Universität Zürich[UZH]
Physik-Institut

PAUL SCHERRER INSTITUT

PHY213 Kern- und Teilchenphysik II (FS 2020)

Intensity Frontier: Charged Lepton Flavour Violation

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Overview

- Why searching for charged lepton flavour violation?
- How can LFV occur?
- How to search for charged LFV?
  - $\mu \rightarrow e\gamma$
  - $\mu \rightarrow e$ conversion
  - $\mu \rightarrow eee$

Quark and lepton sector in the SM

- In the quark sector, mass matrices for u_L and d_L cannot be diagonalized at the same time → CKM matrix

$$\bar{Q}_L{}^i\, Y_D{}^{ik}\, d_R{}^k\, \mathrm{H} \rightarrow \bar{d}_L{}^i\, M_D{}^{ik}\, d_R{}^k + \ldots \qquad M_D = \mathrm{diag}(m_d, m_s, m_b)$$

$$\bar{Q}_L{}^i\, Y_U{}^{ik}\, u_R{}^k\, \mathrm{H_c} \rightarrow \bar{u}_L{}^i\, M_U{}^{ik}\, u_R{}^k + \ldots \qquad M_U = V^{+} \times \mathrm{diag}(m_u, m_c, m_t)$$

- In the lepton sector, with m_ν=0 and no right-handed neutrinos, mass matrix for charged leptons is diagonal

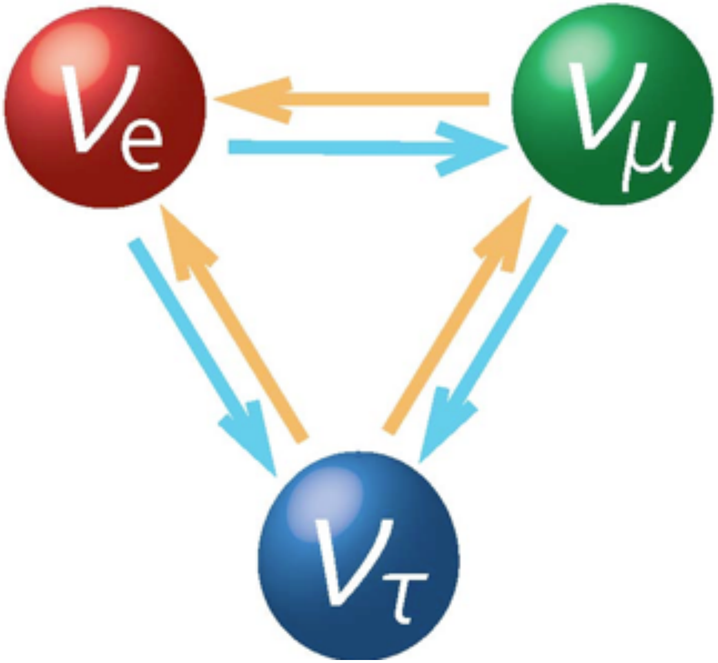
$$L_L{}^i\, Y_D{}^{ik}\, e_R{}^k\, \mathrm{H} \rightarrow l_L{}^i\, M_E{}^{ik}\, e_R{}^k + \ldots \qquad M_E = \mathrm{diag}(m_e, m_\mu, m_\tau)$$

→ lepton flavor is conserved

→ no charged lepton flavor transitions at tree level

Neutrino oscillations

- Even though m_ν=0 in the SM, we know from experiment that neutrino oscillations occur and $m_\nu \neq 0$

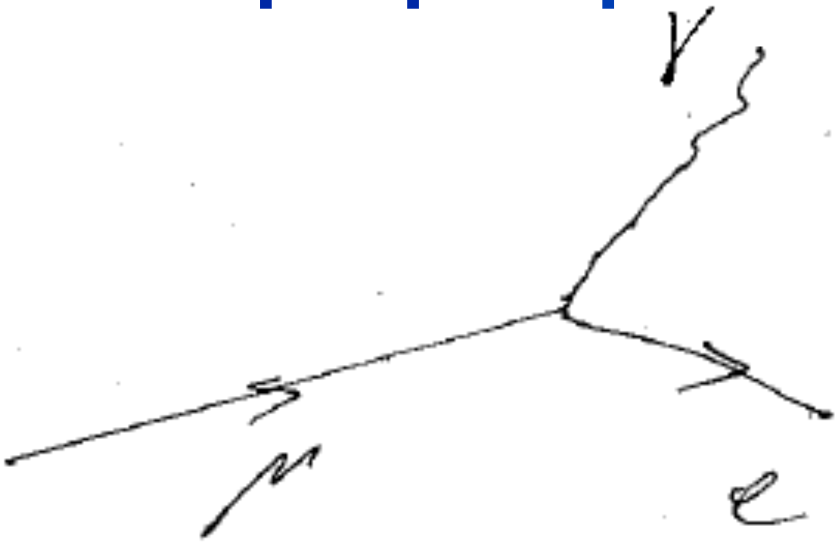


→ Neutral lepton flavor violation does happen!

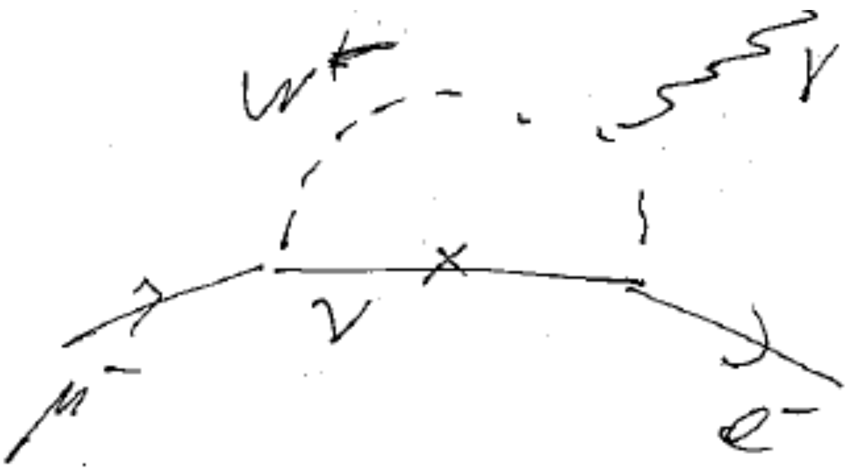
Example μ→eγ

→ no such vertex in SM

Example μ→eγ

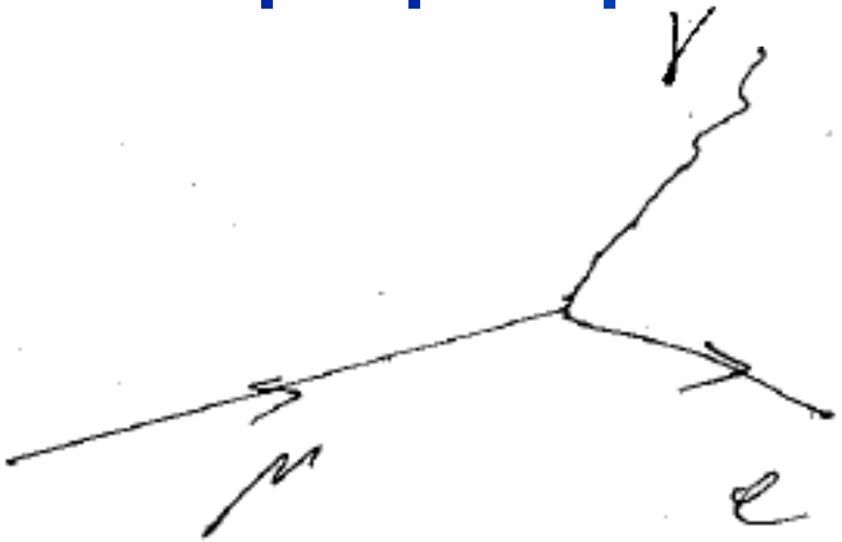


→ no such vertex in SM

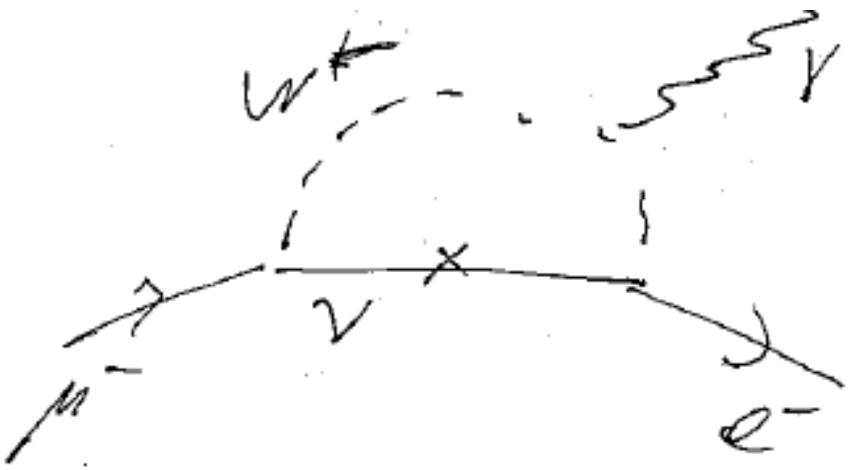


→ perfectly fine 1-loop diagram in extended SM with massive neutrinos

Example μ→eγ



→ no such vertex in SM

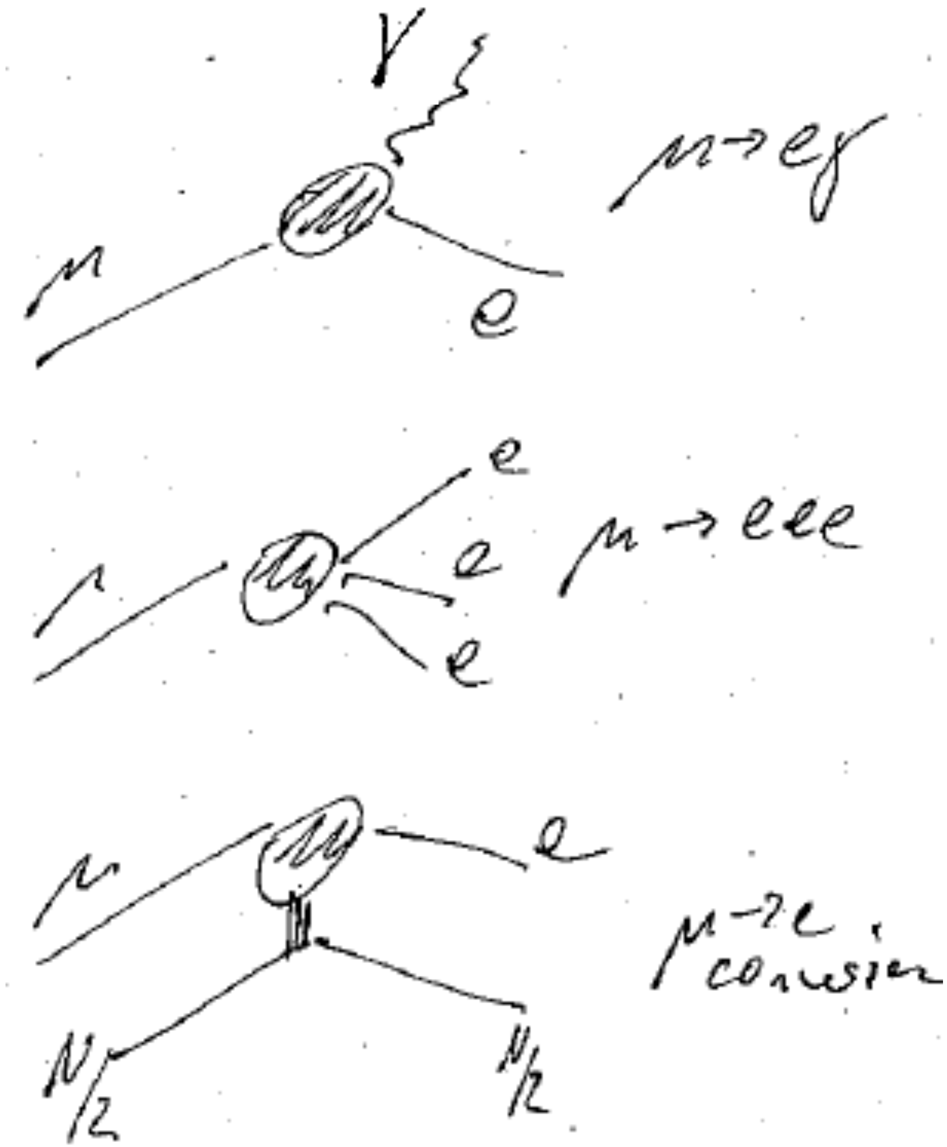


→ perfectly fine 1-loop diagram in extended SM with massive neutrinos

However: branching fraction is very small, as there is very little time to oscillate (heavy W boson)

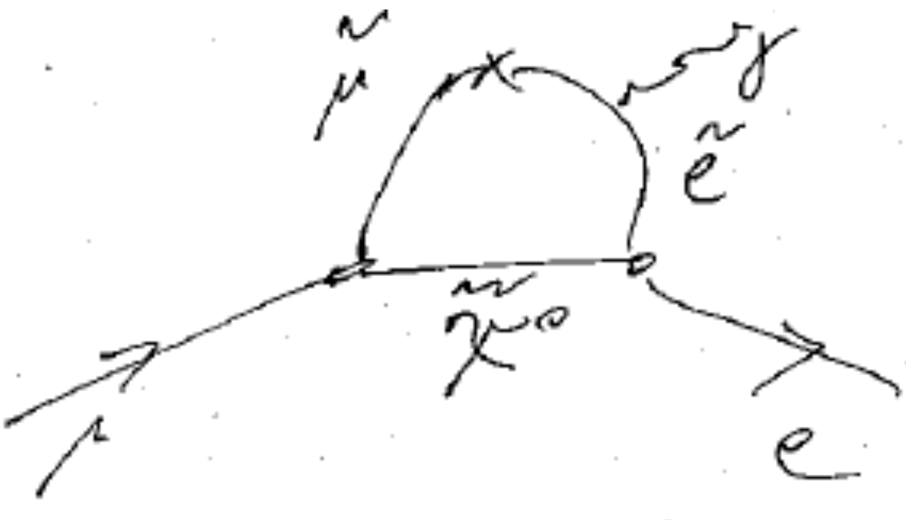
$$BR(\mu \to e\gamma) = \frac{3\alpha_{em}}{32\pi}\left|\sum_i U^\dagger_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{m^2_W}\right|^2 < 10^{-54}$$

Other examples



+ same with τ's

New physics models: Supersymmetry

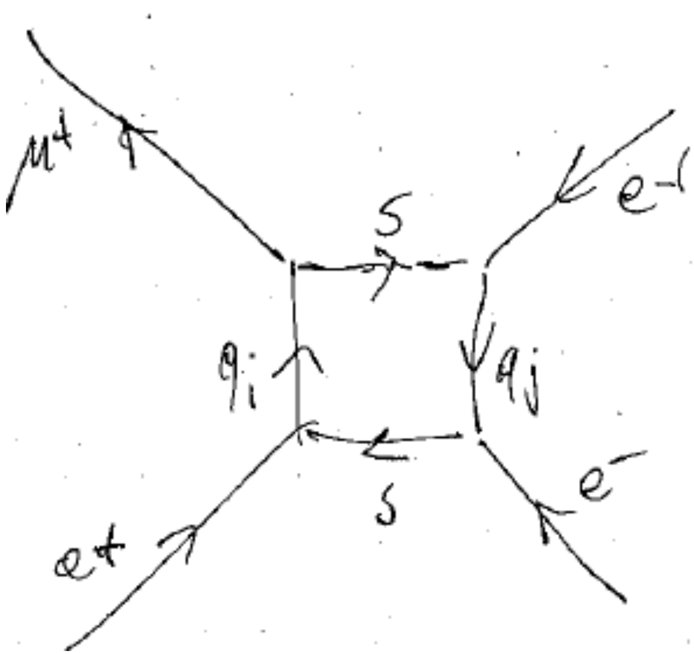


- Bosonic partners to all fermions, in particular "sleptons" with their own mass matrix (not necessarily diagonal at the same time as m_l)

- Slepton and neutralino masses likely not different by 10 orders of magnitude → higher branching ratio than in the SM

New physics models: GUT

GUT: Symmetry incorporating all SM symmetries plus additional particles coupling to quarks and leptons (leptoquarks)



- LQ typically much, much heavier than quarks → m→eγ stays suppressed
- can lead to enhancement in m→eee

Other models

- Models with additional Higgs bosons
- Models with right-handed neutrinos
- Models including any new force with off-diagonal couplings (Z' in additional gauge symmetries, KK-excitations in extra-dimension models)

→ Predict lepton flavour violation

→ Typically (for heavy new particles) larger enhancement for tau decays by $(m_\tau/m_\mu)^2 \sim 290$

→ However: can produce as many muons per second as taus in a year...

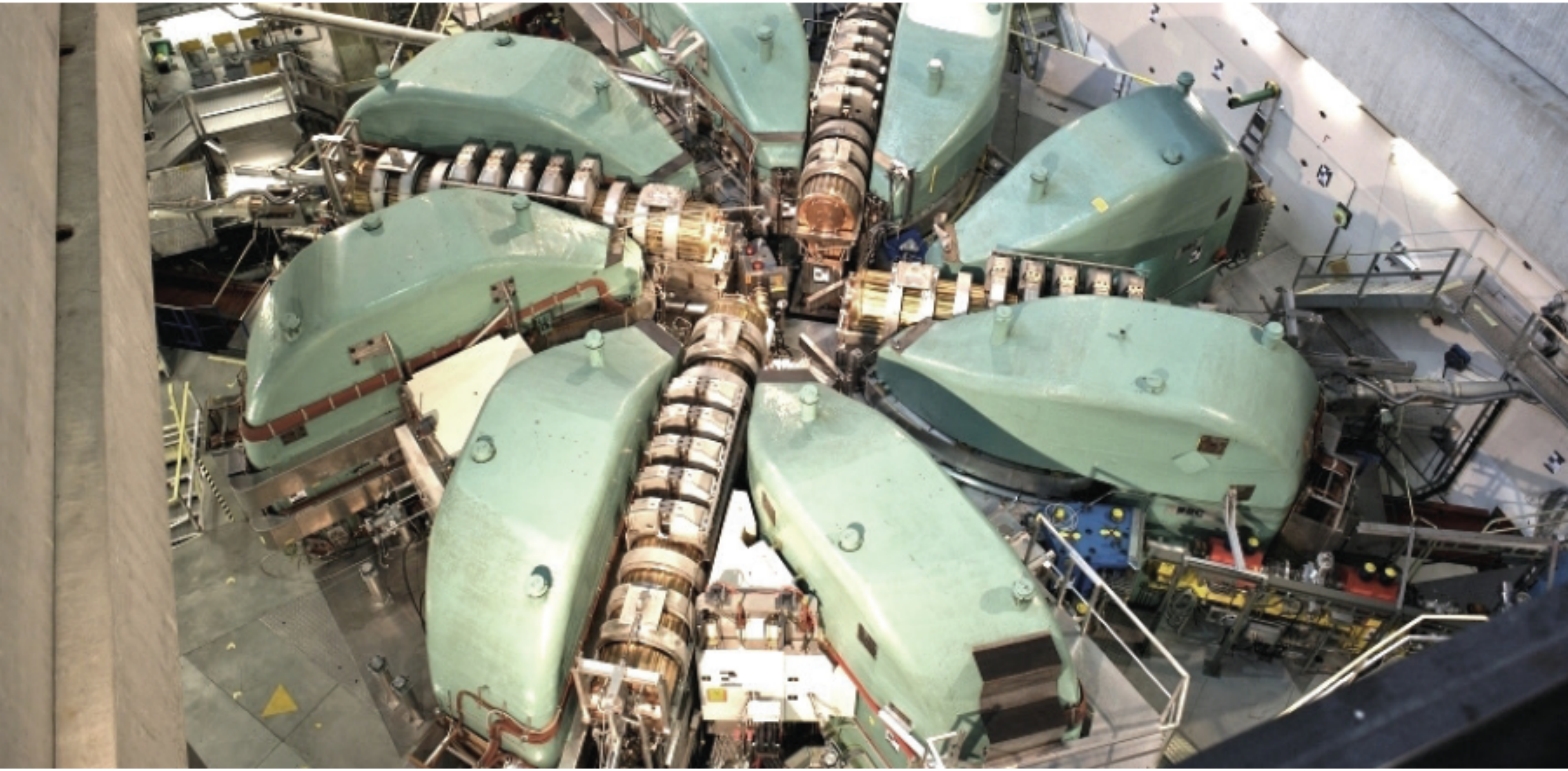
Charged LFV experiments

Muons – how to get to high intensity

Paul Scherrer Institute in Villigen, Switzerland

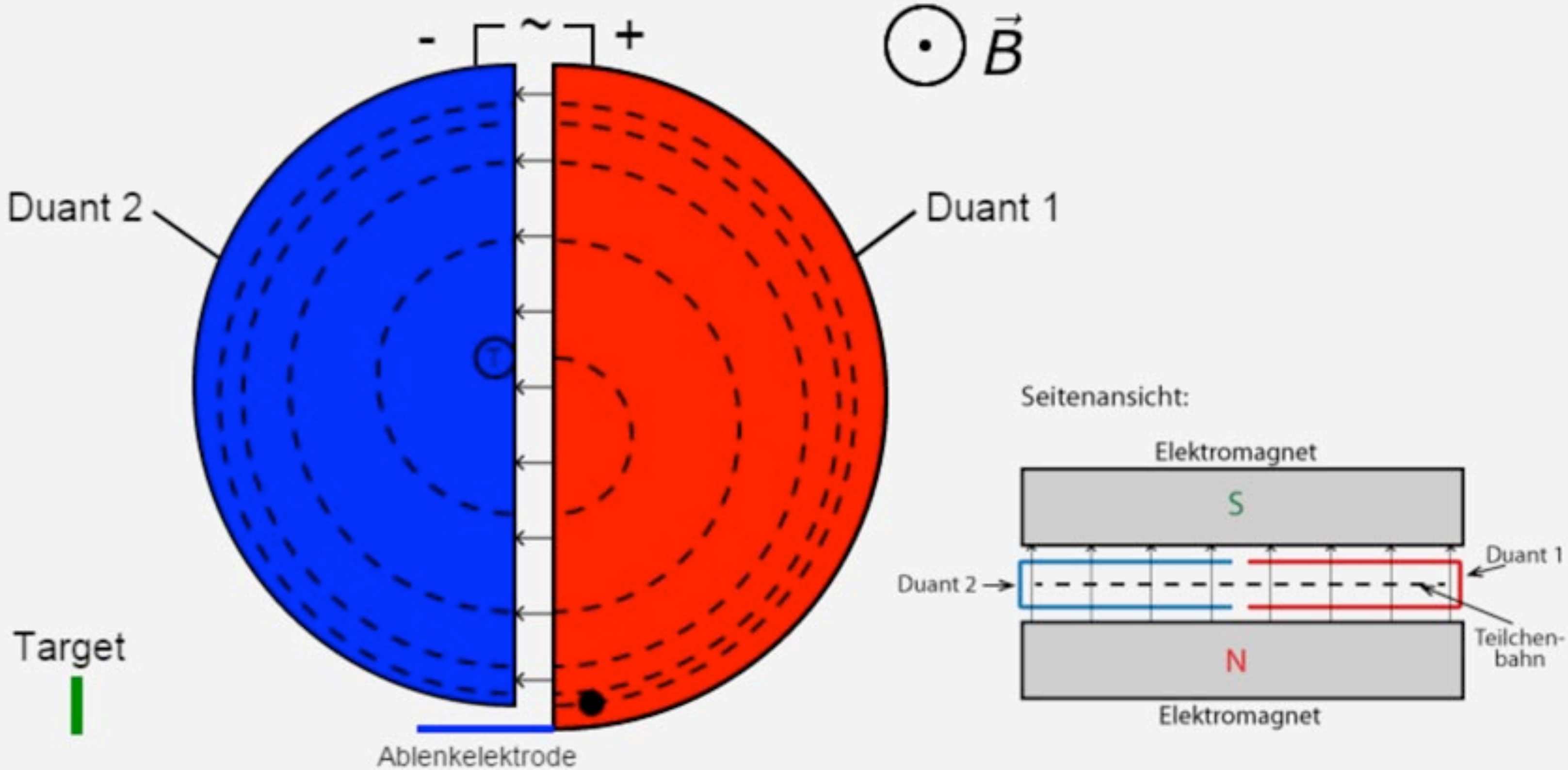
Muons – how to get to high intensity

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



→ continuous beam

Cyclotron



$$F_{Lorentz} = F_{Zentripetal} \Rightarrow q \cdot v \cdot B = \frac{m \cdot v^2}{r} \Rightarrow v = \frac{r \cdot q \cdot B}{m}$$

