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The Challenges of a Storage Ring-based Higgs Factory

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Caveat emptor

This is a zero-order pedagogical look
based on basic accelerator physics
My numbers are not CERN's numbers,
but they are quite close (~5%)

For a more precise analysis
based on a real lattice design look at
arXiv: 1112.2518.pdf
by F. Zimmermann and A. Blondel

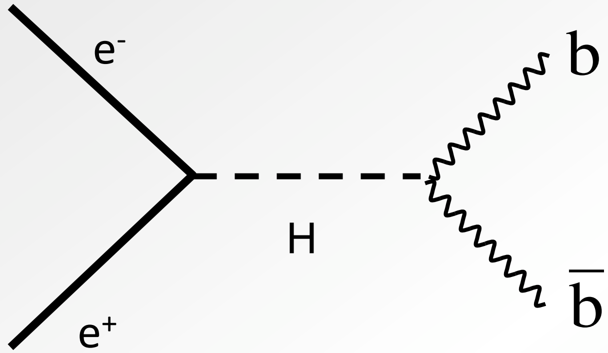
Scenario: LHC has discovered the Higgs

- Your HEP friends want to study its properties
  - "Monte Carlo studies show that you need ~ 25 K Higgs for a paper that can get the cover of Nature"
  - They & their students don't want to be on shift for a lifetime
- They comes to you, his favorite machine builder

  "We *need* to build a factory to produce 6000 Higgs per year. Projected costs (€ 15 B) all but killed the ILC. Now we know that we don't need 500 GeV. What about something half that energy?"
- You reply,
  - "You don't understand about linacs. Half the energy costs you 75% of the original price."

"Let's try something different - a storage at CERN .
After all LEP 2 got up to 209 GeV."

What LEP2 might have seen
How can we produce a Higgs with e^+e^-?



They respond, "Exactly, but they did not see anything!

The cross-section ~ 2 fb. They would have had to run for decades.

A muon collider would be ideal. The σ_H is 40,000 times larger."

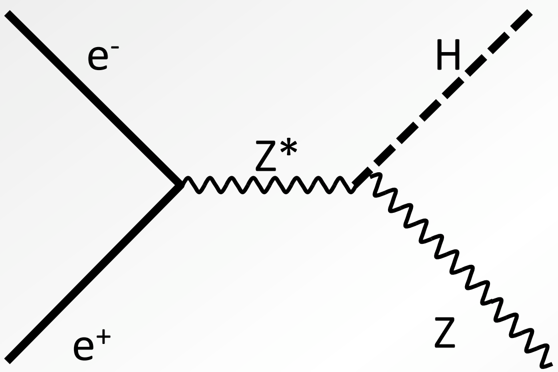
"True," you reply, "be we don't even know if it is possible.

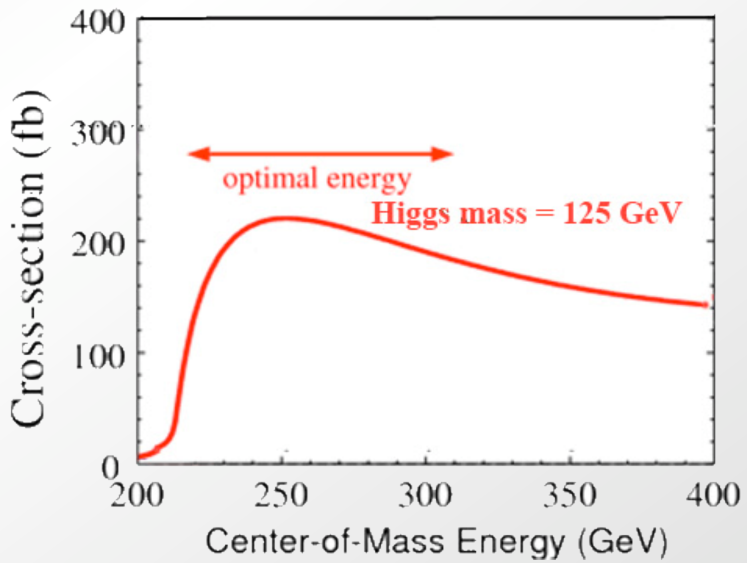
Let's go back to storage rings. How much energy do you need?"

