PIONEER

A next-generation rare pion decay experiment

David Hertzog

On behalf of the emerging PIONEER Collaboration

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[18] Okayama University
[19] Brookhaven National Laboratory
[20] KEK
[21] Indiana University
[22] University of Victoria
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[24] Fermilab
[25] ETH Zurich
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[27] Stoney Brook University
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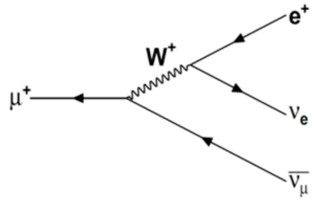
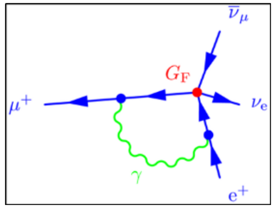
Lepton Flavor Universality is a simple concept:
The weak interaction is the same for e / μ / τ leptons

- The weak-interaction "strength" is associated with the Fermi Constant, G_F
- Muon decay provides the most precise measurement
  - Technically it determines G_μ, which is usually just called G_F … because we believe in LFU !



G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)

$$\frac{1}{\tau_{\mu^+}} = \frac{{G_F}^2 m_\mu^5}{192\pi^3}(1+q)$$



PRL 106, 041803 (2011)
Phys. Rev. D 87, 052003 (2013)

PHYSICAL REVIEW D, VOLUME 60, 093006

Fermi constants and "new physics"

William J. Marciano
Brookhaven National Laboratory, Upton, New York 11973
(Received 25 March 1999; published 7 October 1999)

Questioning the validity of what others took to be true…

See Marciano's talk in Monday session

Status now? Strong hints of problems with various *B* decay channels and leptons*

$B \to D^{(*)}\tau\nu$ / $B \to D^{(*)}\mu\nu$; charged currents

$B \to K^{(*)}\mu\mu$ / $B \to K^{(*)}ee$; neutral currents

O(10%) deviations from universality !

Yet, in the measured ratio ($\pi \to e\nu$ / $\pi \to \mu\nu$) we deduce that

$$\frac{g_e}{g_\mu} = 0.9990 \pm 0.0009 \quad (\pm 0.09\%)$$

If the LFUV measurements are confirmed, it's not clear where the new physics is coming from

*See upcoming talks by Sara Celani (LHCb) and Alberto Martini (Belle II)

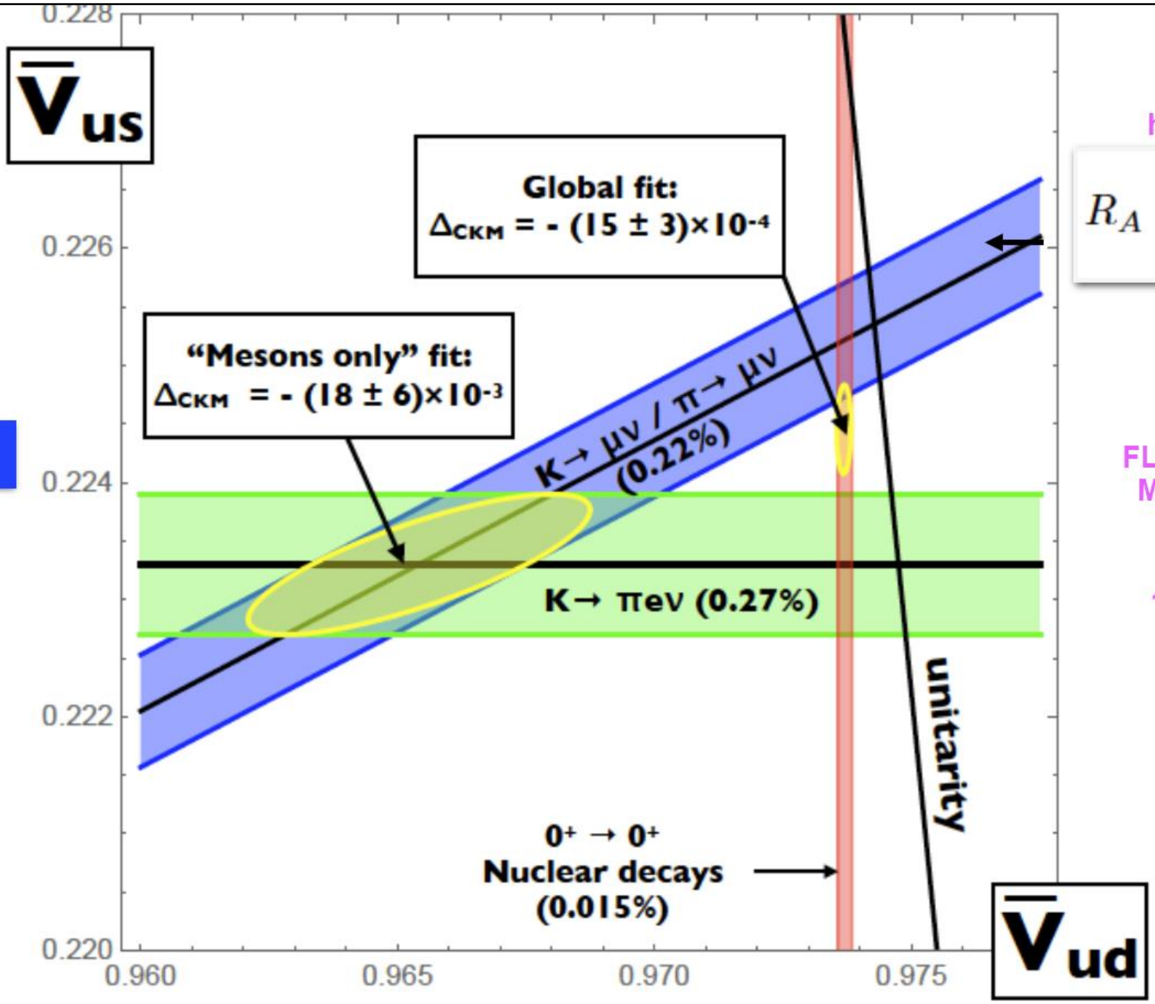
Vincenzo Cirigliano LANL, slides from DND-2020 Workshop

Additional hints of SM violations: Non-unitarity of CKM first row?

(or measurement or radiative correction problems?)

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

Two anomalies



Marciano, hep-ph/0402299, PRL

$$R_A = \frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$$

Flavianet WG, 1005.2323, EPJC
FLAG report, 1902.08191
MILC Coll.,1809.02827.

Hardy-Towner, 1411.5987, PRC 2020

Radiative Corrections fo V_{ud} from Seng et al, 1807.10197, PRL

Vincenzo Cirigliano LANL, slides from DND-2020 Workshop

Additional hints of SM violations: Non-unitarity of CKM first row?

