PIONEER - a next generation pion decay experiment

Thomas Brunner
McGill University

non official logo!

Slides courtesy to Chloé Malbrunot at TRIUMF

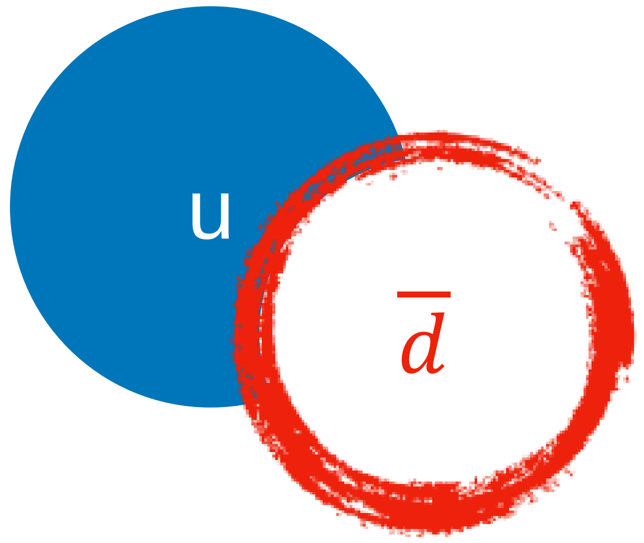
W. Altmannshofer, O. Beesley, H. Binney, E. Blucher, T. Brunner , D. Bryman*, L. Caminada, S. Chen, V. Cirigliano, S. Corrodi, A. Crivellin, S. Cuen-Rochin, A. DiCanto, L. Doria, A. Gaponenko, A. Garcia, L. Gibbons, C. Glaser, M. Escobar Godoy, D. Göldi, S. Gori, T. Gorringe, D. Hertzog*, Z. Hodge, M. Hoferichter, S. Ito, T. Iwamoto, P. Kammel, B. Kiburg, K. Labe, J. LaBounty, U. Langenegger, C. Malbrunot, S.M. Mazza, S. Mihara, R. Mischke, A. Molnar, T. Mori, J. Mott, T. Numao, W. Ootani, J. Ott, K. Pachal, C. Polly, D. Počanić, X. Qian, D. Ries, R. Roehnelt, B. Schumm, P. Schwendimann, A. Seiden, A. Sher, R. Shrock, A. Soter, T. Sullivan, M. Tarka, V. Tischenko, A. Tricoli, B. Velghe, V. Wong, E. Worcester, M. Worcester, C. Zhang

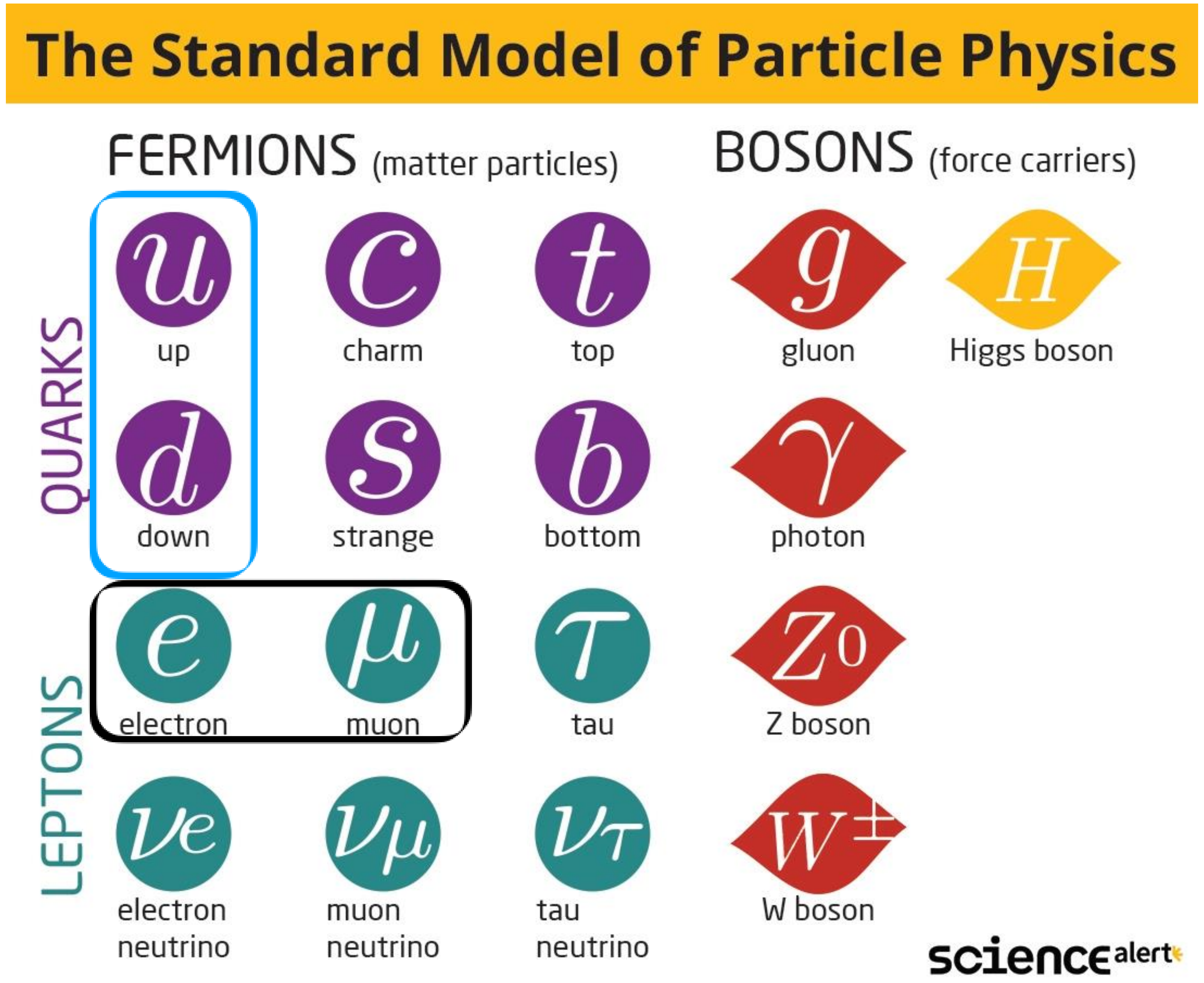
(*: co-spokespersons)

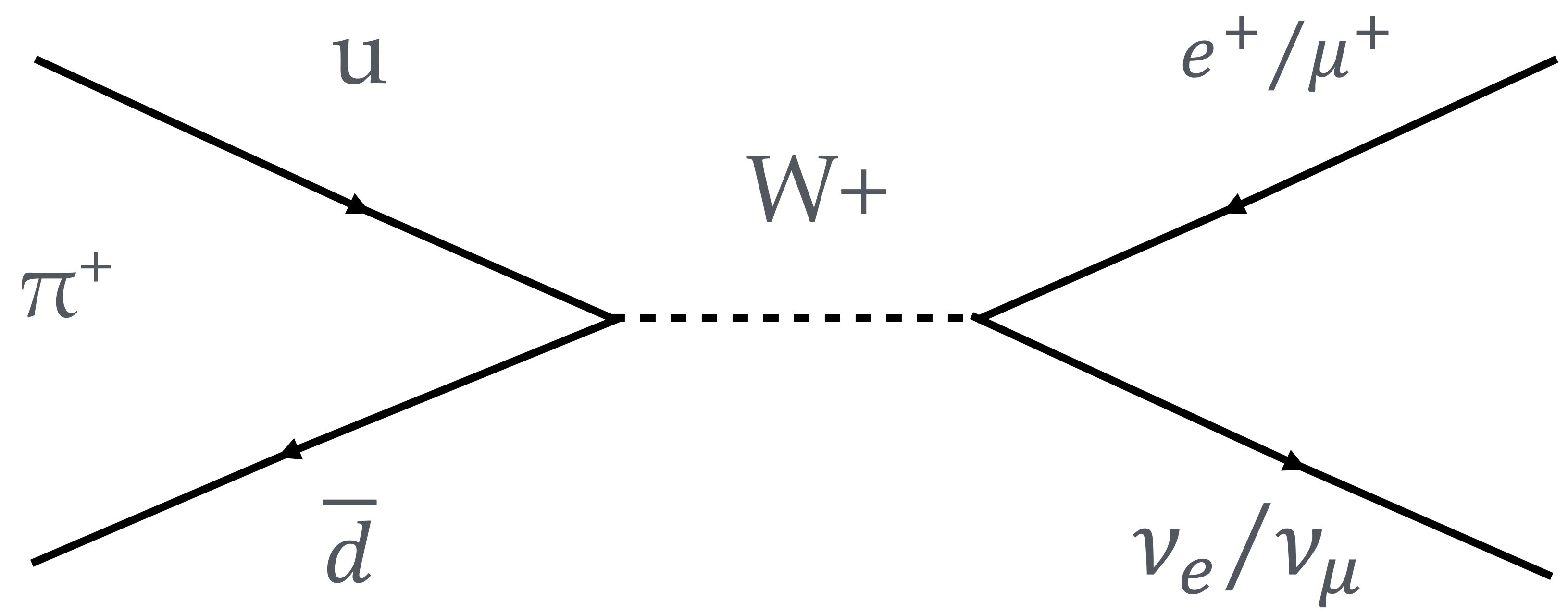
University of California Santa Cruz, University of Washington, University of Chicago, Mc Gill University, University of British Columbia, TRIUMF, Paul Scherrer Institute, Tsinghua University, Institute for Nucl. Theory, University of Washington, Argonne National Laboratory, University of Zurich, CERN, Tec de Monterrey, Brookhaven National Laboratory, University of Mainz, Fermilab, Cornell University, University of Virginia, ETH Zurich, University of Kentucky, University of Bern, KEK, University of Tokyo, Stony Brook University, University of Victoria, Inst. Div, BNL

A very short introduction to pions

pion: π^+







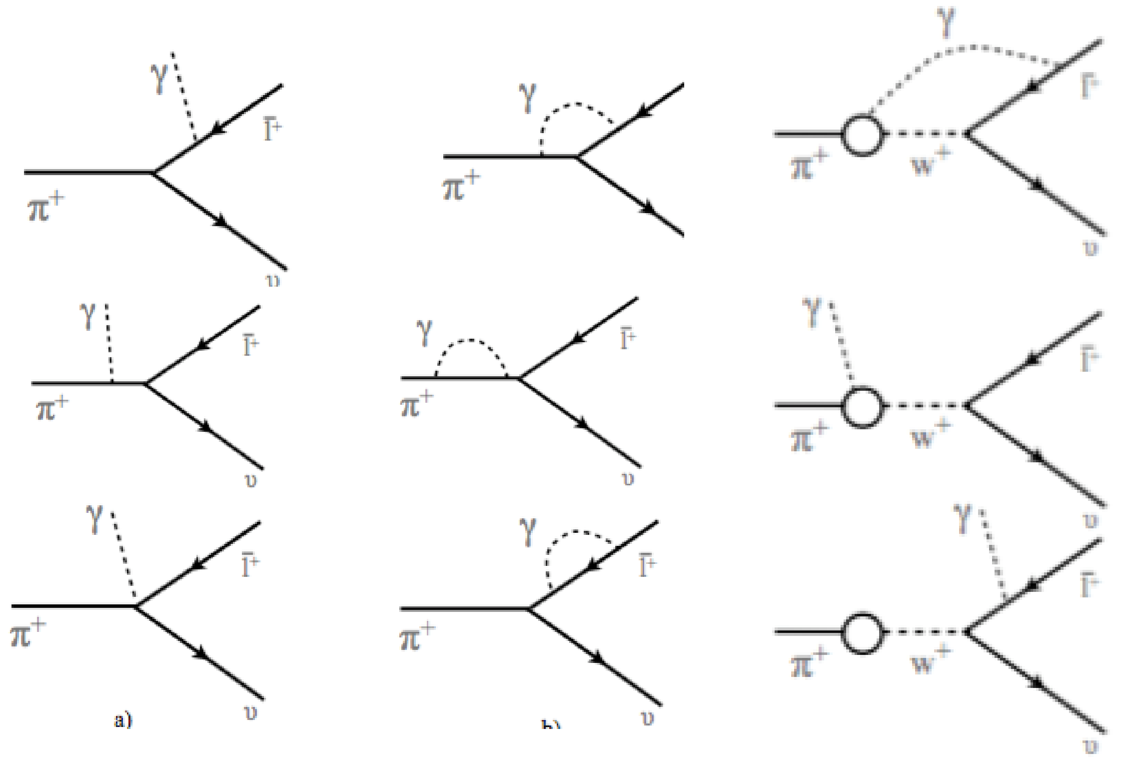
$$R^{\pi} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$

$$R^{\pi} = R_0^{\pi} \times \left[1 + \frac{\alpha}{\pi}\left\{F\left(\frac{m_e}{m_\pi}\right) - F\left(\frac{m_\mu}{m_\pi}\right) + \frac{m_\mu^2}{m_\rho^2}\left(c_2 \ln \frac{m_\rho^2}{m_\mu^2} + c_3\right) + c_4 \frac{m_\pi^6}{m_e^2 m_\rho^4}\right\} + c_5\left(\frac{\alpha}{\pi} \ln \frac{m_\mu}{m_e}\right)^2 + \ldots\right]$$

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

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

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

x 15

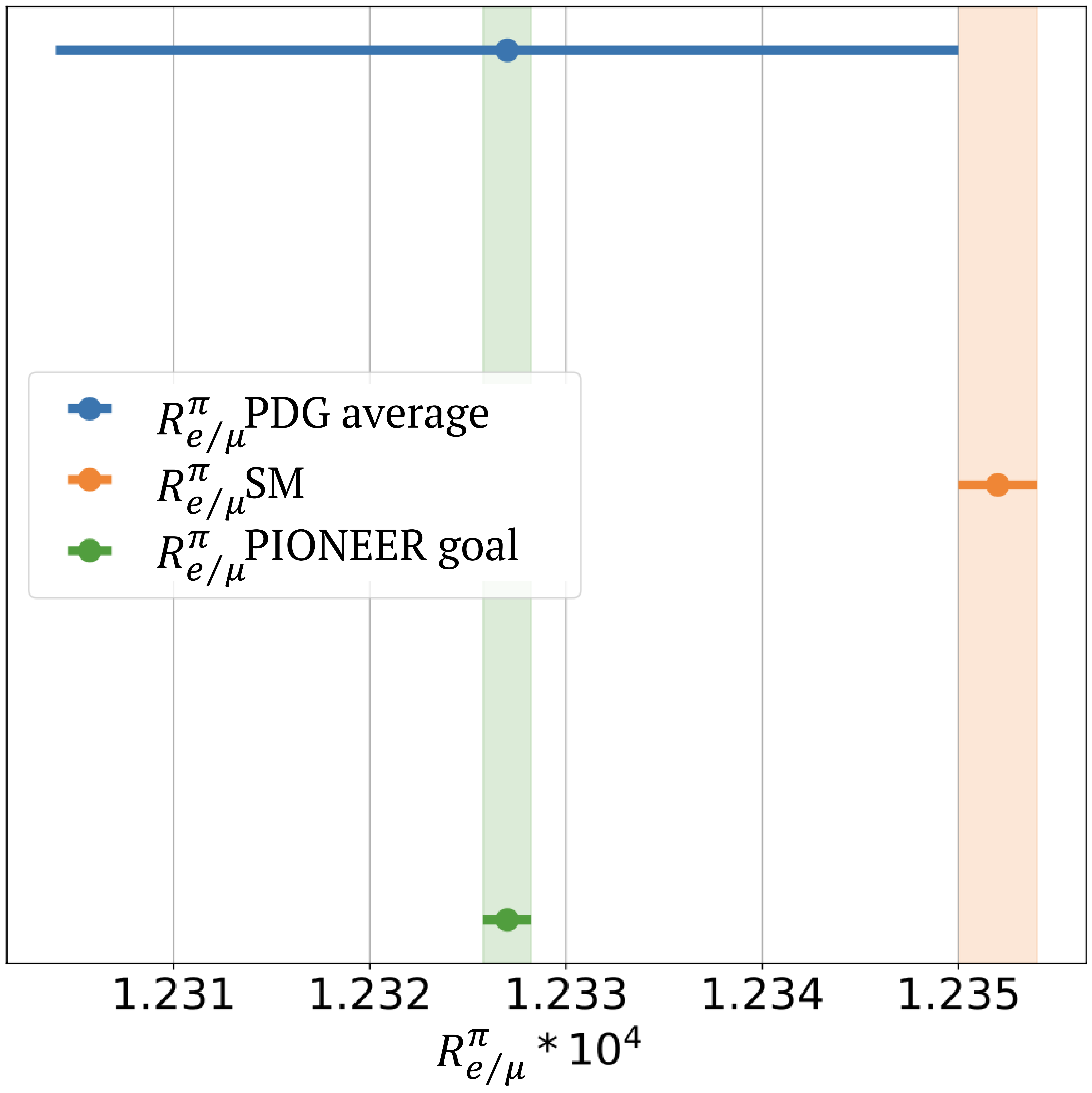
Precision low energy experiment on observables that can be very accurately calculated in the SM: highly sensitive tests of NP.

