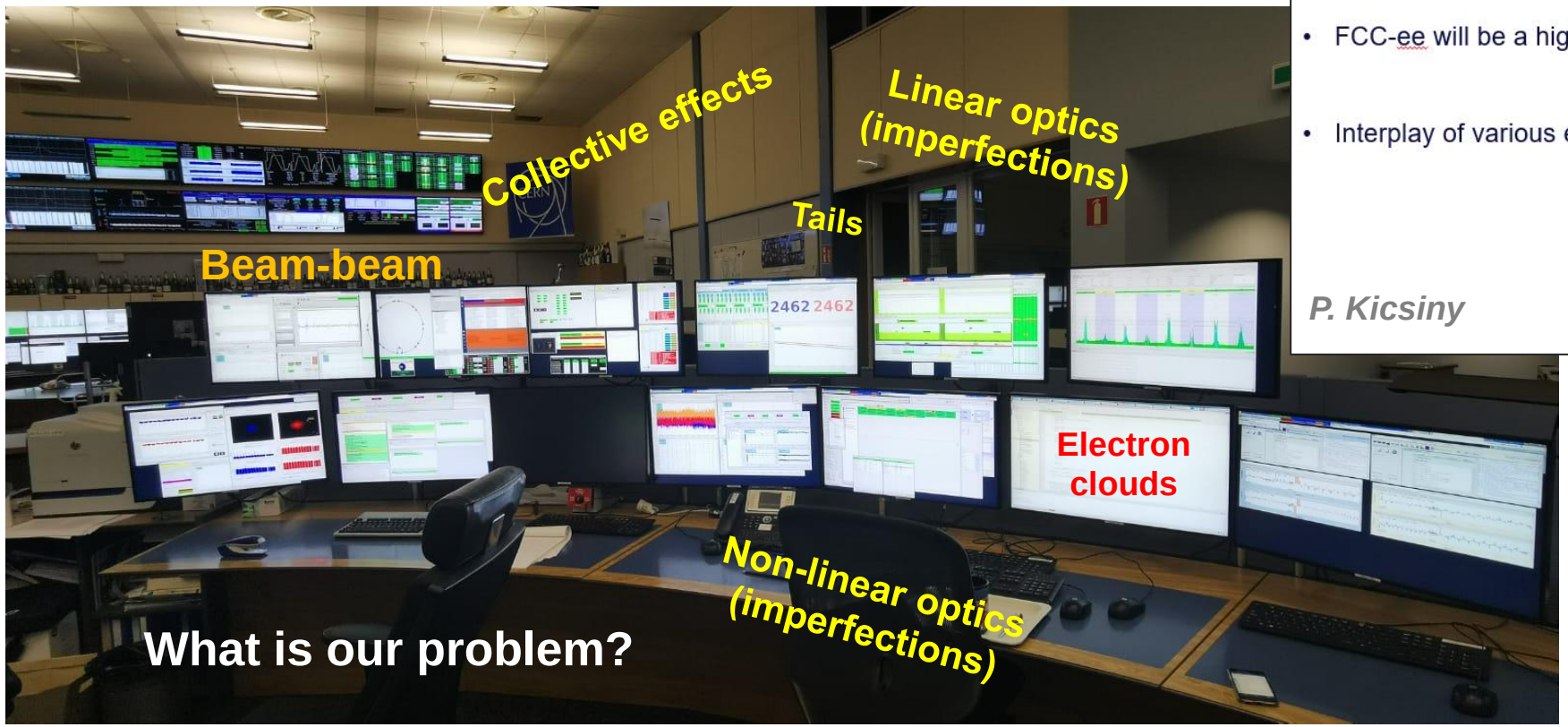
Beam-beam from the control room
LEP1, LEP2, LHC – 3 beam-beam stories

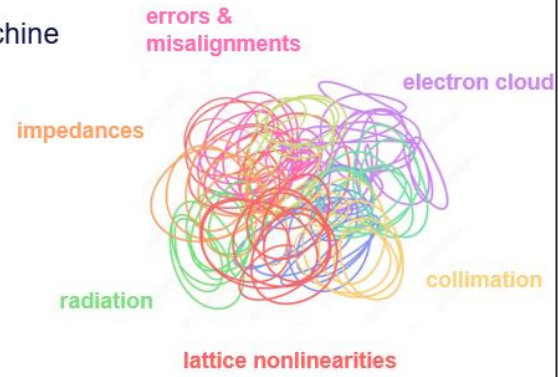
J. Wenninger, (ex-LEP) LHC operation

In CRs full interplay of effects

- Beam-beam (BB) is an important aspect of collider physics and operation, but in a control room, BB is never alone – many factors conspire and couple to degrade machine performance.
  - Importance of **close contact between operation and modelling**.
  - “Tuning parameters” are not always orthogonal.



