Energy Calibration with Energy Loss Measurements

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Outline

- Introduction
- Energy from Coherent Damping
- The Energy Sawtooth
- Energy from Synchrotron Tune
- Summary

Introduction

- Average beam energy for relativistic particles:

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

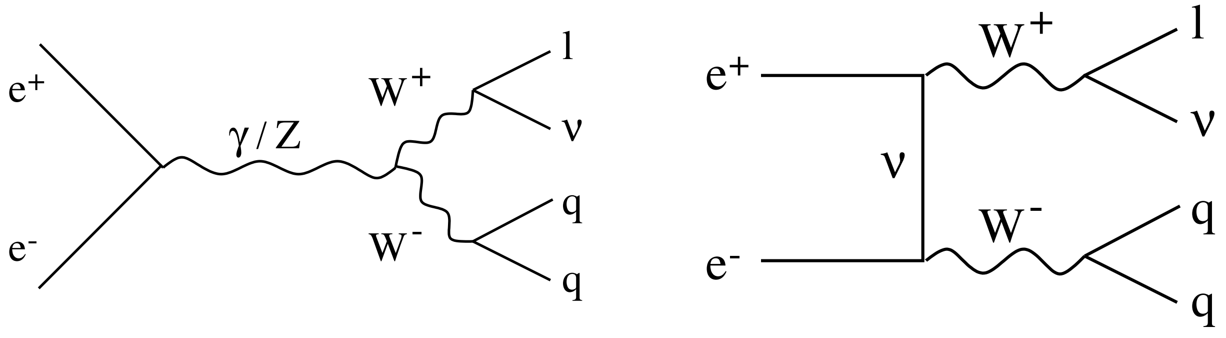
- Integrated bending field at 45 GeV $\approx 10^3$ Tm

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

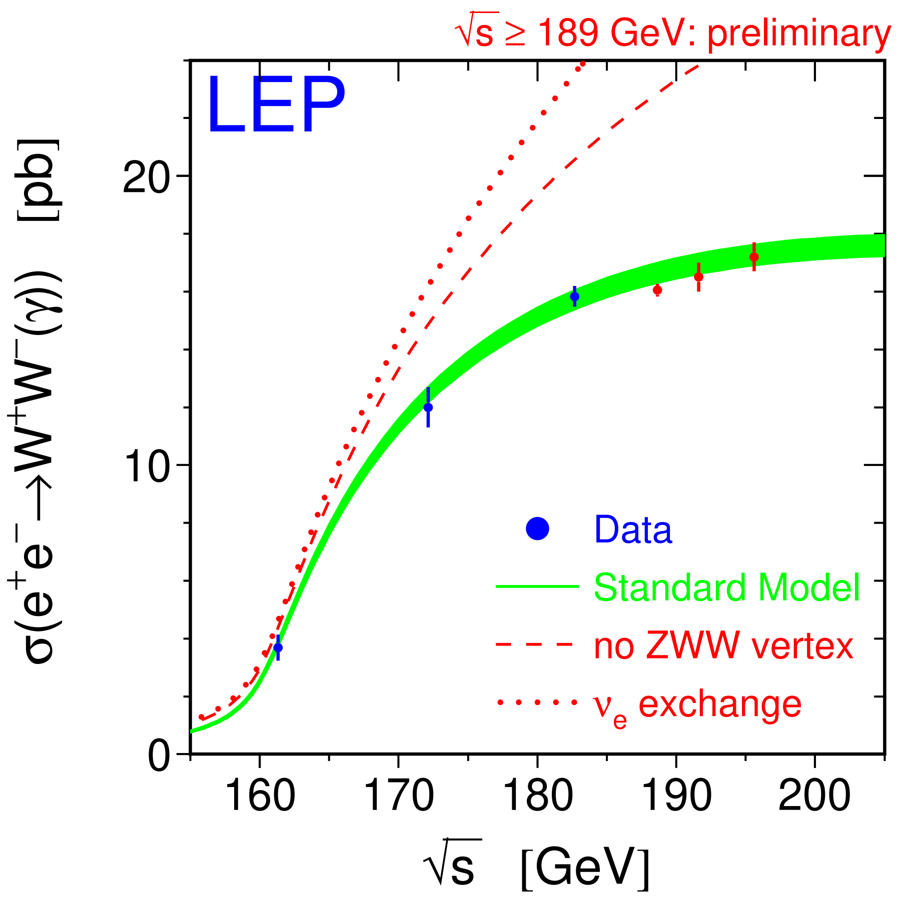
- Energy accuracies:
  - LEP before RDP: $\Delta E/E \approx 5\ 10^{-4}$ (magnets)
  - LEP1 final: $\Delta E/E \approx 2\ 10^{-5}$
  - LEP2 (present): $\Delta E/E \approx 2\ 10^{-4}$
  - LEP2 target: $\Delta E/E \approx 1\ 10^{-4}$

WW Production Cross Section

- WW production in the Standard Model:



Quantum mechanics at work...



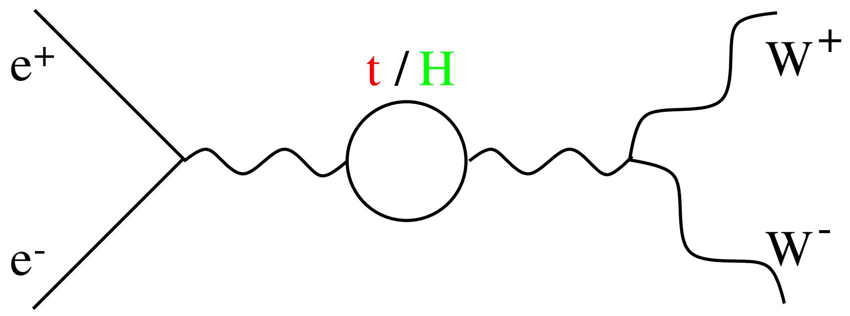
Tests of the Standard Model

- Check of Standard Model:

$$\sin^2\theta_W = 1 - \frac{m_Z^2}{m_W^2}$$

⊳ compare $\sin^2\theta_W$ and (m_Z, m_W)

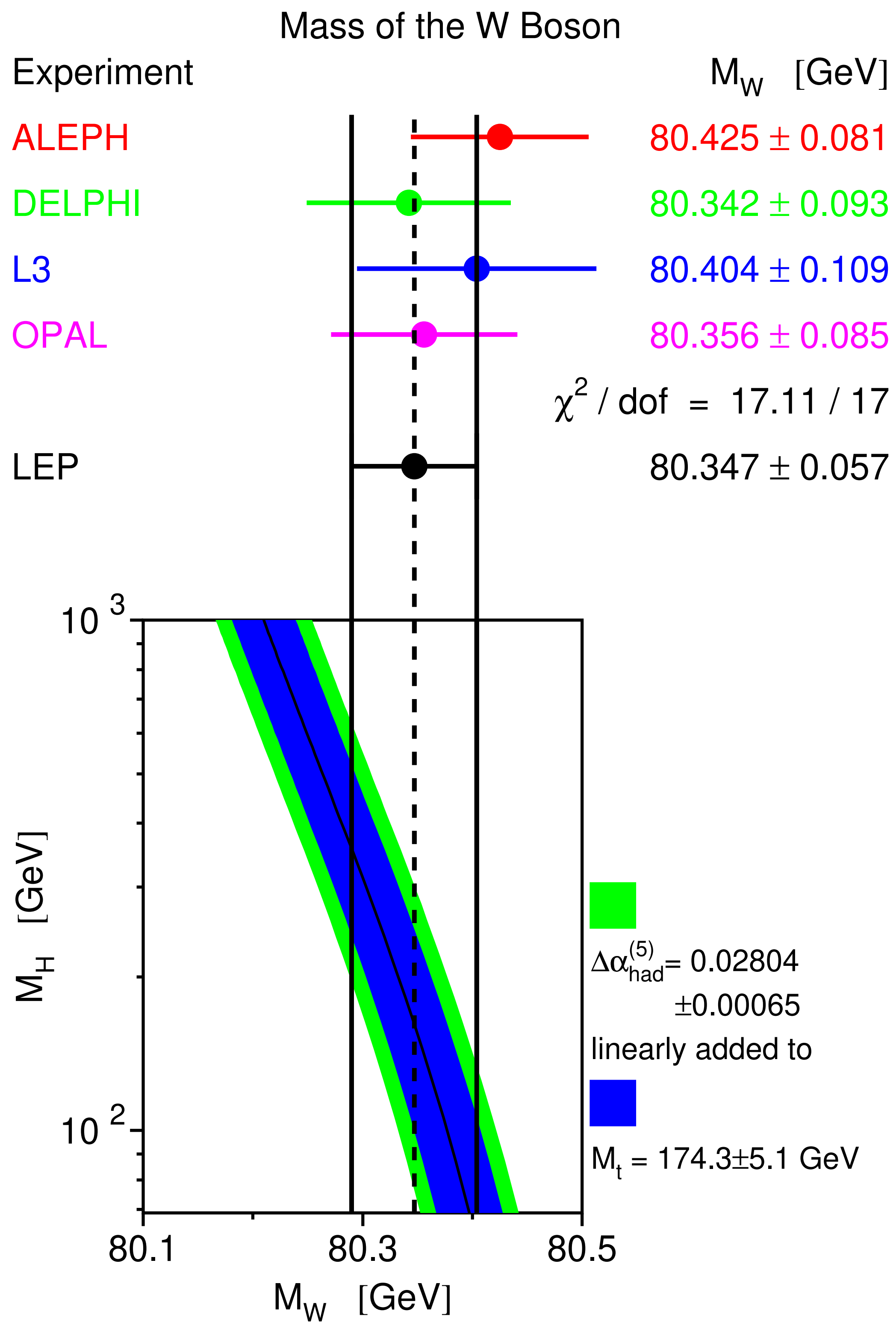
- Check at the level of quantum corrections:



➜ sensitivity to m_t and m_H

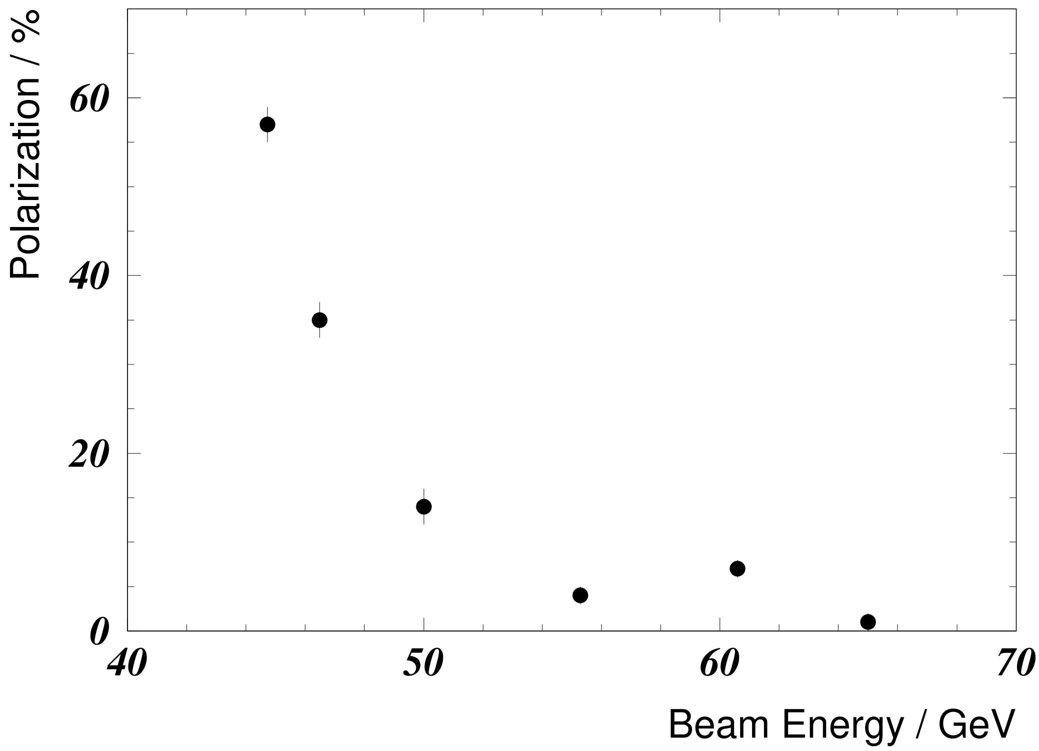
⊳ measure m_Z and m_W as precise as possible

W Mass and the Higgs (EWWG)



Energy Calibration at LEP

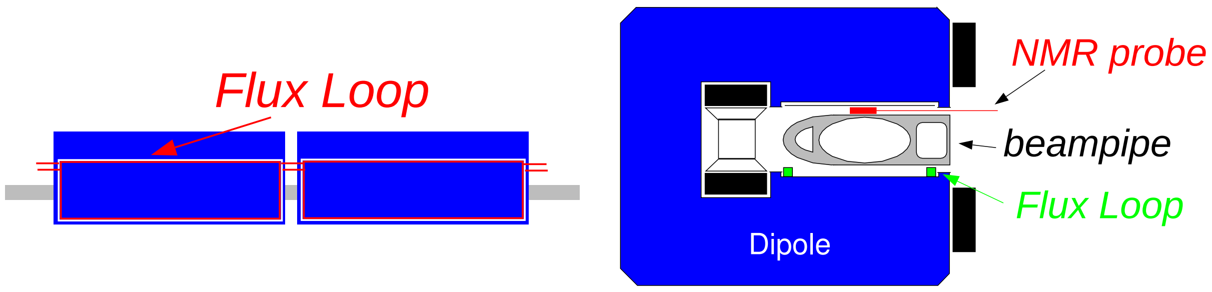
- precise energy determination with resonant depolarization (RDP)
- works only for energies from 40 to 60 GeV



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

Magnetic Measurements

- Energy and magnetic field: $E_{\text{beam}} \propto \oint_C B ds$



- Idea:
  - measure magnetic field using NMR probes and flux-loop cables
  - calibrate field measurements at low energies with RDP and extrapolate to high energy

