

# Precision Higgs Physics at High-Energy Electron-Proton Colliders

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,

**Abstract.** The Higgs boson and its physics have become a central topic of modern particle physics and a key parameter in the evaluation of future high energy collider projects. This paper provides a summary and overview on the potential of future luminous, energy frontier electron-proton colliders, especially the LHeC, the HE-LHC and the FCC-eh, for precision Standard Model measurements of the properties of the Higgs boson in deep inelastic scattering. Detailed analyses are presented on the prospects for accurate measurements of the Higgs boson decays into pairs of bottom and charm quarks. An extended study is performed for estimating the precision on the Higgs couplings in the most abundant decay channels, based on measurements in the charged and weak neutral current DIS reactions. The addition of  $ep$  information to the expected HL-LHC Higgs coupling measurements is demonstrated to lead to major improvements on the Higgs results one can expect to come from the LHC facility at large.

## 1. Introduction

The Higgs boson was discovered in 2012 by ATLAS [1] and CMS [2] at the Large Hadron Collider (LHC). It is the most recently discovered and thus least explored part of the Standard Model. The Higgs boson ( $H$ ) is of key importance as it is related to the

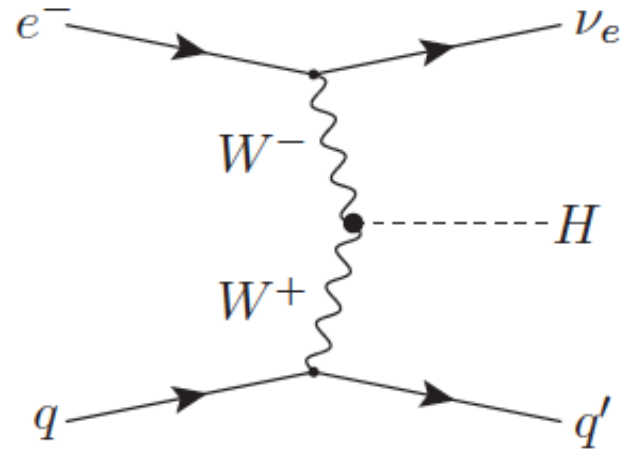


Fig.1a: Higgs boson production in charged current DIS to leading order.

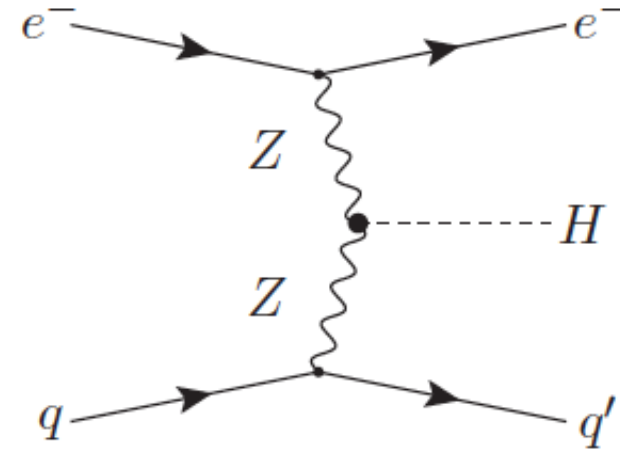


Fig.1b: Higgs boson production in neutral current DIS to leading order.

## 2. Higgs in ep

### *2.1. Electron-Proton Colliders*

HERA was the first  $ep$  collider built [12]. Its cms energy was  $\sqrt{s} = 2\sqrt{E_e E_p} = 0.3 \text{ TeV}$  determined by colliding beams of 26.7 GeV electron energy ( $E_e$ ) and 920 GeV proton energy ( $E_p$ ). The integrated luminosity for physics, registered in 15 years of operation

### *2.2. Kinematics and Cross Sections*

The kinematics of deep inelastic scattering is characterised by the negative four-momentum transfer ( $q$ ) squared,  $Q^2 = -q^2$  and the fraction Bjorken  $x$  of the proton's momentum carried by the struck parton. These are related to the cms energy squared

Needs eta and phi distributions

### *2.3. Detector Issues*

Needs a moment of time to relate the detector tables from Peter to Delphes assumptions