- FCC-ee will be a highly complex machine
- Interplay of various effects



P. Kicsiny

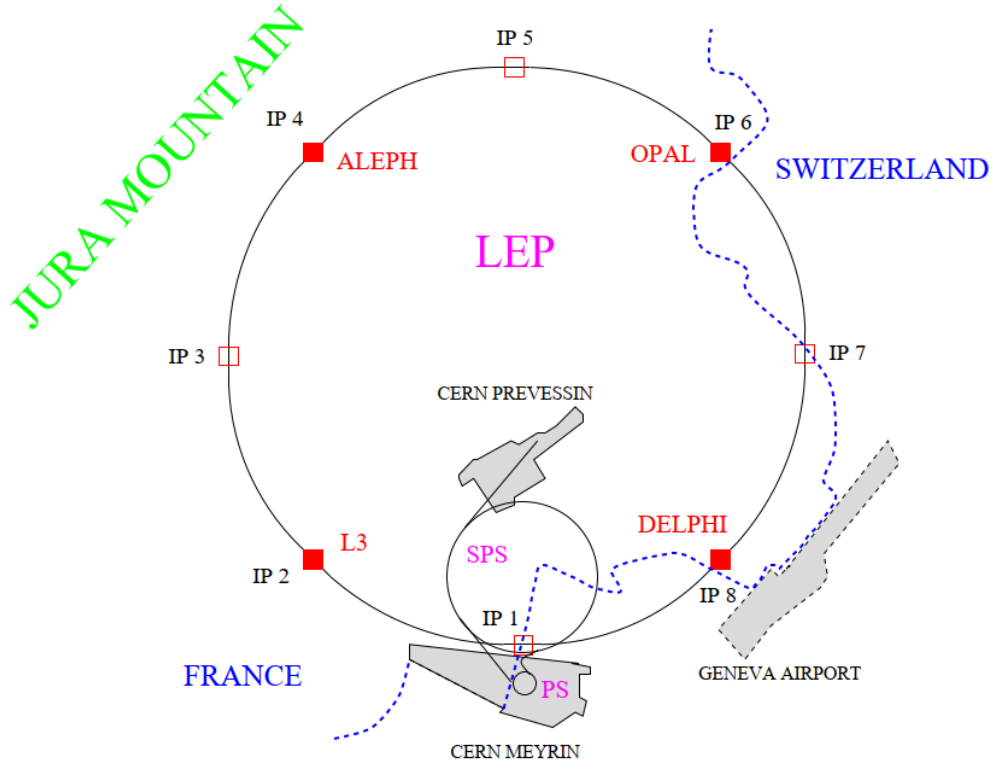
LEP

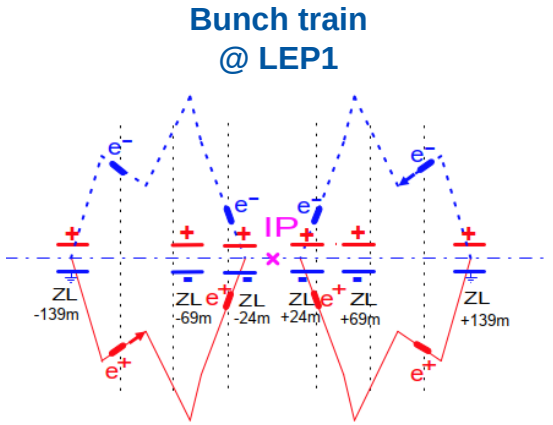
The 26.7 km LEP ring was designed before the emergence of the “factory” concept (PEPII, KEKB – second half of the 1990’s):

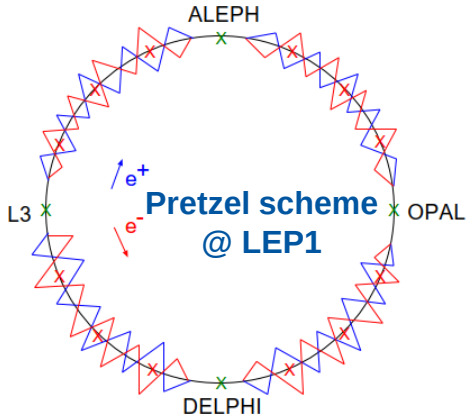
- **Single ring**, 4-12 bunches, beams separated with electrostatic elements.
- **No crossing angle, no crab waist, no hour-glass**.
- Injection at 20 GeV, later 22 GeV, followed by ramp, squeeze, collisions at 43 – 104.5 GeV.
- H. Shopper (former CERN DG): “final choice of **circumference** selected in view of **LHC**”.

Gentle **competition** between **SLC*** and **LEP** at 45 GeV.

- LEP : statistics & energy calibration (Z mass and width)
- SLC : longitudinal polarization







(*) Stanford Linear Collider

The Standard Model of particle physics in the 1990s

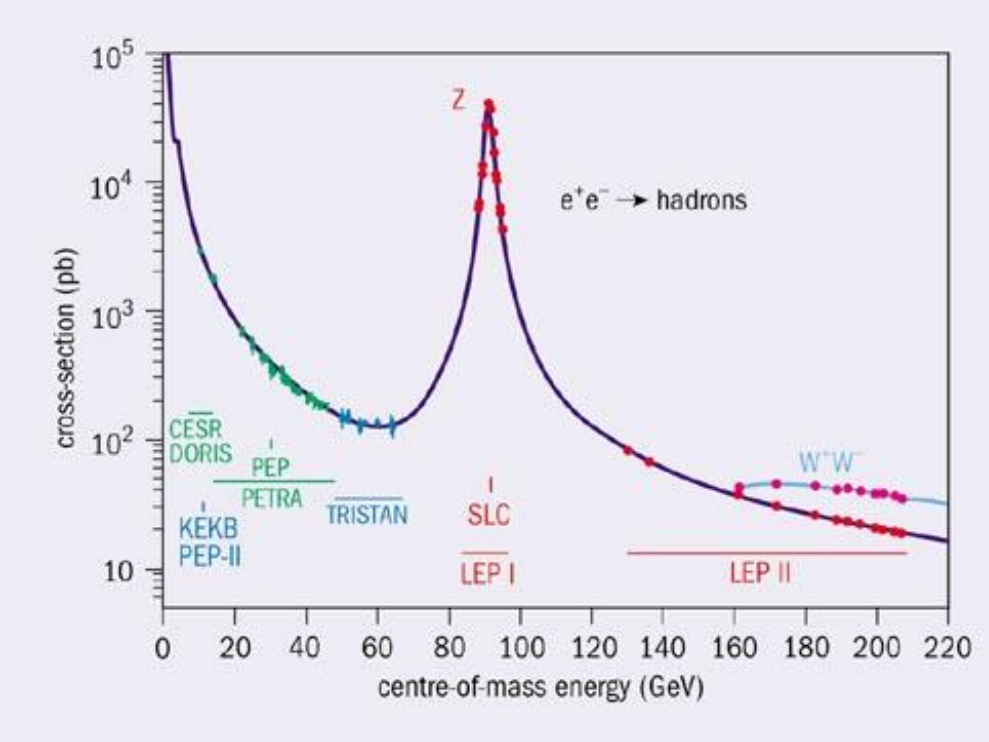
When LEP operation started, **the Standard Model (SM) had holes – missing particles –** and was **not much constrained.**

Many physicists hoped to discover top quark and Higgs at LEP.

