Update on Rare Pion and Muon Decay Measurements the PIBETA and PEN Experiments

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Outline

The PIBETA–PEN Program of Measurements

1st phase: The **PIBETA** expt.: Runs: 1999–2001; 2004

- $\pi^+ \to \pi^0 e^+ \nu_e$
  - SM checks related to CKM unitarity
- $\pi^+ \to e^+ \nu_e \gamma$(or e^+e^-)
  - F_A/F_V, π polarizability (χPT calibration)
  - tensor coupling besides $V - A$ (?)
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$(or e^+e^-)
  - departures from $V - A$ in $\mathcal{L}_{weak}$

2nd phase: The **PEN** expt. Since 2006 – ongoing

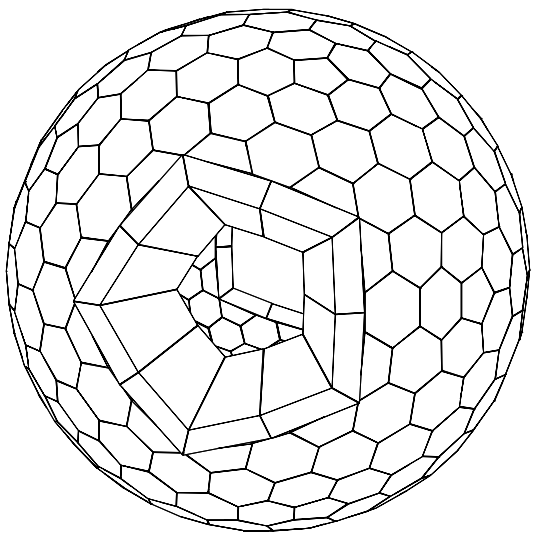
- $\pi^+ \to e^+ \nu_e$
  - e-μ universality
  - pseudoscalar coupling besides $V - A$
  - ν sector anomalies, Majoron searches, m_{h+}, PS l-q's, V l-q's, ...

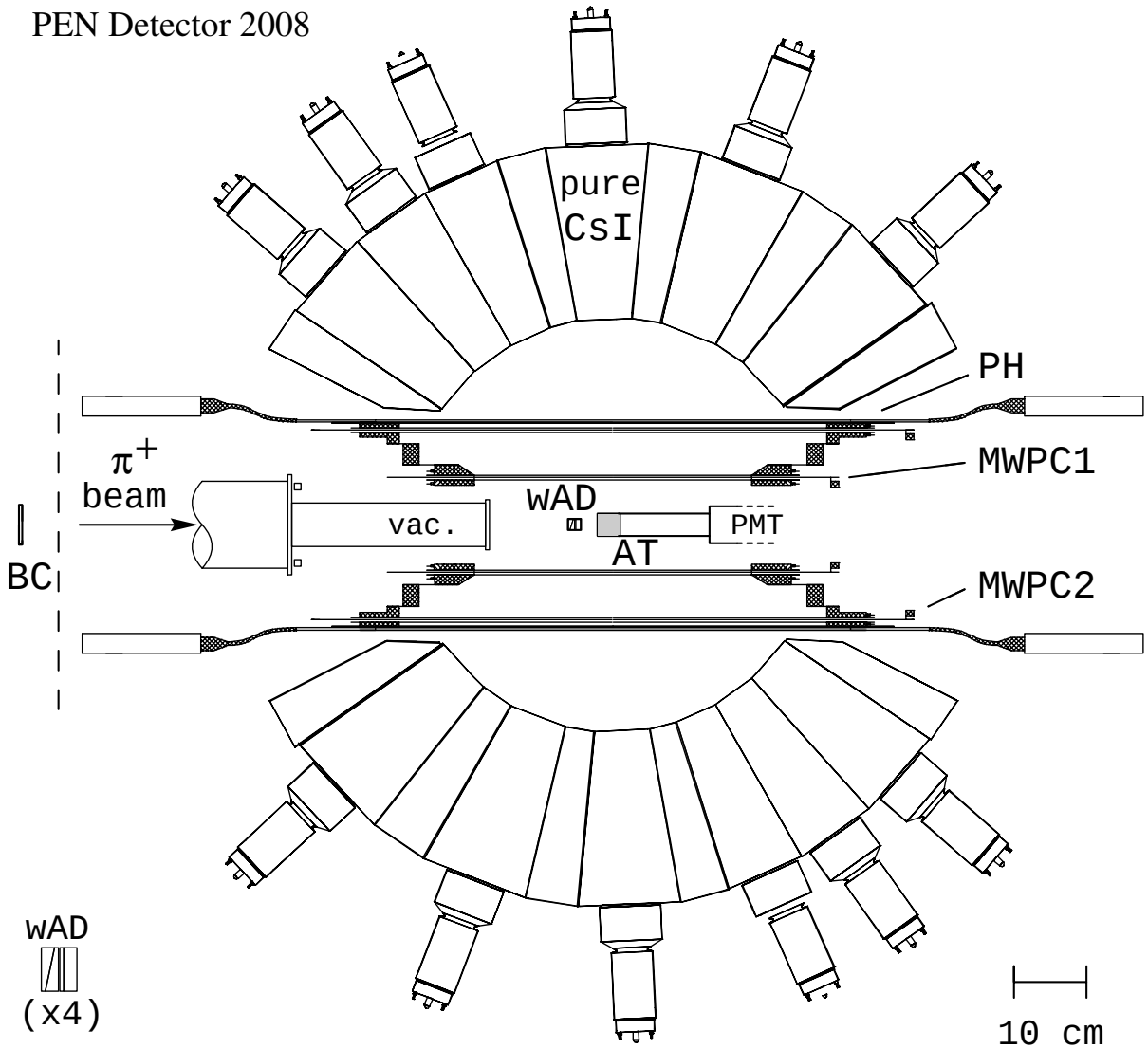
Known and Measured Pion and Muon Decays

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

The PIBETA/PEN Apparatus

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





Pion Beta Decay:

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

1999–2001 data set

Quark-Lepton (Cabibbo) Universality

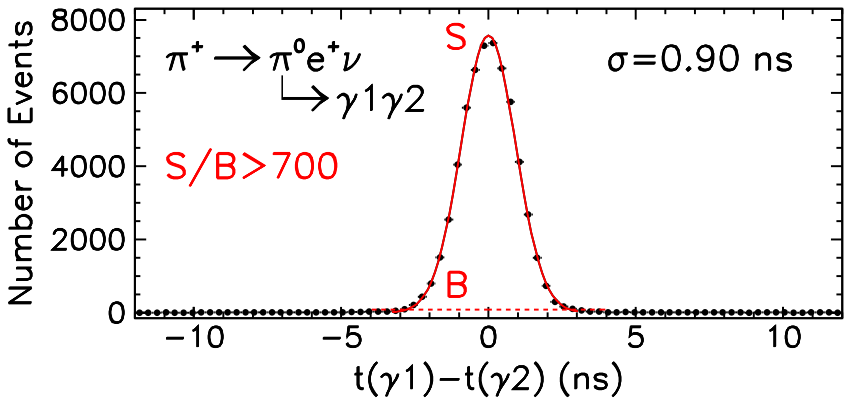
The basic weak-interaction **V-A** form persists in hadronic weak decays

