The FCC-ee machine

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Acknowledgements

- I would like to thank
  - the pioneers of the modern circular Higgs factory idea: **Roy Aleksan, Alain Blondel, John Ellis, Patrick Janot, Frank Zimmermann**

A. Blondel F. Zimmermann M. Koratzinos J. Ellis P. Janot R. Aleksan

  - The whole FCC community
  - In particular A. Blondel, M. Benedikt, F. Zimmermann, K. Oide, A. Butterworth, D. Shatilov for the liberal use of material

Why?

The backdrop

- The Standard Model is complete, but it is not a complete theory
- Major problems:
  - What is the origin of lepton/baryon asymmetry?
  - What is the origin of dark matter?
  - What is the nature of neutrinos?
  - What is the solution to the hierarchy problem?
  - (plus even more profound questions)

Where is the new physics?

- The Higgs is light and SM-like
- No indication of new physics so far
- => the energy scale of new physics (Beyond the Standard Model) Λ has been pushed above ~few $\times$ 100GeV
- The new LHC run will extend this by a factor ~2
- A new project will be needed to push the Λ reach to O(10) to O(100)TeV
- (although there is no guarantee of discovery, the fine-tuning needed goes with the square of Λ, making the SM increasingly problematic)

Precision needed – Higgs sector

- New physics at an energy scale of 1 TeV would translate typically into deviations δg_{HXX} of the Higgs boson couplings to gauge bosons and fermions, g_{HXX}^{SM}, of up to 5% with respect to the Standard Model predictions, with a dependence that is inversely proportional to the square of the new energy scale Λ:

$$\frac{\delta g_{HXX}}{g_{HXX}^{SM}} \leq 5\% \times \left(\frac{1TeV}{\Lambda}\right)^2$$

Therefore the Higgs boson couplings need to be measured with a per-cent accuracy or better to be sensitive to 1 TeV new physics, and with a per-mil accuracy to be sensitive to multi-TeV new physics.

A possible strategy

1. A first step could require a facility that would measure the Z, W, top-quark and Higgs-boson properties with sufficient accuracy to provide sensitivity to new physics at a much higher energy scale.
2. This stage could then be followed by a second step that would aim at discovering this new physics directly, via access to a much larger centre-of-mass energy than the LHC.
3. (The details of the optimal strategy for the next large facility can only be finalized once the results of the LHC run at 13 TeV are known.)

The FCC project answers points (1) and (2) above: a new circular tunnel can house a high-luminosity Z,W,t,H factory (E_{CM} 90 to 350GeV) and later on a 100TeV collider

How much luminosity is needed?

The desire from our experimental colleagues to make full use of expected accuracies, translates to the following table with the desired statistics. The question is, what kind of luminosities can be achieved and, therefore, how long would this physics programme have to be?

	$\sqrt{s}$ (GeV)	No. of events
Z	90	10^{12}
W	160	5×10^{7}
H	240	3.5×10^{6}
t	340-370	1.7×10^{6}

⇨ See talk by A. Blondel, this workshop

(Answer: with the luminosities that will be presented, ~10 years of physics will cover these physics goals)

History of the FCC and milestones: from an idea to an international collaboration

The brief history of FCC

The paper that revived the idea: arXiv:1112.2518 [hep-ex]

CERN-OPEN-2011-047

12 December 2011

Version 2.1

A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson

Alain Blondel[1], Frank Zimmermann[2]

[1]DPNC, University of Geneva, Switzerland; [2]CERN, Geneva, Switzerland

First international discussions: HF2012 at Fermilab:
http://indico.fnal.gov/conferenceDisplay.py?confId=5775

Following a recommendation of the European Strategy report, in fall 2013 CERN Management set up the FCC project, with the main goal of preparing a Conceptual Design Report by the time of the next European strategy update (~2018)

FCC kick-off meeting took place on 12-15 February 2014 at University of Geneva
http://indico.cern.ch/event/282344/timetable/#20140212.detailed
Very successful, almost 350 participants, strong international interest

Links established with similar studies in China and in the US, already a series of successful workshops

European Strategy Update 2013

Extracts: Design studies and R&D at the energy frontier

(The committee urges CERN) ...“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

d) ***CERN should undertake design studies for accelerator projects in a global context,***

- *with emphasis on* ***proton-proton and electron-positron high-energy frontier machines****.*
- *These design studies should be coupled to a vigorous accelerator* ***R&D programme, including high-field magnets and high-gradient accelerating structures****,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***

- http://cds.cern.ch/record/1567258/files/esc-e-106.pdf

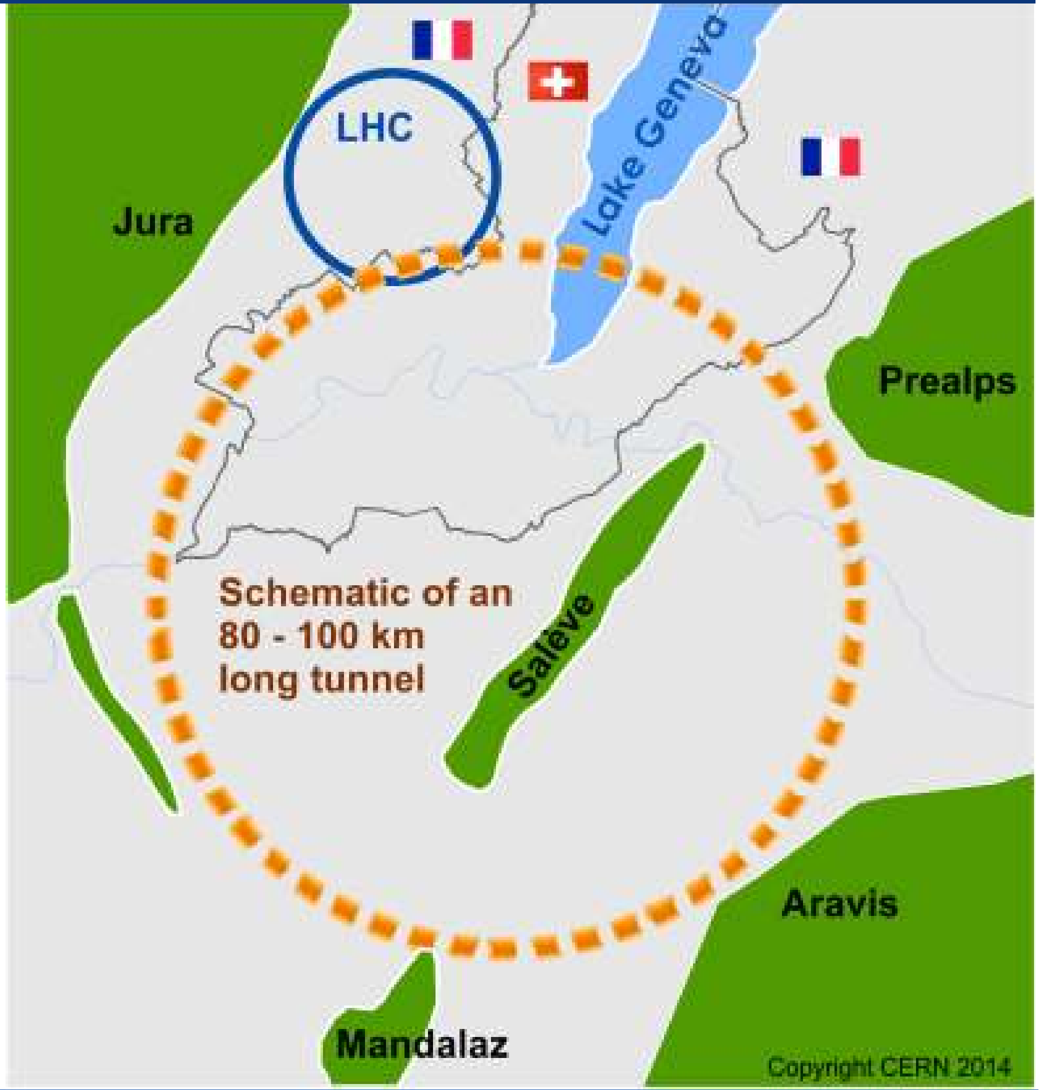
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

International FCC collaboration (CERN as host lab) to study:

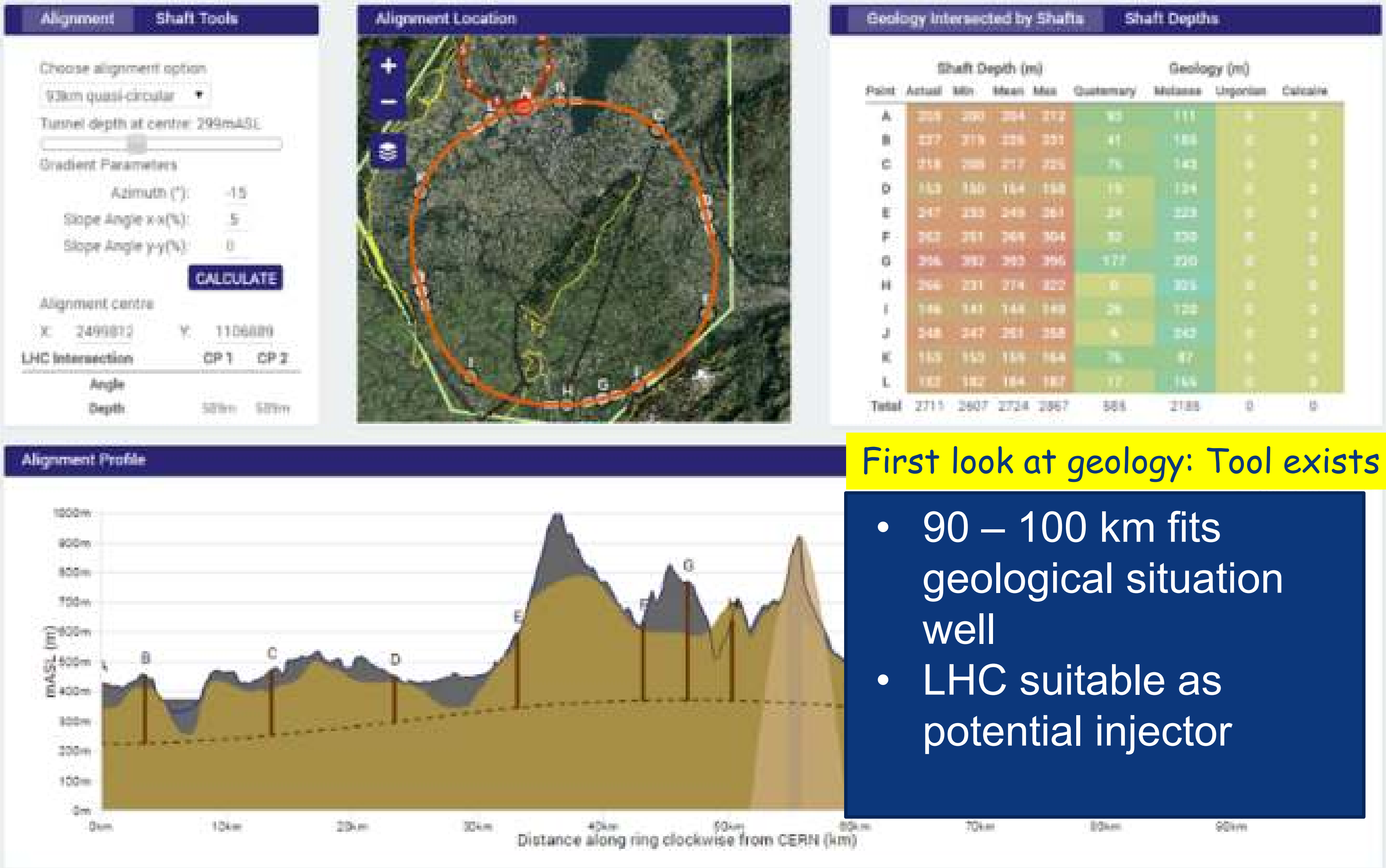
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km infrastructure** in Geneva area
- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (FCC-he) option**



Site studies



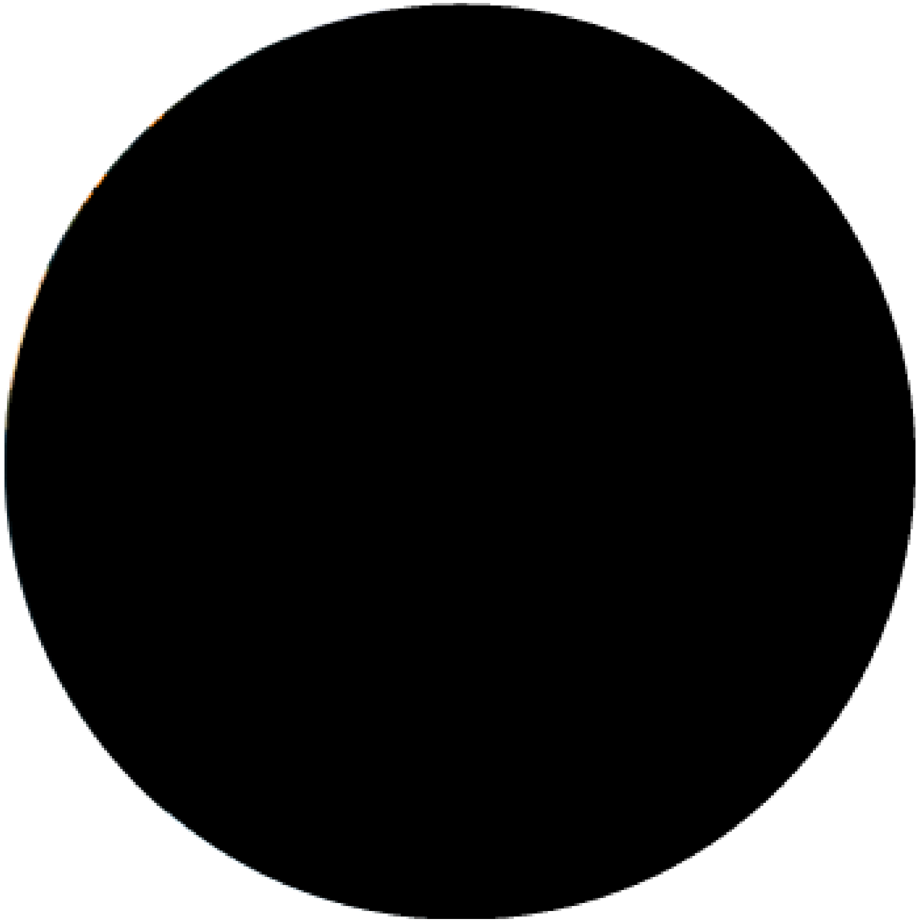
First look at geology: Tool exists

- 90 – 100 km fits geological situation well
- LHC suitable as potential injector

