# Higgs mass analysis with FullSim

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# Overview

## Analysis strategy – performed using IDEA Delphes simulation

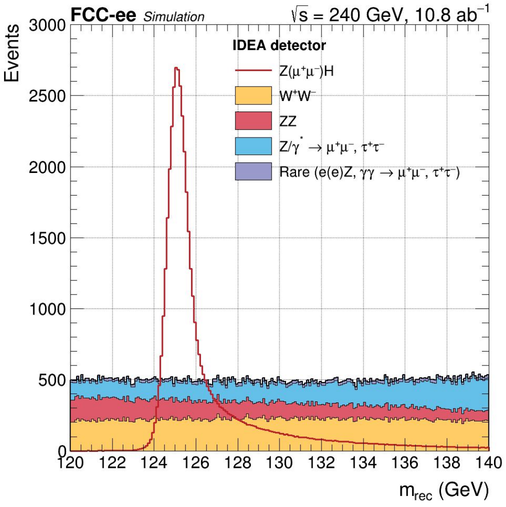
- Electron and muon final states
- Tight selection on Z(ll)H → two opposite-sign leptons
- Compute recoil and fit shape analytically with Crystal Ball and Gauss

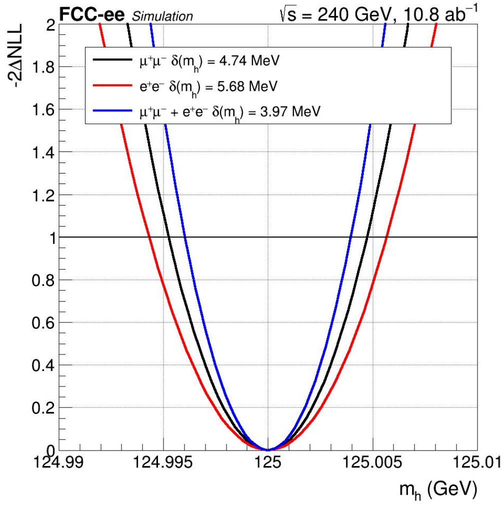
$$M_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

| Final state | Stat. (MeV) | Stat. + Syst. (MeV) |
|---|---|---|
| Electron | 4.95 | 5.68 |
| Muon | 3.92 | 4.74 |
| Combined | 3.07 | 3.97 |

## Uncertainty driven by

- Lepton momentum resolution → tracker and material budget
- Beam Energy Spread → machine
- Statistically limited, dominant systematic center-of-mass energy



# Detector configurations

**Nominal configuration**

**Crystal ECAL to Dual Readout**

**Nominal 2 T → field 3 T**

**IDEA drift chamber → CLD Si tracker**

**Impact of Beam Energy Spread**

**Perfect (=gen-level) momentum resolution**

| Final state | Muon | Electron | Combination |
|---|---|---|---|
| Nominal | 3.92(4.74) | 4.95(5.68) | 3.07(3.97) |
| Inclusive | 3.92(4.74) | 4.95(5.68) | 3.10(3.97) |
| Degradation electron resolution | 3.92(4.74) | 5.79(6.33) | 3.24(4.12) |
| Magnetic field 3T | 3.22(4.14) | 4.11(4.83) | 2.54(3.52) |
| Silicon tracker | 5.11(5.73) | 5.89(6.42) | 3.86(4.55) |
| BES 6% uncertainty | 3.92(4.79) | 4.95(5.92) | 3.07(3.98) |
| Disable BES | 2.11(3.31) | 2.93(3.88) | 1.71(2.92) |
| Ideal resolution | 3.12(3.95) | 3.58(4.52) | 2.42(3.40) |
| Freeze backgrounds | 3.91(4.74) | 4.95(5.67) | 3.07(3.96) |
| Remove backgrounds | 3.08(4.13) | 3.51(4.58) | 2.31(3.45) |

