

Using the $H \rightarrow$ invisible decay channel for calorimeter benchmarking

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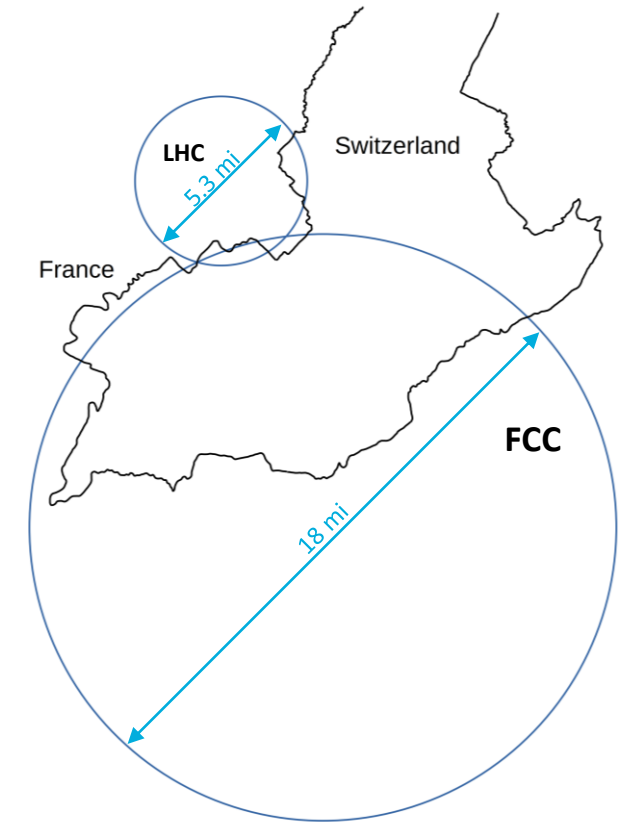
Future Circular Collider – e^+e^-

The FCC-ee will allow us to probe electroweak, flavor, Higgs, and Top physics with unrivaled precision.

Targeted Process	Z	WW	H (ZH)	ttbar
Beam Energy [GeV]	45	80	120	182.5
Total Integrated Luminosity	150	10	5	1.5

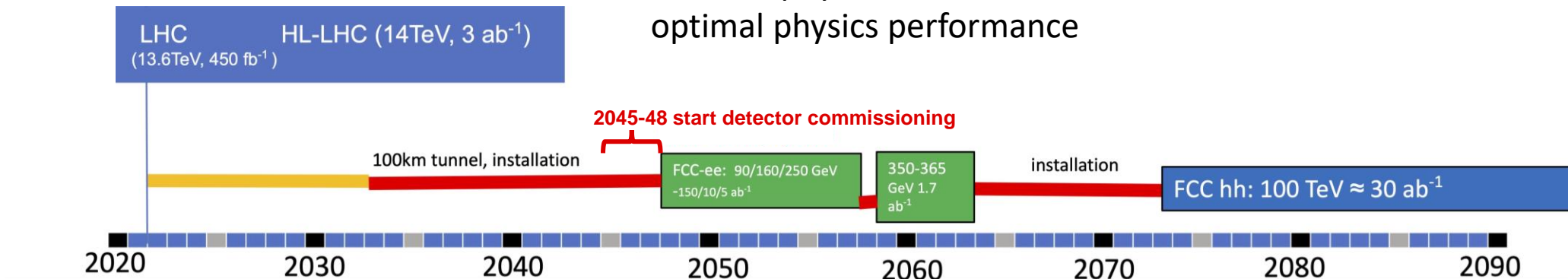
[Report of the Snowmass 2021 \$e^+e^-\$ -Collider Forum](#)

Particularly motivated by the need to study the Higgs Boson in greater detail



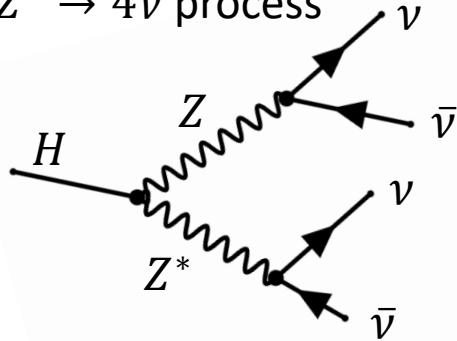
[FCC-ee in 10 slides](#)

Possibly 2045-48 start date – Requires targeted R&D to make the best physics case and achieve optimal physics performance