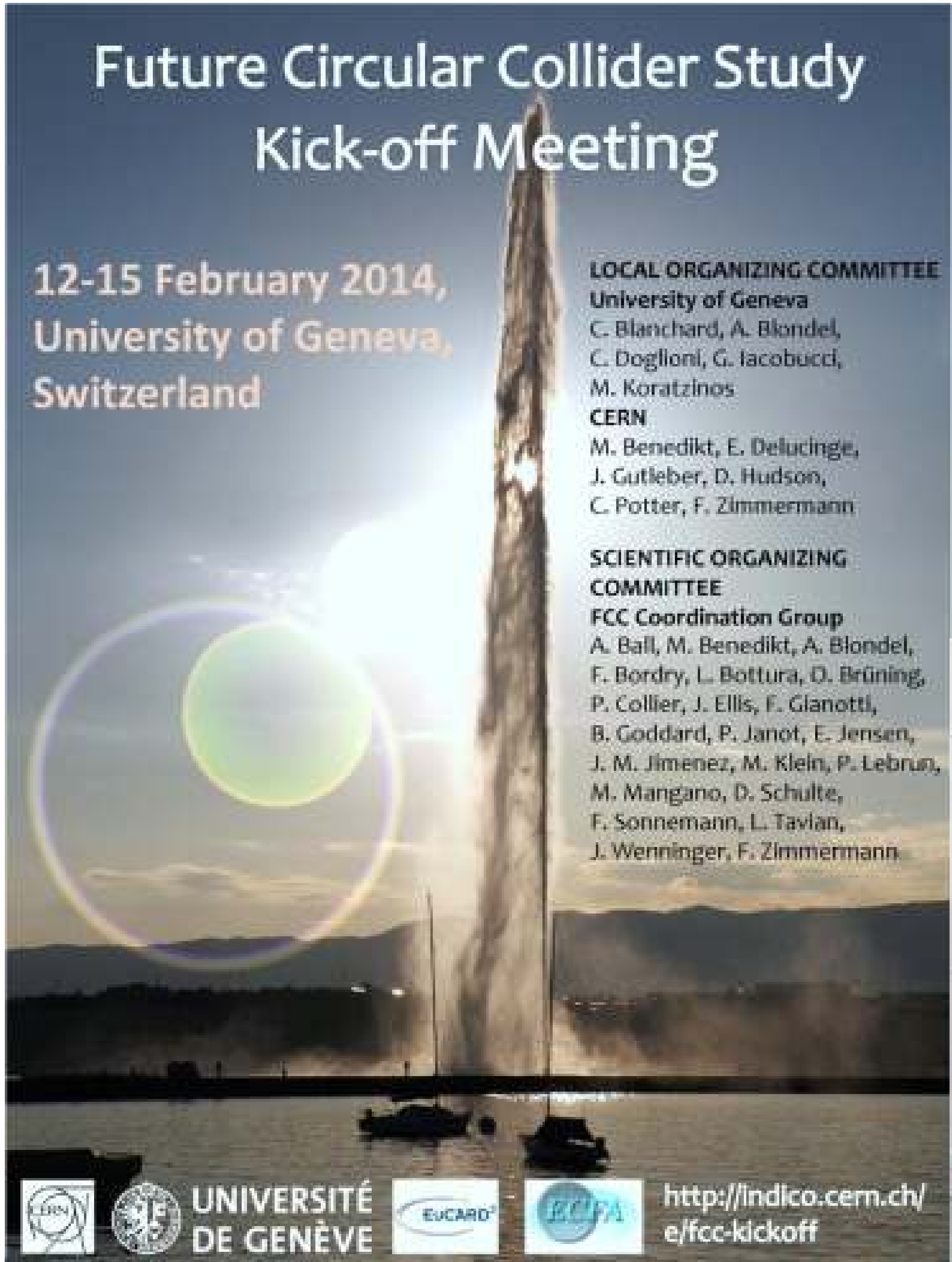
J. Osborne & C. Cook

FCC International Collaboration

- 58 institutes
- 22 countries + EC



Status: July 30, 2015



FCC Kick-off Meeting
University of Geneva
12-15 February 2014

~340 participants

Principles of circular machines

The circular e+e- collider approach

For the high luminosities aimed at, the beam lifetimes due to natural physics processes (mainly radiative Bhabha scattering) are of the order of a few minutes – the accelerator is 'burning' the beams up very efficiently

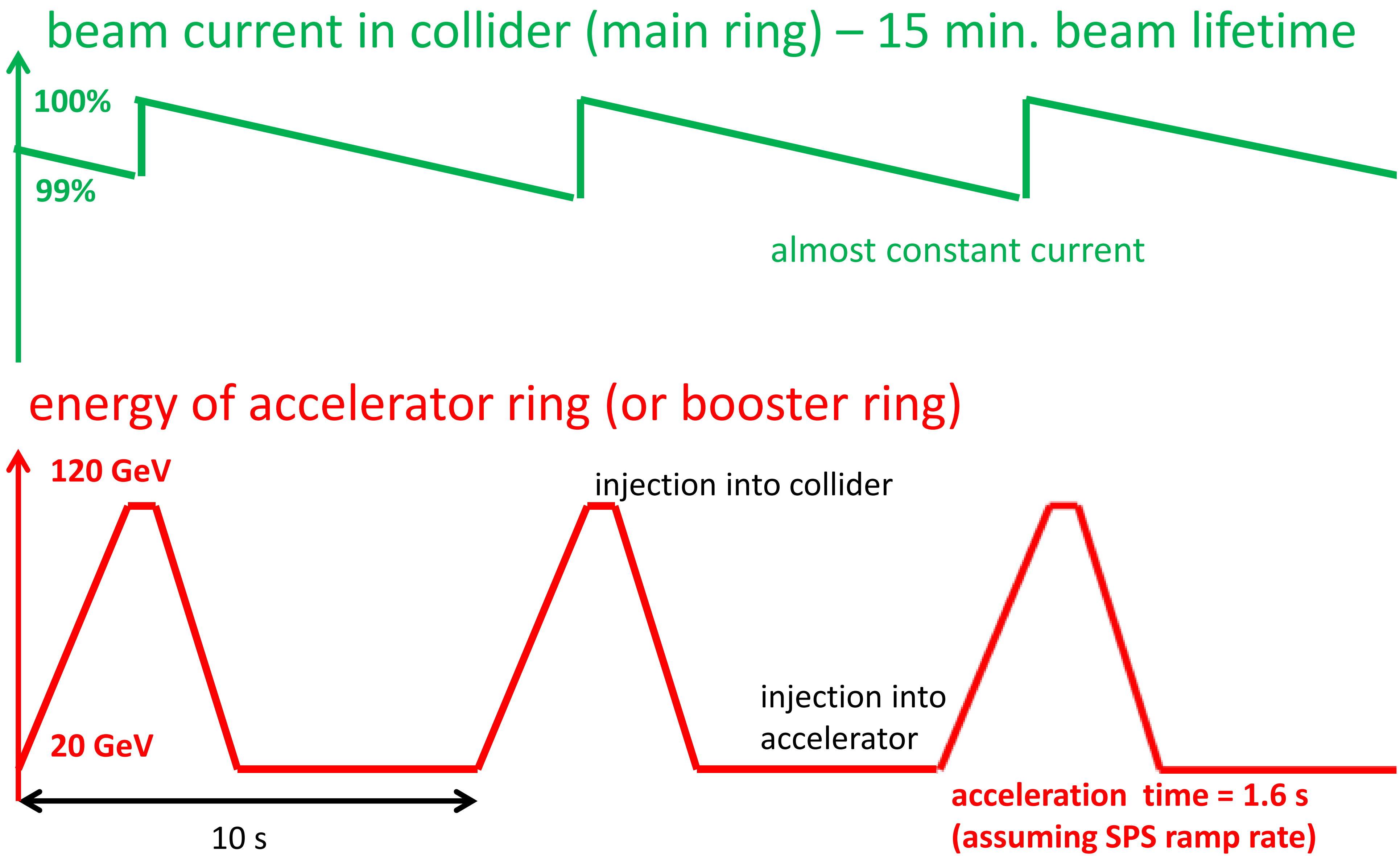
A "top-up" scheme (*a la* B factories) is a must

A. Blondel

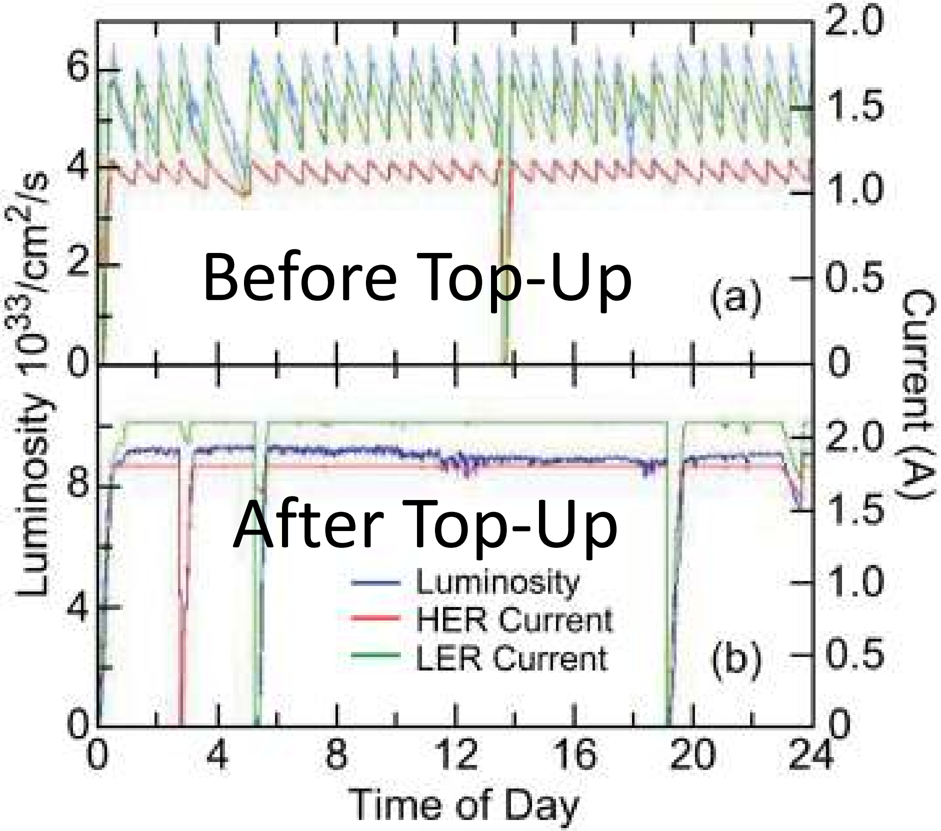
- Booster ring the same size as main ring, tops up the main ring every ~O(10s)
- Main ring does not ramp up or down

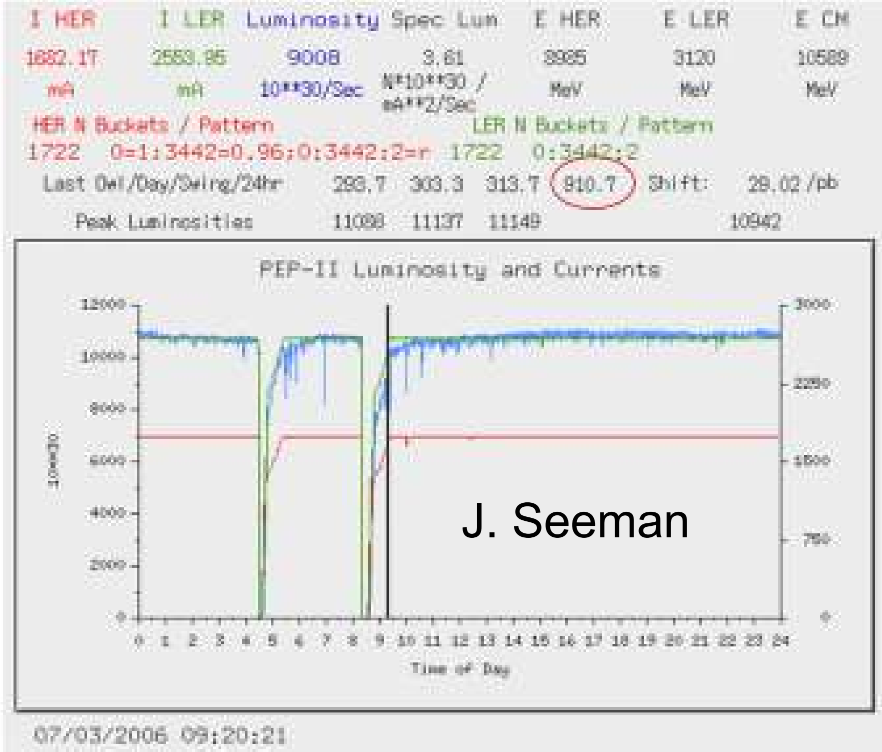
- What kind of luminosities can be achieved?
- How big a ring needs to be?
- How much power will it consume?

