Perspectives for Higgs measurements at Future Circular Collider

Ang LI
(APC-Paris, Université de Paris, CNRS/IN2P3)

On behalf of the FCC Collaboration
PANIC – September 5 2021

Outline

- **Physics Motivation**
- **Introduction to the Future Colliders**
- **Higgs measurements at Future Circular Collider**

Physics motivation

❖ Higgs physics at LHC

- Higgs boson was discovered in 2012 with ATLAS and CMS
- Third family Yukawa couplings
- Indicate new physics around the TeV

❖ Puzzles of the Standard Model

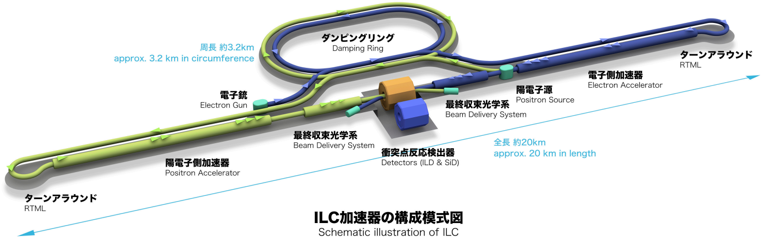
- Dark matter
- Neutrino mass
- Different Higgs models

Future Colliders

❑ Future Linear Colliders:

1. International Linear Collider (ILC)

1) e^+e^- at 500 GeV, 1000 GeV
2) 30-50 km



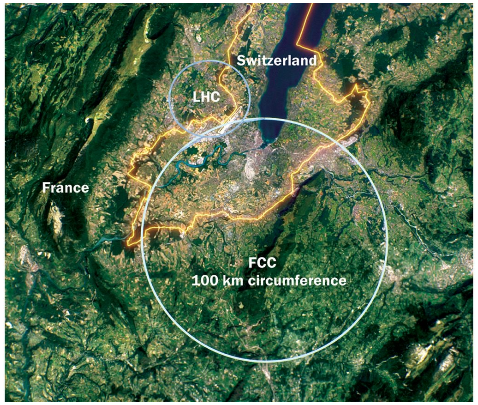
2. The Compact Linear Collider (CLIC)

1) e^+e^- at 380 GeV, 1.5 TeV and 3 TeV
2) 11-50 km

❑ Future Circular Colliders:

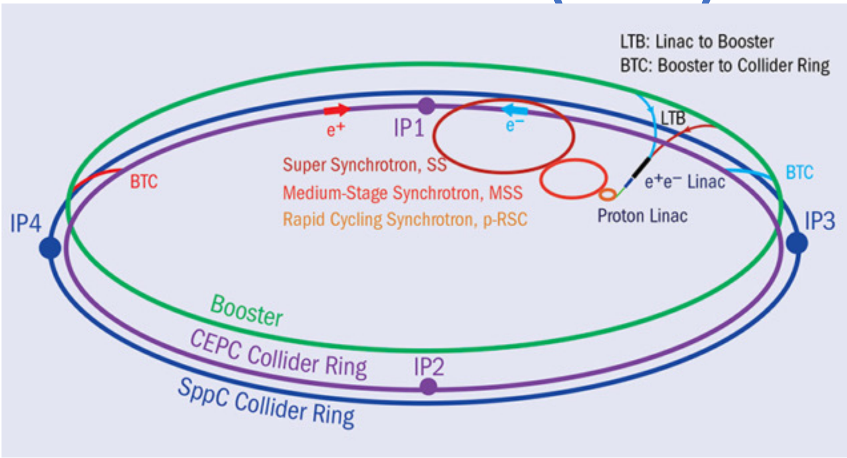
1. The Future Circular Collider (FCC)

1) FCC-ee: e^+e^- at ~100-400 GeV
2) FCC-hh: $p-p$ at 100 TeV
3) FCC-ee + FCC-hh = FCC-INT
4) Circumference ~90 km (LHC: 27 KM)



2. Circular Electron Positron Collider (CEPC)

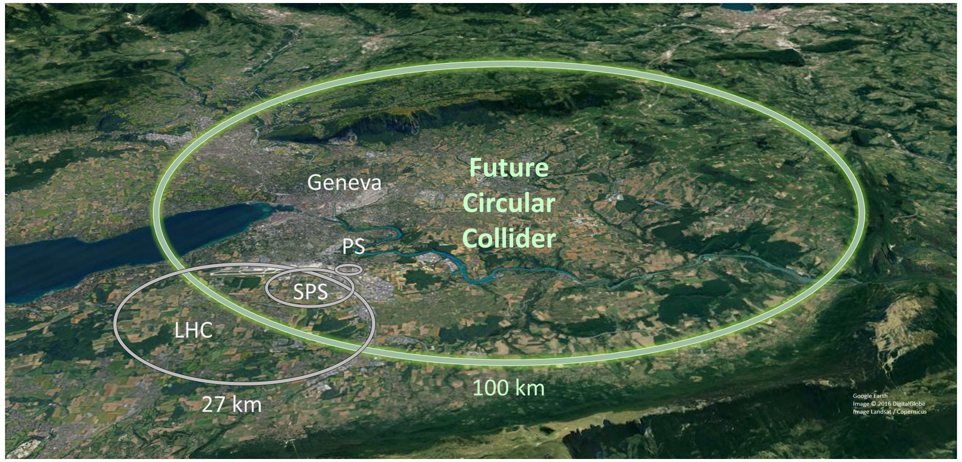
1) e^+e^-
2) SppC



FCC integrated program

Comprehensive cost-effective program maximizing physics opportunities

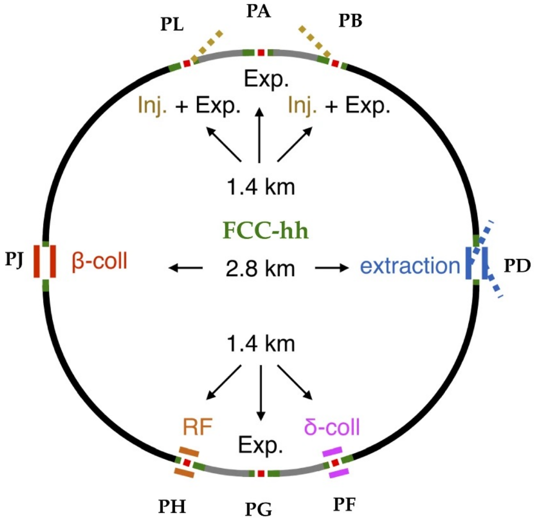
- ❑ Stage 1: FCC-ee (~90 km tunnel) as first generation Z, Higgs and top factory at high luminosities
- ❑ Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier (with ion and eh options)

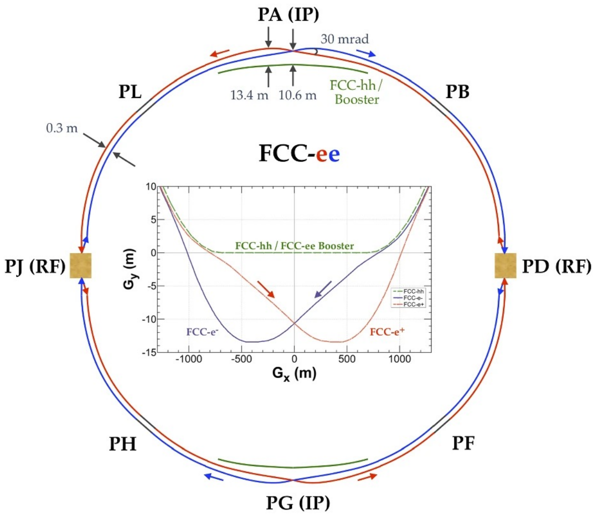


Complementary physics

- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- FCC-INT project plan is fully integrated with HL-LHC exploitation and provides for natural continuation of LHC

