Exotic Higgs Decay at the Large Hadron Electron Collider

Chen Zhang (张宸) (Peking University)

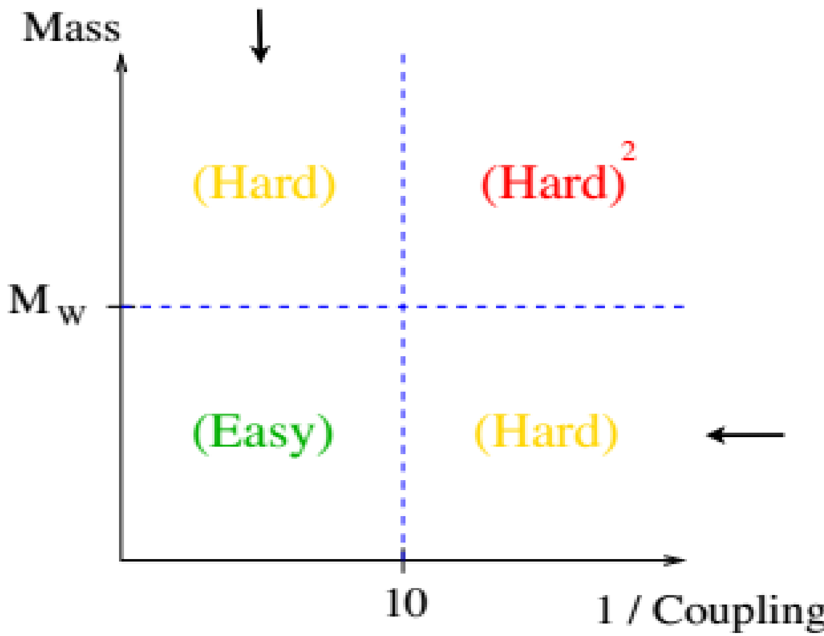
2nd CLHCP @Peking University

Dec 17th, 2016

Based on
Phys. Rev. D 94, 011702 (2016) in collaboration with Yi-Lei Tang and Shou-hua Zhu
arXiv: 1608.08458 in collaboration with Shang Liu, Yi-Lei Tang and Shou-hua Zhu

Motivation for Exotic Higgs Decay Searches

- Two major possibilities for NP to evade current searches (picture from D. E. Morrissey)



Exotic Higgs Decays

Strategy of Exotic Higgs Decay Searches: Collider Type Considerations

- **(HL-)LHC**
  - Large signal cross sections
  - Large backgrounds
  - Large pile-up
    - Higher thresholds needed to control systematics
    - Significant impact on the performance of objects like jet and MET

Significant impact on exotic Higgs decay searches

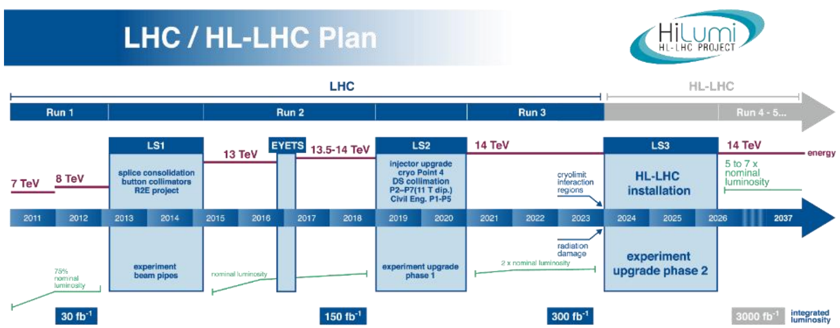
- **Electron-positron collider**
  - Small backgrounds
  - Pile-up negligible
  - Small signal cross sections
  - As long as the Br is not too small, e+e- machine will provide an ideal environment for probing exotic Higgs decay.

Electron-Positron colliders (e.g. CEPC, FCC-ee) are ideal for studying most of the exotic Higgs decays.

However, what if such lepton colliders are not available before the end of HL-LHC? Does there exist any other option?

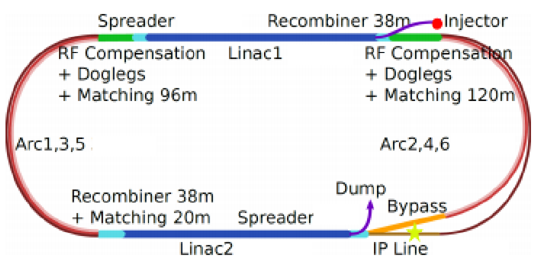
What is the LHeC?

- The LHeC is a proposed electron-proton collider expected to run **synchronously** with the HL-LHC.



60 GeV acceleration with Recirculating Linacs:

Animation from A. Bogacz (JLab) @ ERL'15



➔ Three accelerating passes through each of the two 10 GeV linacs (efficient use of LINAC installation!)

➔ 60 GeV beam energy

What is the LHeC?