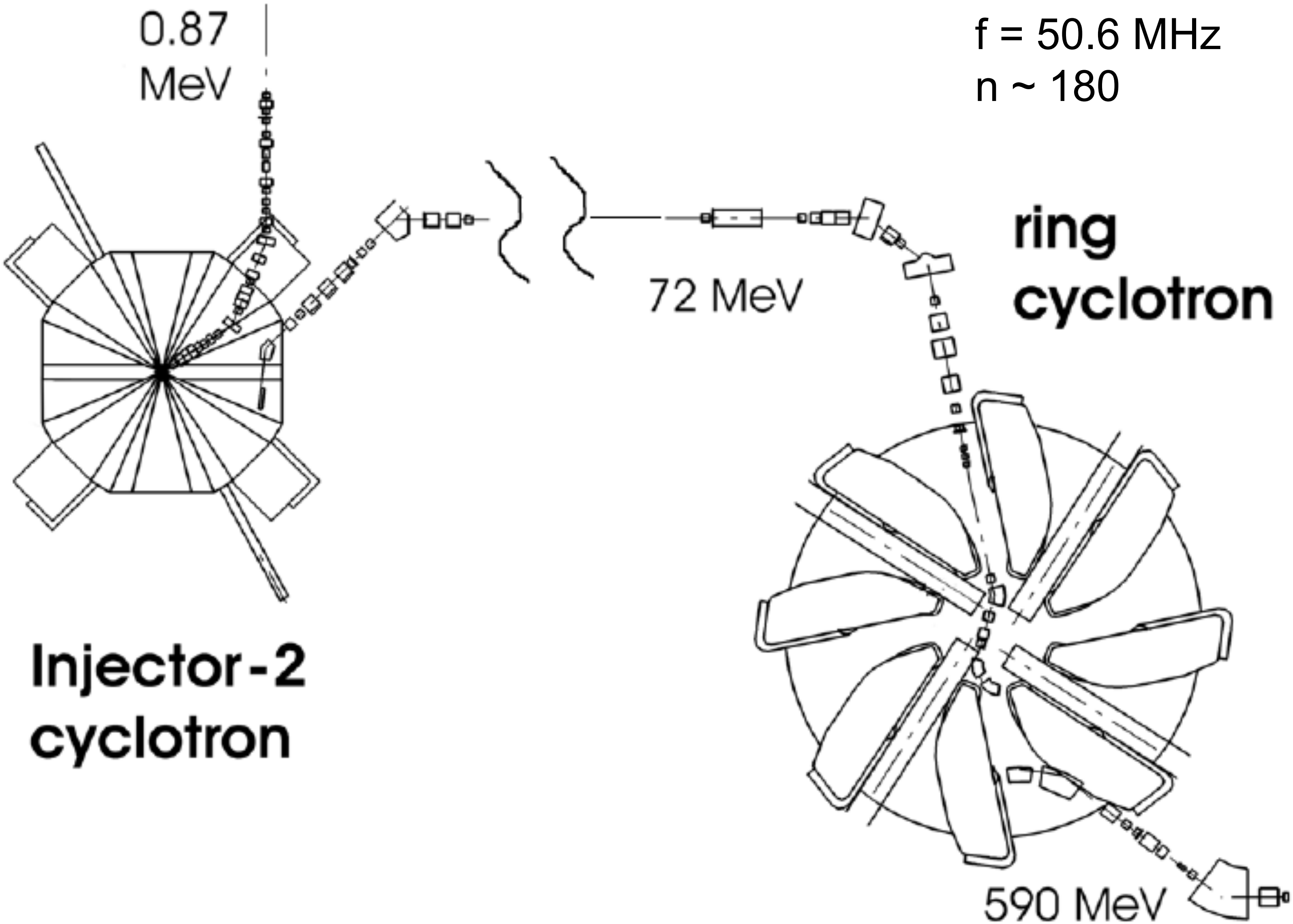
$$2\pi \cdot f \cdot r = \frac{r \cdot q \cdot B}{m} \Rightarrow f = \frac{q \cdot B}{2\pi \cdot m} \qquad T = \frac{1}{f} = \frac{2\pi \cdot m}{q \cdot B}$$

$$v = \sqrt{\frac{2}{m} \cdot q \cdot U \cdot n}$$

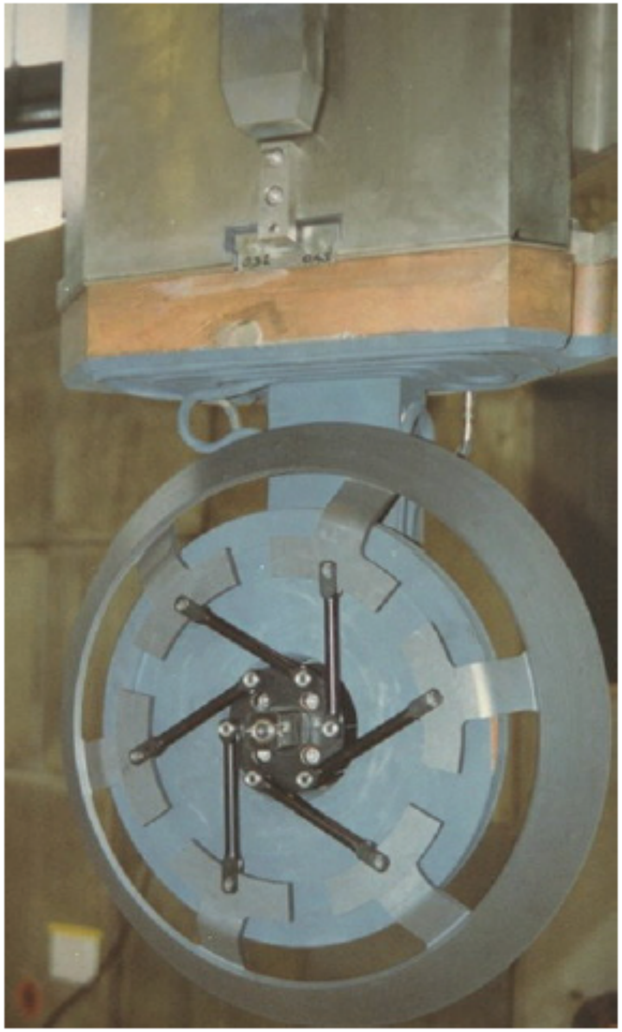
→ T independent of r
→ works for non-relativistic velocities v<0.1c

PSI high-intensity proton accelerator (HIPA)

