Measuring jets and mass with precision

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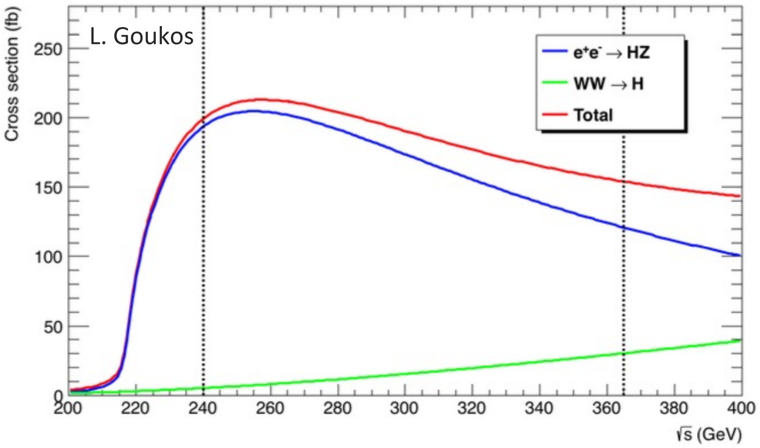
Outline

- Final states with jets – benchmarks in the mid-term report
  - Relevant to hadronic calorimeters
- Detector requirements to measure jets and masses
  - Full detector needed, but focused on calorimeters
- Calorimeter technologies
  - CLD, IDEA, ALLEGRO detector benchmarks
- Results from case studies
  - Higgs hadronic final states, Higgs invisible width, search for heavy neutral leptons
- Next steps
  - Physics software, detector benchmarks, physics performance

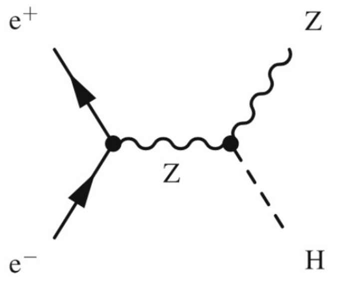
Disclaimer: all studies presented here are performed with fast simulation (DELPHI), unless indicated otherwise

Higgs measurements: couplings and width

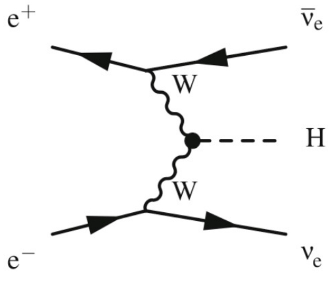
Dominant Higgs production modes:



Higgs-strahlung (ee → ZH)



VBF (ee → ννH via WW fusion)



BR (H → hadrons) ~ 80%

BR (Z → hadrons) ~ 70%

Huge statistics, a clean environment, knowledge of the center-of-mass energy and momentum conservation in all three space dimensions → outstanding precision for

- Higgs cross sections and couplings to Z, W, and top, bottom, charm quarks
- Higgs total width Γ_H, as well as its invisible (H → νννν) width (dark matter search)

Higgs program requires the measurement of jets, masses and missing momentum with unprecedented precision, as well as efficient jet flavor tagging

Search for heavy neutral leptons

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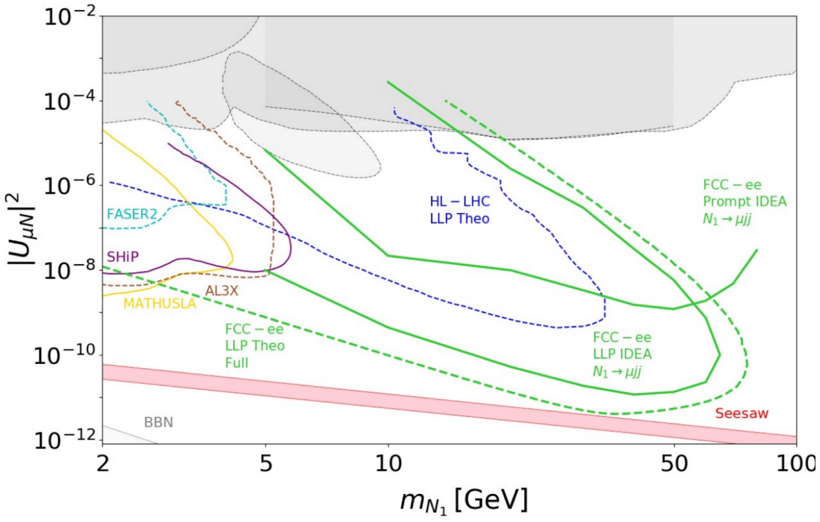
Tera-Z run → huge sensitivity gain for feebly-coupled new particles in the 1-91 GeV range

