Physics at Lepton Colliders

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INFN Bologna

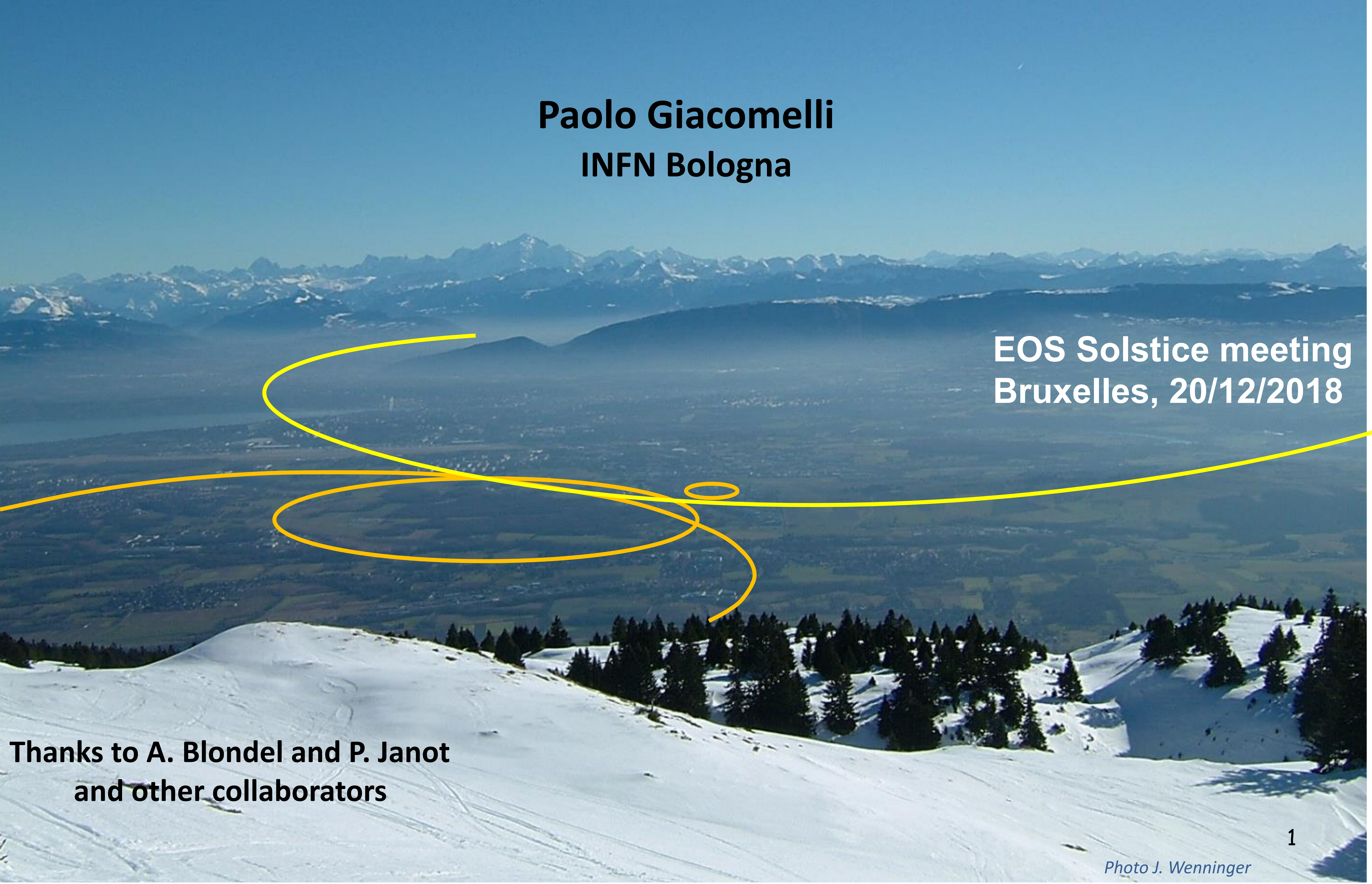

Photo J. Wenninger

EOS Solstice meeting
Bruxelles, 20/12/2018

Thanks to A. Blondel and P. Janot and other collaborators

Overview

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- **The proposed future Lepton Colliders**

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- **The proposed future Lepton Colliders**
  - **Circular Colliders**

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  - **Linear Colliders**

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- **Discovery potential**

Istituto Nazionale di Fisica Nucleare

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  - Linear Colliders
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- EW observables

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Caveat

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Cannot possibly cover all the physics landscape!

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A personal selection applied…

The Future Circular Colliders
CDR and cost review to appear Q4 2018 for ESU

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- ***Ultimate goal:*** ~16 T magnets
  100 TeV pp-collider (*FCC-hh*)

→ defining infrastructure requirements

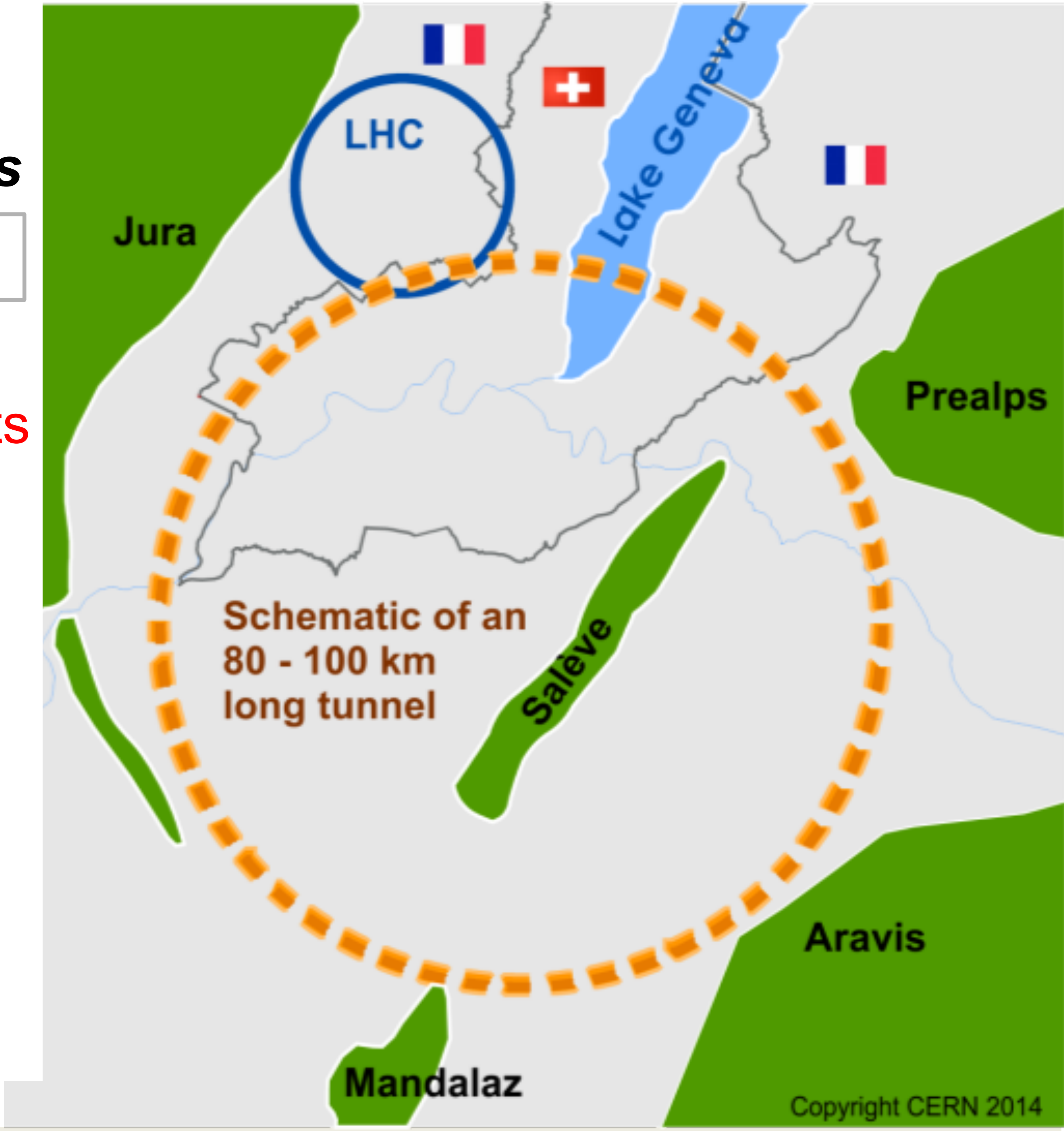
Two possible first steps:

- e^+e^- collider (*FCC-ee*)
  High Lumi, E_{CM} =90-400 GeV

- *HE-LHC* 16T ⇒ 27 TeV
  in LEP/LHC tunnel

Possible addition:

- *p-e* (*FCC-he*) option



From European Strategy in 2013: "ambitious post-LHC accelerator project"
Study kicked-off in Geneva in Feb 2014

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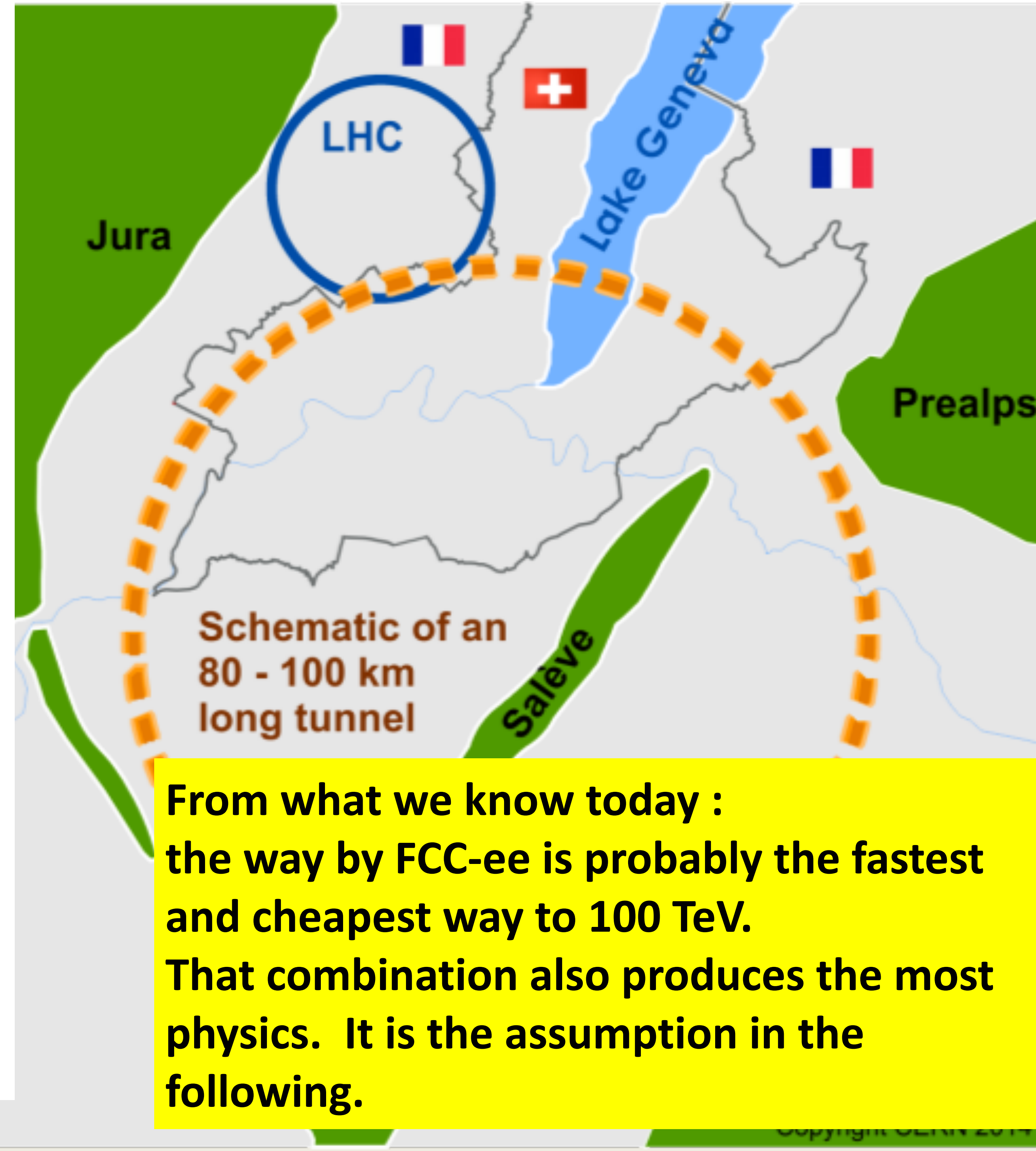

From what we know today :
the way by FCC-ee is probably the fastest and cheapest way to 100 TeV.
That combination also produces the most physics. It is the assumption in the following.

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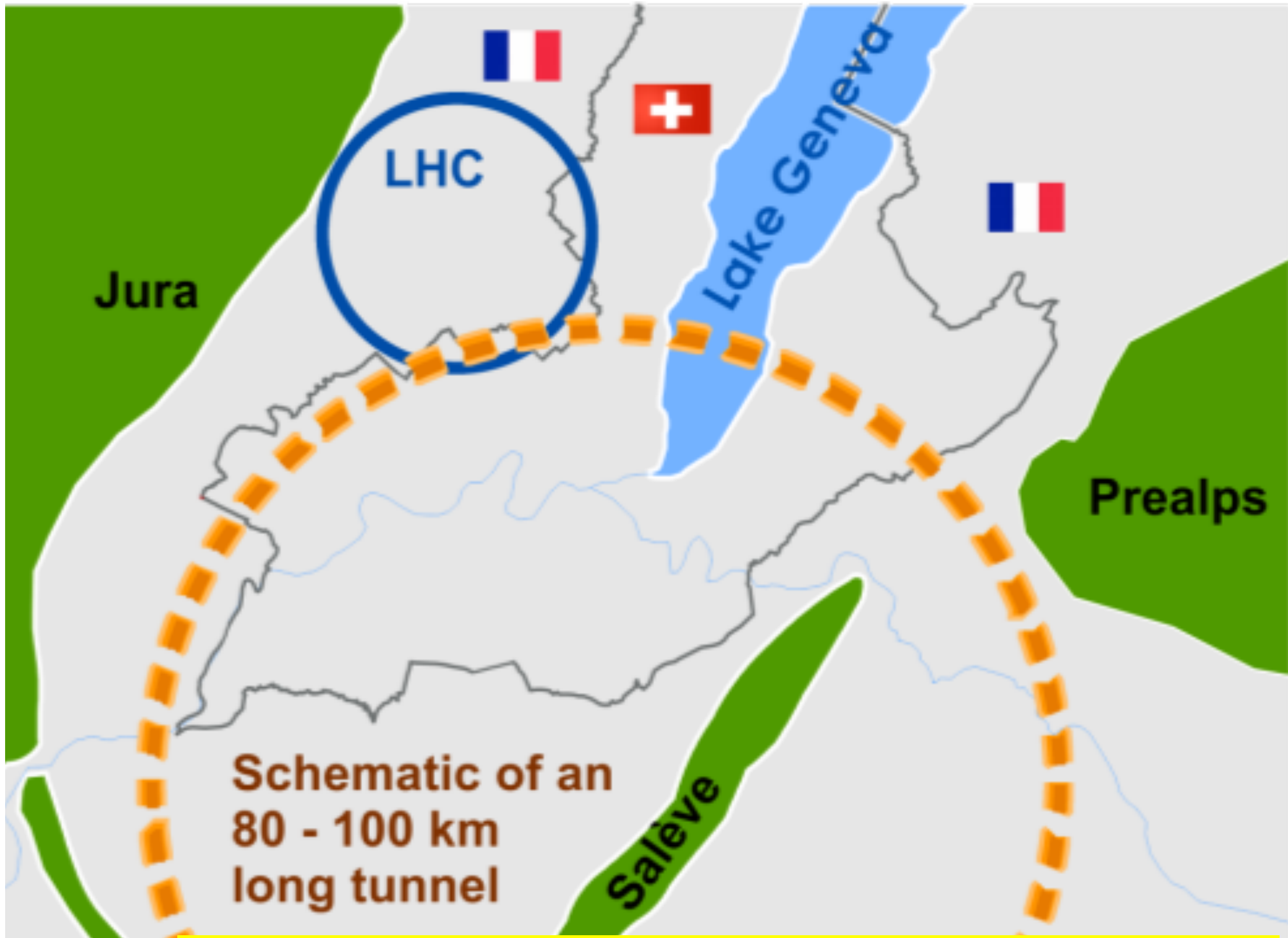

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also a good start for μC!

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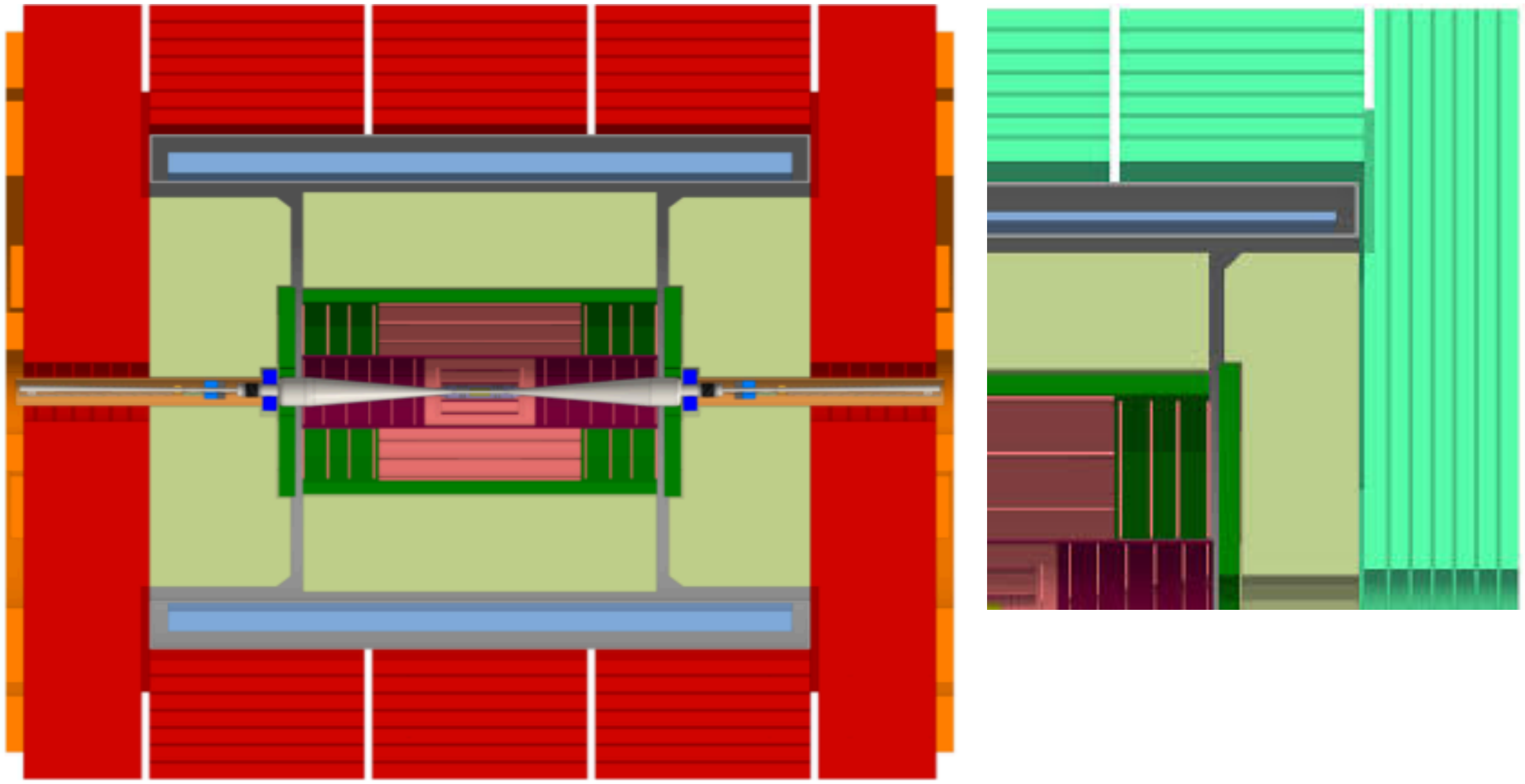
Circular colliders: FCC-ee detectors

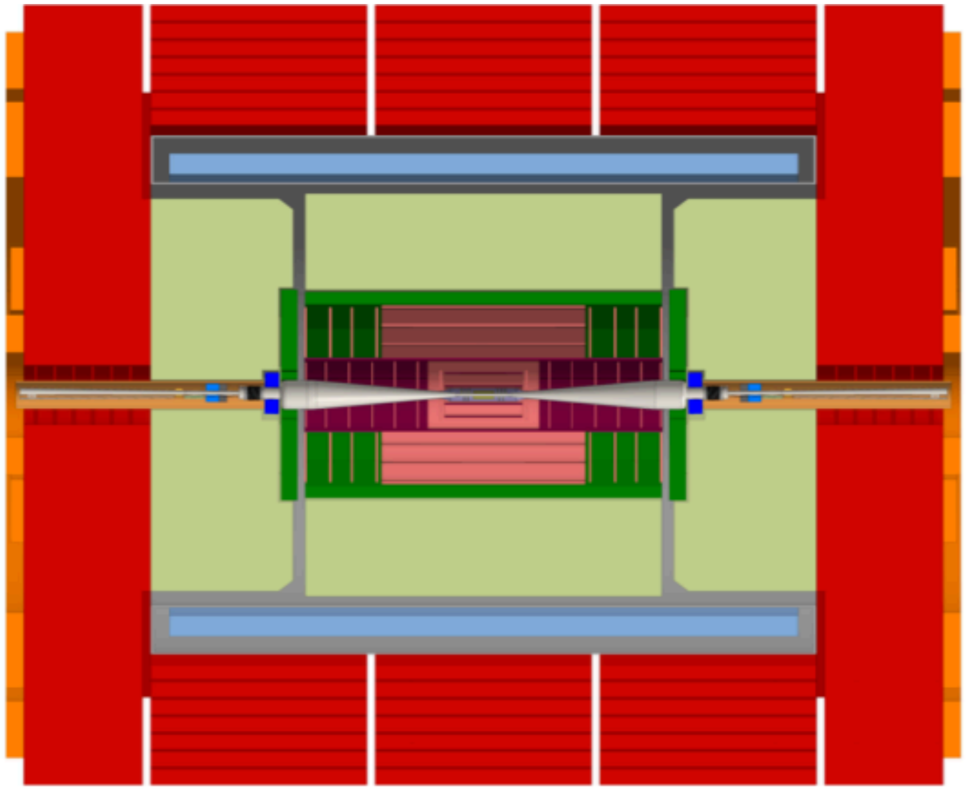
Circular colliders: FCC-ee detectors

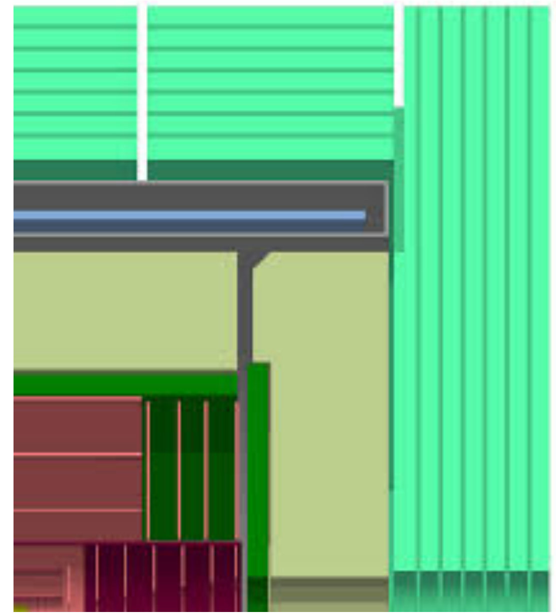


CLD

2 T solenoid
Full Si tracker
SiW HG EM calorimeter
Sci.-steel HG HCAL calorimeter
Muon detector with RPCs

Circular colliders: FCC-ee detectors





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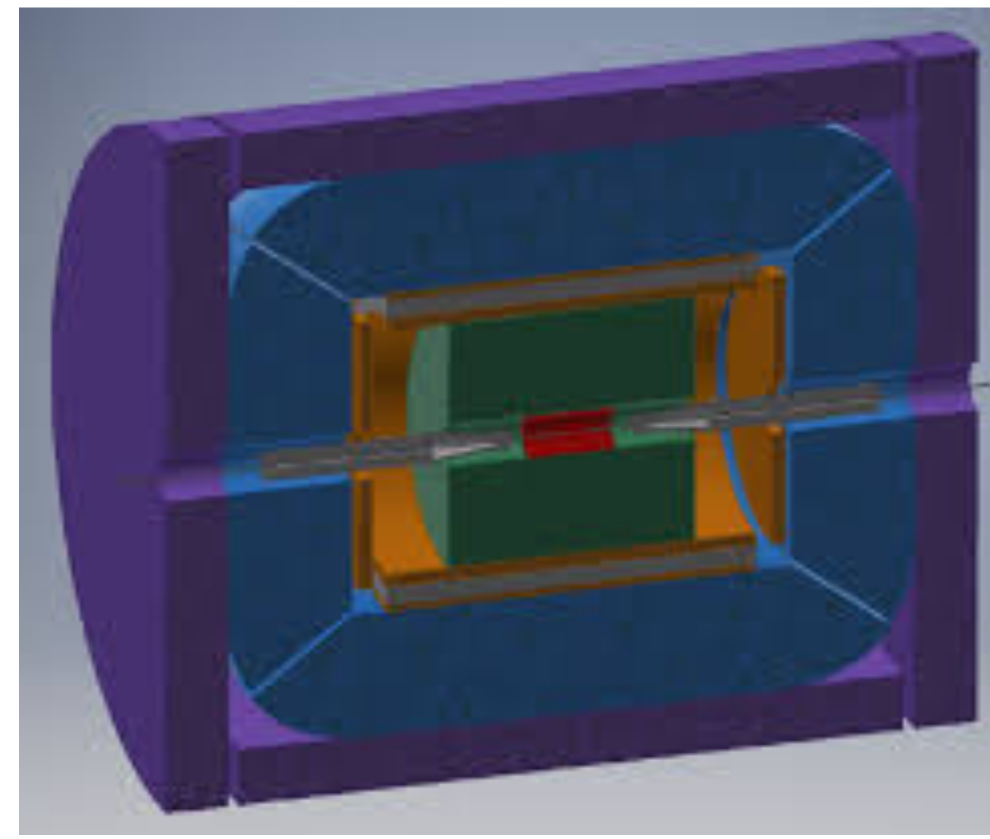
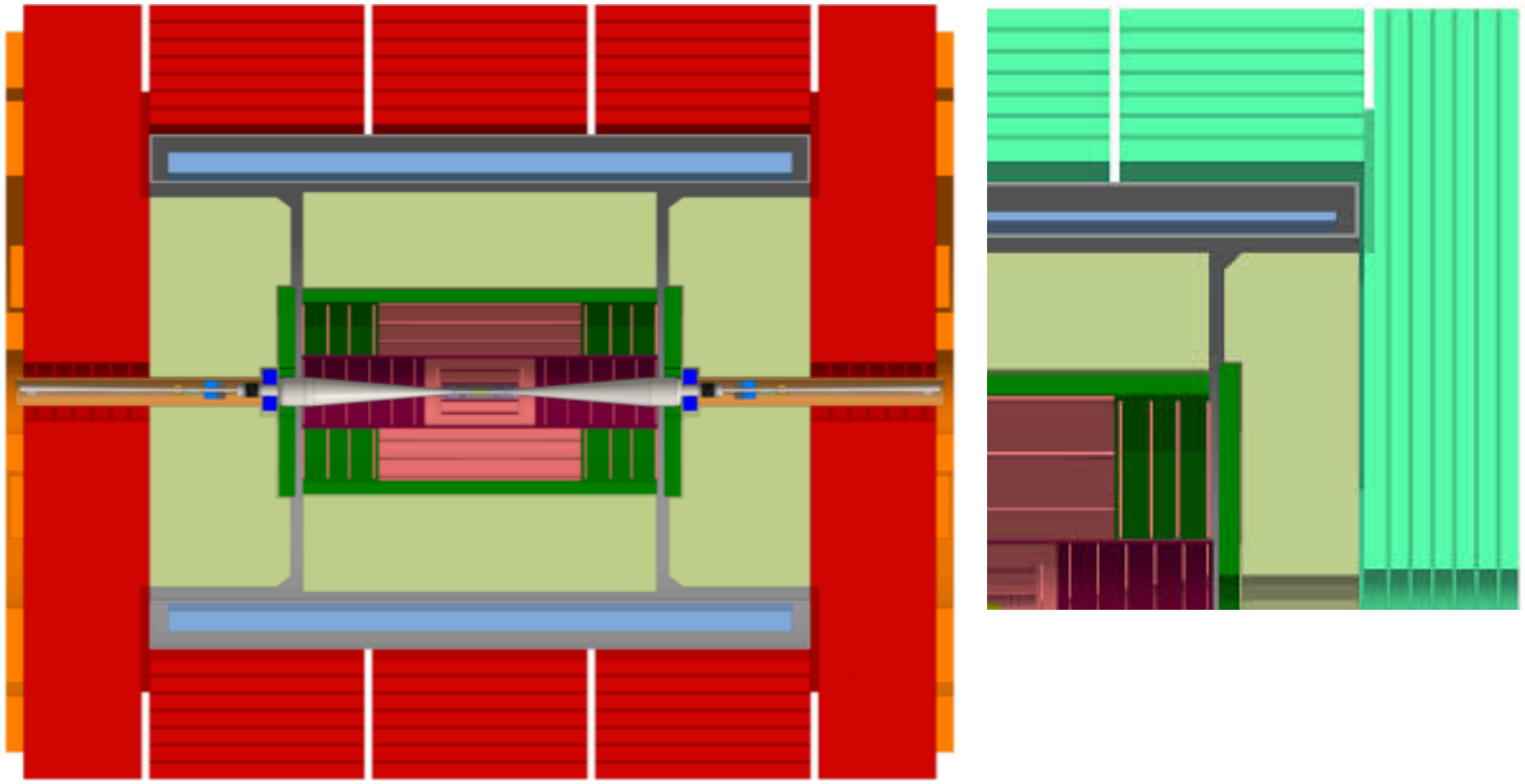


2 T thin solenoid
Si vertex
Wire chamber
Dual Readout calorimeter
MPGD-based Muon detector

Circular colliders: FCC-ee detectors



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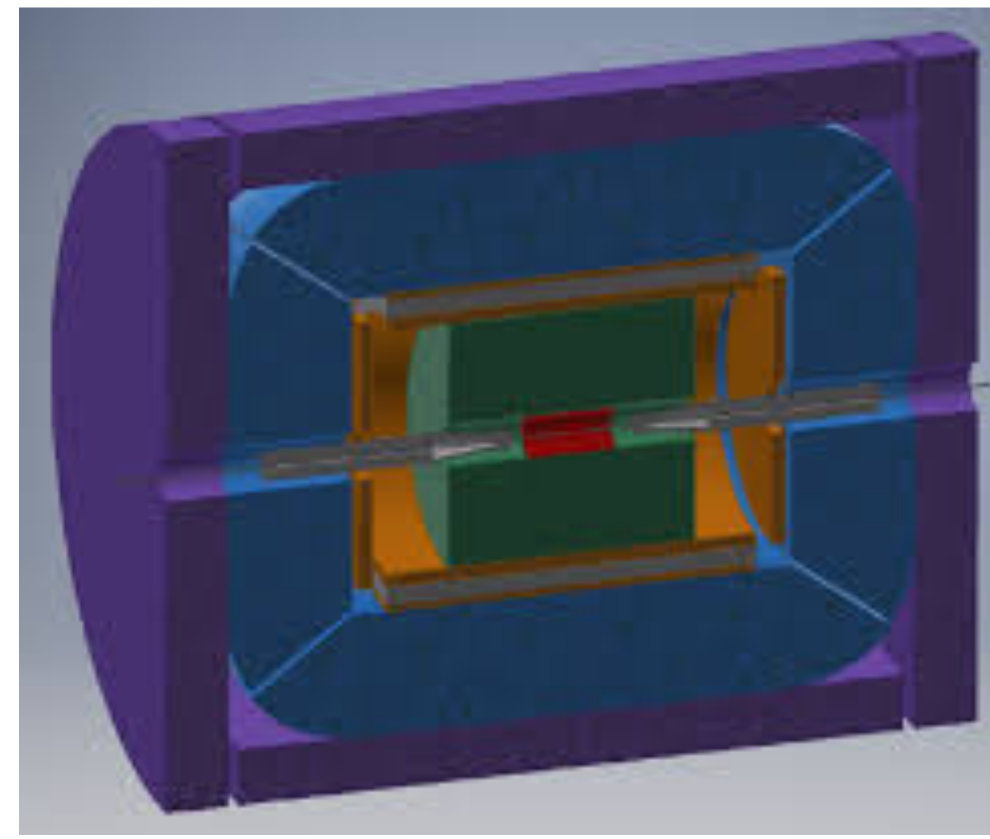

2 T thin solenoid
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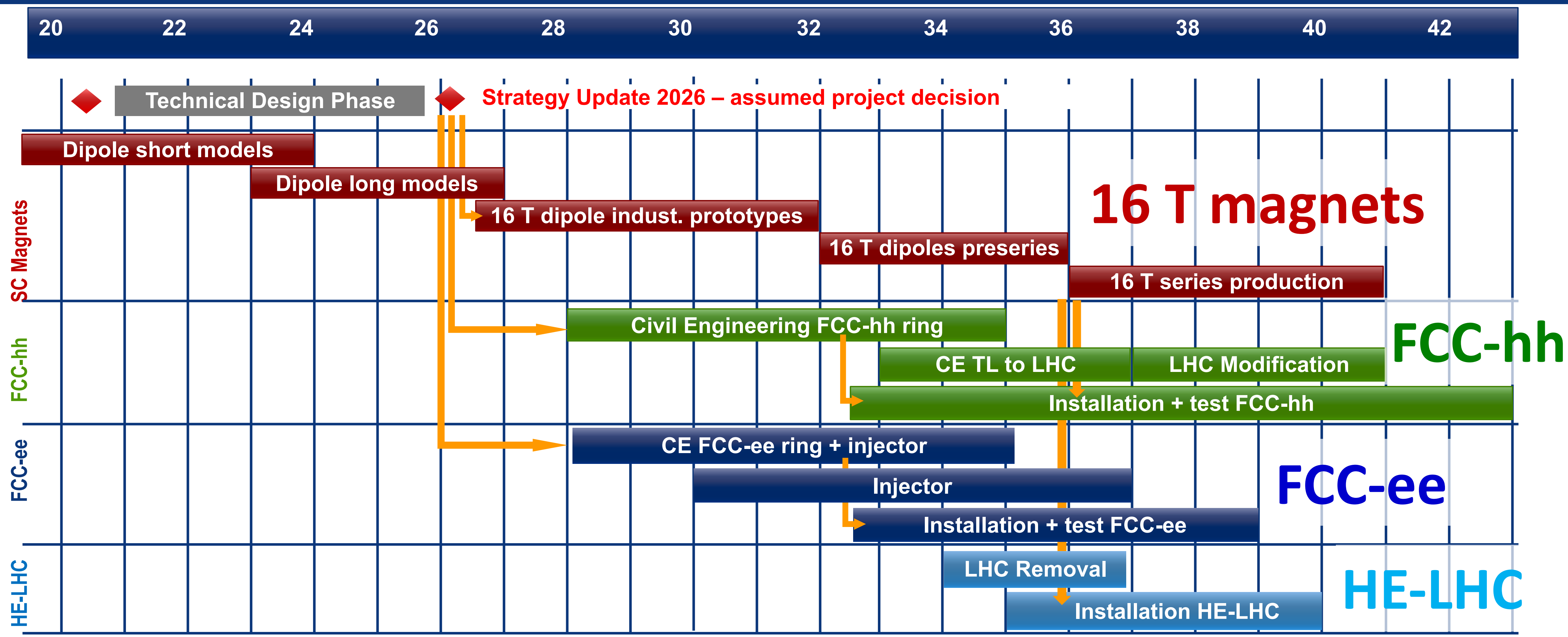
CDR to be published in January 2019

Possible Timeline of the FCCs

Technical Schedule for each of the 3 options



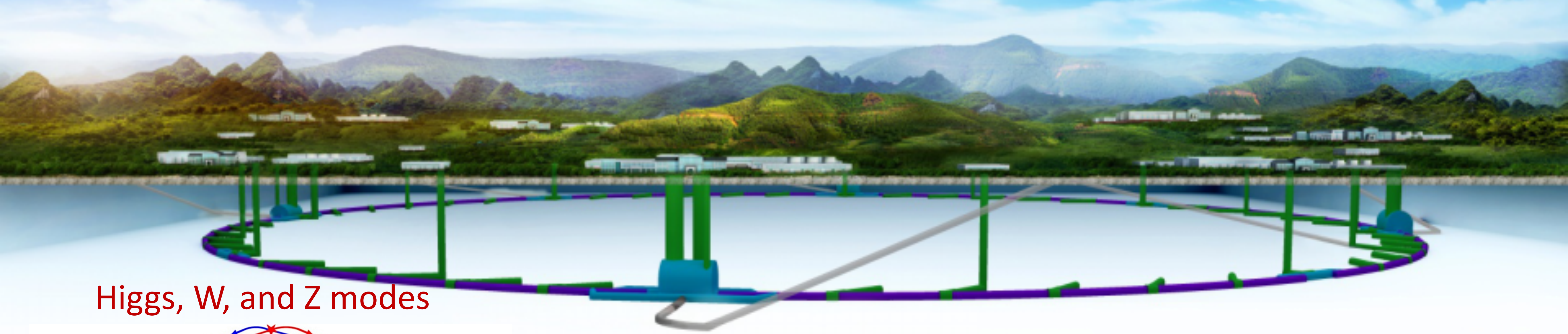
schedule constrained by 16 T magnets & CE

