Moving forward

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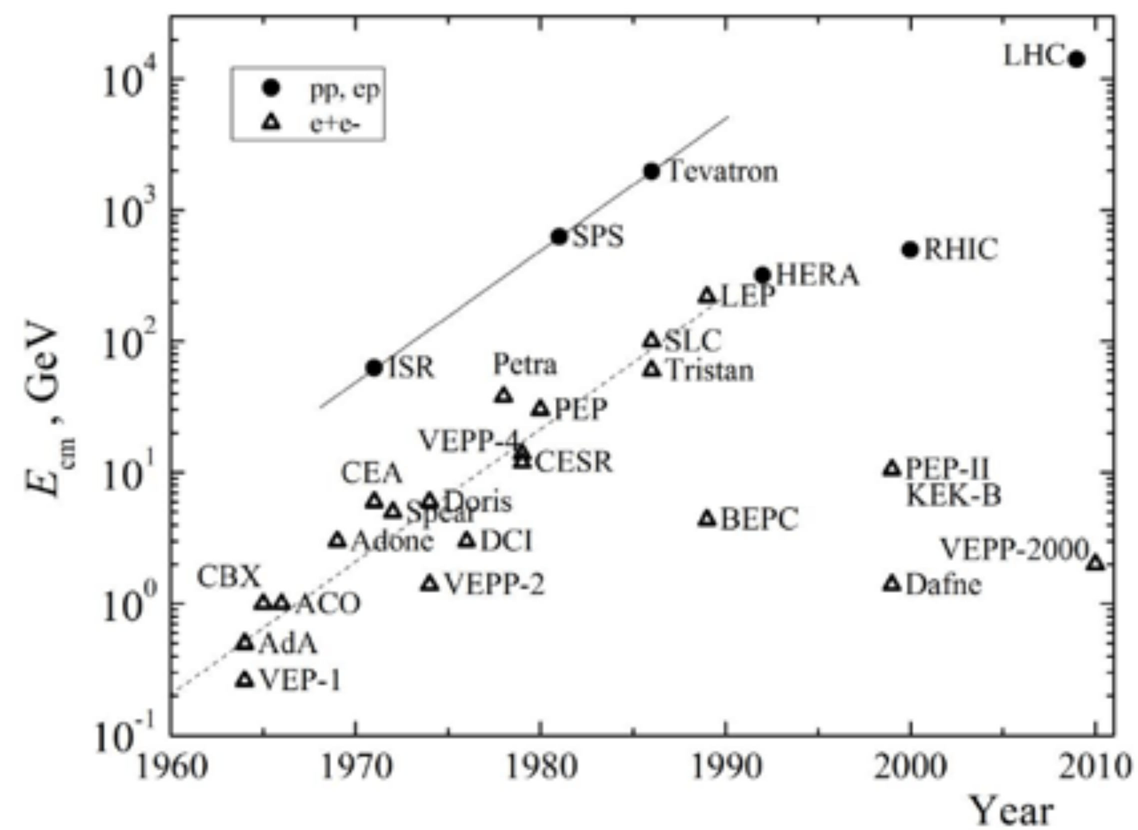
Credo

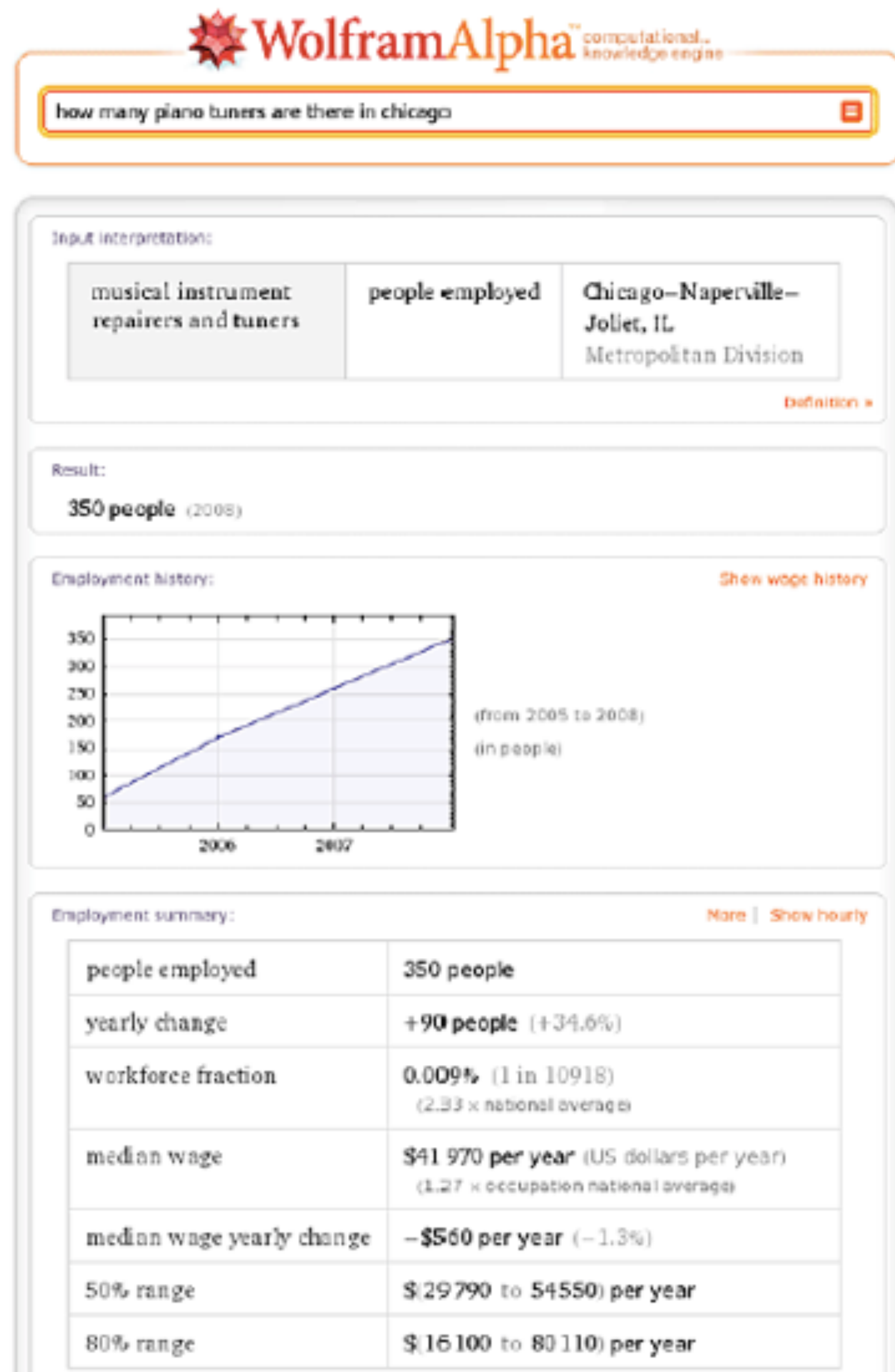
- Accelerator-based particle physics is the fundamental core of our subject - allows us to perform reproducible experiments.
- Historical precedent: 100-fold increase in Energy for both hadron and lepton colliders (in ~50 years).
- Access to the highest energy will continue to require colliders.
- Does an advanced technological civilisation have another high-energy collider in its future? Certainly, yes.
- When?



Livingston plot (1954)

Fermi estimates
Piano tuners in Chicago

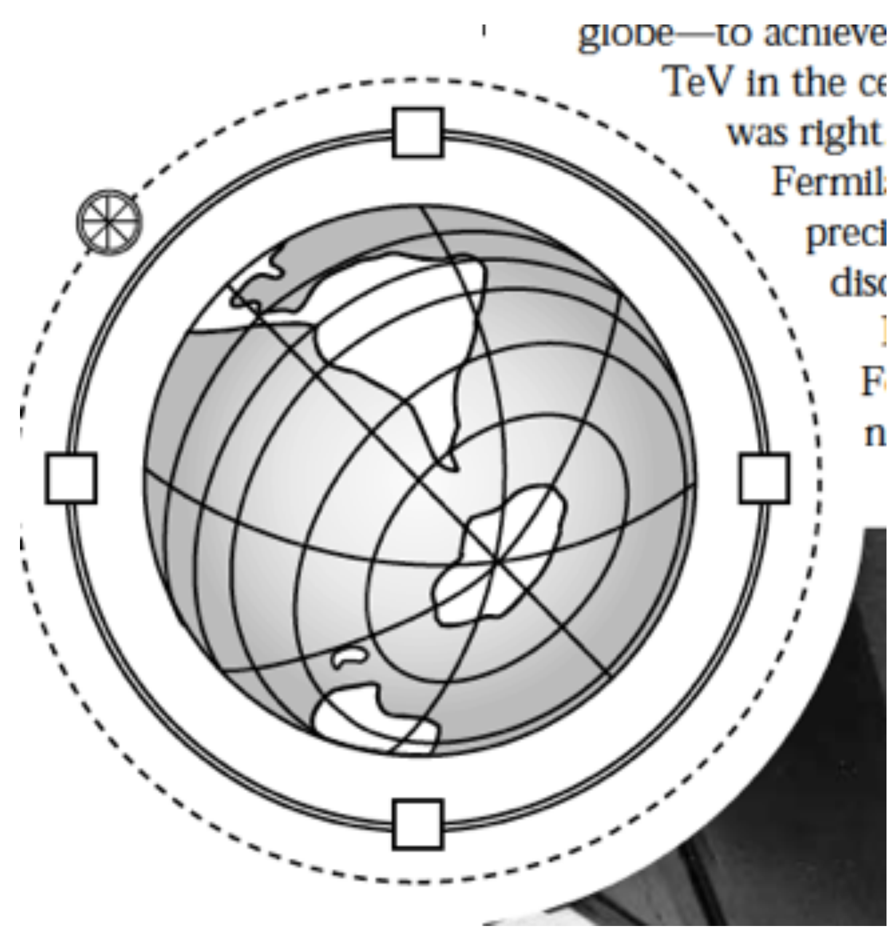
- Graduate school admission question.
- How many piano tuners are there in Chicago?



New accelerators, Fermi-estimates

- In 1954 Enrico Fermi pointed out that a $\sqrt{s}$=3TeV fixed-target accelerator would need to encircle the earth and cost \$170B.

- He was unduly pessimistic, because human ingenuity invented particle colliders and superconducting magnets.



Menu

- Accelerator basics
- Accelerator costs
- Future Hadron colliders HL-LHC,HE-LHC,FCC(pp)
- e+e- FCC(ee),CepC,ILC
- Muon collider.

Acceleration of particles

- The equation of motion for an electron acted on by a Lorentz force is

$$\frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \wedge \vec{B})$$

We have $E^2 = \vec{p}^{\,2} c^2 + m_0^2 c^4$ so that $E\frac{dE}{dt} = c^2 \vec{p} \cdot \frac{d\vec{p}}{dt}$

$$\frac{dE}{dt} = \frac{ec^2}{E}(\vec{p} \cdot \vec{E} + \vec{p} \cdot \vec{v} \wedge \vec{B}) = \frac{ec^2}{E}\vec{p} \cdot \vec{E}$$

A magnetic field cannot change a particle's energy; to accelerate we need a magnetic field.

