Results and opportunities in pion and muon decays

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Outline

Overview and status of allowed π and μ decays

Pion beta decay: $\pi^+ \to \pi^0 e^+ \nu$

Radiative pion decay: $\pi^+ \to e^+ \nu\gamma$

Allowed muon decays: ordinary and radiative

The π_{e2} decay: $\pi^+ \to e^+ \nu$

Summary

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})	✓
	$e^+\nu\gamma$	$1.61\,(23) \times 10^{-7}$	($\pi_{e2\gamma}$)	✓
	$\pi^0 e^+\nu$	$1.025\,(34) \times 10^{-8}$	(π_{e3}, π_β)	✓
	$e^+\nu e^+e^-$	$3.2\,(5) \times 10^{-9}$	(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 ✓		
	$e^+\nu\bar{\nu}\gamma$	0.014 (4) ✓		
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

Pions, muons, fundamental interactions & symmetries

- Why isn't $\pi \to e$ the dominant decay mode?
  Deep link to **V − A** nature of the **weak interaction** $\Longleftrightarrow$ **PV**;
- Pion triplet (π^+, π^0, π^-), are the **Goldstone bosons** in the spontaneous breaking of **Chiral Symmetry**;
- Explicit breaking of χ**S**: $\mathbf{m_\pi^2 \propto m_q}$ (Gell-Mann–Oakes–Renner rel.);
- **Conserved Vector Current**: $\Longleftrightarrow$ $\mathbf{SU(2)_V}$;
- Why is the beta energy spectrum in $\mu \to e$ decay continuous (3-body decay, **NO** $\mu \to e\gamma$)? $\Rightarrow$ **Lepton Flavor Conservation**.

Today there are **many** excellent precise measurements exploring these topics: FAST, MEG, MULAN, Muon(g-2), TWIST,. . .

Recent π, μ allowed decay measurements

- $\pi^+ \to \pi^0 e^+ \nu_e$ .... PIBETA ('99–'01)
  - SM checks related to CKM unitarity
- $\pi^+ \to e^+ \nu_e \gamma$(or e^+e^-) .... PIBETA ('99–'04), PEN ('06–)
  - F_A/F_V, π polarizability (χPT calibration)
  - tensor coupling besides $V - A$ (?)
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ .... TWIST (2003–04)
  - departures from $V - A$ in $\mathcal{L}_{\mathrm{weak}}$
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$(or e^+e^-) .... PIBETA ('04), PEN ('06–)
  - departures from $V - A$ in $\mathcal{L}_{\mathrm{weak}}$
- $\pi^+ \to e^+ \nu_e$ .... { PEN (2006–) / PiENu ('06–) }
  - e-μ universality
  - pseudoscalar coupling besides $V - A$
  - ν sector anomalies, Majoron searches, m_{h+}, PS l-q's, V l-q's, ...
  - search for signs of SUSY (MSSM)

Pion beta decay:

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

(PIBETA: 1999–2001 runs)

Quark-Lepton (Cabibbo) Universality

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

$$\mathcal{M} \propto \langle e|l^{\alpha}|\nu_e\rangle \to \bar{u}_e\gamma^{\alpha}(1-\gamma_5)u_{\nu}$$

is replicated in hadronic weak decays

$$\mathcal{M} \propto \langle p|h^{\alpha}|n\rangle \to \bar{u}_p\gamma^{\alpha}(G_V - G_A\gamma_5)u_n \quad \text{with} \quad G_{V,A} \simeq 1 \, .$$

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

3 **q** generations lead to the Cabibbo-Kobayashi-Maskawa (CKM) matrix (1973):

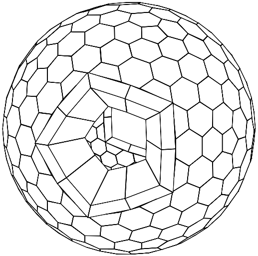
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

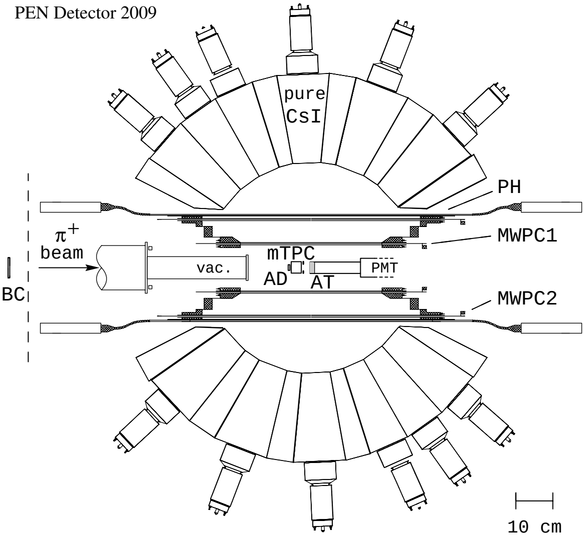
CKM unitarity cond.: $\Delta V^2 = 1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) \stackrel{?}{=} 0$, stringently tests the SM.