f = 50.6 MHz
n ~ 180

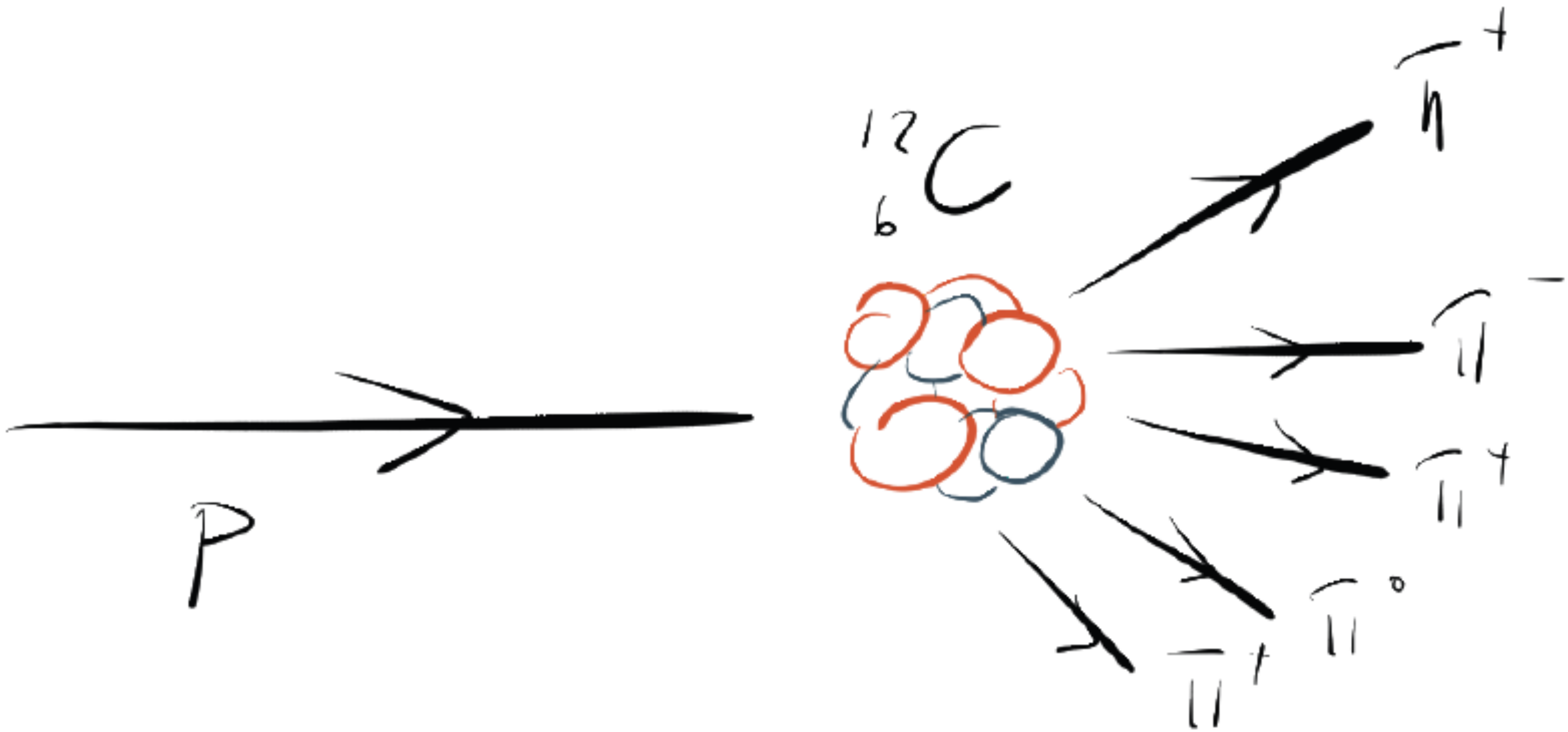


Muons – how to get to high intensity

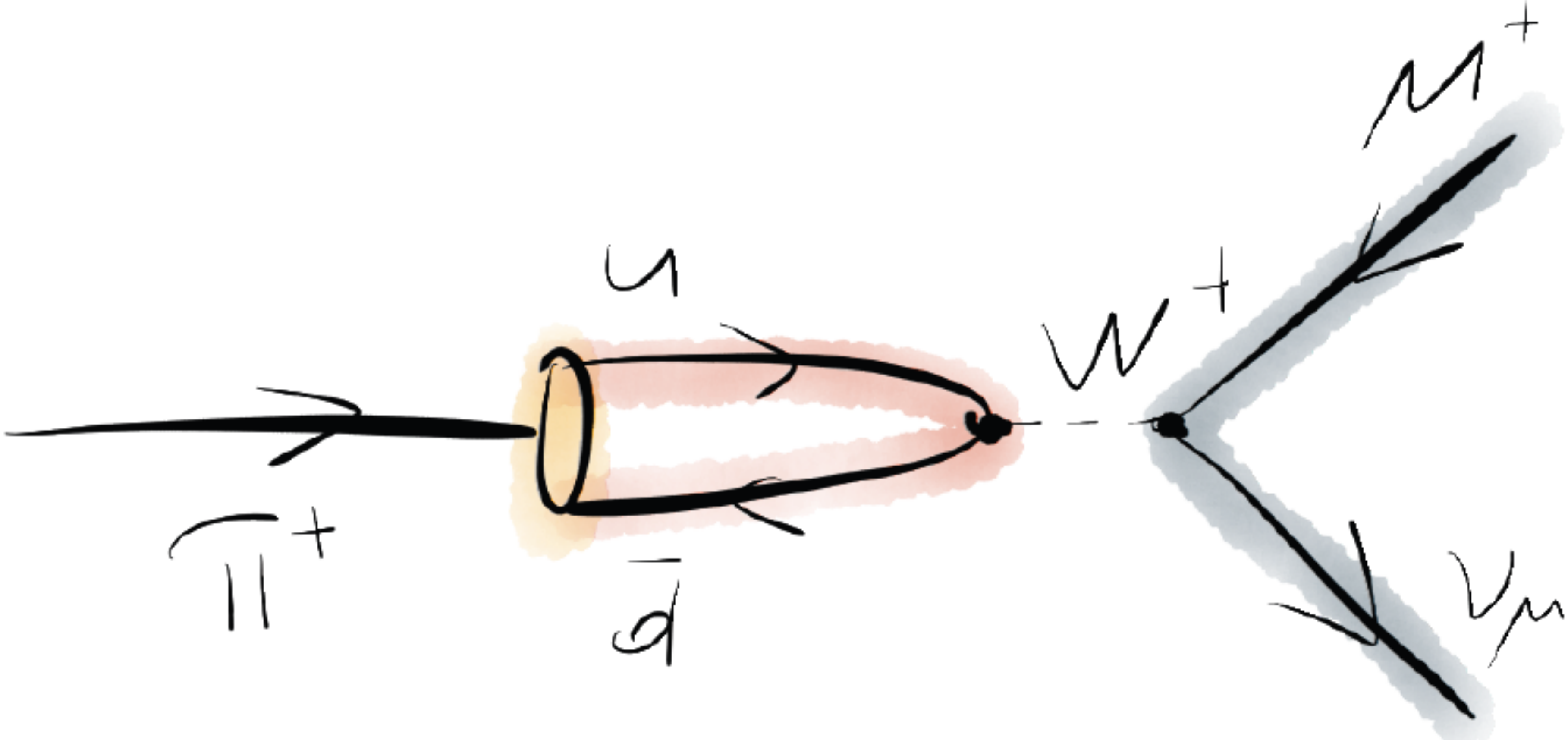


- Rotating carbon wheel as target
- Hit with proton beam

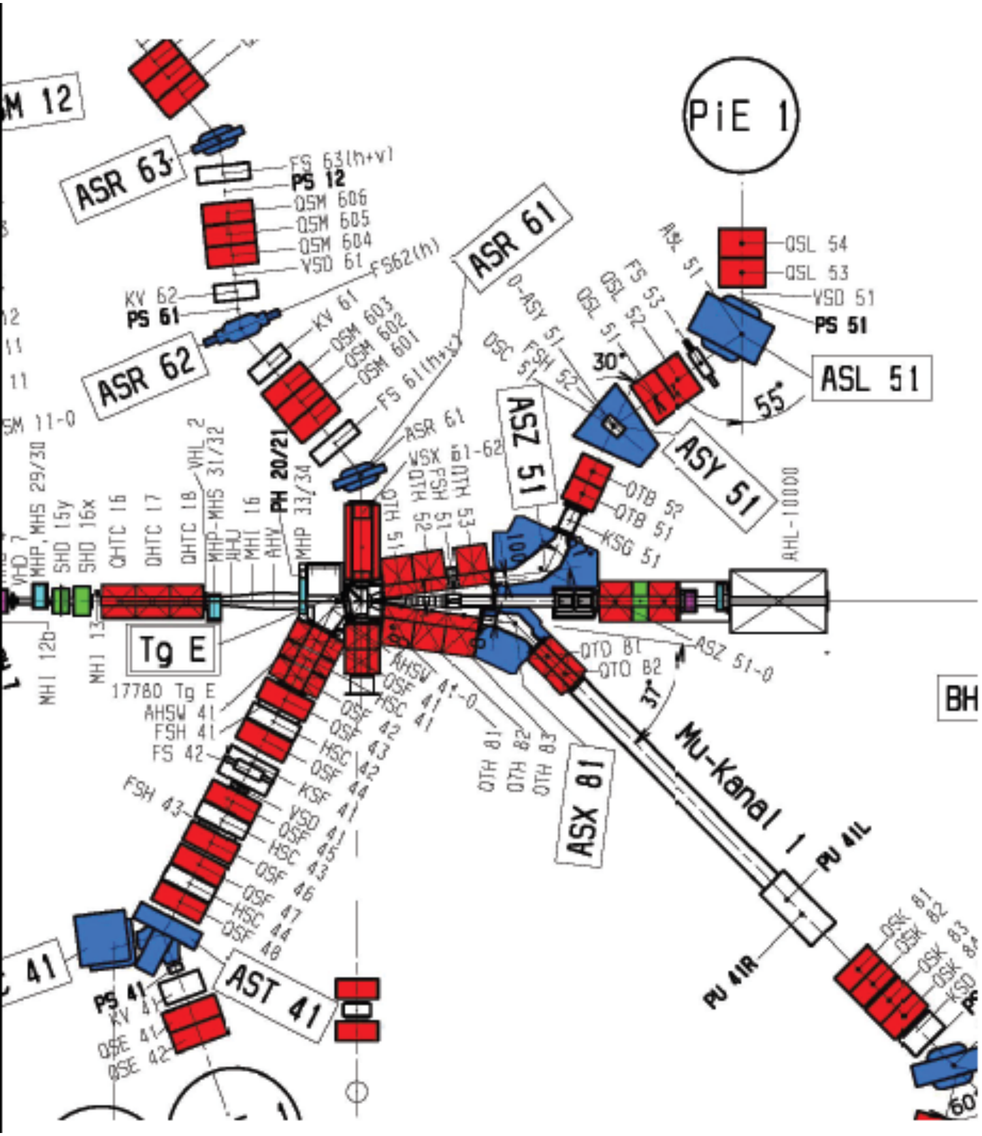
Pion production



Pion decay

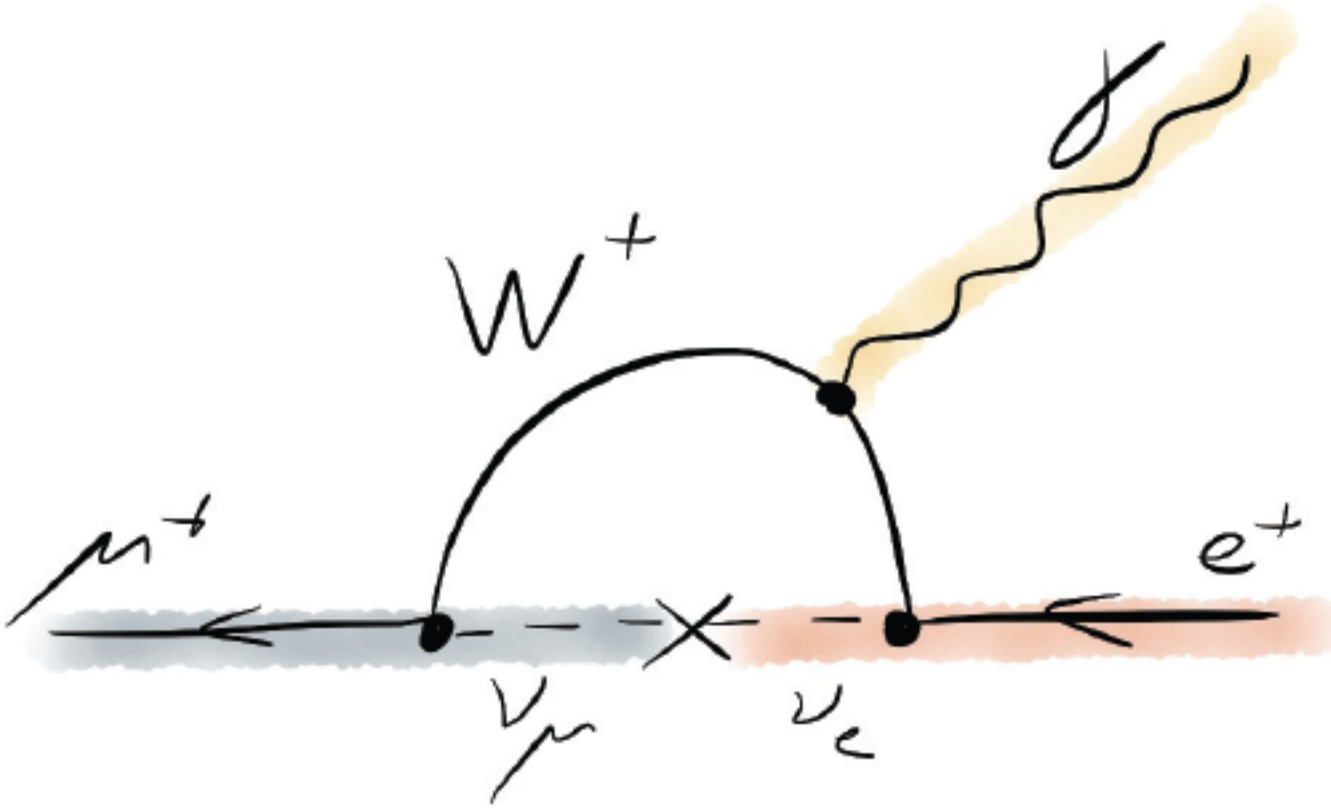


Muon beamlines



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

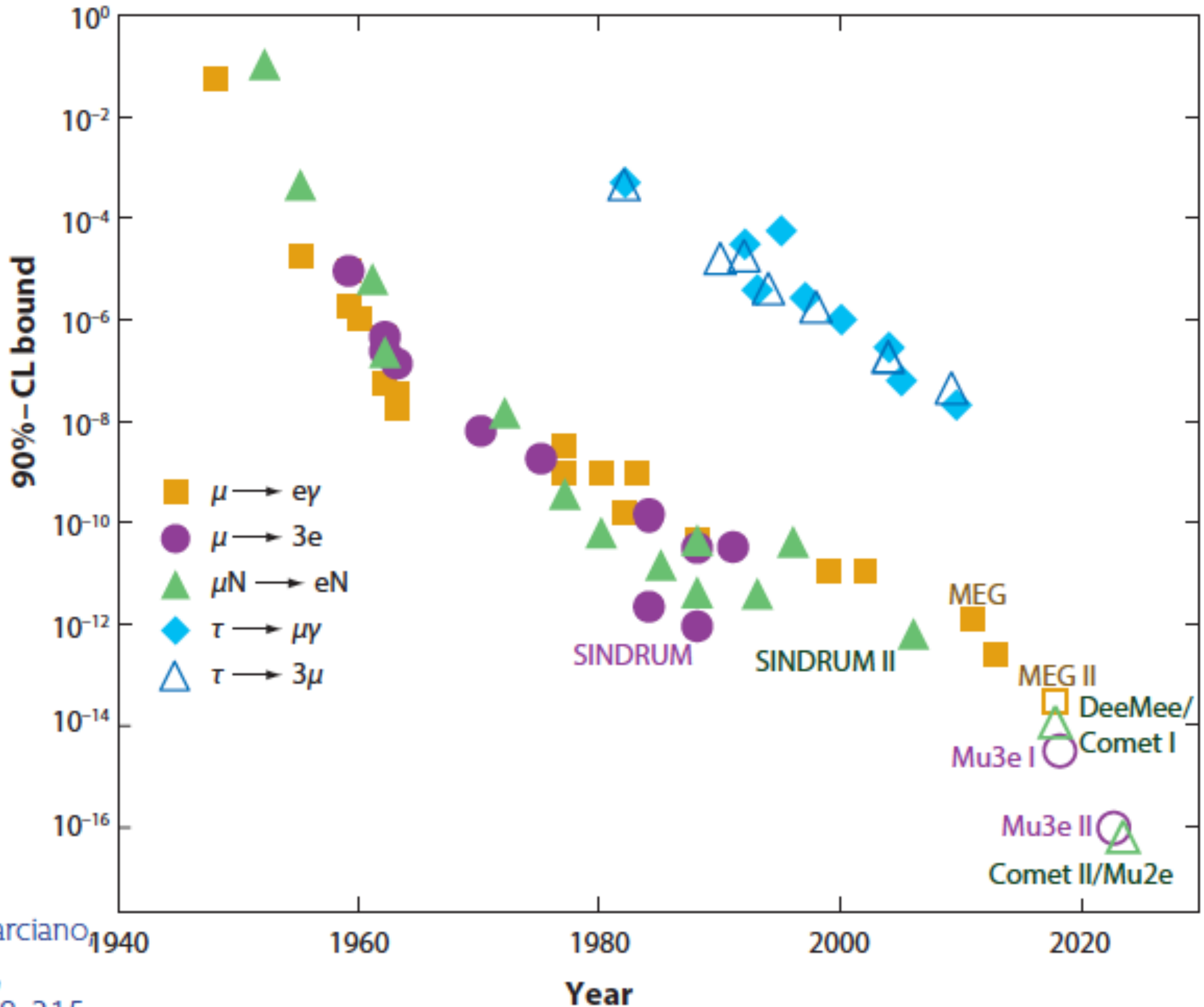
Lepton flavor violation experiments



Standard Model branching fractions of

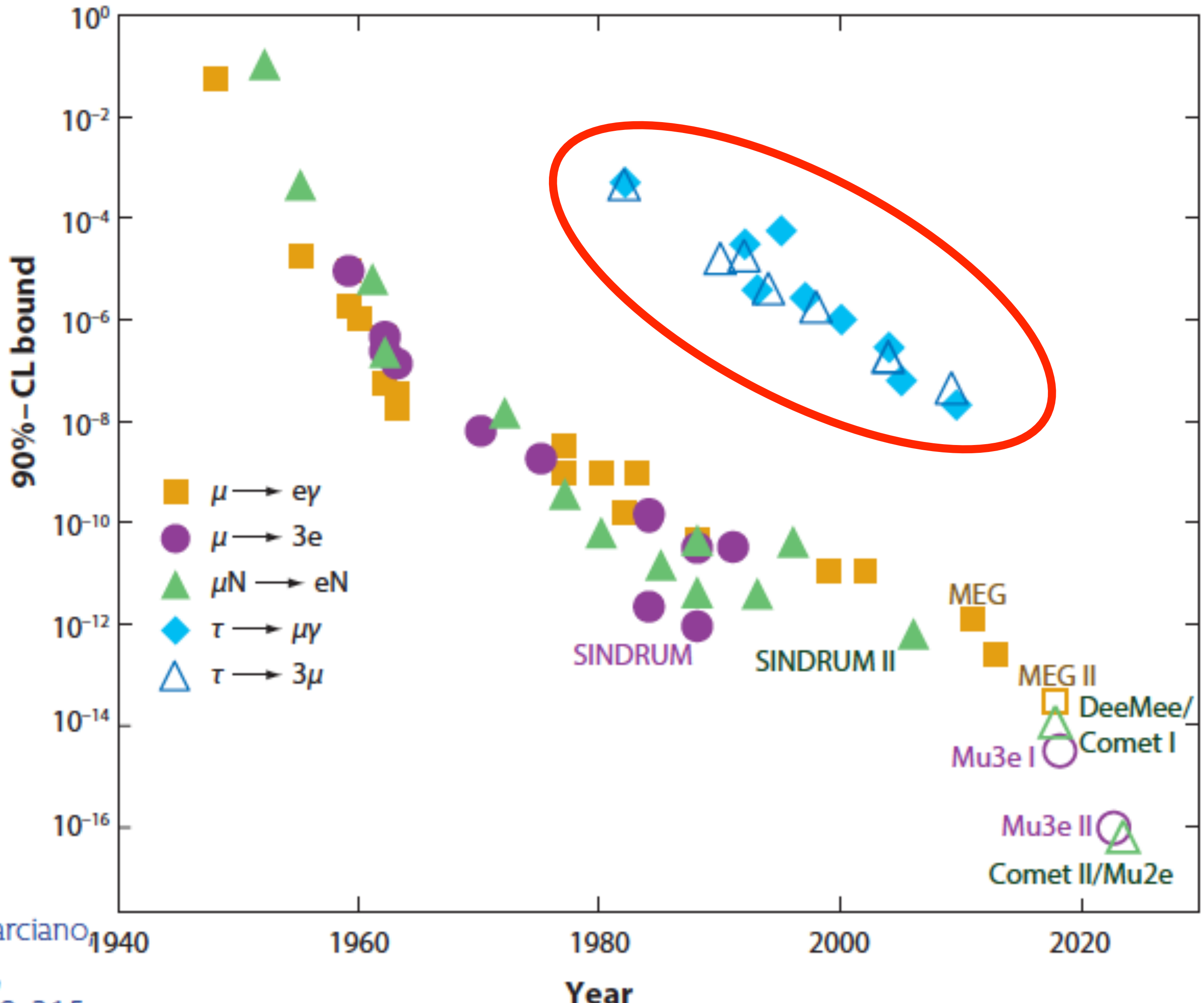
10^{-50ish}

History of LFV experiments



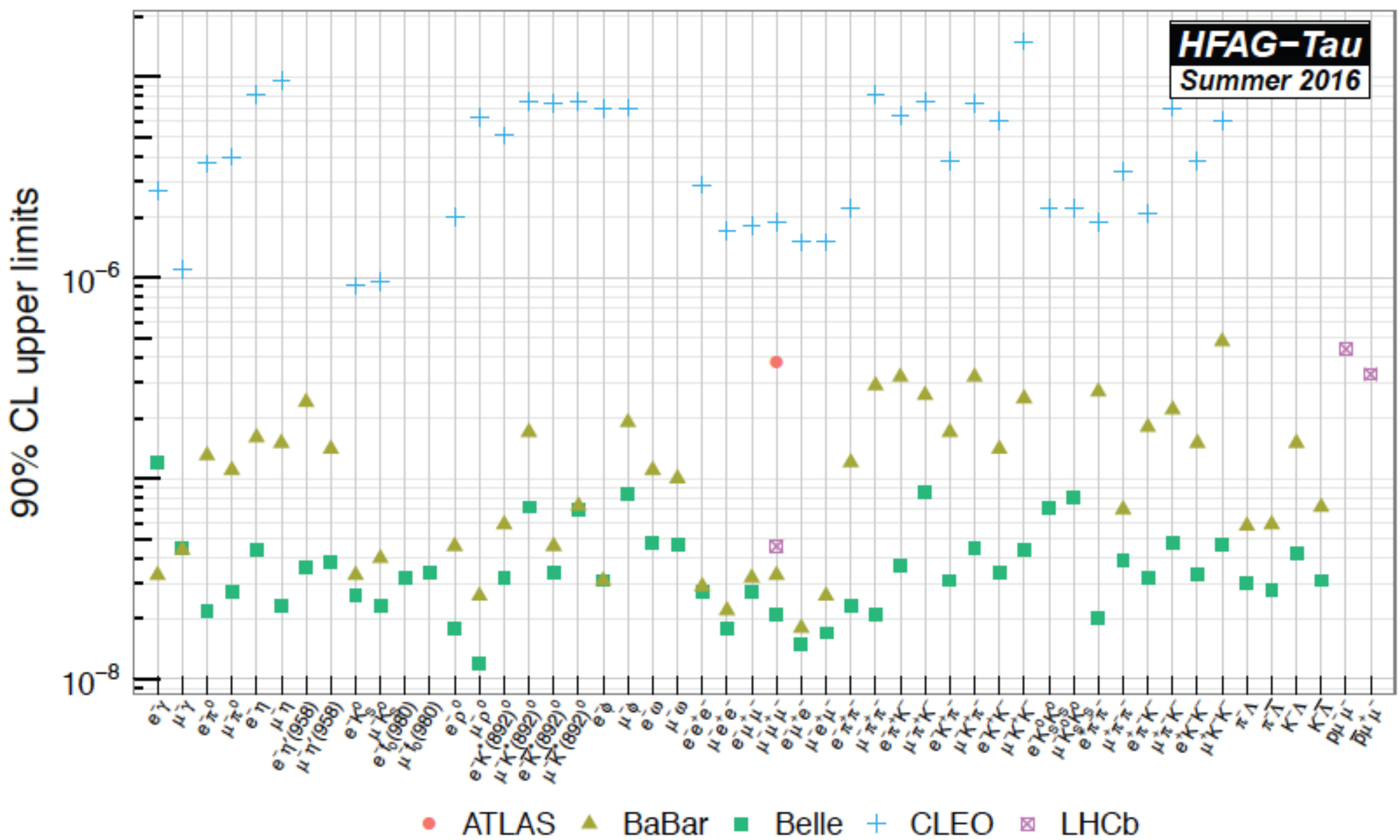
(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

History of LFV experiments

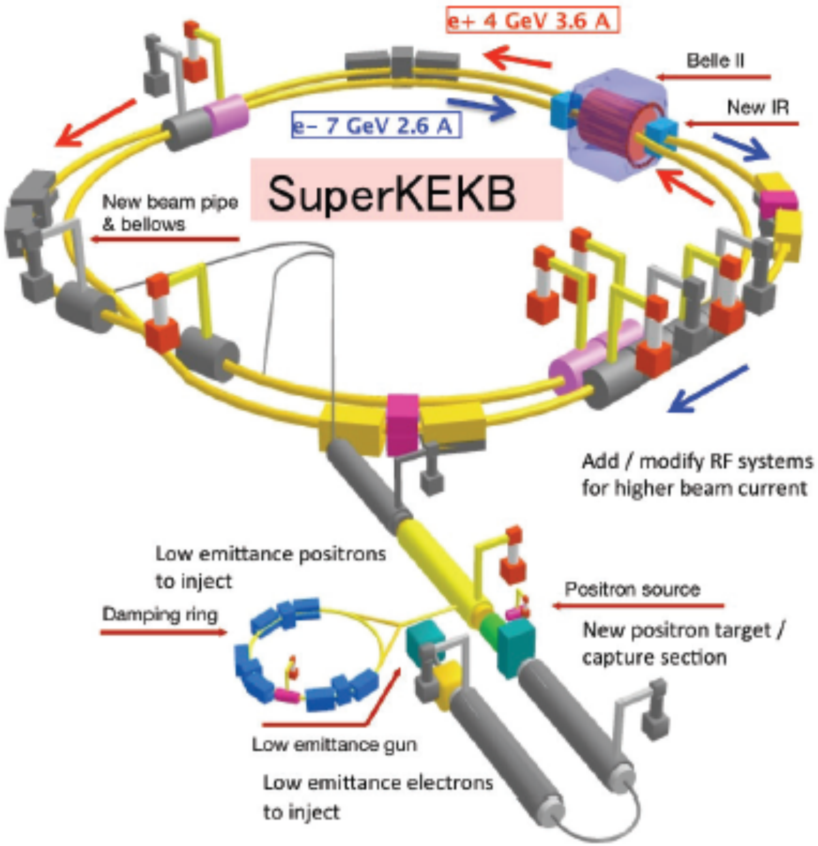


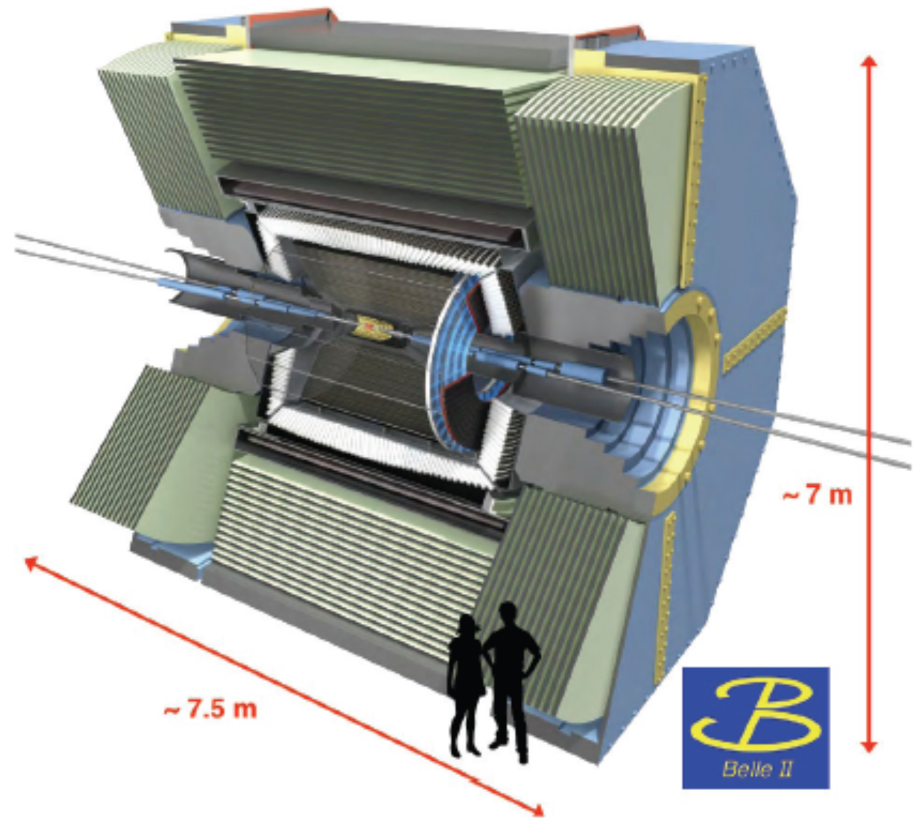
(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

Lepton flavor violating τ decays



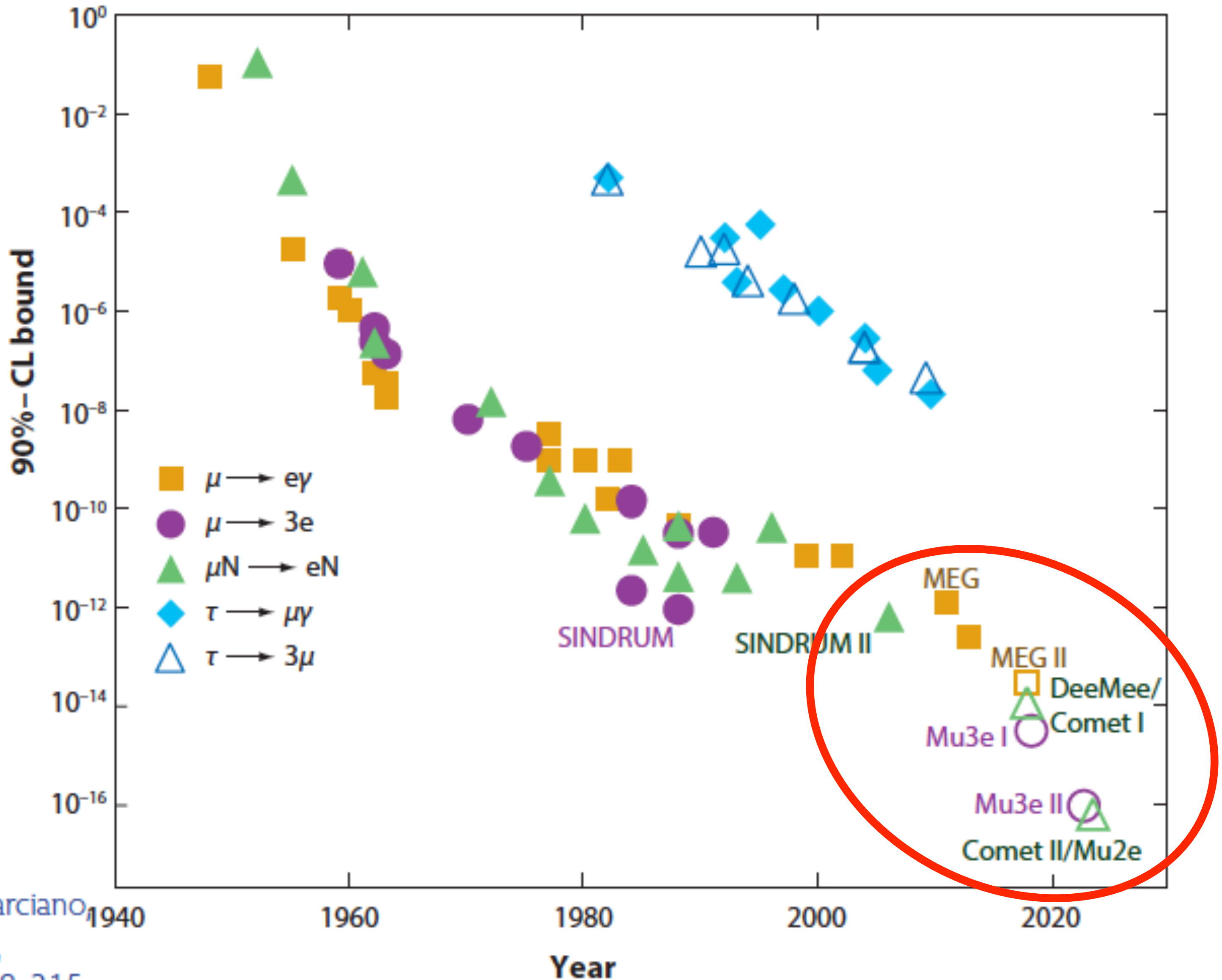
BELLE-2 @ SuperKEKB





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

History of LFV experiments



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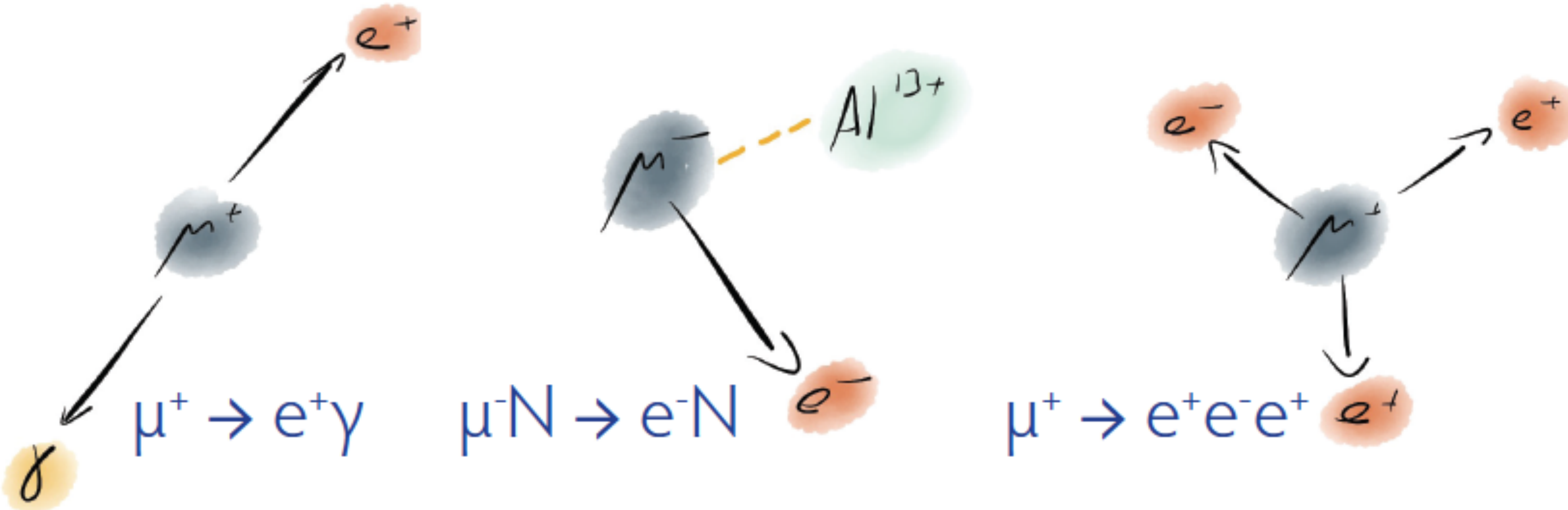
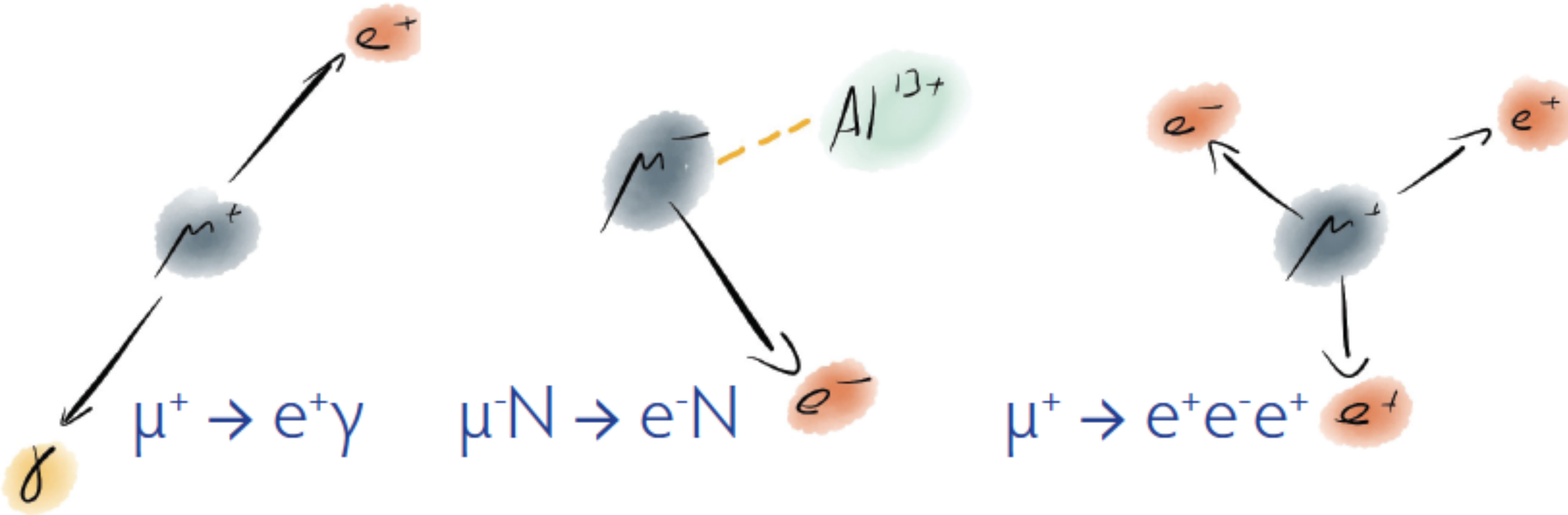
LFV muon decays