Bending magnetic field

- A synchrotron has a bending field produced by several bending magnets
- Field changes as momentum increases to keep particles in fixed orbit.
- Balance of centrifugal force and Lorentz force for bending radius ρ

Continuous magnetic fields have a practical limitation to ~20-30T.

$$\frac{mv^2}{\rho} = evB \quad \Longrightarrow p = eB\rho$$

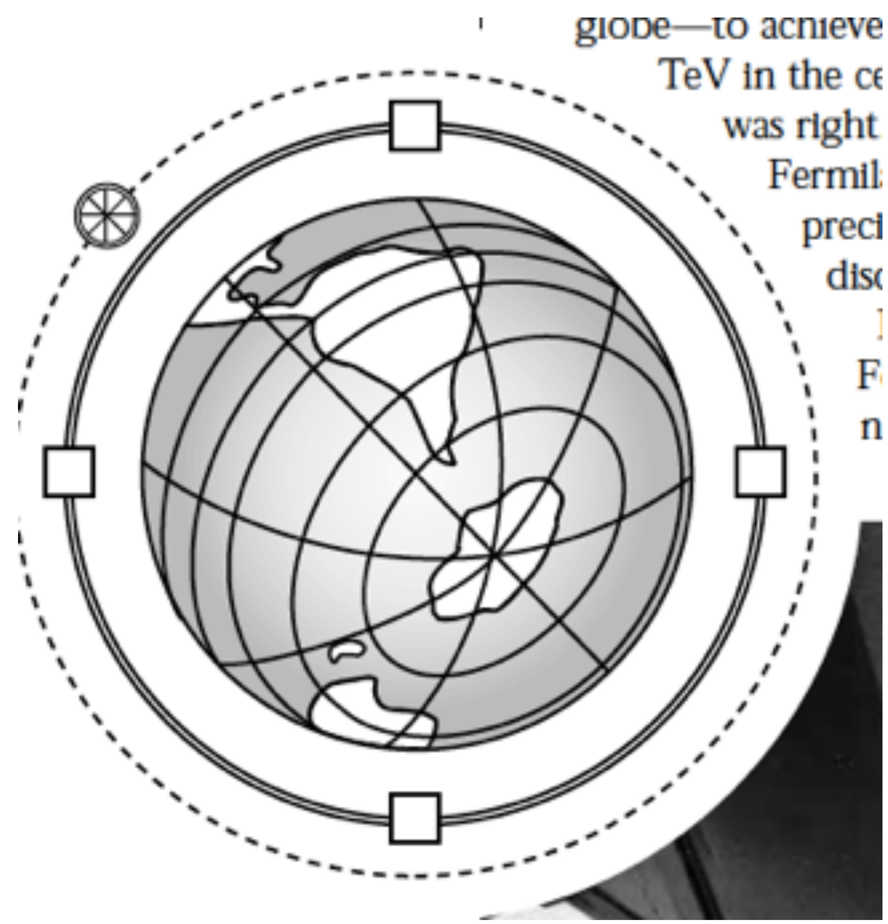
$$\frac{pc}{e}[eV/c] = c[m/s]B[T]\rho[m] \quad \Longrightarrow (pc/e)[TeV/c] = 0.299B[T]\rho[km]$$

	p[GeV/c]	B[T]	ρ
LHC14	7000	8.33	2.800[km]
LHC33	16500	20	2.800[km]
μ-Higgs factory	62.5	8.33	50[m]
μ-collider	500	8.33	200[m]
100TeVpp	50000	16	10.4[km]

Table 1: Bending radius of various proposed machines

Fermi machine

- $\rho = 6371 km$
- $B = 1 Tesla$
- $p = 1904 TeV/c$
- $\sqrt{s} = \sqrt{(2*0.938/1000*p)} = 1.89 TeV$



Synchroton radiation

- After one turn the synchrotron radiation energy loss per particle grows as the fourth power Lorentz gamma factor $\gamma = \frac{E}{m_0}$
- Depends sensitively on the beam energy and the rest mass $m_e : m_\mu : m_p = 1 : 207 : 1836$ and also on the bending radius
- In a circular accelerator the energy loss per particle per turn is

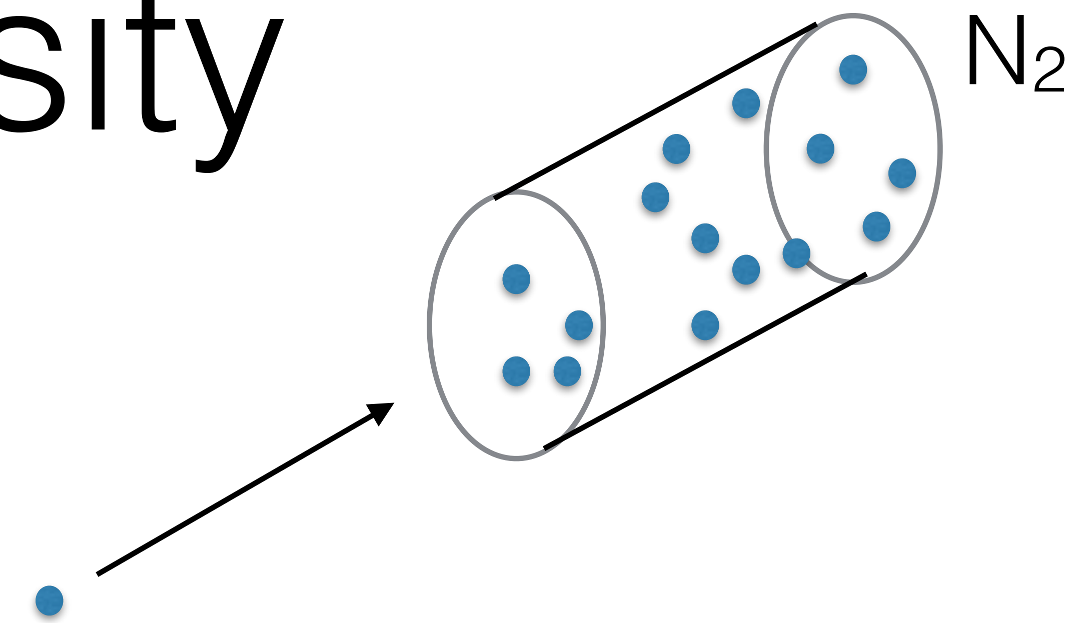
$$\Delta E[\mathrm{GeV}] = \frac{6.034 \times 10^{-18}}{\rho[\mathrm{m}]} \left(\frac{E[\mathrm{GeV}]}{m_0[\mathrm{GeV/c^2}]} \right)^4$$

At LEP, energy is halved after 650 revolutions in a time of 59ms

Machine	ΔE [GeV]	E	m	ρ	
LEPI	0.180	50 GeV	0.511 MeV	3100[m]	Important
LEPII	2.850	100 GeV	0.511 MeV	3100[m]	
μ Higgs	14.6×10^{-9}	62 GeV	0.106 GeV	50 [m]	
LHC	6.93×10^{-6}	7 TeV	0.938 GeV	2700[m]	Negligible
100TeV	0.0049	50TeV	0.938 GeV	10,000[m]	Significant

Table 2: Synchtroton energy lossses per turn per particle

Luminosity



- Cylindrical bunches have a cross sectional area A and contain N_1, N_2 particles

- A given particle in Bunch 1 will interact with a fraction $N_2 \frac{\sigma_{int}}{A}$

- Total number of such interactions is $\frac{N_1 N_2 \sigma_{int}}{A}$

- If the frequency of bunch interactions is *f*, then the interaction rate is $R = f \frac{N_1 N_2}{A} \sigma_{int}$

- Hence the luminosity per bunch is

$$\mathcal{L} = f \frac{N_1 N_2}{A}$$

$$R = \mathcal{L} \sigma_{int}$$

- More sophisticated calculation for Gaussian beams, colliding head-on, Nb number of bunches. σ_x, σ_y are the transverse sizes of the Gaussian.

$$\mathcal{L} = f \frac{N_1 N_2 N_b}{4\pi \sigma_x \sigma_y}$$

V. Shiltsev, arXiv:1404.4097

Phenomenological Model of Accelerator costs

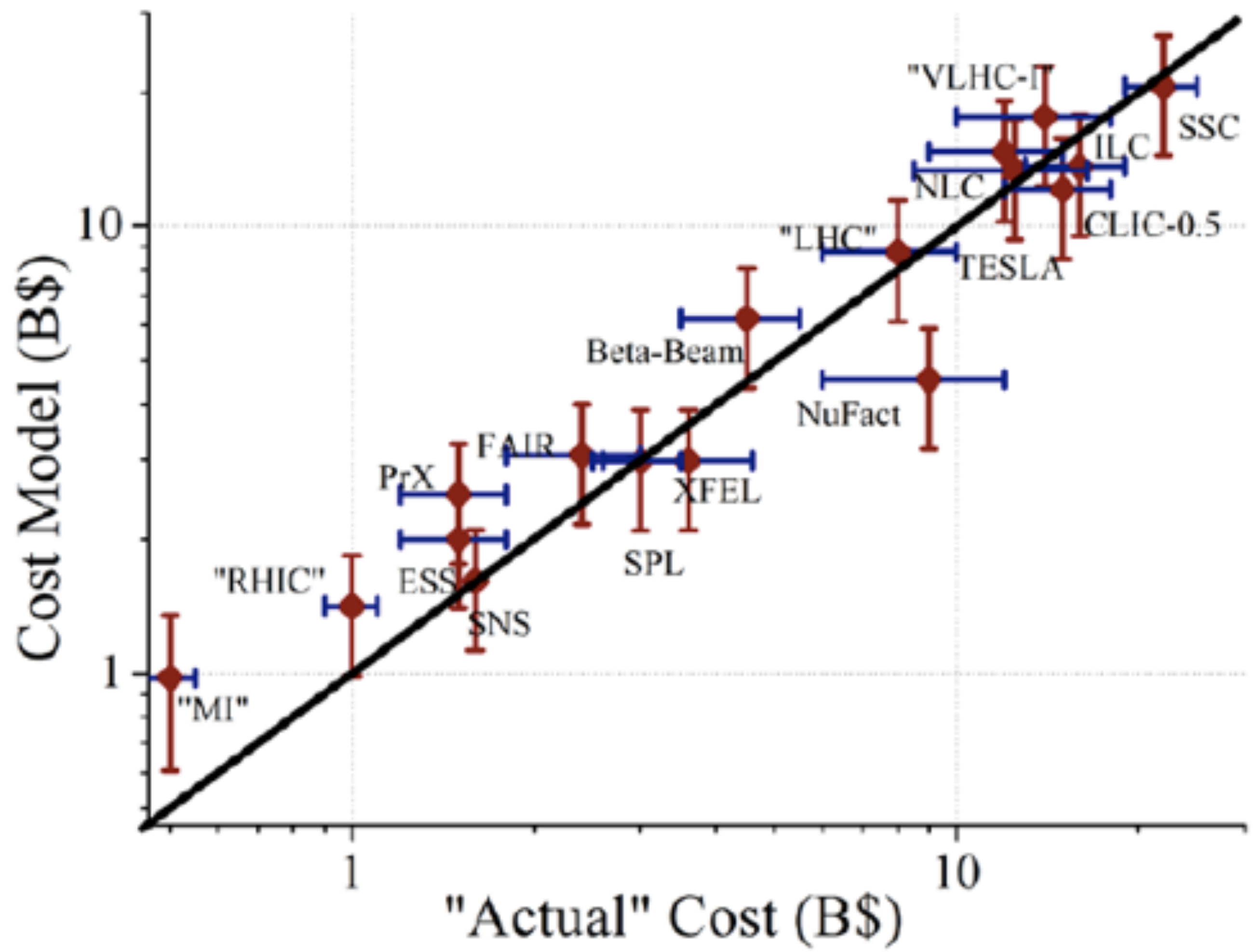
- Total project cost [TPC] divided into three components
    - Civil Engineering and construction
    - Accelerator components
    - Facility Infrastructure

$$\mathrm{TPC} = \alpha\left(\frac{L}{10[\mathrm{km}]}\right)^{\frac{1}{2}} + \beta\left(\frac{E}{1[\mathrm{TeV}]}\right)^{\frac{1}{2}} + \gamma\left(\frac{P}{100[\mathrm{MW}]}\right)^{\frac{1}{2}}$$

- Phenomenological formula parametrised in terms of tunnel length[L], centre-of-mass Energy[E] and total site AC power [P]
- Coefficient beta is technology dependent

$$\begin{aligned}
\alpha &= \$2B \\
\gamma &= \$2B \\
\beta &= \$1\mathrm{B}\ (\mathrm{NCmagnets}), \\
\beta &= \$2\mathrm{B}\ (\mathrm{SCmagnets}), \\
\beta &= \$8\mathrm{B}\ (\mathrm{NCRF}), \\
\beta &= \$10\mathrm{B}\ (\mathrm{SCRF})
\end{aligned}$$

Validation of cost model



- Model good to about 30%
- Lots of inverted commas around Actual!

