Higgs studies for FCC-ee

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ILC@DESY General Project Meeting
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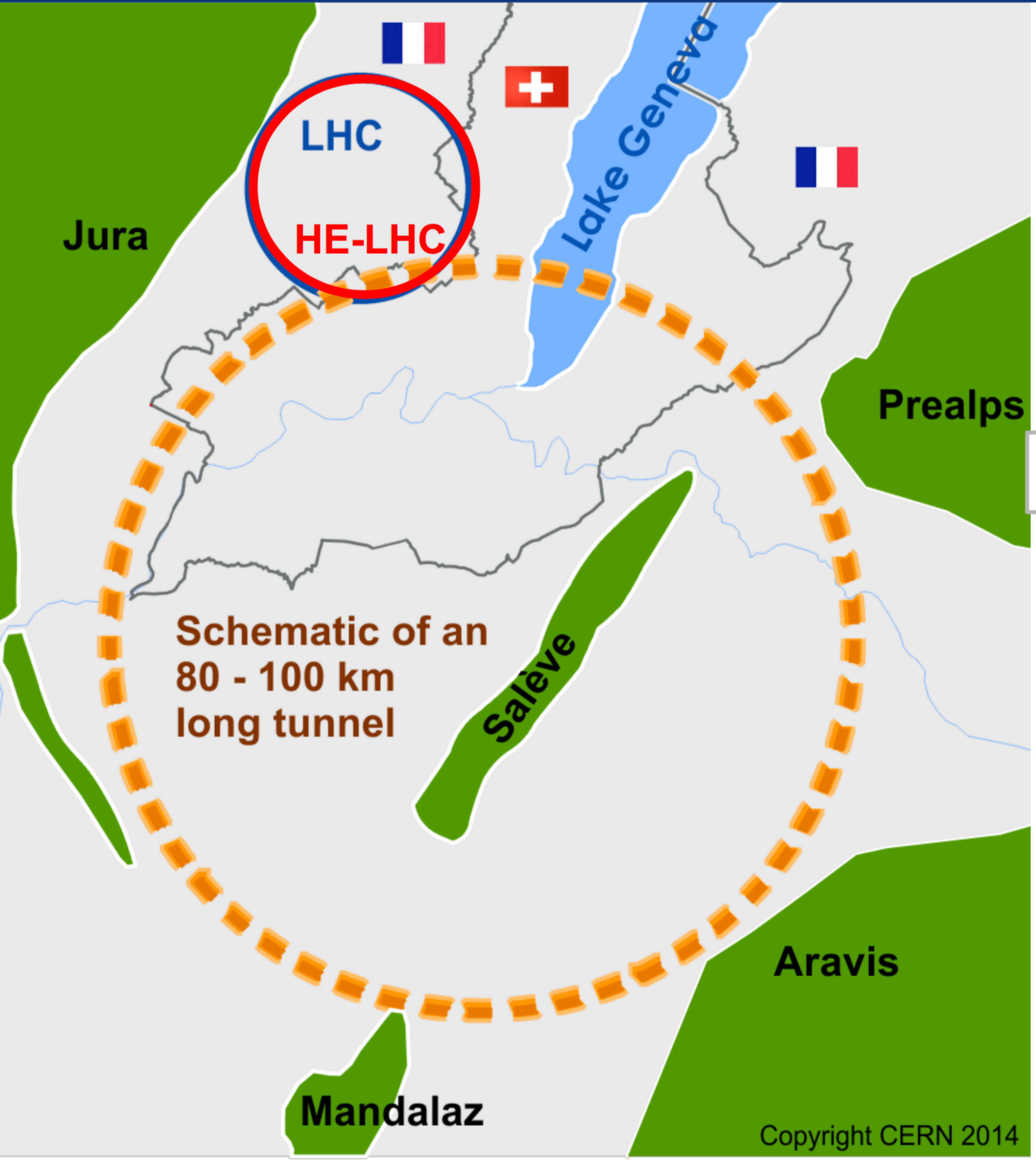
Future Circular Collider (FCC) Study

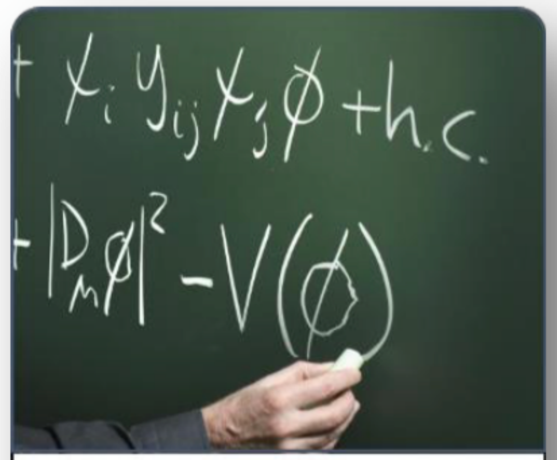


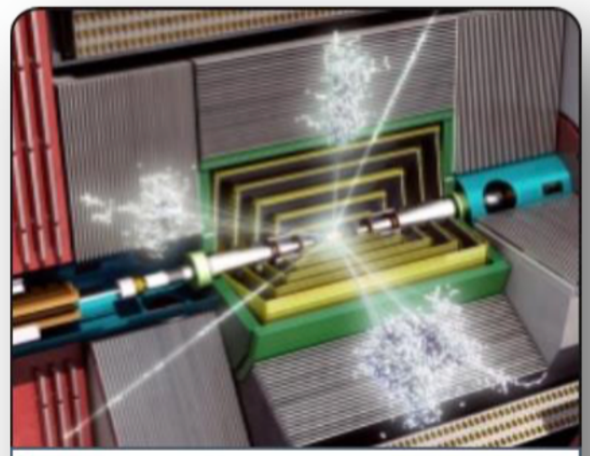
International FCC collaboration (CERN as host lab) to study:

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

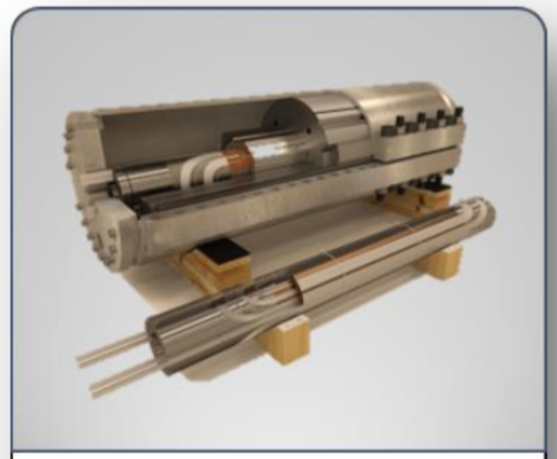
~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e⁻ from ERL


Physics Cases


Experiments

Collider Designs


R&D Programs


Infrastructures

Cost Estimates

Slide from Michael Benedikt

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar	
beam energy [GeV]	45	80	120	175	182.5
beam current [mA]	1390	147	29	6.4	5.4
no. bunches/beam	16640	1300	328	40	33
bunch intensity [10^{11}]	1.7	2.3	1.8	3.2	3.35
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.2
total RF voltage [GV]	0.1	0.75	2.0	8.8	10.3
long. damping time [turns]	1273	236	70	23	20
horizontal beta* [m]	0.15	0.2	0.3	1	1
vertical beta* [mm]	0.8	1	1	1.6	1.6
horiz. geometric emittance [nm]	0.27	0.84	0.63	1.34	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.7	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 7.5	3.15 / 5.3	2.75 / 3.82	2.76 / 3.78
luminosity [10^{34} cm^{-2}s^{-1}]	>200	>32	>7	>1.7	>1.5
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / 24	38 / 18	37 / 24	36 / 25

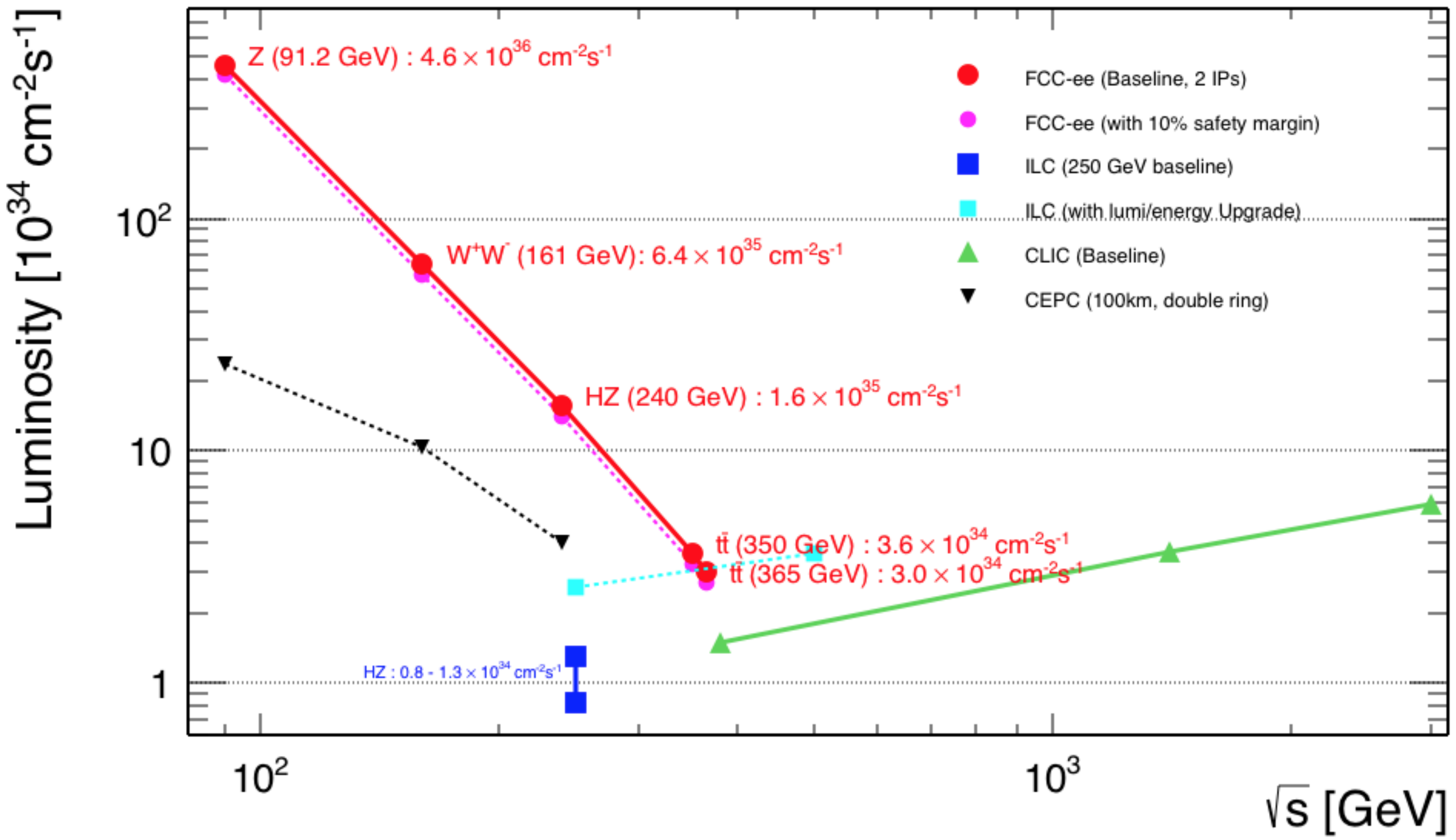
FCC-ee operation model

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ yr	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	32	8.3 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: **1 year**				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.5	0.38 ab^{-1}/year	**1.5 ab^{-1}**	**4**

total program duration: 14 years ***- including machine modifications***

phase 1 (*Z*, *W*, *H*): 8 years, **phase 2 (top): 6 years**

FCC-ee baseline luminosities



Not only about luminosity and c.m.s. energy:

- Beam polarisation
- Beamstrahlung and beam energy spread
- Bunch structure (important for detectors)
- Number of interaction points

In each detector:

- 100 000 Z / second
- 10 000 W / hour
- 1500 Higgs bosons / day
- 1500 top quarks / day

In total:

- 5×10^{12} Z
- 10^8 WW
- 10^6 HZ
- 10^6 tt

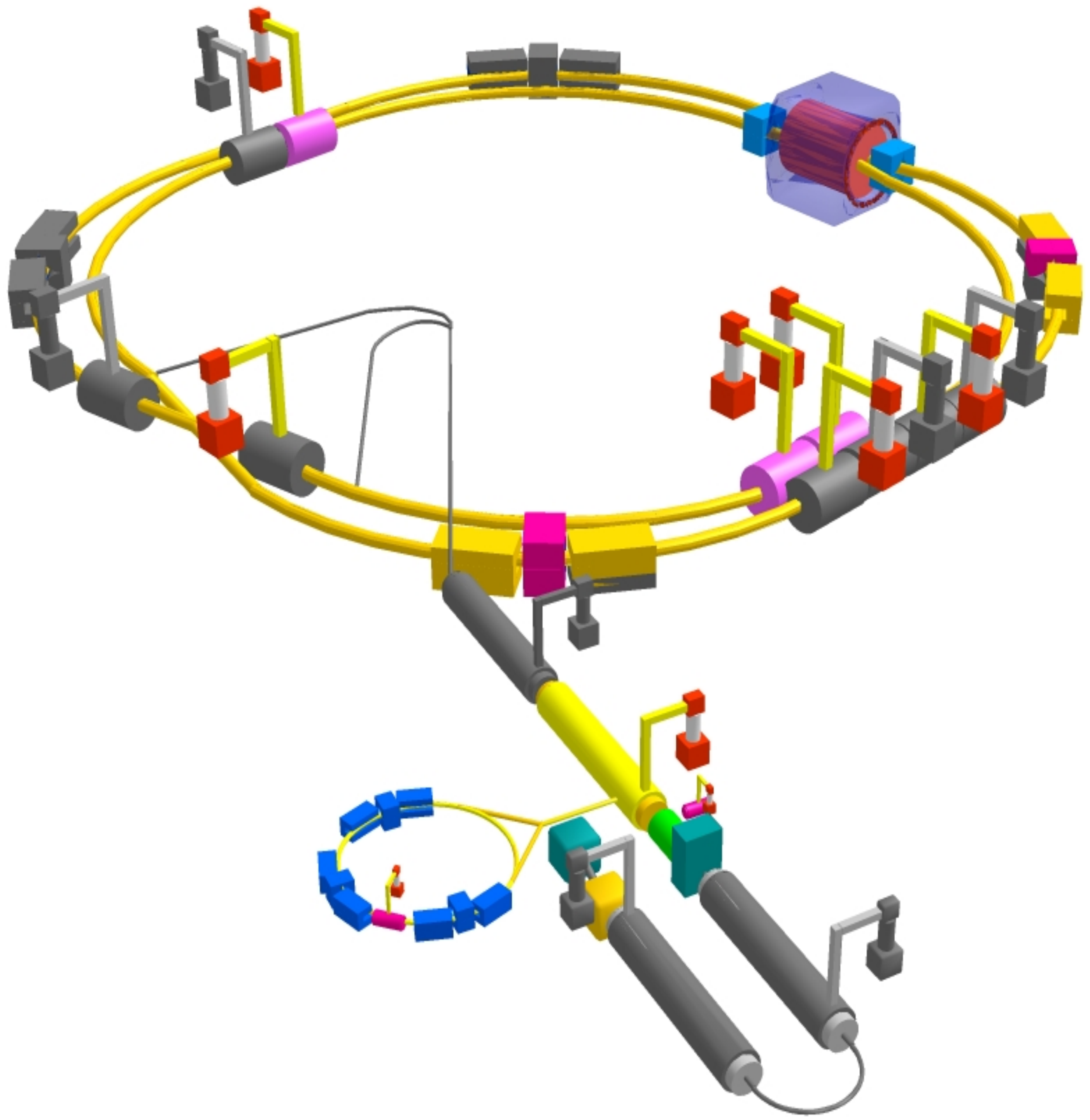
FCC-ee baseline luminosities

Backed up by a solid design study (2014-2017)

Most operational parameters are being commissioned at SuperKEKB

Why is the luminosity so much higher than LEP?

- Design inspired by B-factories
  - Fix 100 MW Synchrotron Radiation (SR) at all energies
  - Two separate rings for e+ and e-
  - Larger ring (×4)
  - Asymmetric IP
  - Strong vertical focusing
  - Crab-waisted crossing
  - Larger energy acceptance
  - Continuous injection



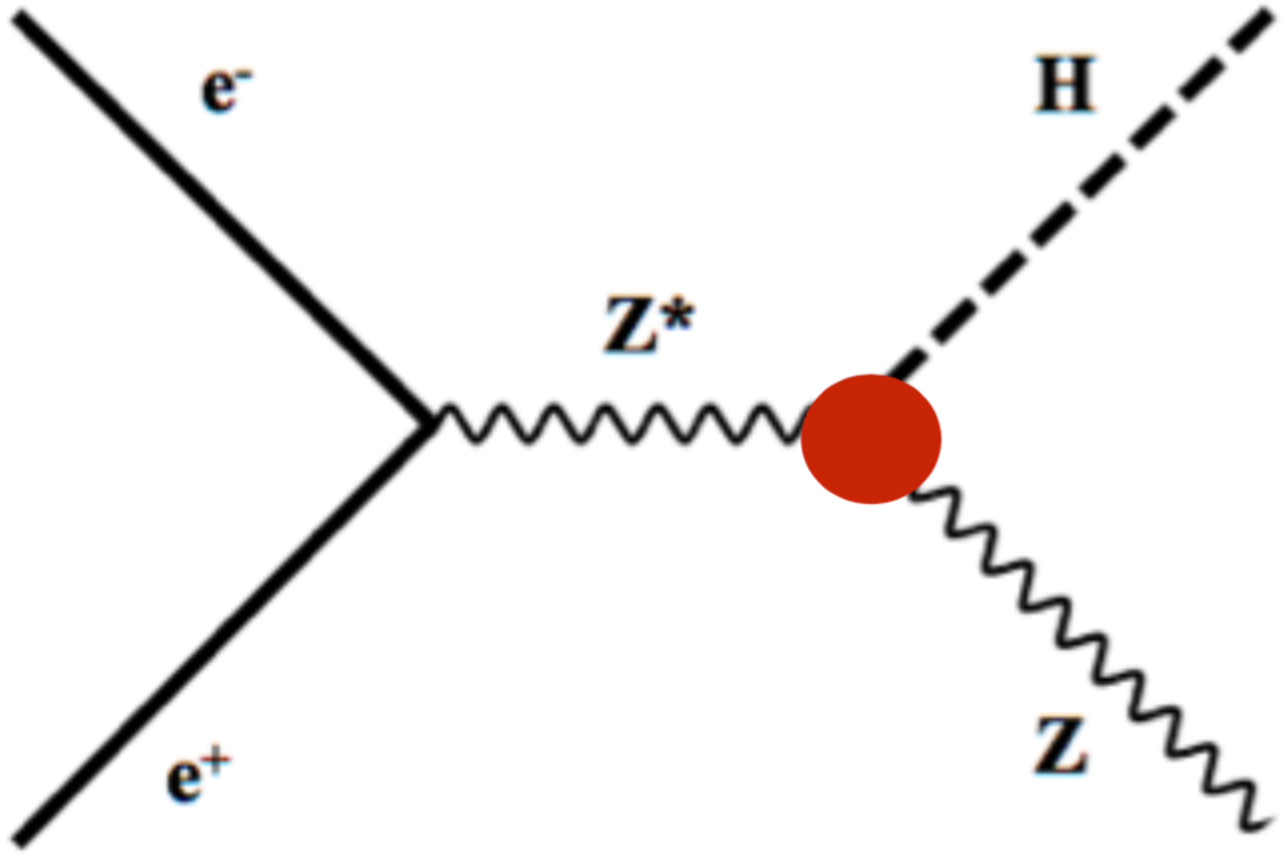
For more details, talk from P. Janot:
https://indico.cern.ch/event/666889/

