Higgs mass analysis with FullSim

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Joint Software Physics Performance meeting
October 21, 2024

Overview

This presentation is a follow-up on the last presentation (Sept. 30 link)

- Issues with muon momentum scale understood: technical issues related to muon guns in hepmc and MC particle boost
- Today presenting updates on the Z($\mu\mu$)H channel
- Also look briefly at electrons – Z(ee)H channel

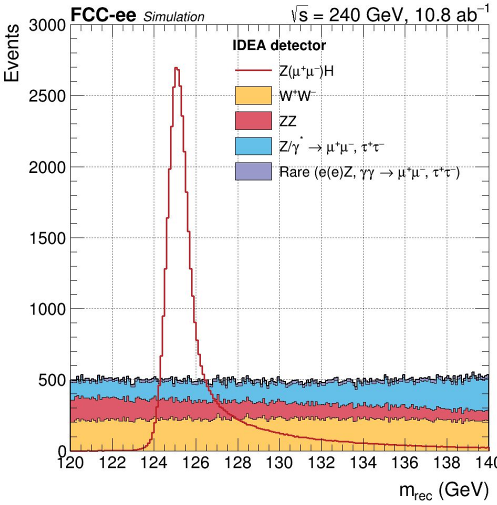
Overview

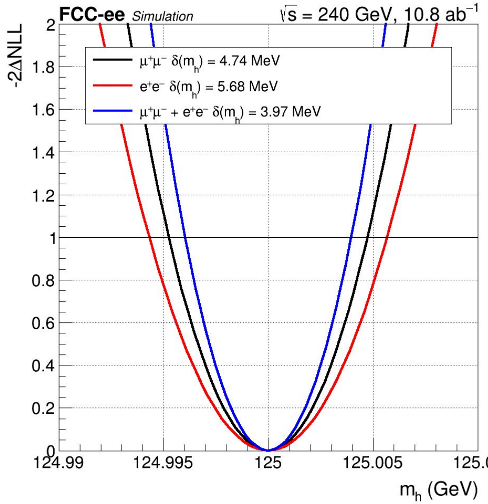
Analysis strategy – performed using IDEA Delphes simulation

- 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

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 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 IDEA+Si tracker implementation 1–2 years ago (see card here)
