Probing Bottom Quark Yukawa Coupling in an Effective Higgs Decay at Future Electron-Proton Colliders

Institute for Research in Fundamental Sciences

Wednesday Weekly Seminar

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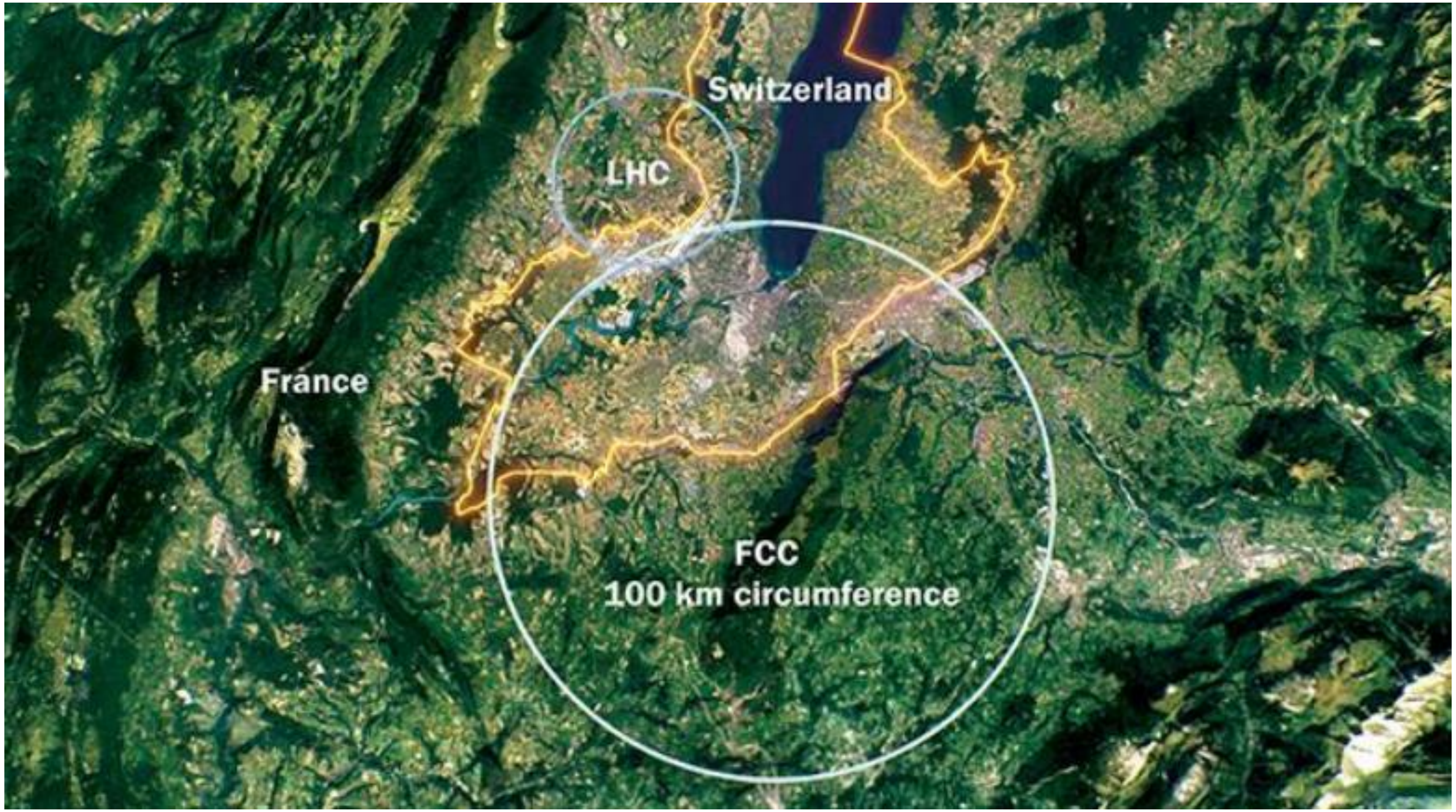
OUTLINE

- Introduction & Motivation
- Theoretical framework
- Data Simulation
- Analysis strategy
- Results & discussion
- Conclusion



INTRODUCTION

- After the Higgs boson discovery, the focus shifted toward understanding its couplings to other particles, in particular to the fermions.
- Exploring CP nature of the Higgs couplings has become very important.

CP violation in the Higgs sector → impact on Baryogensis problem

The Yukawa coupling of H to the 3rd generation fermions is larger.

Therefore, studying of CP properties with them play an important role.

INTRODUCTION

A crucial aspect ⇨ Measurement of the b-quark Yukawa coupling

- To check the consistency of the SM and BSM.
- Extensive studies have been performed over the years to assess the feasibility of this measurement.
- Nevertheless, the observation of the H → bb decay remains very challenging at the LHC.

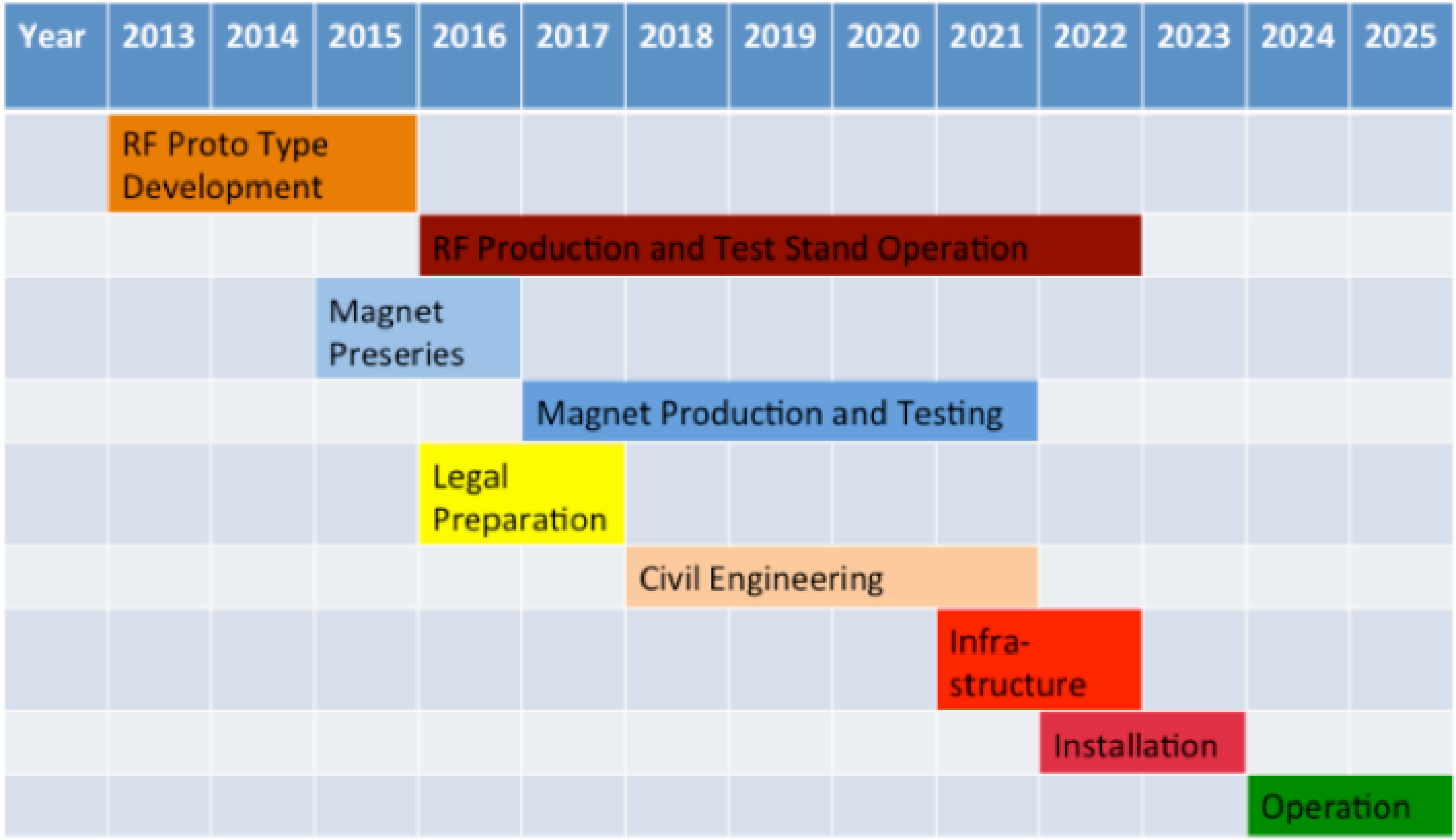
Recently, there has been a consideration for high energy ep collisions at the LHC.

