Exotic Higgs Decay at the Large Hadron Electron Collider

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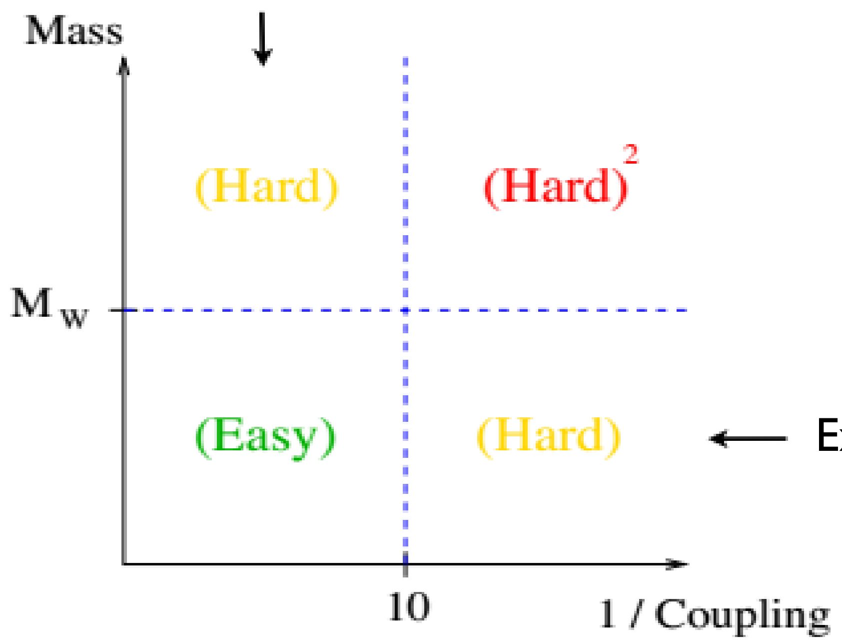
Based on
Phys. Rev. D 94, 011702 (2016) in collaboration with Yi-Lei Tang and Shou-hua Zhu
arXiv: 1608.08458 in collaboration with Shang Liu, Yi-Lei Tang and Shou-hua Zhu

Motivation for Exotic Higgs Decay Searches

- Two major possibilities for NP to evade current searches (picture from D. E. Morrissey @ HC 2016)

Gluino Searches



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

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

D. Curtin et al., PRD 90 (2014) 075004

See talks given by W. Yao and Z. Liu for detail.

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?

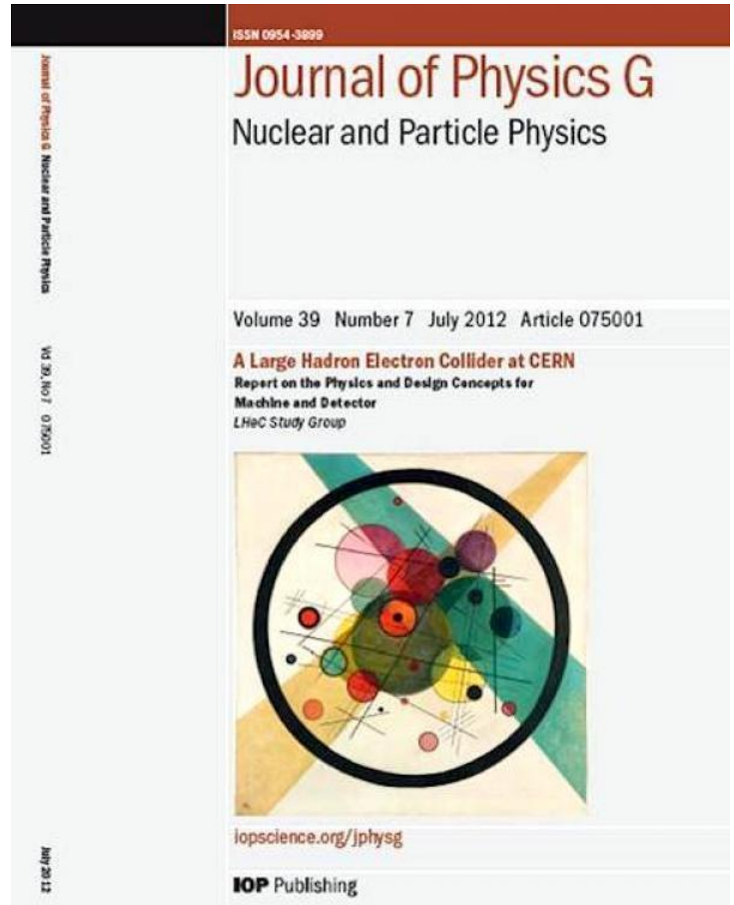
PHYSICS OF ep COLLISIONS IN THE TeV ENERGY RANGE

