Measurements of the Muon Decay Spectrum from *TWIST*

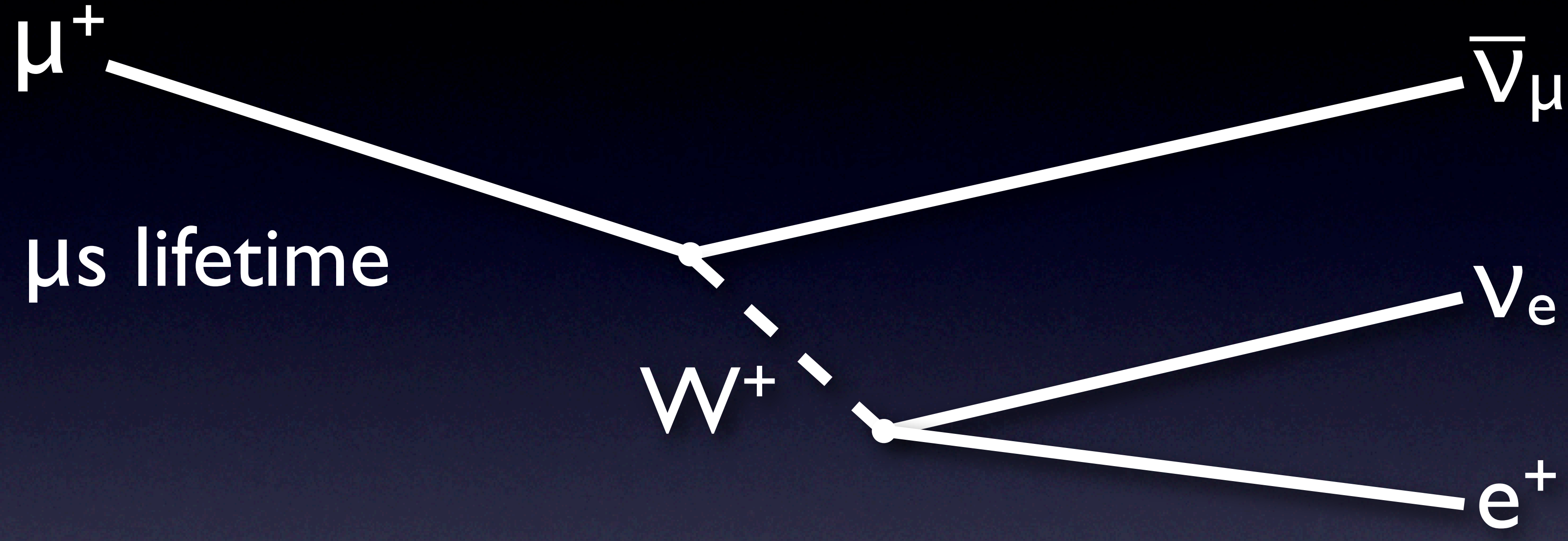
Robert MacDonald, University of Alberta
for the *TWIST* collaboration

- Physics of Muon Decay
- *TWIST* experiment
- *TWIST* results to date
- Implications

CAP Congress, 17-20 June 2007

High precision experiment with ambitious goals -- as much as an order of magnitude improvement over previous decay spectrum measurements.

Muon Decay



2 μs lifetime

- EM radiative corrections calculable
- Strong interactions are at < 1e-6 level

Very clean environment for studying the weak interaction.

Radiative Corrections calculated to next-to-leading log alpha^2.

Muons really have only one decay mode plus RCs. Simplifies data!

“4-fermion” interaction at muon decay energies: simplifies interpretation!

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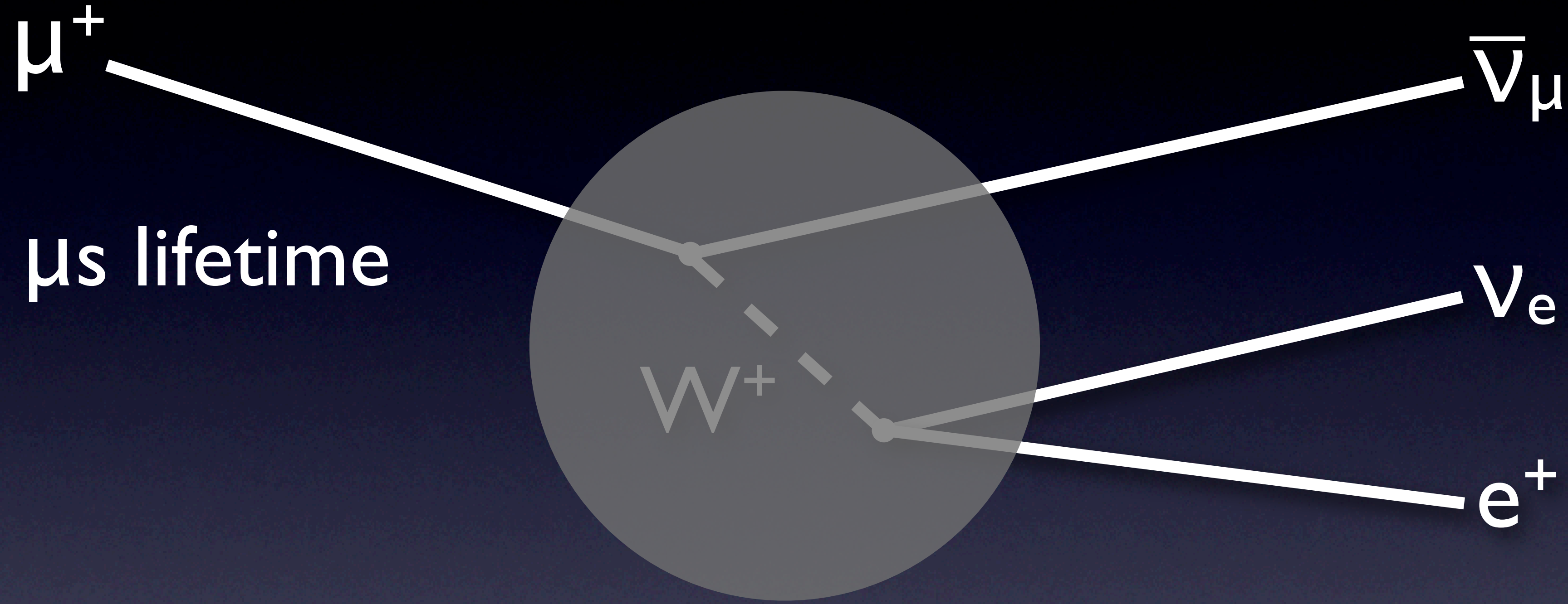

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Decay Matrix Element

$$M = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\epsilon=L,R \\ m=L,R \\ \kappa=S,V,T}} g^{\kappa}_{\epsilon m} \langle \psi_{e_\epsilon} | \Gamma^{\kappa} | \psi_{\nu_e} \rangle \langle \psi_{\nu_\mu} | \Gamma_{\kappa} | \psi_{\mu_m} \rangle$$

Notation of Fetcher & Gerber (PDG).

Most general local, derivative-free four fermion interaction.

Each interaction has its own coupling constant.

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In Standard Model (“V-A”):

$$g^{V}_{LL} = 1$$

$$g^{\kappa}_{\epsilon m} = 0 \quad \text{otherwise}$$

Notation of Fetcher & Gerber (PDG).

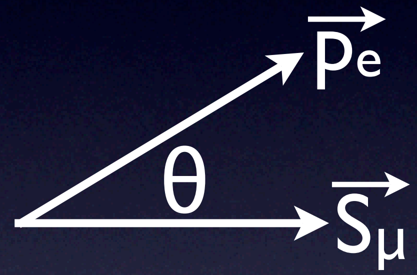
Most general local, derivative-free four fermion interaction.

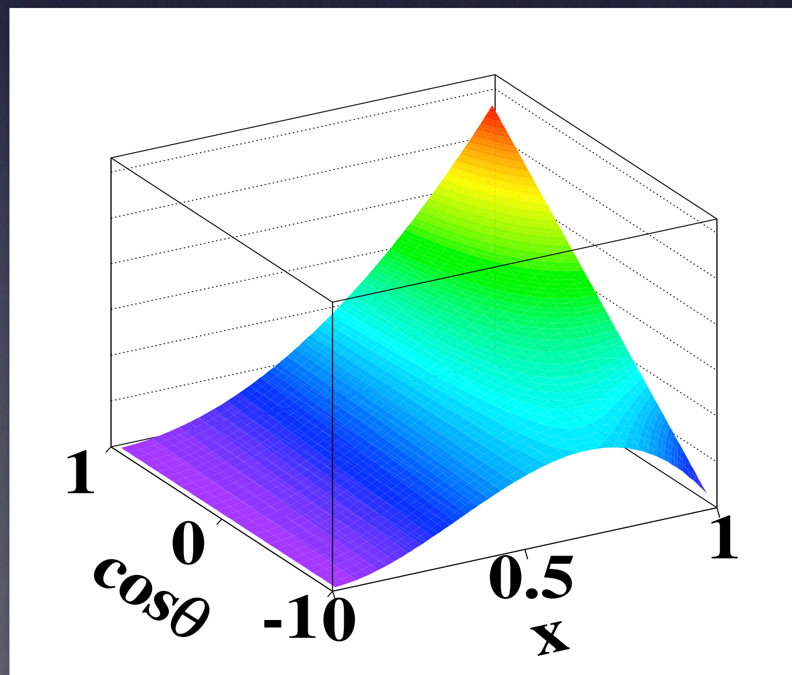
Each interaction has its own coupling constant.

Decay ("Michel") Spectrum

$$\frac{d^2\Gamma}{dx\,d(\cos\theta)} \propto F_{IS}(x;\rho,\eta) + F_{AS}(x;\delta)P_\mu\xi\,\cos\theta$$

$$x = \frac{E}{E_{\max}}$$





Decay spectrum by Michel, Kinoshita & Sirlin (ignoring RCs)

The Michel Parameters are bilinear combinations of the coupling constants. (See PDG.)
theta = theta_spin!

TWIST is insensitive to eta, at least directly. And note that xi appears as PmuXi! :(

TWIST plans a 10x improvement, except eta. Already published 2-3x.