A rich physics program — Very exciting prospects — Direct extraction of y_b

INTRODUCTION

INSTITUTE FOR RESEARCH IN FUNDAMENTAL SCIENCES

- **Tentative schedule for the LHeC project.**



INTRODUCTION

- **Other ep colliders more than LHeC at CERN:**

FCC-ee | FCC-hh | FCC-eh

- **Benchmarks:** $E_e = 60\,\text{GeV}$

	Unit	LHeC	HE-LHeC	FCC-eh	FCC-eh
E_p	TeV	7	13.5	20	50
$\sqrt{s}$	TeV	1.30	1.77	2.2	3.46

$$\sqrt{s} = 2\sqrt{E_p E_e}$$

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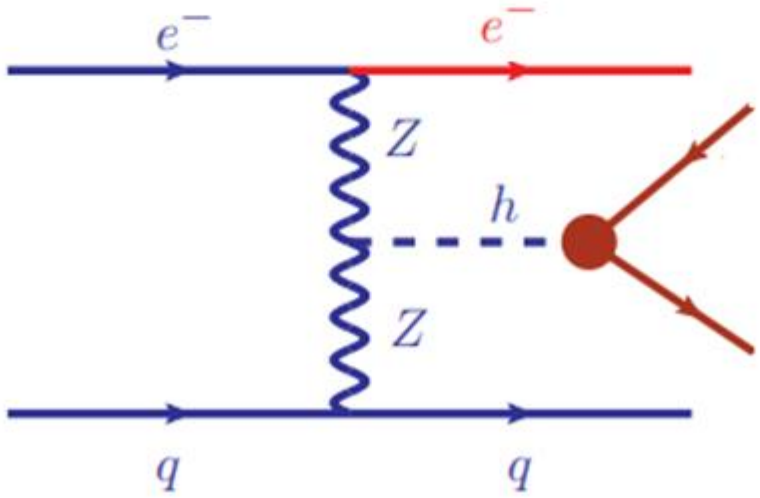
INTRODUCTION

- **Higgs Production at ep collision:**
- **Leading order SM diagrams for *Neutral Current (NC)*:**



$$eq \to eHq$$

VBF process

INTRODUCTION

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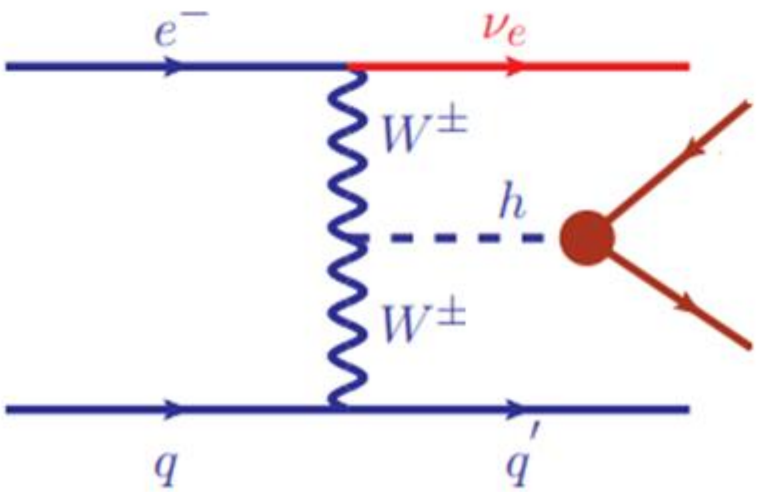
- **Leading order SM diagrams for *Charged Current (CC)*:**

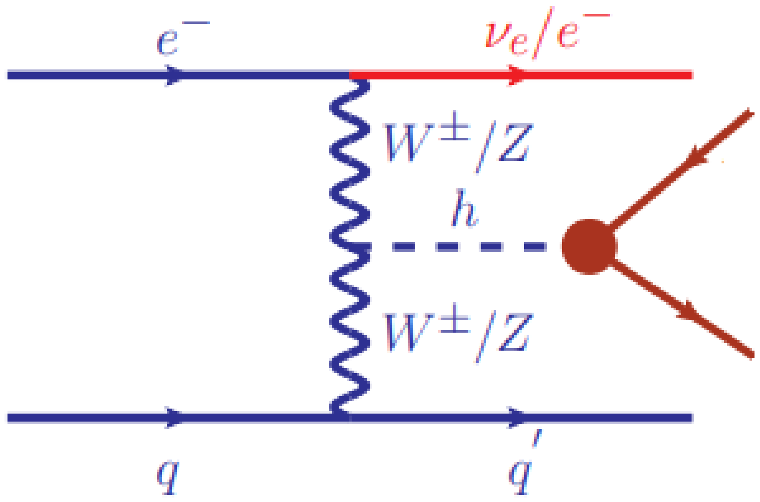


$eq \to \nu_e H q'$

VBF process

INTRODUCTION

- **Higgs Production at ep collision:**
- **Leading order SM diagrams for CC (NC) processes:**