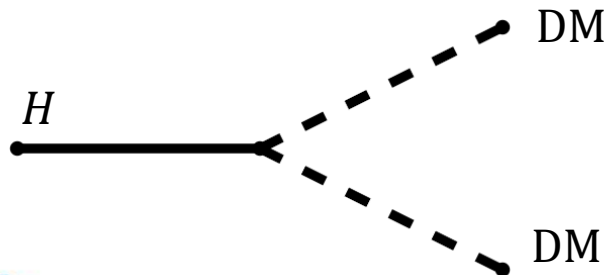
Higgs

$H \rightarrow$ invisible in Standard Model via
 $H \rightarrow ZZ^* \rightarrow 4\nu$ process

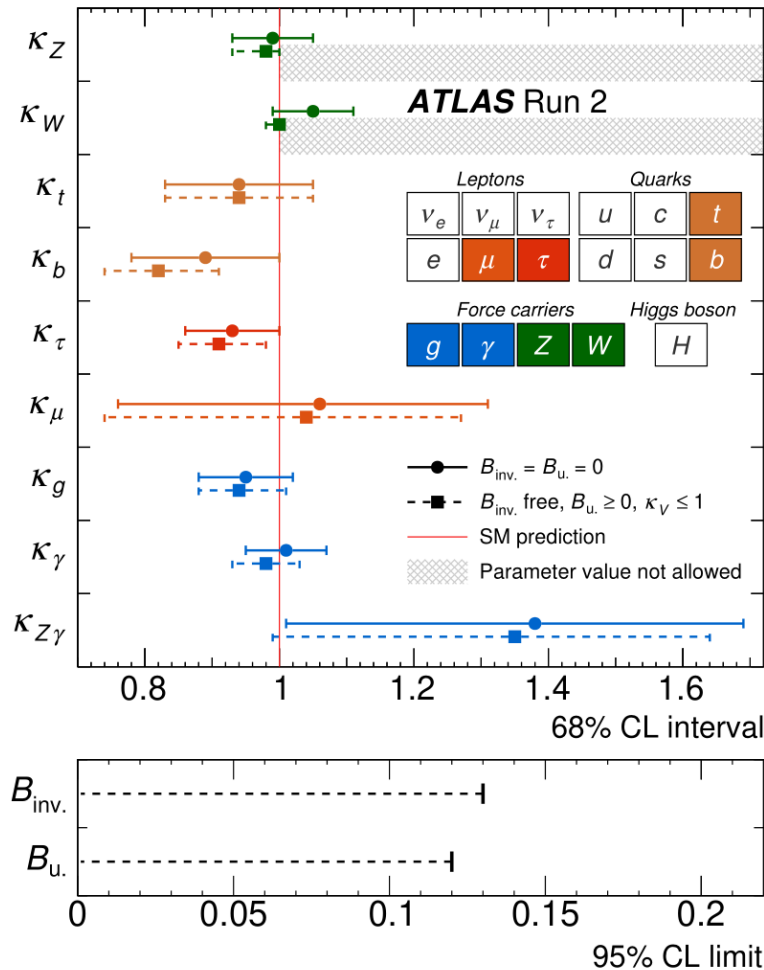


Standard Model $BR(H \rightarrow \text{inv}) = 0.1\%$
 But possibly enhanced by BSM physics

$$\mathcal{L} \supset \lambda_{HHS} \phi^2 S + \lambda_{\phi S} \phi^2 S^2$$



Constraints on Higgs coupling modifiers



$B_{\text{inv.}}$ - invisible decays

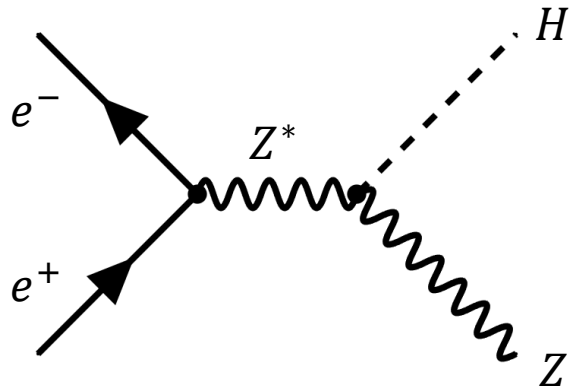
B_u - undetected decays

Up to order of magnitude improvement in Higgs coupling precision

Higgs coupling to	HL-LHC [%]	FCC-ee + HL-LHC [%]
ZZ	1.5	0.17
WW	1.7	0.41
$b\bar{b}$	3.7	0.64
$\tau^+\tau^-$	3.4	0.66
gg	2.5	0.89
$c\bar{c}$	-	1.3
$\gamma\gamma$	1.8	1.3
γZ	9.8	10
$\mu^+\mu^-$	4.3	3.9
$t\bar{t}$	3.4	3.1
Γ_{total}	5.3	1.1