G. Altarelli*), B. Mele*) and R. Rückl,
CERN, Geneva, Switzerland
(Presented by G. Altarelli)

ABSTRACT

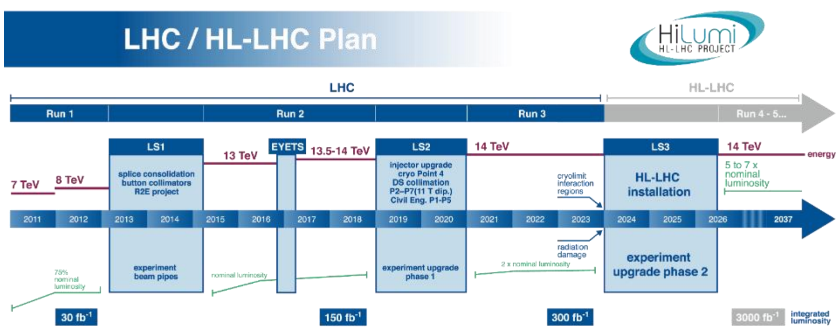
We study the physics of electron-proton collisions in the range of centre-of-mass energies between $\sqrt{s}$ = 0.3 TeV (HERA) and $\sqrt{s}$ = (1-2) TeV. The latter energies would be achieved if the electron or positron beam of LEP [E_e = (50-100) GeV] is made to collide with the proton beam of LHC [E_p = (5-10) TeV].

CERN-ECFA workshop, Lausanne, March 1984:
a Large Hadron Collider in the LEP tunnel



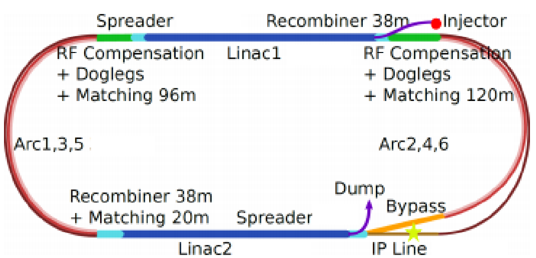
What is the LHeC?

- 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?

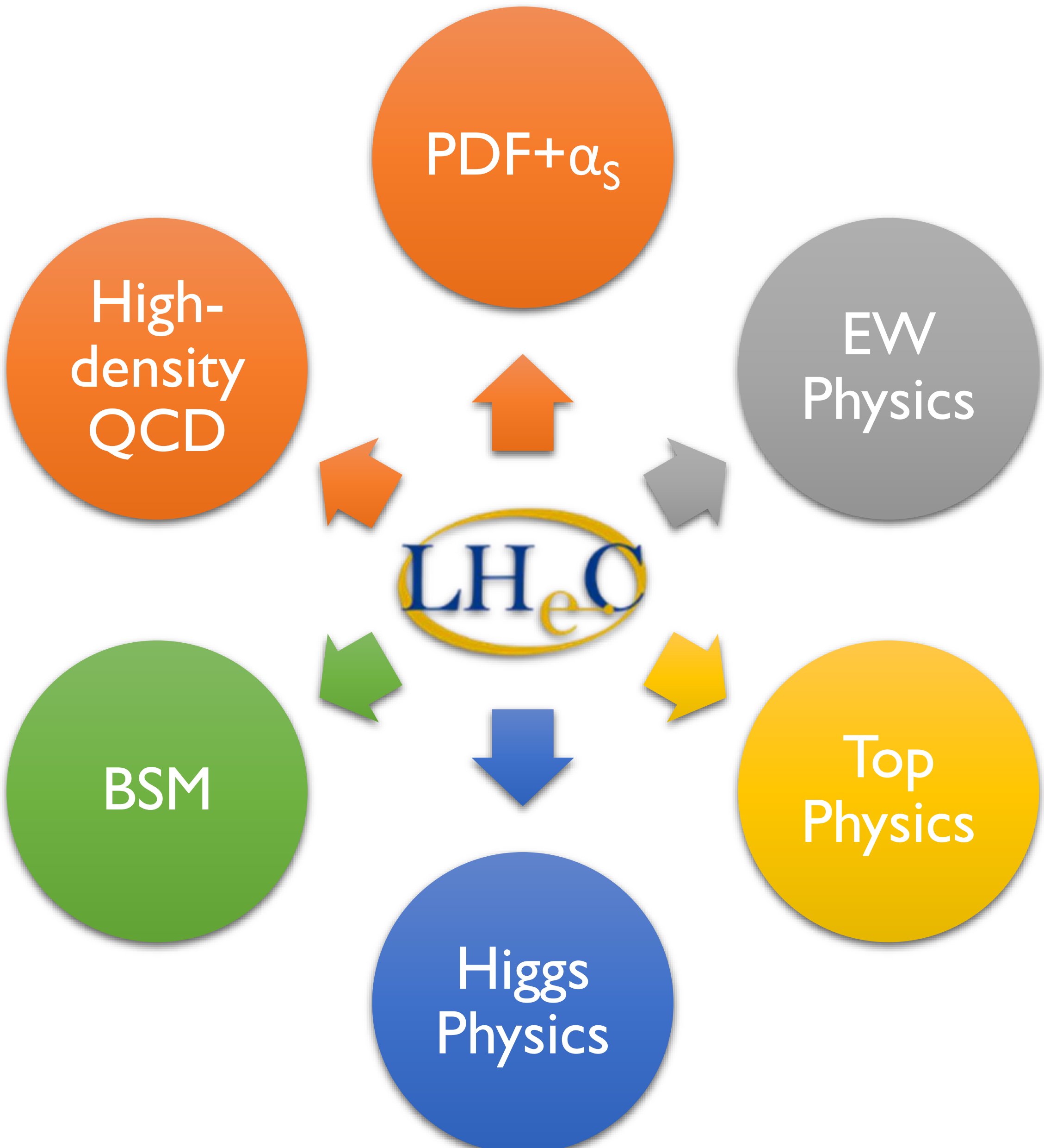
- Proposed LHeC parameters:
  - 7 TeV proton beam (from HL-LHC)
  - 60 GeV electron beam (with -80%~-90% polarization) (limited by power consumption)
  - Luminosity as high as 1 ab^{-1}