### 3. Formalism

The Higgs production in deep inelastic  $ep$  scattering proceeds via charged and neutral current scattering as is illustrated in Fig. 1a and 1b, respectively. The scattering cross sections, including the decay into a pair of particles  $A_i$  can be written as

$$\sigma_{CC}^i = \sigma_{CC} \cdot \frac{\Gamma^i}{\Gamma_H} \quad \text{and} \quad \sigma_{NC}^i = \sigma_{NC} \cdot \frac{\Gamma^i}{\Gamma_H}. \quad (1)$$

## 4. Higgs Decay into Bottom and Charm Quarks

### 4.1. *Signal and Background Event Simulations*

### 4.2. *Boosted Decision Tree Analysis*

Uta checking WW, being written

## 5. Accessing Further Decay Channels

Following the detailed studies of the  $b\bar{b}$  and  $c\bar{c}$  decay channels, presented above, a coarser analysis was established for other frequent decay channels both in NC and CC. Here acceptances and backgrounds were estimated with Madgraph, and efficiencies, distinguishing leptonic and hadronic decay channels for  $W$ ,  $Z$ , and  $\tau$ , were taken from prospective studies on Higgs coupling measurements at the LHC [25]. This provided a systematic scale factor,  $f$ , on the pure statistical error  $\delta_s$ , which comprised the signal-to-background ratio,  $S/B$ , and the product of acceptance,  $A$ , and extra reconstruction efficiency  $\epsilon$ , according to

$$f = \sqrt{\frac{1 + \frac{B}{S}}{A \cdot \epsilon}} \quad (4)$$

The error on the signal strength  $\mu_i$  for each of the Higgs decay channels  $i$  is determined as  $\delta\mu_i/\mu_i = f_i\delta_s$ . To good approximation these factors apply to LHeC, HE-LHeC

<b>DRAFT 25.3.</b>	$b\bar{b}$	WW	gg	$\tau\tau$	cc	ZZ	$\gamma\gamma$
branching fraction	0.582	0.214	0.082	0.063	0.029	0.026	0.0023
statistical error ( $\delta_s$ ) / %	0.09	0.15	0.25	0.28	0.42	0.43	1.47
acceptance (A)	0.14	0.10	0.40	0.40	0.11	0.10	0.40
signal/background (S/B)	9	0.2	0.1	0.2	0.43	0.33	0.5
extra efficiency ( $\epsilon$ )	1	0.5	0.5	0.43	1	0.5	0.7
scale factor $f$	2.8	11	7.4	5.9	5.5	9.0	3.3

## 6. Higgs Coupling Analyses

### 6.1. Results on ep

### 6.2. Joint LHeC and HL-LHC Higgs Physics

#### 6.2.1. Determination of Higgs Couplings in pp and ep

#### 6.2.2. Parton Distributions

Text being written  
Max+Jorge  
Figures + Fits update

DRAFT 31.3. $\delta\mu$ / %	$b\bar{b}$	WW	gg	$\tau\tau$	cc	ZZ	$\gamma\gamma$
LHeC NC	2.4	14.7	16.6	14.8	21.5	34.6	43.1
LHeC CC	0.80	5.2	5.9	5.3	7.2	12.4	15.4
FCC-eh NC	0.83	4.3	4.8	4.30	7.1	10.1	12.5
FCC-eh CC	0.27	1.6	1.8	1.6	2.3	3.9	4.8

