Muon Radiative decay and Limits on non-(V-A) weak interaction(s)

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- Motivation
- Radiative Muon Decay
- The PIBETA/PEN Apparatus
- Results and Summary

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- Muons are an excellent window into the Weak interaction.
  - Strong interactions are absent to very good approximation.
  - Electromagnetic interactions are precisely understood.
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  - MuLAN, FAST, TWIST, MEG, $g-2$, Mu2e ...
- Measure $B(\ \mu^+ \to \mathrm{e}^+\nu\overline{\nu}\gamma\ )$ over broad region of phase space
  - Increase precision of Michel Parameter $\overline{\eta}$
  - Consistency check of Michel Parameter ρ

Muon Decay Observables

$\boldsymbol{\mu^+ \longrightarrow e^+ \nu \bar{\nu}}$

Adapting to PIBETA experimental conditions:

- unpolarized muons
- unobserved e^+ polarization
- neglect the small term $\sim \eta x_0 \lesssim 10^{-4}$

$$\Rightarrow \frac{d\Gamma}{dx} = \frac{m_\mu}{\pi^3} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2} \left[x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) \right]$$

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! PIBETA can measure ρ by observing the e^+ energy spectrum !

Radiative Muon Decay Observables

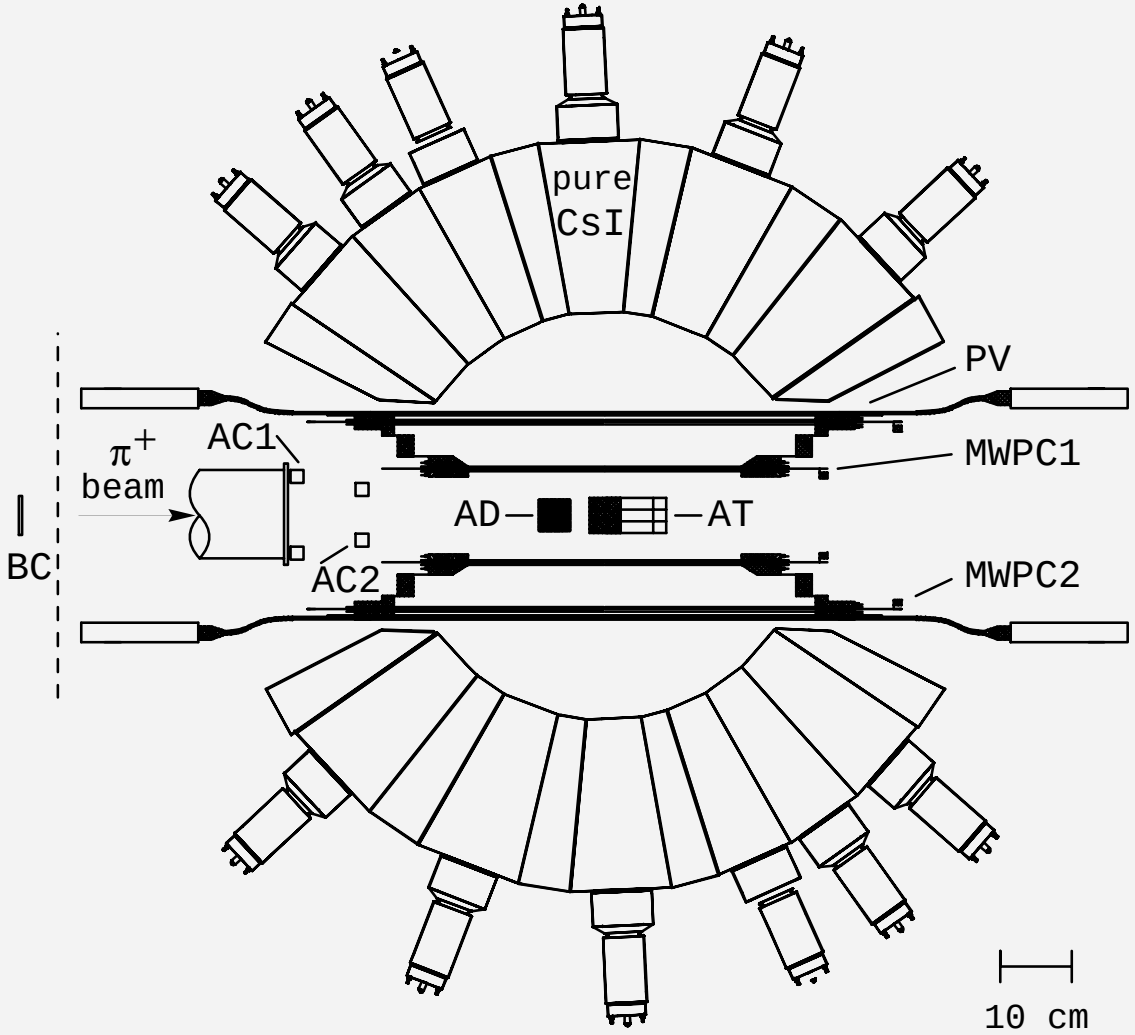
$\mu^+ \to e^+ \nu \bar{\nu} \gamma$

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

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

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

The PIBETA/PEN Detector



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- Stop π^+s in the active target
  - $\approx 100\,\%$ decay via $\pi^+ \rightarrow \mu^+\nu$
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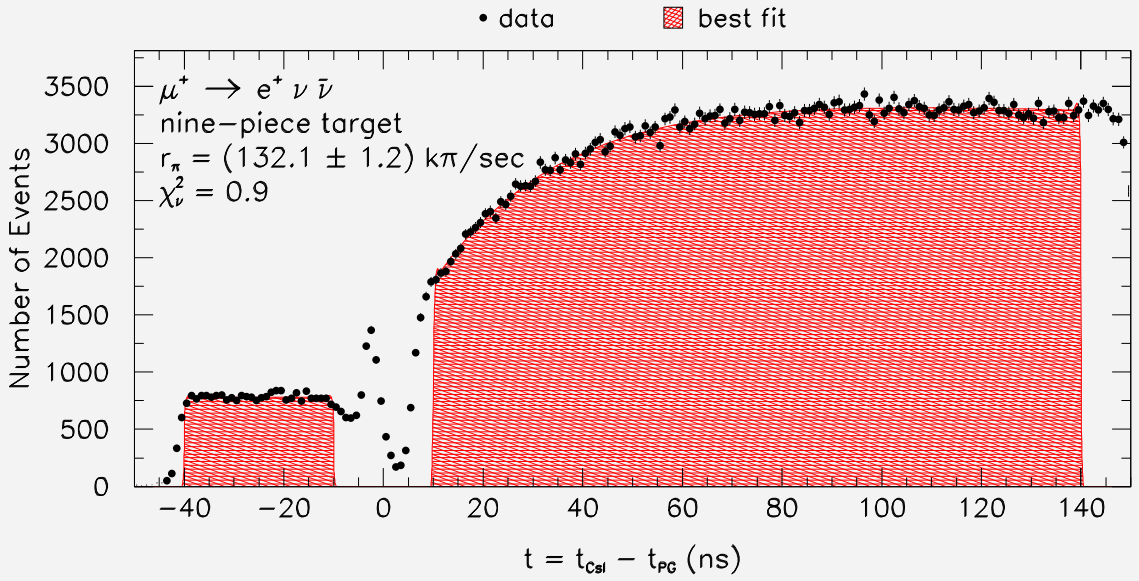
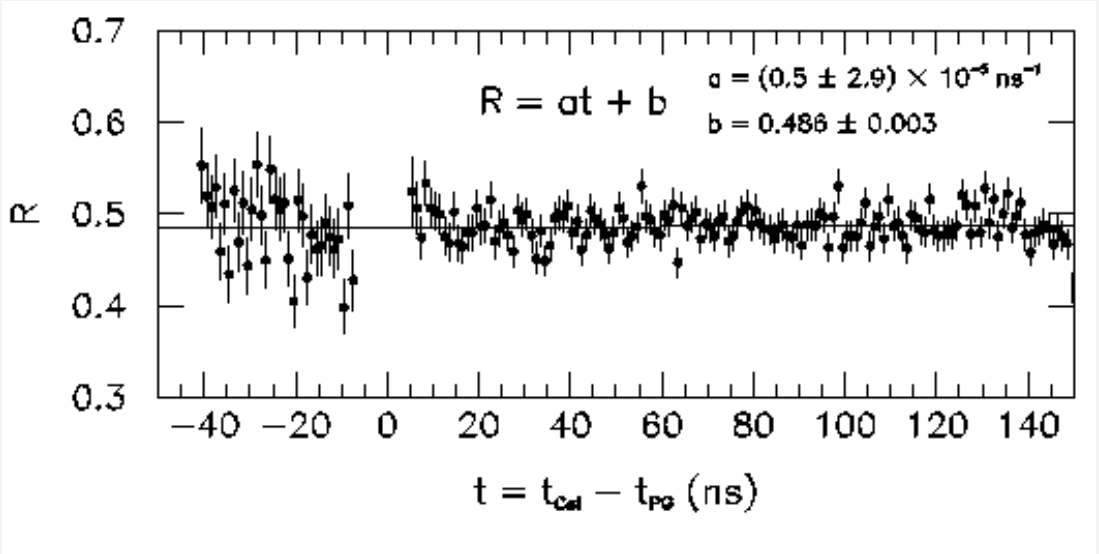
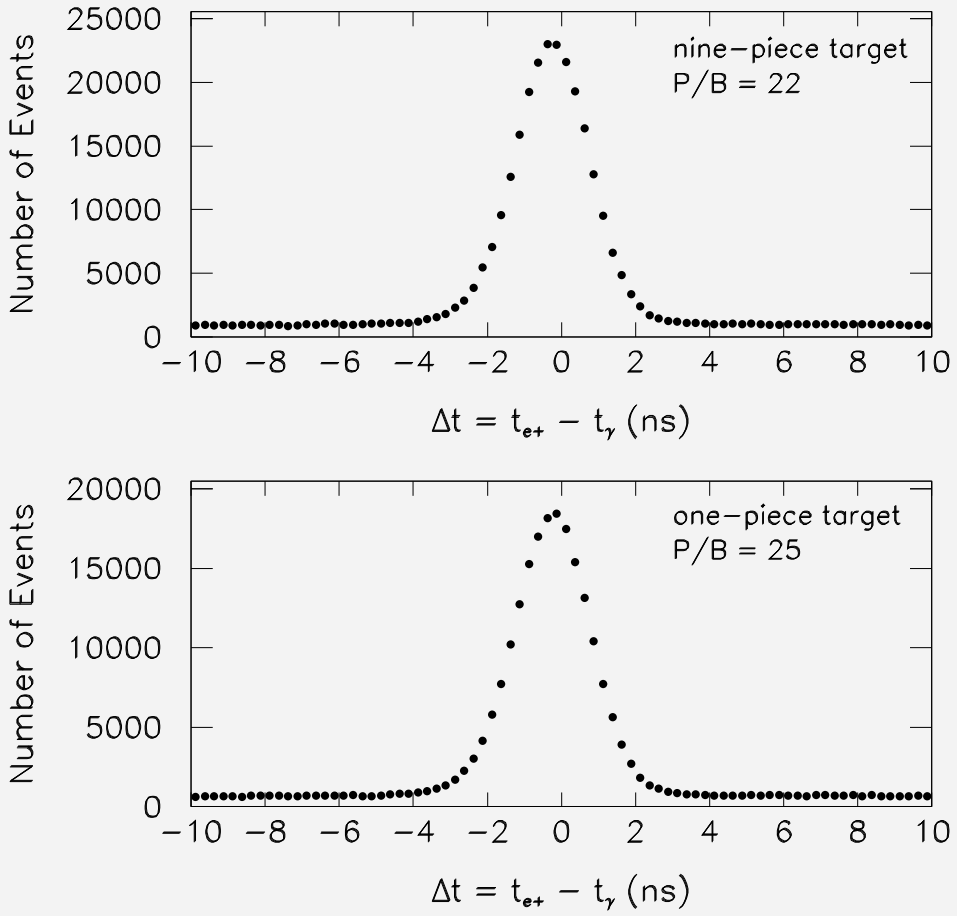
- PEN digitized beam elements waveforms = reduced systematics