- In the meantime more recent implementation available (FCCeeDetWithSiTracking)

FullSim CLD: version CLD_o2_v05, Key4hep 2024-04-12 (central production)

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

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
- Also the MC particles are saved with boost enabled

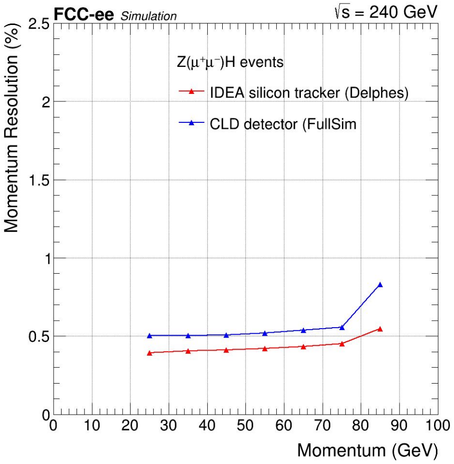
```
Vec_rp unBoostCrossingAngle(Vec_rp in, float angle) {
    Vec_rp result;
    float ta = std::tan(angle);
    for (size_t i=0; i < in.size(); ++i) {
        auto & p = in[i];
        edm4hep::ReconstructedParticleData newp = p;
        float e = p.energy;
        float px = p.momentum.x;
        float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

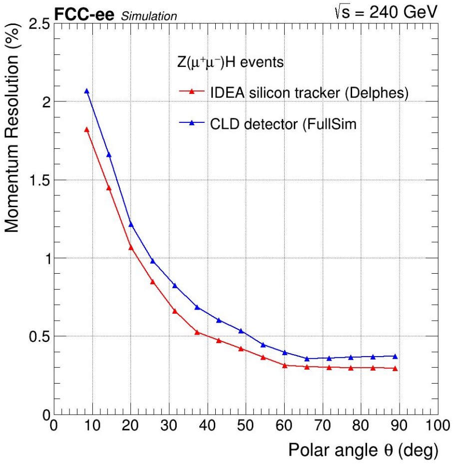