top-up injection: schematic cycle



top-up injection at PEP-II





J. Seeman

average luminosity ≈ peak luminosity

similar results from KEKB

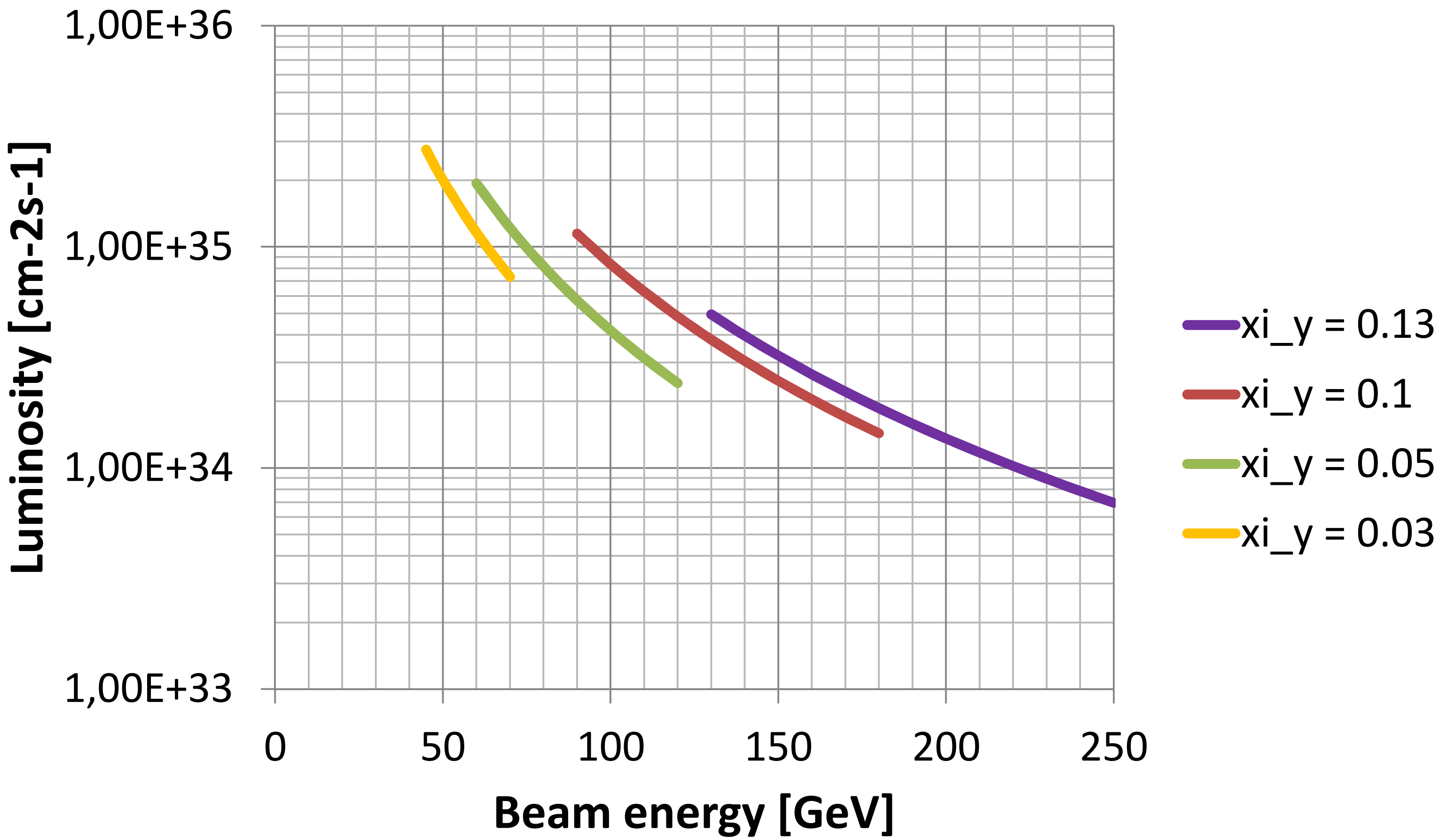
Luminosity of a circular lepton collider

$$\mathcal{L} = const \times P_{tot} \frac{\rho}{{E_0}^3} \xi_y \frac{R_{hg}}{\beta_y^*}$$

The maximum luminosity is bound by the total power dissipated, the maximum achievable beam-beam parameter, the bending radius, the beam energy, the amount of vertical squeezing β_y^* , and the hourglass effect, a geometrical factor (which is a function of σ_z and β_y^*)

$$\mathcal{L} = 6.0 \times 10^{34} \left(\frac{P_{tot}}{50MW}\right)\left(\frac{\rho}{10km}\right)\left(\frac{120GeV}{E_0}\right)^3 \left(\frac{\xi_y}{0.1}\right)\left(\frac{R_{hg}}{0.83}\right)\left(\frac{1mm}{\beta_y^*}\right) cm^{-2}s^{-1}$$

Luminosity for different beam-beam parameters



Luminosity for an 11km radius machine, with 50MW power consumption, beta*_y of 1mm (and longitudinal beam size of 1.2mm)

The beam-beam parameter ξ

$$\xi_y = \frac{N_b r_e \beta_y^*}{2\pi\gamma\sigma_x\sigma_y}$$

- The beam-beam parameter (closely related to tune shift) is a measure of the blow-up of one beam as it goes through the other and has a maximum value on every implementation
- Increasing the beam current or squeezing more when the beam-beam limit has been reached will not increase luminosity
- The more damping in the machine (higher energy, smaller radius) the higher the maximum beam-beam parameter
- There is a lot of literature as to what the maximum ξ_y can be as a function of radius, energy, etc.

Max. beam-beam parameter

$$\xi_y{}^{max} = f(\lambda_d)$$

Where

$$\lambda_d = \frac{1}{f_{rev}\,\tau\,n_{IP}}$$

Is the damping decrement (τ is the transverse damping time). More conveniently:

$$\lambda_d = \left(\frac{U_0}{E}\right)\frac{1}{n_{IP}}$$

Is the fractional energy loss from IP to IP. In terms of energy and bending radius:

$$\lambda_d \propto \frac{E_0{}^3}{\rho\ \ n_{IP}}$$

Max. beam-beam parameter

Using the Assmann & Cornelis analysis (based on LEP and LEP2 data):

$$\xi_y{}^{max} \propto \lambda_d{}^{0.4}$$

Fitting to the LEP and LEP2 data gives:

$$\xi_y^{\max} \approx \frac{0.5}{\tau_s^{0.4}}$$

0.5 → 0.57

Beamstrahlung

- Beamstrahlung is a phenomenon that affects future, very-high-squeeze machines.
- A single hard photon exchange between an electron and the collective electromagnetic field of the opposing bunch changes the momentum of the electron. This can have two adverse effects in a circular accelerator:
  - The bunch length is increased (main effect at low beam energies)
  - The electron can fall out of the momentum acceptance of the machine and beam lifetime is affected
- (In a linear accelerator, beamstrahlung modifies the E_{CM} profile which is no longer monochromatic)
- Beam lifetime increases with $\eta \frac{\sigma_x \sigma_z}{N_b}$ i.e it depends on the momentum acceptance η, the beam sizes in x and z (but not in y!) and the electron bunch population N_b

Beamstrahlung lifetime formula

For the record, the beamstrahlung formula (Bogomyagkov et al) is

$$\tau_{BS} = \frac{8}{3}\frac{\pi R}{n_{IP} c}\sqrt{\frac{2\eta}{\alpha\gamma}}\frac{1}{\sigma_z {r_e}^2}\left(\frac{\sigma_x \sigma_z}{\sqrt{2} N_b}\right)^{3/2} e^u$$

Where

$$u = \frac{\sqrt{2}\alpha}{3\gamma {r_e}^2}\eta\frac{\sigma_x \sigma_z}{N_b}$$

Where
R: bending radius
n_{IP}: number of IPs
α: fine structure constant
γ: Lorenz factor of beam
$\sigma_{x,y,z}$:beam sizes
N_b: number of electrons in a bunch

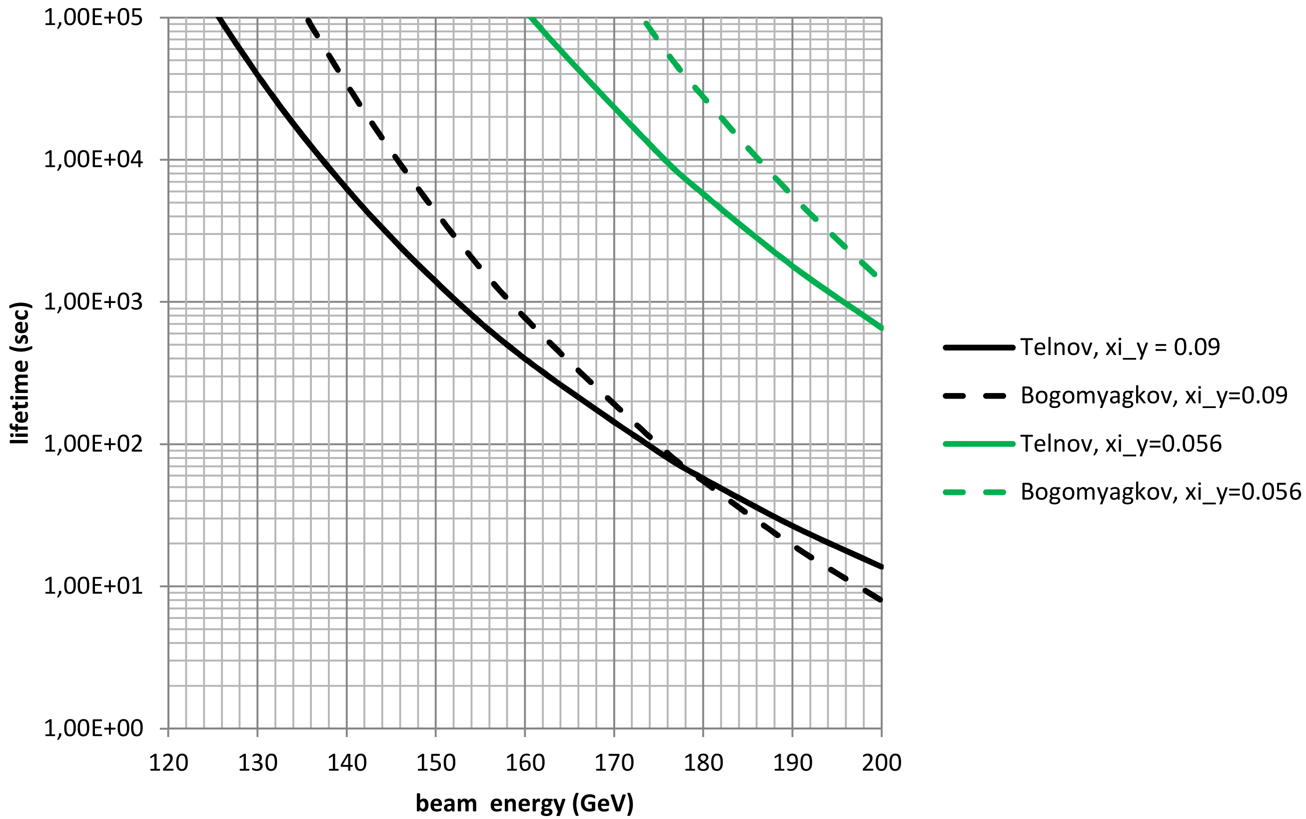
Beamstrahlung becomes important a high energies (where it limits the beam lifetime to unacceptably now values) since u effectively sales with γ^{-2}

Beamstrahlung lifetime

- For the two formulas in the market (difference is small):

TLEP-175 parameters with two different values of xi_y.

Mom. Acceptance = 2%



V. Telnov, "Restriction on the energy and luminosity of e+e- storage rings due to beamstrahlung," Phys. Rev. Letters 110, 114801 (2013) arXiv:1203.6563.

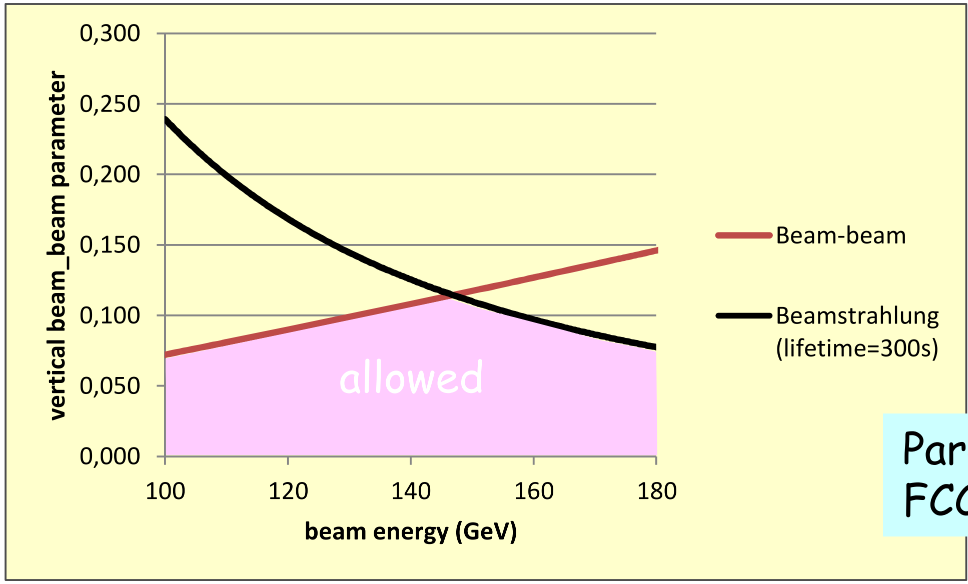
A. Bogomyagkov et al, "Beam-beam effects investigation and parameters optimization for a circular e+e- collider TLEP to study the Higgs boson," arXiv:1311.1580v1.

