LEP Operation and Performance

Mike Lamont, CERN

Outline:

1) Brief History

2) Injection & TMCI

3) Beam-beam tune shift & Luminosity performance

4) Optimisation

5) Equipment

6) Operations, controls and instrumentation

6) Polarization

6) Other issues

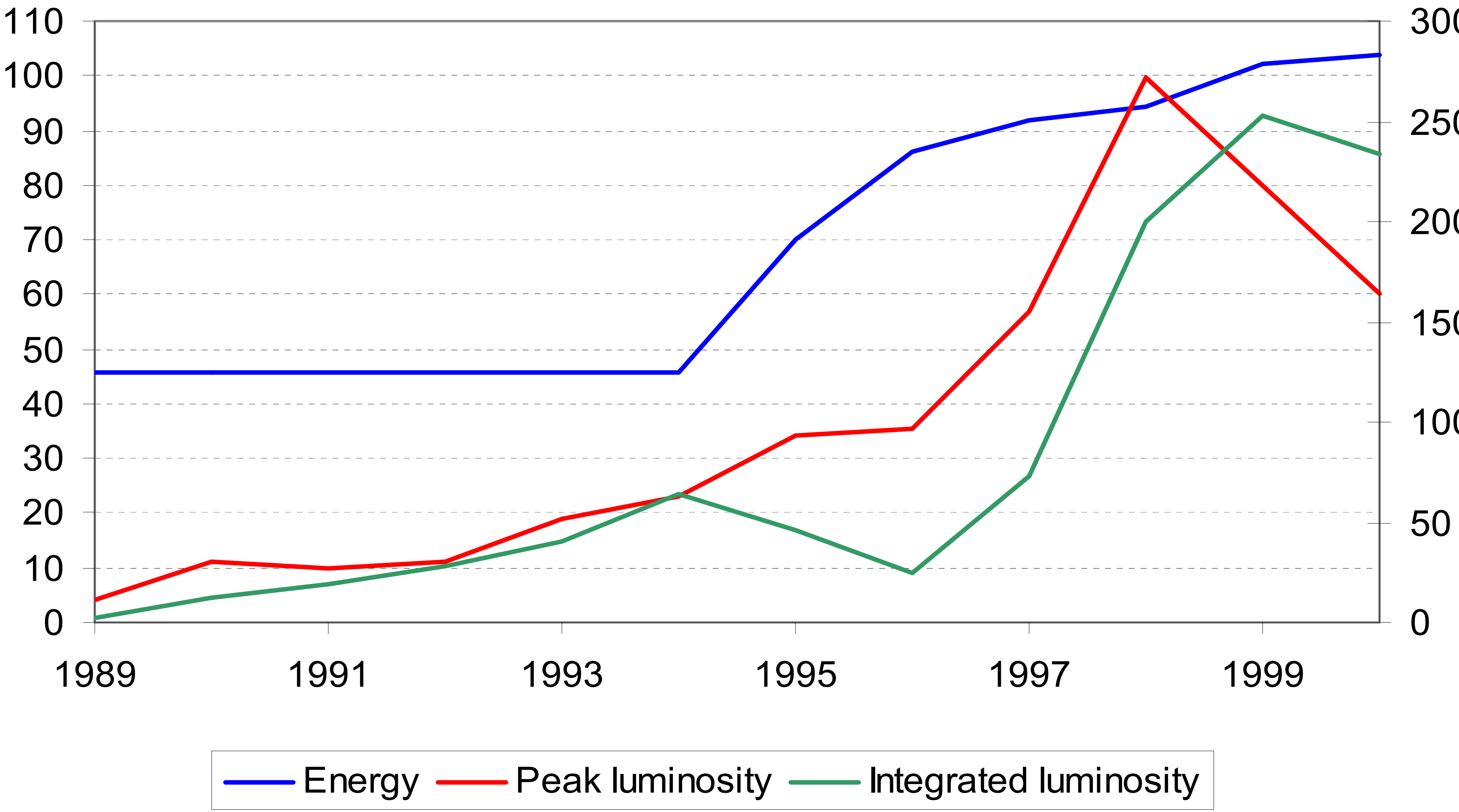
7) Conclusion

Will try and concentrate
on physics & lessons that
might be relevant to
future machines.

LEP - The Largest Particle Accelerator to Date…

1989	First operation
1989-1995	The Z-years (precision studies)
1996-1999	The W-years (precision studies)
2000	The Higgs-year (almost a discovery?)
Nov 2000	Start of dismantlin

1989-2000



110
100
90
80
70
60
50
40
30
20
10
0
300
250
200
150
100
50
0
1989
1991
1993
1995
1997
1999
Energy
Peak luminosity
Integrated luminosity

History

YEAR	OPTICS	COMMENT	BUNCH SCHEME
1989	60/60	Commissioning	4 on 4
1990	60/60		4 on 4
1991	60/60	90/90 tested	4 on 4
1992	90/90	Pretzel commissioned	4 on 4/ Pretzel
1993	90/60		Pretzel
1994	90/60		Pretzel
1995	90/60	Tests at 65-68 GeV	Bunch trains
1996	90/60	108/90 tested	4 on 4
1997	90/60	108/90 & 102/90 tests	4 on 4
1998	102/90		4 on 4
1999	102/90		4 on 4
2000	102/90	Higgs discovery mode	4 on 4

1989 - commissioning

14th July:	first beam
23rd July:	circulating beam
4th August:	45 GeV
13th August:	colliding beams

These people are to blame for what followed

1990 – operational teething troubles

Luminosity: 2 - 3 10^{30} cm^{-2} s^{-1}

Beam current around 3 mA

Pretzel test

Lots of waist scans

BIG beam sizes…

8.6 pb^{-1}

Conclusion from Chamonix 91

- a 70/76 team has been set up
- a dispersion team has been set up
- a dynamic aperture team has been set up
- a closed obit team has been set up
- an intensity limitation team has been set up
- a longitudinal oscillation team has been set up
- a crash pretzel team has been set up
- a beam-beam team already exists!

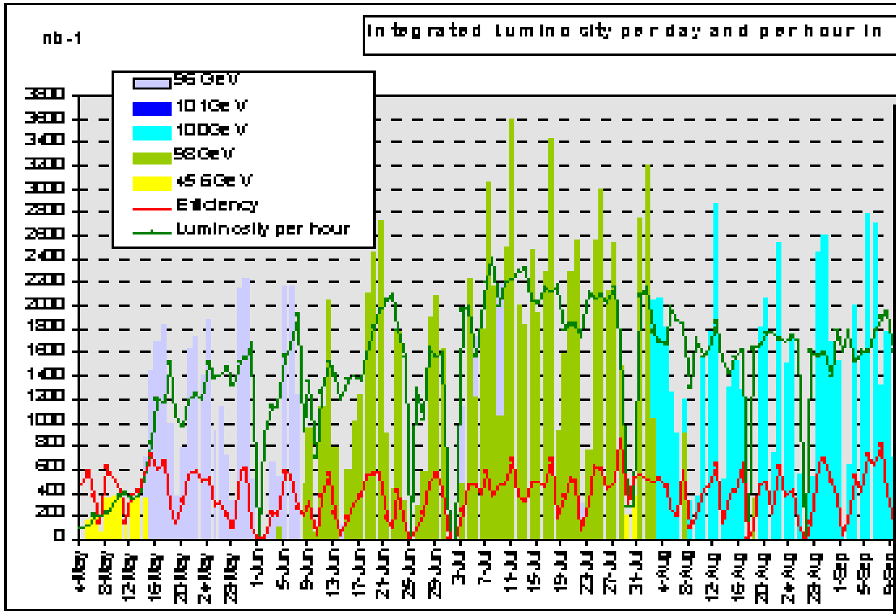
1999 - cruising

Overall performance

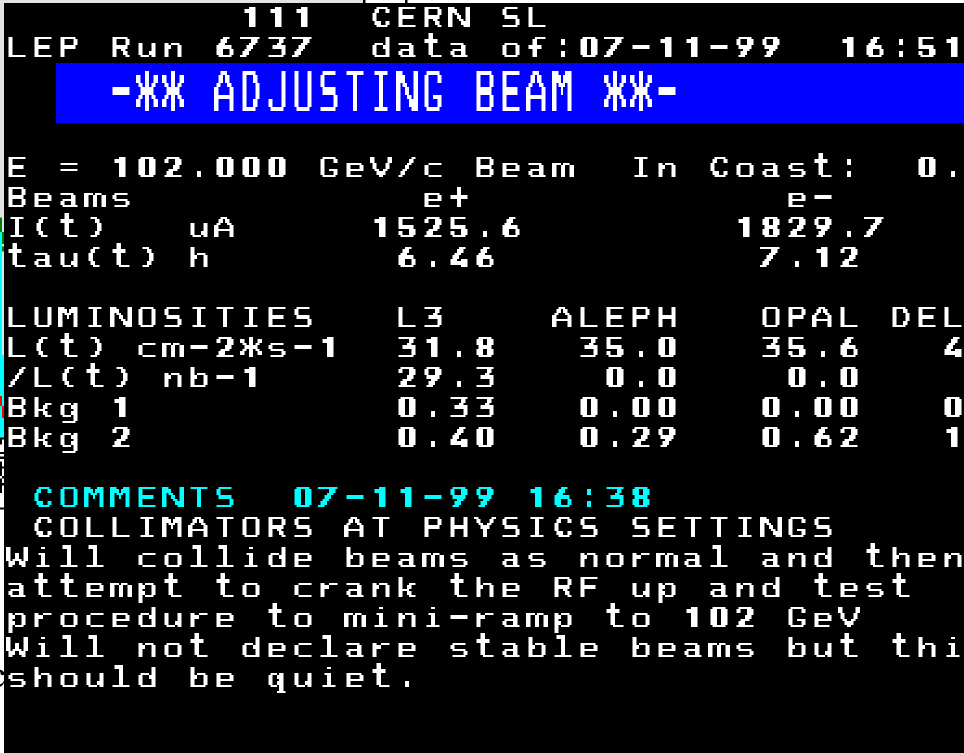
	98GeV	100GeV	101GeV
max current	~ 6.2 mA	~ 5.5 mA	~ 5.0 mA
max bbts	~ 0.083	~ 0.074	~ 0.073
peak luminosities	~ 10^{32} cm^{-2} s^{-1}	~ 8 10^{31} cm^{-2} s^{-1}	~ 8 10^{31} cm^{-2} s^{-1}
integrated	~ 200 nb^{-1}/hour	~ 150 nb^{-1}/hour	~ 140 nb^{-1}/hour
	~ 2 pb^{-1}/day average	~ 1.5 pb^{-1}/day average	~ 1.1 pb^{-1}/day average
	~ 4 pb^{-1}/24hour best	~ 3 pb^{-1}/24hour best	~ 3 pb^{-1}/24hour best

253 pb^{-1}

BORING!



LEPC November99



```
          111   CERN SL
LEP  Run 6737   data of:07-11-99   16:51
   -** ADJUSTING BEAM **-

E = 102.000 GeV/c Beam   In Coast:   0.
Beams             e+              e-
I(t)     uA     1525.6          1829.7
tau(t)   h         6.46            7.12

LUMINOSITIES     L3     ALEPH    OPAL   DEL
L(t) cm-2*s-1   31.8    35.0     35.6     4
/L(t) nb-1      29.3     0.0      0.0
Bkg 1            0.33    0.00     0.00    0
Bkg 2            0.40    0.29     0.62    1

 COMMENTS   07-11-99 16:38
 COLLIMATORS AT PHYSICS SETTINGS
Will collide beams as normal and then
attempt to crank the RF up and test
procedure to mini-ramp to 102 GeV
Will not declare stable beams but thi
should be quiet.
```

Performance

- Two distinct regimes:
  - 45.625 GeV characterised by working well into the soft beam-beam limit and approaching the hard limit.
  - 80.5 GeV and above
    - Staged installation of RF cavities
    - Maximum collision energy (c.m.) raised to 209 GeV
    - Accelerator physics regime of ultra-rapid damping
    - Not beam-beam limited
- 2000: Operational strategy to maximize discovery reach with operation in the regime of ultra-rapid damping

Injection

- A lot of effort in to pushing the bunch current in anticipation of high energy,
- Efficiency always variable, synchrotron injection used
- In the end limited way below maximum by RF system (power levels and stability)
- Fundamental limit at LEP TMCI which was eventually reached despite more practical problems – coherent tune shift & resonances (in particular synchro-betatron)
  - Increase injection energy
  - Removal of copper RF cavities
  - Increase of synchrotron tune
  - wigglers
- Some evidence that long-range beam-beam reduced TMCI limit

Injection limits in 1998

Transverse mode coupling instability (TMCI):

(ignore hardware, RF consideratio

Experimentally found 1998 to be around ~ 1 mA

$$I_{th} = \frac{2\pi\, E\, f_{rev}\, Q_s}{e \sum \beta\, k_\perp(\sigma_s)}$$

+ 1.5 %

Raise Q_s (also helps RF)

Avoi
SBR

Influence from beam-beam: Lower TMCI threshold by ~ 12 %

Synchro-betatron resonances (SBR):

$$Q_v = n \cdot Q_s \qquad \text{with } n = 1, 2, 3$$

(coherent and incoherent)

Longitudinal single-bunch instability: Not understood. Avoided with bunch lengthening.

LEP working Points:

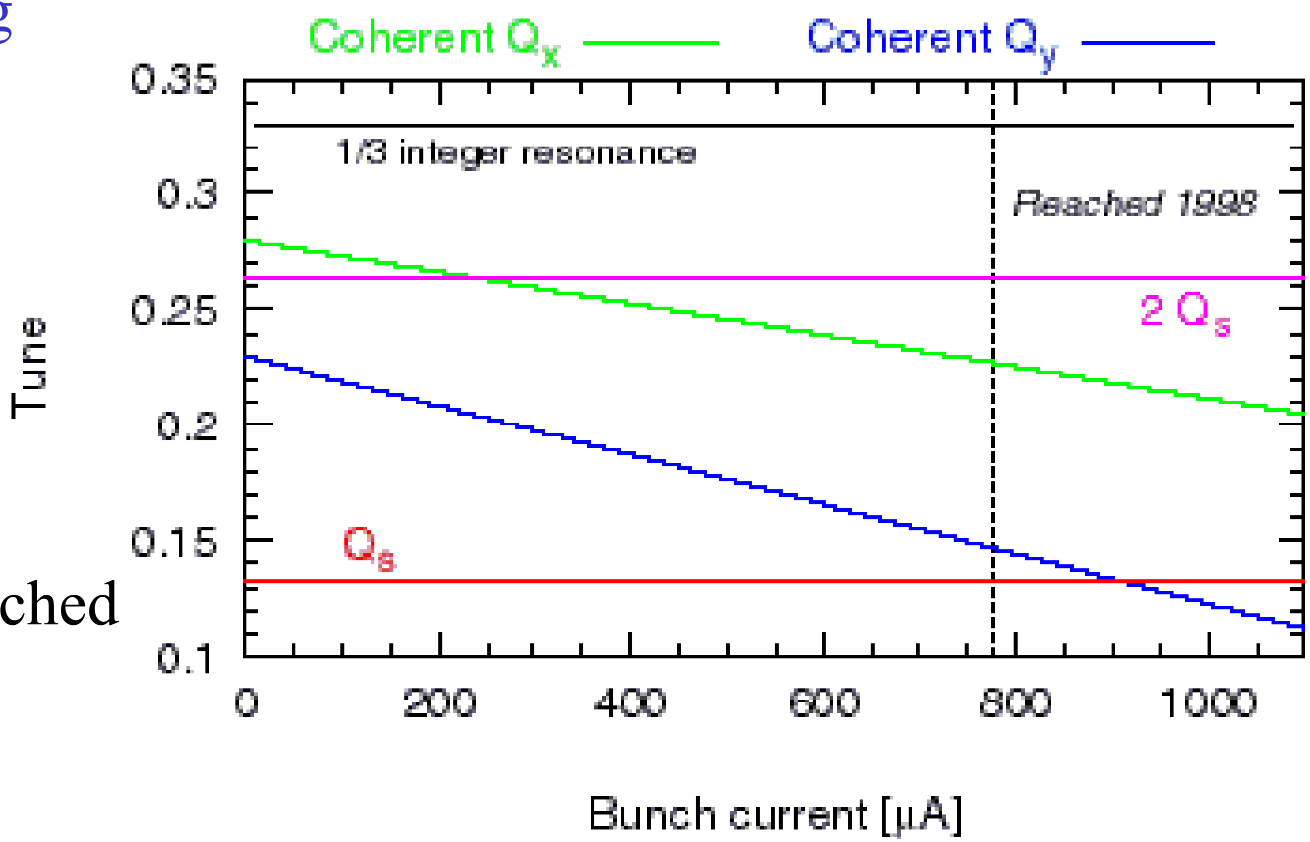
(MD-results by P. Collier, G. Roy, R. Assmann and K. Cornelis, M. Lamont, M. Meddahi)