PIONEER: closing the precision gap

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

Final PIENU data analysis with full data set targeting **0.1% precision**

PEN experiment at PSI aiming at similar precision

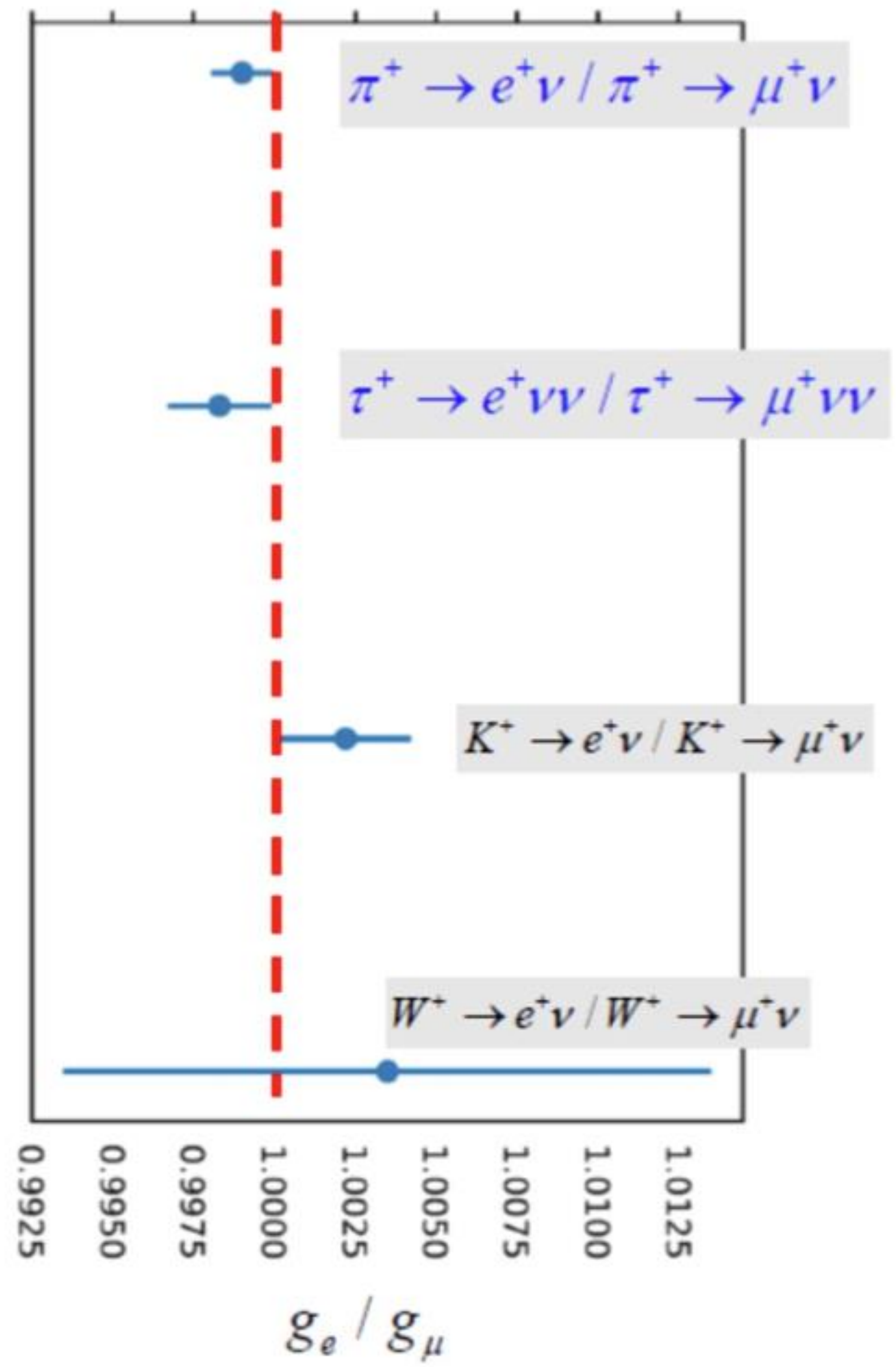


Physics case 1: Testing Lepton Flavor Universality

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

$$R^{\pi} = \frac{\pi^+ \to e^+\nu(\gamma)}{\pi^+ \to \mu^+\nu(\gamma)}$$ provides the best test of universality in charged current weak interaction

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



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

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

BUT

Several tensions in the flavour sector, potentially hinting toward LFU violation (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?

Physics case 2: Sensitivity to new coupling and NP at very high mass scales

$\Longrightarrow$ possible interpretation of universality violation

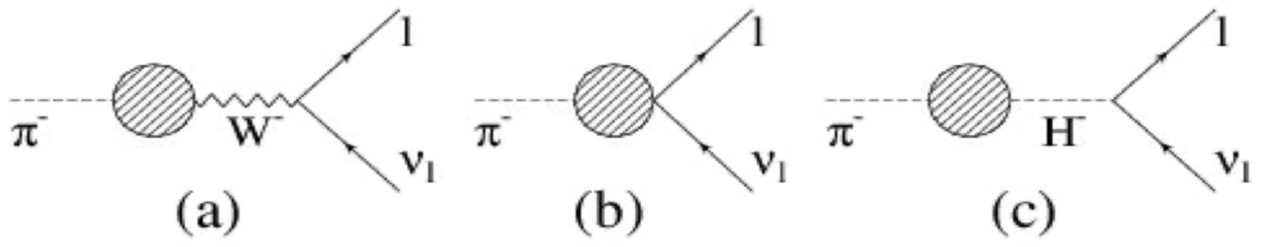
$$R^{\pi}_{SM} = \frac{\pi^+ \to e^+\nu(\gamma)}{\pi^+ \to \mu^+\nu(\gamma)}$$

calculated at the 0.01% level

$\pi^+ \to e^+\nu$ 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 $\rightarrow \Lambda_{eP} \sim 3000$ TeV

Physics case 2: Sensitivity to new coupling and NP at very high mass scales

- Sensitive to many other new physics scenarios
  - Leptoquarks
  - Induced scalar currents
  - Excited gauge bosons
  - Compositeness
  - SU(2)xSU(2)xSU(2)xU(1)
  - Hidden sector ….

- Many exotic searches performed by the PIENU collaboration :
  e.g. sterile neutrinos
  which have implications for leptogenesis

ELSEVIER
Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Search for heavy neutrinos in $\pi \to \mu\nu$ decay

PHYSICAL REVIEW D **97,** 072012 (2018)

Editors' Suggestion

Improved search for heavy neutrinos in the decay $\pi \to e\nu$

PHYSICAL REVIEW D **102,** 012001 (2020)

Search for the rare decays $\pi^+ \to \mu^+\nu_\mu\nu\bar{\nu}$ and $\pi^+ \to e^+\nu_e\nu\bar{\nu}$

PHYSICAL REVIEW D **101,** 052014 (2020)

Improved search for two body muon decay $\mu^+ \to e^+X_H$

PHYSICAL REVIEW D **103,** 052006 (2021)

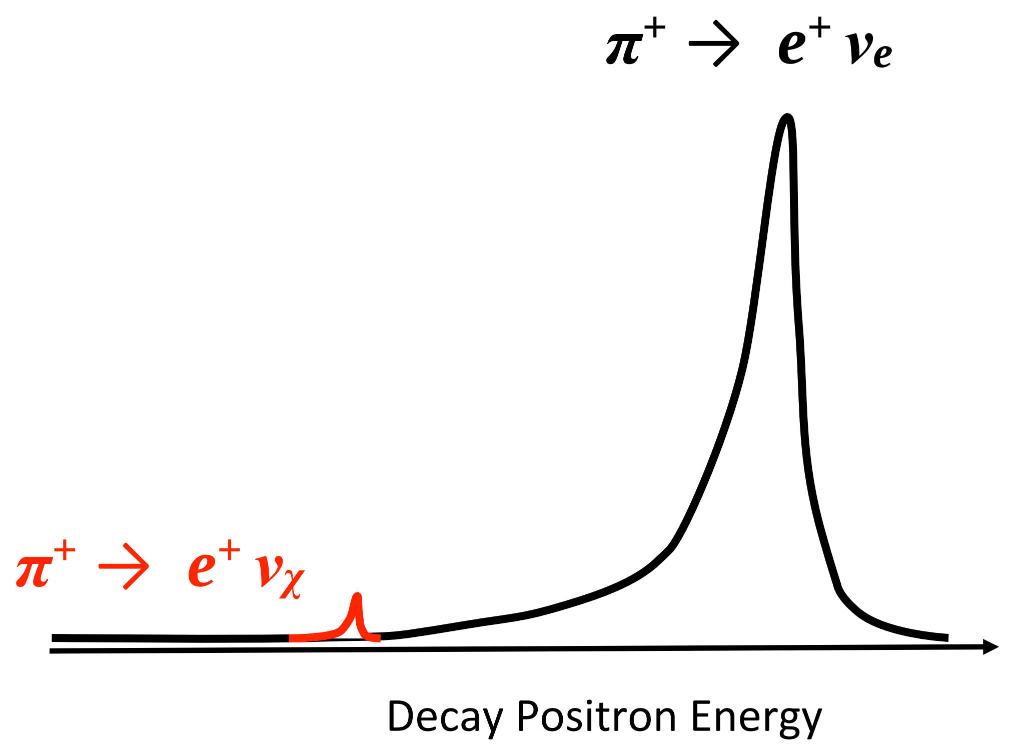
Search for three body pion decays $\pi^+ \to l^+\nu X$

recent searches performed by the **PIENU** collaboration

⇓

PIONEER will improve on all those searches by ~1 order of magnitude

Physics case 3: Sensitivity to NP at "lower" mass scales



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

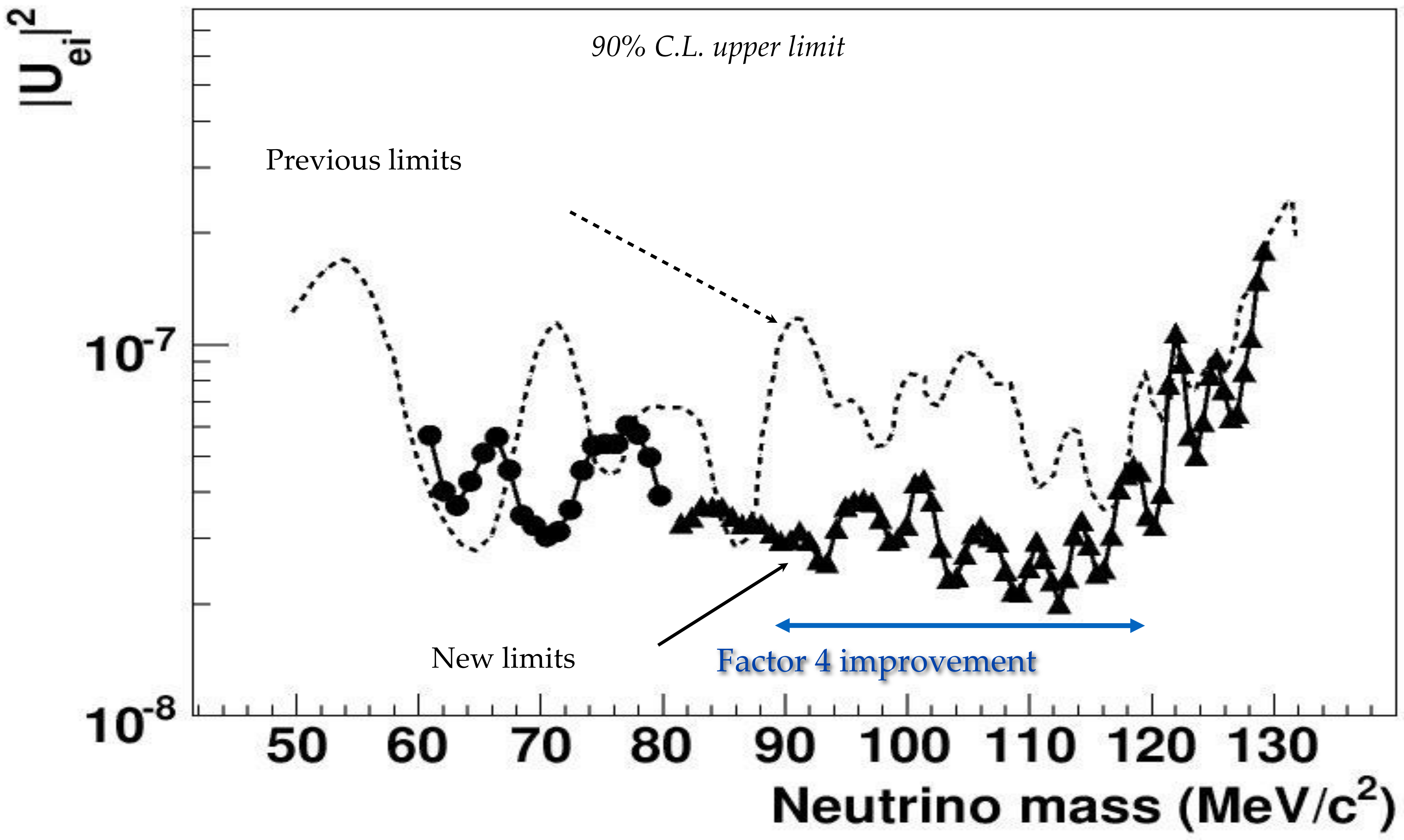
R.E Shrock Phys.Rev.D 24, 1232 (1981),
Phys. Lett. B 96, 159 (1980)

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

Heavy υ — Conventional υ — Kinematic factor

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

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



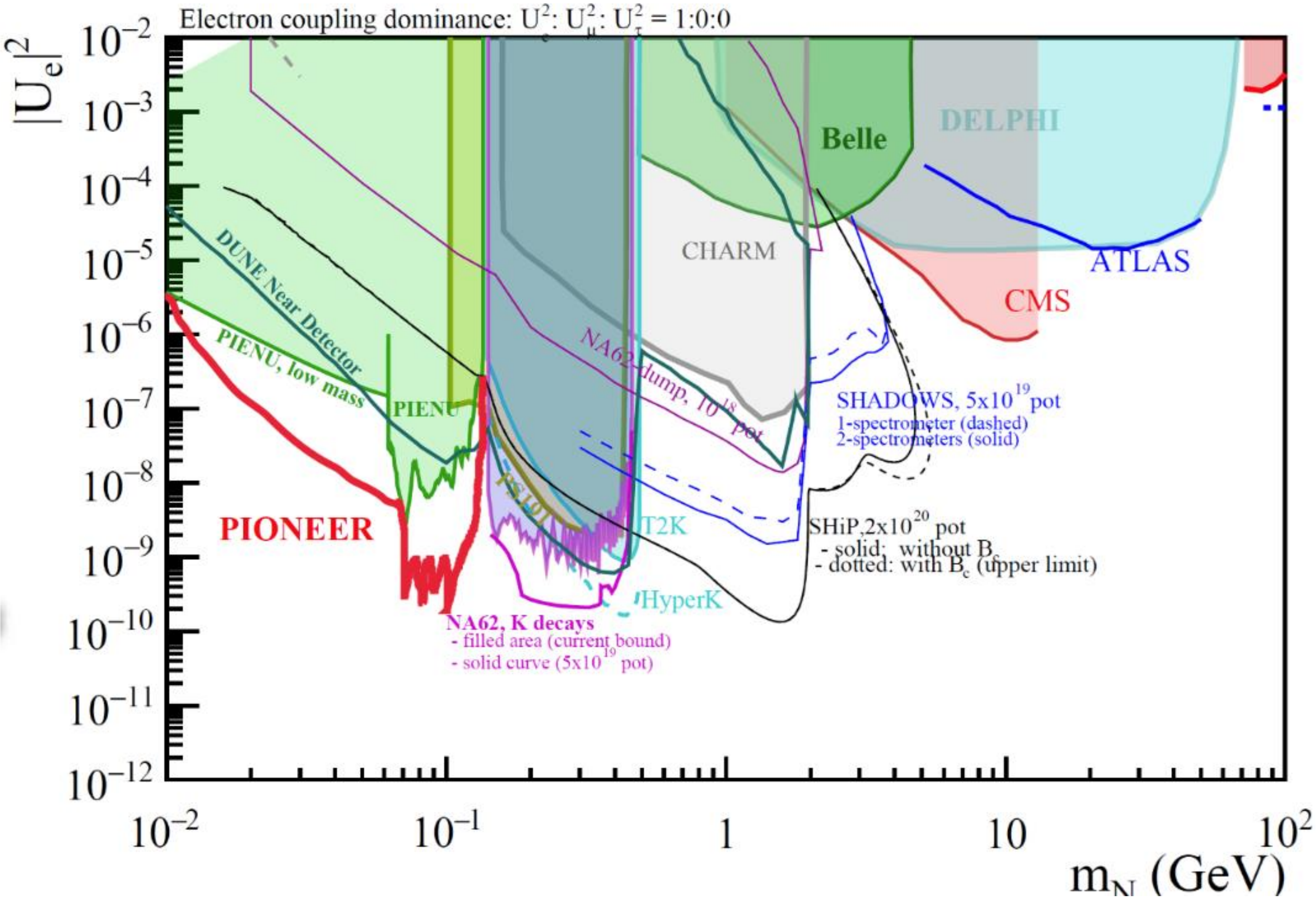
M.Aoki et al., Phys. Rev. D 84, 052002 (2011)

More recent and stronger bounds provided by PIENU :
PRD 97.072012 (2018)
PLB 798 (2019) 134980 [in $\pi \to \mu\nu$ decay]

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

PIONEER expected to have an order of magnitude improved sensitivity

Limits on couplings of heavy neutrinos to electrons



Asli M. Abdullahi et al. "The Present and Future Status of Heavy Neutral Leptons". *2022 Snowmass Summer Study*. Mar. 2022. arXiv: 2203.08039 [hep-ph]

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

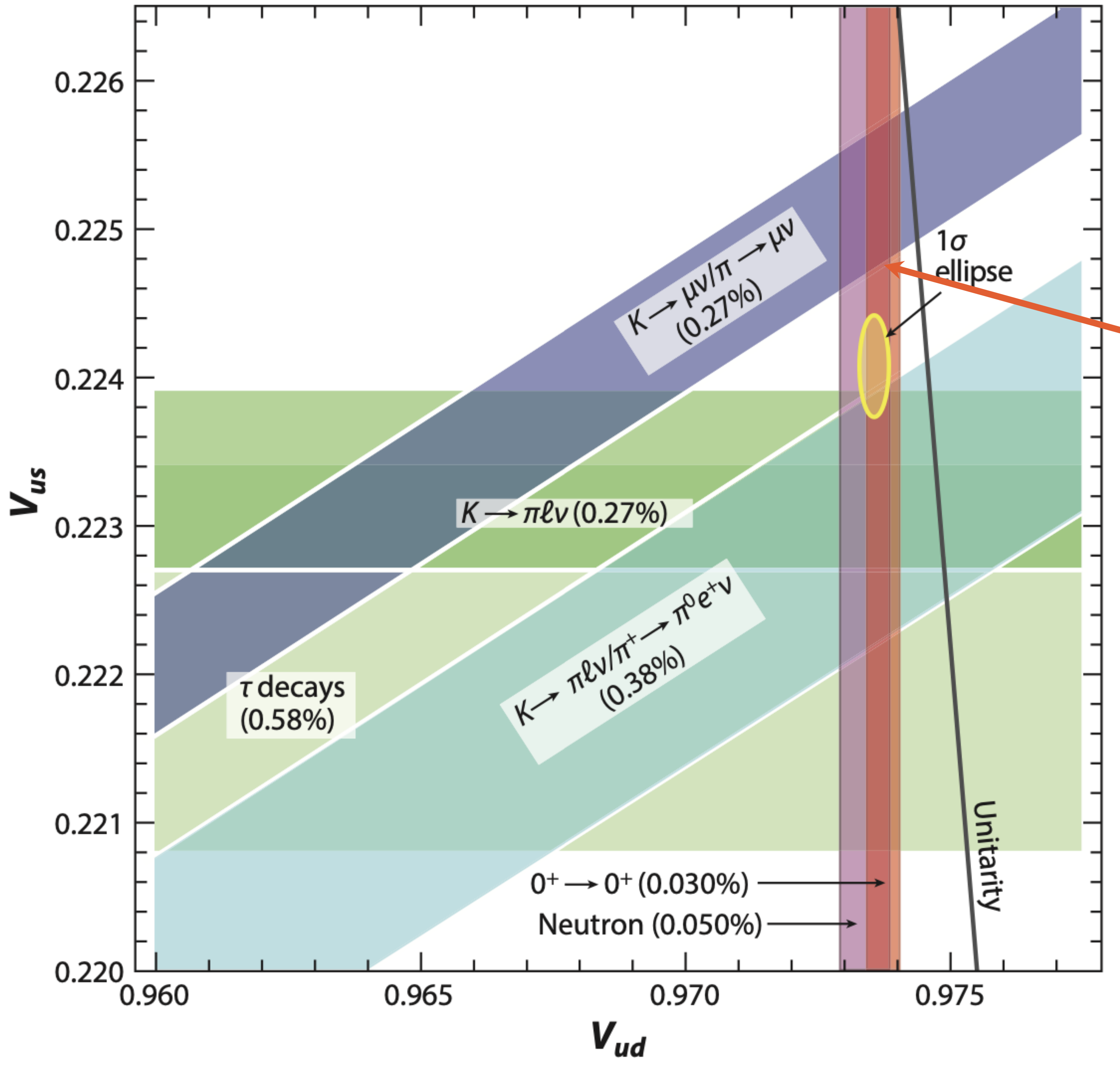
K/π decays

super-allowed β decays, neutron

$\frac{B(K\rightarrow\pi l\nu)}{B(\pi^{+}\rightarrow\pi^{0}e^{+}\nu)}$: Theoretically clean method to obtain $\frac{V_{us}}{V_{ud}}$

