Part III
Prospects for Higgs studies in future colliders

M.Bachtis (CERN-PH)

Introduction

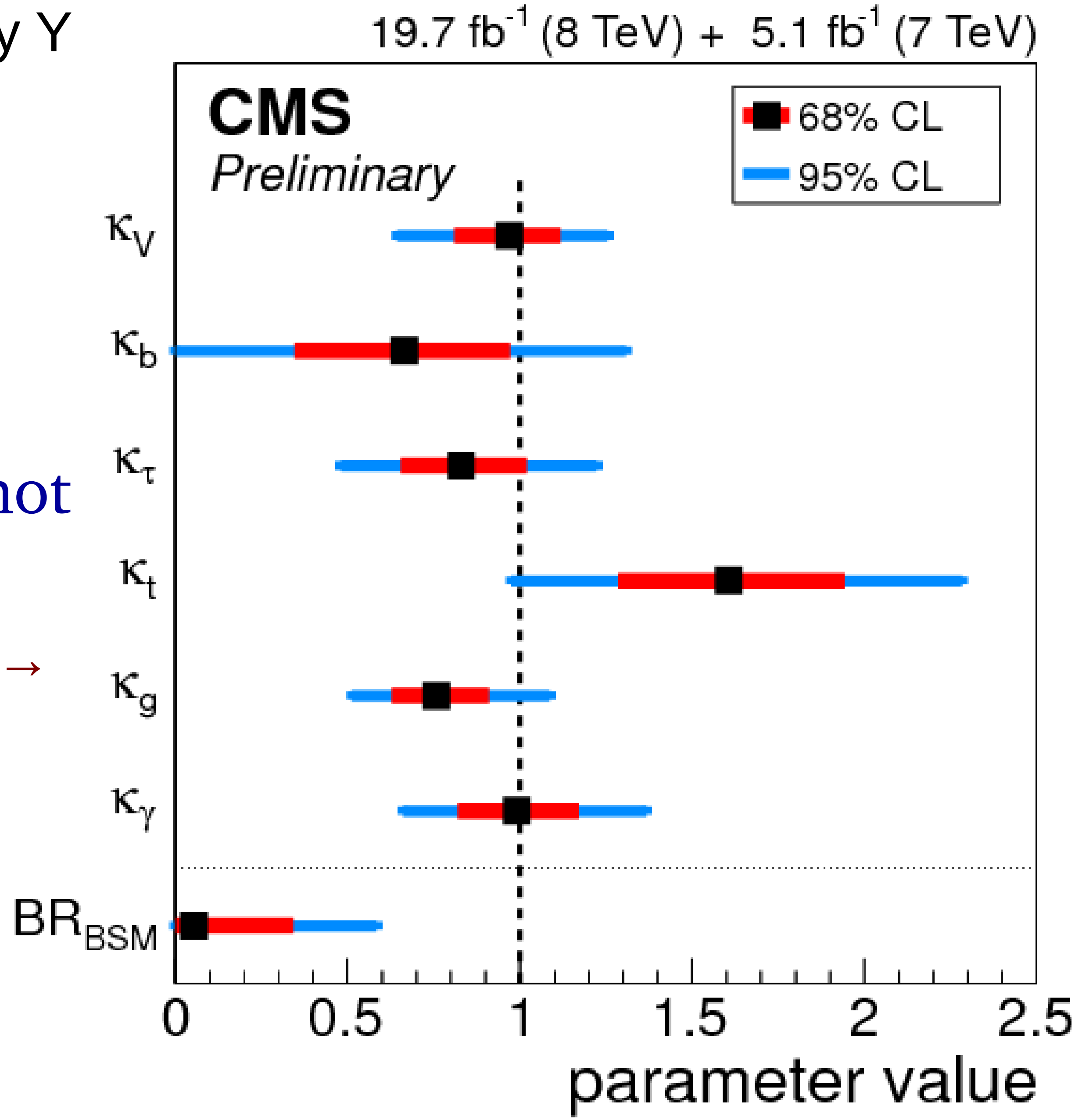
- In the previous lectures we described
  - How the Higgs couplings are measured
  - How the Higgs couplings can reveal hints for new physics
- In this lecture
  - What is the ultimate precision we can get with the LHC
  - Proton vs e^+e^- collisions?
  - How we study the Higgs in e^+e^- collisions?
  - What are the prospects for future colliders

Couplings measurements @ LHC

For a production X and decay Y

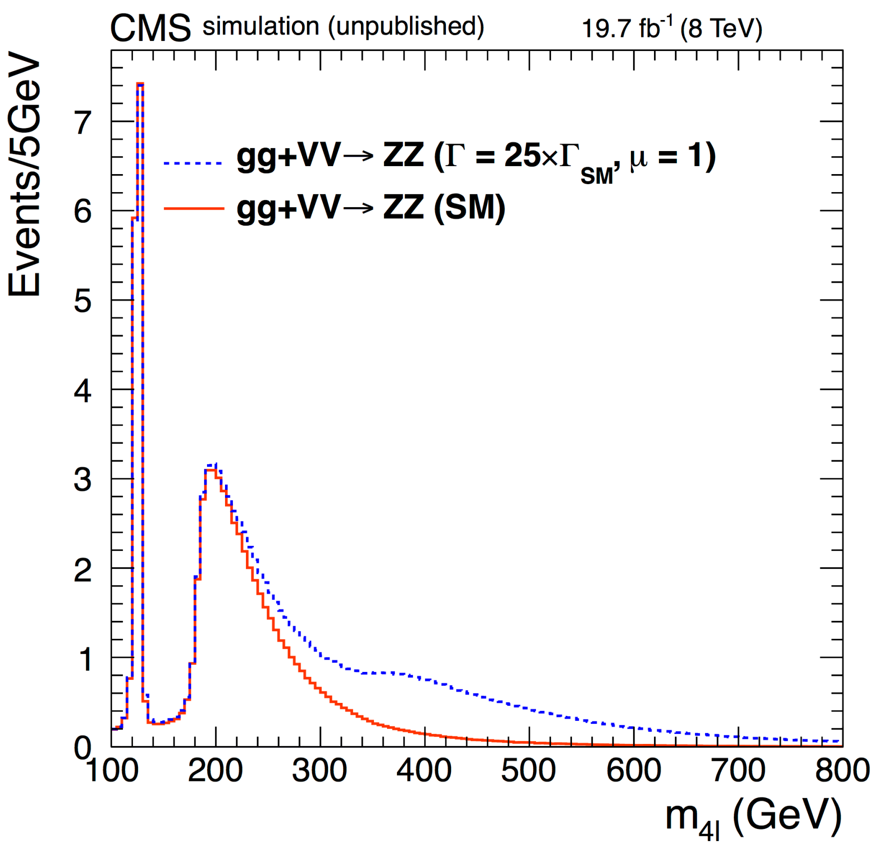
$$\mu = \frac{\kappa_X^2 \kappa_Y^2}{\frac{\sum_l \kappa_l^2 BR(H \to ll)}{1 - BR(H \to BSM)}}$$

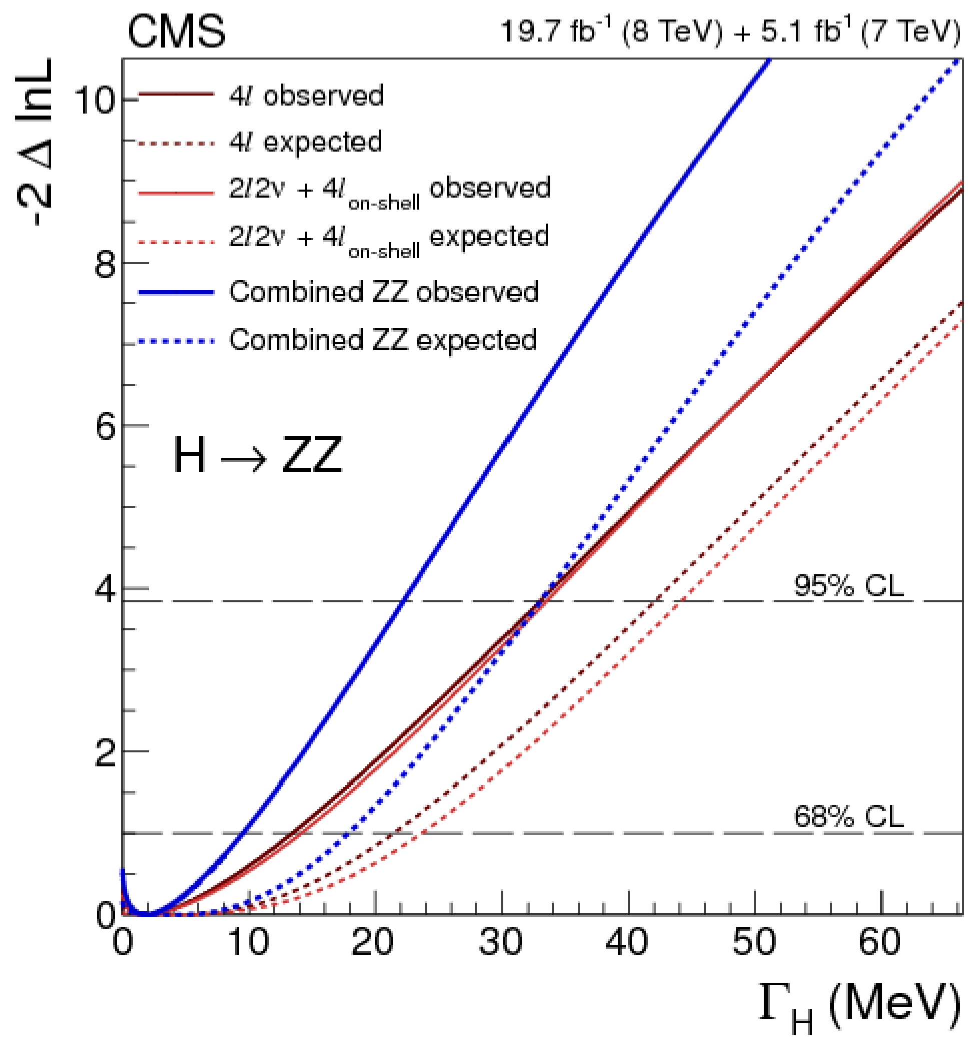
- Caveats
  - The total width cannot be measured
    - e.g, no access to H → cc/mumu
  - Many model assumptions
  - **Theoretical systematics**



Width from off-shell H → ZZ*

- New technique in the market
  - Look at off-shell Higgs events and estimate the width
- Already 200% precision achieved with current data





Theoretical systematics will limit it when statistics Increase but maybe a 30% uncertainty is possible

Theoretical systematics

- In hadron collisions all calculations are involving loops in QCD
  - Very difficult and large systematic error due to the QCD scale
  - PDFs also contribute large errors
- In gluon fusion process @ 125 GeV
  - Uncertainty due to the QCD scale: 7%
  - Uncertainty due to the PDF : 7%
- Numbers correlated between experiments
  - Limits the maximum precision !!

