Beam-beam effects overview

and their impact on collider design and performance

Xavier Buffat, Tatiana Pieloni, Lenny Rivkin

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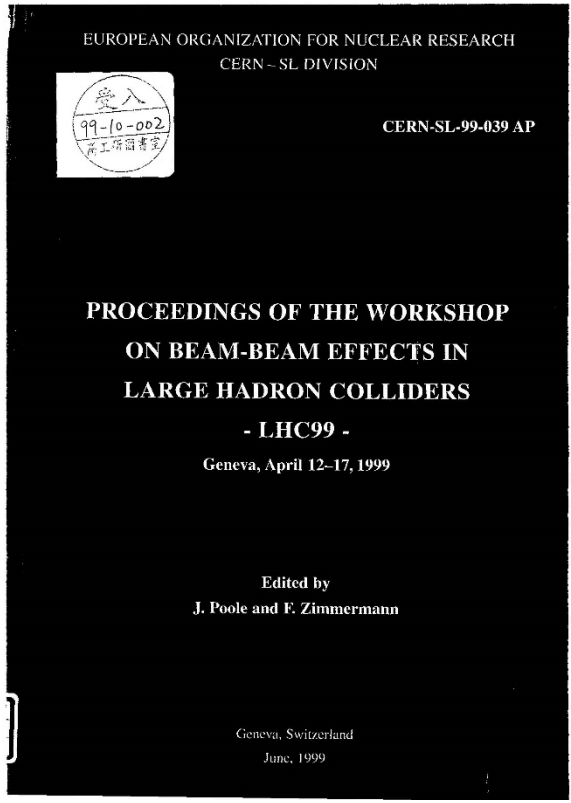
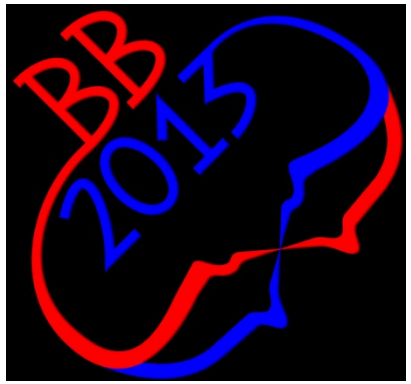
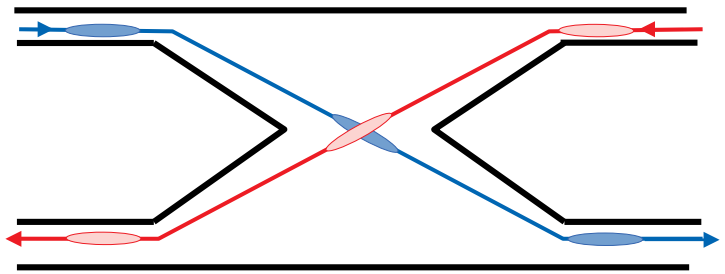
Workshops on beam-beam effects in circular colliders

- 1999 (CERN)
- 2001 (Fermilab)
- 2013 (CERN)
- 2018 (LBNL)
- 2024 (EPFL)





Electron-positron collider evolution

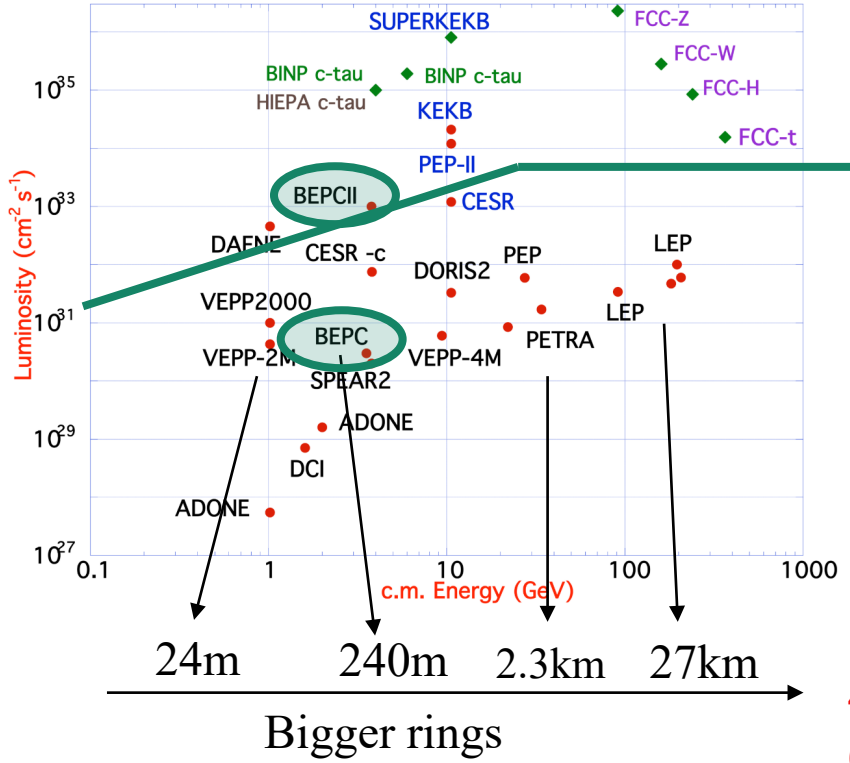


- Two separate beam pipes “Factories”
  - Allows for many bunches (reaching total currents of few A) without parasitic encounters
  - Imposes a large crossing angle