→ earliest possible physics starting dates

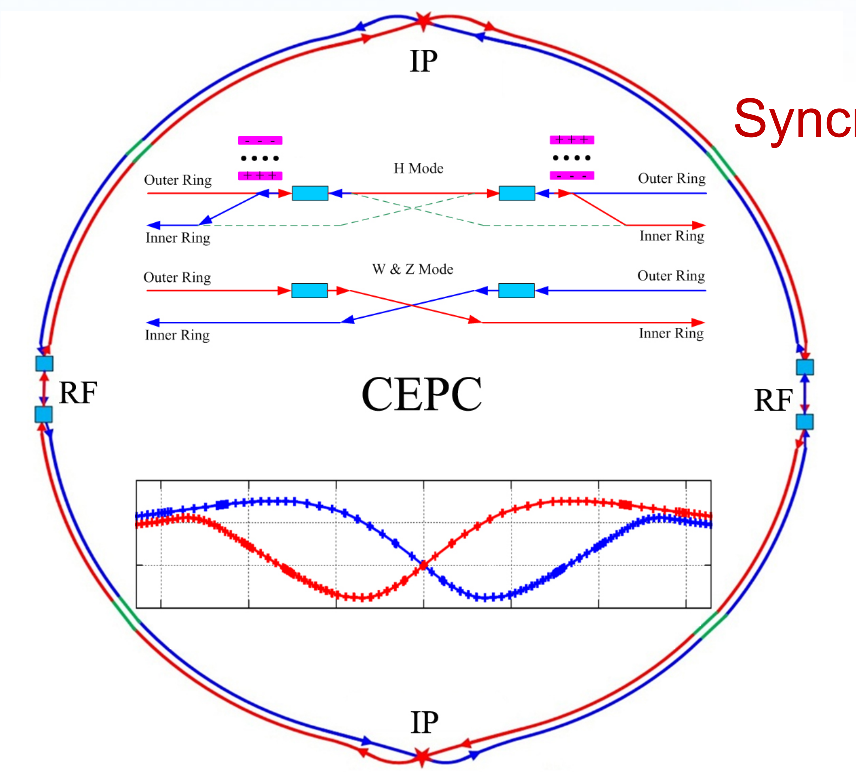
- **FCC-ee: 2039**
- **FCC-hh: 2043**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

Circular colliders: CEPC

CDR published in November 2018

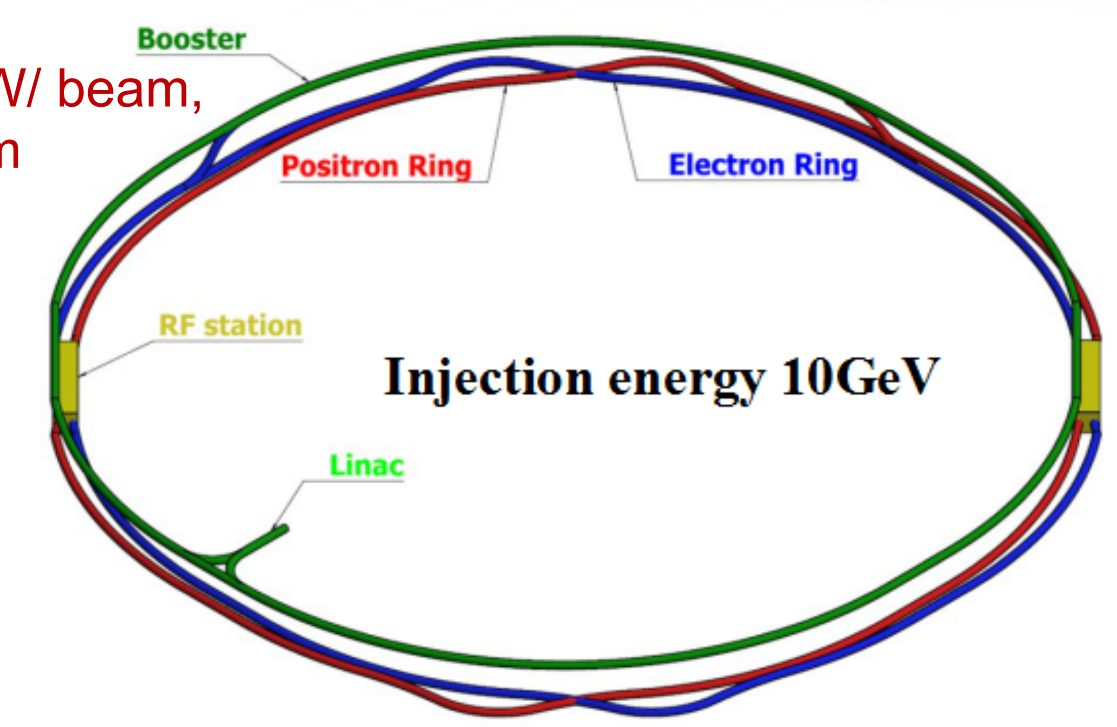


Higgs, W, and Z modes



CEPC collider ring (100km)

Syncrotron Radiation power 30MW/ beam, upgradable to 50MW/beam



CEPC booster ring (100km)

Center of mass energy **91** - **240** GeV

Max. luminosity ($\sqrt{s}$=240 GeV) **3 x 10^{34}** cm^{-2}s^{-1}

Later install SPPC (pp collider) $\sqrt{}$**s** = **100-120** TeV

CEPC Site Selections

Huanghe Company participated

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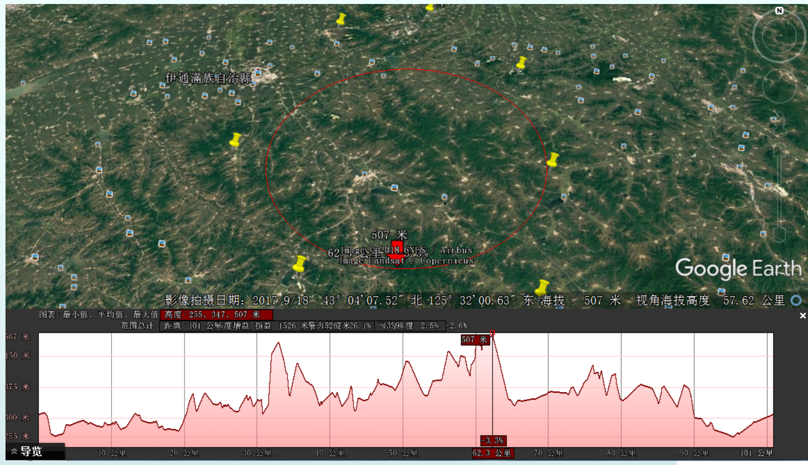

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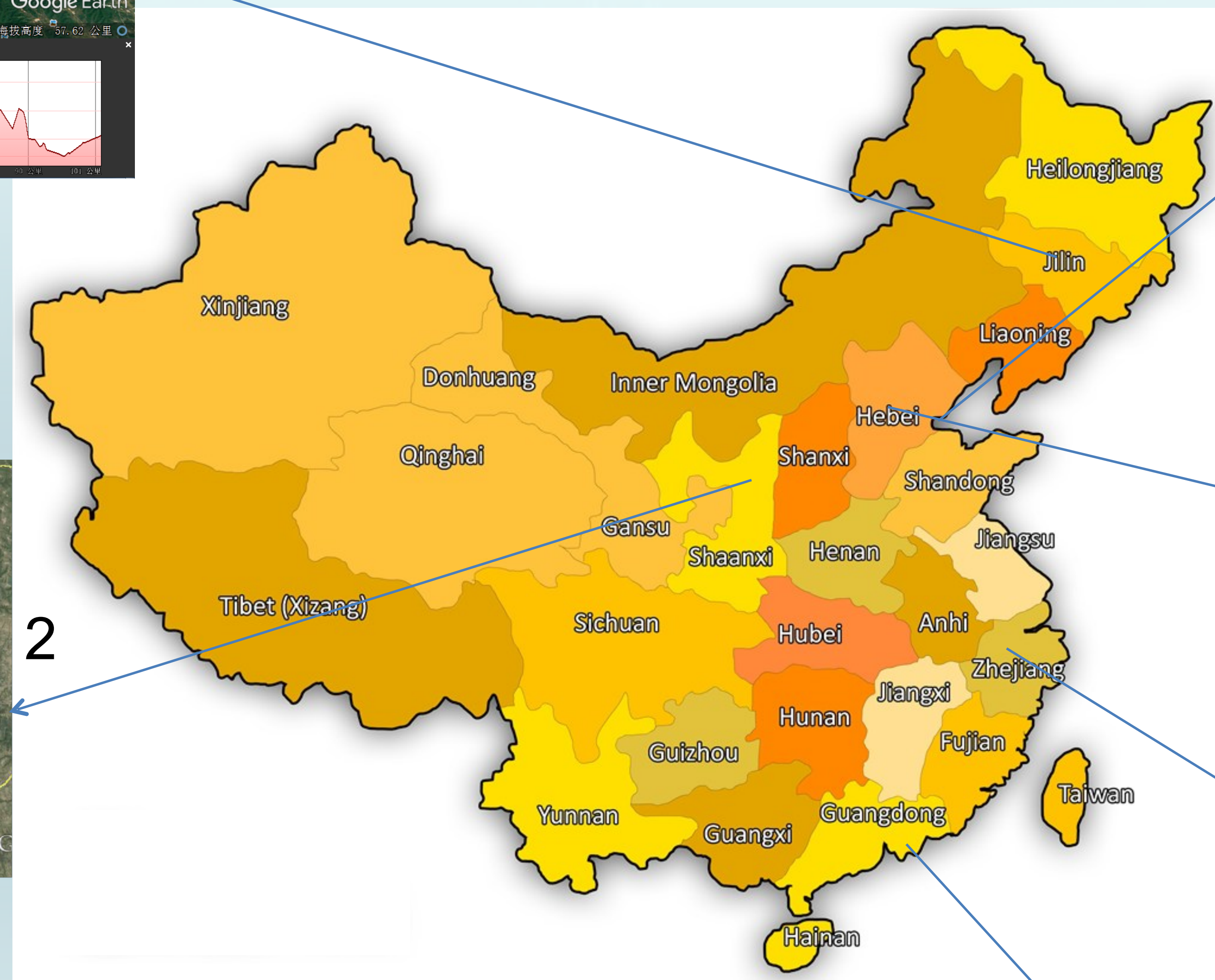

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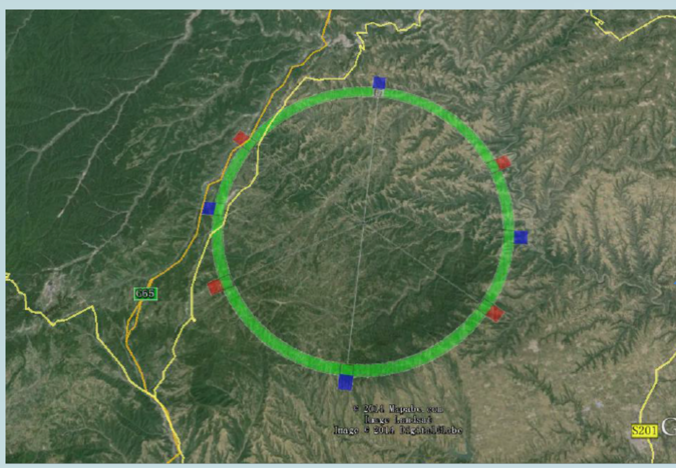

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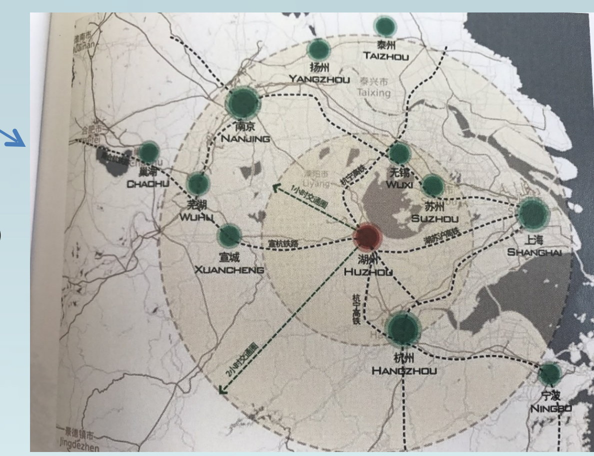


3

1) Qinhuangdao, Hebei Province （Completed in 2014）

2) Huangling, Shanxi Province （Completed in 2017)

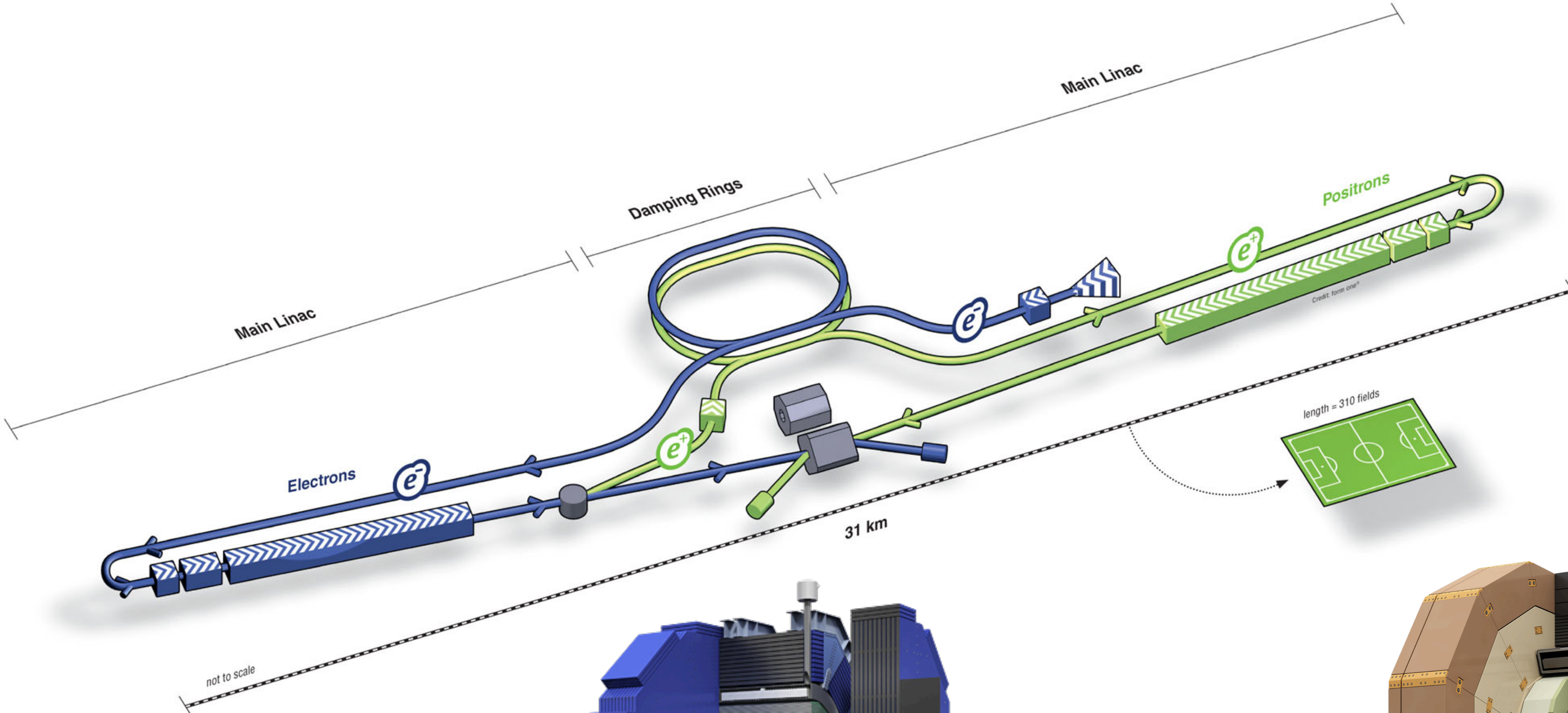
3) Shenshan, Guangdong Province(Completed in 2016)

4) Baoding (Xiong an), Hebei Province (Started in August 2017)

5) Huzhou, Zhejiang Province (Started in March 2018)

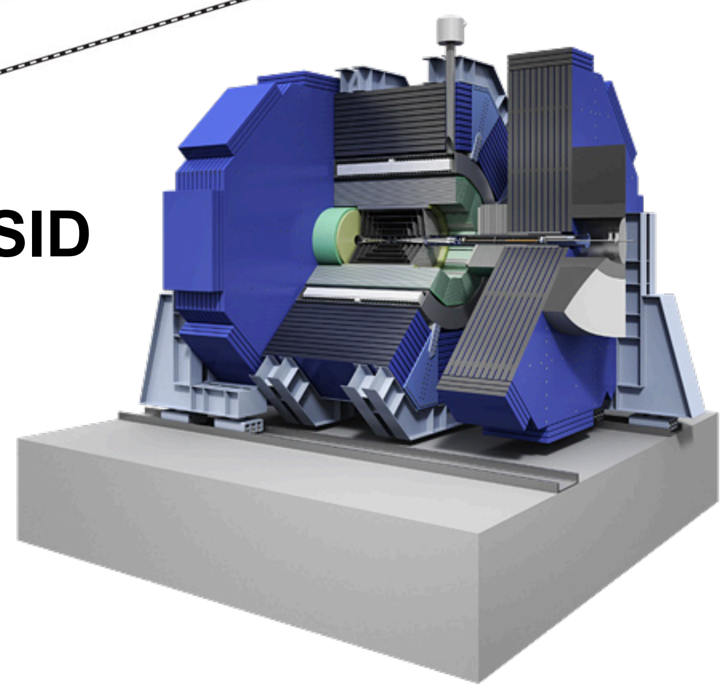
6) Chuangchun, Jilin Province (Started in May 2018)

Linear colliders: ILC

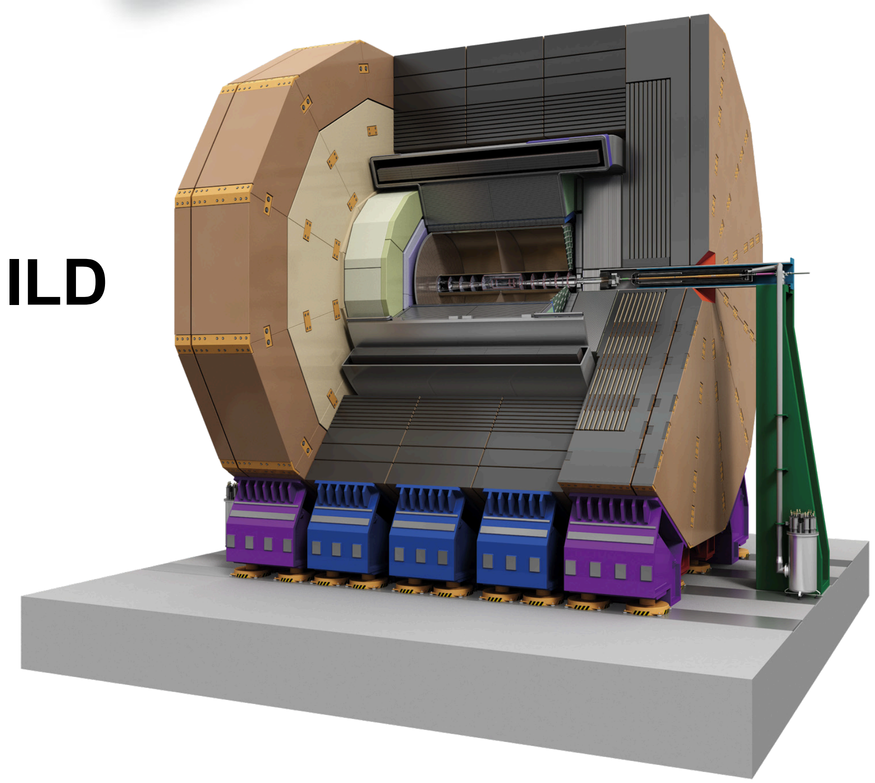


Length ~20 km
for √s=250 GeV

SID



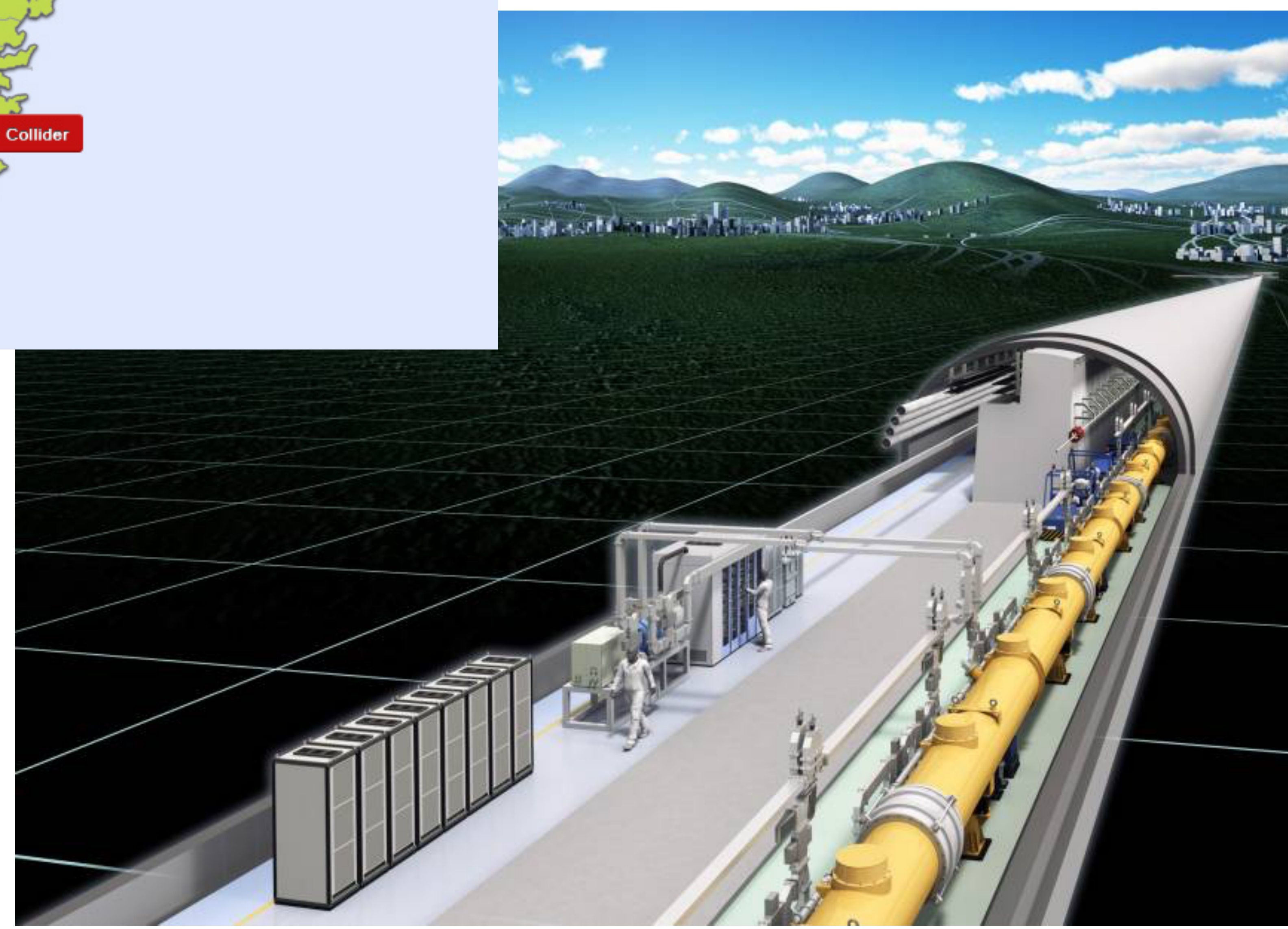
ILD



Center of mass energy 250 GeV, upgradable to 500 GeV and possibly to 1 TeV
Accelerating gradient 31.5 MeV/m
Max. luminosity (√s=250 GeV) 1.5 x 10^{34} $cm^{-2}s^{-1}$

Linear colliders: ILC

To be hosted by Japan
Site selected is Kitakami



Decision pending by Japan since 2013…

XFEL built at DESY is a 10% version of the ILC.

Linear colliders: ILC

To be hosted by Ja

Site selected i

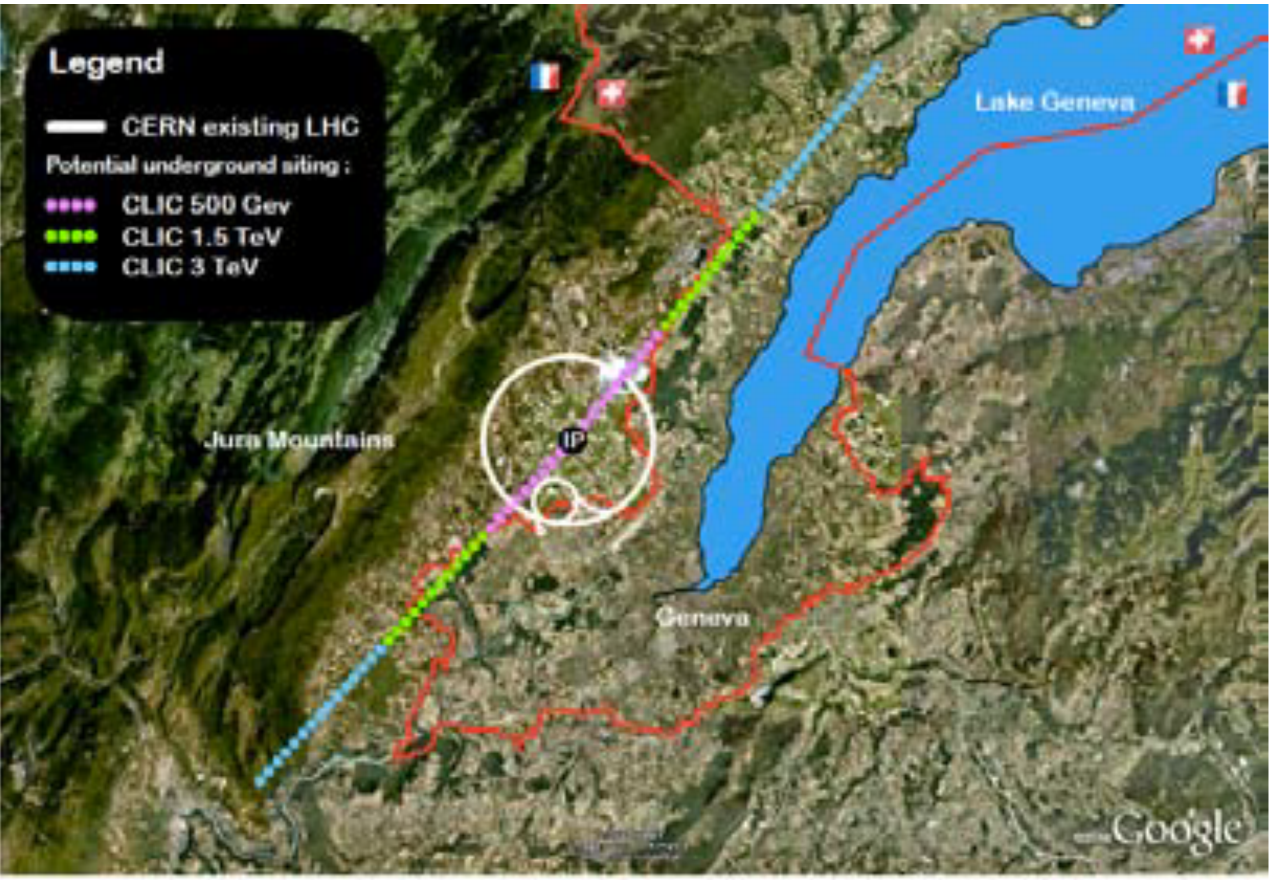
Deci

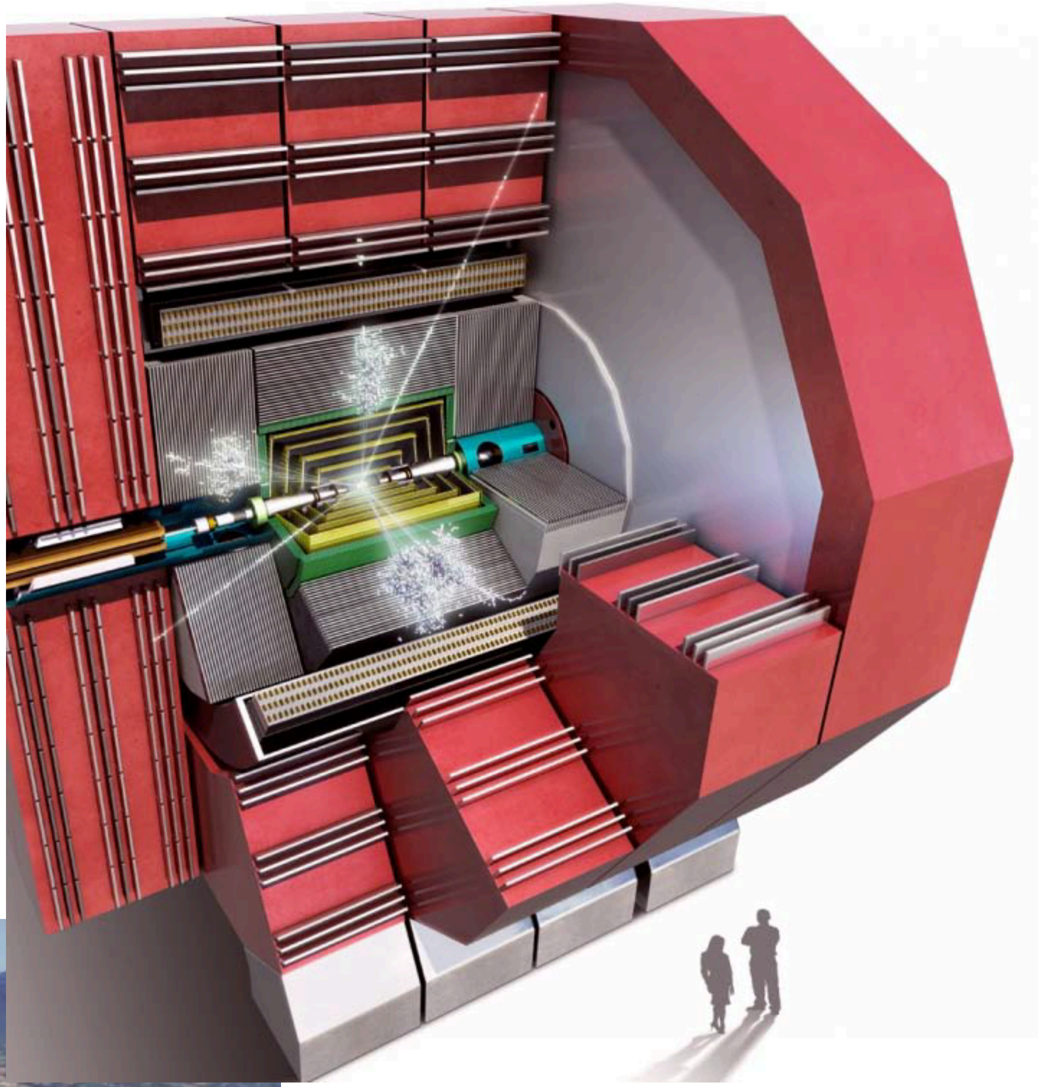
XF… DESY is a 10% … of the ILC.

19/12/2018 **Breaking News!!**

Japan's Science Council does not support ILC!

Linear colliders: CLIC

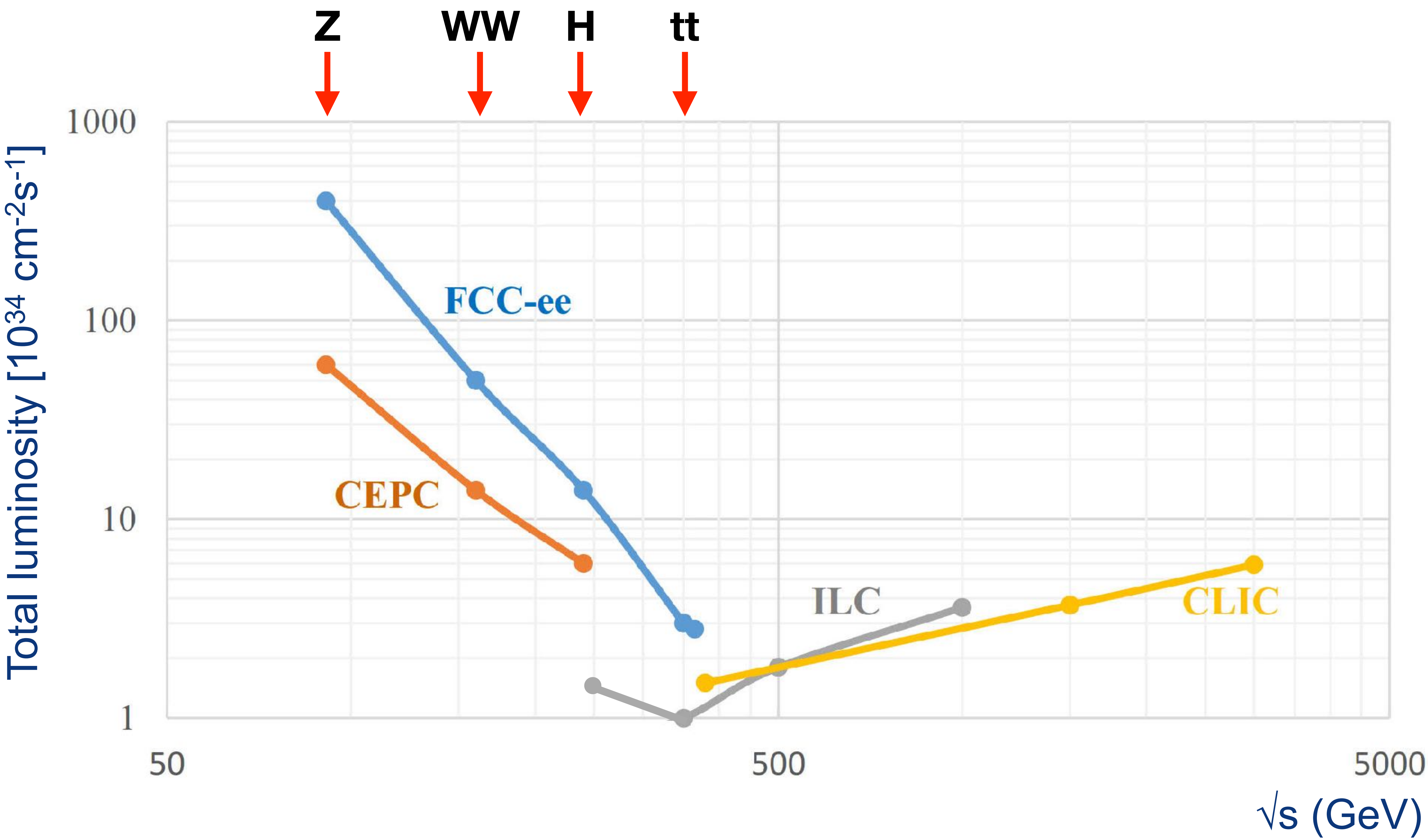




4 T solenoid
Si tracker
HG calorimeter
Muon detector

Center of mass energy 380 GeV, upgradable to 1.5 TeV and possibly to 3 TeV
Accelerating gradient ~100 MeV/m
Max. luminosity ($\sqrt{s}$=380 GeV) 1.5 x 10^{34} $cm^{-2}s^{-1}$

Future lepton colliders luminosities



Clear advantage in luminosity for circular colliders vs. linear colliders.

Linear colliders (CLIC) have higher energy reach, but less than a pp collider.

FCC-ee Run Plan

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold	365 GeV
Lumi/IP (10^{34} cm^{-2}s^{-1})	100	200	31	7.5	0.85	1.5
Lumi/year (2 IP)	26 ab^{-1}	52 ab^{-1}	8.1 ab^{-1}	1.95 ab^{-1}	0.22 ab^{-1}	0.39 ab^{-1}
Physics goal (ab^{-1})	150		10	5	0.2	1.5
Run time (year)	2	2	1	3	1	4

indicative: total ~15 years

O(1/3) of the machine cost comes O(10) years after start

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Event statistics :

			E_{CM} errors:	
Z peak	**E_{cm} : 91 GeV**	**5×10^{12} $e^+e^- \rightarrow Z$**	**LEP x 10^5**	100 keV
WW threshold	**E_{cm} : 161 GeV**	**10^8 $e^+e^- \rightarrow WW$**	**LEP x 2.10^3**	300 keV
ZH threshold	**E_{cm} : 240 GeV**	**10^6 $e^+e^- \rightarrow ZH$**	**Never done**	1 MeV
$t\bar{t}$ threshold	**E_{cm} : 350 GeV**	**10^6 $e^+e^- \rightarrow t\bar{t}$**	**Never done**	2 MeV

FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

- **EXPLORE the 10-100 TeV energy scale**
  - With precision measurements of the properties of the Z, W, Higgs, and top particles
    - 20-50 fold improved precision on ALL electroweak observables (EWPO)
      - ➔ m_Z, Γ_Z, m_W, m_{top}, $\sin^2\theta_w^{eff}$, R_b, $\alpha_{QED}(m_z)$, $\alpha_s(m_z)$, top EW couplings …
    - 10 fold more precise Higgs couplings measurements
      - ➔ Break model dependence with Γ_H accurate measurement
- **DISCOVER that the Standard Model does not fit**
  - Then extra weakly-coupled and Higgs-coupled particles exist
  - Understand the underlying physics through effects via loops
- **DISCOVER a violation of flavour conservation / universality**
  - e.g., with $B^0 \rightarrow K^{*0}\tau^+\tau^-$ or $B_S \rightarrow \tau^+\tau^-$ in 10^{12} bb events
- **DISCOVER dark matter as invisible decays of Higgs or Z**
- **DISCOVER very weakly coupled particles in the 5-100 GeV mass range**
  - Such as right-handed neutrinos, dark photons, …
    - May help understand dark matter, universe baryon asymmetry, neutrino masses

NB Not only a «Higgs Factory», «Z factory» and «top» are important for 'discovery potential'

EW observables at FCC-ee

Observable	Measurement	Current precision	FCC-ee 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 / EW
R_l	Peak	20.767 ± 0.025	0.001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	g → bb
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	<0.000005 *	Beam energy
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.004	< 0.004	QED / EW
$\alpha_s(m_Z)$	R_l	0.1196 ± 0.0030	0.00001	<0.0002	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.6	< 0.6	EW Corr.
Γ_W (MeV)	Threshold scan	2085 ± 42	1.5	<1.5	EW Corr.
N_ν	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, ll	2.92 ± 0.05	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	173340 ± 760 ± 500	20	<40	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	40	<40	QCD corr.
λ_{top}	Threshold scan	μ = 1.2 ± 0.3	0.08	< 0.05	QCD corr.
ttZ couplings	√s = 365 GeV	~30%	~2%	<2%	QCD corr

* work to do: check if we can improve

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$\alpha_s(m_Z)$	R_l	0.11[illegible]	0.00001	<0.0002	New Physics
m_W (MeV)	Threshold scan	[illegible]	0.6	< 0.6	EW Corr.
Γ_W (MeV)	Threshold [illegible]	2085 ± 42	1.5	<1.5	EW Corr.
N_ν	e^+e^-[illegible]	2.92 ± 0.05	0.001	< 0.001	?
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λ_{top}	Threshold scan	μ = 1.2 ± 0.3	0.08	< 0.05	QCD corr.
ttZ couplings	√s = 365 GeV	~30%	~2%	<2%	QCD corr

Great improvement across all the measurements !

