Results from pion and muon decays

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"Beta-decay weak interaction studies
in the era of the LHC"
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How can they contribute in the LHC era?

(Are these even beta decays?)
(Do they belong in this workshop?)

Outline

Introduction and overview of π, μ decays

The PIBETA & PEN experiments at PSI

The $\pi^+ \to \pi^0 e^+ \nu$ (π_{e3}), pion beta decay

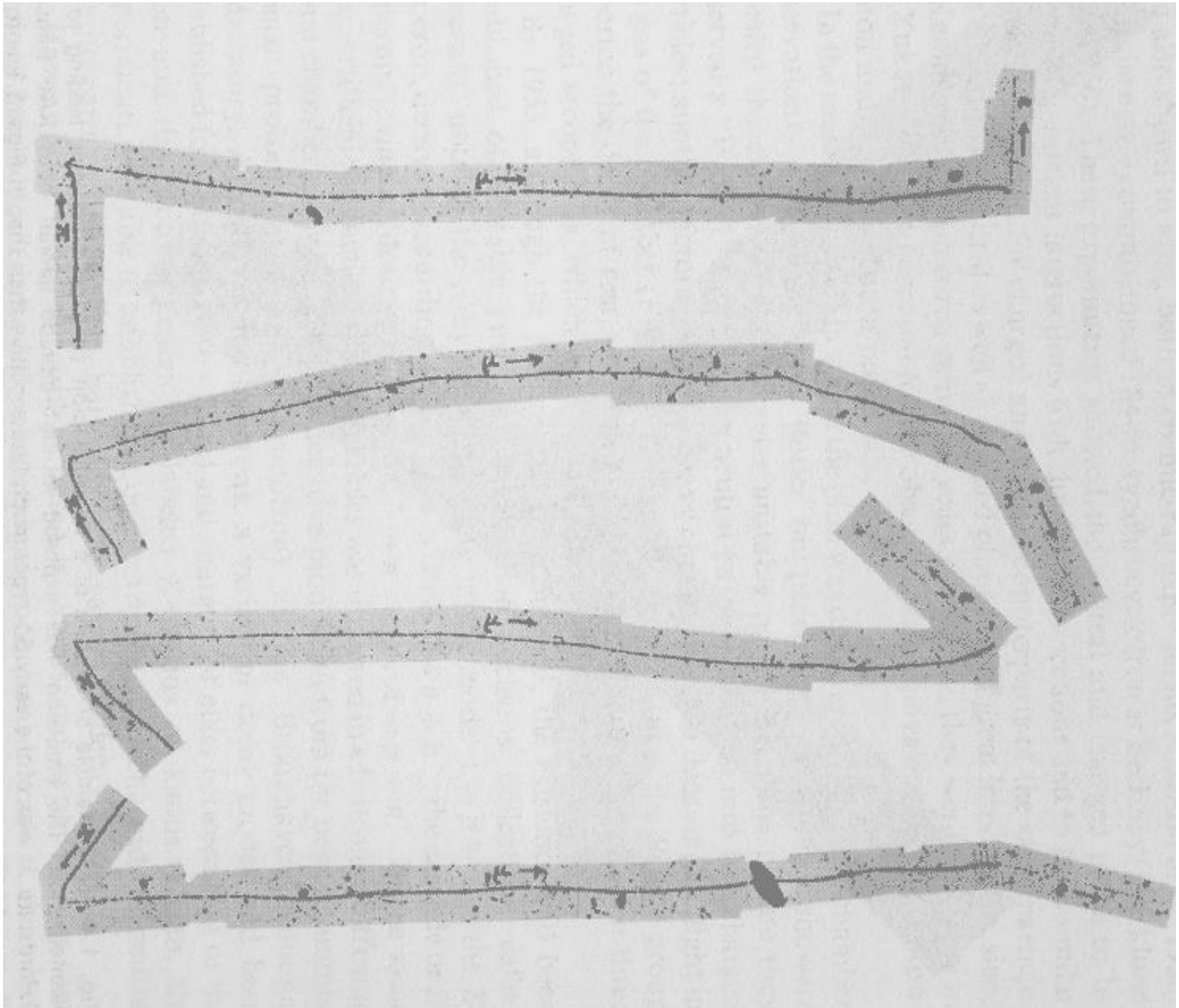
The $\pi^+ \to e^+ \nu_e$ (π_{e2}), electronic decay

The $\pi^+ \to e^+ \nu_e \gamma$ ($\pi_{e2\gamma}$), radiative decay

Radiative muon decay

Summary

Discovery of the pion: Cecil Powell's emulsion tracks 1947



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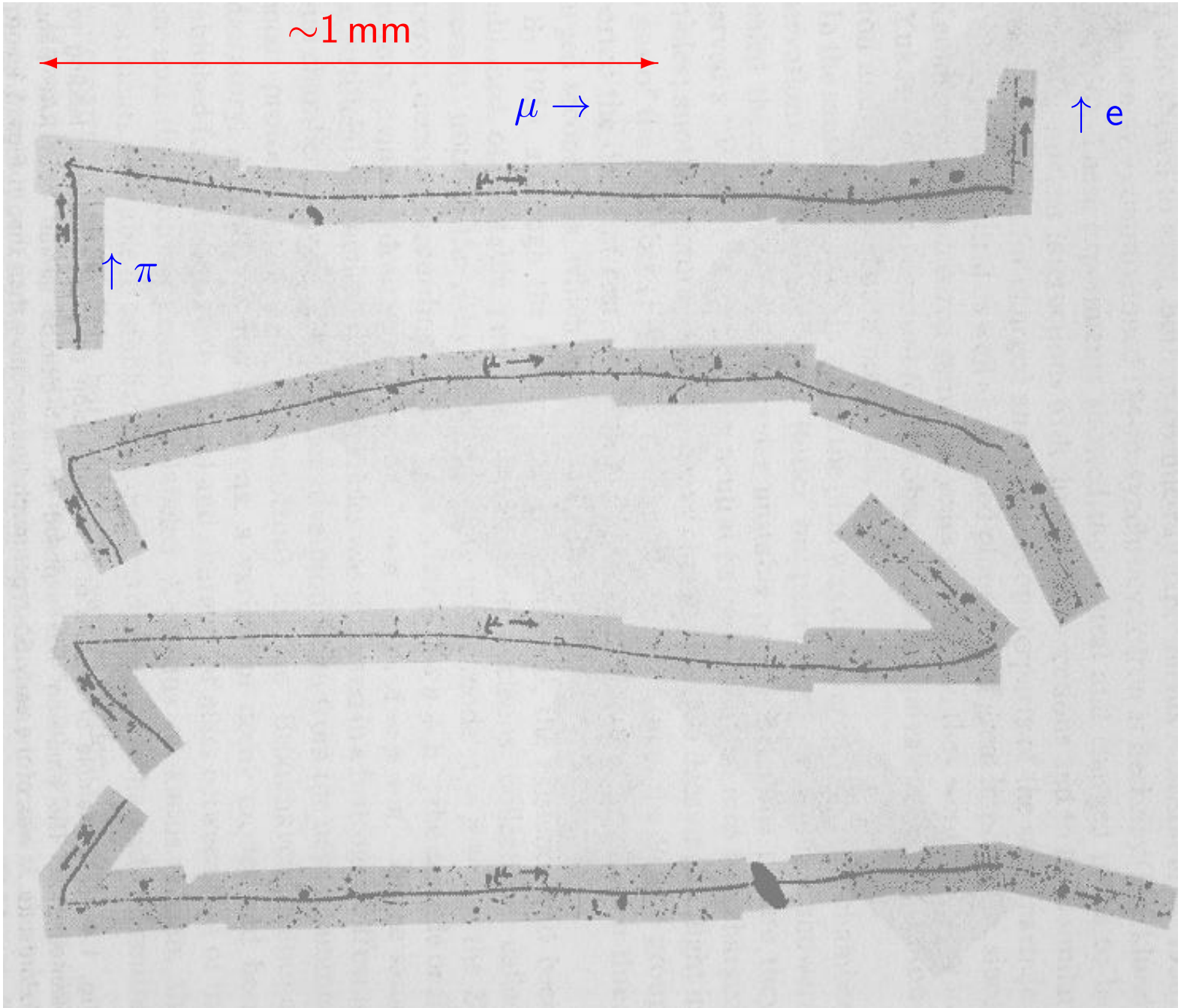
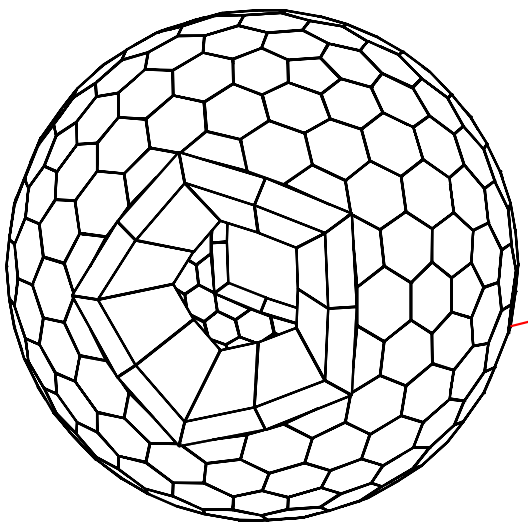


