Higgs to Invisible:
Full Simulation and Detector variation

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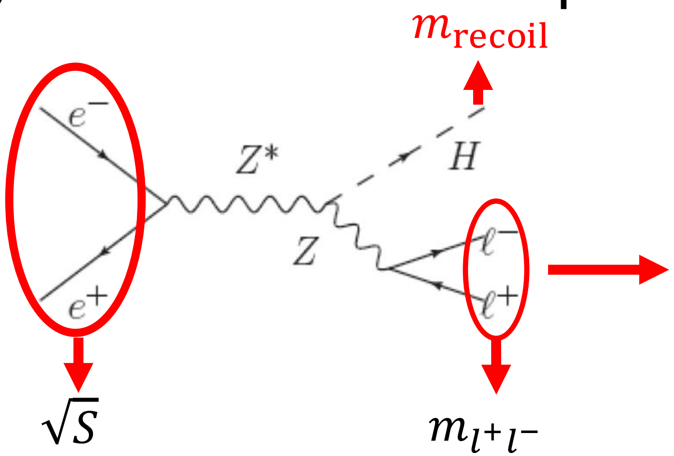
Introduction

❖ **Higgs decays to neutrinos**

❖ **Potentially connected to BSM models**

❖ **Difficult at Hadron Collider**

- Know initial states information (no PDF involved)
- Energy conservation at Lepton Collider



Invisible: $H \to ZZ \to 4\nu$

Visible: Muons, electrons, quarks

} $\sqrt{s}$

❖ **Previous analysis done by A. Mehta and N. Rompotis (Liverpool group)**

Event Simulation

❖Fast Simulation (Winter2023):

- p8_ee_WW_ecm240
- p8_ee_ZZ_ecm240

❖Full Simulation (Local production):

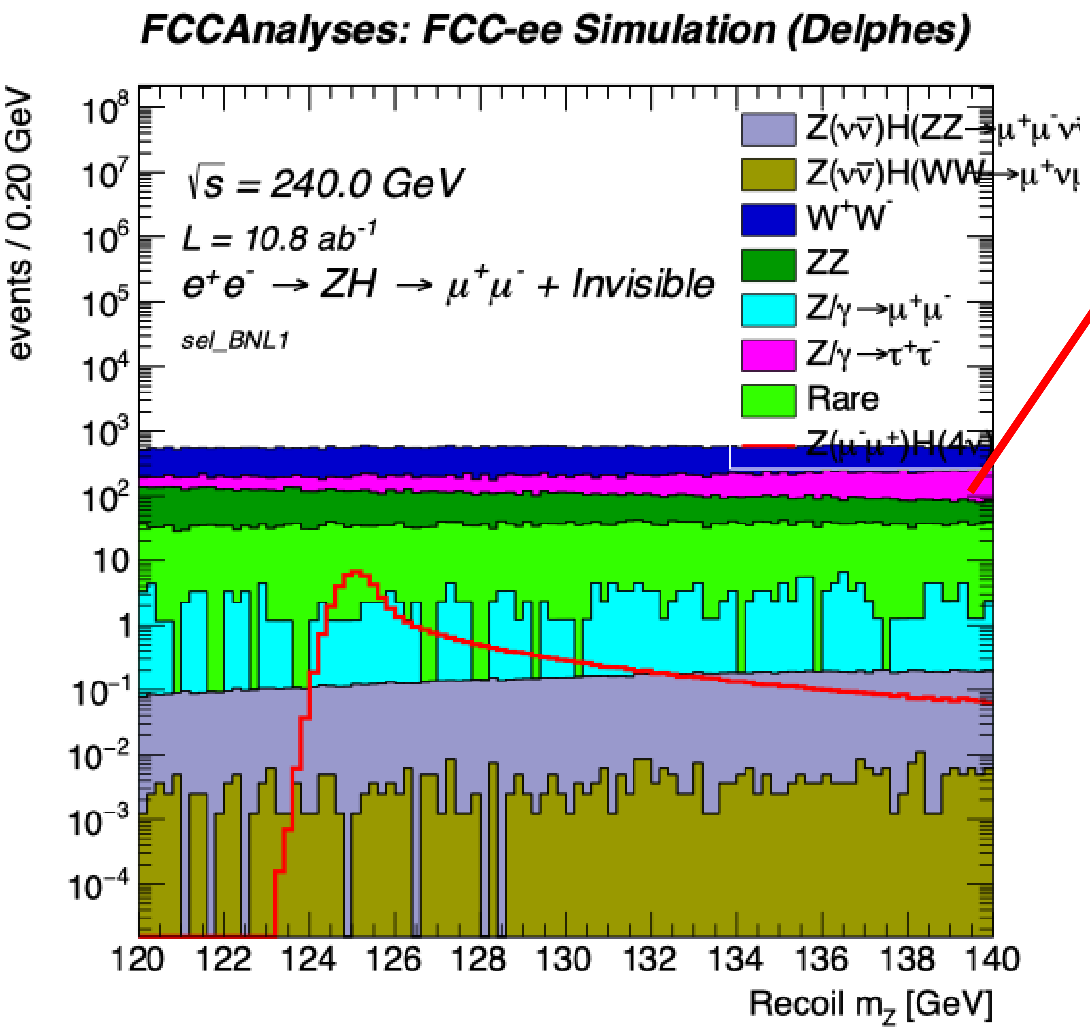
- Whizard + Pythia6 for stdhep
- ddsim for full simulation
- k4run CLDReconstruction.py for reconstruction

