Overview of PIENU results and the PIONEER experiment

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on behalf of the **PIENU** & **PIONEER** Collaborations

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PIENU measurement & Phase I of PIONEER

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

one of the most precisely calculated observables involving quarks in the SM

Marciano and Sirlin , PRL 71 3629 (1993)
Cirigliano and Rosell , PRL 99 231801 (2007)
D. Bryman et al. , Annu. Rev. Nucl. Part. Sci. (2011) 61:331–54

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

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

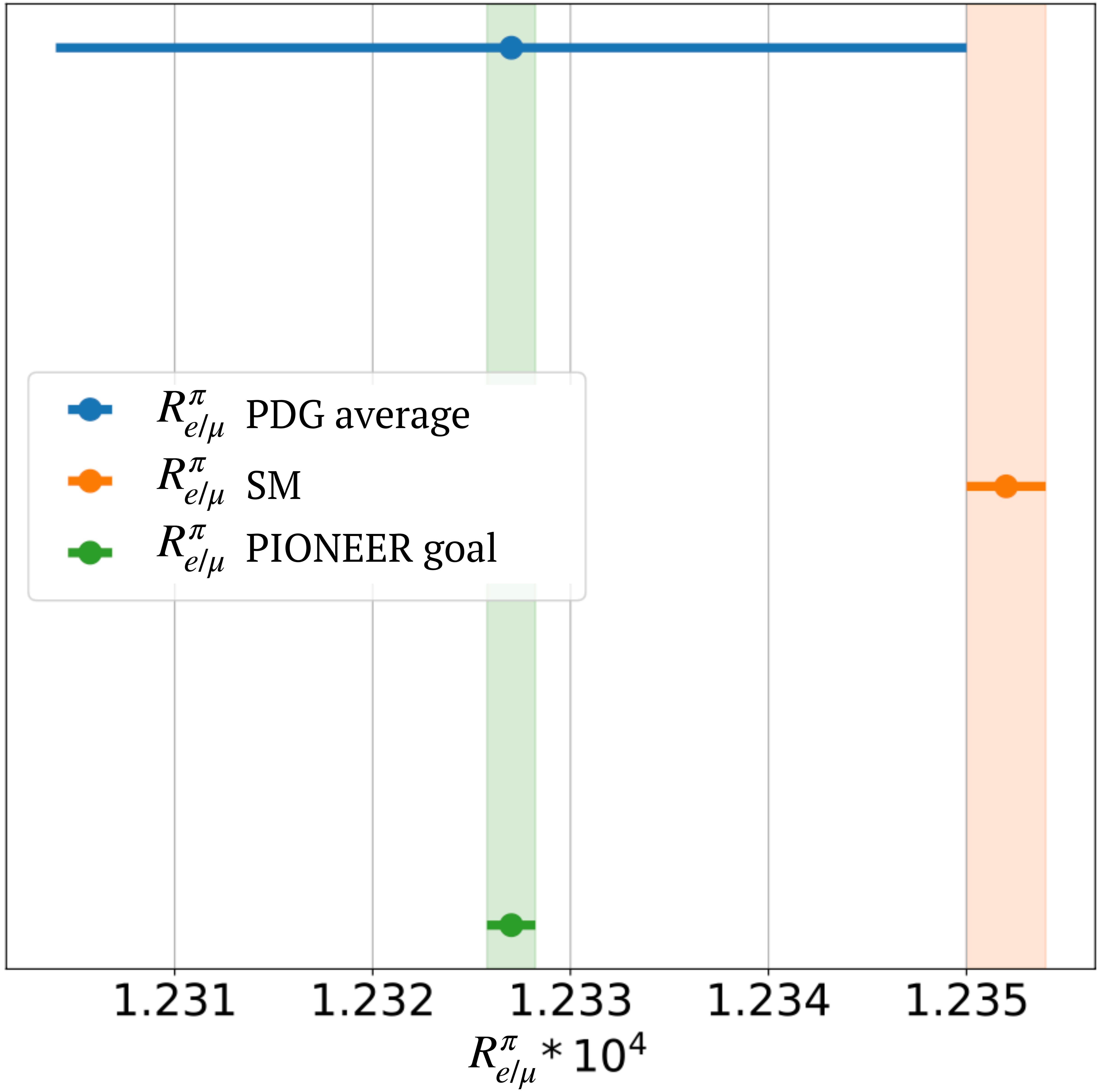
x 15

Precision low energy experiment on observables that can be very accurately calculated in the SM : highly sensitive to New Physics

PDG average dominated by the PIENU 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

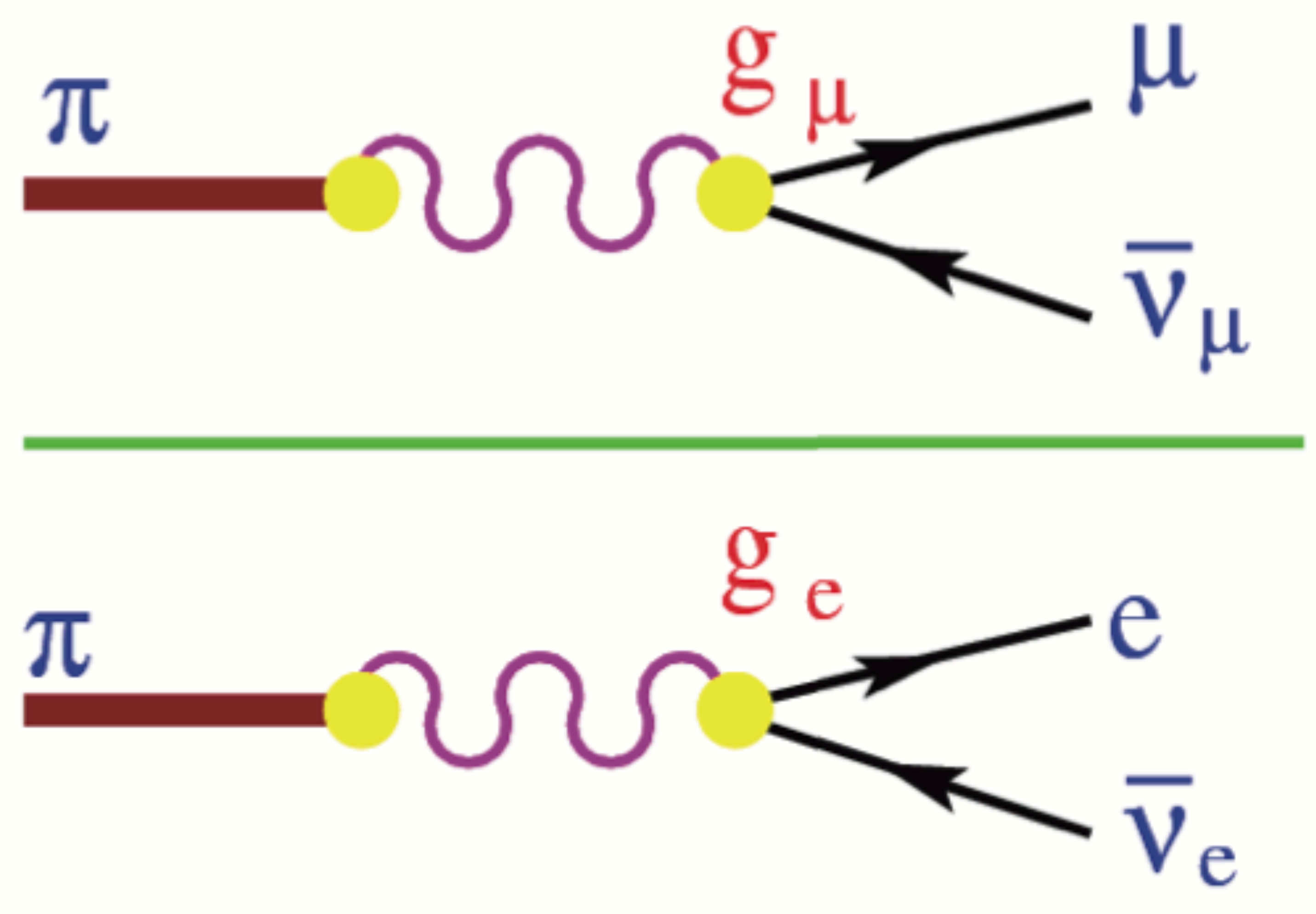


Physics case I : Testing Lepton Flavour Universality

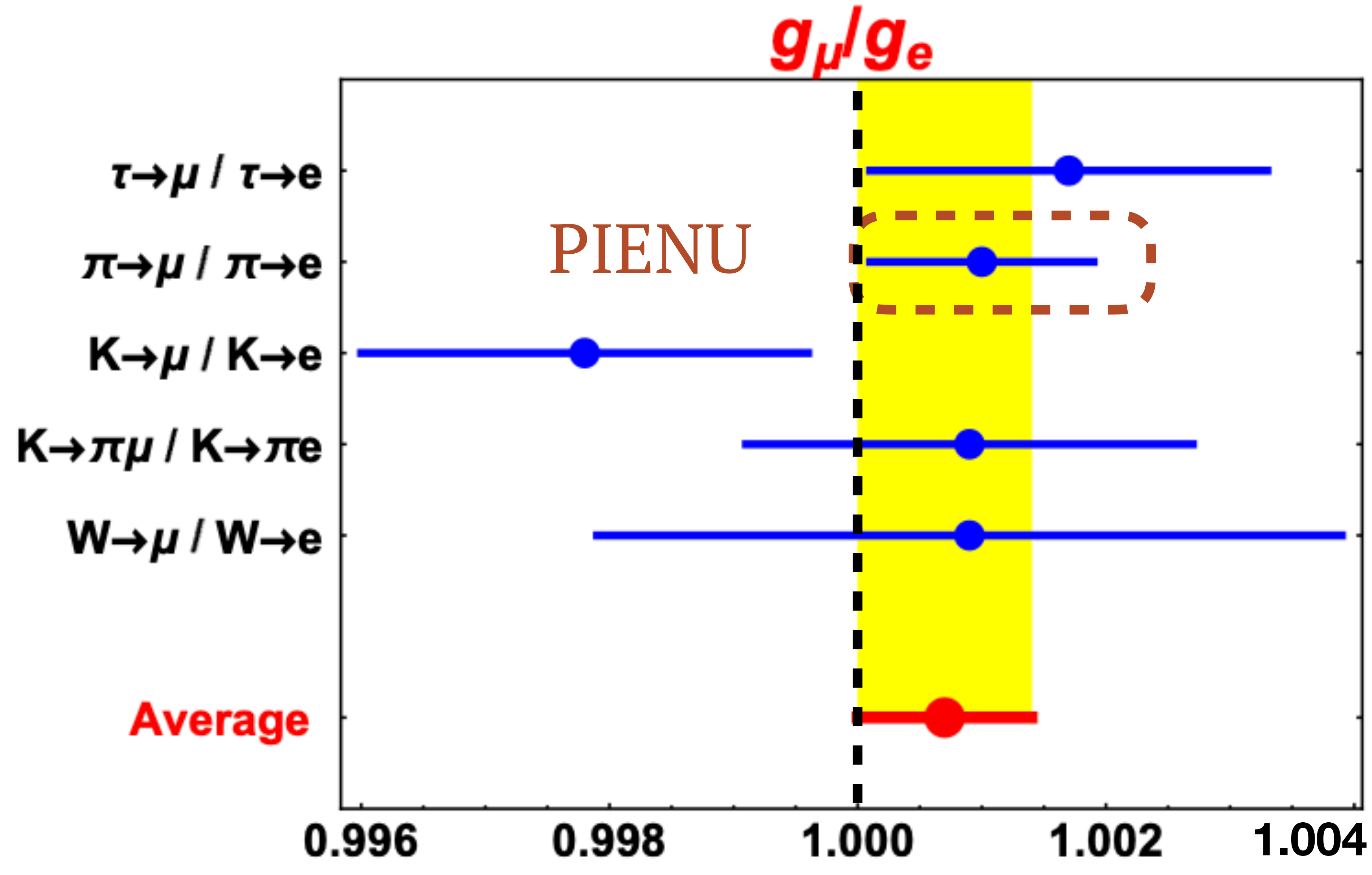
Weak interaction is the same for $e/\mu/\tau$ leptons

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

provides the best test of universality in charged current weak interaction



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



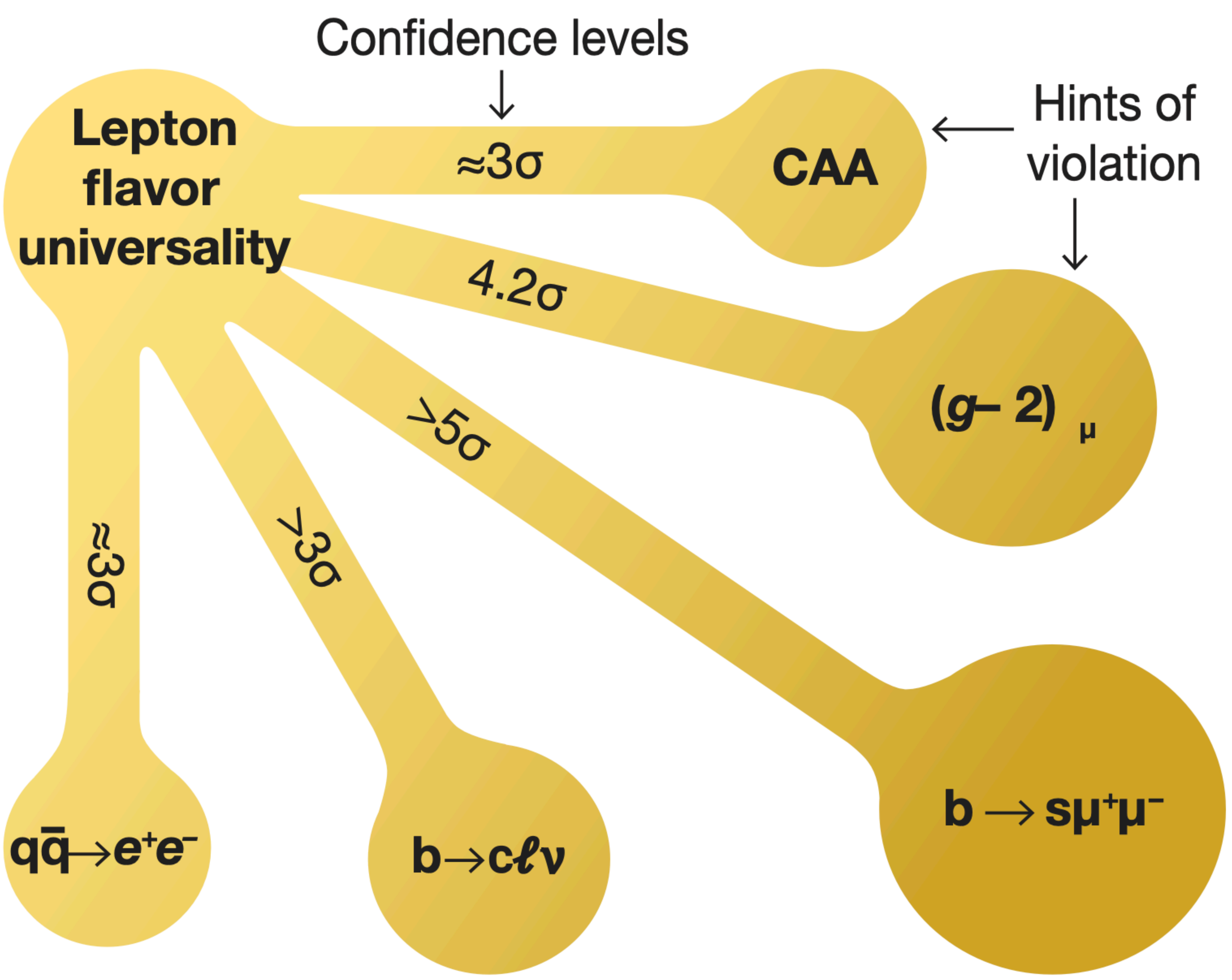
From A. Pich's talk
Rare Pion Decay Workshop
Santa Cruz 06-08 Oct 2022

