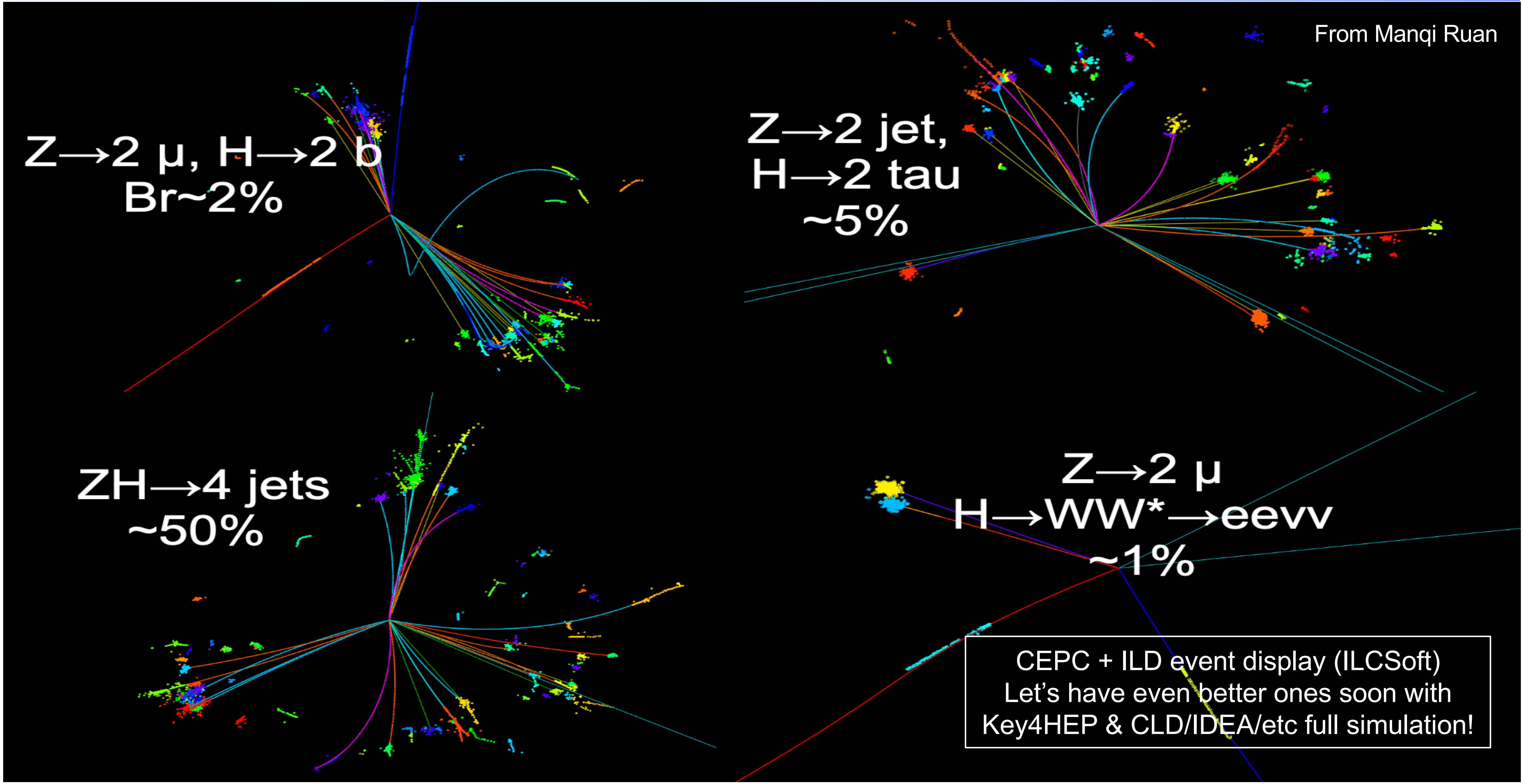
Higgs physics studies at FCC: Introduction