- **Signal**
- **ee->ZH →**
  (Z->mumu) (H->ZZ->4nu)
  (Z->ee) (H->ZZ->4nu)
  (Z->qq) (H->ZZ->4nu)

- **ee->ZH →**
  (Z->nunu) (H->ZZ->ee nunu)
  (Z->nunu) (H->ZZ->mumu nunu)
  (Z->nunu) (H->ZZ->qq nunu)
  (Z->nunu) (H->qq)
- **ee->ZZ →**
  (Z->ee)(Z->nunu)
  (Z->mumu)(Z->nunu)
  (Z->qq)(Z->nunu)
  (Z->ee)(Z->qq)
  (Z->mumu)(Z->qq)
  (Z->qq)(Z->qq)
- **ee->WW →**
  (W->munu)(W->munu)
  (W->enu)(W->enu)
  (W->lv)(W->qq)
- **ee->tautau→**
  Inclusive tau decay

More background

- **Fast Sim**
- **IDEA**



$$Z/\gamma \to \tau^+\tau^-$$

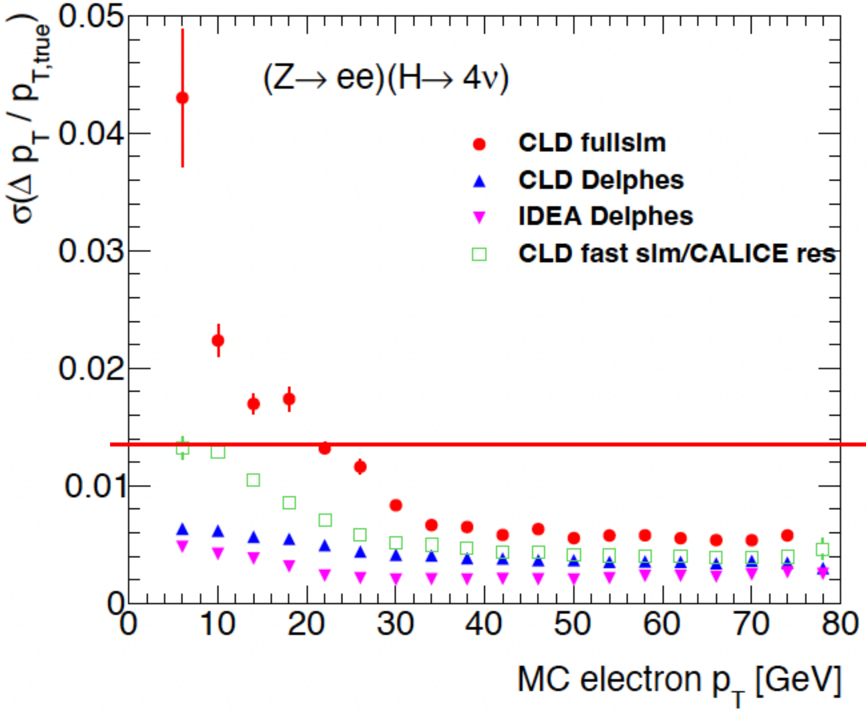
- $\tau \to \mu + 2\nu$, Br = 17.4%
- Previous analysis only considered $e^+e^- \to \mu^+\mu^-$ not $e^+e^- \to \tau^+\tau^- \to \mu^+\mu^-$

