LEP Energy Calibration

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LEP W Physics Jamboree

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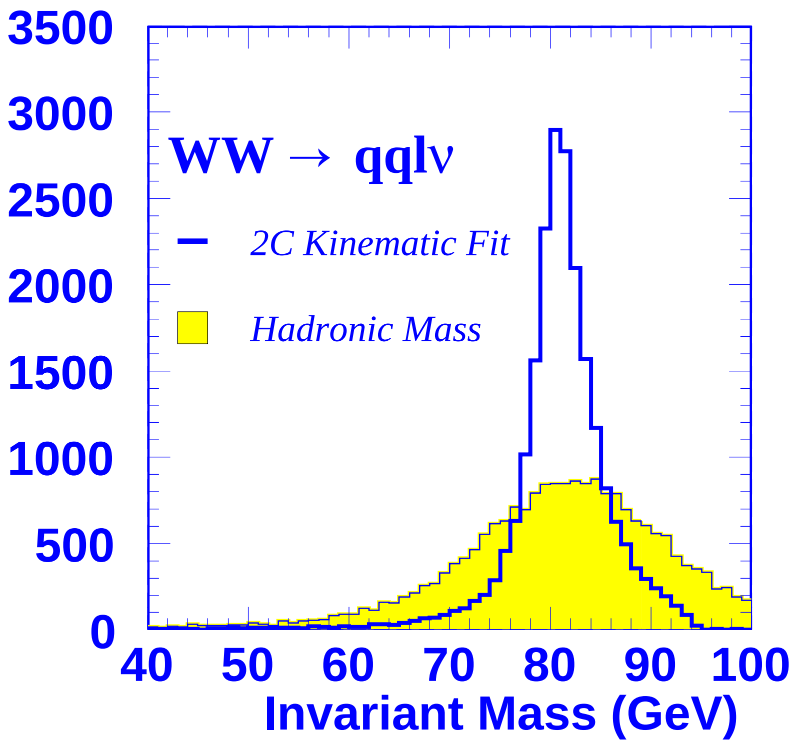
for the
LEP Energy Working Group

- Magnetic Extrapolation
- Energy Loss (Q_S vs. V_{RF})
- Spectrometer
- Radiative Returns

LEP II Energy Needs

Kinematic Fits



- Improved resolution on M_W
- Reduced detector uncertainties
- Need to know Beam Energy $\frac{\delta M_W}{M_W} \approx \frac{\delta E_{Beam}}{E_{Beam}}$

⇛ Scale Error common to all experiments

LEP II Combined

Expected Statistical Error: $\delta M_W \sim 20 MeV$

Beam Energy Goal: $\delta E_{Beam} \sim 10 MeV$

⇛ Precision of $\delta E_{beam}/E_{beam} < 1\text{x}10^{-4}$

Resonant Depolarization

High Precision technique used extensively at LEP I

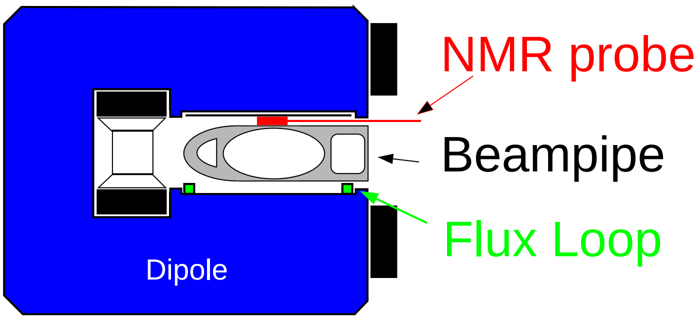
Spin Precession Frequency: $\nu_s = \frac{g_e - 2}{2m_e c^2}\langle E_{Beam}\rangle$