PDG value, mostly constrained by **PIENU** results :

$$\frac{g_\mu}{g_e} = 1.0010 \pm 0.0009 \quad (\pm 0.09\%)$$

Physics case I : Testing Lepton Flavour Universality

Several new tensions in the flavour sector, potentially hinting toward LFUV



CAA, Cabibbo angle anomaly

- 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?

From A. Crivellin & M. Hoferichter SCIENCE (2021) Vol 374, Issue 6571 DOI: 10.1126/ science.abk2450

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

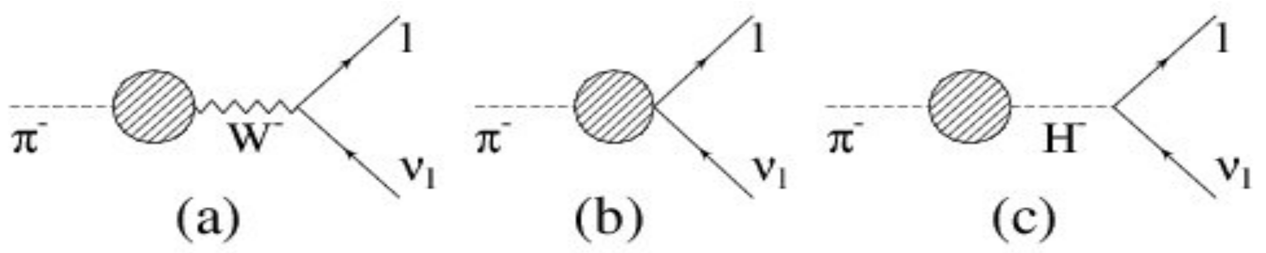
Physics case II: Sensitivity to new coupling and NP at very high mass scales

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

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

PIONEER PHASE I goal:

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

D. Bryman et al. , Annu. Rev. Nucl. Part. Sci. (2011) 61:331–54

Physics case III : Sensitivity to new coupling and NP at very high & low mass scales

- Sensitive to many other new physics scenarios
  - Leptoquarks
  - Induced scalar currents
  - Excited gauge bosons
  - Compositeness
  - Hidden sector ….

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

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

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)

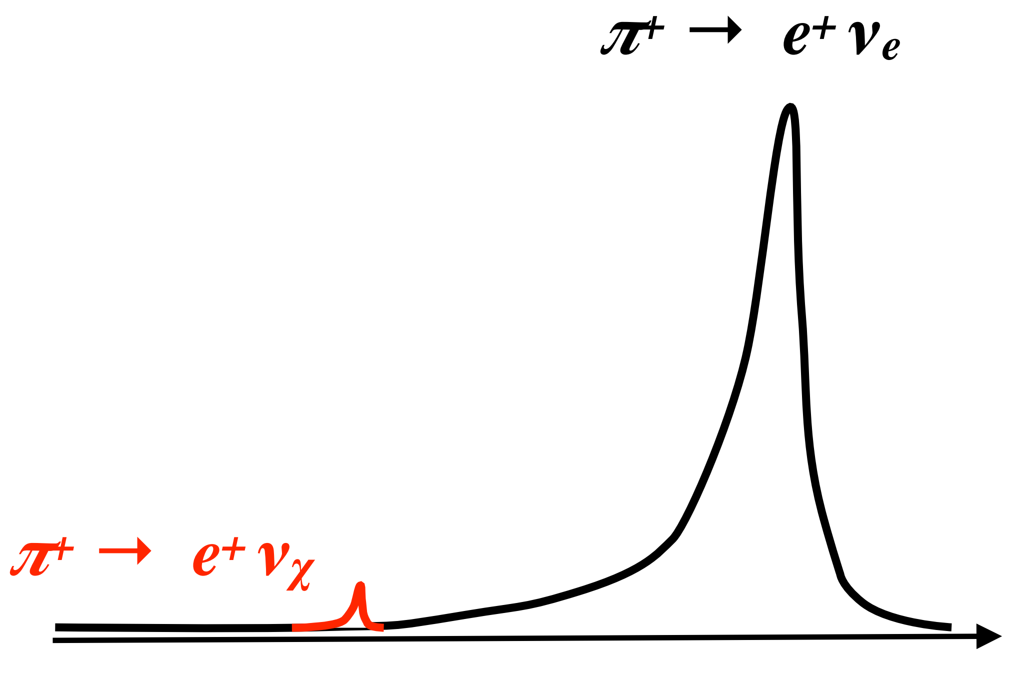
Search for three body pion decays $\pi^+ \to l^+\nu X$

recent searches performed by the **PIENU** collaboration

$\Downarrow$

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

Example of massive neutrino search in PIENU



If the heavy 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)

Heavy υ

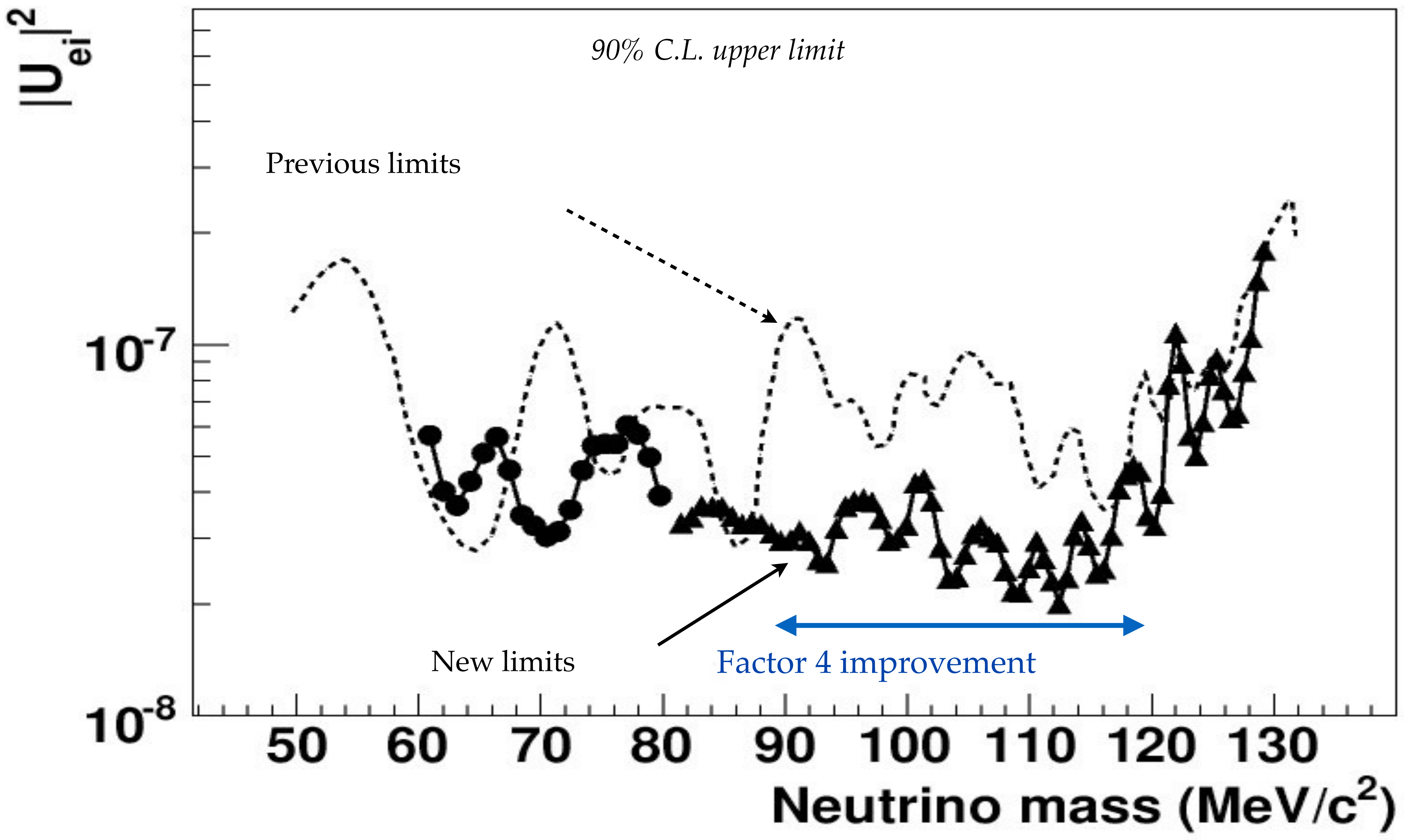
Kinematic factor

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

Conventional υ

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

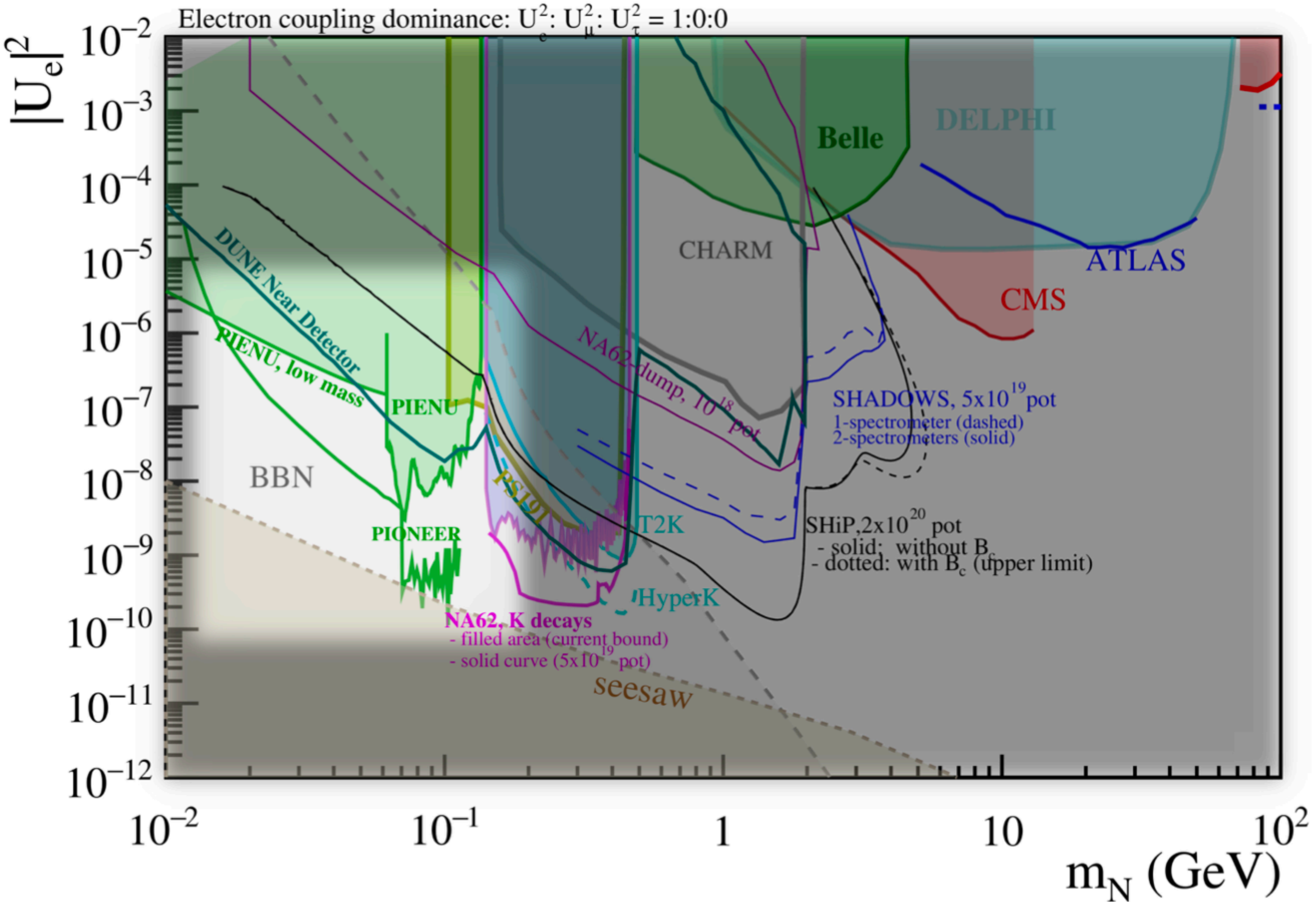
$$\ell = e, \mu, \tau, \chi_1, \chi_2 ... \chi_k$$



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



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]