Phys.Rev.D 101 (2020) 9, 091301

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



dominant uncertainties : hadronic and nuclear corrections

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

PIONEER Phase II goal:

Improve $B(\pi^{+}\rightarrow\pi^{0}e^{+}\nu)$ precision by >3 → $\frac{V_{us}}{V_{ud}} < \pm0.2\%$

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

PIONEER Phase III goal:

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

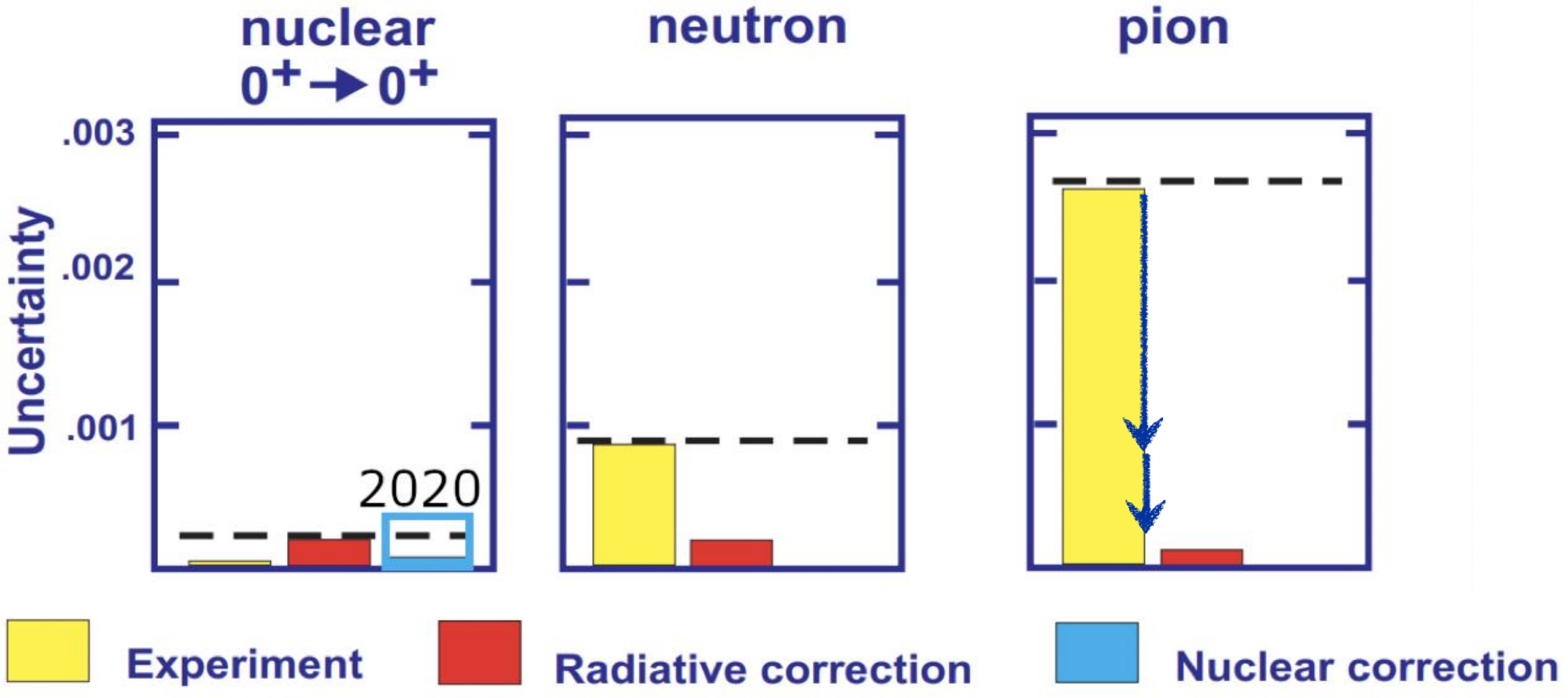
$\pi^{+}\rightarrow\pi^{0}e^{+}\nu$ is the theoretically cleanest method to obtain V_{ud}

PIBETA exp. ($\pm0.6\%$)

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

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

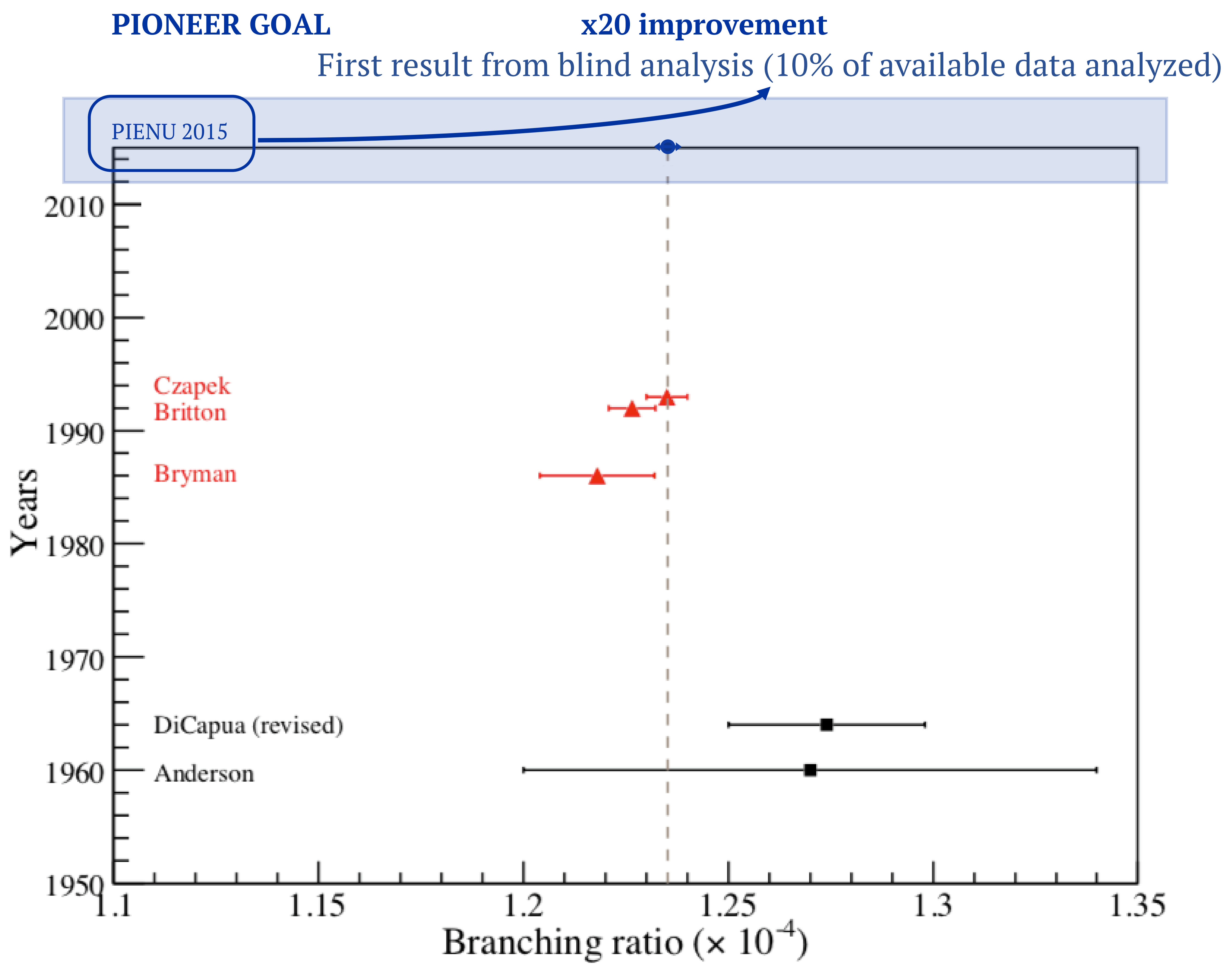
Physics case 4: Testing CKM unitarity V_{ud}



Courtesy of Leendert Hayen, talk at ELECTRO2022

Previous R^{π} experiments

- PIENU at TRIUMF (M13)
- PEN at PSI (same precision goal: different setup)
- several previous pion decay measurements



PDG 2018 ±0.19%

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1.2327±0.0023 OUR AVERAGE						
1.2344±0.0023±0.0019	400k	AGUILAR-AR...	15	CNTR	+	Stopping π^+
1.2346±0.0035±0.0036	120k	CZAPEK	93	CALO		Stopping π^+
1.2265±0.0034±0.0044	190k	BRITTON	92	CNTR		Stopping π^+
1.218 ±0.014	32k	BRYMAN	86	CNTR		Stopping π^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.273 ±0.028	11k	[1] DICAPUA	64	CNTR		
1.21 ±0.07		ANDERSON	60	SPEC		

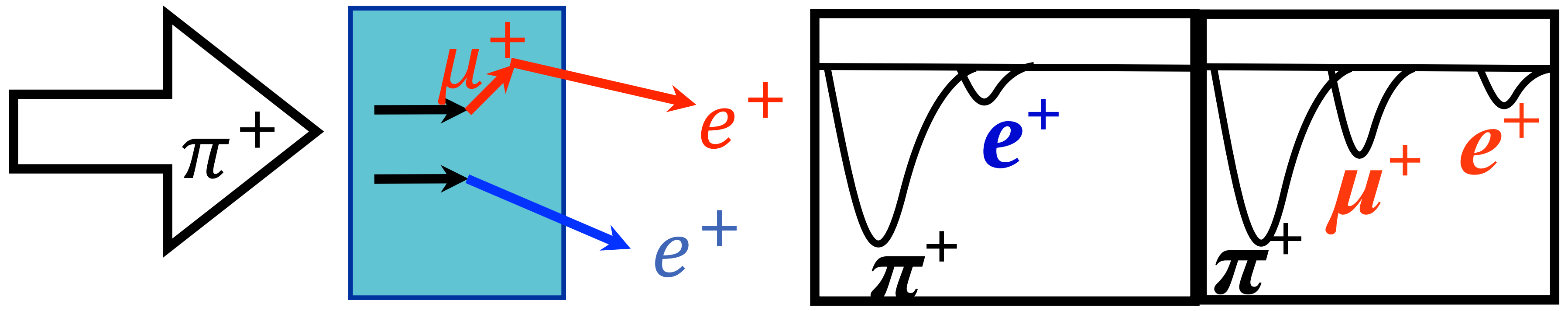
[1] DICAPUA 64 has been updated using the current mean life.

Final goal of PIENU (using full data set) and of PEN: 0.1% (factor ~2 over current precision)

PIONEER goal: 0.01% uncertainty

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

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

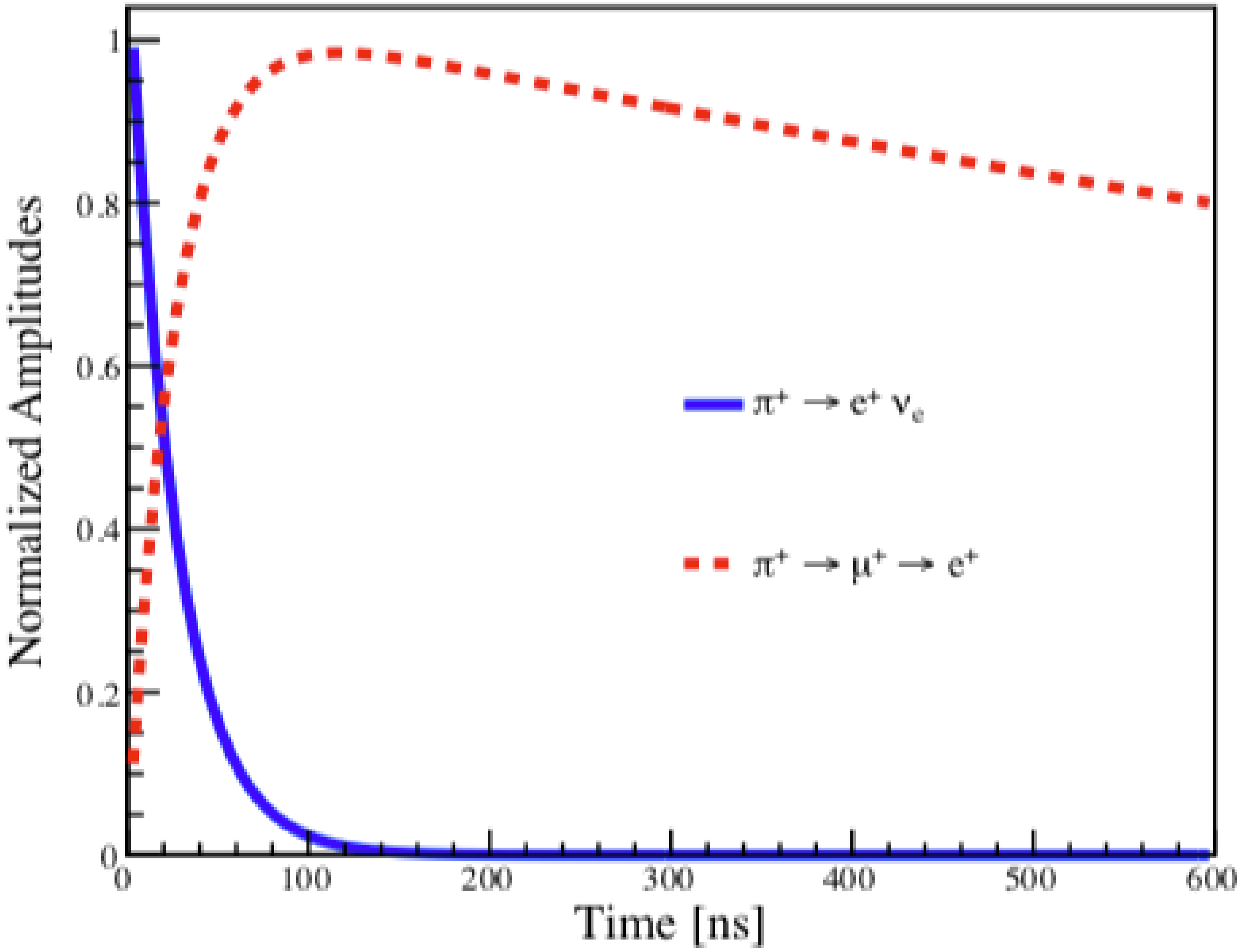


What π decay to "normally": $B(\pi^+ \to \mu^+\nu(\gamma)) = 0.999877 \pm 0.0000004$
Helicity suppressed decay: $B(\pi^+ \to e^+\nu_e(\gamma)) = (1.2327 \pm 0.00023) \times 10^{-4}$
Pion β decay: $B(\pi^+ \to e^+\nu_e\pi^0) = (1.036 \pm 0.006) \times 10^{-8}$

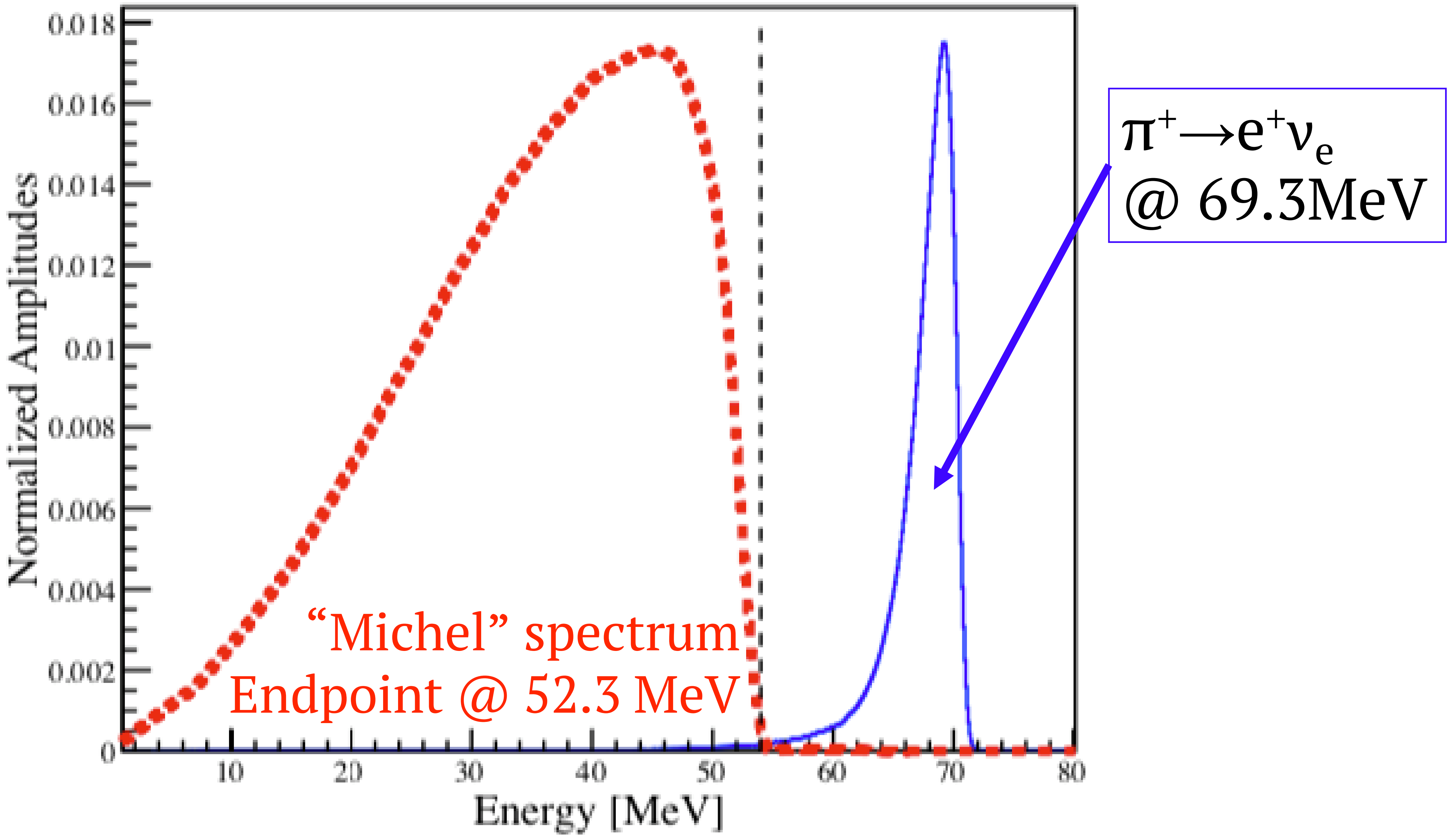
Reminders:
Pion lifetime: 26 ns
Muon lifetime: 2197 ns

