Searching for new physics with low-energy pions

Credit: iStock/unpict

Chloé Malbrunot
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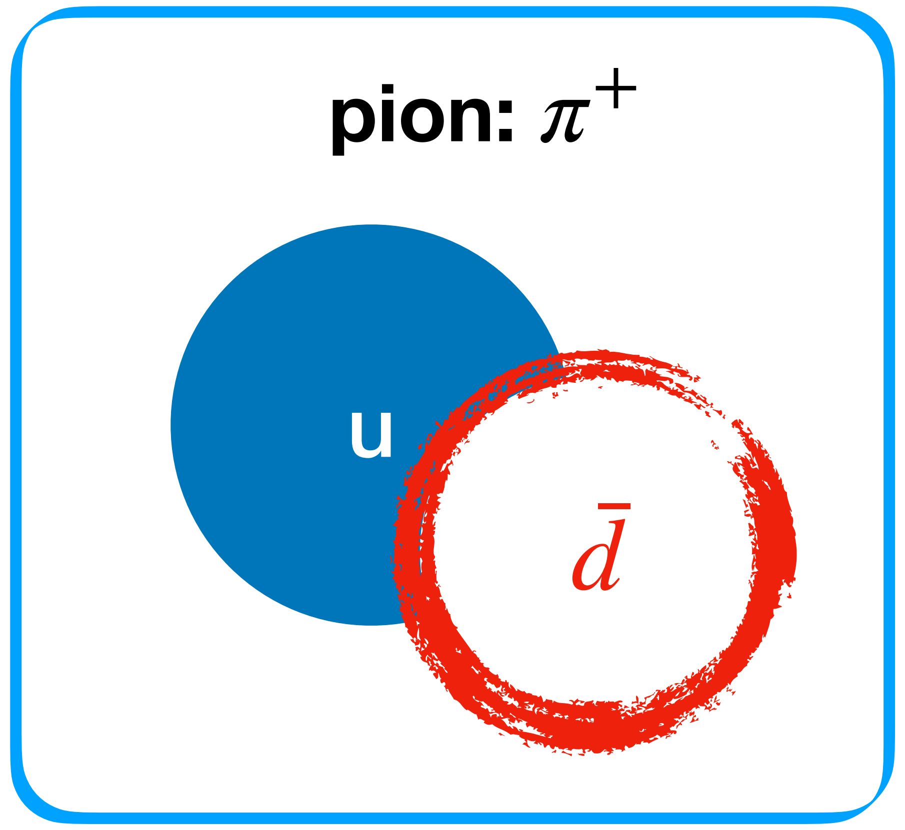
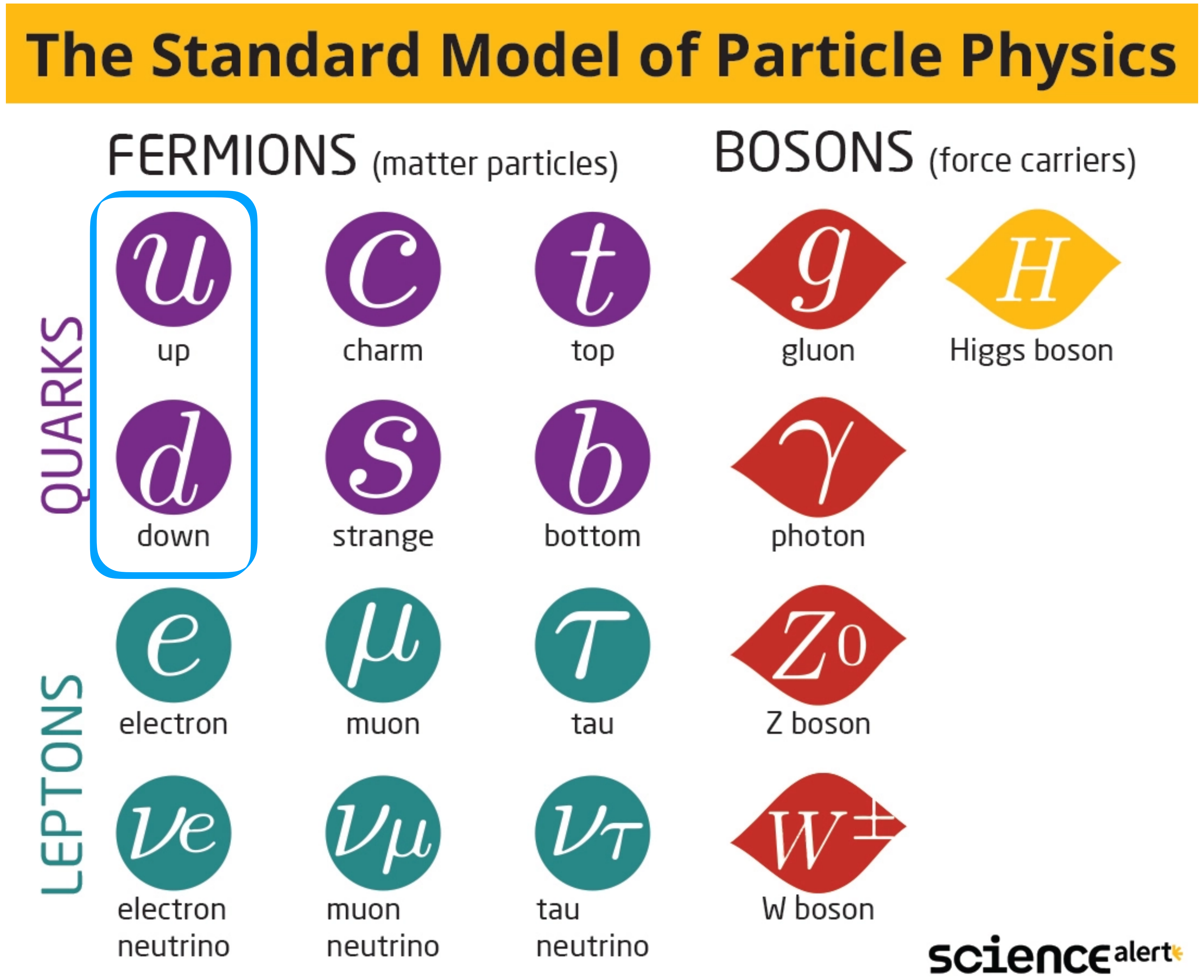
TRIUMF
McGill University
University of British Columbia

Flavour physics with pions



The mediator: 介



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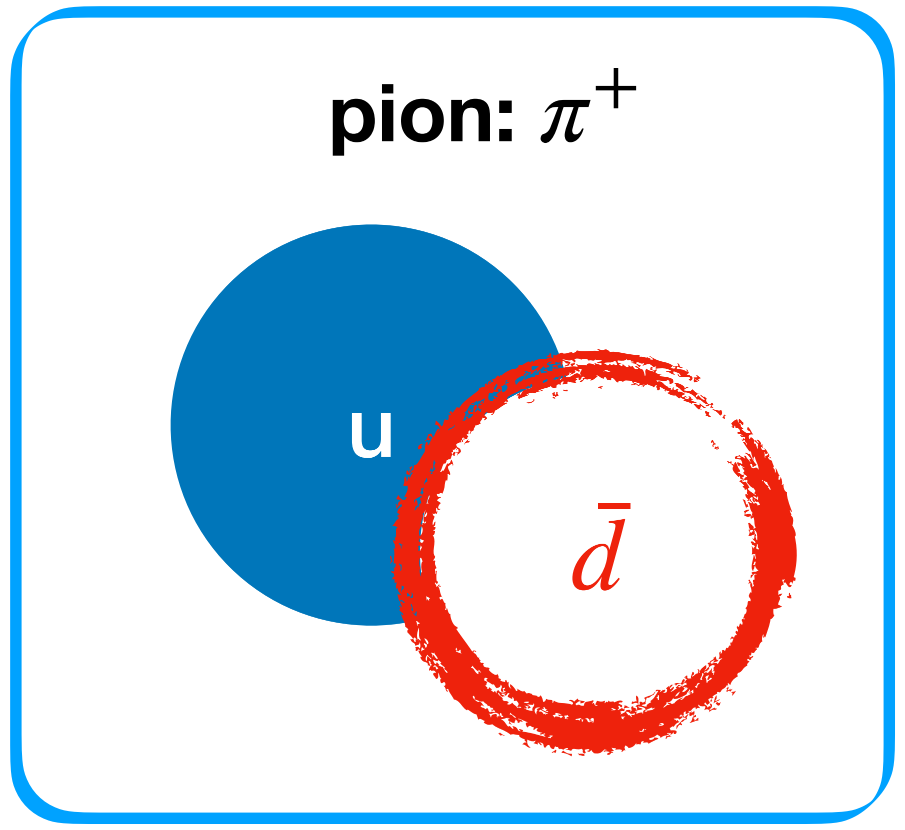

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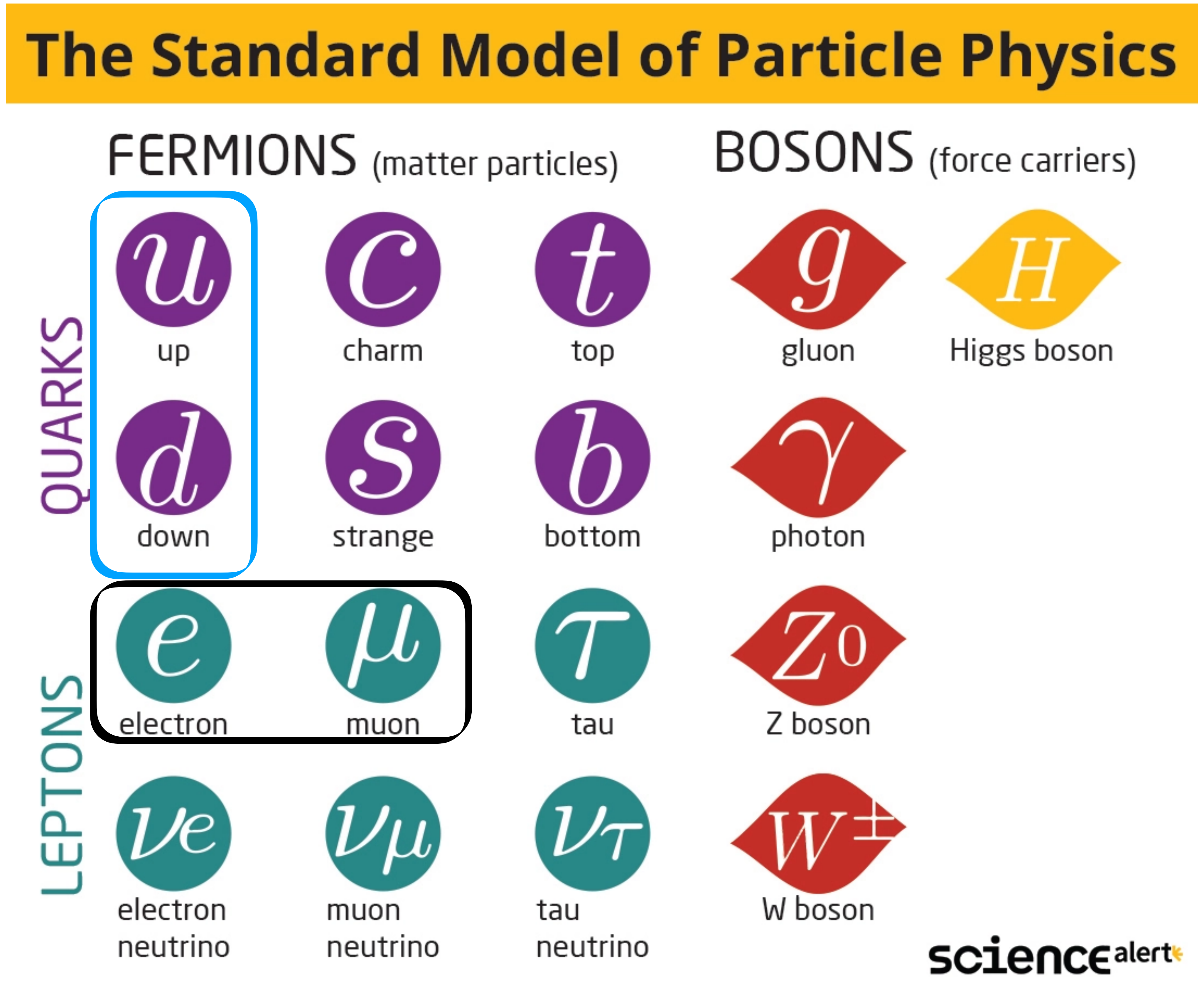
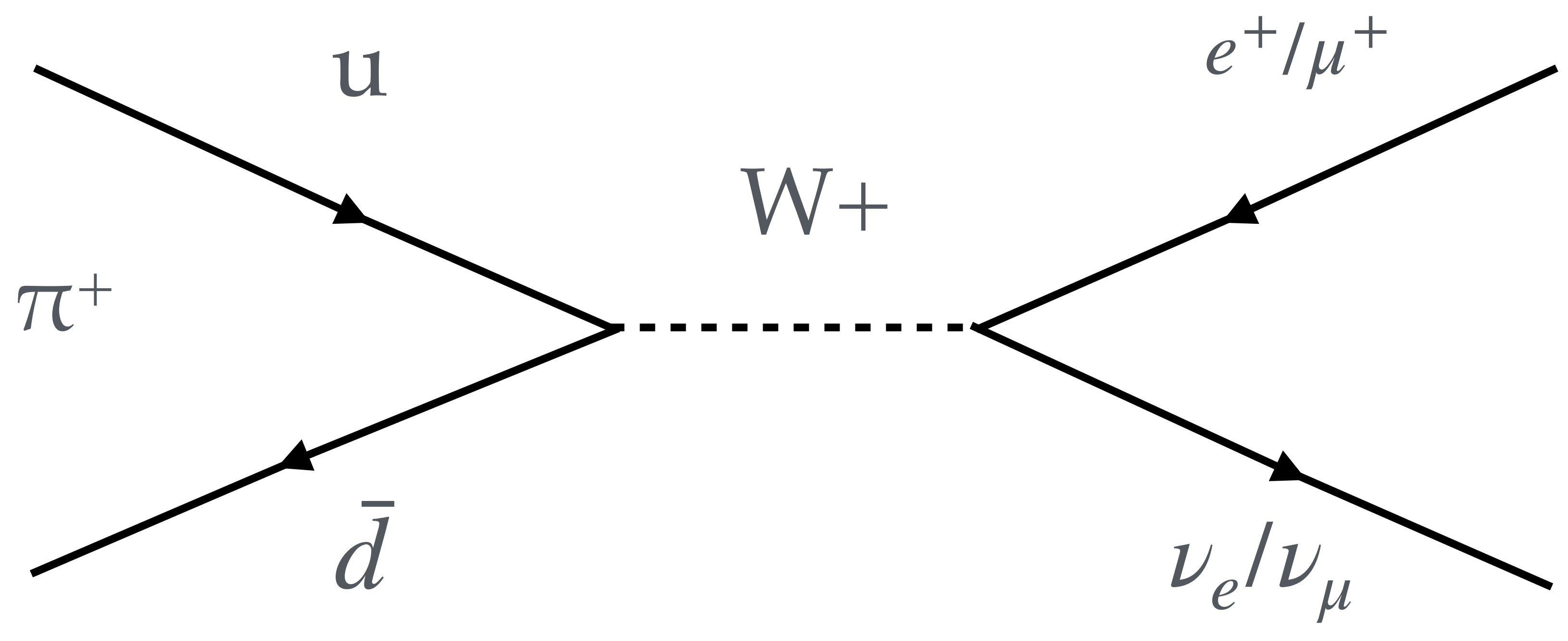




$$\boxed{R^{\pi}_{e/\mu}} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$

$$R^{\pi} = R^{\pi}_{0} \times \left[1 + \frac{\alpha}{\pi}\left\{F\left(\frac{m_e}{m_\pi}\right) - F\left(\frac{m_\mu}{m_\pi}\right) + \frac{m_\mu^2}{m_\rho^2}\left(c_2 \ln\frac{m_\rho^2}{m_\mu^2} + c_3\right) + c_4\frac{m_\pi^6}{m_e^2 m_\rho^4}\right\} + c_5\left(\frac{\alpha}{\pi}\ln\frac{m_\mu}{m_e}\right)^2 + \ldots\right]$$

M. Terent'ev: Yad. Fiz. 18(870) (1973)

S. Berman: Phys.Rev.Lett. 1(12), 468 (1958)
T. Kinoshita: Phys.Rev.Lett. 2(11), 477 (1959)
T. Goldman, W.Wilson: Phys.Rev.D 14(9), 2428 (1976)
W. Marciano, A. Sirlin: Phys.Rev.Lett. 36(24), 1425 (1976)

V.Cirigliano, I.Rosell: Phys.Rev.Lett. 99(23), 231801 (2007)

one of the most precisely known observable involving quarks in the SM

$$= (1.23534 \pm 0.00015) \times 10^{-4} \quad (\pm 0.012\%) \quad \text{(SM)}$$

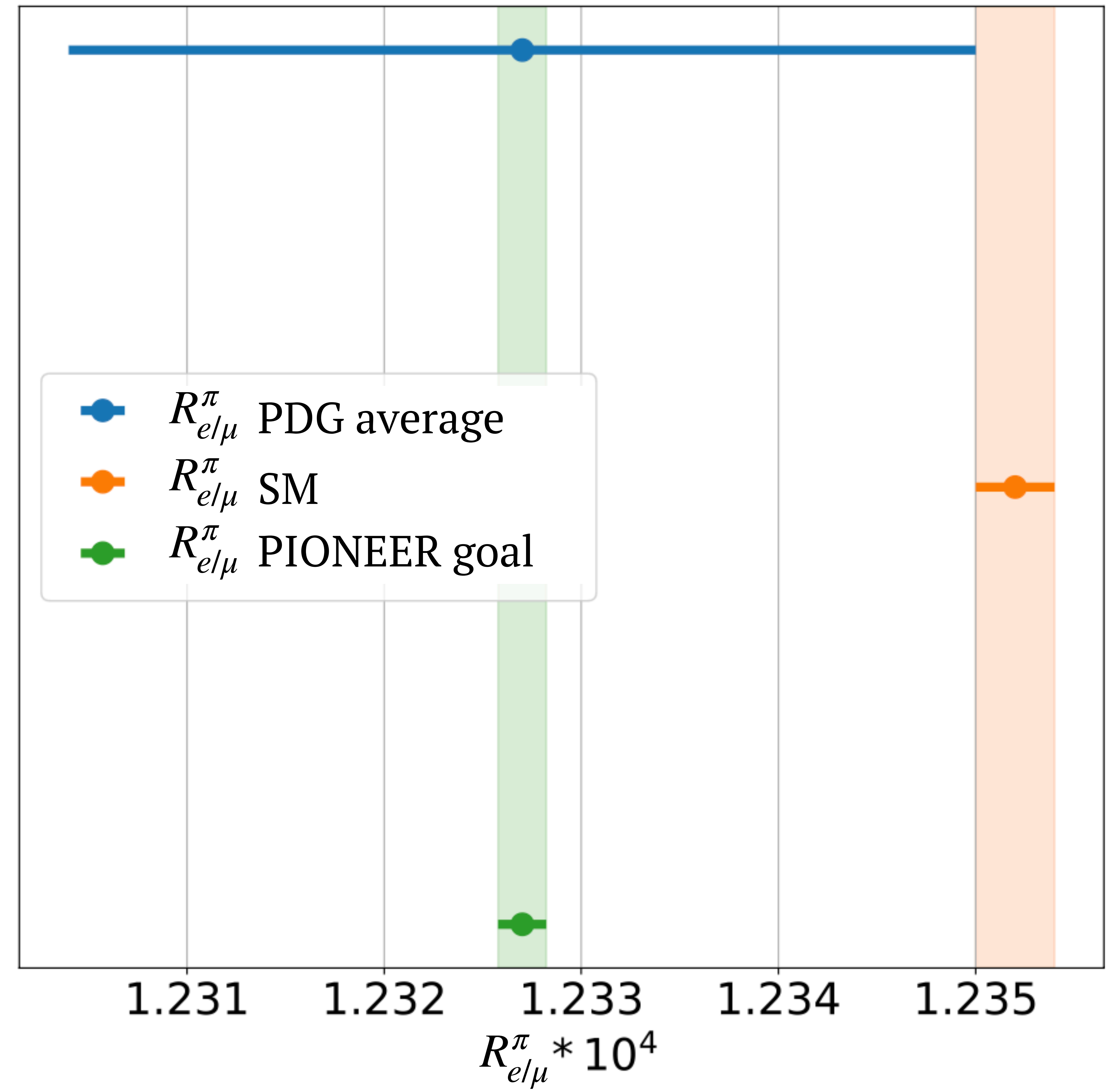
$$= (1.2327 \pm 0.0023) \times 10^{-4} \quad (\pm 0.187\%) \quad \text{(exp.)}$$

x 15

Precision low energy experiment on observables that can be very accurately calculated in the SM : highly sensitive tests of NP

PIONEER: closing the precision gap

PDG average dominated by the PIENU @ TRIUMF result blind analysis based on partial data set (~10% of full statistics)



A bit of history on R^{π}

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \sim \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 1.3 \times 10^{-4}$$

1940/50's : Development of V-A structure of weak interaction

1950's: Many experimental confirmation of the V-A theory

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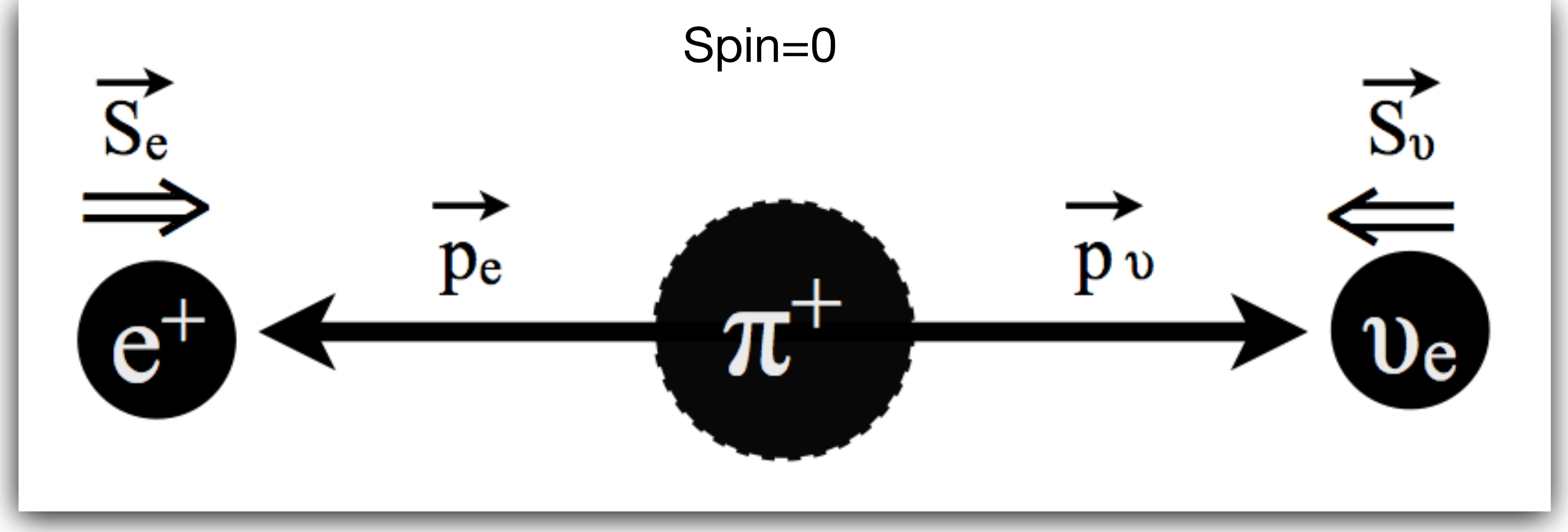

Weak Interaction

Neutrinos: left-handed helicity
= directions of spin and motion are opposite

Positron is forced into the wrong helicity

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'Phase space' term ~ 5.5

'Helicity suppression' term ~ 2.3×10^{-5}

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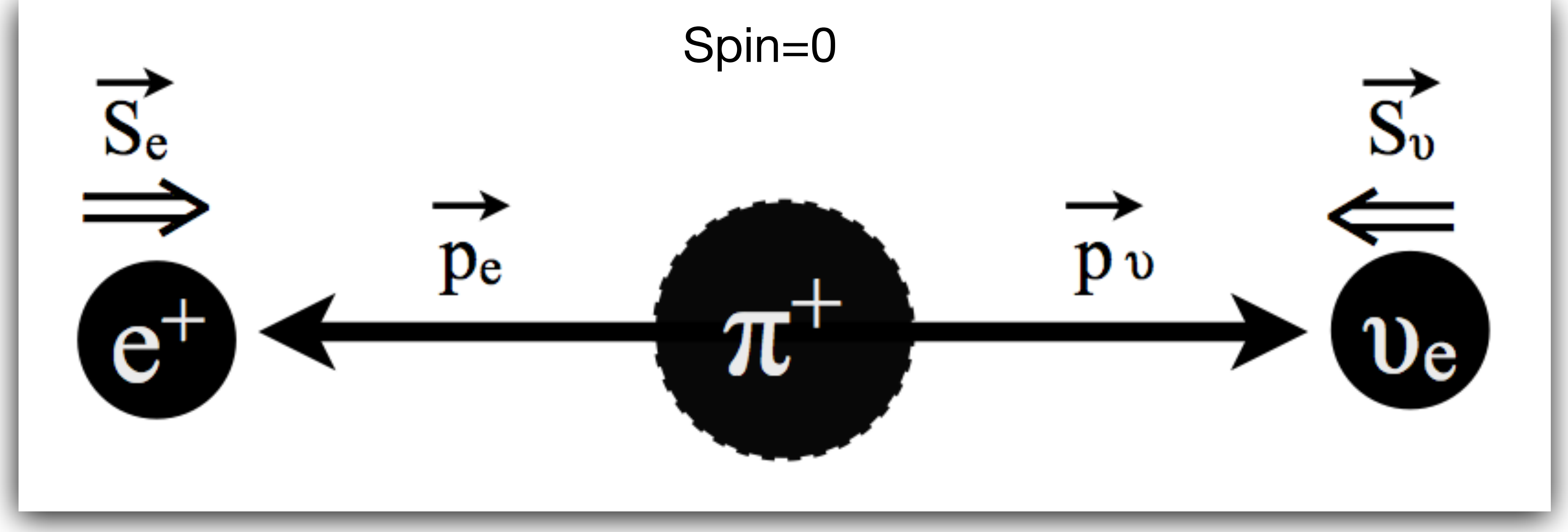

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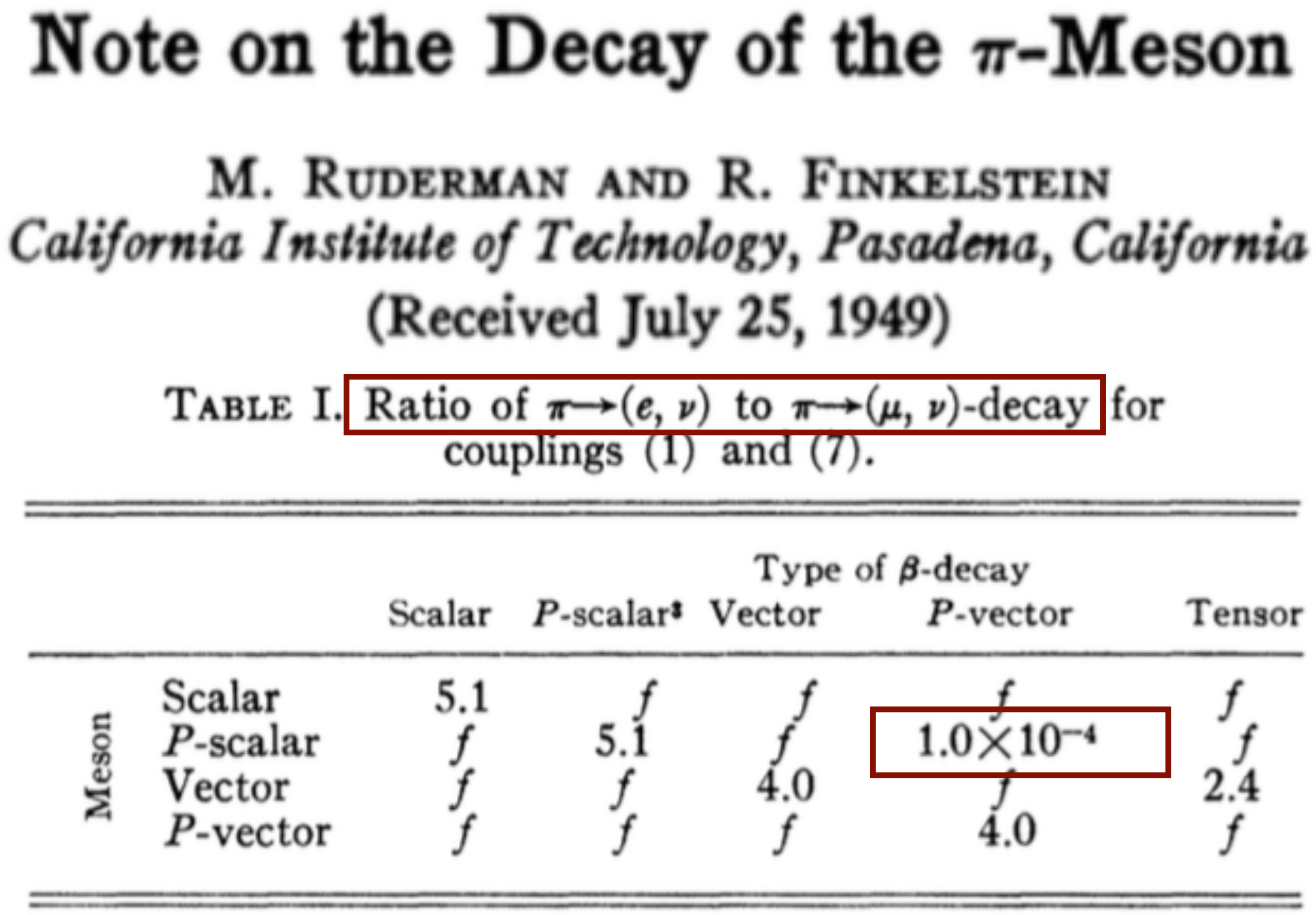


Note on the Decay of the π-Meson

M. RUDERMAN AND R. FINKELSTEIN
California Institute of Technology, Pasadena, California
(Received July 25, 1949)

TABLE I. Ratio of $\pi\to(e,\nu)$ to $\pi\to(\mu,\nu)$-decay for couplings (1) and (7).