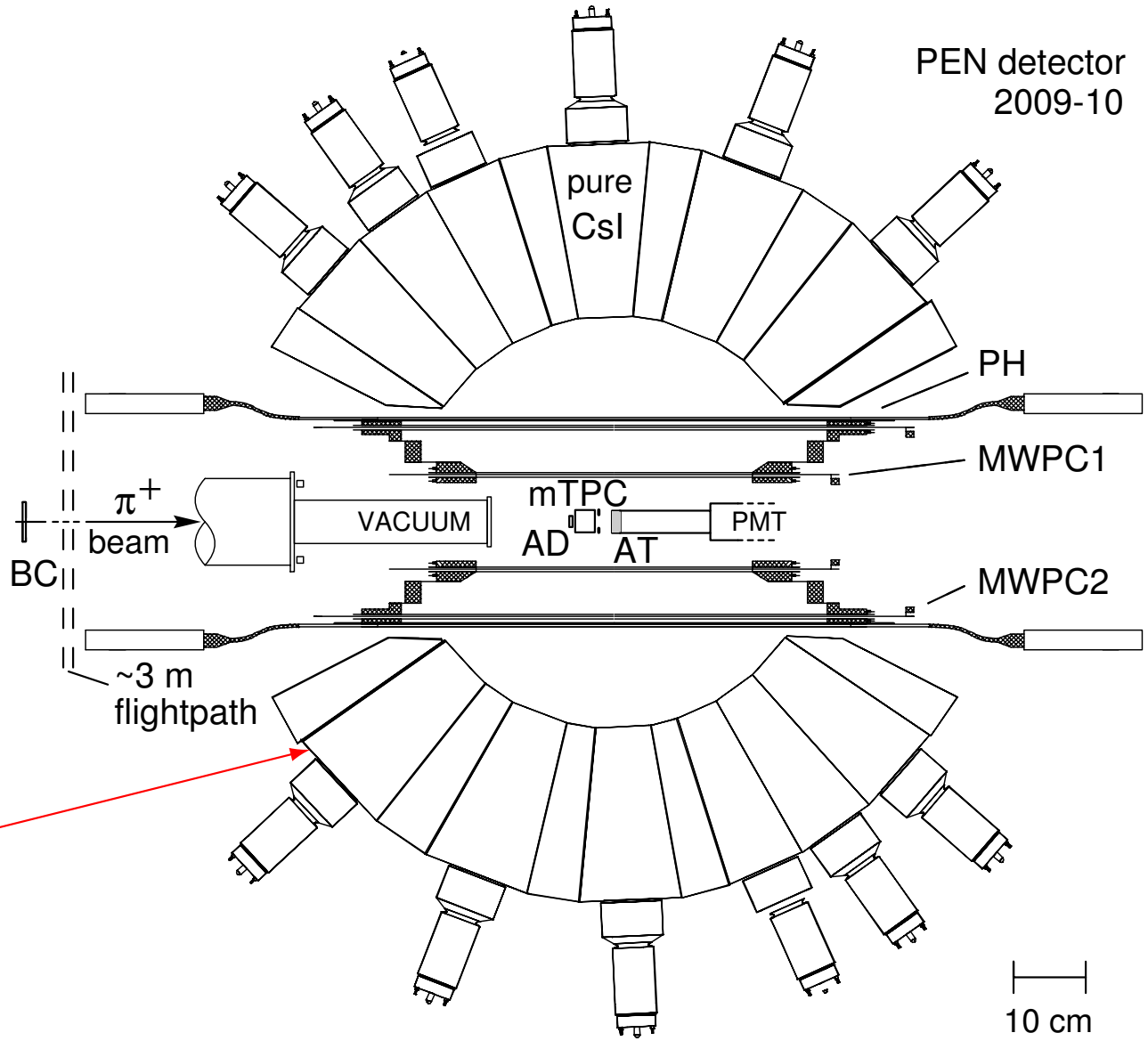
Known and measured pion and muon decays

Decay		*BR*		
$\pi^+ \to$	$\mu^+\nu$	$0.9998770\,(4)$	$(\pi_{\mu 2})$	
	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	$(\pi_{\mu 2\gamma})$	
	$e^+\nu$	$1.230\,(4) \times 10^{-4}$	(π_{e2})	✓
	$e^+\nu\gamma$	$7.39(5) \times 10^{-7}$	$(\pi_{e2\gamma})$	✓
	$\pi^0 e^+\nu$	$1.036\,(6) \times 10^{-8}$	$(\pi_{e3},\ \pi_\beta)$	✓
	$e^+\nu e^+e^-$	$3.2\,(5) \times 10^{-9}$	(π_{e2ee})	
$\pi^0 \to$	$\gamma\gamma$	$0.98798\,(32)$ ✓		
	$e^+e^-\gamma$	$1.198\,(32) \times 10^{-2}$	(Dalitz)	
	$e^+e^-e^+e^-$	$3.14\,(30) \times 10^{-5}$		
	e^+e^-	$6.2\,(5) \times 10^{-8}$		
$\mu^+ \to$	$e^+\nu\bar{\nu}$	~ 1.0 ✓	(Michel)	
	$e^+\nu\bar{\nu}\gamma$	$0.014\,(4)$ ✓	(RMD)	
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

The PIBETA/PEN apparatus

- πE1 beamline at PSI
- stopped π^+ beam
- active target counter
- 240-detector, spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms
- stable temp./humidity





Pion beta (π_{e3}) decay:

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

$$\mathbf{BR} \sim 10^{-8}$$

A theoretically clean path to access CKM V_{ud}

π_{e3} decay: quark-lepton (Cabibbo) universality

The basic weak-interaction **V-A** form (e.g., μ decay):

$$\mathcal{M} \propto \langle \mathbf{e}|\mathbf{l}^{\alpha}|\nu_{\mathbf{e}}\rangle \rightarrow \bar{\mathbf{u}}_{\mathbf{e}}\gamma^{\alpha}(\mathbf{1}-\gamma_{\mathbf{5}})\mathbf{u}_{\nu}$$

is replicated in hadronic weak decays

$$\mathcal{M} \propto \langle \mathbf{p}|\mathbf{h}^{\alpha}|\mathbf{n}\rangle \rightarrow \bar{\mathbf{u}}_{\mathbf{p}}\gamma^{\alpha}(\mathbf{G_V}-\mathbf{G_A}\gamma_{\mathbf{5}})\mathbf{u}_{\mathbf{n}} \quad \text{with} \quad \mathbf{G_{V,A}} \simeq \mathbf{1}\ .$$

Departure from $\mathbf{G_V = 1}$ (**CVC**) comes from weak quark (Cabibbo) mixing:
$\mathbf{G_V = G_\mu \cos\theta_C (= G_\mu V_{ud})}$ $\quad \mathbf{\cos\theta_C \simeq 0.97}$

3 **q** generations lead to the Cabibbo-Kobayashi-Maskawa (CKM) matrix (1973): $\begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \end{pmatrix}$

CKM unitarity cond.: $\mathbf{\Delta V^2 = 1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) \stackrel{?}{=} 0}$,
stringently tests the SM. Until 2004 appeared violated by $\sim \mathbf{3\sigma}$!

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π_{e3} decay rate in the SM (a pure vector $0^- \to 0^-$ decay)

$$\Gamma = \Gamma_0(1+\delta_\pi) = \frac{G_F^2 |V_{ud}|^2 \Delta^5}{30\pi^3} f(\epsilon, \Delta) \left(1 - \frac{\Delta}{2m_+}\right)^3 (1+\delta_\pi)\,,$$

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where

$$\Delta = m_+ - m_0 = 4.5936(5)\,\text{MeV} \qquad \text{and} \qquad \epsilon = \left(\frac{m_e}{\Delta}\right)^2 \simeq \frac{1}{81}$$

while

$$f(\epsilon,\Delta) = \sqrt{1-\epsilon}\left(1-\frac{9}{2}\epsilon-4\epsilon^2\right) + \frac{\epsilon^2}{4}\ln\left(\frac{1-\sqrt{1-\epsilon}}{\sqrt{\epsilon}}\right) - \frac{3}{7}\frac{\Delta^2}{(m_+ + m_0)^2} \simeq 0.941$$

and $\delta_\pi \sim 0.035$ is the sum of radiative/loop corrections with $\sim 0.05\%$ relative uncertainty.

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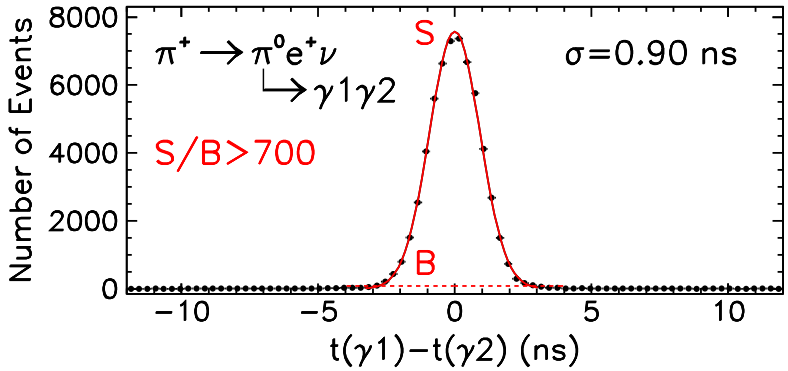
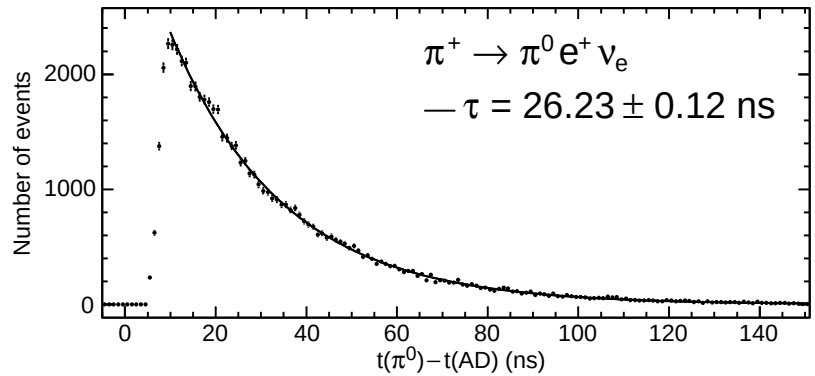
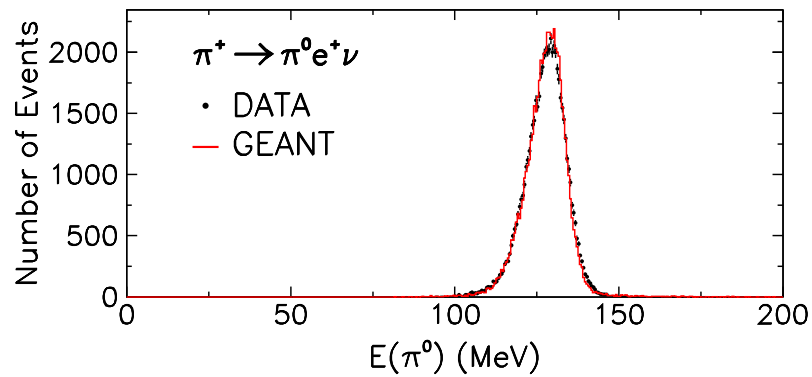
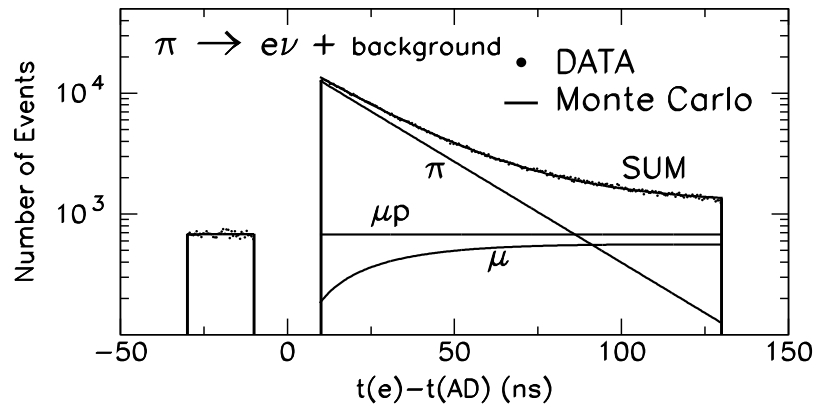
Prior to 2004, Γ and B measured with about 4 % precision.