# Higgs mass analysis with FullSim

**Delphes-based Higgs mass analysis done using IDEA detector with drift chamber**

**IDEA with silicon tracker available in Delphes: replace drift chamber by CLD-like silicon tracker**

- Compare FullSim CLD with FastSim IDEA silicon tracker
- Valid as the muon momentum is driven by the tracker
- Not necessarily true for electrons (calorimeter dependent momentum resolution)

**FastSim Delphes:** Winter2023 campaign

- Samples produced with original CLD-like implementation 1–2 years ago (see card here)
- In the meantime more recent implementation available (FCCeeDetWithSiTracking)
- See comparison next slide – but need to understand what Delphes card corresponds to the FullSim detector

**FullSim CLD:** version CLD_o2_v05, Key4hep 2024-04-12

**3 samples produced**

- Central 125 GeV, 2 mass variations +/- 50 MeV
- 2 M events per sample
- Backgrounds kept Delphes

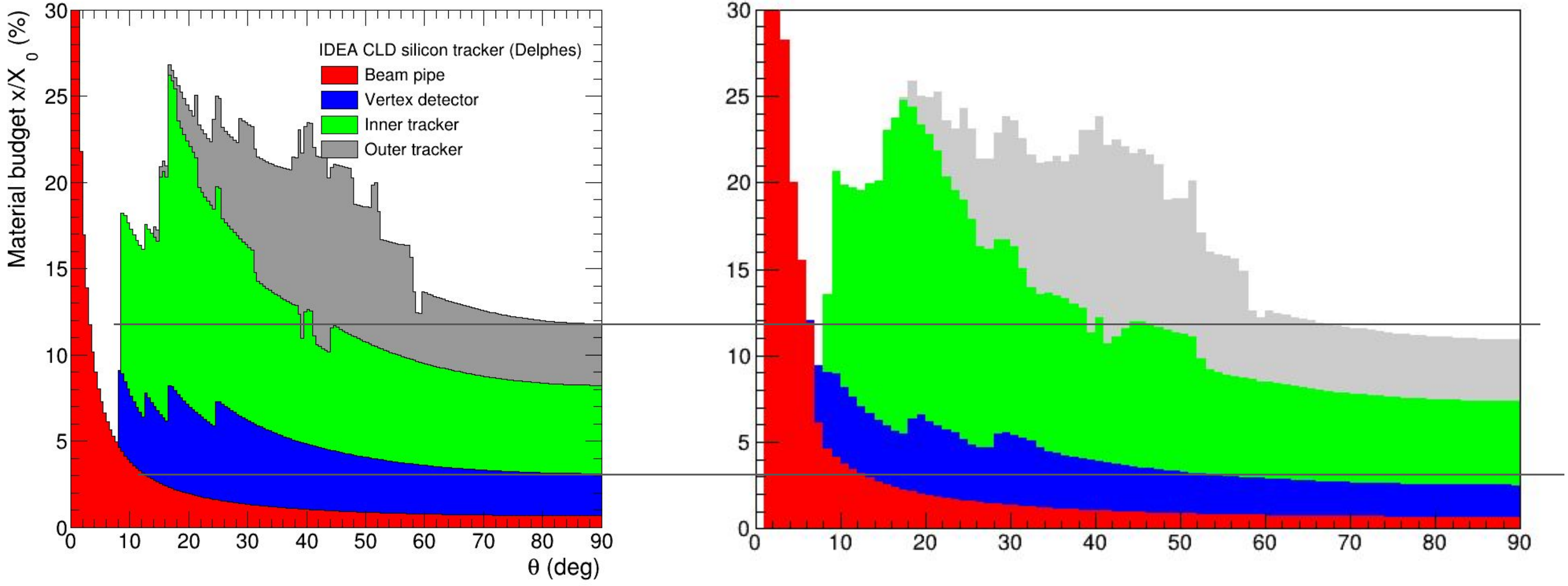
| Sample | Events | Sample size |
|---|---|---|
| Delphes | 2 M | 16 GB |
| FullSim | 2 M | 2.3 TB |