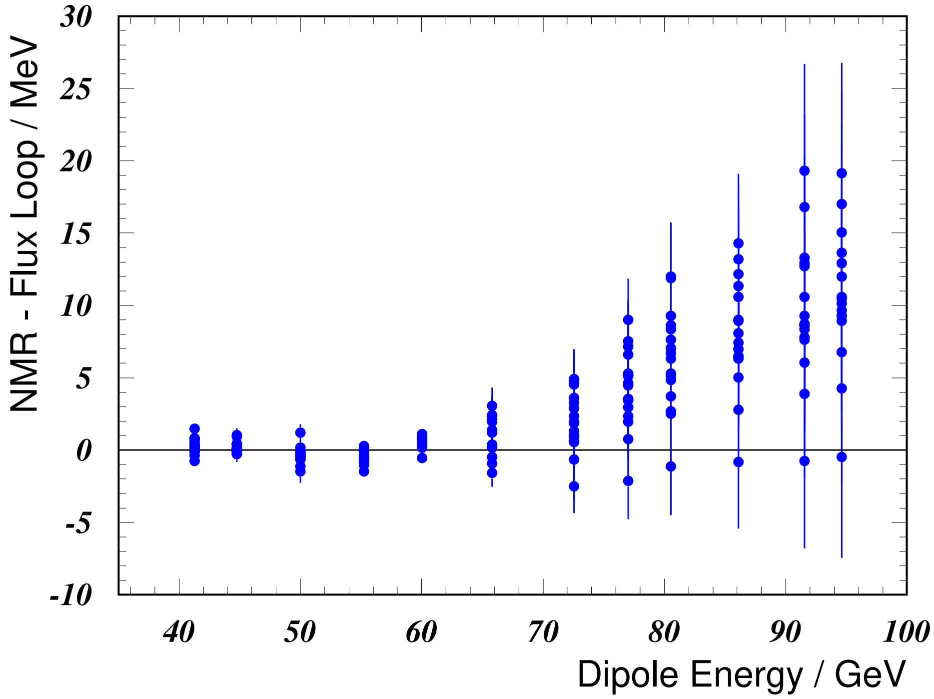
✘ differences between flux-loop and NMR up to ~ 15 MeV at highest energies

✘ largest contribution to energy error of $\mathcal{O}(20\text{ MeV})$

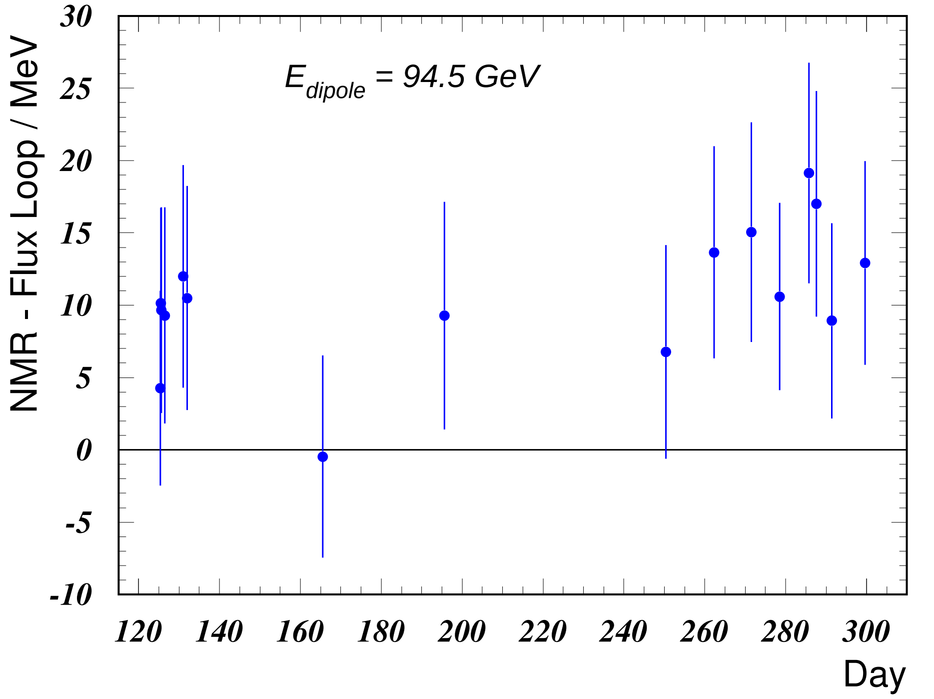
⊳ cross-check needed/wanted

Extrapolation Errors

- Cross-check flux loop - NMR:

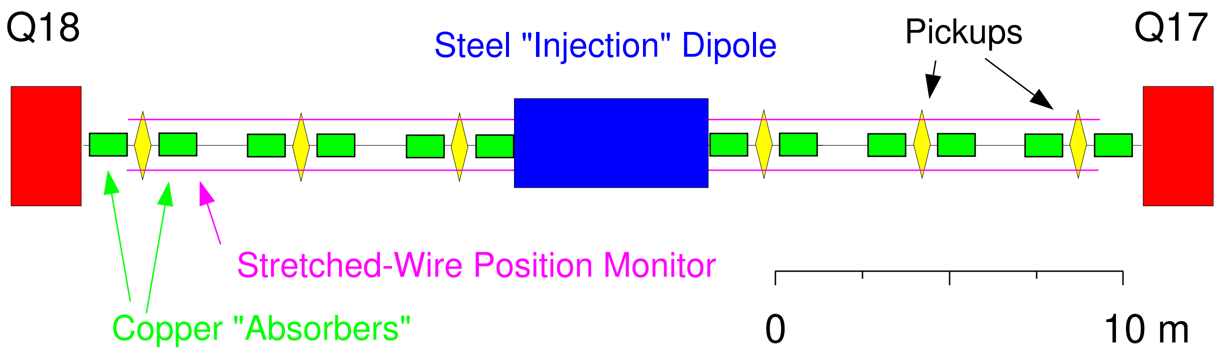


- Time dependence:



The Spectrometer

- Details: John Matheson, SL Seminar



- Idea:

- determine $\int B ds$ with high accuracy
- measure deflection angle θ $(\sim \int B ds / E)$
- calibrate at low energy with RDP and measure energy directly at high energy

✘ for a 10^{-4} ($\sim$ 10 MeV) precision, the position has to be measured to 1 μm!

- Status:

- first prel. results promising ($\Delta E \sim 15$ MeV)
- work going on....

Energy Loss Measurements

- Basic Idea:

- Energy loss per turn depends on beam energy:

$$U_0 = \frac{C_\gamma}{\rho} E_0^4$$

→ measure observables depending on energy loss

- Coherent Damping

- Radiation damping depends on energy loss

- Energy Sawtooth

- Horizontal position depends on actual energy
  → position change over an arc $\propto U_0$

- Q_s as function of RF voltage

- $Q_s^2 = \left(\frac{\alpha_c h}{2\pi E}\right) \sqrt{V_{RF}^2 - U_0^2}$
- measure Q_s for different RF voltages
- extract energy directly from a fit

Energy from Coherent Damping

- Coherent Damping at LEP

- composed of radiation and head-tail damping:

$$1/\tau_{coh} = 1/\tau_0 + 1/\tau_{head-tail}$$

- Synchrotron Radiation Damping

$$1/\tau_0 = \frac{1}{2}\,\frac{U_0\ f_{rev}}{E_0}\,J_x$$

- Head-tail Damping:

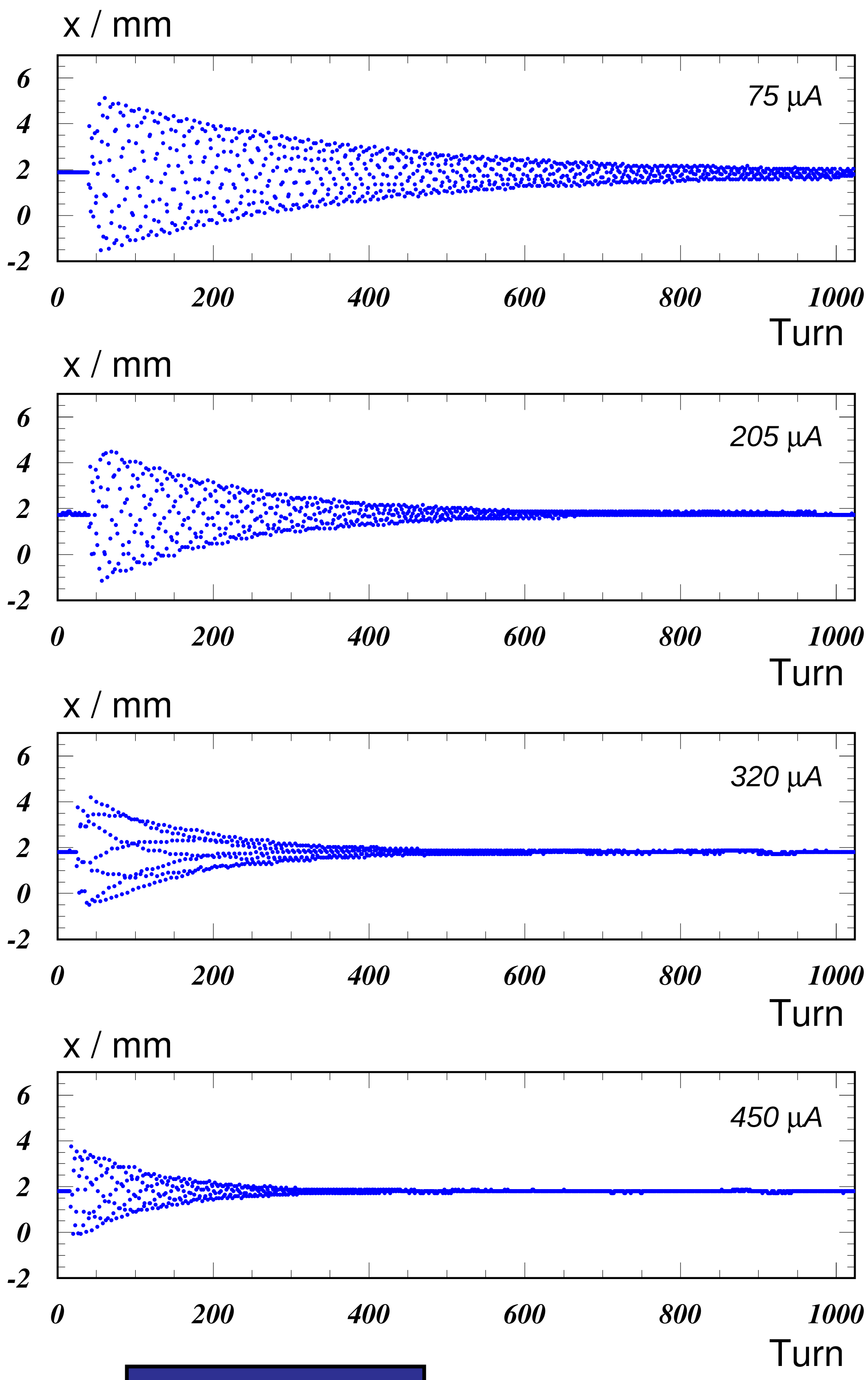
$$1/\tau_{head-tail} \propto \frac{\sigma_s Q'}{E_0} I_b$$

→ Measure coherent damping rate for different currents and extrapolate to $I_b = 0\ \mu A$

- Input Information:

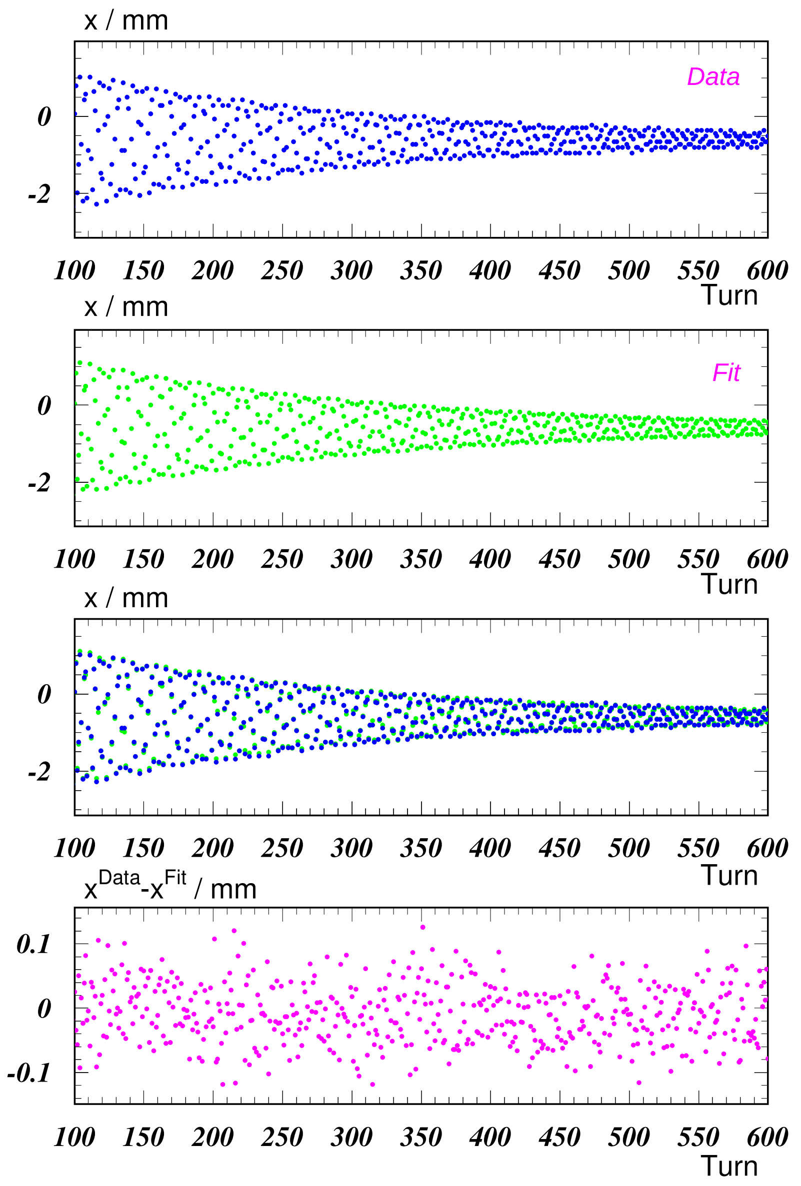
- Data from *"1000-turn measurements"* (center-of-charge position of a bunch after a single excitation measured over 1024 consecutive turns.)

