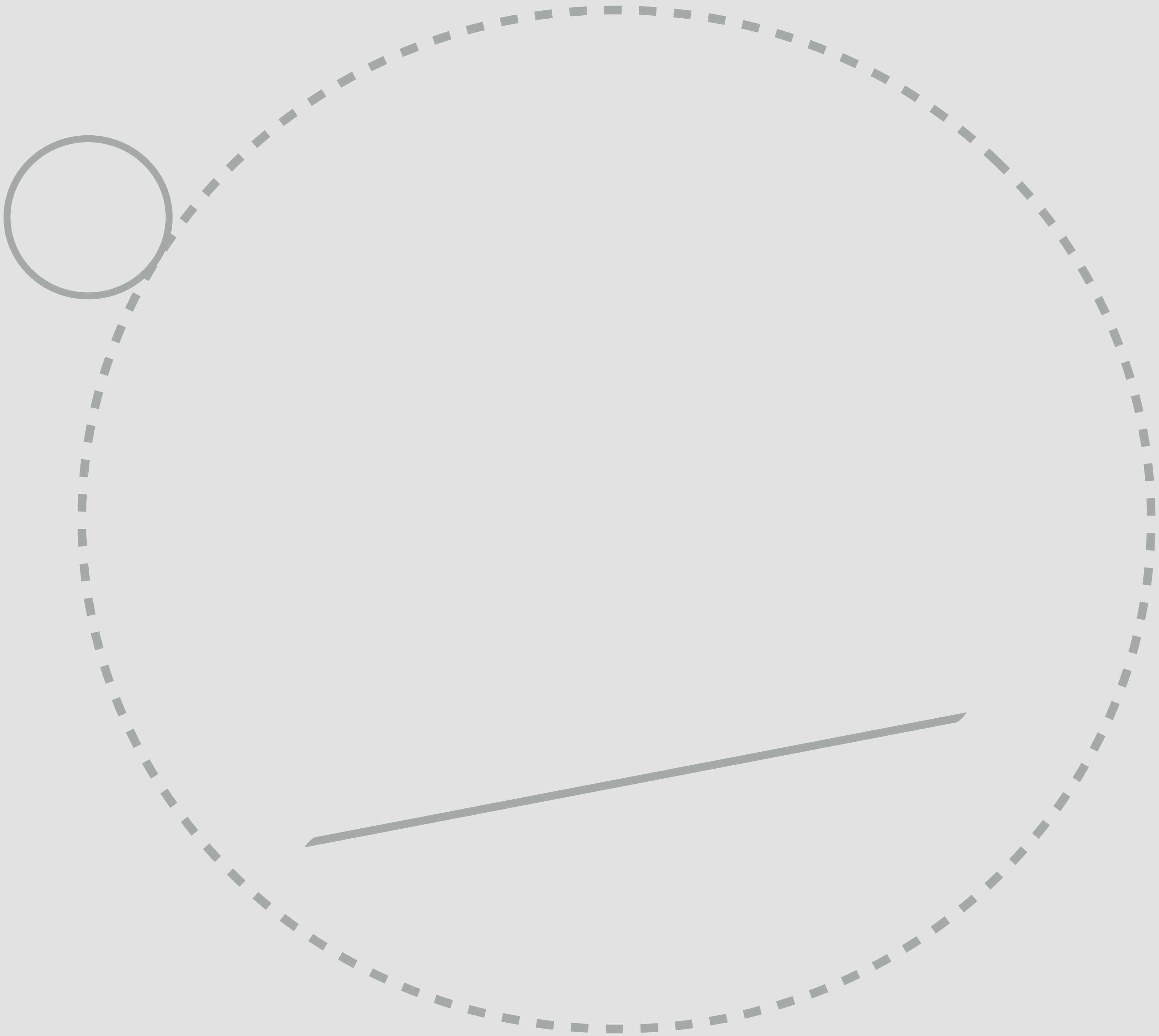
THE HIGGS BOSON

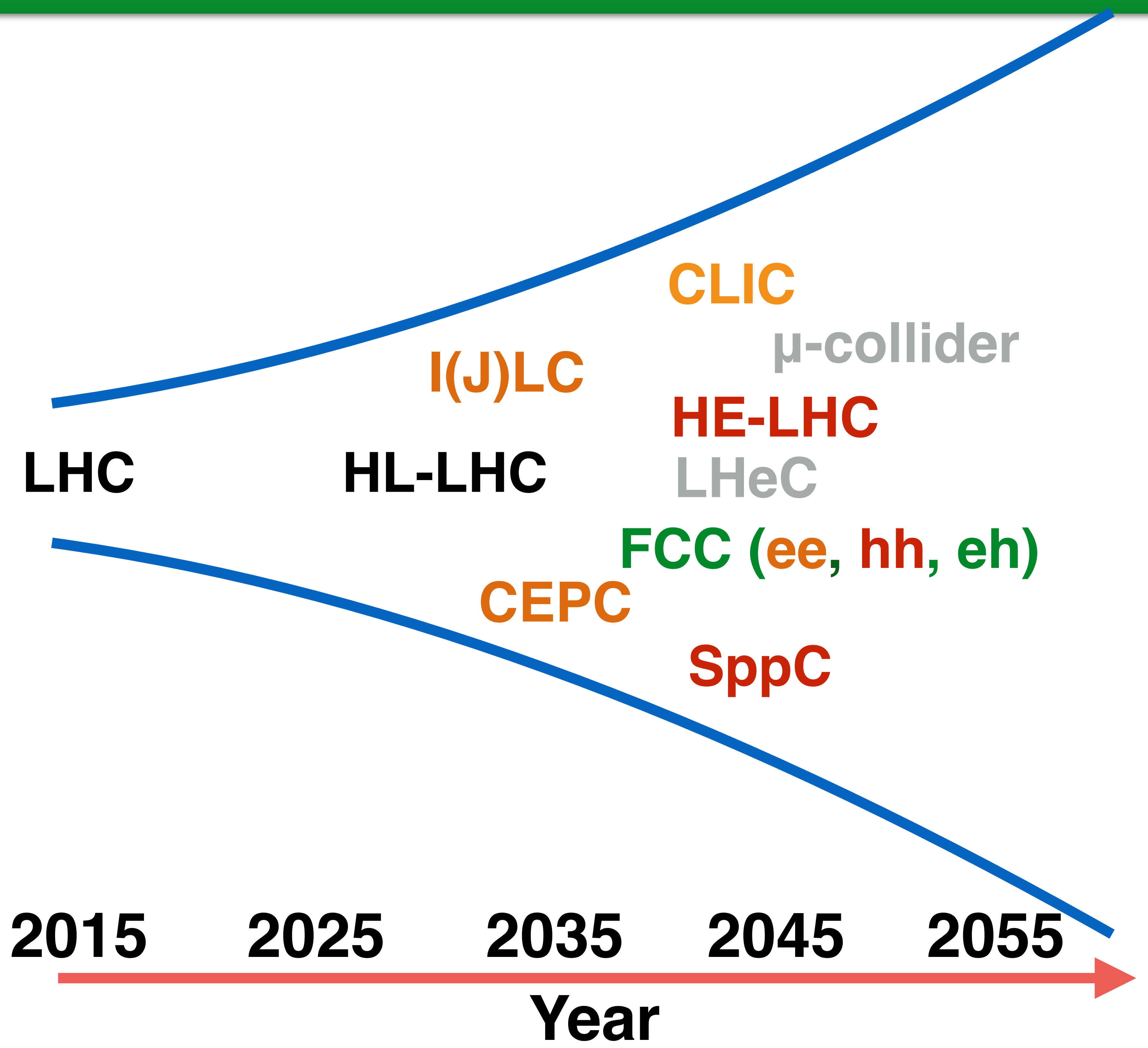
at future colliders

Markus Klute

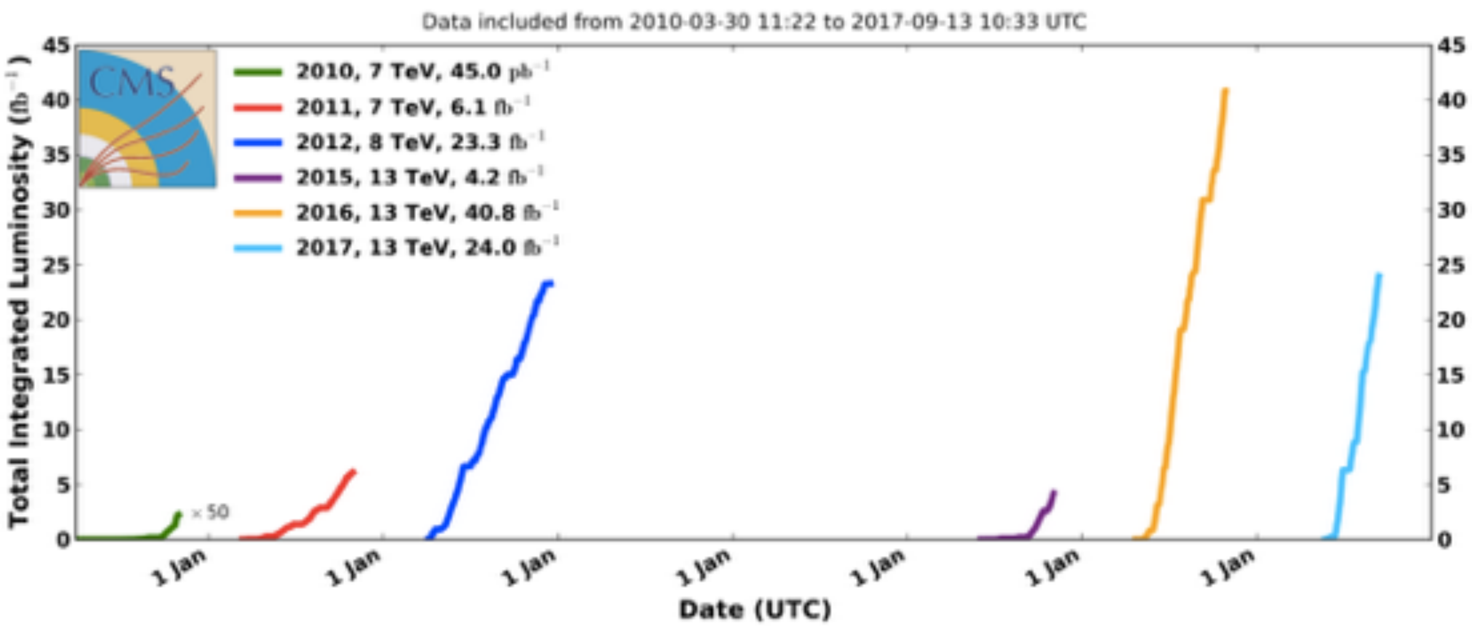
Future Collider Landscape

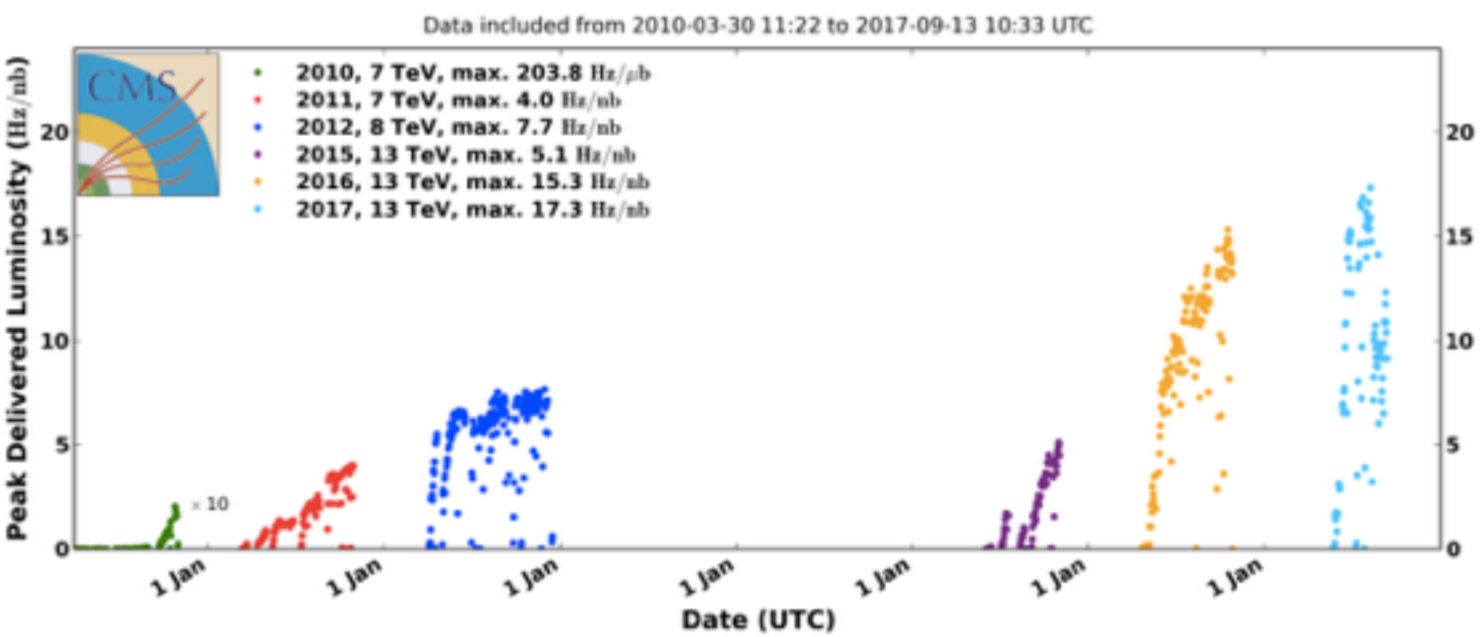


Future Collider Outlook



The Future Starts Now: LHC



