Calibration of centre-of-mass energies at LEP2 for a precise measurement of the W boson mass

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Report on final analysis. Paper in preparation

CERN, 16/3/04

Outline of Seminar

E_{cm} and the W mass measurement

Tools of energy calibration:
- Resonant depolarisation and the NMR magnetic model
- Other ingredients of the energy model

Tests of the NMR model: ← Bulk of talk!
- Flux Loop
- Spectrometer
- Q_s

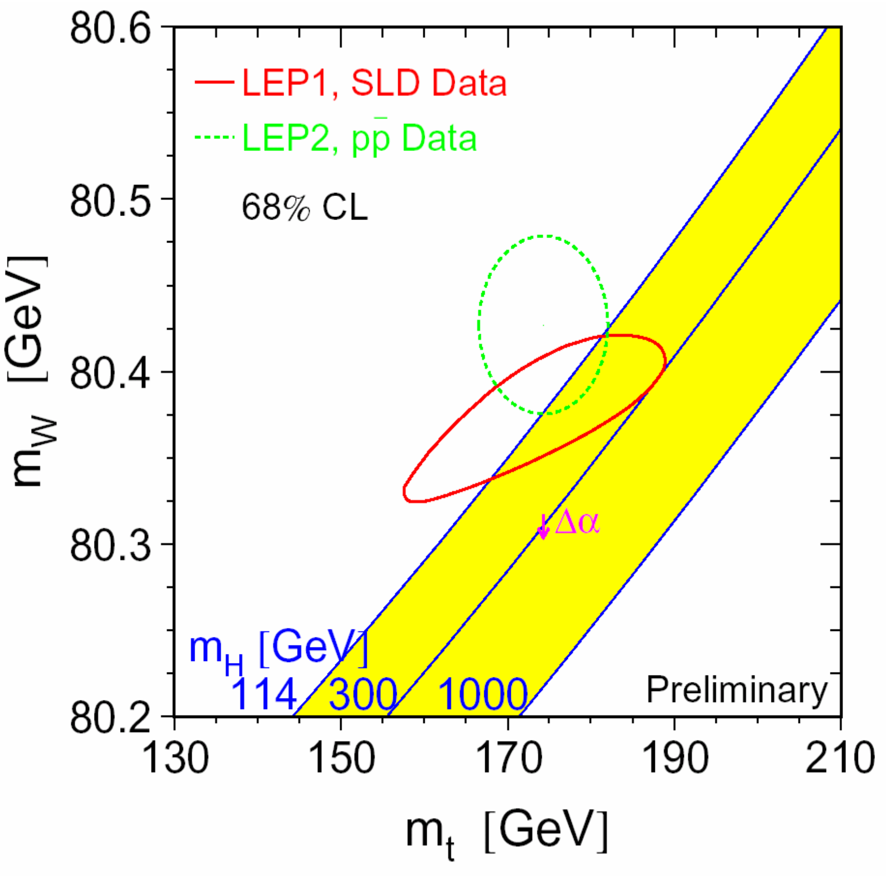
Other uncertainties – error summary

Conclusions

W mass at LEP 2

Most important result from LEP 2 is the W mass measurement

- Check agreement with LEP1/SLD predictions
- Points us to the Higgs
- When the Higgs is found, a stringent consistency test can be performed



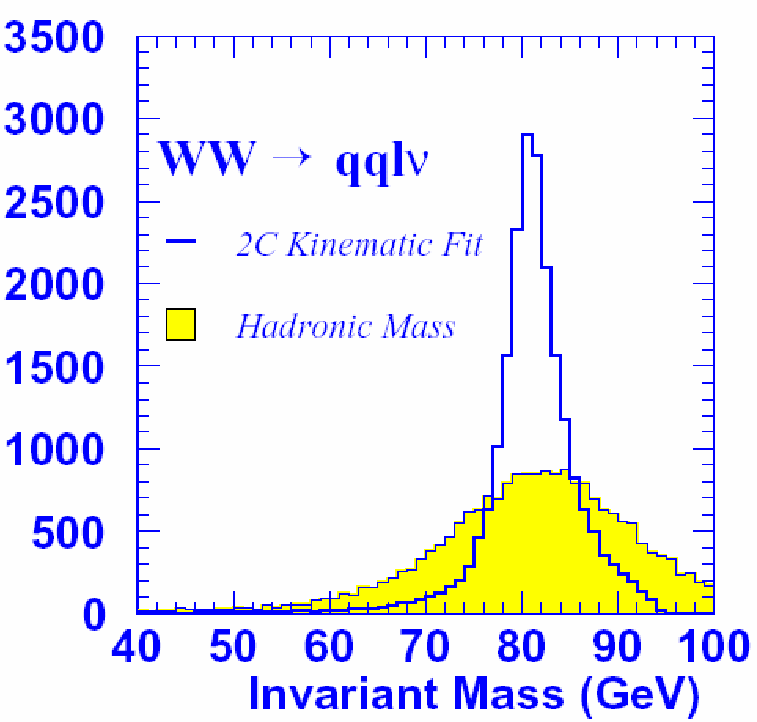
The need to know E_{CM}

W mass measurement exploits kinematic fit with E_{CM} as constraint

$$\delta M_W / M_W = \delta E_{CM} / E_{CM}$$

LEP2 statistical error on M_W is about 30 MeV. Sets goal of:

$$\delta E_{CM} / E_{CM} = 1\text{-}2 \times 10^{-4}$$



E_{cm} is the only W mass error fully correlated between all experiments and channels!

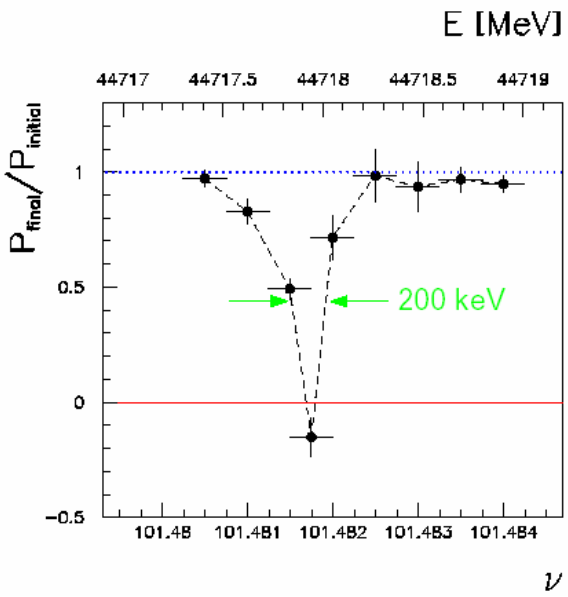
Resonant Depolarisation (RDP)

- Wait for transverse polarisation to build up
- Precession frequency, ν_s , directly proportional to E_b

$$E_b = 2 \nu_s m_e c^2 / (g_e - 2)$$

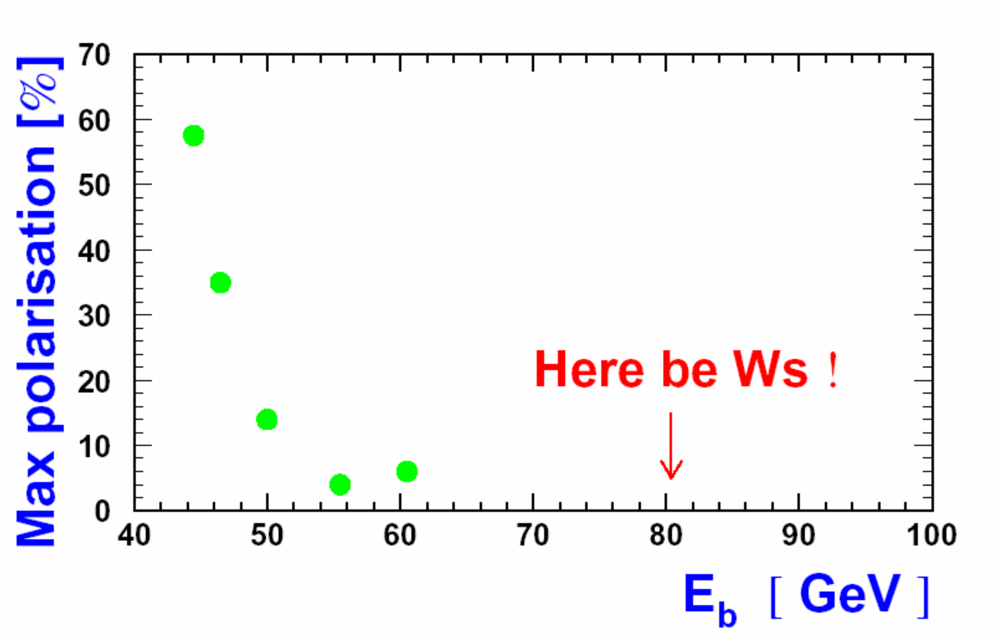
- Monitor polarisation whilst exciting beam with transverse oscillating B field

Intrinsic precision of RDP is 10^{-6} ! RDP is the tool that made LEP1 Z scans such a success:



RDP at LEP 2

RDP is however no use at W production energies!



Machine imperfections that destroy polarisation become more and more important with energy

This because energy spread of beam increases

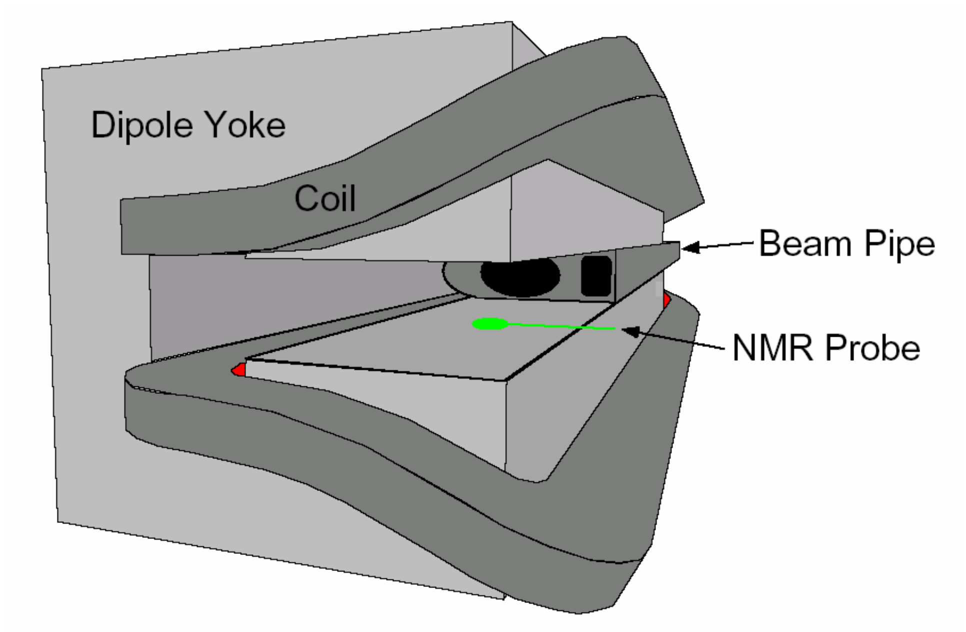
Negligible polarisation levels above 60 GeV!

So we need *indirect* means of E_b determination at LEP2

NMR magnetic model

Fundamental expression of LEP2 E_b calibration:

$$E_b = (ec/2\pi) \oint B\, ds$$



Magnetic measurements available from 16 NMRs in selected dipoles

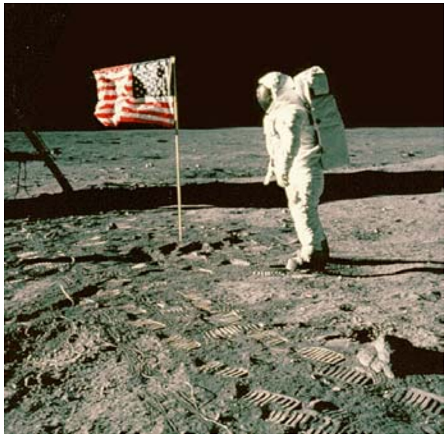
Calibrate NMR readings against RDP over interval where both exist (41-61 GeV) in 2 parameter fit. Apply at high energy.

Average of probe predictions defines the LEP2 energy scale!

Other Ingredients in Energy Model

There are many other ingredients in the energy model which are needed as corrections to the NMR scale

eg. quadrupole effects coming from ring distortions driven by the pull of the moon and the level of the lake…



…and changes of dipole field within a fill caused by parasitic currents on the beampipe from trains.

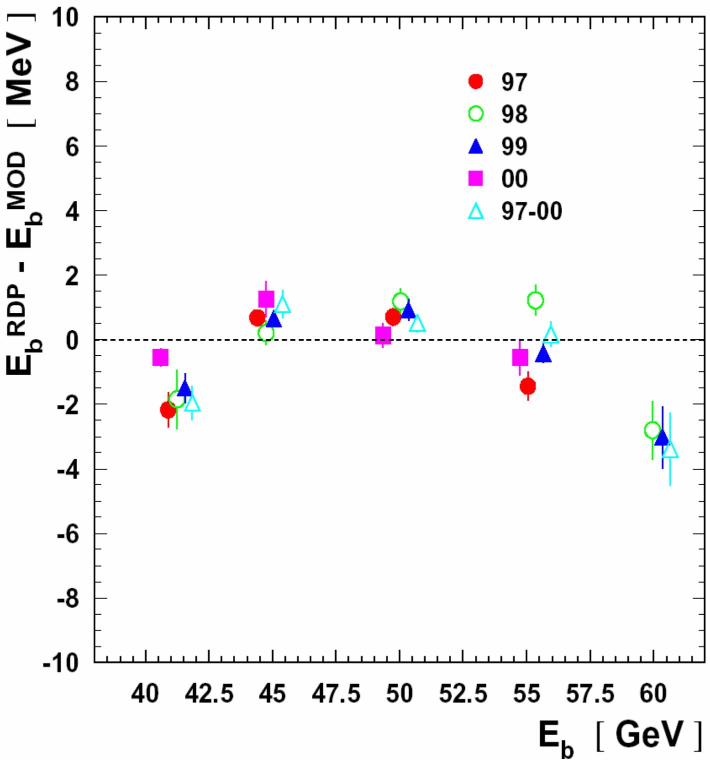
For nice overview see J.Wenninger LEPFEST talk!

These are implemented following LEP1 experience

How reliable is the NMR model ?

- Study fit residuals year-by year. Stable behaviour! Evidence of (small) non-linearity. How does this evolve at high energy?

- 16 NMRs, but 3200 dipoles! Is our sample representative?



For reliable W mass measurement, the validity of the model at high energy needs to be demonstrated!

Overview of NMR model tests

3 independent methods have been used to assess the validity of the NMR model at high energy

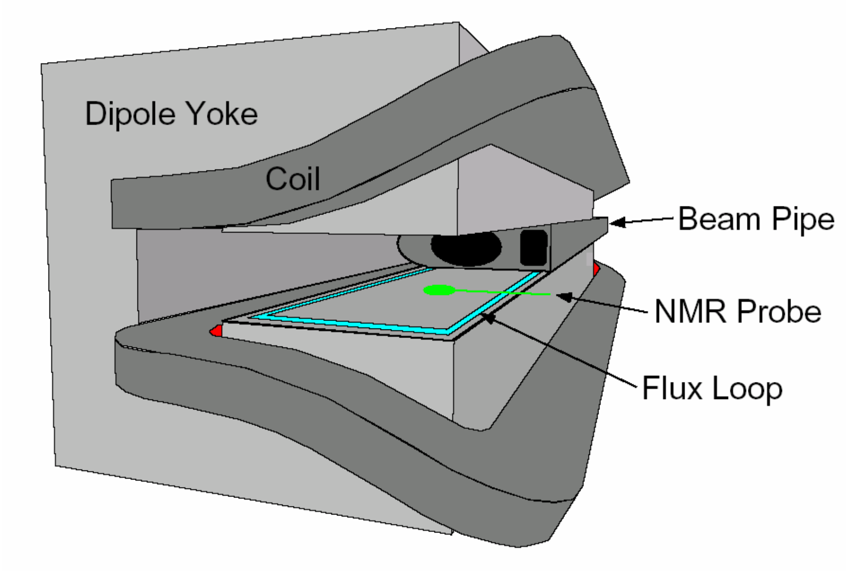
Flux-loop
Compare NMR behaviour with more complete magnetic sampling provided by flux-loop

Spectrometer
Measure deflection of beam in magnet of known integrated field

Synchrotron tune (Q_s) analysis
Fit variation of Q_s with RF voltage.
From this extract E_b.