Number of electrons in a bunch

- Note that in this game, N_b is effectively treated as a free parameter. What is defined by the SR power is the total current, but we can fit the fixed number of electrons in a few or more bunches.
- Number of bunches is inversely proportional to the number of electrons in a bunch (total number of electrons is fixed by SR power)
- So, for a given beam size, we can always chose N_b to run at the maximum allowed beam-beam parameter.
- At low energies, for instance, (for head-on collisions) we can increase beam spot sizes and at the same decrease the number of bunches, and achieve the same luminosity

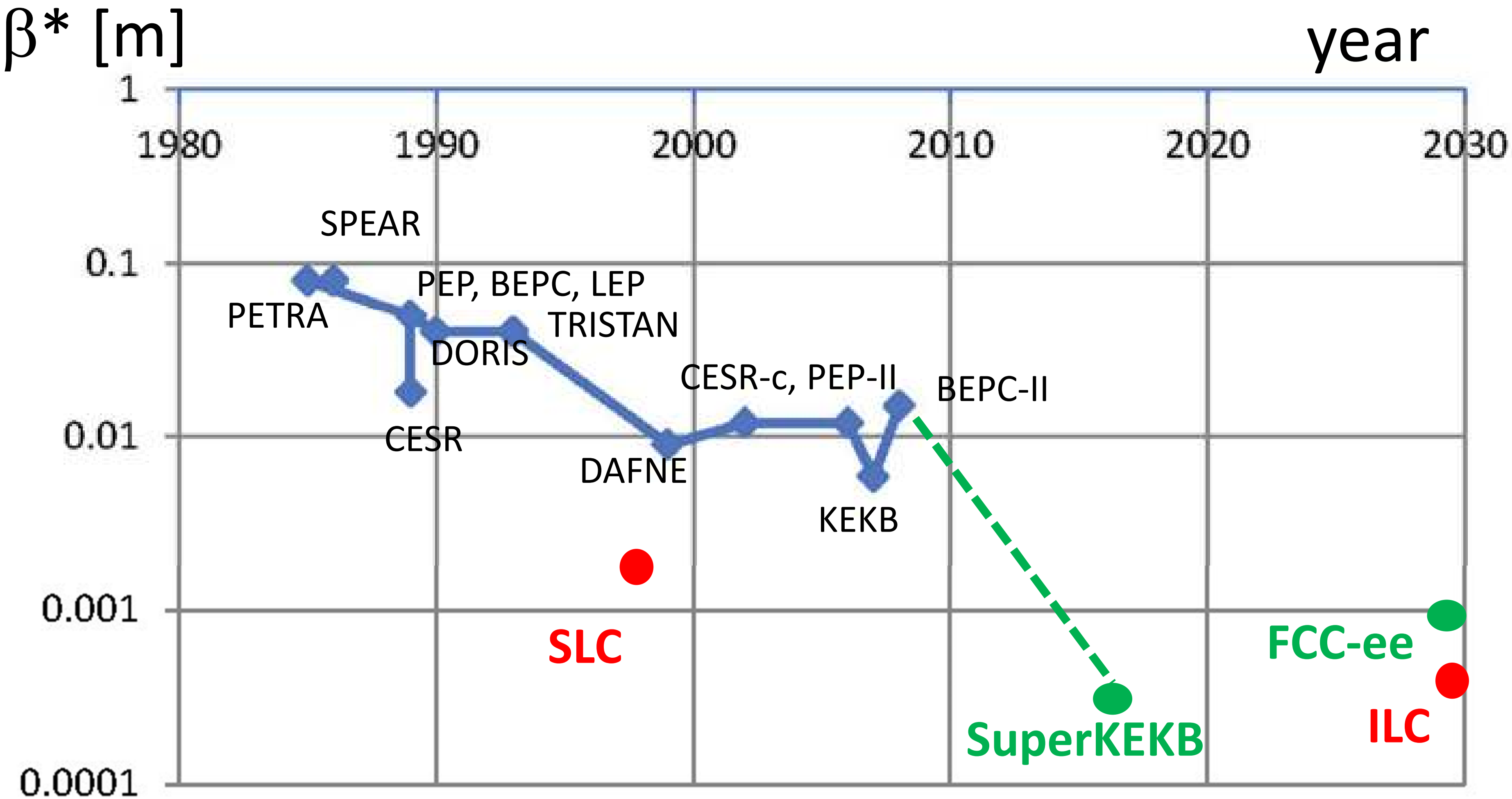
Two limits for the beam-beam parameter

- Putting the two limits together defines the performance of a circular accelerator
- At low energies the beam-beam parameter ξ saturates at the beam-beam limit
- At high energies, the beamstrahlung limit arrives first



Parameters of FCC-ee-175

vertical β* history



$$\sigma^* = \sqrt{\varepsilon \beta^*}$$

Condition for a ‘balanced’ machine

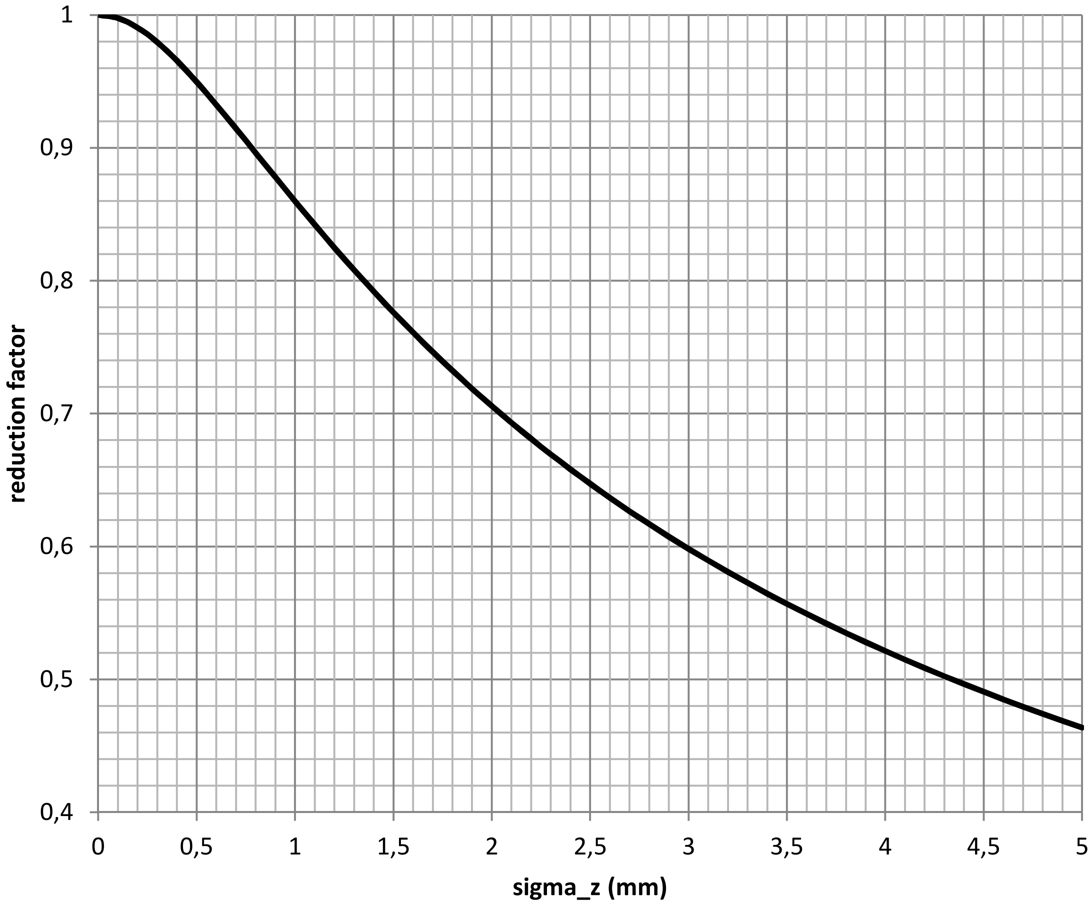
To get equal beam-beam parameters in the horizontal and vertical planes the simple condition that needs to be met is:

$$\xi_x = \xi_y \quad \Rightarrow \quad \frac{\beta_x^*}{\beta_y^*} = \frac{\epsilon_x}{\epsilon_y}$$

Hourglass effect

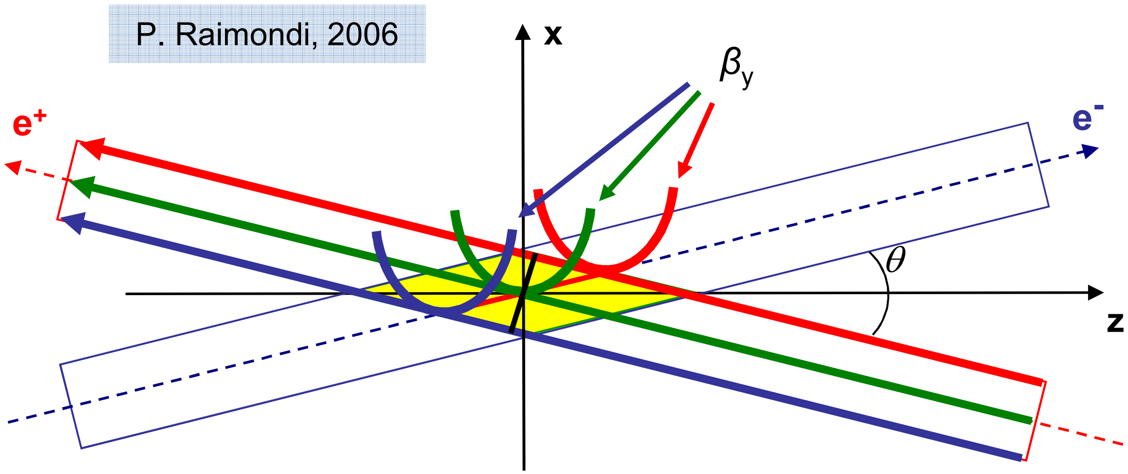
Luminosity is lost if the beam longitudinal size is comparable to the beta* value. This is described by the 'hourglass factor' R_{hg}

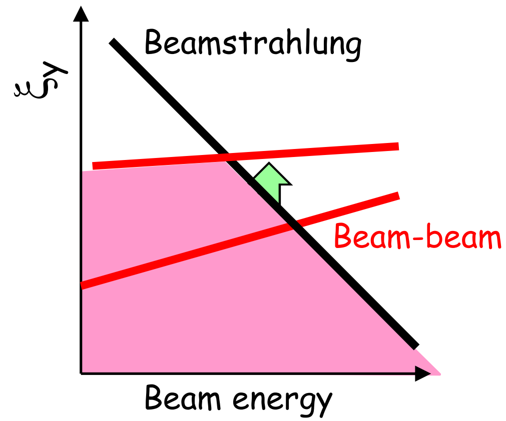
Performance drop going from 1mm to 2mm beta*y: ~20%



Can we do better?

- Using the crab waist scheme we can gain substantially wrt the beam-beam limit



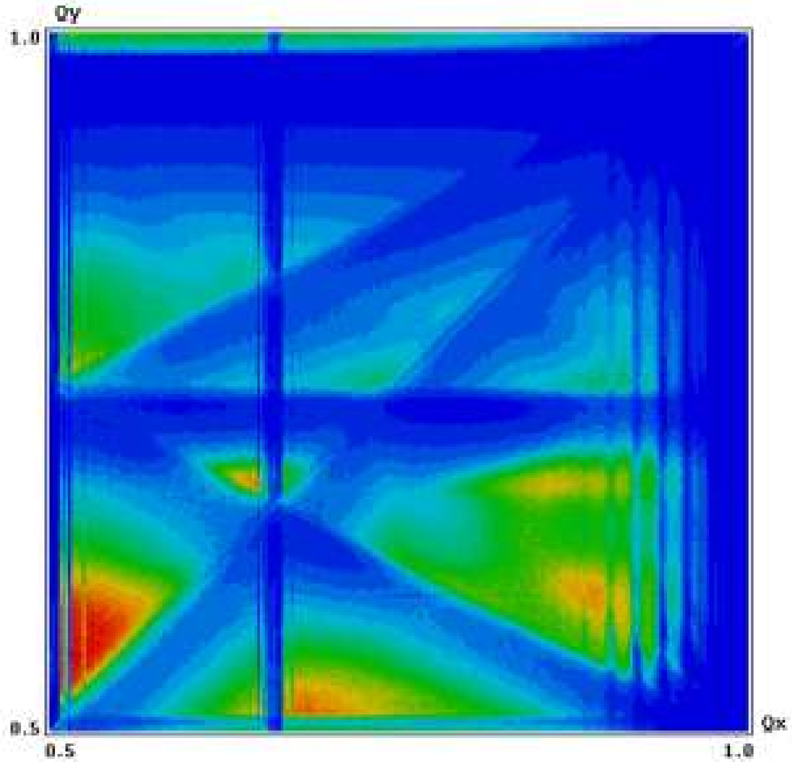


$$\phi = \frac{\sigma_z}{\sigma_x} tg\left(\frac{\theta}{2}\right)$$ – Piwinski angle, should be >> 1

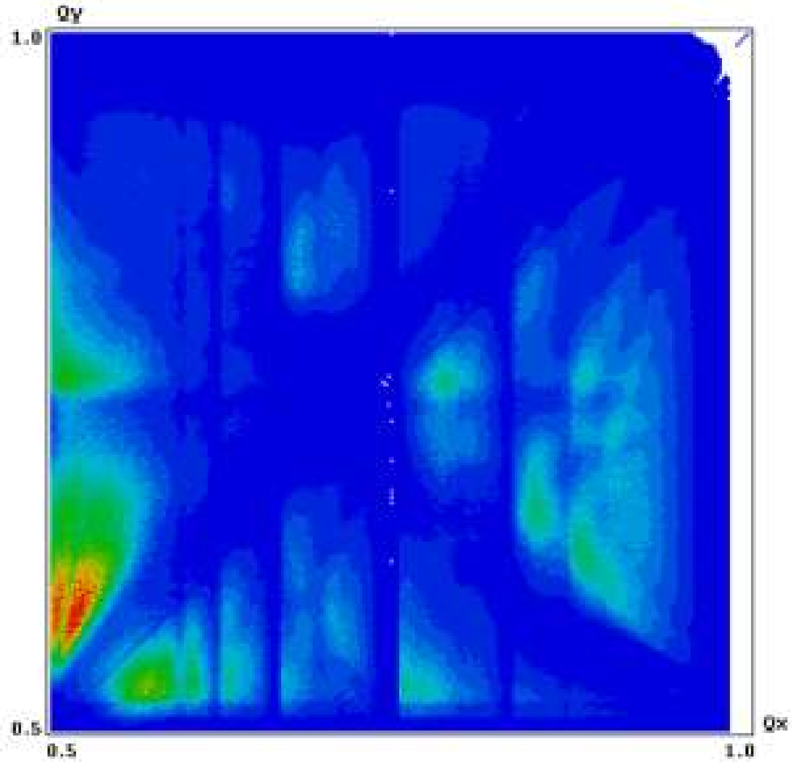
Colliding at an angle, with long beams suppresses instabilities (in other words the machine can operate at larger beam-beam values)