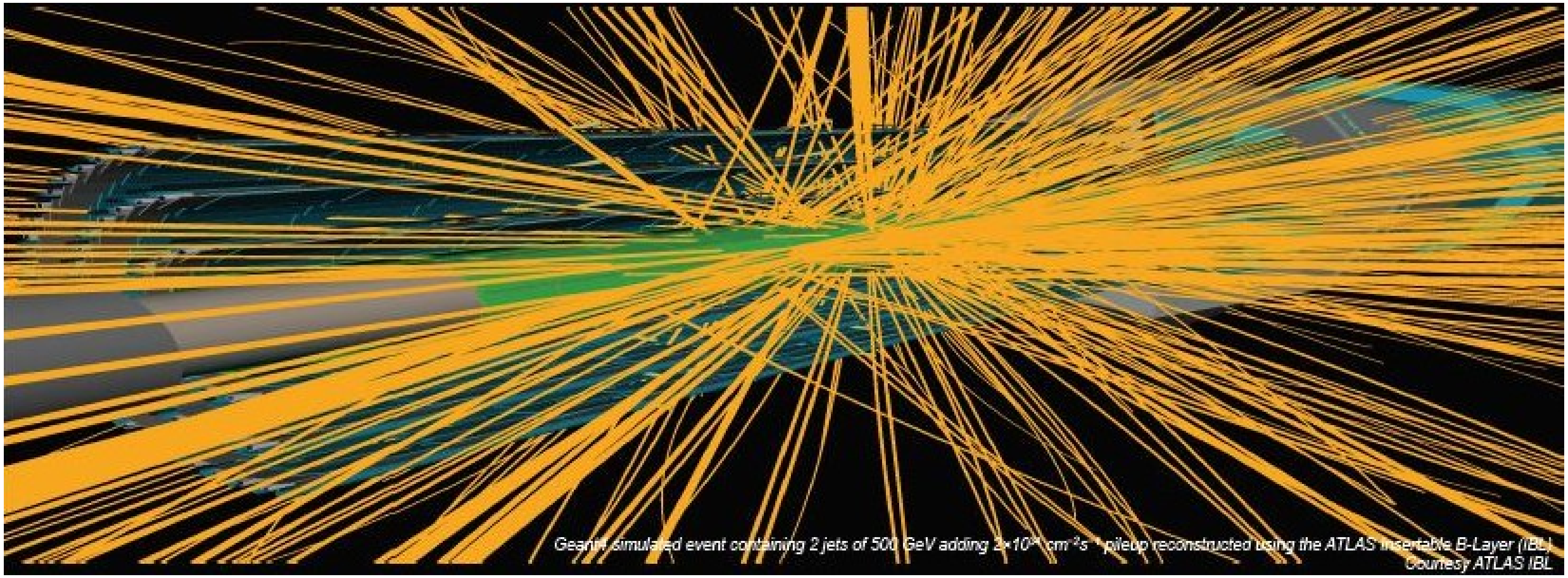
Where will LHC next runs takes us?

- Currently we have $25fb^{-1}$
- With $1000fb^{-1}$,couplings at 5 % level
- Probably will not be able to measure the self coupling
  - via ggH → HH
- Projections assuming that theoretical systematics improve

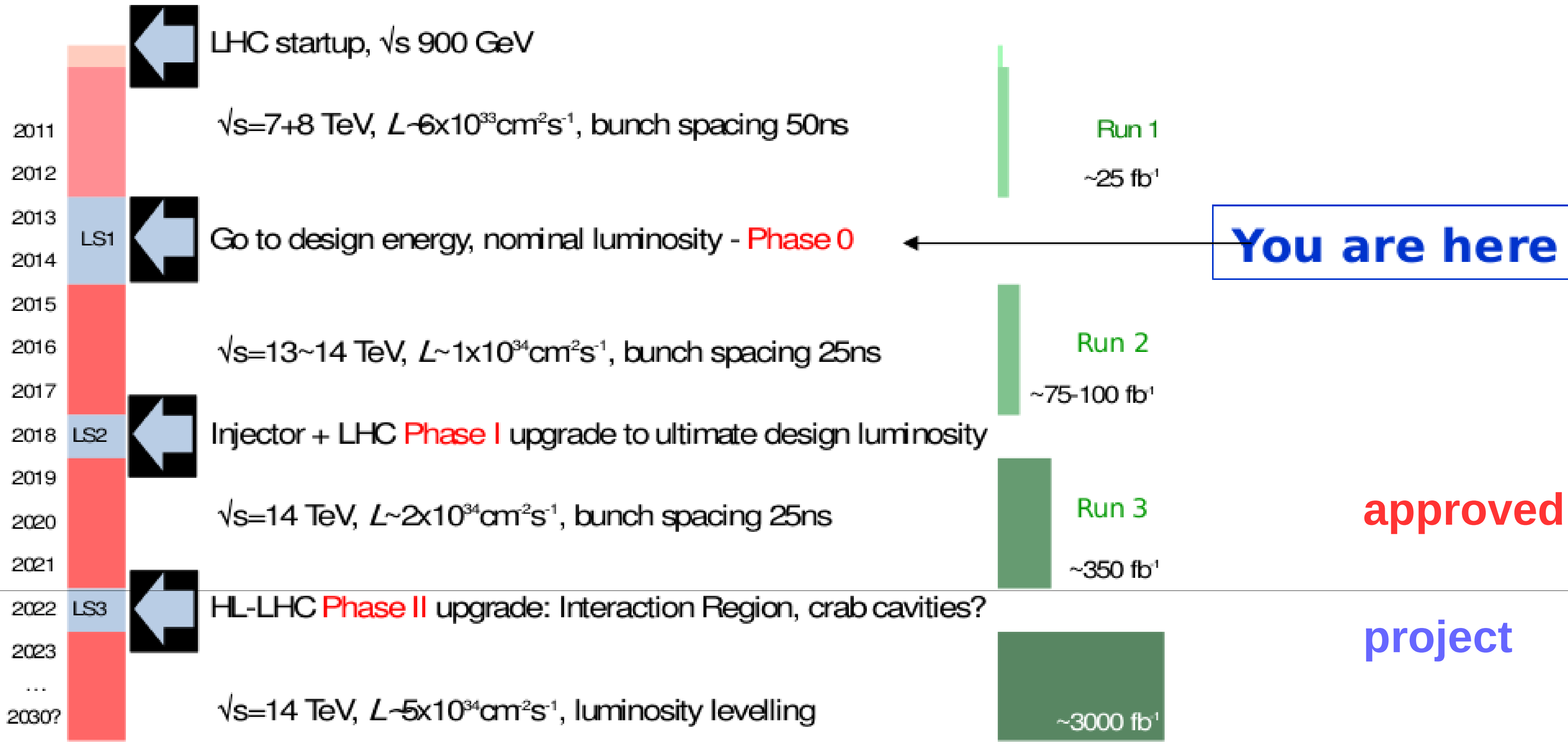
Coupling	LHC (1 ab-1)
κW	3-5%
κZ	3-5%
κγ	3-5%
κg	4-6%
κb	6-10%
κτ	4-6%
κμ	~17%
κZγ	~22%
κt	10-12%
κH	?

What about HL-LHC?

- Accelerator and Experiments preparing proposal for high luminosity LHC
- Making possible to get 3x more luminosity
- Much larger pileup(140 events in the detector)!
  - Experiments need to be upgraded to cope with the new conditions



LHC upgrade stages



-The HL-LHC project is actively a new machine.

-The upgrade cost per experiment approaches 30% of the experiment construction cost

Higgs @ HL-LHC

Coupling	LHC (1 ab-1)	HL-LHC
κW	3-5%	2-5%
κZ	3-5%	2-4%
κγ	3-5%	2-5%
κg	4-6%	3-5%
κb	6-10%	4-7%
κτ	4-6%	2-5%
κμ	~17%	~10%
κZγ	~22%	~12%
κt	10-12%	7-10%
κH	?	30-50% ?