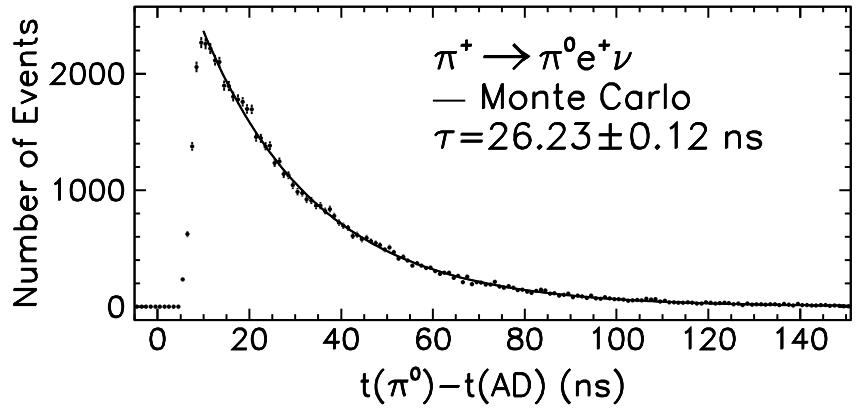
$$\mathcal{M} \propto \langle \mathbf{p}|\mathbf{h}^{\alpha}|\mathbf{n}\rangle \longrightarrow \bar{\mathbf{u}}_{\mathbf{p}}\gamma^{\alpha}(\mathbf{G_V} - \mathbf{G_A}\gamma_5)\mathbf{u_n} \quad \text{with} \quad \mathbf{G_{V,A}} \simeq \mathbf{1}\ .$$

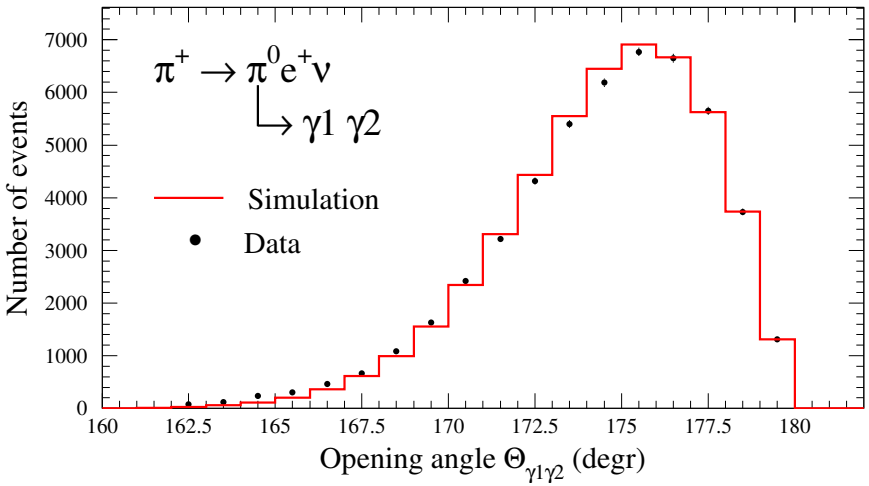
Departure from $\mathbf{G_V = 1}$ (**CVC**) comes from weak quark (Cabibbo) mixing: $\mathbf{G_V = G_\mu \cos\theta_C (= G_\mu V_{ud})} \quad \mathbf{\cos\theta_C \simeq 0.97}$

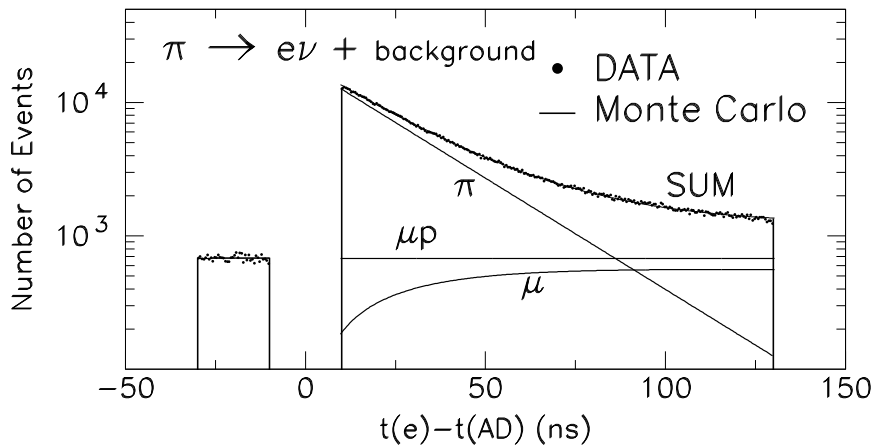
CKM unitarity cond.: $\mathbf{\Delta V^2 = 1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) \stackrel{?}{=} 0}$, stringently tests the SM.

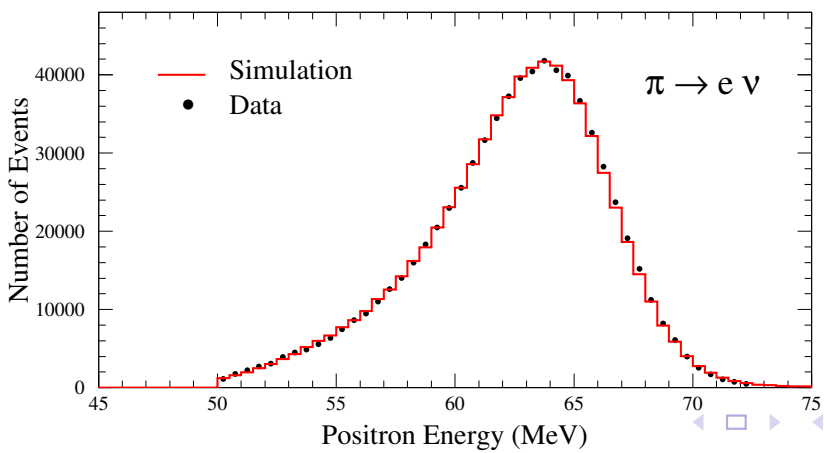
Prior to 2004 there was a **persistent $\sim 2.5\sigma$ shortfall** in $\mathbf{\Delta V^2}$, motivating many experiments to determine CKM m.e.'s, esp. $\mathbf{V_{ud}}$ and $\mathbf{V_{us}}$.


Number of Events
8000
6000
4000
2000
0
$\pi^+ \to \pi^0 e^+ \nu$
$\hookrightarrow \gamma 1 \gamma 2$
S/B>700
S
B
σ=0.90 ns
−10
−5
0
5
10
t(γ1)−t(γ2) (ns)


Number of Events
2000
1000
0
$\pi^+ \to \pi^0 e^+ \nu$
— Monte Carlo
τ=26.23±0.12 ns
0
20
40
60
80
100
120
140
t(π⁰)−t(AD) (ns)


Number of events
7000
6000
5000
4000
3000
2000
1000
0
$\pi^+ \to \pi^0 e^+ \nu$
$\hookrightarrow \gamma 1\ \gamma 2$
Simulation
Data
160
162.5
165
167.5
170
172.5
175
177.5
180
Opening angle $\Theta_{\gamma 1 \gamma 2}$ (degr)


Number of Events
10^4
10^3
$\pi \to e\nu$ + background
DATA
Monte Carlo
π
SUM
μp
μ
−50
0
50
100
150
t(e)−t(AD) (ns)


Number of Events
40000
30000
20000
10000
0
Simulation
Data
$\pi \to e\ \nu$
45
50
55
60
65
70
75
Positron Energy (MeV)