Thy uncertainty for bb 0.5%



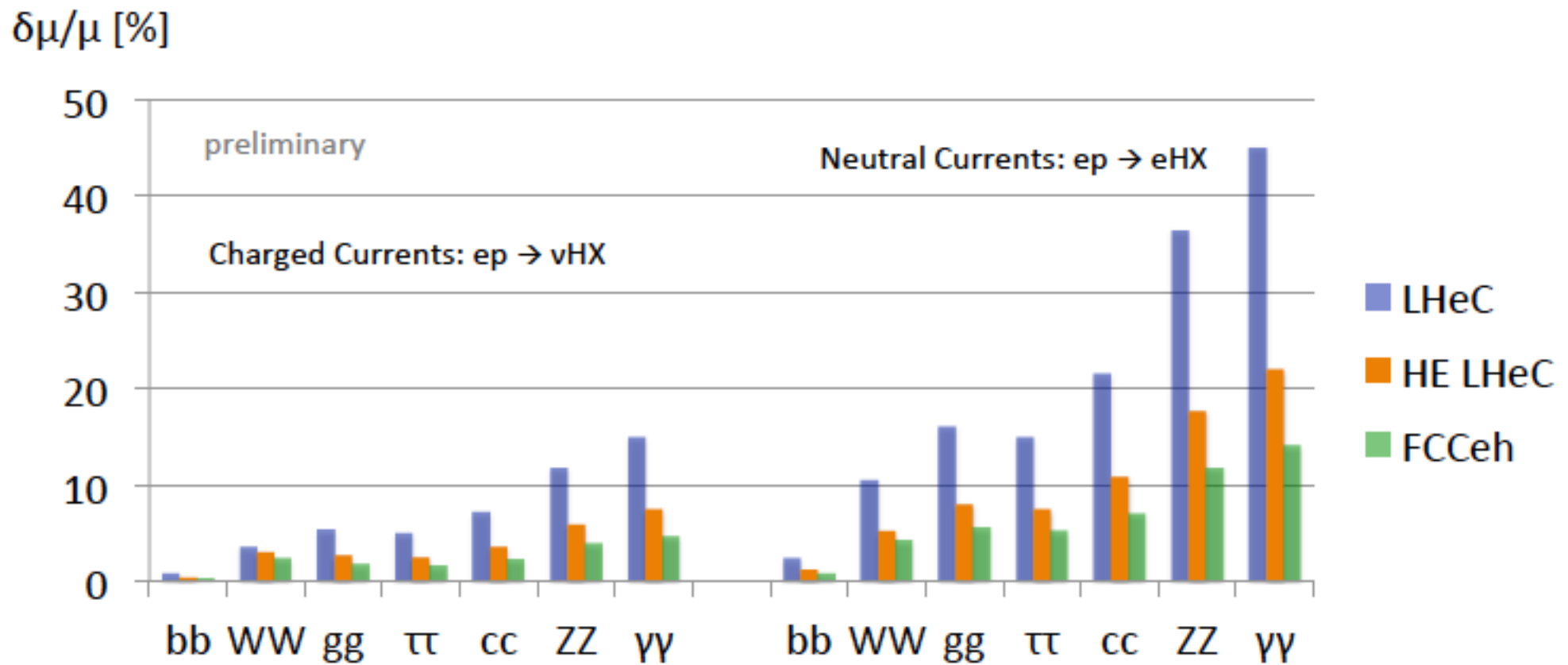


Figure 3: Uncertainties of signal strength determinations in the seven most abundant SM Higgs decay channels for the FCC-eh (green,  $2 \text{ ab}^{-1}$ ), the HE LHeC (brown,  $2 \text{ ab}^{-1}$ ) and LHeC (blue,  $1 \text{ ab}^{-1}$ ), in charged and neutral current DIS production.

