TWIST

The TRIUMF Weak Interaction Symmetry Test

A close look at Muon Decay

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TWIST: Universities of Alberta, British Columbia, Northern British Columbia, Montreal, Saskatchewan; TRIUMF, Texas A&M, Valporaiso, KIAE - Russia

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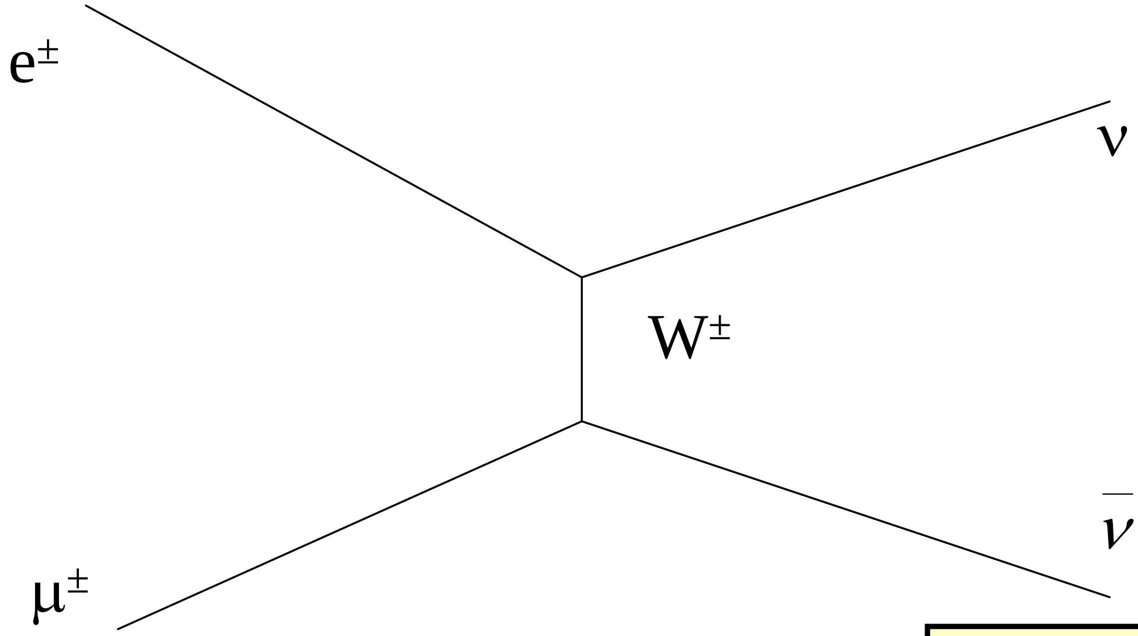
Outline

- Background on muon decay
- The E614 Experiment
- Sensitivity to new physics

The Standard Model for μ decay



(V-A) Interaction is built in

- parity violation is perfect
- exchange particle is known

Only one coupling is non-zero in the Standard Model

$\|g^S_{RR}\| \equiv 0$	$\|g^V_{RR}\| \equiv 0$	$\|g^T_{RR}\| = zero$
$\|g^S_{LR}\| \equiv 0$	$\|g^V_{LR}\| \equiv 0$	$\|g^T_{LR}\| \equiv 0$
$\|g^S_{RL}\| \equiv 0$	$\|g^V_{RL}\| \equiv 0$	$\|g^T_{RL}\| \equiv 0$
$\|g^S_{LL}\| \equiv 0$	$\|g^V_{LL}\| \equiv 1$	$\|g^T_{LL}\| = zero$

- The operator (V-A) satisfies the requirement that the Weak interaction violates parity.

- (V-A) violates parity perfectly

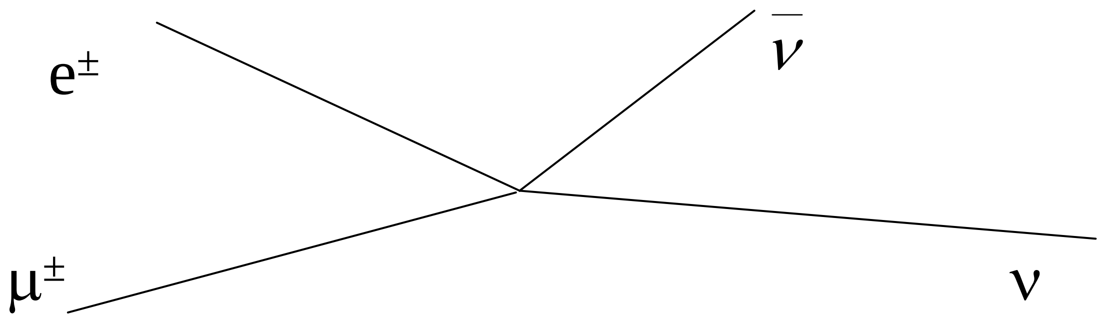
- The (V-A) operator projects out the left-handed (negative helicity) component of the wave function

$$\bar{\psi}\gamma^{\mu}(1-\gamma^{5})\psi = \bar{\psi}\gamma^{\mu}(1-\gamma^{5})\begin{bmatrix}\psi_{+}\\ \psi_{-}\end{bmatrix}$$

$$= \bar{\psi}\gamma^{\mu}\begin{bmatrix}0 & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}\psi_{+}\\ \psi_{-}\end{bmatrix} = \bar{\psi}\gamma^{\mu}\psi_{-}$$

- the (V-A) theory therefore states that leptons with positive helicity do not undergo weak interactions.

A more general interaction - which does not presuppose the W



$$rate \sim \left| \sum_{\substack{\gamma = S,V,T \\ i,j = R,L}} g_{ij}^{\gamma} \langle \bar{\psi}_{ei} | \Gamma^{\gamma} | \psi_{\nu_e} \rangle \langle \bar{\psi}_{\nu_\mu} | \Gamma_{\gamma} | \psi_{\mu j} \rangle \right|^2$$

Scalar	$\bar{\psi}\psi$
Vector	$\bar{\psi}\gamma^{\mu}\psi$
Tensor	$\bar{\psi}\sigma^{\mu\nu}\psi$
Axial Vector	$\bar{\psi}\gamma^{5}\gamma^{\mu}\psi$
Pseudoscal ar	$\bar{\psi}\gamma^{5}\psi$

Allows for possible

- scalar
- vector
- tensor

interactions of right-handed and left-handed leptons

The preceding - in terms of the Michel parameters

$$rate \sim x^2\left[3-3x+\frac{2}{3}\rho(4x-3)+P_\mu\xi\cos(\theta)\left(1-x+\frac{2}{3}\delta(4x-3)\right)\right]$$

Where the Michel parameters are defined to simplify the above expression

For example-

$$\rho \equiv \frac{3}{4}\left[|g_{LL}^{V}|^2+|g_{RR}^{V}|^2+|g_{LR}^{T}|^2+|g_{RL}^{T}|^2\right]$$

$$+\frac{3}{16}\left[|g_{LL}^{S}|^2+|g_{RR}^{S}|^2+|g_{LR}^{S}|^2+|g_{RL}^{S}|^2\right]$$

$$-\frac{3}{4}\left[\mathrm{Re}\left(g_{LR}^{S}g_{LR}^{T*}\right)+\mathrm{Re}\left(g_{RL}^{S}g_{RL}^{T*}\right)\right]$$

$= 3/4$ when $|g_{LL}^{V}|^2 = 1$

and other couplings are zero

A fourth parameter, η, contributes to order (m_e/m_μ)

Similar expressions exist defining ξ, δ, and η.