Introduction of the Introduction

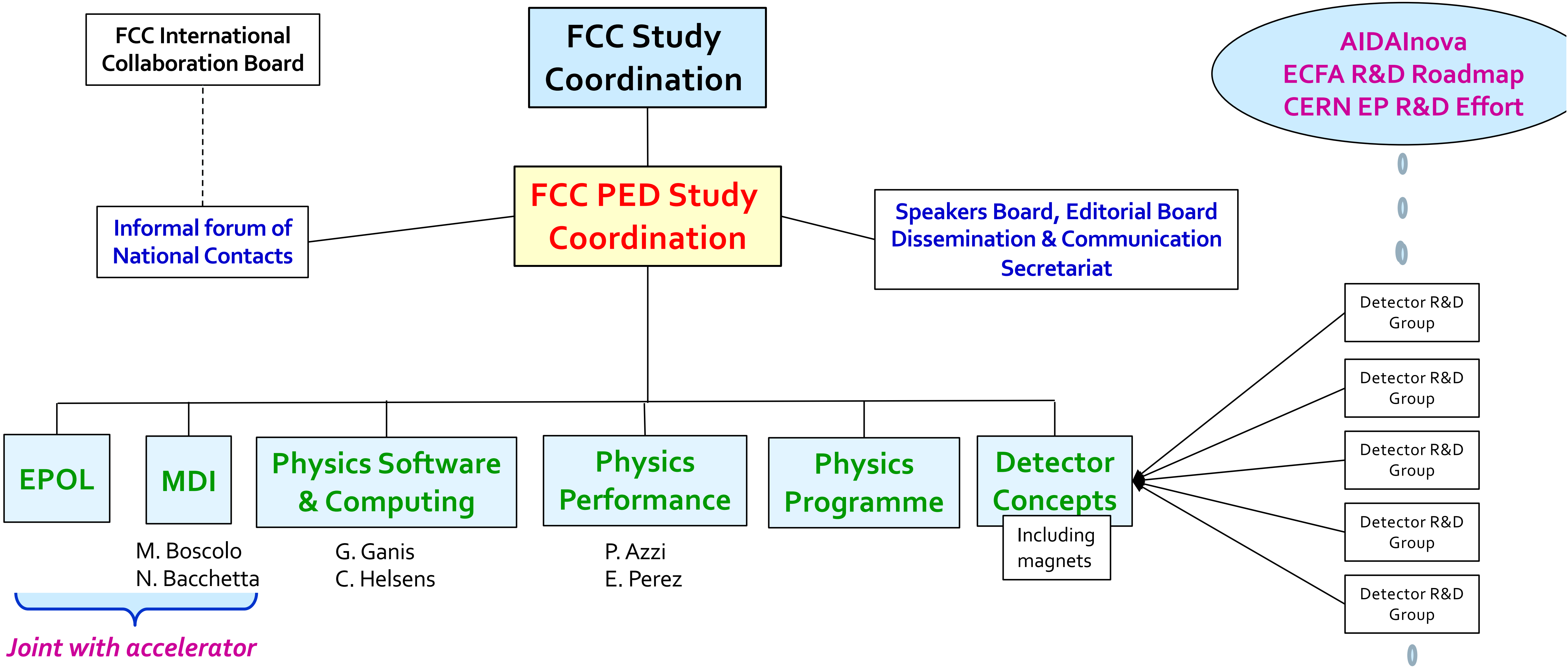
- **Mandate from Greg for this presentation:**
  - "Give an overview of the Higgs studies@FCC to do <u>in the few years to come</u>, and of the associated challenges [No detector]"

I will focus on FCC-ee

- **Related mandate of the FCC Physics, Experiments, and Detector Studies (PED)**
  - "Deliver a detailed FCC Physics CDR++, so that enough knowledge and material be available for FCC-ee proto collaborations to progressively take over"
    - Suite of experimental studies, with extensive understanding of detector requirements
      - ➔ So that systematic uncertainties match the statistical power of FCC-ee
    - Detector Concepts that satisfy the detector requirements
    - Simulation and Reconstruction Software to enable the experimental studies
    - Extended physics programme, including new ideas
      - ➔ With (plans for) theoretical calculations and MC generators, with the required precision
- **Higgs studies @ FCC in the years to come are consistent with this mandate**
  - Note: "Study the Higgs" is only a part of the FCC physics programme
    - The above list applies to the Z, W, top, and New Physics programme too.

Possible organizational chart for FCC PED

- Higgs studies will have impact in virtually all aspects



Status of Higgs Studies after ESU2020

- Results often presented as a list of Higgs couplings and expected relative precision
  - For the proposed Higgs factories: and their energy upgrades:

J. De Blas et al., arXiv:1905.03764

FCC-ee

Numbers without/with HL-LHC

κ fit

EFT fit

Collider	HL-LHC	ILC_{250}	CLIC_{380}	CEPC_{240}	$\mathrm{FCC\text{-}ee}_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years	10	11.5	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5	0.30 / 0.29	0.50 / 0.44	0.19 / 0.18	0.18 / 0.17
g_{HWW} (%)	1.7	1.8 / 1.0	0.86 / 0.73	1.3 / 0.88	0.44 / 0.41
g_{Hbb} (%)	5.1	1.8 / 1.1	1.9 / 1.2	1.3 / 0.92	0.69 / 0.64
g_{Hcc} (%)	SM	2.5 / 2.0	4.4 / 4.1	2.2 / 2.0	1.3 / 1.3
g_{Hgg} (%)	2.5	2.3 / 1.4	2.5 / 1.5	1.5 / 1.0	1.0 / 0.89
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	1.9 / 1.1	3.1 / 1.4	1.4 / 0.91	0.74 / 0.66
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	15. / 4.2	– / 4.4	9.0 / 3.9	8.9 / 3.9
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	6.8 / 1.3	– / 1.5	3.7 / 1.2	3.9 / 1.2
$g_{\mathrm{HZ}\gamma}$ (%)	11.	– / 10.	– / 10.	8.2 / 6.3	– / 10.
g_{Htt} (%)	3.4	– / 3.1	– / 3.2	– / 3.1	10. / 3.1
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 27./24. (4IP)
Γ_{H} (%)	SM	2.2	2.5	1.7	1.1
$\mathrm{BR_{inv}}$ (%)	1.9	0.26	0.65	0.28	0.19
$\mathrm{BR_{EXO}}$ (%)	SM (0.0)	1.8	2.7	1.1	1.1

