BSM Physics @ ep Colliders

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DESY Theory - Fellow's Meeting 2017
Dec. 12, 2017

Outline

Self-introduction

ep Colliders: LHeC / FCC-eh

Singly Charged Higgs

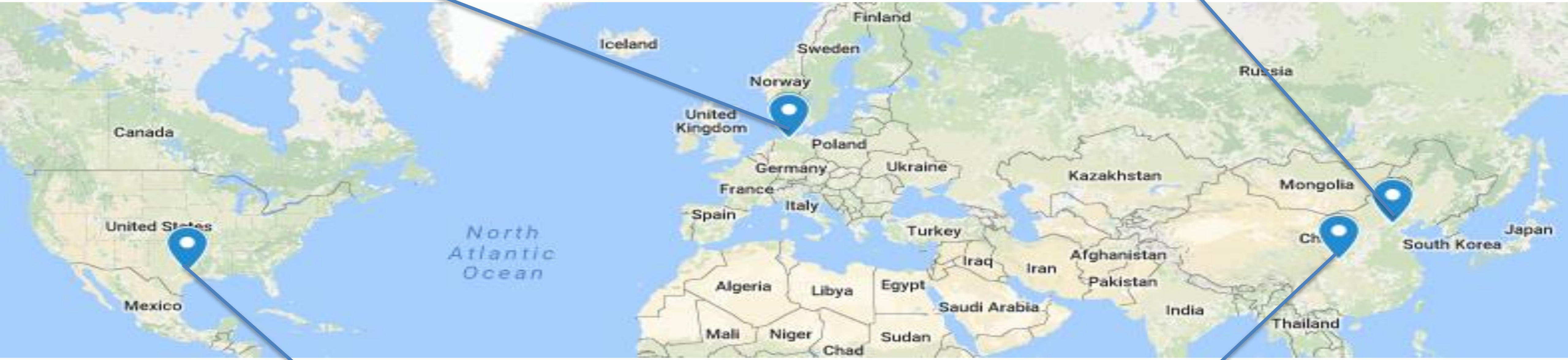
[by Georges Azuelos, Hao Sun, and Kechen Wang]

Summary

Personal Experience

Postdoc in DESY
March 2016 – March 2018
Hosted by *Christophe Grojean*

Postdoc in CFHEP, IHEP, Beijing
Aim to build CEPC & SPPC in China
September 2014 – March 2016



Ph. D. in Texas A&M U, US
August 2008 - August 2014
Advisor: *Bhaskar Dutta*

Born in Hanzhong, China

Research Interests

Phenomenology of BSM physics at *pp*, e^-e^+, *ep* colliders

- SUSY particle searches
  - Stop search @ *pp* colliders (LHC)
    Stop coannihilation, Bino-Higgsino DM, fully hadronic final state, Compressed scenarios.
  - EW sector search @ *pp*, *ep*
    Slepton, SUSY DM using VBF.

- Higgs physics
  - Higgs @ *pp*, e^-e^+ (CEPC, ILC, CLIC)
    Constraining a Natural SUSY Model ← Higgs coupling measurements;
    Constraining EFT Operators ← Higgs measurements in $e^+ e^- \to HZ$ & $e^+ e^- \to WW$.
  - BSM Higgs @ *ep*

- Neutrino physics
  - Sterile neutrinos @ *pp*
    Discovering & Distinguishing Dirac / Majorana ← tri-lepton final state
    Discovering @ 100 TeV ← $2l + 2j$ final state
  - Sterile neutrinos @ *ep*