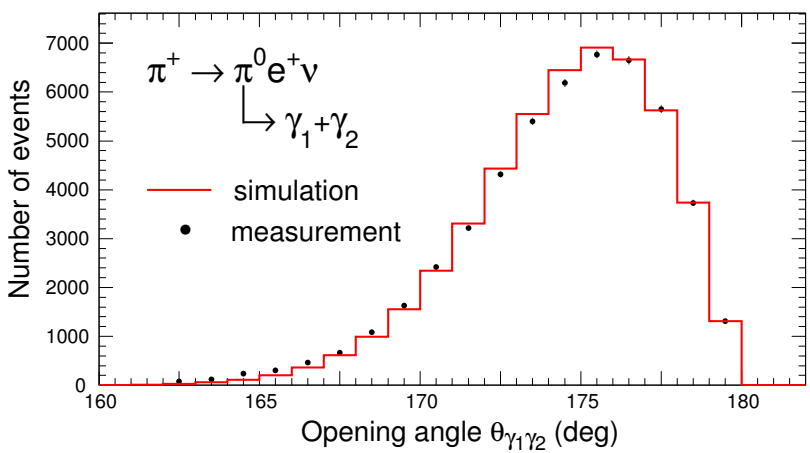
PIBETA results; 1999-2001 runs

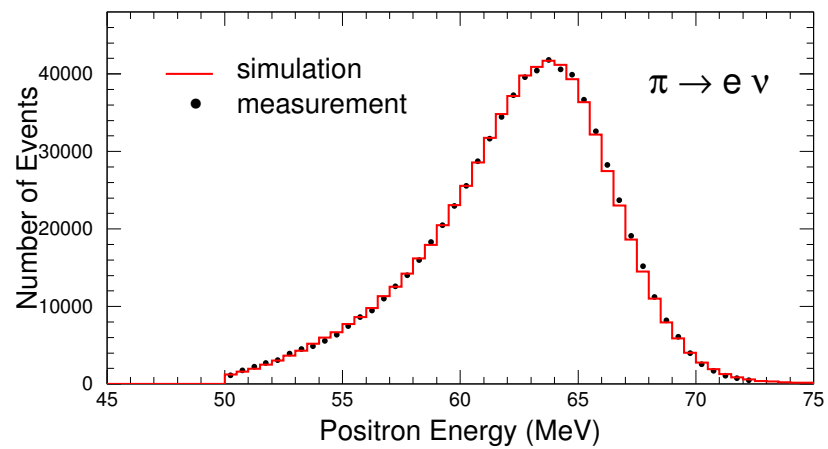












PIBETA result for $\pi^+ \to \pi^0 e^+ \nu$ (π_β) decay [PRL **93**, 181803 (2004)]

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

$$B_{\pi\beta}^{\text{exp-t}} = [1.040 \pm 0.004\,(\text{stat}) \pm 0.004\,(\text{syst})] \times 10^{-8}\,,$$

$$B_{\pi\beta}^{\text{exp-e}} = [1.036 \pm 0.004\,(\text{stat}) \pm 0.004\,(\text{syst}) \pm 0.003\,(\pi_{e2})] \times 10^{-8}\,,$$

McFarlane et al. [PRD 1985]: $B = (1.026 \pm 0.039) \times 10^{-8}$

SM Prediction (PDG):

$B = \quad 1.038 - 1.041 \times 10^{-8} \quad$ (90% C.L.)

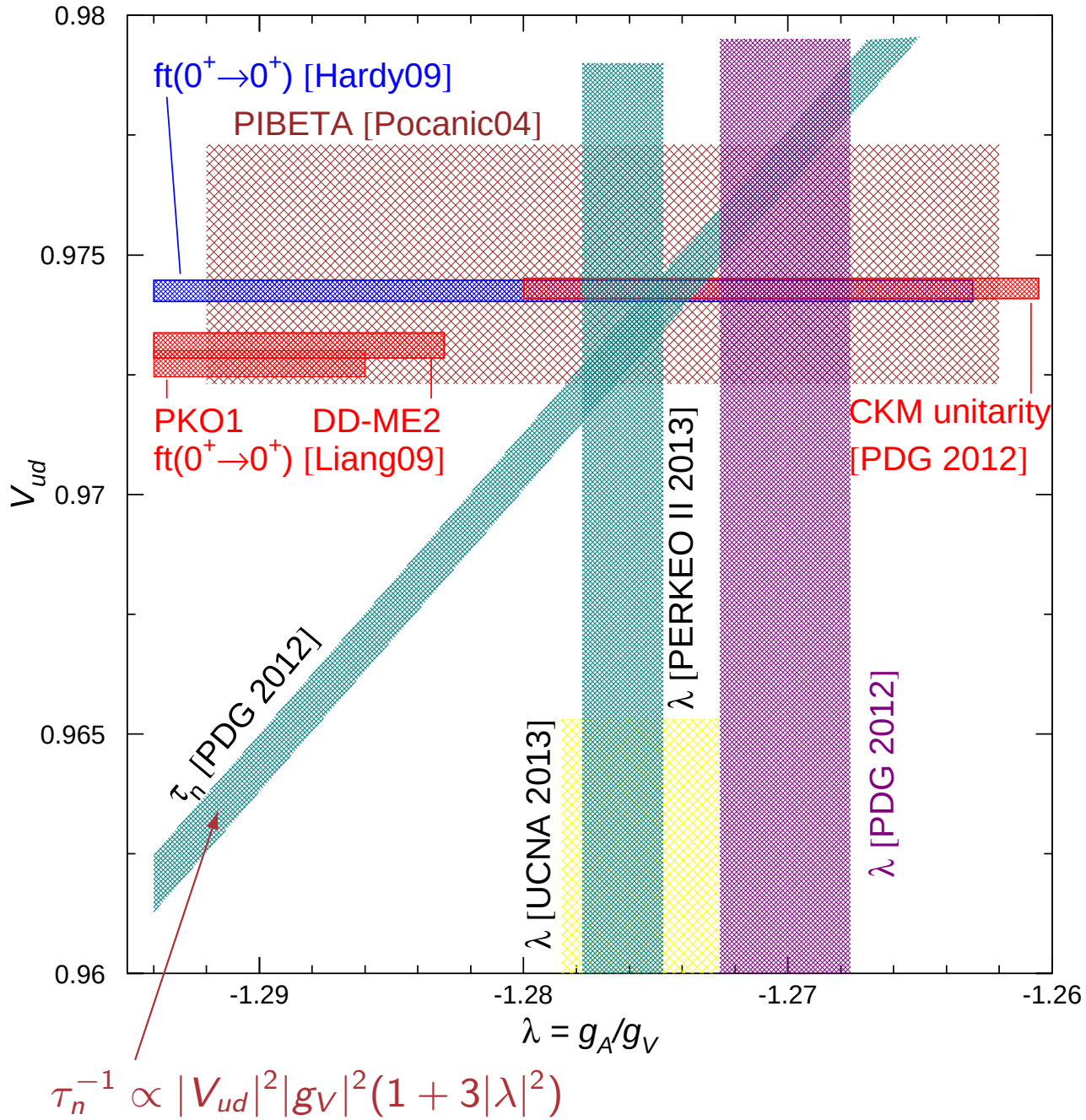
$\quad\quad (1.005 - 1.007 \times 10^{-8} \quad$ excl. rad. corr.)

$\Rightarrow$ Most sensitive test of CVC/radiative corr. in a meson to date!

PDG 2013: $V_{ud} = 0.97425(22)$

PIBETA: $V_{ud} = 0.9748(25)$ or $V_{ud} = 0.9728(30)$.

Current status of V_{ud}:



Neutron β decay results need to be sorted out before returning to π_{e3}.

The electronic (π_{e2}) decay:

$$\pi^+ \longrightarrow e^+ \nu$$

BR $\sim 10^{-4}$

π_{e2} decay: SM calculations, lepton universality

- Early evidence for $V-A$ nature of weak interaction.

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_e^2}{g_\mu^2}\,\frac{m_e^2}{m_\mu^2}\,\frac{(1-m_e^2/m_\mu^2)^2}{(1-m_\mu^2/m_\pi^2)^2}\,(1+\delta R_{e/\mu})$$

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WHY SHOULD WE CARE?