# Comparison of tracker material budget

Left – “old” Delphes IDEA CLD silicon tracker implementation (see card here)

- Used for sample generation

Right – CLD FullSim tracker

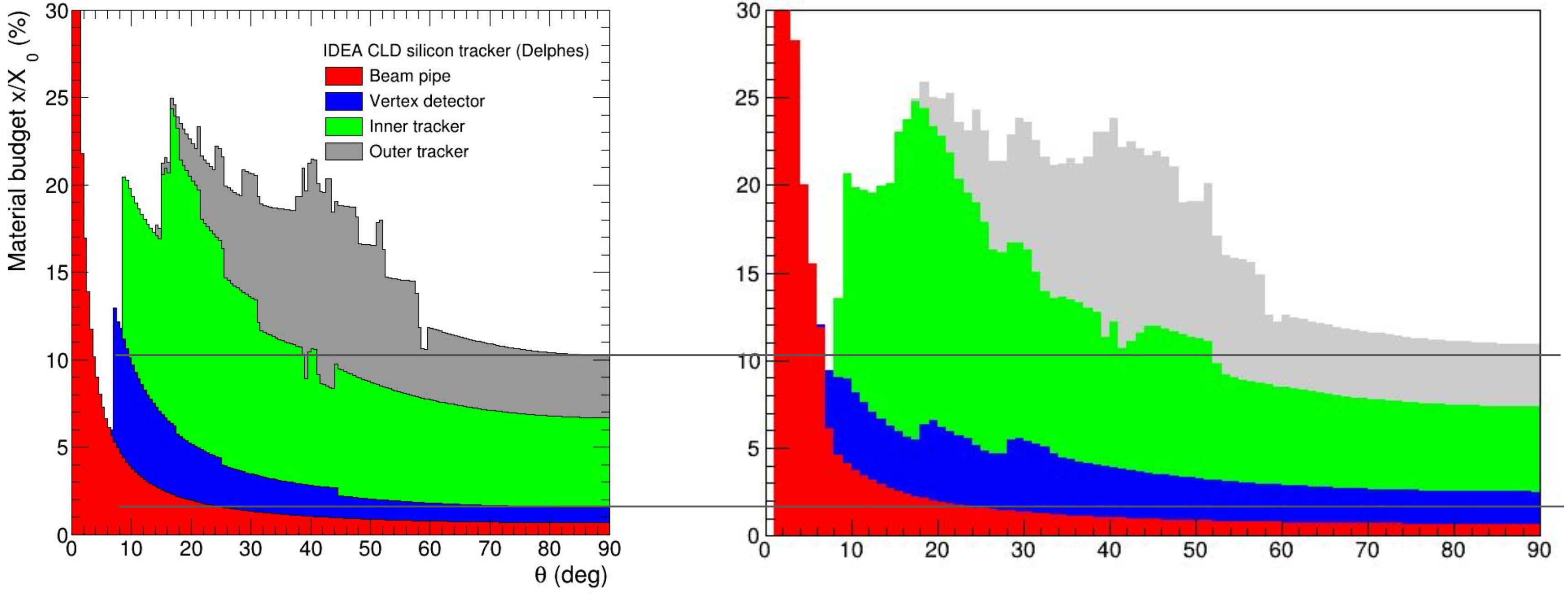


# Comparison of material budget

Left – “new” Delphes IDEA CLD silicon tracker implementation (see card here)

