A Precision Measurement of the Charge Asymmetry of Semi-leptonic Kaon Decays behind a Regenerator at KTeV

G. Colin Bown

Enrico Fermi Institute

University of Chicago

4 May 2004

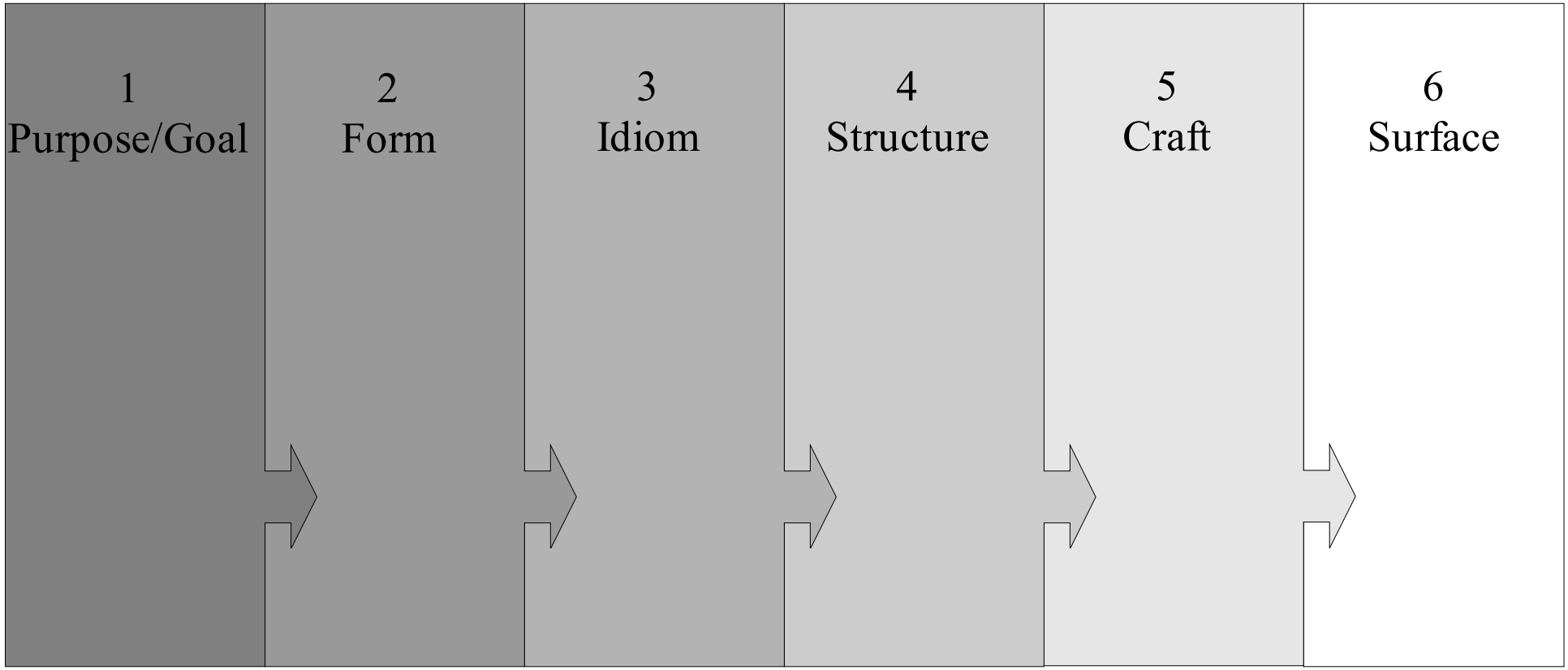
Ars longa,

vita brevis.

My Comic Art?

Purpose

Understanding Comics by Scott McCloud has an excellent description of the many layers a skilled practitioner must manipulate to create fine art.



My Comic Art?

Purpose

Understanding Comics by Scott McCloud has an excellent description of the many layers a skilled practitioner must manipulate to create fine art.

1 Purpose/Goal	2 Form	3 Idiom	4 Structure	5 Craft	6 Surface
Understand Fundamental Behavior of the Universe	High Energy Particle Physics	Neutral Kaon Propagation and Decay	KTeV	Measuring Ke3 Asymmetry Downstream of a Regenerator	Sexy Plots, Compelling Numbers, Public Enthusiasm

My Comic Art?

Purpose

Understanding Comics by Scott McCloud has an excellent description of the many layers a skilled practitioner must manipulate to create fine art.

1 Purpose/Goal	2 Form	3 Idiom	4 Structure	5 Craft	6 Surface
Understand Fundamental Behavior of the Universe	High Energy Particle Physics	Neutral Kaon Propagation and Decay	KTeV	Measuring Ke3 Asymmetry Downstream of a Regenerator	Sexy Plots, Compelling Numbers, Public Enthusiasm
		Nobel Prize	Named Chair	Ph.D., Tenure	Applause

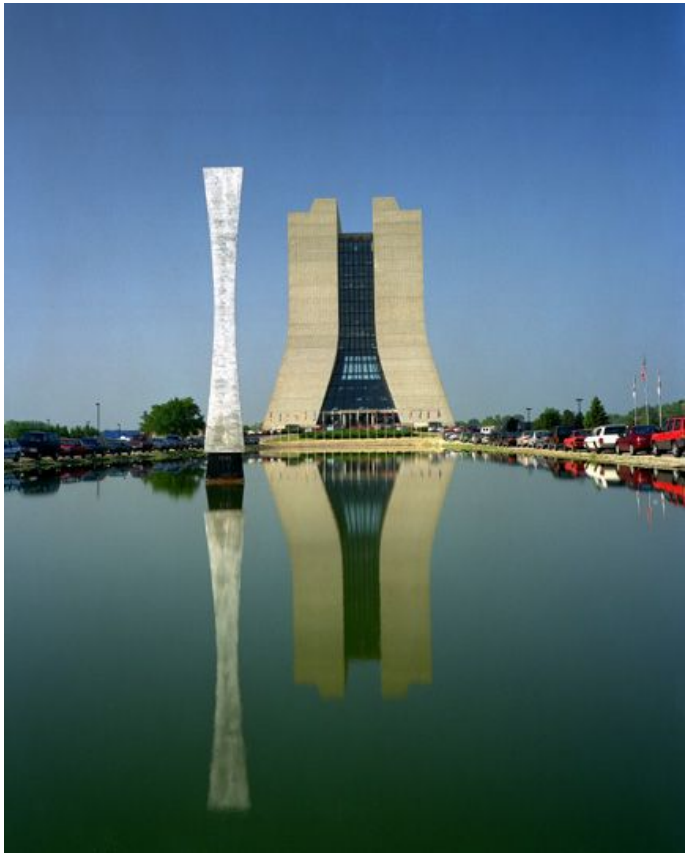
Purpose/Goal

- What underlying Fields/Particles/Symmetries determine the observable dynamics of the universe?
- How do these underlying Fields/Particles/Symmetries interact with each other?

Fermilab Fixed Target Program

Form

- Begin with protons, a well understood particle
- Confine and accelerate
- Produce new particles
- Study their behavior



Symmetry Violation

Form

- 1928 - Wigner introduces Parity, ***P***, to Quantum Mechanics.
- 1928 - P.A.M. Dirac's field theory implies a Charge conjugation operator, ***C***, that connects particles to corresponding anti-particles.
- 1950 - Purcell and Ramesy encourage experimental tests of Parity Conservation (EDM).
- 1955 - Bell (and others) outline ***CPT*** conservation.
- 1956, Jun - Lee and Yang question Parity Conservation and suggest that the Weak sector might be particularly fertile grounds for further tests.
- 1957, Jan - Wu (β-decay); Garwin, Lederman, Weinrich and Friedman, Telegdi ($\pi^+ \rightarrow \mu^+ \rightarrow e^+$) observe ***P*** and ***C*** violation.
- 1964 - Christenson, Cronin, Fitch and Turlay observe indirect ***CP*** violation in the decay of long lived Kaons.
- 1999 - KTeV (Peter Shawhan's Thesis) observes direct ***CP*** Violation.

Neutral Kaon System

Idiom

- Propagation eigenstates are superpositions of the strangeness eigenstates.

$$\left|K_S\right\rangle = \left\{(1+\epsilon)\left|K^0\right\rangle + (1-\epsilon)\left|\overline{K^0}\right\rangle\right\}\frac{1}{\sqrt{2(1+|\epsilon|^2)}}$$

$$\left|K_L\right\rangle = \left\{(1+\epsilon)\left|K^0\right\rangle - (1-\epsilon)\left|\overline{K^0}\right\rangle\right\}\frac{1}{\sqrt{2(1+|\epsilon|^2)}}$$

- This allows the prediction of the decay rate to any mode given an initial state, $\left|\Psi\right\rangle \sim \left|K_L\right\rangle + \rho\left|K_S\right\rangle$

- And the ratio of decay amplitudes $\eta = \frac{\left\langle Mode\middle|H\middle|K_L\right\rangle}{\left\langle Mode\middle|H\middle|K_S\right\rangle}$

$$Rate(\tau) = \left|\left\langle Mode\middle|H\middle|K_L\right\rangle\right|^2 \cdot \left(e^{-\tau\Gamma_L} + \left|\frac{\rho}{\eta}\right|^2 e^{-\tau\Gamma_S} + \left|\frac{\rho}{\eta}\right| e^{-\tau\Gamma_{AVE}}\cos(\Delta m\,\tau + \phi_\rho - \phi_\eta)\right)$$

The KTeV Detector

Structure

- KTeV is designed to have high rate and well understood acceptance for both charged and neutral decay modes.

$$6\Re\left(\frac{\epsilon'}{\epsilon}\right)=1+\left(\frac{\eta_{00}}{\eta_{+-}}\right)^2$$

- Direct CP violation is the flagship measurement.

Regeneration

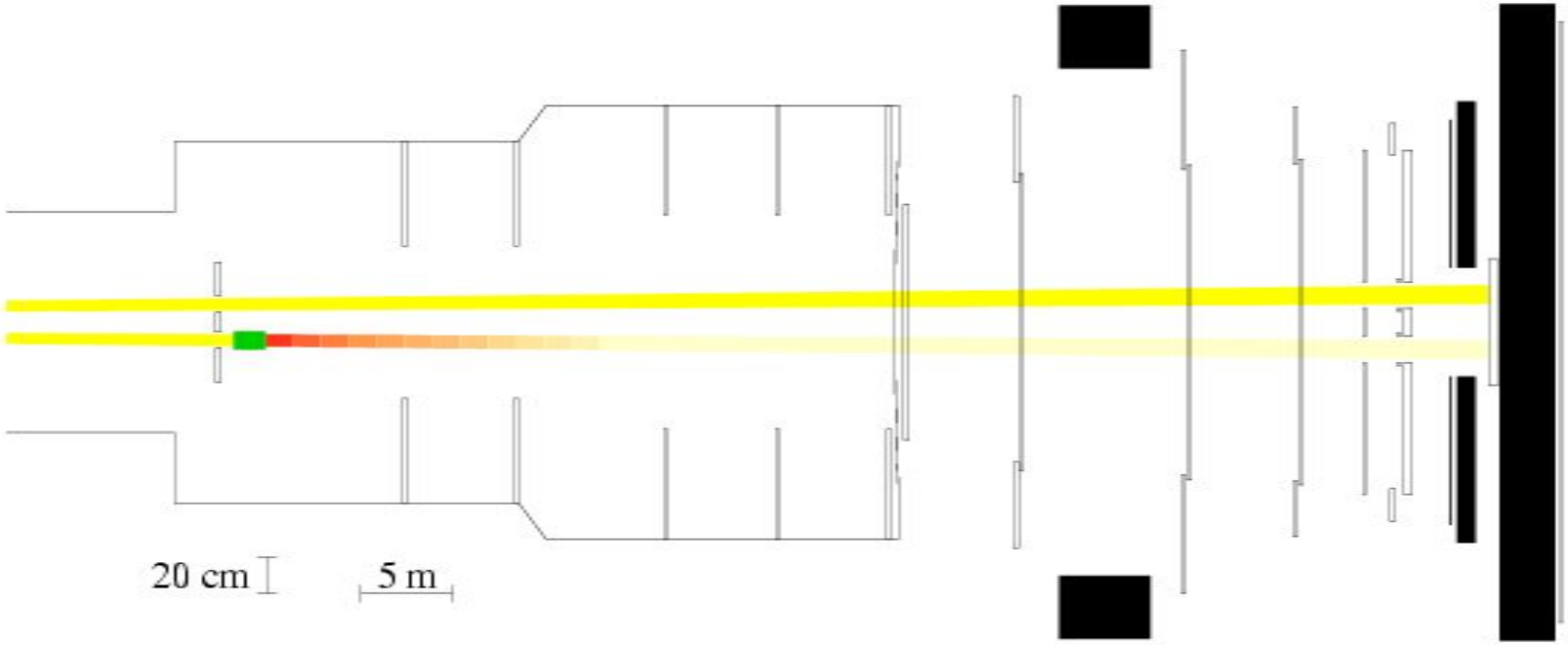
$$\left|K_L\right\rangle \longrightarrow \boxed{\text{Regenerator (1.1 H +1 C)}} \longrightarrow \left|K_L\right\rangle + \rho\left|K_S\right\rangle$$

Due to an asymmetry between the interaction of S=1 and S=-1 states, an initial K_L state "regenerates" a K_S component on passage through a block of material.

$$\rho = \underbrace{i}_{180^o}\, \pi N L \underbrace{\left(\frac{f-\bar{f}}{k}\right)}_{\Phi_{\frac{f-\bar{f}}{k}}} \underbrace{\Delta L}_{geometry}$$

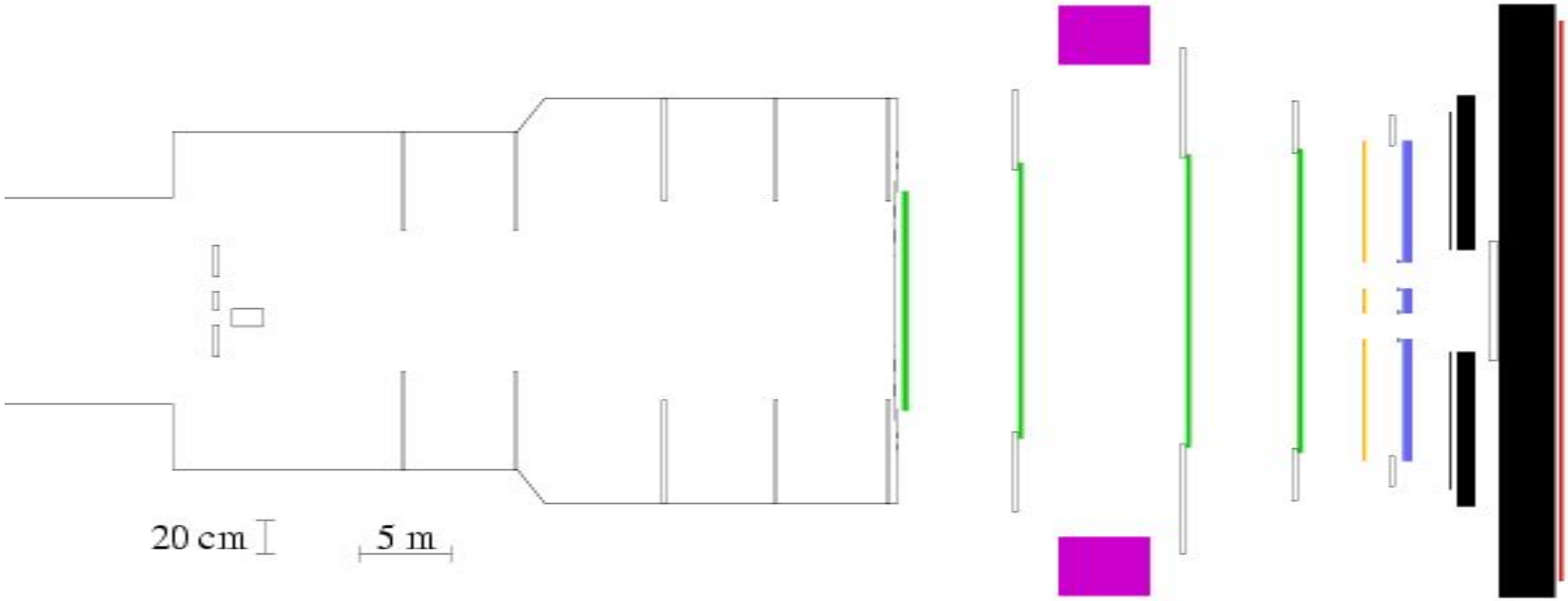
$$\Delta L = \frac{1-e^{-i(\lambda_S-\lambda_L)l}}{i(\lambda_S-\lambda_L)l}; \quad l = \frac{L}{\beta\gamma}; \quad \lambda_{S,L} = m_{S,L} - \frac{i}{2}\Gamma_{S,L}$$

Kaon Beams



800 GeV protons on BeO target
Charged
Hyperons decay, leaving K_L and neutrons
Regeneratormakes K_S by coherent regeneration
Regenerator alternates beams once per minute

Detector Elements for K_{e3} Decays



Drift chambers measure positions of particles
Bend angle in analysis magnet gives particle momentum
Calorimeter distinguishes pions from electrons
Trigger hodoscope is used to form first-level trigger
Muon hodoscope vetoes $K \rightarrow \pi\mu\nu$ in first-level trigger
Second-level trigger uses hit counting, pattern recognition