Higgs coupling to Z bosons

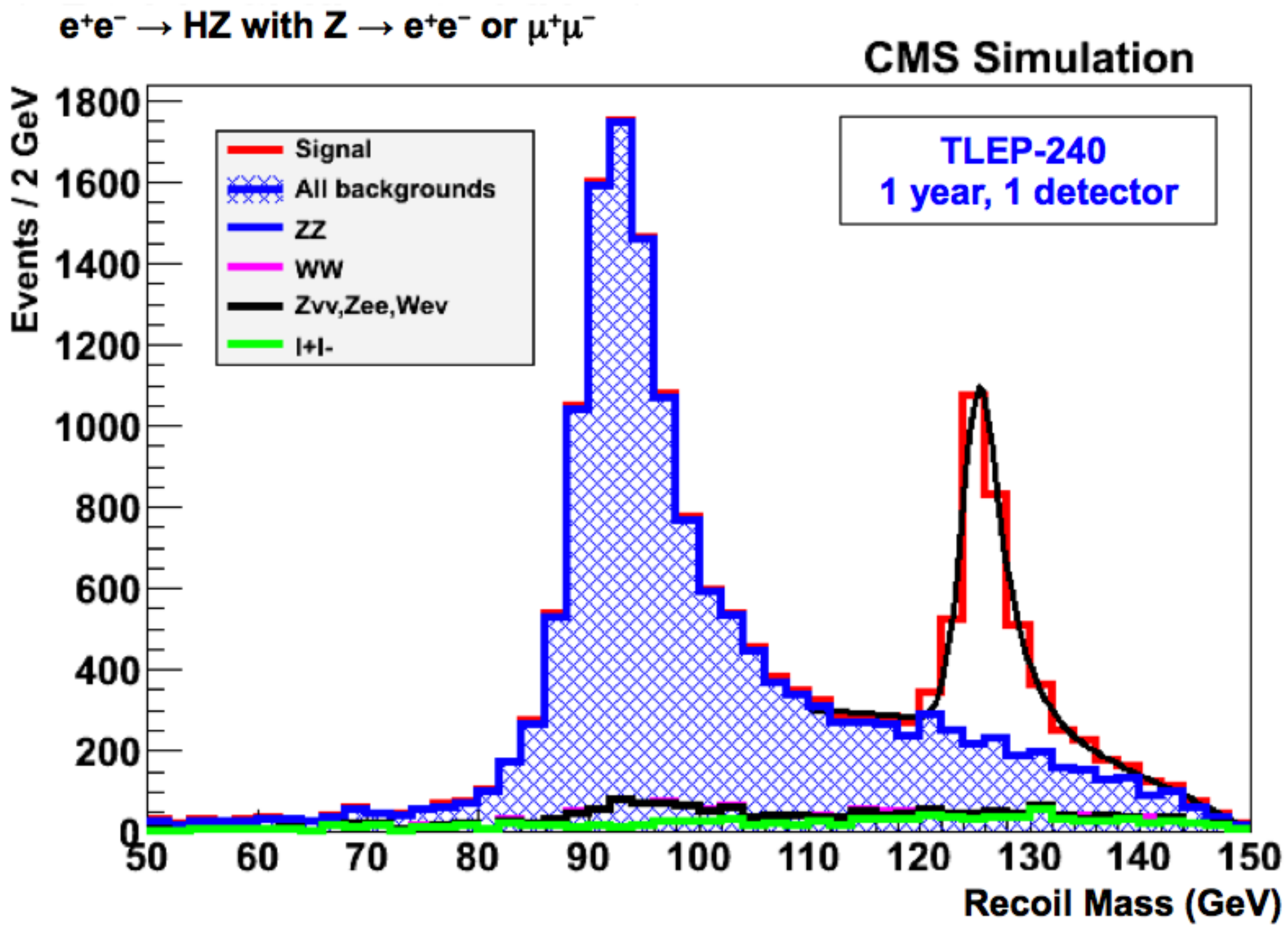
Model independent measurement of HZ coupling with recoil method

- Decay mode independent Higgs boson tagging
- Only leptonic decays at 240 GeV considered so far

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



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

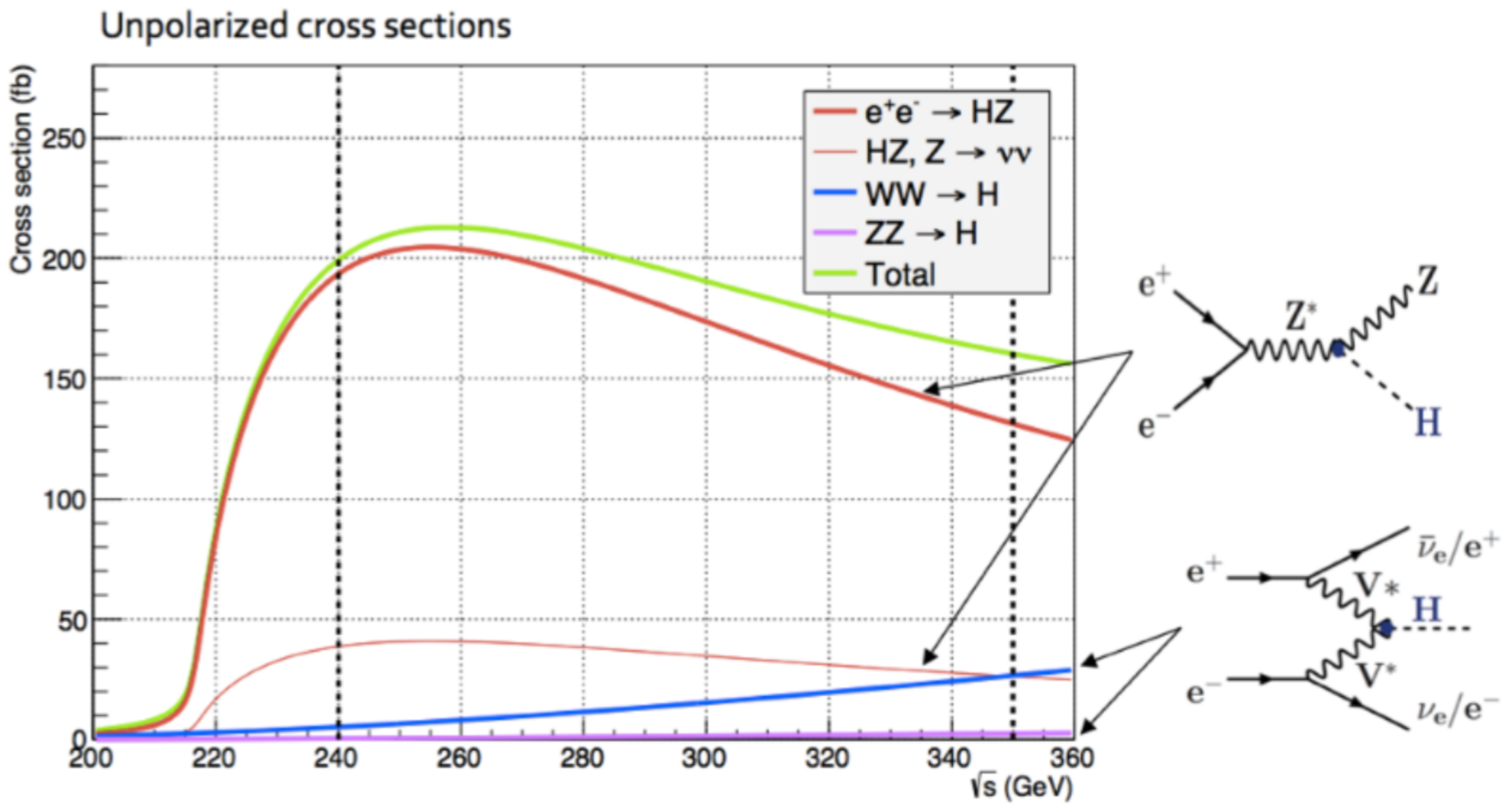


Higgs boson total width

Extract Higgs boson total width from a combination of measurements in a model independent way

1) Tagging Higgs final states

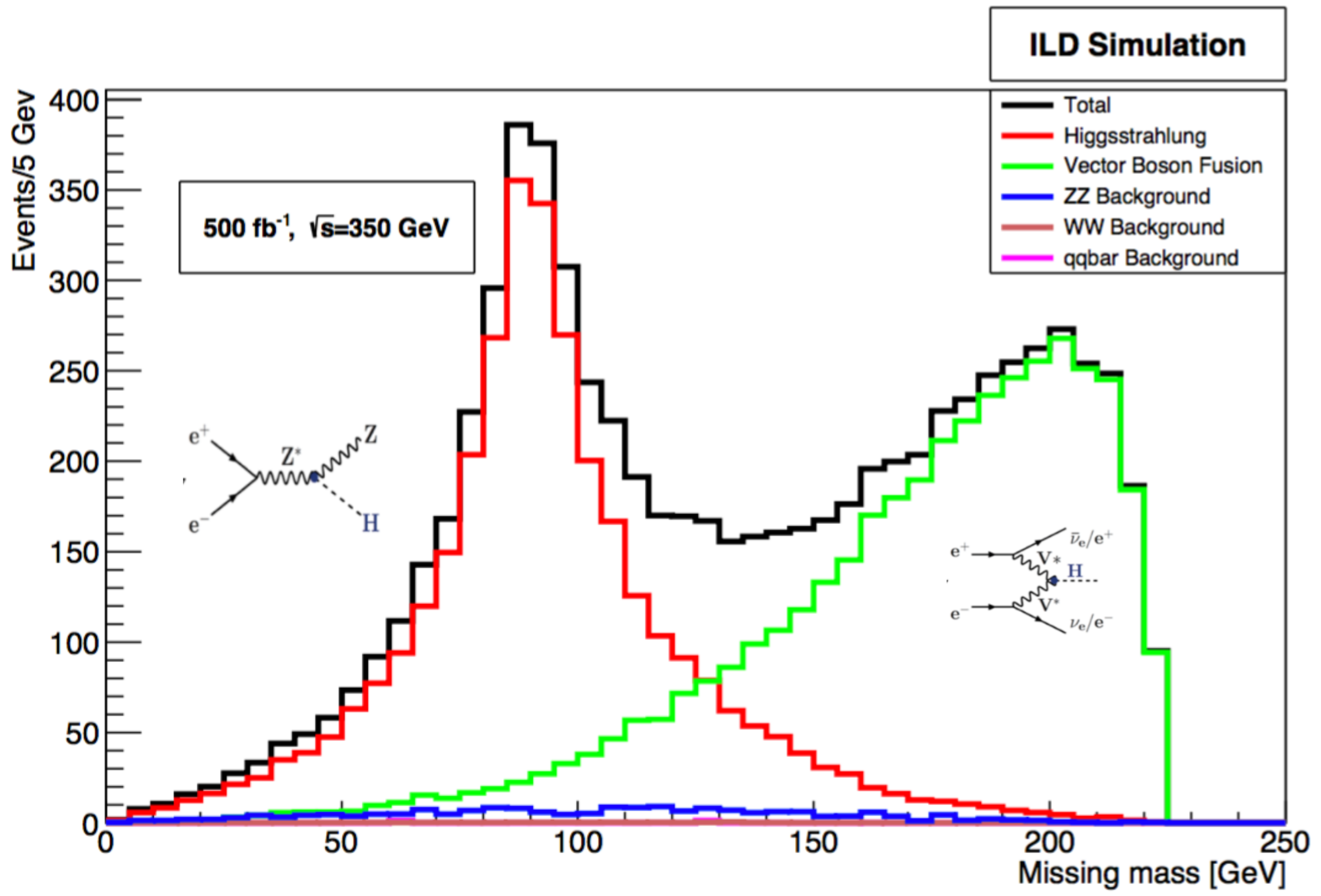
$$\sigma(ee \to ZH) \cdot BR(H \to ZZ) \propto \frac{g_{HZ}^4}{\Gamma}$$



2) Measurement of VBF production at 350 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) Combined fit

Higgs boson couplings

Measurements based on same scheme as at the ILC

- Absolute coupling measurements enabled by HZ cross section and total width measurement
- Tagging individual Higgs final states to extract various Higgs couplings

Most complete study from TLEP case study arXiv:1308.6176

- Full simulation with CMS detector, apart from:
  - Vertex detector similar to a linear collider (lifetime-based c-tagging)
  - Luminosity measurement with Bhabha scattering
- Statistical uncertainties shown for current operation model with 2 IP ($5\ ab^{-1}$ at 240 GeV and $1.5\ ab^{-1}$ at 350GeV)
- Data at 350 GeV further constrain total width
  - Only used H→bb in WW fusion production so far

in %	FCC-ee 240 GeV	+FCC-ee 350 GeV
g_{HZ}	0.21	0.21
g_{HW}	1.25	0.43
g_{Hb}	1.25	0.64
g_{Hc}	1.49	1.04
g_{Hg}	1.59	1.18
$g_{H\tau}$	1.34	0.81
$g_{H\mu}$	8.85	8.79
$g_{H\gamma}$	2.37	2.12
Γ_H	2.61	1.55