- Proposed LHeC parameters:
  - 7 TeV proton beam (from HL-LHC)
  - 60 GeV electron beam (with -80%~-90% polarization) (limited by power consumption)
  - Luminosity as high as 1 ab^{-1}
  - Detector (including tracker) supposed to have very large pseudorapidity coverage

~200000 Higgs bosons with much smaller backgrounds compared to the HL-LHC!

O. Bruening, LHeC Accelerator Studies and Considerations, talk at LHeC 2015 Workshop

A. Gaddi, LHeC Detector: Preliminary Engineering Study, talk at LHeC 2015 Workshop

What is the LHeC:

Relevance of the LHeC for Higgs Physics

- Reducing PDF & α_S uncertainties for (HL-)LHC Higgs signal strength measurement
- Probing bottom Yukawa at 1~2% precision and charm Yukawa at O(10%) precision

  ECFA LHC workshop proceedings 1990; T. Han et al., PRD 82, 016009 (2010)

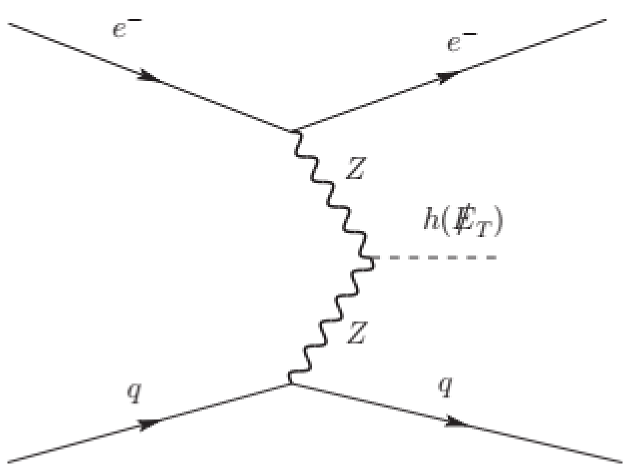
  LHeC CDR, JPG 39, 075001 (2012);

  U. Klein, talk at LHeC workshop 2015; M. Tanaka, talk at LHeC workshop 2015.

- Exotic Higgs decays
  - Invisible Higgs decay
  - Higgs to 4b

LHeC Invisible Higgs Decay

Y. L. Tang, **CZ**, S. Zhu, Phys. Rev. D 94, 011702 (2016)



- Well-motivated decay channel for Higgs physics
- VBF or ZH production needed at the HL-LHC
- LHeC signal: NC channel
- Backgrounds:
  - Wje
  - Wjν
  - Zje
  - Other (top, PHP, e+multijet, etc.)

LHeC Invisible Higgs Decay

(parton level analysis)

- Beam
  - 7 TeV proton + 60 GeV electron
  - electron is -90% polarized
- Energy smearing

$$\frac{\sigma}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta, \alpha = \begin{cases} 0.6\sqrt{GeV} \text{ for jets} \\ 0.05\sqrt{GeV} \text{ for leptons} \end{cases}, \beta = \begin{cases} 0.03 \text{ for jets} \\ 0.0055 \text{ for leptons} \end{cases}$$

- Basic cuts

$$p_{Tj} > 20 \text{ GeV}, |\eta_j| < 5.0,$$
$$p_{Tl} > 20 \text{ GeV}, |\eta_l| < 5.0, \Delta R_{jl} > 0.4$$

LV pT threshold: 5 GeV for muon, 7 GeV for electron and 20 GeV for visible hadronic tau.
LV eta coverage ~ 5.0
Hadronic tau tagging efficiency: 70%
Tau decay treated in collinear approximation.
Assumptions on visible tau momentum:
Leptonic decaying tau: 1/3
Hadronic decaying tau: 1/2

- Cut flow after basic cuts

Convention: Proton direction corresponds to positive pseudorapidity.

(1) $\not{E}_T > 70$ GeV.
(2) Missing energy isolation: $I > 1$ rad.
(3) Pseudorapidity gap of the jet and the electron satisfies $\eta_j - \eta_e > 3.0$.
(4) The azimuthal angle difference of the electron and the jet satisfies $\Delta\phi_{ej} \equiv |\phi_j - \phi_e| < 1.2$.
(5) The pseudorapidity of the electron satisfies $\eta_e \in [-1.2, 0.6]$.
(6) Inelasticity cut: the inelasticity variable y is defined as $y = \frac{p_1 \cdot (k_1 - k_2)}{p_1 \cdot k_1}$, where p_1 is the 4-momenta of the initial proton, k_1 is the 4-momenta of the initial electron, and k_2 is the 4-momenta of the outgoing electron. Then we require $y \in [0.06, 0.5]$.
(7) Lepton veto: additional electron, muon, or tagged hadronic τ are vetoed.