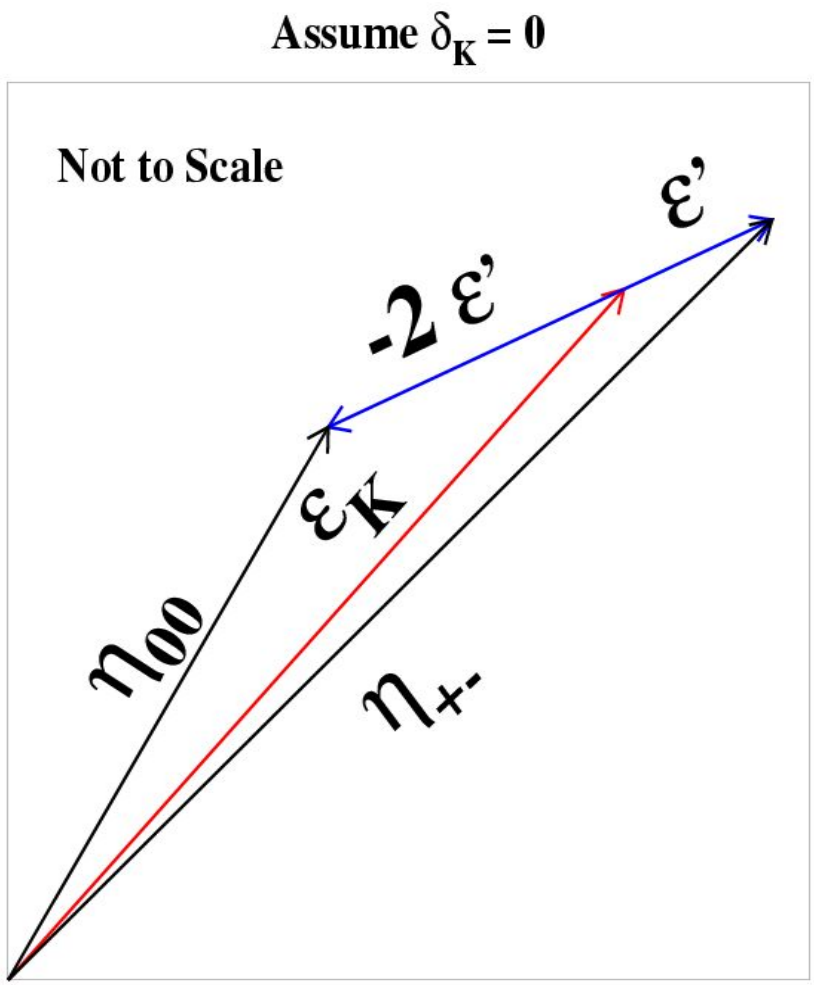
Precision Kaon Measurements

Structure

- ***CPT*** violation in decay amplitudes might manifest itself in many ways.
- Precise measurements of as many independent quantities as possible serve to limit the size of any such violation

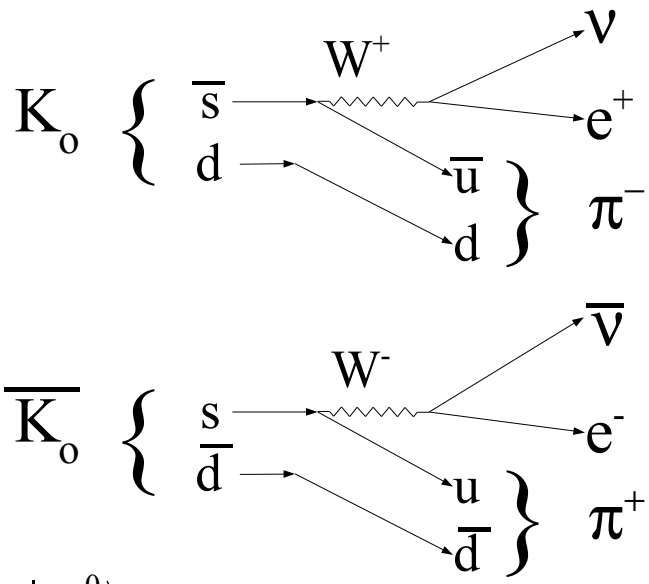
$$\phi_{+-} \quad \phi_{00}$$

$$\Delta\phi \quad \delta_L$$



$\Delta S = \Delta Q$

- The charge of the lepton tags the flavor of the strange quark
- Violations predicted by the standard model are very small since they involve a second heavy gauge boson.
- This violation is parameterized by *x*.

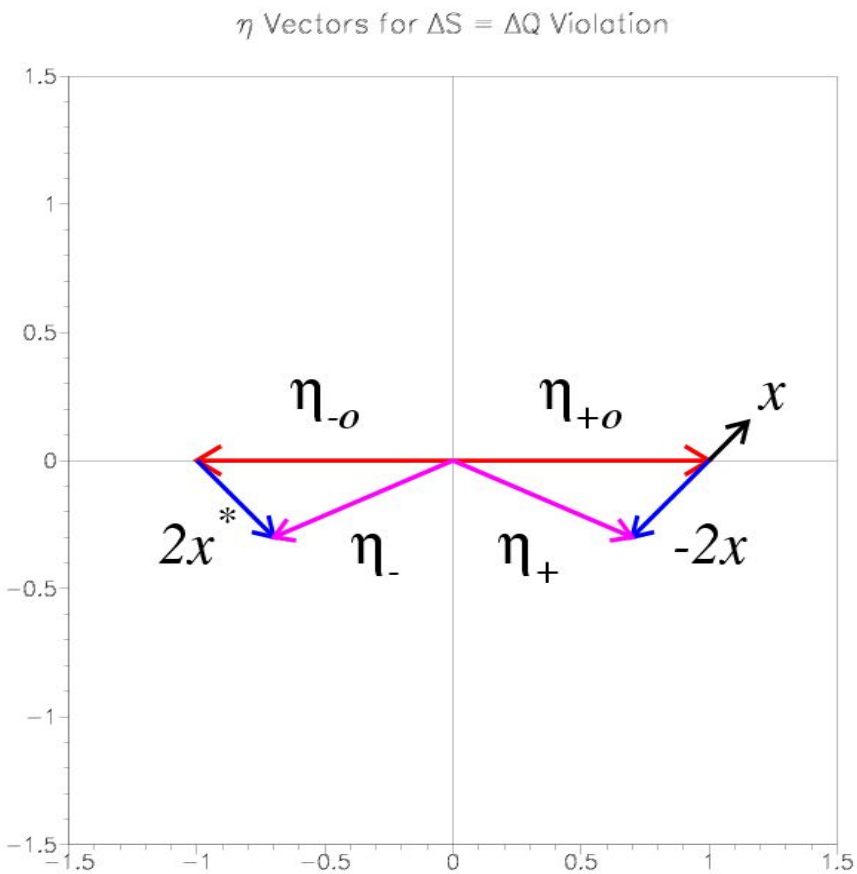


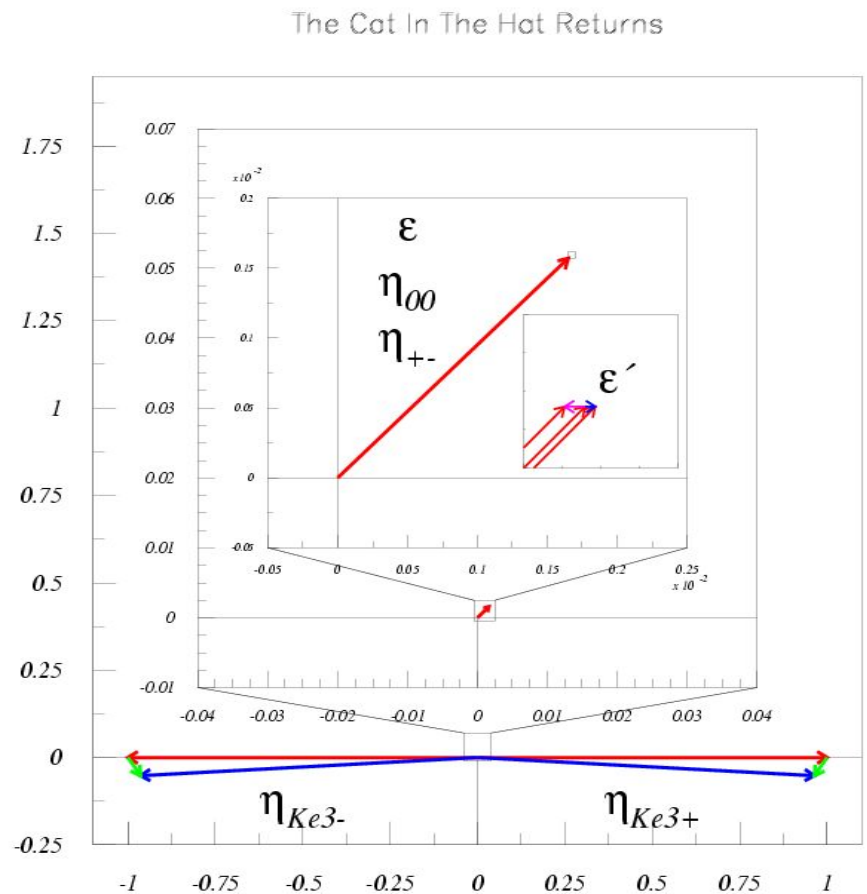
$$x = \left(\frac{\Delta S \neq \Delta Q}{\Delta S = \Delta Q} \right) = \frac{\langle K^+_{e3} | M | \overline{K^0} \rangle}{\langle K^+_{e3} | M | K^0 \rangle} \overset{CPT}{\rightarrow} x^* = \frac{\langle K^-_{e3} | M | K^0 \rangle}{\langle K^-_{e3} | M | \overline{K^0} \rangle}$$

$$\eta_{\pi^- e^+ \nu} = 1 - 2x\,; \quad \eta_{\pi^+ e^- \bar{\nu}} = -1 + 2x^*$$

The η Plane

Structure



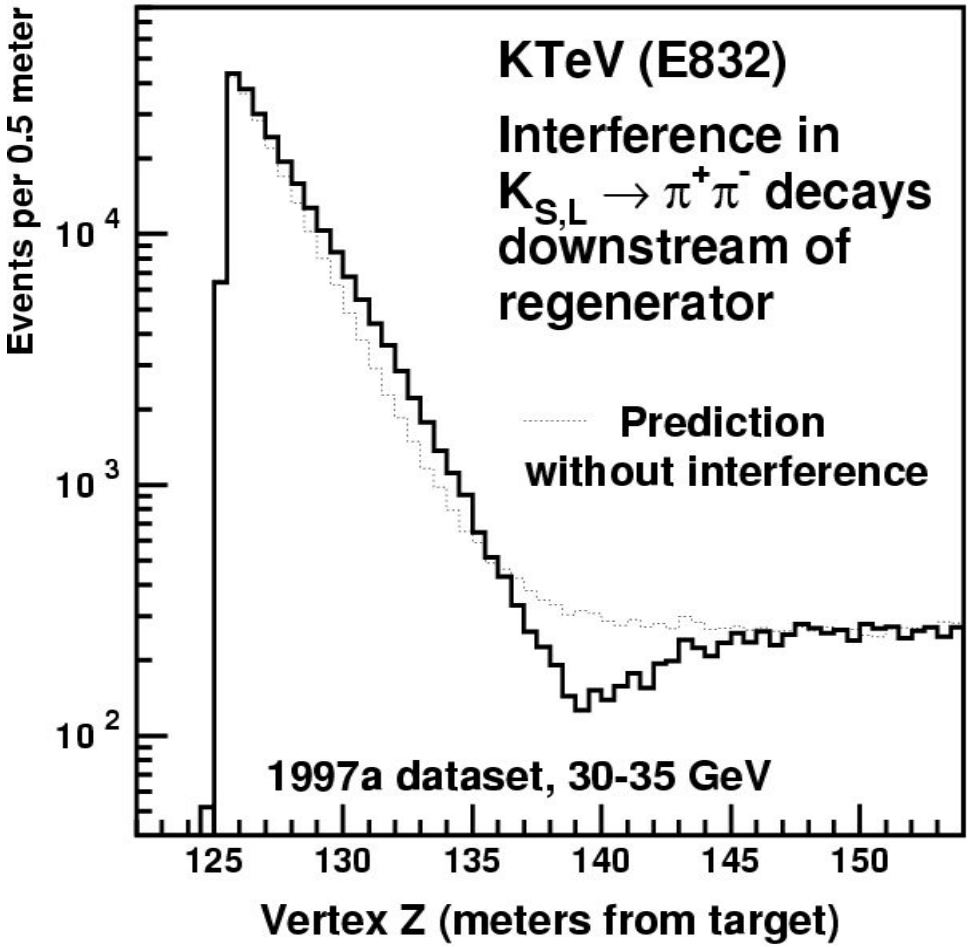


$$\eta = \frac{\langle Mode | H | K_L \rangle}{\langle Mode | H | K_S \rangle}$$

Measuring Phases

$$Rate_{\pi^+\pi^-}(\tau) \sim e^{-\tau\Gamma_L} + \left|\frac{\rho}{\eta_{+-}}\right|^2 e^{-\tau\Gamma_S} + \left|\frac{\rho}{\eta_{+-}}\right| e^{-\tau\Gamma_{AVE}} \cos(\Delta m\,\tau + \phi_\rho - \phi_{+-})$$

- To measure ϕ_{+-}, we must know ϕ_ρ



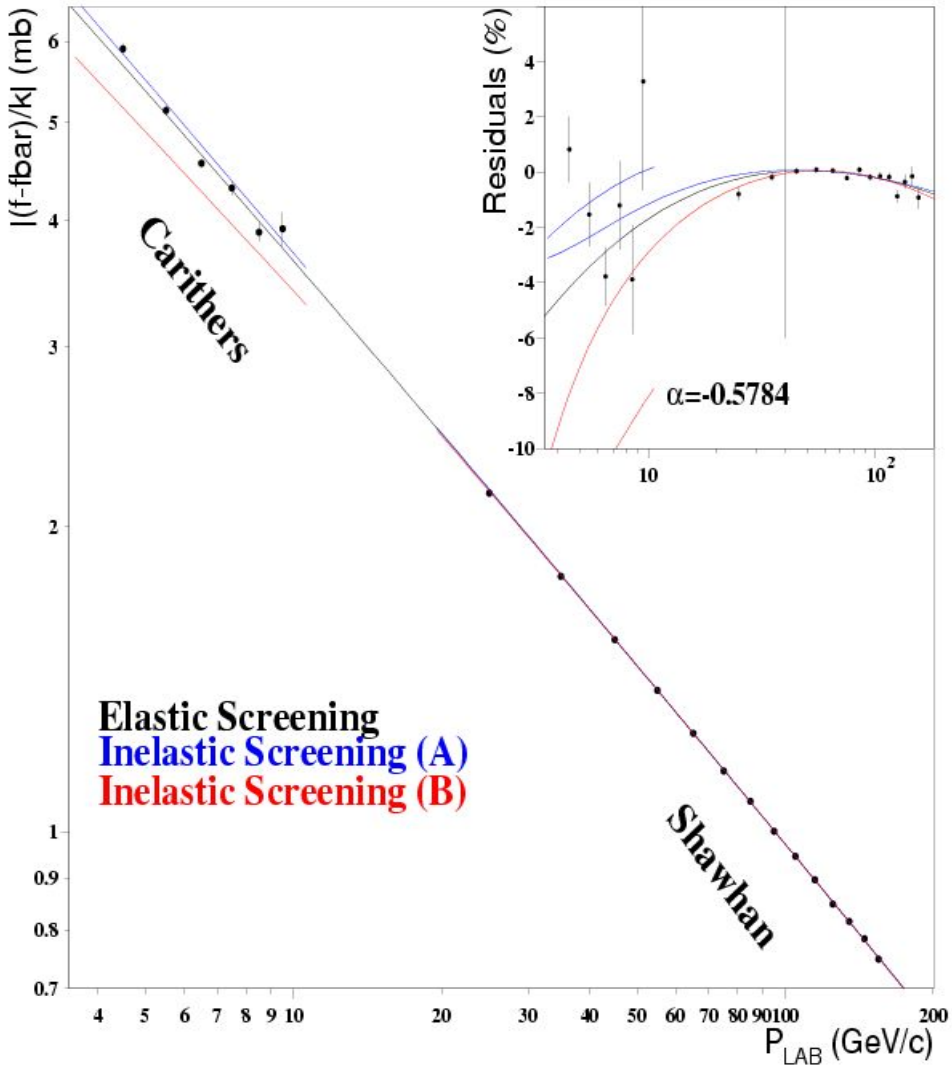
Analyticity

Craft

- Causality in the scattering process and the analyticity of functions give rise to a dispersion relation between the phase and the amplitude.

$$\left|\frac{f-\bar{f}}{k}\right| \sim p^{\alpha}$$

$$\phi_{\frac{f-\bar{f}}{k}} = -\frac{\pi}{2}(1+\alpha)$$



Analyticity?

Craft

- Kleinknecht, Luitz (Phys.Lett. B336, 1994) argue that the systematic error associated with analyticity for the measurement of ϕ_{+-} is 3°.
- The counter-claim by Briere, Winstein (Phys.Rev.Lett. 75,3 1995) is that any realistic addition of scattering terms cannot lead to systematic difficulties larger than 0.35°.

