

# Perspectives for Higgs measurements at Future Circular Collider

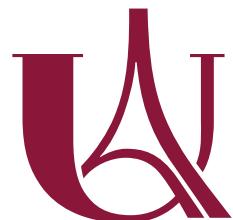
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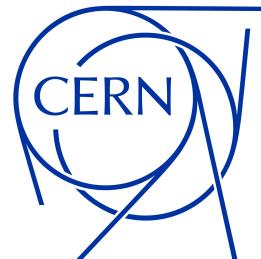
(APC-Paris, Université de Paris, CNRS/IN2P3)

Journées de Rencontre des Jeunes Chercheurs

October 17-23 2021



Université  
de Paris



FUTURE  
CIRCULAR  
COLLIDER

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

## ❖ Higgs physics at LHC

- Discovery of Higgs boson in 2012
- Measurement of Higgs properties after the Higgs discovery
- Third family ( $t$ ,  $b$  and  $\tau$ ) Yukawa couplings

## ❖ Puzzles of the Standard Model

- Dark matter?
- “Missing” anti-matters?
- Different Higgs models?

		QUARKS			GAUGE BOSONS		
mass →	$\approx 2.3 \text{ MeV}/c^2$	$u$	$c$	$t$	$g$	$H$	
charge →	2/3	up	charm	top	gluon	Higgs boson	
spin →	1/2						
mass →	$\approx 4.8 \text{ MeV}/c^2$	$d$	$s$	$b$	$\gamma$		
charge →	-1/3	down	strange	bottom	photon		
spin →	1/2						
mass →	$0.511 \text{ MeV}/c^2$	$e$	$\mu$	$\tau$	$Z$		
charge →	-1	electron	muon	tau	Z boson		
spin →	1/2						
mass →	$<2.2 \text{ eV}/c^2$	$\nu_e$	$\nu_\mu$	$\nu_\tau$	$W$		
charge →	0	electron neutrino	muon neutrino	tau neutrino	W boson		
spin →	1/2						

# Future Colliders

## ❑ Future Linear Colliders:

## 1. International Linear Collider (ILC)

- 1)  $e^+e^-$  at 250GeV, 500 GeV and 1000 GeV
  - 2) 30-50 km



## 2. The Compact Linear Collider (CLIC)

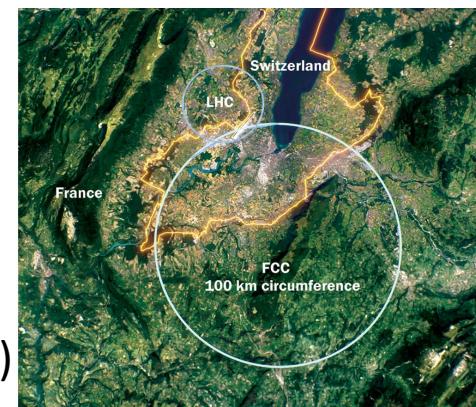
- 1)  $e^+e^-$  at 380 GeV, 1.5 TeV and 3 TeV
  - 2) 11-50 km



## ❑ Future Circular Colliders:

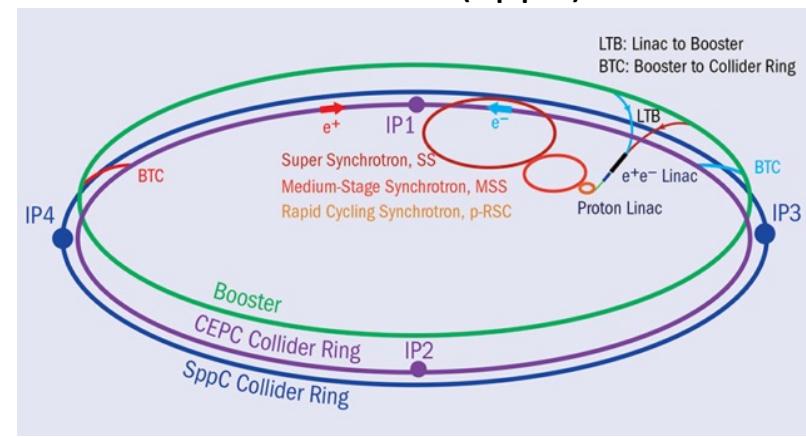
## 1. The Future Circular Collider (FCC)

- 1) FCC-ee:  $e^+e^-$  at  $\sim 125\text{-}365$  GeV, as first-generation Z, Higgs and top factory at high luminosities
  - 2) FCC-hh:  $p - p$  at 100 TeV as natural continuation of LHC at energy frontier
  - 3) Circumference  $\sim 90$  km (LHC:  $\sim 27$  KM)

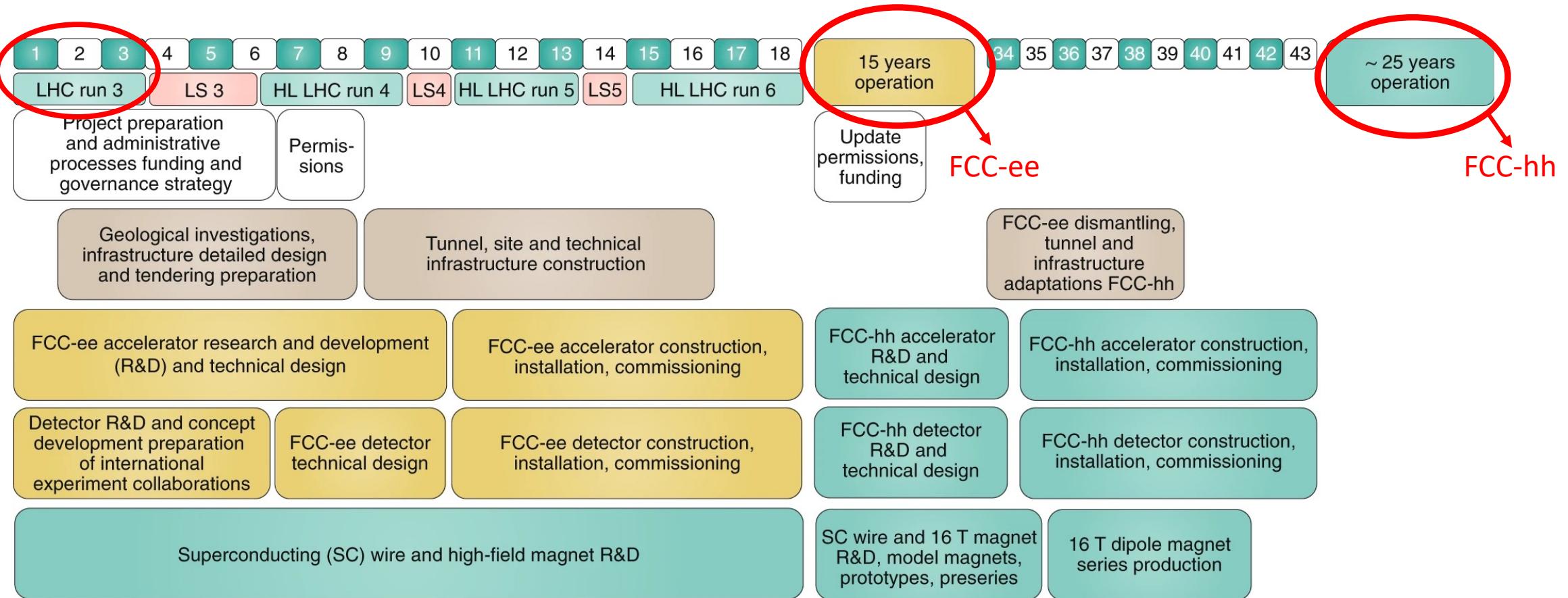


## 2. Circular Electron Positron Collider (CEPC)

- 1)  $e^+e^-$  with similar parameters as FCC-ee
  - 2) Super Proton–Proton Collider (SppC)