PIBETA Result for π_β Decay [PRL **93**, 181803 (2004)]

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

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

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

SM Prediction (PDG, 2006):

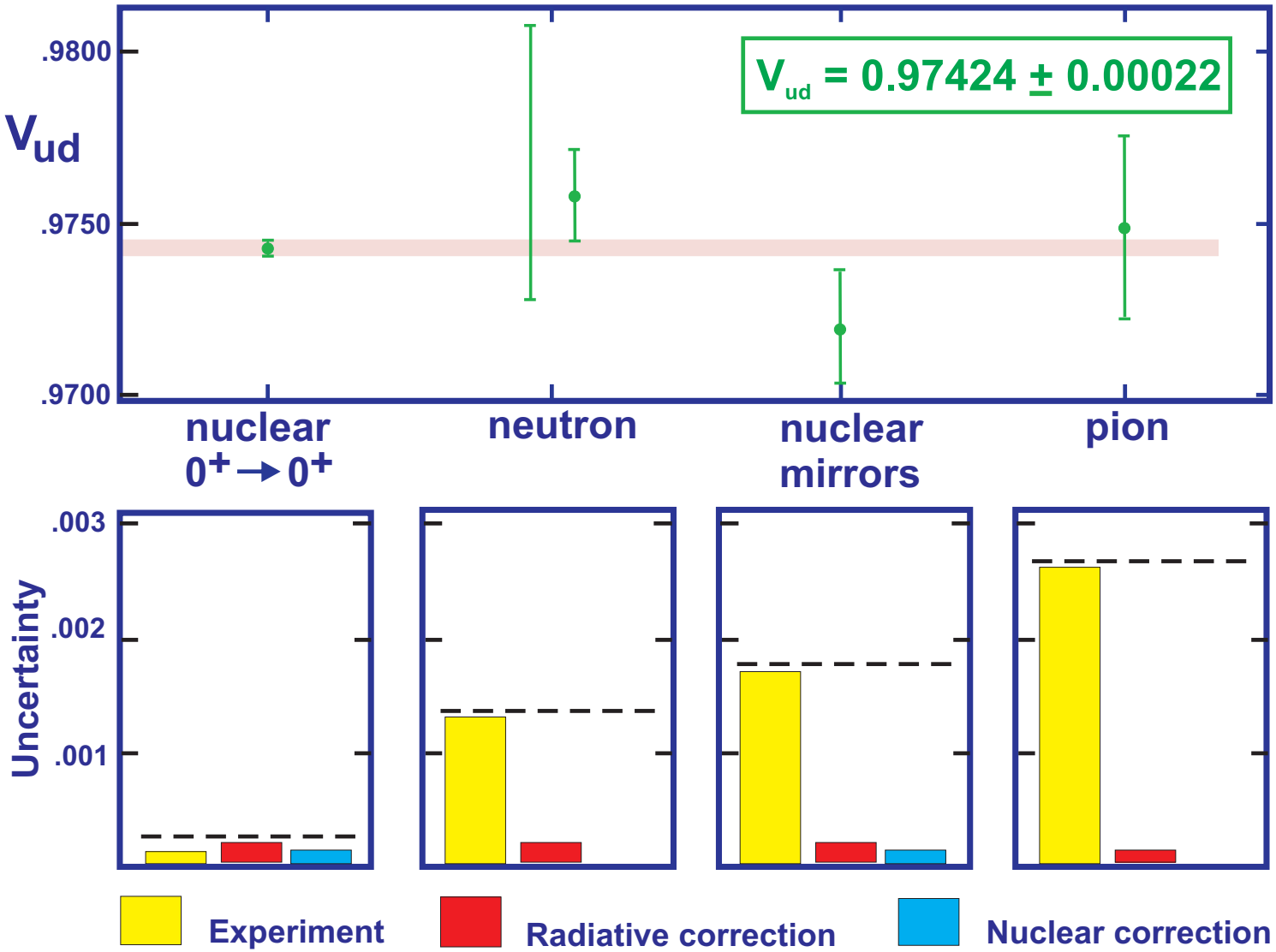
$B =$ $1.038 - 1.041 \times 10^{-8}$ (90% C.L.)

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

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

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

Present Status of V_{ud}



(Courtesy of John Hardy, May 2009)

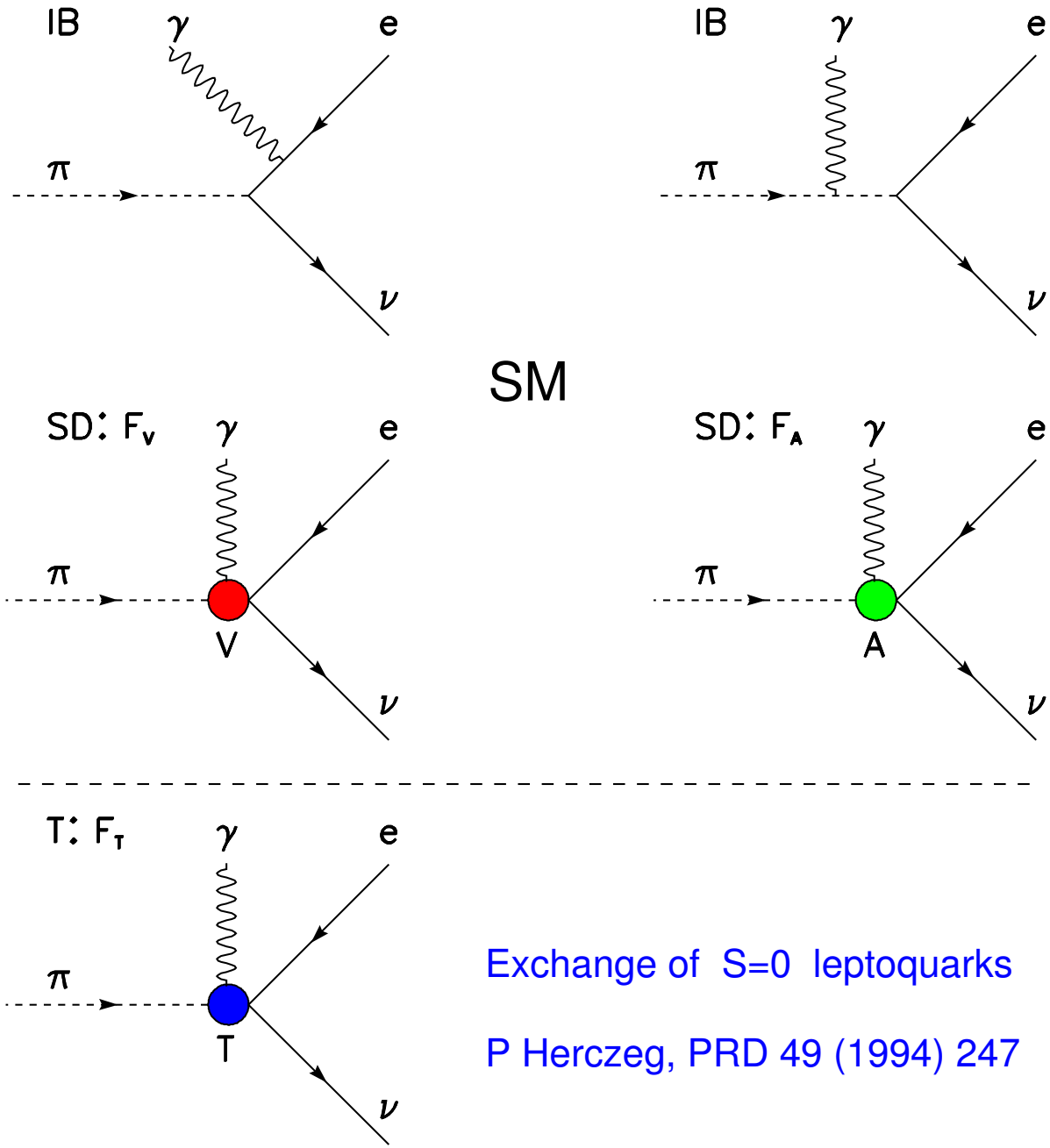
Radiative pion decay:

$\pi \longrightarrow e\nu\gamma$

1999-2001 & 2004 data sets

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

Standard **IB** *and*
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):

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

The structure-dependent amplitude:

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

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

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

$F_A \times 10^4$	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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Results, $V - A$ fit [1999-01 data, PRL **93**, 181804 (2004)]

Best-fit $\pi \longrightarrow e\nu\gamma$ branching ratios obtained with:
$\mathbf{F_V = 0.0259}$ (fixed) and $\mathbf{F_A = 0.0115(4)}$ (fit)
$\chi^2/\text{d.o.f.} = \mathbf{25.4}$.
Radiative corrections are included in the calculations.

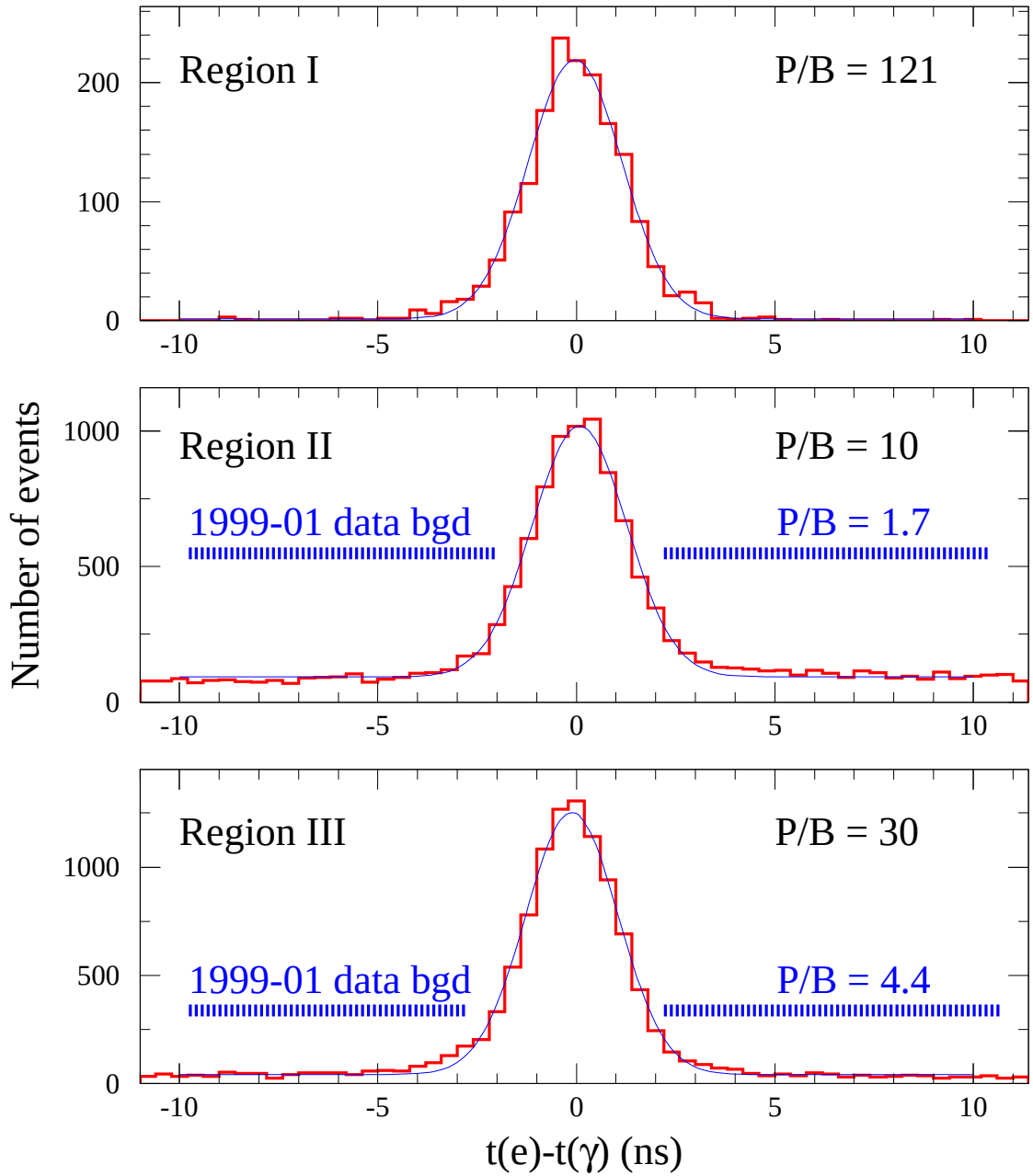
$E_{e^+}^{min}$ (MeV)	E_{γ}^{min} (MeV)	$\theta_{e\gamma}^{min}$	B_{exp} $(\times 10^{-8})$	B_{the} $(\times 10^{-8})$	no. of events
50	**50**	**–**	**2.71(5)**	**2.583(1)**	**30.6 k**
10	**50**	**40°**	**11.6(3)**	**14.34(1)**	**5.2 k**
50	**10**	**40°**	**39.1(13)**	**37.83(1)**	**5.7 k**