Model-independent fit, statistical uncertainties only

Higgs boson couplings

Factor ~10 improvement for most couplings compared to HL-LHC

- Model dependent fit for HL-LHC results
- Results for one LHC experiment
- Nice complementarity (and synergy) with e^+e^- colliders

Periodic returns to the Z-peak for calibrations

Experimental precision must be accompanied by theoretical precision programme

- Control of parametric uncertainties (c.f. arXiv:1404.0319)
- Higher order calculations for EWPO
- Significant work needed for Higgs production in e^+e^- (2 loop EW)
- Higgs decays mostly under control to meet experimental precision

in %	HL-LHC	FCC-ee
g_{HZ}	2-4	0.21
g_{HW}	2-5	0.43
g_{Hb}	5-7	0.64
g_{Hc}	-	1.04
g_{Hg}	3-5	1.18
$g_{H\tau}$	5-8	0.81
$g_{H\mu}$	5	8.79
$g_{H\gamma}$	2-5	2.12
Γ_H	5-8%	1.55

arXiv:1307.7135 arXiv:1308.6176

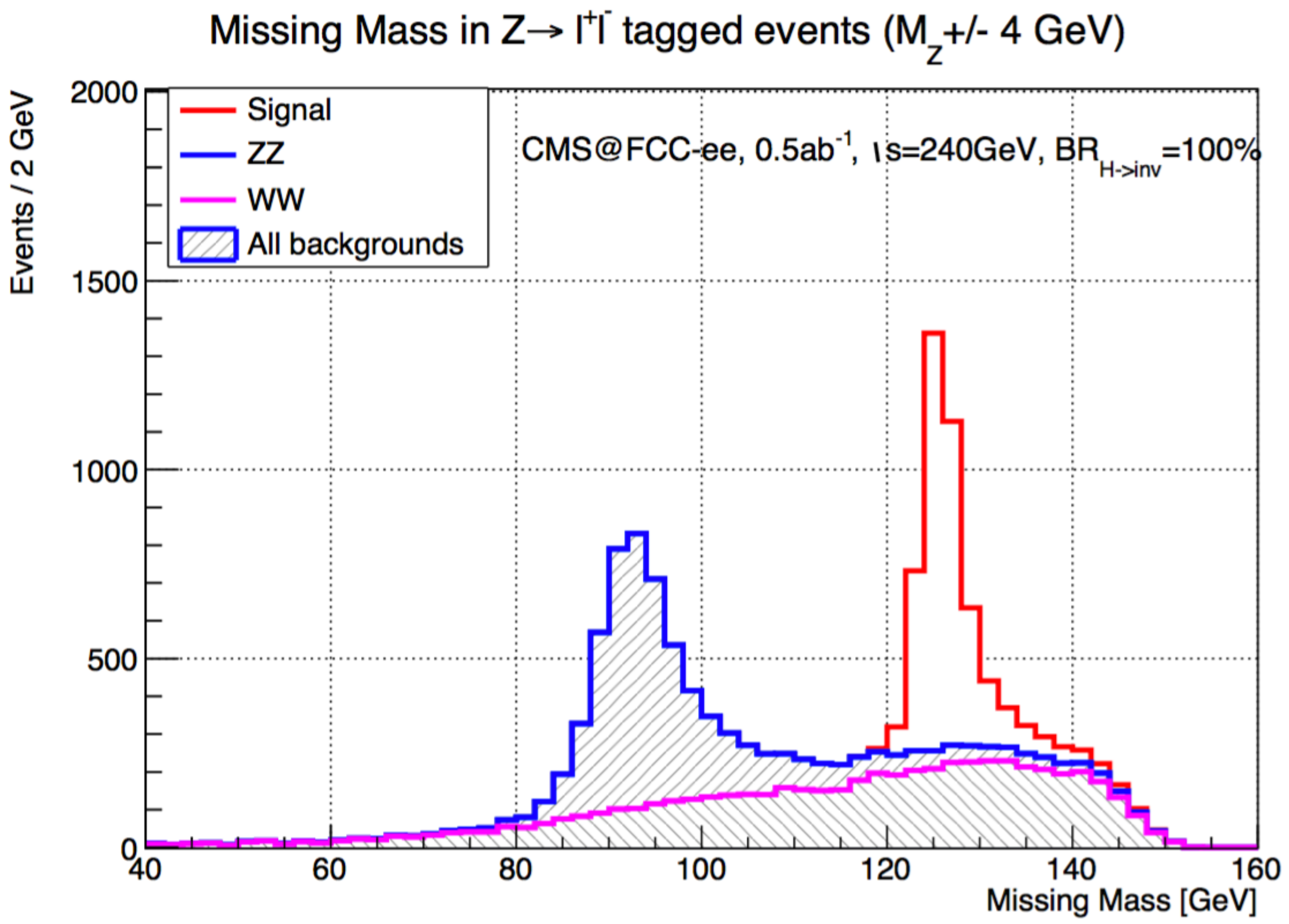
FCC: model-independent fit, statistical uncertainties only

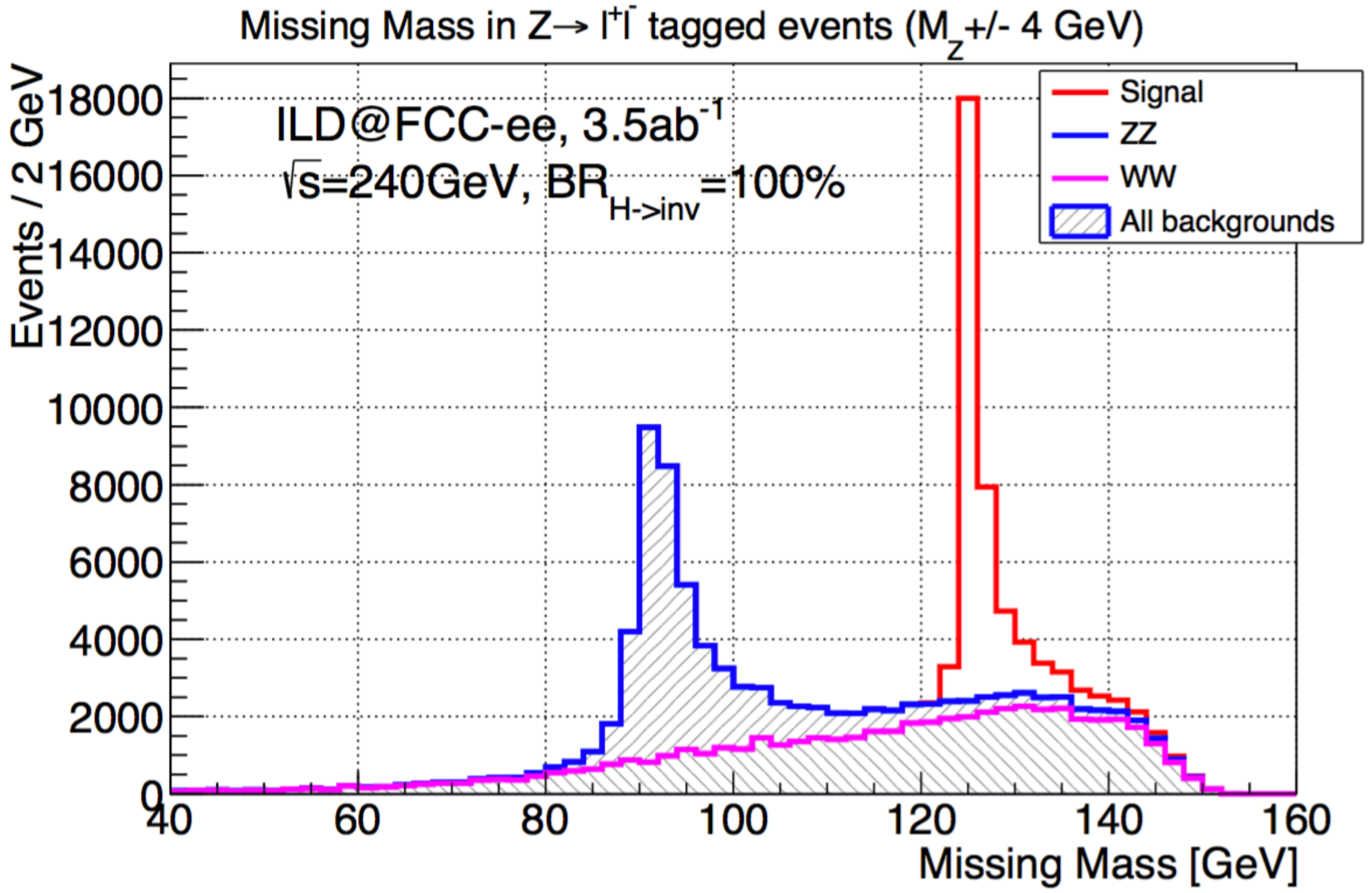
Towards the FCC CDR

FCC CDR to be ready by the end of 2018

Current focus of the group is to re-compute / study Higgs measurements in order to:

- Analyse impact of detector performance
- Establish Higgs results with a detector proposed for FCC-ee
- Lower priority: improve results by adding missing channels, e.g. Z(had)H and analysis optimisation





