From heavy ion resonances to Standard Model tests:

a lifetime in subatomic physics of an apprentice of Nikola Cindro

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Highlights in HI Physics
Nikola Cindro Symposium
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Outline

Early days: neutron physics, HI resonances; switch to ME physics

Rare pion and muon decays

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

Radiative pion e2 decay: $\pi^+ \to e^+ \nu \gamma$

Radiative muon decay: $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$

The PEN Experiment: $\pi^+ \to e^+ \nu$

Precision n beta decay program at SNS

Summary

Early days as Nikola's student: neutron physics

- 1973–1976 Undergraduate student with scholarship from Laboratory for Nuclear Structure (LNS), Institute Rudjer Bošković.
- Summer of 1975, summer and fall 1976, worked on research project in neutron-induced reactions (n,p), (n,pn), (n,2n) . . .
- December 1976 completed and defended Diploma (BSc) thesis on *"Inclusion of preequilibrium emission into the evaporation code NUKRE for neutron-induced reactions"*
- January 1977, joined LNS, started graduate school in Nuclear Physics, University of Zagreb.

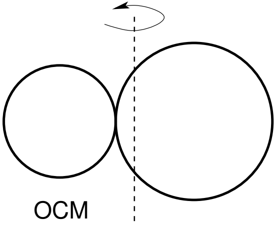
Quasimolecular resonances in HI; OCM

MSc and PhD work with Nikola Cindro on "quasimolecular resonances" (QMR) in heavy ion collisions.

In 1978-79 developed the Orbiting Cluster Model (OCM) of QMR:

- postulate simple nature: orbiting touching spheres, in the entrance channel:

$$E_J = \frac{\hbar}{2\,\mathcal{I}_{\mathrm{OC}}} J(J+1)$$



- observability governed by small spreading width $\Gamma^{\downarrow}$; phenomenologically parametrized.
- Experimental searches for QMR in: ^{9}Be+^{12,13}C, ^{12}C+^{24}Mg (Demokritos), ^{14}C+^{14}C, ^{28}Si+^{24,26}Mg (LANL), ^{16}O+^{16}O (Stanford), ^{28}Si+^{32}S (Strasbourg).
- MSc in 1980; DSc in 1981, with N.C.

1984–1995: Transition to medium energy physics

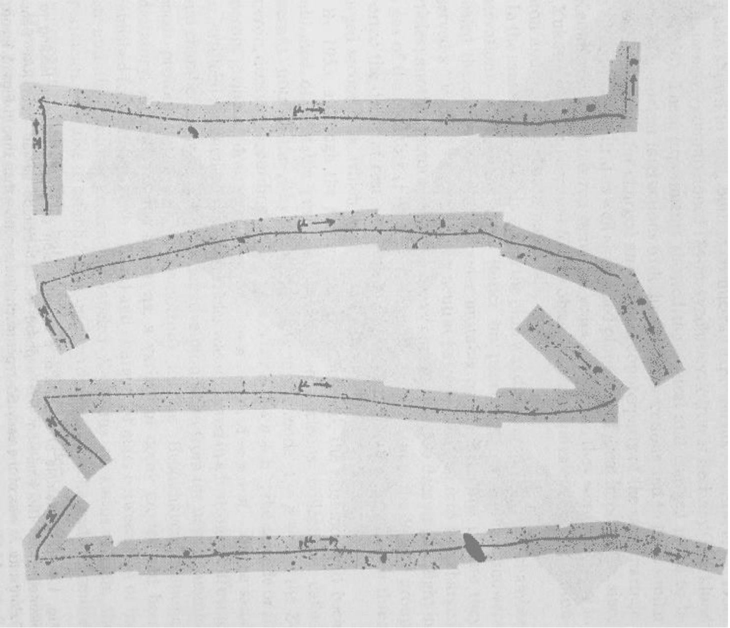
1984–1987: Nuclear excitations and properties with intermediate energy probes (postdoc at Stanford U.)