$\pi^+ \to e^+\nu\gamma$ (S/B) 2004

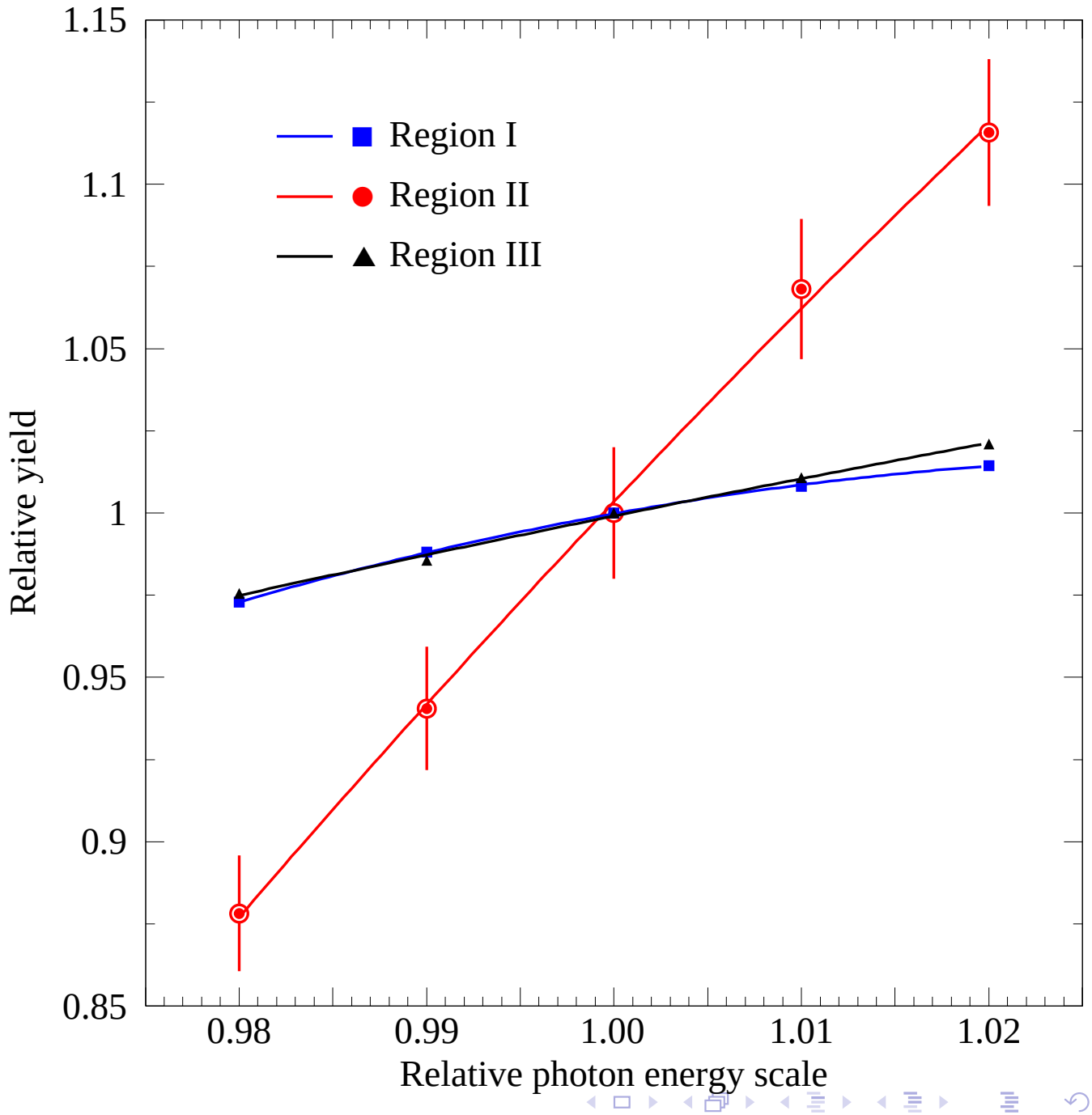
Region I:
$E_\gamma, E_{e^+} > 51.7\,\text{MeV}$

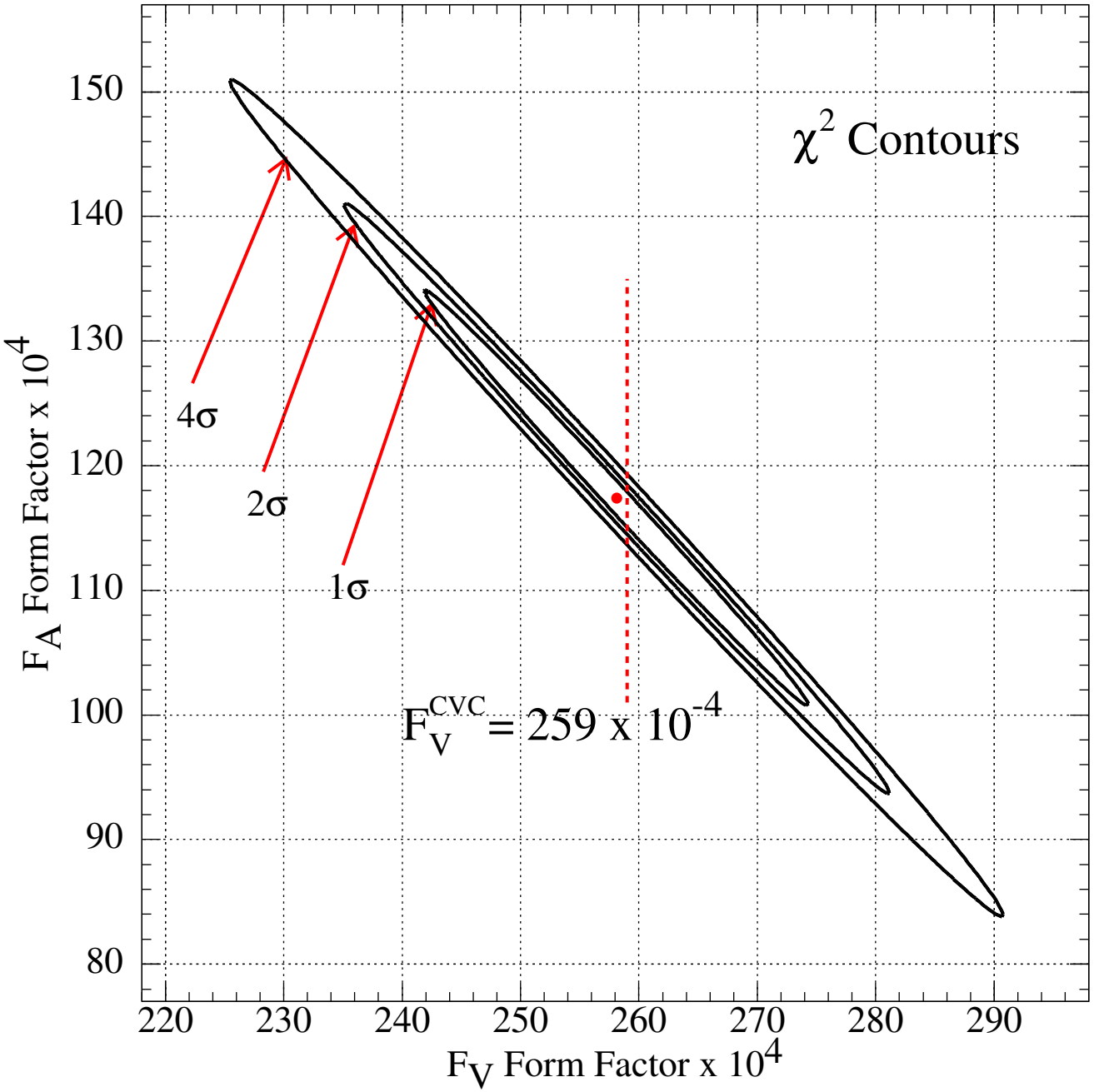
Region II:
$E_\gamma > 55.6\,\text{MeV}$
$20 < E_{e^+} < 51.7\,\text{MeV}$
$(\theta_{e\gamma} > 40^\circ)$

