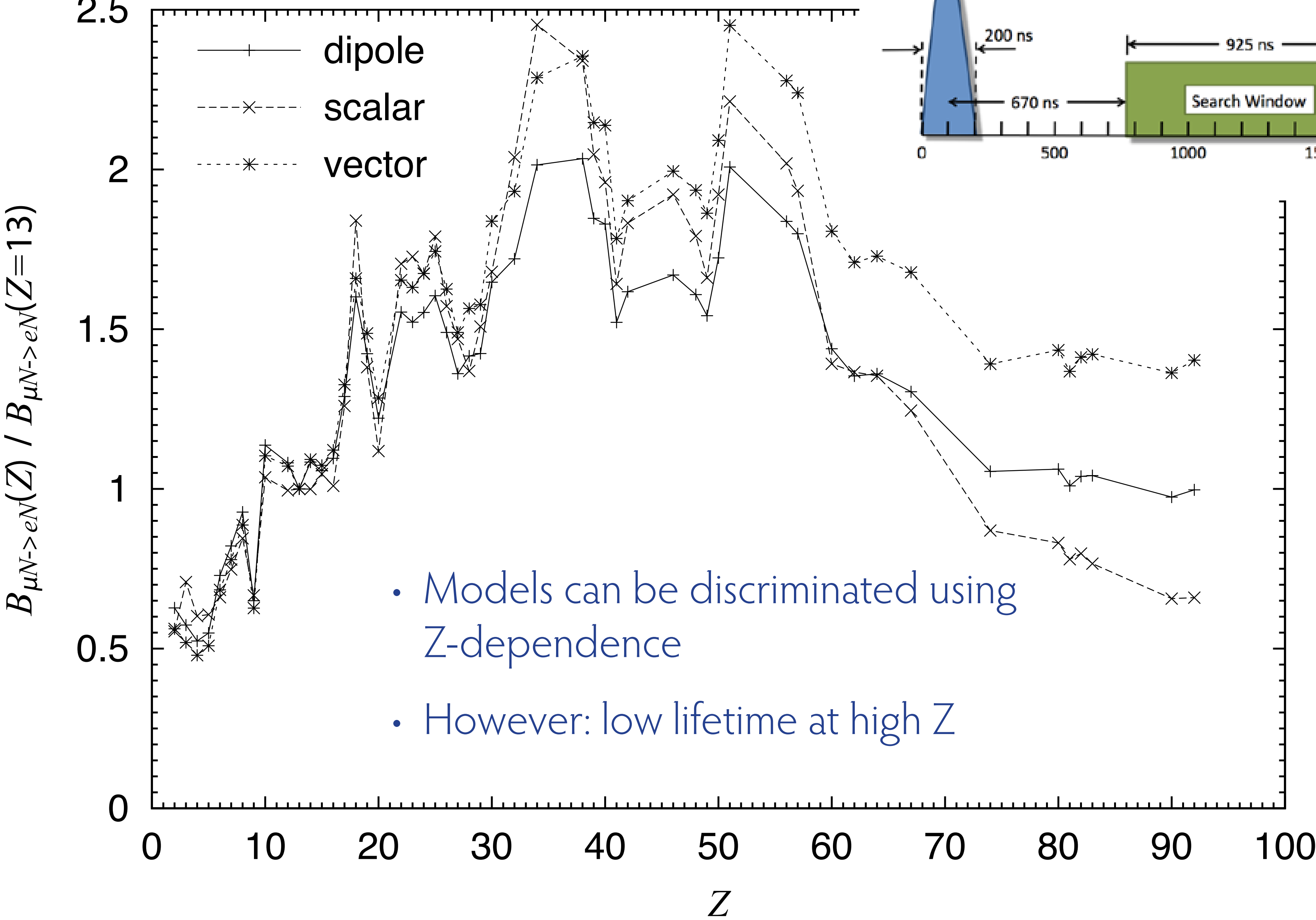


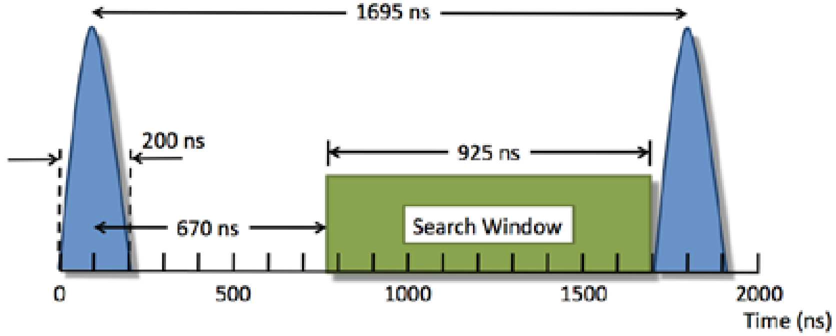
Beam induced background



- Proton beam produces pions, photons, (antiprotons) etc.
- Wait until things become better...

Z-dependence





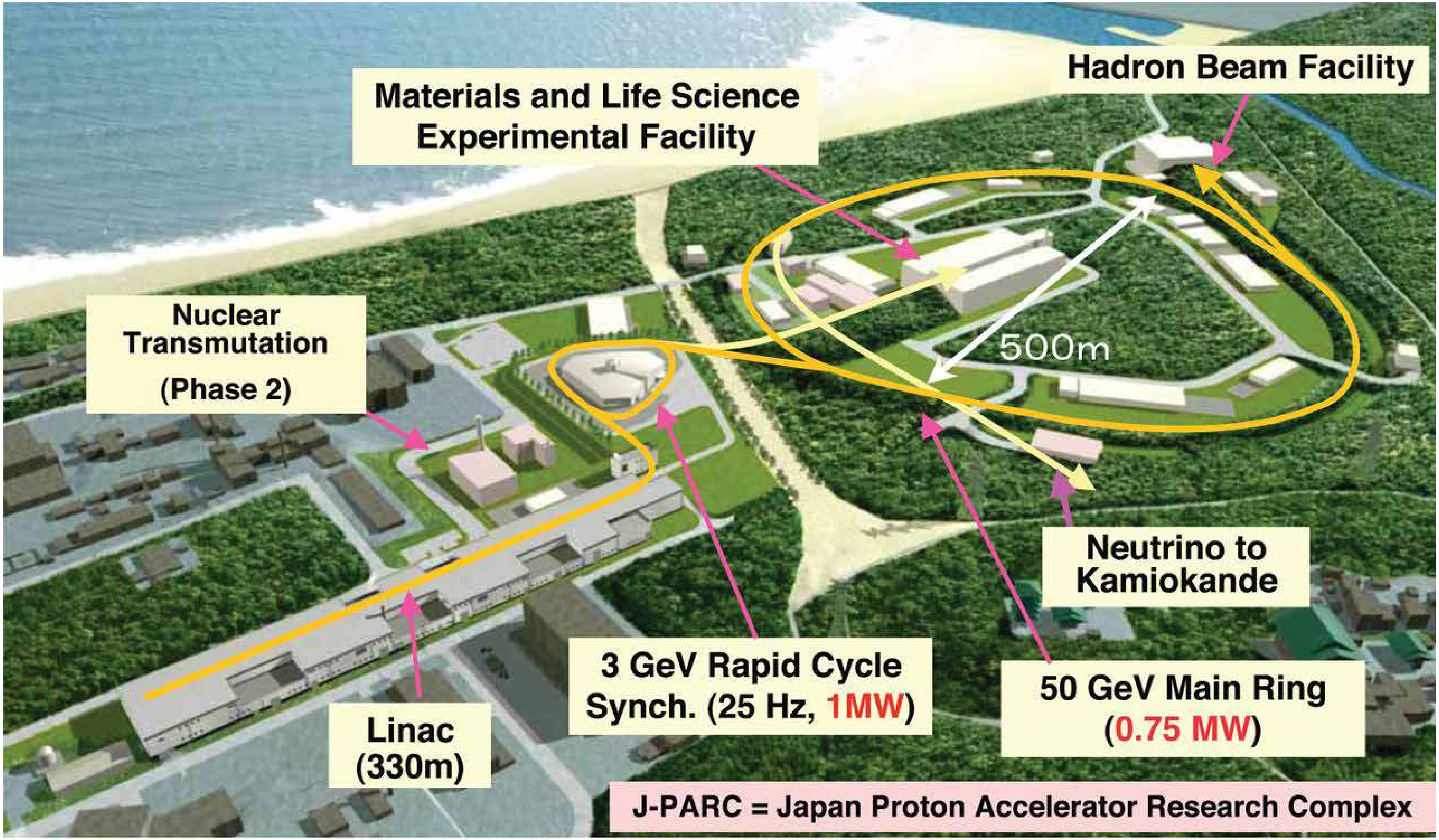
- Models can be discriminated using Z-dependence
- However: low lifetime at high Z

Muons from Fermilab...

- Re-use part of the Tevatron infrastructure
- Proton pulses every 1700 ns
- $> 10^{10}$ μ/s

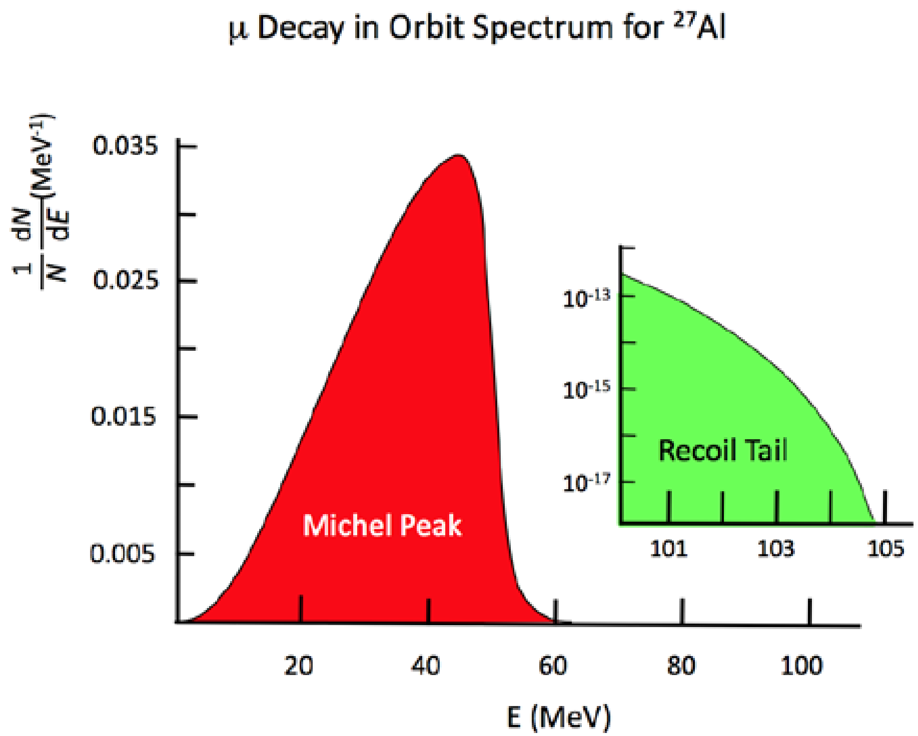
- Project X would give another 2 orders of magnitude at an energy below the antiproton threshold

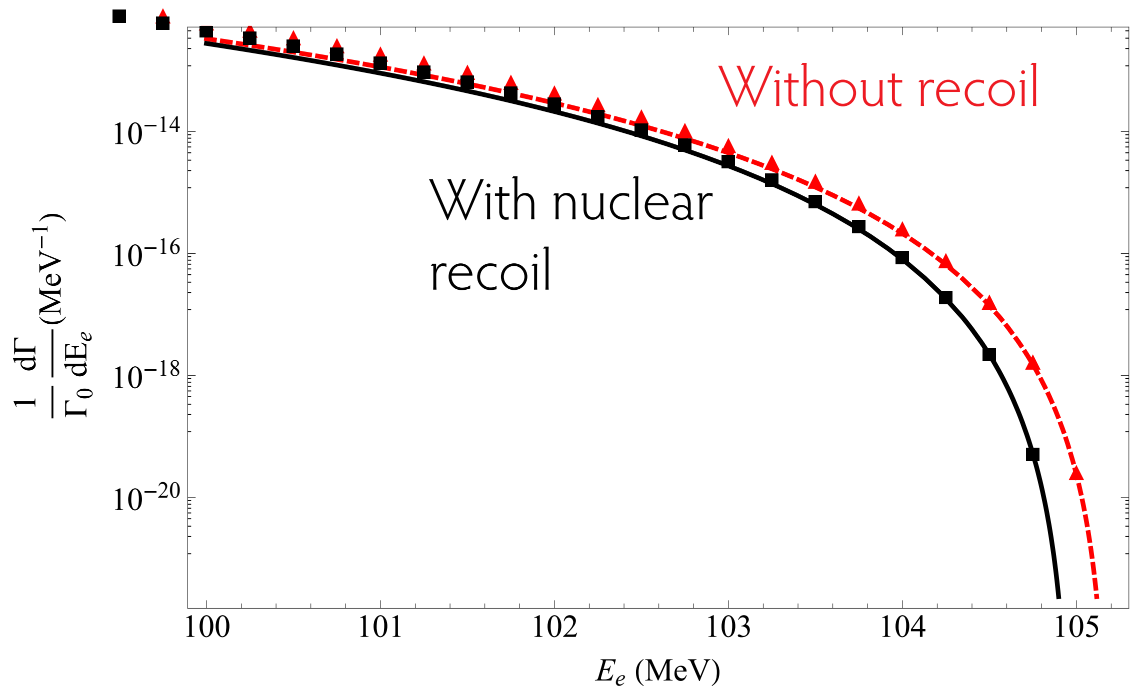
… and J-PARC



- 10^{11} μ/s from 8 GeV/c protons

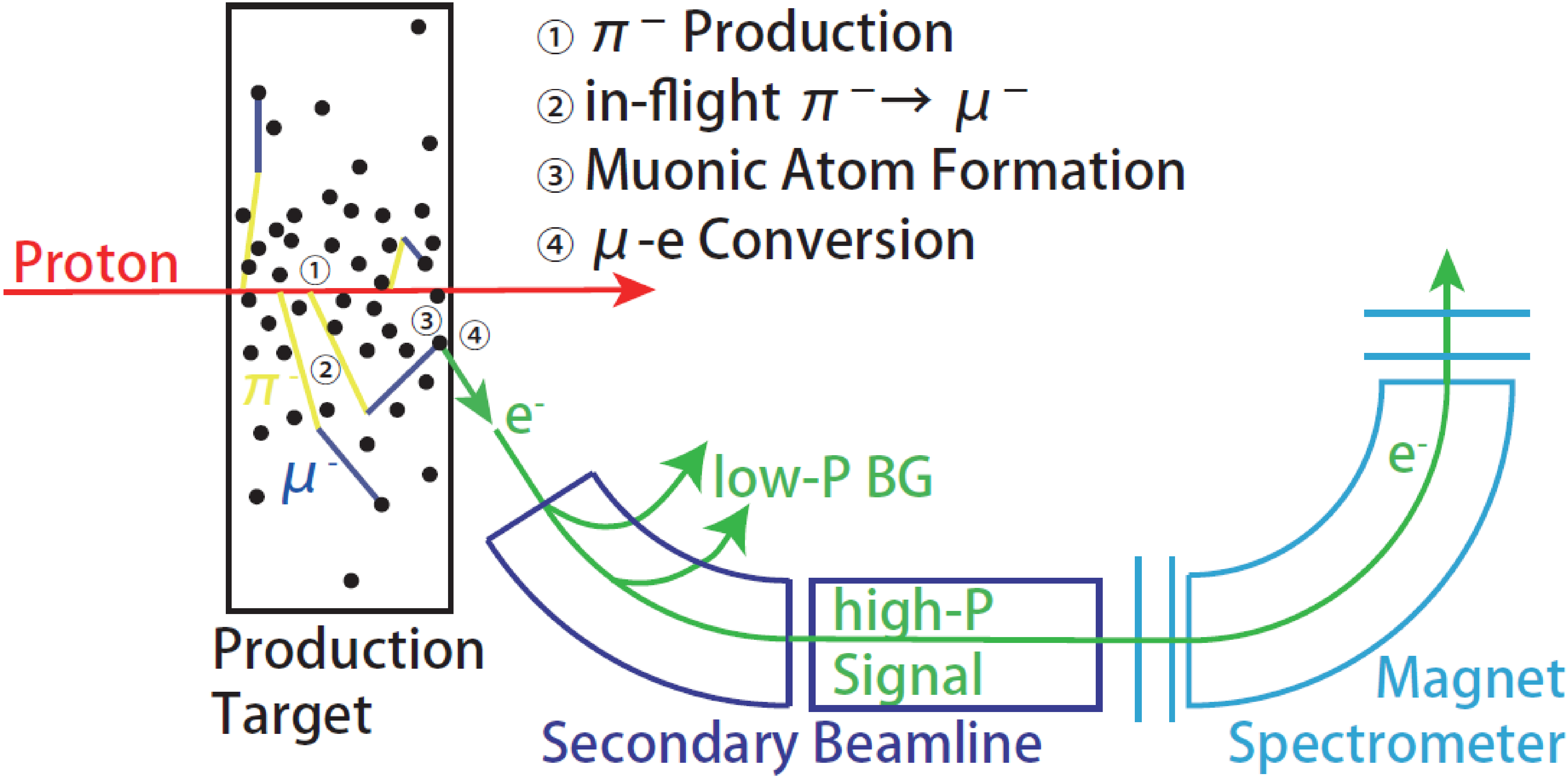
Deacy-in-orbit background





- Nuclear recoil allows for electron energies above $m_\mu/2$
- Calculation by Czarnecki, Garcia i Tormo and Marciano, Phys. Rev. D84 (2011)
- Requires excellent momentum resolution

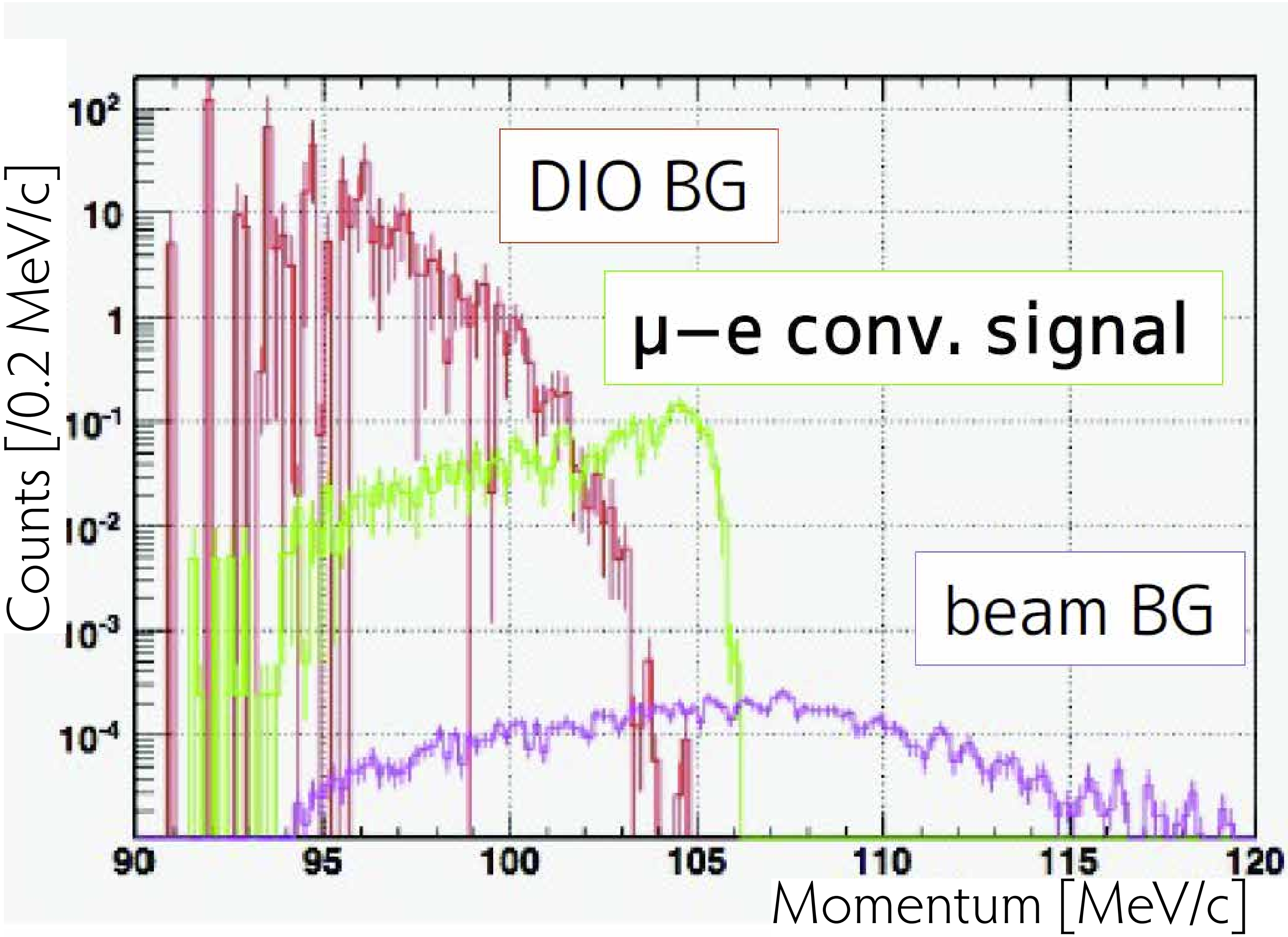
Experimental concept - DeeMee



Yohei Nakatsugawa, NuFACT2014

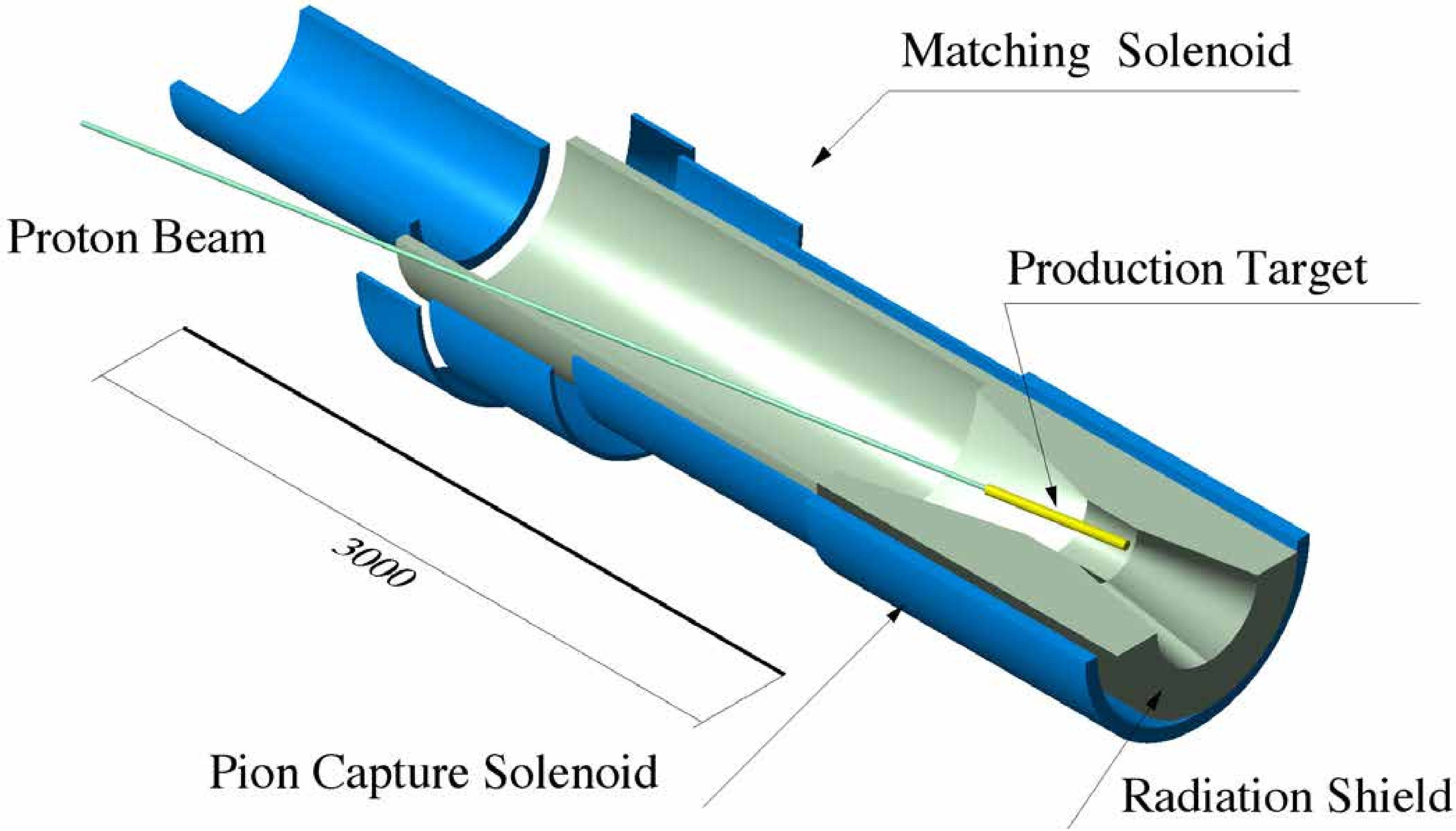
Sensitivity - DeeMee

- Expect 2.1×10^{-14} single event sensitivity for one year running



Yohei Nakatsugawa, NuFACT2014

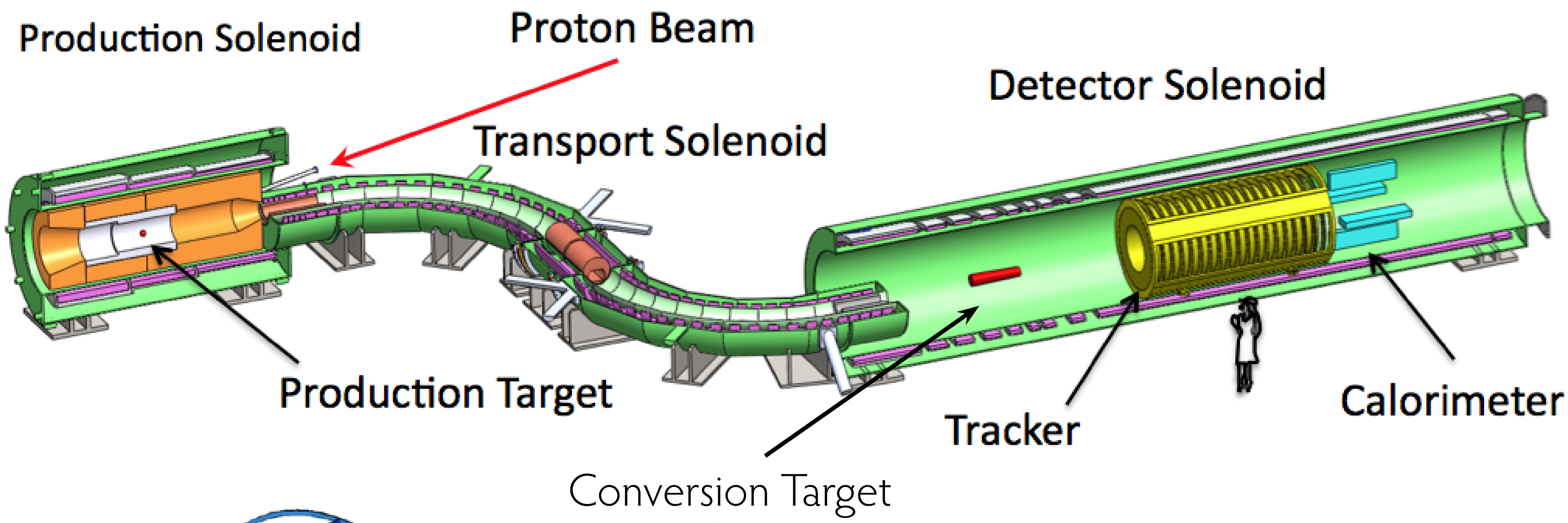
Production target inside a solenoid

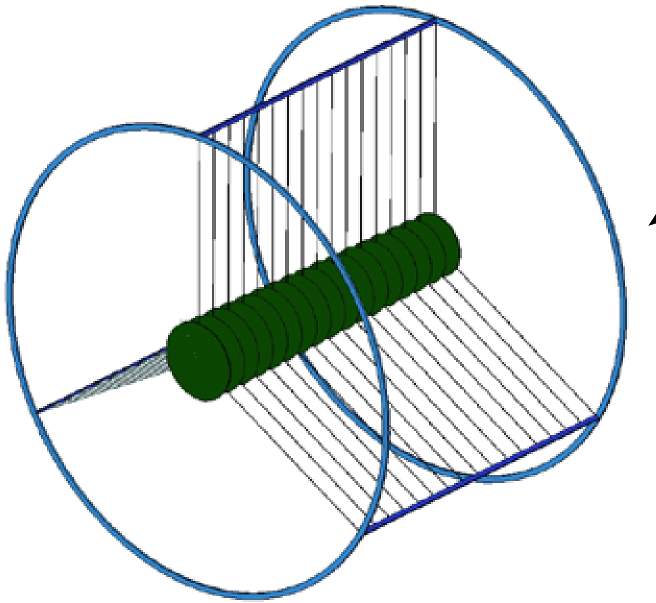


Capture most pions produced in target

Shielding of superconducting magnet very challenging

Experimental layout - Mu2e

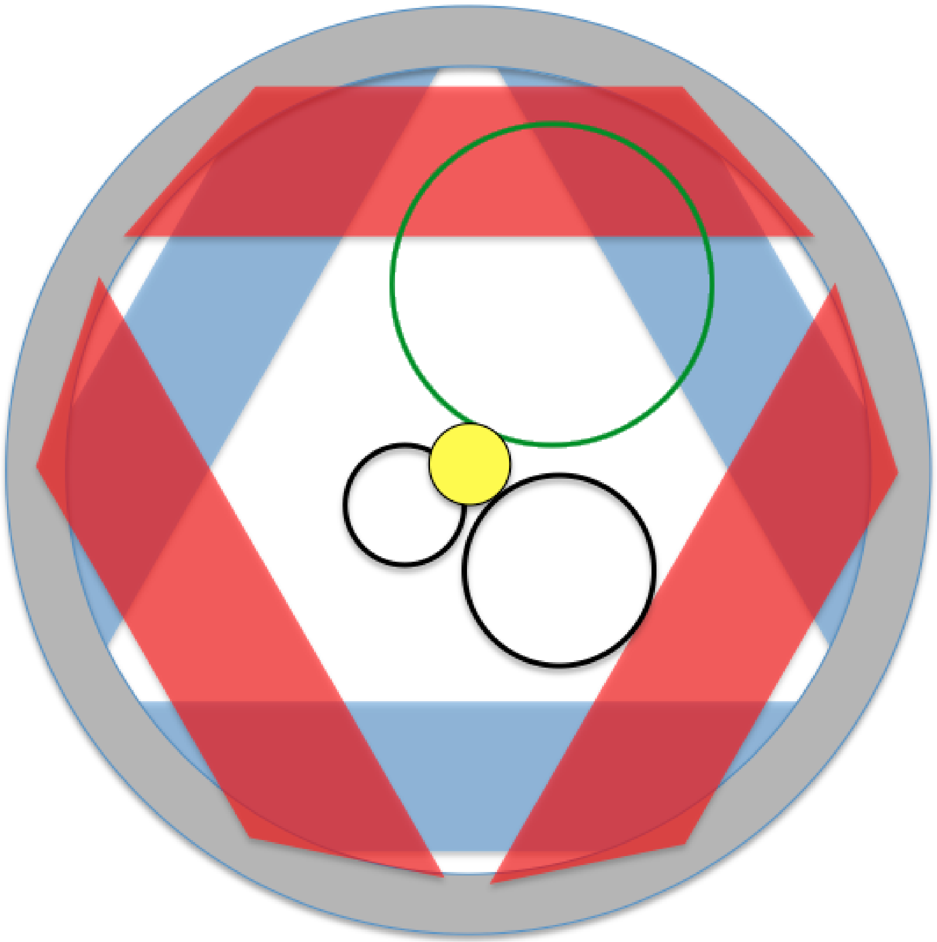


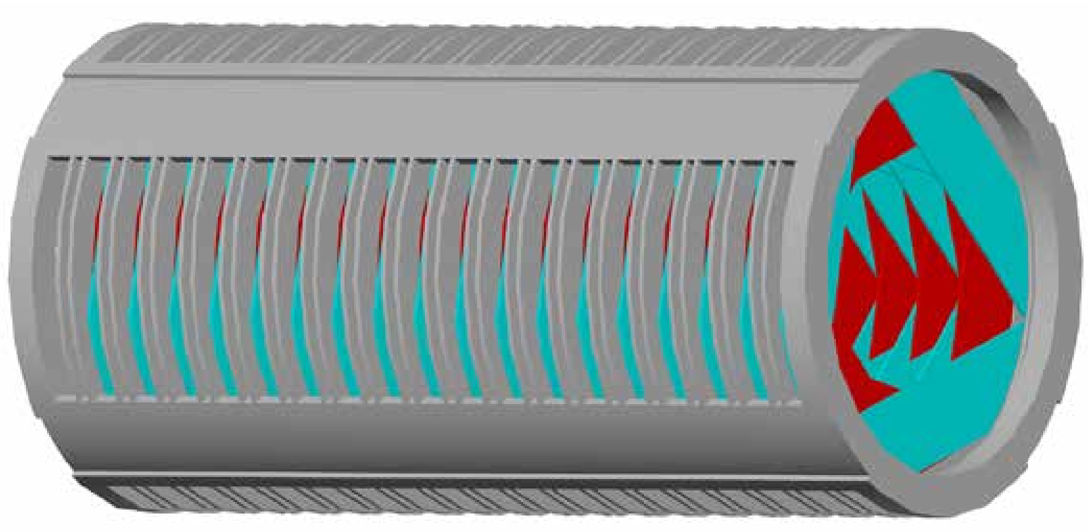


Mu2e CDR

- Separate muon production and conversion target
- Not shown: cosmic ray veto and absorbers