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



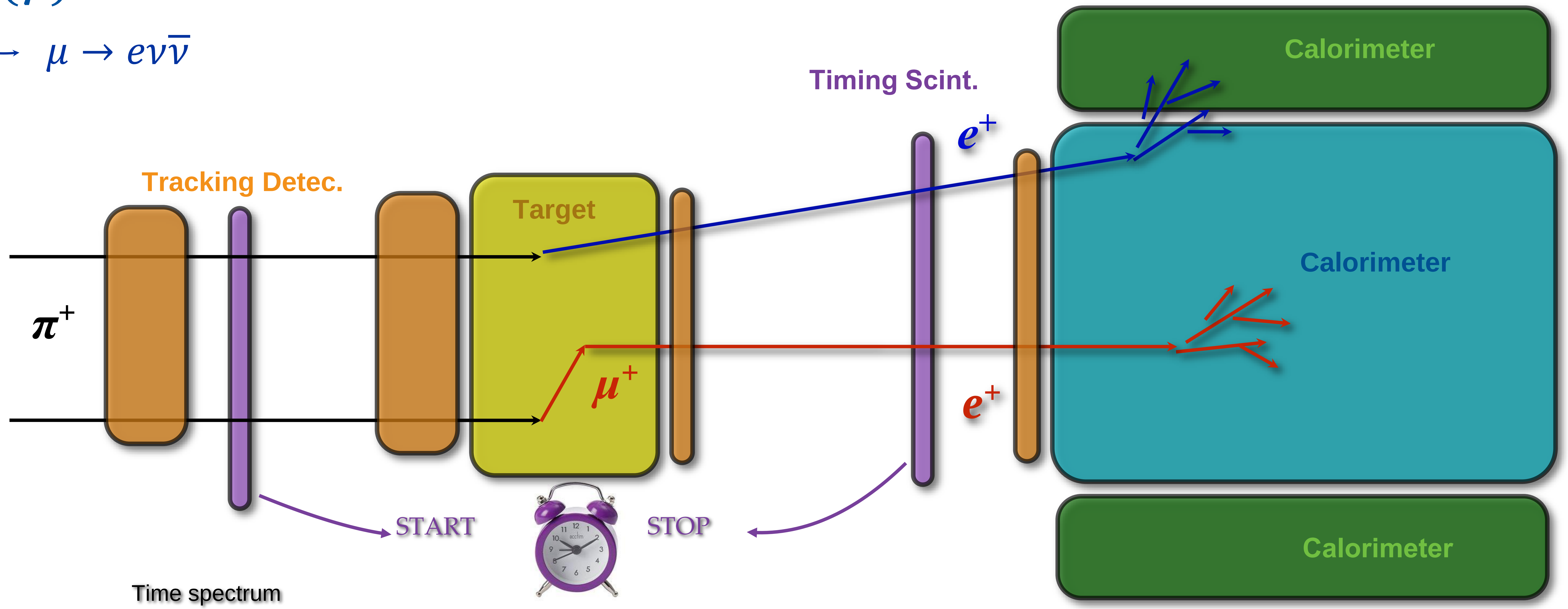
Time spectrum



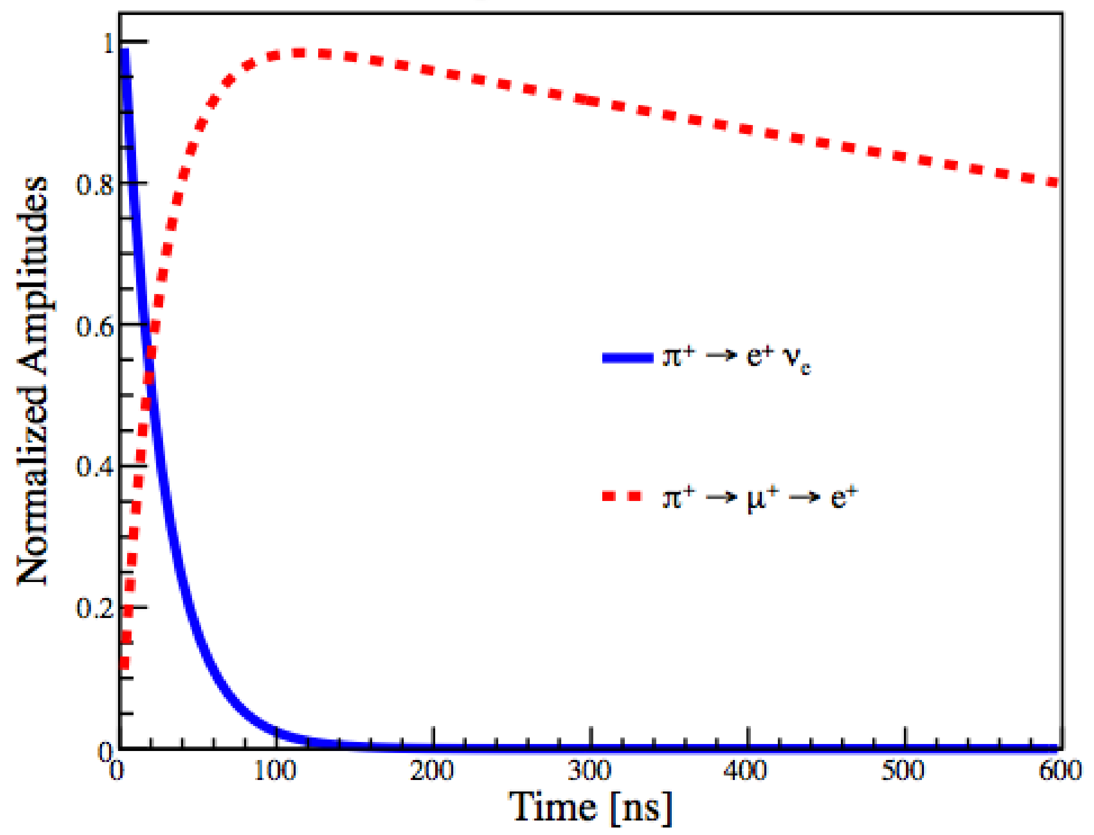
e^+ energy spectrum

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

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



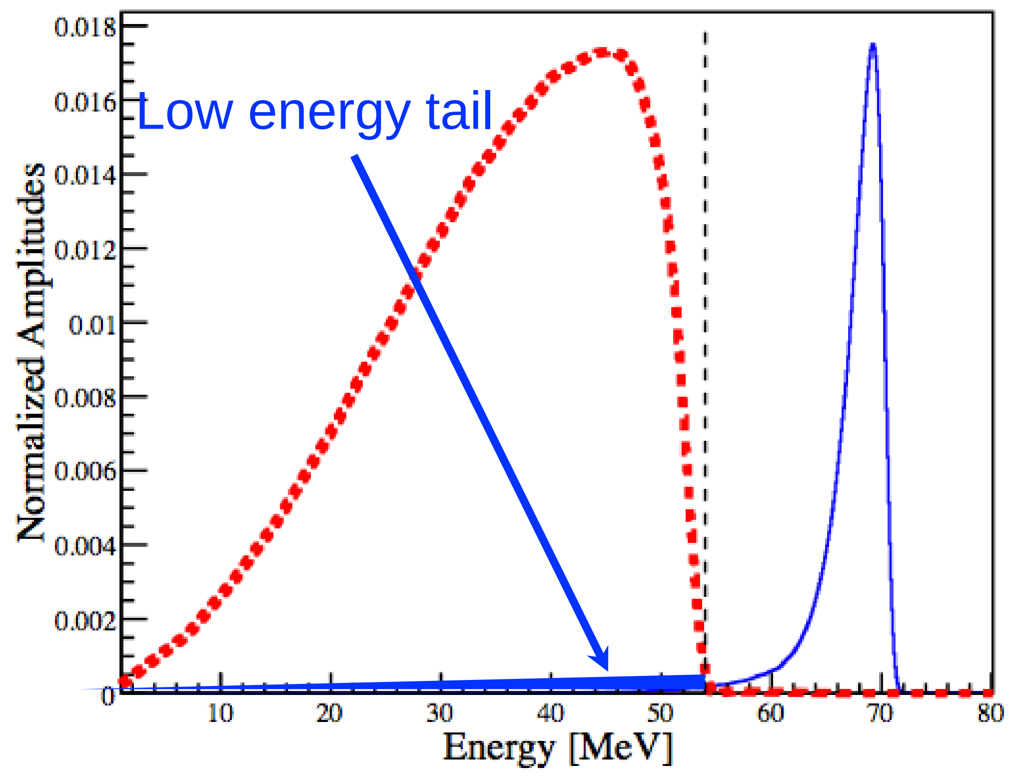
Time spectrum



Characteristics

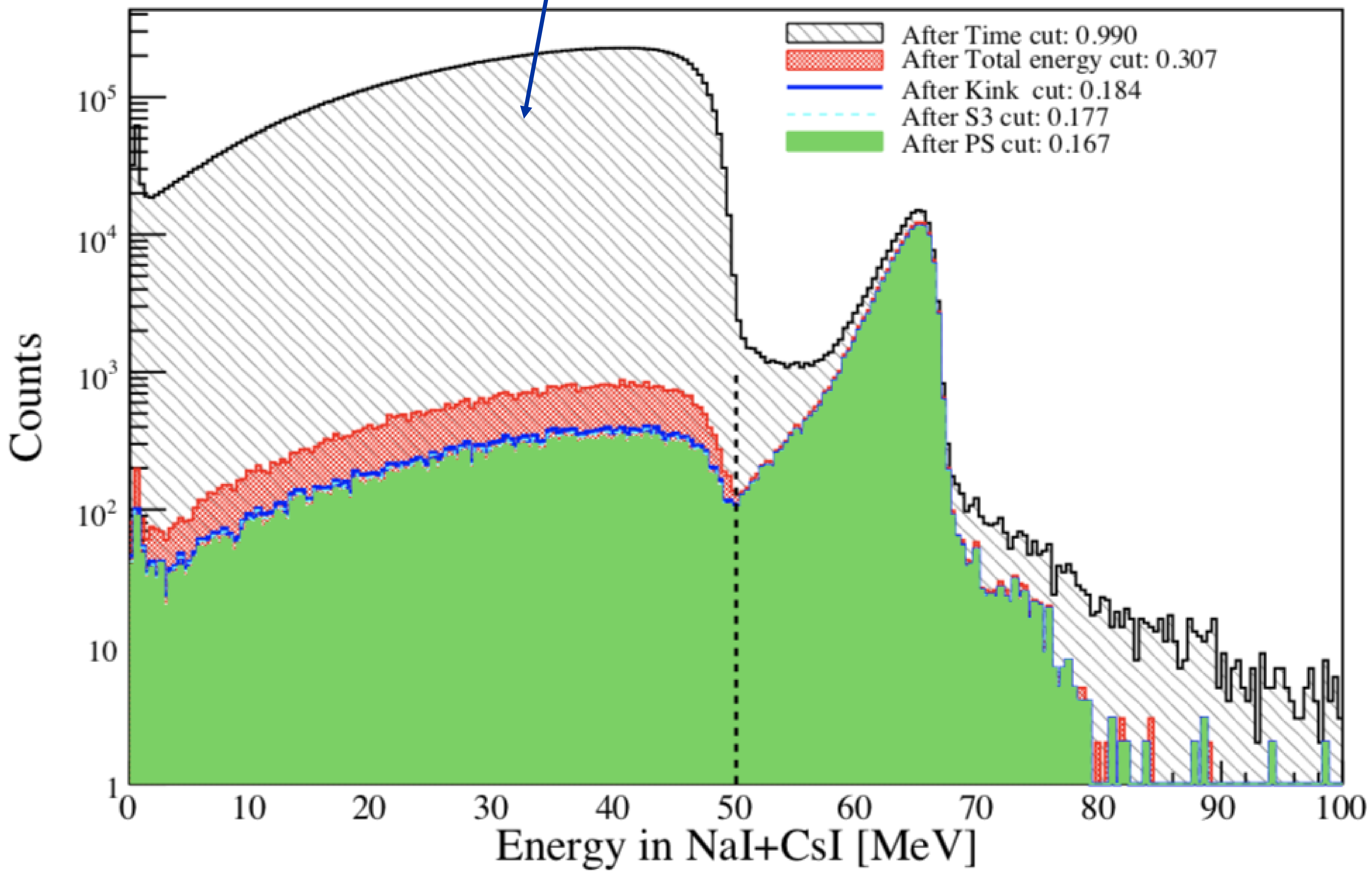
- High purity pion beam
- Large calorimeter and excellent resolution
- High speed pulse digitization
- Good vertex reconstruction (DIF)

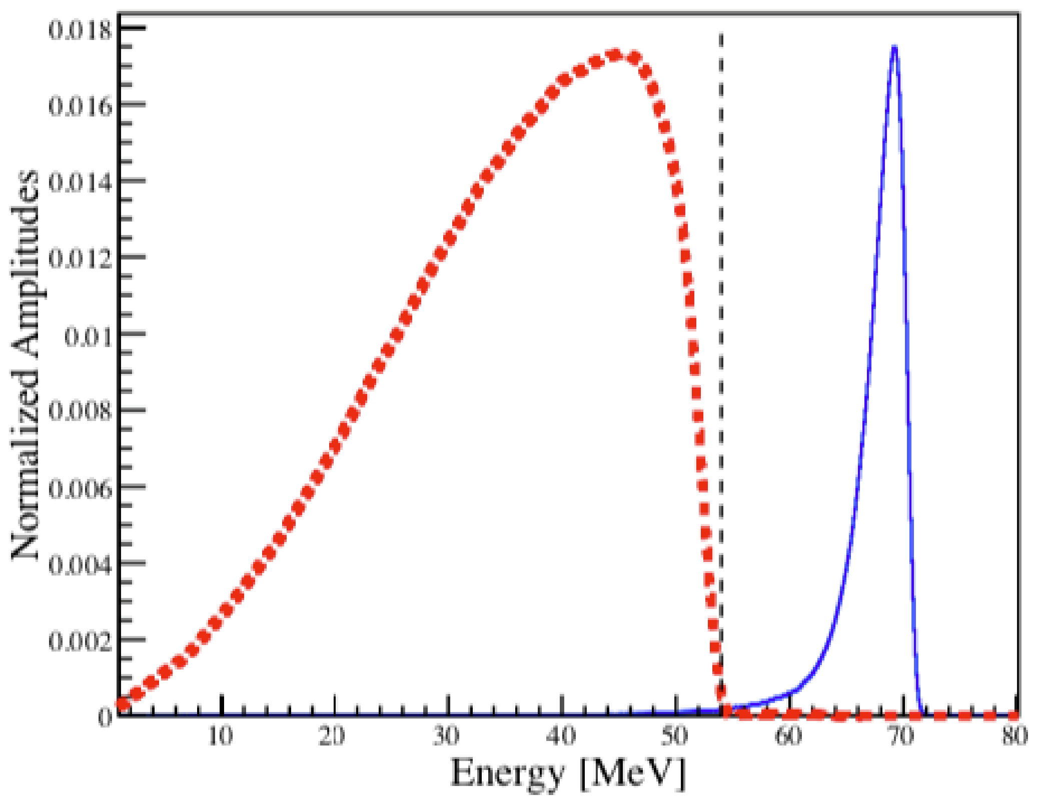
Energy spectrum

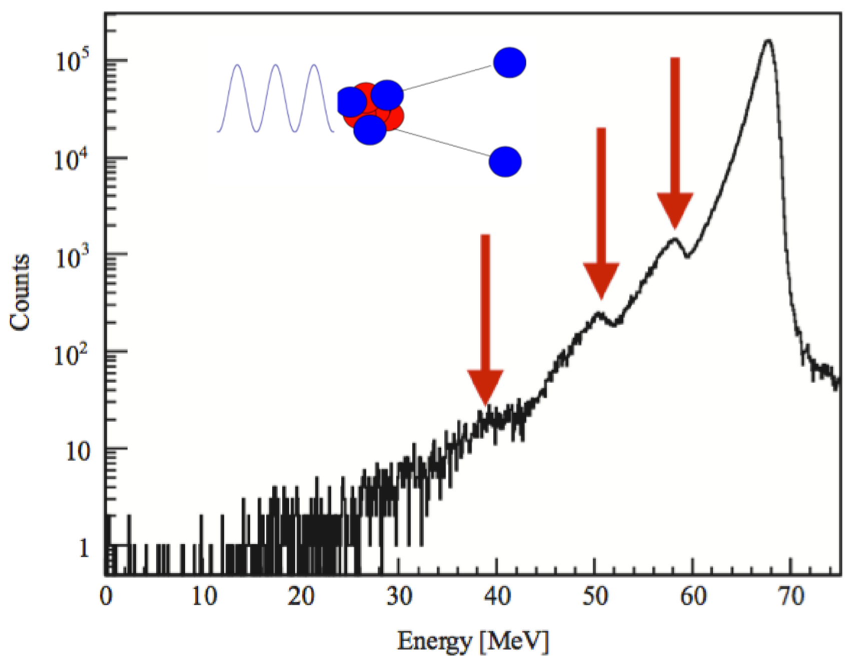


$R^{\pi} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$: main systematic in the PIENU experiment