- **(n,p)** at 118 and 65 MeV (isovector GT GR; IUCF, UC Davis)
- **(e,e'p)** on light nuclei in the GR region (MIT Bates)
- $(\pi^{\pm}, \pi^{0})$ on light and medium heavy nuclei (LAMPF)
- nucleon pair emission in μ^- **capture** in light nuclei (SIN/PSI)

1988–present: Shift to fundamental interactions, symmetries, hadron properties, SM tests (after arrival at UVa)

- threshold $\pi^+ p \to \pi^+ \pi^0 p$ (π-π scatt. length; χ symm; LAMPF)
- $\pi^- p \to \pi^0 n$ low energy angular distributions (LAMPF)
- series of **e⁻ DIS nucleon spin structure** experiments: (E143, E155, E155x at SLAC; RSS, SANE, CLAS at CEBAF)
- program of **rare π and μ decays** (PIBETA and PEN at PSI)

Cecil Powell et al., 1947 discovery of pion in emulsions



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 Program of Measurements

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

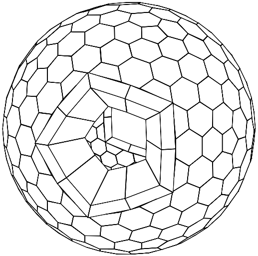
- $\pi^+ \to \pi^0 e^+ \nu_e$
  - SM checks related to CKM unitarity
- $\pi^+ \to e^+ \nu_e \gamma$(or e^+e^-)
  - F_A/F_V, π polarizability (χPT calibration)
  - tensor coupling besides $V - A$ (?)
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$(or e^+e^-)
  - departures from $V - A$ in $\mathcal{L}_{\text{weak}}$

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

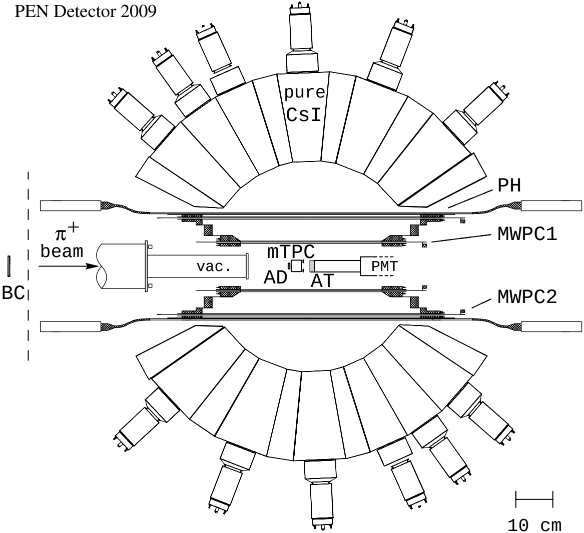
- $\pi^+ \to e^+ \nu_e$
  - e-μ universality
  - pseudoscalar coupling besides $V - A$
  - ν sector anomalies, Majoron searches, m_{h^+}, PS **l-q**'s, V **l-q**'s, ...

The PIBETA/PEN Apparatus

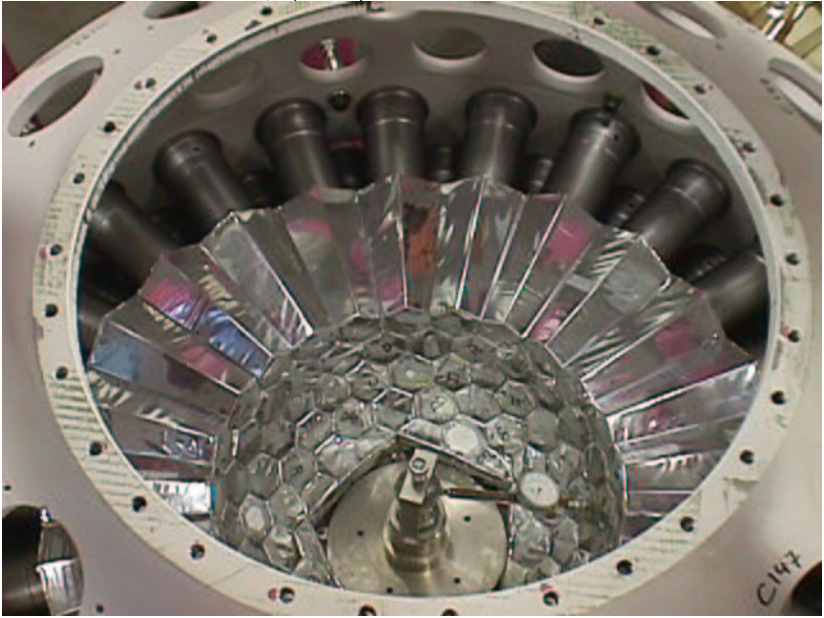
stopped π^+ beam
active target counter
240-det. CsI calorimeter
central tracking
digitized waveforms
stable temp./humidity