Typical deviations for new physics:

$$\Delta \frac{g}{g_{SM}} < 5\% \left(\frac{1TeV}{\Lambda}\right)^2$$

For a 5sigma deviation, <1% precision needed

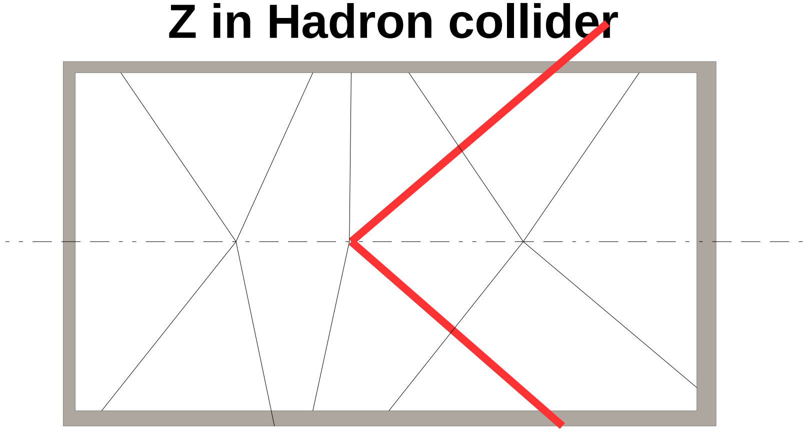
HL-LHC probably cannot provide such precision

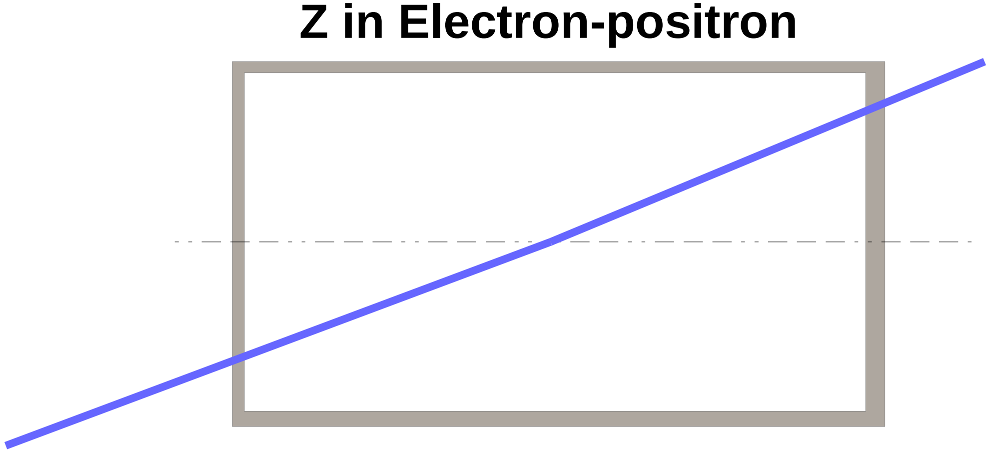
Remember → It is not only the Higgs!

- In case we can produce new physics at LHC energies, we might be able to see it with large luminosity
- One example is the Tevatron
  - Designed to discover the top quark
  - However with 5x more data, Tevatron would have an observation of the Higgs
    - If the LHC was not there to discover it first
- The next LHC run will give us a better clue on what to expect

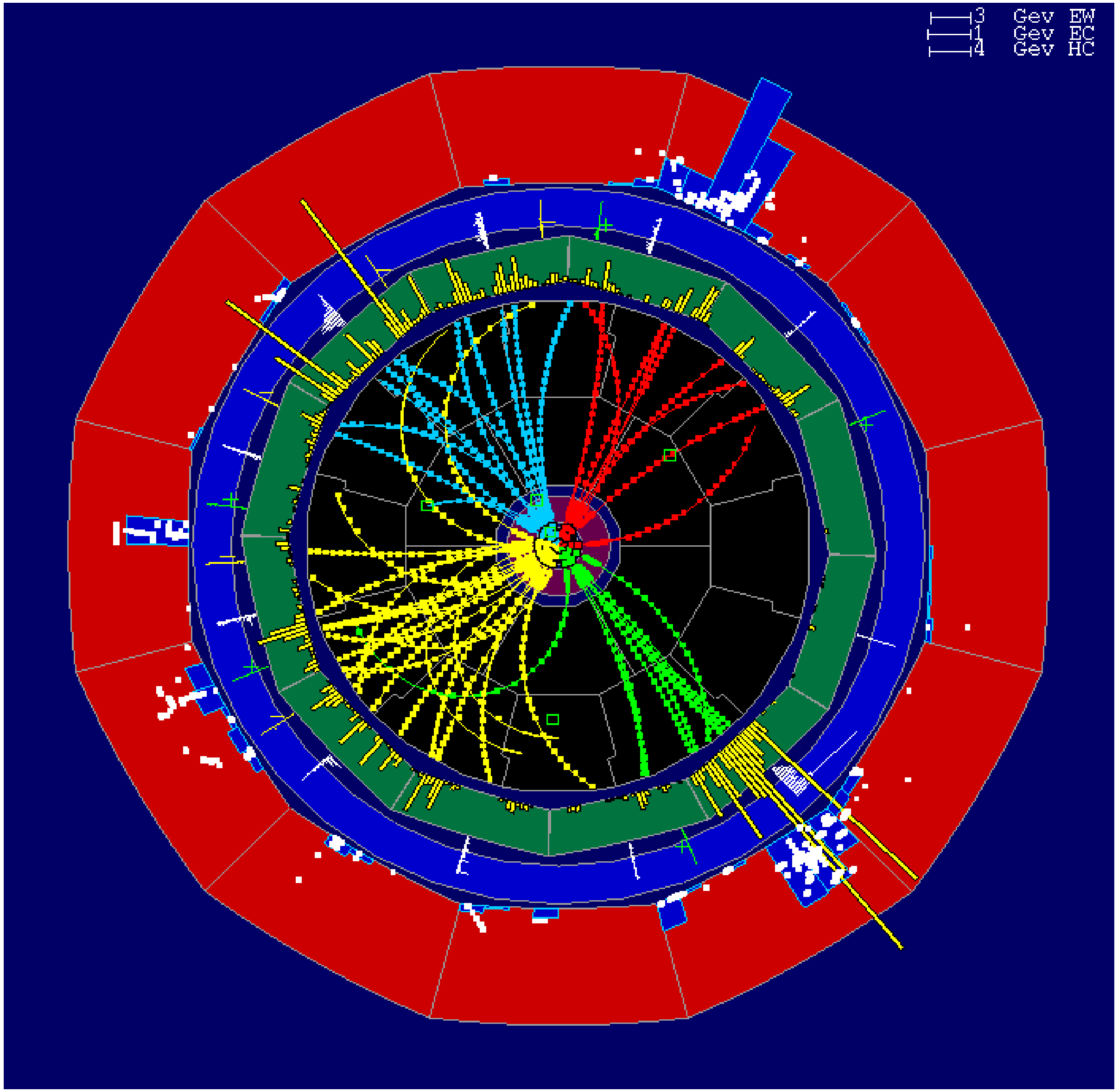
The quest for precision: e^+e^-

- Lepton colliders are ideal for precision measurements
- The center of mass energy is known !
- No problems with high pileup!
- No PDFs since we collide leptons
- No high order QCD calculations for the theorists!



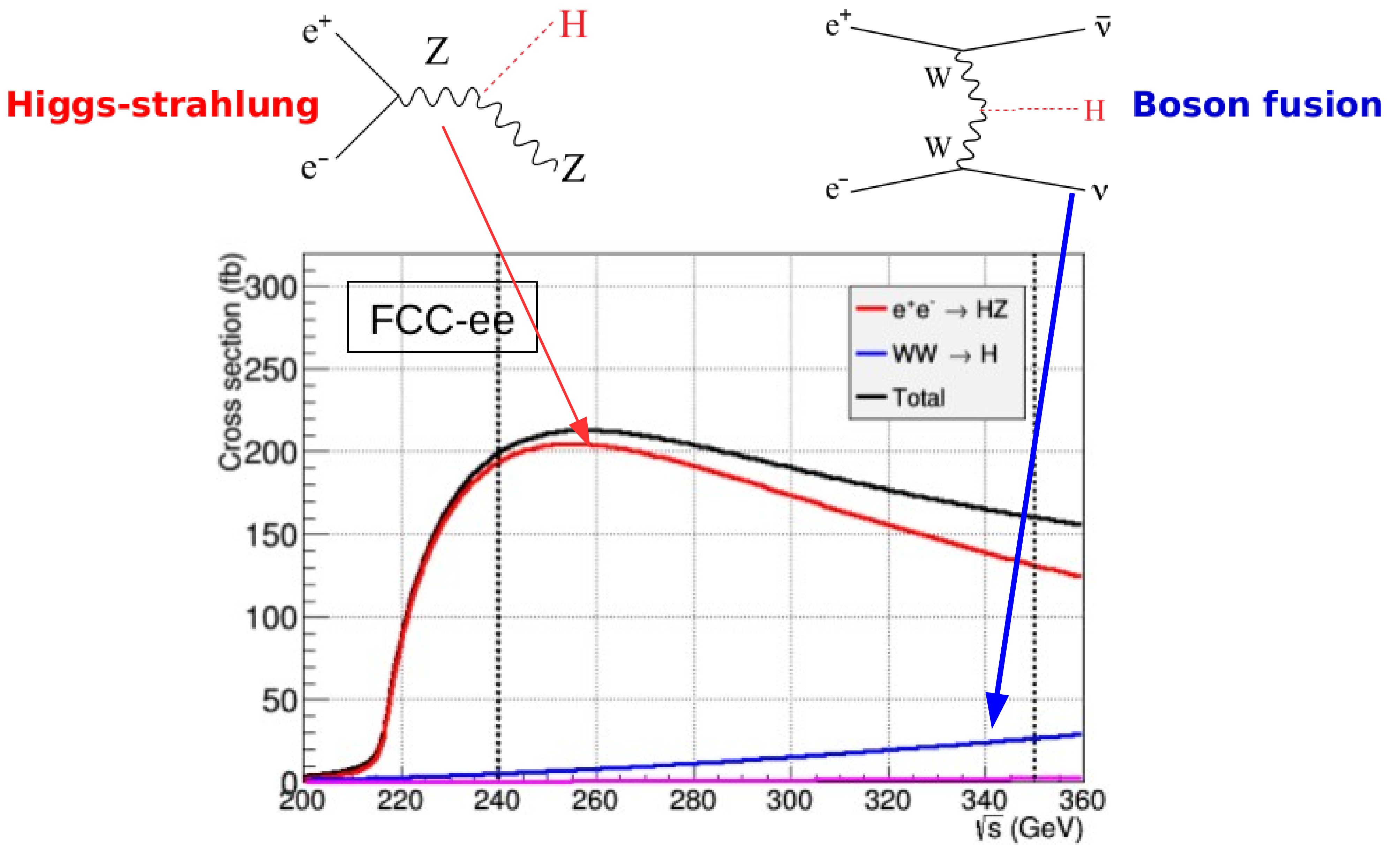


The quest for precision: e^+e^-



As clean as it can be.....

