The Measurement of Q' by Head-Tail Phase Shift Analysis

BNL2002

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Outline

- Motivation
- The Head-Tail measurement principle
- The Head-Tail monitor of the SPS (2000)
- Improvements & Developments in 2001/2002
- Simulations and Robustness Study for LHC
- Conclusions

Motivation

LHC

- Problems with existing methods for Q' measurement

→ Variation of Beam Momentum and Tune Tracking

- LHC momentum acceptance small
- tight tolerances on betatron tune

→ Amplitude of synchrotron side-bands

- Qs too low to distinguish side-bands from main tune peak
- affected by resonant behaviour not linked to Q'

→ Width of betatron tune peak

- requires knowledge of $\Delta p/p$
- affected by other sources of damping/decoherence.

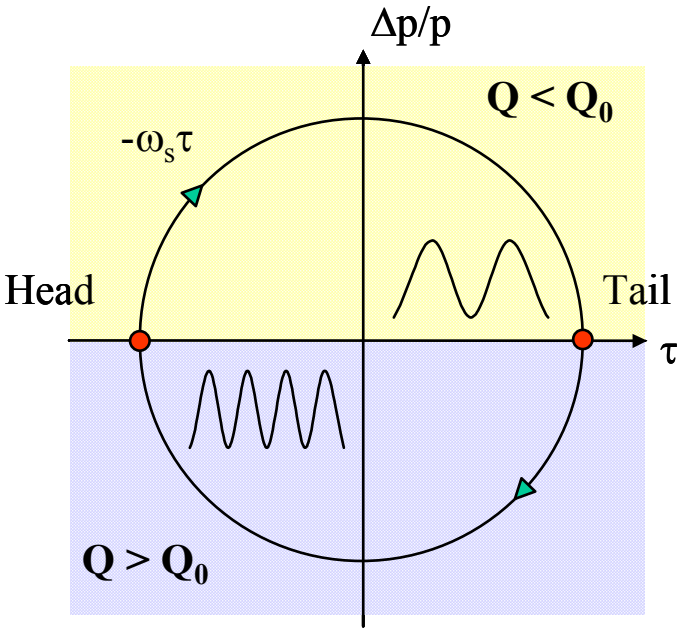
⇒ Test new "Head-Tail" technique in the CERN-SPS

The Head-Tail Principle

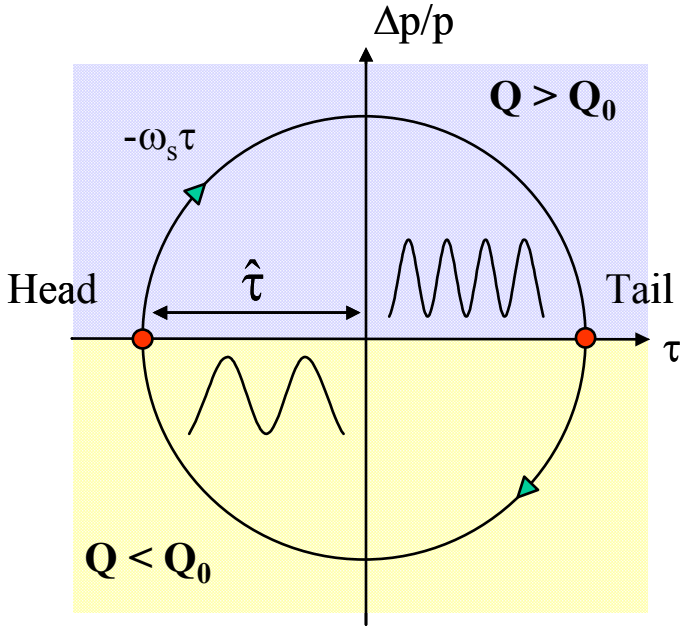
- The Principle:
  - → Apply single transverse kick and observe resulting betatron motion.
  - → Chromaticity will determine the pattern of this motion.
  - → By following the time evolution of any two positions within the bunch a phase-difference is obtained from which the chromaticity can be calculated.
- Assumptions used in the Theory:
  - → The displacement due to the kick is much larger than the betatron oscillations performed by the particles in the unperturbed bunch.
    - i.e. when the kick is applied all particles are assumed to have the same betatron phase.
  - → The synchrotron frequency is the same for all particles in the bunch.
    - This assumption holds as long as the measurements are performed close to the centre of the bunch.
  - → The presence of higher order fields such as octupolar fields are not taken into consideration.

The Head-Tail Principle

Negative Chromaticity (Above Transition)

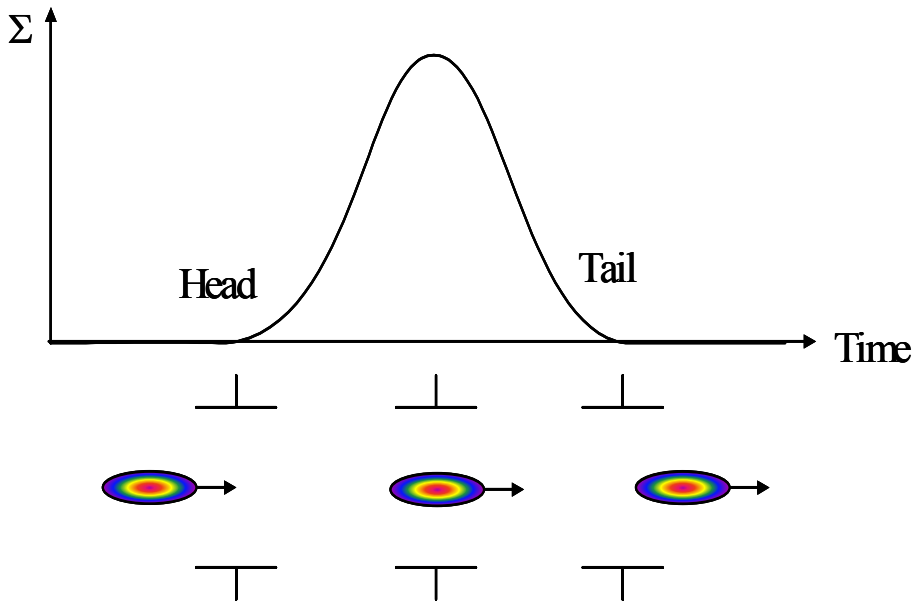


Positive Chromaticity (Above Transition)



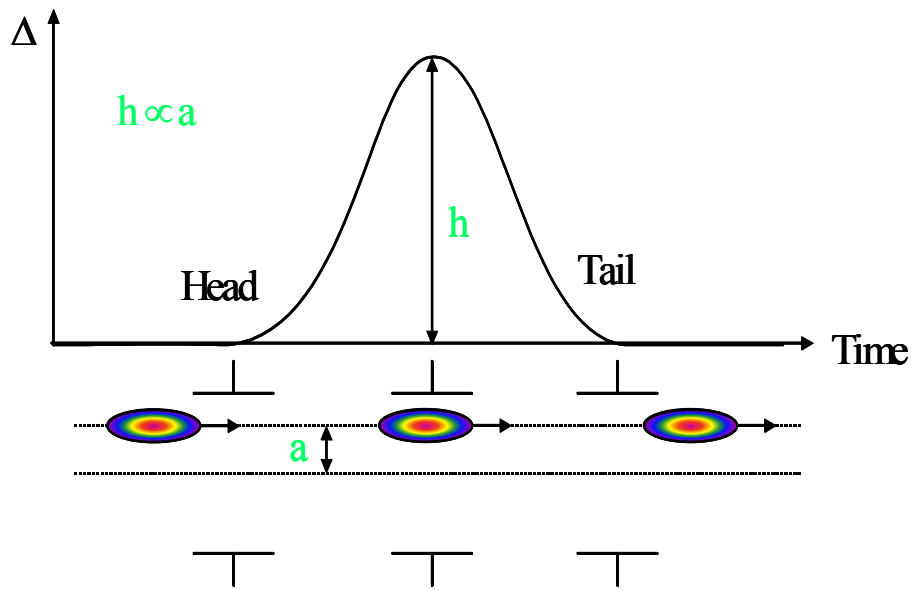
The Head-Tail Principle

Σ Signal - Longitudinal Bunch Profile



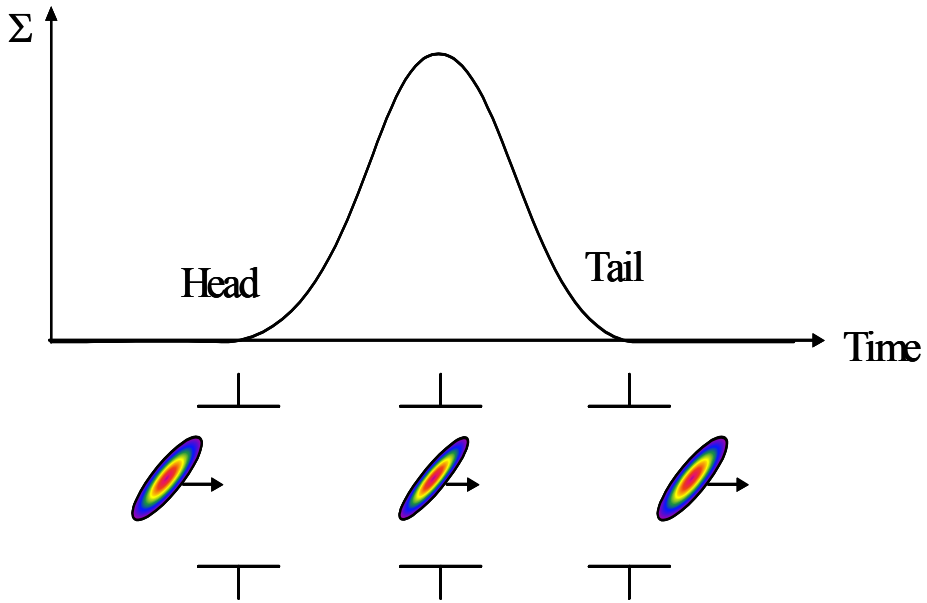
Response for
Zero Chromaticity

Δ Signal - Transverse Bunch Position



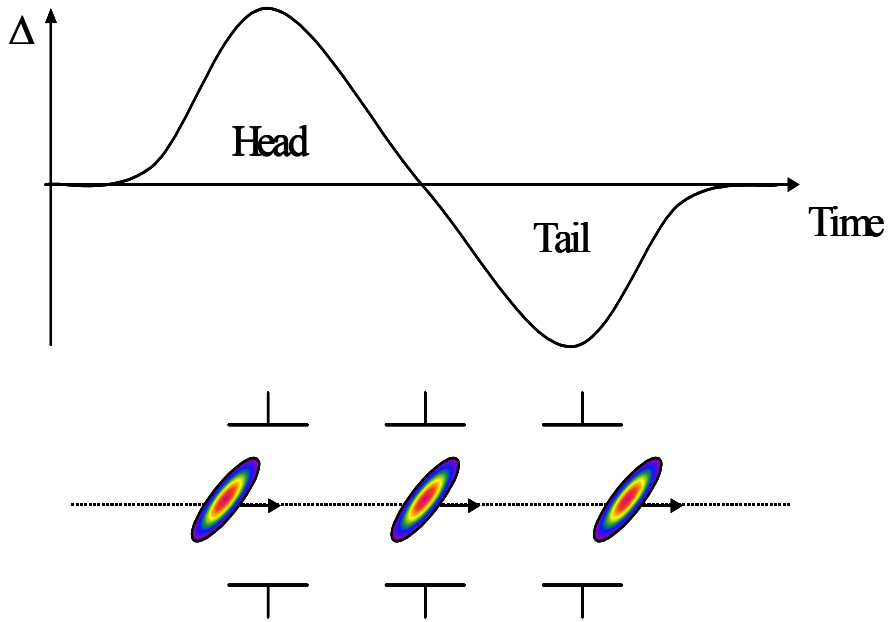
The Head-Tail Principle

Σ Signal - Longitudinal Bunch Profile



Response for
Non-Zero Chromaticity

Δ Signal - Transverse Bunch Position



The Head-Tail Principle

The phase difference as a function of the number of turns from an initial kick is given by

$$\Delta\psi(n) = -\omega_\xi \Delta\tau \left(\cos(2\pi n Q_s) - 1\right)$$

where ω_ξ is the chromatic frequency and is defined as $\omega_\xi = Q_0\ \omega_0 \frac{\xi}{\eta}$

The maximum phase shift is obtained after half a synchrotron period, when $nQ_s = ½$