Crab cavities (KEKB) [Funakoshi13]

Crab waist (DAPHNE, SuperKEKB) [Raimondi06, Zobov10]

  - Single bunch current remains limited by the beam-beam tune shift



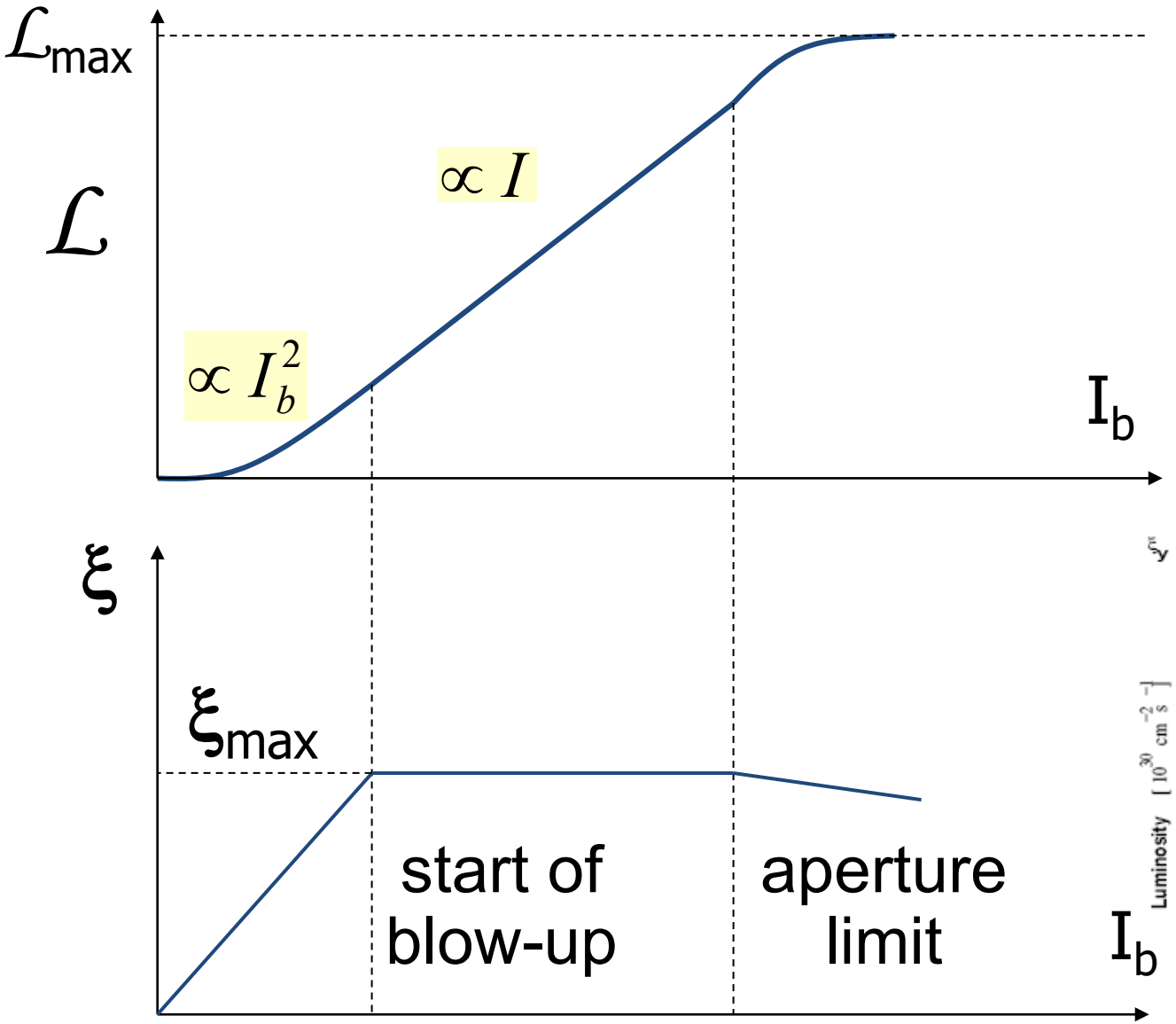
- Single beam pipe
  - Number of bunches limited by parasitic encounters
  - Single bunch current limited by the beam-beam tune shift (‘beam-beam limit’)