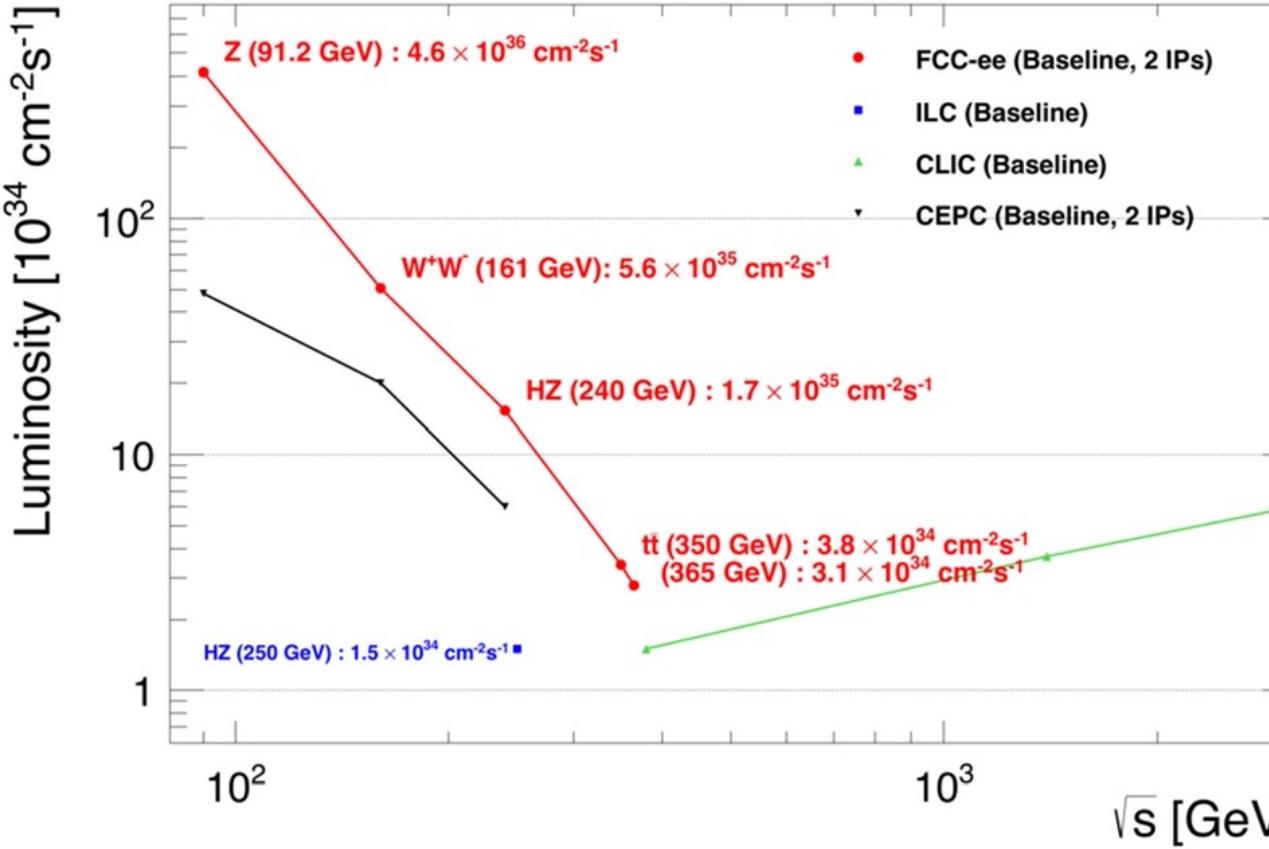


# FCC integrated program



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

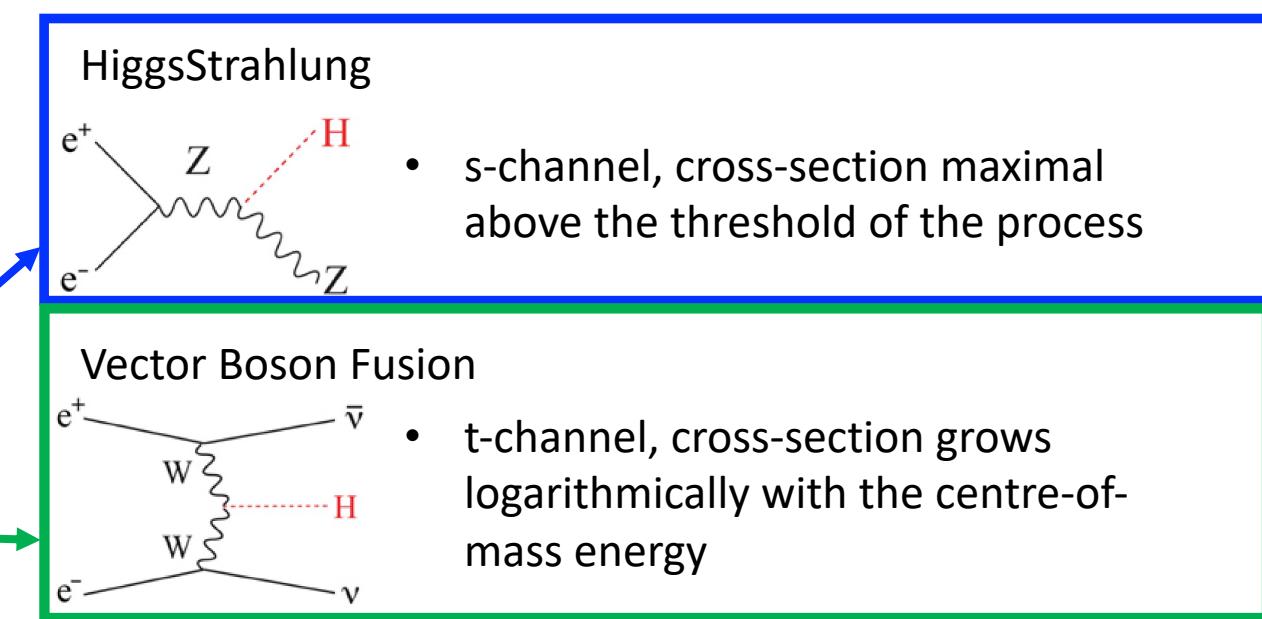
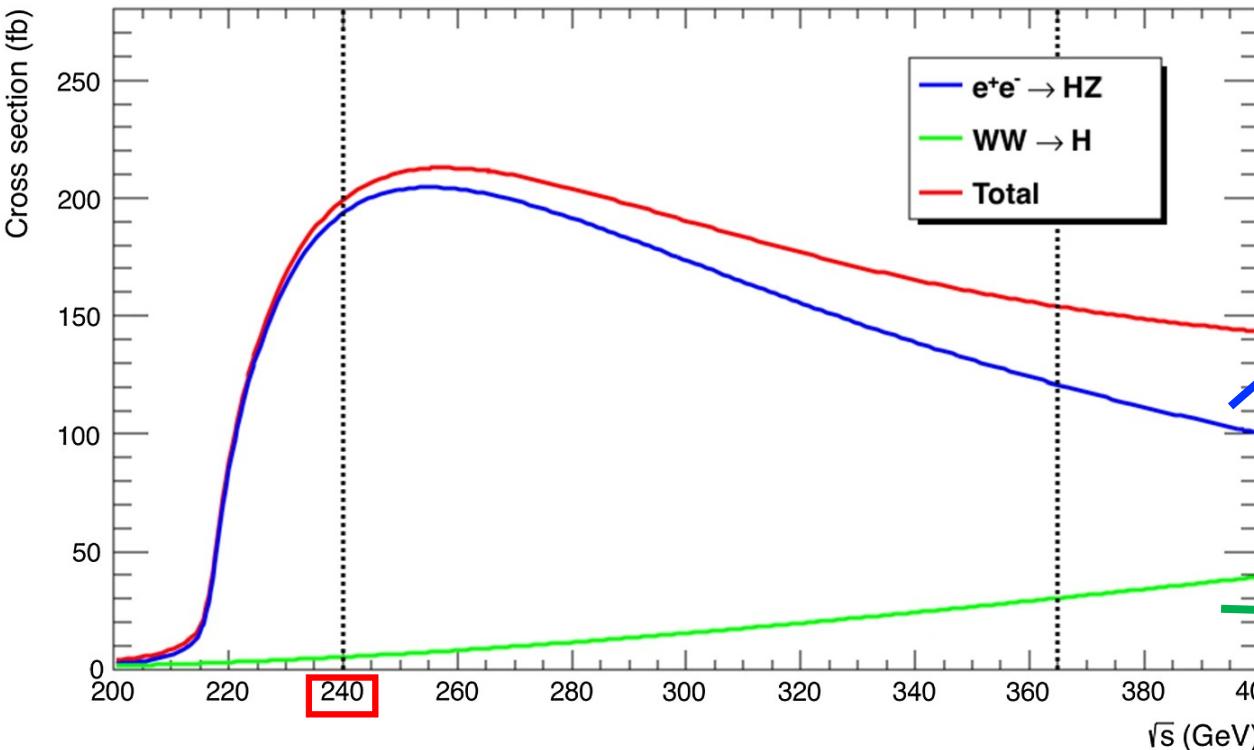


## FCC Physics Opportunities

- The luminosity of FCC on each operation point is larger than CEPC
- For FCC-ee
  - $5 \times 10^{12}$  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 ( $\text{ab}^{-1}$ )	Event statistics
FCC-ee-Z	4	88–95	150	$3 \times 10^{12}$ 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</bar>
FCC-ee-tt(2)	4	365	1.5	$10^6$ t <bar>t events</bar>

# Higgs production at Future Circular Collider (FCC)



## FCC-ee as a Higgs factory

➤ Total Cross-section maximizes at  $\sqrt{s} \sim 260$  GeV

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

1. ZH optimal event rate is at  $\sqrt{s} \sim 240$  GeV :  $\sigma \sim 200$  fb  $\sim 10^6$  events (@  $L = 5 ab^{-1}$ )
2. With data at  $\sqrt{s} \sim 365$  GeV,  $1.8 \times 10^5$  ZH and  $0.45 \times 10^5$  WW-fusions (~30%) (@  $L = 1.5 ab^{-1}$ )  
(useful for measuring self-coupling and  $\Gamma_H$  precisely)

# FUTURE CIRCULAR COLLIDER "Higgs recoil mass" technique at Future Circular Collider (FCC)

- Goal: precise measurements of ZH cross section (per mille) and Higgs mass  $\sim$  MeV

Current best result:  $m_H = 125.38 \pm 0.14 (\pm 0.12)$  GeV @ CMS

The  $\sigma_{ZH}$  accuracy could reach 0.5%

determine  $g_{HZZ}$  and Higgs width ( $\Gamma_H$ )

Electron Yukawa coupling measurement via

s-channel  $e^+e^- \rightarrow H$  @  $\sqrt{S} = m_H$  ( $\Gamma_H = 4.2$  MeV)