Analyzing FullSim vs FastSim samples

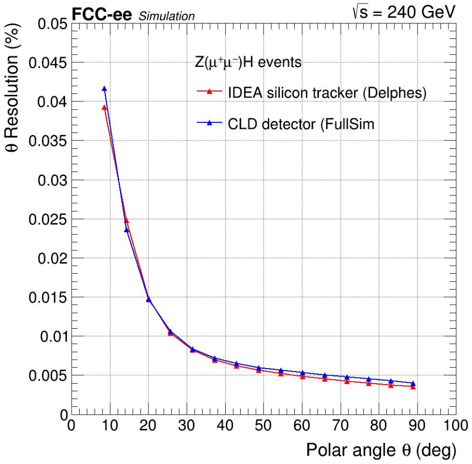
Harmonize FastSim and FullSim collections

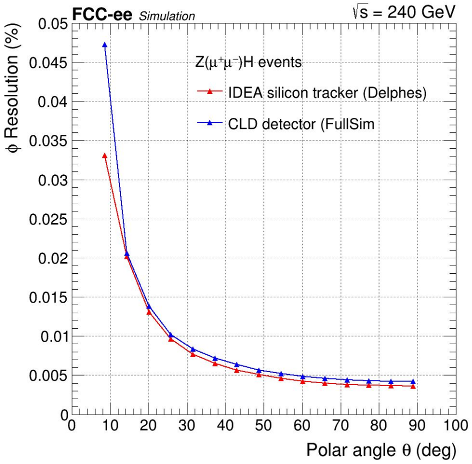
```
if 'FullSim' in dataset.name:
    df = df.Define("ReconstructedParticles", "FCCAnalyses::unBoostCrossingAngle(PandoraPFOs, -0.015)")
    df = df.Define("Particle", "FCCAnalyses::unBoostCrossingAngle(MCParticles, -0.015)")
    df = df.Define("muons_all", "FCCAnalyses::sel_type(13, ReconstructedParticles)")
    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
```

Z($\mu\mu$)H – momentum and angular resolutions





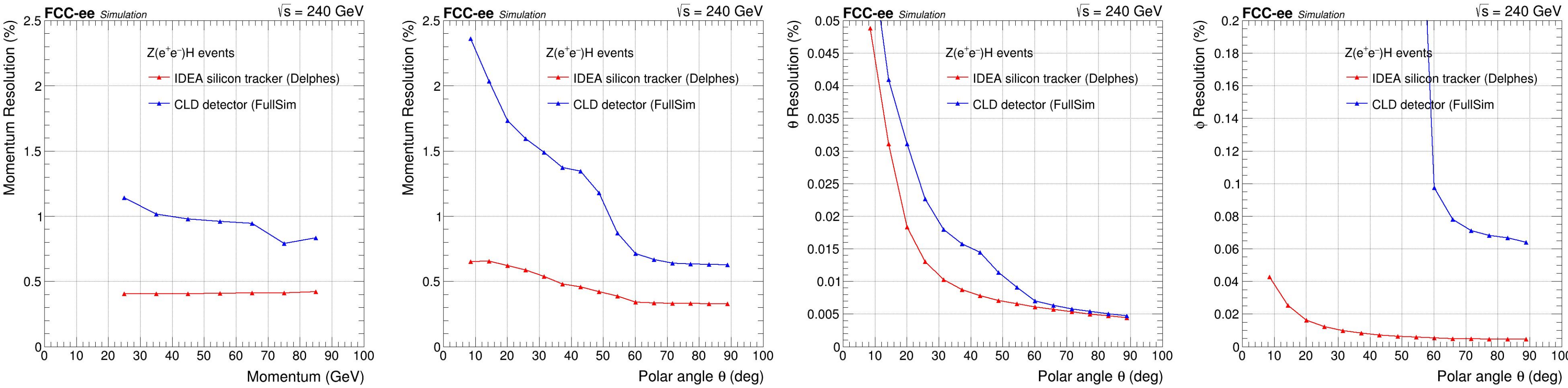




Muon resolutions based on Z($\mu\mu$)H events

- Slightly worse momentum in FullSim (residual difference in material budget, smearing)
- Angular resolutions OK

