Possibilities/reconstruction with a high granularity Calorimeter in FCC

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Workshop FCC France, Annecy
Nov 30 - Dec 2, 2021

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Future collider projects

ILC project

- Recent evolution of ILC project was to build a 250 GeV ee collider.
- Evolution to reduce the initial construction cost.
- Original ILC project, a 500 GeV to 1 TeV ee collider.
- ILC TDR base physics studies scenario : 250 fb^{-1} at 250 GeV, 500 fb^{-1} at 500 GeV, 1000fb^{-1} at 1000 GeV.
- Jet energy range in ILC larger than in FCC-ee.

Main differences

- FCC has higher instantaneous and integrated luminosity.
- ILC has beam polarisation.

Similar physics

ILC jets requirements $\sim$ FCC-ee jets requirements.

Higgs decays

Higgs branching ratio

$\mathcal{O}(10\%)$		$\mathcal{O}(1\%)$		$\mathcal{O}(0.1\%)$		$\mathcal{O}(0.01\%)$	
		gg	(8.6%)	$\gamma\gamma$	(0.23%)		
		$\tau^+\tau^-$	(6.3%)			$\mu^+\mu^-$	(0.02%)
$b\bar{b}$	(58%)	$c\bar{c}$	(2.9%)			$s\bar{s}$	(0.02%)
W^+W^-	(21%)	ZZ	(2.6%)	$Z\gamma$	(0.15%)		

Goal is to measure these BR at the percent or sub-percent level.
This requires very good jet flavor-id (b, c, gluon) and good di-jet mass resolution (W-Z id).

Higgs production

Higgs factory = Higgsstrahlung at $\sqrt{s} \sim 250$ GeV.

Jets requirements

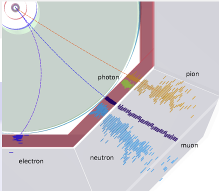
b, c and gluon tagging

- needed to access the H $\rightarrow b\bar{b}$, $c\bar{c}$ and gg branching fraction.
- needs good vertex detector.
- ILC design goal on impact parameter resolution:

$$5\mu\text{m} \oplus \frac{10\mu\text{m}}{p(GeV)\sin^{\frac{3}{2}}\theta}$$

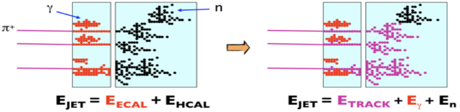
WW and ZZ Branching Ratio

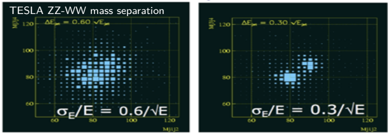
- Br(H→ZZ)=0.1 Br(H→WW). %-level precision:
  - needs good di-jets mass resolution.
  - so needs good jet energy resolution.
- ILC design goal:
  - 3 to 4 % resolution on jet energy above $\sim$ 50 GeV
  - $\frac{\Delta E_{jet}}{E_{jet}} \lesssim \frac{30\%}{\sqrt{E(\text{GeV})}}$
- Goal met in ILD with High Granularity calorimeter and Particle Flow Algorithm (PFA).



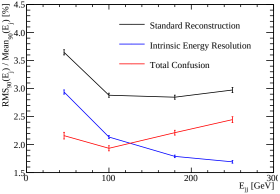
Particle Flow Algorithm (PFA)

- ILC/FCC physics program requires W/Z$\rightarrow q\bar{q}$ mass separation.
- $\Rightarrow$ jets resolution $[50, 500]$ GeV better than $\sim 3-4$ % $\sim 30\%/\sqrt{E}$.
- Use optimal sub-detector for jet energy estimation :
  tracker ($\sim 60\%$), ECAL ($\sim 30\%$), HCAL ($\sim 10\%$).
- Separate energy depositions from close-by particles.





Extensive studies have been done with ILD detector option 1 and PandoraPFA algorithm.
At higher jet energy (E$\gtrsim$100 GeV), dominant contribution to resolution is confusion.
See Steven Green, Cambridge University Thesis 2017



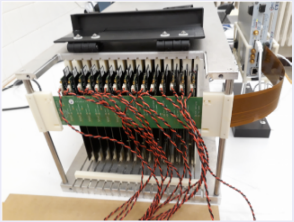
Electromagnetic calorimeters for ILD

See Vincent's talk yesterday

Some CALICE ECAL prototypes

ILD option 1, CEPC baseline

Silicon W-ECAL



- Towards technological prototype
- 15 ($\rightarrow$ 30) layers, W absorber.
- 525 μm thick Si-wafer, 5×5 mm^2 pads read by 12 bit ADC.
- 18×18 cm^2 active area.

ILD option 2, CEPC option

Scintillator Strip W-ECAL

- Towards technological prototype
- 30 layers, 3.5 mm thick W + 1-2 mm thick scintillator.
- strip 5×45 mm^2, alternating orthogonal orientation (effective cell size 5×5 mm^2).
- Multi (1600) Pixel Photon Counter reads 9 strips.