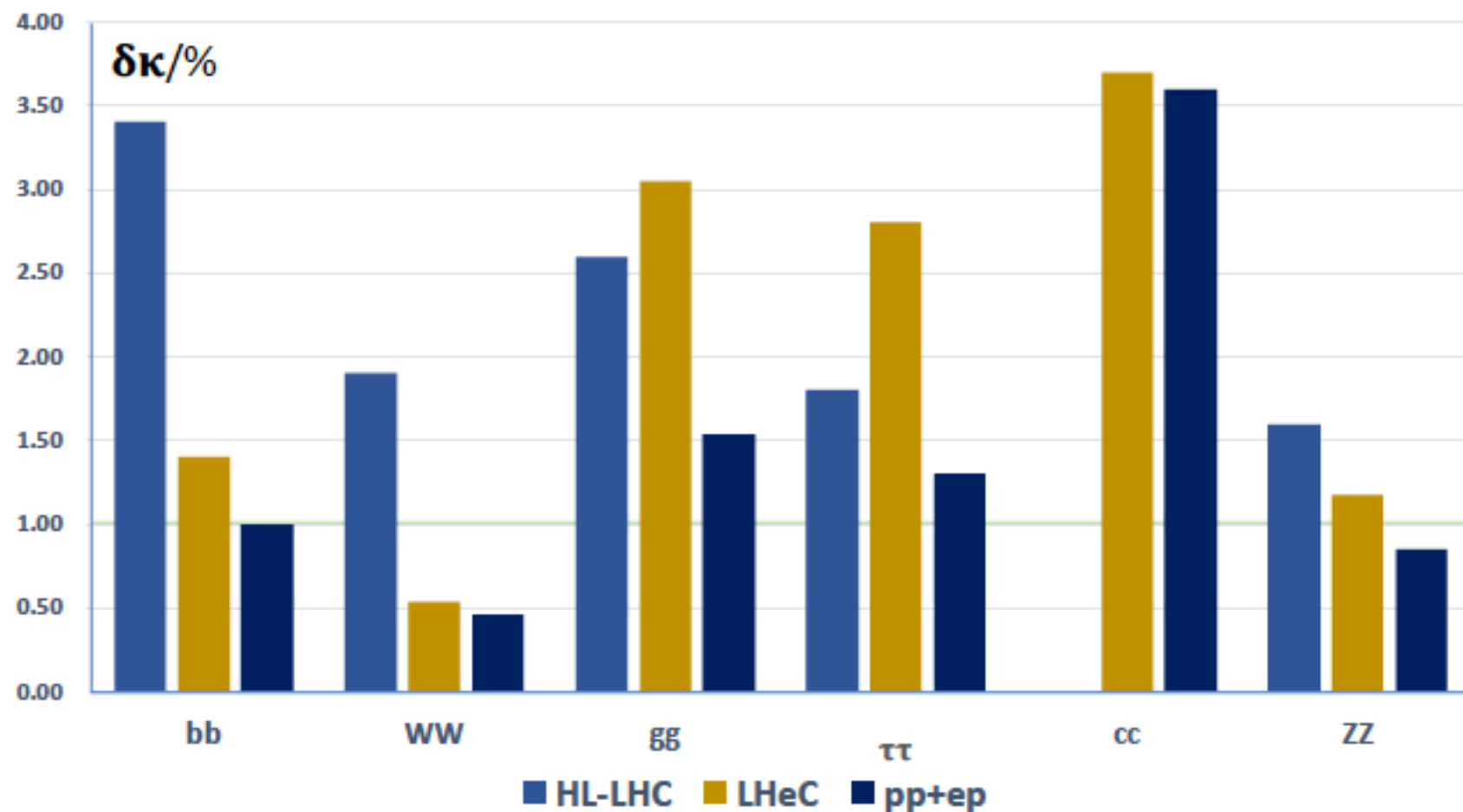
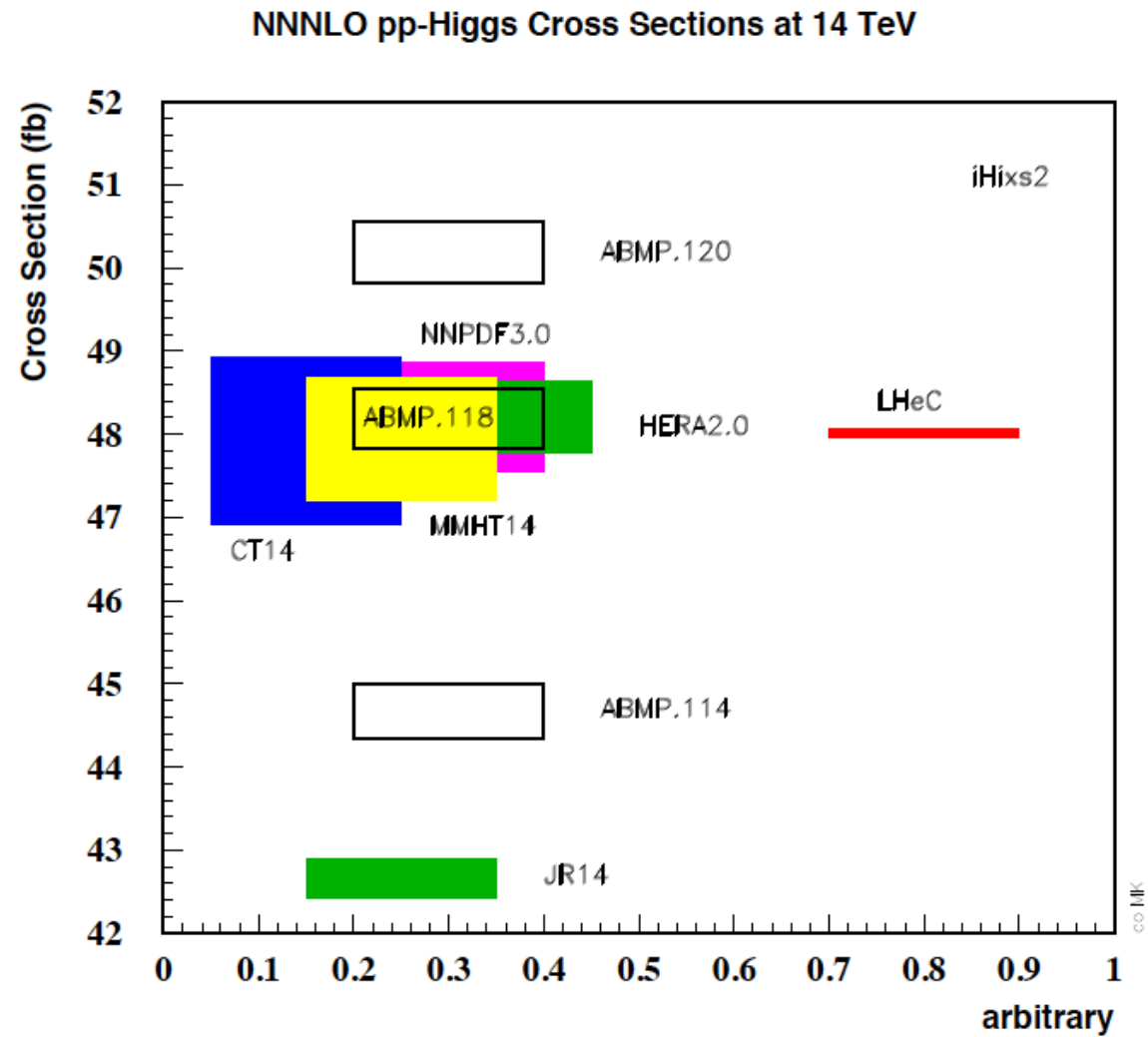