Treatment of tau decay checked with TauDecay package.
(K. Hagiwara, T. Li, K. Mawatari and J. Nakamura, 1212.6247)

Event generation and analysis tools: FeynRules, MG5_aMC@NLO, MadAnalysis
PDF: NNPDF2.3 LO

LHeC Invisible Higgs Decay: Results

Statistical Significance

$$Z = \sqrt{2((S+B)\ln(1+S/B)-S)}$$

Signal (100% invisible)~1.8fb

Total background~2.7fb

Br(h->inv)=6%@2σ level with 1 ab^{-1}
(Parton level, assuming κ_V=1.0)

$$C^2_{\mathrm{MET}} = \kappa_V^2 \times \mathrm{Br}(\mathrm{h} \to invisible)$$

Cross Section (fb)	Basic Cuts	$\not{E}_T > 70$ GeV	$I > 1$	$\eta_j - \eta_e > 3.0$	$\Delta\phi_{ej} < 1.2$	$\eta_e \in [-1.2, 0.6]$	$y \in [0.06, 0.5]$	Lepton Veto
Signal ($C^2_{\mathrm{MET}} = 1$)	16.1	8.80	8.23	4.68	2.37	2.16	1.77	1.77
Wje	816	158	143	51.7	13.9	11.3	9.13	1.96
$Wj\nu$	192	102	101	5.68	2.36	1.33	0.387	0.387
Zje	42.7	13.8	12.1	1.64	0.683	0.464	0.326	0.326

TABLE I: The cross section (in unit of fb) of the signal and major backgrounds after application of each cut in the corresponding column. Other backgrounds contribute less than 0.1 fb in total after all cuts and are not displayed in the table.

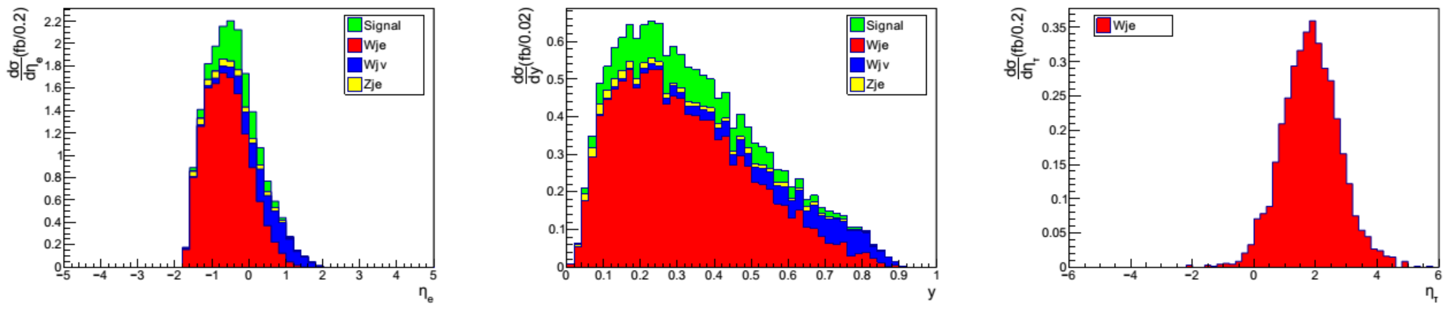


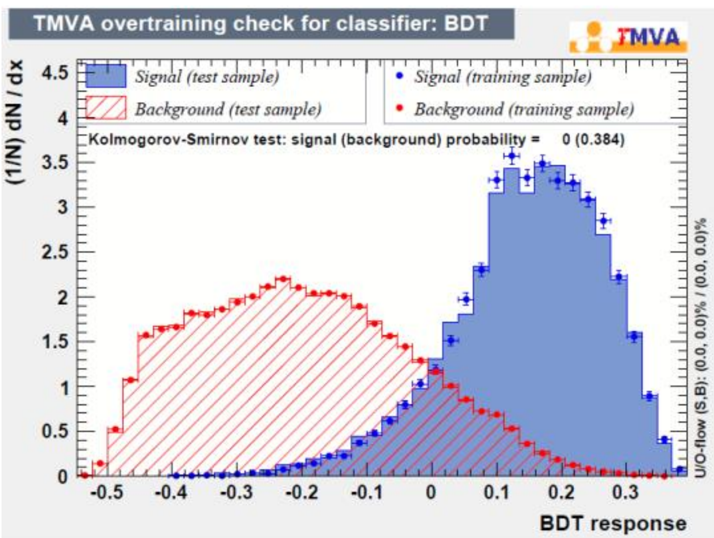
FIG. 2: Left: η_e distribution of the signal and major backgrounds just before the η_e cut. Middle: y distribution of the signal and major backgrounds just before the y cut. Right: τ lepton pseudorapidity distribution of the $Wje(W \to \tau\nu)$ background just before the lepton veto.

LHeC Invisible Higgs Decay: Results

Detector level study with MVA

- Probing 4.6% Br @ 2σ with 1 ab^{-1}.