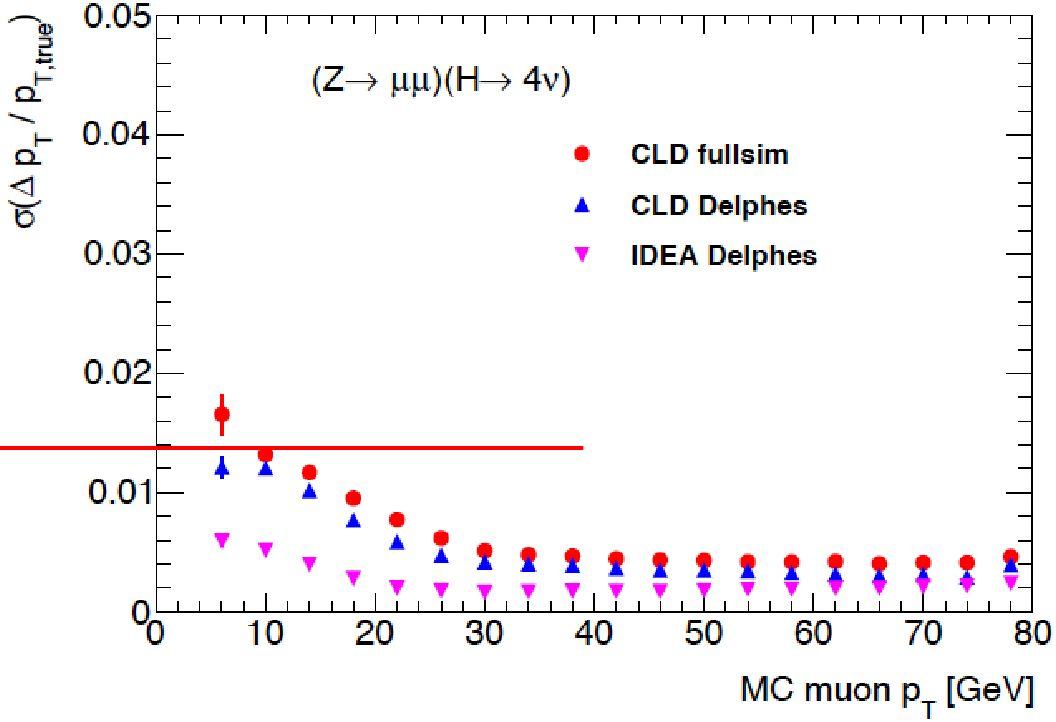
More plots

Selection and analysis

- Boost all final state particles to COM frame as defined by the crossing angle.
- Select tight electrons/muons with p > 10 GeV and isolation fraction < 0.5
- **Lepton Channel:**
  - Exactly two same flavor, opposite sign e (μ)
  - $p_T^{visible} > 10\ \mathrm{GeV}$
  - $|m_Z - 91.0| < 4\ \mathrm{GeV}$
- **Hadronic Channel:**
  - No good leptons
  - $p_T^{visible} > 15\ \mathrm{GeV}$
  - $86\ \mathrm{GeV} < m_{vis} < 105\ \mathrm{GeV}$
- Apply bremsstrahlung recovery to selected leptons:
  - find highest-momentum photon with $\Delta\theta(l,\gamma) < 0.05$
  - Add to the lepton if it passes the NN cut
- Calculate missing momentum from sum of all visible particles
- Calculate recoil mass