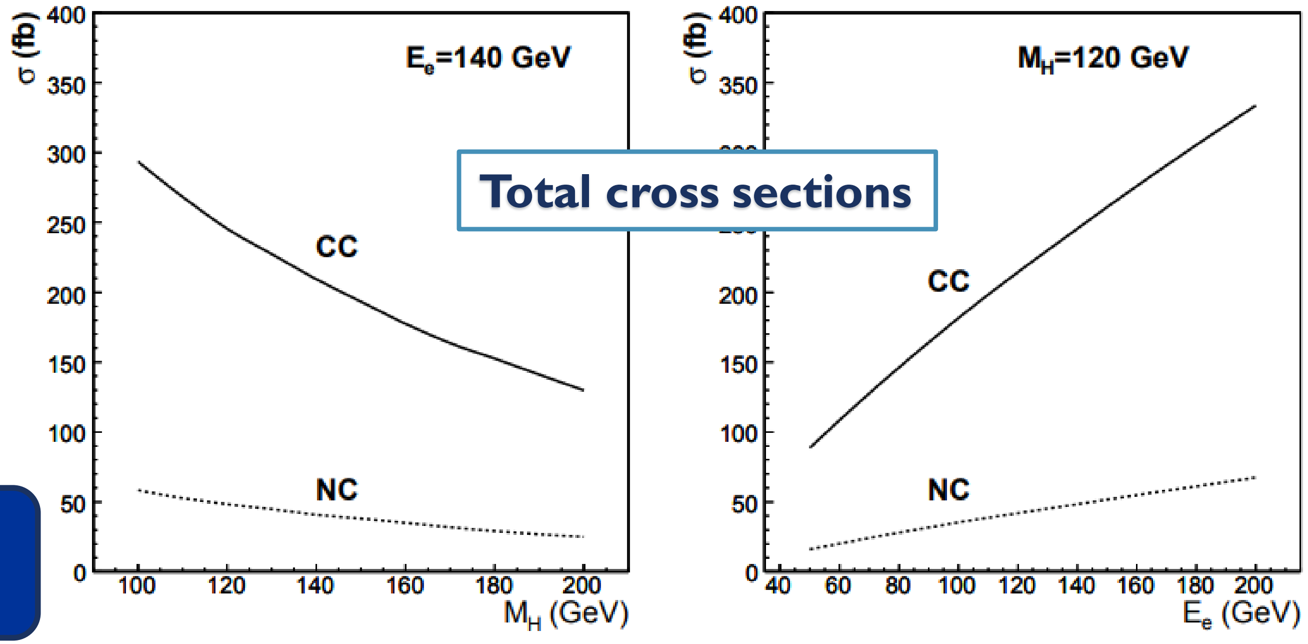


the production rate of CC is larger than NC process by about a factor of 4 − 6

- **VBF processes:**

$$eq \to \nu_e H q' \quad \text{and} \quad eq \to eHq$$

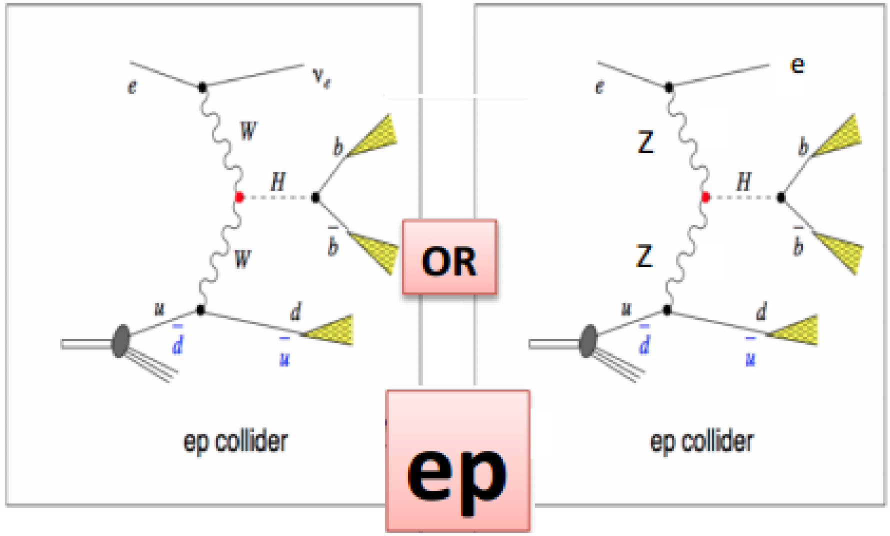
Total cross sections



INTRODUCTION

- **VBF Higgs Production**

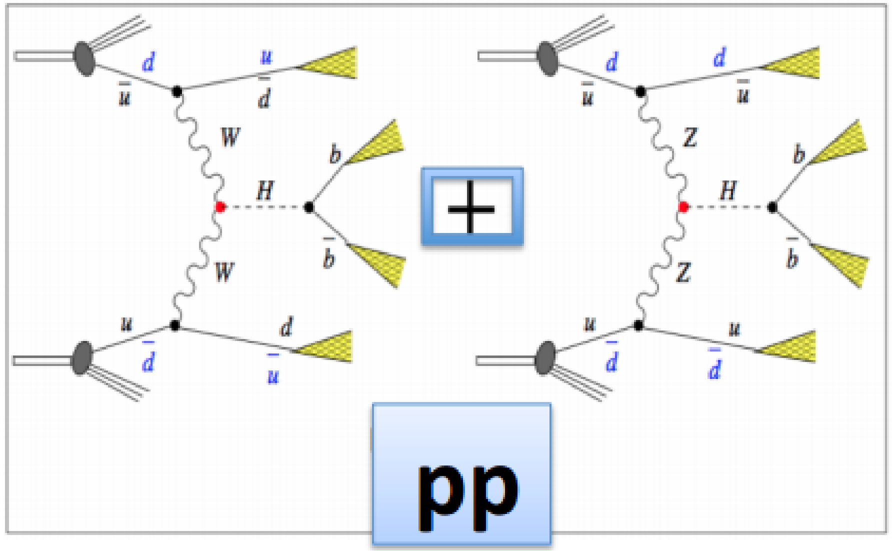
ep V.S. pp



ep: Higgs production in ep comes uniquely from either CC or NC DIS via VBF

Clean bb final state, S/B >1
e-h Cross Calibration for Precision ep
Clean, precise reconstruction and easy distinction of ZZH and WWH
without pile-up:
<0.1@LHeC up to 1@FCCeh events

VBF: Small theoretical uncertainties!



pp: Higgs production in pp comes predominantly (~80%) from gg→ H :
high rates crucial for rare decays
However, only small VBF fraction

Pile-up in pp at 5 10^{34} cm^{-2} s^{-1} is 150@25ns
FCC-hh: pile-up 500-1000 (!)
S/B very small for bb
Final precision in pp needs accurate N^3LO PDFs & α_s

THEORETICAL FRAMEWORK

- ***Standard Model Effective Field Theory (SMEFT)***

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i \mathcal{O}_i}{\Lambda^2}$$

- **A proper formalism of the impacts of new physics is to consider SM as an effective theory.**
- **SMEFT is a powerful tool to examine deviations from the SM.**
- **Non-standard couplings can be parameterized by operators of d > 4. The leading effects for collider observables typically enter at d=6.**

THEORETICAL FRAMEWORK

- **The effective Lagrangian for mass and Yukawa terms:**[arXiv:9909265]

