The Final Measurement of the Muon Decay Parameters from the $\mathcal{TWIST}$ Experiment

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For the **T**RIUMF **W**eak **I**nteraction **S**ymmetry **T**est Collaboration

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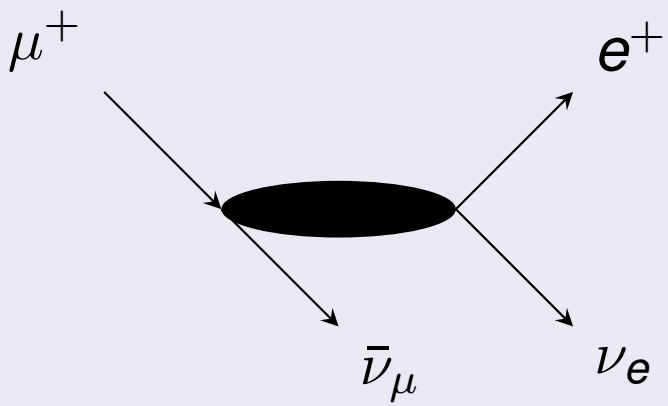
Muon Decay as a Probe for the Weak Interaction

- General Lorentz invariant, derivative-free, interaction[1]

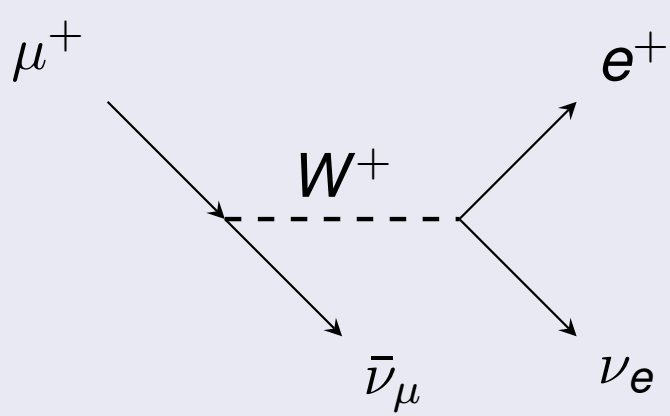
$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \epsilon,\mu=R,L}} g^{\gamma}_{\epsilon\mu} \langle \bar{e}_{\epsilon} | \Gamma^{\gamma} | (\nu_e)_n \rangle \langle (\bar{\nu}_{\mu})_m | \Gamma_{\gamma} | \mu_{\mu} \rangle .$$

General Case



$\Rightarrow$

Standard Model (V-A): $g^V_{LL} = 1$



[1] W. Fetscher, H.J. Gerber, and K.F. Johnson, *Phys. Lett.* **B173 (1986) 102**

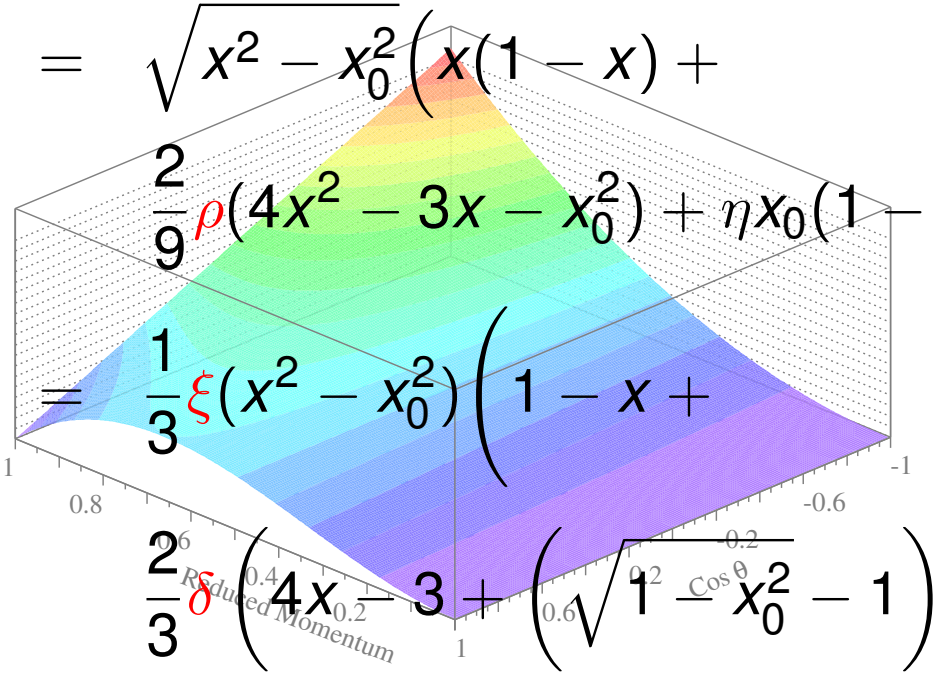
Decay Spectrum Parametrization

- Given in energy and angle as [2]

$$\frac{\partial^2\Gamma}{\partial x \partial \cos\theta} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_F^2 \left(F(x) - |P_\mu| \cos\theta\, G(x)\right) + R.C., x = \frac{E_e}{W_{e\mu}}$$

$$F(x) = \sqrt{x^2 - x_0^2}\left(x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)\right)$$

$$G(x) = \frac{1}{3}\xi(x^2 - x_0^2)\left(1 - x + \frac{2}{3}\delta\left(4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right)\right)$$