CW has an advantage in beam stability

Tune scans:
- **blue:** resonances, beams disappear quickly
- Red: safe area, possible running point

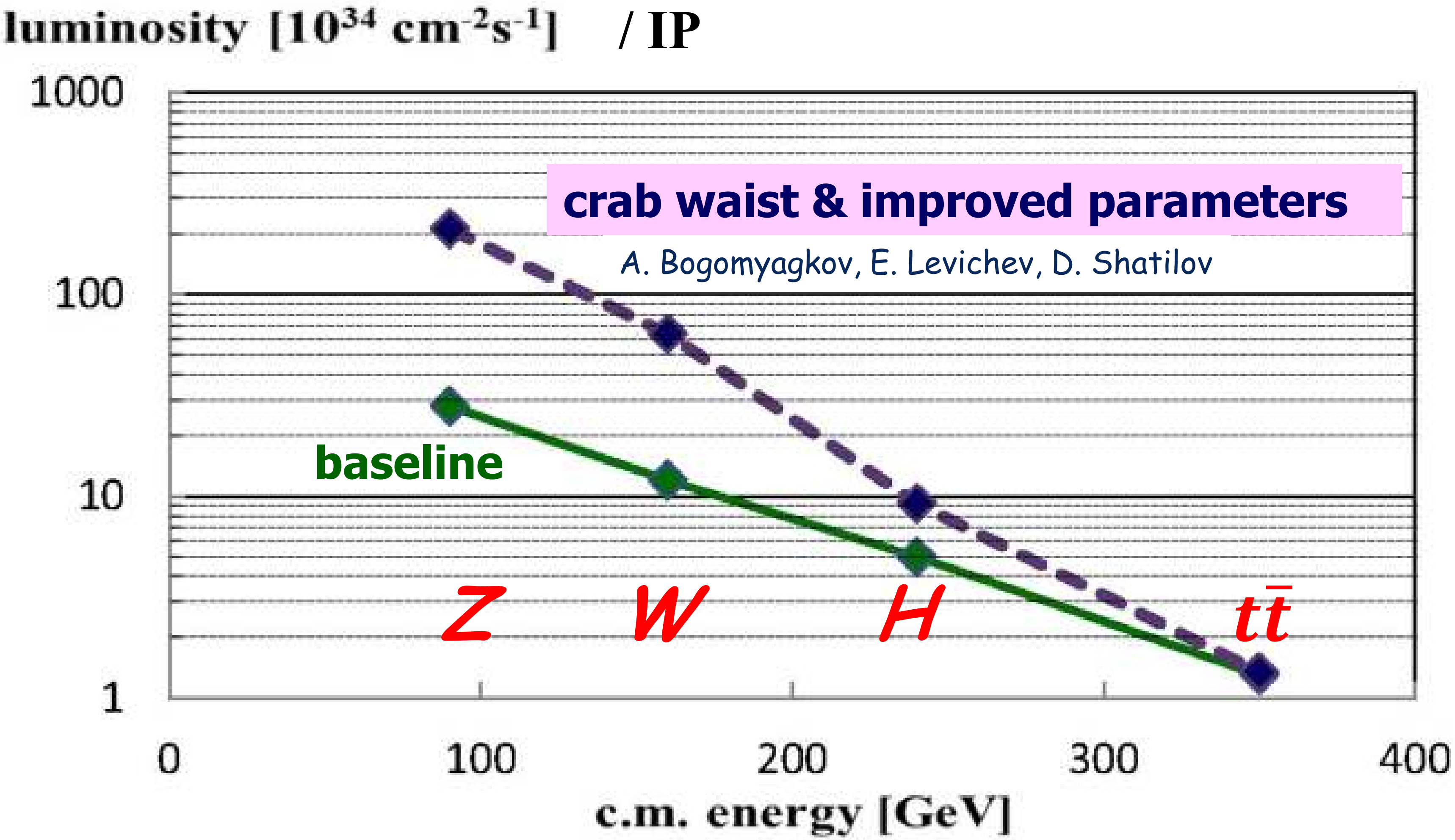


Typical tune scan for CW scheme with high beam-beam parameter (~0.2) for a Super c-τ factory



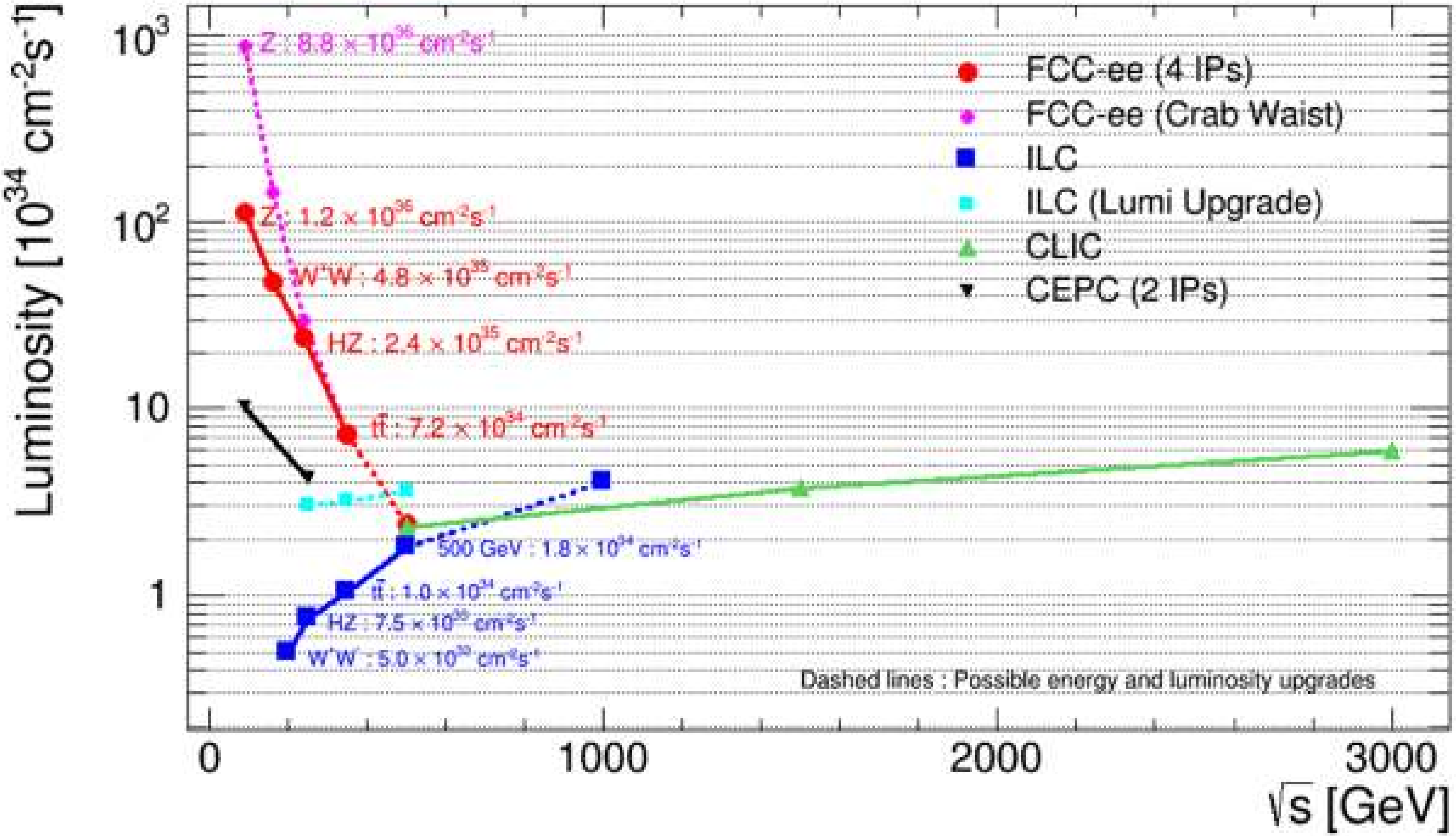
Tune scan for FCC-ee head-on collision scheme without CW (120 GeV)

FCC-ee luminosity vs energy



The crab waist approach looks very promising and might well become our baseline approach

Advertised luminosity of e+e- colliders



LEP1: 0.2×10^{32}
LEP2: 1.2×10^{32}

Linear colliders: energy reach
Circular colliders: high lumi for Z,W,t,H
Crossover: ~400-500GeV

FCC-ee major design considerations/challenges

FCC-ee major design choices

- Separate booster – main ring at constant energy
- Separate beam pipes for electrons and positrons. This gives
  - flexibility regarding final focus optics
  - No real limit on the number of bunches – no parasitic collisions
  - No problems with energy sawtooth (paths of electrons and positrons in the arc are not identical)
- Very low vertical emittance. This will be achieved with
  - very low horizontal emittance (small FODO length compared to the size of the arcs, strong focusing (90^0 optics)
  - Small coupling between planes – careful IP design

FCC-ee major design choices

- Large momentum acceptance at high energies to mitigate beamstrahlung problems (2%). This again necessitates a very careful IP design
- Running at constant RF power (50MW per beam). This creates problems at low energies (at the Z) due to the very high luminosities and beam currents
- Horizontal bends close to the IP are needed to be able to correct chromaticity and deliver the expected performance. However, bends create SR. This has two effects:
  - If it shines on the experiments it creates problems
  - The SR power lost around the interaction region is a source of inefficiency

Emittances

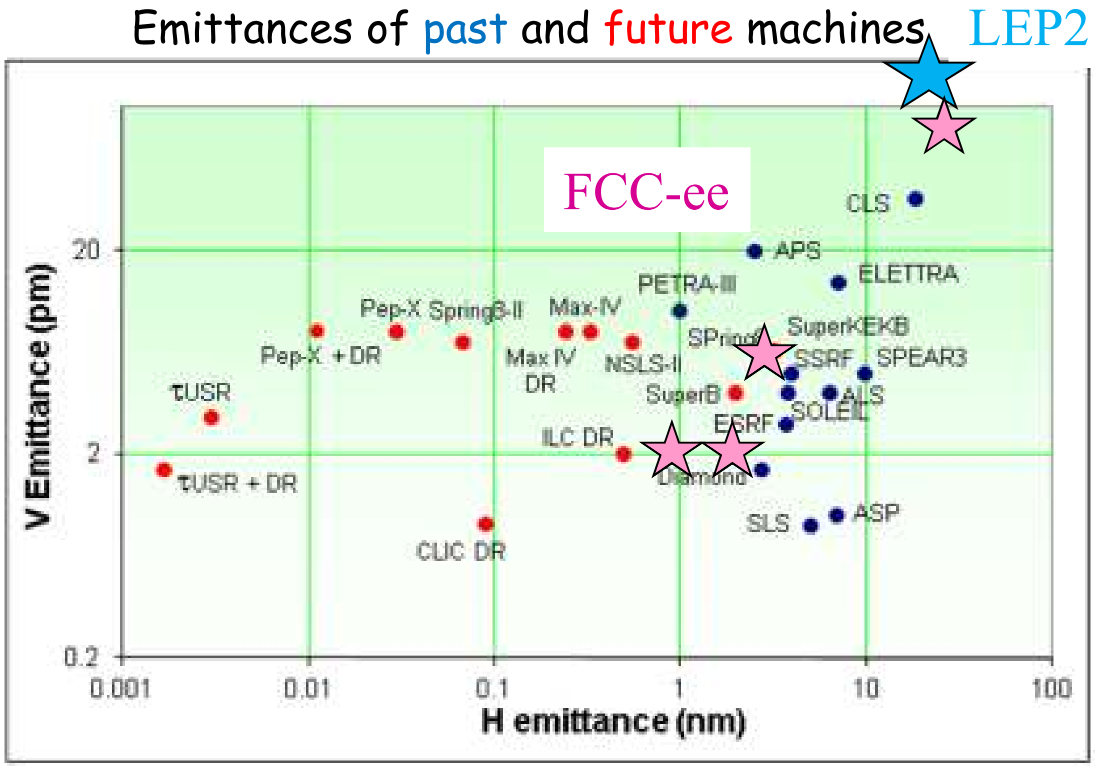
- Low emittances (especially vertical) is essential for delivering the luminosity promised and for mitigating the beamstrahlung problem
- FCC-ee is a very large machine, scaling of achievable emittances (mainly vertical) is not straightforward (Coupling, spurious vertical dispersion).
- Low emittances tend to be more difficult to achieve in colliders as compared to light sources or damping rings (beam-beam)

- FCC-ee parameters:
  - $\varepsilon_y/\varepsilon_x = 0.001$ or 0.002,
  - $\varepsilon_y \geq \approx 2$ pm

  with a ring ~50-100 larger than a typical light source.