By ~1993, the Z mass and width measurements at LEP pointed to a **heavy top (~180 GeV)**, out of reach of LEP.

The top quark was **discovered at the TEVATRON in 1995**.

The SM constraints on the Higgs boson mass were weak, in the last two years, 1999-2000, **LEP was in Higgs hunting mode**, focus was on **highest beam energy** and no longer on highest luminosity.



Exiting times, discovery years !

LEP 1 – E ~ 45 GeV

Beam-beam limited at ξ_y ~ 0.04.

Beam-beam controlled with **emittance wigglers** (in D^x != 0 areas). Performance optimization versus flip-flop…

- Wigglers at full steam at start of collisions, lowered with intensity.

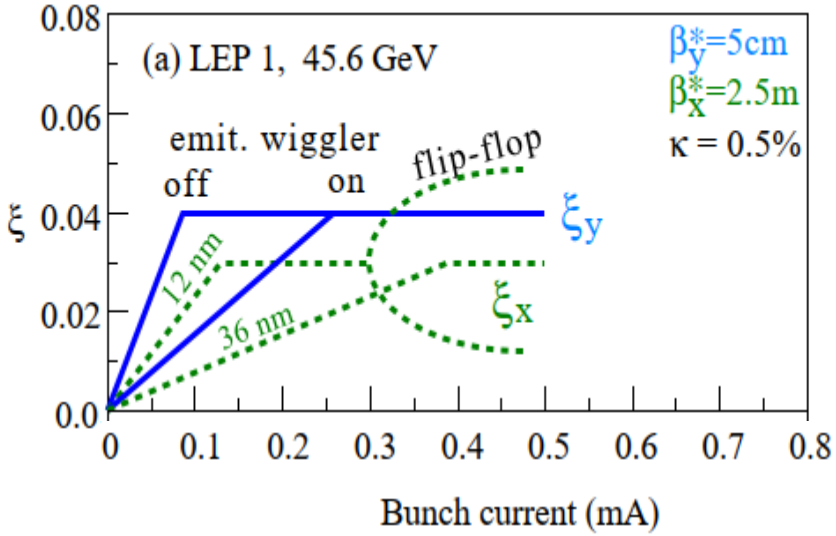
Peak performance depended on orbit and uncontrolled factors.

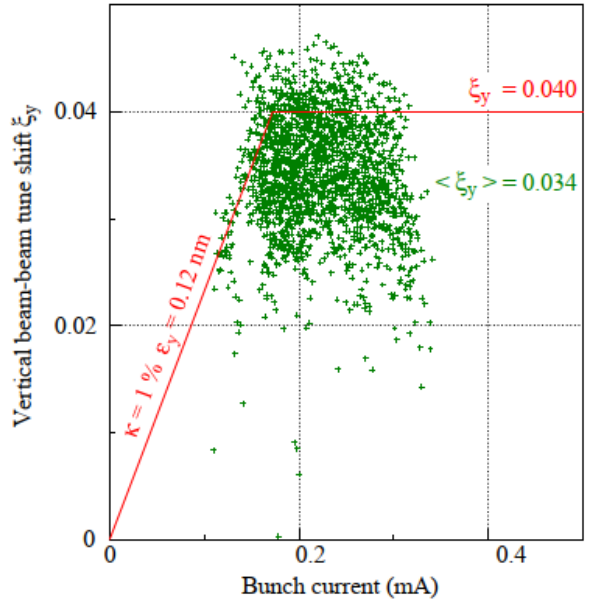
- Favorite OP game was to **re-seed the orbit** (‘bare’ correction) and hope for an increase in luminosity…

Fighting **experimental backgrounds** – sometimes difficult, tense interactions with experiments → also for LEP2

Following the needs of the energy calibration program, begin **systematic logging of beam observables** (ORACLE DB).

Don’t save on instrumentation and data logging !





LEP 2 – E > 80 GeV

Beam-beam is no longer an “issue”, the **strong radiation damping** at LEP2 (E >= 80 GeV) lifts the beam-beam limit.

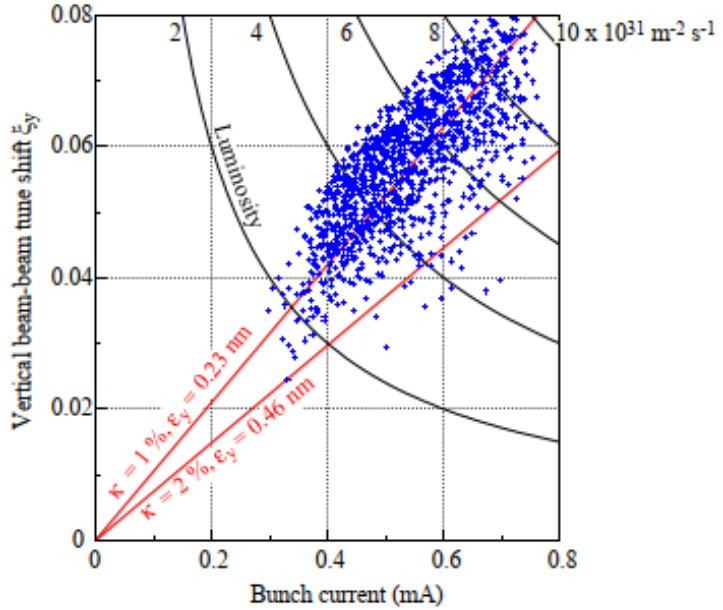
Concurrent **change of the lattice** (→ FCC-ee) to **lower** ε_x.