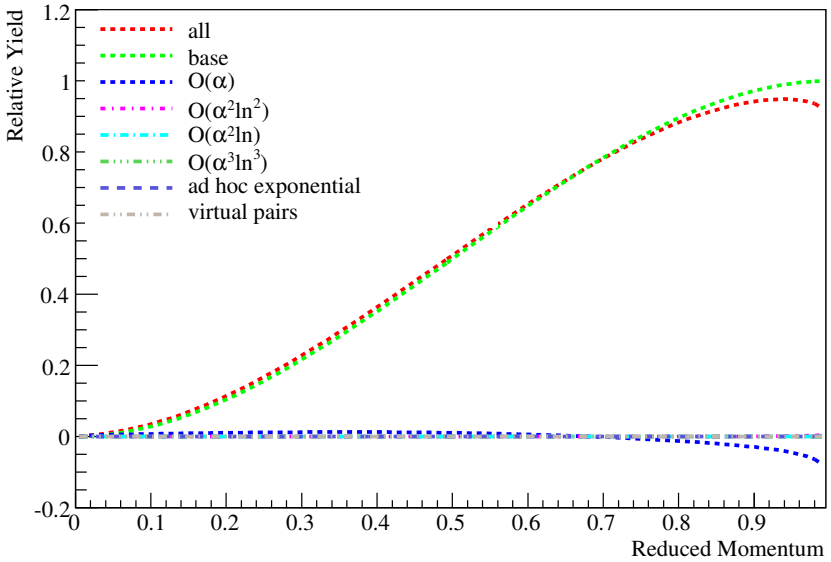
In the Standard Model

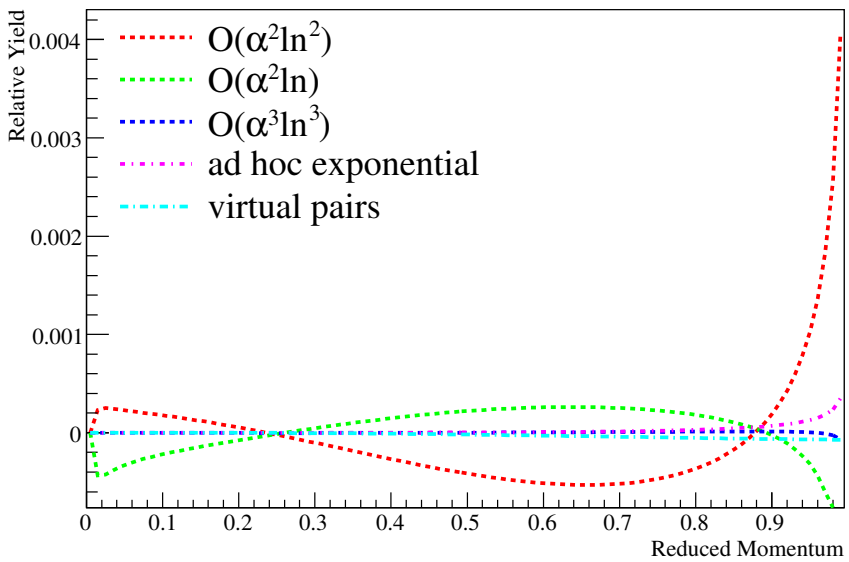
ρ	=	0.75
η	=	0
δ	=	0.75
$P_\mu^\pi \xi$	=	1

- deviations represent new physics

[2] K. Nakamura et al. (Particle Data Group), J. Phys. G **37**, 075021 (2010)

