# Double Higgs boson production at FCC-he and prospects for measurements of the Higgs boson self-coupling

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December 05, 2014
KRUGER 2014

# Outline

- Motivation
- Double Higgs at the LHC
- LHeC/FCC-he
- Double Higgs production at FCC-he
- Effective Couplings in Higgs sector
- Conclusion

# Motivation: Di-higgs production

- The measurement of the Higgs boson self coupling, $\lambda$, is essential to reconstruct the scalar potential in the SM.

- It would lead to a better understanding of the EWSB mechanism.

- If it is SM Higgs: $\lambda = \frac{m_h^2}{2v^2} \approx 0.13$.

- Mulitple Higgs boson production will provide opportunity to access new Higgs interaction which are totally unconstrained by current LHC data.

- Double Higgs production will give access to multiple Higgs interactions, such as $\lambda$ in addition to $HVV$, $Hff$ and if there is some new physics beyond SM.

- Some of the studies among many:
  - Boudjema, Chopin, Z. Phys. C73 (1996) 8
  - Asakawa et al, PRD 82 (2010) 115002
  - Djouadi et al, Eur. Phys. J. C10 (1999) 45, hep-ph/0001169

# Di-higgs production at the LHC

- Di-higgs producton at the hadron collider can be classified into the following processes according to their strengths:[Baglio et al JHEP 1304 (2013) 151]
  - the gluon fusion: $gg \to hh$,
  - the vector boson fusion : $VV \to hh$, where $V = W, Z$
  - the double Higgs-strahlung: $V \to Vhh$
  - the associated production of the Higgs pair with top pair: $pp \to t\bar{t}hh$
- Owing to the dependence on higher order of electroweak coupling and smaller phase space, the cross section of the above processes are smaller at least by two orders of magnitude compared to the single Higgs production.
- At the LHC, the Higgs pair production cross section for a centre of mass energy of $\sqrt{s} = 14$ TeV:
  - $\sigma(pp \to gg \to hhX) \approx 40$ fb Florian et al, PRL 111 (2013) 201801
  - $\sigma(pp \to (WW, ZZ) \to hhX) \approx 2$ fb Baglio et al, JHEP 1304 (2013) 151
  - $\sigma(pp \to V^* \to VhhX) \approx 0.5$ fb Baglio et al, JHEP 1304 (2013) 151

# $e^{\pm}$ Beam Options: RR and LR

"*To discover all hidden treasures, it is a wise strategy to prepare for all possibilities.*" Electrons at the LHC: a new beginning *by Max Klein, Herwig Schopper* (CERN courier June 2014)
LHeC:

- Ring-Ring: Intense $e^-$ proton beam interact in LHC tunnel → realised with an $e^-$ storage ring and the LHC proton beams, $E_e = 50 - 100$ GeV, $E_p = 7$ TeV.
- Linac-Ring: High energy $e^-$ proton collision can be realised by accelerating $e^{\pm}$ in a linear accelator (linac), $E_e = 60 - 140$ GeV, $E_p = 7$ TeV circulating in LHC (fully decoupled from the LHC operation and upgrades)

Future Circular Collider (FCC-he):

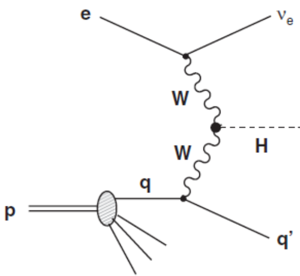
- Ring-Ring: $E_e(max) = 250$ GeV, $E_p = 50$ TeV
- Linac-Ring: Potential reuse of LHeC energy recovery linac (ERL) with $E_e = 60$ GeV and FCC-hh $E_p = 50$ TeV
- For more about project: https: lhec.web.cern.ch LHeC Study Group 2012 J. Phys. G **39** **075001**

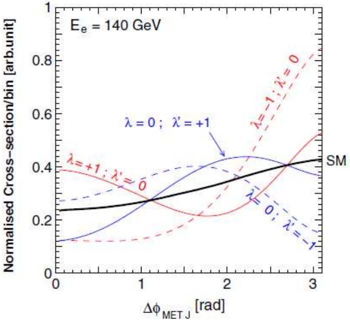
# Physics at LHeC and FCC-he

- Precision QCD and Electroweak Physics
  - Inclusive DIS
  - Determination of PDF
  - Gluon distibution
  - ”c” and ”b” production ... etc
- Physics at high Parton Densities
- New Physics
  - KK gravitons in extra-dimension
  - Leptoquarks and leptogluons
  - Excited leptons and other new heavy leptons
  - New physics in boson-quark interactions
  - Sensitivity to a Higgs-boson