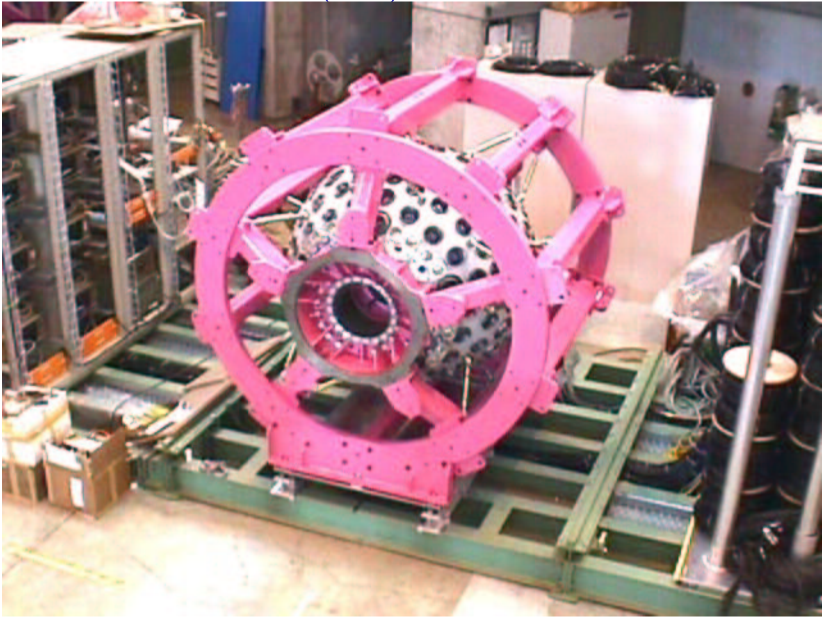
PEN Detector 2009



PIBETA Detector Assembly (1998)



PIBETA Detector on Platform (1998)



Pion Beta Decay:

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

1999–2001 data set

Quark-Lepton (Cabibbo) Universality

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

$$\mathcal{M} \propto \langle \mathbf{e} | \mathbf{l}^{\alpha} | \nu_{\mathbf{e}} \rangle \rightarrow \bar{\mathbf{u}}_{\mathbf{e}} \gamma^{\alpha} (1 - \gamma_5) \mathbf{u}_{\nu}$$

is replicated in hadronic weak decays

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

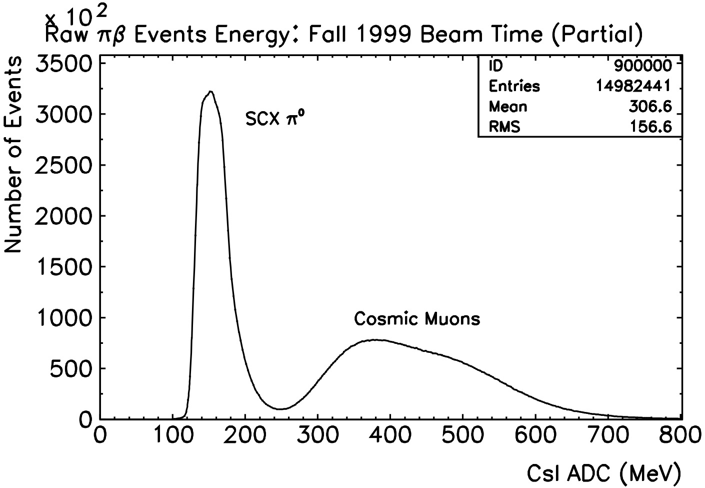
Departure from $\mathbf{G_V = 1}$ (**CVC**) comes from weak quark (Cabibbo) mixing: $\mathbf{G_V = G_\mu \cos\theta_C (= G_\mu V_{ud})}$ $\mathbf{\cos\theta_C \simeq 0.97}$