		Type of β-decay				
		Scalar	*P*-scalar[a]	Vector	*P*-vector	Tensor
Meson	Scalar	5.1	*f*	*f*	*f*	*f*
	P-scalar	*f*	5.1	*f*	1.0×10^{-4}	*f*
	Vector	*f*	*f*	4.0	*f*	2.4
	P-vector	*f*	*f*	*f*	4.0	*f*

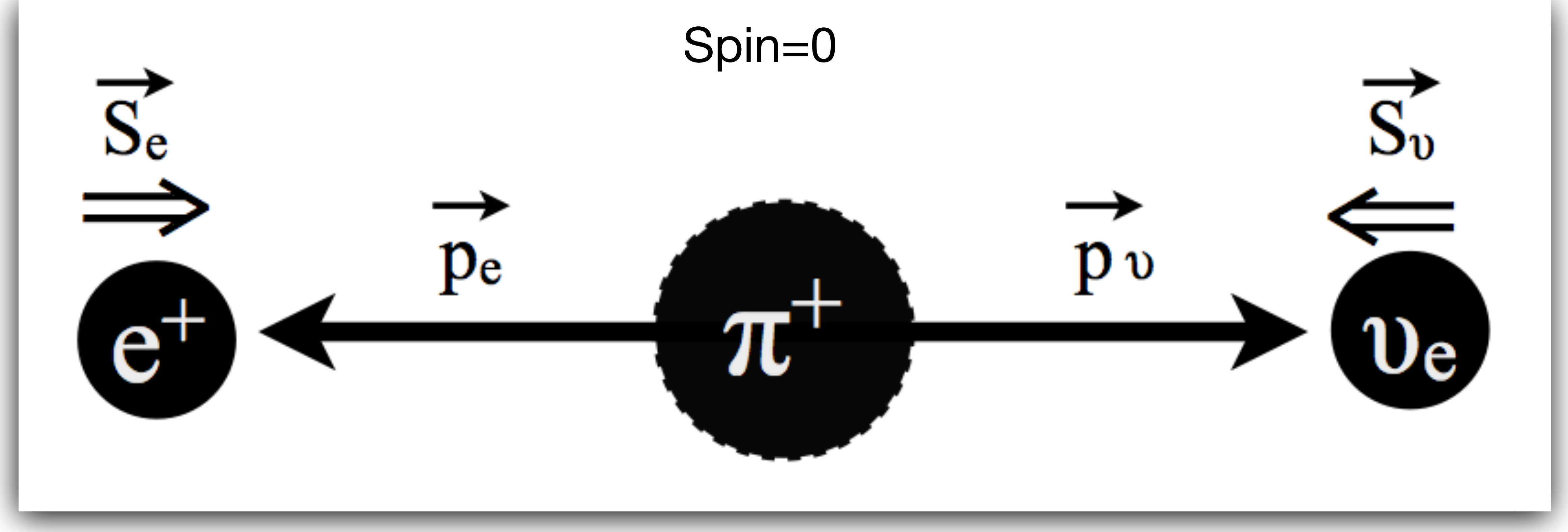
A bit of history on R^{π}

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \sim \underbrace{\frac{m_e^2}{m_\mu^2}}_{\text{'Helicity suppression' term} \sim 2.3 \times 10^{-5}} \underbrace{\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2}_{\text{'Phase space' term} \sim 5.5} \sim 1.3 \times 10^{-4}$$

1940/50’s : Development of V-A structure of weak interaction

1950’s: Many experimental confirmation of the V-A theory

1956-1957: Negative experimental results BR<10^{-5}



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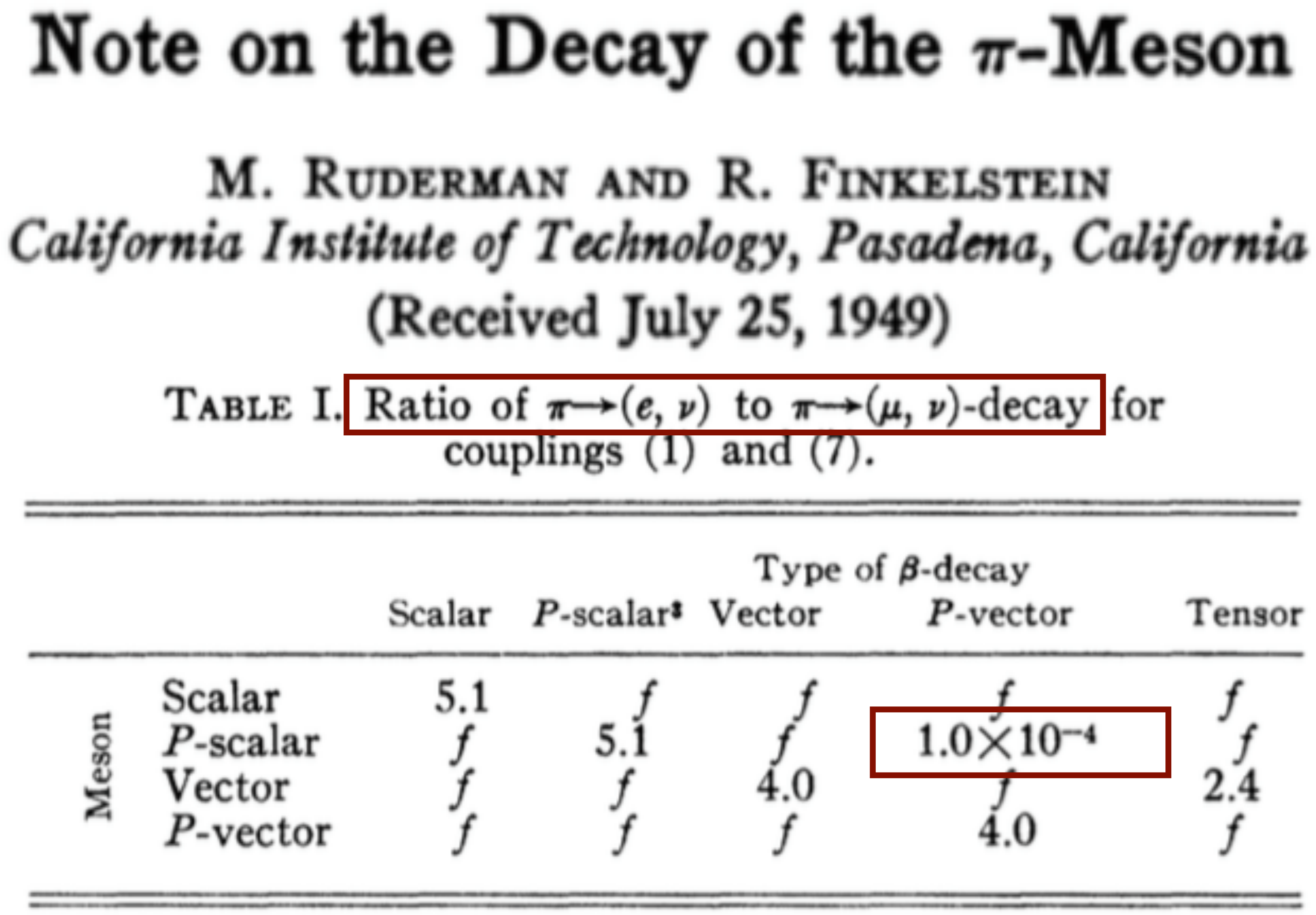

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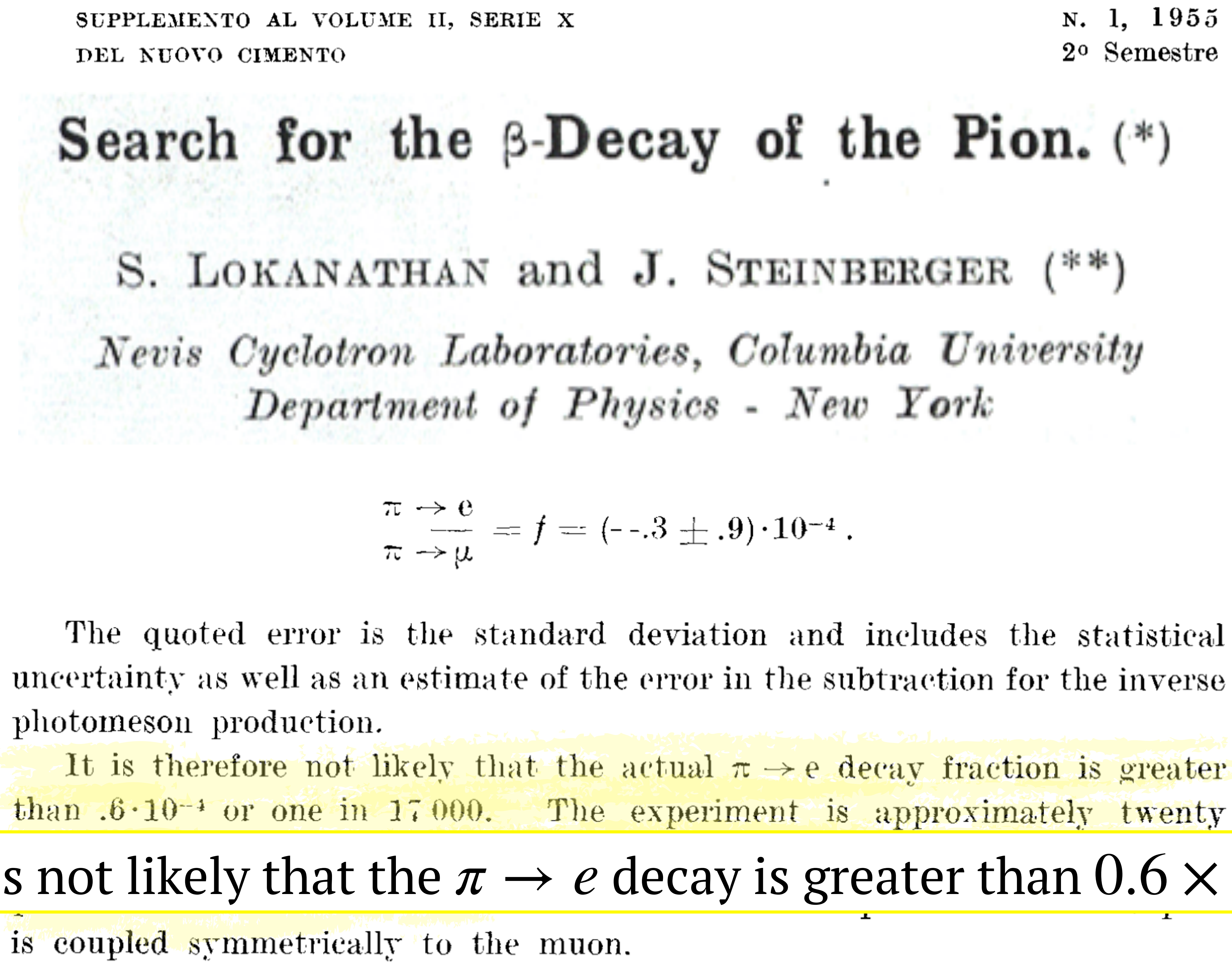
The $\pi \rightarrow e\nu$ puzzle …

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \rightarrow e\nu)}{\Gamma(\pi \rightarrow \mu\nu)} \sim \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 1.3 \times 10^{-4}$$



SUPPLEMENTO AL VOLUME II, SERIE X
DEL NUOVO CIMENTO

N. 1, 1955
2° Semestre

Search for the β-Decay of the Pion. (*)

S. LOKANATHAN and J. STEINBERGER (**)

Nevis Cyclotron Laboratories, Columbia University
Department of Physics - New York

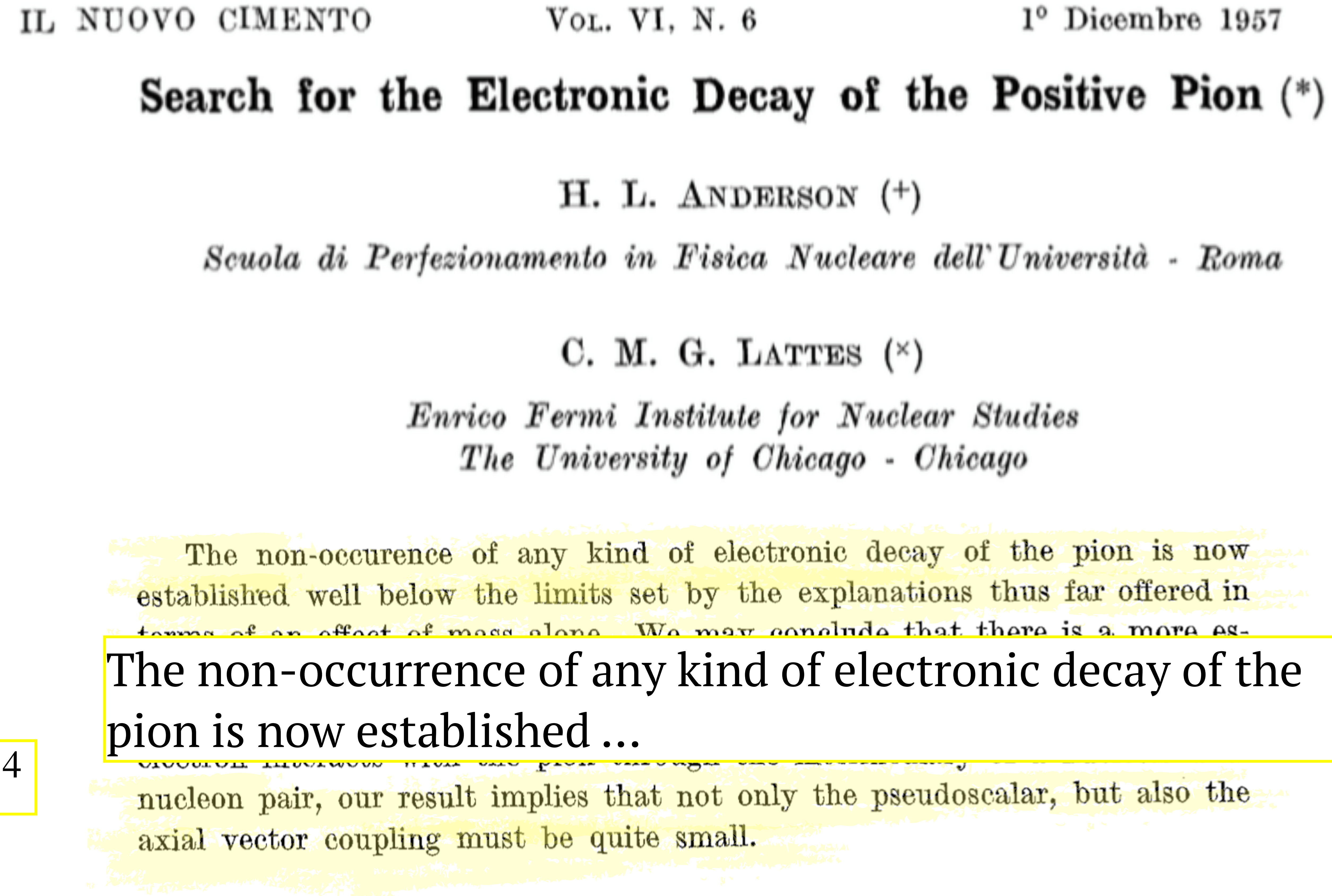
$$\frac{\pi \rightarrow e}{\pi \rightarrow \mu} = f = (-.3 \pm .9)\cdot 10^{-4}\,.$$

The quoted error is the standard deviation and includes the statistical uncertainty as well as an estimate of the error in the subtraction for the inverse photomeson production.

It is therefore not likely that the actual π → e decay fraction is greater than $.6\cdot 10^{-4}$ or one in 17 000. The experiment is approximately twenty

is coupled symmetrically to the muon.

It is not likely that the $\pi \rightarrow e$ decay is greater than 0.6×10^{-4}



IL NUOVO CIMENTO VOL. VI, N. 6 1° Dicembre 1957

Search for the Electronic Decay of the Positive Pion (*)

H. L. ANDERSON (+)

Scuola di Perfezionamento in Fisica Nucleare dell'Università - Roma

C. M. G. LATTES (×)

Enrico Fermi Institute for Nuclear Studies
The University of Chicago - Chicago

The non-occurence of any kind of electronic decay of the pion is now established well below the limits set by the explanations thus far offered in terms of an effect of mass alone. We may conclude that there is a more es-

nucleon pair, our result implies that not only the pseudoscalar, but also the axial vector coupling must be quite small.

The non-occurrence of any kind of electronic decay of the pion is now established …

The $\pi \to e\nu$ puzzle … resolved in 1958

At a small lab that opened 4 years prior on the outskirts of Geneva, Switzerland

CERN circa 1958

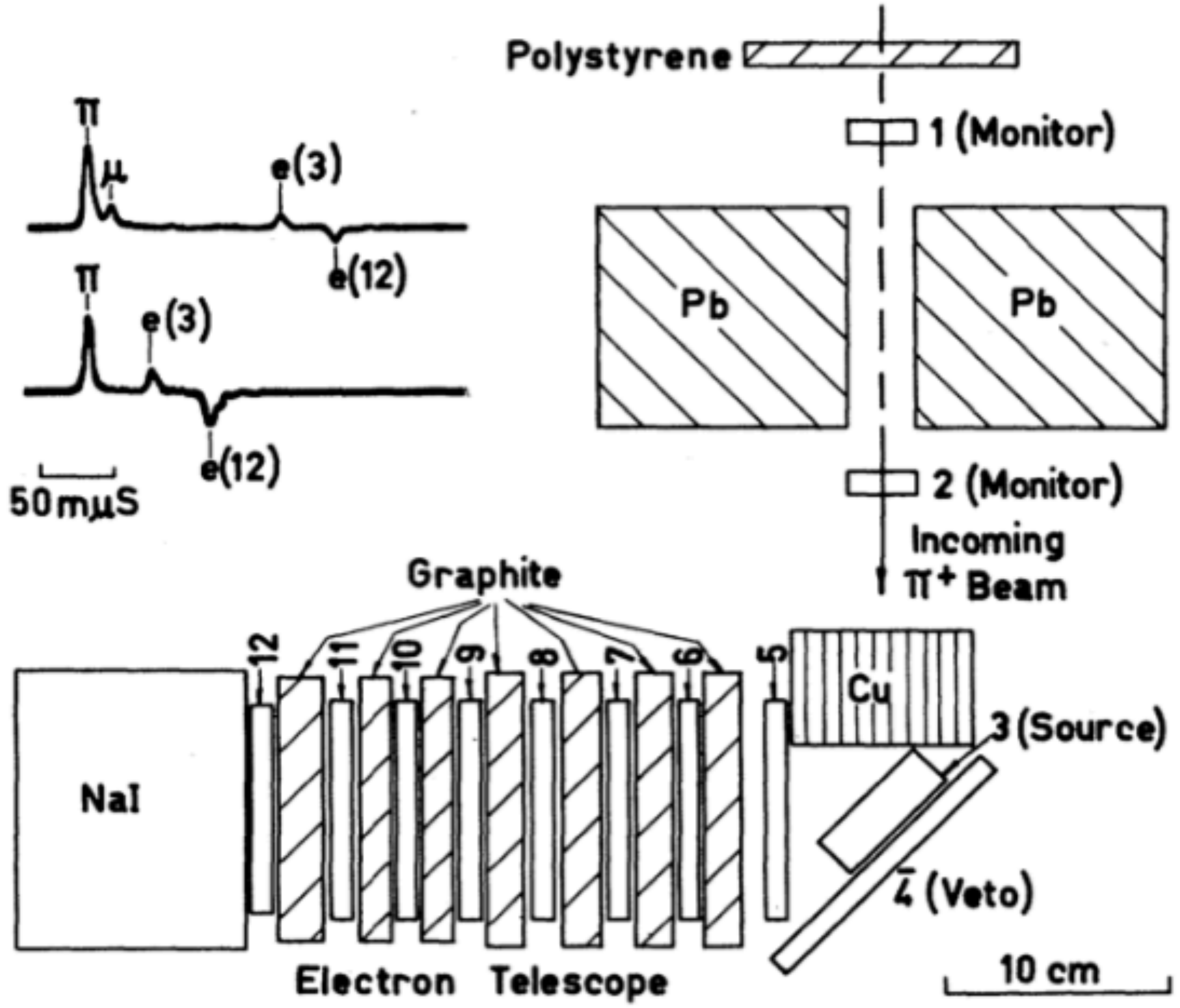


FIG. 1. Experimental layout, and (inset) typical π-μ-e and π-e pulse.

~ 40 $\pi \to e\nu$ events

CERN70: A first discovery

14 February 2024 · *Voir en français*

Part 3 of the **CERN70** feature series

Giuseppe Fidecaro was among the small group of physicists who performed the first experiment at CERN to provide results in 1958 that would spread the Laboratory's name around the world

A few months after CERN's first accelerator, the Synchrocyclotron (SC), was commissioned, a first experiment was launched. At the time, weak interactions were among the most hotly debated topics in high-energy physics. Scientists were puzzled, for example, about the decay of the particle known as the pion. The particle was known to decay into two other particles: a muon and a neutrino. According to theory, it should also sometimes decay into an electron and a neutrino, but this type of decay had never been observed before.

In August 1958, at CERN's Synchrocyclotron, Tito Fazzini, Giuseppe Fidecaro, Alec Merrison, Helmut Paul and Alvin Tollestrup observed this decay for the first time, at a rate in line with predictions of the theory of the weak interaction.

It was CERN's first major discovery.

https://home.cern/fr/news/series/cern70/cern70-first-discovery

A bit of history on R^{π}

"Particle rush"
Development of SM

Discovery of Pion

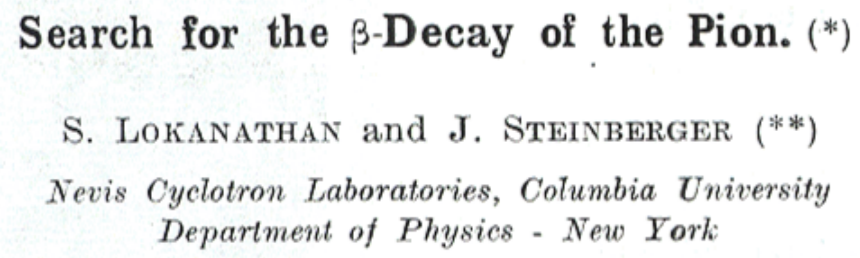
1947

Nature 159:694-697

No **electronic decay** observed
PUZZLE!

1955

Supl. Nuovo cimento 2:151



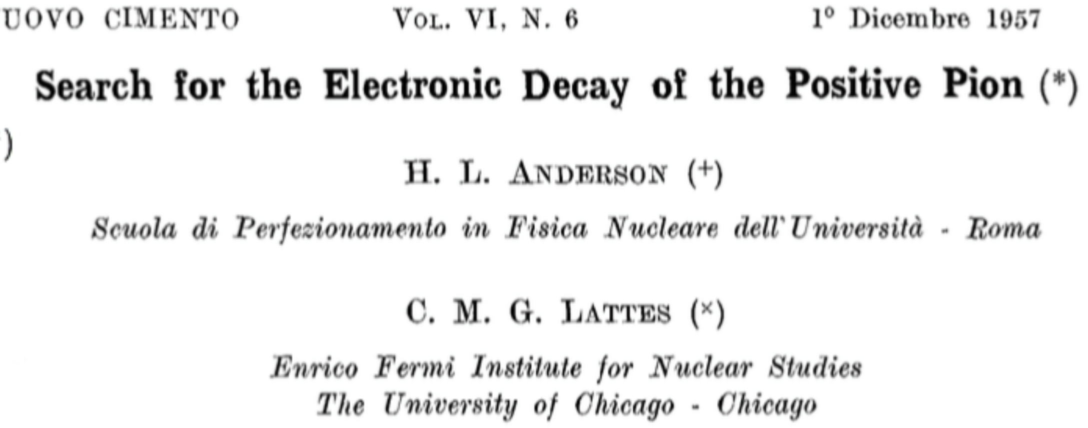
Search for the β-Decay of the Pion. (*)

S. Lokanathan and J. Steinberger (**)

Nevis Cyclotron Laboratories, Columbia University
Department of Physics - New York

1957

Il Nuovo Cimento **VI**, 6



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H. L. Anderson (+)

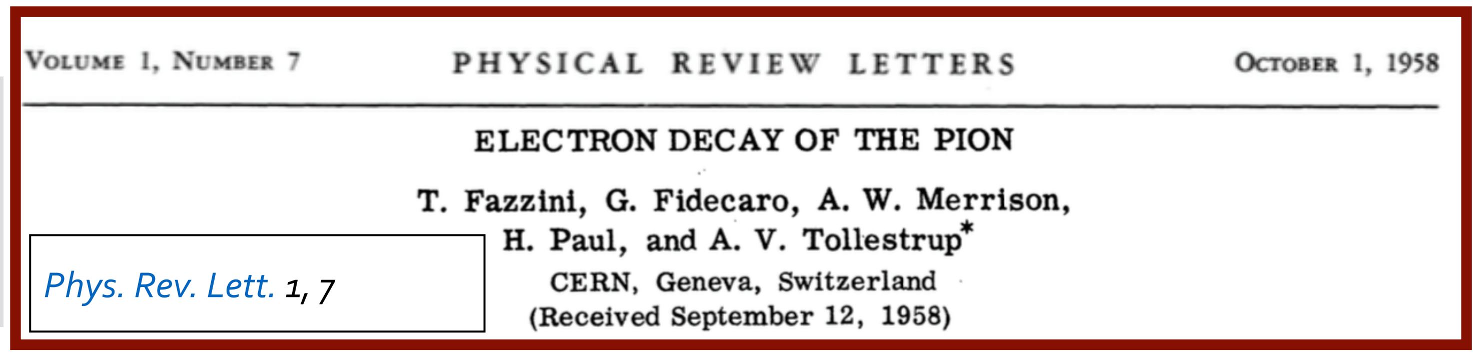
Scuola di Perfezionamento in Fisica Nucleare dell'Università - Roma

C. M. G. Lattes (×)

Enrico Fermi Institute for Nuclear Studies
The University of Chicago - Chicago

1958

First experimental observation of the **electronic decay** at CERN **about** 65 years ago!