F. Zimmermann et al.,
MOPWO054, Proceedings of IPAC 2013

  - Detector (including tracker) supposed to have a very large pseudorapidity coverage (up to 5)

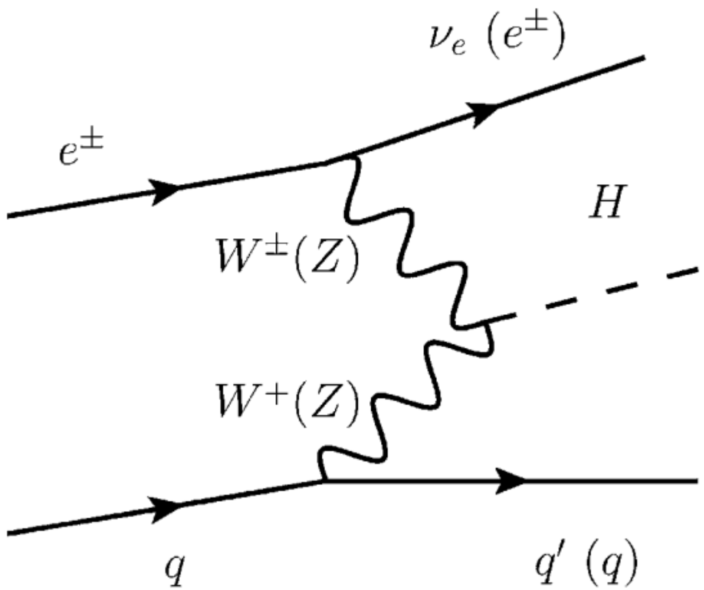
O. Bruening, LHeC Accelerator Studies and Considerations, talk at LHeC 2015 Workshop

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



For more information on specific topics, see slides in:
http://lhec.web.cern.ch/talks-seminars

Higgs Boson Production in ep Collision: Single Production



$$P^T_{V/f}(x, p_T^2) = \frac{g_V^2 + g_A^2}{8\pi^2} \frac{1+(1-x)^2}{x} \frac{p_T^2}{(p_T^2 + (1-x)M_V^2)^2},$$

$$P^L_{V/f}(x, p_T^2) = \frac{g_V^2 + g_A^2}{4\pi^2} \frac{1-x}{x} \frac{(1-x)M_V^2}{(p_T^2 + (1-x)M_V^2)^2},$$

$$\sigma(fa \to f'X) \approx \int dx\ dp_T^2\ P_{V/f}(x, p_T^2)\ \sigma(Va \to X).$$

- VBF-like topology for CC and NC production
- Understanding using effective W approximation:
  - No divergence when the pT of final state quark tends to zero, in contrast to QCD parton.
  - Because of the 1/x behavior for the gauge boson distribution, the outgoing parton energy (1-x)E tends to be high.
  - At high pT, the contribution from the longitudinally polarized gauge bosons is relatively suppressed

T. Han & B. Mellado, PRD 82, 016009 (2010)

Higgs Boson Production in ep Collision:

Single Production

Uta Klein, DIS2015

Total event rates for 1ab^{-1}.