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

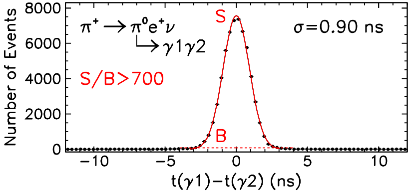
$$\begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \end{pmatrix}$$

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

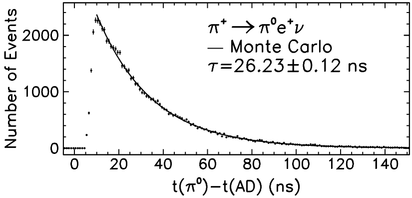
Online "$\pi\beta$" Energy Spectrum:



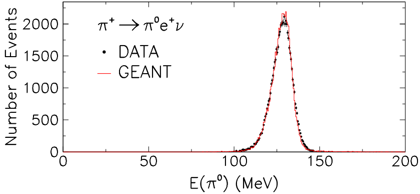
True $\pi\beta$ events buried deep under overwhelming background!



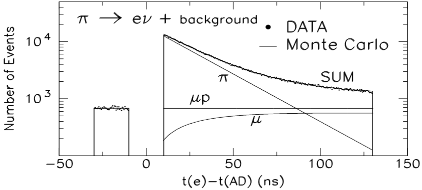
Number of Events
$\pi^+ \to \pi^0 e^+ \nu$
$\to \gamma1\gamma2$
S
B
S/B>700
σ=0.90 ns
$t(\gamma1)-t(\gamma2)$ (ns)



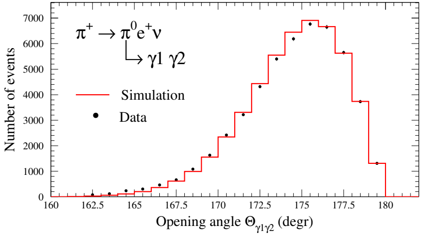
Number of Events
$\pi^+ \to \pi^0 e^+ \nu$
— Monte Carlo
τ=26.23±0.12 ns
$t(\pi^0)-t(AD)$ (ns)



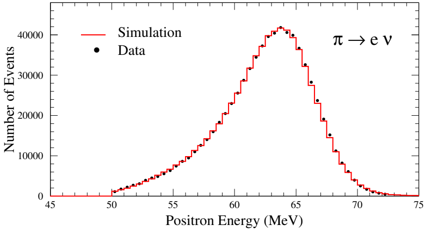
Number of Events
$\pi^+ \to \pi^0 e^+ \nu$
DATA
GEANT
$E(\pi^0)$ (MeV)



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



Number of events
$\pi^+ \to \pi^0 e^+ \nu$
$\to \gamma1\ \gamma2$
Simulation
Data
Opening angle $\Theta_{\gamma1\gamma2}$ (degr)



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

PIBETA result for π_β decay [D.P. et al., 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.)

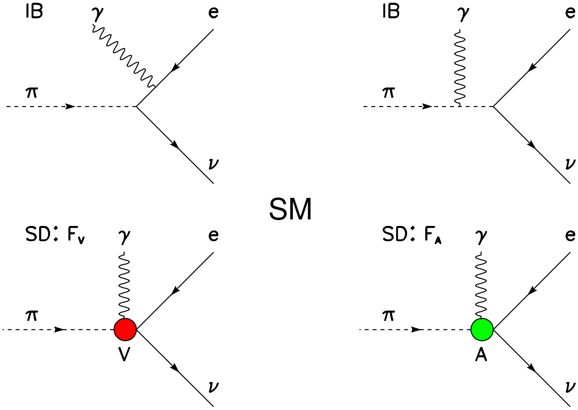
Radiative pion decay:

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

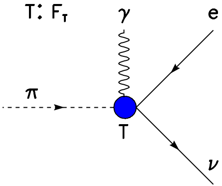
1999-2001 & 2004 data sets

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

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:

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

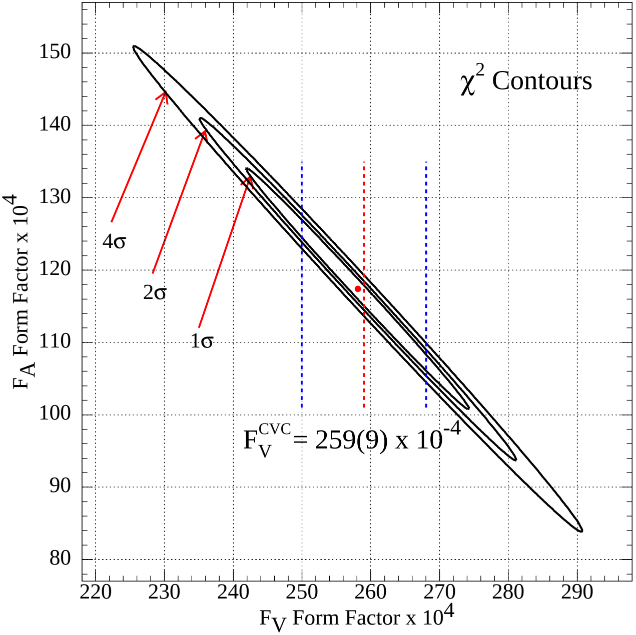
The SM branching ratio ($\gamma \equiv F_A/F_V$; $x = 2E_\gamma/m_\pi$; $y = 2E_e/m_\pi$),

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

Available data on pion form factors

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

$F_A \times 10^4$	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)	

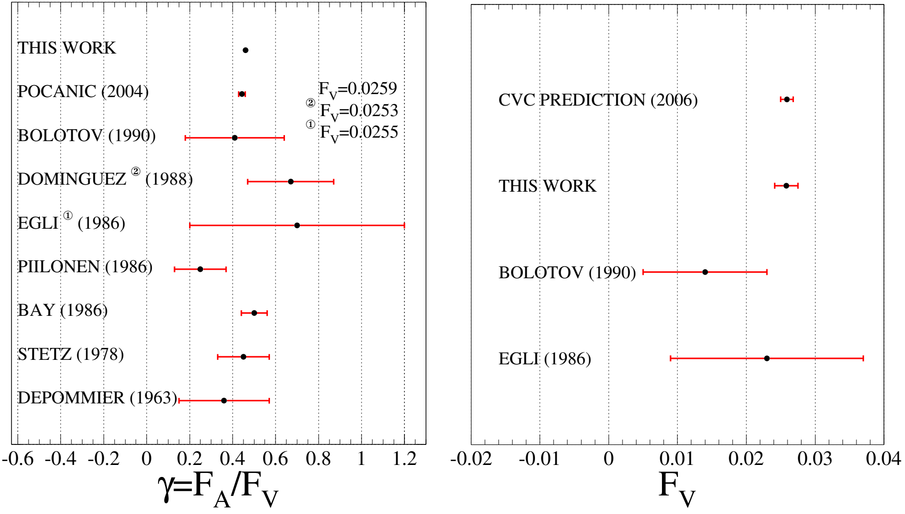


Best values of pion Form Factor Parameters:

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

$F_V = 0.0258 \pm 0.0017$ (14×)

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

$a = 0.10 \pm 0.06$ ($q^2_{e\nu}$ dep. of F_V) (∞)

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

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

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

$\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17}\ \text{s}$
- current PDG avg: 8.4 (4)
- PrimEx PRL '10: 7.82 (22)

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

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

Radiative muon decay:

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

2004 data set

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:

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

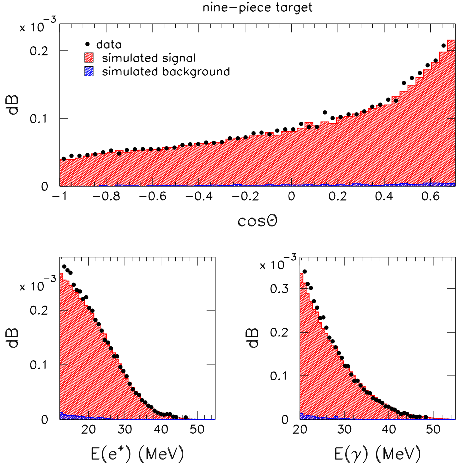
Michel parameters of radiative muon decay: $\boldsymbol{\mu \to e\nu_\mu\bar{\nu}_e\gamma}$

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

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

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

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



PRELIMINARY

(new analysis+data are forthcoming)