Trilinear Higgs-self coupling

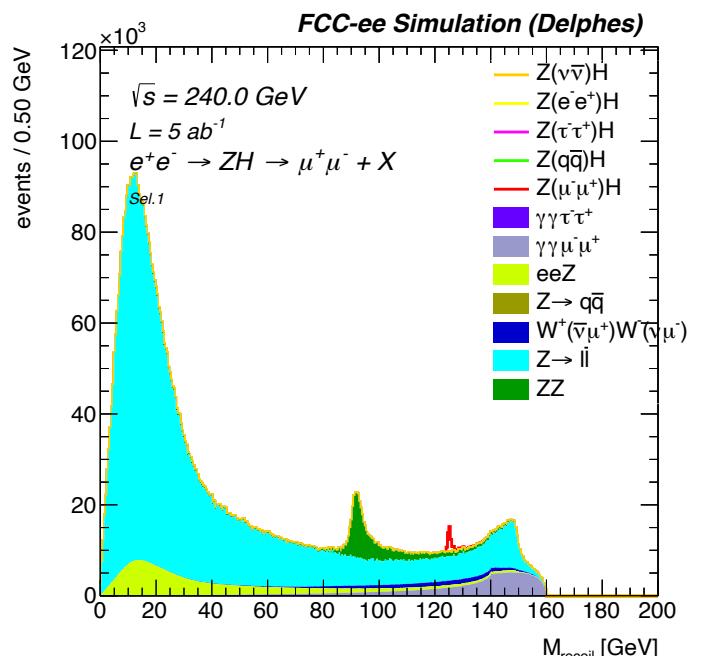
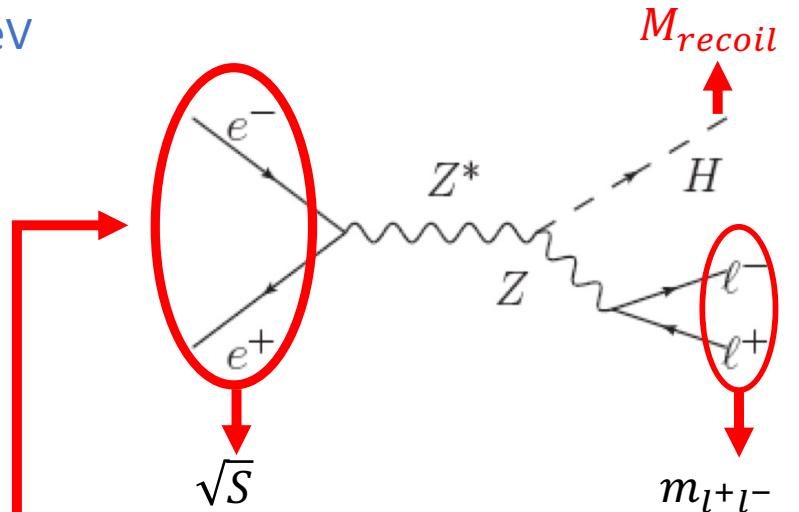
- Signal:  $e^+e^- \rightarrow ZH \rightarrow l\bar{l} + X$

ZH is the dominant Higgs production process @ 240 GeV  $e^+e^-$  machine

- $M_{recoil}$  from the Z production without measuring the Higgs production final state

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

- 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



# Signal, Background and Selections

## Monte-Carlo campaign (“Spring2021”):

- $\sqrt{s} = 240 \text{ GeV}$
- Luminosity:  $L = 5 \text{ ab}^{-1}$
- ISR and FSR on
- Beam Energy Spread (BES) sets to  $0.165\% = \pm 198 \text{ MeV}$
- IDEA detector; detector response modelled with Delphes

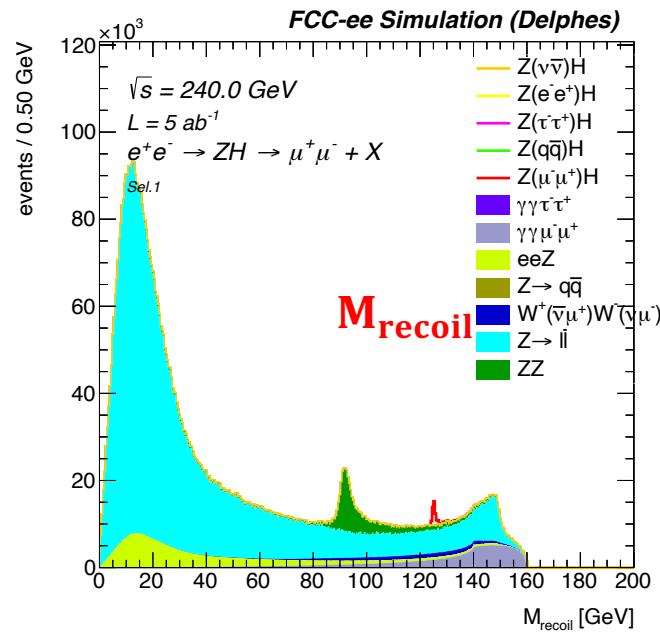
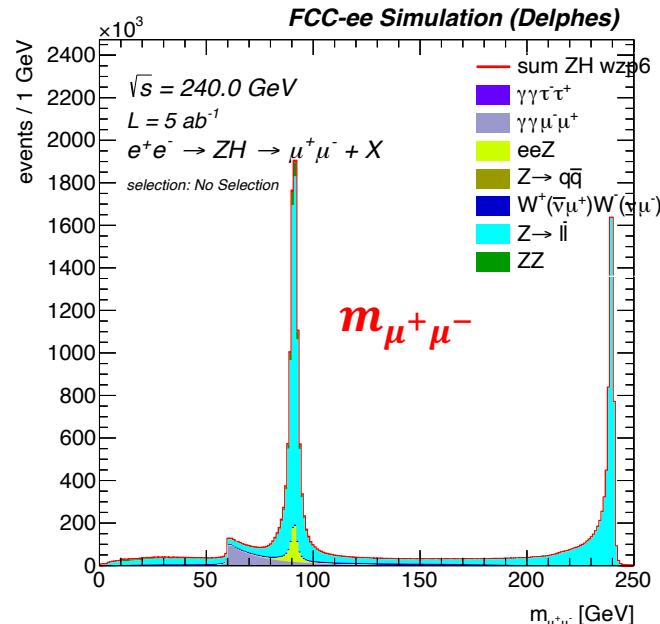
### • Signals:

1.  $Z(\mu^+\mu^-)H$  (Whizard)
2.  $Z(\tau^+\tau^-)H$  (Whizard)
3.  $Z(q\bar{q})H$  (Whizard)
4.  $Z(\nu\bar{\nu})H$  (Whizard)
5.  $Z(e^+e^-)H$  (Whizard)

### • Backgrounds:

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

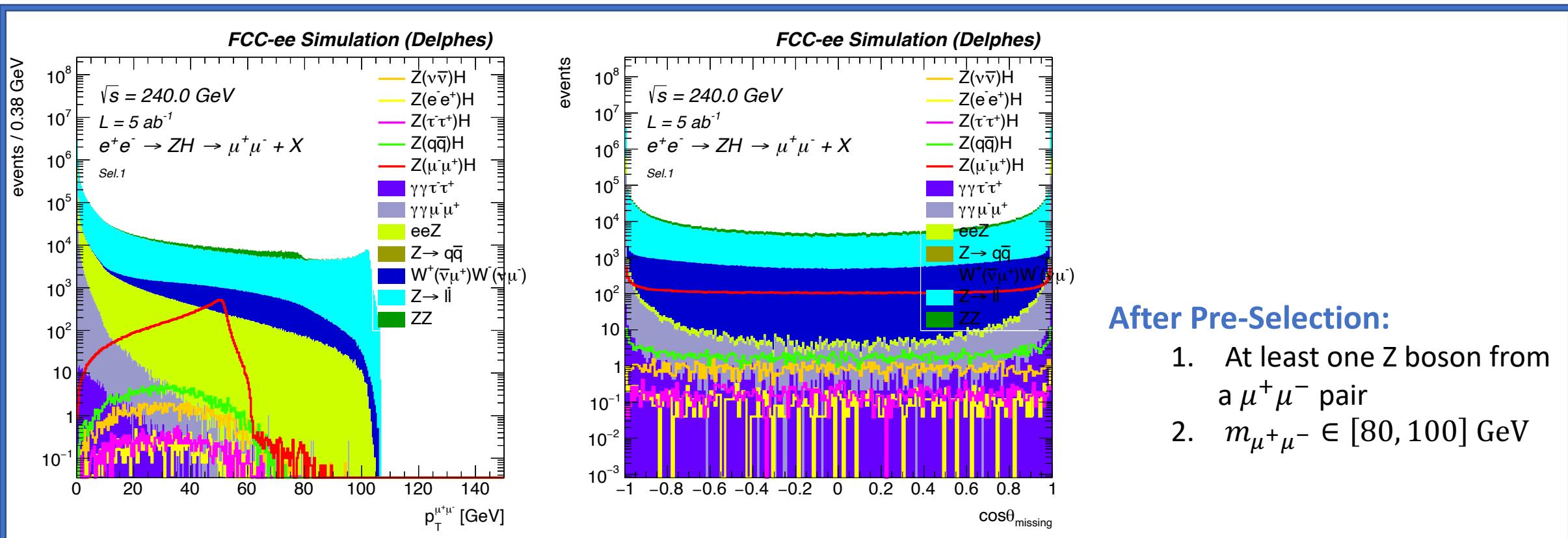
	mumuH	WW_mumu	ZZ(inclusive)	Zll
$\sigma \cdot L$	33822	1289600	6794950	68893500
NEVENTS	$10^6$	$10^7$	$10^7$	$0.99 \cdot 10^7$
NEVENTS/ $\sigma \cdot L$	29.57	7.75	1.47	0.14