- From Kleinknecht:

Since the theoretical uncertainties from the integration over unexplored momentum domains in the dispersion method cannot easily be reduced, the most promising route for improving on the precision of the knowledge of the regeneration phase is probably a new measurement of this charge asymmetry with improved statistical precision

Asymmetry in Semi-leptonic K_{e3} Decays

Craft

- The branching ratios are:

$$\left|\left\langle \pi^- e^+ \nu \middle| H \middle| K_L \right\rangle\right|^2 = \frac{1+2\Re(\epsilon)-2\Re(x)}{1+|\epsilon|^2}\left|\left\langle \pi^- e^+ \nu \middle| H \middle| K^0 \right\rangle\right|^2 \quad ,$$

$$\left|\left\langle \pi^+ e^- \bar{\nu} \middle| H \middle| K_L \right\rangle\right|^2 = \frac{1-2\Re(\epsilon)-2\Re(x)}{1+|\epsilon|^2}\left|\left\langle \pi^+ e^- \bar{\nu} \middle| H \middle| \overline{K^0} \right\rangle\right|^2 \quad .$$

- The charge asymmetry is:

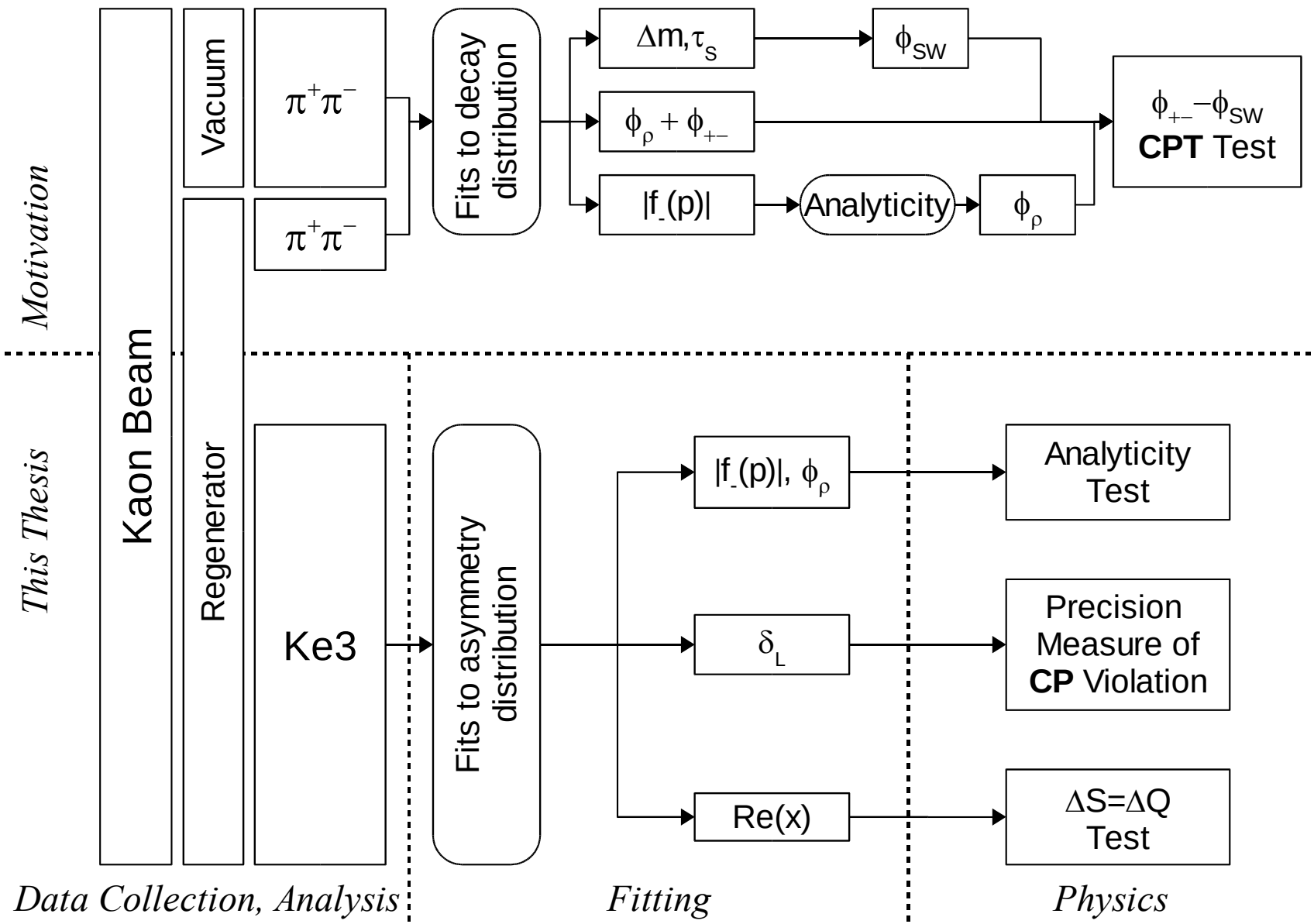
$$\frac{N_{\pi^- e^+ \nu} - N_{\pi^+ e^- \bar{\nu}}}{N_{\pi^- e^+ \nu} + N_{\pi^+ e^- \bar{\nu}}} = \frac{1-2\Re(x)}{|1-2x|}\left(2|\rho|\, e^{-\frac{\tau}{2}(\Gamma_S-\Gamma_L)} \cos(\Delta m\ \tau + \phi_\rho) + 2\Re(\epsilon)\right) \quad .$$

- Fantastic! Observations of this asymmetry allow measurements of three parameters,

$$\Re(x), \quad \phi_{\frac{f-\bar{f}}{k}}, \quad \delta_L \quad .$$

Surface

Overview


Surface
Motivation
This Thesis
Kaon Beam
Vacuum
Regenerator
$\pi^+\pi^-$
$\pi^+\pi^-$
Ke3
Fits to decay distribution
Fits to asymmetry distribution
$\Delta m, \tau_S$
ϕ_{SW}
$\phi_\rho + \phi_{+-}$
$|f_-(p)|$
Analyticity
ϕ_ρ
$\phi_{+-} - \phi_{SW}$
CPT Test
$|f_-(p)|, \phi_\rho$
δ_L
Re(x)
Analyticity Test
Precision Measure of **CP** Violation
$\Delta S = \Delta Q$ Test
Data Collection, Analysis
Fitting
Physics

Data Collection

Craft

- KTeV's 1997 run was very successful:
  - Fermilab provided 2.3 x 10^{17} protons on target
  - 24 x 10^{9} Level 1 triggers
  - 12 x 10^{9} Level 2 triggers
  - 5 x 10^{8} Regenerator Ke3 tags written to tape

Obstacles

- Incomplete Momentum Reconstruction
- Scattered Kaon Backgrounds
- Detector Asymmetries

Craft

Obstacles

Craft

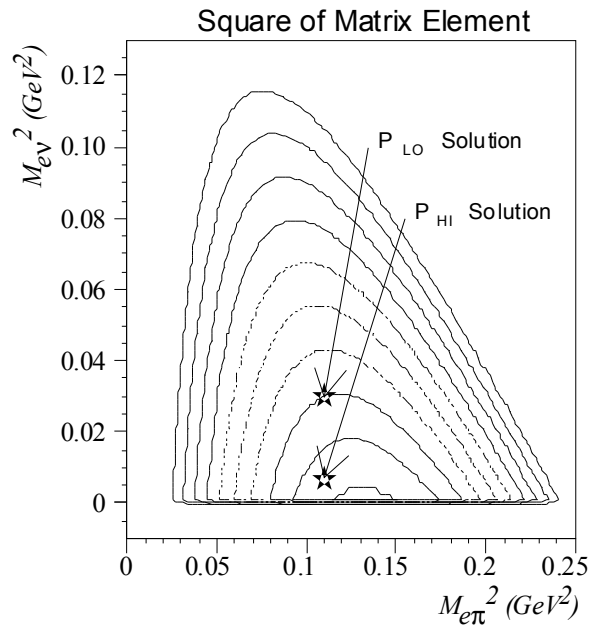
- Incomplete Momentum Reconstruction
  - Must find some parameter correlated to real momentum.
  - The migration between observed and actual momentum must be predicted and corrected for by using a detailed Monte Carlo simulation of the detector.
  - Our chosen parameter is the 'Most Probable' momentum.
- Scattered Kaon Backgrounds
- Detector Asymmetries

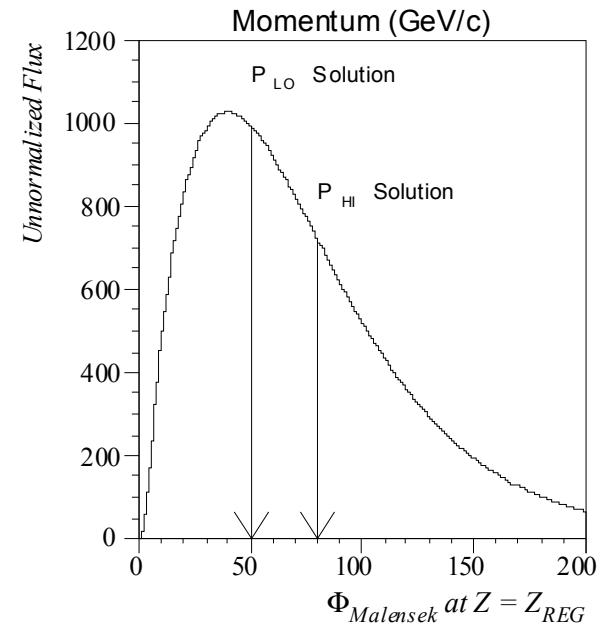
'Most Probable' Momentum

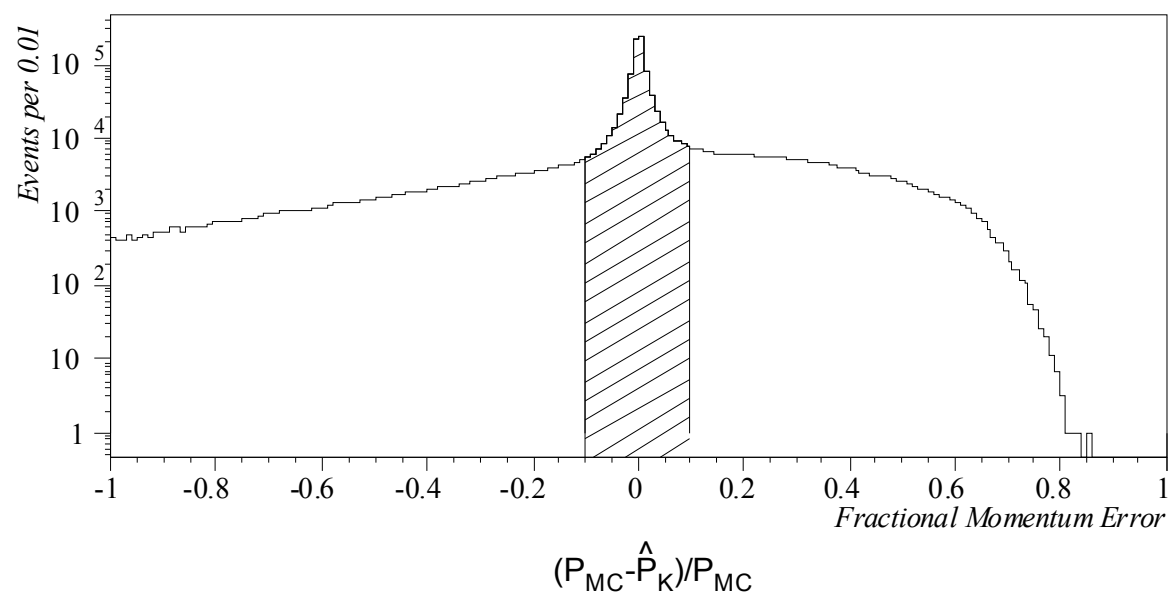
Craft

- Given the observed kinematic quantities, two solutions for the parent momentum are possible.
- The ratio of the probability for these two solutions depends only on the flux and the matrix element.

$$R_P = \frac{\Phi(P_{HI}) \cdot \boldsymbol{M}(P_{HI})^2}{\Phi(P_{LO}) \cdot \boldsymbol{M}(P_{LO})^2}$$







Obstacles

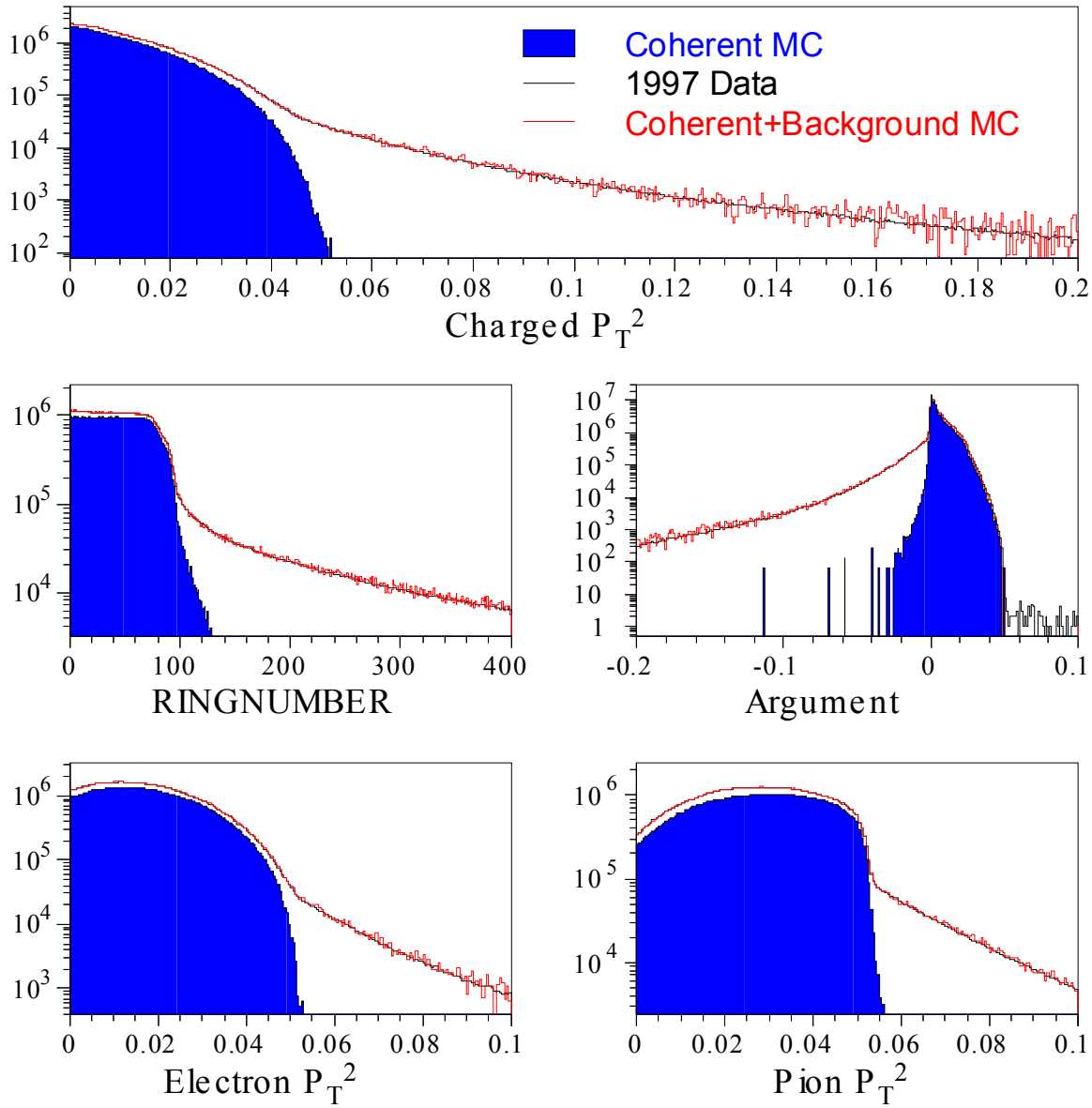
Craft

- Incomplete Momentum Reconstruction
- Scattered Kaon Backgrounds
  - In $K_{\pi 2}$ decay the p_T^2 is fully reconstructed and proves to be a powerful discriminator against kaons which scatter in the regenerator.
  - A large (~10%) irreducible background coming from kaon scatters in the regenerator must be simulated and accounted for.
- Detector Asymmetries

Variables Sensitive to Scatters

Craft

- Coherent P_T^2 and Argument distributions are limited by kinematic cut-offs.
- RINGNUMBER is limited by the beam shape.
- Incoherent tails are evident in all distributions.

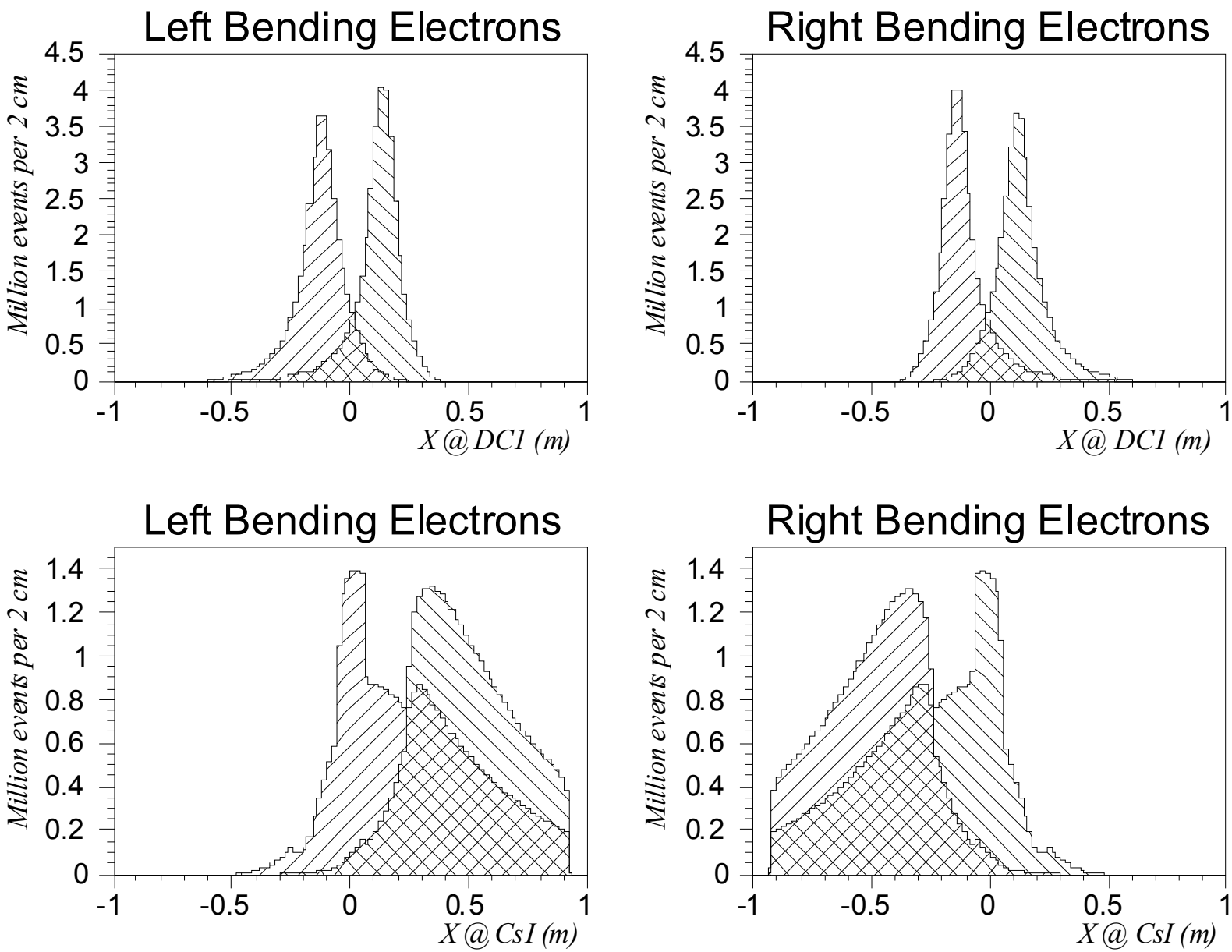


Obstacles

Craft

- Incomplete Momentum Reconstruction
- Scattered Kaon Backgrounds
- Detector Asymmetries
  - By reversing the magnet polarity and forming an appropriate ratio asymmetries related to geometric acceptance and to beam fluxes cancel
  - To accommodate this analysis all distributions must be partitioned by lepton charge state (+/-), magnet polarity (↑/↓), and regenerator position (E/W).