1000-Turn Measurements



Energy Loss

Extraction of Damping Time

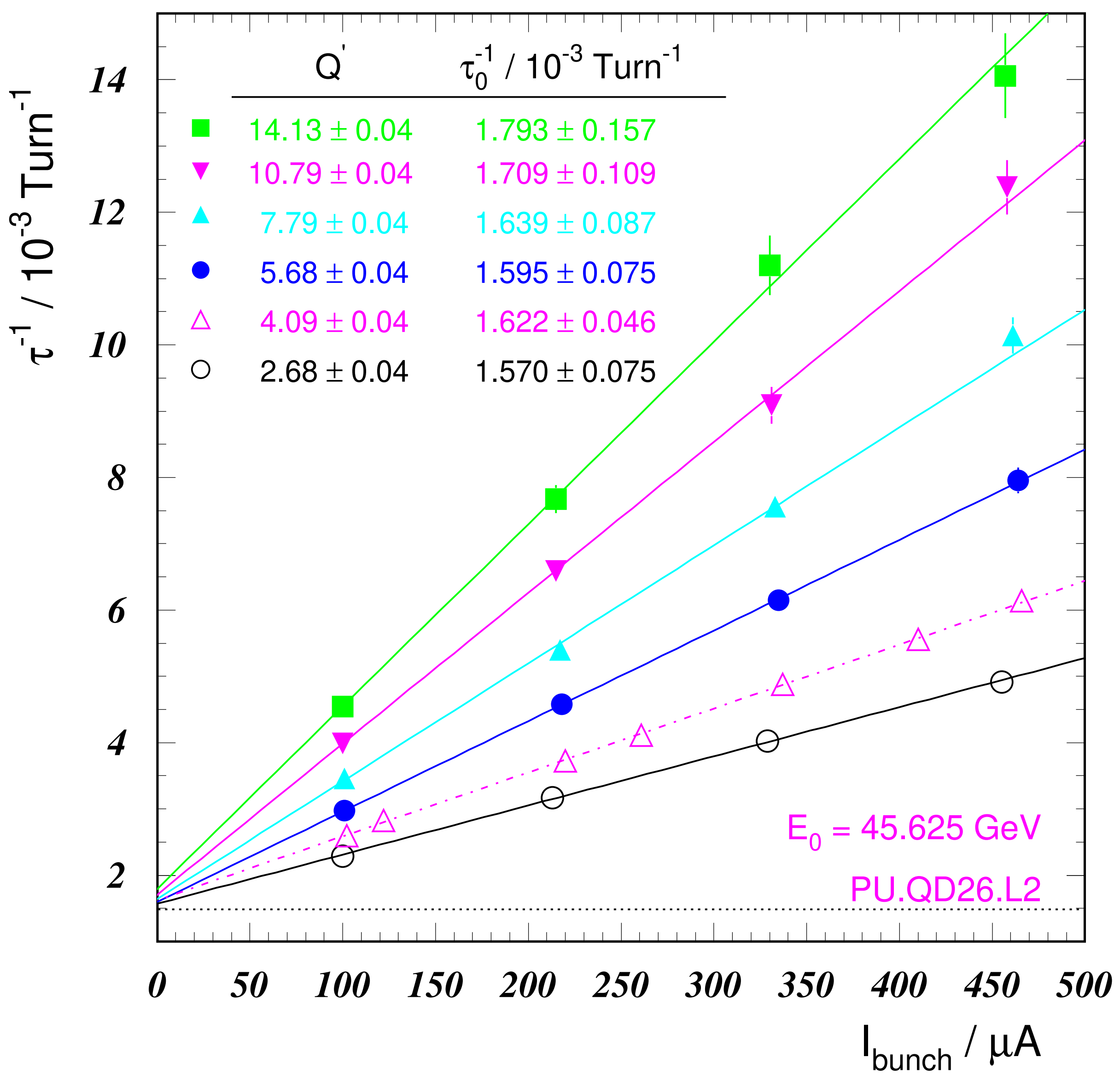


$$x(t) = x_0 + A_0 e^{-t/\tau} \sin\left(2\pi\Phi(t) + \varphi\right)$$

$$\Phi(t) = tQ_0 + \frac{\tau}{2}\alpha_q A_0^2 \left(1 - e^{-2\ t/\tau}\right)$$

Damping and Chromaticity

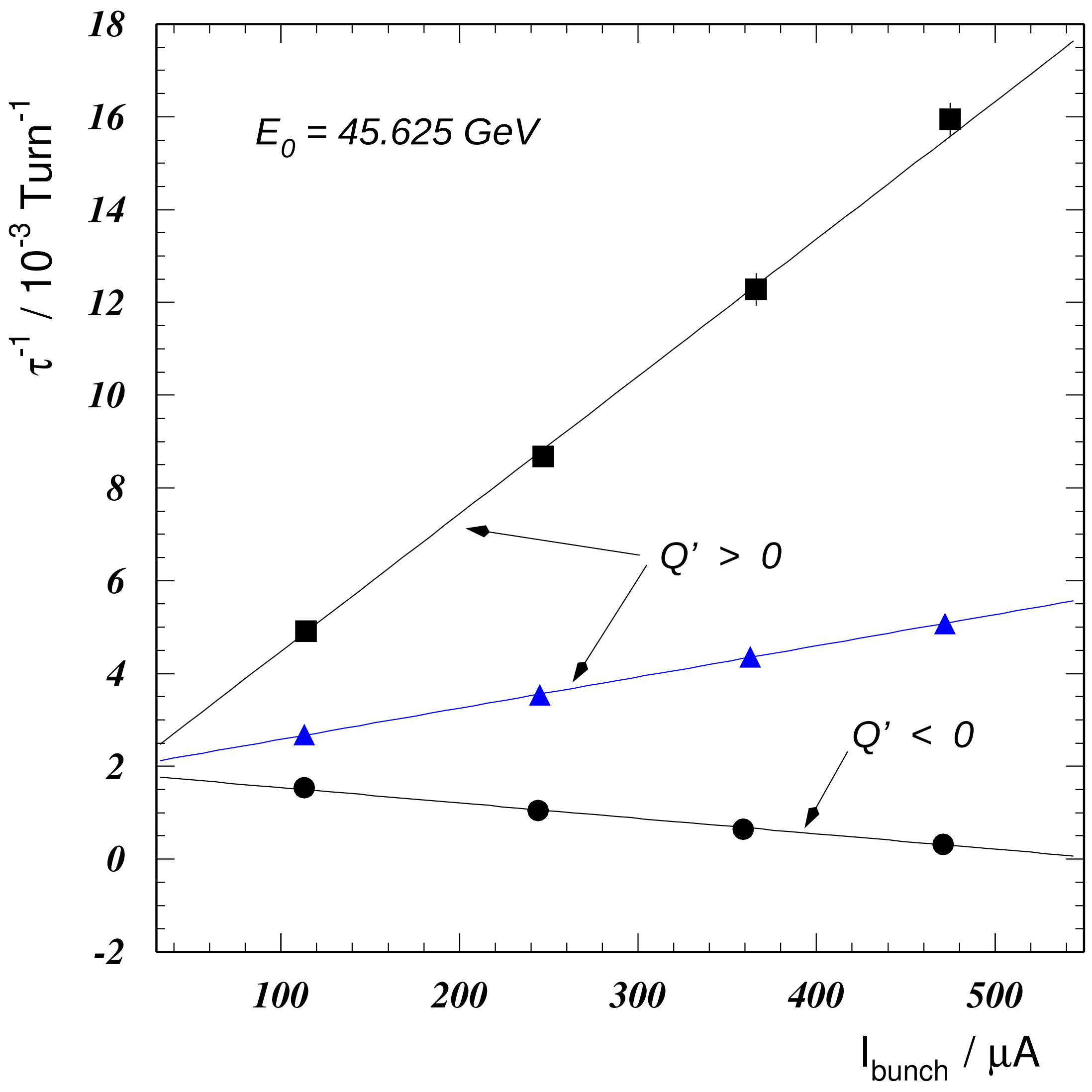
- Measurement at 45.625 GeV:



$$1/\tau_{head-tail} \propto \frac{W_0 \sigma_s Q'}{E_0\ \alpha_c} I_b$$

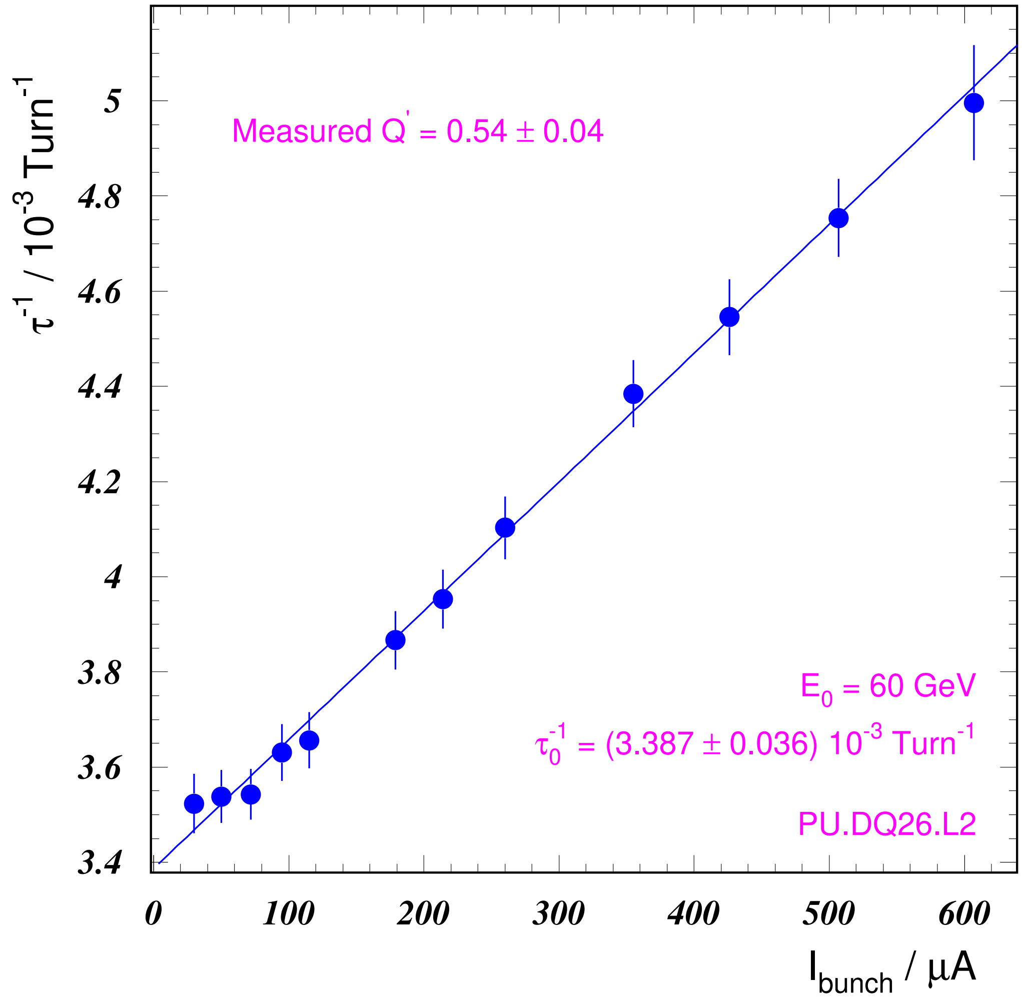
Damping and Chromaticity II

- Measurement at 45.625 GeV:



⇒ Counterbalance radiation and head-tail damping with chromaticity and bunch current

Coherent Damping and Energy Loss



Energy loss in MeV

	Energy	Measured	Expected
■	60.000 GeV	382 ± 4	380
■	45.625 GeV	126 ± 9	127

✘ Energy uncertainty $\mathcal{O}(0.3-2\%)$

Open a Parenthesis

Optics at LEP2

- Emittance depends on E_0 and Q_x

$$\varepsilon_x \propto \frac{E_0^2}{Q_x^3}$$

- To counteract ε_x growth with E_0

  ⊳ increase Q_x ↗

- Choice of optics

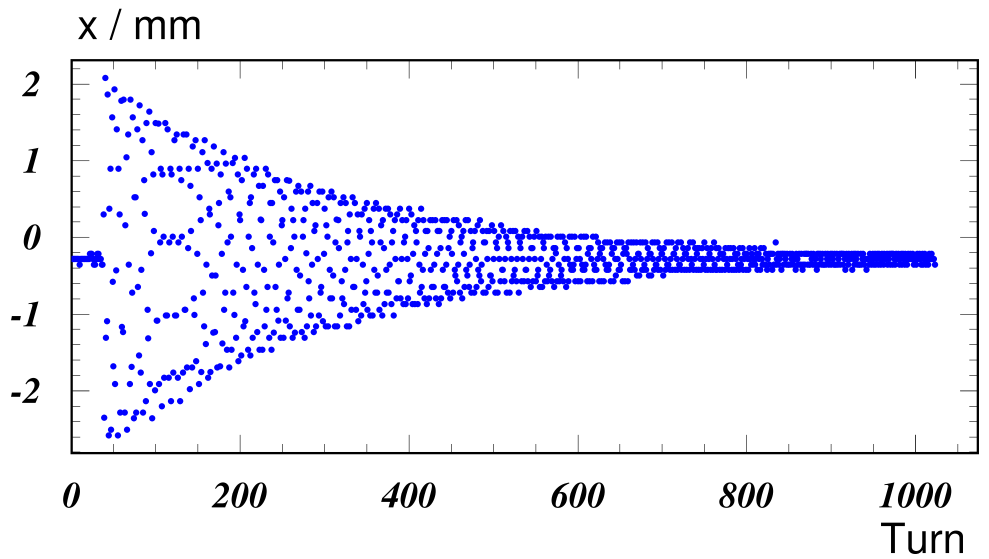
→ higher phase advance ($90^\circ \rightarrow 102^\circ/108^\circ/131^\circ$)

→ requires stronger sextupoles

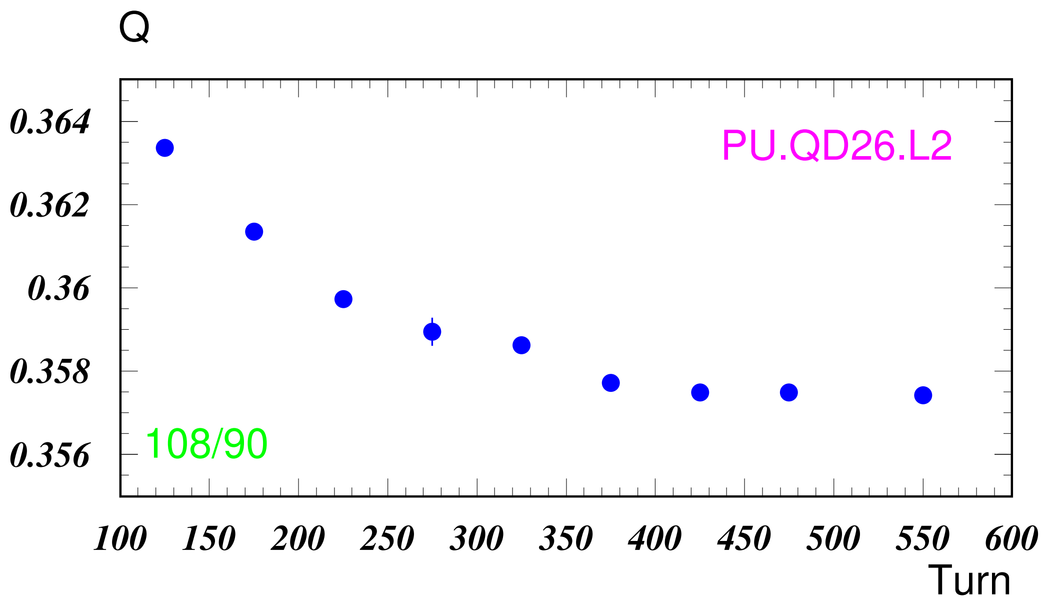
→ delicate: nonlinear fields cause an-harmonic oscillations...