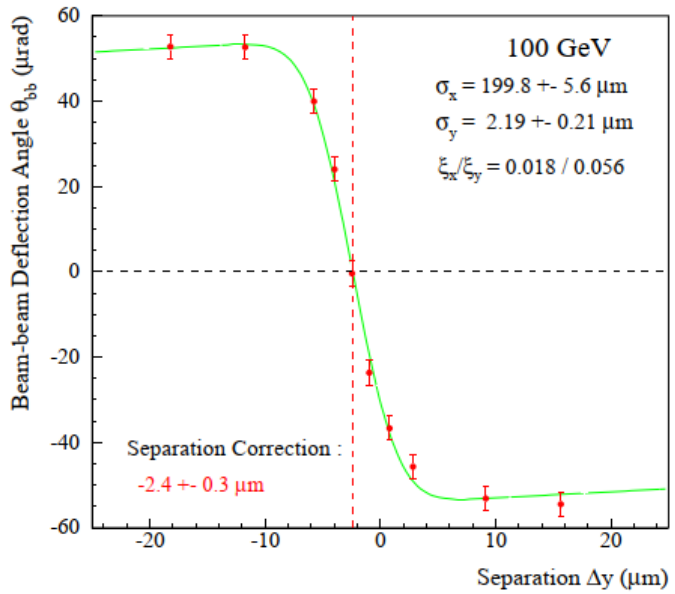
Fast coherent **beam-beam deflection scans** used every fill to optimize beam overlap (pioneered at SLC).

Orbit remained critical, more deterministic approach with **combined vertical dispersion+orbit** correction – **lattice error corrections**.

- First optics measurements with beam excitation and turn-by-turn BPM acquisition. But no corrections yet.
- Optimal tune WP was found by … accident.

From beam-beam limit surfers at LEP1, OP team becomes **expert RF cavity tuners & fixers** (“only“ **3 GV RF system**).





The end of LEP – transition to LHC

LEP2 operation was stopped in November 2000.

Many physicists in the LEP community wanted to continue LEP, but CERN resources were needed to build on the LHC.

- At the time, **the lower limit on the mass was 114.4 GeV/c^2** (HZ production), CM energy ~209 GeV.
- The Higgs boson was eventually discovered in 2012 at LHC with a mass of **125 GeV/c^2**.

A difficult and heavily debated decision – emotional.

- Fortunately, social networks did not exist...

Next transition: HL-LHC → FCC-ee

LHC – machine protection dominated regime

How to handle **100x more stored beam energy than at SPS and TEVATRON** was from the **key challenge of LHC operation**.

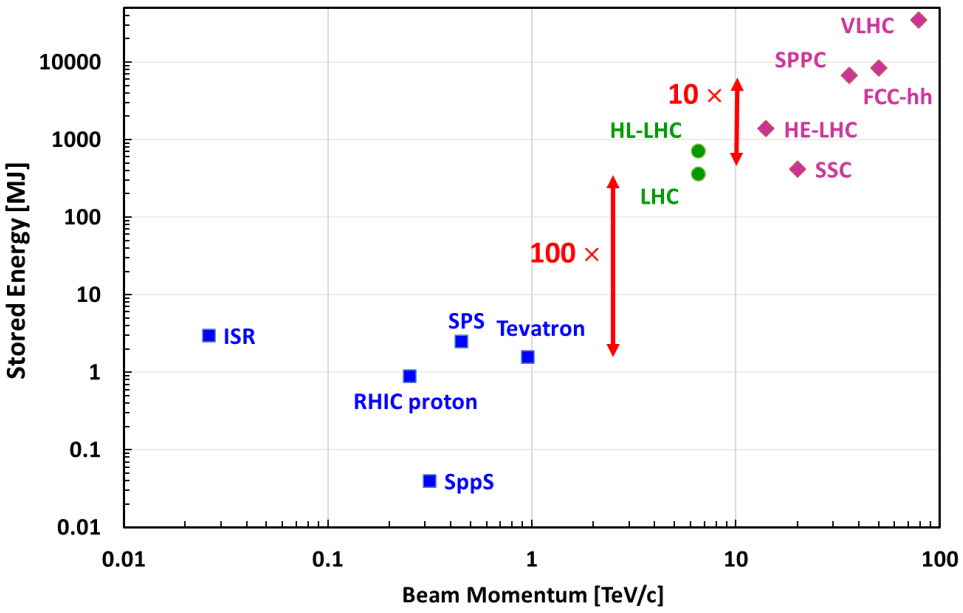
- Reached 420 MJ @ 6.8 TeV (per beam).

Operation at LHC is **dominated by machine protection rather than beam-beam** – even nowadays.

- **Machine setup with <0.1% of the nominal intensity**.
- Validation of protection (collimation, absorbers, loss points).
- Intensity ramp up in ~6 steps with checkpoints.

Limited flexibility during high intensity operation (by procedure and/or interlocks) – **some tuning done at SuperKEKB / proposed for FCC-ee is "beyond limits"**.

- Complicates diagnostics and cure of issues: beta* waist shifts, luminosity asymmetries etc to be studied at << lower intensity.