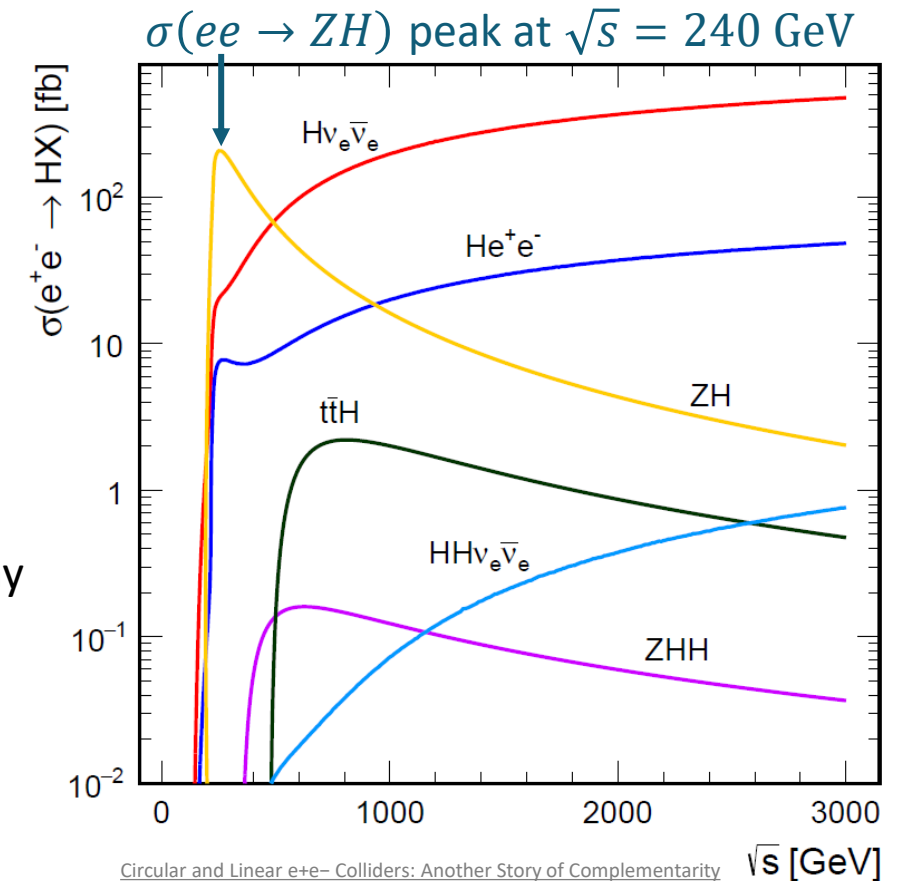
Higgs → invisible

Dominant Higgs production mode at FCCee: $ee \rightarrow ZH$



ee -collider advantages for $H \rightarrow$ invisible

- ZH production dominant → tag on Z decay
- colliding particles' 4-momenta known
- low pileup environment



$BR(H \rightarrow \text{inv})$ limits at 95% CL :	LHC (300 fb^{-1})	HL-LHC (3000 fb^{-1})	FCCee (5000 fb^{-1})
No systematics	7.5%	2.9%	0.19%
Realistic scenario	17%	6.2%	-
Conservative scenario	22%	14%	-

All limits based on ZH production alone.
VBF production @ LHC allows for improved limits