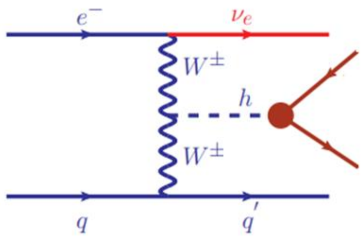
$$\mathcal{L}_f = \frac{y_f v}{\sqrt{2}}\left[1+\frac{v^2}{2\Lambda^2}\frac{X_R^f+iX_I^f}{y_f}\right]\overline{f_L} f_R + \frac{y_f}{\sqrt{2}}\left[1+\frac{3v^2}{2\Lambda^2}\frac{X_R^f+iX_I^f}{y_f}\right]\overline{f_L} f_R h + \frac{3v}{2\sqrt{2}\Lambda^2}\left(X_R^f+iX_I^f\right)\overline{f_L} f_R hh + \frac{1}{2\sqrt{2}\Lambda^2}\left(X_R^f+iX_I^f\right)\overline{f_L} f_R hhh$$

- **Λ : the energy scale of new physics**
- **y_f :Yukawa coupling for the relevant fermion**
- **$X_{R,I}$: Real and Imaginary part of coefficients of the dimension-six terms.**

DATA SIMULATION

- LHeC & FCC-eh benchmarks

C.M. Energy (TeV)	1.3	3.46	3.46	3.46
Integrated luminosity (ab^{-1})	1.0	1.0	2.0	10.0



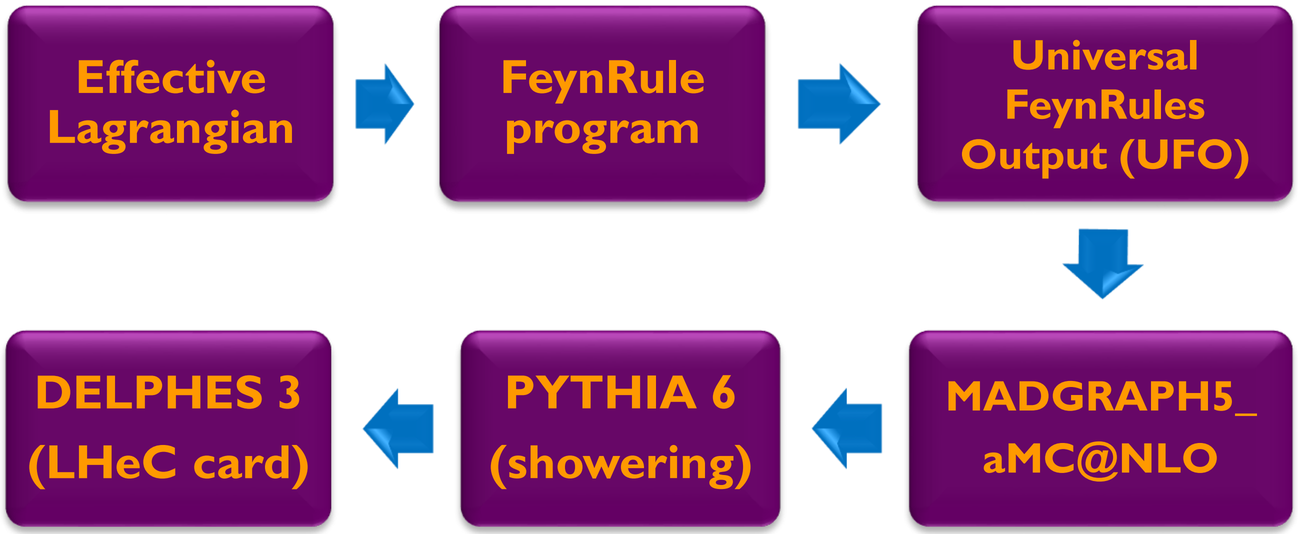
- Signal process:

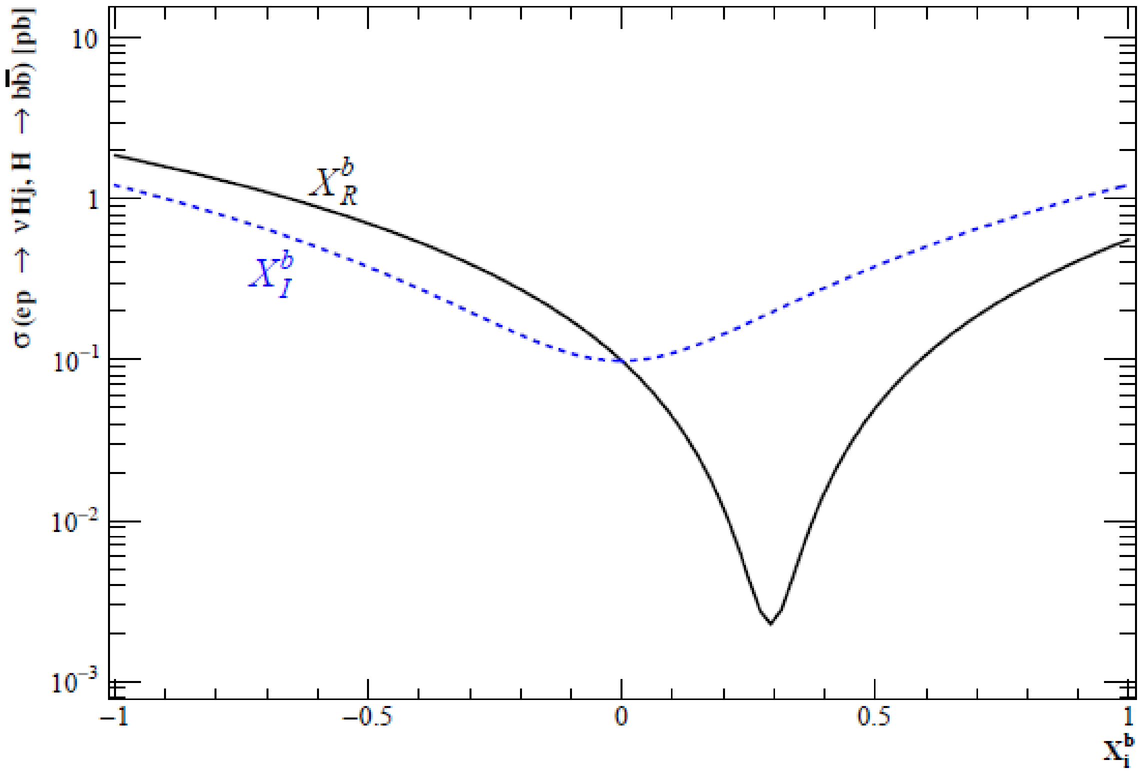
$e^- p \to H j \nu_e$, where $H \to b\bar{b}$ in the effective Lagrangian

- Background processes:

- $e^- p \to Z j \nu_e, Z \to b\bar{b}$
- $e^- p \to Z j \nu_e, Z \to c\bar{c}$
- $e^- p \to Z j \nu_e, Z \to jj$
- $e^- p \to b\bar{b} j \nu_e$
- $e^- p \to c\bar{c} j \nu_e$
- $e^- p \to \bar{t} j \nu_e, \bar{t} \to W^- \bar{b}, W^- \to jj$
- $e^- p \to H j \nu_e, H \to b\bar{b}$ in the SM