1998 standard working point (SWP):

$Q_h = 0.28$
$Q_v = 0.23$
$Q_s = 0.132$

(chromaticities ~ 1-2)

780 µA per bunch reached with two beams…



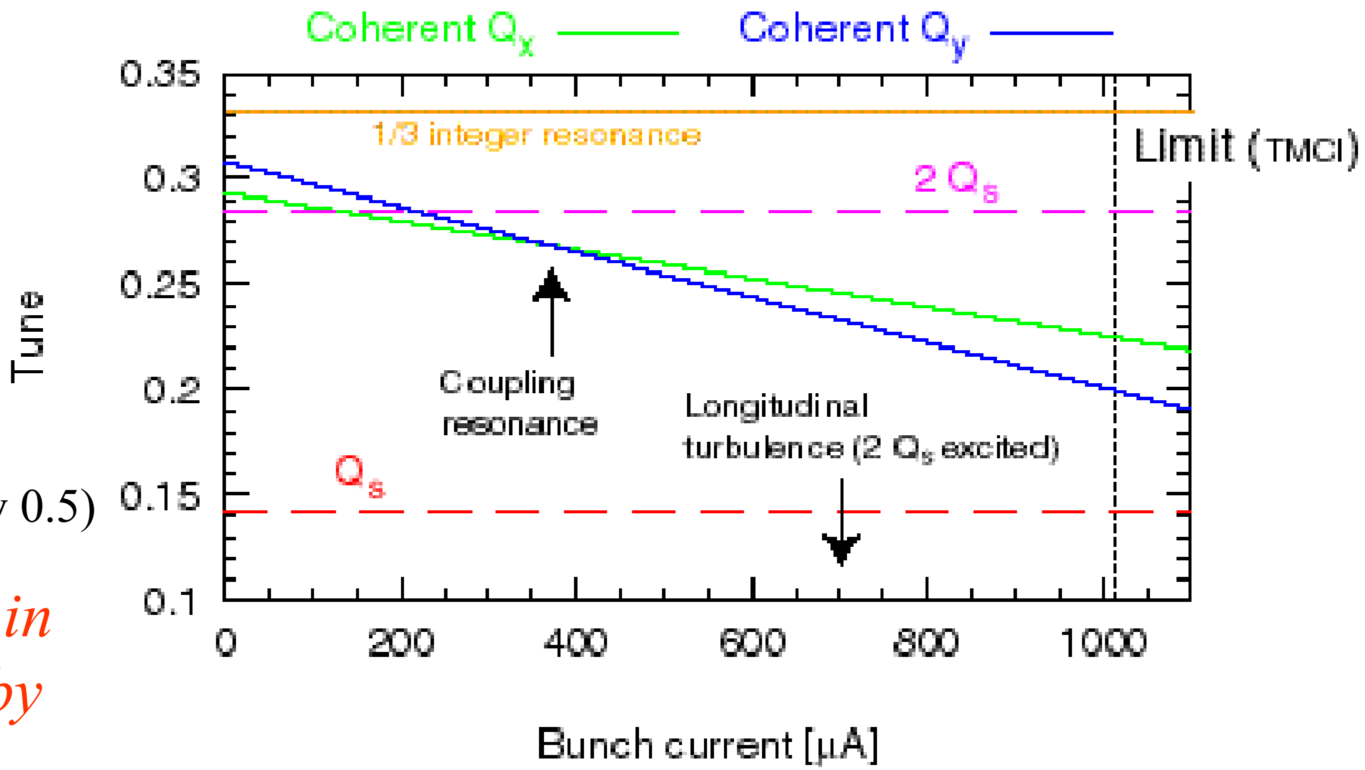
Extended up to ~ 940 µA in single electron bunch MD

New working point (Cornelis, Lamont, Meddahi):

High Q_v working point:

$Q_h = 0.29$
$Q_v = 0.30$
$Q_s = 0.142$

(lowered chromaticities by 0.5)

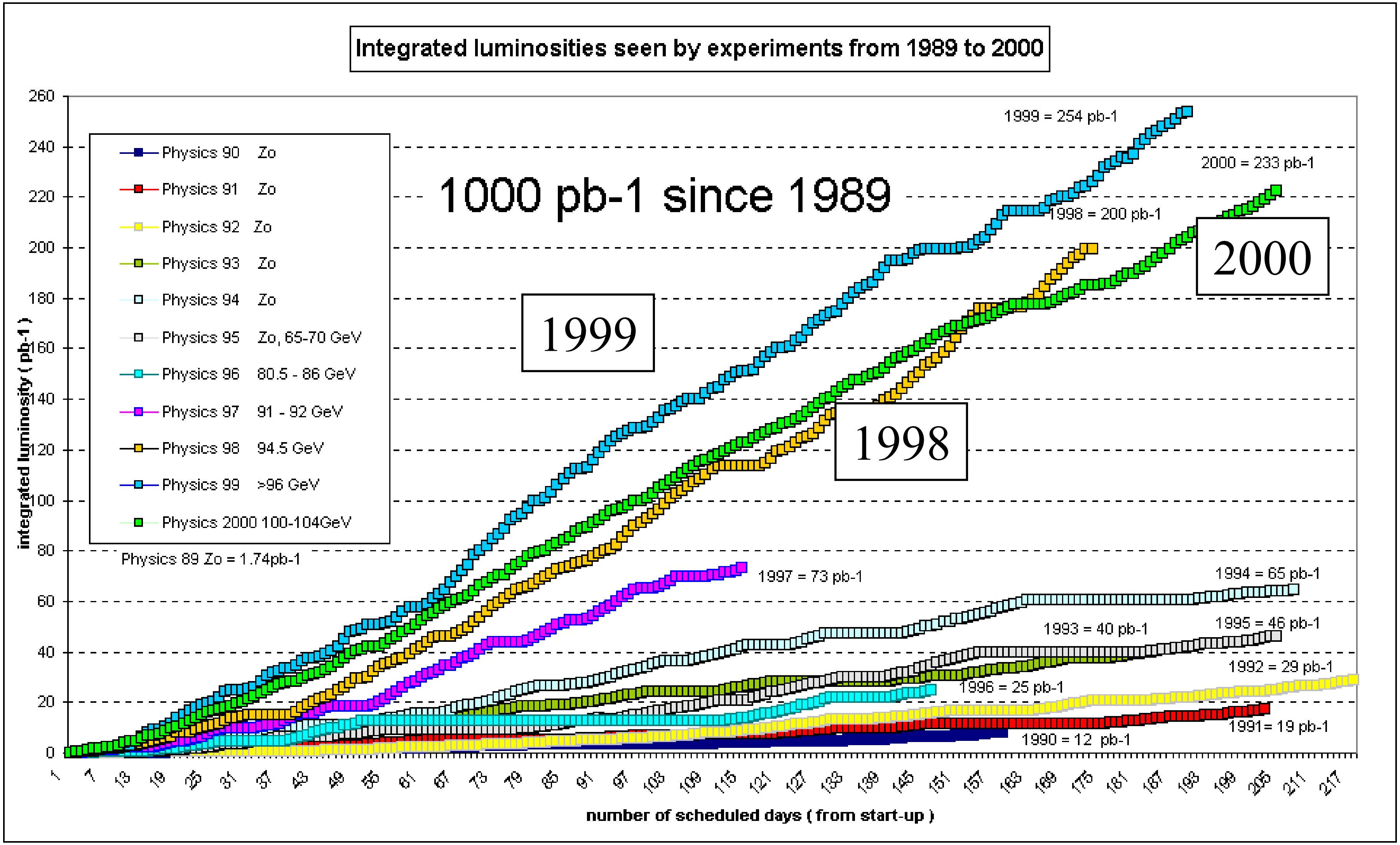


1030 µA per bunch in 4 bunches (limited by TMCI).

(single beam, separators off)

$Q_s > 0.144$ inconclusive. $Q_s = 0.16, 0.166, 0.174$ with 850 µA per bunch.
(low injection efficiency 20%, injection would require re-optimisation).

Overview of Luminosity and Energy Performance



Why was high energy so good for LEP?

With the **strong transverse damping** (**60 turns at 104 GeV**)…

… second beam-beam limit (tails, resonances) is overcome
… beam-beam limit is pushed upwards
… we then profit from smaller IP spot size and higher currents
… 1/3 resonance can be jumped
… beams can be ramped in collision with collimator closed

… but also…

… no radiative spin polarization above 61 GeV (energy calibration)

Unique experience with ultra-strong damping at LEP

Vert. beam-beam parameter:

$$\xi_y = \frac{r_e \cdot m_e \cdot \beta_y^* \cdot i_b}{2\pi\, e \cdot f_{rev} \cdot E \cdot \sigma_x \cdot \sigma_y} \propto \frac{L}{i_b}$$

Observed in LEP (1994-2000):

Energy [GeV]	ξ_y (max) per IP	Damping [turns]	
45.6	**0.045**	**721**	*Beam-beam limited*
65.0	0.050	249	
91.5	0.055	89	*Beam-beam limit not reached*
94.5	0.075	81	
98.0	**0.083**	**73**	
101	0.073	66	
102-104	0.055	63	

$\xi_y \propto 1/E^3$ naively

Strong damping

⇓

Beam-beam limit pushed upwards

$\sigma_x\sigma_y$ from 45.6 GeV to 98 GeV:

Reduced by factor ~ 1.6 (factor ~2 in σ_y)

Peak luminosity:

10^{32} cm^{-2} s^{-1}

Luminosity Performance at High Energy

Beam behavior at high energy:

Larger emittances / energy spread ($\varepsilon \sim E^2$, $\sigma_E/E \sim E$)

- Less luminosity
- Higher backgrounds

Solenoid coupling is weaker ($\theta \sim 1/E$ with B=const)

- Residual coupling contributes less to vertical emittance

Strong transverse damping ($\tau \sim 1/E^3$, 60 turns at 104 GeV)

- Second beam-beam limit (tails, resonances) is overcome
- Higher beam-beam tune shifts with higher beam-beam limit
- 1/3 resonance can be jumped
- Beams can be ramped in collision

Horizontal beam size:

$$\sigma_x = \sqrt{\beta_x \varepsilon_x} \propto \sqrt{\beta_x / J_x} \cdot D_x^{rms} \cdot E$$

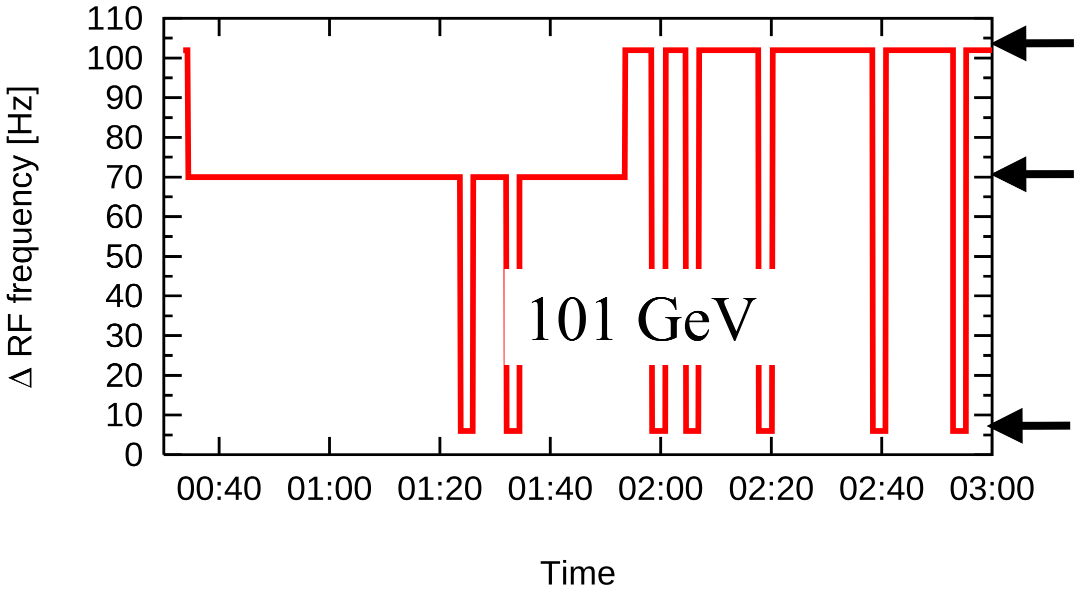
Compensate increase with energy (smaller luminosity, larger background):

1) **High Q_x optics** with smaller D_x^{rms} (D. Brandt et al, PAC99)

2) **Smaller β_x^*** (2.0 m - 1.5 m - 1.25 m)

3) **Increase** damping partition number **J_x** via RF frequency

Automatic control
$J_x = function\ (U_{RF})$



$J_x = 1.6$
(smaller

$J_x = 1.4$

Safety setting
$J_x = 1.04$
(larger σ

For highest energy reach: ***Reduce J_x.***

What Is the Energy Dependence of the Beam-beam Limit?

Scaling empirically fitted by Keil, Talman, Peggs, …

Several points in a given machine, similar configuration for LEP.

Independent cross-check of previous results, however:

- Beam-beam limit reached at 45.6 GeV
- Beam-beam limit not reached

Can we infer the beam-beam limit at high energy?

Look at functional dependence of beam-beam parameter on bunch current…

Vertical Beam-beam Blow-up

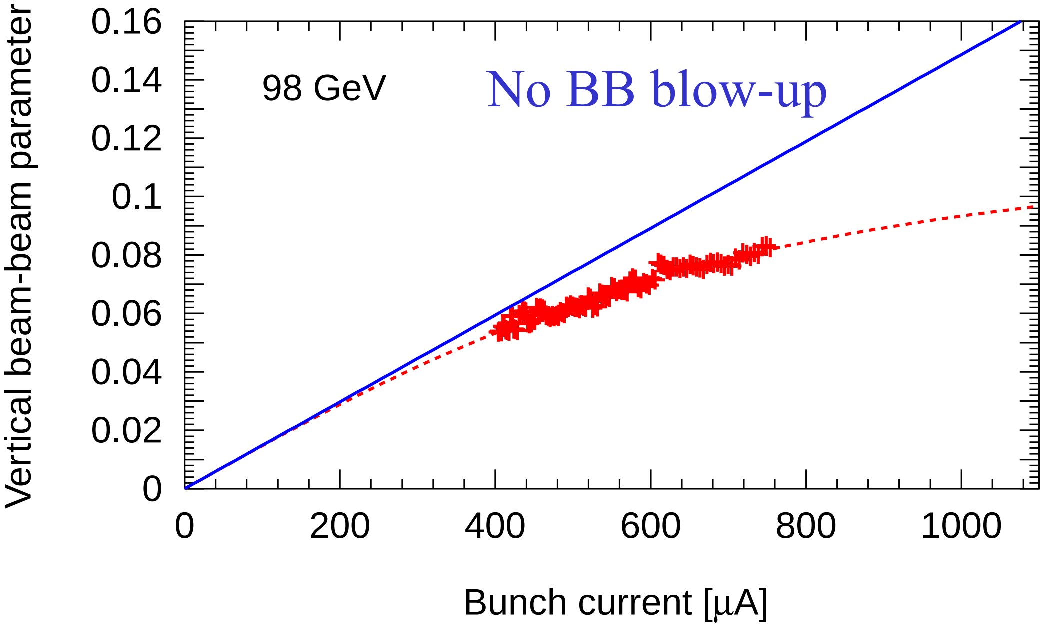
Simple model used to fit unperturbed emittance and beam-beam limit:

$$\xi_y = \sqrt{\frac{1}{A + (B \cdot i_b)^2}} \cdot i_b$$

Two fit parameters A and B:

$$A = \left(\frac{2\pi\, e\, f\, \gamma}{r_e}\right)^2 \cdot \frac{\beta_x^*}{\beta_y^*} \cdot \varepsilon_x^0 \cdot \varepsilon_y^0$$

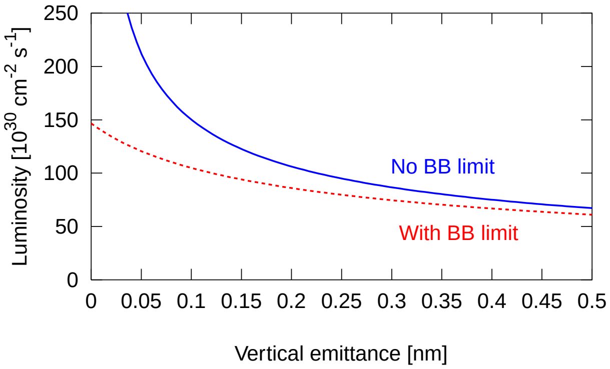
$$B = \frac{1}{\xi_y(i_b \to \infty)}$$



ξ_y (asymp) = 0.115

ε_y (no BB) = 0.1 nm

Limited gain in luminosity with ε_y:



Model of Beam-beam Parameter Versus Bunch Current:

Dependence of vertical beam-beam tune param. on bunch current I (in the regime of strong synchrotron radiation, K. Cornelis):

$$\xi_y = \sqrt{\frac{1}{A + (B \cdot i)^2}} \cdot i$$

Two fit parameters A and B:

$$A = \left(\frac{2\pi\, e\, f\, \gamma}{r_e} \right)^2 \cdot \frac{\beta_x^*}{\beta_y^*} \cdot \varepsilon_x^0 \cdot \varepsilon_y^0$$

$$B = \frac{1}{\xi_y (i \to \infty)}$$

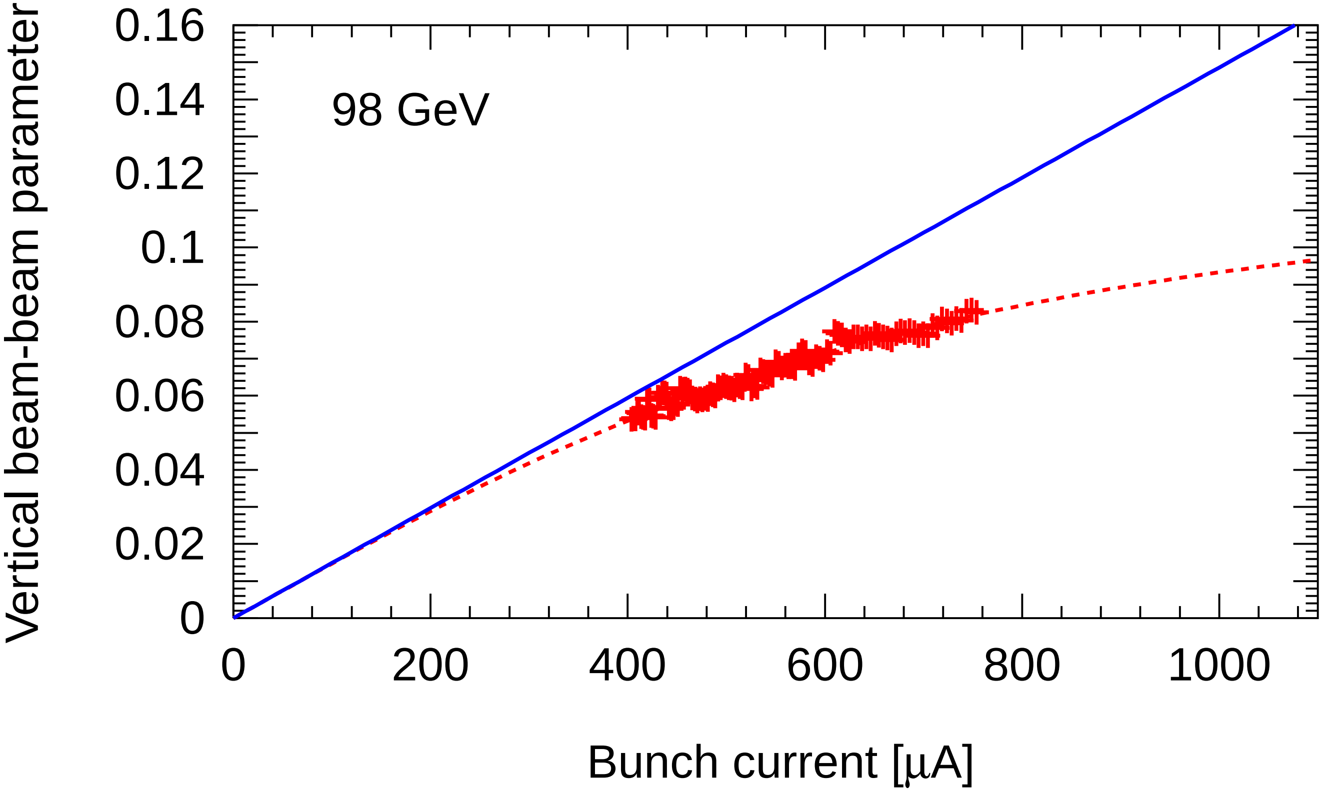
Knowing all other parameters, A is just given by the unperturbed vertical emittance. Without a beam-beam limit:

$$\xi_y = \sqrt{\frac{1}{A}} \cdot i$$

B gives the asymptotic beam-beam limit of the vertical beam-beam parameter:

- Beta beat due to beam-beam not included
- Tune dependent resonances are not included
- Beam-beam tune shift might see other limits

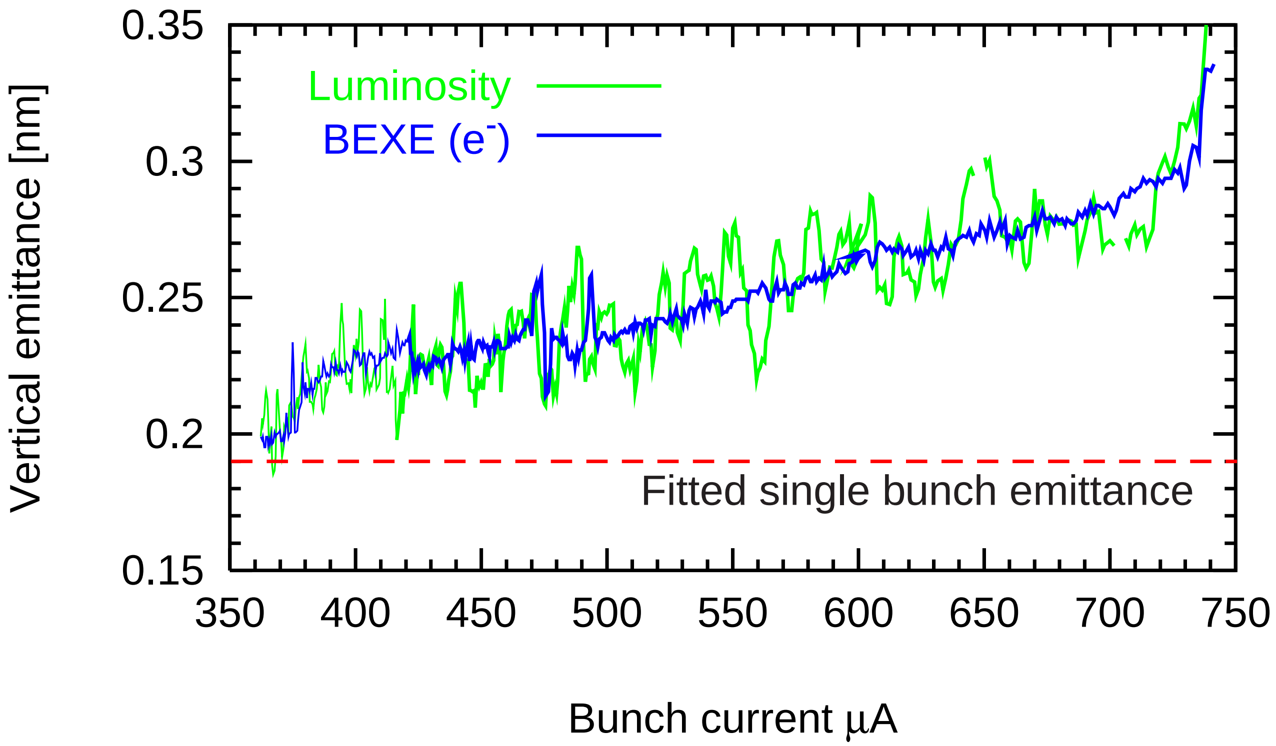
Example from 98 GeV:



Unperturbed vertical emittance $\varepsilon_y = 108$ pm

Beam-beam limit $\xi_y = 0.115$

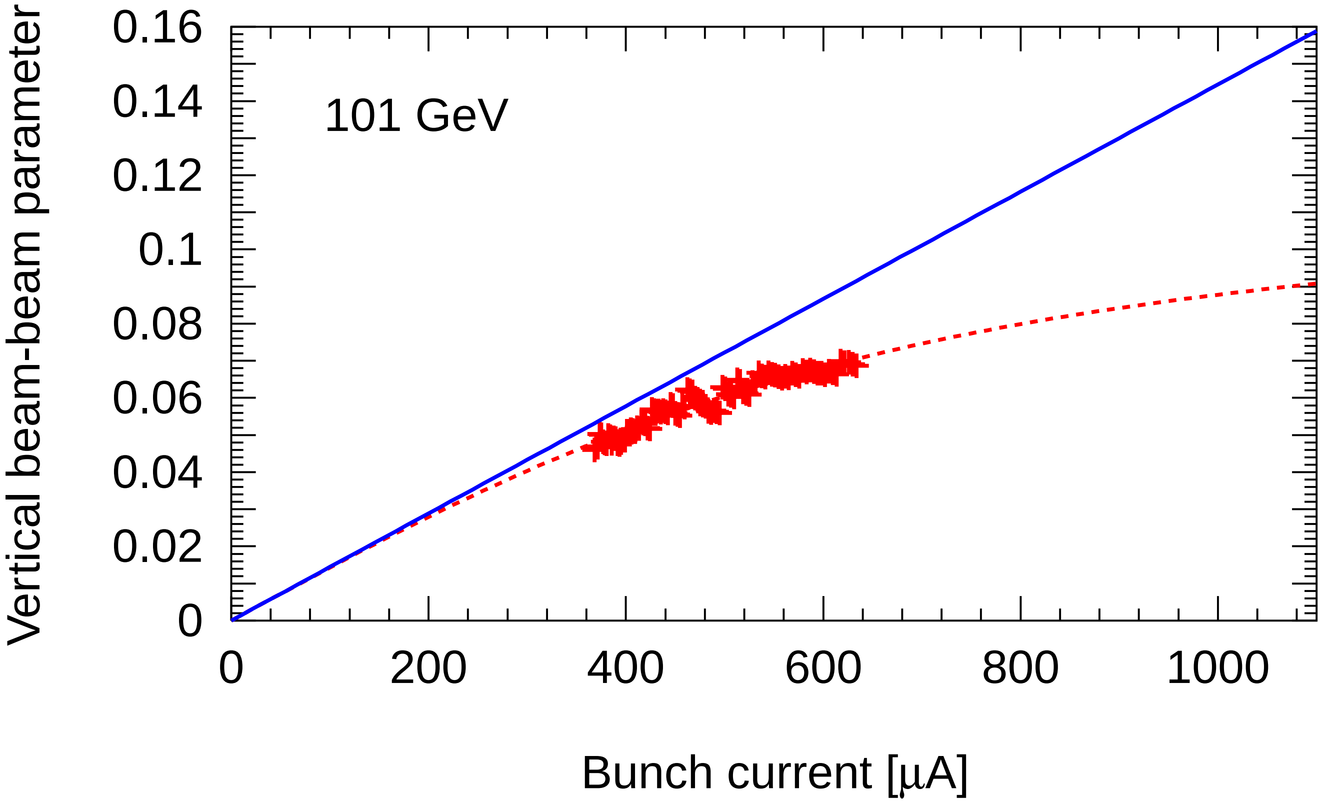
Emittance blow-up for fill in 1998:



Clear beam-beam blowup of 50-100%!

(consistently observed from x-ray synchrotron radiation and luminosity)

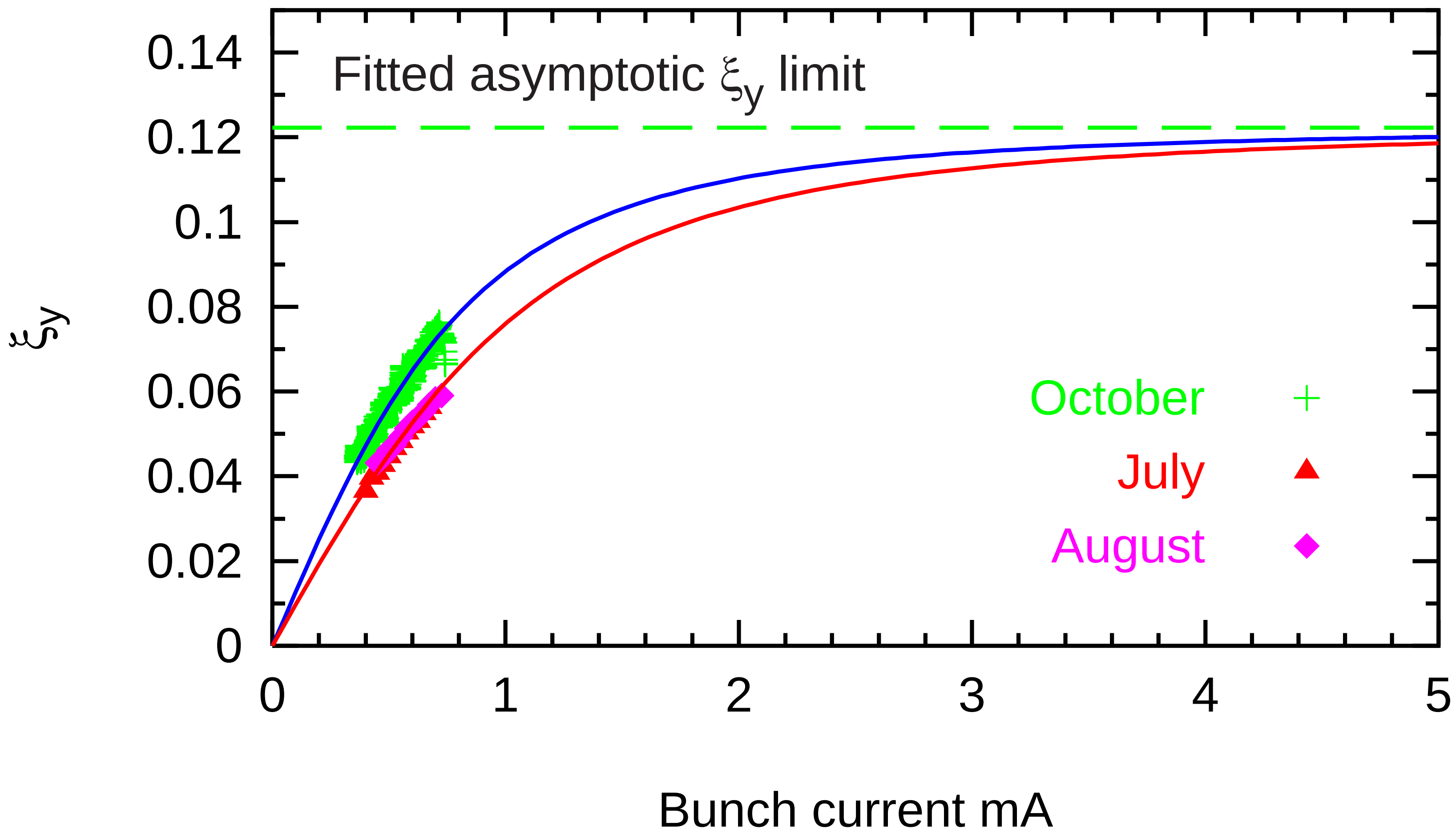
Example From 101 GeV



Unperturbed vertical emittance $\varepsilon_y = 82$ pm

Beam-beam limit $\xi_y = 0.111$

Similar Asymptotic Limits Suggested



Predictions

Energy	Damping decrement δ	BB-limit
45.6 GeV	3.5e-4	0.045
101 GeV	3.8e-3	0.115

Scaling:

$$\xi_y^\infty \propto \delta^{0.4}$$

Exponent 0.40 instead of 0.27!