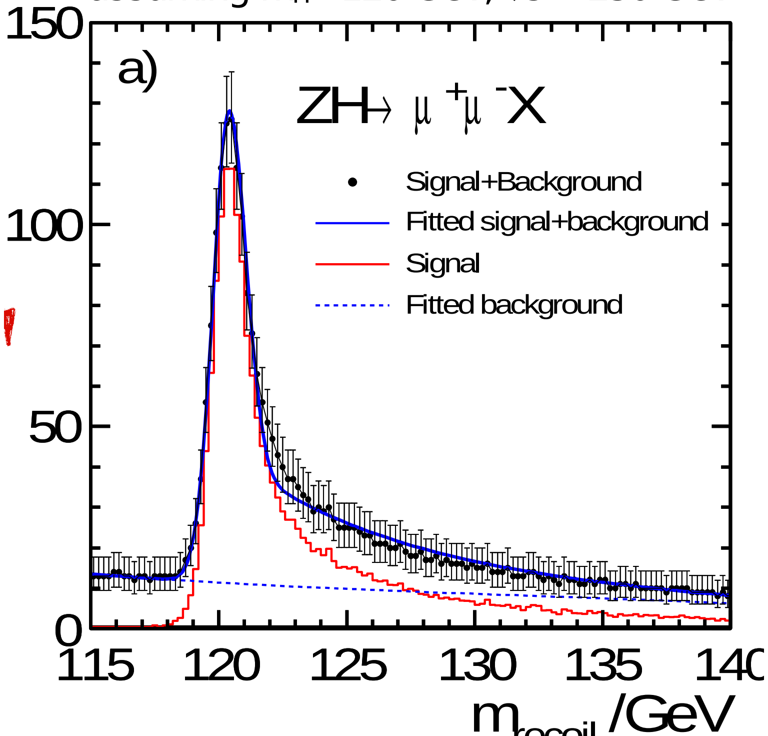
Higgs production @ e$^+$e$^-$

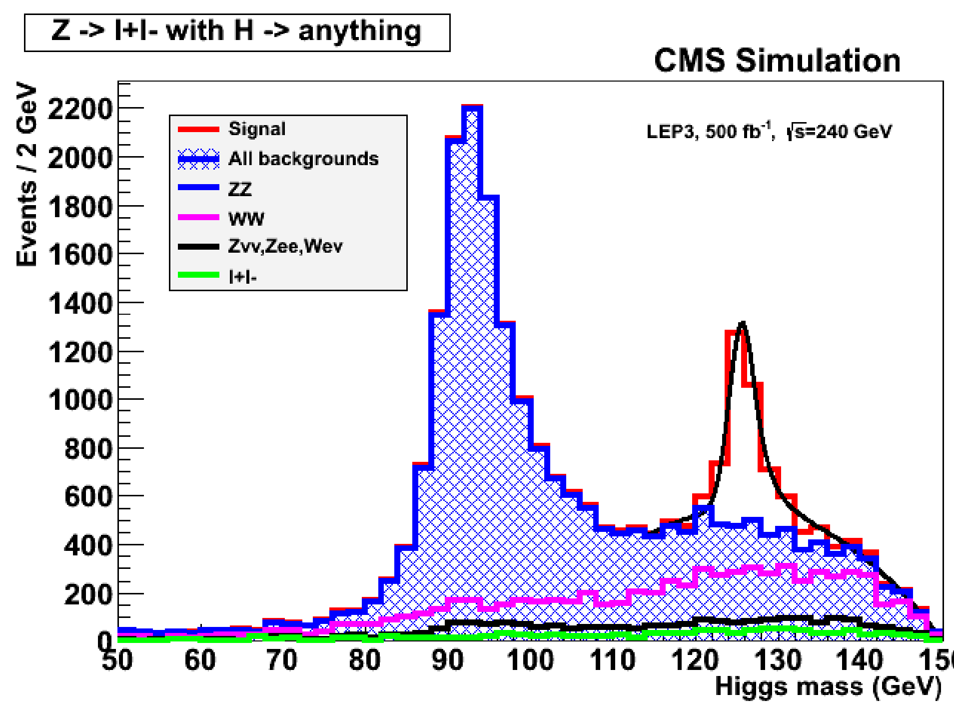


The magic of e⁺e⁻ collisions

- Calculation of the missing mass in ZH
  - Working group exercise yesterday!
- Reconstructing a Z pair and knowing the CM energy we can reconstruct the missing Higgs mass
  - Without requiring any Higgs decay mode

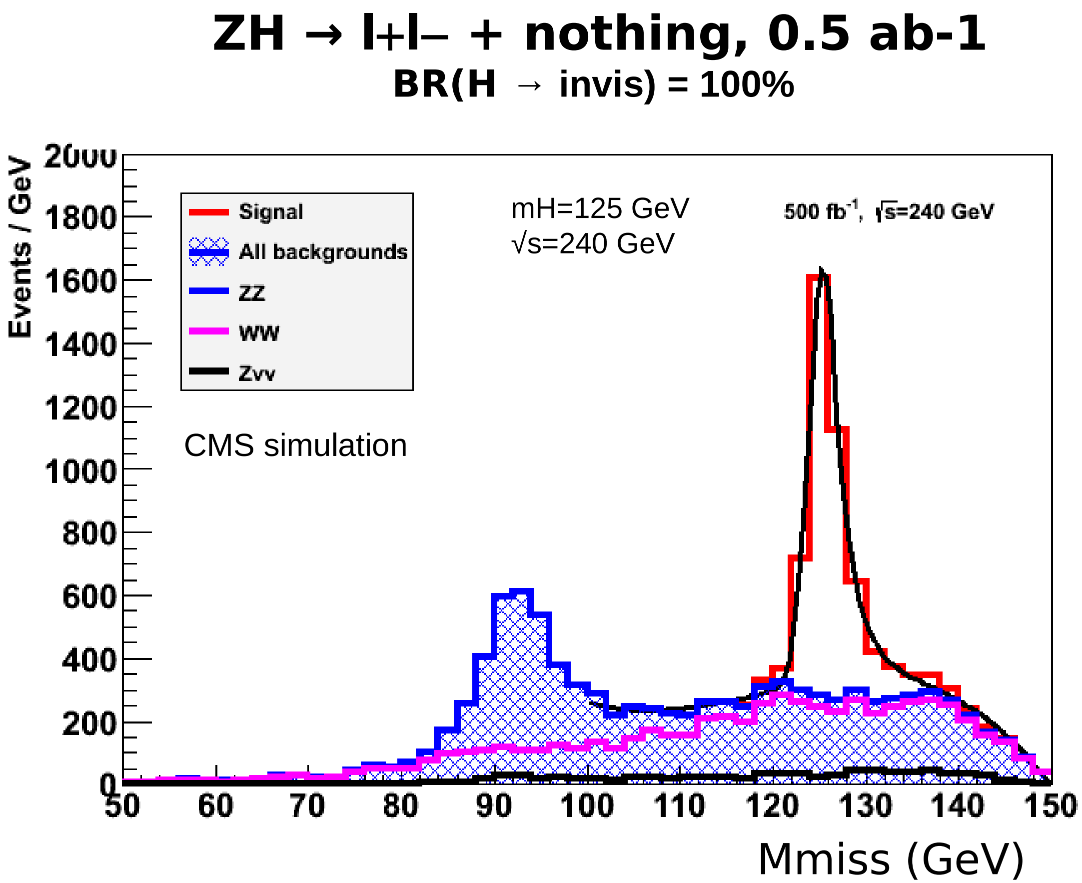
assuming m_H =120 GeV; √s = 250 GeV





Direct search for invisible decays

- Use ZH mode and reconstruct the missing higgs mass
- Then require that there is nothing else in the detector