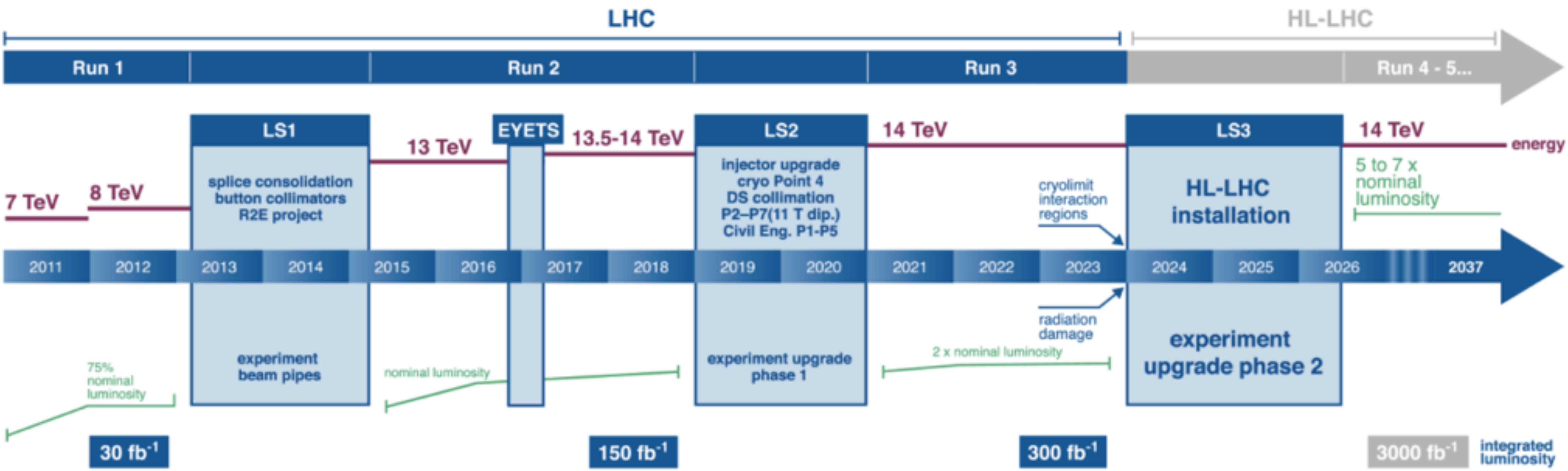


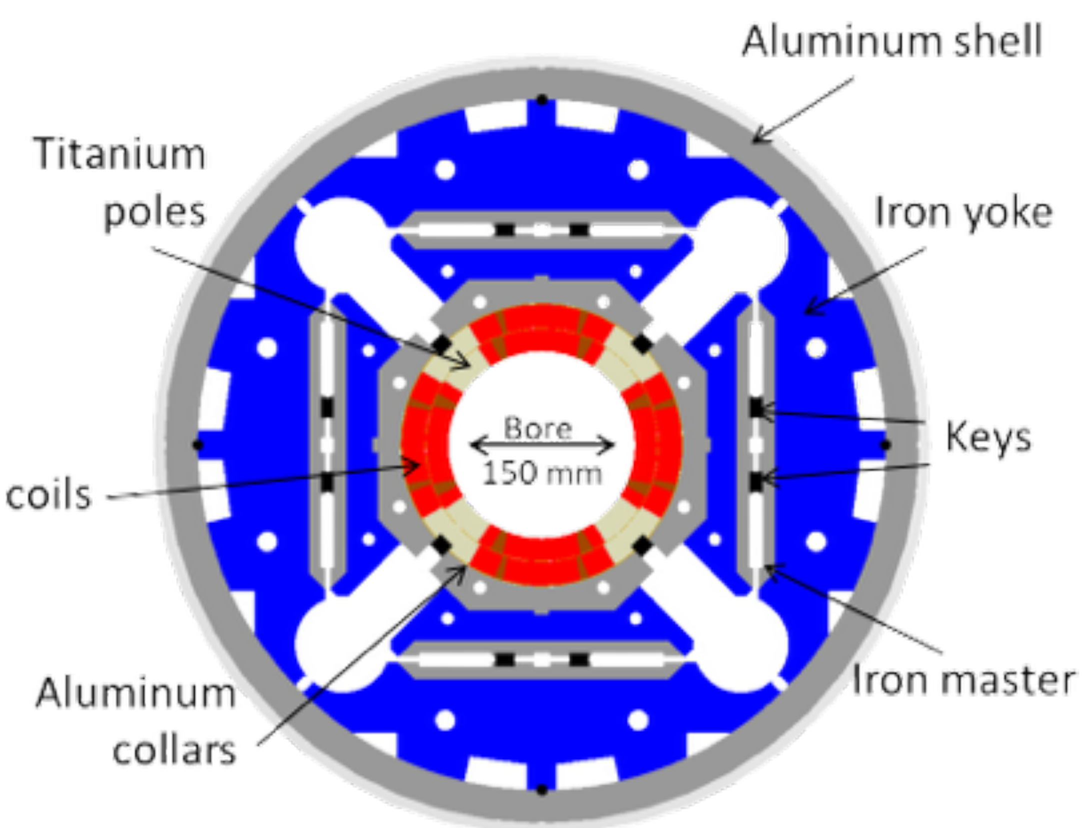
Run II ATLAS & CMS results with 300 fb^{-1} not excluded

	$\sqrt{s}$ [TeV]	L [fb^{-1}]
2010	7	0.045
2011	7	6
2012	8	23
2015	13	4
2016	13	41
2017	13	40
2018	13	60
2019	13	?
2021	~14	60
2022	~14	60
2023	~14	60
2024	~14	?