  (Preliminary results by S. Kawaguchi and M. Kuze, Tokyo Institute of Technology)

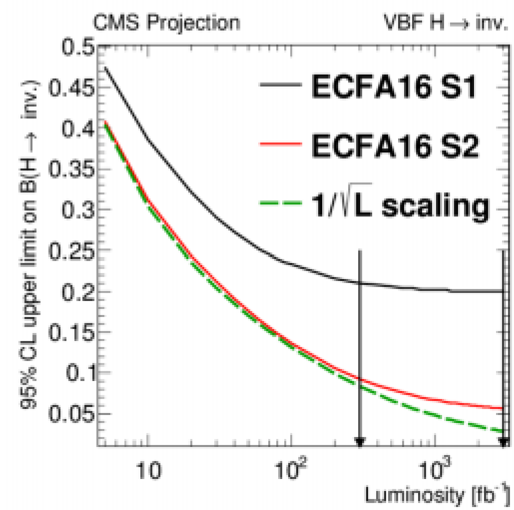


Comparison with the HL-LHC

ZH Channel (ATLAS)

BR($H \to$inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)

VBF Channel projection (CMS): probing 5% Br @ 95%CL with very optimistic assumptions on systematics.



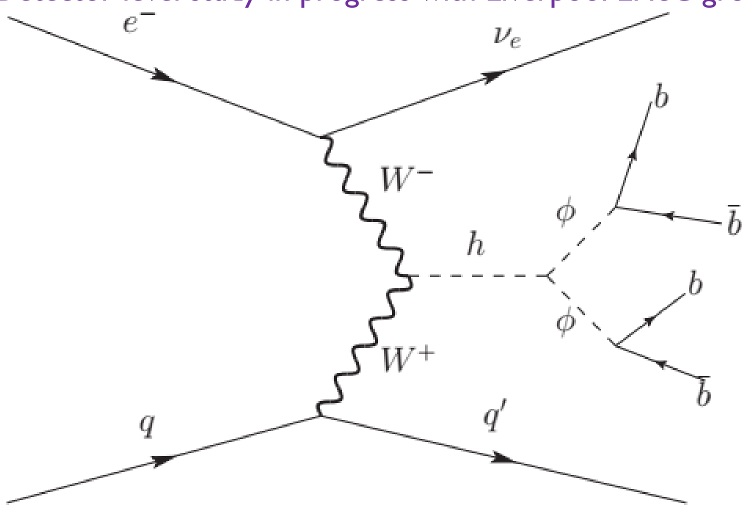
LHeC Higgs to 4b

K. Cheung et al., PRL 99, 031801 (2007)
M. Carena et al., JHEP 0804, 092 (2008)
D. E. Kaplan et al., PRD 83, 115004 (2011)
D. E. Kaplan et al., PLB701, 70 (2011)
J. Cao et al., JHEP 1311, 018 (2013)
D. Curtin et al., PRD 90, 075004 (2014)
ATLAS, 1606.08391

ϕ: a spin-0 particle from new physics.

$$eq \to \nu_e h q' \to \nu_e \phi\phi q' \to \nu_e b\bar{b}b\bar{b}q'$$

Shang Liu, Yi-Lei Tang, **CZ** and Shou-hua Zhu, 1608.08458
Detector level study in progress with Liverpool LHeC group.



$$C_{4b}^2 = \kappa_V^2 \times \mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}^2(\phi \to b\bar{b})$$

- Well motivated signature in extended Higgs sector.
- Difficult to probe at hadron colliders.
- LHeC signal: here using CC channel.
- Backgrounds: CC multijet, CC t/h/W/Z+jets, PHP multijet.
- PHP backgrounds assumed to be negligible after MET requirements and electron tagging.
- Current analysis is done at parton level.

ϕ mass range targeted in this study: [20,60]GeV, scanned in 1 GeV step.

LHeC Higgs to 4b: Event Selection

- Jet energy smearing $\frac{\sigma_E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta \quad \alpha = 0.45\ \mathrm{GeV}^{1/2}, \beta = 0.03$
- Basic cuts: requiring at least 5 jets satisfying $p_{Tj} > 20\ \mathrm{GeV}, |\eta_j| < 5.0, \Delta R_{jj} > 0.4$

(Electron tagged events are excluded. Charged leptons are vetoed.)

- MET: (E_0=40GeV as default) $\not{E}_T > E_0$
- 4b-tagging At least 4 b-tagged jets in $|\eta| < 5.0$

$$\text{(A)}\ \epsilon_b = 70\%, \epsilon_c = 10\%, \epsilon_{g,u,d,s} = 1\%$$

$$\text{(B)}\ \epsilon_b = 70\%, \epsilon_c = 20\%, \epsilon_{g,u,d,s} = 1\%$$

$$\text{(C)}\ \epsilon_b = 60\%, \epsilon_c = 10\%, \epsilon_{g,u,d,s} = 1\%$$

$$\text{(D)}\ \epsilon_b = 60\%, \epsilon_c = 20\%, \epsilon_{g,u,d,s} = 1\%$$

- 4b invariant mass window: $|m_{4b} - m_h| < 20\ \mathrm{GeV}$
- 2b invariant mass window: for the "correct" grouping $|m_{2b,i} - m_\phi| < 10\ \mathrm{GeV},\ i = 1, 2$