* work to do: check if we can improve

Higgs Factory

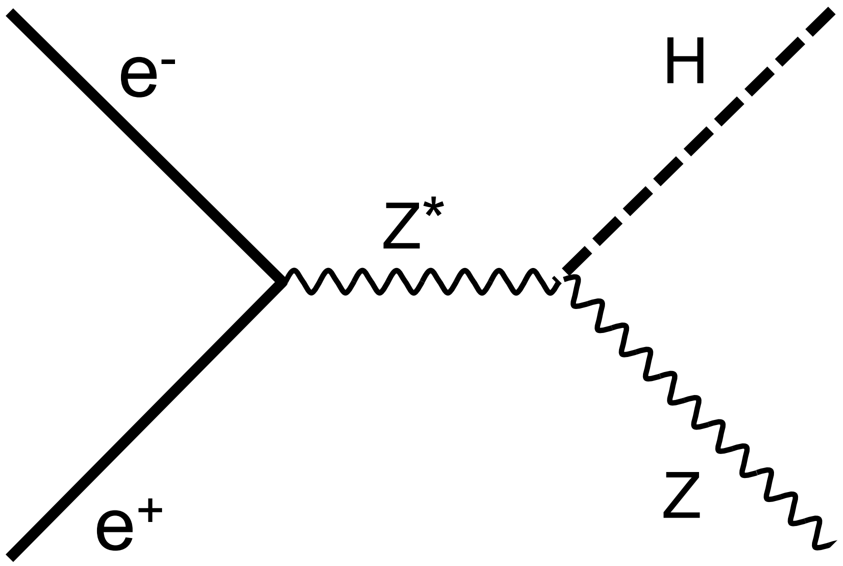
Higgs provides a very good reason why we need a lepton (e^+e^- or $\mu\mu$) collider

Higgs production at an e^+e^- collider

"Higgstrahlung" process close to threshold

Production cross section has a maximum at near threshold ~200 fb

$10^{34}/cm^2/s$ ➔ 20'000 HZ events per year

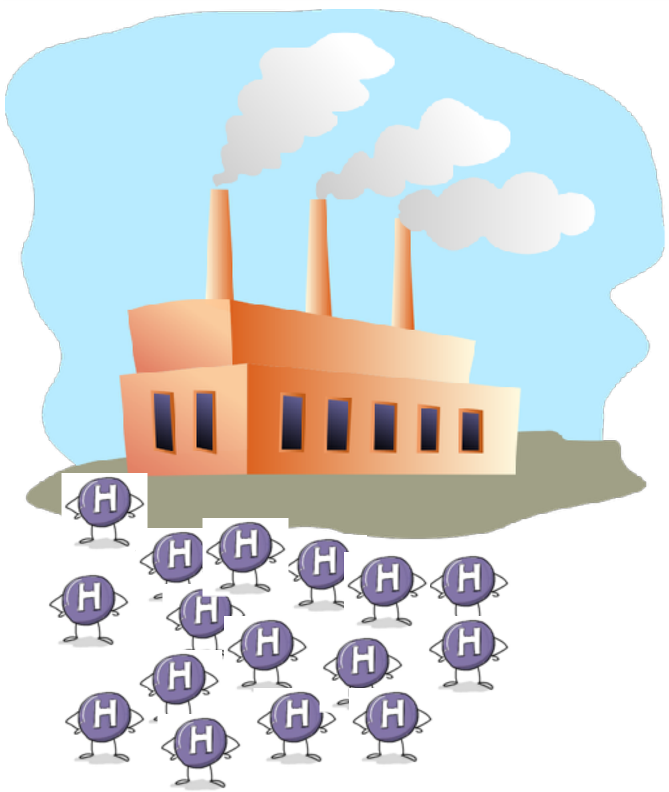


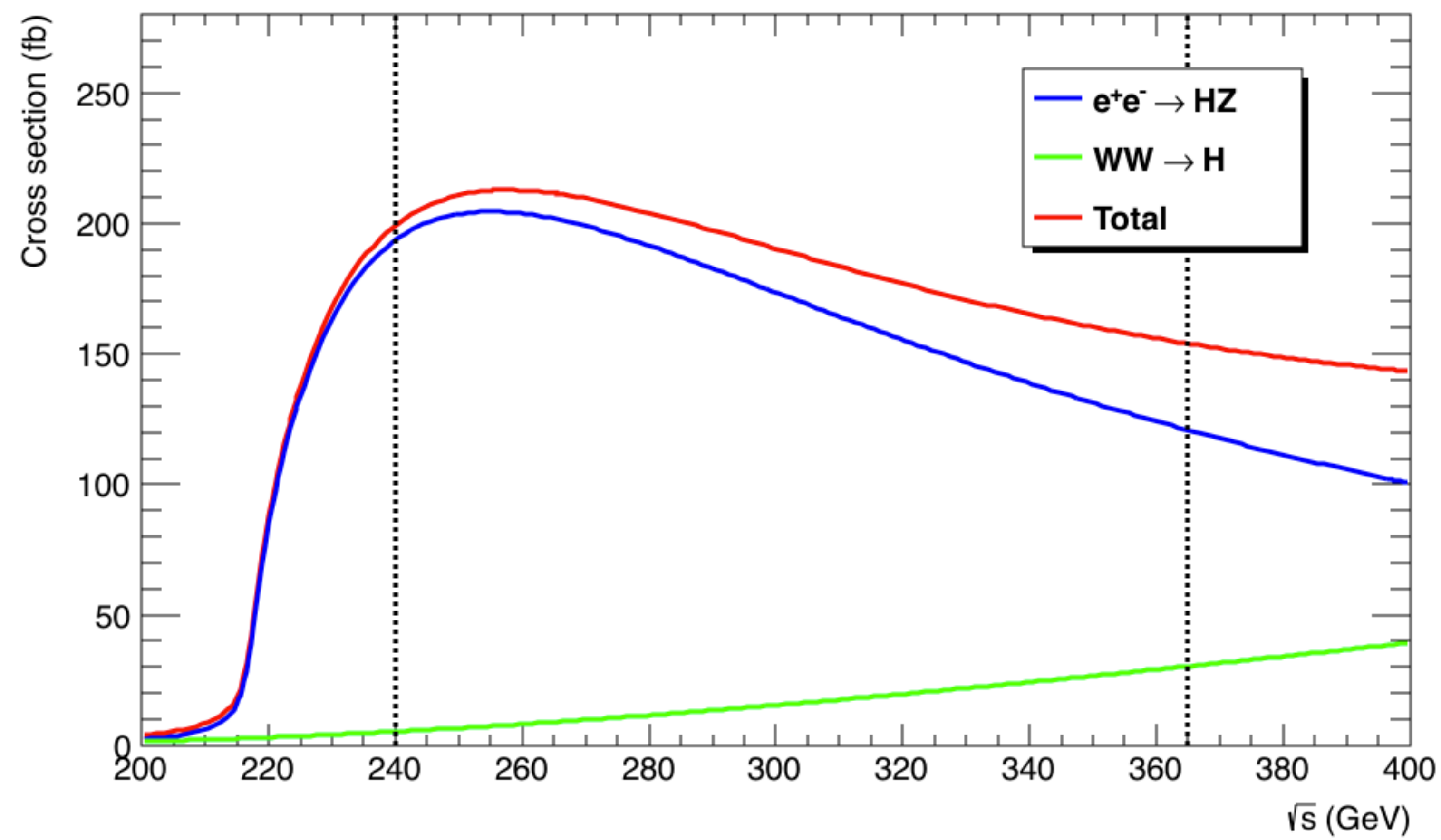
Z – tagging
by missing mass

For a Higgs of 125 GeV, a centre of mass energy of 240-250 GeV is optimal
➔ kinematical constraint near threshold for high precision in mass, width, selection purity

Higgs production at FCC-ee

FCC-ee
5 ab-1@240 GeV
~1.5 ab^{-1}@365 GeV





Higgs Factory!

	FCC-ee 240 GeV	FCC-ee 365 GeV
Total Integrated Luminosity (ab^{-1})	5	1.5
# Higgs bosons from $e^+e^- \to HZ$	1,000,000	180,000
# Higgs bosons from fusion process	25,000	45,000

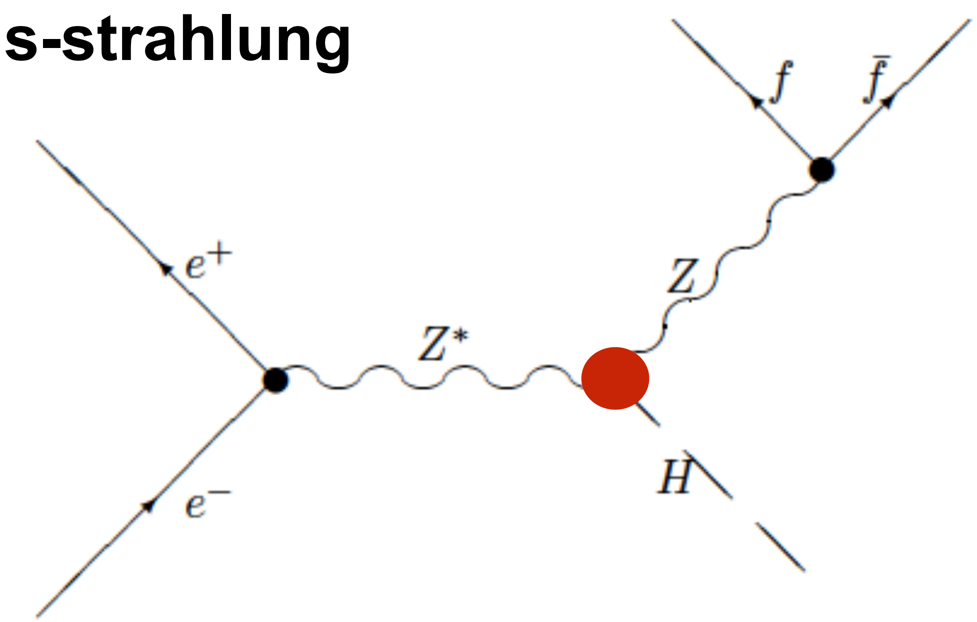
Higgs couplings to Z

➡ **Recoil method provides a unique opportunity for a decay-mode independent measurement of the HZ coupling**

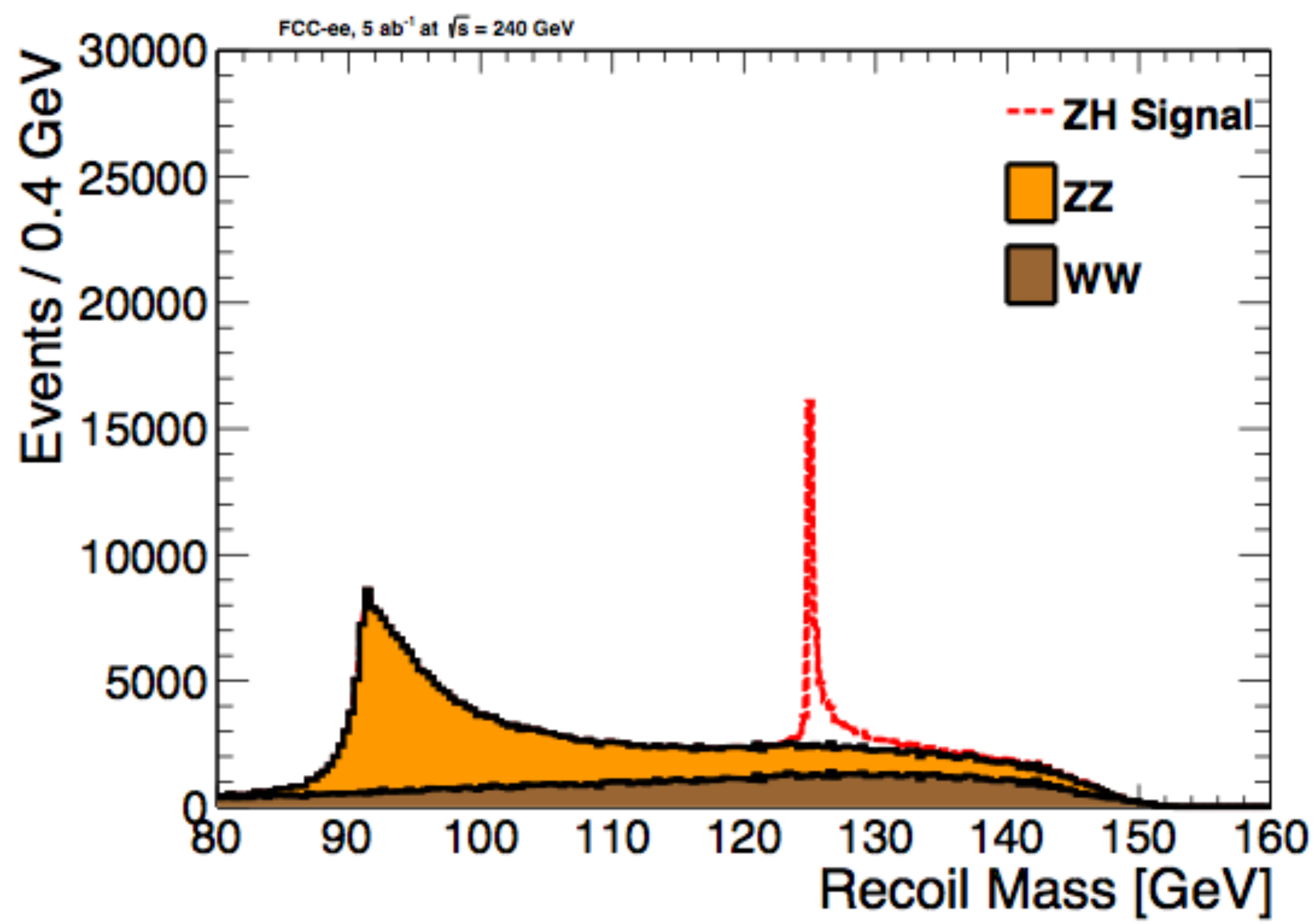
- Higgs events are tagged with the Z boson decays, independently of Higgs decay mode, $m_{recoil} = m_H$
- Expected precision **0.7%** on the ZH cross section
- Using only leptonic Z decays and only a measurement at 240 GeV so far

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

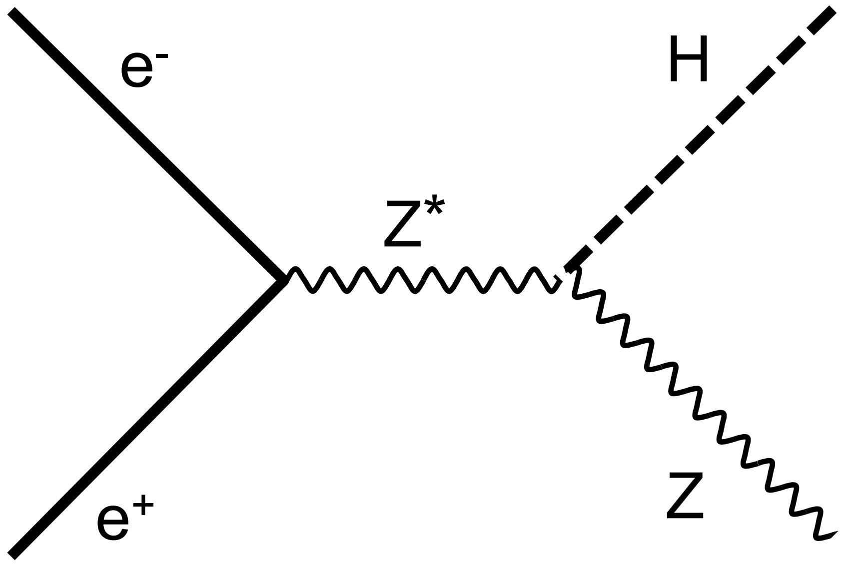
Higgs-strahlung



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



Z-tagging by missing mass



total rate $\propto g_{HZZ}^2$

ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$

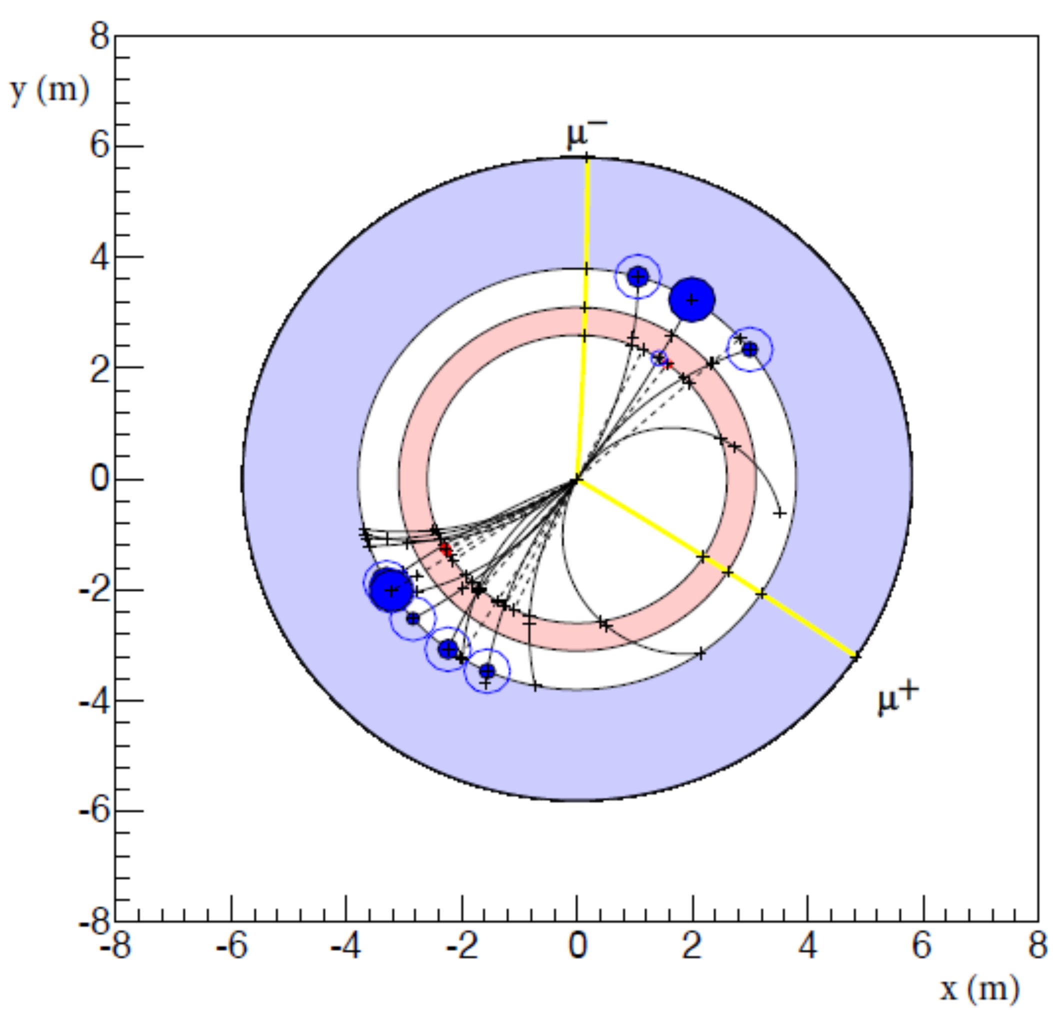
→ **measure total width** Γ_H

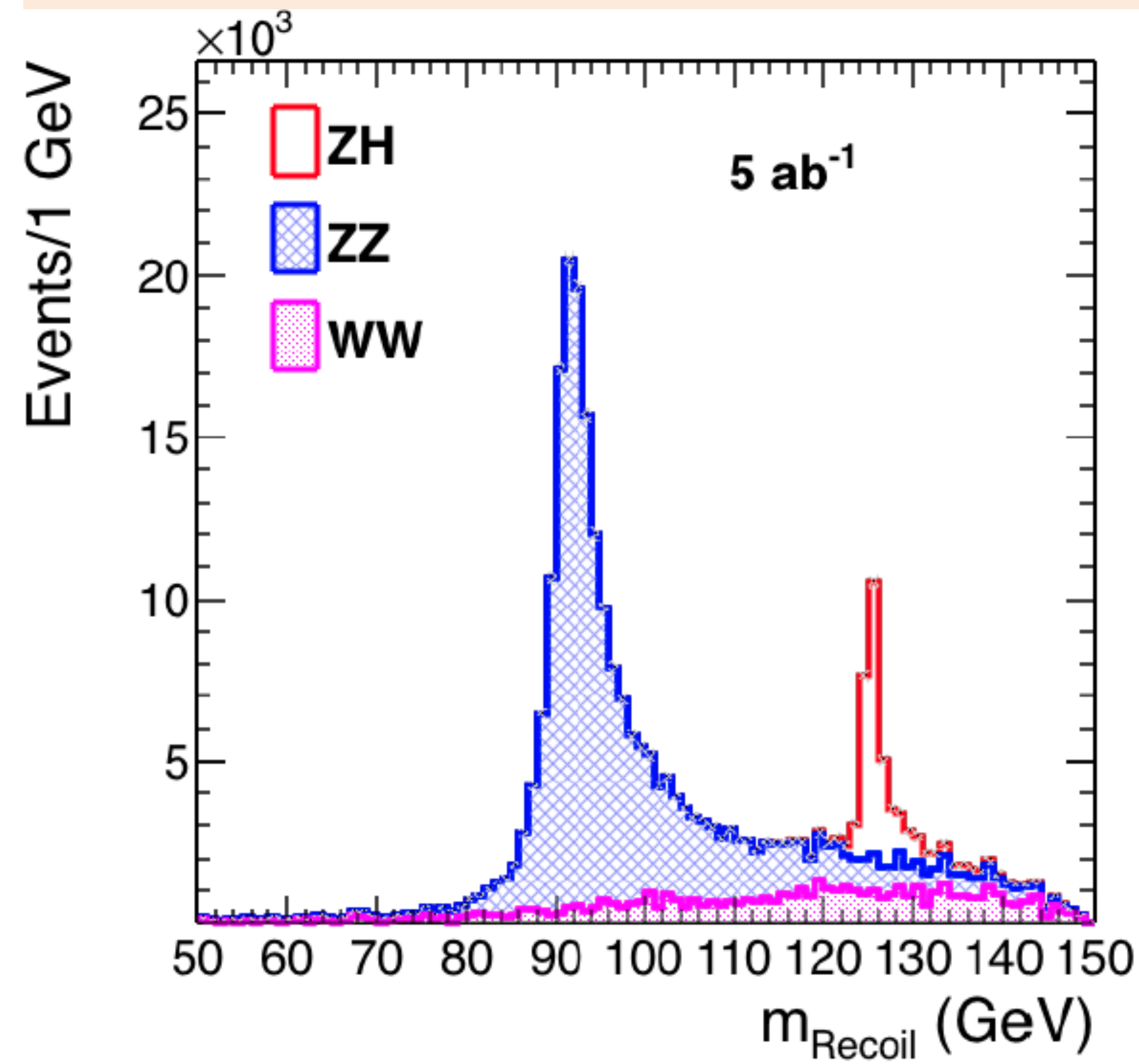
g_{HZZ} **to ±0.2%** and many other partial widths

empty recoil = invisible width

'funny recoil' = exotic Higgs decay

easy control below threshold





Higgs boson width

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

- **1) tagging Higgs final states**

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

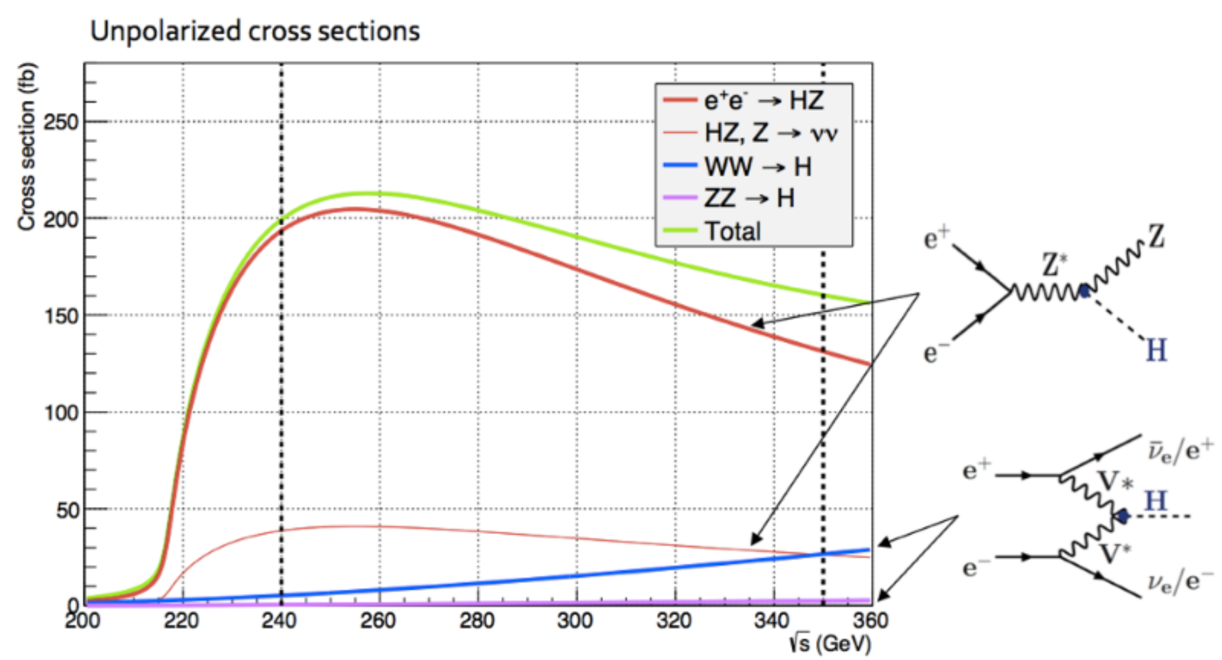
- **2) measurements of vector boson fusion production at 365 GeV**

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

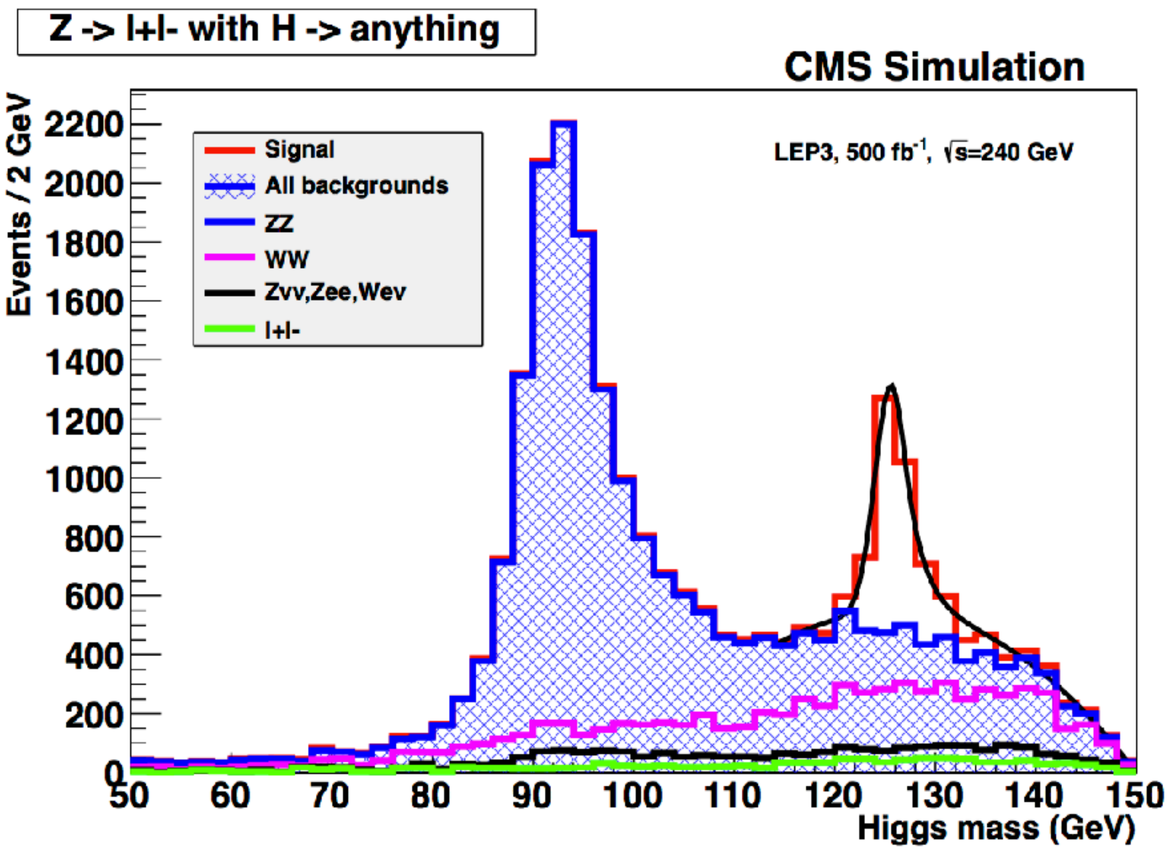
$$\propto \frac{g_{HZ}^2 \cdot \cancel{g_{HW}^2}}{\Gamma} \cdot \frac{g_{HZ}^2 \cdot \cancel{g_{Hb}^2}}{\cancel{\Gamma}} \cdot \frac{\cancel{\Gamma}}{\cancel{g_{HW}^2} \cdot \cancel{g_{Hb}^2}} = \frac{g_{HZ}^4}{\Gamma}$$

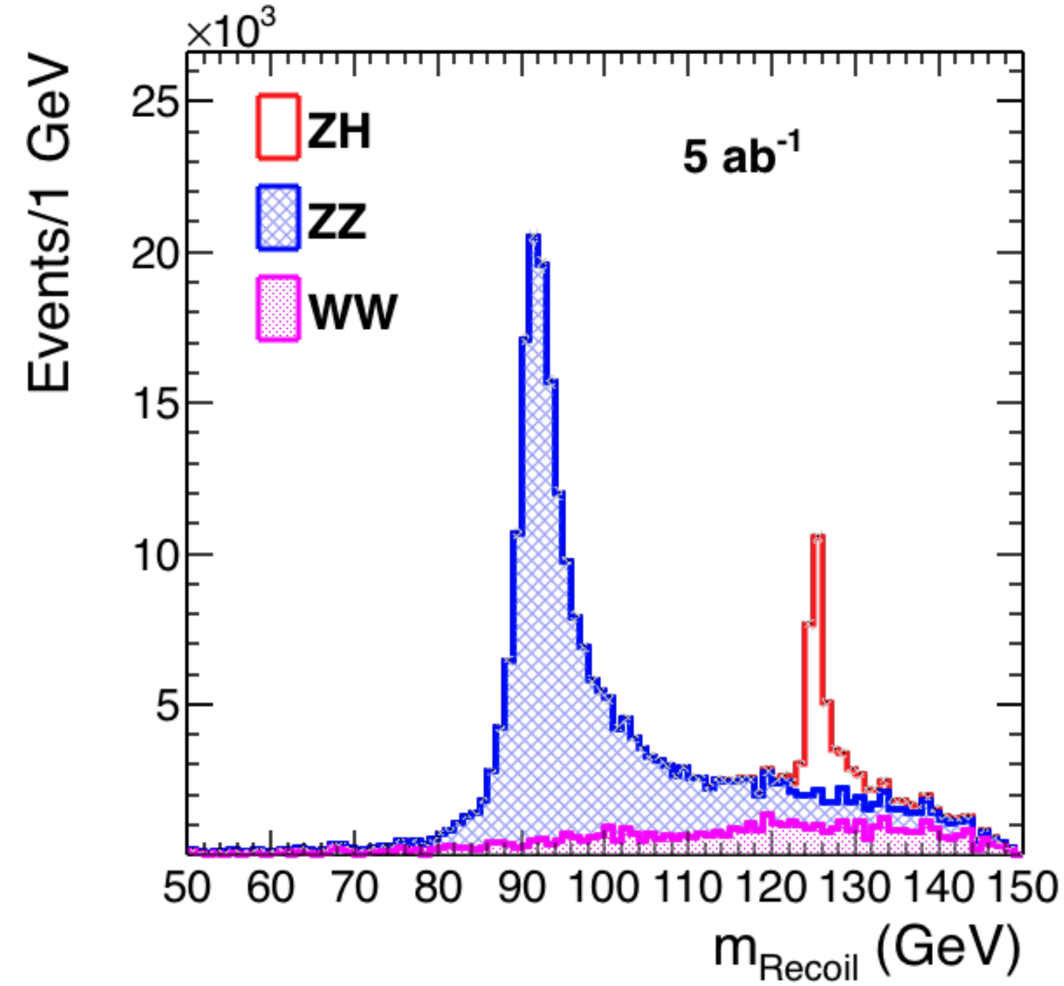
- **3) combination of all measurements**