The Expression becomes considerably simpler in the Standard Model

$$rate \sim x^2\left[3-3x+\frac{2}{3}\cancelto{3/4}{\rho}(4x-3)+P_\mu\xi\cos(\theta)\left(1-x+\frac{2}{3}\delta(4x-3)\right)\right]$$

For example-

Standard Model Values

$$\rho \equiv \frac{3}{4}\left[|\cancelto{1}{g^V_{LL}}|^2+|\cancelto{0}{g^V_{RR}}|^2+|\cancelto{0}{g^T_{LR}}|^2+|\cancelto{0}{g^T_{RL}}|^2\right]$$
$$+\frac{3}{16}\left[|\cancelto{0}{g^S_{LL}}|^2+|\cancelto{0}{g^S_{RR}}|^2+|\cancelto{0}{g^S_{LR}}|^2+|\cancelto{0}{g^S_{RL}}|^2\right]$$
$$-\frac{3}{4}\left[\mathrm{Re}\left(\cancelto{0}{g^S_{LR}}\cancelto{0}{g^{T*}_{LR}}\right)+\mathrm{Re}\left(\cancelto{0}{g^S_{RL}}\cancelto{0}{g^{T*}_{RL}}\right)\right]$$

$$=3/4 \quad when\ |g^V_{LL}|^2=1$$
$$and\ \ other\ couplings\ are\ zero$$

Similar expressions exist defining ξ, δ, and η.

This simple model may be too simple

exchange particle:

spin 0	*spin 1*	*spin 2*
$\lvert g^{S}_{RR} \rvert < 0.066$	$\lvert g^{V}_{RR} \rvert < 0.033$	$\lvert g^{T}_{RR} \rvert \equiv 0$
$\lvert g^{S}_{LR} \rvert < 0.125$	$\lvert g^{V}_{LR} \rvert < 0.060$	$\lvert g^{T}_{LR} \rvert < 0.036$
$\lvert g^{S}_{RL} \rvert < 0.424$	$\lvert g^{V}_{RL} \rvert < 0.110$	$\lvert g^{T}_{RL} \rvert < 0.122$
$\lvert g^{S}_{LL} \rvert < 0.55$	$\lvert g^{V}_{LL} \rvert > 0.96$	$\lvert g^{T}_{LL} \rvert \equiv 0$

All but one of these terms has been set to zero in the Standard model for simplicity

The Weak Interaction may not be purely (V-A)

We propose to study 10^8 μ^+ decays

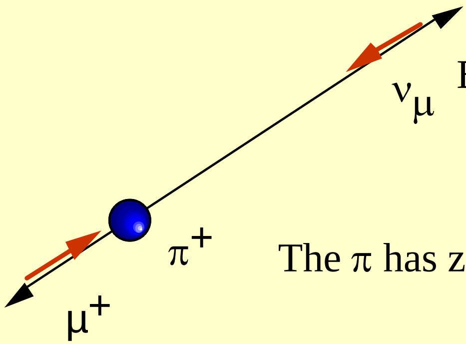
Goal:

- to determine the Michel parameters to a few parts in 10^4

- to test for weak couplings inconsistent with the Standard Model

Secondary beams at TRIUMF

μ polarization due to 2-body decay

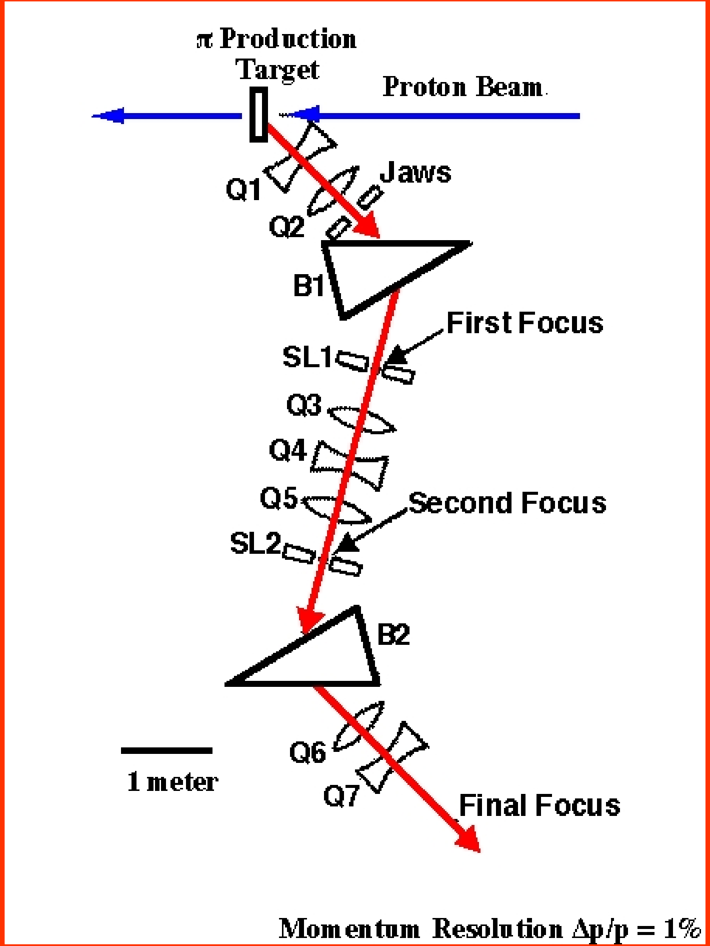


Back to back to conserve linear momentum

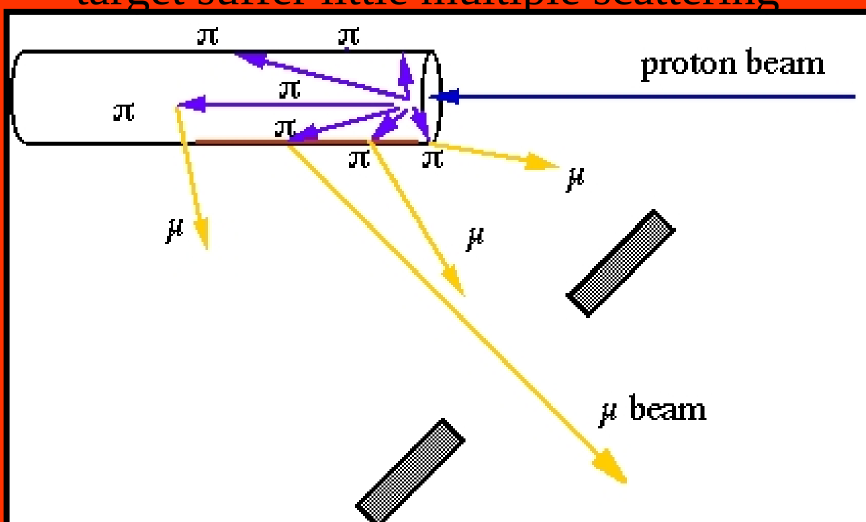