LFV muon decays

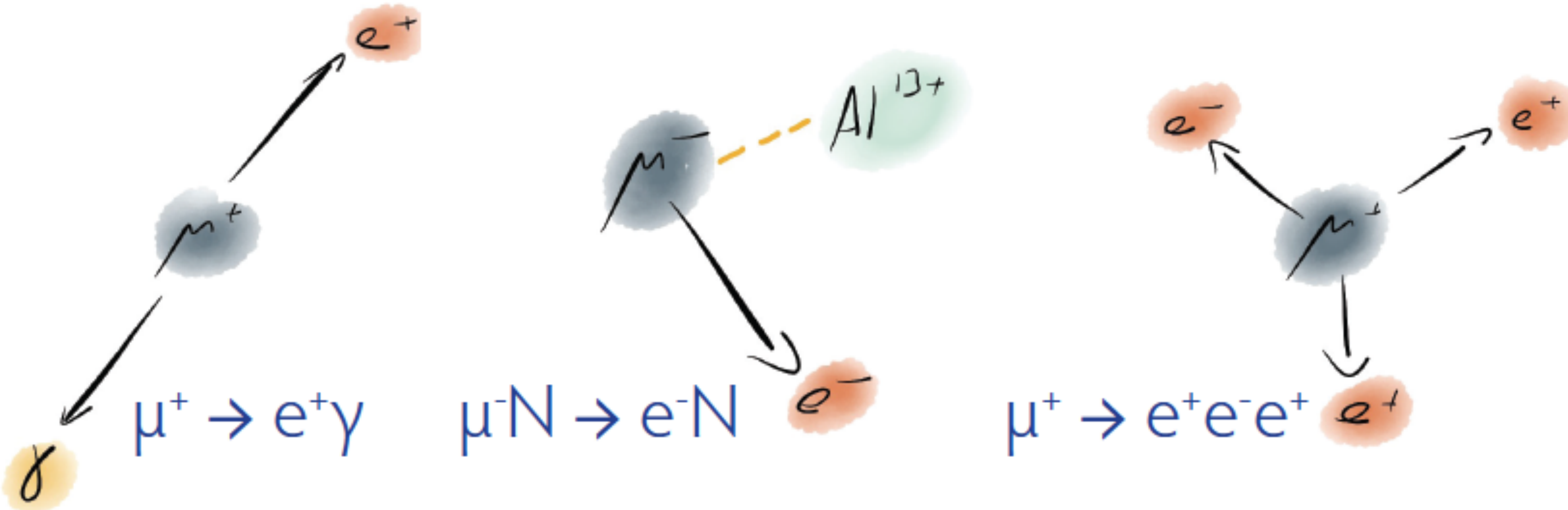


MEG (PSI)
$B(\mu^+ \to e^+\gamma) < 4.2 \cdot 10^{-13}$
(2016)

SINDRUM II (PSI)
$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$
(2006)
relative to nuclear capture

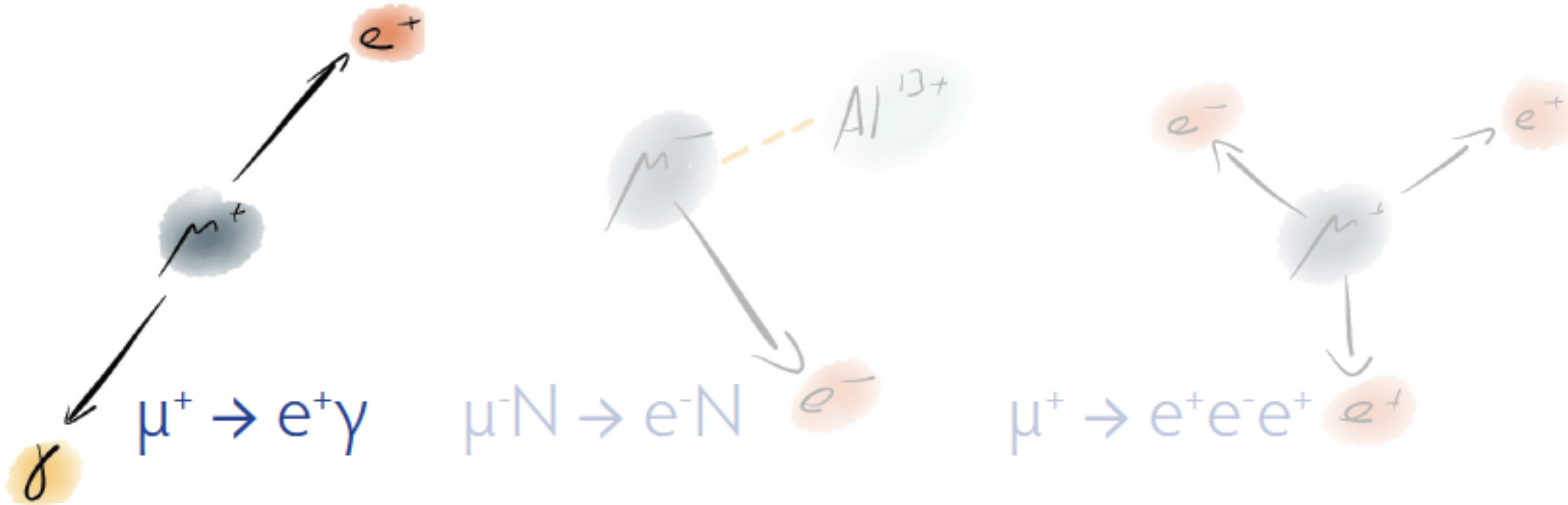
SINDRUM (PSI)
$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$
(1988)

LFV muon decays



$\mu^+ \to e^+\gamma$	$\mu^-N \to e^-N$	$\mu^+ \to e^+e^-e^+$
MEG-II	Mu2e, DeeMee, COMET, PRISM	Mu3e
@ PSI	@ Fermilab, J-PARC, BNL	@ PSI

LFV muon decays



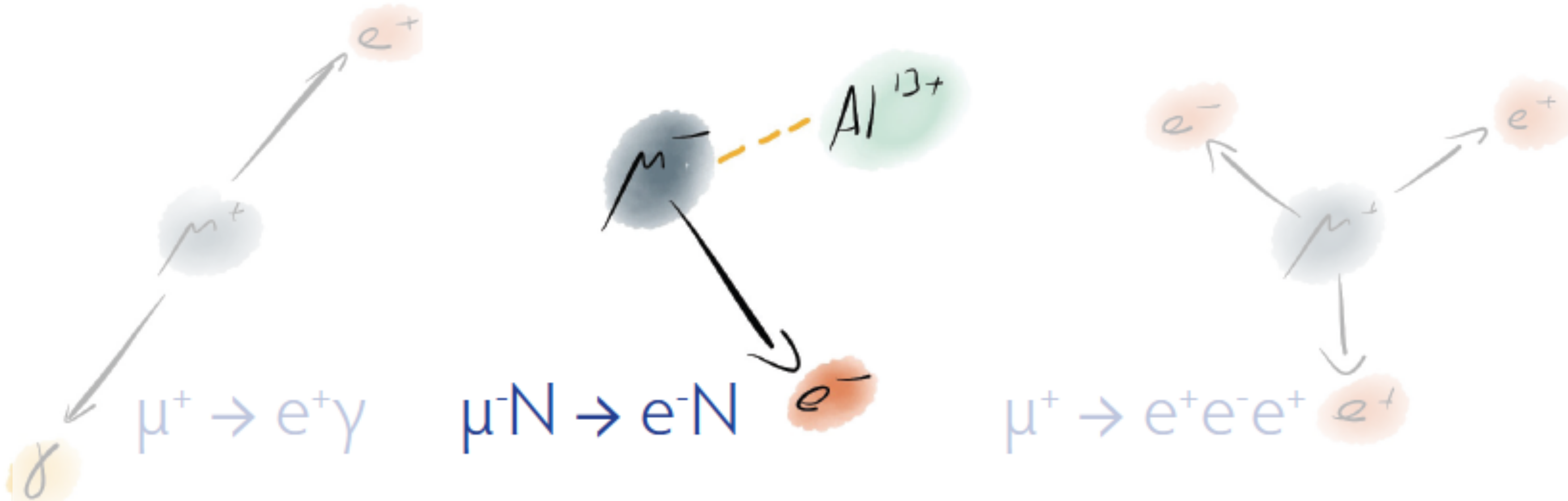
Kinematics

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

Background

- Accidental background
- Radiative decay

LFV muon decays



Kinematics

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

Background

- Accidental background
- Radiative decay

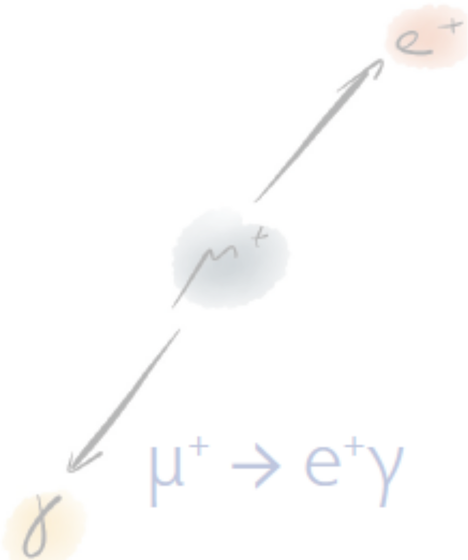
Kinematics

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

Background

- Decay in orbit
- Antiprotons, pions, cosmics

LFV muon decays



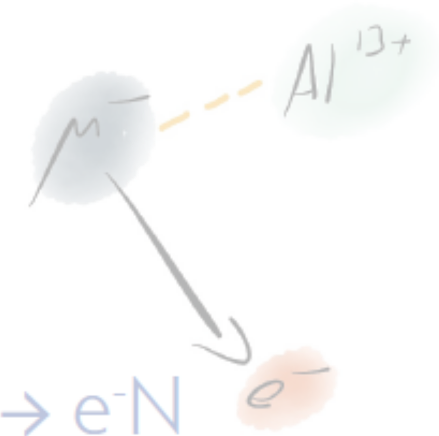
$\mu^+ \to e^+\gamma$

Kinematics

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

Background

- Accidental background
- Radiative decay



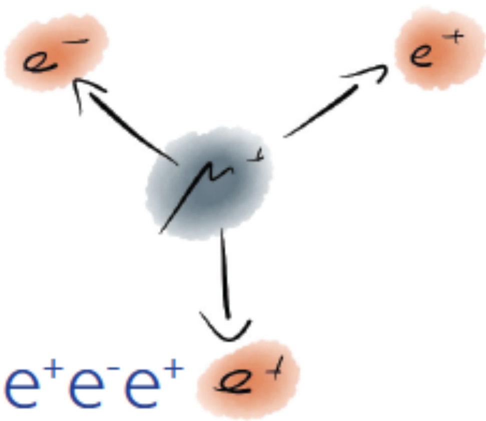
$\mu^- N \to e^- N$

Kinematics

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

Background

- Decay in orbit
- Antiprotons, pions, cosmics



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

Kinematics

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

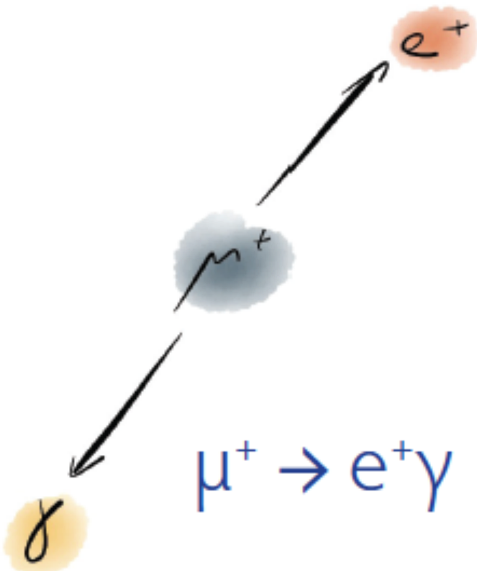
Background

- Internal conversion decay
- Accidental background

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

MEG/MEG-II

MEG signal and background

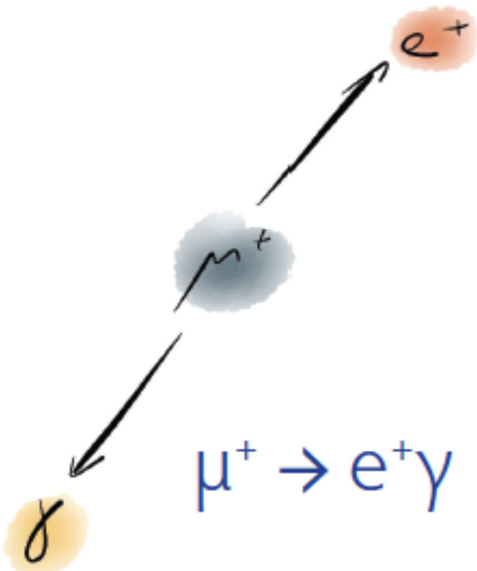


$$\mu^+ \to e^+\gamma$$

Kinematics

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

MEG signal and background

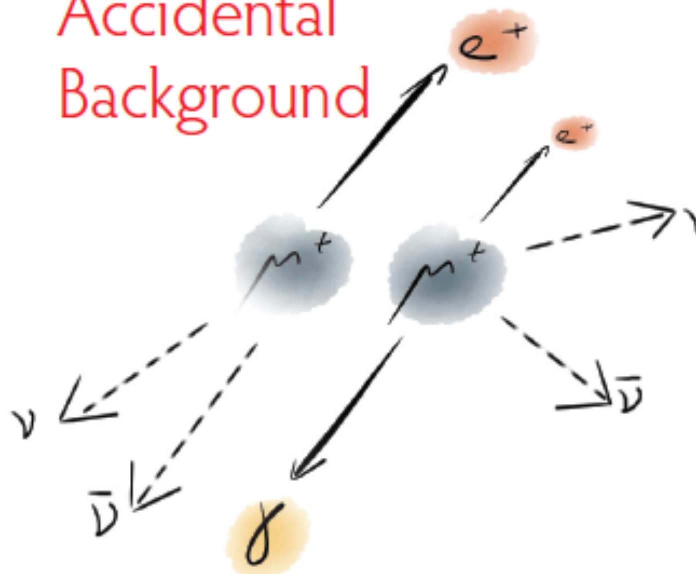


$\mu^+ \rightarrow e^+\gamma$

Kinematics

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

Accidental Background

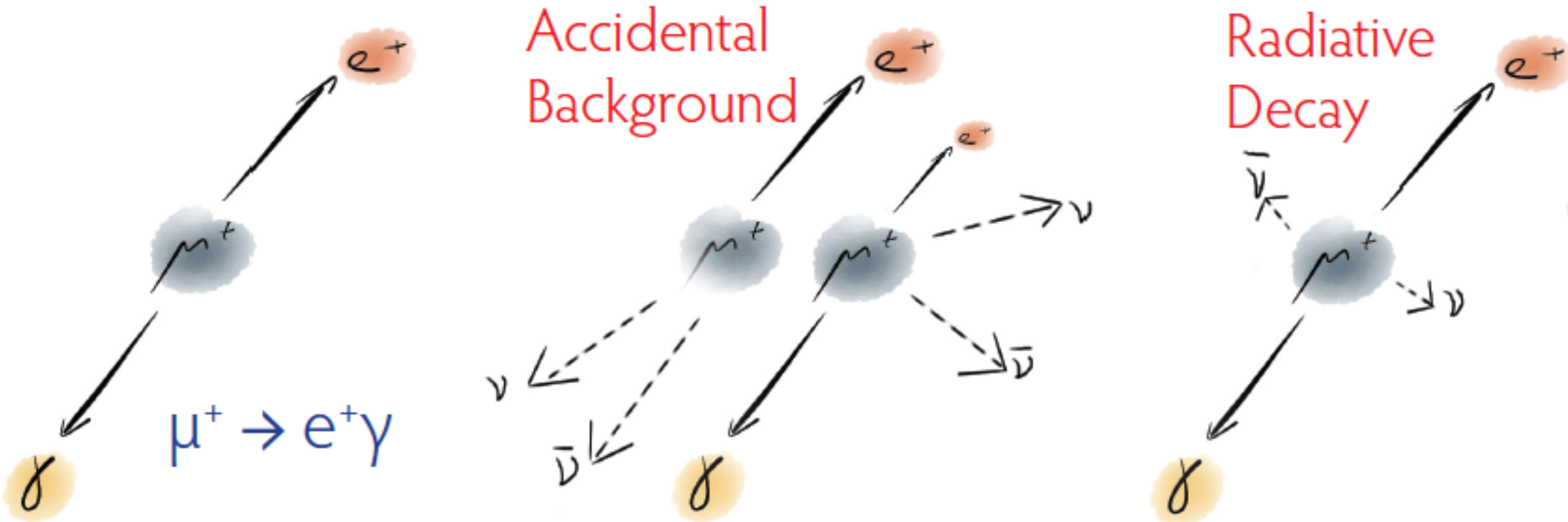


- Not exactly in time
- Not exactly same vertex
- e^+, γ energies somewhat off
- Not exactly back-to-back

- Muon lifetime 2.2 μs
- Single muon in target experiments limited to < 450'000 μ/s
- New experiments operate at 10^7++ μ/s

→ Many muons on target at any time

MEG signal and background



Kinematics

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

- Not exactly in time
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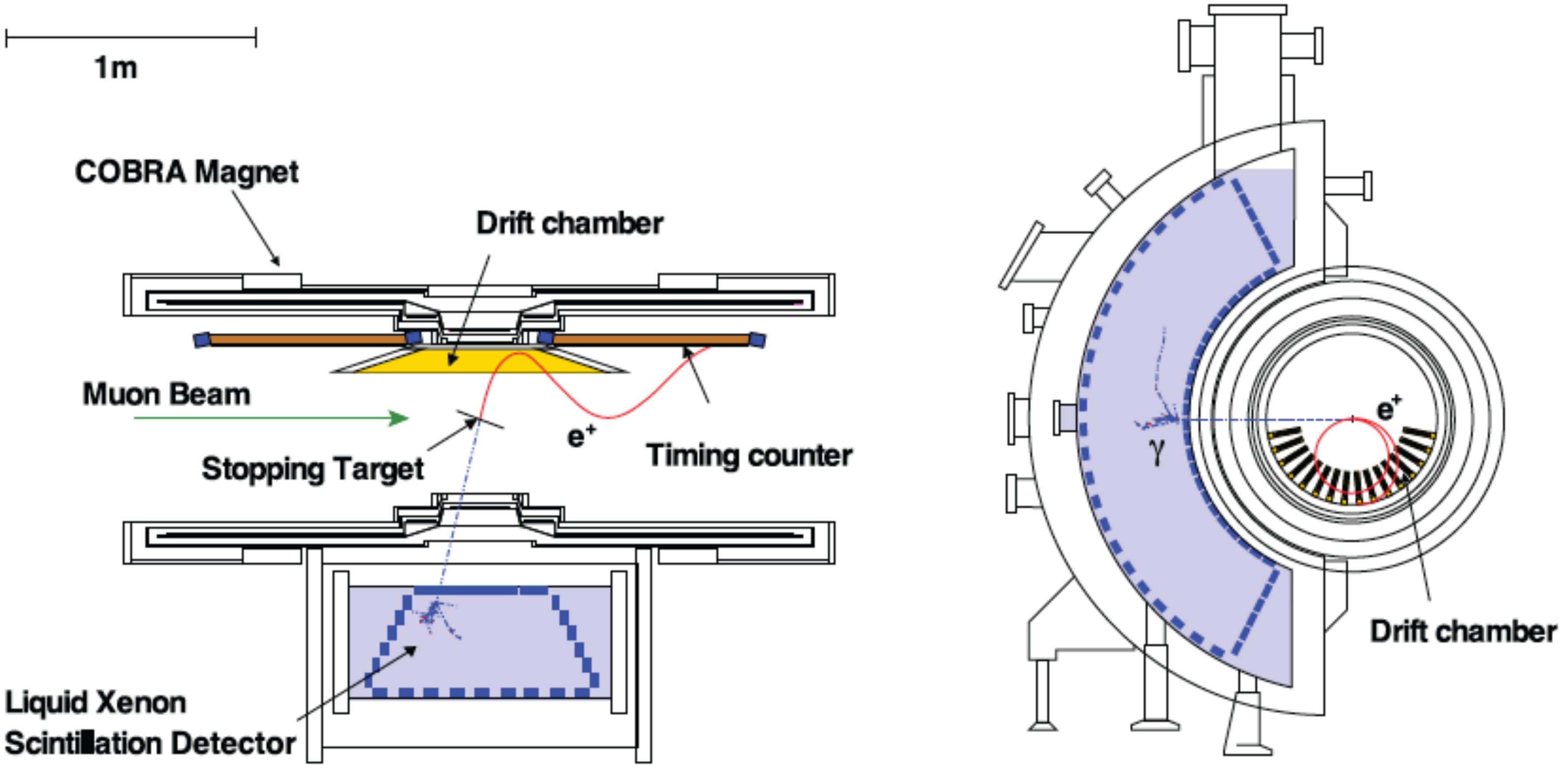
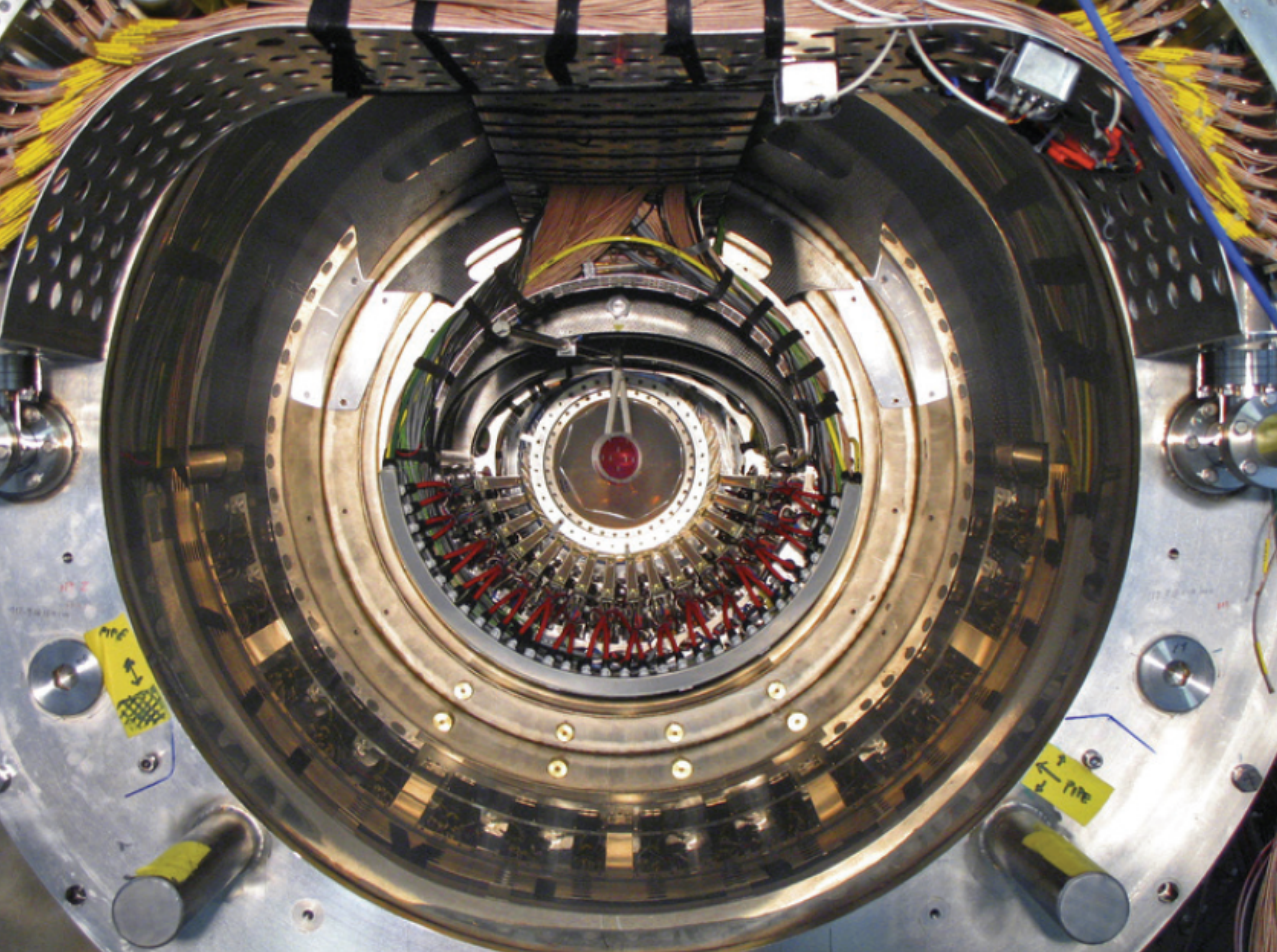
The MEG detector