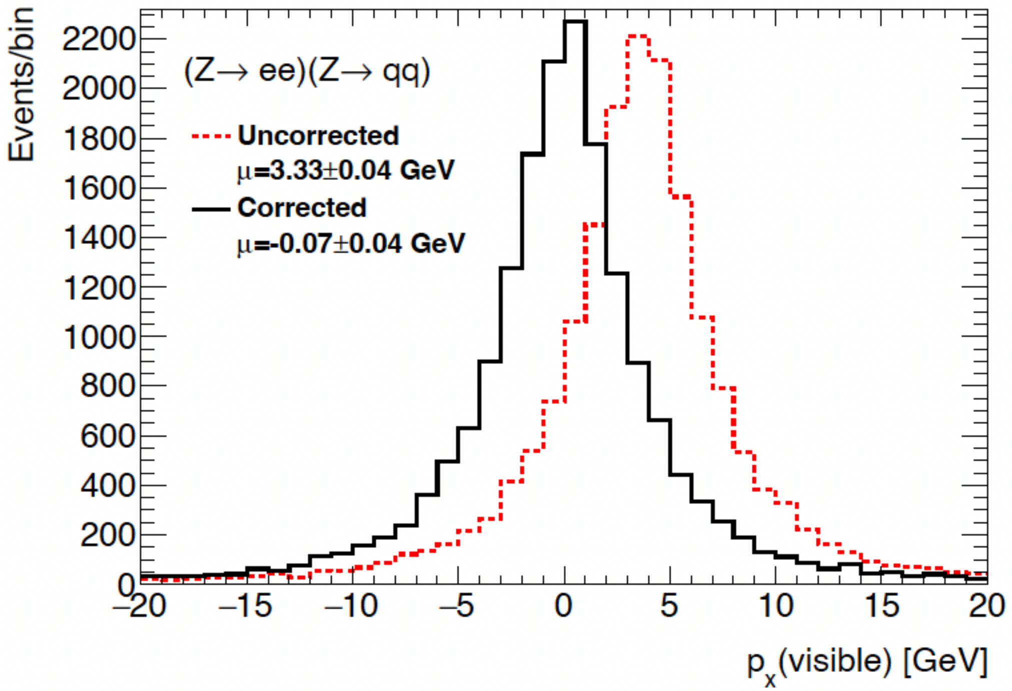
Resolution study between fast sim and full sim





- Using WHIZARD (Z → ee/μμ)(H → 4ν) samples
- Same samples processed with CLD full sim and CLD and IDEA Delphes fast sim
- Resolution is worse for CLD than IDEA, fast sim
- Changing resolution in fast sim to the CALICE resolution gets closer to fullsim
- This is more pronounced for muon than electron
- Resolution is worse for full sim than for fast sim, especially at low p_T