Flux loop (FL)

Copper loops connected in series allow the change of flux to be measured through (almost) all dipoles



No useful way to extract absolute E_b value from FL

Rather, ramp machine in dedicated experiments and compare evolution of FL readings with NMRs

→ FL provides method of testing NMR sampling representability

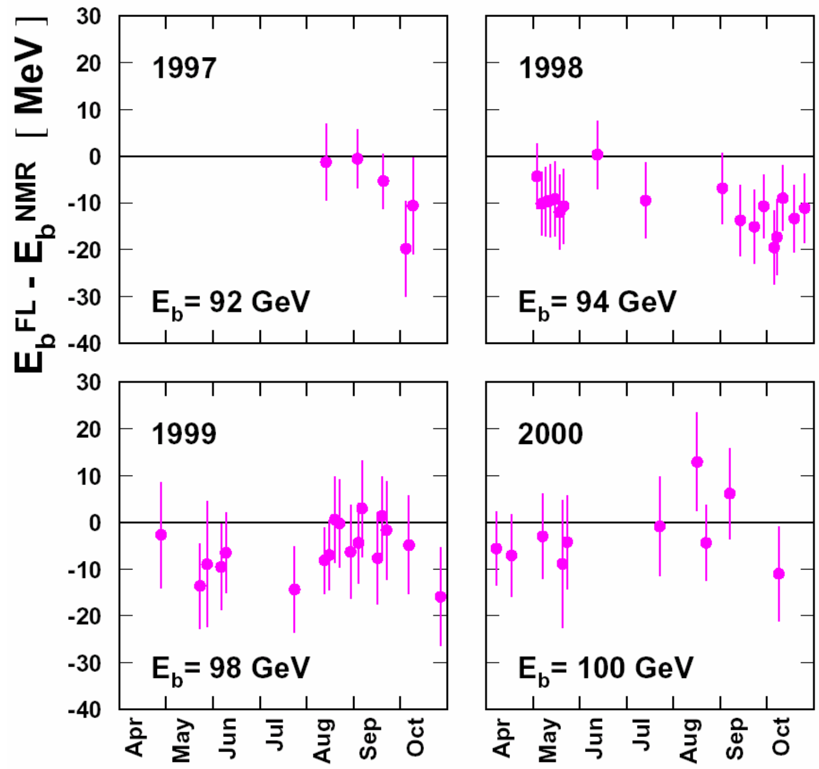
Flux Loop Results, year by year

If FL values are proportional to true E_b, can make fit of NMR vs FL, à la NMR vs RDP fit

Having made fit at fields corresponding to low energies, compare fit predictions and FL values at high energy

Fit prediction agrees with FL, within a few MeV. No evidence of significant non-linearity!

FL value – NMR prediction
(expressed as equivalent energy; each entry is a separate ramp, averaged over all available NMRs)

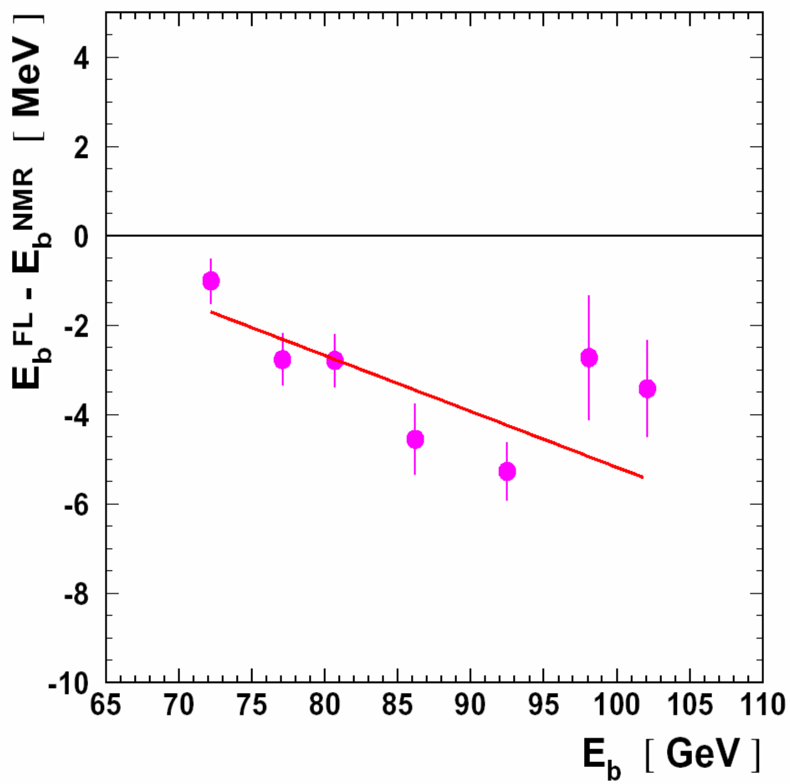


Flux Loop Results vs Energy

FL results can be integrated over all years, and the dependence on energy studied.

Results suggest a *small* offset in the NMR model, and one which evolves *slowly* with energy.

FL -NMR prediction vs E_b

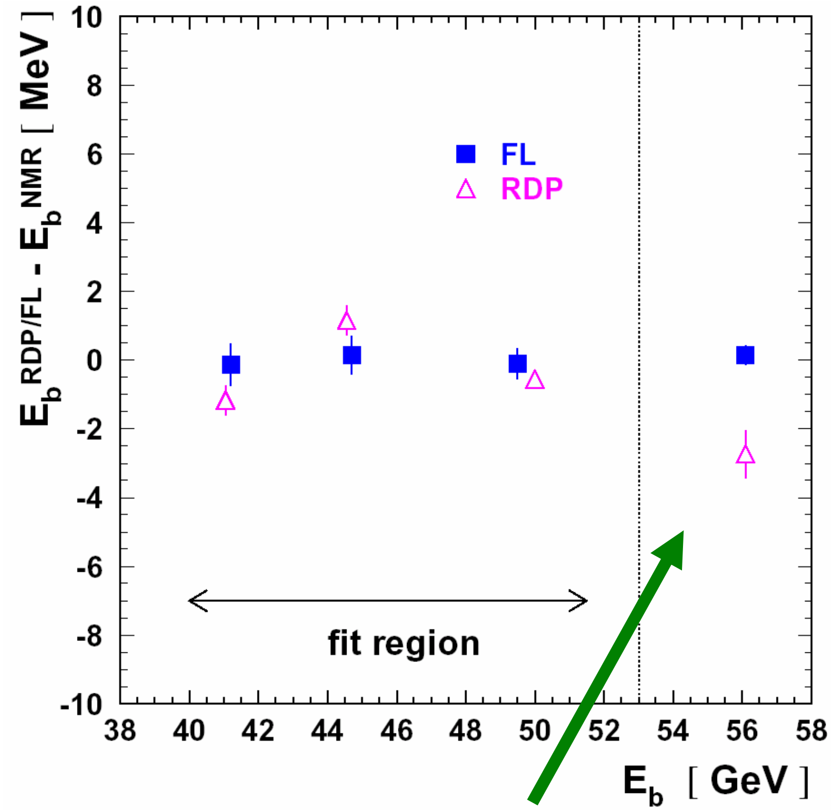


Flux Loop Error Assignment

Lack of redundant info in the FL data hinders rigorous error assignment

Best indication comes from comparing low energy RDP-NMR and FL-NMR residuals

Re-do fits in 41-50 GeV region and study residuals at 55-61 GeV



This difference extrapolated up to high energy quantifies the linearity of the FL itself.

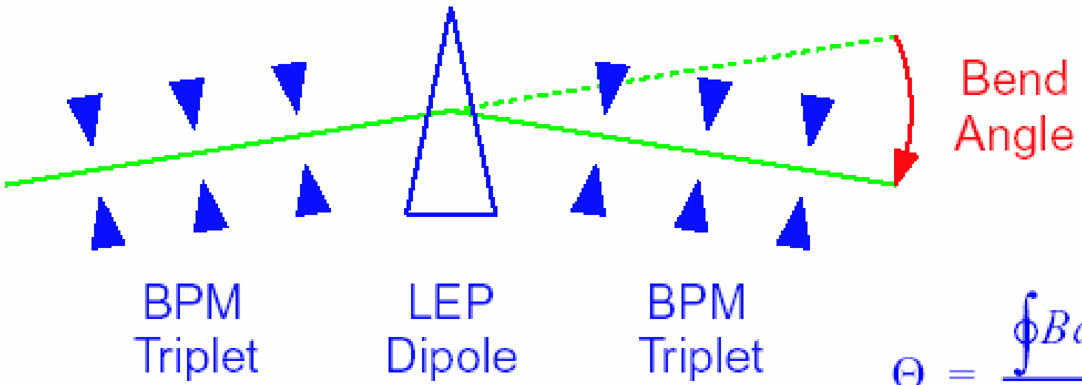
Flux Loop Summary

Error assignment comes primarily from residual analysis (15 MeV at E_b=100 GeV). Additional components arise from considering linearity of dipole area lying outside FL cable & uninstrumented magnets in eg. injection region (sum to 5 MeV at E_b=100 GeV). All errors scale with E_b.

Example E_b	72 GeV	100 GeV	106 GeV
FL-NMR Offset [MeV]	-1.7	-5.2	-6.0
Assigned error [MeV]	7.5	15.8	17.6

LEP In-Line Energy Spectrometer

Idea ('97): measure deflection of beam in magnet of LEP lattice



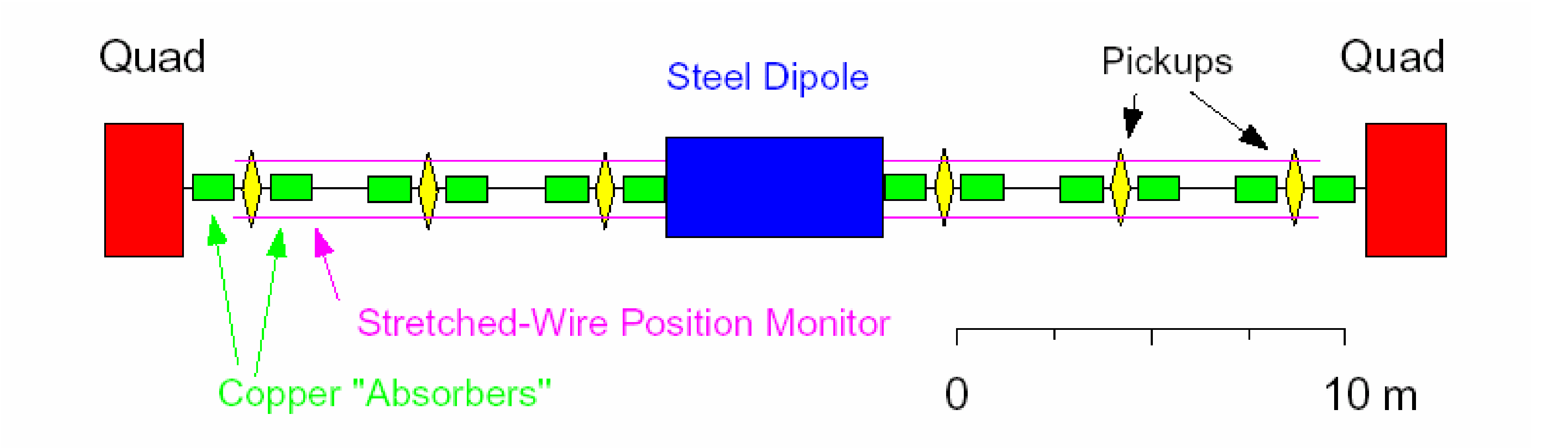
$$\Theta = \frac{\oint B\,dl}{E_{Beam}}$$

Required precision makes absolute measurement impossible…

…rather make 2 consecutive measurements close in time in same fill: one at reference energy in regime well understood by RDP; the second at the energy of interest.

Spectrometer Layout

Spectrometer installed close to IP3 and commissioned during 1999. Data taking for E_b measurements in 2000.



Required precision on position measurements ~ 1 micron; on $\int B.dl$ ~10^{-5} . Recall these accuracies must be attained on measurements of ***changes*** between reference & high energy

Spectrometer Dipole

Spectrometer magnet a custom built 5.75m steel dipole similar to those in LEP injection region

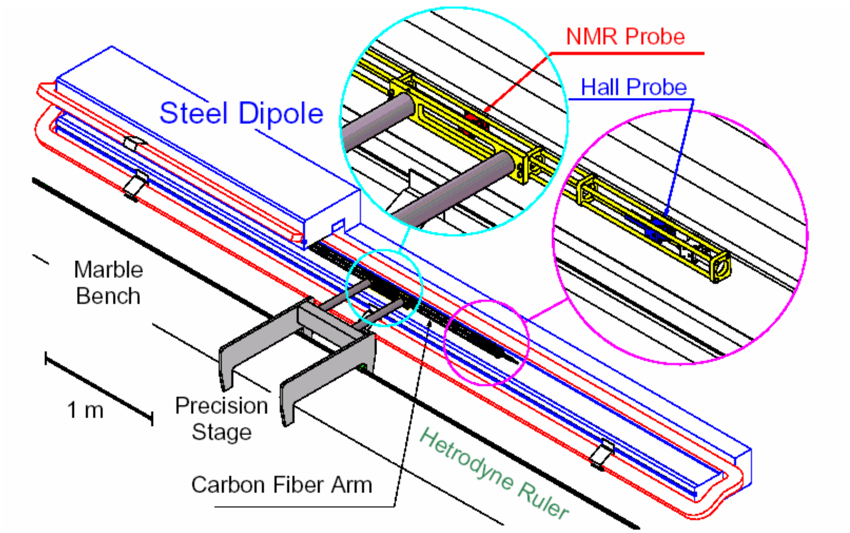
Temperature regulated with dedicated water-cooling (limits temperature rise to 3-4 degrees during ramp)

In mapping laboratory

Local field measurements come from 4 NMR probes positioned on precision mounts

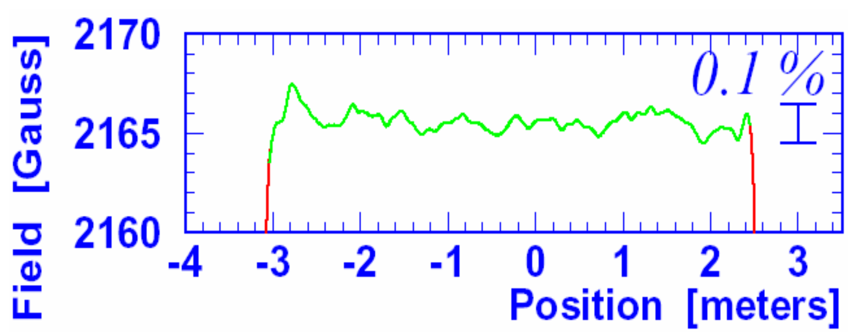
Magnet Mapping Campaigns

In 1998-99, prior to installation, magnet ∫B.dl was mapped on precision test stand in lab under wide variety of excitation currents, temperatures etc