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







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

Low energy tail from $\pi^+ \to e^+\nu_e$ buried under the Michel spectrum caused by:

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

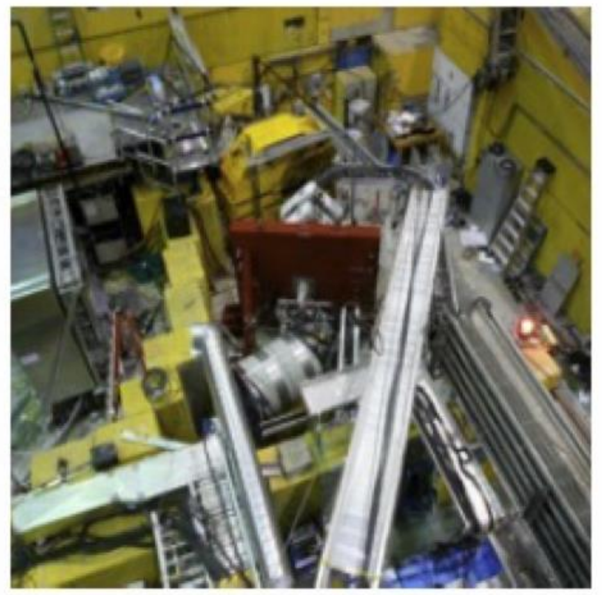
Main source of systematics : estimated using data (suppression of $\pi \to \mu \to e$ decays)

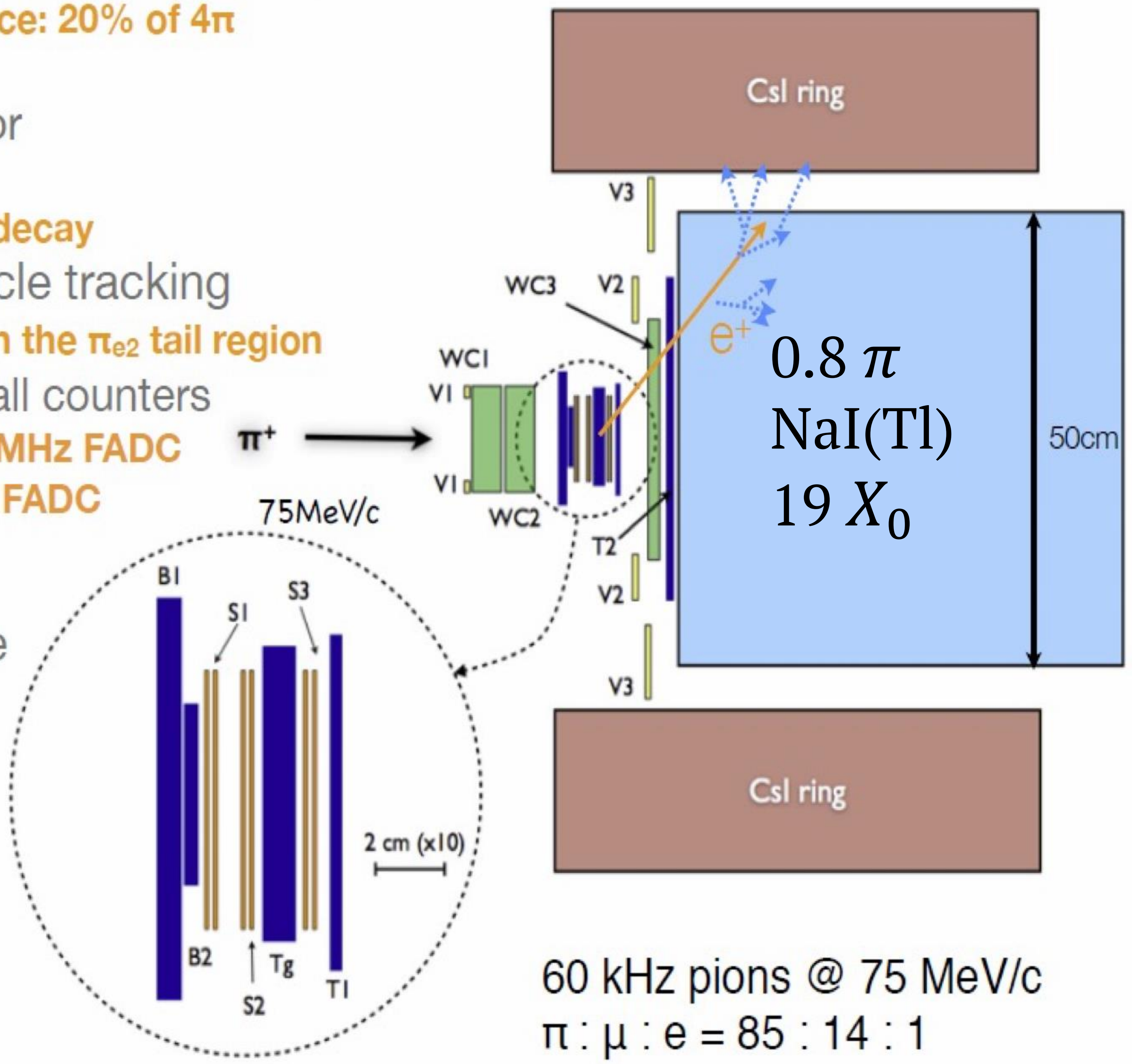
PIONEER: building on previous experiences - PIENU and PEN

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



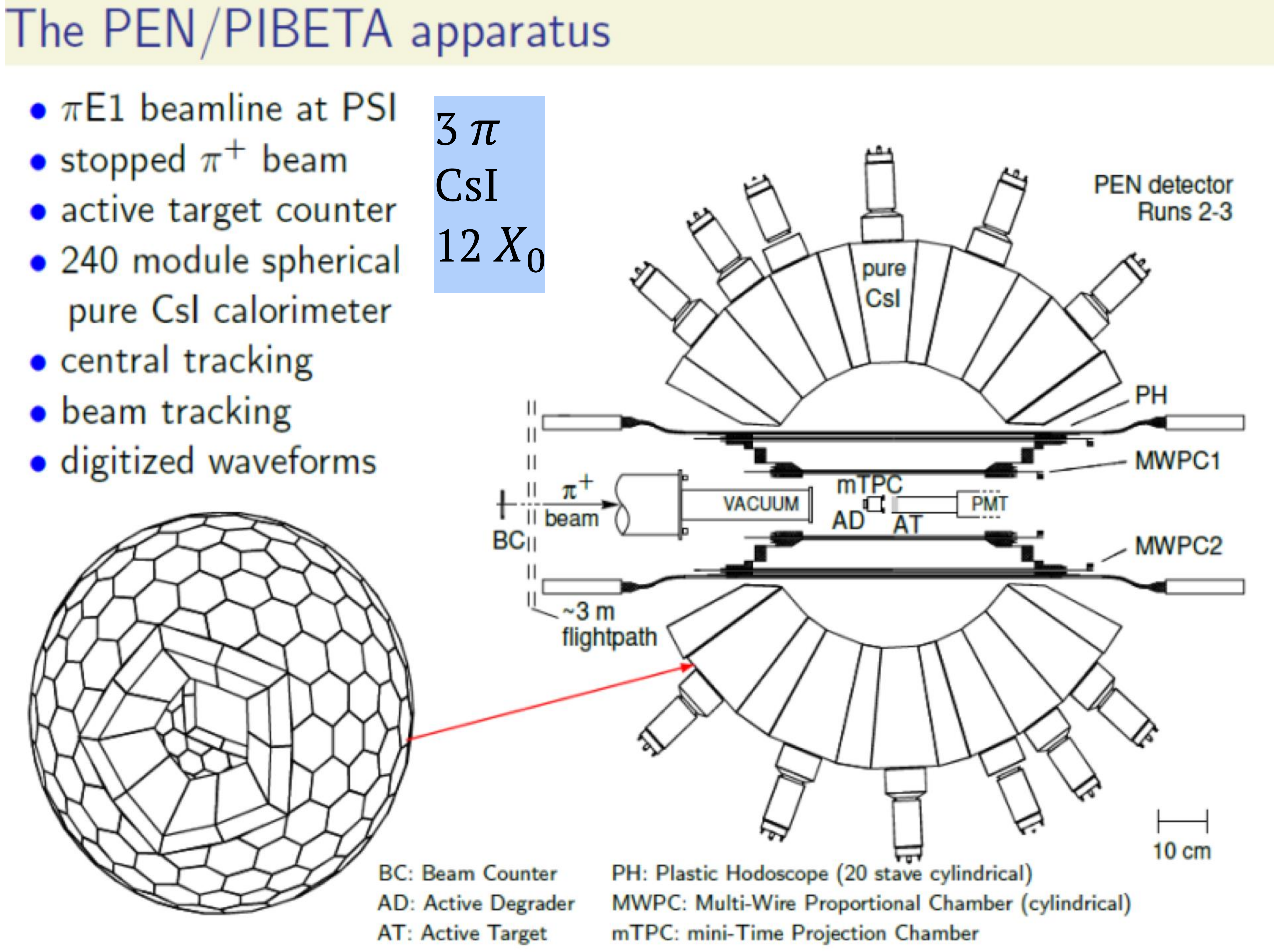


0.8 π
NaI(Tl)
19 X_0

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

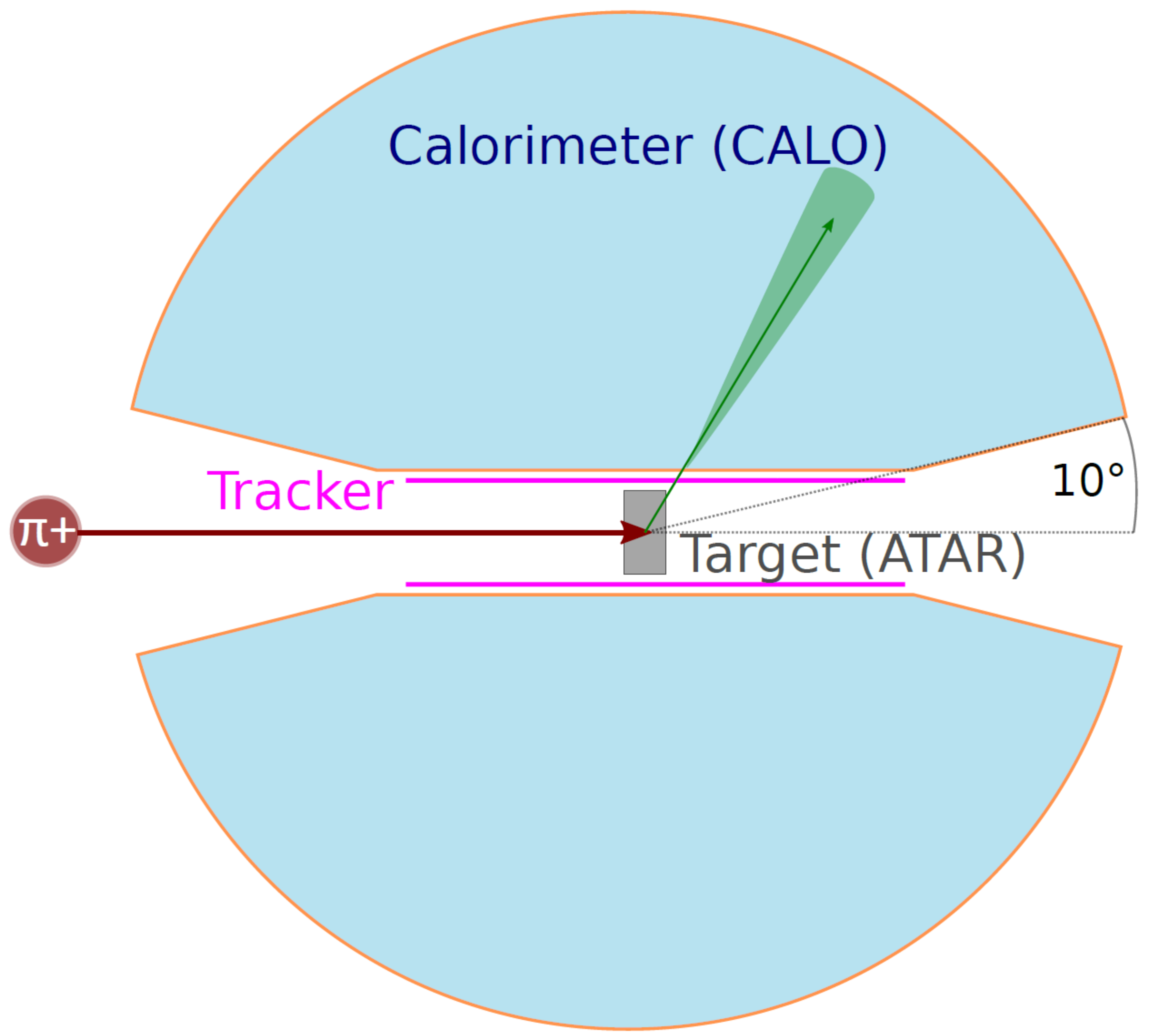


3 π
CsI
12 X_0

Good geometry but calorimeter depth too small

Functioning principle of PIONEER

- Intense pion beam is stopped in active target (ATAR, envisioned resolution: 150μm in space and <1ns in time)
- Electromagnetic calorimeter (CALO) surrounds target.
- Cylindrical tracker used to link locations of pions stopping in the target to showers in the calorimeter.



PIONEER DETECTOR CONCEPT - best of both worlds

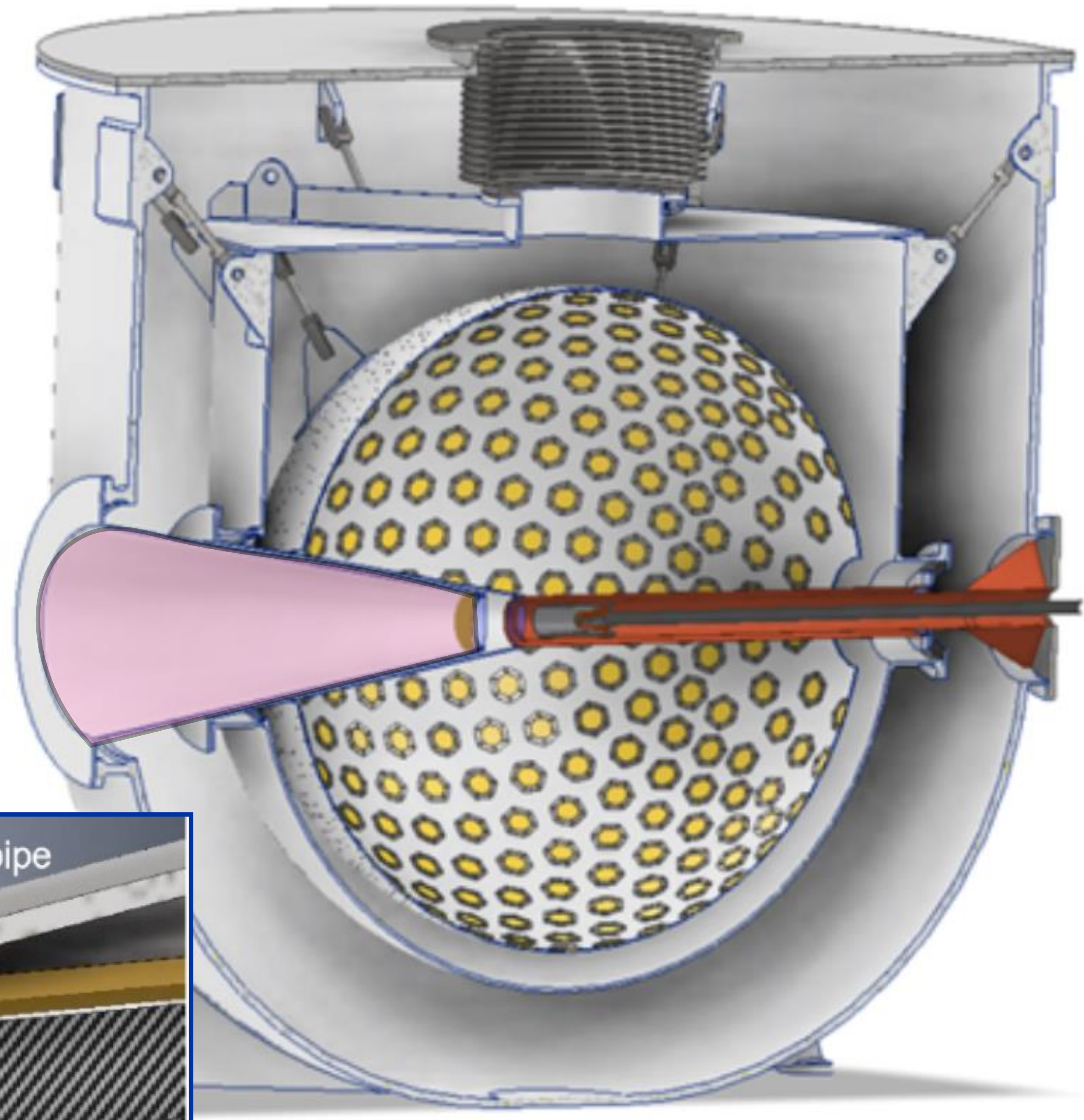
Building on previous experiences (PIENU and PEN/PIBETA) : use of emerging technologies (LXe, LGADs)