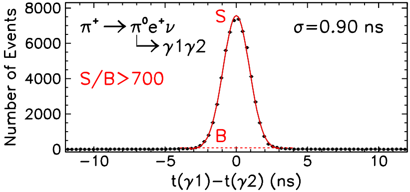
Prior to 2004 there was a **persistent $\sim 2.5\sigma$ shortfall** in ΔV^2, motivating many experiments to determine CKM m.e.'s, esp. V_{ud} and V_{us}.

The PIBETA/PEN apparatus

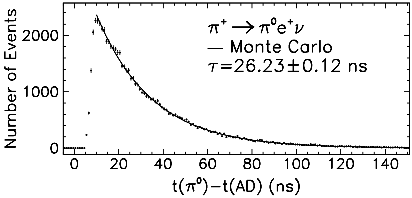
stopped π^+ beam
active target counter
240-det. CsI calorimeter
central tracking
digitized waveforms
stable temp./humidity



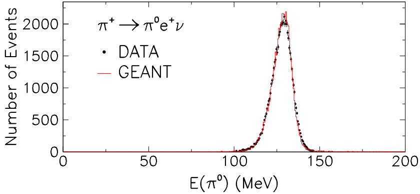




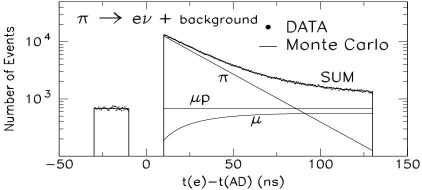
Number of Events
$\pi^+ \to \pi^0 e^+ \nu$
$\to \gamma 1 \gamma 2$
S
B
σ=0.90 ns
S/B>700
t(γ1)−t(γ2) (ns)



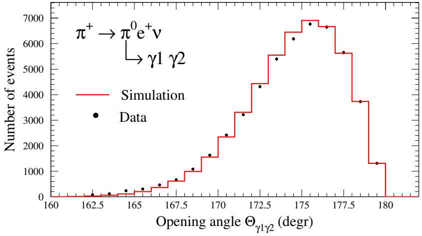
Number of Events
$\pi^+ \to \pi^0 e^+ \nu$
— Monte Carlo
τ=26.23±0.12 ns
t(π^0)−t(AD) (ns)



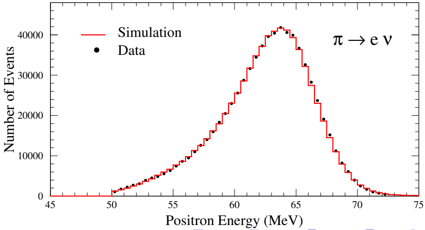
Number of Events
$\pi^+ \to \pi^0 e^+ \nu$
DATA
GEANT
E(π^0) (MeV)



Number of Events
$\pi \to e\nu$ + background
DATA
Monte Carlo
SUM
π
μp
μ
t(e)−t(AD) (ns)



Number of events
$\pi^+ \to \pi^0 e^+ \nu$
$\to \gamma 1\ \gamma 2$
Simulation
Data
Opening angle $\Theta_{\gamma 1 \gamma 2}$ (degr)



Number of Events
Simulation
Data
$\pi \to e\ \nu$
Positron Energy (MeV)

PIBETA result for π_β decay [PRL **93**, 181803 (2004)]

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

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

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

SM Prediction (PDG):

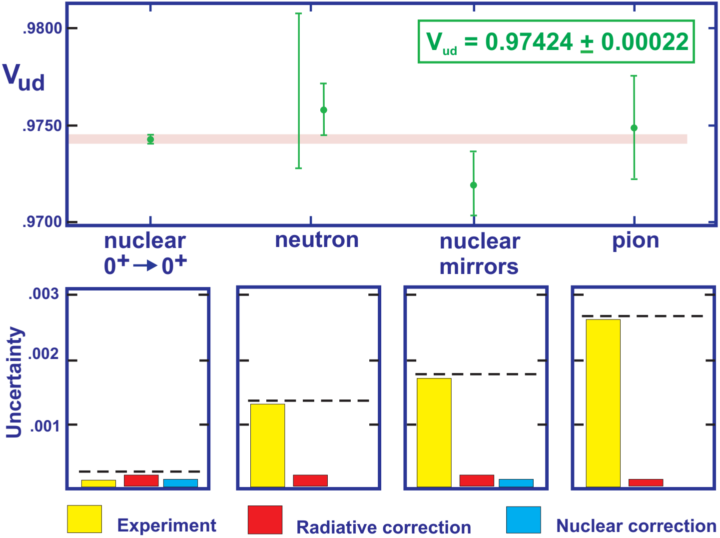
$B =$ $1.038 - 1.041 \times 10^{-8}$ (90% C.L.)