Radiative Corrections

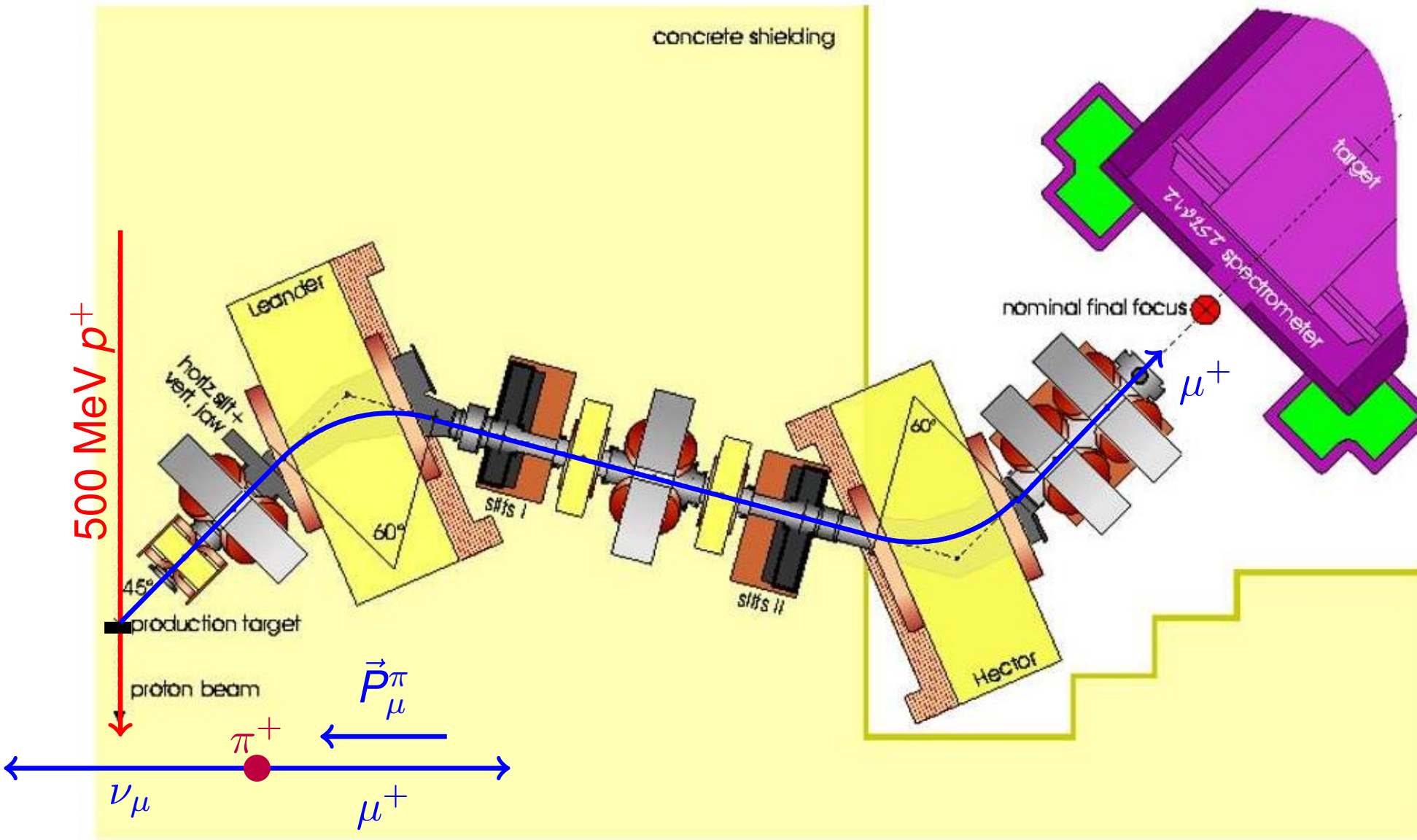




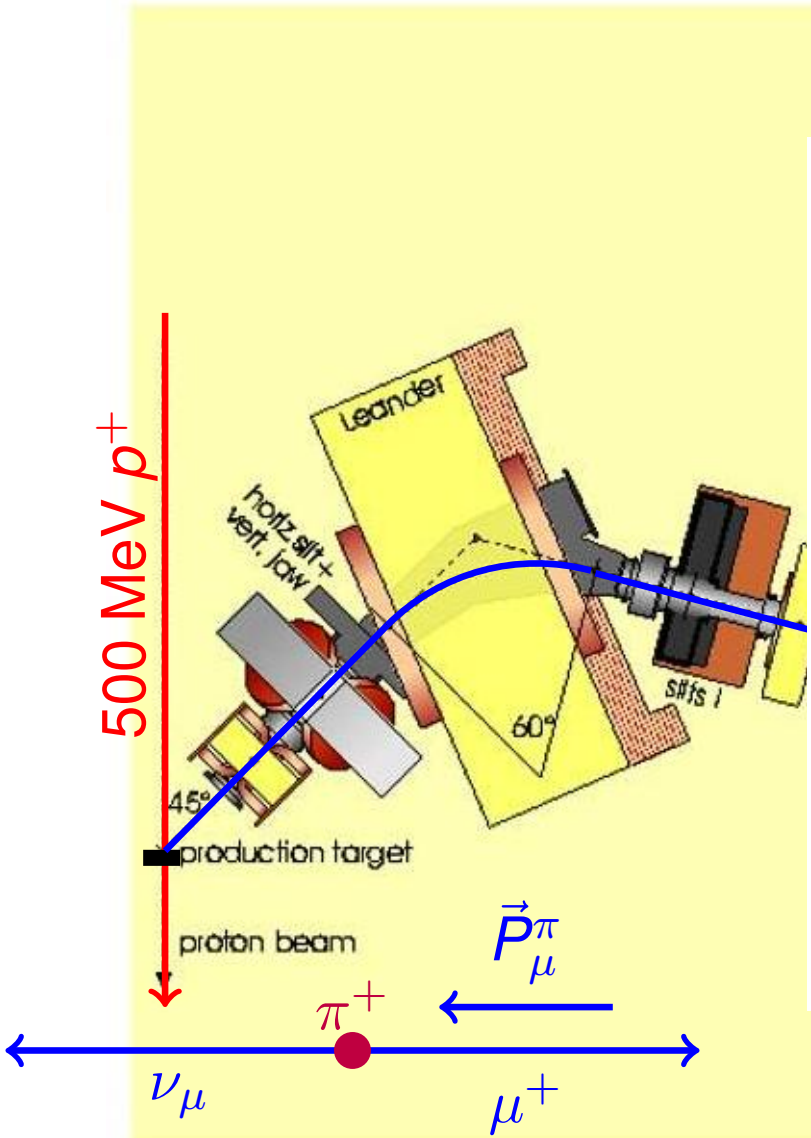
- Highest order correction contributes variations in spectrum at 10^{-5} level.
- Known second order leading logarithmic corrections make this measurement possible.[3]
- Contribution of higher order corrections represent systematic uncertainties.

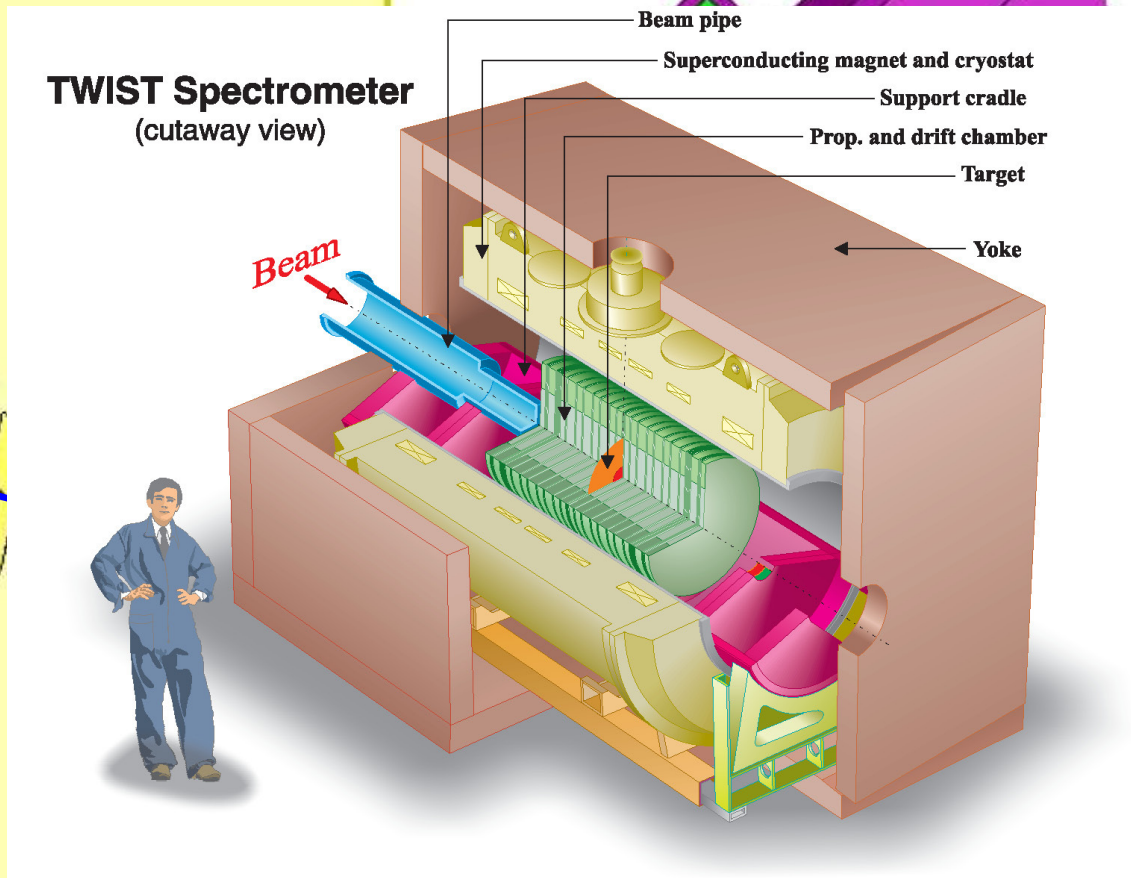
[3] Arbuzov et. al., PR**D65** (2002) 1130067