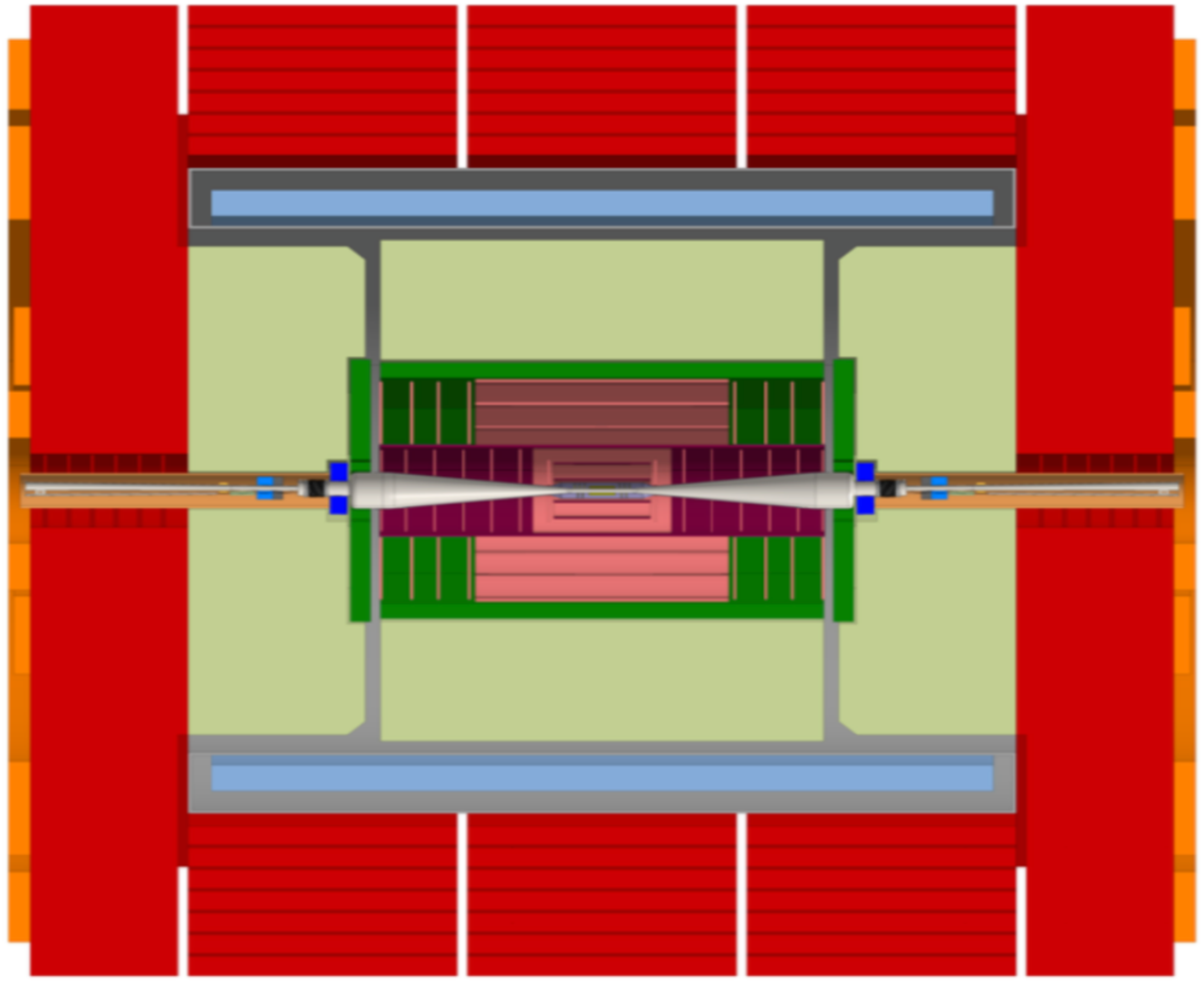
	$BR_{95\%limit}$	$BR_{5\sigma}$
CMS-like	$0.92 \pm 0.32\%$	$2.5 \pm 0.2\%$
ILD-like	$0.63 \pm 0.22\%$	$1.7 \pm 0.1\%$

For 3 ab^{-1}

FCC-ee detector

The CLIC detector is being adapted for FCC-ee

- Smaller beam pipe radius (15mm)
  - Inner pixel layer closer to IP
- Not instrumented from 0 to 150 mrad
- Smaller B field
  - Larger tracker radius (1.5 → 2.2m)
- Smaller energies
  - Thinner HCAL (4.2m → 3.7m)
- Continuous operation
  - Increased cooling
  - Thicker pixel/tracker layers
  - Reduced calorimeter granularity



Further detector concept dedicated for FCC-ee (with light wire drift chamber and dual readout fibre calorimeter)

Analysis tools

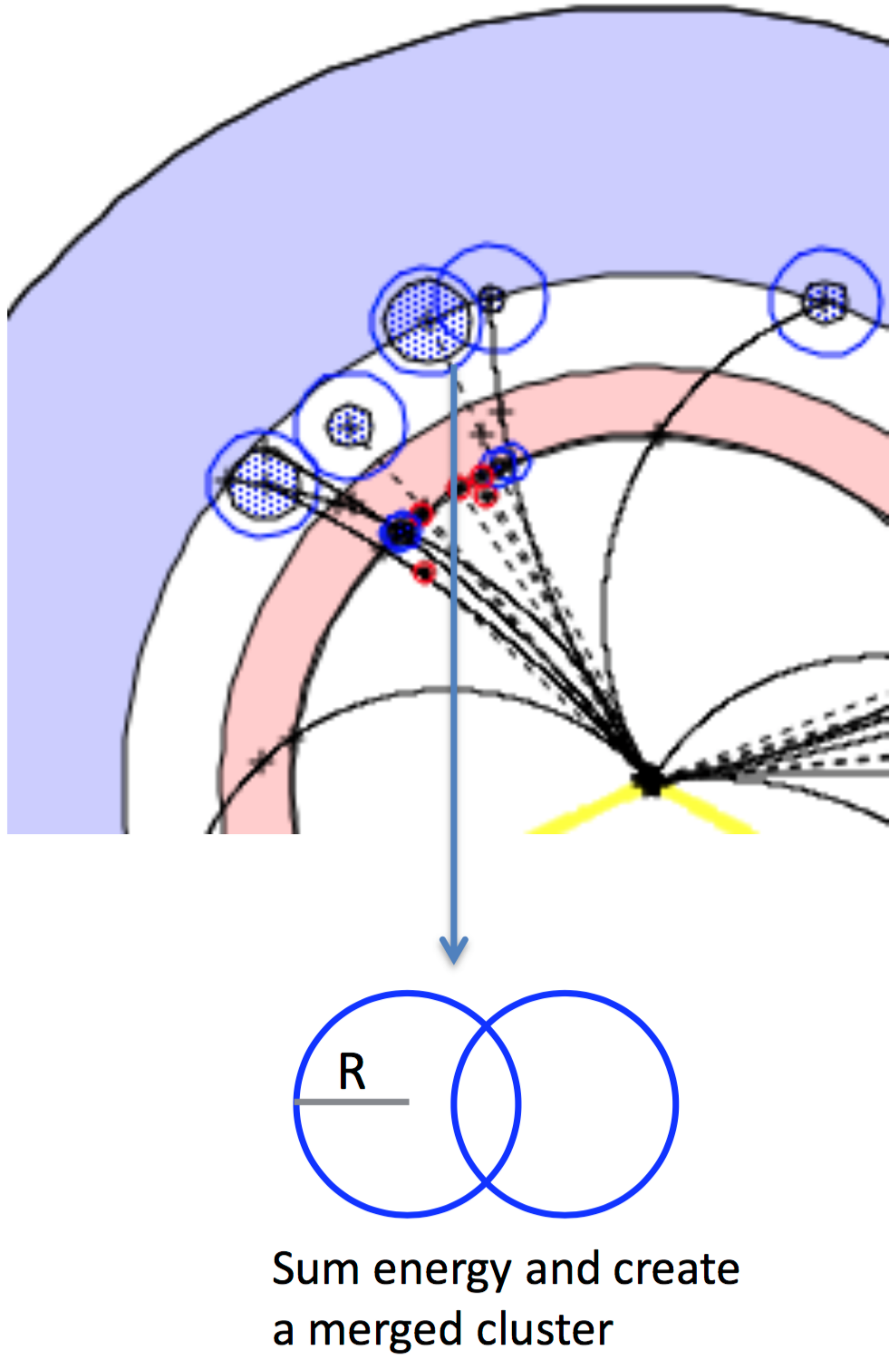
Need a fast simulation and detector modelling

Mainly use a framework developed by Colin Bernet (called papas) based on a full PF algorithm similar to CMS

- Validated to full CMS simulation
- Delphes is also used (gives further cross check)

Generic analysis framework based on python called heppy (HEP in Python)