# Event Selections

## Event-Selection:

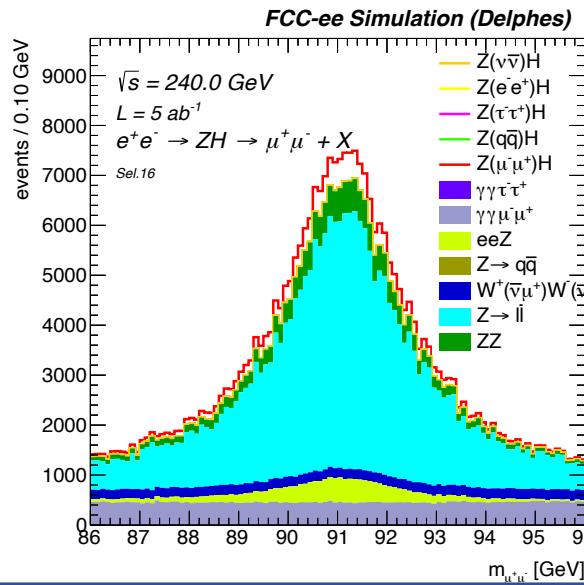
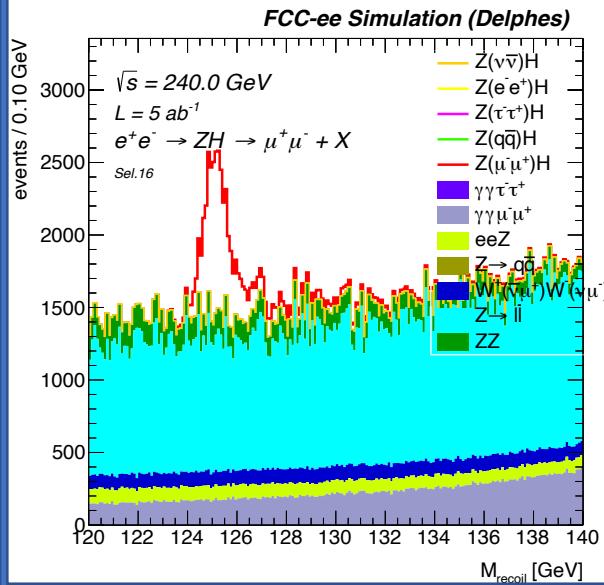
1. At least one Z boson from a  $\mu^+\mu^-$  pair
2.  $m_{\mu^+\mu^-} \in [86, 96]$  GeV → focus on Z resonance space
3.  $M_{\text{recoil}} \in [120, 140]$  GeV → Signal exhibits sharp peak around  $\sim 125$  GeV,
4.  $p_T^{\mu^+\mu^-} \in [20, 70]$  GeV → Signal mainly within this region, Low  $p_T^{\mu^+\mu^-}$  cuts back-to-back events ( $Z/\gamma^* \rightarrow ll$ )
5.  $|\cos \theta_{\text{missing}}| < 0.98$  → Polar angle of missing momentum, reduce  $\gamma\gamma$  processes. ISR emitted approximately collinear with the incoming beams escapes detection in the beam pipe



## After Pre-Selection:

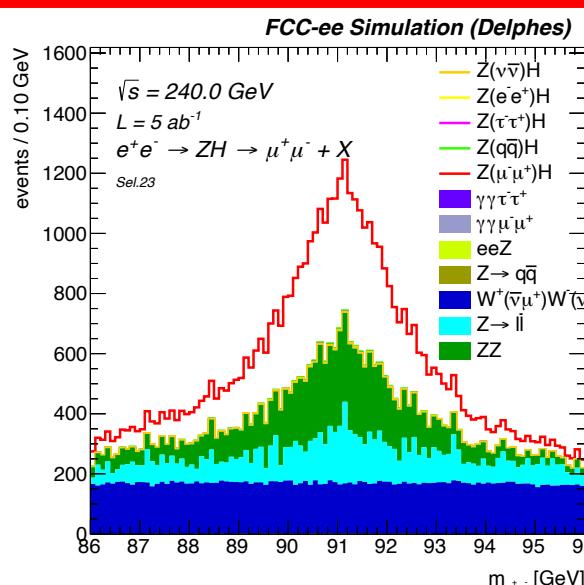
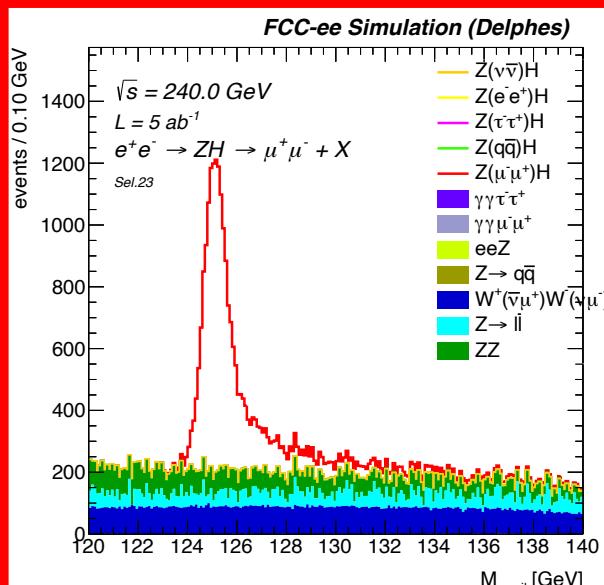
1. At least one Z boson from a  $\mu^+\mu^-$  pair
2.  $m_{\mu^+\mu^-} \in [80, 100]$  GeV

# Evolution of $m_{\mu^+\mu^-}$ and $M_{recoil}$ distributions



## APC-0-Selection:

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



## APC-2-Selection:

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

## Signals:

- $Z(\mu^+\mu^-)H$  (Whizard)

## Backgrounds:

- $ZZ$ (inclusive), (Pythia)
- $W^+(\bar{\nu}\mu^+)W^-(\nu\mu^-)$ , (Pythia)
- $Z \rightarrow l^+l^-$ , (Pythia)

## Additional Backgrounds:

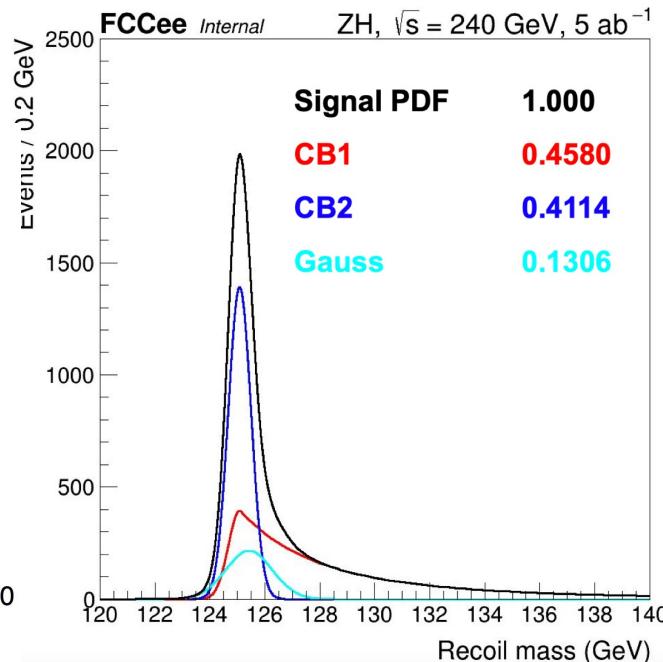
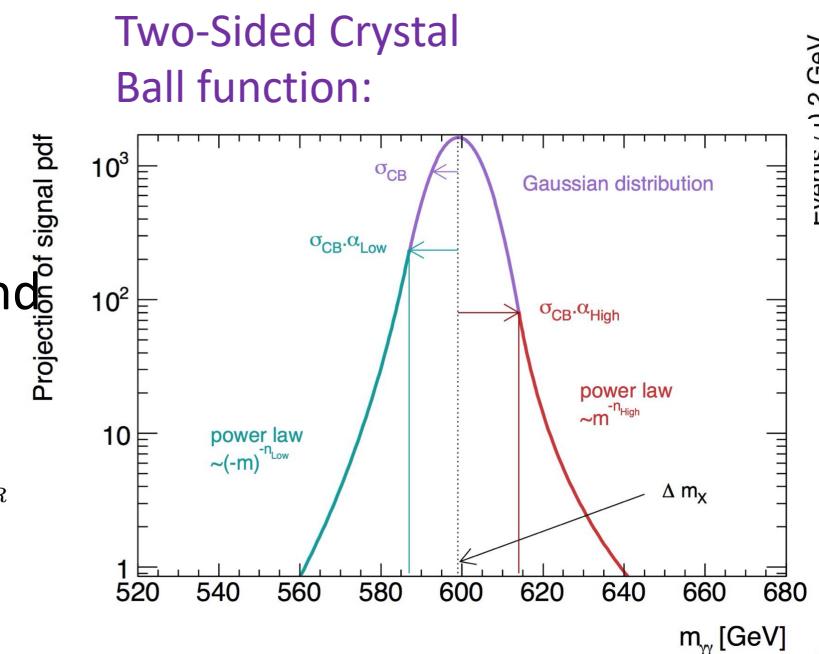
- $Z \rightarrow q\bar{q}$ , (Pythia)
- $eeZ$ , (Whizard)
- $\gamma\gamma \rightarrow \mu^+\mu^-$ , (Whizard)
- $\gamma\gamma \rightarrow \tau^+\tau^-$  (Whizard)

# Fitting model and parameter settings

## • Fitting functions

- Signal: 2CBG
- Background: Second Order Polynomial
- $S + B = n_{\text{sig}} * \text{signal} + n_{\text{bkg}} * \text{background}$

$$f_S(x; \vec{\theta}) = \begin{cases} \left(\frac{n_L}{|\alpha_L|}\right)^{n_L} \exp\left(\frac{-|\alpha_L|^2}{2}\right) \left(\frac{n_L}{|\alpha_L|} - |\alpha_L| - \frac{x-\mu}{\sigma}\right)^{-n_L}, & \text{for } \frac{x-\mu}{\sigma} \leq -\alpha_L \\ \exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right), & \text{for } -\alpha_L < \frac{x-\mu}{\sigma} < \alpha_R \\ \left(\frac{n_R}{|\alpha_R|}\right)^{n_R} \exp\left(\frac{-|\alpha_R|^2}{2}\right) \left(\frac{n_R}{|\alpha_R|} - |\alpha_R| + \frac{x-\mu}{\sigma}\right)^{-n_R}, & \text{for } \frac{x-\mu}{\sigma} \geq \alpha_R, \end{cases}$$