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

PDG 2008: $V_{ud} = 0.9742(3)$

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

Present Status of V_{ud}



(Courtesy of John Hardy, May 2009)

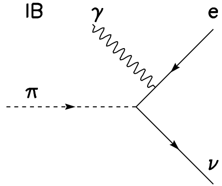
Radiative pion decay:

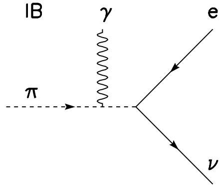
$$\pi^+ \to e^+\nu\gamma$$

PIBETA: 1999-2001 & 2004 runs
(PEN: 2008–2010 runs)

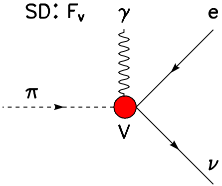
$\pi^+ \to e^+\nu\gamma$:

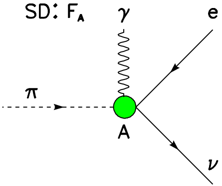
Standard **IB** *and*
V − A *terms*



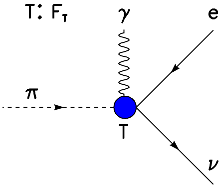


SM





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):

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

The structure-dependent amplitude:

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

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

$$\begin{aligned} \frac{d\Gamma_{\pi e2\gamma}}{dx\, dy} = & \frac{\alpha}{2\pi} \Gamma_{\pi e2} \Big\{ IB\,(x,y) + \left(\frac{F_V m_\pi^2}{2 f_\pi m_e} \right)^2 \\ & \times \left[(1+\gamma)^2\, \mathbf{SD^+}\,(x,y) + (1-\gamma)^2\, SD^-\,(x,y) \right] \\ & + \left(\frac{F_V m_\pi}{f_\pi} \right) \left[(1+\gamma)\, S_{\rm int}^+\,(x,y) + (1-\gamma)\, S_{\rm int}^-\,(x,y) \right] \Big\} \, . \end{aligned}$$

Available data on pion form factors

$$|F_V| \overset{\text{CVC}}{=} \frac{1}{\alpha}\sqrt{\frac{2\Gamma(\pi^0 \to \gamma\gamma)}{\pi m_{\pi^0}}} = 0.0259(9) \,.$$

$F_A \times 10^4$	reference	note
106 ± 60	Bolotov et al. (1990)	$(F_T = -56 \pm 17)$
135 ± 16	Bay et al. (1986)	
60 ± 30	Piilonen et al. (1986)	
110 ± 30	Stetz et al. (1979)	
116 ± 16	world average (PDG 2004)	

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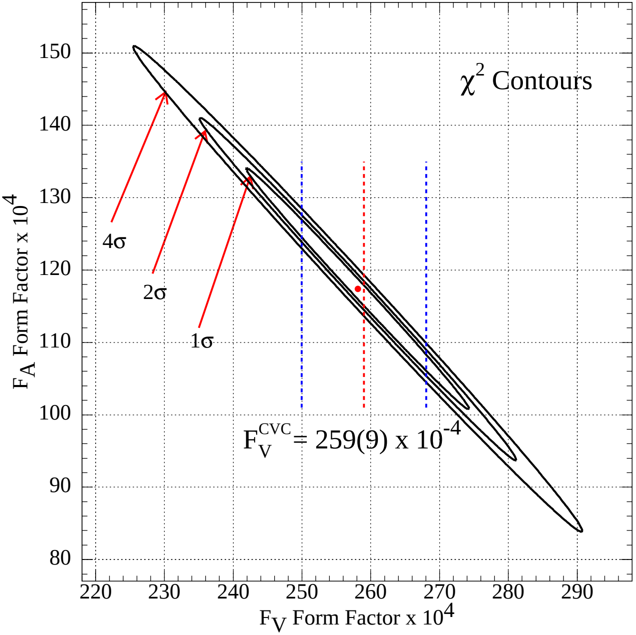
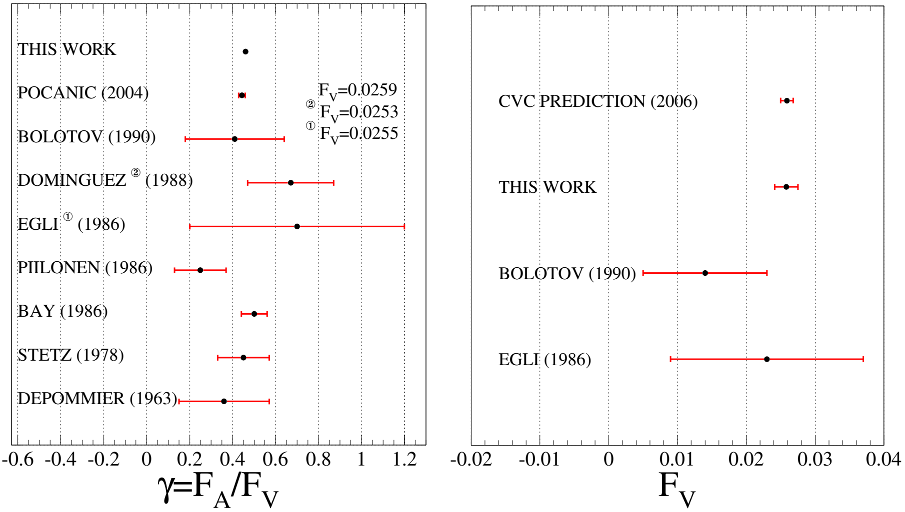