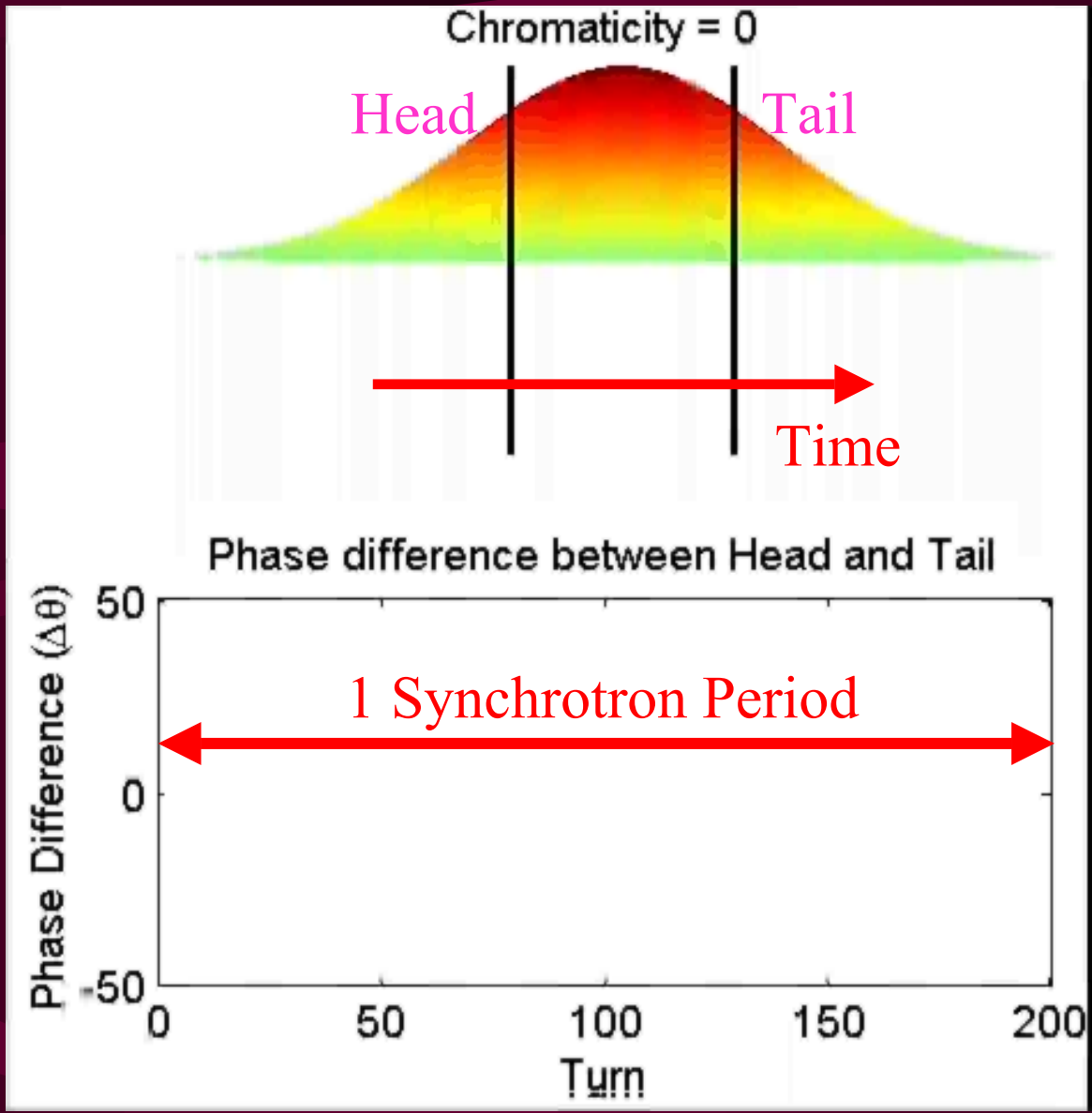
$$\Delta\psi_{MAX} = -2\omega_\xi \Delta\tau$$

The relative chromaticity can therefore be written as

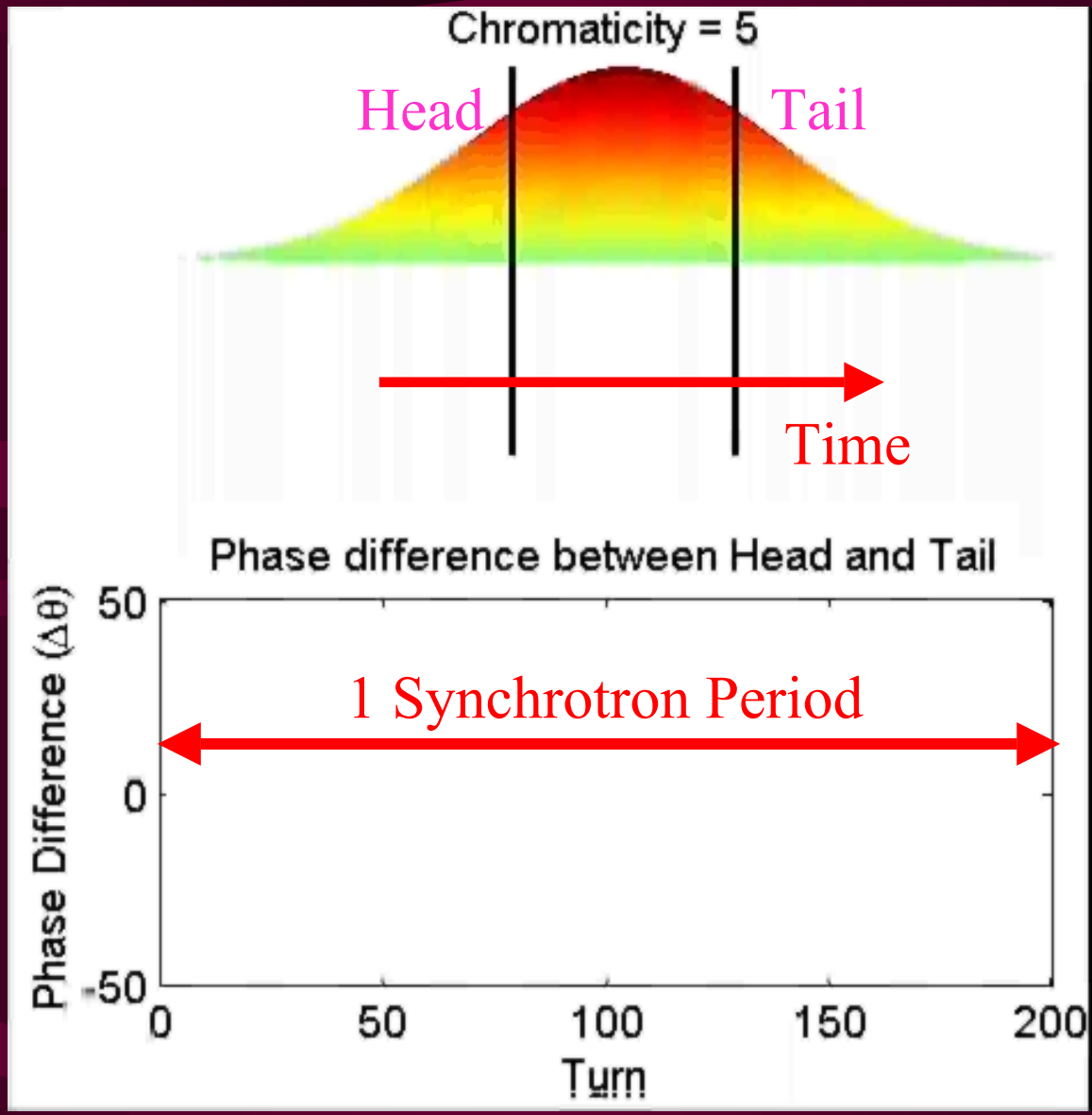
$$\xi = \frac{-\eta\ \Delta\psi(n)}{Q_0\ \omega_0 \Delta\tau \left(\cos(2\pi n Q_s) - 1\right)} = \frac{\eta\ \Delta\psi_{MAX}}{2\ Q_0\ \omega_0\ \Delta\tau}$$

ξ	=	relative chromaticity	$\Delta\psi$	=	head-tail phase difference
η	=	$1/(\gamma)^2 - \alpha$	$\Delta\tau$	=	time between the sampling of head and tail
Q_s	=	synchrotron tune	Q_0	=	betatron tune
ω_0	=	angular revolution frequency	n	=	number of turns since the initial kick