FCC-INT

Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50
$g_{\mathrm{H}\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46
$g_{\mathrm{H}\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43
$g_{\mathrm{H}\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32
$g_{\mathrm{HZ}\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95
g_{HHH} (%)	27.	10.	9.	3. – 4.
Γ_{H} (%)	1.1	1.0	1.6	0.91
$\mathrm{BR_{inv}}$ (%)	0.23	0.22	0.61	0.024
$\mathrm{BR_{EXO}}$ (%)	1.4	1.4	2.4	1.0

ee

hh

hh

ee

hh

ee

- Two basic observations from the perusal of these two tables
  - FCC is unbeatable on both fronts (FCC-ee/hh statistics, FCC-ee/hh unique complementarity)
  - Everything seems to be done already → Nothing to do in the next few years ?

Nothing to do in the next few years?

- The FCC-ee results come from the observables in this table
  - All projected precisions come from full simulation
    - arXiv:1708.08912 — Extrapolated from unpolarized ILC_{250} at $\sqrt{s}$ = 240 GeV
    - arXiv:1608.07538 — Extrapolated from $CLIC_{380}$ at $\sqrt{s}$ = 365 GeV
  - The final fits have been performed by the ECFA group (arXiv:1905.03764)
    - κ fit private versions exist
  - Very few analyses are documented in the FCC context
    - σ_{HZ}, BR(H →bb, WW, ττ, γγ, μμ, invis.) @ 240 GeV (invis.: arXiv:1605.00100)
      - → With CMS full simulation (!) (arXiv:1208.1662)
      - → With CLD Delphes card (FCC week 2018 (Colin Bernet))
    - None return the ILC / CLIC extrapolated performance
  - Only statistical uncertainties are given
    - Systematic uncertainties / cross-channel contaminations expected to be small, but not evaluated
    - Realistic and powerful measurement techniques need to be implemented and documented for all
    - Common tools/code to be developed; Detector/Theory requirements to be extracted/ascertained

FCC-ee CDR, EPJ ST **228**, 261–623(2019)

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

Small cross-channel correlations not (yet) included in the fits
H → Z γ and Z → H γ still to be analysed (for the HZγ coupling)
eeH (Z boson fusion process) not included
Only configuration with 2IP is shown

Nothing to do in the next few years?

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  - The final fits have been ...
    - κ fit priv...
  - Ver...

FCC-ee ...

			±3.0
		±12	±10
		±1.8	±8
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Higgs studies are therefore an ideal and very strong entry point

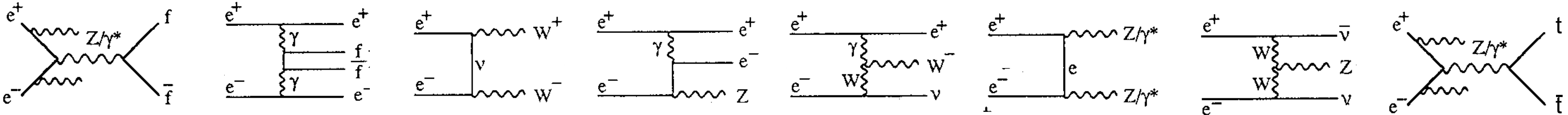
- For ILC/CLIC experts to be part and parcel of and become influential in the FCC project.
- For young physicists to learn from the best experts; and participate in FCC physics, software & detector development.
- For the FCC PED Studies to prepare for the future on common grounds.

Fits to and combination of measurements

- A common combination algorithm should be developed, documented, and shared
  - To evaluate, a common grounds, the effect of any improvement
    - In the event selection and the underlying physics tools (e.g., jet clsutering, kinematic fits, …)
    - In the event reconstruction (e.g., particle flow, tracking, vertexing, clustering, flavour tagging …)
    - In the detector performance (lepton/jet energy and angular resolutions, particle ID, vertexing ,…)
    - In the operation model (2 vs 4 IPs; luminosity & centre-of-mass energies; beam energy spread, …)
  - To digest and evaluate the effect of the complete channel correlation matrix
    - e.g., correlation / cross contamination between H $\rightarrow$bb, cc, gg (and other hadronic final states)
  - To deal with and evaluate the effect of (exp. and th.) systematic uncertanties
  - Able to include (e.g., angular, energy, tagging) distributions or event classes
    - As opposed to the sole statistical uncertainties on the numbers of events
  - Able to work in different frameworks
    - κ framework and EFT framework
      - ➔ Combined with EW measurements in the latter
- Ideal entry point for ATLAS and CMS Higgs combination experts.