Region III:
$20 < E_\gamma < 51.7\,\text{MeV}$
$E_{e^+} > 55.6\,\text{MeV}$
$(\theta_{e\gamma} > 40^\circ)$



e/γ shower E scale



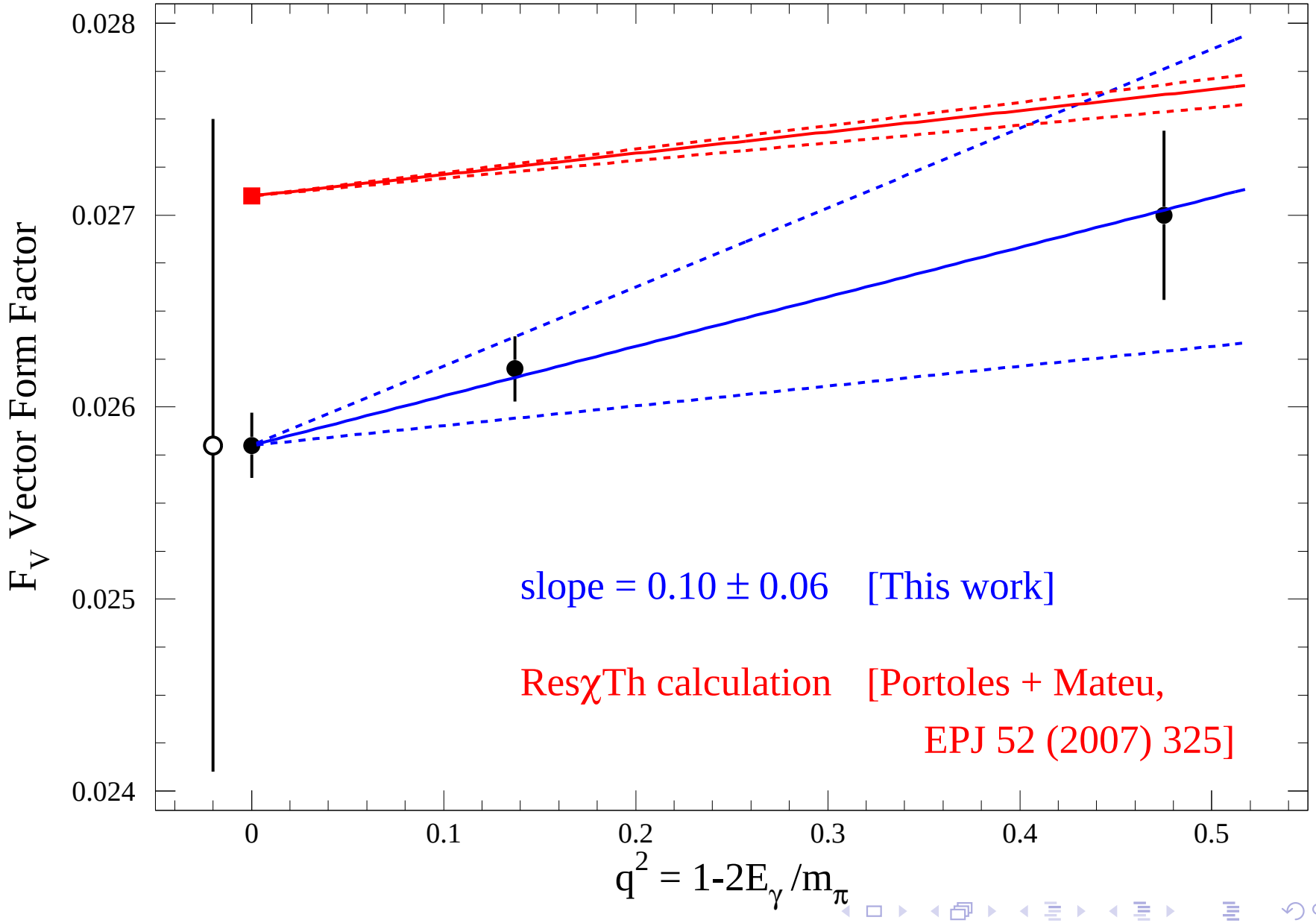


Best values of pion Form Factor Parameters:

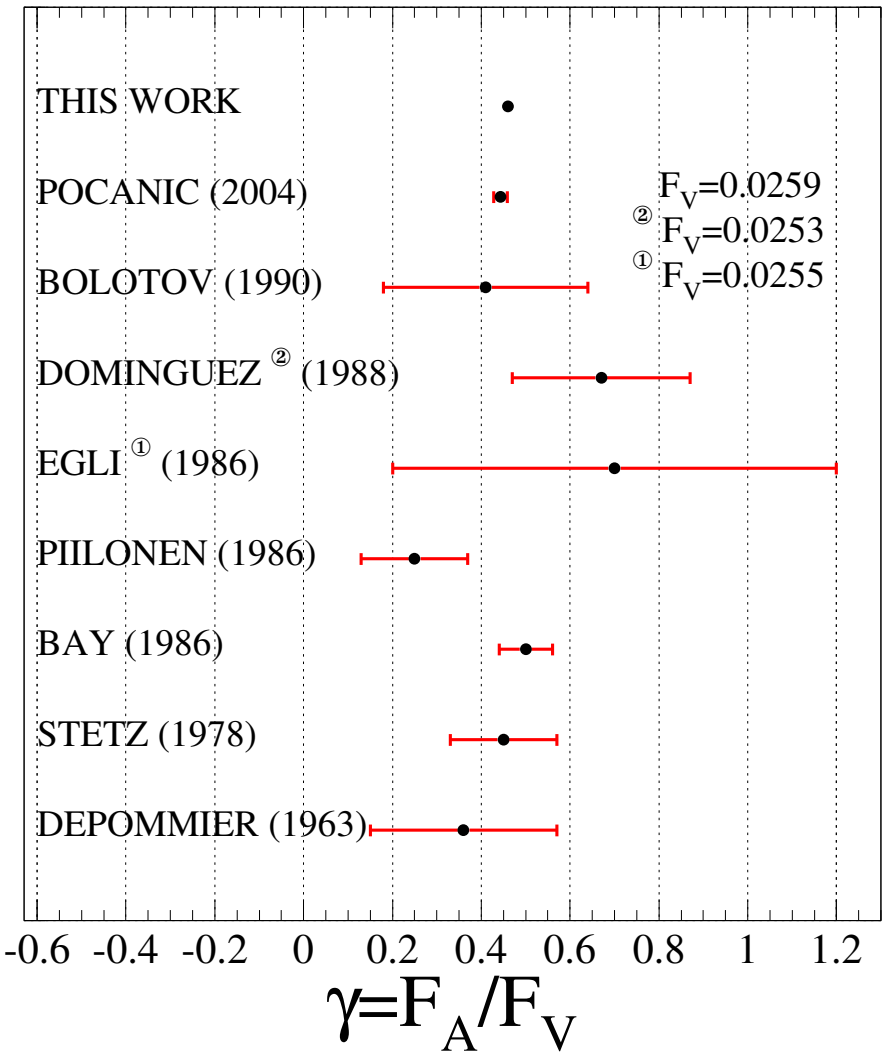
Combined analysis of 1999-2001 and 2004 data sets