Precision obtainable on $\delta\Gamma_H/\Gamma_H \sim 1.6\%$

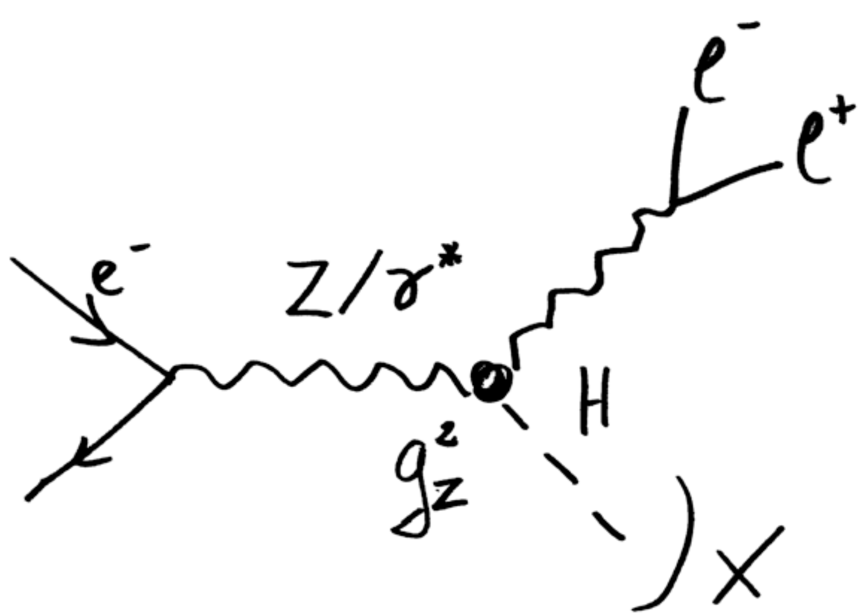


Higgs boson couplings, ZH→ℓℓX





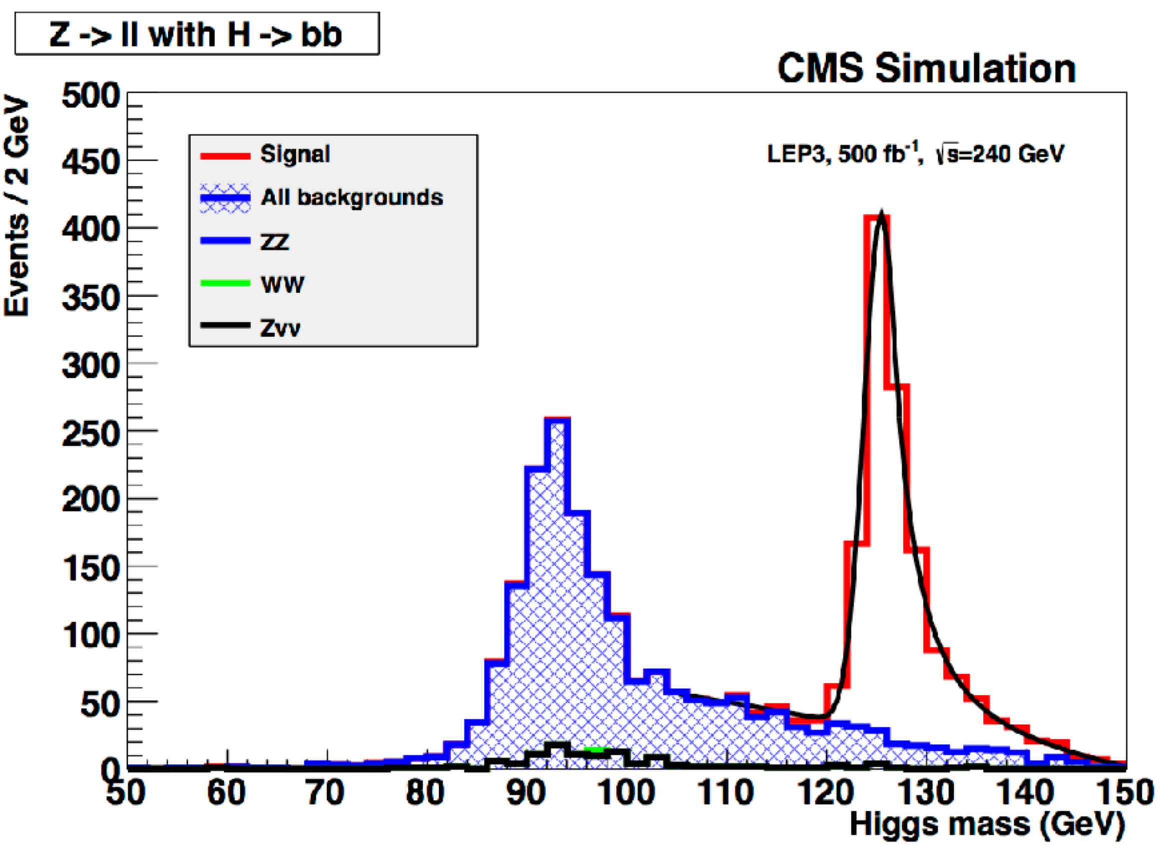
C. Bernet
FCC week 2018

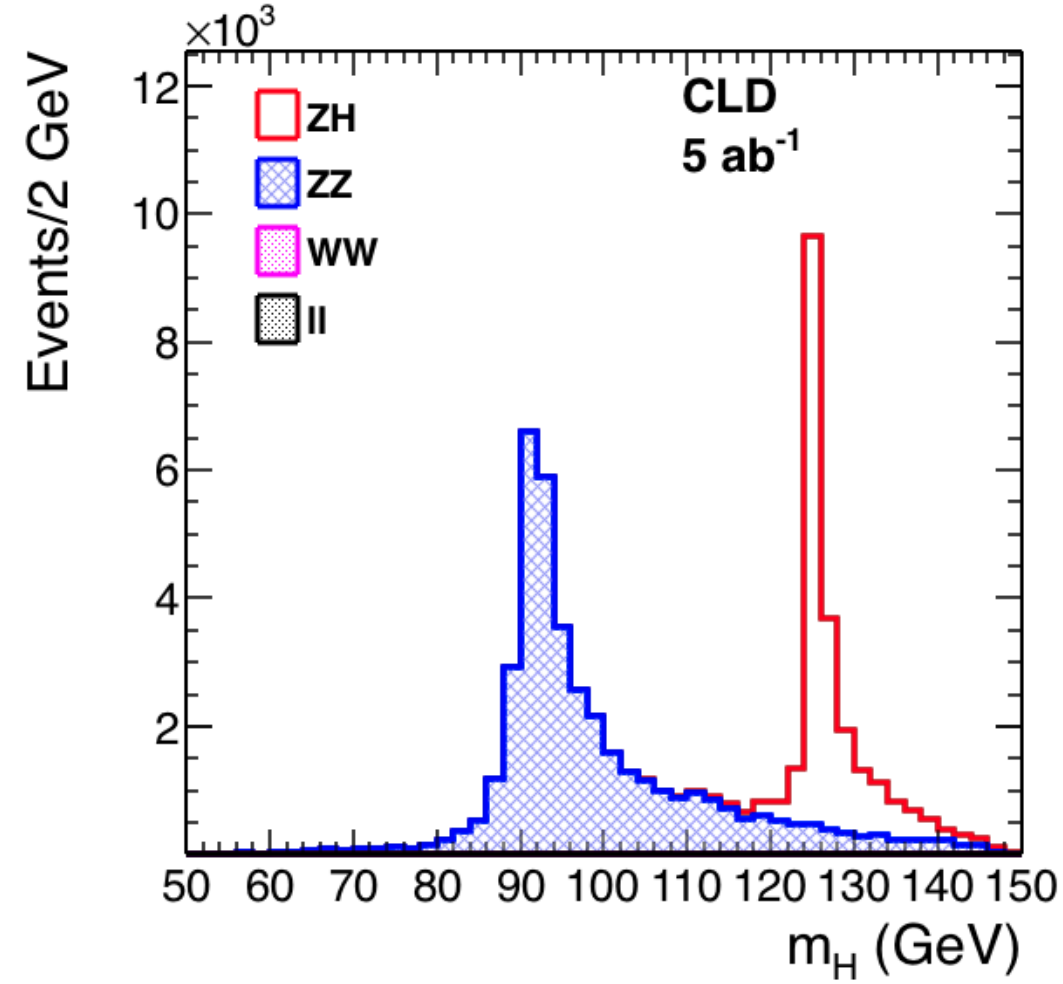


Ongoing work, should lead to better results in TDR

CLD: 15% improvement due to higher lepton efficiency

Higgs boson couplings, ZH→ℓℓbb





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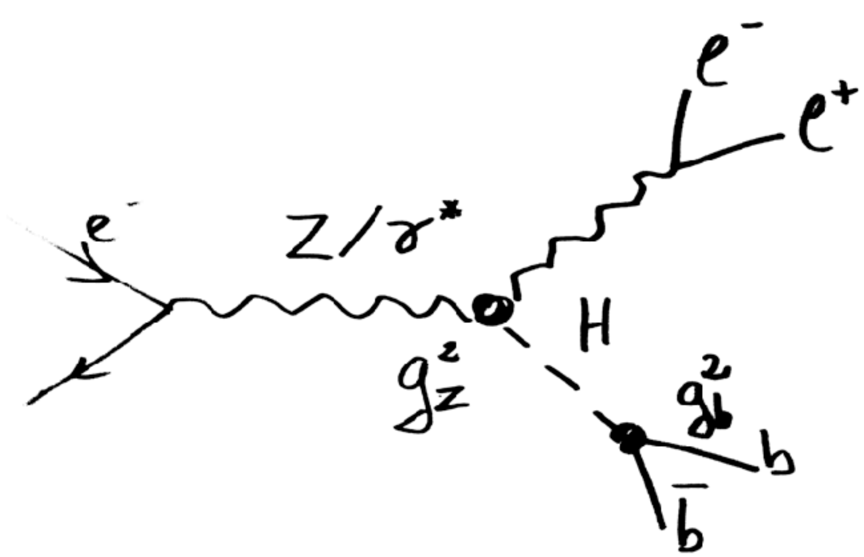
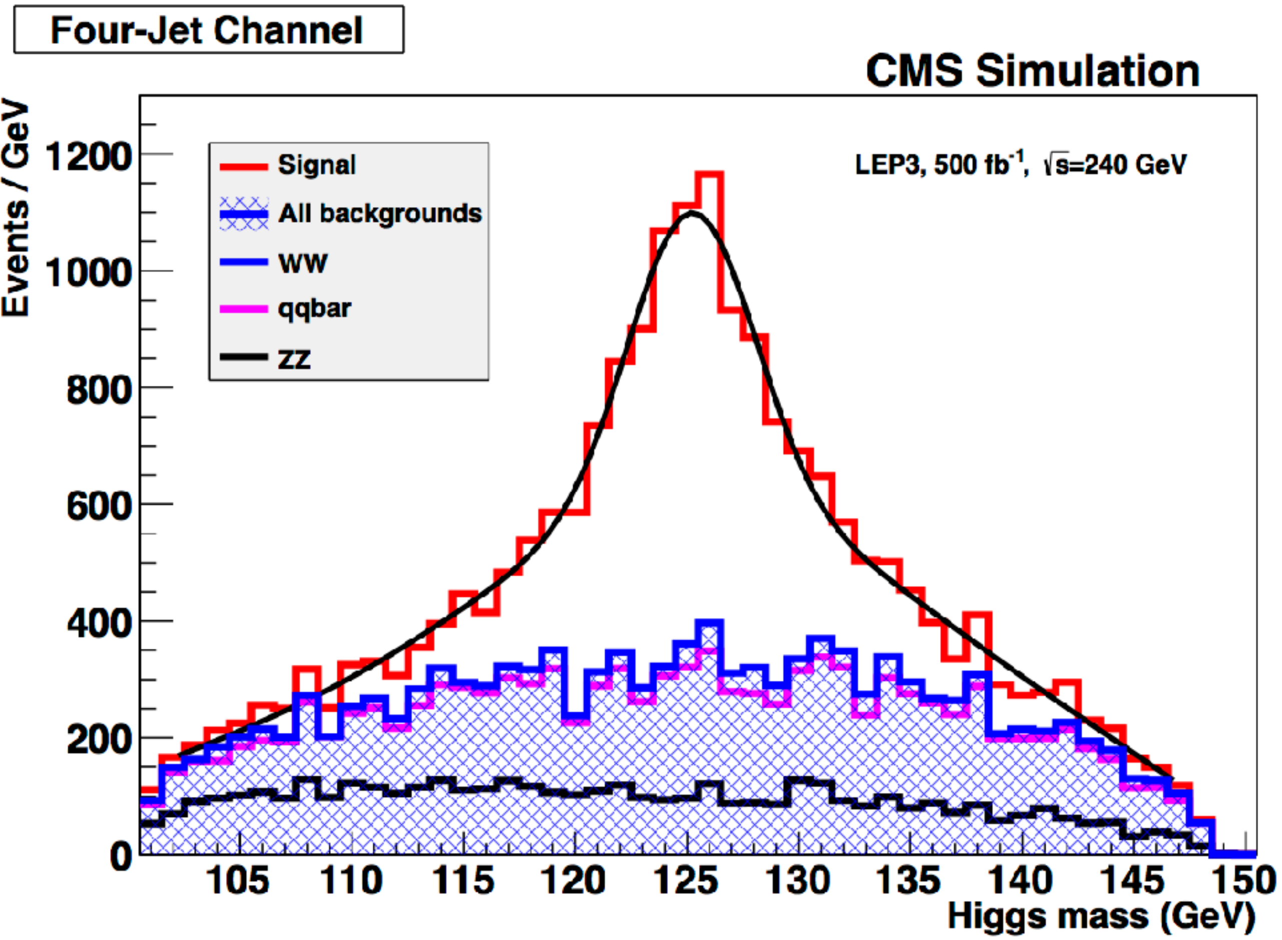
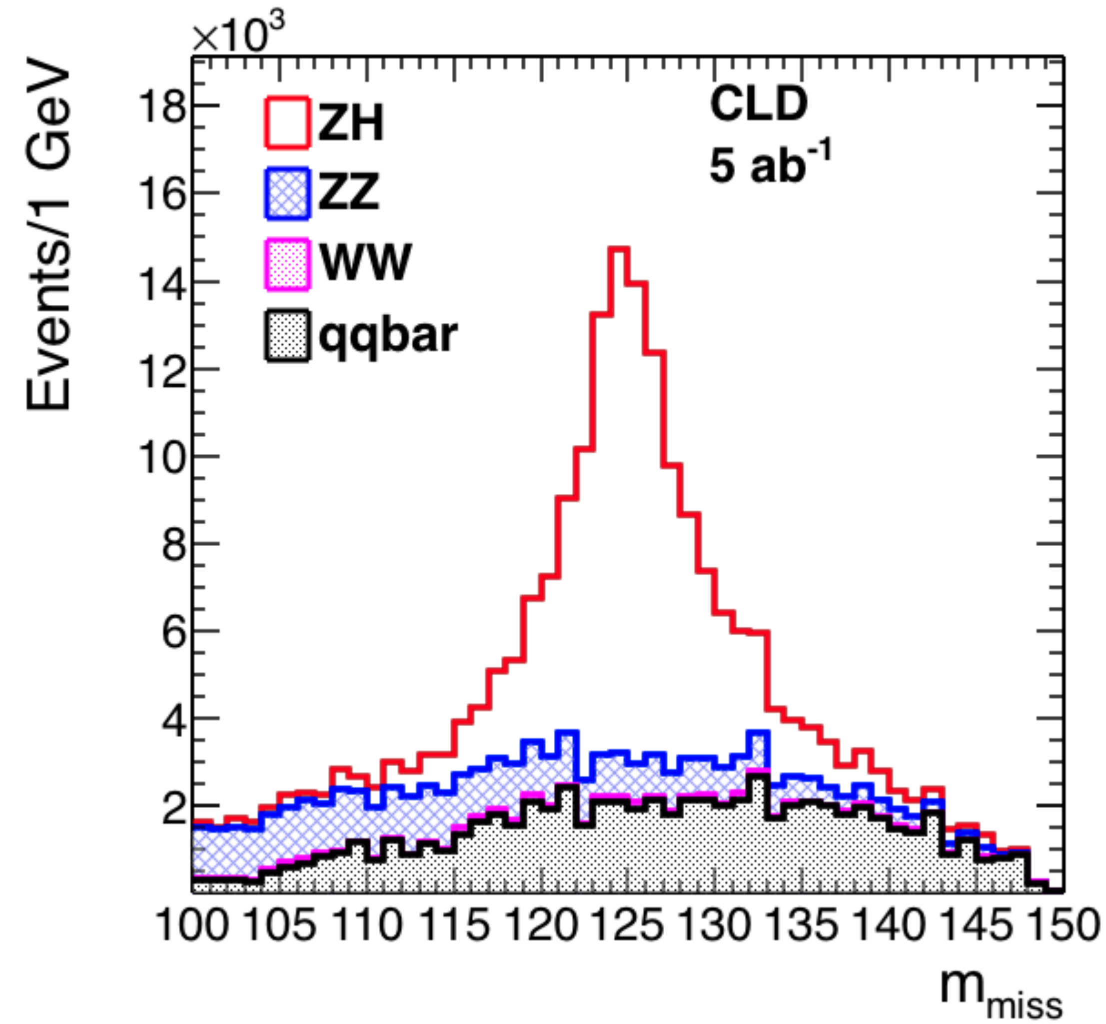


Ongoing work, should lead to better results in TDR

CLD: 20% improvement due to higher lepton efficiency and better b tagging

Higgs boson couplings, ZH→qqbb





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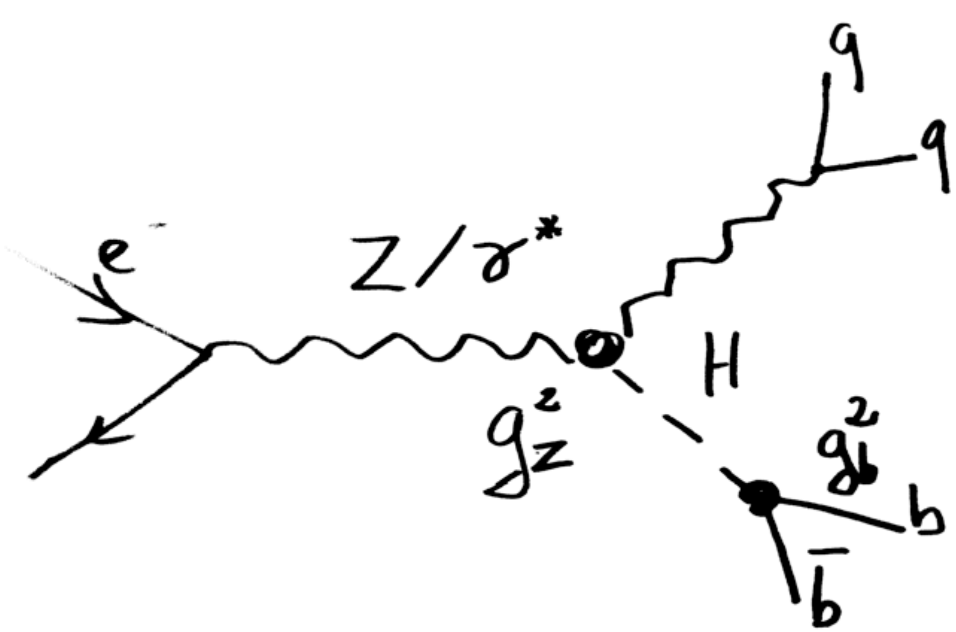


Ongoing work, should lead to better results in TDR

CLD: 35% improvement due to better b tagging and particle flow

Higgs boson couplings

➡ **Precision Higgs coupling measurements**

- Absolute coupling measurements enabled by HZ cross section and total width measurement
- Data at 365 GeV constrain total width
  - only used $H \to bb$ in fusion production so far
- Tagging individual Higgs final states to extract various Higgs couplings
- Couplings extracted from model-independent fit
- Statistical uncertainties are shown for 5 ab^{-1}@240 GeV and 1.5 ab^{-1}@365 GeV (from arXiv:1308.6176)
  - all measurements are under review / are being redone
  - possible improvements of 10-35% on cross section measurements

in %	FCC-ee 240 GeV	+FCC-ee 365 GeV	+HL-LHC
δg_{HZZ}	0.25	0.22	0.21
δg_{HWW}	1.3	0.47	0.44
δg_{Hbb}	1.4	0.68	0.58
δg_{Hcc}	1.8	1.23	1.20
δg_{Hgg}	1.7	1.03	0.83
$\delta g_{H\tau\tau}$	1.4	0.8	0.71
$\delta g_{H\mu\mu}$	9.6	8.6	3.4
$\delta g_{H\gamma\gamma}$	4.7	3.8	1.3
δg_{Htt}			3.3
$\delta \Gamma_H$	2.8	1.56	1.3

Several couplings improve further by doing a combined fit with HL-LHC

Comparison with other e^+e^- colliders

Collider	μ Coll$_{125}$	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240}$	FCC-ee$_{365}$
Years	6	15	7	6	7	3	4
Lumi (ab^{-1})	0.005	2	0.5	3	5	5	1.5
δm_H (MeV)	0.1	14	110	10	5	7	6
$\delta\Gamma_H / \Gamma_H$ (%)	6.1	3.8	6.3	3.7	2.6	2.8	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	2.8	1.8	1.3	1.4	0.68
$\delta g_{HW} / g_{HW}$ (%)	3.9	1.7	1.3	1.7	1.2	1.3	0.47
$\delta g_{H\tau} / g_{H\tau}$ (%)	6.2	1.9	4.2	1.9	1.4	1.4	0.80
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	6.4	n.a.	6.1	4.7	4.7	3.8
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	13	n.a.	12	6.2	9.6	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	n.a.	0.35	0.80	0.32	0.25	0.25	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	2.3	6.8	2.3	1.8	1.8	1.2
$\delta g_{Hg} / g_{Hg}$ (%)	n.a.	2.2	3.8	2.1	1.4	1.7	1.0
BR_{invis} (%)$_{95\%CL}$	SM	< 0.3	< 0.6	< 0.5	< 0.15	< 0.3	< 0.25
BR_{EXO} (%)$_{95\%CL}$	SM	< 1.8	< 3.0	< 1.6	< 1.2	< 1.2	< 1.1

Green = best
Red = worst

Comparison with other e^+e^- colliders

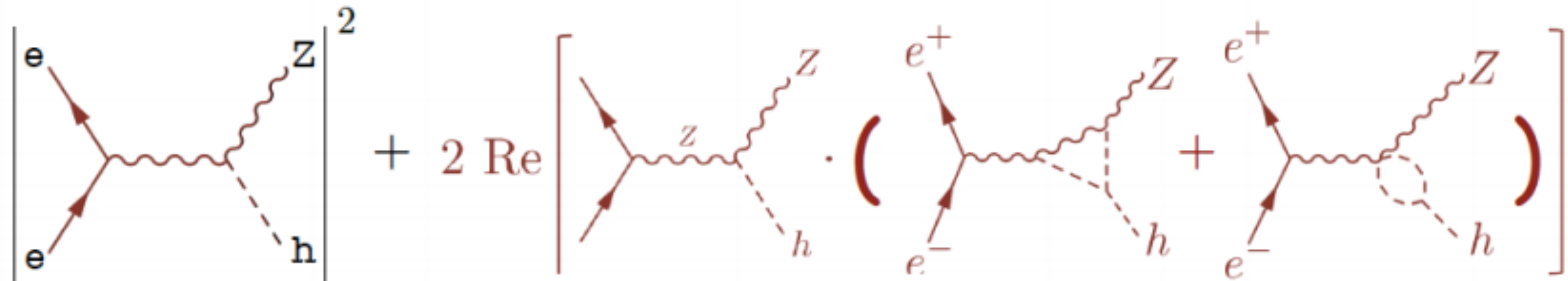
Collider	μ $Coll_{125}$	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240}$	$FCC\text{-}ee_{365}$
Years	6	15	7	6	7	3	[illegible]
Lumi (ab^{-1})	0.005	2	0.5	3	5	5	[illegible]
δm_H (MeV)	0.1	14	110	10	5	[illegible]	6
$\delta\Gamma_H / \Gamma_H$ (%)	6.1	3.8	6.3	3.7	[illegible]	[illegible].8	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	2.8	[illegible]	[illegible].3	1.4	0.68
$\delta g_{HW} / g_{HW}$ (%)	3.9	1.7	1.[illegible]	[illegible]	1.2	1.3	0.47
$\delta g_{H\tau} / g_{H\tau}$ (%)	6.2	1.9	[illegible]	1.9	1.4	1.4	0.80
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	[illegible]	[illegible]	6.1	4.7	4.7	3.8
$\delta g_{H\mu} / g_{H\mu}$ (%)	[illegible]	[illegible]	n.a.	12	6.2	9.6	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	[illegible]	0.35	0.80	0.32	0.25	0.25	0.22
δg_{Hc}[illegible]	n.a.	2.3	6.8	2.3	1.8	1.8	1.2
[illegible]%)	n.a.	2.2	3.8	2.1	1.4	1.7	1.0
[illegible]$_{invis}$ (%)$_{95\%CL}$	SM	< 0.3	< 0.6	< 0.5	< 0.15	< 0.3	< 0.25
BR_{EXO} (%)$_{95\%CL}$	SM	< 1.8	< 3.0	< 1.6	< 1.2	< 1.2	< 1.1

FCC-ee and CepC have a clear edge over linear colliders

Green = best
Red = worst

Higgs self-coupling

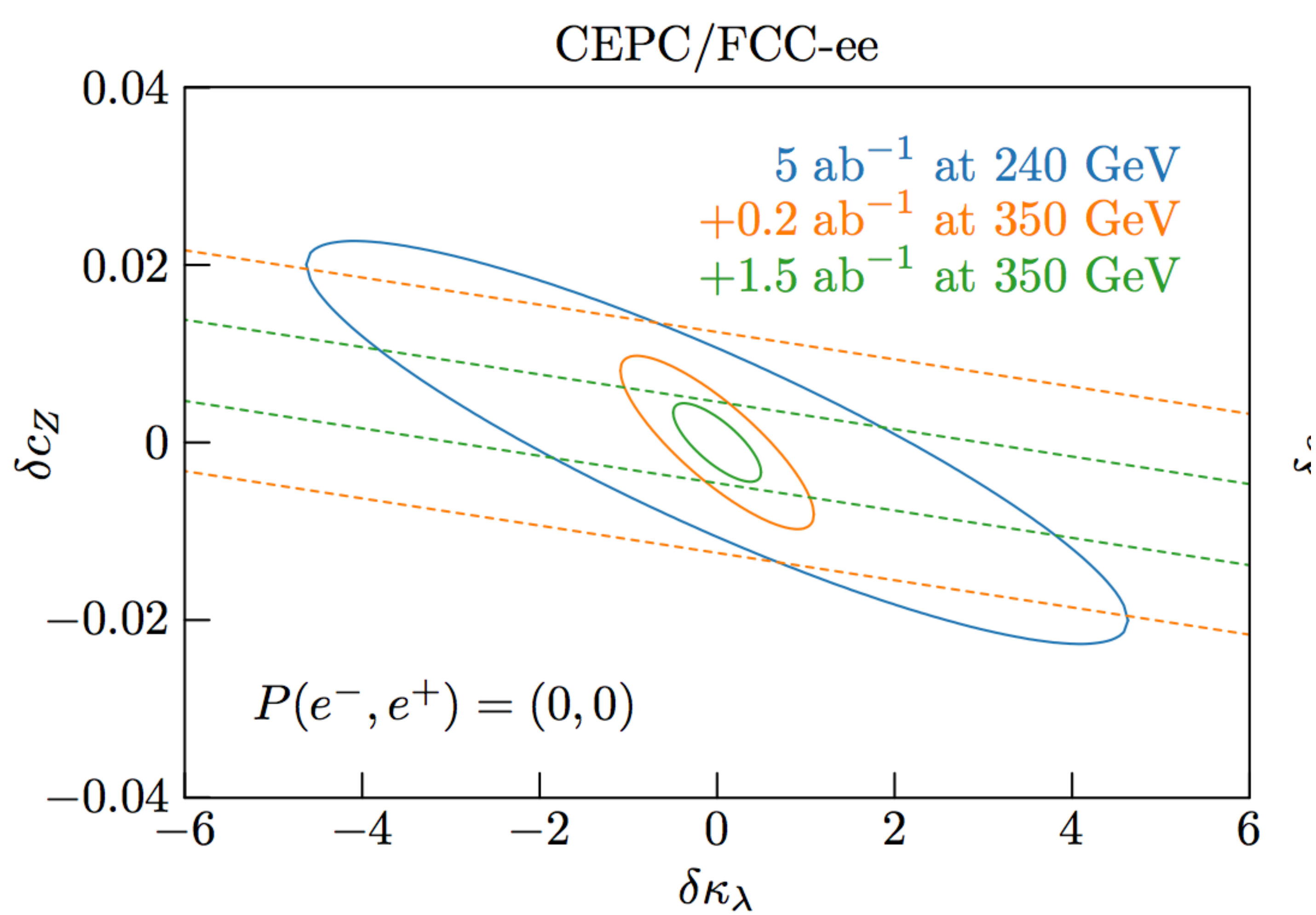
$\sigma_{Zh} =$



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

➡ Very large HZ datasets allow g_{ZH} measurements of extreme precision

➡ Indirect and model-dependent probe of Higgs self-coupling



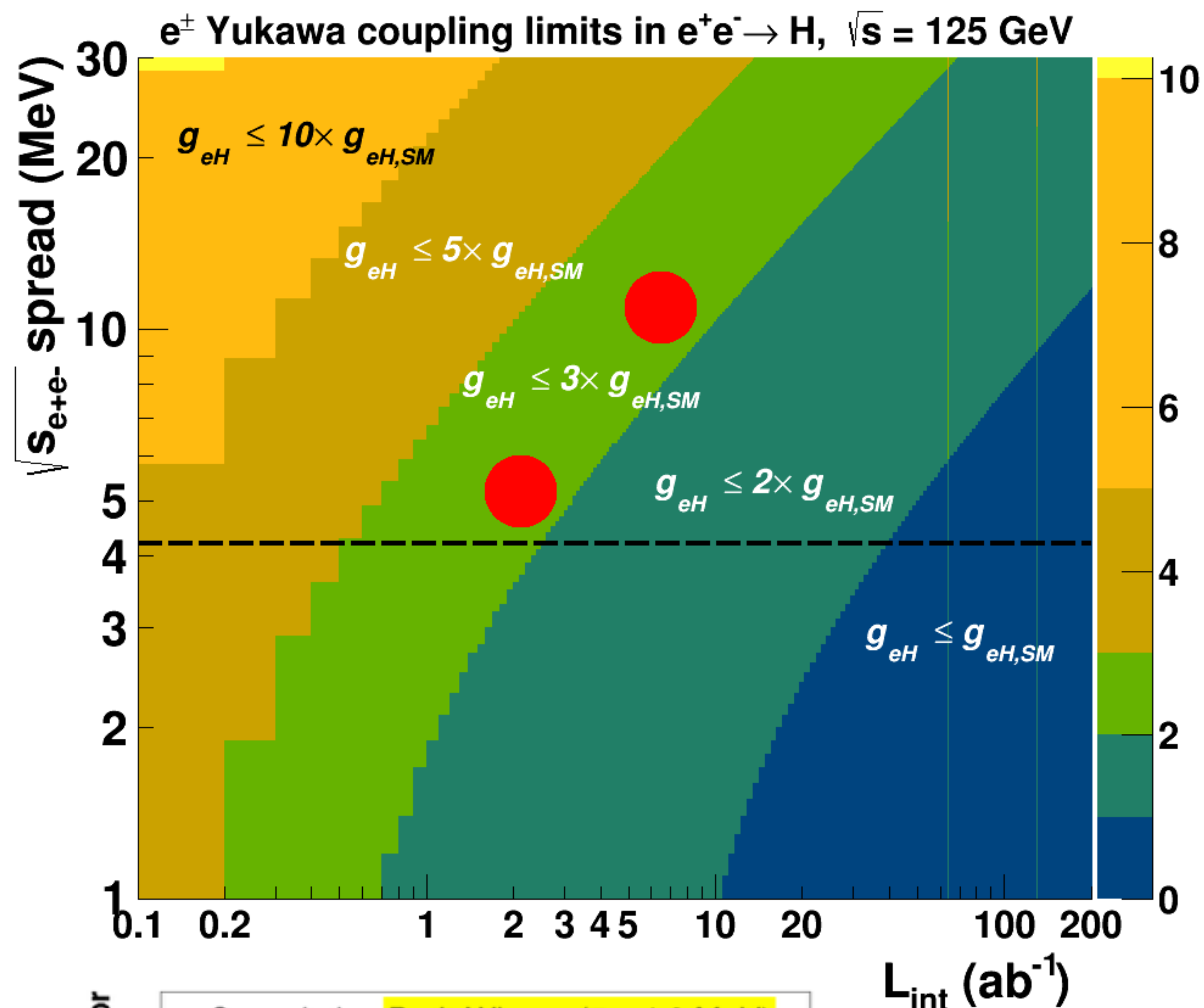
A precision on $\delta\kappa_\lambda$ of ±40% can be achieved, and of ±35% in combination with HL-LHC.

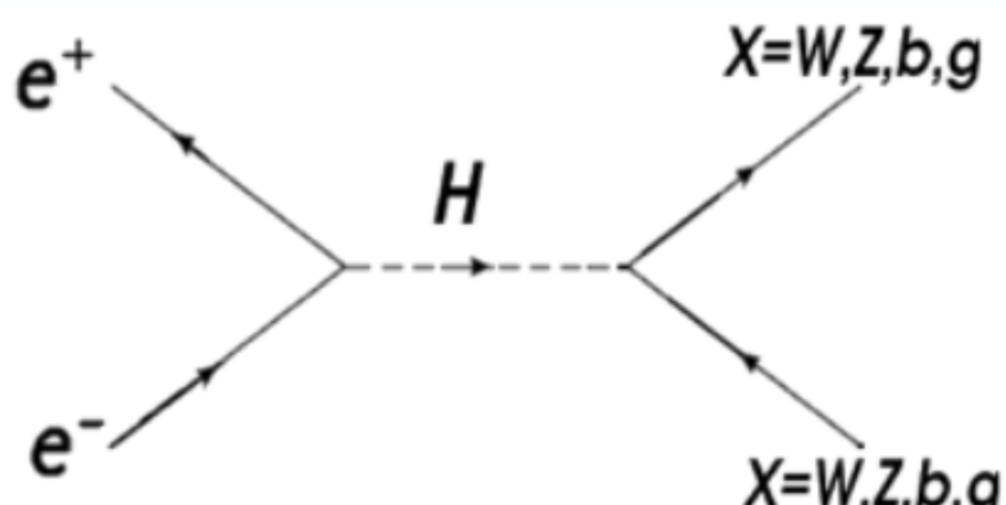
If c_Z if fixed to its SM value, then the precision on $\delta\kappa_\lambda$ improves to ±20%

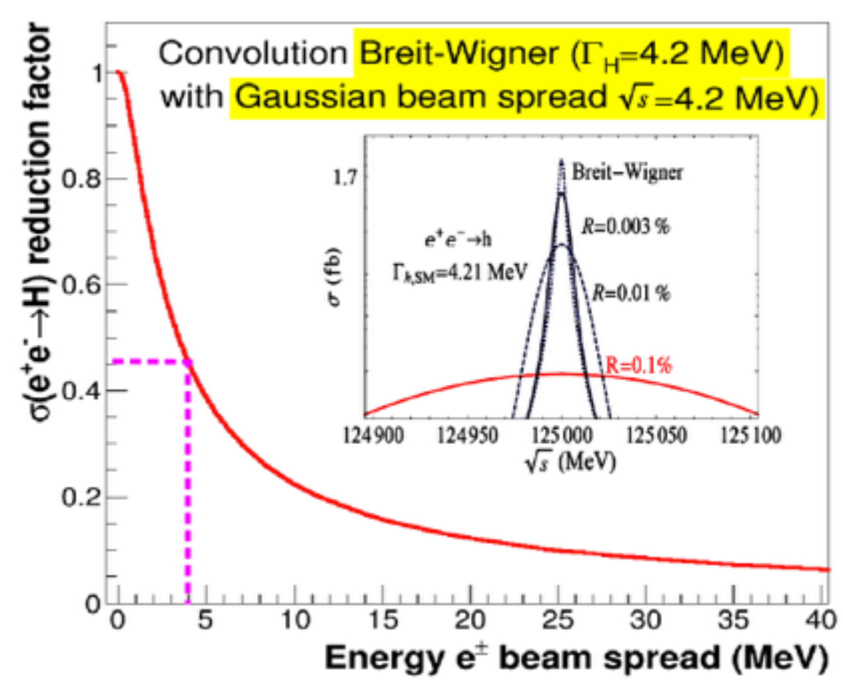
electron Yukawa coupling

➡ s-channel Higgs production

- unique opportunity for measurement close to SM sensitivity
- highly challenging; σ(ee→H) = 1.6 fb;
- various Higgs decay channels studied
- studied monochromatization scenarios
  - baseline: 6 MeV energy spread, L = 2 ab^{-1}
  - optimized: 10 MeV energy spread, L = 7 ab^{-1}
  - limit ~3.5 times SM in both cases

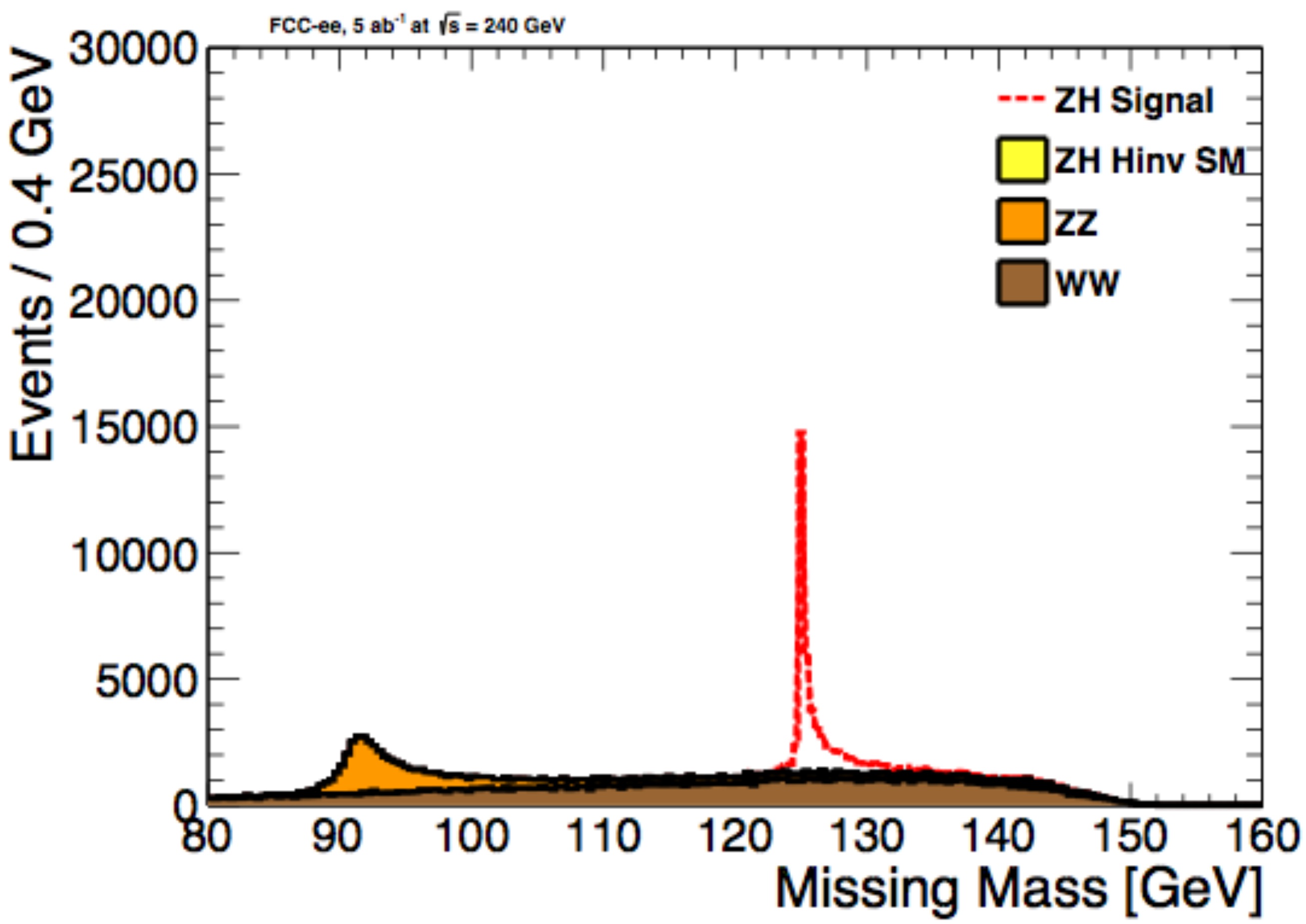






Higgs invisible decays

Higgs boson to invisible decays are predicted for instance in the Higgs-portal model of Dark Matter.