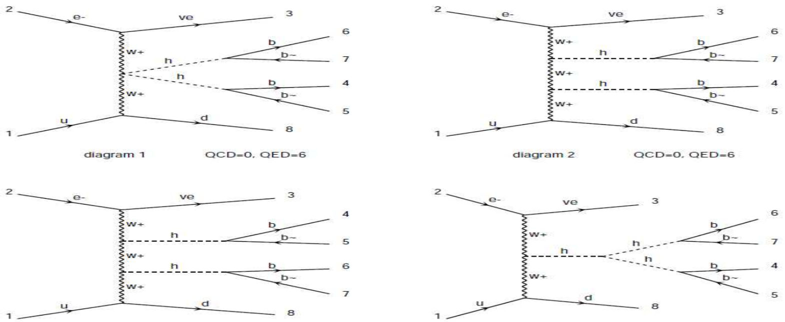
# Higgs at LHeC

- "Higgs boson searches and the $Hb\bar{b}$ coupling at the LHeC", B. Mellado, Tao Han, PRD **82** 016009 (2010)
  - use of forward jet tagging as a means to secure the observation and to significantly improve the purity of the Higgs boson signal in $H \to b\bar{b}$
- "Azimuthal angle probe of Anomalous $HWW$ couplings at a High energy e p Collider" , B. Mellado et al, PRL 109, 261801 (2012)
  - $\Gamma^{SM}_{\mu\nu} = -gM_V g_{\mu\nu}$
  - $\Gamma^{BSM}_{\mu\nu}(p,q) = \frac{g}{M_V}[\lambda(p \cdot q g_{\mu\nu} - p_\nu q_\mu) + \lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma$



# Di-higgs production at $e^-$ p Collider




- CC production channel: $e^-p \to \nu_e hhj, h \to b\bar{b}$
- NC production channel: $e^-p \to e^-hhj, h \to b\bar{b}$
- Advantage: reduced QCD background and no pile-up

# Analysis: Framework

- Event generation:
  - SM CC double Higgs production: $e^- p \to \nu_e hhj$, $h \to b\bar{b}$
  - CC and NC backgrounds ($b\bar{b}b\bar{b}j$, $b\bar{b}jj$, $zzj$, $t\bar{t}j$)

- PYTHIA (modified for ep) [Uta Klein]
  - Fragmentation
  - Hadronization

- Fast detector simulation by Delphes-3.0.11 with modified cards
  - Forward jet rapidity coverage
  - BTagging efficiency and rapidity dependence

- Higgs mass: $m_H = 125$ GeV

- For FCC-he: $E_p = 50$ TeV, $E_e = 60$ GeV

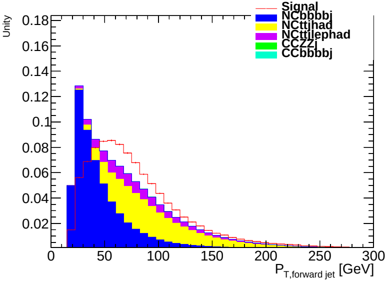
# Analysis: Cross-sections S, B

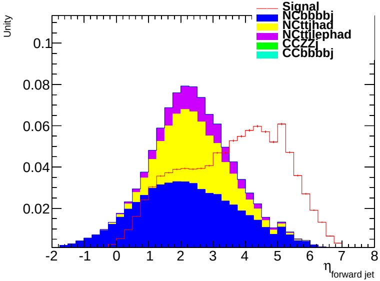
| Process | $\sigma$ | $N_{Total}^{MC-gen}$ |
|---|---|---|
| Sig: | 2.40e-01 | 240000 |
| CCbbbbj: | 8.20e-01 | 480000 |
| CCbbjjj: | 6.50e+03 | 480000 |
| CCzzj($z \to bb$): | 7.40e-01 | 480000 |
| CCttj(hadronic): | 3.30e-01 | 480000 |
| CCttj(lephad): | 1.22e-01 | 480000 |
| NCbbbbj: | 3.60e+03 | 380000 |
| NCbbjjj: | 2.50e+04 | 334084 |
| NCzzj($z \to b\bar{b}$): | 1.65e-02 | 480000 |
| NCttj(hadronic): | 1.40e+02 | 480000 |
| NCttj(lephad): | 4.90e+01 | 480000 |