Intrinsic Resolution: $\delta E_{Beam} \approx 200 keV$

$\Rrightarrow$ Only works up to $E_{Beam} \sim 60$ GeV

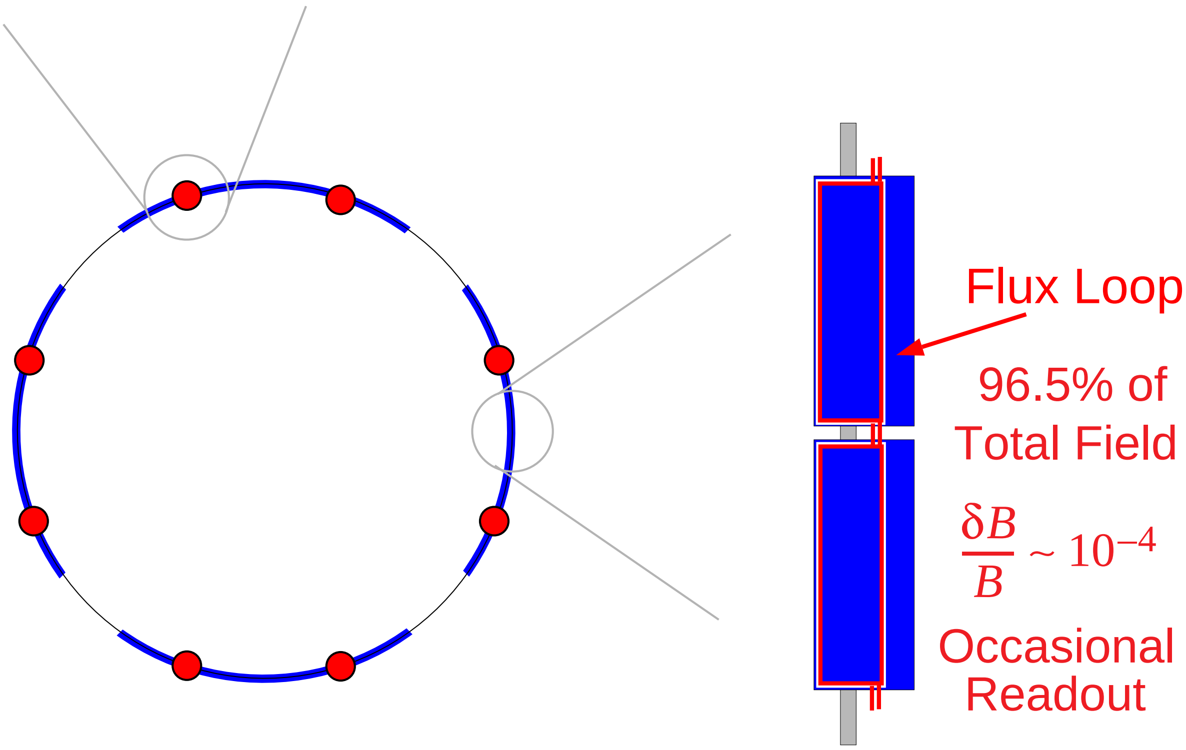
Total Bending Field

$E_{Beam} \propto \oint B_\perp dl$



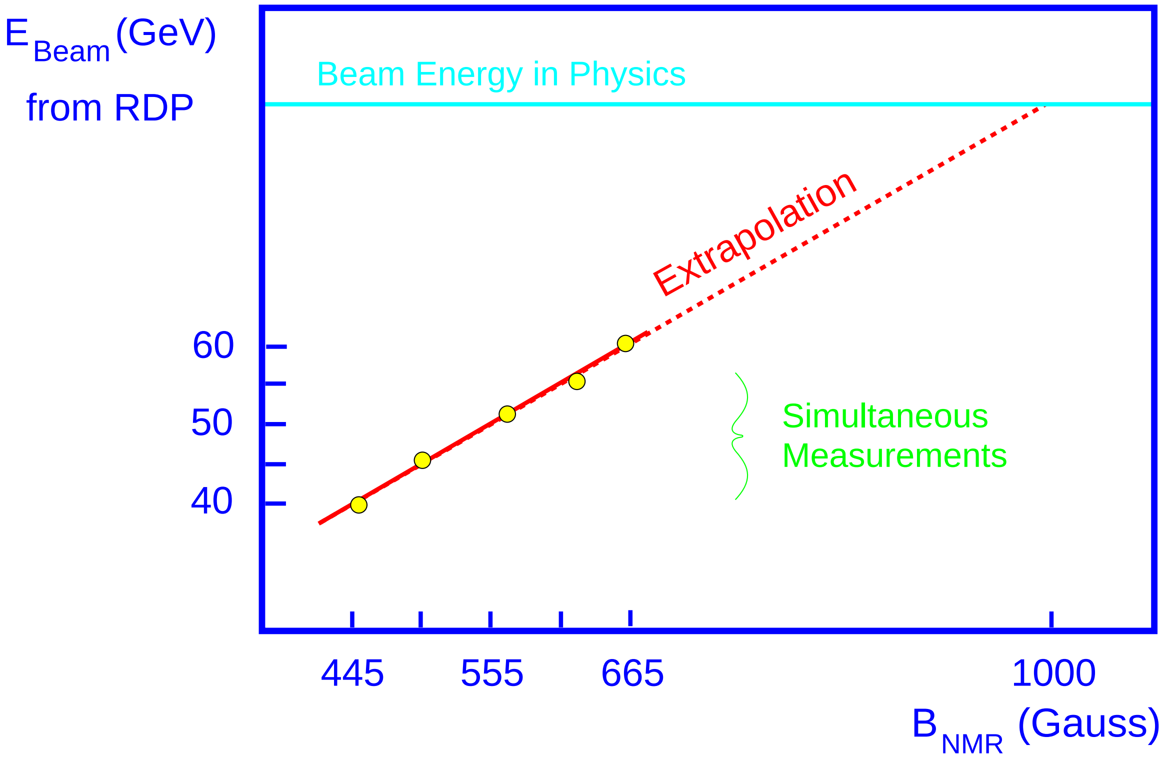
16 Probes $\frac{\delta B}{B} \sim 10^{-6}$