* MK estimates in red and speculation on potential change in scheduling purple

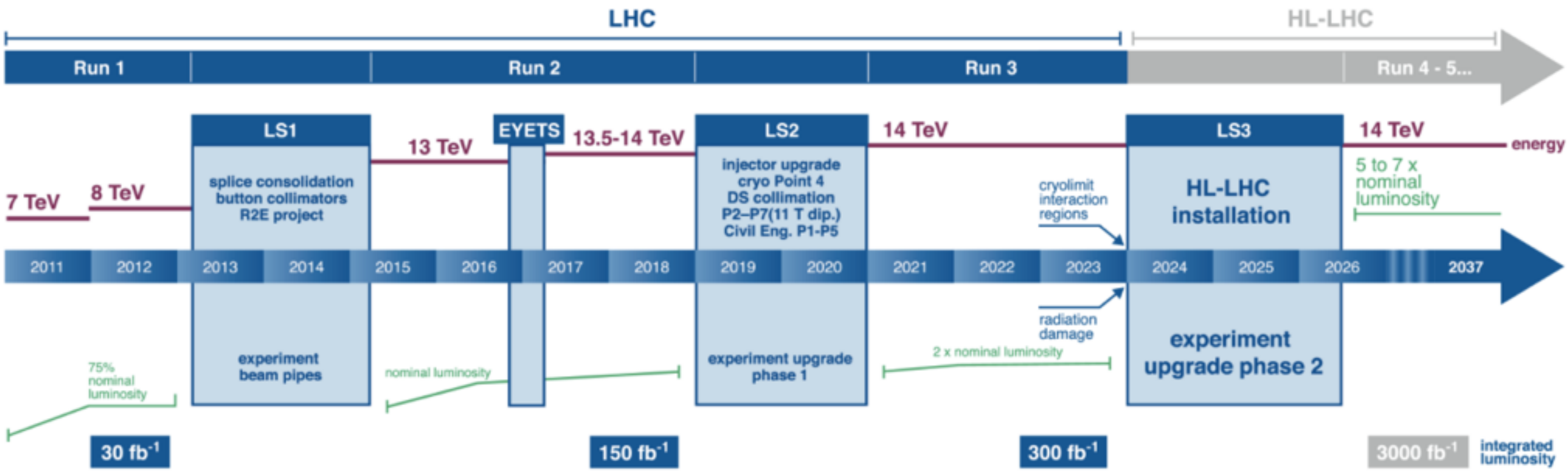
HL-LHC

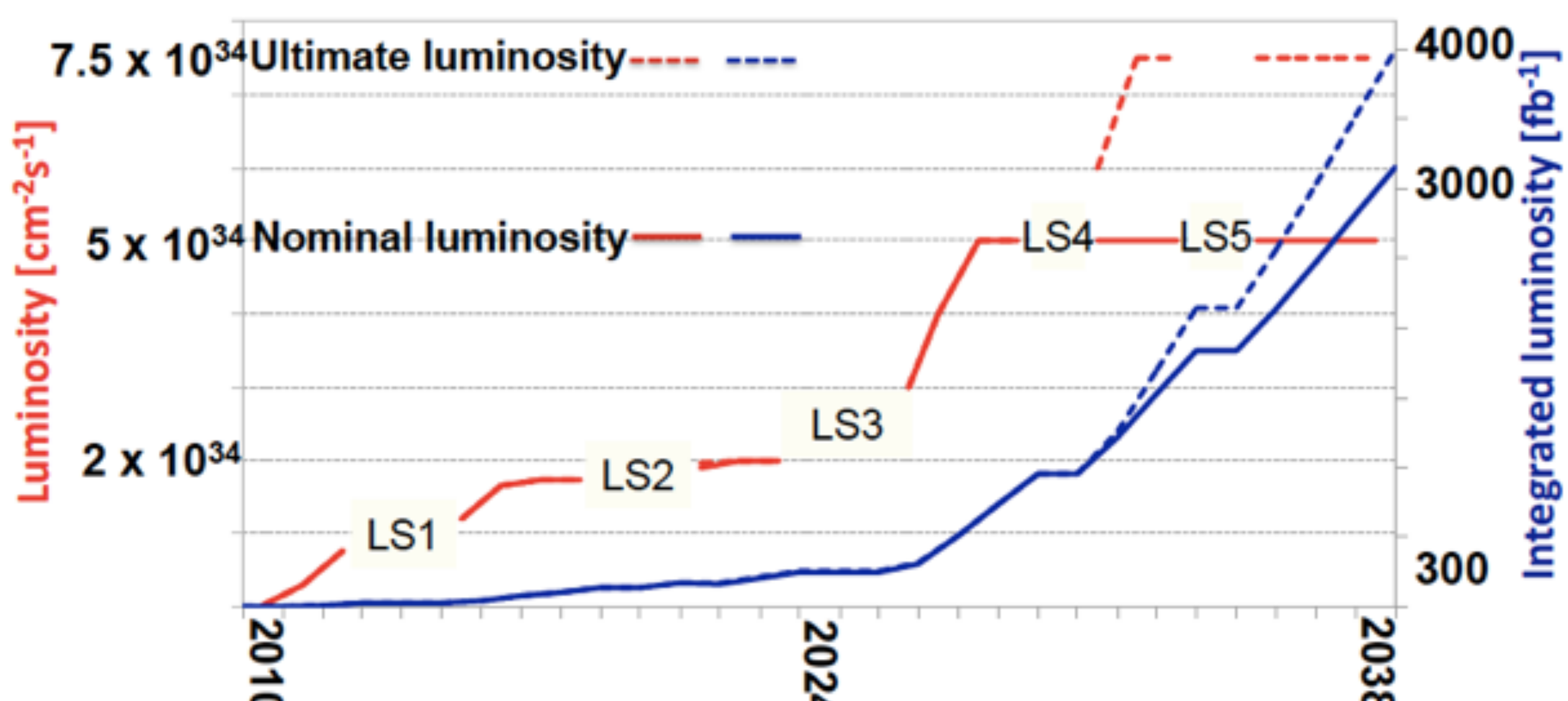




- ➡ **LHC dipoles stretched NbTi technology to its limit**
  - 8.3T in central region via operation at 1.8k
- ➡ **HL-LHC needs new technology in iteration region: Nb_3SN**
  - 12T quadrupoles with 150mm aperture to shrink β*
- ➡ **Operating and upgrading the LHC is a very significant investment**

HL-LHC


LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
splice consolidation
button collimators
R2E project
experiment
beam pipes
EYETS
LS2
injector upgrade
cryo Point 4
DS collimation
P2–P7(11 T dip.)
Civil Eng. P1-P5
experiment upgrade
phase 1
LS3
HL-LHC
installation
experiment
upgrade phase 2
7 TeV
8 TeV
13 TeV
13.5-14 TeV
14 TeV
14 TeV
energy
5 to 7 x
nominal
luminosity
cryolimit
interaction
regions
radiation
damage
2 x nominal luminosity
nominal luminosity
75%
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2037
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity


7.5 x 10^34
Ultimate luminosity
5 x 10^34
Nominal luminosity
2 x 10^34
Luminosity [cm-2s-1]
4000
3000
300
Integrated luminosity [fb-1]
LS1
LS2
LS3
LS4
LS5
2010
2024
2038

HL-(HE)-LHC

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

from 30 October 2017 to 1 November 2017
Europe/Zurich timezone

Search...

- Overview
- Working Groups: conveners and mailing lists signup
- Timetable
- Logistics (housing etc)
- Registration
- Participant List
- Call for Abstracts

Contact for administrative assistance

hllhc-physics.support@c...

This is the kickoff event for a series of meetings, running throughout 2018, with plenary events and intermediate periods of working group activities.

The main goal of the Workshop is to review, extend and further refine our understanding of the physics potential of the High Luminosity LHC.
The workshop aims to stimulate new ideas for measurements and observables, to extend the LHC discovery reach, to improve the modeling of LHC phenomena towards measurements at ultimate precision, and to prepare to exploit the HL-LHC data to the fullest possible extent.

The Workshop will also provide the opportunity to begin a more systematic study of physics at the HE-LHC, a new pp collider in the LHC ring with CM energy in the range of 27 TeV.

The activity of the Workshop will extend over a one year period, driven by working groups covering the following areas:

1. **QCD, EW and top quark physics**
2. **Higgs and EWSB**
3. **BSM**
4. **Flavour**
5. **Heavy Ions**

The results of the Workshop will be documented in a Yellow Report, to be completed in time (~end 2018) for submission to the next review of the European strategy for particle physics.

Several rooms have been pre-booked in the CERN Hostel, available on a fist-come first-served basis. See the "Logistics" link in the Menu to the left for details.