Z(ee)H – momentum and angular resolutions

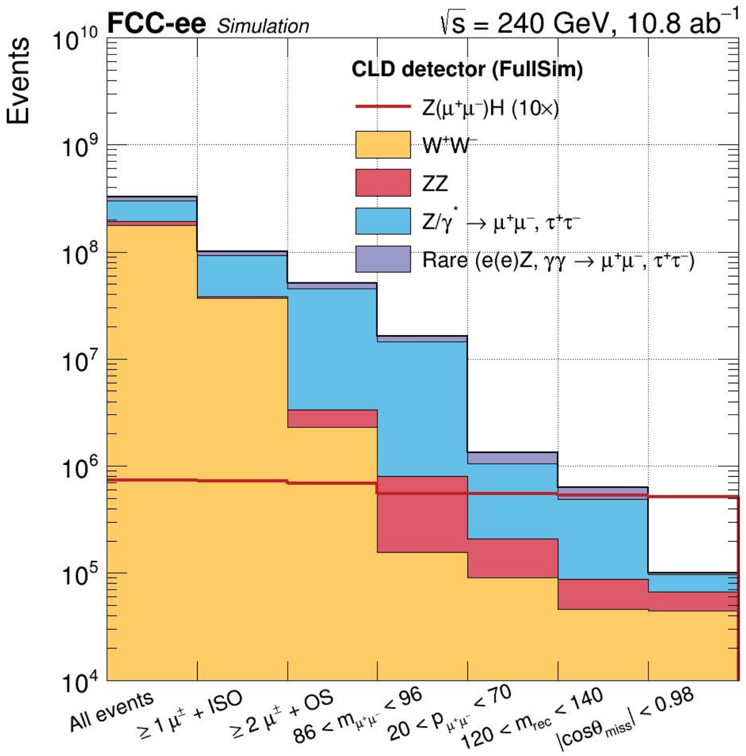


Electron resolutions based on Z(ee)H events

- Visibly worse momentum in FullSim
- No Bremsstrahlung recovery in CLD reconstruction

Comment: resolutions extracted using quantiles 0.5(q84 – q16) → very sensitive to brem tails*

Comparison cutflow (muon)

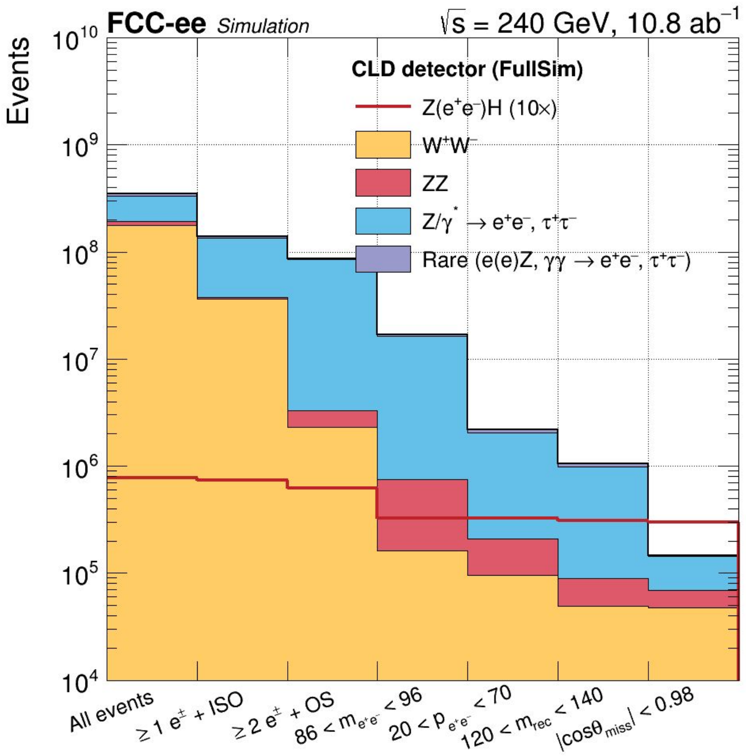


Cutflow event yields		
Cut variable	**Delphes**	**Full Sim**
All events	73100	73100
1 muon	72200	72300
2 OS muons	67800	69000
$86 < m_{\mu\mu} < 96$	54900	55600
$20 < p_{\mu\mu} < 70$	54500	55200
Recoil	53100	53700
$\lvert\cos(\theta_{miss})\rvert$	48800	51400

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

Comparison cutflow (electron)

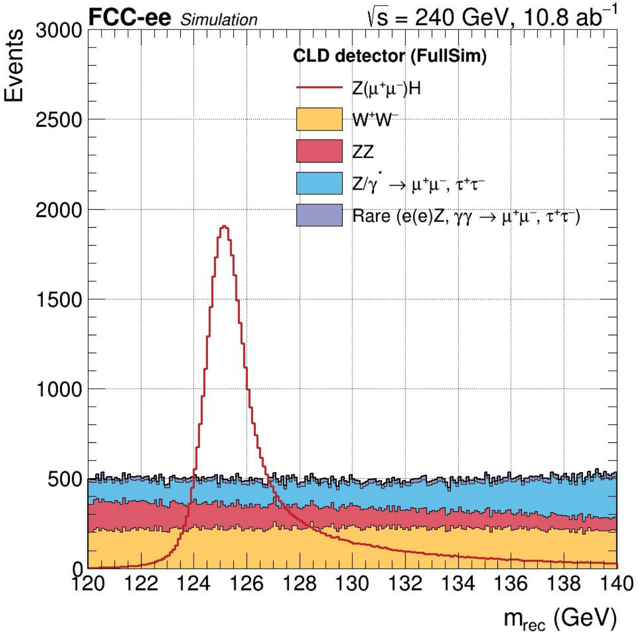