LHeC Higgs to 4b: Results

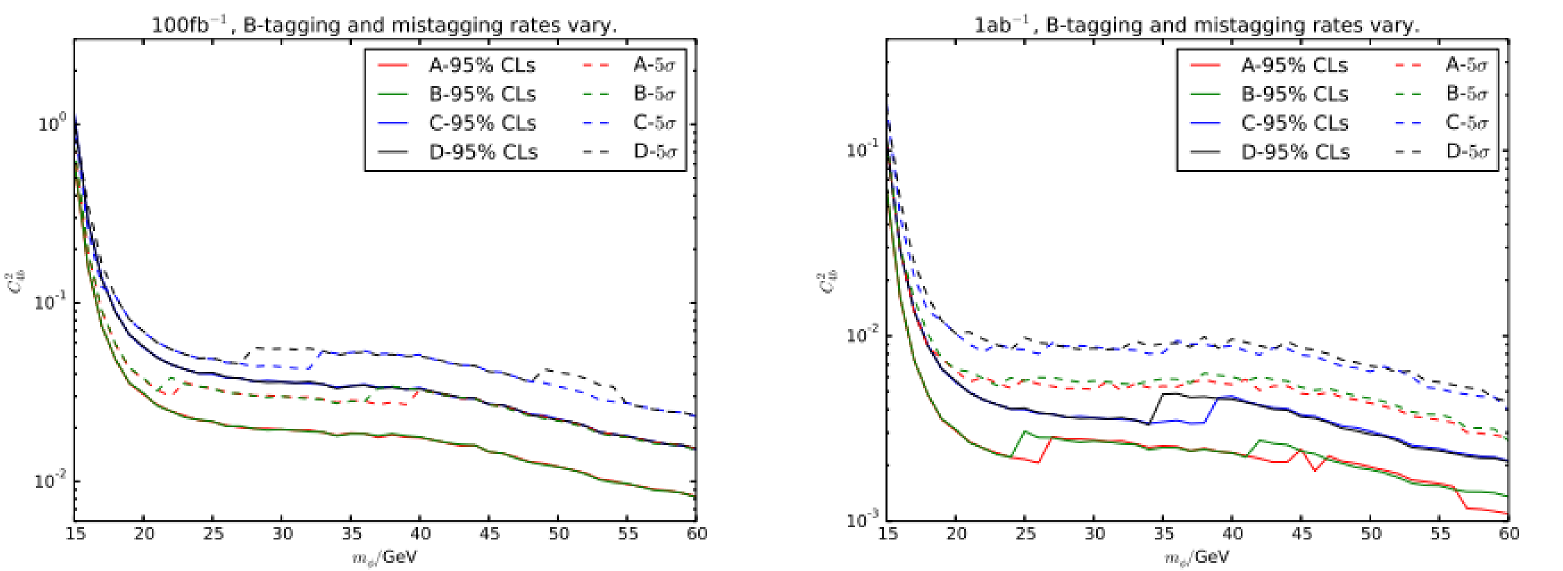
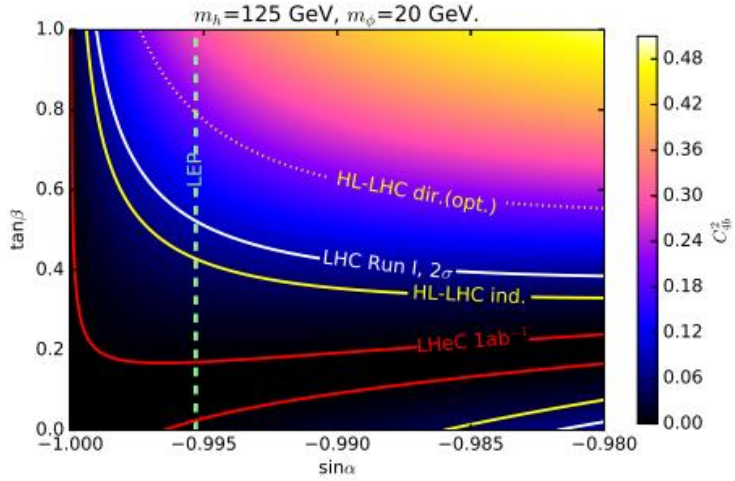
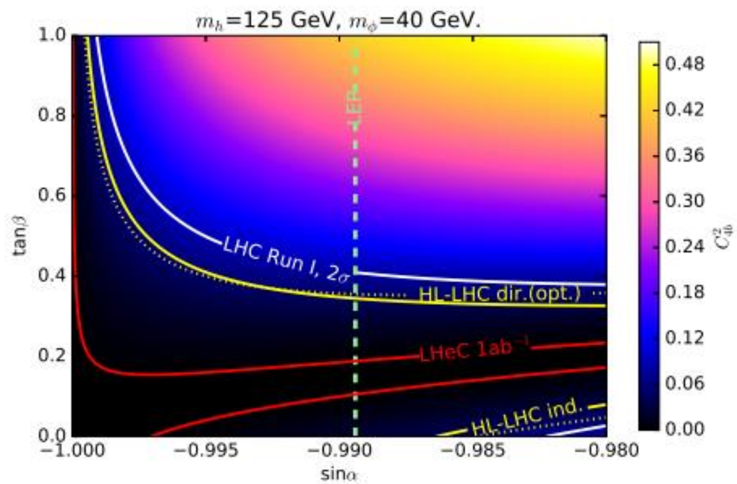