VLLC33 ($\delta = 0.01$):

$$\xi_y^\infty \approx 0.17$$

Total tune shift still smaller than in LEP (4 IP's)

(0.056 for VLLC34 with $\delta = 6e\text{-}4$)

Use model to predict luminosity:

From model get the luminosity incl BB:

$$L = \left(\frac{n_b \, \gamma}{2 \, e \, r_e \, \beta_y^*} \right) \cdot \frac{i_b^2}{\sqrt{A + \left(B \cdot i_b \right)^2}}$$

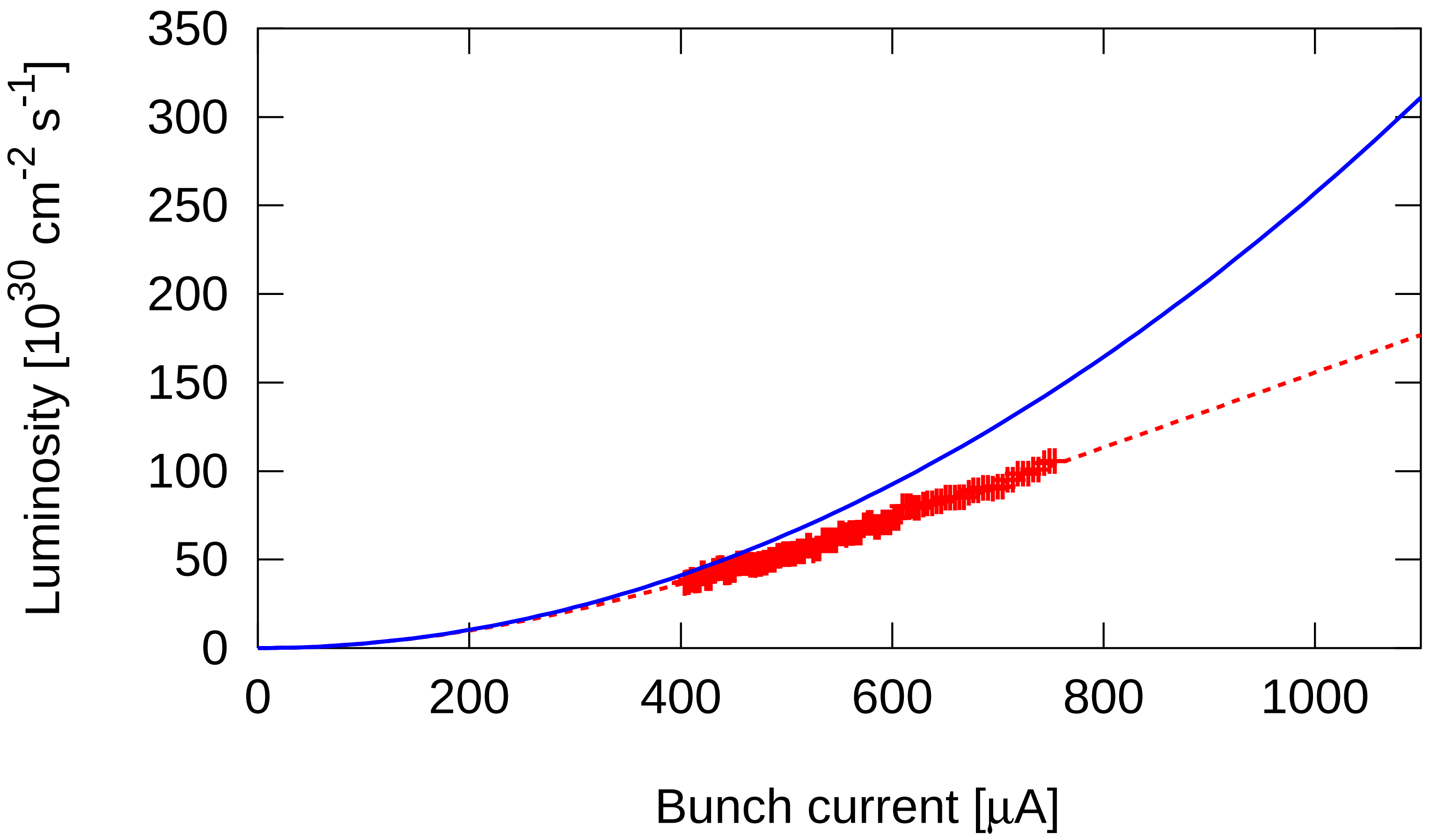
In the BB limit:

$$L = \left(\frac{n_b \, \gamma}{2 \, e \, r_e \, \beta_y^*} \right) \cdot \xi_y^\infty \cdot i_b$$

For a given BB limit, the increase of luminosity with current is proportional to the energy γ (el.-magn. field of beam scales as 1/γ)

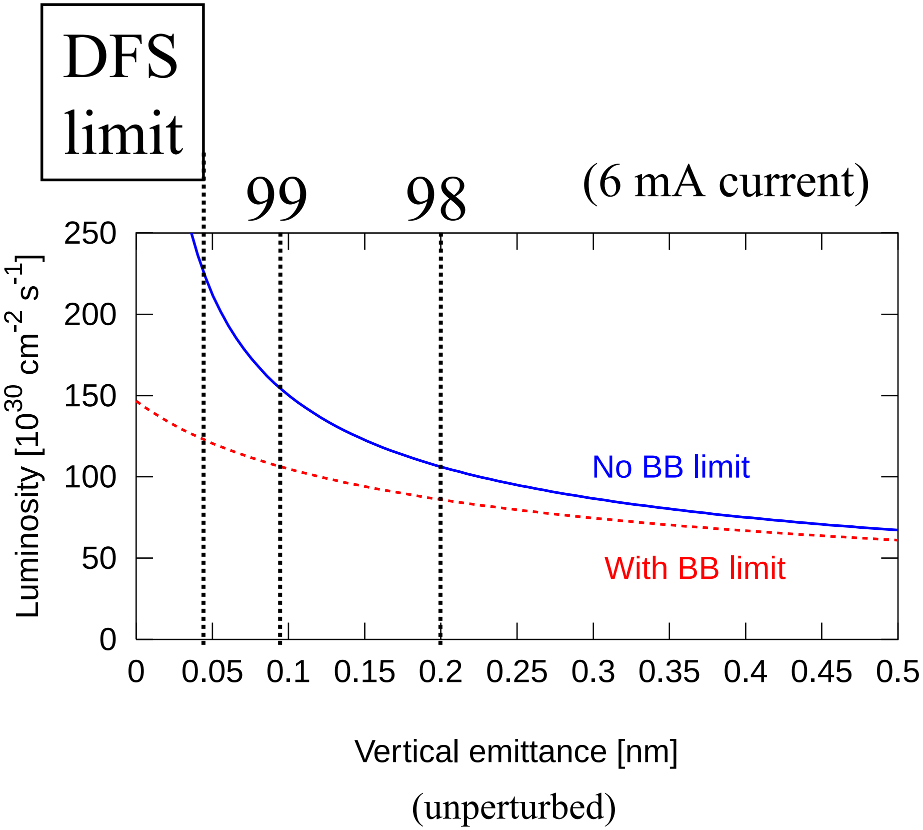
Compare BB fit to luminosity data:

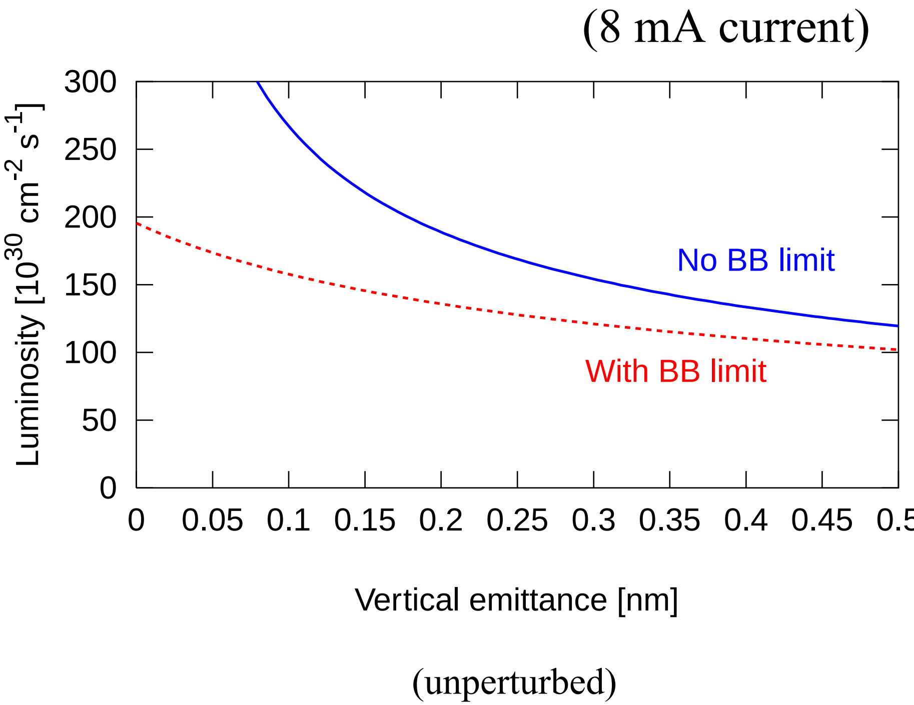
98 GeV



- Very well described
- Simple “squared scaling” not adequate

What happens for emittance (unperturbed) improvement:





LEP luminosity limit due to beam-beam: **2.0 10^{32} cm^{-2} s^{-1}**

(expected at maximum possible current)

Optimisation

- Horizontal beam size given by synchrotron radiation and optics
- Working point – beam-beam
- Vertical emittance
  - Coupling, global & local
  - Residual dispersion - golden orbits and dispersion free steering
- Vertical beam size at interaction point:
  - β^*_X and β^*_y
  - Dispersion at IP

Thereafter:
Reproducibility

Vertical emittance:

1999/2000: $\beta_y^* = 5$ cm

$$\varepsilon_y \propto \left(C \cdot D_y^{rms} \cdot E \right)^2 + K \cdot \varepsilon_x + \ldots$$

$\propto E$ (solenoids

- **Initial tuning** of coupling, chromaticity, orbit, dispersion, …
- **Vertical orbit** to get smallest RMS dispersion
- **Coupling** to get smallest global coupling

} *Peak luminosity*

- **Local** dispersion, coupling, β-function at IP } *Luminosity balance*

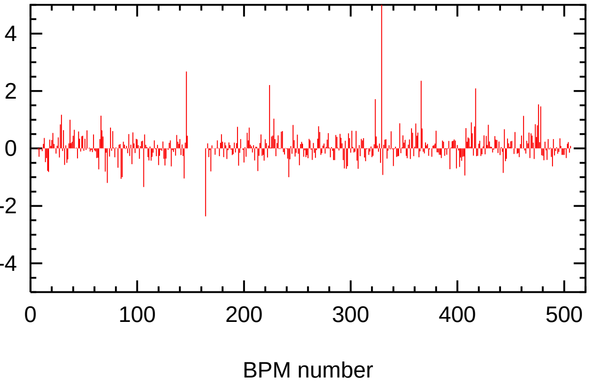
“**Golden orbit**” strategy for optimization:
Trial and error! Complement with:

Dispersion-free steering (DFS): 1) Measure orbit and dispersion
2) Calculate correctors to minimize both

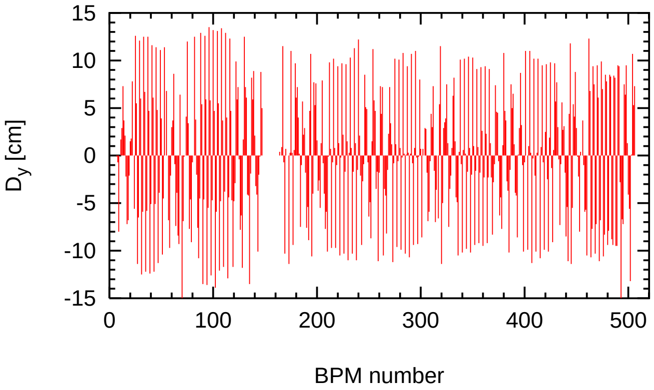
Note: Global correction generally also improves local dispersion/coupling!

Measured single beam performance of DFS in LEP:

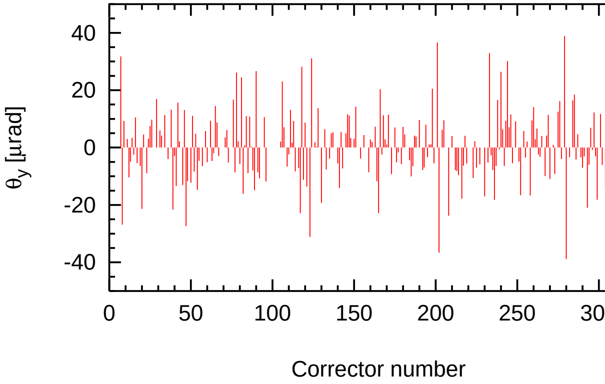
ORBIT



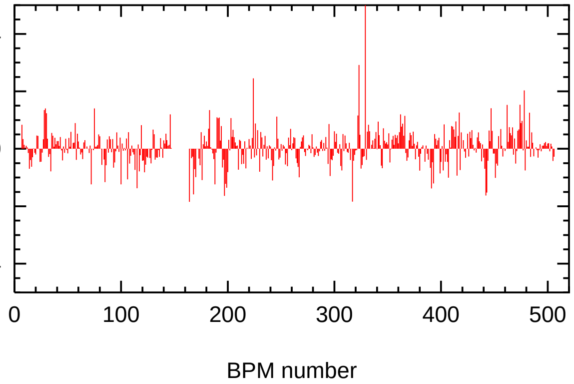
DISPERSION

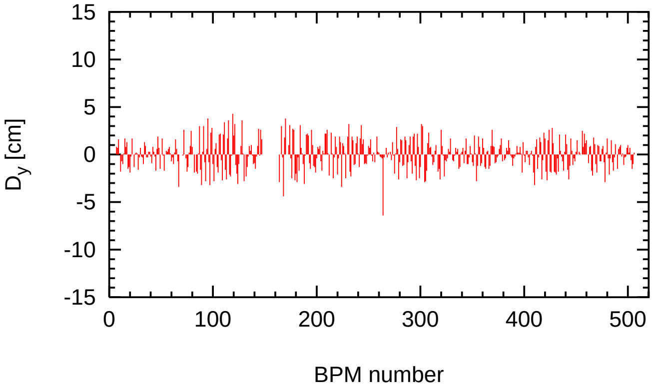


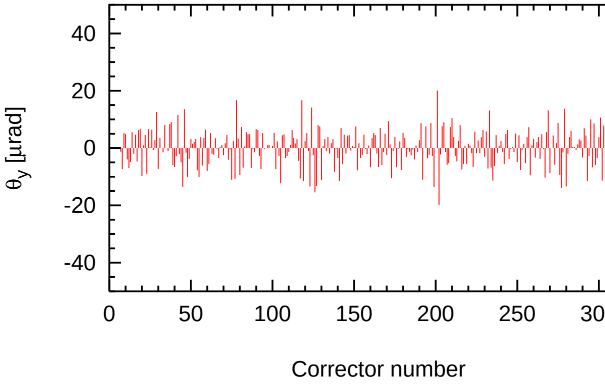
CORR. KICKS



DFS: Simultaneously optimize orbit, disp., cor





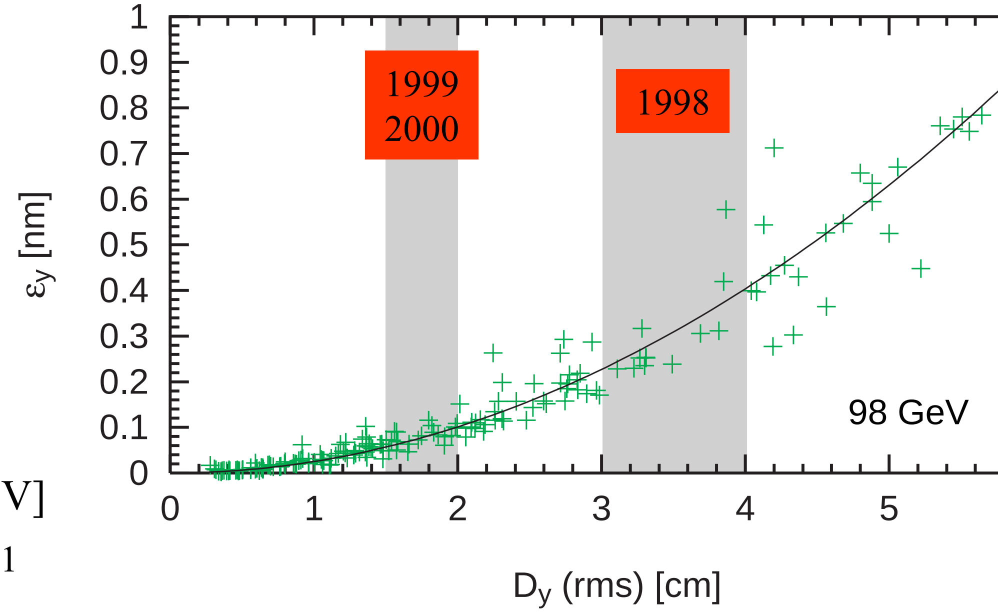


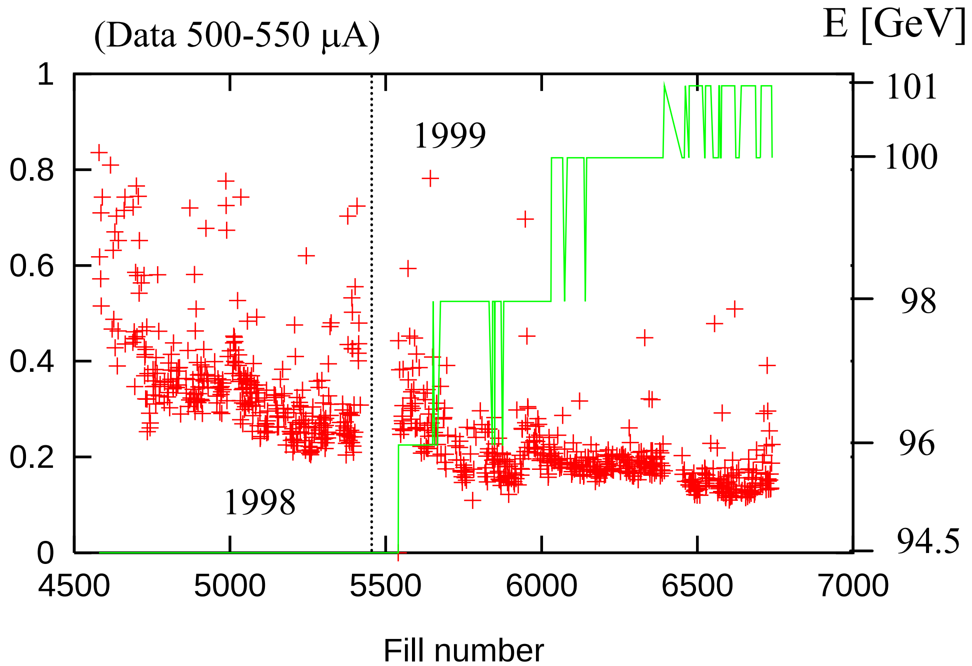
(same algorithm as implemented for the SLC linac)

Vertical optimization

Reduction of RMS dispersion

(DFS + change of separation optics)


(simulated)


(Data 500-550 µA)

Reduction of vertical emittance

Emittance ratio: 0.5%

(ii) Choice of RF frequency:

Damping partition number **J_x** used to reduce horizontal beam size **σ_x**:

$$\sigma_x = \sqrt{\beta_x \varepsilon_x} \propto \sqrt{\beta_x / J_x} \cdot D_x^{rms} \cdot E$$

Increase with
beam energy.