Continuous Readout

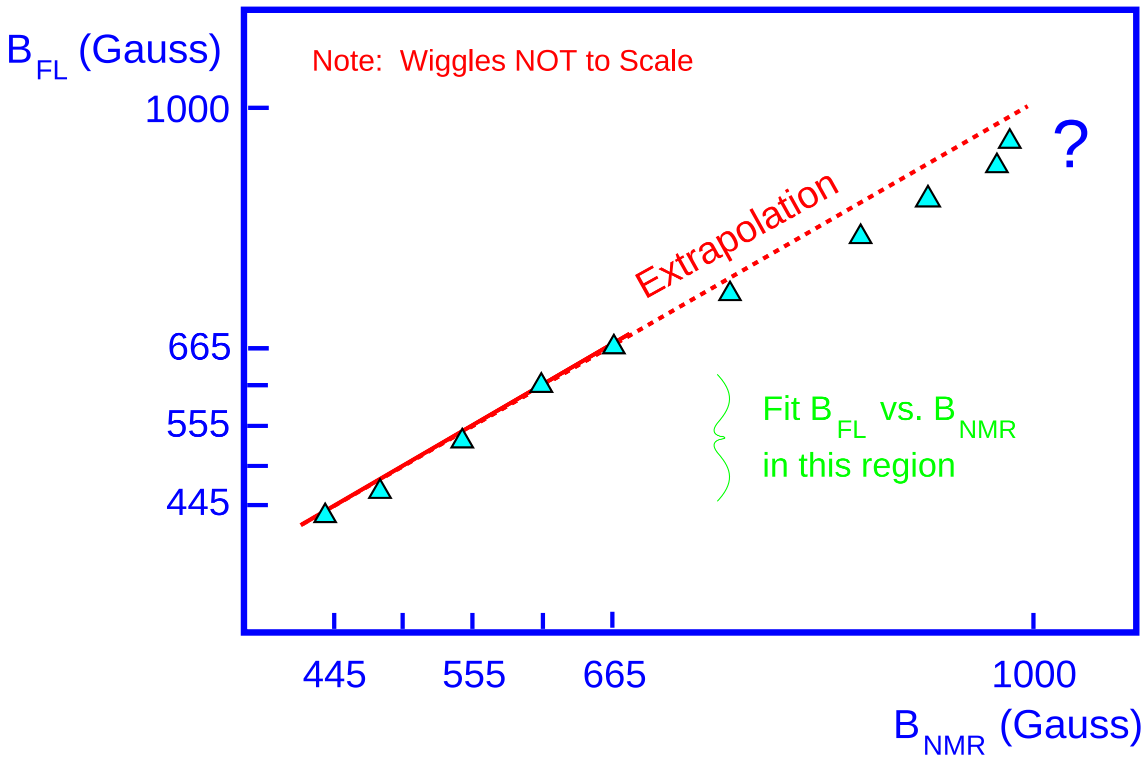


Magnetic Extrapolation

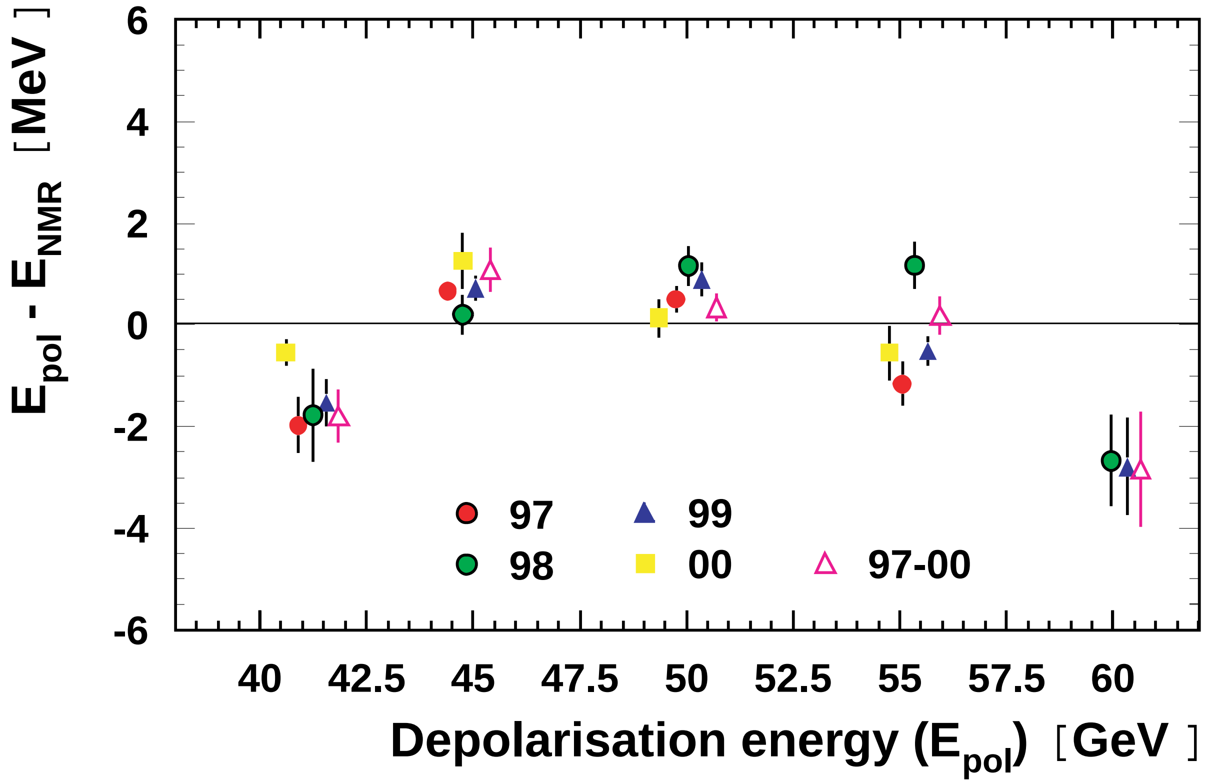
Step 1: Calibrate NMRs with RDP

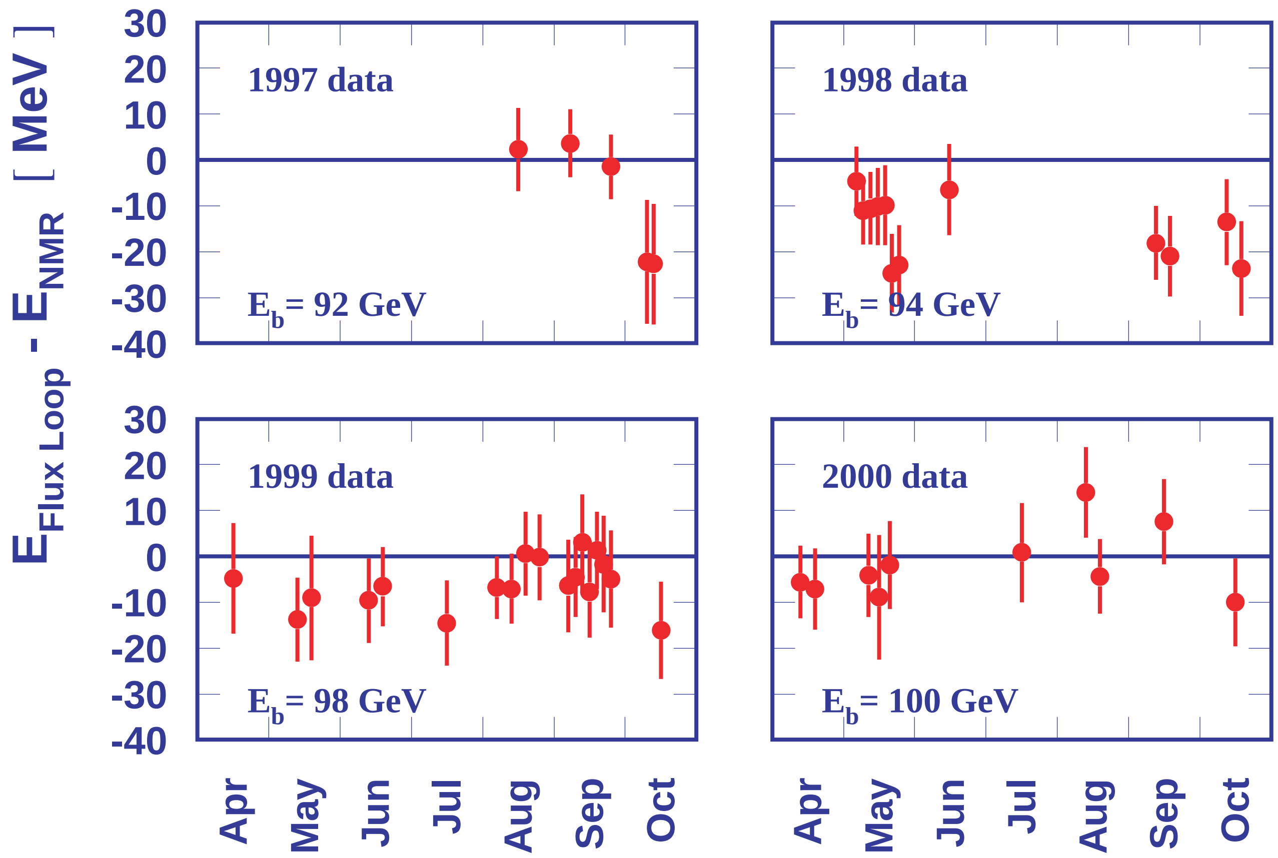


Step 2: Cross Check Linearity with Flux Loop



Extrapolation Data





Extrapolation Errors

Systematic Uncertainty	δE_{beam} (MeV) 1998	2000
NMR - FL Comparison	16	16
NMR Calibration	9	13
BFS Calibration	-	13
IP Specific Corrections	4	5
Other Errors	8	5
Total	20	25