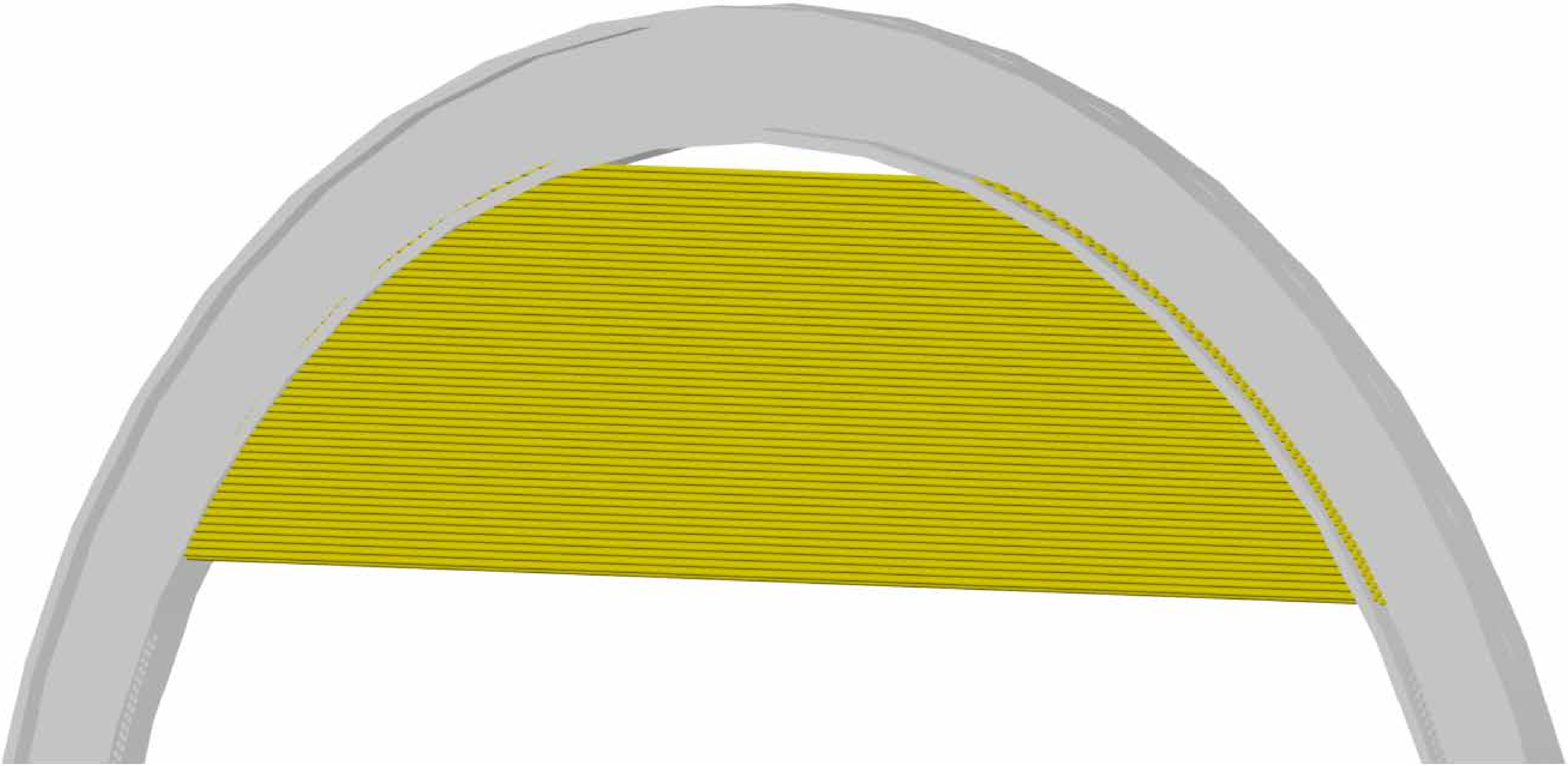
Mu2e Tracker

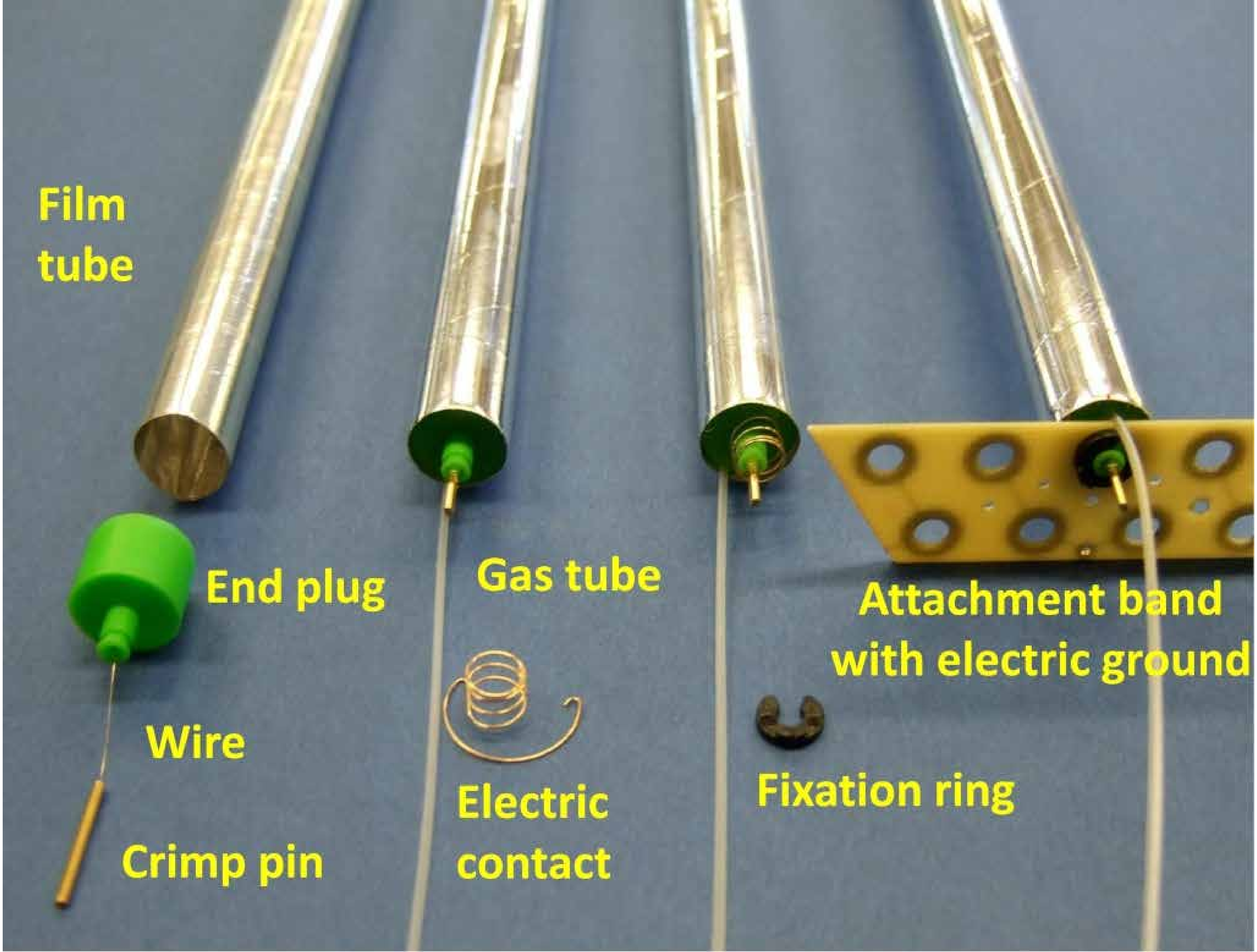




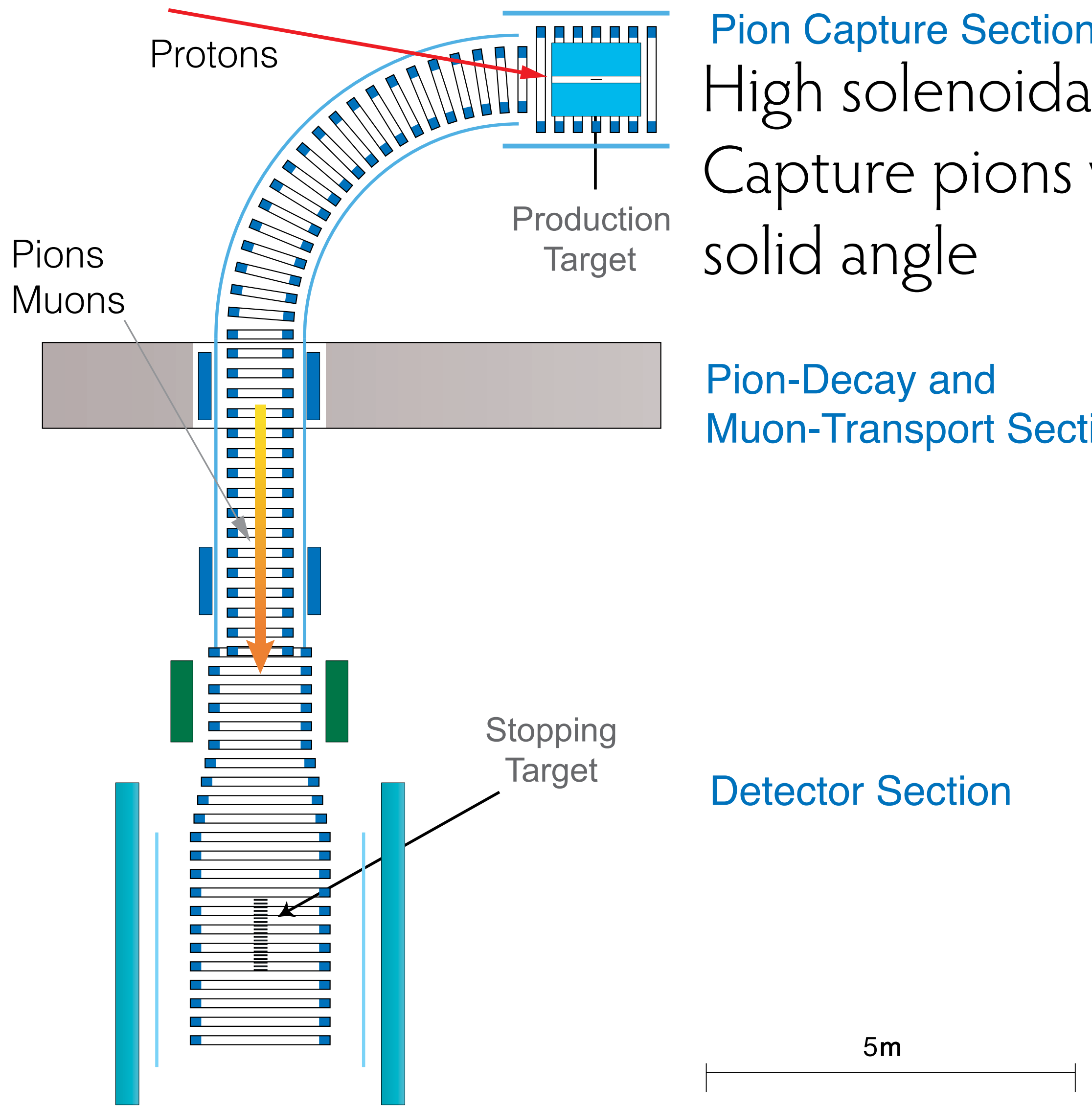
- Straw tubes in vacuum
- Outside of radius of Michel electrons

Mu2e CDR




Film
tube
End plug
Gas tube
Attachment band
with electric ground
Wire
Electric
contact
Fixation ring
Crimp pin

Experimental layout - COMET Phase I



Pion Capture Section

High solenoidal field

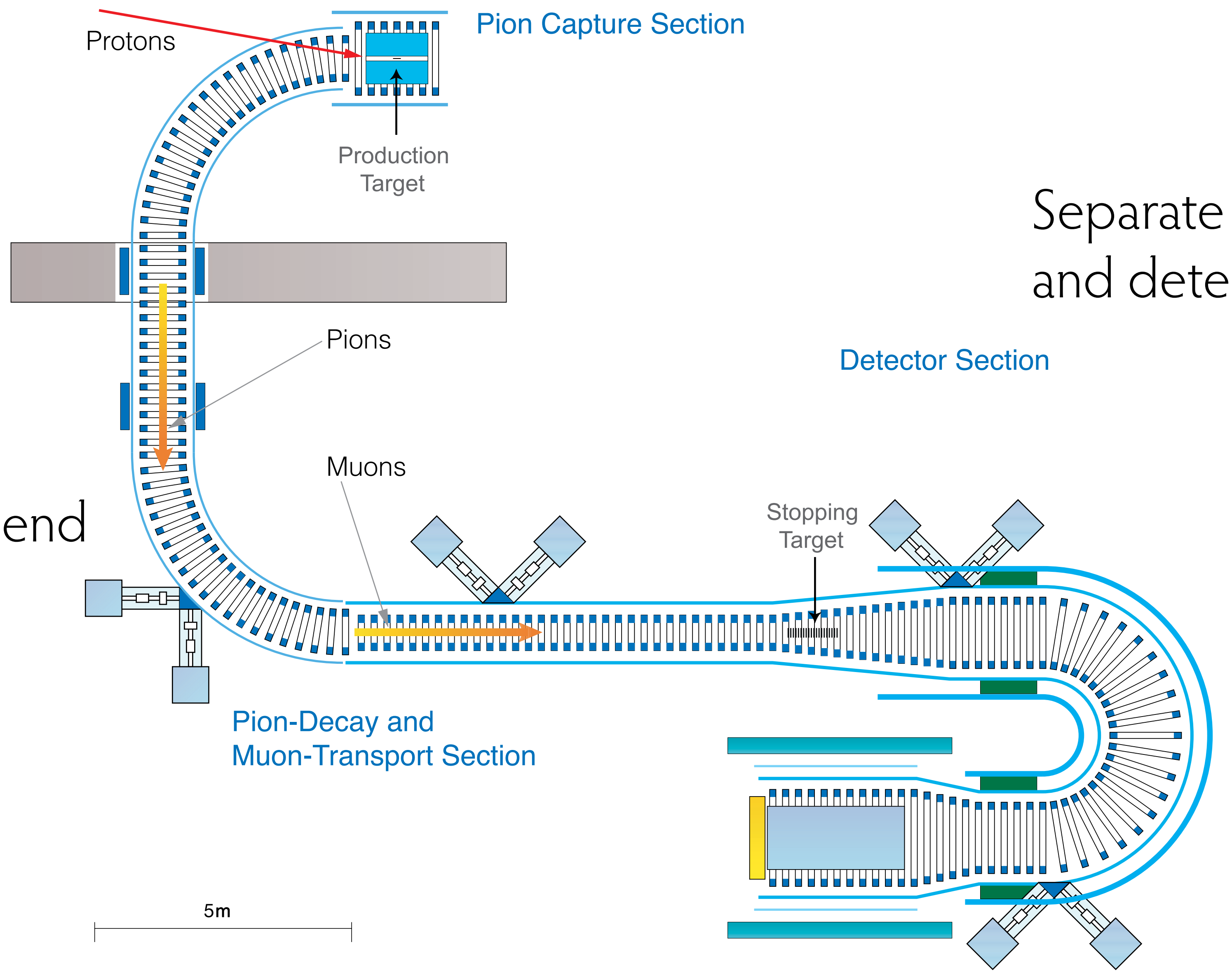
Capture pions with large solid angle

Pion-Decay and Muon-Transport Section

Detector Section

Comet CDR

Experimental layout - COMET Phase II



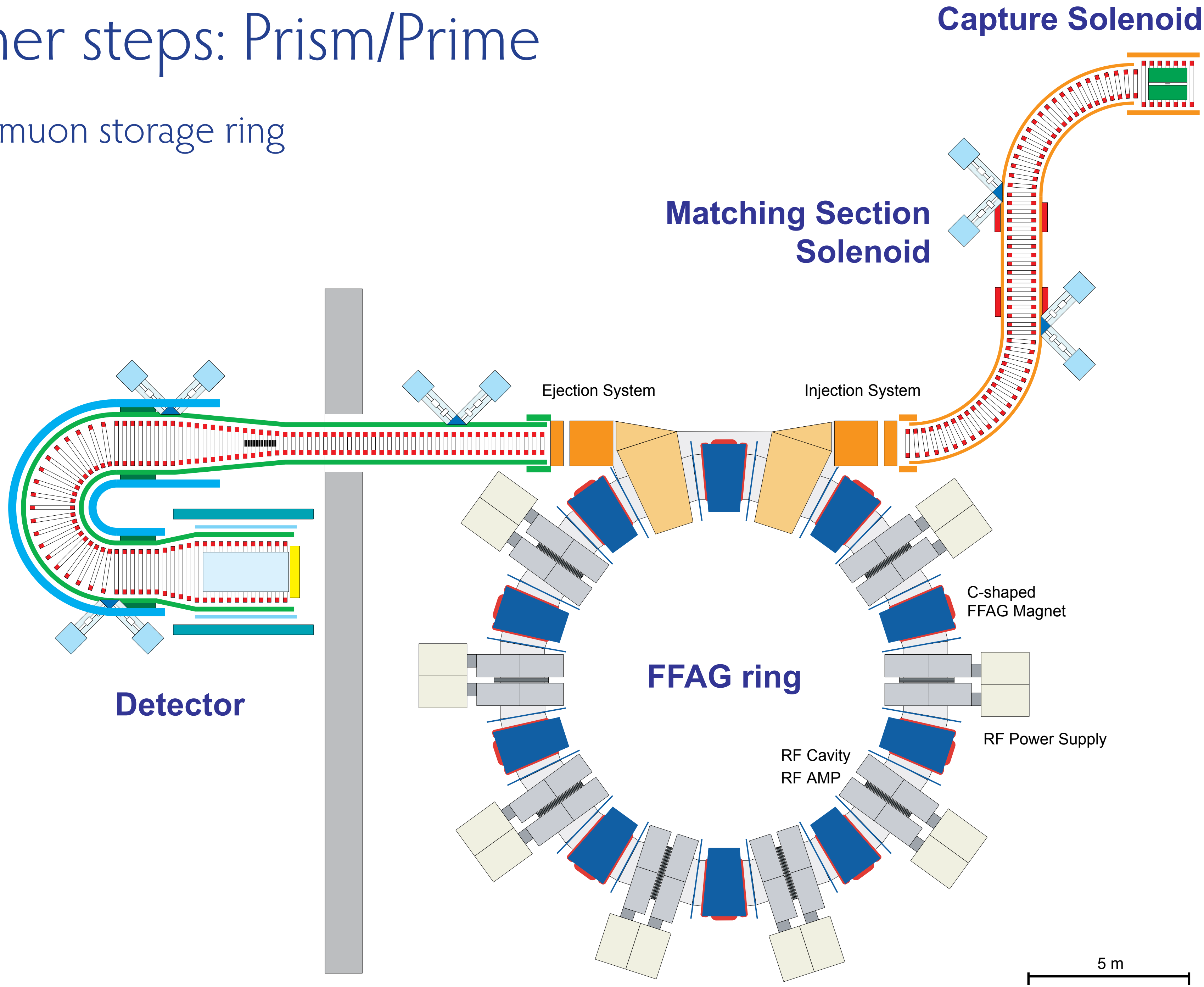
Separate muon decay and detector region

One more bend

Comet CDR

Further steps: Prism/Prime

Add a muon storage ring



Conversion: Expected sensitivities

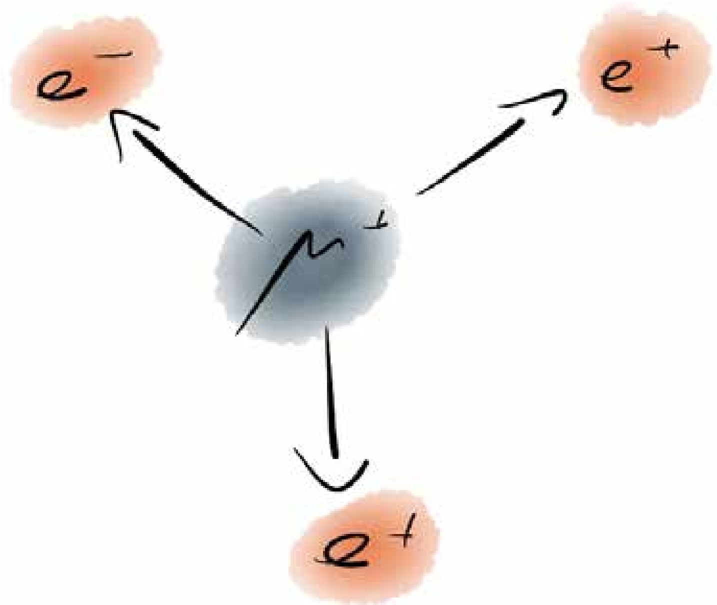
- Comet Phase I and DeeMee might get to $\sim 10^{-14}$ as early as 2016
- Both Comet Phase II and Mu2e will start around 2020
- Should get single event sensitivities well below 10^{-16}
- Prism/Prime and Mu2e with Project X explore paths to 10^{-18}

Tracking it all:

Searching for $\mu^+ \rightarrow e^+e^-e^+$ with

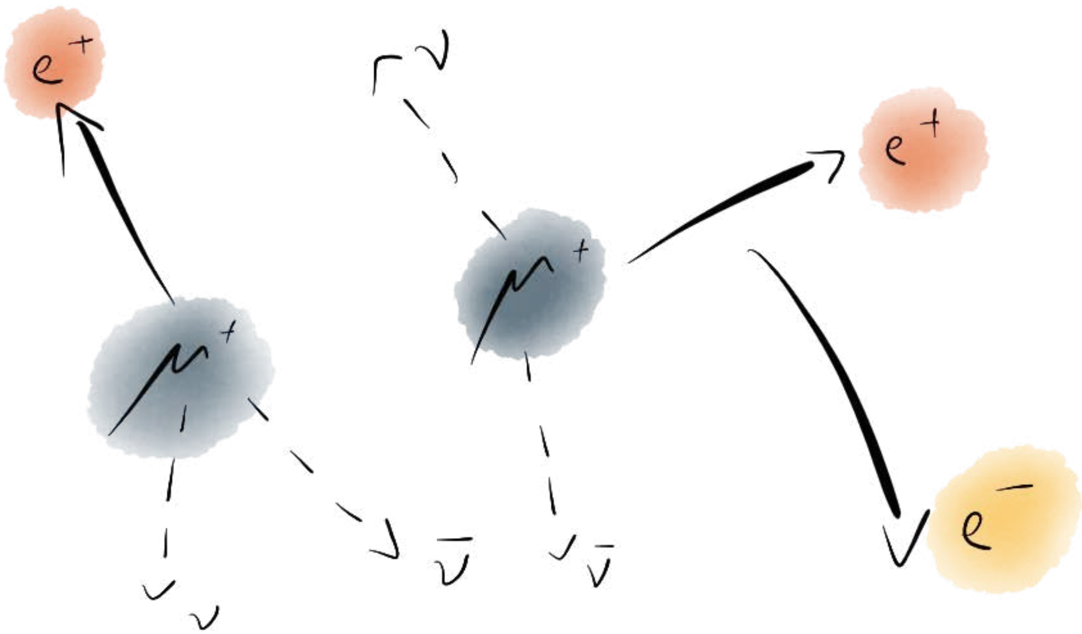
Mu3e

The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- $\Sigma\, p_e = m_\mu$
- Maximum momentum: $\frac{1}{2}\, m_\mu = 53$ MeV/c

Accidental Background



- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha (electron-positron) scattering,
  - Mis-reconstruction

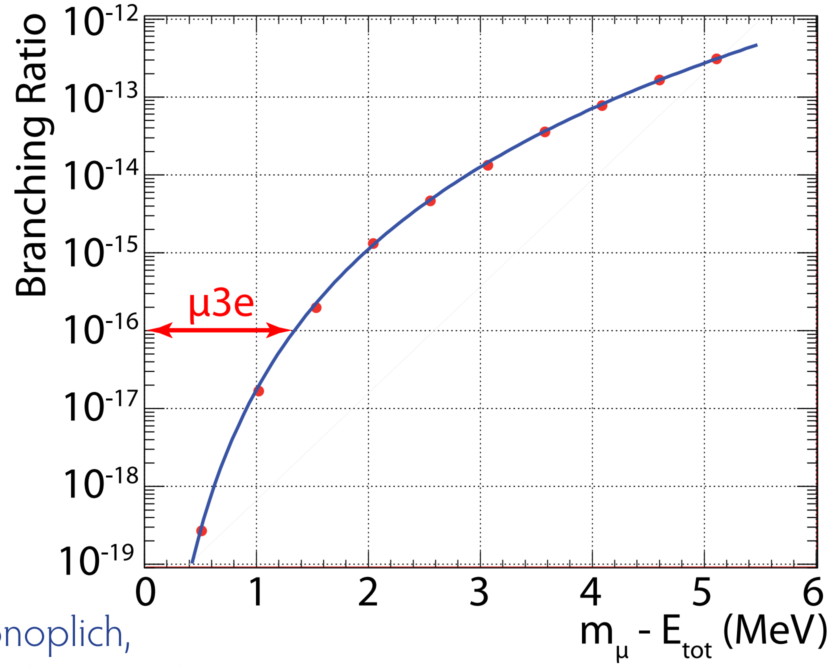
- Need very good timing, vertex and momentum resolution

Internal conversion background

- Allowed radiative decay with internal conversion:

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

- Only distinguishing feature:
  Missing momentum carried by neutrinos

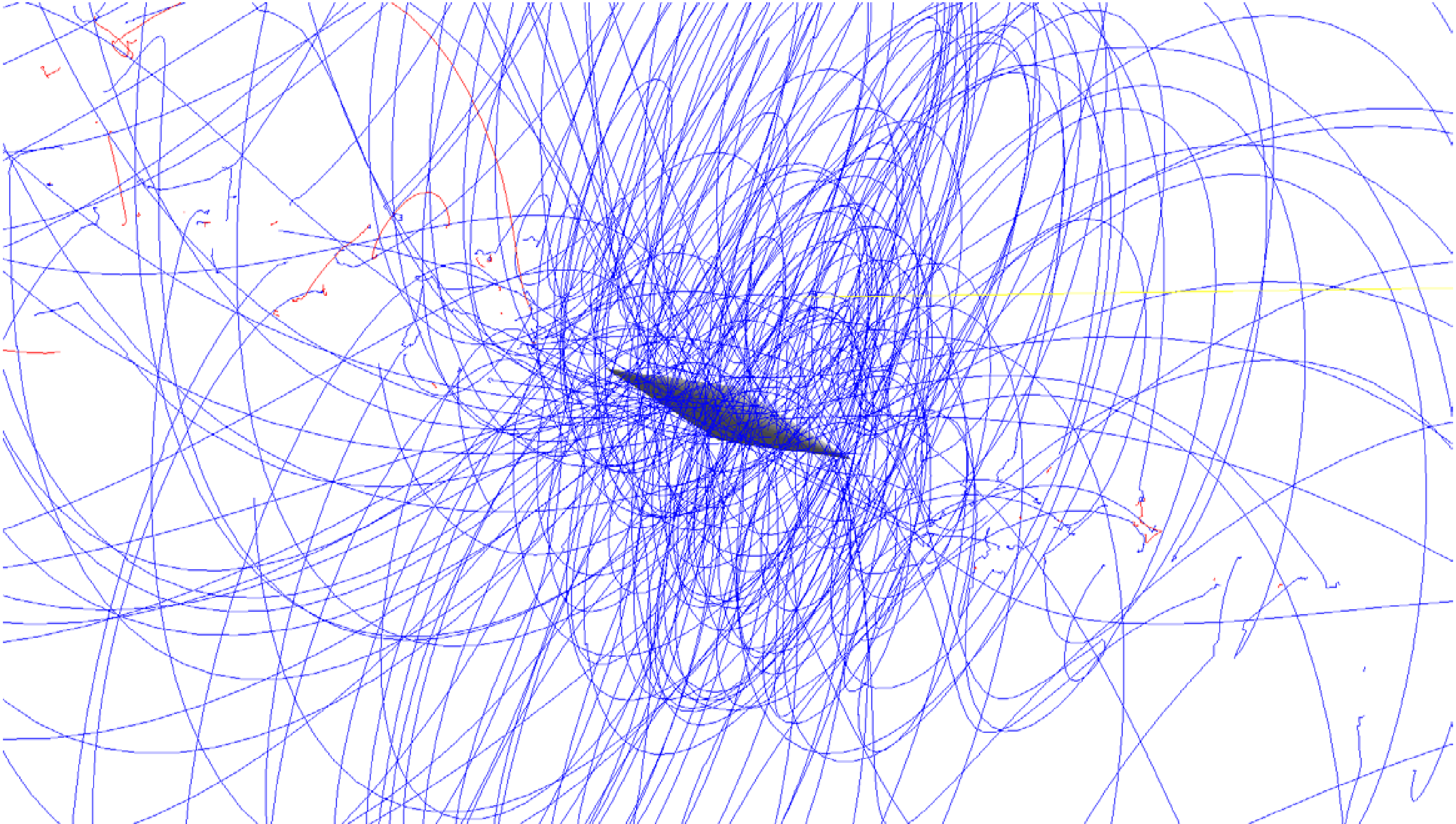


(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

- Need excellent momentum resolution

2 Billion Muon Decays/s

50 ns, 1 Tesla field



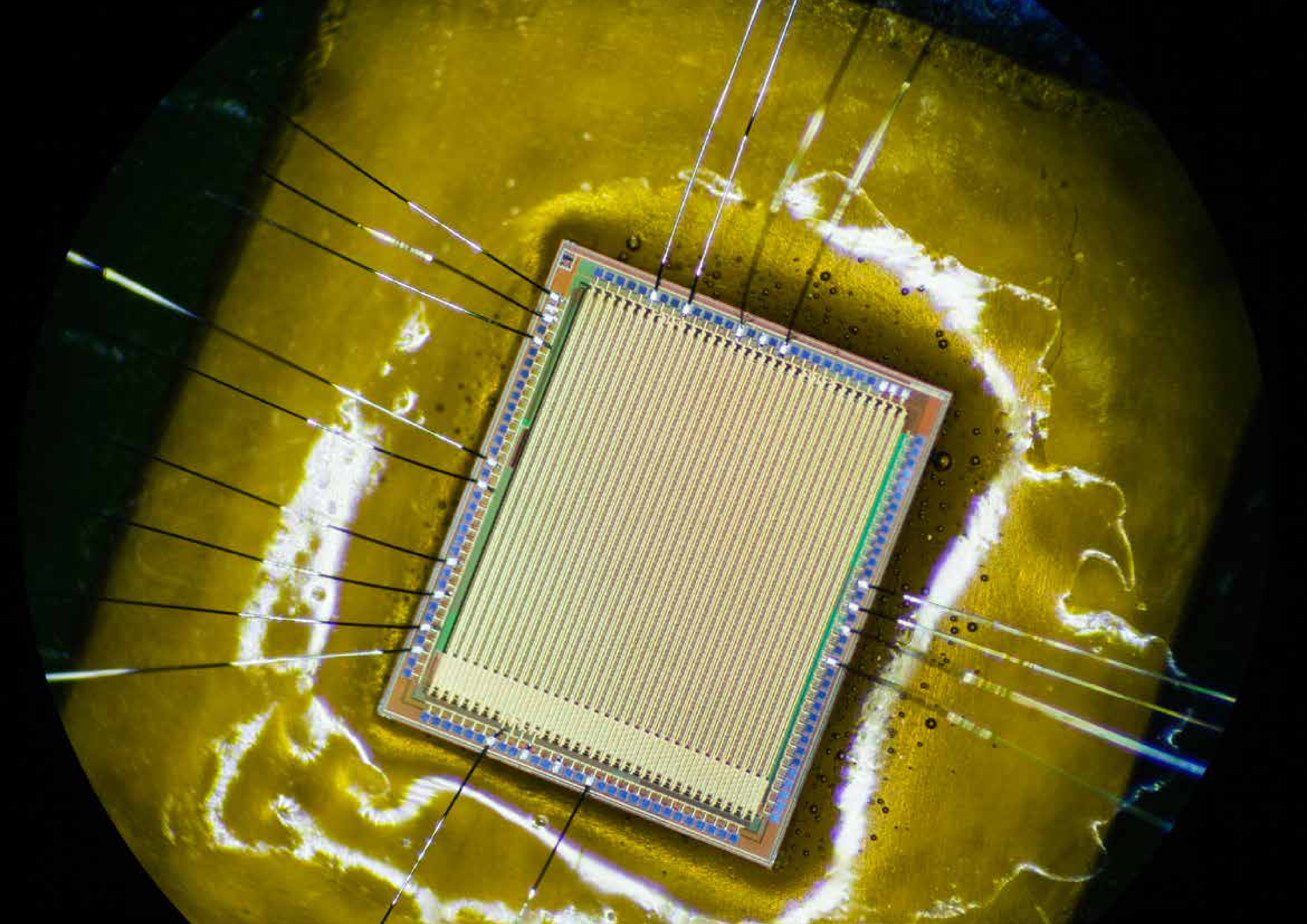
Detector Technology

- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)

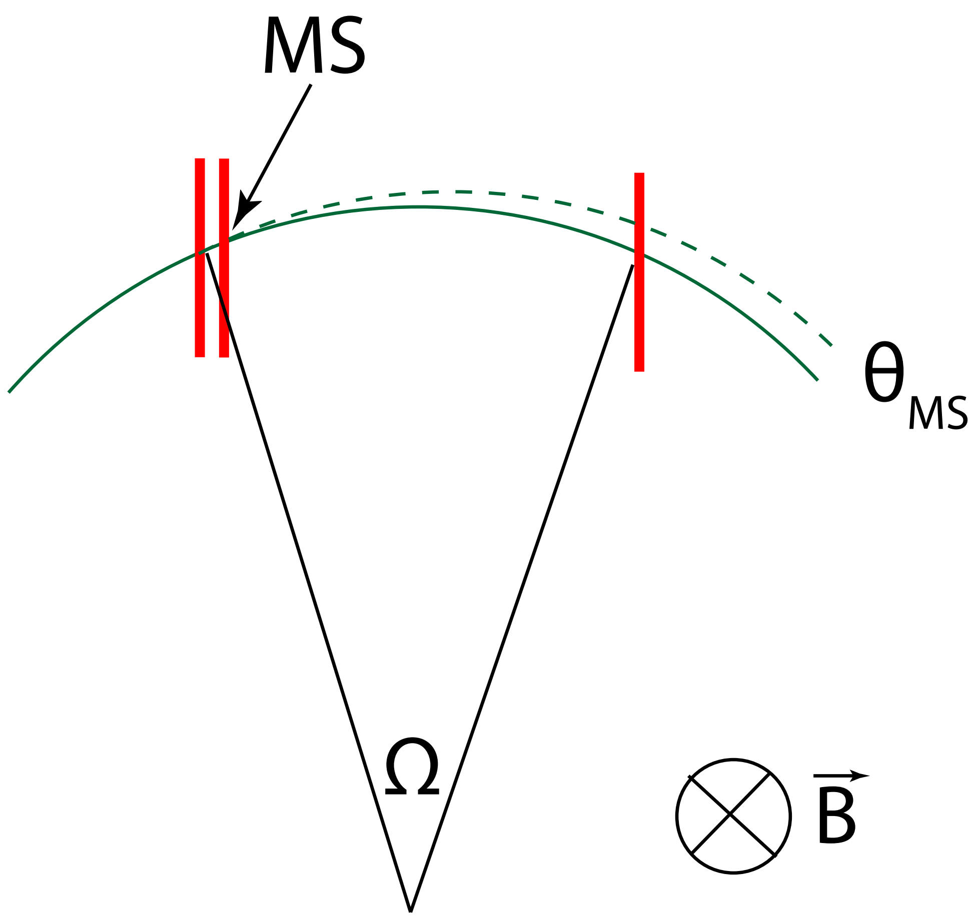
Detector Technology

- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)

- Gas detectors do not work (space charge, aging, 3D)
- Silicon strips do not work (material budget, 3D)
- Hybrid pixels (as in LHC) do not work (material budget)



Momentum measurement

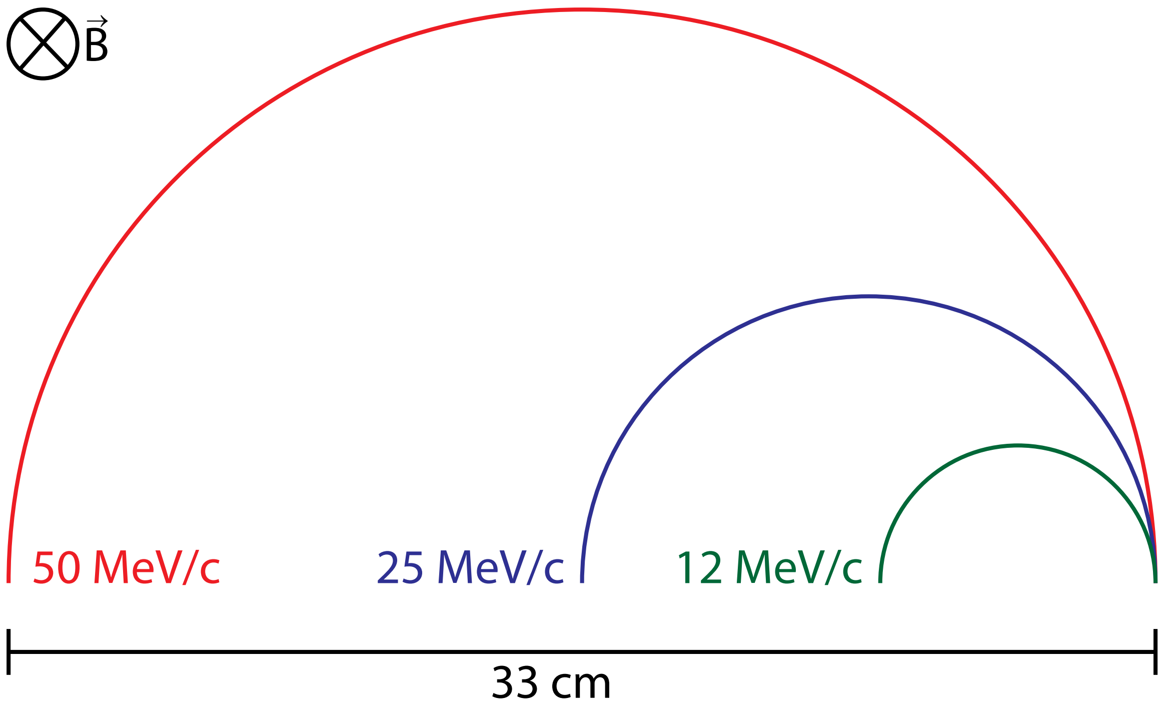


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

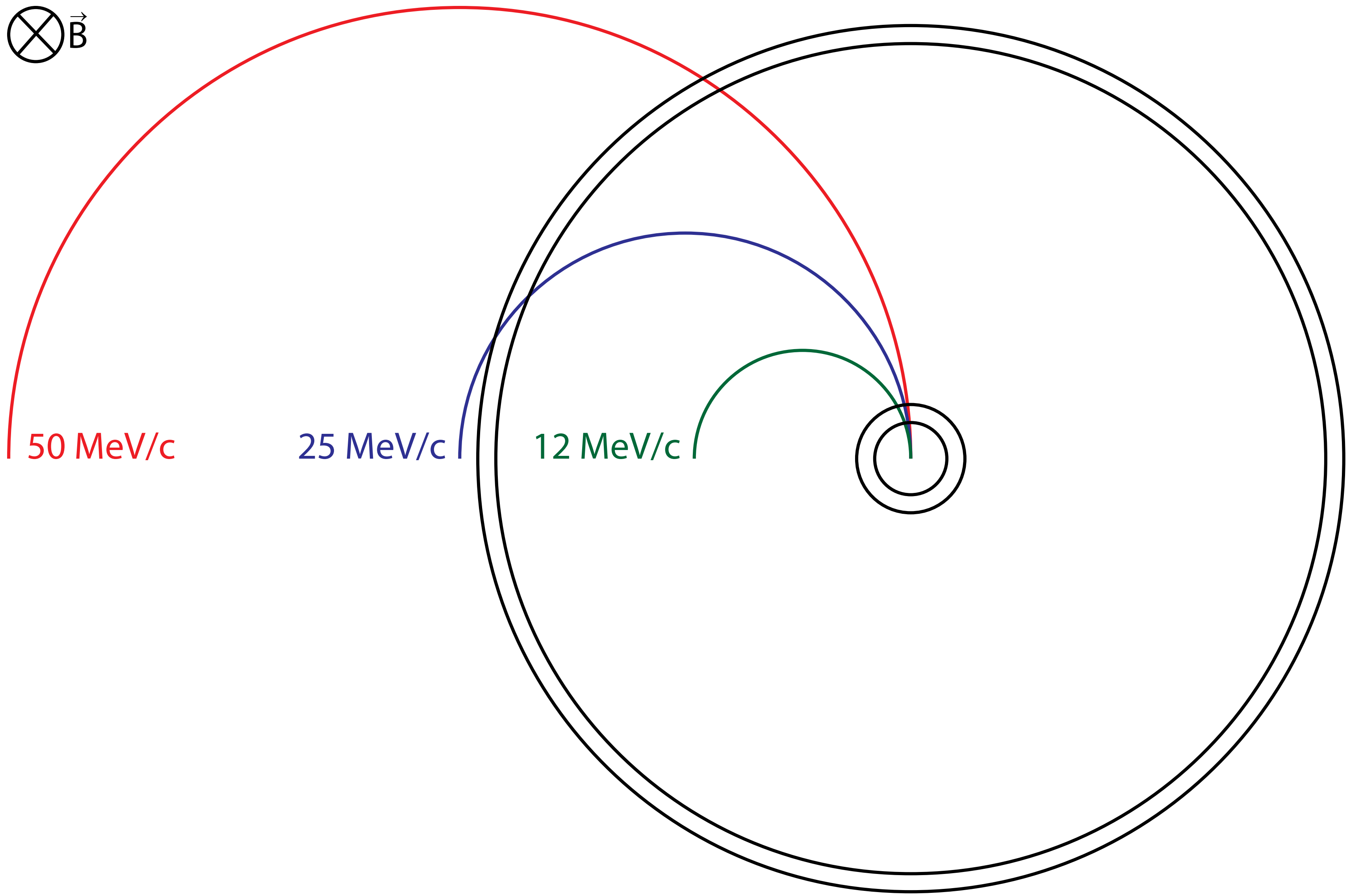
$$\sigma_P/P \sim \theta_{MS}/\Omega$$

- Precision requires large lever arm (large bending angle Ω) and low multiple scattering θ_{MS}