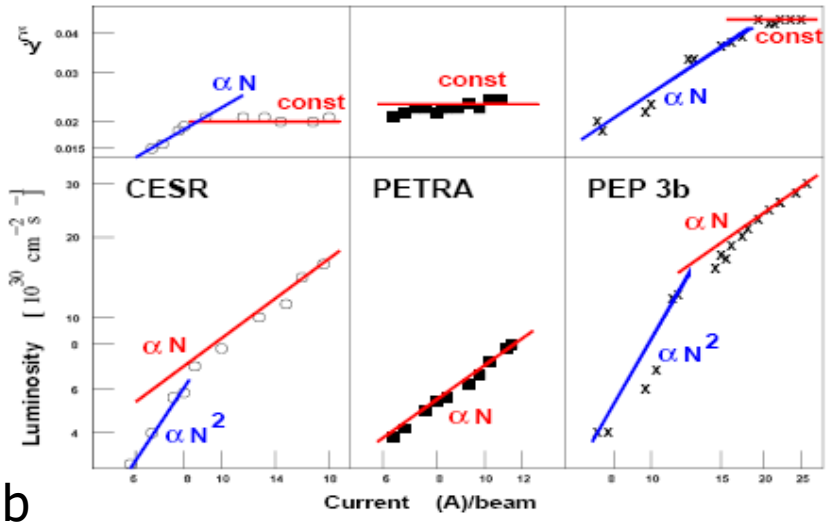
4-beam compensation (DCI) [Derbenev73]

Round beams (VEPP-2000) [Danilov96, Shwartz16]

Beam - beam limit

$$\mathcal{L} \propto \frac{I_b^2}{A^*}$$

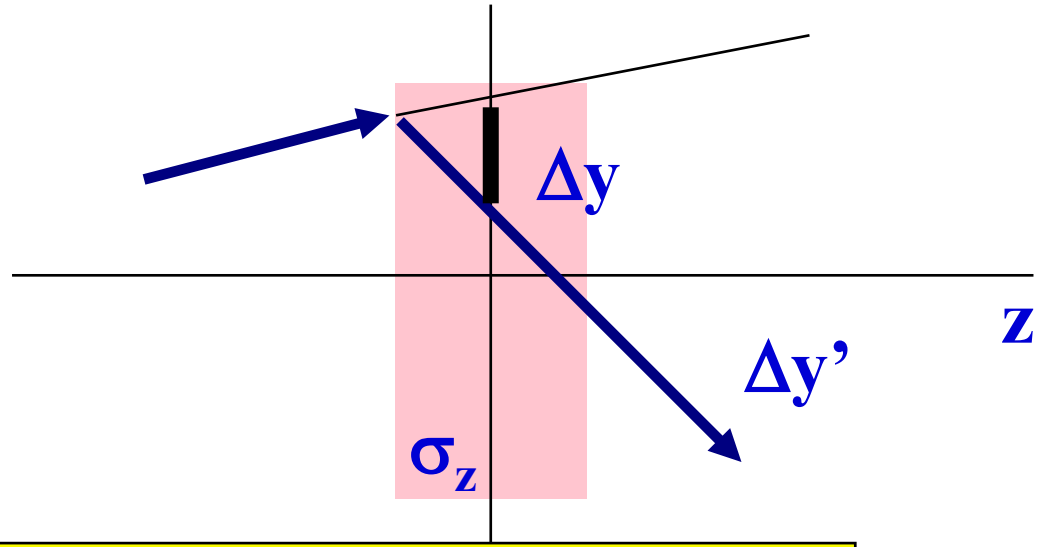




Beam – beam effects in linear and circular colliders

- Near the axis the other bunch is equivalent to a focusing lens

$$\frac{1}{f_{x,y}} = \frac{2Nr_e}{\gamma\sigma_{x,y}\left(\sigma_x + \sigma_y\right)}$$



- Disruption is defined as:

$$D_{x,y} \equiv \frac{2Nr_e}{\gamma}\frac{\sigma_z}{\sigma_{x,y}\left(\sigma_x + \sigma_y\right)} \quad \left(= \frac{\sigma_z}{f_{x,y}} \text{ for a Gaussian}\right)$$

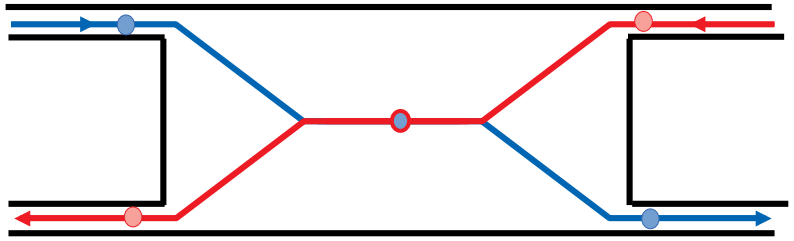
- and it can be viewed as:

- to connect it to the storage ring jargon

$$\frac{\Delta y}{\sigma_y} = -\frac{\sigma_z}{f_y} = -4\pi\xi_y\frac{\sigma_z}{\beta_y^*}$$

$$\frac{\Delta y'}{\sigma_{y'}} = -\frac{\beta_y^*}{f_y} = -4\pi\xi_y$$

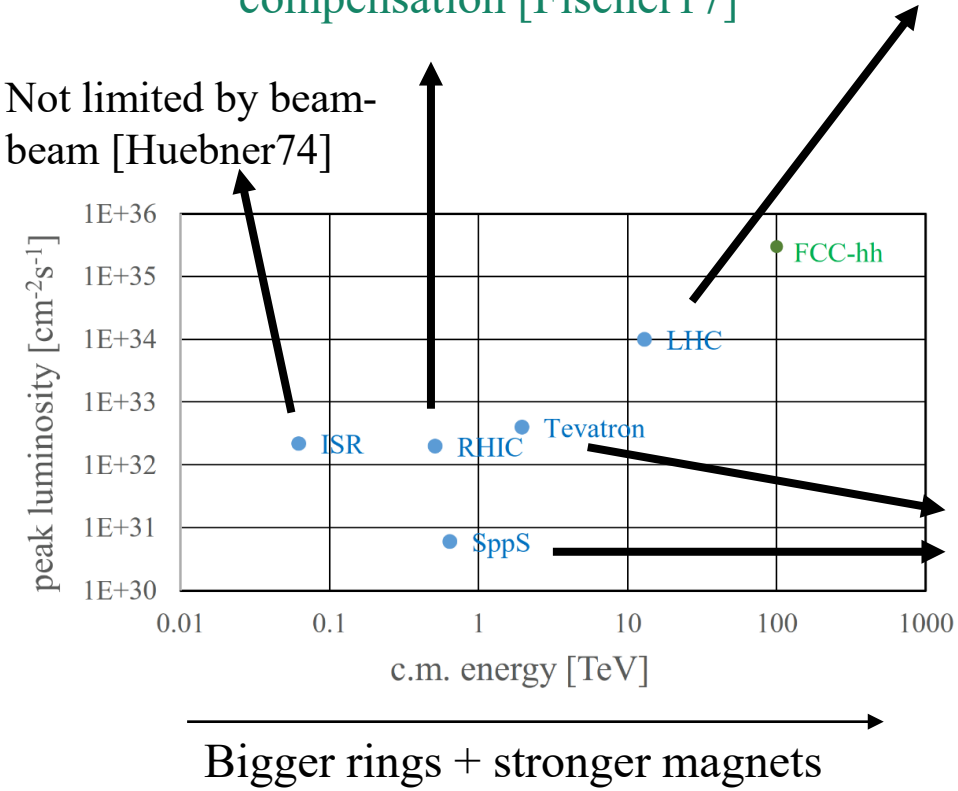
Hadron collider evolution

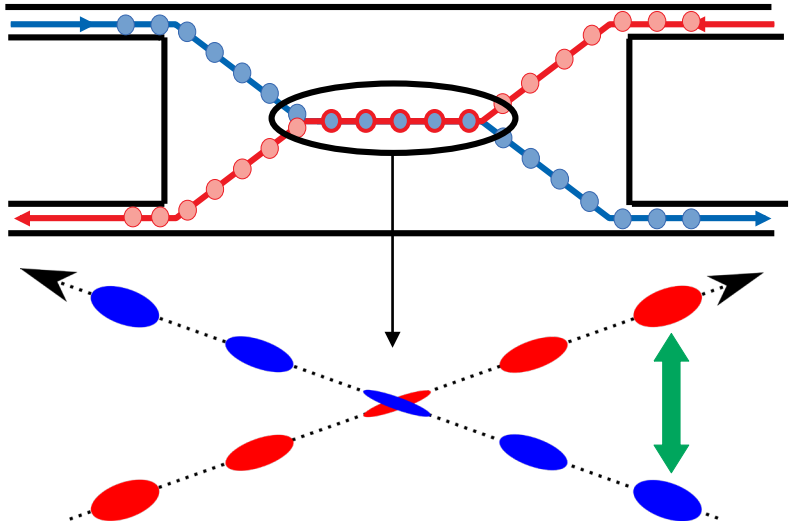


- Limited by beam-beam tune shift

→ Electron lens ‘non-linear’ compensation [Fischer17]

Not limited by beam-beam [Huebner74]





- Limited by parasitic encounters

→ Current carrying wire [Sterbini24]

→ Crab cavity [HL-LHC]

Number!

Not same for each bunch! “Pacman”

- Single pipe p-pbar colliders
  - Number of bunches limited by parasitic encounters →
  - Challenging p-bar production

Electron lens ‘tune shift’ compensation [Shiltsev07]

Finite bunch length effect

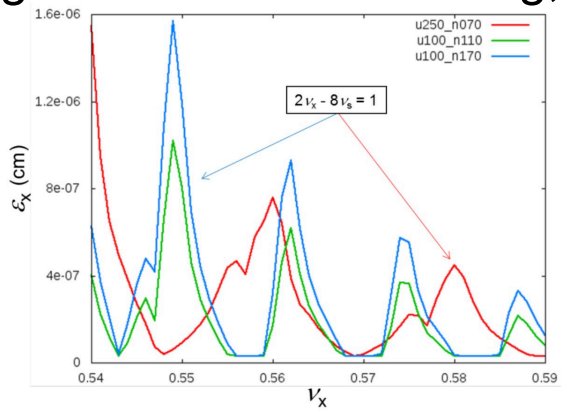
- Important development for the understanding of parasitic encounters for both e^+e^- and pp (self-consistent orbit / optics, non-linear dynamics)
  - → The current trend for either designs (and also e-p) is to increase the number of bunches and minimize number of parasitic encounters by having two separate beam pipes
  - → **Finite bunch length effect (crossing angle, hourglass)**

$$\mathcal{L} \approx \frac{I_{tot}\gamma\xi}{r_0\beta^*}R_{HG} \qquad (\sigma_y = \sigma_x)$$