Best values of pion form factor parameters:

Combined analysis of 1999-2001 and 2004 data sets

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

Experimental history of pion F_A and F_V



Summary of pion form factor and B.R. results

$$F_V = 0.0258 \pm 0.0017 \qquad (14\times)$$

$$F_A = 0.0119 \pm 0.0001^{\rm exp}_{(F_V^{\rm CVC})} \qquad (16\times)$$

$$a = 0.10 \pm 0.06 \qquad (\infty)$$

$$-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4} \qquad 90\,\%\ \text{C.L.}$$

Derived pion polarizability and π^0 lifetime (at L.O.):

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

$$\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17}\,\text{s} \qquad \begin{cases} \text{current PDG avg: } 8.4\,(5) \\ \text{PrimEx p'print: } 8.32\,(23) \end{cases}$$

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

Above results will be improved with new PEN data and analysis.

Allowed muon decays:

$\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ (TWIST 2003–05)

$\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$ (PIBETA 2004, PEN 2008–10)

Michel parameters of muon decay: $\mu \to e\nu_\mu\bar{\nu}_e$

$$\frac{d^2\Gamma}{dx\ d(\cos\theta)} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2} \times$$
$$\times \left[\mathbf{F_{IS}}(x) + P_{\mu^+}\cos\theta\,\mathbf{F_{AS}}(x)\right]\left[1 + \vec{P}_{e^+}(x,\theta)\cdot\hat{\zeta}\right]$$

Isotropic part:

$$\mathbf{F_{IS}}(x) = x(1-x) + \frac{2}{9}\boldsymbol{\rho}(4x^2 - 3x - x_0^2) + \boldsymbol{\eta}\,x_0(1-x)$$

Anisotropic part:

$$\mathbf{F_{AS}}(x) = \frac{1}{3}\boldsymbol{\xi}\sqrt{x^2 - x_0^2}\left(1 - x + \frac{2}{3}\boldsymbol{\delta}\left[4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right]\right)$$

Michel parameters of radiative muon decay: $\mu \to e\nu_\mu\bar{\nu}_e\gamma$

$$\frac{d^3B(x,y,\theta)}{dx\,dy\,2\pi\,d(\cos\theta)} = f_1(x,y,\theta) + \bar{\eta} f_2(x,y,\theta) + (1 - \frac{4}{3}\rho) f_3(x,y,\theta)$$

$$\rho = \frac{3}{4} - \frac{3}{4}\Big[|g^V_{LR}|^2 + |g^V_{RL}|^2 + 2|g^T_{LR}|^2 + 2|g^T_{RL}|^2 + \Re(g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR})\Big] \overset{\text{SM}}{\equiv} \frac{3}{4},$$

$$\bar{\eta} = \left(|g^V_{RL}|^2 + |g^V_{LR}|^2\right) + \frac{1}{8}\left(|g^S_{LR} + 2g^T_{LR}|^2 + |g^S_{RL} + 2g^T_{RL}|^2 + 2\left(|g^T_{LR}|^2 + |g^T_{RL}|^2\right)\right) \overset{\text{SM}}{\equiv} 0.$$

Experimental Limits (90 % C.L.) on $\mathbf{g}^{\gamma}_{\alpha\beta}$

$\lvert g^{\gamma}_{\alpha\beta}\rvert$	S	V	T
LL	0.550	>0.960	$\equiv 0$
LR	0.088	0.036	0.025
RL	0.417	0.104	0.104
RR	0.067	0.034	$\equiv 0$
max. values:	$\lvert g^{S}_{\alpha\beta}\rvert$	$\lvert g^{V}_{\alpha\beta}\rvert$	$\lvert g^{T}_{\alpha\beta}\rvert$
	≤ 2	≤ 1	$\leq \frac{1}{\sqrt{3}} \approx 0.58$

[Most recent global fit by C.A Gagliardi et al., PR D **72** (2005) 073002]