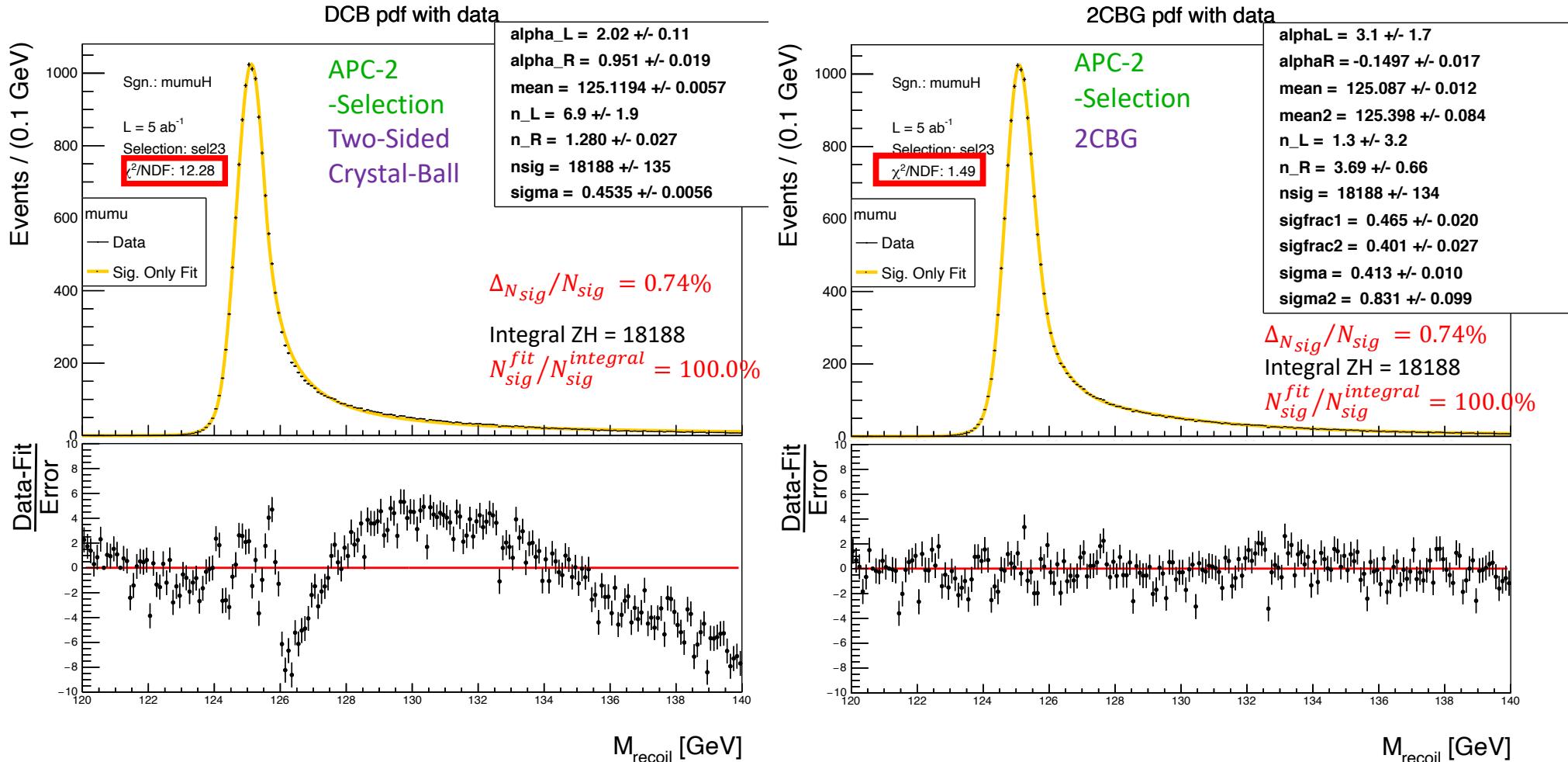


- Initial signal modelling using Two-Sided Crystal-Ball (DSCB) , further optimized to 2CBG:
  - Two CB functions (left and right), sharing mean and width
  - Added Gaussian to cope with the high tails
  - Gaussian suppressed in norm ( $\text{sigfrac1} + \text{sigfrac2} > 0.8$ )
  - In total 10 “free” parameters (+1 normalization)

$\text{pdf}(M_{\text{recoil}})$

$$= \text{sigfrac1} \cdot \text{CB}(M_{\text{recoil}}; \mu, \sigma, \alpha_L, n_L) + \text{sigfrac2} \cdot \text{CB}(M_{\text{recoil}}; \mu, \sigma, \alpha_R, n_R) + (1 - \text{sigfrac1} - \text{sigfrac2}) \cdot \text{Gauss}(M_{\text{recoil}}; \mu_2, \sigma_2)$$

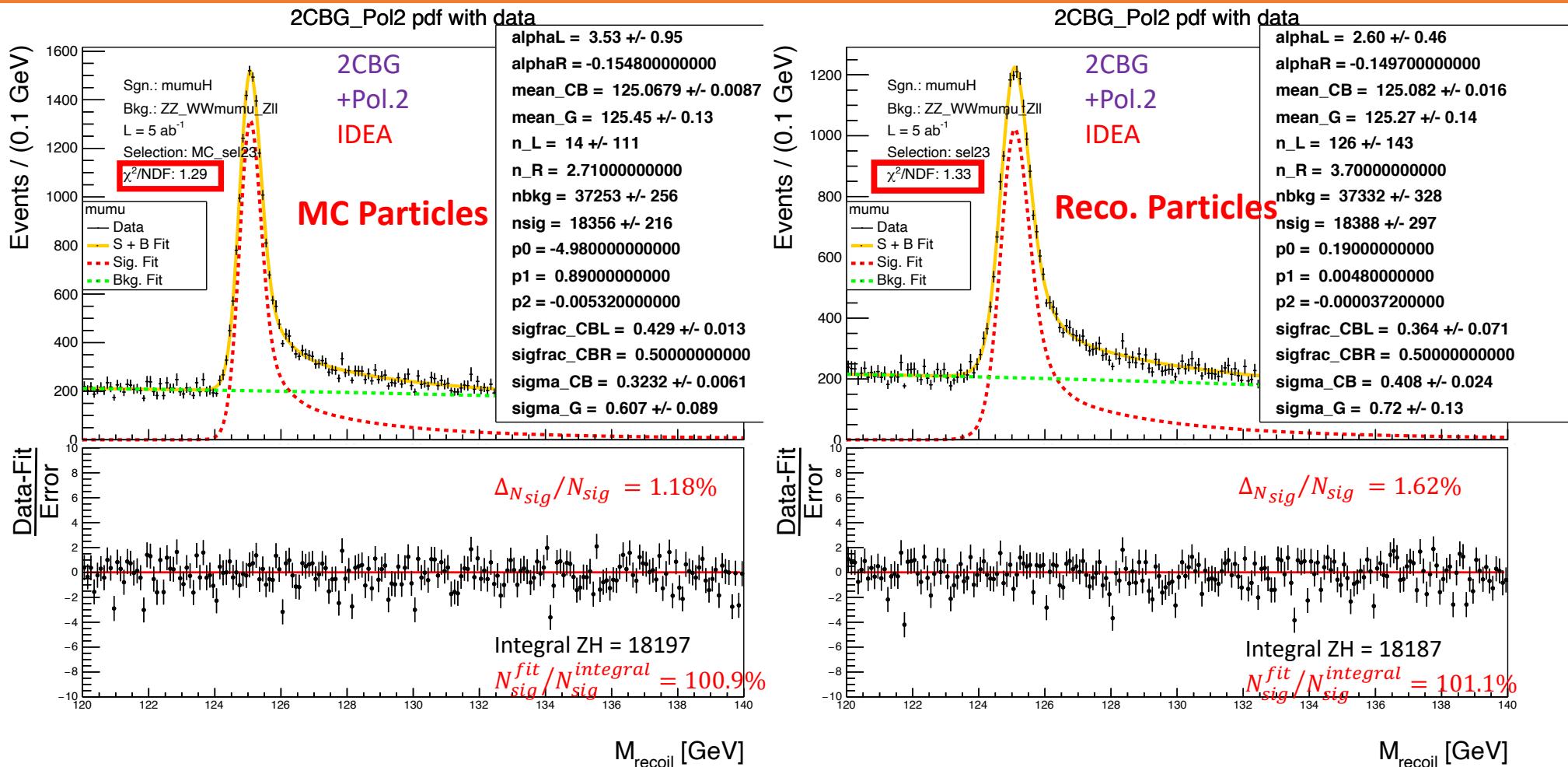
# Signal Only fit with different p.d.f. in the Higgs region (120-140 GeV)



$Z(\mu^+ \mu^-)H$	$\sigma_{CB}(\text{GeV})$	$M_{CB}(\text{GeV})$	$\chi^2/NDF$
DSCB	0.4535	125.1194	12.28
2CBG	0.4130	125.0870	1.49

- Compared to Two-Sided Crystal-Ball ( $\chi^2/NDF \sim 12.3$ ), 2CBG function has better description of the signal  $\chi^2/NDF$  decreases to  $\sim 1.5$
- Still a little wiggle between 122-130 GeV