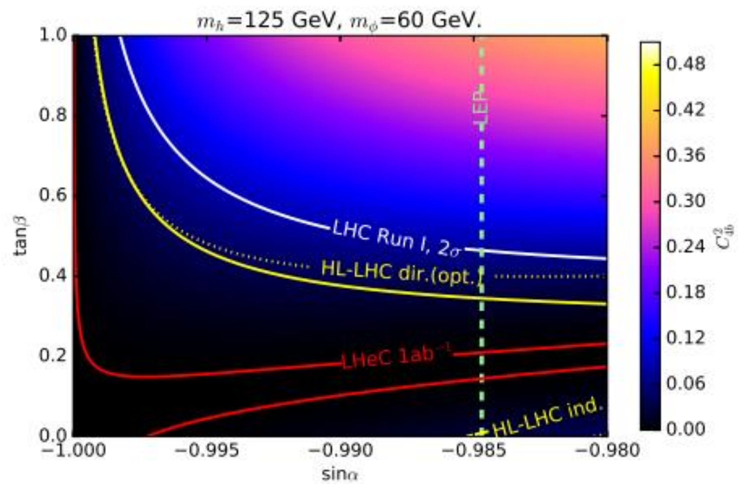
FIG. 3: Expected 95% CLs exclusion limit (solid line) and 5σ discovery reach (dashed line) in the (C^2_{4b}, m_ϕ) plane at the LHeC. Left: 100 fb^{-1} luminosity. Right: 1 ab^{-1} luminosity. Different color corresponds to different $b-$tagging scenarios $\boxed{A}$ $\boxed{B}$ $\boxed{C}$ $\boxed{D}$ (see the text and legend). $E_0 = 40$ GeV is assumed.

95% CLs upper limit of C_{4b}^2 for 20, 40, 60 GeV phi mass with 1 ab^{-1}: 0.3%, 0.2%, 0.1% (E_0=40GeV)
For E_0=60GeV, corresponding limits change to: 0.5%, 0.4%, 0.2%

Interpretation (SM+real singlet scalar)







Conclusion and Discussion

- Exotic Higgs decays are well-motivated BSM signatures which are worth serious investigations.
- The LHeC is a proposed electron-proton collider expected to run synchronously with the HL-LHC, with luminosity up to 1 ab^{-1}. The default electron beam is 60 GeV, possibly with high polarization.
- If a lepton collider with sufficient mass of energy is not available before the end of the HL-LHC, then it would be important to consider DIS as an additional probe of exotic Higgs decays which may yield better or comparable sensitivities due to cleaner environment.
- It is worthwhile to also consider other exotic Higgs decay searches at the LHeC, especially those which suffer from large backgrounds, pile-up effects and systematic uncertainties. For example, Higgs to bb+MET.

Backup

Cut Flow Tables for LHeC Higgs to 4b Study

Cross Section (fb)	Signal	Total Background	CC Multijet	CC h+jets	CC t+jets	CC Z+jets	CC W+jets
Basic cuts (5)	7.67	–	353	0.81	119	15.0	26.7
$\not{E}_T > E_0$ (6)	4.33	–	256	0.46	66.8	12.8	21.2
$b-$tagging (7)	1.06	–	8.6E-03	3.3E-03	8.1E-02	1.0E-02	2.2E-03
$4b$ mass window (8)	1.04	–	1.3E-03	1.7E-03	3.2E-03	2.4E-04	5.7E-05
$2b$ mass window (9)	0.97 (0.59)	3.5E-04 (2.4E-04)	1.3E-04	6.9E-05	1.4E-04	5.6E-06	1.4E-06

TABLE I: The cross section (in unit of fb) of the signal and major backgrounds after application of each cut in the corresponding row. Lepton veto and electron anti-tagging is implicit in basic cuts. Signal corresponds to $C_{4b}^2 = 1, m_\phi = 20$ GeV. Here we assume $b-$tagging performance scenario (A) and a $b-$tagging pseudorapidity coverage $|\eta| < 5.0$. $E_0 = 40$ GeV is assumed except that in the last row for the signal and total background we show in parentheses the values corresponding to $E_0 = 60$ GeV.

Cross Section (fb)	Signal	Total Background	CC Multijet	CC h+jets	CC t+jets	CC Z+jets	CC W+jets
Basic cuts (5)	11.5	–	359	0.81	118	14.9	26.6
$\not{E}_T > E_0$ (6)	7.52	–	260	0.46	66.7	12.7	21.1
$b-$tagging (7)	1.85	–	8.5E-03	3.3E-03	8.1E-02	1.0E-02	2.2E-03
$4b$ mass window (8)	1.81	–	1.3E-03	1.7E-03	3.2E-03	2.5E-04	6.0E-05
$2b$ mass window (9)	1.70 (1.12)	1.4E-03 (9.9E-04)	2.6E-04	4.2E-04	6.3E-04	5.4E-05	1.0E-05

TABLE II: The cross section (in unit of fb) of the signal and major backgrounds after application of each cut in the corresponding row. Lepton veto and electron anti-tagging is implicit in basic cuts. Signal corresponds to $C_{4b}^2 = 1, m_\phi = 40$ GeV. Here we assume $b-$tagging performance scenario (A) and a $b-$tagging pseudorapidity coverage $|\eta| < 5.0$. $E_0 = 40$ GeV is assumed except that in the last row for the signal and total background we show in parentheses the values corresponding to $E_0 = 60$ GeV.