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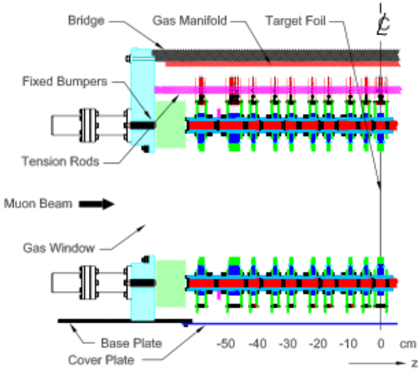
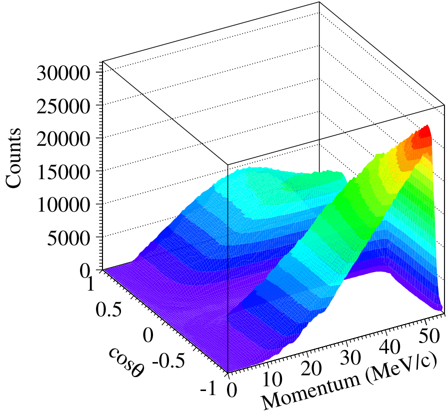
OMD study: TWIST experiment (TRIUMF)



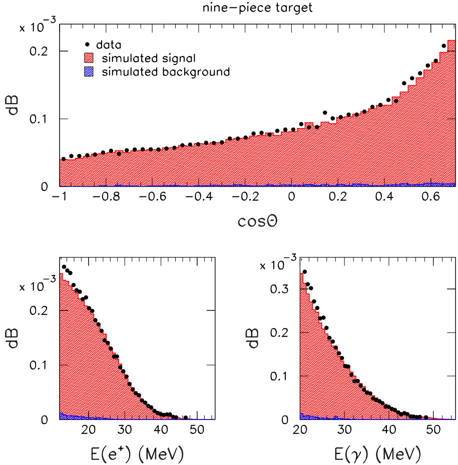


Main results:

$$\rho = \mathbf{0.7501\,(5)} \qquad \text{and} \qquad \delta = \mathbf{0.7507\,(7)}\,,$$

MacDonald, et al., Phys. Rev. D **78** (2008) 032010.

RMD differential branching ratio   [B. VanDevender, PhD thesis]



PRELIMINARY

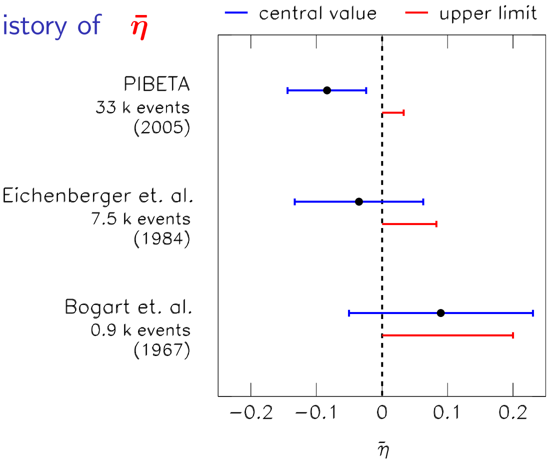
(new analysis+data)

due to small-angle bremsstrahlung uncertainties in GEANT

$$B^{\rm exp} = [4.40 \pm 0.02\ ({\rm stat.}) \pm 0.09\ ({\rm syst.})] \times 10^{-3}$$ **14×!**

$$B^{\rm theo} = 4.30 \times 10^{-3} \qquad (E_\gamma > 10\,{\rm MeV},\ \theta > 30^\circ)$$

Experimental History of $\bar{\eta}$



PIBETA preliminary (B. VanDevender, PhD thesis; 2004 data set):

$$\bar{\eta} = -0.084 \pm 0.050(\text{stat.}) \pm 0.034(\text{syst.})$$

$$\Rightarrow \bar{\eta} \leq 0.033;\ \text{new world average: } \boxed{\bar{\eta} \leq 0.028}\ (68\,\%\ \text{c.l.})$$

reduced by a factor of 2.5.

The π_{e2} decay:

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

PEN and PiENu experiments (2006–)

$\pi \to e\nu$ decay: SM calculations; measurements

Modern theoretical calculations: $$B_{calc} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{calc} =$$

$$\begin{cases} 1.2352\,(5) \times 10^{-4} & \text{Marciano and Sirlin, [PRL } \mathbf{71} \text{ (1993) 3629]} \\ 1.2354\,(2) \times 10^{-4} & \text{Finkemeier, [PL B } \mathbf{387} \text{ (1996) 391]} \\ 1.2352\,(1) \times 10^{-4} & \text{Cirigliano and Rosell, [PRL } \mathbf{99}\text{, 231801 (2007)]} \end{cases}$$

Experiment, world average [current PDG]:

$$\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{exp} = (1.230 \pm 0.004) \times 10^{-4}$$

N.B.:

PEN, PiENu aim at: $\frac{\delta B}{B} \simeq 5 \times 10^{-4}$

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PEN, PiENu aim at: $\dfrac{\delta B}{B} \simeq 5 \times 10^{-4}$

π_{e2} Decay and the SM

$B(\pi_{e2})$ in SM dominated by $(V-A)$ helicity suppression. Deviations primarily due to PS int. terms. Most general 4-fermion π_{e2} amplitude:

$$\frac{G_F}{\sqrt{2}}\Big[\left(\bar{d}\gamma_\mu\gamma^5 u\right)\left(\bar{\nu}_e\gamma^\mu\gamma^5(1-\gamma^5)e\right) f^e_{\mathrm{AL}} + f^e_{\mathrm{PL}}\left(\bar{d}\gamma^5 u\right)\left(\bar{\nu}_e\gamma^5(1-\gamma^5)e\right)\Big] + \text{r.h. } \nu \text{ term}$$

In the SM: $f^\ell_{\mathrm{AL}} = 1$, while $f^\ell_{\mathrm{xR}} = f^\ell_{\mathrm{Px}} = 0$, with $\ell = e, \mu$.