Horizontal Detuning with Amplitude

Horizontal center-of-charge position as a function of turn number from *1000-Turn-Measurements*:



⇒ Damping time from global fit



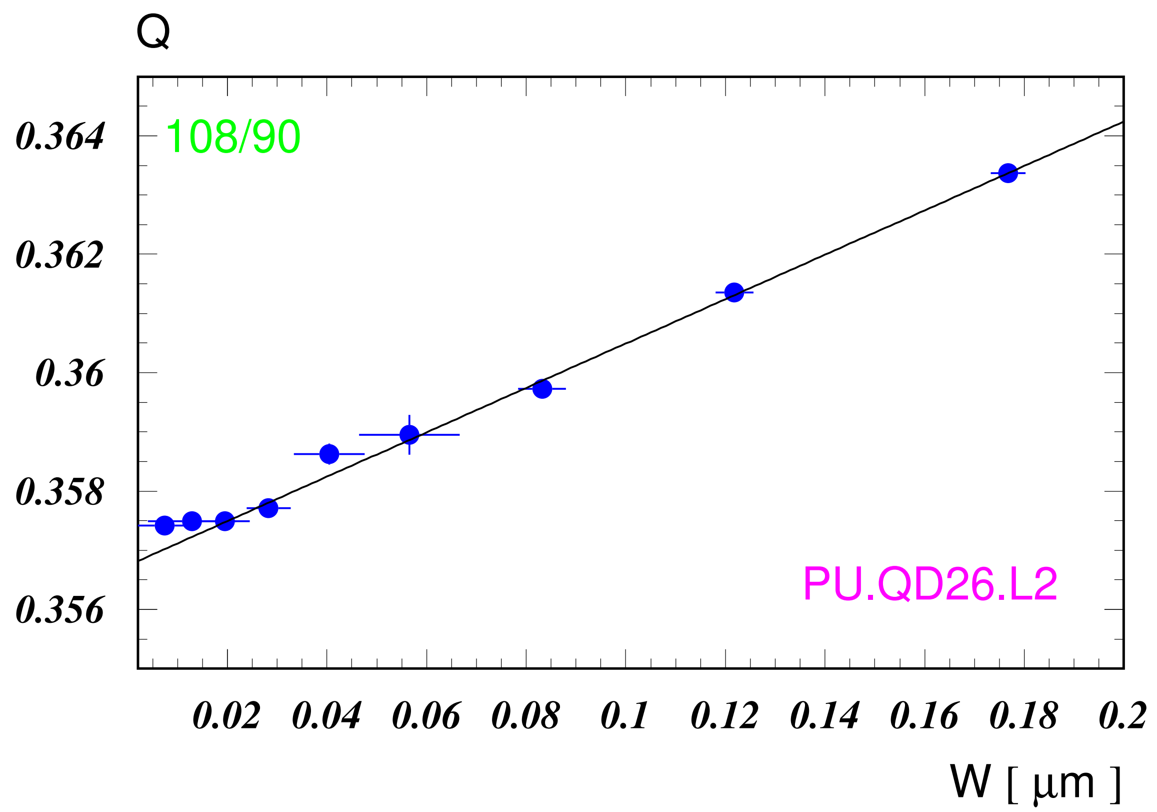
⇒ Q as function of turn number

Energy Loss

Extracting the Detuning

Q as function of Courant-Snyder invariant:

$$Q = Q_0 + \frac{\partial Q_x}{\partial W_x}\, W$$



- Tune depends on (amplitude)^2:

$$W = \frac{1+\alpha^2}{\beta}x^2 + 2\alpha x x' + \beta x'^2 \quad \approx \quad A^2/\beta$$
$$(A = A_0 e^{-t/\tau})$$

- If dependence too strong, particles with large amplitudes can hit resonances...

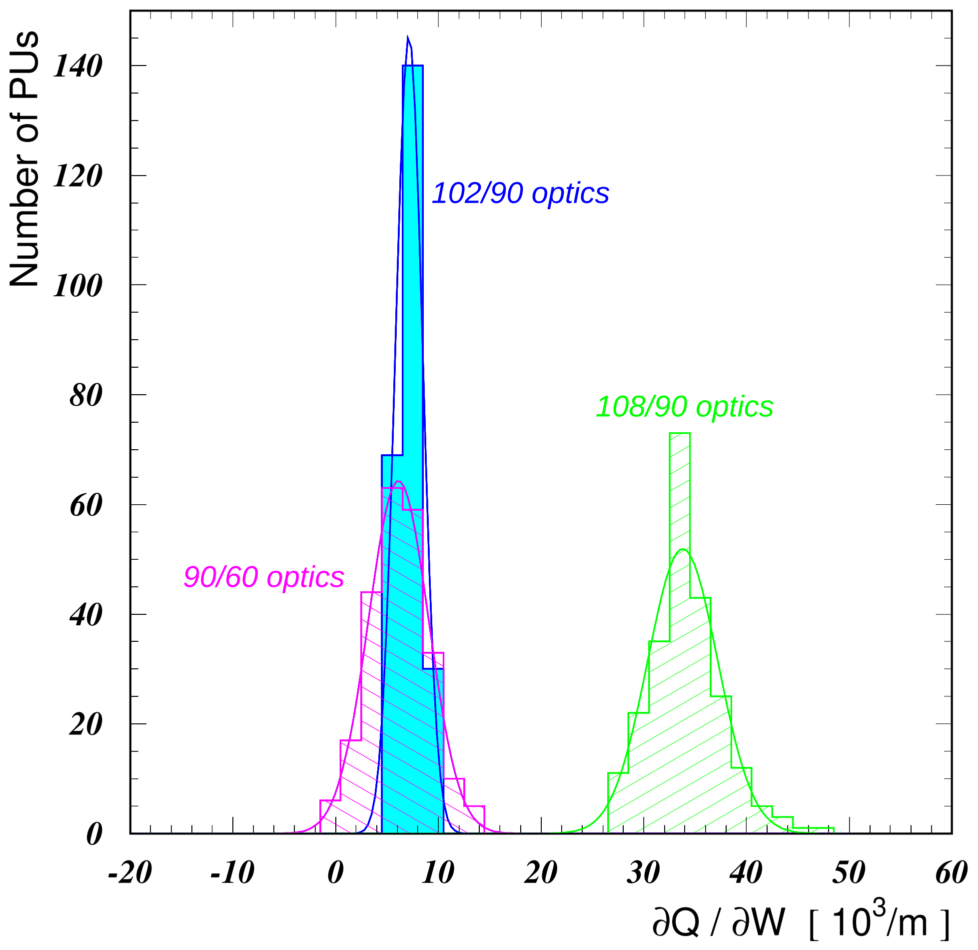
Energy Loss

Systematic Studies

- Dependence on damping time
  - Identical analyses on simulations for several energies and for all optics
  - Bias from damping time τ dependence is small
- Dependence on tune spread
  - Determine detuning for same I_b and different Q' $\rightarrow$ conservative estimate from spread ($\Delta Q_{Q'} \approx \mathcal{O}(10^{-2})$, $\Delta Q_W \approx \mathcal{O}(10^{-3})$)
- Binning effects in tune evaluation
  - Redo all analyses on simulations with an increased number of bins ($9 \rightarrow 18$)

$\Rightarrow$ Systematic error results from total spread

Measurements for Physics Optics



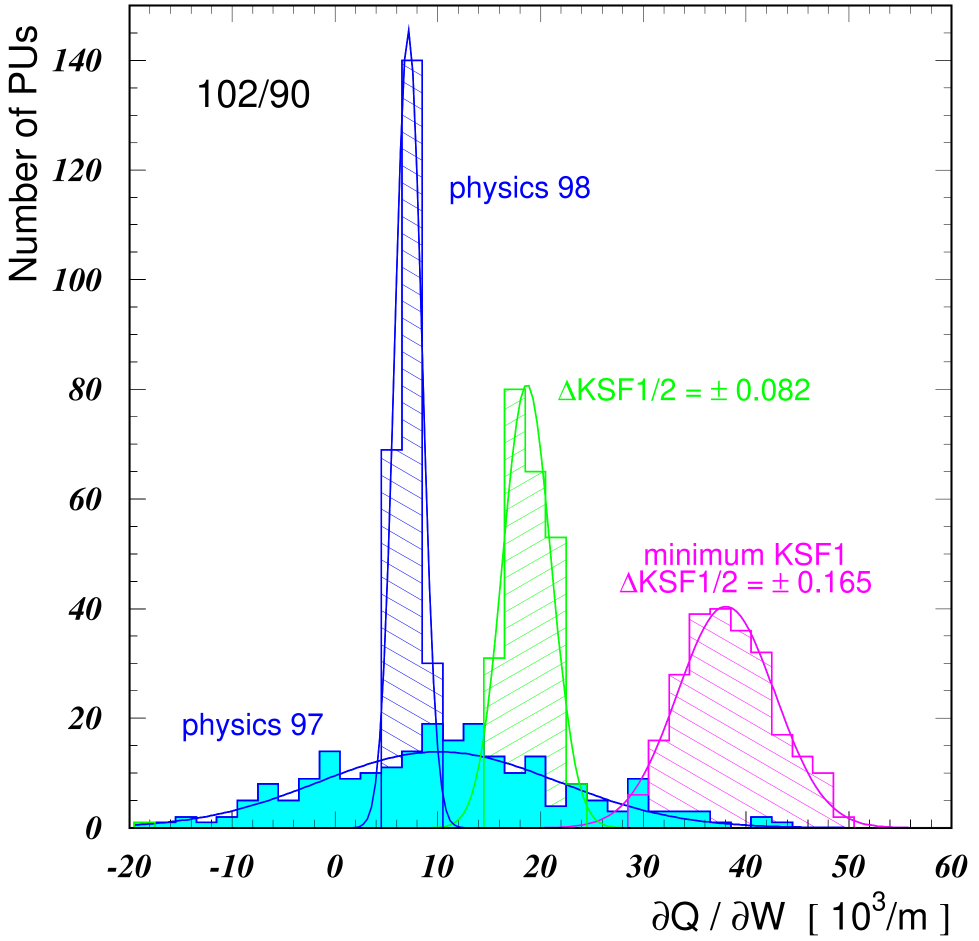
$\Rightarrow$ $\partial Q_x / \partial W_x$ in 10^3 / m:

		Measured			MAD
■	90/60 :	6.2	±	0.8	1.7
■	102/90 :	7.2	±	1.0	7.8
■	108/90 :	34.0	±	1.0	25.0

(error: stat. $\oplus$ sys.)

Energy Loss

Measurements for the 102/90 Optics

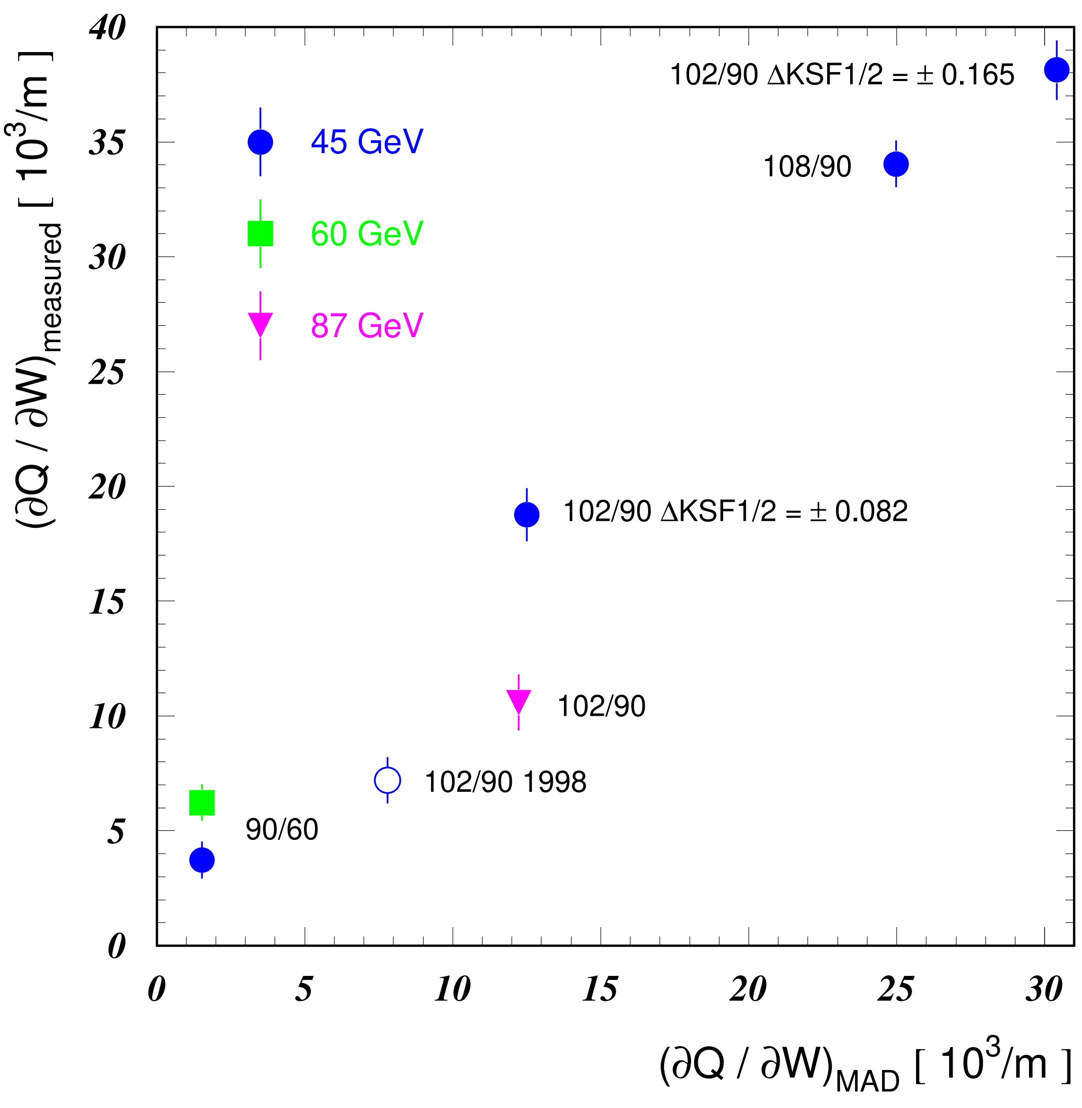


$\Rightarrow$ $\partial Q_x / \partial W_x$ in 10^3 / m:

	Measured			MAD
102/90 physics 1997:	10.6	±	1.2	12.2
102/90 ΔKSF = ±0.082:	18.8	±	1.2	12.5
102/90 ΔKSF = ±0.165:	38.1	±	1.3	30.4
102/90 physics 1998:	7.2	±	1.0	7.8

(errors: stat. $\oplus$ sys.)