- Also used in CMS

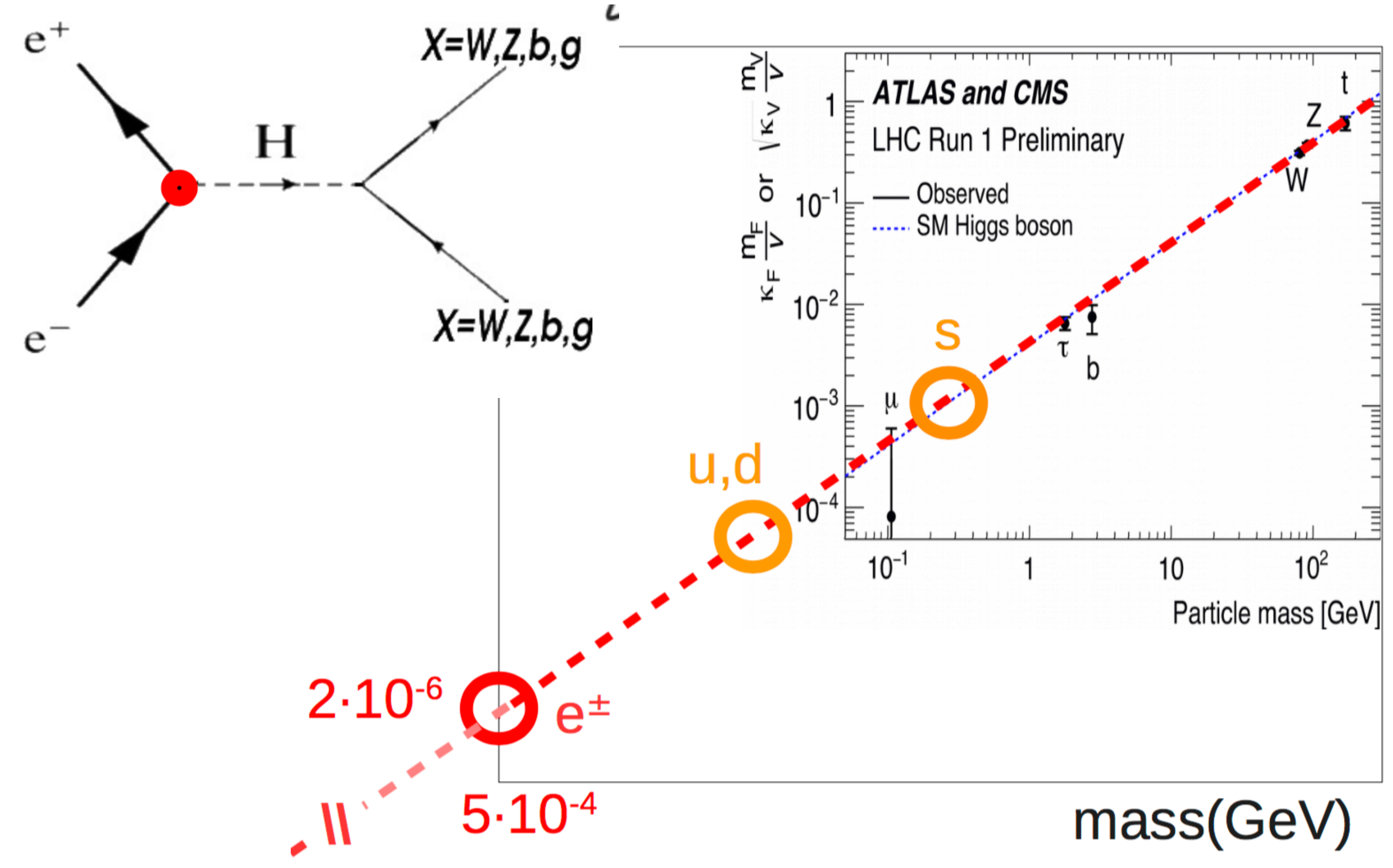


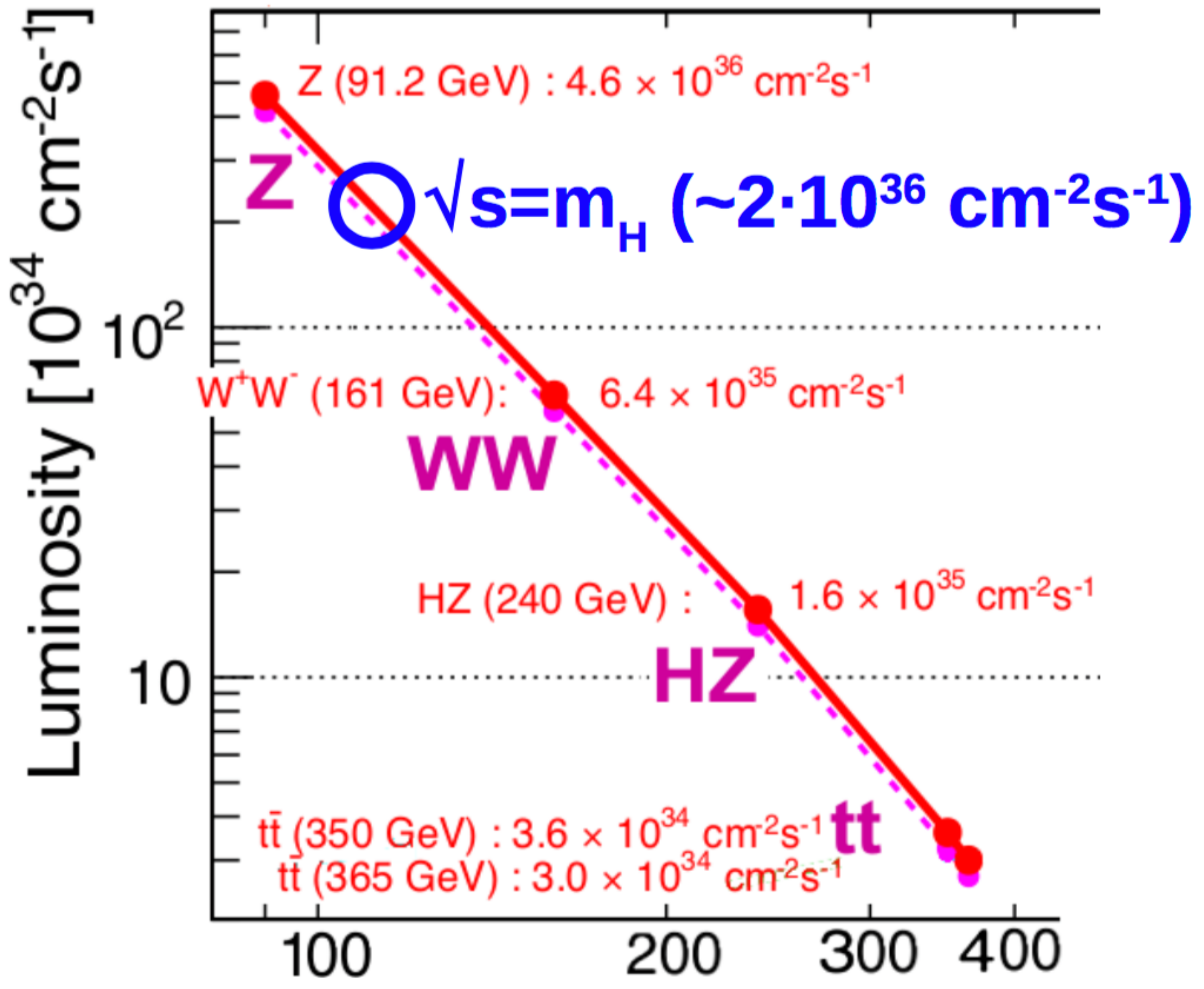
Resonant Higgs production study

Higgs decay to ee is unobservable:
BR(H→ee) = $5 \cdot 10^{-9}$

Resonant Higgs production considered so far only for muon collider: σ(μμ→H)=70 pb

Tiny e Yukawa coupling: σ(ee→H)=1.64 fb





In theory, FCC-ee running at H pole-mass:
L_{int} = 20 ab^{-1}/yr would produce O(30.000) H's

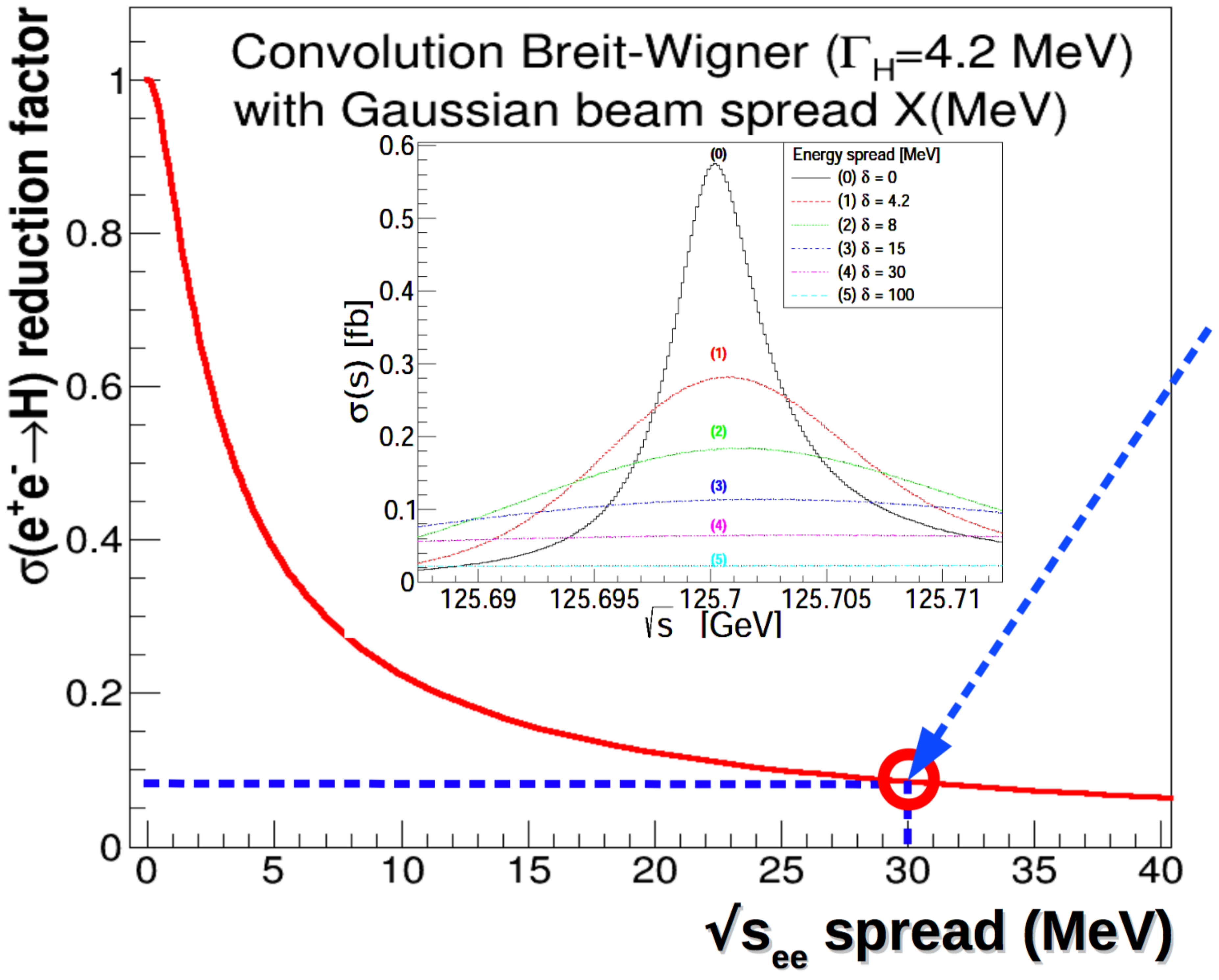
Life is more difficult

- Strong cross section reduction through beam energy spread and ISR
- Large backgrounds

More realistic cross sections

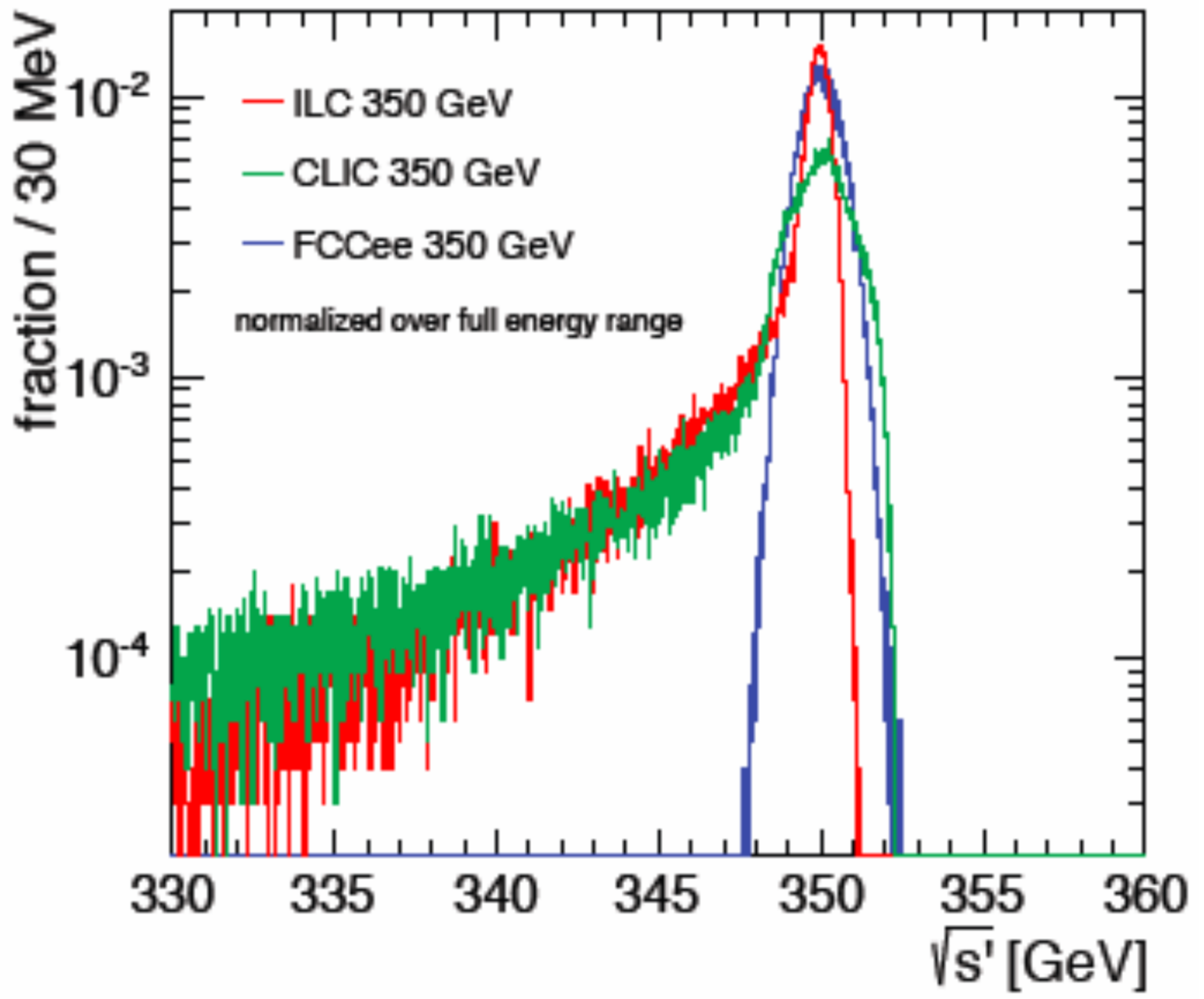
Higgs production greatly suppressed off resonant peak