The Head-Tail Principle



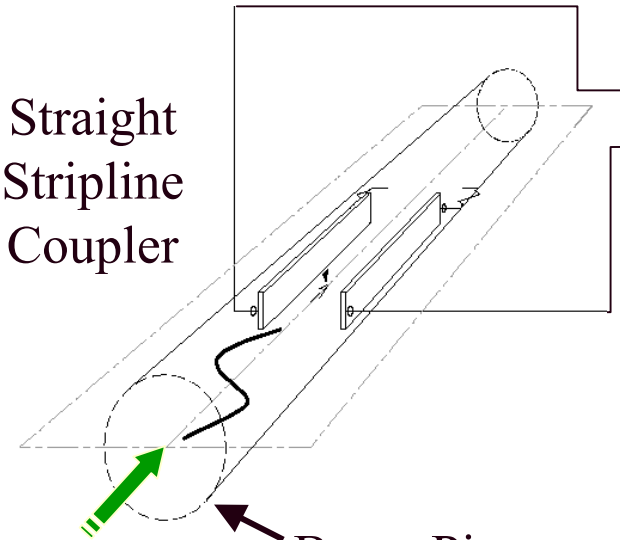
The Head-Tail Principle



CERN-SPS System Set-up

SPS Tunnel

Straight Stripline Coupler



Beam

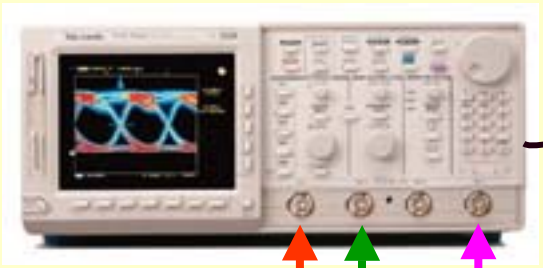
Beam Pipe

Hybrid

Sum

Difference

Fast (2GS/s per channel) Digital Oscilloscope



Bunch Synchronous Trigger

VME Acquisition via GPIB

GPIB link

UNIX User Interface

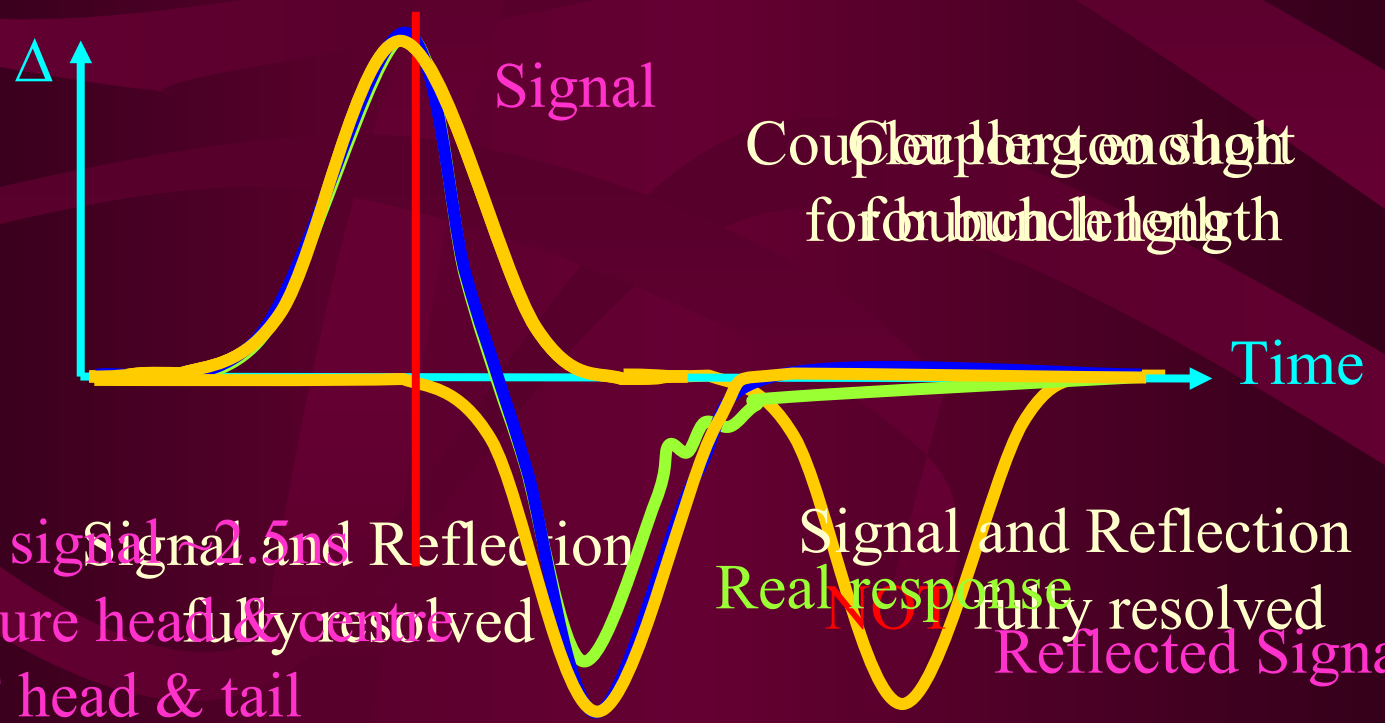
The CERN-SPS Head-Tail Monitor

Pick-up

- Straight stripline coupler - 37cm long

  → completely resolves a bunch < 2.5ns in length

  NOT the case in the CERN-SPS where bunch length is ~4ns



Useable signal < 2.5ns

⇒ measure head & centre

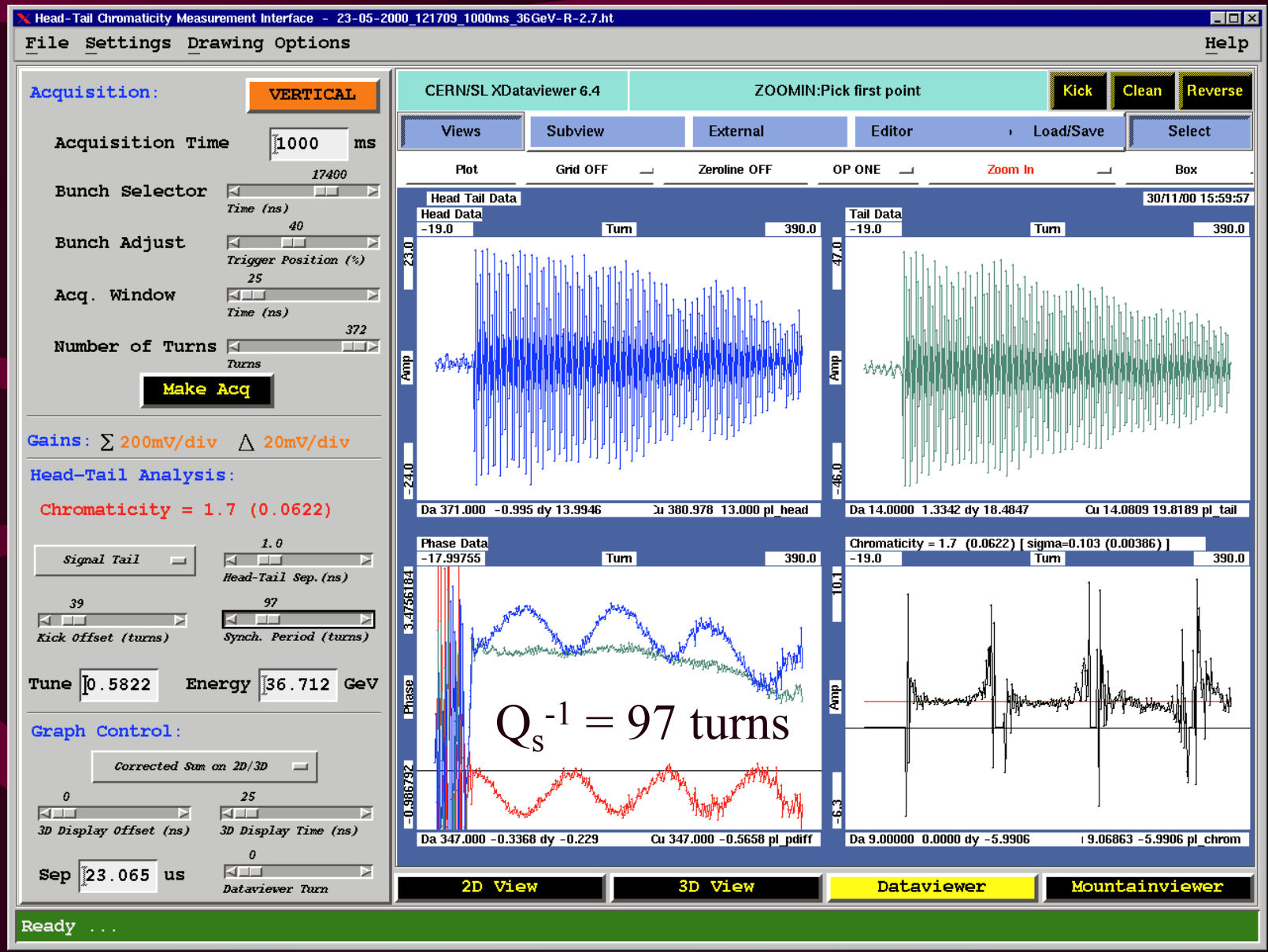
NOT head & tail

Measurements Conditions

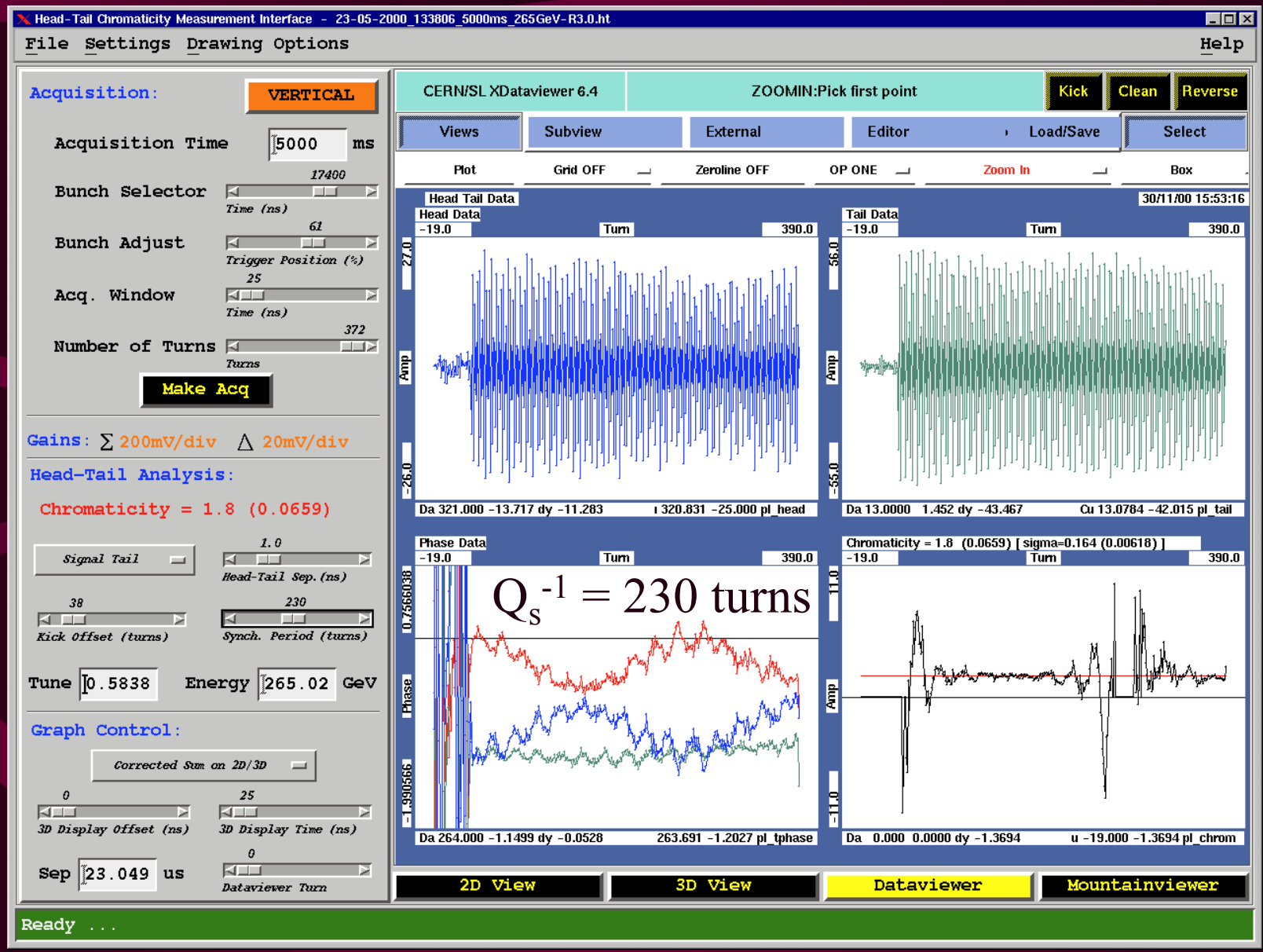
- Measurements performed during CERN-SPS "25ns Run"
  - → LHC batch of 84 bunches with 25ns bunch spacing
  - → Acceleration from 26GeV to 450GeV
  - → Intensity of ~ 2×10^{10} protons per bunch

- Q' measured mainly in the vertical plane
  - → Transverse Damper switched OFF in measurement plane
  - → Beam excited using a single kick from the Q-kickers

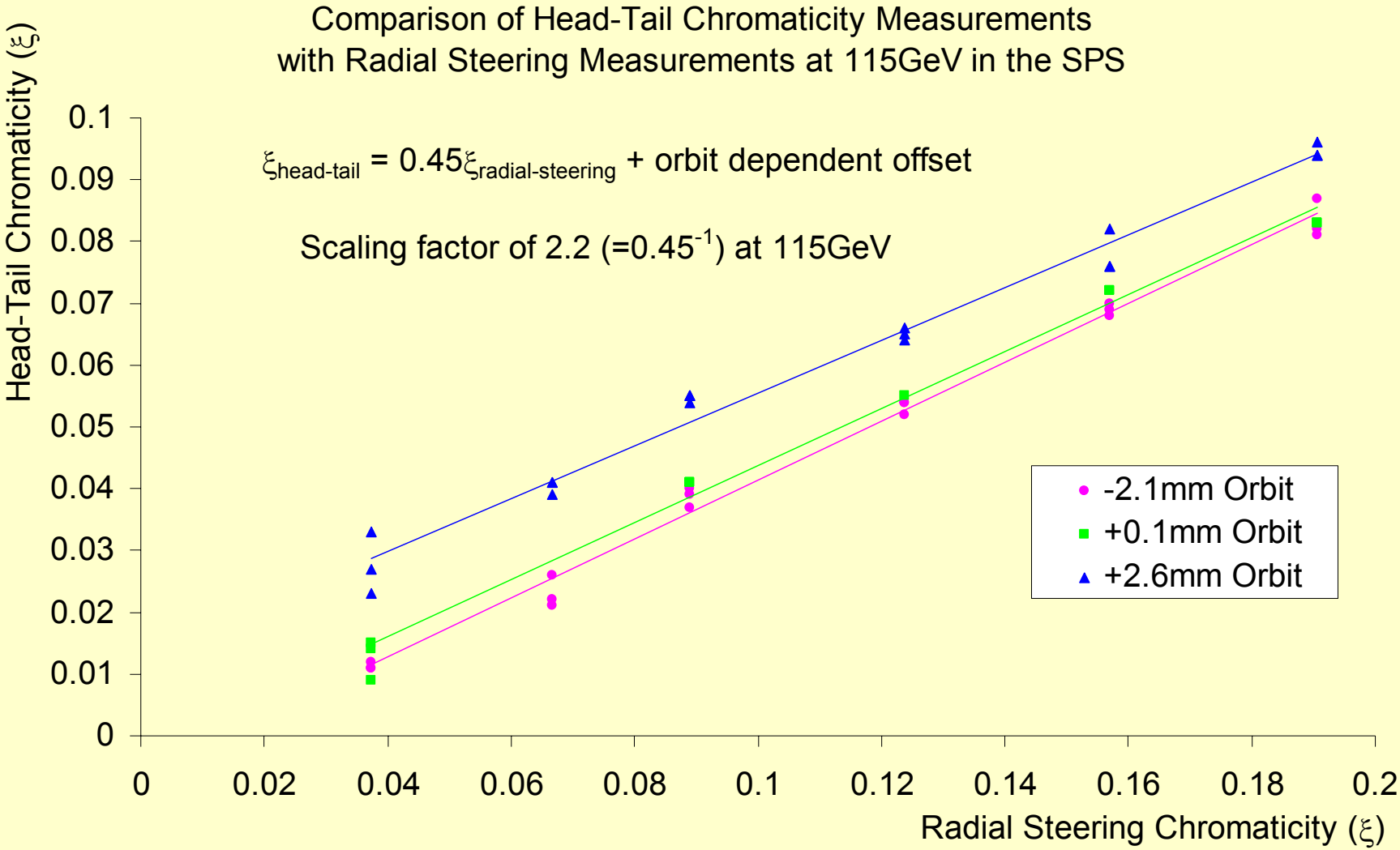
Measuring Q'


Head-Tail Chromaticity Measurement Interface - 23-05-2000_121709_1000ms_36GeV-R-2.7.ht
File Settings Drawing Options Help
Acquisition: VERTICAL
Acquisition Time 1000 ms
Bunch Selector 17400 Time (ns)
Bunch Adjust 40 Trigger Position (%)
Acq. Window 25 Time (ns)
Number of Turns 372 Turns
Make Acq
Gains: Σ 200mV/div Δ 20mV/div
Head-Tail Analysis:
Chromaticity = 1.7 (0.0622)
Signal Tail
1.0 Head-Tail Sep. (ns)
39 Kick Offset (turns)
97 Synch. Period (turns)
Tune 0.5822 Energy 36.712 GeV
Graph Control:
Corrected Sum on 2D/3D
0 3D Display Offset (ns)
25 3D Display Time (ns)
Sep 23.065 us
0 Dataviewer Turn
CERN/SL XDataviewer 6.4
ZOOMIN:Pick first point
Kick Clean Reverse
Views Subview External Editor Load/Save Select
Plot Grid OFF Zeroline OFF OP ONE Zoom In Box
Head Tail Data
30/11/00 15:59:57
Head Data
Tail Data
Phase Data
Chromaticity = 1.7 (0.0622) [sigma=0.103 (0.00386)]
Turn
Amp
Phase
$Q_s^{-1} = 97$ turns
2D View 3D View Dataviewer Mountainviewer
Ready ...

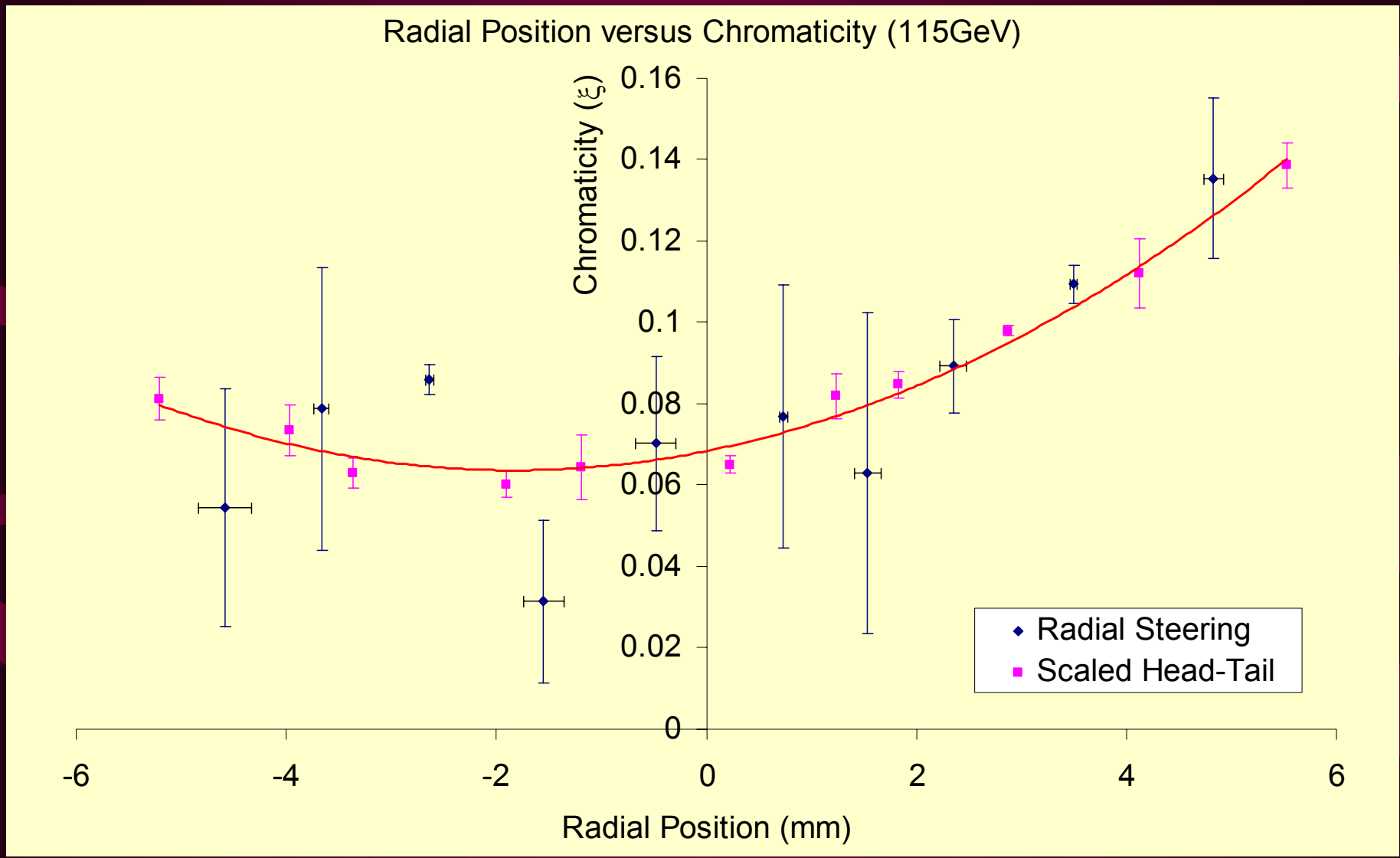
Measuring Q'