Reach of π_{e2} decay beyond the SM (New Physics)

$$\mathcal{L}_{\rm NP} = \left[\pm \frac{\pi}{2\Lambda_V^2} \bar{u}\gamma_\alpha d \pm \frac{\pi}{2\Lambda_A^2} \bar{u}\gamma_\alpha\gamma_5 d \right] \bar{e}\gamma^\alpha(1-\gamma_5)\nu$$
$$+ \left[\pm \frac{\pi}{2\Lambda_S^2} \bar{u} d \pm \frac{\pi}{2\Lambda_P^2} \bar{u}\gamma_5 d \right] \bar{e}(1-\gamma_5)\nu \,, \quad (\Lambda_i \ldots \text{scale of NP})$$

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At $\Delta R^\pi_{e/\mu}/R^\pi_{e/\mu} = 10^{-3}$, π_{e2} decay is directly sensitive to:

$$\boxed{\Lambda_P \leq 1000\,\text{TeV}} \qquad \text{and} \qquad \boxed{\Lambda_A \leq 20\,\text{TeV}}\,,$$

and indirectly, through loop effects to $\boxed{\Lambda_S \leq 60\,\text{TeV}}$.

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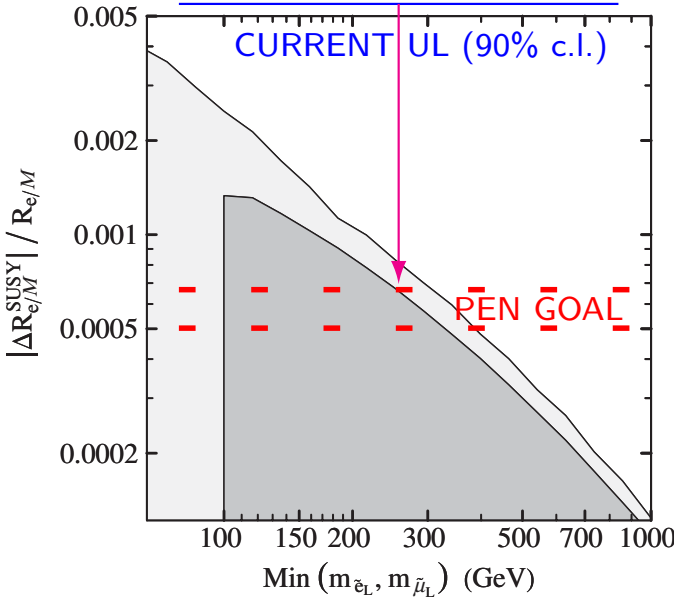
In general multi-Higgs models with charged-Higgs couplings

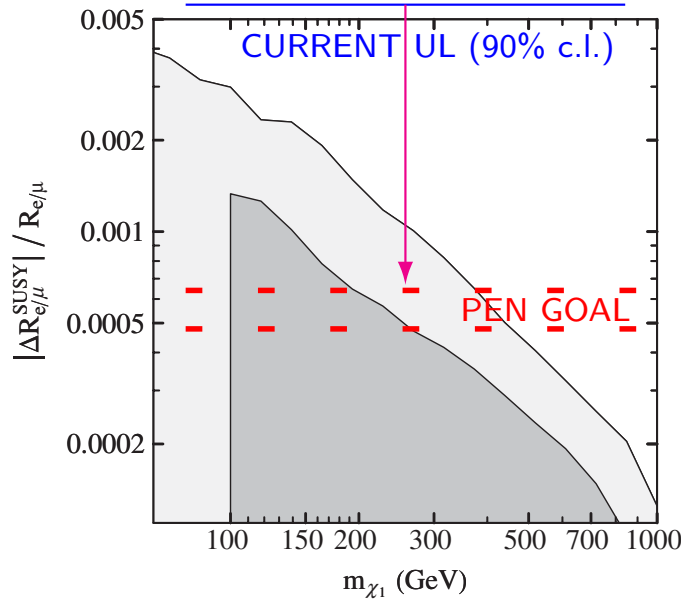
$\lambda_{e\nu} \approx \lambda_{\mu\nu} \approx \lambda_{\tau\nu}$, at 0.1 % precision, $R^\pi_{e\mu}$ probes $\boxed{m_{H^\pm} \leq 400\,\text{GeV}}$.

MSSM calculations (R parity cons.) [Ramsey-Musolf et al., PR D**76** (2007) 095017]

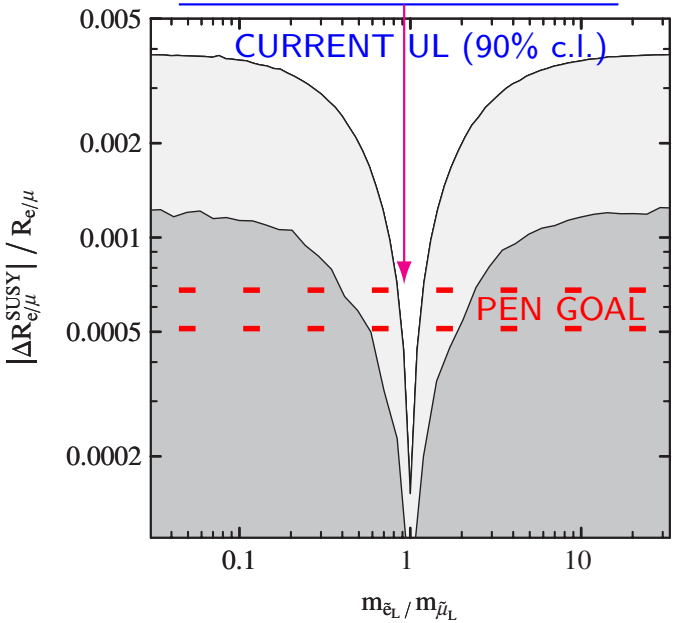
minimal selectron, smuon masses:



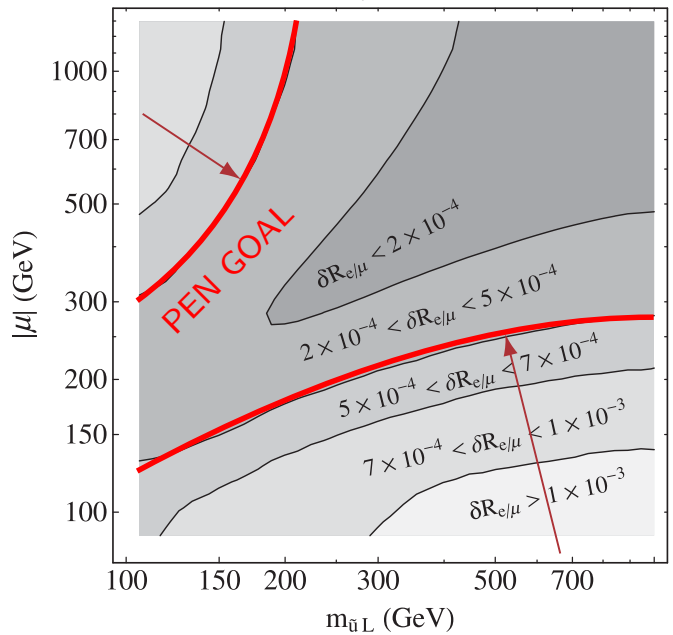
lowest mass chargino:



slepton mass degeneracy:



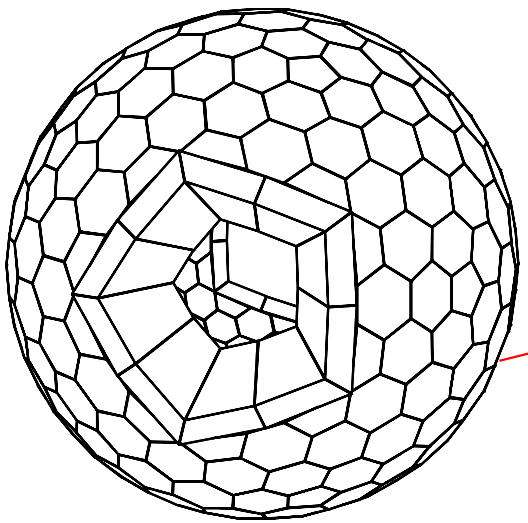
Higgsino mass param's. μ, $m_{\tilde{u}_L}$:

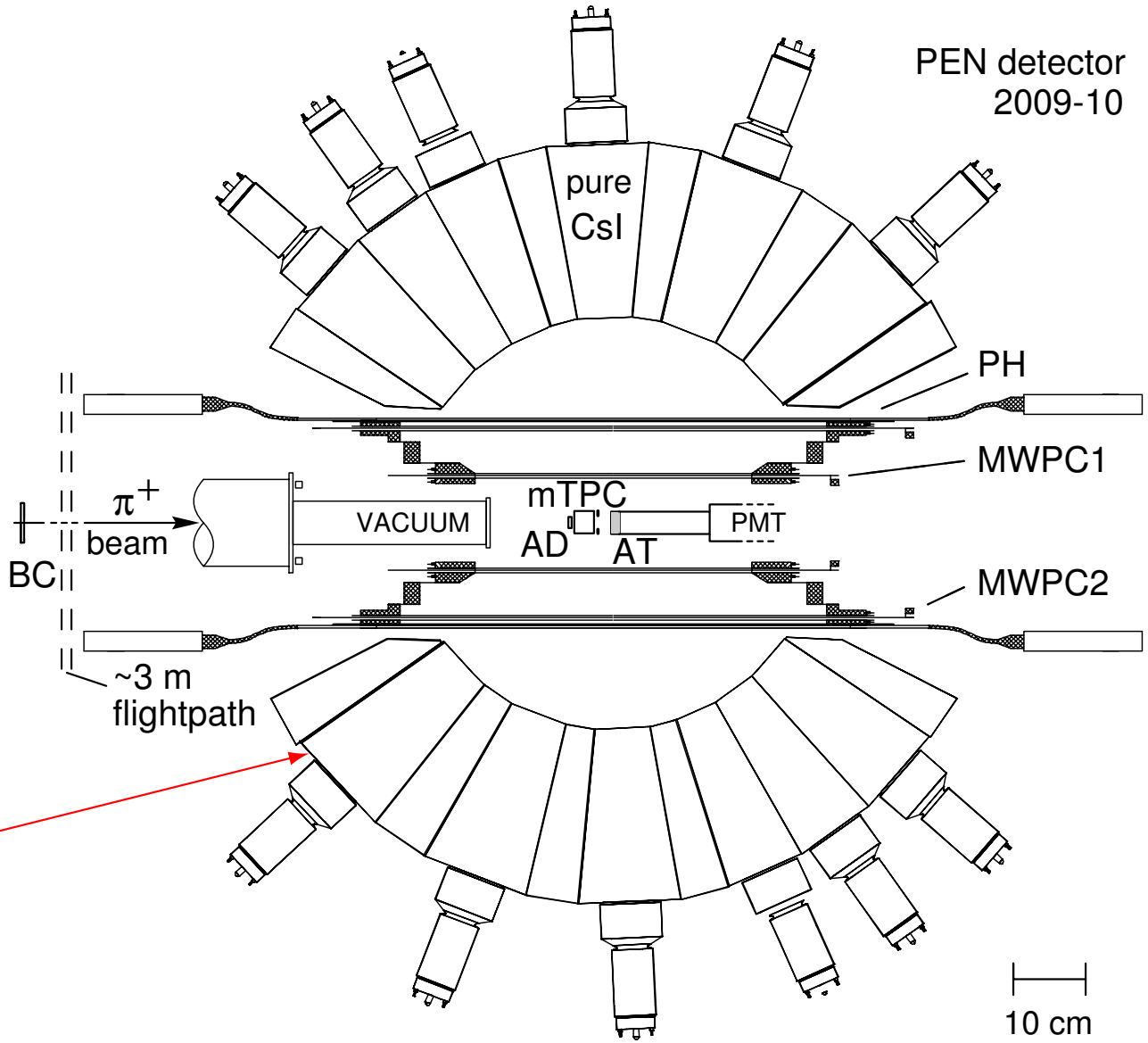


(R parity violating scenario constraints also discussed.)

