LEP Energy from the Synchrotron Tune Q_s

A.-S. Müller
CERN and Mainz University

Outline

- Introduction
- The Synchrotron Tune
- Extracting the Beam Energy
- Summary

Introduction

- Average beam energy for relativistic particles:

$$E_0 = \frac{ec}{2\pi} \oint_C ds B$$

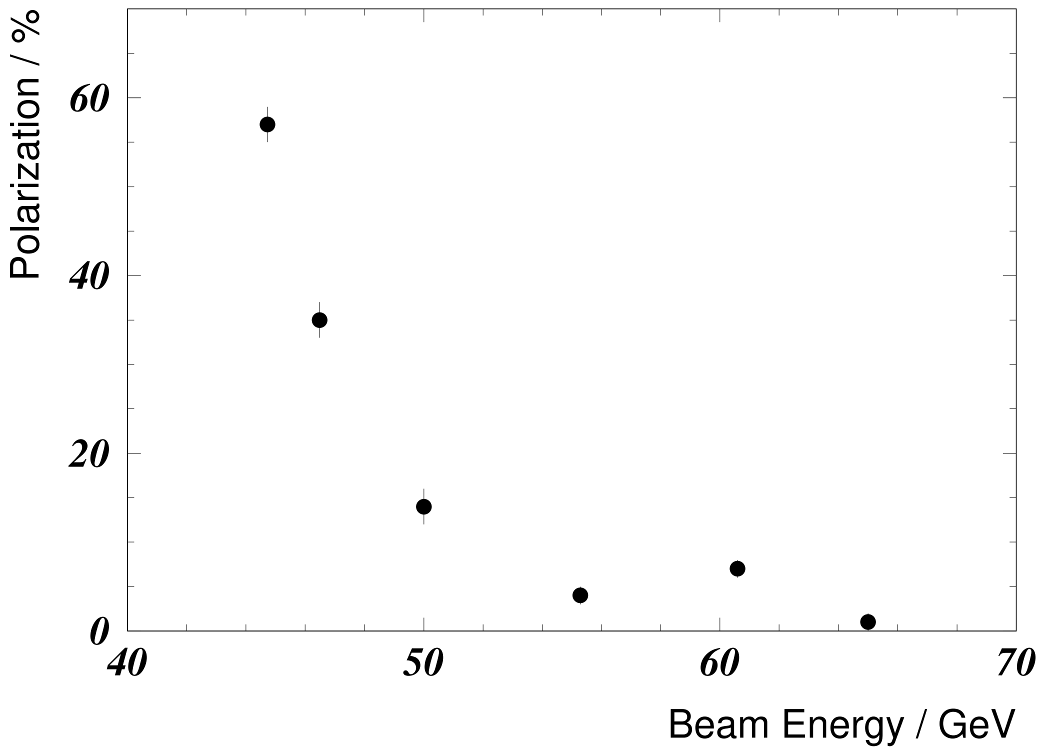
- Integrated bending field at 45 GeV $\approx 10^3$ Tm

- Good knowledge of dipole bending fields allows to monitor beam energy E_0

- Energy accuracies:
  - LEP before RDP: $\Delta E/E \approx 5\ 10^{-4}$ (magnets)
  - LEP1 final: $\Delta E/E \approx 2\ 10^{-5}$
  - LEP2 (present): $\Delta E/E \approx 2\ 10^{-4}$
  - LEP2 target: $\Delta E/E \approx 1\ 10^{-4}$