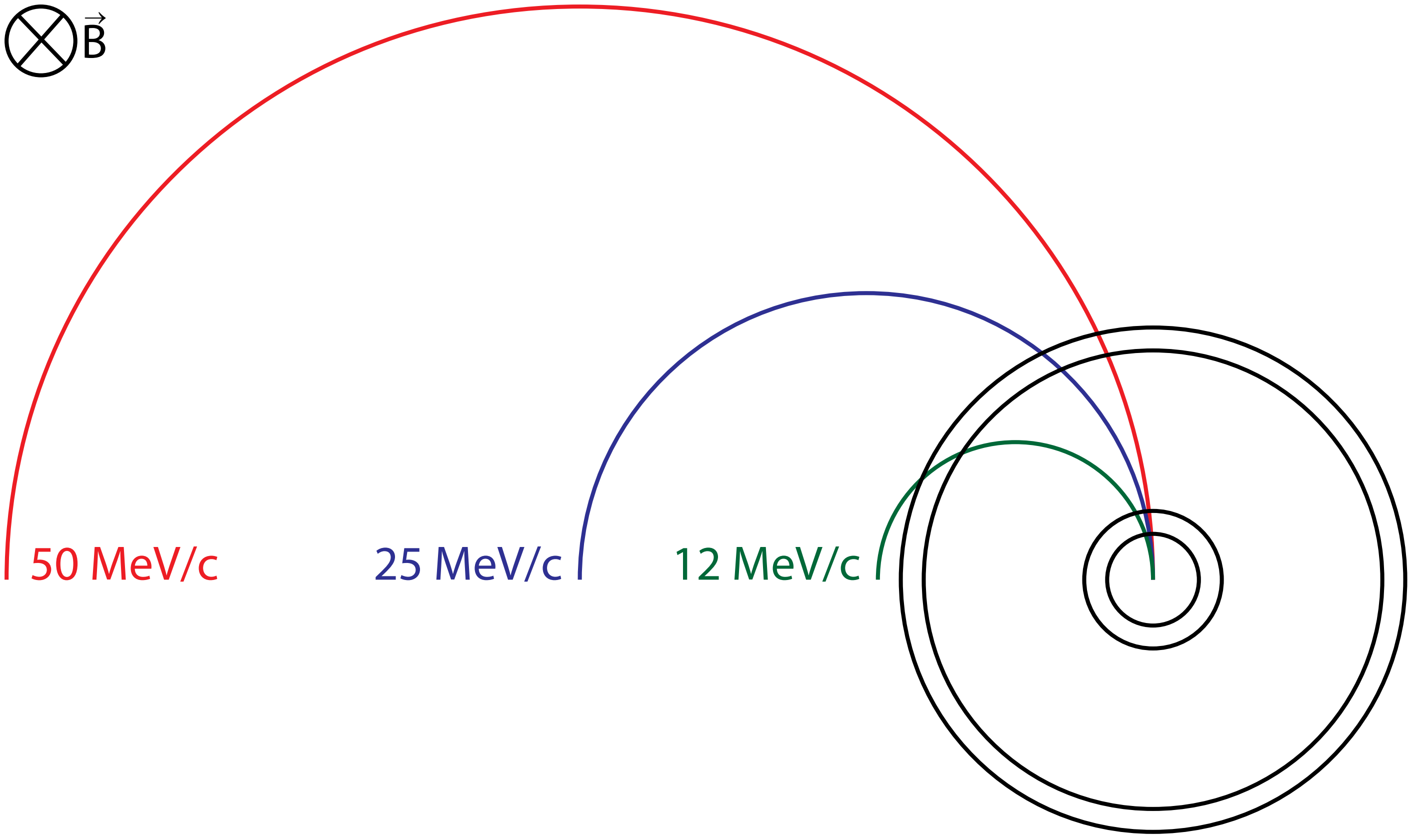
Precision vs. Acceptance



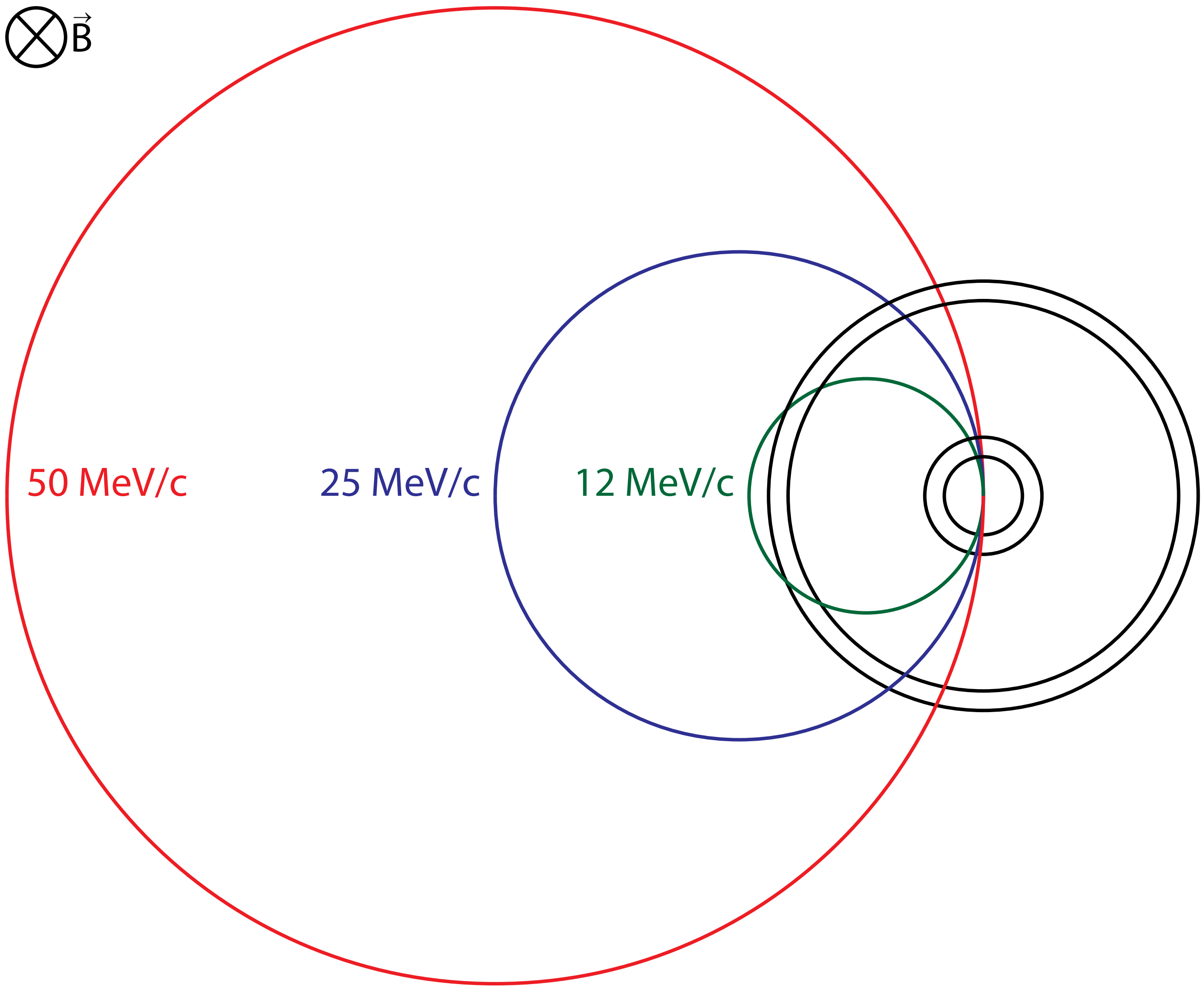
Precision vs. Acceptance



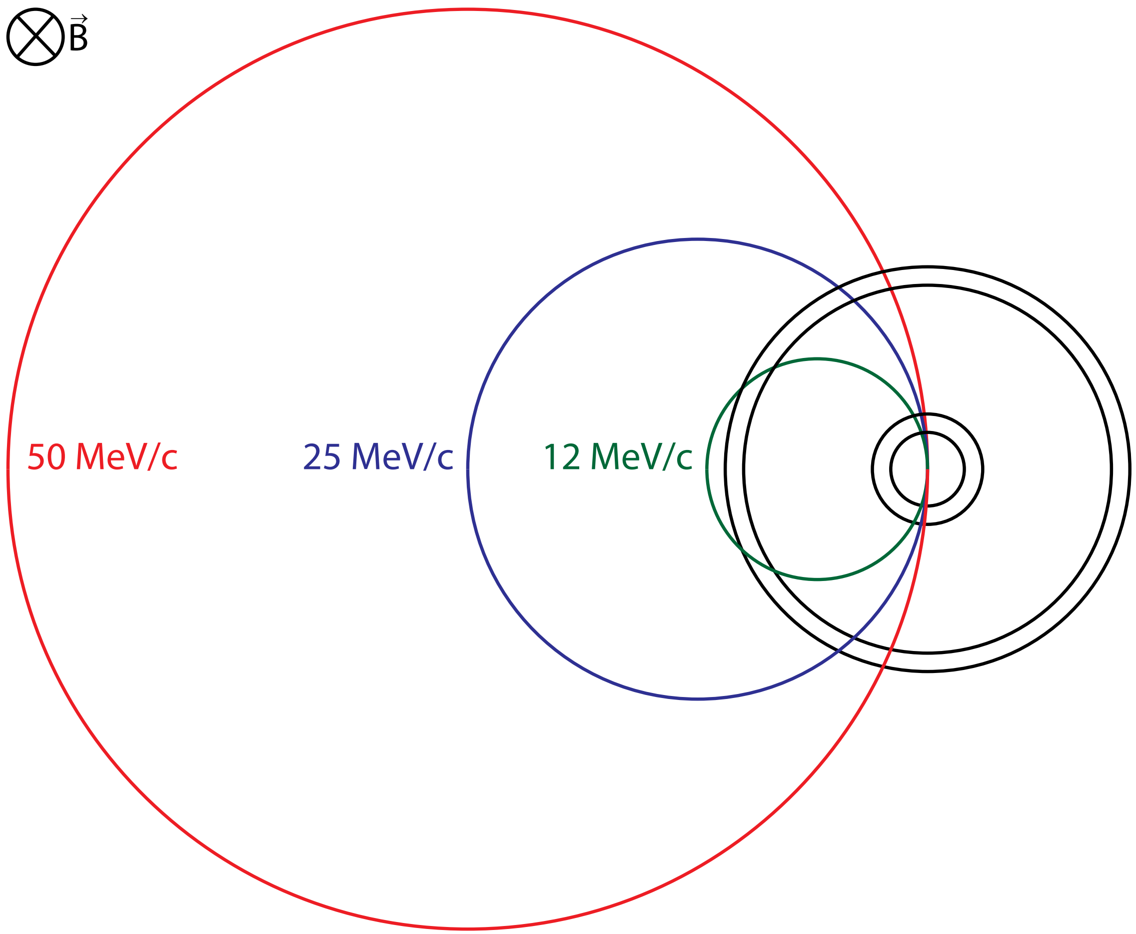
Precision vs. Acceptance

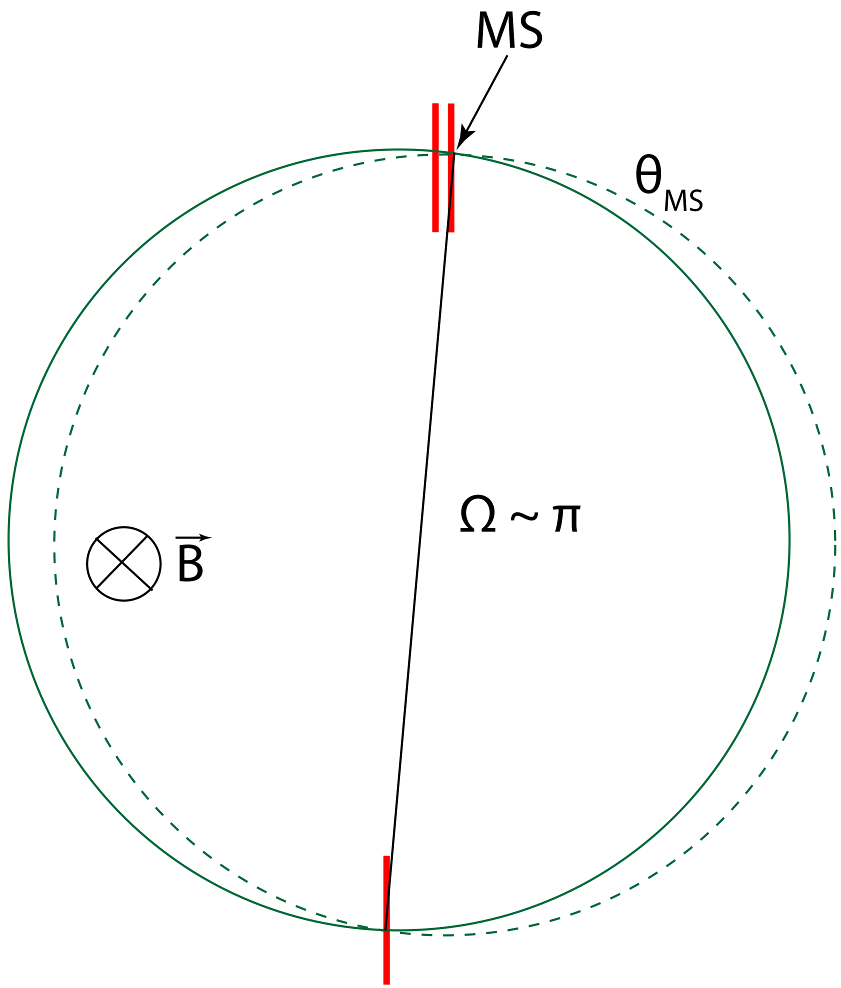


Precision vs. Acceptance

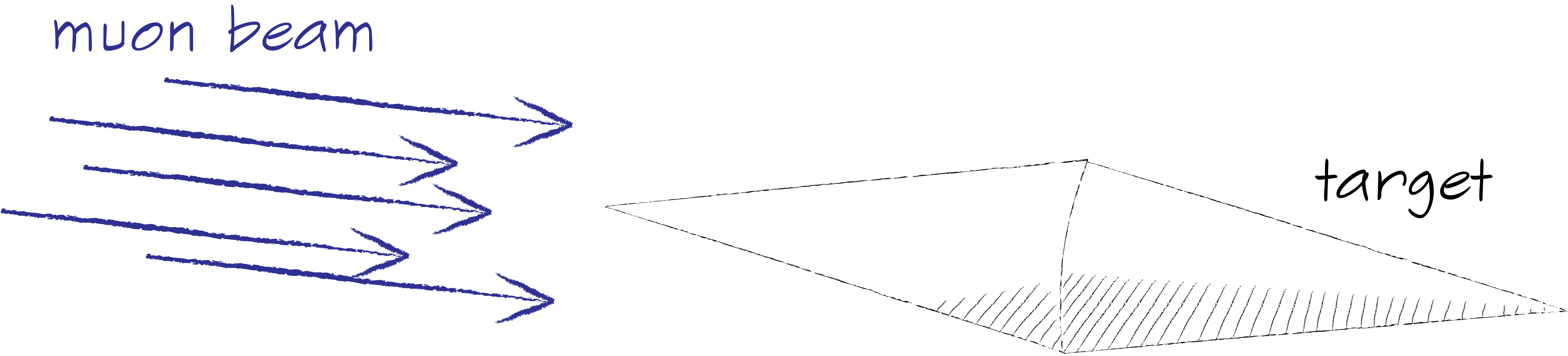


Precision vs. Acceptance

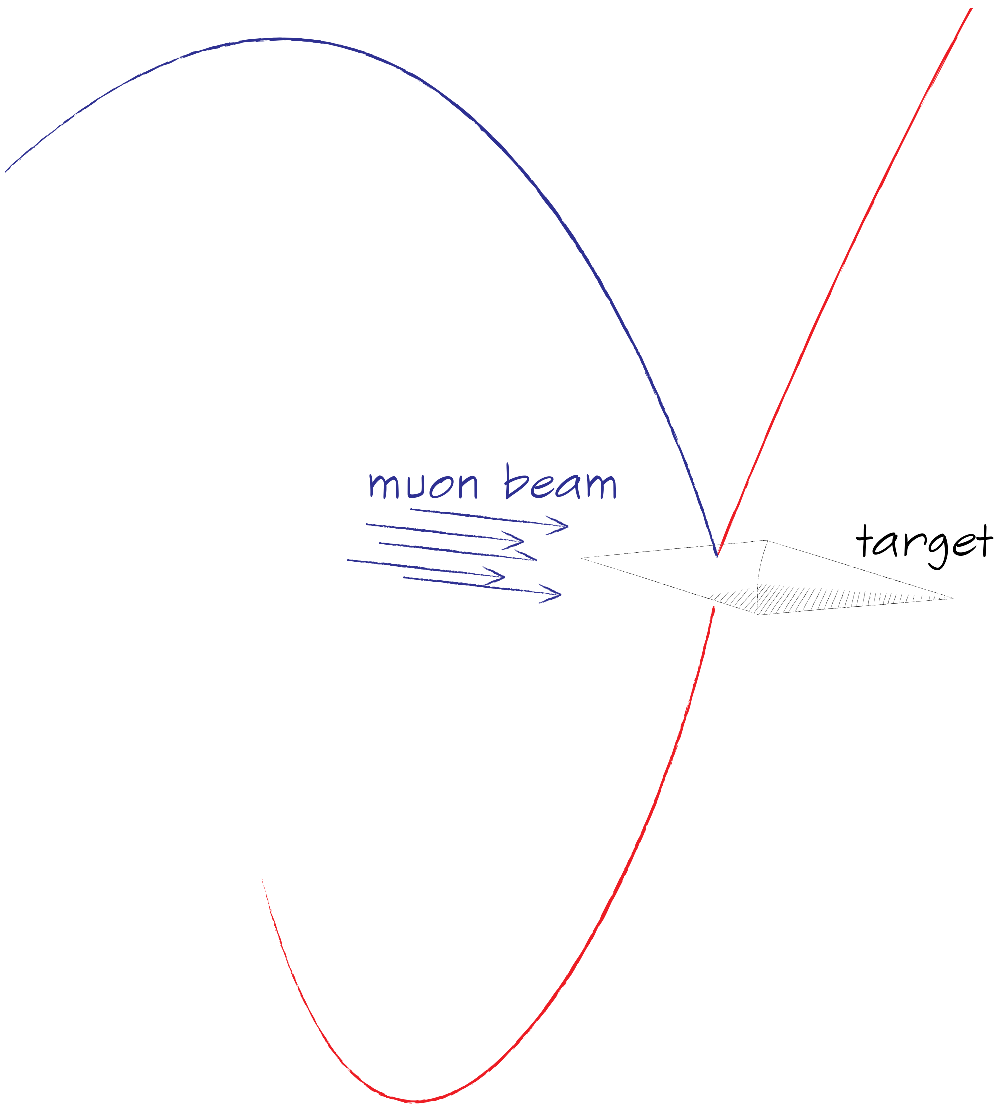




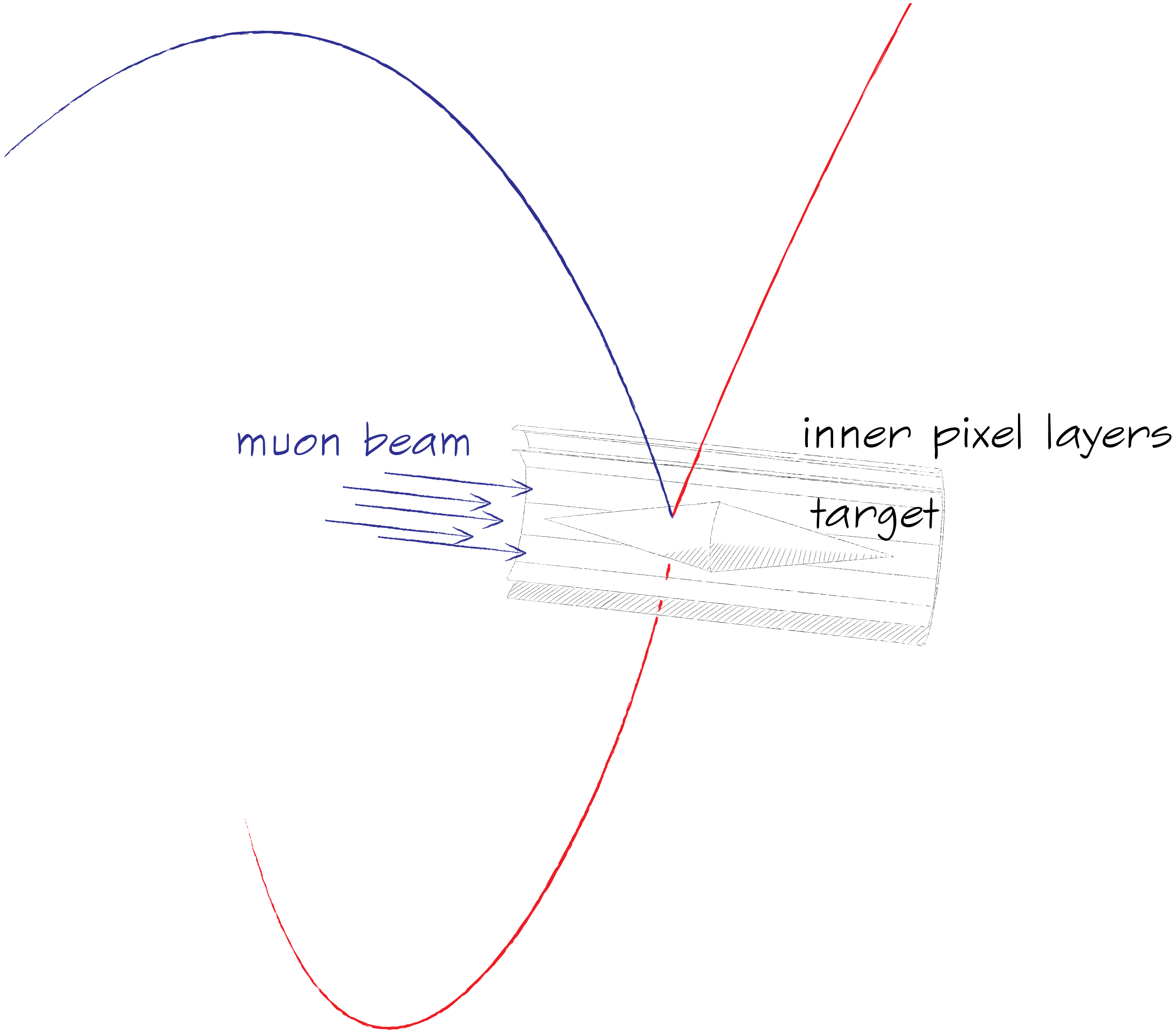
Detector Design



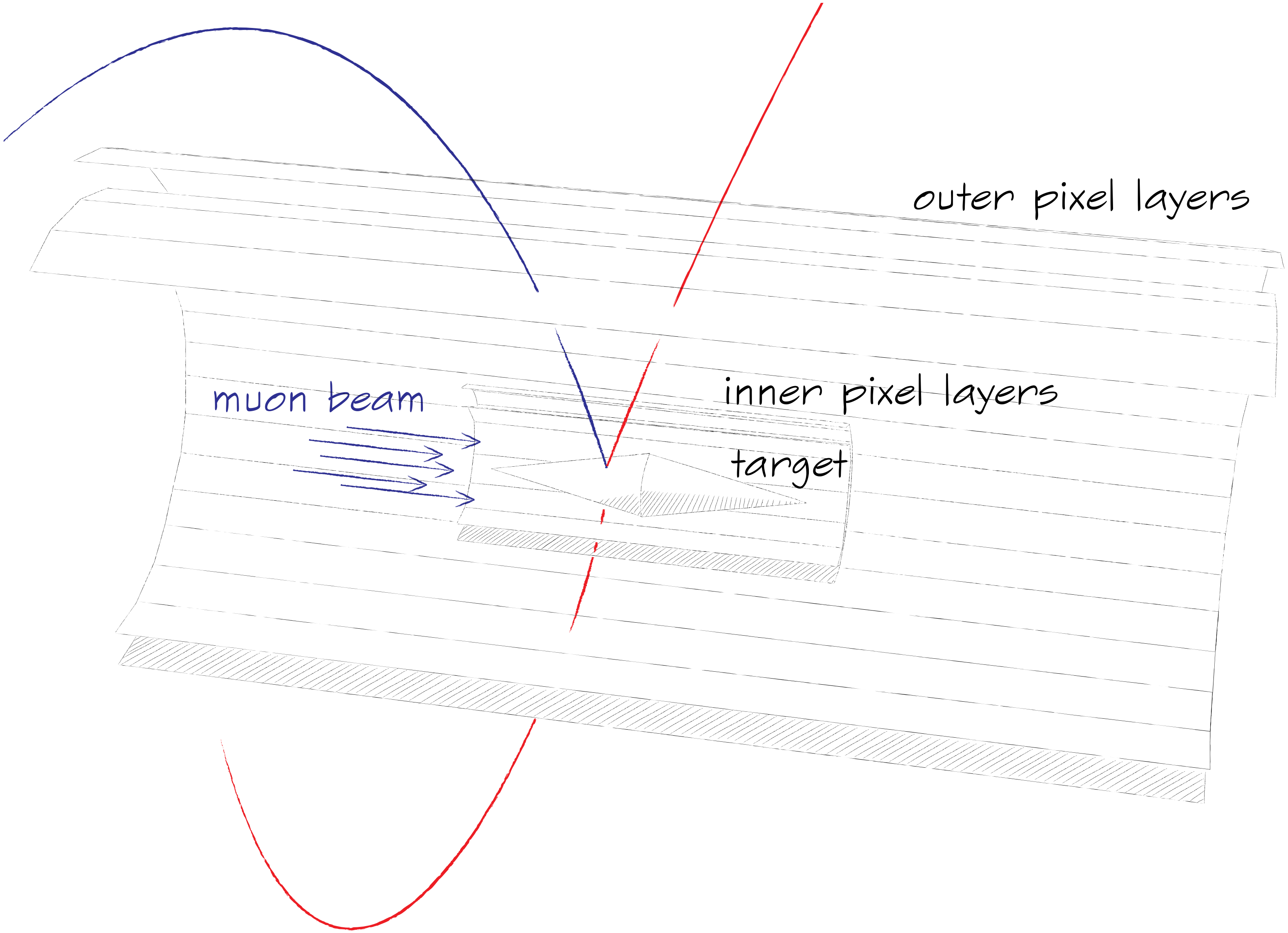
Detector Design



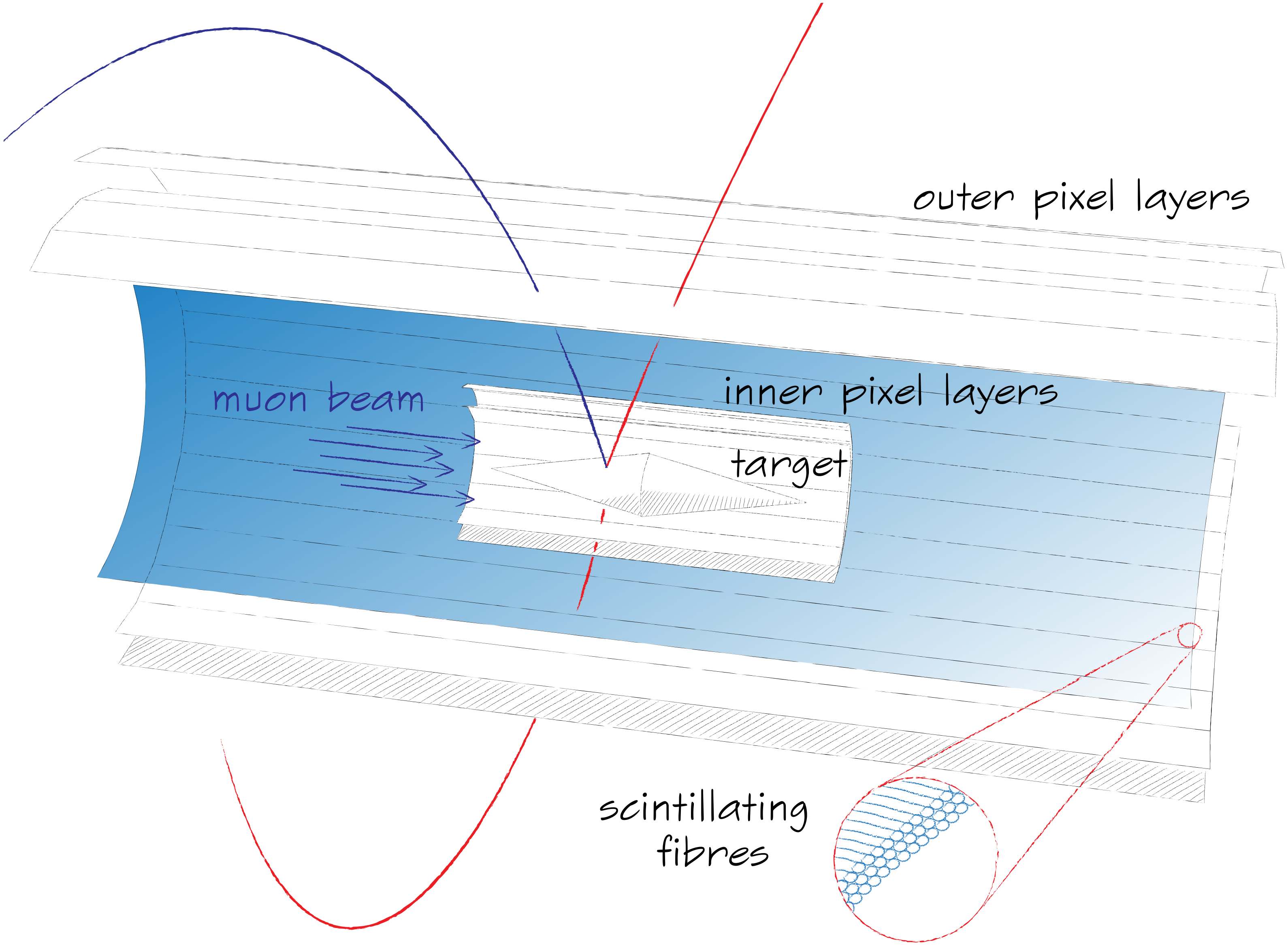
Detector Design



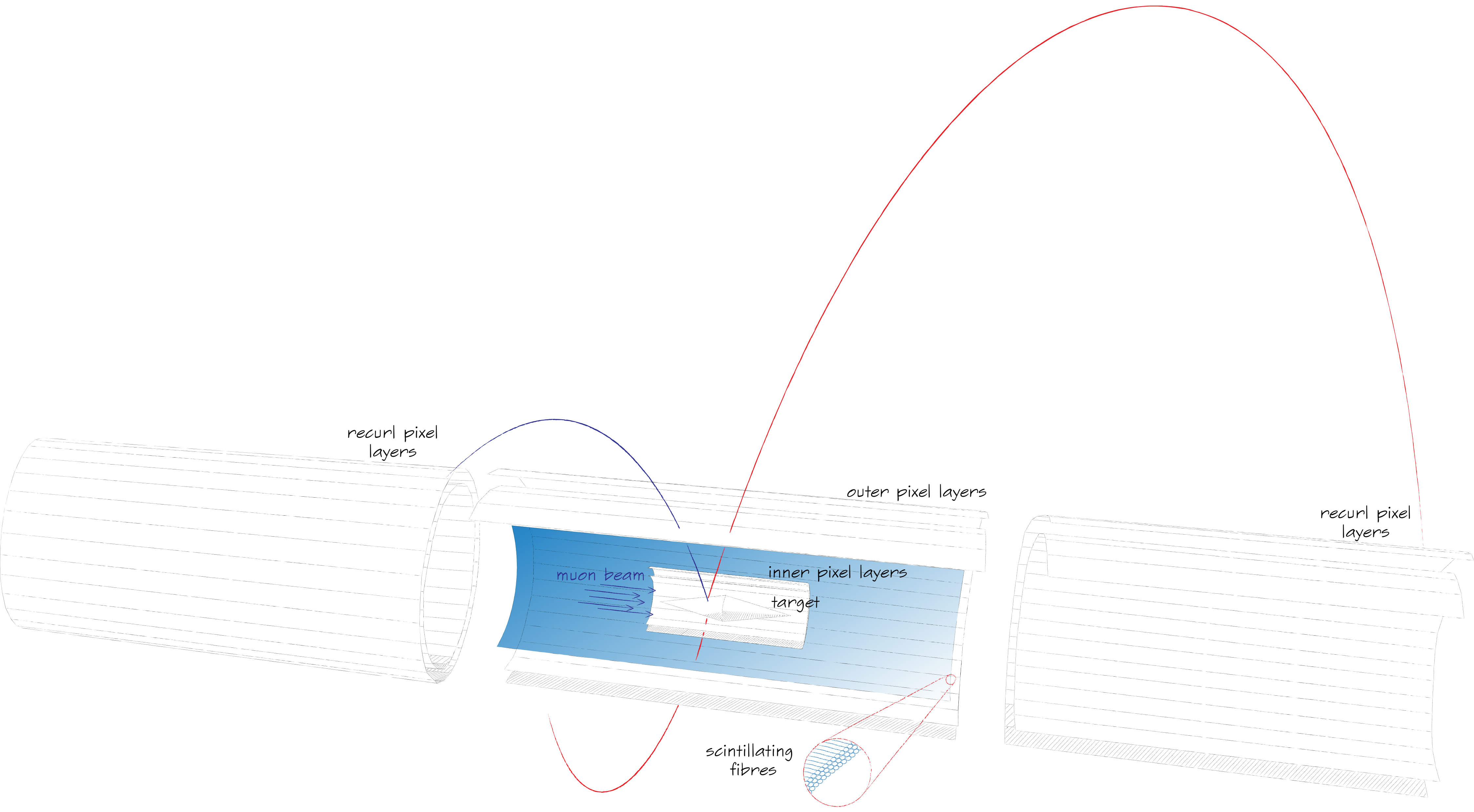
Detector Design



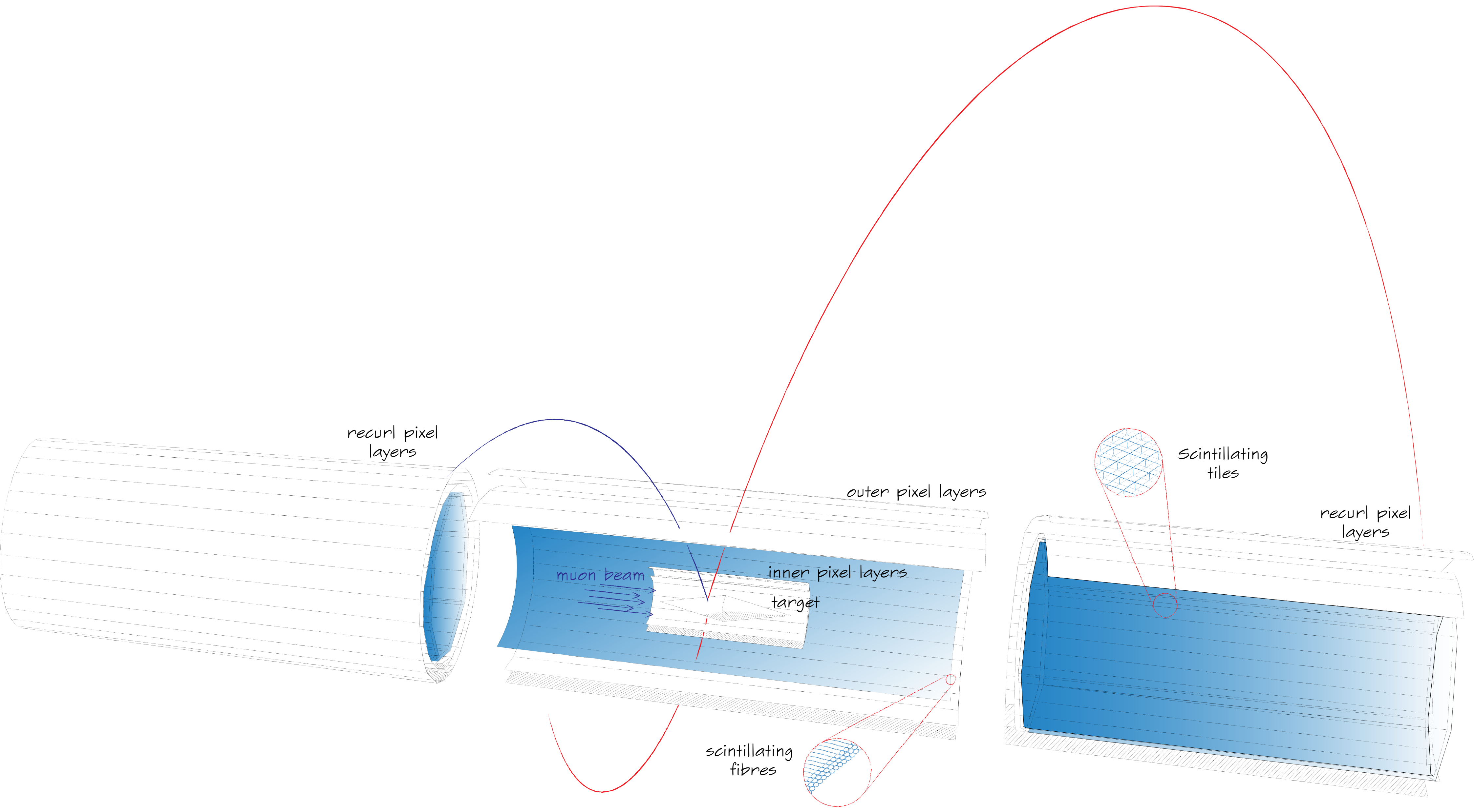
Detector Design



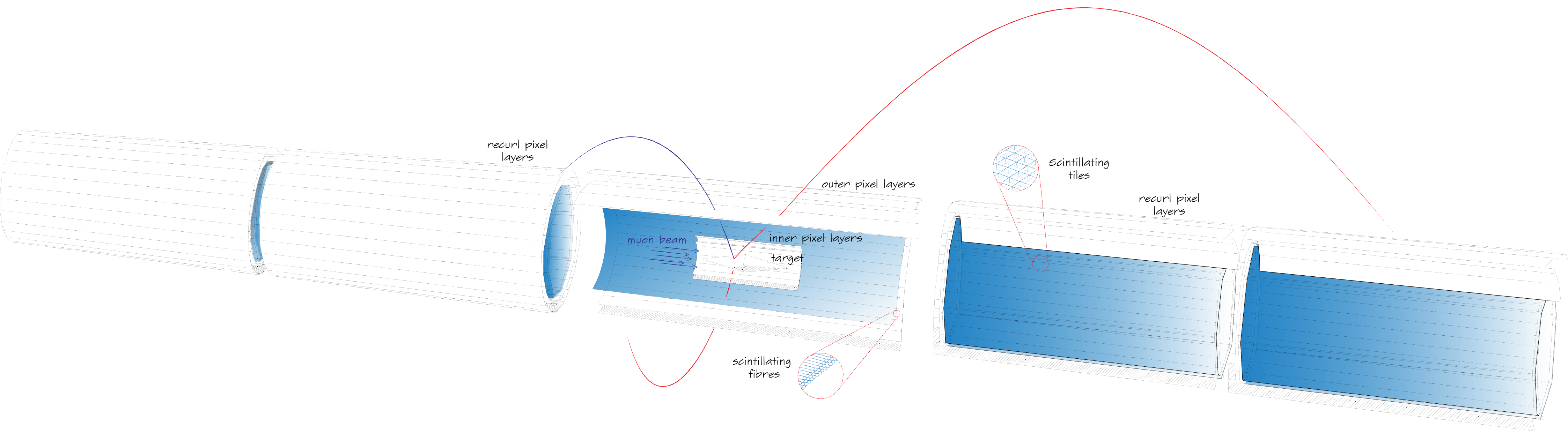
Detector Design



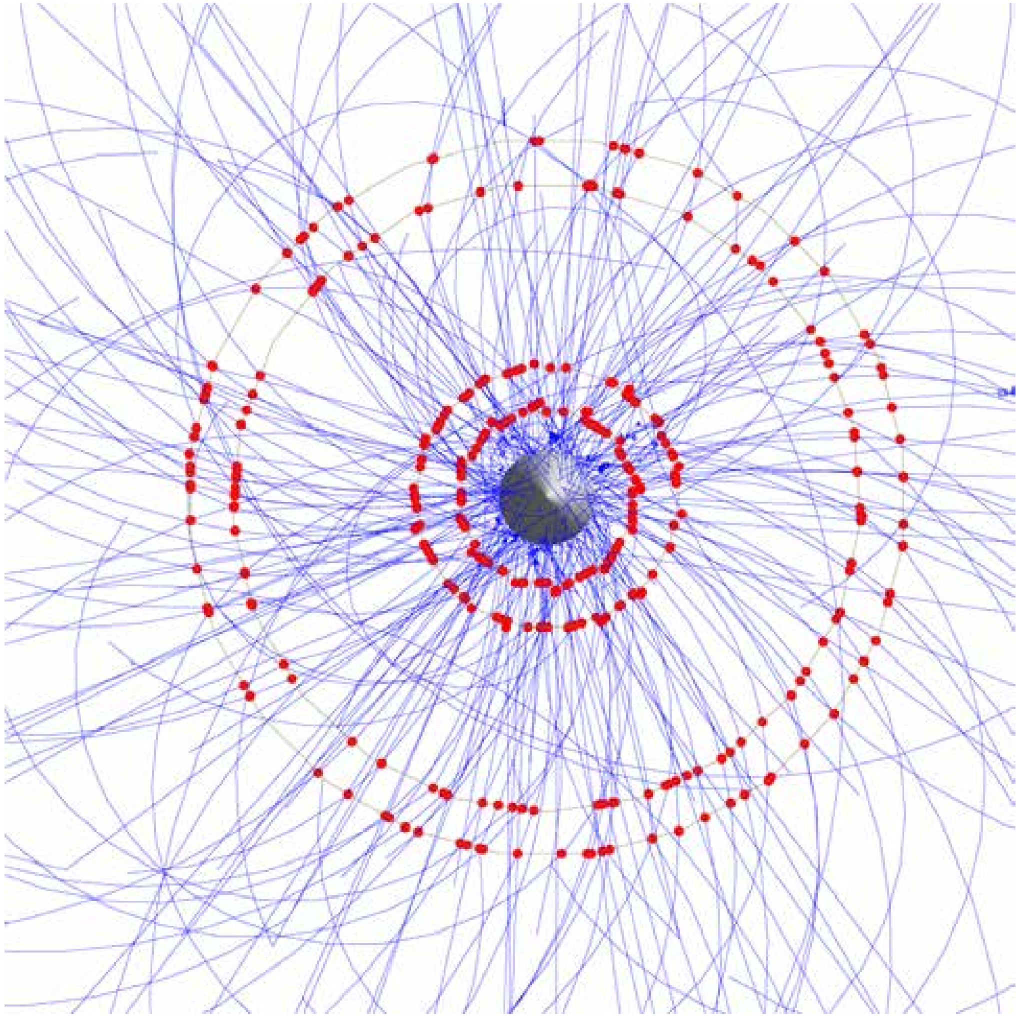
Detector Design



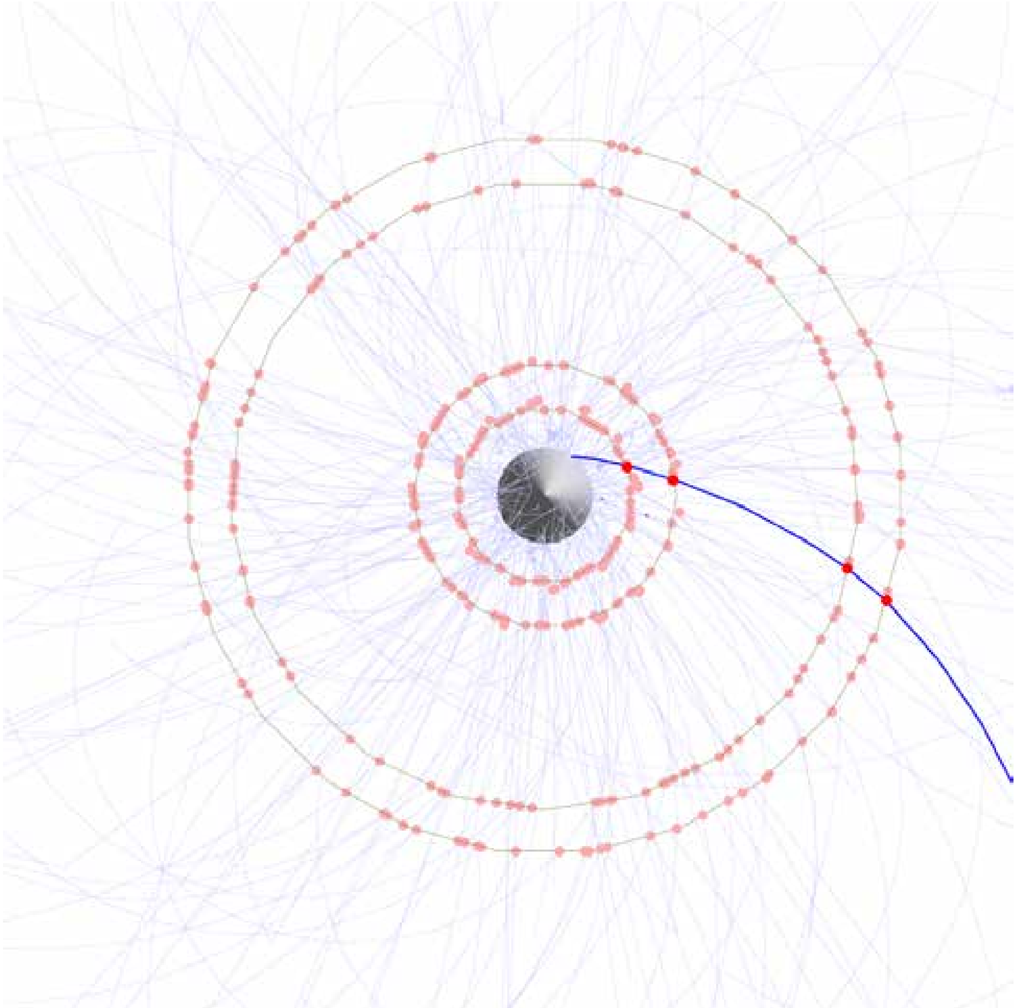
Detector Design



Timing measurements

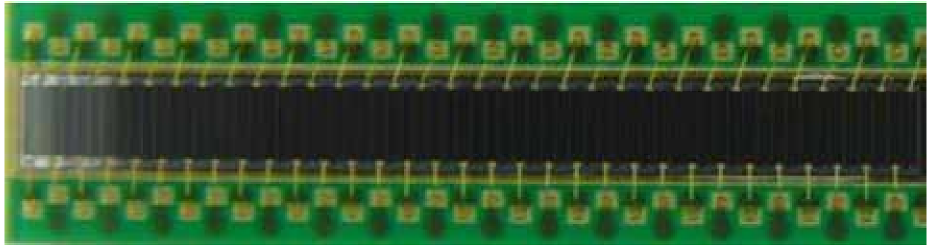


Pixels: O(50 ns)

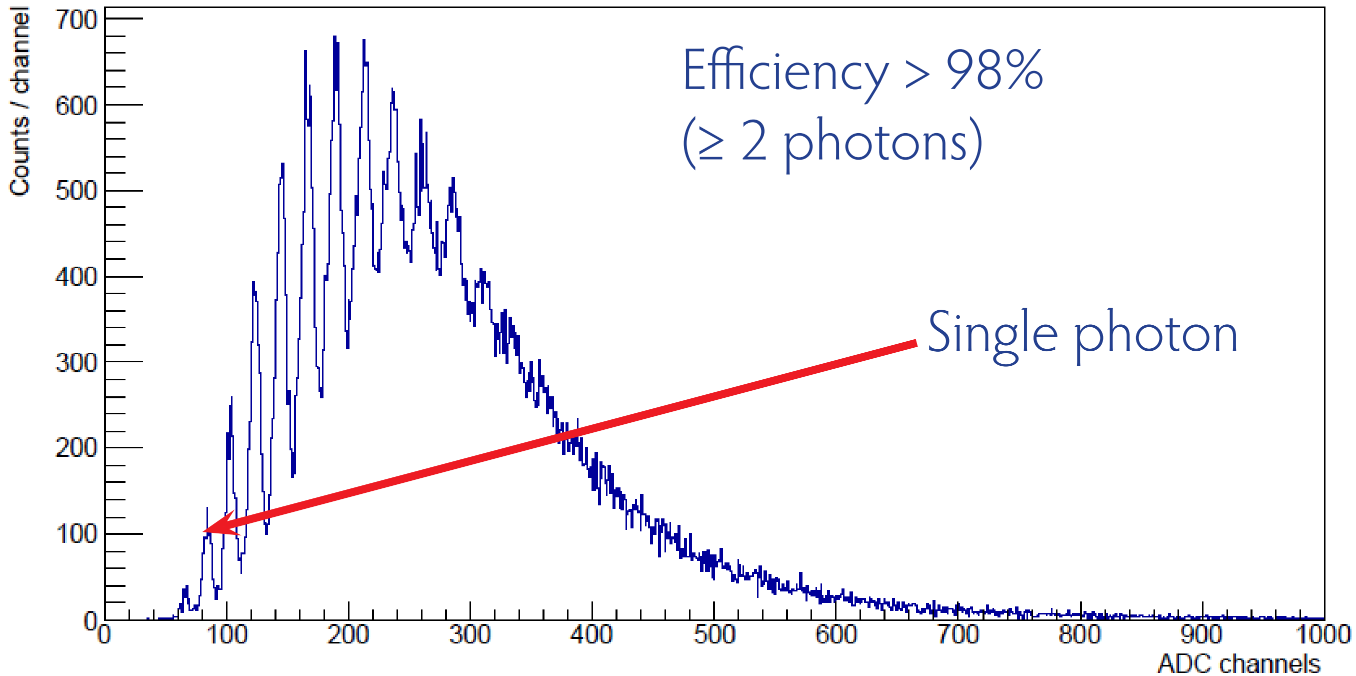


Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

Timing Detector: Scintillating Fibres

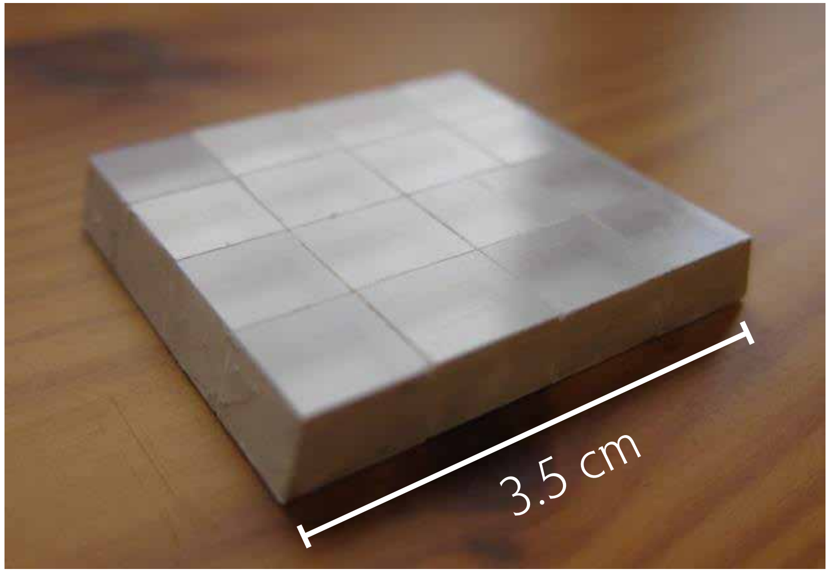


- 3 layers of 250 μm scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC)
- Timing resolution $\mathcal{O}$(1 ns) (measured with sodium source)