Monte Carlo generators

- Review (non) existing MC generators: what do they include, what do they miss?
  - **For backgrounds** (PYTHIA, WHIZARD, KKMC, …)

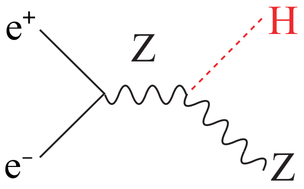


$e^+e^- \to q\bar{q}, l^+l^-$ | $\gamma\gamma \to qq, l^+l^-$, $m > 30$ GeV | $e^+e^- \to W^+W^-$ | $e^+e^- \to Ze^+e^-$ | $e^+e^- \to We\nu$ | $e^+e^- \to ZZ$ | $e^+e^- \to Z\nu\bar{\nu}$ | $e^+e^- \to t\bar{t}$

At $\sqrt{s}$ = 240 GeV (Total cross section varies like 1/s or log s) — At $\sqrt{s}$ = 365 GeV

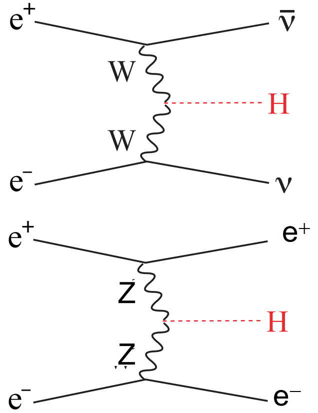
62 pb | **30 pb** | **16 pb** | **3.8 pb** | **1.4 pb** | **1.3 pb** | **32 fb** | **~0.6 pb**

  - **For signal** (PYTHIA, WHIZARD, HZHA, …)



194 fb

At $\sqrt{s}$ = 240 GeV



30 fb

3 fb

At $\sqrt{s}$ = 365 GeV

  - **Interface with FCCSW, with ISR and BES**
  - **Document shortcomings**
    - Approximations, missing higher orders or graphs …
    - Evaluate systematic effect on measurements
      - ➔ And requirements on theory
  - **Make basic configuration available for production**
  - **Plan for development**

Monte Carlo generators

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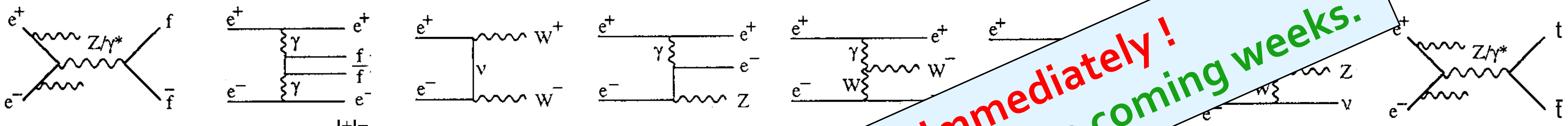
  - For backgrounds (PYTHIA, WHIZARD, KKMC, …)



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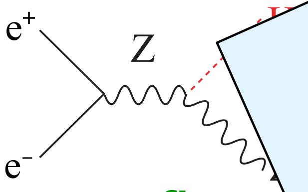
  - For signal (PYTHIA, W…



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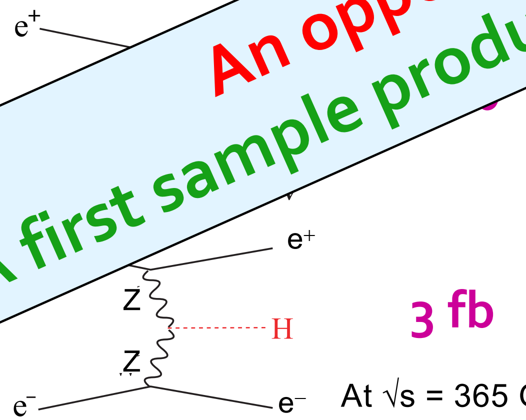

3 fb

At $\sqrt{s}$ = 365 GeV

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  - Make basic configuration available for production
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An opportunity to contribute immediately !

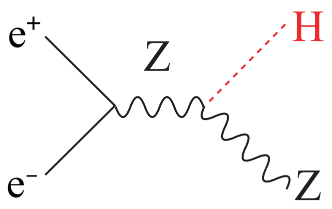
A first sample production is planned within the coming weeks.