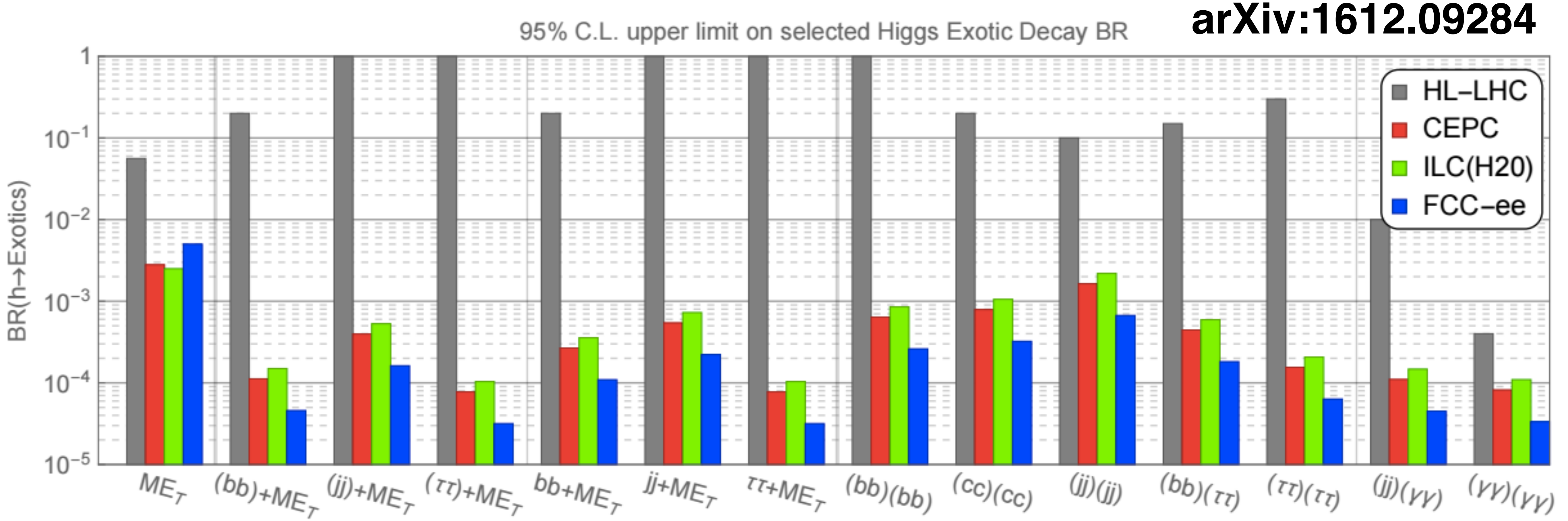


- Follows FCC-ee ZH cross section measurement
- for visualization BR(H->inv) = 100%
- 95%CL upper limit using 5ab^{-1} is 0.47%
- Study using leptonic Z decays in Eur. Phys. J. C (2017) 77: 116
- Hadronic Z decays under study. Show similar performance

BSM Higgs

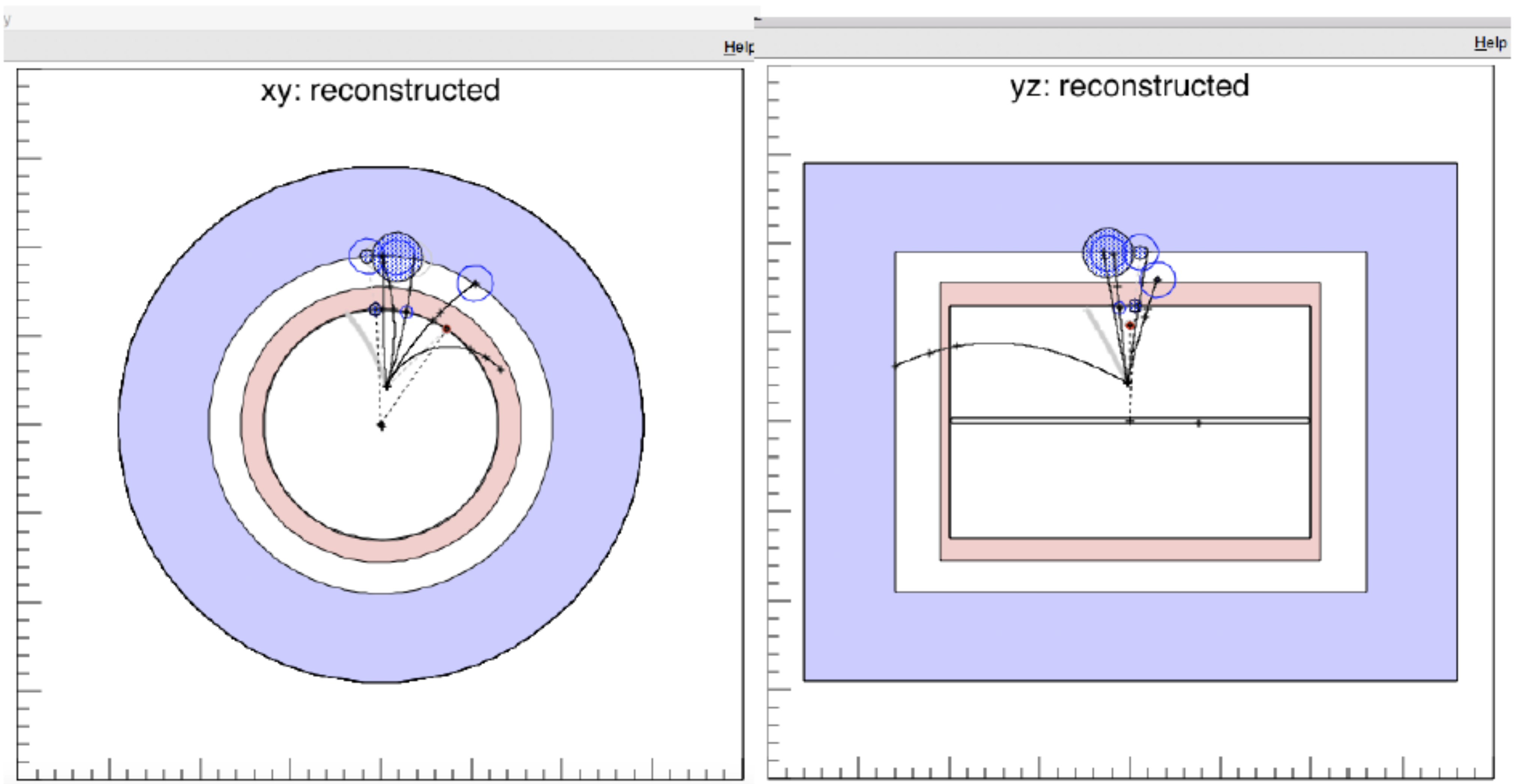
➡ Excellent opportunities for BSM Higgs searches

arXiv:1612.09284



Heavy neutrino at FCC-ee

Simulation of heavy neutrino decay in a FCC-ee detector



100 TeV

FCC-hh parameters

Hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (1.1)		2.5 (1.25)	(2.5) 3.75
IP $\beta^{*}_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	30	28	(5) 1
peak #events / bunch Xing	170	1000 (500)	800 (400)	(135) 27
stored energy / beam [GJ]	8.4		1.4	(0.7) 0.36
SR power / beam [kW]	2400		100	(7.3) 3.6
transv. emit. damping time [h]	1.1		3.6	25.8
initial proton burn off time [h]	17.0	3.4	3.0	(15) 40

FCC-hh discovery potential highlights

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FCC-hh physics is dominated by three features:

- **Highest center of mass energy → a big step in high mass reach!**
  - **ex: strongly coupled new particles up to >30 TeV**
  - **Excited quarks, Z', W', up to ~tens of TeV**
  - **Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV**
  - **Sensitivity to high energy phenomena in e.g. WW scattering**

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- **HUGE production rates for single and multiple production of SM bosons (H, W, Z) and quarks**
  - Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau$/ZZ, ttH/ttZ @<% level
  - Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling
  - detection of rare decays $H \to V\gamma$ (V= ρ, φ, J/ψ, Υ, Z…)
  - search for invisibles (DM searches, RH neutrinos in W decays)
  - renewed interest for long lived (very weakly coupled) particles.
  - rich top and HF physics program

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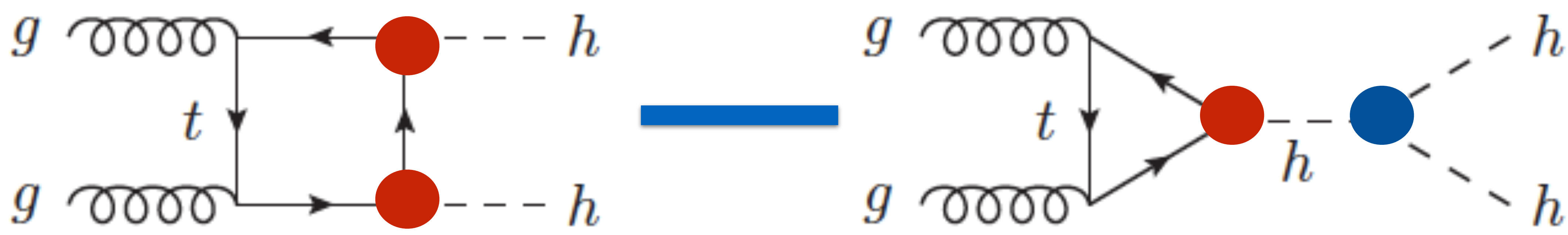
  - **renewed interest for long lived (very weakly coupled) particles.**
  - **rich top and HF physics program**

- **Cleaner signals for high P_t physics**
  - **allows clean signals for channels presently difficult at LHC (e.g. $H \rightarrow bb$)**

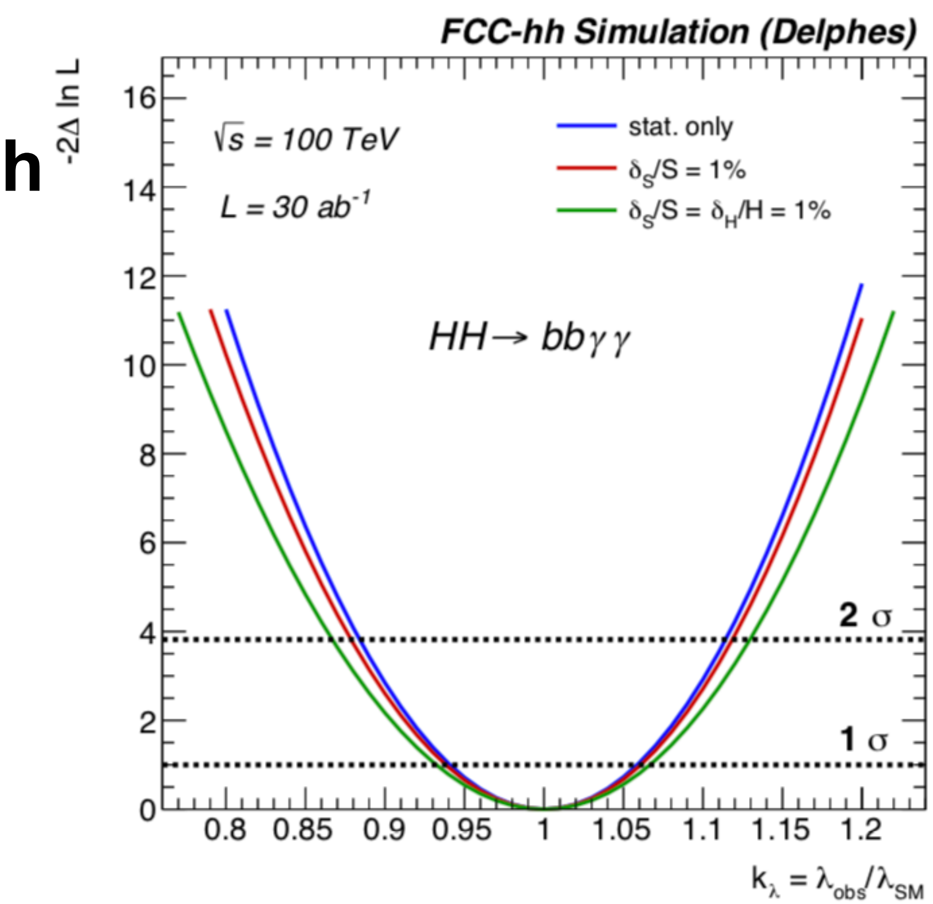
Higgs self-coupling at FCC-hh



$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

EFT Lagrangian

- ➡ **Enormous di-Higgs samples produced at FCC-hh**
  - σ(100 TeV) / σ(14 TeV) ≅ 40
  - L (FCC-hh) / L (HL-LHC) ≅ 10
  - Naively, factor 20 smaller statistical uncertainty
- ➡ **Studied a number of final states**
  - bbγγ most sensitive channel



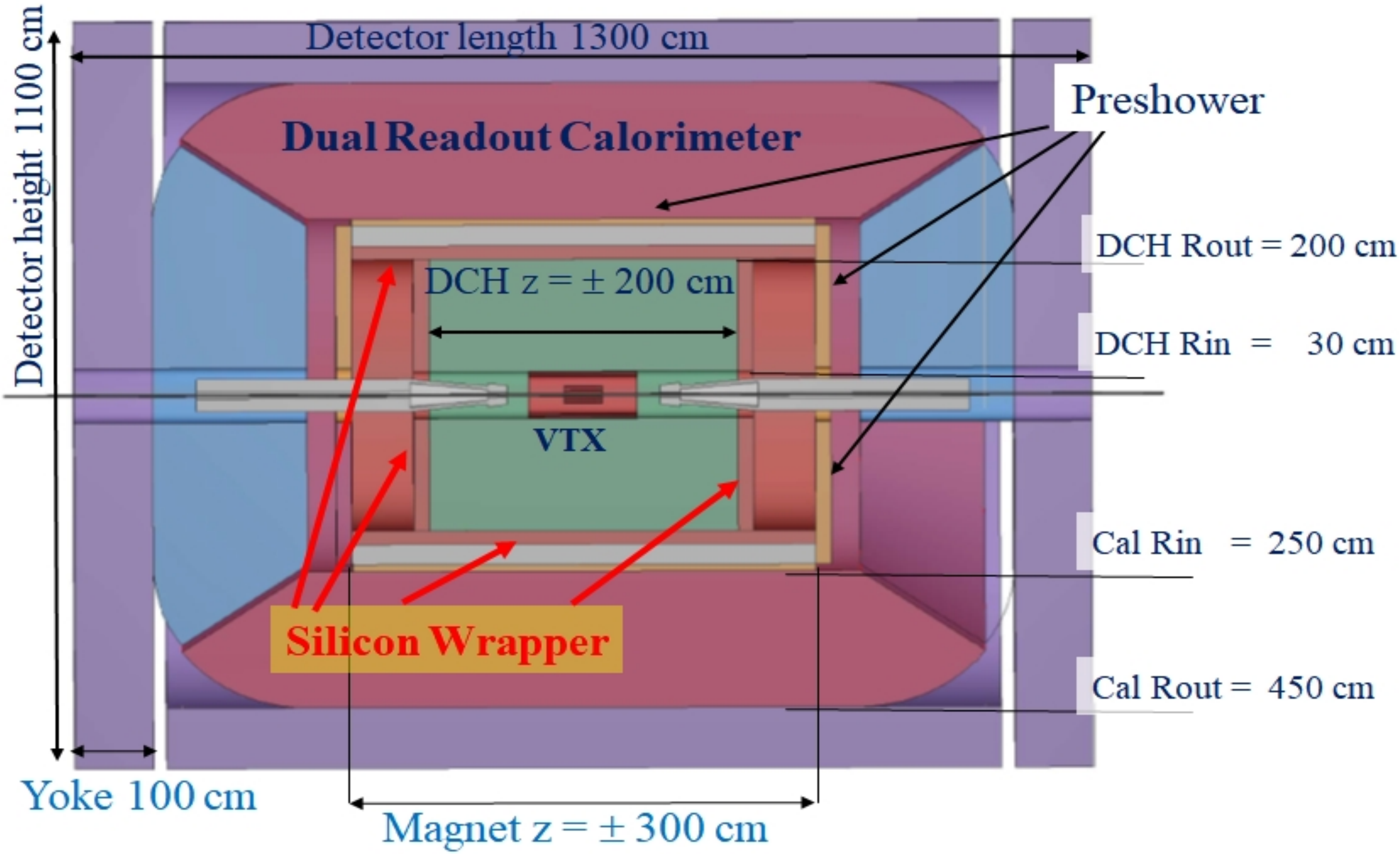
δμ ≅ 2-4%

δϰ ≅ 5%

Details in arXiv:1606.09408 and arXiv1802.01607

IDEA detector layout

IDEA detector layout



Detector for circular lepton collider

IDEA detector concept

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IDEA detector concept based on:

- Si vertex detector
- Excellent particle-ID (wire chamber)
- Very low material budget
- Thin Magnet 2 Tesla field
- Preshower
- Dual readout calorimeter
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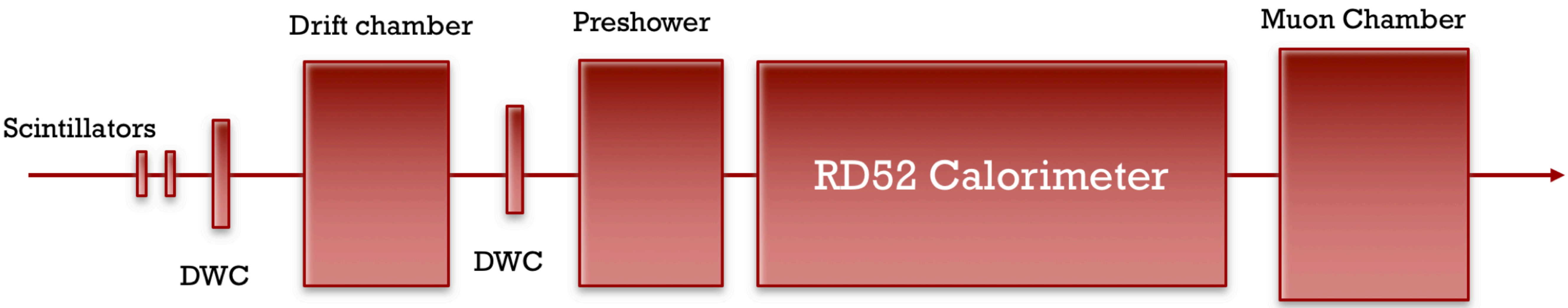

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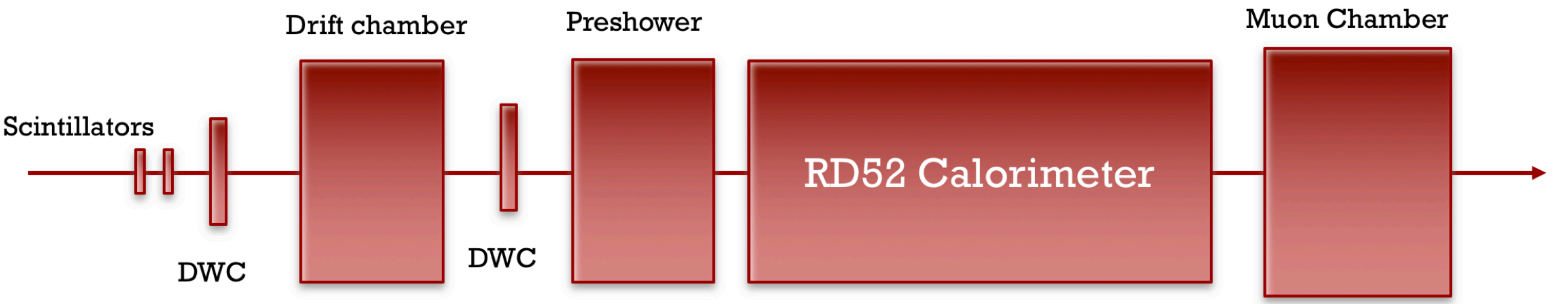

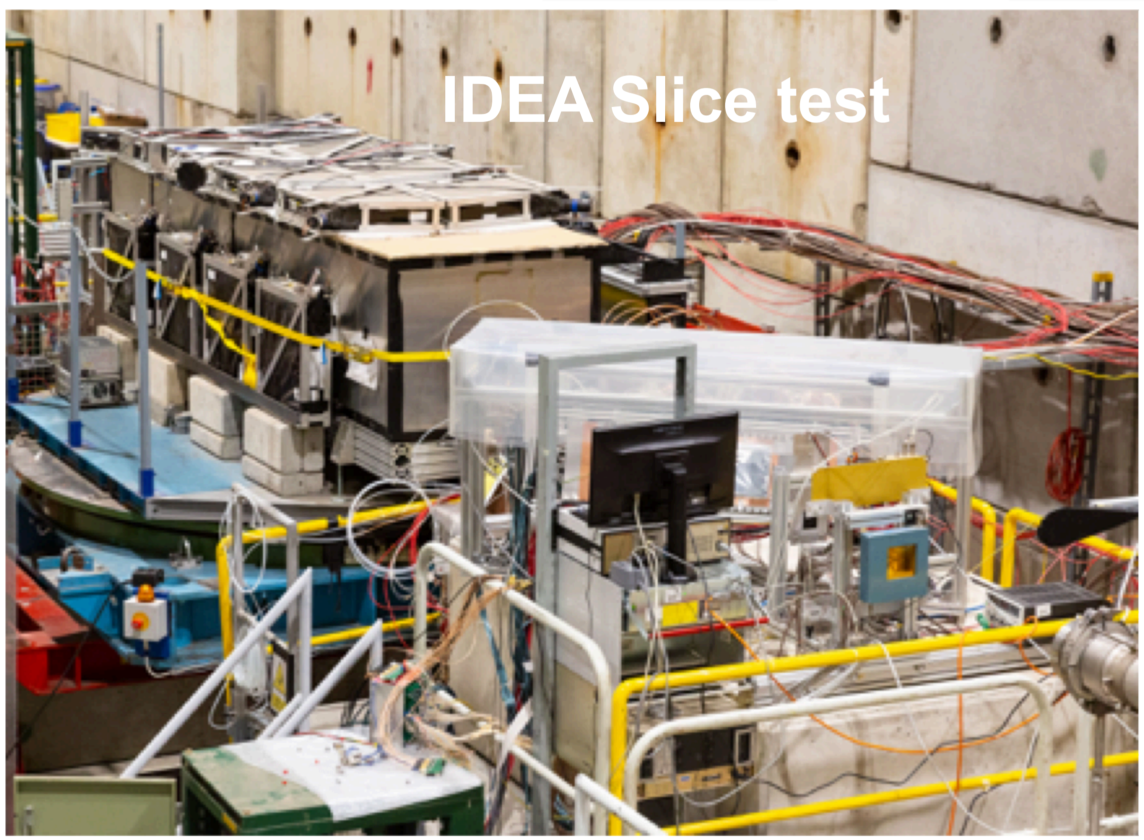

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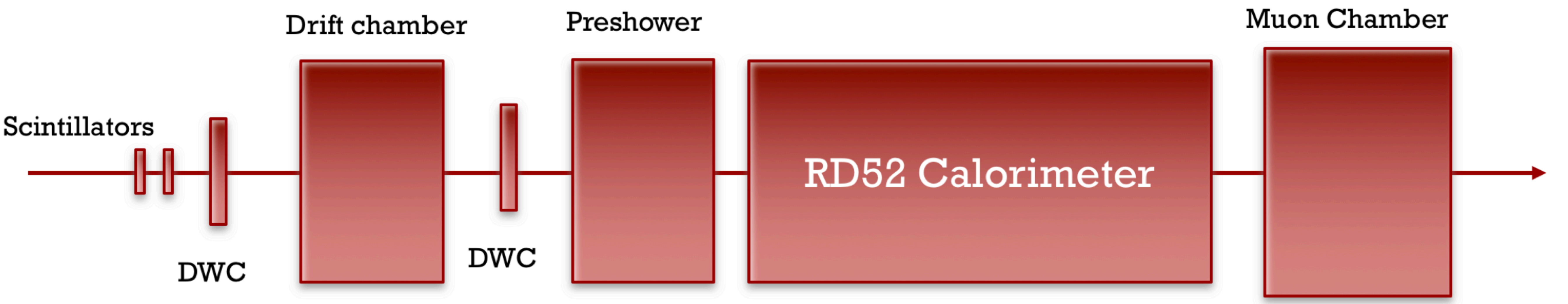

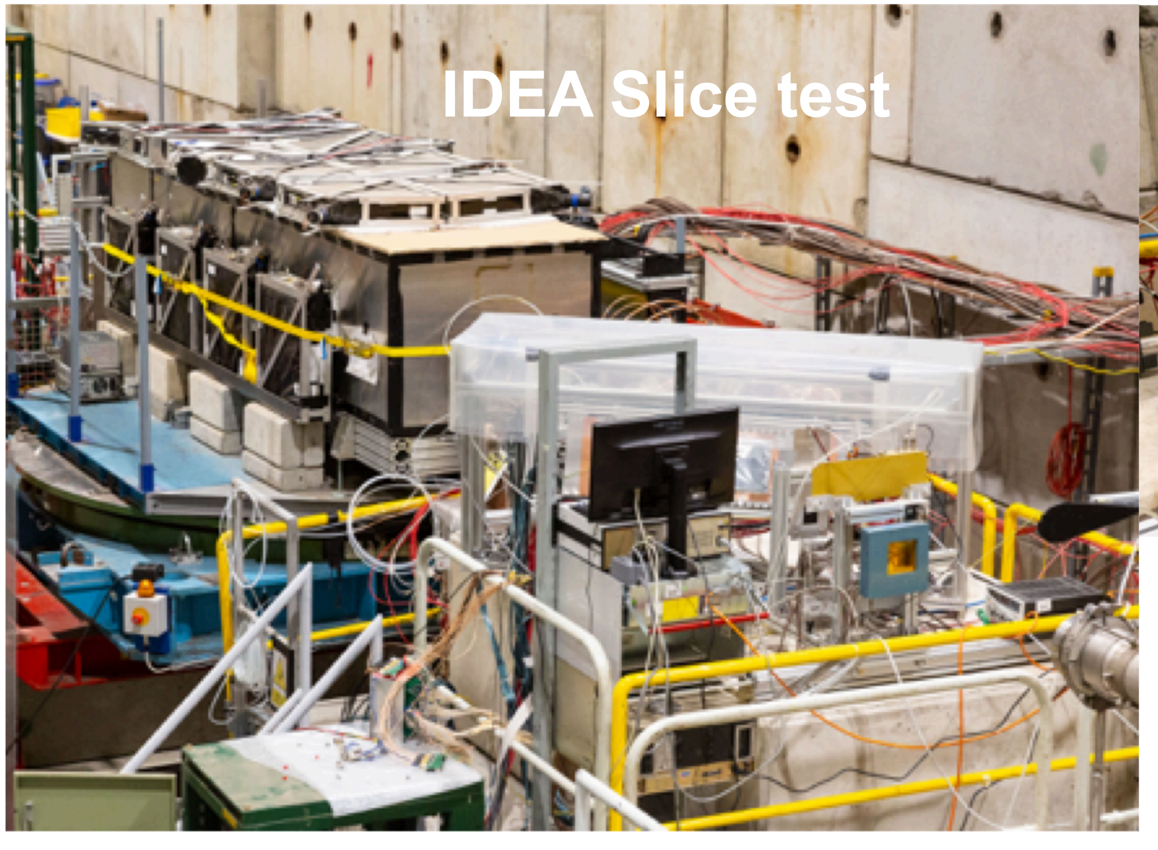

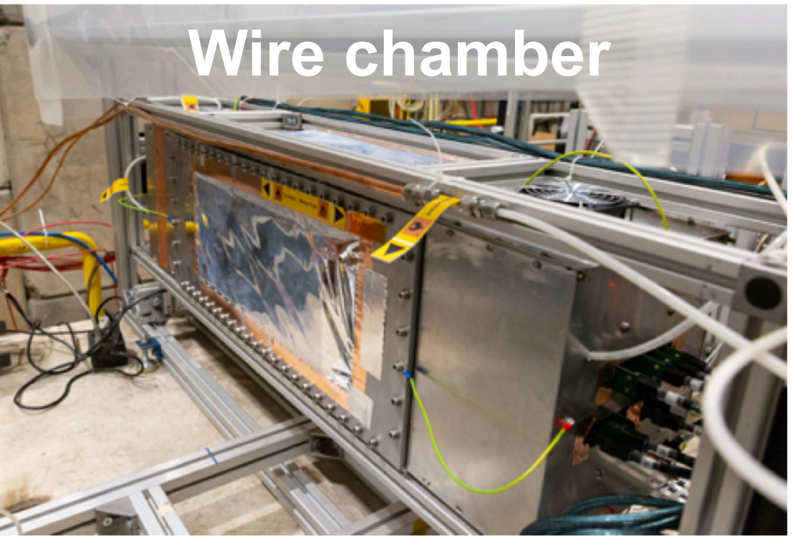

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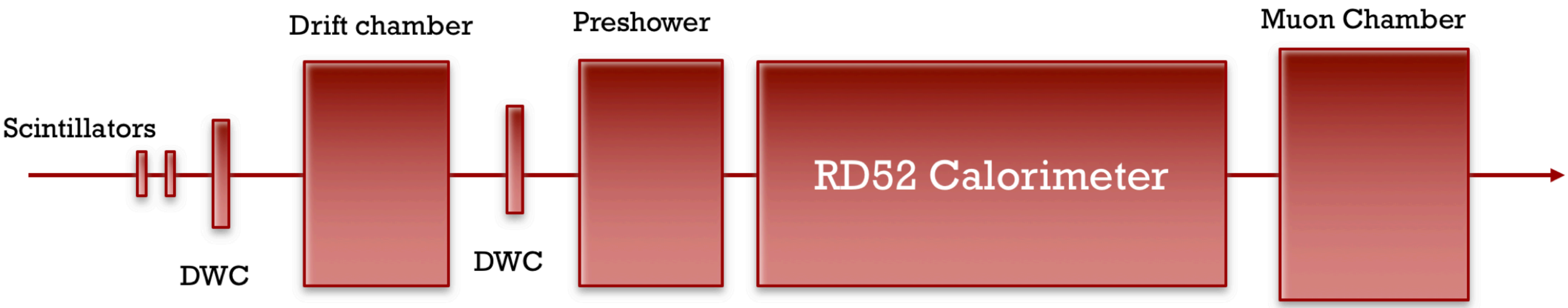
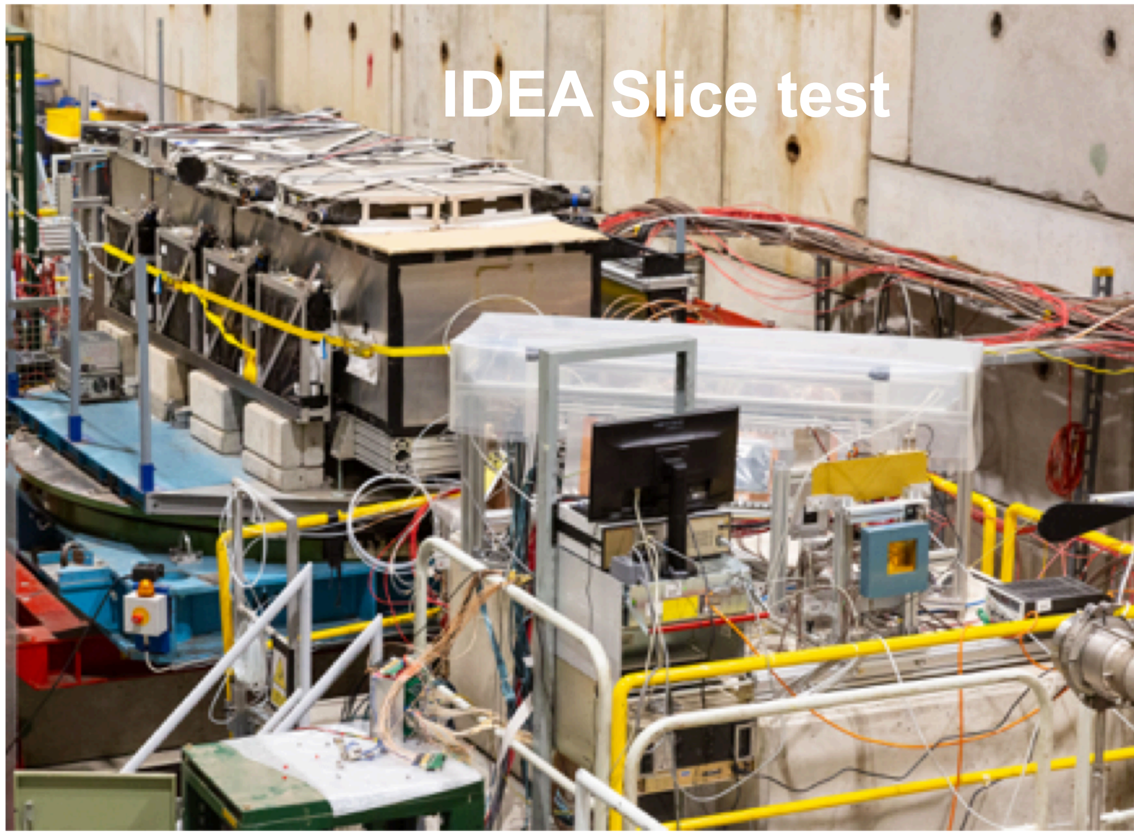
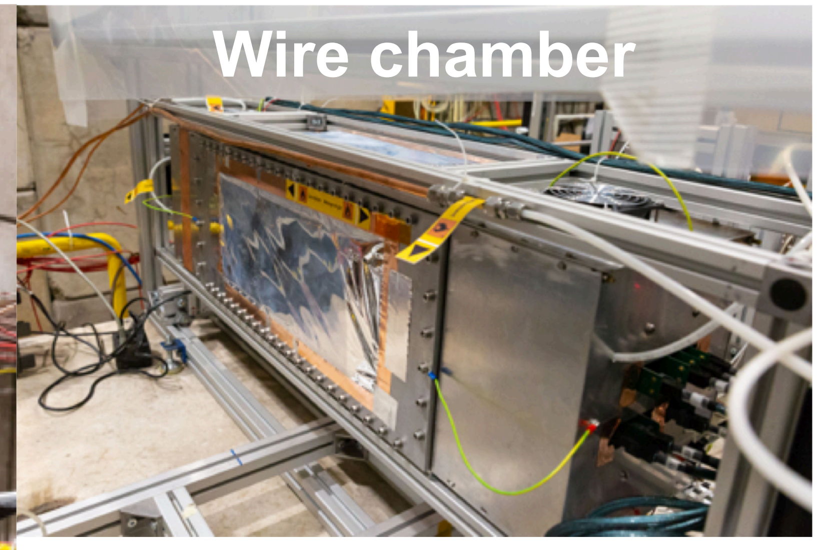
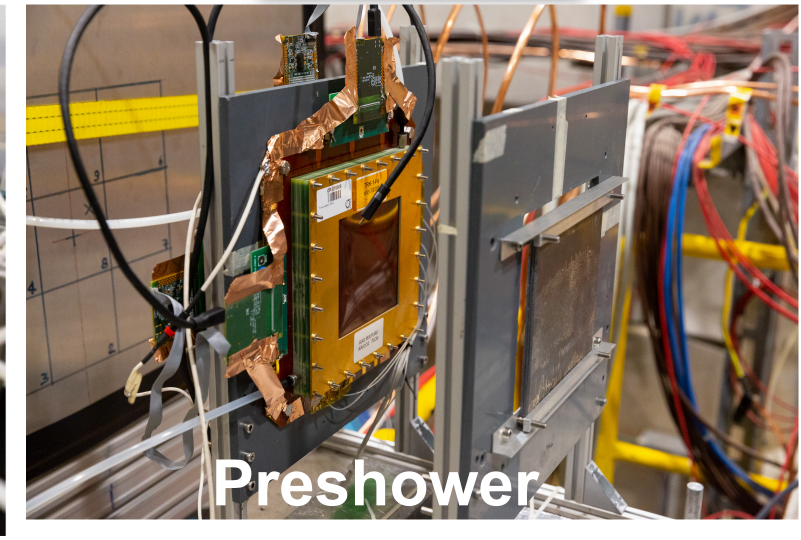


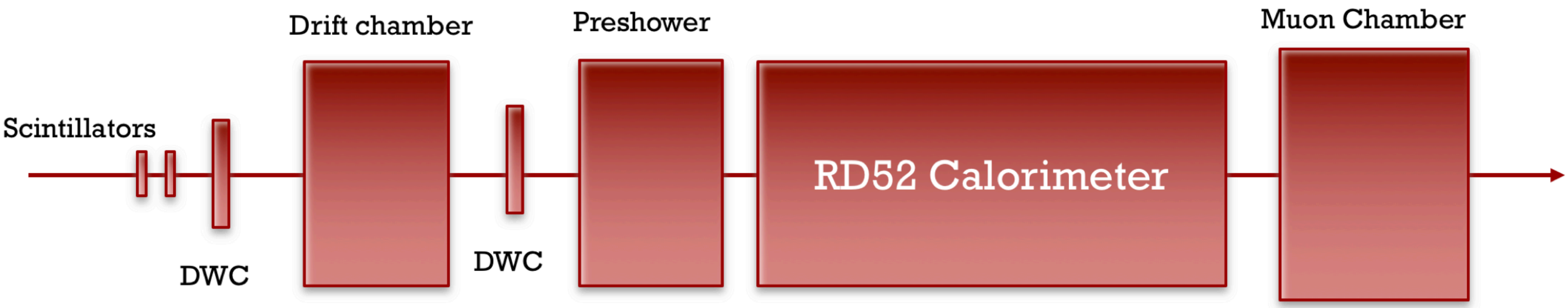


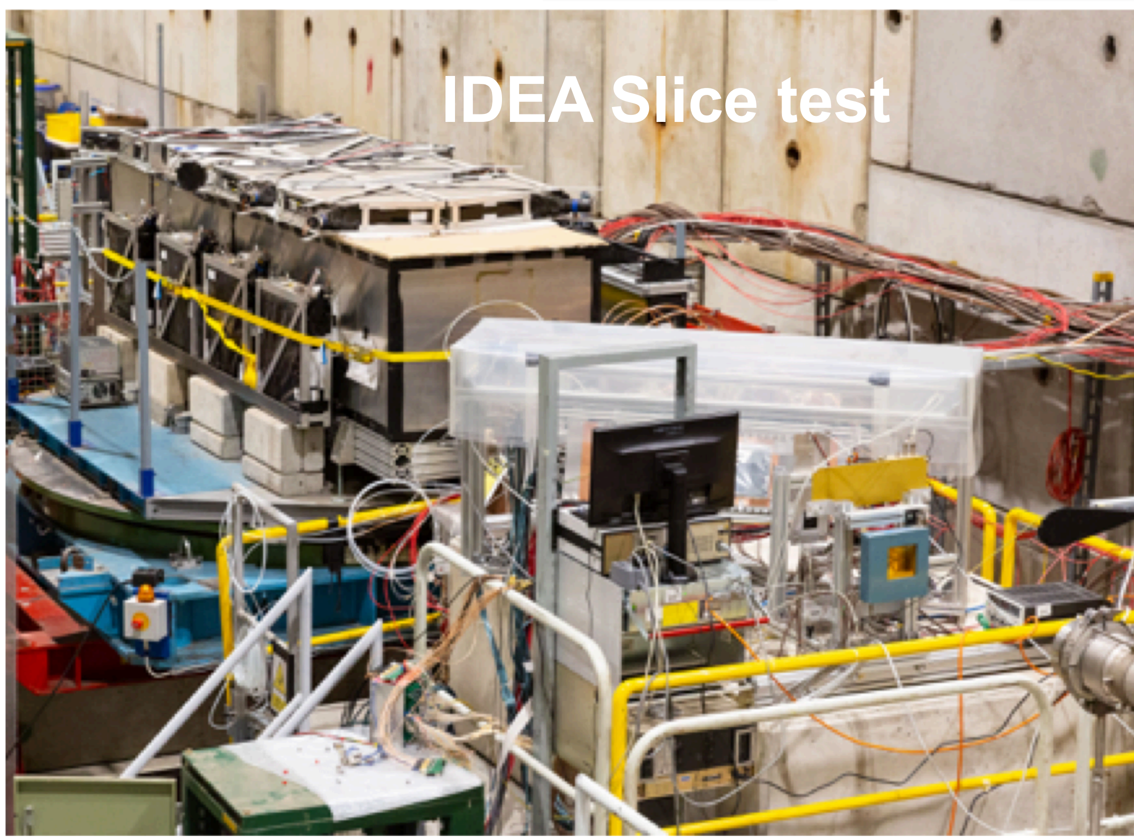


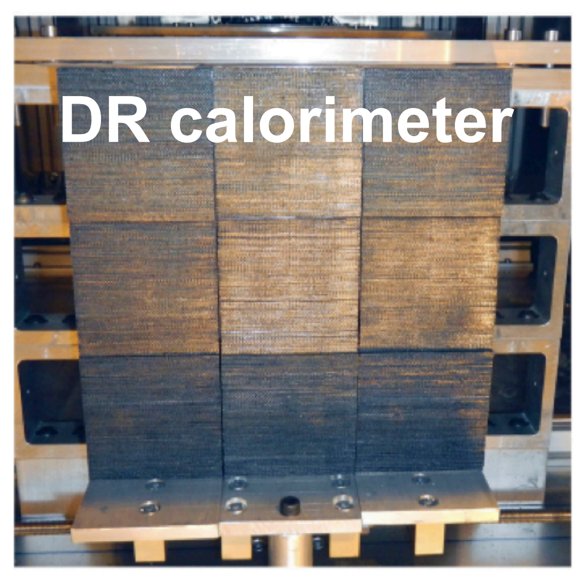


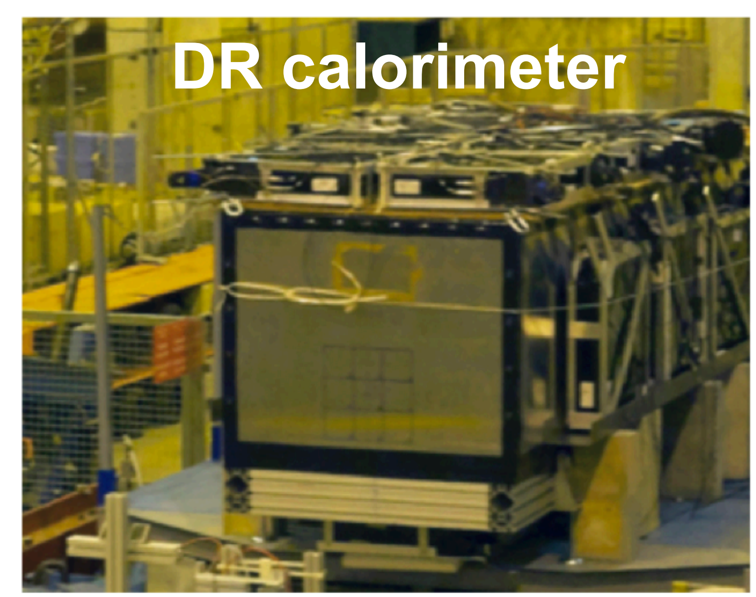
IDEA slice test

Performed in September 2018 at the CERN H4 beam line









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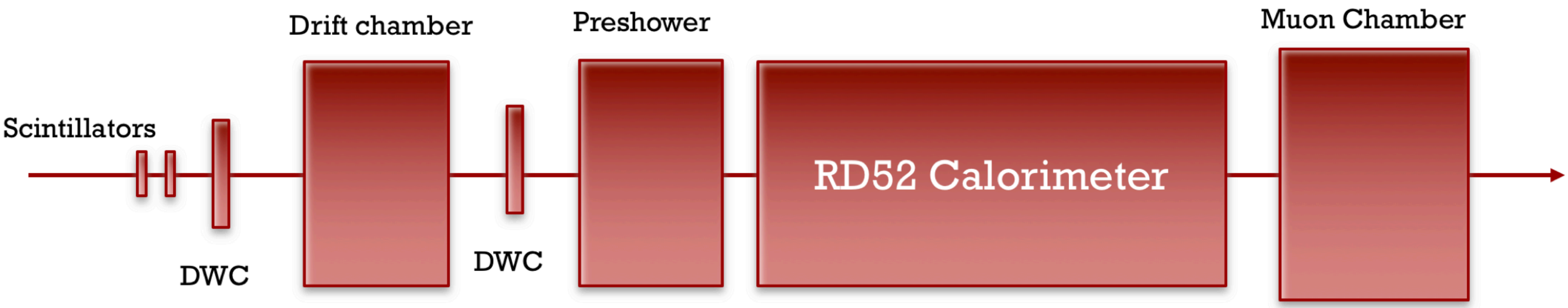