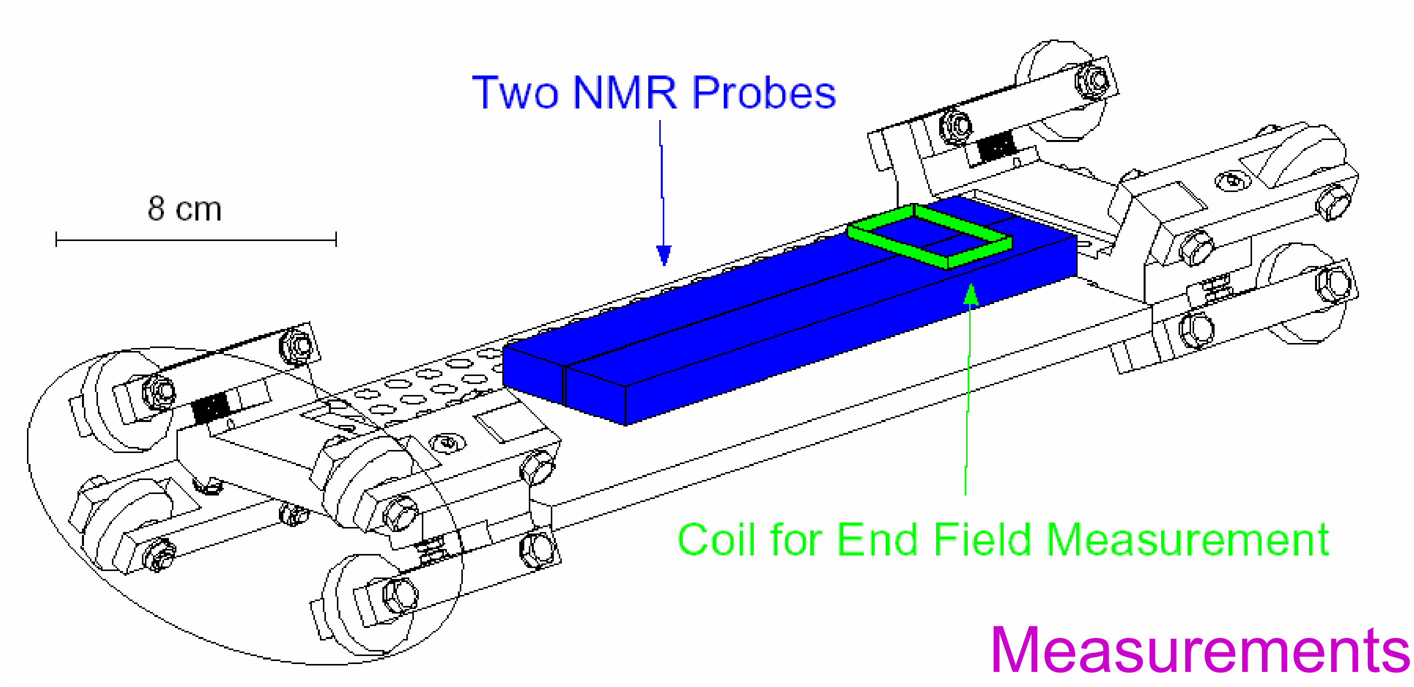
Measurements made by moving arm carrying NMR probe for core field, Hall probe for end fields

A second campaign in 2001-02 was conducted post-dismantling



In-situ Mole Mapping

A complementary method was developed to measure ∫B.dl within the vacuum-pipe itself – the mapping 'mole'

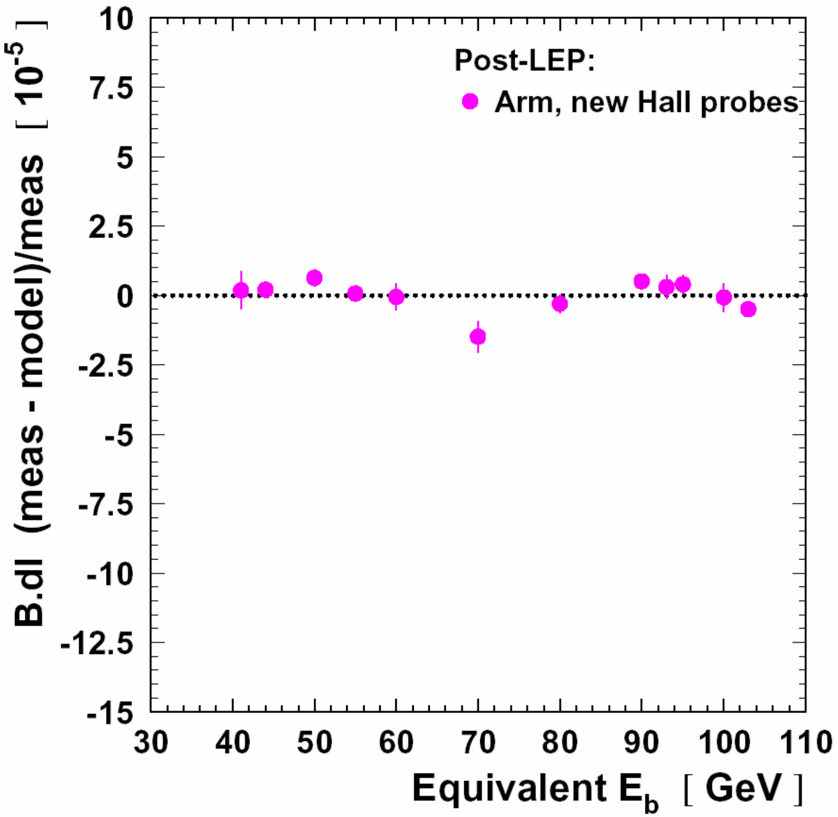


Measurements made in the lab and in the tunnel.

Residuals of Mapping Model

Develop model to relate measured ∫B.dl s with local readings from fixed NMRs. Account for temperature variations.

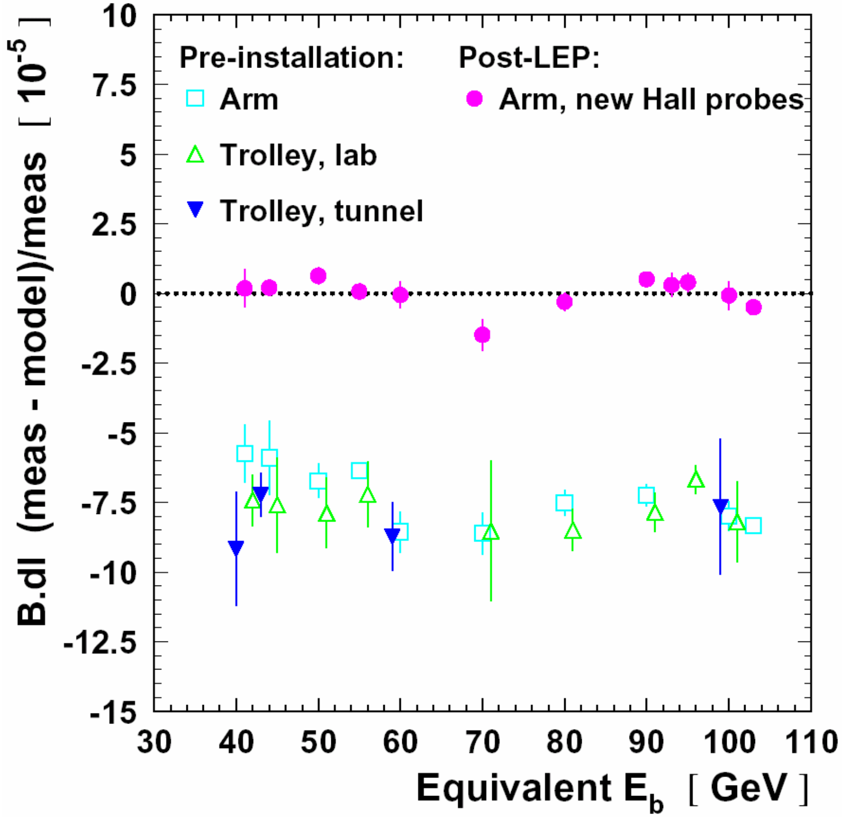
Model based on post-LEP campaign shows excellent residuals ($<10^{-6}$). Use to predict ∫B.dl during physics



Comparison with other measurements

Look at residuals of this model with pre-installation and mole measurements

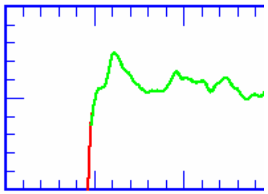
- Mole measurements agree very well with pre-installation arm results
- Offset of 8×10^{-5} between post-LEP results and all other data!

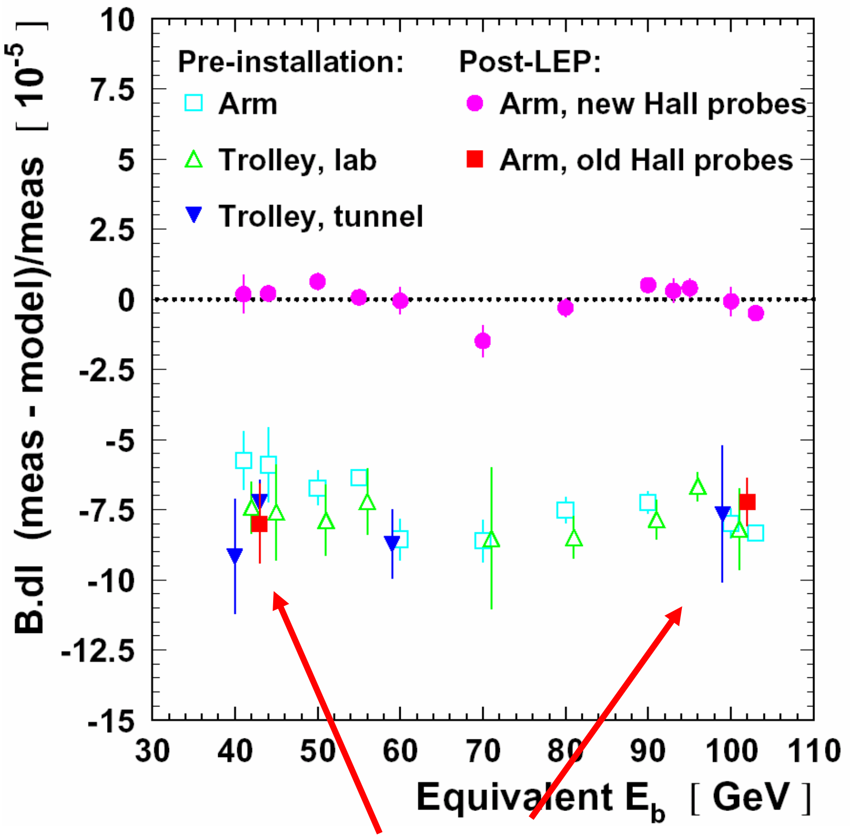


Understanding of Mapping Shift

Likely explanation: bias in measurement of end fields in earlier campaigns.

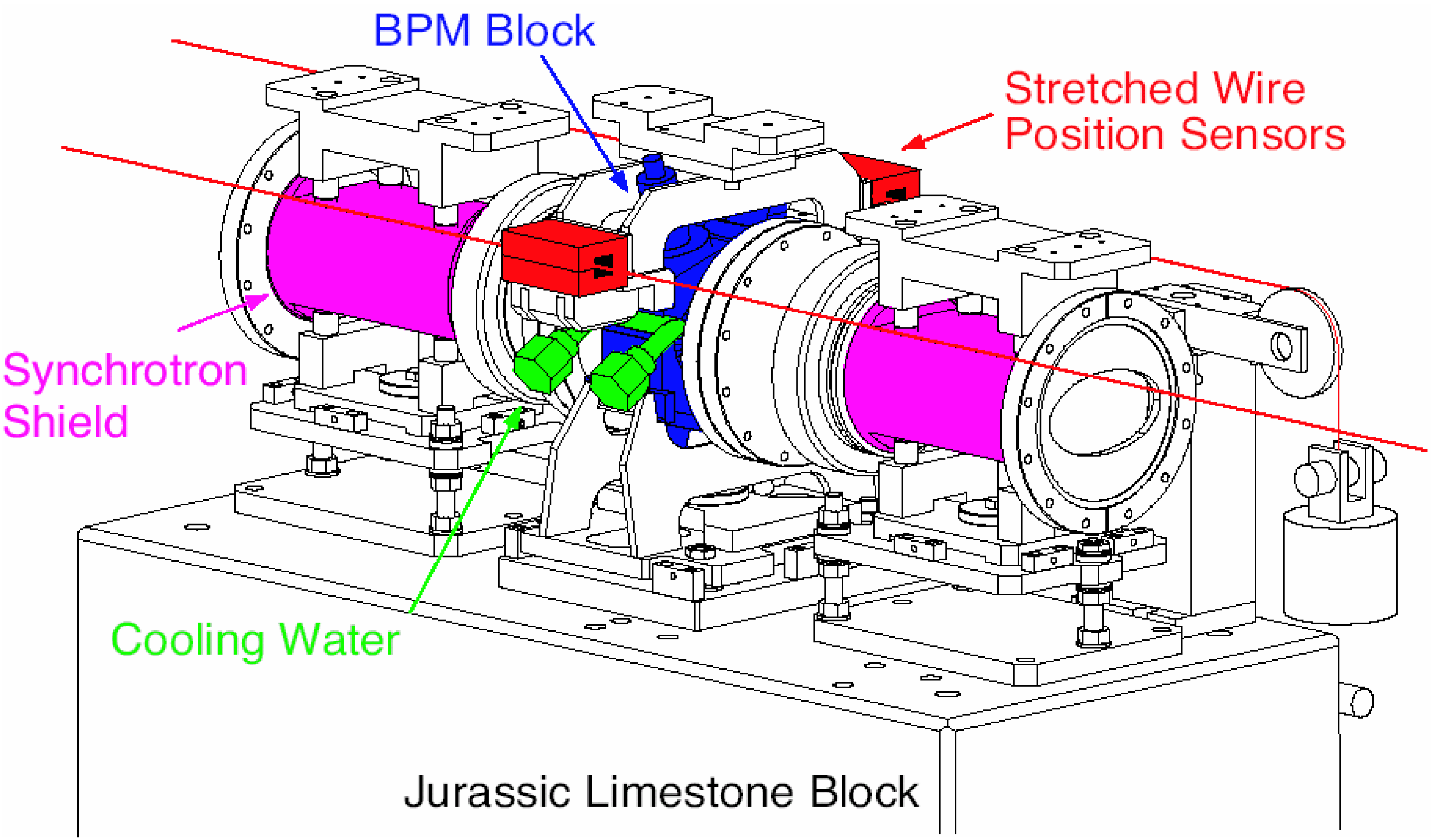
Hall-probe size (+ that of mole coil) not suited to variation scale of end-field



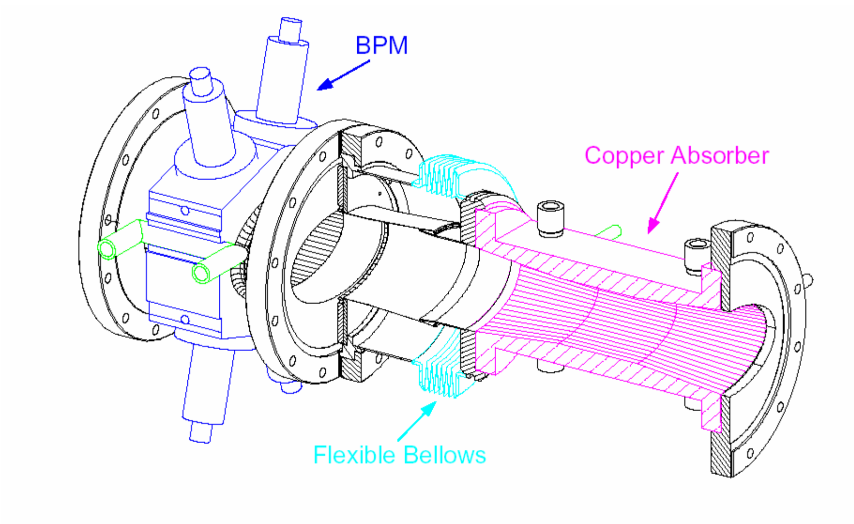


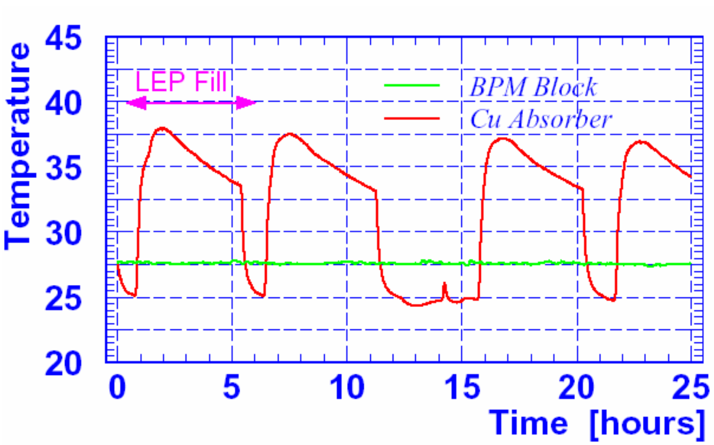
Post-LEP campaign had smaller Hall-probes. Hypothesis confirmed by making new maps with old Hall-probes.