Strong helicity suppression amplifies sensitivity to f^e_{PL}:

$$\frac{B^{\mathrm{obs}}_{\pi e2} - B^{\mathrm{SM}}_{\pi e2}}{B^{\mathrm{SM}}_{\pi e2}} = \frac{\Delta B}{B^{\mathrm{SM}}} = \ldots \simeq \frac{2m_\pi^2}{m_e(m_u+m_d)} f^e_{\mathrm{PL}} \simeq \boxed{7700 f^e_{\mathrm{PL}}}\ !$$

Tgt accuracy of the PEN experiment, $\Delta B/B \simeq 5\times 10^{-4}$, translates into attractive mass limits:

Example mass bounds from PEN goal accuracy

(a) Charged Higgs, m_{H+} [Shanker, NP B204 (82) 375]

Given a mixing angle suppression $S \approx 10^{-2}$, we get

$$f^e_{PL} \approx S\frac{m_t m_\tau}{m^2_{H+}} \qquad \text{yielding} \qquad \boxed{m_{H+} > 6.9\ \text{TeV}}\,.$$

(b) Pseudoscalar leptoquarks, m_P

Given an estimated effective Yukawa coupling of $y \simeq 1/250$, we can find m_P, mass of the color-triplet PS l-q:

$$f^e_{PL} \approx \frac{\sqrt{2}}{G_F}\frac{y^2}{2m^2_P} \qquad \text{yielding} \qquad \boxed{m_P > 3.8\ \text{TeV}}\,.$$

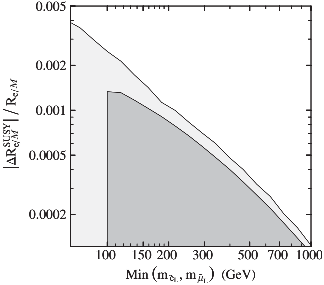
(c) Vector leptoquarks, M_G

Following Shanker who assumes gauge coupling $g \simeq g_{SU(2)}$, we get:

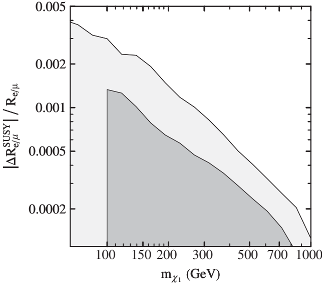
$$f^e_{PL} \approx \frac{4M^2_W}{M^2_G} \qquad \text{yielding} \qquad \boxed{M_G > 630\ \text{TeV}}\,.$$

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

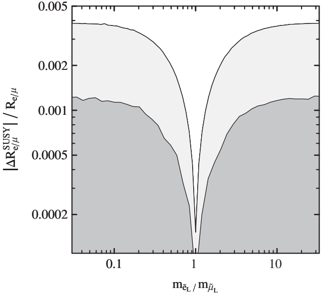
minimal selectron, smuon masses:



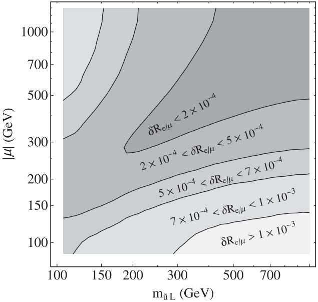
lowest mass chargino:



slepton mass degeneracy:



Higgsino mass param. μ and $m_{\tilde{u}_L}$:



RPV scenario constraints also discussed.

Lepton universality (and neutrinos)

From

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

$$R_{\tau/\pi} = \frac{\Gamma(\tau \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_\tau^2}{g_\mu^2} \frac{m_\tau^3}{2m_\mu^2 m_\pi} \frac{(1 - m_\pi^2/m_\tau^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} \left(1 + \delta R_{\tau/\pi}\right)$$