Dominant reaction channel with sufficient σ

- $e^+ + e^- \Longrightarrow Z^* \Longrightarrow H + Z$

- $M_H + M_Z = 125 + 91.2 = 216.2\ \mathrm{GeV}/c^2$





==> set our CM energy at the peak σ: **~240 GeV**

Physics "facts of life" of a Higgs factory
Will this fit in the LHC tunnel?

- Higgs production cross section ~ 220 fb (2.2 x 10^{-37} cm^2)
- Peak $\mathcal{L} = 10^{34}$ cm^{-1} s^{-1} ==> $< \mathcal{L} >$ ~ 10^{33} cm^{-1} s^{-1}
- ~30 fb^{-1} / year ==> 6600 Higgs / year
- Total e^+e^- cross-section is ~ 100 pb • (100GeV/E)^2
  - Will set the luminosity lifetime

We don't have any choice about these numbers

Oh, and don't use more than 200 MW of electricity

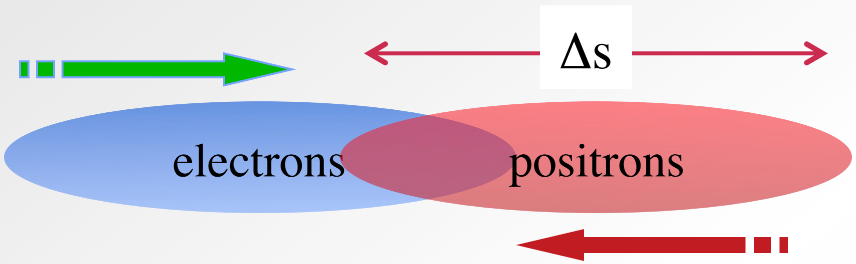
Road map for the analysis

- How do "facts of life" affect the peak luminosity
  - First some physics about beam-beam interactions

  ==> Luminosity as function of I_{beam} and E_{beam}
  - What $ß^*$ is needed?
- What is the bunch length, σ_z, of the beam?
- How does rf system give us σ_z
  - What are relevant machine parameters, α_c, f_{rev}, f_{rf}, ϕ_{synch}, etc.
  - But first, what is ΔE/E
- How synchrotron radiation comes in
  - What is the rf system
  - What sets the beam size at the IP
- What are life time limitations
- Conclusions

Storage ring physics: Beam-beam tune shifts

Space charge fields at the Interaction Point



At the IP space charge cancels; but the currents add ==> the IP is a "lens"

i.e, it adds a gradient error to the lattice, ($k_{space\ charge}\Delta s$)

where ($k_{space\ charge}\Delta s$) is the kick ("spring constant') of the space charge force

Therefore the tune shift is

$$\Delta Q = -\frac{1}{4\pi}\beta^*(s)(k\Delta s)$$

For a Gaussian beam, the space charge kick gives

$$\Delta Q \approx \frac{r_e}{2}\frac{\beta^* N}{\gamma A_{int}}$$

Effect of tune shift on luminosity

- The luminosity is $$\mathcal{L} = \frac{f_{coll} N_1 N_2}{4 A_{\text{int}}}$$
- Write the area in terms of emittance & β at the IR (β^*)

$$A_{\text{int}} = \sigma_x \sigma_y = \sqrt{\beta_x^* \varepsilon_x} \circ \sqrt{\beta_y^* \varepsilon_y}$$

- For simplicity assume that

$$\frac{\beta_x^*}{\beta_y^*} = \frac{\varepsilon_x}{\varepsilon_y} \Rightarrow \beta_x^* = \frac{\varepsilon_x}{\varepsilon_y} \beta_y^* \Rightarrow \beta_x^* \varepsilon_x = \frac{\varepsilon_x^2}{\varepsilon_y} \beta_y^*$$