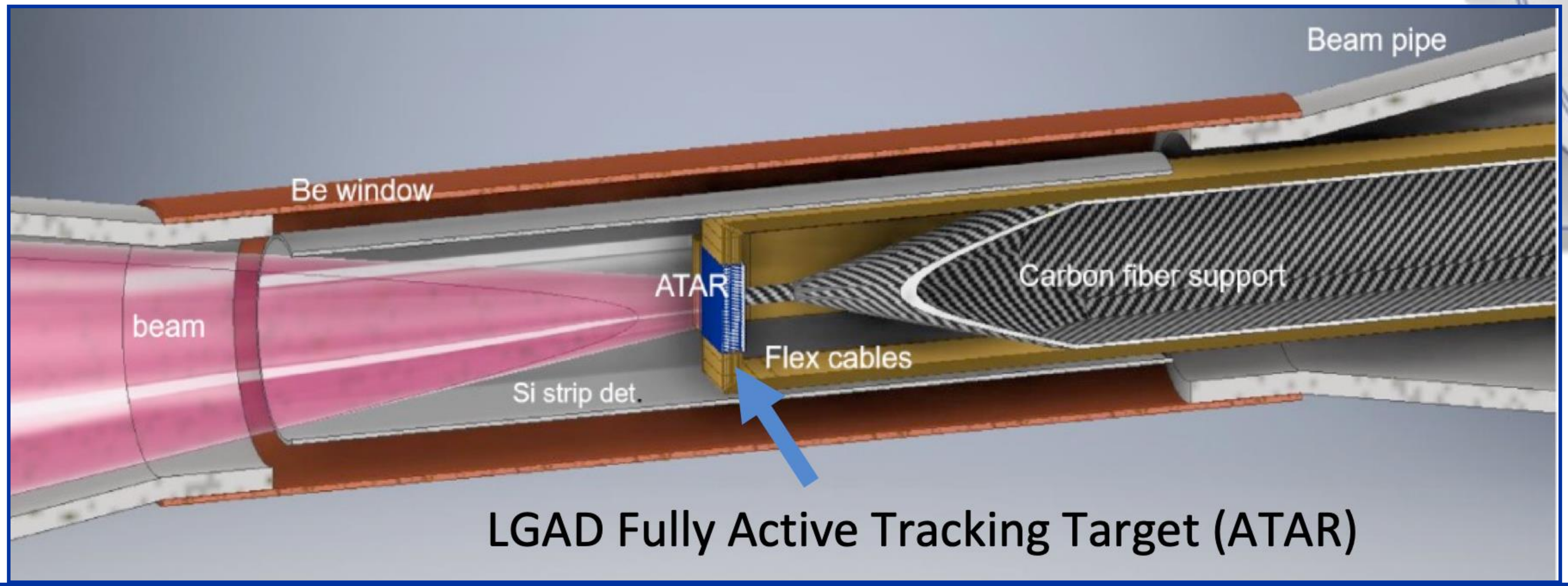
- 25 $X_0, 3\pi$ sr calorimeter ➞ Reduce tail corrections (x5) ➞ Improve uniformity (x5)
  Fast scintillator response (LXe) ➞ Reduce pile-up uncertainties (x5)

- active target ("4D") based on LGADs technology ➞ Reduce tail correction uncertainty (x10)
  Fast pulse shape ➞ allow $\pi \rightarrow \mu \rightarrow e$ decay chain observation

- Fast electronics and pipeline DAQ ➞ Improve efficiency

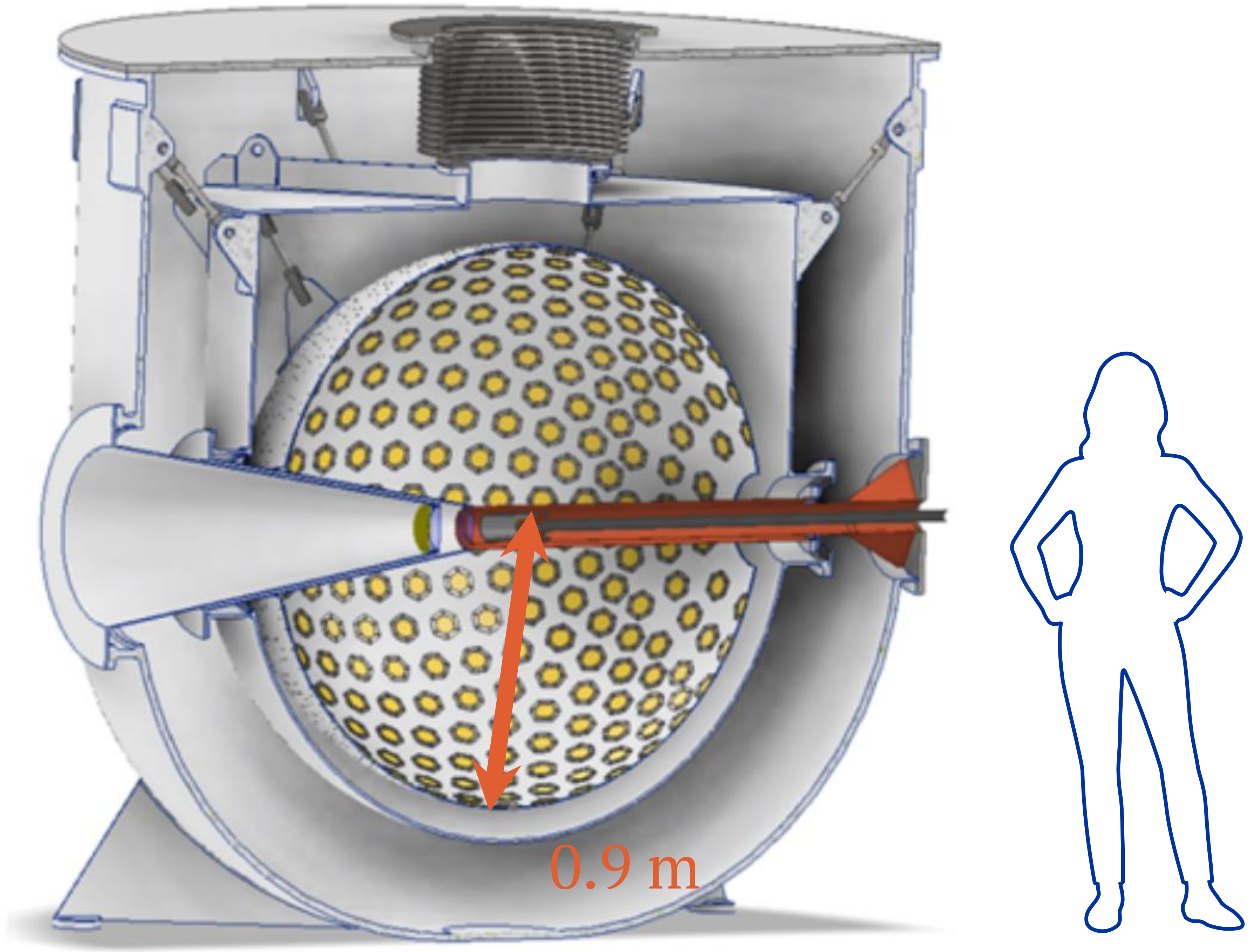
- Intense Pion beam at PSI

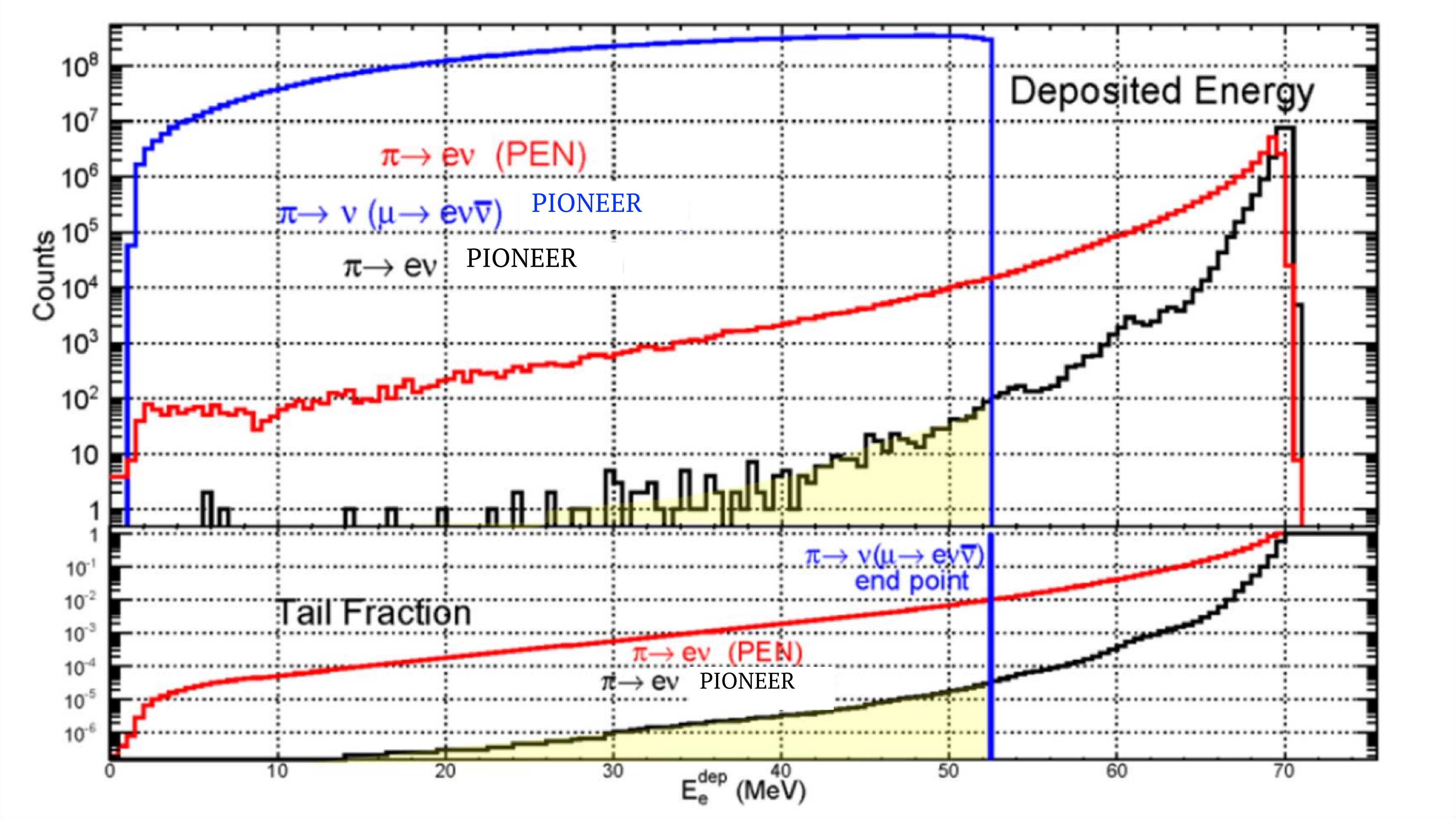




PIONEER DETECTOR CONCEPT : Calorimeter

- 25 $X_0, 3\pi$ sr calorimeter → High energy resolution, fast, symmetric → Much better tail suppression (PIENU: 3% → PIONEER 0.5%)



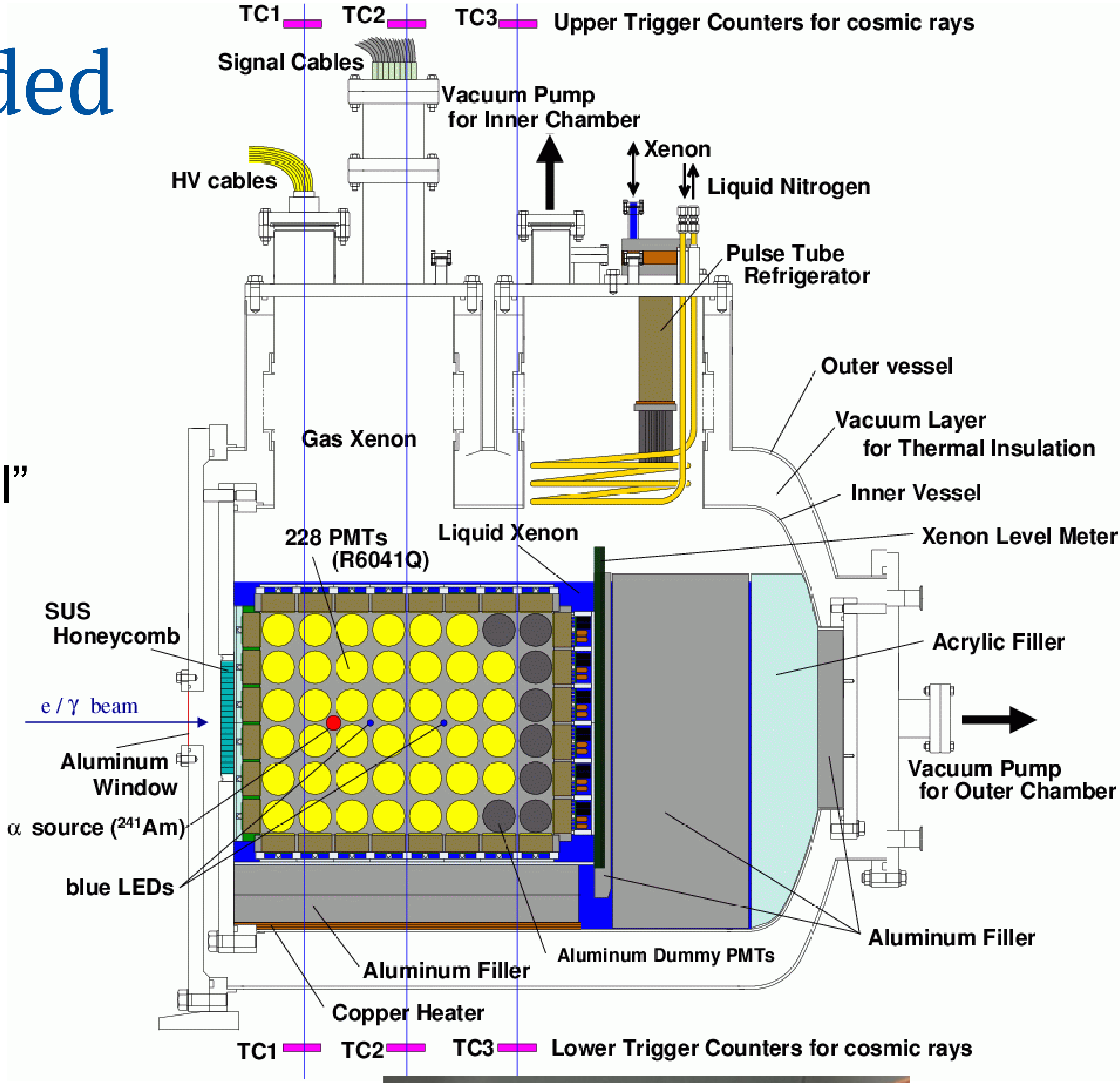


<u>Advantages</u>:
- uniform/homogeneous volume
- fast response
- Excellent energy resolution (goal: 1.5%@ 70MeV)

<u>Question marks</u>
- energy resolution at 70 MeV
- handling pileup
- cost
- photonuclear events (need data to benchmark simulations)
- choice & performance of photosensors

PIONEER DETECTOR CONCEPT : Prototyping needed

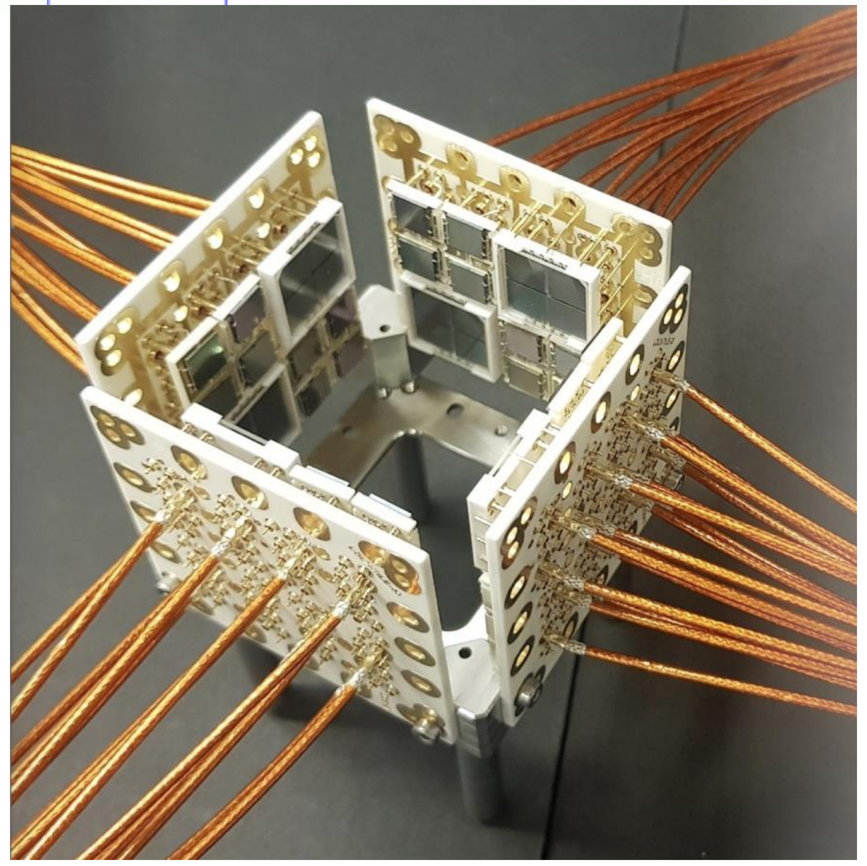
MEG large prototype: ~100 l LXe at PSI



Inform PIONEER on the technology choice for the calorimeter
Axial length of the prototype is up to 25 X_0 = baseline radius for the PIONEER LXe “ball”

<u>Objectives</u>

Using a high momentum resolution 70 MeV e^+ beam et PSI:
- **Measure energy resolution / benchmark simulations**
- Measure detector lineshape
- Study shower leakages
- Measure contribution of photonuclear reactions
- Test of entrance window
- Technological upgrades test (cabling, choice of material for PMT PCBs, purity monitor)
- Training of the collaboration on cryogenic liquid handling
- R&D : effect of optical coating on energy resolution, optical segmentation
test of new generation photosensors