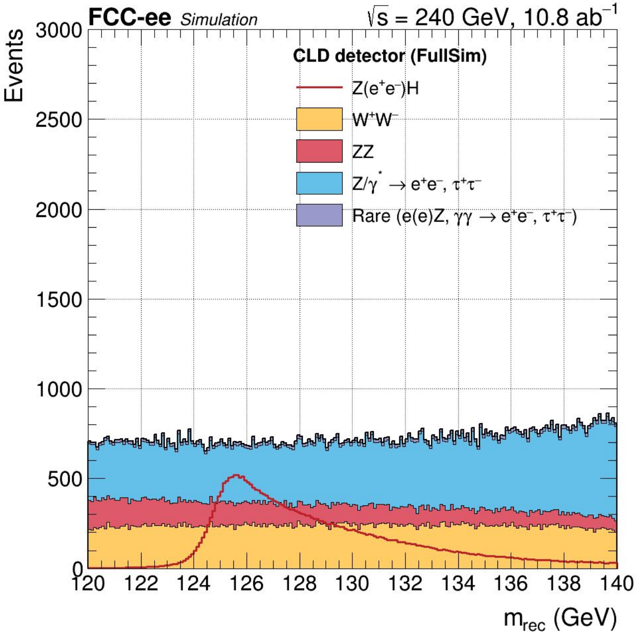
Cutflow event yields		
Cut variable	**Delphes**	**Full Sim**
All events	77300	77300
1 muon	76000	74100
2 OS muons	69900	61800
$86 < m_{ee} < 96$	51400	32600
$20 < p_{ee} < 70$	51000	32300
Recoil	49600	30800
$\|\cos(\theta_{miss})\|$	45600	29600

Good agreement of event yields except the m(ee) cut

→ Events leaking to the low-mass tail due to poor resolution

Final recoil distributions





Uncertainty on Higgs mass (muon)

FullSim recoil distribution slightly worse than Delphes

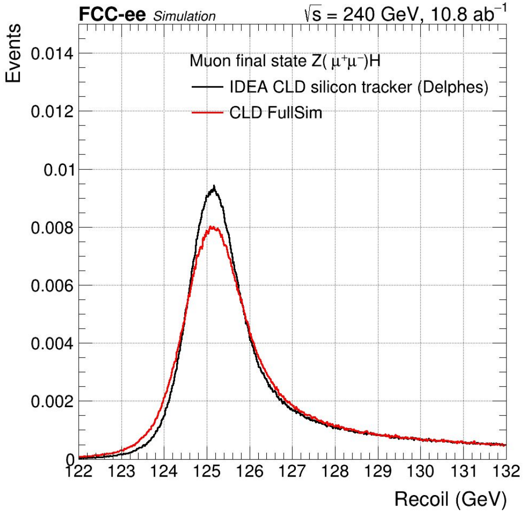
Repeat the fit producer as for the Delphes analysis

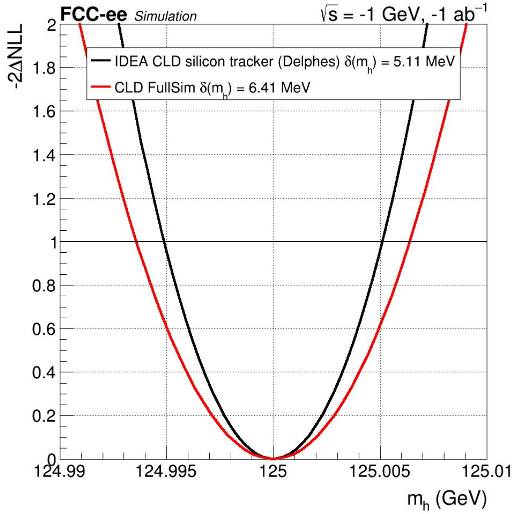
- Fit recoil distributions with Crystal Ball and Gauss
- Statistical-only fit, no systematics

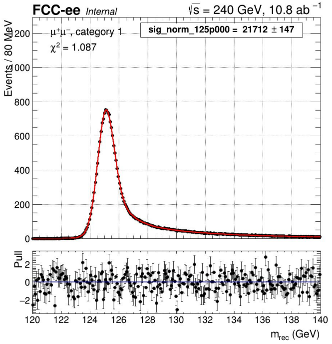