√s= **1.3 TeV** √s= **3.5 TeV**

Higgs in e^-p		CC - LHeC	NC - LHeC	CC - FHeC
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$	0.029	5 700	700	123 000
$H \to \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \to \mu\mu$	0.00022	50	5	1 000
$H \to 4l$	0.00013	30	3	550
$H \to 2l2\nu$	0.0106	2 080	250	45 000
$H \to gg$	0.086	16 850	2 050	365 000
$H \to WW$	0.215	42 100	5 150	915 000
$H \to ZZ$	0.0264	5 200	600	110 000
$H \to \gamma\gamma$	0.00228	450	60	10 000
$H \to Z\gamma$	0.00154	300	40	6 500

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.

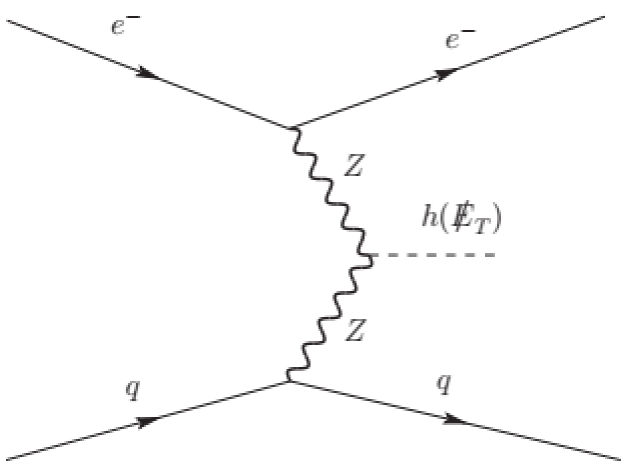
- Exotic Higgs decays
  - Invisible Higgs decay
  - Higgs to 4b

LHeC Invisible Higgs Decay

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

=>Cut based, parton level, probing

Br(h->invisible)=6%@2σ level with 1 ab^{-1}.

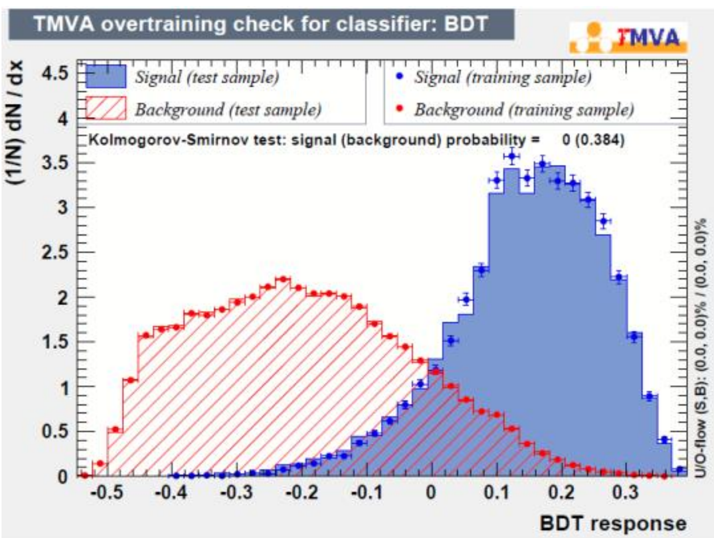


- Well-motivated decay channel for Higgs & DM physics
- VBF or ZH production needed at the HL-LHC
- LHeC signal: NC channel
- Backgrounds: Wje, Wjv, Zje, other (top, e+multijet, PHP)
- Event selection considerations:
  - MET requirements
  - VBF-like selections
  - Electron kinematics
  - Lepton veto

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)

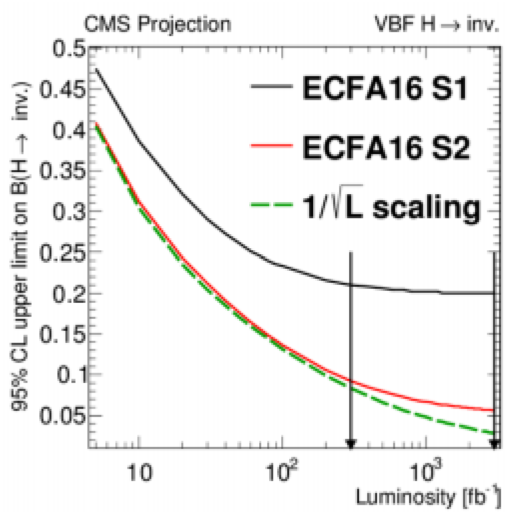


Comparison with the HL-LHC

ZH Channel (ATLAS-PHYS-PUB-2013-014)

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 5.6% Br @ 95%CL with based on extrapolation.