- E.g., heavy neutral leptons (HNL): Production via $e^+e^- \to Z \to \nu N$ with long-lived $N \to \ell q\bar{q}$
  - Limit on the N-ν_e mixing extended orders of magnitude, close to seesaw limit



Eur. Phys. J. Special Topics 228, 261-623 (2019) arXiv:1910.11775

- Small beam pipe and clean environment
- SM background suppressed due to displaced vertex of the *N* decay
  - Long lifetimes ~ 3 [cm] / |U²| (M [GeV])^6 (N-ν_e mixing parameter $|U|^2$)
- Final state with missing momentum and jets

$$\nu\ell q\bar{q}$$

Requires outstanding precision for jets, missing momentum, secondary vertices, hadronic shower structure

Physics observables, physics objects, detectors

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Physics observables $\Longrightarrow$ reqs. on physics object properties $\Longrightarrow$ reqs. on detectors

Precision on hadronic final states $\Longrightarrow$ requirements on the whole detector in the context of

Particle Flow (PFlow)-based reconstruction

- Containment and hermeticity
  - Instrumentation in full solid angle for high acceptance and missing momentum measurements
  - Tracker thick enough (but low density) for optimal secondary vertex reconstruction (to minimize conversions)
  - Large HCAL material budget to minimize leakage (energy response & resolution, missing momentum)
- Alignment and calibration
  - Relative alignment at the O(μm) precision level (particle matching across subdetectors)
  - Excellent single particle calorimeter response linearity (compensation) and resolution for precise calibration
- Tracker and calorimeter granularity
  - Higgs recoil mass resolution limited by BES (0.13-0.16%) and not track momentum resolution
  - High granularity EM calorimeter plays a crucial role in photon ID within jets
  - High granularity HAD calorimeter for neutral hadrons ID, correct assignment of particles to jets, jet substructure for flavor tagging

Calorimetry at FCC-ee: Eur. Phys. J. Plus 136, 1195 (2021)

Single particle, jet, and invariant mass resolution

PFlow optimizes jet energy resolution (JES) by individually reconstructing each particle using the best measurement from each subdetector

- Energy of charged particles measured best in the tracker, photon energy in the ECAL, and HCAL key to measure neutral hadrons

Single particle calorimeter resolution:

$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} \oplus C$$

$\frac{S}{\sqrt{E}}$: Stochastic term - sampling fluctuations

C : Dead material, non-uniformities

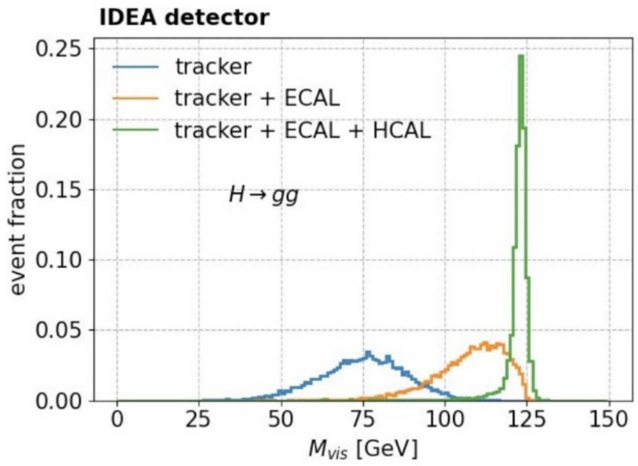
ee → ZH → νν j j

Visible (Higgs) invariant mass

$$\sigma^2(E_{\rm vis}) = \sum_{i\in {\rm tr}} \sigma^2_{\rm tr}(E^{(i)}_{\rm tr}) + \sum_{i\in\gamma} \sigma^2_{\rm ecal}(E^{(i)}_{\gamma}) + \sum_{i\in {\rm nh}} \sigma^2_{\rm hcal}(E^{(i)}_{\rm nh})$$

Tracks 65% | 25% Photons | 10% Neutral hadrons K_L^0 and n

- σ_{Mvis} (and σ_{jet}) dominated by neutral hadron (HCAL) uncertainty for low energy jets (HCAL granularity matters)
- H, WW, ZZ: 3-4% invariant mass resolution needed