TWIST Experiment



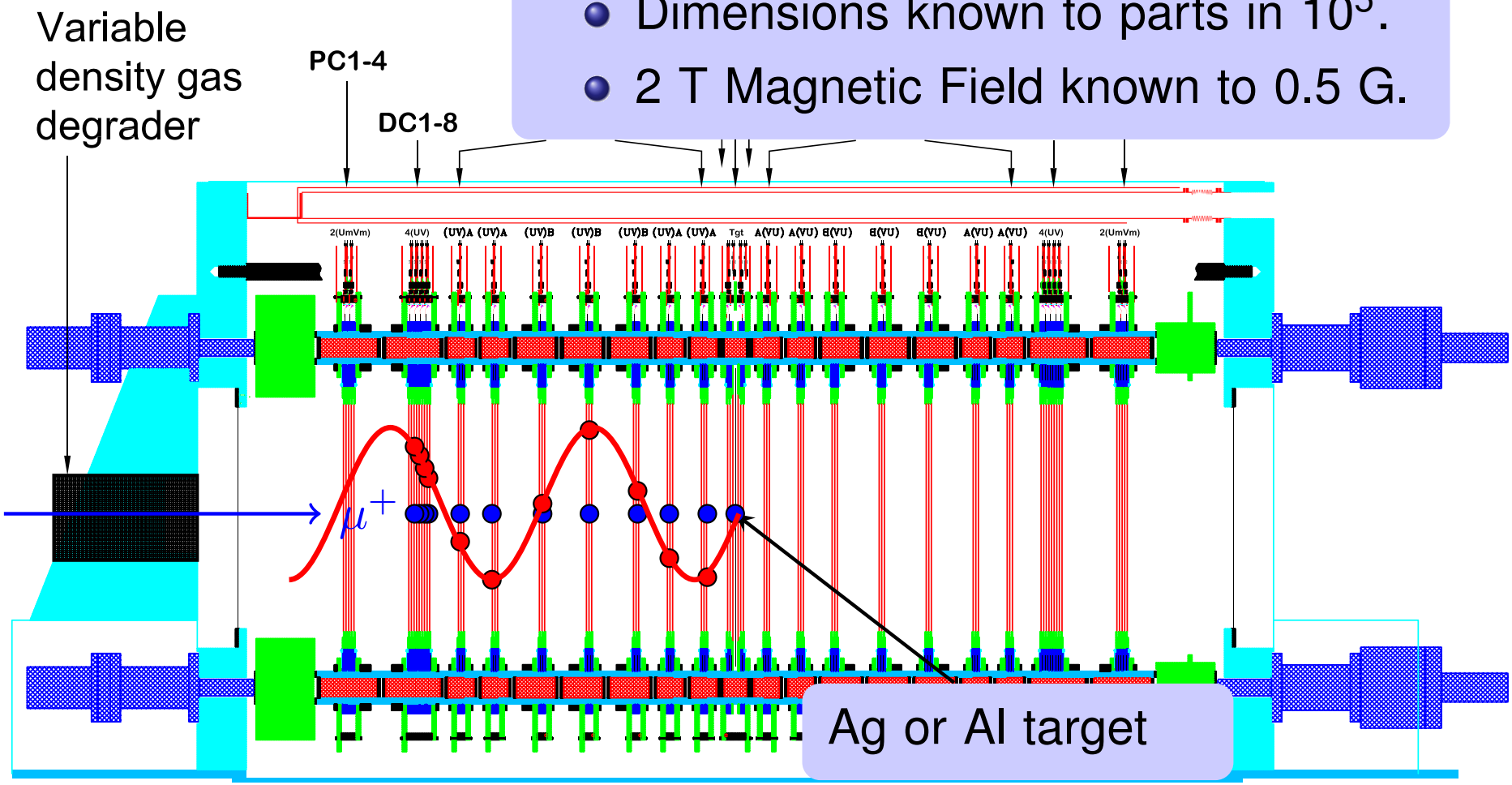
TWIST Experiment



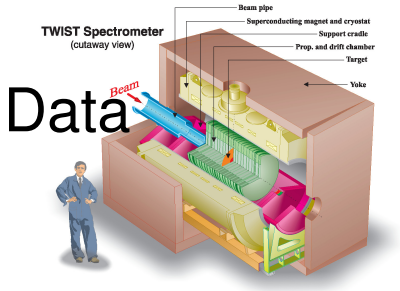


TWIST Spectrometer

- Dimensions known to parts in 10^5.
- 2 T Magnetic Field known to 0.5 G.



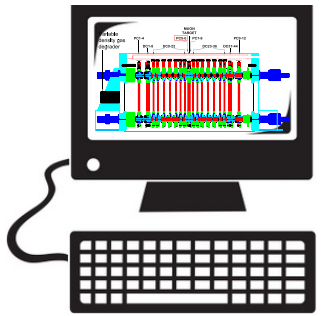
TWIST Analysis Overview



Data

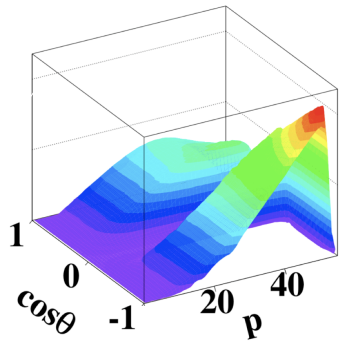
ρ_0, δ_0, ξ_0

Simulation



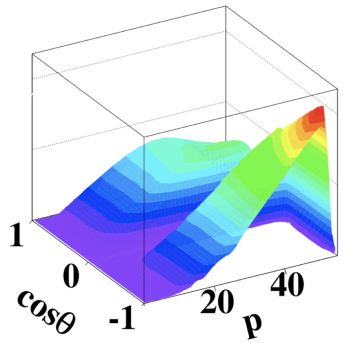
e^+ Track Analysis

e^+ Track Analysis



DATA - MC Fit

$\Delta\rho, \Delta\delta, \Delta\xi$



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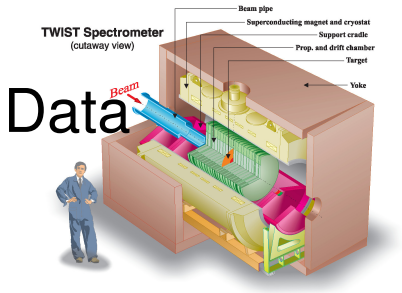
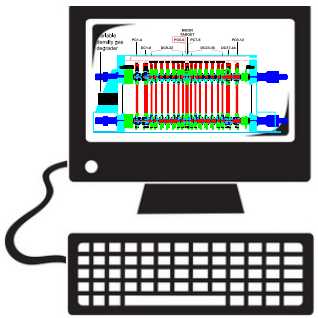


Data

ρ_0, δ_0, ξ_0

Simulation



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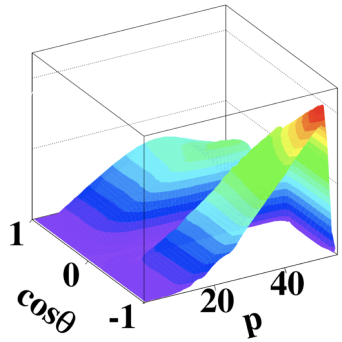
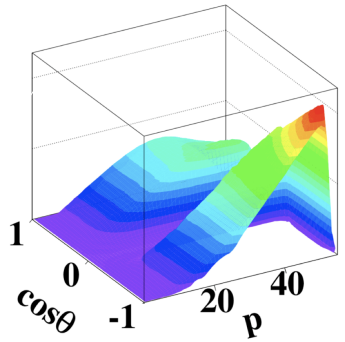