- **Very challenging target for a ring of this size!**

Emittances of past and future machines



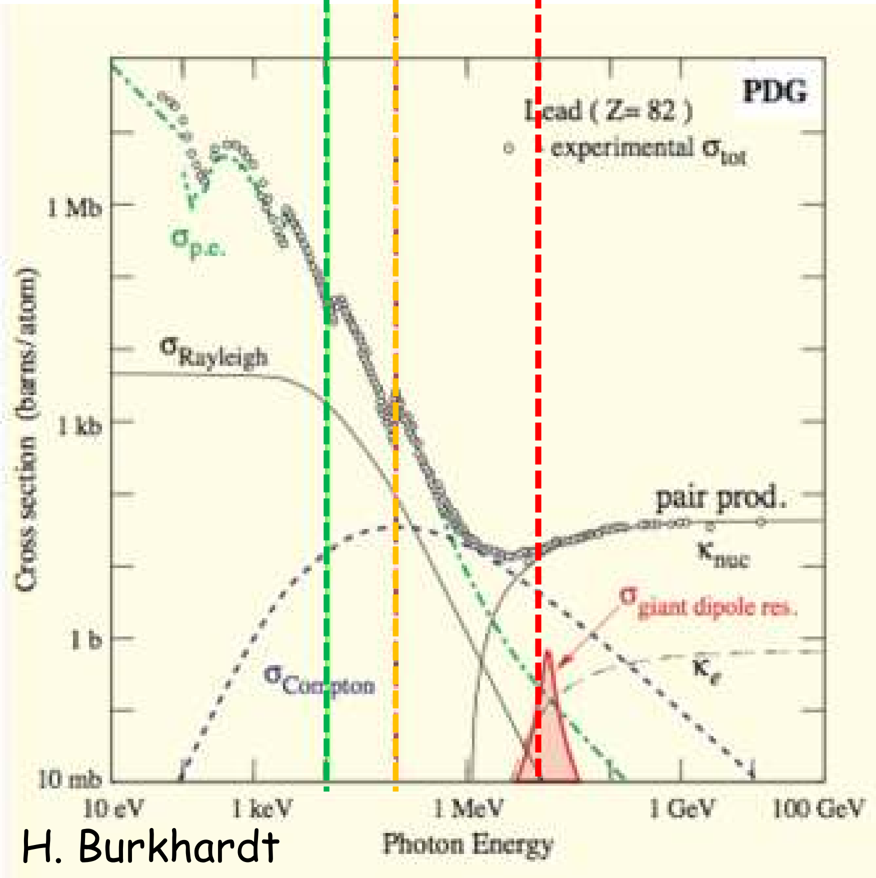
R. Bartolini, DIAMOND

SR spectrum and absorption

<10keV easy

>100keV difficult

>10MeV impossible

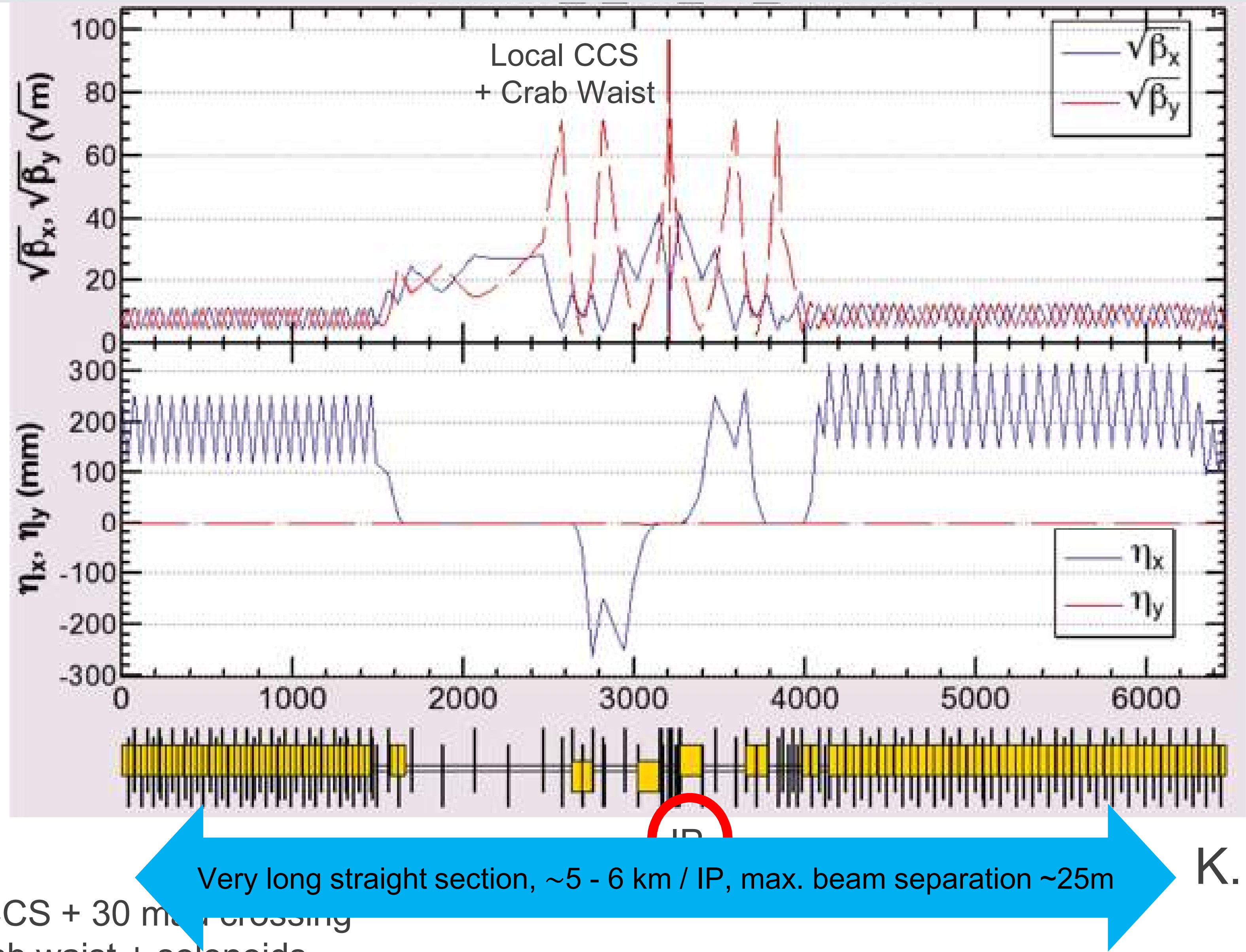


Some critical photon energies:

- superKEKb: ~2keV (LER)
- FCC-hh: ~5keV
- LEP1: ~70keV
- LEP2: ~700keV (arc)
- FCC-ee: ~350keV (arc, 175GeV)

Most importantly: minimize the amount of SR radiation shining at the experiments and its critical energy

An example optics around the IR

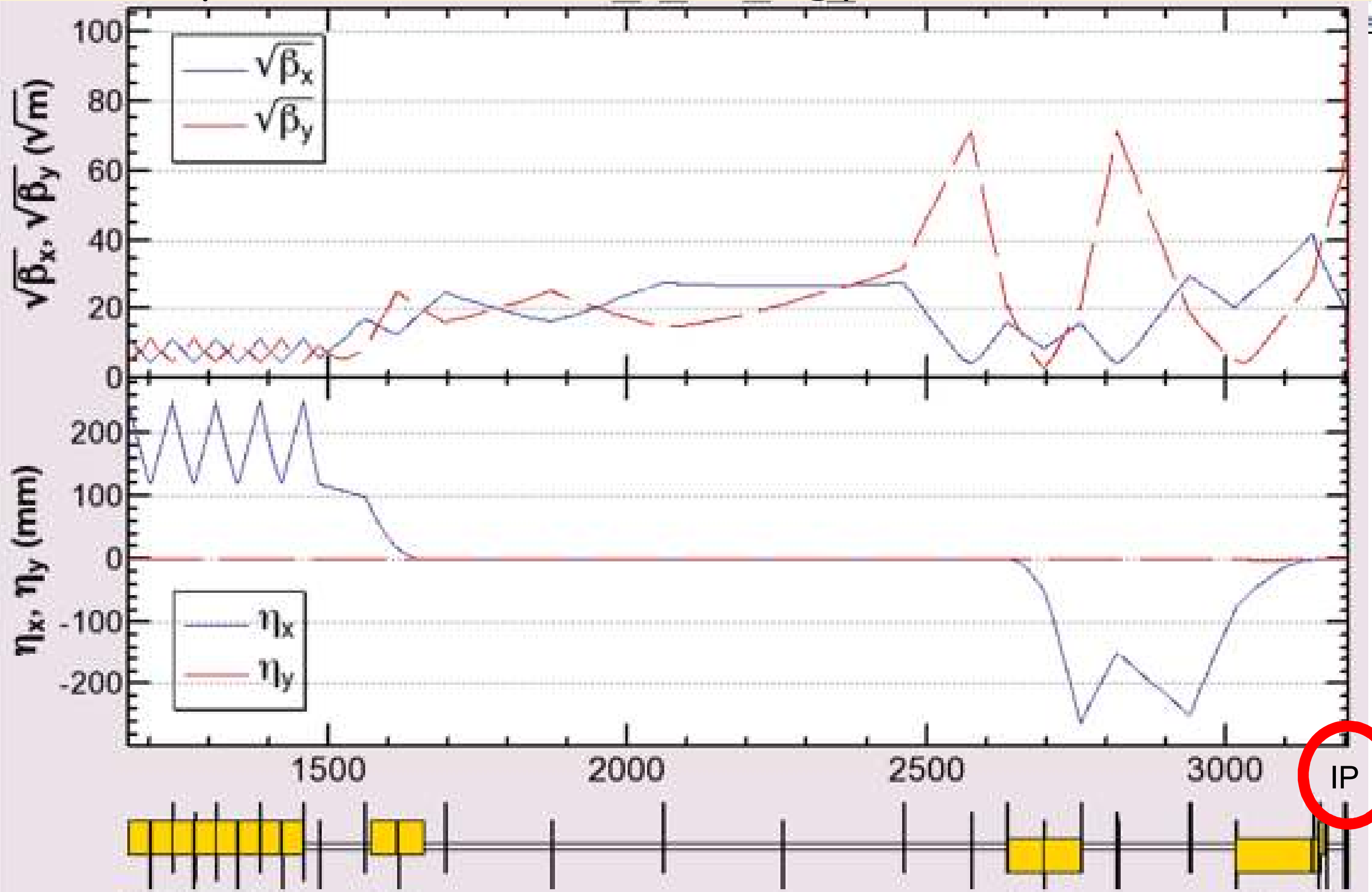


K. Oide

Local CCS + 30 m... crossing
+ crab waist + solenoids

These plots of beam optics are not always the latest ones.

SR (power and critical energy) at the IR



u_c	891	202	314	100	100	46	keV
P_{SR}/dipole	16.7	1.1	3.7	0.79	0.05	0.01	kW

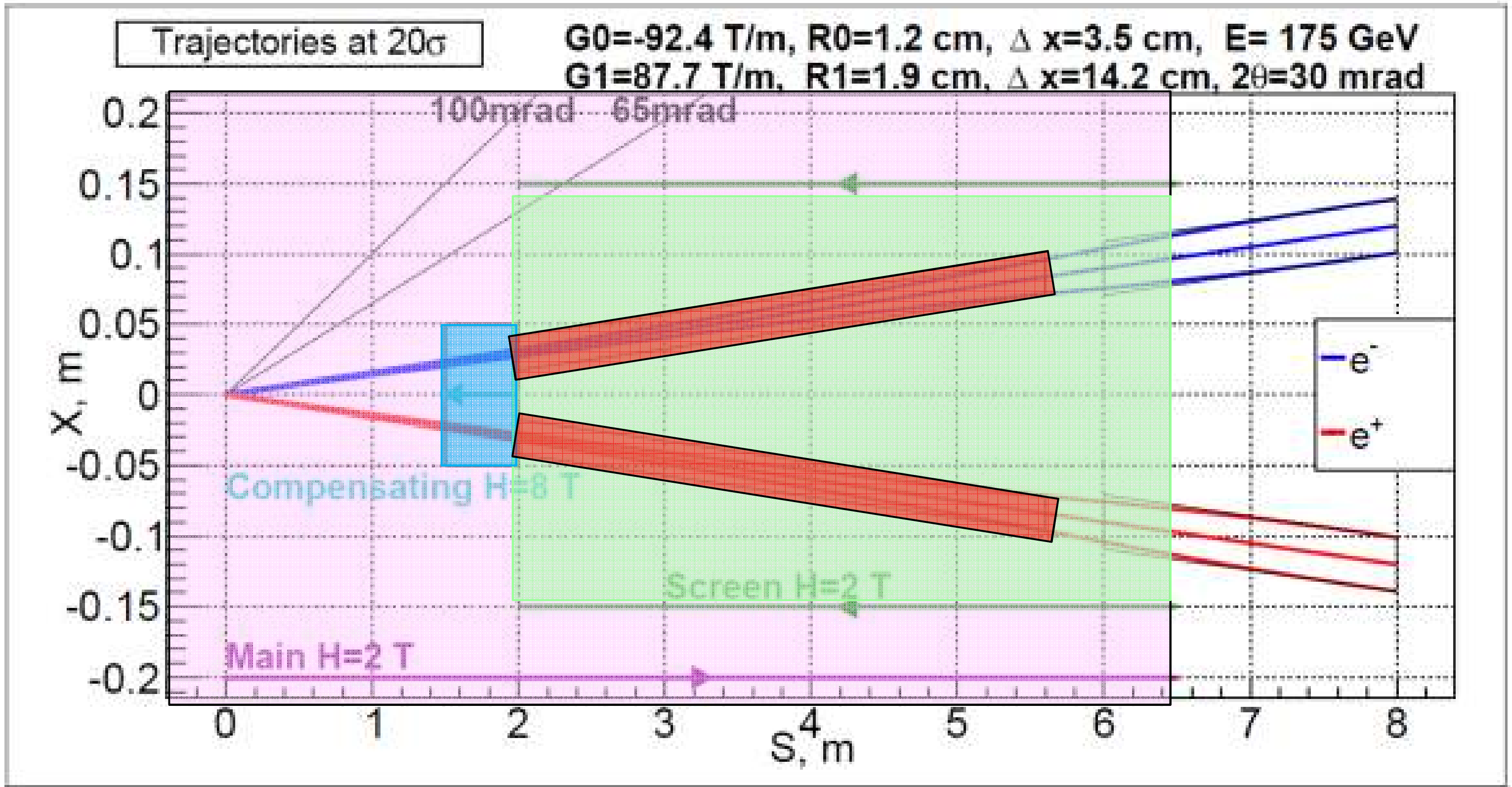
The critical energy and power of the SR from the dipoles looks manageable

K. Oide

These plots of beam optics are not always the late ones.