Detuning Overview

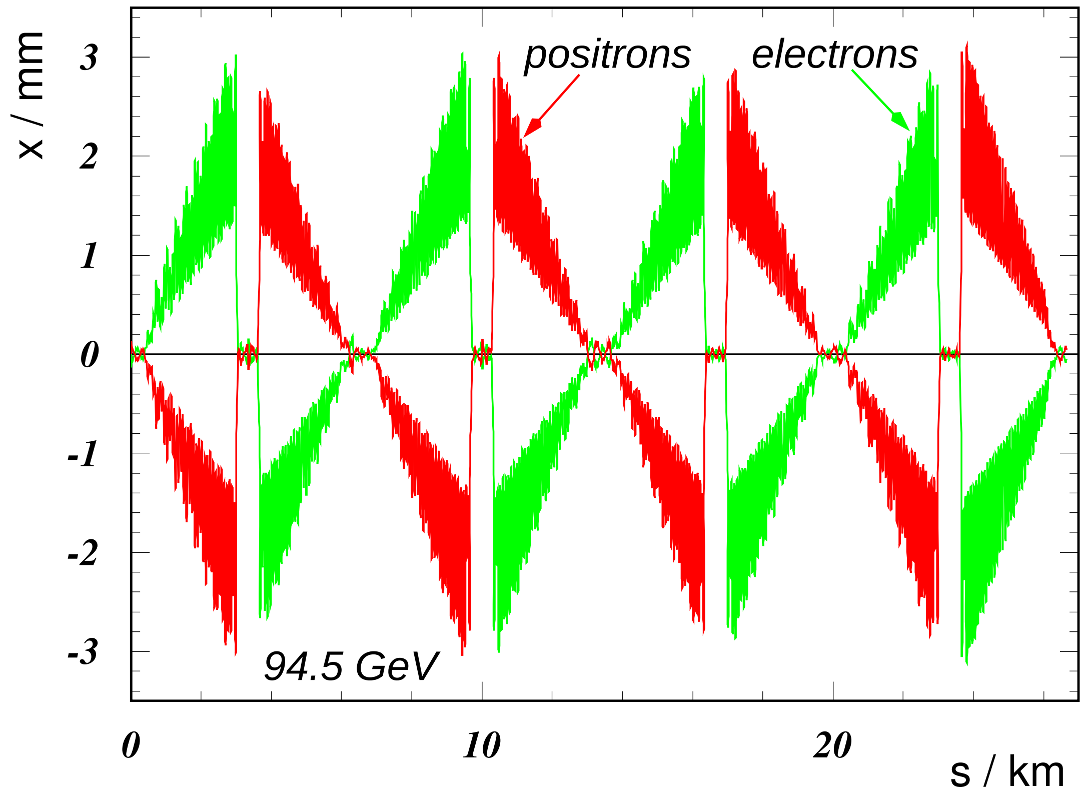


- In general good agreement with MAD
- Differences: unmodelled nonlinearities?

Close the Parenthesis

The Energy Sawtooth

- Horizontal e^- and e^+ positions along the ring:

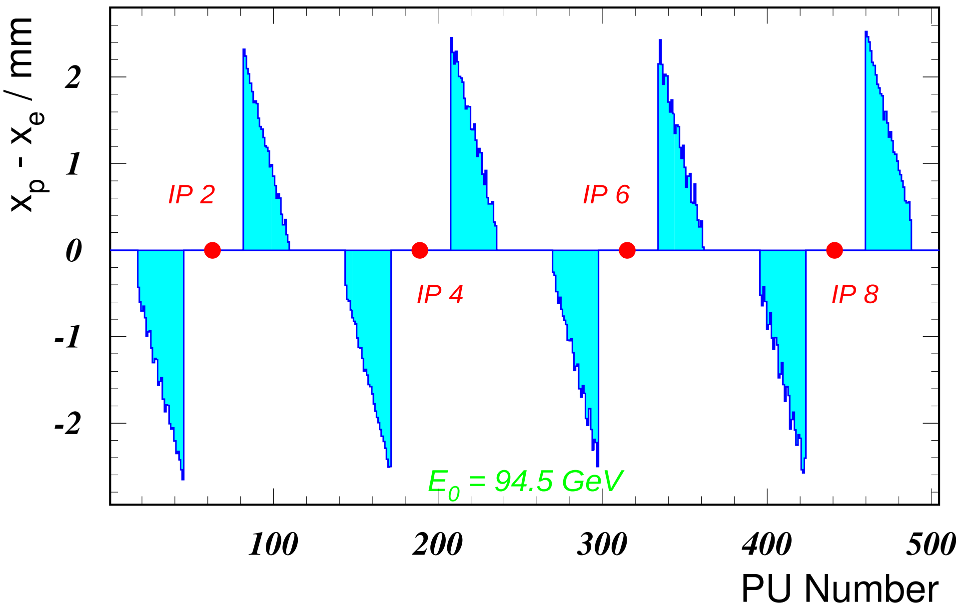


- Sawtooth like orbits are due to
  - continuous energy loss in the arc sections
  - localized energy gains from the RF system

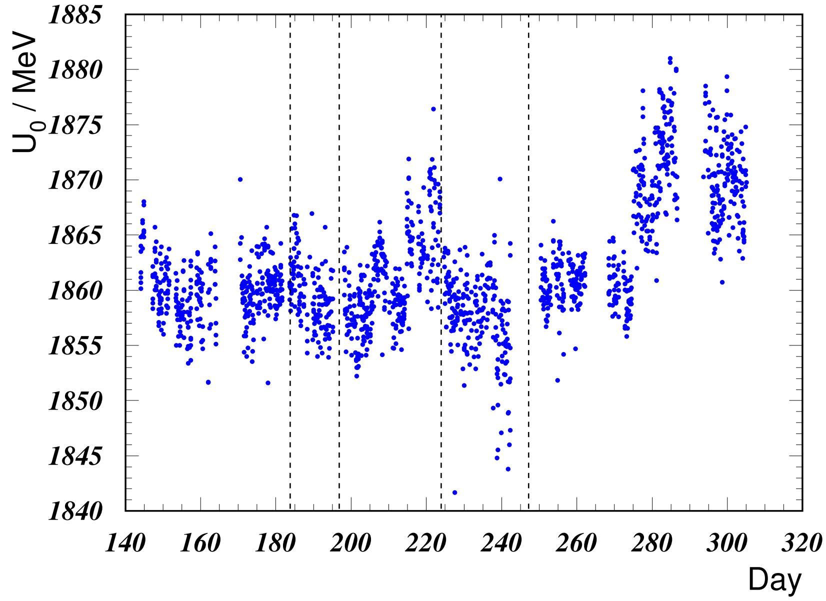
- e^- e^+ symmetry:
  - some systematic effects cancel in difference

Extracting the Energy Loss

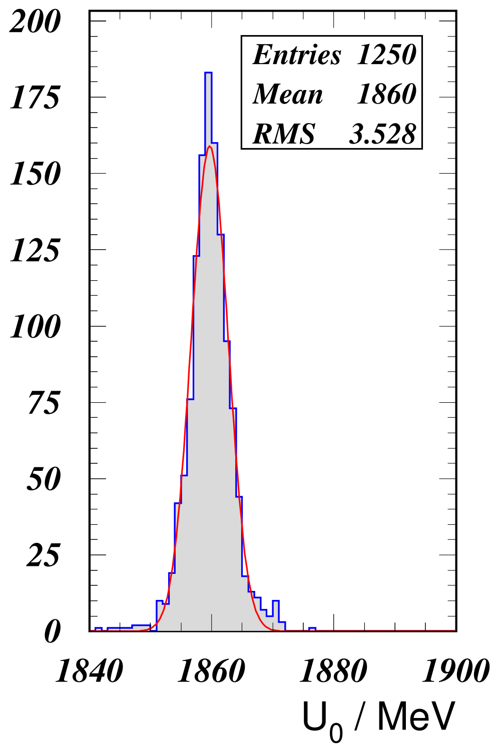
- Example of measured e^+e^- difference orbit



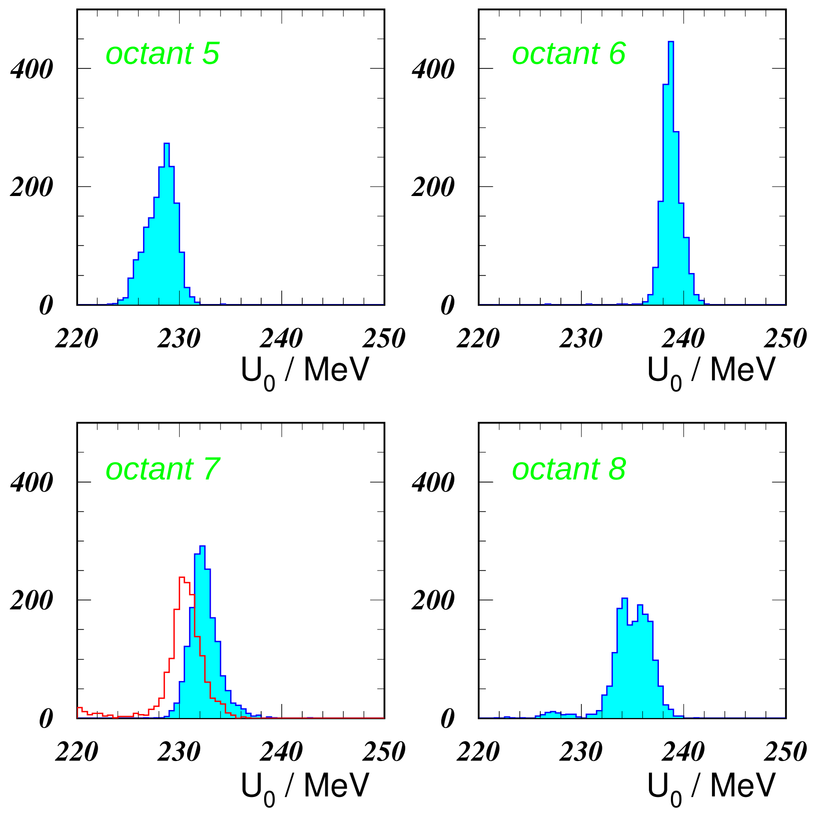
- Fit straight line + oscillation to arc BPMs (reject set of “bad” BPMs)
- Energy loss rate from $U/E \propto \Delta(x_{e^+} - x_{e^-})$



Systematics



- ✔ potential accuracy good
  $\Delta E/E \approx 5 \cdot 10^{-4}$
- ✔ completely parasitic
- ✘ sudden jumps
- ✘ result depends on selected BPMs
- ✘ differences between octants are not understood



⩾ Systematics not under control!

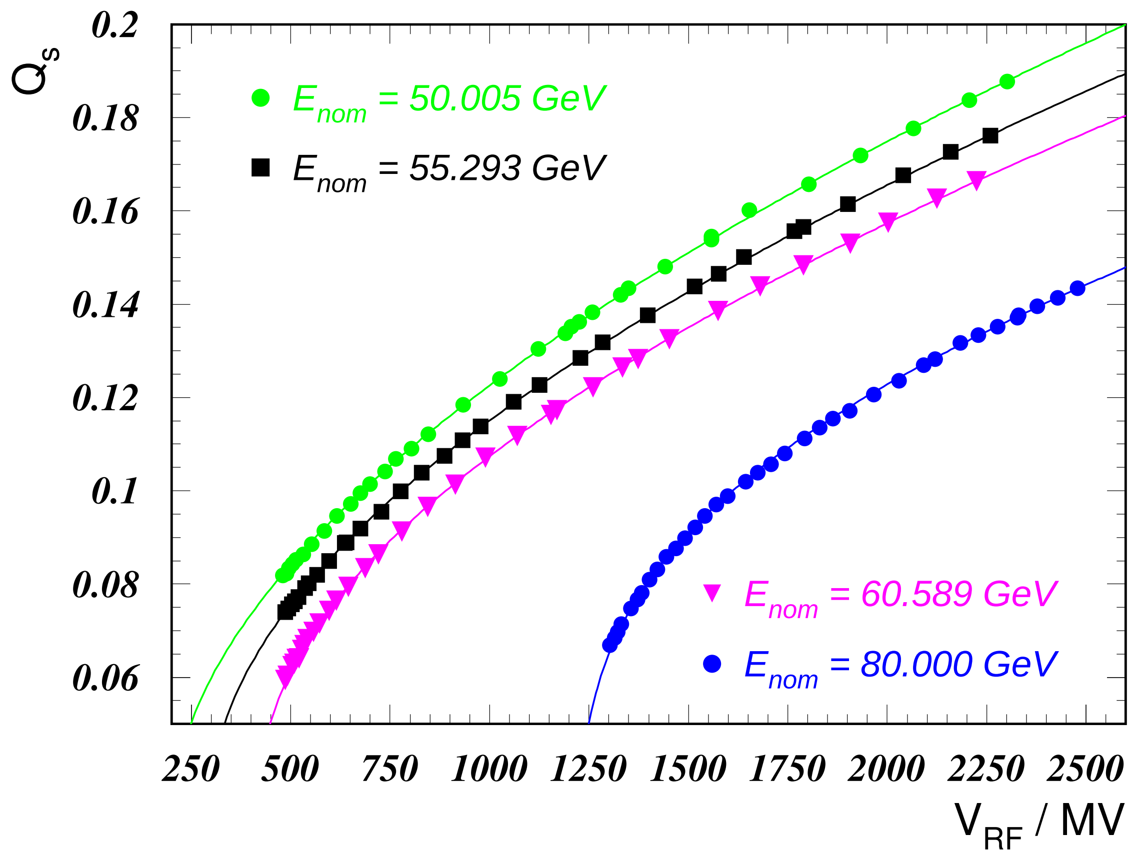
Energy from Q_s

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

- Q_s depends on RF voltage and beam energy:

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

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

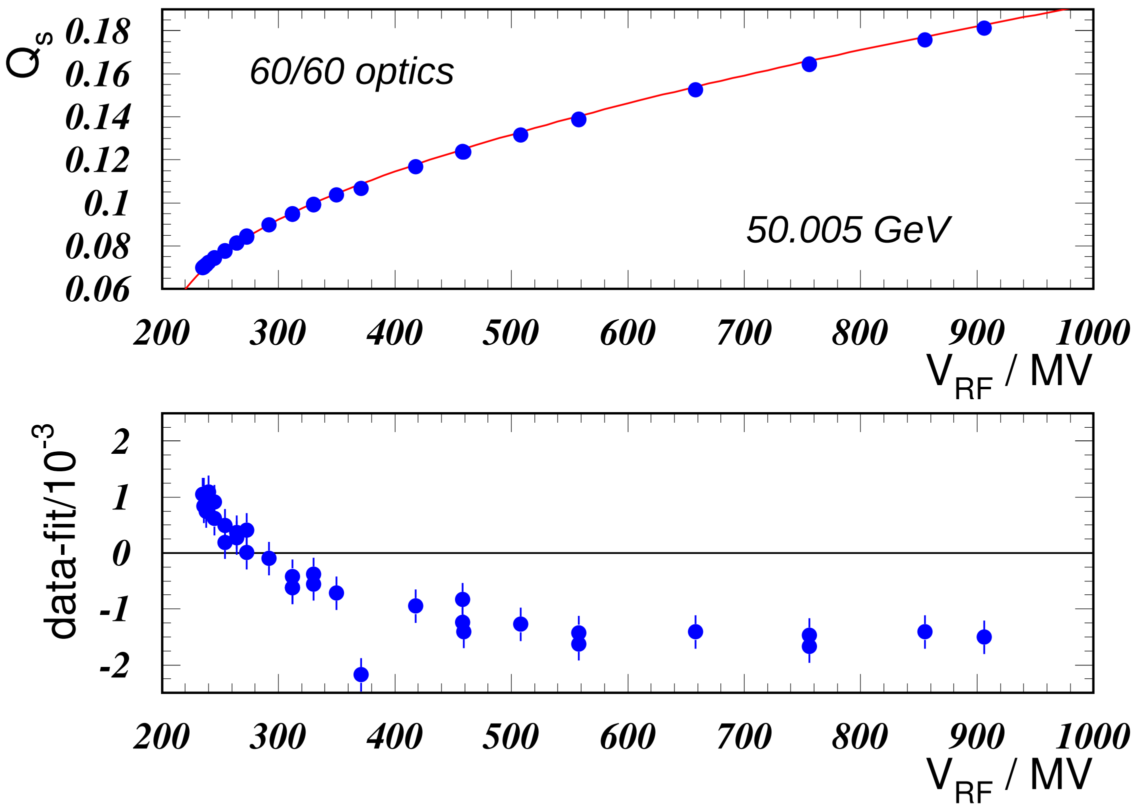


Extracting the Energy...

- Textbook ansatz:

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

- A first fit:



- Refinements are needed:

• Voltage correction factor: $V_{RF} \to g\, V_{RF}$
(determined from separate dataset)

Total Energy Loss

$$\tilde{U}_0 = \frac{C_\gamma}{\rho} E^4 + K$$

- $\mathcal{O}(400\ \mathrm{MeV})$ synchrotron radiation in dipoles
- Additional contributions K from
  - synchrotron radiation due to position offsets in quadrupoles – $\mathcal{O}(0.2\ \mathrm{MeV})$
  - synchrotron radiation due to finite beam size in quadrupoles – $\mathcal{O}(0.3\ \mathrm{MeV})$
  - momentum offsets for non-central orbits (centr. frequency, tide effects) – $\mathcal{O}(0.3\ \mathrm{MeV})$
  - synchrotron radiation in corrector magnets used for beam steering – $\mathcal{O}(0.1\ \mathrm{MeV})$
  - parasitic mode losses due to the resistive part of the longitudinal impedance (depends on the bunch current) – $\mathcal{O}(1\ \mathrm{MeV})$ for 50 μA

(numbers given for $E_{\mathrm{beam}} = 60.6$ GeV)

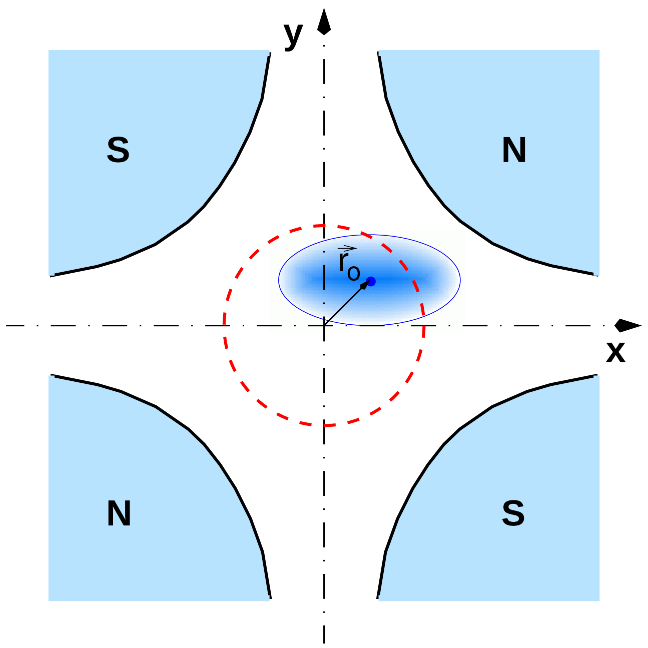
Losses in Quadrupoles

- Energy loss of a charge distribution:

$$\Delta E_i = \frac{C_\gamma\, l_i}{2\pi}\, k^2\, E^4\, (\sigma_u^2 + u_0^2)$$

u_0 : centre-of-charge position
σ_u : beam size
l_i : quadrupole length
k : normalized quadrupole strength

(general property of probability density functions)

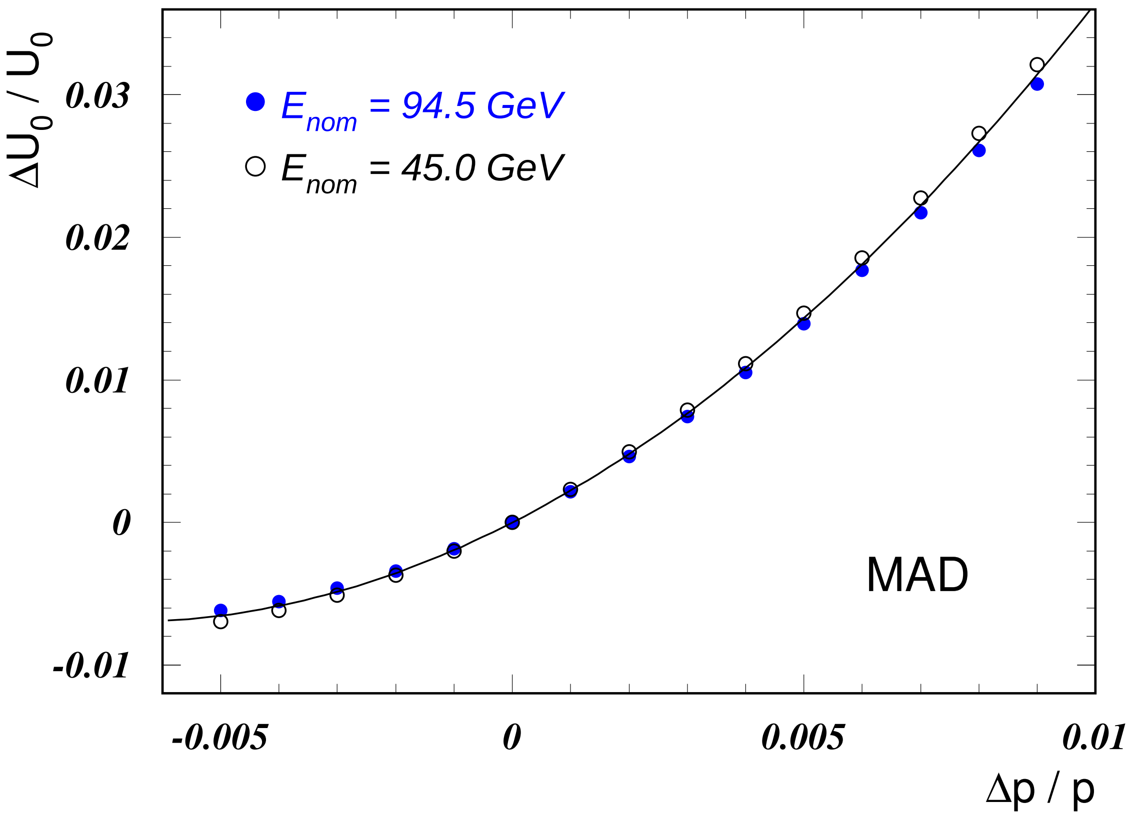


Momentum Offset

- Momentum offset:

$$\frac{\Delta p}{p} = -\frac{1}{\alpha_c}\,\frac{(f_{RF} - f^{c}_{RF})}{f_{RF}}$$

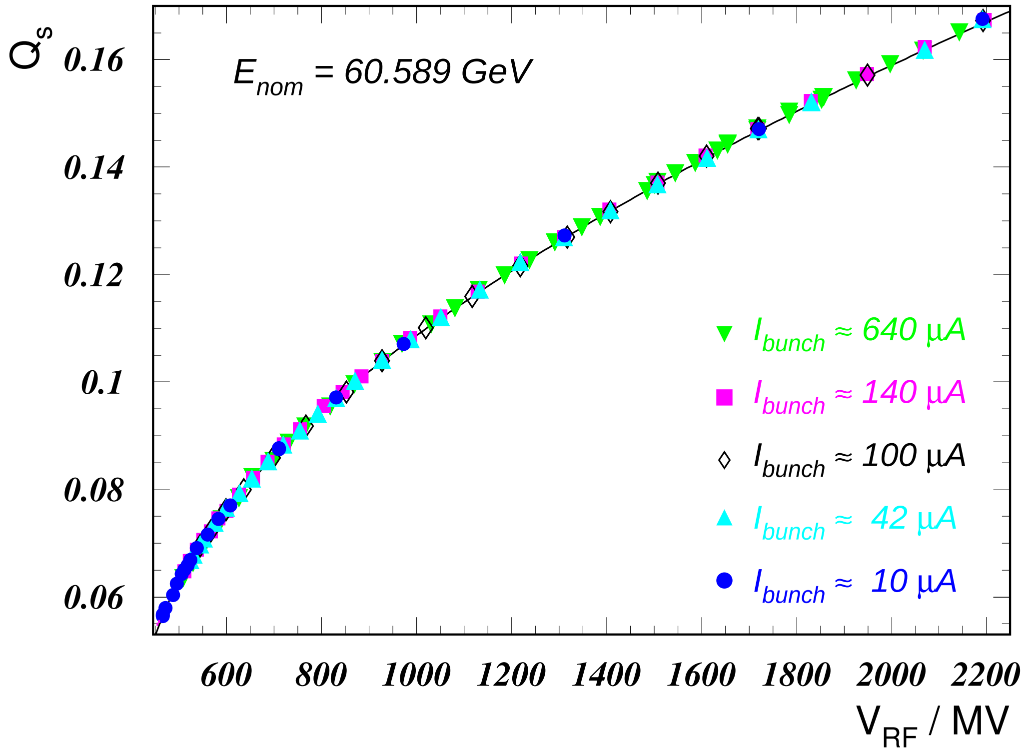
- Change in energy loss per turn:

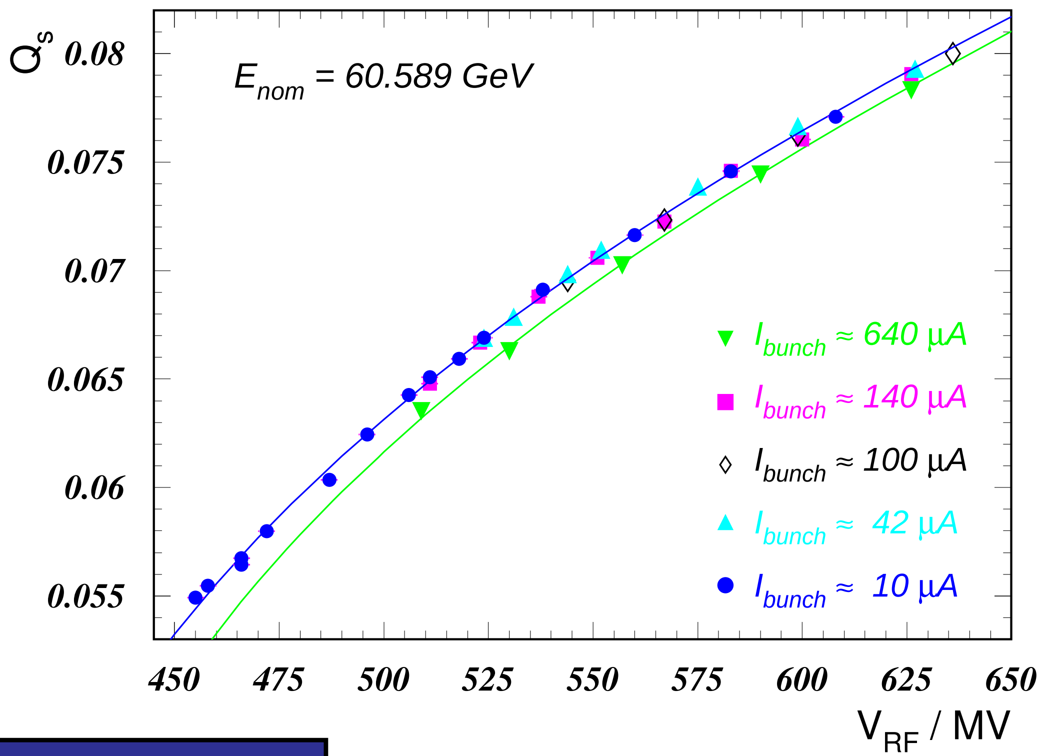


Typical $\Delta p/p \approx 10^{-4} - 10^{-5}$

Parasitic Mode Losses

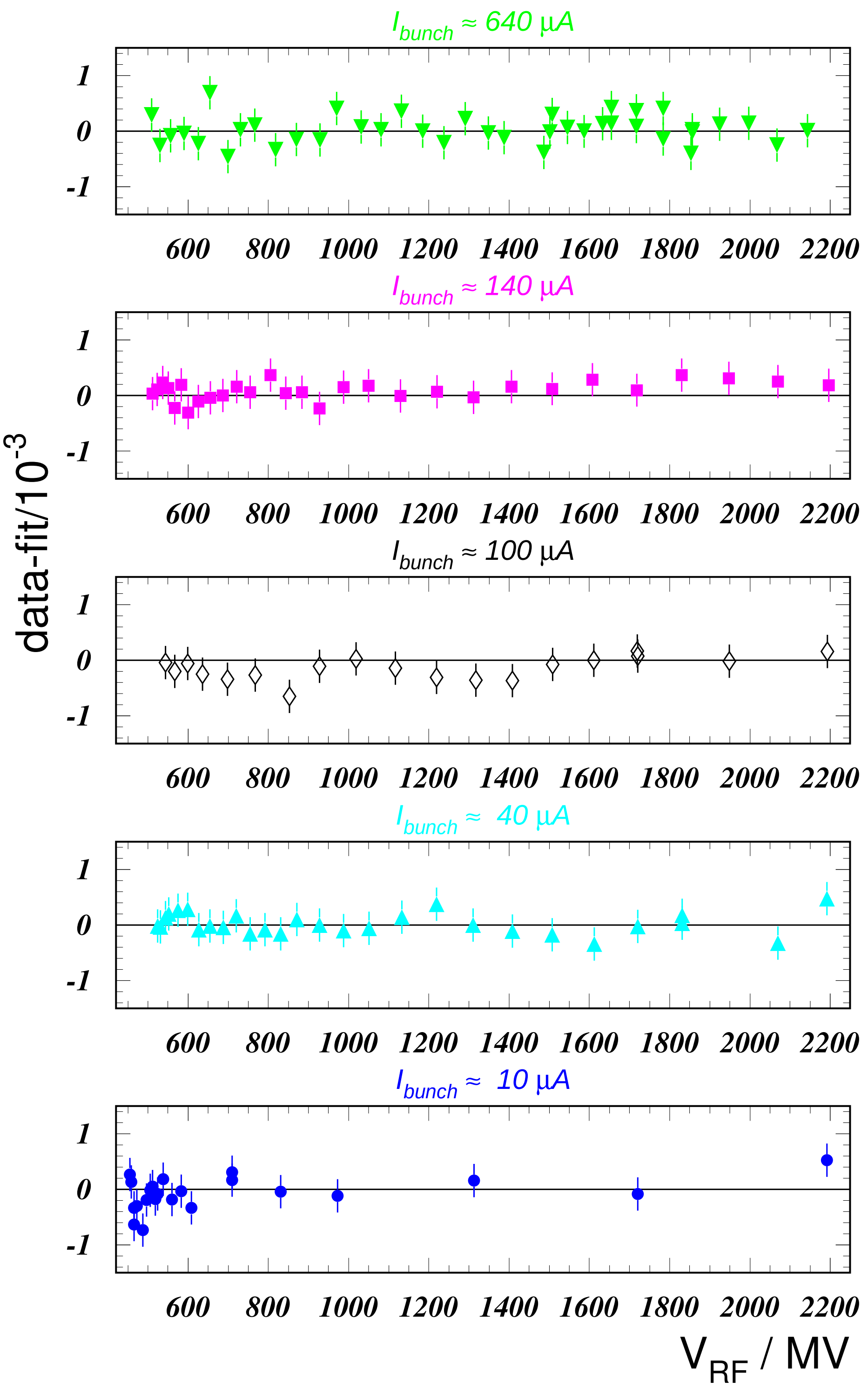
- Loss depends on bunch current: $\Delta E \propto I_b$





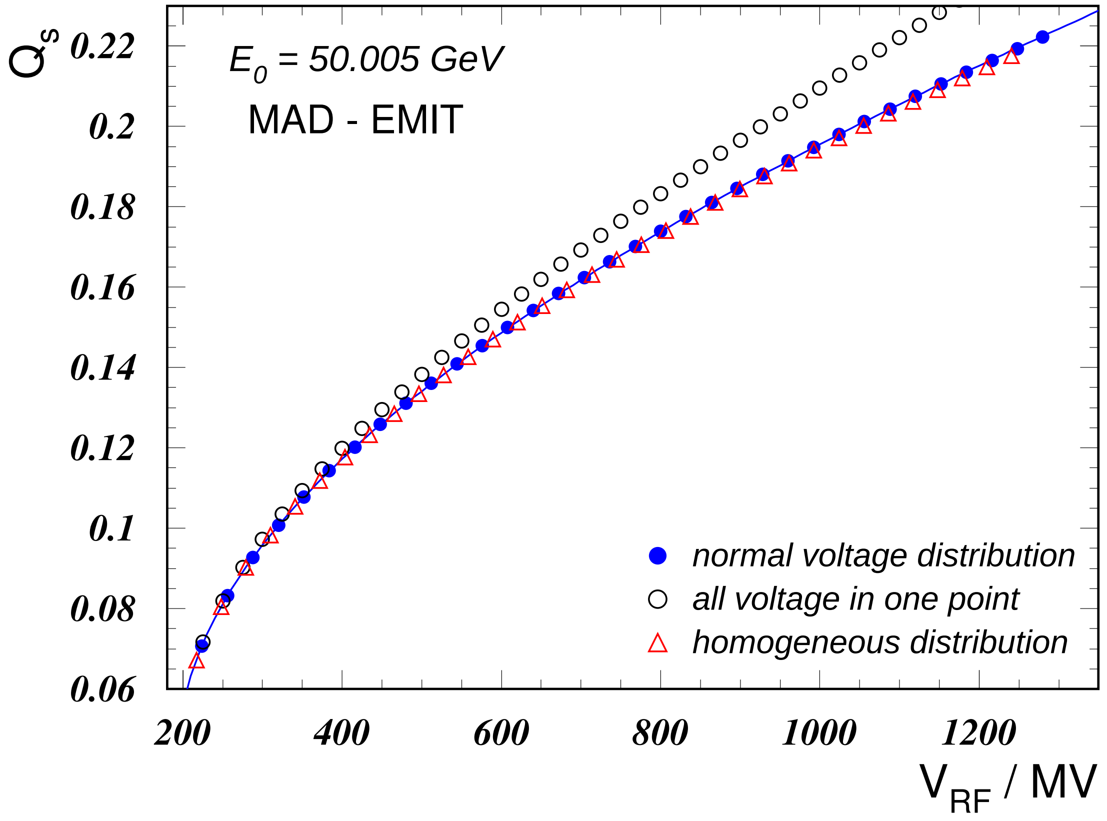
Energy Loss

Simultaneous Fit



RF Distribution

- Q_s for different RF configurations:



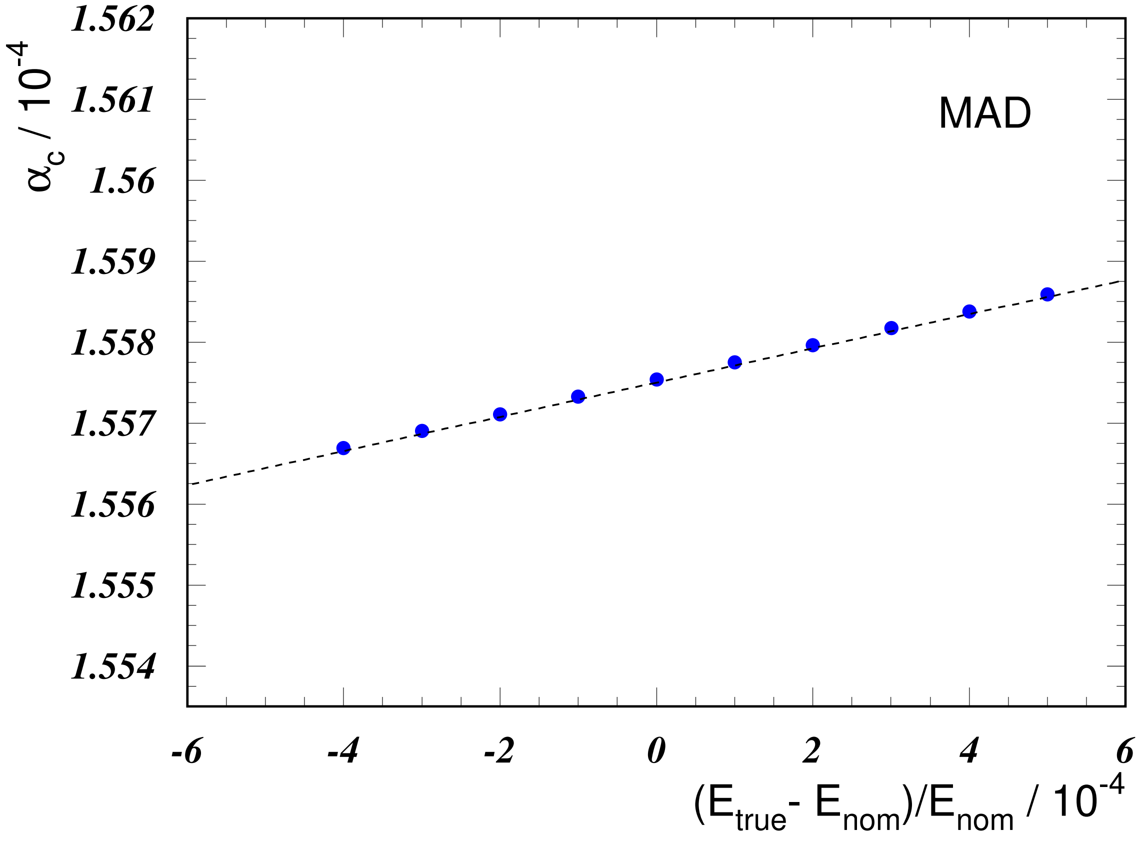
> simple model only valid in the limit of a homogenous RF distribution!

- add to fit model a term $\sim V_{RF}^4$

Momentum Compaction Factor

"Energy dependence" of α_c:

- difference between true and nominal dipole field
  → mismatch of dipoles and quadrupoles



⋗ $\delta E \sim 10 - 15$ MeV
(if not corrected)

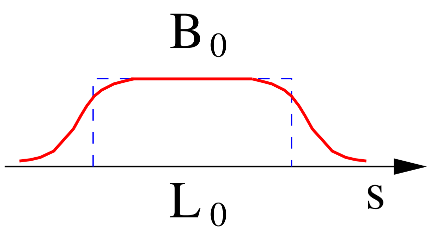
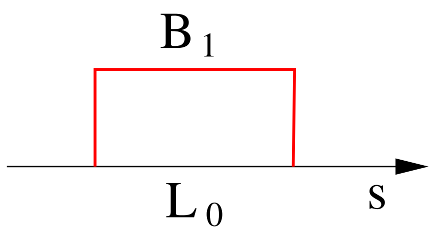
Energy Loss

Bending Radius and Fringe Fields

- In the fit: $\left(\frac{1}{\rho}\right)\left(1-\Delta\left(\frac{1}{\rho}\right)\right)$

  with $(1/\rho)$ from MAD

- MAD overestimates the energy loss:

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

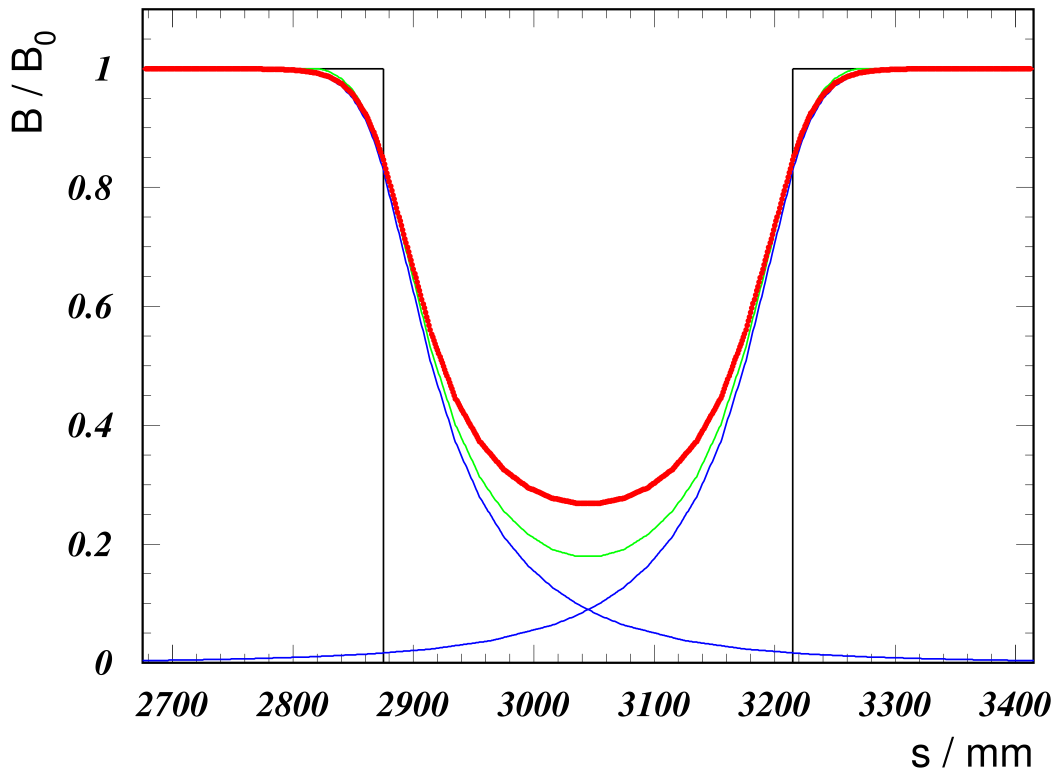
Data/fits prefer correction $\mathcal{O}(0.3\%)$

✘ exp. correction from magn. models larger!