⇛ Preliminary 2000 Results

$$\delta M_W = 20 MeV \text{ (2000 data)}$$

Energy Scale Cross-Checks

- Energy Loss (Q_s vs V_{RF})
- LEP Spectrometer
- Radiative Return Analysis

⇛ Verify LEP II Energy Scale

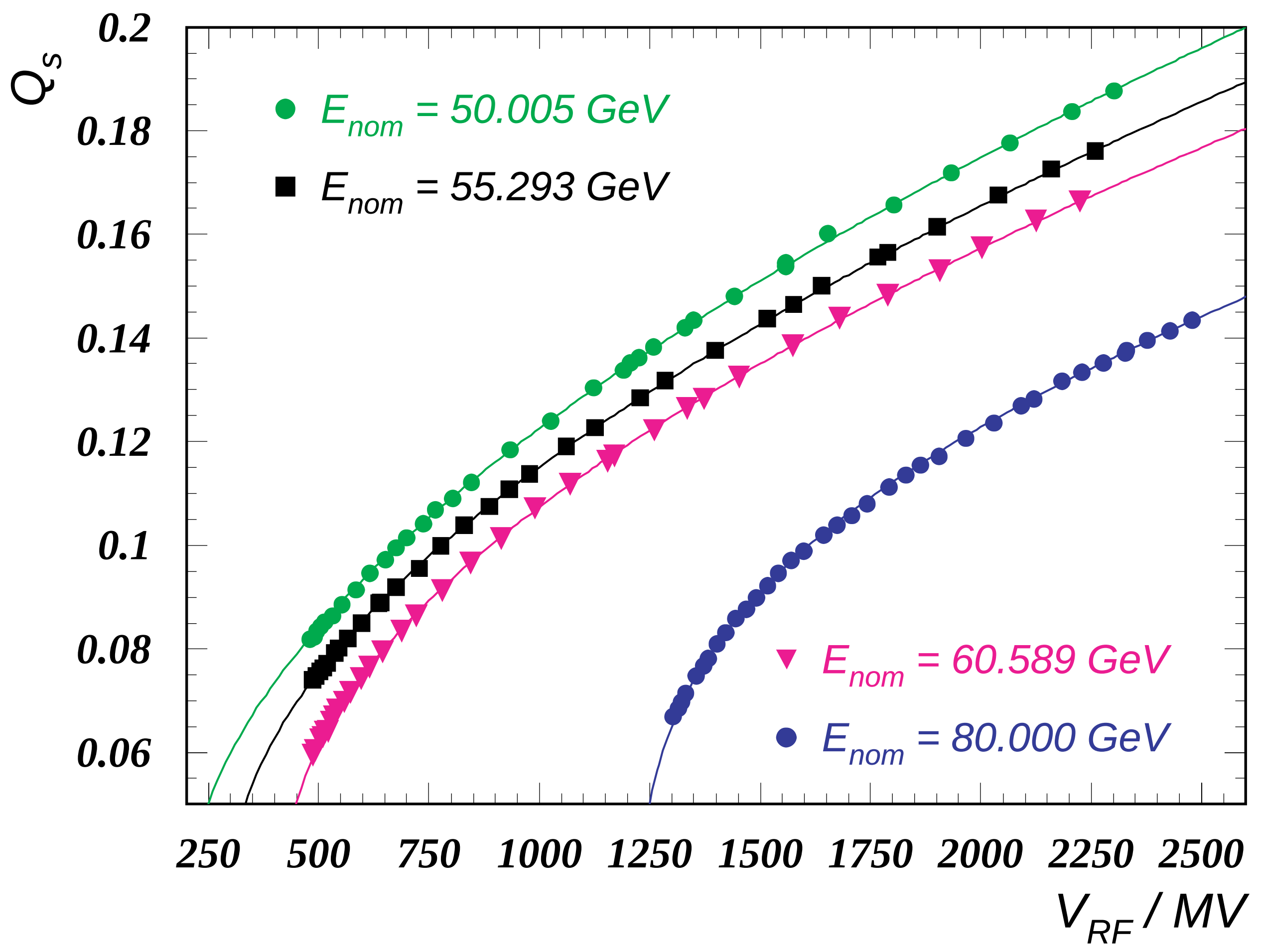
Reduce Uncertainty if Possible

Synchrotron Oscillations

$$Q_s^2 = \left(\frac{\alpha_c h}{2\pi E}\right)\sqrt{e^2 V_{RF}^2 - U_0^2}$$

Q_s depends on Beam Energy, RF Voltage, and Energy Loss

Measure Q_s vs V_{RF}



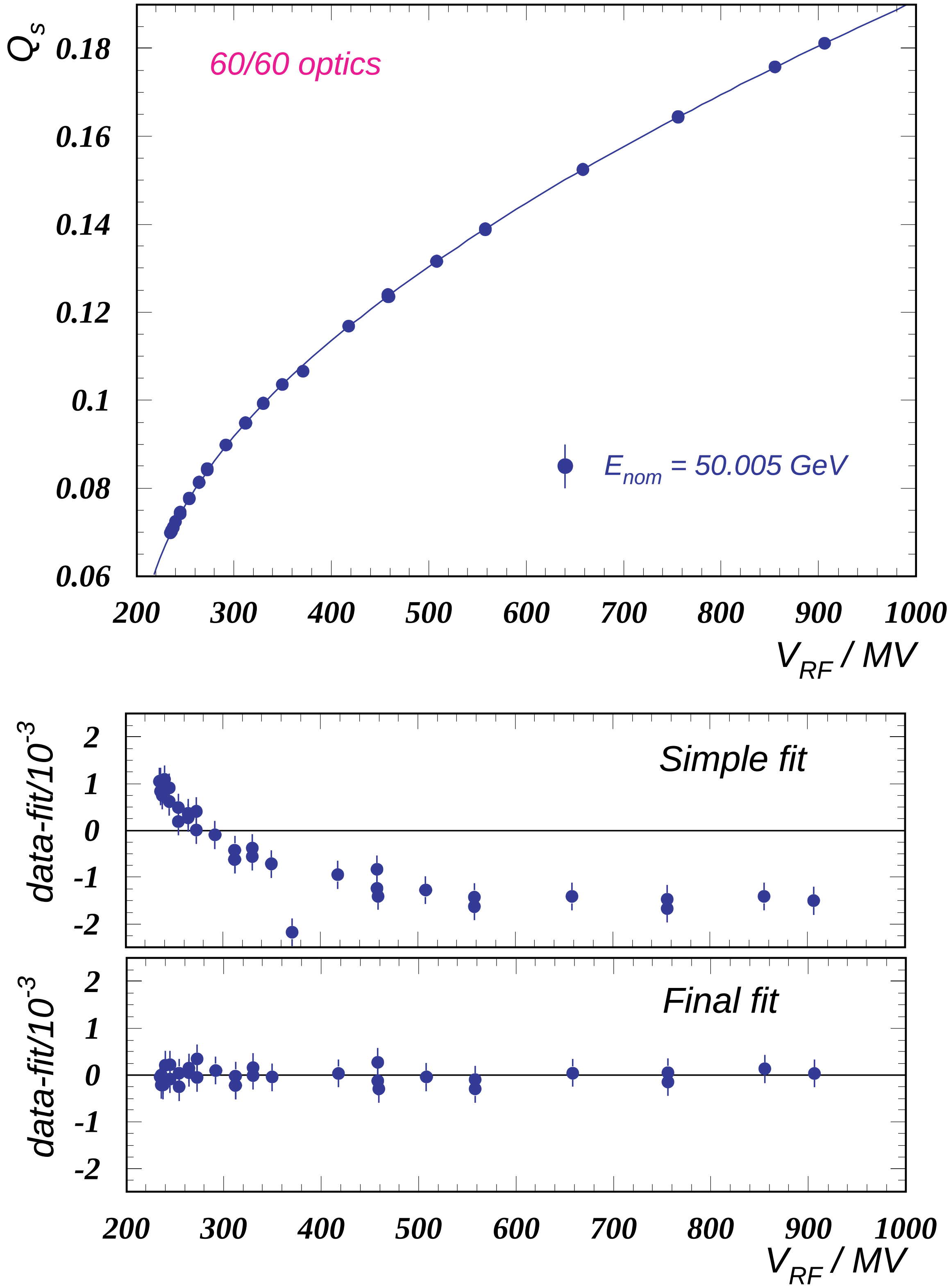
Use low energy points for calibration

Use high energy points to check extrapolation

The Final Fit

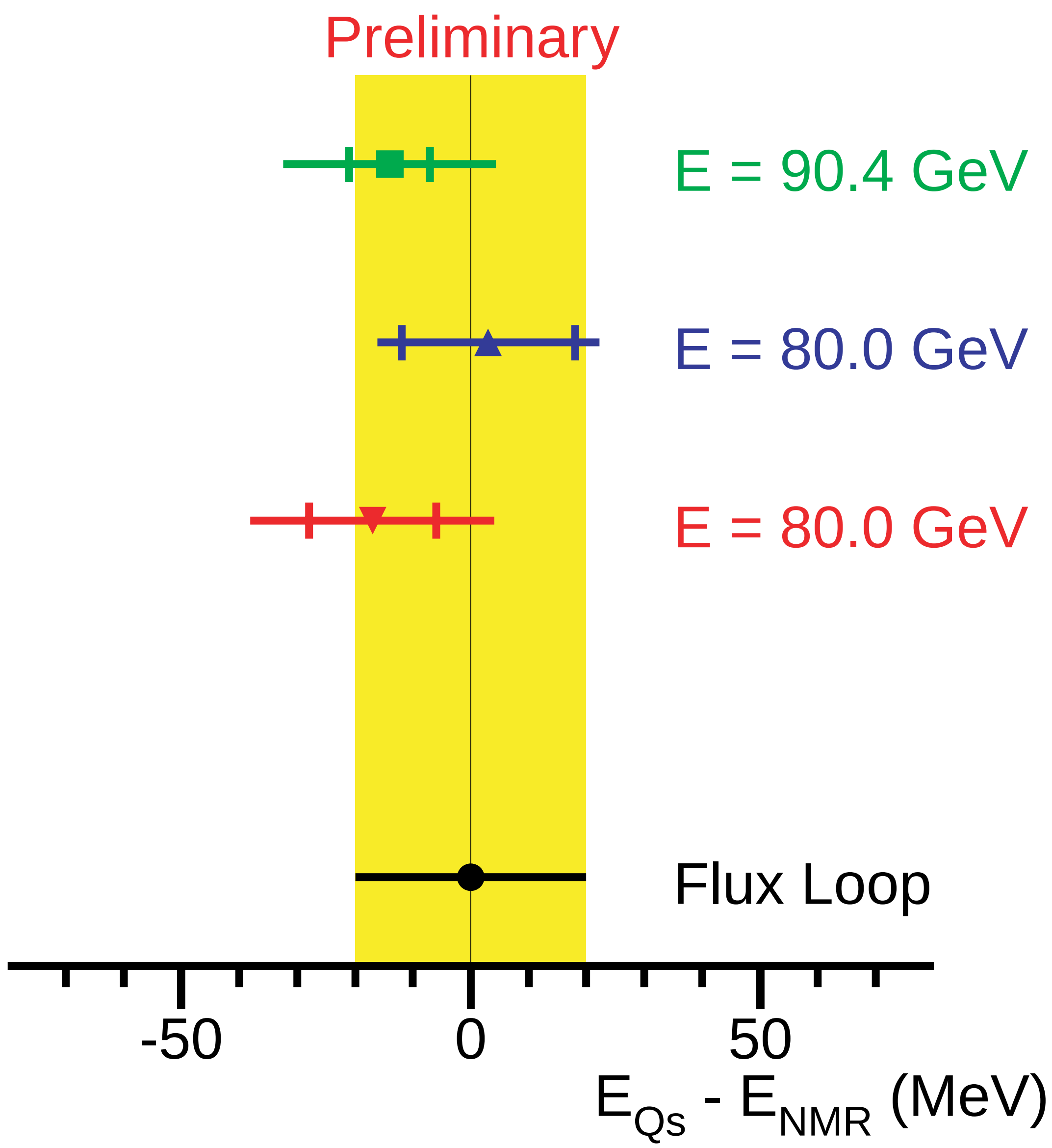
$$Q_s^4 = \left(\frac{\alpha_c h}{2\pi}\right)^2 \left\{ \frac{e^2 g^2 V_{RF}^2}{E_c^2} + M g^4 V_{RF}^4 - \frac{1}{E_c^2}\left(\frac{C_\gamma}{\rho}E^4 + K\right)^2 \right\}$$