Muon Decay Time Spectrum: $\mu^+ \rightarrow e^+\nu\bar{\nu}$



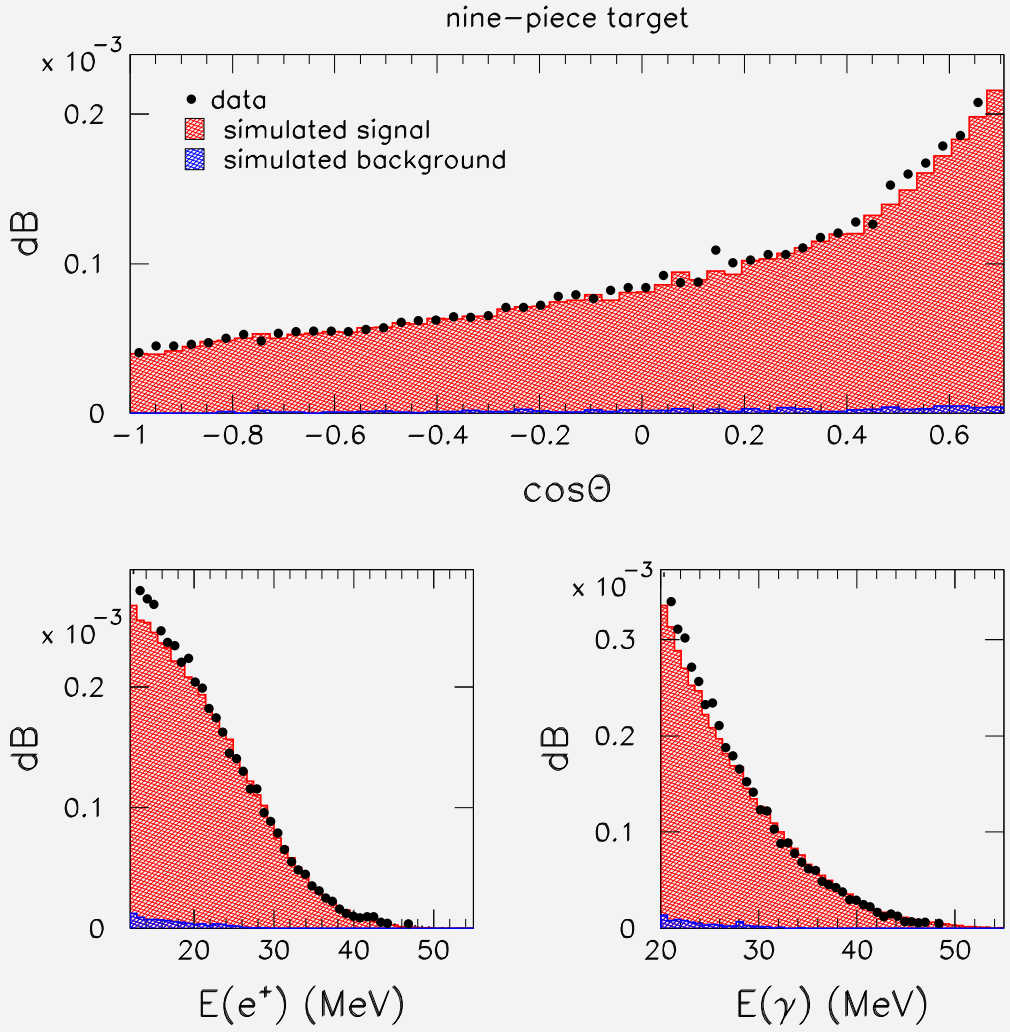


$\mu^+ \to e^+\nu\bar{\nu}\gamma$ Event Signal: $\Delta t \equiv t_{e+} - t_\gamma$ $\sigma_{\Delta t} \approx 1$ ns



The "out-of-time" background ($5 < |\Delta t| < 10$ ns) is subtracted from the "in-time" signal ($|\Delta t| \leq 5$ ns).