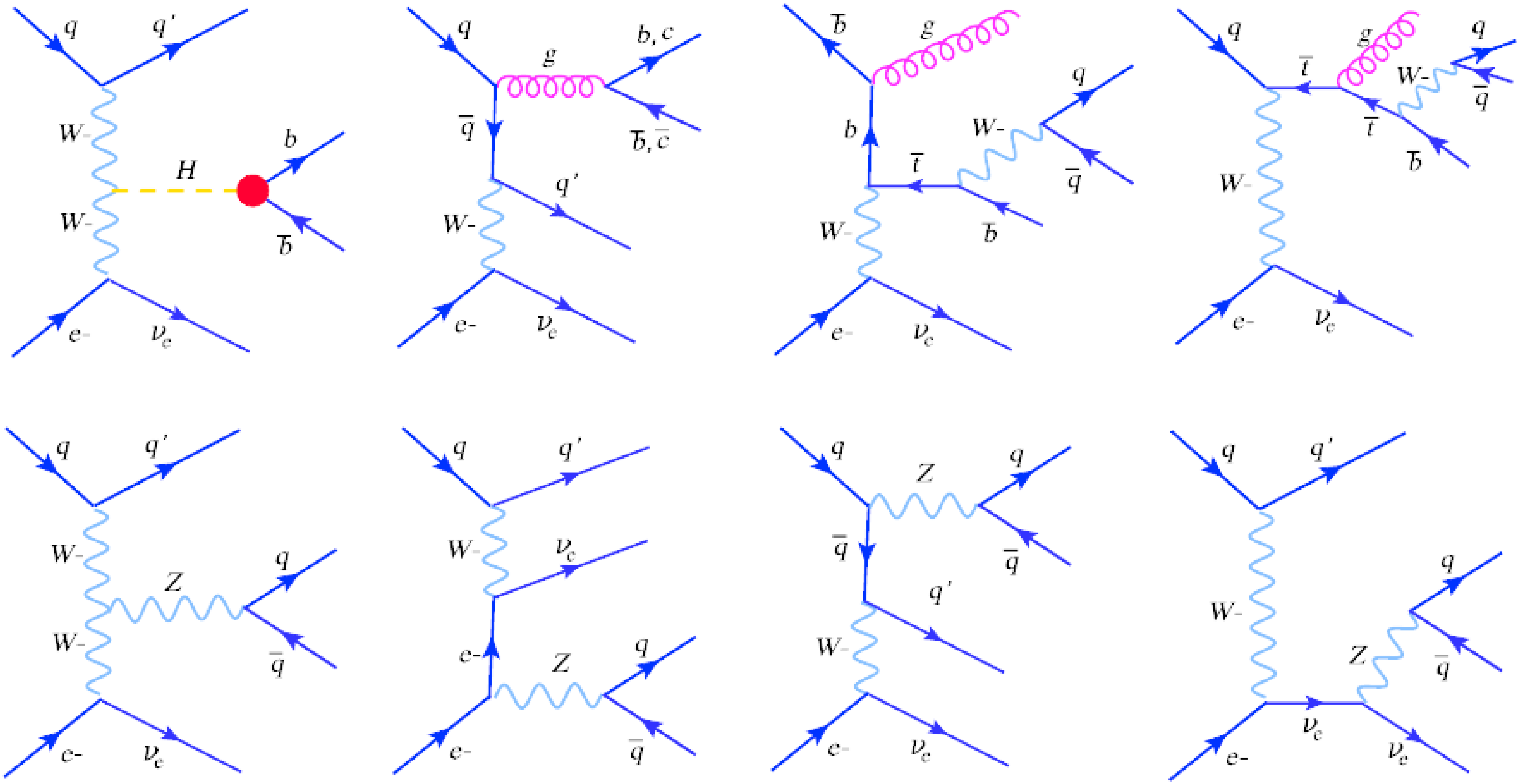
DATA SIMULATION





- Two different signal samples ≡ Two I and R coefficients
- Dimension-six operator coefficients $X_{I,R}$, with Λ = 1 TeV.

DATA SIMULATION



ANALYSIS STRATEGY

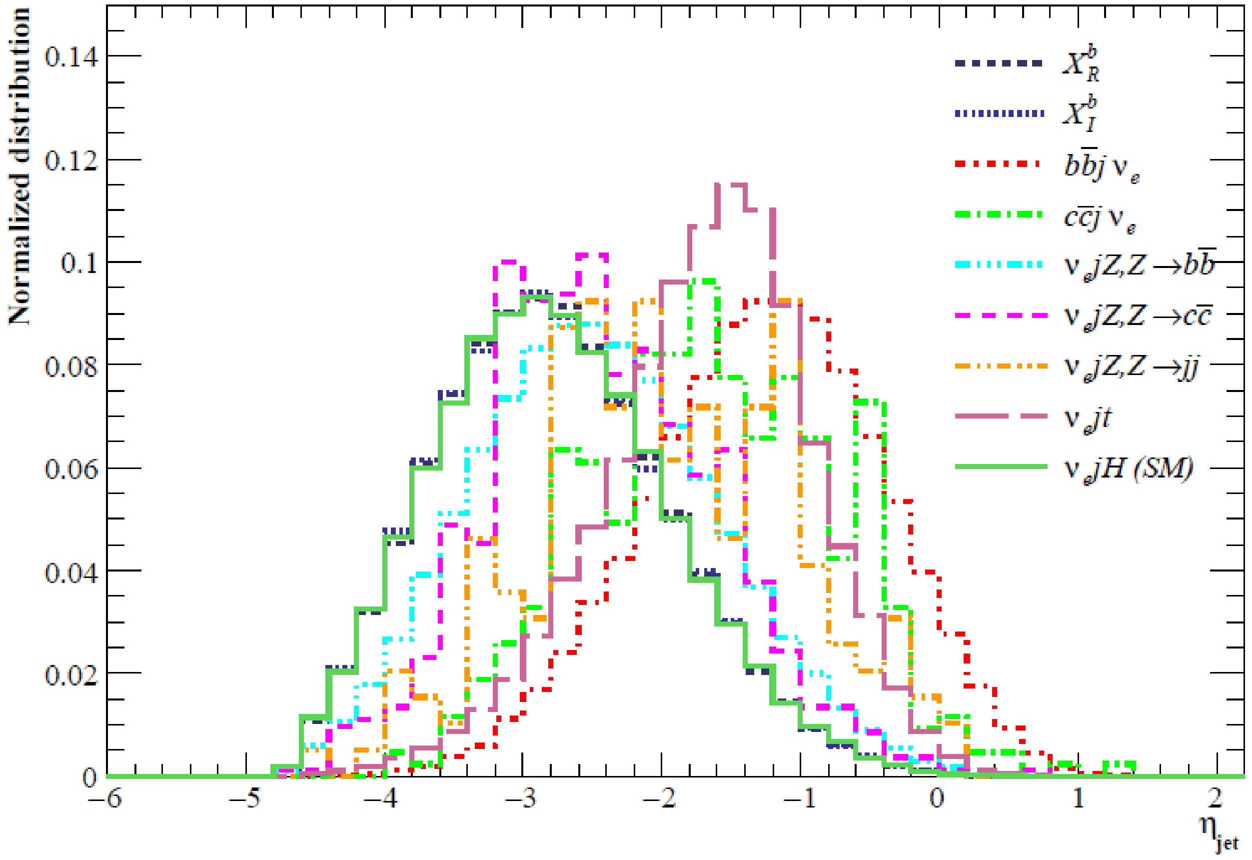
Event selection (pre-selection cuts)