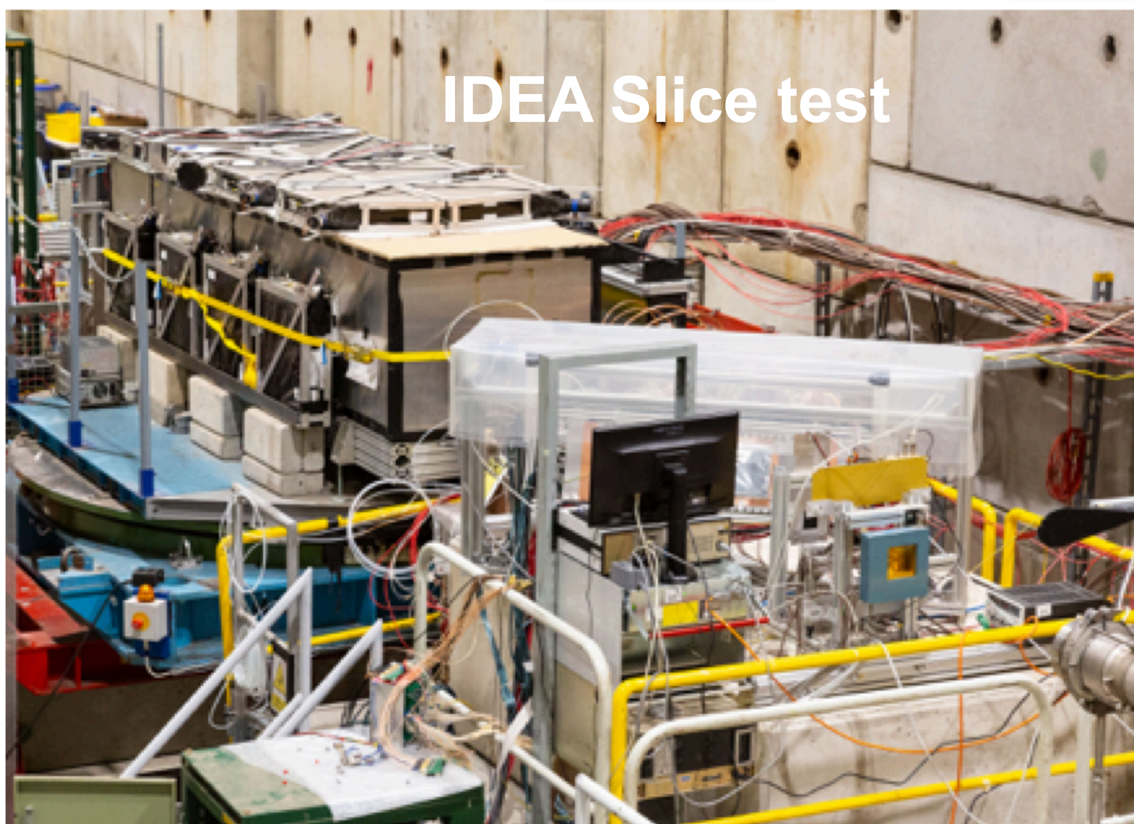

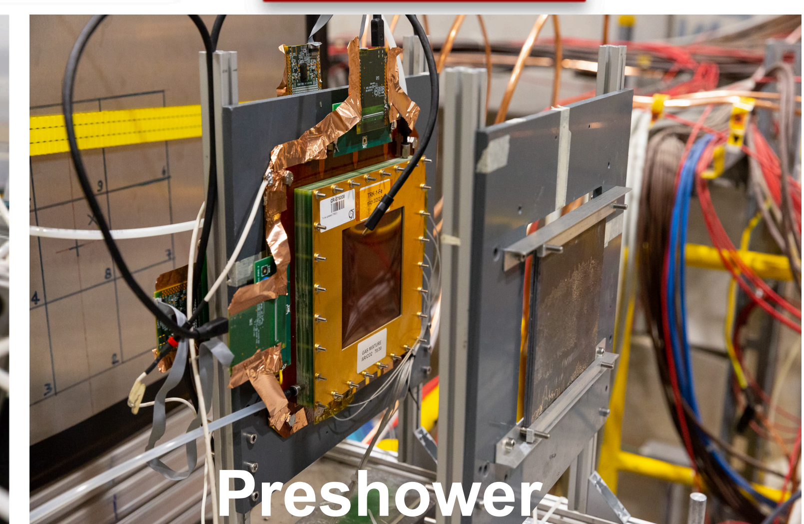

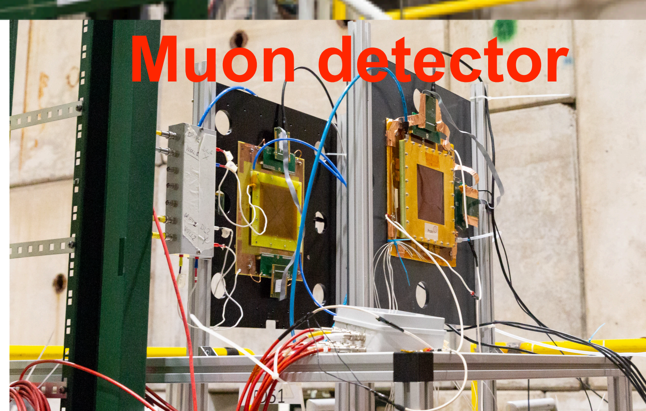

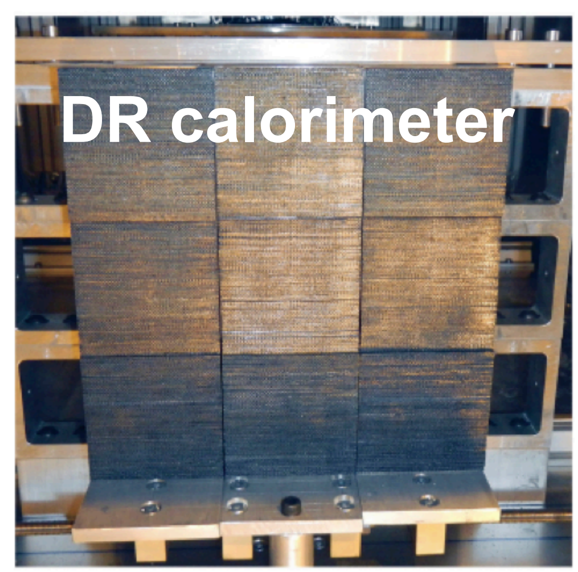

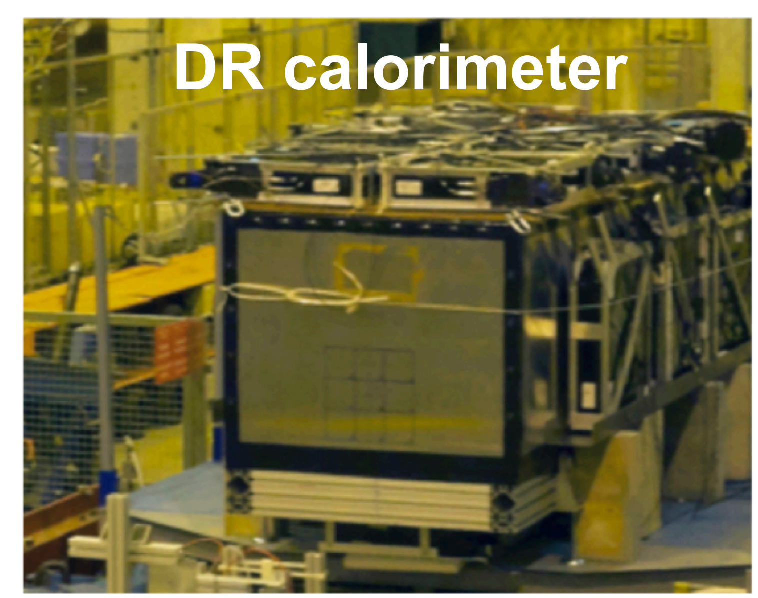

Conclusions

- Several future lepton colliders are being proposed
  - Circular: **FCC-ee** and **CEPC**
  - Linear: **ILC** and **CLIC**
- Circular colliders have much larger luminosities, while linear colliders can reach higher energies
- Circular lepton colliders can later be replaced by very high energy pp colliders
  - the sequential implementation of a **lepton** and a **hadron** collider maximises the physics reach
- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities

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FCC-ee and CEPC promise the best EW and Higgs measurements

Backup

A successful model!

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

CERN 76-18
8 November 1976

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

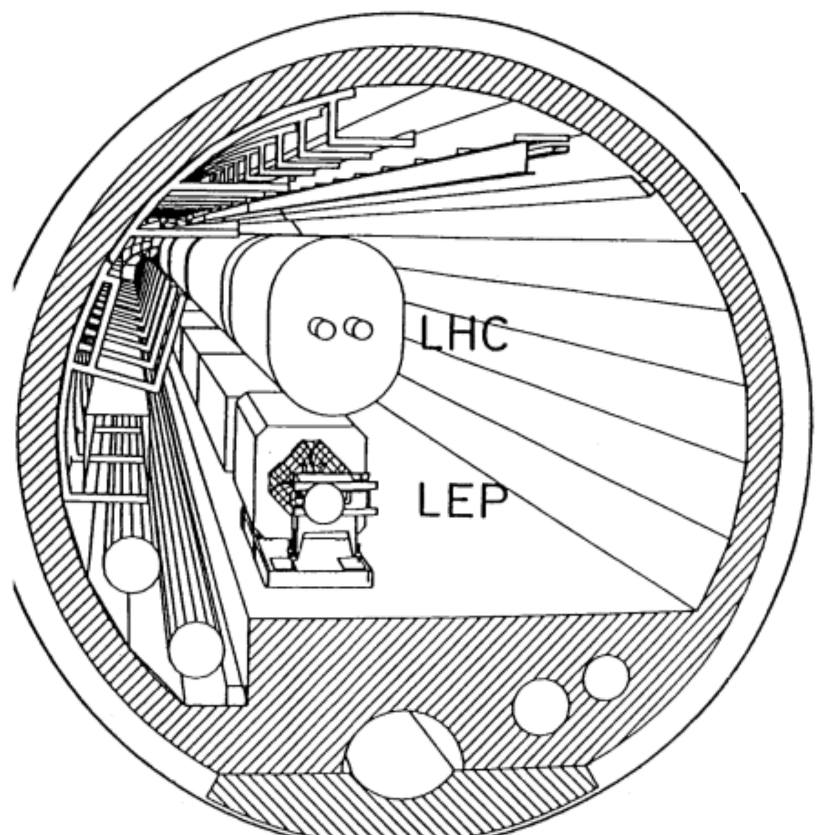
ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people know that we would be running HL-LHC in that tunnel >**60 years later?**

ECFA 84/85
CERN 84-10
5 September 1984

e+e- 1989-2000



p p 2009-2039

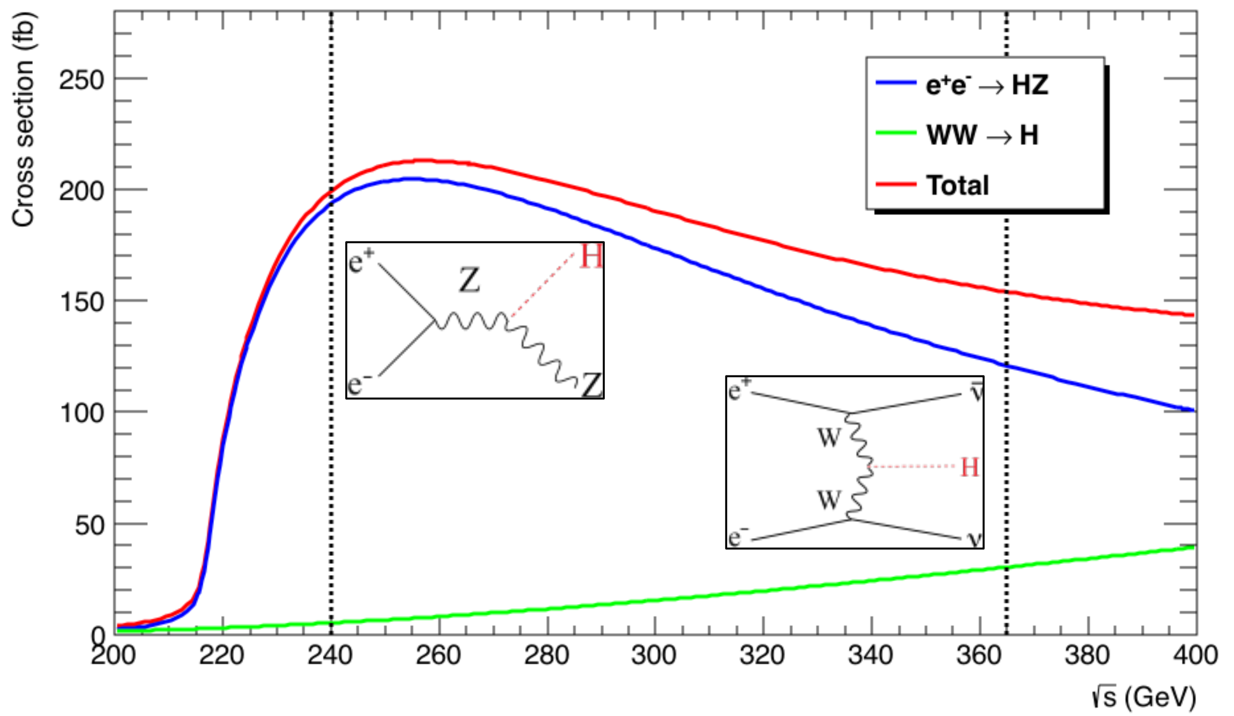
LARGE HADRON COLLIDER
IN THE LEP TUNNEL

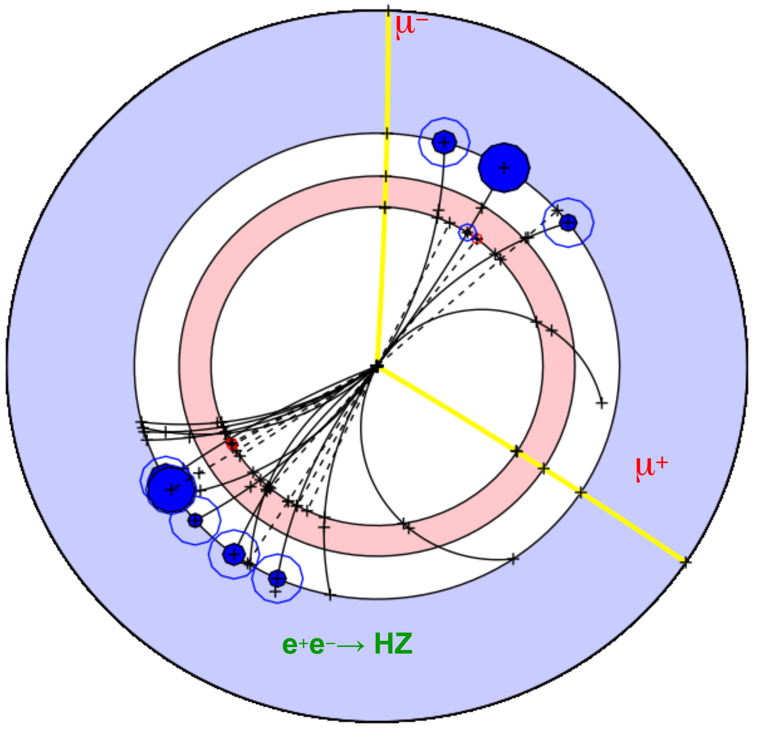
Vol. I

Let's not be SHY!

Circular e^+e^- colliders: FCC-ee, CepC

- **Basic measurements similar for all e^+e^- colliders**
  - Some differences in experimental conditions





  - $e^+e^- \to HZ$ at $\sqrt{s}$ = 240-250 GeV : Higgs boson are tagged with a Z and $m_{Recoil} = m_H$
    - Measure σ_{HZ} ($\propto g_{HZ}^2$) independently of H decay: absolute determination of g_{HZ}
    - Measure $\sigma_{HZ} \times BR(H \to \text{invisible})$ and many exclusive decays $\sigma_{HZ} \times BR(H \to XX)$
    - Infer Higgs width Γ_H from $\sigma_{HZ} \times BR(H \to ZZ)$ ($\propto g_{HZ}^4/\Gamma_H$)
    - Fit couplings g_{HX} from $BR(H \to XX)$ and Γ_H in a model-independent manner
  - $e^+e^- \to HZ$ completed with WW fusion at $\sqrt{s}$ = 350-365 GeV at FCC-ee
    - Improves all precisions, especially on g_{HW} and Γ_H
    - First glance at top Yukawa coupling λ_t and Higgs self coupling λ_H (next slides)

«First look of the physics case of TLEP» (original name of FCC-ee): 398 quotes today

HEP 398 records found 1 - 25 jump to record: 1

1. **Probing TeV scale origin of neutrino mass at lepton colliders**
   P.S. Bhupal Dev, Rabindra N. Mohapatra, Yongchao Zhang. Mar 29, 2018. 48 pp.
   e-Print: **arXiv:1803.11167 [hep-ph] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

2. **Review of top and EW physics at future colliders**
   Marcel Vos (Valencia U., IFIC). 2017. 10 pp.
   Published in **PoS EPS-HEP2017 (2017) 471**
   Conference: C17-07-05 Proceedings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Link to PoS server; Link to Fulltext
   Detailed record

3. **Electroweak Physics at Future e^+e^- Colliders**
   Elizabeth Locci (Saclay), On Behalf Of The Fcc Design Study Group. 2018. 10 pp.
   Published in **PoS EPS-HEP2017 (2018) 449**
   Conference: C17-07-05 Proceedings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Link to PoS server; Link to Fulltext
   Detailed record

4. **Muon g-2 and dark matter in models with vector-like fermions**
   Enrico Maria Sessolo (NCBJ, Warsaw), Kamila Kowalska (Tech. U., Dortmund (ma
   Published in **PoS EPS-HEP2017 (2017) 338**
   Conference: C17-07-05 Proceedings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Link to PoS server; Link to Fulltext
   Detailed record

Much more than a Higgs factory!

HEP 430 records found 1 - 25 jump to record: 1

1. **Future Circular Collider Study (FCC)**
   Tobias Golling (Geneva U.). 2016. 6 pp.
   Conference: C15-08-31.1, p.559-564 Proceedings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Link to Fulltext
   Detailed record

2. **A Deeper Probe of New Physics Scenarii at the LHC**
   A. Djouadi (Orsay, LPT). 2017. 12 pp.
   Conference: C17-07-09.3, p.44-55 Proceedings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Link to Fulltext
   Detailed record

3. **Effective Field Theory Approaches to Particle Physics Beyond the Standard Model**
   Zhengkang Zhang (Michigan U.). 2018. 246 pp.
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Link to Fulltext; Link to Fulltext
   Detailed record

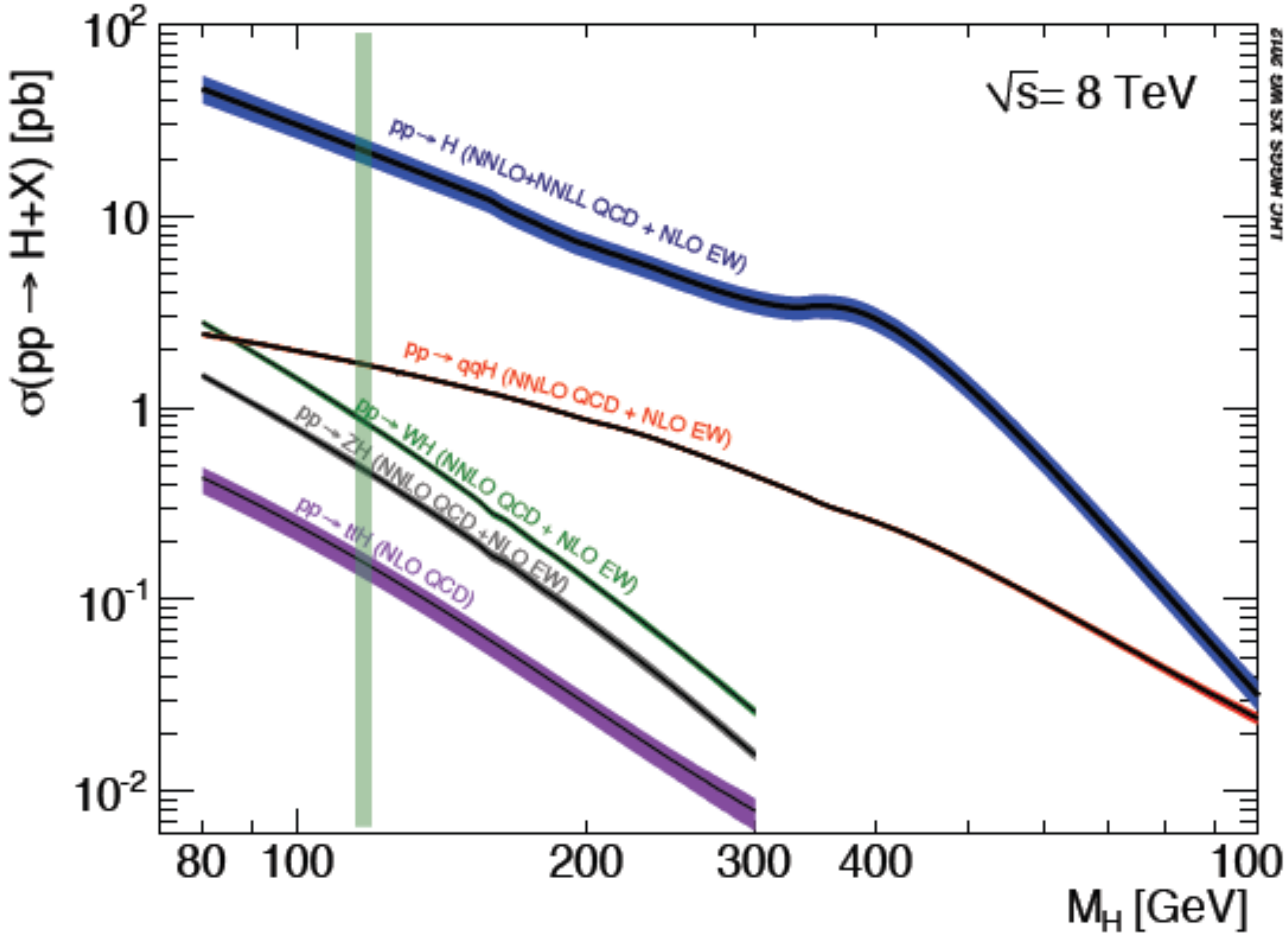
4. **Measuring the triple Higgs self-couplings in two Higgs doublet model**
   Nasuf Sonmez. Jun 23, 2018. 15 pp.
   17-FEN-054, 17-FEN-054
   e-Print: **arXiv:1806.08963 [hep-ph] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

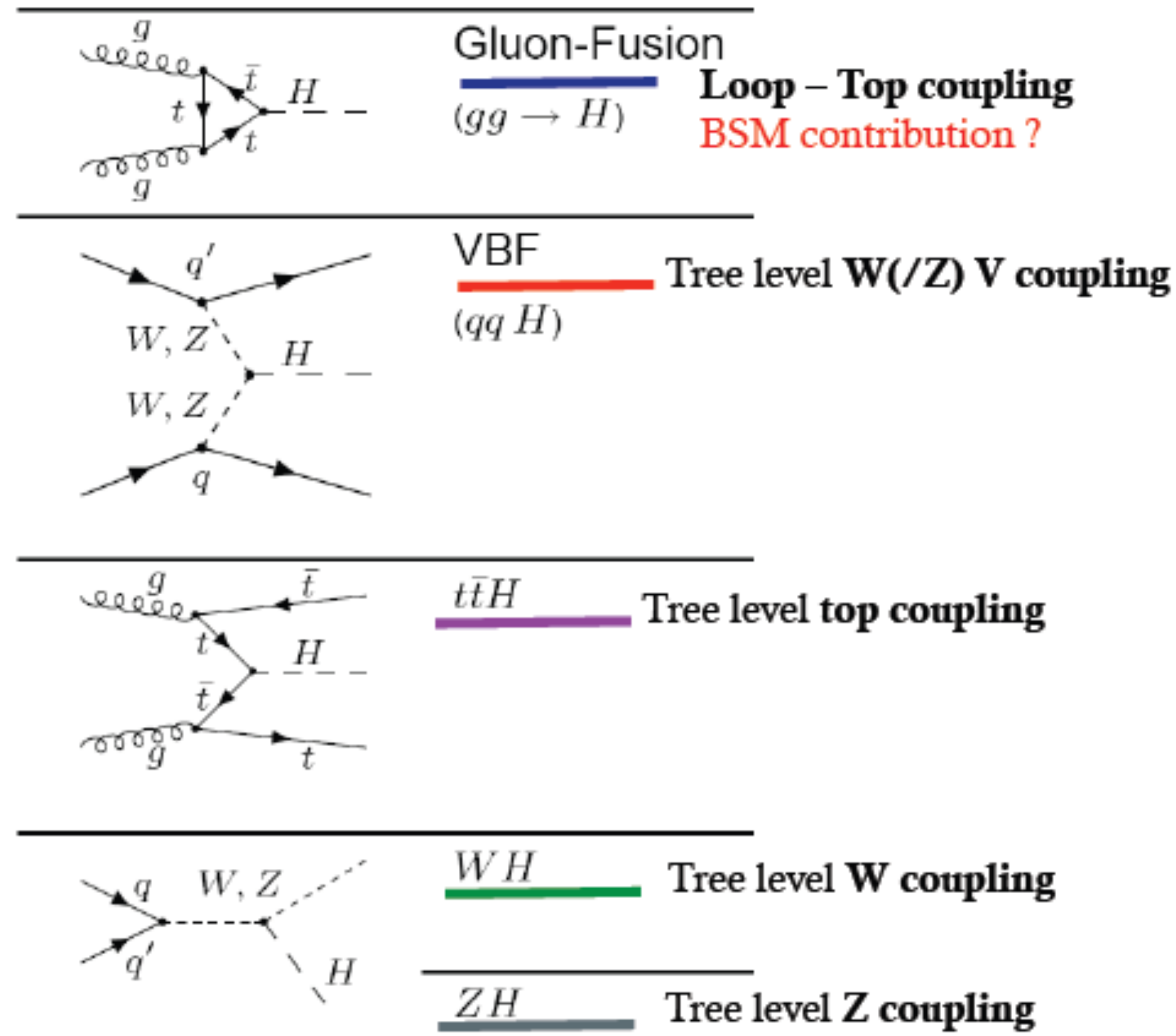
5. **Doubly-Charged Scalars in the Type-II Seesaw Mechanism: Fundamental Symmetry Tests and High**
   P.S. Bhupal Dev (McDonnell Ctr. Space Sci.), Michael J. Ramsey-Musolf (Massachusetts U., Amherst & Caltech, Kellogg Lab), Yo
   ACFI T18-10, ACFI-T18-10
   e-Print: **arXiv:1806.08499 [hep-ph] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service
   Detailed record

6. **The Higgs boson decays with the lepton flavor violation**
   O.M. Boyarkin, G.G. Boyarkina, D.S. Vasileuskaya (Belarus State U.). 2018. 18 pp.
   Published in **Int.J.Mod.Phys. A33 (2018) no.17, 1850103**
   DOI: 10.1142/S0217751X18501038
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   Detailed record

7. **α_s status and perspectives (2018)**
   David d'Enterria. Jun 15, 2018. 5 pp.
   Conference: C18-04-16.1
   e-Print: **arXiv:1806.06156 [hep-ex] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

Higgs production at LHC





THE LHC is a Higgs Factory…BUT

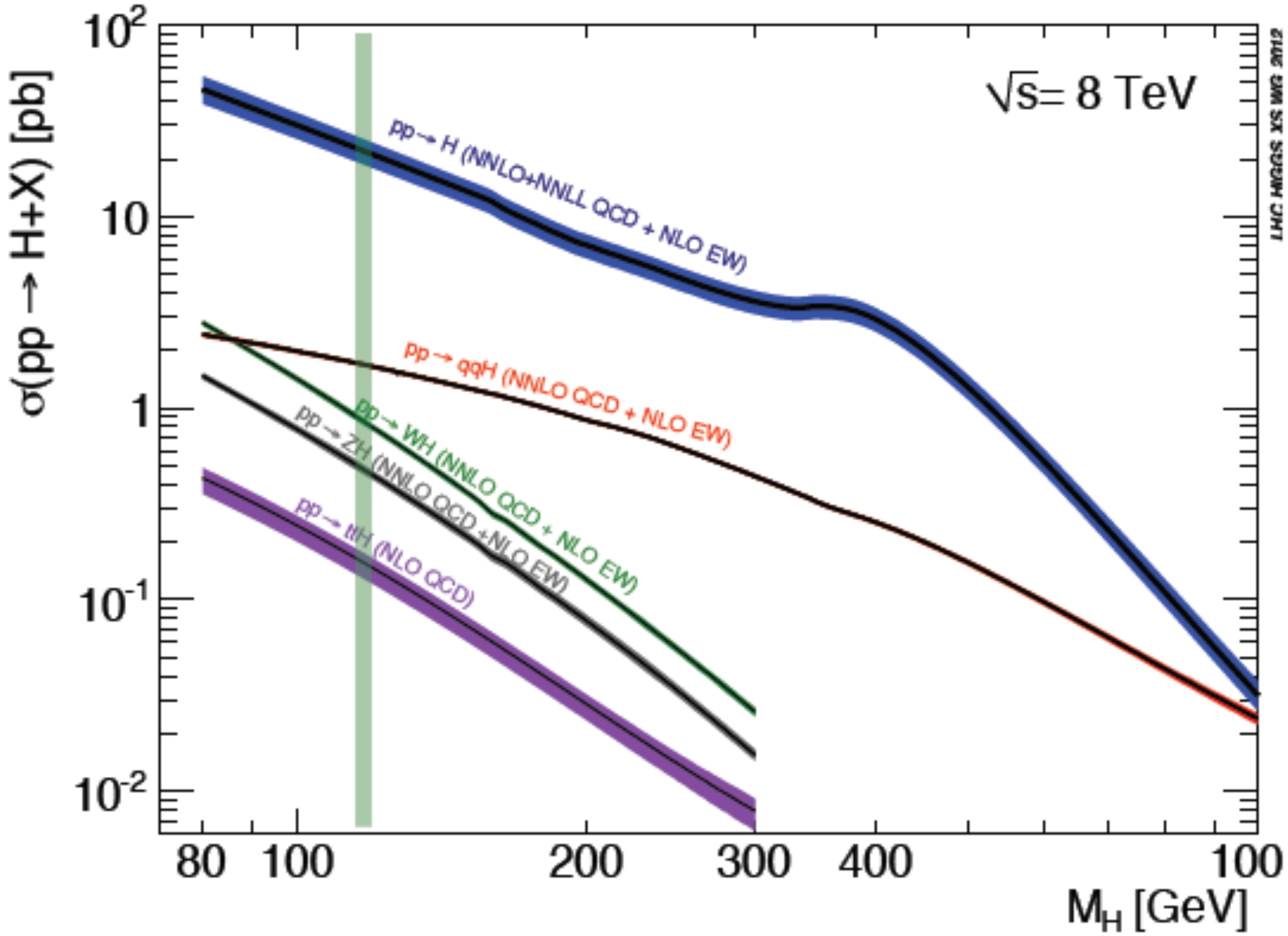
several tens of Million Higgs already produced… > than most Higgs factory projects.

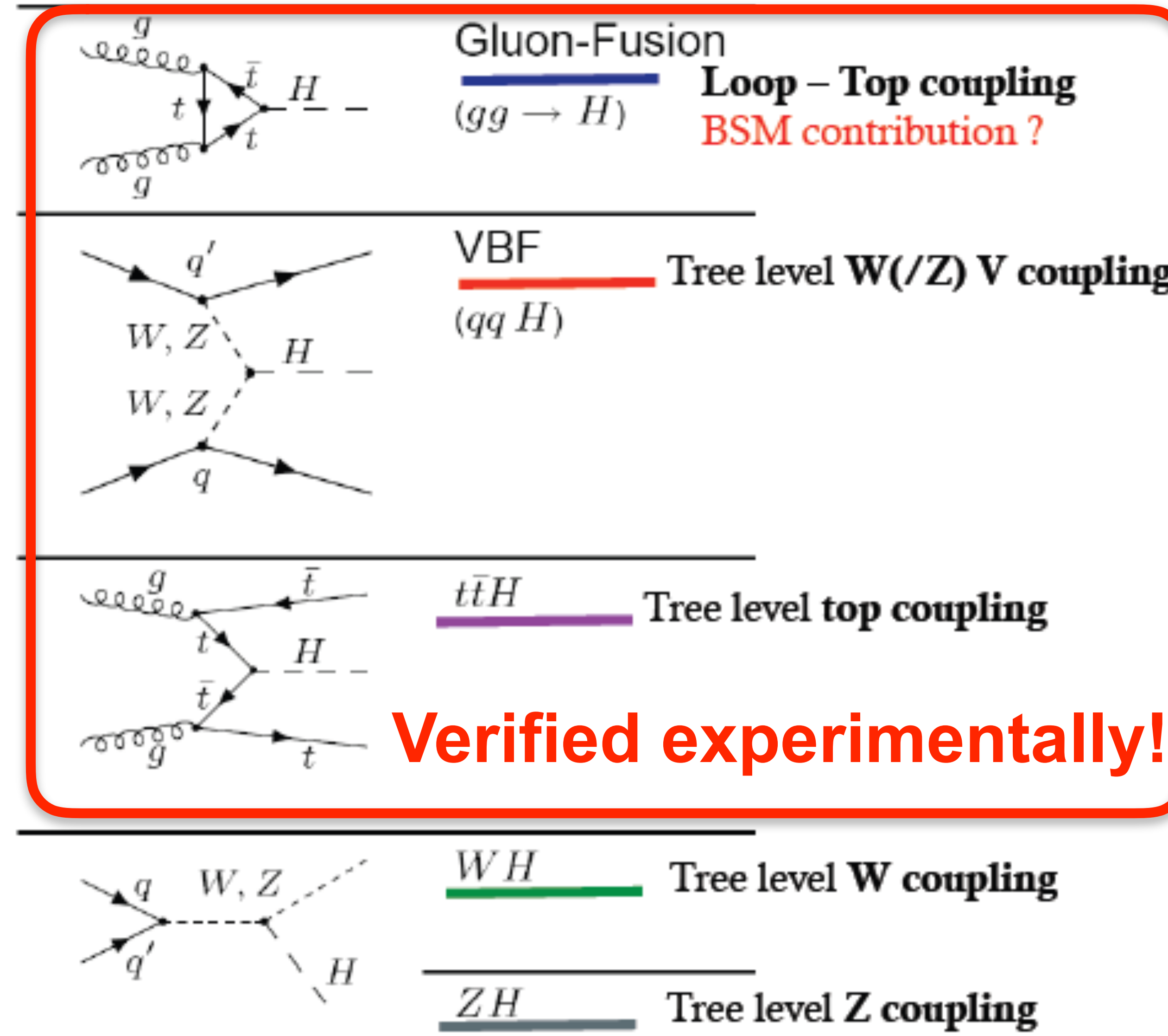
$$\sigma_{i\to f}^{\text{observed}} \propto \sigma_{\text{prod}} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

relative error scales with
1/purity and 1/√efficiency of signal

difficult to extract the couplings because σ_{prod} uncertain and Γ_H is unknown (invisible channels) → must do physics with ratios.

Higgs production at LHC





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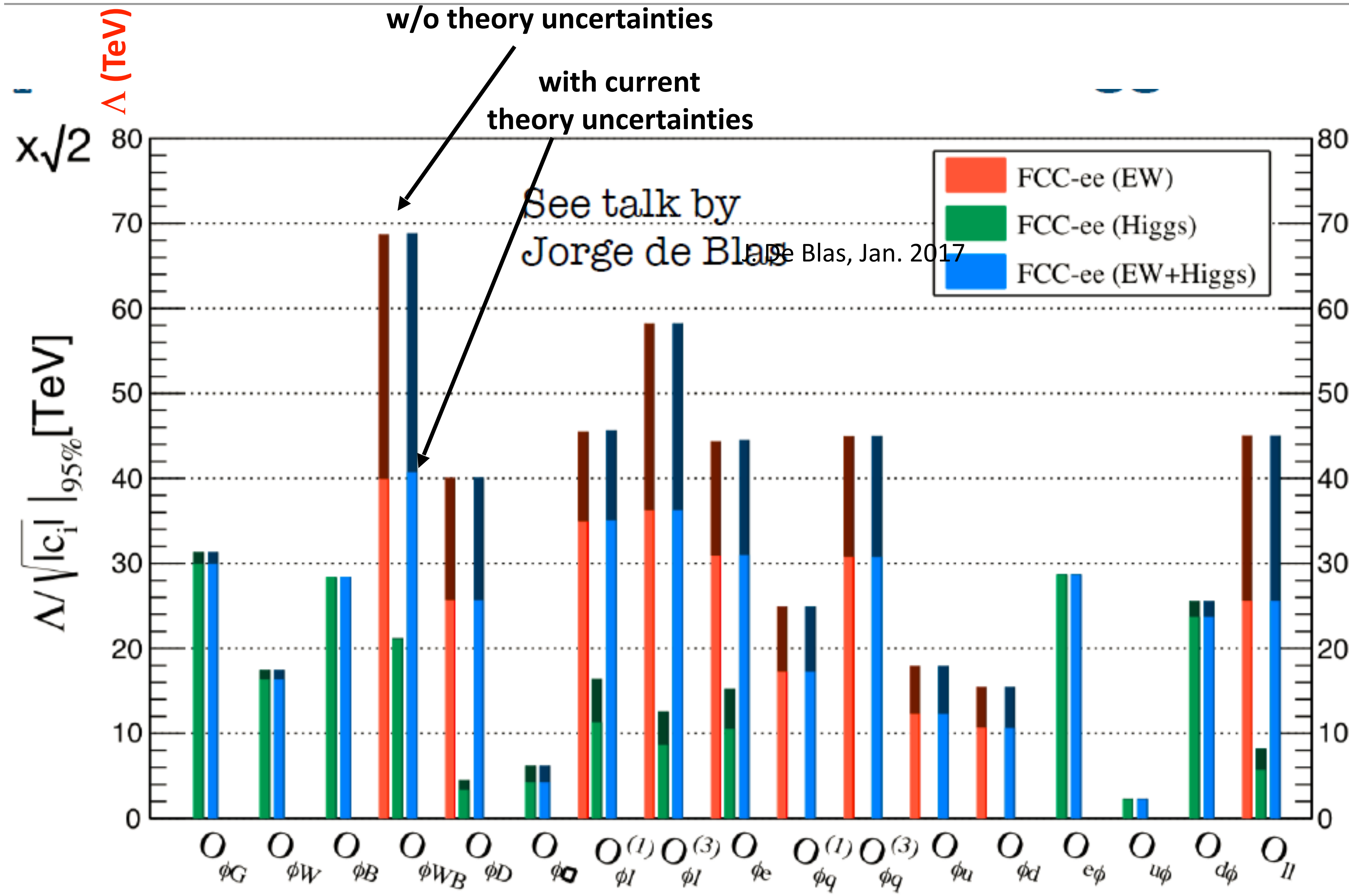
FCC-ee indirect reach

many EFTs



Conclusion from Precision Calculations Mini-Workshop in January 2018:
The necessary theoretical work is doable in 5-10 years perspective, due to steady progress in methods and tools, including the recent completion of NNLO SM corrections to EWPOS. This statement is conditional to a strong support by the funding agencies and the overall community. Appropriate financial support and training programs for these precision calculations are mandatory.