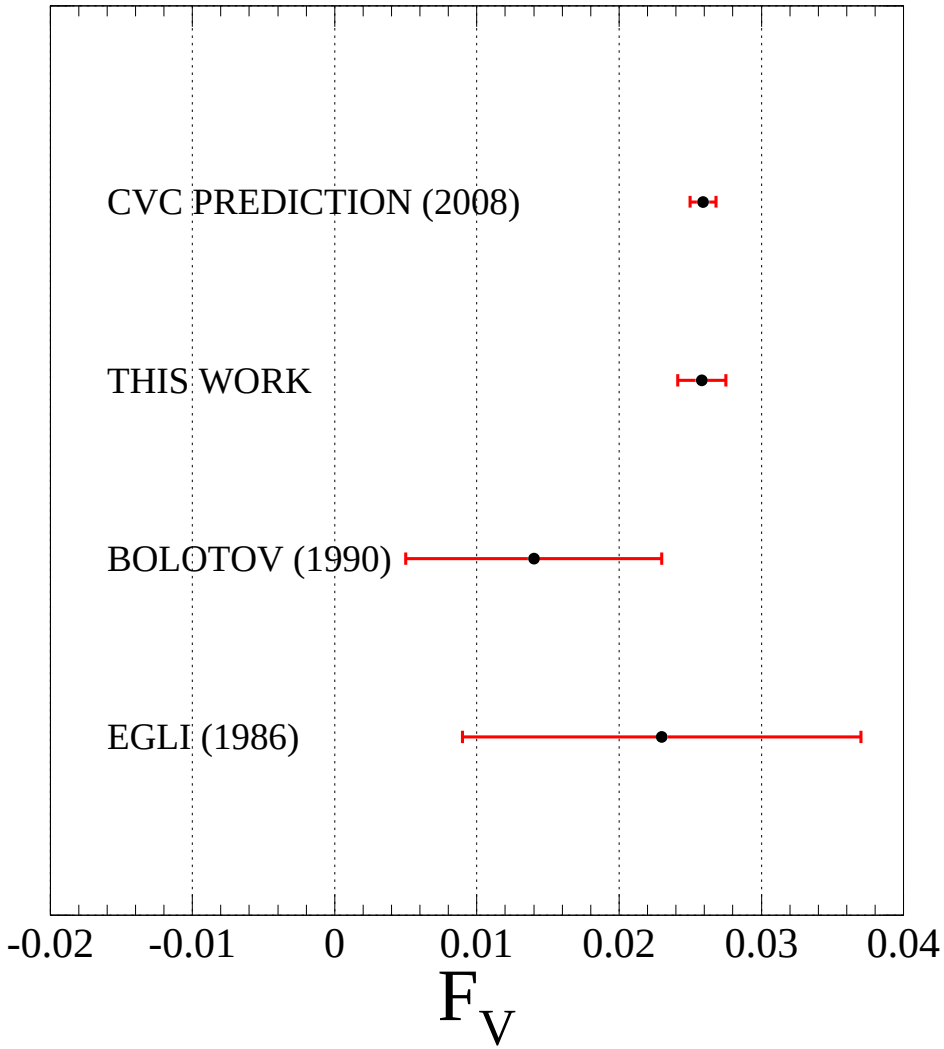
[M. Bychkov, 2008]

$q^2(e\nu)$ dependence



Experimental History of Pion F_A and F_V





Summary of Pion Form Factor Results

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

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

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

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

Derived pion polarizability and π^0 lifetime:

$$L_9^r + L_{10}^r = 0.00145(1)_{exp}(5)_{Fv} \ /\ 0.0014^{+3}_{-2} \text{ (3-param. fit)}$$

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

$$\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17}\ \text{s} \qquad \text{PDG: 8.4(6)}$$

Also:

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

Radiative muon decay:

$\mu \longrightarrow e\nu\bar{\nu}\gamma$

2004 data set

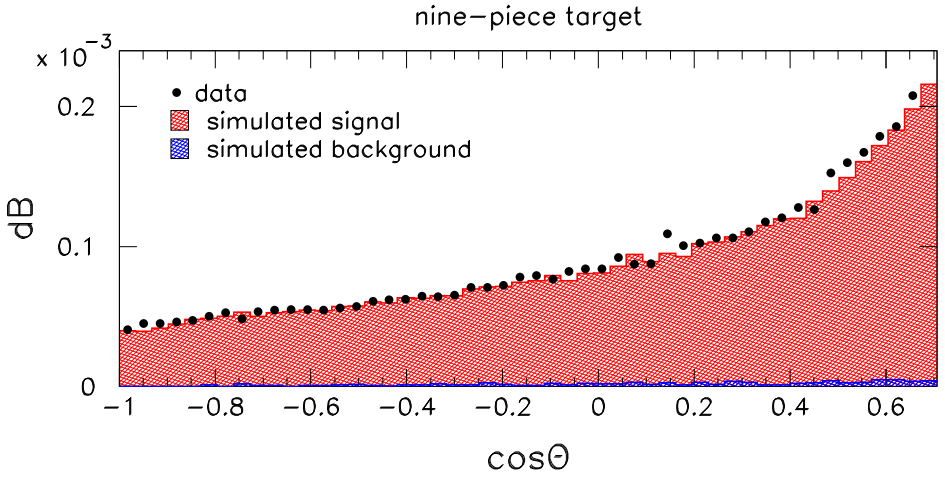
Michel Parameters of Radiative Muon Decay: $\mu \longrightarrow e\nu\bar{\nu}\gamma$

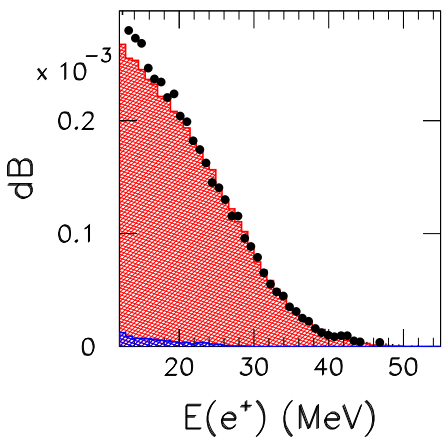
$$\frac{d^3B(x,y,\theta)}{dx\,dy\,2\pi\,d(\cos\theta)} = f_1(x,y,\theta) + \bar{\eta} f_2(x,y,\theta) + (1 - \frac{4}{3}\rho) f_3(x,y,\theta)$$

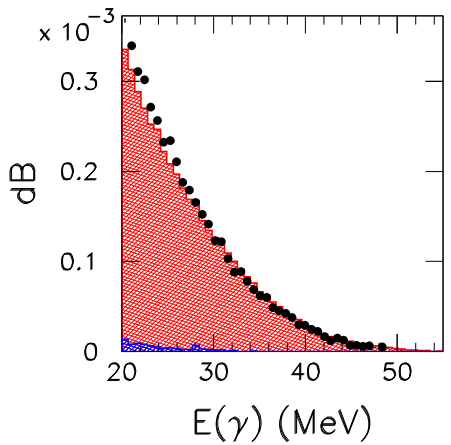
$$\rho = \frac{3}{4} - \frac{3}{4}\Big[|g_{LR}^V|^2 + |g_{RL}^V|^2 + 2|g_{LR}^T|^2 + 2|g_{RL}^T|^2 + \Re(g_{RL}^S g_{RL}^{T*} + g_{LR}^S g_{LR}^{T*})\Big] \overset{\text{SM}}{\equiv} \frac{3}{4},$$

$$\bar{\eta} = \left(|g_{RL}^V|^2 + |g_{LR}^V|^2\right) + \frac{1}{8}\left(|g_{LR}^S + 2g_{LR}^T|^2 + |g_{RL}^S + 2g_{RL}^T|^2\right) + 2\left(|g_{LR}^T|^2 + |g_{RL}^T|^2\right) \overset{\text{SM}}{\equiv} 0.$$

Differential Branching Ratio [B. VanDevender, Ph.D. Thesis]







due to small-angle bremsstrahlung uncertainties in GEANT

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

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

RMD analysis: Fit of $\bar{\eta}$ and ρ [B. VanDevender's thesis]

data set	$\bar{\eta}$	ρ
nine-piece target	-0.066 ± 0.070	0.750 ± 0.010
	-0.065 ± 0.065	0.75 (fixed)
one-piece target	-0.115 ± 0.085	0.751 ± 0.011
	-0.111 ± 0.077	0.75 (fixed)