Volume 1, Number 7 PHYSICAL REVIEW LETTERS October 1, 1958

ELECTRON DECAY OF THE PION

T. Fazzini, G. Fidecaro, A. W. Merrison, H. Paul, and A. V. Tollestrup*
CERN, Geneva, Switzerland
(Received September 12, 1958)

Phys. Rev. Lett. 1, 7

… and "simultaneously" at Columbia University

Phys. Rev. Lett. 1, 249

1959

… and confirmed at Univ. of Chicago

Phys. Rev. Lett. 2, 64

x3

First precise measurement (~5%)

1964

Di Capua et al.

Phys. Rev. 133(5B):B1333–B1340

~x2

"Precision area"
Search for BSM

1986

TRIUMF by Bryman et al.

Phys. Rev. D 3(5):1211–1221

x2.5

1992

TRIUMF by Britton et al.

Phys. Rev. Lett. 68:3000–3003

1993

PSI by Czapek et al.

Phys. Rev. Lett. 70 (1) 17-20

~x2

2015

TRIUMF by Aguilar Arevalo et al.

Phys. Rev. Lett. 115:071801

Most precise measurement (~0.2%)

PIONEER ***x20***

Physics case 1: Testing Lepton Flavor Universality

Weak interaction is the same for $e/\mu/\tau$ leptons

$$R^{\pi} = \frac{\pi^+ \rightarrow e^+\nu(\gamma)}{\pi^+ \rightarrow \mu^+\nu(\gamma)}$$

provides the best test of universality in charged current weak interaction

PDG value, mostly constrained by **PIENU (@ TRIUMF)** results :

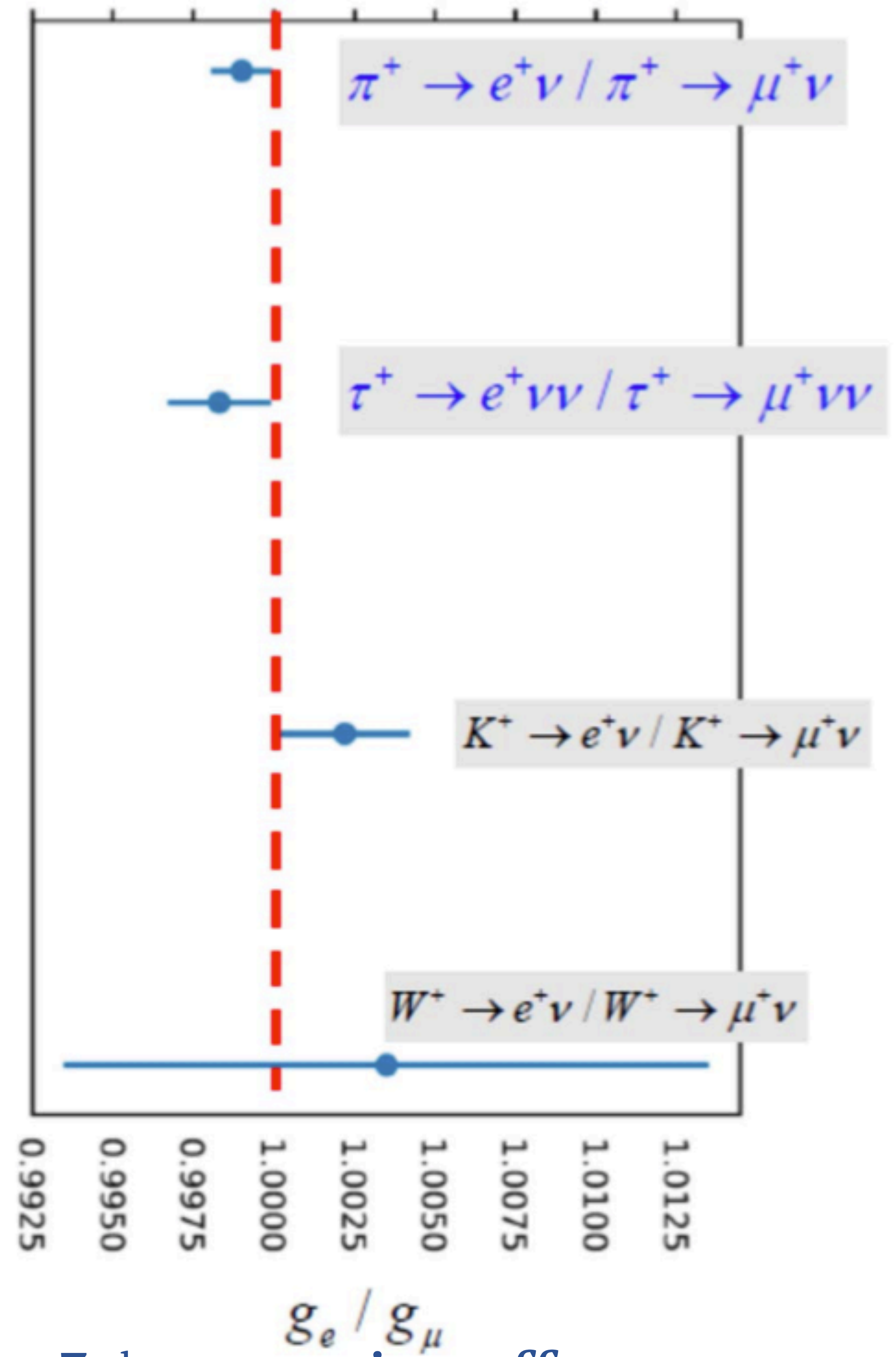
$$\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \quad (\pm 0.09\%)$$

BUT

Several tensions in the flavour sector, potentially hinting toward LFUV

- B decays O(10%) deviations from universality.
  Both heavy quarks and leptons involved!
- Muon g-2
  Deviation (4.2 σ) from theory - new physics?
- CKM unitarity tests from β and K decays (2 - 3 σ)
  Maybe related to LFUV?

Charged LFU tested at $\mathcal{O}(10^{-3})$



Precise measurements of 1st and 2nd generation decays could be used to distinguish between models explaining 3rd generation effects…

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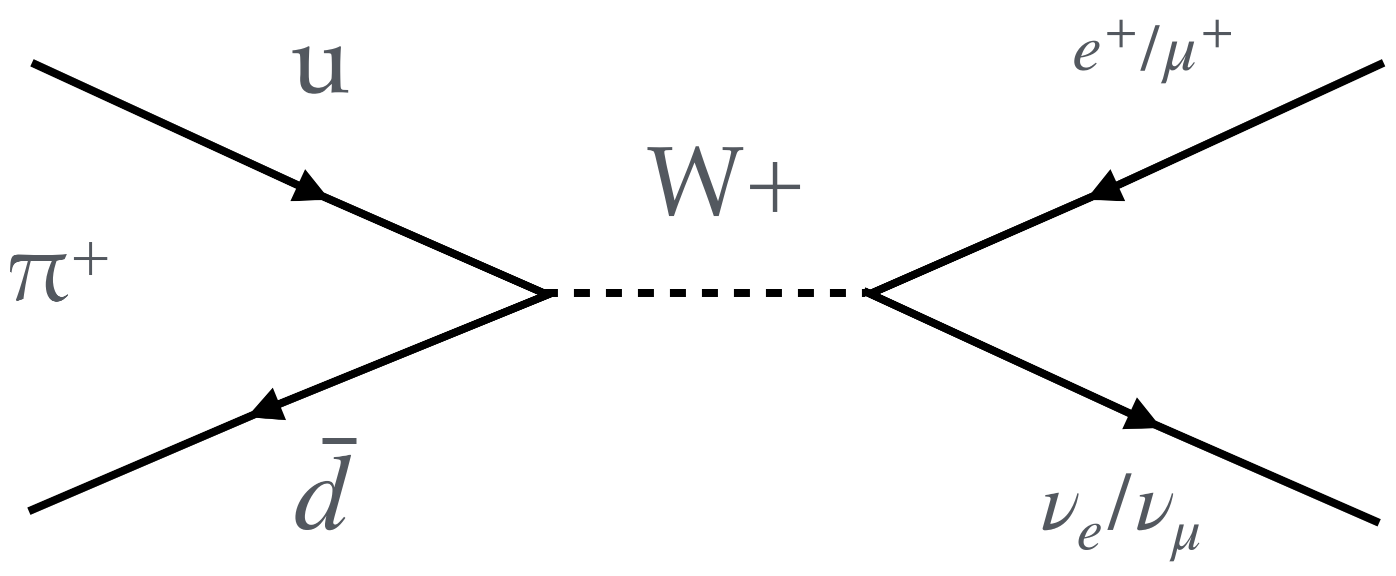

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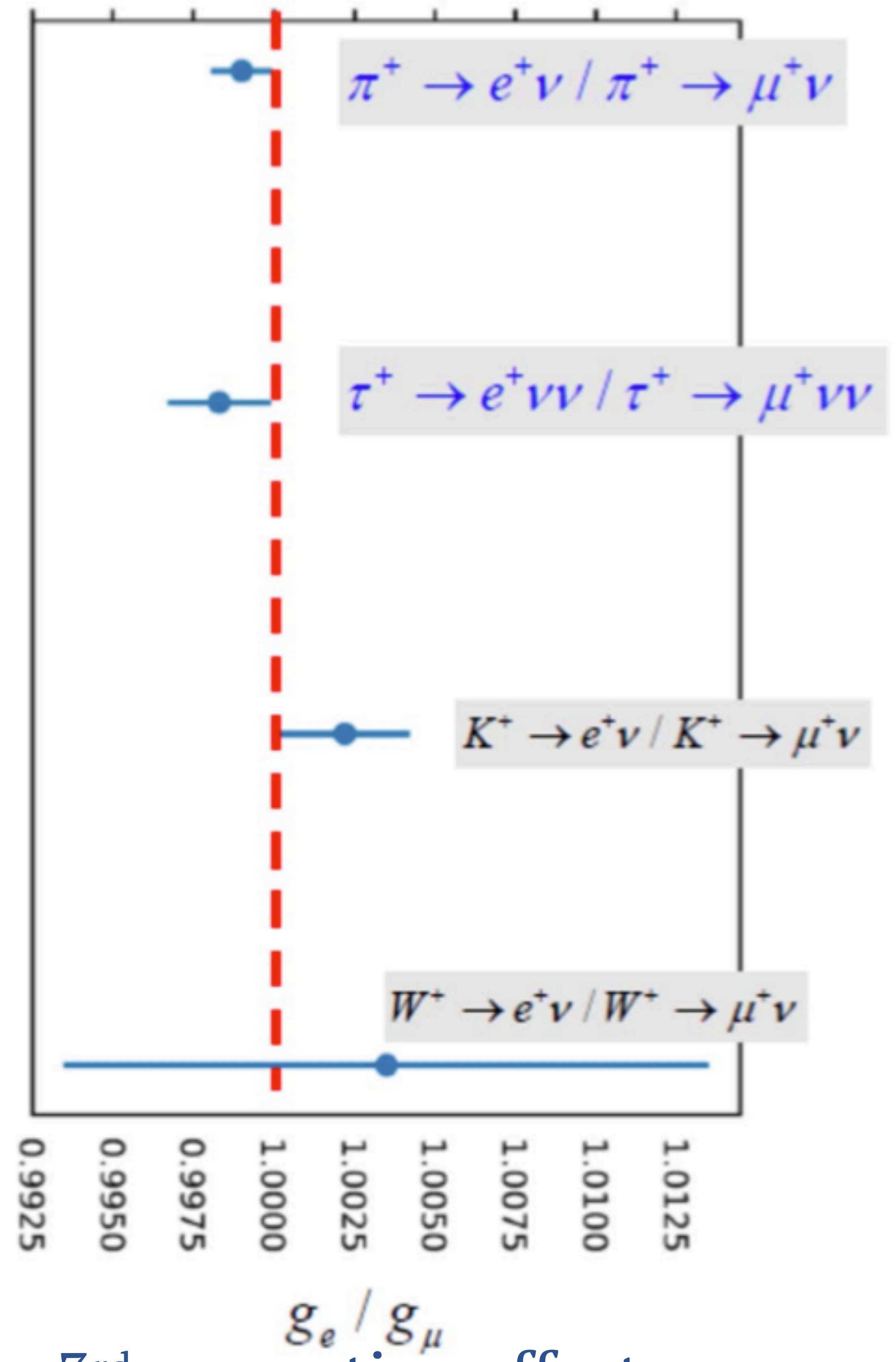

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Precise measurements of 1st and 2nd generation decays could be used to distinguish between models explaining 3rd generation effects…

Physics case 2: Sensitivity to new coupling and NP at very high mass scales $\Longrightarrow$ possible interpretation of universality violation

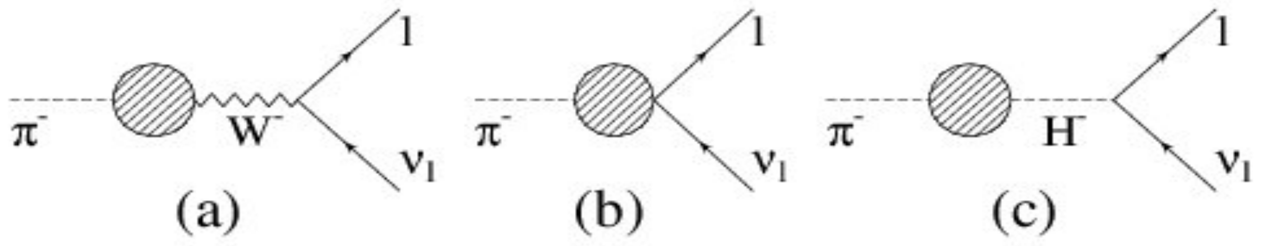
$$R^{\pi}_{SM} = \frac{\pi^+ \rightarrow e^+\nu(\gamma)}{\pi^+ \rightarrow \mu^+\nu(\gamma)}$$

calculated at the 0.01% level

$\pi^+ \rightarrow e^+\nu$ is helicity-suppressed (V-A)

$\Rightarrow R^{\pi}$ is extremely sensitive to presence of new pseudoscalar or scalar couplings

Pseudoscalar interactions



Charged Higgs (non-SM coupling)

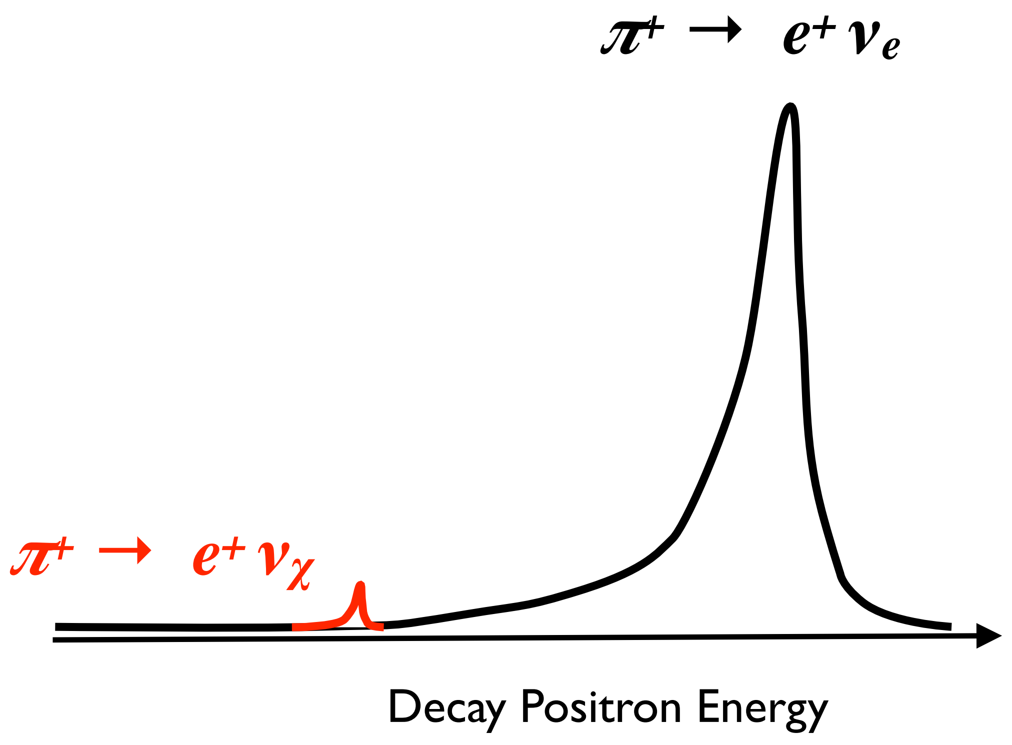
$$1 - \frac{R^{New}_{e/\mu}}{R^{SM}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2_{eP}} \frac{m^2_\pi}{m_e(m_d + m_u)} \sim (\frac{1TeV}{\Lambda_{eP}})^2 \times 10^3$$

Marciano…

PIONEER PHASE 1 goal:

0.01 % measurement → $\Lambda_{eP} \sim 3000$ TeV

Physics case 3: Exotics decays. Example of first sterile massive neutrino search



If the heavy neutrino mass is M_ν= 60~130 MeV/c^2 **additional low energy positron peak** can be detected in the $\pi^+ \rightarrow e^+$ spectrum

R.E Shrock Phys.Rev.D 24, 1232 (1981),
Phys. Lett. B 96, 159 (1980)

Heavy υ

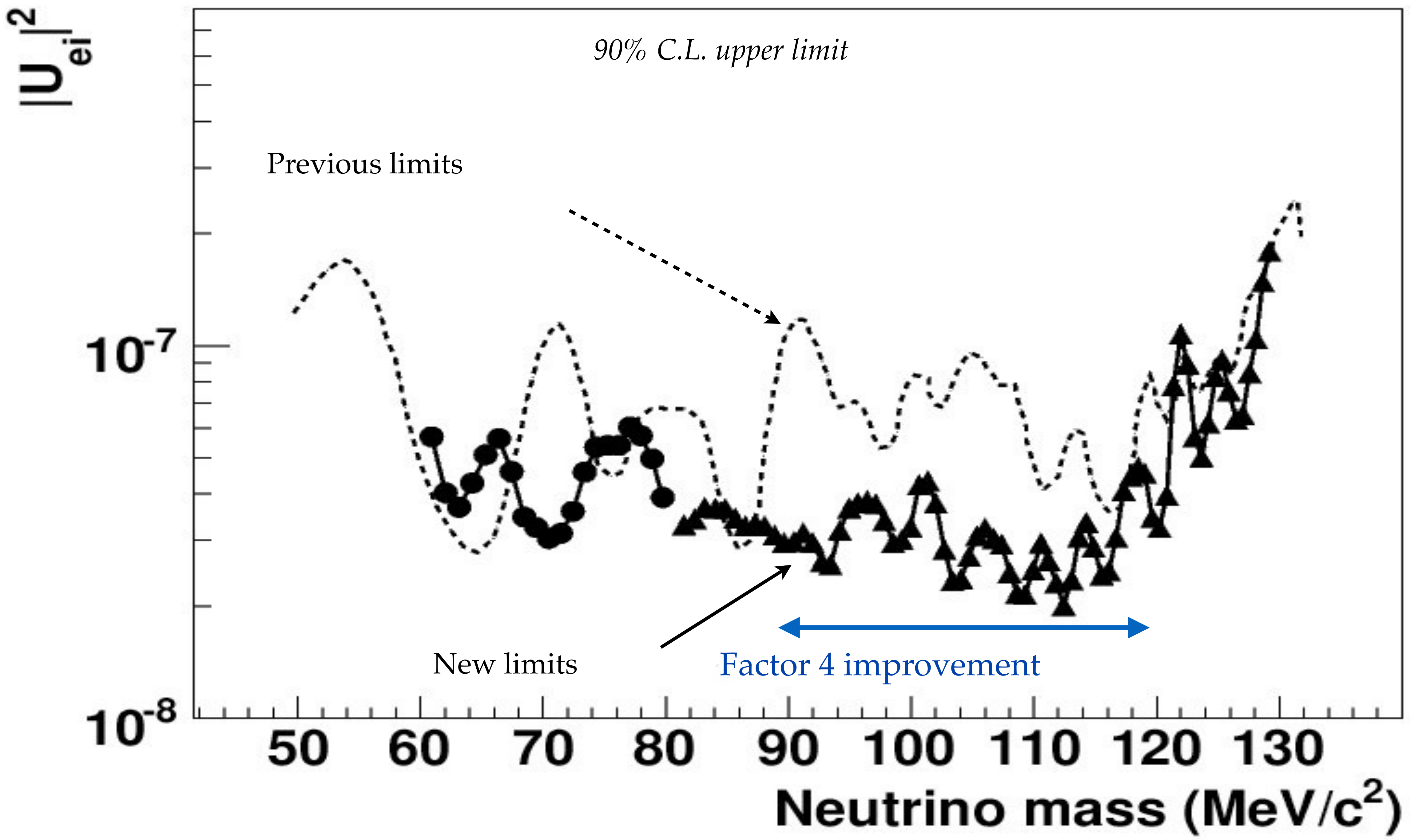
Kinematic factor

$$R_{ei} = \frac{\Gamma(\pi \rightarrow e\nu_i)}{\Gamma(\pi \rightarrow e\nu_l)} = |U_{ei}|^2 \rho_{ei}$$

Conventional υ

$$\nu_\ell = \Sigma_{i=1}^{3+k} U_{\ell i} \nu_i$$

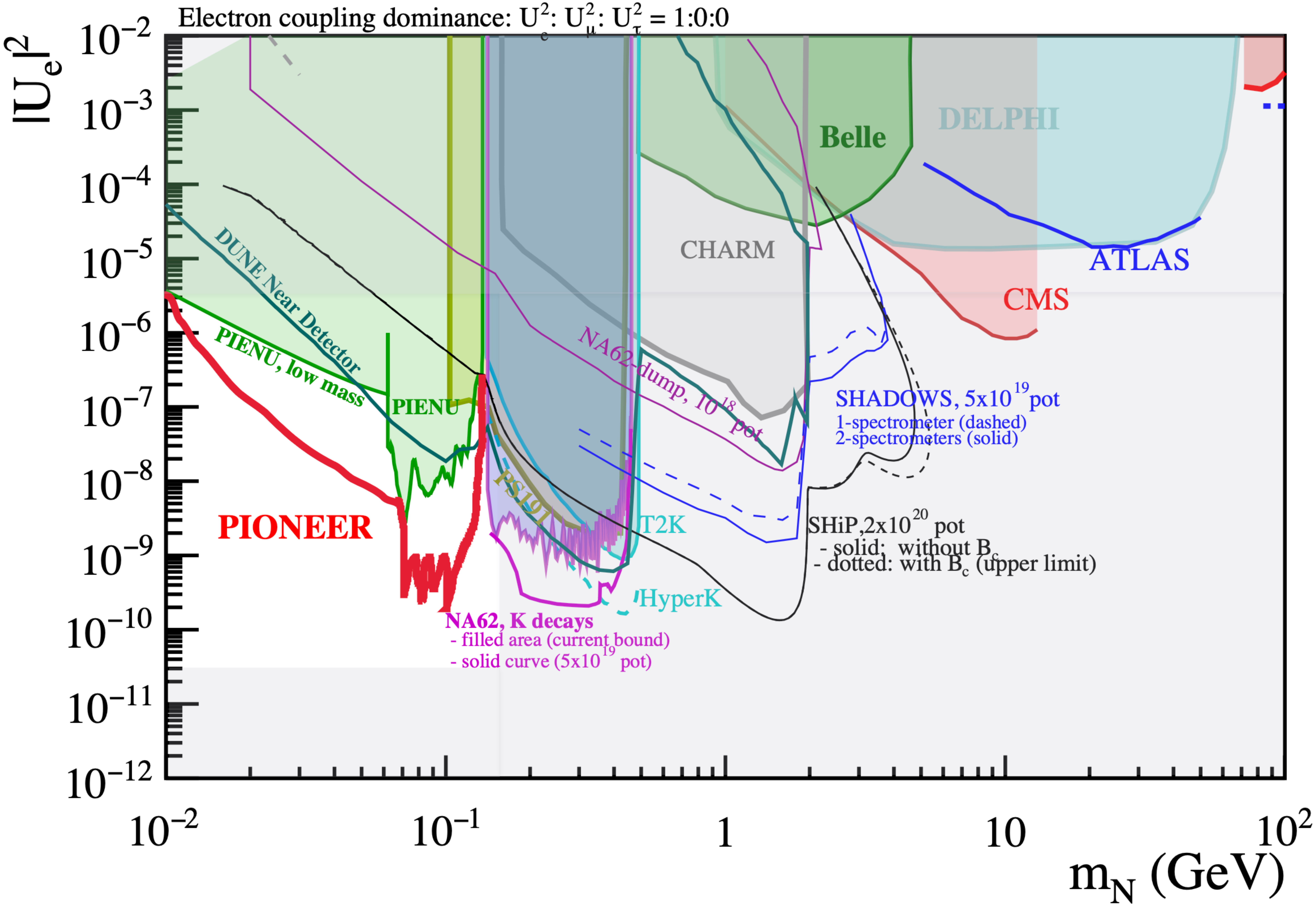
$$\ell = e, \mu, \tau, \chi_1, \chi_2 \ldots \chi_k$$



M.Aoki et al., Phys. Rev. D 84, 052002 (2011)

More recent and stronger bounds provided by PIENU :
PRD 97.072012 (2018)
PLB 798 (2019) 134980 [in π → μν decay]

Comprehensive constraints on sterile neutrinos in the MeV to GeV mass range
D. A. Bryman and R. Shrock, Phys. Rev. D 100, 073011


Electron coupling dominance: U_e^2: U_μ^2: U_τ^2 = 1:0:0
$|U_e|^2$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-2}
10^{-1}
1
10
10^{2}
m_N (GeV)
Belle
DELPHI
CHARM
ATLAS
CMS
DUNE Near Detector
PIENU, low mass
PIENU
PS191
NA62-dump, 10^{18} pot
SHADOWS, 5×10^{19} pot
1-spectrometer (dashed)
2-spectrometers (solid)
PIONEER
T2K
SHiP, 2×10^{20} pot
- solid: without B_c
- dotted: with B_c (upper limit)
HyperK
NA62, K decays
- filled area (current bound)
- solid curve (5×10^{19} pot)