Head-Tail Chromaticity Measurement Interface - 23-05-2000_133806_5000ms_265GeV-R3.0.ht
File Settings Drawing Options Help
Acquisition: VERTICAL
Acquisition Time 5000 ms
Bunch Selector 17400 Time (ns)
Bunch Adjust 61 Trigger Position (%)
Acq. Window 25 Time (ns)
Number of Turns 372 Turns
Make Acq
Gains: Σ 200mV/div Δ 20mV/div
Head-Tail Analysis:
Chromaticity = 1.8 (0.0659)
Signal Tail
1.0 Head-Tail Sep.(ns)
38 Kick Offset (turns)
230 Synch. Period (turns)
Tune 0.5838 Energy 265.02 GeV
Graph Control:
Corrected Sum on 2D/3D
0 3D Display Offset (ns)
25 3D Display Time (ns)
Sep 23.049 us
0 Dataviewer Turn
CERN/SL XDataviewer 6.4
ZOOMIN:Pick first point
Kick Clean Reverse
Views Subview External Editor Load/Save Select
Plot Grid OFF Zeroline OFF OP ONE Zoom In Box
Head Tail Data
30/11/00 15:53:16
Head Data
Tail Data
Turn
Amp
Phase Data
Chromaticity = 1.8 (0.0659) [sigma=0.164 (0.00618)]
$Q_s^{-1} = 230$ turns
2D View 3D View Dataviewer Mountainviewer
Ready ...

Measuring Q'


Comparison of Head-Tail Chromaticity Measurements
with Radial Steering Measurements at 115GeV in the SPS
$\xi_{head\text{-}tail} = 0.45\xi_{radial\text{-}steering}$ + orbit dependent offset
Scaling factor of 2.2 (=0.45^{-1}) at 115GeV
Head-Tail Chromaticity (ξ)
Radial Steering Chromaticity (ξ)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
-2.1mm Orbit
+0.1mm Orbit
+2.6mm Orbit

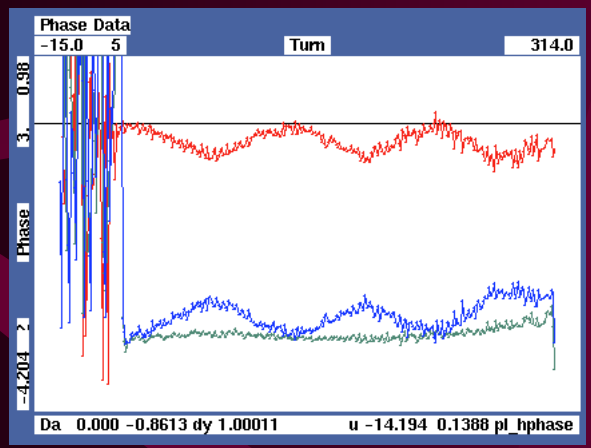
Measuring Q'' and Q'''

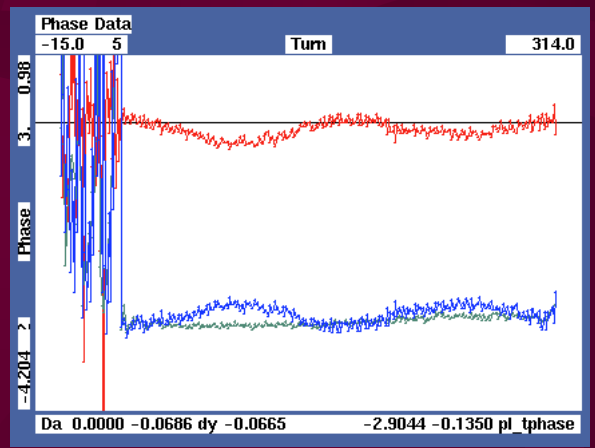


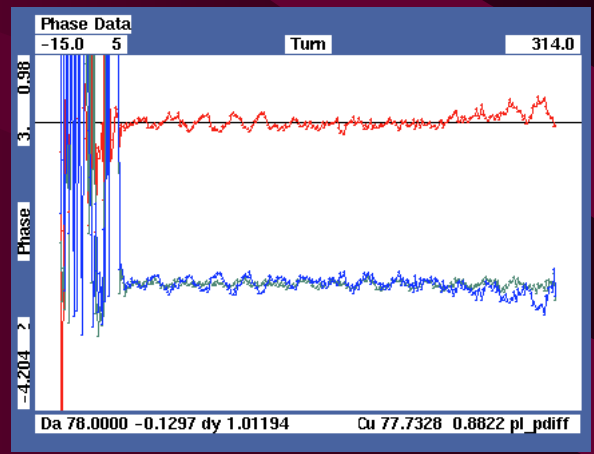
Multiple Q' Measurements

- Several Q' Measurements on SAME SPS elementary cycle
  - → rate limited to 0.5Hz by GPIB data transfer & scope reset time
  - → demonstrated on SPS using 3 Q-kickers

1000ms : 36GeV → 3000ms : 115GeV → 5000ms : 265GeV







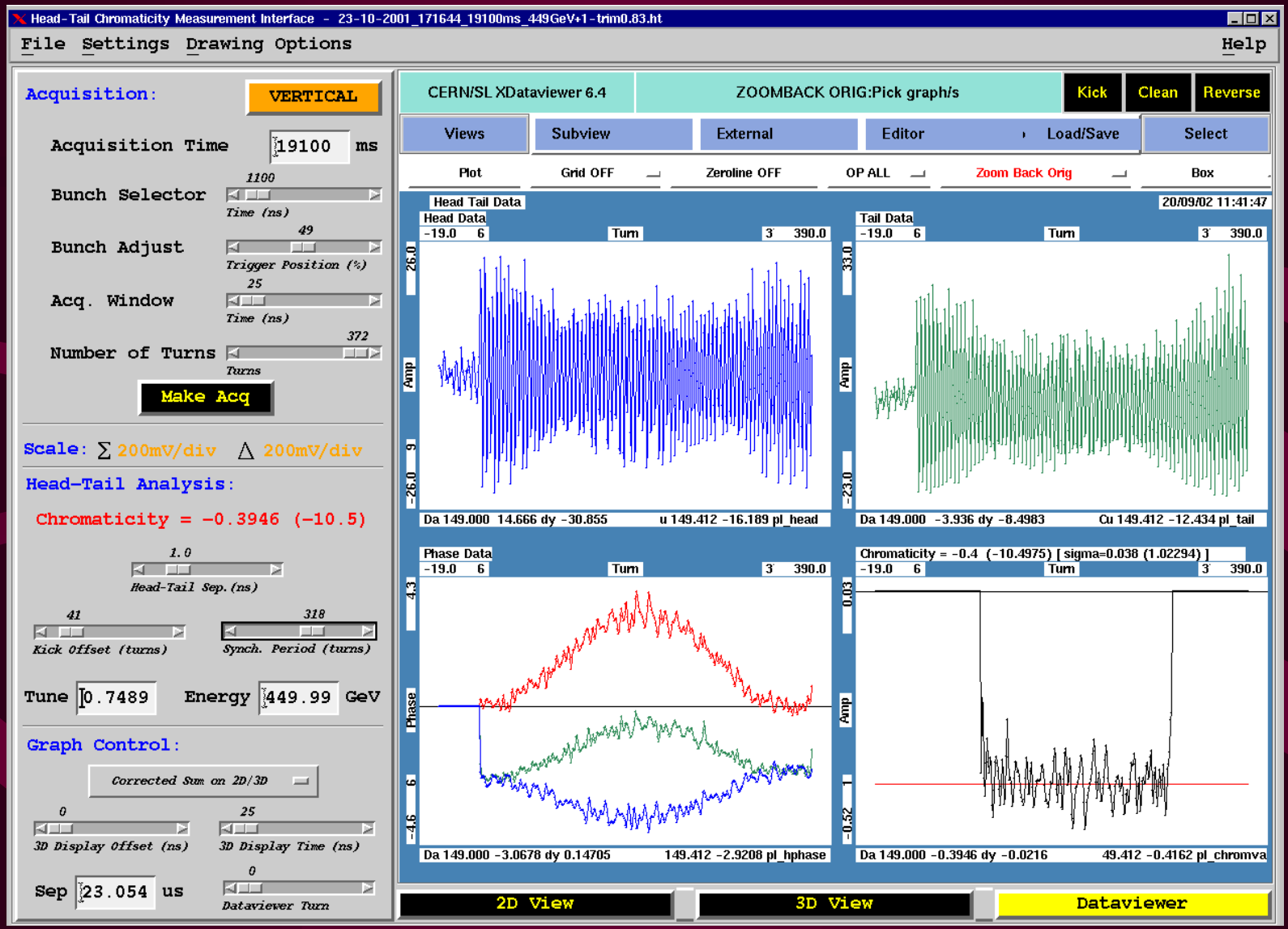
ξ=0.036 ξ=0.037 ξ=0.005

Improvements and Developments in 2001/2002

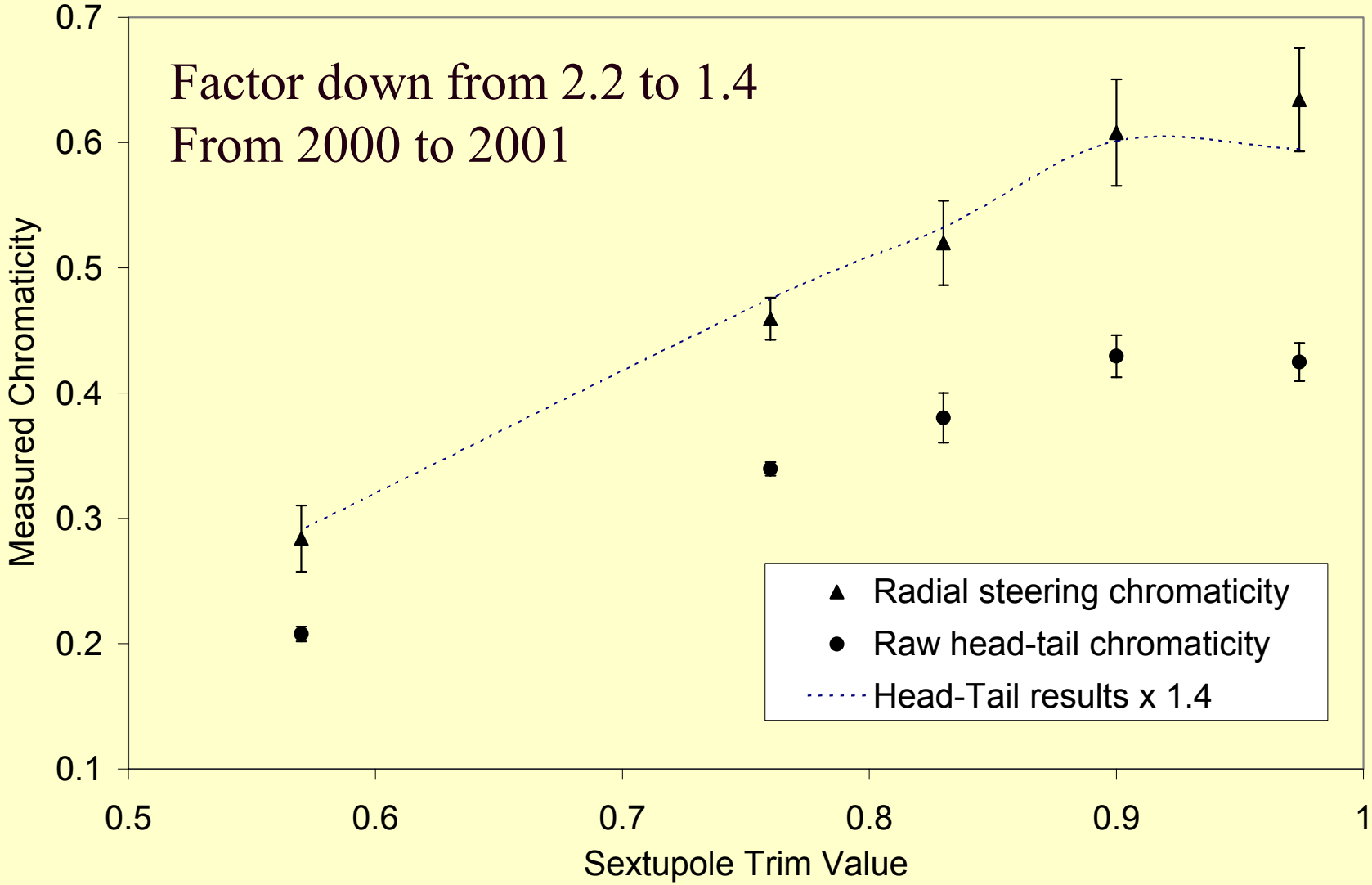
- Added 60cm long coupler
  → can fully resolve bunches up to 4ns in length
- Added low loss cables & reduced cable length
  → increase in the overall system bandwidth
- Performed more complete simulations
  → originally intended to find source of missing factor
    - Turned out to be hardware related

  → developed into a robustness study for the technique
    - Effect of accelerating buckets
    - Effect of Q'' and Q'''