Energy Calibration at LEP

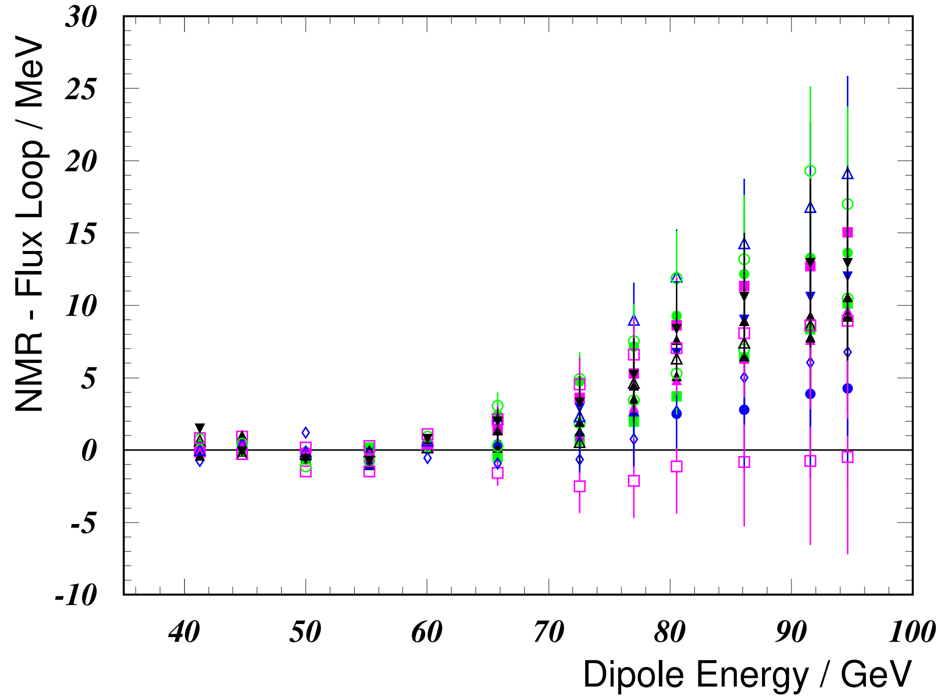
- precise energy determination with resonant depolarization (RDP)
- works only for energies from 40 to 60 GeV



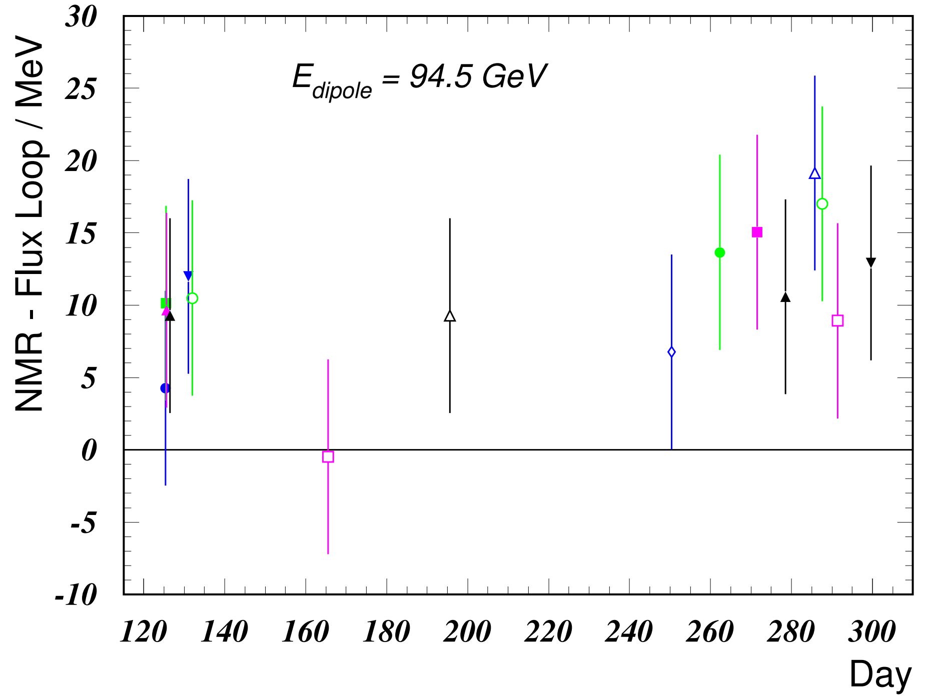
- Extrapolations are needed:
  - Standard method: magnetic measurements
  - Methods under development: spectrometer, synchrotron tune, ...
- Alternative: radiative returns to the Z

Extrapolation Errors

- Cross-check flux loop - NMR:



- Time dependence:



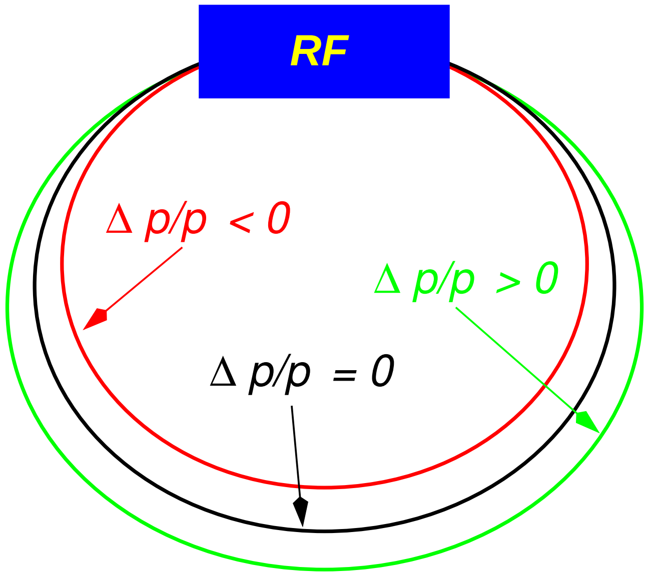
Energy Errors '97, '98 and '99

Source of uncertainty	Error [MeV]		
	1997	1998	1999
Extrapolation from NMR-pol.:			
NMR rms/$\sqrt{N}$ at E_{phys}	10	8	11
different E_{pol} fills	5	4	3
FL test of extrapolation:			
NMR-FL difference at E_{phys}	20	15	15
Field not measured by FL	5	5	5
Optics difference	4	6	4
Corrector effects	3	4	2
IP specific corr. ($\delta E_{cm}/2$):			
RF model	4	4	5
Total error	25	20	21

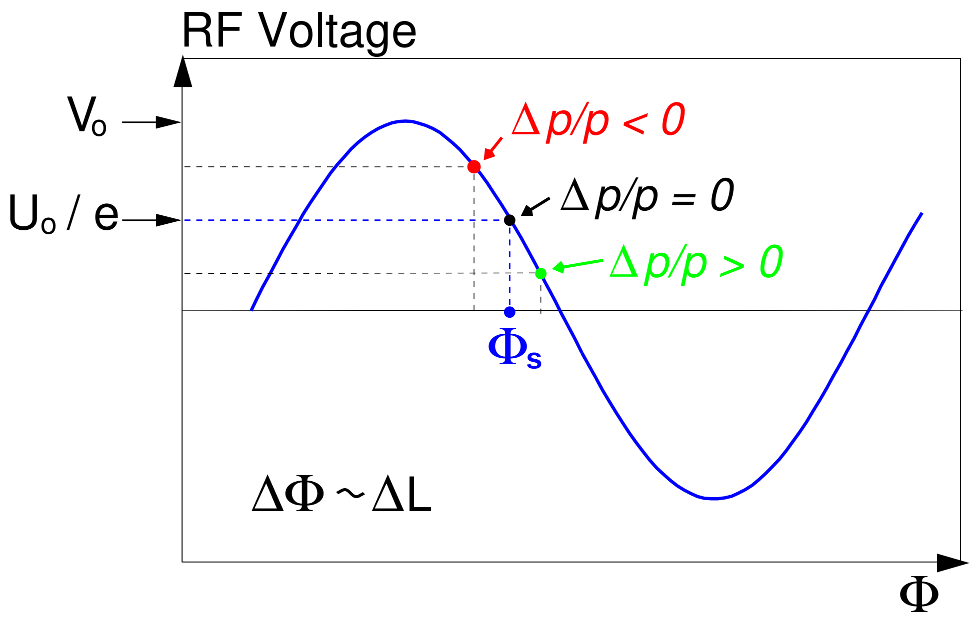
(1999 errors preliminary)

The Synchrotron Tune Q_s

- Synchrotron oscillation:



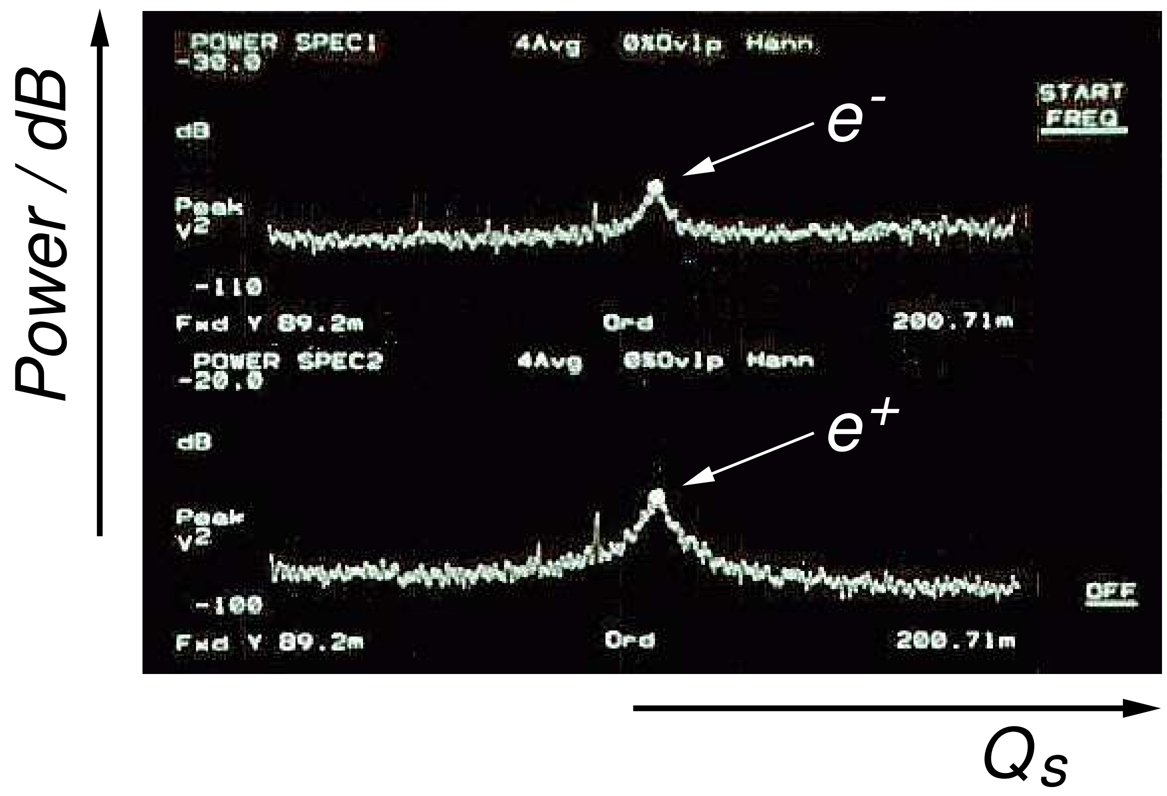
Particles oscillate around the stable phase Φ_s with the frequency Ω



- Synchrotron tune: $Q_s = \dfrac{\Omega}{\omega_{rev}}$

Measurement of Q_s

- Measurement:
  - bunch oscillation detected with pickup
  - phase difference between bunch and RF
  - synchrotron tune from power spectrum
- Q_s power spectrum:

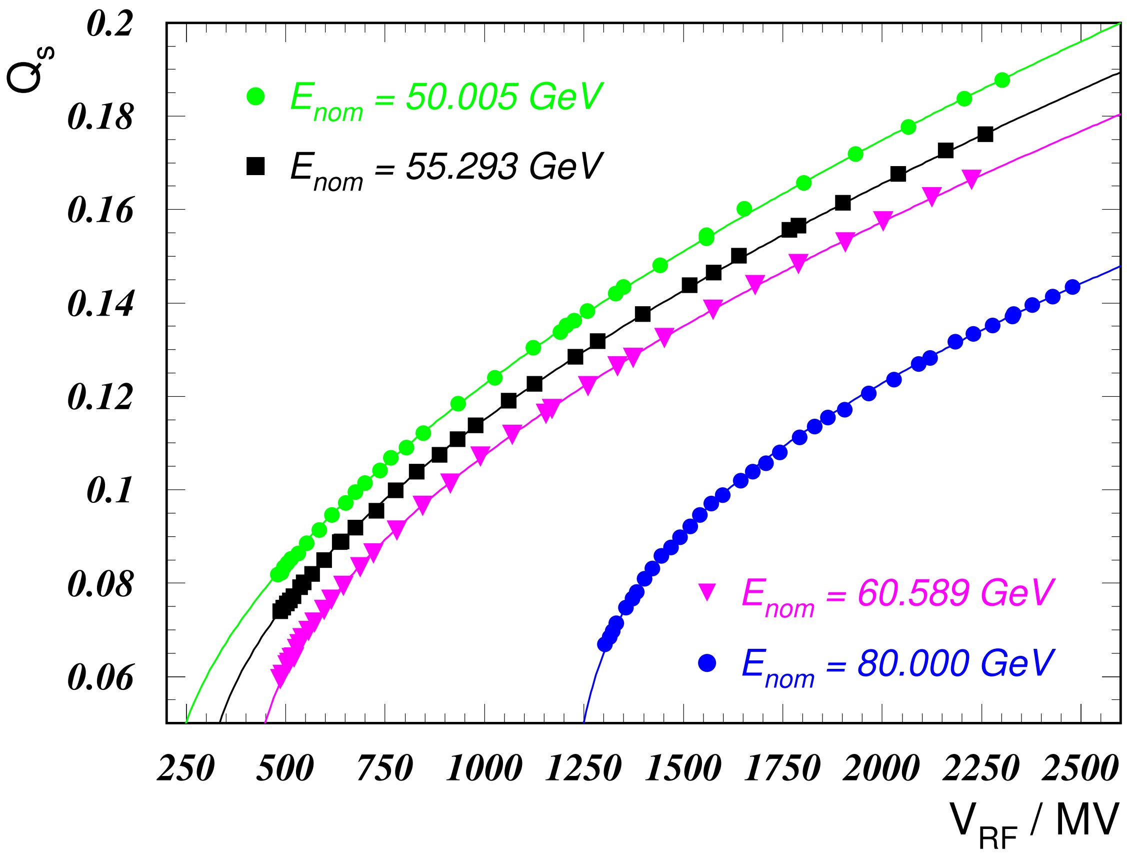


Q_s and RF Voltage

→ first pointed out by H. Burkhardt and A. Hofmann as a means to determine the energy loss at LEP

- Synchrotron tune Q_s depends on
  - total RF voltage
  - beam energy

- Measurements of Q_s as function of V_{RF}:



Extracting the Beam Energy

Textbook ansatz:

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

α_c : momentum compaction factor
ρ : bending radius
C_γ: Sand's synchrotron radiation constant
h : harmonic number

Effects to be taken into account:

- Voltage calibration: $V_{RF} \rightarrow g\ V_{RF}$
  (to be determined from separate datasets)
- Higher order terms $\propto V_{RF}^4$? (from models)
- Tide effects! (from models)
- Total energy loss: $(C_\gamma/\rho)E^4 \rightarrow ((C_\gamma/\rho)E^4 + K)$
  (calculations and dedicated measurements)
- Knowledge of machine parameters (α_c, ρ)

Procedure of Q_s Fitting

- Requirements:

  - Set of measurements
    at {50, 55, 60} GeV (known energy!)

  - Voltage calibration:
    adjust voltage correction factor g to match E for all low energy datasets

    $\gtrdot$ $\langle g \rangle \pm \Delta g$

  - Additional energy losses:
    evaluate losses from other sources than dipoles with simulations and dedicated measurements