The π has zero angular momentum

=> no angular momentum in the final system

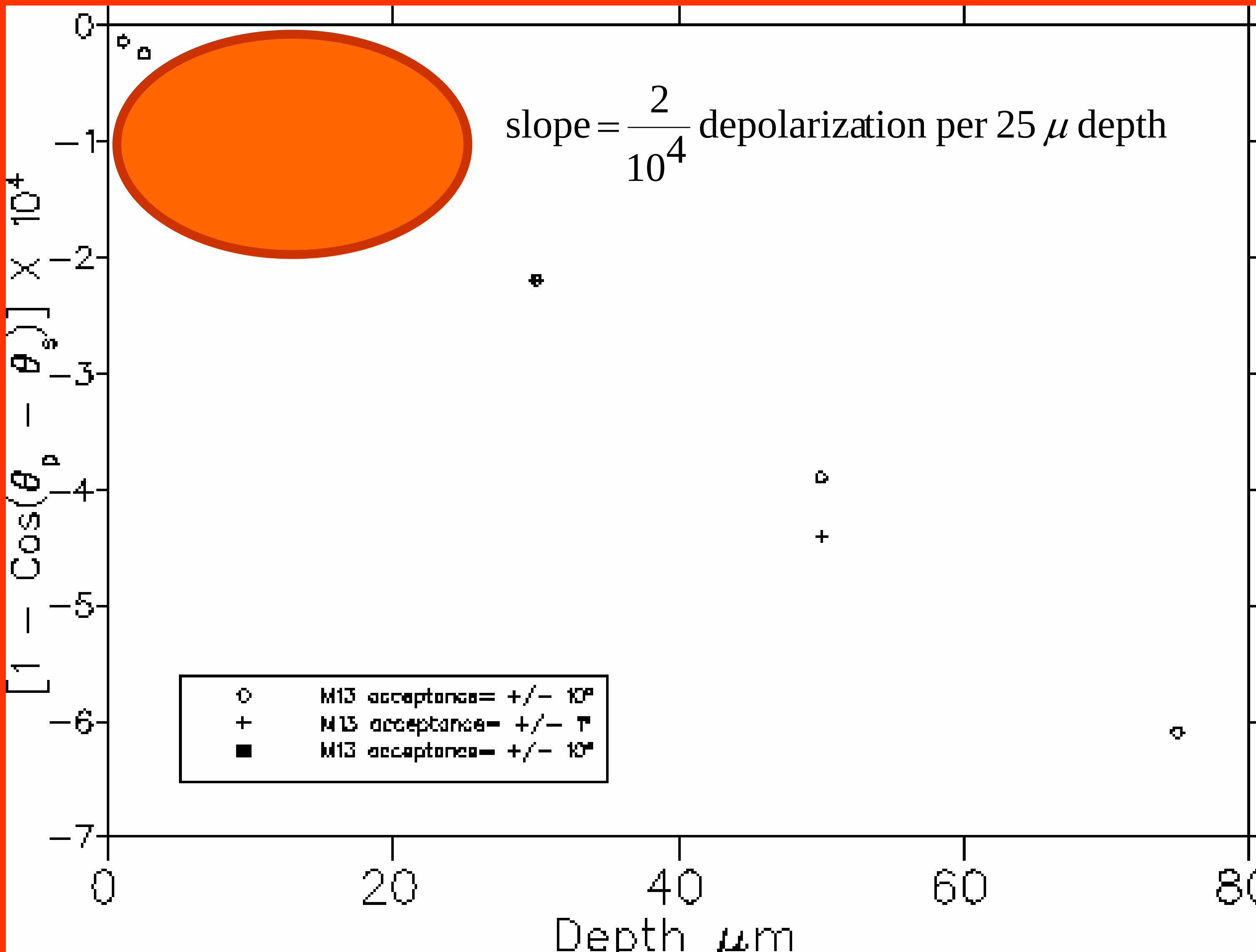
Channel resolution ~ 1% allows selection of μ produced within 25 microns of target surface



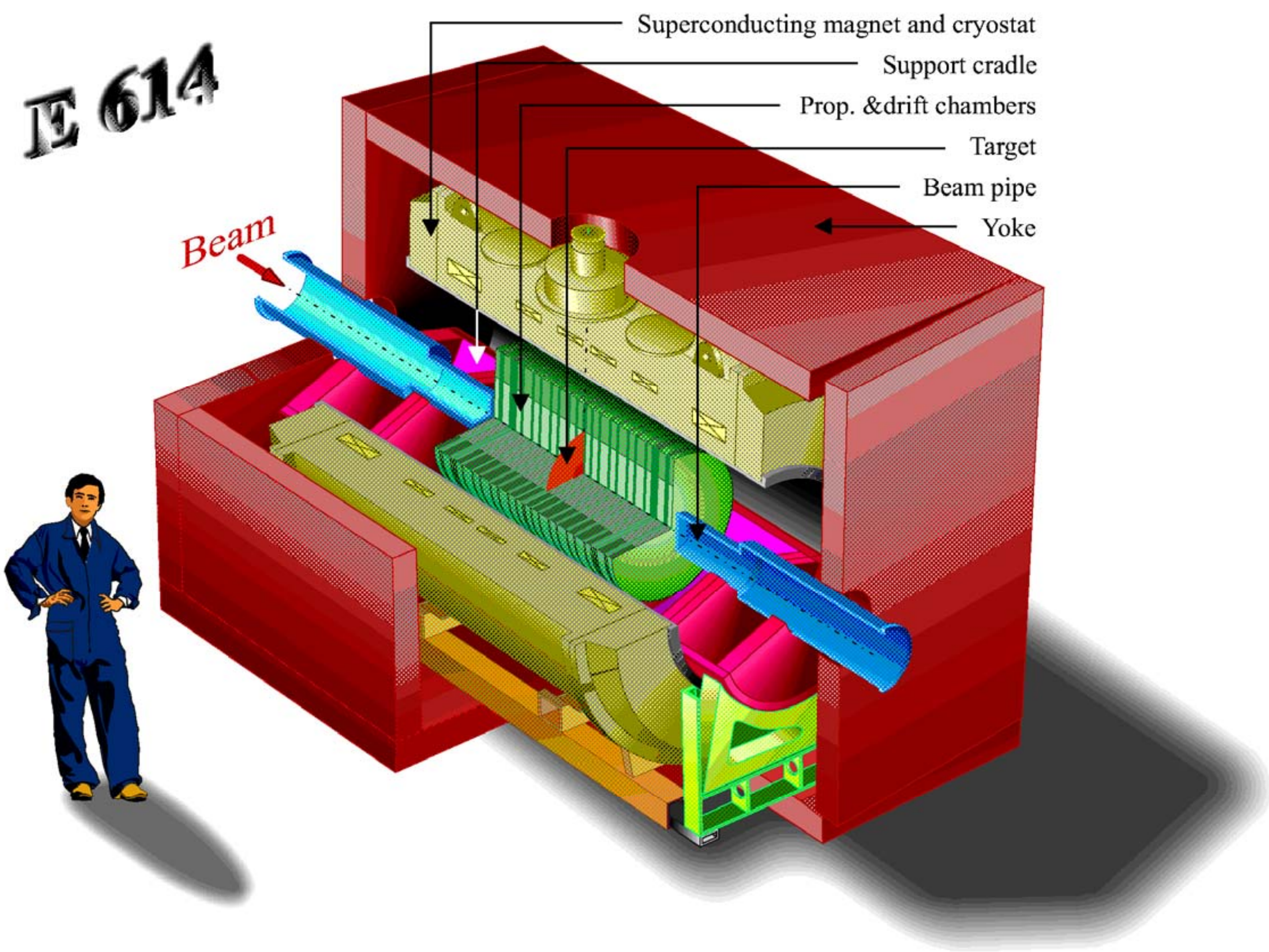
μ selected from the surface of the production target suffer little multiple scattering