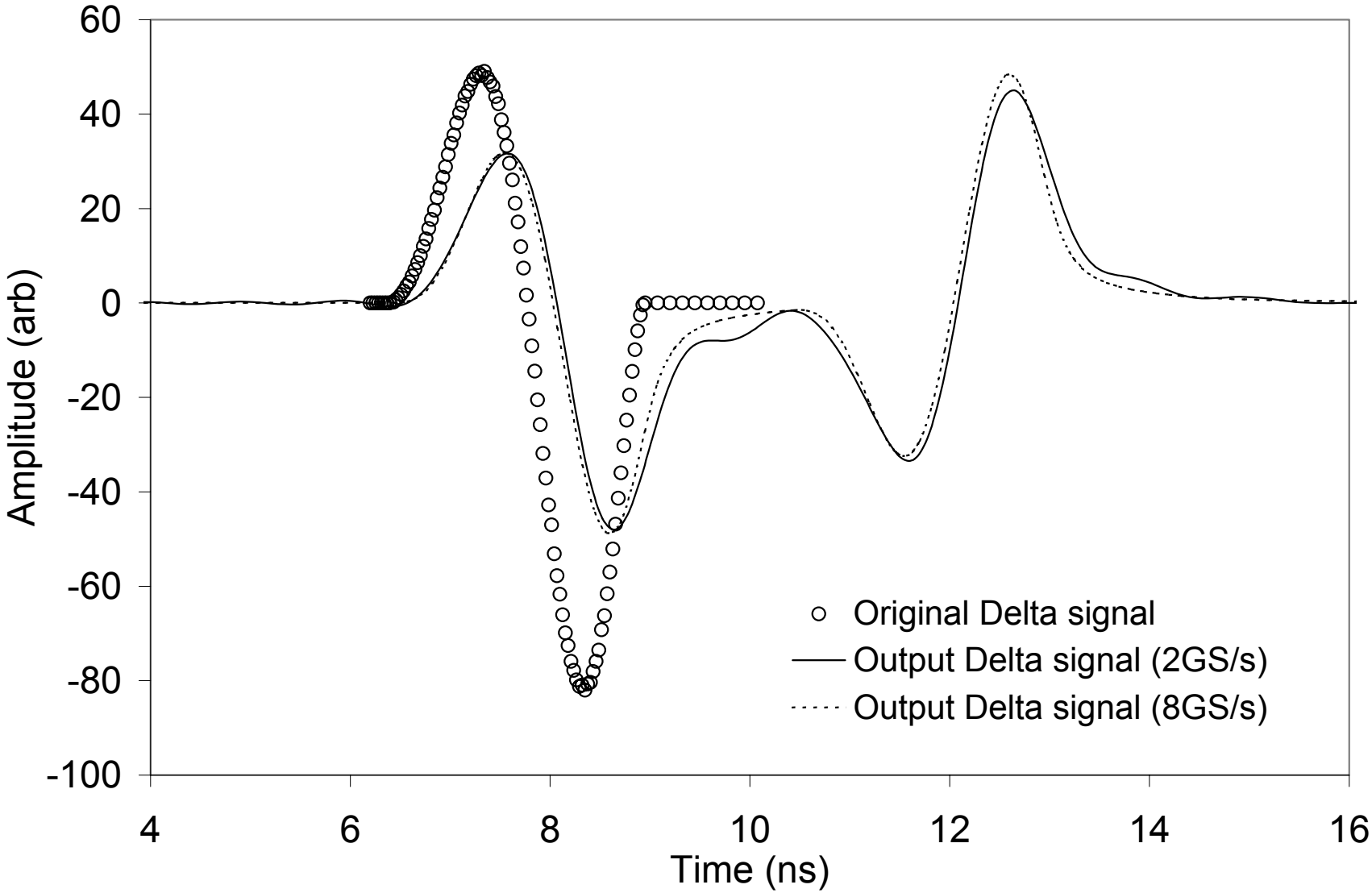
Measuring Q' (long coupler)