Cross Section (fb)	Signal	Total Background	CC Multijet	CC h+jets	CC t+jets	CC Z+jets	CC W+jets
Basic cuts (5)	29.5	–	358	0.81	119	14.9	26.6
$\not{E}_T > E_0$ (6)	17.4	–	257	0.46	66.8	12.7	21.1
$b-$tagging (7)	4.28	–	8.6E-03	3.2E-03	8.1E-02	1.0E-02	2.2E-03
$4b$ mass window (8)	4.18	–	1.3E-03	1.7E-03	3.3E-03	2.6E-04	6.4E-05
$2b$ mass window (9)	3.63 (2.28)	1.4E-03 (9.2E-04)	3.2E-04	2.9E-04	7.4E-04	3.9E-05	1.6E-05

TABLE III: The cross section (in unit of fb) of the signal and major backgrounds after application of each cut in the corresponding row. Lepton veto and electron anti-tagging is implicit in basic cuts. Signal corresponds to $C_{4b}^2 = 1, m_\phi = 60$ GeV. Here we assume $b-$tagging performance scenario (A) and a $b-$tagging pseudorapidity coverage $|\eta| < 5.0$. $E_0 = 40$ GeV is assumed except that in the last row for the signal and total background we show in parentheses the values corresponding to $E_0 = 60$ GeV.

Statistical Treatment (LHeC Higgs to 4b)

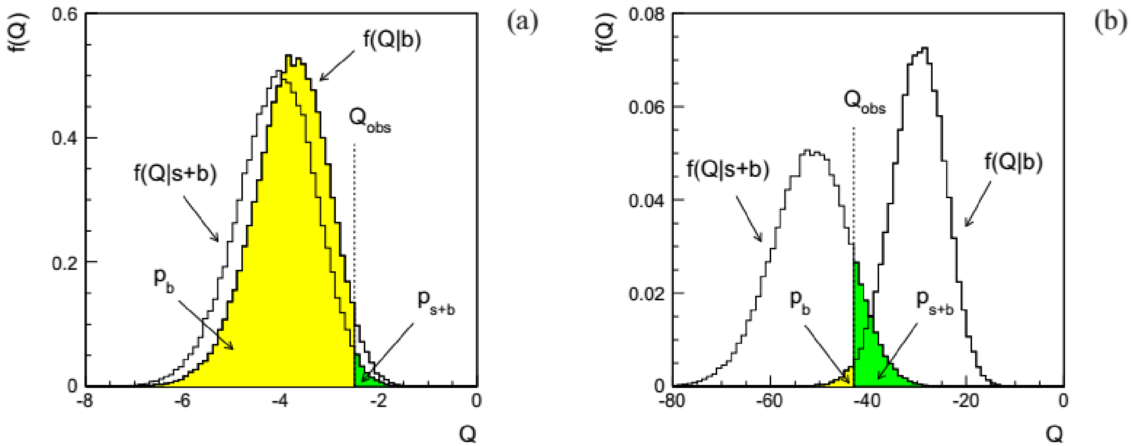


Fig. 8 (a) Distributions of the statistic Q indicating low sensitivity to the hypothesized signal model; (b) illustration of the ingredients for the CL_s limit.

$$\mathrm{CL}_s = \frac{P(Q \geq Q_{\mathrm{obs}}|s+b)}{P(Q \geq Q_{\mathrm{obs}}|b)} = \frac{p_{s+b}}{1-p_b} \,.$$