- Difference in material budget of the vertex detector

Right – CLD FullSim tracker



# Analyzing FullSim vs FastSim samples

**Leptons taken from PandoraPFOs collection – select on “type” == PDGID**

**FullSim samples produced with crossing angle of 15 mrad**

- All the MC particles are boosted priori before propagating through the detector
- Requires to boost back all particles to the COM frame

```
Vec_rp unBoostCrossingAngle(Vec_rp in, float angle) {
    Vec_rp result;
    float ta = std::tan(angle);
    for (size_t i=0; i < in.size(); ++i) {
        auto & p = in[i];
        edm4hep::ReconstructedParticleData newp = p;
        float e = p.energy;
        float px = p.momentum.x;
        float e_prime = e * sqrt(1 + ta*ta) + px * ta;
        float px_prime = px * sqrt(1 + ta*ta) + e * ta;
        newp.momentum.x = px_prime;
        newp.energy = e_prime;
        result.push_back(newp);
    }
    return result;
}
```

# Analyzing FullSim vs FastSim samples

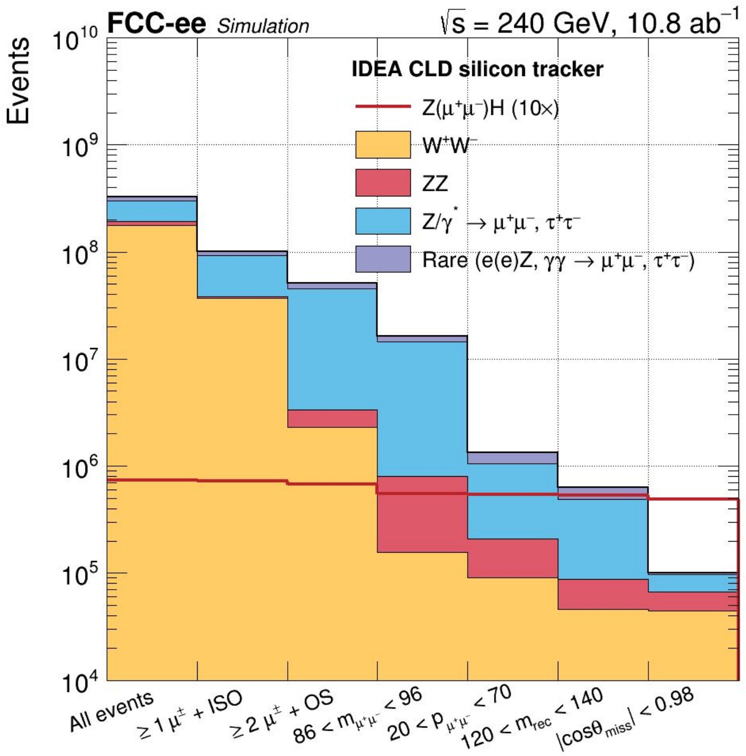
## Harmonize FastSim and FullSim collections

```
if 'FullSim' in dataset.name:
    df = df.Define("ReconstructedParticles", "FCCAnalyses::unBoostCrossingAngle(PandoraPFOs, -0.015)")
    df = df.Define("muons_all", "FCCAnalyses::sel_type(13, ReconstructedParticles)")
    df = df.Alias("Particle", "MCParticles")
    df = df.Alias("Particle0", "_MCParticles_parents.index")
    df = df.Alias("Particle1", "_MCParticles_daughters.index")
    df = df.Alias("MCRecoAssociations0", "_RecoMCTruthLink_rec.index")
    df = df.Alias("MCRecoAssociations1", "_RecoMCTruthLink_sim.index")
else:
    df = df.Alias("Particle0", "Particle#0.index")
    df = df.Alias("Particle1", "Particle#1.index")
    df = df.Alias("MCRecoAssociations0", "MCRecoAssociations#0.index")
    df = df.Alias("MCRecoAssociations1", "MCRecoAssociations#1.index")

    df = df.Alias("Muon", "Muon#0.index")
    df = df.Define("muons_all", "FCCAnalyses::ReconstructedParticle::get(Muon, ReconstructedParticles)")

## generic analysis selection goes here
```