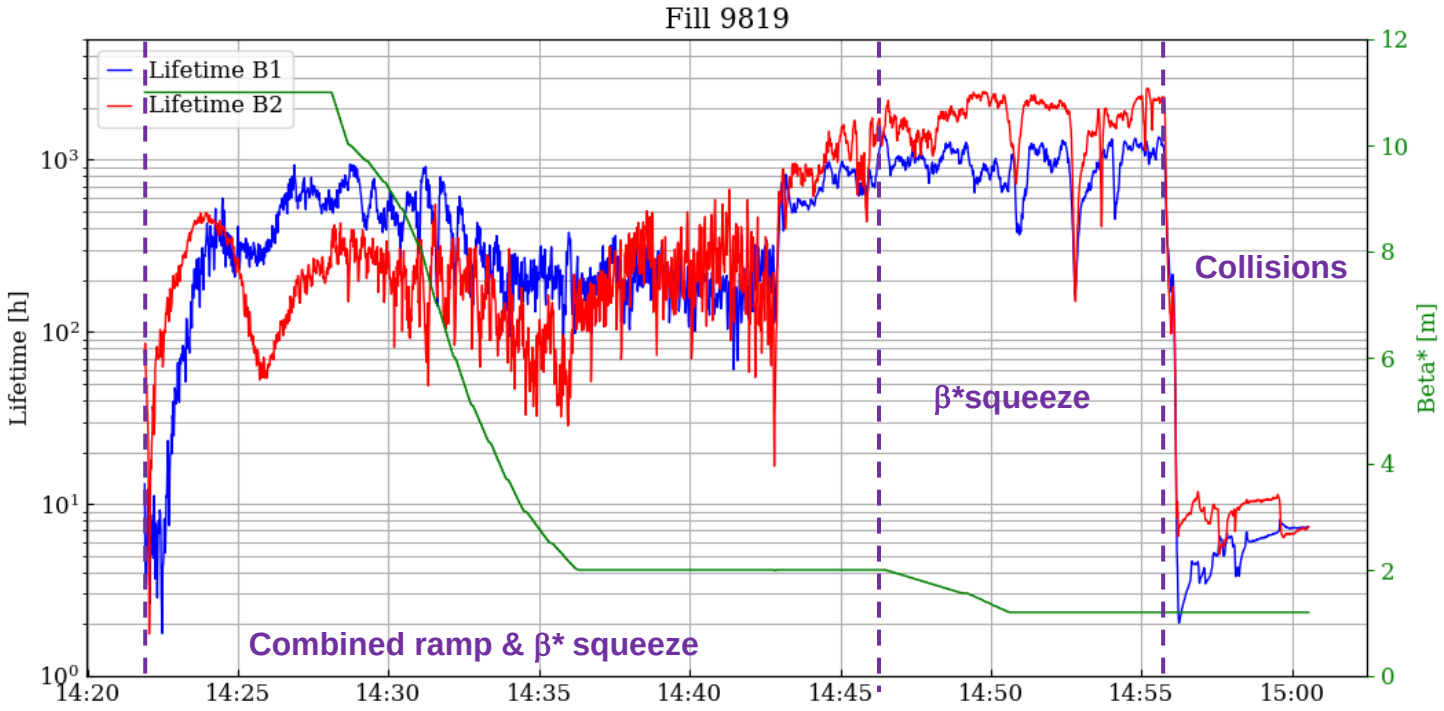


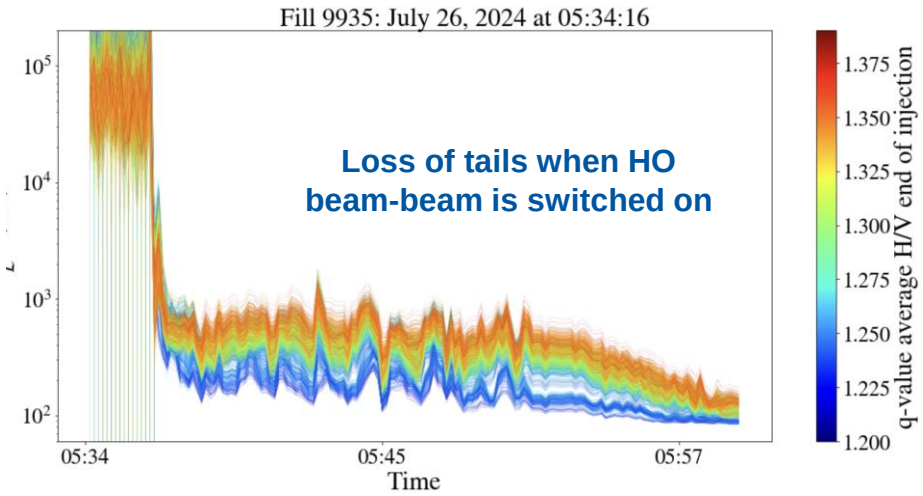
With 20 MJ stored beam energy, FCCee @ Z may also be limited in "freedom of tuning" during operation

Beam-beam and tails

The **most critical moment** of the cycle: **collapsing the beam separation for collisions** → switch on HO beam-beam – has triggered **beam dumps** due to excessive losses for lifetime drops below ~1 hour.

- Tails expelled; phase prone to trigger instabilities (most of them → emittance growth).