Good for luminosity and backgrounds in experiments…

J_x controlled with RF frequency f_{RF}.

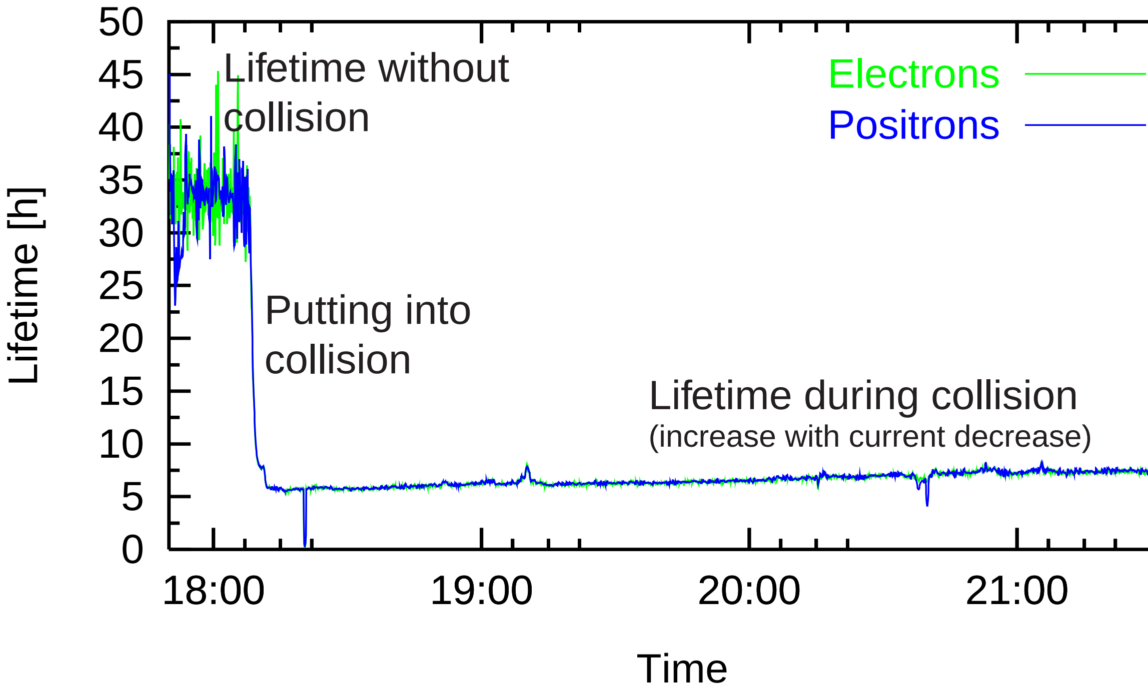
$\Delta f_{RF} = 0$ Hz $J_x = 1.00$

$\Delta f_{RF} = 100$ Hz $J_x = 1.55$ **ΔE_{max} = - 0.7 GeV**

Pay with **reduction of maximum beam energy**.

In 2000: Keep RF frequency shift small (~ -50 to +20 Hz).

LEP lifetime without surprises:



(E.g. H. Burckhardt, R.Kleiss.
Beam Lifetimes in LEP. EPAC94)

Different regimes:

1) Without collision:

Lifetime τ_0 due to particles lost in Compton scattering on thermal photons, beam-gas scattering.

We assume 32 hours.

2) In collision:

Lifetime due to particles lost in radiative Bhabha scatt. or beam-beam bremsstrahlung.

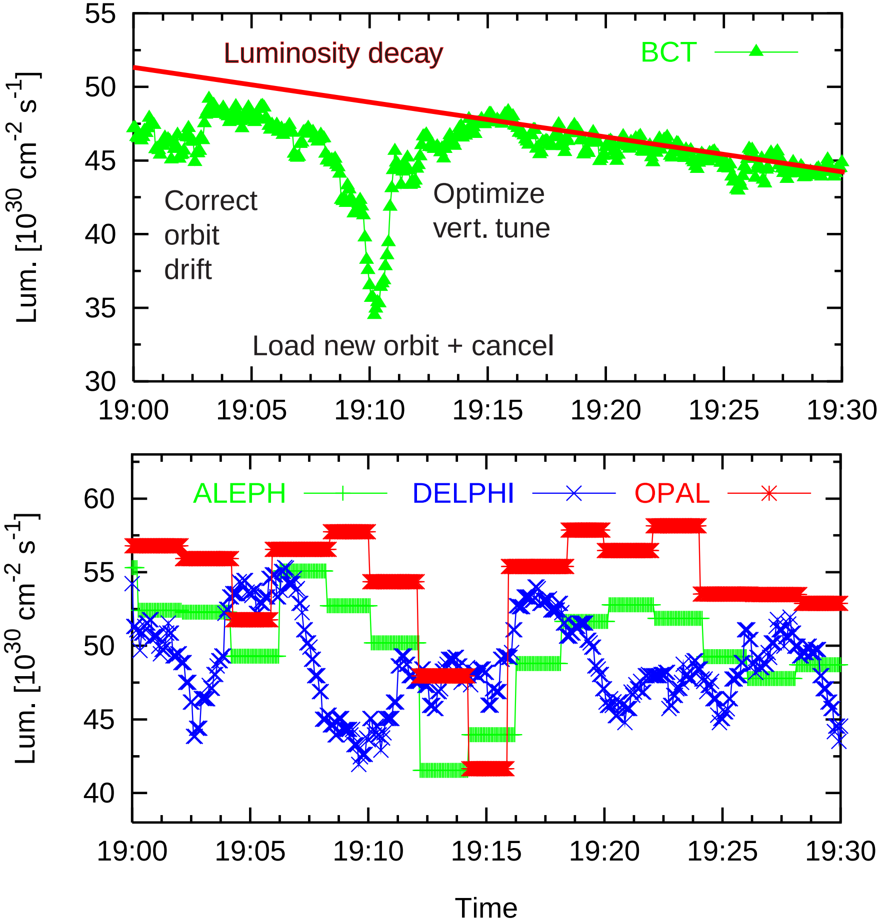
Lifetime at High Energy Used As Fastest Luminosity Signal:

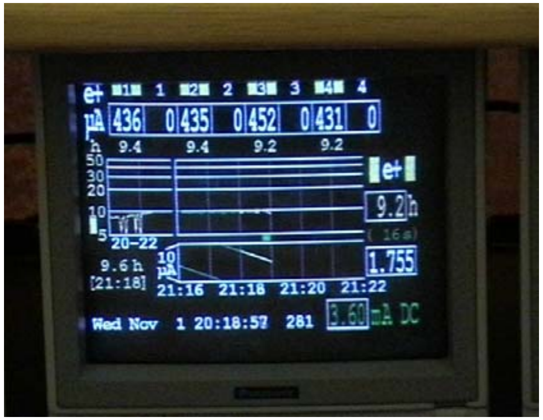
Formulas in convenient units
for LEP2 parameters
(94.5 GeV):

$$L[10^{30}cm^{-2}s^{-1}] = 671.2 \cdot i_{bunch}\,[mA] \cdot \left(\frac{1}{\tau\,[h]} - \frac{1}{\tau_0\,[h]} \right)$$

BCT

$$\xi_y \approx \frac{1}{3 \cdot \tau\,[h]}$$





No effect from tails, resonances, …

Operations

- Standard techniques:
  - Measure & correct beta*
  - Beta beating, coupling…
  - Essential, of course, good diagnostics, established measurement techniques: Q-loop, Fast displays of lifetimes, beam sizes, Orbit feedback, Bunch current equalisation
- First years:
  - Lack of basic high-level control facilities
  - Poor data management
  - Interfaces to crucial beam instrumentation missing in control room
  - Poor and unreliable, incoherent data acquisition systems

Optimization of Turn-around

Year	Recover [min]	Filling [min]	Ramp / Squeeze [min]	Adjust [min]	Total [min]	# fills
1998	23.9	45.0	22.3	19.1	**110.3**	436
1999	22.2	30.9	23.9	15.5	**92.5**	653
2000	12.9	23.5	12.7	15.9	**65.0**	344
Diffe-rence	**-9.3**	**-7.4**	**-11.2**	**+0.4**	**-27.5**	

Faster degauss, optimize procedure

Less current

Twice the ramp speed

BFS

time

Reproducibility

Average turn-around time improved by **~ 28 minutes**!

Typical 2000 turn-around: ~ 45 minutes

Hardware

- Specialised groups: power converters, RF, beam instrumentation, kickers, separators, vacuum, dedicated expertise (electronics, controls, hardware)
- Over designed? Possibly but all hardware managed to withstand the extremely hard push to high energy
- Good availability with experience
- Access system – always a problem

- Hardware performance

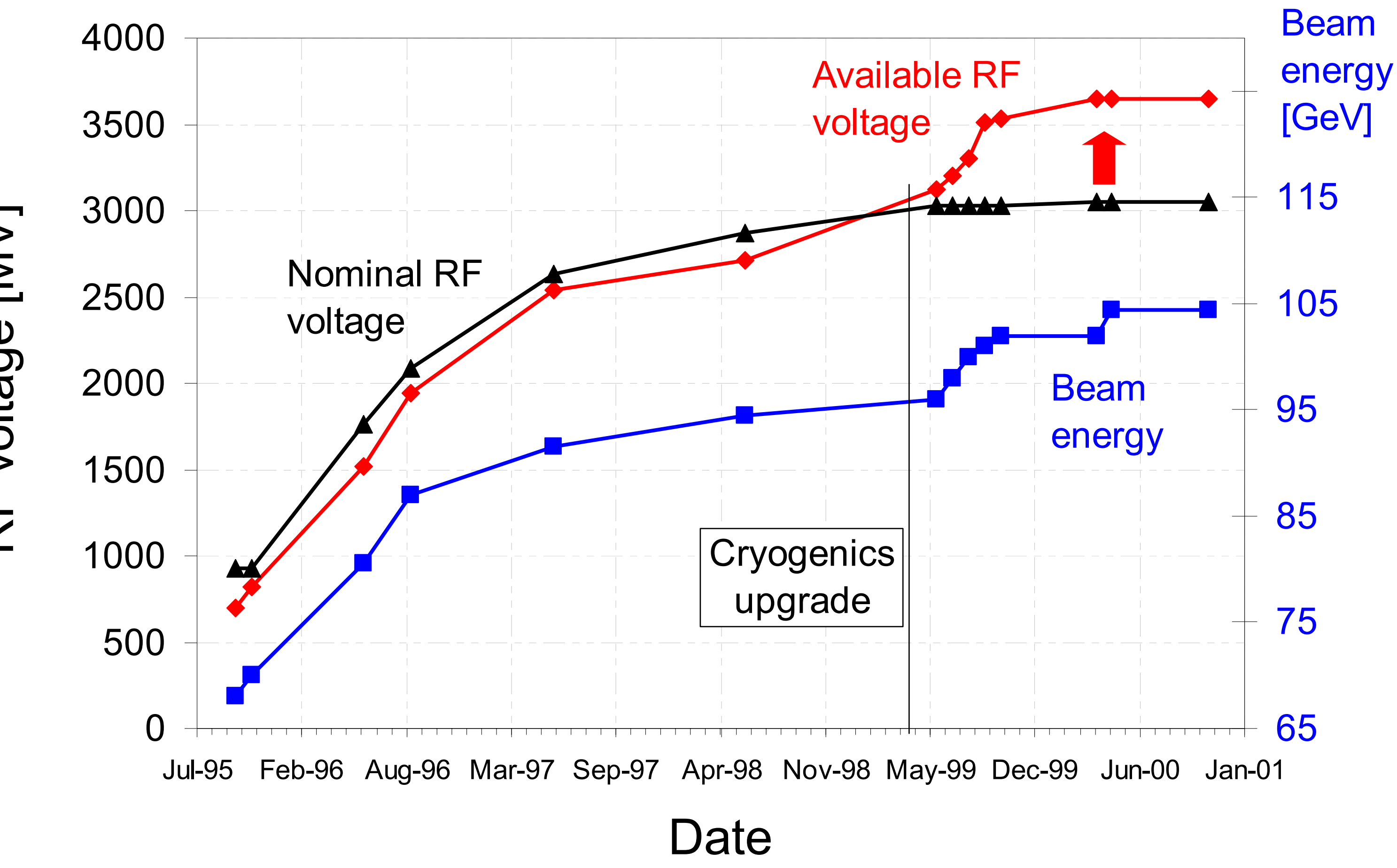
Vacuum system
Magnets
Power supplies
Instrumentation etc

… excellent without major worries

- Effects from LHC civil engineering

No limiting effect on LEP operation (some realignment)

RF voltage (design and actual):



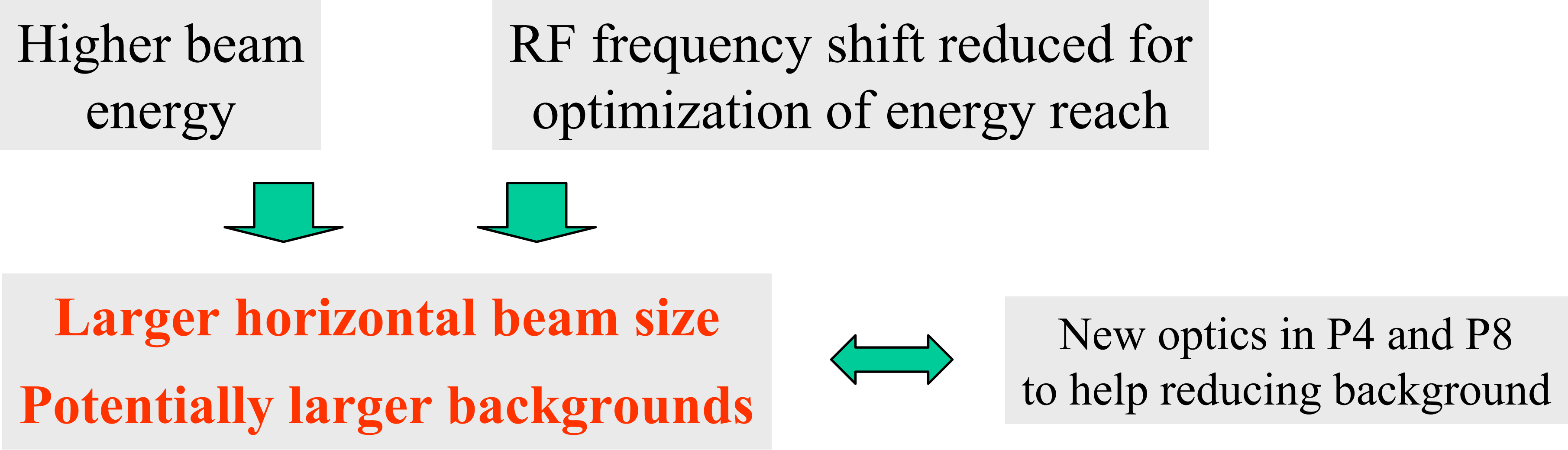
Improvements:

- **Progressive installation of additional RF cavities**
- **Increase accelerating gradient**

Beam energy follows available RF voltage…

6) Other issues:

- Background in the experiments:



Higher beam energy

RF frequency shift reduced for optimization of energy reach

Larger horizontal beam size

Potentially larger backgrounds

New optics in P4 and P8 to help reducing background

Steady state conditions: **Very good**. Required continuous follow-up o collimators, orbit, tunes, … $Q_h > 0.33$ required