Several EFTs will achieve sensitivity exceeding 50 TeV (decoupling physics!)

junction with FCC-hh EFTs under progress by Jorge de Blas

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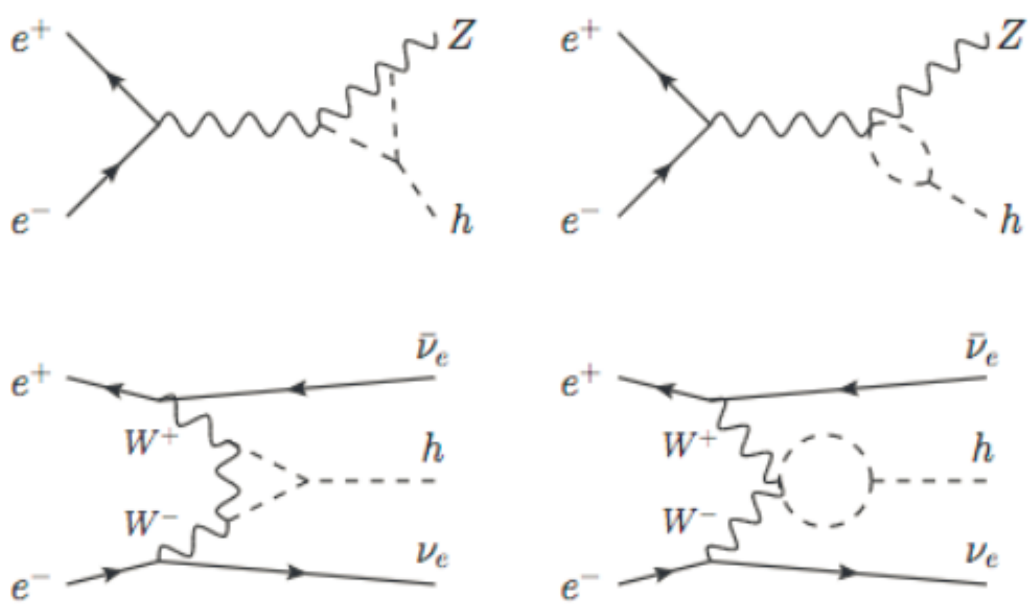
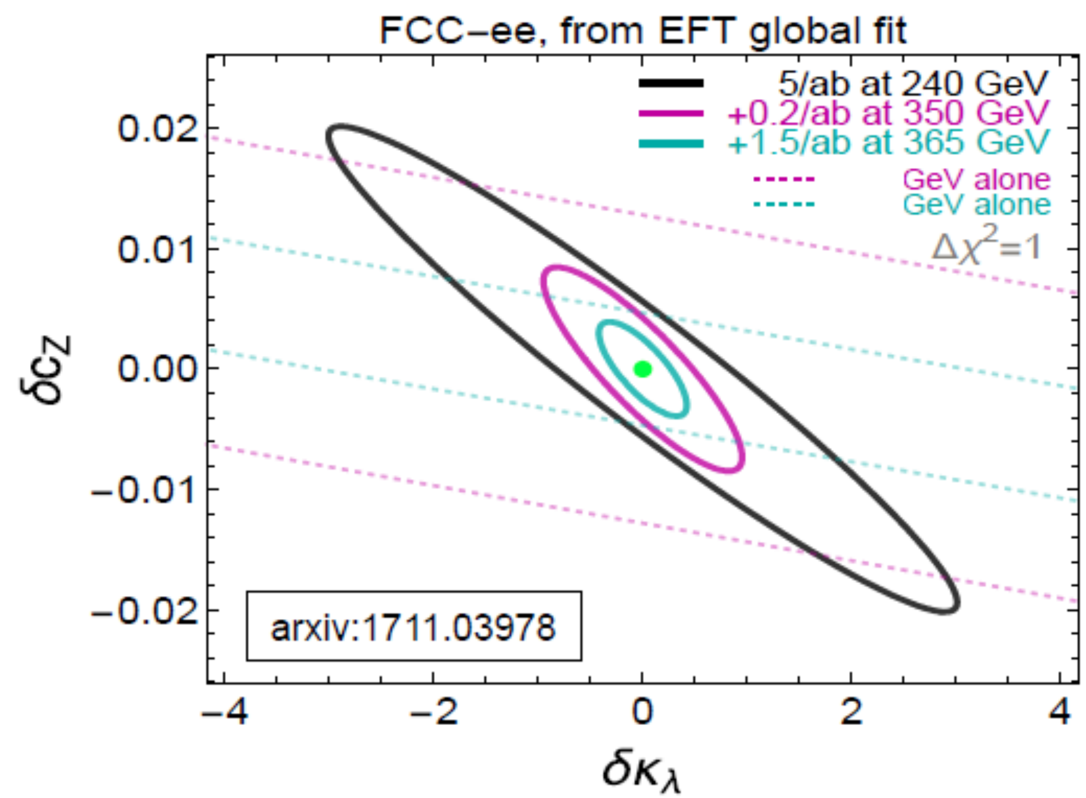
Istituto Nazionale di Fisica Nucleare

Higgs self-coupling λ_H (How H, W, Z get masses…)

The FCC-ee does not produce pairs of Higgses from which one can extract λ_H but the ZH cross-section receives a E_{cm} - dependent correction from it.

- √s dependence of the "effective" g_{HZ} and g_{HW} to the Higgs self-coupling
  - Accessible from the high-precision runs at 240, (350), and 365 GeV
    - Arising from Higgs-triangle and -loop diagrams





- Higgs self-coupling precision at FCC-ee : ~40%
  - Improved to ~20% if g_{HZ} is fixed to its SM value
- Unique FCC-ee synergy between the runs at 240 and 365 GeV
  - Calls for the highest luminosity (4IP's ? Longer runs ?)

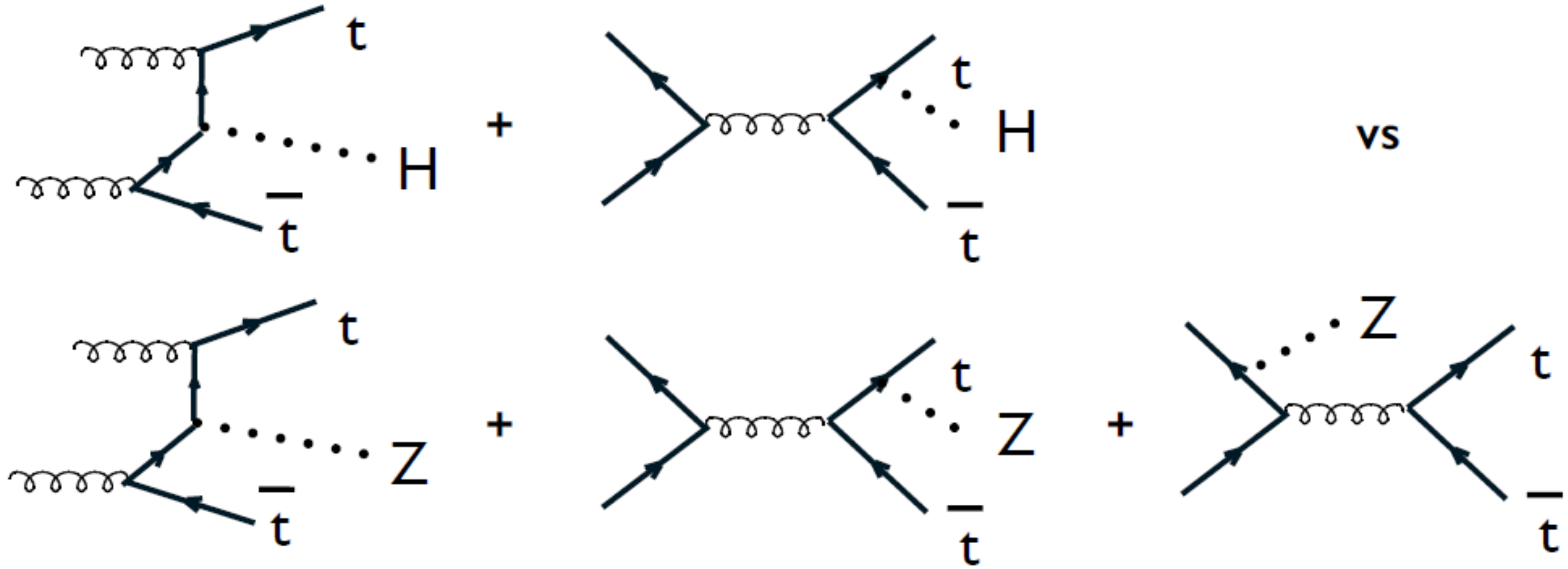
Patrick Janot — Higgs properties @ Circular Lepton Colliders, 1 June 2018

investigating now : the possibility of reaching 5σ observation of Higgs self coupling at FCC-ee:
4 detectors
+ recast of running scenario

Istituto Nazionale di Fisica Nucleare

Top Yukawa coupling from $\sigma(ttH)/\sigma(ttZ)$

arXiv:1507.08169



To the extent that the qqbar → tt Z/H contributions are subdominant:

- Identical production dynamics:
  - o correlated QCD corrections, correlated scale dependence
  - o correlated α_S systematics
- $m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:
  - o correlated PDF systematics
  - o correlated m_{top} systematics

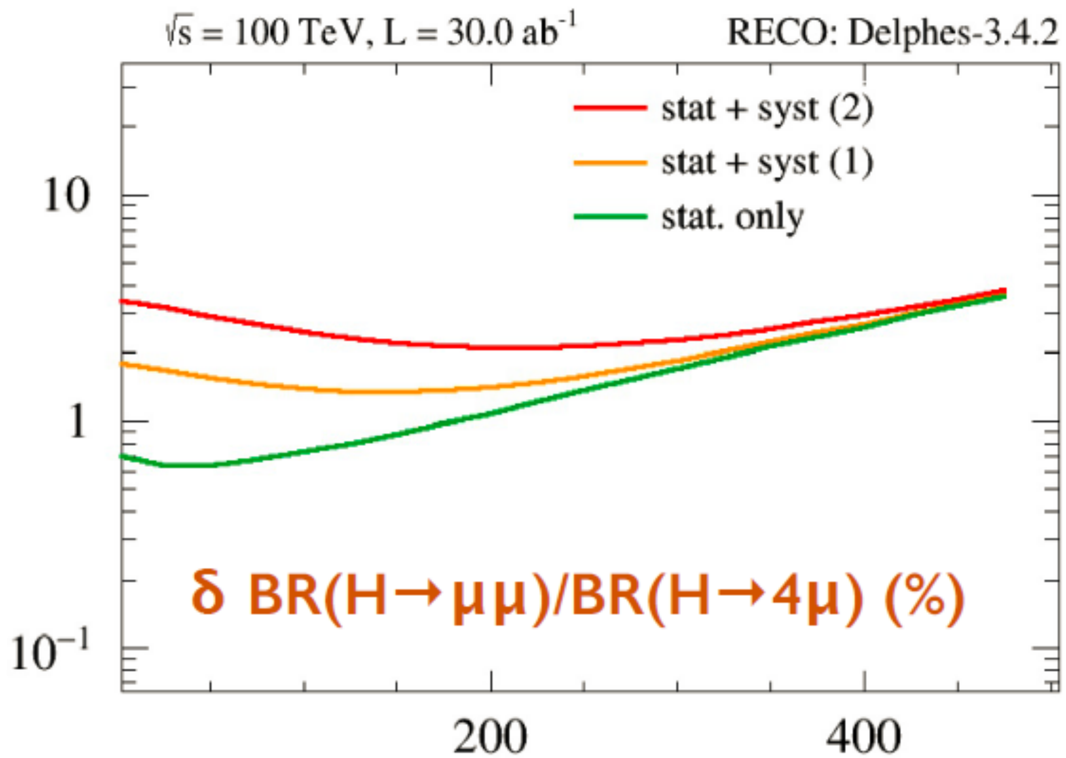
For a given y_{top}, we expect $\sigma(ttH)/\sigma(ttZ)$ to be predicted with great precision

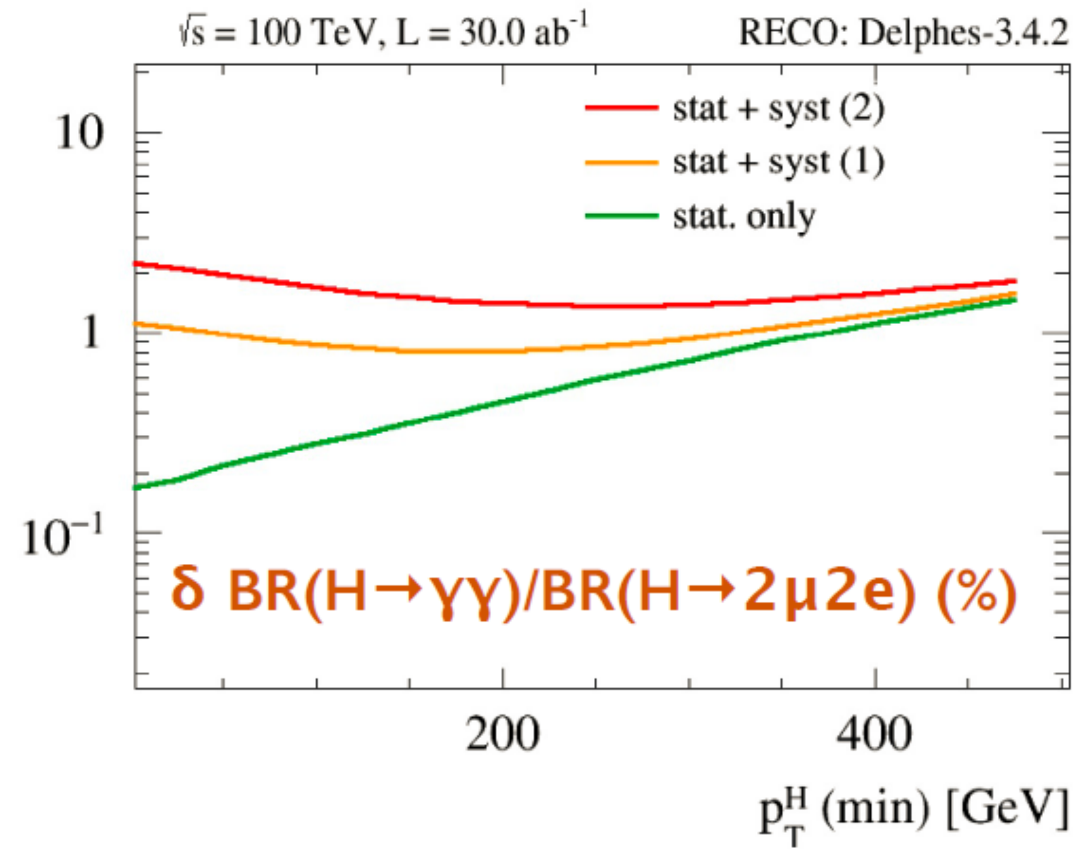
14

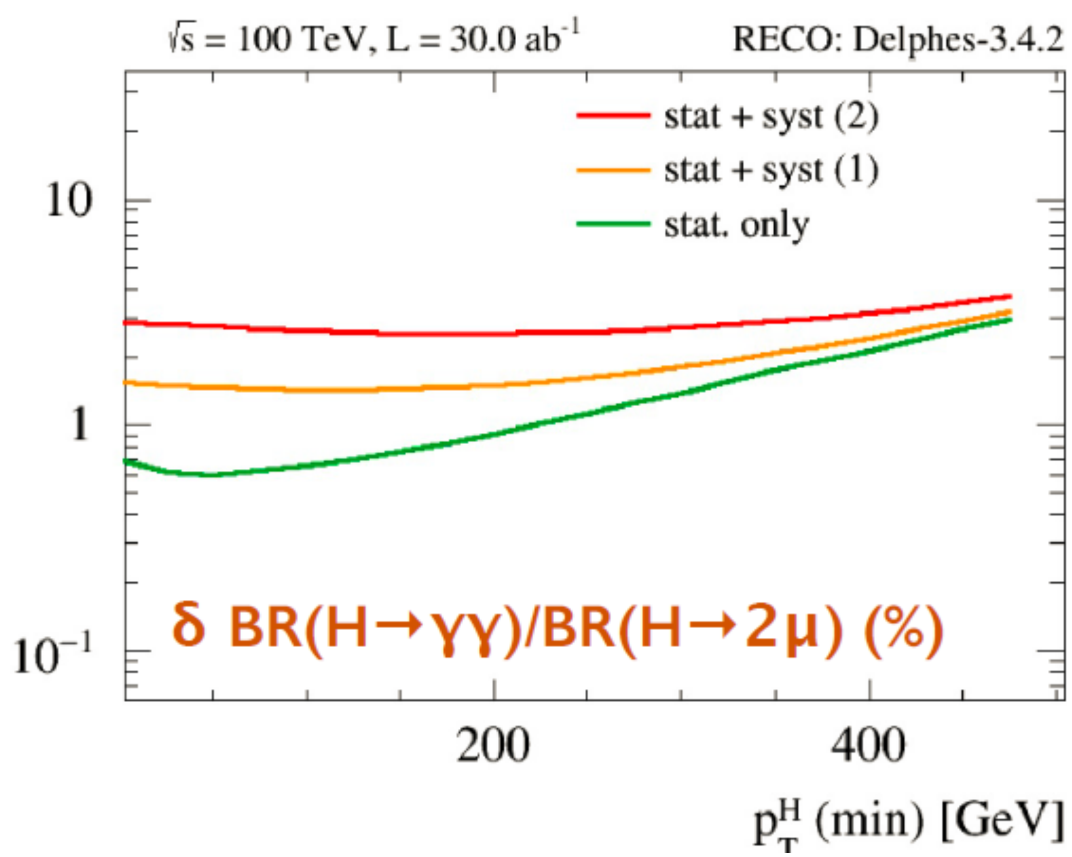
- δy_t (stat + syst TH) ~ 1%

Ratios of BRs

For rare decays (μμ, γγ, γZ) normalize to H→ ZZ well measured at FCC-ee



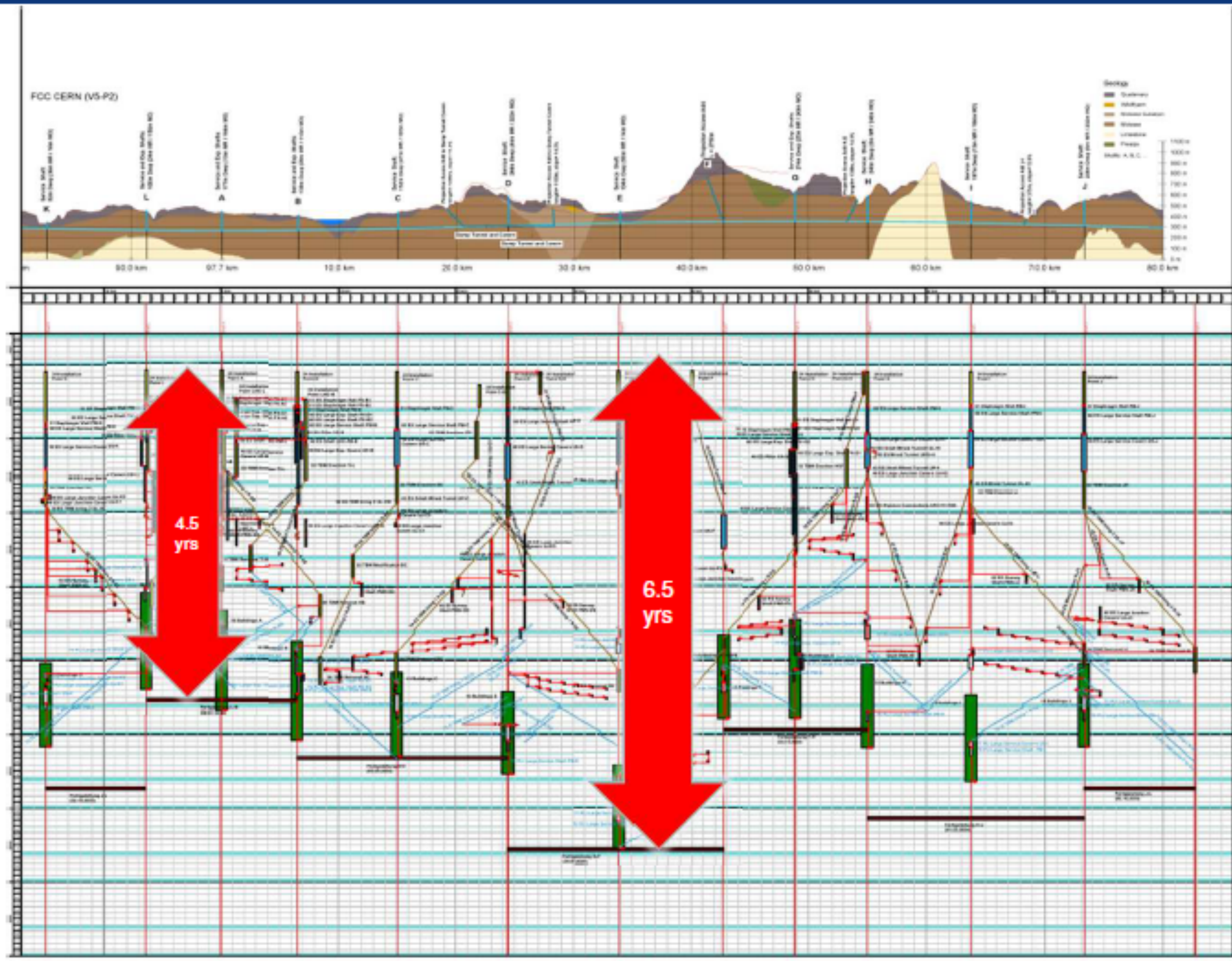


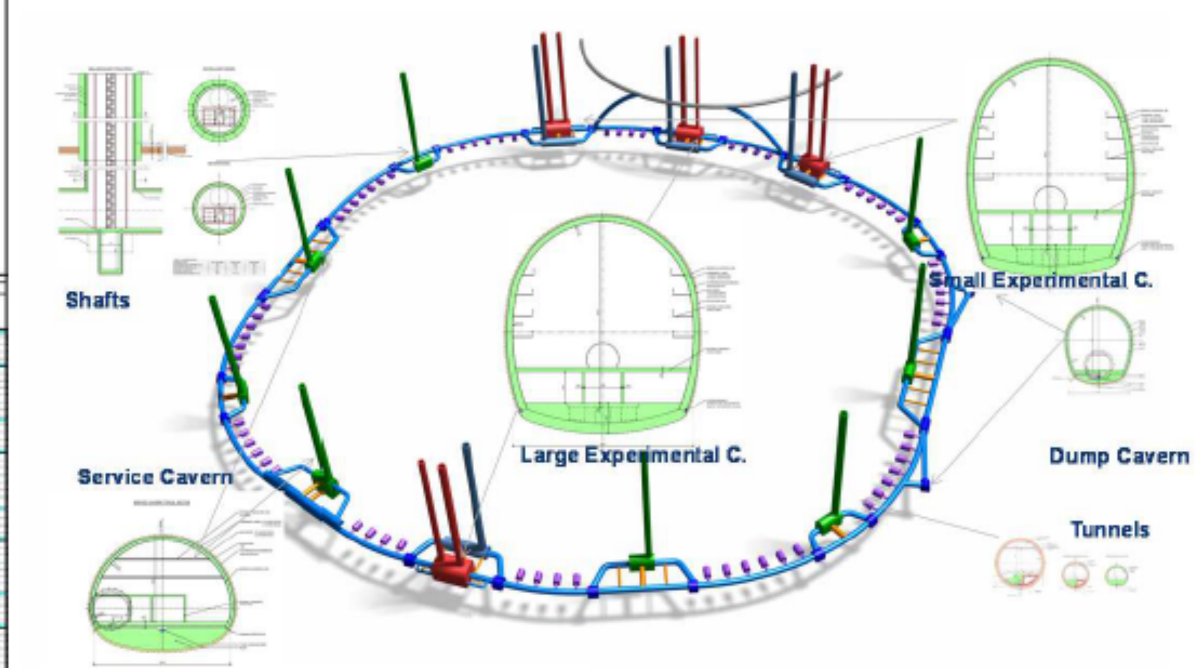


Normalize to BR(4l) from ee at 1% level => absolute sub-% for couplings

M.Selvaggi 13

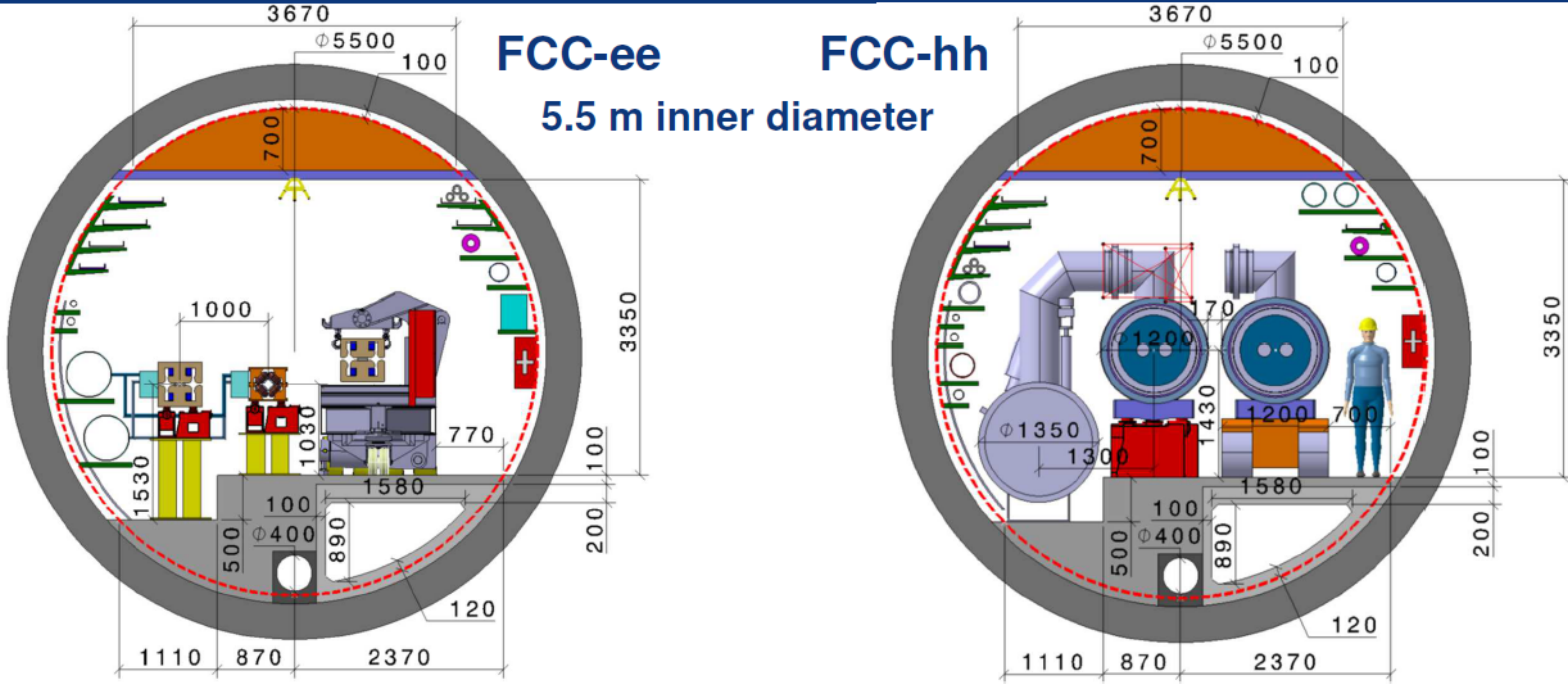
CE schedule studies





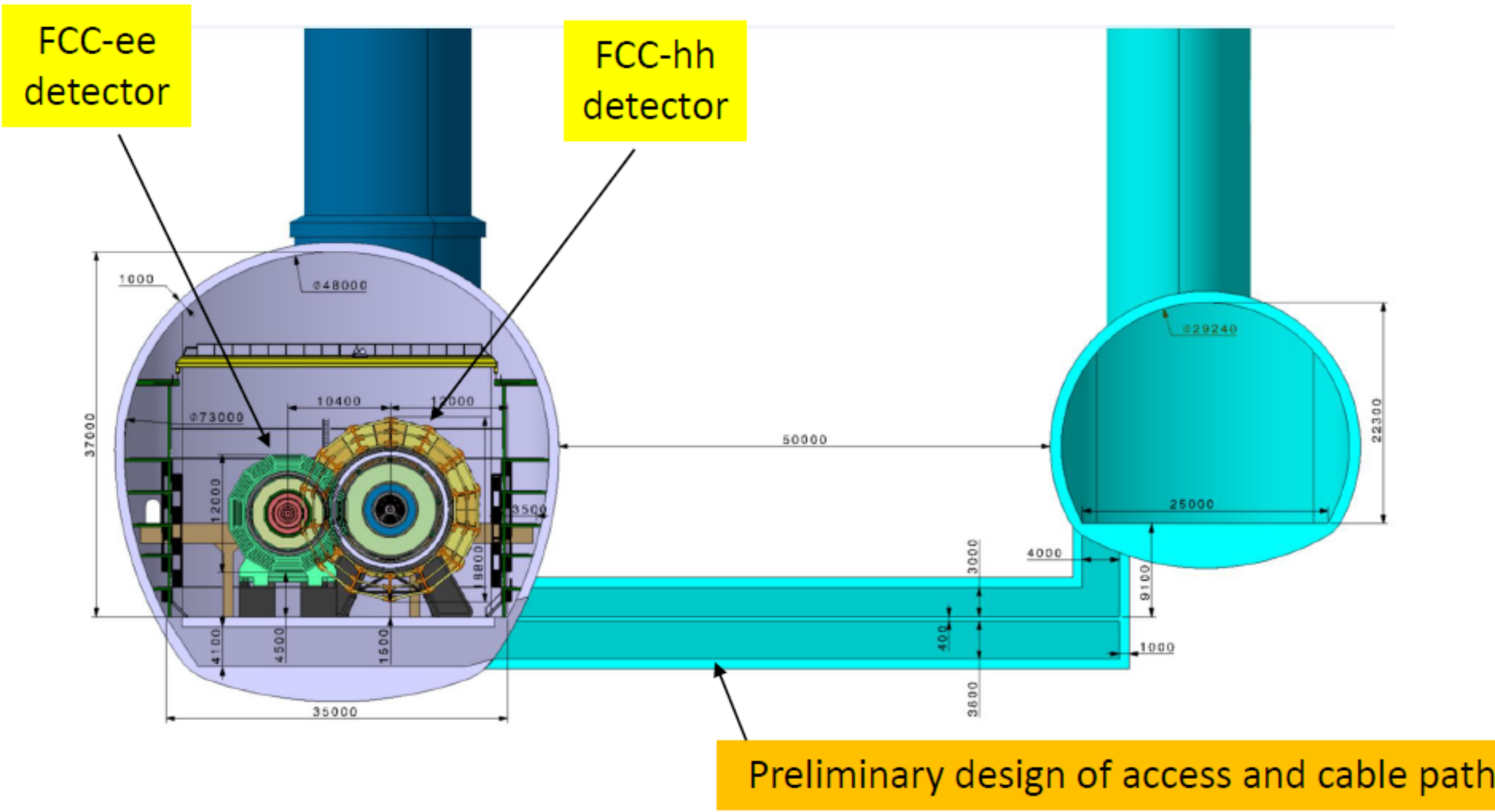
- Total construction duration 7 years
- First sectors ready after 4.5 years

FCC – tunnel integration in arcs

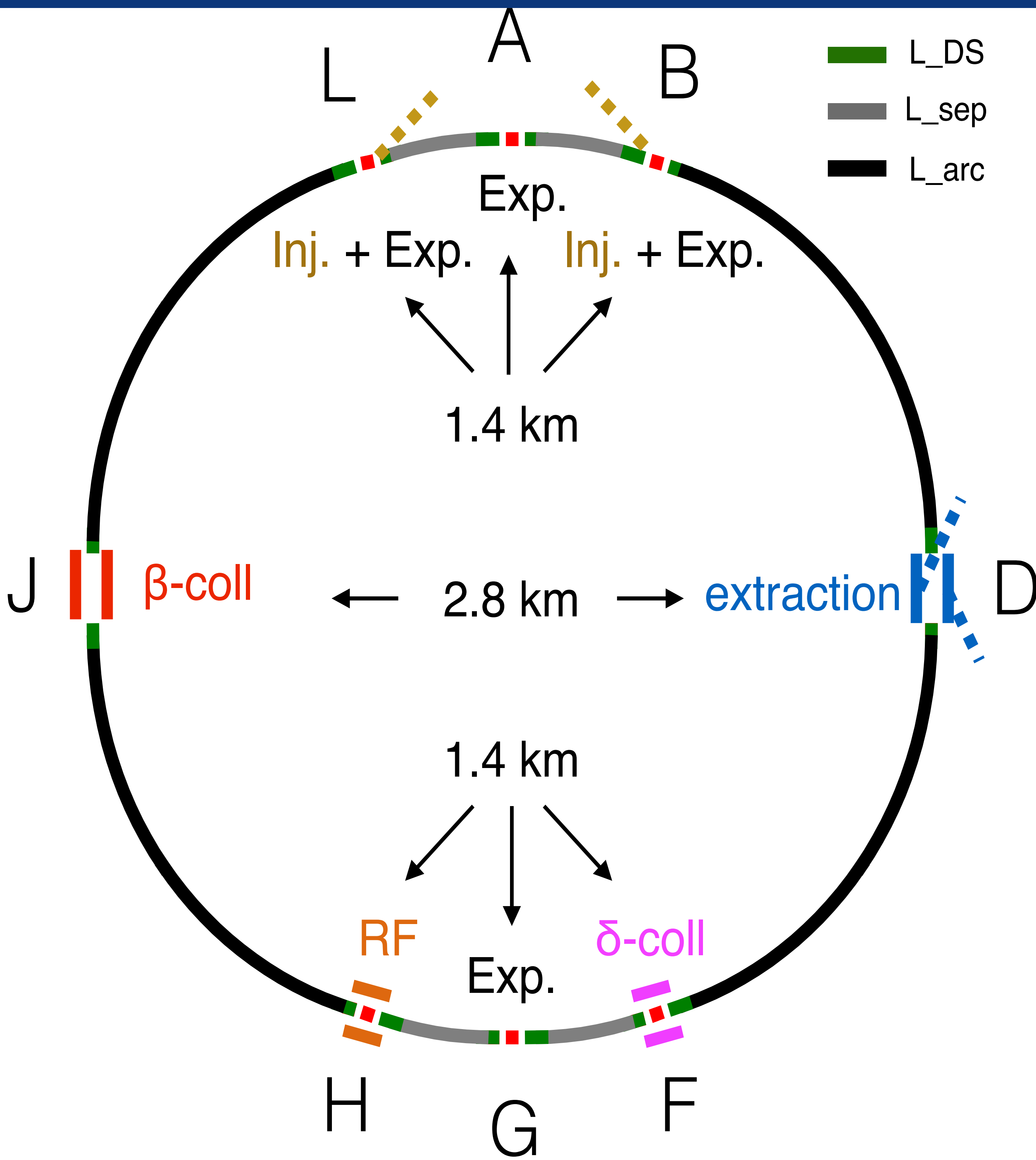


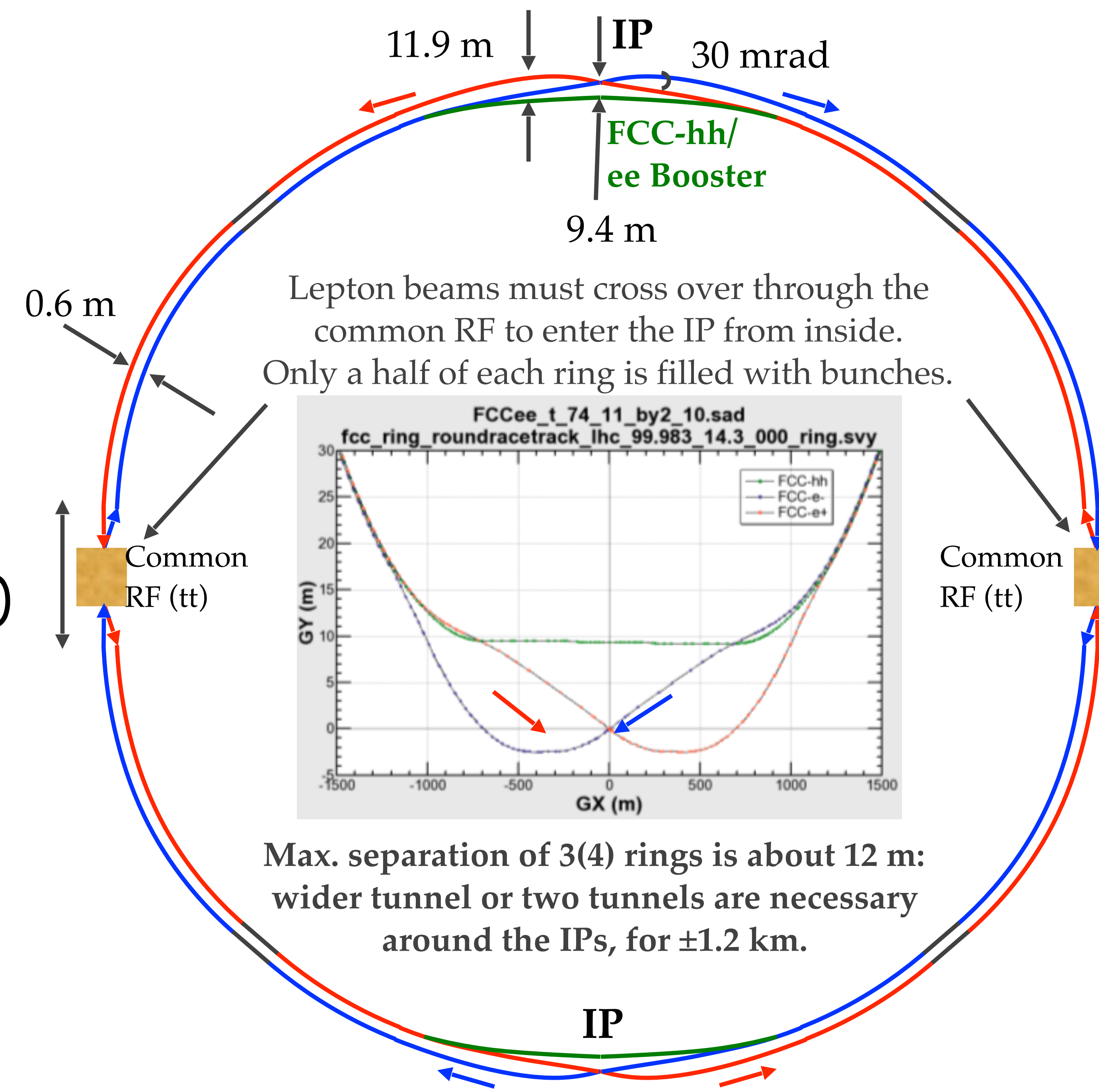
The same cavern

Distance between detector cavern and service cavern 50 m.



common layouts for hh & ee





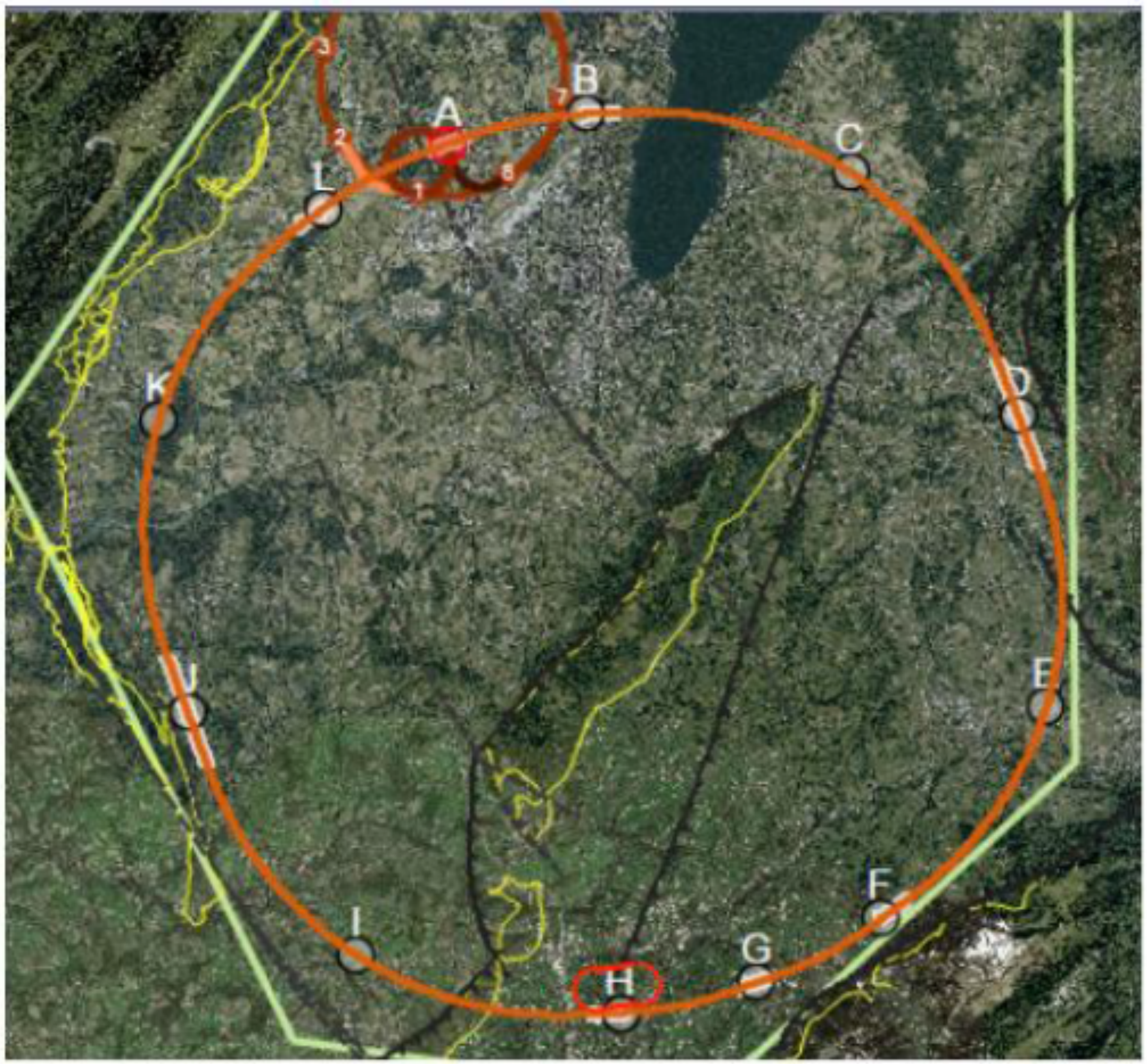
2 main IPs in A, G for both machines

FCC-ee 1, FCC-ee 2,

FCC-ee booster (FCC-hh footprint)

Asymmetric IR for ee, limits SR to expt

FCC-eh and ERL



FCC-eh

LHeC or FCC-eh function as an add-on to LHC or FCC-hh respectively: additional 10 km circumference Electron Recirculating Linac (ERL).