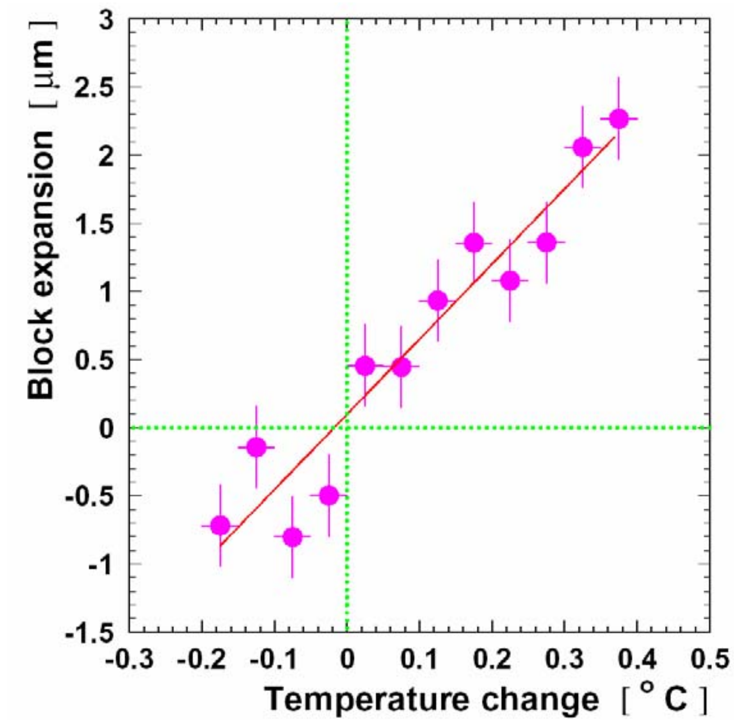
Spectrometer BPM Station



Synchrotron Radiation Protection







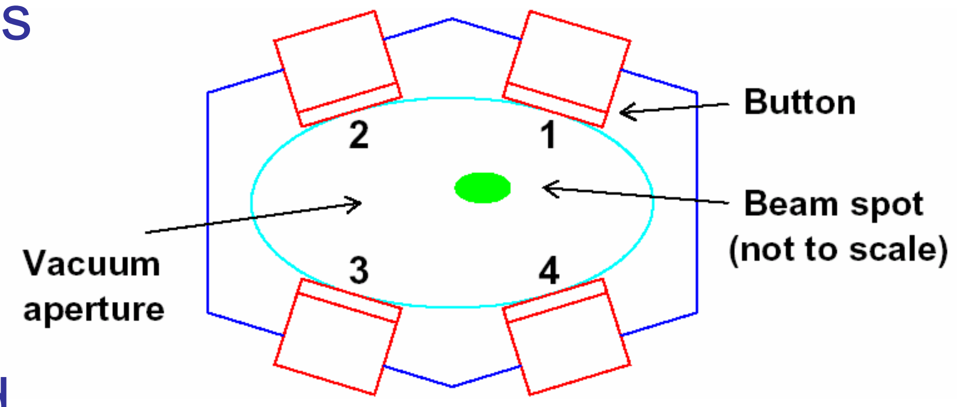
Residual expansions (5.5 microns / °C) and movements followed by stretched wire sensors

Position Measurements

Position measurements provided by conventional LEP elliptical BPMs

$$x_{BPM} \sim \frac{(S_1 - S_3) - (S_2 - S_4)}{(S_1 + S_2 + S_3 + S_4)}$$

Equipped with custom-designed readout electronics built on common amplifier chain for all 4 buttons.

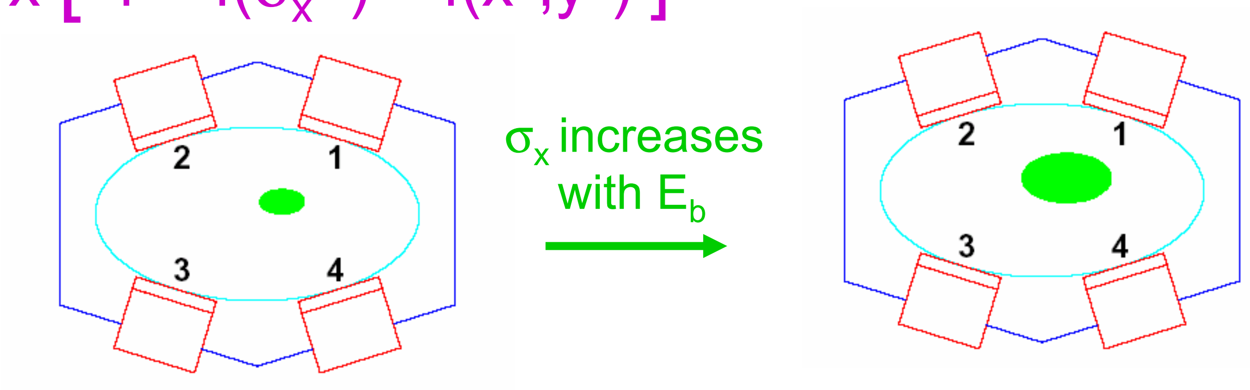


Stability under a variety of operating conditions verified in sequence of bench tests.

Geometrical Biases

BPM shape and shape of beam spot leads to higher order terms in response depending on both position & beam size. Studied in dedicated simulation NIM A 466 (2001) 436-447.

$$x_{BPM} \sim x \left[1 + f(\sigma_x^2) + f(x^2, y^2) \right]$$

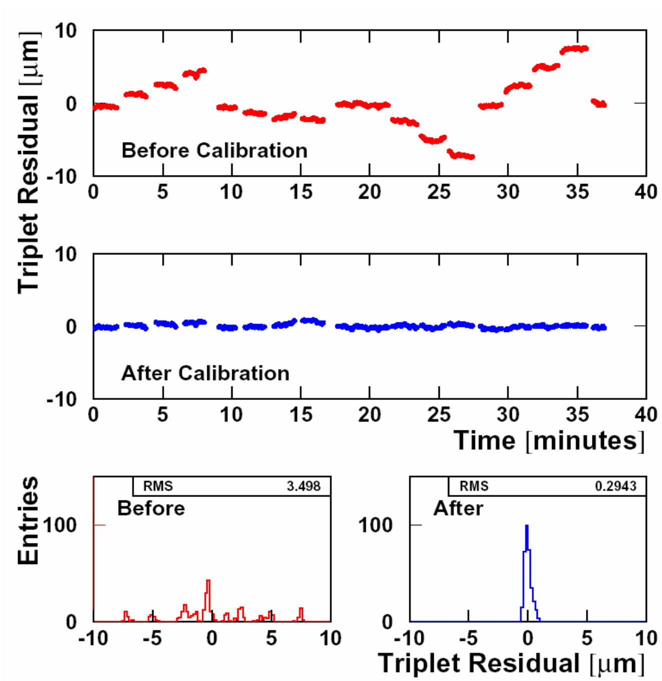


Biases change with energy and from BPM to BPM!

Solution: take care to steer beam close to centre of BPMs and keep in same place for reference and high energy measurement

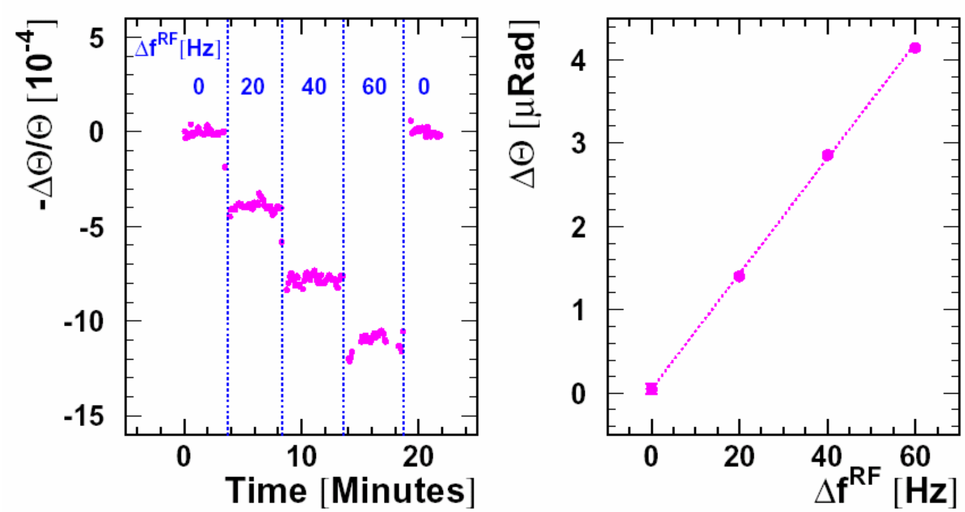
BPM Calibration

Relative Gain Calibration: fix relative response of each BPM (+ cross-talk) from sequence of ‘bumps’ and rotations carried out at least once each spectrometer experiment



Resolution of triplet residual < 1 micron

Absolute gain scale: fix this to 5% by looking at change in bend angle as E_b is changed by known amount through RF frequency manipulations



Spectrometer Datasets

Spectrometer high energy calibrations consisted of 17 single beam fills, distributed equally between e^- and e^+, each of which had:

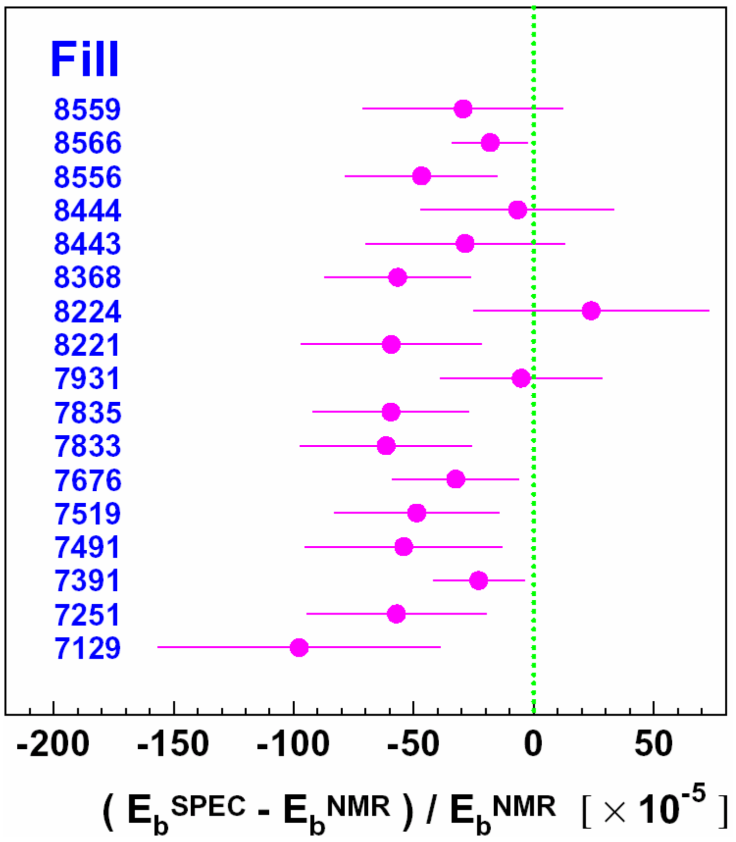
- Reference point at (known) low energy, eg. 50 GeV
- High energy point, usually around 93 GeV

Also several ‘low energy’ fills when several measurements were made in 41-61 GeV range.

Plus a few fills at intermediate energies, eg. 70 GeV

Raw Spectrometer Results

From observed change in bend angle, determine change in E_b between reference point & high energy. As reference point is well known through NMR model (reliable at ~50 GeV!), can determine difference between NMR model and spectrometer estimate at high energy.



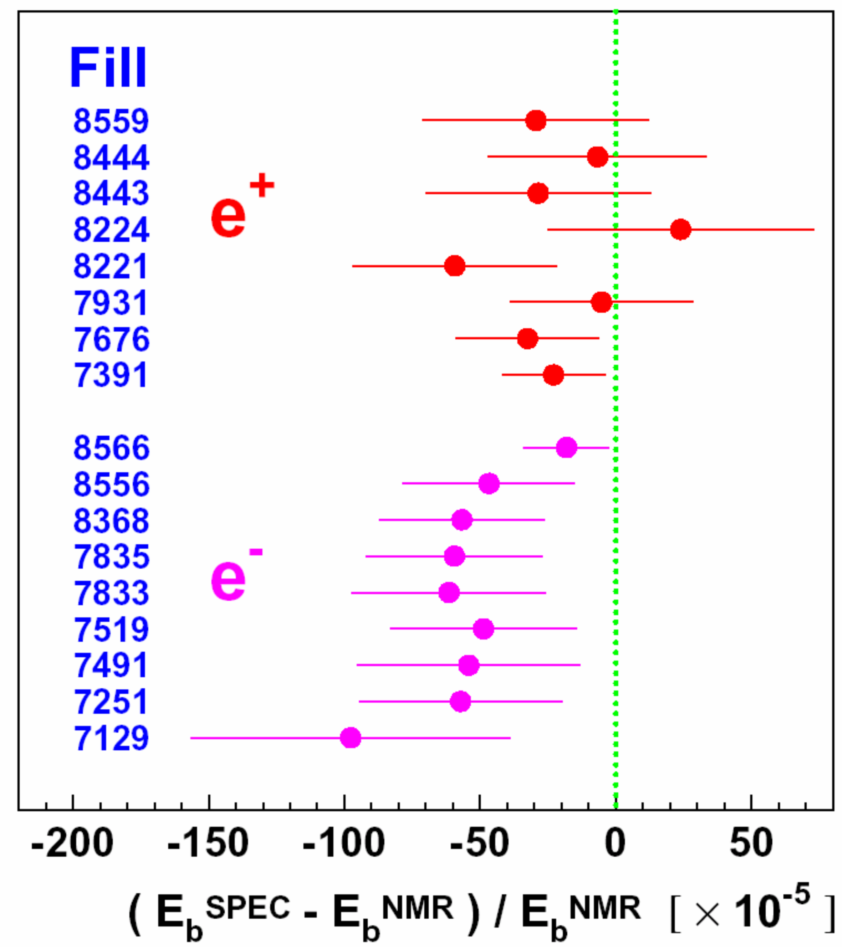
Significant negative offset…

Division into electron/positron fills

Significant scatter in raw results. Much of this is associated with the difference between electron and positron results.