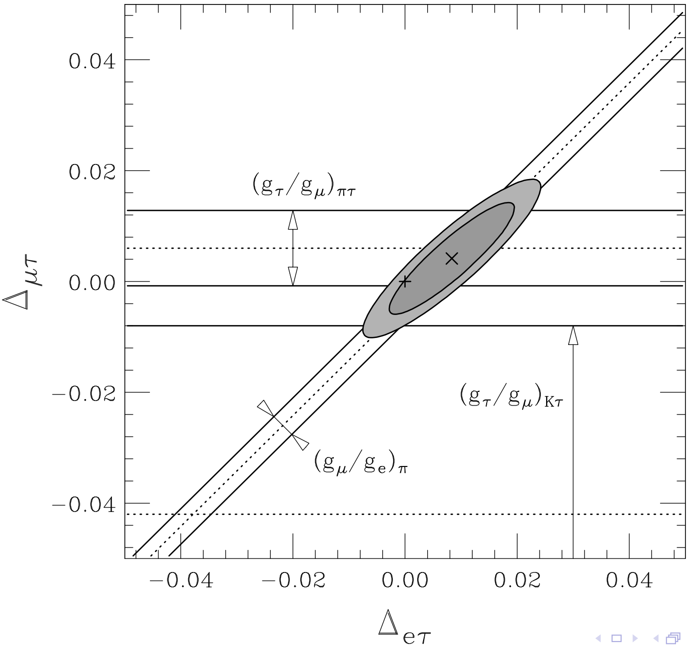
one can evaluate

$$\left(\frac{g_e}{g_\mu}\right)_\pi = 1.0021 \pm 0.0016 \quad \text{and} \quad \left(\frac{g_\tau}{g_\mu}\right)_{\pi\tau} = 1.0030 \pm 0.0034\,.$$

For comparison

$$\left(\frac{g_e}{g_\mu}\right)_W = 0.999 \pm 0.011 \quad \text{and} \quad \left(\frac{g_\tau}{g_e}\right)_W = 1.029 \pm 0.014\,.$$

[Presently allowed level of LUV could account for “NuTeV anomaly.”]



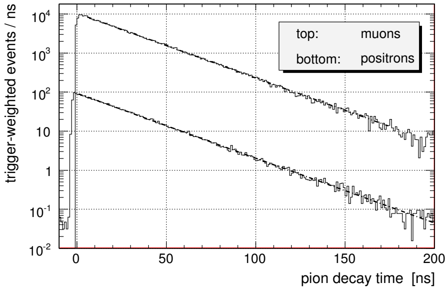
Loinaz et al., PRD **70** (2004) 113004

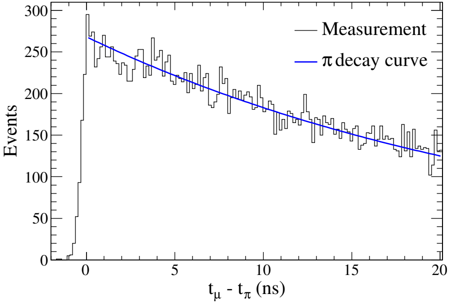
$$\Delta_{\ell\ell'} = 2\left(\frac{g_\ell}{g_{\ell'}} - 1\right)$$

PEN experiment: status and plans

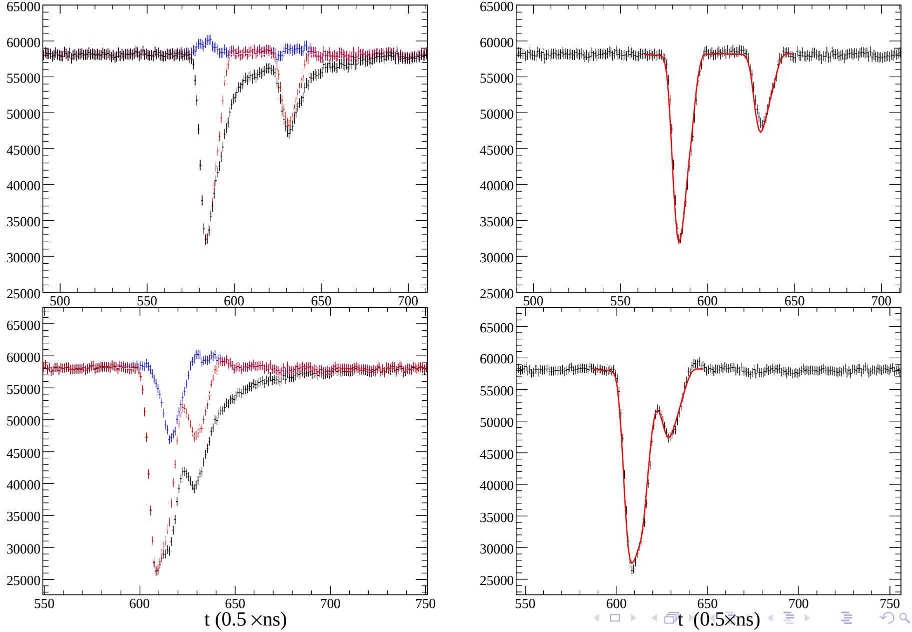
- Approved in 2006; development runs: 2007, '08; data runs '09, '10.
- Improved beam tracking (miniTPC) implemented in '09, '10 runs.
- $> 20\,\mathrm{M}\ \pi_{e2}$'s recorded $\Rightarrow (\delta B/B)_{\mathrm{stat}} \simeq 2 \times 10^{-4}$.