- In that case

$$A_{\text{int}} = \varepsilon_x \beta_y^*$$

- And

$$\mathcal{L} = \frac{f_{coll} N_1 N_2}{4 \varepsilon_x \beta_y^*} \sim \frac{I_{beam}^2}{\varepsilon_x \beta_y^*}$$

To maximize luminosity,
Increase N to the tune shift limit

- We saw that

$$\Delta Q_y \approx \frac{r_e}{2} \frac{\beta^* N}{\gamma A_{\text{int}}}$$

Or, writing N in terms of the tune shift,

$$N = \Delta Q_y \frac{2\gamma A_{\text{int}}}{r_e \beta^*} = \Delta Q_y \frac{2\gamma \varepsilon_x \beta^*}{r_e \beta^*} = \frac{2}{r_e} \gamma \varepsilon_x \Delta Q_y$$

Therefore the tune shift limited luminosity is

$$\mathcal{L} = \frac{2}{r_e} \Delta Q_y \frac{f_{coll} N_1 \gamma \varepsilon_x}{4 \varepsilon_x \beta_y^*} \sim \Delta Q_y \left(\frac{IE}{\beta_y^*} \right)$$

Tune shift limited luminosity of the collider

$$L = \frac{N^2 c\gamma}{4\pi\varepsilon_n \beta^* S_B} = \frac{1}{e r_i m_i c^2} \frac{N r_i}{4\pi\varepsilon_n} \left(\frac{EI}{\beta^*} \right) = \frac{1}{e r_i m_i c^2} \frac{N r_i}{4\pi\varepsilon_n} \left(\frac{P_{beam}}{\beta^*} \right) \qquad i = e,p$$

Linear or Circular

Tune shift

In practical units for electrons

$$\mathcal{L}_{peak} = 2.17 \circ 10^{34} \left(1 + \frac{\sigma_x}{\sigma_y} \right) \Delta Q_y \left(\frac{1\ \text{cm}}{\beta^*} \right) \left(\frac{E}{1\ \text{GeV}} \right) \left(\frac{I}{1\ \text{A}} \right)$$

Experimentally, at the tune shift limit $\left(1 + \frac{\sigma_x}{\sigma_y} \right) \Delta Q_y \approx 0.1$ for electrons

$$\mathcal{L}_{peak} = 2.17 \circ 10^{33} \left(\frac{1\ \text{cm}}{\beta^*} \right) \left(\frac{E}{1\ \text{GeV}} \right) \left(\frac{I}{1\ \text{A}} \right)$$

We can only choose I(A) and ß*(cm)

- For the LHC tunnel with $f_{dipole} \sim 2/3$, $\rho_{curvature} \sim 2700$ m
- Remember that

$$\rho(\mathrm{m}) = 3.34 \left(\frac{p}{1\ \mathrm{GeV/c}}\right)\left(\frac{1}{q}\right)\left(\frac{1\ \mathrm{T}}{B}\right)$$

- Therefore, $B_{max} = 0.15$ T
- Per turn, each beam particle loses to synchrotron radiation

$$U_o(keV) = 88.46 \frac{E^4(GeV)}{\rho(m)}$$

or 6.54 GeV per turn

I_{beam} = 7.5 mA ==> ~100 MW of radiation (2 beams)