Channel acceptance => ~ 0.0001 depolarization due to multiple scattering in production target

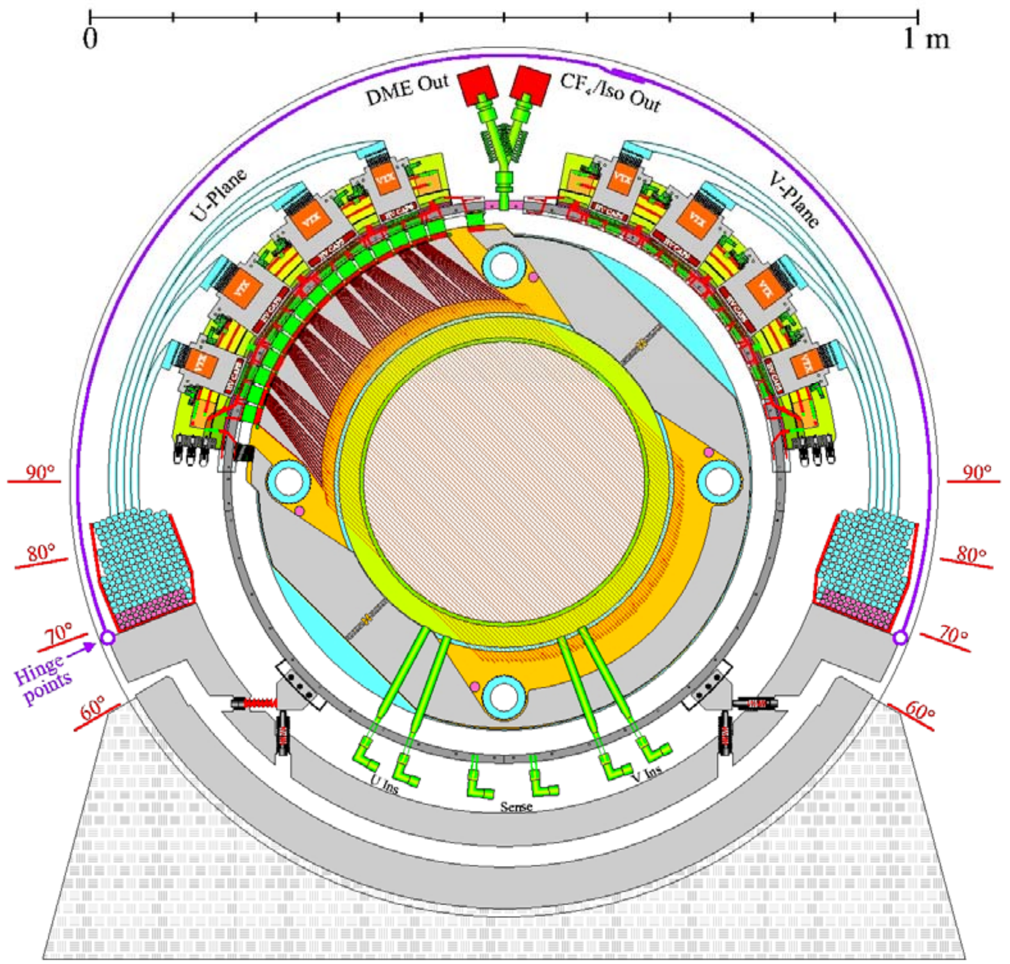


The E614 spectrometer

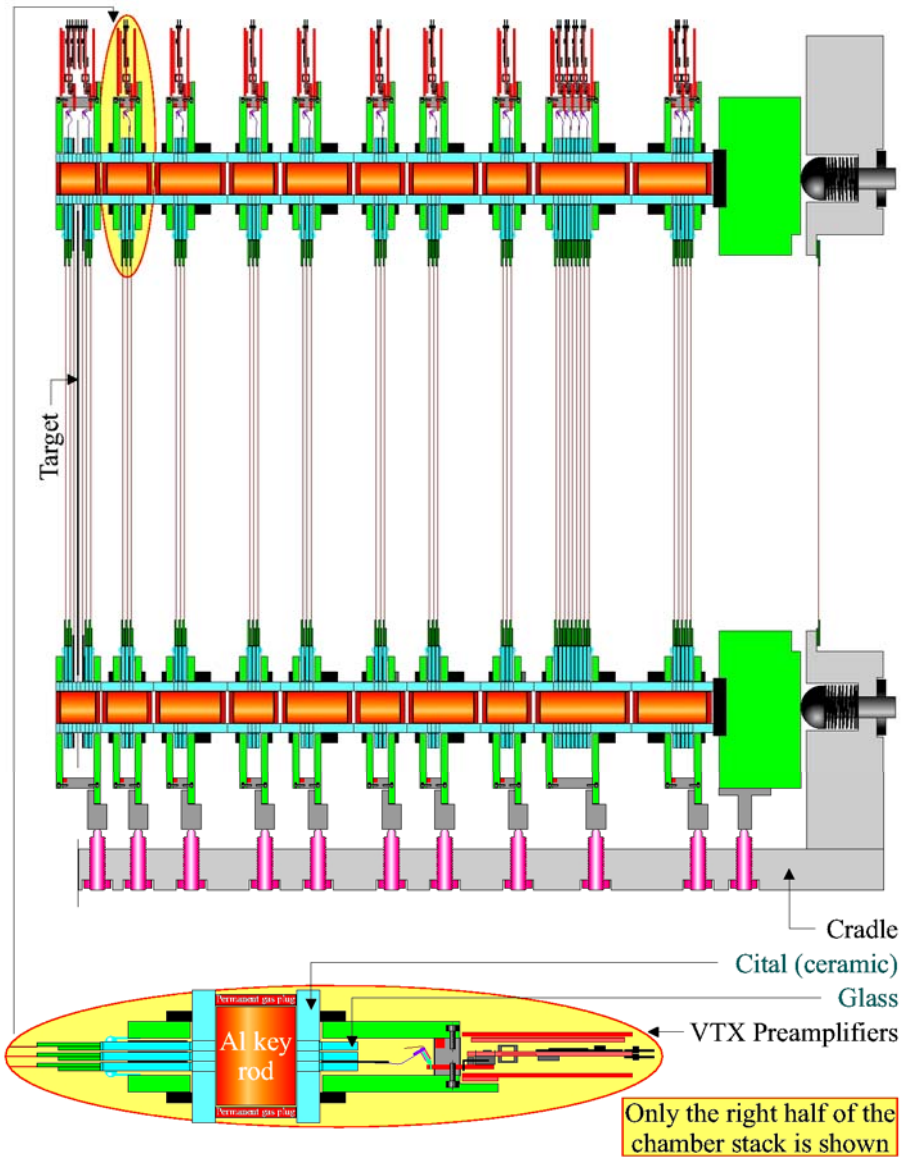


E614 Chamber Planes

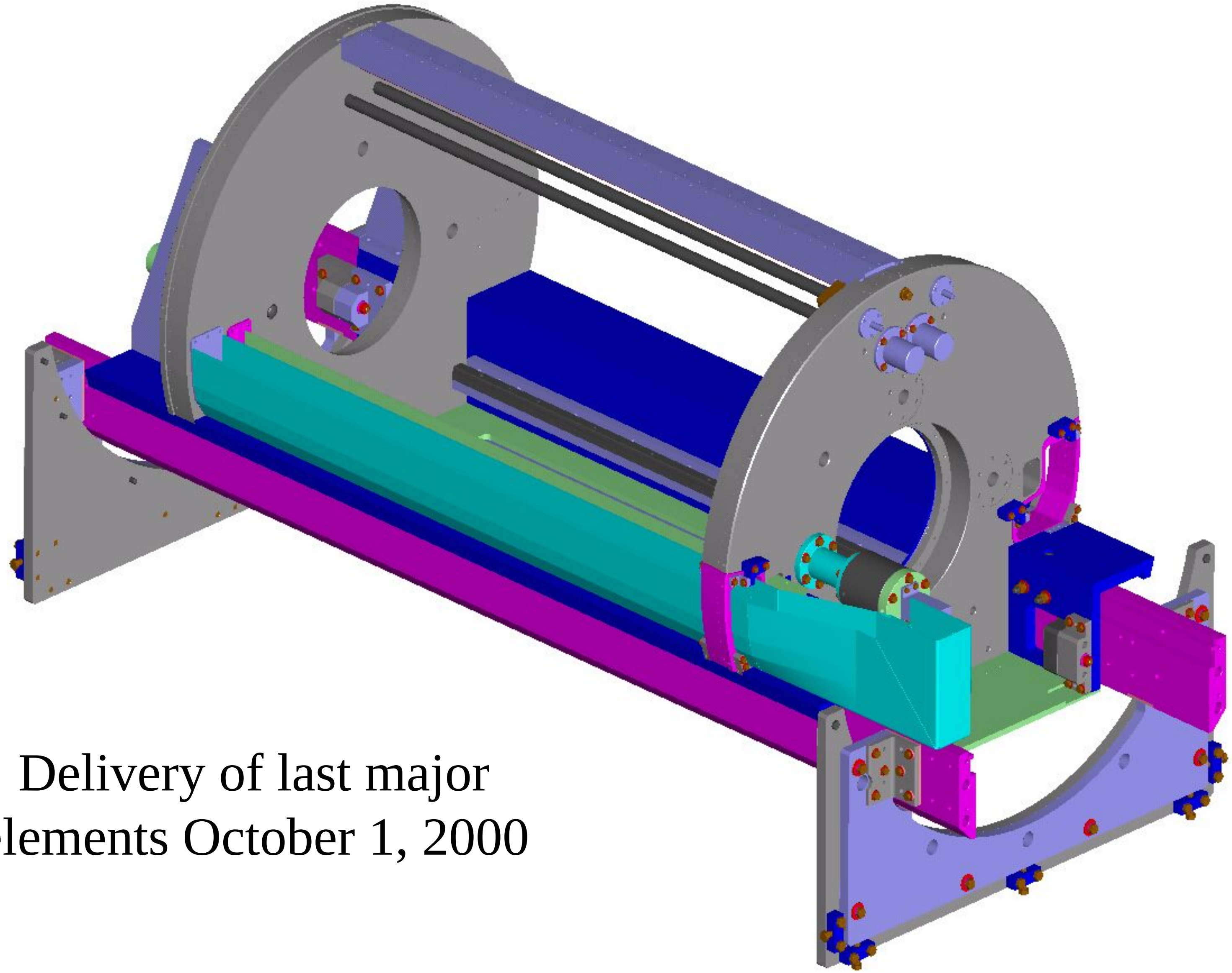
80 sense wires (20 μm Φ) + 2x3 guard wires at 4 mm distance. 22 pairs of drift chambers (each one U and V plane) with DME gas, 6 pairs of proportional chambers with CF_4 / Isobutane. ~5000 wires with VTX preamplifiers