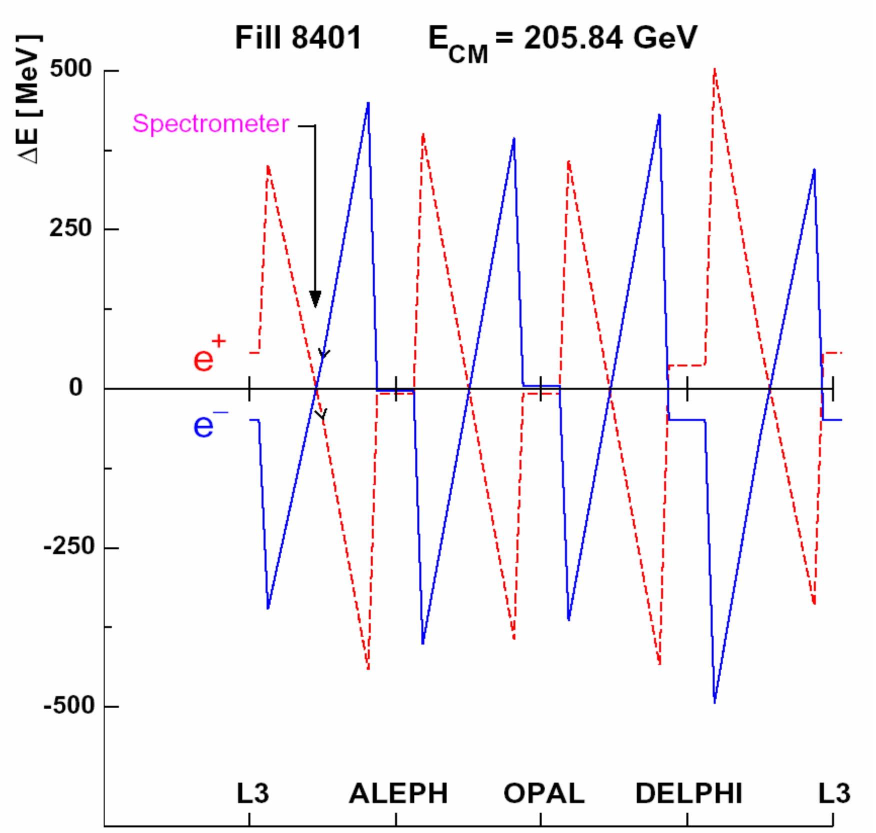
Electron results ~30 MeV lower than positron results

This behaviour arises from error in sawtooth correction



RF Sawtooth

Local energy varies from mean because of synchrotron radiation and replenishment from RF system: the sawtooth

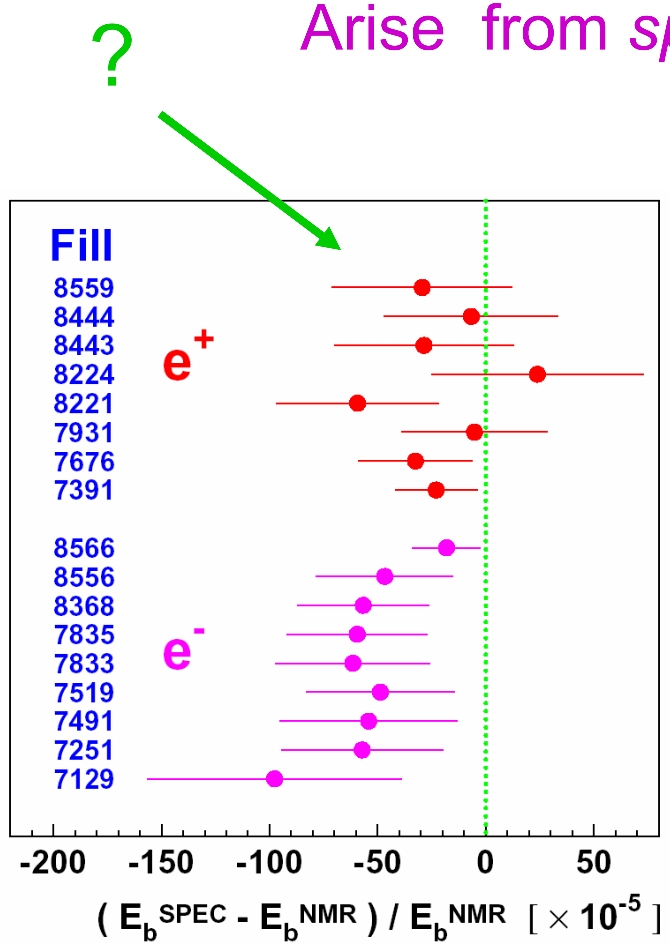


Sawtooth correction needed to relate spectrometer measurement to RF model. Sawtooth modelled in dedicated program, with per beam accuracy of ~10 MeV

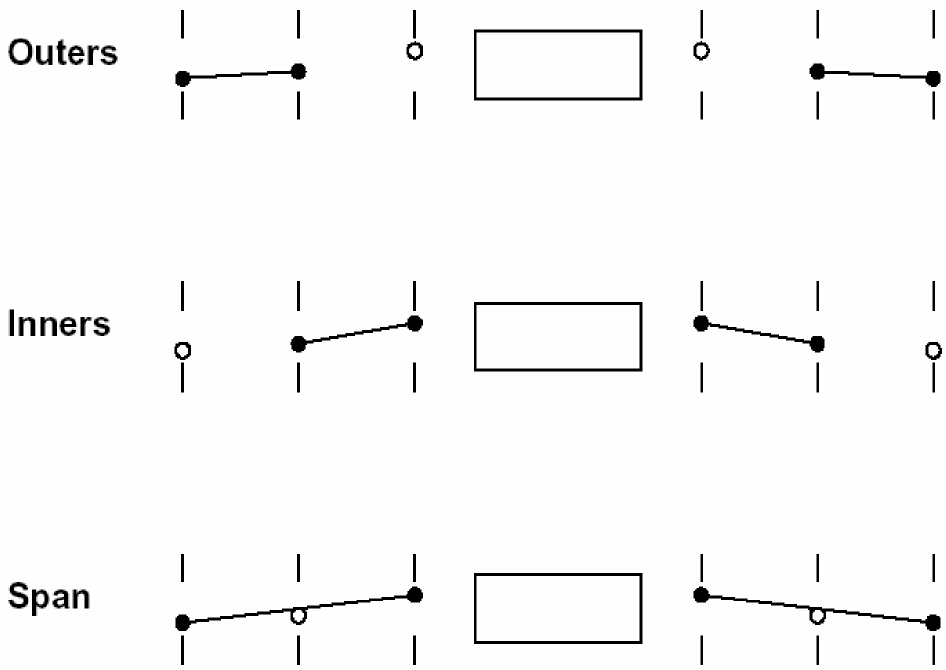
This represents a ~20 MeV accuracy in e^- vs e^+… …but accuracy in *mean* result ~5 MeV

What do Error Bars Mean?

Arise from *spread* in results from different BPMs.



9 combinations in total, 3 of which are of particular interest:

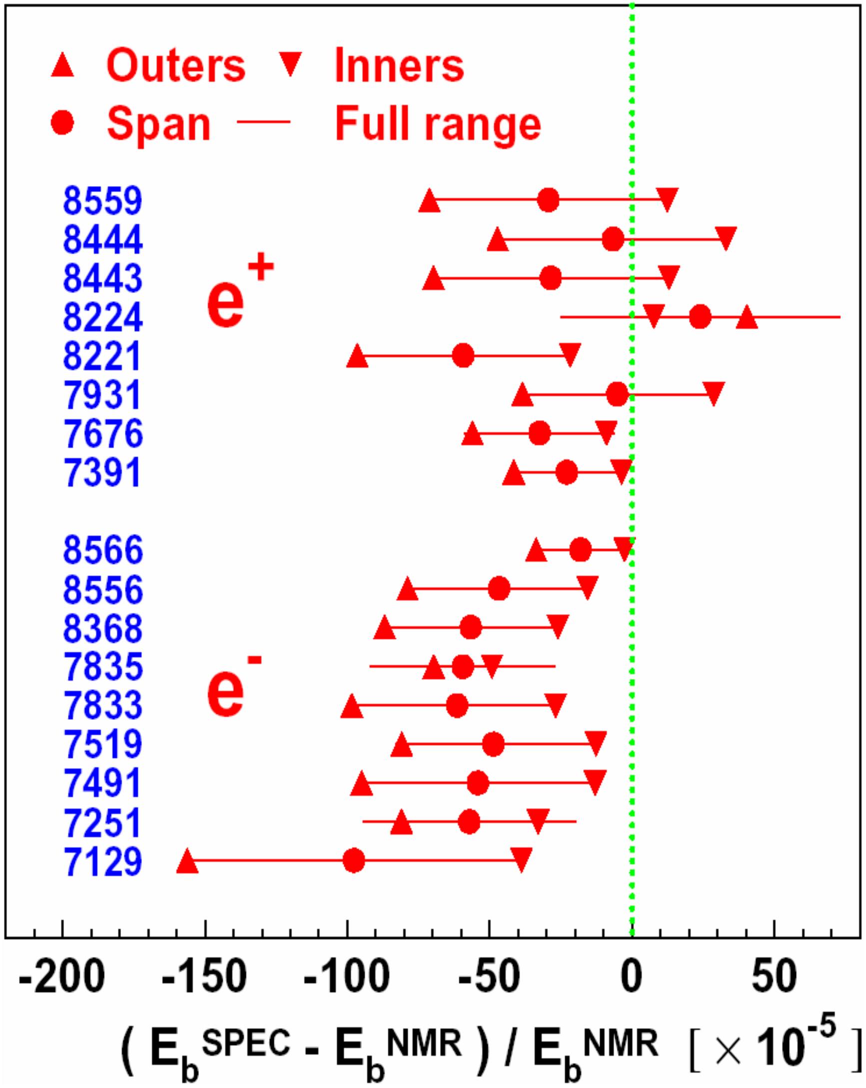


BPM Results: by combination

Different combinations give significantly different estimates of energy.

Outers estimate is systematically low, inners is systematically high; span between the two

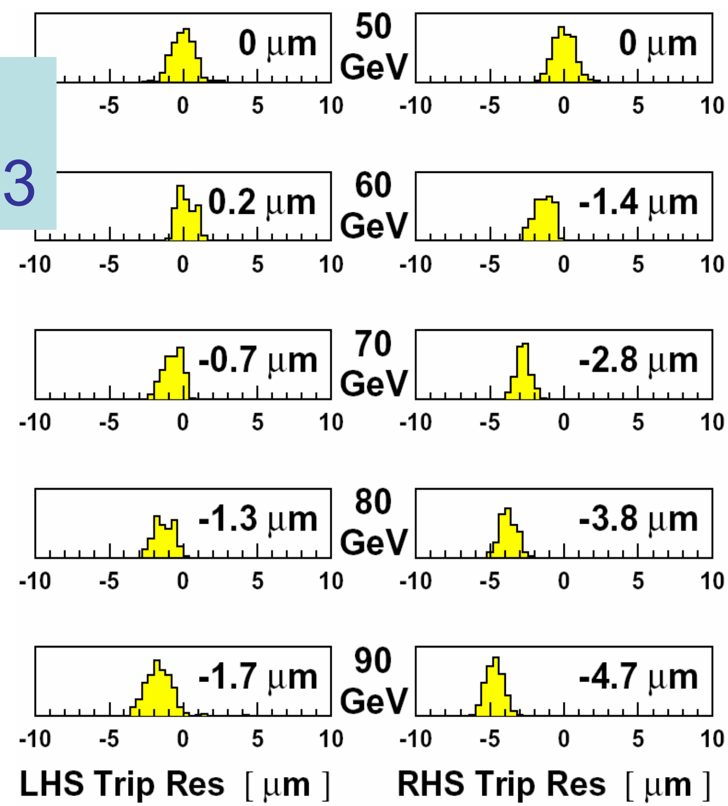
Need to assess which combination is more trustworthy !



Triplet residual behaviour

BPMs calibrated at low energy; hence centred triplet residuals

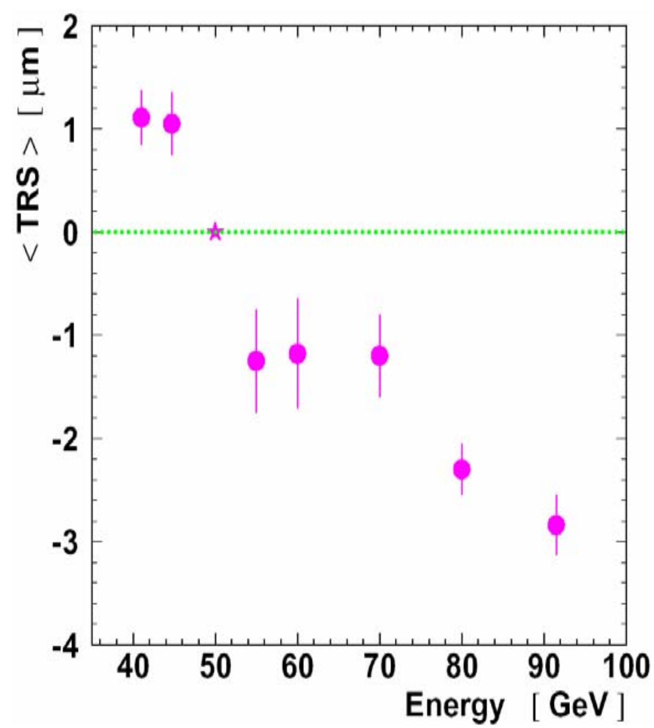
Fill 8443



Triplet residuals observed to shift in both arms by a few microns

<TRS> = shift in triplet residuals averaged over both arms

<TRS> vs energy averaged over fills



TRS: Considerations and Strategy

Origin of TRS not clear. Effect is equivalent to relative motion between BPMs – but this motion is not physical as it is not tracked by the stretched wire monitoring system

- Synchrotron radiation? Unlikely – no current dependence seen. Also effect *linear* in E_b
- Residual bunch size (+length) effects? Possible – beam size rises with energy. TRS artificially produced by wiggler manipulations.

Consequence for analysis: straight average of raw results will provide a biased estimator. Rather study evolution of results from each combination vs <TRS> and see which set of BPMs shows least dependence on effect.