S. Kostoglou

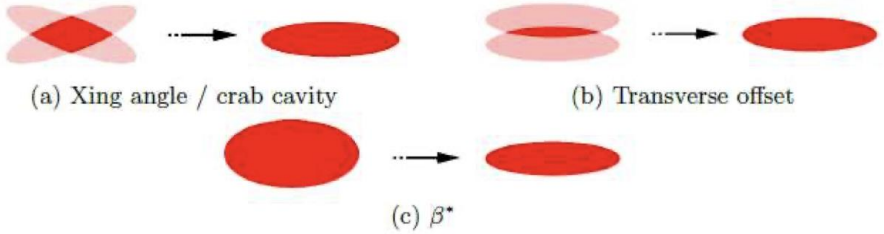
Luminosity levelling

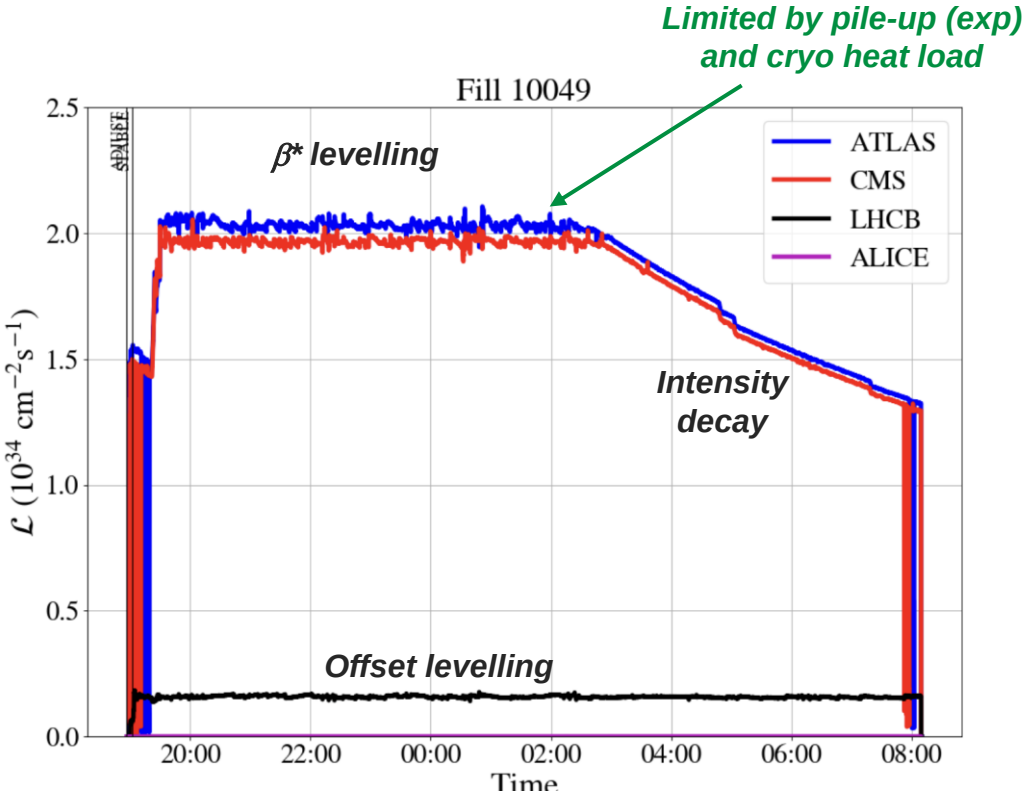
From the start, **different luminosity targets** of the LHC experiments called for **levelling of luminosity**.

- **2011**: levelling ALICE & LHCb by **transverse offsets**.
- **2017**: levelling **crossing angle** down to enhance luminosity at end of fills and **prepare experiments "psychologically"** for more complex manipulations.
- **2018**: first levelling by β*.
- Since **2022**: combined levelling of all experiments (β*, offset) – **β* range: 120 cm to 30 cm**.

Complex manipulations with 2 x 420 MJ !

T. Pieloni

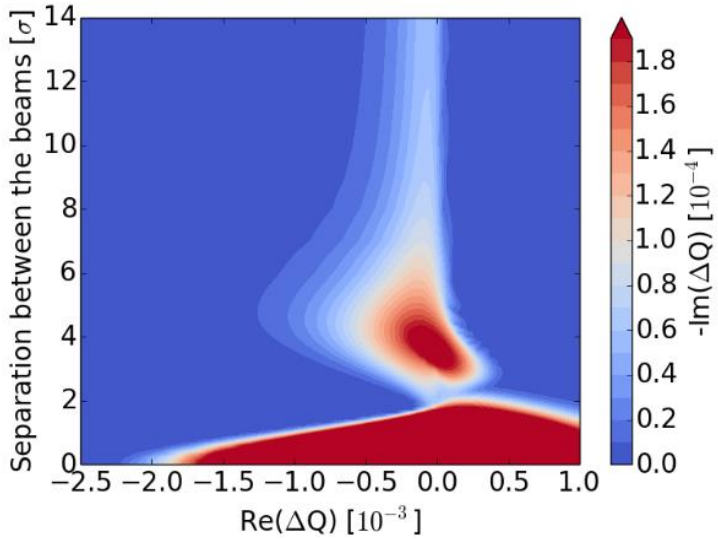




Beam-beam is not the limit

Beam-beam never stopped (progress of) operation. LHC was pushed progressively in number of bunches and bunch intensity.

- Instabilities during collisions were encountered, lifetimes have been lower than desired… Overcome with octupoles, damper, chromaticity, change of procedures.



X. Buffat

LHC operation confirms:

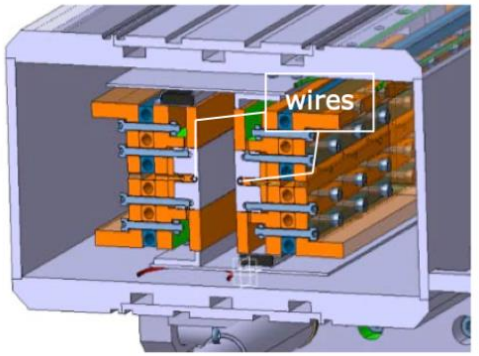
But must collide ~ HO !

Beam-beam effects do contribute to stability!
Quote by A. Chao from BB2013 "Colliding beams will never become unstable"

Two performance **jokers – you always gain**:

- **Lower emittances** : never HO BB issue, tune shift > 2x design ~0.007/IP.
- **Smaller β*** always gave full benefits (limited by aperture margins).
  - Coupled with improved optics corrections, linear and non-linear.
  - Luminosity reduction from crossing angle, enhanced LRBB effects → **BB wire tests**.