CERN management "chose" I;
That leaves β* as the only free variable

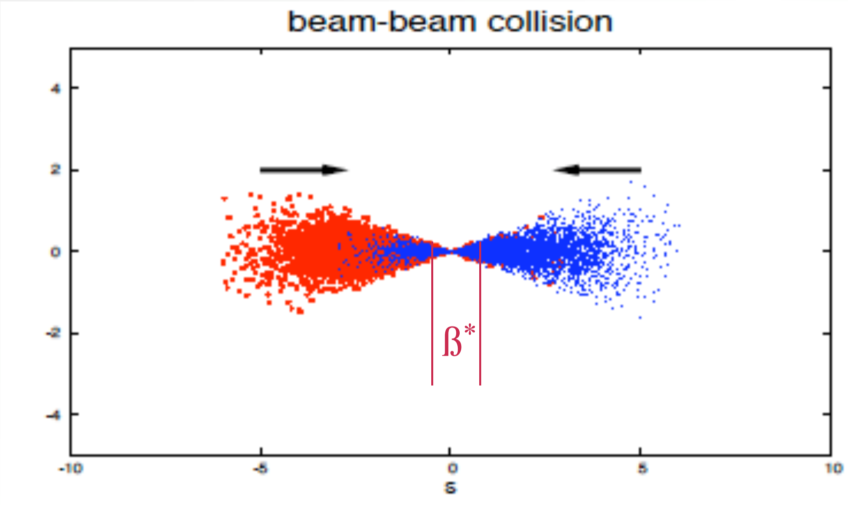
- Then

$$L_{peak} \approx 1.9 \circ 10^{33} \left(\frac{1\ \mathrm{cm}}{\beta^*} \right)$$

- Therefore to meet the luminosity goal

$<\beta^*_x \beta^*_y>^{1/2} \sim 0.2$ cm   *(10 x smaller than LEP 2)*

- Is this possible? Recall that is the depth of focus at the IP



The "hourglass effect" lowers $\mathcal{L}$

For maximum luminosity

==> $\sigma_z \sim \beta^* \sim 0.2$ cm

Bunch length, $\sigma_{z,}$ is determined by ω_{rf} & V_{rf}

- The analysis of longitudinal dynamics gives

$$\sigma_z = \frac{c\alpha_C}{\Omega_{sync}} \frac{\sigma_p}{p_0} = \sqrt{\frac{c^3}{2\pi q} \frac{p_0 \beta_0 \eta_C}{h\, f_0^2\, \hat{V} \cos(\varphi_S)}}\, \frac{\sigma_p}{p_0}$$

where $\alpha_c = (\Delta L/L) / (\Delta p/p)$

- If the beam size is ~100 μm in most of the ring

$$\frac{\Delta L}{L} < \frac{0.01}{280000} \approx 3 \times 10^{-7}$$

for electrons to stay within σ_x of the design orbit

- To know bunch length & α_c we need to know $\Delta p/p \sim \Delta E/E$

Bunch length, σ_{z}, is determined by ΔE/E

- For electrons to a good approximation

$$\Delta E \approx \sqrt{E_{beam} < E_{critical,\,photon} >}$$

and

$$\varepsilon_c[keV] = 2.218\frac{E[GeV]^3}{\rho[m]} = 0.665 \cdot E[GeV]^2 \cdot B[T]$$

- So $\varepsilon_{crit} \approx 1.5$ MeV ==> ΔE/E ≈ .0035

- Therefore for electrons to remain near the design orbit

$$\alpha_c = (\Delta L/L) / (\Delta p/p) \sim 8 \times 10^{-5}$$

(was 1.8×10^{-4} for LEP2)

The rf-bucket contains ΔE/E in the beam

- As $U_o \sim 6.5$ GeV,

  $V_{rf,max} > 6.5$ GeV + "safety margin" to contain ΔE/E

- Some addition analysis

$$\left(\frac{\Delta E}{E}\right)_{\max} = \sqrt{\frac{q\hat{V}_{\max}}{\pi h \alpha_c E_{synchronous}}\left(2\cos\varphi_s + (2\varphi_s - \pi)\sin\varphi_s\right.}$$

where h is the harmonic number ($\sim C_{LEP3} / \lambda_{rf} \sim 9 \times 10^4$)