DATA - MC Fit

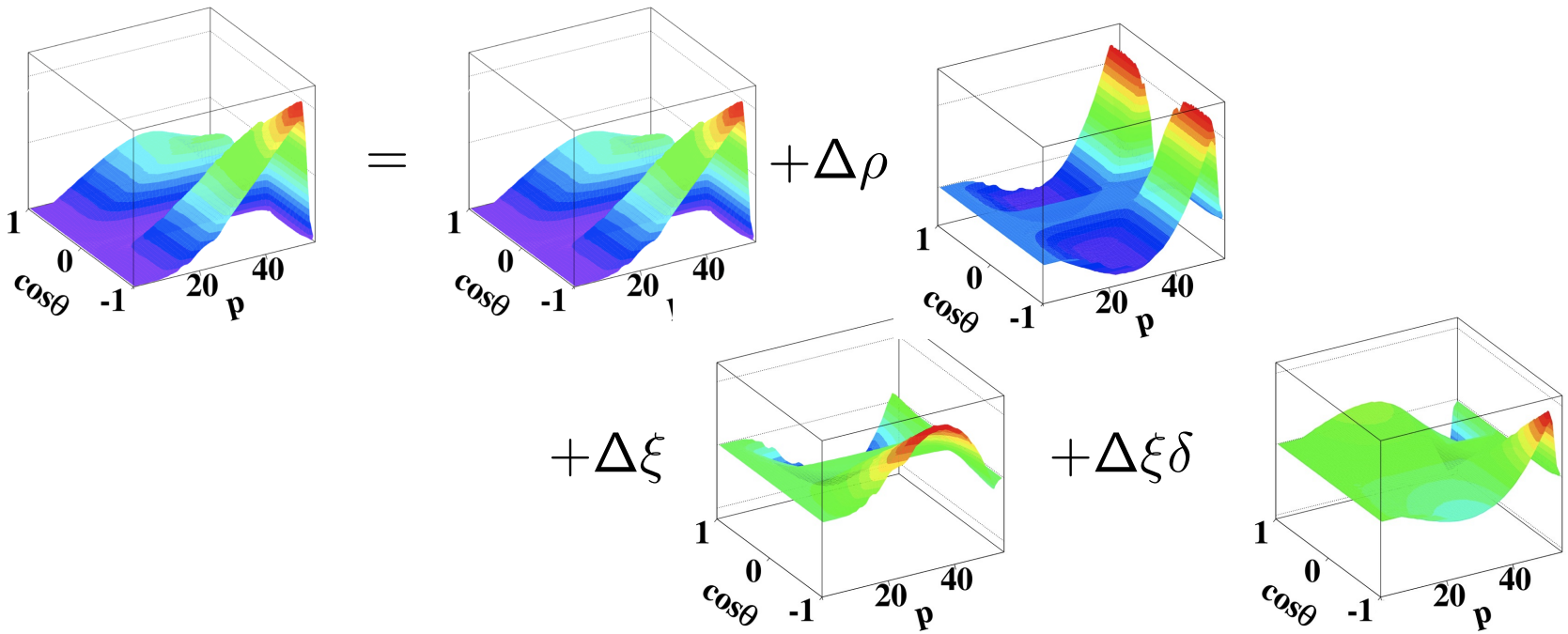


$\Delta\rho, \Delta\delta, \Delta\xi$

ρ_f, δ_f, ξ_f

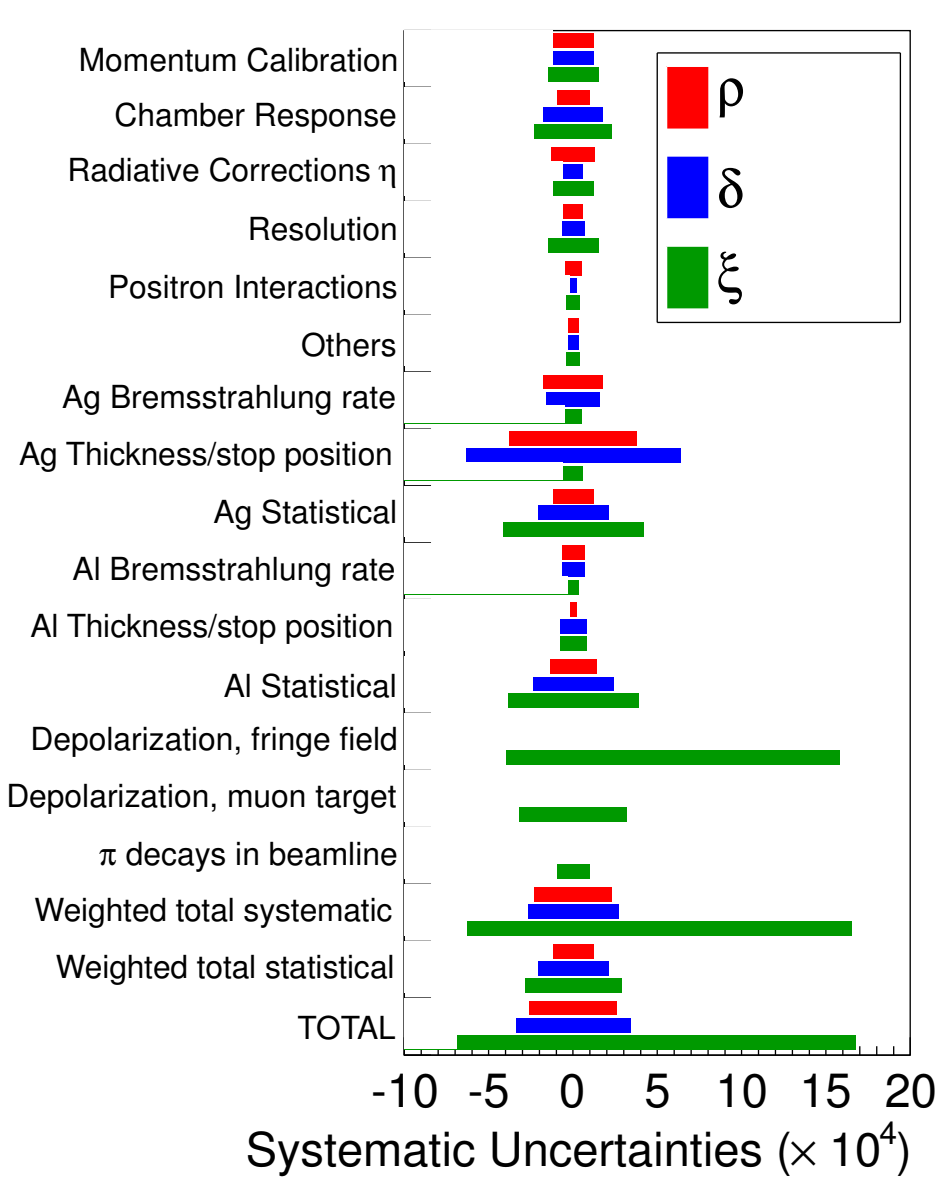
Spectrum Fits

- Sum of simulated spectra used as fitting function



- Relies on the linear behaviour of the spectrum in ρ, $P_\mu\xi$, and $P_\mu\xi\delta$.
- Parameter differences optimized using a χ^2 statistic.