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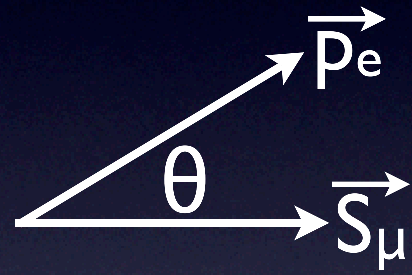
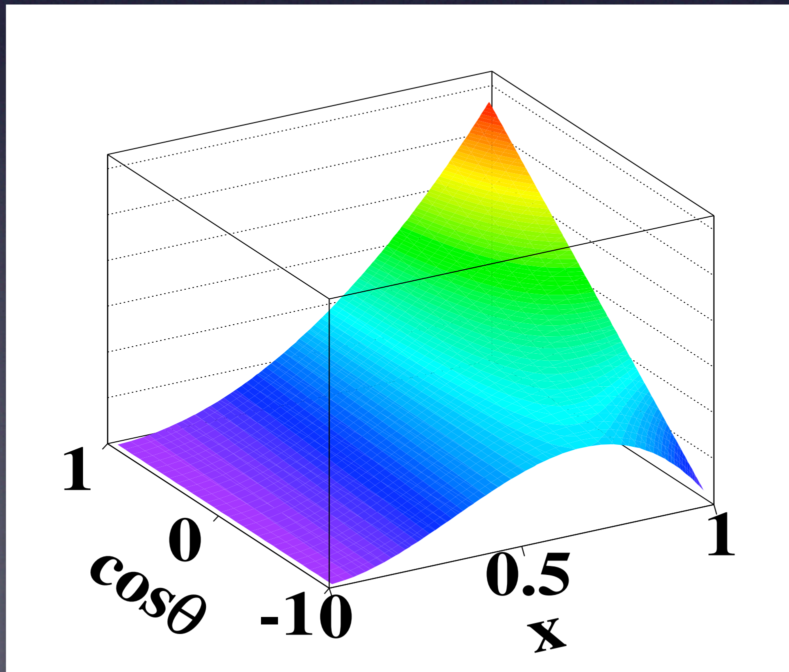


	Pre-TWIST	SM
ρ	0.7518 ± 0.0026	0.75
η	-0.007 ± 0.013	0
$P_\mu\xi$	1.0027 ± 0.0085	1
δ	0.7486 ± 0.0038	0.75



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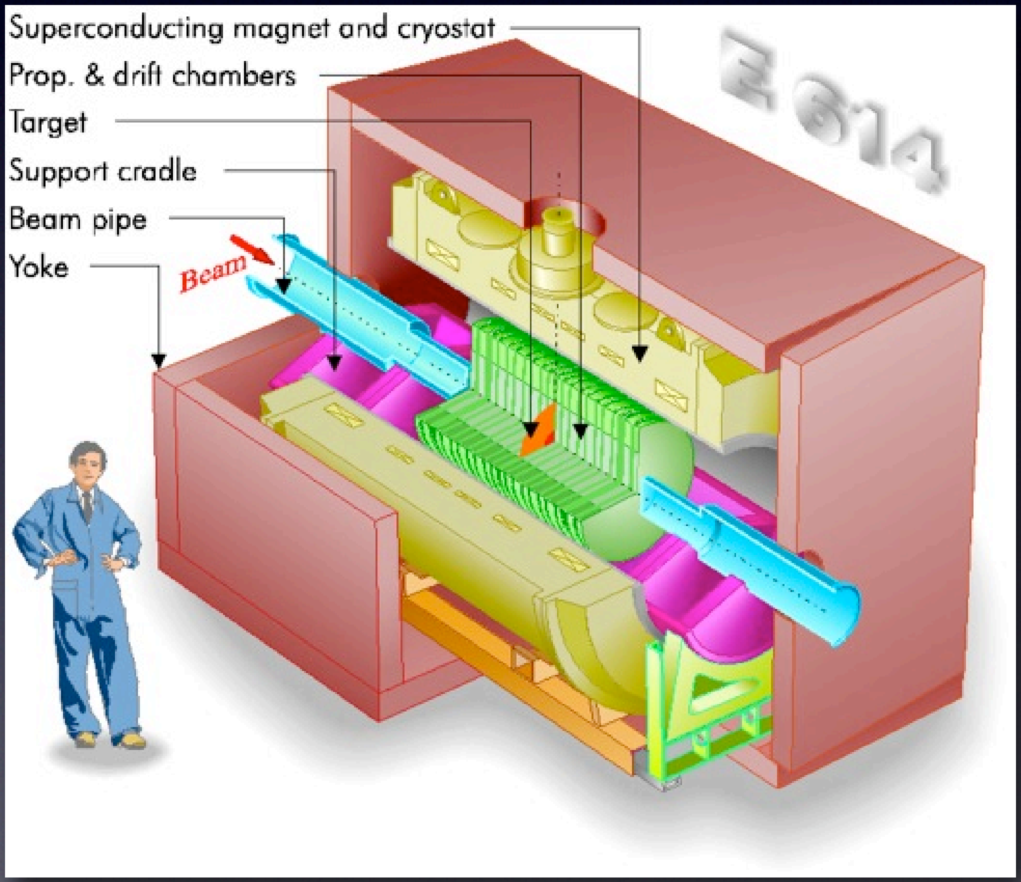
The *TWIST* Experiment

TRIUMF Weak Interaction Symmetry Test

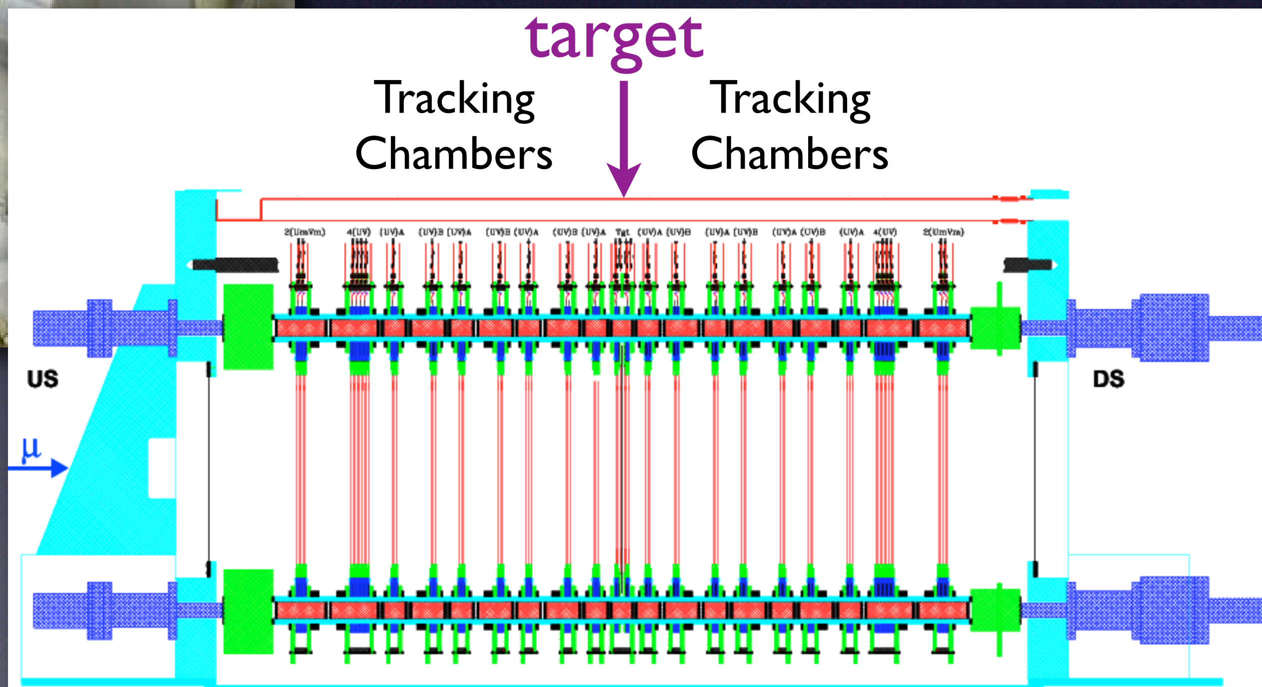


Trigger: thin scintillator. (Unbiased!)

Muons enter field in vacuum, slow in chambers and stop in target.

Magnetic field: maintains mu+ polarization; allows e+ momentum measurement

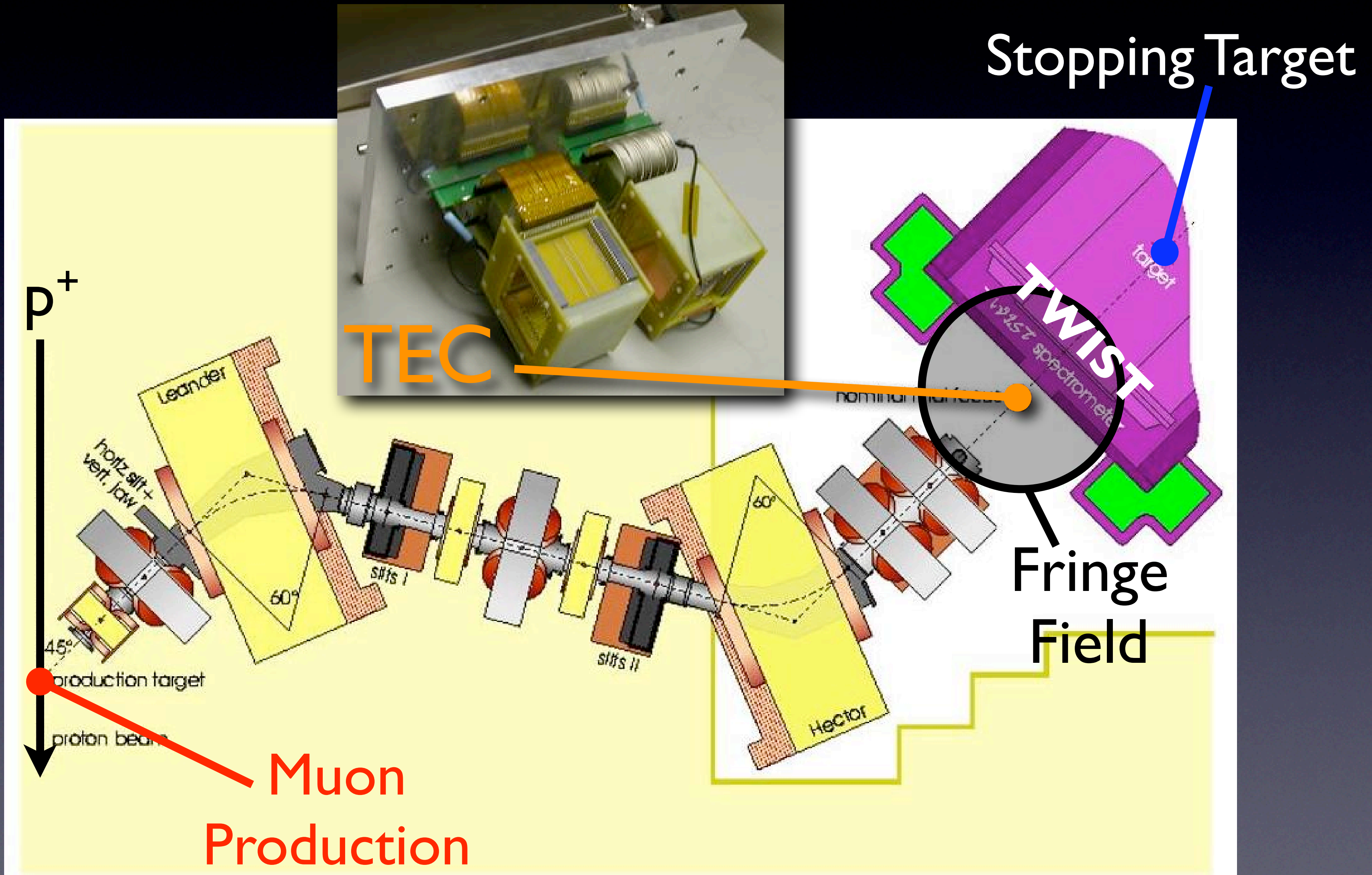
The *TWIST* Detector



Simple design (incl. planar chambers)

Symmetric, high-precision construction

Muon Beam Monitor



Pions decay at rest --> polarized muons

Muon beam emittance in fringe field very important to polarization.

TEC located at our nominal final focus, just entering the solenoid fringe field.
X and Y chambers measure beam profile in position and angle.

Very low mass.

Take data with and without TEC.