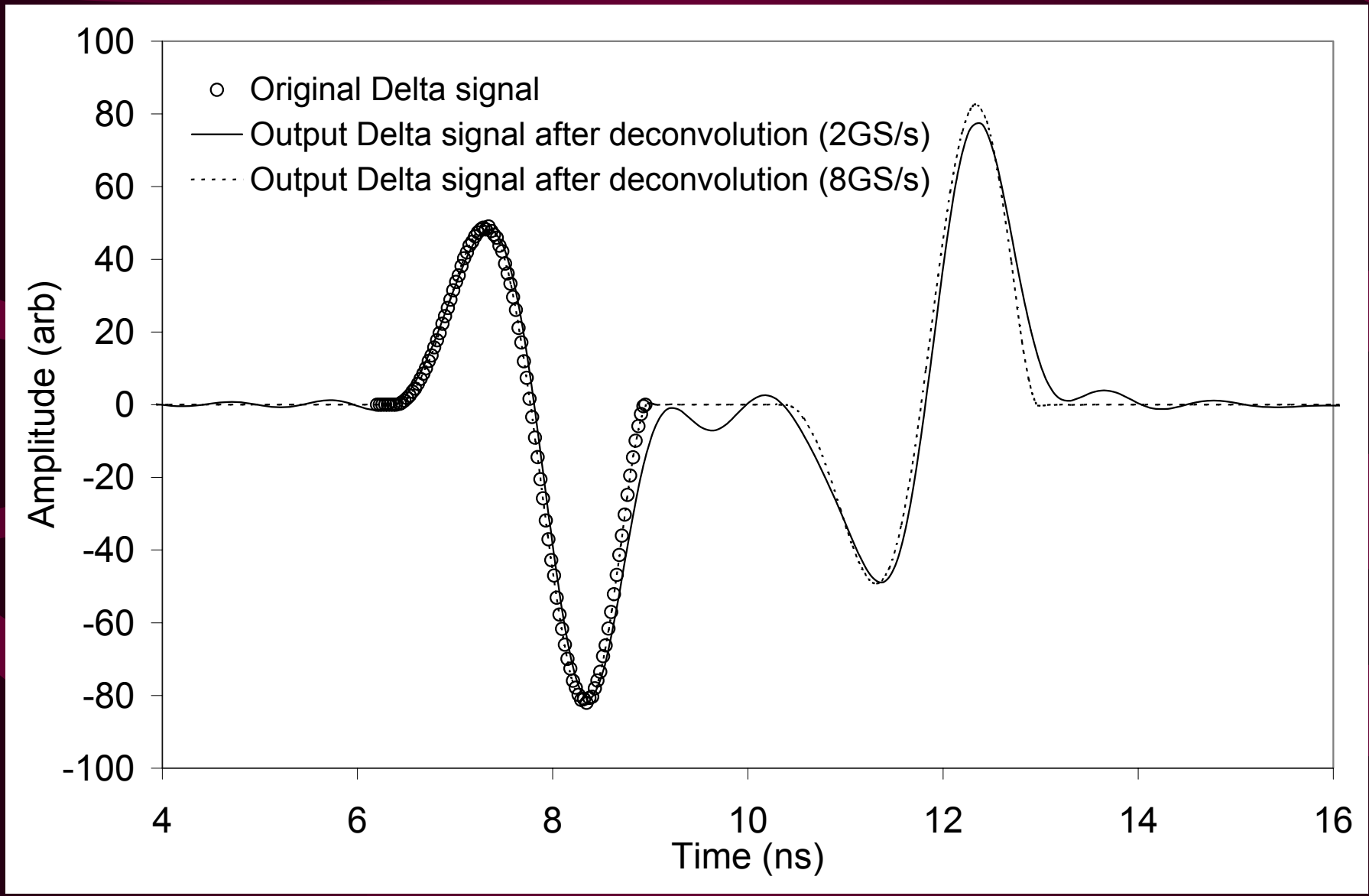
Understanding the Scaling Factor



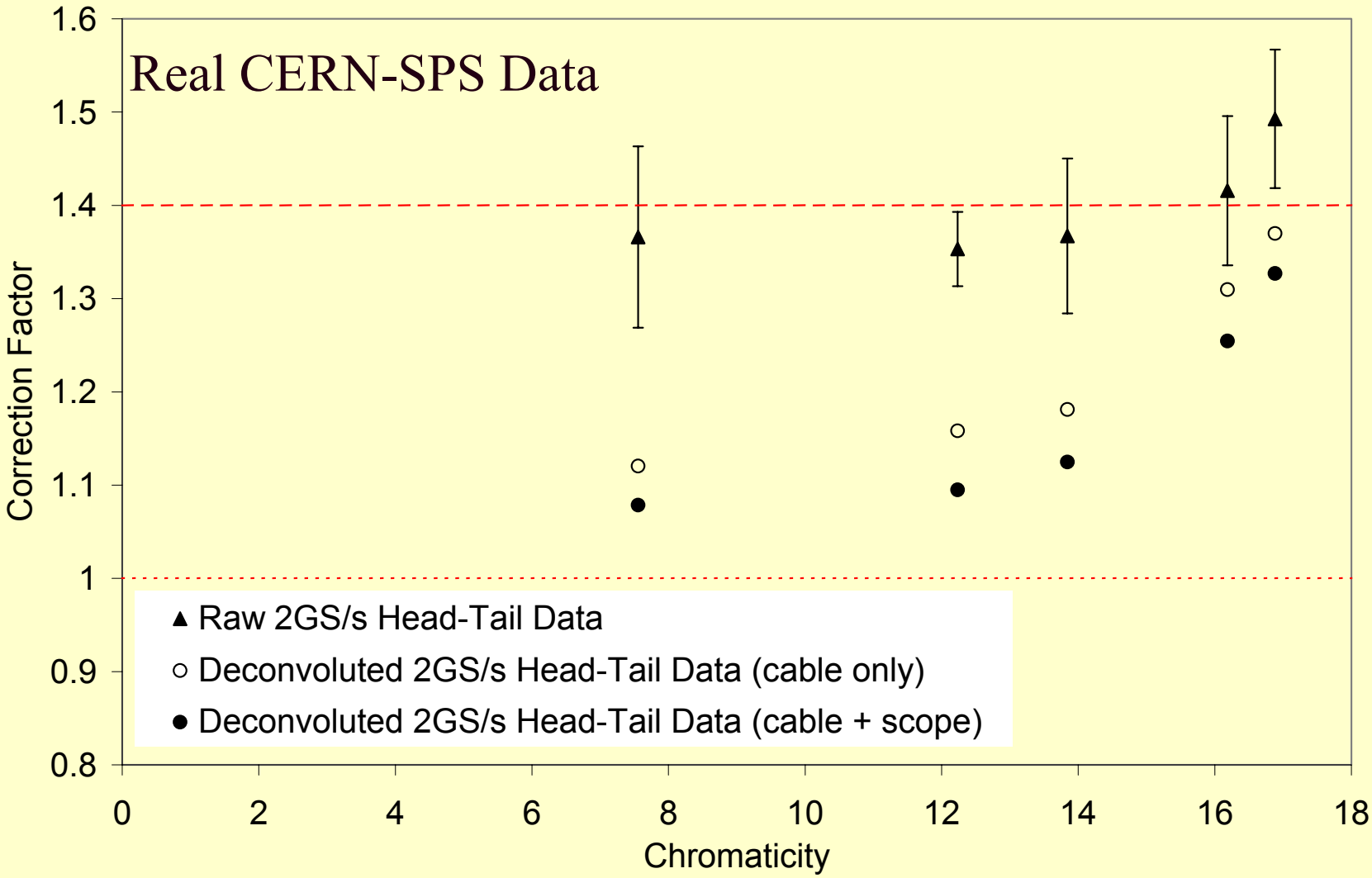
Signal Output



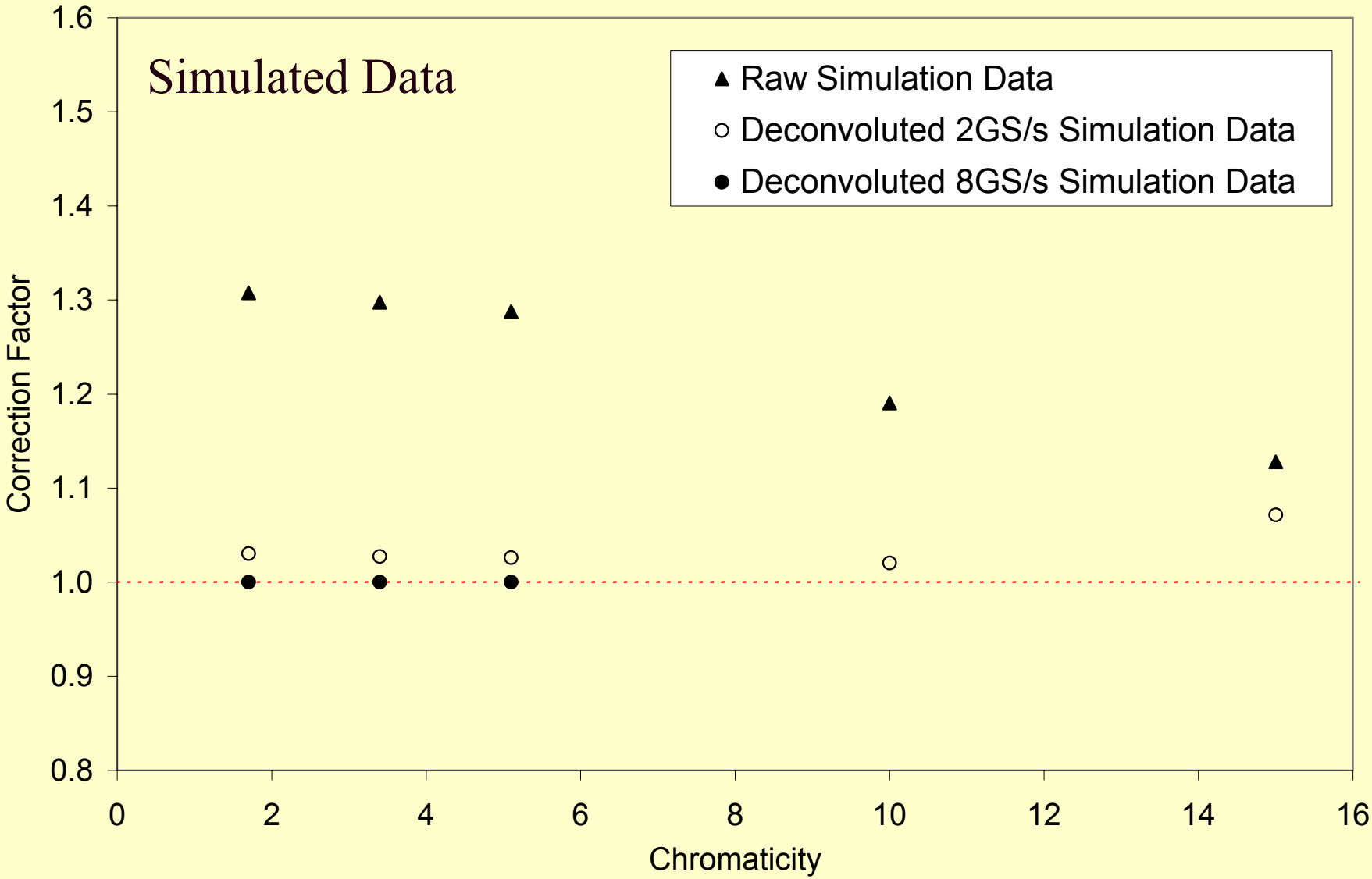
Signal Output



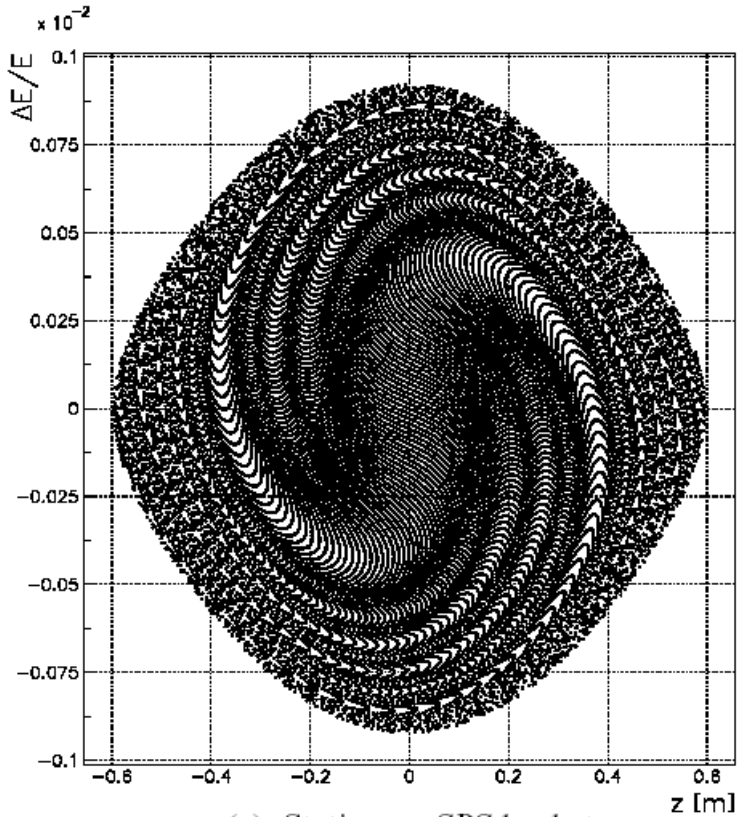
Effect of Deconvolving Cable Response



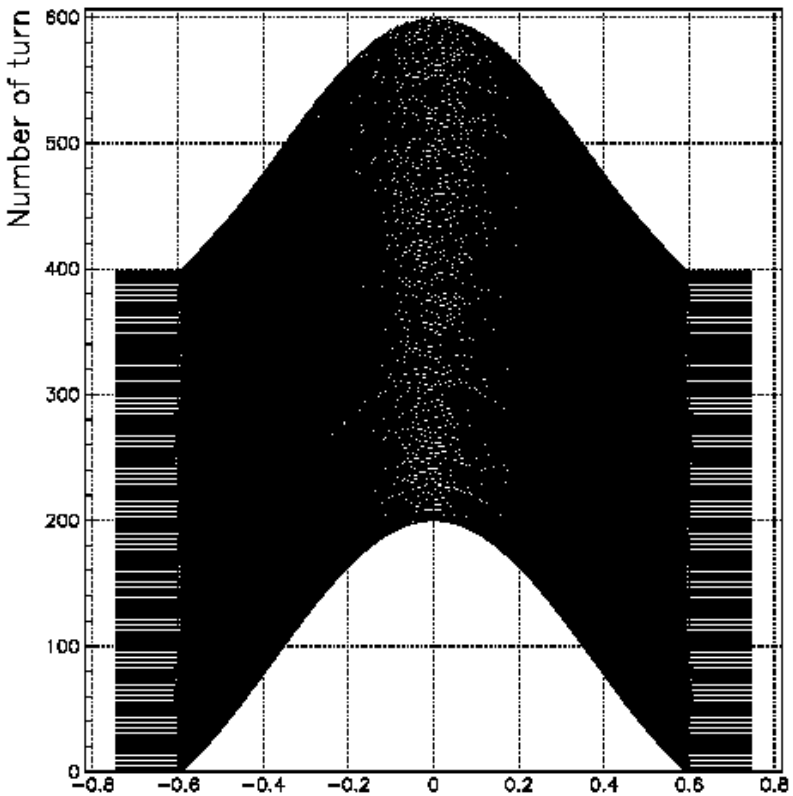
Effect of Sampling Rate



Simulations

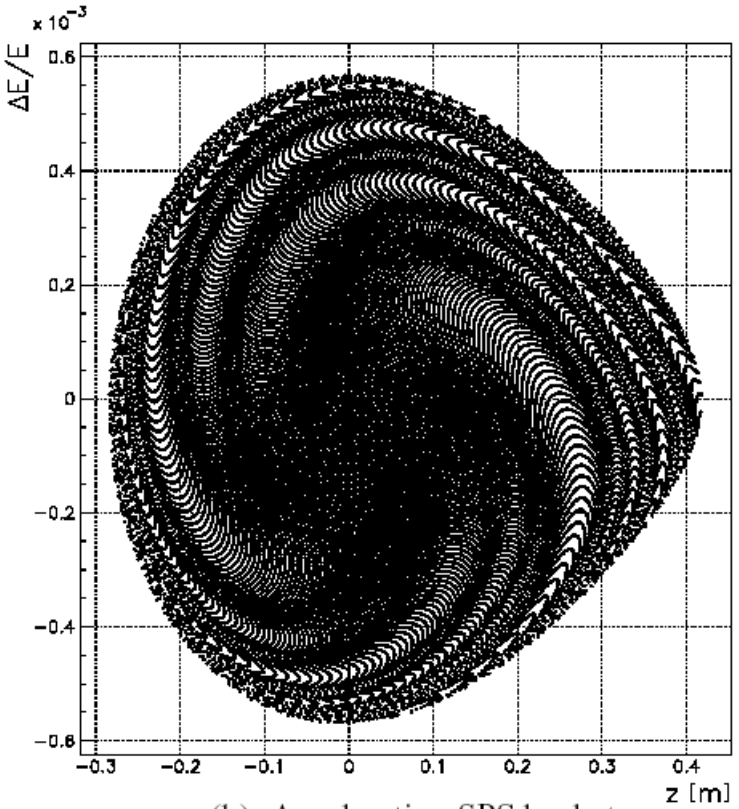


(a): Stationary SPS bucket
at 303.91 GeV ($V_{\mathrm{RF}} = 3.87$ MV, $\phi_s = 0$)

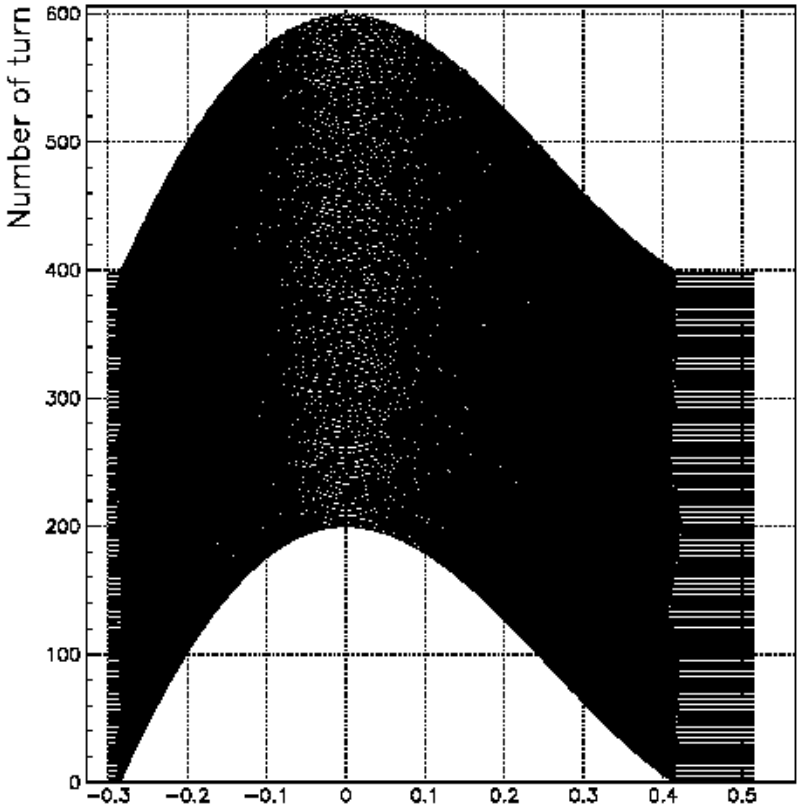


(c)

Simulations



(b): Accelerating SPS bucket
at 303.91 GeV ($V_{\mathrm{RF}} = 3.87$ MV, $\phi_s = 27.7°$)

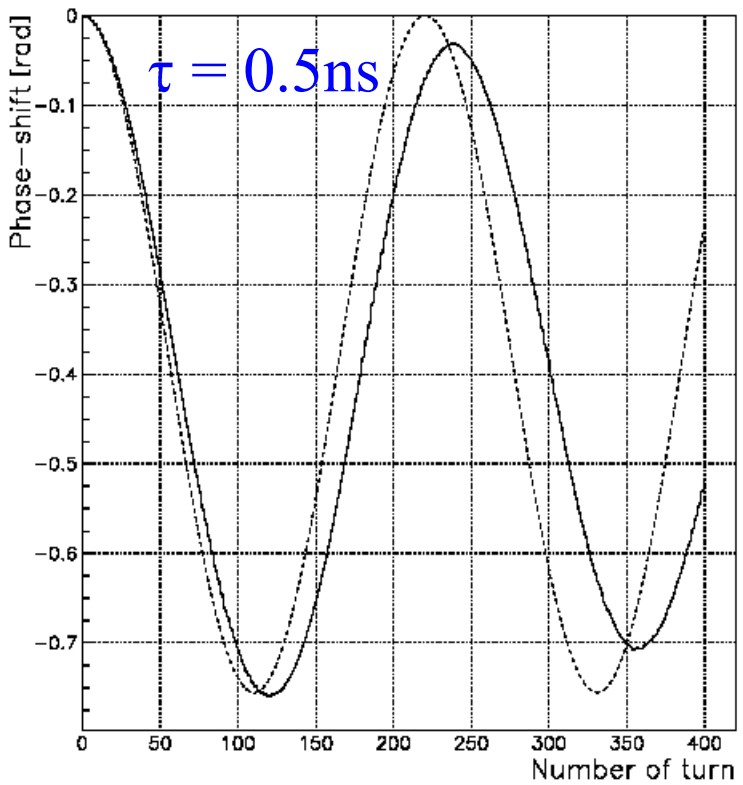


(d)

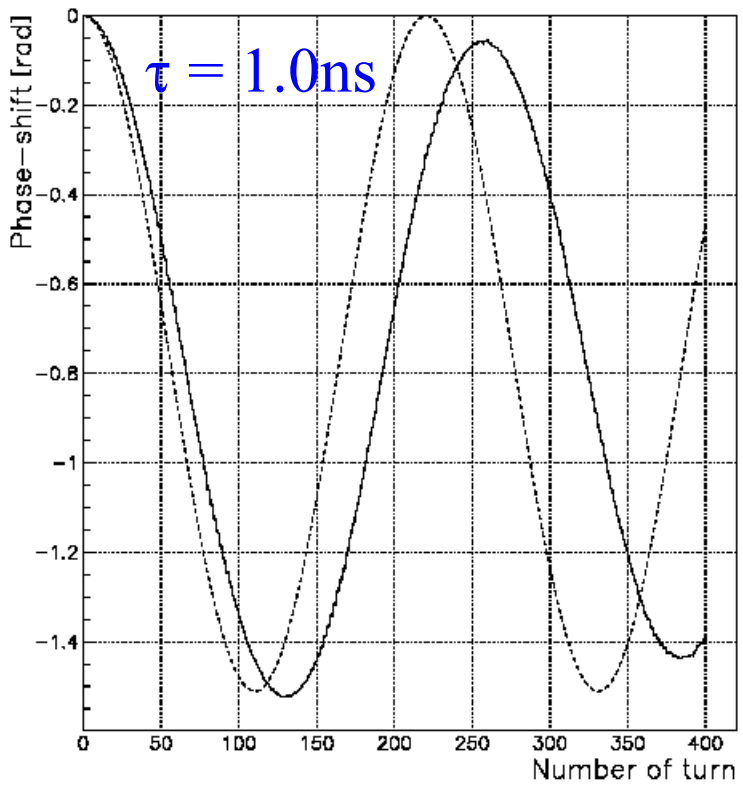
Tracking v Analytical Approach

Stationary Bucket:

- Measurement at Bunch Head w.r.t. Bunch Centre
- Comparison of tracking (solid lines) & analytical estimate (dashed)
- Error in ϕ_{MAX} negligible



(e): Betatron phase-shift [rad]



(f): Betatron phase-shift [rad]