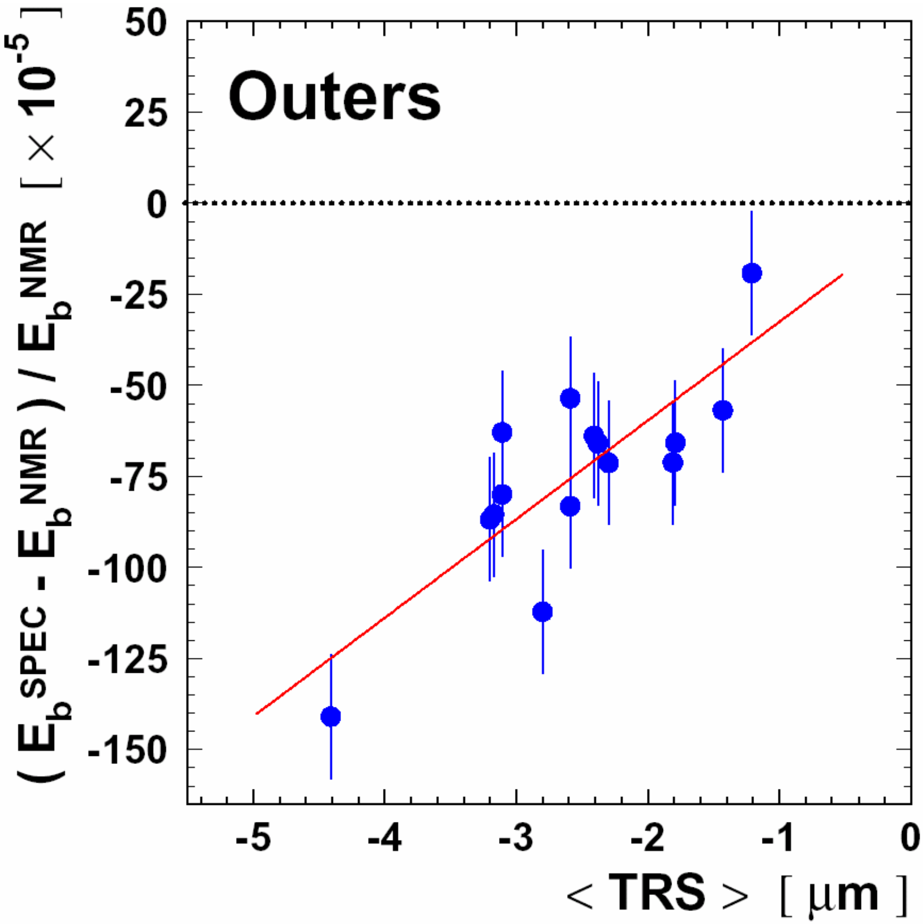
Results from Outers

Plot outer results vs <TRS>

Certainly not flat! (slope is $27 \pm 6 \times 10^{-5}$ / micron)

Error bars 17×10^{-5} : assigned from chi2 of fit

(Remove bias from error in RF sawtooth in fit & plot)

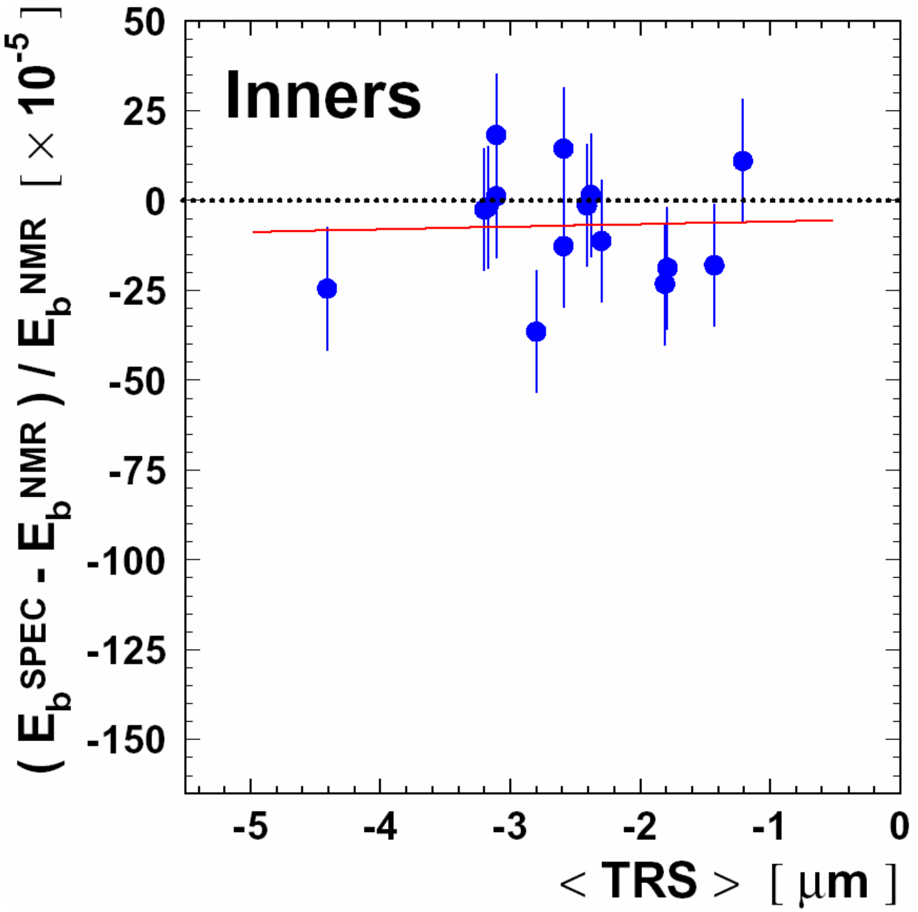


Results from Inners

Slope 0 ± 6 x 10^{-5} / micron

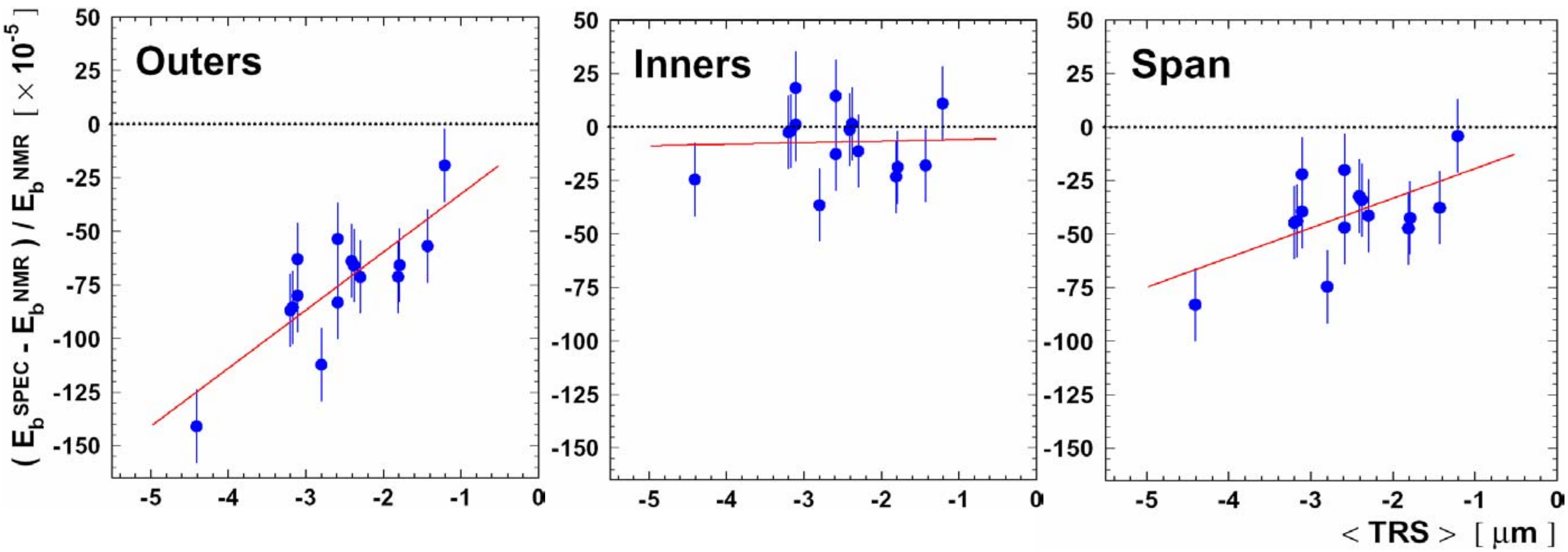
Inners show very little dependence on <TRS>

Inners provide a less biased estimator of energy



Results by BPM Combination

Span lies between outers & inners (slope 14 ± 6 x 10^{-5} / micron)



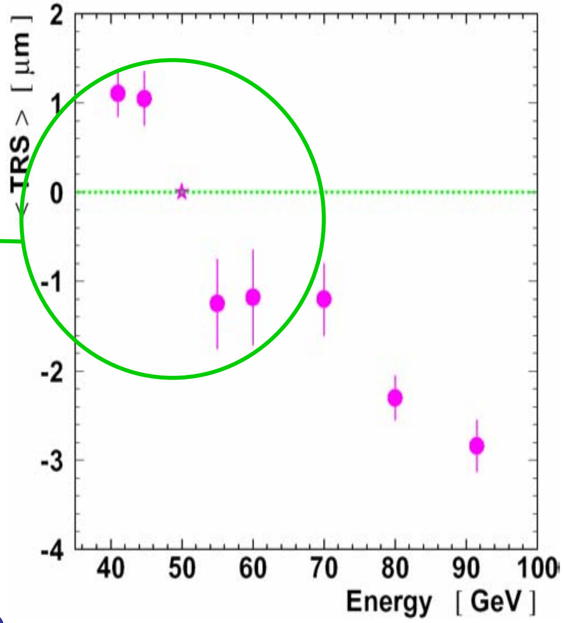
From fits can extrapolate back to situation of zero systematic:

Offset = -6 ± 15 x 10^{-5}

Result identical for each combination!

Cross-check on low energy data

If analysis of high energy data are correct we would expect to see similar behaviour at low energy

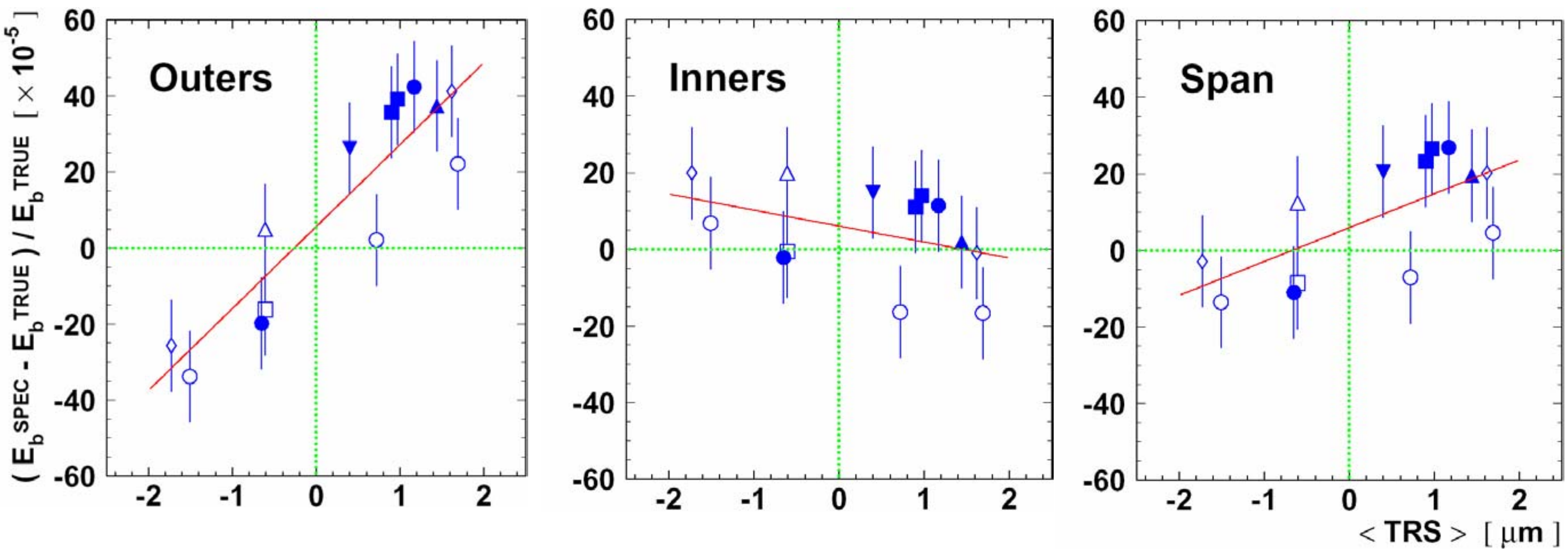


Furthermore, since energy scale is known in 41-61 GeV regime, we can compare spectrometer results to true energy!

Low Energy Results

Fits to low energy data give entirely consistent slopes!

$22 \pm 3 \times 10^{-5}$ /micron $-4 \pm 3 \times 10^{-5}$ /micron $9 \pm 3 \times 10^{-5}$ /micron



Also, spectrometer agrees well with true energy at <TRS>=0

Spectrometer Summary

Error assignment (shown in terms of relative energy eg. (Spec – NMR)/ NMR

Contribution	Value [$\times 10^{-5}$]
High energy scatter	15.0
Validity at low energy	10.0
BPM gains	0.5
Beam size	4.0
Integrated dipole field	1.5
Sawtooth model	5.0
WPS correction	2.2
Ambient bending field	0.7
Total	19.3

Result for E_b :

Spec-NMR = -5 ± 18 MeV

evaluated at $E_b \approx 92$ GeV

Without TRS systematic maybe 10 MeV precision would have been possible?

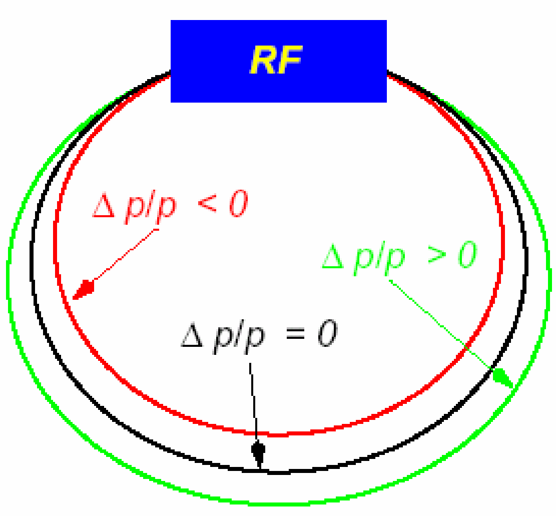
(Intermediate energy points also give result at $E_b \approx 70$ GeV:

Spec-NMR = -1 ± 10 MeV

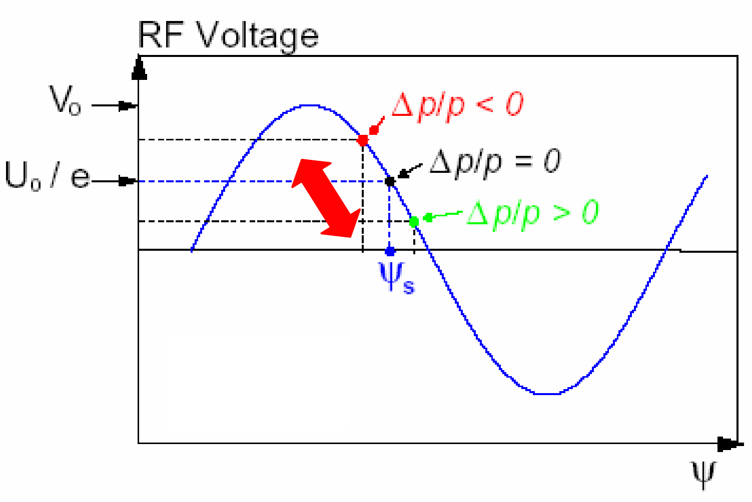
75% correlated with 92 GeV result)

Energy Loss & Synchrotron Oscillations

Synchrotron tune, Q_s , is ratio of synchrotron oscillation frequency to revolution frequency. Depends on RF voltage, V_{RF}, and energy loss per turn, U_0:



$$Q_s^2 \sim (1/E_b) \sqrt{(e^2 V_{RF}^2 - U_0^2)}$$



U_0 in turn depends E_b^4.