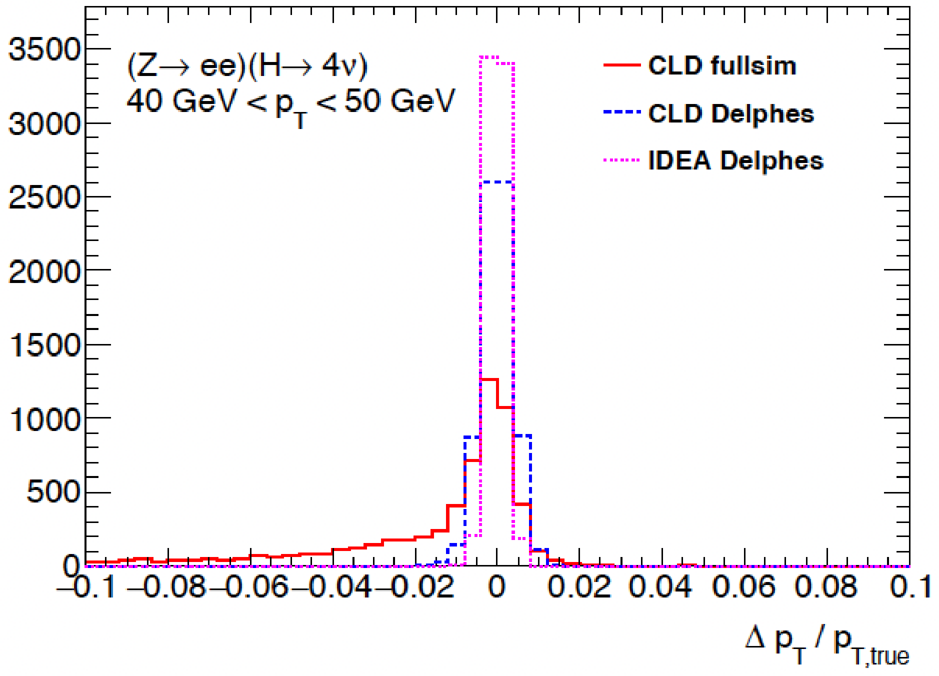
Effect on the crossing angle

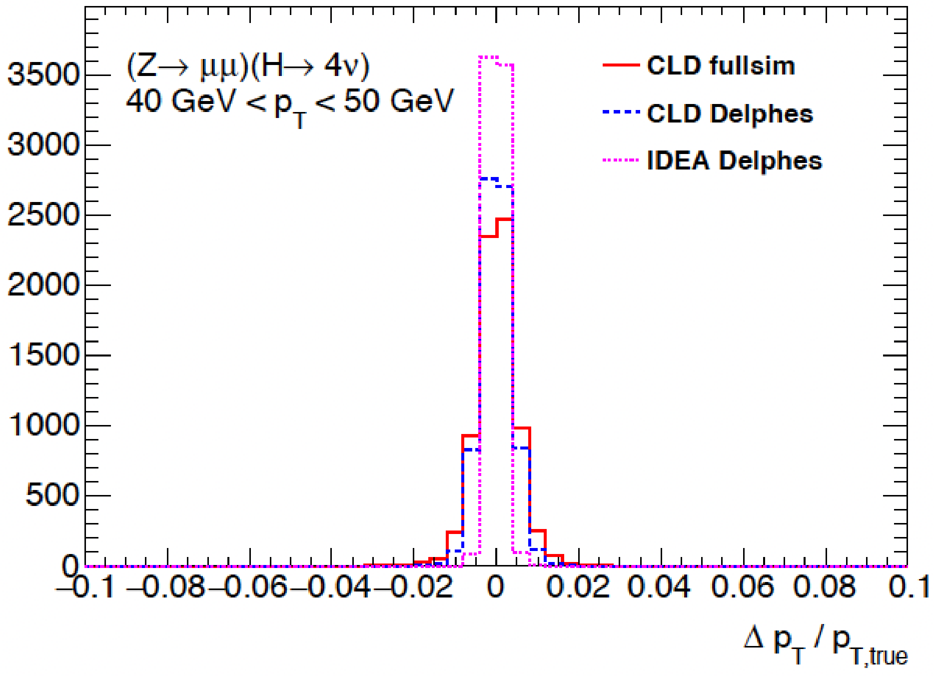


- These plots correspond to one p_T slice: $40\ \mathrm{GeV} < p_T < 50\ \mathrm{GeV}$
- $p_x^{visible}$: x component of the total momentum for the ZZ samples with final states $qqqq$, eeqq and $\mu\mu qq$
- Correction: boost in the negative x direction by $\beta = \sin(\frac{\theta}{2})$

  where total crossing angle of 0.03 rd.
- This effect is not seen/included in fast simulation.

Resolution study between fast sim and full sim





- These plots correspond to one p_T slice: $40\ \mathrm{GeV} < p_T < 50\ \mathrm{GeV}$
- We note the low-end tail on the electron resolution that is not reproduced by the fast simulation.

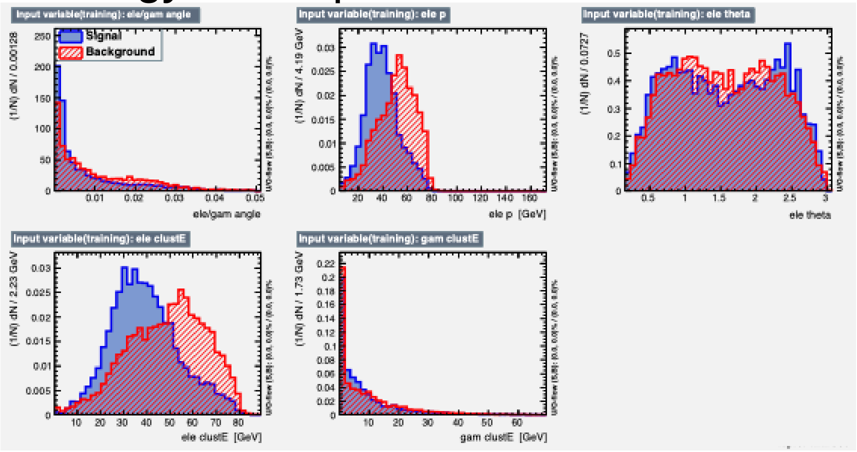
Bremsstrahlung recovery

❖ **Electrons traversing the detector radiate photons at small angles (bremsstrahlung)**
- Leads to large low-mass tail in $m_{e^+e^-}$
- Not taken into account in Fast Sim
- Try to correct by finding the highest-momentum photon within a 0.05-radian cone around the lepton