Physics case 4: Testing CKM unitarity $\boxed{V_{ud}}$, $\boxed{\dfrac{V_{us}}{V_{ud}}}$

tested in K decays

tested in super-allowed β decays, neutron

tensions in the first row CKM unitarity test
3σ **(or even more…)**

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}.$$

$$|V_{ud}|^2 + |V_{us}|^2 + |Vub|^2 = 1$$

Since $|V_{ub}| \ll |V_{us}|$, the third term can be neglected and the first row can be studied in a 2D plane

~3σ tension in the first-row of CKM unitarity test

Often referred to as the
Cabbibo Angle Anomaly (or CAA)

Physics case 4: Testing CKM unitarity $\boxed{V_{ud}}$, $\boxed{\frac{V_{us}}{V_{ud}}}$

tested in K/π decays

tested in super-allowed β decays, neutron

PIONEER Phase II goal: *Phys.Rev.D* 101 (2020) 9, 091301

Improve $B(\pi^+ \to \pi^0 e^+ \nu)$ precision by >3 $\frac{V_{us}}{V_{ud}} < \pm 0.2\,\%$

Offers a new complementary constraint in the $V_{us} - V_{ud}$ plane

PIONEER Phase III goal:

Improve $B(\pi^+ \to \pi^0 e^+ \nu)$ precision by an order of magnitude

$\pi^+ \to \pi^0 e^+ \nu$ is the theoretically cleanest method to obtain V_{ud}

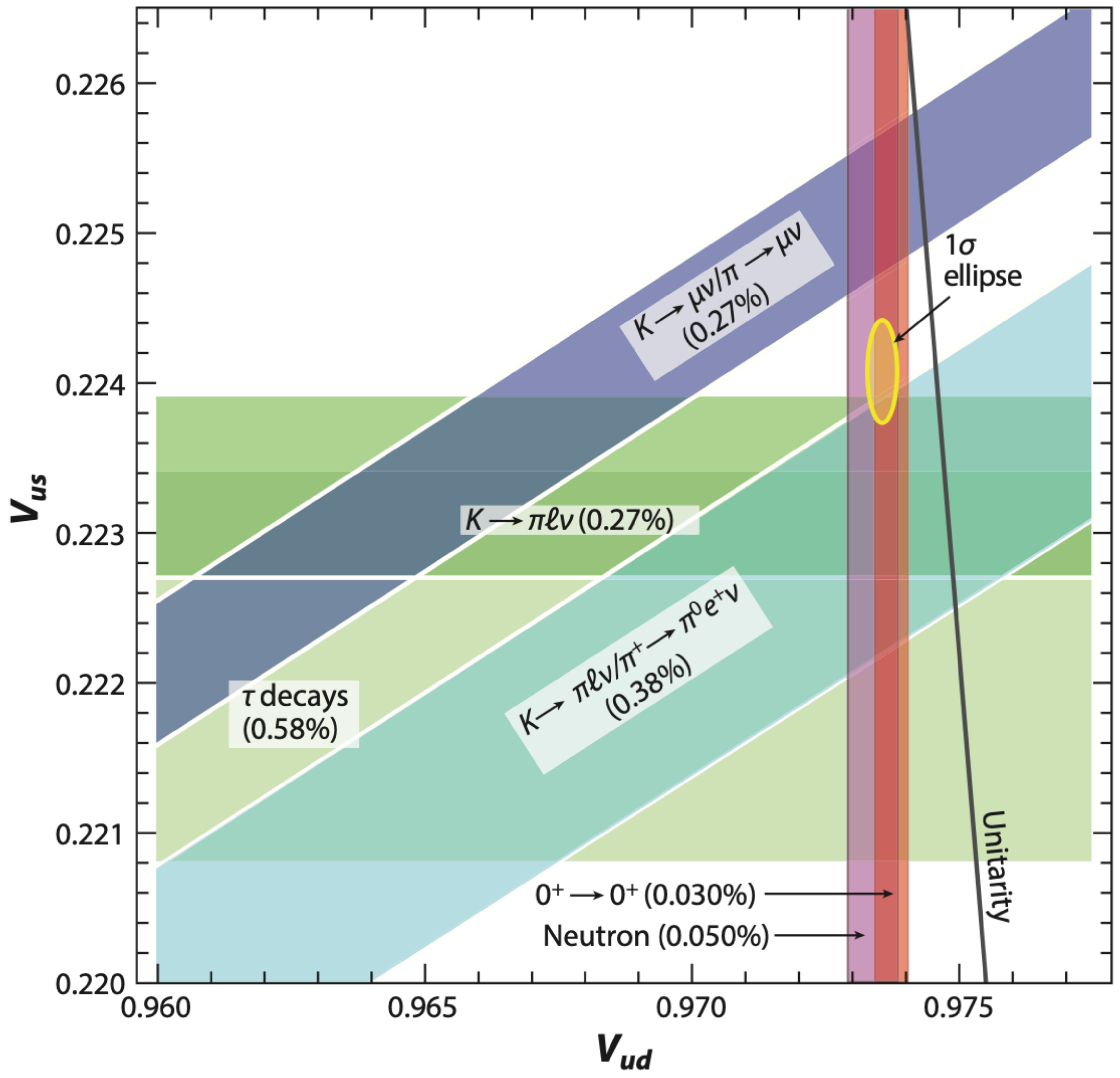
PIBETA exp. ($\pm 0.6\%$)

$$B(\pi^+ \to \pi^0 e^+ \nu) = (1.038 \pm 0.004_{stat} \pm 0.004_{syst} \pm 0.002_{\pi e2}) \times 10^{-8}$$

Presently not competitive precision for V_{ud} but would be with an order of magnitude improvement (same precision as β decays)

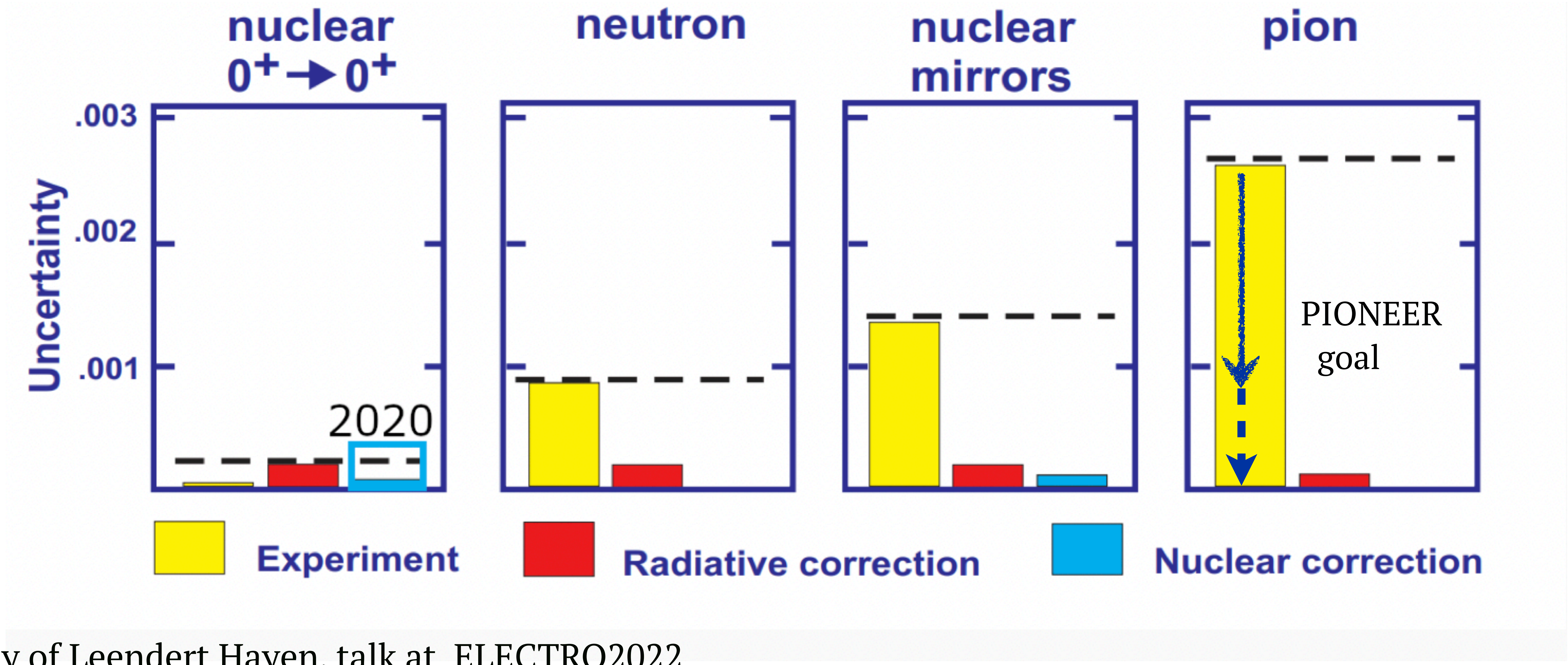
tensions in the first row CKM unitarity test

3σ (or even more…)



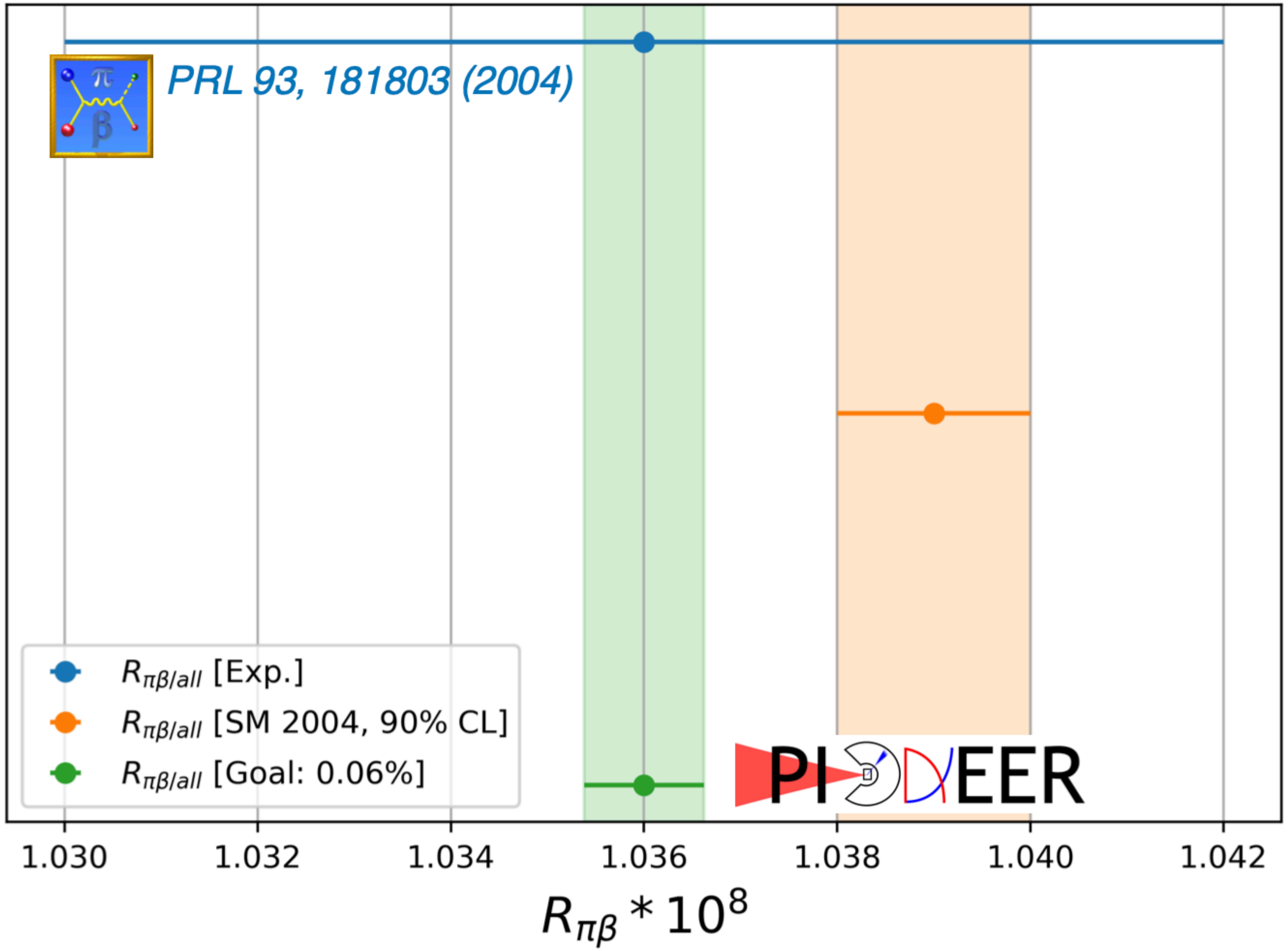
D. Bryman et al. Annu. Rev. Nucl. Part. Sci. 2022. 72:69–91

Physics case 4: Testing CKM unitarity V_{ud}



Courtesy of Leendert Hayen, talk at ELECTRO2022

Physics case 4: Testing CKM unitarity V_{ud}



Current best measurement from PIBETA at PSI

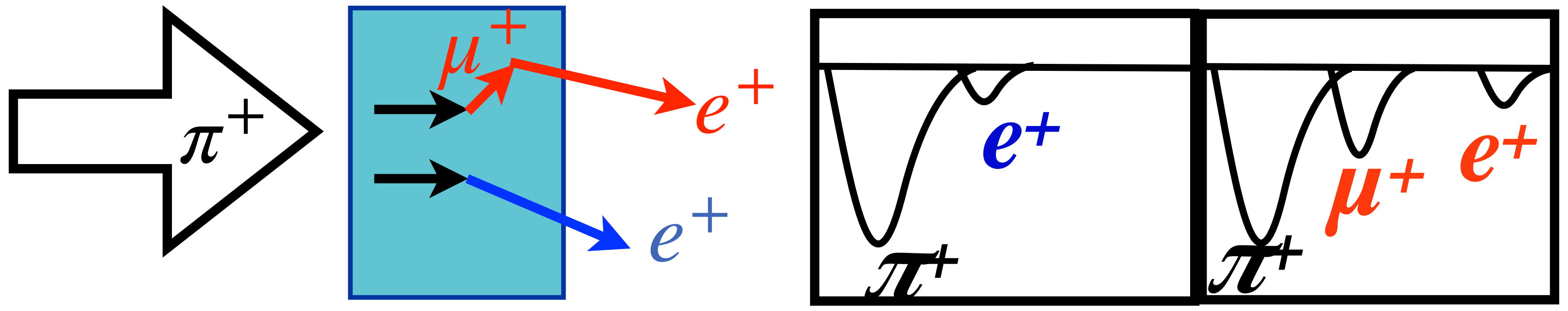
$$R_{\pi\beta}^{Exp} = 1.036(0.006) \times 10^8$$

PIONEER goal is to measure $R_{\pi\beta}$ to 0.06% precision

Ten-fold improvement over current world best

Constraint on $|V_{ud}|$ comparable to super-allowed beta decay

$R^\pi = \dfrac{\pi \to e\nu(\gamma)}{\pi \to \underbrace{\boxed{\mu}}_{\mu \to e\nu\bar{\nu}}\nu(\gamma)}$: how is it measured?



What π decay to "normally": $B(\pi^+ \to \mu^+\nu(\gamma)) = 0.999877 \pm 0.0000004$

Helicity suppressed decay: $B(\pi^+ \to e^+\nu_e(\gamma)) = (1.2327 \pm 0.00023) \times 10^{-4}$

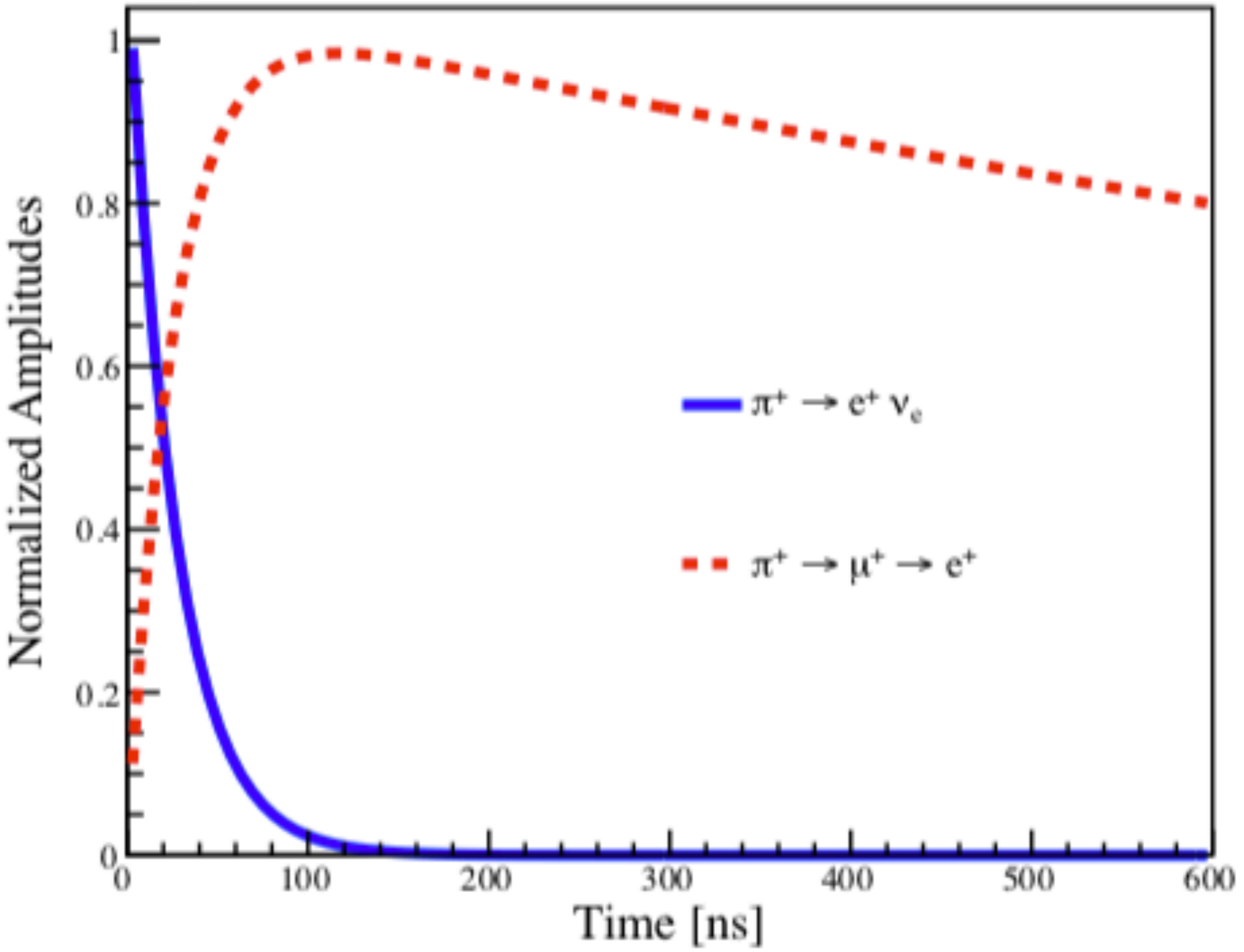
Pion β decay: $B(\pi^+ \to e^+\nu_e\pi^0) = (1.036 \pm 0.006) \times 10^{-8}$

Reminders:

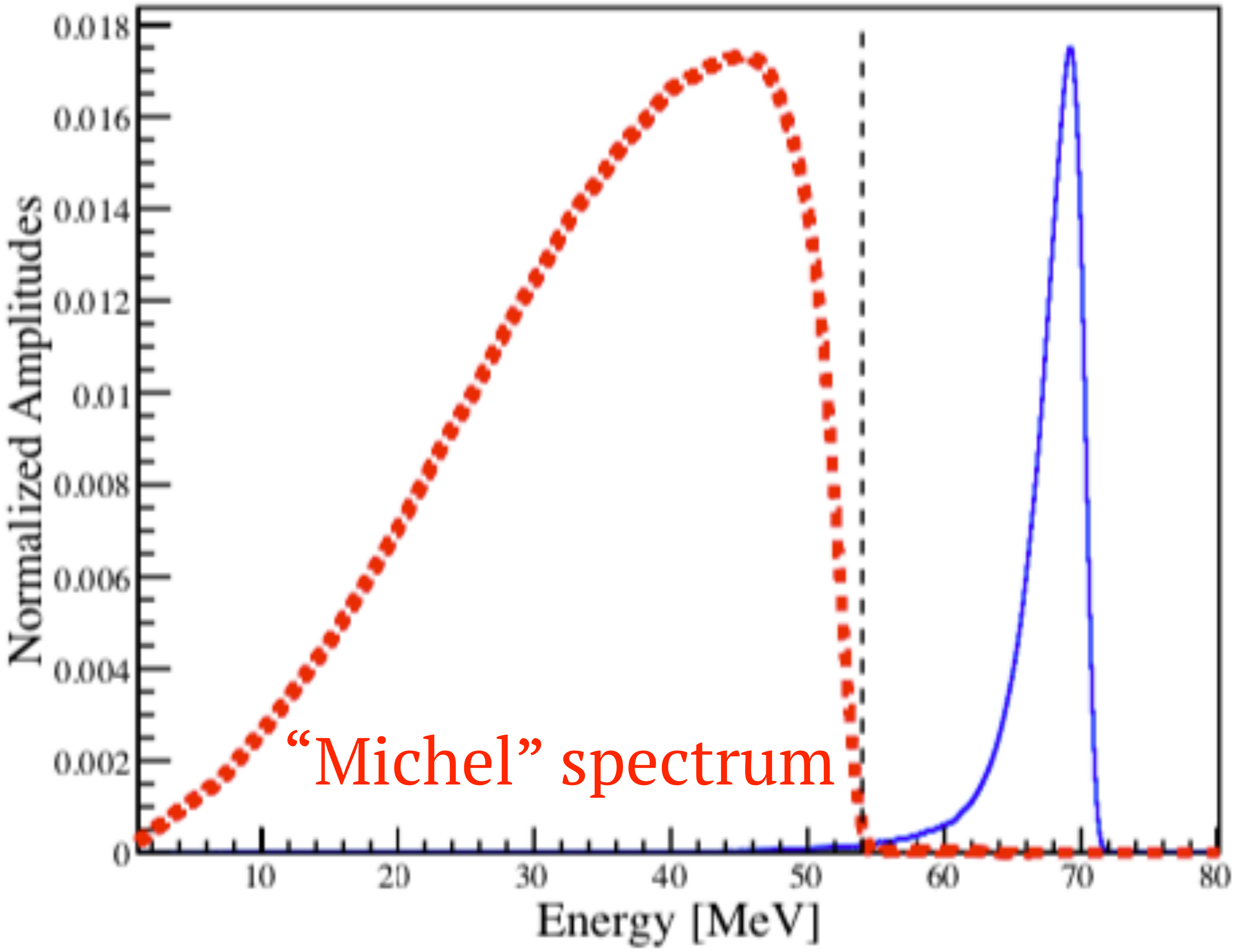
Pion lifetime:	26 ns
Muon lifetime:	2197 ns
Pion mass:	139.6 MeV
Muon mass:	105.7 MeV

Measure precisely e^+ energy spectrum and $t_{e^+} - t_{\pi^+}$

$\Longrightarrow$ different time and energy spectra - discrimination between the two decays



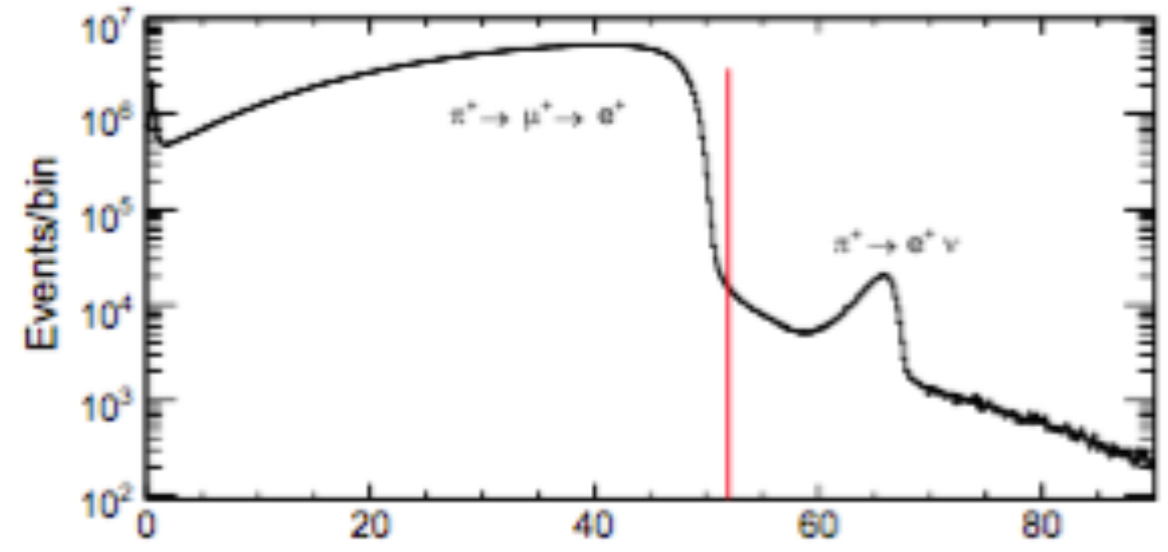
Time spectrum



e^+ energy spectrum

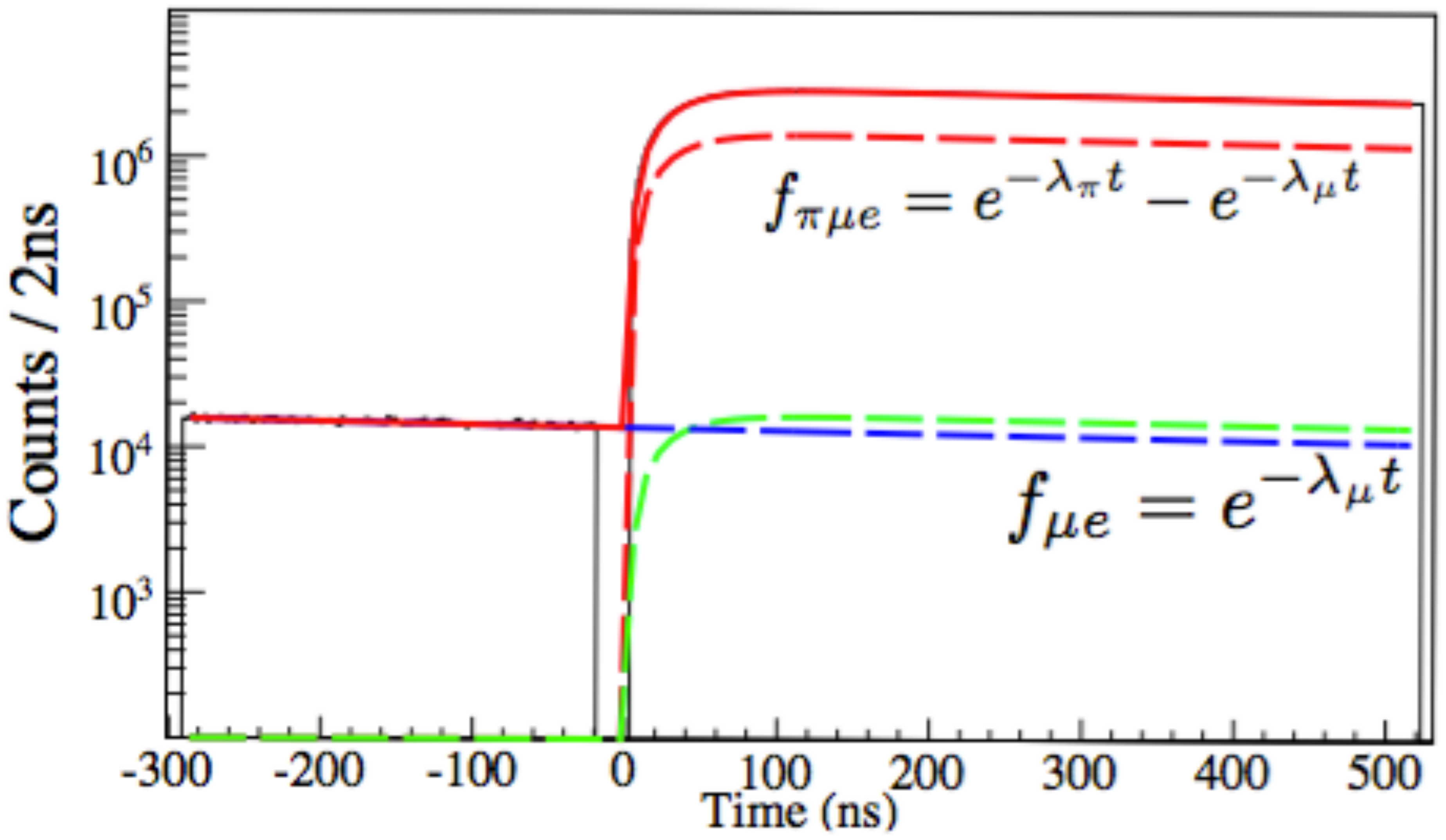
$R^\pi = \dfrac{\pi \to e\nu(\gamma)}{\pi \to \boxed{\mu}\nu(\gamma)}$: how is it measured?