$\mu^+ \to e^+\nu\bar{\nu}\gamma$ Differential Branching Ratio



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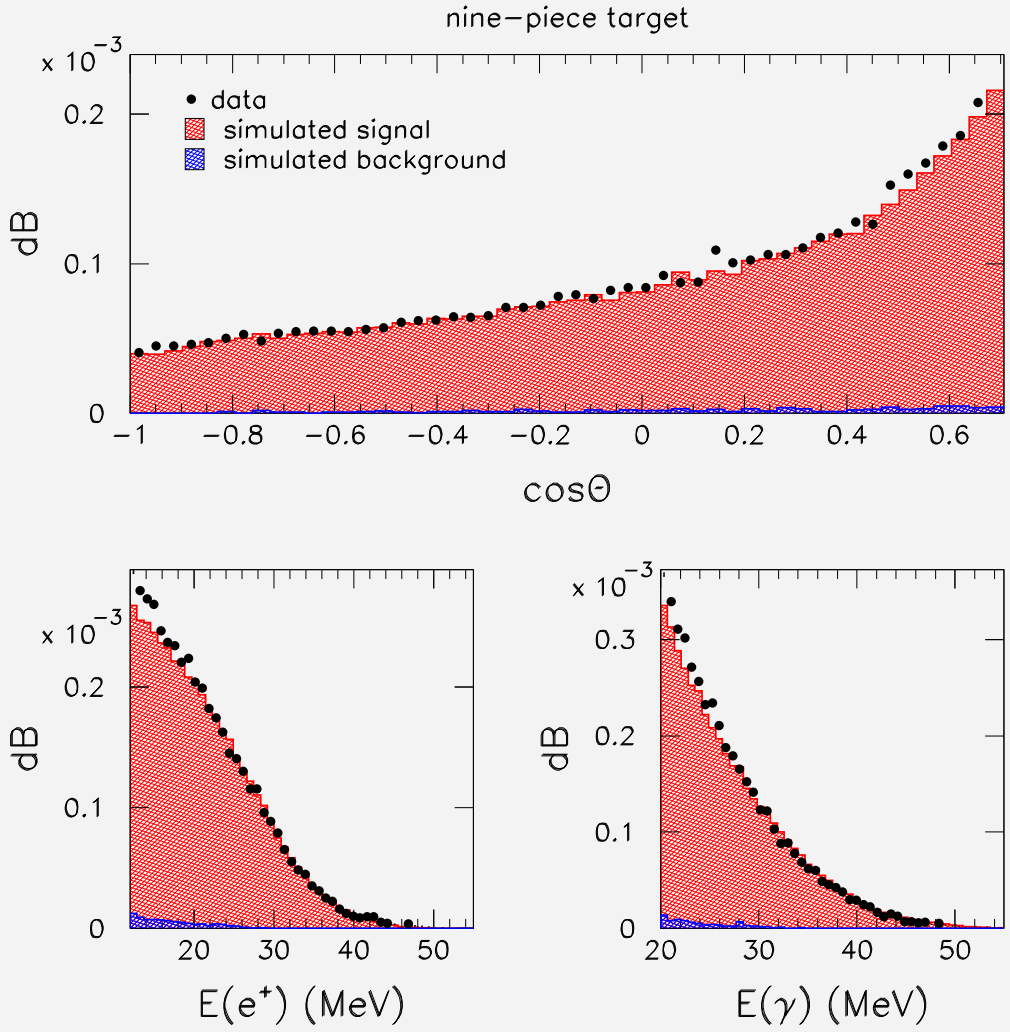
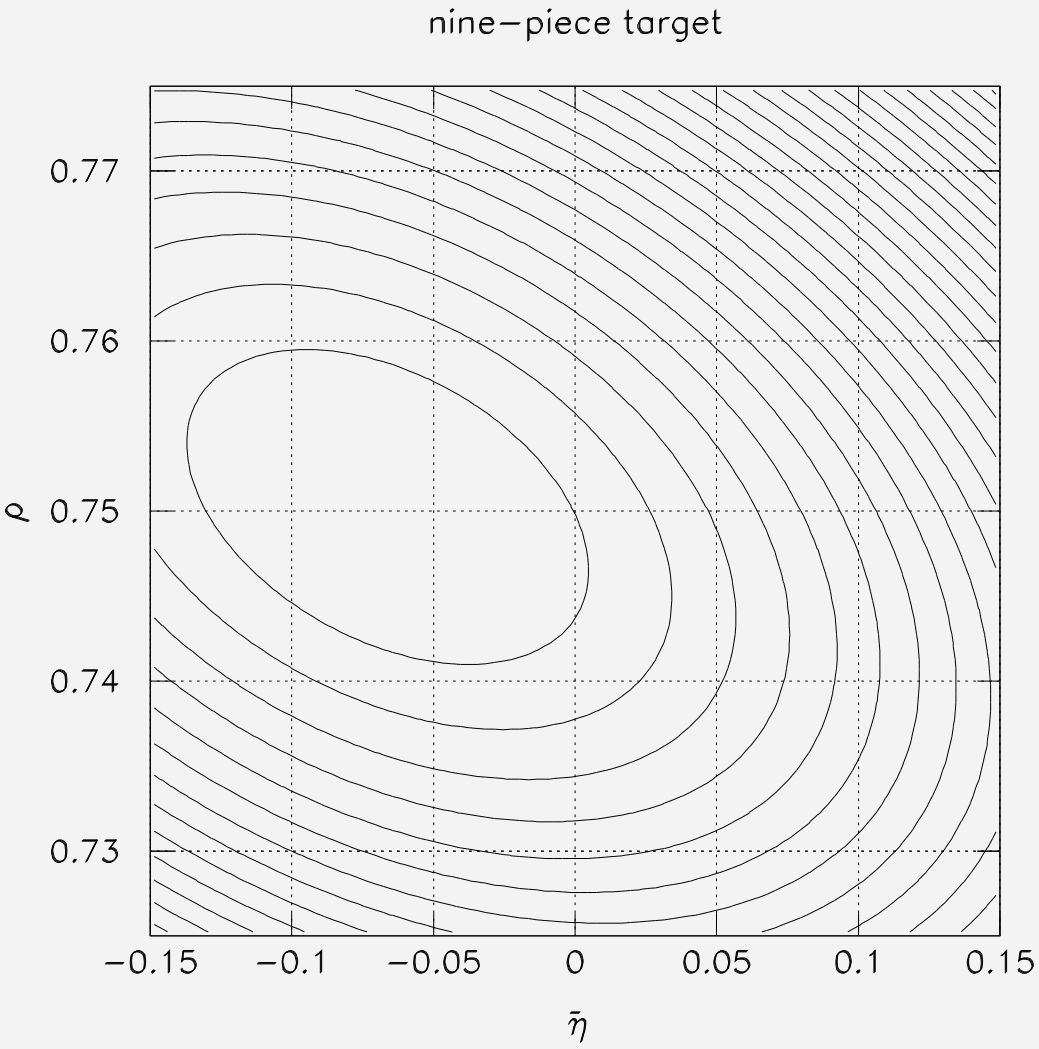


$$B^{\rm exp} = [4.40 \pm 0.02\ (\text{stat.}) \pm 0.09\ (\text{syst.})] \times 10^{-3}$$ **14×!**