G. Sterbini, P. Belanger

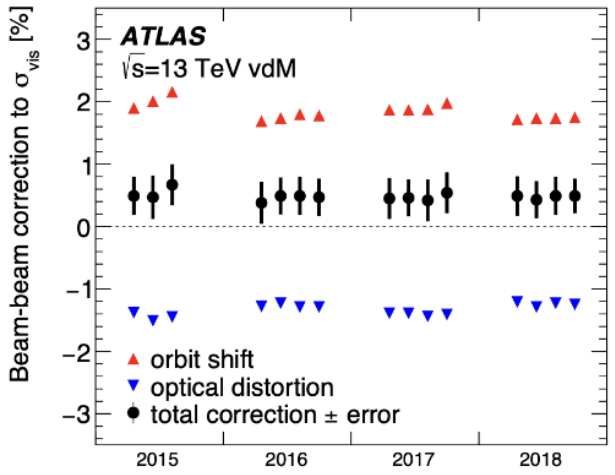


Beam-beam observables

Measurement of **beam-beam impact on observables** and associated simulation show **(very) good agreement**.

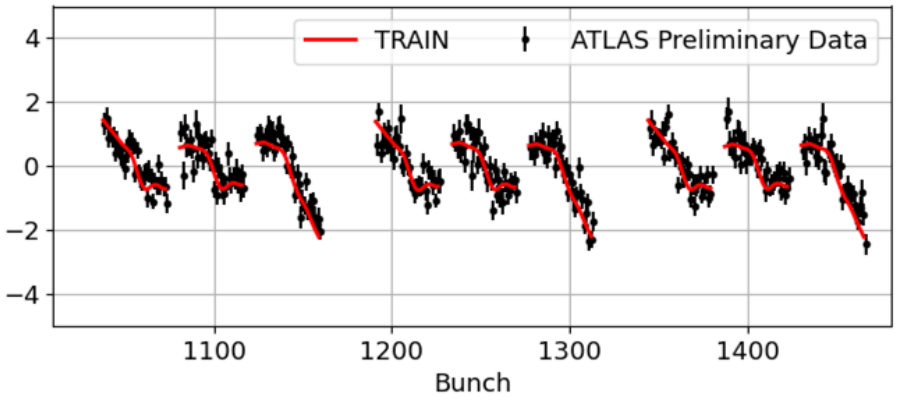
- Beam-beam correction for precise **luminosity normalization**.
  - Initial LHC estimate ~5%, now ~1% syst. error on luminosity.
- LRBB induced **orbit differences**.
- Beam-beam impact on **beam optics**.
- Measurement and possibly correction of **BB driven RDT**.

J. Wanzcyk

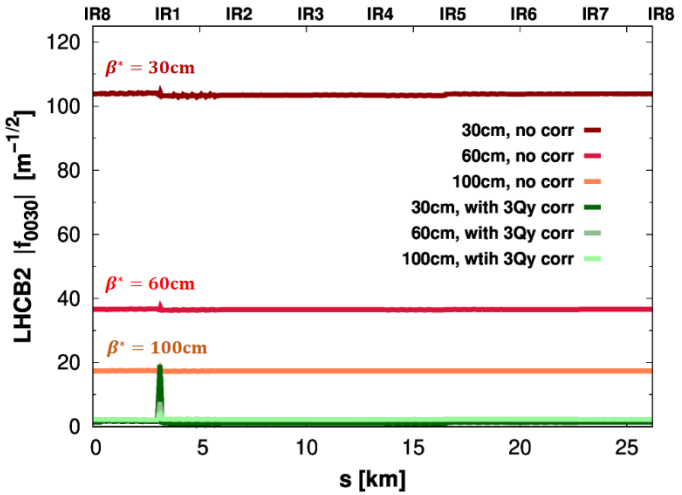


DOI: 10.1140/epjc/s10052-023-11747-w

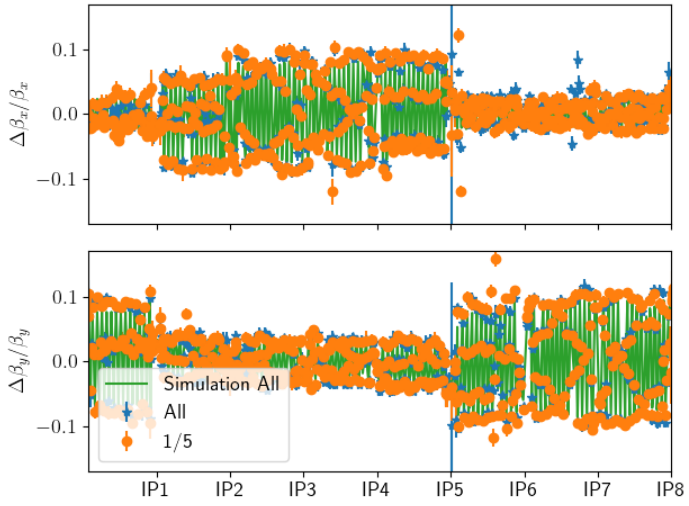
M. Hostettler



E. Maclean



T. Persson



Beam-beam and machine protection

Beam-beam becomes relevant for **machine protection** at HL-LHC.

- Sudden **missing beam-beam kick** during **beam dump**: kicks the opposing beam to 1 sigma amplitudes – a fast beam-beam kicker.
- **Fast crab-cavity failures** can kick parts of a bunch at large amplitudes → HL-LHC.