Previous $R^{\pi}_{e/\mu}$ experiments

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

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

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

Theory of the Fermi Interaction

R. P. Feynman and M. Gell-Mann
California Institute of Technology, Pasadena, California
(Received September 16, 1957)

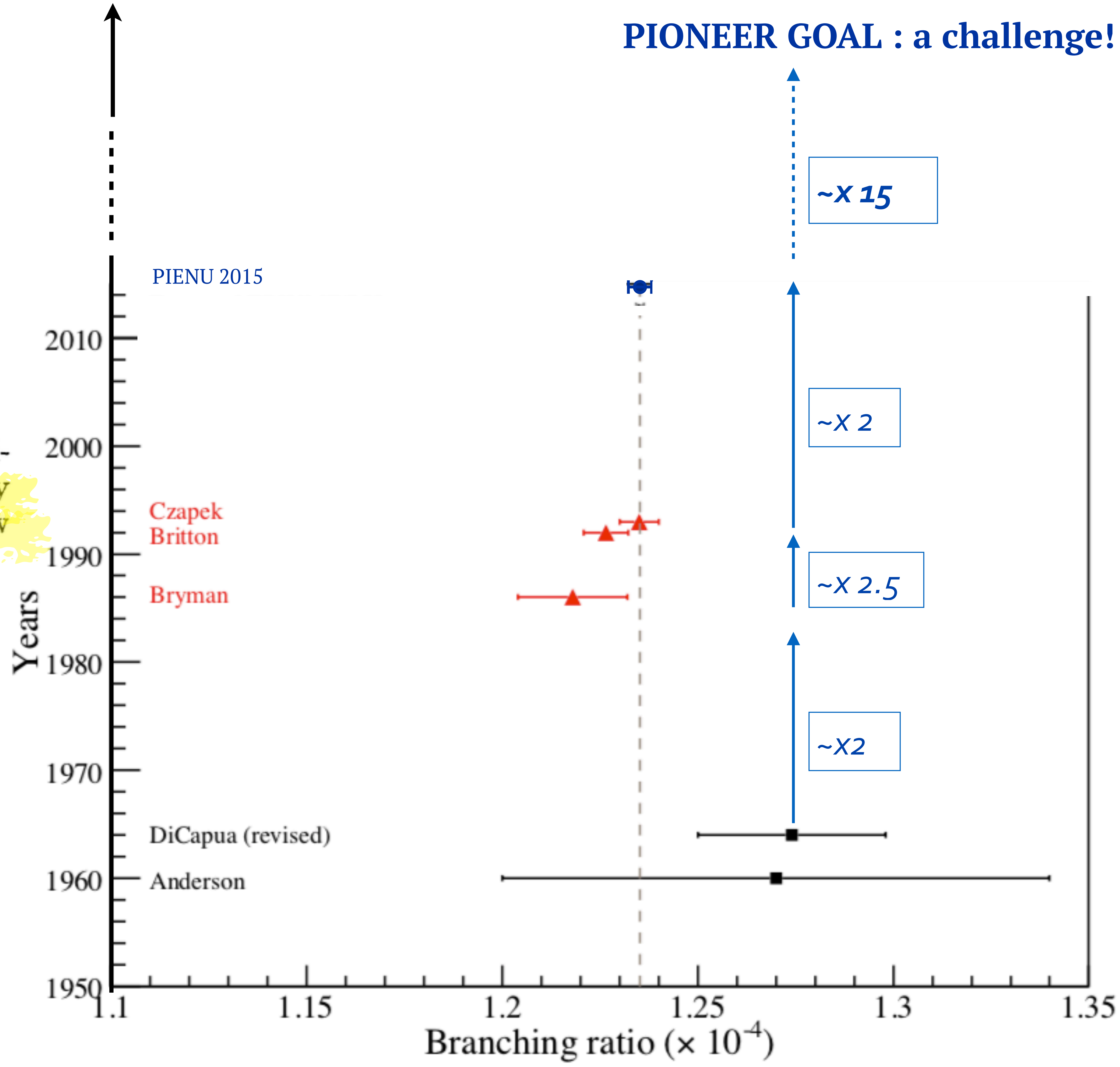
Experimentally[16] no $\pi \to e + \nu$ have been found, indicating that the ratio is less than 10^{-5}. This is a very serious discrepancy. The authors have no idea on how it can be resolved.

1958: First positive experimental result at CERN (PRL 1,7 (1958))

PDG 2018 $\boxed{\pm 0.19\ \%}$

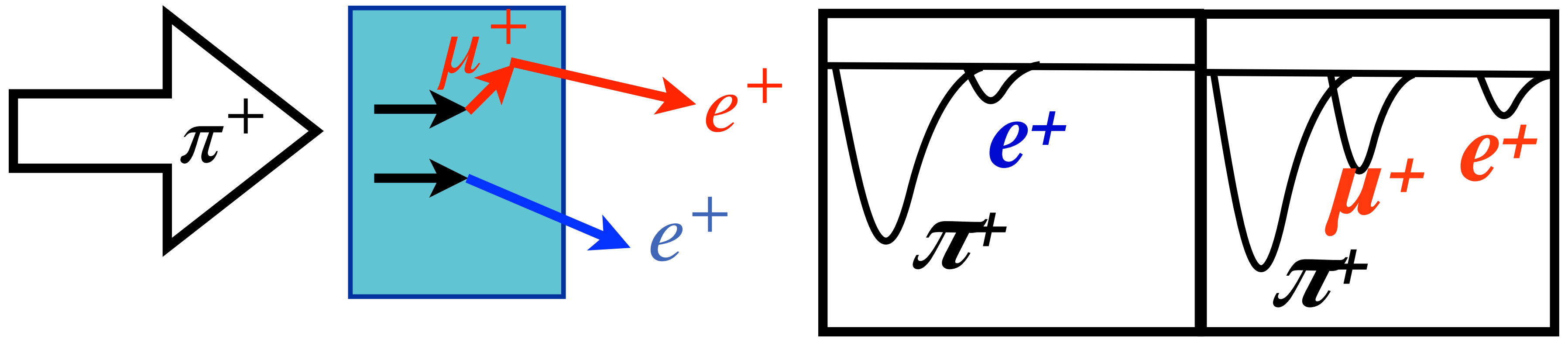
VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1.2327±0.0023 OUR AVERAGE						
1.2344±0.0023±0.0019	400k	AGUILAR-AR...	15	CNTR	+	Stopping π^+
1.2346±0.0035±0.0036	120k	CZAPEK	93	CALO		Stopping π^+
1.2265±0.0034±0.0044	190k	BRITTON	92	CNTR		Stopping π^+
1.218 ±0.014	32k	BRYMAN	86	CNTR		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.