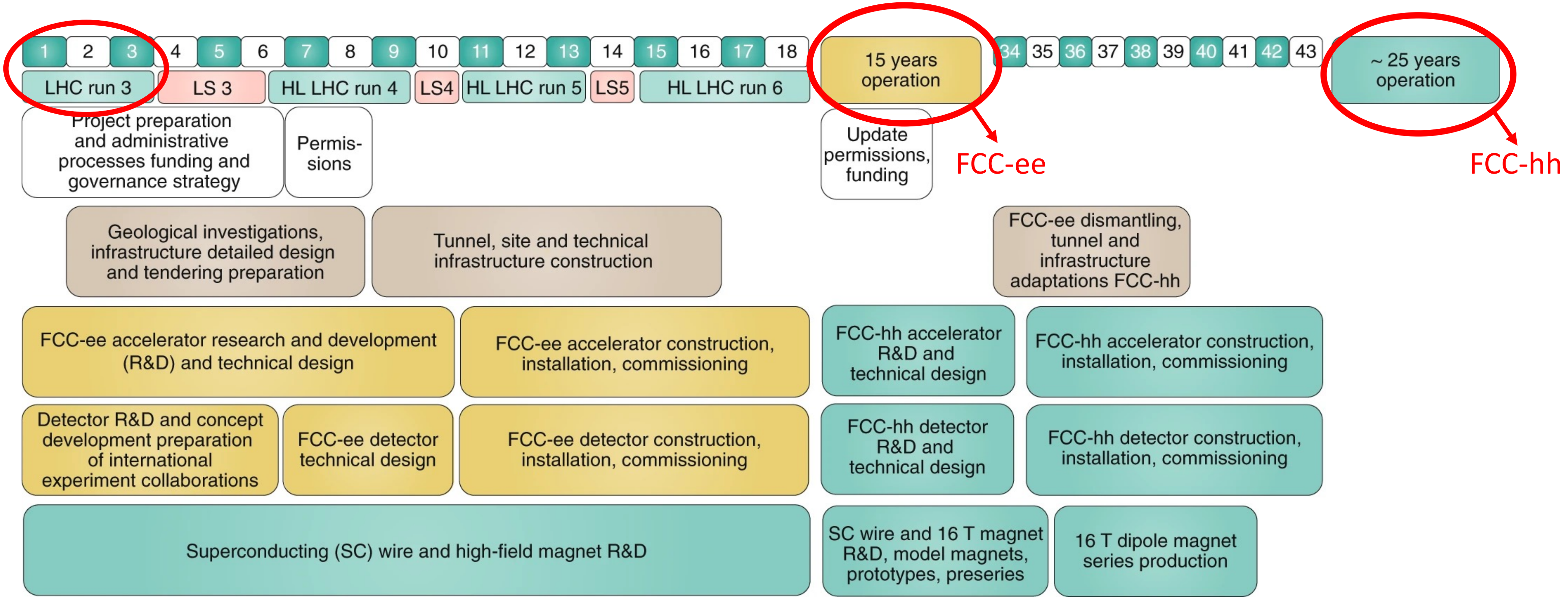
Current layout has two interaction points (IPs), but studying the possibility of having 4 IPs





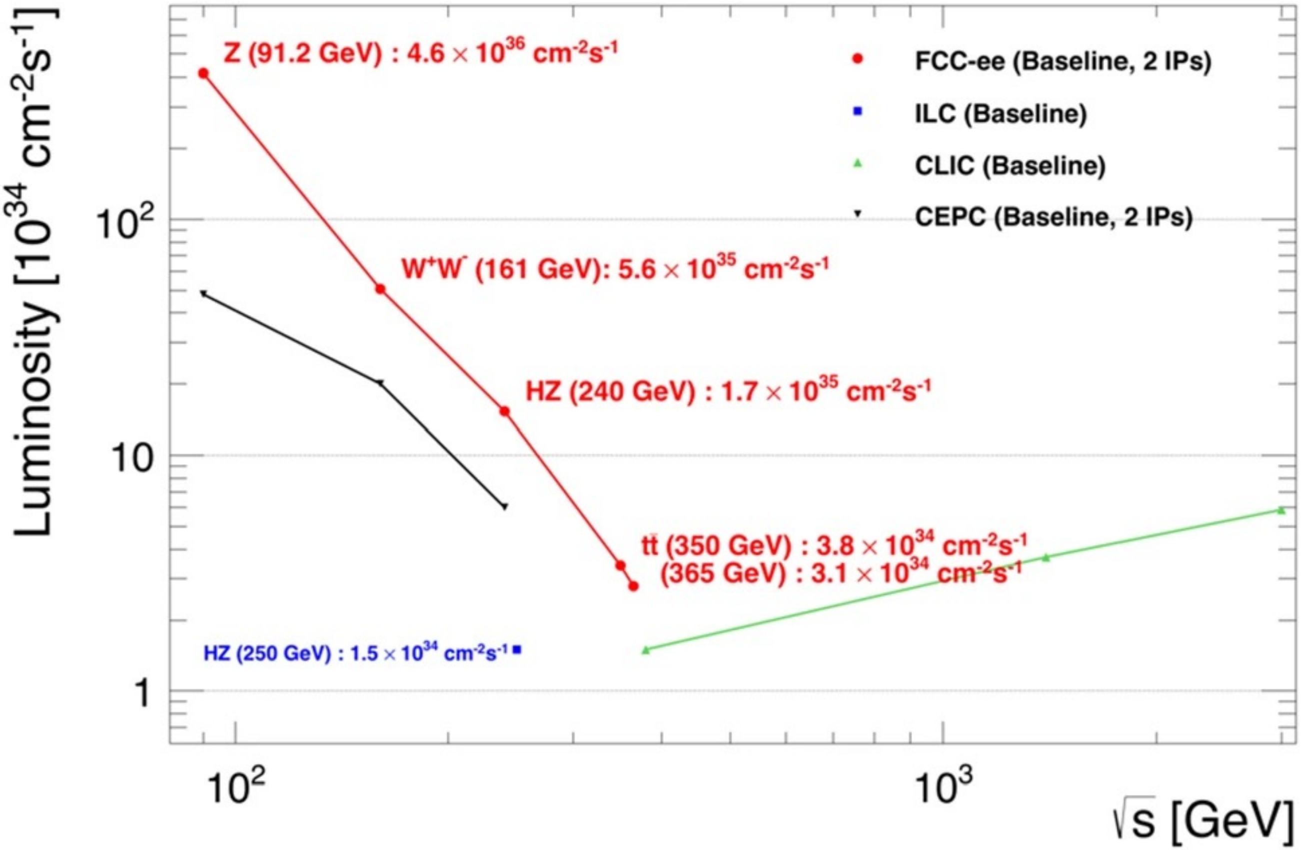
[FCC Physics Opportunities]

FCC integrated program



1. On the 18 years of preparation
   1) Feasibility study (5 year)
   2) then civil constructions
   3) then machine and detectors construction
2. 15 years of FCC-ee on different energy points
3. ~10 years to change the magnets between, and change the detectors
4. 25 years of FCC-hh