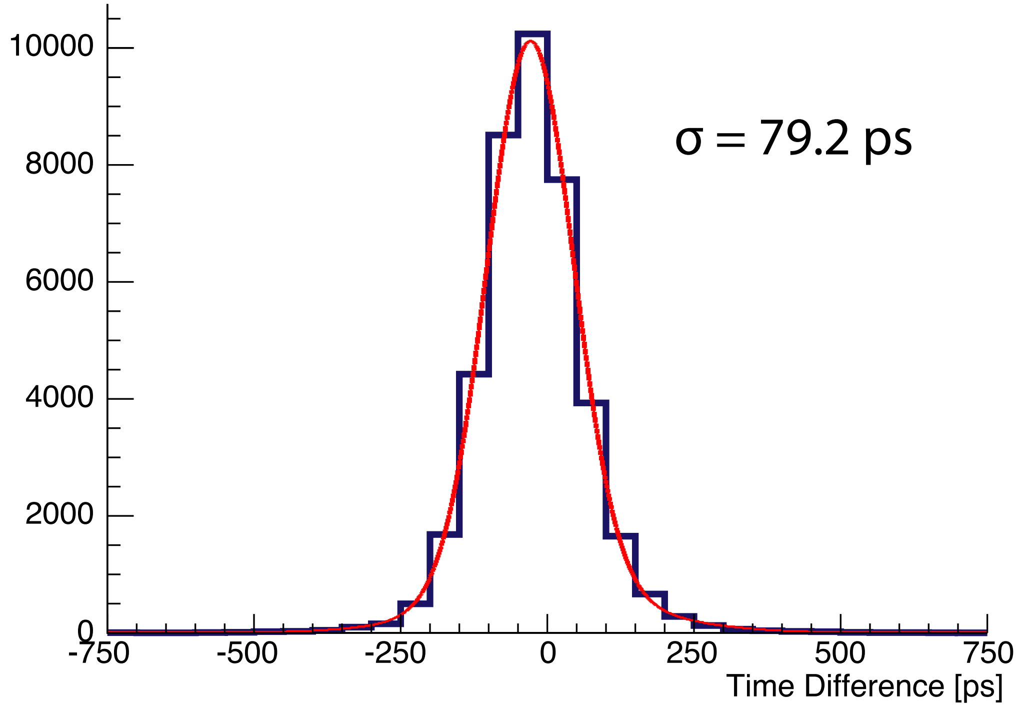


Timing Detector: Scintillating tiles

Front

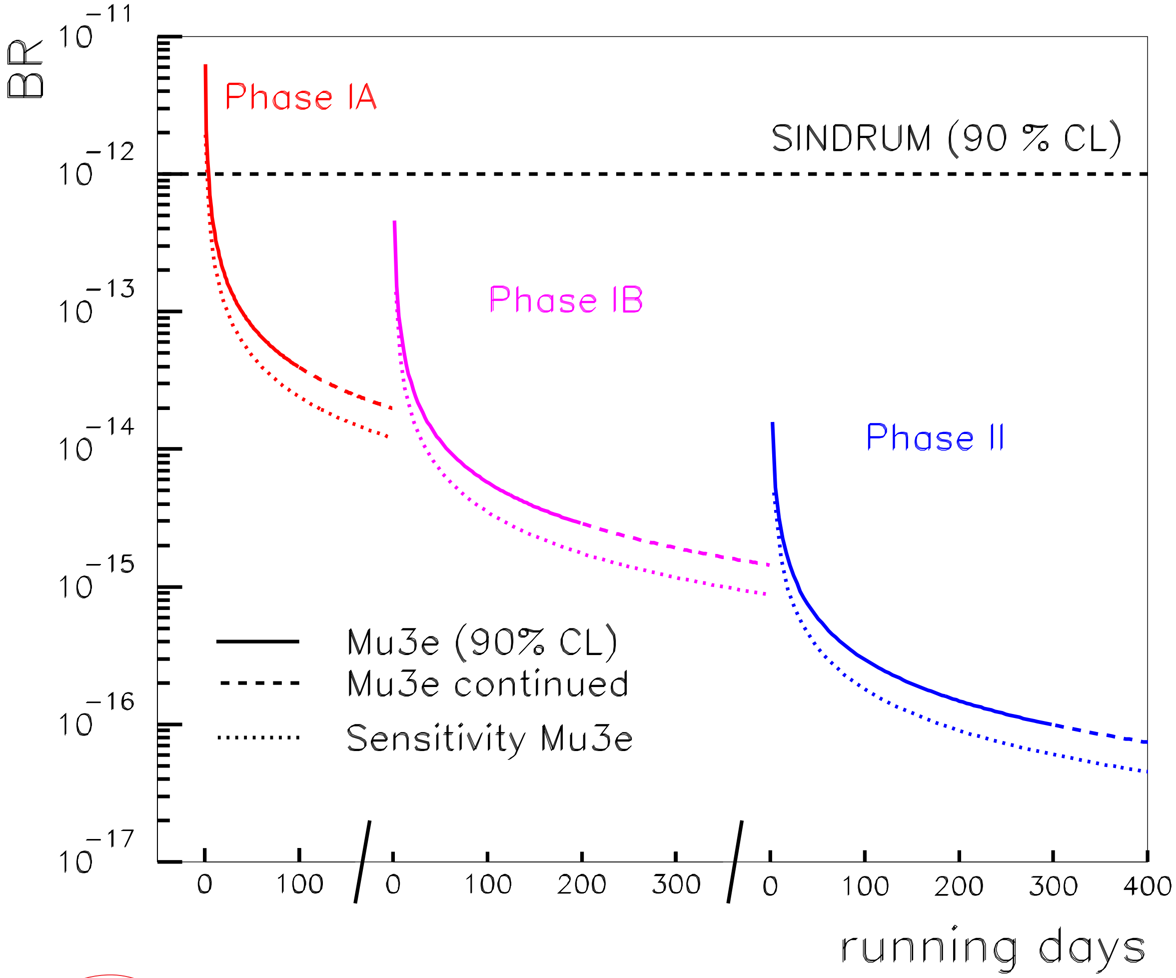


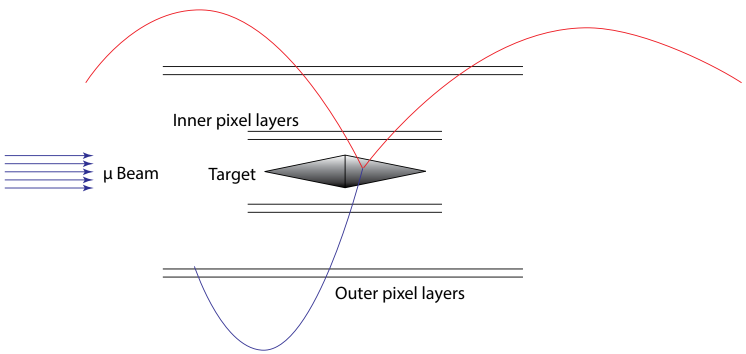
Back



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

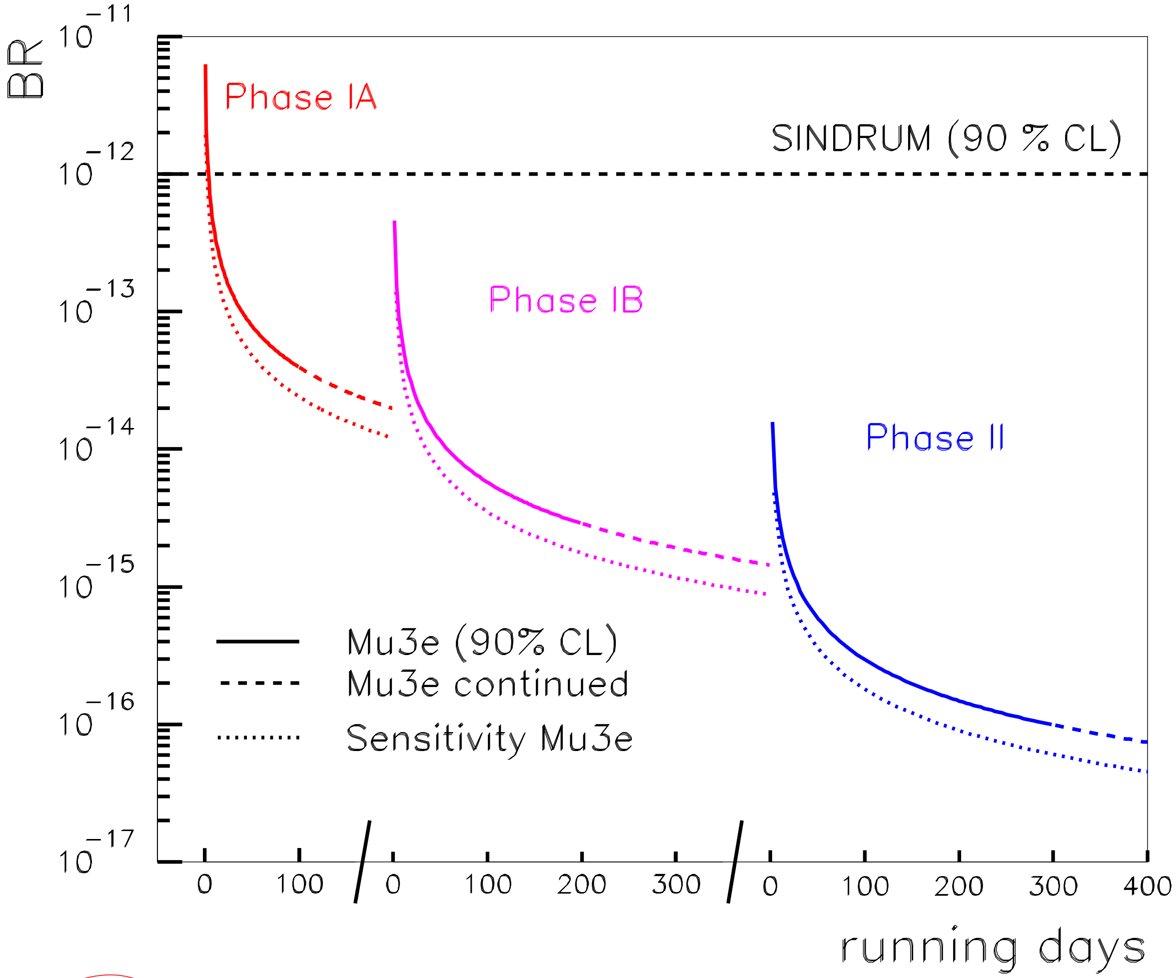
Sensitivity

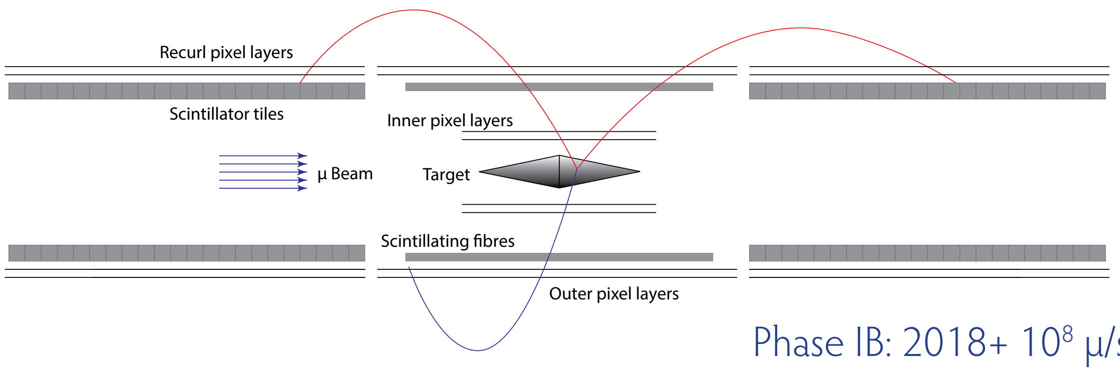




Phase IA: Starting 2017 10^7 μ/s

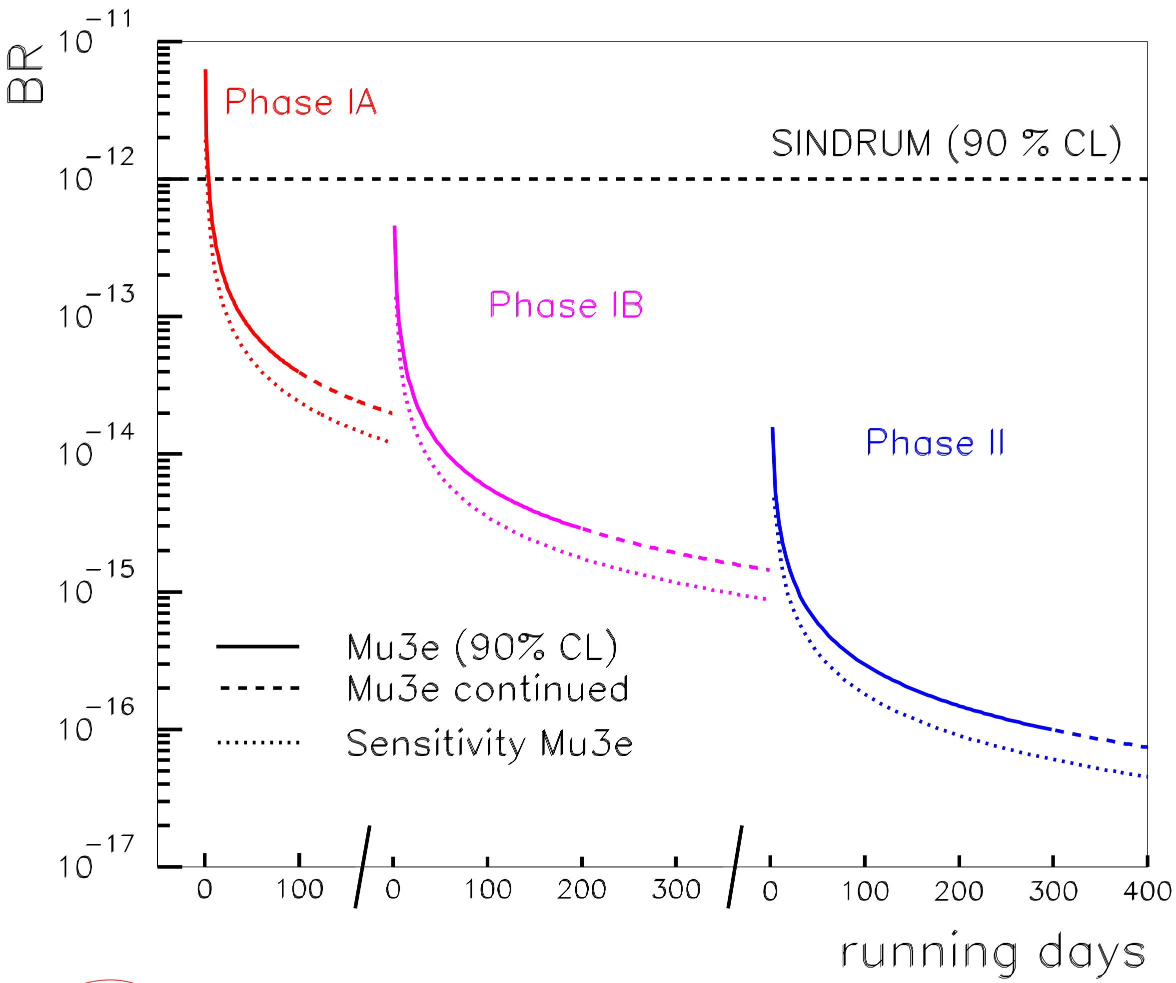
Sensitivity

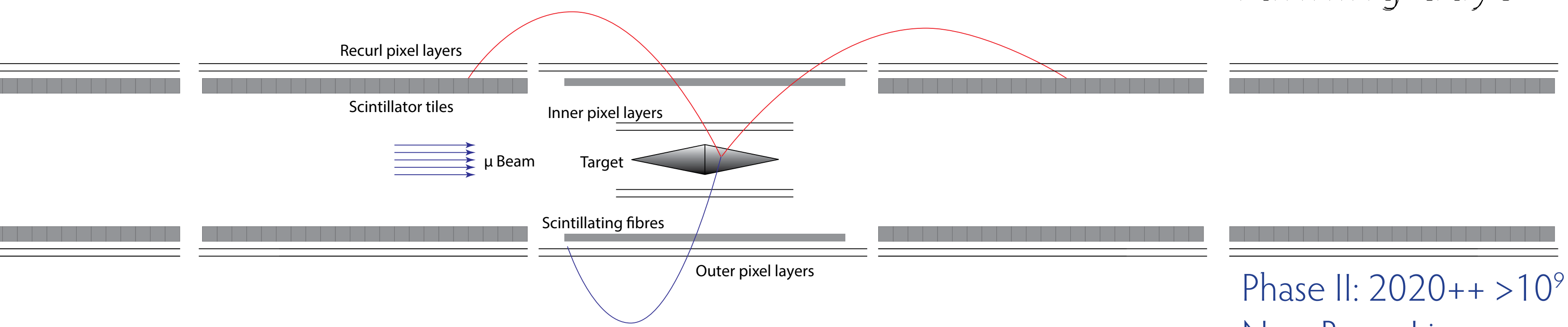




Phase IB: 2018+ 10^8 μ/s

Sensitivity

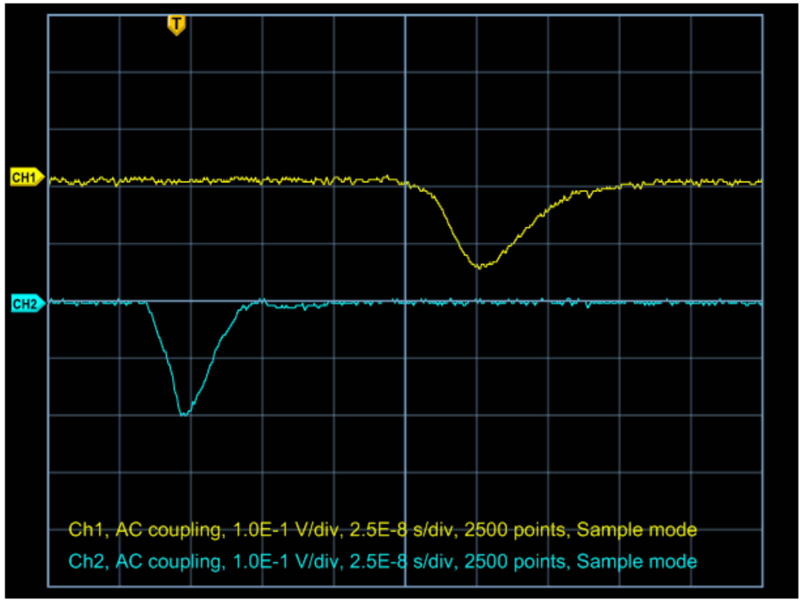




Phase II: 2020++ >10^9 μ/s
New Beam Line

Challenge:
High Speed Data Acquisition

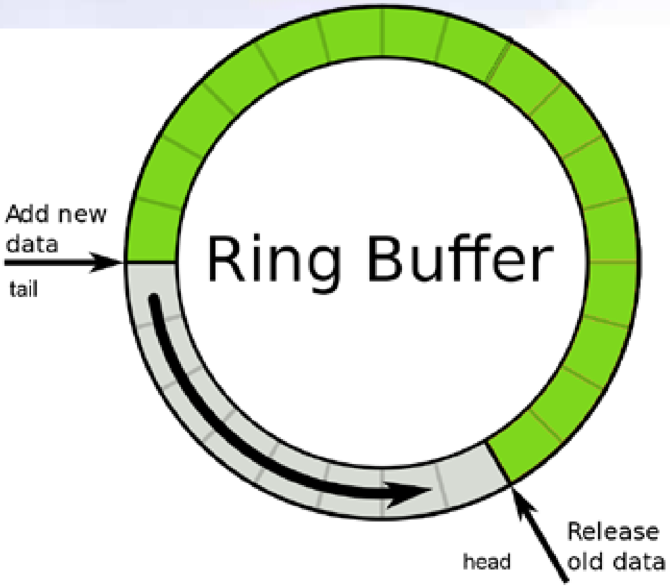
Data acquisition



- Thousands to millions of detector channels
- Fast analog signals (ns down to ps)
- Want digitized time and/or amplitude

- Digitizing at 100 MHz and 8 bit
  100 MByte/s - per channel

Buffers



- Buffer signal for a while
- Either analogue: cable, switched capacitor array
- Or digital: Memory in ring buffer configuration

- Only digitize/store when interesting
- Need to somehow generate a trigger signal

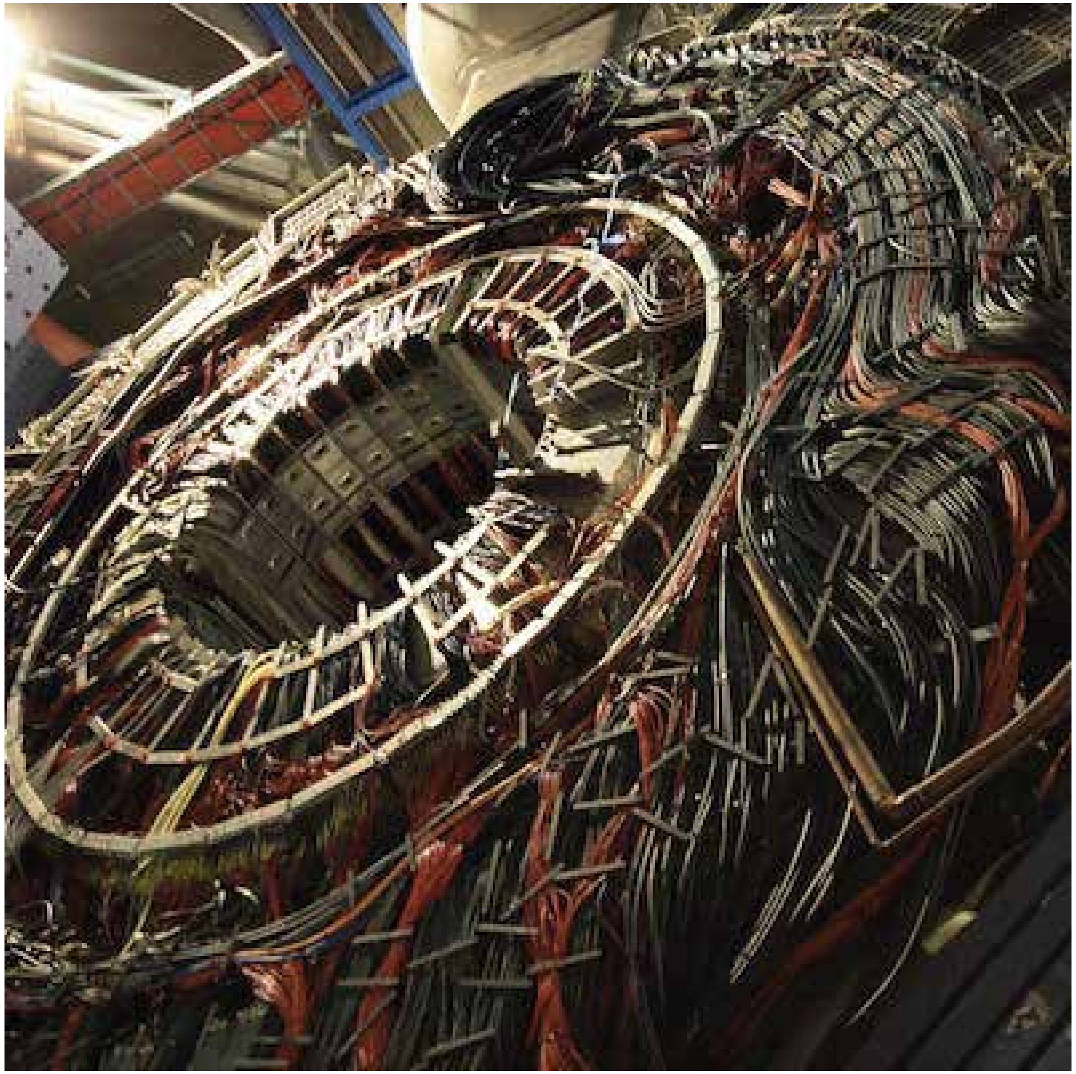
Triggers

- Use subset of channels

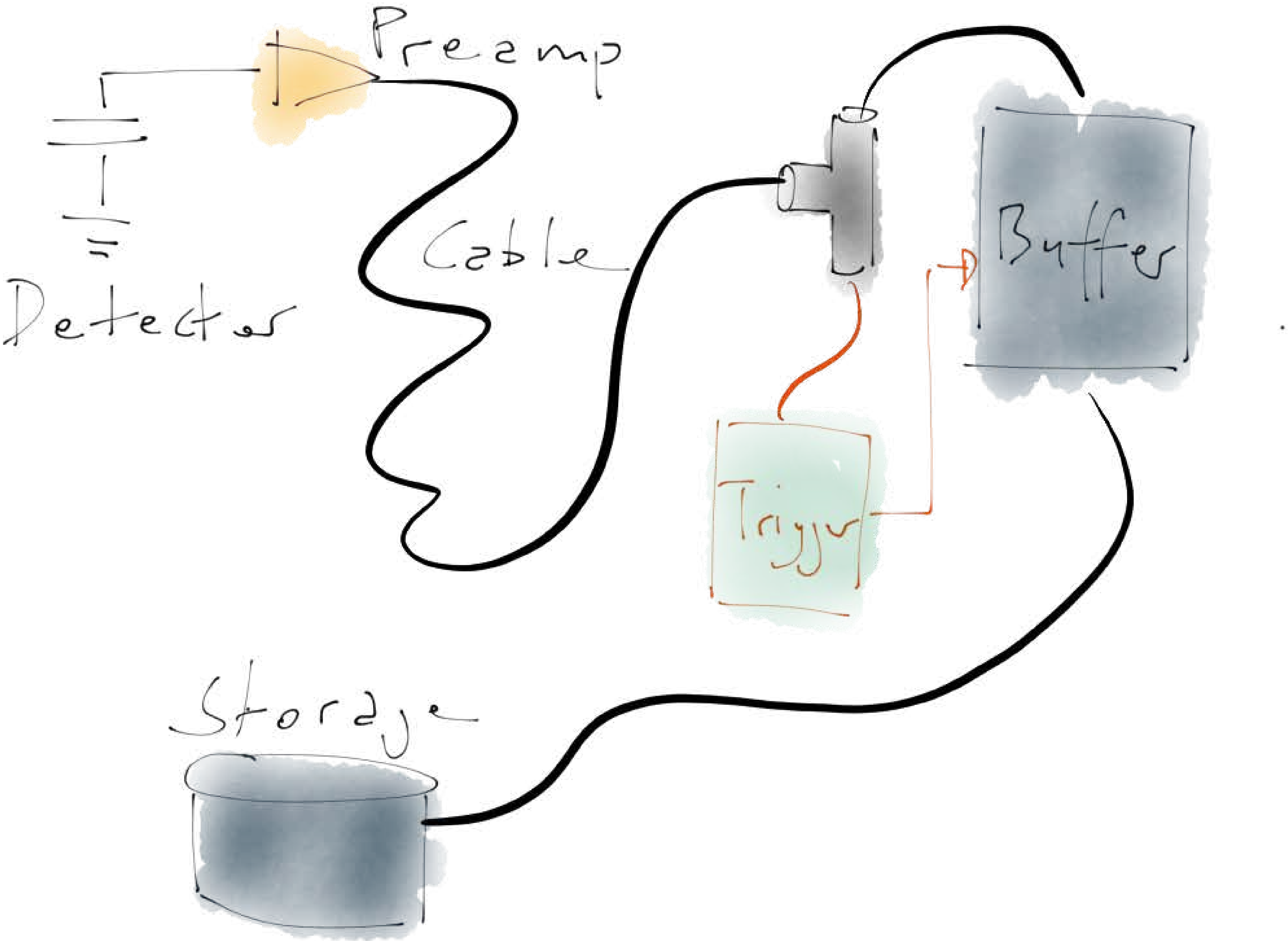
or

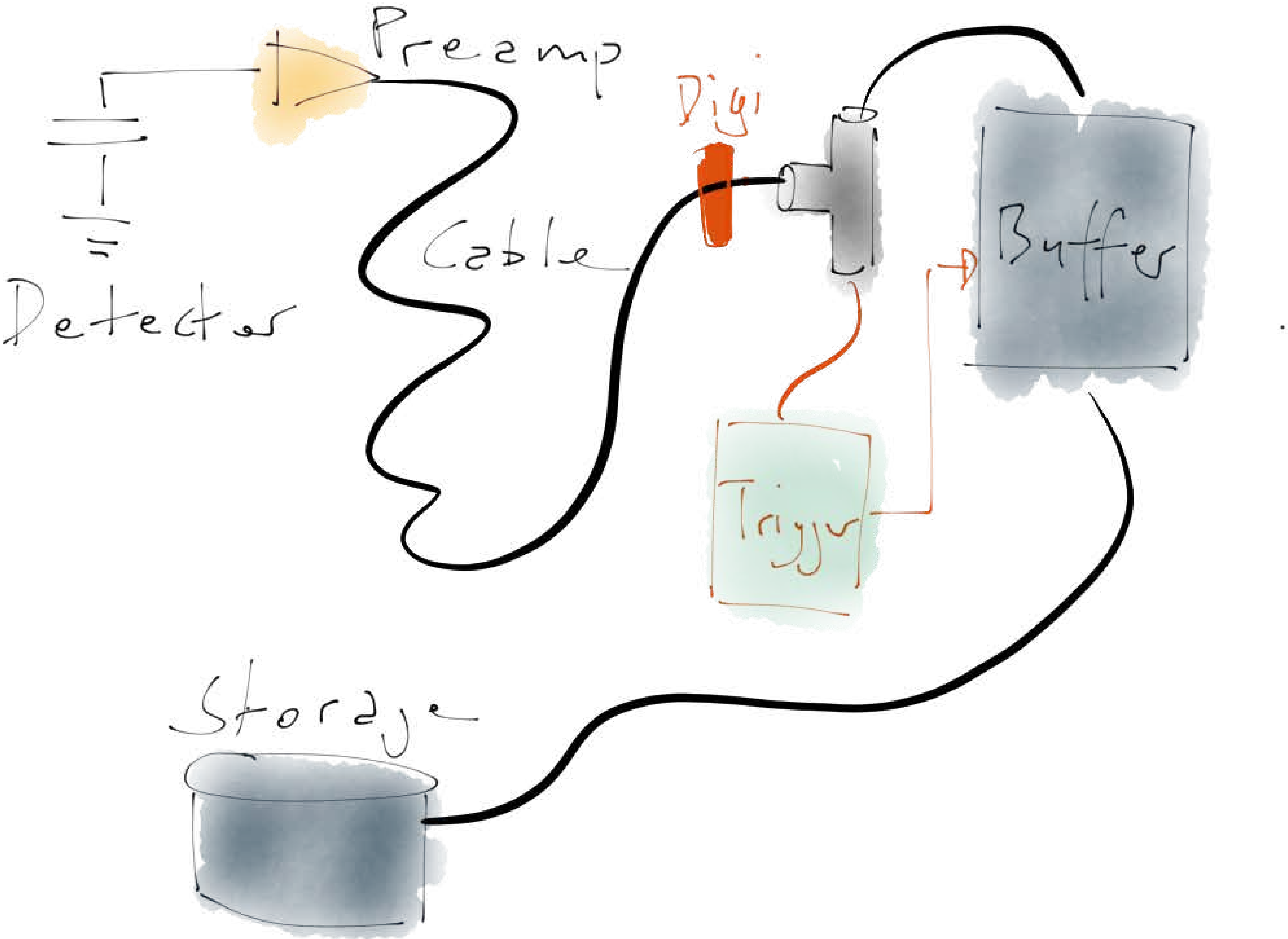
- Use sum of channels
- Compare with some threshold: Typical for energy or on/off measure- ments
- Can also do very complex things like particle tracking (more upon request...)