The PEN/PIBETA apparatus

- stopped π^+ beam
- active target counter
- 240-detector, spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms
- stable temp./humidity





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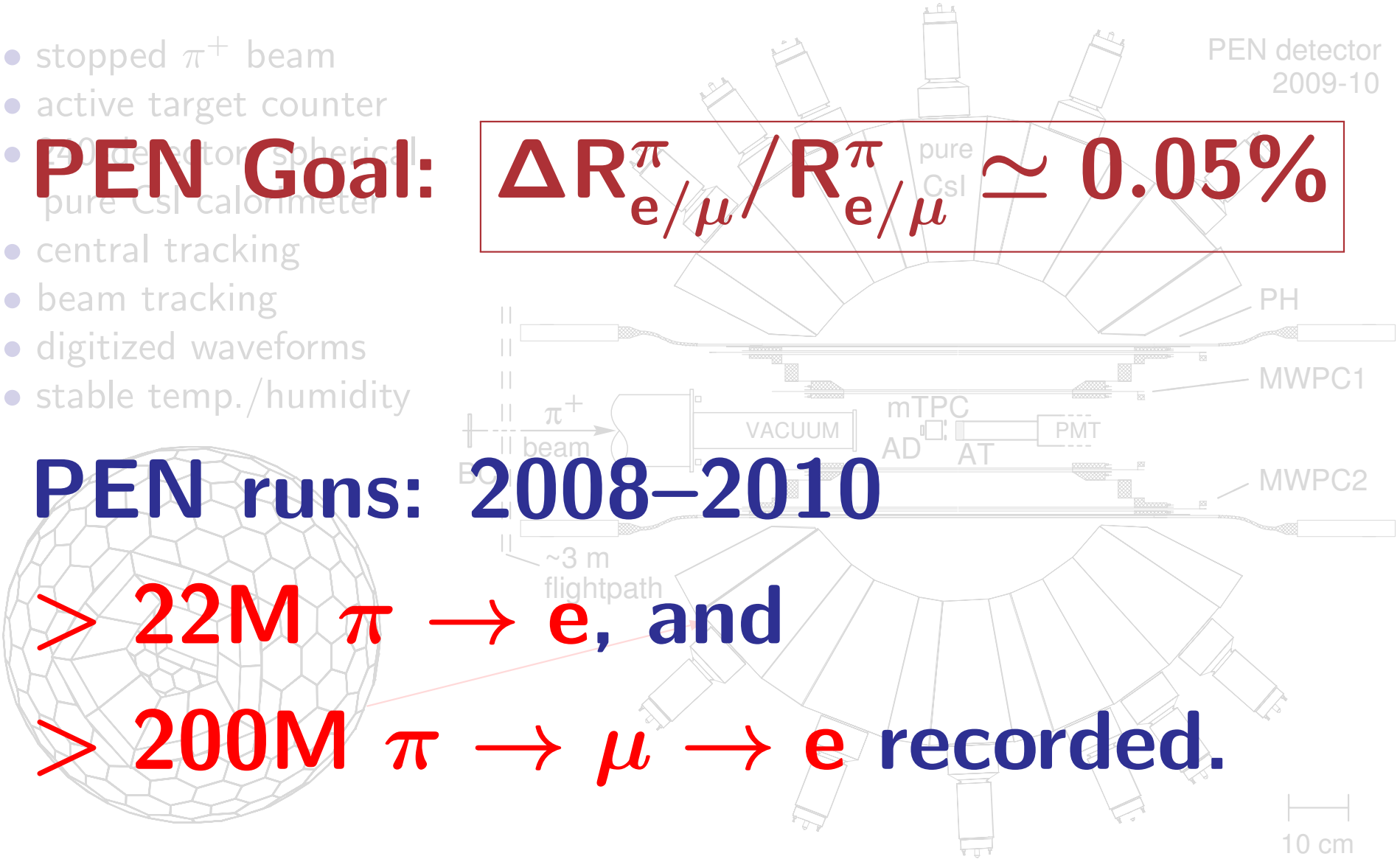
PEN Goal: $\boldsymbol{\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu} \simeq 0.05\%}$



PEN runs: 2008–2010

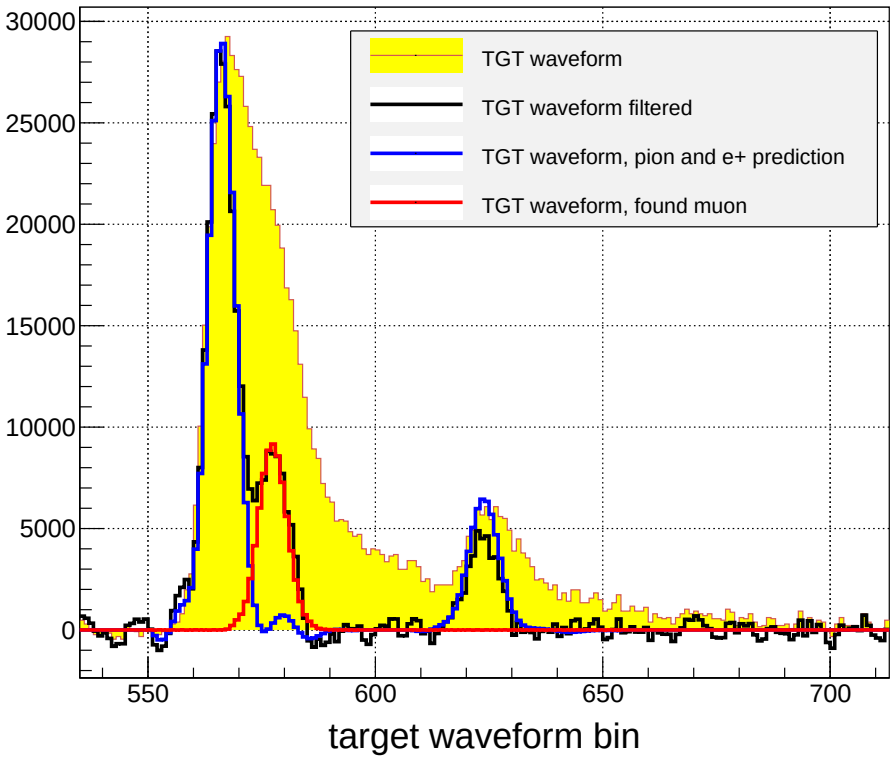
> 22M $\pi \to e$, and

> 200M $\pi \to \mu \to e$ recorded.

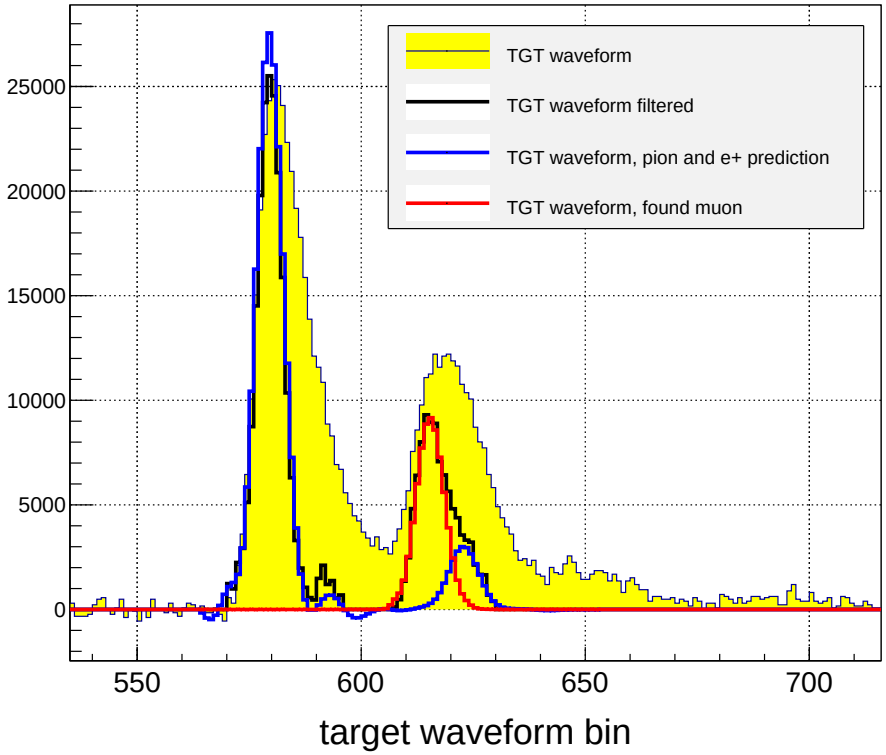
Highlights and challenges of PEN analysis (under way)

Active target waveforms: separating the decay particle pulses!