# Comparison cutflow




| Cutflow event yields | | |
|---|---|---|
| **Cut variable** | **Delphes** | **Full Sim** |
| All events | 73100 | 73100 |
| 1 muon | 72200 | 72300 |
| 2 OS muons | 67800 | 69000 |
| $86 < m_{\mu\mu} < 96$ | 54900 | 55600 |
| $20 < p_{\mu\mu} < 70$ | 54500 | 55200 |
| Recoil | 53100 | 53700 |
| $\lvert\cos(\theta_{miss})\rvert$ | 48800 | 51400 |

Vero good agreement of event yields within 1 %, except the $\lvert\cos(\theta_{miss})\rvert$

Can be expected as missing energy is sensitive to the detector as a whole + PF performance

# Uncertainty on Higgs mass

**FullSim recoil distribution slightly worse than Delphes**

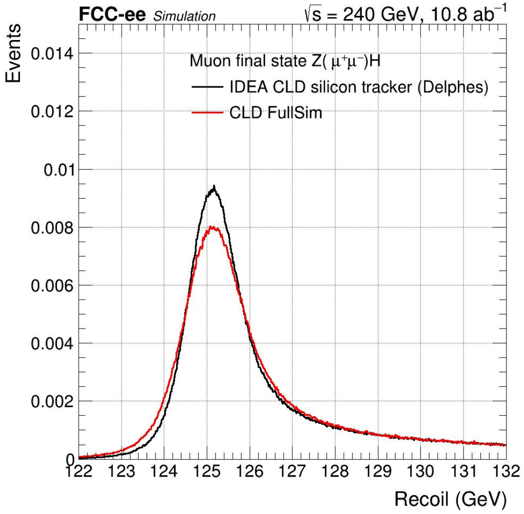
**Repeat the fit producer as for the Delphes analysis**

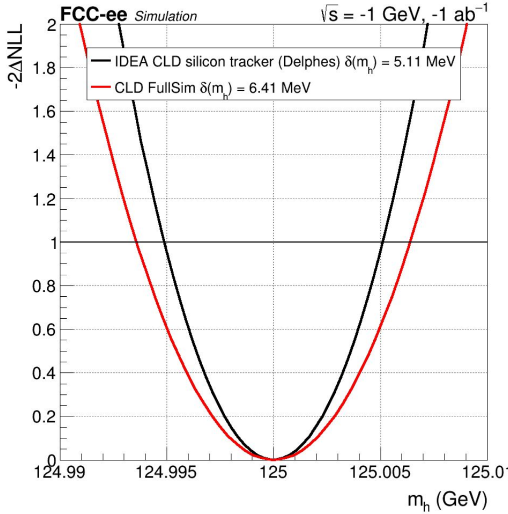
- Fit recoil distributions with Crystal Ball and Gauss
- Statistical-only fit, no systematics

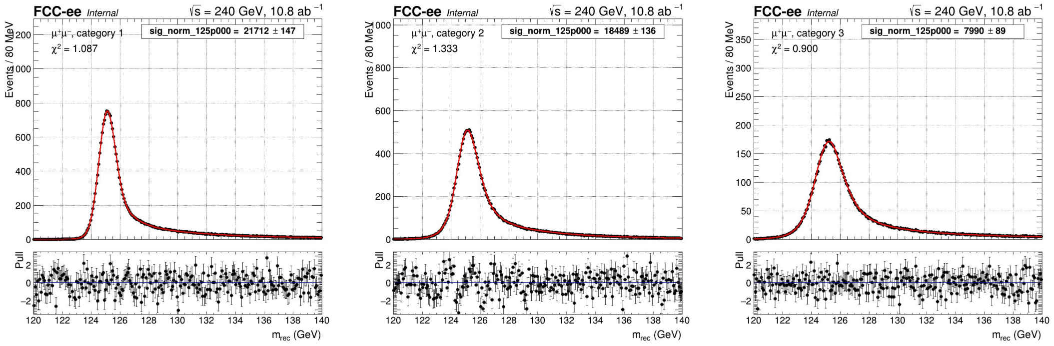
| Config | Uncertainty |
| --- | --- |
| Delphes | 5.11 MeV |
| FullSim | 6.41 MeV |