How do we measure the width in e^+e^-

- With the missing mass technique we can measure directly just the cross section

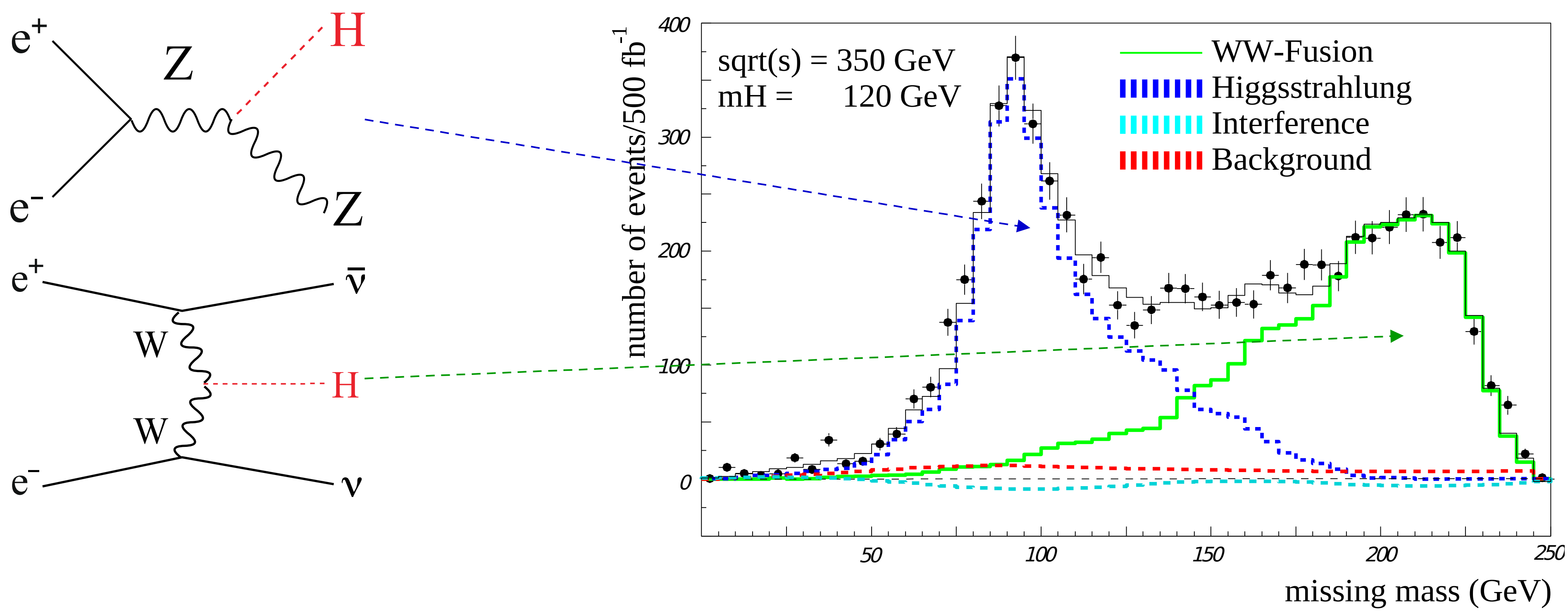
$$\sigma(ZH) \approx \kappa_Z^2$$

- Then by measuring the H → ZZ decay via e.g ZH → ZZZ

$$\sigma(ZH) \times BR(H \to ZZ) \approx \frac{\kappa_Z^4}{\Gamma/\Gamma_{SM}}$$

- Combining the above equations we measure directly the Higgs width
- One can combine the WWH production with H → WW for improved sensitivity

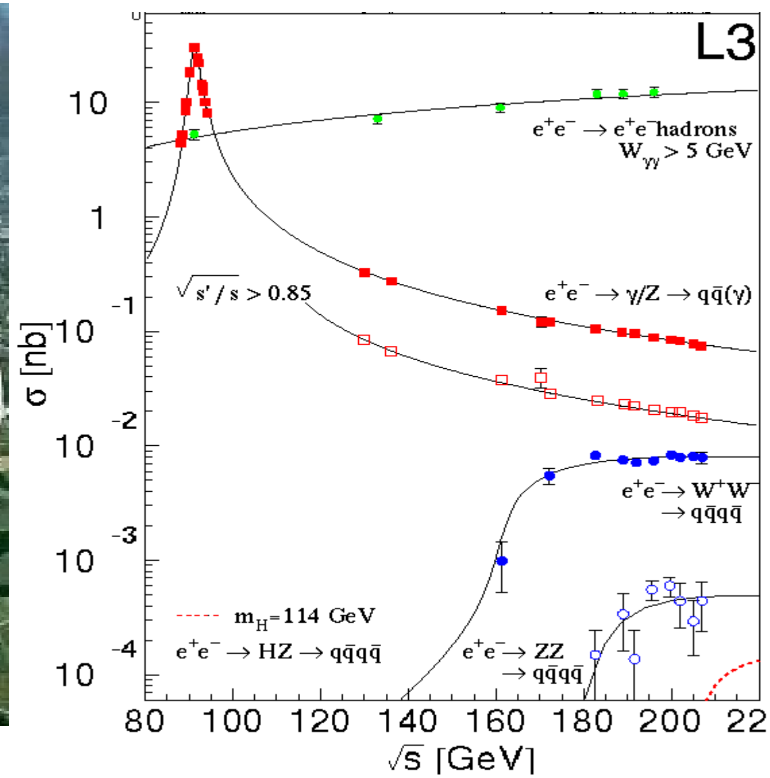
Probing the WWH mode



- Measuring the missing mass in the bbνν final state
- Background from ZH (H → bb / Z →νν)

Do we need circular or linear?

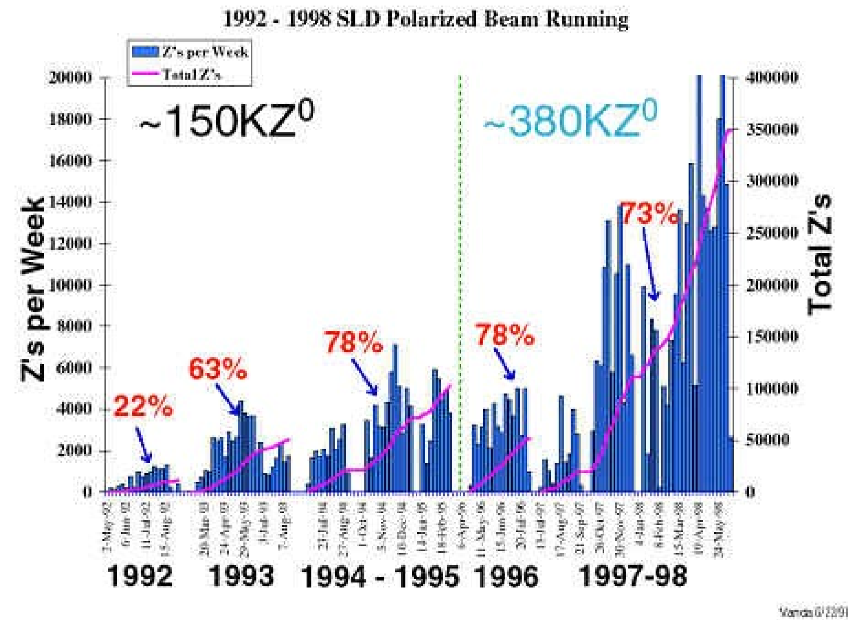
High energy e^+e^- machines



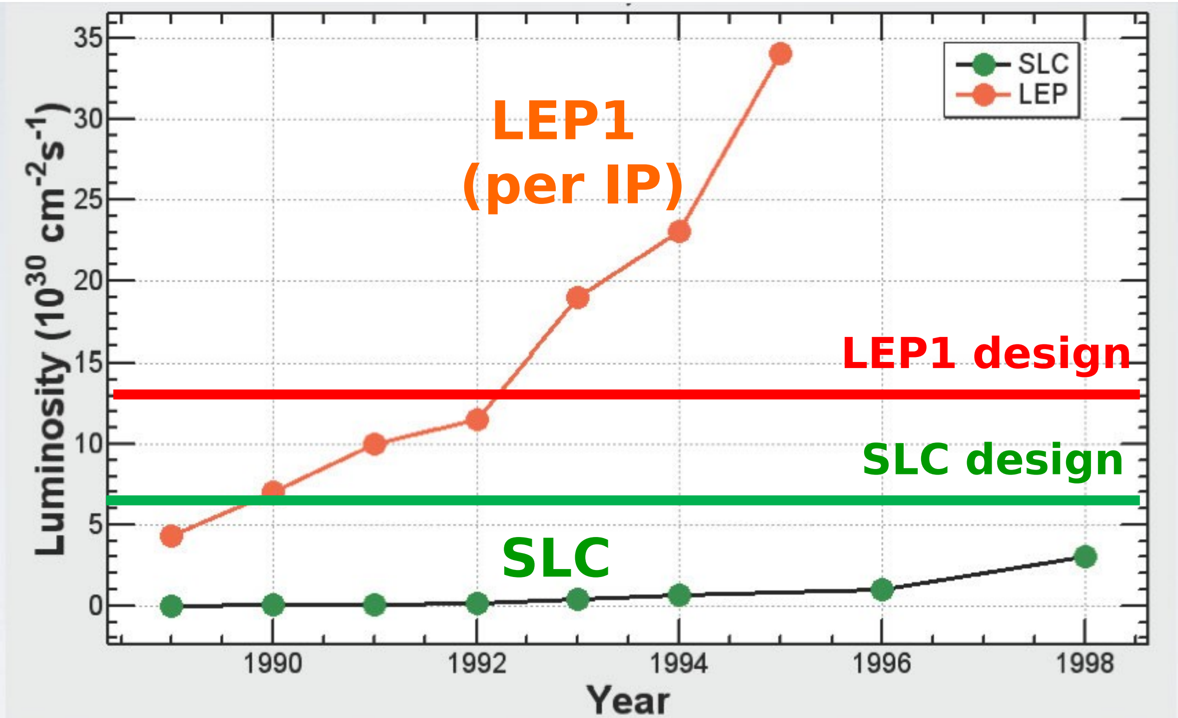
- LEP: largest e^+e^- circular collider so far
  - 26.7 km circumference
  - Energy of 88-209 GeV
  - 4 detectors [ALEPH, DELPHI, L3, OPAL]
  - 20M Z decays and 40000 WW events