Systematics Summary



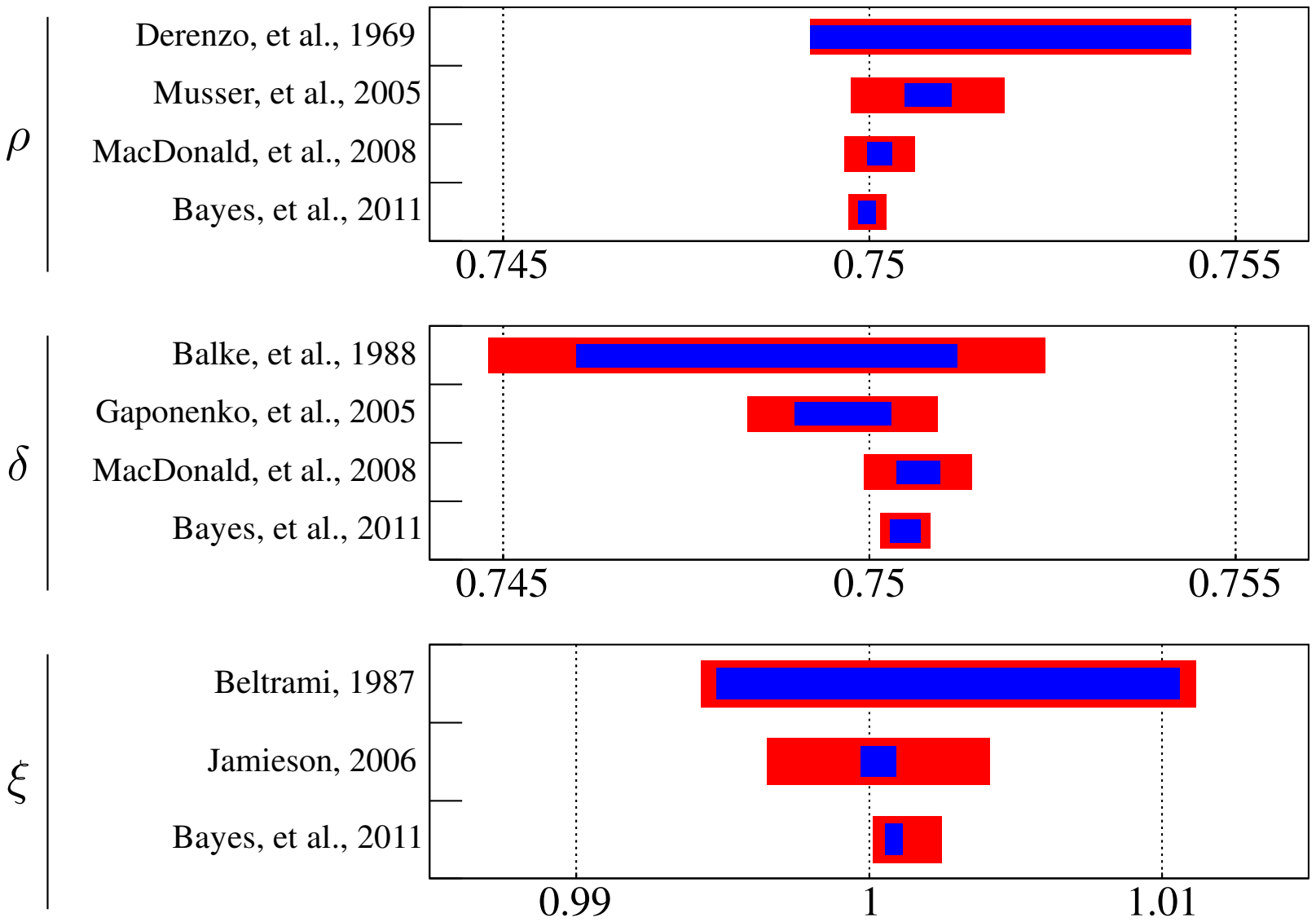
Systematics categorized as

- Common
- Silver target only
- Aluminium target only
- P_μ^π specific

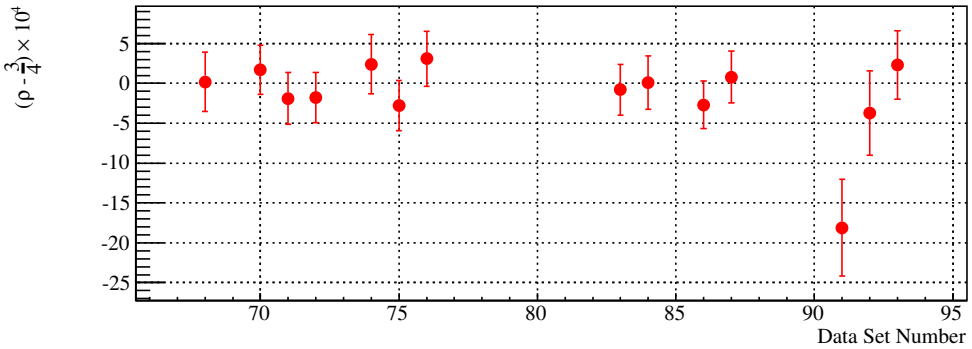
Measured Results

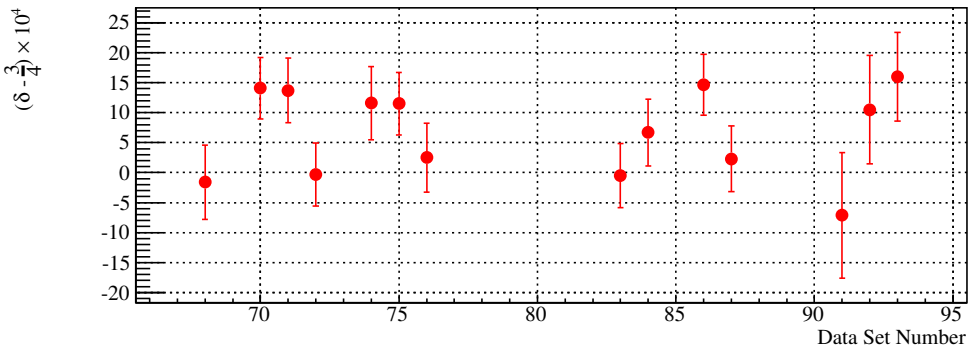
	Units of $\times 10^{-4}$		
	Ave. Diff.	Stat.	Sys
ρ	95.1	± 1.2	± 2.3
δ	51.3	± 2.1	± 2.7
ξ	80.3	± 2.9	$^{+16.5}_{-6.3}$

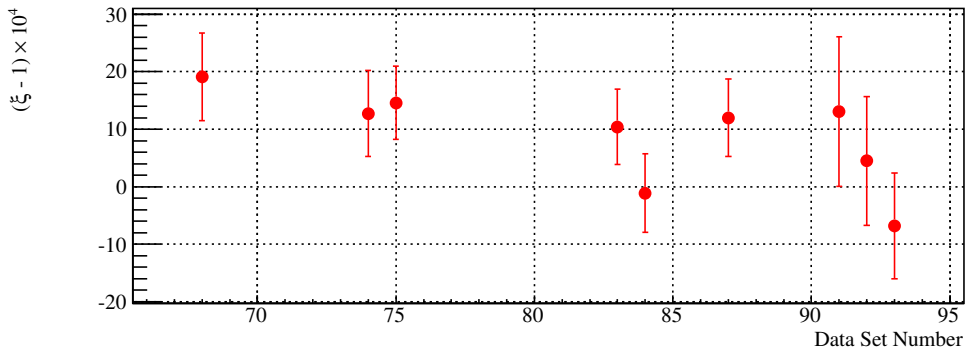
Decay Parameters



Consistency of Results







- Differences between SM and results corrected for blind parameters and bias.