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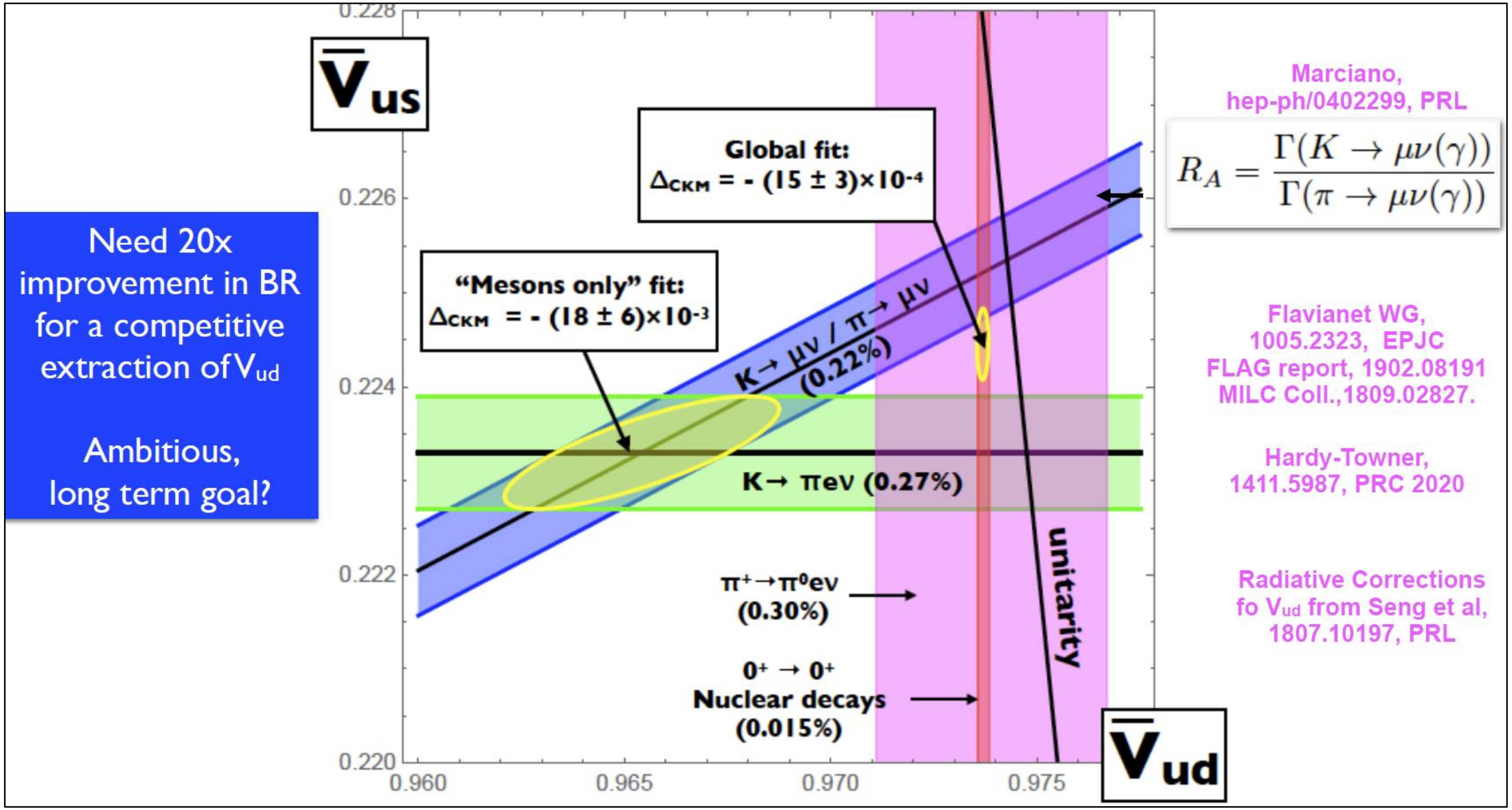
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$



Vincenzo Cirigliano LANL, slides from DND-2020 Workshop

Additional hints of SM violations: Non-unitarity of CKM first row?

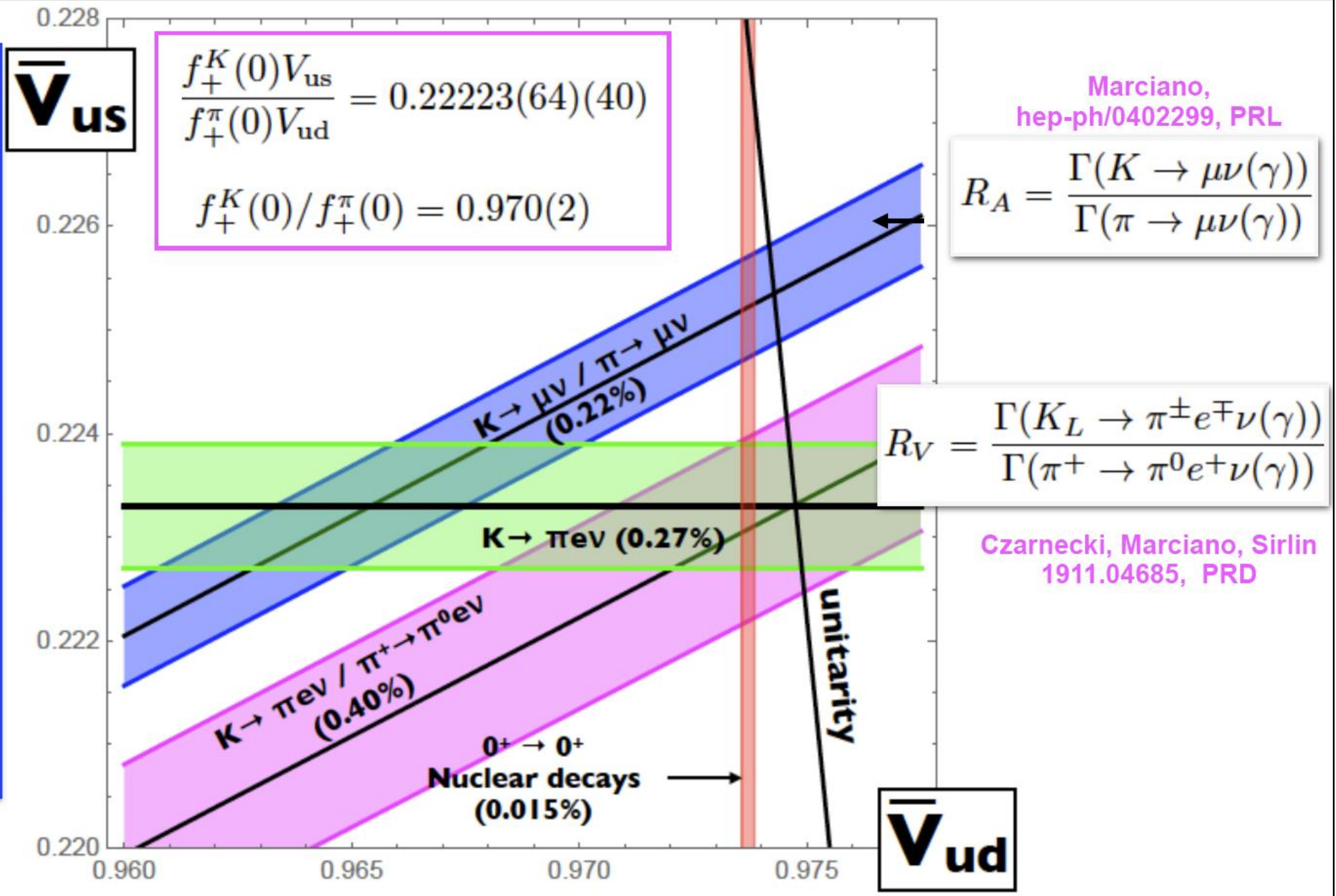
(or measurement or radiative correction problems?)

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

R_V is nearly competitive with R_A. Hints to yet another tension!

3x improvement in PIBETA BR, along with modest improvement in K form factor and BRs, would lead to competitive V_{us}/V_{ud} @ 0.2%.

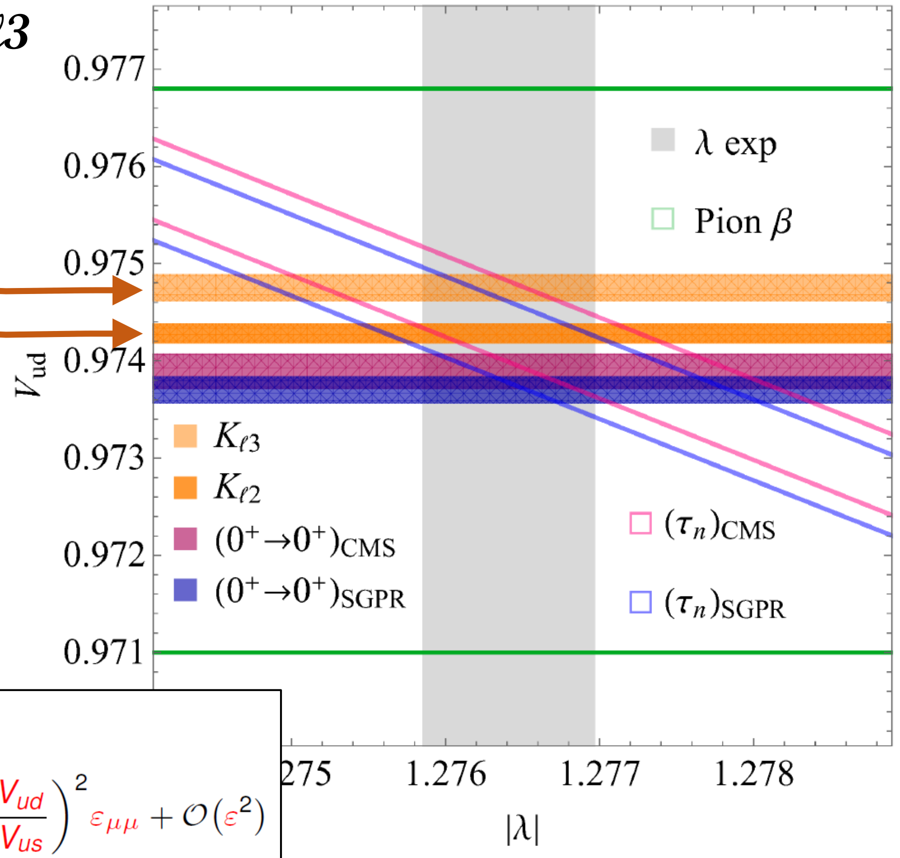
Realistic short term goal?