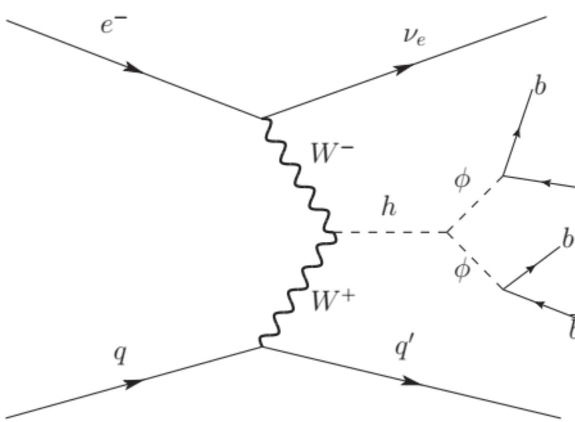
CMS DP 2016/064

LHeC Higgs to 4b

Shang Liu, Yi-Lei Tang, **CZ** and Shou-hua Zhu, 1608.08458

Detector level study in progress with Liverpool LHeC group.

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



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

- 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.

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

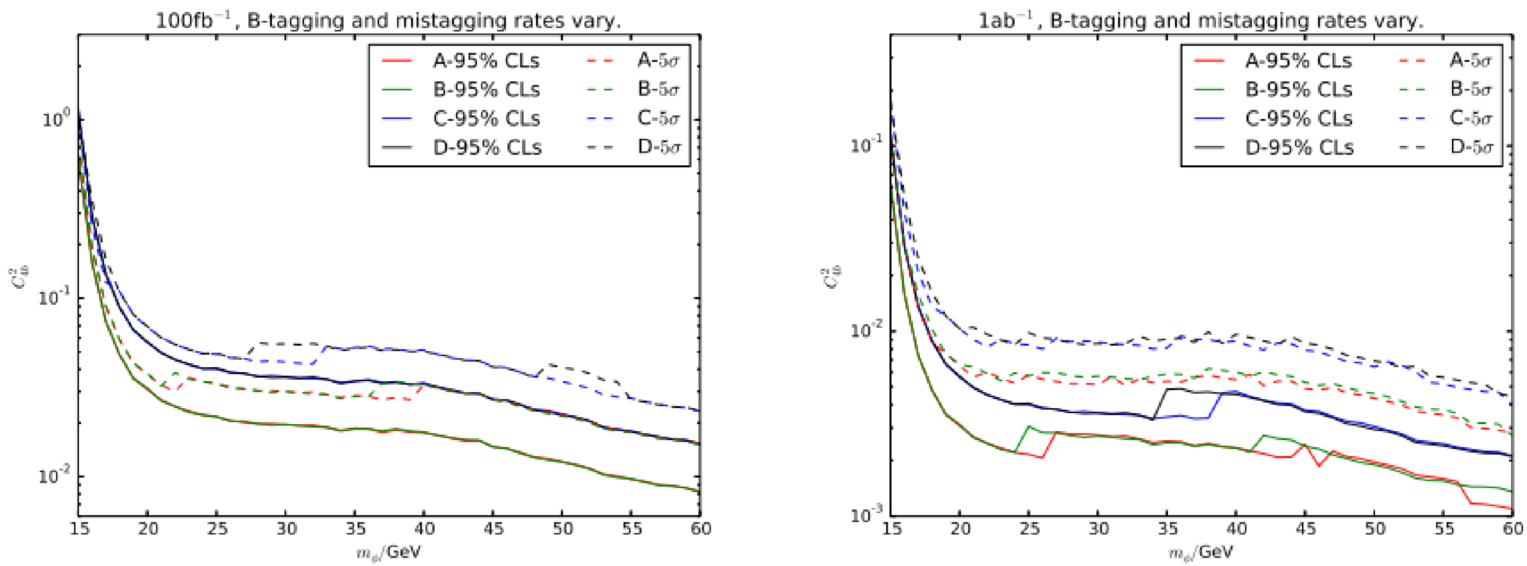


FIG. 3: Expected 95% CLs exclusion limit (solid line) and 5σ discovery reach (dashed line) in the (C_{4b}^2, m_ϕ) plane at the LHeC. Left: 100 fb^{-1} luminosity. Right: 1 ab^{-1} luminosity. Different color corresponds to different $b-$tagging scenarios (A)(B)(C)(D) (see the text and legend). $E_0 =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