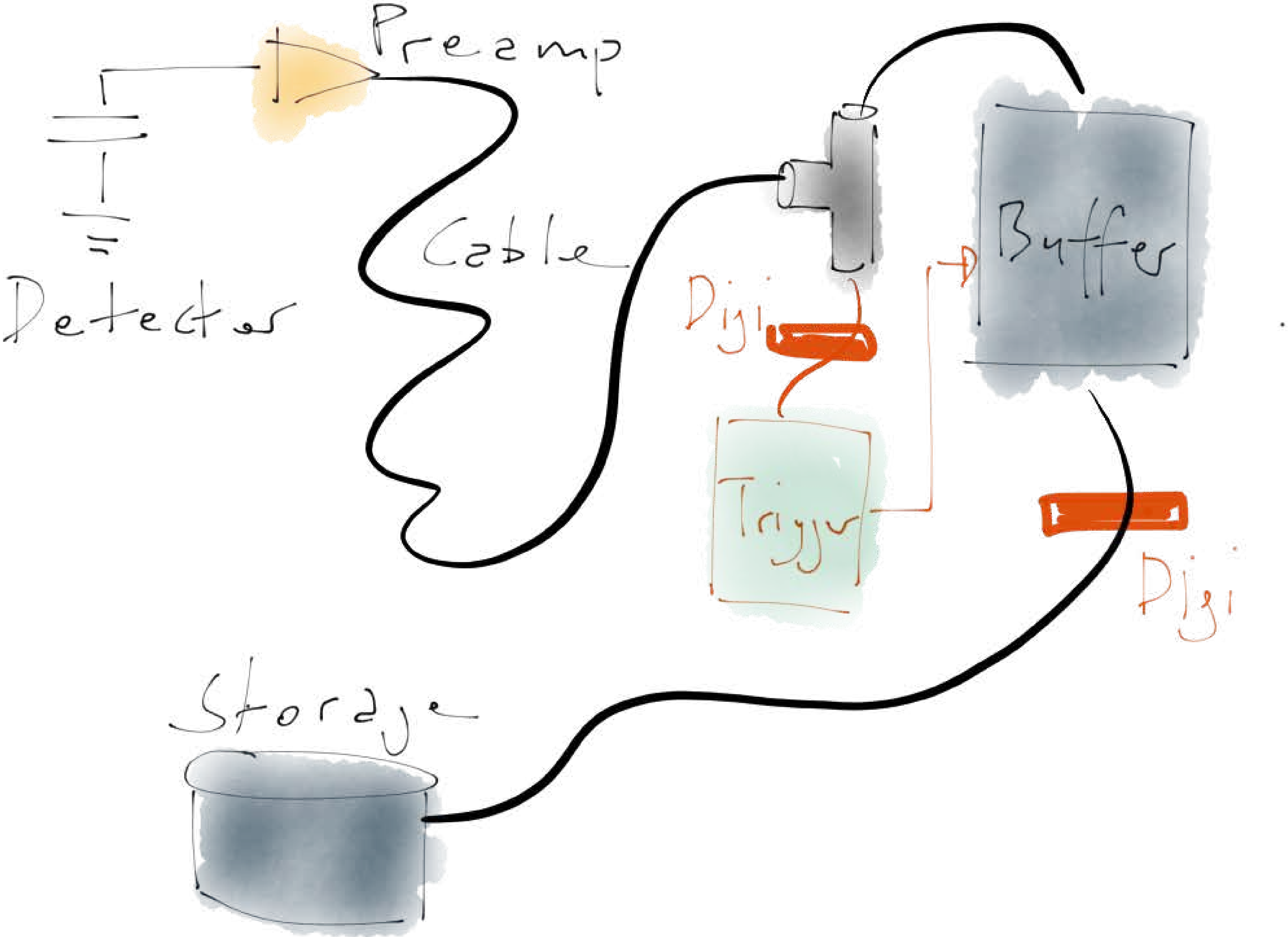
Getting data out

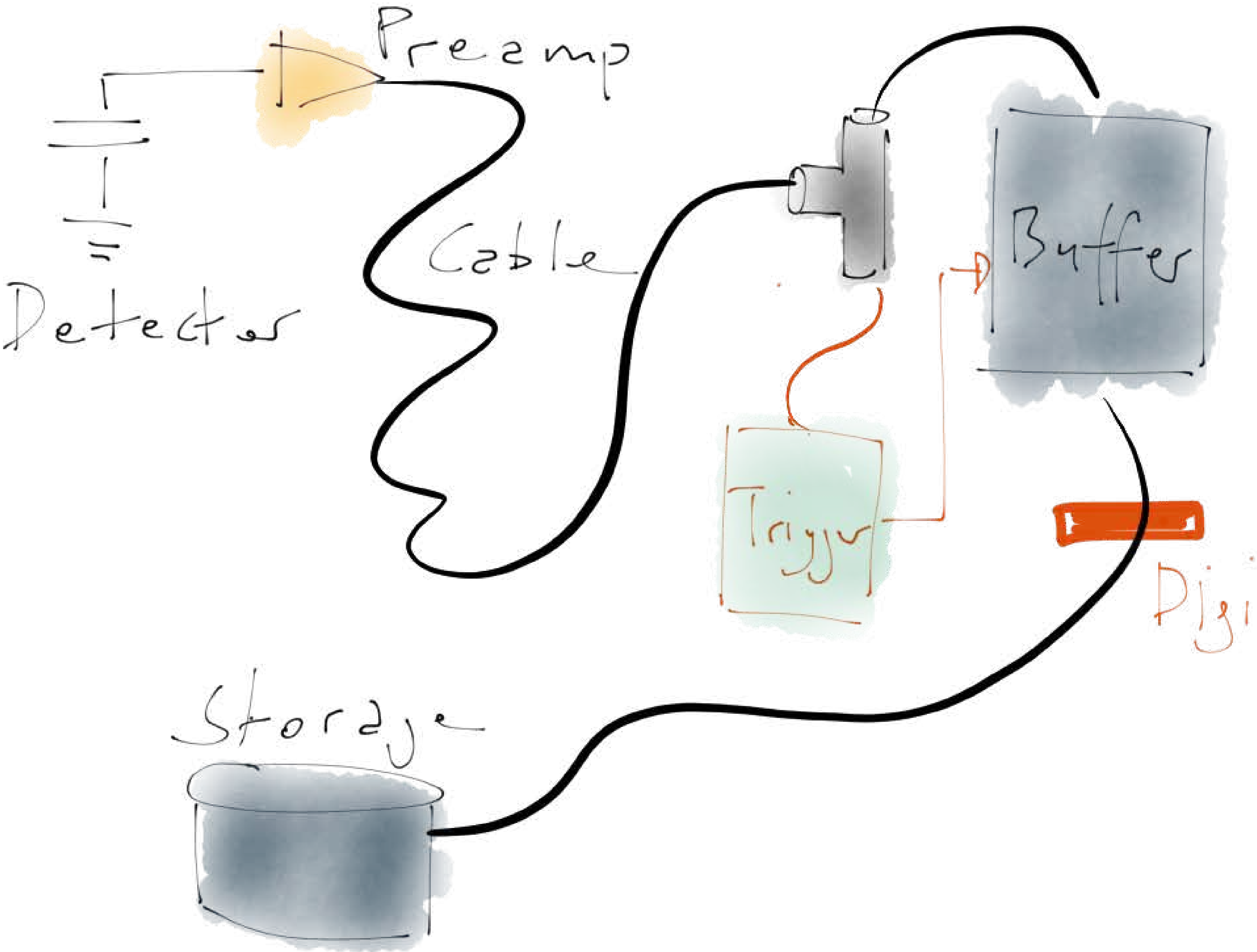


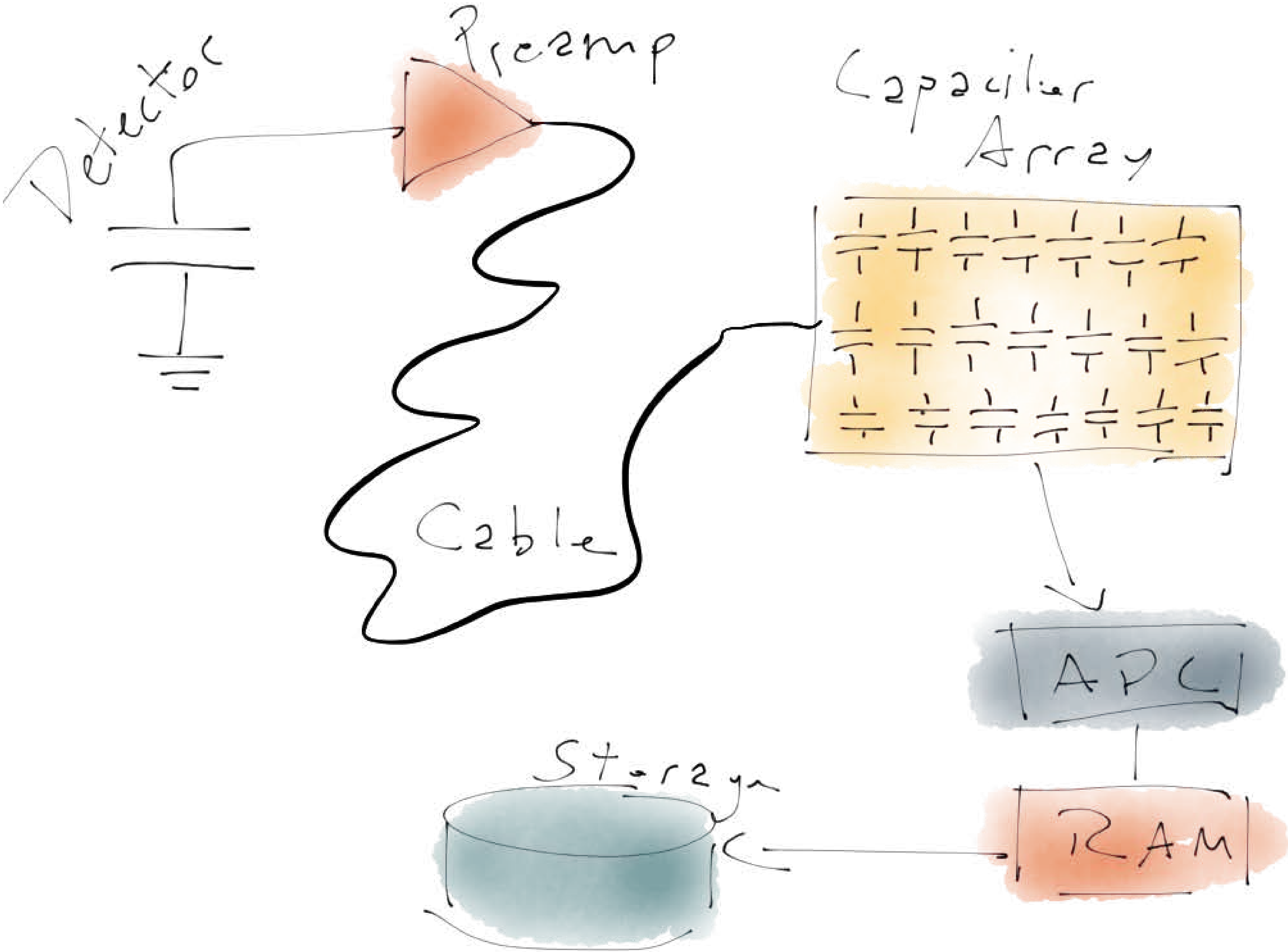
- No space, cooling, power in detector for
  buffer,
  digitalization,
  trigger electronics
- Get data out: The cabling challenge

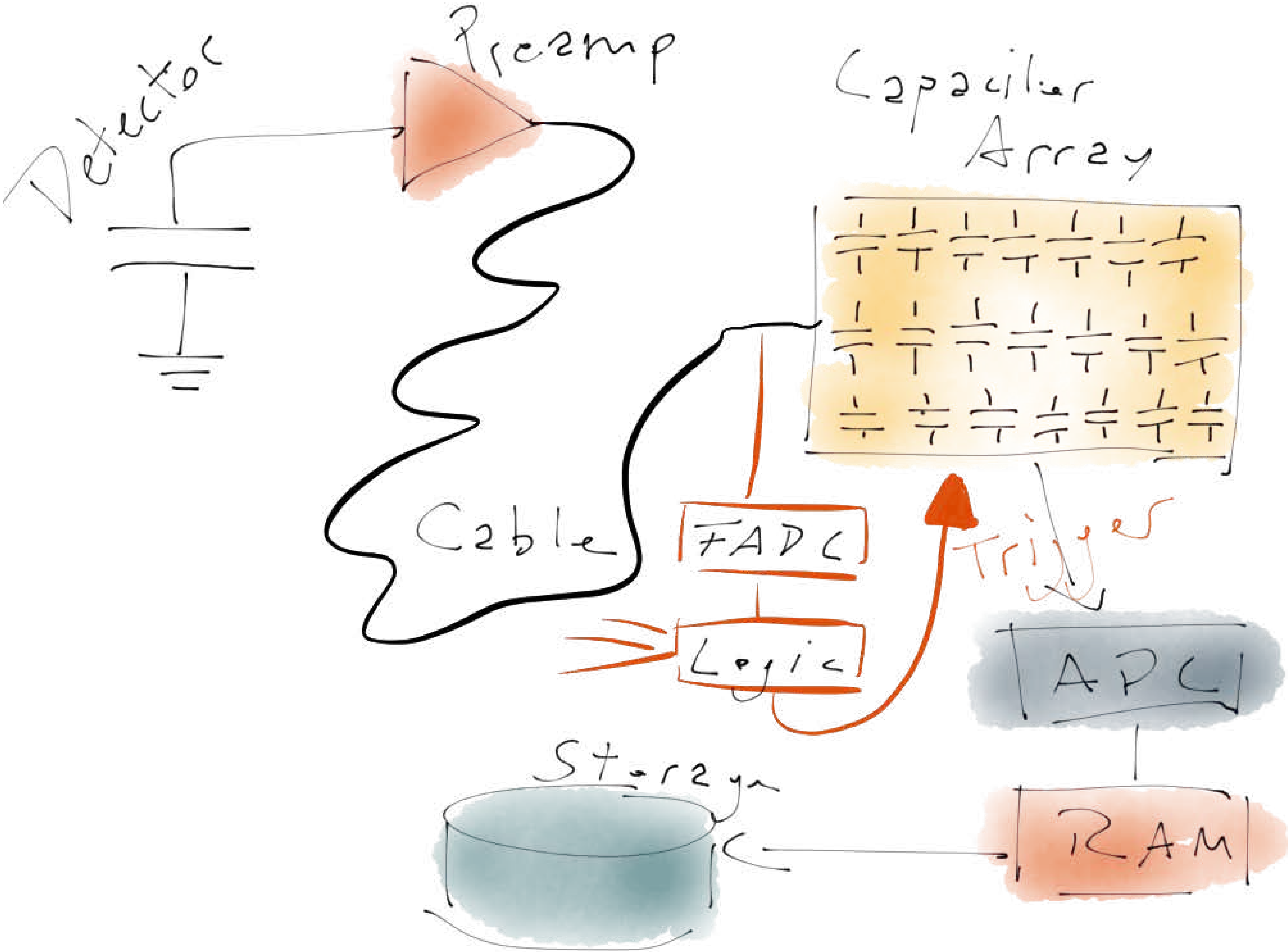

Preamp
Detector
Cable
Buffer
Trigger
Storage


Preamp
Digi
Detector
Cable
Buffer
Trigger
Storage

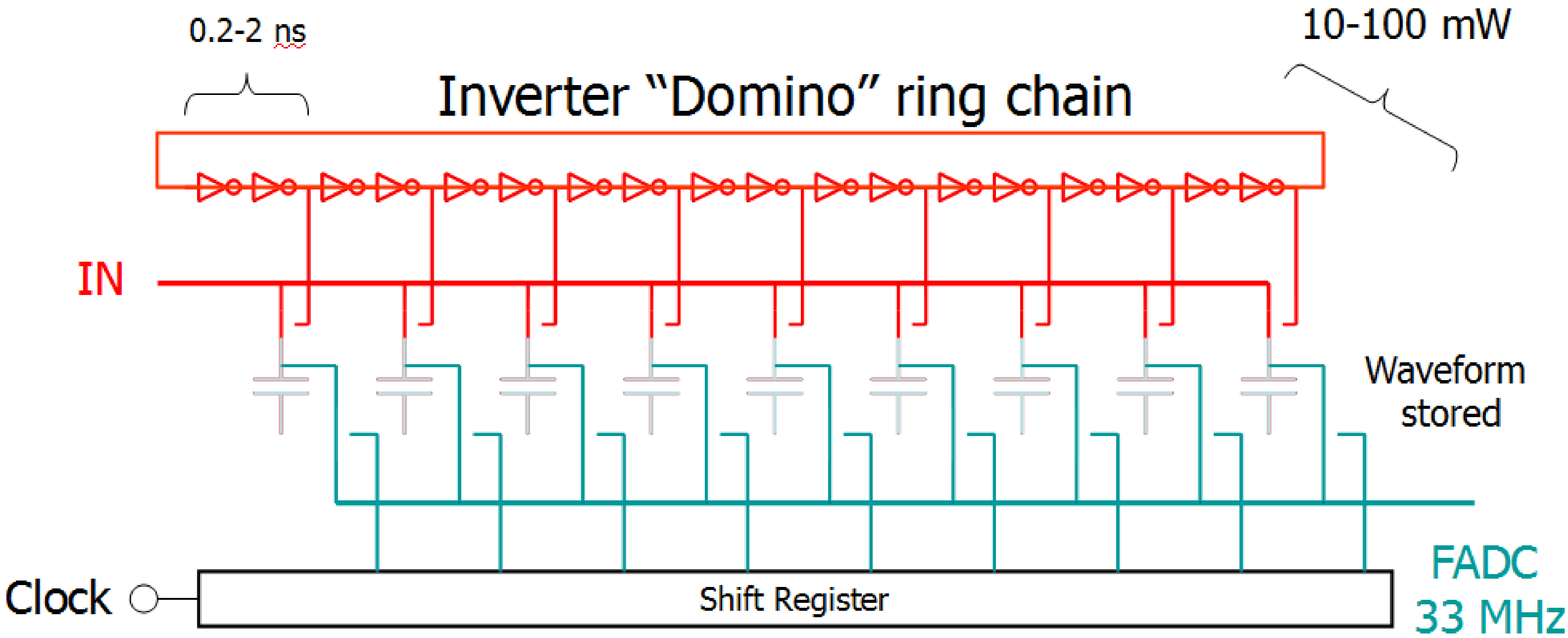

Preamp
Cable
Detector
Buffer
Digi
Trigger
Digi
Storage


Preamp
Detector
Cable
Buffer
Trigger
Digi
Storage


Detector
Preamp
Capacitor Array
Cable
ADC
RAM
Storage


Detector
Preamp
Capacitor
Array
Cable
FADC
Logic
Trigger
ADC
RAM
Storage

Switched Capacitor Arrays - the DRS Chips



"Time stretcher" GHz → MHz

MAGIC Readout System

S. Ritt, PSI

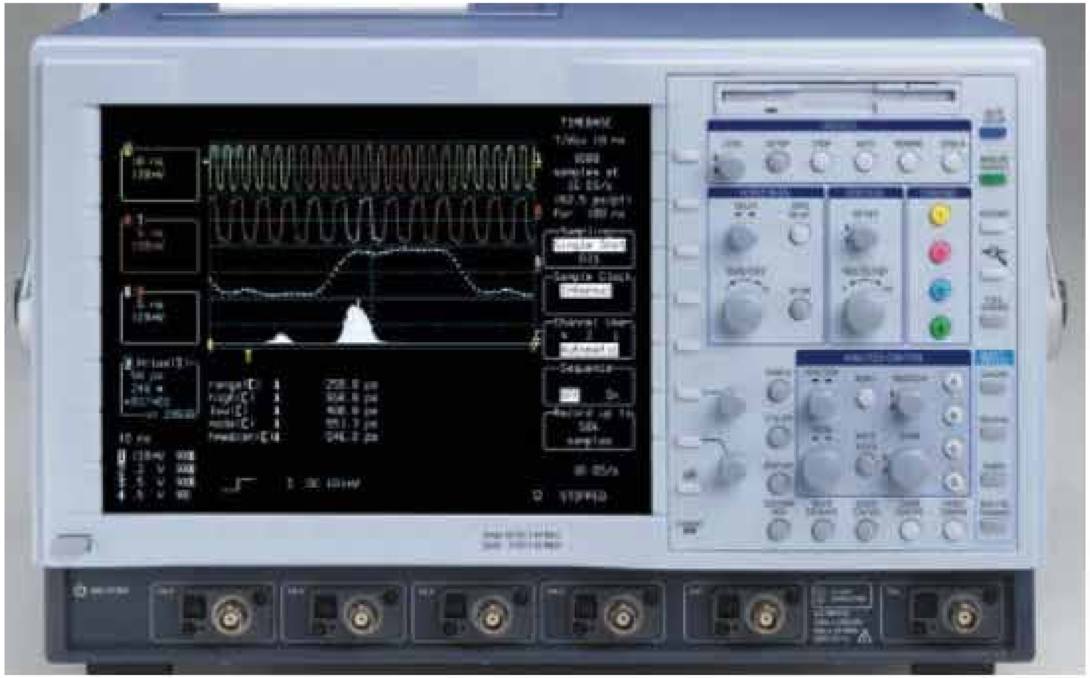
Old system:

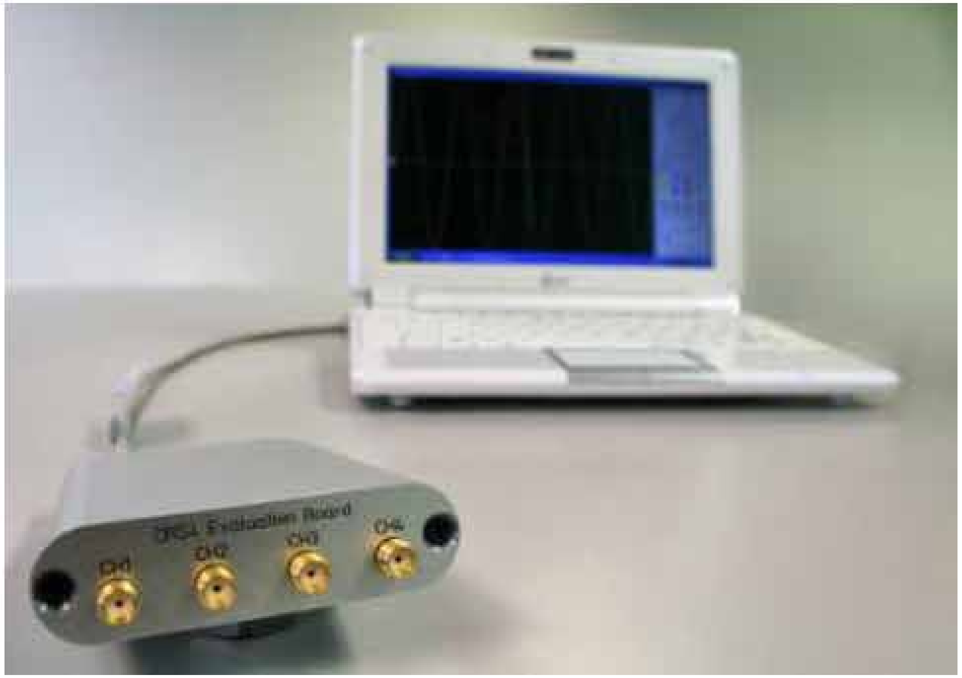
- 2 GHz flash (multiplexed)
- 512 channels
- Total of five racks, ~20 kW

New system:

- 2 GHz SCA (DRS4 based)
- 2000 channels
- 4 VME crates
- Channel density 10x higher

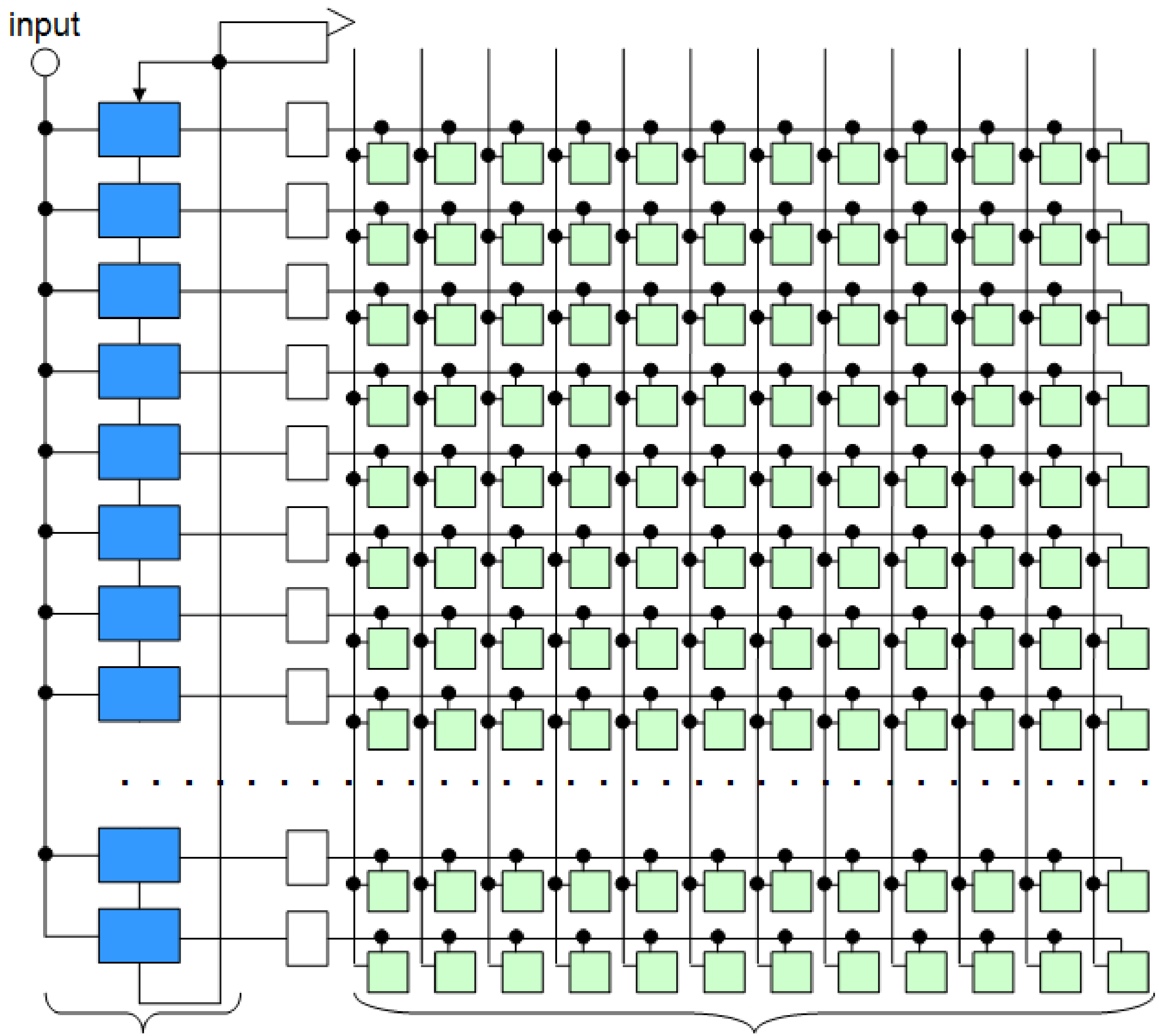
DRS USB Oscilloscope





Next Generation

- 32 fast sampling cells (10 GSPS)
- 100 ps sample time, 3.1 ns hold time
- Hold time long enough to transfer voltage to secondary sampling stage with moderately fast buffer (300 MHz)
- Shift register gets clocked by inverter chain from fast sampling stage

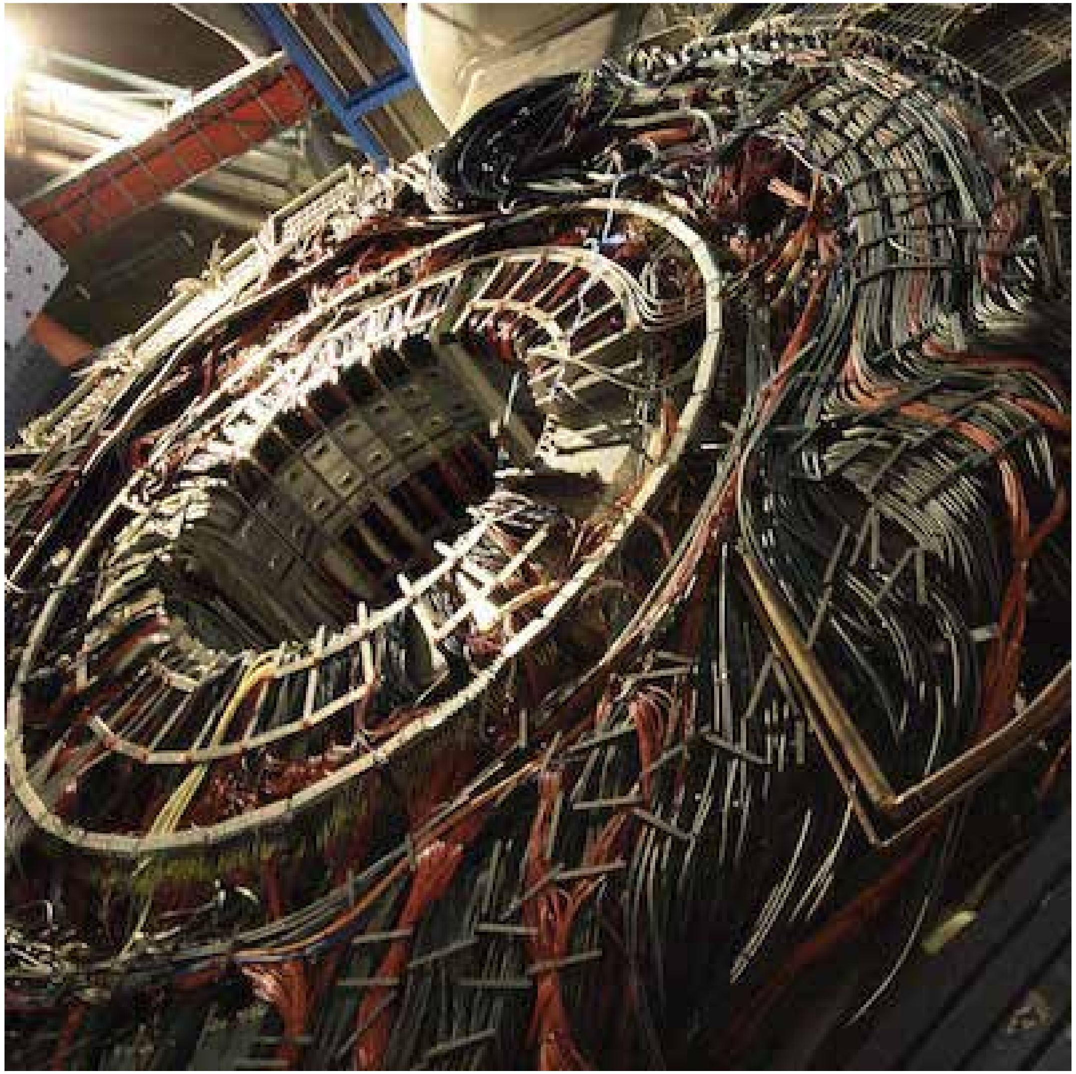


S. Ritt, PSI

Or use a completely different approach...