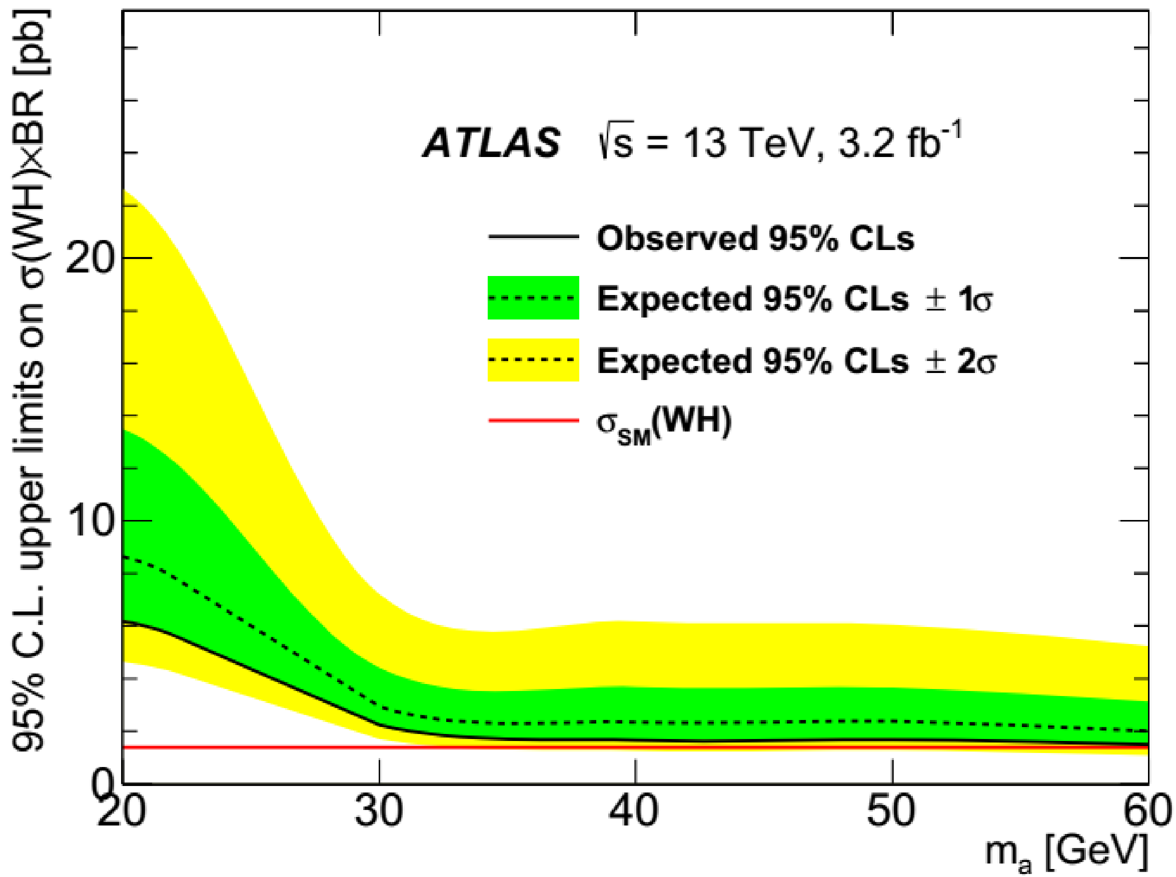
A. L. Read, J. Phys. G28, 2693 (2002)

G. Cowan, 1307.2487

Statistical Treatment (LHeC Higgs to 4b)

- 5σ Discovery:
  - CDF[PoissonDistribution[b],Median[PoissonDistribution[s+b]]-1] >= CDF[NormalDistribution[0,1],5]
- 95% CLs exclusion:
  - CDF[PoissonDistribution[s+b],Median[PoissonDistribution[b]]] ÷ CDF[PoissonDistribution[b],Median[PoissonDistribution[b]]] = alpha

Sensitivity Comparison (LHeC Higgs to 4b)



ATLAS, 1606.08391

Interpretation (LHeC Higgs to 4b)

- Higgs singlet extension of the SM: adding a real singlet scalar to SM, assuming a Z_2 symmetry (which is spontaneously broken) to simplify parameter space.
- Lagrangian: $\mathcal{L}_s = (D^\mu \Phi)^\dagger D_\mu \Phi + \partial^\mu S \partial_\mu S - V(\Phi, S)$ $\quad V(\Phi, S) = -m^2 \Phi^\dagger \Phi - \mu^2 S^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger \Phi S^2$
- Rotation to mass eigenstates:

$$\Phi \equiv \begin{pmatrix} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix}, S \equiv \frac{h' + x}{\sqrt{2}} \qquad \begin{pmatrix} \phi \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix}$$

- Parameter counting: 5 parameters with 2 already fixed.

$$m_\phi, m_h, \alpha, v, \tan\beta \equiv \frac{v}{x}$$

- The remaining parameters can be chose as the mass of the additional scalar, the mixing angle between two scalars, and the ratio of the vevs.

T. Robens et al., EPJC 75, 104 (2015)

Interpretation (LHeC Higgs to 4b)

D. Curtin et al., JHEP 06, 025 (2015)

Final State	$\mathrm{Br}(h \to 2s \to 2f2f')/\mathrm{Br}(h \to 2s)$
$b\bar{b}b\bar{b}$	0.77
$b\bar{b}\tau^+\tau^-$	0.10
$\tau^+\tau^-\tau^+\tau^-$	3.5×10^{-3}
$b\bar{b}\mu^+\mu^-$	3.7×10^{-4}
$\tau^+\tau^-\mu^+\mu^-$	2.5×10^{-5}
$\mu^+\mu^-\mu^+\mu^-$	4.5×10^{-8}

Table 1. $\mathrm{Br}(h \to 2s \to 2f2f')/\mathrm{Br}(h \to 2s)$ in the SM+S model, with $m_s = 40\,\mathrm{GeV}$. These numbers are relatively constant across the mass range $15\,\mathrm{GeV} \leq m_s \leq 60\,\mathrm{GeV}$.