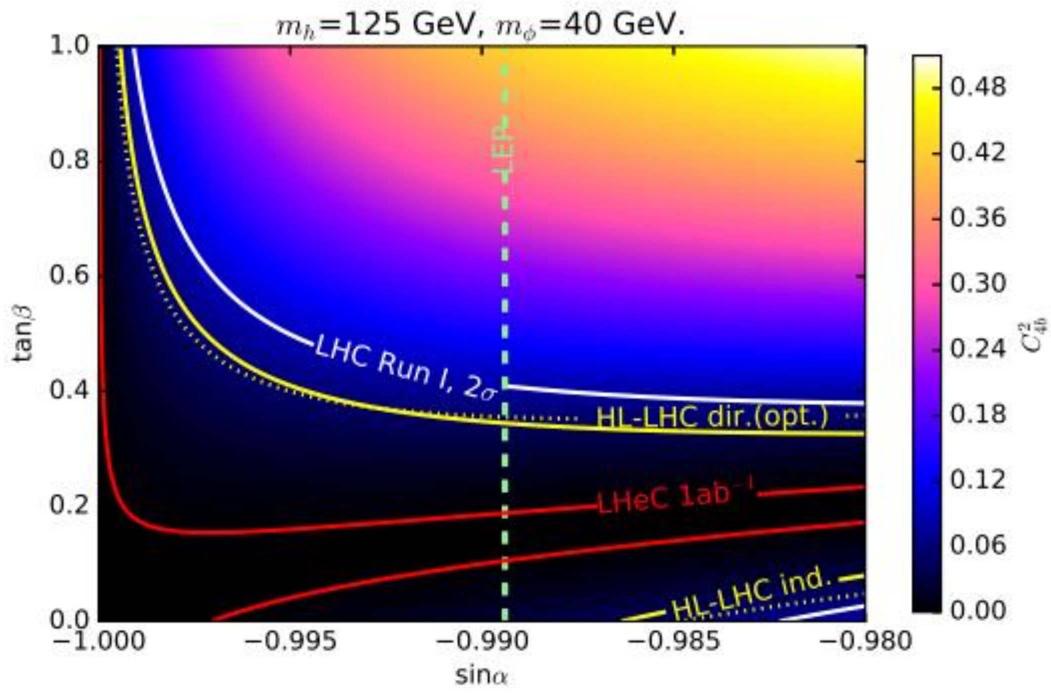
$$\mathcal{L}_s = (D^\mu \Phi)^\dagger D_\mu \Phi + \partial^\mu S \partial_\mu S - V(\Phi, S)$$

$$\begin{aligned} V(\Phi, S) \; = & \; -m^2 \Phi^\dagger \Phi - \mu^2 S^2 + \lambda_1 (\Phi^\dagger \Phi)^2 \\ & + \lambda_2 S^4 + \lambda_3 \Phi^\dagger \Phi S^2 \end{aligned}$$

$$\Phi \equiv \begin{pmatrix} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix}, S \equiv \frac{h' + x}{\sqrt{2}}$$

$$\begin{pmatrix} \phi \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix}$$

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



For phenomenological constraints, see:

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

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

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

Signal (100% invisible)~1.8fb

Total background~2.7fb

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

Statistical Significance

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

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

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.