	χ^2/ndf
ρ	16.5/13
δ	14.8/13
ξ	8.7/8

Measured Values

$$\rho = 0.74997 \pm 0.00012 \pm 0.00023$$
$$\delta = 0.75049 \pm 0.00021 \pm 0.00027$$
$$P_\mu^\pi \xi = 1.00084 \pm 0.00029^{+0.00165}_{-0.00063}$$

Revision Due to $P_\mu^\pi \xi\delta/\rho$

Endpoint Anisotropy

$P_\mu^\pi \xi\delta/\rho = 1.00179^{+0.00156}_{-0.00063}$
> 0.99909 (90% C.L.)

- $P_\mu^\pi \xi\delta/\rho > 1$ by 2.9σ

- $P_\mu^\pi \xi\delta/\rho$ changed in Ag and Al targets by 3.9 σ

- Prompted review of systematics after black box opening

Changes in the Revised analysis

- Motivated categorization of systematics
- Corrected parameter weighting
- Identified systematics from mean stopping position

Change between blind and revised results

	Units of $\times 10^4$	
	Value	σ_{total}
ρ	-1.4	-0.3
δ	-2.3	+0.1
$P_\mu \xi$	0	-0.2

Global Analysis

e^+ spectrum measurements are a subset of muon decay parameters

Parameter	Value	Reference
Current TWIST decay parameters		
ρ	0.74997 ± 0.00028	
δ	0.75049 ± 0.00033	
ξ	$1.00084^{+16.9}_{-11.9}$	
Previous decay parameters		
ρ	0.7518 ± 0.0026	PDG average (2003)
δ	0.7486 ± 0.0038	Balke,1988
$P_\mu \xi$	1.0027 ± 0.0085	Beltrami,1987
$P_\mu \xi \delta / \rho$	0.99787 ± 0.00082	Jodidio,1986
Parameters from positron Polarization		
ξ'	1.00 ± 0.04	PDG average (2003)
ξ''	0.65 ± 0.36	Burkard,1985
$\bar{\eta}$	0.02 ± 0.08	PDG average (2003)
α / A	0.015 ± 0.052	Burkard,1985
β / A	0.002 ± 0.018	Burkard,1985
η	0.071 ± 0.037	Danneberg,2005
η''	0.105 ± 0.052	Danneberg,2005
α' / A	-0.047 ± 0.052	Burkard,1985
	-0.0034 ± 0.0219	Danneberg,2005
β' / B	0.017 ± 0.018	Burkard,1985
	-0.0005 ± 0.00080	Danneberg,2005

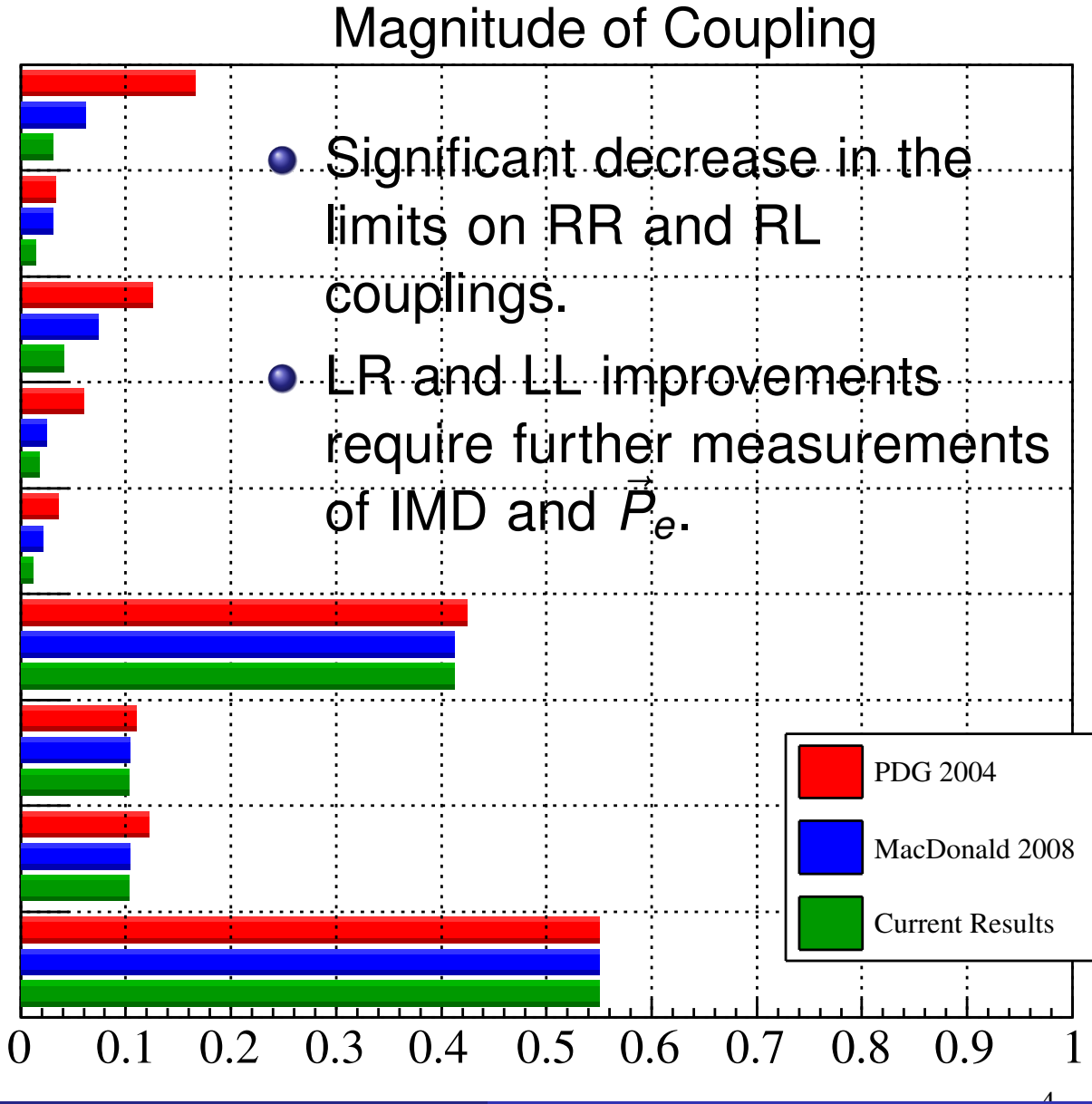
- Required for limits on interaction probabilities and coupling constants