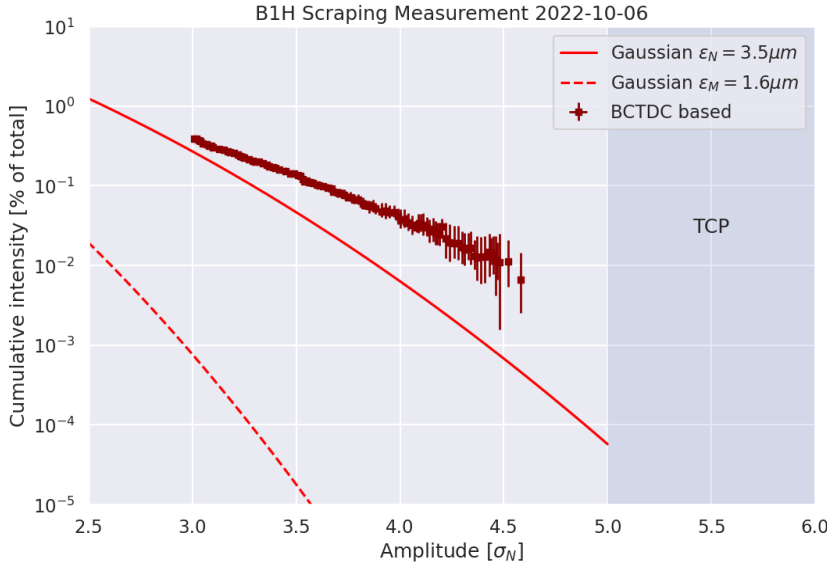
C. Montanari

With a densely populated tail, **1-10 MJ** can impact and potentially **damage collimators** during such fast failures.

- **Importance of beam tails** beyond background to experiments and lifetimes.
- Understanding tails from injectors and tail evolution is an important study item.

Interplay with non-linearities breaking collimation hierarchies.

F. Van Dee Veken



Over 10 years of LHC operation

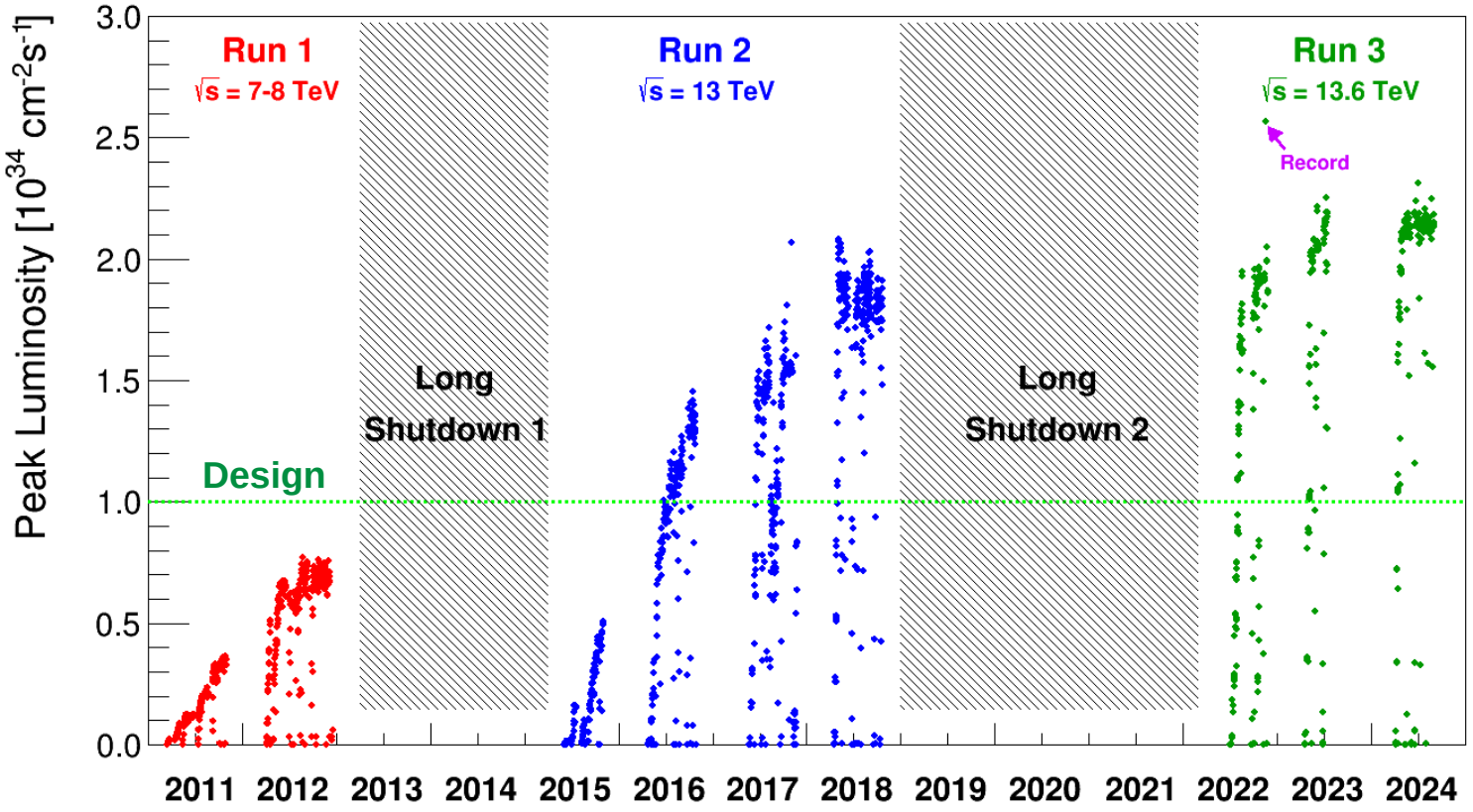
Peak L pushed **> 2 x design**

- Limited by experiments and cryo system!

Ingredients:

- **Higher bunch currents** (HL upgrades)
- Much **smaller beam emittances** (injectors).
- Much **smaller β*** (use of aperture).
- Complex **optics manipulations with colliding beams – beam control**.

But also thanks to excellent understanding of the machine with efficient exchange between operation and modelling.



Thank you for your attention !

LHC event on your 200 CHF banknote