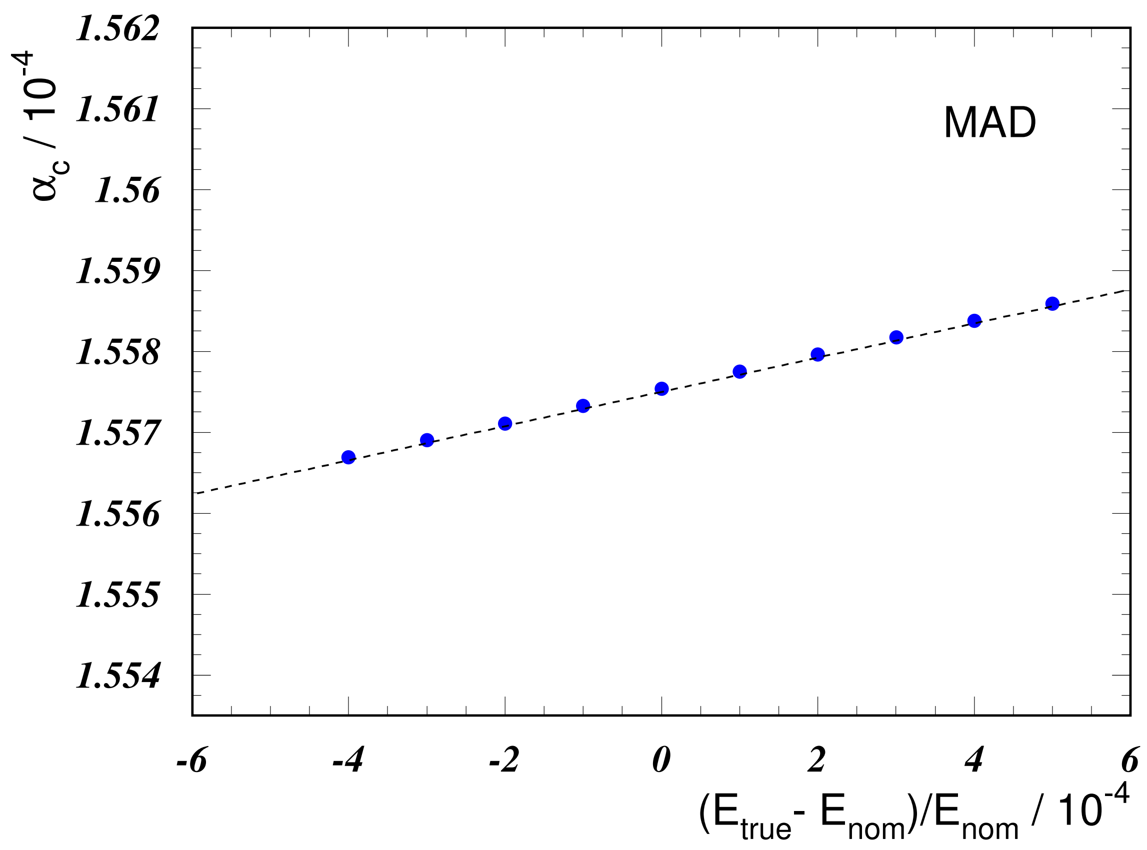
    $\gtrdot$ $K \pm \Delta K$

- Extract precise energy

  → from measurements at {80, 90} GeV

Momentum Compaction Factor

- Error on α_c from optics mismatch:
  - difference between true and nominal dipole field
    → mismatch of dipoles and quadrupoles



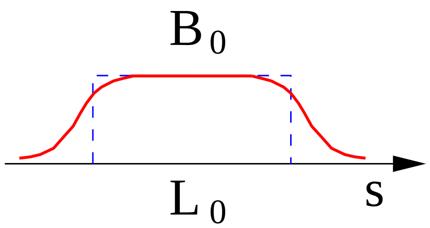
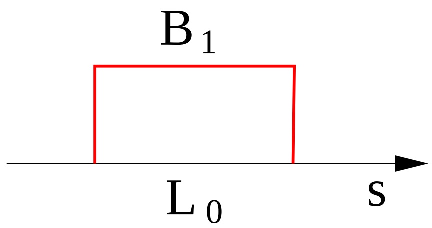
⊳ bias of $\delta E \sim 10$ MeV
(if not corrected)

Bending Radius and Fringe Fields

- Bending radius from LEP model ("MAD"):

$$\rho_{MAD} = 3025.85 \text{ m}$$

- MAD overestimates the energy loss:

	"LEP"		"MAD"
"shape" Ω :			
$\int B ds$:	$B_0 \int \Omega ds$	$=$	$B_1 L_0$
$U_0 \sim \int B^2 ds$:	$B_0^2 \int \Omega^2 ds$	$<$	$\frac{B_0^2}{L_0} \left(\int \Omega ds\right)^2$