Higgs → invisible measurement

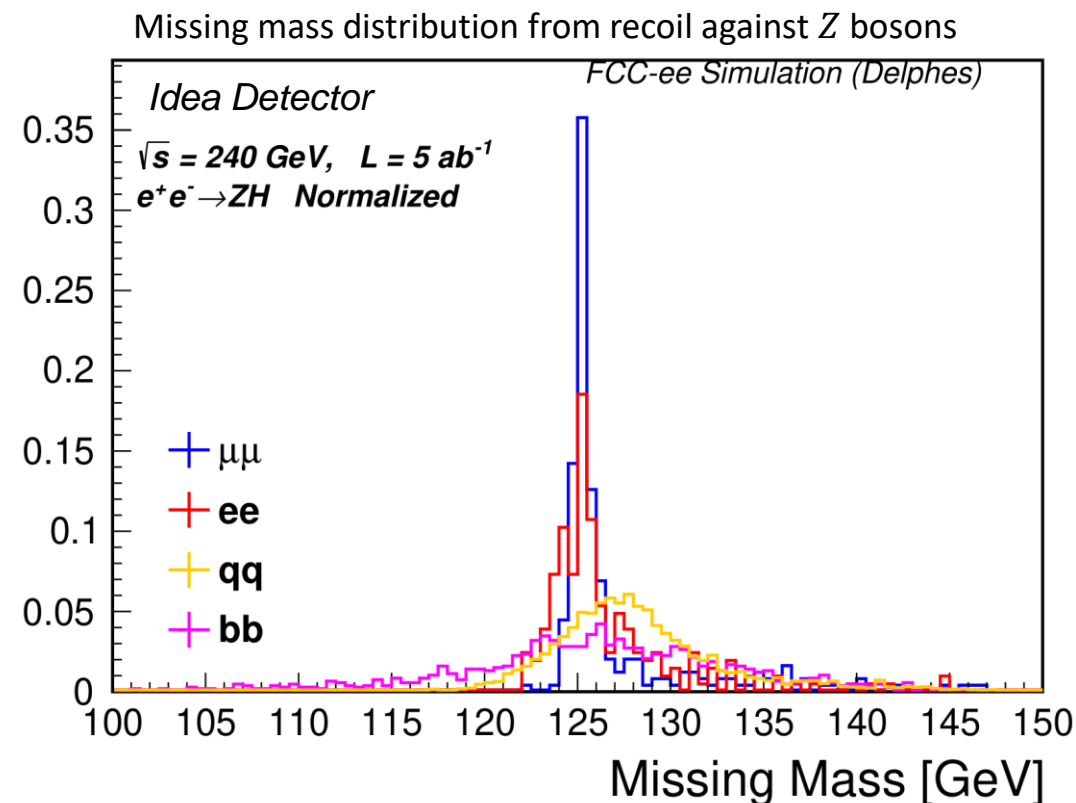
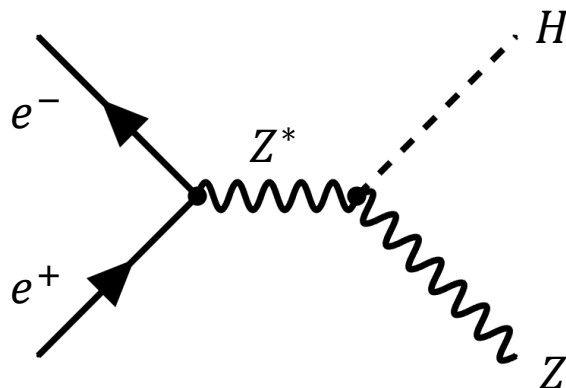
- We can reconstruct the Higgs' kinematics from its recoil against Z bosons

