Jets measurements requirements for Higgs boson physics at FCC (ee)

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Future collider projects

- Rough historical view: TESLA $\rightarrow$ ILC/CLIC $\rightarrow$ CEPC/FCC -ee
- ILC Energy plan:
  - 91 GeV/ 250 GeV/ 350-400 GeV
  - then 500 GeV $\rightarrow$ 1 TeV
- FCC Energy plan:
  - 91 GeV/ 240 GeV/ 350-365 GeV
  - then FCC-hh

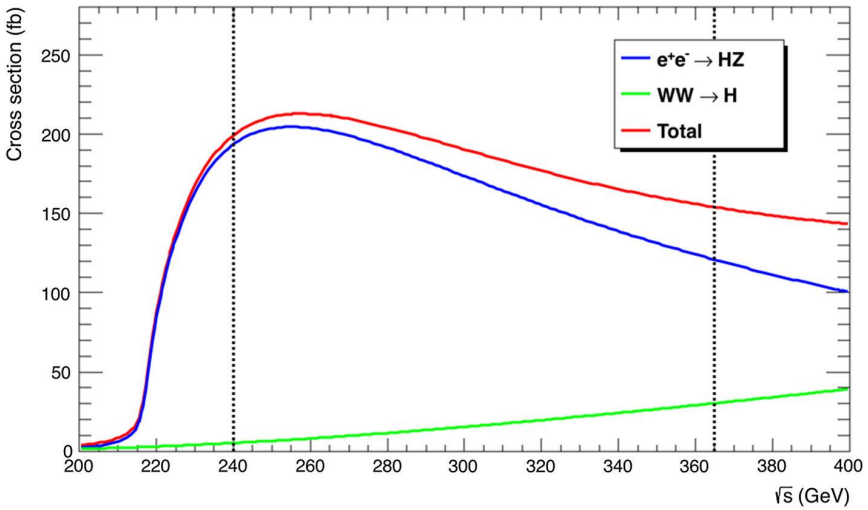
Main differences

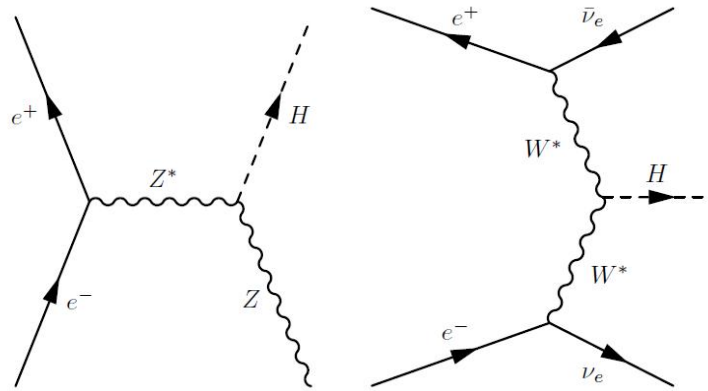
- FCC has higher instantaneous and integrated luminosity.
- ILC has beam polarisation.

Similar physics

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

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





Higgsstrahlung

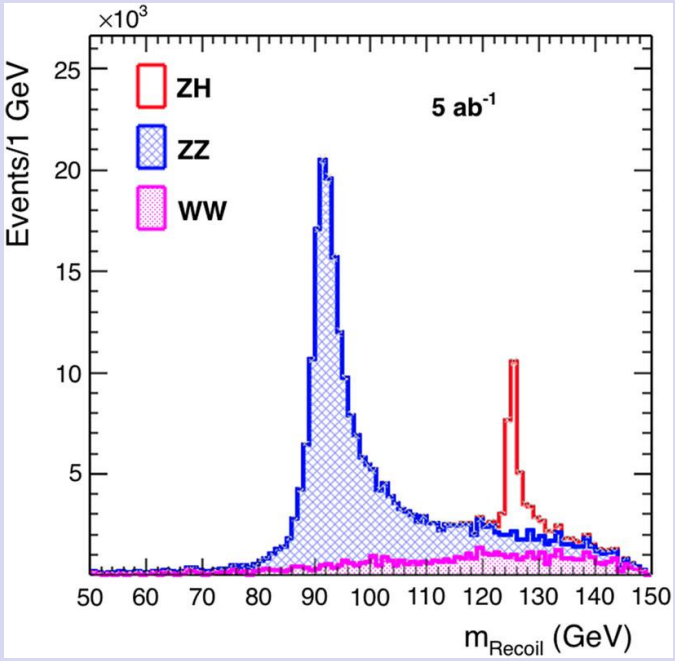
- Dominant production mode.
- FCC luminosity 5 ab^{-1}.
- Cross-section $\sim$ 200 fb.
- One million Higgses.

Higgs mass

$e^+ e^- \rightarrow HZ$

- Z recoil mass
- with $Z \rightarrow e^+ e^-$ or $\mu^+\mu^-$
- golden mode: $Z \rightarrow \mu^+\mu^-$
  - ILC @ 250 GeV: expected δm_H =14 MeV.

FCC-CLD with $Z \rightarrow l^+l^-$



No constraint on jets measurements.

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).

A Chuck Norris challenge

Ability to distinguish gluon jets from light quark jets would open access to BR(H$\rightarrow s\bar{s}$).

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:

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

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
  - $\frac{\Delta E_{jet}}{E_{jet}} \sim \frac{30\%}{\sqrt{E(\mathrm{GeV}}}$

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

⇒ $\sigma_{stat} < 1\%$.