Occasional spikes: RF trips with negative RF frequency shift
Related current loss

5b) Energy increase of LEP from 1999 to 2000:

LEP 2000 preparation: **105 GeV** (optics, power supplies, etc checked)

Gain from 1999 physics to 2000:

Maximum energy: 101.0 GeV ⇒ 104.4 GeV

Improvements:

8 additional Cu RF units	+ 0.14 GeV	RF system
Higher RF gradient	+ 0.96 GeV	
Less RF margin	+ 1.50 GeV	Operational procedures
Reduced RF frequency	+ 0.70 GeV	
Bending length	+ 0.20 GeV	
Total	**+ 3.50 GeV**	

Reduced luminosity production, potentially higher backgrounds

2000: conclusions

*LEP operated in "**discovery mode**":*

Beam energy increased by 3.4 GeV

- Increase of RF voltage (3650 MV), excellent stability
- Change of operational strategy (ramp during physics fill, …)
- Reduced shift of RF frequency
- Increase of average bending radius

Push beam energy on cost of luminosity

- Reduce beam current (5 mA instead of 6.2 mA)
- Run with small J_x, large horizontal beam size
- Mini-ramp to quantum lifetime limit
  (zero margin in RF voltage)
- Lose all fills with RF trips

2000 was the second productive LEP year

Luminosity production rate lower than 1999 but still excellent (as in 199

Luminosity improvement in 1999 with better tuning: + 20 %
Price to pay for energy increase in 2000: - 20 %

Transverse spin-polarization in LEP

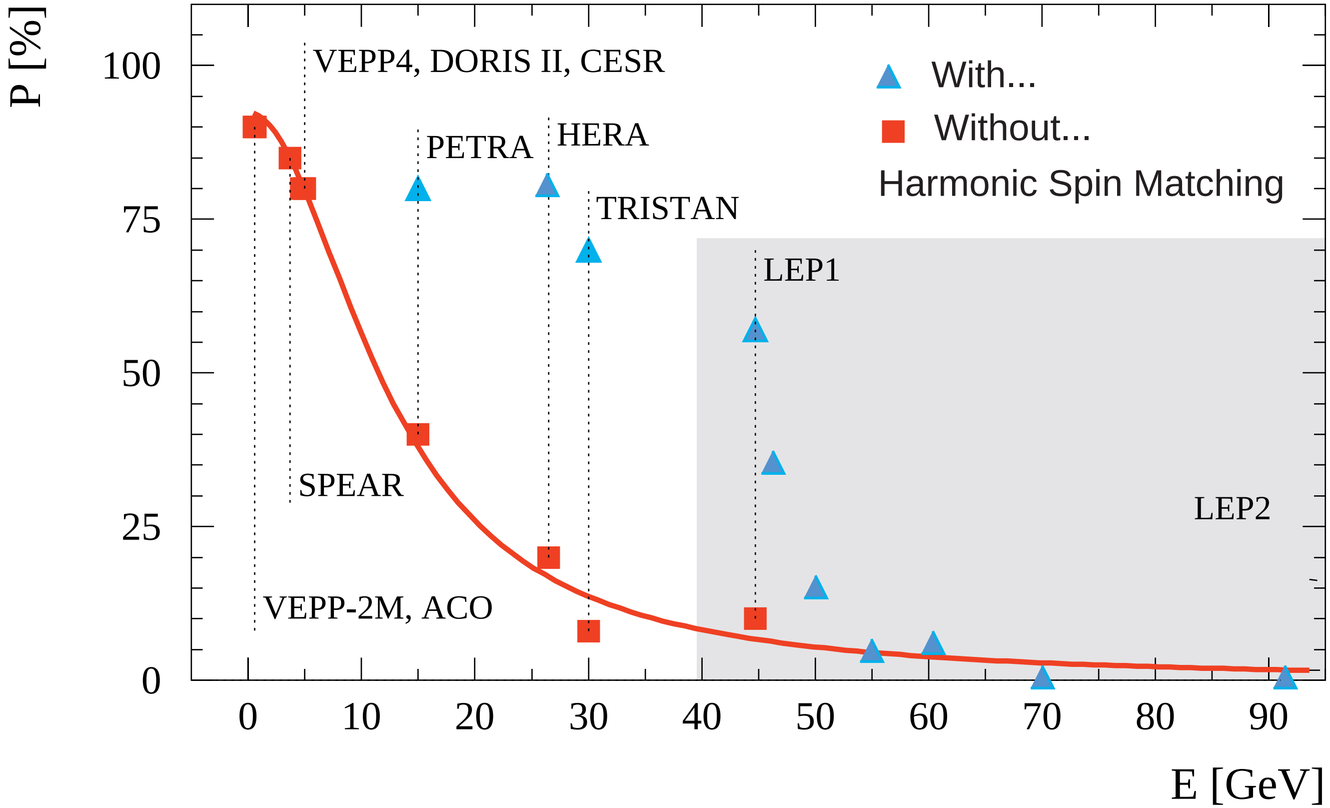
Unique at LEP:

Large range of energies	22 GeV	to	104.5 GeV
Polarization studied from	41 GeV	to	98.5 GeV

Explore spin dynamics in unique regime

Bench marking of theoretical predictions

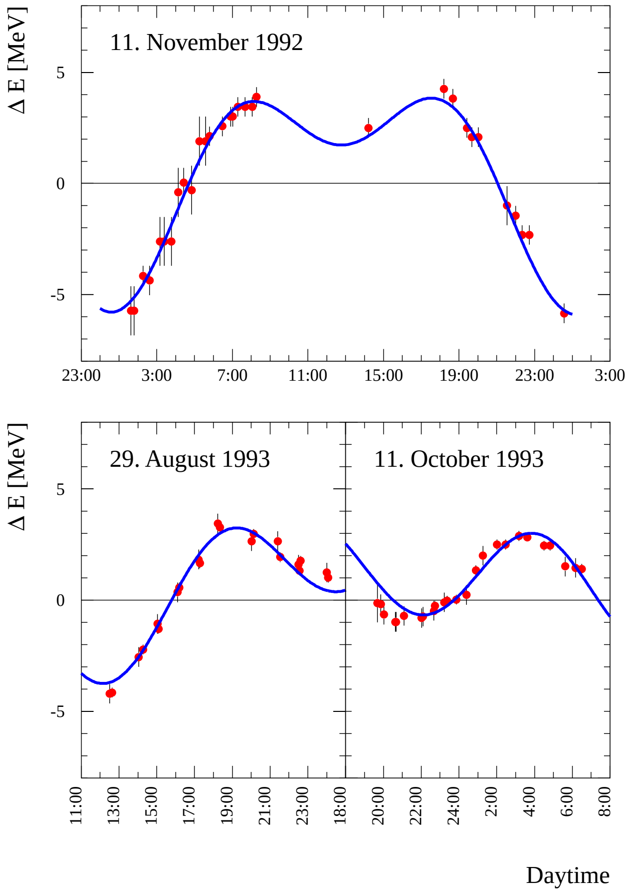
Sharp drop-off!

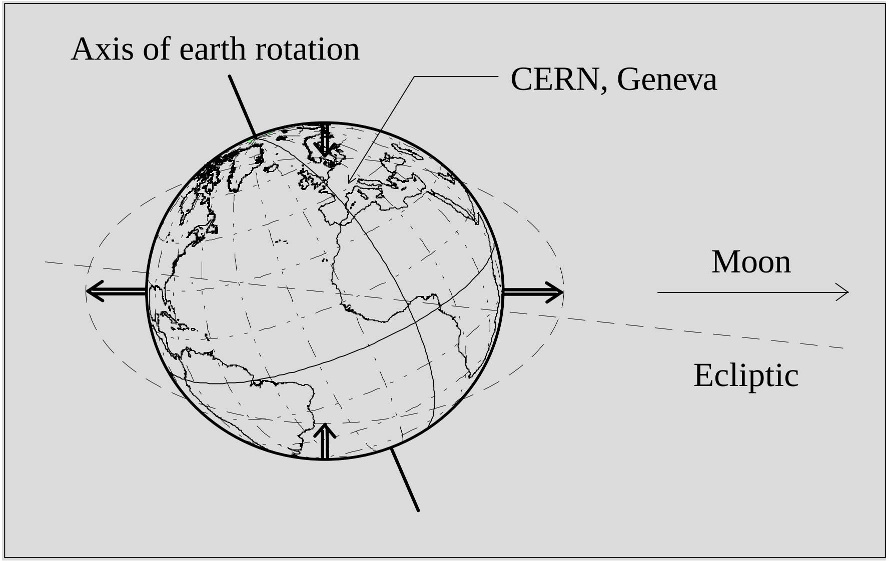


Use of Polarization at LEP:

Precise determination of the LEP beam energy **(10^{-5} relative accuracy, ~ 1 MeV)**

Precise measurement of the Z mass and width





Small changes of energy accurately measured

(energy change from 1mm circumference change)

heory by Derbenev, Kontratenko, Skrinsky (With LEP Parameters):

Spin
une

$$\nu = \frac{E}{440.6486\,\mathrm{MeV}}$$

Polarization buildup rate

$$\lambda = \frac{1}{\tau_p} = 3.9\cdot 10^{-19}\cdot \nu^5$$

Synchrotron tune

ν_γ

Spin tune spread

$$\sigma_\nu = \nu \cdot \frac{\sigma_E}{E} \approx 6.67\times 10^{-6}\cdot \nu^2$$

Resonance strength

$$|w_k|^2 \approx 1.94\times 10^{-10}\cdot \nu^2$$

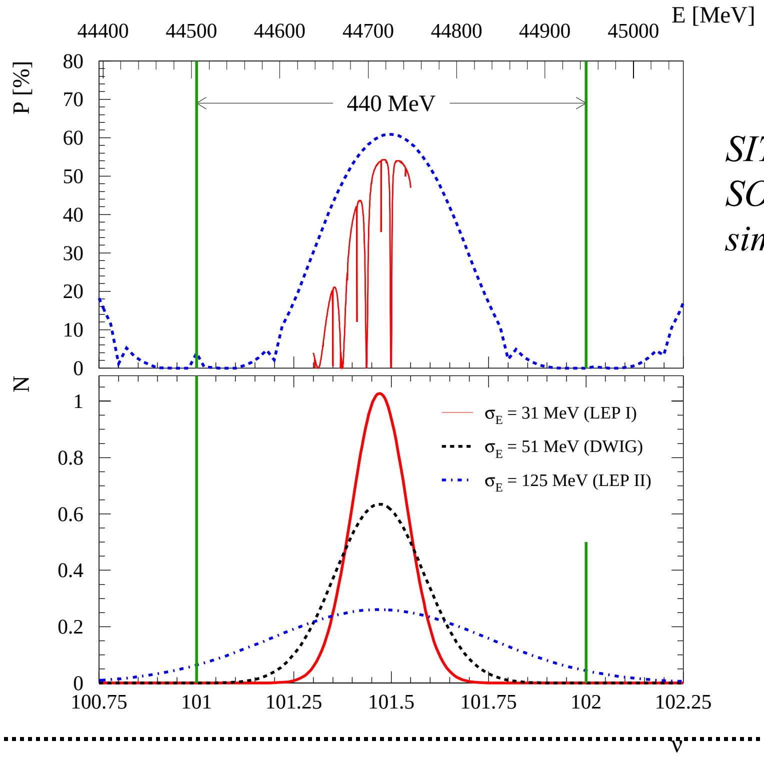
Condition for correlated spin resonance passings:

$$\alpha = \frac{\nu^2 \lambda}{\nu_\gamma^3} << 1$$

true

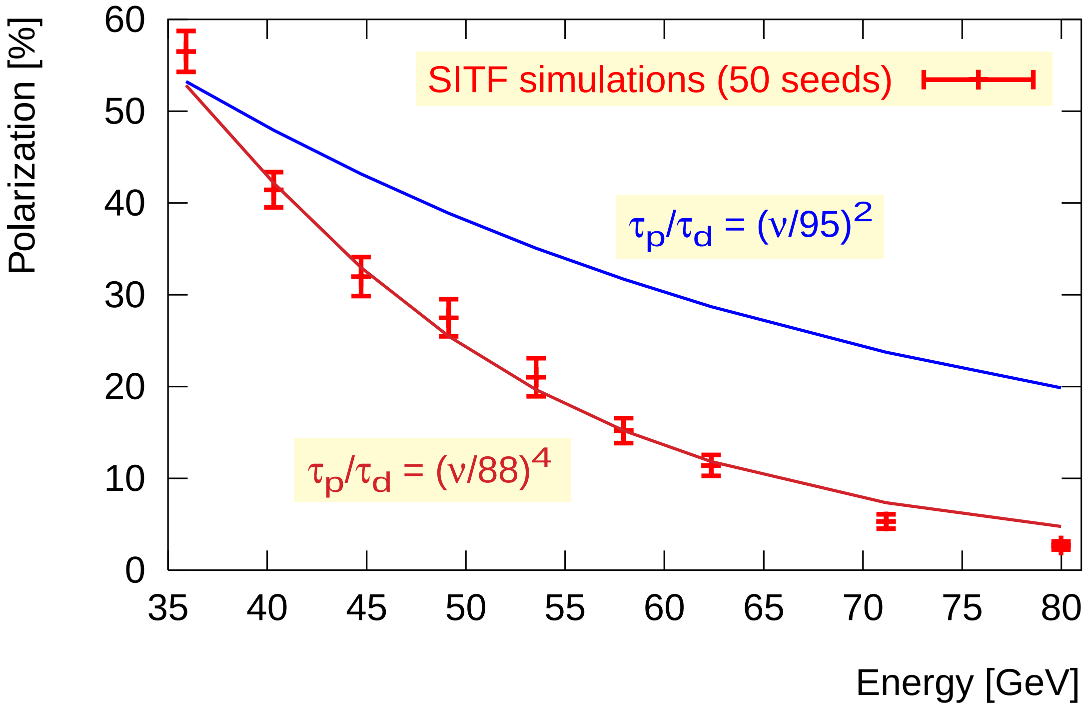
$$= \frac{11}{18}\,\nu^2 \sum_{k,m} \frac{|w_k|^2 \,\left\langle T_m^2(\Delta/\nu_\gamma)\right\rangle}{\left[\left(k-\bar{\nu}-m\nu_\gamma\right)^2-\nu_\gamma^2\right]^2}$$

$$^2_m\rangle = I_m\left(\frac{\sigma_\nu^2}{2\nu_\gamma^2}\right)\cdot\exp\left(-\frac{\sigma_\nu^2}{2\nu_\gamma^2}\right)$$



SITF
SODOM
simulations

Energy Dependence of Polarization:



Simulation confirms $1/E^4$ dependence of polarization!