FCC-ee Luminosities

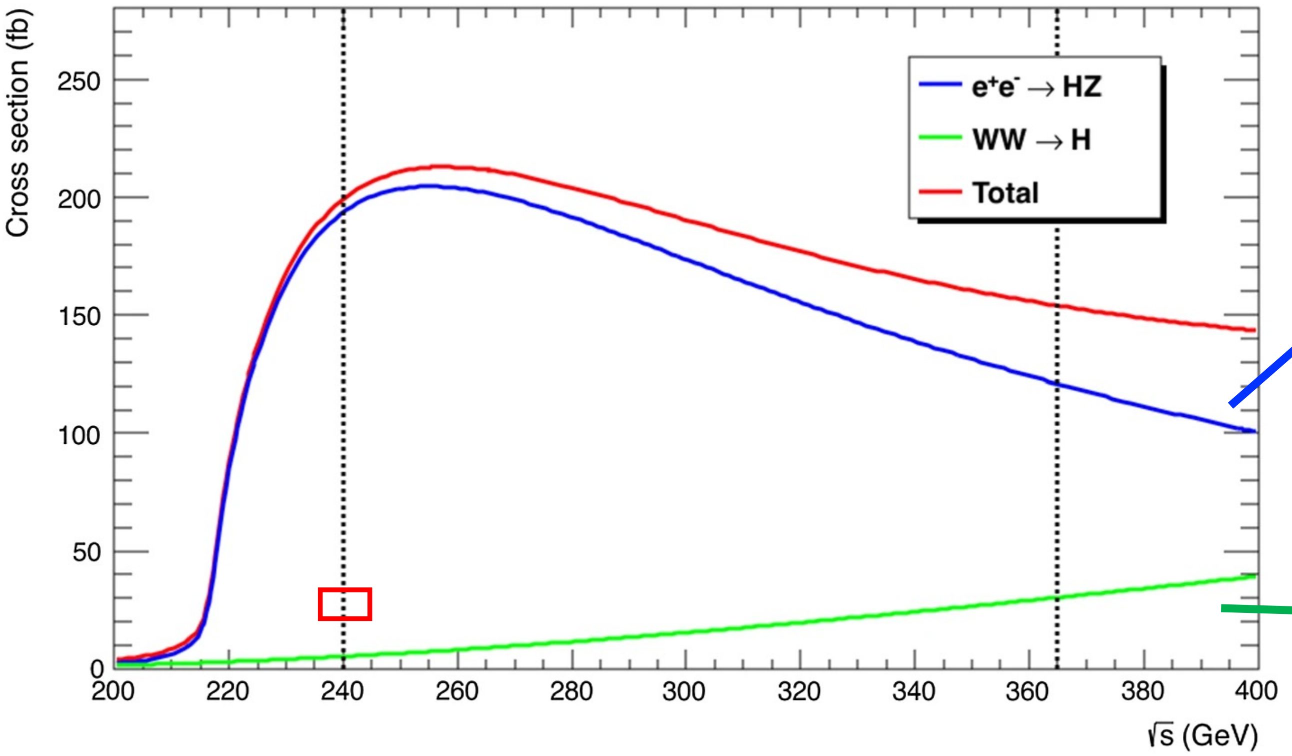


[FCC Physics Opportunities]

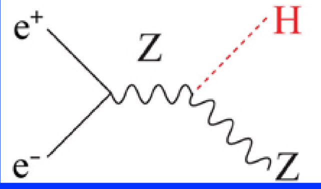
- Luminosity as a function of centre-of-mass for the FCC-ee with two interaction points (IPs)
- Luminosity ranging from $2\times10^{36}\text{cm}^{-2}\text{s}^{-1}$ per IP (Z pole) to $1.5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ per IP (top energies)
- The luminosity of FCC on each operation point is larger than CEPC
- For FCC-ee
  - 5×10^{12} Z boson (5 order of magnitude more than LEP)
  - 10^8 WW events at WW threshold
  - 10^6 ZH events at 240 GeV

Phase	Run duration (years)	Centre-of-mass energies (GeV)	Integrated luminosity (ab^{-1})	Event statistics
FCC-ee-Z	4	88–95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158–162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt(1)	1	340–350	0.2	$t\bar{t}$ threshold scan
FCC-ee-tt(2)	4	365	1.5	10^6 $t\bar{t}$ events

Higgs production at Future Circular Collider (FCC)

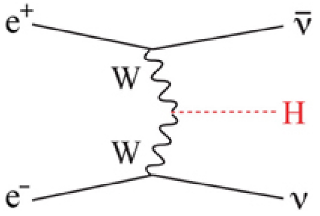


HiggsStrahlung



- s-channel, cross-section maximal above the threshold of the process

Vector Boson Fusion



- t-channel, cross-section grows logarithmically with the centre-of-mass energy

❖FCC-ee as a Higgs factory

➢ For the Higgs-strahlung ($e^+e^- \rightarrow ZH$):

1. Total Cross-section presents maximum at $\sqrt{s} \sim 260$ GeV
2. Event rate per unit of time is largest at $\sqrt{s} \sim 240$ GeV : $\sigma \sim 200$ fb ~ 10^6 events (@ $L = 5\ ab^{-1}$)
3. Complemented with data at $\sqrt{s} \sim 365$ GeV, 1.8×10^5 ZH and 0.45×10^5 WW-fusions (~30%) (@ $L = 1.5\ ab^{-1}$)

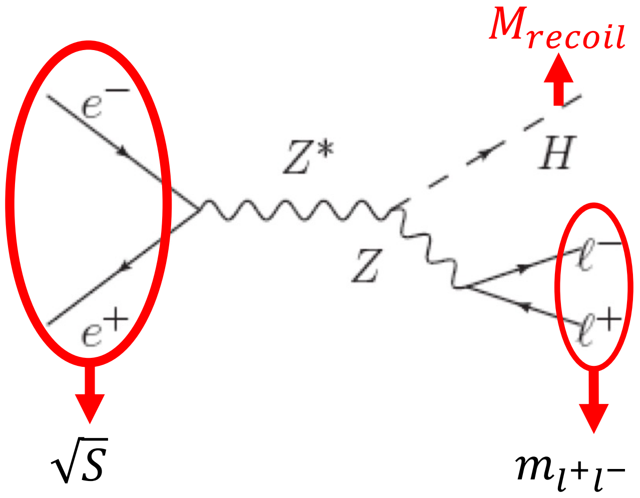
   (useful for measuring self-coupling and Γ_H precisely)

“Higgs recoil mass” technique at Future Circular Collider (FCC)

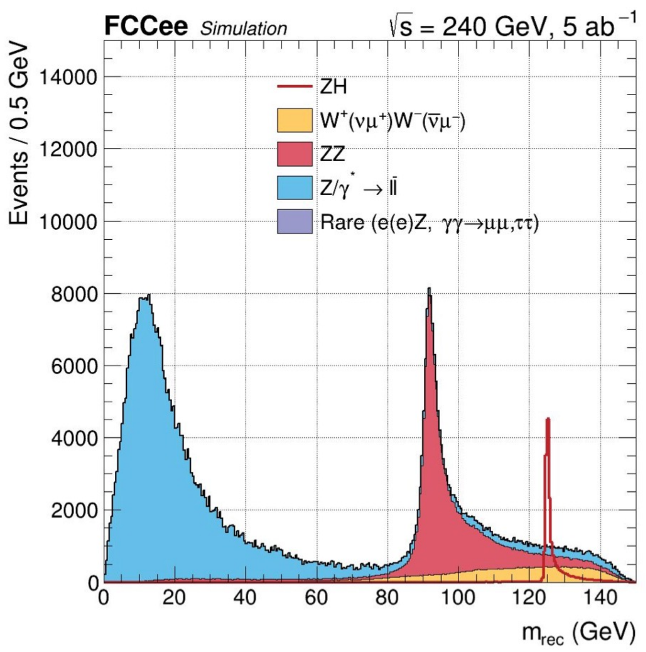
- Goal: Measurement of the ZH total cross section and Higgs boson mass
- Signal: $e^+e^- \rightarrow ZH \rightarrow l\bar{l} + X$

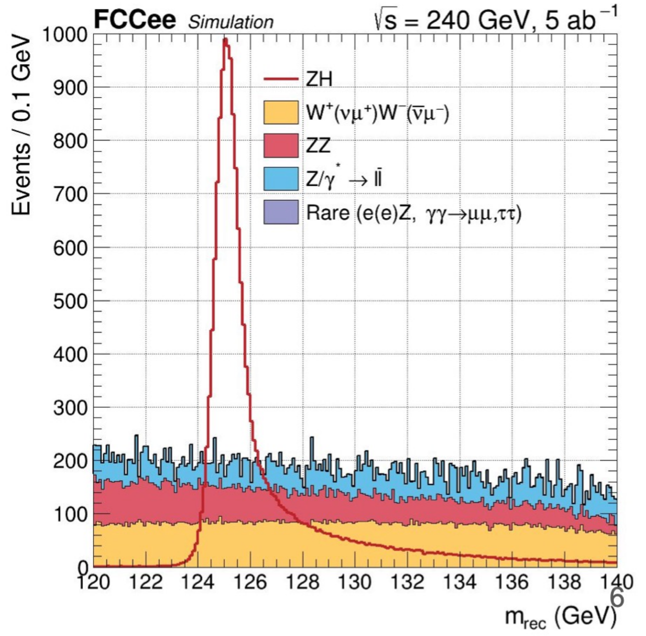
  ZH is the dominant Higgs production process @ 240 GeV e^+e^- machine
- Use events with a Z decaying leptonically, and reconstruct M_{recoil} from the Z production without measuring the Higgs production final state

$$\boxed{M_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2}$$



- The reconstructed M_{recoil} is sensitive to the precise knowledge of the centre-of-mass energy and ISR
- Model-independent study
- WW, ZZ and $Z/\gamma \rightarrow l\bar{l}$ Backgrounds @ 240 GeV
- This approach allows for precise measurements of ZH cross section (per mile) and Higgs mass (~ MeV)