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

⇒ $\sigma_{stat} \sim 11\%$.

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

⇒ $\sigma_{stat} \sim 3\%$.

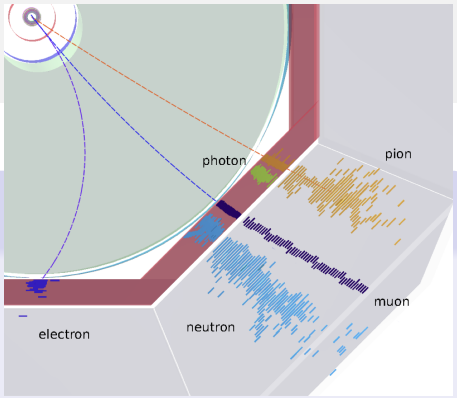
- Reaching percent-level precision on BR(H→ZZ) requires W-Z identification in hadronic decays.
- Extract Higgs total width by combining σ(HZ) and BR(H→ZZ) measurements.

Understanding the jet energy resolution needed

ee→ZH→ZVV full hadronic

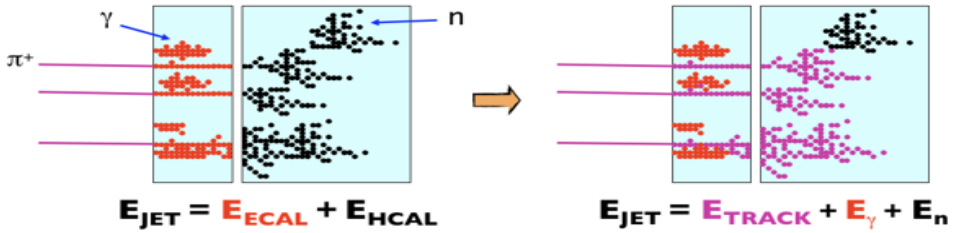
- Reconstruct Z in ee, $\mu\mu$ or $q\bar{q}$ and H in 4 jets.
- 10^6 ZH events yield $\sim$ 74000 H→WW and 9800 H→ZZ.
- A 1% contamination of ZZ by WW implies less than 98/74000=1.3×10^{-3} fraction of W events reaching the Z mass.
- $1.3\times10^{-3} \sim 3\sigma$
- $\sigma = \frac{m_Z - m_W}{3} = 3.45 GeV \Rightarrow \frac{3.45}{m_W} \sim$ 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.

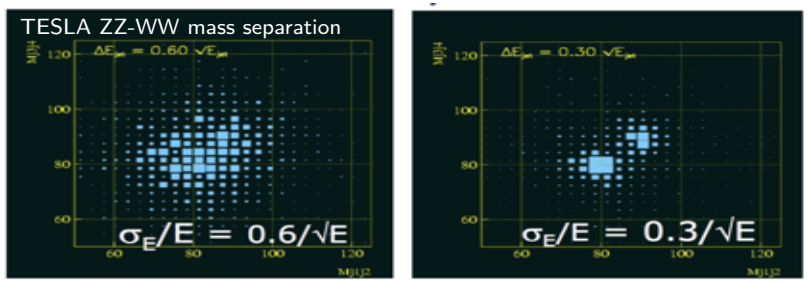
Reaching jet energy resolution

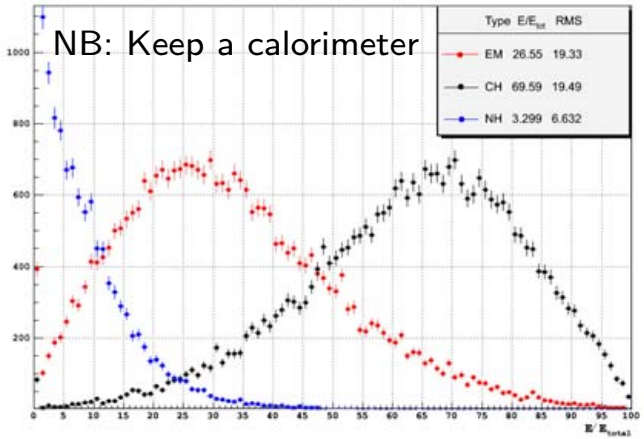


Particle Flow Algorithm (PFA)

- 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.







The WW fusion

WW fusion

- Cross section increases with $\sqrt{s}$
  - More relevant at $\sqrt{s}$ =365 GeV.
  - surpasses ee→ZH at $\sqrt{s}$ ∼500 GeV.
- Helps measuring HWW coupling.
- Higgs total width by combining σ(WW fusion) and BR(H→WW) measurements, independent of HZZ coupling.
- Can test HWW coupling CP properties.

Higgs CP measurements

- in Yukawa coupling: best done from H→ $\tau\tau$ decay with ee→ZH at 250 GeV.
- in HZZ coupling: best done with ee→ZH at 250 GeV.
- in HWW coupling: best done with WW fusion at higher energies.

None of the above brings new constraints on jets measurements.

Summary

- Jets are a key tool to measure Higgs Branching Fraction with precision at the percent level.
  - Wanted: hadronic W-Z separation.
    - Energy resolution below 3-4%.
    - Particle Flow Approach.
    - High granularity calorimeters.
    - Going from 4D (hit position+energy information) to 5D (add timing) calorimeters in CALICE (SDHCAL) and CMS HGCAL. (See V. Boudry's talk).
  - Wanted: excellent jet flavour tagging.
    - Precise vertex reconstruction.
- ZZ Branching fraction is a key input to measure the Higgs width.