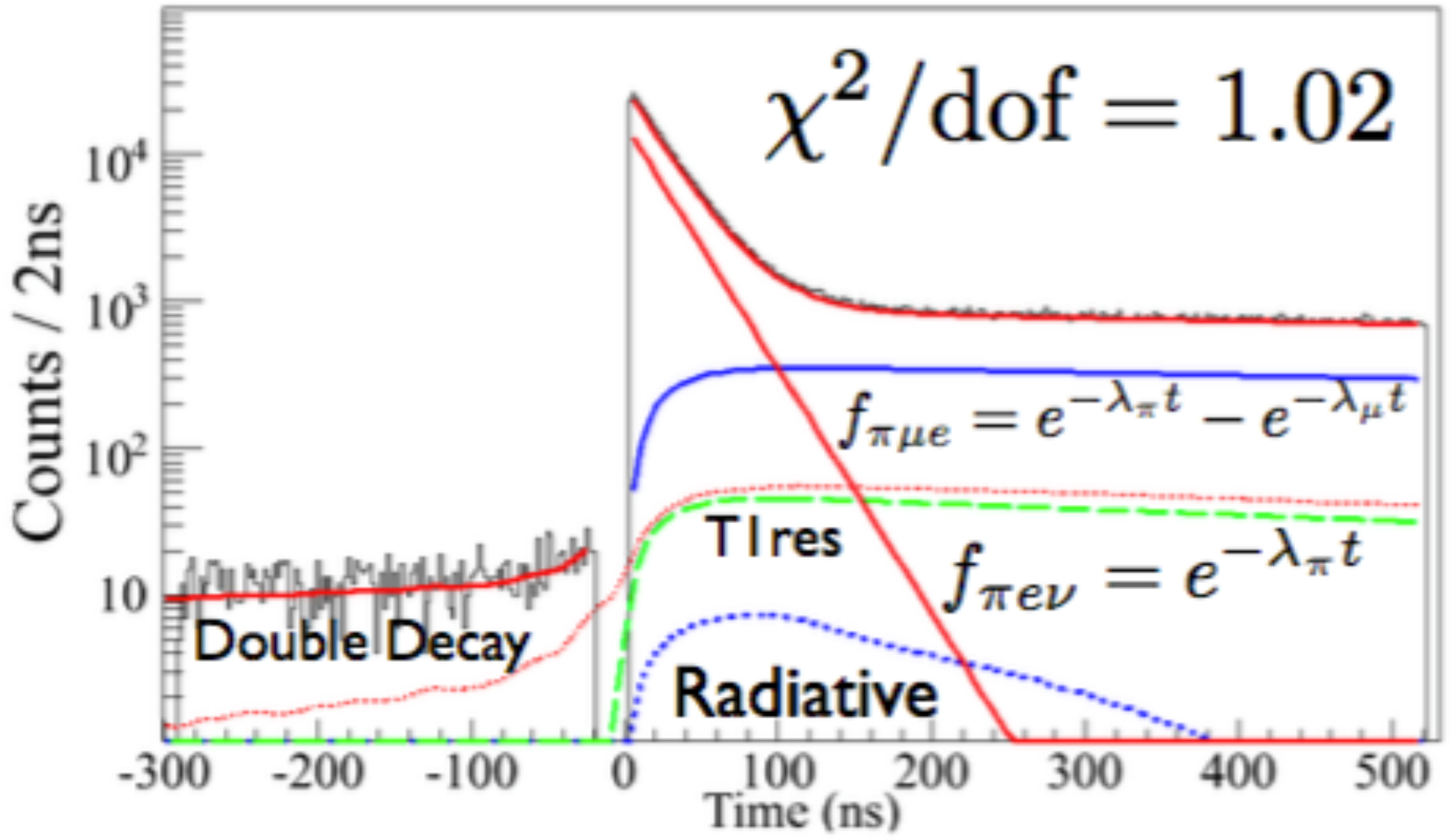
$\hookrightarrow \mu \to e\nu\bar{\nu}$



E<52MeV

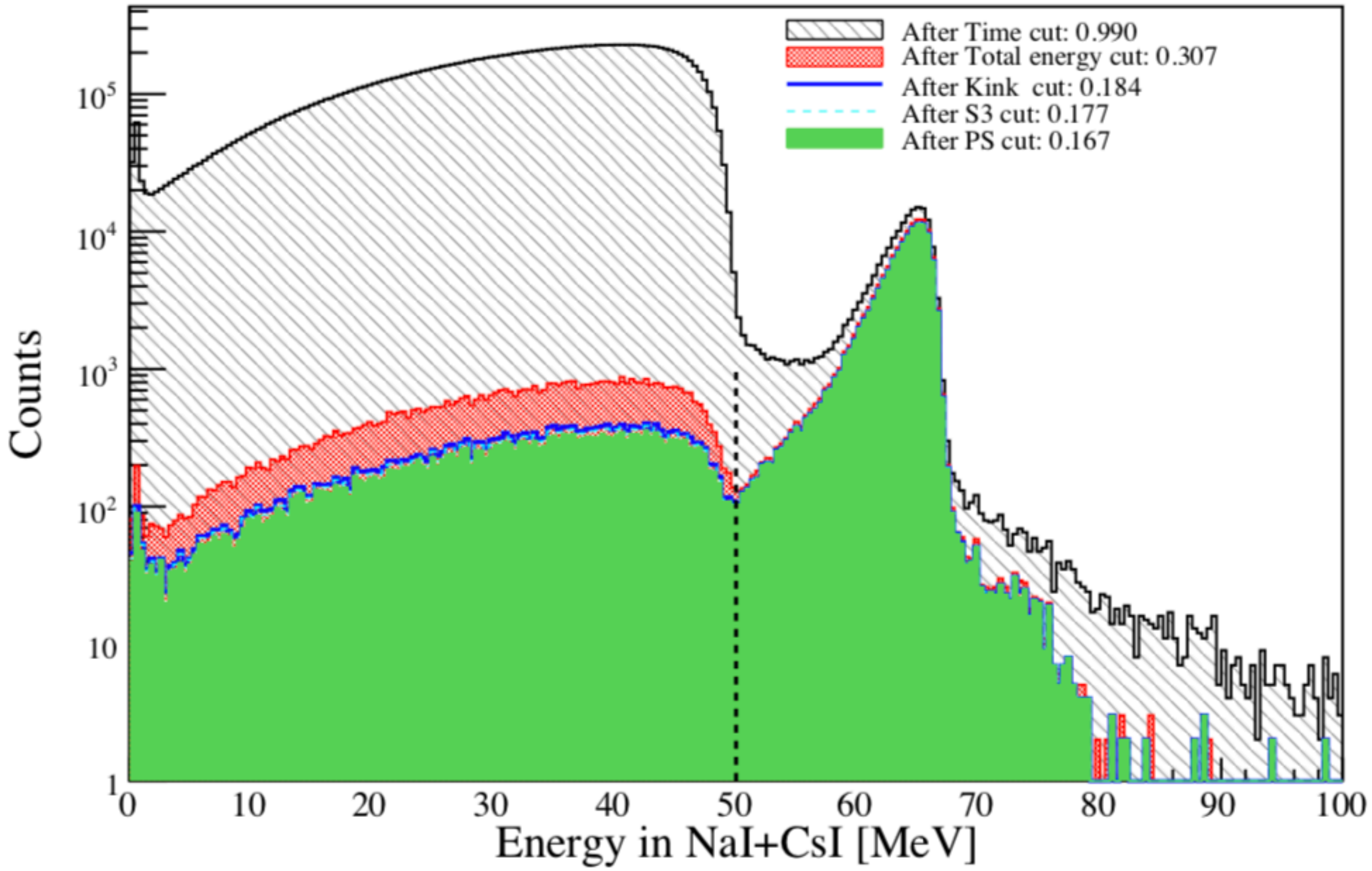
E>52MeV

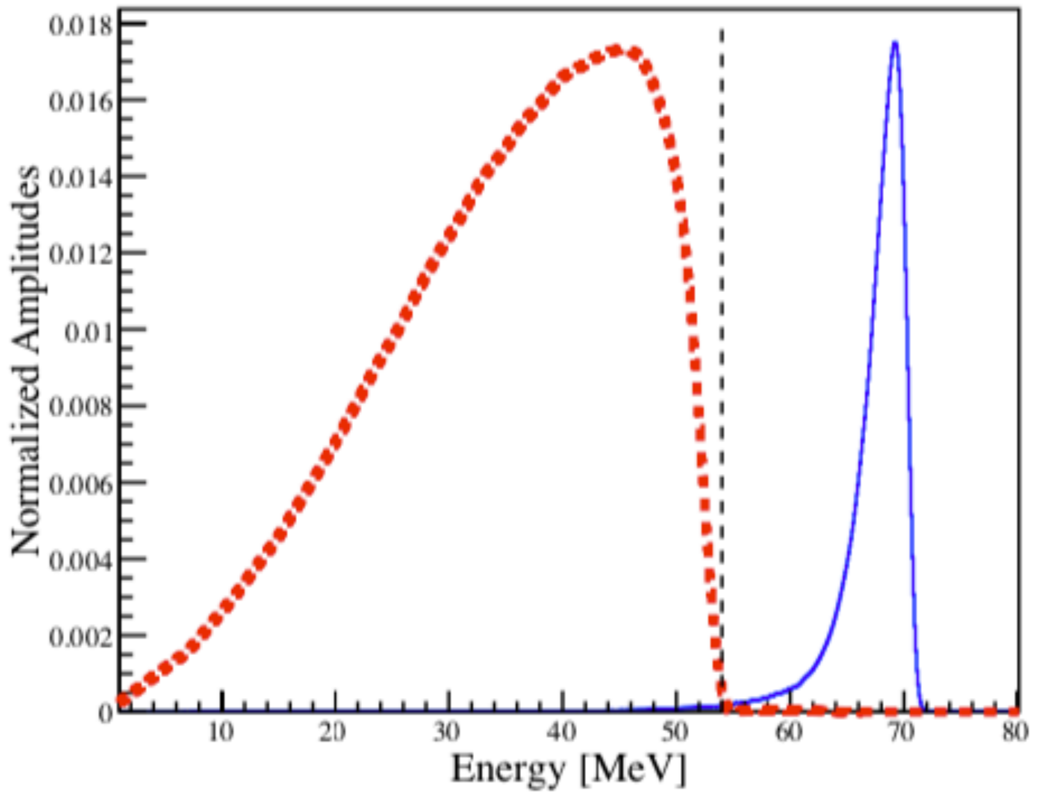


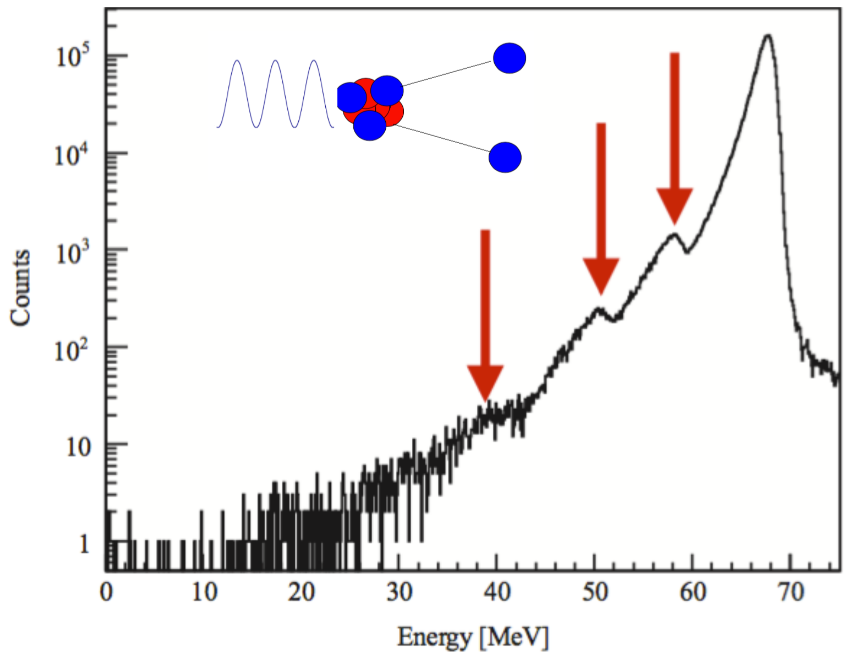


$R^{\pi} = \dfrac{\pi \to e\nu(\gamma)}{\pi \to \boxed{\mu}\nu(\gamma)}$: main systematic in the PIENU experiment

$\mu \to e\nu\bar{\nu}$







A. Aguilar-Arevalo et al., Nuclear Instruments and Methods in Physics Research A 621 (2010) 188–191

Low energy tail buried under the Michel spectrum caused by:

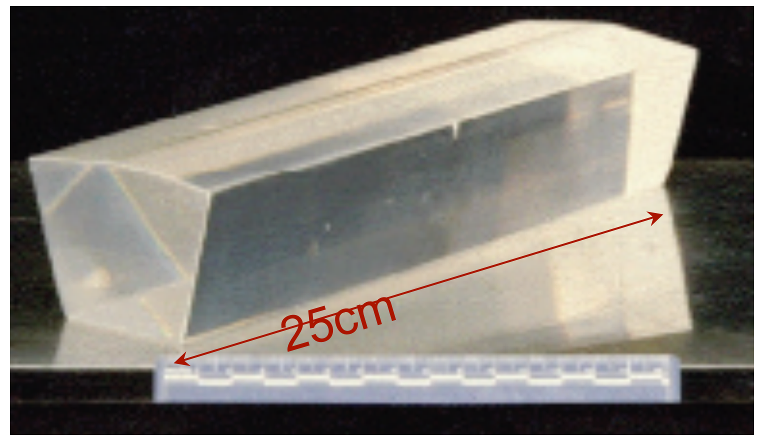
- finite energy resolution of the calorimeter
- photo-nuclear interactions (^{127}I(ɣ,n))
- shower leakage
- geometrical acceptance
- radiative decays
- etc

Main source of systematics : estimated using data (suppression of $\pi \to \mu \to e$ decays)

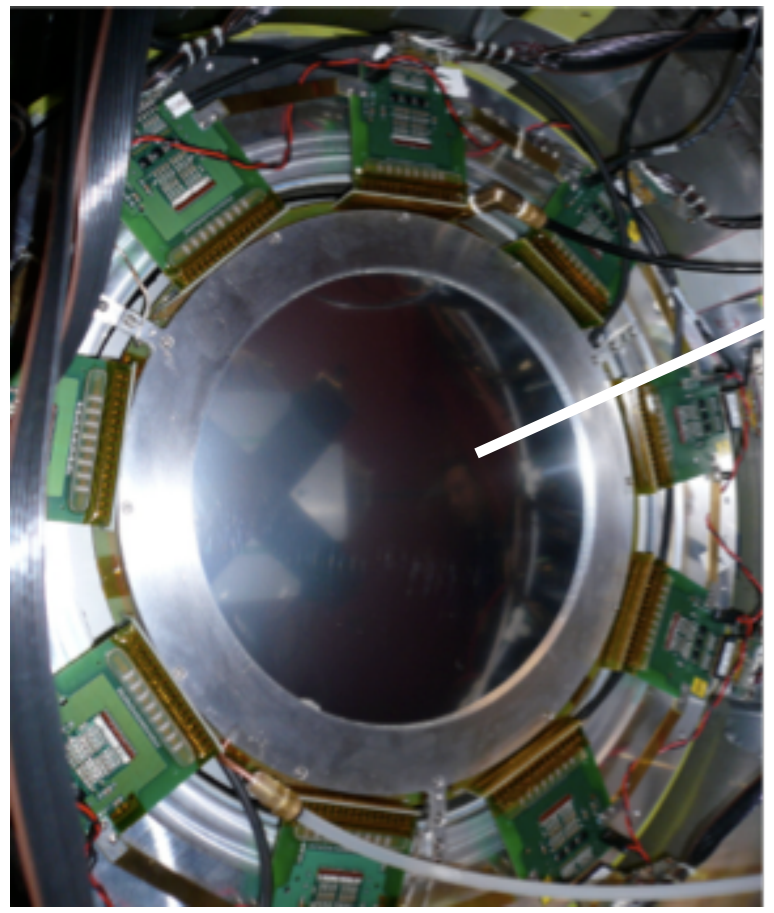
M13 area at TRIUMF

M13 area at TRIUMF

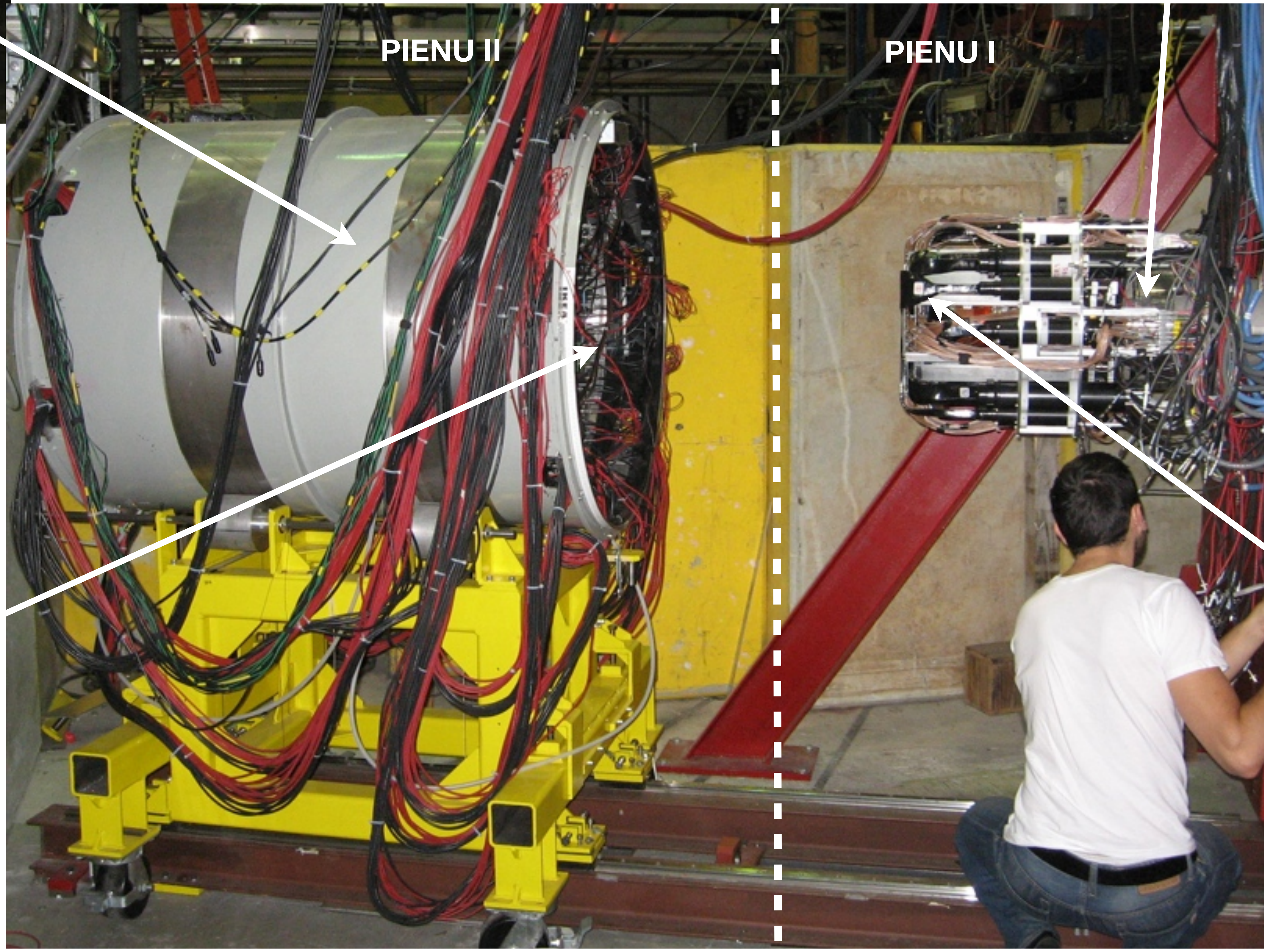
Monolithic NaI(Tl) crystal surrounded by 97 pure CsI crystals



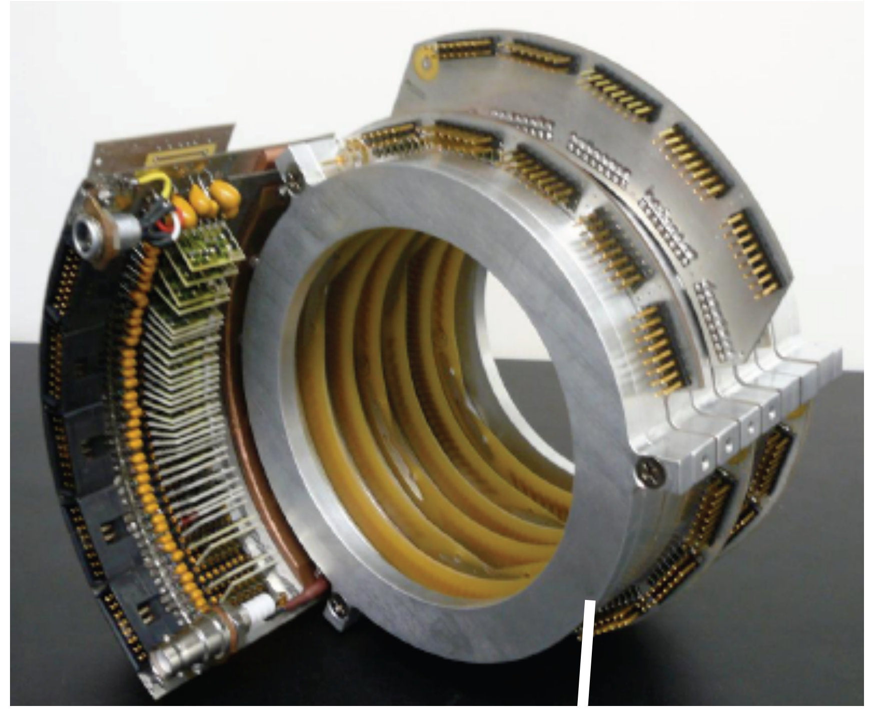
CsI crystal



Acceptance Wire Chamber

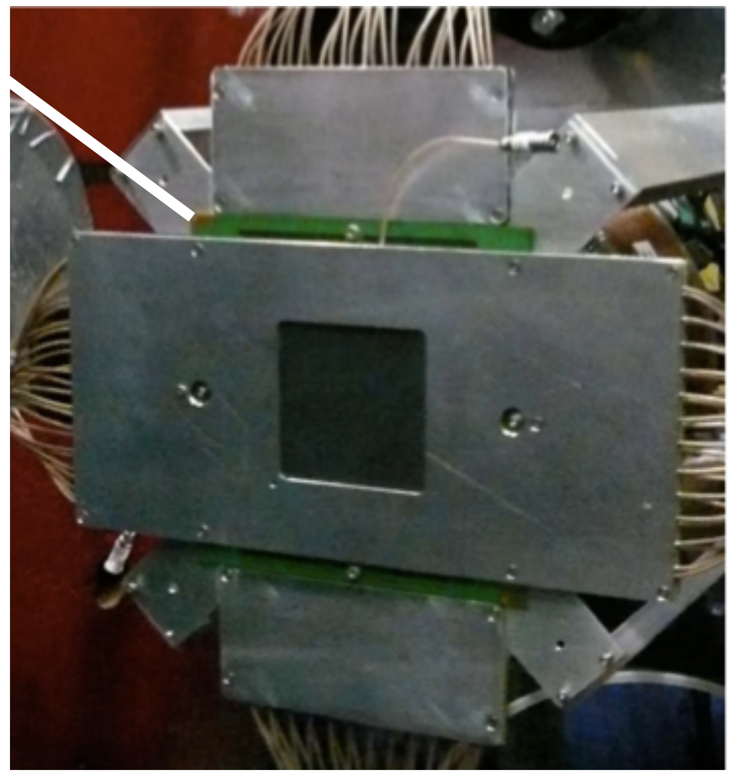


π^+



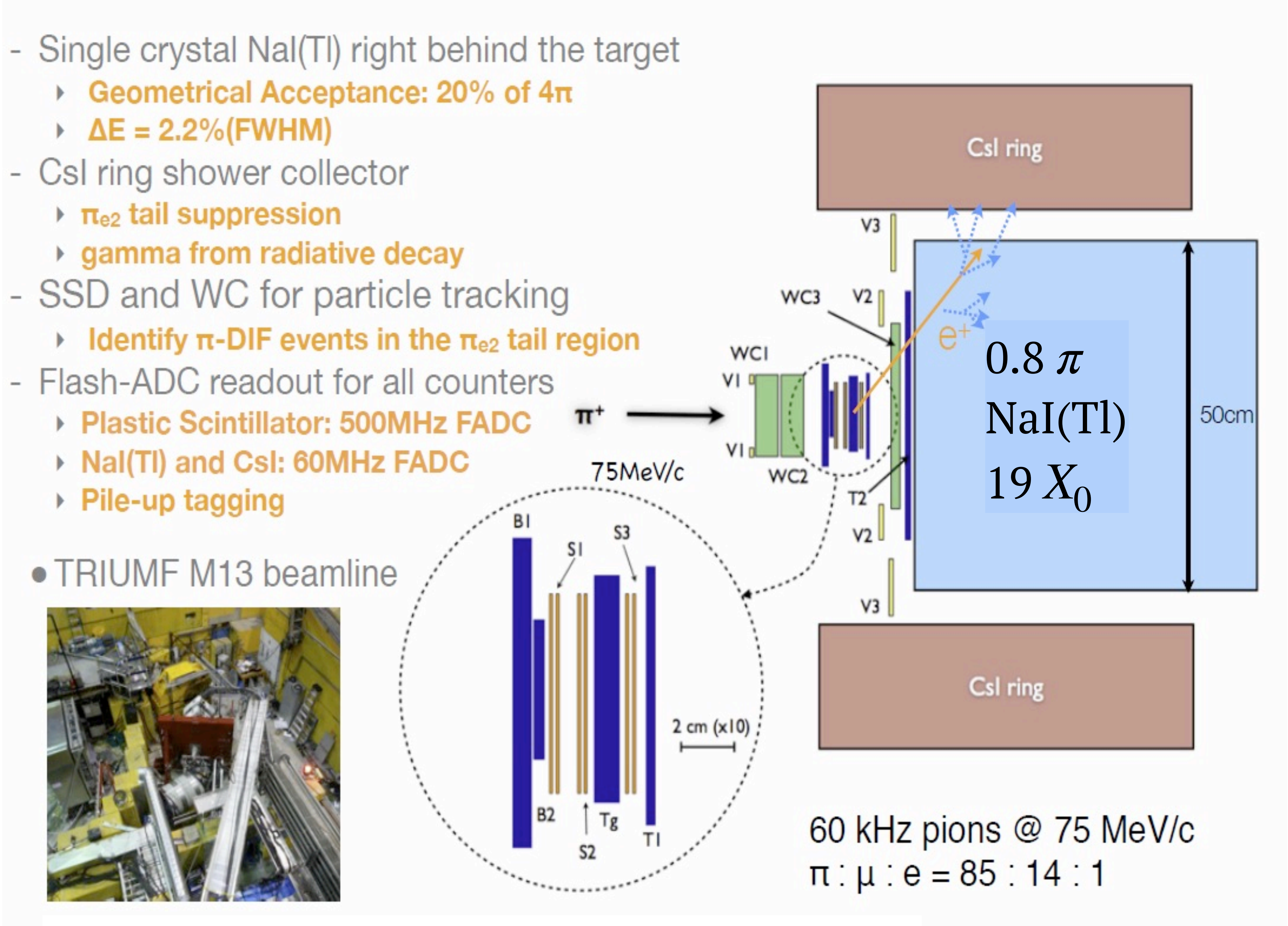
Beam Wire Chamber

Silicon Trackers



PIONEER: building on previous experiences - PIENU and PEN

PIENU @ TRIUMF



- Single crystal NaI(Tl) right behind the target
  - **Geometrical Acceptance: 20% of 4π**
  - **ΔE = 2.2%(FWHM)**
- CsI ring shower collector
  - **π_{e2} tail suppression**
  - **gamma from radiative decay**
- SSD and WC for particle tracking
  - **Identify π-DIF events in the π_{e2} tail region**
- Flash-ADC readout for all counters
  - **Plastic Scintillator: 500MHz FADC**
  - **NaI(Tl) and CsI: 60MHz FADC**
  - **Pile-up tagging**