Streaming Readout

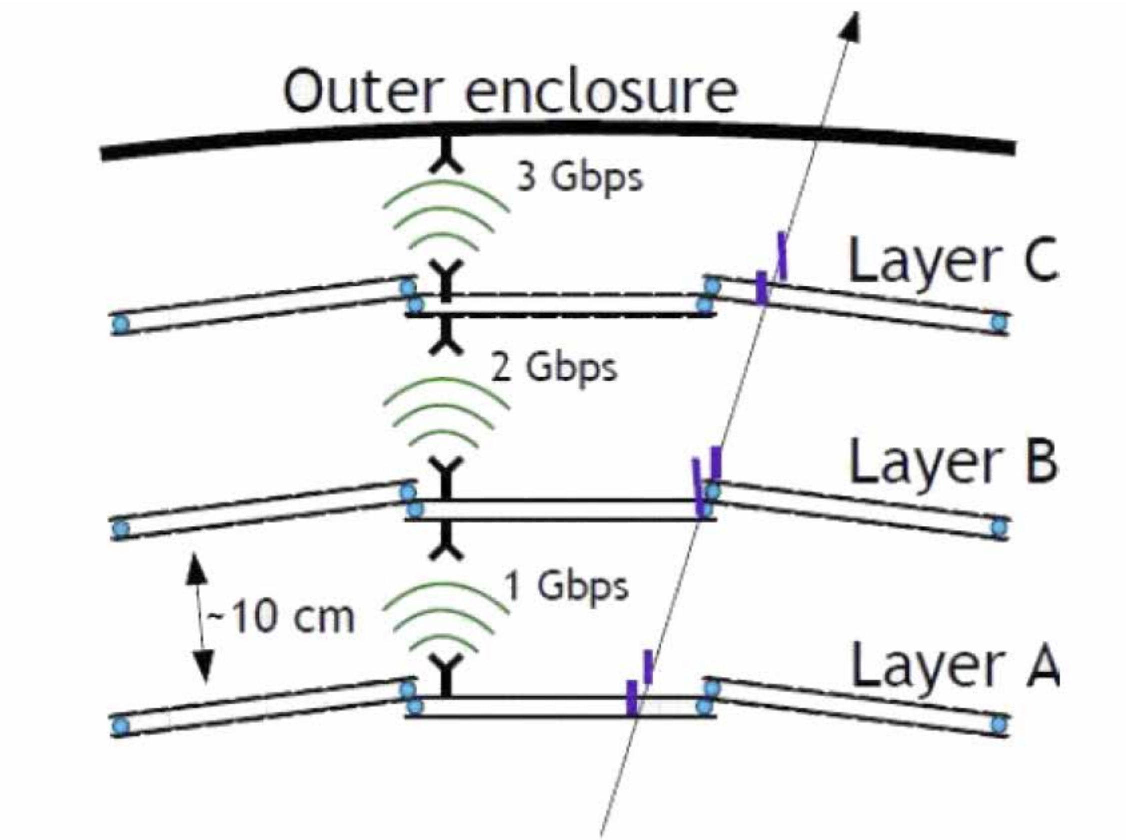
Getting data out



- No space, cooling, power in detector for
  buffer,
  digitalization,
  trigger electronics

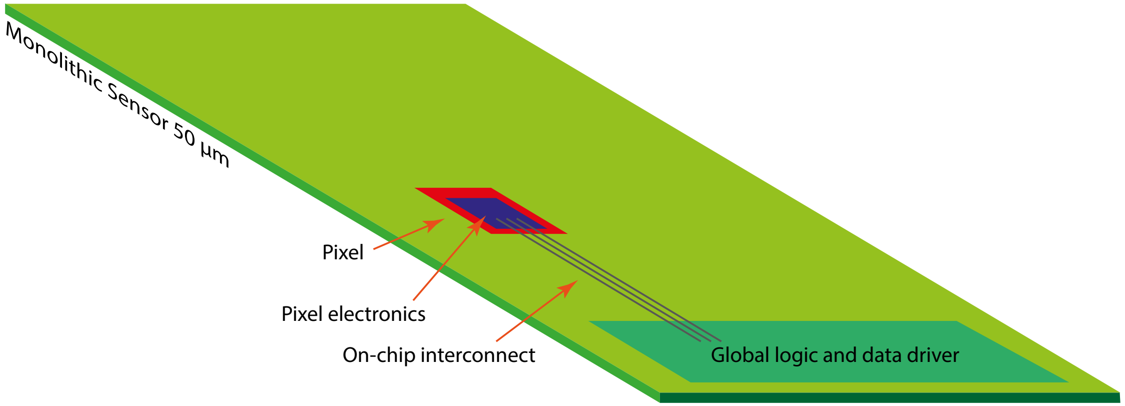
- Really?

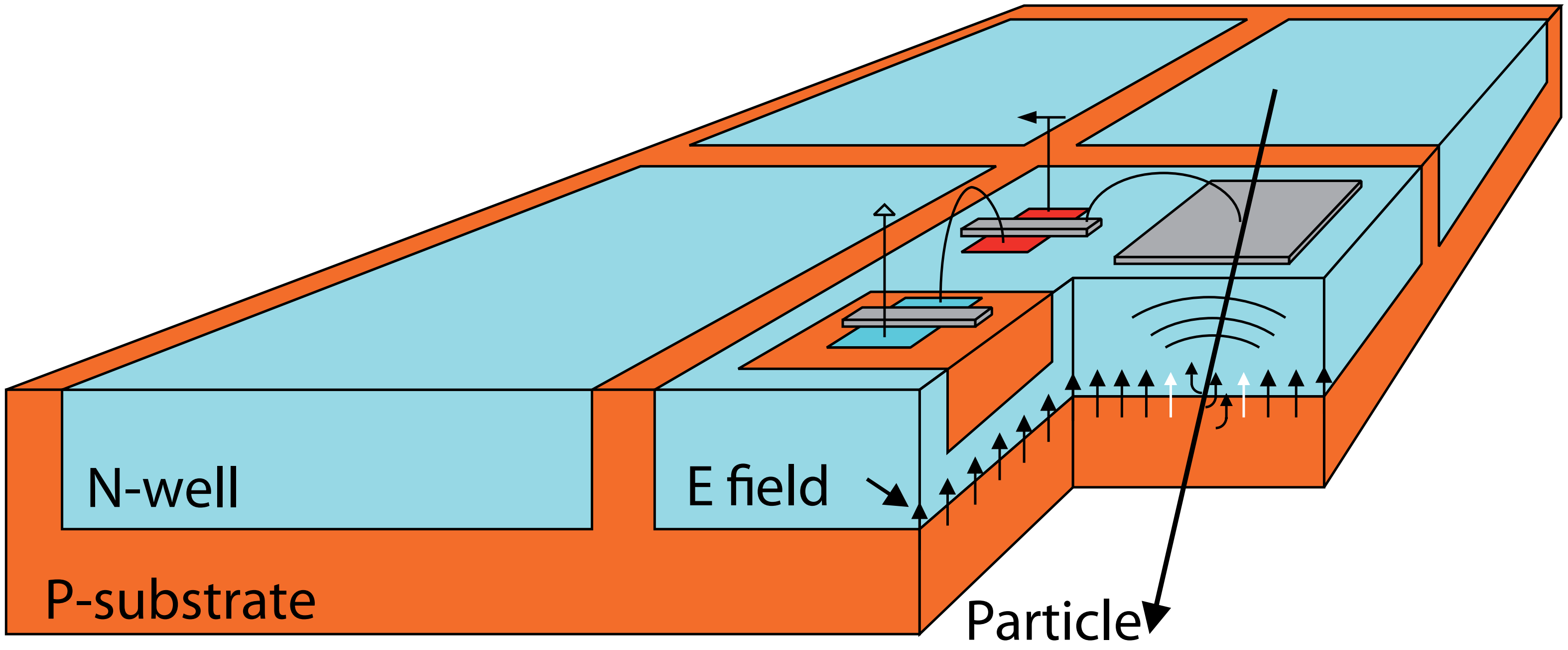
Getting data out



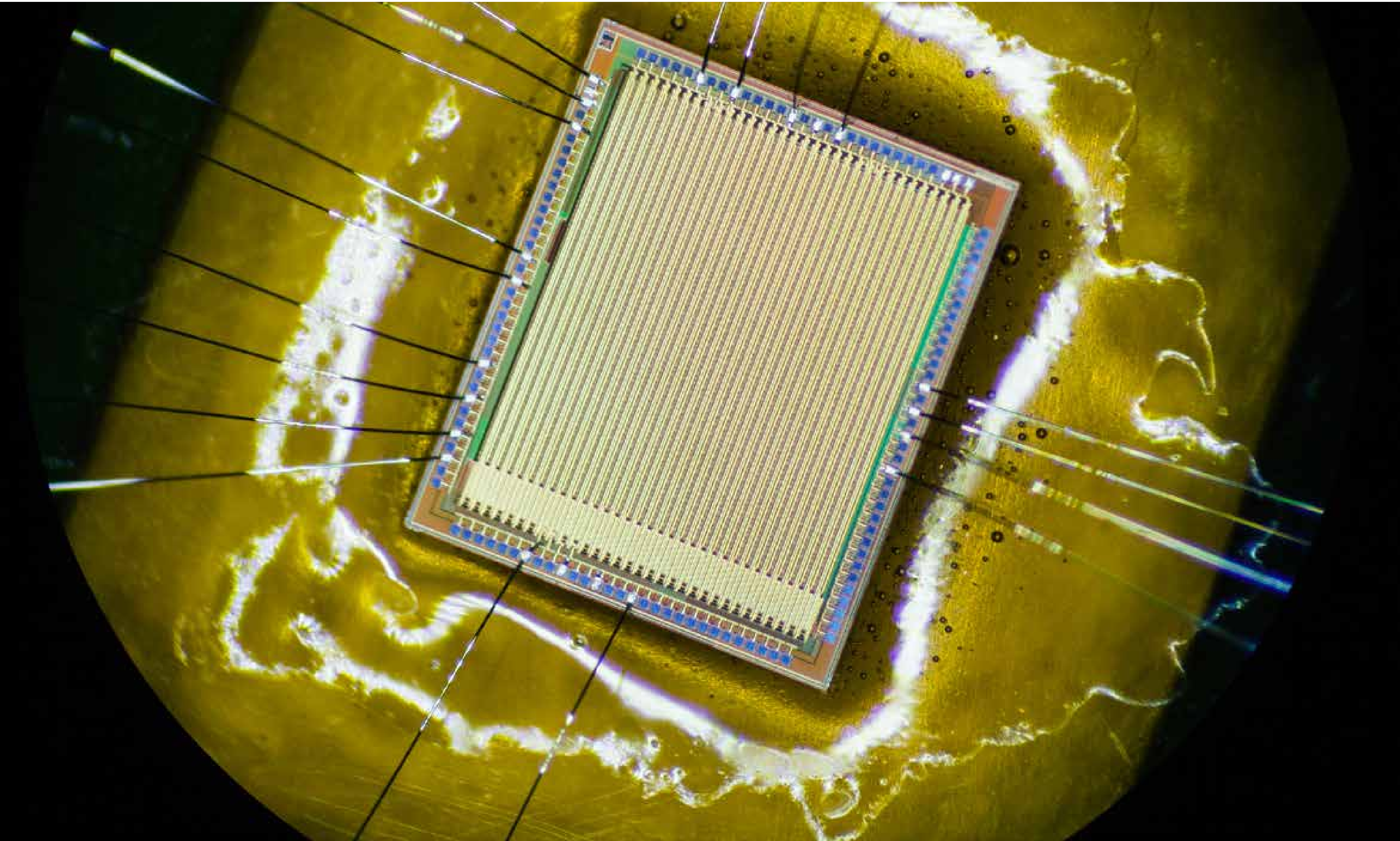
- No space, cooling, power in detector for
  buffer,
  digitalization,
  trigger electronics

Use custom integrated circuits!

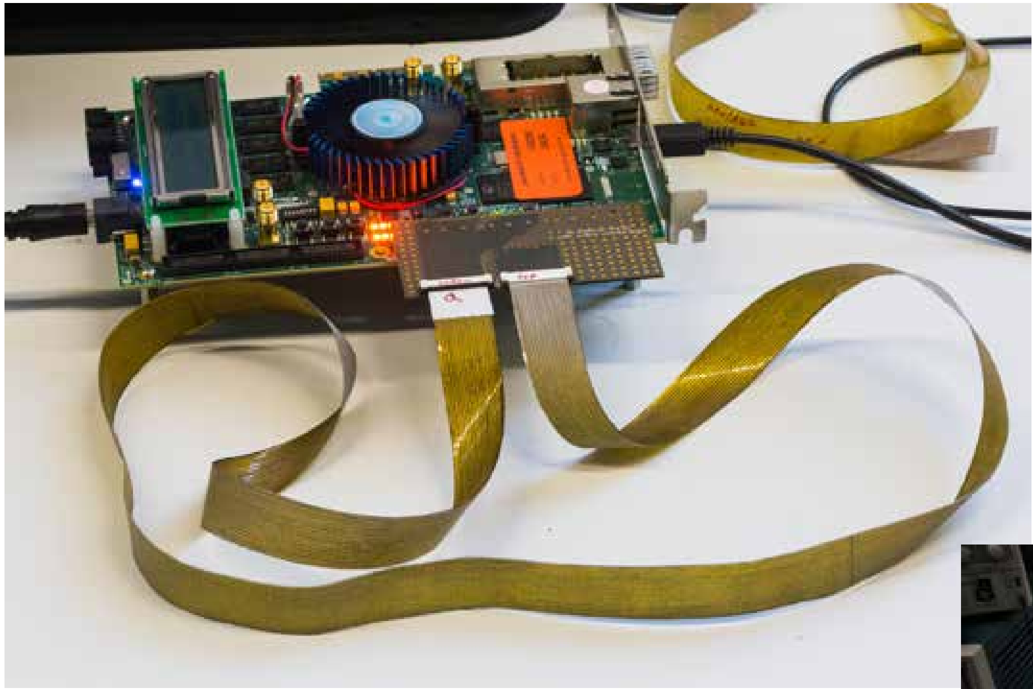




Digital electronics is tiny....

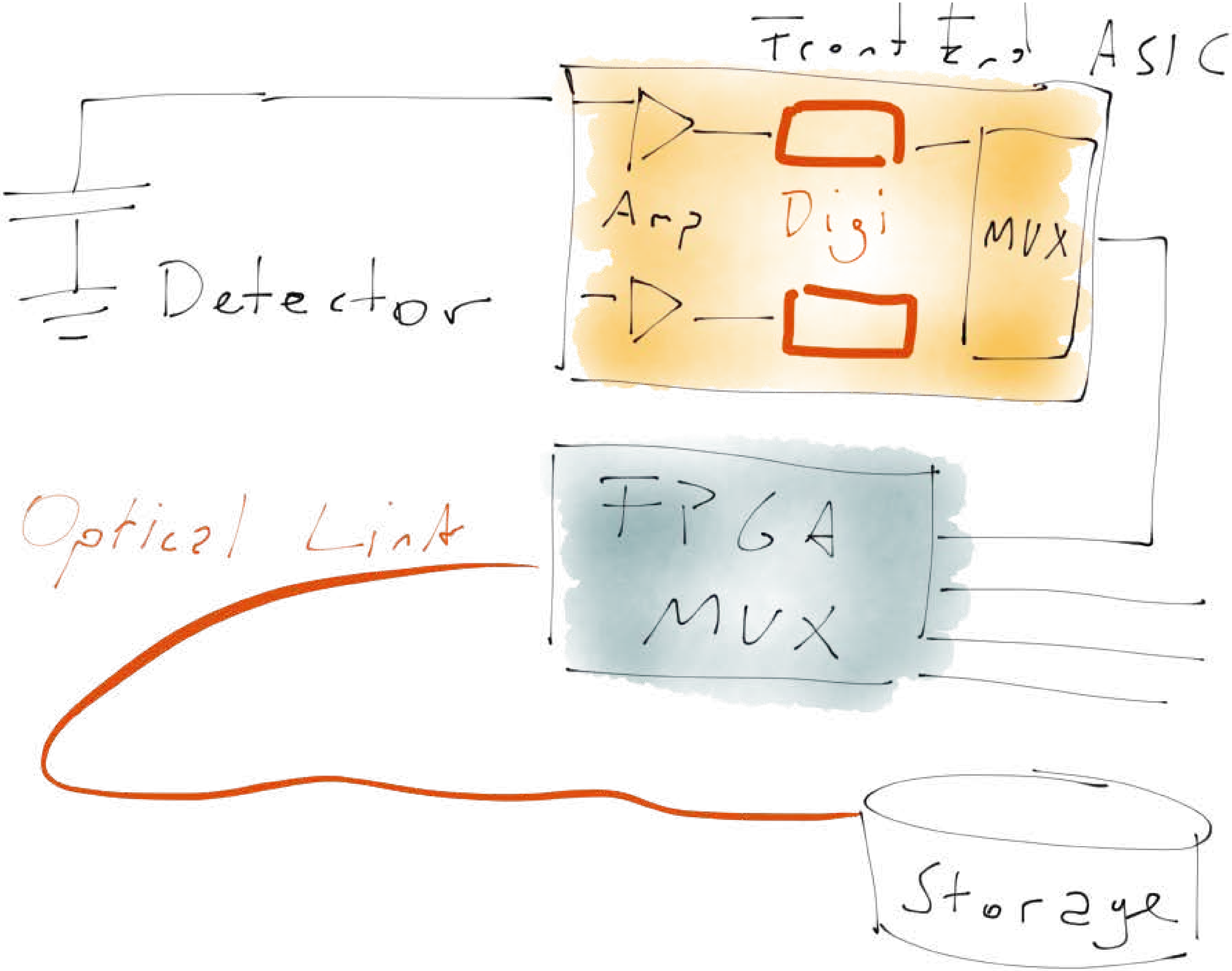


Fast links on thin cables

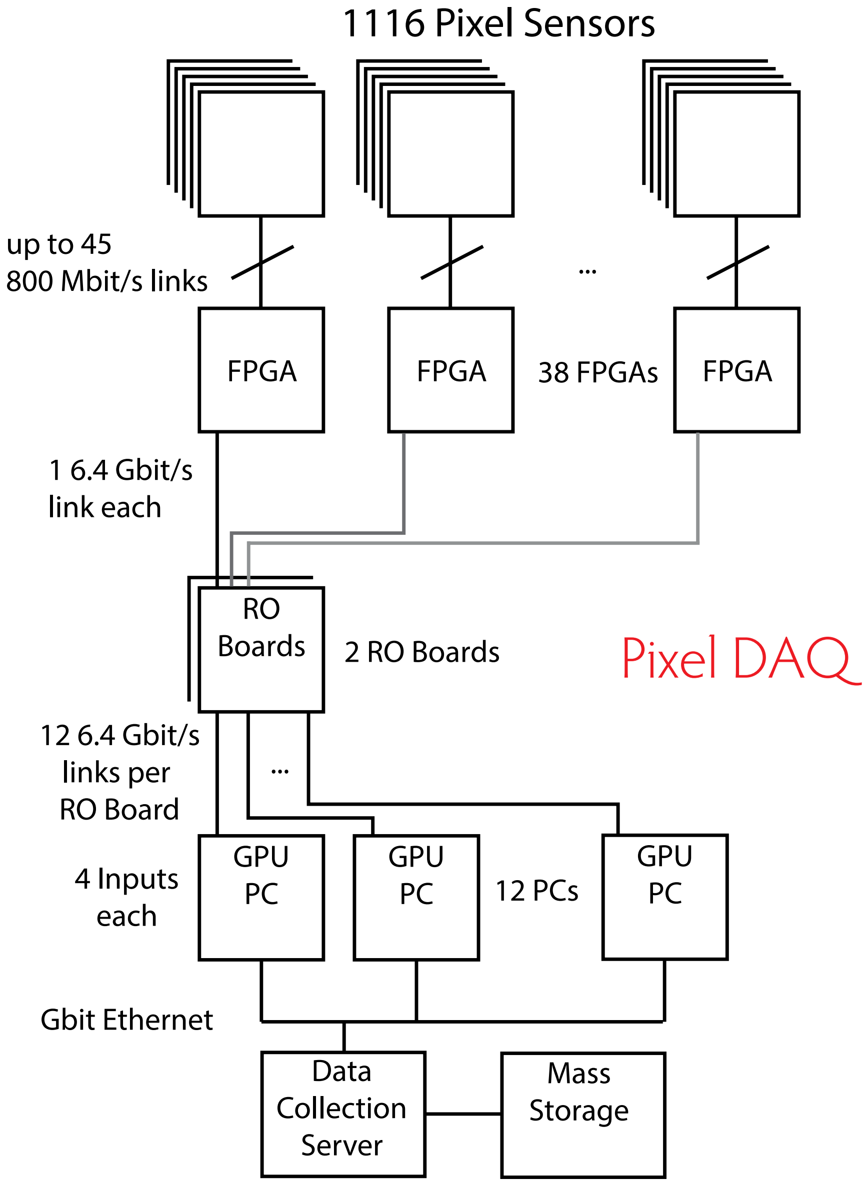


- Up to 1.6 GBit/s over one differential pair to an FPGA

- Multiplex data and send via optical link 10 GBit/s easy, more possible


Front End ASIC
Amp
Digi
MUX
Detector
FPGA
MUX
Optical Link
Storage

Data Acquisition



- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- O(50) PCs with GPUs

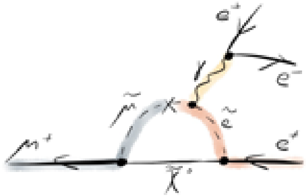
Online filter farm

Online software filter farm

- PCs with FPGAs and Graphics Processing Units (GPUs)
- Online track and event reconstruction
- 10^9 3D track fits/s achieved
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s

Backup Material

A general effective Lagrangian



Tensor terms (dipole) e.g. supersymmetry

$$L_{\mu \to eee} = 2 G_F (m_\mu A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_L \bar{\mu}_L \sigma^{\mu\nu} e_R F_{\mu\nu}$$

Four-fermion terms e.g. Z'

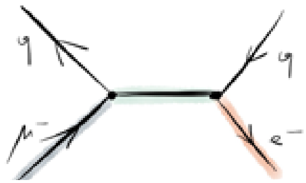
$$+ g_1 (\bar{\mu}_R e_L)(\bar{e}_R e_L) \qquad + g_2 (\bar{\mu}_L e_R)(\bar{e}_L e_R)$$

scalar

$$+ g_3 (\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R) \qquad + g_4 (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$

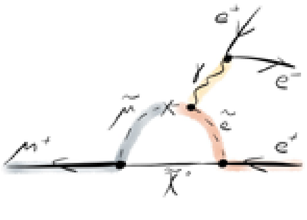
$$+ g_5 (\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_L \gamma^\mu e_L) \qquad + g_6 (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_R \gamma^\mu e_R) \; + H.C.)$$

vector

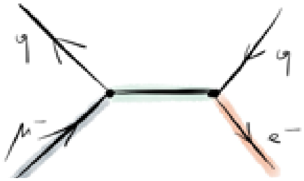


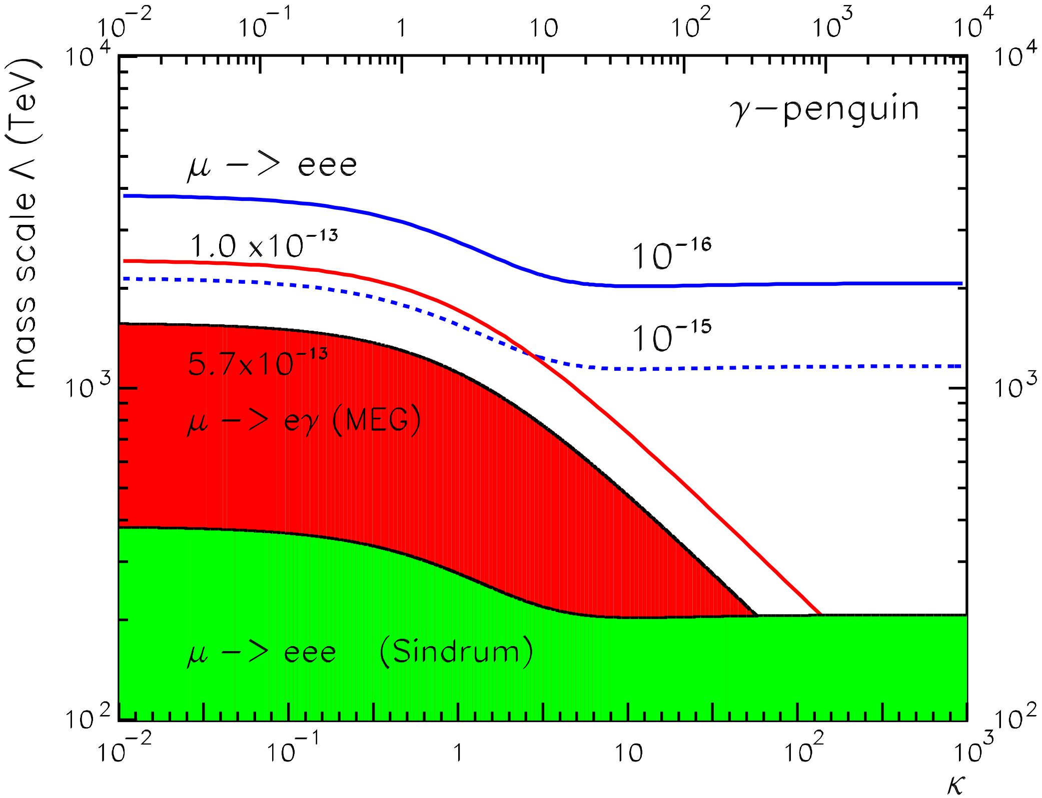
(Y. Kuno, Y. Okada,
Rev.Mod.Phys. 73 (2001) 151)

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



$$L_{LFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$

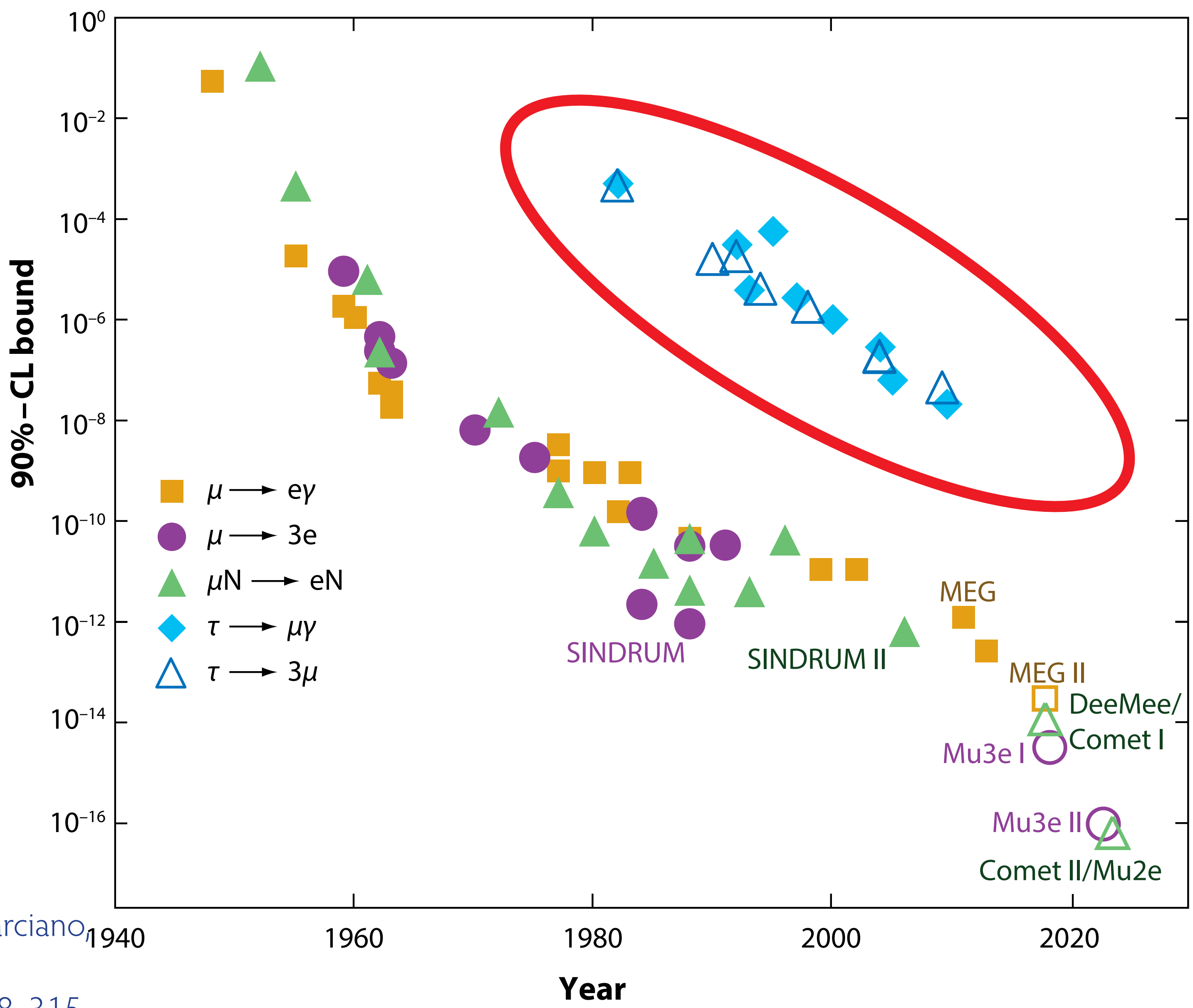




- One loop term and one contact term
- Ratio κ between them
- Common mass scale Λ
- Allows for sensitivity comparisons between $\mu \to eee$ and $\mu \to e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):