Momentum Compaction | RF Voltage Calibration | Realistic RF Distribution | Dipole Losses | Other Losses



Q_s Measurements

1998 - 1999 Results



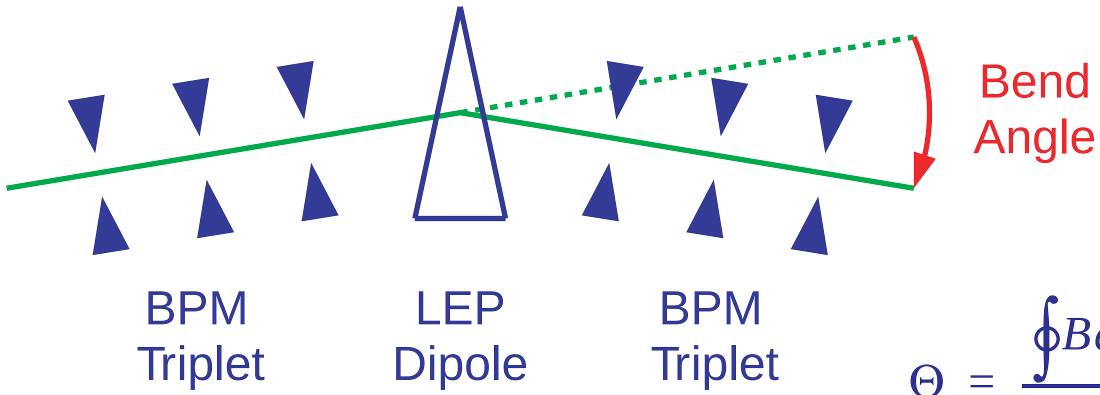
Inner error bars indicate statistical component

⇛ Good agreement with Flux Loop

2000 Status

- Auxiliary measurements made of model parameters
- Three additional energy measurements performed

Inline Spectrometer Concept



$$\Theta = \frac{\oint B dl}{E_{Beam}}$$

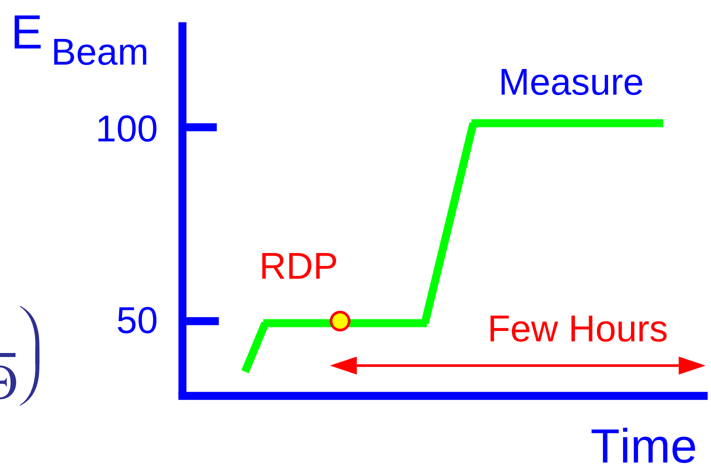
- Use dipole which ramps with LEP
- $\oint B dl$ from Local NMR and precision Field Map
- BPM Triplets measure bend angle Θ

$$\Theta = 4.8 mRad \Rrightarrow \delta x_{BPM} \sim 1 \mu m$$

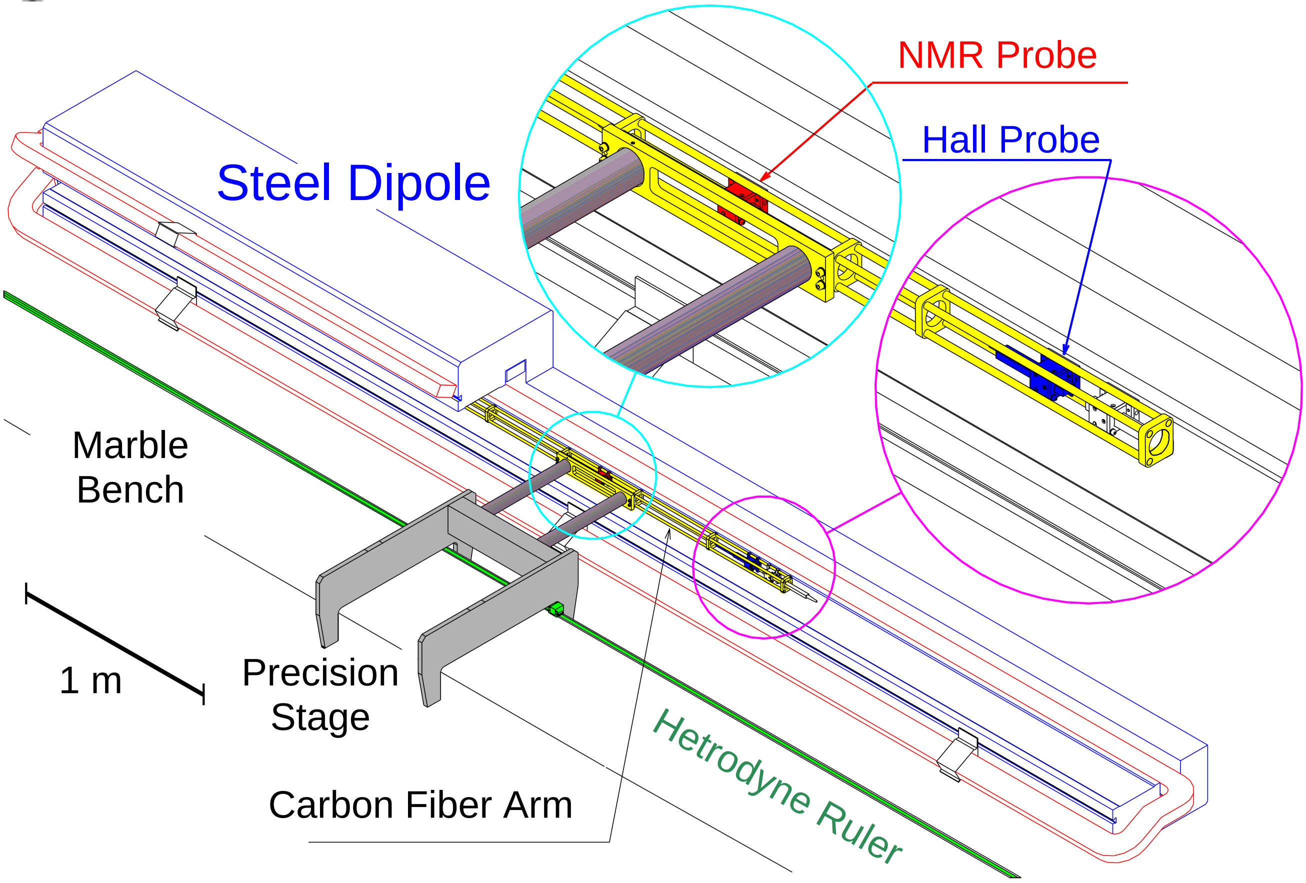
Relative Energy Measurement

- Calibrate Spectrometer using RDP
- Ramp immediately to Physics Energy
- Direct Measurement of E_{Beam} in ratio