- TRIUMF M13 beamline

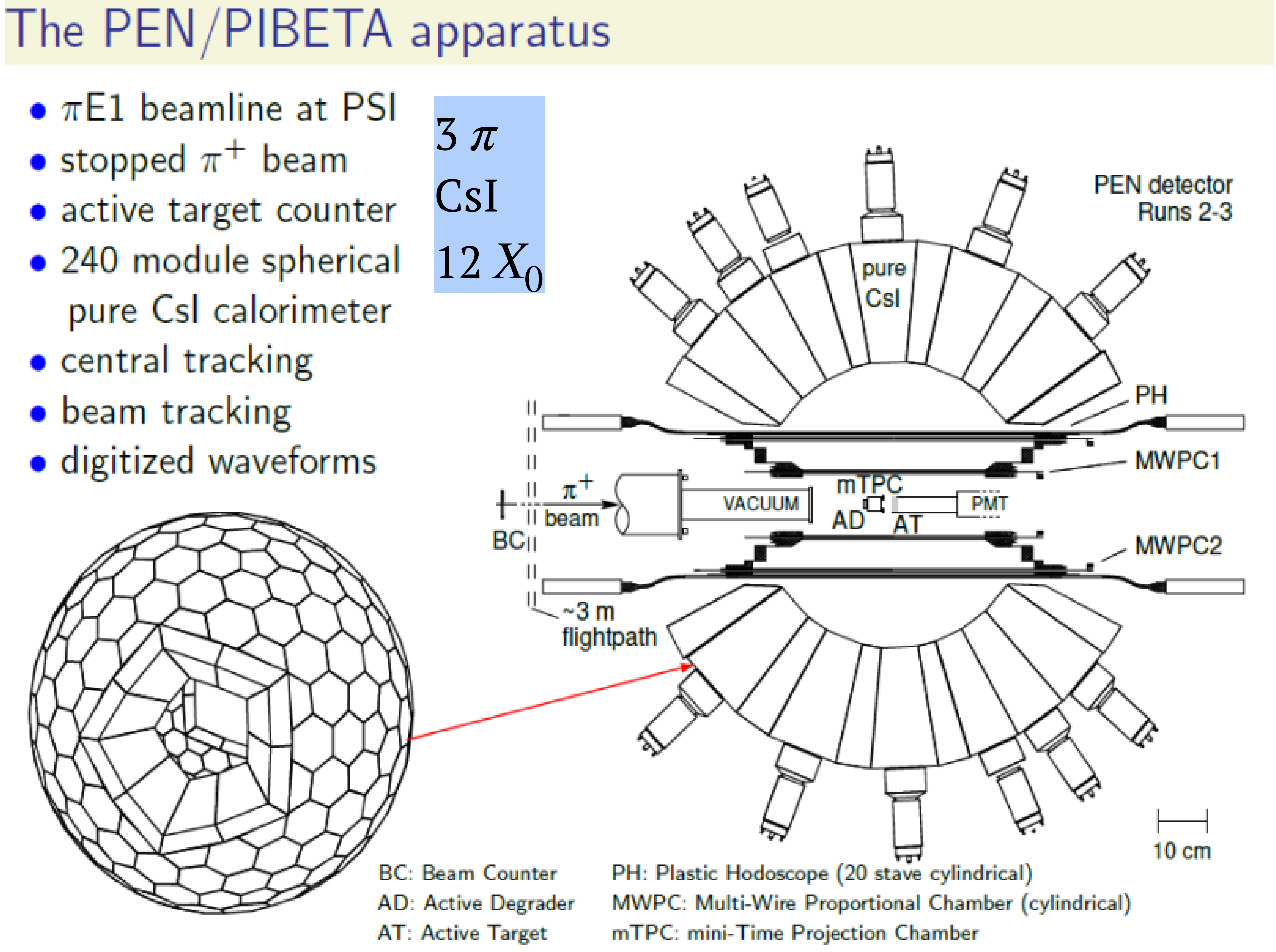
0.8 π
NaI(Tl)
19 X_0

60 kHz pions @ 75 MeV/c
π : μ : e = 85 : 14 : 1

NaI slow but excellent resolution (1% σ at 70 MeV)

non uniformity, small solid angle

PEN @ PSI



The PEN/PIBETA apparatus

- πE1 beamline at PSI
- stopped π^+ beam
- active target counter
- 240 module spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms

3 π
CsI
12 X_0

BC: Beam Counter
AD: Active Degrader
AT: Active Target

PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)
mTPC: mini-Time Projection Chamber

Good geometry but calorimeter depth too small

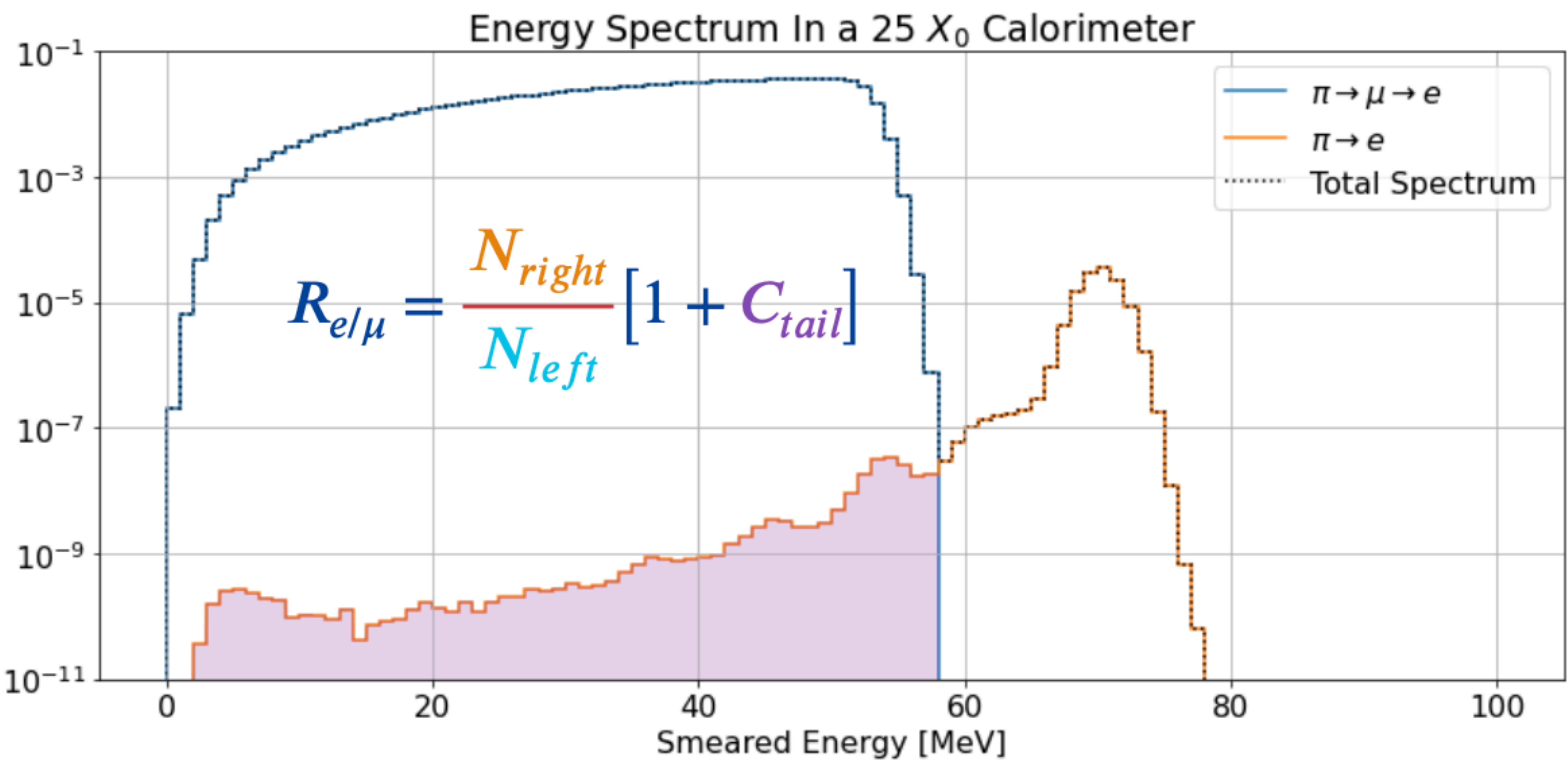
PIONEER DETECTOR CONCEPT - best of both worlds

- Building on previous experiences (PIENU and PEN/PIBETA) : use of emerging technologies (LXe, LGADs)
  - Guiding principles to the design of the experiment

1. **Collect very large datasets** of rare pion decays (2e8 $\pi \to e\nu$ during Phase I)
→ 3π sr calorimeter, intense pion beam at PSI

2. **Tail must be less than 1% of total signal**
→ Shower containment in the calorimeter
→ 25 X_0 calorimeter, high energy resolution (improve uniformity), reduce pile-up (fast detectors)

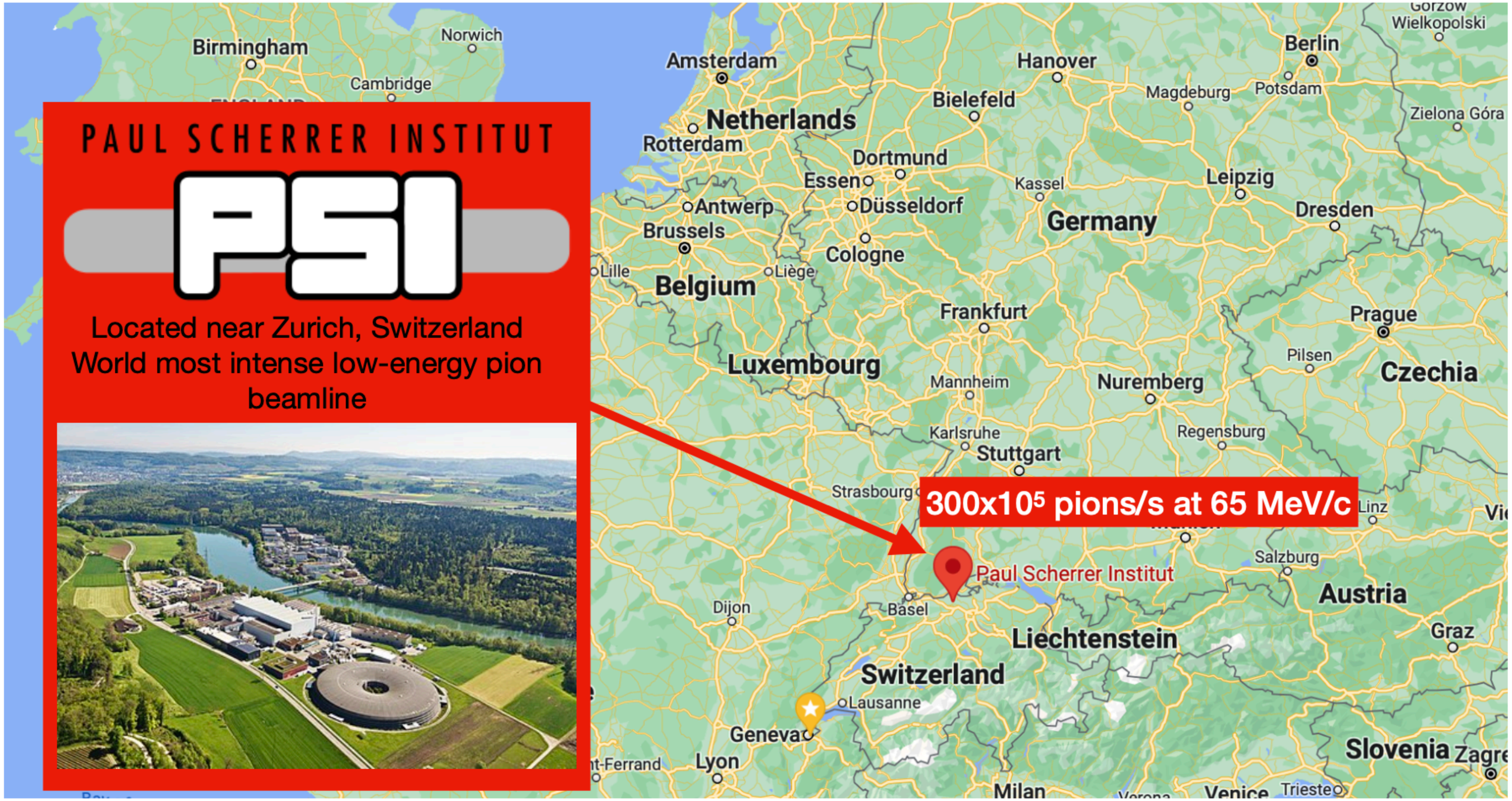
3. **Tail must be measured with a precision of 1%**
→ Event identification in the active target
→ highly segmented and fast target (5D detector)



$$R_{e/\mu} = \frac{N_{right}}{N_{left}}\left[1 + C_{tail}\right]$$

Guiding principles to the design of the experiment:

1. **Collect very large datasets of rare pion decays (2e8 $\pi^+ \rightarrow e^+\nu_e$ during Phase I)**
2. Tail must be less than 1% of total signal → Shower containment in the calorimeter
3. Tail must be measured with a precision of 1% → Event identification in the active target


PAUL SCHERRER INSTITUT

PSI

Located near Zurich, Switzerland
World most intense low-energy pion beamline

300x10^5 pions/s at 65 MeV/c

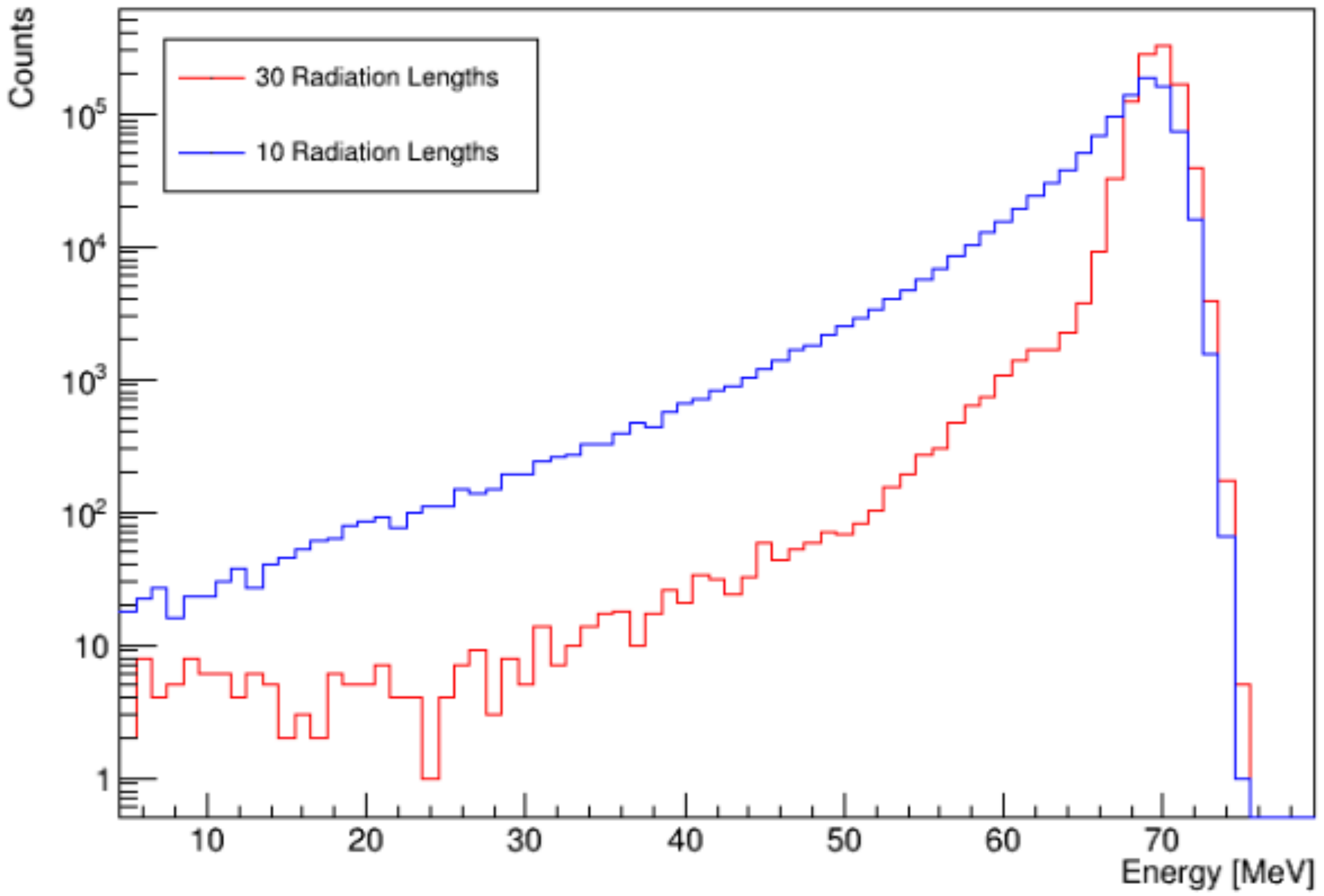
PIONEER DETECTOR CONCEPT - THE CALORIMETER

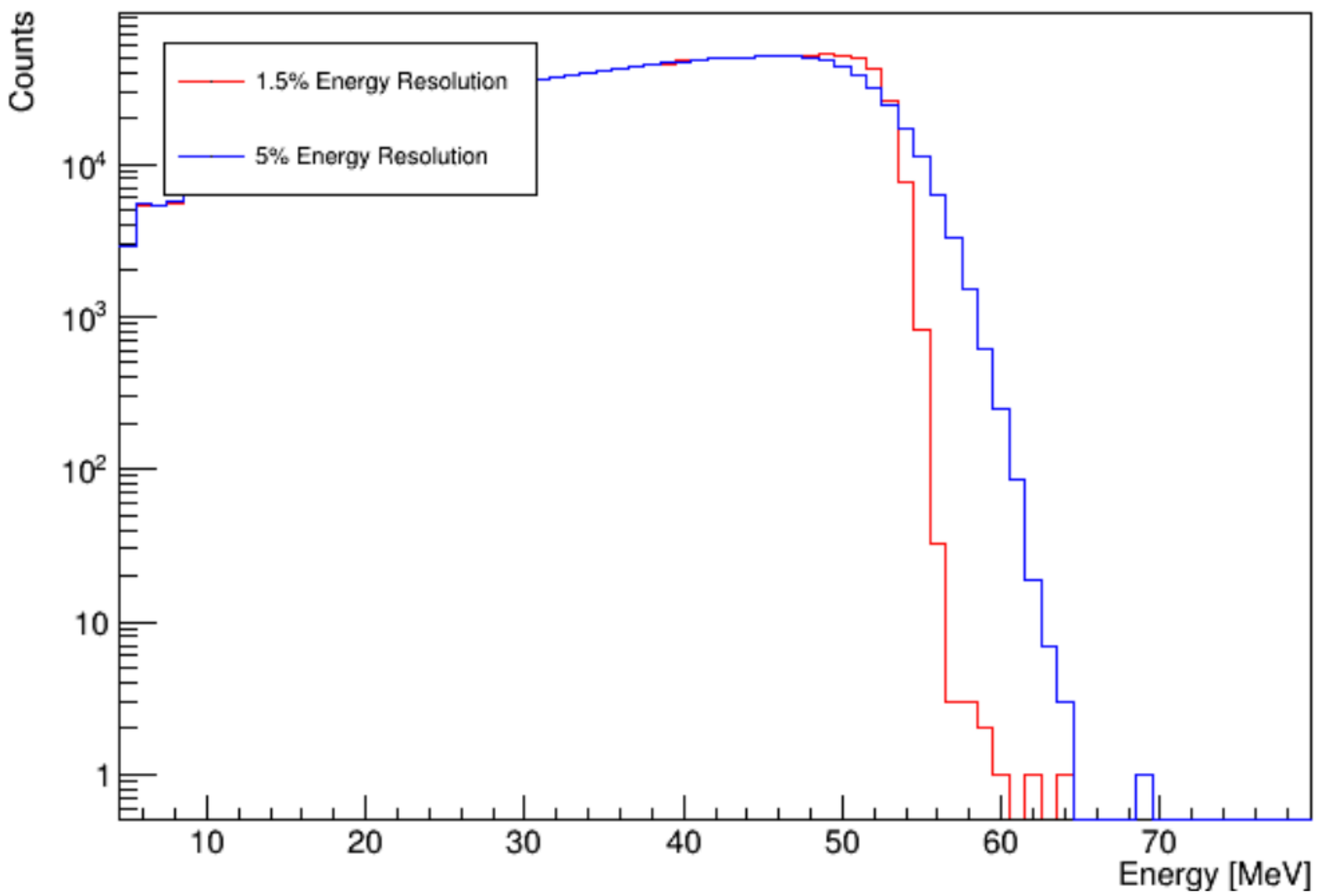
Guiding principles to the design of the experiment:

1. Collect very large datasets of rare pion decays (2e8 $\pi^+ \rightarrow e^+\nu_e$ during Phase I)
2. **Tail must be less than 1% of total signal → Shower containment in the calorimeter**
3. Tail must be measured with a precision of 1% → Event identification in the active target

Main Contender
Liquid Xenon

- fast response
- dense
- highly homogeneous response
- very bright
- proven high energy resolution
- Detector can be reshaped

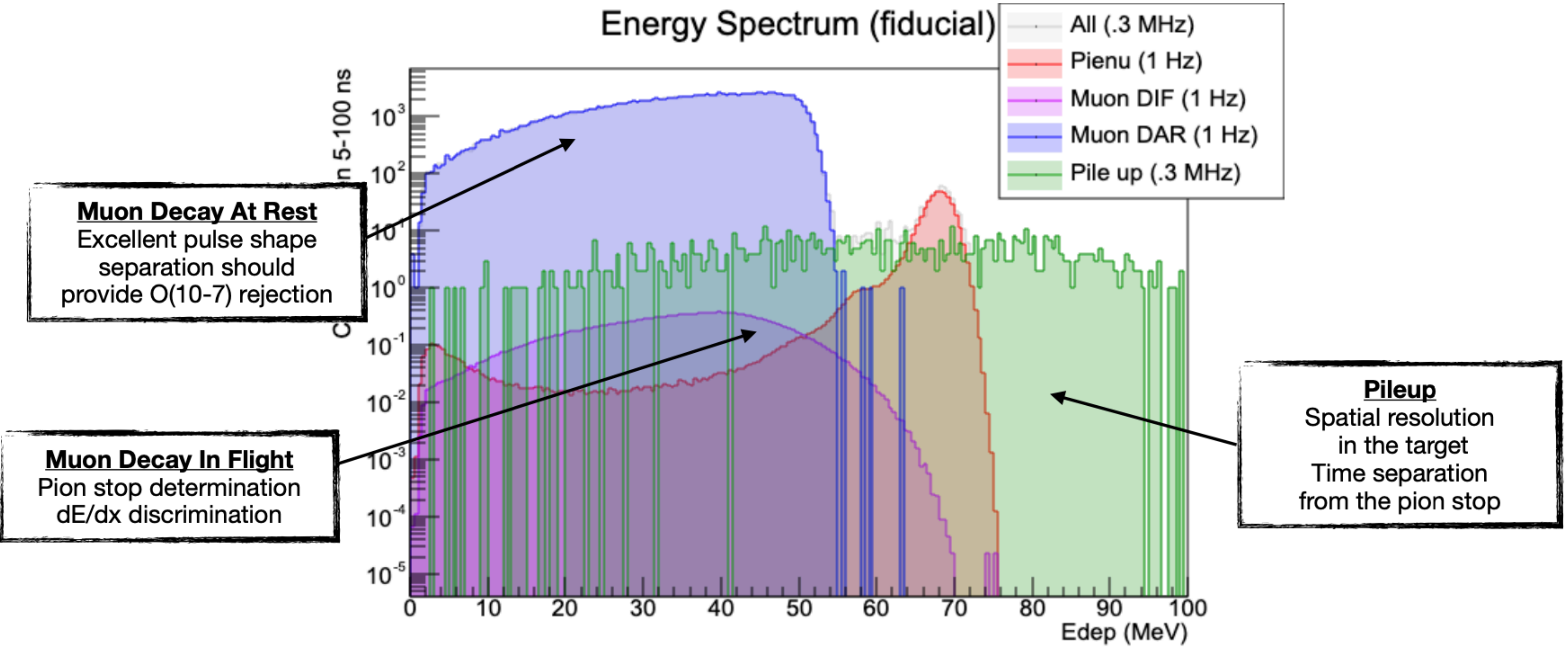

$\pi \rightarrow e\nu$ signal


$\pi - \mu - e$ background

Target: ~25 X_0, 2% energy resolution at 70 MeV

Main question: how well can LXe handle pile-up in a high rate environment?