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

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



What π decays 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

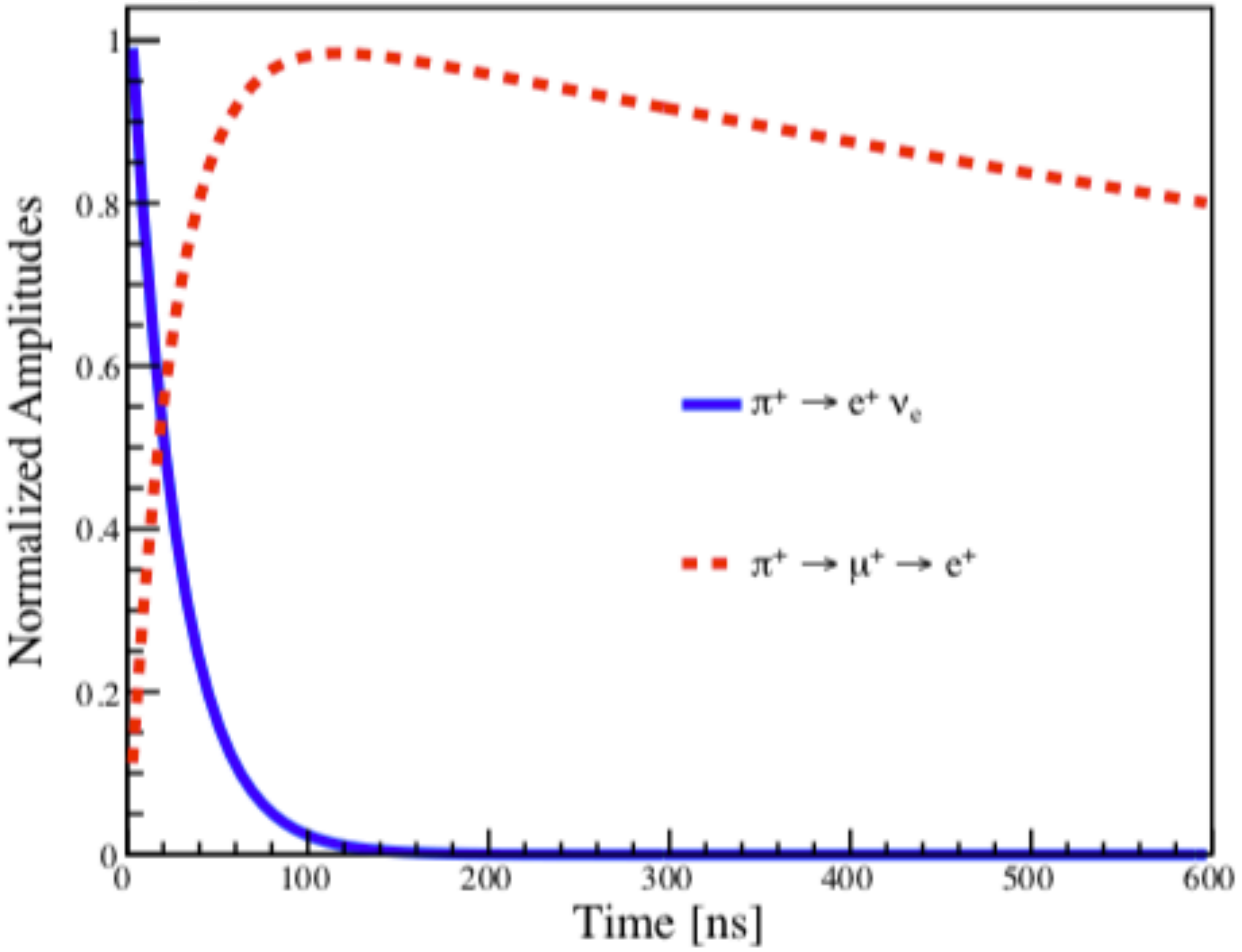
Muon lifetime: 2197 ns

Pion mass: 139.6 MeV

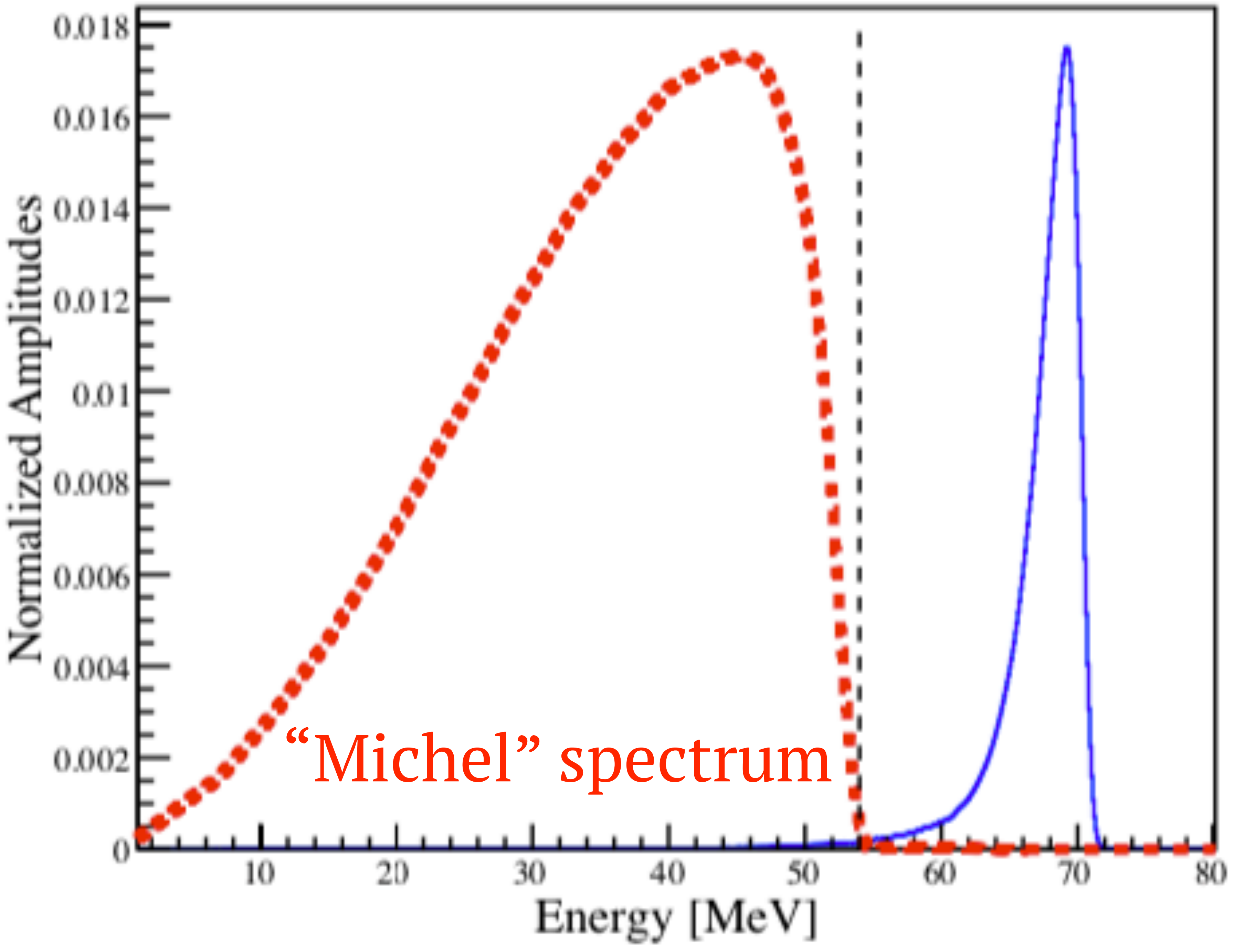
Muon mass: 105.7 MeV

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

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



Time spectrum

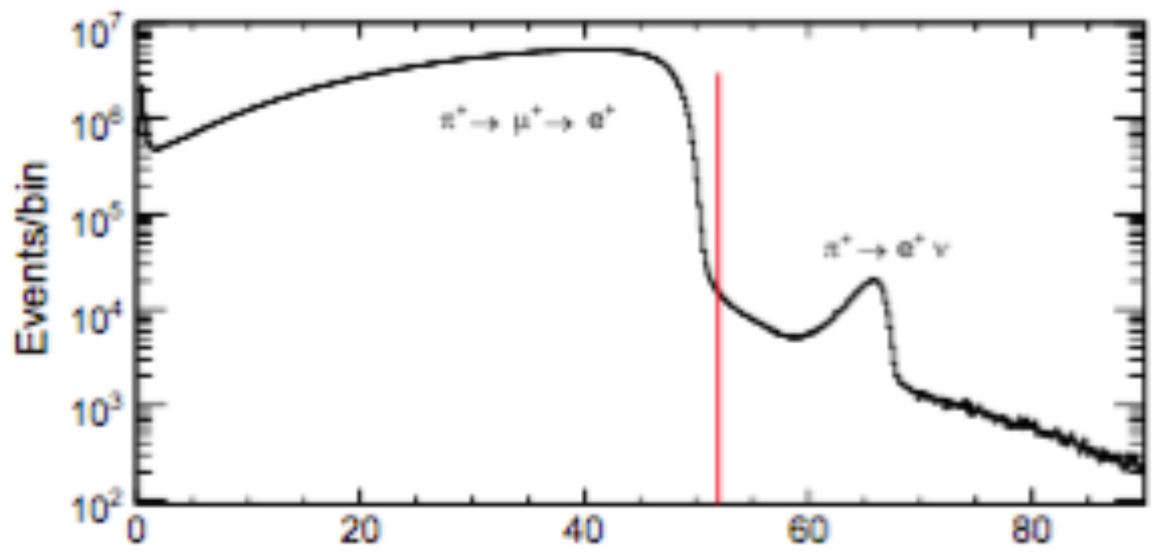


e^+ energy spectrum

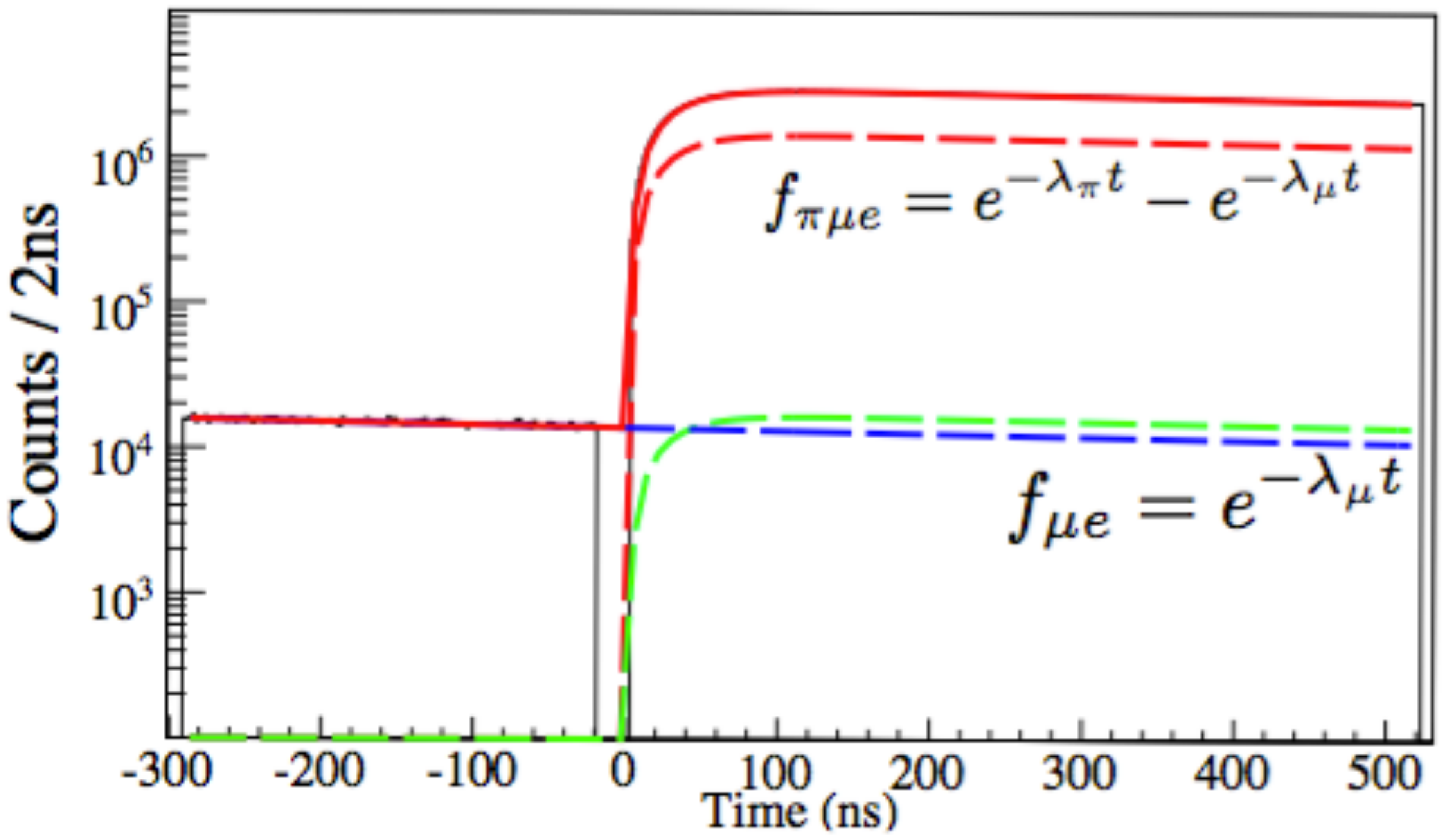
$$R^{\pi}_{e/\mu} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$: how is it measured?