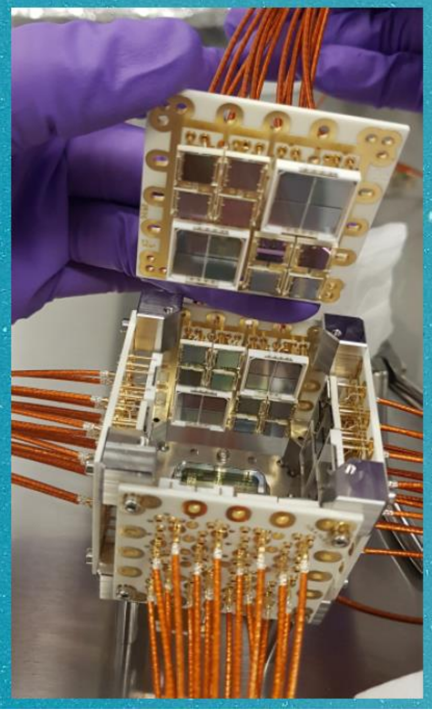
2L LXe cryostat at McGill : LoLX

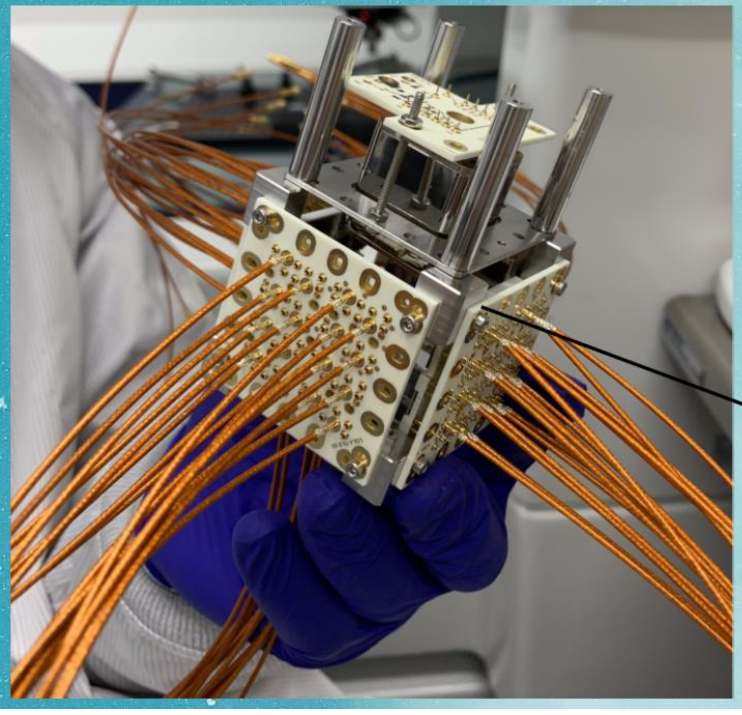
LoLX Experiment

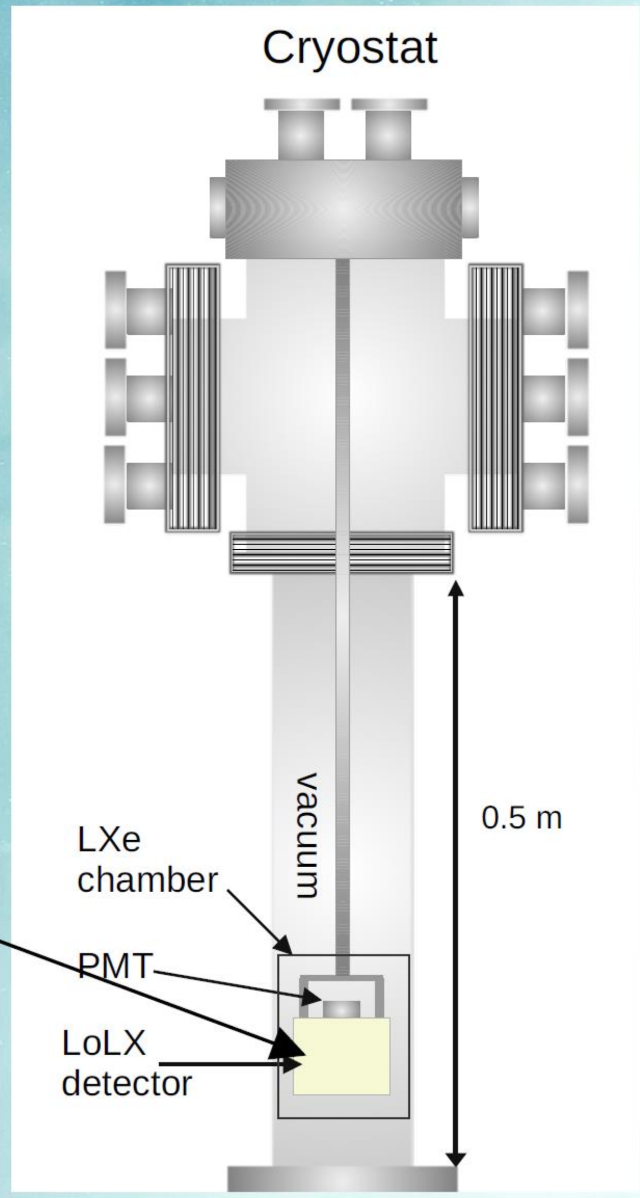
See talk in M1-1 by Stephanie Bron

LoLX: Light-only Liquid Xenon experiment

- Small cube instrumented with photosensors
- Cube immersed in liquid xenon (LXe)
- Placed in a cryostat to cool down xenon to 160K (-110C)







Physics goals

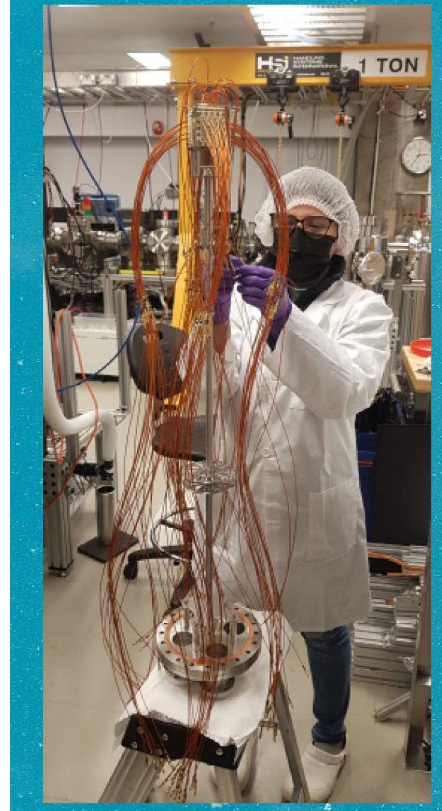
1) Study **light in liquid Xenon** and **validate simulations**
2) Photosensor **R&D**: silicon photomultipliers (SiPMs), new sensor technologies, etc.
3) Gain experience in **operating SiPMs** over long time periods – impact on devices?

Inform **future rare-decay experiments** (neutrinoless double beta decay, lepton flavor universality)

	LoLX	nEXO	PIONEER
LXe	4-5 kg	5 tons	7 tons
E field	no	yes	no
Energy	$\sim 0.2 - 2$ MeV	~2.5 MeV	0-70 MeV
Trigger rate	100 Hz	O(Hz)	1-10 MHz
Number SiPMs	80	50’000	N/A

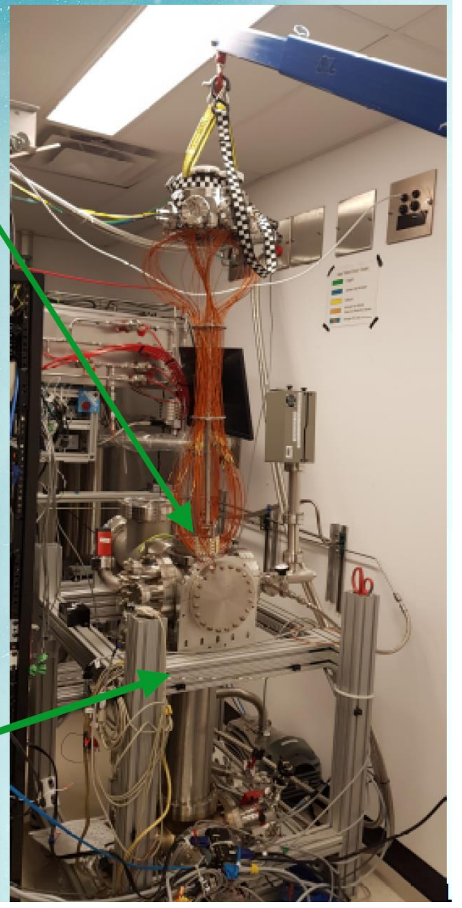
PIONEER: talk from Kate Pachal and from Thomas Brunner
nEXO: talk from Samin Majdi and Soud Al Kharusi

Cabling and insertion in cryostat at McGill



cabling

feedtrough



LoLX cube

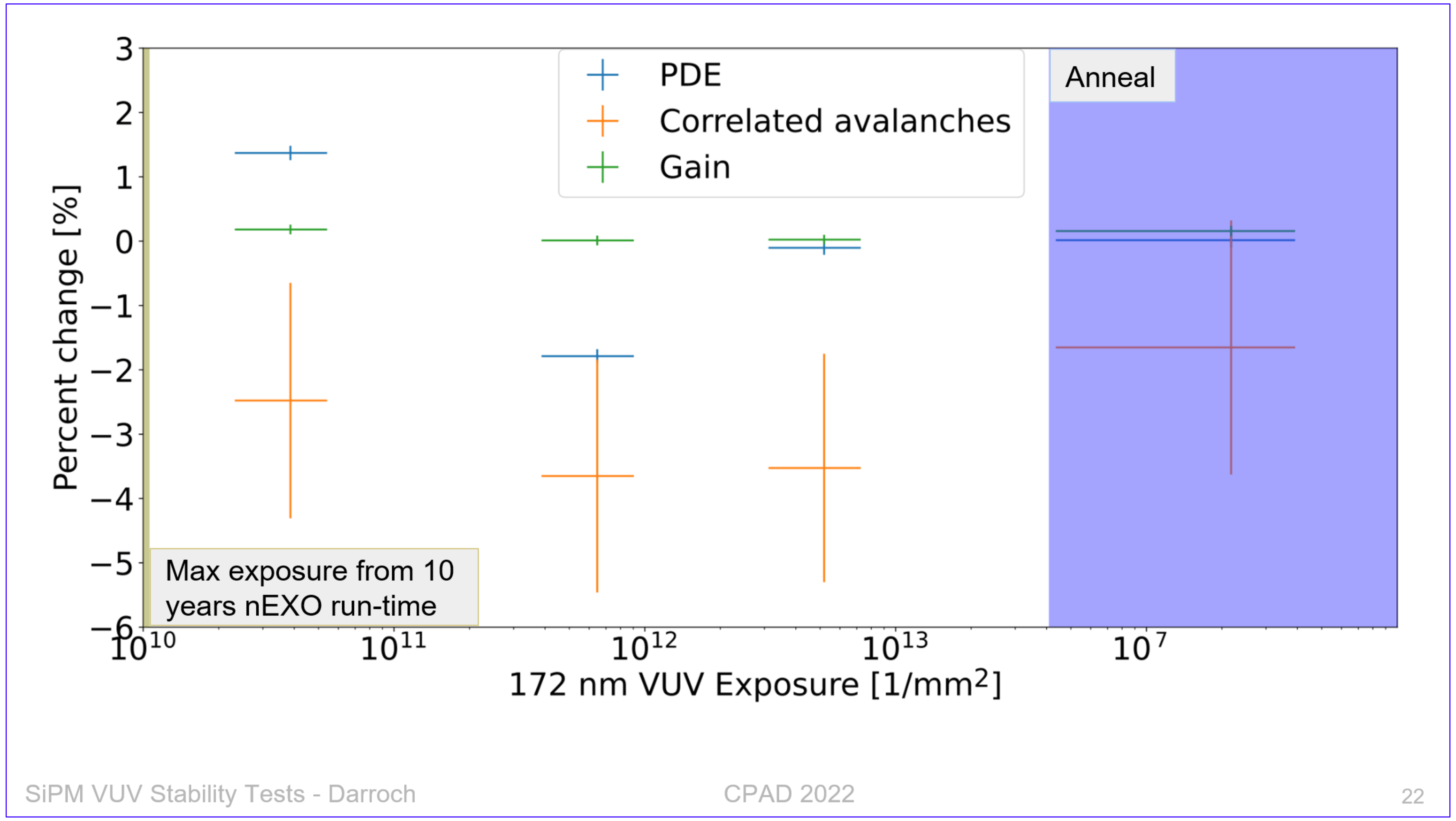
cryostat

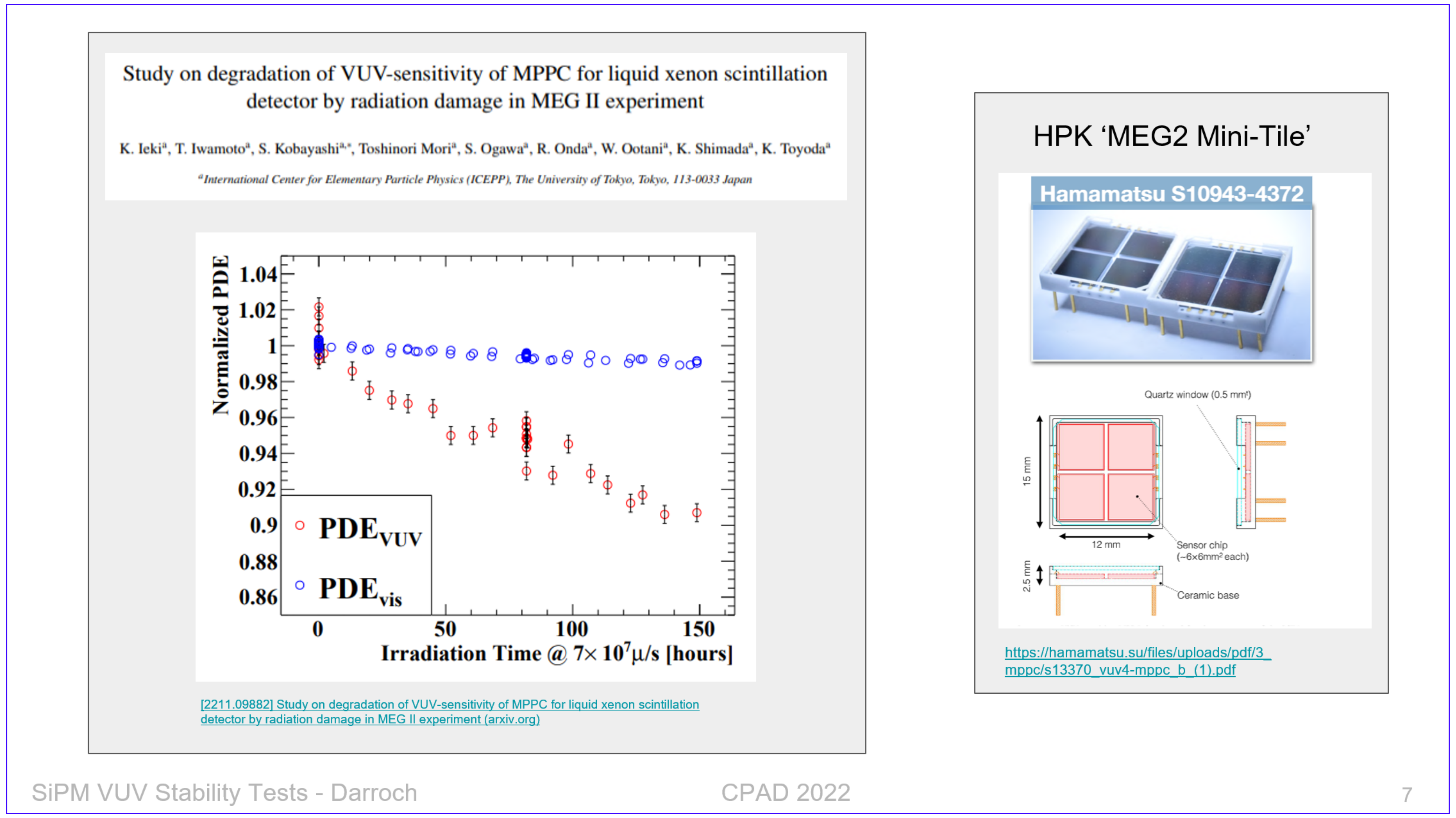
In future upgrade to LoLX: investigate effect of purity on light emission.

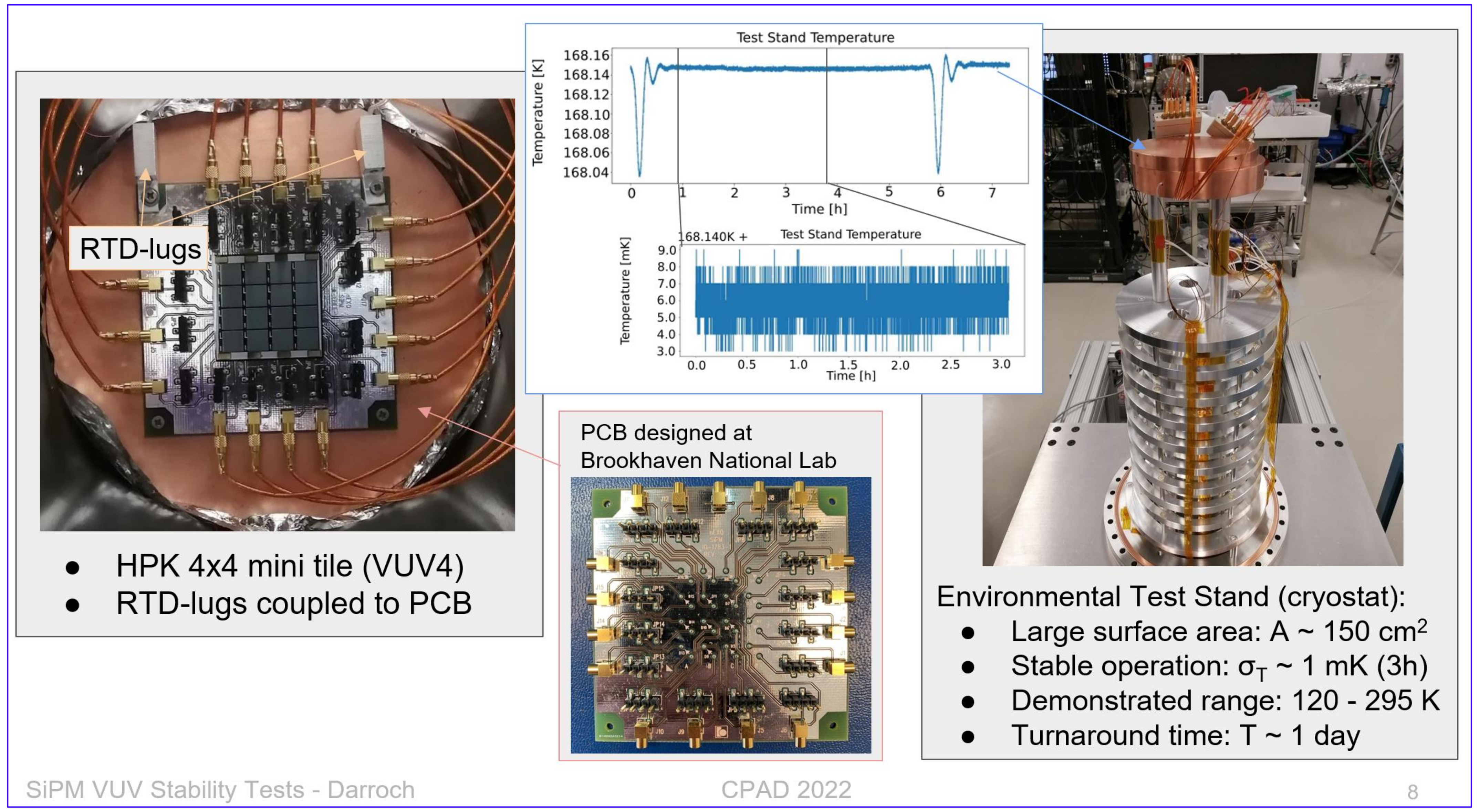
Possible SiPM degradation?