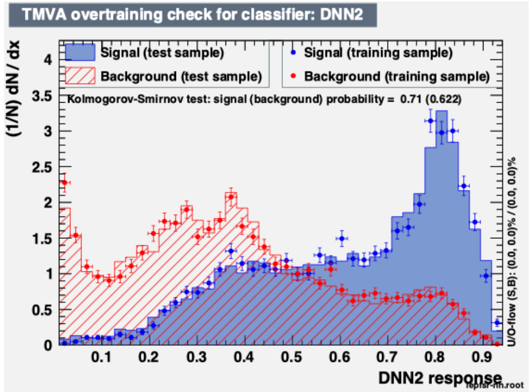
❖ **Train a NN to decide whether to add the photon to the lepton**
- ❖ Classify leptons based on whether adding the photon makes its momentum
- ❖ it closer to or further from the momentum from MC truth
- ❖ If closer, than we say the photon should be added (`signal’)
- ❖ If farther, then we say the photon should not be added (`background’)

❖ **Used DNN method from TMVA.**
- Two hidden layers with tanh activation functions with 14 and 6 nodes.
- Output node used a linear activation function

❖ **NN input variables**
- Angle between lepton and photon
- Lepton momentum
- Lepton polar angle (theta)
- Energy of the lepton's calorimeter cluster
- Energy of the photon's calorimeter cluster



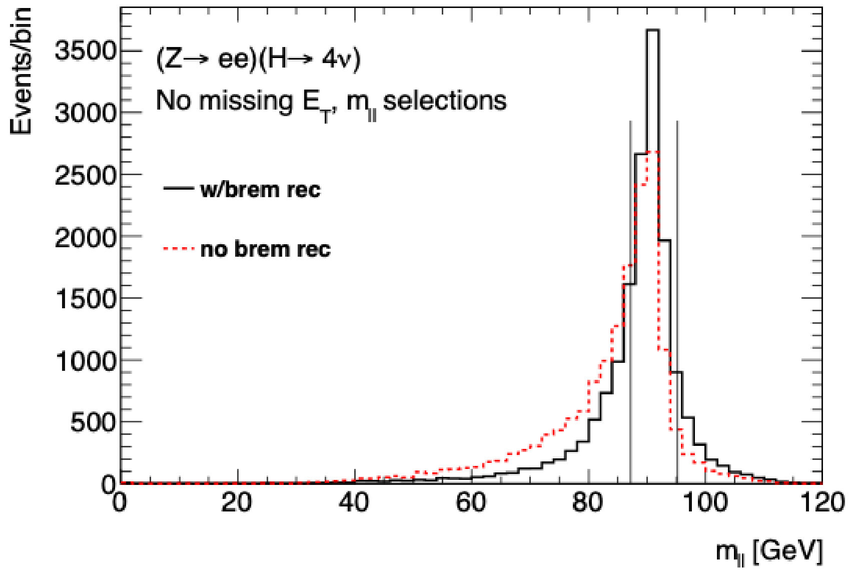
❖ **Choose to add the photon if NN output > 0.5**