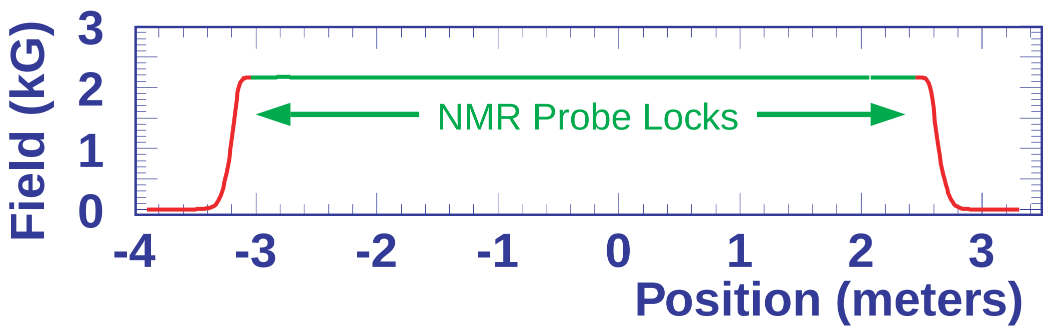
$$\frac{E^{100}_{Beam}}{E^{50}_{Beam}} = \frac{\oint B dl \big|_{100}}{\oint B dl \big|_{50}} \left(\frac{\Theta}{\Theta + \Delta\Theta} \right)$$



Magnet Mapping



Need $\oint B dl$ as $f(B_{Ref})$



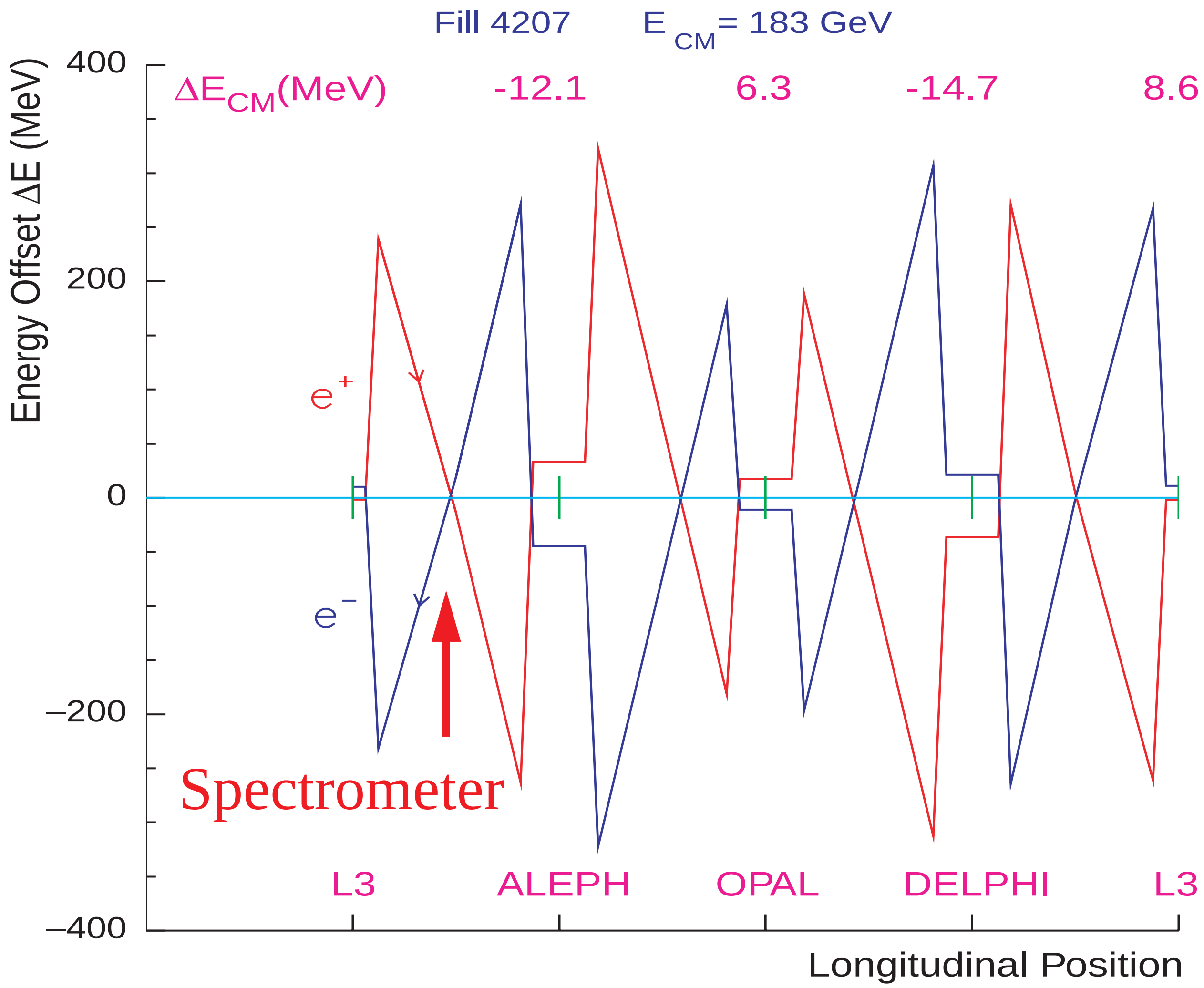
NMR Probe: $\delta B/B \sim 10^{-6}$ over 90%

Hall Probe: $\delta B/B \sim 10^{-4}$ over 10%

Precision of ~ 3×10^{-5} achieved in 1999

Magnet is currently being re-mapped

RF Sawtooth



Nearly 3 GeV lost per revolution at E_b = 100 GeV

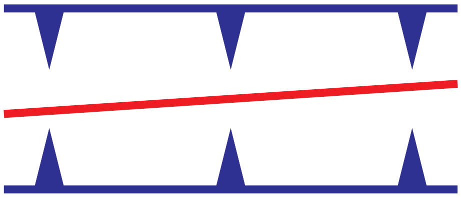
RF Model

- Constrained with experimental data
- Dedicated data taken in 2000 to measure IP phase errors
- Single-beam spectrometer data particularly sensitive