A Physics Case suggesting they might be related !

Start by *assuming* unitarity. The V_{ud} you get by taking: $|V_{ud}|^2 = 1 - |V_{us}|^2$

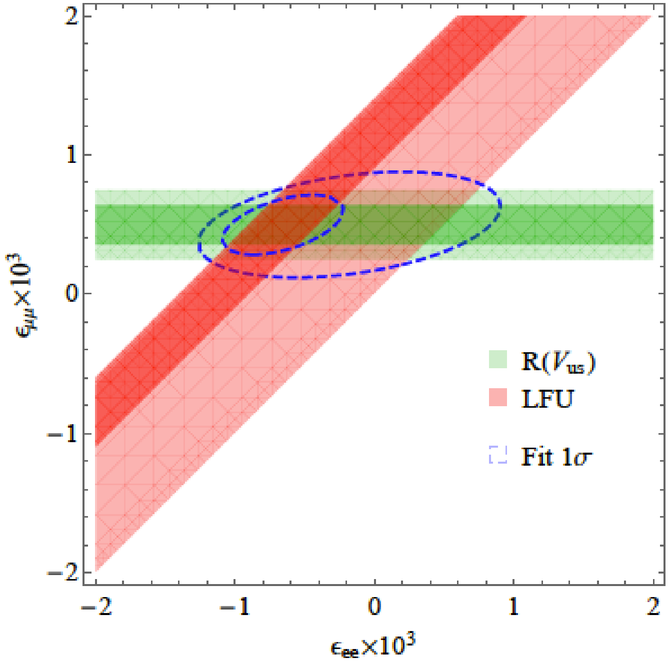
Is different for what is implied by using $K_{\ell 2}$ and $K_{\ell 3}$ than the "standard" V_{ud} from beta decay



Is this tension a sign of LFUV ??

Modifies Fermi constant in **muon decay**

$$\frac{1}{\tau_\mu} = \frac{(G_F^{\mathcal{L}})^2 m_\mu^5}{192\pi^3}(1 + \Delta q)(1 + \varepsilon_{ee} + \varepsilon_{\mu\mu})^2$$



Construct ratio Crivellin, MH 2020

$$R(V_{us}) \equiv \frac{V_{us}^{K_{\mu 2}}}{V_{us}^{\beta}} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1 - (V_{ud}^{\beta})^2 - |V_{ub}|^2}} = 1 - \left(\frac{V_{ud}}{V_{us}}\right)^2 \varepsilon_{\mu\mu} + \mathcal{O}(\varepsilon^2)$$

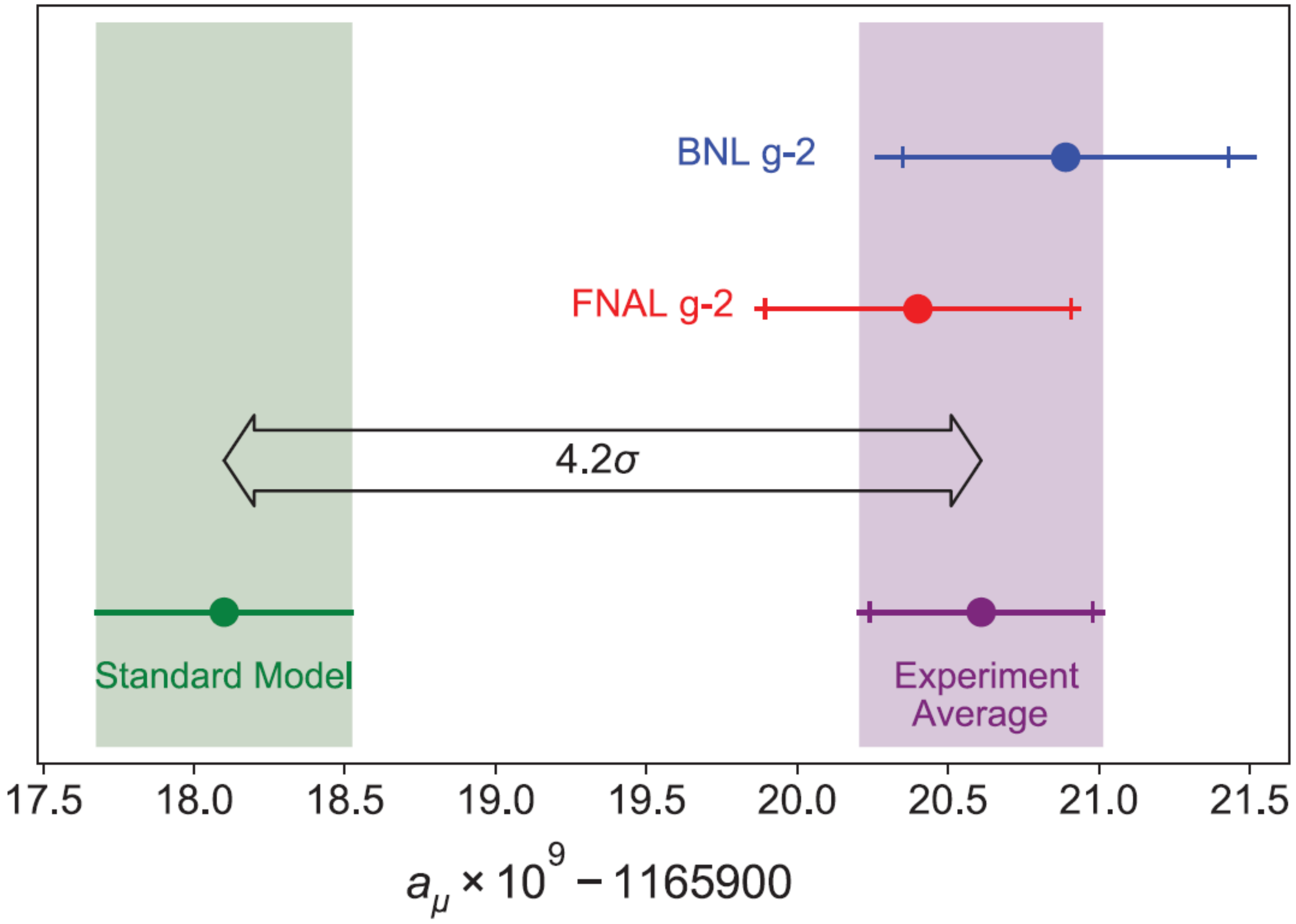
$\hookrightarrow$ LFUV effect enhanced by $(V_{ud}/V_{us})^2 \sim 20$!

Crivellin-Hoferichter 2002.07184, PRL

See many talks on Thursday

And, yet another violation of SM predictions when examined with high precision: Muon g-2

- Direct links not so easy, but what ***is*** going on?



Introducing: *PIONEER*

-- a next-generation experiment to address LFUV and CKM unitarity with order of magnitude improvements compared to current measurements

GOALS:

- Measure $R_{e/\mu} = \dfrac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)}$: $O(\pm 0.01\%)$

- Measure $R_{\pi\beta} = \dfrac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\pi^+ \to all)}$: $O(\pm 0.05\%)$

- Improve search sensitivities by more than an order of magnitude

e.g. $\pi \to e\nu_H ; \pi \to \mu\nu_H ; \pi \to (e/\mu)\nu\nu\bar{\nu} ; \pi \to (e/\mu)\nu X$

The basics of pion decay and why these experiments are hard

	$\pi^+ \rightarrow$	BR
What a pion decays to "normally" →	$\mu^+ \nu_\mu$	(99.98770 ± 0.00004) %
	$\mu^+ \nu_\mu \gamma$	$(2.00 \pm 0.25) \times 10^{-4}$
The helicity suppressed "e" branch →	$e^+ \nu_e$	$(1.230 \pm 0.004) \times 10^{-4}$
	$e^+ \nu_e \gamma$	$(7.39 \pm 0.05) \times 10^{-7}$
The "beta decay" branch →	$e^+ \nu_e \pi^0$	$(1.036 \pm 0.006) \times 10^{-8}$
	$e^+ \nu_e e^+ e^-$	$(3.2 \pm 0.5) \times 10^{-9}$
	$\mu^+ \nu_\mu \nu \bar{\nu}$	$< 9 \times 10^{-6}$
	$e^+ \nu_e \nu \bar{\nu}$	$< 1.6 \times 10^{-7}$