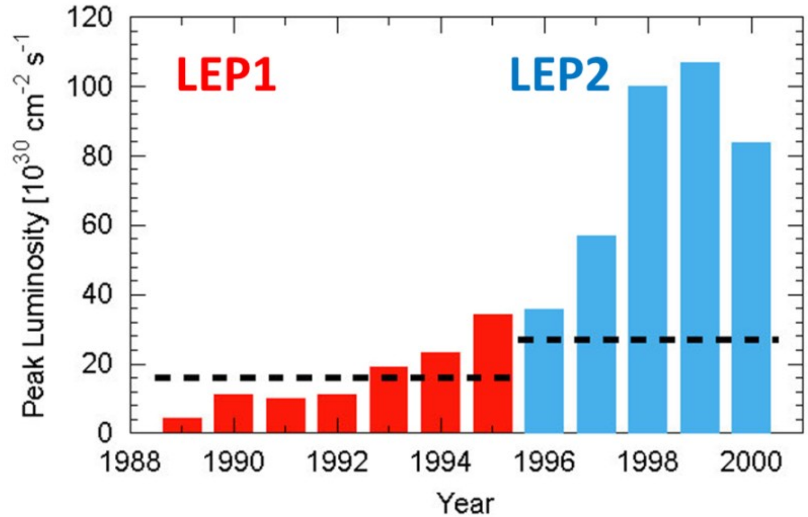
High energy e⁺e⁻ machines

- SLC: largest linear collider
  - 2 miles long
  - CM energy of 91 GeV
  - Polarized electron beam
  - 1 detector
  - 400000 Z events



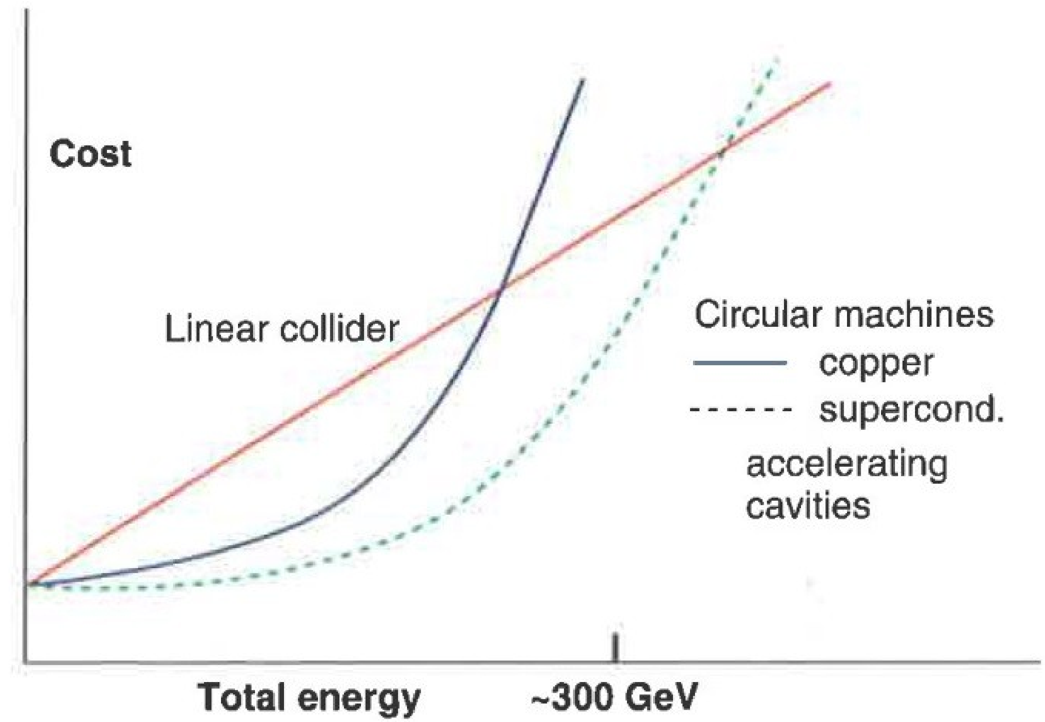
LEP and SLC performance





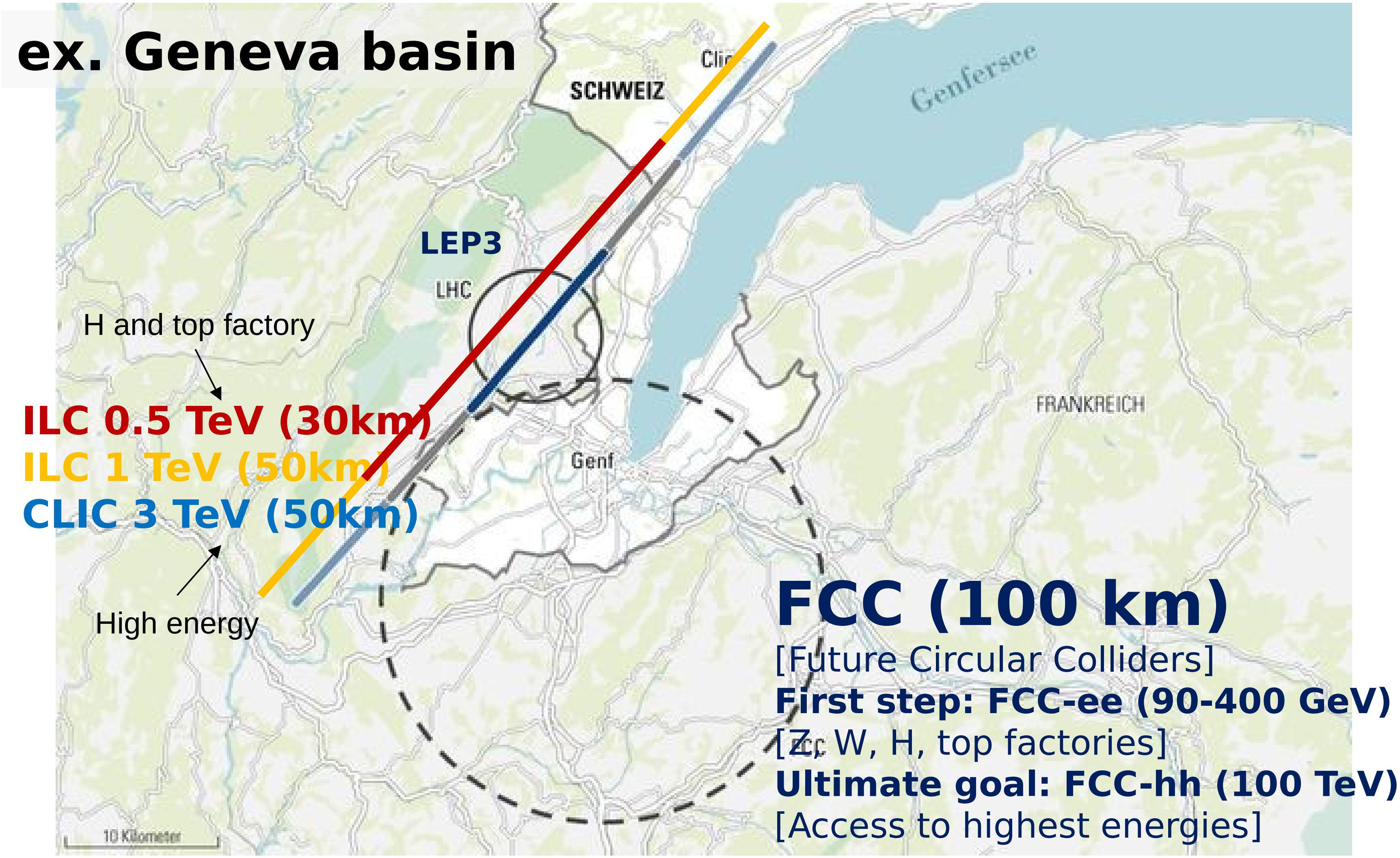
- LEP exceeded all expectations doing 3x better than expected
- SLC achieved about 50% of the design specifications
- In general linear colliders → more difficult machines
  - Does not have to be the same next time around

Why linear?



- Energy loss by synchrotron radiation $\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$
  - In circular machines
- Energy loss grows per turn
  - 3.5 GeV /turn @ LEP2