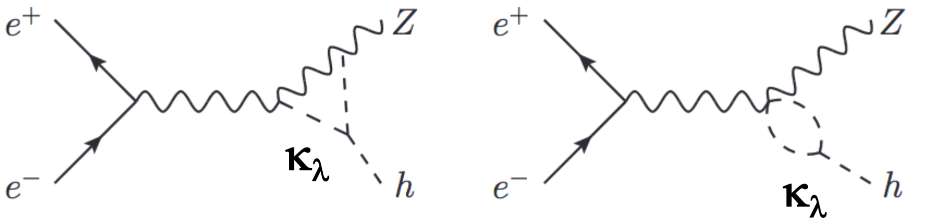
High-priority case studies

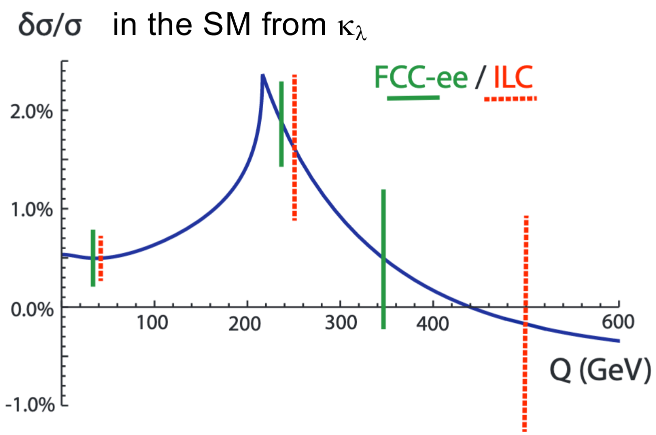
- Case studies are associated to important FCC physics benchmark measurements
  - They are focused on establishing the tools needed to address the following issues
    - Evaluate the detector characteristics needed to reduce the experimental uncertainties to a level that matches the expected statistical uncertainty
    - Identify other sources of systematic biases for which ways to reduce their effect to a level that matches the expected statistical uncertainty are to be sought
    - Improve the expected statistical accuracy, either by increasing efficiency of the physics tools, or by refining the data analysis, or by finding complementary final states, or by optimizing the set of centre-of-mass energies and luminosities, etc.
    - Quantify the relevance and benefits of a configuration with four interaction points, and the need for regular calibration runs at the Z
  - Collaborative development is the desired mode of operation for case studies
    - With up-to-date documentation for all available tools, methods, and case study analysis code, as well as for the developing results, and their publication.
  - Preliminary list of case studies: https://www.overleaf.com/read/dyjpdszrqxhz

Measurement of the Higgs cross section, σ_{HZ}

- **Sensitive to the HZZ and HHH couplings**
  - **Tree level** + **One-loop correction**







  - **Measurement at two $\sqrt{s}$ values (240, 365 GeV) allow determination of both κ_Z and κ_λ**
    - Current FCC precision obtained from Higgs events tagged with $Z \to e^+e^-, \mu^+\mu^-$
      - ➔ And selected from the mass recoiling against the lepton pair $m^2_{rec} = s + m^2_{ll} - 2\sqrt{s}(E_+ + E_-)$

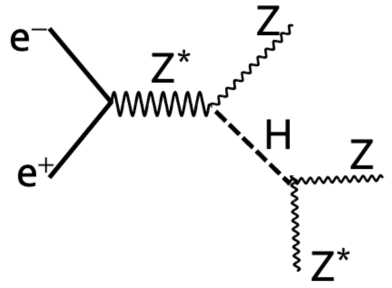
        Independently of how the Higgs boson decays
    - Some questions (among many)
      - ➔ What are the systematic uncertainties? Can they be controlled?
      - ➔ Can we improve the current precision with a better lepton energy resolution? With Z angular distr.?
      - ➔ Is the choice of centre-of-mass energies optimal for κ_λ and κ_Z determination?
      - ➔ Can we tag Higgs events with Z hadronic decays, independently of how the Higgs boson decays?

        Particle Flow & detector requirements on dijet mass (to select the Z) and recoil mass (to select the Higgs) resolution?

        Jet clustering tuned to Z finding ?

Measurement of the Higgs width, Γ_H

- **The total width comes as an output of the coupling fit, specifically:**
  - $\sigma_{ZH} \propto \kappa_Z^2$; $\sigma_{ZH} \times BR(H \to XX) \propto \frac{\kappa_Z^2 \times \kappa_X^2}{\Gamma_H}$; $\sigma_{WW \to H} \times BR(H \to XX) \propto \frac{\kappa_W^2 \times \kappa_X^2}{\Gamma_H}$
    - The ZH cross section gives κ_Z
    - The ZH production followed by the $H \to ZZ^*$ decay gives a first measurement of Γ_H (Mostly @ 240 GeV)
  - Final state with three Z's (of which one off shell)
    - First possibility is to look for events with at least 3 or 4 leptons, with one pair compatible with a Z
      - ➔ (Undocumented) analysis showed – 10 years ago – that a background-free signal sample can be obtained
        First step: try to reproduce this result, whether the $Z \to ll$ decay(s) comes from the Higgs decay or not.
    - Final states with less leptons (start with 2) require delicate jet clustering and kinematic fits
      - ➔ Many constraints to use
        Total energy and momentum (4), Z masses (2), Higgs mass (1)
      - ➔ Six partons in the final states
        Over-constrained fit if measured parton directions and lepton energies are fixed
        Maybe use the many constraints to guide jet clustering ?
      - ➔ Background from signal itself, ZH with $H \to WW^*$
        Requires independent measurement of $BR(H \to WW^*)$ and detector characteristics to disentangle ZZZ^* and ZWW^*



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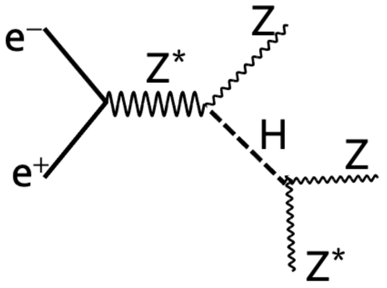


A very interesting and educational project for several months

Outcome: detector requirements and innovative tools for leptons and jets

Measurement of the Higgs width, Γ_H

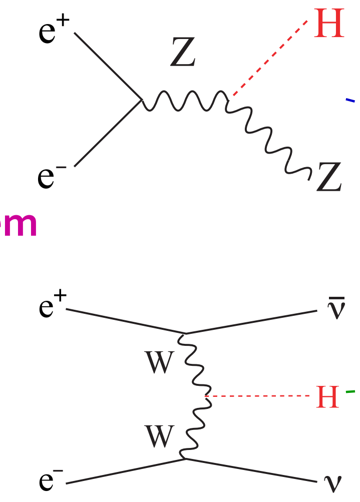
- The total width also benefits greatly from the 365 GeV data sample