**Out-of-the box FullSim**

**25% worse than Delphes**



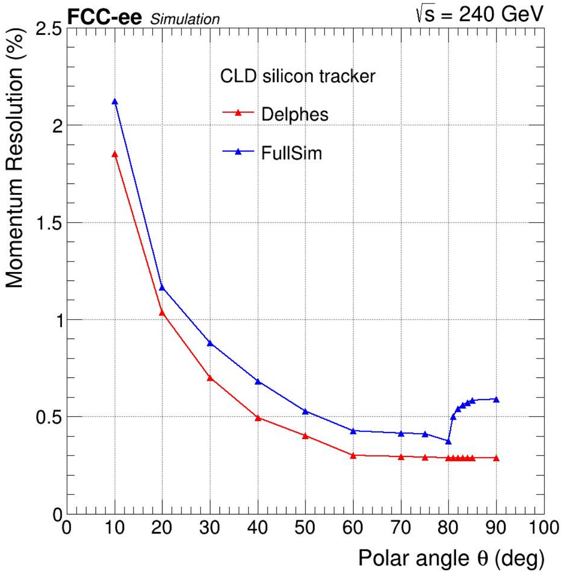



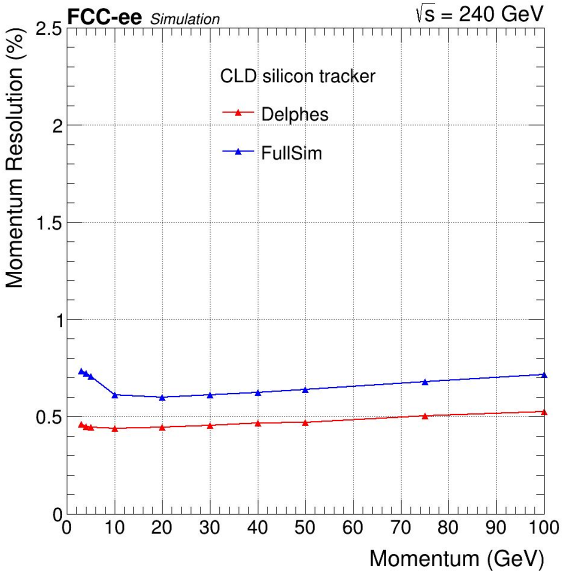
# Validation with Particle Gun

**Independent validation with muon gun**

- Produced muon gun (hepmc3) and propagated same events to Delphes and FullSim
- Several samples as function of theta and momentum