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

Small angle bremstrahlung simulation dominates the systematics

Dependence on $\overline{\eta}$ and ρ



$\overline{\eta}$ and ρ both free

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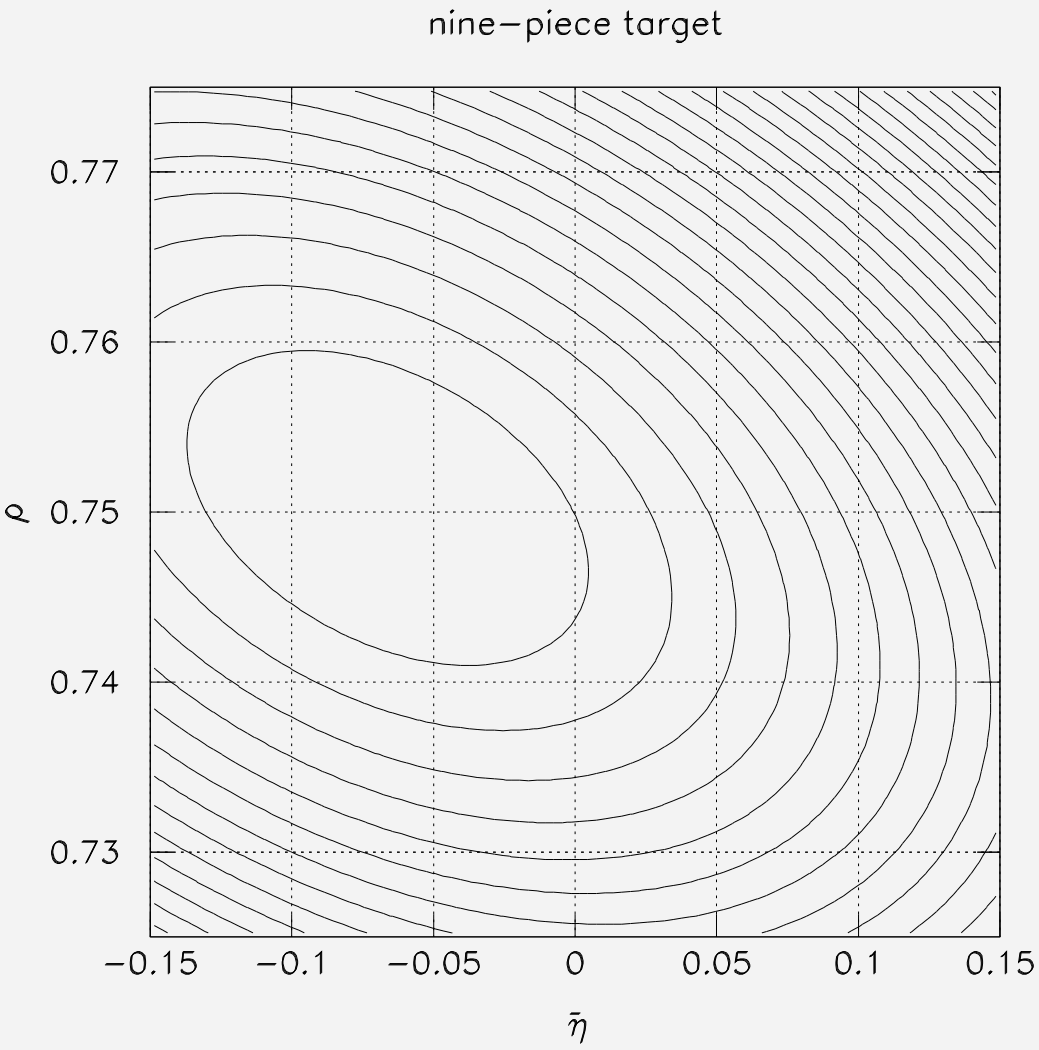

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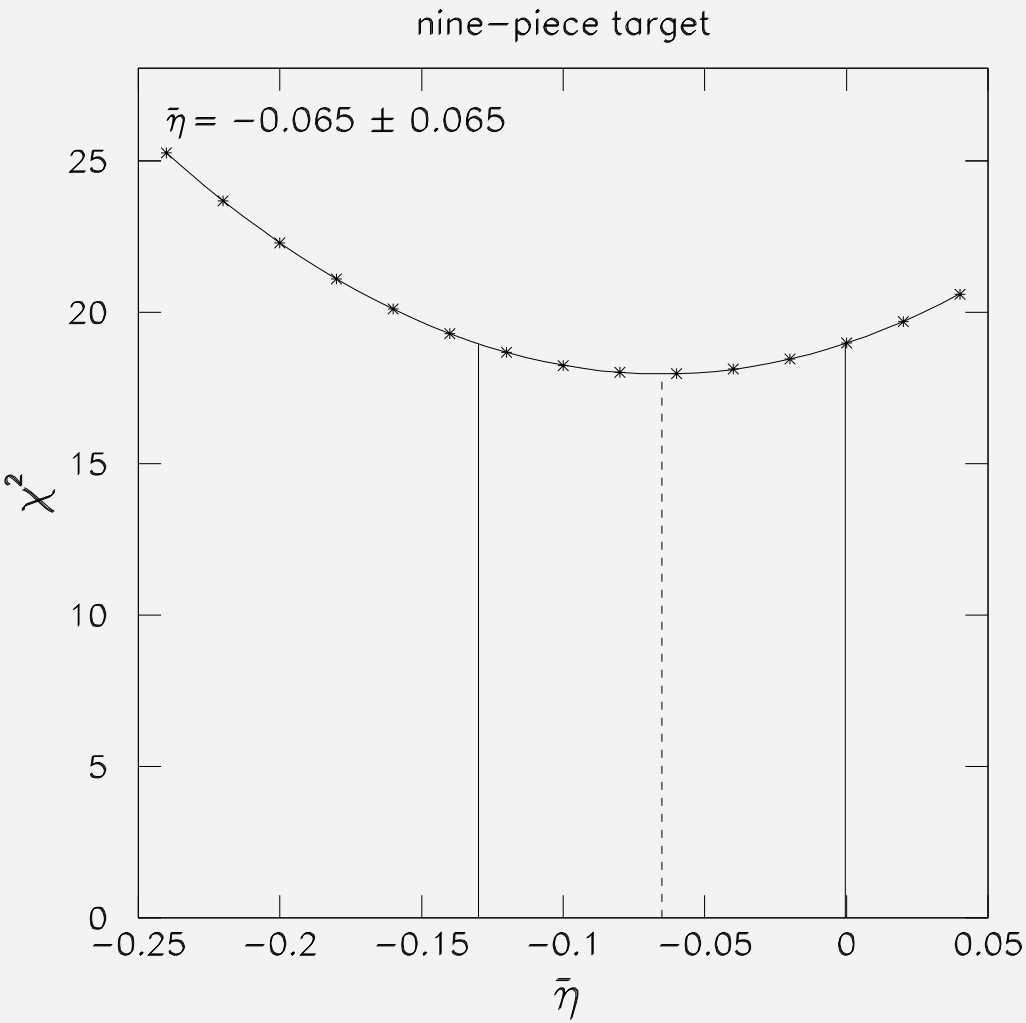