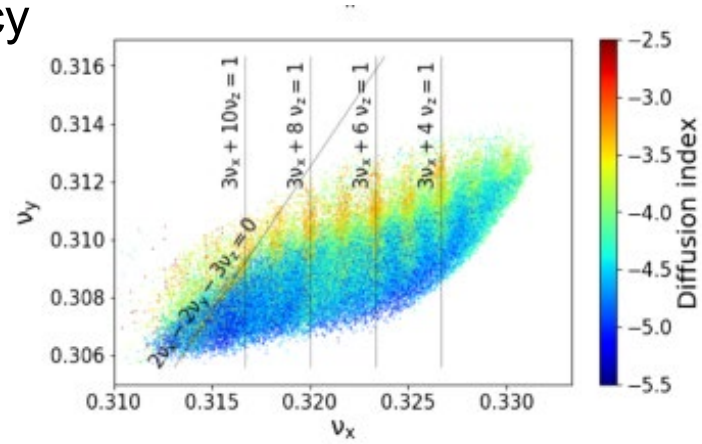
$$\mathcal{L} \approx \frac{\gamma}{2er_e}\frac{I_{tot}\xi_y}{\beta_y^*}R_{HG} \qquad (\sigma_y \ll \sigma_x)$$

- Large efforts to understand and increase the maximum beam-beam tune shift including synchrobetatron effects [Piwinski87, …, Hirata92, …, Xu21]
  - → Constraints on transverse/longitudinal tunes, Piwinski angle, hourglass parameter, lattice driven resonances
  - → (Partial) mitigation: crab waist tuning, Crab cavity frequency

FCC-ee Z horizontal tune scan including crab waist [Shatilov17]



EIC with crab cavity, including RF curvature [Xu21]



Classic "Mini – β" schemes

- Luminosity

$$\mathcal{L} \propto \frac{N^2}{A^*} \qquad A^* = 4\pi\sigma_x\sigma_y$$

- Tune shift

$$\xi_y \propto \frac{N}{A^*} < \xi_{\max} \quad \Rightarrow \quad N \propto A^*$$

We want large current,
fill large collision area!

- Required large emittance: "fill the aperture"

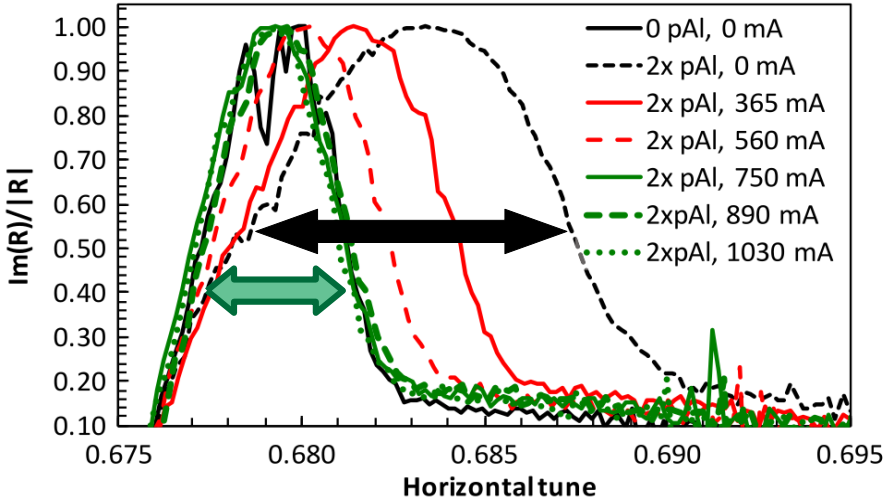
$$\mathcal{L} \propto A^*$$

- With the advent of small emittance collider rings

Luminosity per unit power!
Fill dynamic aperture
to the limit of transverse density