E614 Chambers - half detector

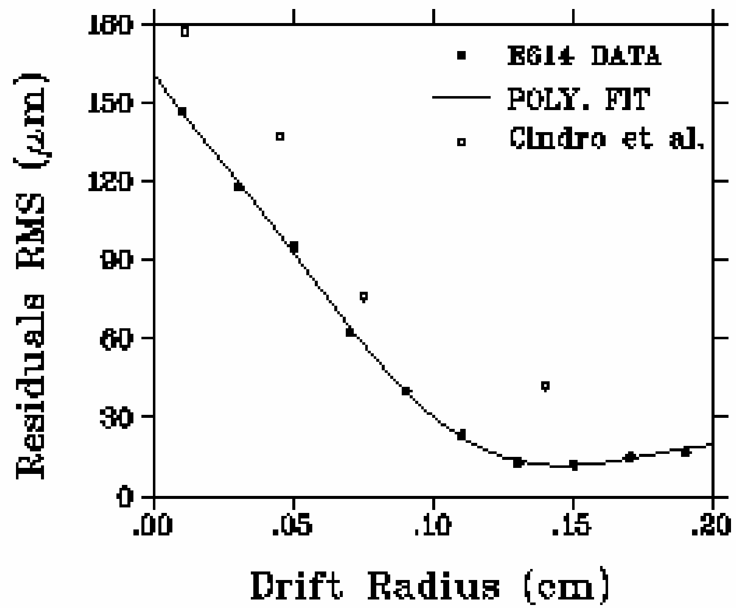


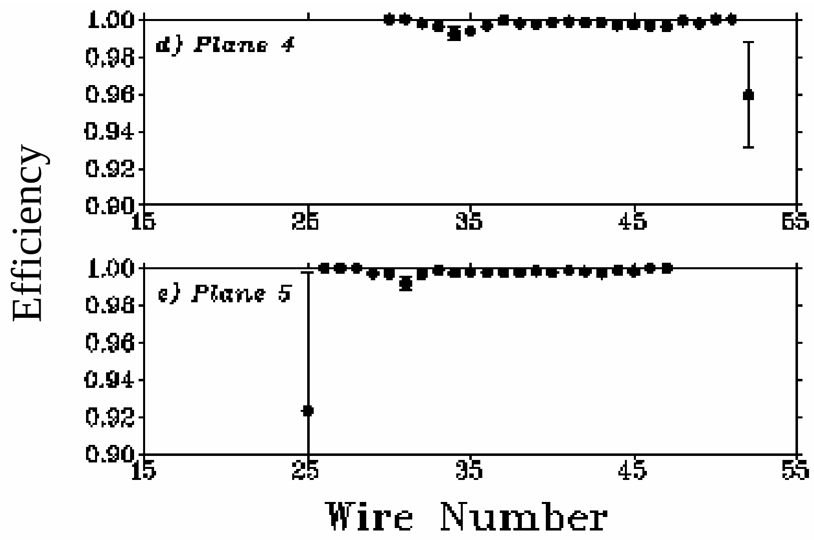
Detector Cradle- slides into solenoid

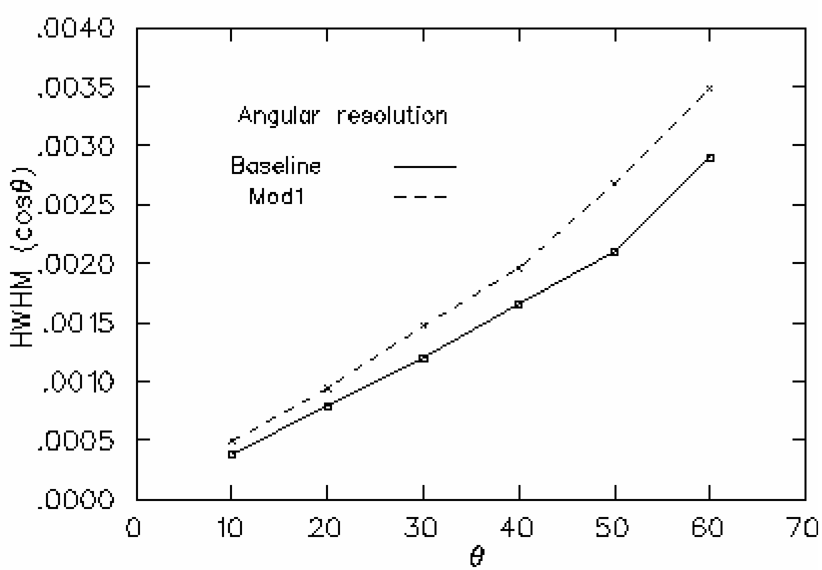


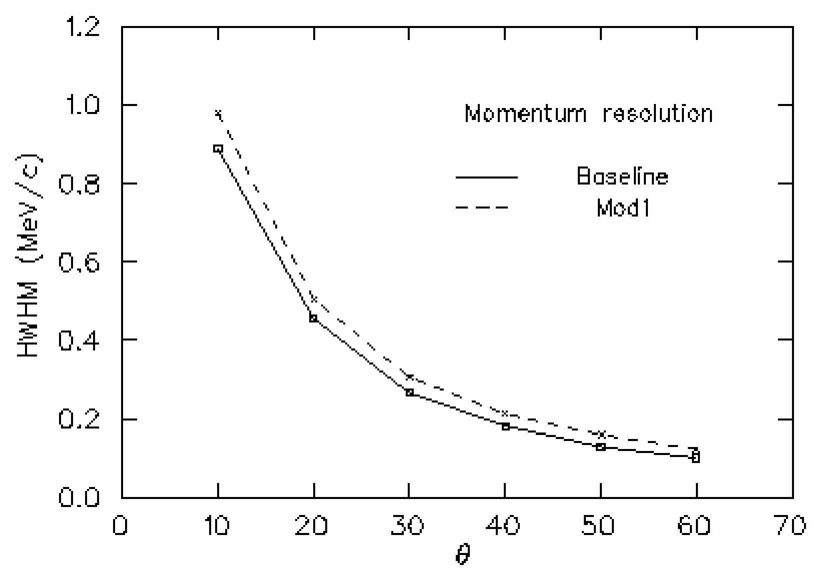
Delivery of last major elements October 1, 2000

Spectrometer Resolution









E614 Precision

Accepted Experimental Values

$$\rho = 0.7518 \pm 0.0026$$

$$P_\mu \xi = 1.0027 \pm 0.0085$$

$$\delta = 0.7486 \pm 0.0038$$

$$\eta = -0.007 \pm 0.013$$

E614 Proposal

$$\sigma_\rho = \pm 0.00005 \pm 0.00009$$

$$\sigma_{P_\mu \xi} = \pm 0.00010 \pm 0.00010$$

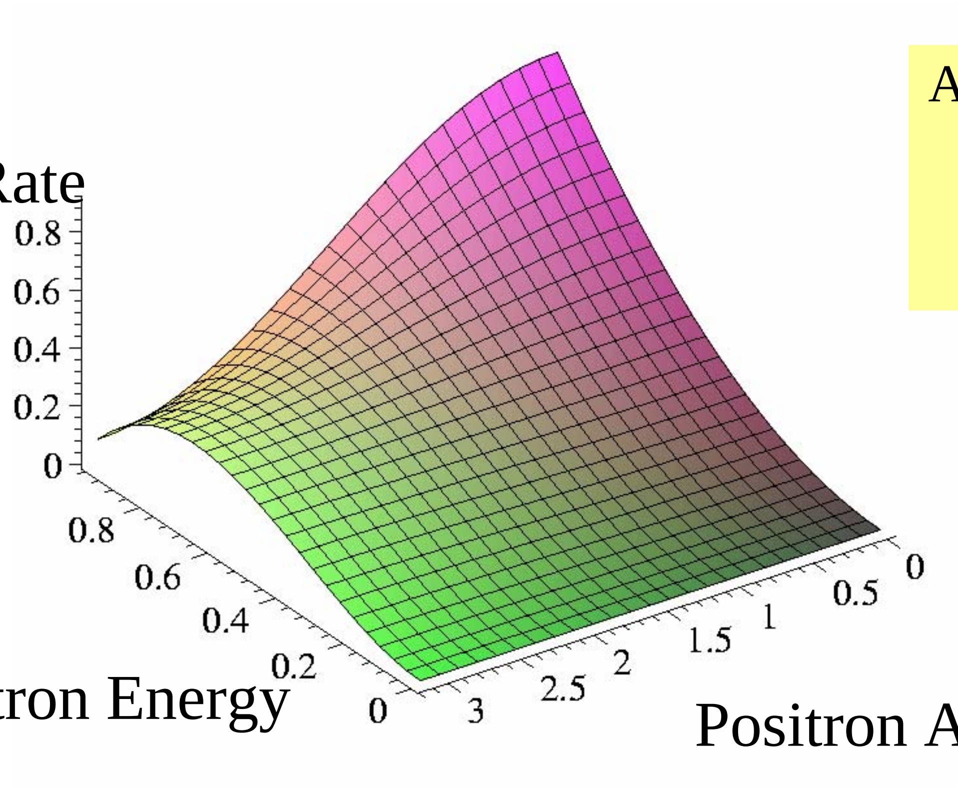
$$\sigma_\delta = \pm 0.00008 \pm 0.00010$$

$$\sigma_\eta \approx \pm 0.003$$

25-60 fold improvement in precision on the Michel parameters

3-10 fold improvement in couplings

Deviations from the Standard Model



Any (extra) non-zero couplings will distort the shape of the probability distribution