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


PIPE
PIPE

MEG results

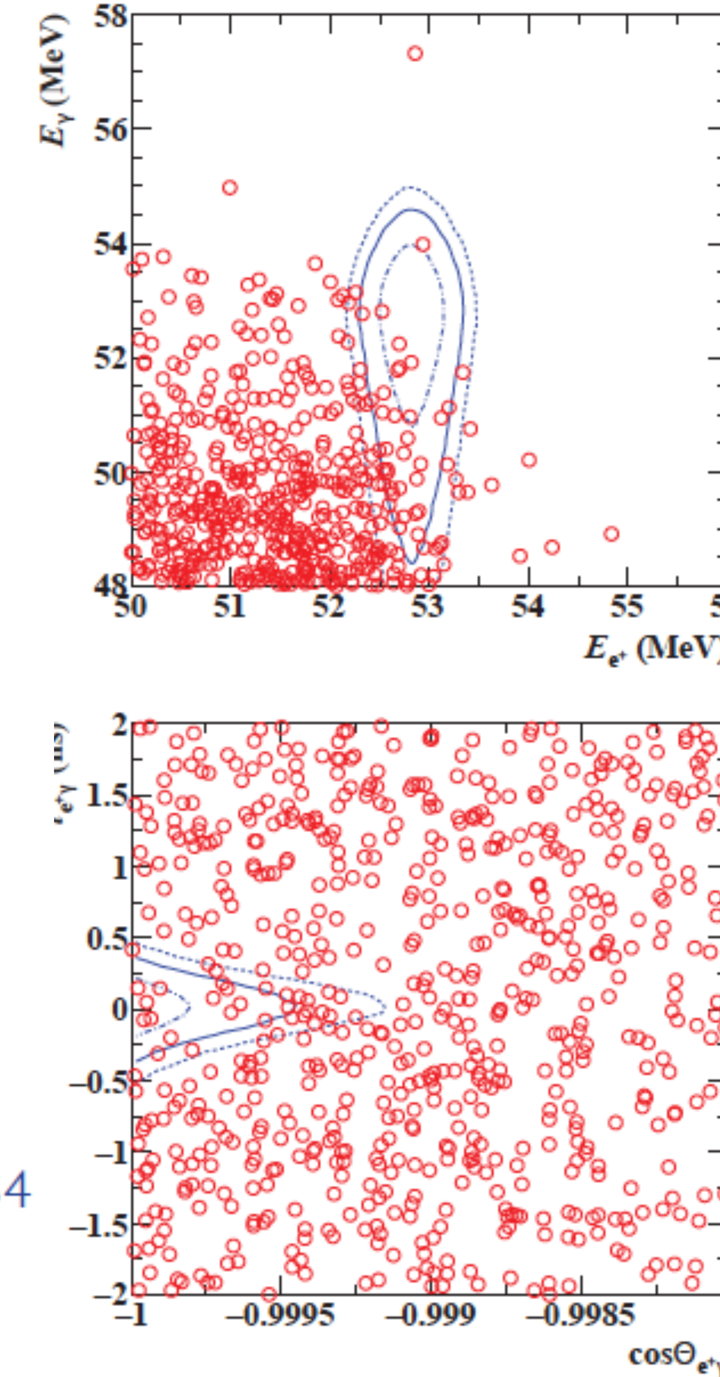
- Five observables

$(E_g, E_e, t_{eg}, \vartheta_{eg}, \phi_{eg})$

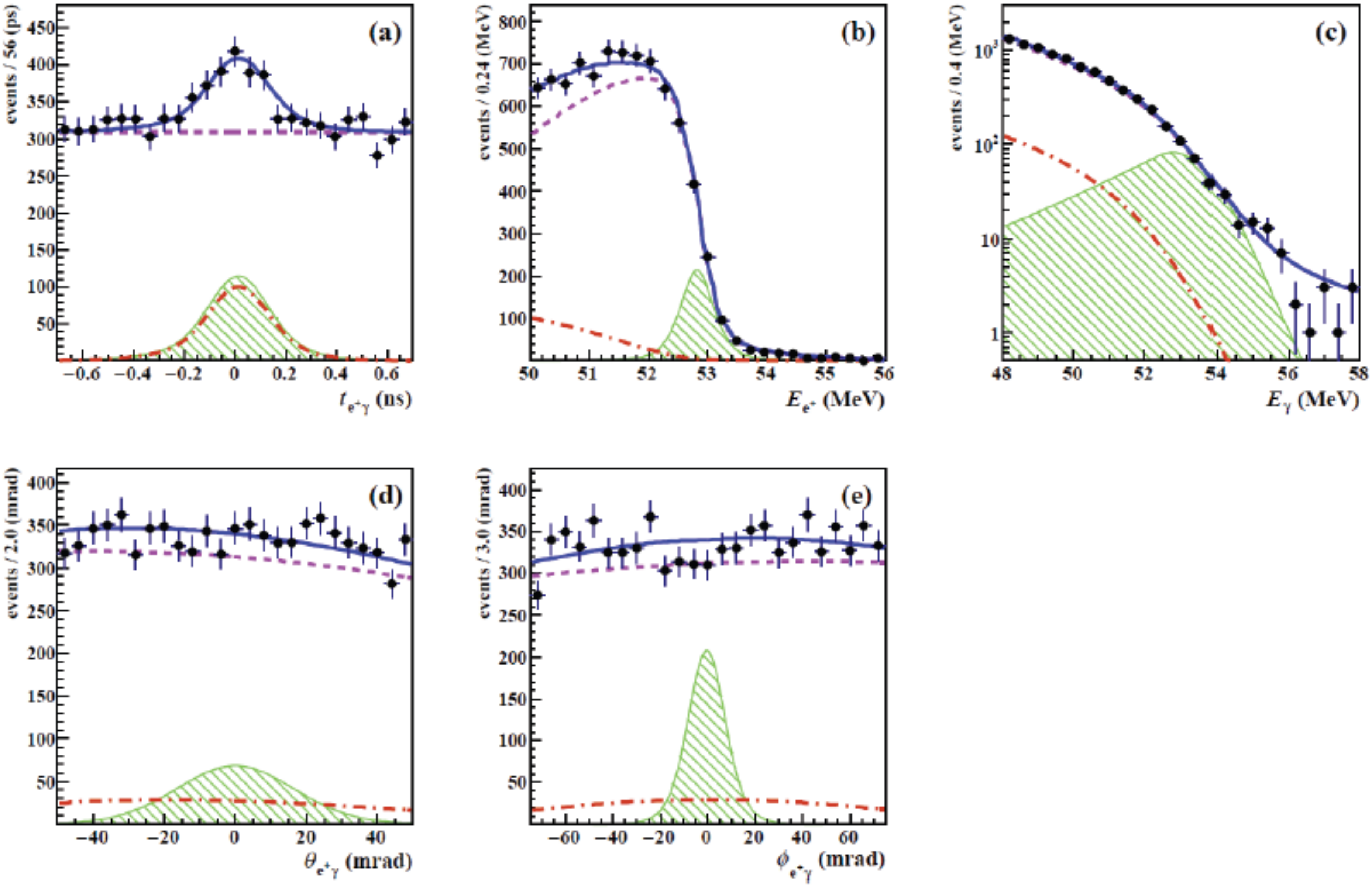
- 2009-2013 data
- Blue: Signal PDF, given by detector resolution
- No signal seen
- Upper limit at 90% CL:

$BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$

A. M. Baldini et al. Eur.Phys.J. C76 (2016) no.8, 434



Resolution



(a)
(b)
(c)
(d)
(e)
events / 56 (ps)
events / 0.24 (MeV)
events / 0.4 (MeV)
events / 2.0 (mrad)
events / 3.0 (mrad)
$t_{e^+\gamma}$ (ns)
E_{e^+} (MeV)
E_γ (MeV)
$\theta_{e^+\gamma}$ (mrad)
$\phi_{e^+\gamma}$ (mrad)

How to improve sensitivity?

Angela Papa (Mainz Seminar)

- More sensitive to the signal...

high statistics

$$SES = \frac{1}{R \times T \times A_g \times \varepsilon(e^+) \times \varepsilon\,(\text{gamma}) \times \varepsilon(\text{TRG}) \times \varepsilon(\text{sel})}$$

Beam rate

Acquisition time

Geometrical acceptance

Detector efficiency

Selection efficiency

- More effective on rejecting the background...

high resolutions

$$B_{acc} \sim R \times \boxed{\Delta E_e \times (\Delta E_{gamma})^2 \times \Delta T_{egamma} \times (\Delta \Theta_{egamma})^2}$$

Positron Energy resolution

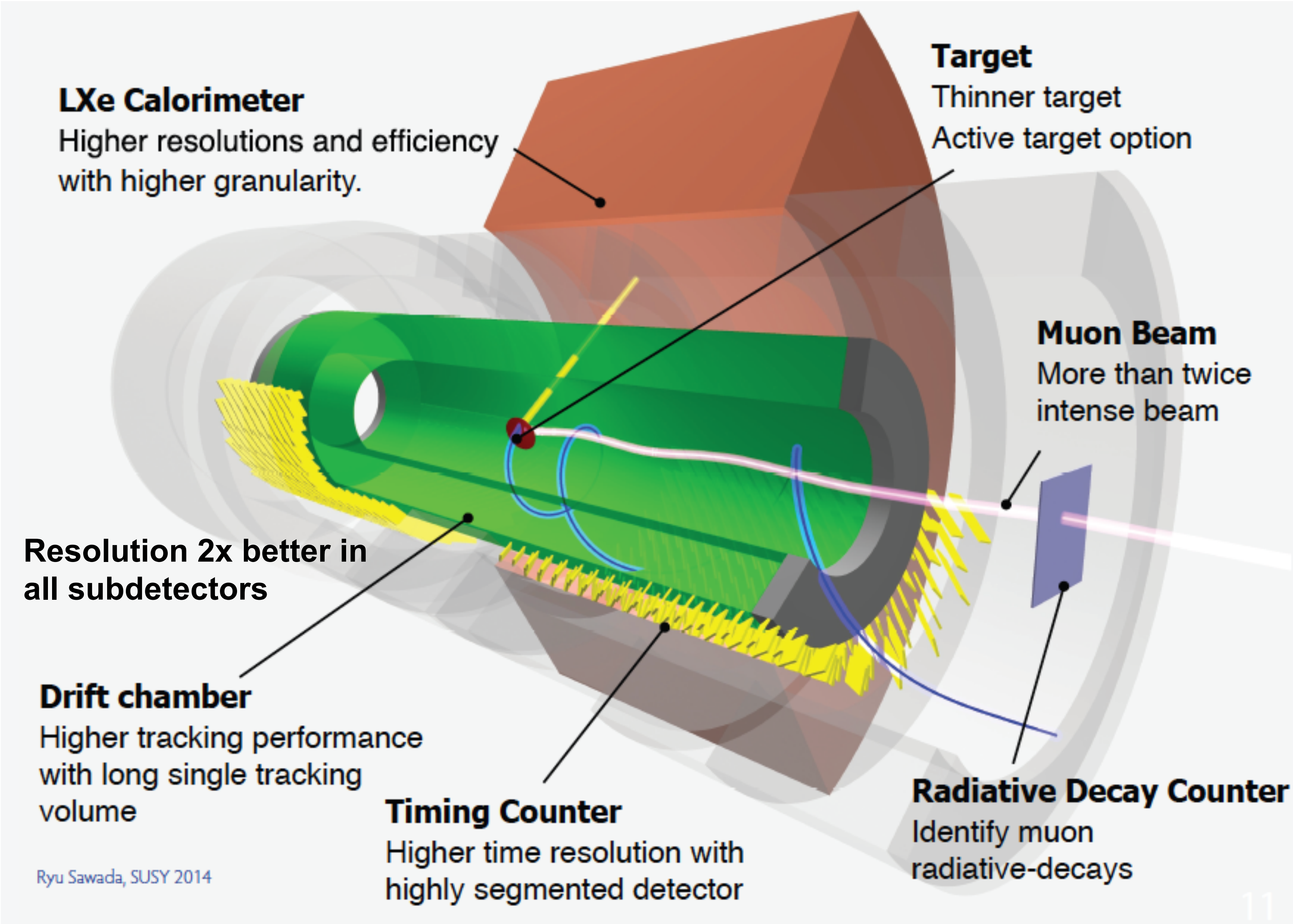
Gamma Energy resolution

Relative timing resolution

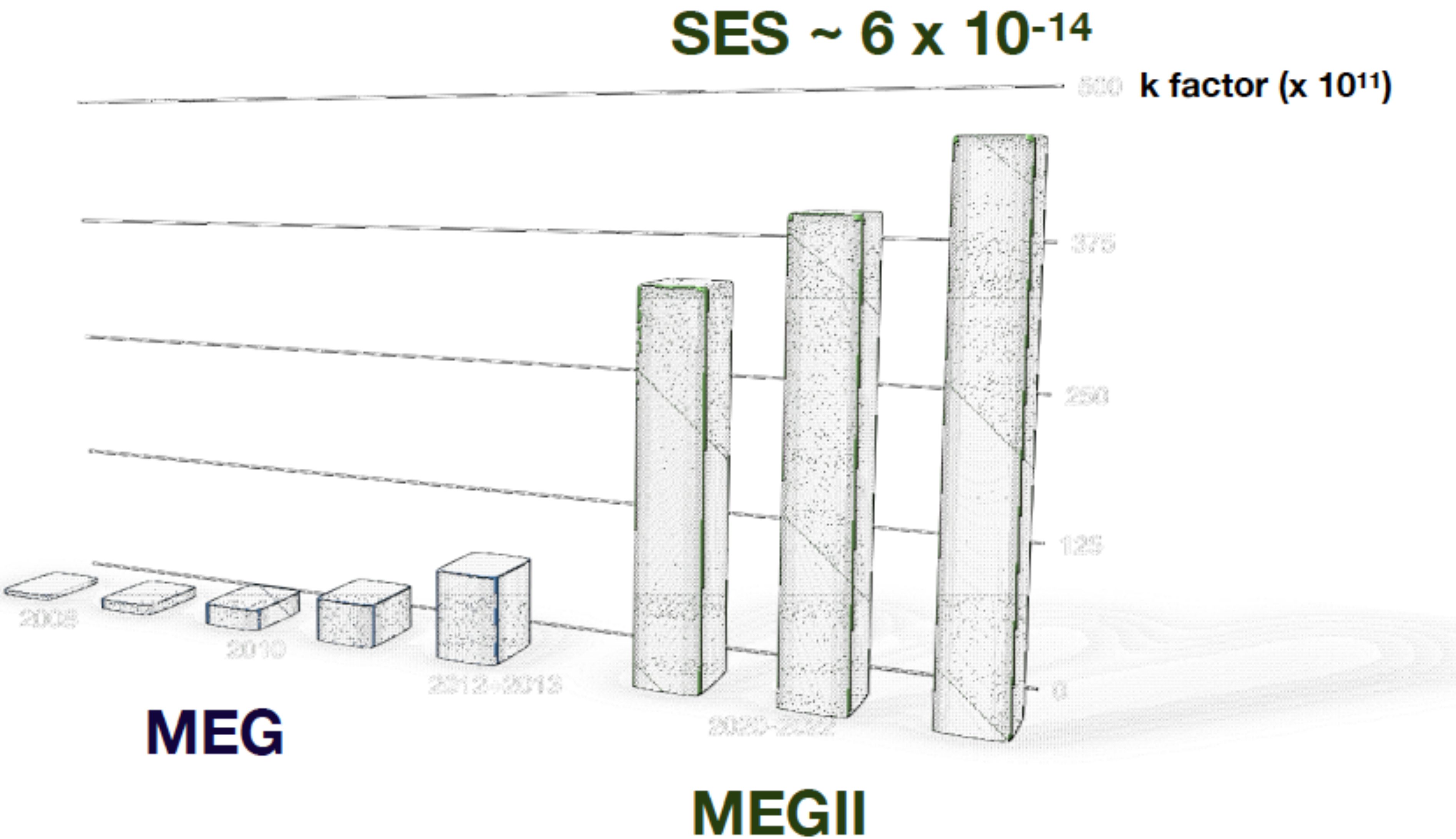
Relative angular resolution

27

The MEG-II detector



MEG-II projections



Searching for $\mu \to e$ conversion with

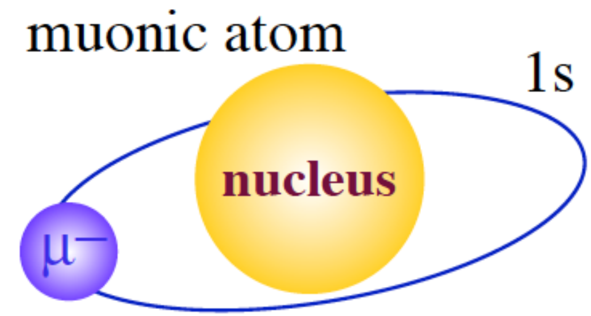
Mu2e, DeeMee, COMET, PRISM

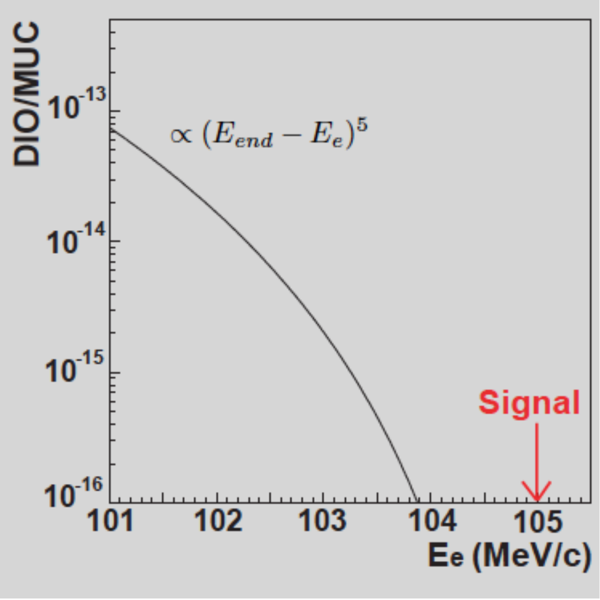
Conversion: Experimental method

- Low energy muons stop at target and are captured by the nucleus. Then cascade to 1s state.
- They either get captured by the nucleus or decay in orbit.
- Or they are converted to an electron in the muonic atom

  → signal

$E_e \approx m_\mu - B_\mu$
$= 105$ MeV



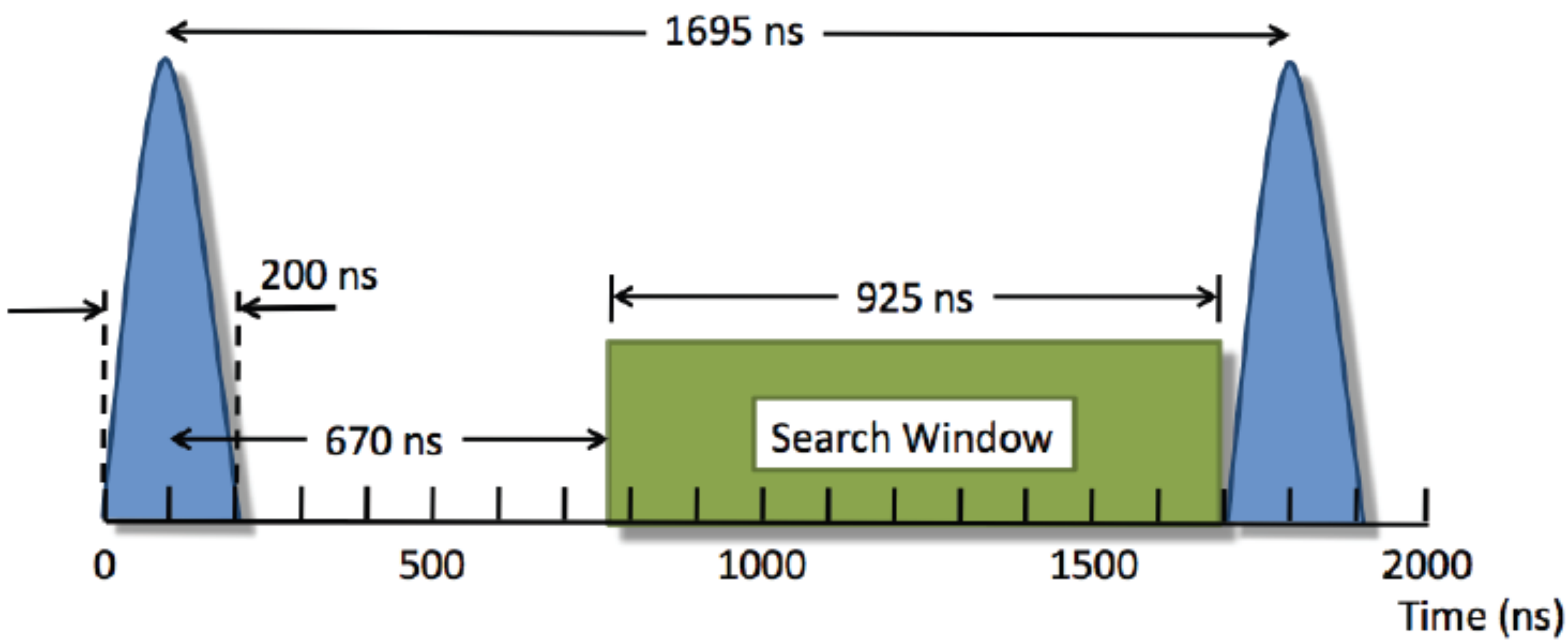


- Background: anything that can produce an electron with E=105 MeV (beam background, decay in orbit, cosmics)

  → need pulsed beam
- No accidental background

  → can work with higher muon rates

Beam induced backgrounds



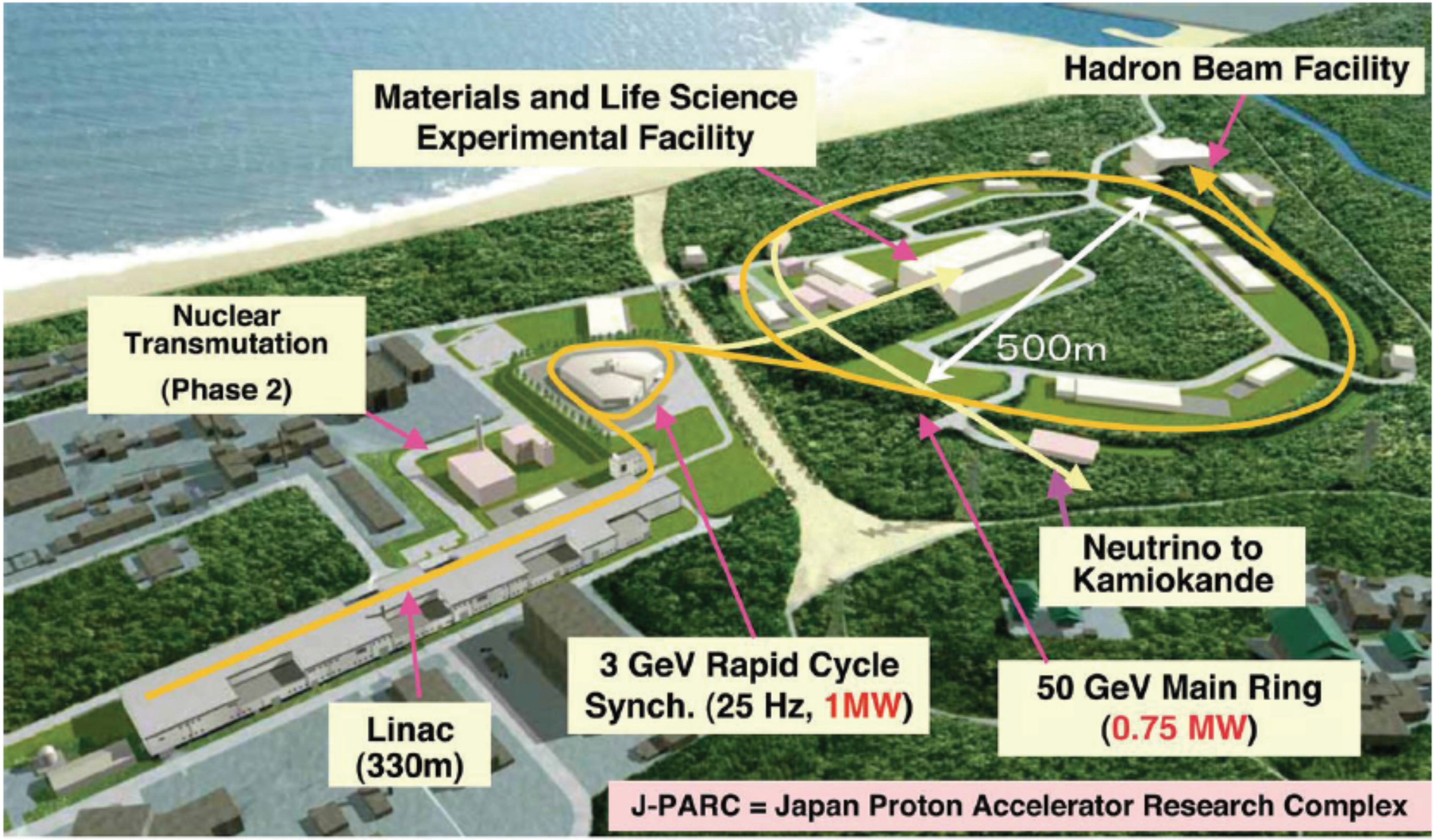
- Proton beam produces pions, photons, (antiprotons) etc.
- Wait until things become better...