Figure 4: PRELIMINARY Uncertainties of coupling constant determinations using the kappa framework at the LHC in the six most frequent decay channels from the combination of ATLAS and CMS prospects at HL-LHC (blue,  $3\text{ ab}^{-1}$ ), the LHeC (gold,  $1\text{ ab}^{-1}$ ) and the combination of  $pp$  and  $ee$  (dark blue).





Think of showing xg plot  
with 50fb-1 vs 1ab-1  
Done by Claire+Max

Figure 5: Cross sections of Higgs production calculated to N<sup>3</sup>LO using the iHix program [?] for existing PDF parameterisation sets (left side) and for the LHeC PDFs (right side). The widths of the areas correspond to the uncertainties as quoted by the various sets. The LHeC uncertainty band (red) includes the expected uncertainty due to the PDFs and the precision measurement of  $\alpha_s$ . [TO BE DONE]

## 7. Further Prospects

### 7.1. The $t\bar{t}H$ Coupling

### 7.2. Higgs Decay into Invisible

Masahiro: done

The Higgs decay into invisible particles could be a key to BSM physics. The SM branching ratio of  $H \rightarrow ZZ \rightarrow 4\nu$  is only 0.1%. Any sizable decay rate into invisible particles would thus indicate an exotic decay, for example to dark matter particles. Its non-observation would give the SM cross section measurement, reconstructing more

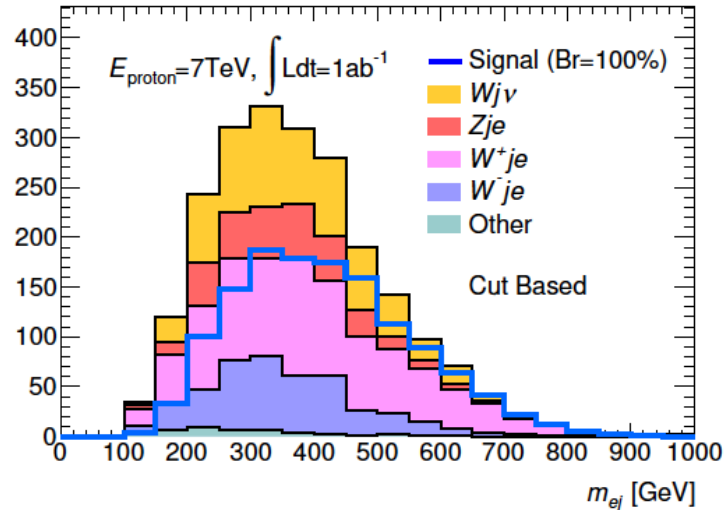


Figure 6: Electron-jet invariant mass distribution for the Higgs to invisible decay signal (normalized to 100% branching ratio) and the stacked backgrounds for an integrated luminosity of  $1\text{ ab}^{-1}$  at the LHeC after all selection cuts.