- Exactly 2 b-tagged jet
- At least 3 jets (Including 1 forward jet)

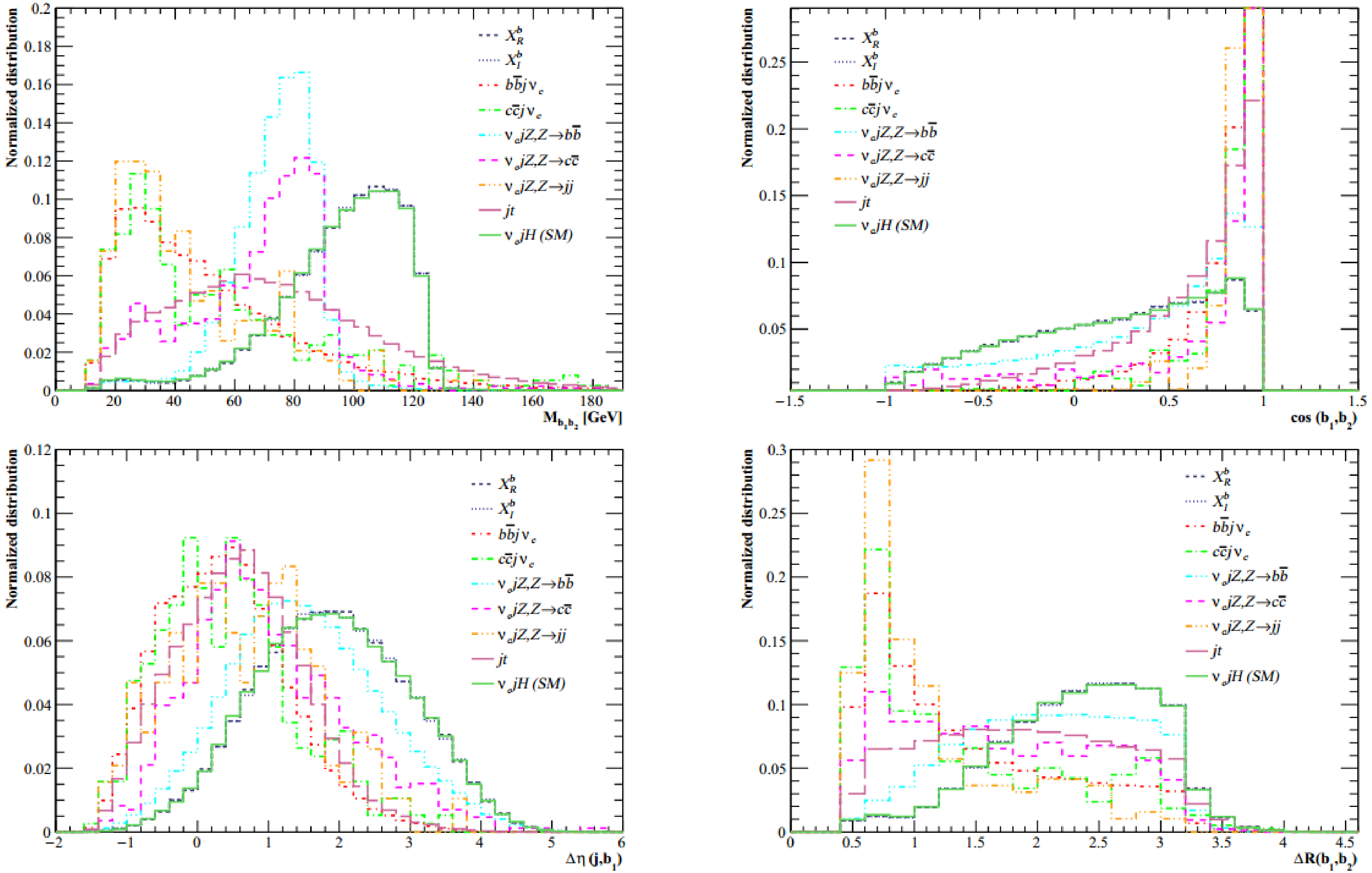
- $P_T > 20$ GeV for all jets
- $|\eta| \leq 2.5$ for b-tagged jets
- $\Delta R > 0.5$ GeV for all objects
- $-5 \leq \eta \leq 1$ for forward jet

To enhance the sensitivity, we perform a multivariate analysis (MVA)