Detector Asymmetry



Fitting Asymmetries

Craft

- Expected number of events based on lepton charge and magnet polarity is:

$$N_{\downarrow\pm} = \Phi_{\downarrow} A_{\downarrow\pm} \frac{1 \pm \delta}{2} \quad ,$$

$$N_{\downarrow\pm} = \Phi_{\uparrow} A_{\uparrow\pm} \frac{1 \pm \delta}{2} \quad .$$

- Acceptance and flux differences cancel if $A_{\uparrow+} = A_{\downarrow-}$ and $A_{\uparrow-} = A_{\downarrow+}$:

$$R = \sqrt{\frac{N_{+\downarrow} \cdot N_{+\uparrow}}{N_{-\downarrow} \cdot N_{-\uparrow}}} = \frac{1-\delta}{1+\delta}$$

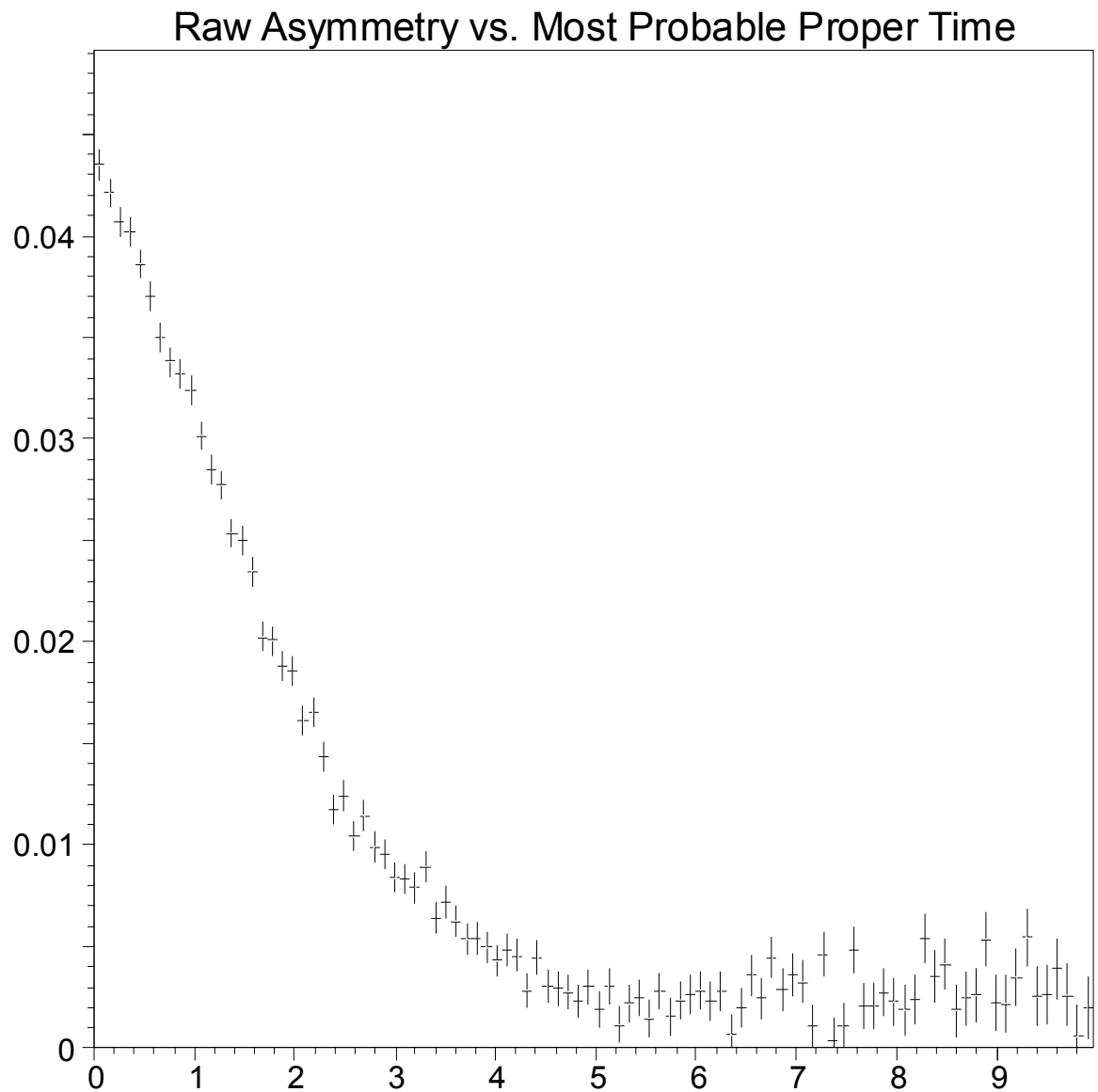
Event Selection

Craft

- Analysis Cuts for Regenerator Ke3's
  - 2 tracks – good vertex χ^2, fiducial cuts (CA,DC's,CSI), separated (DC's, CSI).
  - Vetos quiet
  - Electron ID – E/P > 0.94
  - Pion ID – E/P < 0.85
  - Muon rejection – P_{TRK} > 8 GeV
  - $\pi\pi$ rejection - $|M_{\pi\pi}-M_K|$ > 50 MeV
  - $\pi\pi\pi$ rejection - $M_{\pi\pi}$>400 MeV or $P_{\pi}0$kin < 0
  - Scattered Background Reduction
    - $P_T^2(\pi e)$ < 0.054 GeV^2
    - $P_T^2(\pi)$ < 0.054 GeV^2
    - $P_T^2(e)$ < 0.054 GeV^2
    - RINGNUM < 110
    - $P^*_{\nu||}$ > -0.002 GeV