V. Shiltsev, arXiv:1404.4097

How much is plausible/ possible?

- The CERN subscription is about $1B/year.
- World-wide spending is about $3B/year, of which only a fraction is available for projects
- Spending $1B/year over ten years would allow us to complete a $10B project.

Estimated costs of future facilities

- Costs are in American accounting, i.e. including all labour costs. In European accounting this would be a factor ~2-2.5 smaller.

	E[TeV]	L[km]	P[MW]	$\alpha\beta\gamma$ TPC [$B]	Civil construction cost [$B]
Ce^+e^-C	0.25	54	~ 500	10.2	4.6
FCC-ee	0.25	100	~ 300	10.9	6.3
ILC	0.5	36	163	13.1	3.8
CLIC	3	60	~ 560	23.5	4.9
μ collider	6	20	~ 230	12.9	2.8
LHC-33	33	0	~ 100	4.8	0?
SppC(China)	50	54	~ 300	25.5	4.6
FCC-pp	100	100	~ 400	30.3	6.3

- Power usage is substantial. Rate of energy usage,~1 kW/person.

- A small nuclear power station gives 500MW of power.

The next project

- Every new machine needs to have a guaranteed deliverable, as well as the potential for serendipitous discovery.
- As a temporary goal, let us decide to find out as much about the Higgs boson as we can, and rate potential new machines on that basis.
- Everything is changed if we see something new at the 1TeV scale.

Why precision Higgs physics?

- Partial Widths into WW and ZZ. (Is the Higgs the only agent of EWSB?). Relative couplings fixed by EW symmetry. In standard model $g_{WWH} \cos^2 \theta_W = g_{ZZH}$
- Couplings to fermions, (Is the Higgs sole agent giving fermions their masses?)
- Mass, total width and self-coupling, look for invisible decays associated with BSM, map out Higgs potential.
- Measure couplings to third generation(t,b,τ) and second generation(μ,c).

μ and κ

- Signal strength: ratio between observed and expected rate

$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}.$$

- Scale factor to parameterise deviation from SM coupling.

$$g_{Hff} = \kappa_f \cdot g_{Hff}^{\mathrm{SM}} = \kappa_f \cdot \frac{m_f}{v}$$

$$g_{HVV} = \kappa_V \cdot g_{HVV}^{\mathrm{SM}} = \kappa_V \cdot \frac{2m_V^2}{v}$$

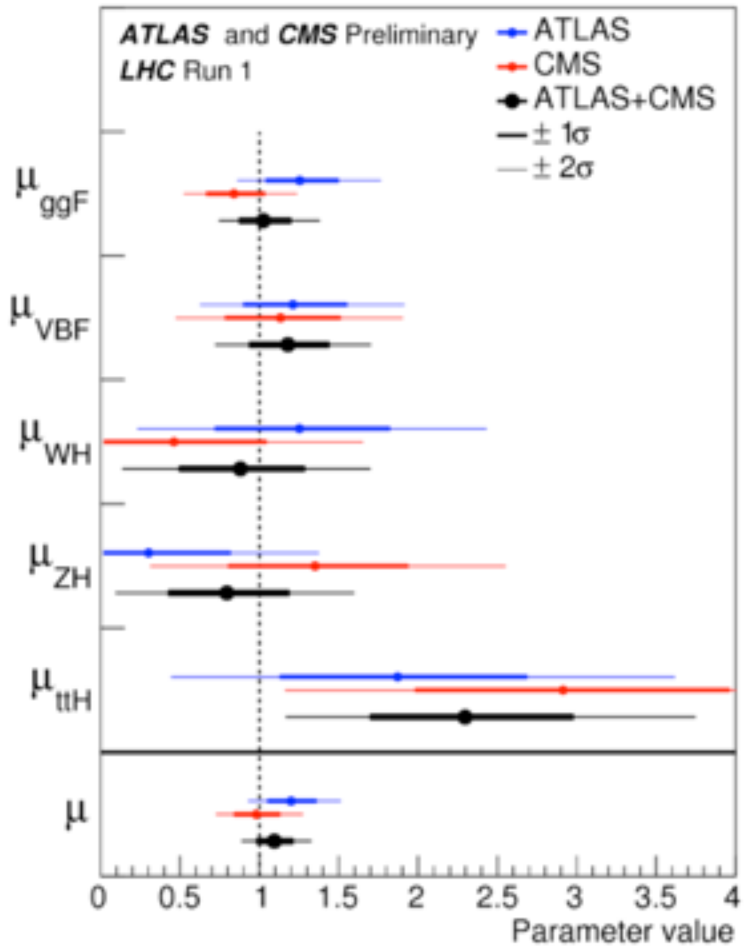
- Additional scale factor for the total width.

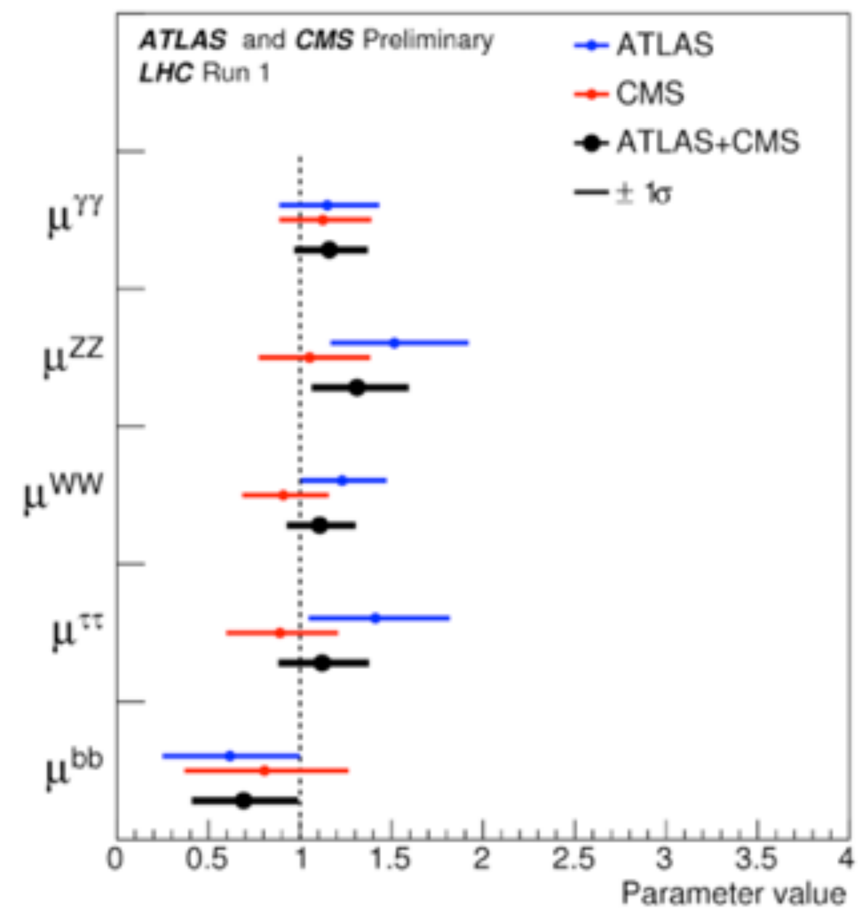
$$\kappa_H^2 = \sum_X \kappa_X^2 \mathrm{BR}_{\mathrm{SM}}(H \to X),$$

- For example

$$\sigma \times \mathrm{BR}(gg \to H \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2},$$

Current situation



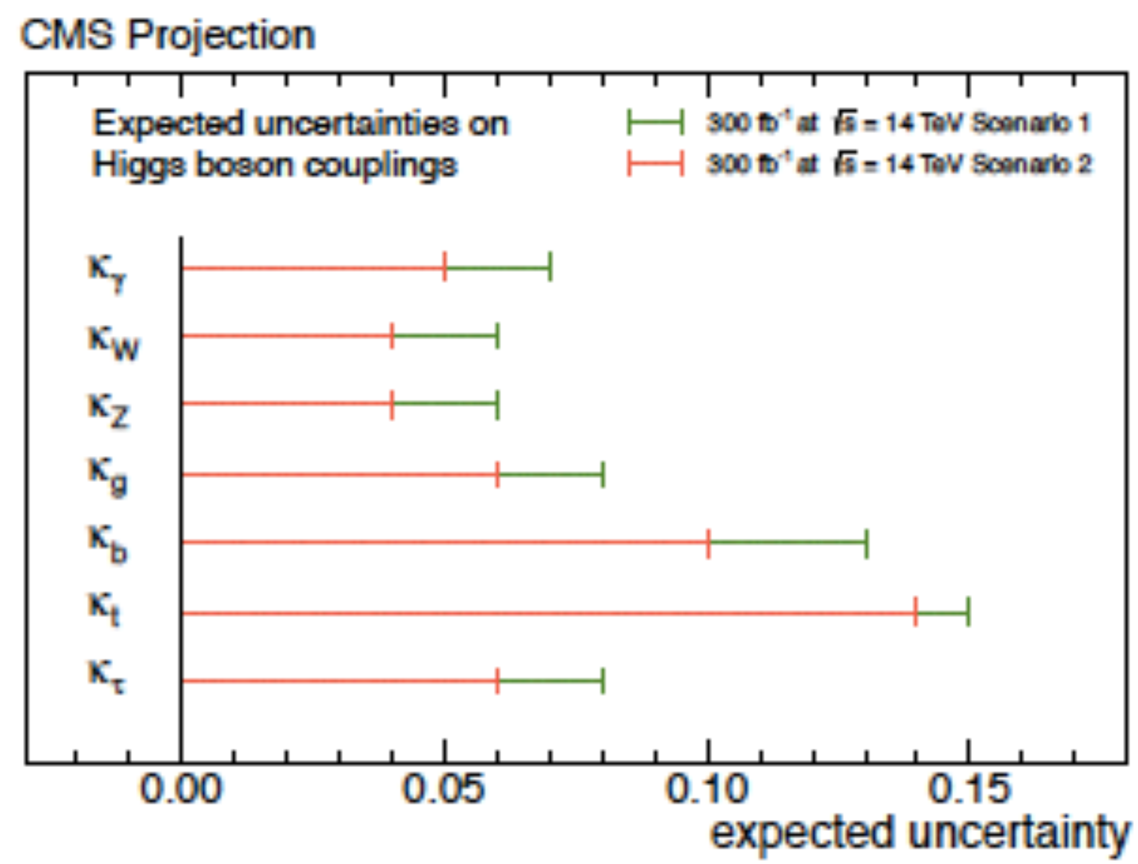


Production process	ATLAS+CMS	ATLAS	CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$	$1.25^{+0.24}_{-0.21}$	$0.84^{+0.19}_{-0.16}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$	$1.21^{+0.33}_{-0.30}$	$1.13^{+0.37}_{-0.34}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$	$1.25^{+0.56}_{-0.52}$	$0.46^{+0.57}_{-0.54}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$	$0.30^{+0.51}_{-0.46}$	$1.35^{+0.58}_{-0.54}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$