Muons from Fermilab...

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

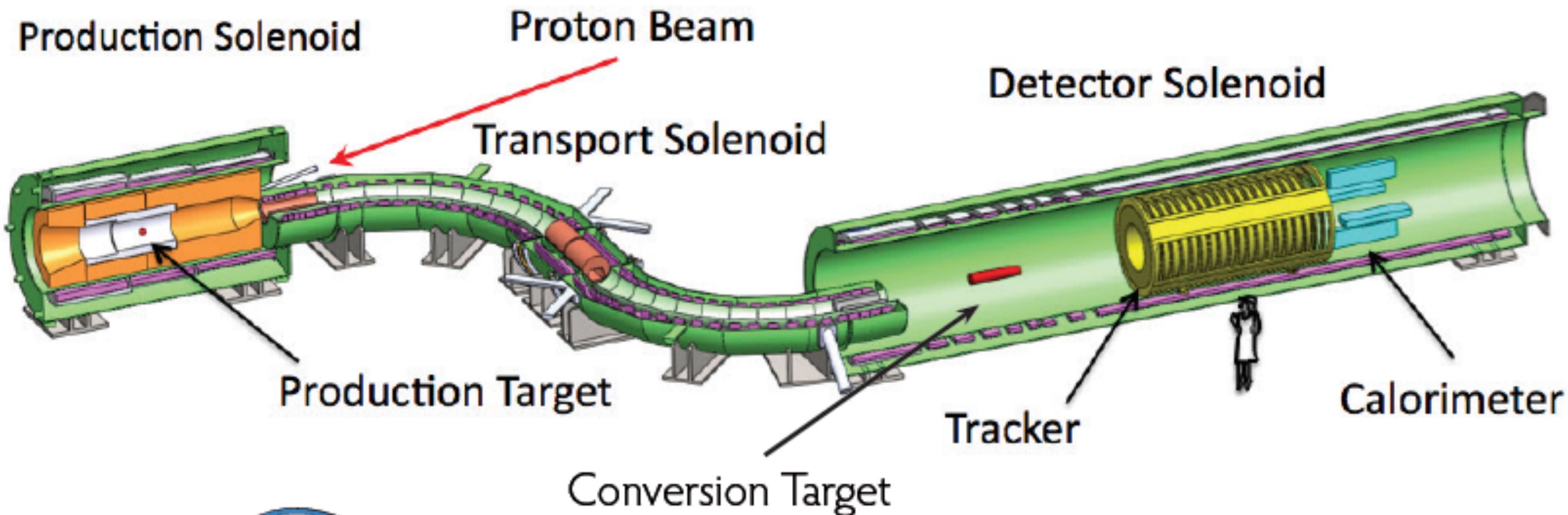
- Project X would give another 2 orders of magnitude at an energy below the antiproton threshold

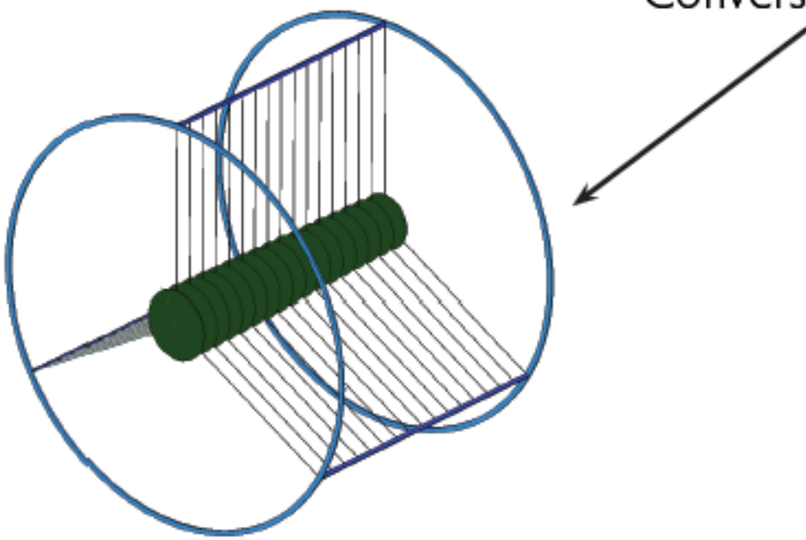
... and at J-PARC



- 10^{11} μ/s from 8 GeV/c protons

Experimental concept – Mu2e



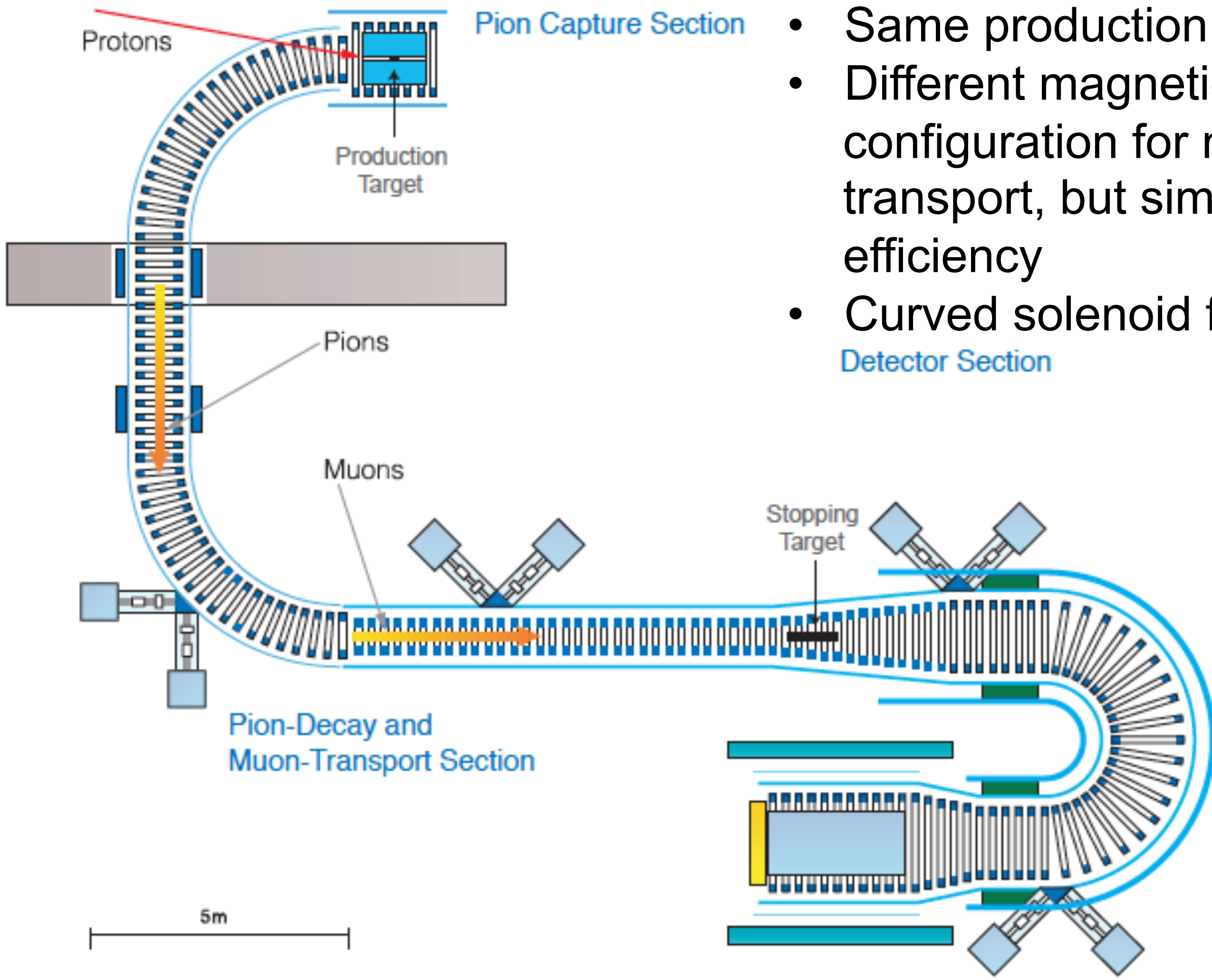


- Tungsten target for pion production
- Transport solenoid:
  - > Long enough for pions to decay (>20m)
  - > Negative charge selection
  - > Low momentum selection (p_μ<75 MeV)
  - > High transport efficiency
- Aluminum target for muon conversion
- Detector solenoid: Select electrons with E=105 MeV
- Detector with excellent energy/ momentum resolution

Experimental concept – Comet

Comparison to mu2e:

- Same production target
- Different magnetic field configuration for muon transport, but similar efficiency
- Curved solenoid for detection

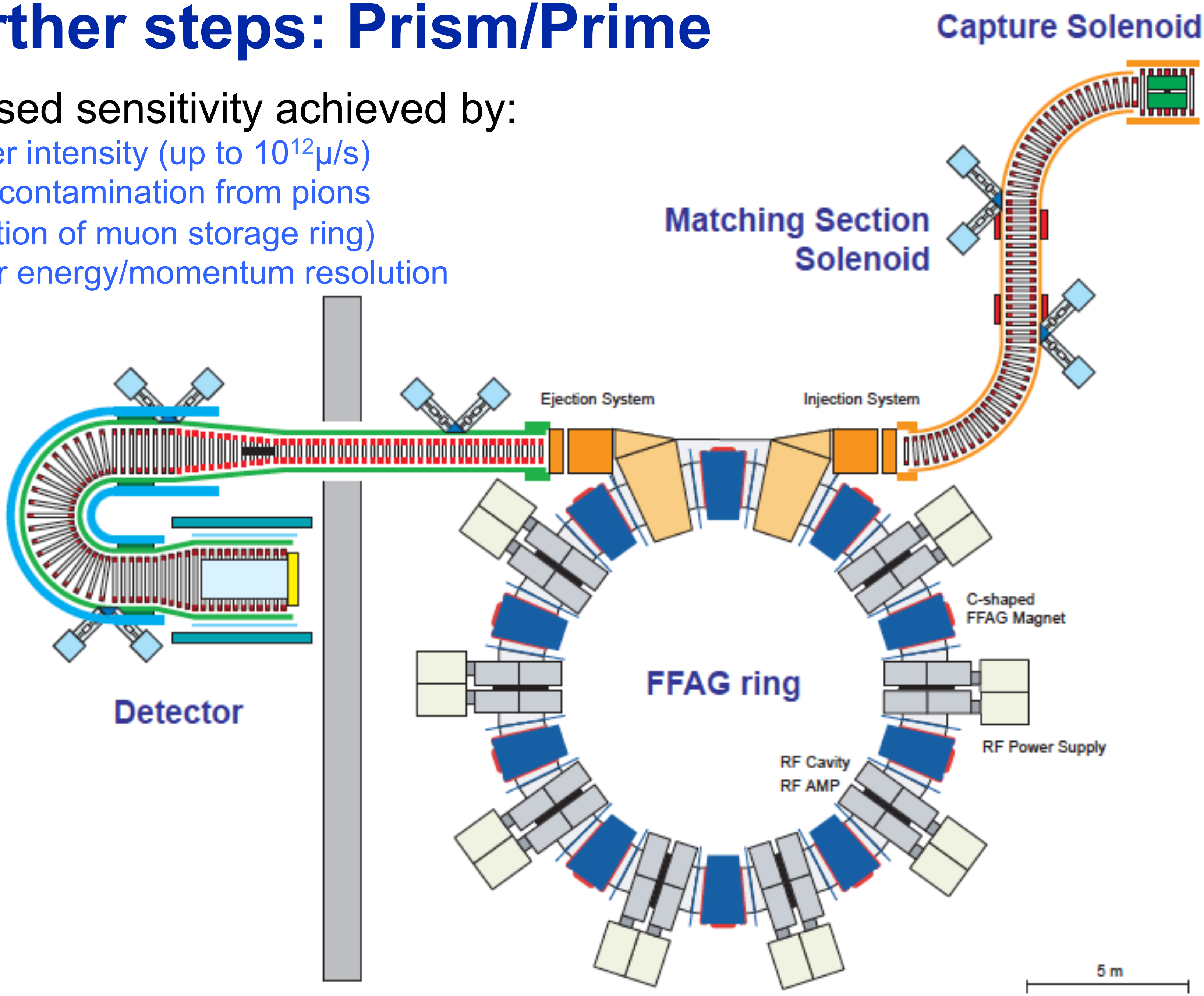


Comet CDR

Further steps: Prism/Prime

Increased sensitivity achieved by:

- Higher intensity (up to $10^{12}\mu/s$)
- Less contamination from pions (addition of muon storage ring)
- Better energy/momentum resolution

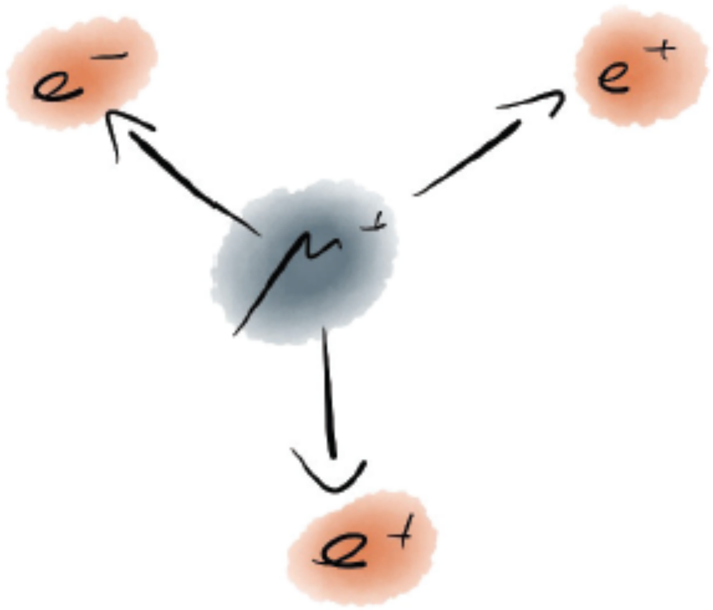


Expected sensitivity

- Comet Phase I and DeeMee might get to $\sim 10^{-14}$
- 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}

Searching for $\mu^+ \rightarrow e^+e^-e^+$ with Mu3e

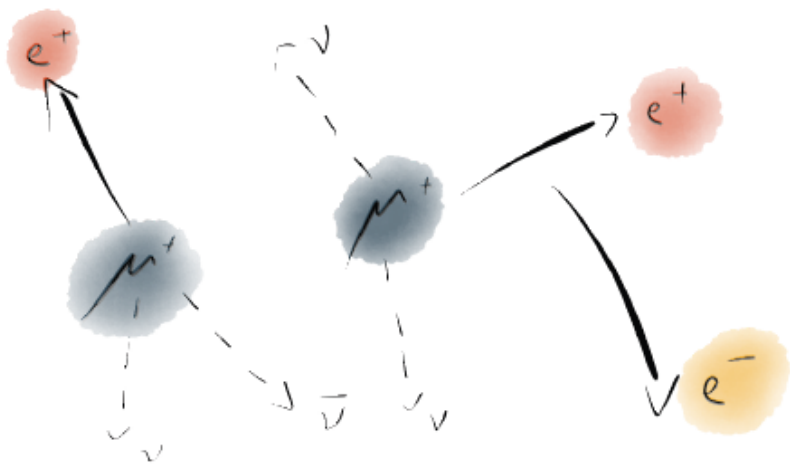
Signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- $\Sigma\, p_e = m_\mu$
- Maximum momentum: ½ m_μ = 53 MeV/c

Backgrounds

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

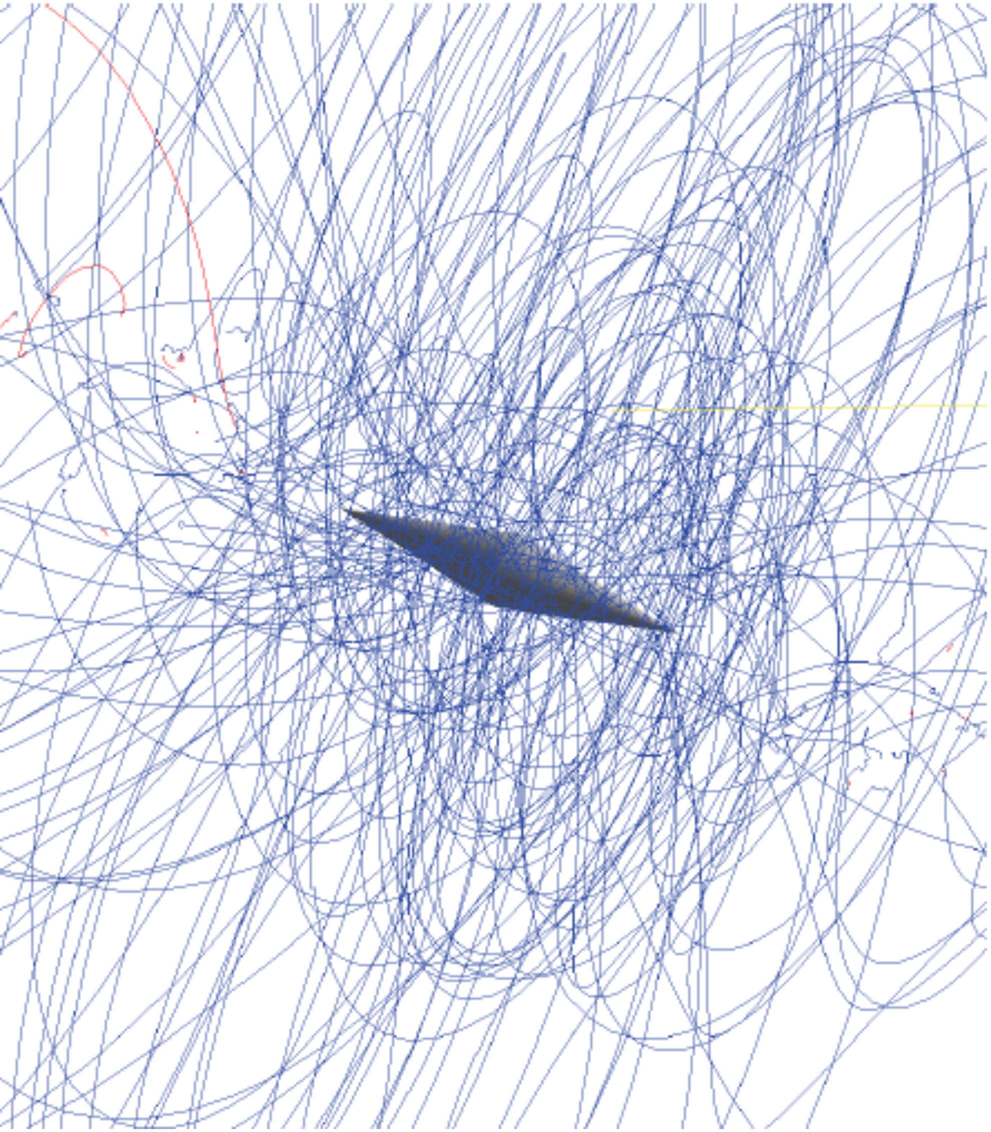
Internal conversion background

- Allowed radiative decay with internal conversion:

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

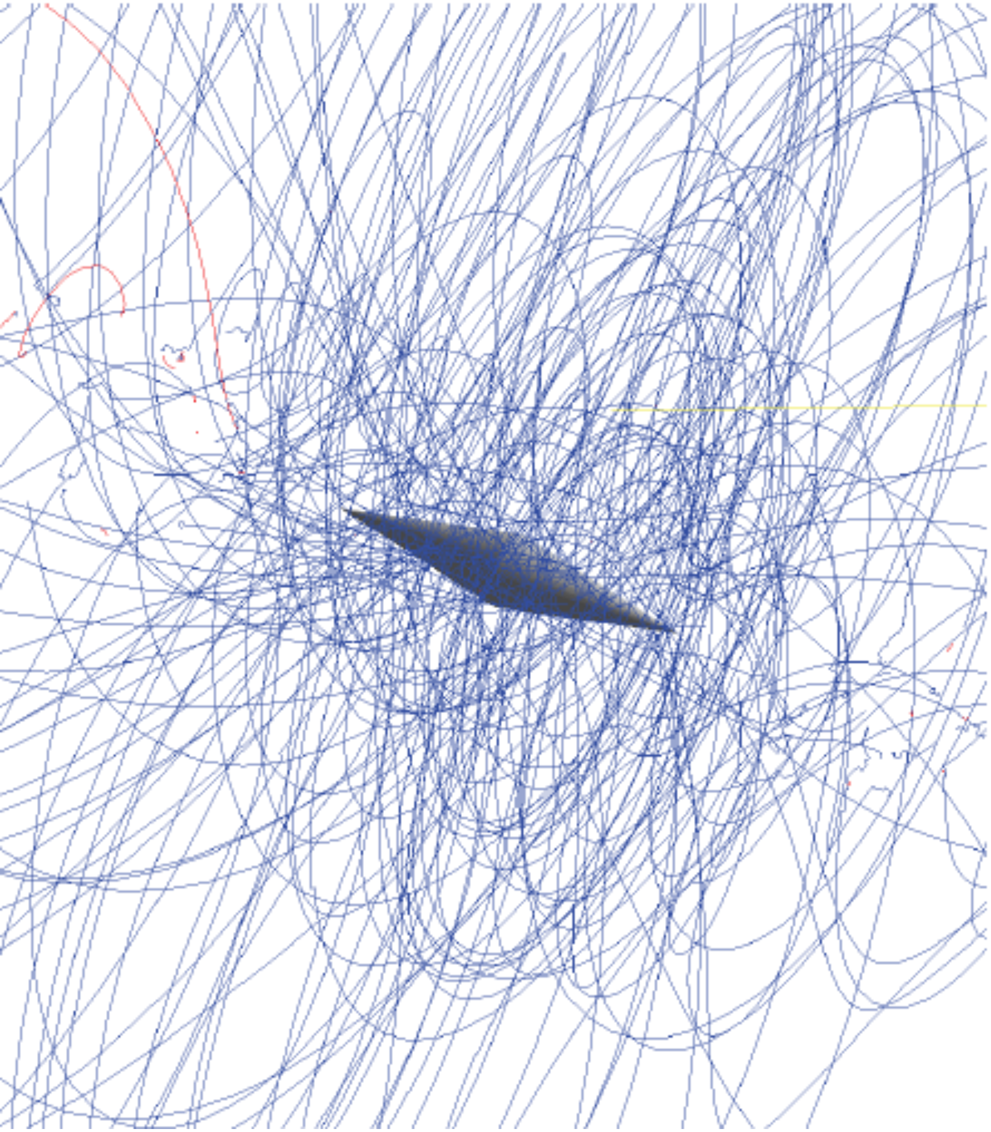
- Only distinguishing feature: Missing momentum carried by neutrinos
- Need excellent momentum resolution

Detector technology: Tracking!