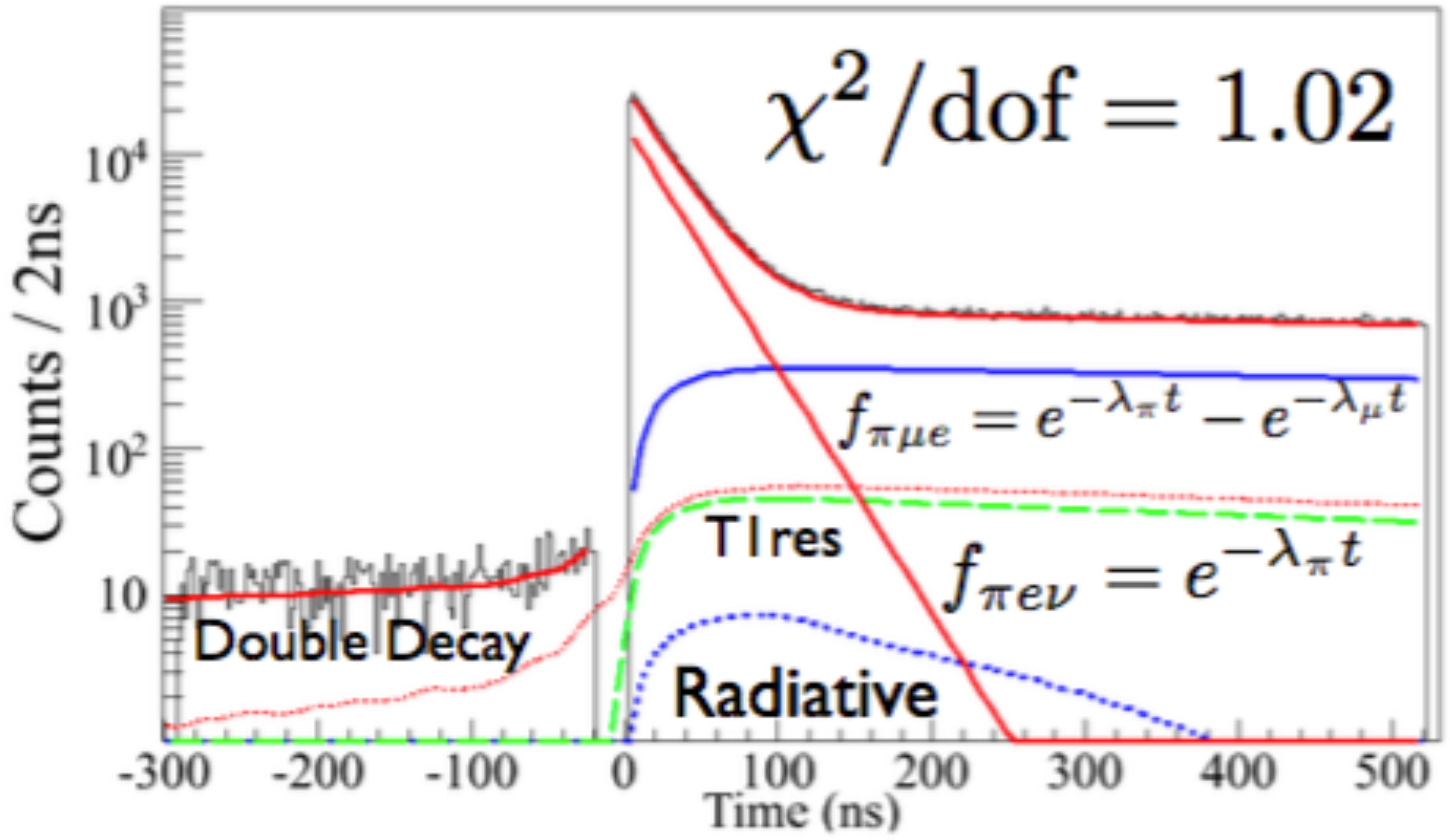
$\mu \to e\nu\bar{\nu}$

E<52MeV



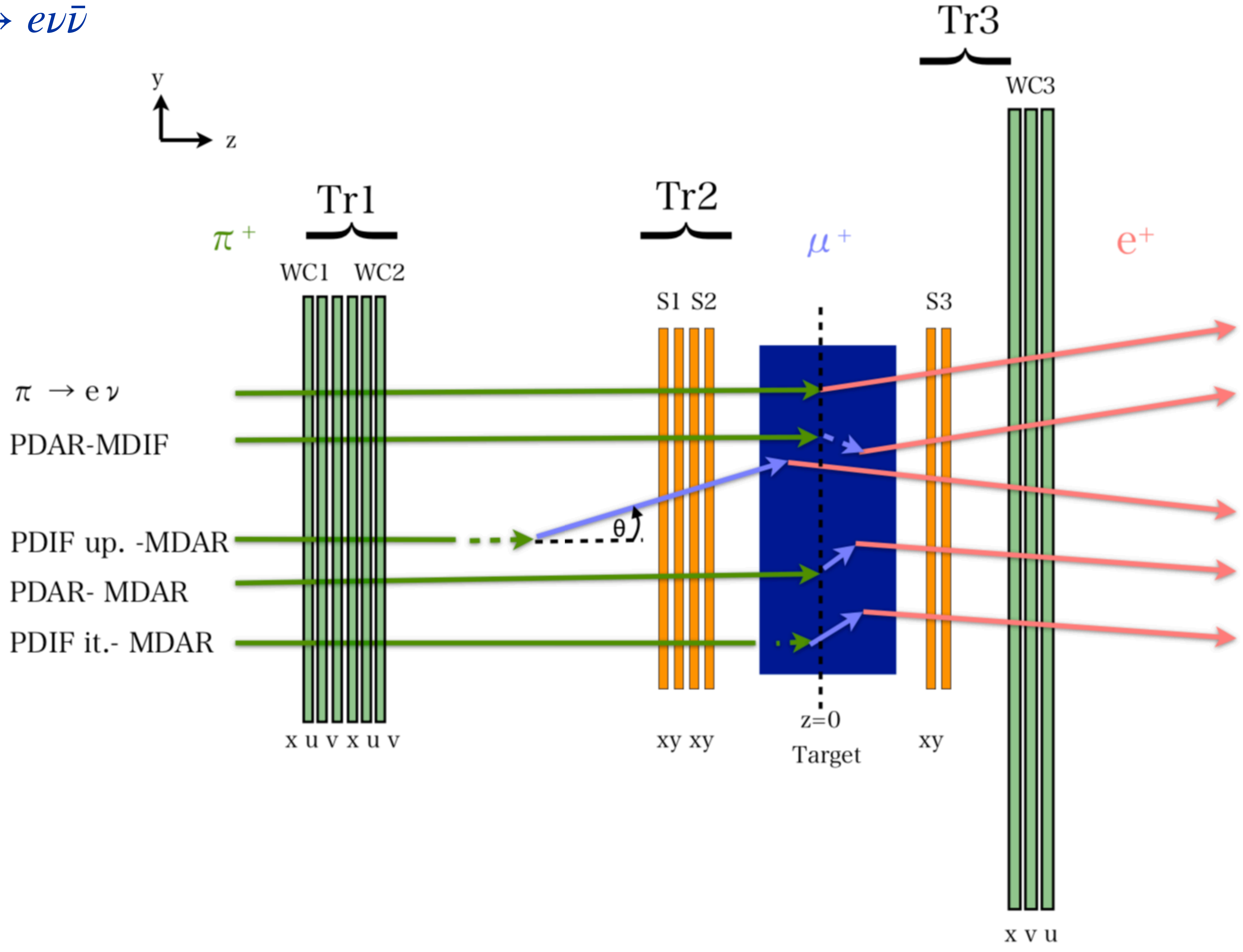
E>52MeV



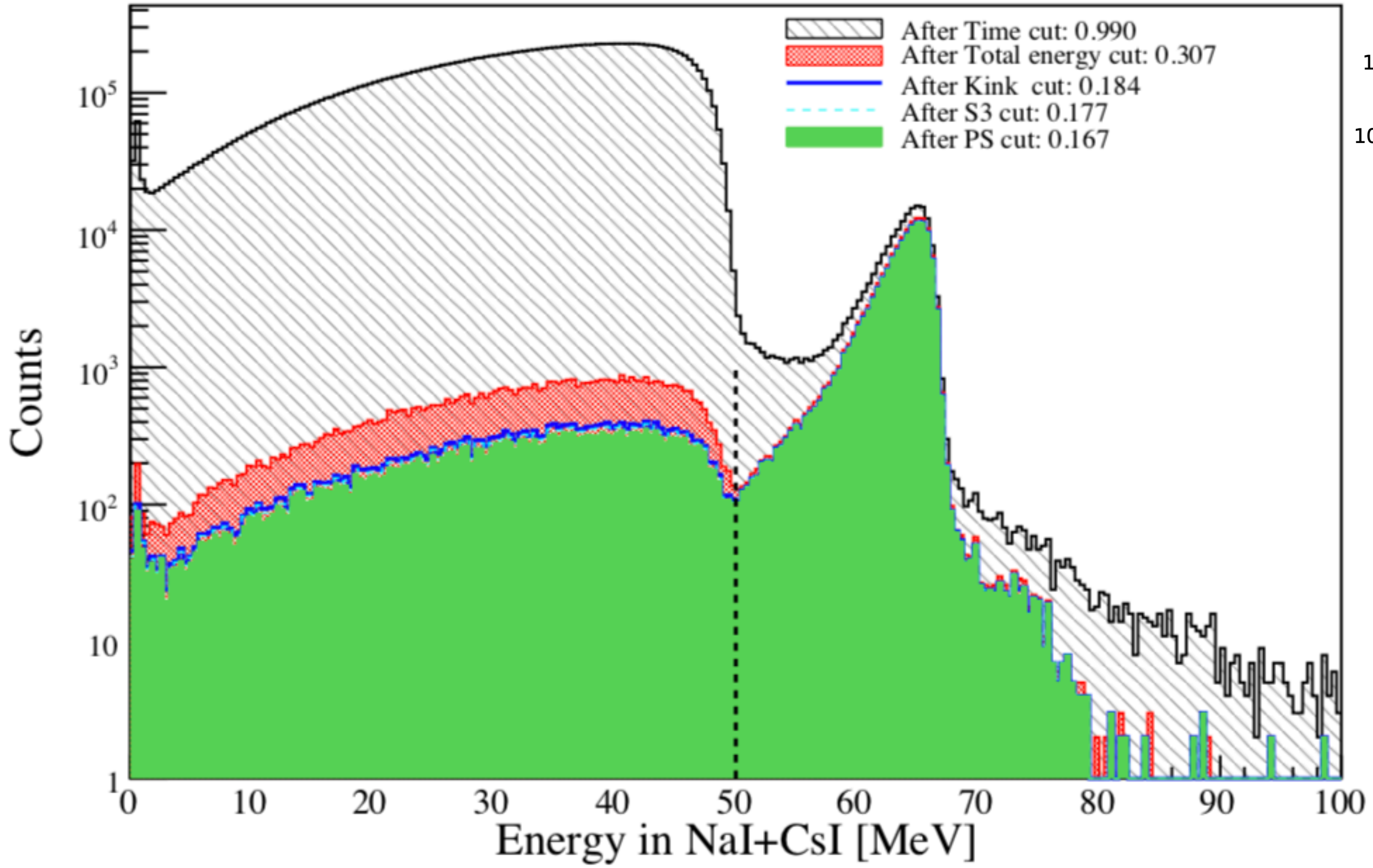


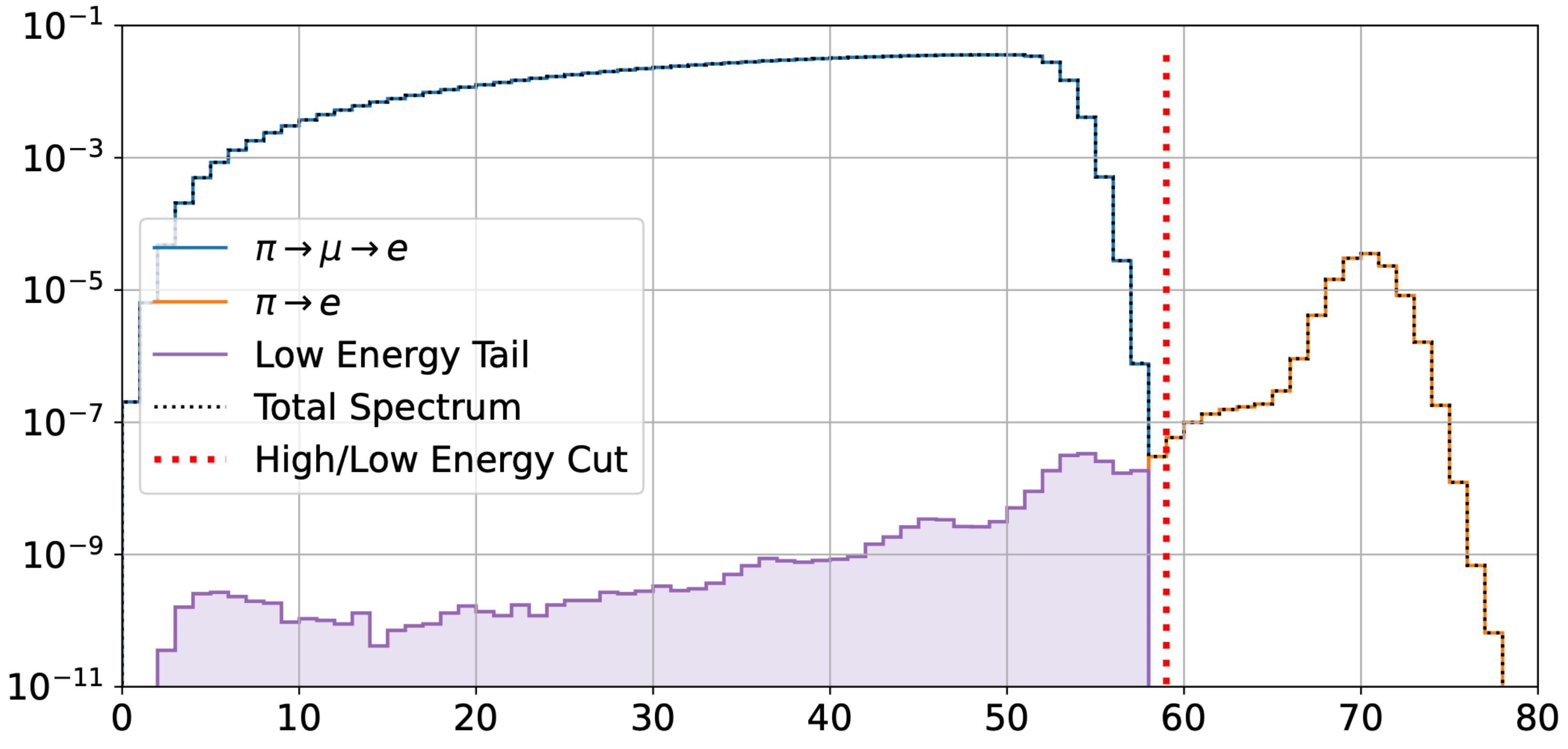
$$R^{\pi} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$: how is it measured?

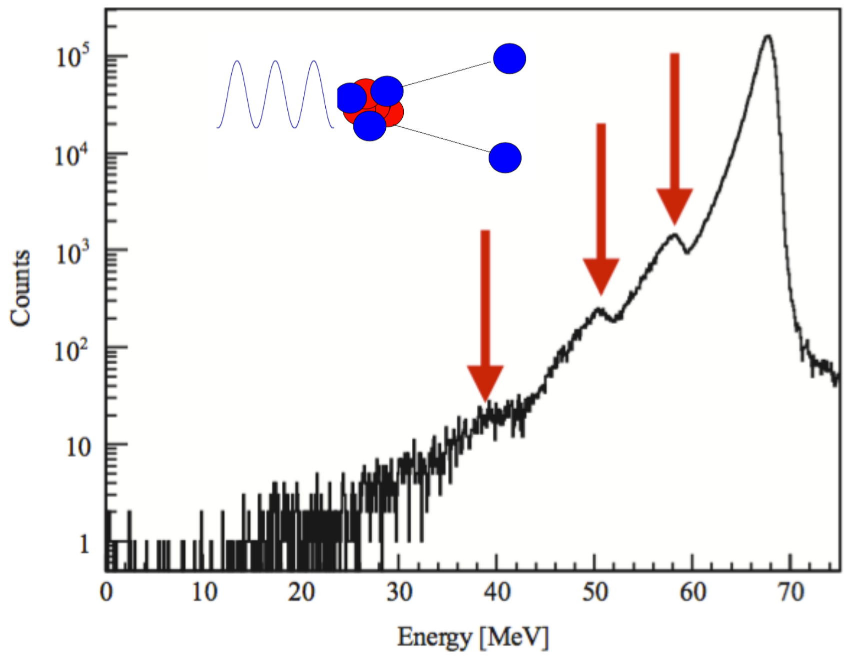
$\mu \to e\nu\bar{\nu}$



Tail correction: major uncertainty. “the devil’s in the (de)tail”







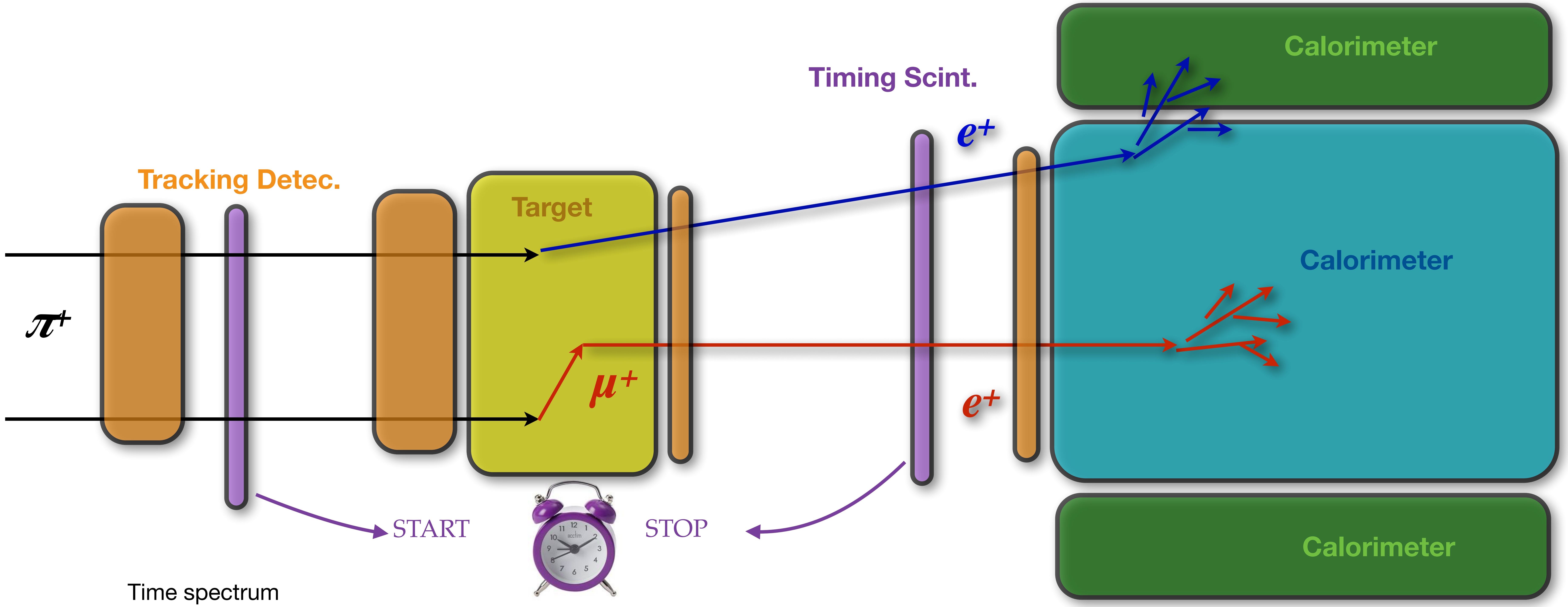
A. Aguilar-Arevalo et al., Nuclear Instruments and Methods in Physics Research A 621 (2010) 188–191

Low energy tail buried under the Michel spectrum caused by:

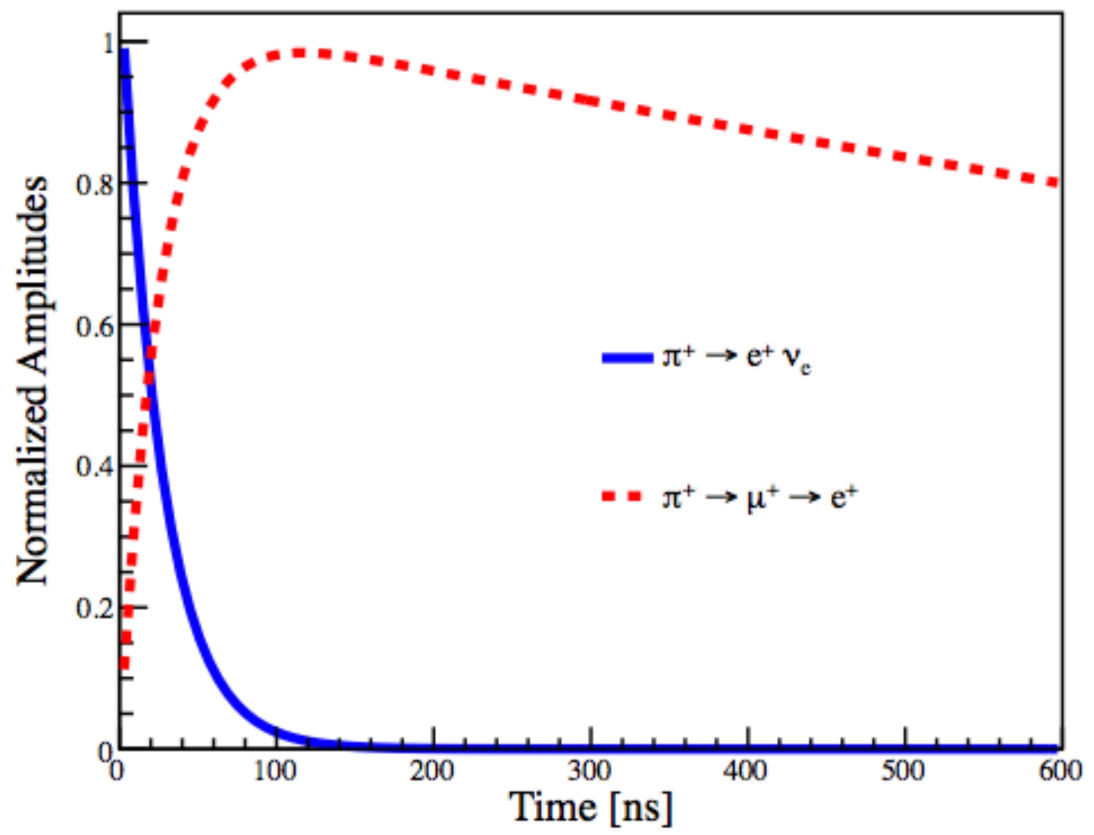
- finite energy resolution of the calorimeter
- photo-nuclear interactions (^{127}I(γ,n))
- shower leakage
- geometrical acceptance
- radiative decays
- etc