Config	Uncertainty
Delphes	5.11 MeV
FullSim	6.41 MeV

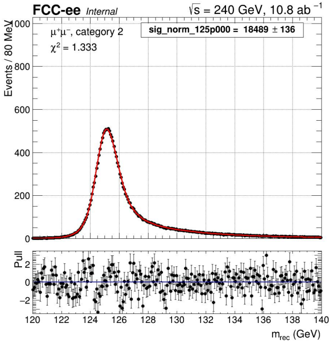
Out-of-the box FullSim

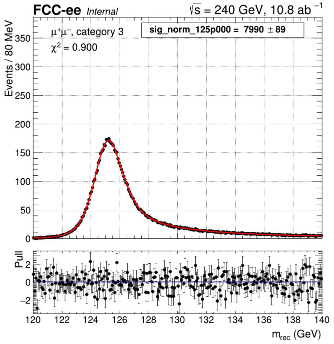
25% worse than Delphes







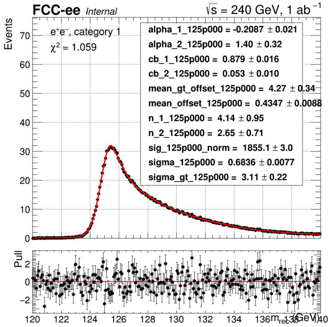


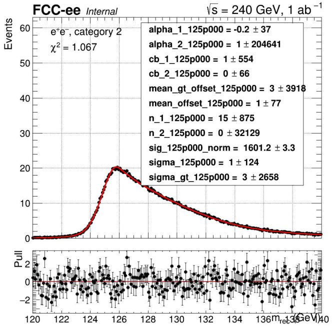


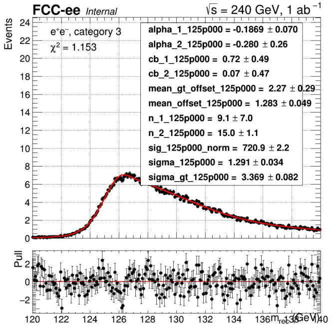
Uncertainty on Higgs mass (electron)

One off-mass sample missing to complete the entire analysis

Given the worse recoil resolution, expected sensitivity from the electron channel will be negligible (< 1%)







Conclusions

Performed Higgs mass analysis using FullSim CLD samples

- In the muon channel, reached 6.41 MeV uncertainty (Delphes-based analysis 5.11 MeV, 25% worse)
- Electrons channel negligible sensitivity due to missing Bremsstrahlung recovery