Higgs Prospects

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

arXiv:1307.7135

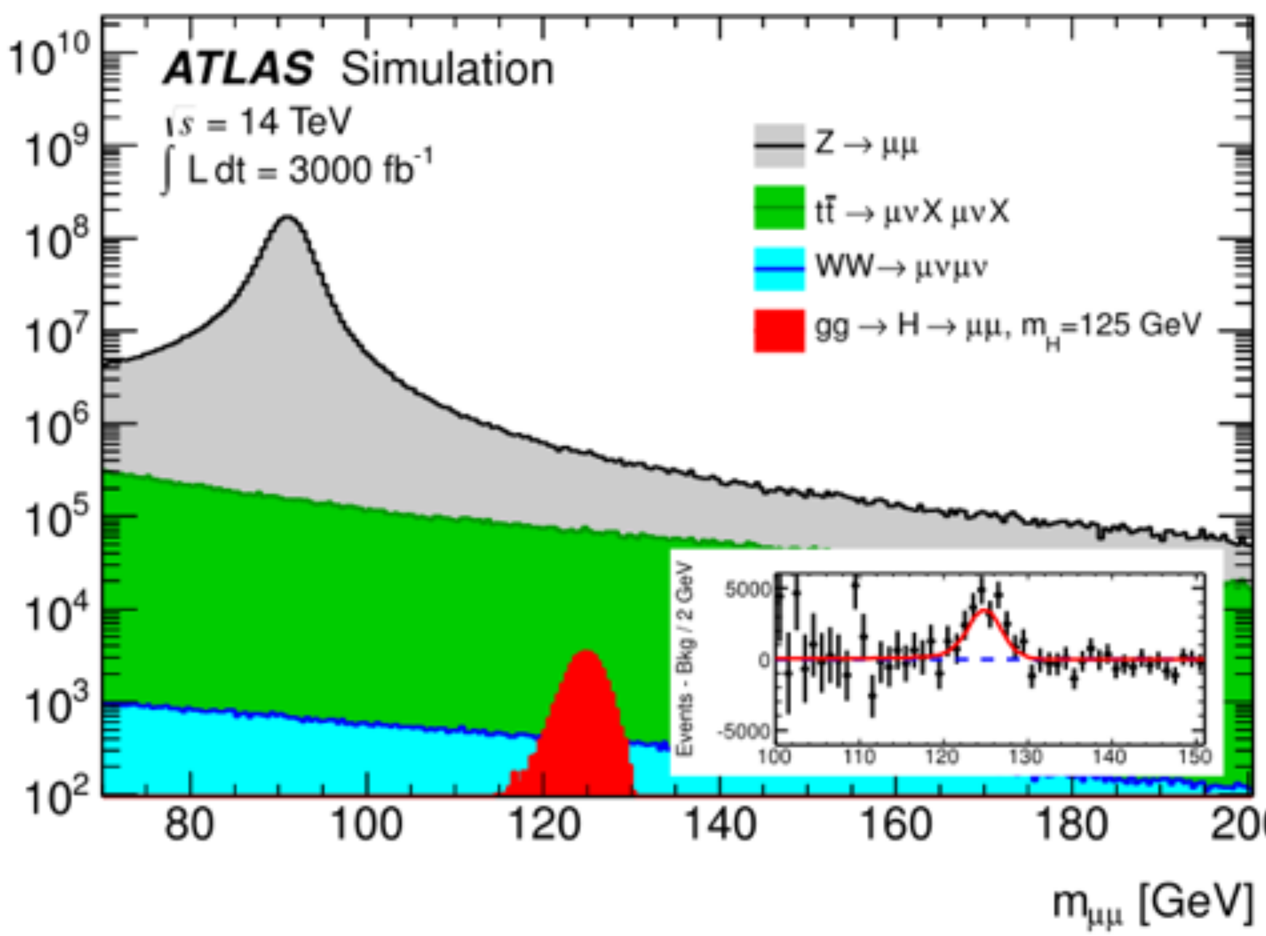
Rare-decays

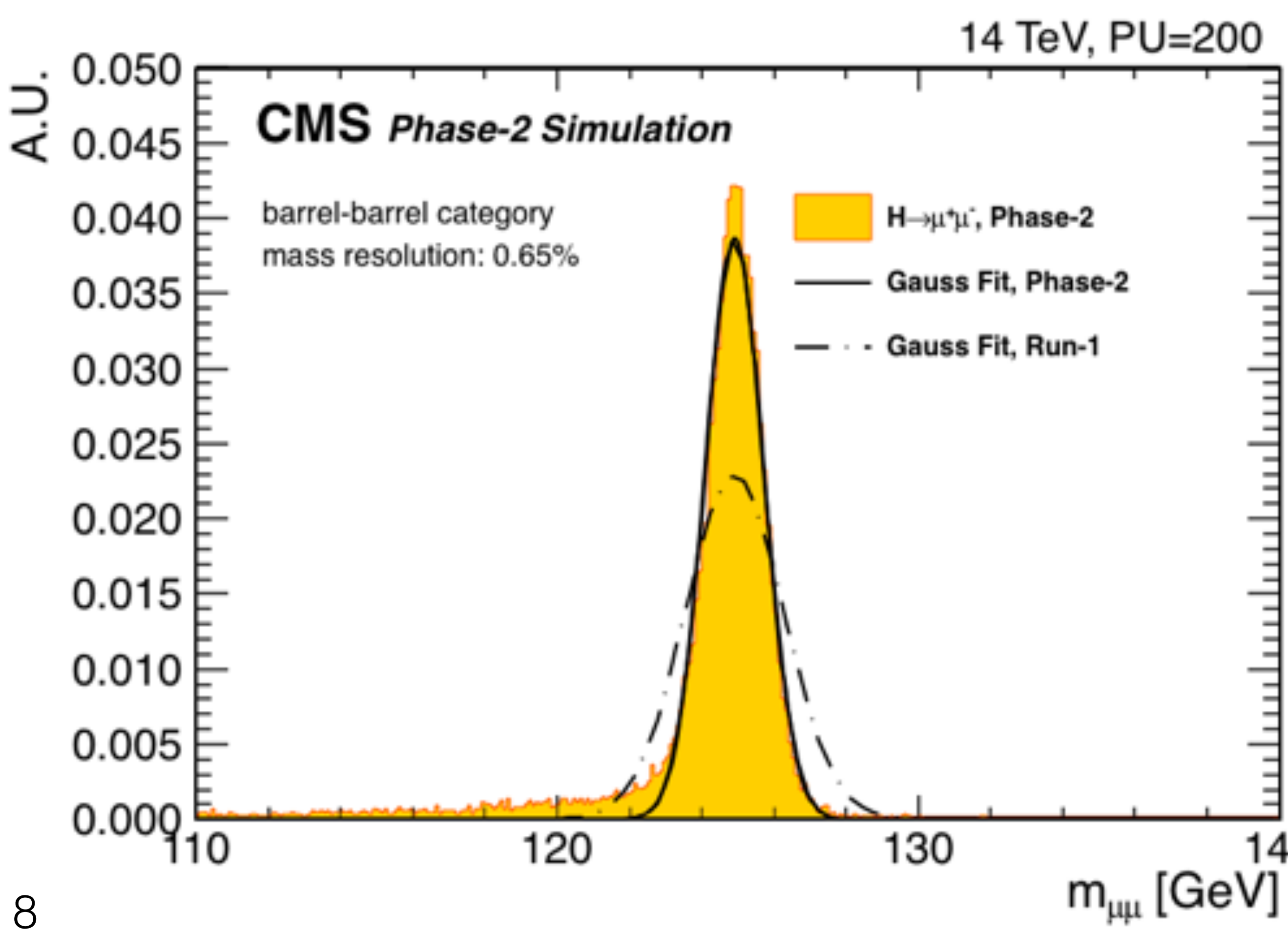
➡ **Projection of kappa-fits**

- Extrapolated from early Run-I analysis
- Many improvements from experiment and theory since
- Expect 4~10% precision from Run-II and 2-5% from HL-LHC

➡ **H → μμ**

- 2nd generation fermion coupling
- search for narrow resonance with huge DY background
- **expect ~5% uncertainty from HL-LHC**

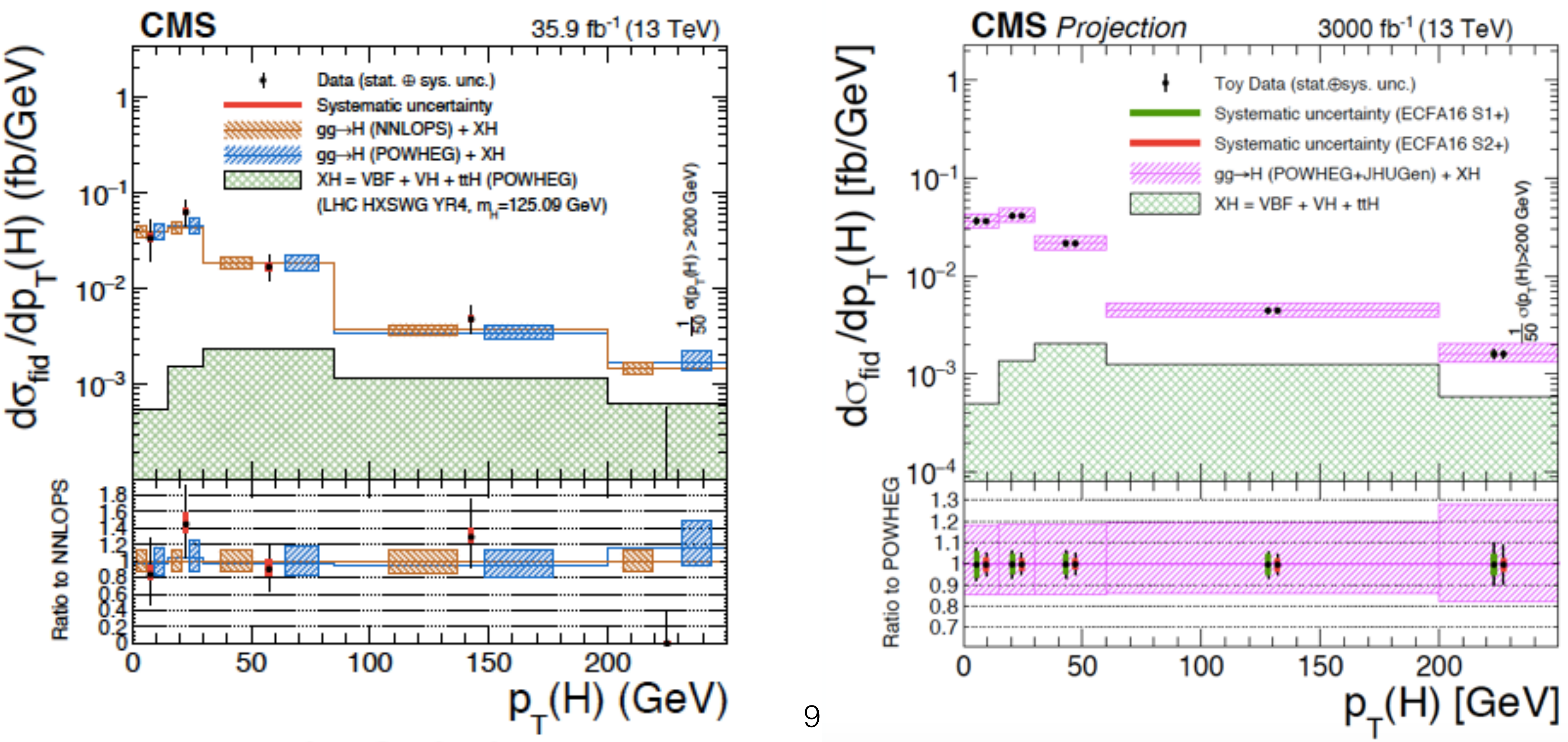




Higgs Prospects

➡ **Expanding studies of prospects to differential measurements**

- really only to give you a flavor
- H→ZZ channel shows 4-10% uncertainty
- other channels should be exploited
- one should assess the sensitivity to NP



High-Energy (HE) LHC

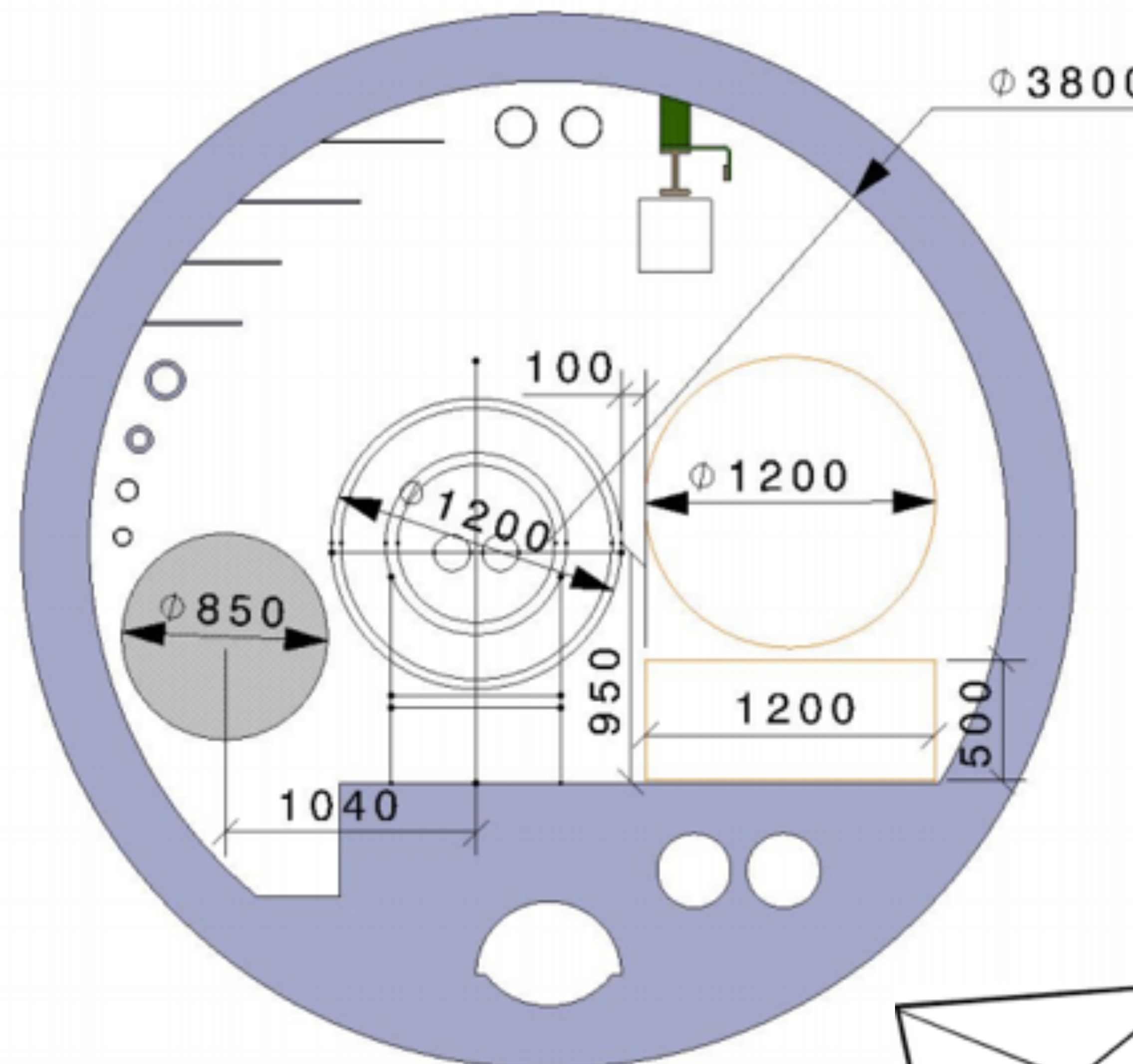
➡ **Machine goals**

- 2x LHC collision energy with FCC-hh magnets
- c.m.energy = 27 TeV ~ 14 TeV x 16T/8.33T
- target luminosity > 4 x HL-LHC
- 25ns baseline, also 5ns option
- use LHC tunnel with compact magnet design