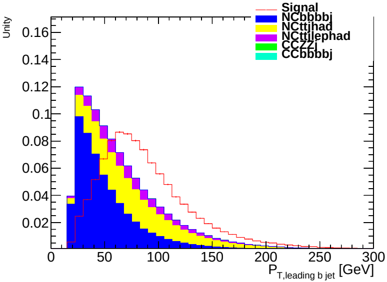
Table : *Cross sections (in fb): $E_e = 60$ GeV, $E_p = 50$ TeV, $j = gu\bar{u}d\bar{d}s\bar{s}c\bar{c}$. Initial cuts: $|\eta| \leq 10$ for jets, leptons and b, $P_T \geq 10$ GeV, $\Delta R_{\min} = 0.4$ for all particles.*

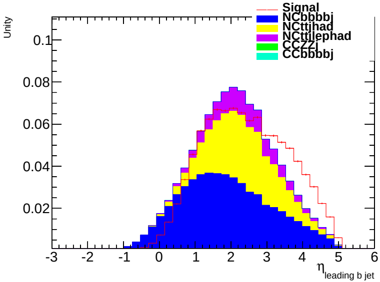
- Cross section ($\sigma$) is after -80% polarization of $e^-$

# Analysis: $p_T, \eta$ Forward Jet, b-Jet

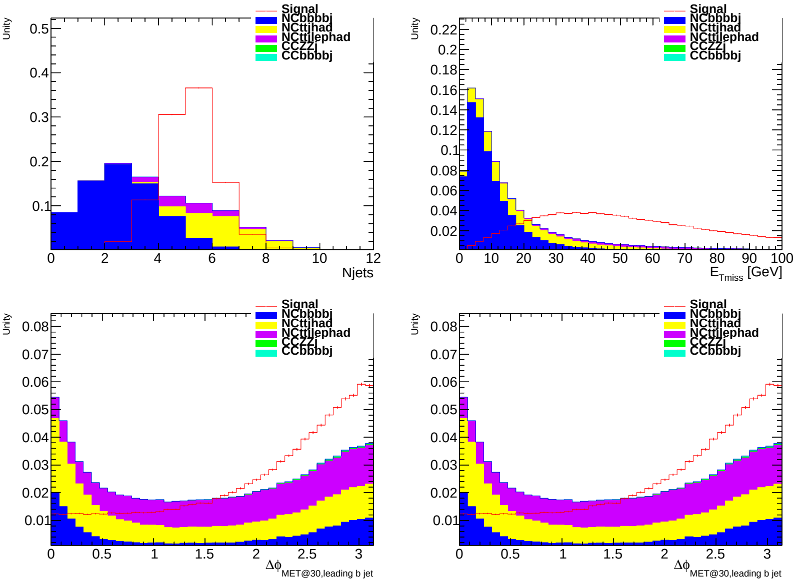


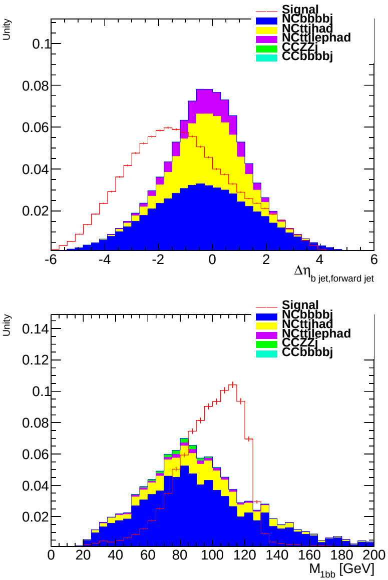



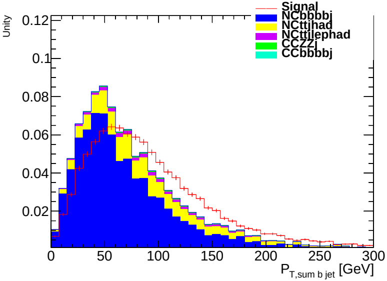
# Analysis: $Njet, E_{T_{miss}}, \Delta\Phi$

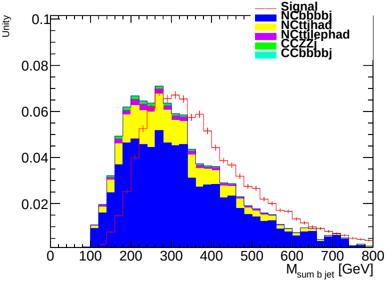


# Analysis: $\Delta\eta$, $M_{ij}$



# Analysis: All b-jet and Cut-flows




Cut-flows optimization:

- $p_T^{jet} > 20$ GeV, $MET > 30$ GeV
- Choosing 4-b and 1-jet (largest pt excluding the 4-b $\rightarrow$ forward-jet)
- $\eta_{forward-jet} > 3.8$
- $MET > 30$ GeV and $\Delta\Phi_{MET,leadingjet} > 0.4$, $\Delta\Phi_{MET,subleadingjet} > 0.4$
- Restrict tow mass regions reconstructed from 4-bs within 90-125 GeV
- Lepton rejection $p_T^{e^-} > 10$ GeV
- Choosing invariant mass of all 4b-jet $> 260$ GeV

# Analysis: Cut-Flows (Events in MC)

| Samples | signal | ccbbbbj | ccbbjjj | ncbbbbj | ncbbjjj | ccttjhad | ccttjlephad |
|---|---|---|---|---|---|---|---|
| 01 INIT | 240000 | 480000 | 480000 | 456493 | 334084 | 480000 | 480000 |
| 02 4b1j | 25614 | 8491 | 251 | 3186 | 136 | 2547 | 1340 |
| 03 forward3.8 | 18520 | 807 | 28 | 606 | 34 | 298 | 159 |
| 04 METdphib1b2 | 12769 | 714 | 22 | 70 | 4 | 257 | 140 |
| 05 M1M2 | 4531 | 42 | 0 | 4 | 0 | 20 | 8 |
| 06 LepRej | 4531 | 42 | 0 | 0 | 0 | 20 | 7 |
| 07 M4b | 4190 | 21 | 0 | 0 | 0 | 15 | 5 |

| ncttjhad | ncttjlephad | cczzj | nczzj | Total bkg | $S/\sqrt{(S+B)}$ |
|---|---|---|---|---|---|
| 480000 | 480000 | 480000 | 480000 | 4.63058e+06 | 108.748 |
| 2584 | 1230 | 42718 | 35929 | 98412 | 72.7312 |
| 333 | 214 | 25629 | 7770 | 35878 | 79.4053 |
| 90 | 140 | 20335 | 1594 | 23366 | 67.1727 |
| 11 | 11 | 641 | 63 | 800 | 62.0568 |
| 2 | 1 | 641 | 13 | 726 | 62.4921 |
| 0 | 0 | 322 | 7 | 370 | 62.0485 |

- Low statistics in some background data
- Still data generation is going on

# Analysis: Cut-Flows (Weights in MC at L = 10 $ab^{-1}$)

| Samples | signal | ccbbbbj | ccbbjjj | ncbbbbj |
|---|---|---|---|---|
| 01 INIT | 2.36e+03 ± 4.82 | 8.19e+03 ± 11.8 | 6.44e+06 ± 9.3e+03 | 4.27e+06 ± 6.32e+03 |
| 02 4b1j | 252 ± 1.58 | 145 ± 1.57 | 3.37e+03 ± 213 | 2.98e+04 ± 528 |
| 03 forward3.8 | 182 ± 1.34 | 13.8 ± 0.485 | 376 ± 71 | 5.66e+03 ± 230 |
| 04 METdphib1b2 | 126 ± 1.11 | 12.2 ± 0.456 | 295 ± 63 | 654 ± 78.2 |
| 05 M1M2 | 44.6 ± 0.663 | 0.716 ± 0.111 | 0 ± 0 | 37.4 ± 18.7 |
| 06 LepRej | 44.6 ± 0.663 | 0.716 ± 0.111 | 0 ± 0 | 0 ± 0 |
| 07 M4b | 41.3 ± 0.637 | 0.358 ± 0.0782 | 0 ± 0 | 0 ± 0 |

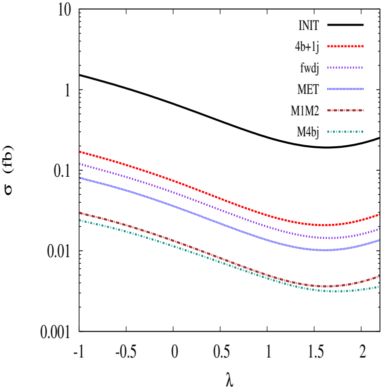
| ncbbjjj | ccttjhad | ccttjlephad | ncttjhad | ncttjlephad |
|---|---|---|---|---|
| 2.46e+08 ± 4.26e+05 | 3.26e+03 ± 4.71 | 1.22e+03 ± 1.77 | 1.37e+06 ± 1.97e+03 | 4.86e+05 ± 701 |
| 1e+05 ± 8.59e+03 | 17.3 ± 0.343 | 3.42 ± 0.0933 | 7.36e+03 ± 145 | 1.24e+03 ± 35.5 |
| 2.5e+04 ± 4.29e+03 | 2.02 ± 0.117 | 0.405 ± 0.0322 | 948 ± 52 | 217 ± 14.8 |
| 2.95e+03 ± 1.47e+03 | 1.75 ± 0.109 | 0.357 ± 0.0302 | 256 ± 27 | 142 ± 12 |
| 0 ± 0 | 0.136 ± 0.0304 | 0.0204 ± 0.00721 | 31.3 ± 9.45 | 11.1 ± 3.36 |
| 0 ± 0 | 0.136 ± 0.0304 | 0.0179 ± 0.00675 | 5.7 ± 4.03 | 1.01 ± 1.01 |
| 0 ± 0 | 0.102 ± 0.0263 | 0.0128 ± 0.0057 | 0 ± 0 | 0 ± 0 |