Reminders:

Pion lifetime: 26 ns
Muon lifetime: 2197 ns

Pion mass: 139.6 MeV
Muon mass: 105.7 MeV

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

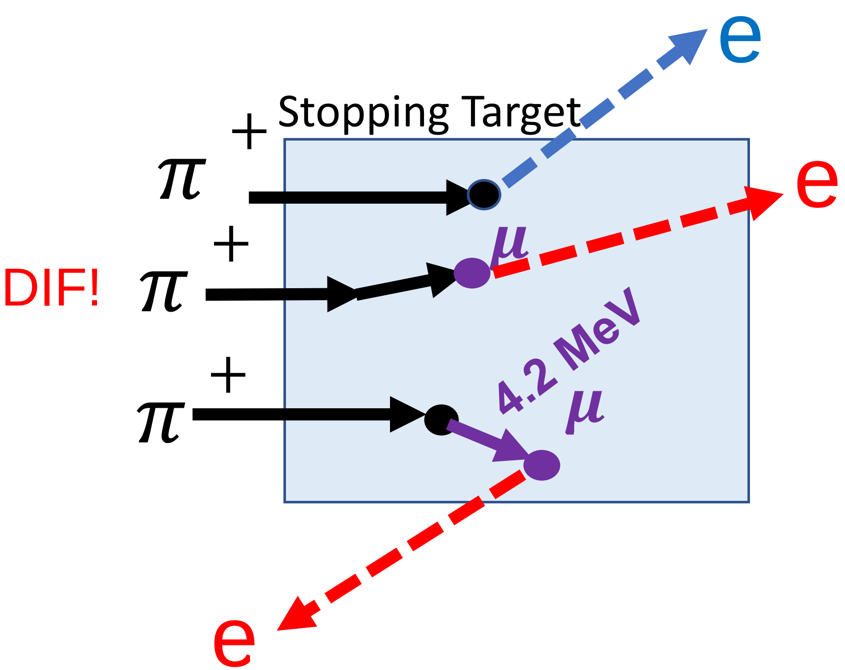
$$R^{(\pi)}_{e/\mu} = (1.2352 \pm 0.0001) \times 10^{-4}$$

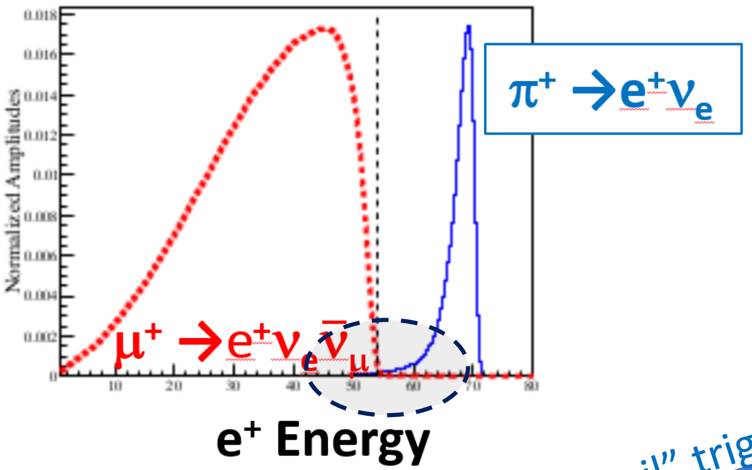
Wow!
>20 times more precise than experiment !

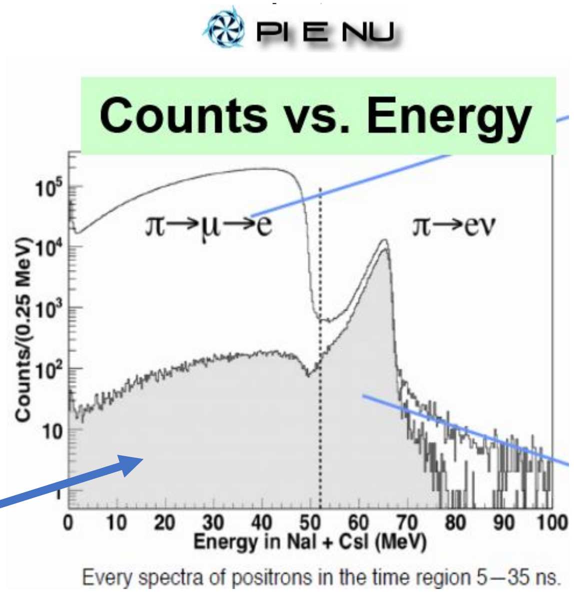
Cirigliano and Rosell PRL 99, 231801 (2007)

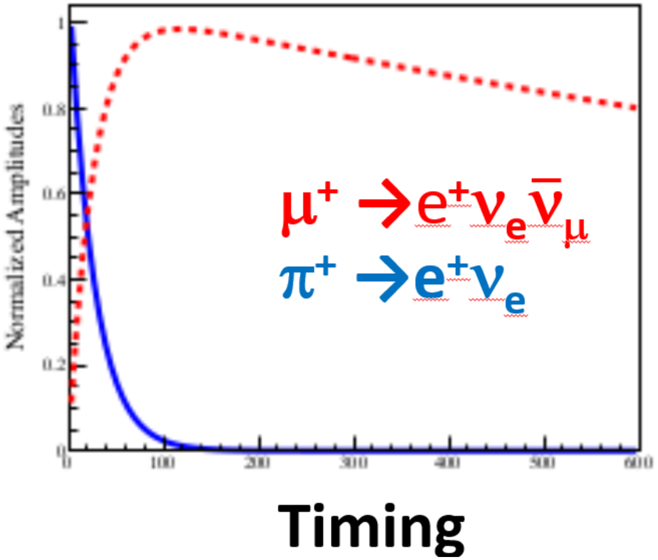
A “simple” experiment: count e^+ from stopped π^+ decay

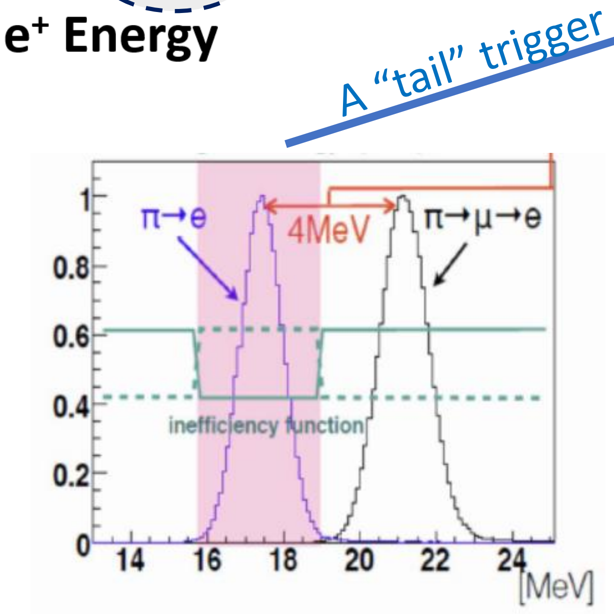
$$\frac{N(\pi \to e\nu)}{N(\pi \to \mu\nu)} \to \frac{N(\pi \to e\nu)}{N(\pi \to \mu \to e\nu\nu)}$$