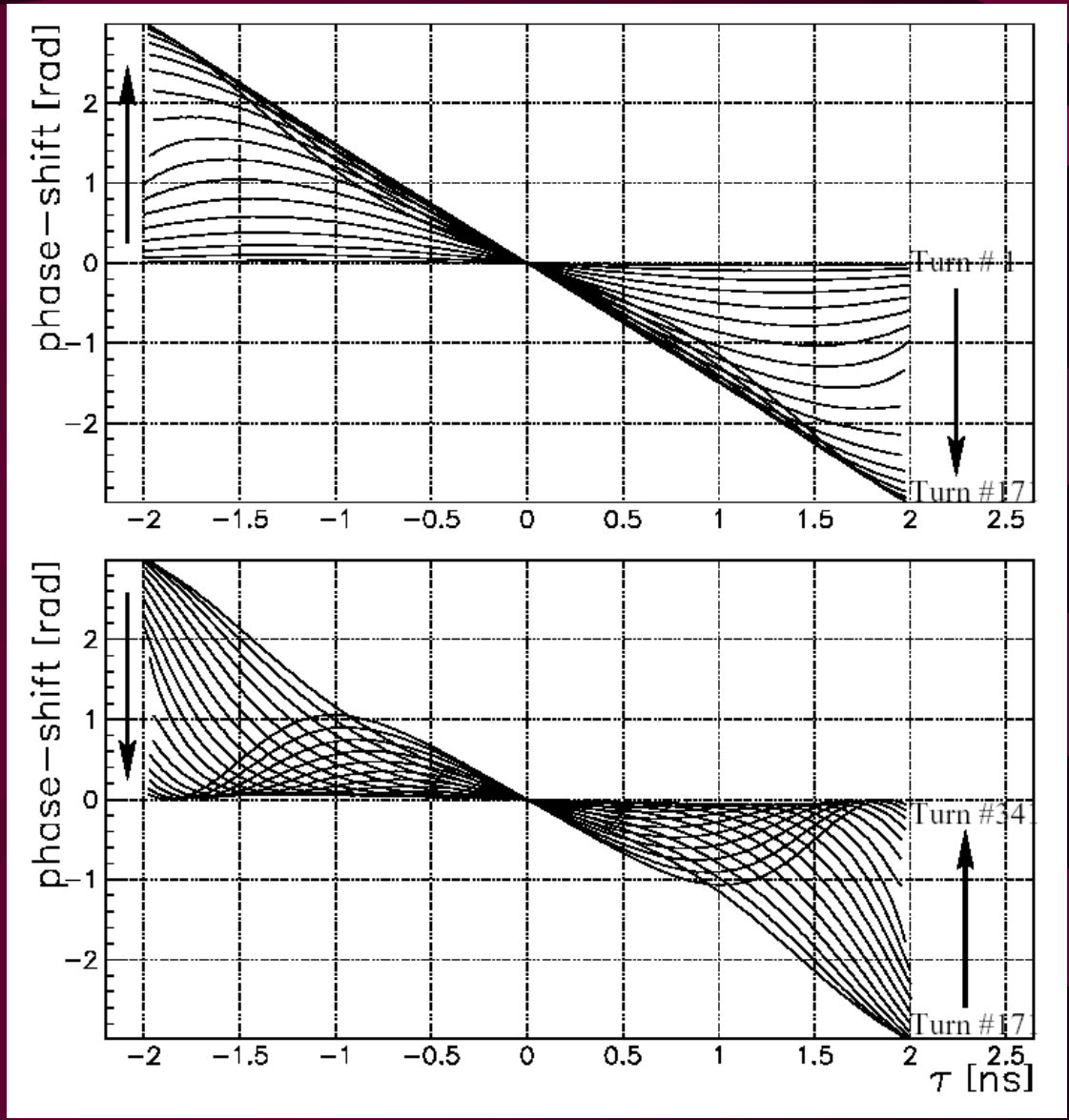
Tracking Results

Stationary Bucket:

- Maximum phase shift reached is linear with distance from centre

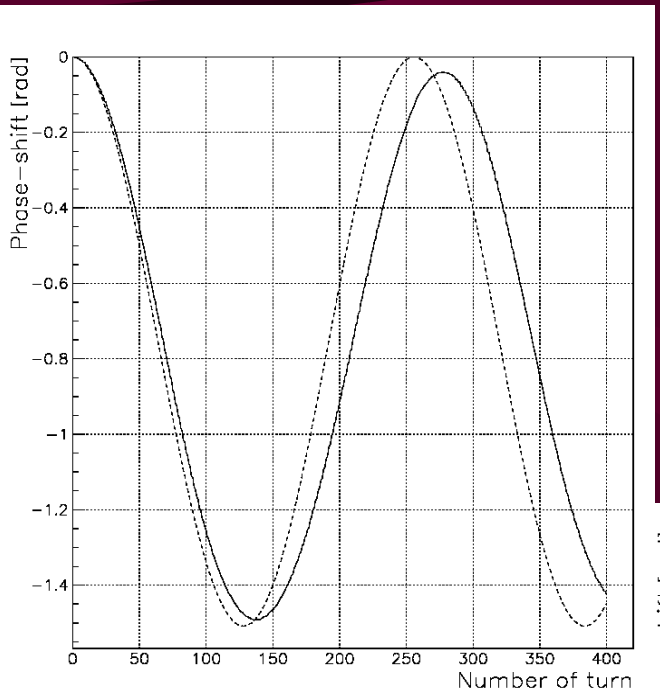
Measurement is valid for:

- Centre to Head
- Centre to Tail
- Symmetric Head to Tail

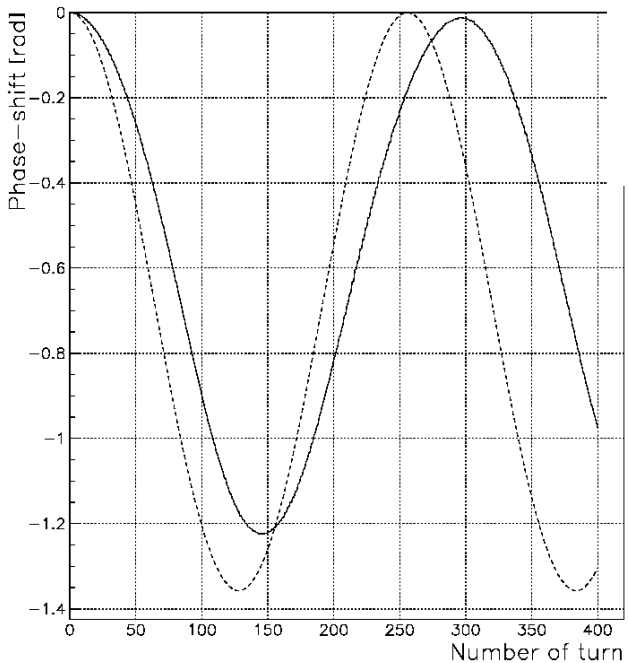


Effect of Acceleration

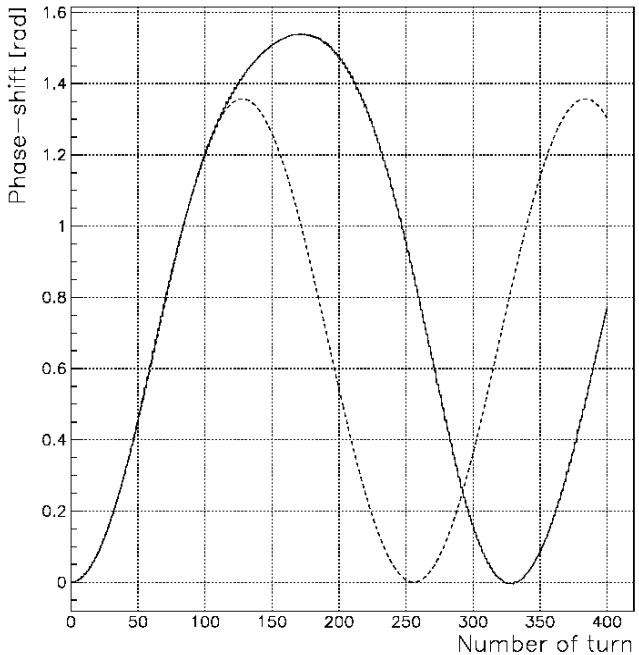
Head & Centre



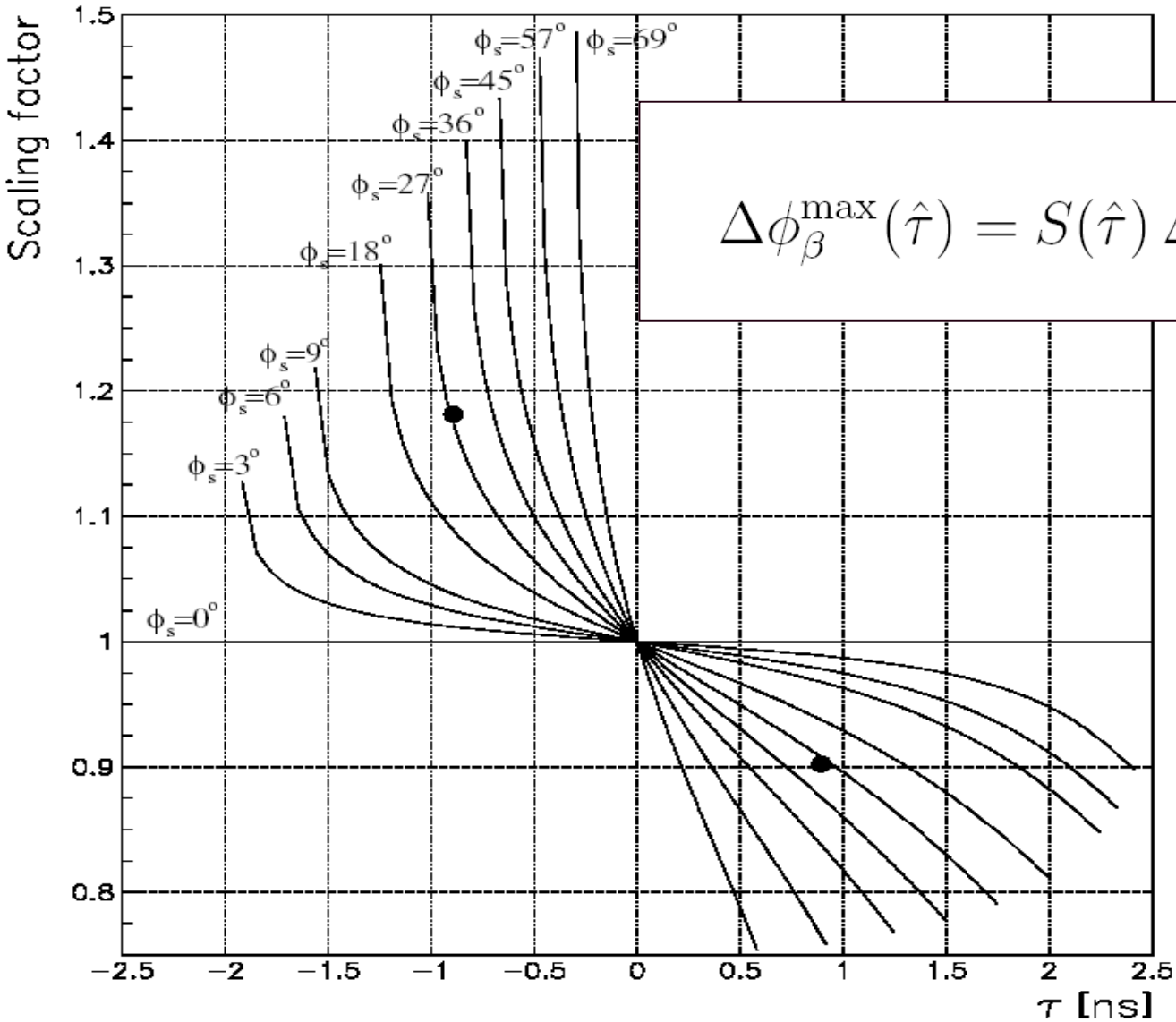
Centre & Tail



Symmetric
Head & Tail

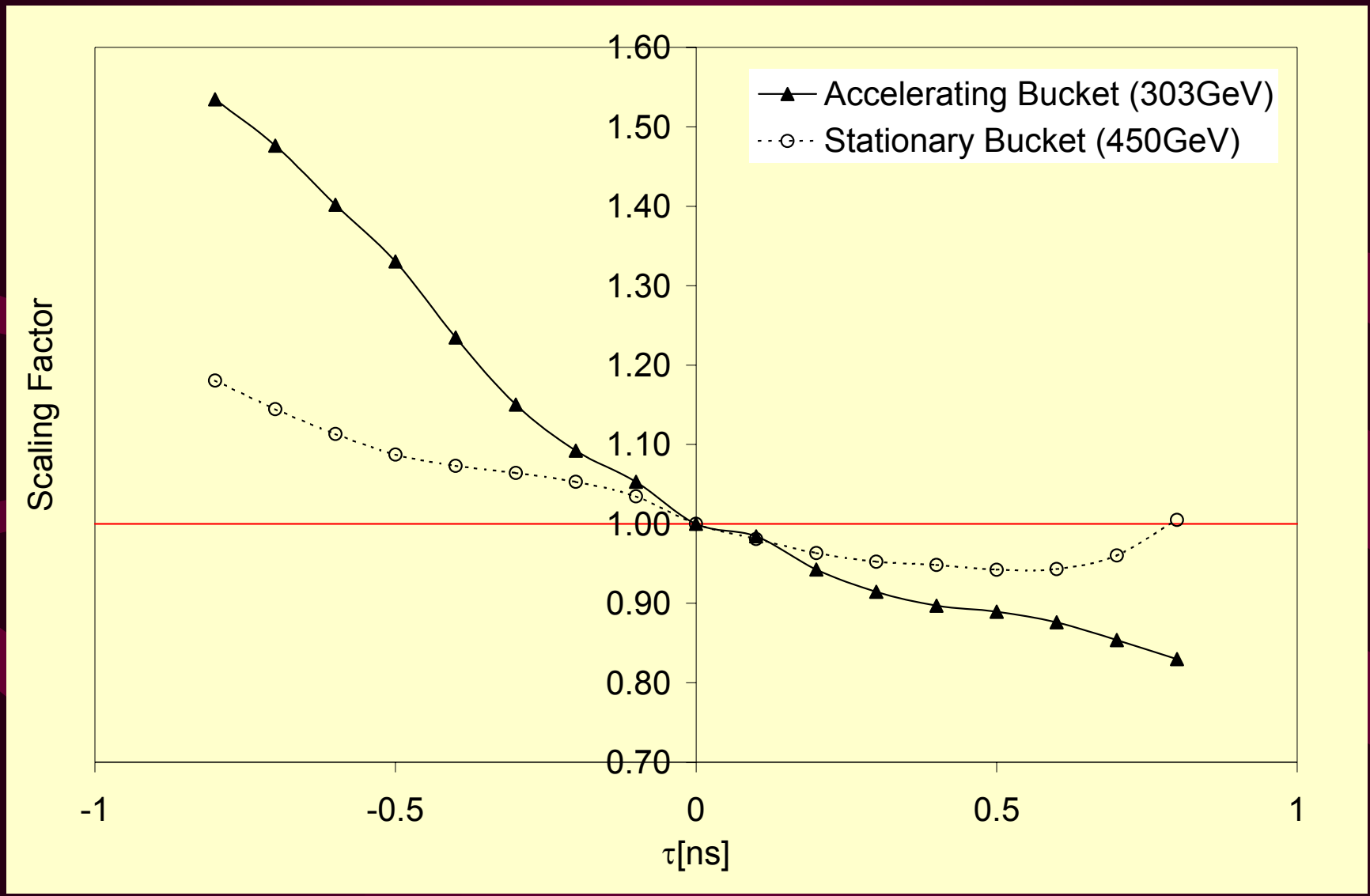


Effect of Acceleration

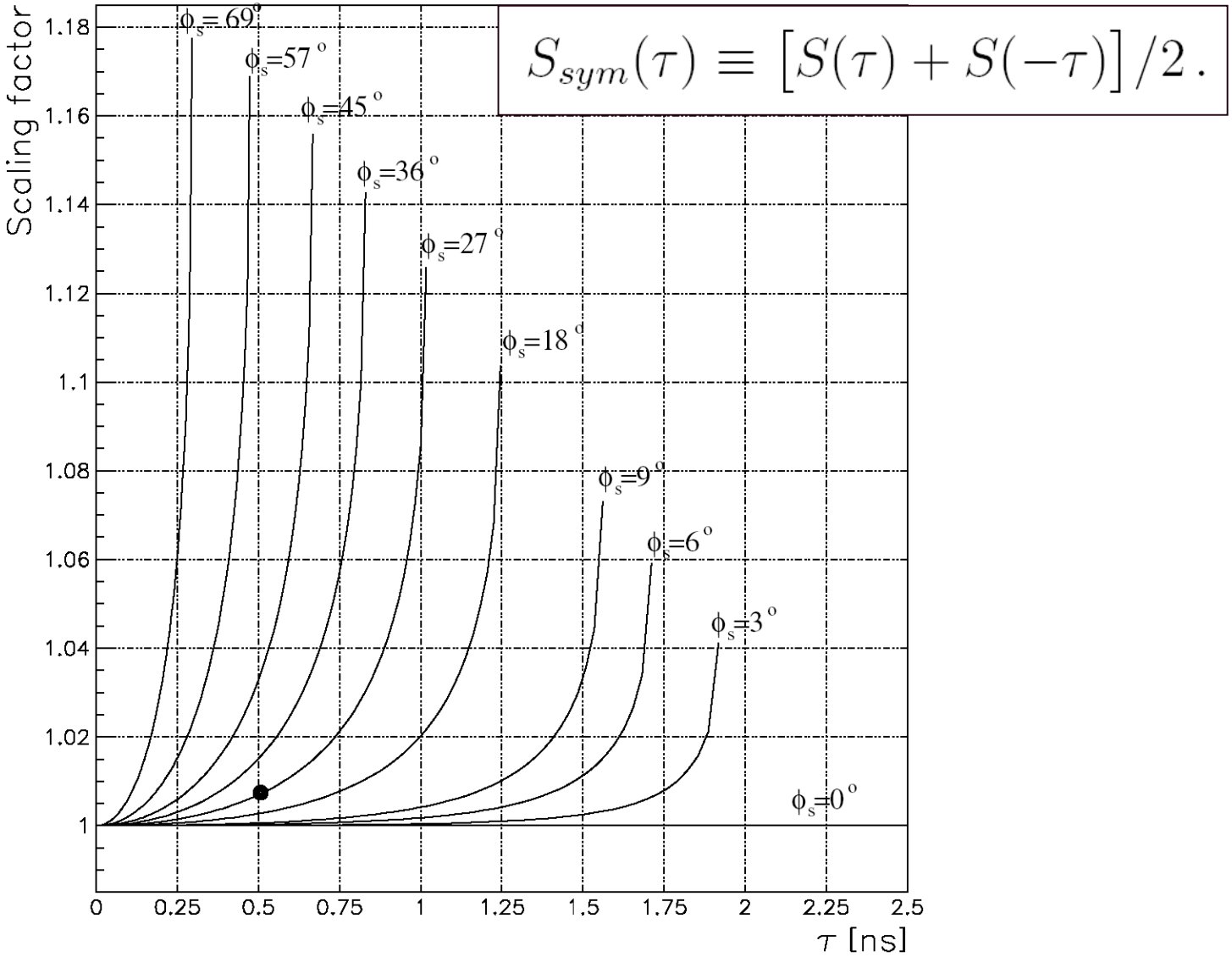


$$\Delta\phi_\beta^{\max}(\hat{\tau}) = S(\hat{\tau})\,\Delta\phi_\beta^{\max,\mathrm{lin.}}(\hat{\tau})$$

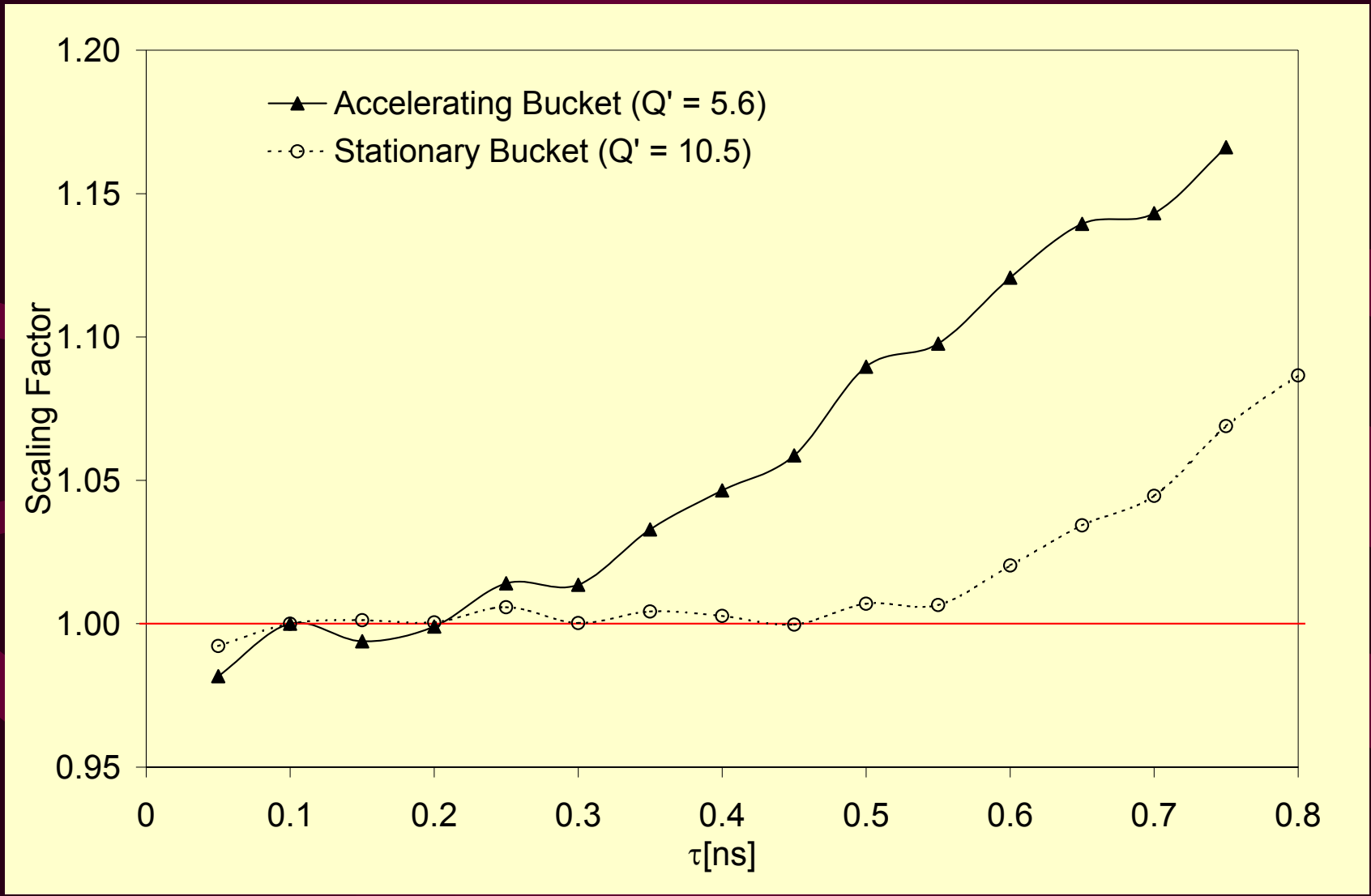
Effects of Acceleration (SPS Data)



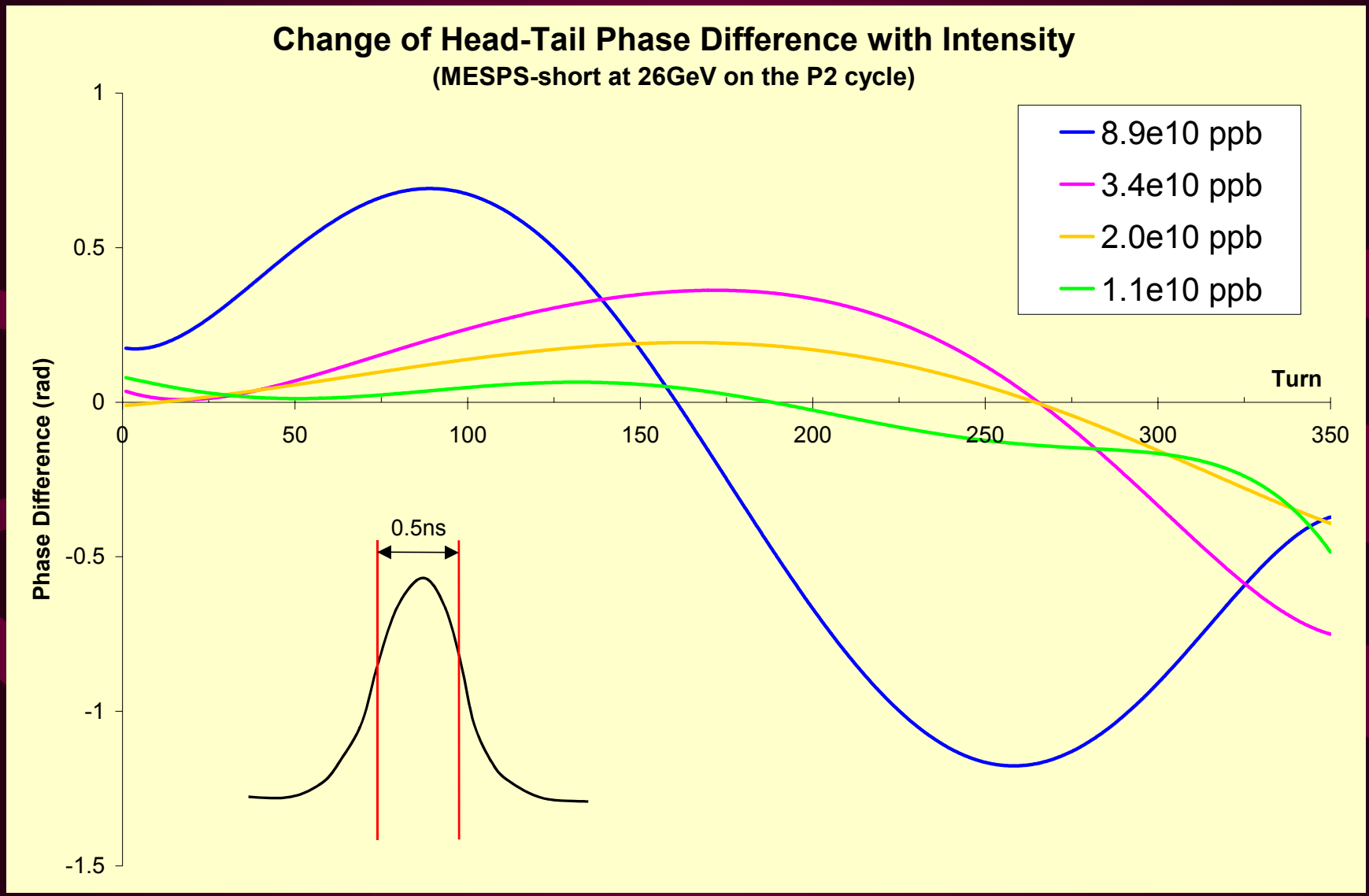
Effect of Acceleration



Effects of Acceleration (SPS Data)



SPS Impedance Effects at Low Energy



Conclusions

- Experimental
  - → Operational Head-Tail Q'-Meas. system demonstrated
  - → Technique also allows Q'' measurement
  - → Chromaticity measurement demonstrated at 0.5Hz
  - → Deconvolution required to remove perturbations due to hardware bandwidth limitations
  - → Useful instrument for other applications
    - transverse instabilities
    - possible use for SPS impedance measurements
- Theoretical
  - → Method applicable for both stationary and accelerating buckets
    - Experimentally verified with the constraint that the measurement be performed symmetrically about the bunch centre
  - → LHC robustness demonstrated for:
    - Non-linear chromaticity (Q'' and Q''')
    - Linear coupling (if arc-by-arc compensated as foreseen for LHC)
    - Impedance (by extrapolation from SPS to LHC)