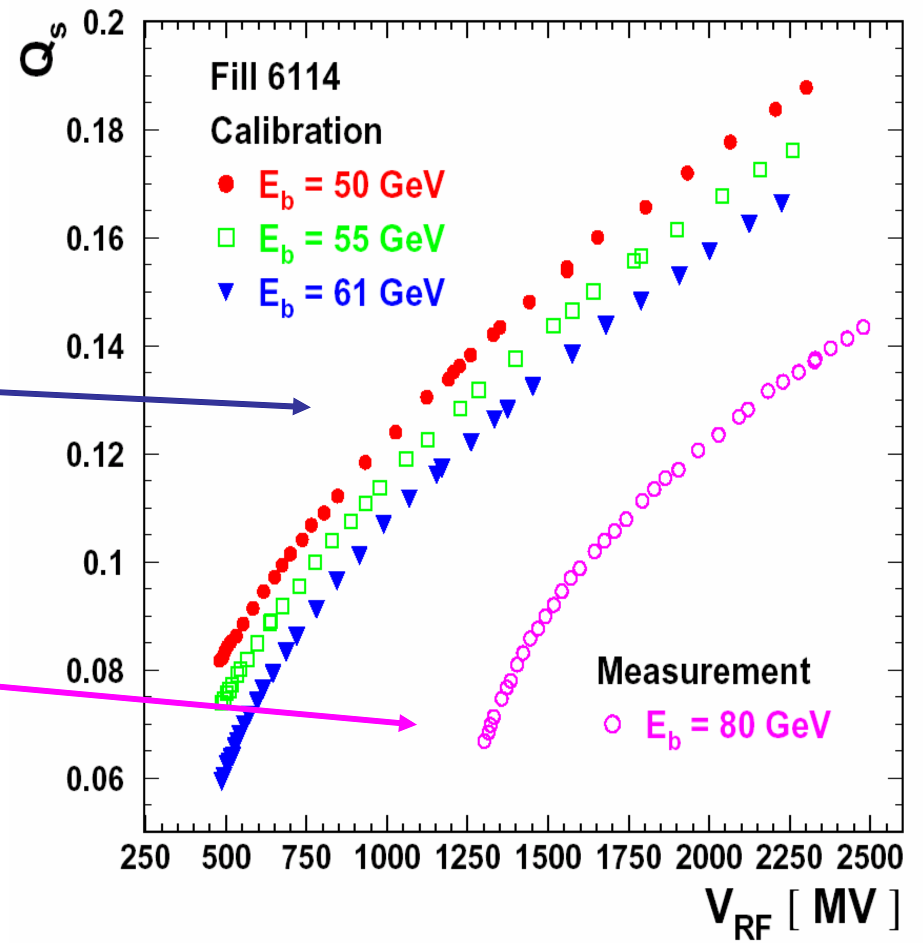
Hence fit of Q_s vs V_{RF} can be used to extract E_b!

Measurement Procedure: RF Calibration

Total RF voltage scale not known a priori sufficiently well for E_b measurement.

Therefore extract from data by performing RF scans at low, known energies, before moving to high energy point.

Need to scan in RF restricts top energy to 80-90 GeV



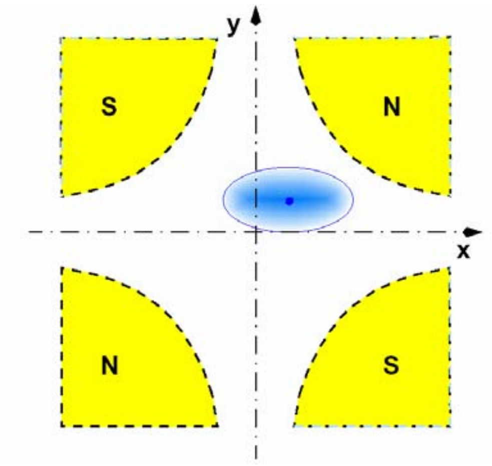
Refining the Q_s vs E_b Model

Naive expression for Q_s vs E_b dependence inadequate for precision measurement:

- Requires correction for precise spatial distribution of RF voltage $\rightarrow$ input from MAD simulation
- Good knowledge of magnetic bending radius, ρ , required, as $U_0 \sim E_b^4 / \rho$. Fix from global fit to all data.
- Expression assumes only source of bending field, and of energy loss, is in dipoles themselves. This not true!

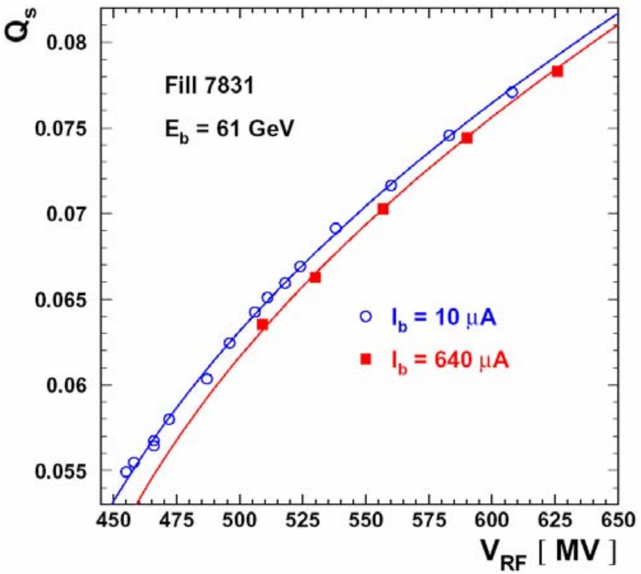
Other Sources of Energy Loss

Off-centre trajectories in quads, and finite beam-size, need to be accounted for



Other effects: correctors, closed orbit distortions etc

As do parasitic mode losses coming from impedance in vacuum chamber walls

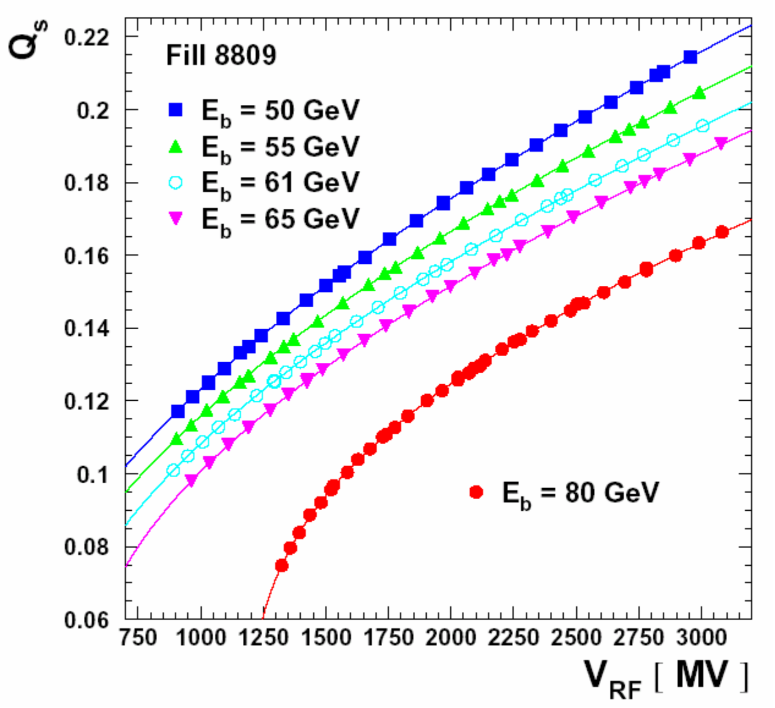


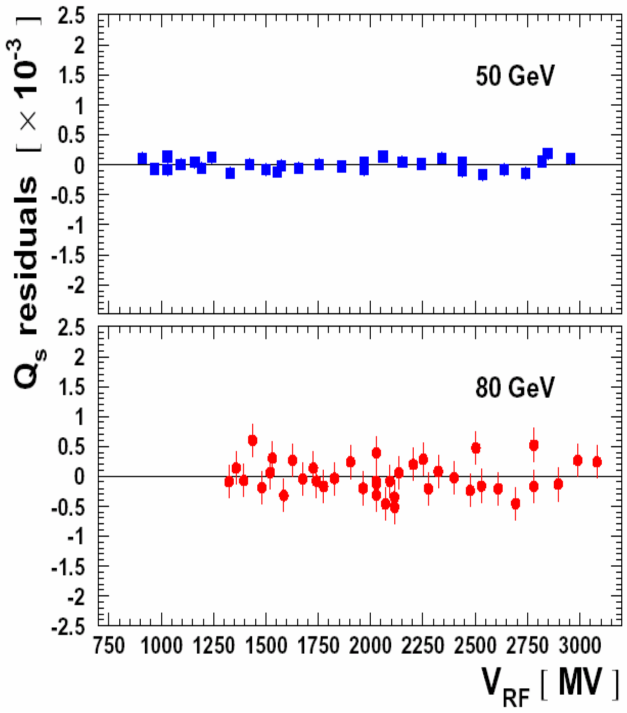
These have a current dependence and can be fixed from experiment

In total: $10^{-4} – 10^{-3}$ correction to U_0 !

Q_s fits to data

Final Q_s model fits data very well





(Q_s signal harder to measure at high energy → larger scatter)

Extract E_b with typical precision of 30 MeV per experiment

Q_s Results

6 measurements in all (5 at 80 GeV, 1 at 90 GeV)

Year	1998	1999		2000		
Fill	5128	6114	6338	8315	8445	8809
E_b [GeV]	91	80	80	80	80	80
$E_b^{Q_s} - E_b^{NMR}$	3	-4	10	-10	-52	-43
Fit error	19	27	28	41	27	17
Bending radius error	3	12	9	7	4	8
Non-linear oscillation error	1	3	3	45	26	48
Model imperfections	8	4	4	4	4	4
Momentum compaction factor error	2	2	2	2	2	2
Total error	21	30	30	62	38	52

All give result in agreement with NMR model !

← Additional error component in 2000 due to non-linear term arising from need to excite oscillations to high amplitude for signal to be seen

Combine results taking account of correlations:

Q_s – NMR = -3 ± 16 MeV at E_b = 85 GeV

Summary of E_b Measurements

We have 3 independent tests of NMR model at high energy:

- Flux Loop
  Continuum of correlated measurements 72-106 GeV
  Offset w.r.t. NMR -2±8 to -6±18 MeV
- Spectrometer
  Main measurement at 92 GeV: -5±18 MeV
  (second 75% correlated measurement at 70 GeV
  -1±10 MeV)
- Q_s vs V_{RF}
  Six measurements which give: -3±16 MeV at 85 GeV

Combining E_b Measurements

Combination 1

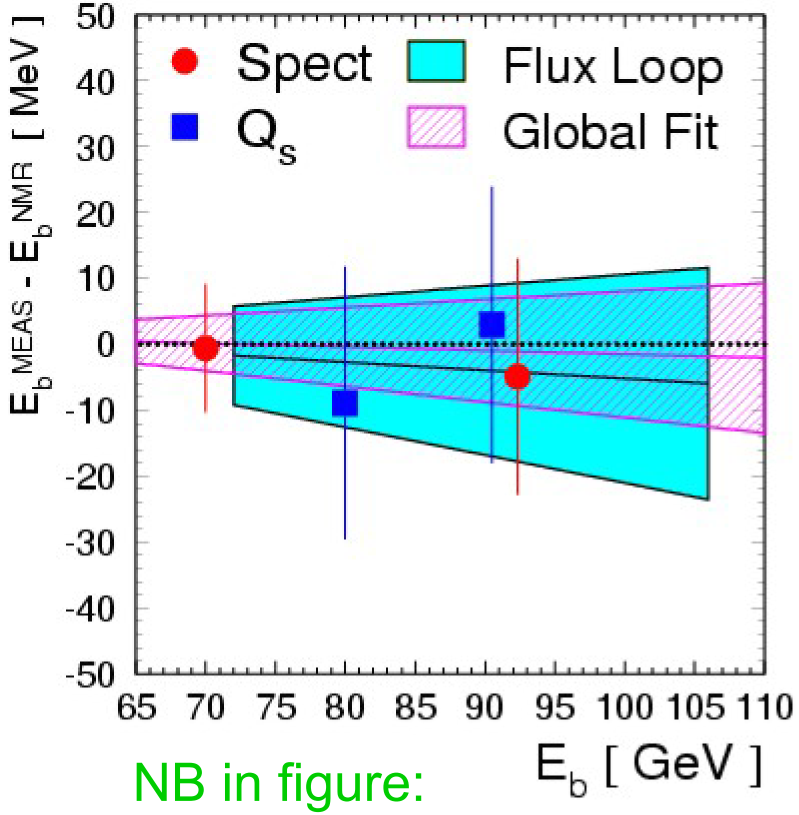
Assume offset constant with E_b. Take 92 GeV spectrometer result; Qs result and FL at 100 GeV.

Offset to NMR model -4 ± 9 MeV

Combination 2

Fit all data allowing for energy dependence. Obtain small slope (-0.1 MeV / GeV) and, at 100 GeV

Offset to NMR model -2 ± 10 MeV



NB in figure:

- 6 Qs measurements binned as 2 points
- There are high correlations between measurements

NMR test summary

Repeat fit with different sub-samples:

- Central values change very little in all cases
- Spectrometer and Q_s together provide rather similar precision to FL alone

Linearity of NMR model is verified with precision of 10 MeV at E_b=100 GeV.

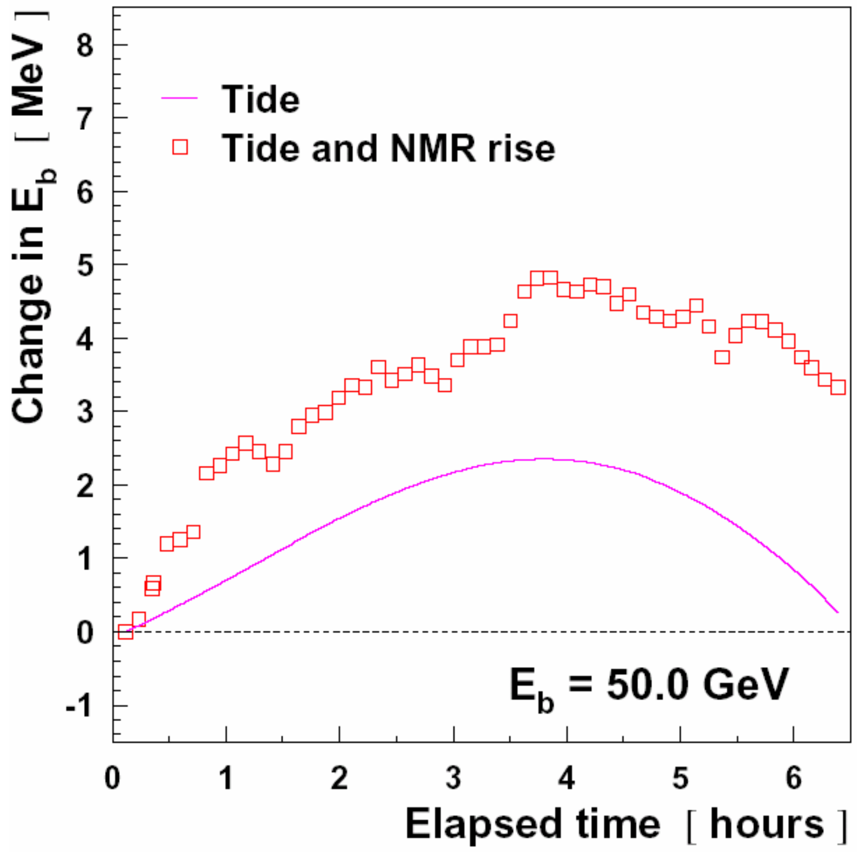
Testing the tide and the trains

According to energy model formulated at LEP1, the energy during a fill can evolve through effects of:

- Tide
- NMR rise due to parasitic currents (trains!) & temperature

During LEP2 a long term experiment was conducted to verify model.