The probability distribution above is equivalent to the expression below

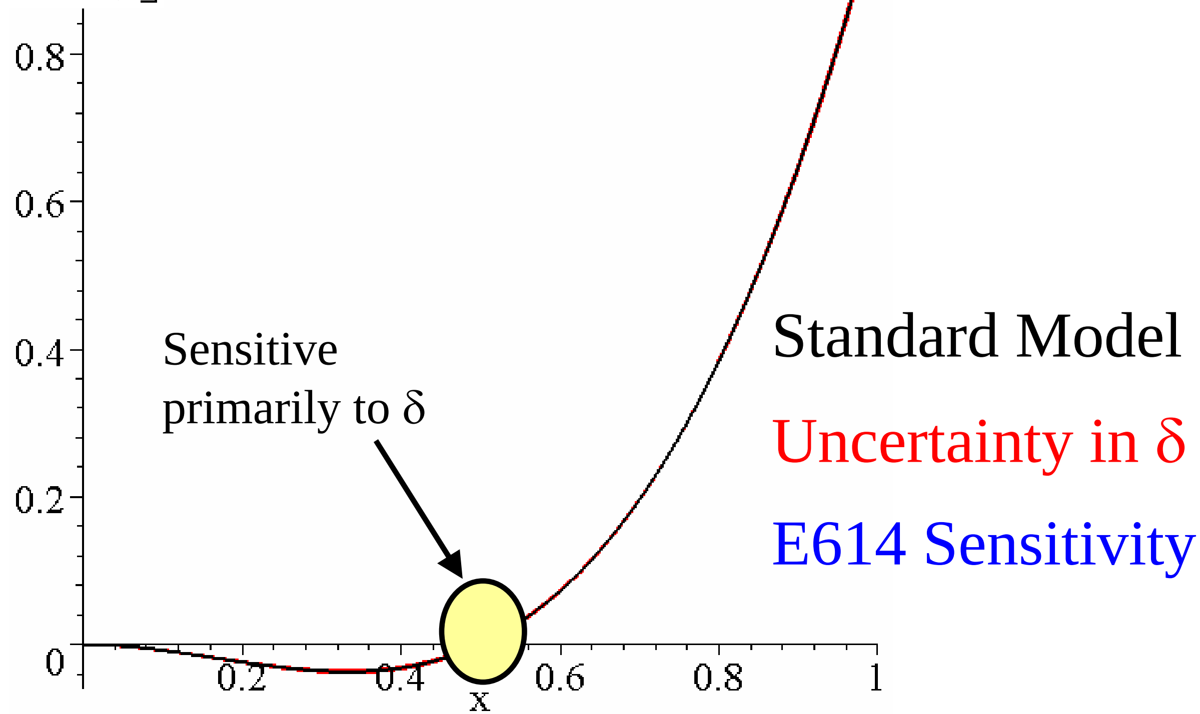
$$rate \sim x^2\left[3-3x+\frac{2}{3}\rho(4x-3)+P_\mu\xi\cos(\theta)\left(1-x+\frac{2}{3}\delta(4x-3)\right)\right]$$

The (forward - backward) distribution goes flat at a value of x dependant (only) upon δ

$$\left[Forward - Backward\right] \sim x^2\left[2P_\mu\xi\cos(\theta)\underline{\left(1 - x + \frac{2}{3}\delta(4x-3)\right)}\right]$$

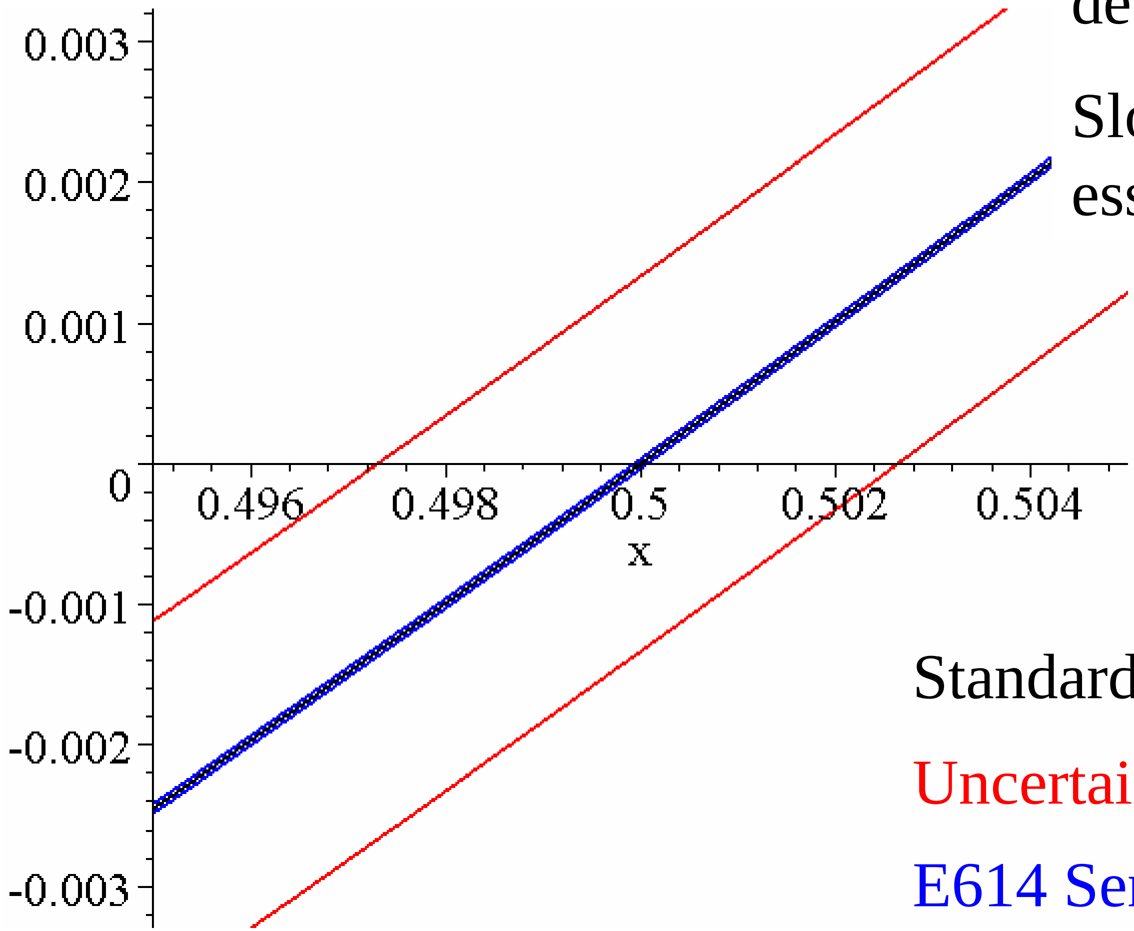
Find x such that term vanishes

$$x^2\left[2P_\mu\xi\left(1 - x + \frac{2}{3}\delta(4x-3)\right)\right]$$



Same as the previous slide - on expanded scale

$$x^2\left[2P_\mu\xi\left(1-x+\frac{2}{3}\delta(4x-3)\right)\right]$$



Zero crossing determines δ

Slope is essentially $P_\mu\xi$

Standard Model

Uncertainty in δ

E614 Sensitivity

Minimal extensions to the Standard Model

Allowing only vector couplings result in simplified Michel parameters

$$\rho \equiv \frac{3}{4}\left[|g^V_{LL}|^2 + |g^V_{RR}|^2 + |\cancel{g^T_{LR}}|^2 + |\cancel{g^T_{RL}}|^2\right]$$
$$+\frac{3}{16}\left[|\cancel{g^S_{LL}}|^2 + |\cancel{g^S_{RR}}|^2 + |\cancel{g^S_{LR}}|^2 + |\cancel{g^S_{RL}}|^2\right]$$
$$-\frac{3}{4}\left[\mathrm{Re}\left(\cancel{g^S_{LR} g^{T*}_{LR}}\right) + \mathrm{Re}\left(\cancel{g^S_{RL} g^{T*}_{RL}}\right)\right]$$