Decay channel	ATLAS+CMS	ATLAS	CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$

Situation in 2022

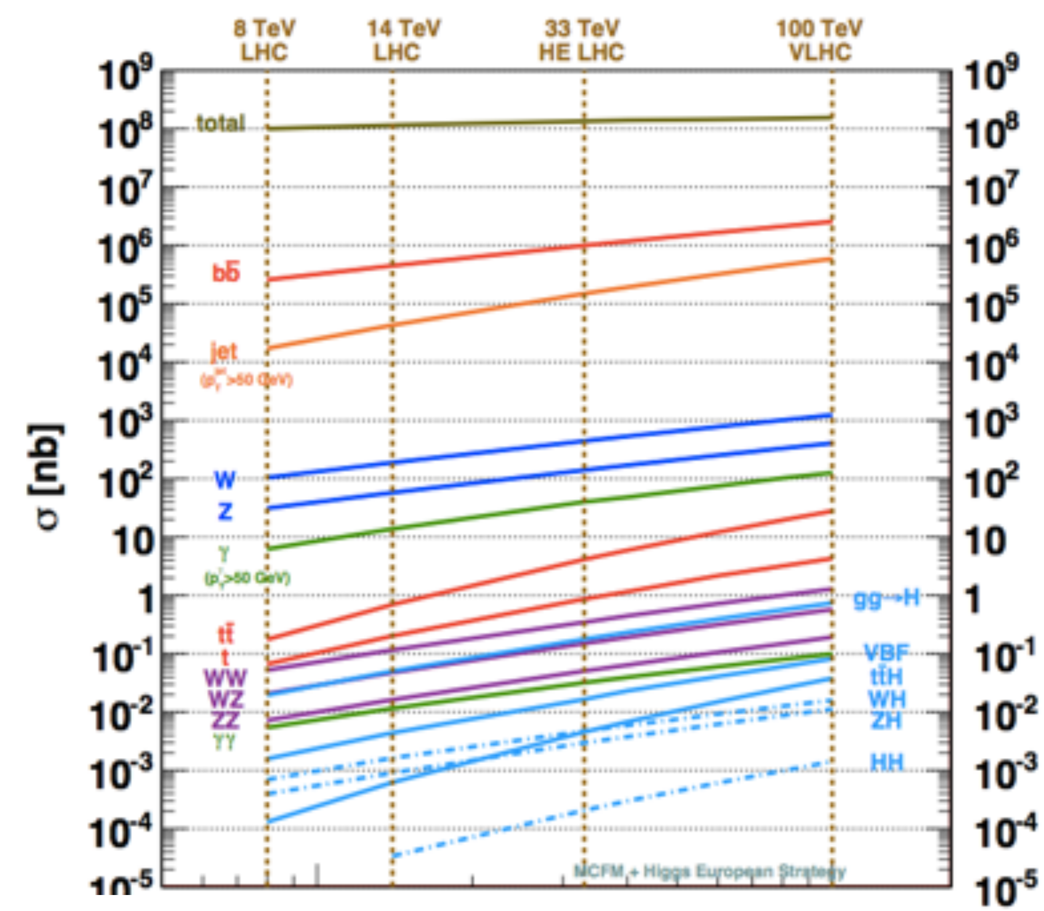
- 300 fb^{-1} @13/14TeV
- Measurement of 5 production modes gg->H,VBF,WH,ZH,ttH
- Six decay modes ɣɣ,ZZ,WW,bb,μμ
- We can expect to following coupling accuracy
- 10-15% fermionic couplings
- 5-6% boson couplings
- 5-10% couplings through loops.



Scenario 1: Syst. unchanged, Statistical improvement
Scenario II: Theoretical Uncertainties x1/2, Other Systematic scale with square root of luminosity

Hadron colliders as Higgs Factories

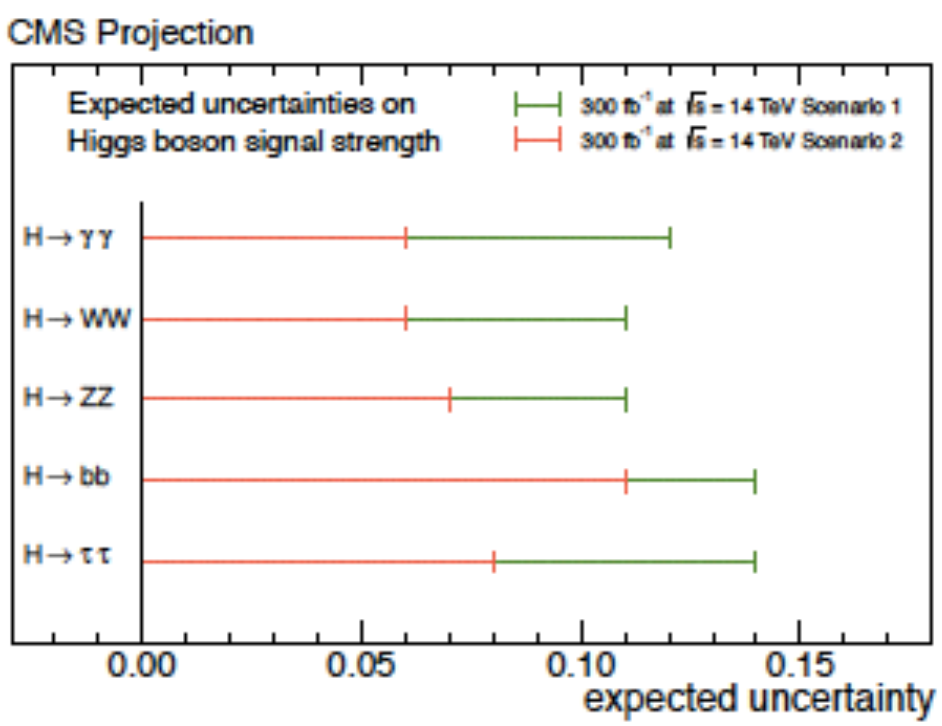
- Real factories vs lepton colliders
- Millions rather than thousands of H-bosons
- Signal to background
- Growth with energy.
- Access to Higgs pair production.

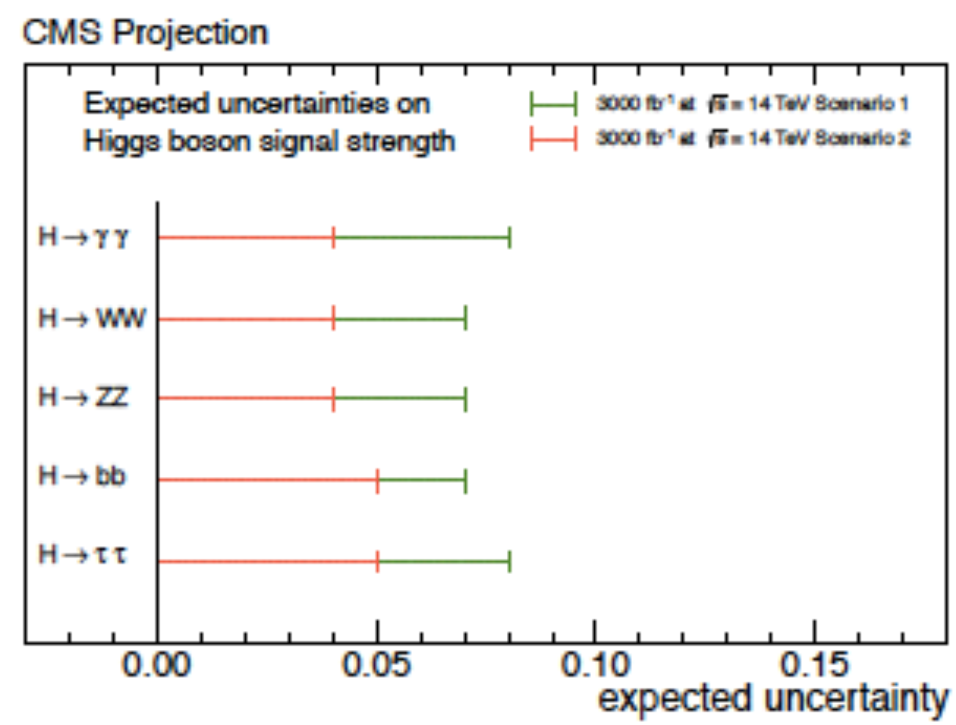


	ggF	VBF	VH	$t\bar{t}H$
H $\rightarrow$ all (3000 fb^{-1}@14 TeV)	149.7×10^6	12.54×10^6	7.14×10^6	1.833×10^6
Cross section [pb]($\sqrt{s} = 14$ TeV)	50.35	4.40	2.53	0.623
Cross section [pb]($\sqrt{s} = 33$ TeV)	178.3	15.47	7.053	4.377
Cross section [pb]($\sqrt{s} = 100$ TeV)	740.3	82.0	27.16	37.9

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/

Uncertainties at LHC after 300 and 3000 fb^{-1}





- LHC-HL can reduce signal strength uncertainties to about 5-7%

Non-observability of Width measurement at hadron collider

$$\text{Rate}_{ij} = \sigma_i \frac{\Gamma_j}{\Gamma_{\text{tot}}} = \kappa_i^2 \sigma_i^{\text{SM}} \frac{\kappa_j^2 \Gamma_j^{\text{SM}}}{\sum_k \kappa_k^2 \Gamma_k^{\text{SM}} + \Gamma_{\text{new}}}$$

- Assume a common rescaling by **κ** this reduces to

$$\text{Rate}_{ij} = \frac{\kappa^4 \sigma_i^{\text{SM}} \Gamma_j^{\text{SM}}}{\kappa^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}.$$

- Choosing special values we obtain the same result as in the standard model

$$\kappa^2 = \frac{1}{1 - \text{BR}_{\text{new}}}$$

$$\text{BR}_{\text{new}} \equiv \frac{\Gamma_{\text{new}}}{\Gamma_{\text{tot}}} = \frac{\Gamma_{\text{new}}}{\kappa^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}.$$

- Hadronic collider measurements cannot simultaneously constrain the couplings, and new contributions to the total width.

For a bound on the Higgs width at a hadronic collider, see Caola & Melnikov 1307.4935

How precisely do we need to know Higgs couplings?

- A hard question
- As precisely as possible?
- As precisely as theoretical errors on couplings?