Predictions of model vs time

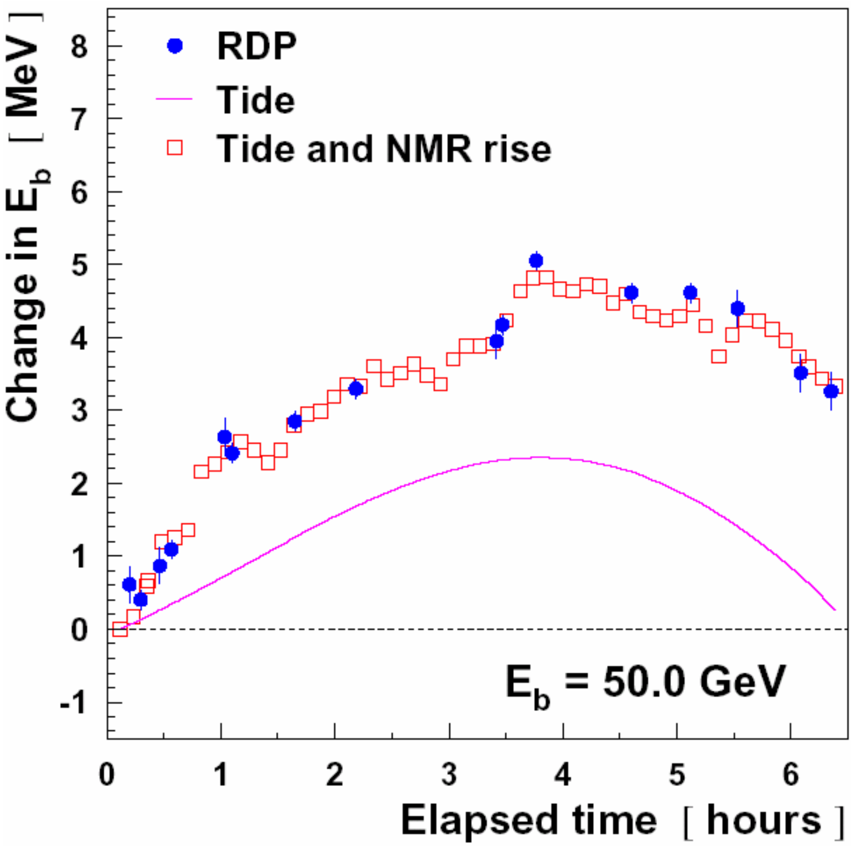


Testing the tide and the trains

Superimpose measurements made by RDP (normalised to model in first 30 minutes)

Excellent agreement confirming good understanding of LEP1

(Good news for m_Z !)



Summary of Errors on E_{cm}

Year	'96		'97	'98		1999			2000	
E_{CM}^{nom} [GeV]	161	172	183	189	192	196	200	202	205	207
NMR model	22.8	25.0	16.5	17.6	18.1	18.8	19.5	19.8	20.4	20.7
RDP	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
f_c^{RF}	0.0	0.0	5.4	5.6	5.8	5.8	6.0	6.0	0.0	0.0
α_c	0.3	0.4	3.5	4.4	4.4	5.2	4.7	3.0	2.3	1.4
ΔE_b in fill	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Hcor/BFS	1.6	1.8	3.4	4.6	0.6	1.0	0.2	0.6	28.6	34.4
QFQD	1.4	1.4	0.6	0.6	0.6	0.8	0.8	0.8	0.8	0.8
RF sawtooth	10.0	10.0	8.0	8.0	8.0	10.0	10.0	10.0	10.0	10.0
e^+e^- difference	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Dispersion	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Total	25.4	27.4	20.3	21.6	21.6	23.2	23.7	23.7	36.9	41.7

Bending Field Spreading (BFS) unique to 2000. Coherent powering of correctors to increase E_b. Calibrated with spectrometer.

Correlation between points ~95% for main years of operation, ~55% for 2000 points

Consequence for W mass

Spring ’03 m_W errors (MeV):

Collision energy measured with relative precision of

≈ 12 x 10^{-5}

(rising to 20 x10^{-5} in 2000)

When weighted by statistics, year-by-year, taking account of correlations, this induces an error on the W mass of

≈ 10 MeV

	S-L	4-j	All
ISR/FSR	8	8	8
Hadronisation	19	18	18
Detector Systs	14	10	14
Colour Reconn	/	90	9
B-E Correlations	/	35	3
Other Systs	4	5	4
Statistical	32	35	29

E_{cm} now contributes a rather small error to m_W

Conclusions

- Knowledge of collision energy enters as fully correlated ingredient in all LEP measurements of the W mass! (Reminiscent of other flagship EW measurements: E_{cm} for Z scan at LEP1 and polarisation for A_{LR} at SLC)

- Energy scale has been cross-checked by 3 independent methods. As a result we know with confidence that uncertainty from E_{cm} in W-mass is small (≈10 MeV) !

- LEP Energy Working group has been a highly successful and interesting collaboration between experiment and machine physicists . A nice example for future facilities!

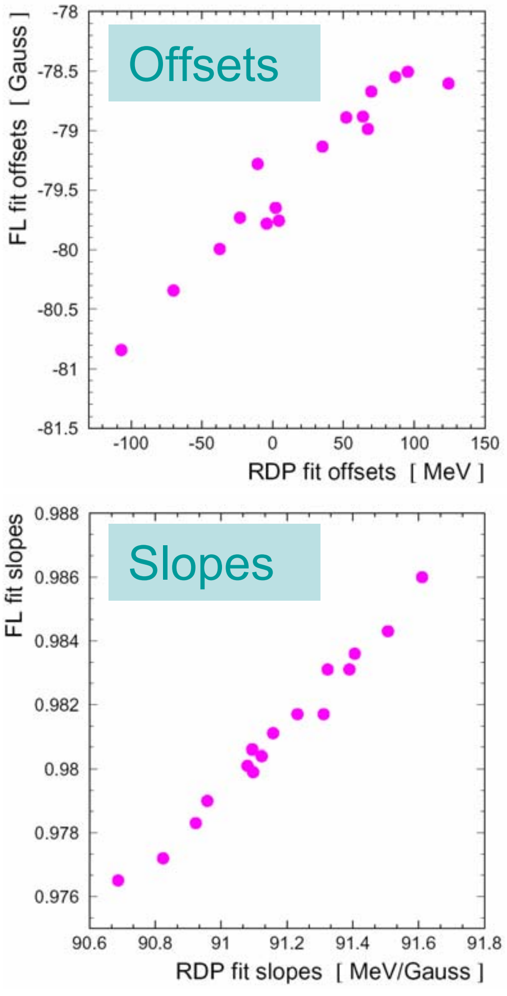
Back Up Slides

Flux Loop Analysis

Make 2 parameter fit of NMRs against FL, à la RDP calibration.

To compare with RDP, restrict fit to fields equivalent to 41-61 GeV

Strong correlation in fit parameters between FL and RDP gives confidence that the FL readings are indeed proportional to E_b



Environmental magnet fields

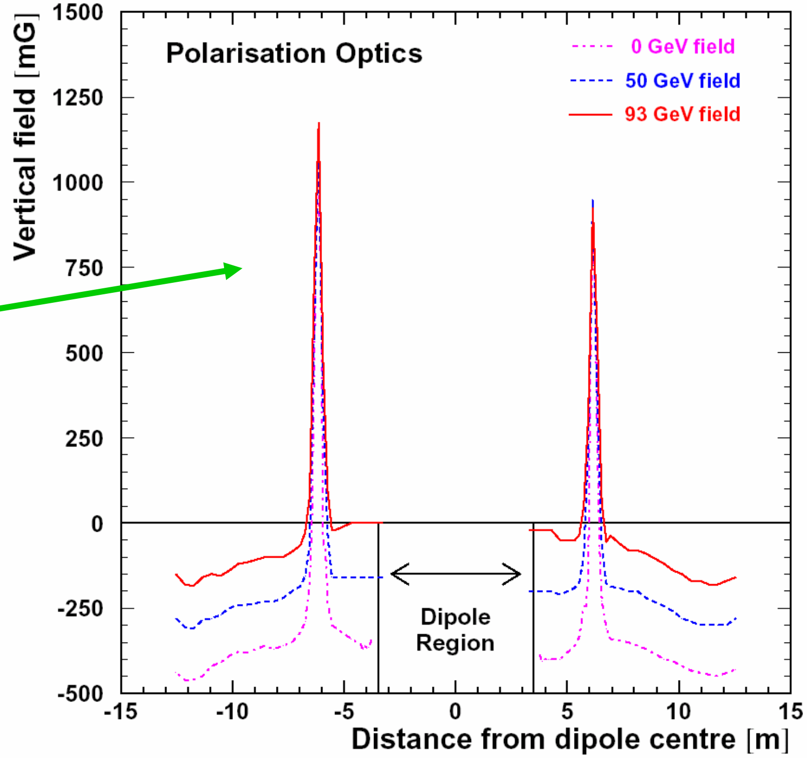
There are other (unwanted!) sources of bending field outside the dipole in the region of the BPM triplets

- Earth field (constant)
- Magnet power cables (field varies with energy)
- Permanent magnets in pumps

Distorts particle trajectories

Apply energy (and optics) dependent correction

Measure field profile vs E_b and monitor continuously at selected points with flux gate

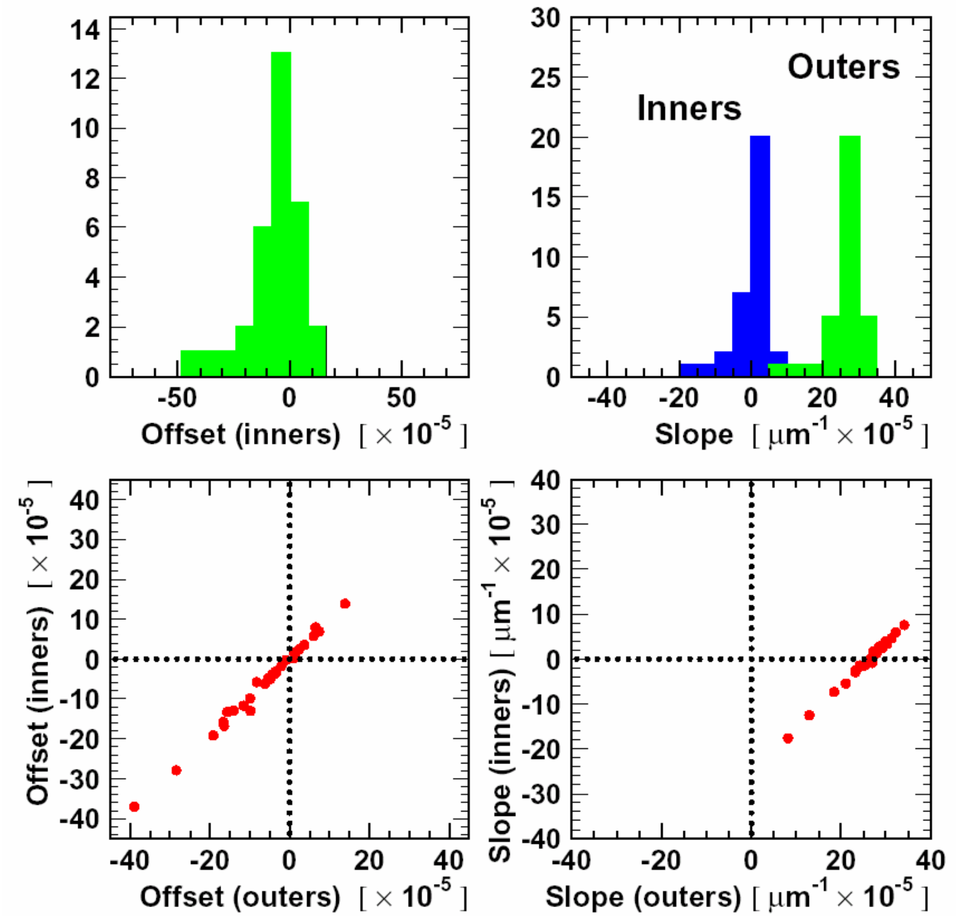


High Energy Robustness Tests

Repeat fit to high energy data taking different sub-samples:

- Early/late fills
- Discarding outliers
- Different optics
- Depending on whether TRS is higher in left or right arm

Obtain stable results



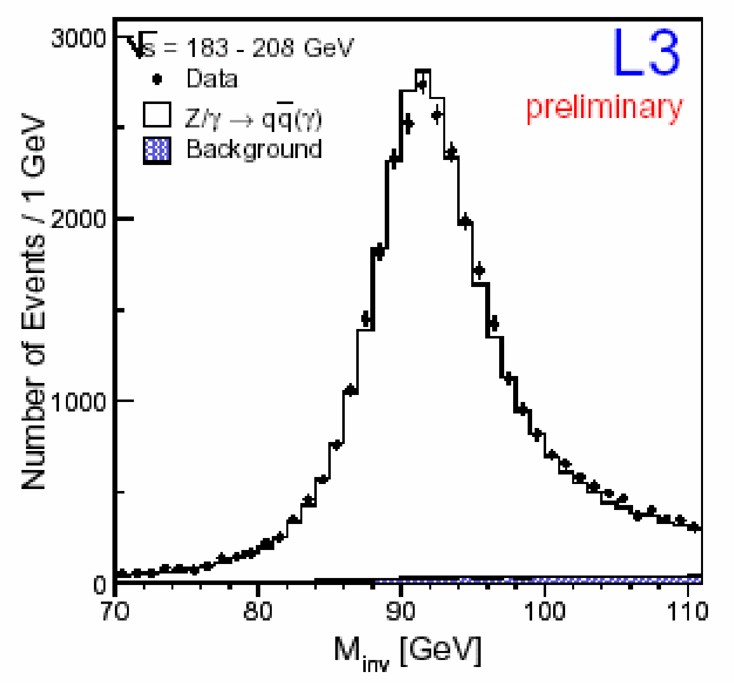
Bending Field Spreading

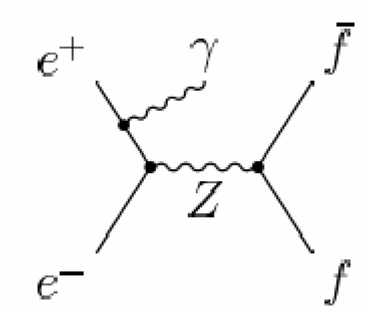
In 2000 alone, there is another component of comparable uncertainty, from the Bending Field Spreading (BFS):

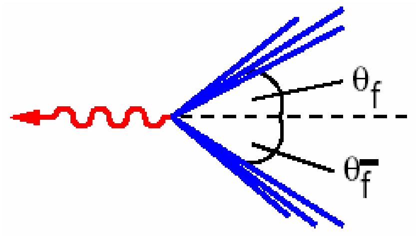
- Horizontal correctors coherently powered to provide source of bending field outside the main dipoles
- By spreading bending field in this manner, higher values of E_b by 200 MeV can be reached for same energy loss. Good for Higgs search!
- Calibrate BFS with spectrometer to 3.5 %

E_{cm} from Radiative Returns

Possible to cross-check E_{cm} estimate using experimental data by selecting $e^+e^- \rightarrow f\bar{f}\gamma$ events where the $f\bar{f}$ invariant mass is close to m_Z







From knowledge of m_Z at LEP1 invert problem and deduce initial collision energy of event

EPS 2003:

$E_{cm}^{rad} - E_{cm}^{LEP} = -28 \pm 42 \pm 40$

(stat) (syst)