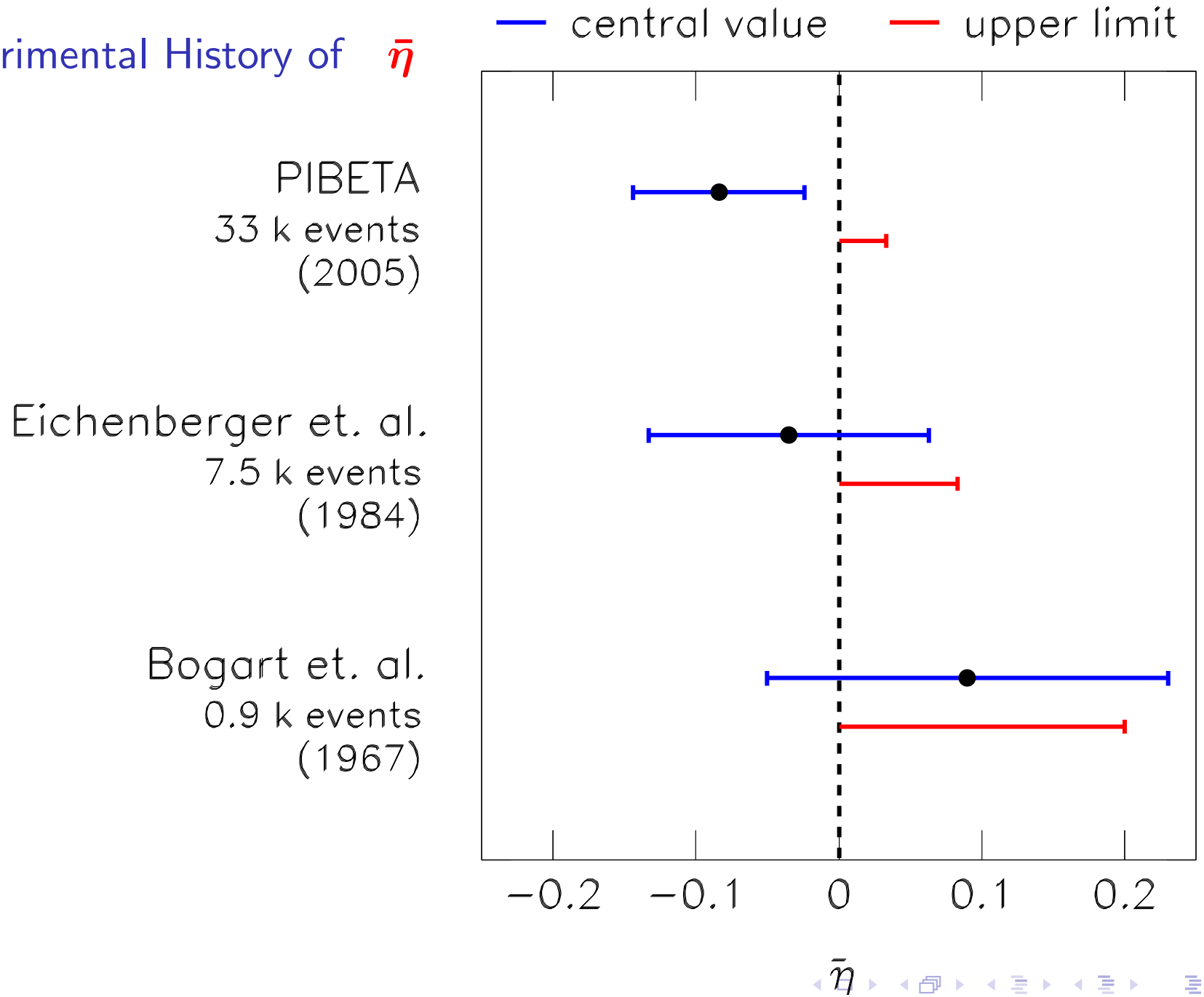
Combined: $\bar{\eta} = \mathbf{-0.084 \pm 0.050(stat.) \pm 0.034(syst.)}$

$\Rightarrow$ $\bar{\eta} \leq \mathbf{0.033}$ (68 % c.l.) or $\bar{\eta} \leq \mathbf{0.060}$ (90 % c.l.)

$\Rightarrow$ new world average: $\bar{\eta} \leq \mathbf{0.028}$ (68 % c.l.) **2.5×**

Currently being updated by new high quality PEN data: (**2**× statistics).

Experimental History of $\bar{\eta}$



The PEN Experiment:

$\pi \longrightarrow e\nu$

Ongoing since 2007

$\pi \longrightarrow e\nu$ Decay: SM Calculations; Measurements

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

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

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 goal: $$\frac{\delta B}{B} \simeq 5 \times 10^{-4}\,.$$

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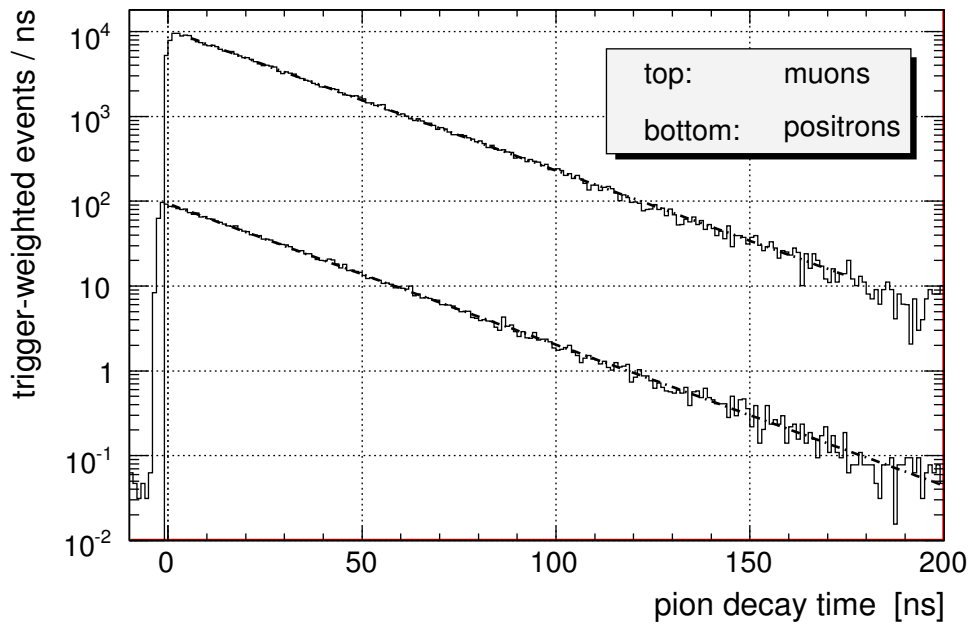
PEN Experiment: Status and Plans

- Approved in 2006; two development runs, in 2007 and 2008,
- Total pions stopped in 2007 and 2008 runs: $> 8 \times 10^{10}$.
  $> 4.7 \times 10^6$ π_{e2}'s recorded $\Rightarrow (\delta B/B)_{\text{stat}} < 5 \times 10^{-4}$.
- Detailed data analysis under way in preparation for a 2009 run, planned to complete the required event statistics.
- Improved beam tracking with a miniTPC ready for implementation.

Pion decays:
$\pi \longrightarrow \mu\nu$,
$\pi \longrightarrow e\nu$:
timing in TGT



- PEN is set to double π, μ radiative data set with higher quality.

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