Intersection of particle physics, cosmology and astrophysics

- Dark matter, Axion

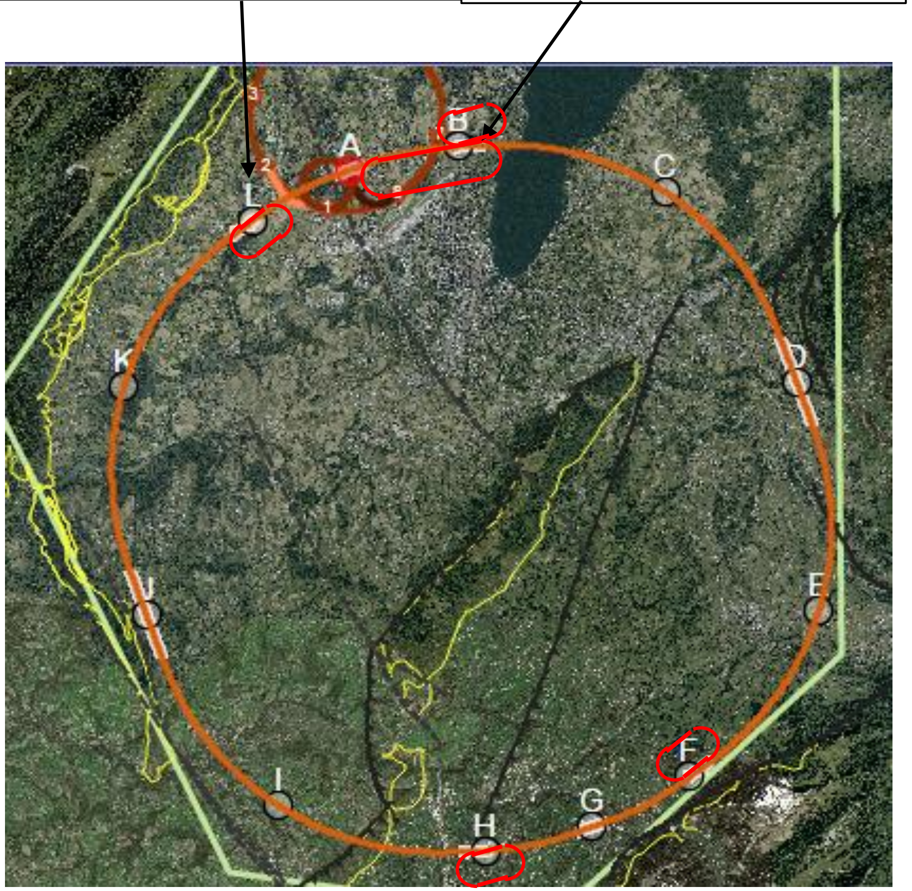
ep Collider Design

Slide based on [Oliver Brüning, FCC week 2017 in Berlin, “FCC-eh Configuration and Performance”]

Layout & Civil Engineering

[C. Cook @ FCC week in Rome]

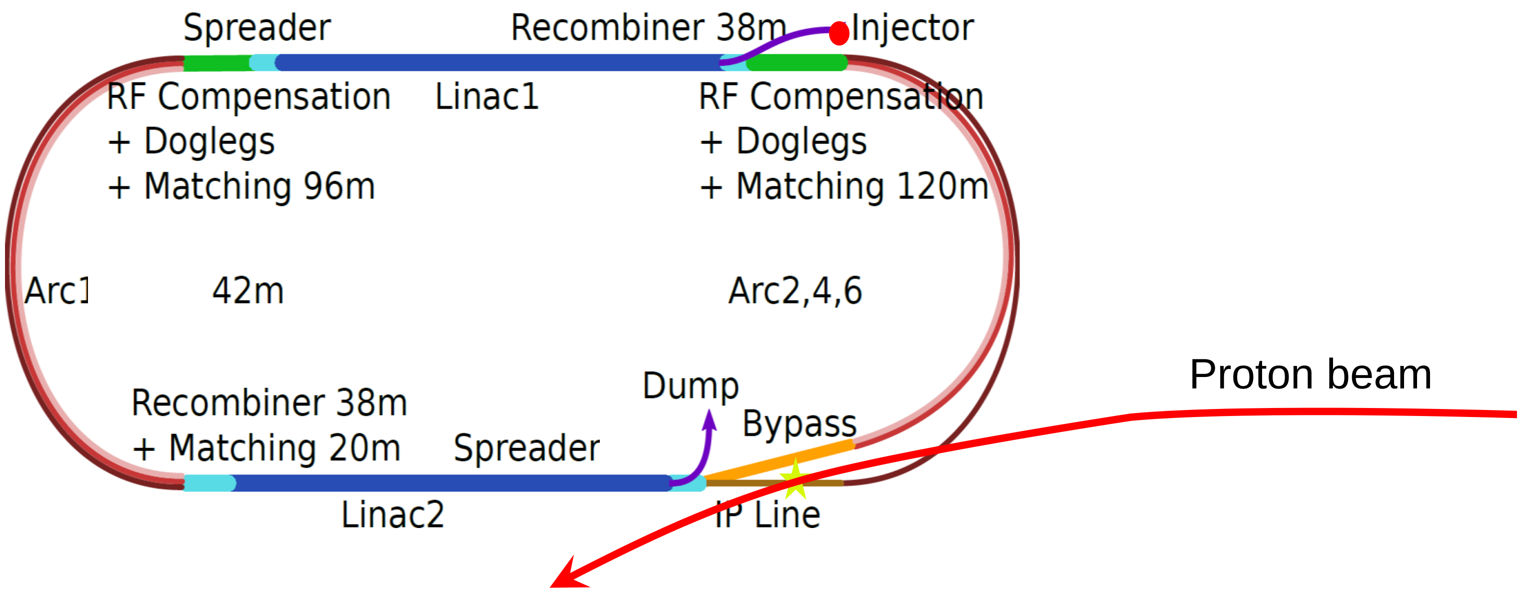
Independent FCC-he Point L, F, H or B	LHeC / FCC-he LHC P8 & FCC PB