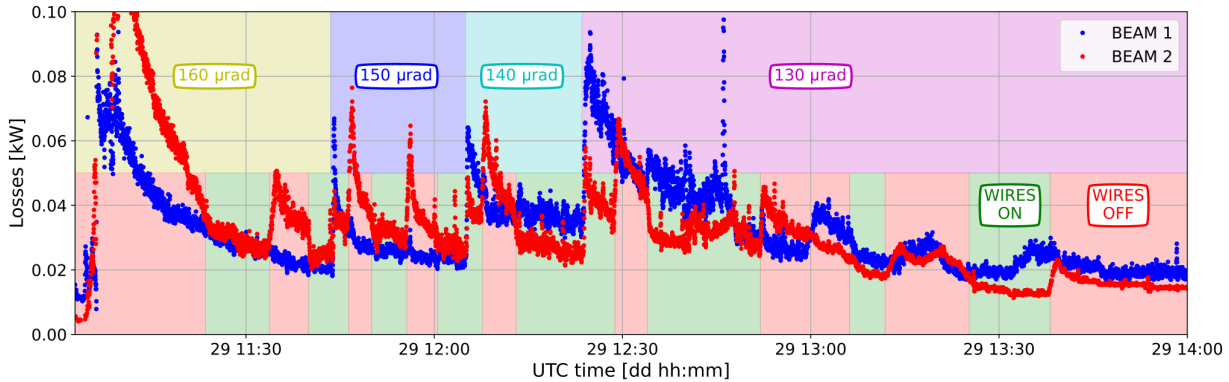
Rise of beam-beam compensation

- In the last 20 years, we observe a rise in successful compensation scheme, based on detailed understanding of side effects such as noise (e-lens), feed-down and non-linear optics control (wire, crab waist, resonance compensation)



- Tune spread reduction measured by beam transfer function with and without electron lens [Fischer17]
- Compensation of **half** the tune shift in order to maintain Landau damping
- → **Two fold increase of luminosity**

- Loss reduction with wires at the LHC (partial system deployed in operation, cf. Guido's talk)

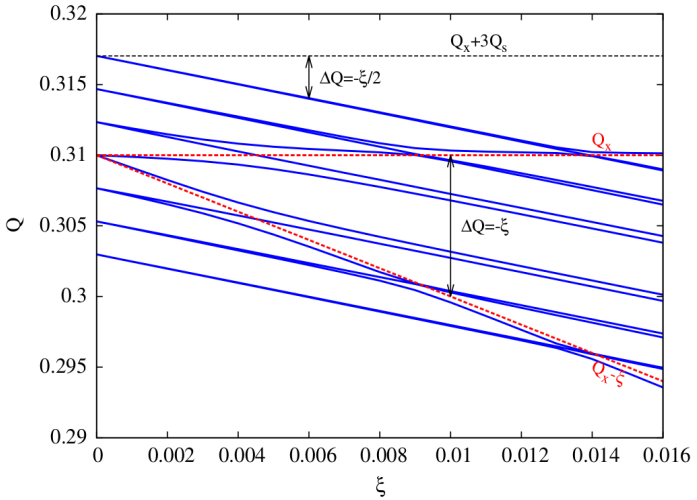


High intensity regime

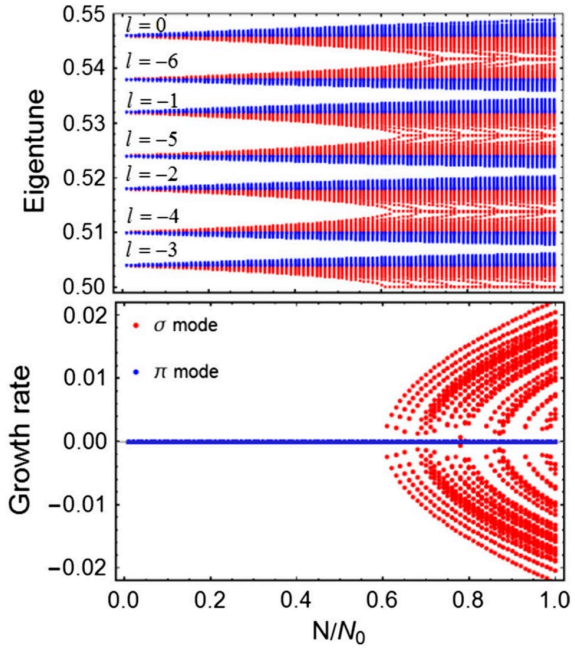
- The failure of the 4-beam compensation scheme highlights the importance of understanding collective instabilities [Derbenev73]
  - Important work to understand stability (Landau damping) of beam-beam modes [Yokoya90, Perevdentsev01, Chao05, Alexahin02] → Several measurements of the σ/π modes + flip-flop effect

$$\mathcal{L} \approx \frac{I_{tot}\gamma\xi}{r_0\beta^*}R_{HG} \quad (\sigma_y = \sigma_x) \qquad \mathcal{L} \approx \frac{\gamma}{2er_e}\frac{I_{tot}\xi_y}{\beta_y^*}R_{HG} \quad (\sigma_y \ll \sigma_x)$$

- The high intensity regime pushes the beam stability
  - The need for tight collimation and a large number of cavities leads to **strong wake fields**
  - Feedback (noise) for the coupled bunch instability



- Coupling instability of beam-beam modes caused by transverse impedance [White14, Zhang23]
- Loss of Landau damping for weak head-tail modes [Buffat14]