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

Schematics of the PIENU experiment



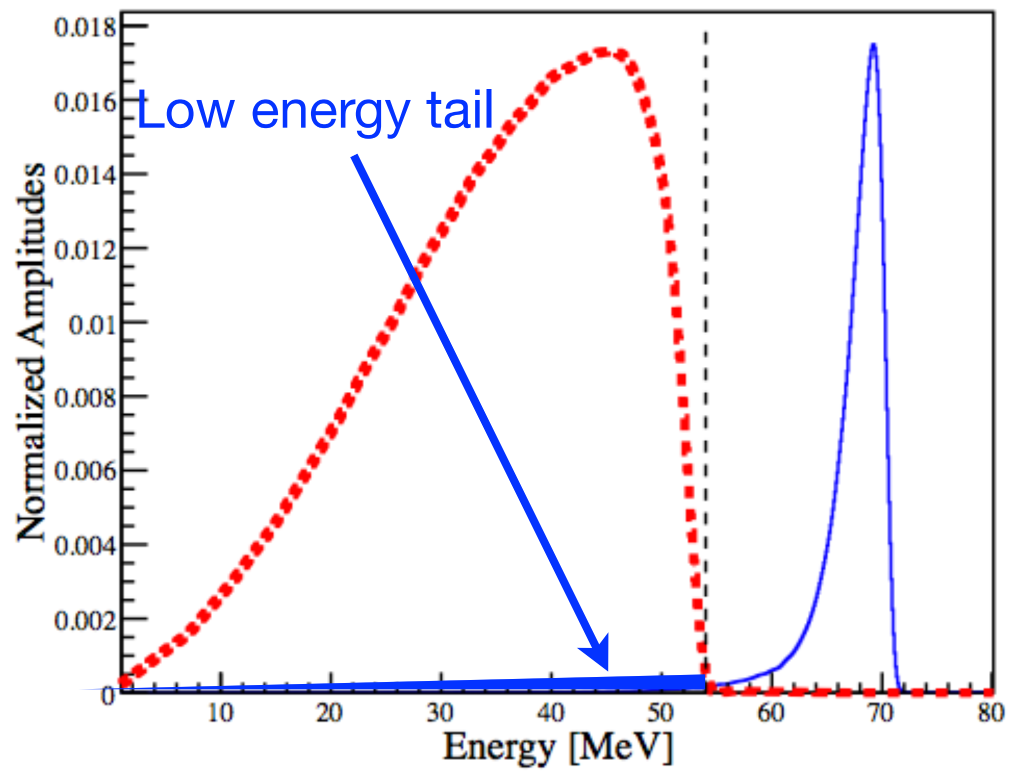
Time spectrum



Characteristics

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

Energy spectrum



PIONEER DETECTOR CONCEPT - best of PIENU and PEN worlds

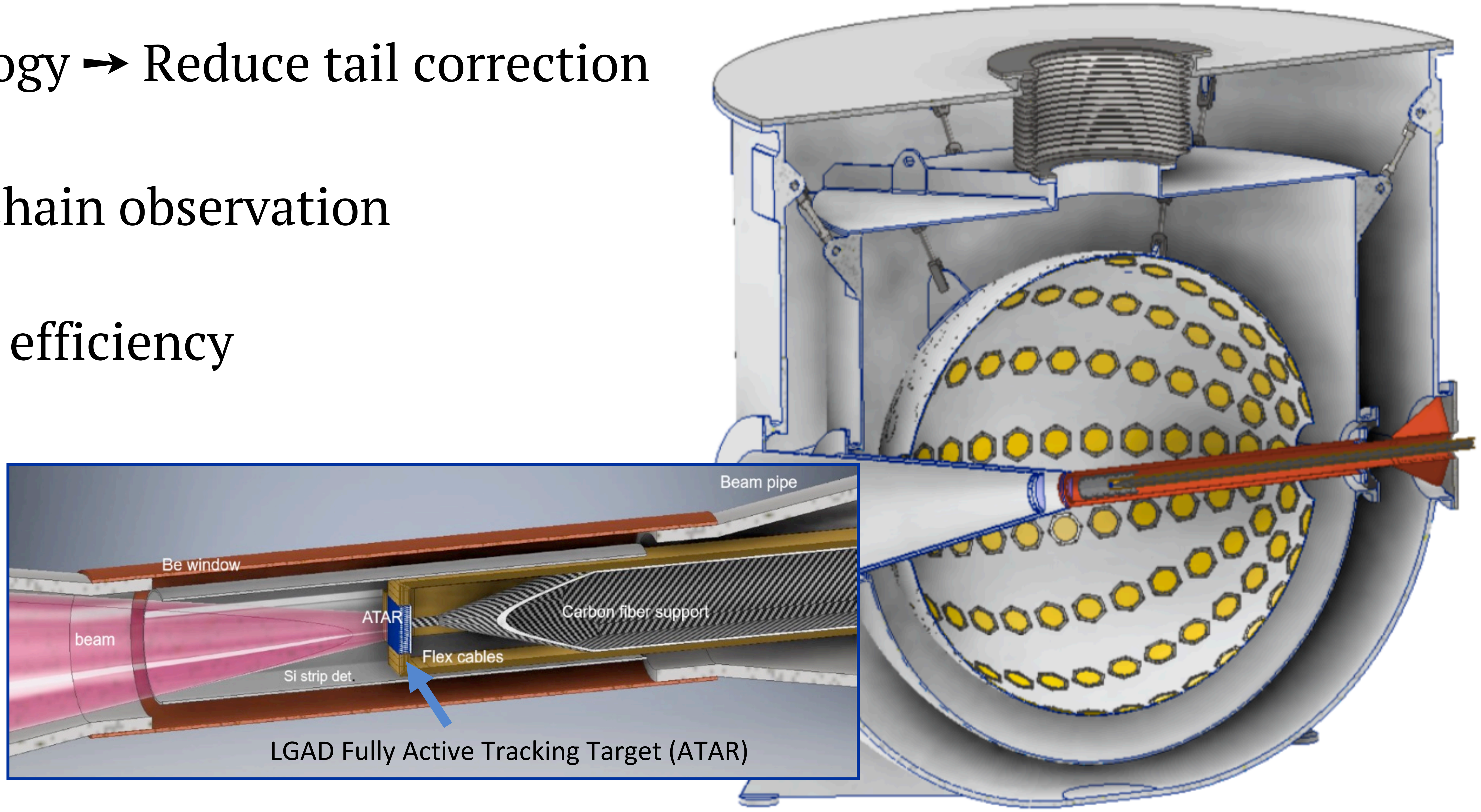
- Building on previous experiences (PIENU and PEN/PIBETA) : use of emerging technologies (LXe, LGADs)

  - 25 X_0, 3π 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 $\pi \to \mu \to e$ decay chain observation

  - Fast electronics and pipeline DAQ ➙ Improve efficiency

  - Intense Pion beam at PSI

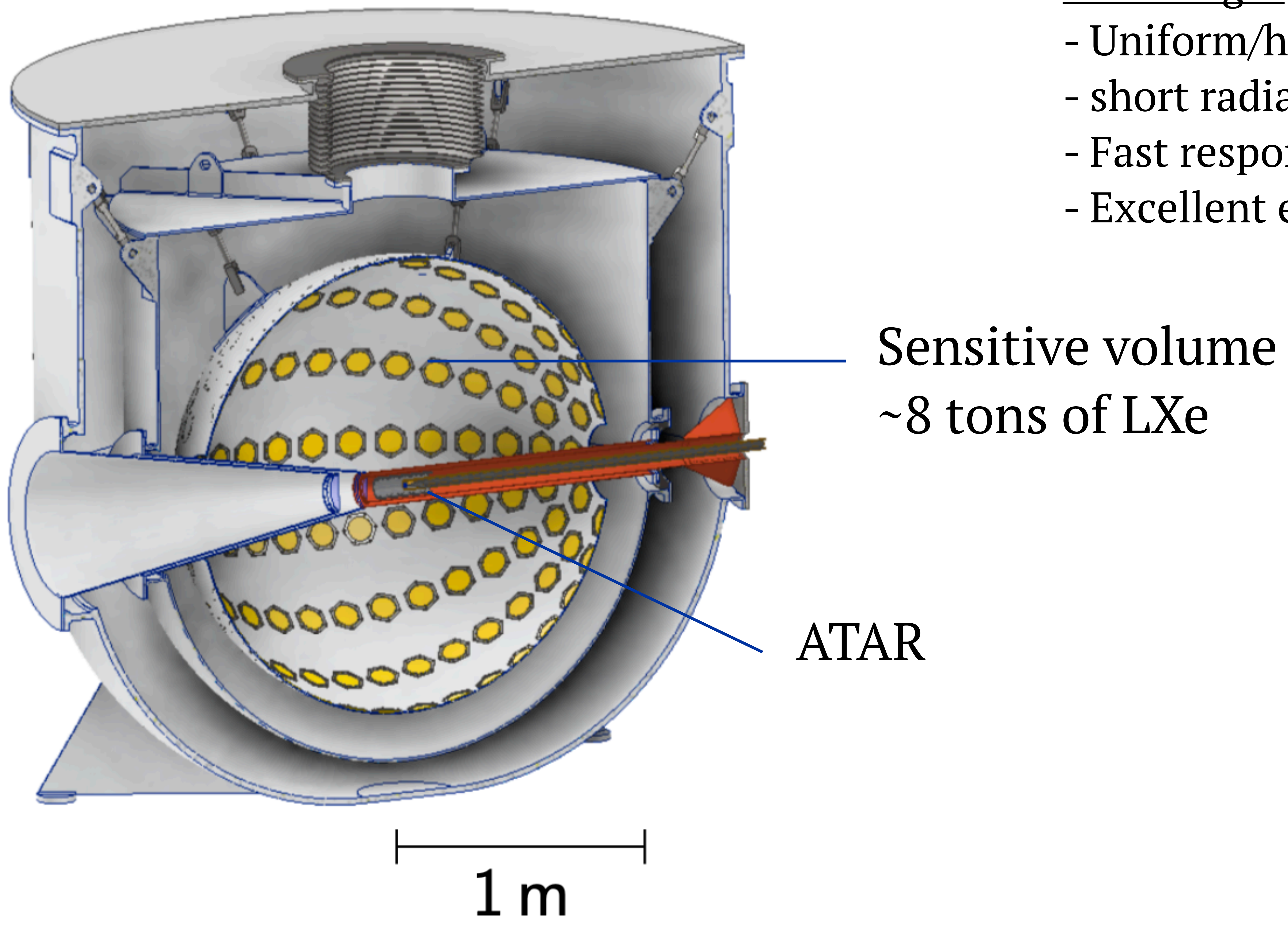


LGAD Fully Active Tracking Target (ATAR)

PIONEER DETECTOR CONCEPT : Calorimeter

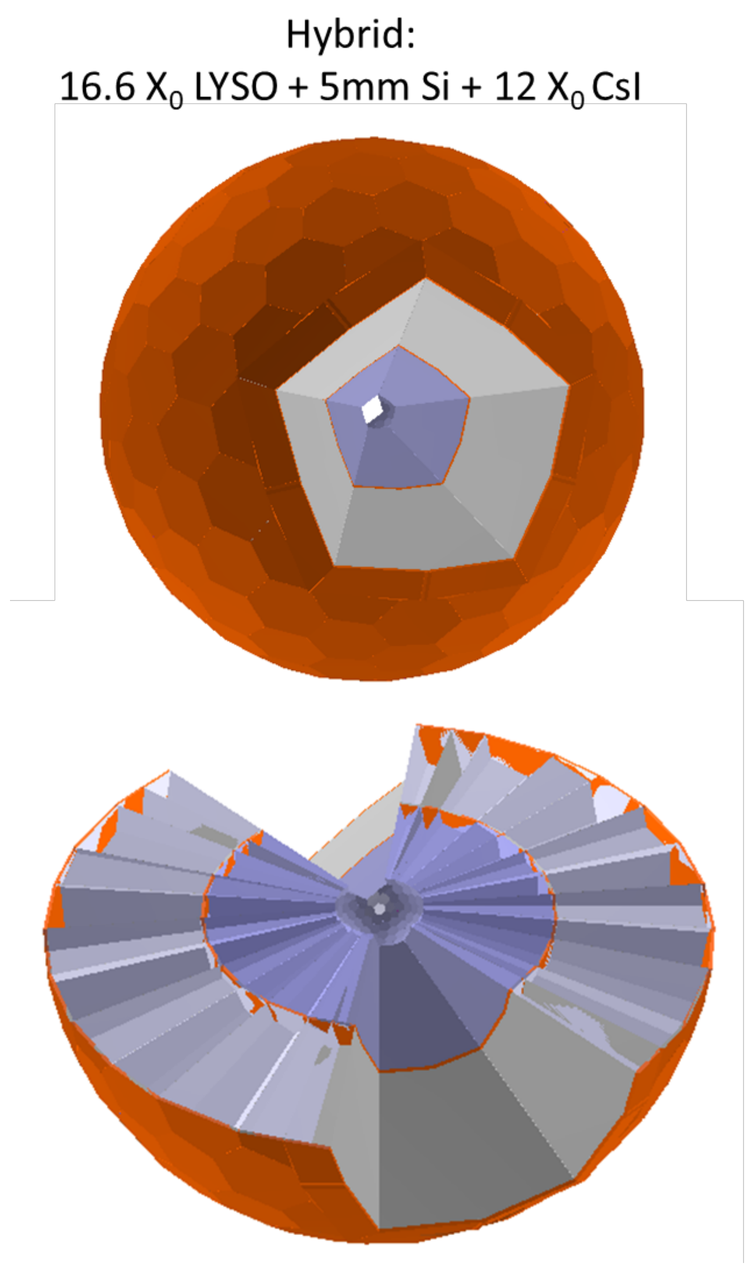
- 25 X_0, 3π sr calorimeter ➙ High energy resolution, fast, symmetric ➙ Much smaller tail, better pileup suppression