➡ **Key technologies**

- FCC-hh magnets & FCC-hh vacuum system
- HL-LHC crab cavities & electron lense

tunnel diameter 3.8 m much smaller than FCC-hh's 6.0 m



High-Energy (HE) LHC

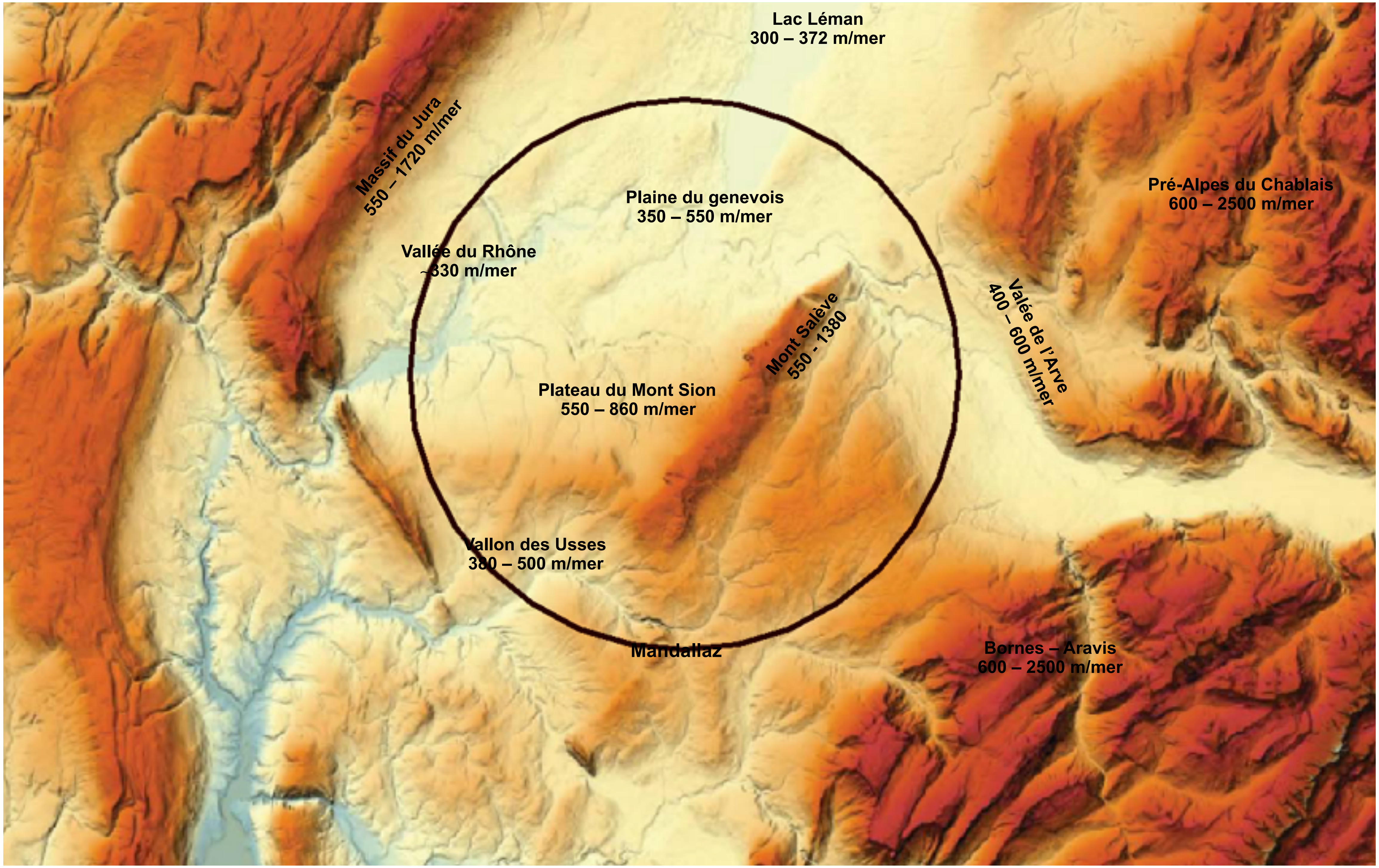
parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
beta* [m]	1.1-0.3		0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)		2.5 (0.5)	(2.5) 3.75

HE-LHC

- ➡ **Simple extrapolation for Higgs Physics**
  - 4 times larger dataset, better detectors, more difficult environment
  - 2.5 times larger cross section for single Higgs production
  - 5 times larger cross section for double Higgs production
- ➡ **Effective statistical gain in Higgs measurements w.r.t HL-LHC**
  - Factor 3 for single Higgs
  - Factor 5 for double Higgs

- ➡ **Mass reach for heavy states increases by about a factor of 2**
- ➡ **Studies are an interpolation between HL-LHC and FCC-hh**

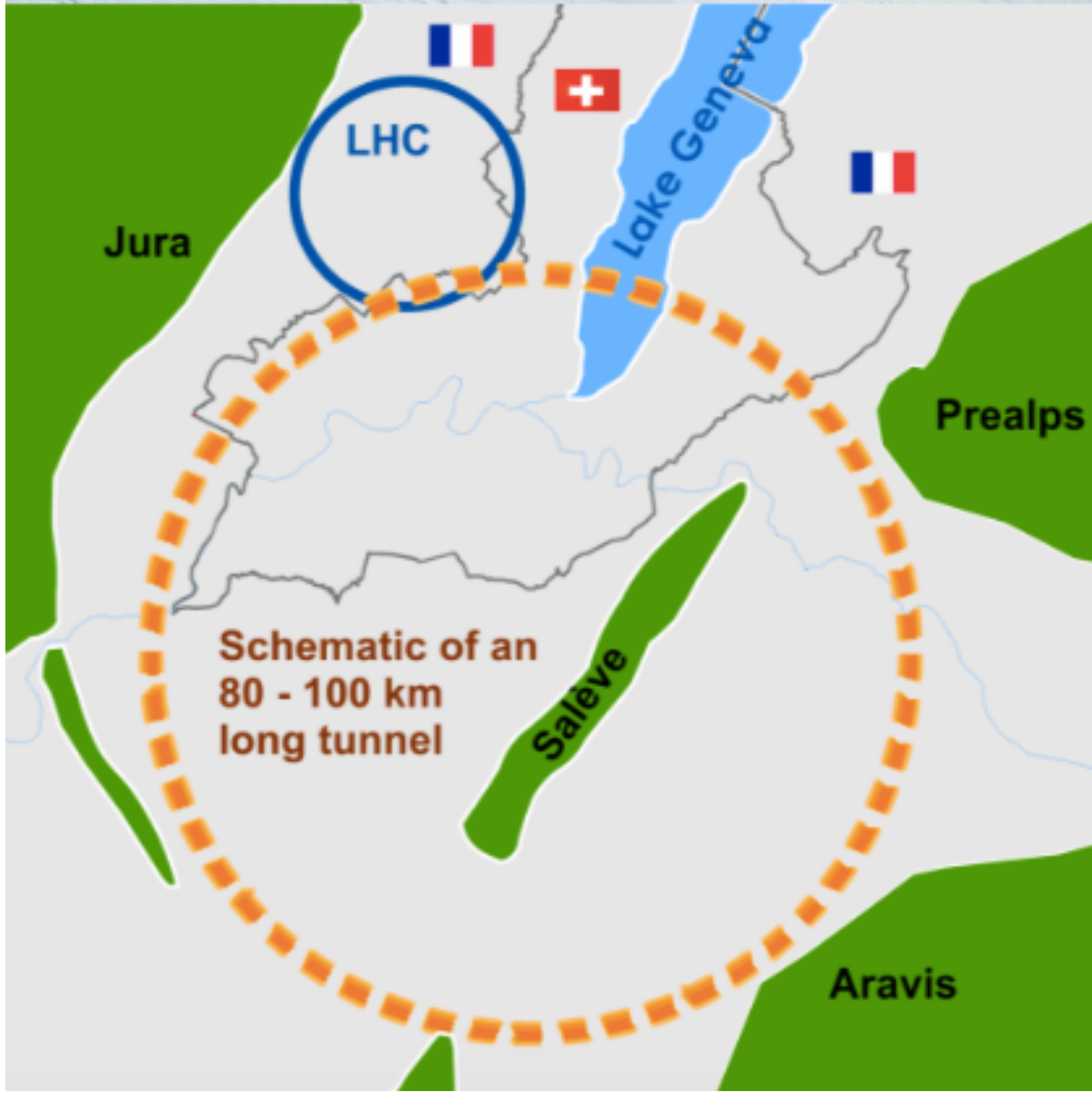
FCC-hh



Lac Léman
300 – 372 m/mer
Massif du Jura
550 – 1720 m/mer
Plaine du genevois
350 – 550 m/mer
Pré-Alpes du Chablais
600 – 2500 m/mer
Vallée du Rhône
~330 m/mer
Mont Salève
550 - 1380
Valée de l'Arve
400 – 600 m/mer
Plateau du Mont Sion
550 – 860 m/mer
Vallon des Usses
380 – 500 m/mer
Mandallaz
Bornes – Aravis
600 – 2500 m/mer

FCC-hh

- ➡ **International FCC collaboration to study**
  - pp collider (FCC-hh)
  - e^+e^- collider (FCC-ee)
  - p-e (FCC-he)
- ➡ 80-100 km infrastructure in Geneva area
- ➡ **Goal:** CDR and cost review next year
- ➡ Similar studies in China
  - e^+e^- collider (CepC)
  - pp collider (SppS)



FCC Modus Operandi

parameter	FCC-hh		SPPC	HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		71.2	>25	14
dipole field [T]	16		20	16	8.3
circumference [km]	100		54	27	27
# IP	2 main & 2		2	2 & 2	2 & 2
beam current [A]	0.5		1.0	1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25	25
beta* [m]	1.1	0.3	0.75	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	20 - 30	12	>25	(5) 1
events/bunch crossing	170	<1020 (204)	400	850	(135) 27
stored energy/beam [GJ]	8.4		6.6	1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		58	3.6	(0.35) 0.18