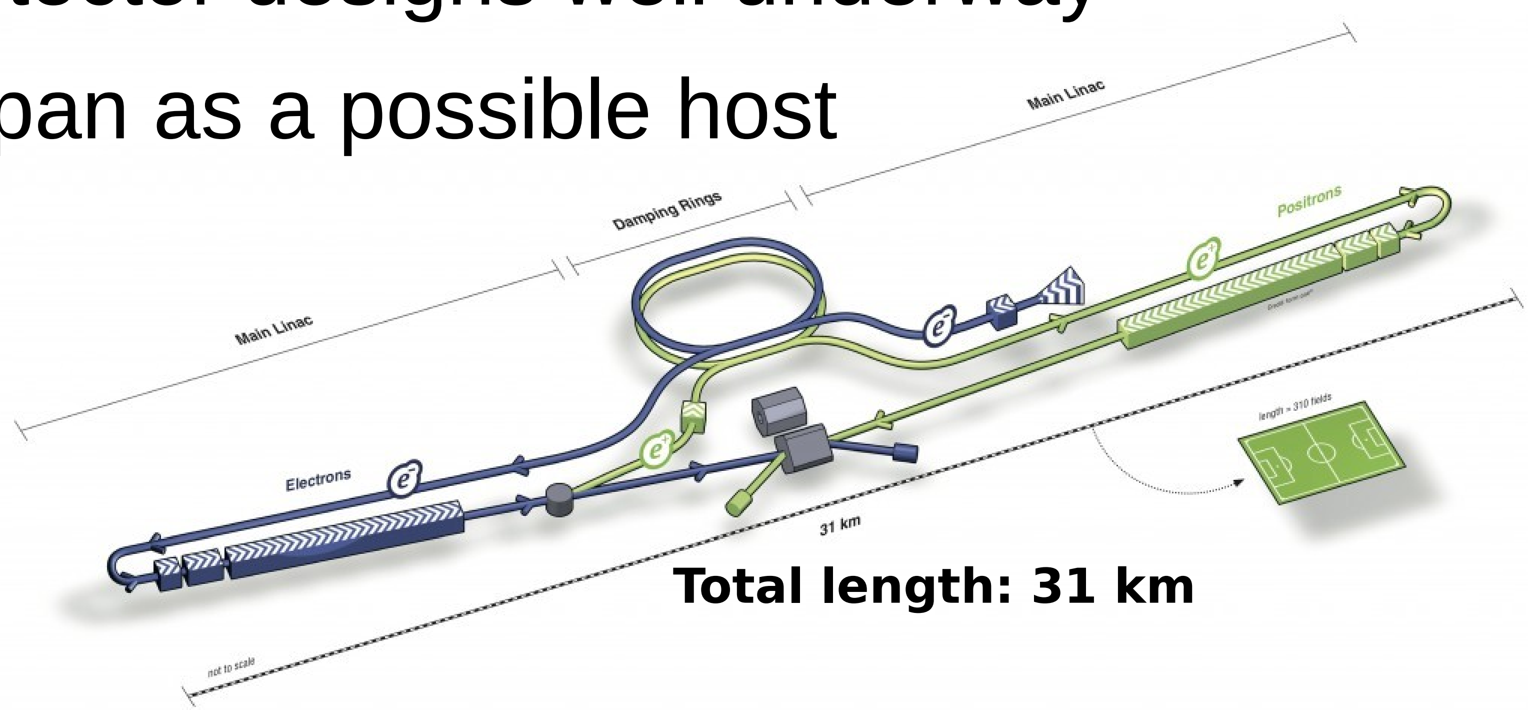
Future proposed machines



23

The International Linear Collider(ILC)

- Maximum energy: 500 GeV
  - Possible upgrade to 1 TeV
- R&D for the last 20 years
- Technical Design report ready
- Detector designs well underway
- Japan as a possible host

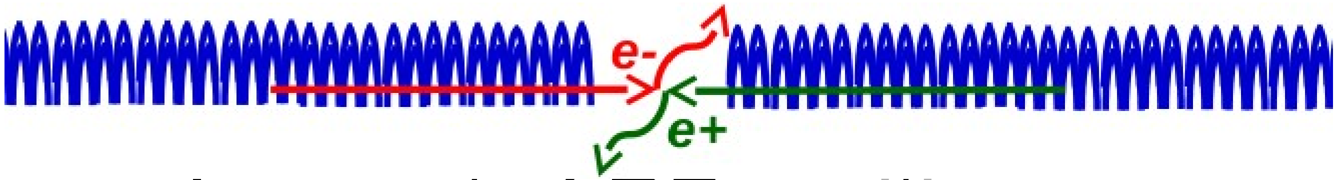


Total length: 31 km

FCC- e^+e^-

- Formerly known as TLEP
- First proposal in 2012 -conceptual report by 2018
- Circular collider in 100km tunnel , maximum CM energy 350 GeV
- Tunnel can then be used to host a 100 TeV proton machine
  - FCC-pp
- CERN as possible host?

How high CM energy is achieved



- ILC uses long set of RF cavities
  - Since beams are lost after collisions
  - The RF system needs to provide the full beam energy
    - O(8km)
- In FCC-ee , beams circulate many times
  - For hours
  - Less RF needed → just compensate synchrotron radiation loss
    - O(800m)

How luminosity is achieved

Number of interaction points

particles/beam

Number of bunches

Colission frequency

Geometrical factor
for crossing angle

$$\mathcal{L} = \frac{n_{IP} N^2 k_b f F H_D}{4\pi \sigma_x^* \sigma_y^*}$$

Factor for beam beam
interactions

You know what this is!

Transverse size of the beam

How luminosity is achieved(circular)

More than one detector
Can be added

Number of bunches increase as CM
Energy decreases [using the available RF]

3kHz
[since beams circulate]]

$$\mathcal{L} = \frac{n_{IP} N^2 k_b f F H_D}{4\pi \sigma_x^* \sigma_y^*}$$

Beam sizes can be conservative

How luminosity is achieved (linear)

One IP by construction

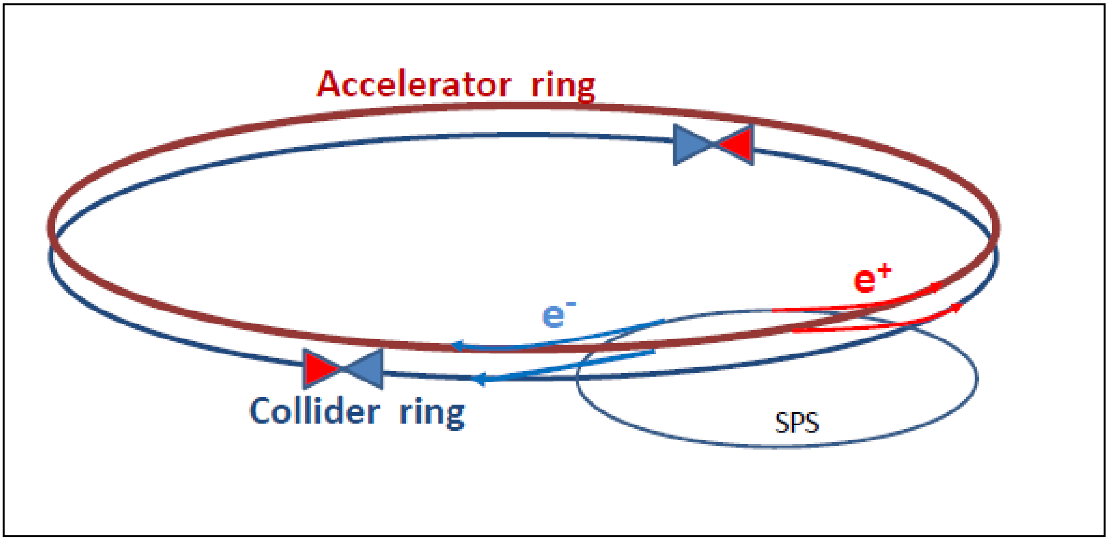
Frequency of 5 Hz [refill time]

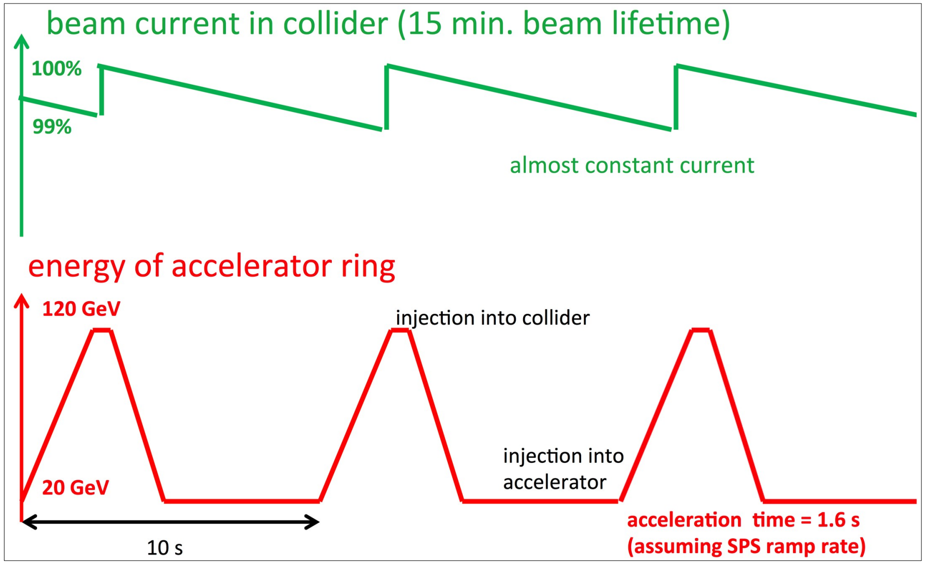
$$\mathcal{L} = \frac{n_{IP} N^2 k_b f F H_D}{4\pi \sigma_x^* \sigma_y^*}$$

Luminosity performance relies Mainly on low beam size!