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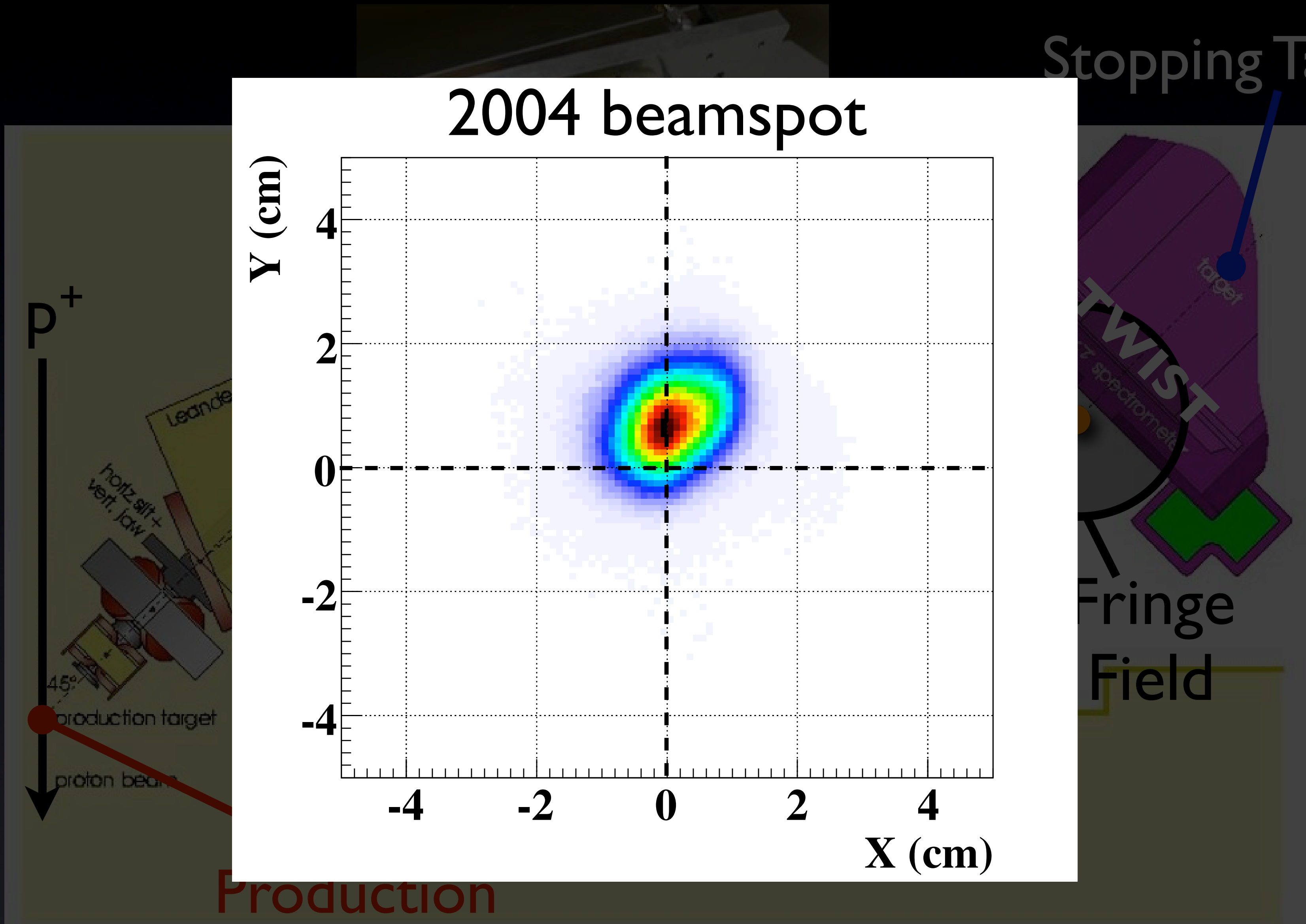

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Blind Analysis

Can study consistency without losing blindness.

Simulation includes detector response.
"Data vs MC" comparison cancels many systematics and spectrum distortions.
- e.g. Delta ray rate.

Main systematics come from differences between MC and reality:
- Input info (chamber drift times, beam profiles, etc)
- Physics processes

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Experimental
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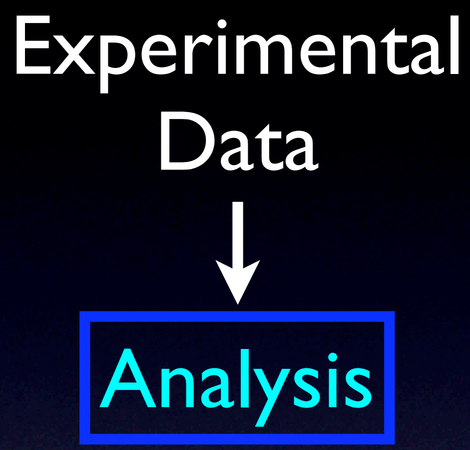

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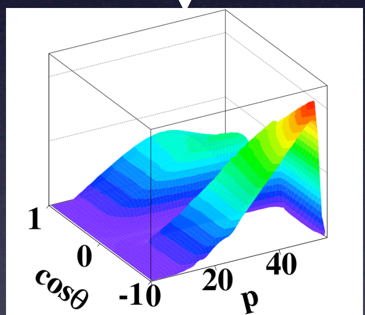

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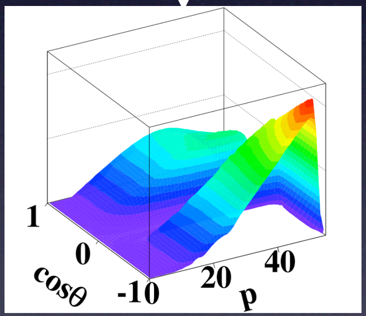

Geant3 Simulation

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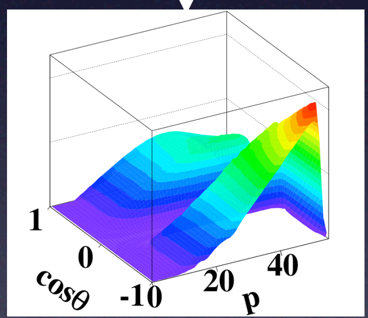

$\rho_{MC}, \delta_{MC}, \xi_{MC}$ → Geant3 Simulation

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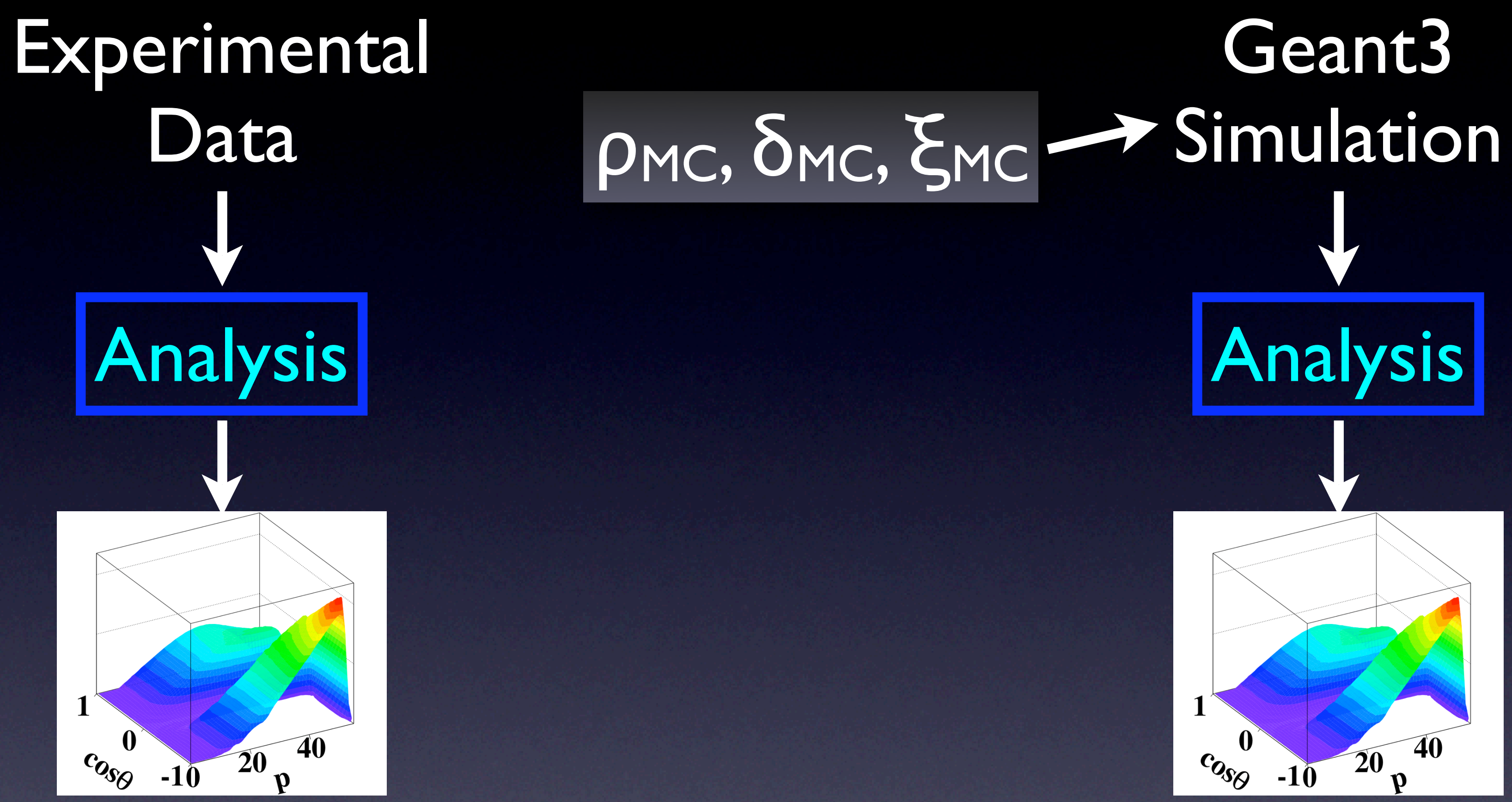

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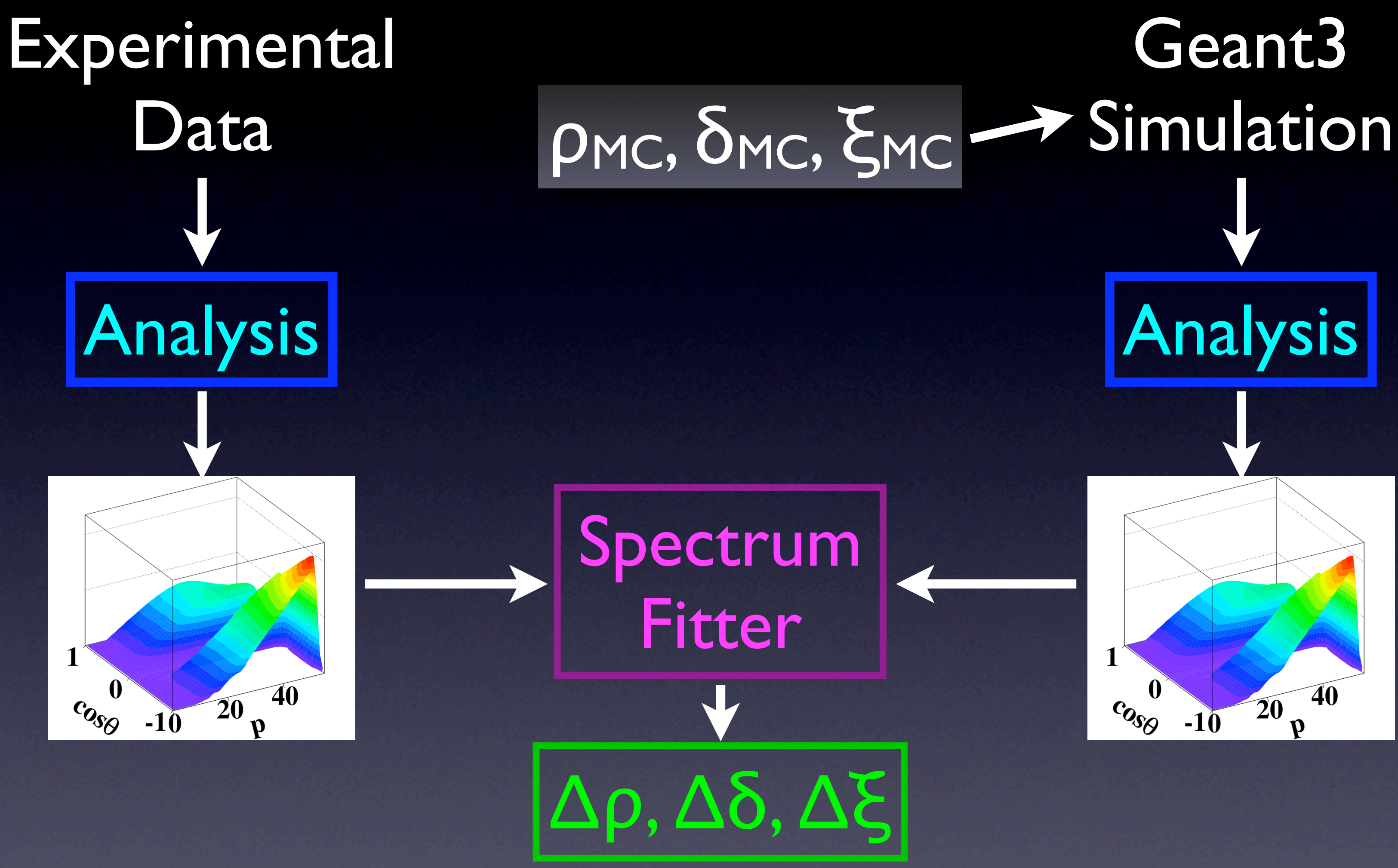