See Lucas Darroch's talk "The stability of HPK VUV4 SiPMs following a large dose of VUV radiation." in W2-6 tomorrow.

Synergetic development between PIONEER and nEXO







PIONEER Schedule

<u>Phase I</u>

Approved by PSI

Low momentum pion beam at 55 MeV/c (±2% Δp/p) @ 300 kHz

2×10^8 $\pi^+\rightarrow e^+\nu_e$ required to achieve 0.01% precision of $R_{e/\mu}$

Expected in 3 years (5 month running/year)

Future:

<u>Phase II</u>

7×10^5 $\pi^+\rightarrow \pi^0 e^+\nu_e$ required to achieve 3-fold improvement on BR

<u>Phase III</u>

7×10^6 $\pi^+\rightarrow \pi^0 e^+\nu_e$ required to achieve 10-fold improvement on BR

Conclusions and opportunities!

- PIONEER is a major 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
- Precision experiment: Sensitive to **very high energy scales**.
- Unique new information on **Lepton Flavor Universality and CKM unitary** with unprecedented precision
- Pion decay: long history of establishing and challenging the SM
- 2-body spectra very sensitive to a wide range of **exotics**
- PIONEER is employing state-of-the-art technology (**LGADs, Noble liquid calorimetry**)
- Time-scale: 10-15 years
- Approved to run at PSI. Expected start of data taking ~ 5 years timescale (first beamtime for beam characterization happened last year)
- Supported by a large, experienced international collaboration: experts from previous PIENU and PEN experiments as well as a wide range of international collaborators from NA62, MEG, muon g-2, ATLAS, PSI scientists and leading theorists: **JOIN US!**

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

BACKUP SLIDES

PIENU 2015 and PIONEER precision

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**

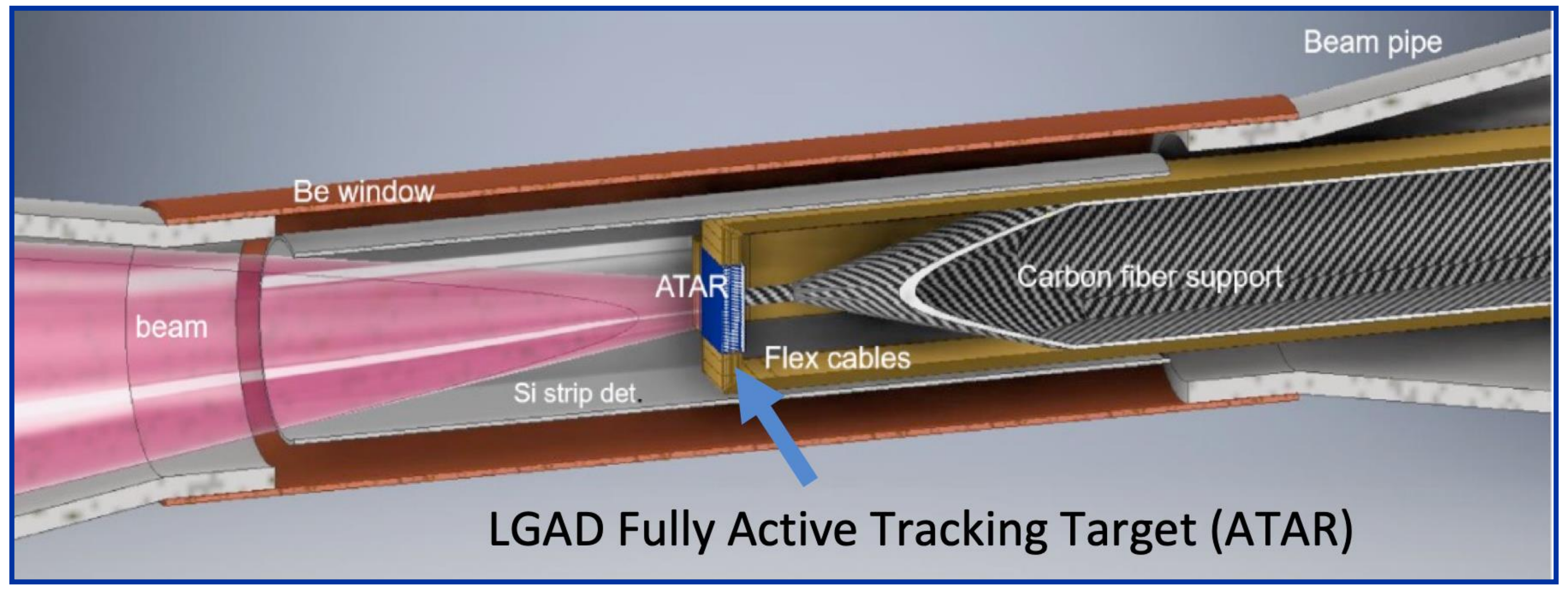
PSI Pion Beam Requirements

Phase	p (MeV/c)	$\Delta p/p$ (%)	ΔZ (mm)	ΔX x ΔY (mm^2)	$\Delta X'$,$\Delta Y'$	R_π (10^6/s)
I	55-70	2	1	10x10	$\pm 10°$	0.3
II,III	≈ 85	≤ 5	3	15x15	$\pm 10°$	20

TABLE I – Required beam properties. ΔZ and $\Delta X \times \Delta Y$ are longitudinal (FWHM) range width and transverse (FWHM) beam sizes at target location, respectively.

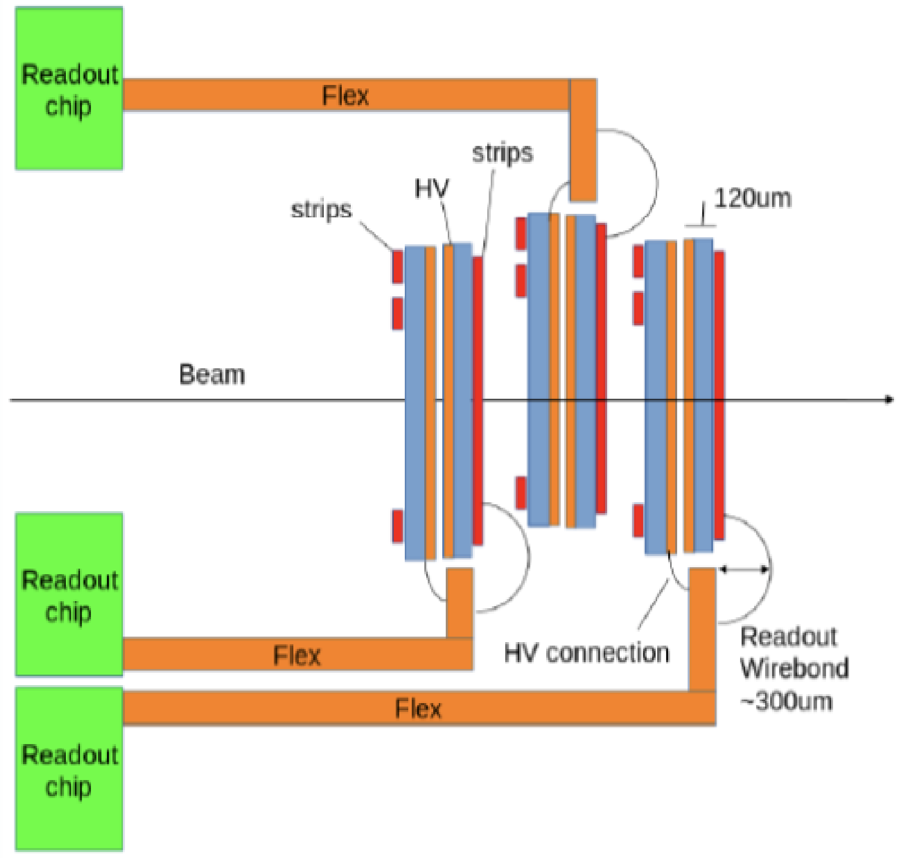
PIONEER DETECTOR CONCEPT : Active Target (ATAR)

- active target ("4D") based on LGADs(Low gain avalanche diode) technology

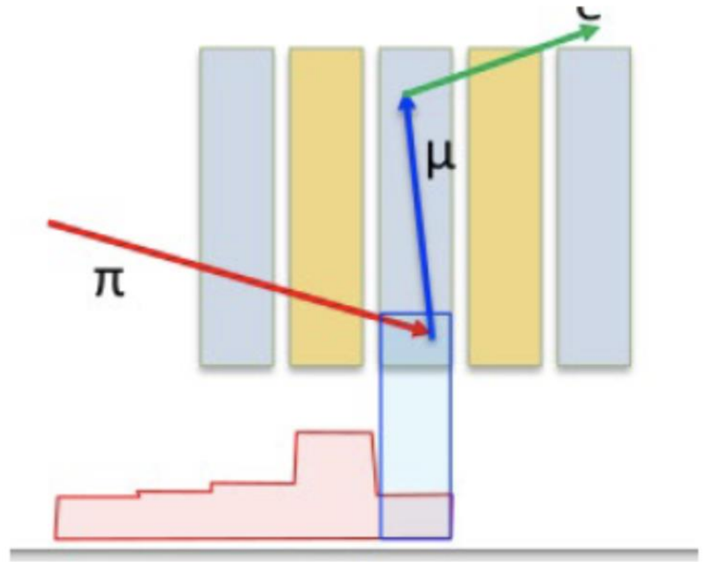


Requirements

- High longitudinal segmentation: to detect the decay in flight of pions and muons
- Compact: less dead material (including air) as possible in between planes and around ATAR
- Fast collection time: separate pulses that are close in time to reconstruct the pion decay chain (<1.5 ns pulse pair resolution is needed)
- Large Dynamic range: detect energy deposit from positrons (MiP) and slow pions/muons (non-MiP)

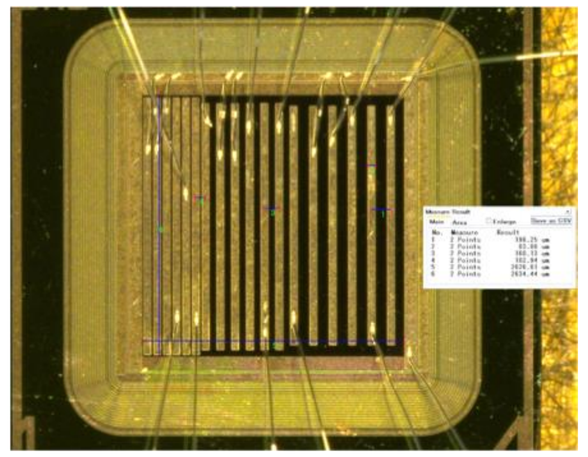


Tentative initial design

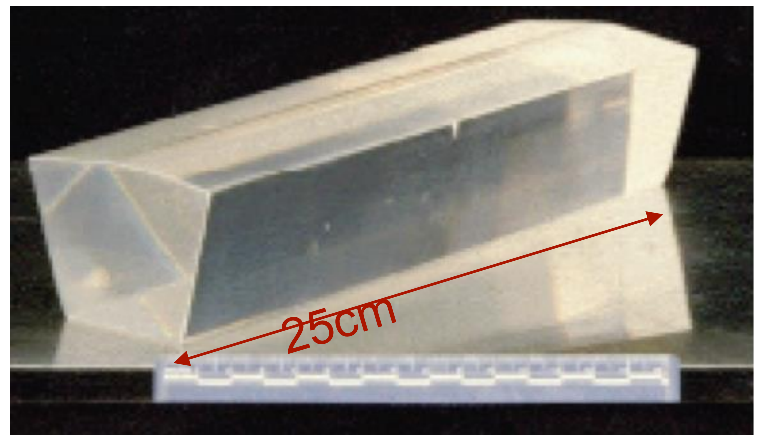


- 48 layers of 120um thick silicon sensors (total of 6 mm in beam direction)
- 100 strips, 2 cm length, with 200 um pitch (2x2 cm area)
- Compromise between granularity, total active area, timing and dead material
- Sensors are packed in stack of 2 with facing HV side and rotated by 90°

Developments led by UCSC

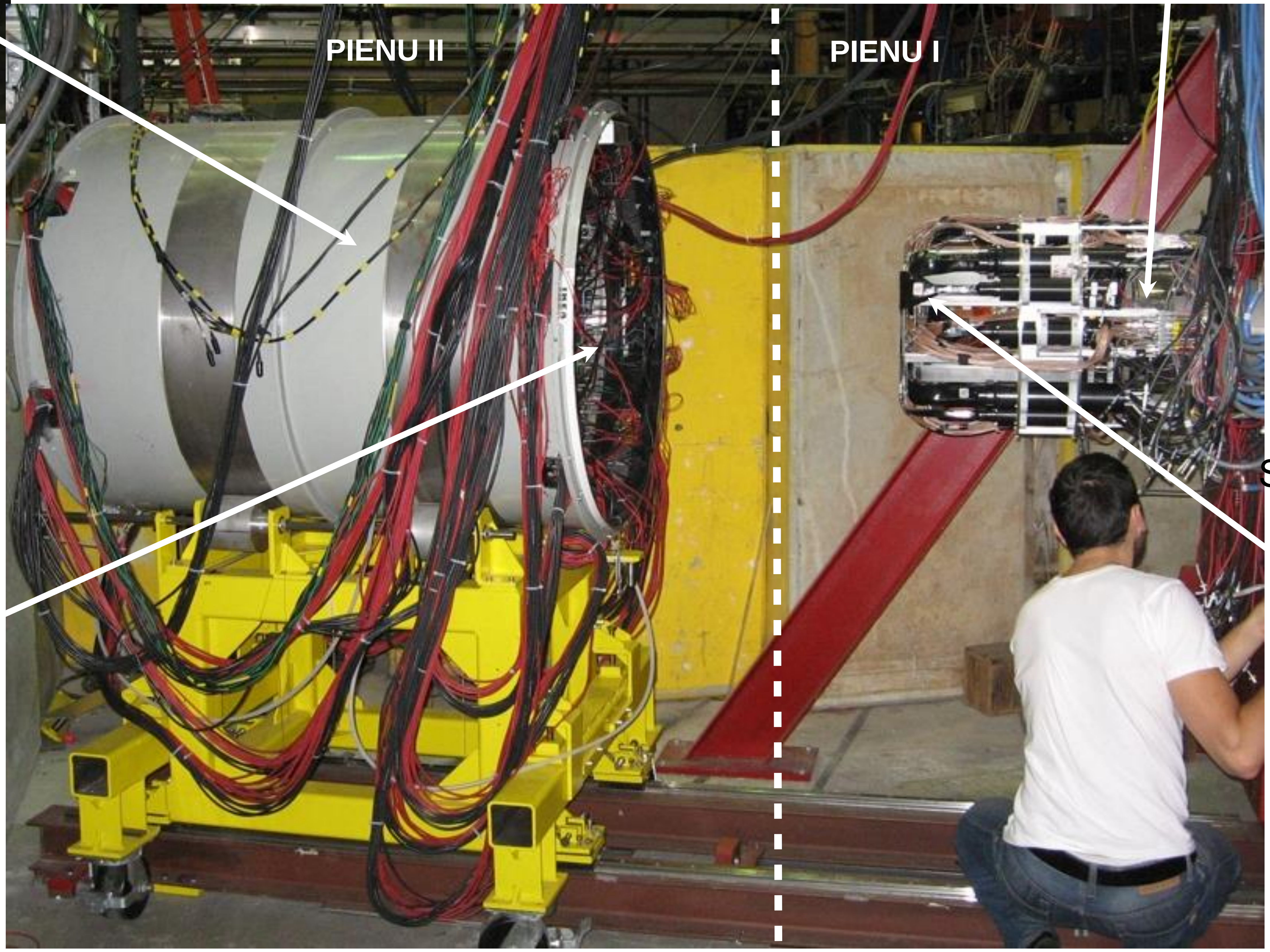


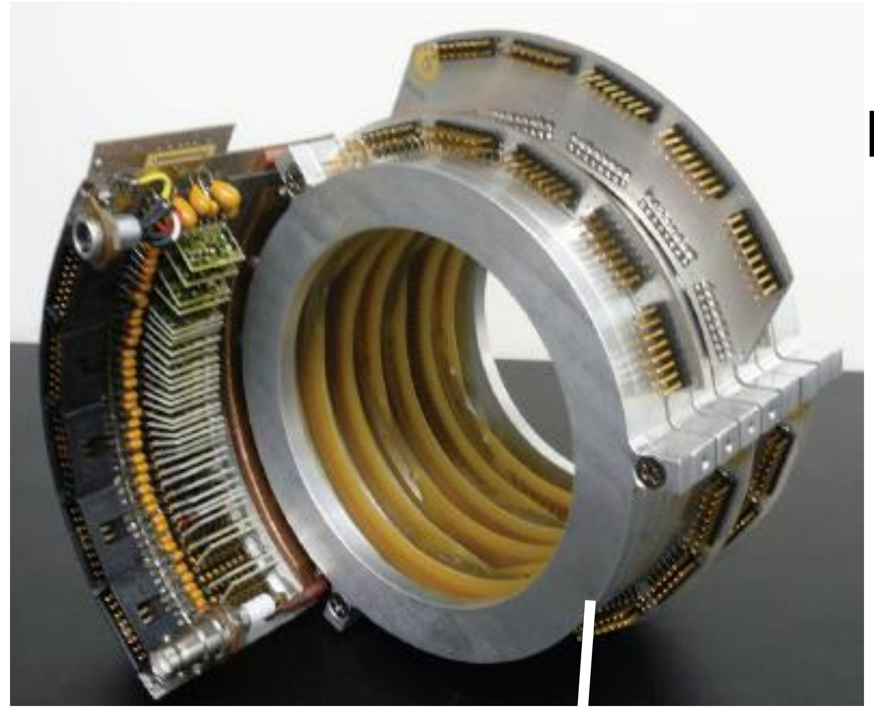
Monolithic NaI(Tl) crystal surrounded by 97 pure CsI crystals



CsI crystal

Acceptance Wire Chamber





Beam Wire Chamber

π^+

Silicon Trackers