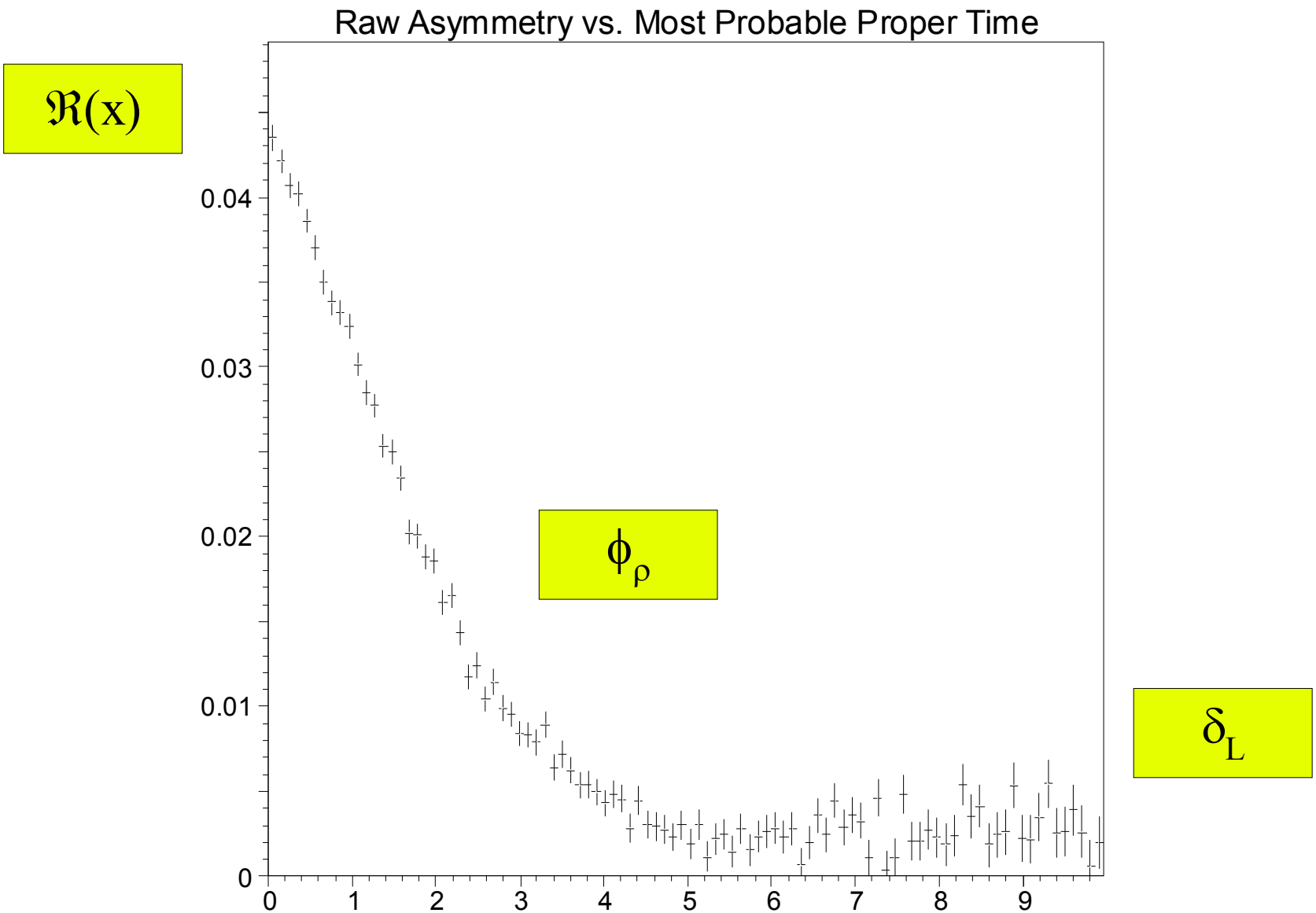
Raw Asymmetry

Surface

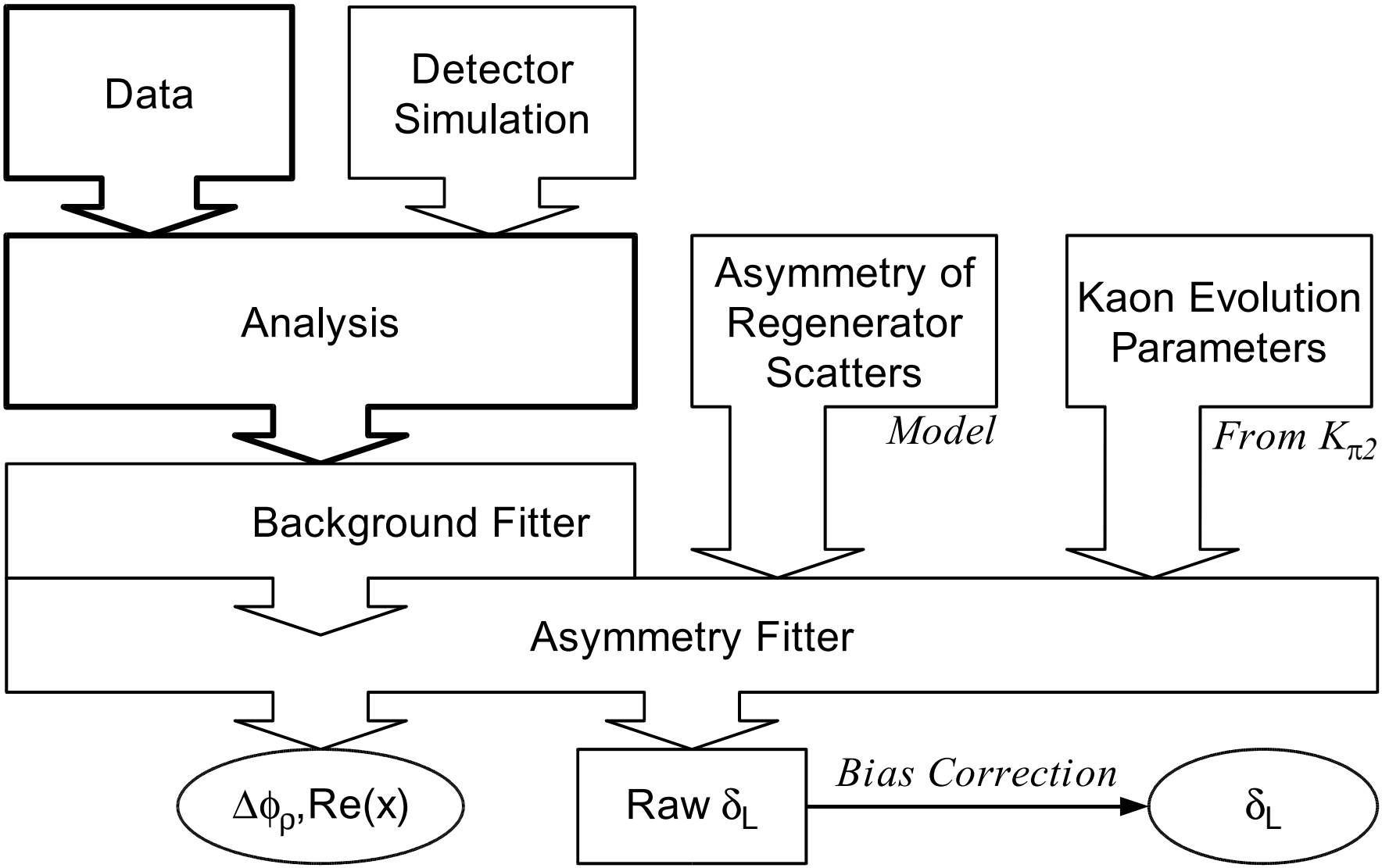


Raw Asymmetry

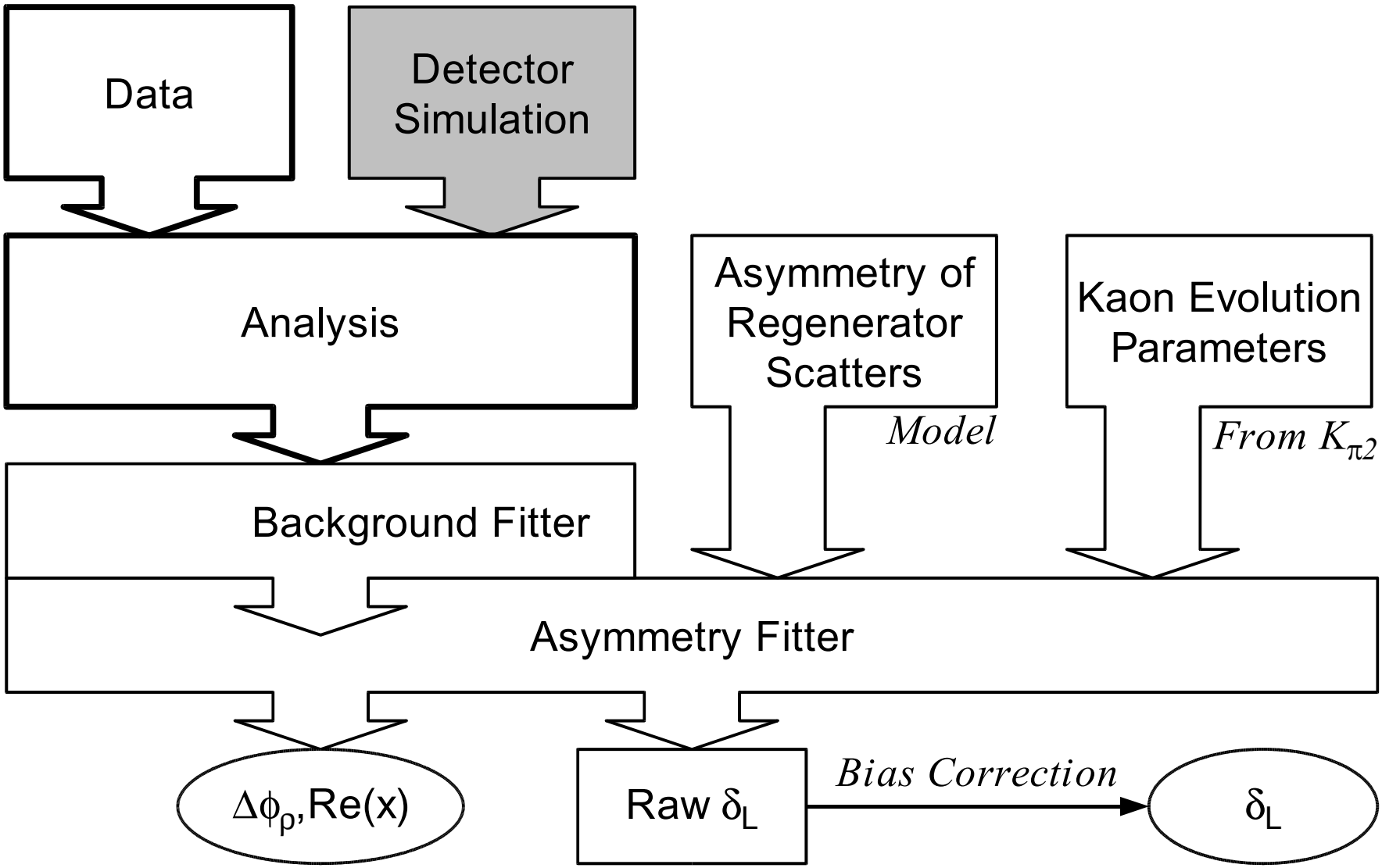
Surface



Fitting Strategy



Fitting Strategy

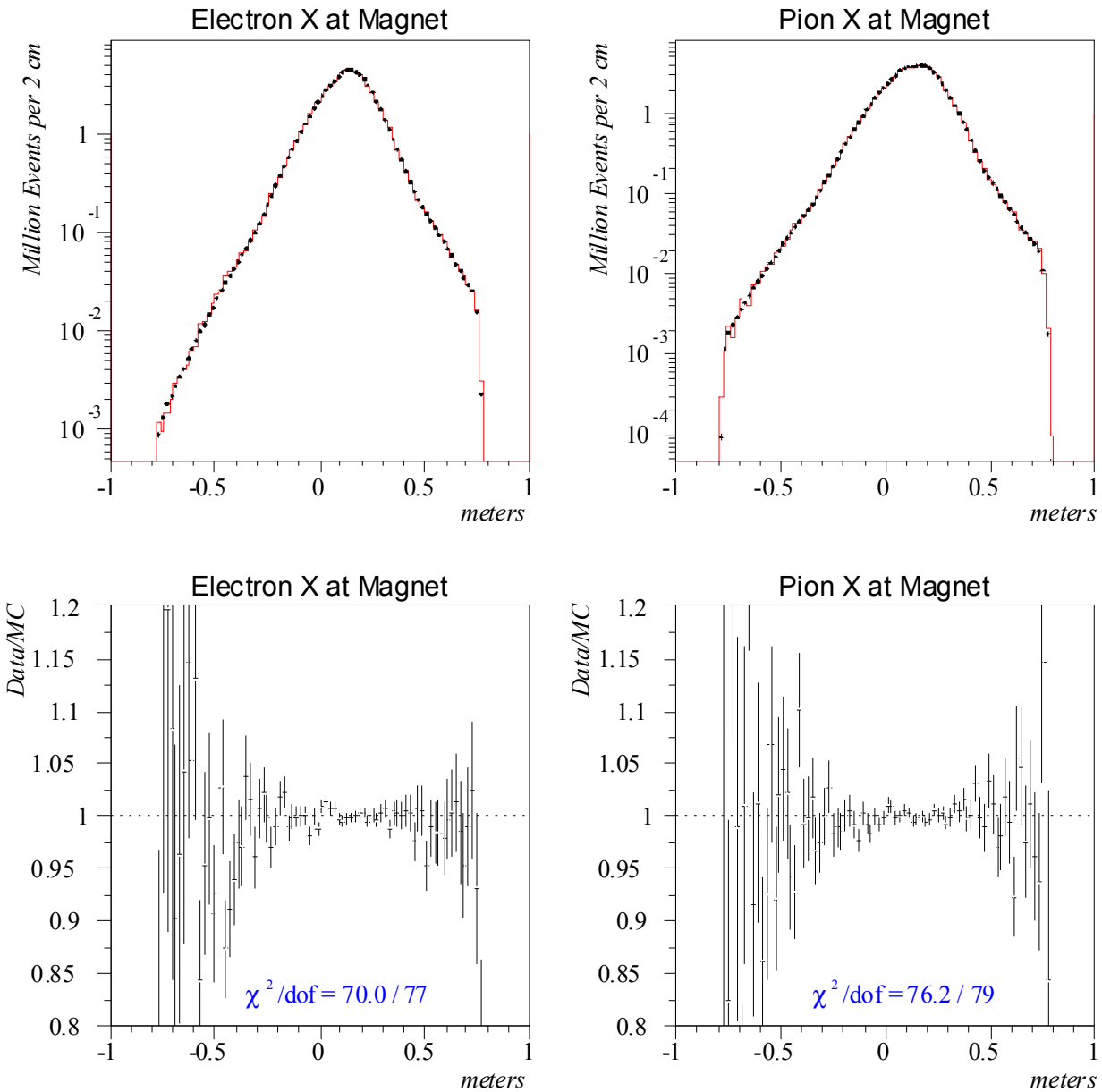


KTeV Monte Carlo

Craft

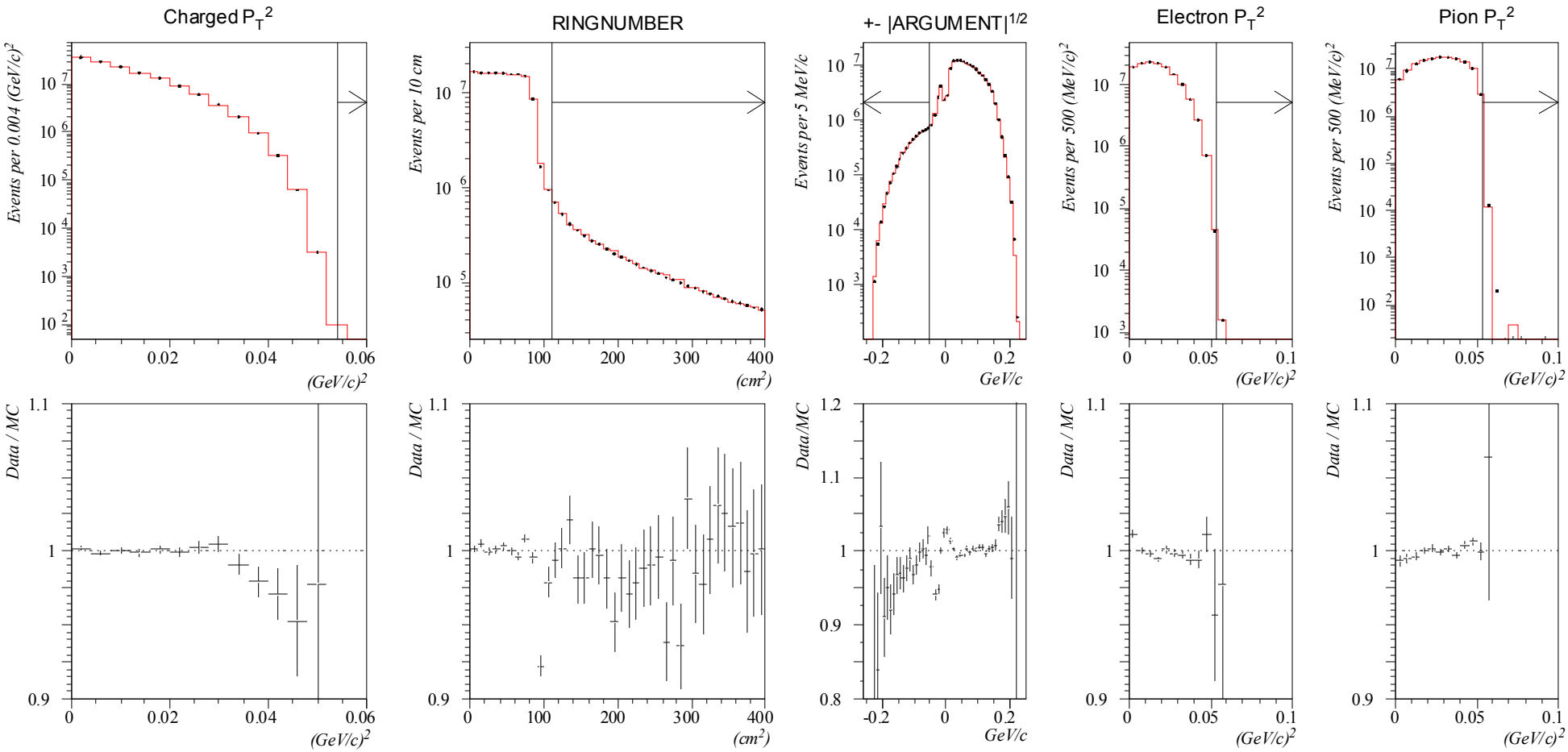
- Simulation of secondary beam
  - Production, target regeneration, absorber regeneration, collimator apertures, downstream collimator scattering, evolution thru regenerator, scattering in regenerator
- Simulation of kaon decay
  - Proper Z distribution, three-body decay, radiative corrections, $K_{e3\gamma}$
- Tracing of decay products
  - Multiple scattering, Bremsstrahlung, photon pair production, pion decay, magnet momentum kick
- Simulation of detector response
  - DC
    - Wire inefficiencies, high-sods, accidentals, Δ–rays
  - CsI
    - Uniformity, energy leakage, location dependence, photo-statistics
  - Trigger Elements
    - Hodoscope gaps

Illumination Overlay

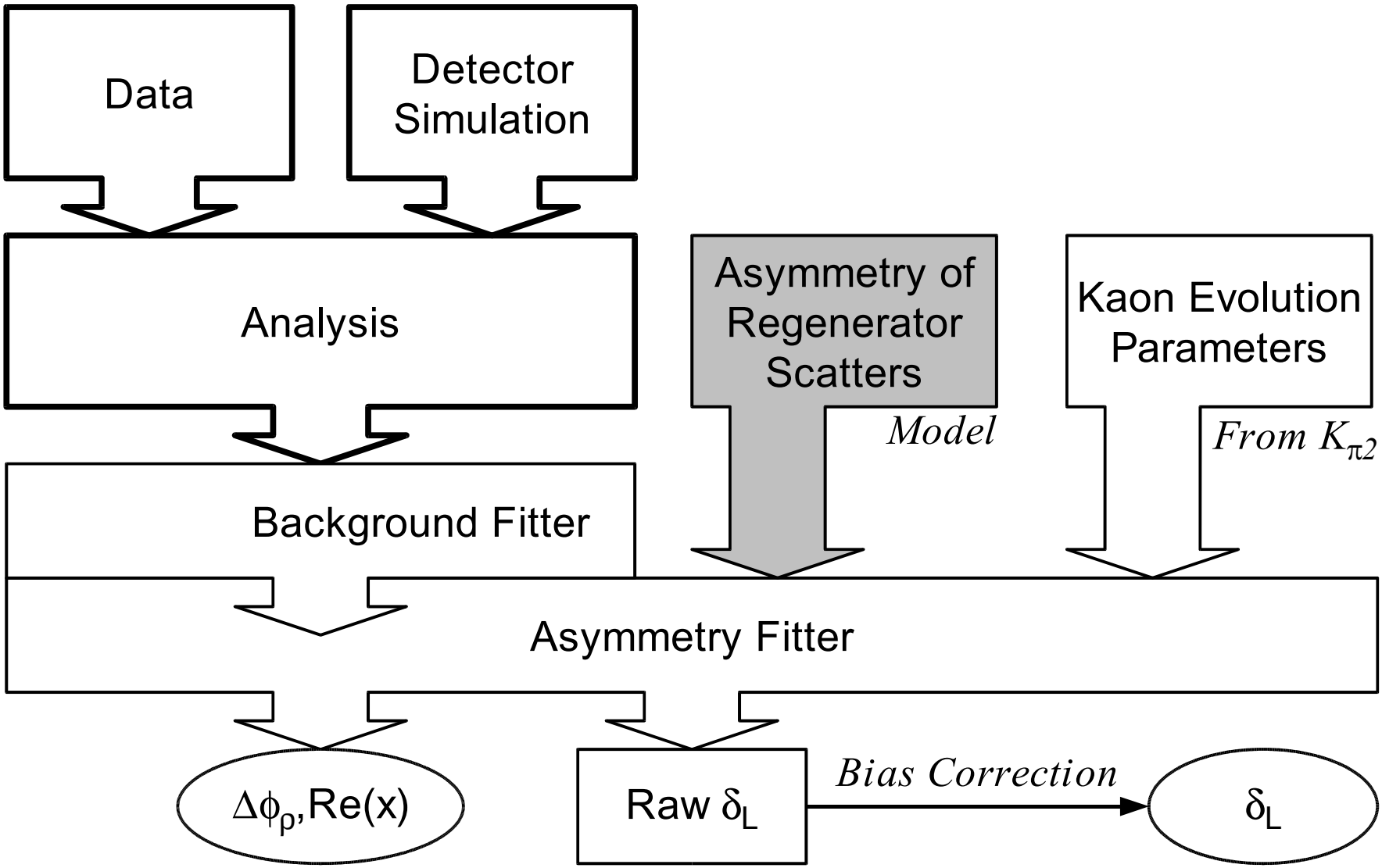


Background Sensitive Distributions

Craft



Fitting Strategy



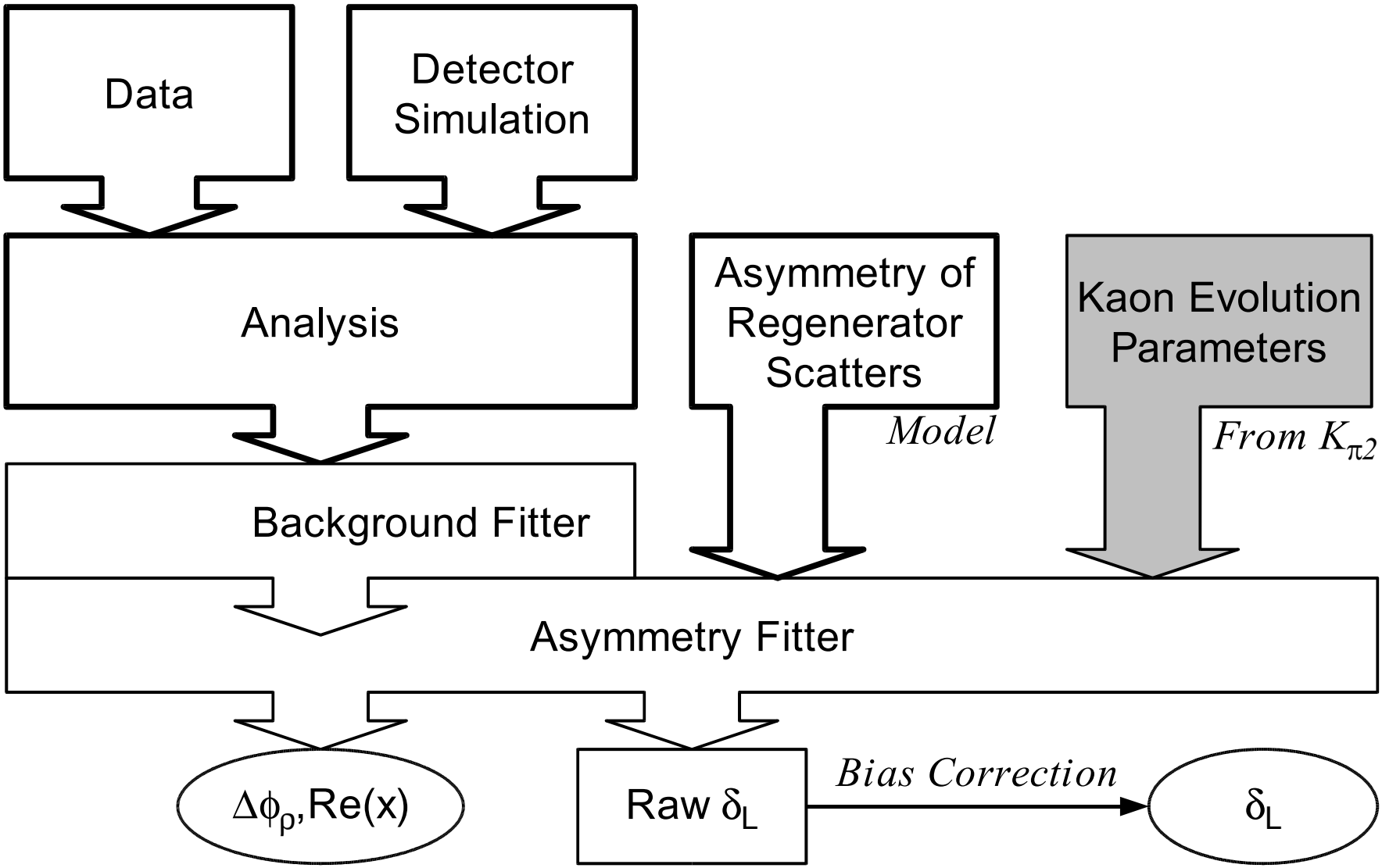
Craft

Regenerator Model

Craft

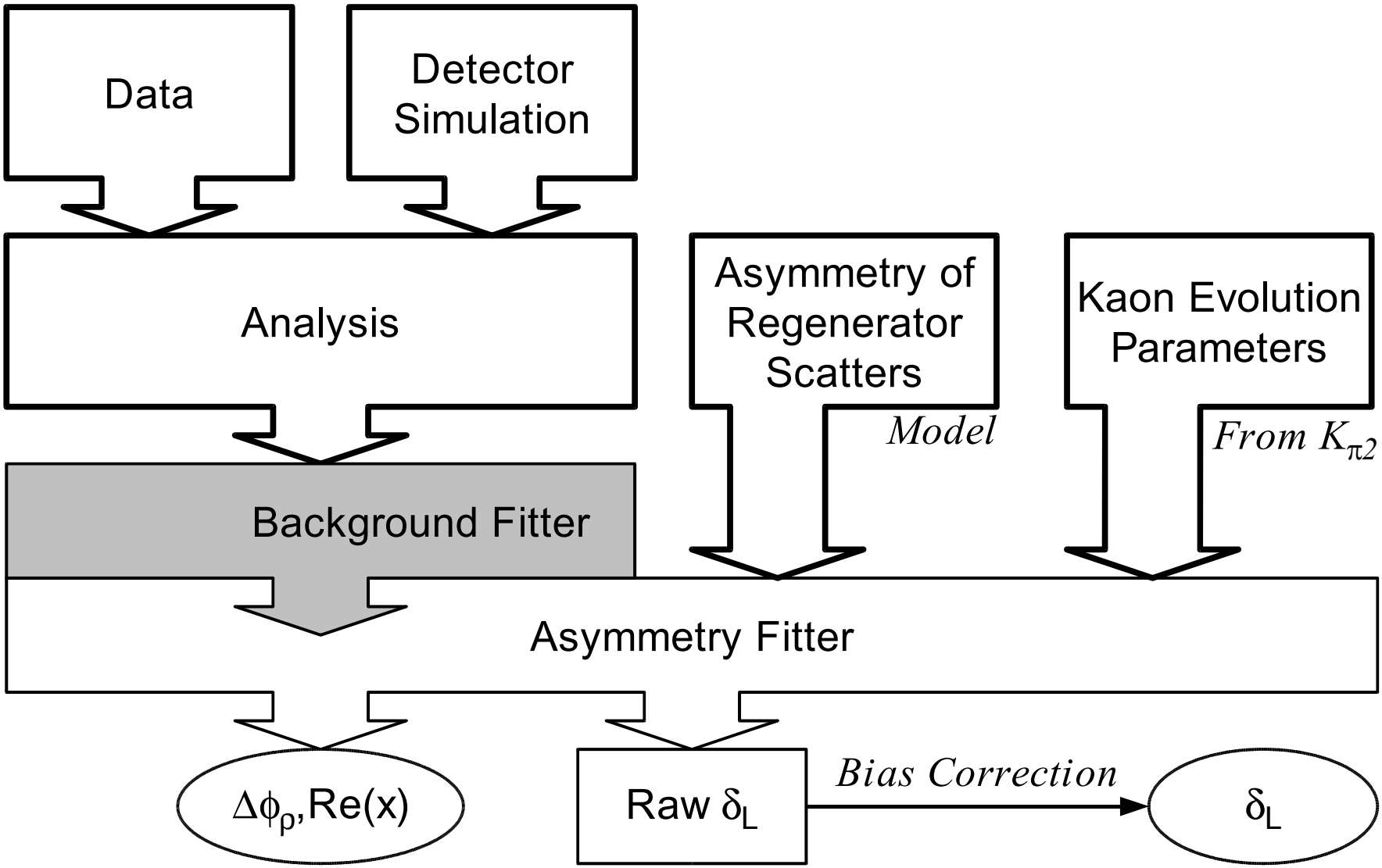
- K-N Regge-exchange model
  - ω,ρ,f,A_2, Pomeron, Odderon??
- Glauber model of elastic nuclear screening
- Inelastic nuclear screening
- Full multiple-scattering model through the length of the regenerator
- Resulting decays are categorized by their scatters:
  - Coherent
  - Single elastic lead scatter
  - Single elastic carbon scatter
  - Double elastic scatter
  - Multiple elastic scatters
  - Inelastic scatters