Pseudorapidity of the forward jet in ep collision



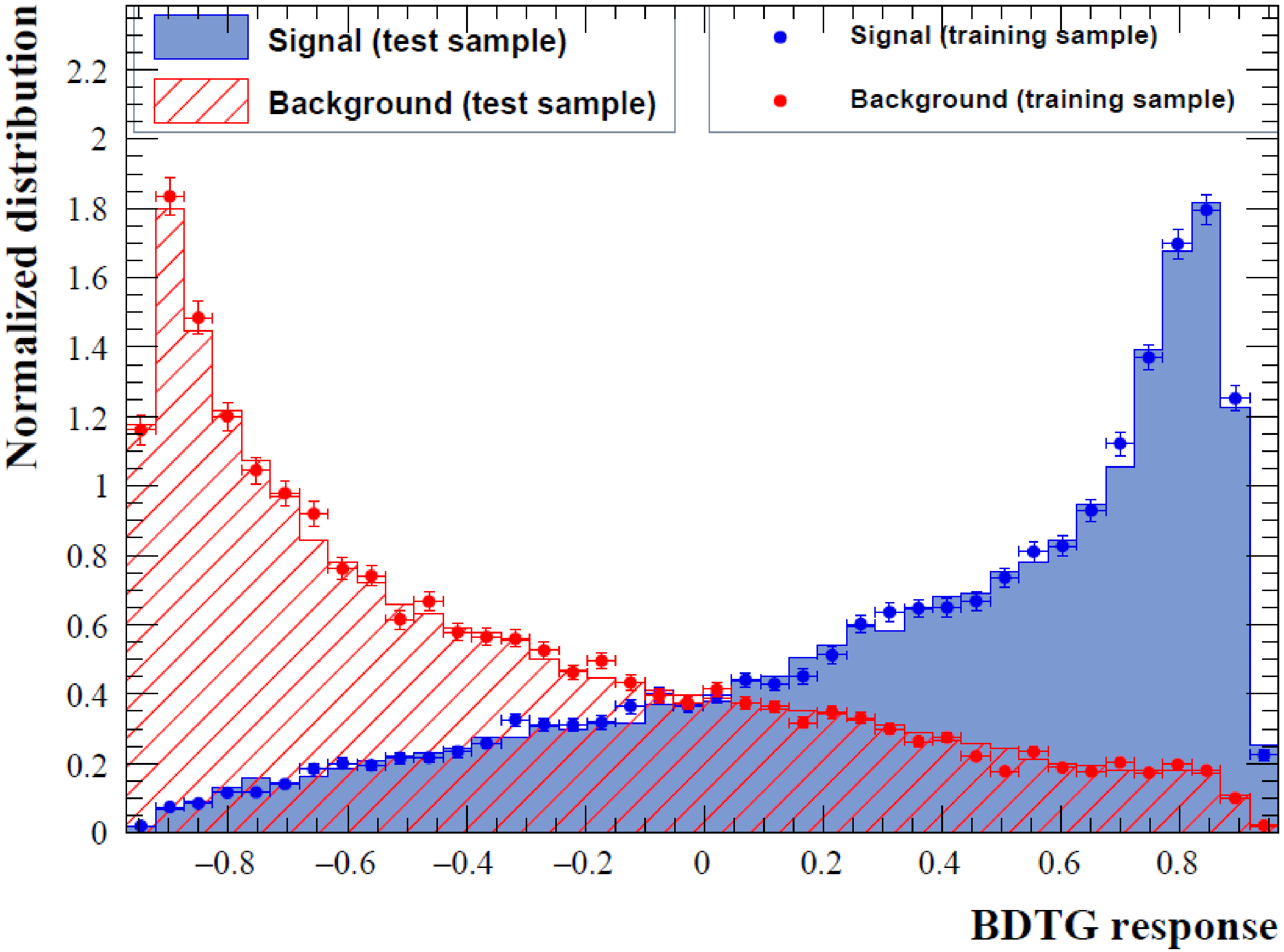
ANALYSIS STRATEGY



ANALYSIS STRATEGY

- **MVA classification output:**

Gradient Boosted Decision Tree



ANALYSIS STRATEGY

- **The efficiencies for signal with $X_I^b = 1.0$ and SM backgrounds**

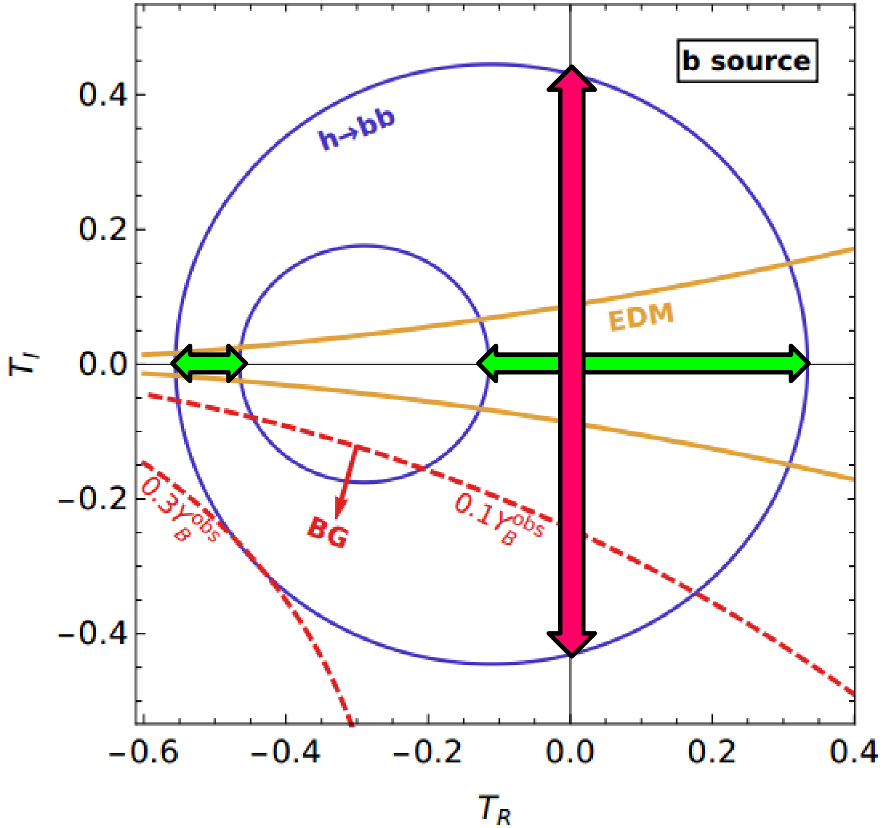
$\sqrt{s}$ [TeV]	Cuts	X_I^b	$Hj\nu$ (SM)	$b\bar{b}j\nu$	$c\bar{c}j\nu$	$Zj\nu(b\bar{b})$	$Zj\nu(c\bar{c})$	$Zj\nu(j_\ell j_\ell)$	$\bar{t}j\nu$
1.3	preselection	0.096	0.086	0.076	4.1×10^{-4}	0.151	7.9×10^{-4}	1.7×10^{-4}	0.086
	MVA	0.085	0.075	8.6×10^{-3}	7.5×10^{-5}	0.090	3.7×10^{-4}	4.4×10^{-5}	0.021
3.46	preselection	0.075	0.066	0.093	2.4×10^{-4}	0.095	4.7×10^{-4}	1.2×10^{-4}	0.042
	MVA	0.066	0.058	0.007	4.6×10^{-5}	0.063	2.8×10^{-4}	5.2×10^{-5}	0.011

RESULTS

- **The coefficients bounds at 95% CL:**

$\sqrt{s}$[TeV], $\mathcal{L}$[ab^{-1}]	X_R^b	X_I^b
1.3, 1	$[-0.0070, 0.609]$	$[-0.0475, 0.087]$
1.3, 2	$[-0.0049, 0.607]$	$[-0.0378, 0.078]$
1.3, 10	$[-0.0022, 0.605]$	$[-0.0213, 0.062]$
3.46, 1	$[-0.0052, 0.596]$	$[-0.0402, 0.076]$
3.46, 2	$[-0.0037, 0.594]$	$[-0.0319, 0.068]$
3.46, 10	$[-0.0016, 0.592]$	$[-0.0179, 0.053]$
arXiv:2003.00099	$\sim [-0.29, -0.25] \cup [-0.07, 0.02]$	$\sim [-0.42, 0.43]$

$$X_i^b \equiv \frac{2\Lambda^2}{v^2} y_b T_i^b ,$$



CONCLUSION

- After the Higgs boson discovery, the focus shifted toward understanding its couplings to other particles, in particular to the fermions. CP violation in the Higgs sector impact on baryogensis
- The Yukawa coupling of h to the 3rd generation fermions is larger.
- A crucial aspect is the measurement of the b-quark Yukawa coupling, and the observation of the H → bb decay remains very challenging at the LHC.
- Recently, there has been a consideration for high energy ep collisions with very exiting prospects.
- Effective Lagrangian with dimension-six operators is used to constrain b Yukawa coupling.
- Data simulation for the LHeC and FCC-eh benchmarks.
- A MVA approach with BDTG method is applied to suppress the background contributions.
- Limits at 95% CL on the coupling coefficients have been obtained for two center-of-mass energies of the LHeC and FCC-eh.
- We show that the MVA increases the sensitivity to the b-quark Yukawa couplings.

فضای هر ظرفی در اثر محتوای خود تنگ‌تر می‌شود مگر ظرف دانش که با تحصیل علوم، فضای آن بازتر می‌گردد.