Process	Cross section (pb)	Relative uncertainty in percent Total	Scale	PDF
Gluon fusion	49.3	$^{+19.6}_{-14.6}$	$^{+12.2}_{-8.4}$	$^{+7.4}_{-6.2}$
VBF	4.15	$^{+2.8}_{-3.0}$	$^{+0.7}_{-0.4}$	$^{+2.1}_{-2.6}$
WH	1.474	$^{+4.1}_{-4.4}$	$^{+0.3}_{-0.6}$	$^{+3.8}_{-3.8}$
ZH	0.863	$^{+6.4}_{-5.5}$	$^{+2.7}_{-1.8}$	$^{+3.7}_{-3.7}$

- Beyond the level of sensitivity associated with the non-observation of BSM particles at the LHC?
- eg MSSM

$$\kappa_V \sim 1 - 0.5\% \left(\frac{400\ \mathrm{GeV}}{M_A}\right)^4 \cot^2\beta$$

$$\kappa_t \sim 1 - \mathcal{O}(10\%) \left(\frac{400\ \mathrm{GeV}}{M_A}\right)^2 \cot^2\beta$$

$$\kappa_b = \kappa_\tau \sim 1 + \mathcal{O}(10\%) \left(\frac{400\ \mathrm{GeV}}{M_A}\right)^2 .$$

Examples of lepton-collider Higgs factories

Factory	Example	Circumference	$\sqrt{s}$	Prospect	Needs
e+e- Linear	ILC	∞	Phase 1 up to 500GeV	1TeV, GigaZ	New physics below 1 TeV?
e+e- Circular	FCC(ee)	100km	Up to 350GeV	FCC(pp)	New tunnel
μ+μ- Circular	muon collider	50m	125 GeV	ν factory $\sqrt{s}$ -> 5 TeV	Cooling, Extensive R&D

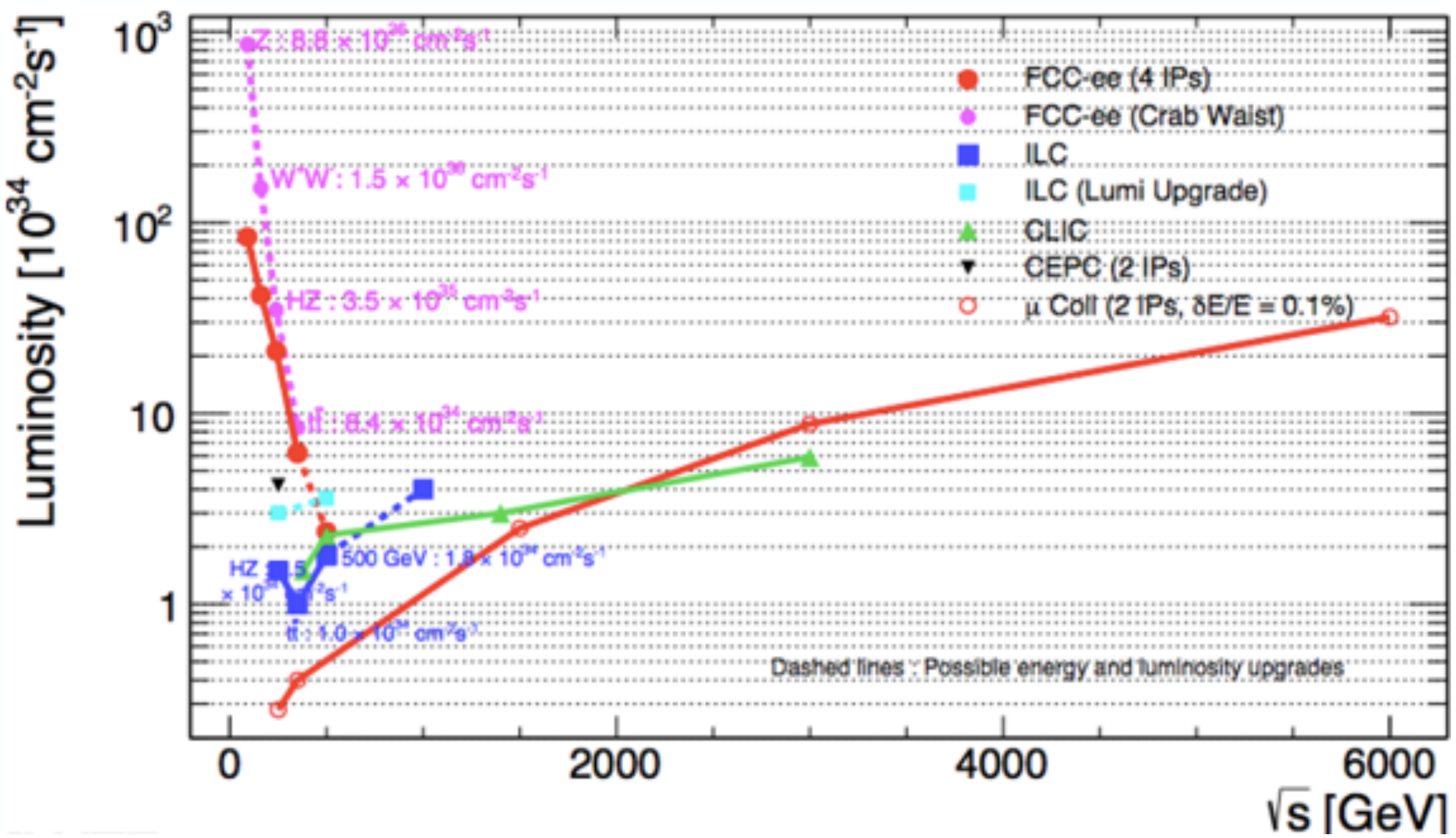
Low energy Higgs factories

- The physics of electron positron colliders is independent of whether the machine is circular or linear.

- What differs is the luminosity.

Luminosity comparison

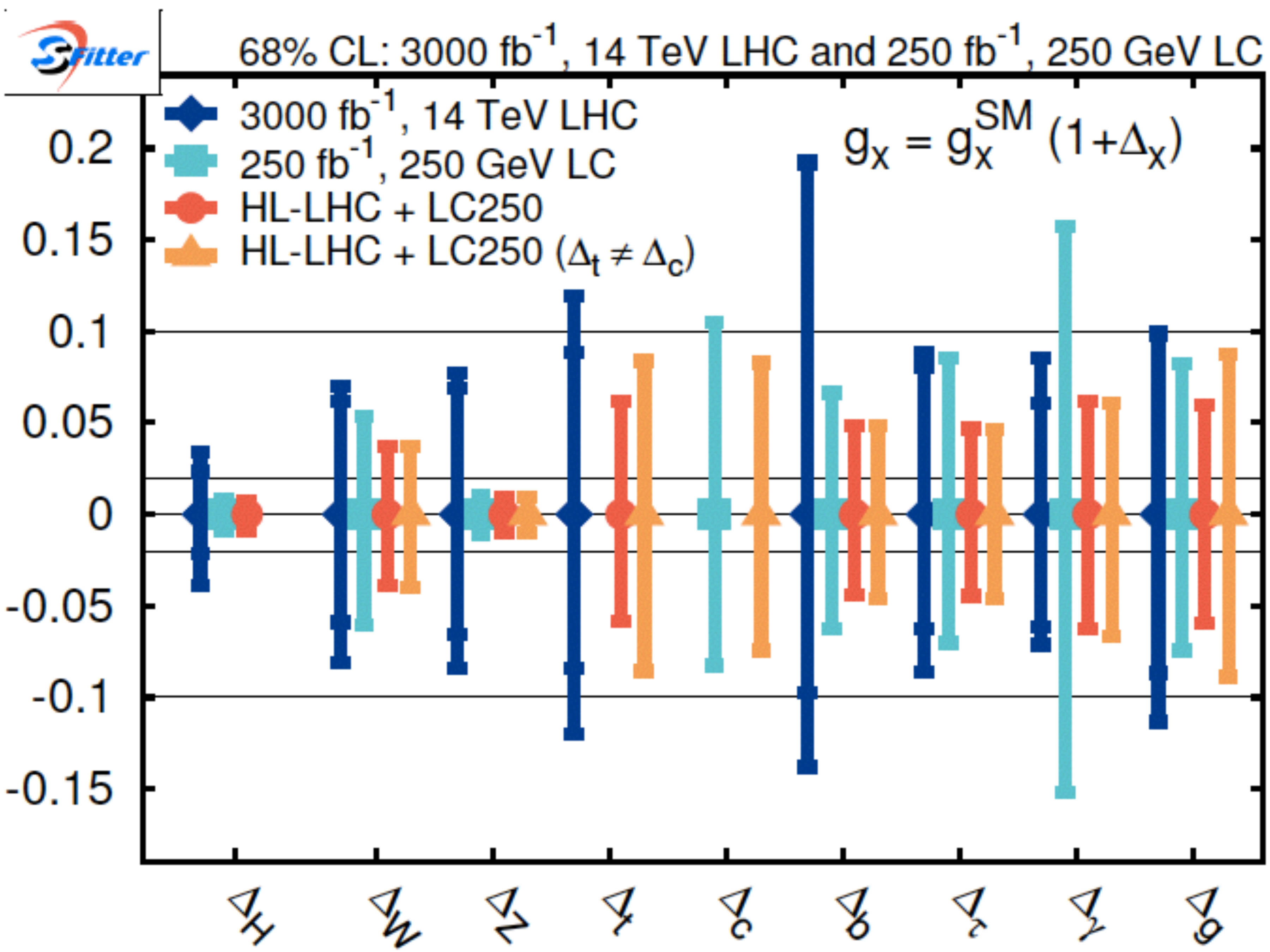
- Luminosity 32x bigger for FCC-ee at ZH peak, (for 4 interaction regions/ detectors).
- Cross section fall like 1/s, so luminosity growth needed at high-energy.



http://tlep.web.cern.ch/content/machine-parameters
and Klute (Higgs Couplings Durham October 2015)

1301.1322

Measurements at LC250



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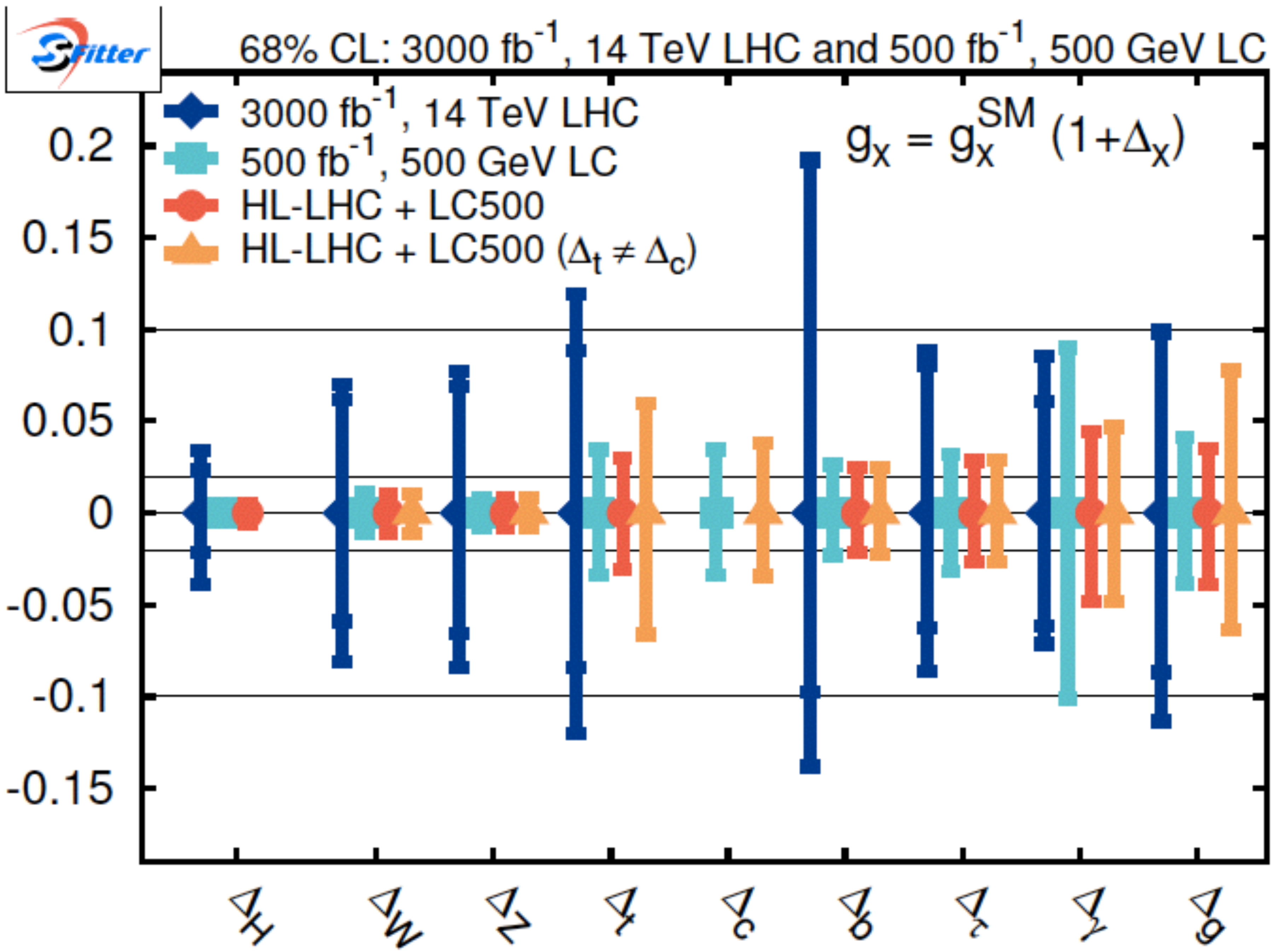
Measurements at LC500



Measuring the total width at e^+e^- collider

- It is possible to identify a Higgs event without looking at the Higgs at all.