Electron Beam

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

LHeC, HE-LHeC, FCC-eh Baselines

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [$10^{33}\text{cm}^{-2}\text{s}^{-1}$]	1	8	12	15

[EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, "A Baseline for the FCC-he"]

[Oliver Brüning, John Jowett, Max Klein, Dario Pellegrini, Daniel Schulte, Frank Zimmermann]

BSM Topics @ ep Colliders

★ Indirect impact from improved PDF

★ Direct Searches
- Leptoquarks: limits, quantum # & couplings
- Contact interactions: eeqq
- Anomalous gauge couplings: VVV, VVVV
- Vector boson scattering
- BSM in the top sector
- RPC SUSY: DM, sleptons
- RPV SUSY: neutralinos, squarks
- BSM Higgs: exotic (invisible) decay, H^{+}, H^{++}
- Sterile neutrinos

★ Ideal to search and study properties of new particles with
→ couplings to electron-quark / vector bosons, EW / VBF production, multi-jets final states

★ Compared with *pp* colliders
→ Some promising: clean environment (samller bkg, low pileup), forward objects
→ Some difficult: small production due to small $\sqrt{s}$

More details,
see [Monica D'Onofrio's talk "BSM searches at FCC-eh *(selected topics)*" in the 1st FCC Physics week, https://indico.cern.ch/event/550509/contributions/2413829/attachments/1398547/2133088/FCCPhysics_BSMJan2017.pdf]
& [Kechen Wang's talk "BSM Physics at Energy-frontier Lepton-hadron Colliders" in the EPS-HEP Conference 2017, https://indico.cern.ch/event/466934/contributions/2583549/attachments/1489690/2314998/EPS-HEP_BSM_at_ep_colliders_2.pdf]

Signal Scenarios for $H_5^{\pm}$ Search

Collider: FCC-eh & LHeC

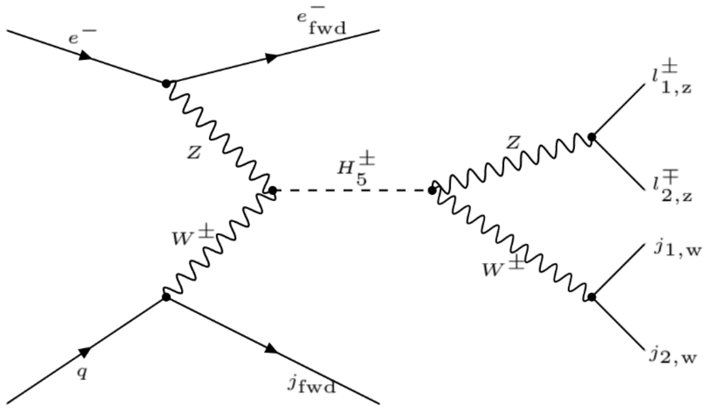
Signal:

Production of H_5^+ & H_5^- in the Georgi – Machacek Model

→ Final state: 1 e^- + 1 j + 1 Z(-> l^+ l^-) + 1 W(-> j j); l = e, μ .

→ Simulation by "MadGraph + PYTHIA + Delphes".

→ BDT analysis.