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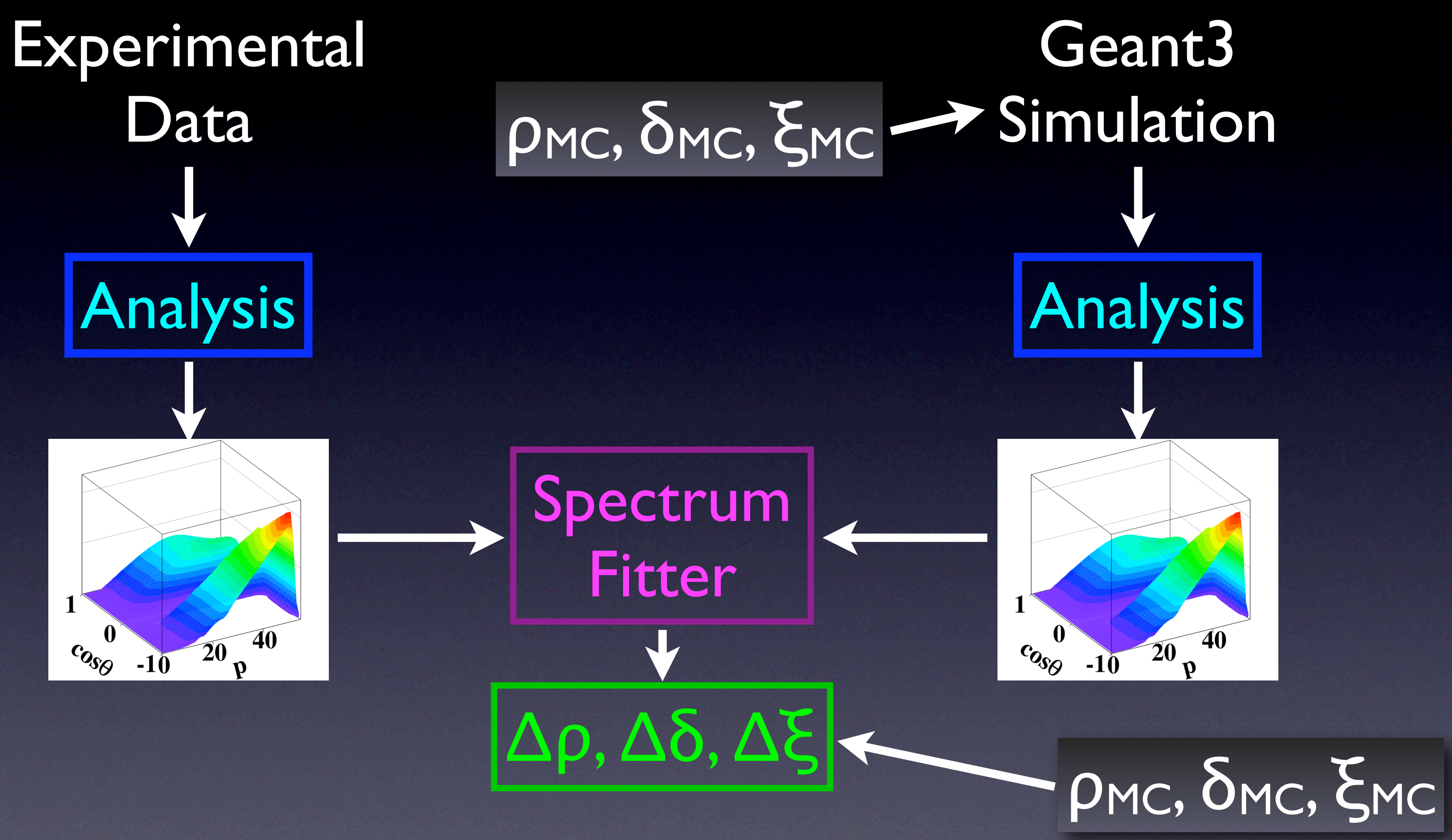

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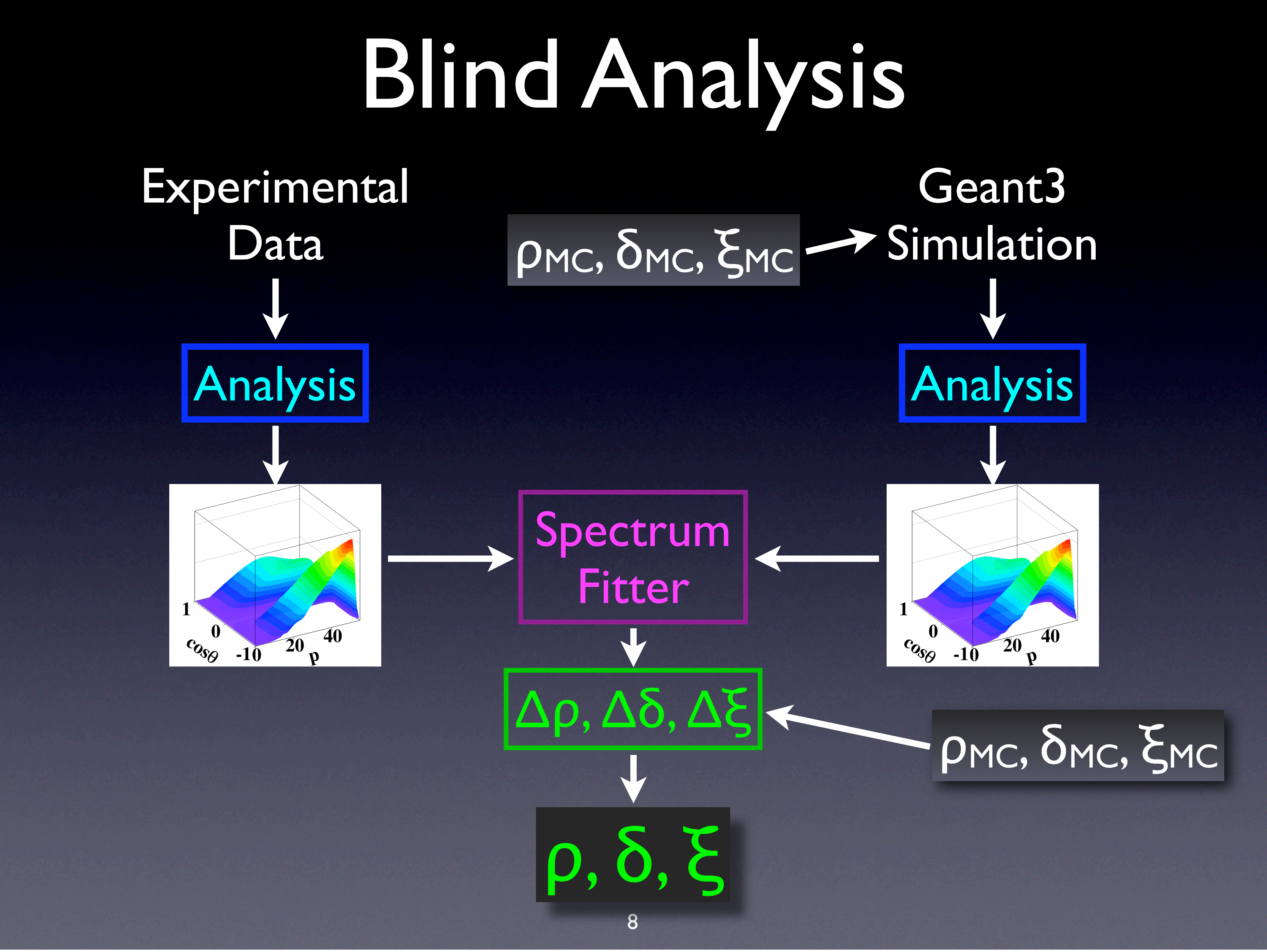

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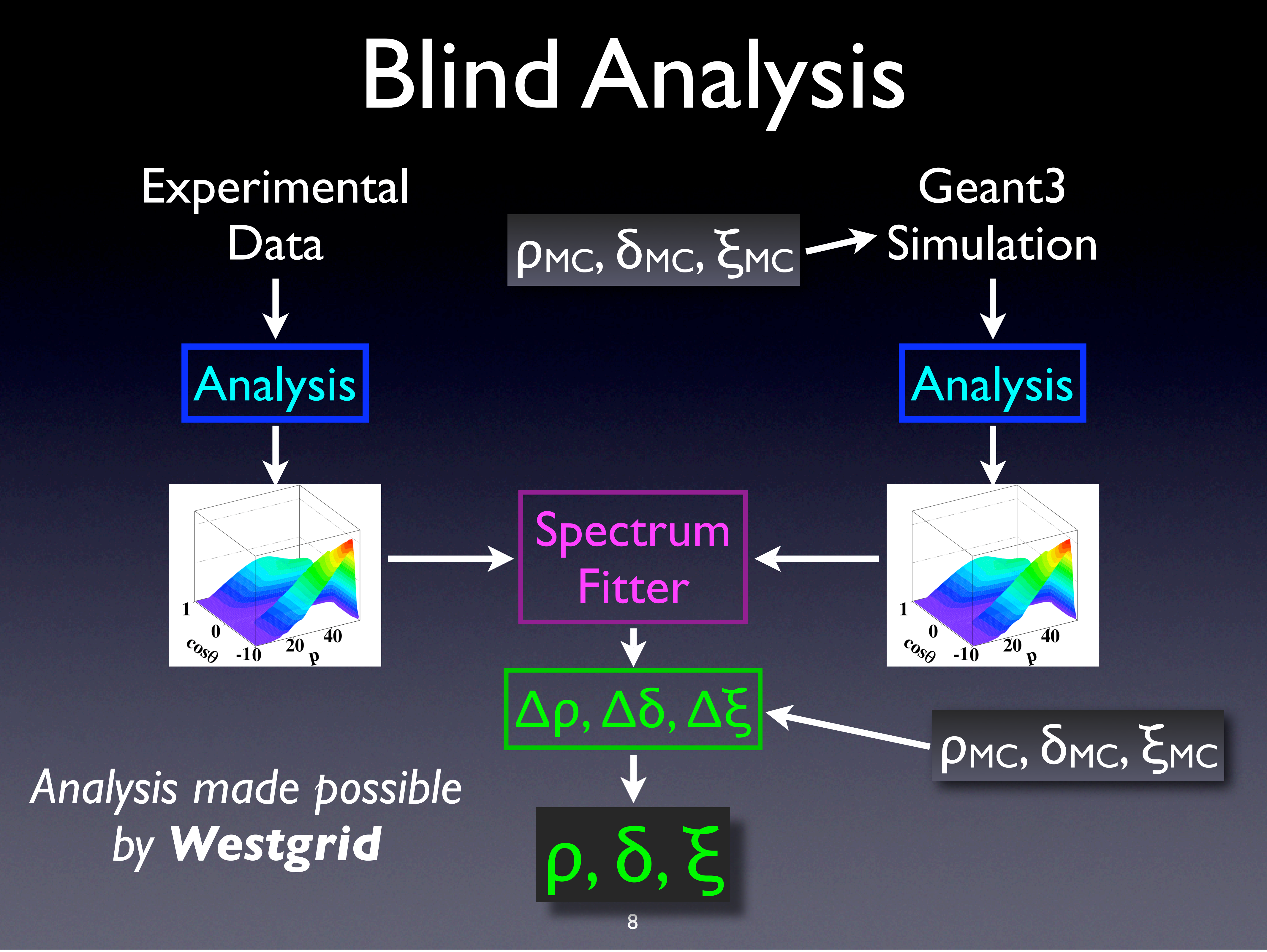

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Spectrum Fitter

$$\frac{d^2\Gamma}{dx\, d(\cos\theta_s)} \propto F_{IS}(x;\rho,\eta) + F_{AS}(x;\delta) P_\mu \xi \cos\theta$$

Michel Spectrum is linear in these parameters. (Very handy!)
- xi and delta appear as a product.