- The greater the over-voltage, the shorter the bunch

$$\sigma_S = \frac{c\alpha_C}{\Omega_{synch}}\left(\frac{\Delta E}{E}\right) = \sqrt{\frac{c^3}{2\pi q}\frac{p_0\beta_0\alpha_C}{h\, f_{rev}^2\, \hat{V}_{\max}\cos(\varphi_S)}}\left(\frac{\Delta E}{E}\right)$$

For the Higgs factory…

- The maximum accelerating voltage must exceed 9 GeV
  - Also yields σ_z = 3 mm which is okay for ß* = 1 mm
- A more comfortable choice is 11 GeV (it's only money)
  - ==> CW superconducting linac for LEP 3 ==> ϕ_{synch}
- Therefore, we need a SCRF linac in 4 pieces
  - Remember that the beam loses ~ 6% of its energy in one turn

    LEP2 lost 3.4 GeV ~ 3% per turn
  - We need a higher gradient than LEP2; 6 MeV/m is not enough
  - 22 MeV/m ==> 500 m of linac *(the same as LEP 2)*
- High gradient ==> f_{rf} > 1GHz ;

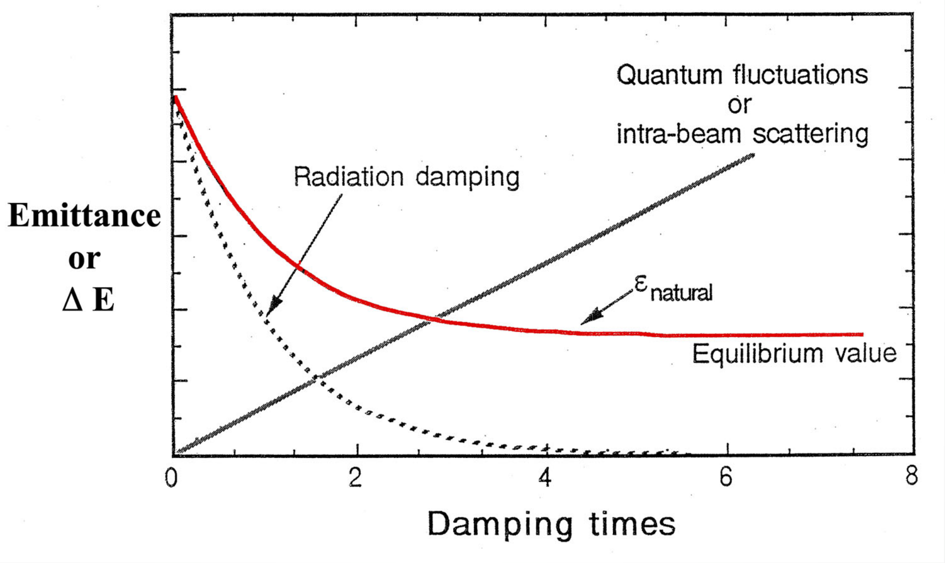
For the Higgs factory…

- The maximum accelerating voltage must exceed 9 GeV
  - Also yields σ_z = 3 mm which is okay for ß* = 1 mm
- A more comfortable choice is 11 GeV (it's only money)
  - ==> CW superconducting linac for LEP 3
  - This sets the synchronous phase
- For the next step we need to know the beam size

$$\sigma_i^* = \sqrt{\beta_i^* \varepsilon_i} \text{ for } i = x, y$$

- Therefore, we must estimate the natural emittance which is determined by the synchrotron radiation ΔE/E

The minimum horizontal emittance for an achromatic transport



$$\varepsilon_{x,\min} = 3.84 \times 10^{-13}\left(\frac{\gamma^2}{J_x}\right)F^{\min} \text{ meters}$$

$$\approx 3.84 \times 10^{-13}\gamma^2\left(\frac{\theta^3_{achromat}}{4\sqrt{15}}\right) \text{ meters}$$

$$\varepsilon_y \sim 0.01\ \varepsilon_x$$

Because α_c is so small, we cannot achieve the minimum emittance

- For estimation purposes we will choose 20 ε_{min} as the mean of the x & y emittances
- For the LHC tunnel a maximum practical dipole length is 15 m
  - A triple bend achromat ~ 80 meters long ==> $\theta = 2.67\times10^{-2}$

$$\langle\varepsilon\rangle \sim 7.6 \text{ nm-rad} \Longrightarrow \sigma_{transverse} = 2.8\ \mu\text{m}$$

How many particles are in the bunch?