First order theory: Includes spin resonances with k_x, k_y, k_s=1

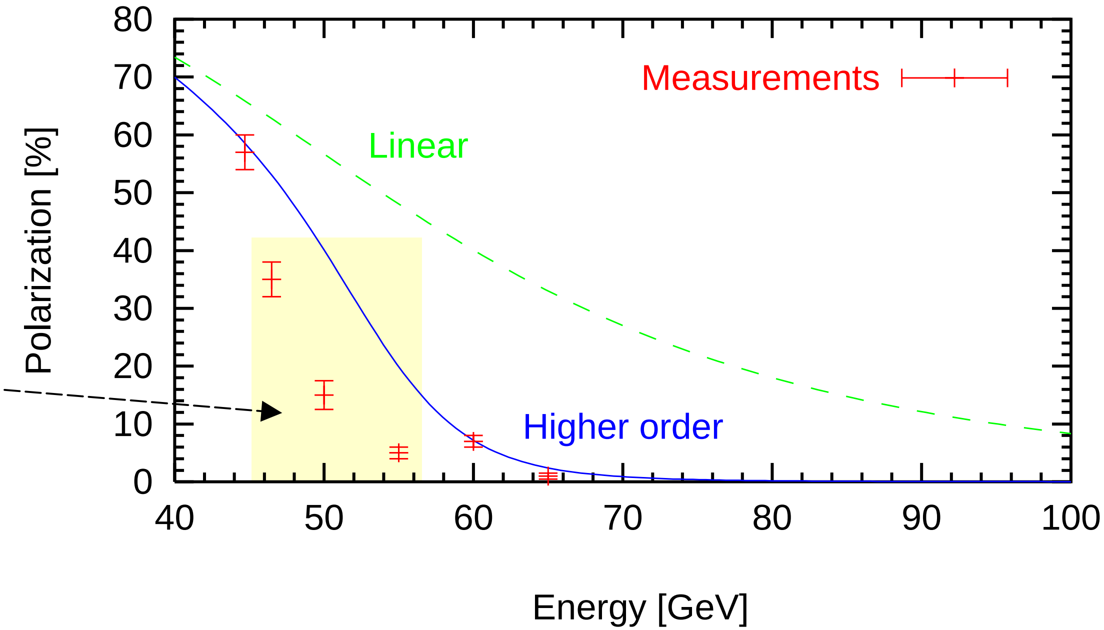
$$\nu_{depol} = k \pm k_x \cdot \nu_x \pm k_y \cdot \nu_y \pm k_s \cdot \nu_s \quad , \quad k_x, k_y, k_s \in N$$

Machine tunes

Synchrotron sidebands determine polarization degree in LEP

Polarization Measurements in LEP:

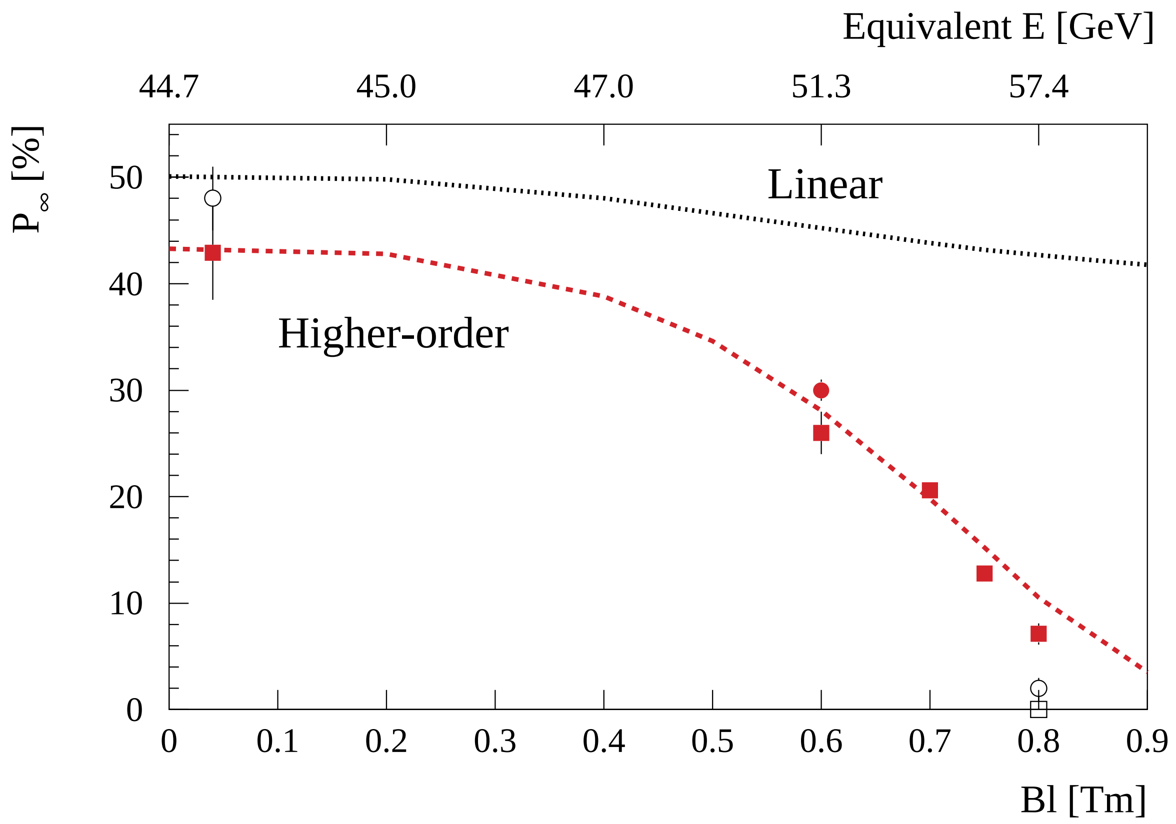
- With 90/60, 60/60 and 102/45 optics.
- Goal for energy calibration: > 5%
- Polarization not always fully optimized.



1998: Polarization and energy calibration has been extended to **60.6 GeV** (P = 7% measured)!

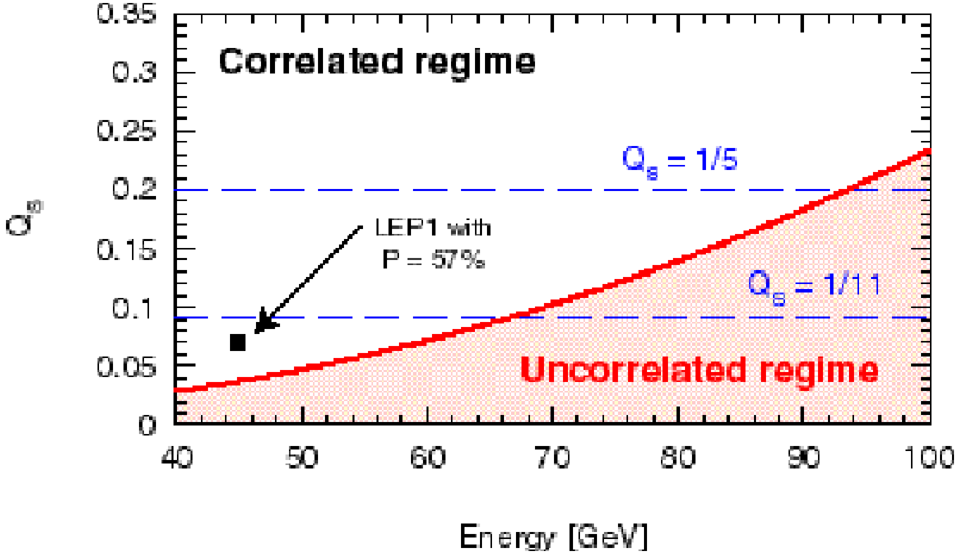
Drop in polarization degree consistent with higher-order theory…

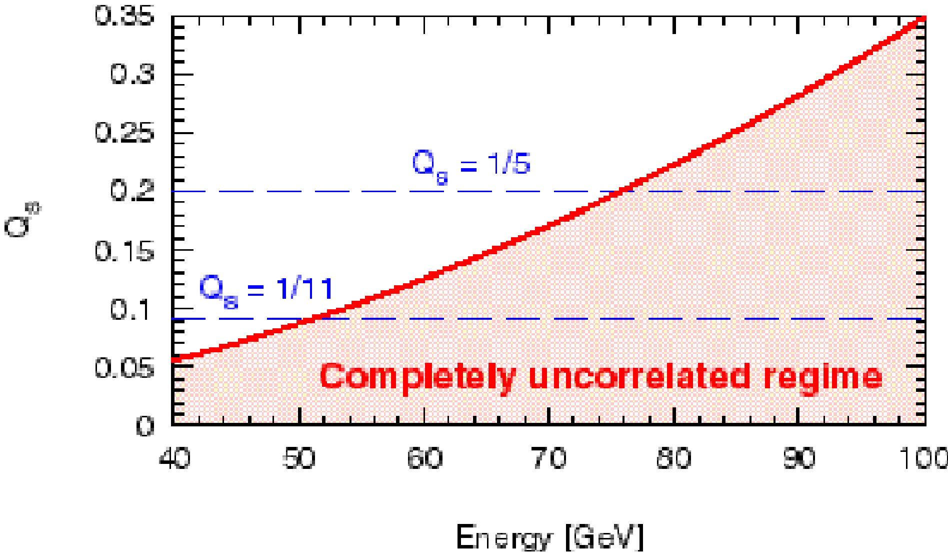
Higher-Order Theory also Confirmed with Wigglers:



Wigglers increase spin tune spread and thus allow “simulating” energy increase...

Evaluate Correlation Criteria for LEP:





- LEP enters uncorrelated regime with high energy and small Q_s!
- If spin resonance passing is uncorrelated it is completely uncorrelated for LEP!
- We can stay in the correlated regime by increasing the value of Q_s!

With:

$$\sigma_\nu = 6.76 \cdot 10^{-6} \cdot \left(\frac{E}{0.44065\,\mathrm{GeV}} \right)^2$$

Theory by Derbenev, Kontratenko, Skrinsky (with LEP parameters):

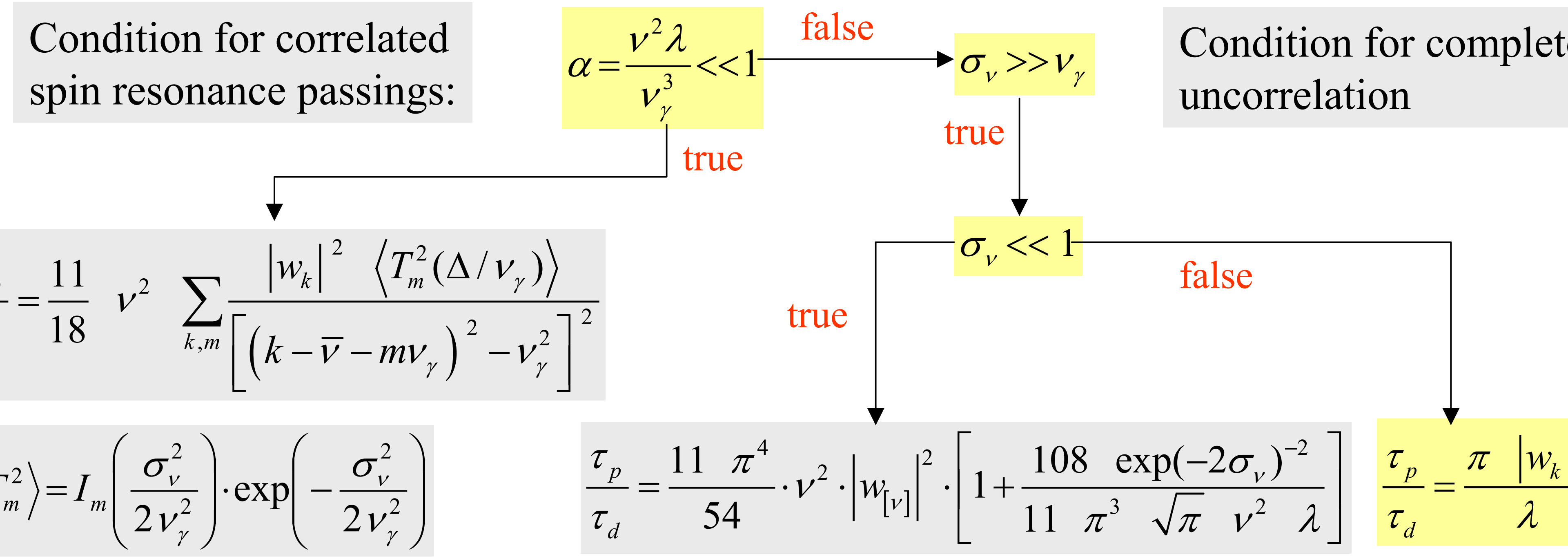
Spin tune $\nu = \frac{E}{440.6486\,\mathrm{MeV}}$

Polarization buildup rate $\lambda = \frac{1}{\tau_p} = 3.9 \cdot 10^{-19} \cdot \nu^5$

Synchrotron tune ν_γ

Spin tune spread $\sigma_\nu = \nu \cdot \frac{\sigma_E}{E} \approx 6.67 \times 10^{-6} \cdot \nu^2$

Resonance strength $|w_k|^2 \approx 1.94 \times 10^{-10} \cdot \nu^2$



Condition for correlated spin resonance passings:

$\alpha = \frac{\nu^2 \lambda}{\nu_\gamma^3} << 1$

false

$\sigma_\nu >> \nu_\gamma$

Condition for complet uncorrelation

true

true

$\sigma_\nu << 1$

false

true

$$= \frac{11}{18} \nu^2 \sum_{k,m} \frac{|w_k|^2 \left\langle T_m^2(\Delta/\nu_\gamma) \right\rangle}{\left[\left(k - \bar{\nu} - m\nu_\gamma\right)^2 - \nu_\gamma^2\right]^2}$$

$$\rangle = I_m\left(\frac{\sigma_\nu^2}{2\nu_\gamma^2}\right) \cdot \exp\left(-\frac{\sigma_\nu^2}{2\nu_\gamma^2}\right)$$

$$\frac{\tau_p}{\tau_d} = \frac{11}{54} \frac{\pi^4}{} \cdot \nu^2 \cdot |w_{[\nu]}|^2 \cdot \left[1 + \frac{108}{11} \frac{\exp(-2\sigma_\nu)^{-2}}{\pi^3 \sqrt{\pi}\, \nu^2 \lambda}\right]$$

$$\frac{\tau_p}{\tau_d} = \frac{\pi\, |w_k}{\lambda}$$

Search for Polarization at Highest LEP Energies:

Expected polarization: Very low, but possible increase at high energies?

New polarization optics (101.5/45 degrees) for measurements at low AND high energy

60.6 GeV		4 %	(7% with 60/60 optics)
70.0 GeV	<	**1%**	
92.3 GeV	<	**1%**	
98.5 GeV	<	**1%**	

No indication of measurable polarization at highest LEP energies!

(first measurements in regime of uncorrelated crossings of spin resonances)

Achievements at LEP:

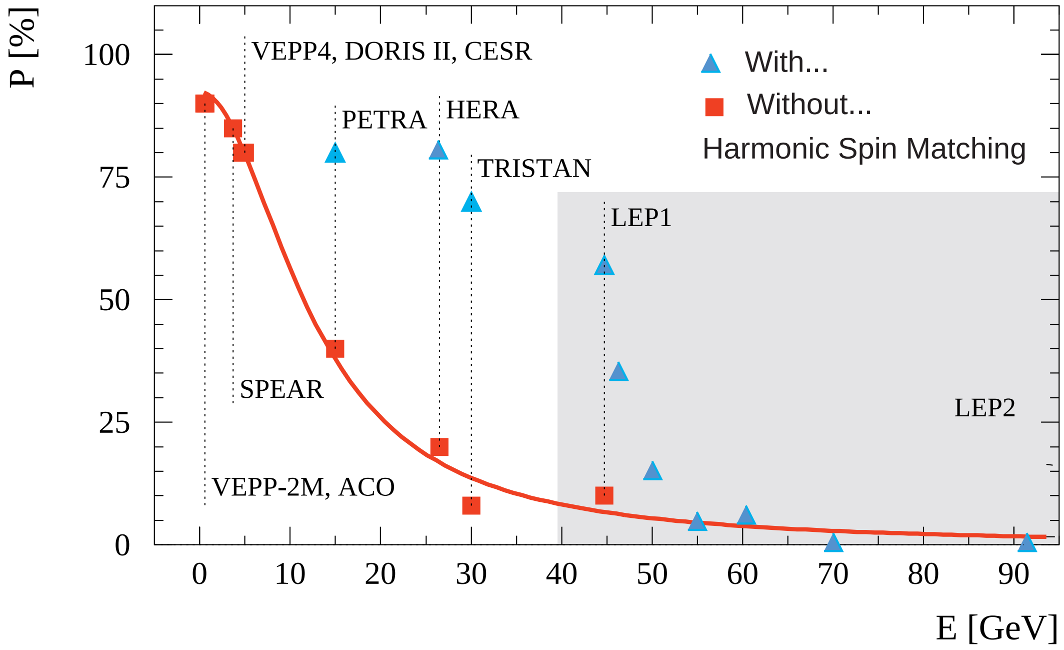
Transverse spin polarization in high energy regime measured.
(way above previously assessed regime)

Sharp drop after LEP1 in agreement with theory/simulations.

Transverse spin polarization crucial for precision measurements of the W and Z properties (energy calibration)

First measurement in regime of uncorrelated spin resonance crossing. No sign of transverse polarization.

New varieties of Harmonic Spin Matching gave up to 57% polarization.



We can trust the polarization theories in LEP regime!