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

Detector technology: Tracking!



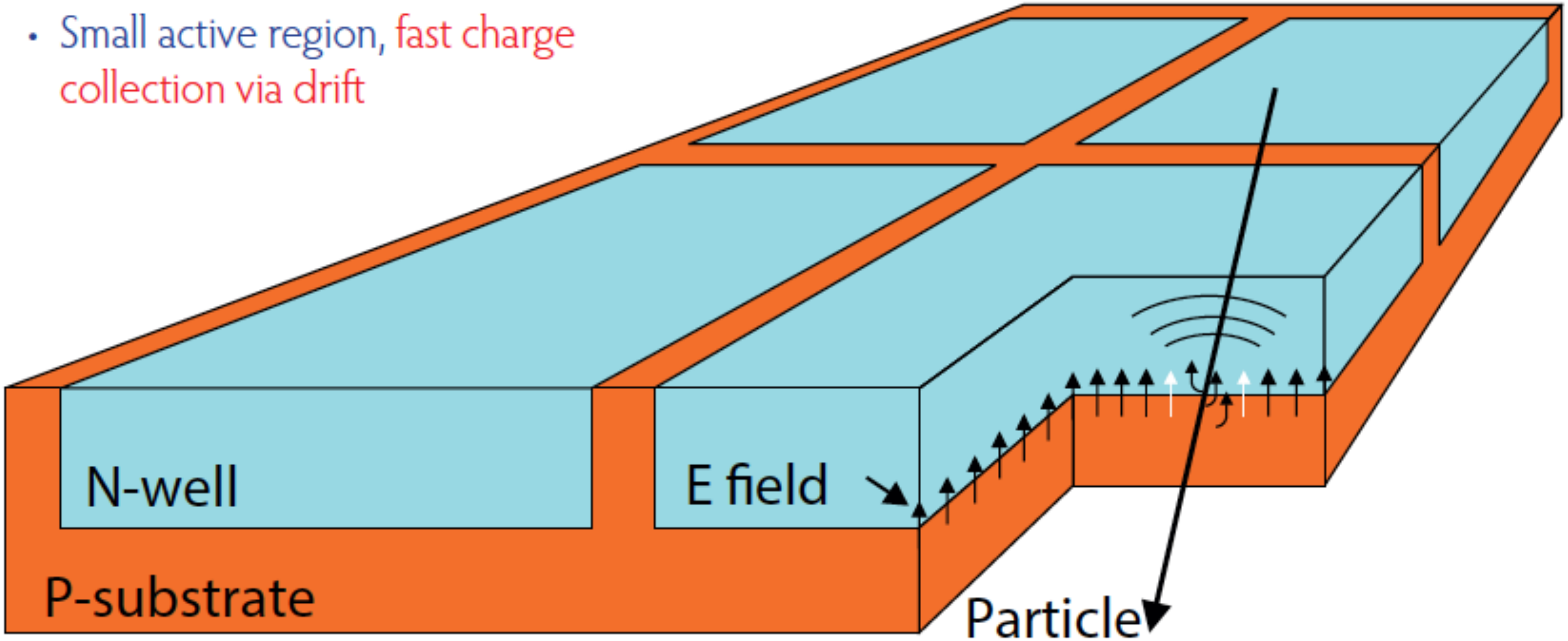
- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)
- Gas detectors do not work (space charge, aging, 3D)
- Silicon strips do not work (material budget, 3D)
- Hybrid pixels (as in LHC) do not work (material budget)

Monolithic active pixel sensors (MAPS)

→ **Fast and thin sensors**

High voltage monolithic active pixel sensors - Ivan Perić

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



Monolithic active pixel sensors (MAPS)

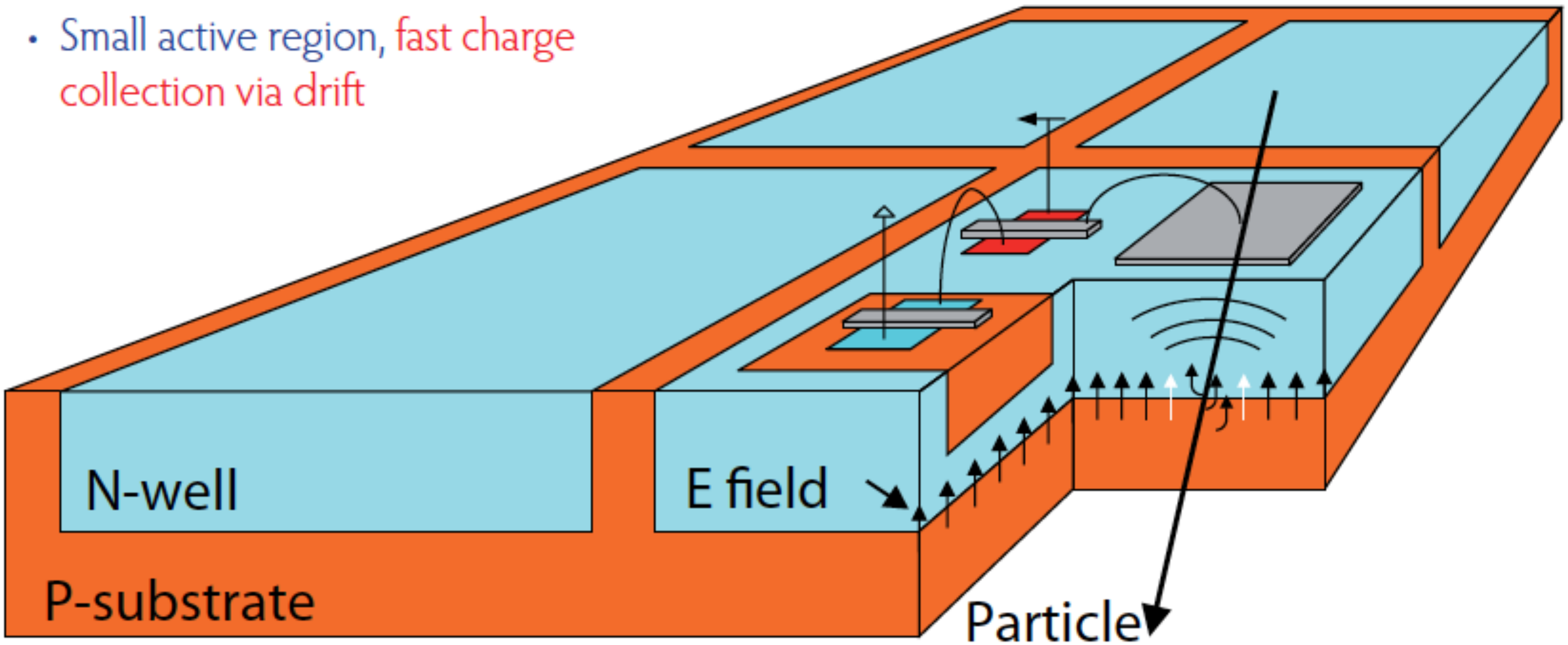
→ Fast and thin sensors

High voltage monolithic active pixel sensors - Ivan Perić

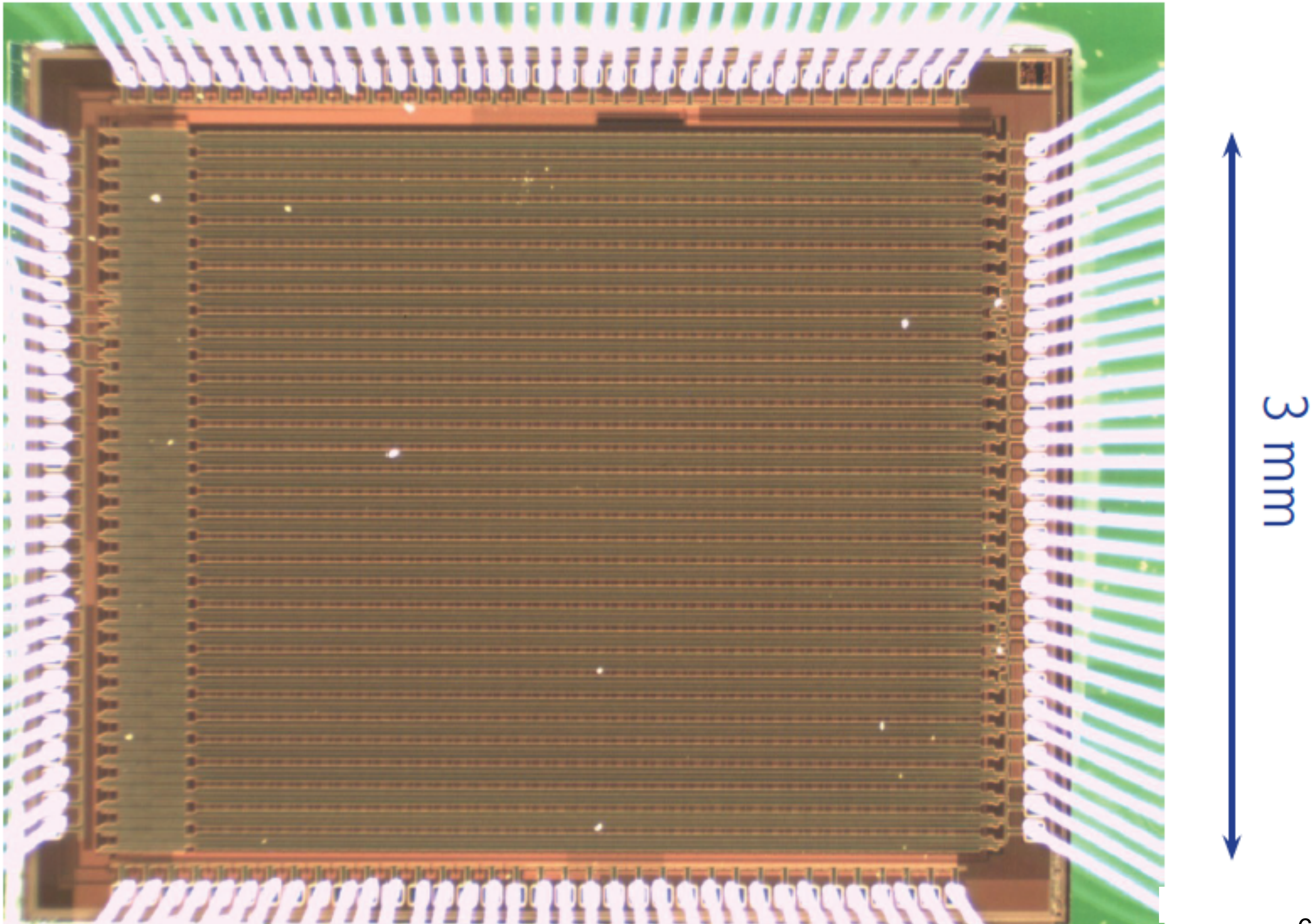
- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift

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

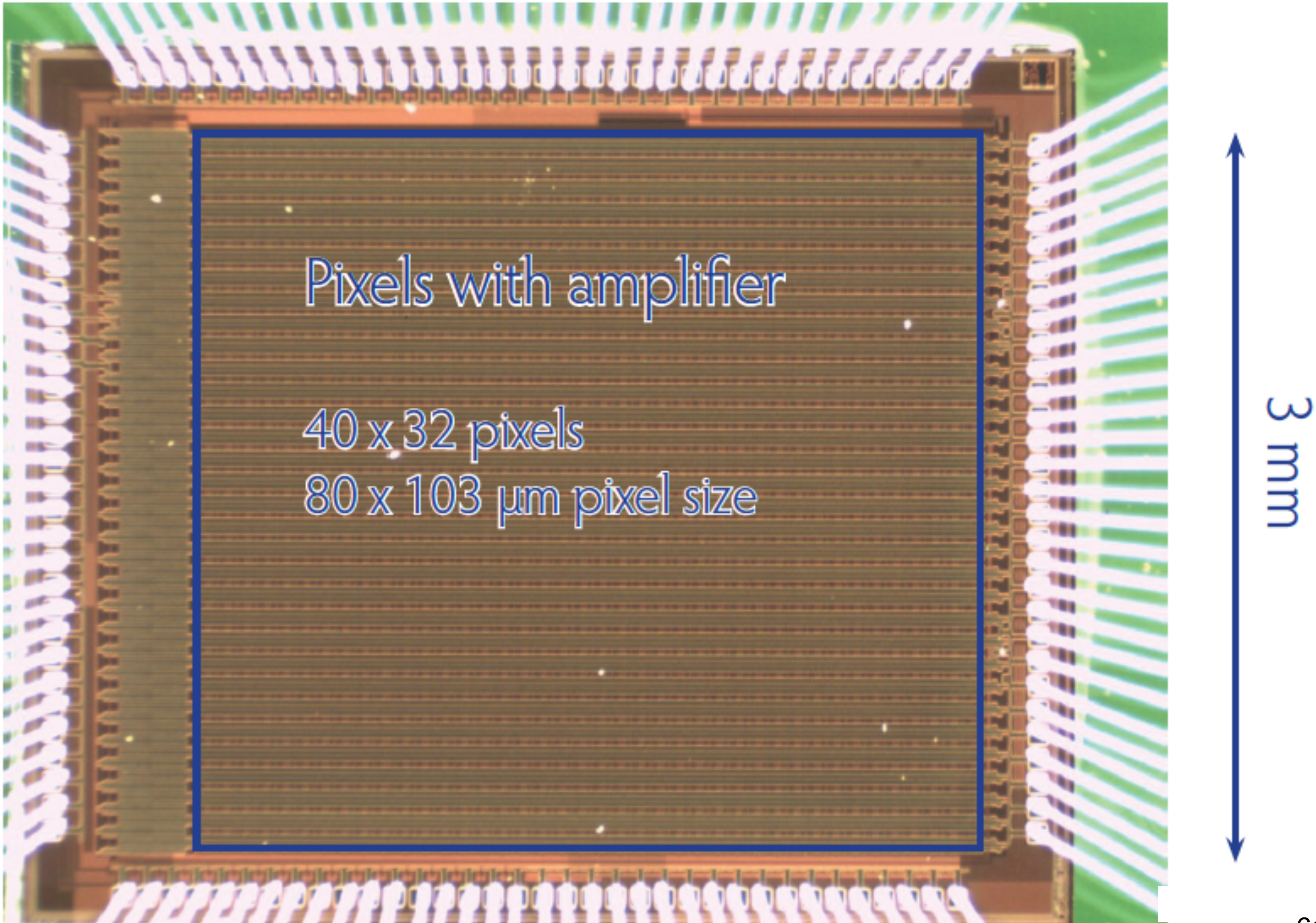
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)



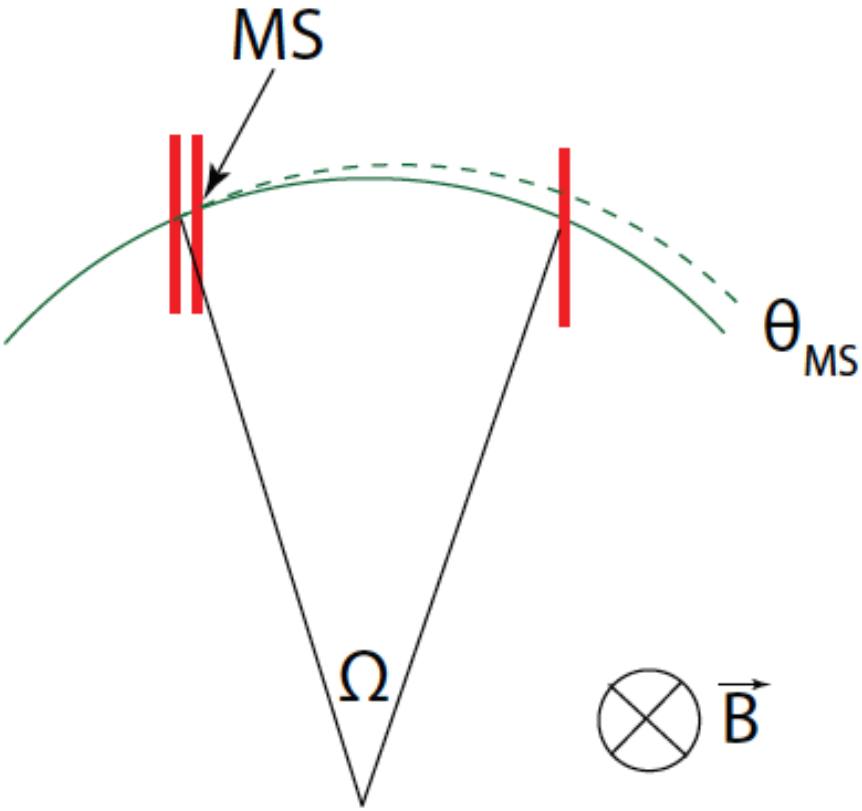
MuPix7



MuPix7


Pixels with amplifier
40 x 32 pixels
80 x 103 µm pixel size
3 mm

Momentum measurement

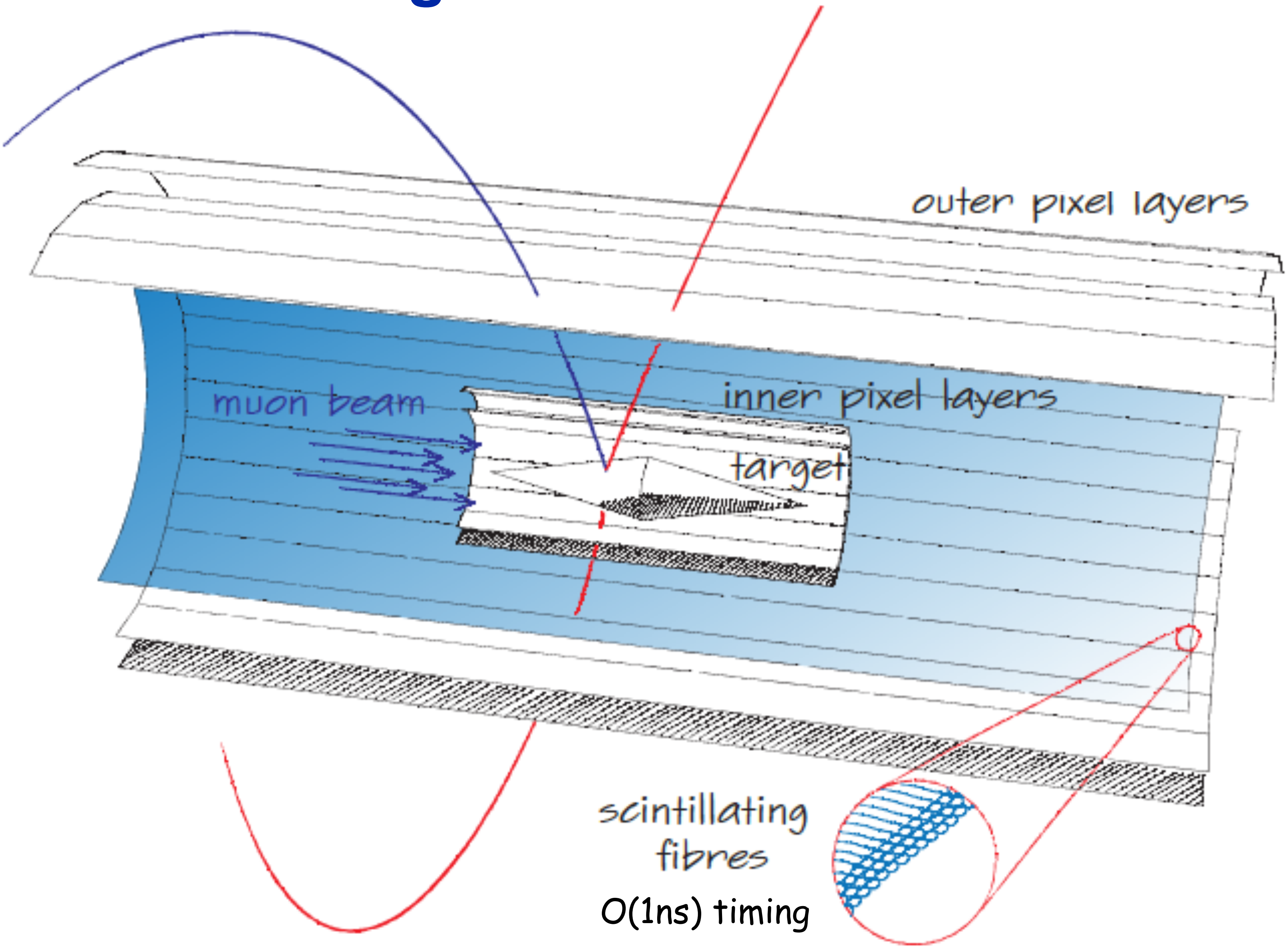


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

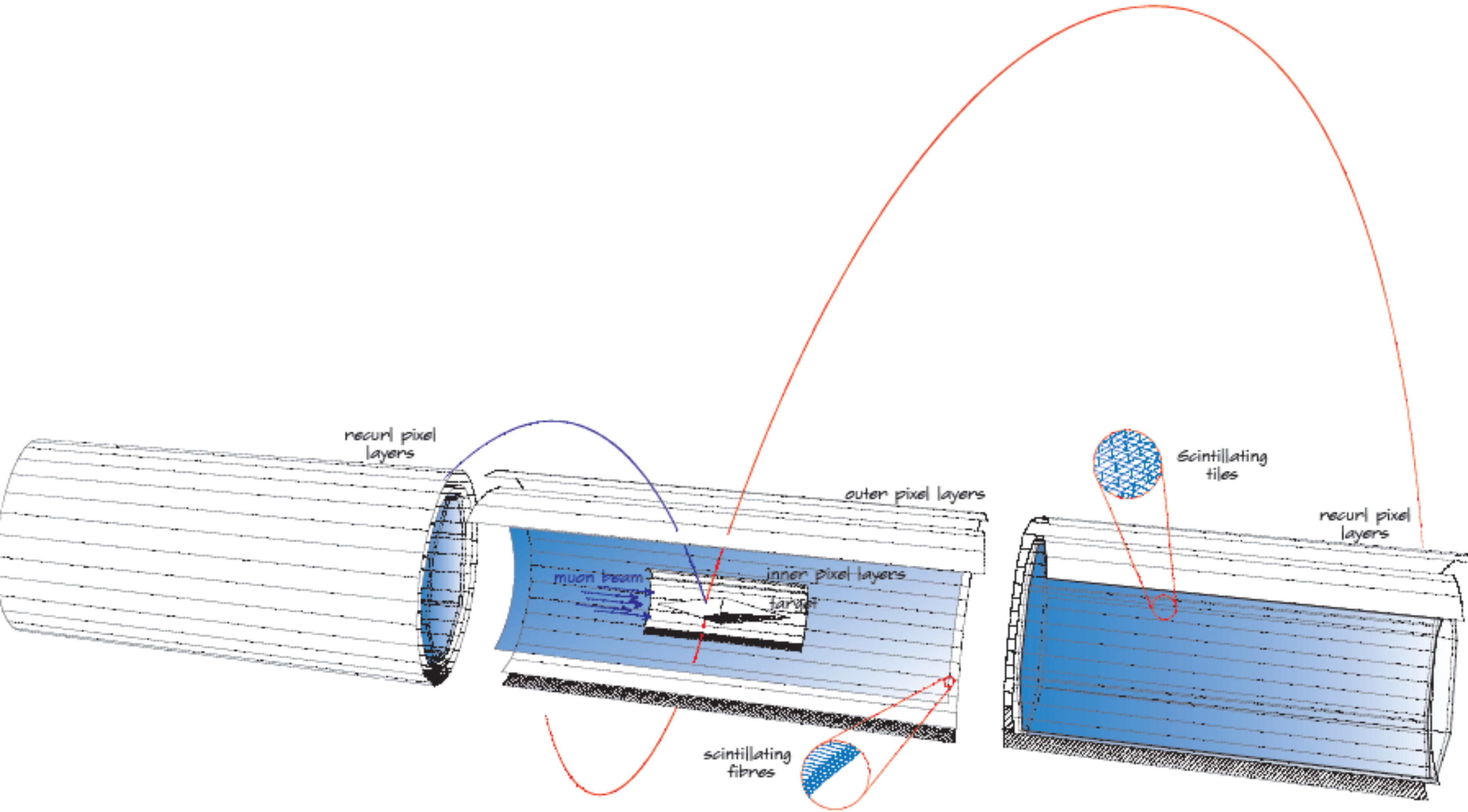
$$\sigma_P/_P \sim \theta_{MS}/_\Omega$$