⇛ Correction of 20 - 50 MeV at IP3

Beam Position Monitors

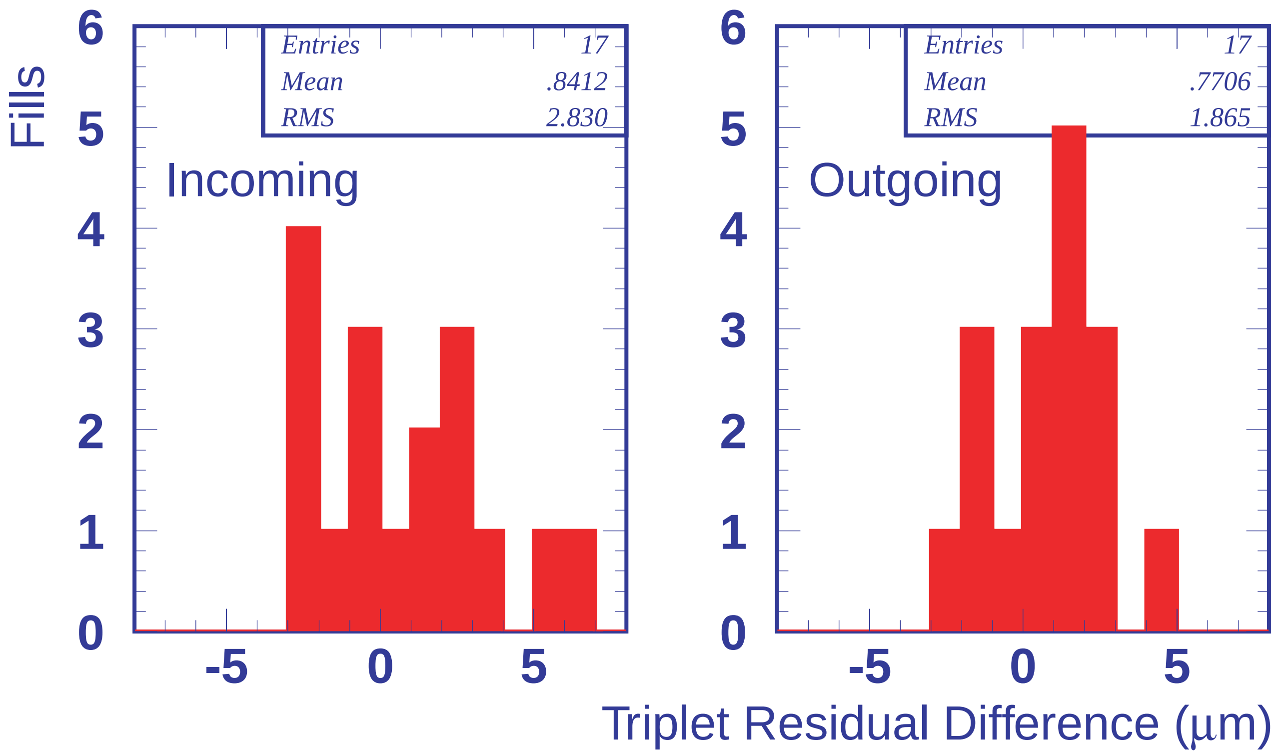
BPM Triplet



Triplet Residual

$$\Rightarrow \quad T = \frac{(x_1 + x_3)}{2} - x_2$$

High Energy Residuals

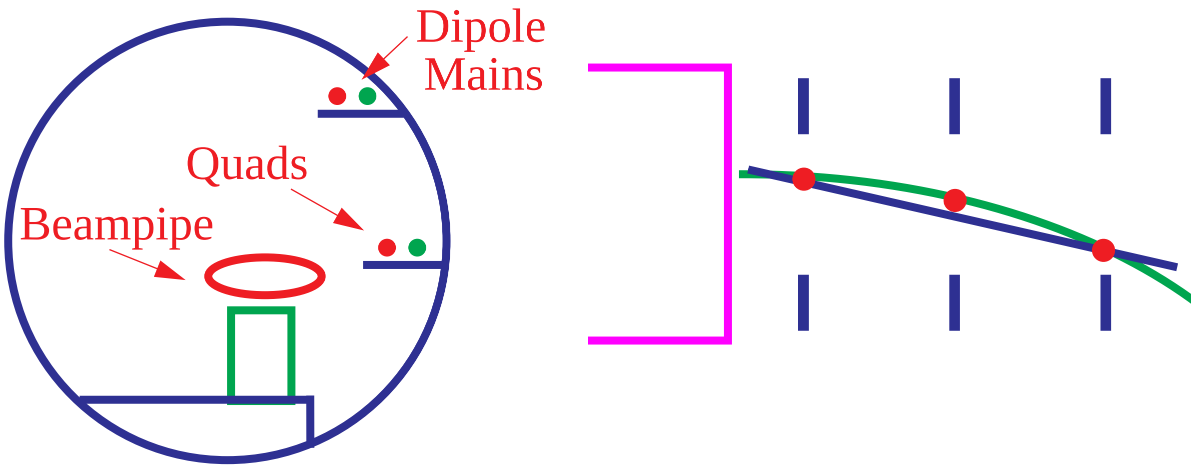


Possible Biases

- Ambient Tunnel Fields
- BPM Gain Calibration
- Electronic Cross-Talk
- Transverse Beam Size Dependence
- Bunch Length Dependence
- Synchrotron Radiation Dependence

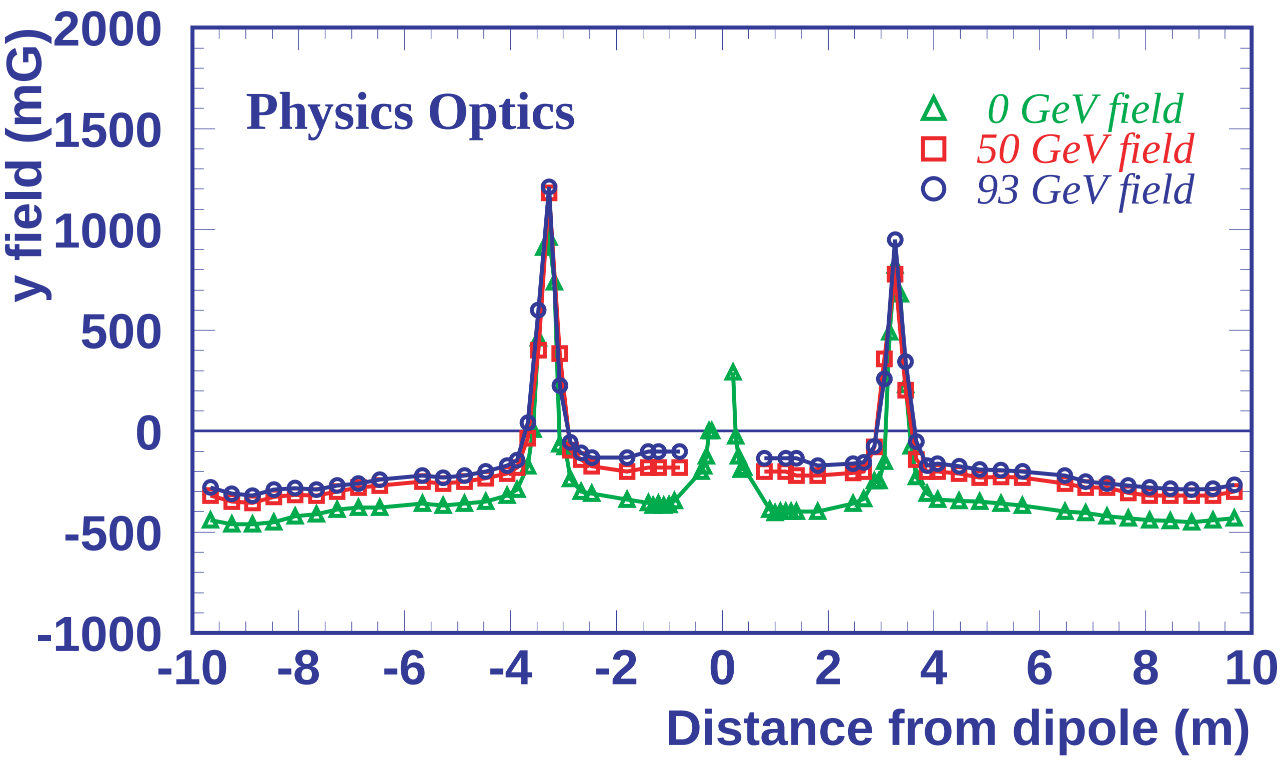
Most effects insignificant, remaining corrected