Fitting Strategy



Craft

Fitting Strategy



Background Fitter

Craft

- Float relative normalization of coherent, elastic and incoherent scatters.
- Float overall momentum slope
- Float scattered momentum slope
- Minimize χ^2 for sideband events for all background sensitive distributions and for P-Z distribution

$$P_T^2 \in [0,0.2]\left(\frac{GeV}{c}\right)^2$$

$$electron\ P_T^2 \in [0,0.2]\left(\frac{GeV}{c}\right)^2$$

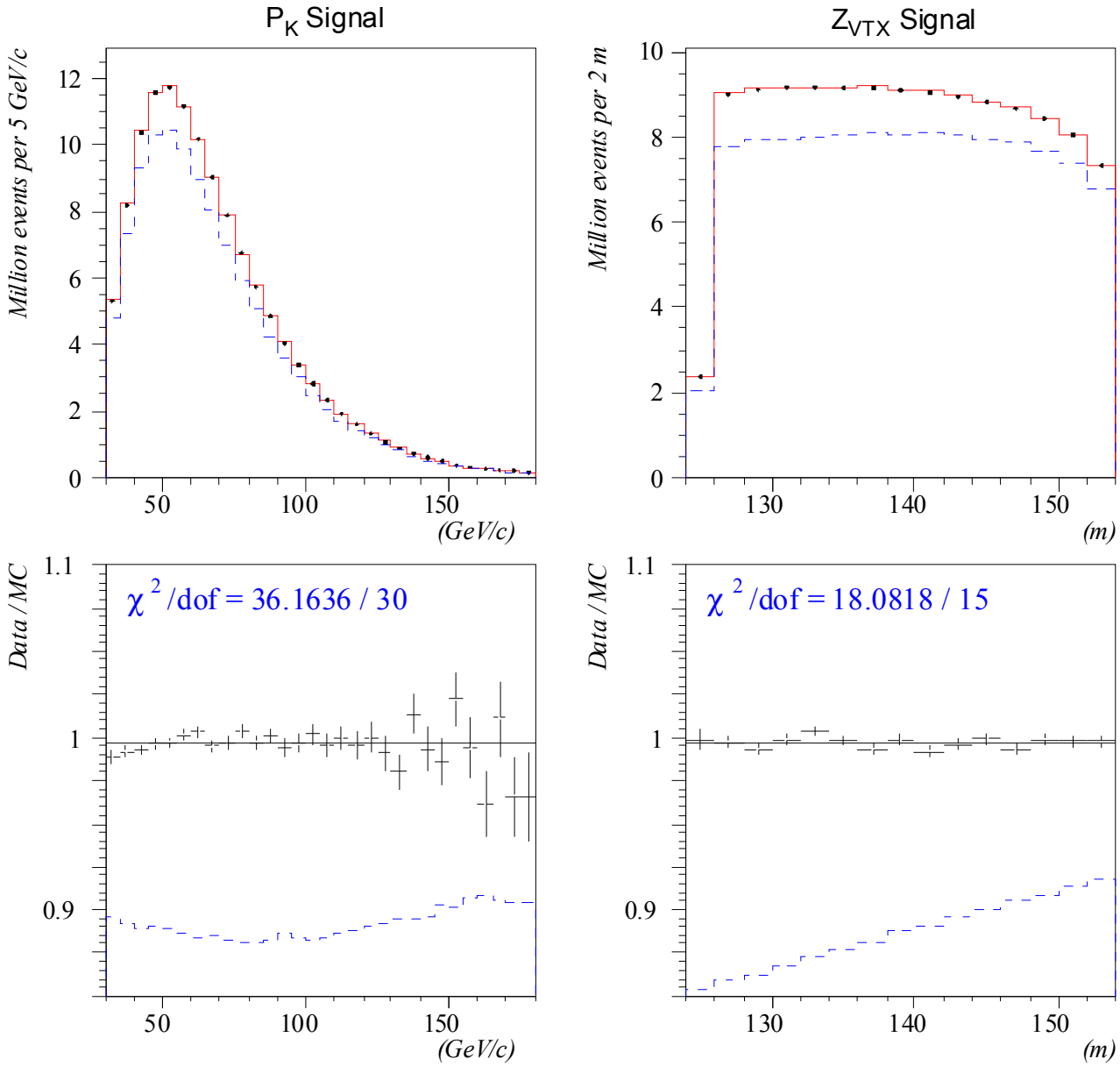
$$pion\ P_T^2 \in [0,0.2]\left(\frac{GeV}{c}\right)^2$$

$$ARGUMENT \in [-0.1,0.04]\left(\frac{GeV}{c}\right)^2$$

$$RINGNUMBER \in [0,400]cm^2$$

Variable	Value
N_{EAST}	98.43±0.12
N_{WEST}	99.07±0.12
$m_{coh} \times 10^4$ GeV	-2.43±0.23
$C_{ela} \times 10^2$	53.92±0.12
$C_{ine} \times 10^2$	78.30±0.70
$m_{scat} \times 10^2$ GeV	-18.75±0.45
χ^2/ D.o.F.	$867.58/(1178-6)$

Background Distributions



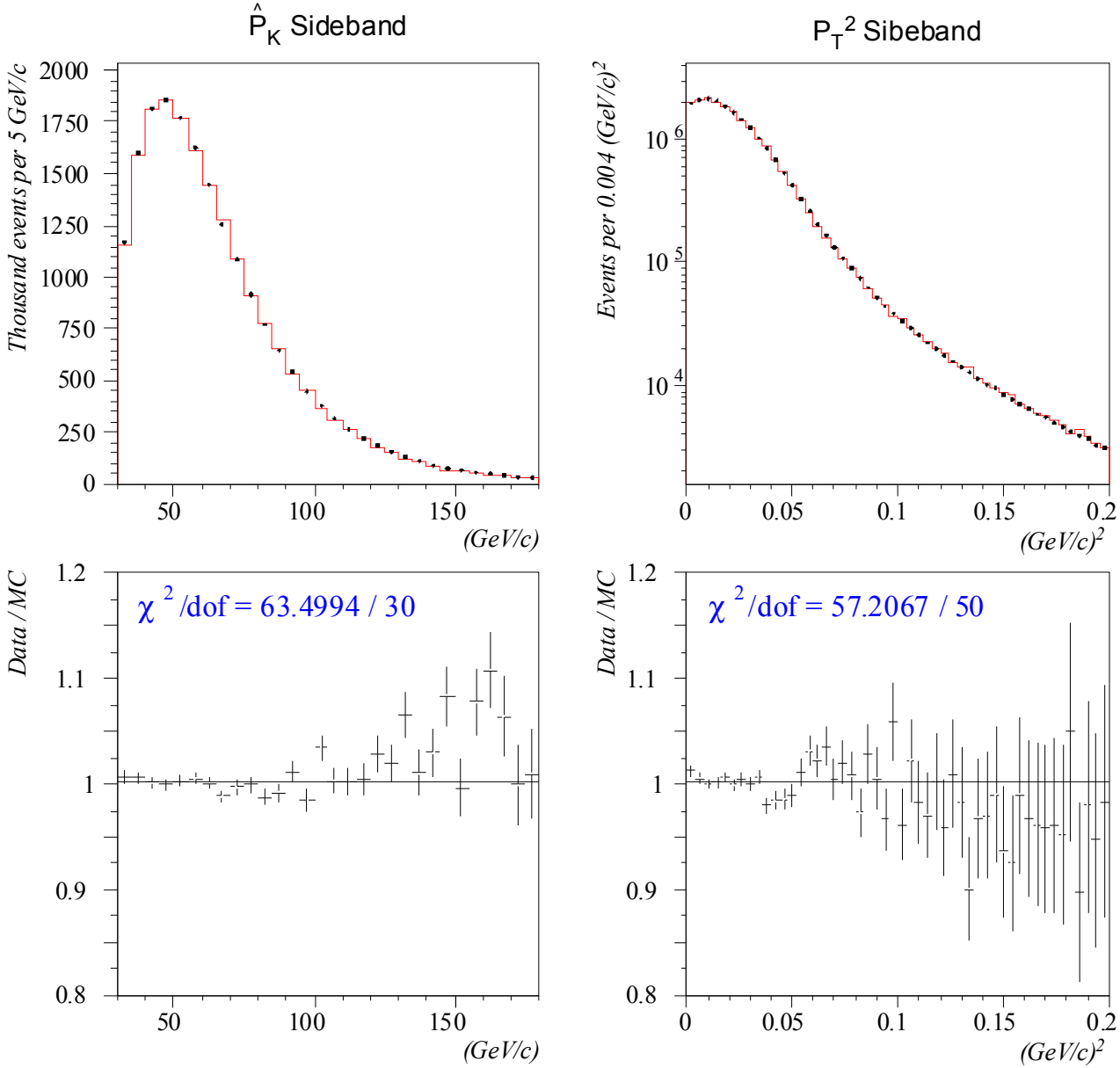
Data

Monte Carlo

Coherent Events

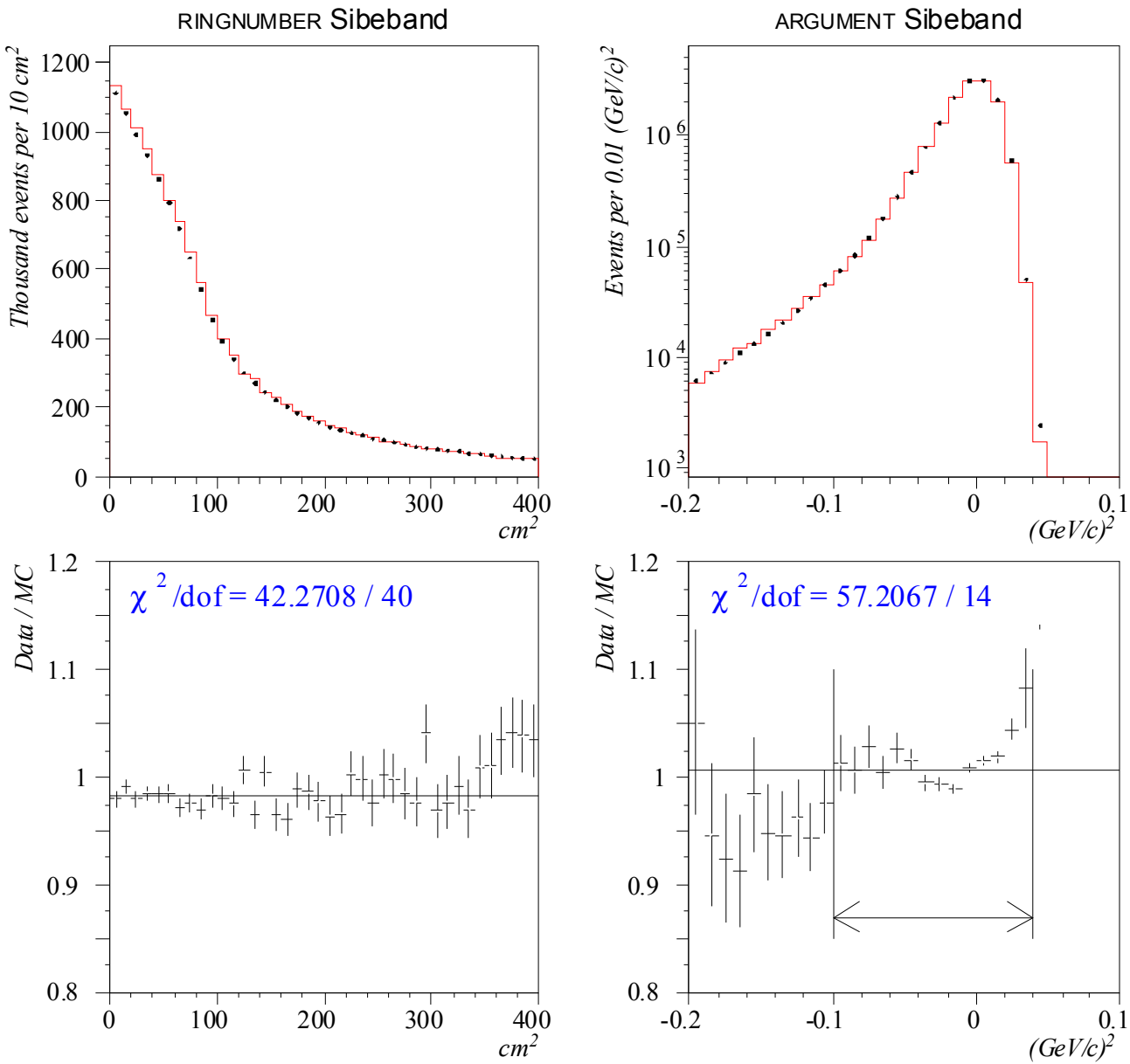
Craft

Background Distributions

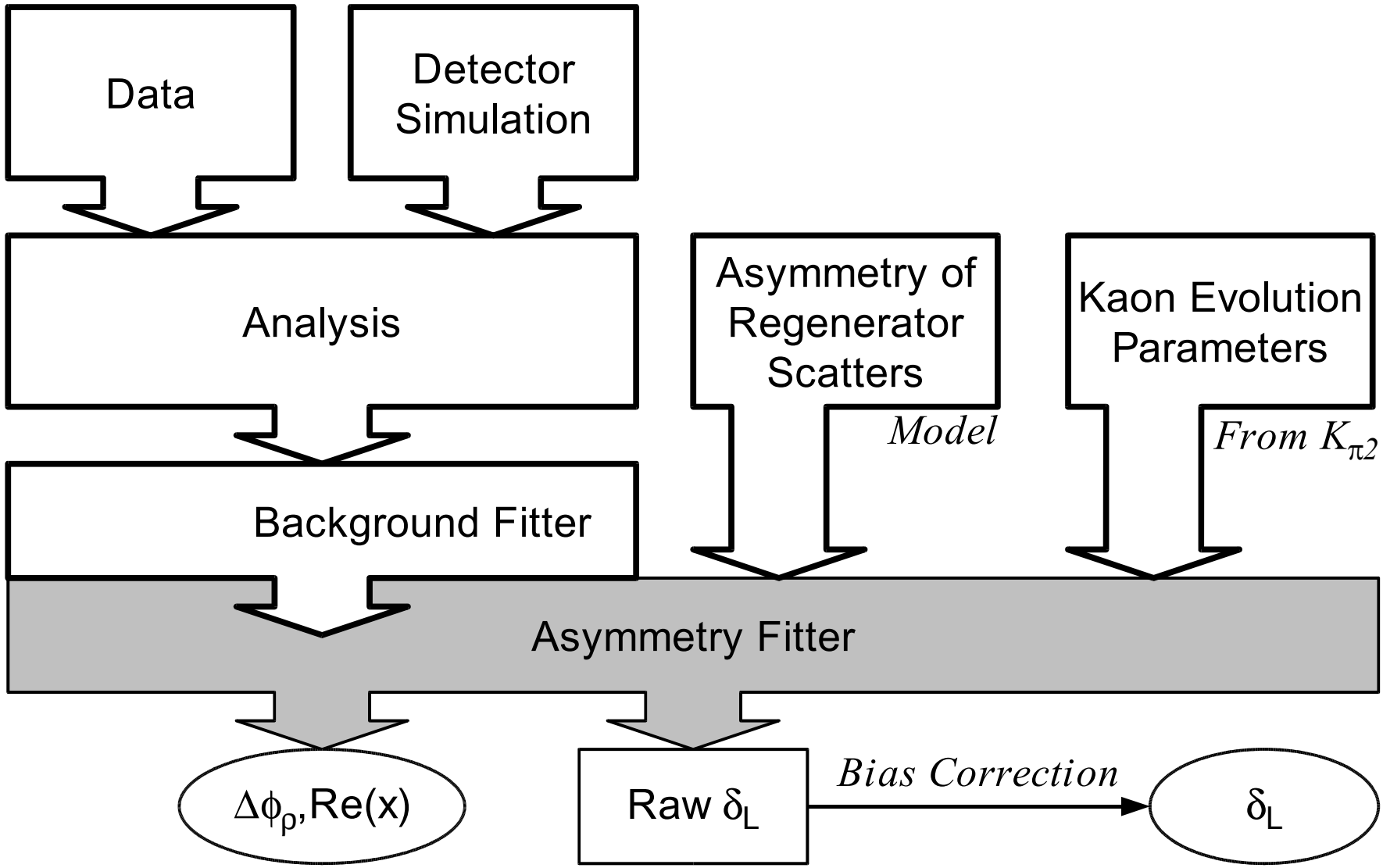


Craft

Background Distributions



Fitting Strategy



Fitting the Asymmetry

Craft

- The fitter produces a prediction for the asymmetry in each bin

m indexes sources
- coherent
- single carbon
- single lead
- two scatters
- multiple scatters
- inelastic

$$\delta(\hat{P}_j, Z_k) = \frac{\sum_{m=1}^{N_S} \delta_m(\hat{P}_j; Z_k) \cdot N_m(\hat{P}_j; Z_k)}{\sum_{m=1}^{N_S} N_m(\hat{P}_j; Z_k)}$$

Flux from Background Fit

$$\delta_m(\hat{P}_j, Z_k) = \frac{\sum_{i=i_{min}}^{i_{max}} M_m(P_i, \hat{P}_j; Z_k) \cdot \delta_m(P_i; Z_k)}{\sum_{i=i_{min}}^{i_{max}} M_m(P_i, \hat{P}_j; Z_k)}$$