  - Obtained with best precision from the ratio $\frac{\sigma_{WW\to H}\times BR(H\to bb)\times\sigma^2_{HZ}}{\sigma_{ZH}\times BR(H\to bb)\times\sigma_{ZH}\times BR(H\to WW^*)}$
    - Final state to study is $bb\nu_e\nu_e$
    - Backgrounds are mostly $e^+e^- \to$ HZ (and interference!), ZZ or γ^*Z (with $Z \to \nu\nu$)
      - ➔ Discrimination from visible hadronic mass (peaking at m_H) and missing mass (not peaking at m_Z)

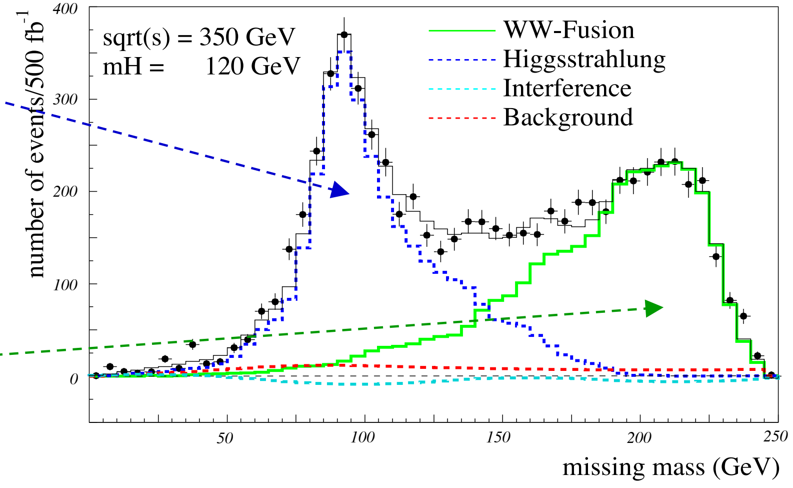
        Use of total energy-momentum conservation is less rewarding here, but m_H constraint helps missing mass.

  - Outcome
    - Detector requirements
      - ➔ Hadronic mass
      - ➔ Missing mass from hadronic system
      - ➔ Particle-Flow reconstruction
      - ➔ Calorimeter granularity
    - Analysis code

NB. Calorimeter alone do not suffice (B field)



From early ILC studies



  - More to do
    - Repeat the analysis at 240 GeV (more difficult, because the missing mass distributions overlap…)

Measurement of $\sigma_{ZH} \times BR(H \to bb, cc, gg)$

Why is it important?

- Measurement of $\sigma_{ZH} \times BR(H \to bb)$ is one of the necessary inputs for Γ_H
  - Requires discrimination of $H \to bb$ from $H \to cc$ and $H \to gg$
    - ➔ b-quark, c-quark, and gluon tagging algorithms essential

      Provide important detector requirements (lifetime tagging, vertex mass, jet shapes, lepton tagging, …)

Another entry point for LHC experts

- Returns κ_b, κ_c, and κ_g
  - κ_c precise determination only possible in e^+e^- collisions
    - ➔ Allows truly model-independent determination of all Higgs couplings and width (unlike @ LHC)
  - κ_g from Higgs decays (only from production cross section @ LHC)
- Another quite educational channel
  - All Z decays (ll, $\tau\tau$, $\nu\nu$, qq) are useful and give rise to different final state / backgrounds / kin. fits …
  - A good example where cross-channel contamination / correlation needs to be dealt with
  - Brings detector requirements for jet energy ($Z \to \nu\nu$) and angular ($Z \to qq$) resolutions
    - ➔ To discriminate with the important backgrounds (all backgrounds from slide 7 contribute significantly)
  - A team is already in place and initiated the work for this case study (contact E. Perez and P. Azzi)
    - ➔ You will be guided and helped in your learning process; your innovative ideas will make a difference.

Determination of m_H

See motivation in D. D'enterria's talk for ee → H

- **Direct determination: all channels contribute**
  - **And provide event-by-event estimates to fit for the Higgs boson mass**
    - Z → ll : $m_{rec}^2 = s + m_{ll}^2 - 2\sqrt{s}(E_+ + E_-)$
    - Z → νν : $m_{resc} = \dfrac{\sqrt{s}E_{vis} - \sqrt{sE_{vis}^2 - (s - m_Z^2)m_{vis}^2}}{m_{vis}}$
    - Z (and H) → hadrons or taus: cluster events to four jets and fix all jet velocities $\beta_i = p_i/E_i$
      - ➔ Determine all jet energies by solving (with a matrix inversion):

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\ \beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\ \beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{s} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

followed by $m_H^{est} = m_{12} + m_{34} - m_Z$

      - ➔ Can/should also try a full 5C kinematic fit (with E, p, m_Z constraints)
    - Requirements on lepton and jet angular and energy resolution, and on beam energy spread
      - ➔ To reach a precision on the Higgs boson mass better than the Higgs width (4.2 MeV)

Exercise: prove all formula of this slide by applying total energy-momentum conservation !
Contact me if you find a typo or a mistake.