$$p_{e^-} + p_{e^+} = p_Z + p_H$$

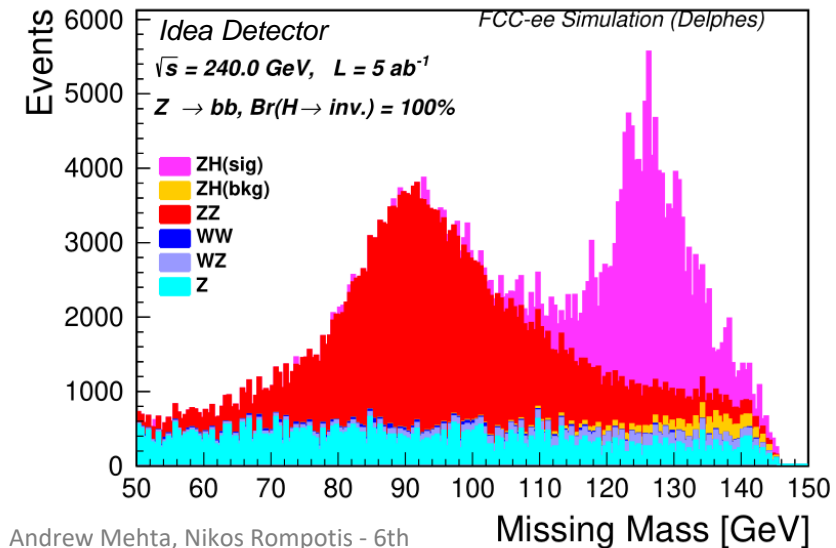
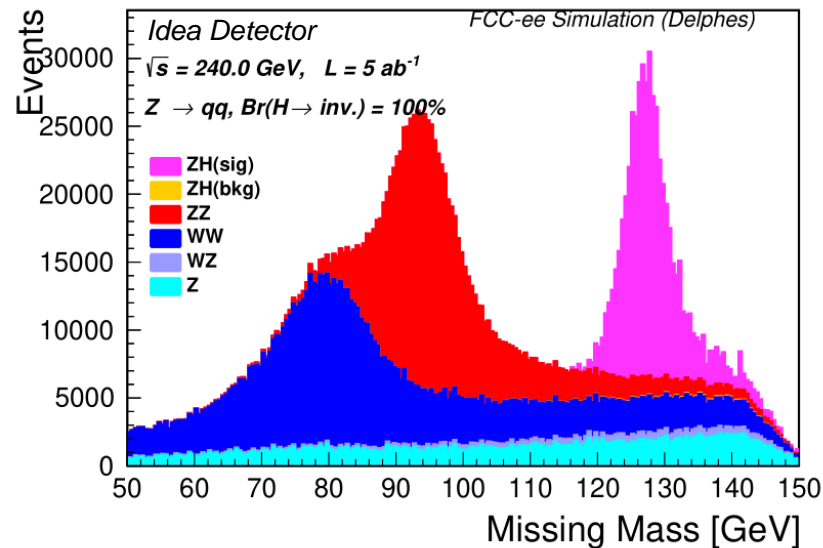
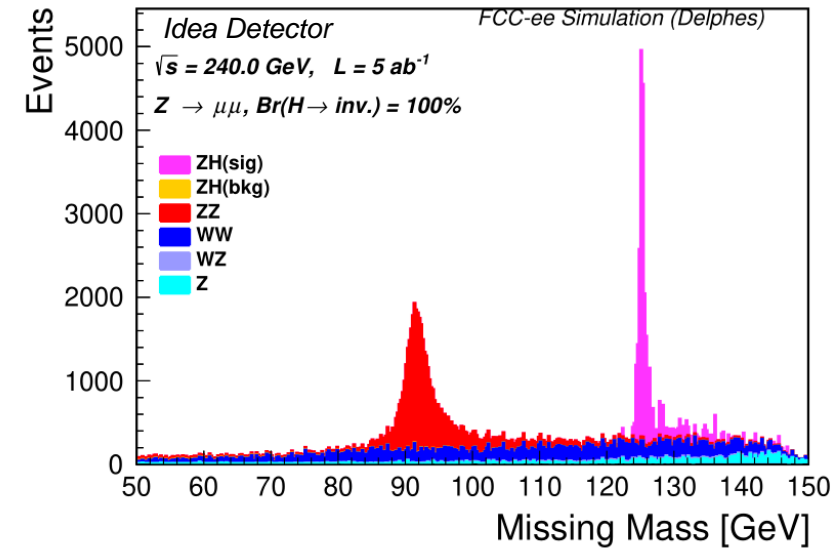
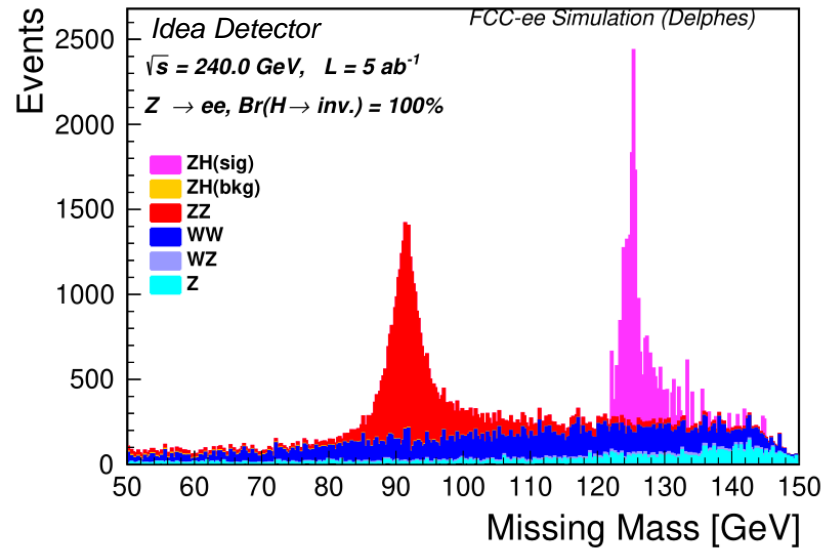
$$\Rightarrow m_H^2 = (2E_e - E_Z)^2 - \vec{P}_Z^2$$