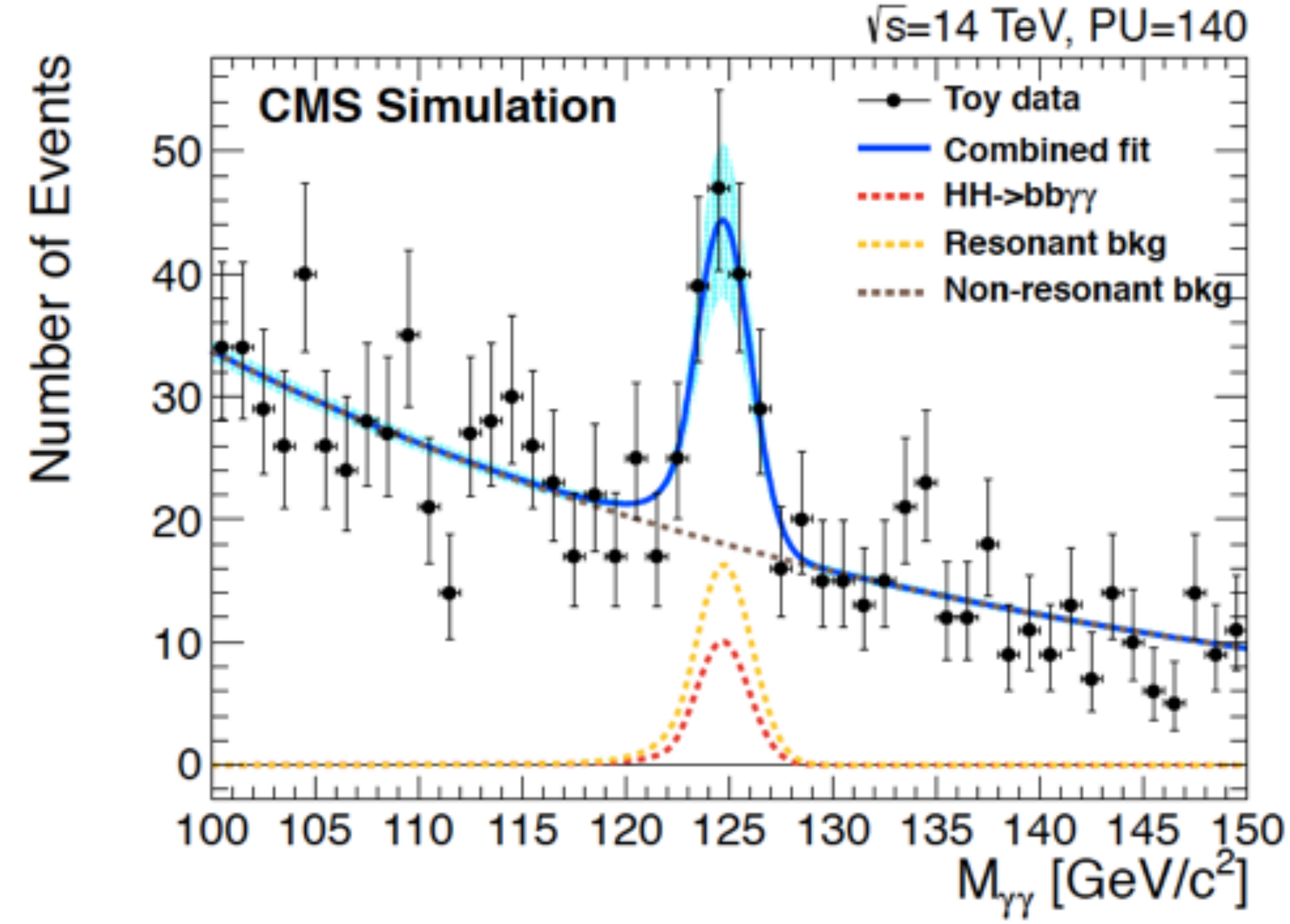
- ➡ **5 year long operation periods**
  - 1y HW commissioning,
  - 2.5y luminosity production
  - 1.5 y shutdown
- ➡ **2 periods at baseline parameter**
  - peak luminosity $5x10^{34}cm^{-2}s^{-1}$
  - HL-LHC like
  - total of 2.5 ab^{-1} per detector
- ➡ **3 periods at ultimate parameters**
  - peak luminosity $3x10^{35}cm^{-2}s^{-1}$
  - total of 15 ab^{-1} per detector
- ➡ Total program: **20 ab^{-1} per detector**

Challenging (interesting) environment for detector design.

Higgs Prospects

➡ **Di-Higgs at HL-LHC**

- studied in detail by ATLAS and CMS
- remains very challenging, i.e. there is no silver bullet
- expect 2σ or 50% procession on XS for one experiment



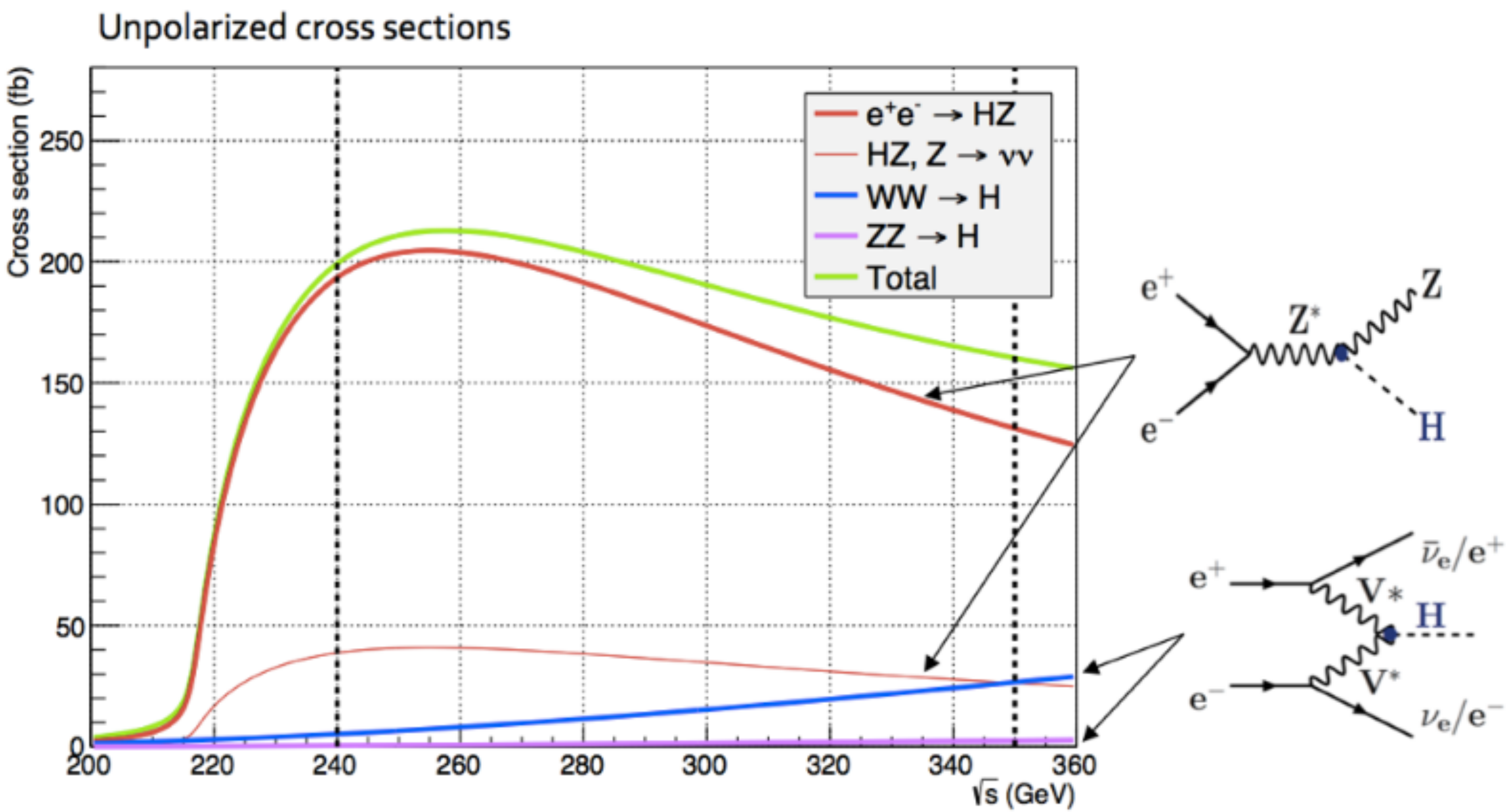
➡ **Di-Higgs at FCC-hh and comparing with HL-LHC**

- similar S/B
- ~10 signal events at HL-LHC
- FCC has larger cross section and luminosity
- FCC has larger acceptance and selection efficiency

Process	Acceptance cuts [fb]	Final selection [fb]	Events ($L = 30$ ab^{-1})
$h(b\bar{b})h(\gamma\gamma)$ (SM)	0.76	0.44	13200
$bbj\gamma$	147	0.203	6110
$t\bar{t}h(\gamma\gamma)$	1.9	0.164	4930
$jj\gamma\gamma$	83	0.082	2460
$b\bar{b}\gamma\gamma$	14.7	0.074	2220
$b\bar{b}h(\gamma\gamma)$	0.10	8.1×10^{-3}	240
Total background	247	0.53	15960

process	precision on σ_{SM}	precision on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	2%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$\sim 25\%$	$\lambda_3 \in [\sim 0.6, \sim 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$\sim 15\%$	$\lambda_3 \in [\sim 0.8, \sim 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$\sim 100\%$	$\lambda_4 \in [\sim -4, \sim +16]$