Collateral effect for FCC-ee

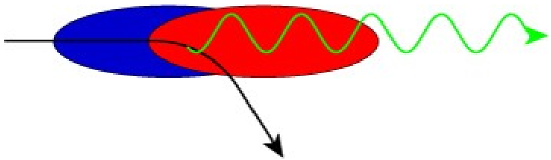
- Beam lifetime [15 mins]
- Due to Bhabba scattering ($e^+e^- \rightarrow e^+e^-$)
  - Burns the beam!
- Solution known from B-factories
  - Top up injection → use 2 rings!
  - Has to be demonstrated



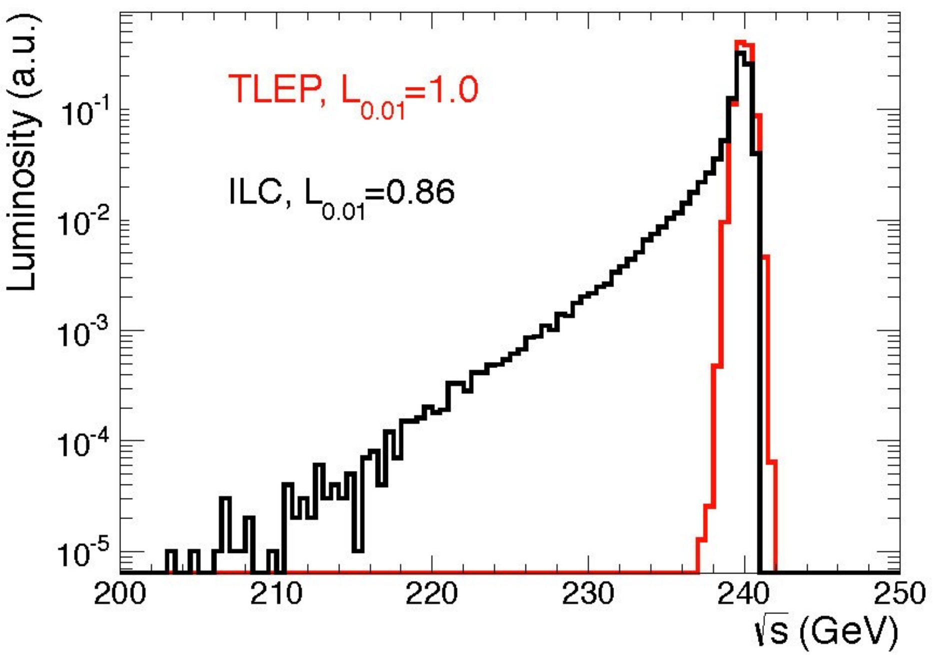


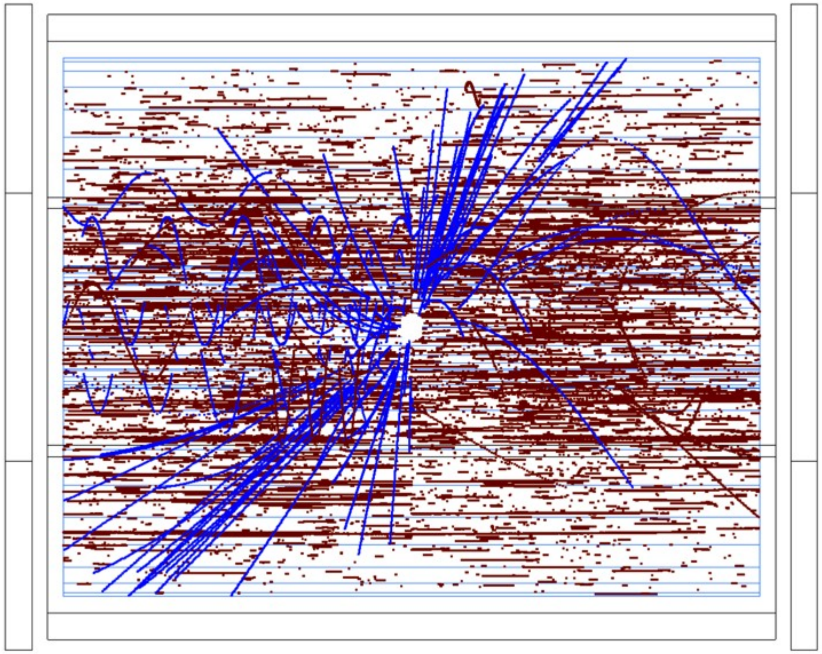
Collateral effect for ILC

- Bremsstrahlung



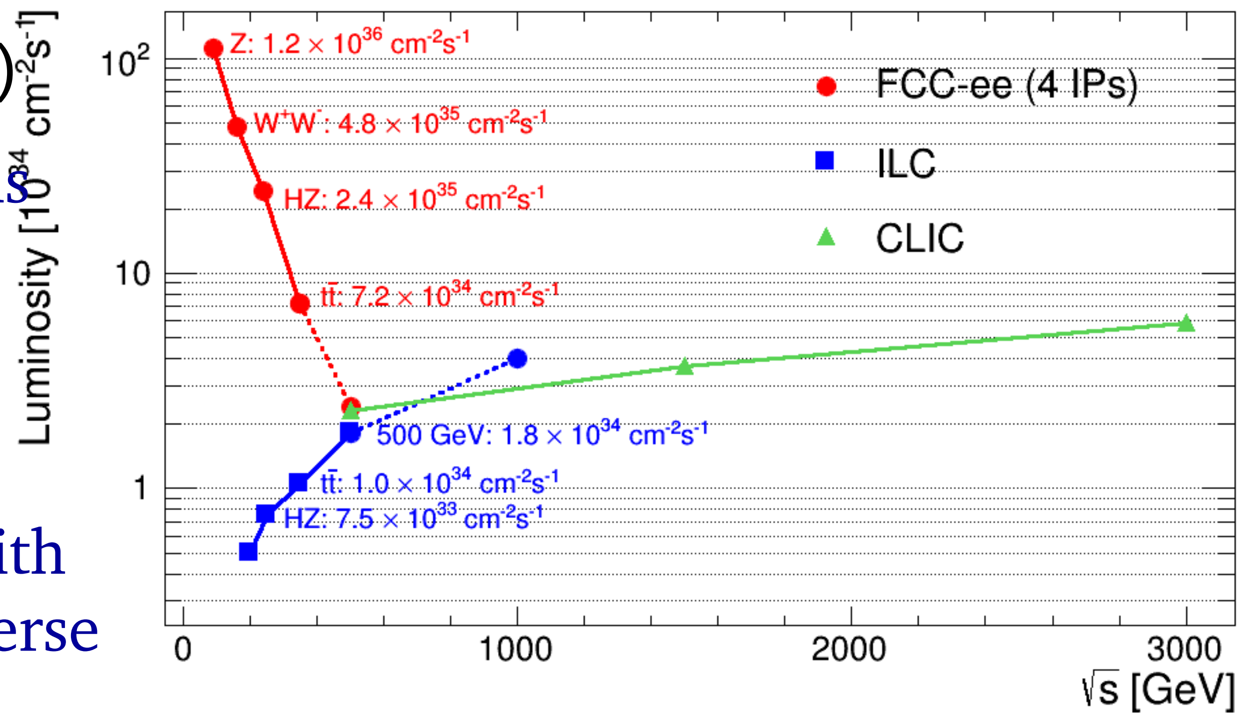
  - Radiation in the field of the opposing beam
  - Degrades beam energy profile
  - Adds additional event content (ala PU) in the detector





FCC-ee vs ILC luminosity

- FCC-ee could host up to 4 detectors (if budget allows)
  - Luminosity increasing as energy drops (more bunches)
- ILC larger energy range
  - Luminosity increases with energy (smaller transverse size of beam)



	ILC-250	**FCC-ee-240**	ILC-350	**FCC-ee-350**
Lumi / IP / year	50 fb^{-1}	**500 fb^{-1}**	70 fb^{-1}	**130 fb^{-1}**
Lumi / 5 yrs	250 fb^{-1}	**10 ab^{-1}**	350 fb^{-1}	**2.6 ab^{-1}**
# of HZ events	70,000	**2,000,000**	65,000	**325,000**
# of WW→H events	1,500	**50,000**	12,000	**65,000**

Luminosity expressed in Higgs results

4IPs for FCC -ee

Coupling	HL-LHC	ILC	FCC-ee
κW	2-5%	1.2%	0.19%
κZ	2-4%	1.0%	0.15%
κb	4-7%	1.7%	0.42%
κc	-	2.8%	0.71%
κτ	2-5%	2.4%	0.54%
κμ	~10%	91%	6.2%
κγ	2-5%	8.4%	1.5%
κg	3-5%	2.3%	0.8%
κZγ	~12%	?	?
BRinvis	~10-15% ?	< 0.9%	< 0.19%
ΓH	~50%?	5.0%	1.0%
κt	7-10%	14%	-
κH	30-50% ?	80%	-

Model-independent results

Sensitive to new physics at tree level (κW, κZ, κb, κc, κτ, κμ)

Sensitive to new physics in loops (κγ, κg, κZγ)

Sensitive to light dark matter (BRinvis, ΓH)

Need higher energy to improve on LHC (κt, κH)

Some conclusions(I)

- ILC can provide energies up to 1 TeV [with upgrade]
  - The precision on the Higgs couplings is ~ x2 better than HL-LHC
  - However many measurements not within a 1% bound for requirements to probe indirectly new physics
  - ILC can probe the top coupling @ 15% level and can look at Higgs self coupling however not with a good accuracy
    - Seems HL-LHC would do better on those
- For all this to be achieved it has to operate with much better success than SLC and reach the design goals
  - Many technical challenges to be addressed but the proposal is at good state

Some conclusions (II)

- A circular machine would provide ultimate precision in Higgs couplings measurement
  - Achieving well below 1% for all measurements+ width
  - And huge luminosity for Z and top studies
  - The threshold is not enough to probe directly the top coupling or the Higgs self coupling
    - It can probe them via indirect measurements
- The technical challenges are not as many as in the case of ILC due to the long experience with LEP and B-factories
  - However still challenges remain and solutions need to be demonstrated

Some conclusions (III)

- If we look further than the Higgs ILC energy could be used to discover new particles [I.e SUSY] produced in pairs [up to 500 GeV]
  - However LHC @ 14 TeV would already discover them
  - In the case of discovery of new physics @ LHC a high energy proton machine or a very high energy linear collider (O(3 TeV)) ala CLIC would become interesting
- The FCC-ee could be the first step step to a 100 TeV proton machine
  - Repeating the success story LEP-LHC
  - Able to discover new physics at the next scale
  - And measure with ultimate precision the remaining Higgs properties (I.e self coupling)
- In any case we should evaluate the results from the next LHC run to decide!