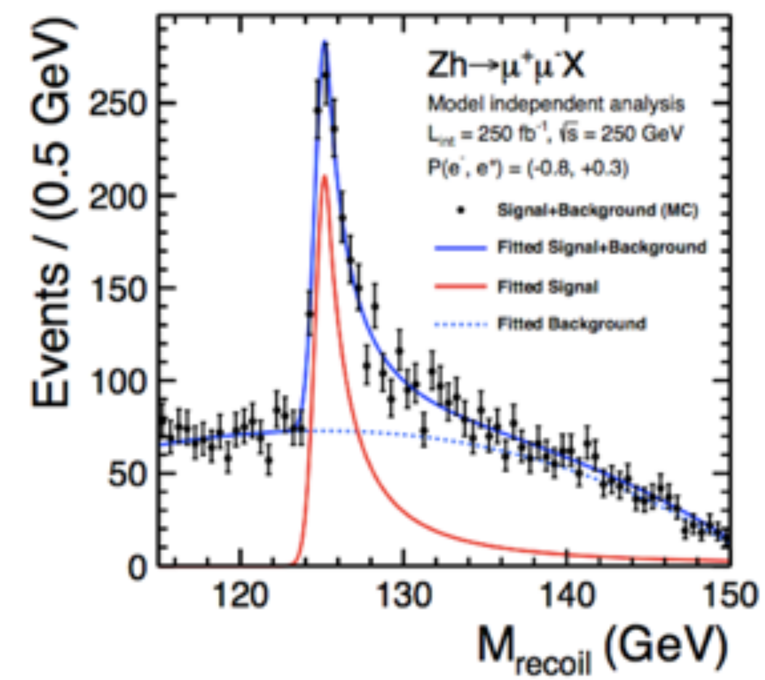
- Total width is given by the quotient of partial width and branching to a given final state.

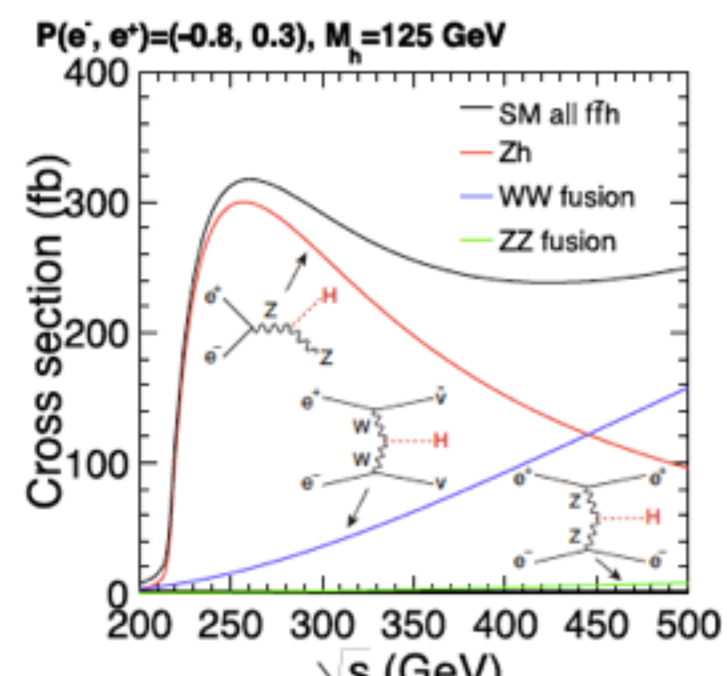
$$\Gamma_{tot} = \frac{\Gamma(H \to ZZ)}{\mathrm{BR(H \to ZZ)}} = \frac{\sigma(e^+e^- \to ZH)\Gamma(H \to ZZ)}{\sigma(e^+e^- \to ZH) \cdot \mathrm{BR(H \to ZZ)}}$$

- The partial width is controlled by the HZZ coupling, just like the total cross section $\Gamma(H \to ZZ) \propto \sigma_{HZ}$

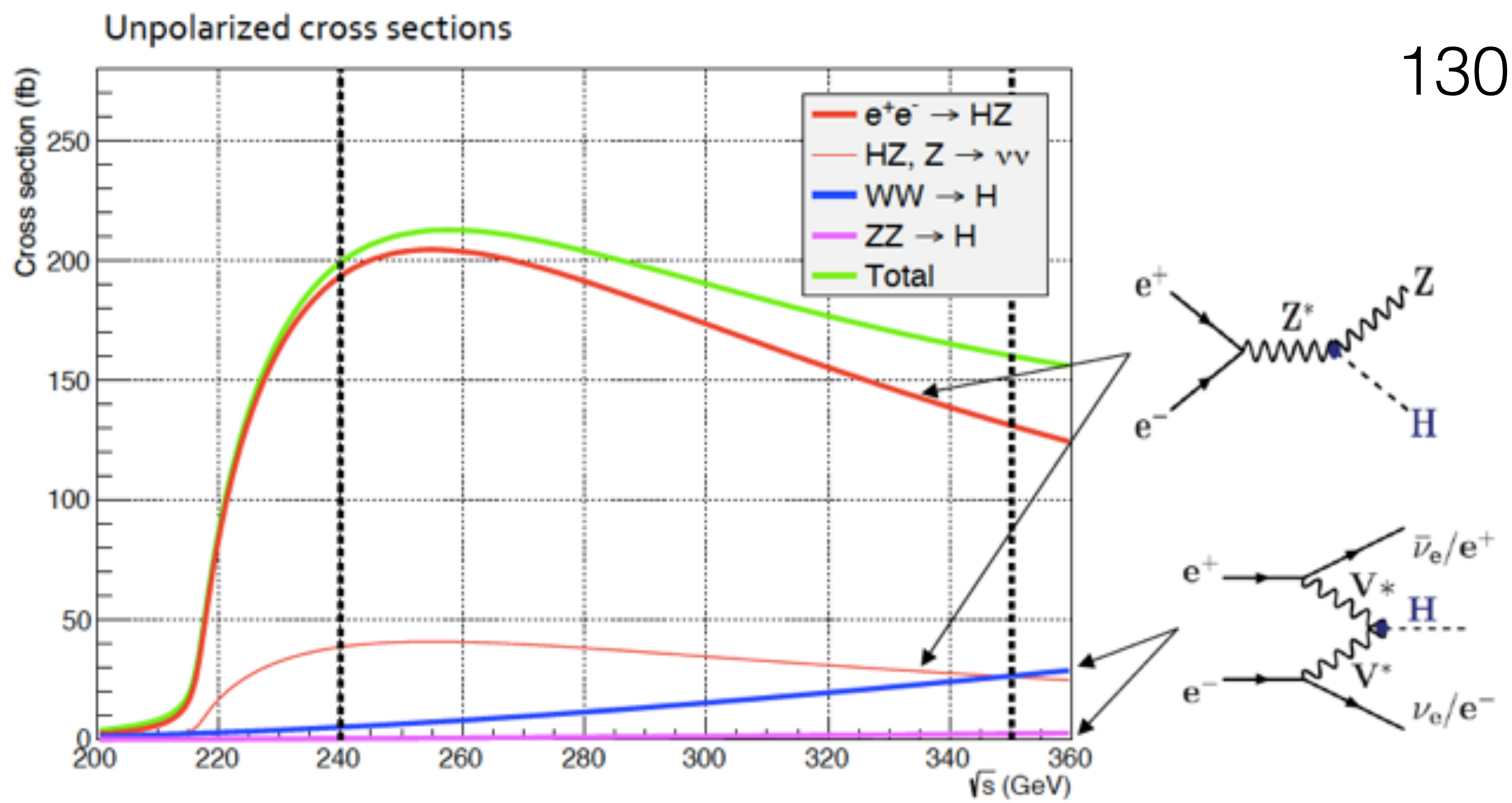
- The total width can be measured with the same precision as $\frac{\sigma_{HZ}^2}{\sigma_{HZ} \cdot BR(H \to ZZ)}$

$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$





Higgs production in e+e-



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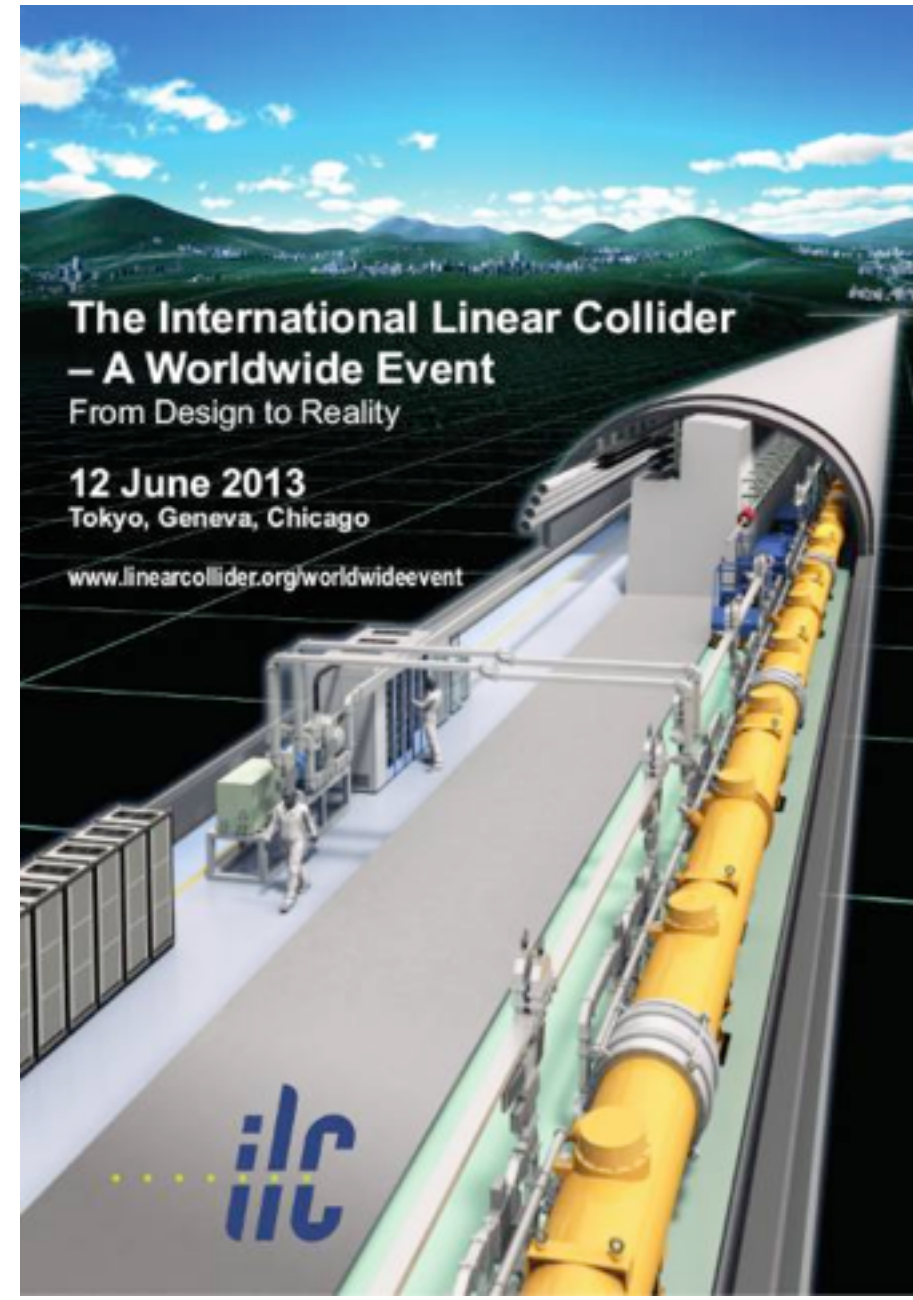
- Comparison with ILC (FCC-ee with 4 detectors!)