Interaction Probabilities

	2008 $(\times 10^{-3})$	2011 $(\times 10^{-3})$
Q_{RR}	< 0.96	< 0.30
Q_{LR}	< 1.38	< 0.63
Q_{RL}	< 42	< 42
Q_{LL}	> 955	> 955

Coupling Constants

	2004	2008	2010
$\lvert g^S_{RR} \rvert$	0.166	0.062	0.031
$\lvert g^V_{RR} \rvert$	0.033	0.031	0.015
$\lvert g^S_{LR} \rvert$	0.125	0.074	0.041
$\lvert g^V_{LR} \rvert$	0.060	0.025	0.018
$\lvert g^T_{LR} \rvert$	0.036	0.021	0.012
$\lvert g^S_{RL} \rvert$	0.424	0.412	0.412
$\lvert g^V_{RL} \rvert$	0.110	0.104	0.103
$\lvert g^T_{RL} \rvert$	0.122	0.104	0.103
$\lvert g^S_{LL} \rvert$	0.550	0.550	0.550



Left-Right Symmetric Models

$$W_L = \cos\zeta W_1 + \sin\zeta W_2 \qquad W_R = e^{i\omega}(-\sin\zeta W_1 + \cos\zeta W_2)$$

- $W_{R(L)}$ mediate $V + A(V - A)$ currents[4]
- ζ is the mixing angle between W_1 and W_2
- ω CP violating phase

Decay Parameters in This Model

$$\rho \simeq \frac{3}{4}\left(1 - 2\left(\frac{g_R}{g_L}\right)^2\zeta^2\right), \delta \equiv \frac{3}{4}, \ \xi \simeq 1 - 2\left(\left(\frac{g_R m_1}{g_L m_2}\right)^4 + \left(\frac{g_R}{g_L}\right)^2\zeta^2\right)$$

$$1 - \frac{P_\mu^\pi \xi\delta}{\rho} \simeq 2\frac{g_R^4 m_1^4}{g_L^4 m_2^4}\left(1 + \frac{\cos^2\theta_1^R}{\cos^2\theta_1^L}\right) + 2\frac{g_R^2}{g_L^2}\zeta^2 + 4\frac{g_R^3 m_1^2 \cos\theta_1^R}{g_L^3 m_2^2 \cos\theta_1^L}\zeta\cos(\alpha+\omega)$$

[4] P. Herczeg, **PRD** 34,3449,(1986)

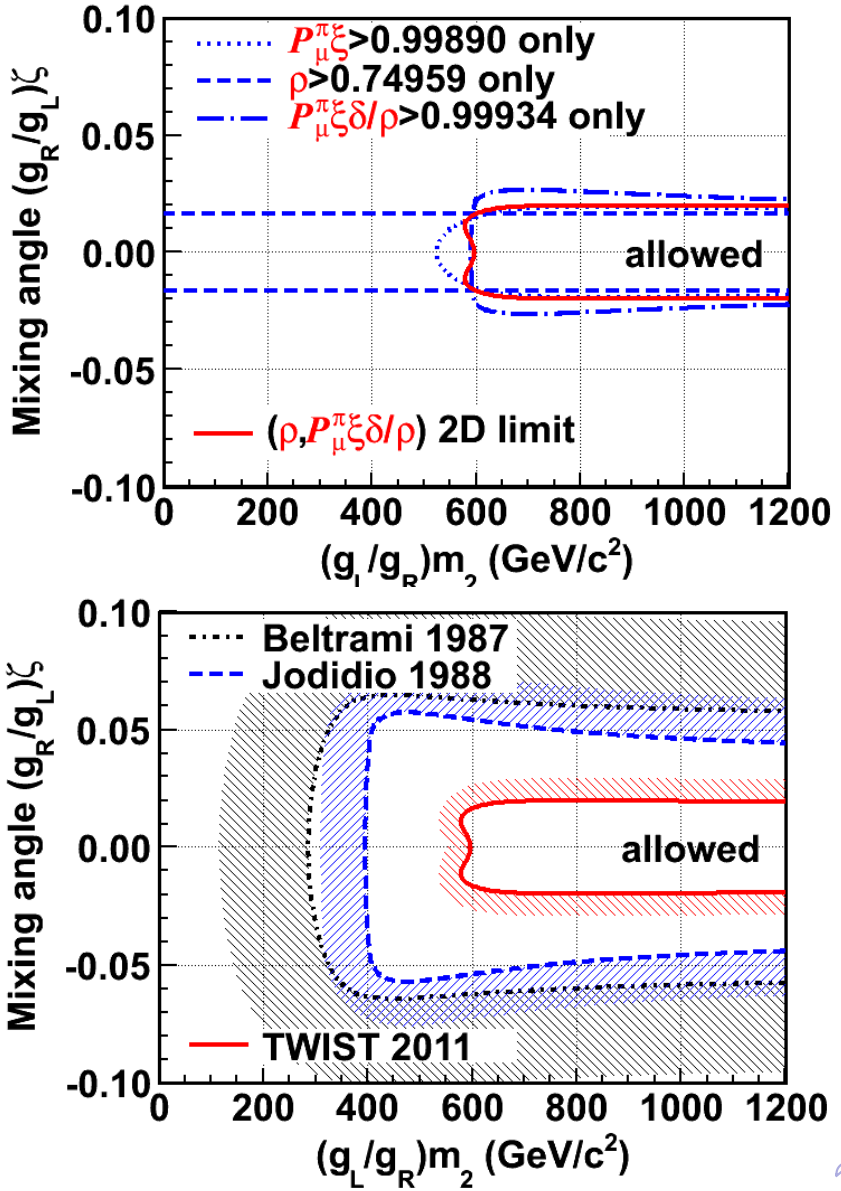
Left-Right Symmetric Models

90% Confidence limits

- $|\frac{g_R}{g_L}\zeta| < 0.02$
- $|\frac{g_R}{g_L}|m_2 > 578$ GeV/c
- Set using a combination of 90% limits on ρ, and $P_\mu \xi\delta/\rho$

Generalized approach to model

- No assumption of model parameters
- W_2 Direct searches assume $g_R = g_L, \omega = 0$



Conclusions

- Order of magnitude improvement in precision of decay parameters has been completed by the TWIST experiment.

$$\begin{aligned} \rho &= 0.74997 \pm 0.00012 \pm 0.00023 \\ \delta &= 0.75049 \pm 0.00021 \pm 0.00027 \\ P_\mu \xi &= 1.00084 \pm 0.00029 ^{+0.00165}_{-0.00063} \\ P_\mu \xi \delta / \rho &= 1.00179 ^{+0.00156}_{-0.00071} \\ &> 0.99909 \text{ (90\% C.L.)} \end{aligned}$$

- $P_\mu \xi \delta / \rho > 1$ has been investigated; no problem with analysis has been identified.
- Limits on weak coupling constants And lift-right symmetric models have been improved.

Thank you

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