A zoom close to the IR: main, compensating and screening solenoids

The 30mrad crossing angle together with the detector solenoid and the small L* will result in emittance blow-up if no measures are taken



Final quads

Main detector solenoid

Quad screening solenoid

Compensating solenoid

This is a very complex layout with stringent space limitations that needs a strong coordinated effort

FCC-ee physics teaser

The physics case of FCC-ee

Physics case published: JHEP01 (2014) 164

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ACCEPTED: December 25, 2013
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First look at the physics case of TLEP

The TLEP Design Study Working Group

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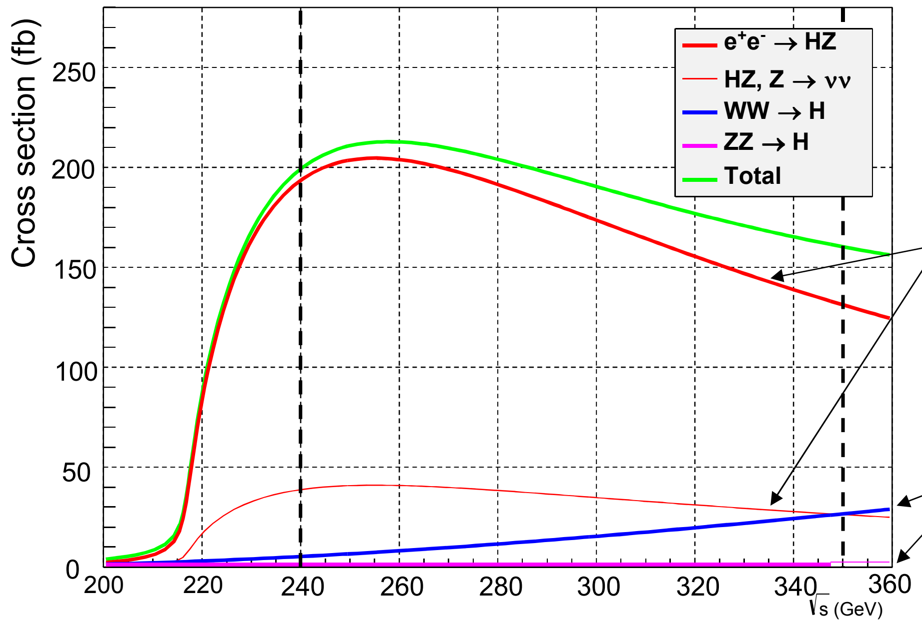
JHEP01(2014)164

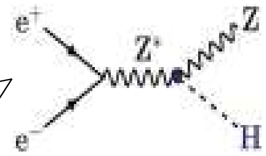
- **Precision measurements**
  - Model independent Higgs properties
    - ➔ Couplings (0.1%) , Γ_H (1%), m_H (8 MeV)
    - ➔ Dark matter (invisible width – 0.1%)
    - ➔ Exploration of new physics with couplings to Higgs boson up to 10 TeV
  - Precise mass measurements
    - ➔ m_Z (< 0.1 MeV), m_W (< 0.5 MeV)
    - ➔ m_{top} (~10 MeV)
  - Electroweak observables, α_S, …
    - ➔ Exploration of new physics with EW couplings up to 100 TeV
- **So far , CMS simulations or "just" paper studies**
- **New ideas have appeared since the paper was published**
  - Higher luminosity with crab waist
  - Smaller energy spread with monochromators
  - Sensitivity to very small couplings
    - ➔ Higgs couplings to 1st generation
    - ➔ Sterile neutrinos

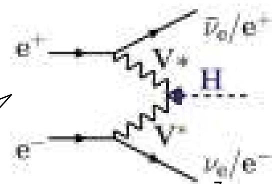
- **It is only the tip of the iceberg**
  - **Thinking out of the box needed until 2018 at least**

Higgs cross sections and expected events

Unpolarized cross sections

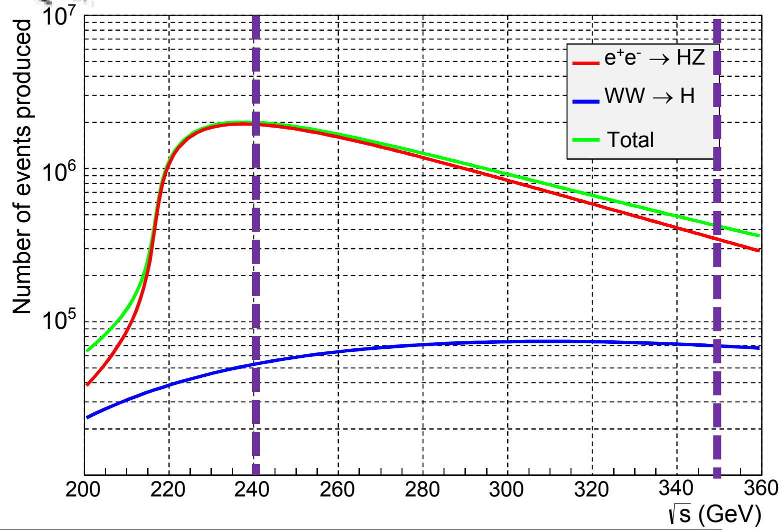






Cross sections for Higgstrahlung and vector boson fusion processes

Xross sections combined with the FCC-ee luminosity profile – five years and for 4 experiments



Opportunities in Higgs physics, ILC, CLIC, FCC-ee

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	(−0.8, +0.3)	(−0.8, +0.3)	(−0.8, +0.2)	(same)	(0, 0)	(0, 0)	(−0.8, 0)	(−0.8, 0)	(−0.8, 0)
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
$BR_{\rm inv}$	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

F. Lediberder

- Higgs couplings, width, branching fraction to exotics. Statistical errors only, model independent fit
- Need to reduce theoretical uncertainties to match

Opportunities in EW precision physics

- Electroweak precision measurements made at LEP with 10^7 Z decays, together with accurate W and top-quark mass measurements from the Tevatron, are sensitive to weakly-coupled new physics at a scale up to ~3 TeV.
- To increase this sensitivity by a factor of 10 to 30 TeV, an improvement in precision by two orders of magnitude is needed, i.e., an increase in statistics by four orders of magnitude to at least 10^{11} Z decays.
- At the same time, the current precision of the W and top-quark mass measurements needs to be improved by at least one order of magnitude, i.e., to better than 1 MeV and 50 MeV respectively, in order to match the increased Z-pole measurement sensitivity.
- These experimental endeavours might well be possible at the FCC-ee.

Opportunities in EW precision physics

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meas.
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0001	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν	Radiative returns $e^+e^- \to \gamma Z, Z \to \nu\nu, ll$	2.92 ± 0.05 2.984 ± 0.008	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	?	12	?	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	μ = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$

Systematic errors dominate!

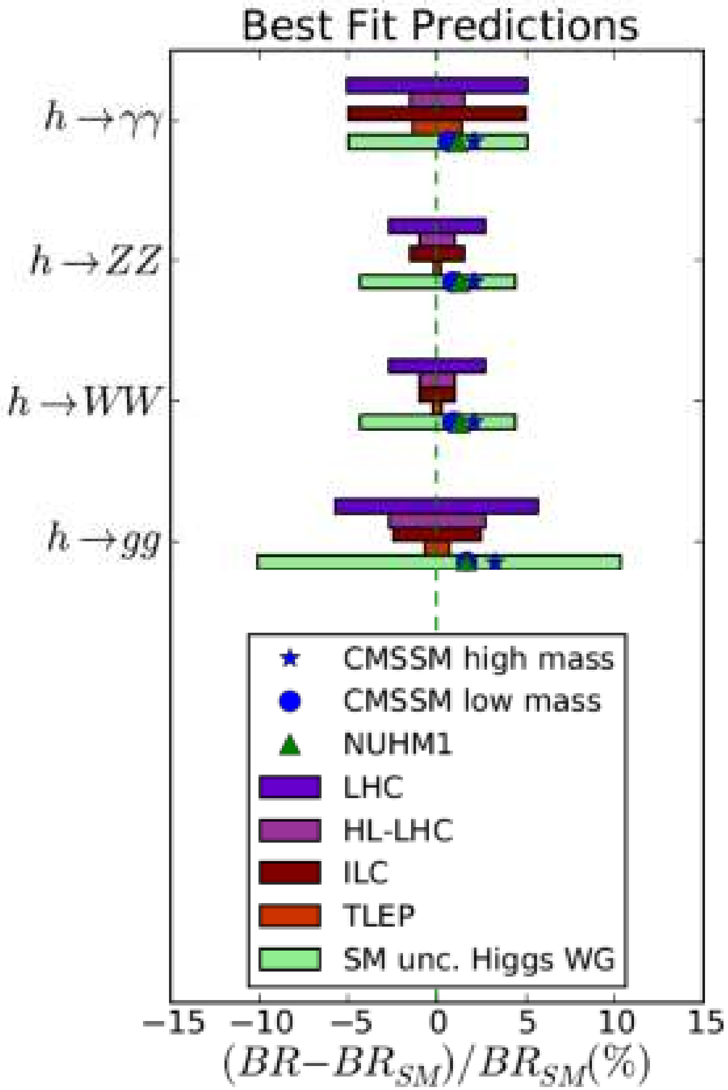
Based on LEP experience – much work ahead.

Polarization at FCC-ee

- Transverse polarization essential for the accurate measurement of lineshape parameters – using the resonant depolarization technique which gives an instantaneous error of ~100keV
- At LEP transverse polarization was used at the Z but not the W
- We aim for a large improvement at FCC-ee:
  - Depolarization measurement of non-colliding bunches every few minutes – most systematic errors of LEP disappear
  - It is expected that polarization will be observable at the WW threshold, making a huge improvement of the measurement of the W mass
  - (However, polarization times at the FCC-ee are very long: need the use of polarization wigglers)
- Longitudinal polarization at the Z is very valuable for the measurement of A_{LR} and $A^{f}_{FB.Pol}$, but is not straight forward to achieve with colliding beams (contrary to linear colliders).

$$\sigma_E \propto \frac{E^2}{\sqrt{\rho}}$$

SUSY and accuracies



Do we have the accuracy needed to see deviations from SM predictions? In the plot on the left we see the predictions of three SUSY models compared to the accuracy of the LHC, HL-LHC, ILC and TLEP. The theory uncertainty is also shown

Only FCC-ee (TLEP) can really probe the accuracy of those models

Note that theoretical uncertainties are currently larger than the deviations of susy models and larger than the FCC-ee projected accuracy. Substantial theoretical effort is needed to reduce the uncertainties in the theoretical calculations of the Higgs properties

The physics case - conclusions

The FCC-ee would provide

i. per-mil precision in measurements of Higgs couplings,
ii. unique precision in measurements of Electroweak Symmetry-Breaking parameters and the strong coupling constant,
iii. a measurement of the Z invisible width equivalent to better than 0.001 of a conventional neutrino species, and
iv. a unique search programme for rare Z, W, Higgs, and top decays.

The FCC project – namely the combination of FCC-ee and FCC-hh offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market.

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Conclusions

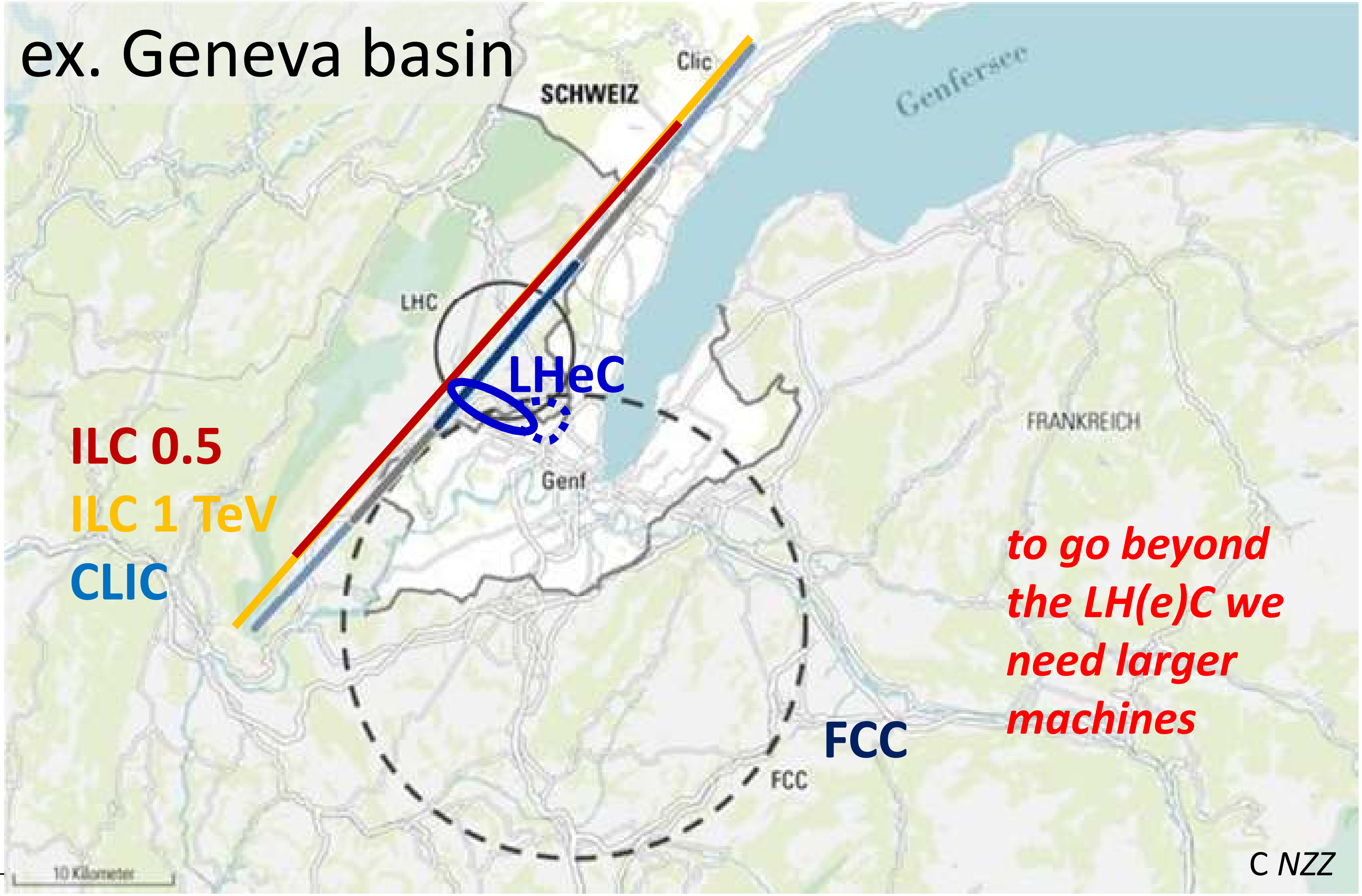
- The FCC-ee project offers unique opportunities to further explore Nature…
- …by changing the name of the game of precision physics – it offers unprecedented statistics at an E_{CM} of 90 GeV (Z), 160 GeV (W), 240 GeV (ZH) and 350 GeV (tt)
- It is based on mature technology, but pushes it to its limits
- And it paves the way for a 100TeV hadron collider