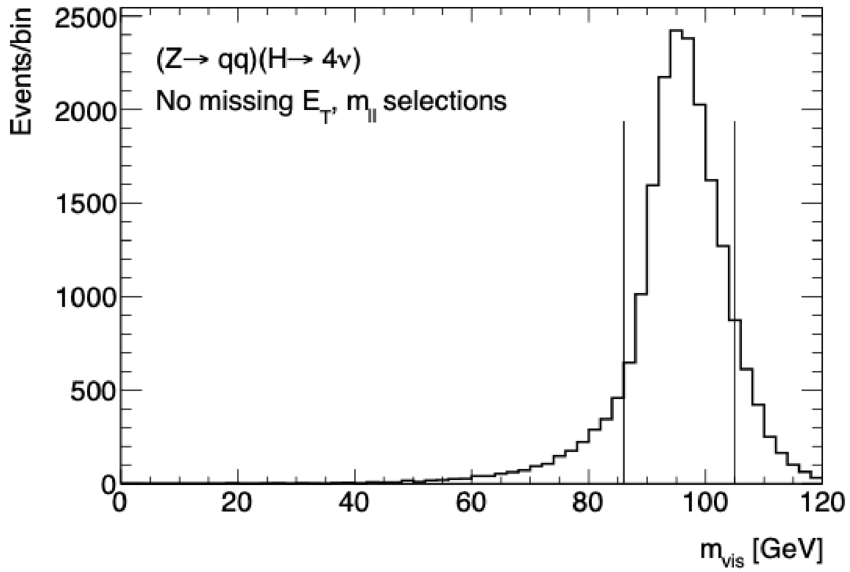
Bremsstrahlung recovery

- Narrows the distribution and makes it more symmetric

- If the photon is not added to the lepton, then it is removed from the set of particles used to calculate the visible momentum
- This also makes the recoil mass distribution more symmetric and closer to m_H



- m_{vis} peaks higher than m_Z
- Could be due to confusion in PandoraPFA, where a neutral cluster close to a charged hadron is being added to the hadron, but its energy is already accounted for in the track
- This has not been definitively verified but may imply that PandoraPFA needs additional tuning for the CLD case



Results

Theory prediction $Br(H \to 4\nu) \sim 10^{-3}$

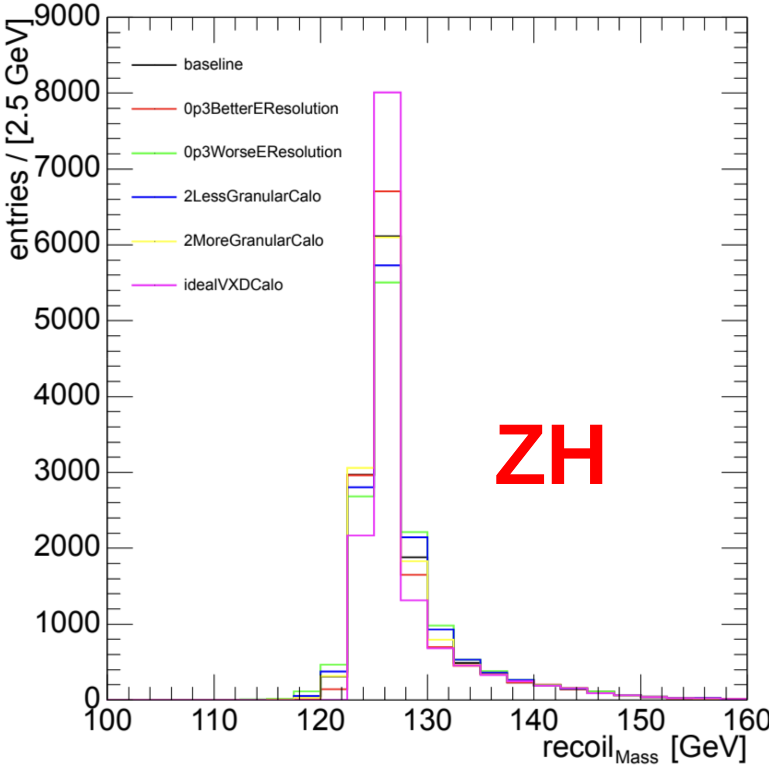
Limit set on $\mathcal{B}(H \to \text{inv})$					
Channels	-2σ	-1σ	Limit	+1σ	+2σ
ee	7.3×10^{-2}	9.9×10^{-2}	1.4×10^{-1}	2.0×10^{-1}	2.8×10^{-1}
$\mu\mu$	2.3×10^{-2}	3.2×10^{-2}	4.5×10^{-2}	6.4×10^{-2}	8.7×10^{-2}
qq	3.5×10^{-3}	4.7×10^{-3}	6.5×10^{-3}	9.1×10^{-3}	1.2×10^{-2}