[ZH Recoil talk at FCC Week]

Expected value of the coupling constanse

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{\boxed{g^2_{\mathrm{HZZ}}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}} \quad \text{and} \quad \sigma_{\mathrm{H}\nu_e\bar{\nu}_e} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HWW}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}},$$

arXiv:2106.15438

- The σ_{ZH} accuracy could achieve 0.5%
- Obtaining the ZH cross section, one can determinate g_{HZZ} and Higgs width (Γ_{H})
- g_{HZZ}, g_{HWW}, $g_{\mathrm{H}gg}$ and $g_{\mathrm{H}\tau\tau}$ are expected to achieve per mile precision

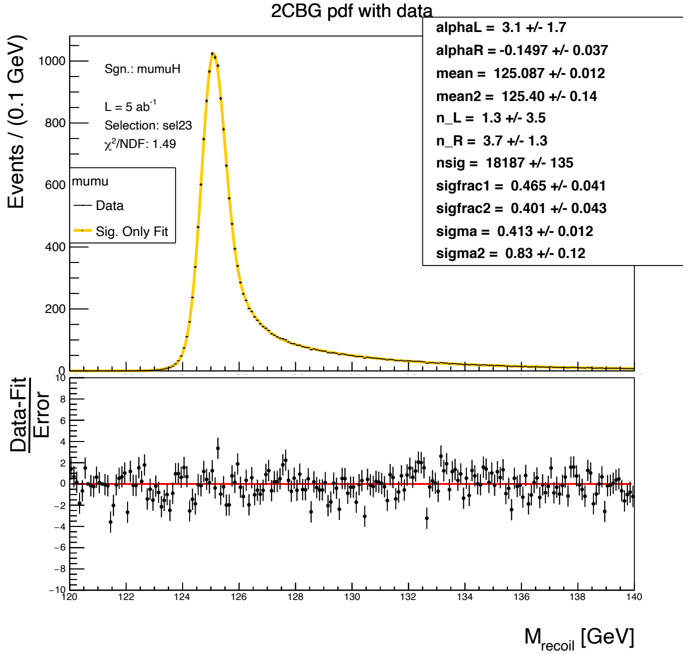
$\sqrt{s}$	240 GeV		365 GeV	
Integrated luminosity	5 ab^{-1}		1.5 ab^{-1}	
$\delta(\sigma\mathcal{B})/\sigma\mathcal{B}$ (%)	ZH	$\nu_e\bar{\nu}_e$ H	ZH	$\nu_e\bar{\nu}_e$ H
$\mathrm{H} \to$ any	±0.5		±0.9	
$\mathrm{H} \to \mathrm{b\bar{b}}$	±0.3	±3.1	±0.5	±0.9
$\mathrm{H} \to \mathrm{c\bar{c}}$	±2.2		±6.5	±10
$\mathrm{H} \to \mathrm{gg}$	±1.9		±3.5	±4.5
$\mathrm{H} \to \mathrm{W^+W^-}$	±1.2		±2.6	±3.0
$\mathrm{H} \to \mathrm{ZZ}$	±4.4		±12	±10
$\mathrm{H} \to \tau^+\tau^-$	±0.9		±1.8	±8
$\mathrm{H} \to \gamma\gamma$	±9.0		±18	±22
$\mathrm{H} \to \mu^+\mu^-$	±19		±40	
$\mathrm{H} \to$ invisible	< 0.3		< 0.6	

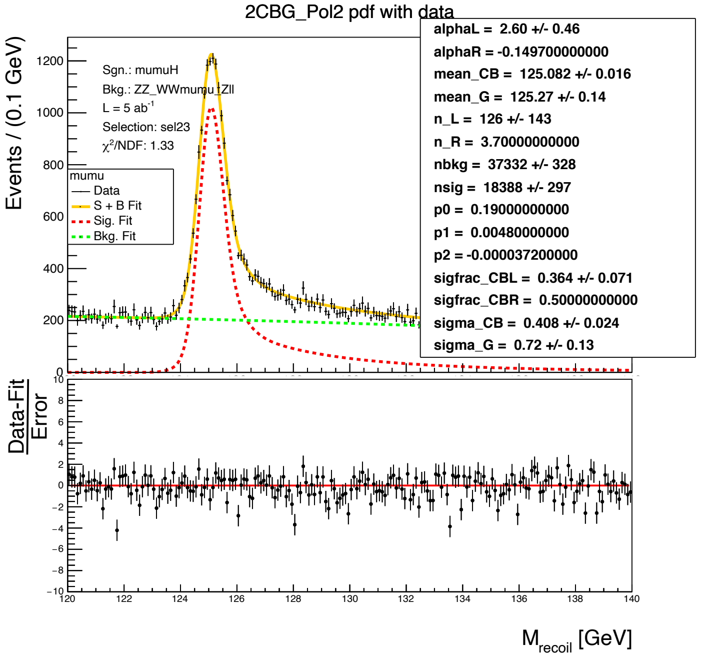
Coupling	Precision (%) (κ framework / EFT)
g_{HZZ}	0.17 / 0.26
g_{HWW}	0.41 / 0.27
g_{Hbb}	0.64 / 0.56
g_{Hcc}	1.3 / 1.2
g_{Hgg}	0.89 / 0.82
$g_{\mathrm{H}\tau\tau}$	0.66 / 0.57
$g_{\mathrm{H}\mu\mu}$	3.9 / 3.8
$g_{\mathrm{H}\gamma\gamma}$	1.3 / 1.2
$g_{\mathrm{HZ}\gamma}$	10. / 9.3
g_{Htt}	3.1 / 3.1
Γ_{H}	1.1

ZH cross section and mH at FCC-ee

ZH “Higgs mass recoil” study preliminary results

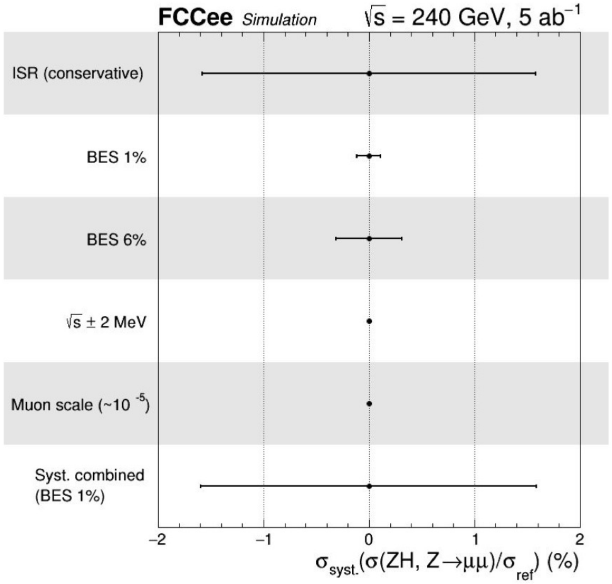
With simple selections (without BDT) and fitting studies



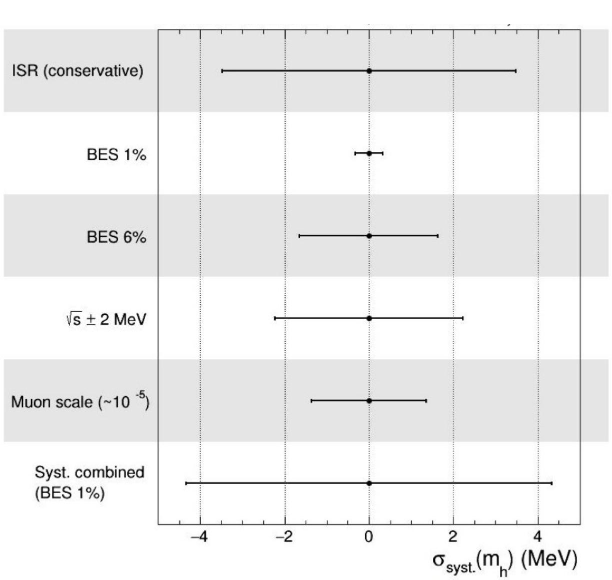


Conclusion:

- Statistical analysis yields Higgs mass uncertainty 6.7 MeV, cross-section 1.1 % (stat-only)
- Inclusion of systematic uncertainties results into 8.0 MeV / 1.9% respectively, where uncertainty from ISR is dominant but conservatively estimated
- Will apply more advanced analysis techniques (BDT…)



Cross section (%)

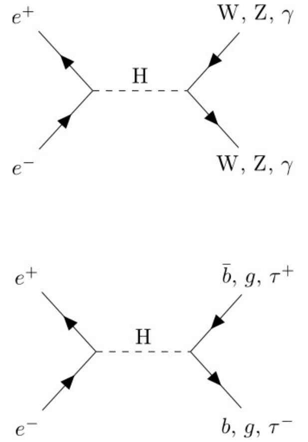


Mass (MeV)

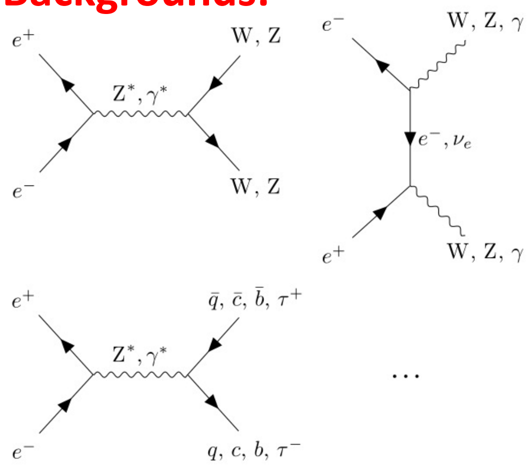
[ZH Recoil talk at FCC Week]

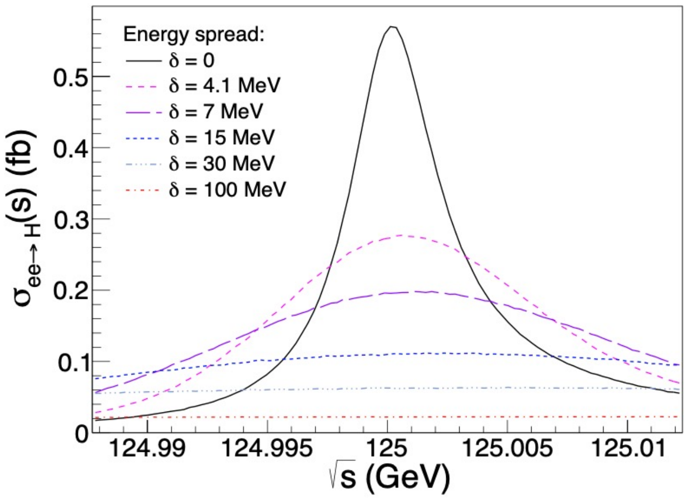
The electron Yukawa coupling via resonant s-channel $e^+e^- \to H$ production

Signals



Backgrounds:





arXiv:2107.02686

$$\sigma_{ee\to H} = \frac{4\pi \Gamma_H \Gamma(H \to e^+e^-)}{(s - m_H^2)^2 + m_H^2 \Gamma_H^2},$$

- Yukawa couplings have been measured so far only for t, b and τ
- At the end of the LHC lifetime, part of the Higgs Yukawa couplings to the second-family fermions (the muon and, maybe, the charm quark) will have been probed
- Higgs decay to e^+e^- is unobservable: $BR(H \to e^+e^-) \propto m_e^2 \approx 5\times10^{-9}$
- Resonant Higgs production was considered so far only for muon collider: $\sigma(\mu^+\mu^- \to H) \approx 70\ pb$
- $\sigma_{ee\to H} = 1.64$ fb $(m_H = 125\ \text{GeV}, \Gamma_H = 4.2\ \text{MeV})$

Challenges:

1. Centre-of-mass energy at Higgs pole (Accurate knowledge of Higgs mass (~MeV)) → (feasible at FCC-ee see ZH recoil study
2. ISR and beam-energy spread (~MeV but still deliver large L_{int}) → $(\delta_{\sqrt{s}}, L_{int}) = (4.1\ \text{MeV}, 10\text{ab}^{-1})$ $\sigma_{e^+e^-\to H} = 280$ ab
3. Existence of multiple backgrounds

Fundamental Physics motivations:

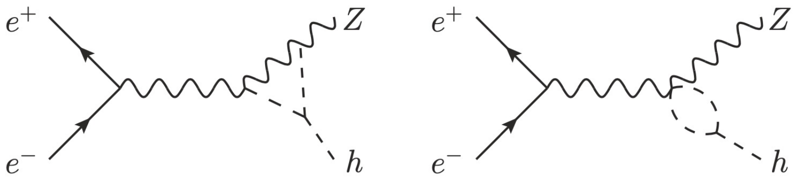
1. Higgs mechanism for first familly of fermions
2. Electron Yukawa coupling is measurable
3. BSM scalar physics connected to electrons at ~ 100 TeV
4. New particle that is quasi-degenerate with Higgs boson mass?

Its feasibility study is still on going

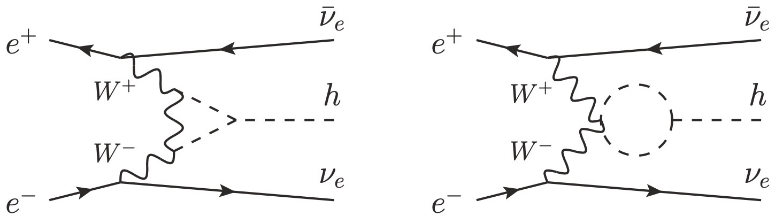
Trilinear Higgs Self-coupling

Trilinear coupling:

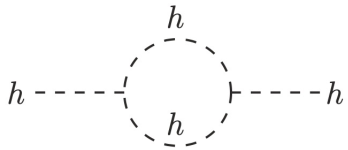
- ❑ Higgs strahlung: $e^+e^- \to ZH$



- ❑ WW-fusion: $e^+e^- \to \nu\bar{\nu}_e H$

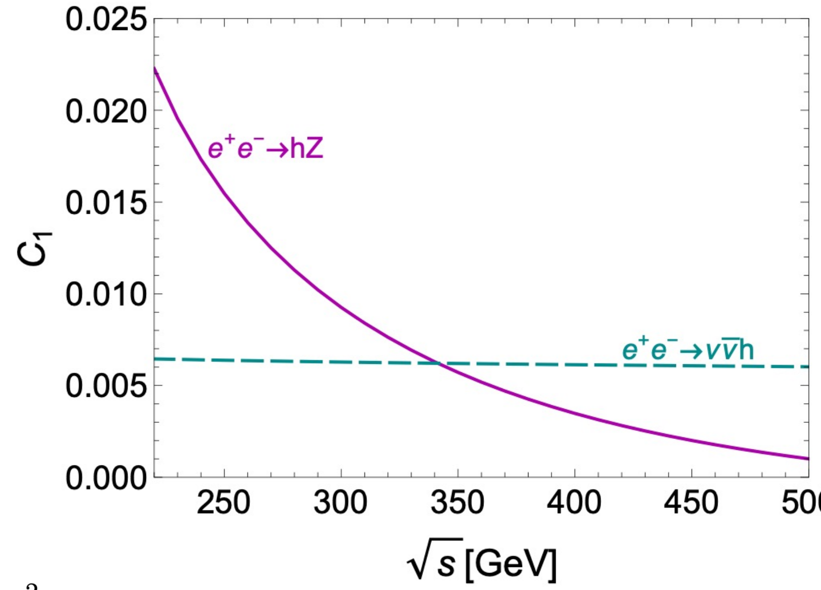


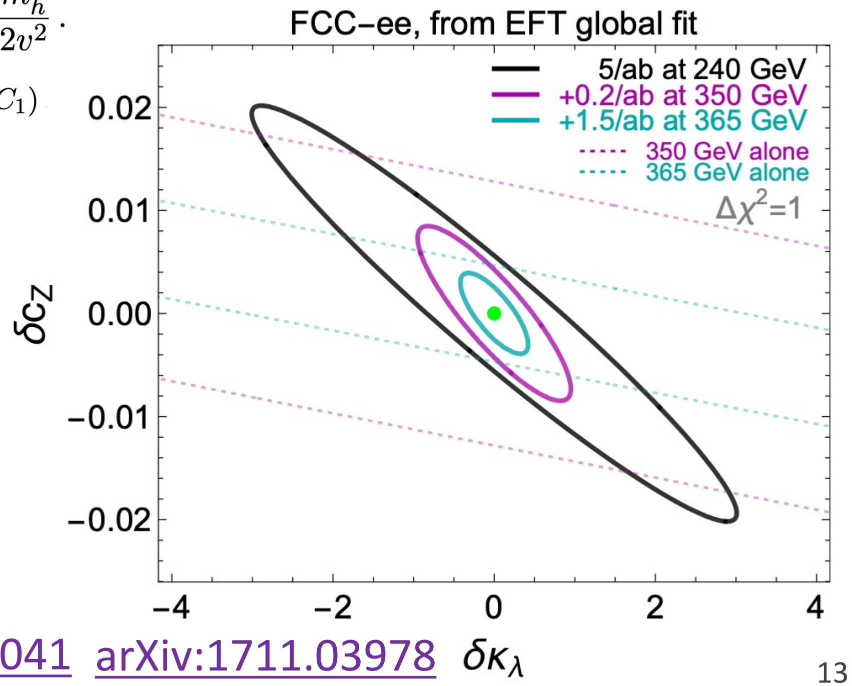
- ❑ Higgs self-energy



$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\mathrm{SM}}}, \qquad \lambda_3^{\mathrm{SM}} = \frac{m_h^2}{2v^2}.$$

$$\Sigma_{\mathrm{NLO}} = Z_H \Sigma_{\mathrm{LO}}(1 + \kappa_\lambda C_1)$$





- Including all the FCC-ee running, a model-independent precision of ±42% can be achieved on k_λ reduced to ±34% in combination with HL-LHC, and to ±12% when only k_λ is allowed to vary
- FCC-hh has the potential to reach a precision of ~ 3-5% of λ_3 from di-Higgs production, in combination with the precise Higgs decay branching ratio measurements from the FCC-ee
- With four IPs, the first 5σ demonstration of the Higgs self-coupling is whin reach in 15 years at FCC-ee

arXiv:1809.10041 arXiv:1711.03978

Conclusion

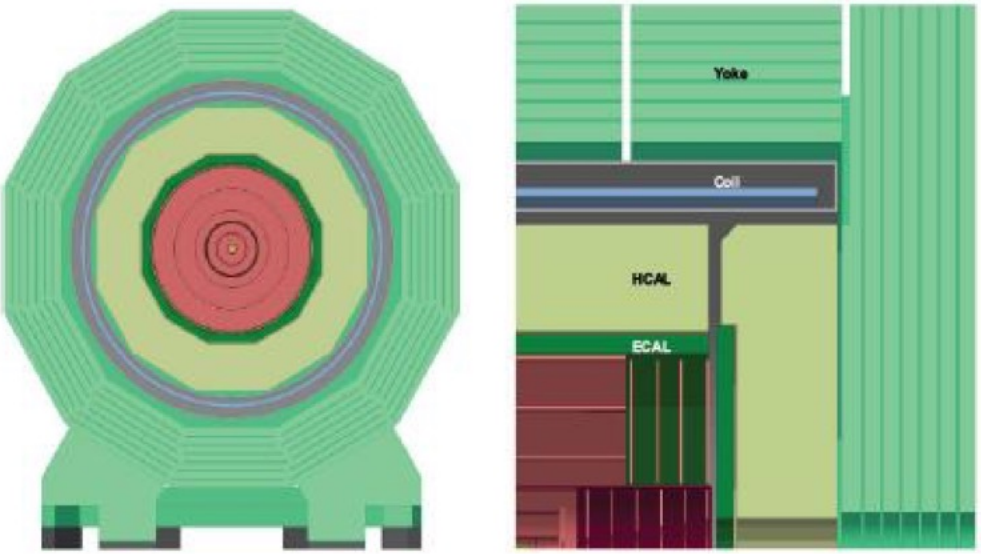
❖Conclusion:

- The Higgs program can be achieved after few years of running
- In the Higgs measurements, the "ZH recoil mass" method will allow for improving the uncertainty of $\mathrm{m_H}$ to several MeV level (while $\Gamma_\mathrm{H} = 4.1\ \mathrm{MeV}$). And measure the g_{HZZ} as a "candle" for other Higgs studies
- Electron Yukawa couplings may arrive high confidential level via resonant s-channel $\mathrm{e^+e^-} \rightarrow \mathrm{H}$ production
- FCC-hh has the potential to reach a precision of ~ 3-5% of λ_3 from di-Higgs production, in combination with the precise Higgs decay branching ratio measurements from the FCC-ee

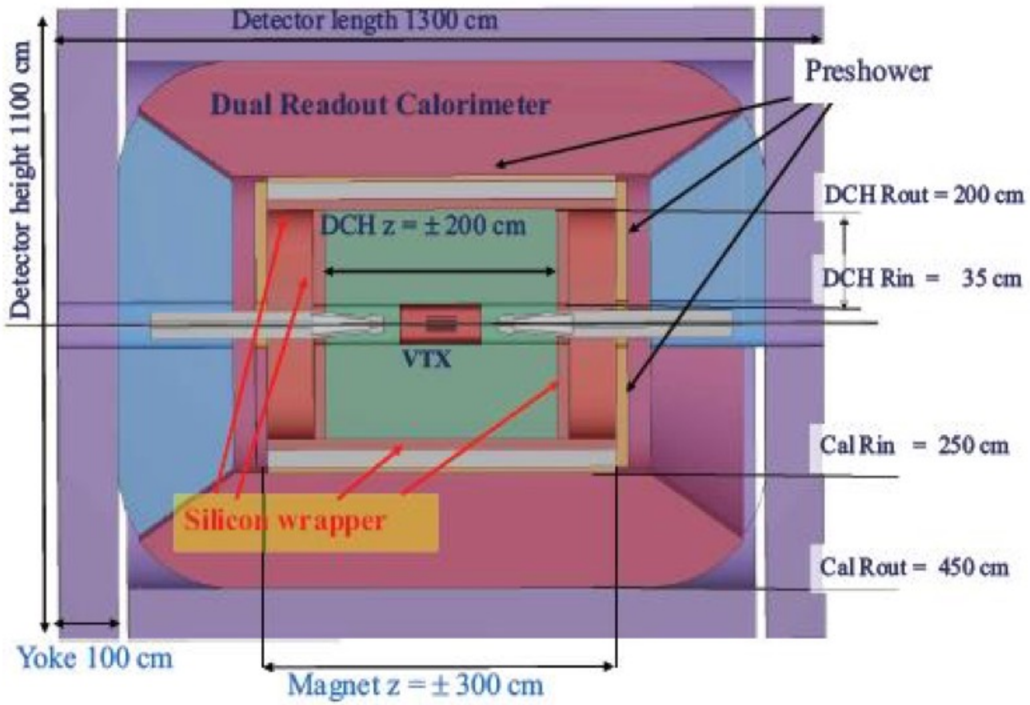
- The FCC collaboration is welcoming new collaborators from all over the world. The next collaboration meeting which is open to everybody is the FCC week 2022 which will take place in Paris (May 20-June 3, 2022)