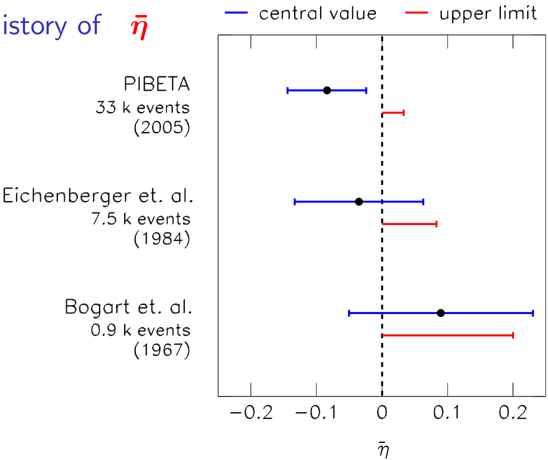
due to small-angle bremsstrahlung uncertainties in GEANT

$$B^{\text{exp}} = [4.40 \pm 0.02\ (\text{stat}) \pm 0.09\ (\text{syst})] \times 10^{-3}$$

14×!

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

Experimental History of $\bar{\eta}$



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

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

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

reduced by a factor of 2.5.

The PEN Experiment:

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

Ongoing since 2006

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

Modern theoretical calculations: $B_{\rm calc} = \left.\dfrac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{calc} =$

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

Experiment, world average [current PDG]:

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

N.B.:

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

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:

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

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

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

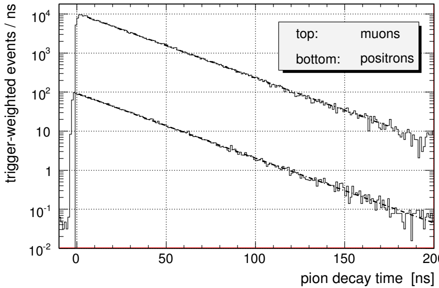
$$\frac{B^{\rm obs}_{\pi e2}-B^{\rm SM}_{\pi e2}}{B^{\rm SM}_{\pi e2}} = \frac{\Delta B}{B^{\rm SM}} = \ldots \simeq \frac{2m_\pi^2}{m_e(m_u+m_d)} f^e_{\rm PL} \simeq 7700 f^e_{\rm PL}\ !$$

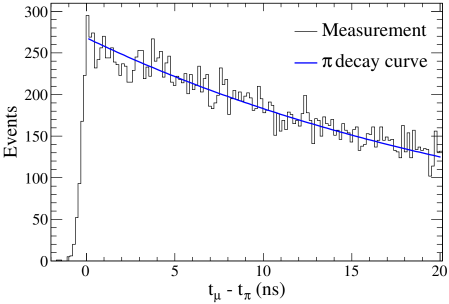
Tgt accuracy of the PEN experiment, $\Delta B/B \simeq 5\times10^{-4}$, translates into attractive mass limits on charged Higgs, PS and V leptoquarks, SUSY particles . . .

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):





Neutron beta decay:

$$\mathbf{n \rightarrow p e^- \bar{\nu}_e}$$

Nab and abBA/PANDA experiments

planned for SNS/FnPB

Neutron decay parameters (SM)

$$\frac{\mathbf{dw}}{\mathbf{dE_e d\Omega_e d\Omega_\nu}} \simeq \mathbf{k_e E_e (E_0 - E_e)^2}$$

$$\times \left[1 + \mathbf{a} \frac{\vec{\mathbf{k}}_e \cdot \vec{\mathbf{k}}_\nu}{\mathbf{E_e E_\nu}} + \mathbf{b} \frac{\mathbf{m}}{\mathbf{E_e}} + \langle \vec{\sigma}_n \rangle \cdot \left(\mathbf{A} \frac{\vec{\mathbf{k}}_e}{\mathbf{E_e}} + \mathbf{B} \frac{\vec{\mathbf{k}}_\nu}{\mathbf{E_\nu}} \right) + \ldots \right]$$

where:

$$\mathbf{a} = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad \mathbf{A} = -2 \frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1 + 3|\lambda|^2}$$

$$\mathbf{B} = 2 \frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1 + 3|\lambda|^2} \qquad \lambda = \frac{G_A}{G_V} \ (\text{with } \tau_n \Rightarrow \text{CKM } \mathbf{V_{ud}})$$

also:

$$\mathbf{C} = \kappa(\mathbf{A} + \mathbf{B}) \quad \text{where} \quad \kappa \simeq \mathbf{0.275}\,.$$