# Signal + Background fit with 2CBG + Pol.2



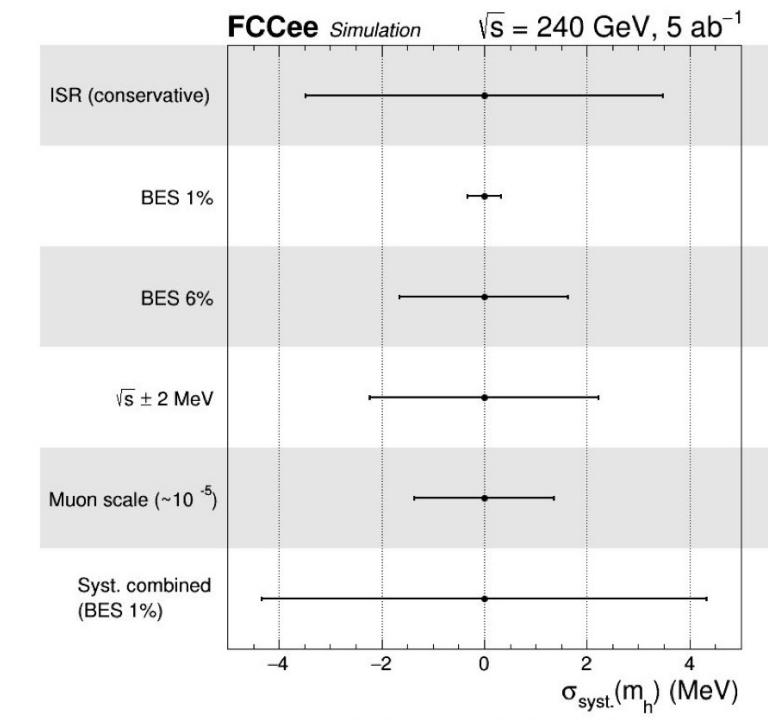
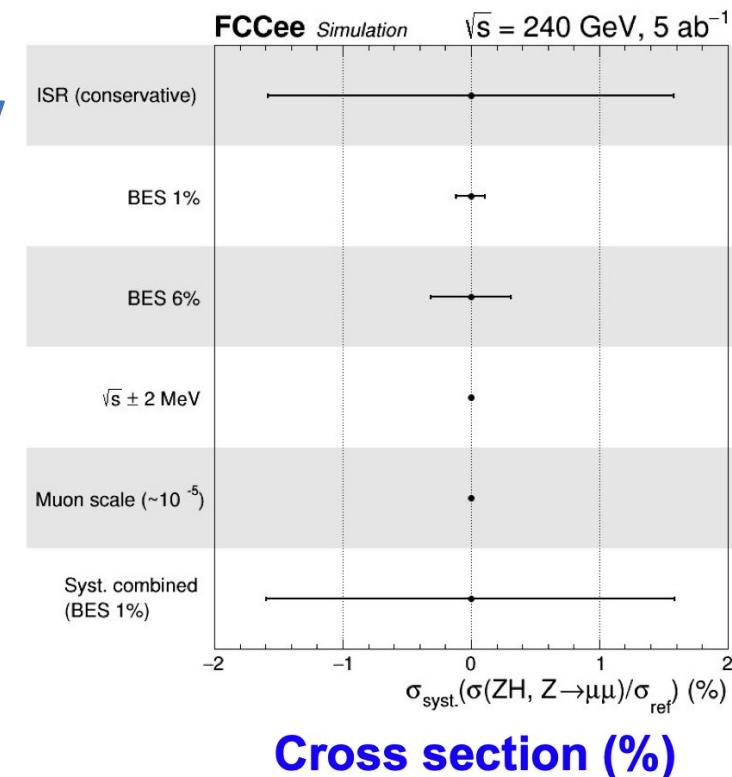
$Z(\mu^+\mu^-)H$	$\sigma_{CB}(\text{GeV})$	$M_{CB}(\text{GeV})$	$\chi^2/NDF$	$\Delta_{N_{sig}}/N_{sig}$	$N_{sig}^{fit}/N_{sig}^{integral}$
MC	0.3232	125.0679	1.29	1.18%	100.9%
Reco.	0.4080	125.0820	1.33	1.62%	101.1%

- ❖ Widths of CB are close to signal only fit
- ❖  $N_{sig}^{fit}/N_{sig}^{integral} \sim 100\%$
- ❖ For MC particles,  $\Delta_{N_{sig}}/N_{sig} = 1.18\%$
- ❖ For reconstructed particles,  $\Delta_{N_{sig}}/N_{sig} = 1.62\%$

# Systematics

## ❖ Systematics:

1. Beam Energy Spread Uncertainty
2. Initial States Radiation
3. Centre-of-mass energy
4. Muon momentum scale

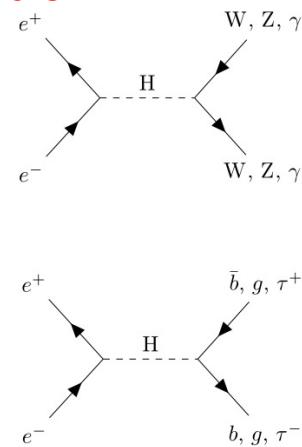


[ZH Recoil talk at FCC Week](#)

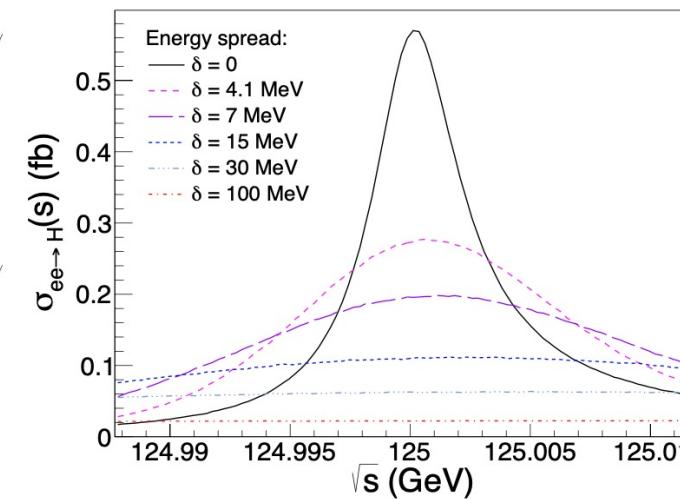
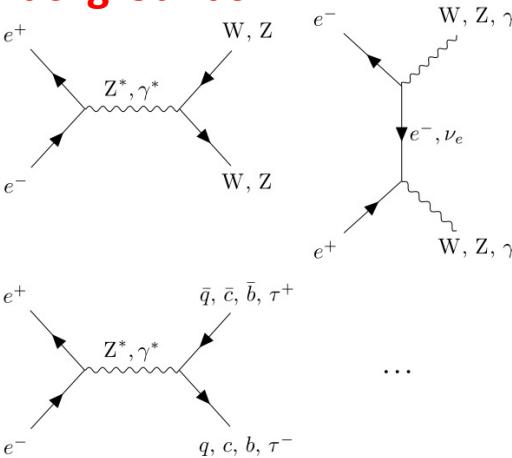
- Statistical analysis yields Higgs mass uncertainty 16 MeV, cross-section 1.6 % (stat-only)
- ISR is the most important systematics uncertainty
- Will apply more advanced analysis techniques (BDT...)

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

## Signals



## Backgrounds:



[arXiv:2107.02686](https://arxiv.org/abs/2107.02686)

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

- Yukawa couplings have been measured so far only for t, b and  $\tau$  ( $\mu, c$  after HL-LHC)
- Higgs decay to  $e^+e^-$  is unobservable:  $BR(H \rightarrow e^+e^-) \propto m_e^2 \approx 5 \times 10^{-9}$
- Peak cross-section:  $\sigma_{ee \rightarrow H} = 1.64 \text{ fb}$  ( $m_H = 125 \text{ GeV}, \Gamma_H = 4.2 \text{ MeV}$ )

## Challenges:

- Centre-of-mass energy at Higgs pole (Accurate knowledge of Higgs mass (~MeV)) → (feasible at FCC-ee with recoil method)
- ISR and beam-energy spread (~MeV but still deliver large  $L_{int}$ ) → If  $(\delta_{\sqrt{s}}, L_{int}) = (4.1 \text{ MeV}, 10 \text{ ab}^{-1})$   
then  $\sigma_{e^+e^- \rightarrow H} = 0.28 \text{ fb}$
- Existence of multiple backgrounds

## Fundamental Physics motivations:

- Electron Yukawa coupling is measurable
- New particle that is quasi-degenerate with Higgs boson mass?