$$= (240 \text{ GeV} - E_Z)^2 - \vec{P}_Z^2$$

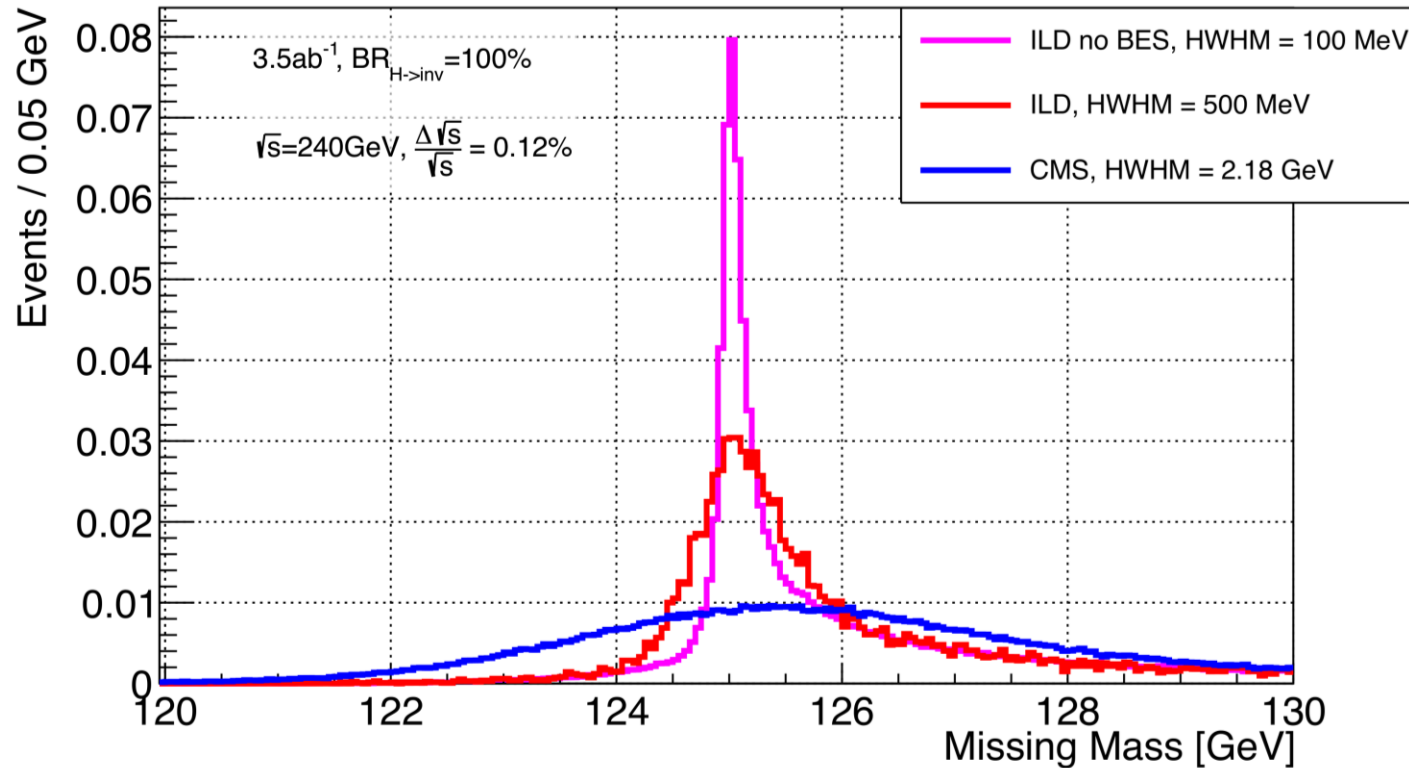
- Consider exclusively events where only Z -bosons seem to decay
- Look for resonance around Higgs mass in distribution of recoil masses: *missing masses*



Reconstructed mass distributions



Detector impact on resolution

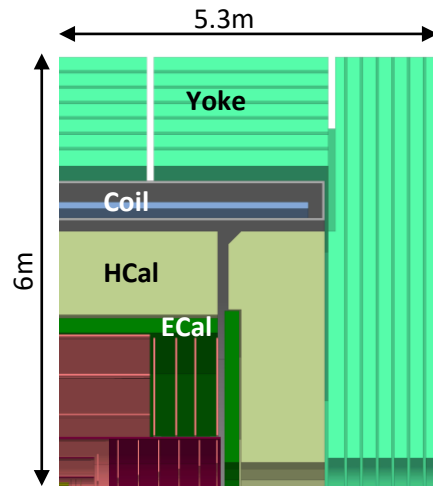


ILD-like detector, no beam energy spread
ILD-like detector
CMS-like detector } 0.12% CoM energy spread

Study the effect of beam energy spread and detector resolution on the search for Higgs boson decays to invisible particles at a future e⁺e⁻ circular collider

FCCee detector concepts

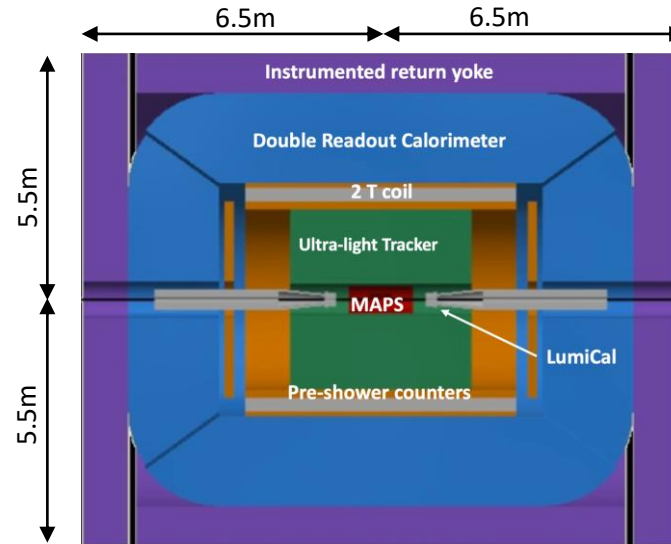
CLD detector



CLD -- A Detector Concept for the FCC-ee

- All silicon tracker (pixels+strips)
- Si-W EM calorimeter
 - $22X_0$, 40 longitudinal layers
- Steel-Scintillator hadronic calorimeter
 - SiPM readout
- Solenoid outside calorimeter