The FnPB neutron decay program at SNS

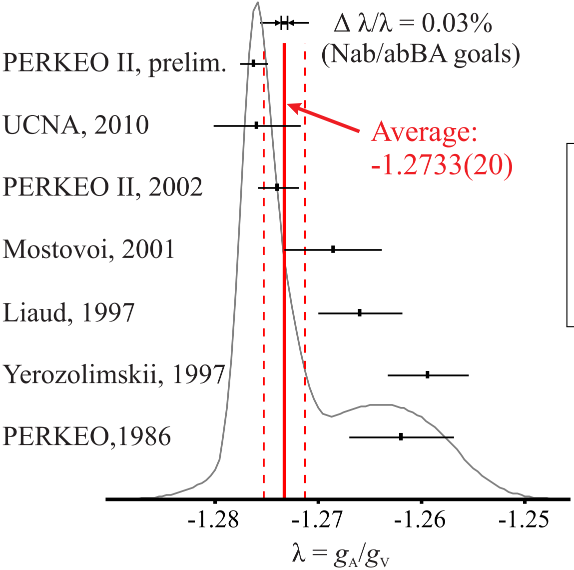
- **Nab**: a precise measurement of
  - **a**, the electron-neutrino correlation in neutron decay, and
  - **b**, the Fierz interference term (never measured in **n** decay).
- **Polarized program** (abBA/PANDA): precise measurements of
  - **A**, the electron asymmetry in neutron decay,
  - **B**, the neutrino asymmetry in neutron decay,
  - **C**, the proton asymmetry in neutron decay;

Goal uncertainties: $\frac{\delta a}{a}, \frac{\delta A}{A}, \frac{\delta B}{B}, \frac{\delta C}{C} \le 10^{-3}$, and

$$\delta b \le 3 \times 10^{-3}.$$

- $\lambda = G_A/G_F$ will be **triply overconstrained!**.
- Non-(V−A) terms in $\mathcal{L}_{weak}$: esp. RH/LH **T** terms, L-R symmetric SUSY ext's, CVC/SCC's, implications in ν sector ...

Status of A and λ in n decay



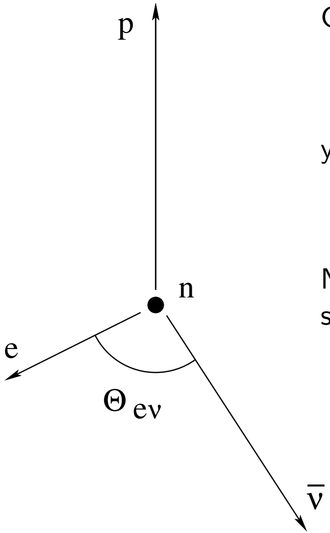
Goals for Δa, ΔA:

$\Rightarrow \Delta\lambda \simeq 3.5 \times 10^{-4}$

i.e., an order of magn. improvement.

$$\frac{\Delta\lambda}{\lambda} \simeq 0.27\frac{\Delta a}{a} \simeq 0.24\frac{\Delta A}{A}$$