Ambient Fields



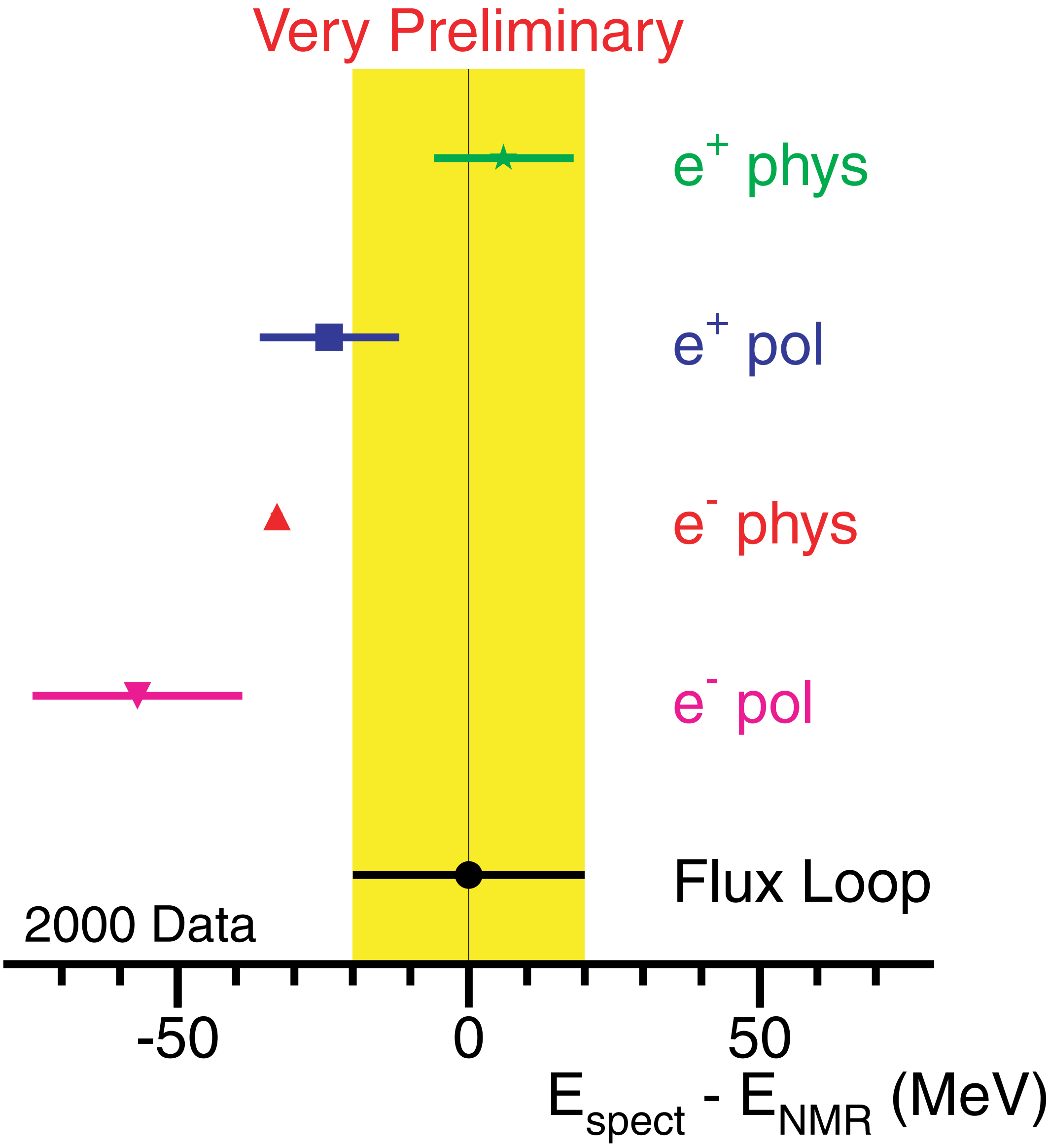
- Additional fields of ~200 mGauss measured
- Expect -2 x 10^{-4} effect with small optics dependence

Tunnel Field Map



Monitored continuously and corrected

Spectrometer Results

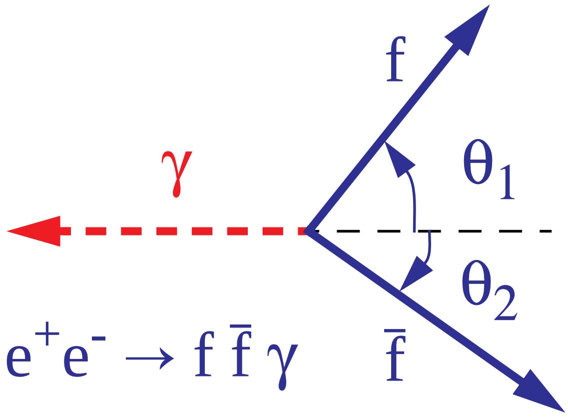


Error Bars indicate RMS of measurements

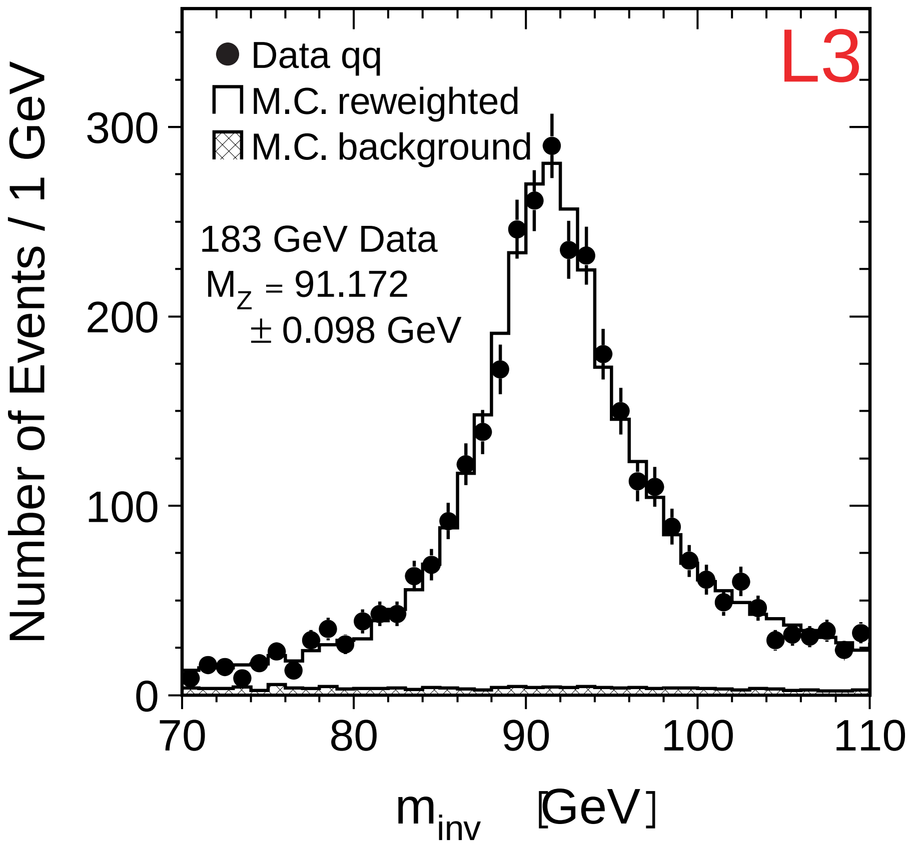
⇛ No disagreement with Flux Loop

Significant systematics still to be understood...

Radiative Returns



$$\frac{s'}{s} = \frac{\sin\theta_1 + \sin\theta_2 - |\sin(\theta_1 + \theta_2)|}{\sin\theta_1 + \sin\theta_2 + |\sin(\theta_1 + \theta_2)|}$$



$q\bar{q}\gamma$ $\Delta E_{beam} \sim 20$ MeV

$\mu\mu\gamma$ $\Delta E_{beam} \sim 50$ MeV

LEP Combined

Stat Only

Systematics

- Theoretical Description
- Hadronization Uncertainties
- Detector Understanding

Preliminary Estimates

$q\bar{q}\gamma$ $\Delta E_{beam} \sim 70$ MeV

$\mu\mu\gamma$ $\Delta E_{beam} \sim 40$ MeV

Conclusions

NMR - Flux Loop Extrapolation

- Good stability seen during LEP II operations
- Precision limited at ~ 15 MeV

Q_s vs V_{RF}

- Direct measurements to reduce/understand systematics
- Results consistent with Flux loop extrapolation
- Work continues to refine model

LEP Spectrometer

- Major effort in 2000 to understand systematics
- Results consistent with Flux loop extrapolation
- Significant work remains...

Radiative Returns

- Significant differences observed
- LEP-wide collaboration ongoing
- Probably more difficult than M_W

$\Rrightarrow$ Work Continues...

Special thanks to CERN/SL division!