Derivative spectra are fully simulated and analyzed just like the MC and data spectra.

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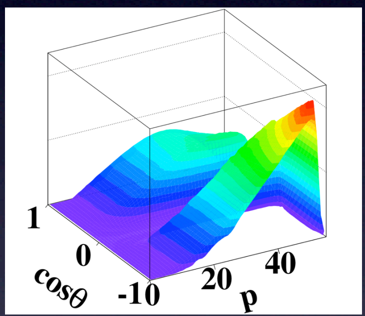
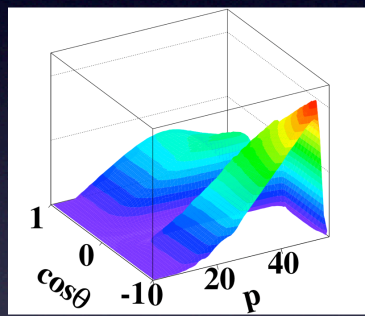
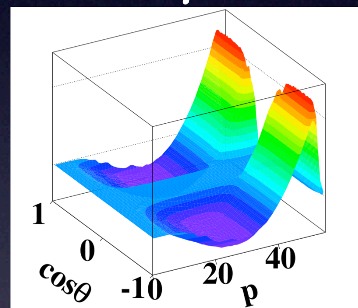
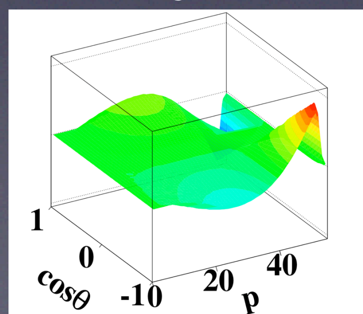
$$N(\alpha_{\mathrm{Data}}) = N(\alpha_{\mathrm{MC}}) + \frac{\partial N}{\partial\rho}\Delta\rho$$

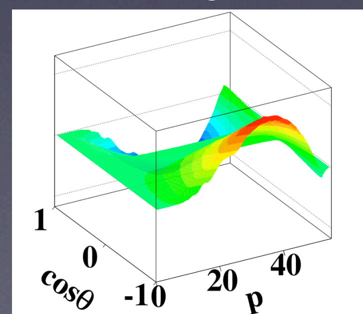






$$+ \frac{\partial N}{\partial\xi\delta}\Delta P_\mu\xi\delta + \frac{\partial N}{\partial\xi}\Delta P_\mu\xi$$





$\alpha = \{\rho, \delta, \xi\}$

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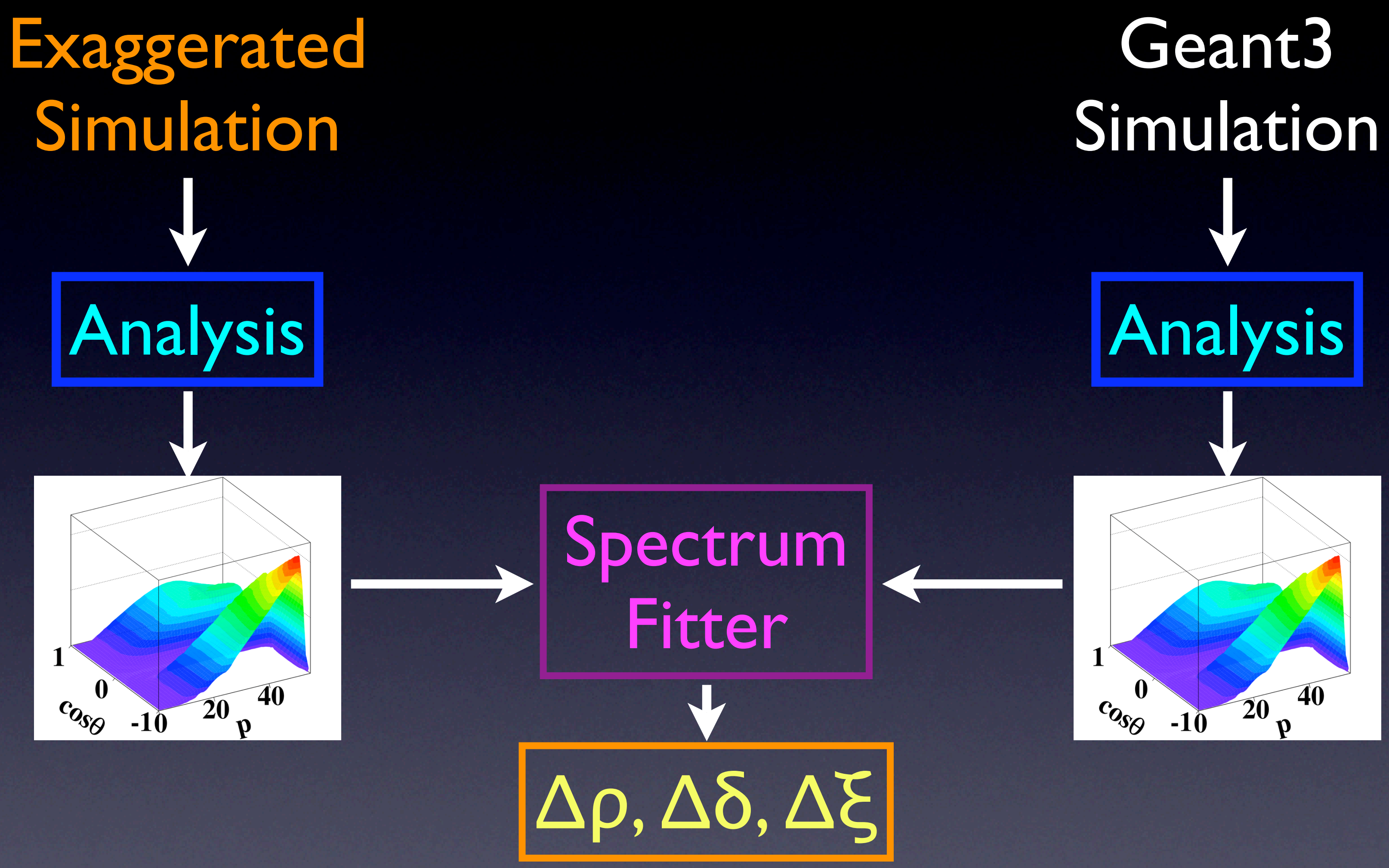
Determining Systematics



Black Box values don’t matter here.

Can also use the same simulation but change the analysis (e.g. alignment, magnetic field).

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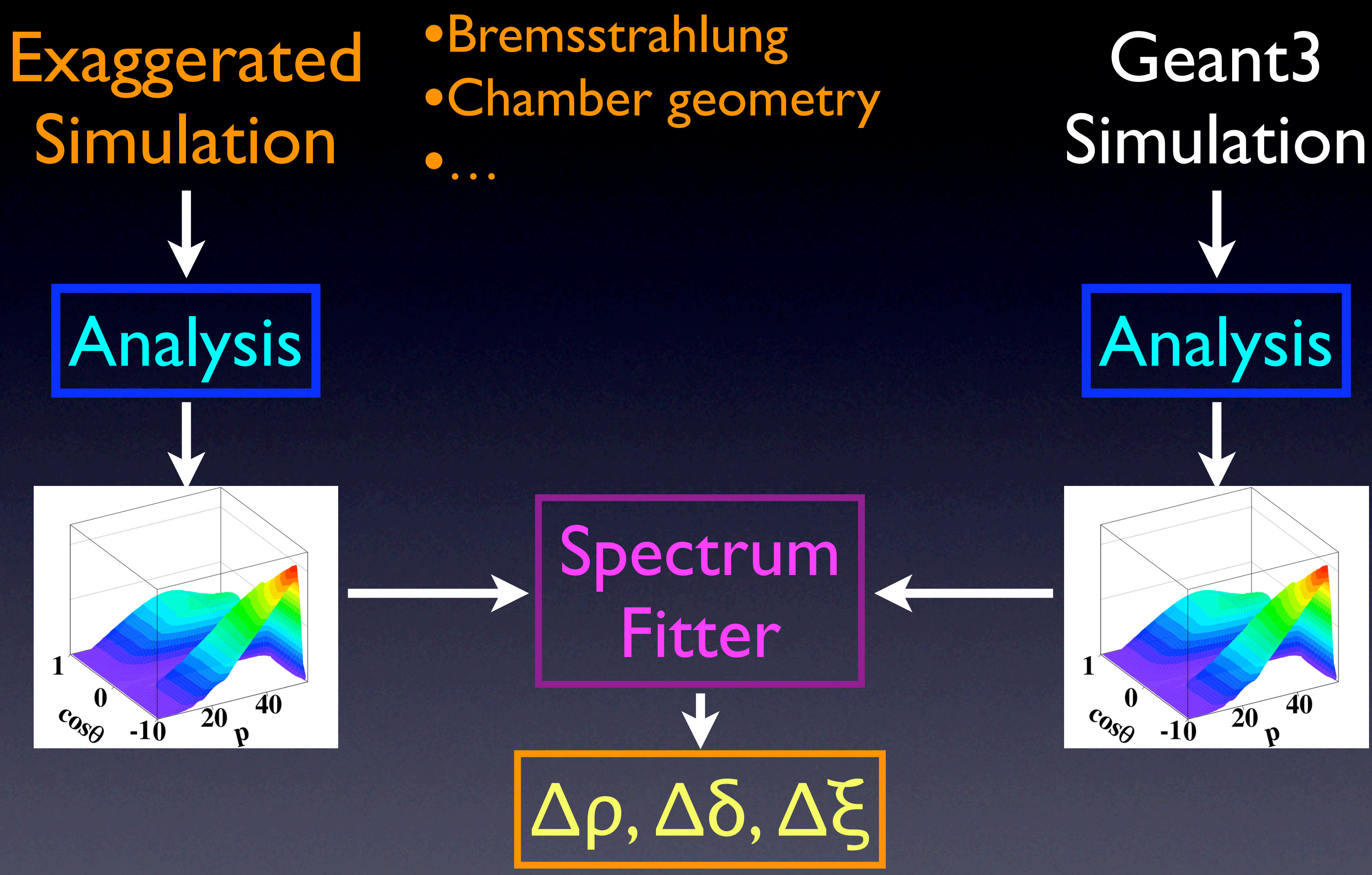