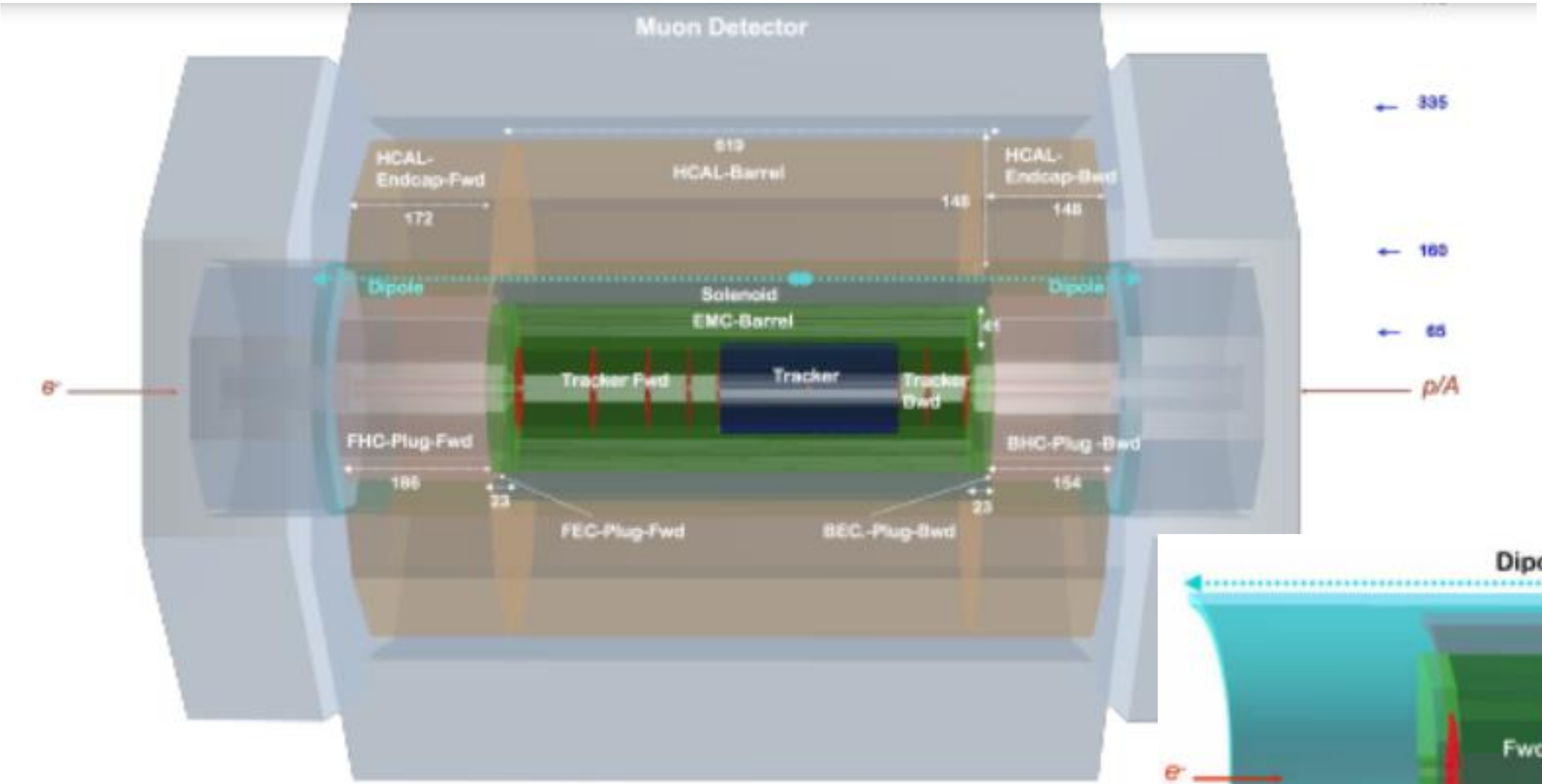
حضرت علی (ع)

BACKUP

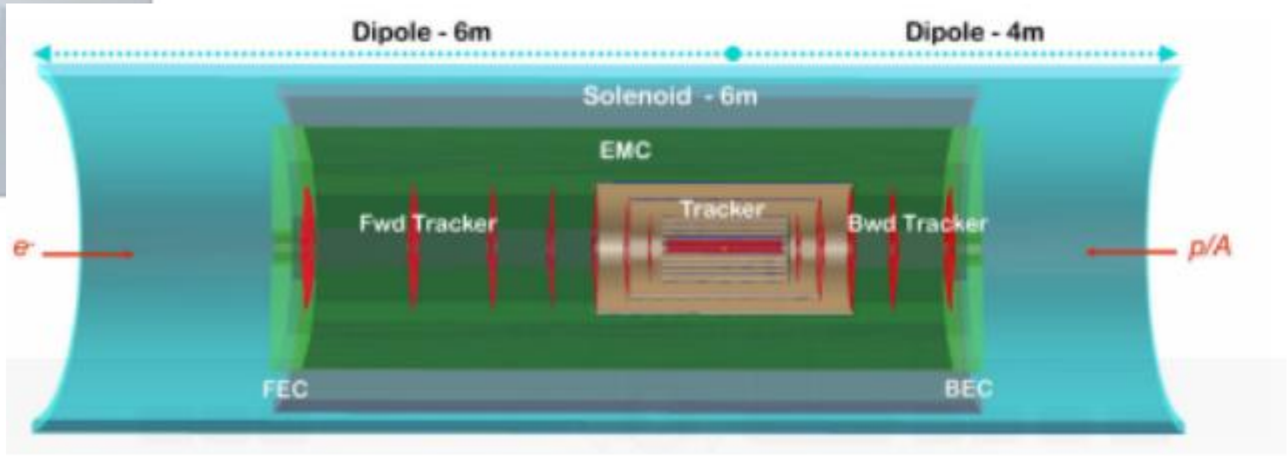
$\sqrt{s}$ [TeV]	$X_I^b = 1.0$	$X_R^b = 1.0$	$Hj\nu$ (SM)	$bbj\nu$	$c\bar{c}j\nu$	$Zj\nu(bb)$	$Zj\nu(c\bar{c})$	$Zj\nu(j_\ell j_\ell)$	$\bar{t}j\nu$
1.3	917.31	425.64	76.67	163.29	253.51	73.48	58.08	207.18	500.77
3.46	3148.5	1465.4	261.68	404.47	723.39	291.51	229.41	817.45	5170.2

The cross sections of $e^- p \to Hj\nu_e$ where the Higgs decays to $b\bar{b}$ as the signal, and main background processes, in unit of fb. The cross section of two signal scenarios are presented according to $X_I^b = 1.0$, $X_R^b = 1.0$, and $\Lambda = 1$ TeV.

BACKUP



Muon Detector
HCAL-Endcap-Fwd
613
HCAL-Barrel
HCAL-Endcap-Bwd
172
148
148
335
160
65
Dipole
Solenoid
Dipole
EMC-Barrel
41
e-
Tracker Fwd
Tracker
Tracker Bwd
p/A
FHC-Plug-Fwd
BHC-Plug -Bwd
186
154
23
23
FEC-Plug-Fwd
BEC.-Plug-Bwd



Dipole - 6m
Dipole - 4m
Solenoid - 6m
EMC
Fwd Tracker
Tracker
Bwd Tracker
e-
p/A
FEC
BEC

BACKUP