PIONEER DETECTOR CONCEPT - THE ACTIVE TARGET



Muon Decay At Rest
Excellent pulse shape
separation should
provide O(10-7) rejection

Muon Decay In Flight
Pion stop determination
dE/dx discrimination

Pileup
Spatial resolution
in the target
Time separation
from the pion stop

This is what real data could look like

Guiding principles to the design of the experiment:

1. Collect very large datasets of rare pion decays (2e8 $\pi^+ \rightarrow e^+\nu_e$ during Phase I)
2. Tail must be less than 1% of total signal → Shower containment in the calorimeter
3. **Tail must be measured with a precision of 1% → Event identification in the active target**

23

PIONEER DETECTOR CONCEPT - THE ACTIVE TARGET

Muon Decay At Rest
Excellent pulse shape separation should provide O(10-7) rejection

Muon Decay In Flight
Pion stop determination
dE/dx discrimination

This is what real data could look like

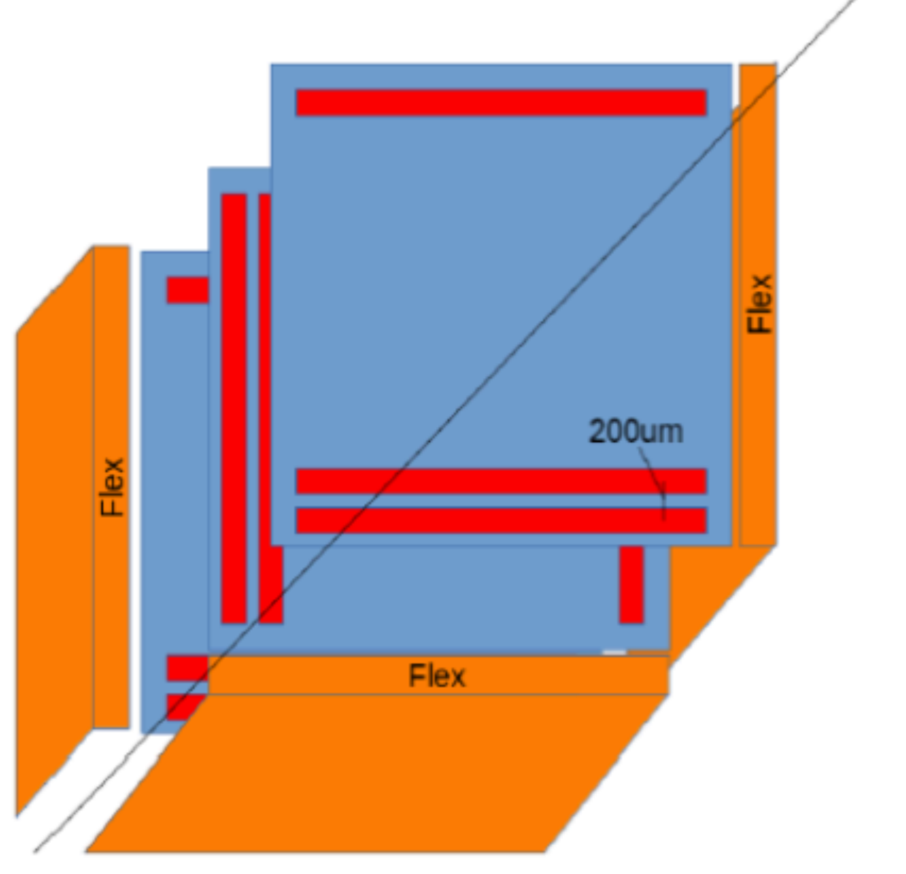
Guiding principles to the design of the experiment:

1. Collect very large datasets of rare pion decays (2e8 $\pi^+ \to e^+\nu_e$ during Phase I)
2. Tail must be less than 1% of total signal → Shower containment in the calorimeter
3. **Tail must be measured with a precision of 1% → Event identification in the active target**

Measuring the tail fraction

tag events with minimal bias while maintaining a decent (>1%) efficiency

PIONEER DETECTOR CONCEPT - THE ACTIVE TARGET

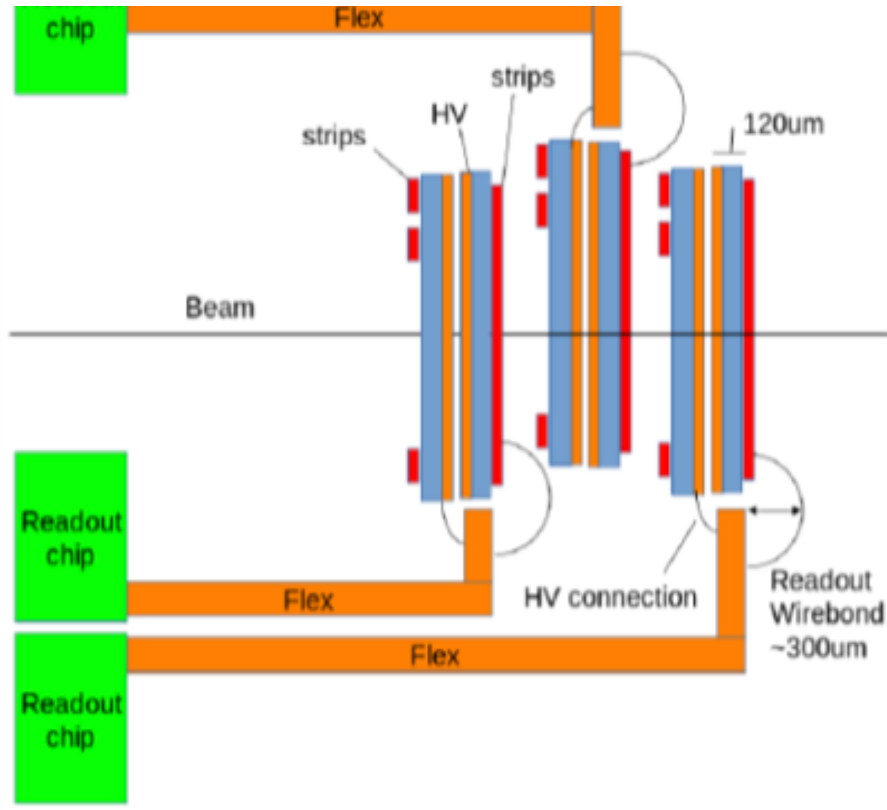


Active target (“4D - 5D!”) based on low-gain avalanche diode (LGAD) technology

Requirements

- Different energy loss of particles through silicon -> needs to accommodate large range of energy scales

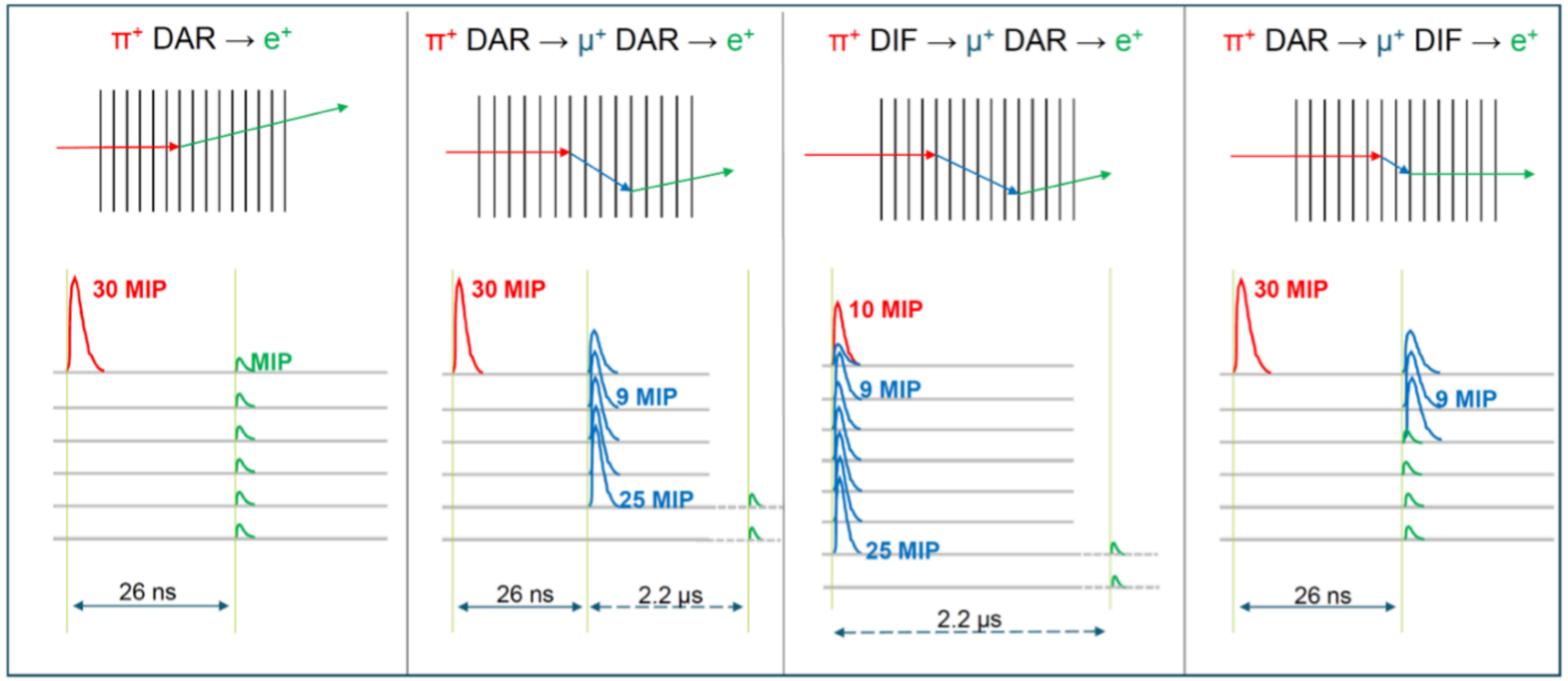
- different time properties: needs to separate signal within 1 ns apart



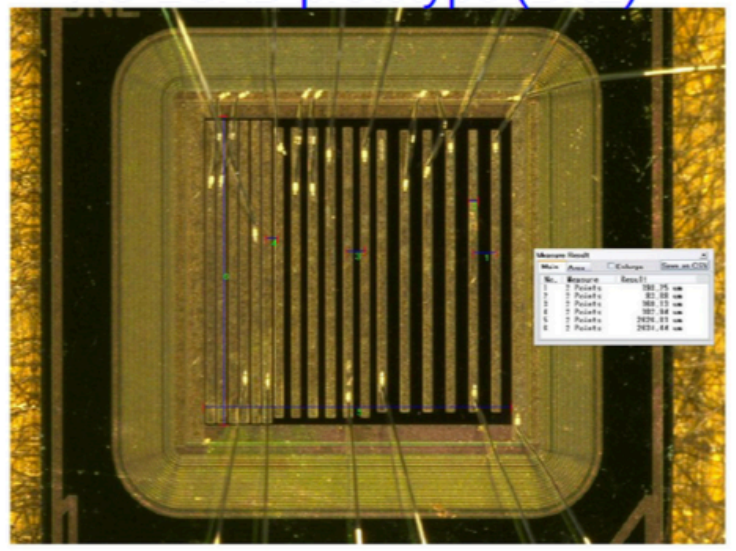
Tentative design

- 48 layers X/Y strips: 120 μm thick
- 100 strips with 200 μm pitch covering 2x2 cm2 area
- Sensors are packed in stack of two with facing HV side and rotate by 90 deg

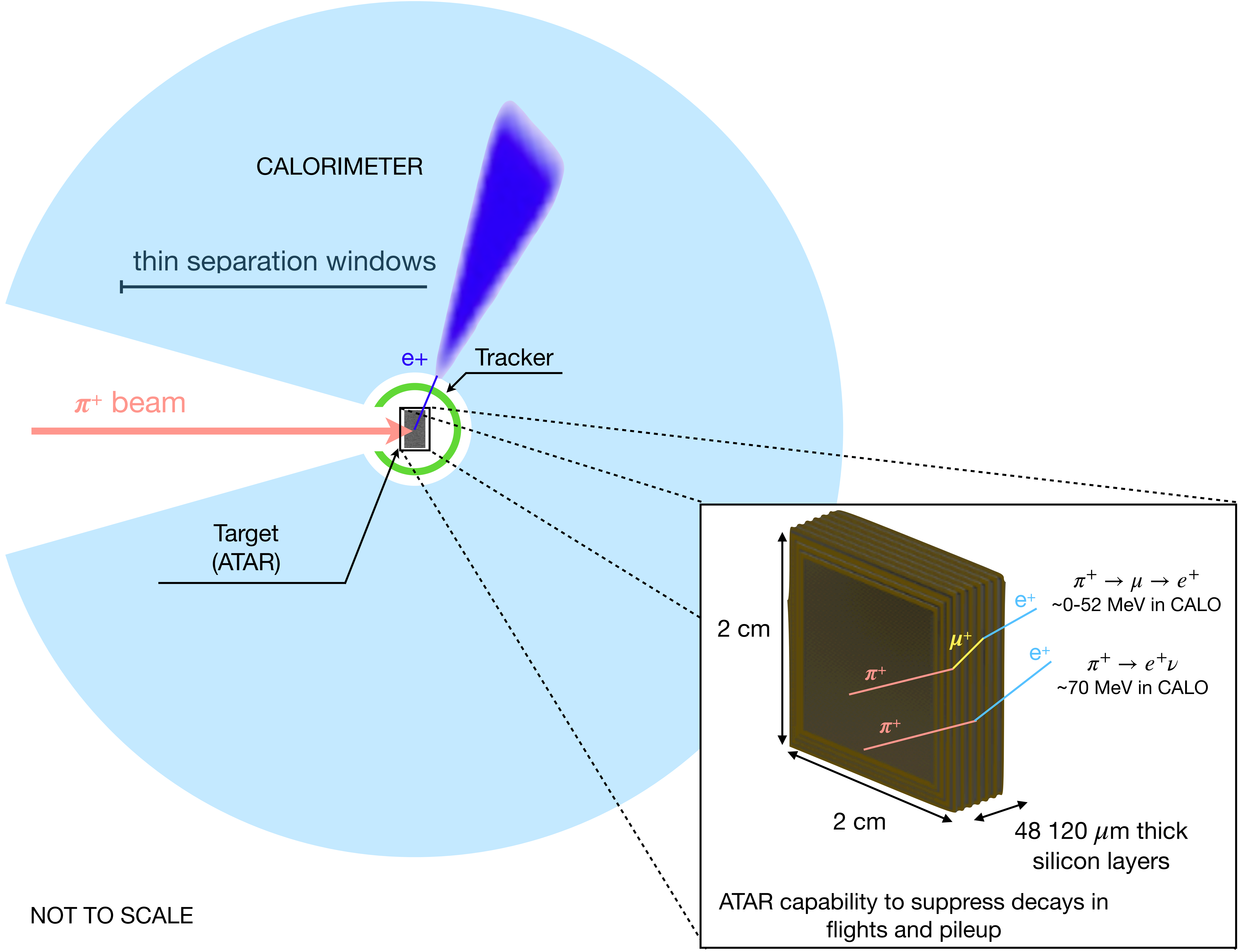
❑ Topology ❑ Calorimetry ❑ Timing



AC-LGAD prototype (BNL)



80 μm-wide strips, 100, 150, 200 μm pitch; 5-15μm resolution



CALORIMETER

thin separation windows

e+

Tracker

π^+ beam

Target (ATAR)

2 cm

2 cm

$\pi^+ \to \mu \to e^+$
~0-52 MeV in CALO

$\pi^+ \to e^+\nu$
~70 MeV in CALO

e+

μ^+

π^+

e+

π^+

48 120 μm thick silicon layers

ATAR capability to suppress decays in flights and pileup

NOT TO SCALE

ATAR capability to suppress decays in flights and pileup

NOT TO SCALE

Conclusions and opportunities!

- High precision rare decays provide very promising windows into NP

- PIONEER : new experiment addressing emerging SM **anomalies in flavor physics**

- Staged goals
  - R^{π} at 0.01% matching theoretical precision
  - Pion β decay at 0.03% (in two steps) matching super-allowed β decay experiments

- Time-scale: 10-15 years

- Approved to run at PSI. Expected start of data taking ~ 5 years timescale.

- Supported by an international collaboration: experts from previous PIENU and PEN experiments as well as a wide range of collaborators from NA62, MEG, muon g-2, ATLAS, PSI scientists and theorists: **JOIN US!**

Snowmass PIONEER white paper: https://arxiv.org/abs/2203.05505
PIONEER PSI proposal: https://arxiv.org/pdf/2203.01981.pdf

PIONEER first collaboration meeting Oct 2023, CENPA University of Washington

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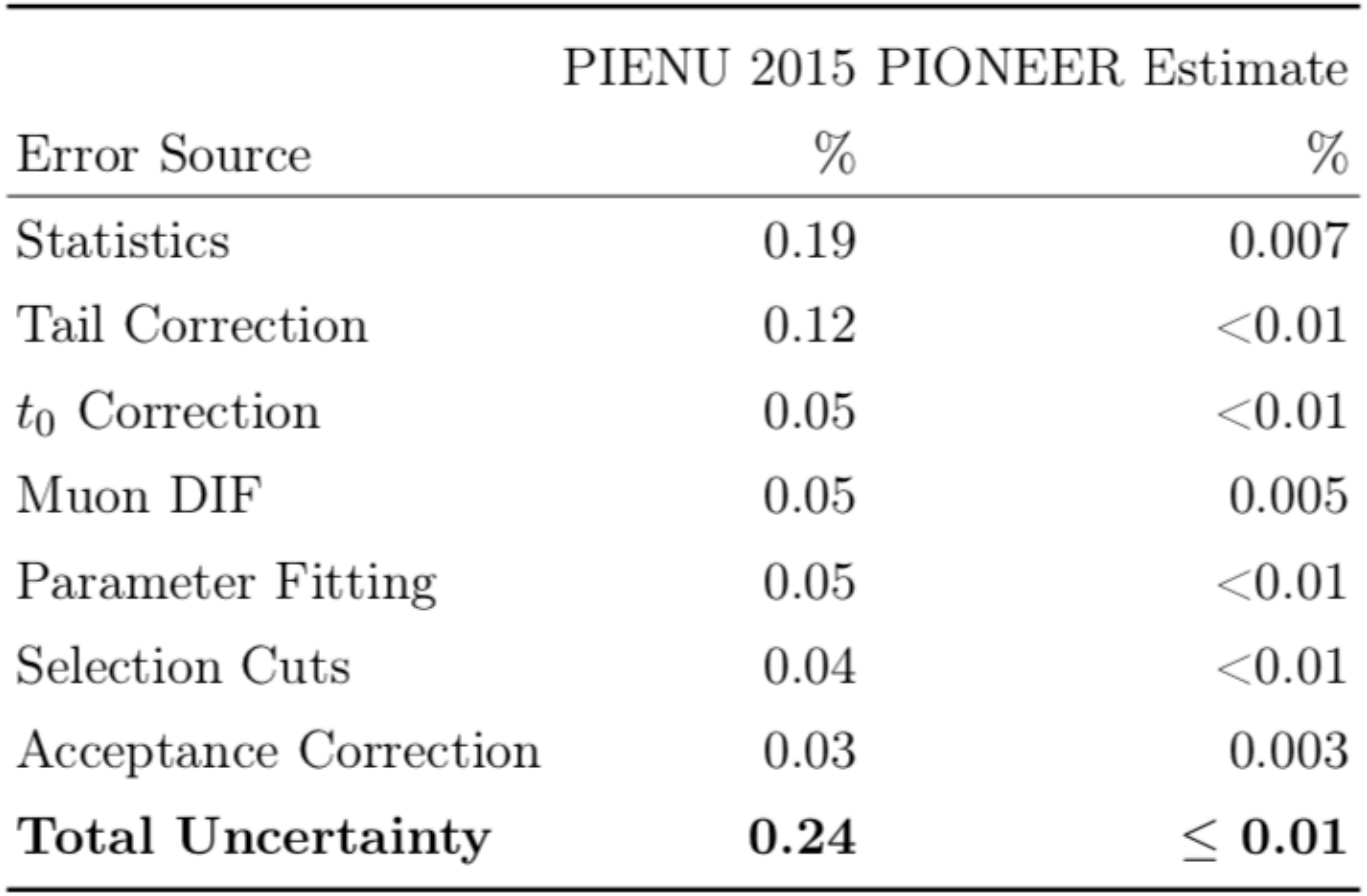
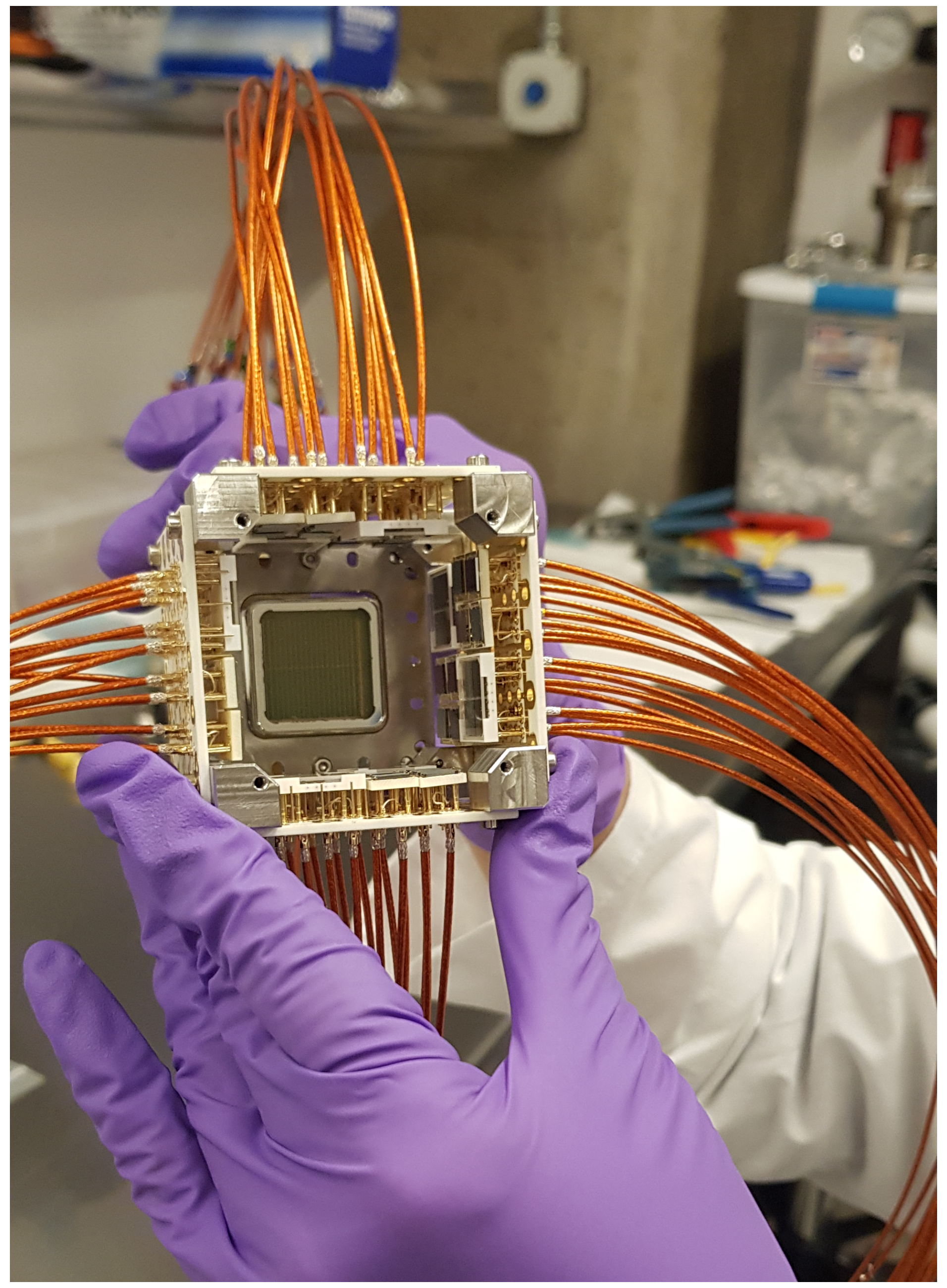
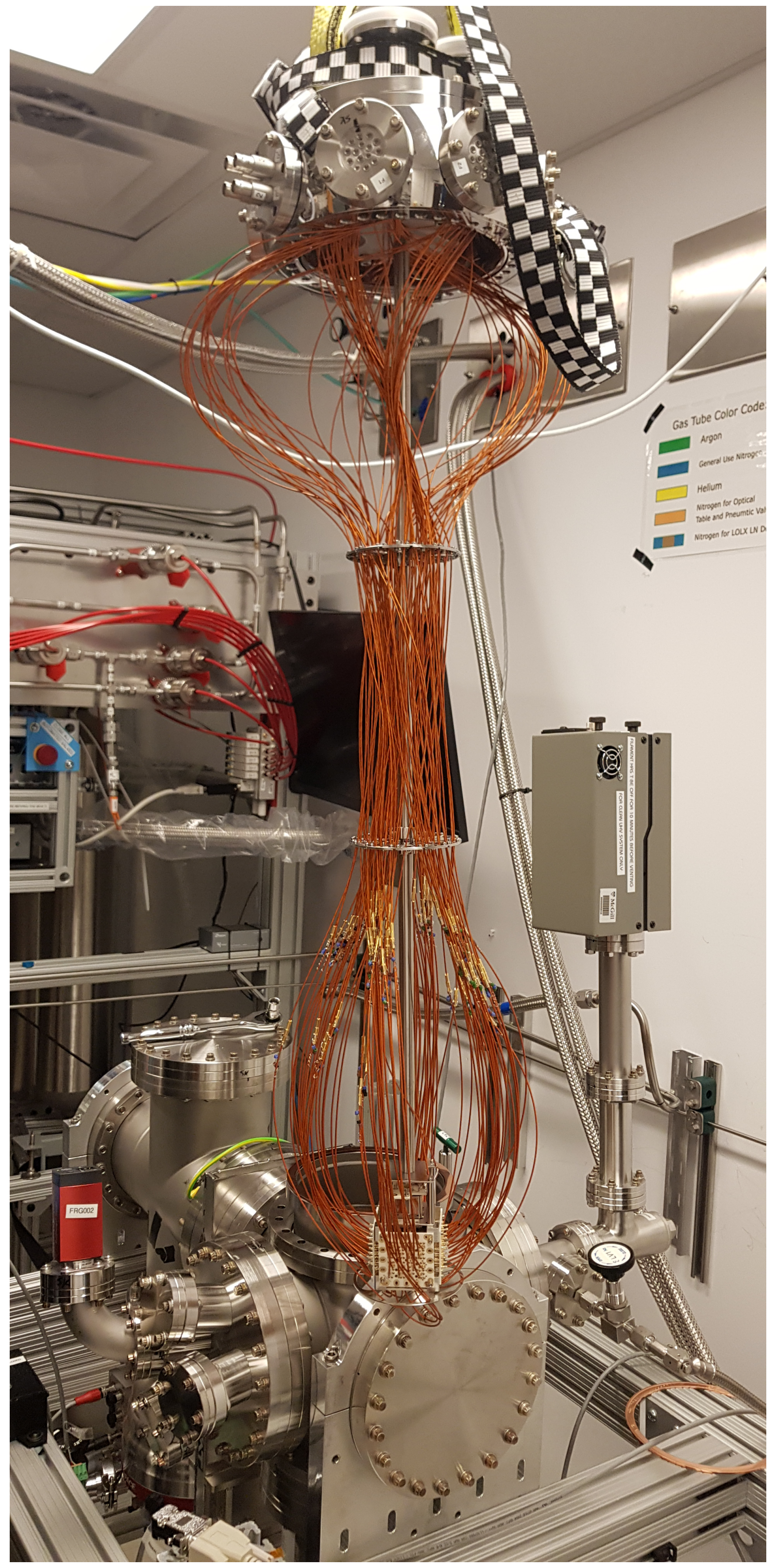
[1]Santa Cruz Institute for Particle Physics (SCIPP), [2]University of Washington, [3]Brookhaven National Laboratory, **[4]McGill University, [5]University of British Columbia [6]TRIUMF**, [7]Paul Scherrer Institute, [8]University of Kentucky, [9]Tsinghua University, [10]Argonne National Laboratory, [11]University Zurich, [12]Tecnologico de Monterrey, [13]Stony Brook University, [14]Johannes Gutenberg University, [15]University of Florida, [16]ETH Zurich, [17]Cornell University, [18]University of Virginia, [19]University of Bern, [20]Kitakyushu College, [21]University of Tokyo, [22]KEK, **[23]University of Victoria**