Brem recovery for electrons essential to gain any sensitivity to Higgs mass (and any analysis for tight selection on m(ee))

- Some work already done
- Emmanuel/Michele: https://repository.cern/records/87nyk-0rg63 → detector requirements for ECAL (granularity, resolution, …)
- Also BNL attempt for MVA-based brem recovery (See last Higgs-perf meeting link)

Analysis workflow and functions will be made available with an example in FCCAnalyses

Backup

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 →

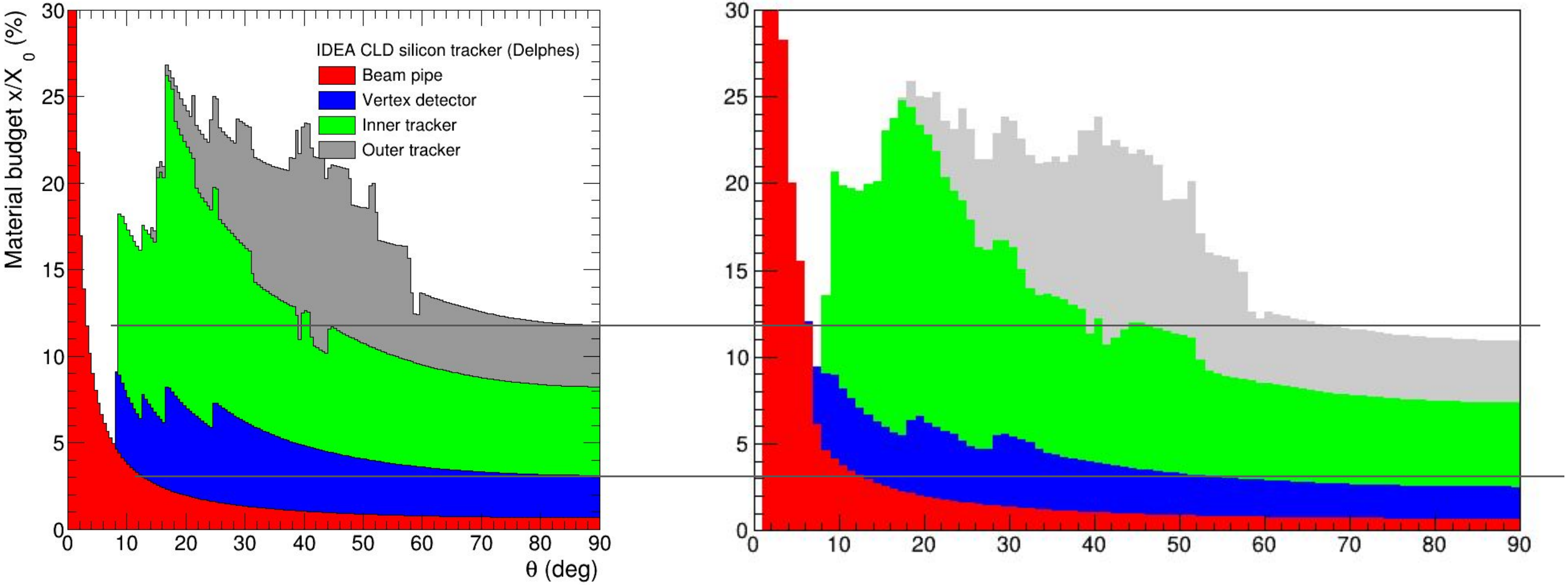
Final state	Muon	Electron	Combination
Nominal	3.92(4.74)	4.95(5.68)	3.07(3.97)
Inclusive	3.92(4.74)	4.95(5.68)	3.10(3.97)
Degradation electron resolution	3.92(4.74)	5.79(6.33)	3.24(4.12)
Magnetic field 3T	3.22(4.14)	4.11(4.83)	2.54(3.52)