Lepton Collider

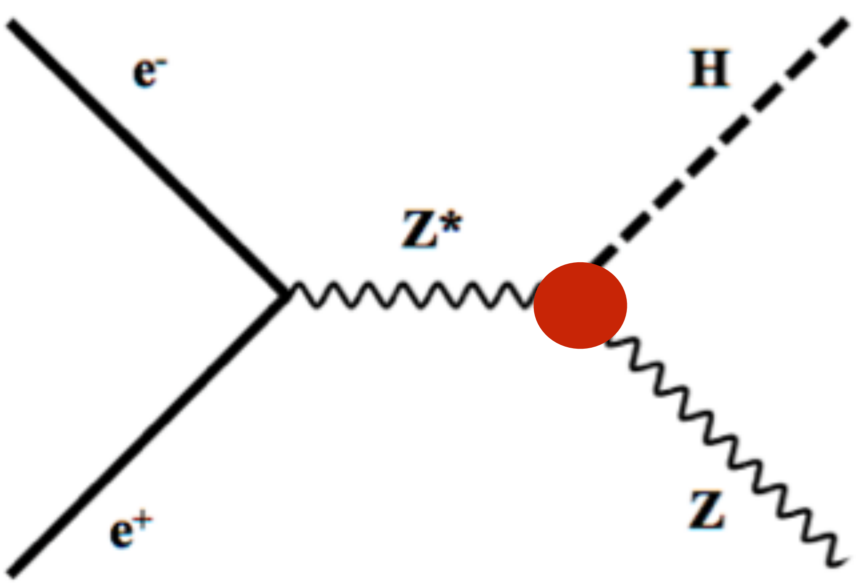


Higgs Physics

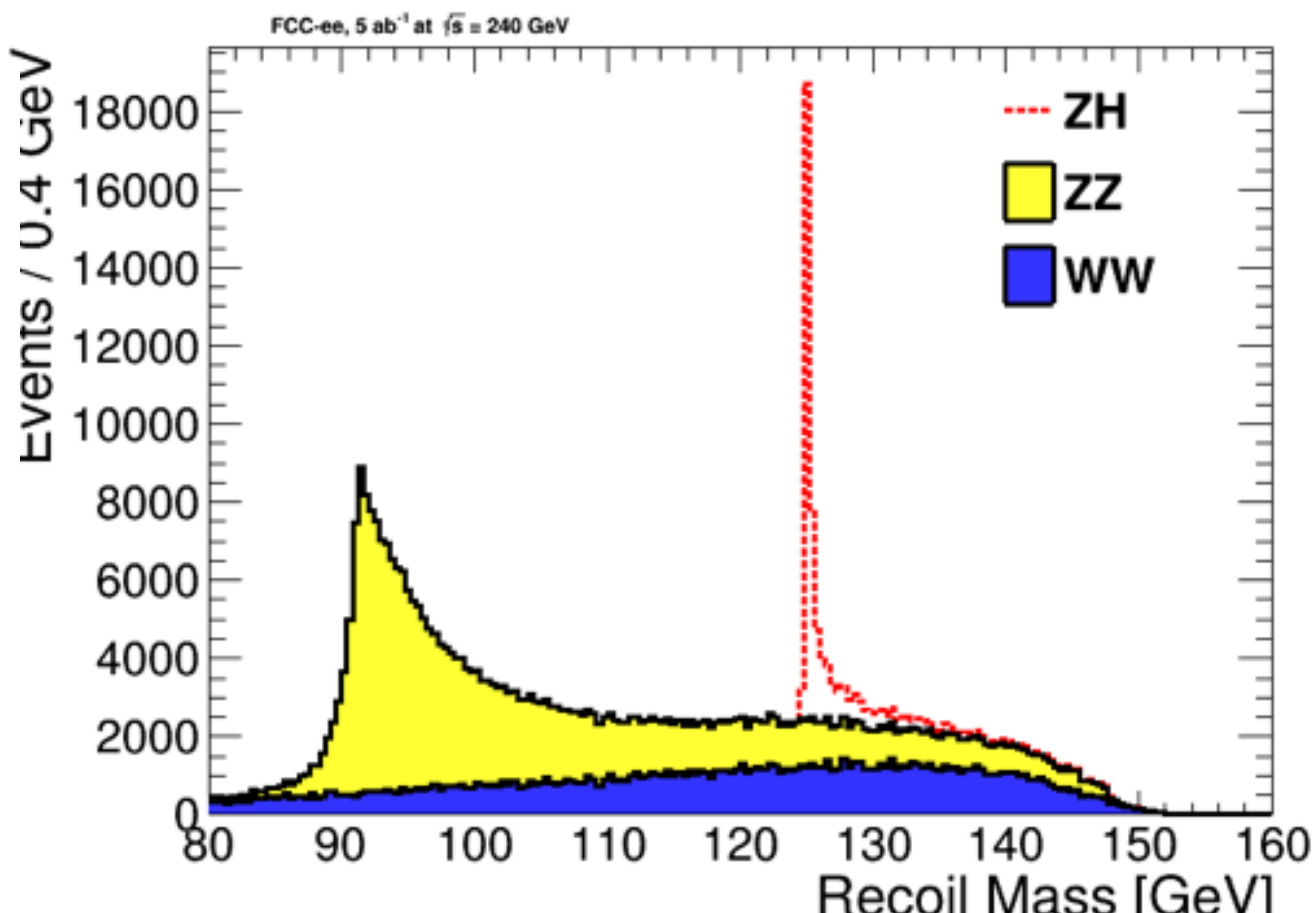
➡ **Recoil method provides unique opportunity for model independent measurement of HZ coupling**

- Higgs events are tagged Higgs decay mode independent
- using only leptonic Z decays and only measurement at 240 GeV so far

$$\sigma(ee \rightarrow ZH) \propto g^2_{HZ}$$



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



Higgs Physics

➡ **Total Higgs boson width can be extracted from a combination of measurements in a model independent way**

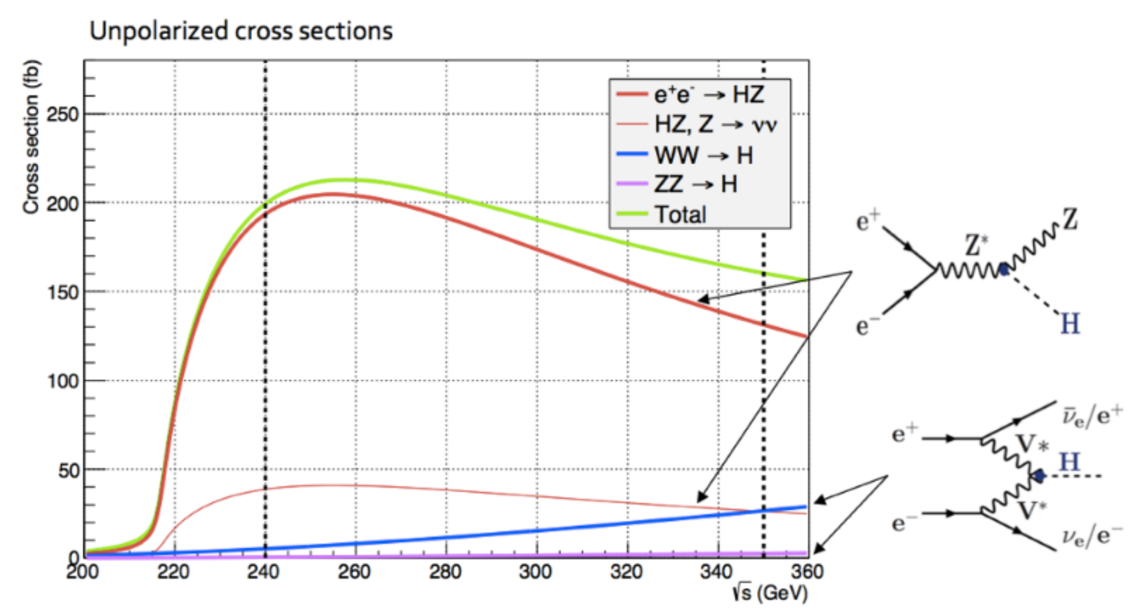
- **1)** tagging Higgs final states

$$\sigma(\mathrm{ee} \to \mathrm{ZH}) \cdot \mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}) \propto \frac{g^4_{\mathrm{HZ}}}{\Gamma}$$

- 2) measurements of vector boson fusion production at 350 GeV

$$\frac{\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{WW})\cdot\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}{\sigma(\mathrm{ee}\to\nu\nu\mathrm{H})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}$$

$$\propto \frac{g^2_{\mathrm{HZ}}\cdot \cancel{g^2_{\mathrm{HW}}}}{\Gamma} \cdot \frac{g^2_{\mathrm{HZ}}\cdot \cancel{g^2_{\mathrm{Hb}}}}{\cancel{\Gamma}} \cdot \frac{\cancel{\Gamma}}{\cancel{g^2_{\mathrm{HW}}}\cdot \cancel{g^2_{\mathrm{Hb}}}} = \frac{g^4_{\mathrm{HZ}}}{\Gamma}$$



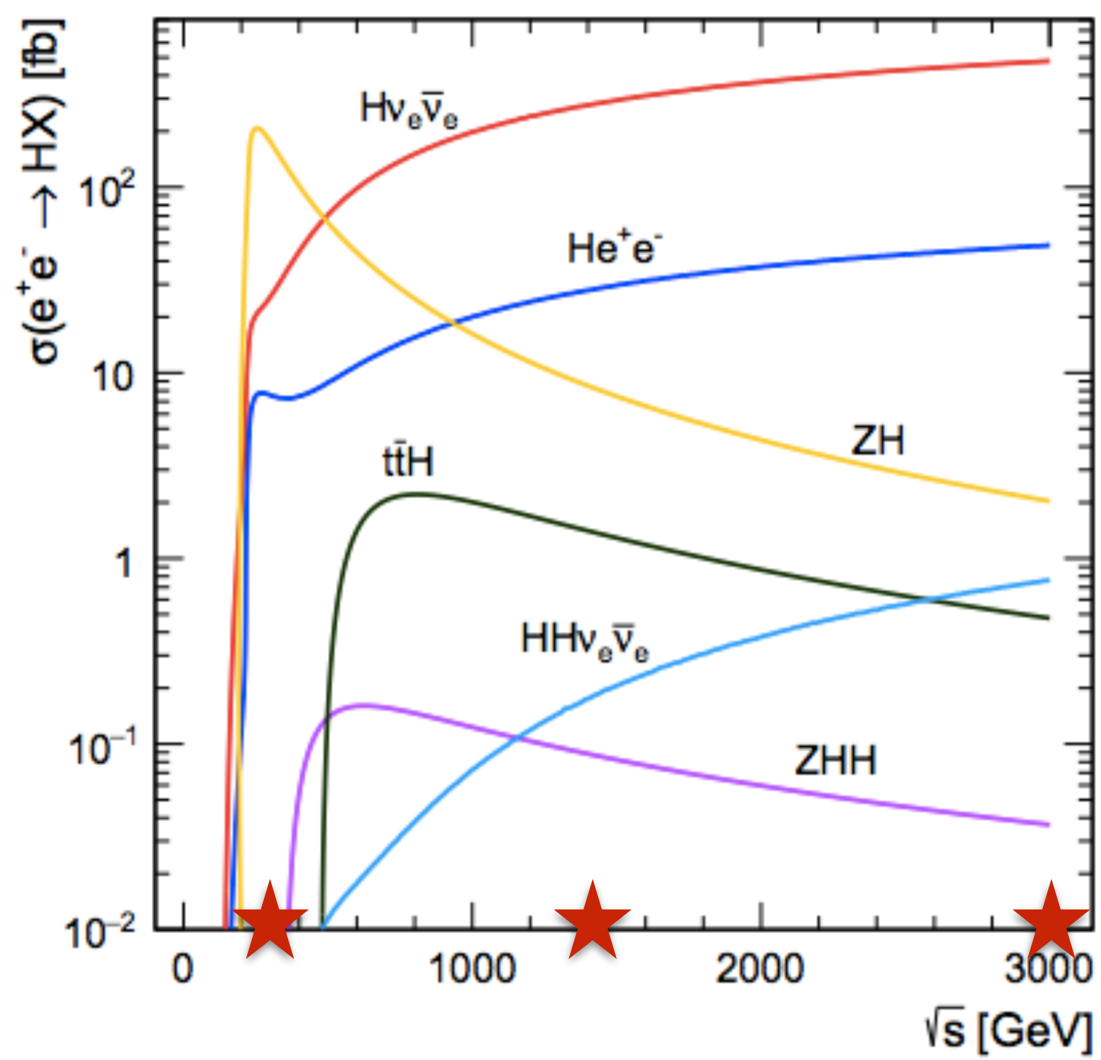
- 3) combination of all measurements

Lepton Collider Updates

- ➡ **CLIC**
  - https://arxiv.org/abs/1608.07538
  - polarization considered for 1.4 and 3 TeV

CDR Vol 2: Physics and Detectors - arXiv:1203.5940
CDR Vol 3: The CLIC Programme - arXiv: 1209.2543
CLIC Snowmass White Paper - arXiv: 1307.5288

Parameter	Relative precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV + 1.5 ab^{-1}	+ 3 TeV + 2 ab^{-1}
g_{HZZ}	0.8 %	0.8 %	0.8 %
g_{HWW}	1.3 %	0.9 %	0.9 %
g_{Hbb}	2.8 %	1.0 %	0.9 %
g_{Hcc}	6.0 %	2.3 %	1.9 %
$g_{H\tau\tau}$	4.2 %	1.7 %	1.4 %
$g_{H\mu\mu}$	–	14.1 %	7.8 %
g_{Htt}	–	4.4 %	4.4 %
$g^{\dagger}_{Hgg}$	3.6 %	1.7 %	1.4 %
$g^{\dagger}_{H\gamma\gamma}$	–	5.7 %	3.2 %
$g^{\dagger}_{HZ\gamma}$	–	15.6 %	9.1 %
Γ_H	6.4 %	3.7 %	3.6 %



Lepton Collider Updates

arXiv:1506.05992

➡ **International Linear Collider (ILC)**

- project is being re-assessed
- cost, physics case, running scenarios
- new results e.g. on interpretation of data arXiv:1708.08912
- JAHEP proposes the Japanese Linear Higgs Factory (ILC250)
  - 1-2/ab in 10 years