	TLEP 240	ILC 250
Total Integrated Luminosity (ab^{-1})	**10**	0.25
Number of Higgs bosons from $e^+e^- \to HZ$	**2,000,000**	70,000
Number of Higgs bosons from boson fusion	**50,000**	3,000

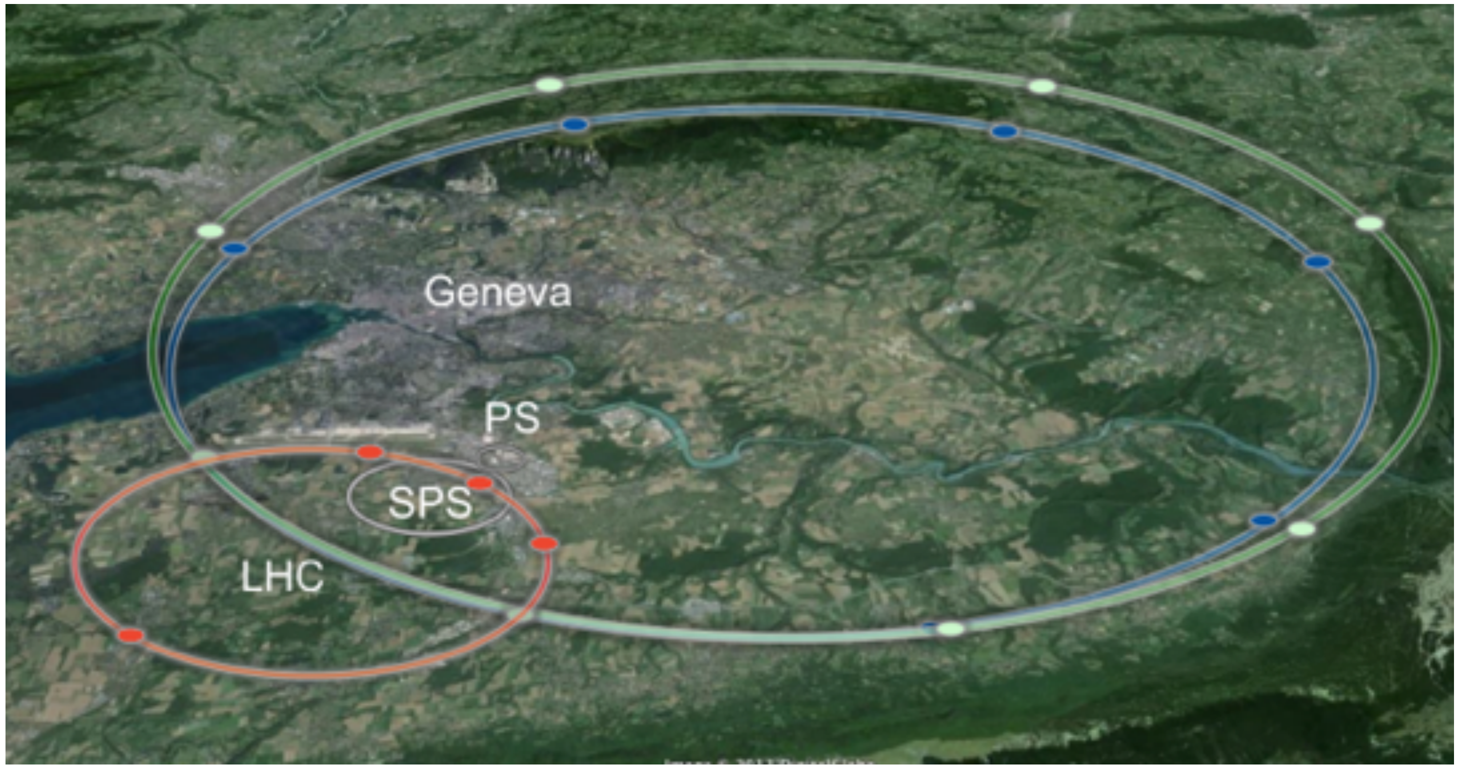
ILC advantages

- A very challenging machine, which now benefits from 20 years of R&D.
- Measurement of Higgs width, using missing mass technique (Common to all e^+e^- colliders).



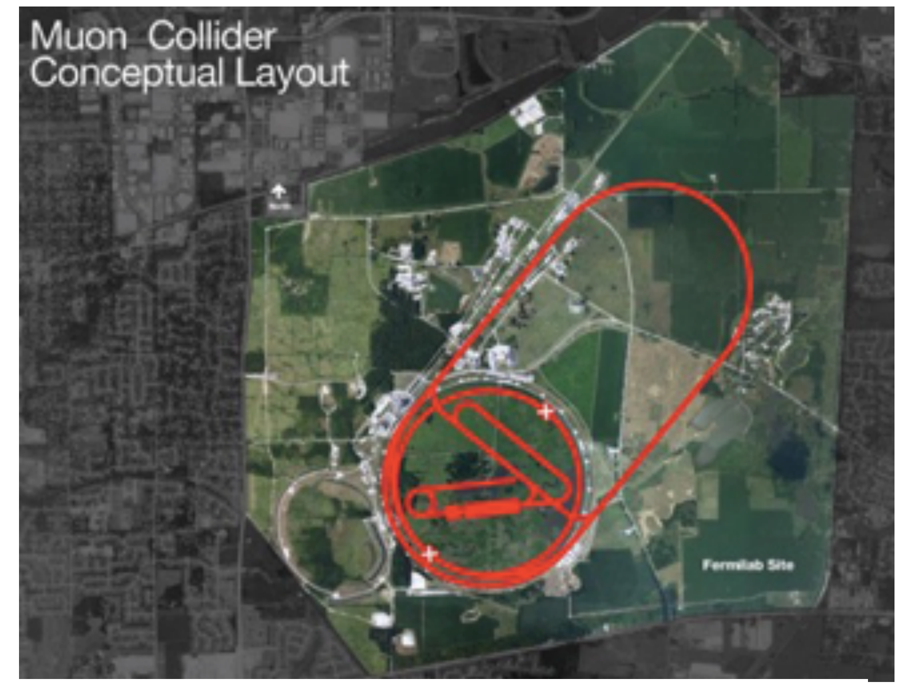
FCC(e+e-) Advantages

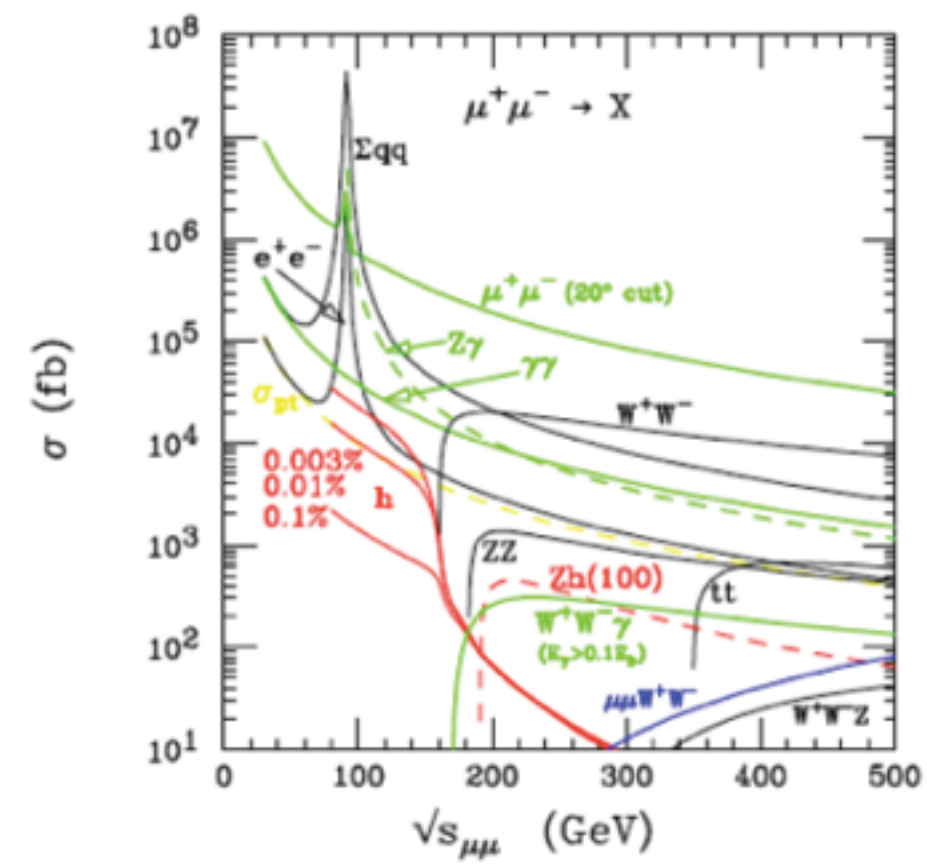
- Luminosity
- Tunnel for further use
- TDR in 2018



Muon collider Higgs Factory

- Compact, fits on CERN/Fermilab site
- Advantages associated with circular geometry
- Multipass acceleration, multipass collisions, more than one detector
- Narrow energy spread, negligible synchrotron radiation. Higgs signal depends on resolution.
- Enhanced cross section for s-channel Higgs production, direct measurement scan of Higgs width.
- A separate ring for every energy (Z,H,ttbar)?
- No obvious constraints limiting scaling to Multi-TeV energy.