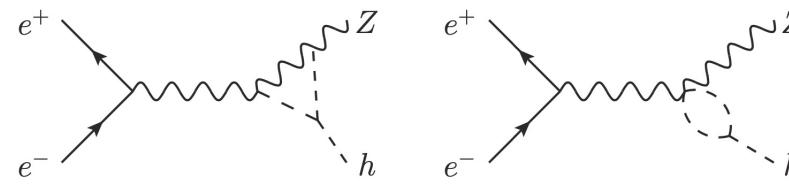
$H \rightarrow gg$	$H \rightarrow WW^* \rightarrow \ell\nu 2j; 2\ell 2\nu; 4j$	$H \rightarrow ZZ^* \rightarrow 2j 2\nu; 2\ell 2j; 2\ell 2\nu$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau_{had}\tau_{had}; c\bar{c}; \gamma\gamma$	Combined
$1.1\sigma$	$(0.53 \otimes 0.34 \otimes 0.13)\sigma$	$(0.32 \otimes 0.18 \otimes 0.05)\sigma$	$0.13\sigma$	$< 0.02\sigma$	$1.3\sigma$

Its feasibility study is still on going

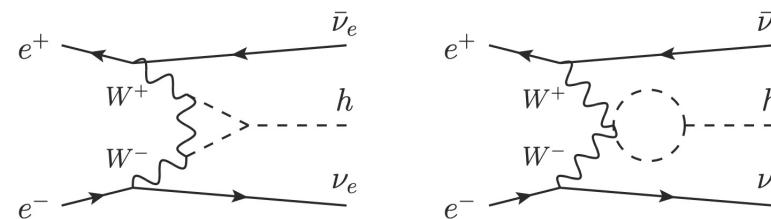
# Trilinear Higgs Self-coupling

## Trilinear coupling:

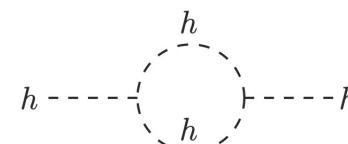
□ Higgs strahlung:  $e^+e^- \rightarrow ZH$



□ WW-fusion:  $e^+e^- \rightarrow \nu\bar{\nu}_e H$



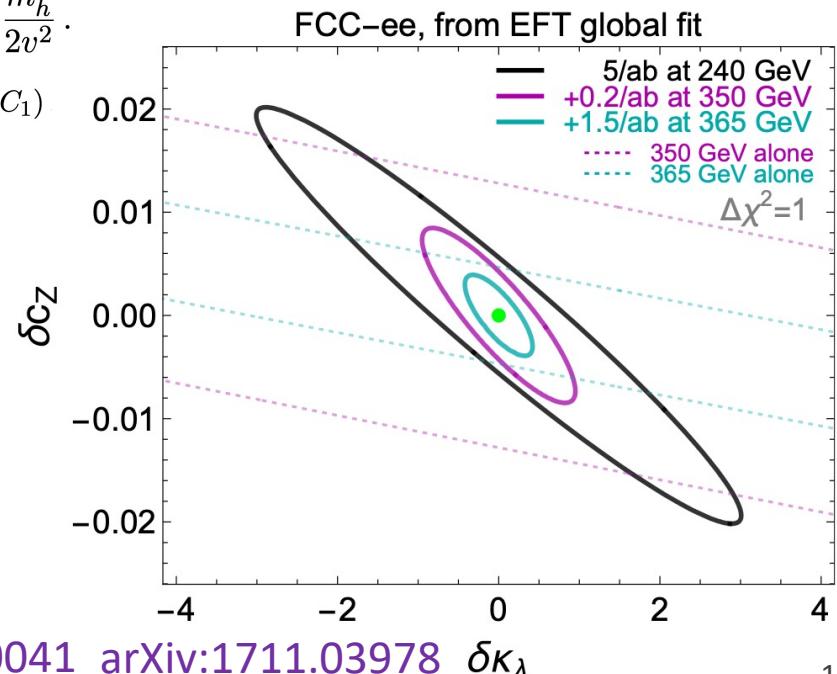
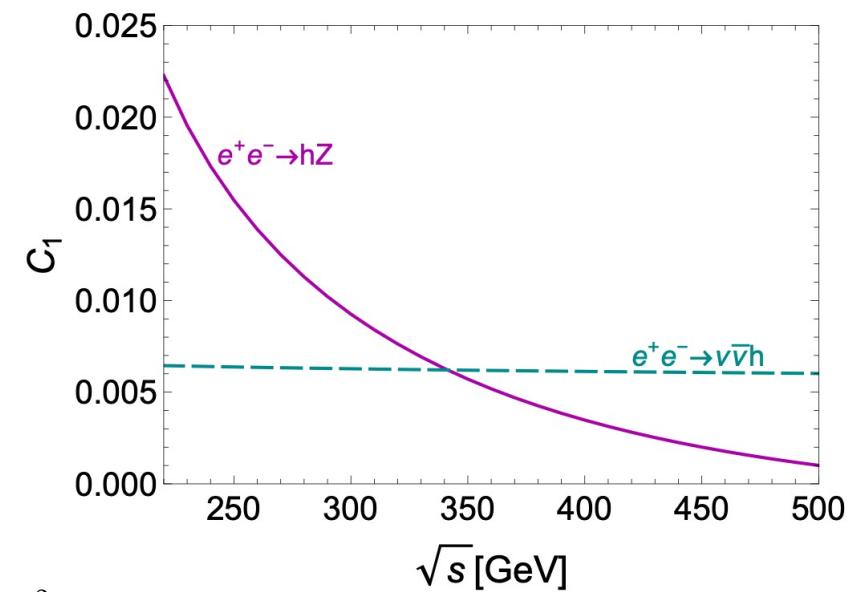
□ Higgs self-energy



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

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

- Including all the FCC-ee running, a model-independent precision of  $\pm 42\%$  can be achieved on  $k_\lambda$  reduced to  $\pm 34\%$  in combination with HL-LHC, and to  $\pm 12\%$  when only  $k_\lambda$  is allowed to vary
- FCC-hh has the potential to reach a precision of  $\sim 3\text{-}5\%$  of  $\lambda_3$  from di-Higgs production, in combination with the precise Higgs decay branching ratio measurements from the FCC-ee
- With four IPs, the first  $5\sigma$  demonstration of the Higgs self-coupling is within reach in 15 years at FCC-ee



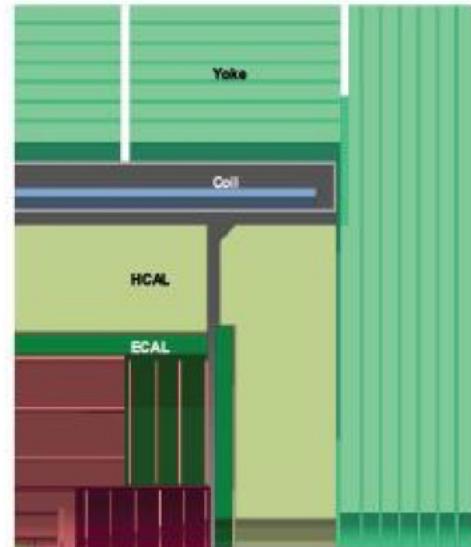
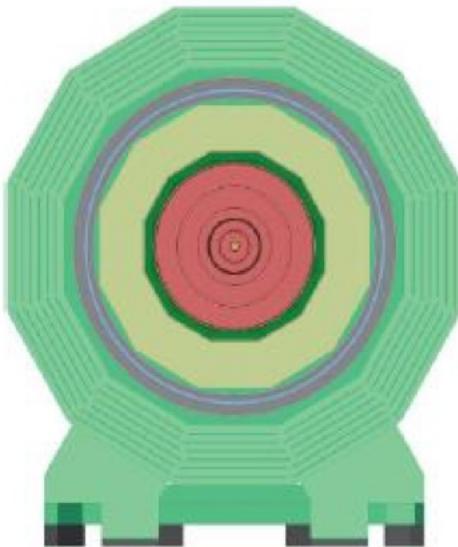
## ❖ Conclusion:

- In the Higgs measurements at the  $e^+e^-$  colliders, the “ZH recoil mass” method will improve the uncertainty of  $m_H$  to several MeV level (while  $\Gamma_H = 4.1$  MeV) and measure the  $g_{HZZ}$  as a “candle” for other Higgs studies
- Optimized event selection to reject main backgrounds
- Signal modelling with customized p.d.f.
- With only basic studies, the uncertainty of Higgs mass is  $\sim 16$  MeV. The uncertainty of cross-section  $\sim 1.6\%$
- Electron Yukawa coupling and trilinear Higgs coupling may be probed at FCC