Single particle, jet, and invariant mass resolution

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Expected energy resolution for the different technologies: measurements when available, otherwise obtained from (DELPHI) simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists

Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [20,45]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8–10 % [24,27,46]	< 1 % [24,27,47]	≈ 40 % [27,28]	≈ 6 % ?	3–4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4–5 % [49]	3–4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5–6 % [30,50]	3–4 % [50]

IDEA [48]
JINST 15 C06015

CLD [20]
LCD-Note-2019-001

Calos for FCC-hh [27]
CERN-FCC-PHYS-2019-0003

Crystal Calos for FCs [30]
J. Instrum. **15**, P11005–P11005 (2020)

Traditionally, the physics drivers for the "ultimate" ~3-4% PFlow jet energy resolution

- High efficiency for W/Z/H boson mass separation
- Separation of boosted objects (at higher energies)

Technologies – HG silicon and SiPM-scintillator-tile calorimeters

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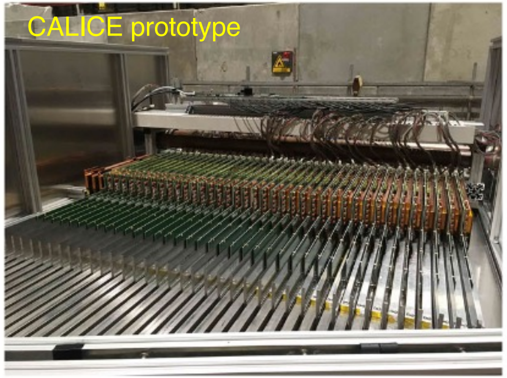
Active material: silicon diodes (EM section) and Scintillating tiles read by SiPMs (hadronic section)

- First generation: CALICE (R&D for LC), many prototypes (scintillator, silicon, steel, tungsten) CALICE-PUB-2022-003
- Second generation: CMS HGCAL endcap, silicon-tungsten and scintillator-steel sections CERN-LHCC-2017-023
- Future generation (FCC-ee): Calorimeters of CLIC-like detector (CLD) benchmark
  - ECAL: 40 silicon-tungsten layers, $23X_0$ deep, silicon area of 4000 m^2 segmented in 160M cells
  - HCAL: 44 scintillator-steel layers, 5.5 λ_I deep, silicon area of 8000 m^2, 9M SiPMs
  - Photon energy resolution ~ 15% (5-100 GeV), 4.5% (50 GeV) and 4% (>100 GeV) with PFlow
  - Hadron resolution ~ 45-50%/$\sqrt{E}$ (ECAL+HCAL), PFlow jets reaches ~4% at high energy
  - W-Z separation power of 2.5σ for 125 GeV bosons



CLIC-like Detector (CLD) benchmark

Design inherited from ILC (-> CLIC -> FCC-ee)

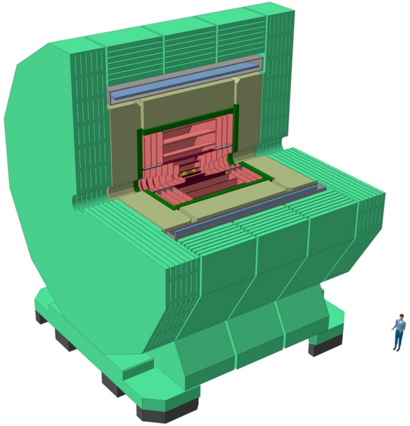
All-silicon vertex and tracking detectors

3D high-granularity calorimeter – CALICE-like

Solenoid outside calorimeter (as in CMS)

Muon system

CLD: LCD-Note-2019-001



Technologies – dual-readout fibre calorimetry

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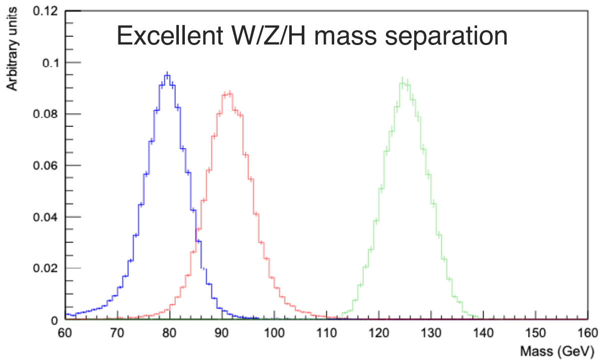
DREAM/RD52 Collaboration: 20-year-long R&D program on dual-readout (DR) calorimetry