Or how many bunches are in the ring?

We already assumed that the luminosity is at the tune-shift limit

❖ We have

$$L = \frac{N^2 c\gamma}{4\pi\varepsilon_n \beta^* S_B} = \frac{1}{e r_i m_i c^2} \frac{N r_i}{4\pi\varepsilon_n}\left(\frac{EI}{\beta^*}\right) = \frac{1}{e r_i m_i c^2} \frac{N r_i}{4\pi\varepsilon_n}\left(\frac{P_{beam}}{\beta^*}\right) \qquad i = e,p$$

Linear or Circular

Tune shift

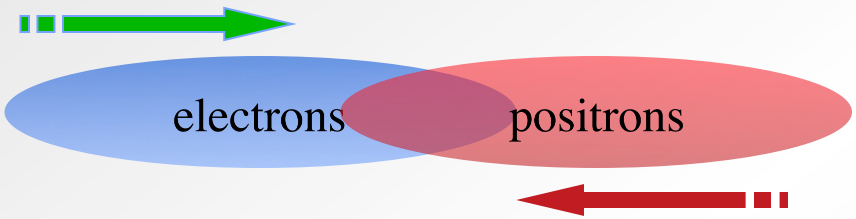
❖ Or

$$Q = \frac{N r_e}{4\pi\varepsilon\gamma} \quad \Rightarrow \quad N = \frac{4\pi\varepsilon\gamma}{r_e} Q$$

❖ So, $N_e \sim 1.3 \times 10^{11}$ per bunch

❖ I_{beam} = 7.5 mA ==> there are only 3 bunches in the ring

Let' s return to
Space charge fields at the collision point



At the IP space charge cancels; currents add

==> strong beam-beam focus

=> Luminosity enhancement

=> Very strong synchrotron radiation (beamstrahlung)

Beamstrahlung is important in linear colliders

What about the beams in LEP-3?

At the collision point…with $\mathcal{L}$ =10^{34}

$$I_{peak} = N_e / 2\sigma_z \implies I_{peak} \sim 1.6 \text{ kA}$$

- Therefore, at the beam edge (σ)

$$B = I(A)/5r(cm) = 1.6 \text{ MG !}$$

- When the beams collide they emit synchrotron radiation (beamstrahlung)

$$\varepsilon_{c,Beams}[keV] = 2.218 \frac{E[GeV]^3}{\rho[m]} = 0.665 \cdot E[GeV]^2 \cdot B[T] = 1.1 \text{ GeV}$$

- But this accumulates over a damping time

$\Delta E_{Beams} \approx (2/J_E)$*Sqrt (number of turns in damping time) $\varepsilon_{c,Beams} \approx 10$ GeV

The rf-bucket must be very large to contain such a big ΔE/E

Beamstrahlung limits beam lifetime & energy resolution of events

At $\mathcal{L}$ =2x10^{33}

- $\beta^* \sim 1.5$ cm ==> 9 GeV of linac is okay
- I_{peak} can be reduced 3 x and …
- The beam size can increase 3 x
- ==> B_{sc} is reduced ~10 x ==> $\Delta E_{Beams} \sim 1$ GeV
  - This is < 1% of the nominal energy
  - Many fewer electrons will be lost