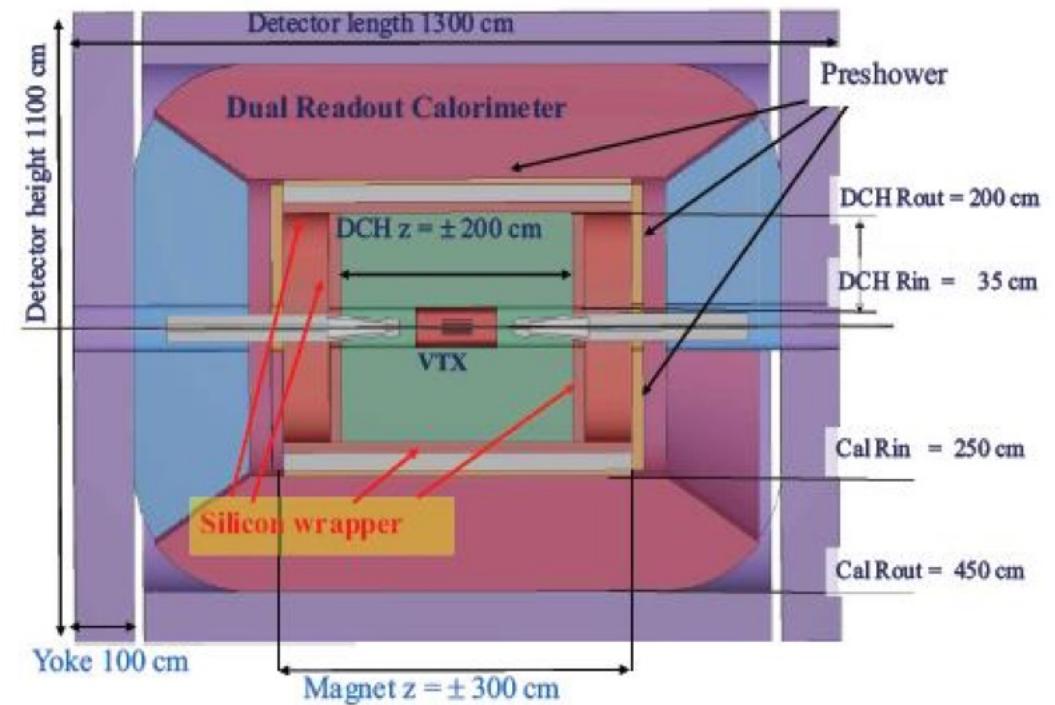
# Backup

# Detectors under study

## CLD



## IDEA

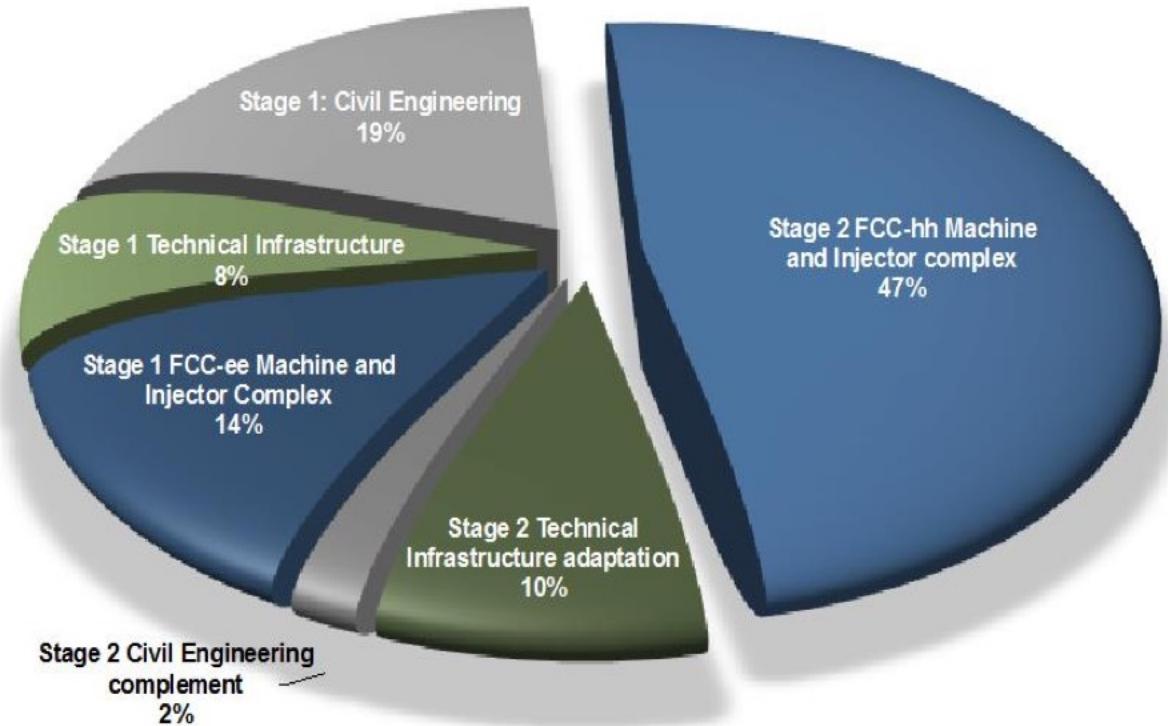


- conceptually extended from the CLIC detector design
  - full silicon tracker
  - 2T magnetic field
  - high granular silicon-tungsten ECAL
  - high granular scintillator-steel HCAL
  - instrumented steel-yoke with RPC for muon detection

- 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/cerenkov fibers
  - $\mu$ Rwell 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
<b>TOTAL construction cost for integral FCC project</b>	<b>28,600</b>



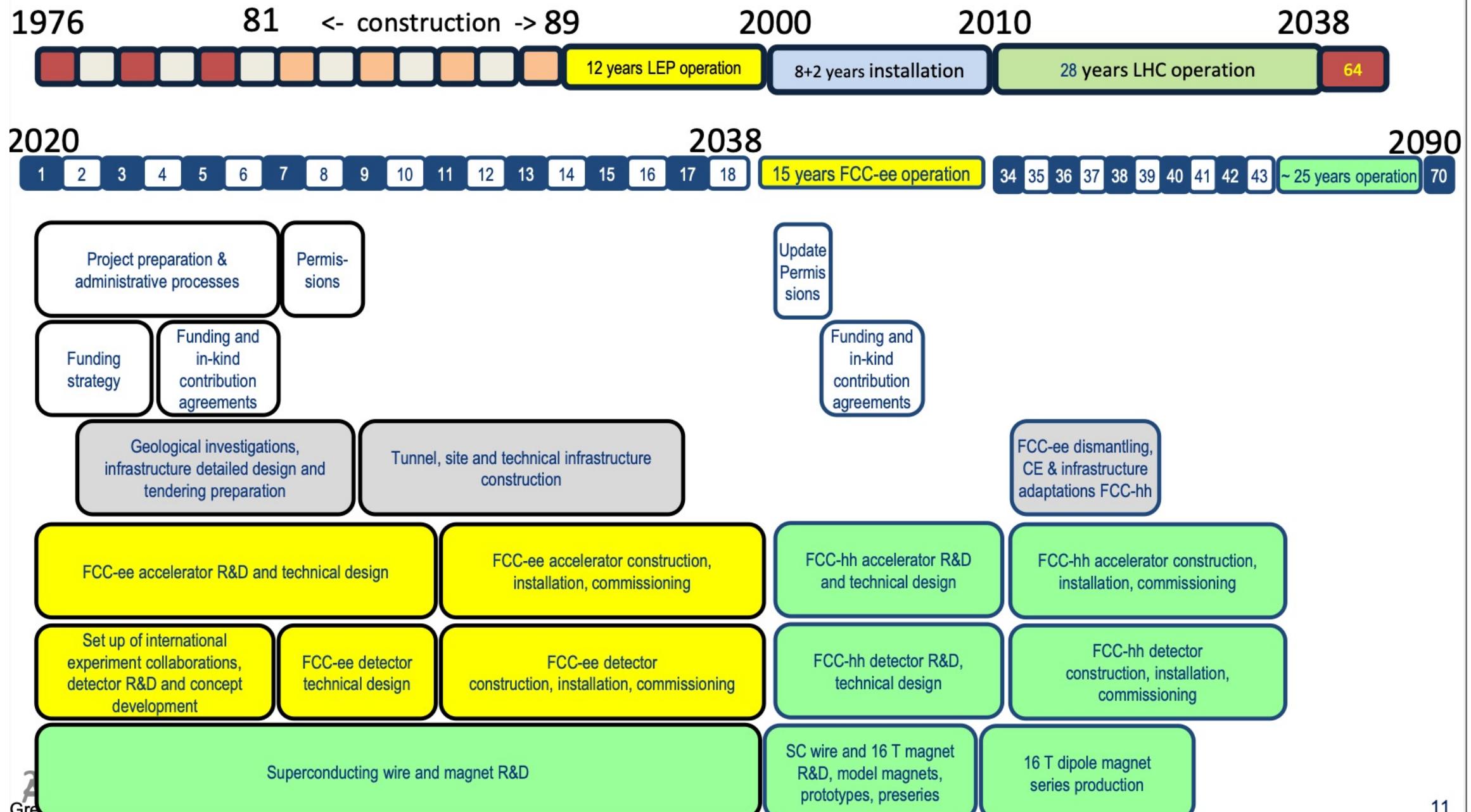
**Total construction cost FCC-ee (Z, W, H) amounts to 10.5 BCHF + 1.1 BCHF (tt).**

- 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



# Number of events, error and number of entries

Sample	Pre-Selection			APC-2-Selection		
	#Events	Error	#Entries	#Events	Error	#Entries
$Z(\mu^+\mu^-)H$	24178.8	28.6	714893	18181.1	24.8	537560
$Z(\tau^+\tau^-)H$	32.7	1.1	873	12.4	0.7	330
$Z(q\bar{q})H$	425.5	5.4	6179	171.5	3.4	2491
<b>Total Signal</b>	<b>24637.0</b>	<b>35.1</b>	<b>721945</b>	<b>18365.0</b>	<b>28.9</b>	<b>540381</b>
$W^+(\nu\mu^+)W^-(\bar{\nu}\mu^-)$	133530.9	131.2	1035444	16927.3	46.7	131260
ZZ(inclusive)	315780.4	463.2	464728	11219.8	87.3	16512
$Z \rightarrow l\bar{l}$	7846308.6	7389.3	1127515	9471.1	256.7	1361
<b>Total Main Bkgs.</b>	<b>8295619.8</b>	<b>7983.8</b>	<b>2627687</b>	<b>37618.2</b>	<b>390.8</b>	<b>149133</b>
$\gamma\gamma\mu\mu$	384090.8	315.2	1484600	4.7	1.1	18
$\gamma\gamma\tau\tau$	304.3	8.0	1456	6.3	1.1	30
$eeZ$	793603.7	286.8	7654357	24.0	1.6	231
$Z \rightarrow q\bar{q}$	0.0	0.0	0	0.0	0.0	0
$Z(\nu\bar{\nu})H$	173.8	3.7	2257	69.3	2.3	900
$Z(e^+e^-)H$	23.4	1.0	587	9.3	0.6	234
<b>Additional Bkgs</b>	<b>1178195.9</b>	<b>614.7</b>	<b>9143257</b>	<b>113.5</b>	<b>6.7</b>	<b>1413</b>

## ➤ APC-2-Selection

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

Compared to Pre-Selection,  
APC-2-Selection keeps  $\sim 75\%$  signals  
but rejects

## ➤ Main background:

- $\sim 87\% WW$
- $\sim 96\% ZZ$
- $\sim 99.88\% Z \rightarrow l\bar{l}$

## ➤ Additional background

- $\sim 99.99\% \gamma\gamma\mu\mu$ ,
- $\sim 99.93\% eeZ$