- Independent readout of scintillation and Cerenkov light allows the cancellation of the effects of the fluctuations in the EM fraction of hadronic showers [Nucl. Instrum. Meth. A 963, 127–129 (2019)]
  - e/h =1 (compensation) → jet energy response linear energy dependence, Gaussian energy distributions
- Calorimeters of IDEA detector benchmark
  - 1-mm-diameter fibres, 1.5–2 mm apart, embedded in copper (iron, lead are options), lateral segmentation at mm level
  - 2 m deep, 7 λ_I , measure position and energy of EM and HAD showers
  - Electron energy resolution ~ 11%/√E+0.8%, reaches 4.5% (50 GeV) and 4% (>100 GeV) with PFlow
  - Hadron resolution ~ 30%/√E, PFlow jets reach ~3-4% at high energy
  - Time resolution ~ 100 ps , allowing shower position long. resolution of ~ 5 cm



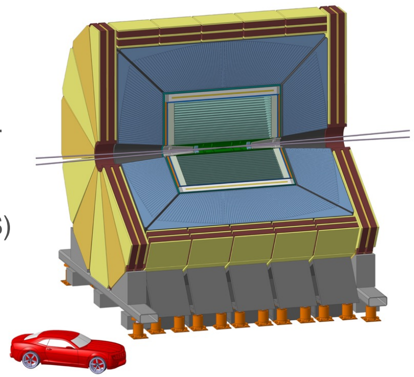
IDEA detector benchmark

Silicon vertex, ultralight (gas) drift tracker

Dual readout fibre calorimeter

Solenoid inside calorimeter (as in ATLAS)

Muon system



Technologies – crystal and noble liquid calorimetry

Segmented **crystal calorimeters** achieve new performance benchmarks for precision timing, particle ID, and e/h response compensation through dual readout [JINST 15(11), P11005 (2020)]

- IDEA modification: EM crystals calorimeter, 20 cm deep (dual readout), added upstream of the DR fibre calorimeter
  - Excellent neutral hadron resolution, $\frac{26\%}{\sqrt{E}} \oplus 2\%$ for crystals combined with DR fibre calorimeter, 3% for low energy photons

High granularity noble liquid calorimetry provides excellent energy resolution, linearity, stability, uniformity, radiation hardness, 4D imaging-ML in combination with PFlow

D0: [Nucl.Instrum.Meth.A338,185–253(1994)]

ATLAS: [CERN-LHCC-2013-017]

- Calorimeter of ALLEGRO detector benchmark:
  - 1536 lead/steel absorbers of 2 mm total thickness, 22 X_0, granularity of 2.5 mrad x 8.2 mrad
  - Photon resolution ~8.-10%/√E, hadron resolution ~40%/√E, PFlow jets reach ~3-4% at high energy

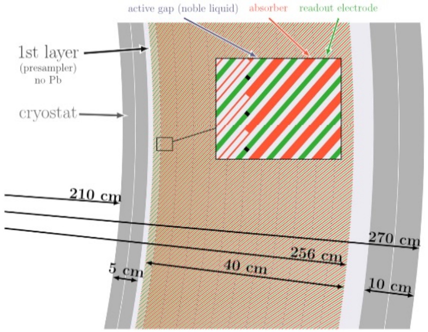
ALLEGRO detector benchmark

Silicon vertex, drift chamber for tracking

HG noble liquid ECAL (Pb+LAr or W+LCr)

CALICE-like HCAL, muon system

Solenoid in cryostat, possible outside ECAL

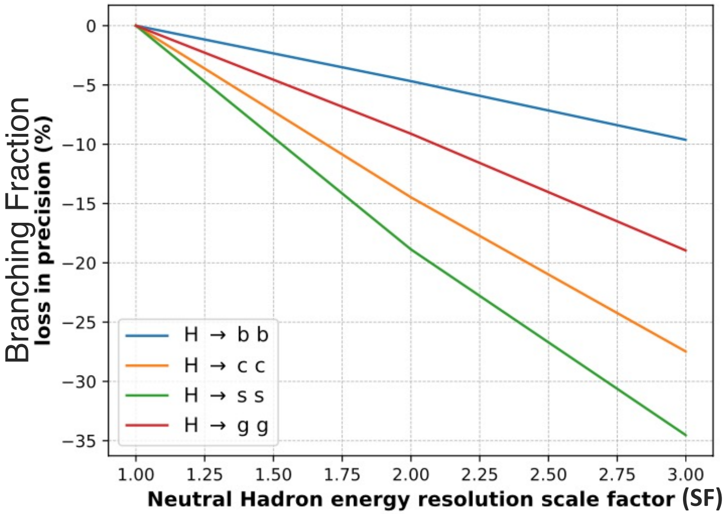


Reconstruction of Higgs hadronic final states

(Case study 1)