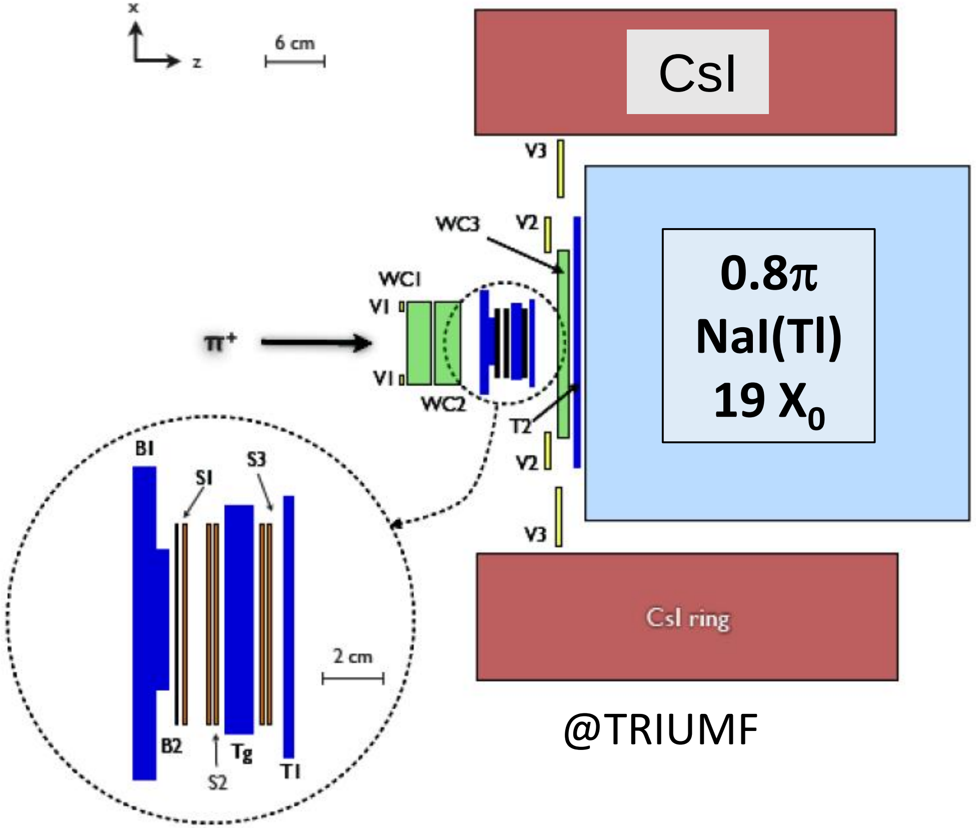


Ideally, in target record:

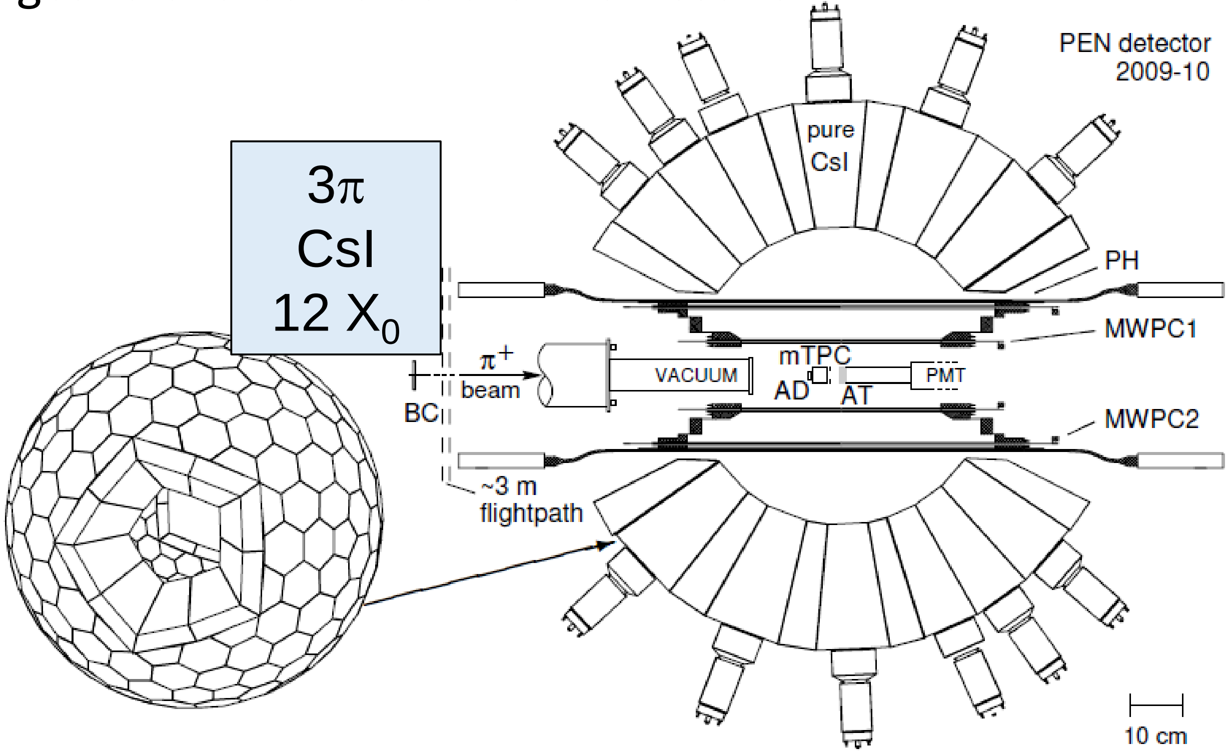
1) Tracks (π/μ/e)
2) Times (fast; high rate)
3) Energy deposited (MIP to Bragg peak range)

Two (rather different) Pion Decay Experiments: PIENU and PEN/PIBETA

Both took data a while ago but have (known) challenges to overcome before final results



@TRIUMF



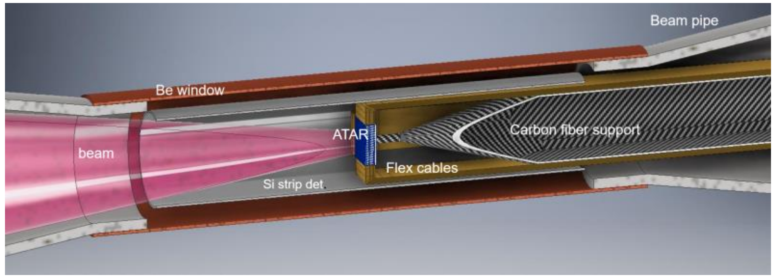
@PSI

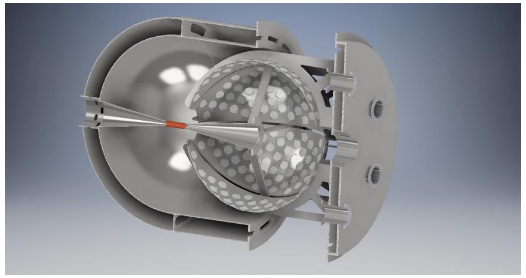
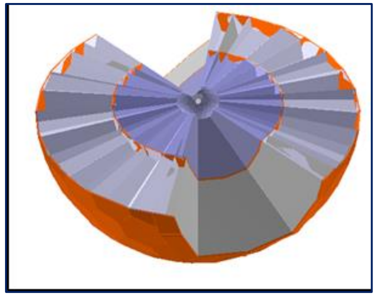
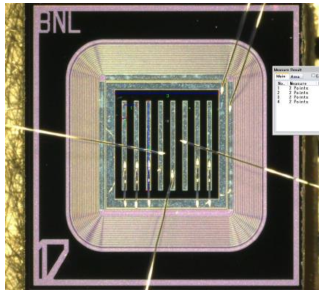
- NaI slow, but excellent resolution
- Single large crystal not uniform enough (material and effective "depth")
- Small solid angle

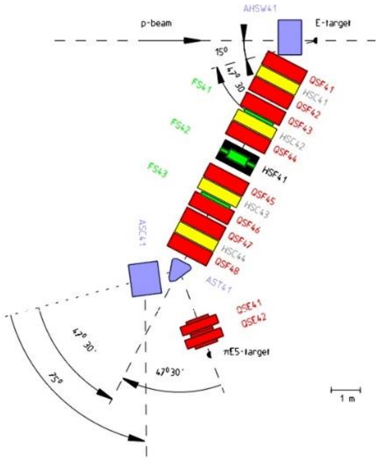
- Good geometry but calorimeter depth of $12X_0$ too small to resolve tail under muon spectrum.

Proposed PIONEER method (illustrate with $\pi^+ \rightarrow e^+\nu_e$ channel)

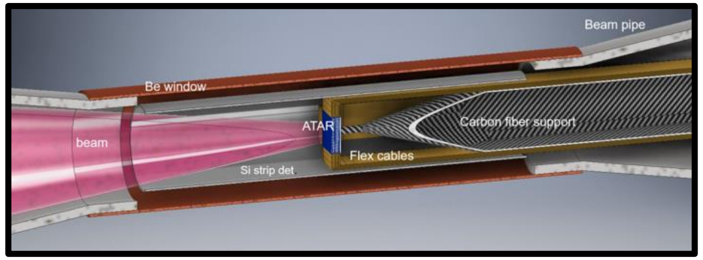
- Active target with "4D" tracking
  - Reduce tail correction (10x) and pileup (5x)
  - Direct observation of $\pi \rightarrow \mu \rightarrow e$ chain
- Calorimeter with large acceptance and ~28 X_0 depth
  - Exploring LXe or L(Y)SO
  - High resolution, fast response, uniformity; tail correction reduction (10x)
- Fast electronics and pipeline DAQ
  - Efficiency, trigger patterns
- Intense pion beam(s) at PSI