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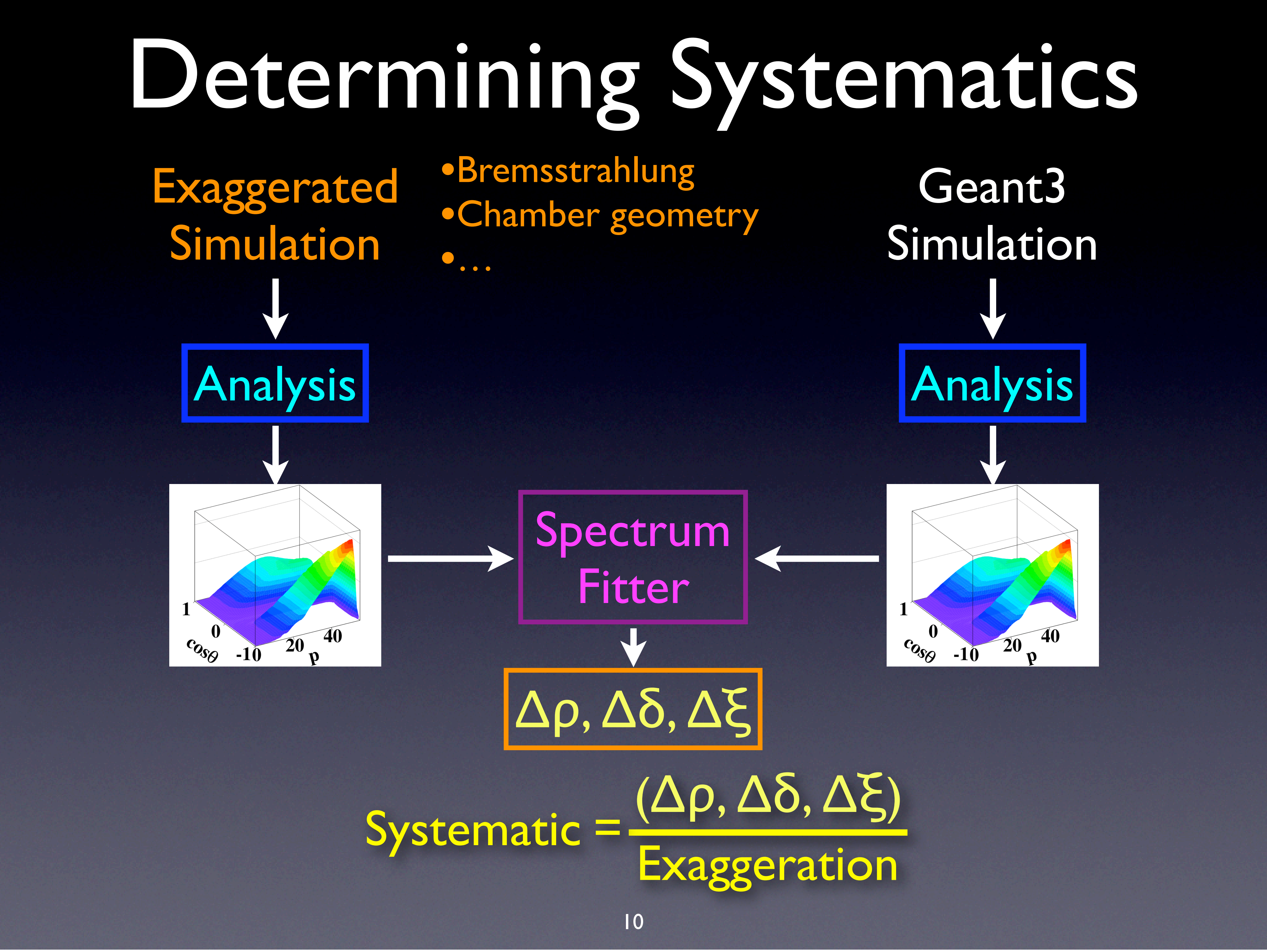

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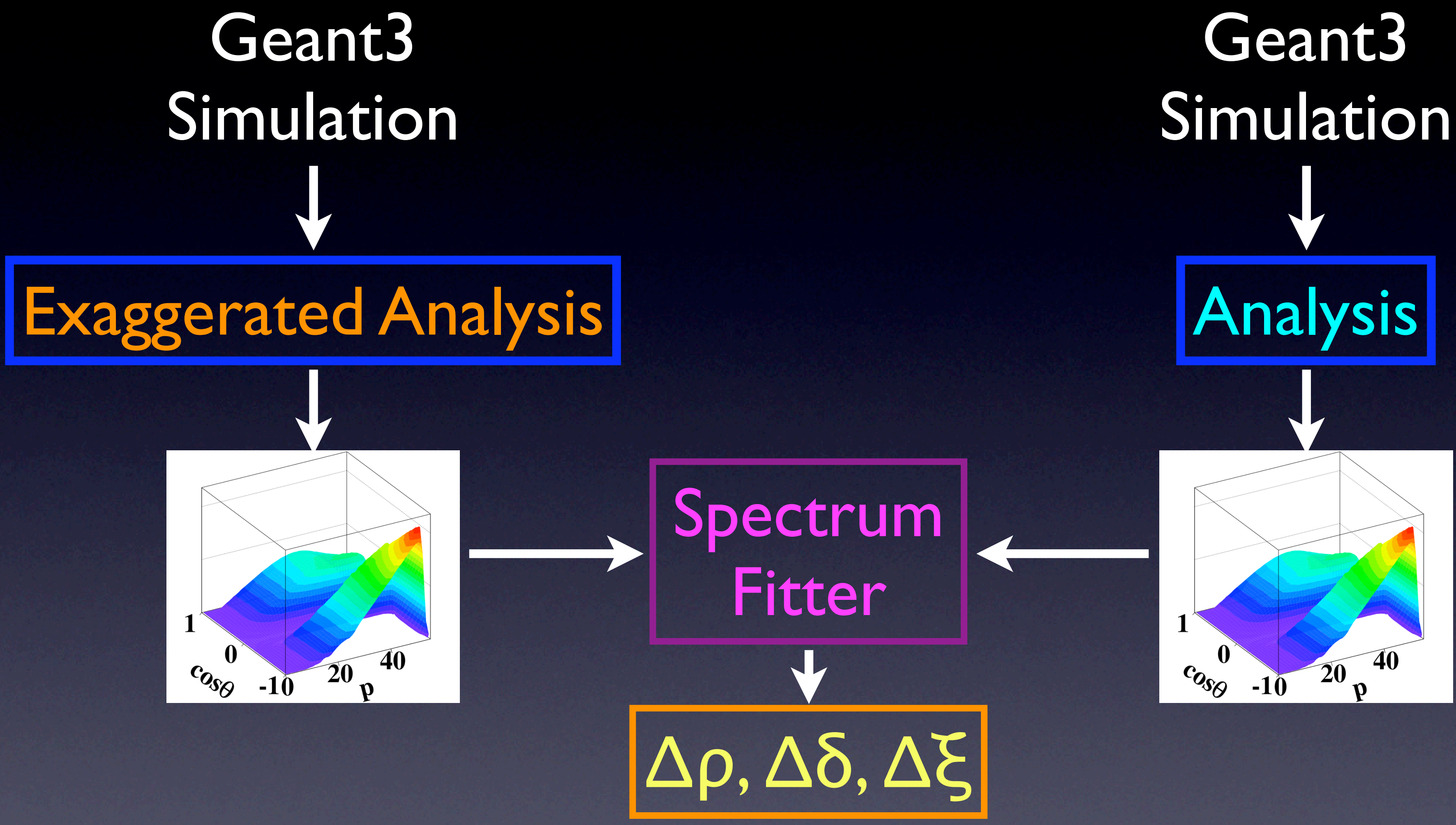

$$\text{Systematic} = \frac{(\Delta\rho, \Delta\delta, \Delta\xi)}{\text{Exaggeration}}$$

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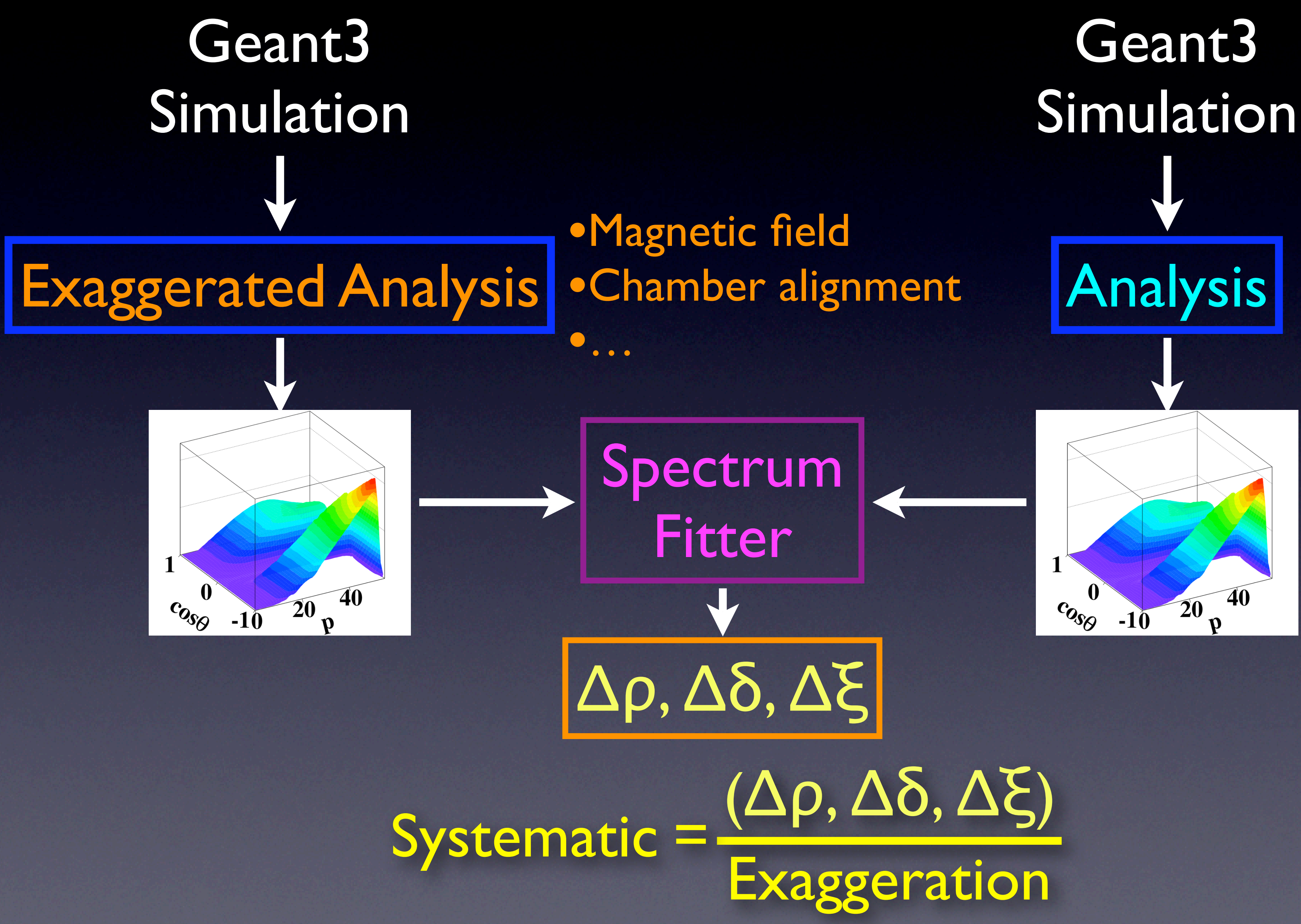