Convolution of Gaussian energy spread of each e± beam with Higgs B.-W. results on an effective cross-section decrease:



For $\sqrt{s}_{spread} \approx$ 30 MeV:

Reduction factor: ×1/12



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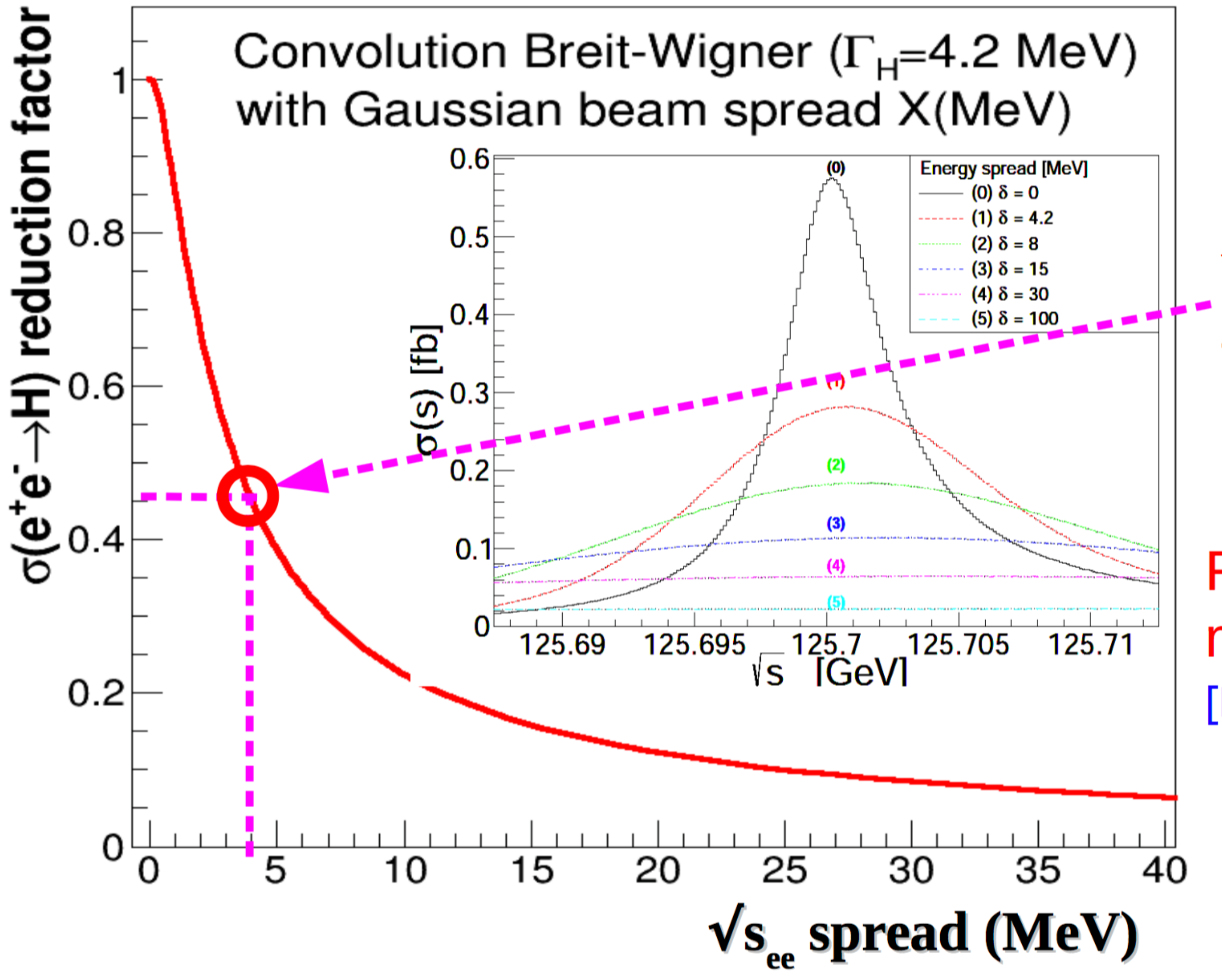
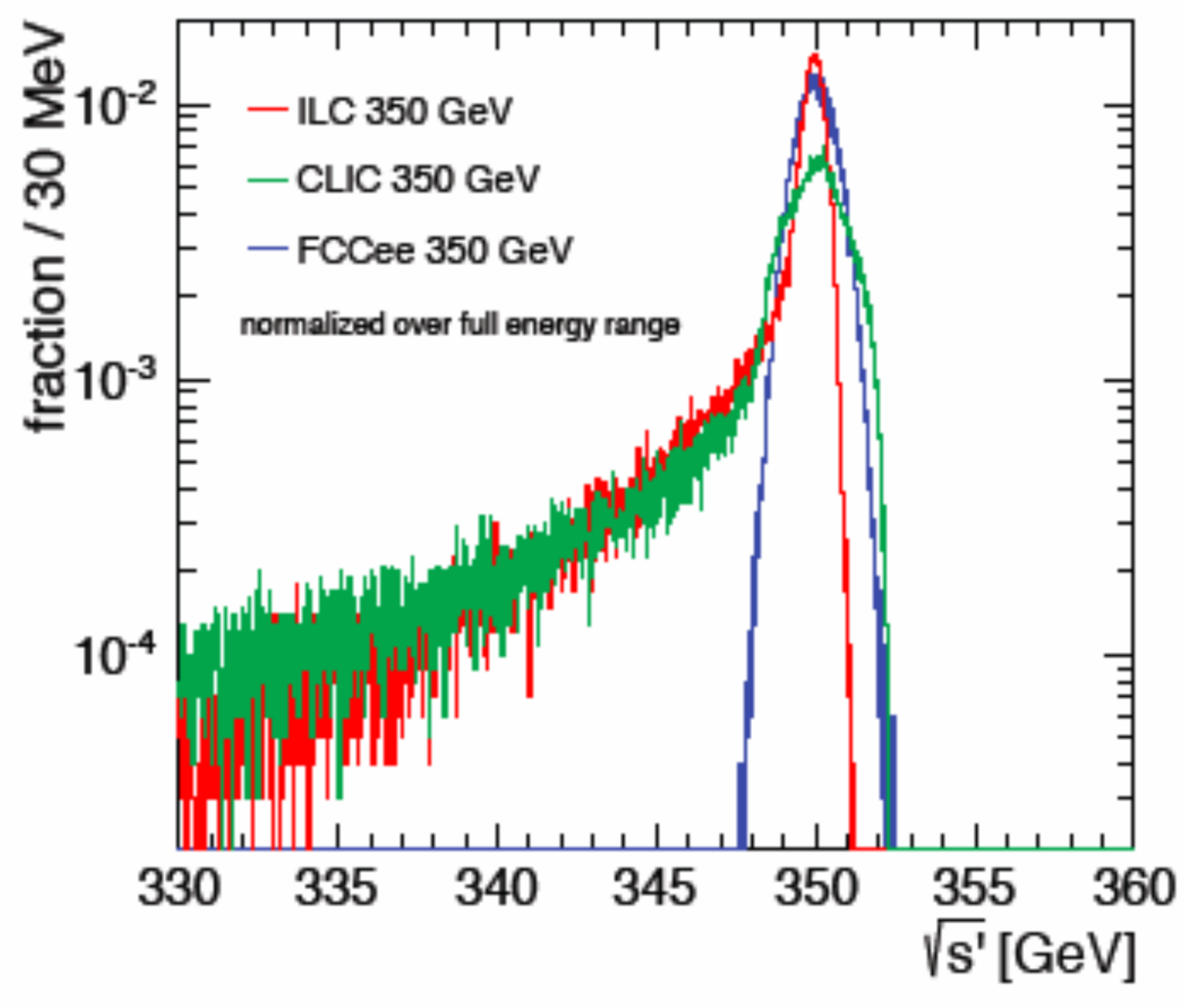


$\sqrt{s}_{spread} = \Gamma_H = 4.2$ MeV

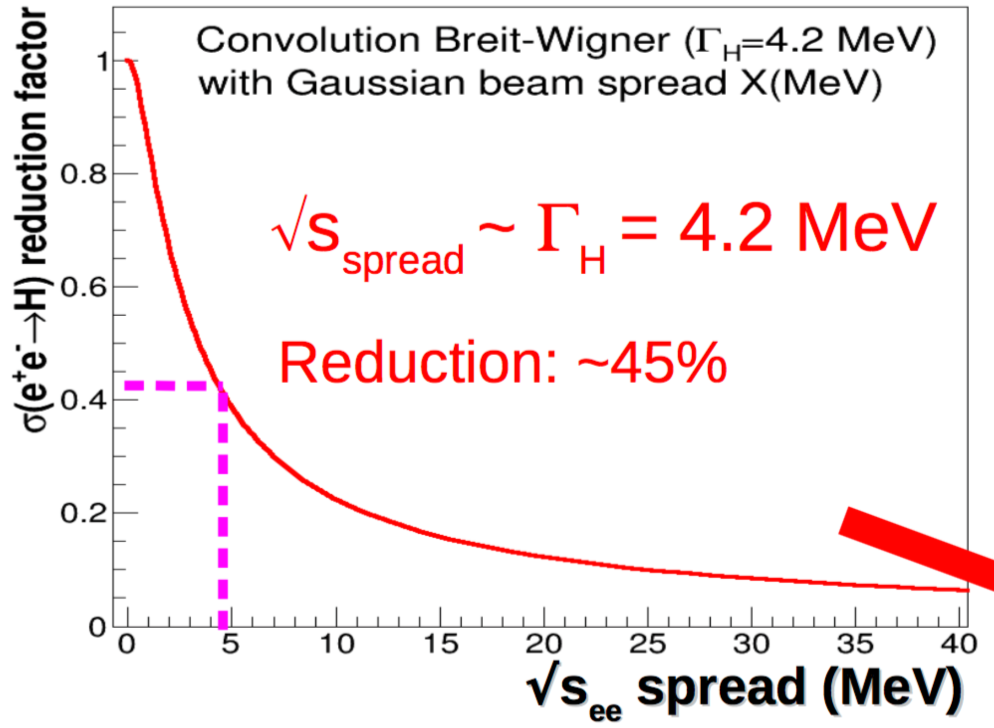
~45% x-section reduction

Reachable with beams monochromatization?