+ template fits, bias understanding, combination, etc .

Determination of m_H

- Requires the measurement of $\sqrt{s}$ with a precision better than 4.2 MeV
  - Primary method at $\sqrt{s}$ = 240 GeV uses radiative fermion pair events: $e^+e^- \to Z(\gamma)$
    - With the photon escaping (one of) the beam pipes, and Z decays to charged leptons or quarks
      - ➔ About 70 million events with 5 ab^{-1} at $\sqrt{s}$ = 240 GeV
      - ➔ About 1 billion events with 12 ab^{-1} at the WW threshold ($\sqrt{s}$ ~ 160 GeV)

        Where systematic biasses can be evaluated (and corrected for) with the resonant depolarization method
    - Final state over-constrained by conservation of energy/momentum and the Z mass
      - ➔ If θ_1 and θ_2 are the fermion polar angles in the e^+e^- centre-of-mass reference frame

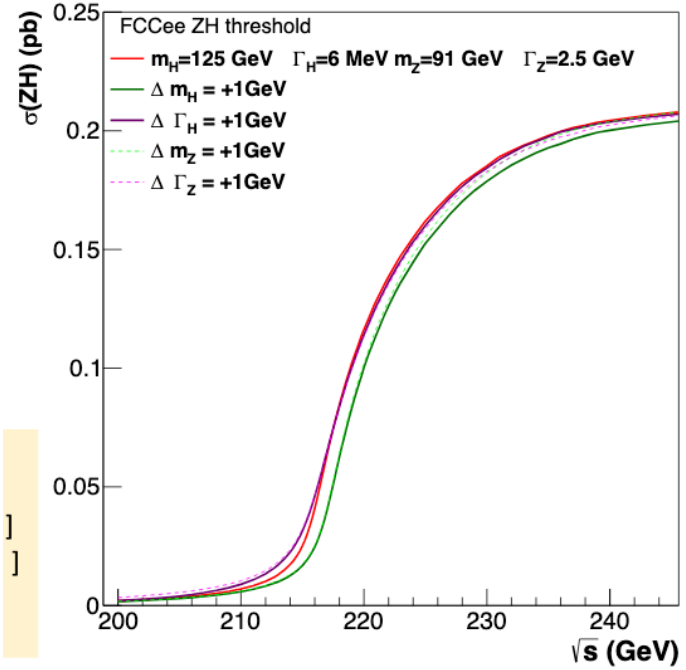
        Estimate of $s = m_Z^2 \times \frac{\sin\vartheta_1 + \sin\vartheta_2 + |\sin(\vartheta_1+\vartheta_2)|}{\sin\vartheta_1 + \sin\vartheta_2 - |\sin(\vartheta_1+\vartheta_2)|}$ (and similar, albeit more involved, expressions in the lab frame)

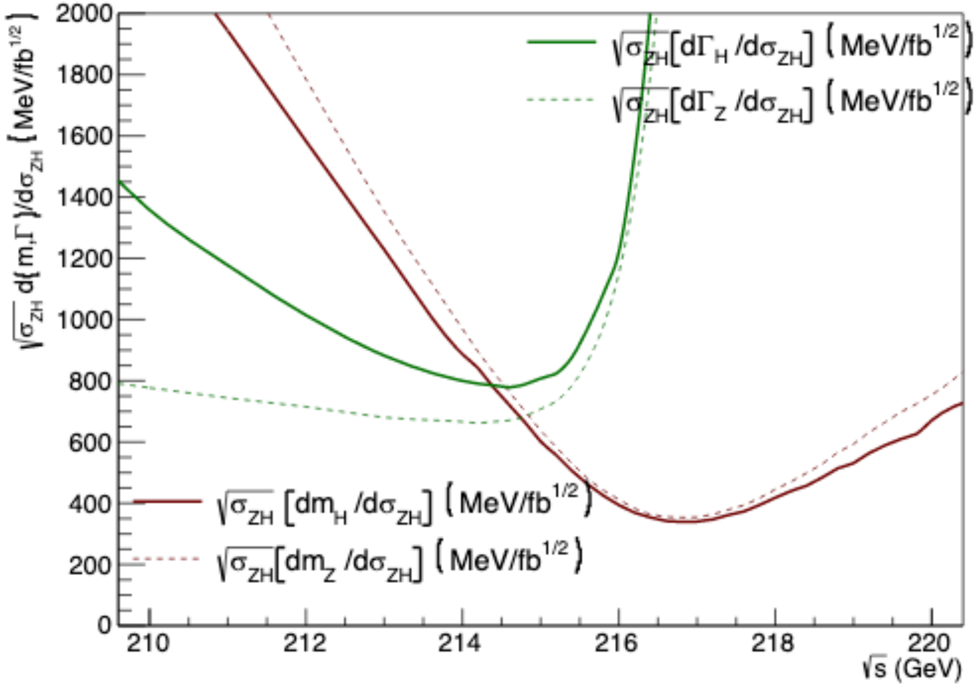
        arXiv:1909.12245
    - Back of the envelope estimate gives a statistical precision of 1.7 MeV on $\sqrt{s}$
      - ➔ Needs thorough analysis of systematic uncertainties to confirm this prospect
  - This method is less effective at $\sqrt{s}$ = 365 GeV (smaller cross section, much larger Z boost)
    - Use WW and ZZ events, with the W and Z mass constraints (and E/p conservation)
      - ➔ Method can be calibrated at $\sqrt{s}$ = 240 GeV