Backup

CLD



IDEA

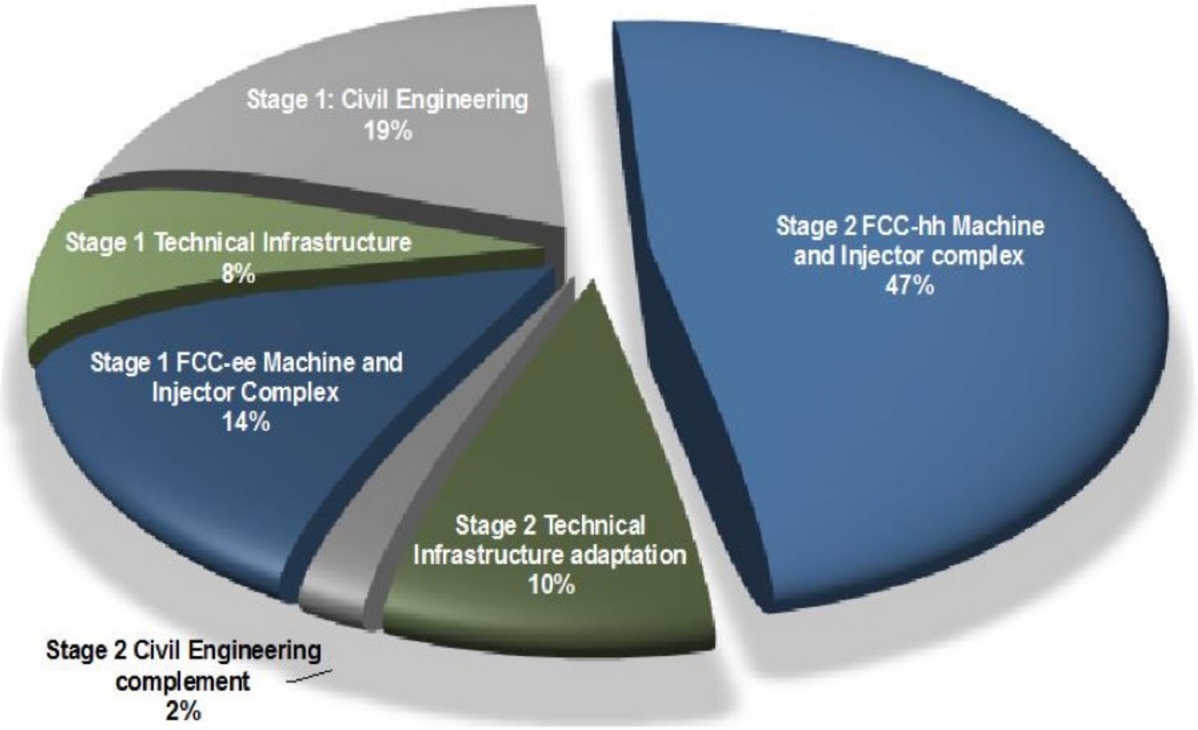


- conceptually extended from the CLIC detector design
  - full silicon tracker
  - 2T magnetic field
  - high granular silicon-tungsten ECAL
  - high granular scintillator-steel HCAL
  - instrumented steel-yoke with RPC for muon detection

- explicitly designed for FCC-ee/CepC
  - silicon vertex
  - low X_0 drift chamber
  - drift-chamber silicon wrapper
  - MPGD/magnet coil/lead preshower
  - dual-readout calorimeter: lead-scintillating/ cerenkhov fibers
- μRwell for muon detection

Detectors under study

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**



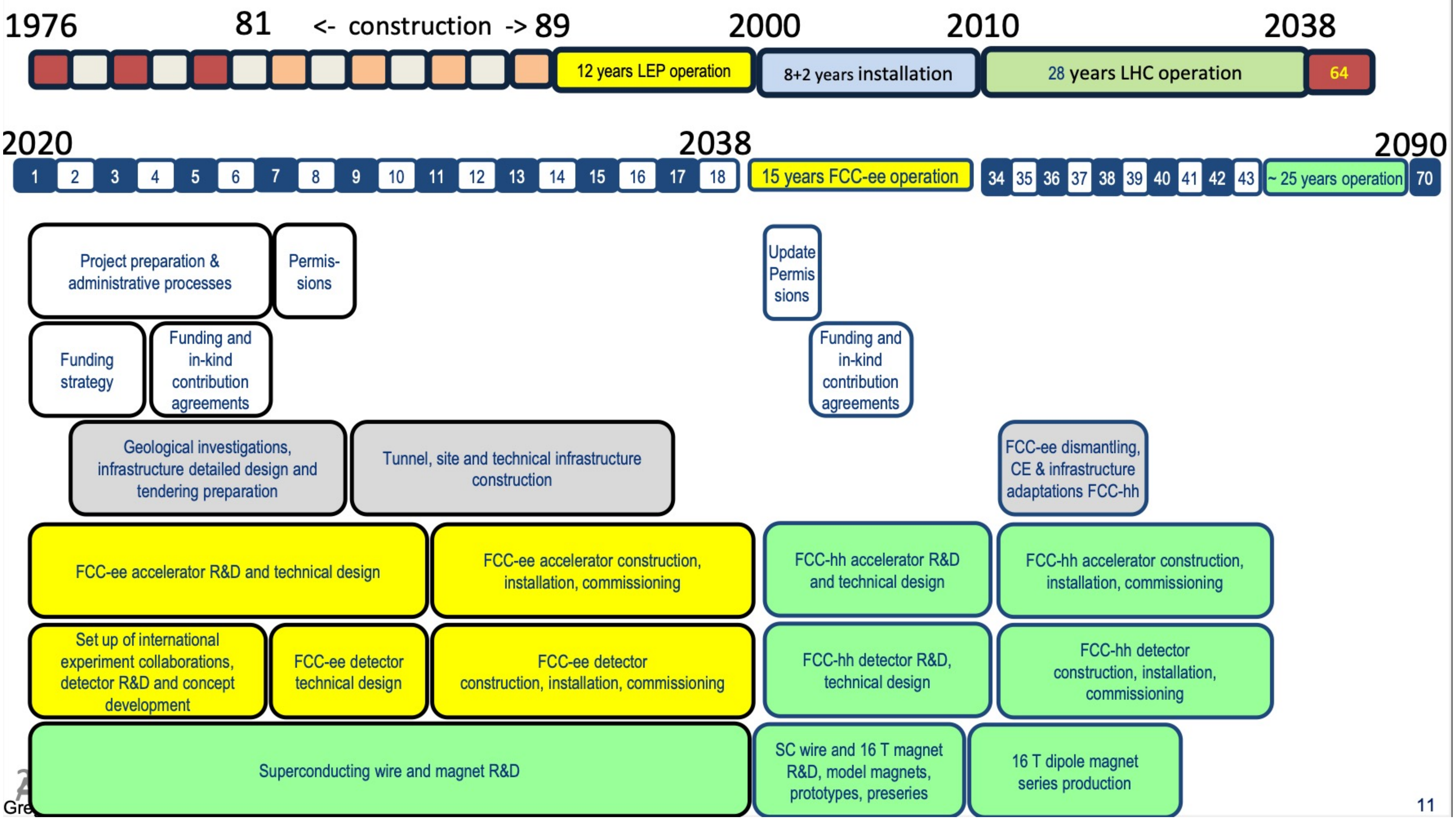
Total construction cost FCC-ee (Z, W, H) amounts to 10.5 BCHF + 1.1 BCHF (tt).

- Associated to a total project duration of ~20 years (2025 – 2045)

Total construction cost for subsequent FCC-hh amounts to 17 BCHF.

- Associated to a total project duration of ~25 years (2035 – 2060) (FCC-hh stand alone 25 BCHF)

FCC timeline with LEP-LHC



Signals, Backgrounds and Selections

- **Signals:**
  1. $Z(\mu^+\mu^-)H$ (Whizard)
  2. $Z(\tau^+\tau^-)H$ (Whizard)
  3. $Z(q\bar{q})H$ (Whizard)   Or   ZH inclusive (Pythia)
  4. $Z(\nu\bar{\nu})H$ (Whizard)
  5. $Z(e^+e^-)H$ (Whizard)