Hadronic calorimeters for ILD

See Vincent's talk yesterday

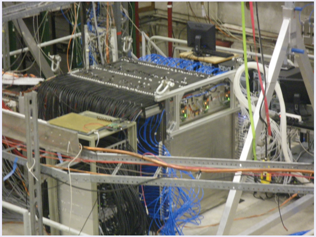
Some CALICE HCAL prototypes

ILD option 1	ILD option 2, CEPC baseline

Scintillator HCAL (AHCAL)

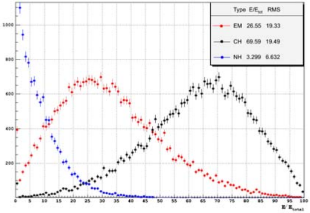
- Towards technological prototype
- 38 layers, Steel or W absorber, 5 mm thick scintillator tiles.
- Tiles size 30×30 mm^2.
- Active area 90×90 cm^2
- Tiles read by 16-bit ADC.

Gaseous SDHCAL



- First complete technological prototype
- 50 layers, steel absorber, 3 mm thick Glass Resistive Plate Chamber
- 1×1 m^2 active area.
- Cell size defined by embedded readout electronic :96×96 pads of 10×10 mm^2 per m^2, 2-bit readout.

PFA energy resolution



Jet component fractions have large fluctuations.

To simplify, assume two components, a charged one, fraction F_{ch}, measured by the tracker with response R_{tr} and a neutral one, fraction $1 - F_{ch}$, measured by the calorimeters with response R_{calo}

$$E_{reco} = R_{tr} F_{ch} E + R_{calo}(1 - F_{ch})E$$

with mean response $\overline{R_{tr}} = 1 + b_{tr}$ and $\overline{R_{calo}} = 1 + b_{calo}$

$$\overline{E_{reco}} = E + E\left(b_{tr}\overline{F_{ch}} + b_{calo}\overline{(1 - F_{ch})}\right)$$

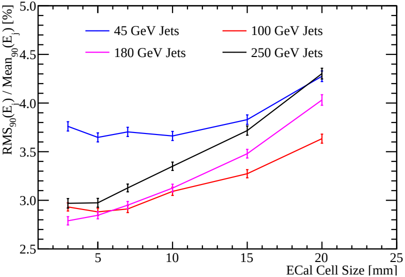
Uncertainties

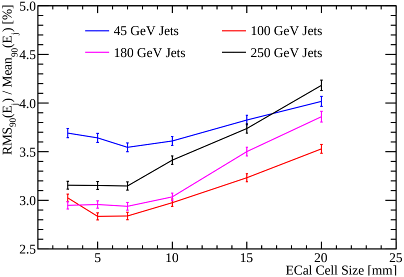
$$\underbrace{Var(E_{reco})}_{\sigma^2_{E_{reco}}} = \underbrace{Var(R_{tr})\overline{F_{ch}}^2 E^2}_{\sigma^2_{E_{tracker}}} + \underbrace{Var(R_{calo})\overline{1 - F_{ch}}^2 E^2}_{\sigma^2_{E_{calo}}} + Var(F_{ch})\left(b_{tr} - b_{calo}\right)^2 E^2$$

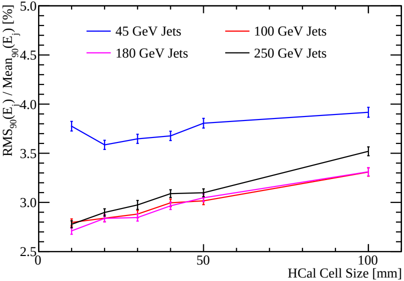
Confusion :

- assign neutral calorimeter hits to charged particles : $b_{calo} \searrow \Rightarrow \overline{E_{reco}} \searrow, \sigma_{E_{reco}} \nearrow$
- assign charged calorimeter hits to neutral particles : $b_{calo} \nearrow \Rightarrow \overline{E_{reco}} \nearrow, \sigma_{E_{reco}} \nearrow$

ILD optimisation studies with PandoraPFA







Jet energy resolution

for varying cell size.

- ↖ Si-W ECAL
- ↑ Scintillator ECAL
- ← Analog HCAL

Jets reconstruction in CEPC

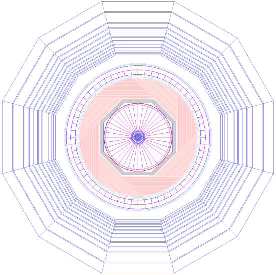
Baseline detectors Si-WECAL and SDHCAL.

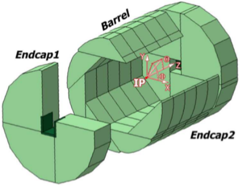
Geometry ILD option 2, "Videau" Gerometry.