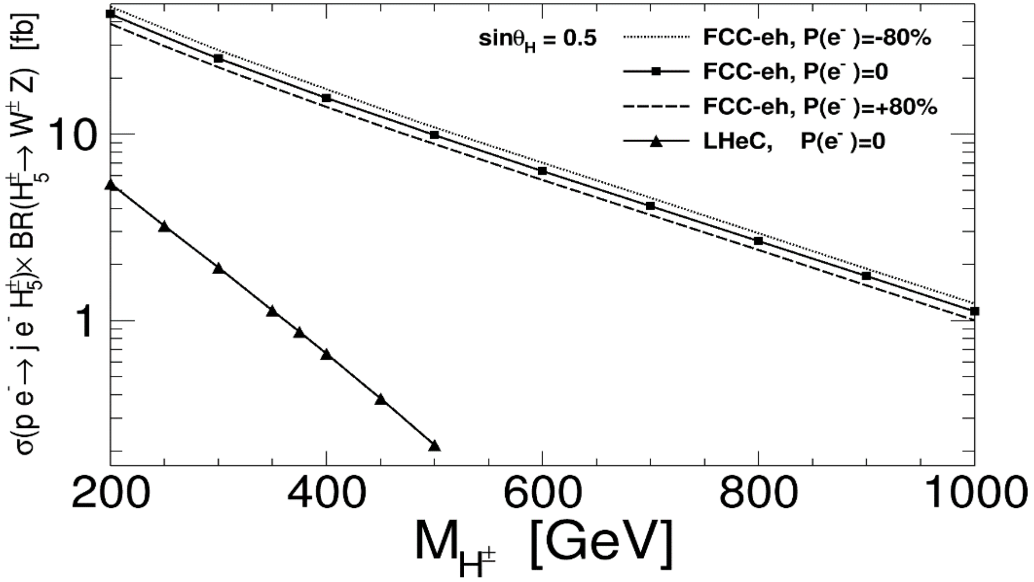
Final state:

1 e^- + 1 j + 1 Z(-> l^+ l^-) + 1 W(-> j j)

l = e, μ

Signal production cross section

p e^- → j e^- $H_5^{\pm}$, ($H_5^{\pm}$ → Z $W^{\pm}$)



Background1: p e- > j e- z v

generate p e- > j e- z w+, z > l+ l-, w+ > j j

add process p e- > j e- z w-, z > l+ l-, w- > j j

add process p e- > j e- z z, z > l+ l-, z > j j

Background2: jets from QCD radiation

generate p e- > j e- z j j, z > l+ l-

Strategy for $H_5^{\pm}$ Search

Final state:
$1\ e^- + 1\ j + 1\ Z(\to l^+ l^-) + 1\ W(\to j\ j)$
$l = e, \mu$

Simulation by "MadGraph + PYTHIA + Delphes".

Pre-selection cuts:

(1) selecting at least 3 jets with $p_T > 20$ GeV;
(2) selecting at least 3 leptons with $p_T > 10$ GeV,
and requiring charges (e^-, e^-, e^+) or (e^-, μ^+, μ^-);
(3) veto b-jets with $p_T > 20$ GeV;
(4) veto taus with $p_T > 10$ GeV.

→ 2 jets with invariant mass closest to the W mass are considered as the jets from W decay.
→ (μ^+, μ^-), or (e^-, e^+) with invariant mass closet to the Z mass are considered as the leptons from Z decay

Analysis at detector-level using the BDT method.

Input observables for BDT Training & Test:

MET, H_T;

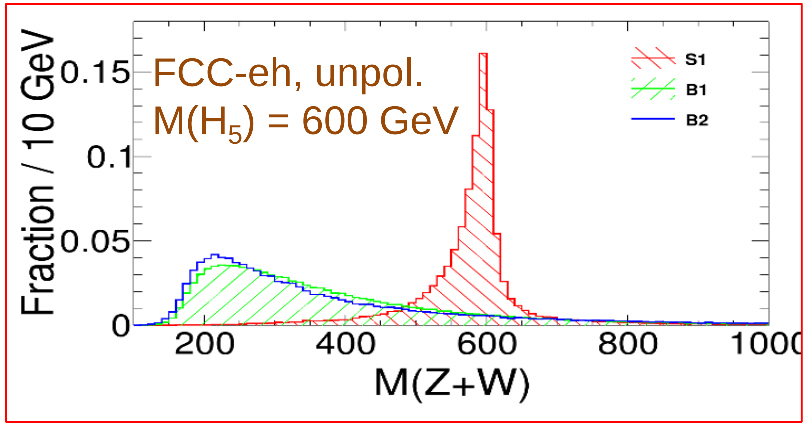
$p_T(e_{fwd})$, $\eta(e_{fwd})$, $p_T(j_{fwd})$, $\eta(j_{fwd})$,
$p_T(e_{fwd}+j_{fwd})$, $\eta(e_{fwd}+j_{fwd})$, $M(e_{fwd}+j_{fwd})$,
$\Delta\eta(e_{fwd}, j_{fwd})$, $\Delta\varphi(e_{fwd}, j_{fwd})$;