➜ Data/fits prefer correction $\mathcal{O}(0.3\%)$

➜ presently $\delta E = 15$ MeV for $\Delta(1/\rho) = 0.1$ %

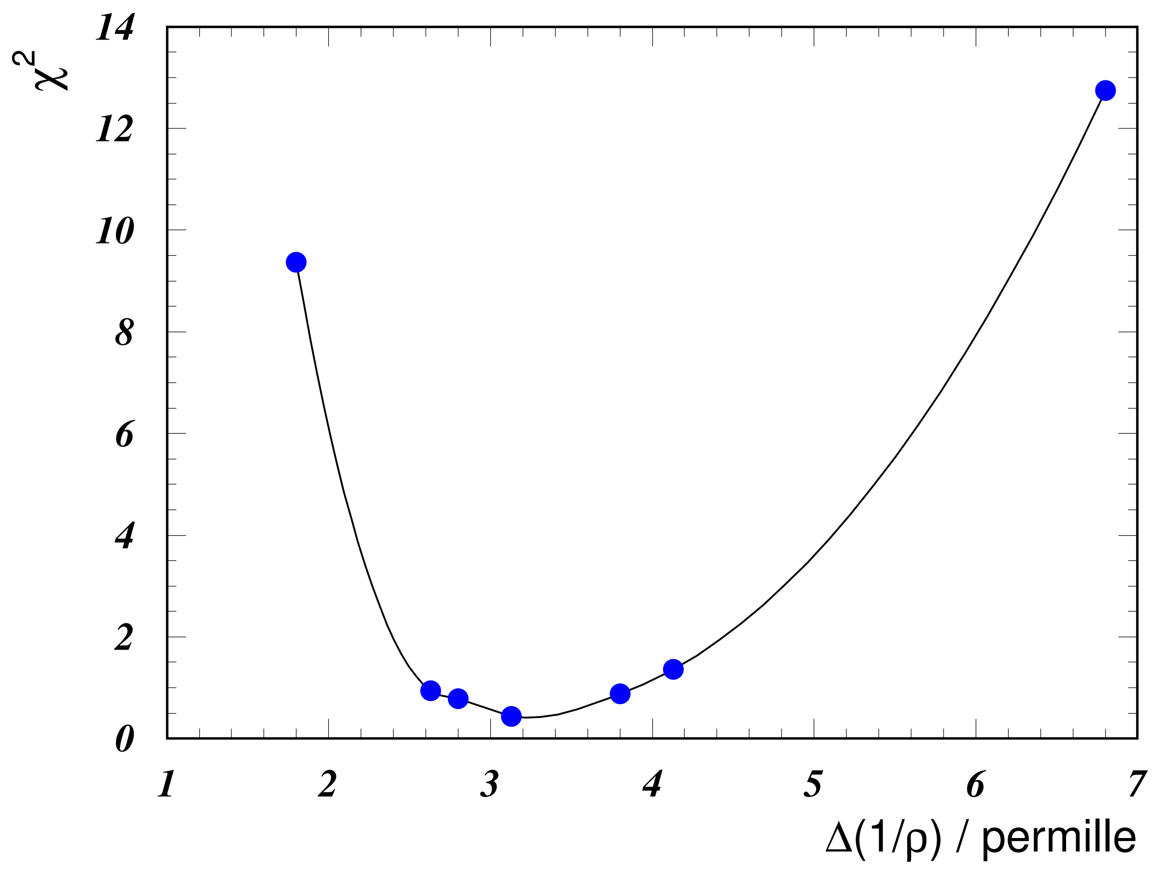
✘ exp. correction from magn. models larger!

A Way to extract LEP's Radius

- Compare E_{Q_s} with reference energy:

$$\rightarrow \quad \chi^2 = \frac{(E_{Q_s} - E_{ref})^2}{(\sigma_{E_{ref}})^2}$$

- Proof of principle with E_{NMR}:



→ expect reduction of uncertainty by dedicated measurements

Results

Preliminary!

E_{nom}	optics	E_{pol}	E_{NMR}	$E_{Q_s} \pm$ stat. $\pm$ sys.	$\Delta E/E$
50.005	60/60	50.020	50.015	$50.044 \pm 0.014 \pm 0.029$	$6.4\ 10^{-4}$
60.589	60/60	60.597	60.594	$60.586 \pm 0.012 \pm 0.021$	$4.0\ 10^{-4}$
80.000	102/90	–	80.012	$79.995 \pm 0.011 \pm 0.018$	$2.6\ 10^{-4}$
80.000	102/90	–	80.001	$80.004 \pm 0.015 \pm 0.012$	$2.4\ 10^{-4}$
90.419	102/90	–	90.458	$90.444 \pm 0.007 \pm 0.017$	$2.0\ 10^{-4}$

(all energies in GeV)

- ✔ good agreement with magnetic measurements
- ✔ error essentially energy independent $\sim$ 20 - 30 MeV
- ✘ current machine parameter bias $\mathcal{O}$(18 MeV) will be reduced

Summary and Outlook

Energy calibration

- ✔ polarization up to 60 GeV
- ✘ extrapolations: FL - NMR ~ 15 MeV

Q_s and total RF voltage

- ✔ independent energy measurement
- ✔ high intrinsic precision
- ✔ energy range from 50 to 90 GeV

Prospects for the future:

- ➜ stand. calibration: 15 - 20 MeV
- ➜ spectrometer : 10 - 15 MeV
- ➜ "Q_s vs voltage" : $<$ 20 MeV