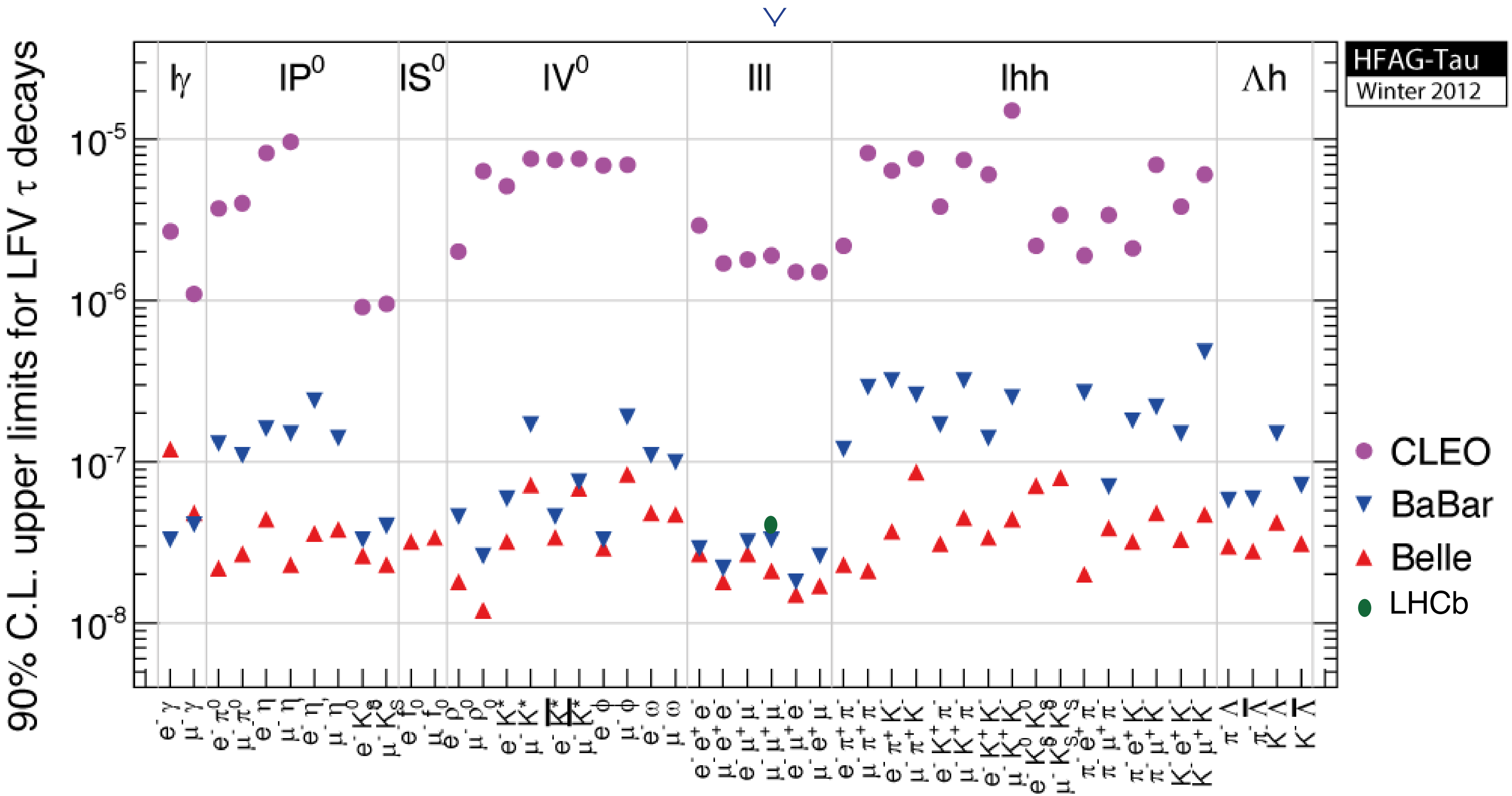
$$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$

History of LFV experiments

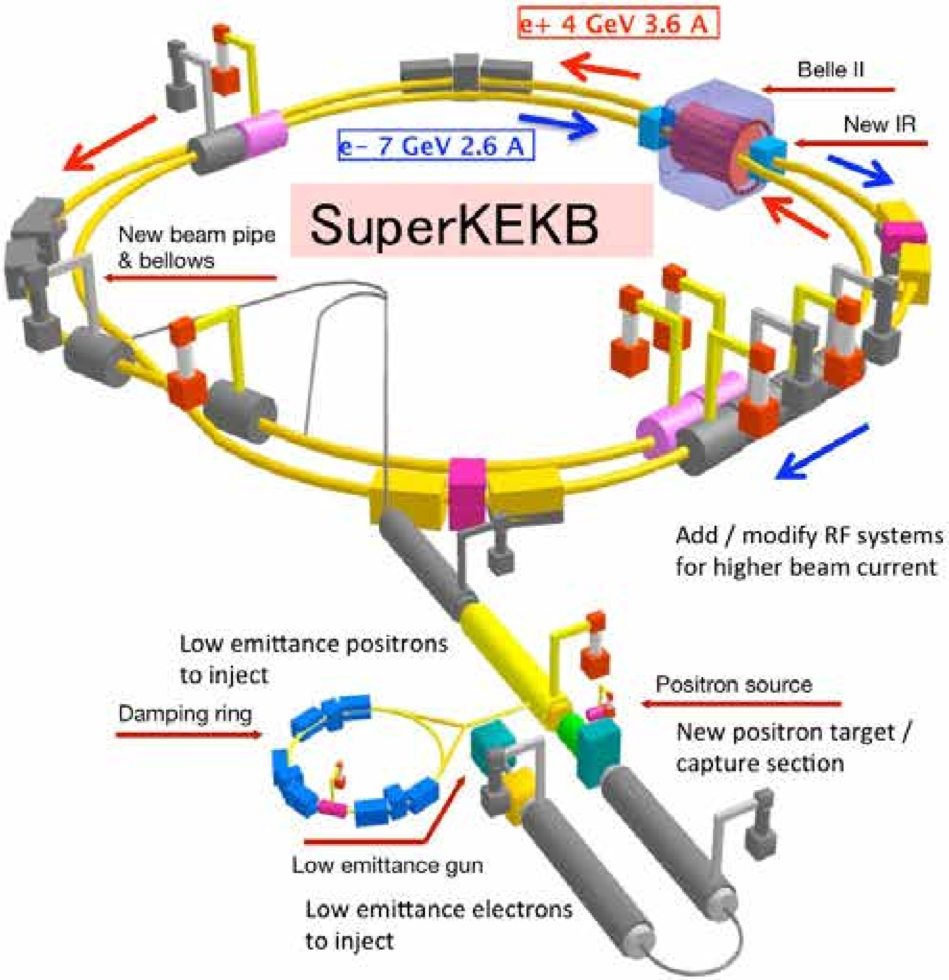


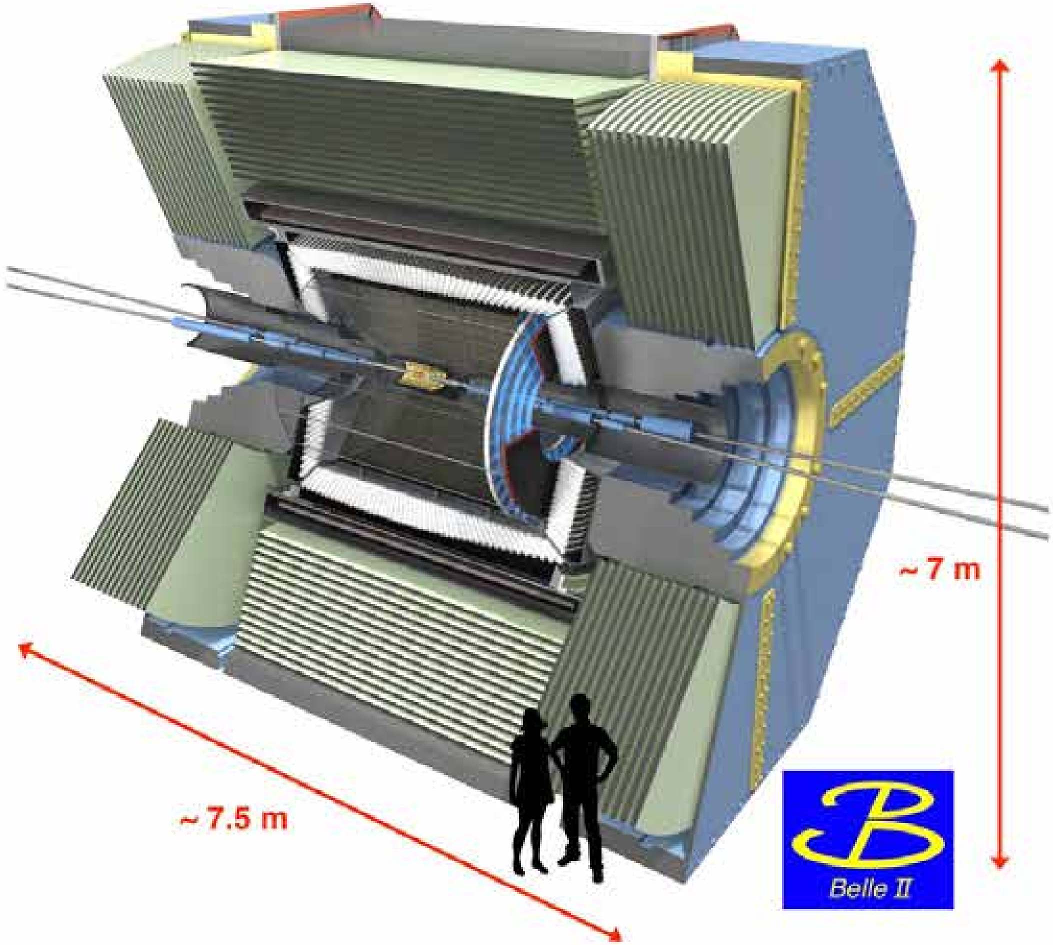
(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

Lepton flavour violating τ-decays



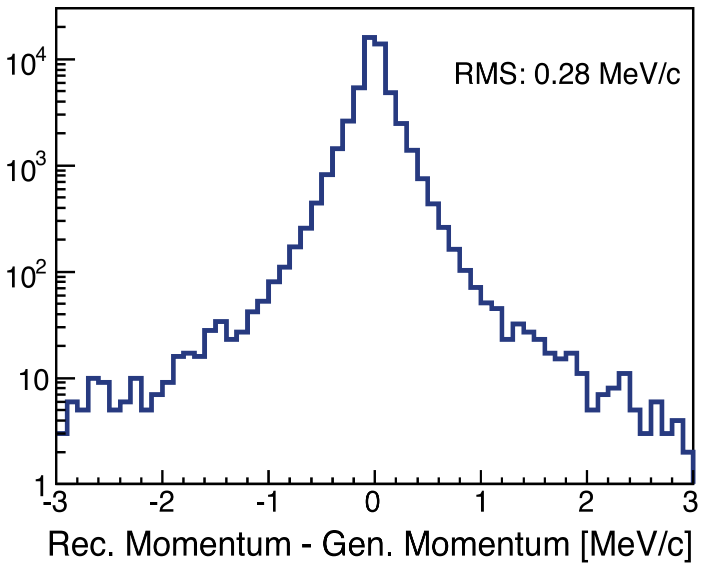
Belle II at Super KEKB



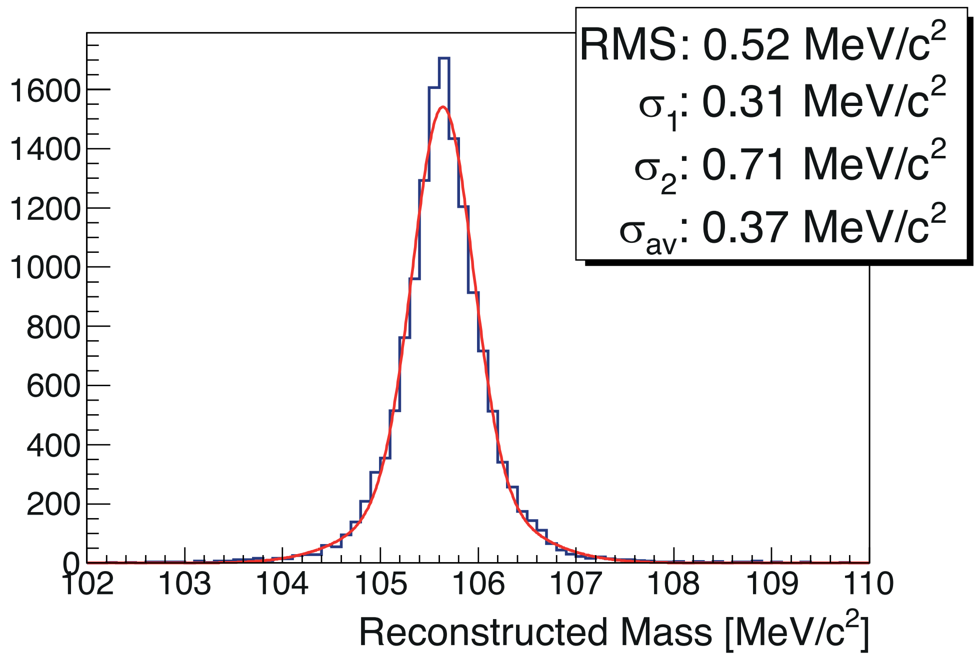


Expect 5× 10^{10} τ pairs - branching fractions of 10^{-9} achievable

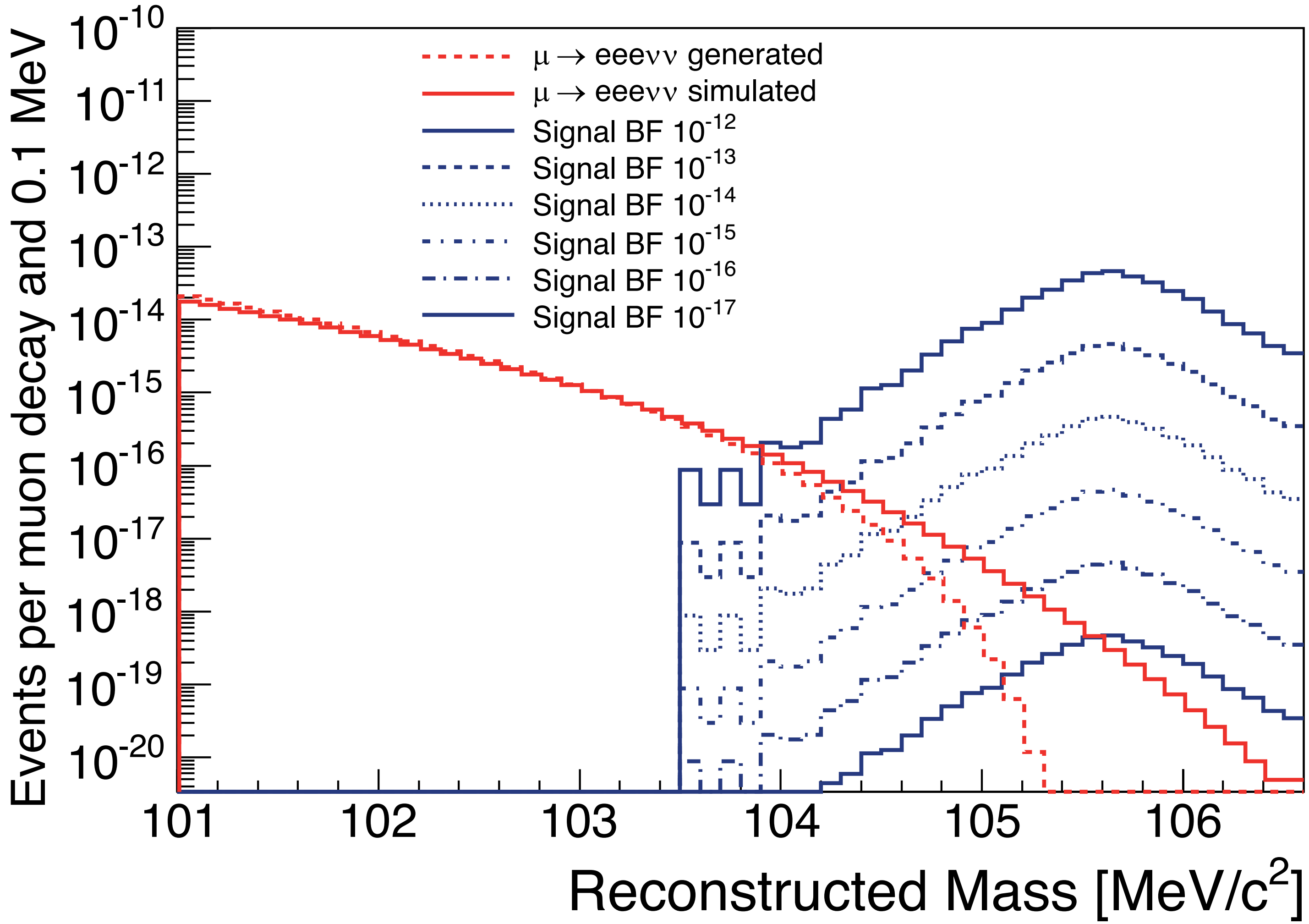
Simulated Performance - Mu3e Phase II



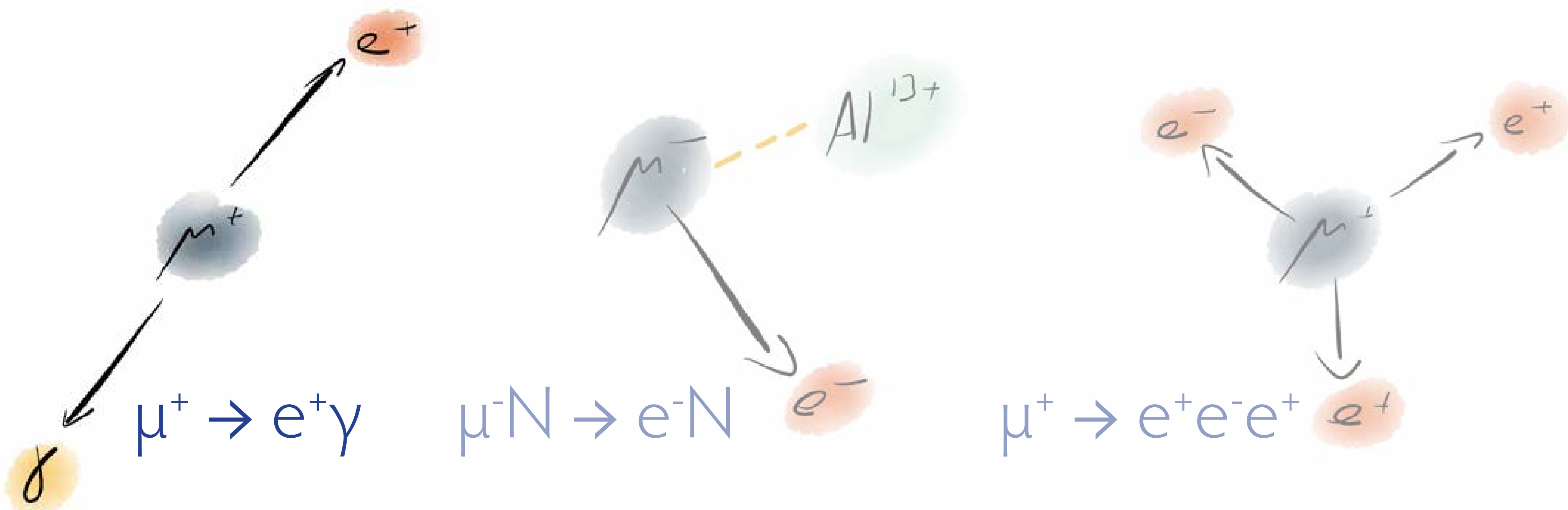
- 3D multiple scattering track fit
- Simulation results:
  280 keV single track momentum
  520 keV total mass resolution



Simulated Performance - Mu3e Phase II



LFV Muon Decays: Experimental signatures

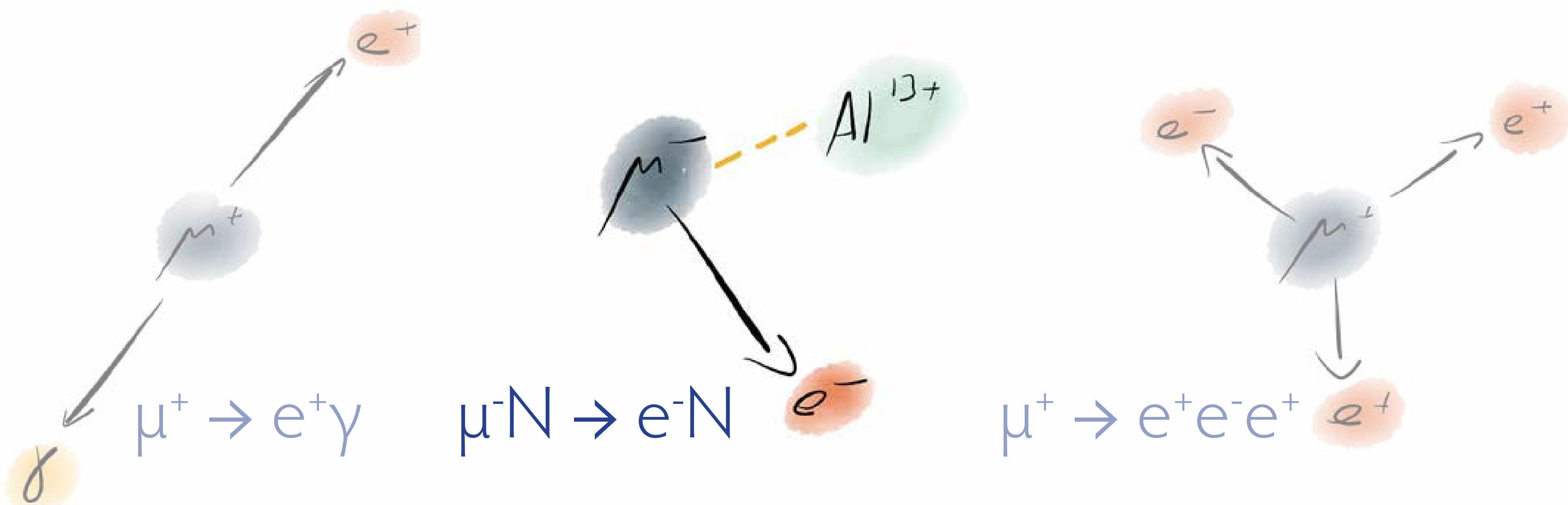


$\mu^+ \to e^+\gamma$ $\mu^-N \to e^-N$ $\mu^+ \to e^+e^-e^+$

Kinematics

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

LFV Muon Decays: Experimental signatures



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

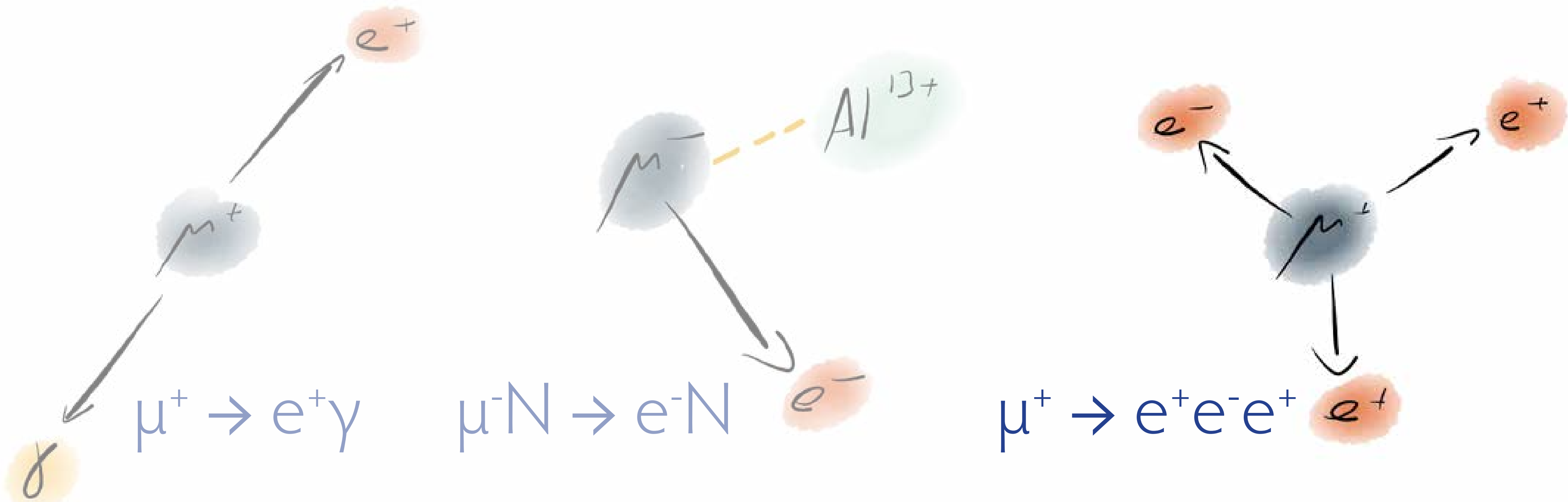
Kinematics

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

Kinematics

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

LFV Muon Decays: Experimental signatures



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

Kinematics

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

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

Kinematics

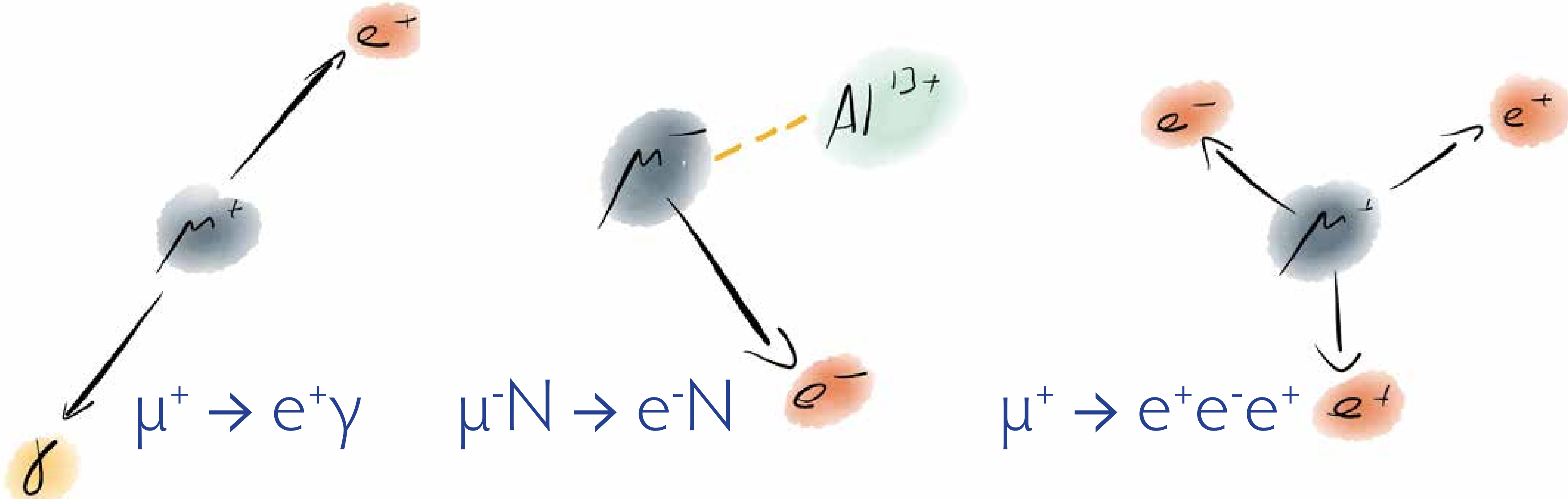
- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

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

Kinematics

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

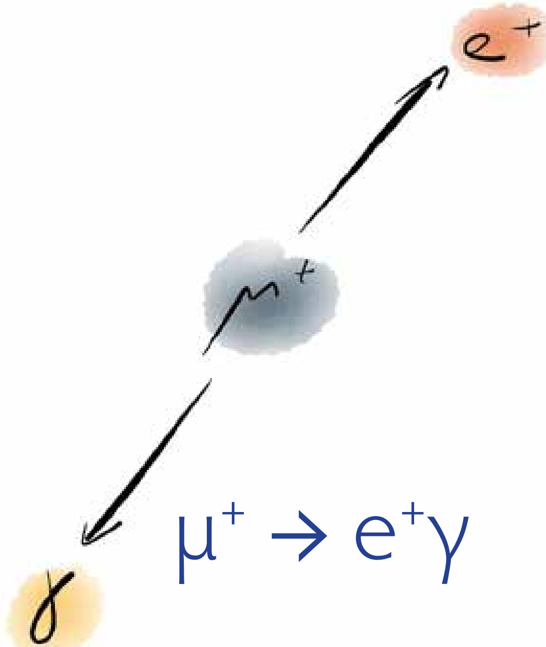
LFV Muon Decays: Experimental signatures



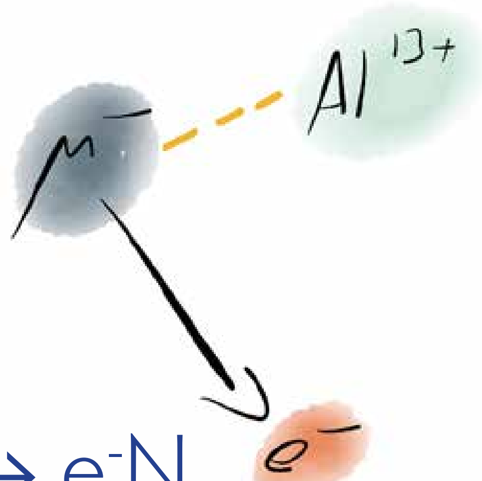
$\mu^+ \to e^+\gamma$ $\mu^-N \to e^-N$ $\mu^+ \to e^+e^-e^+$

Kinematics	Kinematics	Kinematics
• 2-body decay	• Quasi 2-body decay	• 3-body decay
• Monoenergetic e^+, γ	• Monoenergetic e^-	• Invariant mass constraint
• Back-to-back	• Single particle detected	• $\Sigma p_i = 0$
Background	**Background**	**Background**
• Accidental background	• Decay in orbit	• Internal conversion decay
• Radiative decay	• Antiprotons, pions, cosmics	• Accidental background

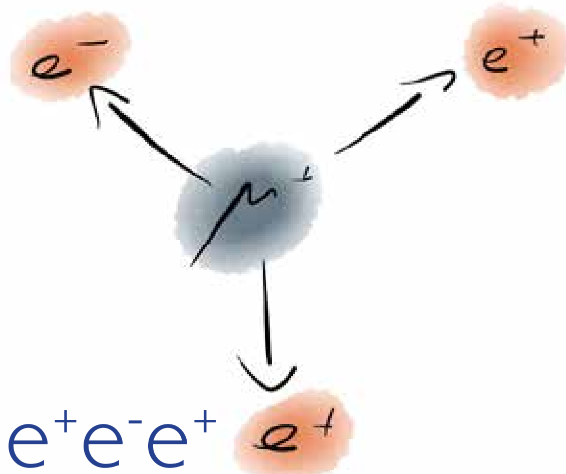
LFV Muon Decays: Experimental signatures



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



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



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

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… …dental background

Continuous Beam