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

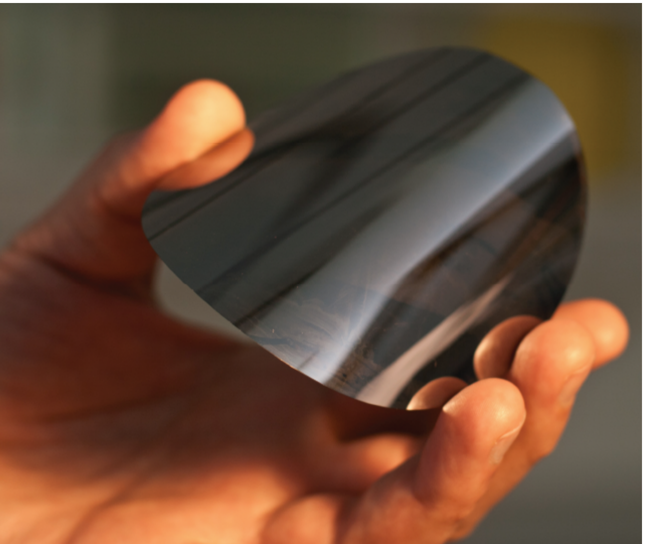
Detector design



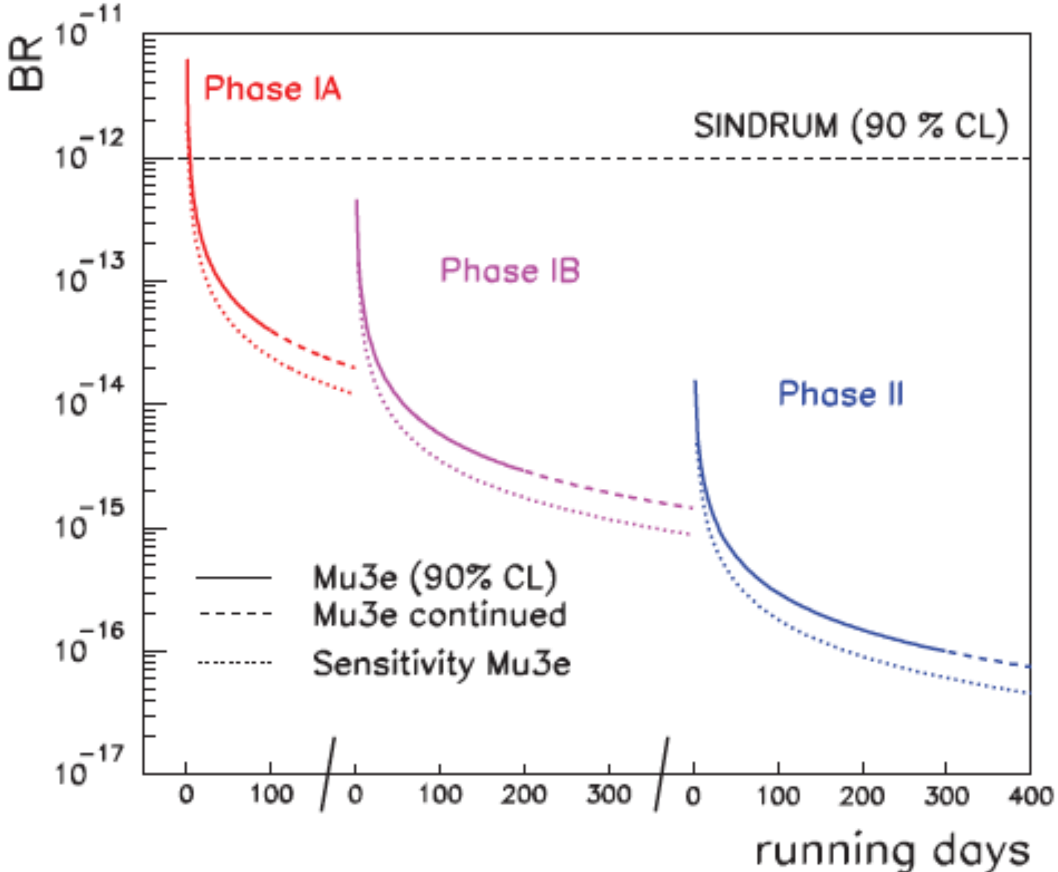
Detector design

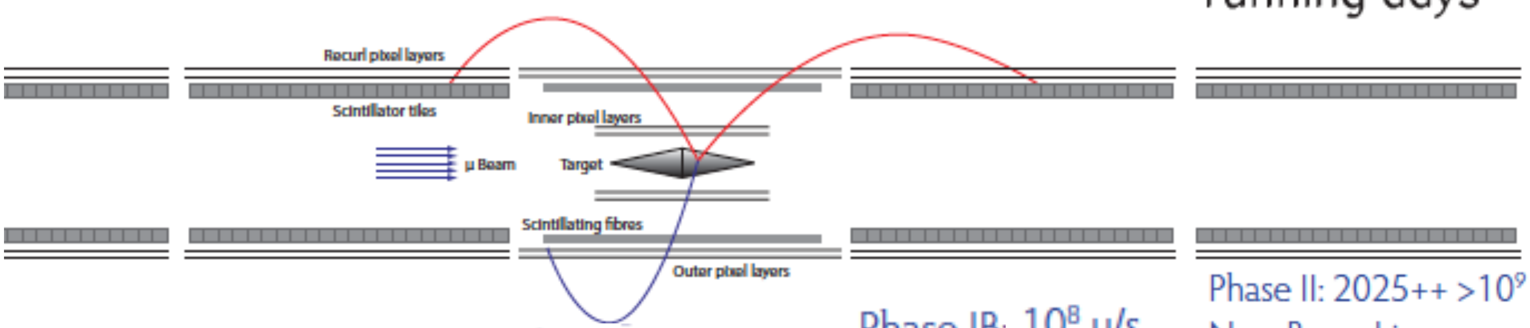


Low mass



Sensitivity





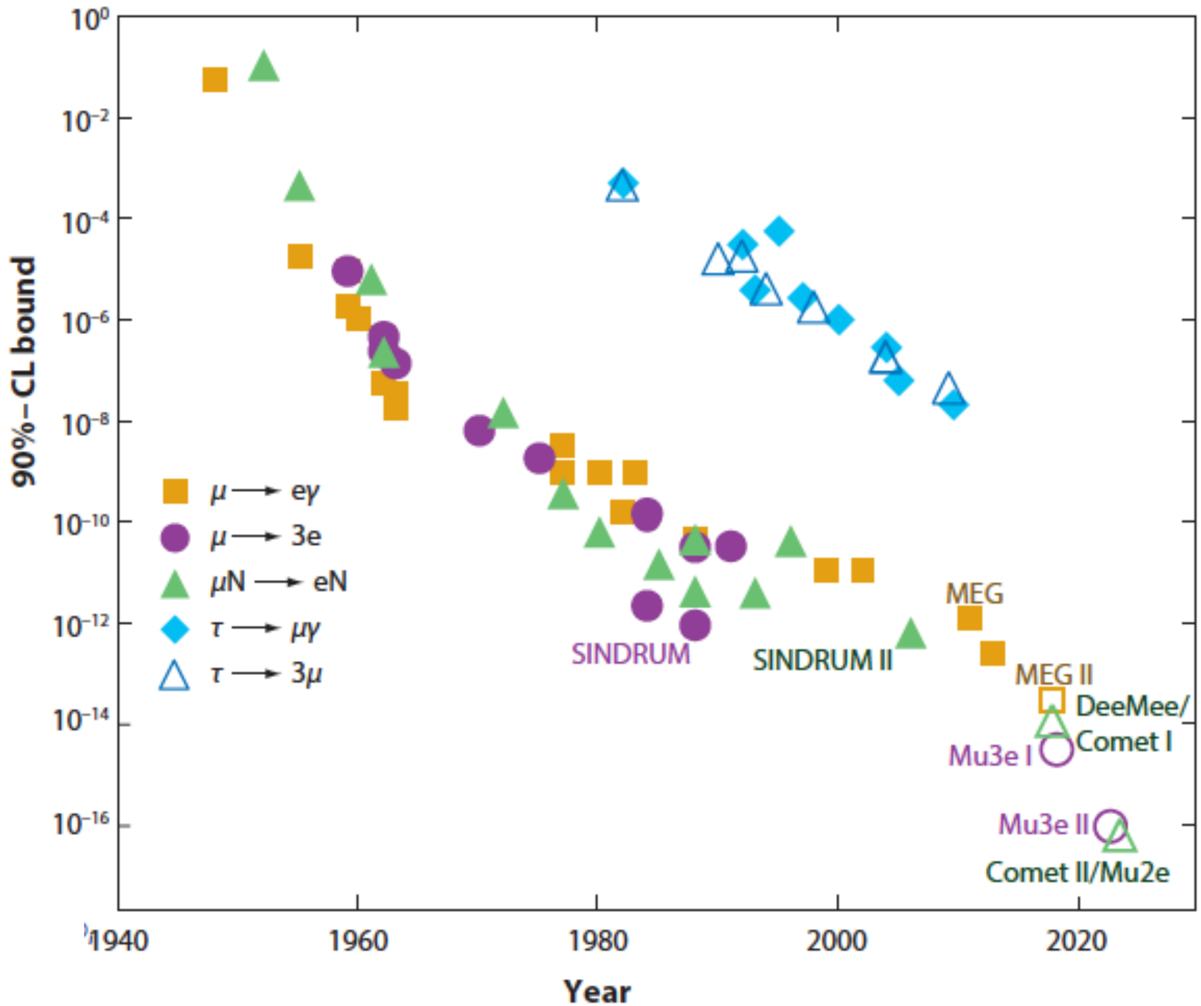
Phase IA: 10^7 μ/s

Phase IB: 10^8 μ/s

Phase II: 2025++ >10^9 μ/s
New Beam Line

Summary

- Search for charged lepton flavor violation as probe for new physics
- New experiments with improved sensitivity



References

- Lecture prepared by N. Berger for HGSFP 2018:
  https://gsfp.physi.uni-heidelberg.de/winterschool_2018/

- More on this topic in Master level class:
  Phy568: Flavour Physics
  https://www.physik.uzh.ch/en/teaching/PHY568/FS2019.html

References

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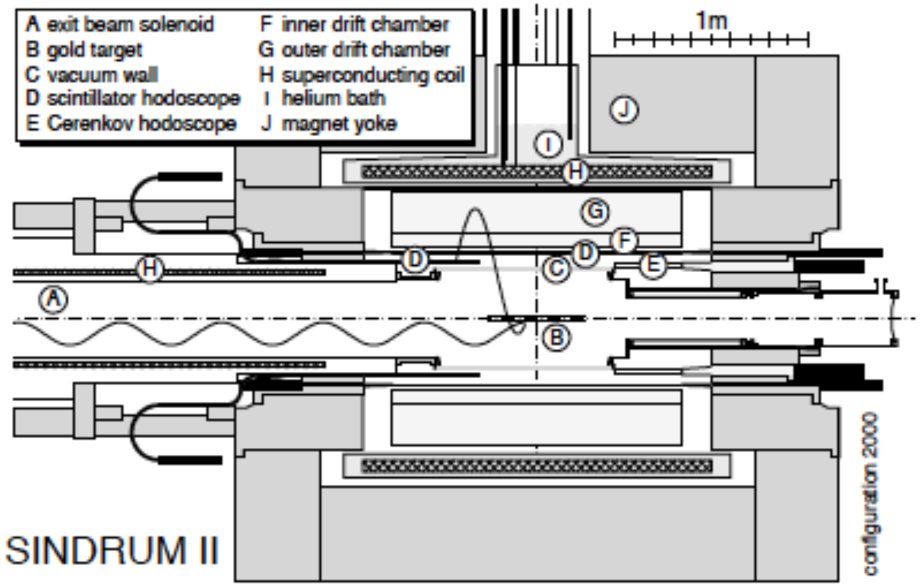
  https://www.physik.uzh.ch/en/teaching/PHY568/FS2019.html

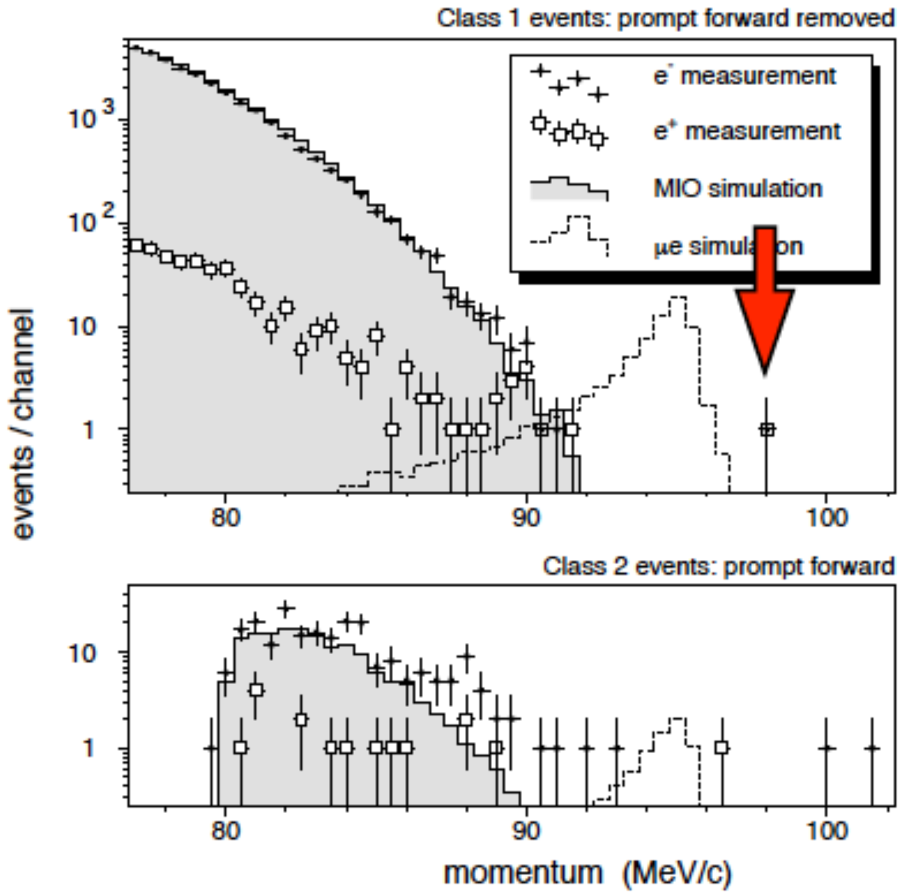
Backup

https://indico.cern.ch/event/880823/contributions/3710659/attachments/1979354/3295507/Pixel_Sensors.pdf.

SINDRUM-II at PSI

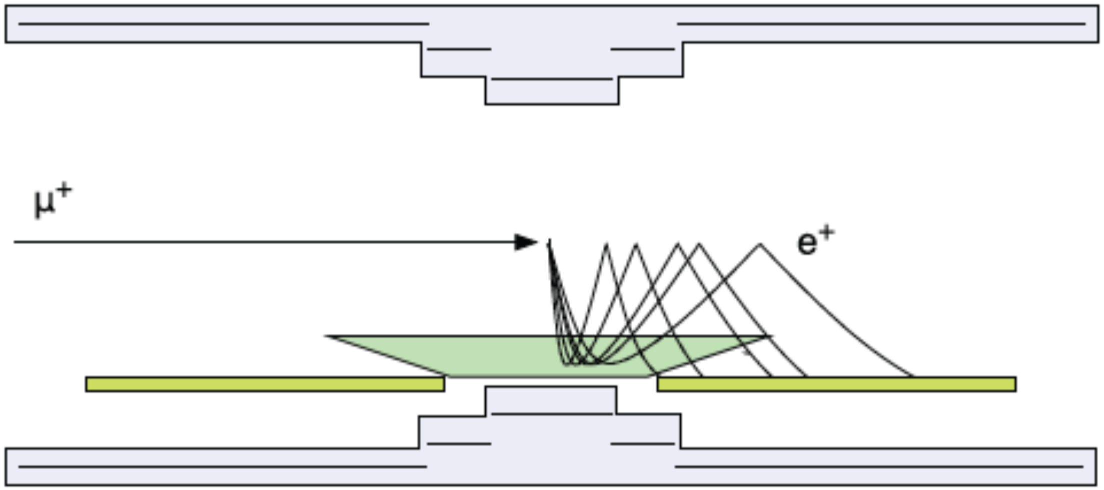


$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$

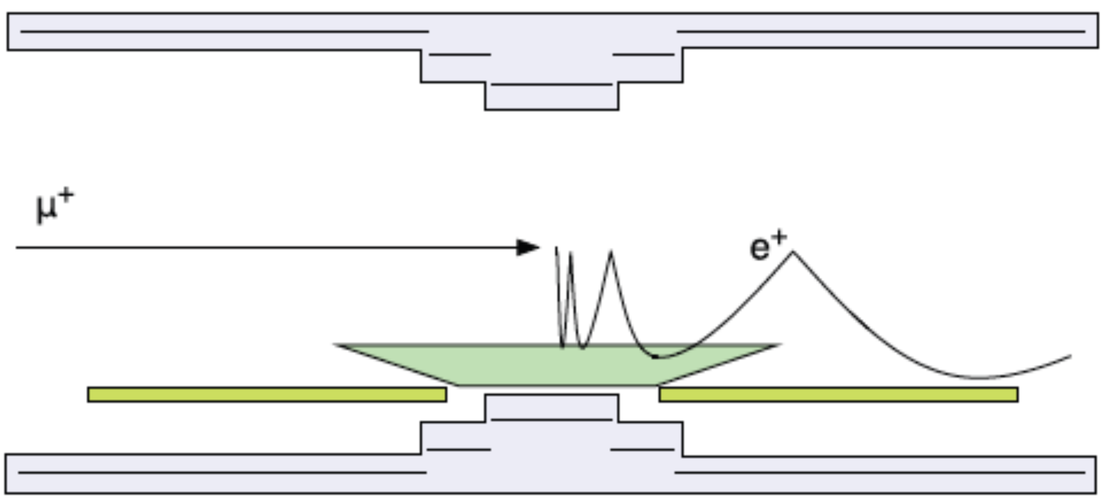


There is one background event above the signal region, and it is speculated that it might come from pion contamination in a beam.

Cobra magnet



Gradient field gives constant bending radius independent of angle

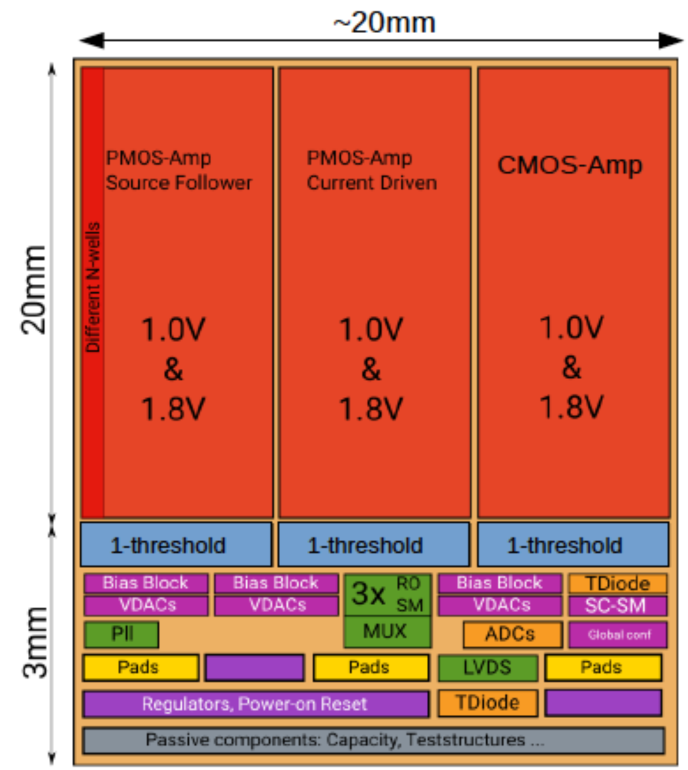


Fast sweep of curlers

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

MuPix10

- MuPix10: Full-size chip of the MuPix family
- Status: Submitted for production, expected to be available in spring 2020
- Chip size: 20x23mm^2
- Pixel size: 80x81μm^2



- Construction of pixel modules for mu3e with MuPix10 from April-October 2020

- For more details see talk by Ivan Peric:

https://indico.cern.ch/event/880823/contributions/3710659/attachments/1979354/3295507/Pixel_Sensors.pdf