1) Active Stopping Target: ATAR

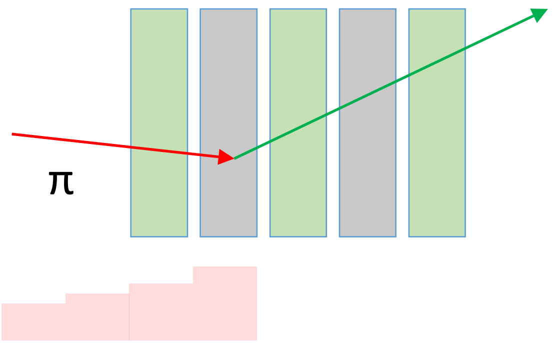


- Motivation

BR = 1.2×10^{-4}

0.2 mm

e (70MeV)

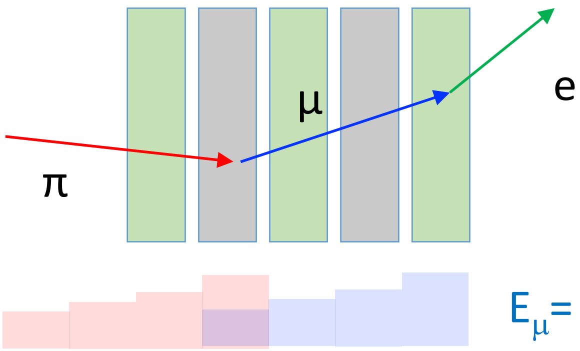


BR ≈ 1

0.2 mm

e (<52 MeV)

e also observed

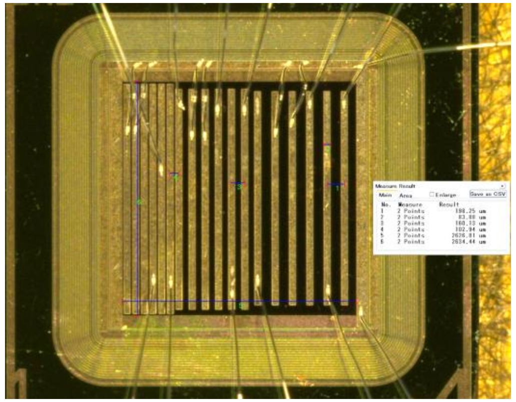


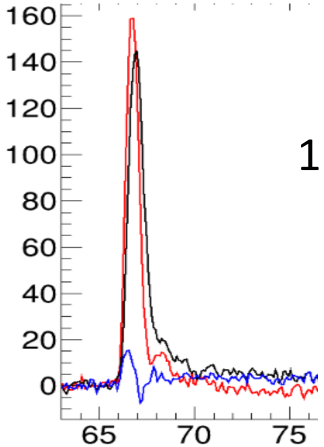
E_{μ}= 4 MeV

- Technology:

4D tracking with LGADs
(low gain avalanche diode)

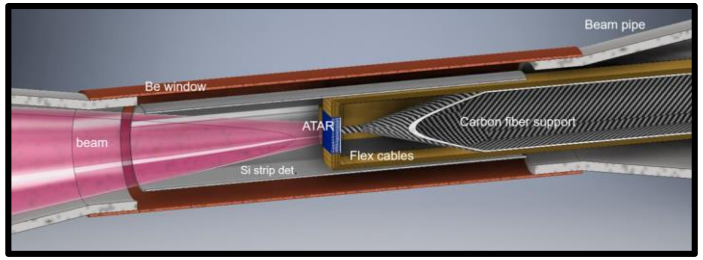
Test chip UCSC



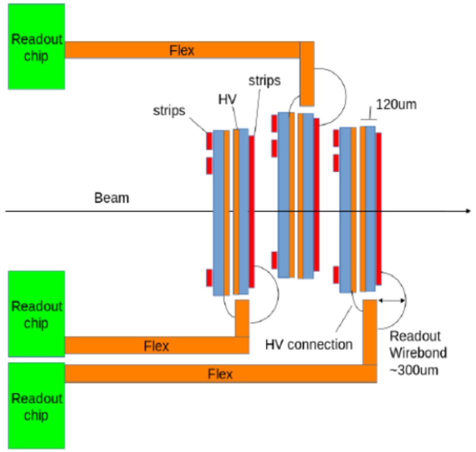


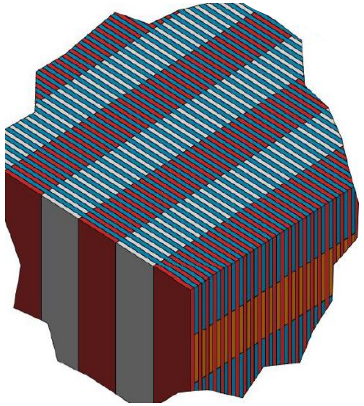
1 ns risetime

ATAR requirements*



- Compact integration with minimal inactive components

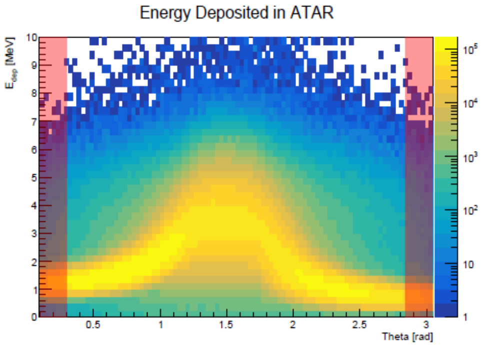


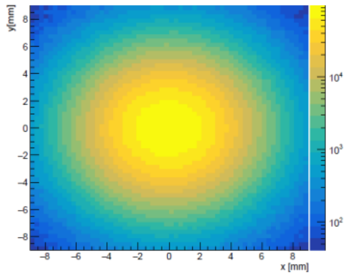


~5000 channels

- Large dynamic range: 30 keV (MIP) - 4000 keV (π, μ)
  - electronics
  - non-linear response due to gain layer saturatio

Planning a beam test campaign using CENPA's Rutherford Backscattering mode of our Van de Graaff