Early pion decay (extremely common)

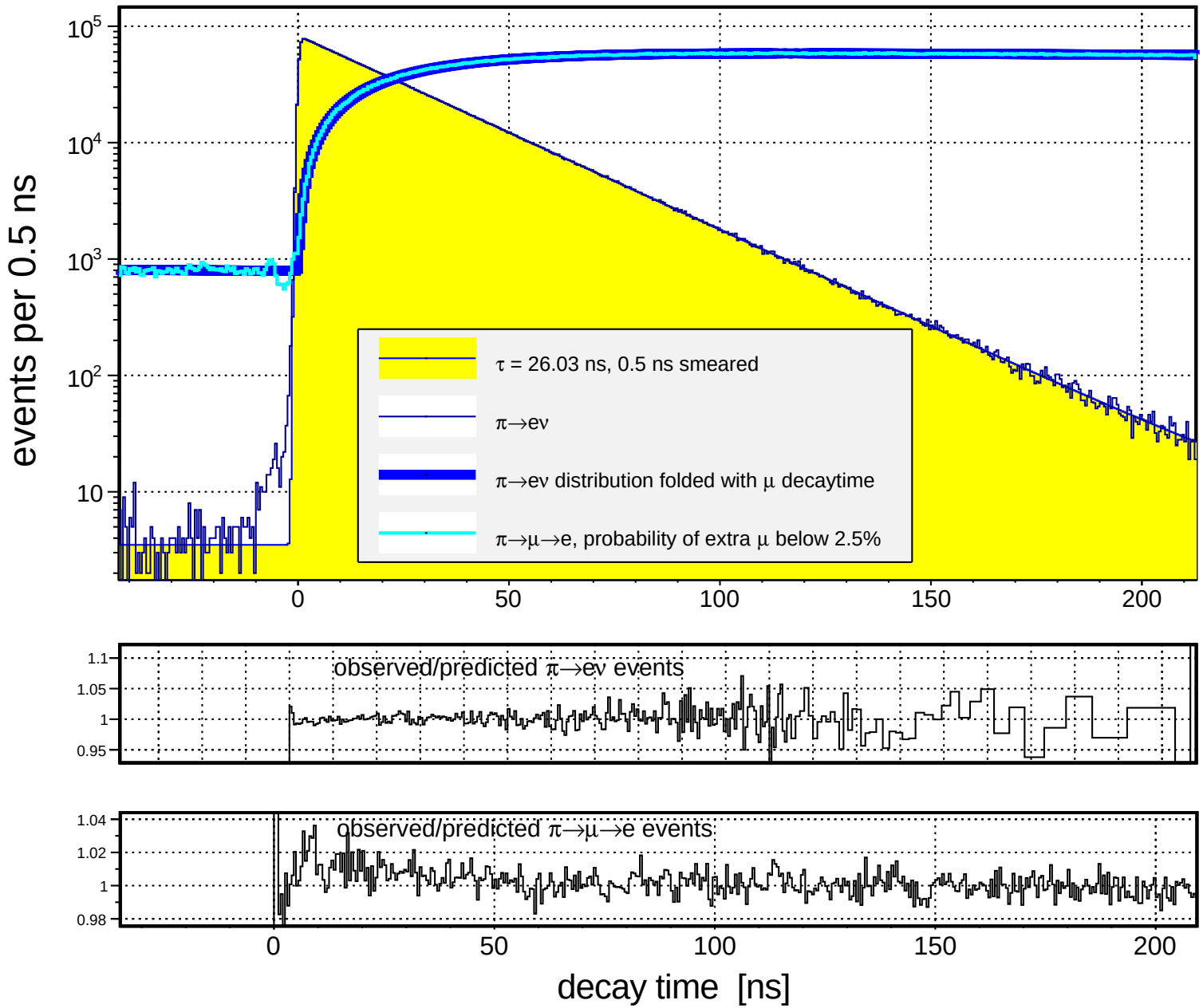


Early muon decay (still annoying)



- π and e^+ pulse time and amplitude predicted from other detector systems (mTPC, MWPCs, PH)!
- Waveform system functions evaluated based on prompt hadronic events.
- Hypotheses with/without a μ pulse evaluated.

PEN: agreement with predictions (2010 data analysis)



Can PIBETA say anything on the π_{e2} BR?

YES!

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We fix V_{ud} to the extraordinarily precise PDG 2013 recommended value

$$V_{ud} = 0.97425 \pm 0.00022$$

and adjust $R^{\pi}_{e/\mu}$ until the extracted value of $V^{\pi\beta}_{ud}$ agrees. This exercise yields

$$\boxed{(R^{\pi}_{e/\mu})^{\text{PIBETA}} = (1.2366 \pm 0.0064) \times 10^{4}},$$

[recall $(R^{\pi}_{e/\mu})^{\text{SM}} = 1.2352(1) \times 10^{-4}$]

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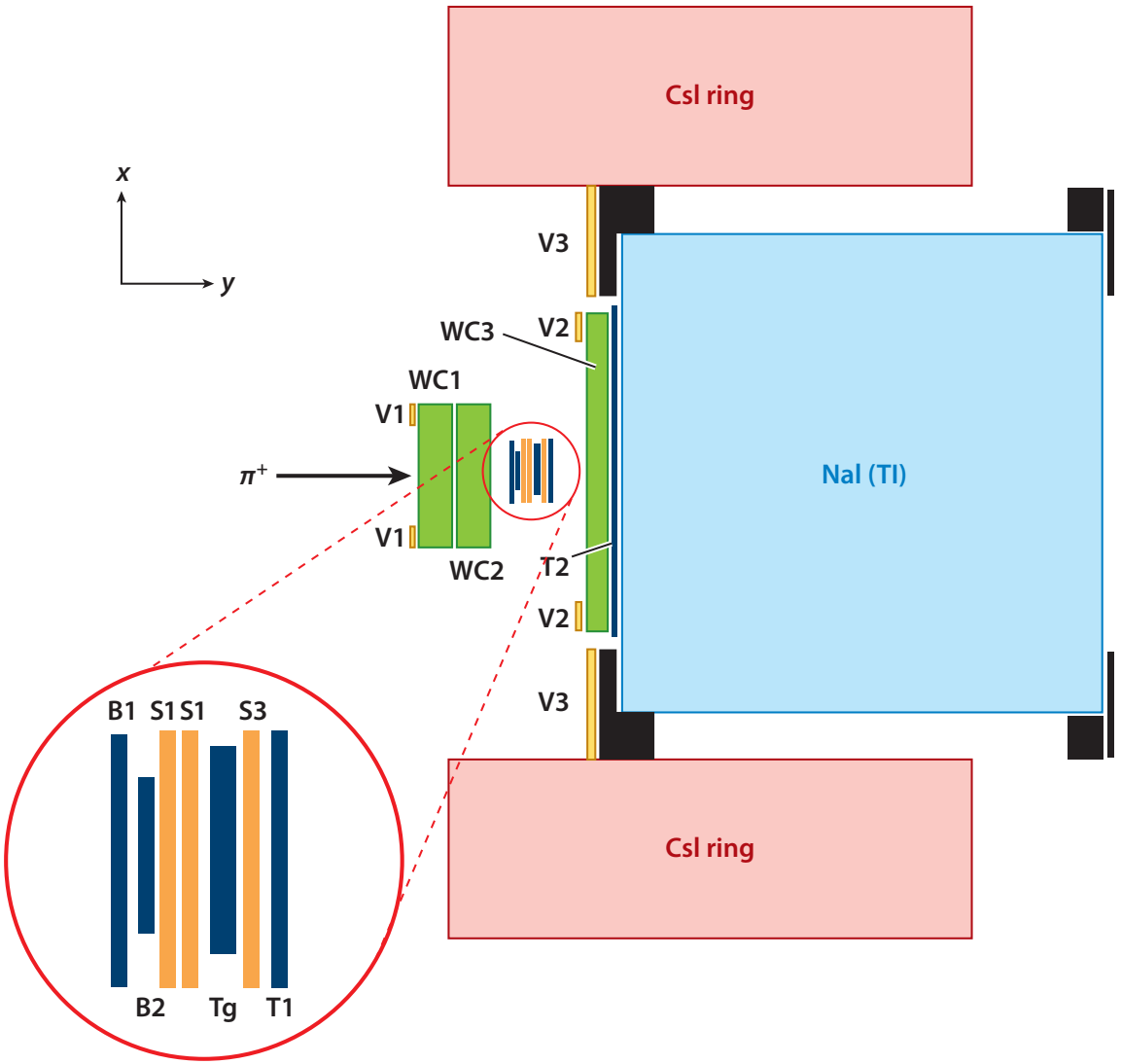
[recall $(R^{\pi}_{e/\mu})^{\text{SM}} = 1.2352(1) \times 10^{-4}$]

Adding the new value to the world data set would move the average slightly to

$$(R^{\pi}_{e/\mu})^{\text{new avg}} = (1.2317 \pm 0.0031) \times 10^{-4}\,.$$

PiENu experiment at TRIUMF



- Goal: $\Delta B/B \simeq 0.001$
- Excellent E resolution
- Very precise tracking with Si-strip detectors and MWPCs
- Data taking completed in 2012
- $\mathcal{O}(10^7)$ π_{e2} events collected
- analysis under way

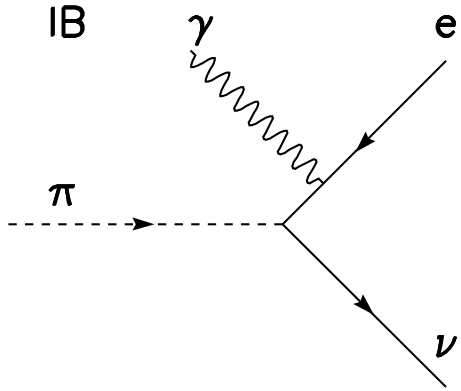
Radiative electronic ($\pi_{e2\gamma}$) decay:

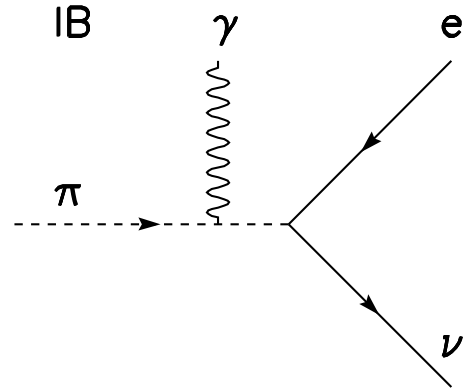
$$\pi^+ \to e^+ \nu_e \gamma$$

$$BR_{\text{non-IB}} \sim 10^{-7}$$

Physics of
$\pi^+ \to e^+\nu\gamma$ (RPD):

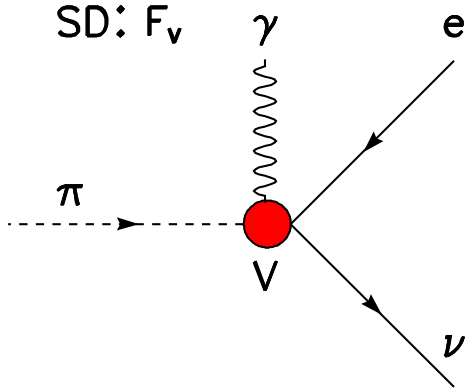
QED IB terms:

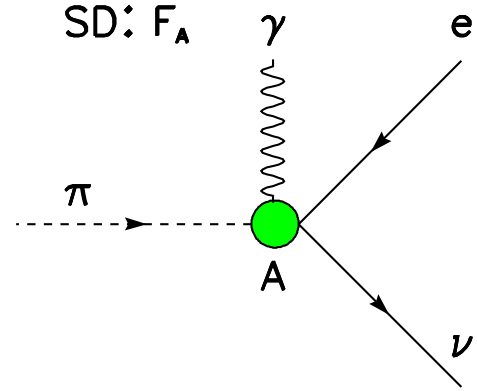




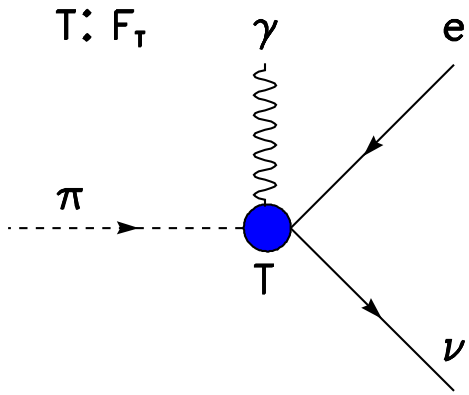
SM

and SD V, A terms:





A tensor interaction, too?



Exchange of S=0 leptoquarks

P Herczeg, PRD 49 (1994) 247

The $\pi \to e\nu\gamma$ amplitude and FF's

The IB amplitude (QED **uninteresting!**):

$$M_{\rm IB} = -i\frac{eG_F V_{ud}}{\sqrt{2}} f_\pi m_e \epsilon^{\mu *} \bar{e} \left(\frac{k_\mu}{kq} - \frac{p_\mu}{pq} + \frac{\sigma_{\mu\nu} q^\nu}{2kq} \right) \times (1-\gamma_5)\,\nu\,.$$

The structure-dependent amplitude (**interesting!**):

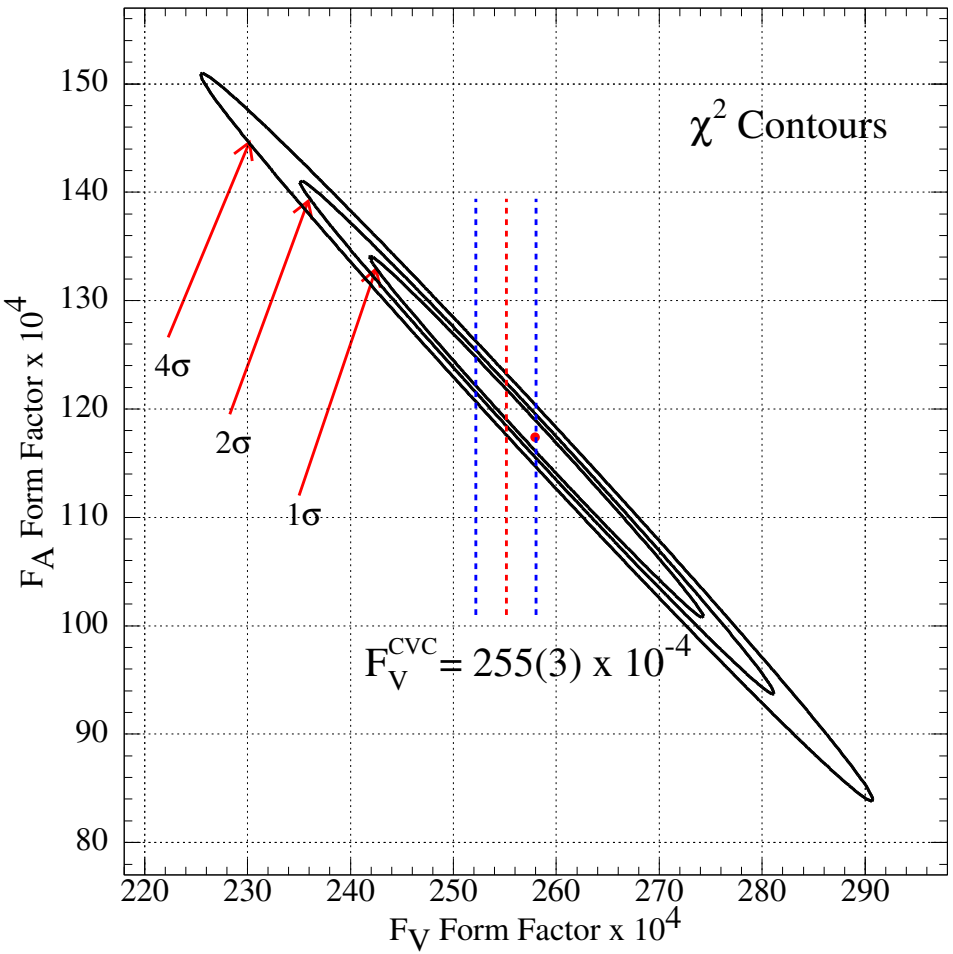
$$M_{\rm SD} = \frac{eG_F V_{ud}}{m_\pi \sqrt{2}} \epsilon^{\nu *} \bar{e}\gamma^\mu (1-\gamma_5)\nu \times \left[F_V \epsilon_{\mu\nu\sigma\tau} p^\sigma q^\tau + iF_A (g_{\mu\nu} pq - p_\nu q_\mu) \right] .$$

The SM branching ratio ($x = 2E_\gamma/m_\pi$; $y = 2E_e/m_\pi$),

$$\begin{aligned} \frac{{\rm d}\Gamma_{\pi e2\gamma}}{{\rm d}x\,{\rm d}y} =& \frac{\alpha}{2\pi}\Gamma_{\pi e2}\Bigg\{ IB\,(x,y) + \left(\frac{m_\pi^2}{2f_\pi m_e}\right)^2 \\ & \times \left[(F_V + F_A)^2\, {\rm SD}^+\,(x,y) + (F_V - F_A)^2\, SD^-\,(x,y) \right] \\ & + \frac{m_\pi}{f_\pi} \left[(F_V + F_A)\, S^+_{\rm int}\,(x,y) + (F_V - F_A)\, S^-_{\rm int}\,(x,y) \right] \Bigg\} . \end{aligned}$$

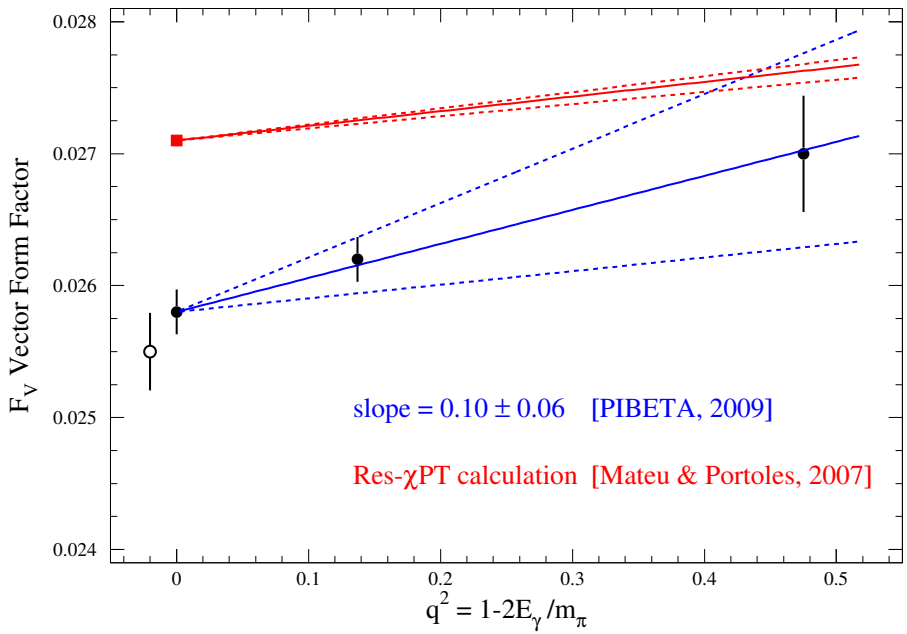
PIBETA results for $\pi \to e\nu\gamma$

Best values of pion Form Factor Parameters:



Combined analysis of 1999-01 and 2004 data sets

[Bychkov et al., PRL **103**, 051802 (2009)]



Summary of PIBETA results on $\pi \to e\nu\gamma$ [PRL **103**, 051802 (2009)]

$\mathbf{F_V = 0.0258 \pm 0.0017}$	**(8×)**
$\mathbf{F_A = 0.0119 \pm 0.0001}^{\text{exp}}_{(F_V^{CVC})}$	**(16×)**
$\mathbf{a = 0.10 \pm 0.06}$ ($\mathbf{q^2}$ dep of $\mathbf{F_V}$)	**(∞)**
$\mathbf{-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4}}$	90 % C.L.