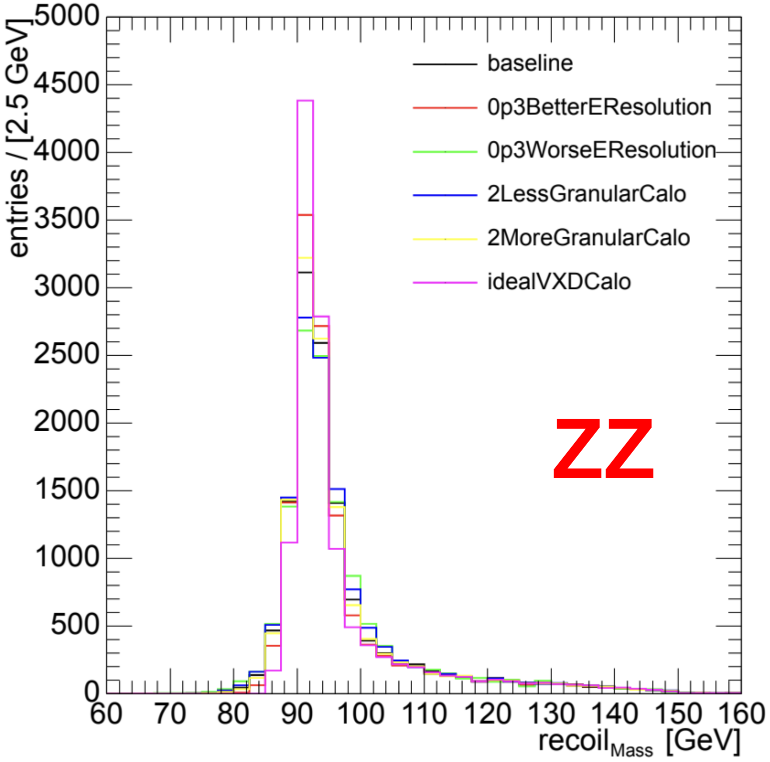
- **Signal:** **Z(mumu, ee, qq)H(ZZ→4nu)**
- **Bkg:** **ZH, ZZ, WW**

Preliminary results

- The limit is obtained by fitting the recoil mass distributions
- The background components (WW+ZZ+ZH) are combined
- To combine Fast and Full Sim, Full Sim channels are vetoed in the fast sim samples.
- The best limit is obtained with qq final state and ee final state is the worse limit

Detector Variation





Z→qq, H→inv.
ZH+ZZ
86 GeV< M_vis < 96 GeV

Preliminary results

Limit on the Higgs to invisible branching ratio for each configuration

Limit set on $\mathcal{B}(H \to \text{inv})$					
Detector config	-2σ	-1σ	Limit	+1σ	+2σ
baseline	3.5×10^{-5}	4.7×10^{-5}	6.7×10^{-5}	9.5×10^{-5}	1.3×10^{-4}
0p3BetterEResolution	3.1×10^{-5}	4.2×10^{-5}	6.0×10^{-5}	8.6×10^{-5}	1.2×10^{-4}
0p3WorseEResolution	3.3×10^{-5}	4.6×10^{-5}	6.5×10^{-5}	9.2×10^{-5}	1.3×10^{-4}
2LessGranularCalo	3.7×10^{-5}	5.0×10^{-5}	7.1×10^{-5}	0.000101	1.4×10^{-4}
2MoreGranularCalo	3.5×10^{-5}	4.8×10^{-5}	6.7×10^{-5}	9.6×10^{-5}	1.3×10^{-4}
idealVXDCalo	2.9×10^{-5}	3.9×10^{-5}	5.6×10^{-5}	7.9×10^{-5}	1.1×10^{-4}

Different calorimeter properties:

- baseline IDEA calorimeter
- 30% better relative energy resolution
- 30% worse relative energy resolution
- two times more granular calorimeter
- two times less granular calorimeter.

Summary

- ✓ **A study on the Higgs → inv at √s = 240 GeV is presented**
- ✓ **A combination of fast and full simulations is used**
- ✓ **The recoil mass is fitted to set limit on B(H → inv)**
  - ➢ The best limit is obtained with qq channel, while ee shows the worst limit results.
- ✓ **A comparison on the lepton reconstruction between CLD full simulation and Delphes simulations of CLD and IDEA is shown**
  - ➢ A study of the efficiency and resolution are performed for this comparison.
  - ➢ A nearly identical efficiency is observed for IDEA and CLD fast sim.
  - ➢ Electron efficiency is worse for full sim than for fast sim, especially at low pT
- ✓ **The crossing angle effect is also studied**
  - ➢ boost in the negative x direction by $\beta = \sin(\frac{\theta}{2})$
- ✓ **Bremsstrahlung recovery:**
  - ➢ Recoil mass shape become more symmetric
- ✓ **Detector variation**

Backup