IDEA detector



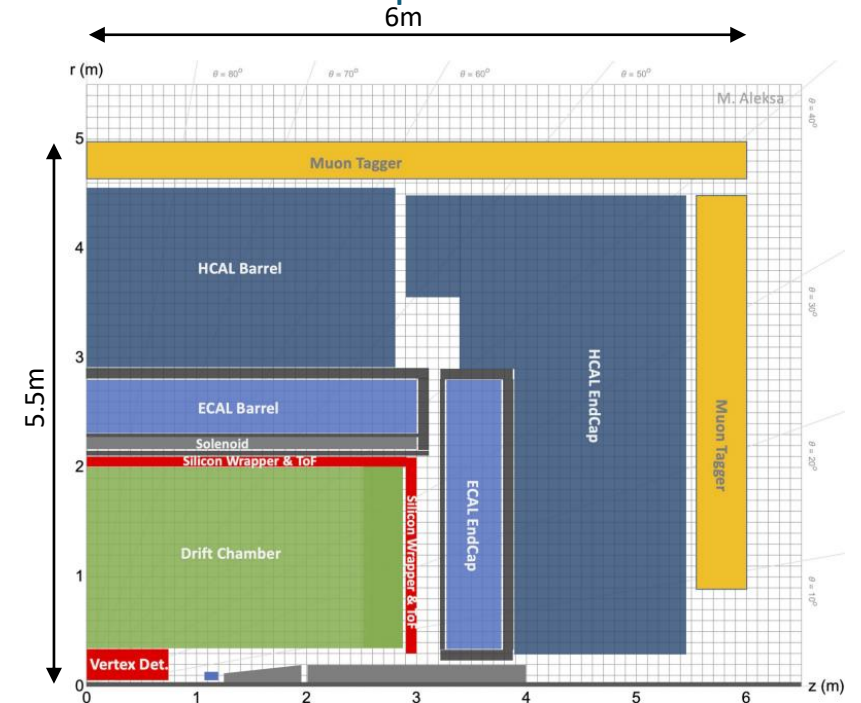
FCC-ee Detector Designs

- MAPS based vertex detector ($1\% X_0$)
- High-precision low-mass drift chamber with surrounding Si microstrip
- pre-shower with MPGD readout
- Lead-Fiber dual readout calorimeter
 - Scintillating fibers for charged particles
 - Clear fibers for Cherenkov light