Migration from Monte Carlo

Fitting the Asymmetry

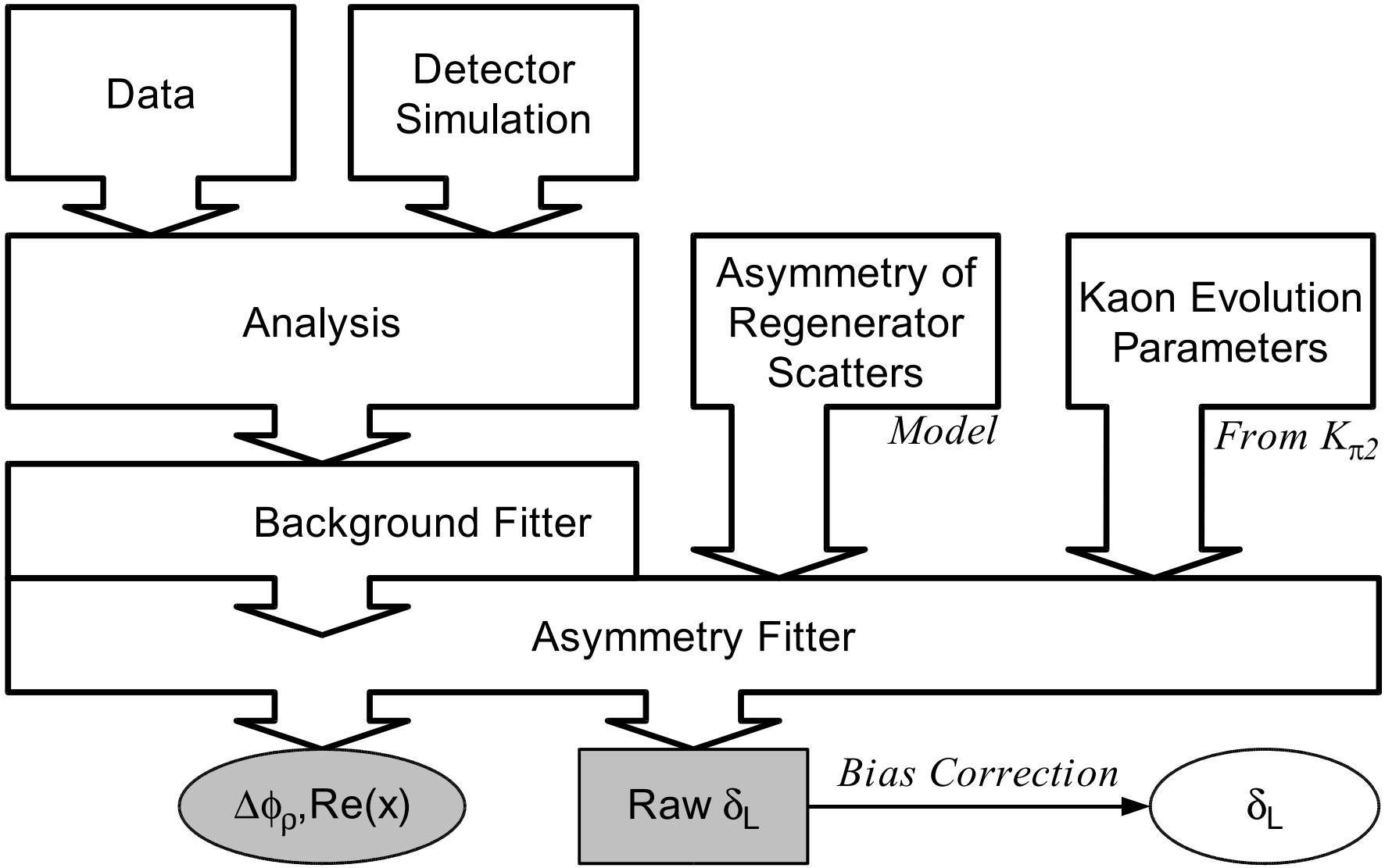
Craft

- A likelihood calculation is done in each bin:
  a) with no constraints, and
  b) constrained by the predicted value of the asymmetry.
- The difference is converted into a χ^2 statistic.

$$\chi^2 = 2 \cdot \left(\log(L_a) - \log(L_b) \right)$$

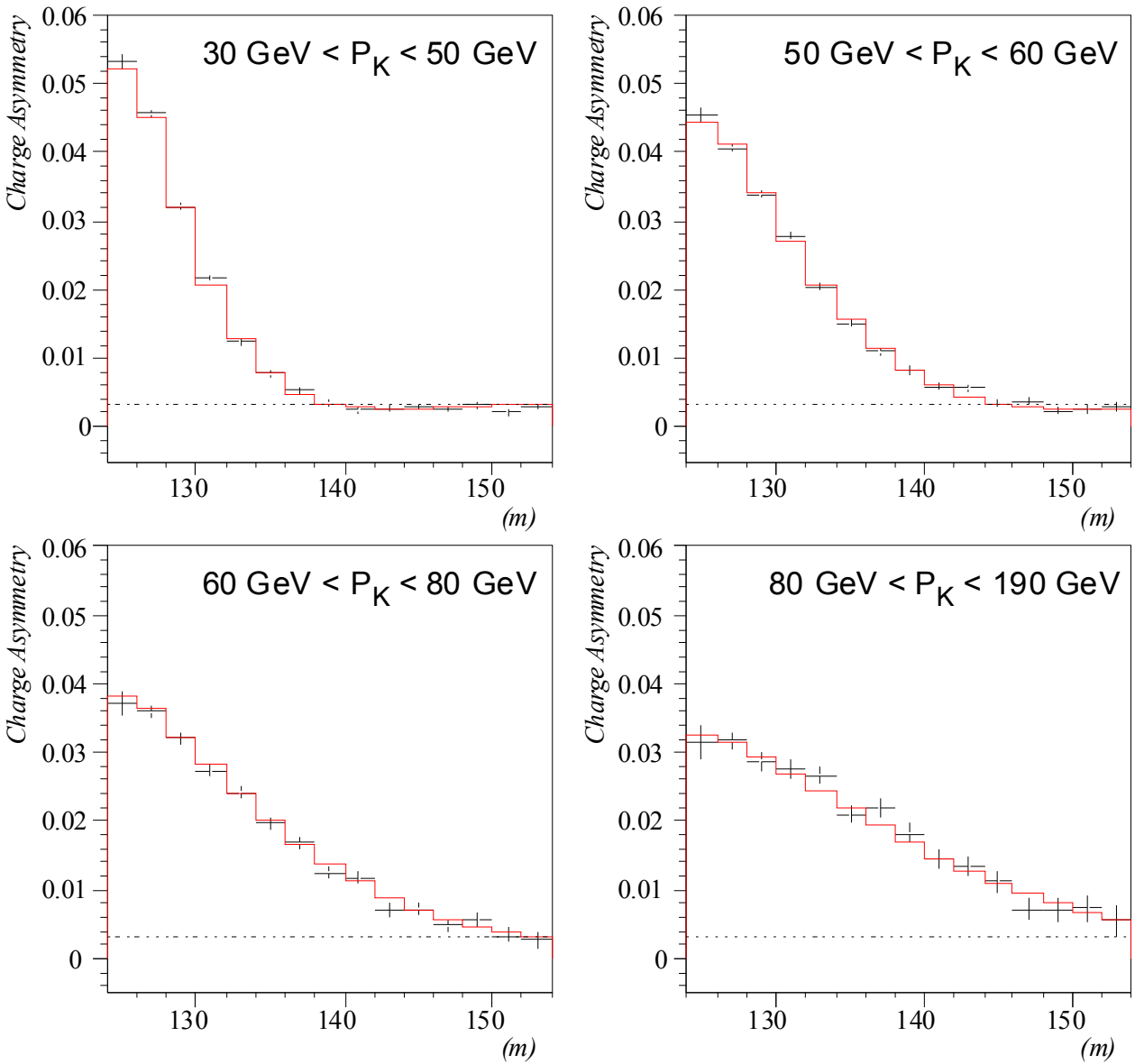
- Fit parameters are then adjusted to minimize the total χ^2.

Fitting Strategy



The Asymmetry Fit

Charge Asymmetry vs. Z_{VTX}



Craft

Fit Results - $\Delta\phi_\rho$

$$\Delta\phi_\rho = \phi_\rho - \left(-90^\circ \cdot (1+\alpha)\right)$$

- Baseline: $\Delta\phi_\rho$ is set to 0 and δ_L is fixed.
- Simple: $\Delta\phi_\rho$ is floated and δ_L is fixed.
- Nominal: $\Delta\phi_\rho$ and δ_L are floated.

Fit	$\Delta\phi_\rho$	Raw $\delta_L \times 10^6$	χ^2/D.o.F.
Baseline	0.0 Fixed	3419 Fixed	$\frac{945.93}{900}$
Simple	$-1.05(83)^\circ$	3419 Fixed	$\frac{944.35}{900-1}$
Nominal	$-0.70(88)^\circ$	3556(93)	$\frac{942.08}{900-2}$

Craft

Fit Results - δ_L

- Nominal: float only δ_L.
- No BG: Fit without any background but also float the magnitude of the regeneration amplitude to match the low proper time asymmetry.

Fit	$\delta_L \times 10^6$	$\frac{f-\bar{f}}{k}$ @70 GeV	χ^2/ D.o.F.
Nominal	3577 ± 89	1.1994 Fixed	$\frac{942.71}{900-1}$
No BG	3556 ± 111	0.9853 ± 0.0076 2.8σ	$\frac{931.04}{900-2}$

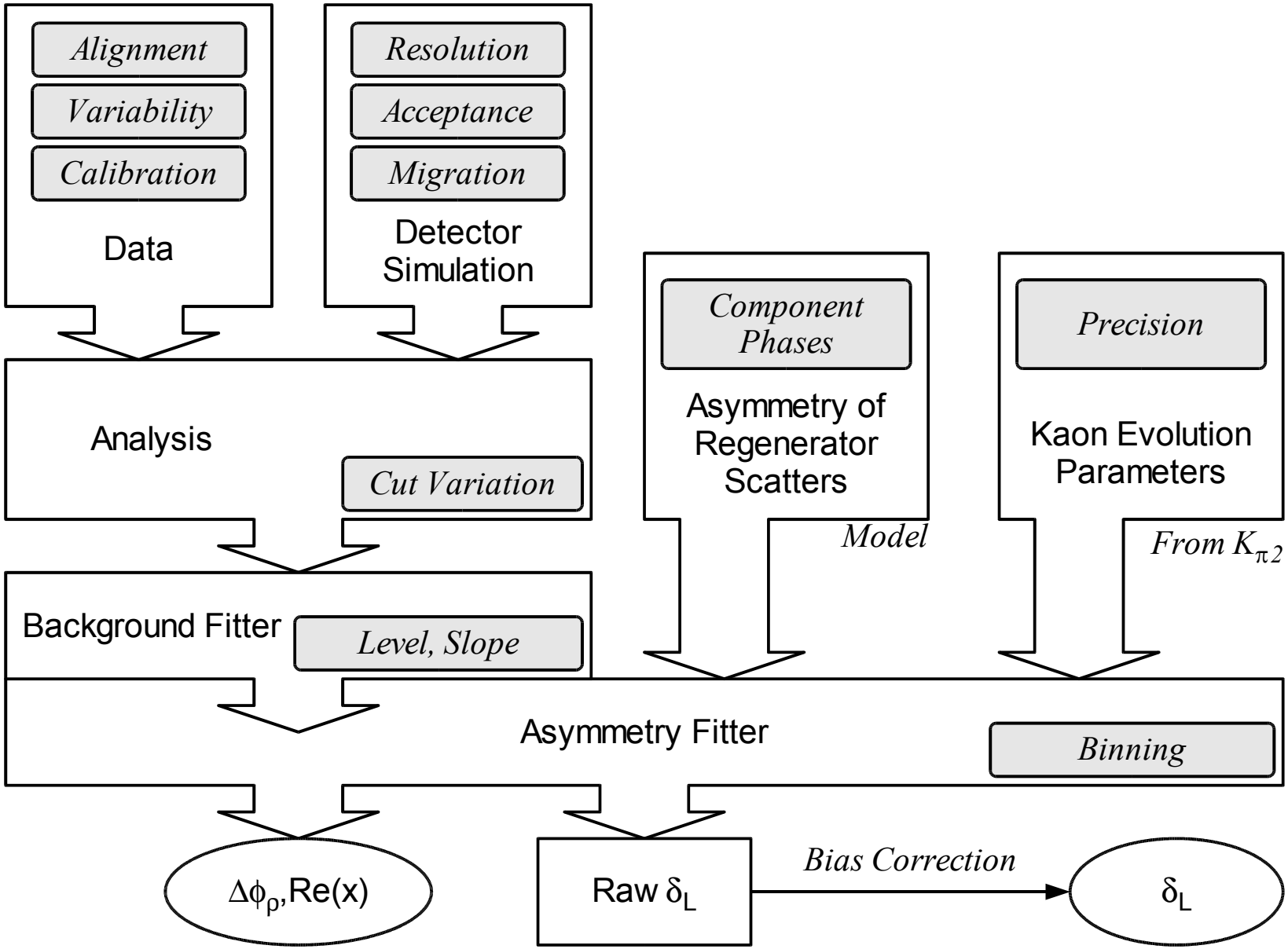
Fit Results - $\Re(x)$

Craft

- Fit with δ_L fixed yield the best statistical error.
- Fit with δ_L floating is preferred to control systematic error.

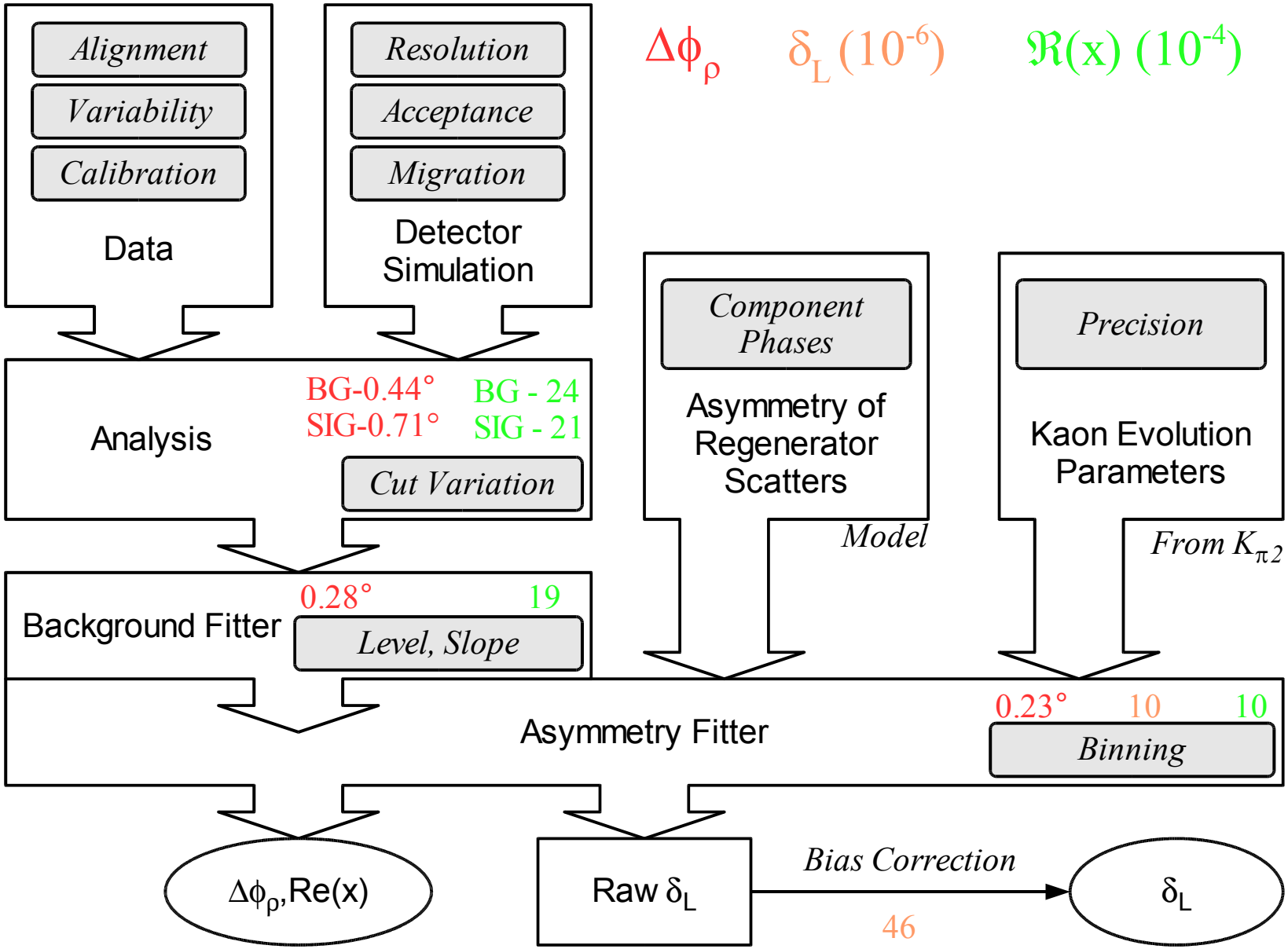
Fit	$\Re(x) \times 10^4$	$\delta_L \times 10^6$	χ^2
Fix δ_L	36 ± 24	3417 Fixed	$\frac{943.6226}{900-1}$
Nominal	12 ± 34	3547 ± 111	$\frac{942.5494}{900-2}$

Systematics



Craft

Systematics



Systematics

- Many, many systematic checks are considered
  - East/West comparisons
  - Up/Down comparisons
  - Time period comparisons
  - Floating kaon evolution parameters
  - Altering binning in the fitter
  - Multiple treatments of the Z_{VTX} resolution
  - Variation of the cutoffs for the background normalization
  - Variation of the background fit parameters
  - Variation of the analysis cuts

Systematics

Craft

Background Cut Variation

Parameter	New Cut	$\delta\Delta\phi_\rho$	$\delta\Re(x)$ $\times 10^4$
RINGNUMBER	110→80	-0.10±0.22°	-5±1
	110→100	-0.13±0.07°	0±10
	110→120	0.01±0.06°	-8±9
P_T^2	0.54→0.50	0.00±0.03°	0±1
	0.54→0.58	0.00±0.02°	0±1
	0.54→0.62	0.00±0.02°	0±1
P_{Te}^2	0.54→0.50	0.00±0.04°	0±1
	0.54→0.58	0.00±0.03°	0±1
	0.54→0.62	0.00±0.01°	0±1
$P_{T\pi}^2$	0.54→0.50	-0.02±0.15°	-5±5
	0.54→0.58	0.02±0.01°	1±1
	0.54→0.62	0.02±0.02°	1±7
ARGUMENT$_{min}$	-0.002→0.000	-0.40±0.24°	-22±9
	-0.002→-0.004	-0.04±0.10°	-3±4
	-0.002→-0.008	0.32±0.19°	10±6
ARGUMENT$_{max}$	∞→0.03	-0.07±0.03°	1±2