Baseline design: LXe (experience from MEG)



Advantages:
- Uniform/homogeneous volume
- short radiation length
- Fast response
- Excellent energy resolution

Question marks
- (un)known issues with VUV SiPM
- handling pileup
- cost…

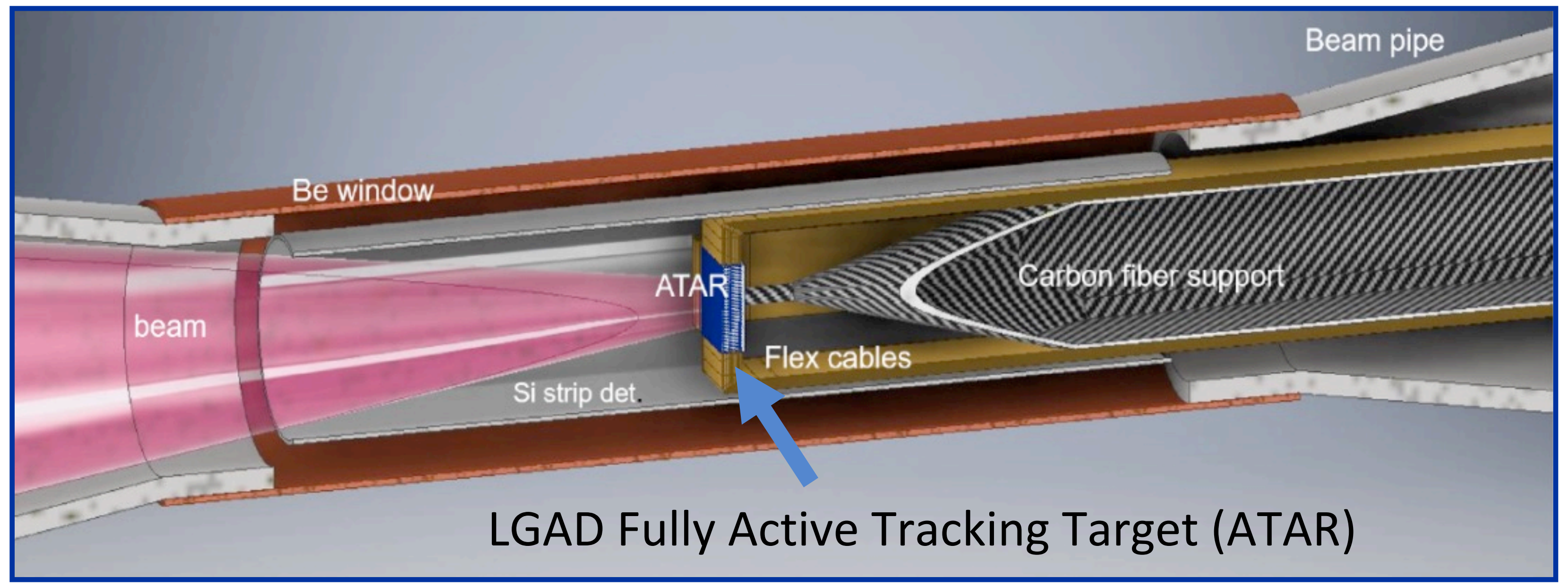


Alternative: crystal calorimeter (CsI in combination with LYSO?)

Advantages:
- Not cryogenic
- fast response
- “natural segmentation”

Question marks
- energy resolution good enough?
- possible to make long crystals?

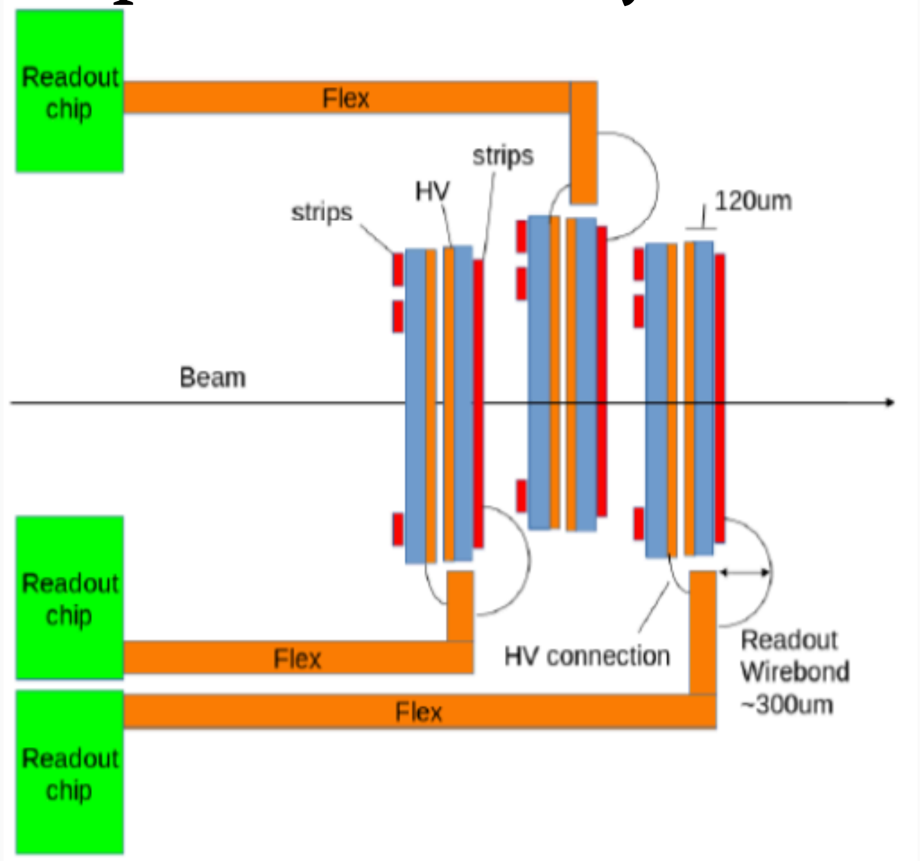
PIONEER DETECTOR CONCEPT : Active Target (ATAR)



LGAD Fully Active Tracking Target (ATAR)

- active target ("4D") based on LGADs(Low gain avalanche diode) technology allowing high level of DIF suppression

Developments led by UCSC

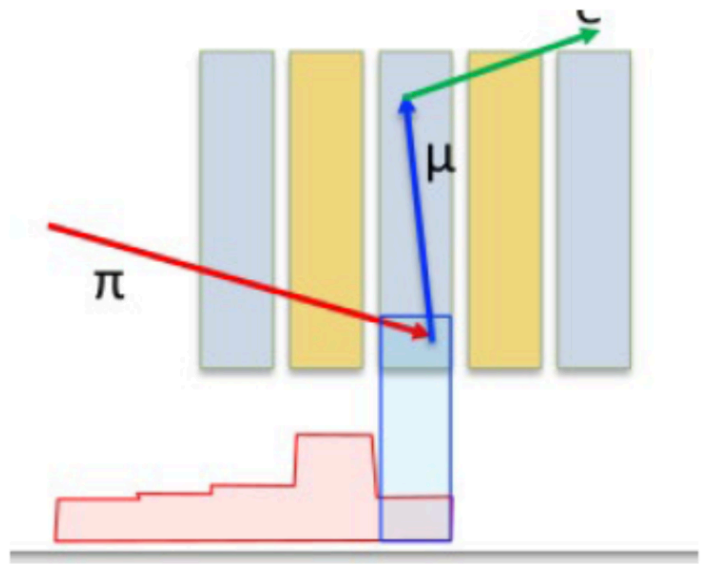


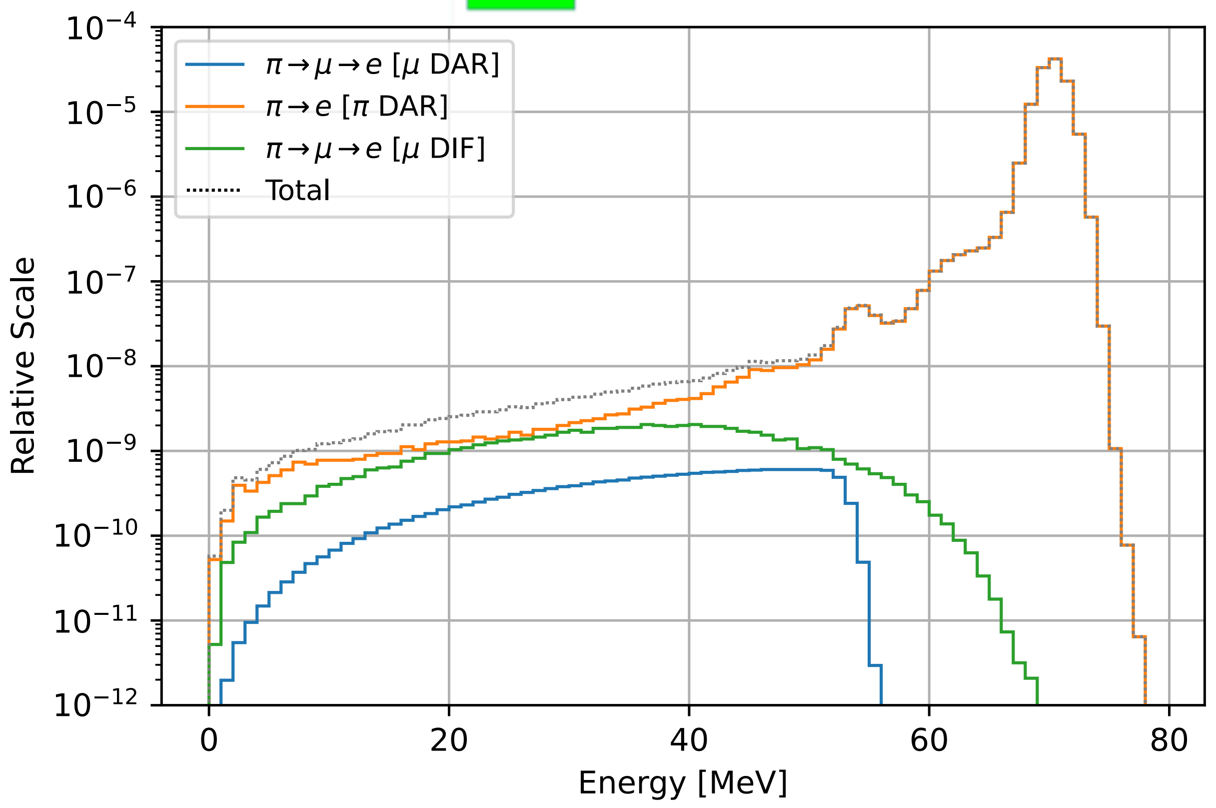
Requirements

- High longitudinal segmentation: to detect the decay in flight of pions
- Compact: minimize dead material (including air) in between planes and around ATAR
- Fast collection time: separate pulses that are close in time to reconstruct the pion decay chain
- Large Dynamic range: detect energy deposit in 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 stacks of 2 with facing HV side and rotated by 90°





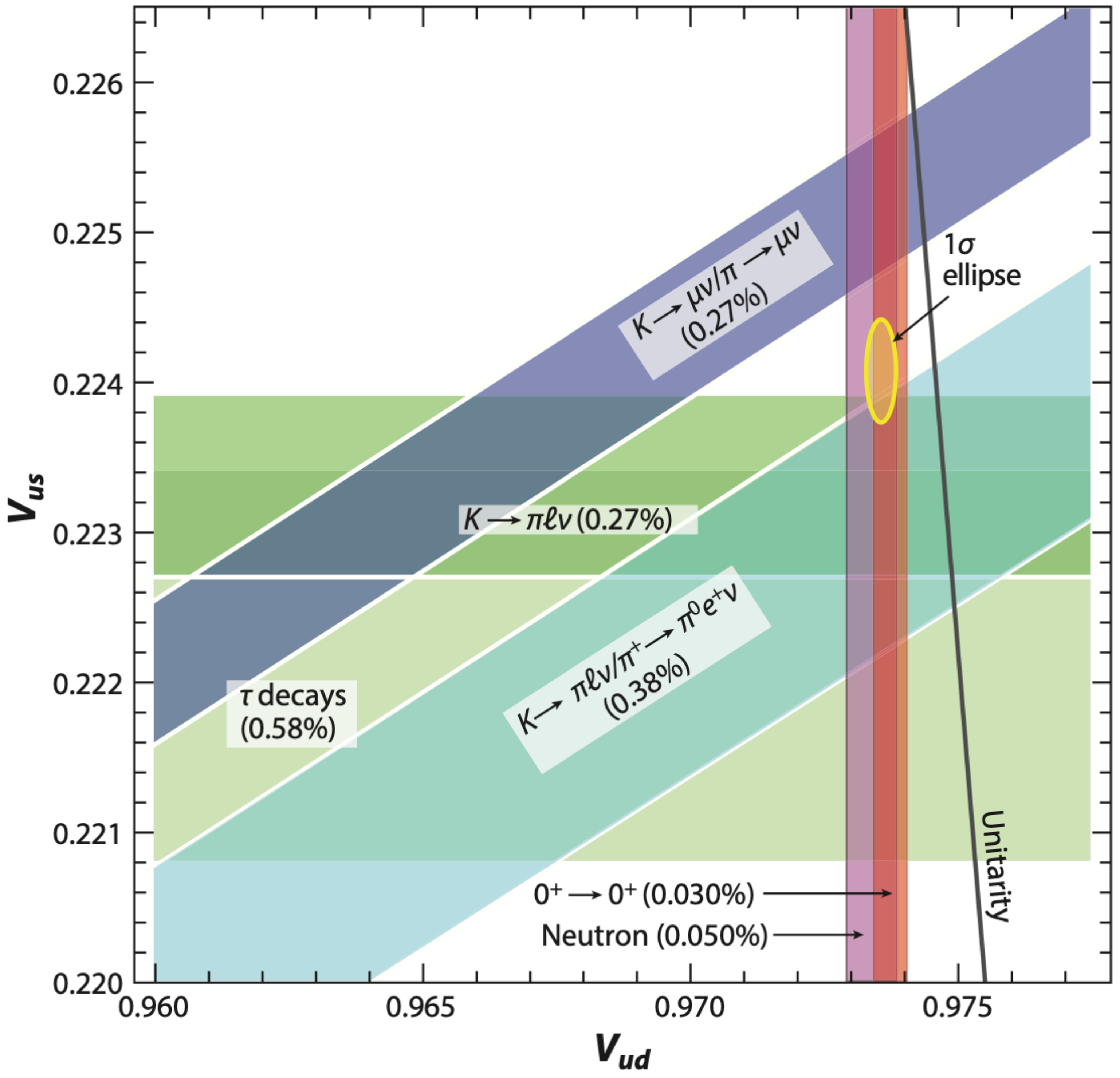
Physics case IV: Testing CKM unitarity $\boxed{V_{ud}}$, $\boxed{\frac{V_{us}}{V_{ud}}}$

tested in K decays

tested in super-allowed β decays, neutron lifetime

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

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



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

PIONEER Phase II goal:

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

A. Czarnecki et al. *Phys.Rev.D* 101 (2020) 9, 091301

PIONEER Phase III goal:

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

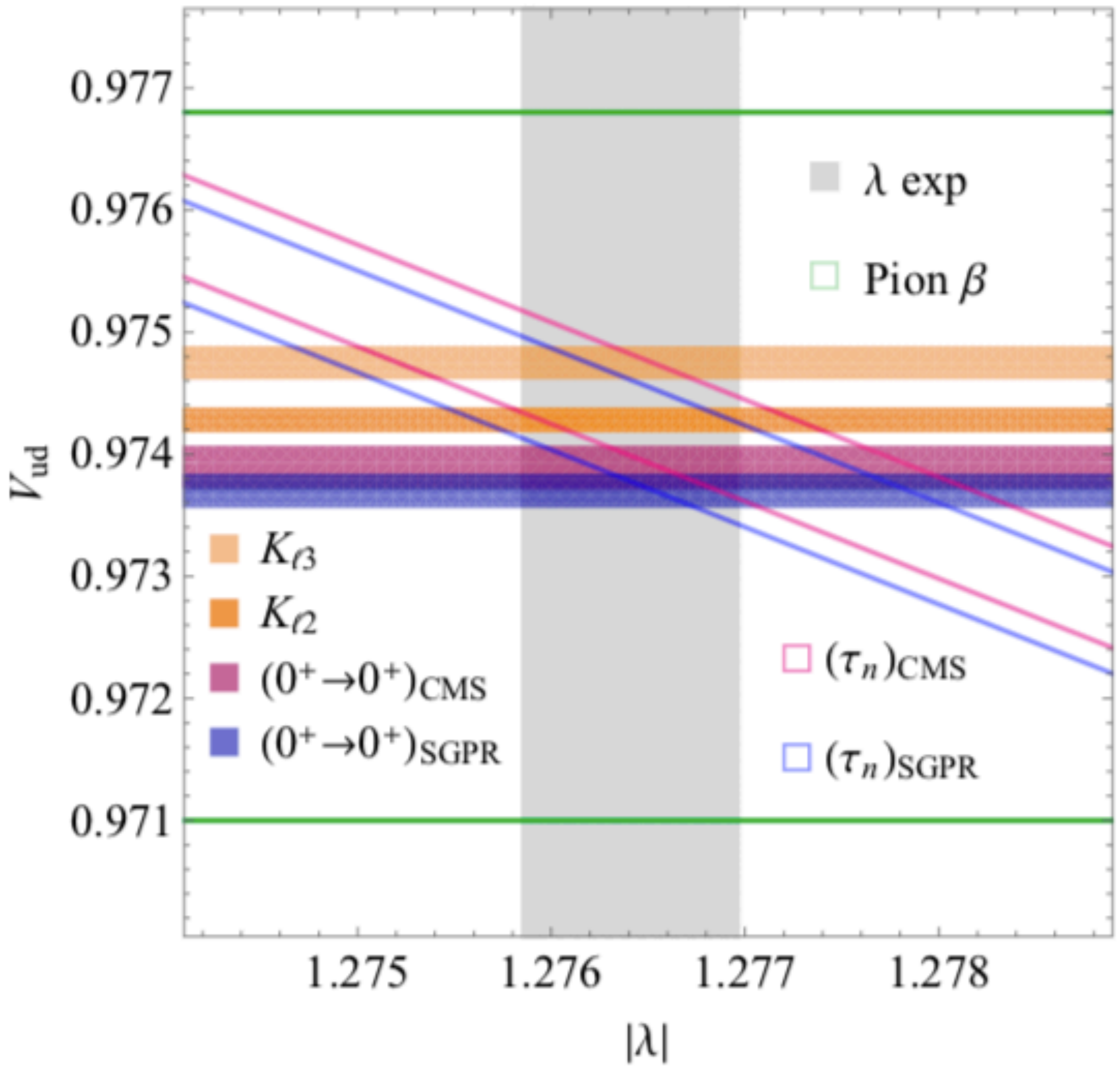
$\pi^+ \to \pi^0 e^+ \nu$ is the theoretically cleanest method to obtain V_{ud}

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

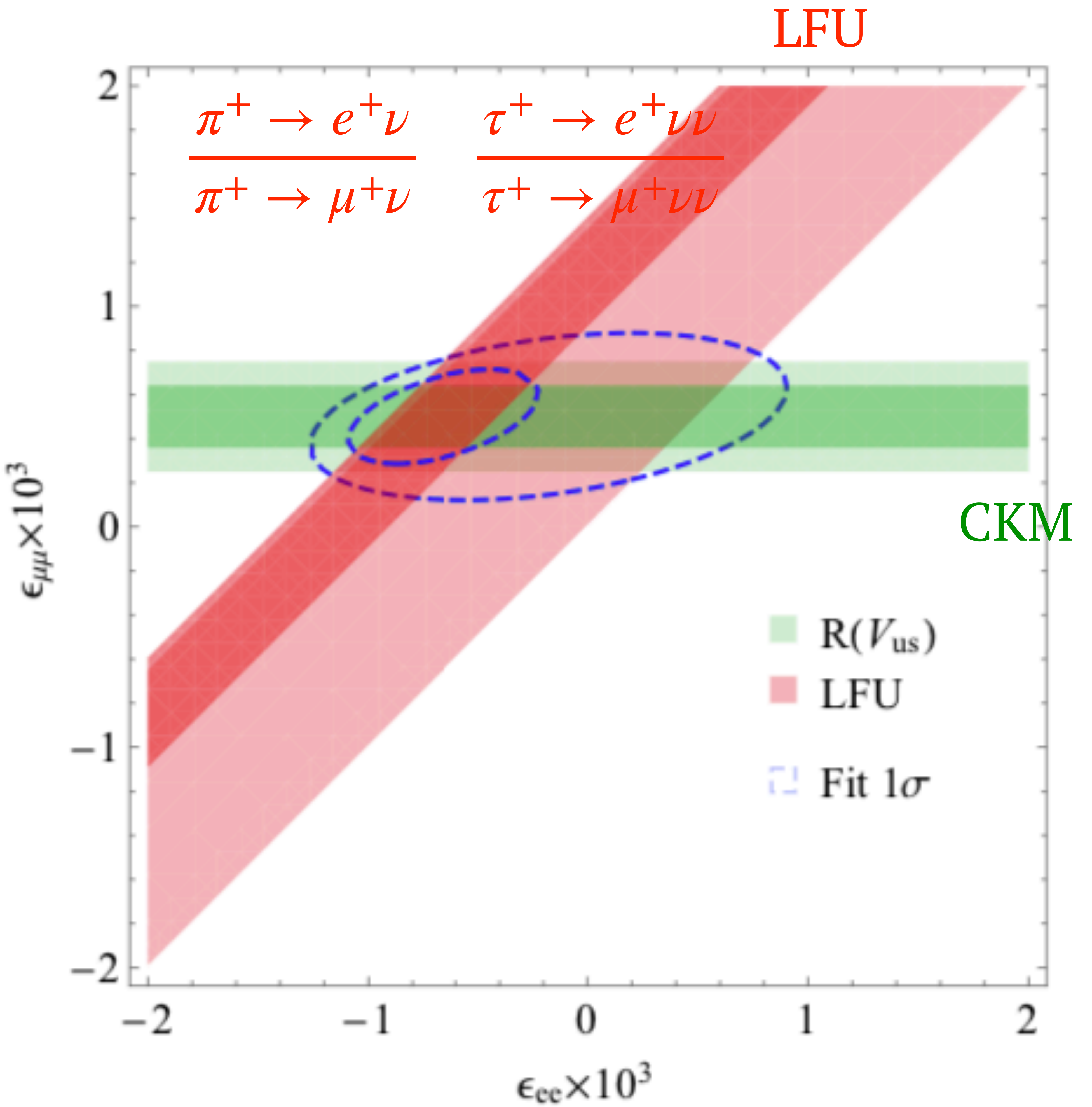
$B(\pi^+ \to \pi^0 e^+ \nu) = (1.038 \pm 0.004_{stat} \pm 0.004_{syst} \pm 0.002_{\pi e2}) \times 10^{-8}$

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

Physics case IVb: LFUV and CKM unitarity might be connected



if CKM first row unitarity assumed V_{ud} value obtained from kaon decays is different from super-allowed beta decay!



V_{ud} tension as a sign for LFUV?

Crivellin & Hoferichter
Phys. Rev. Lett. 125, 111801 (2020)

Modified $W l \nu$ couplings $G_F = G_F^{\mathscr{L}}(1 + \varepsilon_{ee} + \varepsilon_{\mu\mu})$

Conclusions and opportunities!

- PIONEER is a major new experiment addressing emerging SM **anomalies in flavor physics**
  Unique new information on **Lepton Flavor Universality and CKM unitary** with unprecedented precision
- Precision experiment: Sensitive to **very high energy scales**.
- 2-body spectra very sensitive to a wide range of **exotics**

- 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

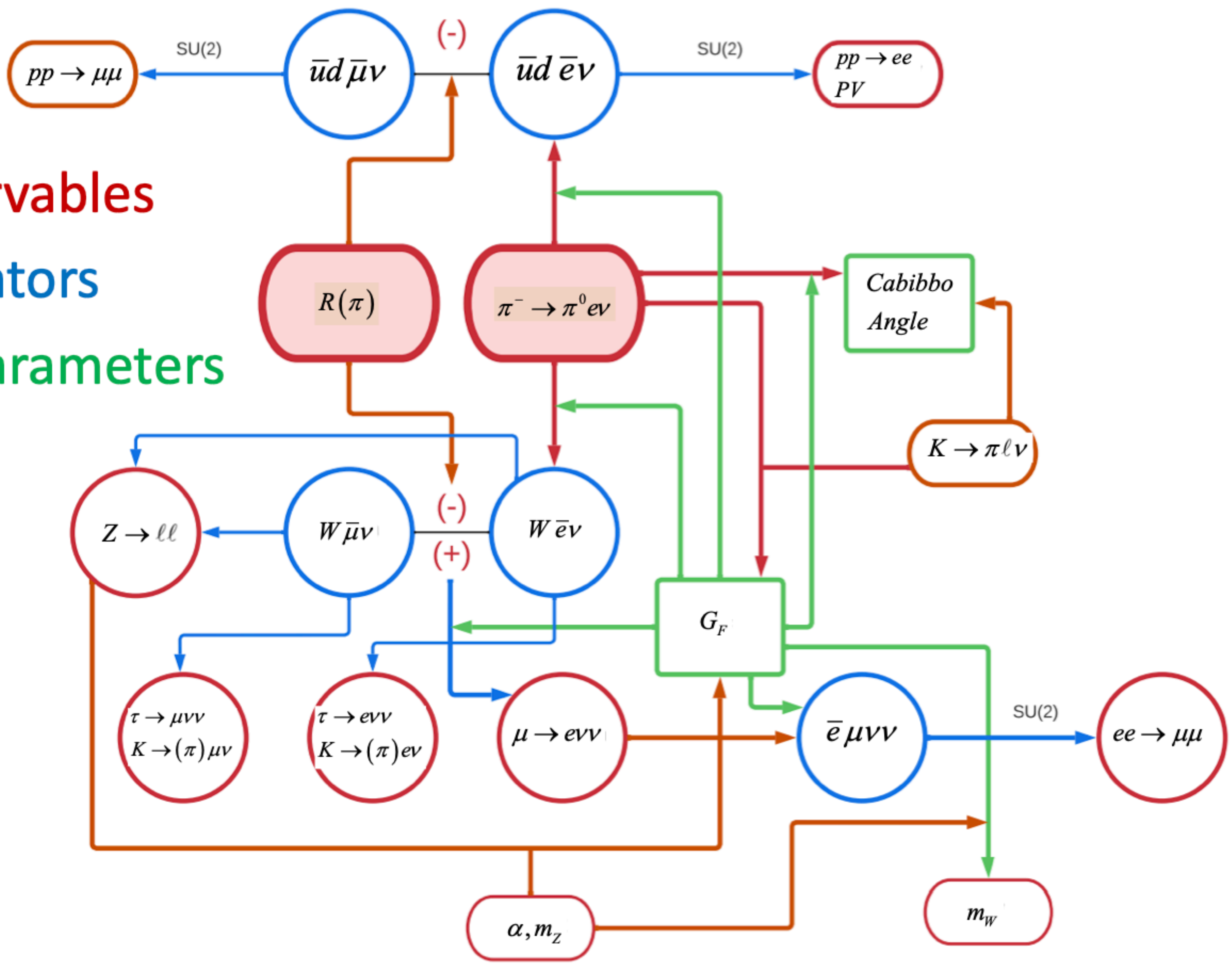
- Approved Phase 1 run at PSI. Expected start of data taking ~ 5 years timescale (first beamtime in PiE5 for beam characterization happened a few months ago)

- PIONEER is employing state-of-the-art technology (**LGADs, Noble liquid calorimetry**)

- 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

- Observables
- Operators
- SM Parameters



From A. Crivellin's talk
Rare Pion Decay Workshop
Santa Cruz 06-08 Oct 2022

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**