	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	500	350	250	500	350	250
G-20	$\int \mathcal{L} dt$ [fb^{-1}]	1000	200	500	4000	-	-
	time [years]	5.5	1.3	3.1	8.3	-	-
H-20	$\int \mathcal{L} dt$ [fb^{-1}]	500	200	500	3500	-	1500
	time [years]	3.7	1.3	3.1	7.5	-	3.1
I-20	$\int \mathcal{L} dt$ [fb^{-1}]	500	200	500	3500	1500	-
	time [years]	3.7	1.3	3.1	7.5	3.4	-
	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	250	500	350	250	350	500
Snow	$\int \mathcal{L} dt$ [fb^{-1}]	250	500	200	900	-	1100
	time [years]	4.1	1.8	1.3	3.3	-	1.9

2/ab @ 250 GeV   +4/ab @ 500 GeV

	full 250 GeV EFT fit	initial ILC [3]	full ILC [3]	full ILC EFT fit
$g(hb\bar{b})$	1.04	1.5	0.7	0.55
$g(hc\bar{c})$	1.79	2.7	1.2	1.09
$g(hgg)$	1.60	2.3	1.0	0.89
$g(hWW)$	0.65	0.81	0.42	0.34
$g(h\tau\tau)$	1.16	1.9	0.9	0.71
$g(hZZ)$	0.66	0.58	0.31	0.34
$g(h\mu\mu)$	5.53	20	9.2	4.95
Γ_h	2.38	3.8	1.8	1.50

uncertainty in %

Lepton Collider Updates

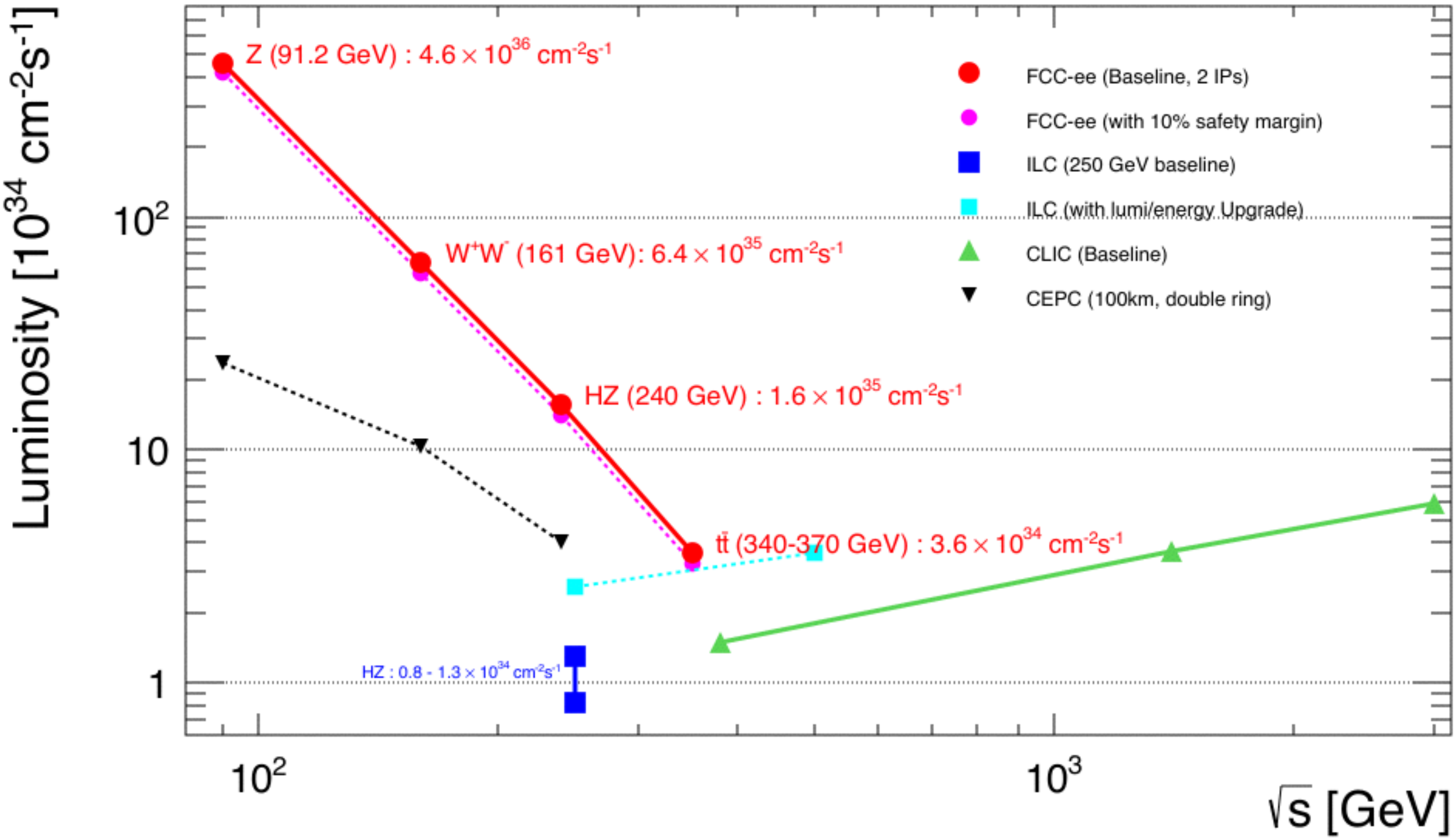
- ➡ **FCC-ee**
  - updated baseline machine parameter for CDR
  - long list of studies and improvements
  - realistic assumptions and simulations used

	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	175
arc cell optics	60/60	90/90	90/90	90/90
emittance hor/vert [nm]/[pm]	0.27/1.0	0.28/1.0	0.63/1.3	1.34/2.7
beta* horiz/vertical [m]/[mm]	0.15/.8	0.2/1	0.3/1	1/2
total RF voltage [GV]	0.10	0.44	2.0	9.5
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.147 / 0.192
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.45 / 3.25
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7
no. of bunches / beam	16640	2000	393	48
beam current [mA]	1390	147	29	6.4
luminosity [10^{34} cm^{-2}s^{-1}]	230	32	7.8	1.8
luminosity lifetime [min]	70	50	42	39
allowable asymmetry [%]	±5	±3	±3	±3

Modus Operandi:
12 years total running time (= LEP)

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ year	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	52 ab^{-1}/year		
W	30	7.8 ab^{-1}/year	10 ab^{-1}	~1
H	7.0	1.8 ab^{-1}/year	5 ab^{-1}	3
top	1.6	0.4 ab^{-1}/year	1.5 ab^{-1}	4

Luminosity vs Energy



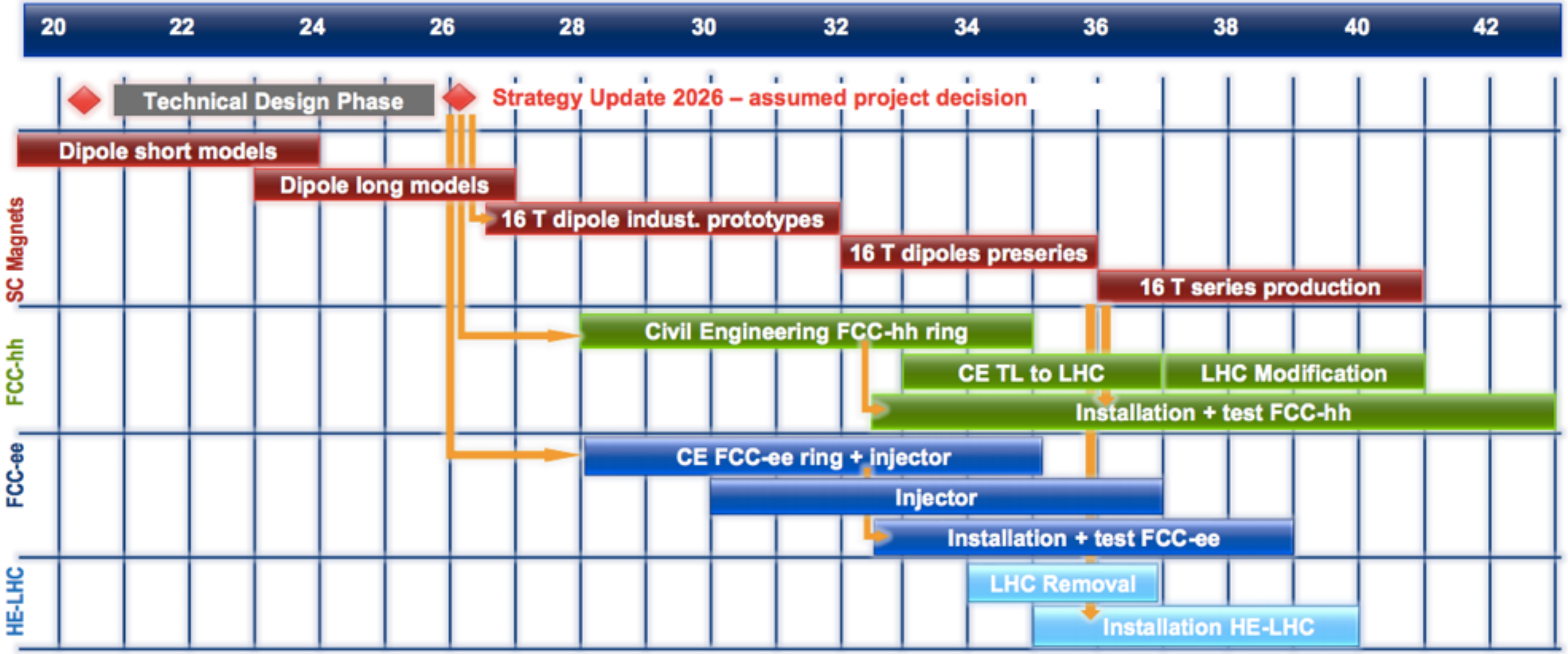
Summary Table

Uncertainties	HL-LHC*	μ-Collider	CLIC	ILC	FCC-ee
m_H [MeV]	40	**0.06**	-	30	8*
Γ_H [MeV]	-	0.17	0.15	0.16	**0.05**
g_{HZZ} [%]	2.0	-	0.8	0.6	**0.2**
g_{HWW} [%]	2.0	2.2	0.9	0.8	**0.4**
g_{Hbb} [%]	4.0	2.3	1.0	1.5	**0.6**
$g_{H\tau\tau}$ [%]	2.0	5	1.7	1.9	**0.8**
$g_{H\gamma\gamma}$ [%]	**2.0**	10	5.7	7.8	2.1
g_{Hcc} [%]	-	-	2.3	2.7	**1.0**
g_{Hgg} [%]	3.0	-	1.7	2.3	**1.2**
g_{Htt} [%]	**4.0**	-	4.4	18	-
$g_{H\mu\mu}$ [%]	4.0	**2.1**	14	20	8.8
g_{HHH} [%]	30	-	**24**	-	-

* Estimate for two HL-LHC experiments

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

CERN Draft Schedule



Conclusion

➡ … and some more points

➡ (HL-)LHC quickly turning Higgs studies into program of precision measurements

- next big goal is the coupling to second generation fermions
- study coupling deviation from SM at O(%)
- differential measurement offer additional handle to …
- evidence for di-Higgs production possible at HL-LHC

➡ Fantastic prospects to probe the Higgs sector with future lepton colliders

- unique measurements of g_{ZH} and total width
- precision measurements of Higgs boson properties (coupling, mass, CP)
- precision Higgs program needs to be accompanied by precision program for m_c, m_b, and α_s
- synergy and complementarity to hadron collider Higgs physics