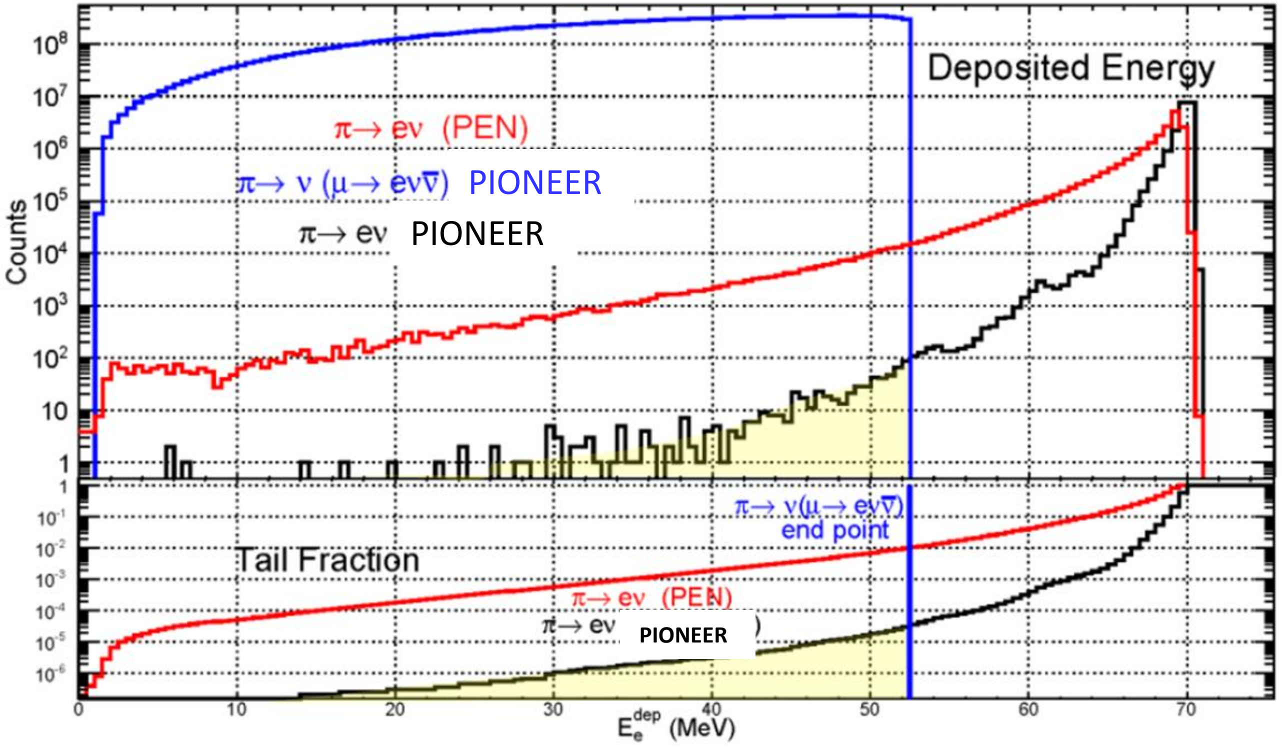


X-Y π stop position

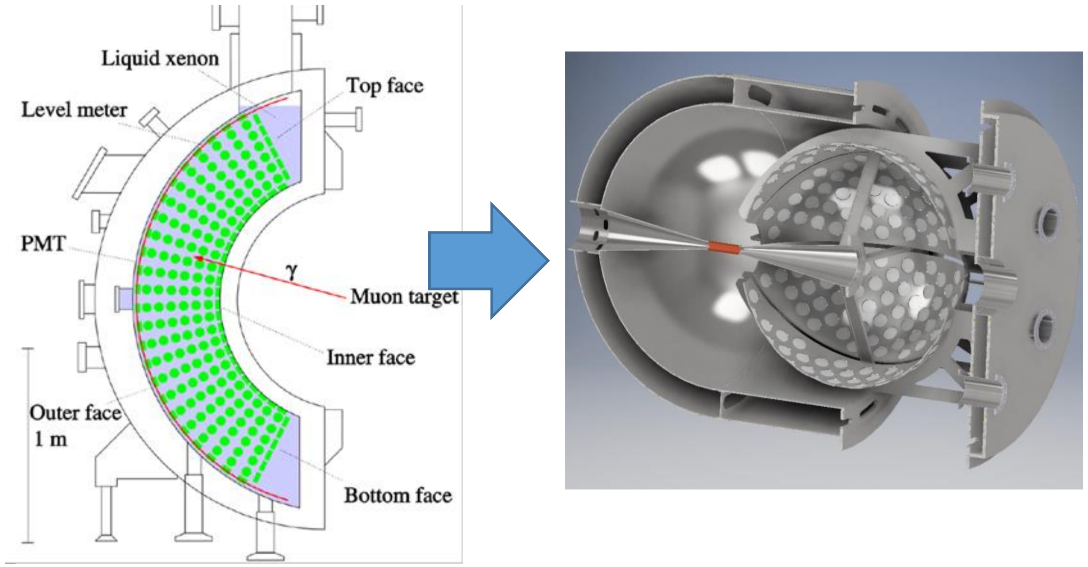
*UCSC group leading development

2) Calorimeter options

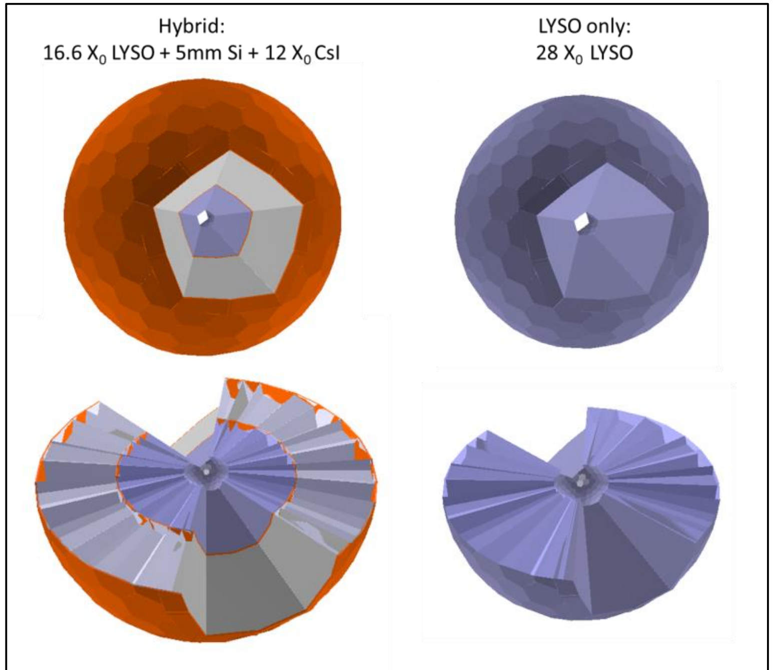
- 28 radiation length deep
- High resolution, fast, symmetric
- Much better $\pi \to e\nu$ **tail** suppression



Option 1: MEG LXe based

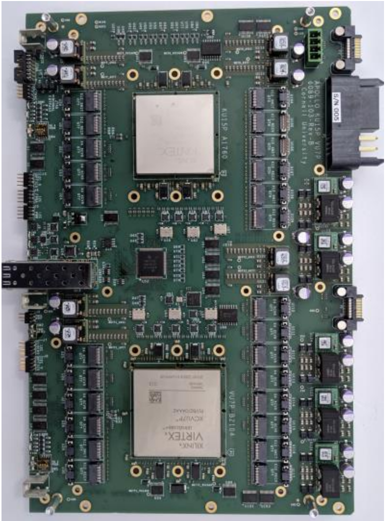


Option 2: LYSO or combined LYSO / CsI using PEN



3) Fast electronics and DAQ

- Leverage significant LHC work: eg., APOLLO boards for DAQ
  - Move lots of data, fast – 104 Firefly™ optical links up to 25 gbps
    - each link: 64 bit words @ 480 MHz
  - Flexible
    - Eg., for calorimeter, 64 bits -> 5 “lanes”
      - 16 bits for realtime sum & triggering
      - 4 12 bit lanes for readout of 4 channels of 1 GSPS ADC’s (eg., Analog AD9234)
      - Transmits master clock, synchronous commands to ADC modules
      - 4 Apollos control / read out 1600 channel calorimeter



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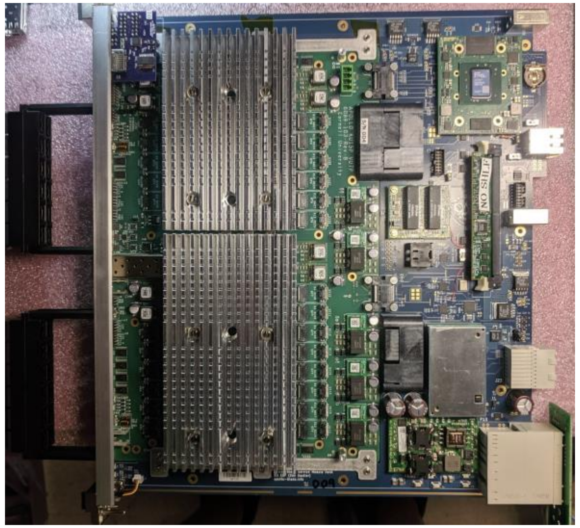
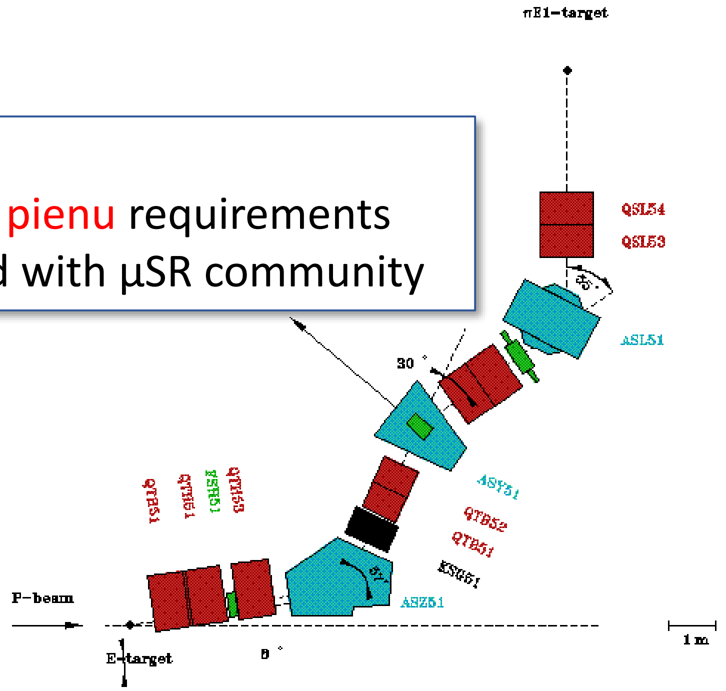