Illustration: decays in the target detector (2008 run):



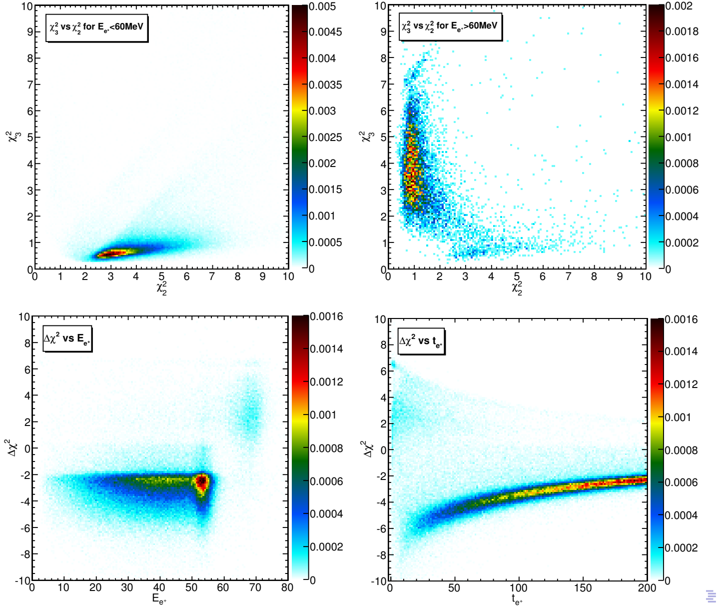


Waveform fitting in PEN [Anthony Palladino]



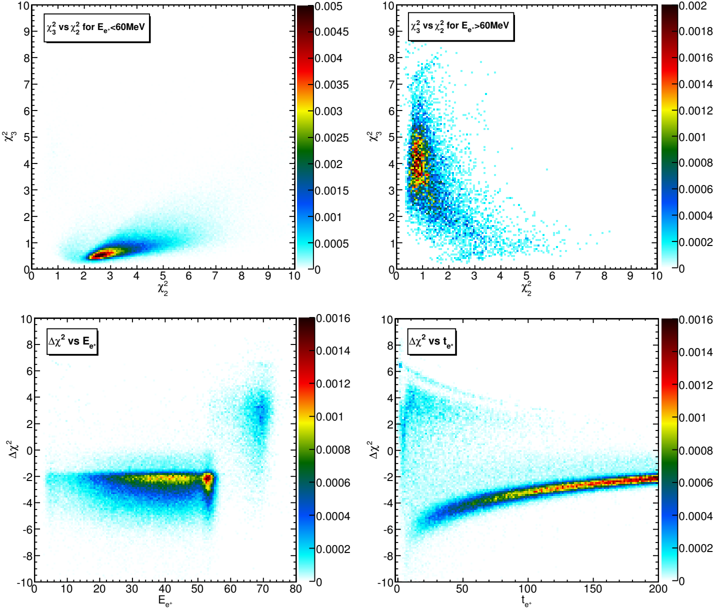
PEN: distinguishing $\pi \to e$ and $\pi \to \mu \to e$ decays (measurement)

[A. Palladino & L.P. Alonzi]

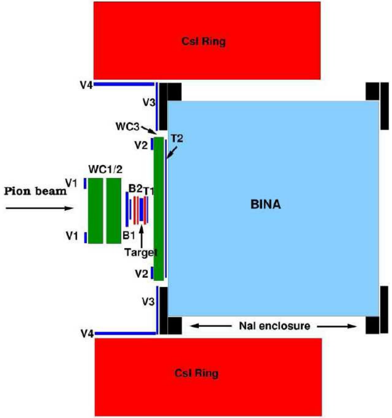


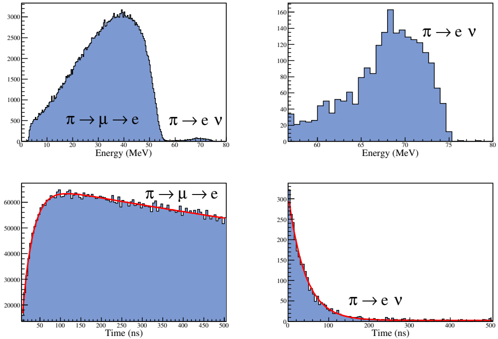
PEN: distinguishing $\pi \to e$ and $\pi \to \mu \to e$ decays (simulation)

[A. Palladino & L.P. Alonzi]



PiENu experiment (TRIUMF)





Acceptance: $\Delta\Omega \simeq 0.2 \times 4\pi$ sr

Excellent energy resolution.

Project started in 2006. Data taking currently under way.

Status of allowed π and μ decays

- *A significant experimental effort is under way 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 necessary for their proper interpretation.*
- *Orders of magnitude improvement in precision has been achieved; more lie in store.*
- *These projects are ideally suited to PSI (and TRIUMF).*
- *Modest scale of investment of resources required.*
- *Unique opportunity for scientific advancement.*
- *Great projects for graduate students and postdocs—full range of professional training.*

Current and former PIBETA and PEN collaborators

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