MAPS – Monolithic Active Pixel sensors
MPGD – Micro Pattern Gas Detector

Detector Challenges at Future Circular Colliders

Noble Liquid Detector

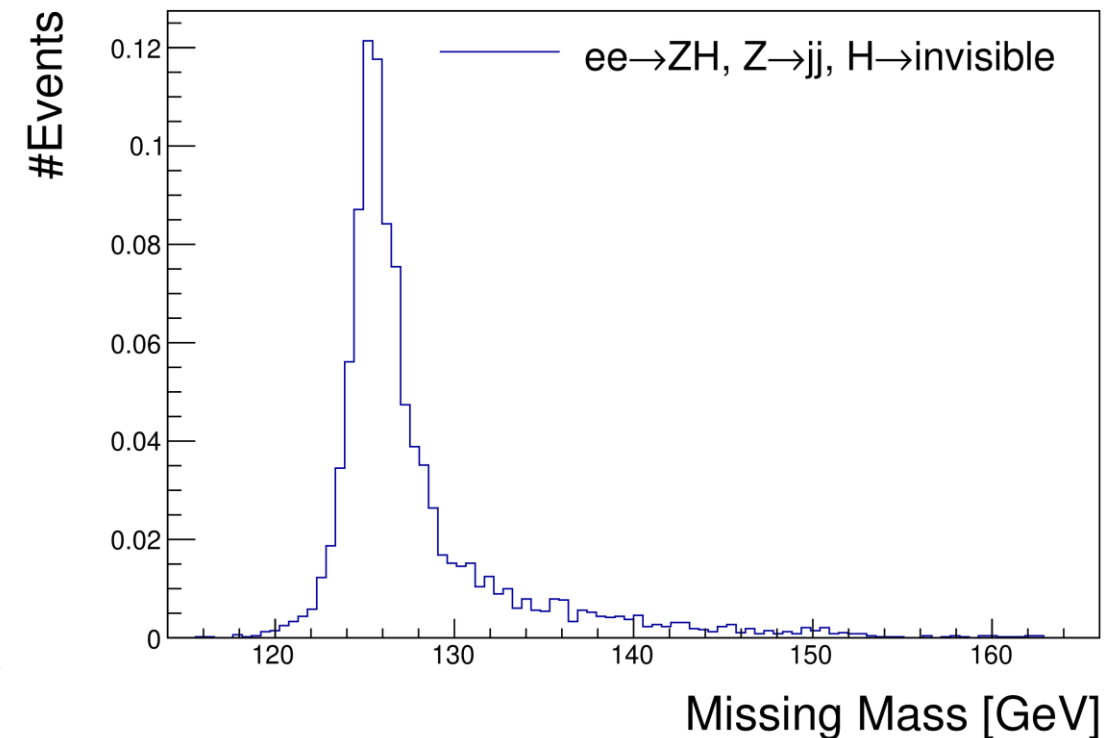


Noble Liquid Gas Calorimeters

- Includes a highly granular noble liquid calorimeter
- Possible design being explored are lead/steel absorbers, stacked azimuthally inclined at 50° w.r.t. radial axis with Liquid Argon as the active medium
- Other options under consideration: Tungsten absorbers and/or Liquid Krypton

$H \rightarrow$ invisible benchmarking

- Use invisible reconstructed mass resolution in $H \rightarrow$ invisible , $Z \rightarrow qq$ as benchmark for calorimeter comparison and optimization
- Preliminary Selection:
 - Exactly two jets, zero muons, zero electrons
 - Reconstruct Z from jets
 - Get invisible mass from Z recoil
 - $MET > 10$ GeV, $60 \text{ GeV} < m_Z < 100 \text{ GeV}$
- Currently using centrally produced FCCee Monte Carlo samples, reconstructed with the IDEA detector
http://fcc-physics-events.web.cern.ch/fcc-physics-events/FCCee/winter2023/Delphesevents_IDEA.php



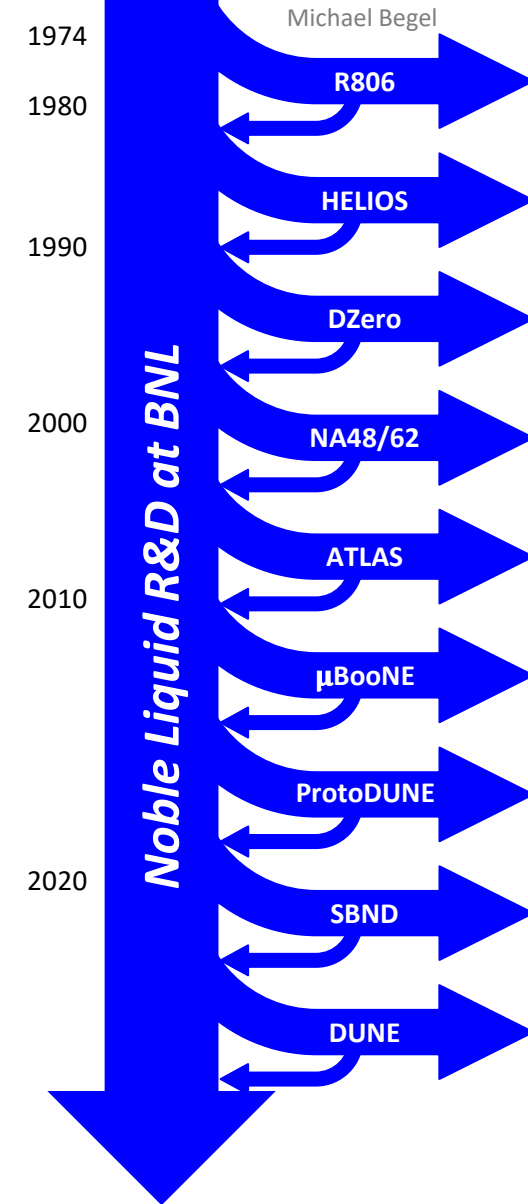
Invisible mass distribution, based on Higgs \rightarrow invisible, with $Z \rightarrow jj$ and the Idea detector

Ongoing efforts

- Prepared Monte Carlo event sample production pipelines for CLD and Noble Liquid detectors
 - Currently evaluating produced samples
- Use these to compare invisible mass resolutions between detectors
- Going forward, benchmark variations of calorimeter parameters
- Visit our repository at github.com/BNL-FCCee/BNL-Analyses
- And reach out to us!



First Liquid Argon sampling electromagnetic calorimeter under test beam at the Alternating Gradient Synchrotron in April 1973



The End

Thank you!