COTS PCIe Firefly interface for DAQ integration

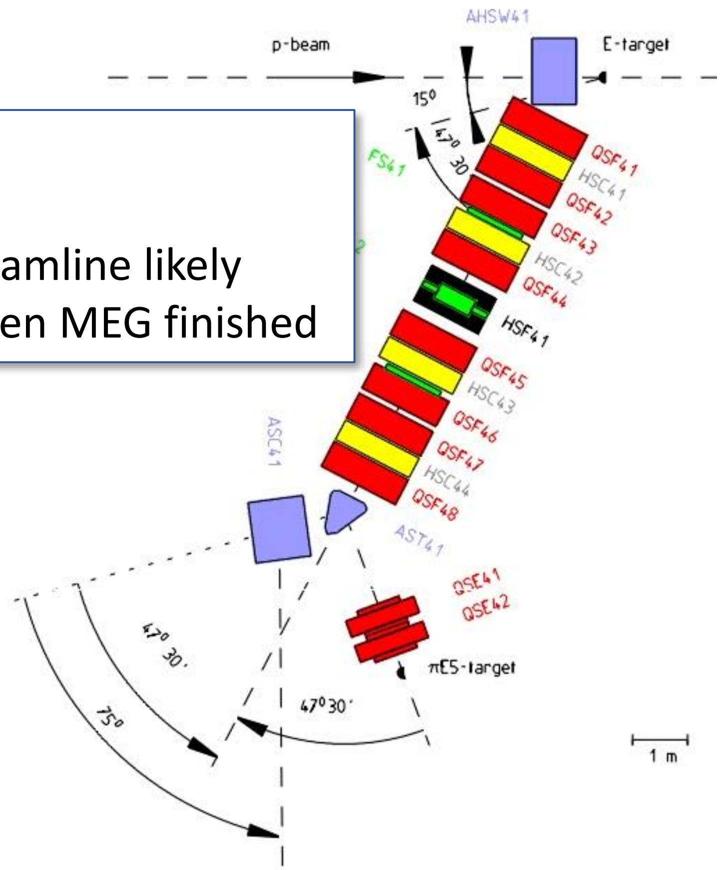
4) PSI Beams

	$\pi^+ \rightarrow e^+ \nu$	$\pi^+ \rightarrow \pi^0 e^+ \nu$
momentum	75 MeV/c, **2x10^5 Hz**, dp/p=1%	75 MeV/c, **3x10^7 Hz**, dp/p=3%
Statistics/yr	10^8	10^6
precision	0.015%	0.1%

πE1:
- fulfills pienu requirements
- shared with μSR community



πE5:
- fulfills piBeta requirements
- world's highest intensity beamline likely available in a few year's when MEG finished

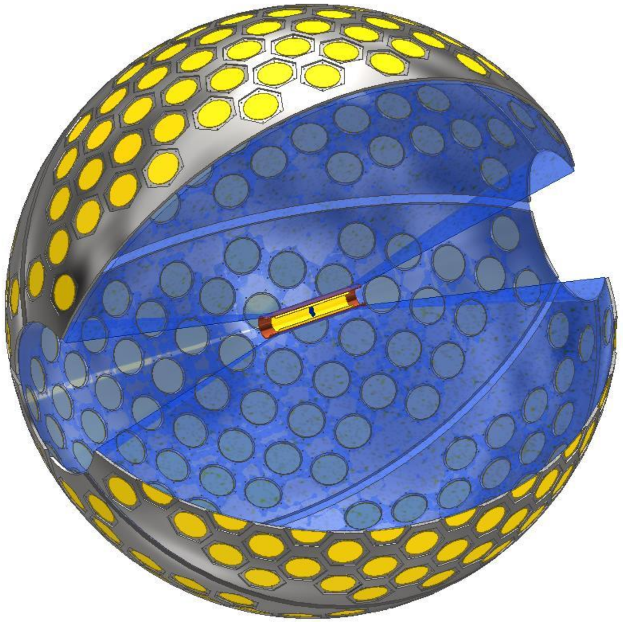


Experiment welcome at PSI

Conclusions and opportunities:

PIONEER

- We are building a team to design a next-generation rare pion decay experiment to address LFUV, CKM unitarity, and some exotic channels
- Will employ state-of-the-art (and beyond) technology .. FUN!
- Goals:
  - Measure $\pi \rightarrow e\nu/\pi \rightarrow \mu\nu$ to ±0.015%, matching SM theory precision
  - Measure pion beta decay rate to ±0.06%
    - Leads to V_{us}/V_{ud} constraint to < 0.1%
- Interested in joining weekly meeting or email list
  - David Hertzog: hertzog@uw.edu
  - Doug Bryman: doug@triumf.gov
  - or any others on the masthead
- Related new open positions
  - Postdoctoral Scholar -- U. Washington
  - Research Assistant Professor – U. Washington



$\pi \to e\nu$: Estimated Uncertainties

To be verified by simulations and prototype measurements.

PIENU (Current)		PIONEER
Statistics	0.19%	0.006%
Tail correction	0.12%	< 0.01% (Calorimeter/ATAR)
t_0 correction	0.05%	-- *(ATAR timing)*
μ decay-in-flight correction	0.05%	*< 0.01% (ATAR)*
Fitting parameters	0.05%	*< 0.01%* (Calorimeter/ATAR) *
Selection cuts	0.04%	*< 0.01%* (Calorimeter/ATAR) *
Acceptance correction	0.03%	*0.005%* (Calorimeter)
Total	0.24%	< 0.02%

* Reductions in uncertainties due to reduced pile-up effects.

$\pi^+ \to \pi^0 e^+ \nu$: Estimated Uncertainties

	PiBeta	PIONEER	
Statistics	0.4%	0.04%	
Systematics	0.4%	<0.04%	(ATAR (β), MC, Photonuclear, π→e ν)
Total	0.64%	**0.06%**	

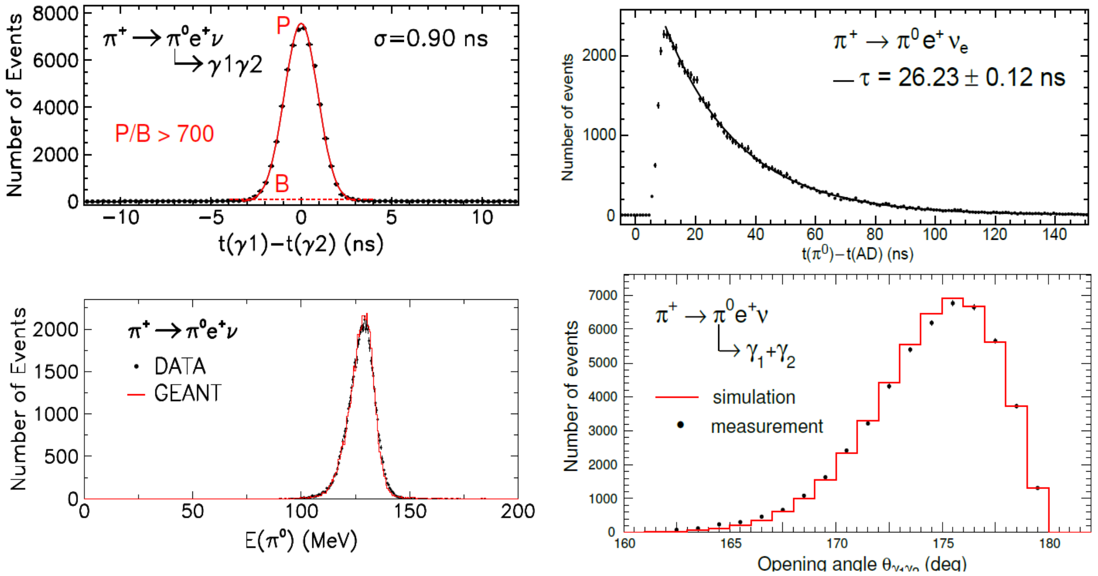
PiBeta result for $\pi^+ \to \pi^0 e^+ \nu$ (π_β) decay [PRL **93**, 181803 (2004)]

Pion beta decay yield normalized to measured $\pi \to e\nu$ events:

$$B(\pi^+ \to \pi^0 e^+ \nu) = (1.038 \pm 0.004_{stat} \pm 0.004_{syst} \pm 0.002_{\pi e2})\ \mathrm{x}10^{-8} \quad (\pm 0.66\%)$$

$$PiBeta: V_{ud} = 0.9738(28)_{exp}(1)_{th}\ ;\ PDG: V_{ud} = 0.97370(14)$$

Key PiBeta spectra: π_{e3} decay (2004)



64000

$\pi^+ \to \pi^0 e^+ \nu$

events

KEY Systematics
Acceptance: 0.19%
Normalization: 0.26%

BACKUP SLIDES

PIONEER