Higgs → 2 jets signal ID in HZ events relies on the calorimeter (and vertex detector) performance:
Mass resolution of Higgs and recoil system, flavor tagging efficiency

Study to measure impact of variation in neutral hadron resolution by a factor of 2 (3) with respect to the baseline) on H → jet-jet, with jet = b, c, s, g, with Z → lepton-lepton



Precision of $\mathrm{H} \rightarrow s\bar{s}$ degrades by 20% (35%)

- A bit larger than similar degradation in the number of ionization clusters per unit length (*dN/dx*) – IDEA gas chamber (*dN/dx* provides particle ID)

The effect the Hcc, Hgg, Hbb couplings is smaller

- Increases as the s/b decreases

SF=1 (dual readout calorimeter: **30%/√E**)
2 (ATLAS type-calorimeter: **50%/√E**)
3 (CMS-type calorimeter: **100%/√E**)

Measurement of the Higgs invisible width

(Case study 2) Higgs to invisible at FCC-ee

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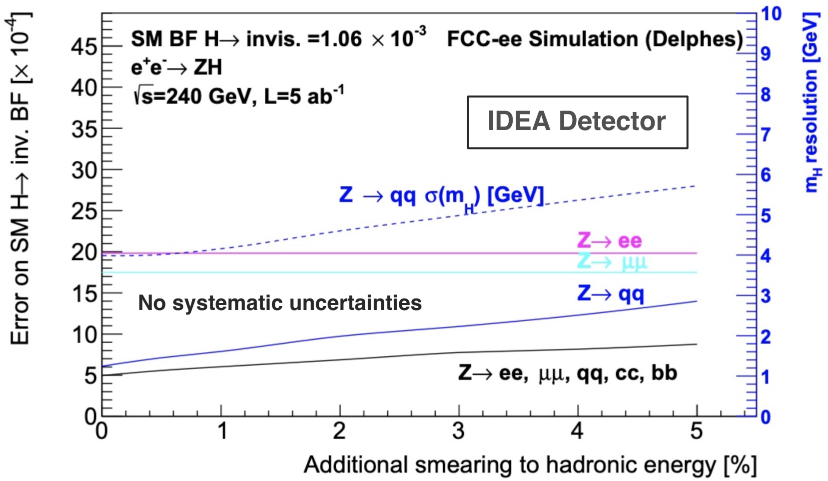
The Standard Model process $H \rightarrow \nu\nu\nu\nu$ has a very small branching fraction of 1.06×10^{-3} (~0.1%)

- Beyond the HL-LHC reach and potentially only observable at the FCC-hh
- Inclusion of a Higgs portal (BSM) predicts decays to dark matter candidates, increasing the Higgs width

Branching fraction measured using $Z \rightarrow ee,\ \mu\mu,\ b\bar{b}, c\bar{c}, q\bar{q}$ to increase stats.

- Novel ML-based flavor tagging algorithm (ParticleNetIDEA*) * Phys. Rev. D 101, 056019



SM BF measured with 35% accuracy! (10 ab^{-1})

Exclusion at the 95% CL of BF < 0.07% or 5σ observation of > 0.18% (adding exotic decays)

130% (80%) uncertainty increase in qq (combined) channel (adding 5% additional Gaussian smearing of hadronic energy)