Silicon tracker	5.11(5.73)	5.89(6.42)	3.86(4.55)
BES 6% uncertainty	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)

Comparison of tracker material budget

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

- Used for sample generation

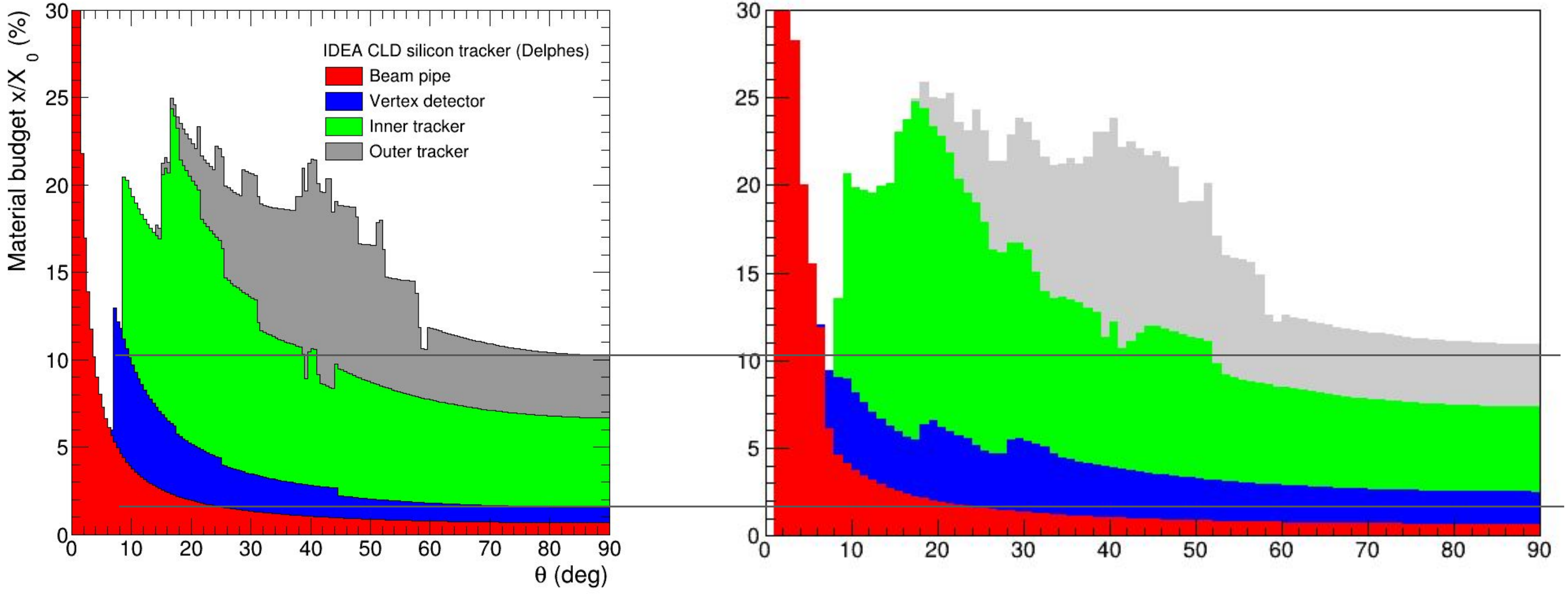
Right – CLD FullSim tracker



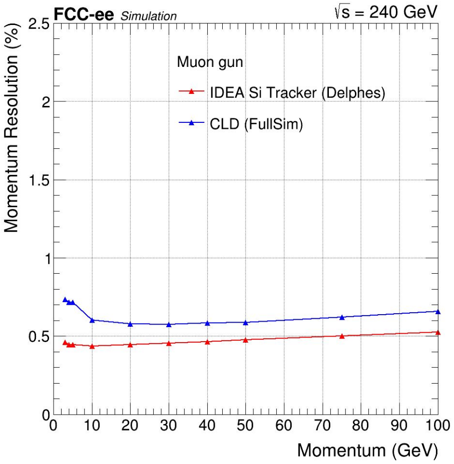
Comparison of material budget

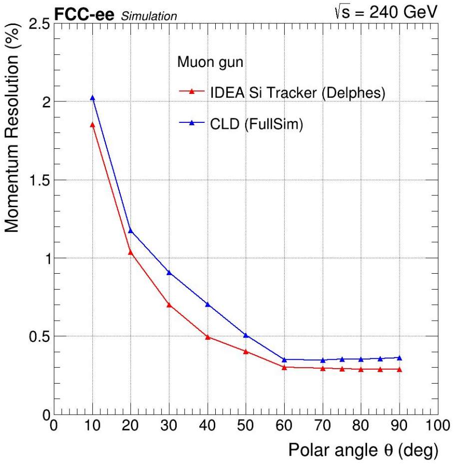
Left – “new” Delphes IDEA CLD silicon tracker implementation (see [card here]())
- Difference in material budget of the vertex detector

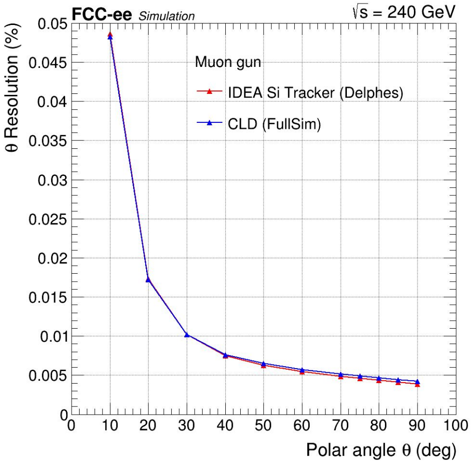
Right – CLD FullSim tracker

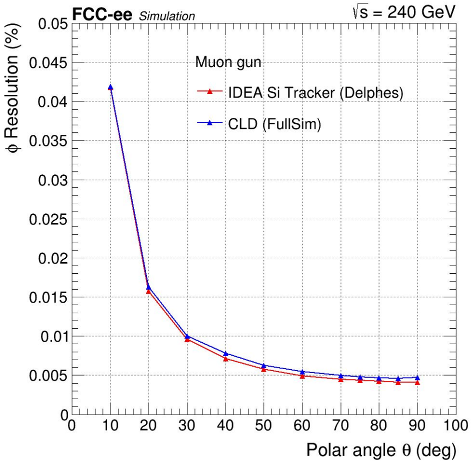


Muon gun – momentum and angular resolutions









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- Angular resolutions OK