**Plotted muon momentum resolution $(p_{reco} - p_{gen})/p_{gen}$**



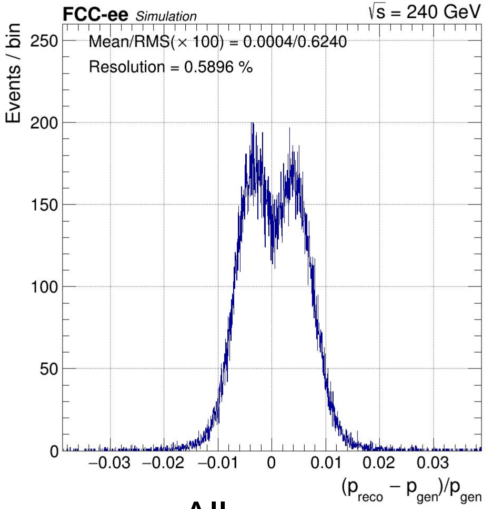



# Validation with Particle Gun

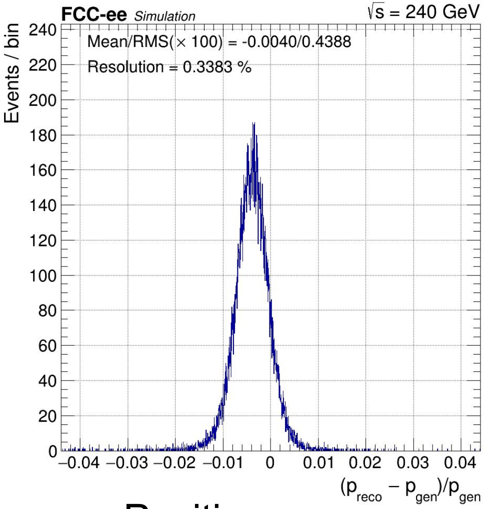
## Independent validation with muon gun

- Produced muon gun (hepmc3) and propagated same events to Delphes and FullSim
- Several samples as function of theta and momentum

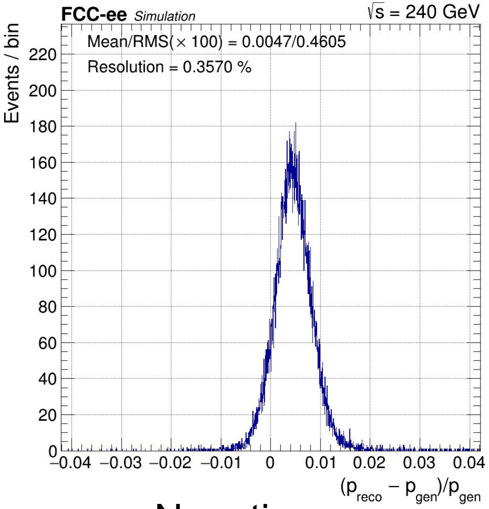
## Charge dependent momentum scale observed:  alignment problem




All muons




Positive muons



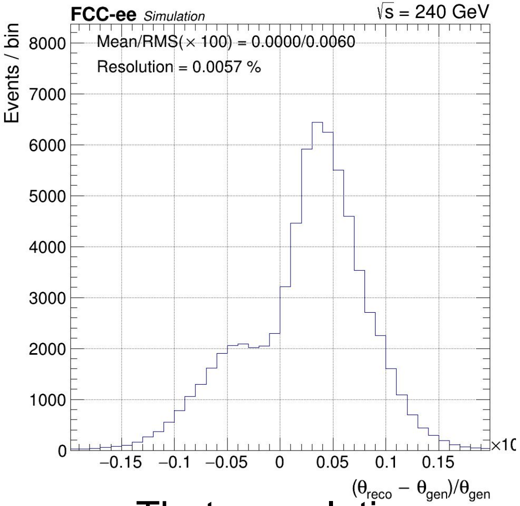

Negative muons

# Validation with Particle Gun

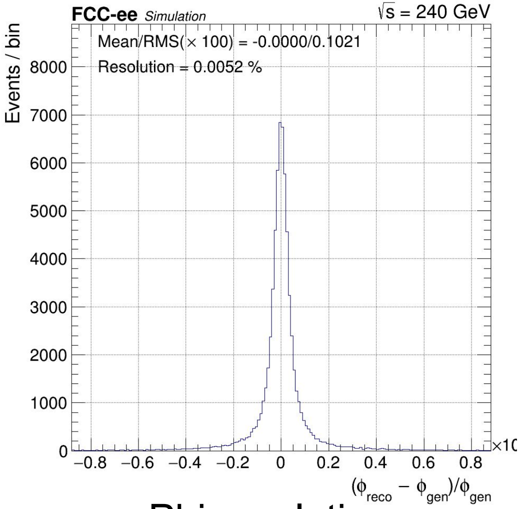
**Independent validation with muon gun**

- Produced muon gun (hepmc3) and propagated same events to Delphes and FullSim
- Several samples as function of theta and momentum