Error Source	PIENU 2015 %	PIONEER Estimate %
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty	**0.24**	**$\leq$ 0.01**

LXe R&D and PROTOTYPING

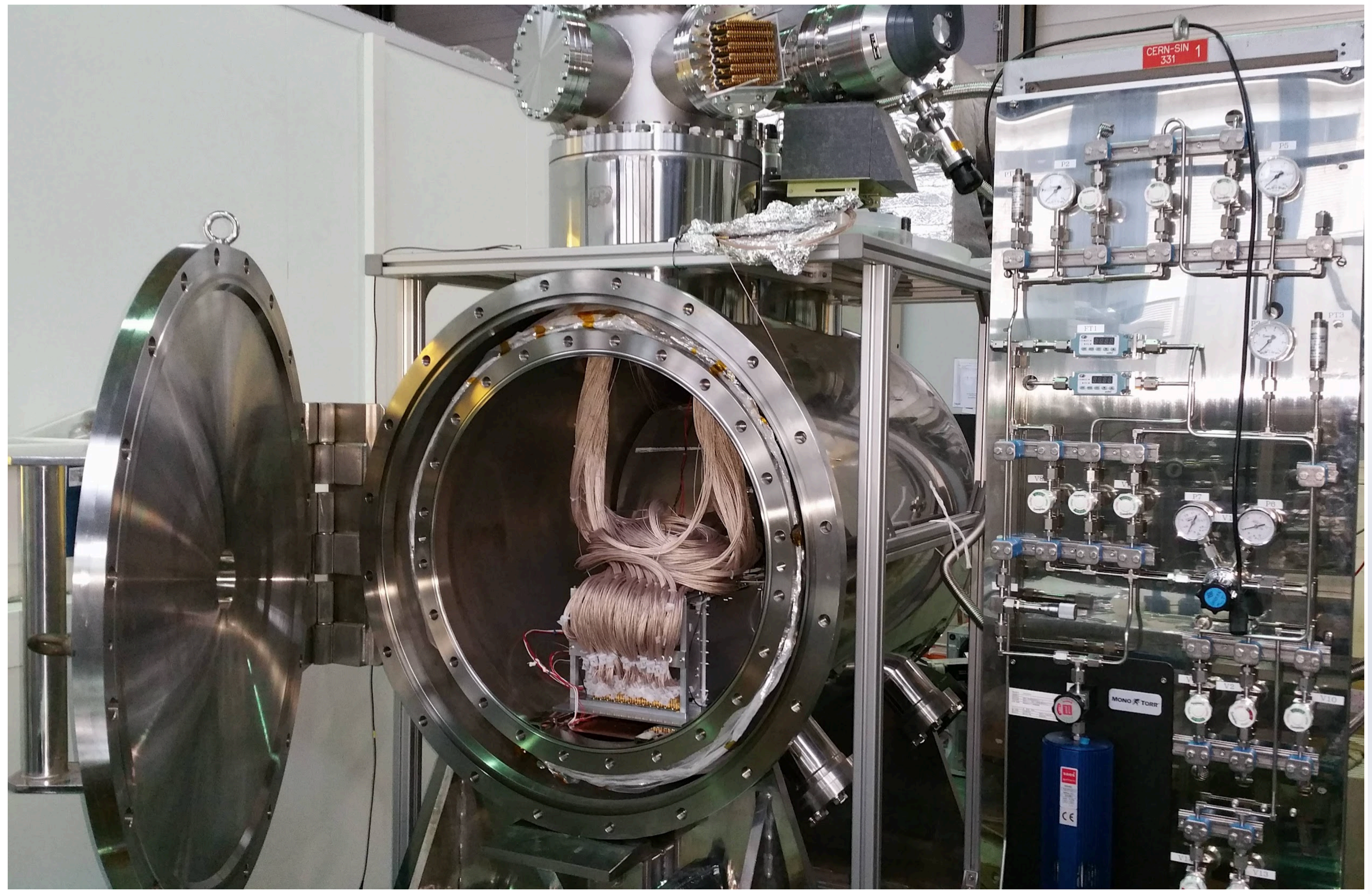


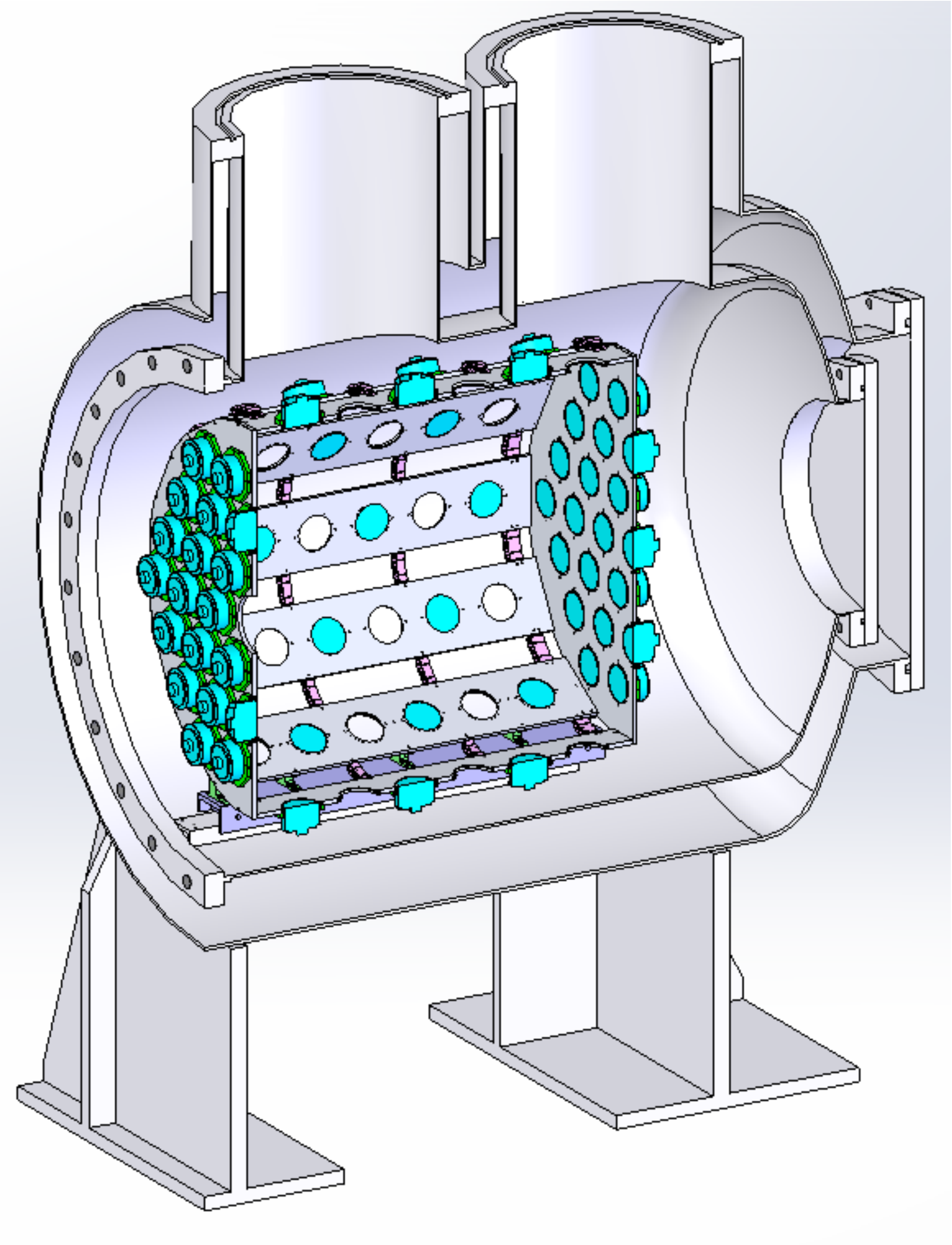


LoLX
2L cryostat at McGill

- Test and characterize photosensor technologies (PDE, response after high irradiation, stability etc)
- Benchmark simulations (G4 with and w/o NEST and optical simulations (Chroma))
- LXe scintillation properties (IR emission, Cerenkov)
- Measure energy resolution at low energies (compare to simulations)
- Data input to NEST at zero-field
- Material test (reflectivity, different coatings, WLS) etc

~100 L cryostat at PSI (former MEG large cryostat)



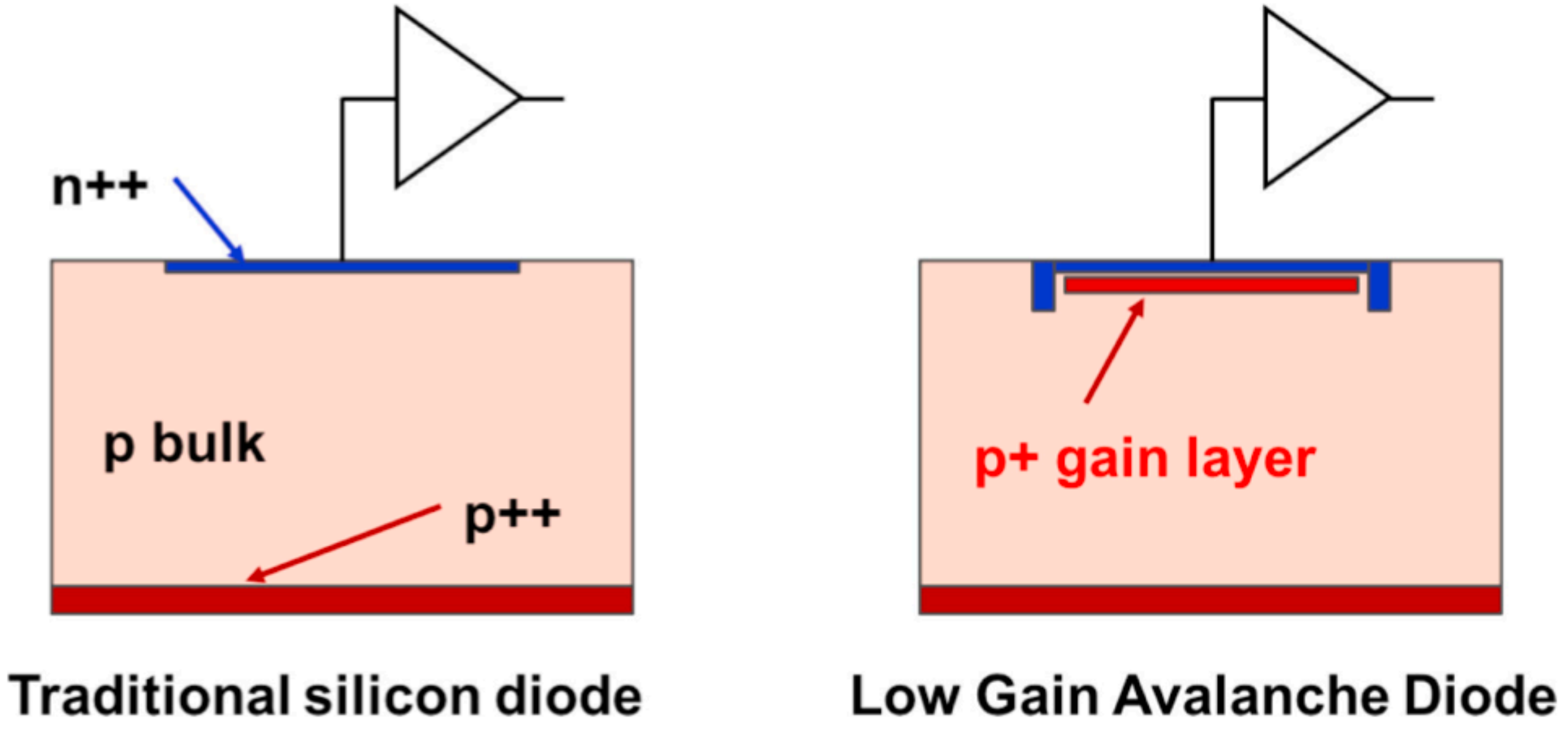


Benchmark/Validate simulations at PIONEER energy scales (0-70 MeV) to allow scaling to PIONEER final calorimeter.
- Measure detector lineshape including contribution of photonuclear reactions
- Measure energy resolution

Main question: how well can LXe handle pile-up in a high rate environment?

Active Target

Low Gain Avalanche Diodes



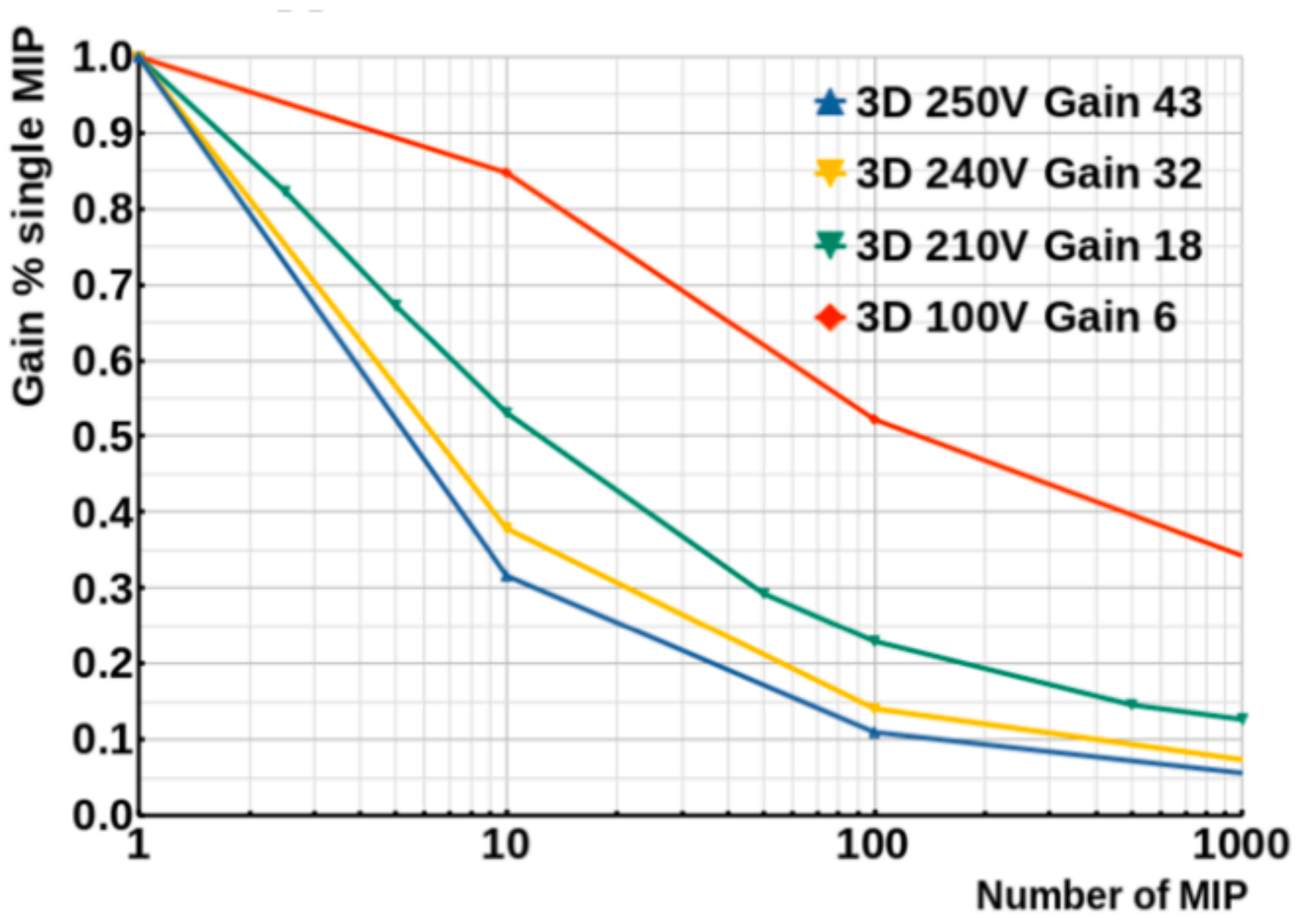
In silicon sensors, when applying a very large electric field (300 kV/cm), electrons (and holes) acquire kinetic energy and can generate additional e/h pairs by impact ionisation → 'avalanche' effect

Obtained by implanting an appropriate acceptor or donor layer when depleted, generate a very high field

The signal amplification allows for thin sensors and very high timing resolution
The gain mechanism saturates for large energy deposit

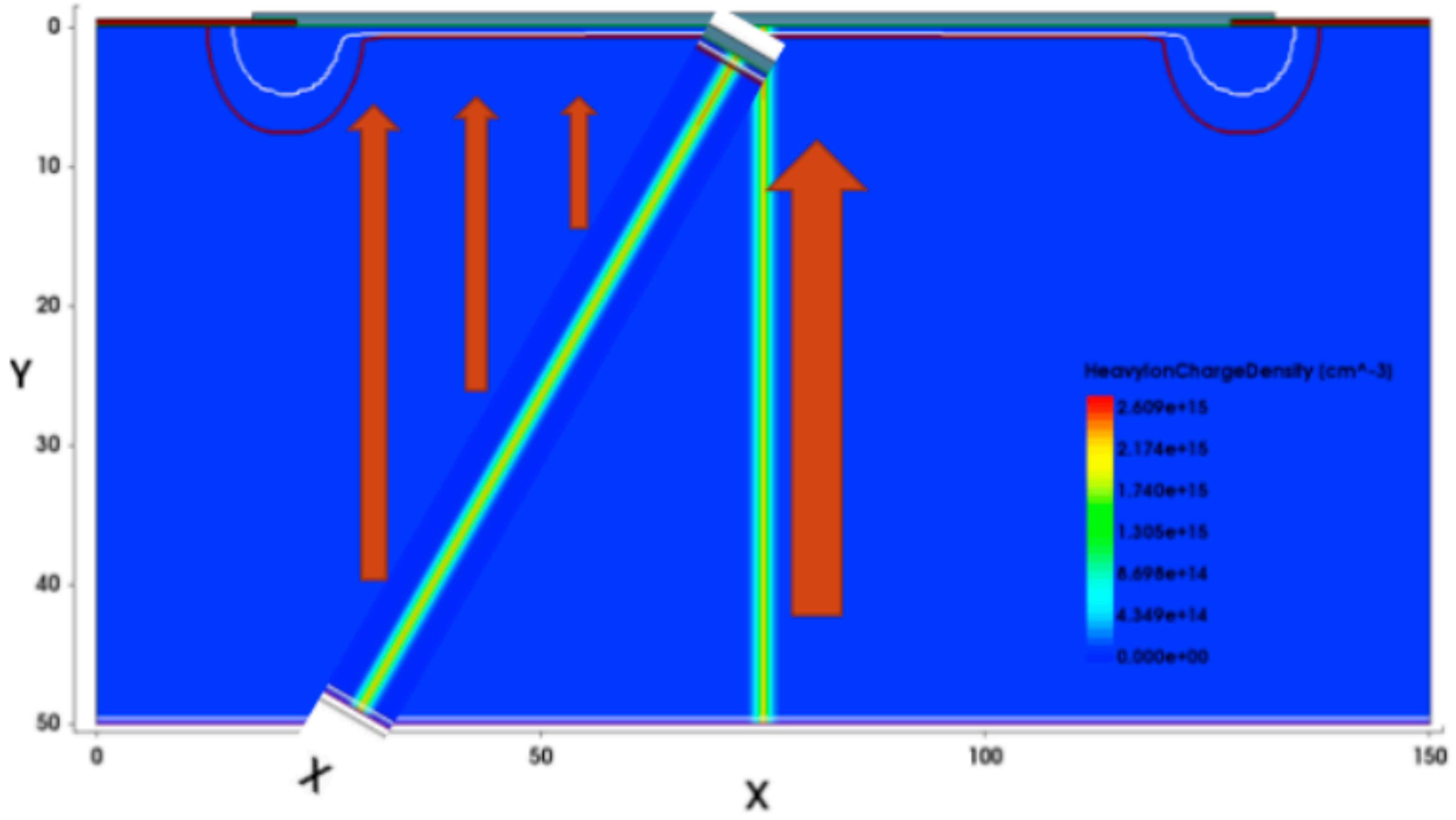
Active Target

Low Gain Avalanche Diodes



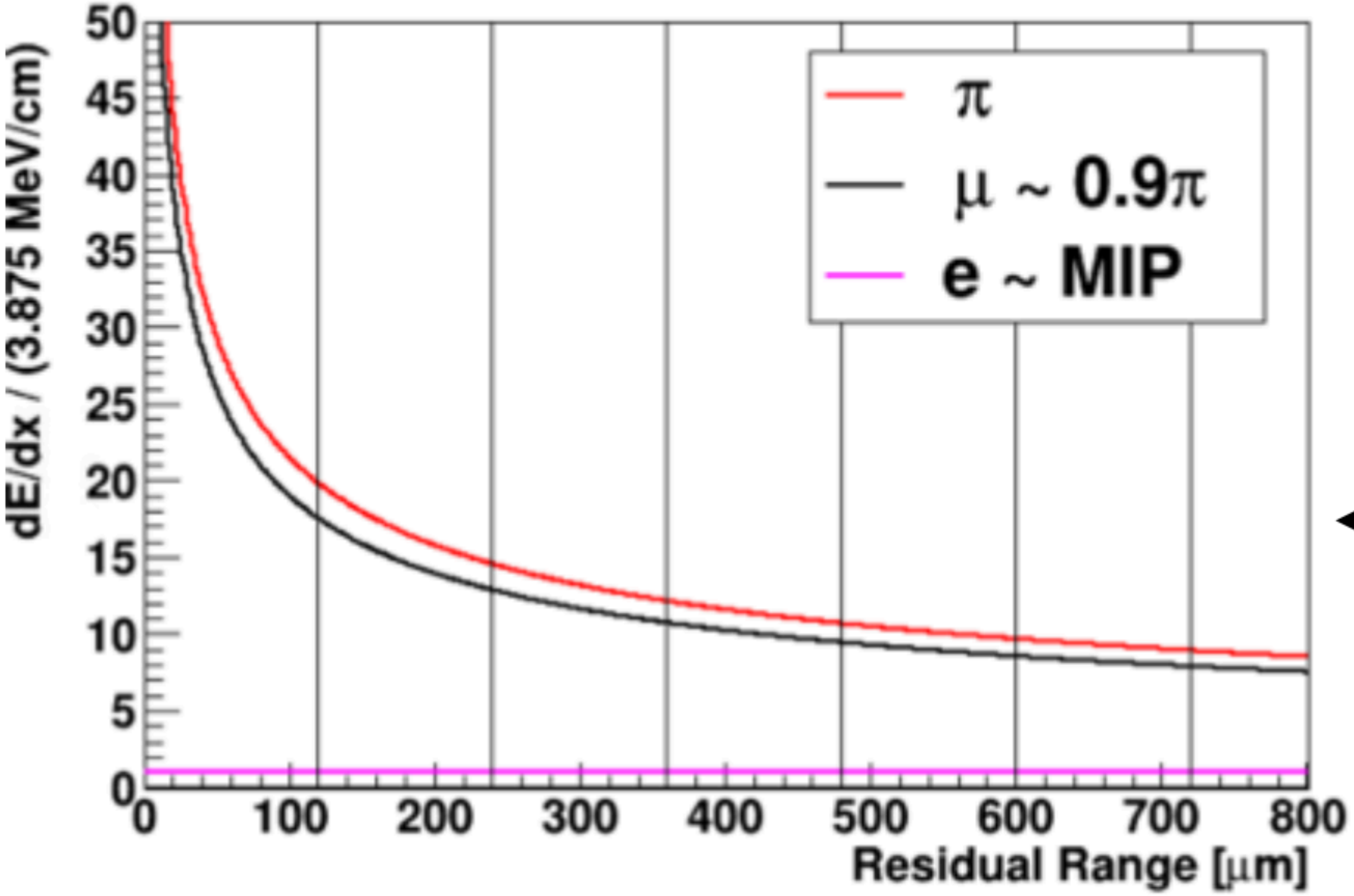
TCAD Simulations:

- Large gain suppression effect with high input charge density
- Gain suppression reduced if input charges are spread more evenly
- Gain of LGAD produced by impact ionization in high field region of gain layer
  - Very sensitive to electric field magnitude



Critical for PIONEER's feasibility to understand the MeV-scale response of LGADs

Performing our own tests



A Particle enters ATAR here

We can learn a lot about a particle travel through material from measuring its energy!

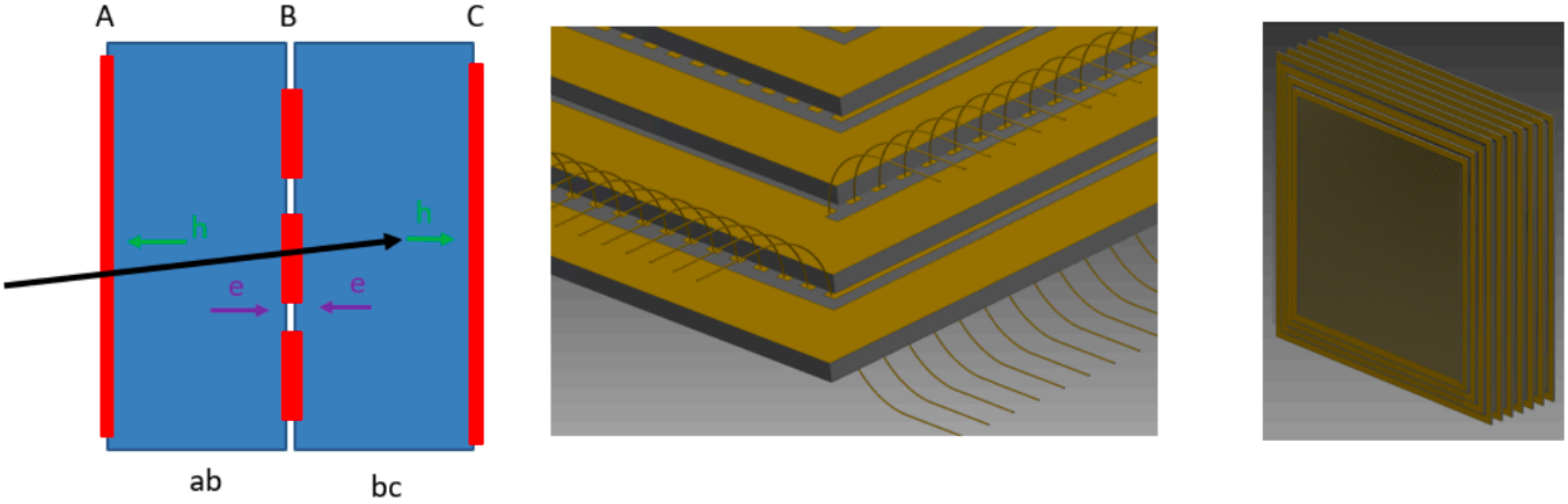


FIG. 9: (Left) illustration of the shared readout scheme, the strip readout in plane B will see induced current for ionization charge in both "ab" and "bc" Silicon layers. The ionization charge in "ab" ("bc") can also be seen in strip readout in plane A (C). (Middle) Pyramidal geometry with shared readout scheme. This scheme considers the i) wire bonding for readout and ii) guard rings that is needed to separate the high voltage between the anode and cathode planes. (Right) Illustration of ATAR with multiple units.