End

Thank you

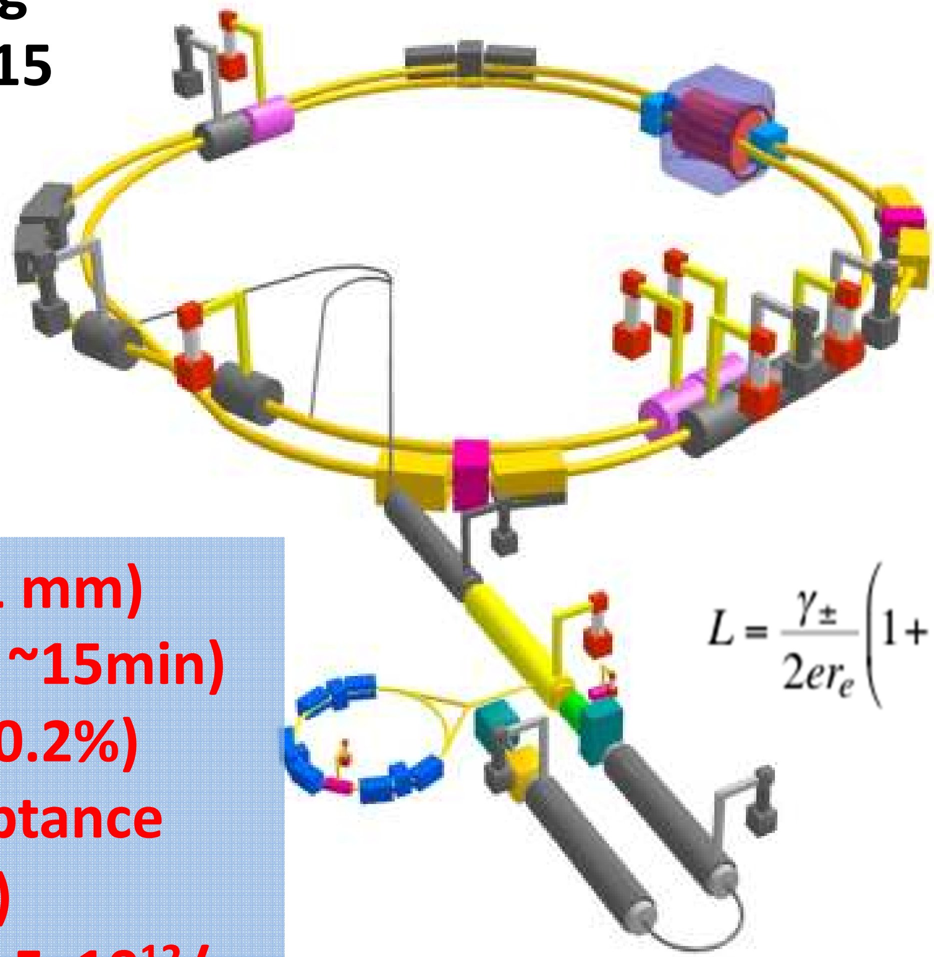
EXTRA SLIDES

proposed linear & circular colliders



SuperKEKB – *FCC-ee* demonstrator

beam commissioning will start in early 2015



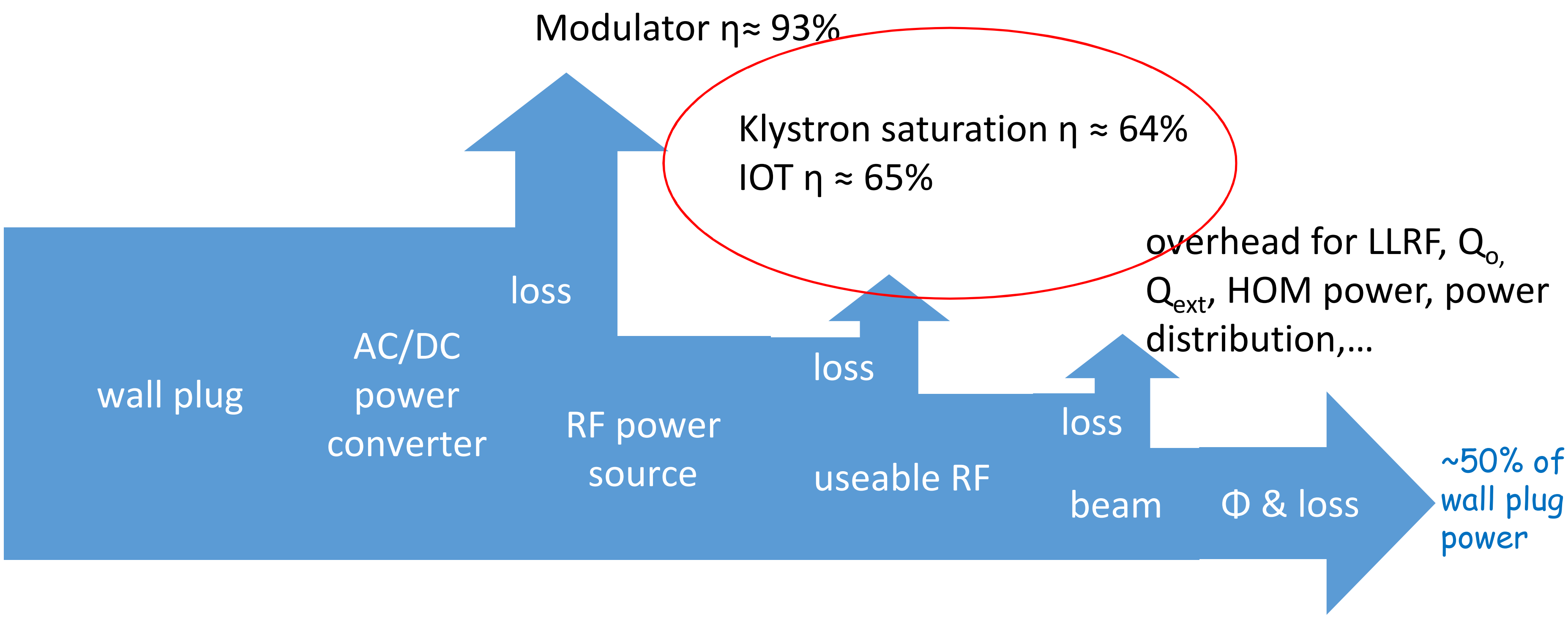
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

- β_y*=300 μm (TLEP: 1 mm)
- lifetime 5 min (TLEP: ~15min)
- $\varepsilon_y/\varepsilon_x$=0.25% ! (TLEP: 0.2%)
- off momentum acceptance (±1.5%, TLEP: ±2%)
- *e*$^+$ production rate (2.5x10^{12}/s, TLEP: <1x10^{11}/s)

Power consumption

- It is more efficient to run at maximum power for the shortest period of time
- One of the first choices was to operate the FCC-ee at 100MW of SR lost for both beams
- The power consumption of the whole facility would be 300MW+
- This is a high energy consumption (~1TWh per year, costing ~50MCHF at current CERN contract prices), but still corresponds to less than 1% of the construction cost of the facility per year
- But “energy costs might not be a true reflection of its value to society”, so every effort should be made to reduce this number
- Largest consumer: RF system, where our efforts must be concentrated

RF power consumption



One single efficiency that, if improved, would have the largest impact: RF power source efficiency

- Klystron efficiency currently ~65%, R&D to take this to ~90%
- Other technologies: IOTs (inductive Output Tube), Solid state amplifiers

comparison of key design parameters

Parameter	LEP2	FCC-ee			ILC		
		Z	H	t	H	500	1 TeV
E (GeV)	104	45	120	175	125	250	500
<I (mA)>	4	1400	30	7	0.000021	.000021	.000027
$P_{SR/b,tot}$ [MW]	22	100	100	100	5.9	10.5	27.2
P_{AC} [MW]	~200	~260	~270	~300	~129	~163	~300
$\eta_{wall\rightarrow beam}$ [%]	~30	30-40	30-40	30-40	4.6	6.4	9.1
$N_{bunch/ring\ (pulse)}$	4	16’700	1’330	98	1312	1312	2450
f_{coll} (kHz)	45	50000	4000	294	6.6	6.6	9.8
$\beta^*_{x/y}$ (mm)	1500/ 50	500 / 1	500 /1	1000/1	13	11	11
ε_x (nm)	30-50	29	1	2	0.04	0.02	0.01
ε_y (pm)	~250	60	2	2	0.14	0.07	0.03
ξ_y (ILC: n_γ)	0.07	0.03	0.09	0.09	(1.12)	(1.72)	(2.12)
n_{IP}	4	4	4	4	1	1	1
$L_{0.01}$/IP	0.012	28	6.0	1.8	0.65	1.05	2.2
$L_{0.01,tot}$ (10^{34} cm^{-2}s^{-1})	0.048	112	24	7.2	0.65	1.05	2.2

Main baseline parameters

- This is work in progress and rapidly evolving

Parameter	Z	W	H	t	LEP2
E (GeV)	45	80	120	175	104
I (mA)	1400	152	30	7	4
No. bunches	16'700	4'490	1'330	98	4
Power (MW/beam)	50	50	50	50	11
E loss/turn (GeV)	0.03	0.33	1.67	7.55	3.34
Total RF voltage(GV)	2.5	4	5.5	11	3.5
$\beta^*_{x/y}$ (mm)	500 / 1	500 / 1	500 / 1	1000 / 1	1500 / 50
ε_x (nm)	29	3.3	1	2	30-50
ε_y (pm)	60	7	2	2	~250
ξ_y	0.03	0.06	0.09	0.09	0.07
L (10^{34} cm^{-2}s^{-1})	**28**	**12**	**6.0**	**1.8**	**0.012**
Number of IPs	4	4	4	4	4
Lumi lifetime (mins)	213	52	21	24	310

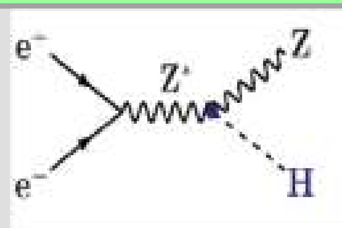
Invisible widths

Main strength of FCC-ee is the capability to study all known particles (W, Z, Higgs, top, …) with very high precision. For example: repeat the whole of the LEP physics programme in a few minutes. Also sensitivity to very rare phenomena (very small couplings).

This represents a formidable challenge to theory: with statistical errors reduced by a factor of as much as 100 compared to LEP, theory needs to follow…

Example: invisible widths:

- Higgs BR_{exotic} measured to 0.16% (4 IPs)
- Z invisible width (ΔN_ν from LEP 0.008):
  - Z lineshape: N_ν measured to 0.0001 (stat)$\pm$0.004(syst)
  - tagged Z (1 year at ECM 160GeV plus data from 240 and 359GeV) ΔN_ν =0.0008
  - Dedicated run at 105 GeV: ΔN_ν =0.0004



2 10^6 ZH events in 5 years

«A tagged Higgs beam».

$$N_v = \frac{\frac{\gamma Z(inv)}{\gamma Z \to ee,\mu\mu}}{\frac{\Gamma_\nu}{\Gamma e,\mu}\ (SM)}$$

Is history repeating itself…?

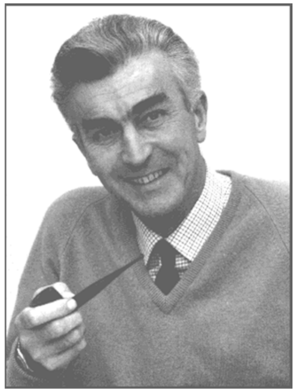
When **Lady Margaret Thatcher** visited CERN in 1982, she asked the then CERN Director-General **Herwig Schopper** ***how big would the next tunnel after LEP be.***

Margaret Thatcher, British PM 1979-90

Dr. Schopper's answer was ***there would be no bigger tunnel at CERN***.

Herwig Schopper
CERN DG 1981-88
built LEP

Lady Thatcher replied that she had obtained ***exactly the same answer from Sir John Adams when the SPS was built 10 years earlier***, and therefore she did not believe him.



John Adams
CERN DG 1960-61 & 1971-75
built PS & SPS

Was lady Thatcher right?

Herwig Schopper, private communication, 2013; curtesy F. Zimmermann