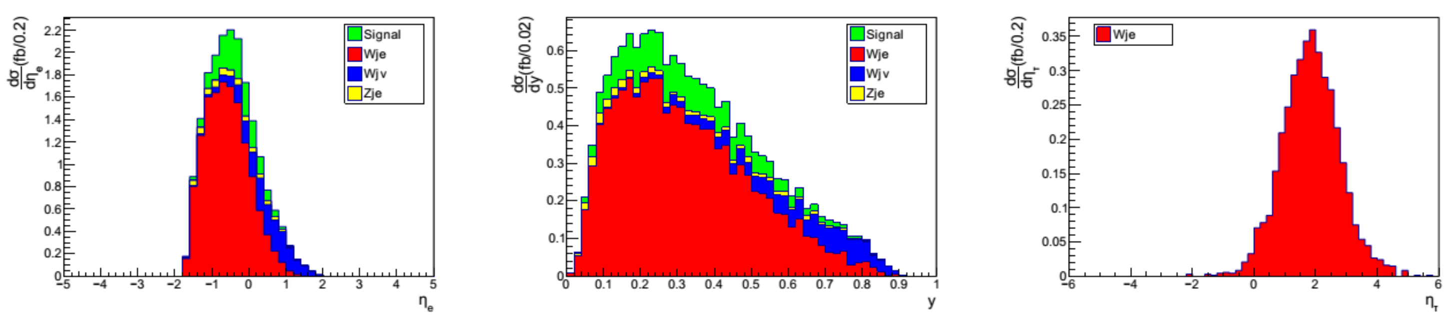
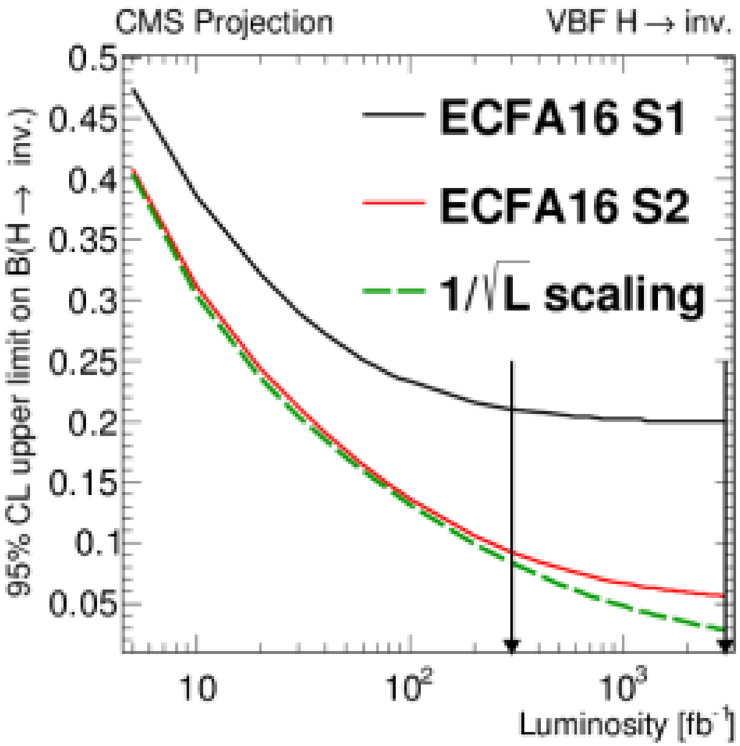


FIG. 2: Left: η_e distribution of the signal and major backgrounds just before the η_e cut. Middle: y distribution of the signal and major backgrounds just before the y cut. Right: τ lepton pseudorapidity distribution of the $Wje(W \to \tau\nu)$ background just before the lepton veto.

VBF H→invisible



Expected 95% upper limit on BR(H→inv) as a function of luminosity. The black solid line, labelled ECFA16 S1, corresponds to a scenario in which systematic uncertainties fixed to the 2015 Run II values. The red solid line, ECFA16 S2, corresponds to a scenario in which the experimental systematic uncertainties decrease with integrated luminosity until a lower bound based on the current understanding of the performance of the upgraded detector at 200 PU is reached, and theoretical uncertainties are scaled by 1/2 compared to the current values. Finally, the dashed green line shows a simple scaling with luminosity of the experimental uncertainties, without a lower bound, and a 1/2 factor for the theoretical uncertainties.

HIG-16-016

	ECFA16 S1	ECFA16 S2	$1/\sqrt{L}$ scaling
$300\ fb^{-1}$	0.210	0.092	0.084
$3000\ fb^{-1}$	0.200	0.056	0.028

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)