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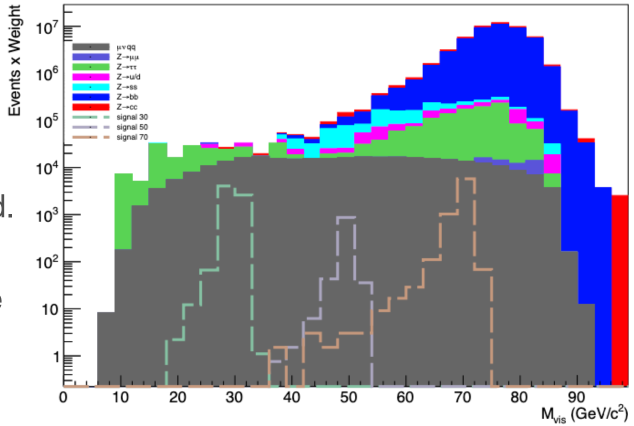
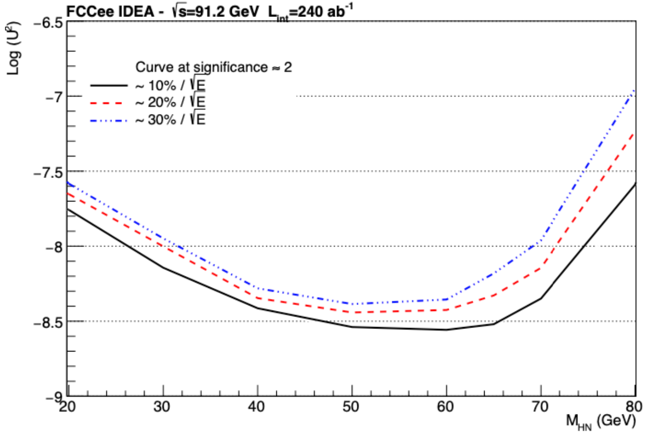
Search for heavy neutral leptons

(Case study 3) Sensitivity of the FCC-ee to decay of an HNL

Feebly interacting particles (e.g., Heavy Neutral Leptons)

- Study on a sample of 8x10[12] Z's decaying to $N_\mu \bar{\nu}_\mu \rightarrow \mu q \bar{q}' \bar{\nu}_\mu$
  - 50% BF and covers the 50-90 GeV range
  - The evt. selection cuts on muon, jet, missing p_T to minimize bkgnd.
  - Discriminant is the HNL visible mass, $M_{HNL}=M_{vis}$
  - Final selection involves sliding cut on M_{vis}, taking into account the observed mass resolution $\sigma = 18\%\sqrt{m_{\mathrm{HNL}}}$





Generated 10k points in parameter space, (mixing=U^2, M_{HNL}) and (lifetime=$c\tau$, M_{HNL}), at a c-of-m energy of 91.2 GeV

Dependence of the 2σ significance of HNL signal on a variation of the visible mass width resolution: 10-30%/$\sqrt{M_{vis}}$

Minimal effect at low M_{HNL} ($Z \rightarrow qq$ background negligible)
Larger at higher M_{HNL} (prompt signal dominates, and the background is higher)

Next steps

- Physics software
  - Complete the implementation of Geant4-based full simulation for all detector benchmarks
  - Full event reconstruction in full simulation
    - Algorithms for single particle reconstruction, PFlow, physics objects
- Detector benchmarks and physics performance
  - Evaluate precision in detector construction, as well as the impact of alignment on performance
  - Develop data-driven methods to reduce the systematic uncertainties
  - Variations of EM calorimeter parameters for improved pion reconstruction efficiency
    - Important in jet flavor identification for electroweak measurements
  - Better assessment of the need for precise timing measurements - LL particles, shower structure
  - Interplay between ECAL-HCAL technologies, materials, granularity (transverse and longitudinal)
  - Mass resolution of color singlets with full simulation and PFlow
    - Impact on, e.g., $H \to cc$ and searches for heavy neutral leptons
  - Explore a larger variety of physics drivers to set constrains on performance metrics

Backup Slides

Next steps

- Detector R&D
  - Engineering procedures for detector assembly and integration
  - Study geometries, shapes, sizes, number of layers, granularities, optimize ECAL-HCAL transition
  - CALICE TB – full HCAL readout, intrinsic time resolution of 1 ns (time/space shower evolution)
    - Study different absorber materials (tungsten), and performance of the combined ECAL+HCAL system
  - Adaptation of noble-liquid sampling calorimetry to an FCC-ee experiment (4D imaging, ML, PFlow)
    - An option for passive (active) material is tungsten (liquid krypton)
  - Study thin carbon-fibre cryostats for noble-liquid calorimetry and thin solenoid coils
  - Study bright, dense crystals, such as LYSO with ultra-fast rise time will be studied and the segmentation optimized for best PFlow performance
  - Large number/density of channels in dual-readout fibre calorimeter calls for innovative read-out architecture to allow efficient information extraction
    - Digital SiPMs (dSiPMs) should allow significant simplification of the readout architecture
  - Front-end ASICs for energy and time measurements in a common architecture for ECAL & HCAL