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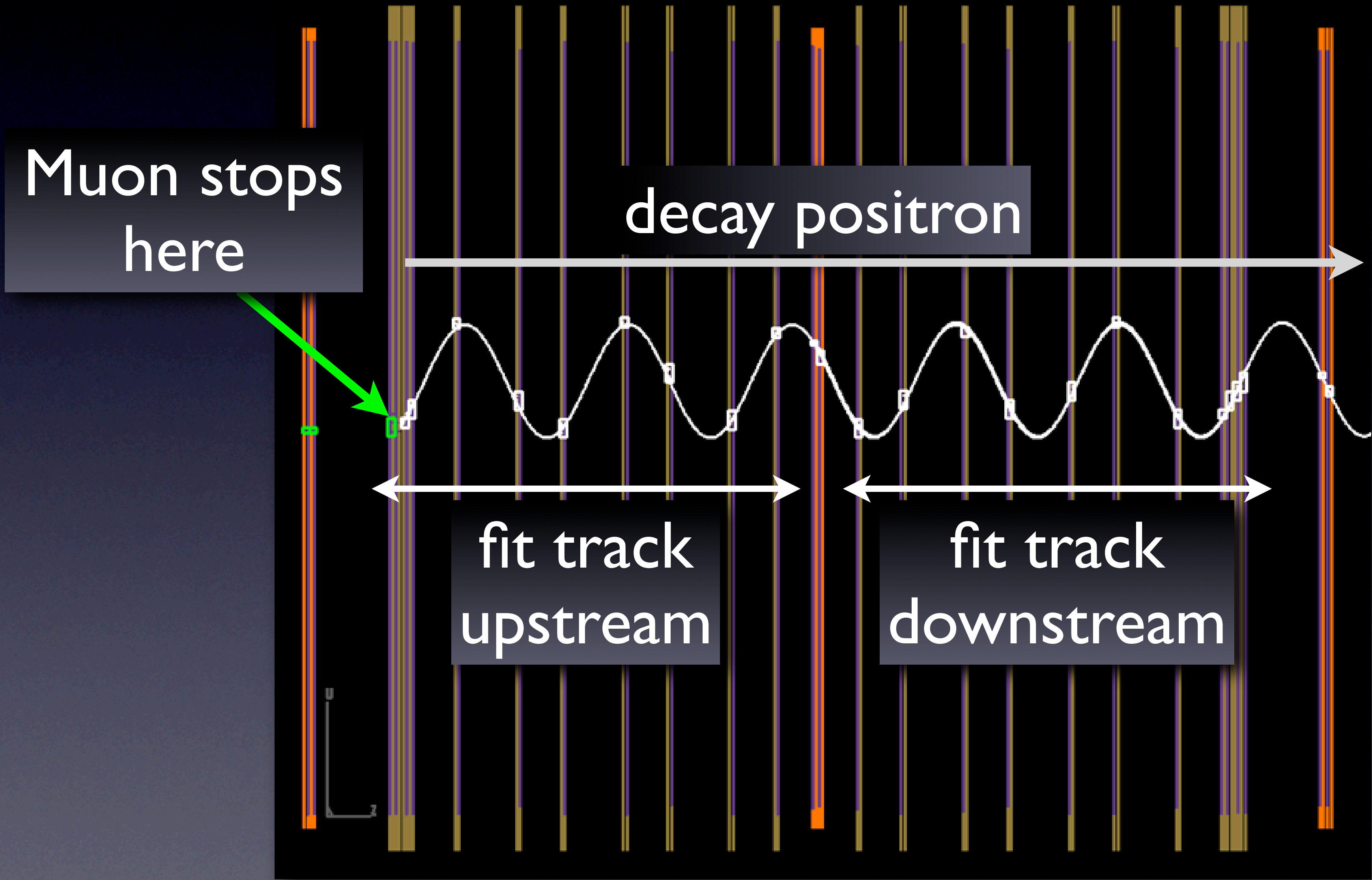
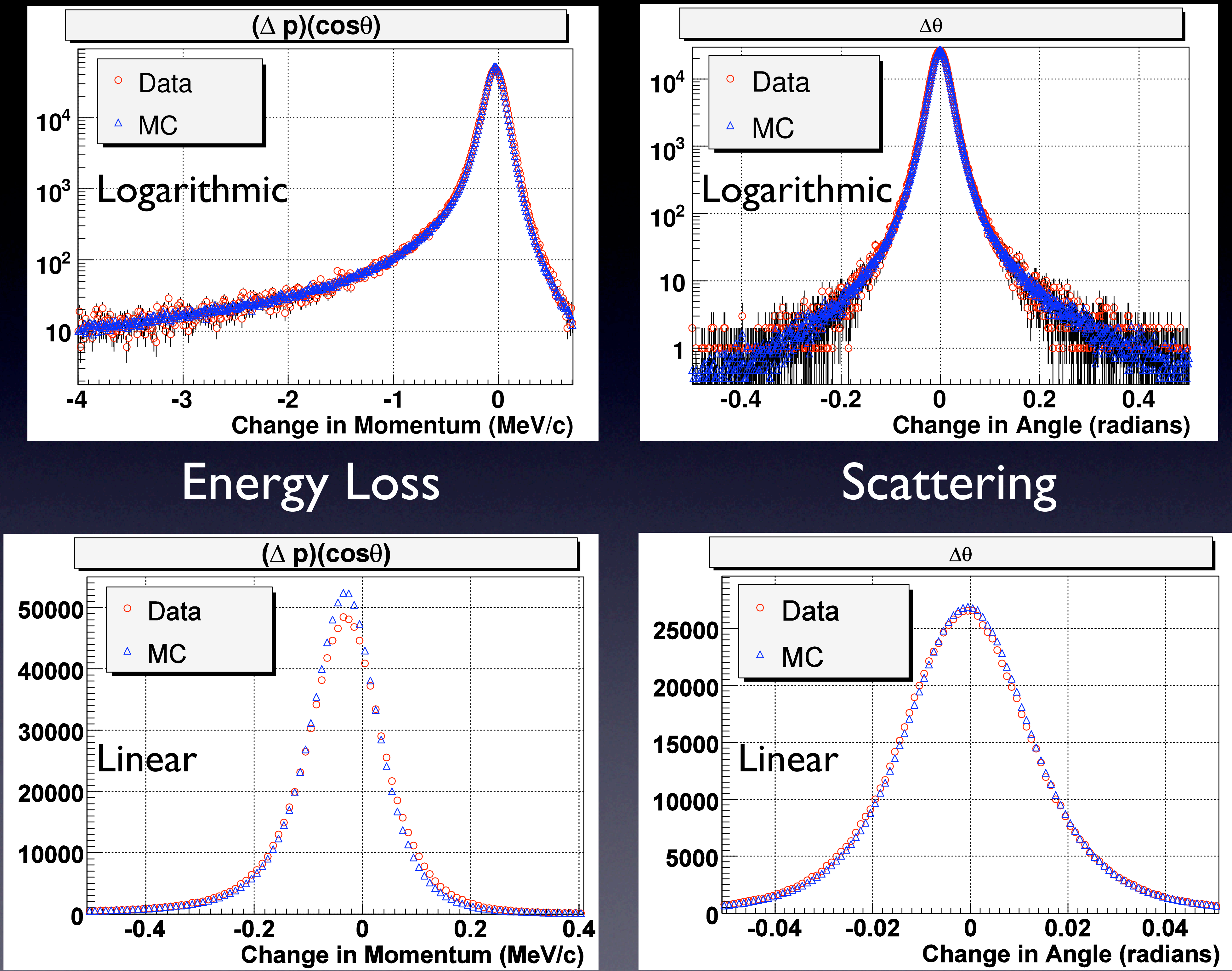
Verifying our Simulation



Do this in data and simulation -- direct comparison!

Difference between the two fits: physics processes (various eloss & scattering), resolution



Top and bottom are lin/log views.

TWIST Monte Carlo provides excellent description of the hard interaction physics.

Multiple scattering well reproduced.

Small differences seen in dE/dx (few keV).

Systematics

Units of 0.0001

ρ *Phys. Rev. Lett.* ***94****, 101805 (2005)*

	TWIST published	current (preliminary)
Total	9.3 syst 4.4 stat	5.4 syst 1.4 stat

δ *Phys. Rev. D* ***71****, 071101(R) (2005)*

	TWIST published	current (preliminary)
Total	11.2 syst 6.6 stat	6.4 syst 2.4 stat

$P_\mu \xi$ *Phys. Rev. D* ***74****, 072007 (2006)*

	TWIST published
Total Direct	38.0 syst 6.0 stat
Indirect uses $P_\mu \xi \delta / \rho$ measurement	40 (90% CL)

Publications linked from our website.
Totals are 2-3x better than pre-TWIST uncertainties!
And these are _current_ leading systematics, and current expectations;
final goals are another factor of two better.

Currently focussing on rho/delta improvements, and taking new data etc.

Theory is also an important systematic now -- 1-3e-4! (next-to-leading log alpha^2)

TWIST is systematics-limited -- polarized muons are abundant at TRIUMF.

Systematics

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ρ *Phys. Rev. Lett.* **94**, *101805 (2005)*

Systematic	TWIST published	current (preliminary)
positron interactions	4.6	2.0
chamber response	5.1	3.2
momentum calibration	2.0	1.1

δ *Phys. Rev. D* **71**, *071101(R) (2005)*

Systematic	TWIST published	current (preliminary)
positron interactions	5.5	1.6
chamber response	5.6	5.2
momentum calibration	2.9	2.2

$P_\mu \xi$ *Phys. Rev. D* **74**, *072007 (2006)*

Systematic	TWIST published
fringe field depolarization	34.0
stopping target depolarization	12.0
chamber response	10.0
positron interactions	3.0
momentum calibration	2.0

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Improving our Systematics

positron interactions	precision target geometry, improved chamber spacing, investigating MC tuning
momentum calibration	new calibration techniques
chamber response	online monitoring, increased instrumentation, drift time measurements
fringe field depolarization	beam monitoring with TEC, beamline alignment & steering
stopping target depolarization	aluminum & silver targets, depolarization studies

these are just examples...

Includes improvements since publication data (taken 2002), and ongoing work.

Limits on Weak Couplings

Recent muon decay global analysis (90% C.L.), including *TWIST* ρ and δ

$\lvert g^S_{RR}\rvert < 0.066(0.067)$	$\lvert g^V_{RR}\rvert < 0.033(0.034)$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.125(0.088)$	$\lvert g^V_{LR}\rvert < 0.060(0.036)$	$\lvert g^T_{LR}\rvert < 0.036(0.025)$
$\lvert g^S_{RL}\rvert < 0.424(0.417)$	$\lvert g^V_{RL}\rvert < 0.110(0.104)$	$\lvert g^T_{RL}\rvert < 0.122(0.104)$
$\lvert g^S_{LL}\rvert < 0.550(0.550)$	$\lvert g^V_{LL}\rvert > 0.960(0.960)$	$\lvert g^T_{LL}\rvert \equiv 0$

Phys. Rev. D ***72**, 073002 (2005)*

TWIST measurements have already made a big impact on weak coupling limits.

eta result includes PSI e+ polarization (Danneberg et al, PRL 94, 021802 (2005)).

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Phys. Rev. D ***72****, 073002 (2005)*

Global analysis also finds η = -0.0036 ± 0.0069, due in part to *TWIST* ρ and δ.

(c.f. pre-TWIST η = -0.007 ± 0.013)

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eta result includes PSI e+ polarization (Danneberg et al, PRL 94, 021802 (2005)).