$\overline{\eta}$ free, $\rho = \rho_{\rm SM} = \frac{3}{4}$ fixed

Final Results for $\overline{\eta}$ and ρ

Fit type	$\overline{\eta}$	ρ
Two-parameter fit	-0.086 ± 0.064	0.750 ± 0.007
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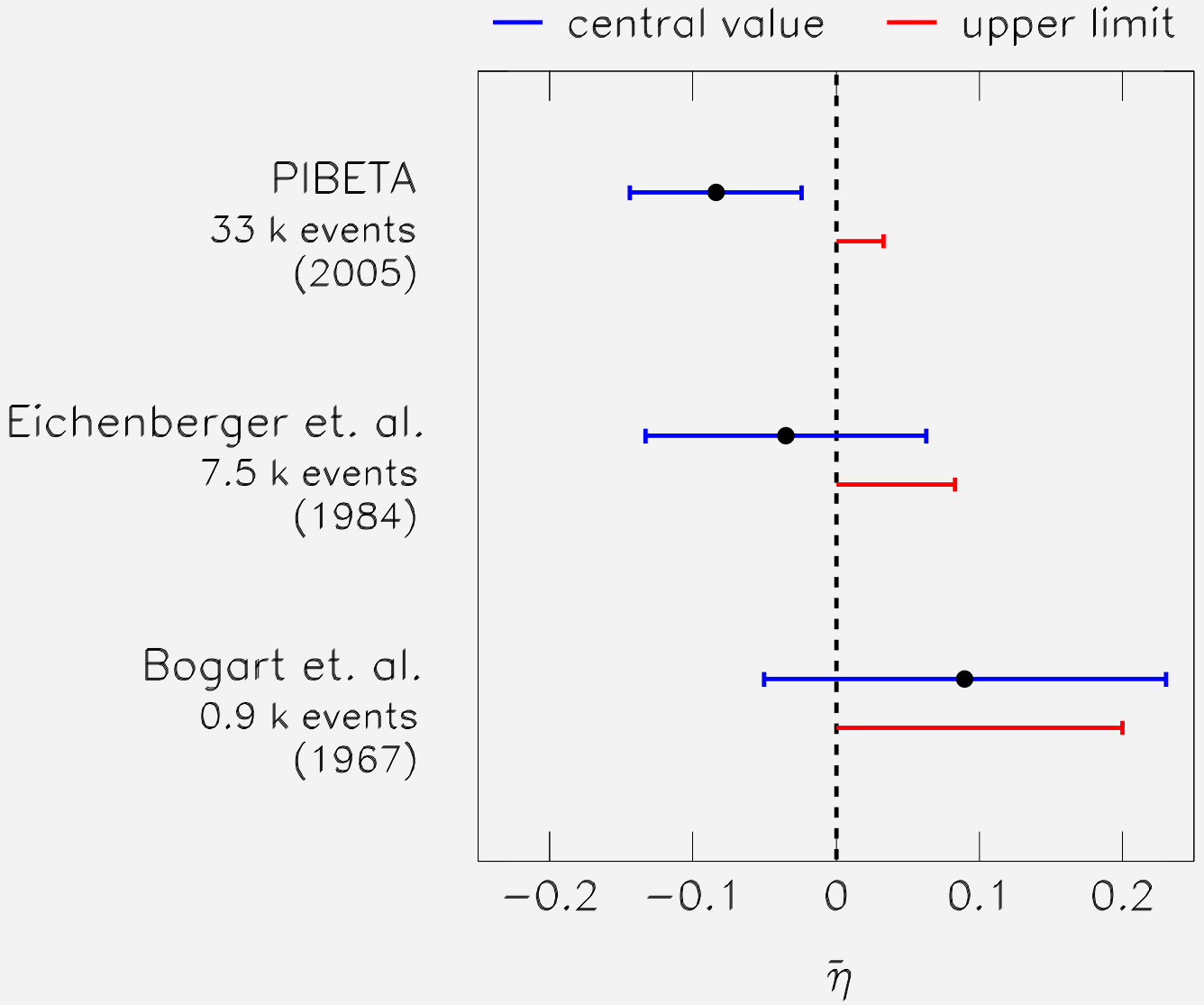
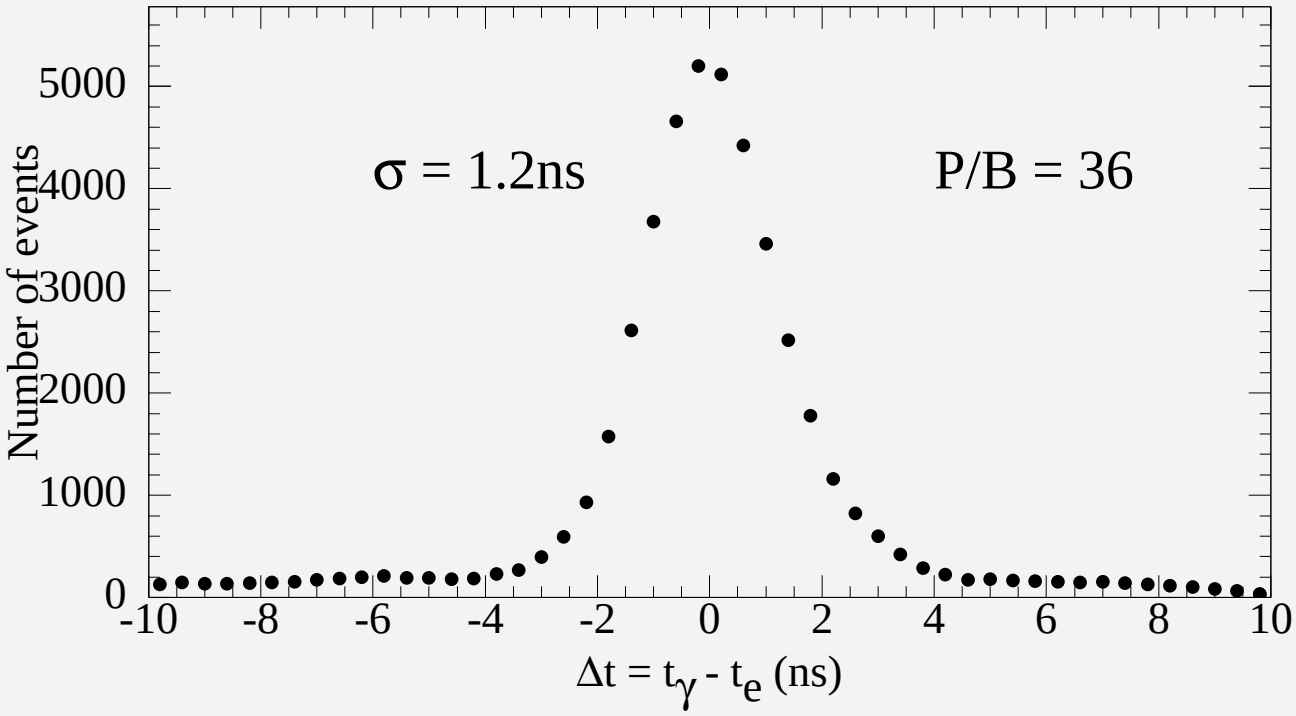
$\Rightarrow \overline{\eta} \leq 0.033$ (68 % c.l.) or $\overline{\eta} \leq 0.060$ (90 % c.l.)

Experimental History of $\overline{\eta}$



What's new?



So far we've collected >150k events and expect the same number in phase III

Summary

- First precise measurement of $B(\ \mu^+ \to \mathrm{e}^+\nu\overline{\nu}\gamma\ )$ over a large phase space
  - 313 events (bubble chamber) $\to 4.2 \times 10^5$ events
  - 30 % uncertainty $\to$ 2 % uncertainty
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- New measurement of Michel parameter $\overline{\eta}$
  - $\overline{\eta} \leq 0.087 \to \overline{\eta} \leq 0.033$ (68 % c.l.)
  - new world average: $\overline{\eta} \leq 0.028$ (68 % c.l.)
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  - reduced by a factor of 2.5
- More results are coming soon
  - We are looking to double the PIBETA statistics w/ better quality data
  - Exciting new possibilities of using digitized beam elements data