        At the expense of losing the W mass direct measurement at this energy.
      - ➔ Expected statistical precision expected to be around 5 MeV (to be thoroughly checked)

Determination of m_H

- **Indirect determination from ZH threshold cross section**
  - **Preliminary study from P. Azzurri (inspired from the W mass at WW threshold)**





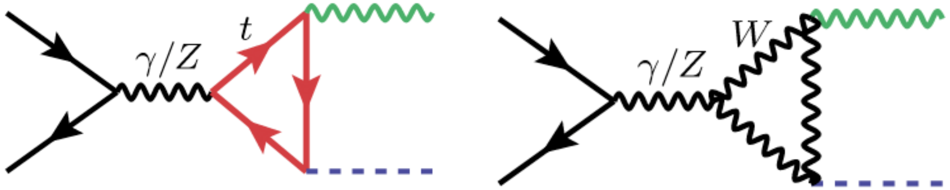
- Optimal centre-of-mass energy $\sqrt{s}$ ~ 217 GeV
  - ➔ m_H precision ~ 350 MeV $\sqrt{\text{fb}^{-1}}$ with 100% efficiency and no backgrounds for all ZH channels (!)
  - ➔ With only the dominant $Z \to ll$ channel, it becomes 40 MeV $\sqrt{\text{ab}^{-1}}$ i.e., ~20 MeV for 5 ab^{-1} at 217 GeV

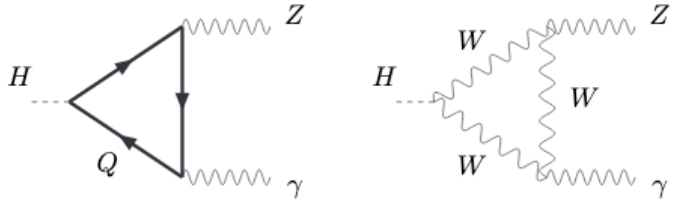
Not sure we should spend a lot of time here now, unless we come with a convincing cross section with $Z \to qq$

Measurement of the HZγ coupling

Motivation

- Sensitive to new physics in loops; Constrains EFT fits; No estimate yet at FCC-ee;
- Can be measured in production … … and in decay





  - 200, 400, 40 Hγ events at 160, 240, 365 GeV
    - ➔ Mono-energetic photon
  - About 1500 ZZγ events at FCC-ee
    - Overconstrained (7C) final state

- Can do better than HL-LHC (~10% relative precision on the HZγ coupling)
  - Synergetic with FCC-hh (production requires the knowledge of Hγγ coupling)
- May bring some detector requirements on photon performance (energy/angular resolution)
- Again, quite an educational channel to study with a clear signature
  - Ideal to start a first study in FCC-ee, and bring it to completion

A lot of other things to do …

More (than) couplings

- $H \to \tau\tau$ and J^{CP} determination (e.g., relative $\pi^\pm$ orientation in $\tau^\pm \to \rho^\pm\nu_\tau \to \pi^\pm\pi^0\nu_\tau$)
  - Calls for detailed tau reconstruction (calorimeter granularity, particle-flow reconstruction)
- $H \to gg$ and unique study of gluon fragmentation
  - Calls for pure gluon selection (among c- and b-quark jets)
- $e^+e^- \to H$ direct production at $\sqrt{s} = m_H$ — See D. D'enterria's presentation
- Electroweak top couplings at $\sqrt{s}$ = 365 GeV — See P. Azzi's presentation
  - Enable precise/absolute measurements of top Yukawa and Higgs self couplings at FCC-hh
- Other FCC-hh / ee synergies
- Invisible and exotic Higgs decays
- Beyond event rates: do kinematic distributions help the EFT fit ?
- Constraints on specific New Physics models from Higgs measurements
  - And synergies with other $\sqrt{s}$
- Precision calculations in the SM of total and differential rates
  - To match statistical uncertainties

Conclusion of the Introduction

- **Higgs studies @ FCC-ee are an excellent bootstrap for your activity in FCC**
  - There is work for many doctoral or post-doctoral physicists in the years to come
  - There is something for every taste here
    - Diverse final states, addressing diverse detector aspects, with diverse software needs
  - You'll never walk alone
    - FCC PED studies are organized on a collaborative basis
      - → Analysis code, physics tools, documentation, will be waiting in FCCSW for your innovations
      - → ILC/CLIC experts, LHC experts, and LEP experts (still for a short while) will also be around to help
  - The outcome will be rewarding
    - Preprints / papers with only a few names (of which, yours) along the way
    - A Physics CDR as a prelude for the recommendation of the FCC project in five years
    - The physics software of the future and detector concepts for the the 2 or 4 IPs of the FCC ring
  - It will be fun all along
    - Adding diversity and new experience to your usual work in HL-LHC
    - The experience gained will enable you to work on the other parts of the FCC-ee programme