**Angular resolutions: θ not centered around zero (ϕ OK)**




Theta resolution




Phi resolution

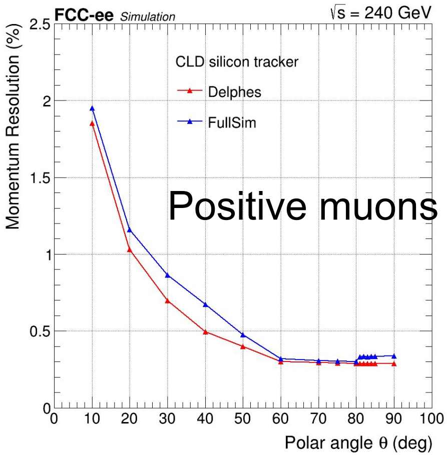
# Charge-dependent resolution

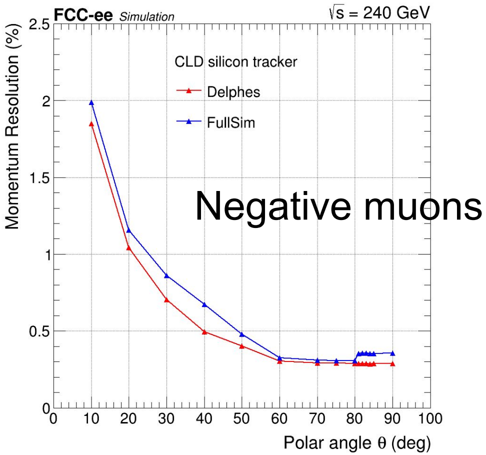
**Restore the charge-dependent muon scale by applying scale factors as function of θ**

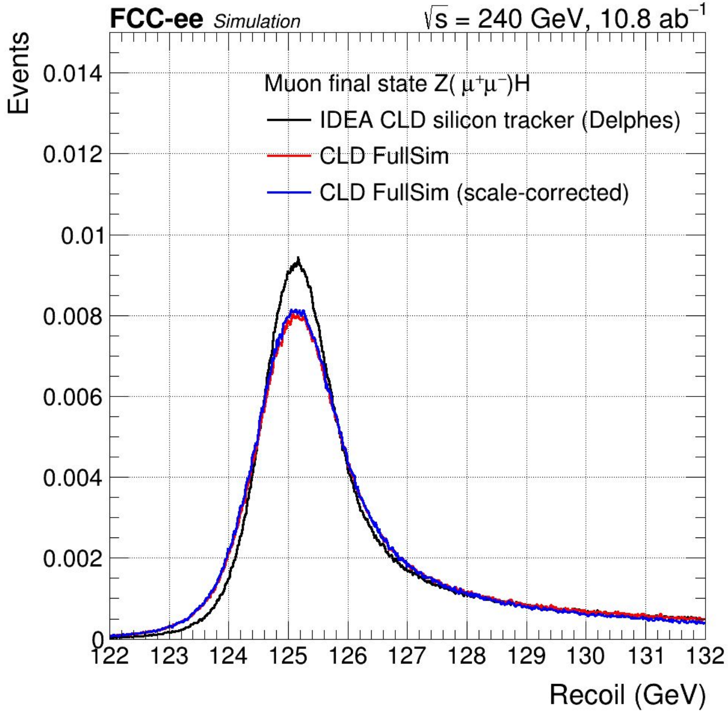
- Effect mostly cancels as it is formed from an opposite lepton pair
- Does not take into account bias in polar angle → bias in recoil

**Looking at charge-dependent resolution**

- Small residual issues still present
- Resolution becomes very close to Delphes in the central region



# Conclusions

**Performed Higgs mass analysis using FullSim CLD samples**

- Out-of-the-box FullSim performs 25% worse than Delphes
- Residual differences under investigation: issue with muon reconstruction degrading its performance
- Promising agreement with charge-dependent resolutions compared to Delphes

**Outlook**

- Understand and fix the muon reconstruction issue and redo the analysis
- Look at electrons