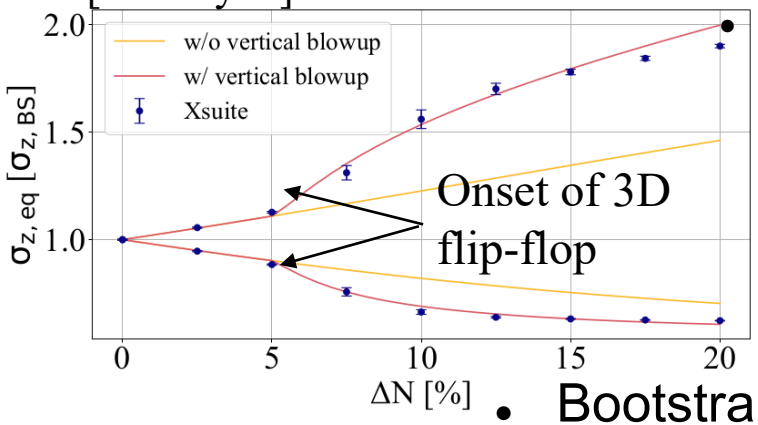


- Coupling instability of beam-beam modes caused by longitudinal impedance [Lin22]

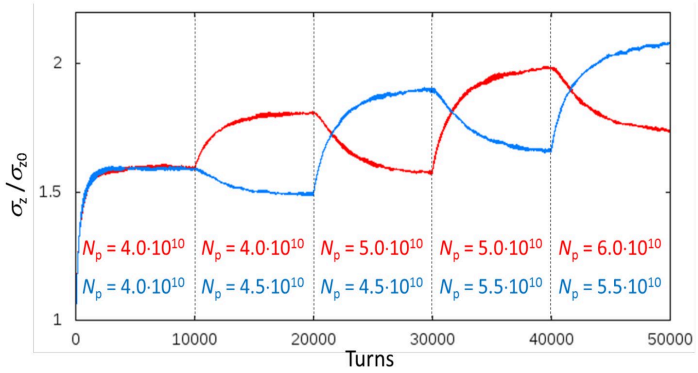
Beamstrahlung

- Beamstrahlung is no longer exclusive to linear colliders
- → The energy spread is no longer defined by the lattice but rather the result from an **equilibrium** between the two beams (blow-up of bunch length decreases beamstrahlung)

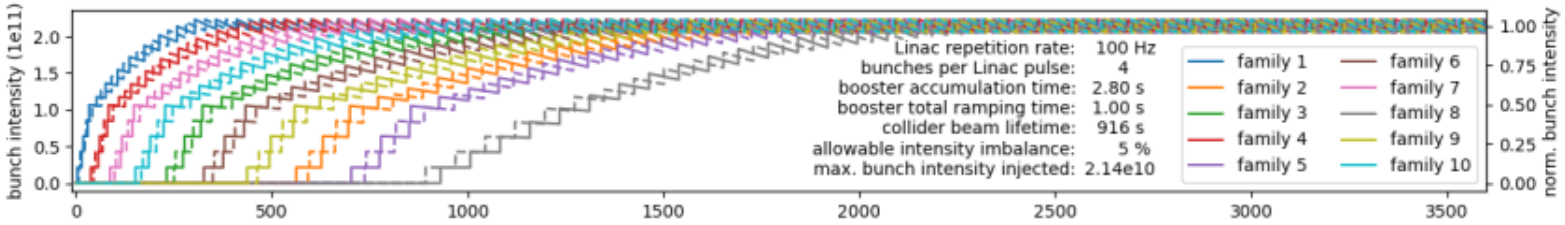
[Kicsiny24]



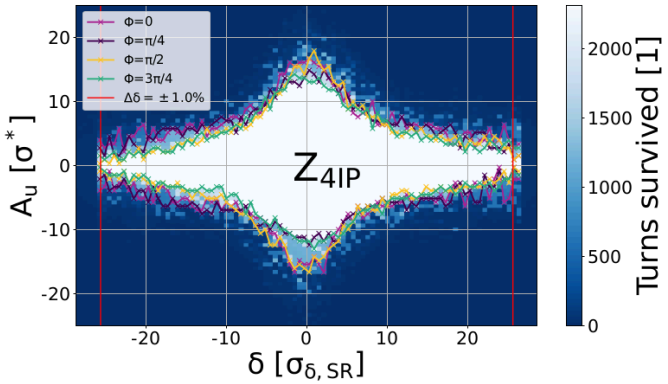
Bootstrap injection to gradually reach the equilibrium bunch length and maintain good enough symmetry between the beams [Shatilov17]



- Bootstrap injection that also mitigate e-cloud instabilities [Bartosik24]



- → The strength of the beam-beam interaction becomes limited by the lattice momentum acceptance (beamstrahlung lifetime)



Muon colliders

- Multibunch operation is disfavored (The luminosity goes linearly with the number of bunches but quadratically with the bunch population)

- With a 'single pipe' acceleration chain, there will be beam-beam interactions in the re-circulating LINACs and rapid cycling synchrotrons, not only in the collider ring.

- Due to the short lifetime, the beam-beam force is strong only for few turns (~100), much larger beam-beam tune shift might be tolerable.

To be studied...