In the context of the model,
Four parameters and four unknowns

$$\xi \equiv |g^V_{LL}|^2 + 3|g^V_{LR}|^2 - 3|g^V_{RL}|^2 - |g^V_{RR}|^2 + 5|\cancel{g^T_{LR}}|^2$$
$$-5|\cancel{g^T_{RL}}|^2 + \frac{1}{4}|\cancel{g^S_{LL}}|^2 - \frac{1}{4}|\cancel{g^S_{LR}}|^2 + \frac{1}{4}|\cancel{g^S_{RL}}|^2 - \frac{1}{4}|\cancel{g^S_{RR}}|^2$$
$$+4\,\mathrm{Re}(\cancel{g^S_{LR} g^{T*}_{LR}}) - 4\,\mathrm{Re}(\cancel{g^S_{RL} g^{T*}_{RL}})$$

$$\xi\delta \equiv \frac{3}{4}\left[|g^V_{LL}|^2 - |g^V_{RR}|^2 - |\cancel{g^T_{LR}}|^2 + |\cancel{g^T_{RL}}|^2\right]$$
$$+\frac{3}{16}\left[|\cancel{g^S_{LL}}|^2 - |\cancel{g^S_{RR}}|^2 - |\cancel{g^S_{LR}}|^2 + |\cancel{g^S_{RL}}|^2\right]$$
$$-\frac{3}{4}\left[\mathrm{Re}(\cancel{g^S_{LR} g^{T*}_{LR}}) - \mathrm{Re}(\cancel{g^S_{RL} g^{T*}_{RL}})\right]$$

$$\eta \equiv \frac{1}{2}\mathrm{Re}\left[g^V_{LL}\cancel{g^{S*}_{RR}} + g^V_{RR}\cancel{g^{S*}_{LL}}\right]$$
$$+\frac{1}{2}\mathrm{Re}\left[g^V_{RL}\left(\cancel{g^{S*}_{LR}} + 6\cancel{g^{T*}_{LR}}\right) + g^V_{LR}\left(\cancel{g^{S*}_{RL}} + 6\cancel{g^{T*}_{RL}}\right)\right]$$

Anticipated sensitivity to new couplings

	Current Limits	E614(A)	E614(B)	E614(C)	E614(D)
$\lvert g^S_{RR}\rvert$	<0.066	—	—	0.020	0.045
$\lvert g^V_{RR}\rvert$	<0.033	0.012	0.014	0.013	0.022
$\lvert g^S_{LR}\rvert$	<0.125	—	—	0.027	0.046
$\lvert g^V_{LR}\rvert$	<0.060	0.012	0.013	0.012	0.018
$\lvert g^T_{LR}\rvert$	<0.036	—	0.009	—	0.013
$\lvert g^S_{RL}\rvert$	<0.424	—	—	—	—
$\lvert g^V_{RL}\rvert$	<0.110	0.012	0.012	0.011	—
$\lvert g^T_{RL}\rvert$	<0.122	—	0.008	—	—
$\lvert g^S_{LL}\rvert$	<0.55	—	—	—	—
$\lvert g^V_{LL}\rvert$	>0.96	>0.99977	>0.99953	—	—

Upper limits (90% CL) for weak coupling constants with current limits taken from the Particle Data Group. Improved limits expected from TWIST based on measurements of ρ, ξ, δ and η assume:

- (A) V, A couplings only,
- (B) V, A and T couplings,
- (C) V, A and S couplings or
- (D) most general V, A, S, and T derivative-free couplings.

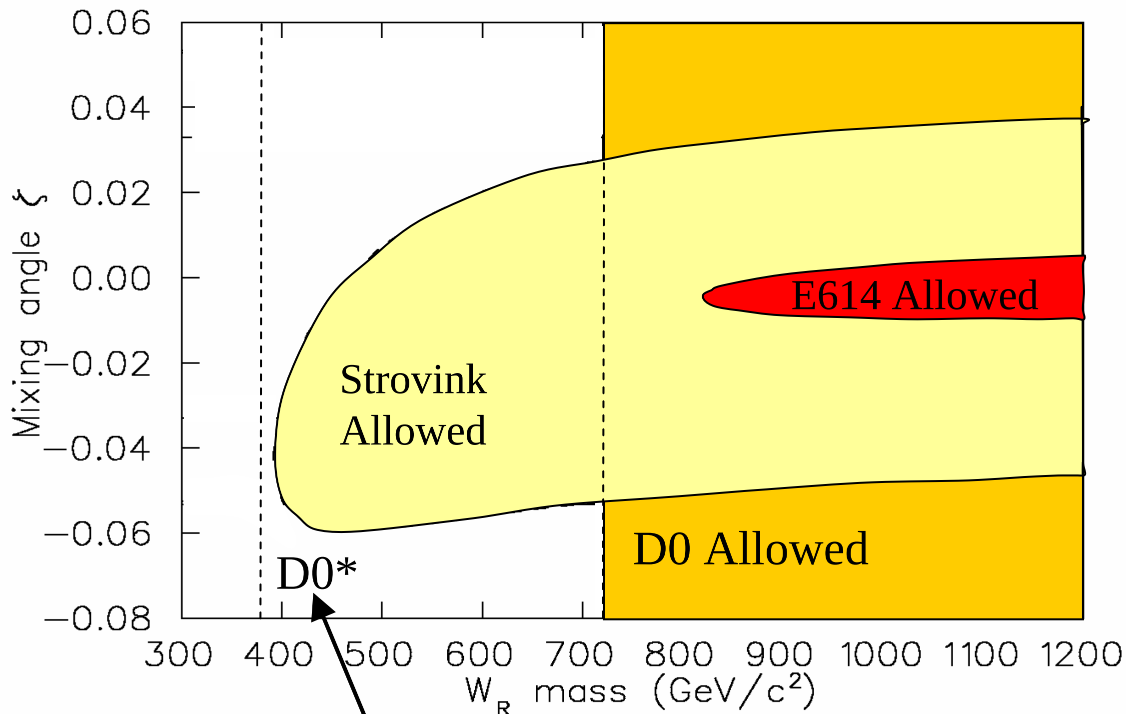
One way of looking at the discovery potential

Assume manifest L-R Symmetry

ie $g_R = g_L$

$CKM_R = CKM_L$

and no cp violation



$V_{ud}^{R} = 0$

$V_{us}^{R} = 1$

Beta decay, $p\bar{p}$ direct production, and muon decay are complimentary

E614 Timeline

- ✓ **WC Review - January 1999**
- ✓ **Mechanical Review - June 1999**
- ✓ **Beam Tests - final prototype - August 1999**
- ✓ **Full WC Production underway - March 2000**
- ➢ **WC Module Completion May 2000 – April 2001**
- ✓ **WC Bench tests beginning June 2000**
- **Yoke delivery Fall 2000**
- **Yoke, Solenoid, and cryogenics assembly: Winter 2000/01**
- **Beam tests, November/December 2000**

- **Preliminary Physics: December 2002**