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Schematic of muon complex

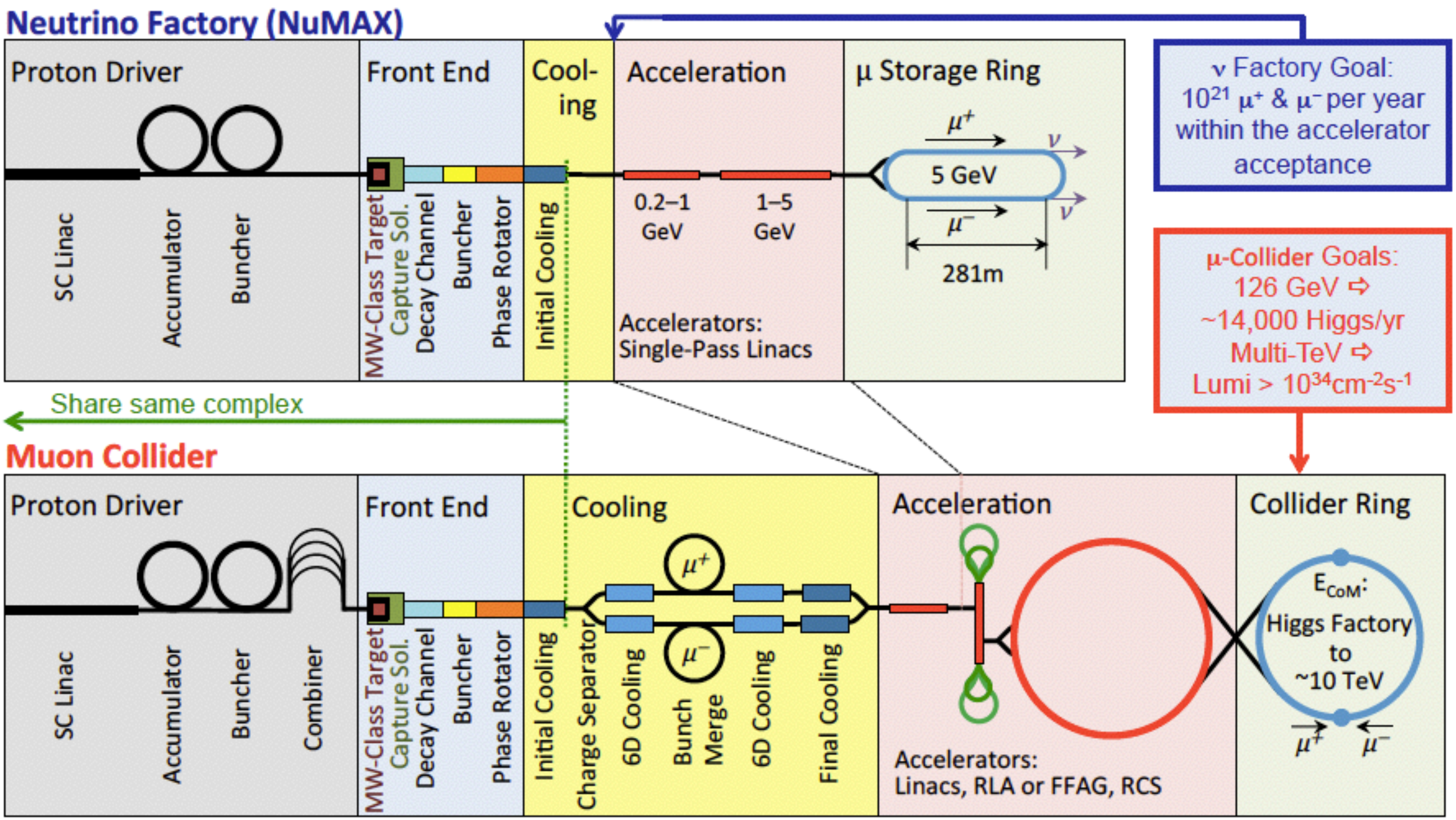
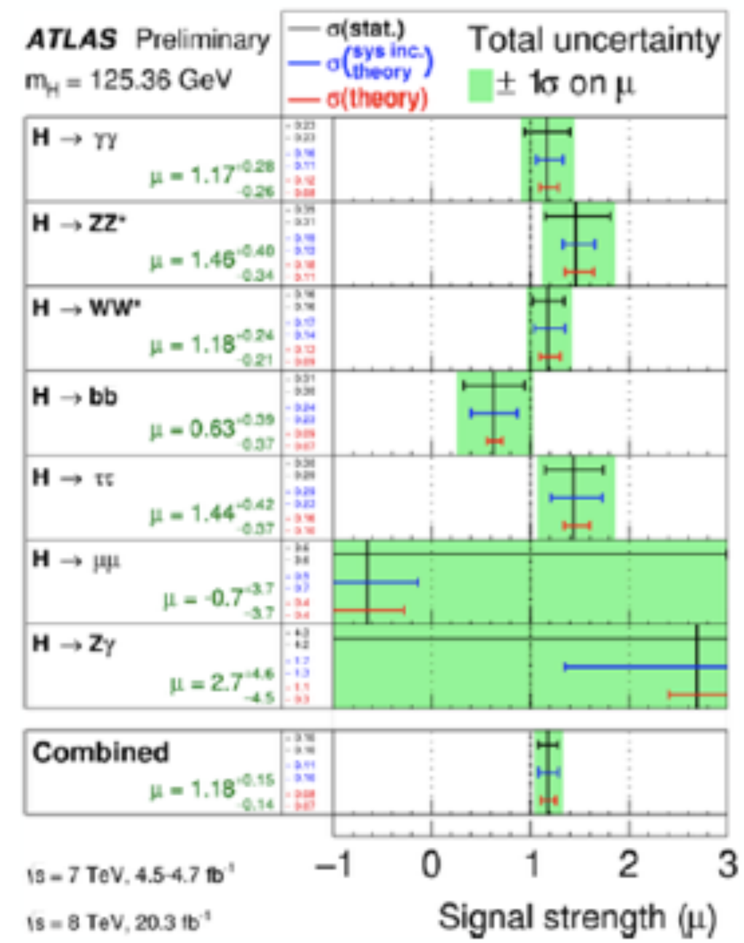


Figure 1: A block diagram showing the key systems needed for a long-baseline neutrino factory capability and a muon collider capability. Much of the infrastructure for each capability could be shared, thus enabling a cost effective multipurpose facility.

Muon-collider Higgs Factory

- Coupling $g_{H\mu\mu}$ not yet measured.
- Muon cooling needs a demonstration of technological feasibility (MICE experiment).
- No access to t-t-H and H-H-H couplings
- Decay backgrounds at High energy

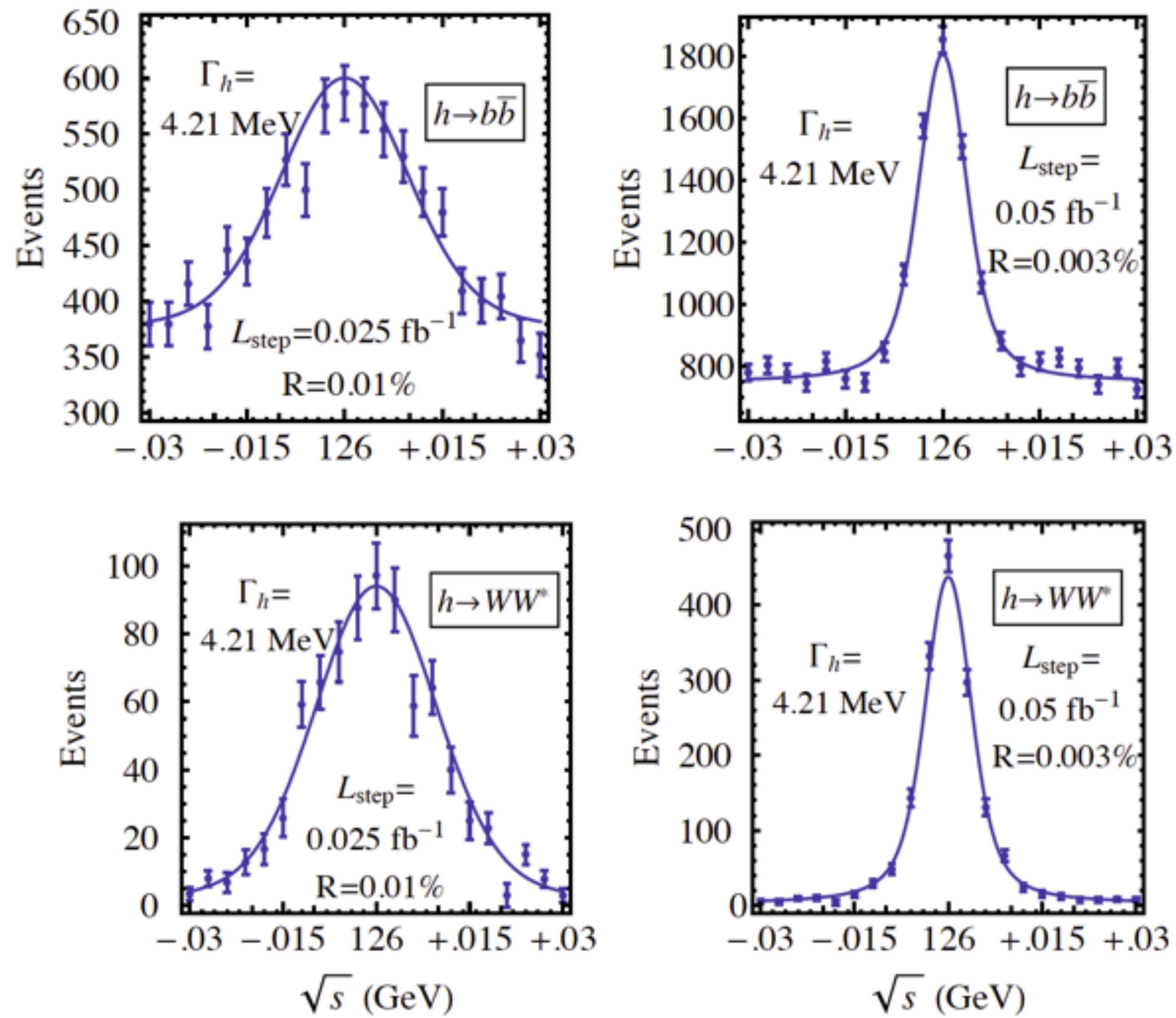


ATLAS-CONF-2015-044

Measuring the Higgs width at Muon collider

1210.7803

With a beam energy resolution of R=0.01% (0.003%) and integrated luminosity of 0.5 fb-1, a muon collider would enable us to determine the Standard-Model-like Higgs width to 0.35 MeV by combining two complementary channels of the WW^* and b\bar b final states



Expected Precision Higgs parameters

Uncertainties	μ-Collider	CLIC	ILC	CEPC	FCC-ee
m_H [MeV]	**0.06**		30	5.5	8
Γ_H [MeV]	0.17	8.5	0.16	0.12	**0.04**
g_{HZZ} [%]	-	2.1	0.6	0.25	**0.15**
g_{HWW} [%]	2.2	2.1	0.8	1.2	**0.2**
g_{Hbb} [%]	2.3	2.2	1.5	1.3	**0.4**
$g_{H\tau\tau}$ [%]	5	2.5	1.9	1.4	**0.5**
$g_{H\gamma\gamma}$ [%]	10	5.9	7.8	4.7	1.5
g_{Hcc} [%]	-	2.4	2.7	1.7	**0.7**
g_{Hgg} [%]	-	2.3	2.3	1.5	**0.8**
g_{Htt} [%]	-	**4.5**	18	-	-
$g_{H\mu\mu}$ [%]	**2.1**	11	20	8.6	6.2
g_{HHH} [%]	-	24	-	-	-

Marcus Klute (Higgs couplings 2015)

for ~10y operation
lots of "!,*,?" in this table

The next 50 years

Muon Collider

ILC

Muon-Higgs Factory

LHC

HL-LHC

FCC(pp) FCC(ee)

CepC

SppC

CLIC

2016

It is your job to set the time-line!