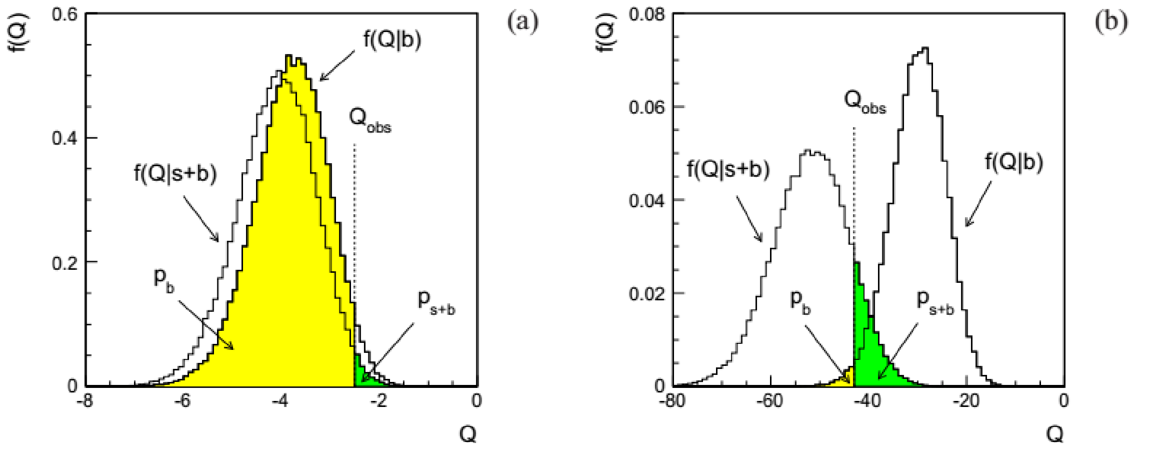


Fig. 8 (a) Distributions of the statistic Q indicating low sensitivity to the hypothesized signal model; (b) illustration of the ingredients for the CL_s limit.

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

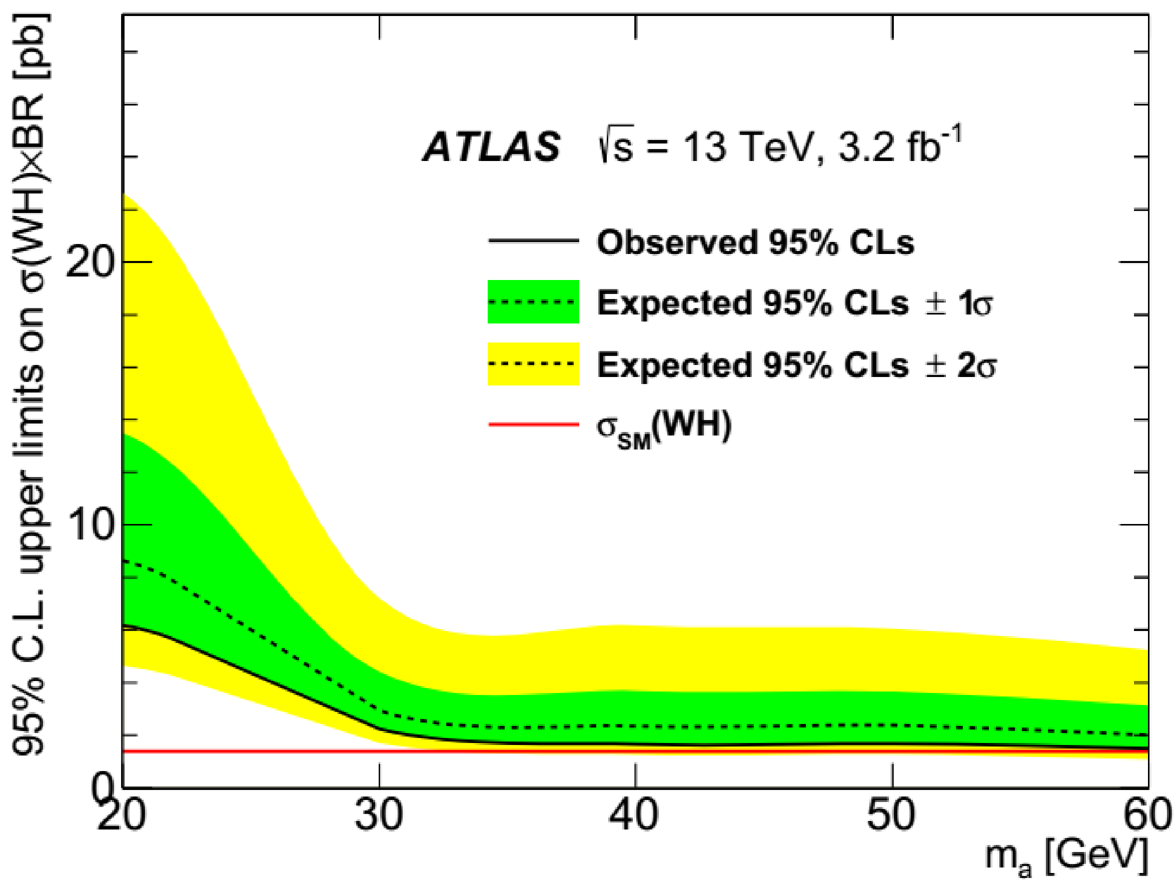
A. L. Read, J. Phys. G28, 2693 (2002)

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)

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 $15\,\mathrm{GeV} \leq m_s \leq 60\,\mathrm{GeV}$.