The possibility to collide FCC-ee with FCC-hh is not considered in the framework of the study

In the case of FCC-eh it could profit from the -- then existing -- FCC-hh, and, perhaps, from considerable RF of the -- then dismantled -- FCC-ee

IMPLEMENTATION AND RUN PLAN

"Ampere-class" machine

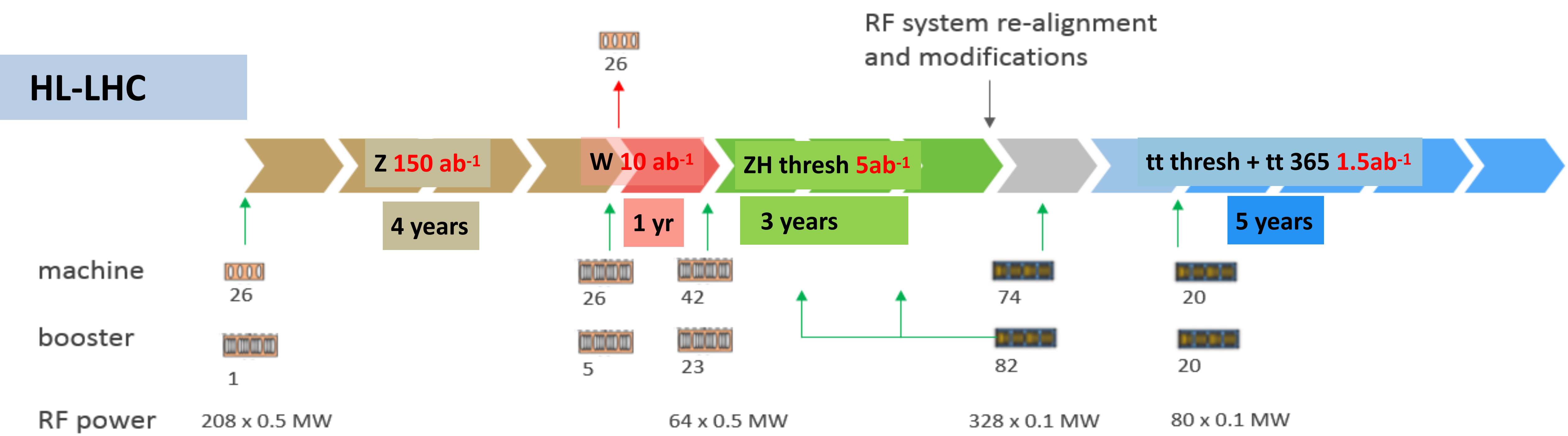
	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

Three sets of RF cavities for FCC-ee & Booster:

- **Installation as LEP (≈30 CM/winter)**
- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities, ≈ 1MW source**
- **high energy (W, H, t): 400 MHz four-cell cavities, also for W machine**
- **booster and t machine complement: 800 MHz four-cell cavities**
- **Adaptable 100 MW, 400 MHz RF power distribution system +High efficiency**

➔ **Spreads the funding profile**



indicative: total ~15 years

O(1/3) of the machine cost comes O(10) years after start

FCC-hh discovery potential

Physics at a 100 TeV pp collider: CERN Yellow Report (2017) no.3

1) Standard Model processes: https://arxiv.org/pdf/1607.01831v1.pdf
2) Higgs and EW symmetry breaking studies: https://arxiv.org/pdf/1606.09408v1.pdf
3) Beyond the Standard Model phenomena: https://arxiv.org/abs/1606.00947
4) Heavy ions at the Future Circular Collider: https://arxiv.org/abs/1605.01389

Now proceeding to ascertain these cross-section calculations with real detector and simulations…

Higgs events rates

SM Higgs: event rates at 100 TeV

	$gg \to H$	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\ \mathrm{ab}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

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HIGGS PHYSICS

Higgs couplings g_{Hxx} precisions

hh, eh precisions assume
SM or ee measurements
FCC-hh : H→ ZZ to serve
as cross-normalization

for ttH, combination of
±4% (model dependent)HL-LHC
with FCC-ee will lead to
ttH coupling to ± 3%...
model independent!

for g_{HHH} investigating now : the
possibility of reaching 5σ
observation at FCC-ee:
4 detectors
+ recast of running scenario

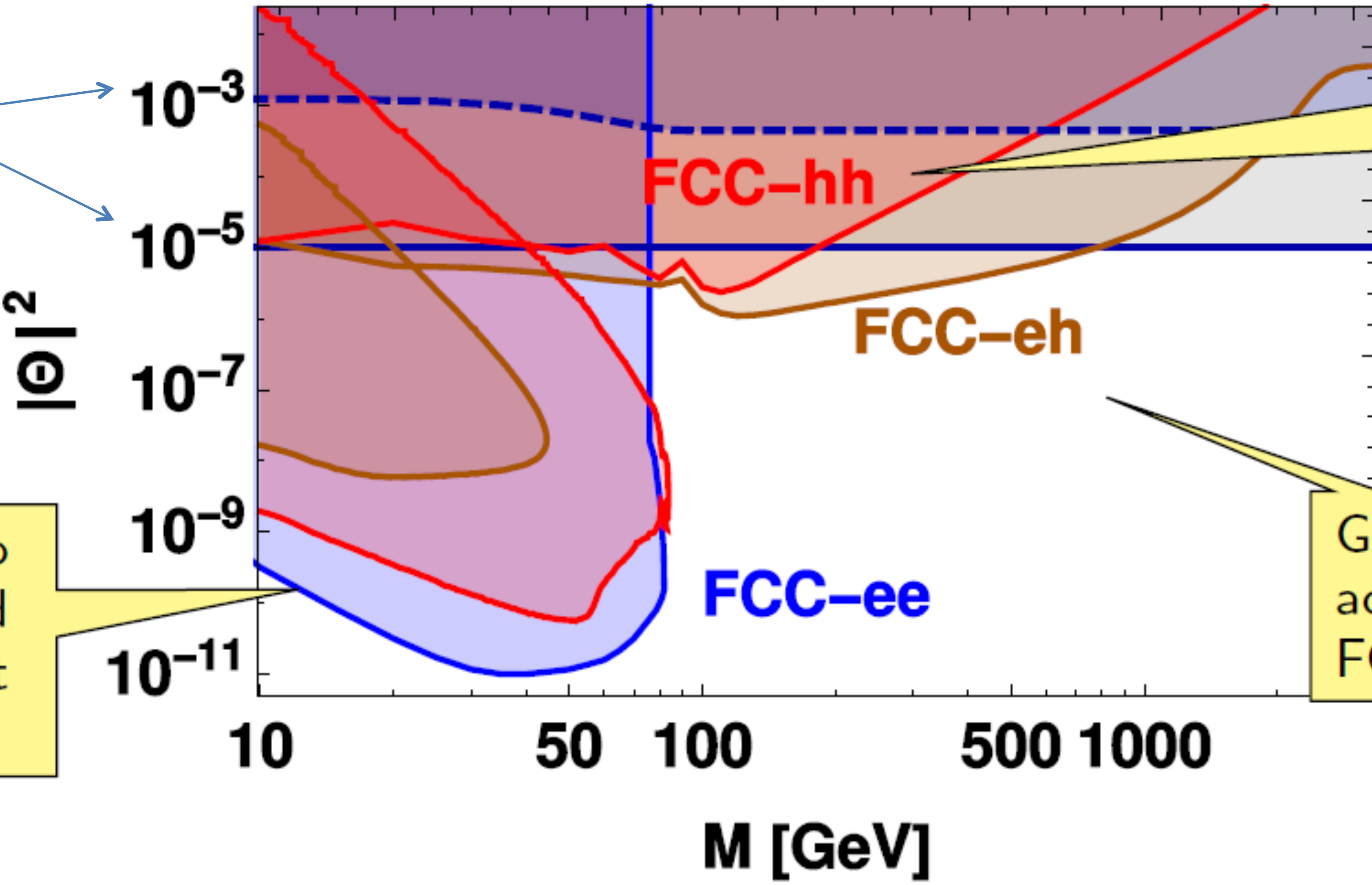
g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.22 %**	**< 1%** *	
WW	**0.47%**		
Γ_H	**1.6%**		
γγ	4.2%	**<1%**	
Zγ	--	**1%**	
ttH	13%	**1%**	
bb	**0.7%**		0.5%
ττ	**0.8%**		
cc	**0.7%**		1.8%
gg	**1.0%**		
μμ	8.6%	**1-2%**	
uu,dd	H→ ργ?	H→ ργ?	
ss	H→ φγ ?	H→ φγ ?	
ee	**ee → H**		
HH	40%	**~3-5%**	20%
inv, exo	<0.55%	**10^{-3}**	5%

Summary

Another example of Synergy and complementarity while ee covers a large part of space very cleanly , its either 'white' in lepton flavour or the result of EWPOs etc Observation at FCC –hh or eh would test flavour mixing matrix!

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search

EWPO sensitivity up to very high mass scales



FCC-hh able to test all flavour combinations.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Good sensitivity reach from FCC-hh & FCC-eh.

detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

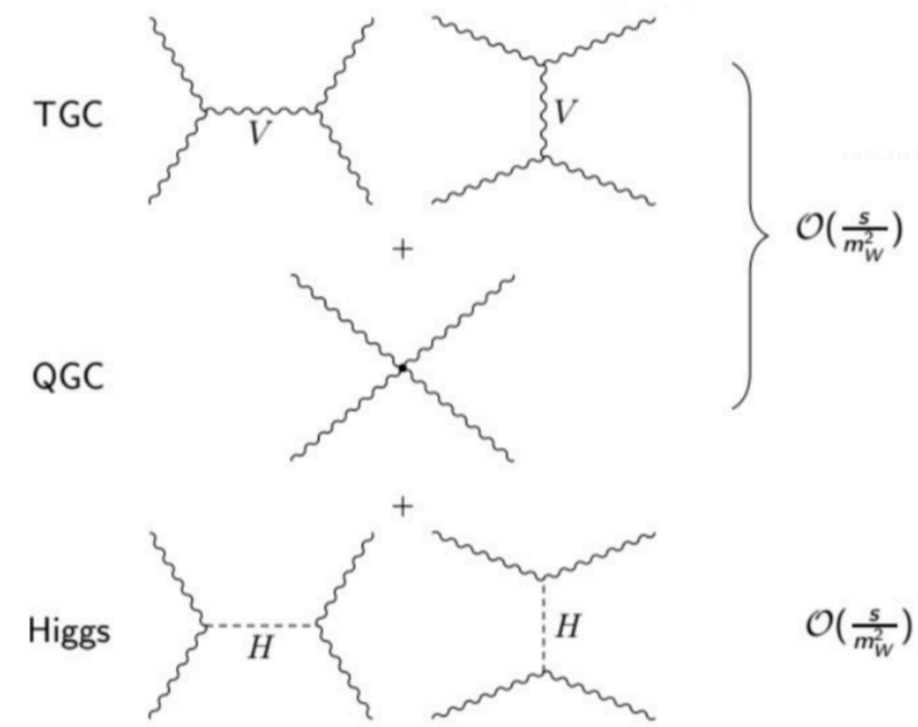
Examples of complementarity

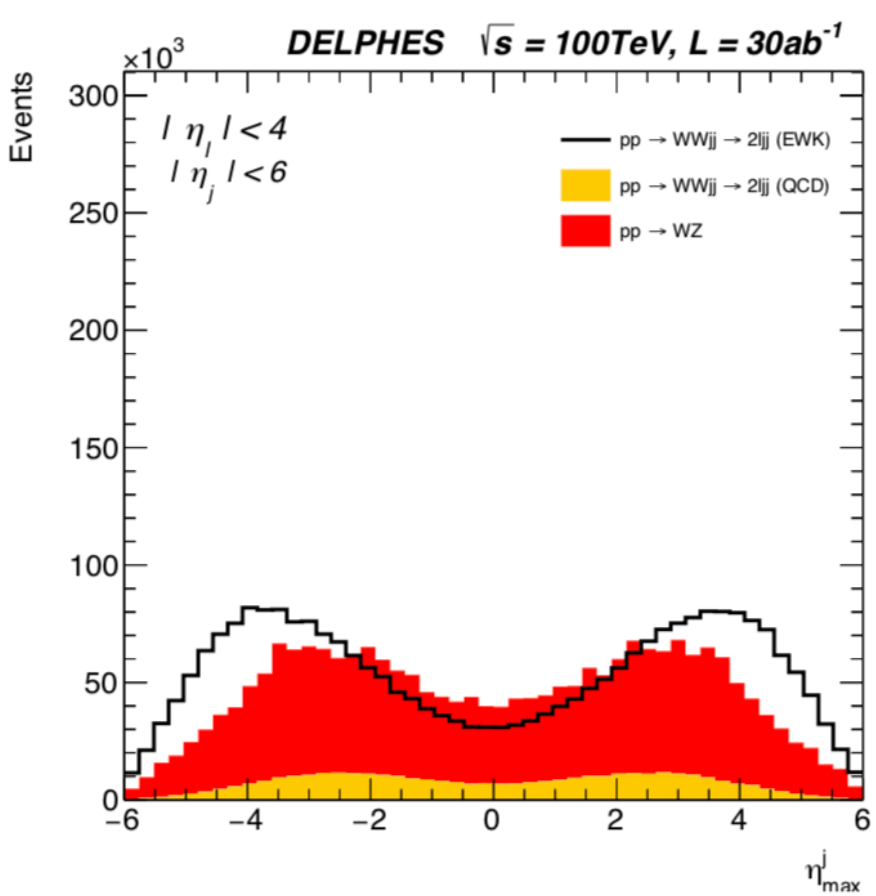
- **Higgs Physics**
  - ee → ZH fixes Higgs width and HZZ coupling , (and many others)
  - FCC-hh gives huge statistics of HH events for Higgs self-coupling and ttH and rare decays, including invisible.
- **Search for Heavy Physics**
  - ee gives precision measurements (m_Z m_W to < 0.6 MeV, m_{top} 10 MeV, etc…) sensitive to heavy physics up to … 100 TeV (for weak couplings)
  - FCC-hh gives access to direct observation at unprecedented energies Also huge statistics of Z, W H and top → rare decays
- **QCD**
  - ee gives $\alpha_s \pm 0.0002$ (R_{had} at Z, W and taus) also H → gg events (gluon fragmentation!)
  - ep provides structure functions and $\alpha_s \pm 0.0002$
  - all this improves the signal and background predictions for new physics signals at FCC-hh
- **Heavy Neutrinos**
  - ee: very powerful and clean, but flavour-blind
  - hh and eh more difficult, but potentially flavour sensitive

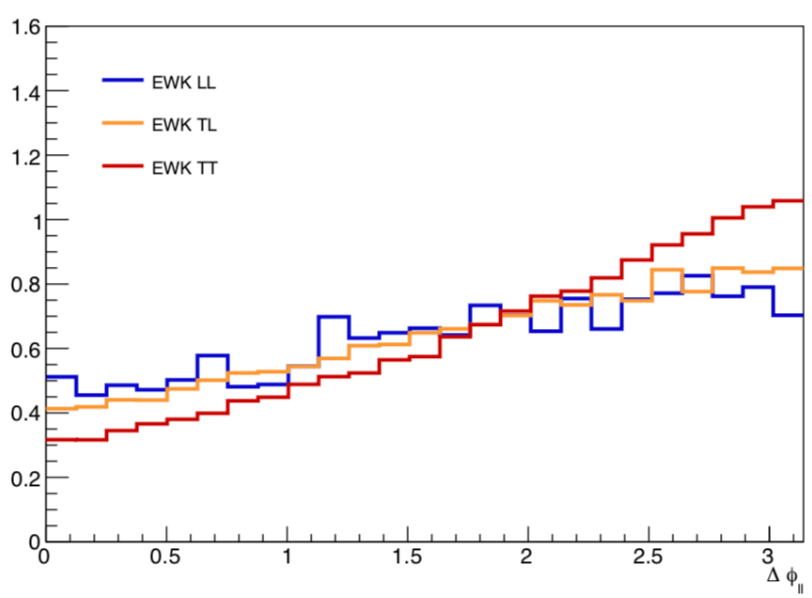
NB this is very much work in progress!!

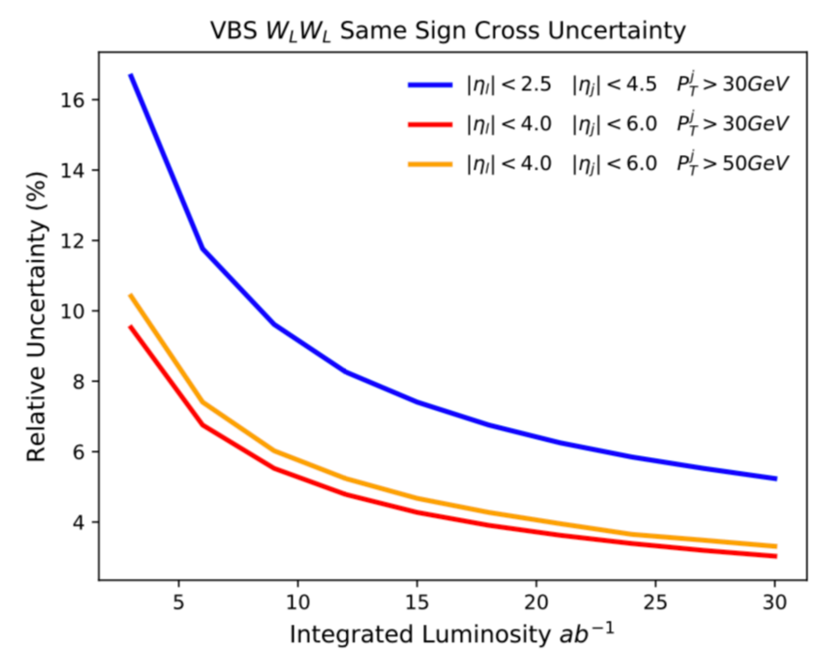
Vector Boson Scattering (VBS)

- First opportunity to **measure precisely the V_LV_L** component that **unitarizes** VBS at high energy (barely 3σ at HL-LHC)
- Sets constraints on **detector acceptance** (fwd jets at **η≈4**)
- Study **$W^{+/-}W^{+/-}$ (same-sign)** channel
- **Large WZ** background at FCC-hh
- **3-4% precision** on **W_LW_L scattering** achievable with full dataset!





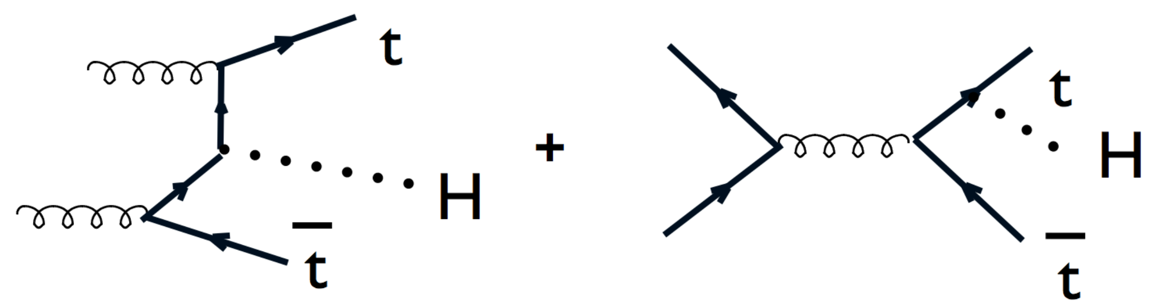




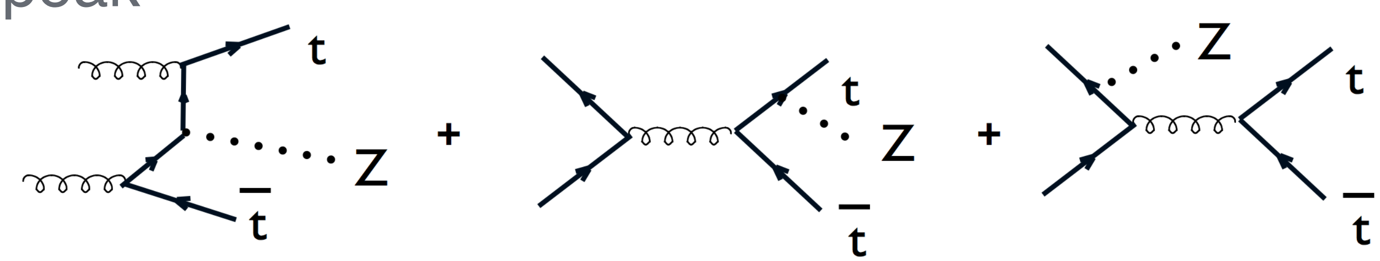
Top Yukawa

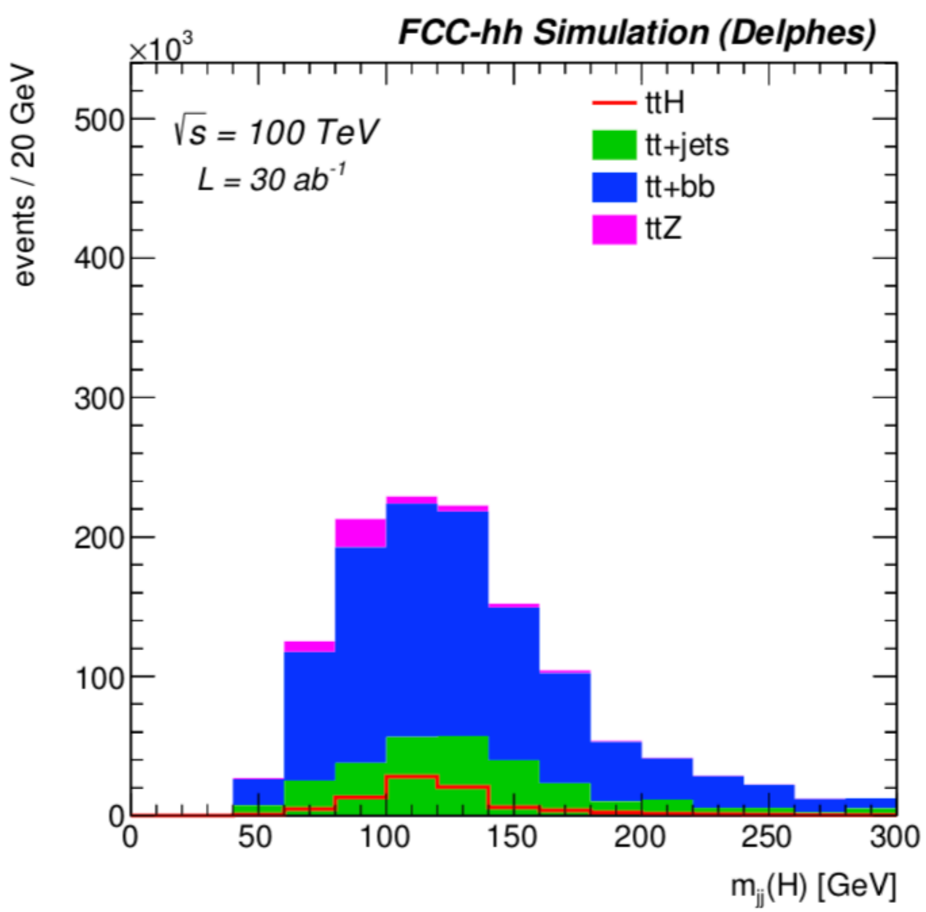
- Production ratio **σ(ttH)/σ(ttZ)**
- Predicted **1%** precision [1507.08169]
- Measure **σ(ttH)/σ(ttZ)** in **H/Z→bb** mode in the boosted regime, in the **semi-leptonic** channel
- Perform simultaneous fit of double **Z** and **H** peak

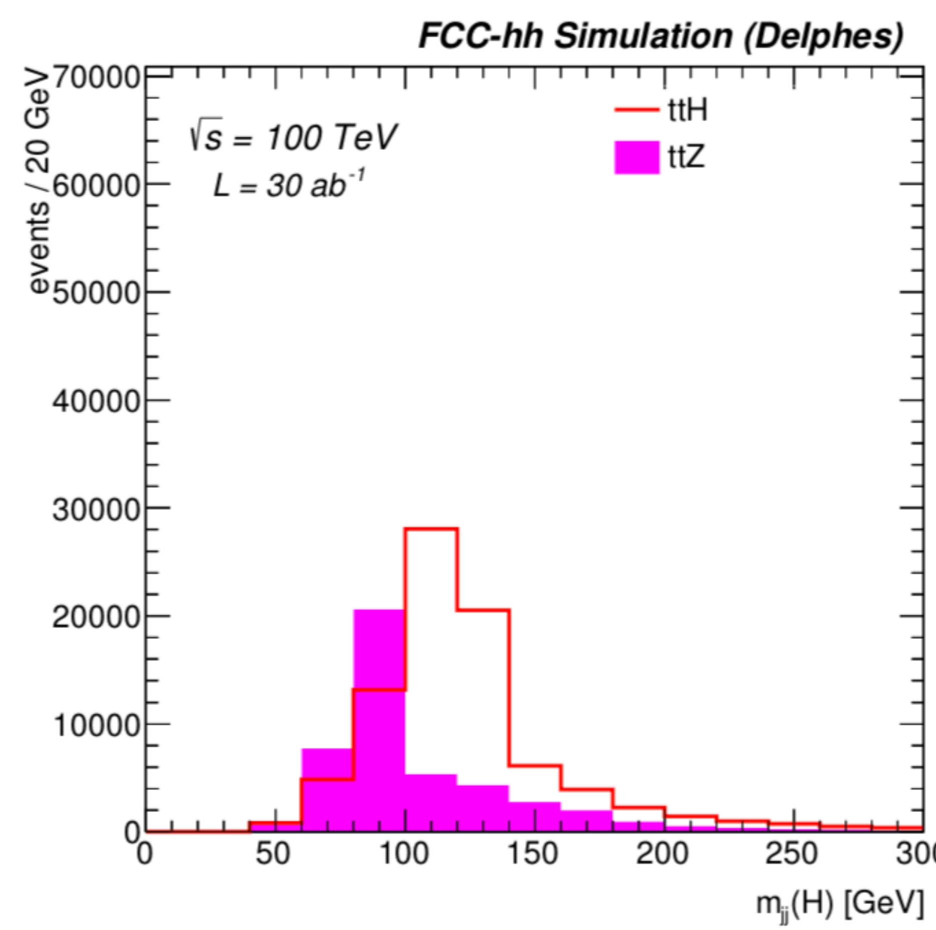
ttH



ttZ







λ_H at FCC-hh

λ_H at the few percent level

Table 1.2: Target precision for the parameters relative to the measurement of various Higgs couplings, the Higgs self-coupling λ, Higgs branching ratios B and ratios thereof. Notice that lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

Observable	Parameter	Precision (stat)	Precision (stat+syst)
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.5%	0.9%
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.2%	1.6%
$\mu = \sigma(t\bar{t}H) \times B(H \to b\bar{b})$	$\delta\mu/\mu$	1%	tbd
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)B(H \to b\bar{b})$	$\delta\lambda/\lambda$	3.5%	5.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.6%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.6%	1.4%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

λ_H at FCC-hh

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To reach a precision on λ_H at the few percent level requires a linear collider of at least 3 TeV

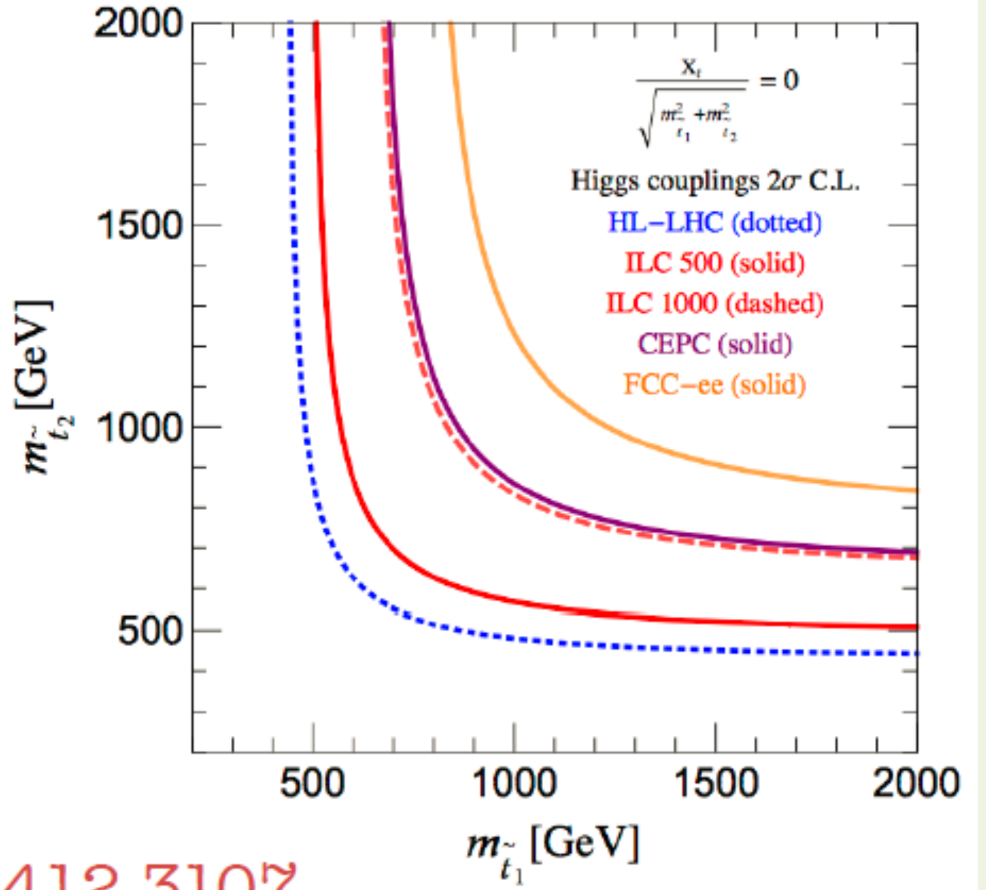
(ILC 500 GeV can obtain a ±30% indication and CLIC 3 TeV estimate is ±10%)

Supersymmetry

In supersymmetry top partner is "stop squark".

FCC-ee

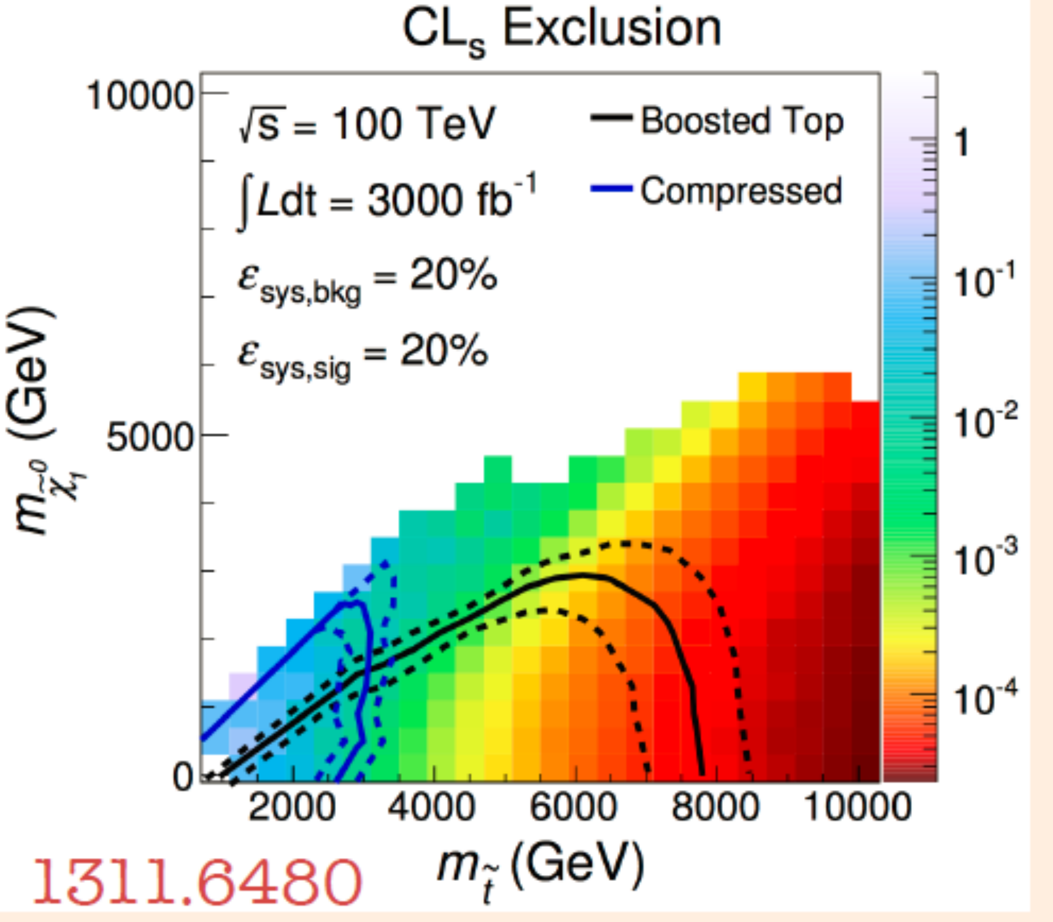
Coloured and charged, stops modify Higgs couplings:



1412.3107

FCC-hh

And show up directly at hadron colliders:



1311.6480

FCC-ee: Indirect, but more "spectrum independent", for a model.
FCC-hh: Direct confirmation, but direct might be hidden.