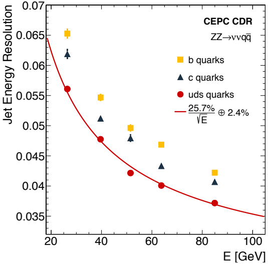
PFA ARBOR

Jet algorithm Durham.

Contrary to PandoraPFA jet studies with ILD, CEPC jet studies uses jet algorithm.







Alternative option for CEPC detector : IDEA

ILC versus FCC/CEPC

Being linear

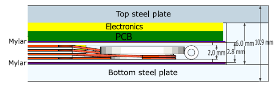
- Lower luminosity but beam polarisation.
- Most of the time idle
  - Time to read data : triggerless
  - Time to cool : embedded electronics with power pulsing $\Longrightarrow$ no cooling, More homogeneous calorimeters

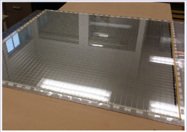
Being circular

- Higher luminosity :
  - higher particle flux
  - Data volume : $\neq$ DAQ/trigger system
- Never idle
  - Data rate : continuous readout, trigger/data paths
  - Add cooling or don't embed electronics

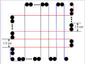
Example of R&D option for circular with SDHCAL

Multigap GRPC





Efficiency = 94%



Cooling issue

- Add water cooling inside absorber.
- Replace part of the absorber with copper plates.
- Power hungry electronics on the side coupled to intertwined strips on PCB.

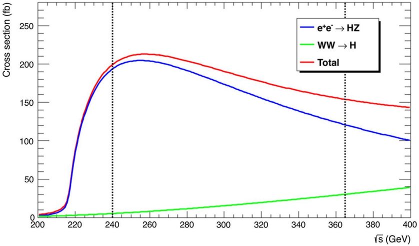
Also add precise time measurements for 5D calorimetry

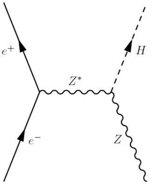
Outlook

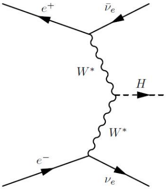
- Jet reconstruction with resolution below 4% has been achieved by ILD above $\sim$ 50 GeV and CEPC above $\sim$ 70 GeV.
- Such resolution requires PFA and high granularity calorimeters.
- ILD PFA studies tends to show that the limiting factor is confusion in HCAL.
- Various R&D strategies can address that limit like reducing cell size or adding precise timing.

Backup

Higgs at $\sqrt{s}$ =240-250 GeV







Higgsstrahlung

- Dominant production mode.
- FCC luminosity 5 ab^{-1}.
- Cross-section $\sim$ 200 fb.
- One million Higgses.

Relax the jet energy resolution ?

Does the higher FCC-luminosity allow to reduce jet energy resolution and not distinguish Z and W di-jets ?
Let's assume, W and Z are not hadronicaly separated.

BR(H→WW)

- ee→ ZH
  - Z→ $f\bar{f}$ with $f = e, \mu, q$: BR=0.766
  - H → WW^*: BR=0.215
    - W → $l\nu$ with $l = e, \mu$: BR=0.20
    - W* → $q\bar{q}'$: BR=0.67
- 10^6 H ⇒∼ 22000 events

$\Rightarrow \sigma_{stat} < 1\%$.

BR(H→ZZ)

- ee→ ZH
  - Z→ $l\bar{l}$ with $l = e, \mu$: BR=0.066
  - H → ZZ^*: BR=0.026
    - Z → $l\bar{l}$ with $l = e, \mu$: BR=0.066
    - Z* → $f\bar{f}$ with $f = e, \mu, q$: BR=0.766
- 10^6 H ⇒∼ 90 events

$\Rightarrow \sigma_{stat} \sim 11\%$.

- Allowing the first Z to decay in quarks:
- 10^6 H ⇒∼ 1000 events

$\Rightarrow \sigma_{stat} \sim 3\%$.

- Reaching percent-level precision on BR(H→ZZ) requires W-Z identification in hadronic decays.
- Extract Higgs total width by combining σ(HZ) and BR(H→ZZ) measurements.

Understanding the jet energy resolution needed

ee→ZH→ZVV full hadronic

- Reconstruct Z in ee, $\mu\mu$ or $q\bar{q}$ and H in 4 jets.
- 10^6 ZH events yield $\sim$ 74000 H→WW and 9800 H→ZZ.
- A 1% contamination of ZZ by WW implies less than 98/74000=1.3×10^{-3} fraction of W events reaching the Z mass.
- $1.3\times10^{-3} \sim 3\sigma$
- $\sigma = \frac{m_Z - m_W}{3} = 3.45GeV \Rightarrow \frac{3.45}{m_W} \sim$ 4.2% mass resolution on hadronic vector bosons.
- In fact, slightly better is needed to take into account both Z and W mass peak width.