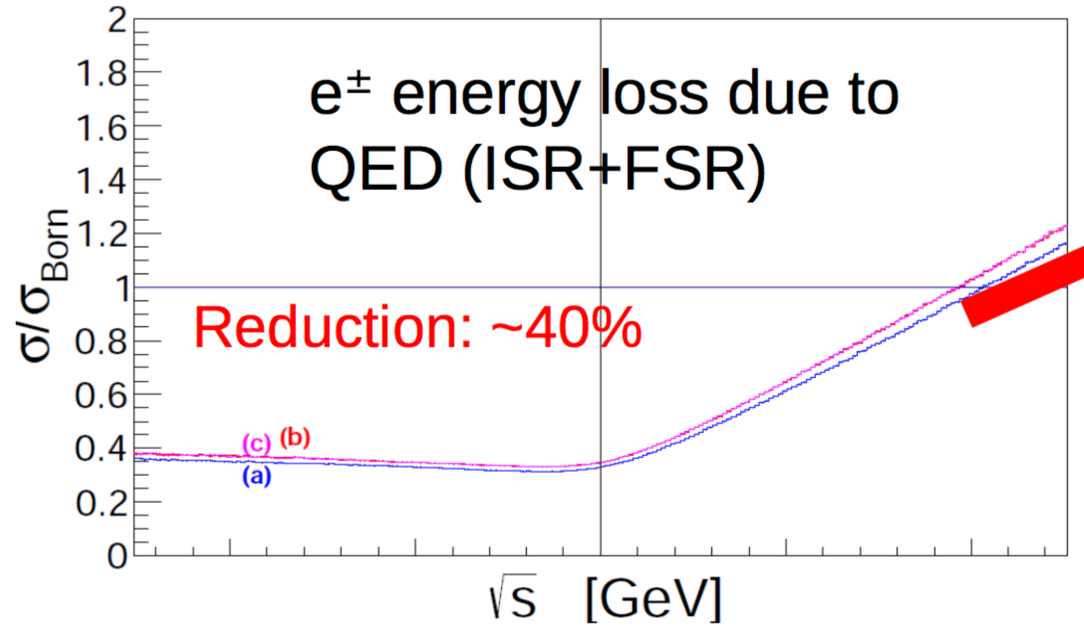
[F.Zimmermann, M.Valdivia-García JACoW-IPAC2017-WEPIK015]



e Yukawa limits



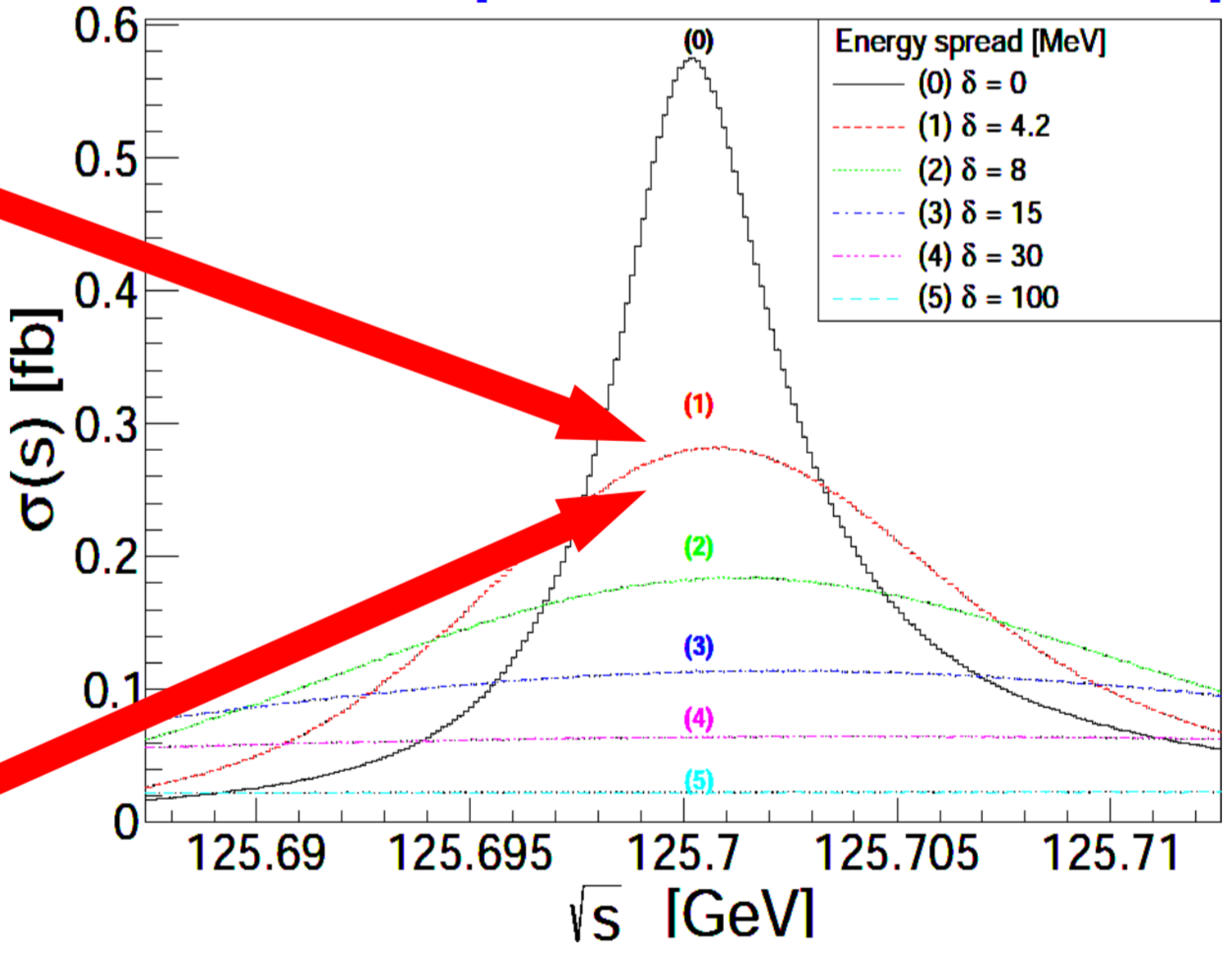
- Extra ~40% reduction due to QED radiation:



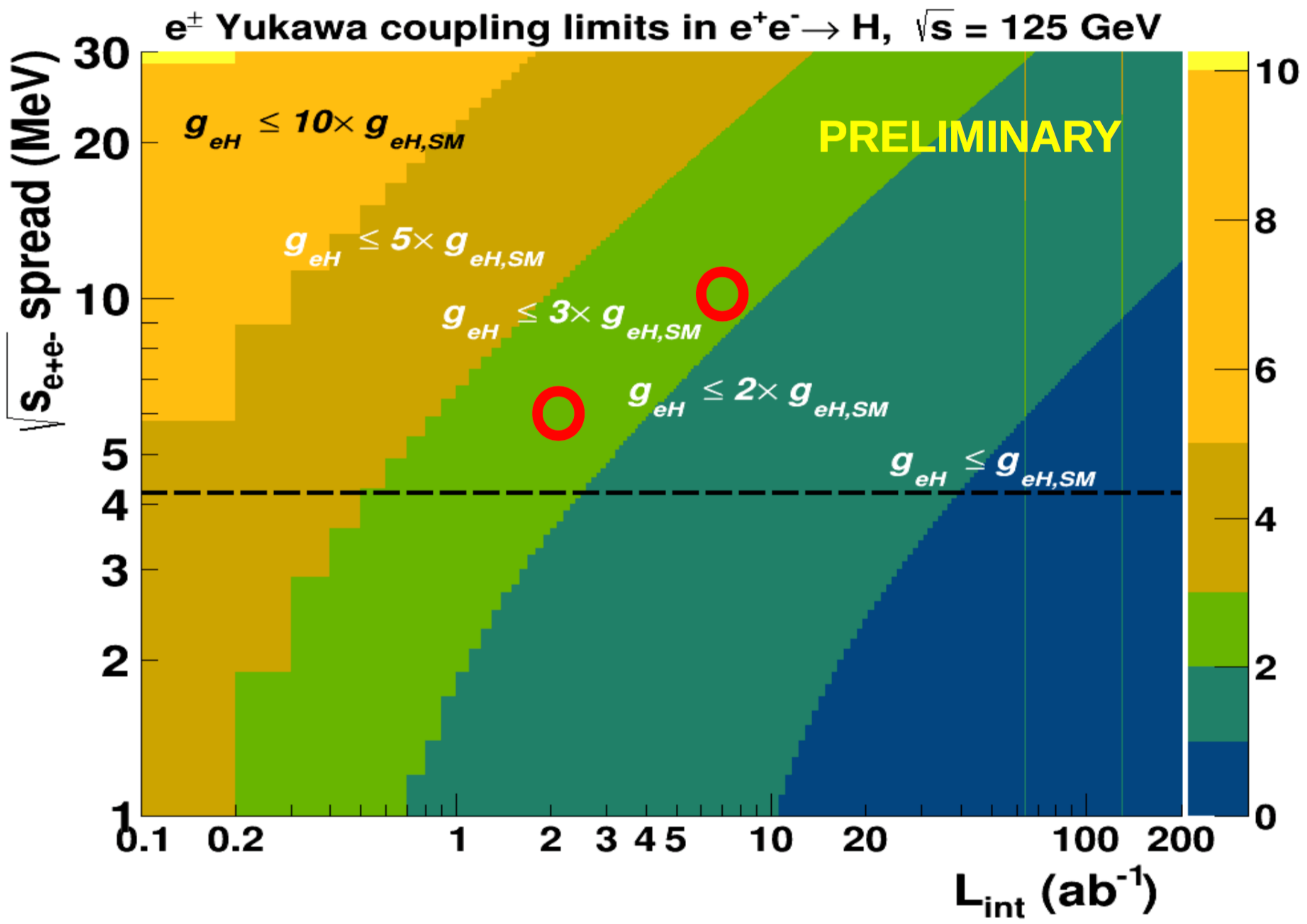
Let's take as monochromatization benchmark: $\sqrt{\sigma_{spread}} \approx \Gamma_H$ = 4.2 MeV

- Full convolution of both effects:

[S.Jadach et. al. arXiv:1509.02406]



$\sigma_{spread+ISR}(e^+e^-\to H)=0.17\times\sigma(e^+e^-\to H)=$290 ab



10 Higgs decays analysed and combined, e.g.

ZZ* (2j2ν): σ = 2.3 ab

Dom. bckgd (ee→ZZ*): σ=213 ab (S/B~10^{-2})

ZZ* (2l2j): σ = 1.14 ab

Dominant bckgd (ee→ZZ*):σ=114 ab (S/B~10^{-2})

After 1y for baseline and optimised monochromatisation

$g_{eH}<2.4\times g_{eH,SM}$ (95% CL)

$g_{eH}< 2.2\times g_{eH,SM}$ (95% CL)

Conclusions

Fantastic prospects to probe the Higgs sector with FCC-ee

But also a broad and exciting precision physics programme in general (from Z to tt)

CDR currently in preparation (to be released by the end of the year)