Precise predictions for future projects…

heory by Derbenev, Kontratenko, Skrinsky (With VLLC33 Parameters

Spin tune

$$\nu = \frac{E}{440.6486\,\mathrm{MeV}}$$

Polarization buildup rate

$$\lambda = \frac{1}{\tau_p} = 8.7 \cdot 10^{-21} \cdot \nu^5$$

Synchrotron tune

$$\nu_\gamma$$

Spin tune spread

$$\sigma_\nu = \nu \cdot \frac{\sigma_E}{E} \approx 2.4 \times 10^{-6} \cdot \nu^2$$

Resonance strength

$$|w_k|^2 \approx 1.94 \times 10^{-10} \cdot \nu^2$$

Condition for correlated spin resonance passings:

$$\alpha = \frac{\nu^2 \lambda}{\nu_\gamma^3} << 1$$

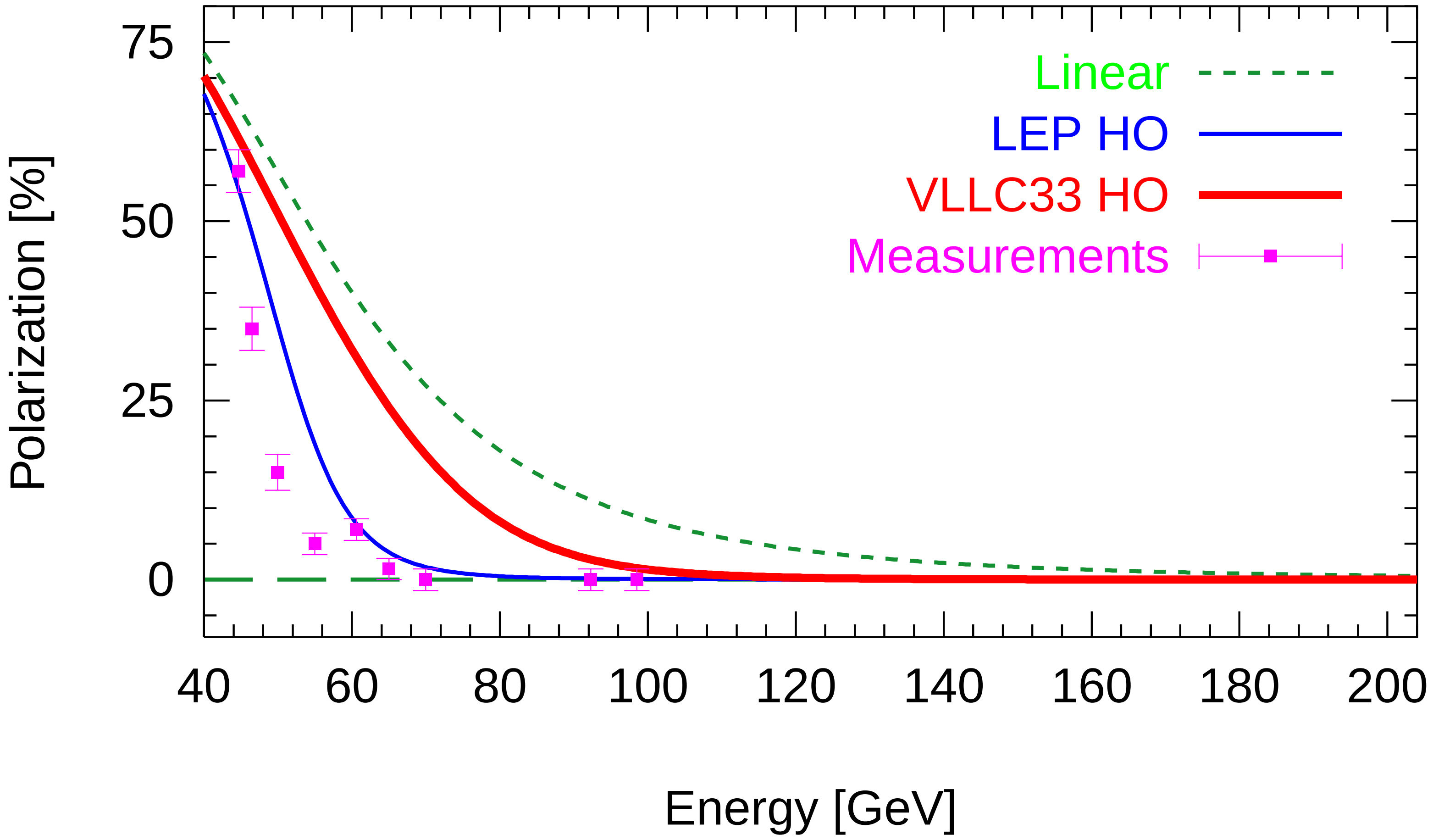
true

$$= \frac{11}{18}\ \nu^2 \sum_{k,m} \frac{|w_k|^2 \ \left\langle T_m^2(\Delta/\nu_\gamma)\right\rangle}{\left[\left(k - \bar{\nu} - m\nu_\gamma\right)^2 - \nu_\gamma^2\right]^2}$$

$$^2_m\rangle = I_m\left(\frac{\sigma_\nu^2}{2\nu_\gamma^2}\right) \cdot \exp\left(-\frac{\sigma_\nu^2}{2\nu_\gamma^2}\right)$$

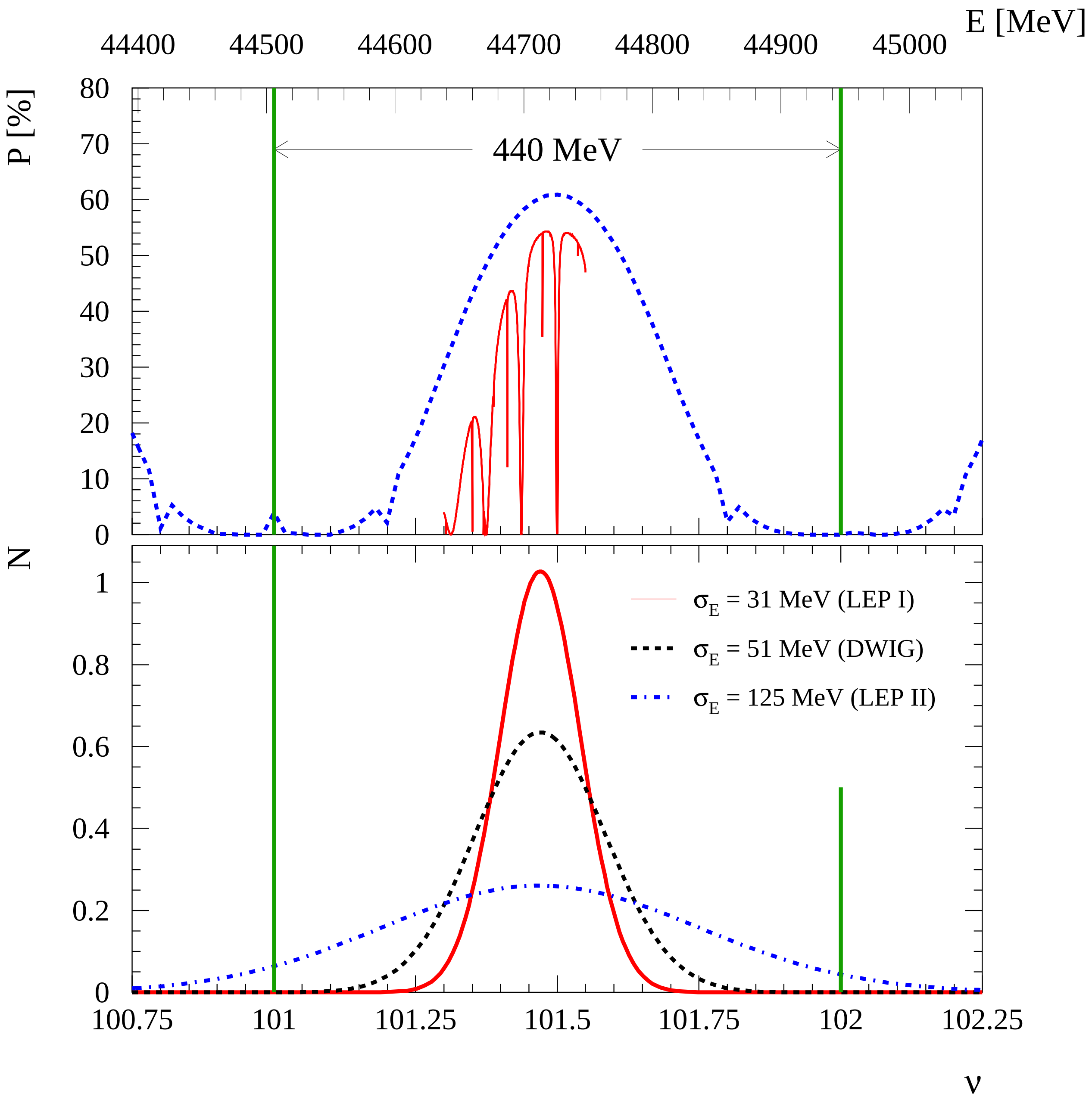
Build-up time τ_p:	1.9 h
Spin tune ν:	417.5
Spin tune spread σ_ν:	0.42
Synchrotron tune:	1/7

What does this mean for VLLC?



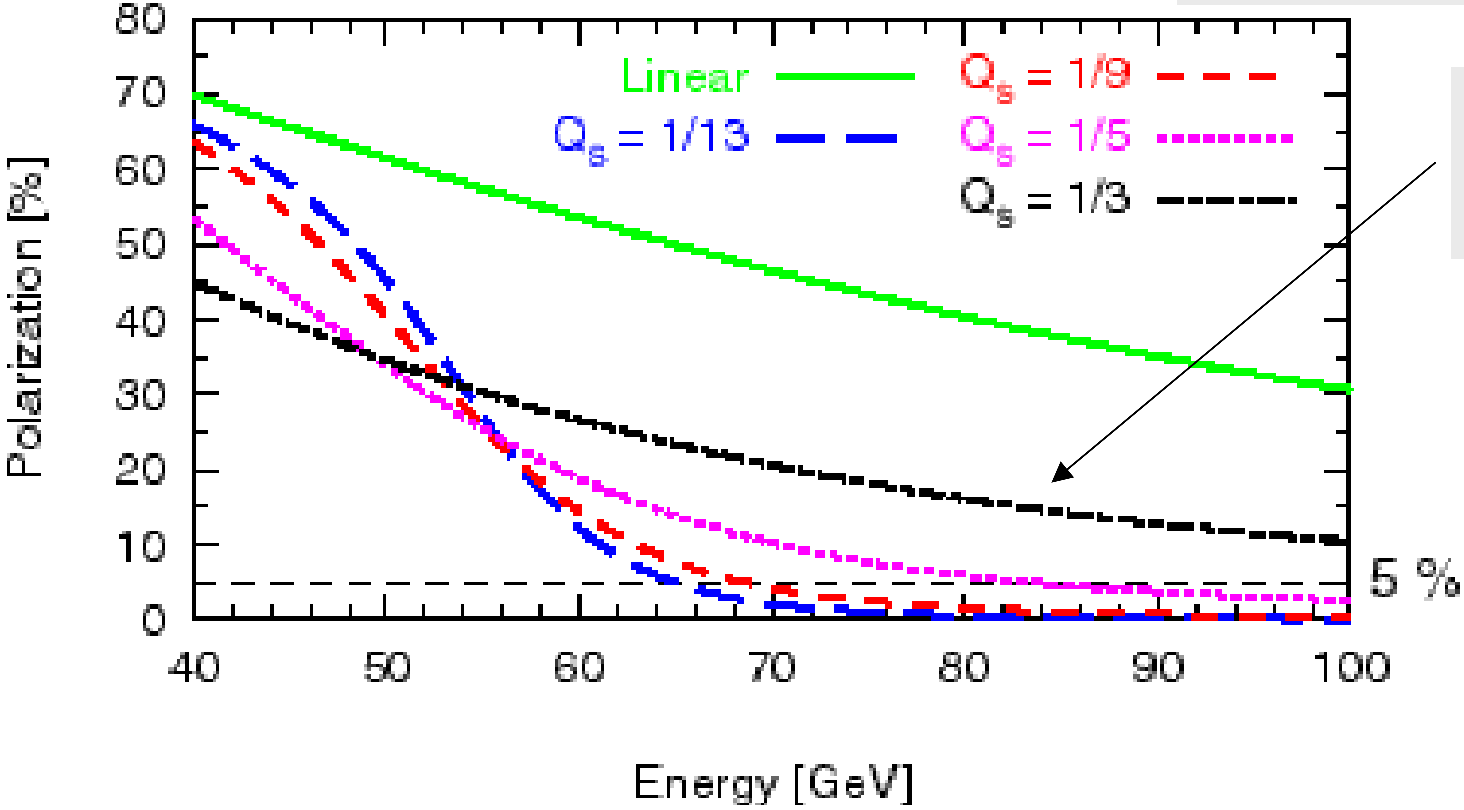
Large spin tune spread ⇨ Enhancement of depolarization

(as in LEP at high energy)


E [MeV]
44400
44500
44600
44700
44800
44900
45000
P [%]
80
70
60
50
40
30
20
10
0
440 MeV
N
1
0.8
0.6
0.4
0.2
0
σ_E = 31 MeV (LEP I)
σ_E = 51 MeV (DWIG)
σ_E = 125 MeV (LEP II)
100.75
101
101.25
101.5
101.75
102
102.25
ν

High Q_s for LEP

Linear / higher-order theory for different Q_s…



Raising Q_s improves polarization for high energies!

Why?

Imagine $Q_s = 1$

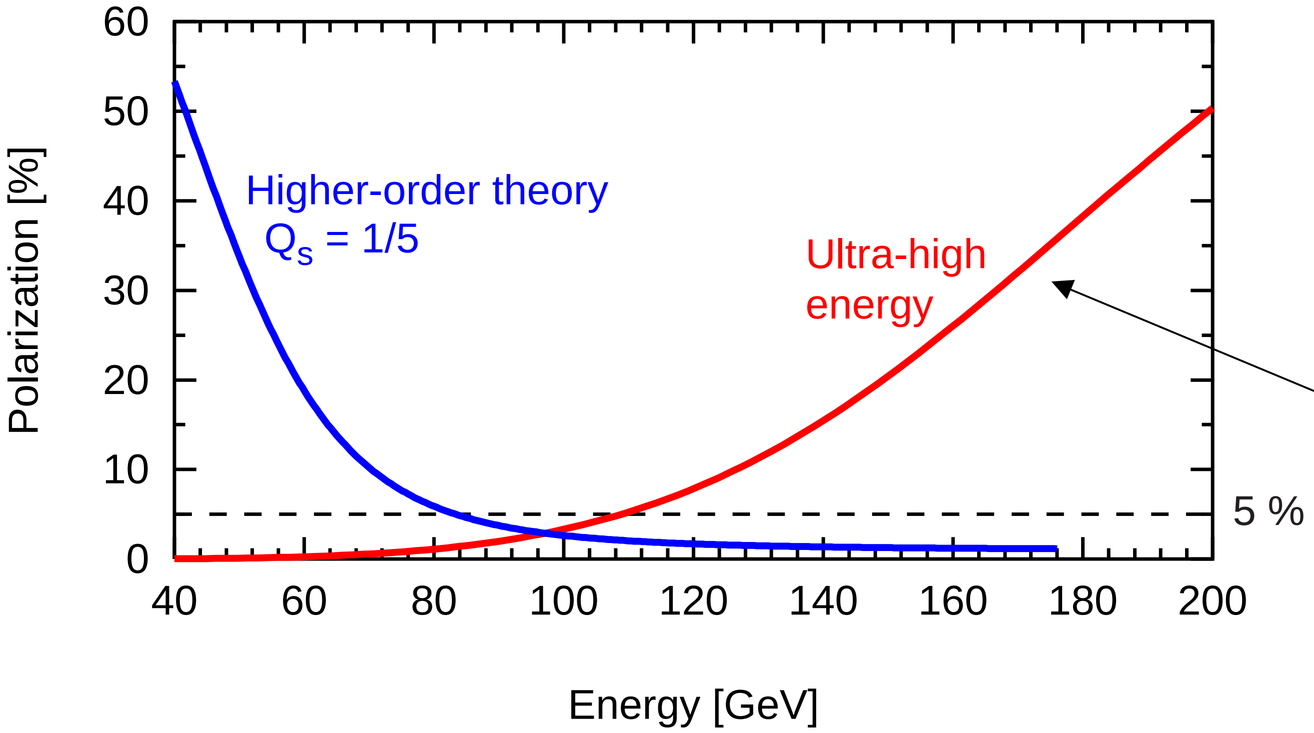
↓

Q_s satellites overlay integer resonances

$(\nu = k + i \cdot Q_s)$

$Q_s = 0.2$: Expect sufficient polarization up to 80-85 GeV!

Polarization increase at Ultra-high energies:



Uncorrelated passings of spin resonances (small Q_s)

Spin tune spread $\sigma_\nu >> 1$

(probably not true at 100 GeV)

Theory predicts: **Polarization comes back at ultra-high energies!**

Why? Fast increase of polarization build-up, increase in depolarization slows down!

Very uncertain regime (who knows what really happens)…

Some preliminary thoughts:

Strong transverse damping: Very nice beam dynamics regime (performance)

Less tails
Less effects from resonances (we can jump them)
Ramp colliding beams at high energy
Higher beam-beam limit

Two thirds of all LEP luminosity collected in the last 3 years (out of 10.5y)

LEP data would indicate a beam-beam limit of 0.17 for VLLC33.

Optimization of vertical orbit to the limit (dispersion/coupling correction for LEP)

Need operational overhead in RF voltage (>= 6 % in LEP) - optimize # klystron

Do not expect significant radiative spin-polarization (even linear level is very low

Sociology

- Good support from equipment groups, good motivation, close interaction with machine in-house expertise.
- Common control room – operations as focus for machine physicists, equipment groups and experiments.Regular informal contact at all levels.
- Comprehensive annual workshops - Chamonix.
- Cross-fertilisation from other labs.
- Stimulated by close contact with experimental physicists.
- Makeup of operations. Ph.Ds on shift