Analysis Cut Variation

Parameter	Shift	$\delta\Delta\phi_\rho$	$\delta\Re(x)$ $\times 10^4$
Max Offmag χ^2	500→1000	0.01° ± 0.13°	0 ± 1
Max Vertex χ^2	100→500	0.08° ± 0.02°	5 ± 1
Max Regenerator	2→18 MIPS	-0.20° ± 0.23°	-11 ± 7
Max Regenerator	2→1.5 MIPS	-0.24° ± 0.20°	-6 ± 3
Max Lead Module	0.7→0.3 MIPS	0.09° ± 0.18°	1 ± 6
Max Lead Module	0.7→2.0 MIPS	-0.04° ± 0.12°	-1 ± 4
Min Elec. EOP	0.94→0.90	-0.09° ± 0.06°	-4 ± 1
Max Elec. EOP	10.00→1.05	0.11° ± 0.05°	5 ± 1
Max π EOP	0.85→0.80	0.11° ± 0.09°	1 ± 2
Max π EOP	0.85→0.90	-0.06° ± 0.06°	-3 ± 2
Min P_π	8→5 GeV	-0.00° ± 0.13°	2 ± 11
Min P_π	8→12 GeV	0.11° ± 0.25°	2 ± 5
Min P_e	8→5 GeV	0.15° ± 0.19°	11 ± 8
Min P_e	8→10 GeV	0.45° ± 0.27°	-2 ± 10
Min P_e	8→12 GeV	0.63° ± 0.39°	-4 ± 15
Min ΔX,Y,R	3→10 cm	-0.10° ± 0.29°	-6 ± 10
Min Cell Sep.	3→0	-0.11° ± 0.29°	-3 ± 11
Min Cell Sep.	3→4	0.11° ± 0.20°	13 ± 8
$P_{\pi^0 KIN}$	0→-0.02	-0.14° ± 0.03°	-4 ± 2

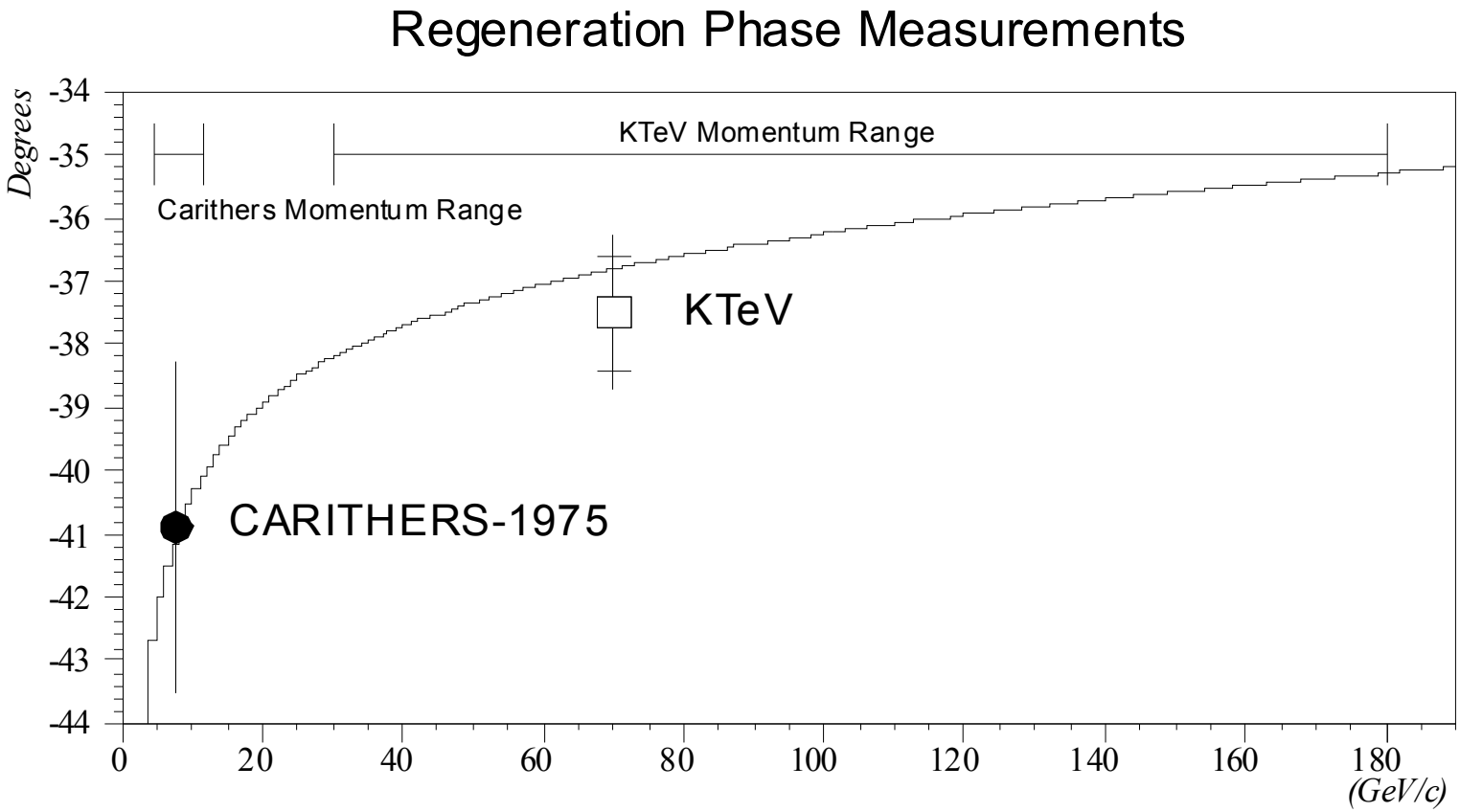
Final Systematic Errors

Craft

Source	Uncertainty		
	$\delta\Delta\phi$	$\delta(\delta L)\times 10^6$	$\delta\Re(x)\times 10^4$
Fitting and Migration	0.23°	10	10
Background Cuts	0.44°		24
Background Fit	0.28°	21	19
Analysis Cuts	0.71°		21
Detector Asymmetry	0.03°	10	4
Asymmetry Correction		46	
	0.91°	53	39

Final Results - Regeneration Phase

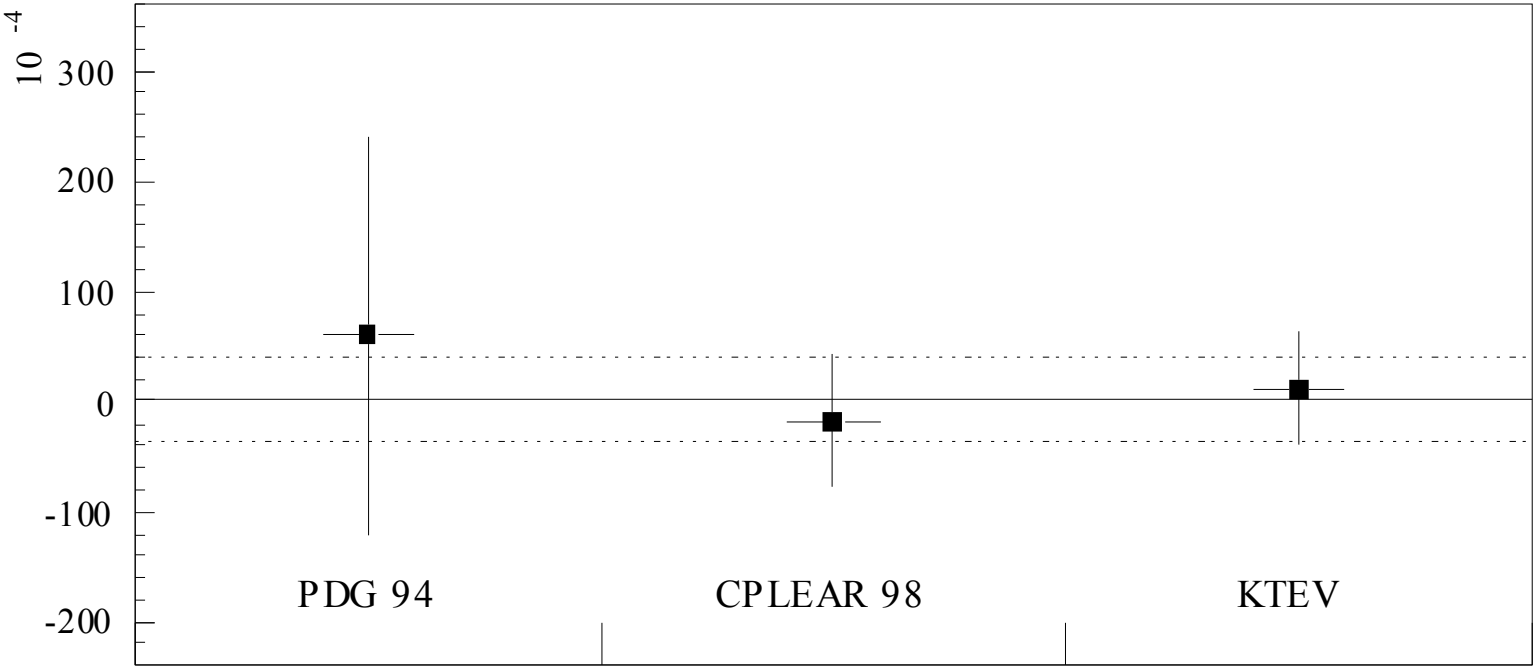
Surface



$$\phi_\rho - \phi_{analyticity} = 0.70^\circ \pm 0.88^\circ (stat) \pm 0.91^\circ (syst)$$

Surface

Final Results - $\Re(x)$

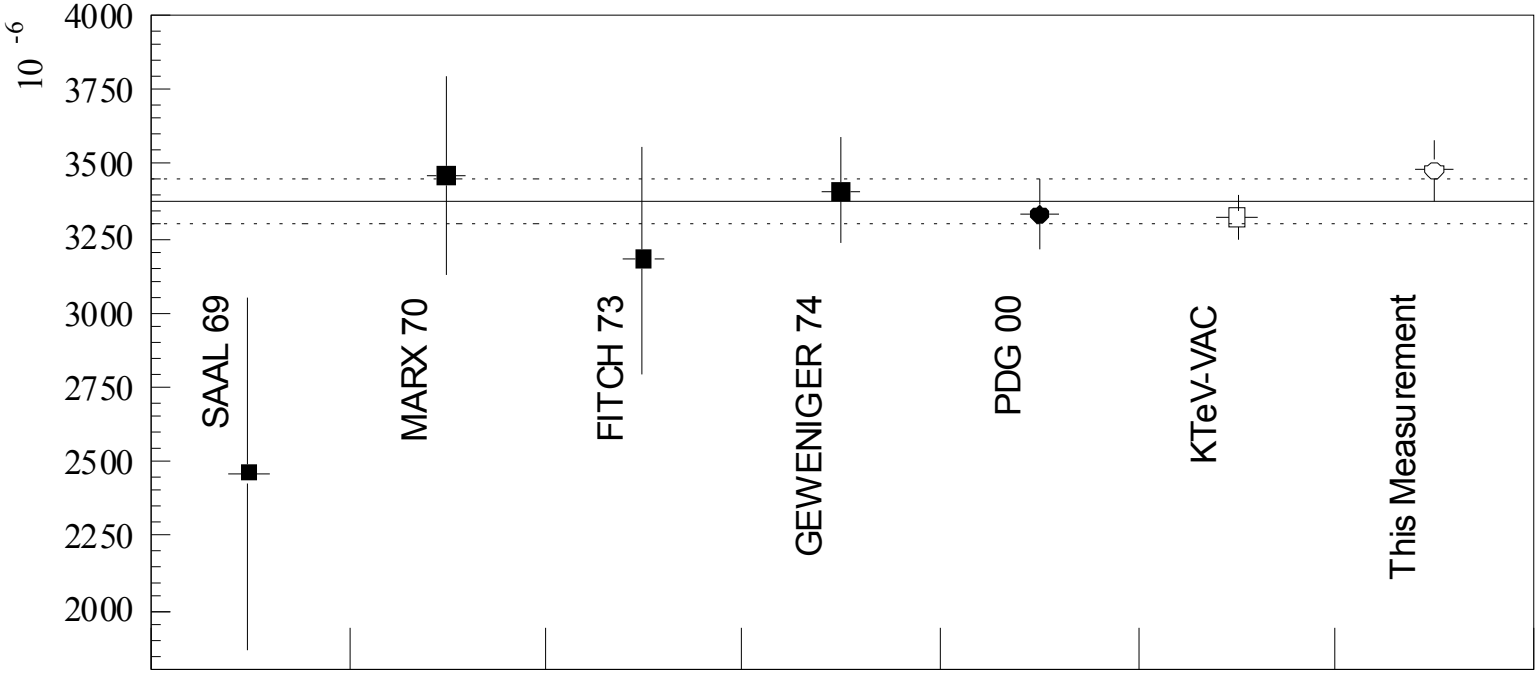


$$\text{KTeV: } \Re(x) = \left(12 \pm 33\,(stat) \pm 39\,(syst)\right) \times 10^{-4}$$

$$\text{World Avg: } \Re(x) = \left(2.4 \pm 38\right) \times 10^{-4}$$

Surface

Final Results - δ_L



KTeV Reg: $\delta_L = \left(3480 \pm 89\,(stat) \pm 53\,(syst)\right) \times 10^{-6}$

KTeV Avg: $\delta_L = \left(3375 \pm 71\right) \times 10^{-6}$

World Avg: $\delta_L = \left(3366 \pm 63\right) \times 10^{-6}$

Surface

Summary

- Regeneration Phase Measurements
  - Analyticity of the Regeneration Amplitude has been affirmed.
    - 1.25 degree precision
    - High energy compared to previous measurements
  - Large shifts in the phase due to hypothetical scattering resonances are ruled out.
- Measurements of Re(x)
  - Consistent with 0 and with standard model
  - World's best precision
- Measurements of δ_L
  - Consistent with previous measurements
  - More precise than pre-KTeV world average

Surface

The Take Away

Ars longa, vita brevis.

- Seneca's translation of Hippocrates

- For us, our art will outlast our lives.
- This is clearly true for the kaon itself. Short lived, but destined to complete a larger pattern.

$$\left|Art_L\right\rangle, \left|Life_S\right\rangle$$

- My translation of Seneca's translation of Hippocrates

- The kaon system inspires more questions:
  - Do art and life have a cross term?
  - Where is my regenerator?
  - What would Hippocrates say?

Surface

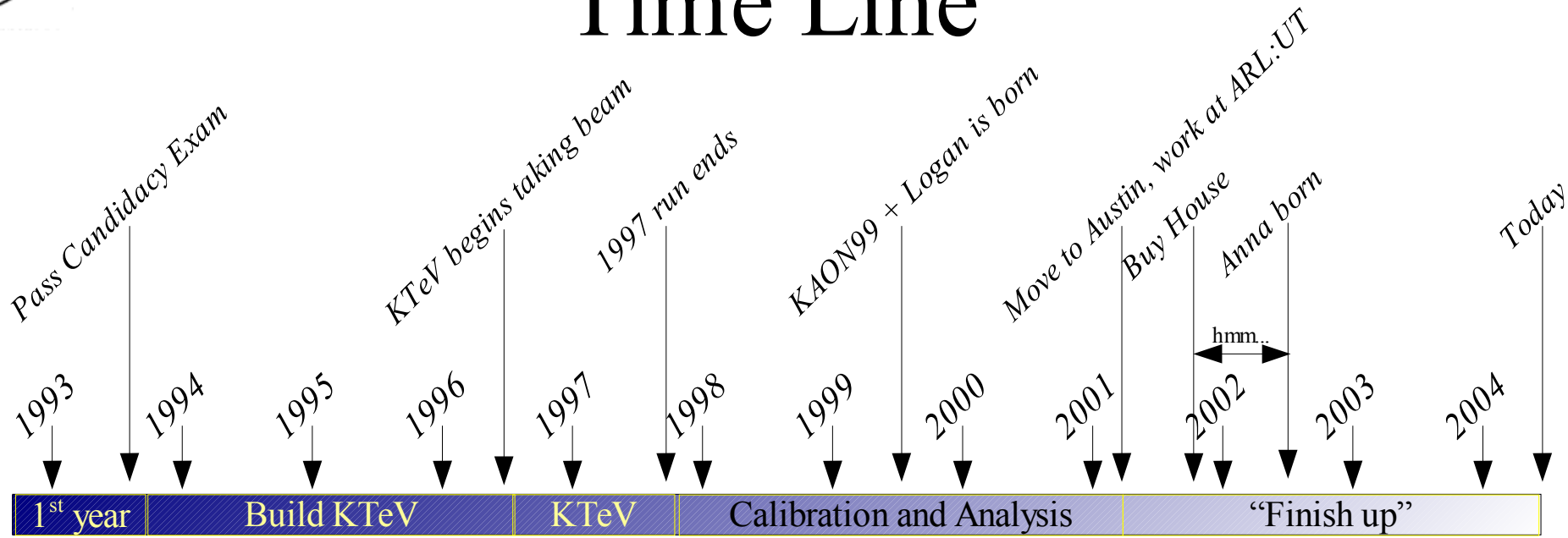
The Take Away

Life is short,
the art long,
opportunity fleeting,
experiment treacherous,
judgment difficult.

- Hippocrates

Remember the Children

Time Line



1st year

Pass Candidacy Exam

Build KTeV

Build HCC

Install HCC

Install E_{TOT}

Repair E_{TOT}

KTeV

Many Owl Shifts

HCC/E_{TOT} Pager

Shift coordinator

Calibration and Analysis

Logistic Regression fitting of HCC thresholds

Kolmogorov-Smirnov fitting of aperture positions

Drift chamber investigations

Synchrotron radiation study

Regenerator MC

New fitter for asymmetry

Systematics, systematics, systematics

"Finish up"

Learn new field

Find final bug in the fitter

Write