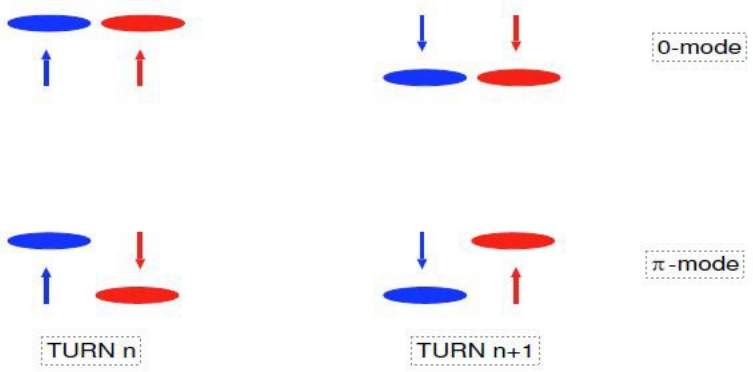
Beam beam limit at LHC: why so much higher?

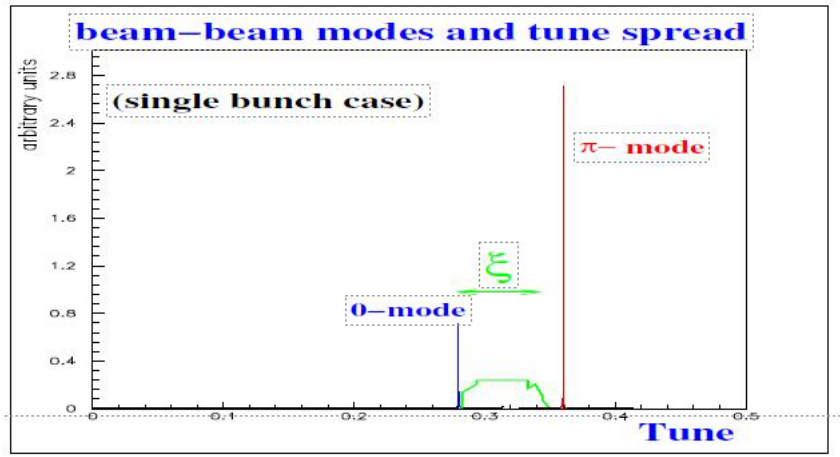
	LEP (e^+e^-)	LHC (pp)
Beam sizes	160 - 200μm · 2 - 4μm	16.6μm · 16.6μm
Intensity N	$4.0 \cdot 10^{11}$/bunch	$1.15 \cdot 10^{11}$/bunch
Energy	100 GeV	7000 GeV
$\beta_x^* \cdot \beta_y^*$	1.25 m · 0.05 m	0.55 m · 0.55 m
Crossing angle	0.0	285 μrad
Beam-beam parameter(ξ)	(+) 0.0700	(−) 0.0034

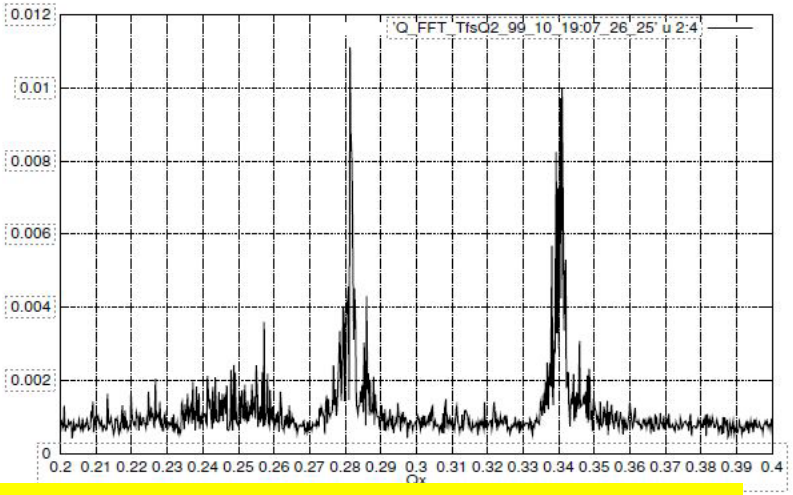
X 2-3?

Diagnostics and observables

- Beam-beam tune shift: is it a good measure of beam-beam interaction?
  - But! Close to integer resonances dynamic beta inflation!
  - **Why is it larger than expected in the new/higher energy machines???**
- Coherent modes (σ and π modes): beautiful observations at LEP







Need tools to measure the nonlinear aspects! Usable and be used!

Rise of interplays

"Although beam-beam simulations have advanced in the past **25 years** or so, more ingredients need to be incorporated to make them more realistic, such as non-linear lattice maps, **field calculations** with bunch length effects, current-dependent effects […] and errors such as jitter and off-center collisions."

(after *M.A. Furman @ eeFACT97)*

Most of these aspects will be discussed this week !

Challenges to design better colliders

Maximum Integrated vs. peak luminosity

- Hadrons: leveling schemes, radiation damping
- Leptons: top-up injection

Machine Detector Interface (MDI)

- Hadrons: pile-up: 10^9 – 10^{11} interactions/s, x100 particles/s
- Hadrons & Leptons: Backgrounds in the detectors!

Improved simulation tools and
… their benchmarking (LHC, SUPERKEKB, etc.)

Relevant observables!

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Thank You

Wishing you a good workshop
and
lots of new ideas