Limits on Right-Handed Muon Decay

$$Q_R^\mu = \frac{1}{4}|g_{LR}^S|^2 + \frac{1}{4}|g_{RR}^S|^2 + |g_{LR}^V|^2 + |g_{RR}^V|^2 + 3|g_{LR}^T|^2$$

Global Analysis gives $Q_R^\mu < 0.007$

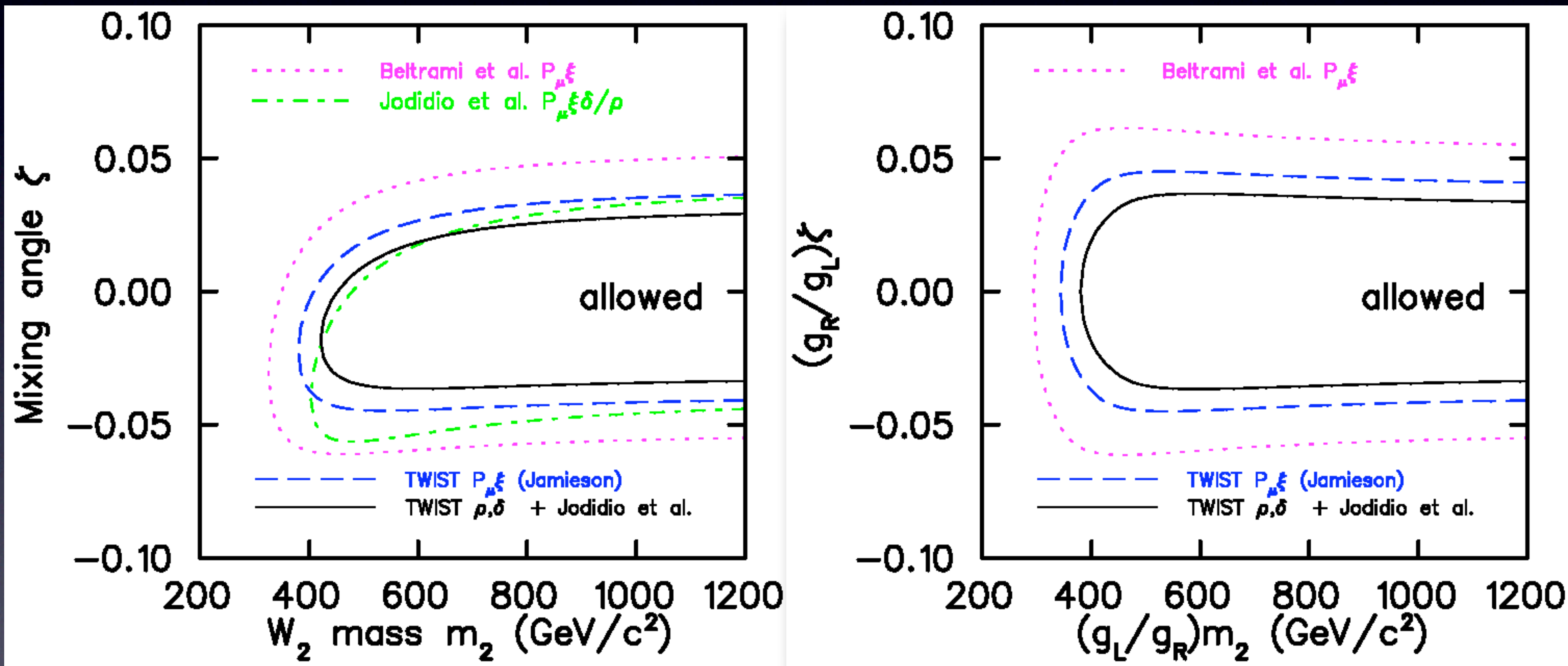
Pre-TWIST: $Q_R^\mu < 0.014$

QmuR: model-independent measure of right-handed muon decay probability.

Particular bilinear combination satisfies certain constraints and normalizations.

Limits on Left-Right Symmetric Models

“Manifest” LRS | General LRS



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

Example of applying TWIST results to a particular (popular) model.

Note the gR/gL in the right plot. “Manifest” means (in part) gR=gL.

TWIST limits similar in both plots.

The *TWIST* Experiment

Extremely high-precision measurements

Systematics well understood

Significant (x2!) improvements in Weak limits

On course for order of magnitude improvement

"Sometimes, if you pay real close attention to the pebbles
you find out about the ocean."
-Terry Pratchett

The *TWIST* Collaboration

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✧ also Saskatchewan
✾ deceased

http://twist.triumf.ca

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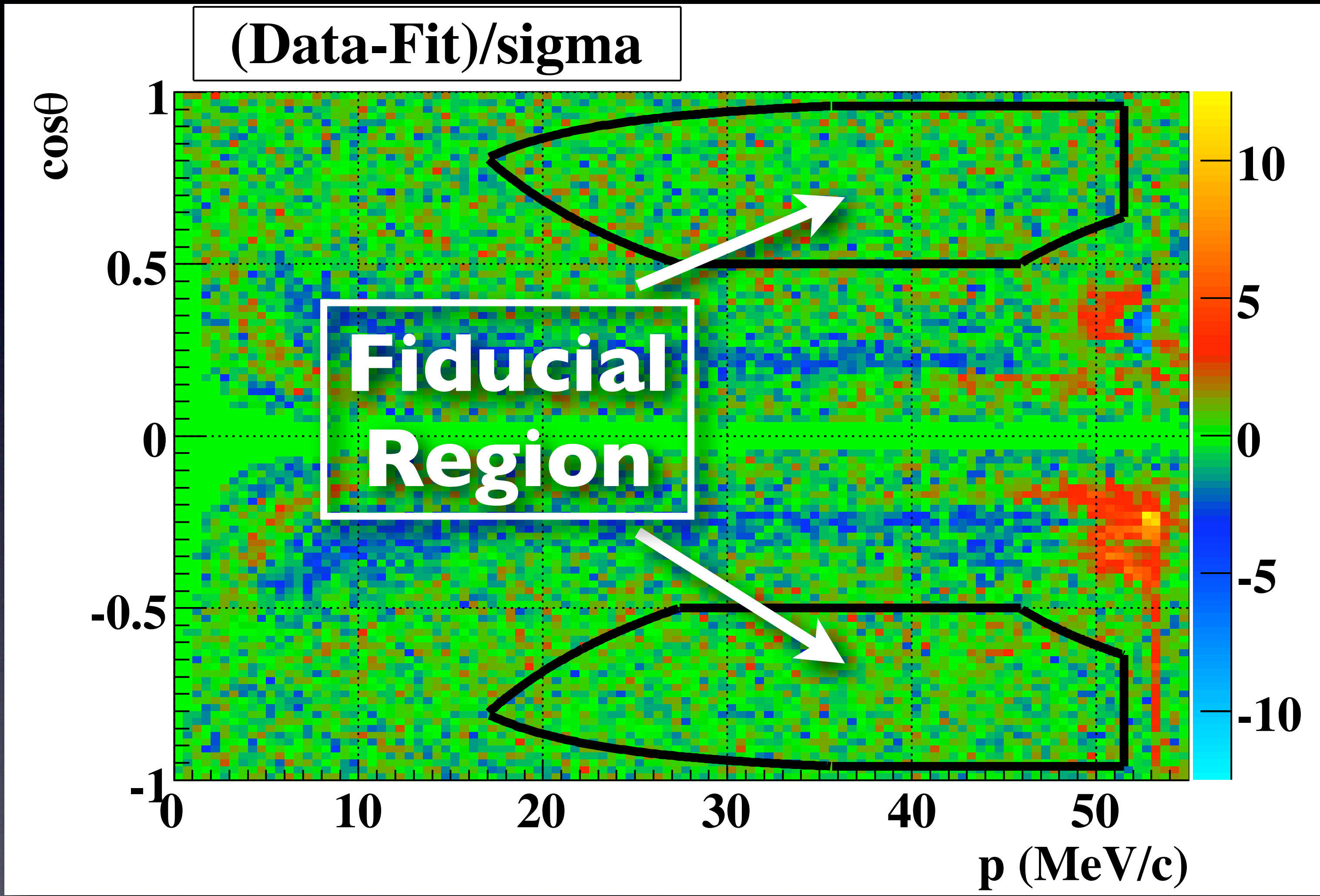
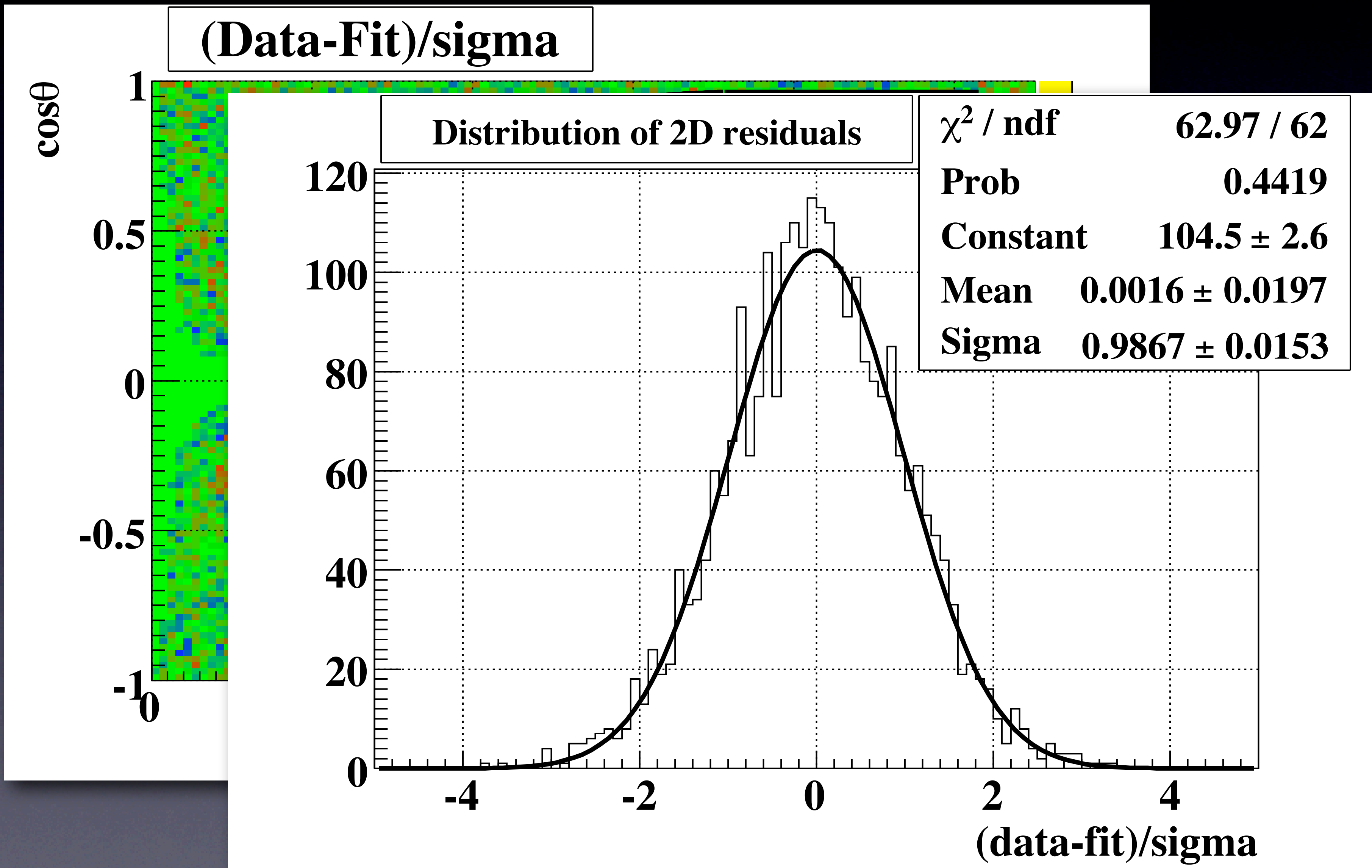
Fit Quality



(Data-Fit)/sigma
cosθ
1
0.5
0
-0.5
-1
0
10
20
30
40
50
p (MeV/c)
10
5
0
-5
-10
Fiducial Region

Fit Quality


(Data-Fit)/sigma
cosθ
1
0.5
0
-0.5
-1
0
Distribution of 2D residuals
χ2 / ndf 62.97 / 62
Prob 0.4419
Constant 104.5 ± 2.6
Mean 0.0016 ± 0.0197
Sigma 0.9867 ± 0.0153
120
100
80
60
40
20
0
-4
-2
0
2
4
(data-fit)/sigma