A much easier machine to build and operate

Yokoya has done a more careful analysis

- Beamstrahlung limited luminosity

$$\mathcal{L} = 4.57 \times 10^{33} \left(\frac{\rho}{1\ km}\right)\left(\frac{P_{SR}}{100\ \mathrm{MW}}\right)\sqrt{\frac{(\Delta E_{beams}/E)}{0.1\%}}\left(\frac{100\ \mathrm{GeV}}{\mathrm{E}}\right)^{4.5}\left(\frac{1\ \mathrm{nm}}{\varepsilon_{\mathrm{y}}}\right)^{1/2}\ \mathrm{cm}^{-2} s^{-1}$$

- This implies very large rings, high beam power, and small vertical emittance

Mechanisms limiting beam lifetime

- Luminosity lifetime

  Total e^+e^- cross-section is ~ 100 pb • $(100 GeV/E)^2$

- Beamstrahlung lifetime

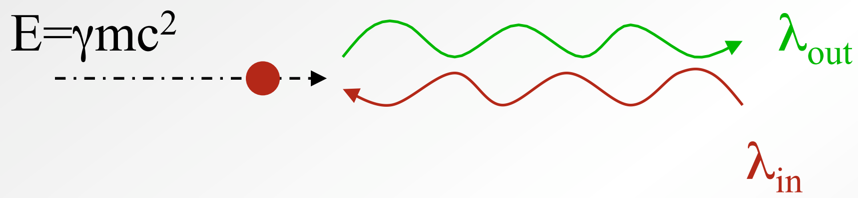
- Beam-gas scattering & bremsstrahlung

- Tousheck lifetime

- And…

And there are other problems

- Remember the Compton scattering of photons up shifts the energy by 4 γ^2



- Where are the photons?
  - The beam tube is filled with thermal photons (25 meV)

- In LEP-3 these photons can be up-shifted as much as 2.4 GeV
  - 2% of beam energy cannot be contained easily
  - We need to put in the Compton cross-section and photon density to find out how rapidly beam is lost

The bottom line:
The beam lifetime is 10 minutes

- We need a powerful injector
- Implies rapid decay of luminosity as operation shrinks away from tune shift limit

==> we need top-off operation

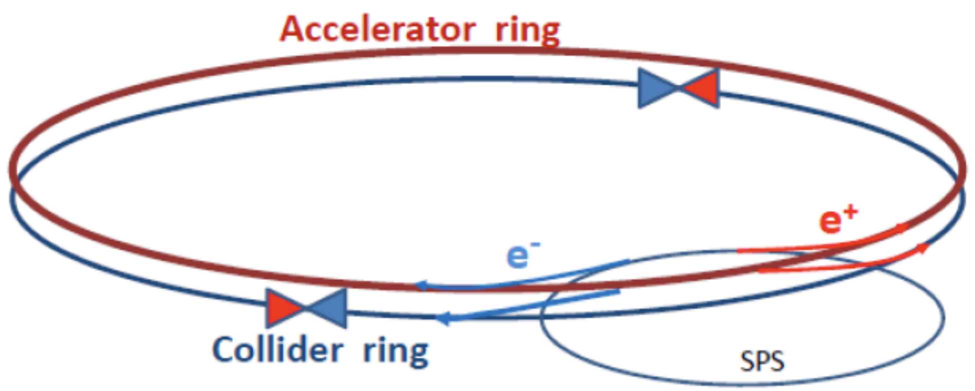


Figure 2 Possible two ring sketch for LEP3: a first ring (accelerator ring) accelerates electrons and positrons up to operating energy (120 eV) and injects them at a few minutes interval into the low emittance collider ring in which the high luminosity $10^{34}/cm^2/s$ interaction points are situated.

From Zimmermann & Blondel

Conclusions (for $\mathcal{L}$ =2x10^{34})

- LEP3 is a machine at the edge of physics feasibility
  - Beamstrahlung issues require more, detailed study
  - Momentum aperture must be very large
  - 240 GeV is the limit in the LHC tunnel
- The cost appears to be << a comparable linear collider
- A very big perturbation of LHC operations
- Cannot run at the same time as the LHC

The LEP3 idea might be a viable alternative as a future HEP project