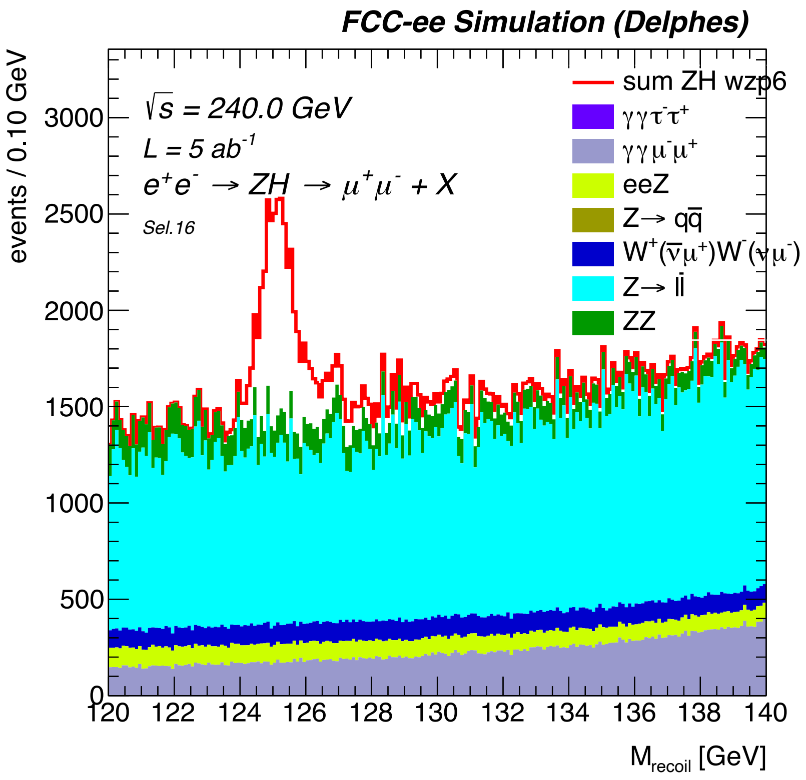
- $\sqrt{s} = 240$ **GeV**
- **ISR and FSR on**
- **Beam Energy Spread**
- **Luminosity:**
  $L = 5\ ab^{-1}$
- **IDEA detector**
- **Spring2021 samples**

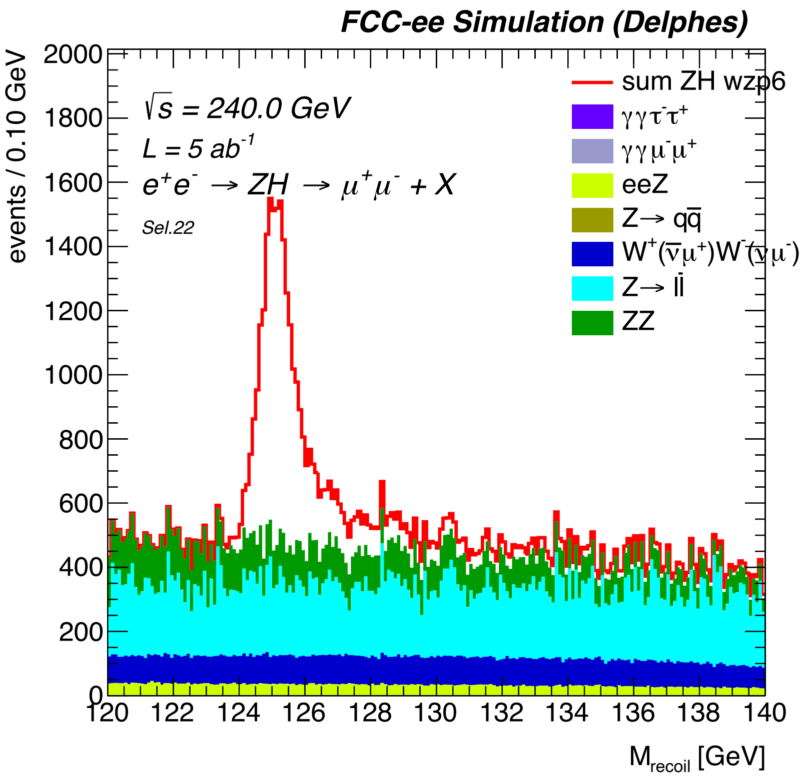
- **Backgrounds:**
  1. ZZ(inclusive), (Pythia)
  2. $W^+(\nu\mu^+)W^-(\bar{\nu}\mu^-)$, (Pythia)
  3. $Z \to l^+l^-$, (Pythia)
  4. $Z \to q\bar{q}$, (Pythia)
  5. eeZ, (Whizard)
  6. $\gamma\gamma \to \mu^+\mu^-$, (Whizard)
  7. $\gamma\gamma \to \tau^+\tau^-$ (Whizard)

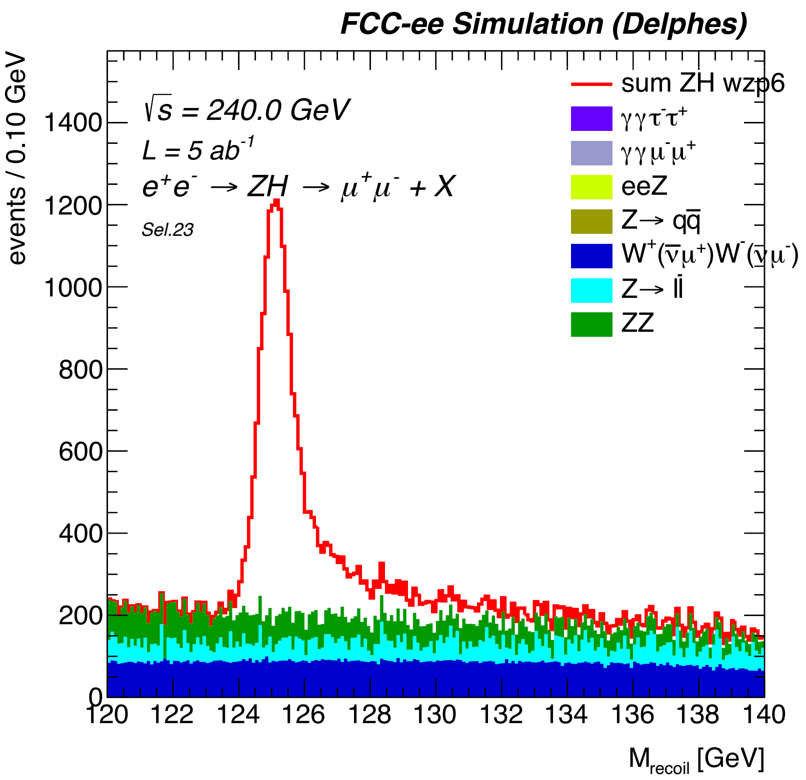
Pre-Selection:
1. At least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [80, 100]$ GeV

	ZH(inclusive)	mumuH	WW_mumu	ZZ(inclusive)	Zll
$\sigma \cdot L$	1006580	33822	1289600	6794950	68893500
NEVENTS	10^7	10^6	10^7	10^7	$0.99 \cdot 10^7$
NEVENTS/$\sigma \cdot L$	9.93	29.57	7.75	1.47	0.14

Evolution of M_{recoil} distribution







APC-0-Selection:

1. At least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [86, 96]$ GeV
3. $M_{\text{recoil}} \in [120, 140]$ GeV

Reconstructed Particle

APC-1-Selection:

1. At least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [86, 96]$ GeV
3. $M_{\text{recoil}} \in [120, 140]$ GeV
4. $p_T^{\mu^+\mu^-} \in [20, 70]$ GeV

APC-2-Selection:

1. At least one Z boson from a $\mu^+\mu^-$ pair
2. $m_{\mu^+\mu^-} \in [86, 96]$ GeV
3. $M_{\text{recoil}} \in [120, 140]$ GeV
4. $p_T^{\mu^+\mu^-} \in [20, 70]$ GeV
5. $|\cos\theta_{missing}| < 0.98$

Fitting model and parameter settings

- **Fitting functions**
  - Signal: 2CBG or Two-Sided Crystal Ball
  - Background: Second Order Polynomial
  - S + B = nsig*signal + nbkg*background

➢ Initial signal modelling using Two-Sided Crystal-Ball (DSCB) , further optimized to 2CBG by Jan: Jan's presentation

- Two CB functions (left and right), sharing mean and width
- Added Gaussian to cope with the high tails
- In total three terms, which can float, but Gaussian suppressed in norm ($sigfrac1 + sigfrac2 > 0.8$)
- In total 10 "free" parameters (+1 normalization)

$$pdf(M_{recoil}) = sigfrac1 \cdot CB(M_{recoil}; \mu, \sigma, \alpha_L, n_L) + sigfrac2 \cdot CB(M_{recoil}; \mu, \sigma, \alpha_R, n_R) + (1 - sigfrac1 - sigfrac2) \cdot Gauss(M_{recoil}; \mu_{2,}\sigma_2)$$