$$\mathbf{B_{\pi_{e2\gamma}}(E_\gamma > 10\,\text{MeV}, \theta_{e\gamma} > 40^\circ) = 73.86(54) \times 10^{-8}} \quad \mathbf{(17\times)}$$

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At L.O. $(l_9 + l_{10})$, F_A, F_V are related to pion polarizability and π^0 lifetime

$$\alpha_E^{\text{LO}} = -\beta_M^{\text{LO}} = (2.783 \pm 0.023_{\text{exp}}) \times 10^{-4}\ \text{fm}^3$$

$$\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17}\,\text{s}$$

- current PDG avg: 8.52 (12)
- PrimEx PRL '10: 8.32 (23)

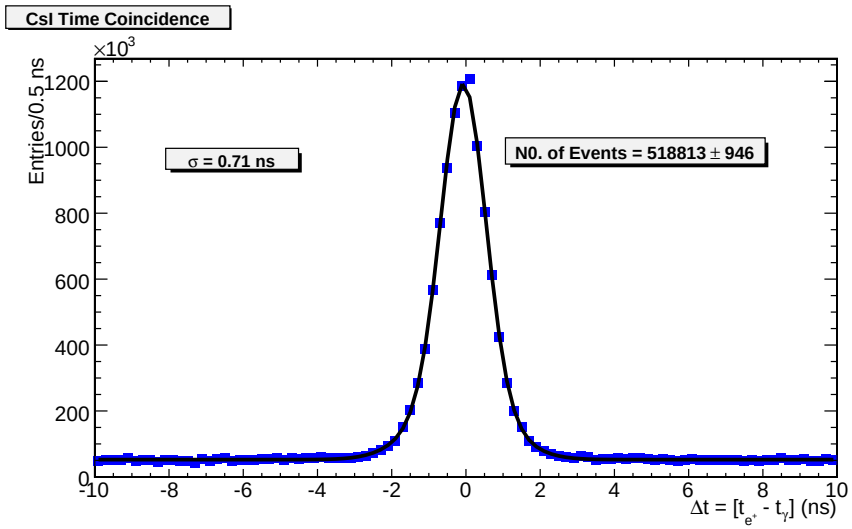
Radiative muon decay:

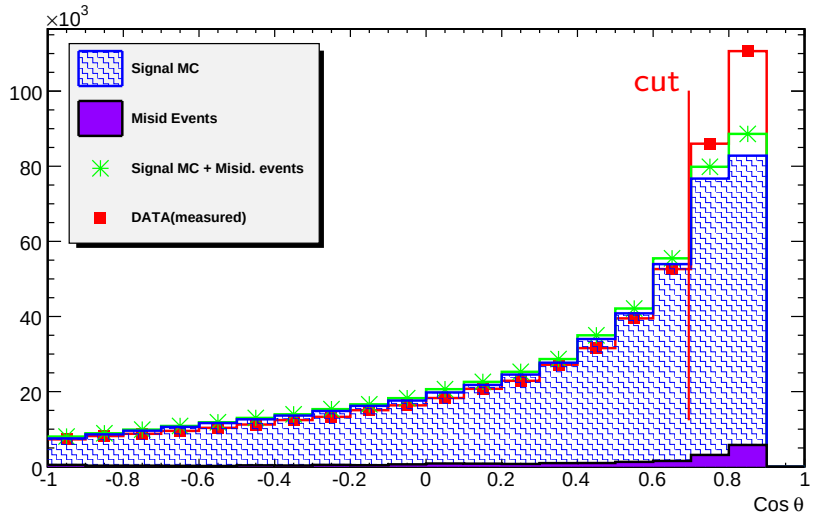
$$\boldsymbol{\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma}$$

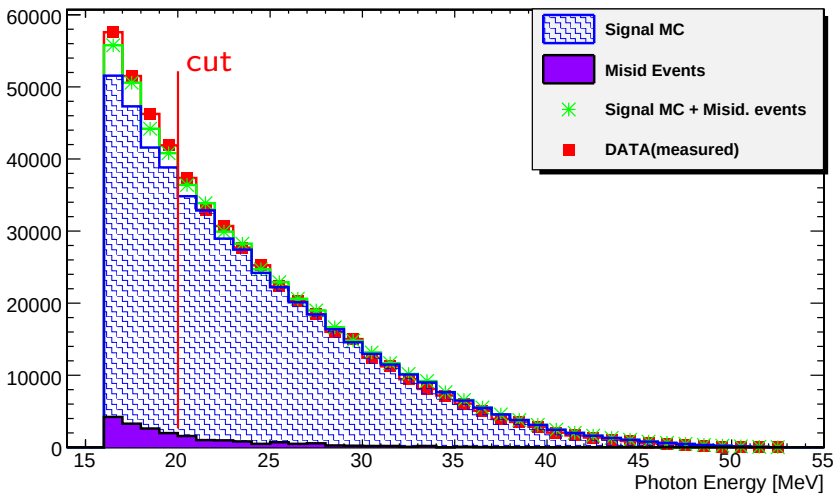
BR $\sim 10^{-3}$ for energetic γ's

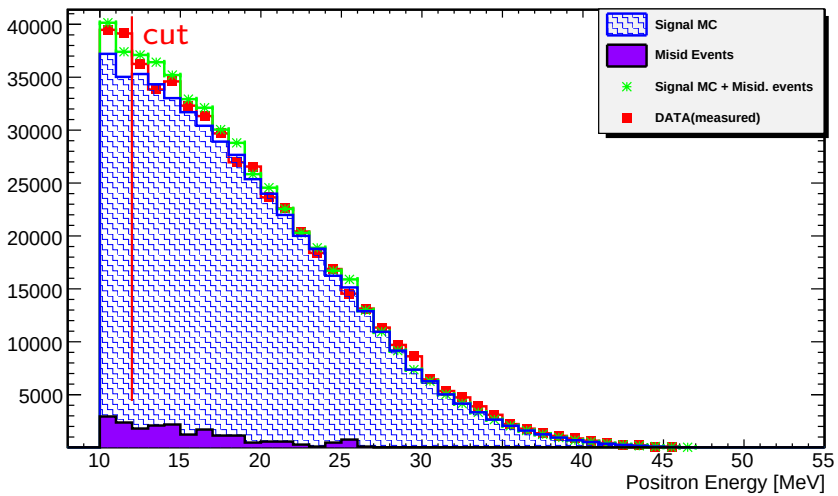
- Sensitive to admixtures beyond $V - A$
- Limiting factor in $\mu \to e\gamma$ LFV searches

Radiative muon decay, $\mu^+ \to e^+\nu\bar{\nu}\gamma$, (new analysis of 2004 data)









"Split clumps" very well accounted for!

RMD preliminary results, cont'd.

Preliminary result for RMD branching ratio (thesis E. Munyangabe):

$$B_{\text{exp}} = 4.365\,(9)_{\text{stat.}}\,(42)_{\text{syst.}} \times 10^{-3}\,, \qquad \boxed{29\times}$$

$$B_{\text{SM}} = 4.342\,(5)_{\text{stat-MC}} \times 10^{-3} \qquad (\text{for } E_\gamma > 10\,\text{MeV},\ \theta_{e\gamma} > 30^\circ)$$

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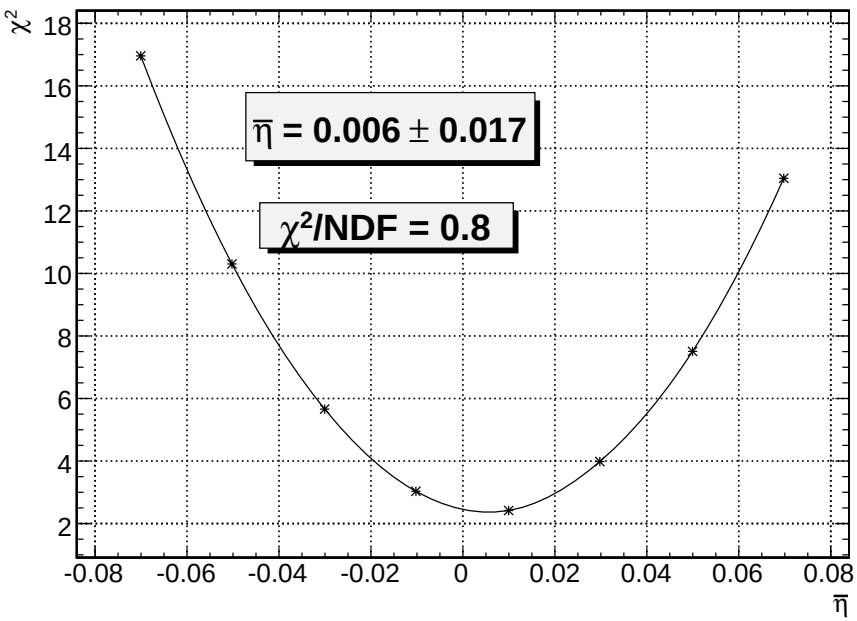

NB: preliminary results!

Analysis of PS subset:
$13\,\text{MeV} < E_\gamma < 45\,\text{MeV}$, and
$10\,\text{MeV} < E_{e^+} < 43\,\text{MeV}$, yields

$$\bar{\eta} = 0.006\,(17)_{\text{stat.}}\,(18)_{\text{syst.}}\,, \text{ or}$$

$$\bar{\eta} < 0.028 \quad (68\%\text{CL})\,.$$

$\boxed{\sim 4\times}$ better than best previous experiment (Eichenberger et al, 84).

Study of allowed π and μ decays in PEN

- A significant experimental effort is under way (in PEN and in other experiments) to make use of the unparalleled theoretical precision in the weak interactions of the lightest particles.
- Information obtained is complementary to expected collider results, and valuable for their proper interpretation.
- Improvements in precision for
  - $\pi \to e\nu$,
  - $\pi \to e\nu\gamma$ (F_V, F_T^{ul}), and
  - $\mu \to e\nu\bar{\nu}\gamma$.

  to be achieved in the near future.
- Decision on future measurement of $\pi^+ \to \pi^0 e^+ \nu$ will await results of current neutron beta decay experiments.

Current and former PIBETA and PEN collaborators

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[g] *Univ. Zürich, Switzerland*
[h] *Arizona State Univ., USA*

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