Fringe Fields

- Possible explanation:

  ➜ Overlap of fringe fields of dipole pairs



Model by M. Sassowsky

$$\int B^2 ds\,(3\text{ pairs}) \neq 3 \times \int B^2 ds\,(1\text{ pair})$$

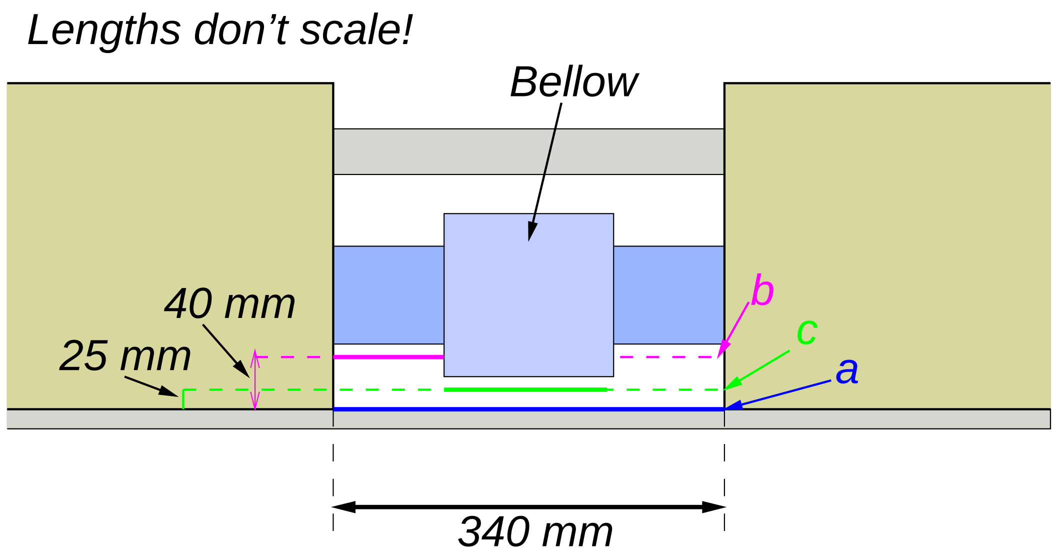
- Impact on energy:

  Shift of $(1/\rho)$ by 0.1 % ➜ $\delta E \sim 15$ MeV

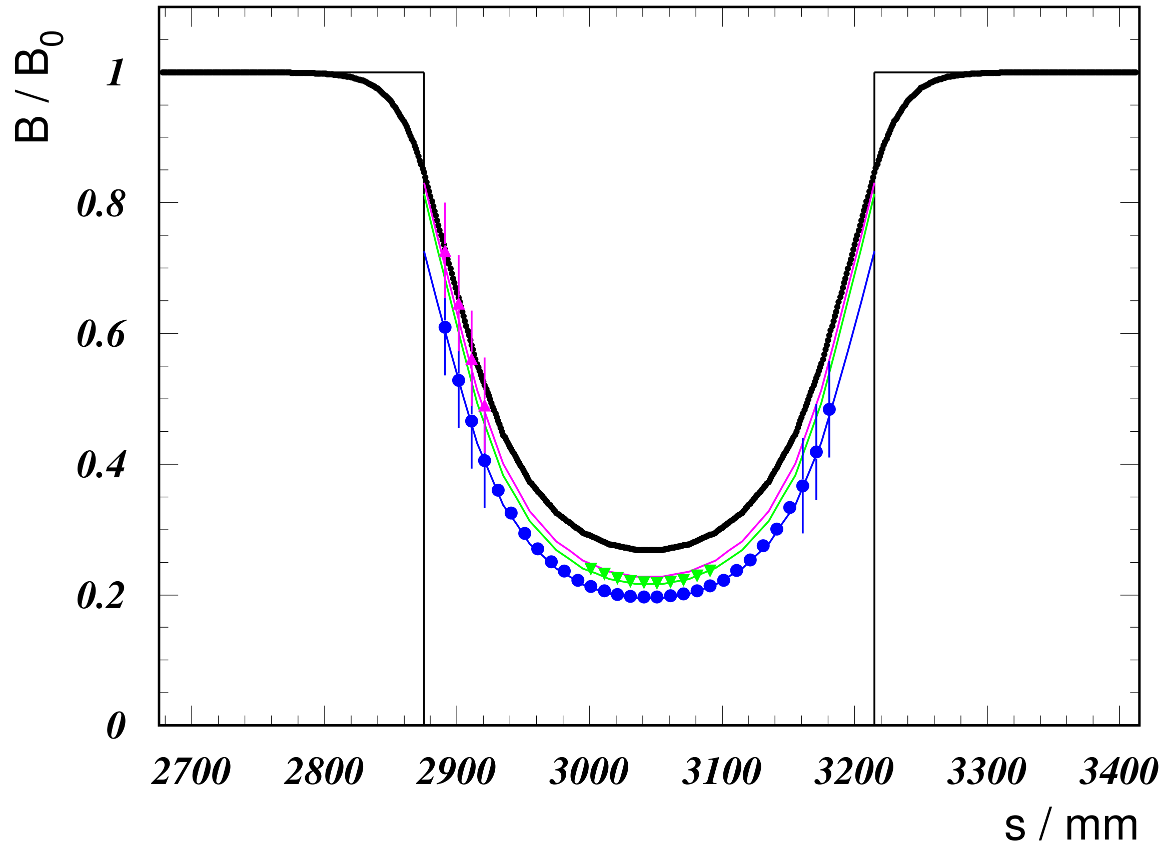
> analysis of measured and model data ongoing...

Energy Loss

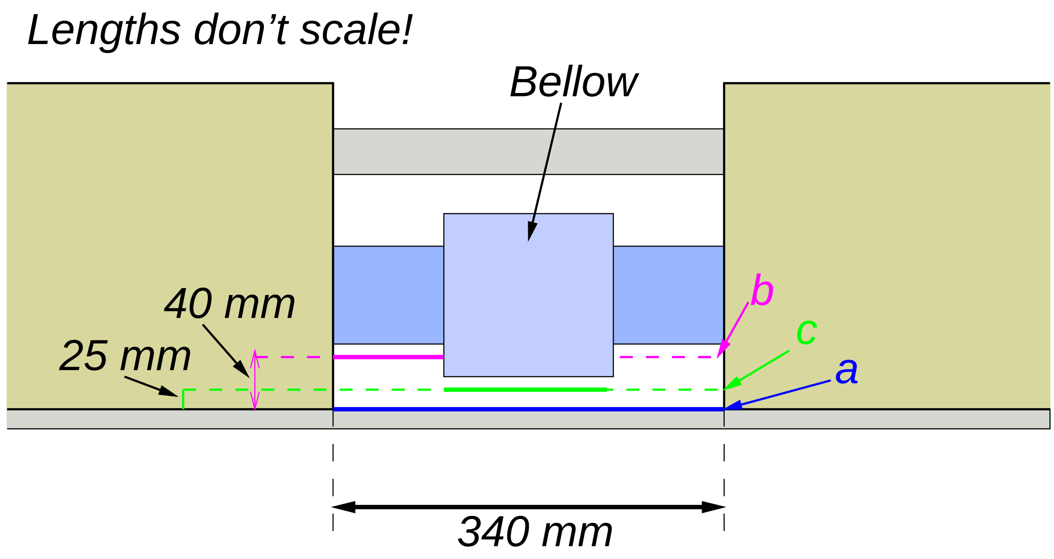
Fringe Fields Measurements



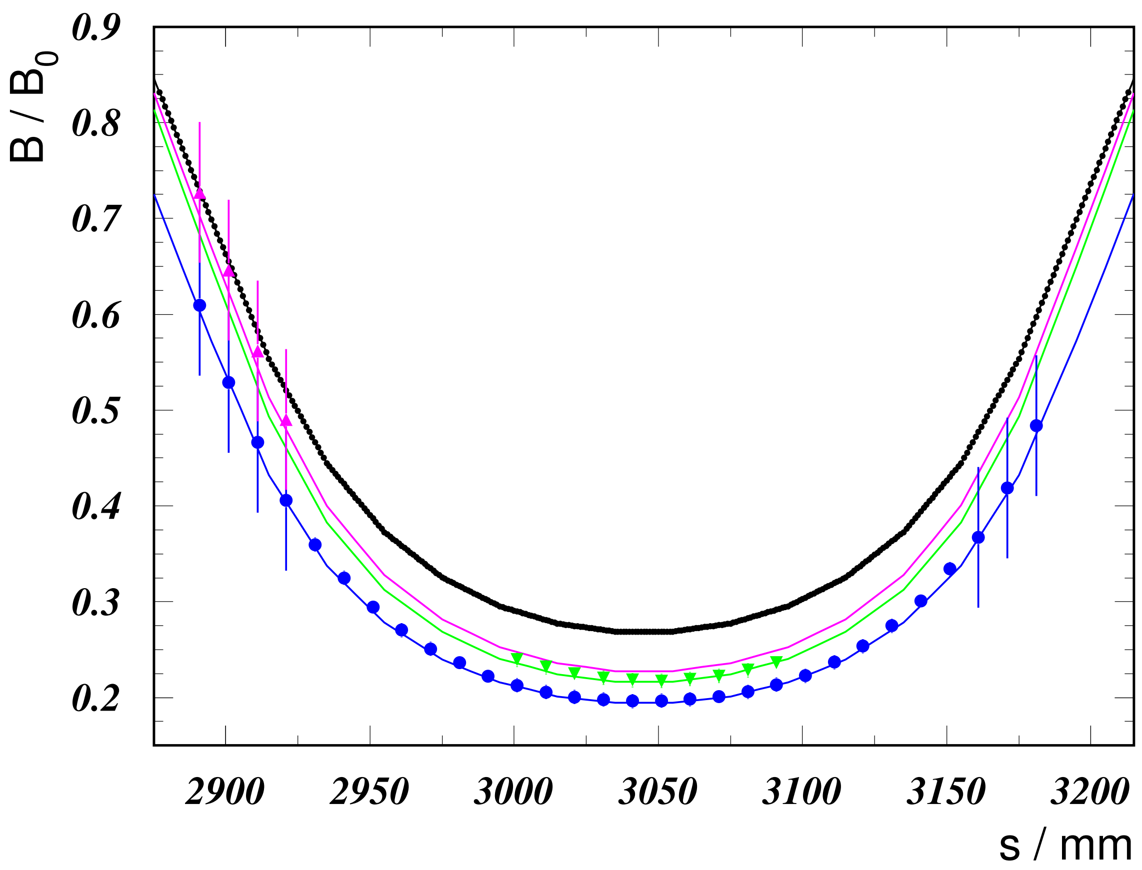
Model: M. Sassowsky



A Closer Look....

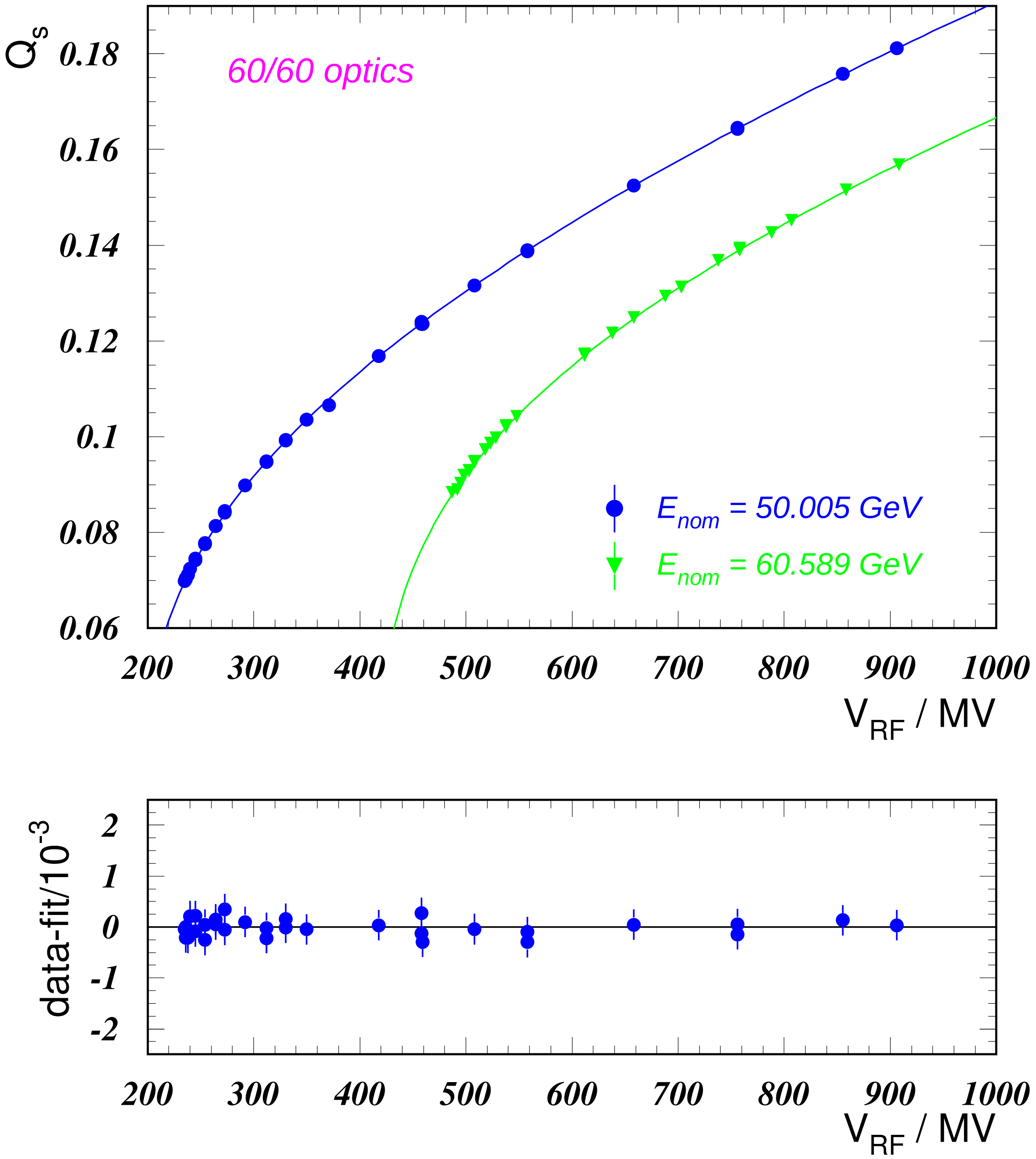


Model: M. Sassowsky



The Final Fit

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



The Voltage Calibration

- Requirements:

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

  $\oplus$

  measurements at {80, 90} GeV

- Procedure:

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

  $\gg \langle g \rangle \pm \Delta g$

- use this $\langle g \rangle$ for high energy fits

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 ~ 20 - 30 MeV
- ✘ machine parameters $\mathcal{O}(20$ MeV$)$ possible bias under study

Summary

- Energy calibration
  - ✔ polarization up to 60 GeV
  - ✘ extrapolations: FL - NMR ~ 15 MeV
- Damping of coherent oscillations
  - ✘ low precision
  - ✔ input to measurement of $\partial Q_x / \partial W_x$
- Energy sawtooth
  - ✔ purely parasitic
  - ✔ intrinsically good accuracy
  - ✘ systematics not under control
- Q_s and total RF voltage
  - ✔ independent energy measurement
  - ✔ high intrinsic precision
  - ✔ energy range from 50 to 90 GeV

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