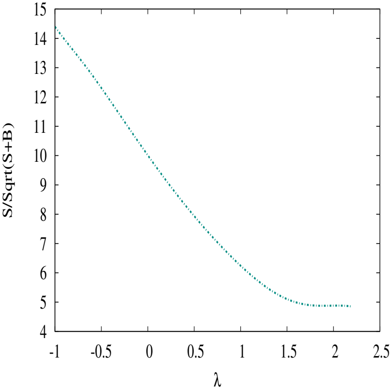
| cczzj | nczzj | Total bkg | $S/\sqrt{(S+B)}$ |
|---|---|---|---|
| 7.36e+03 ± 10.6 | 165 ± 0.238 | 2.59e+08 ± 4.26e+05 | 0.147 |
| 655 ± 3.17 | 12.4 ± 0.0652 | 1.43e+05 ± 8.61e+03 | 0.667 |
| 393 ± 2.46 | 2.67 ± 0.0303 | 3.27e+04 ± 4.3e+03 | 1.01 |
| 312 ± 2.19 | 0.548 ± 0.0137 | 4.62e+03 ± 1.48e+03 | 1.83 |
| 9.83 ± 0.388 | 0.0217 ± 0.00273 | 90.6 ± 21.2 | 3.84 |
| 9.83 ± 0.388 | 0.00447 ± 0.00124 | 17.4 ± 4.17 | 5.66 |
| 4.94 ± 0.275 | 0.00241 ± 0.000909 | 5.42 ± 0.287 | 6.04 |

- Photo-production background further lower the significance a bit !

# Effective Couplings in Higgs-sector:

- $V = \frac{1}{2}M_h^2 h^2 + \lambda\lambda_{SM} v h^3 + \frac{\bar{\lambda}}{4} h^4$, where $\lambda_{SM} = \bar{\lambda} = M_h^2/2v^2 \approx 0.13$



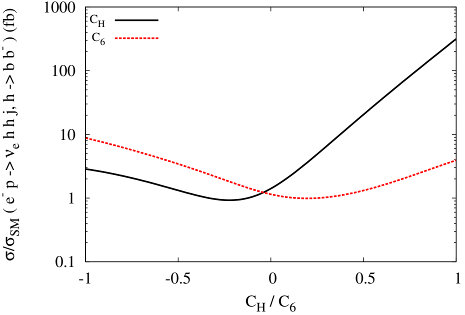



# Effective 6D Couplings in Higgs-sector:

The effective *hhh* and *WWh* vertices ($C_H$ and $C_6$ are coefficients of six dimension operators) which appear in our signal process are as follows (from here $\lambda \equiv \lambda_{SM}$):

$$g_{hhh} = -6i\lambda v - iv\left[15\lambda C_6 + 2\frac{C_H}{v^2}(p_1 \cdot p_2 + p_2 \cdot p_3 + p_3 \cdot p_1 - \frac{9}{2}\lambda v^2)\right] \quad (1)$$

$$g_{hW^-W^+} = iv\frac{e^2}{2s_W^2}\left[\left\{1 - \frac{C_H}{2} + \frac{C_W}{m_W^2}(v^2\frac{e^2}{2s_W^2} + p_2^2 + p_3^2) + \frac{C_{HW}}{m_W^2}(p_2+p_3)^2\right\}\eta^{\mu_2\mu_3} - \frac{C_W}{m_W^2}(p_2^{\mu_2}p_2^{\mu_3} + p_3^{\mu_2}p_3^{\mu_3}) + \frac{C_{HW}}{m_W^2}(p_1^{\mu_2}p_2^{\mu_3} + p_1^{\mu_3}p_3^{\mu_2})\right] \quad (2)$$



# Conclusion:

- Motivation for double higgs production to get $HHH$ coupling
- Possibilities in different colliders
- Feasibility studies at FCC-he (signal vs background)
- Effective couplings
- Further we look for other decay modes $h \to c\bar{c}, \mu^+\mu^-, \tau^+\tau^-$
- Thank You !!

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