Electron–neutrino angle from E_e and E_p



Conservation of momentum in **n** beta decay,

$$\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0\,,$$

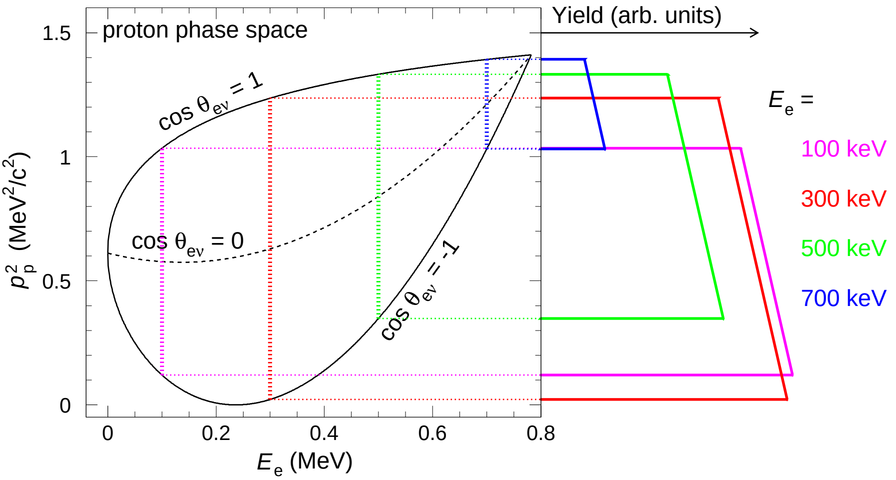
yields

$$p_p^2 = p_e^2 + 2 p_e p_\nu \cos\theta_{e\nu} + p_\nu^2\,.$$

Neglecting proton recoil energy, $E_e + E_\nu = E_0$, so that $p_\nu = E_0 - E_e$. Therefore:

$\cos\theta_{e\nu}$ is uniquely determined by measuring E_e and E_p (or $p_p \Rightarrow \mathrm{TOF}_p$).

Nab Measurement principles: Proton phase space

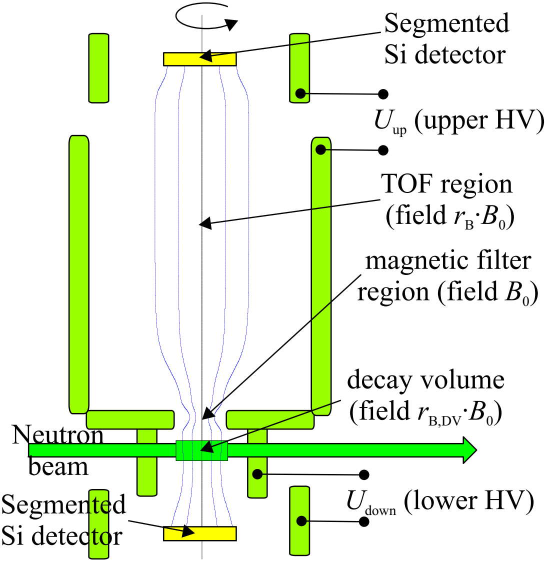


NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

Slope $\propto$ **a**

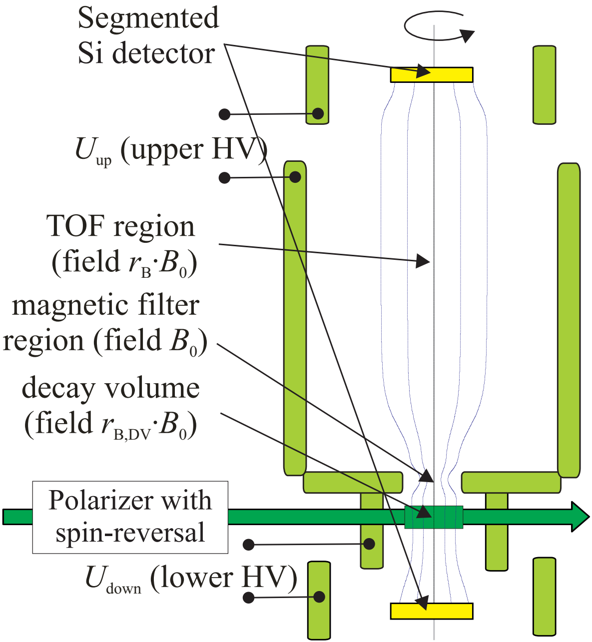
Nab principle of operation

- Collect and detect **both** electron and proton from neutron beta decay (magnetic field, detectors at both ends); **hermeticity**!
- Measure electron energy and proton TOF and reconstruct decay kinematics (Magnetic field shape, silicon detectors at both ends).



abBA/PANDA configuration:

- A: detect electrons in upper, protons in lower detector;
- B/C: detect protons in upper, electrons in both detectors;



Thoughts on Nikola and my path in physics

- A lifetime in subatomic physics initiated in the 1970's under Nikola Cindro's mentorship.
- Nikola's devotion to scientific integrity and accuracy, aggressive pursuit of scientific opportunities, live on in his students.

On low energy SM tests:

- A large experimental effort is under way to exploit the unparalleled theoretical precision in weak interactions of the lightest particles.
- Information is complementary to expected collider results, and necessary for their proper interpretation.
- Orders of magnitude of improvement in precision have been achieved; more lie in store; all in human-scale experiments.

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