Monojet question

Polarisation not important

Inv in CC??

H-inv at HL LHC workshop to be cited

title

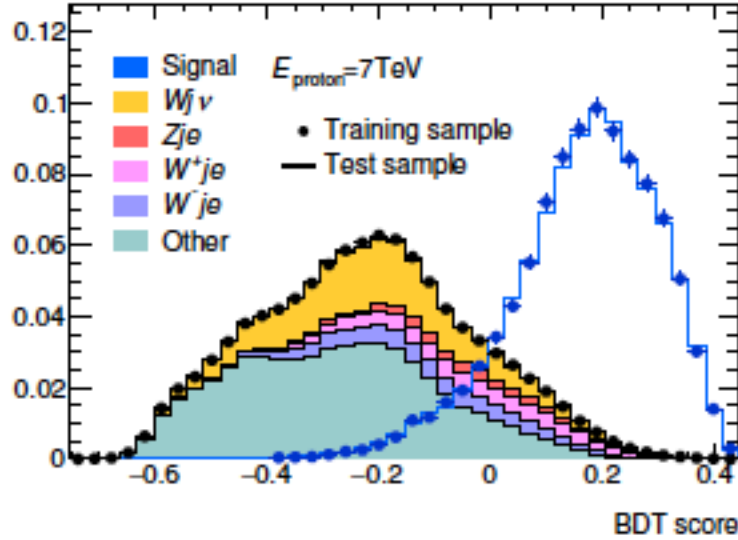


Figure 7: BDT output score distribution for the Higgs to invisible decay signal and the stacked backgrounds (both area normalized) at the LHeC.

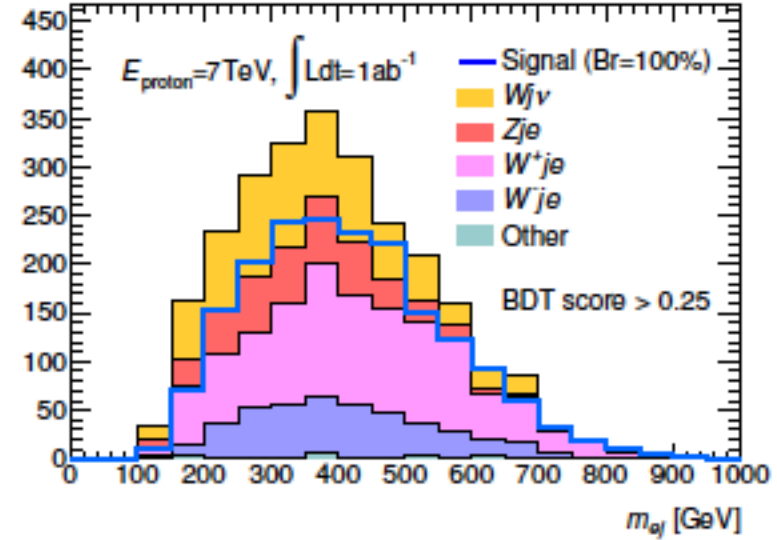


Figure 8: Electron-jet invariant mass distribution for the Higgs to invisible decay signal (normalized to 100% branching ratio) and the stacked backgrounds for an integrated luminosity of  $1 \text{ ab}^{-1}$  at the LHeC after the BDT score cut of 0.25.

## 8. BSM Higgs Physics in ep

Done by Mukesh – to be included here (?) or appendix?

## 9. Summary

## Acknowledgements

Thank you

- [1] G. Aad et al. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys. Lett.*, B716:1–29, 2012.
- [2] S. Chatrchyan et al. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett.*, B716:30–61, 2012.
- [3] F. Englert and R. Brout. Broken Symmetry and the Mass of Gauge Vector Mesons. *Phys. Rev. Lett.*, 13:321–323, 1964. [,157(1964)].

# Time Constraints

1. Mid April the ECFA WG finishes its first draft
2. → 8.4. they have to have ours
3. → Numbers for Jorge and kappa fits to be finished mid this week
4. Our H group should see a draft preferentially before it reaches the ECFA group
5. → need the text in some way by Wednesday/latest Friday
6. 8-12.4. is DIS in Torino
7. We shall submit to the arXiv end of April, unless we can't..

Thanks