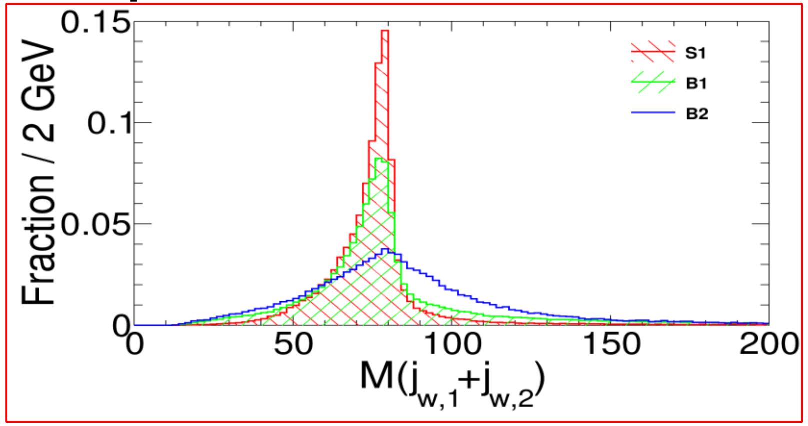
$p_T(j_{w,1})$, $\eta(j_{w,1})$, $p_T(j_{w,2})$, $\eta(j_{w,2})$,
$p_T(j_{w,1}+j_{w,2})$, $\eta(j_{w,1}+j_{w,2})$, $M(j_{w,1}+j_{w,2})$,
$\Delta\eta(j_{w,1}, j_{w,2})$, $\Delta\varphi(j_{w,1}, j_{w,2})$;

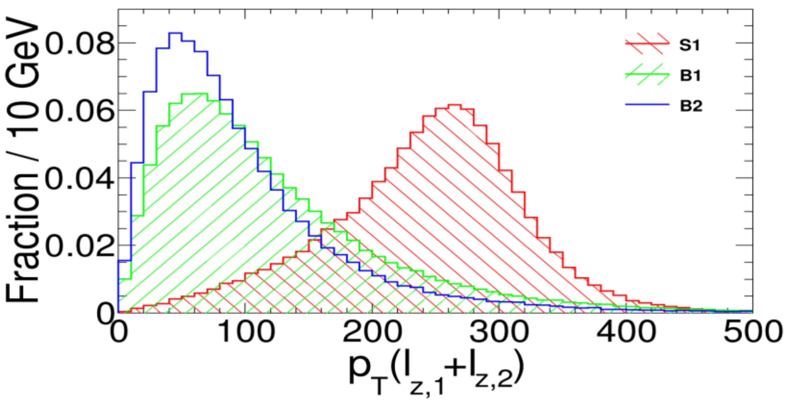
$p_T(l_{z,1})$, $\eta(l_{z,1})$, $p_T(l_{z,2})$, $\eta(l_{z,2})$,
$p_T(l_{z,1}+l_{z,2})$, $\eta(l_{z,1}+l_{z,2})$, $M(l_{z,1}+l_{z,2})$,
$\Delta\eta(l_{z,1}, l_{z,2})$, $\Delta\varphi(l_{z,1}, l_{z,2})$;

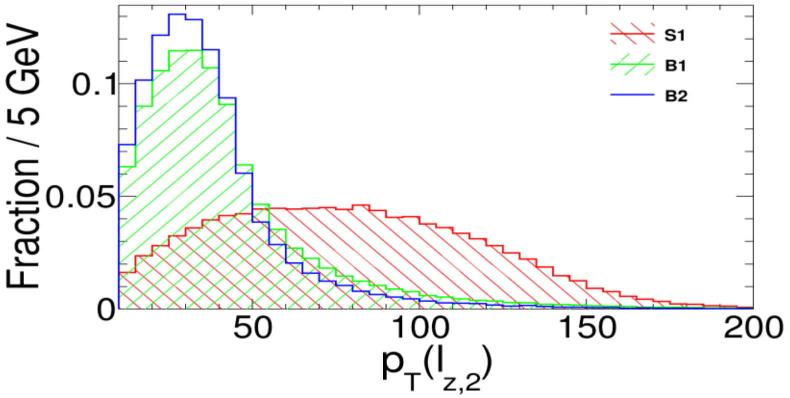
$p_T(Z+W)$, $\eta(Z+W)$, $M(Z+W)$,
$\Delta\eta(Z, W)$, $\Delta\varphi(Z, W)$.

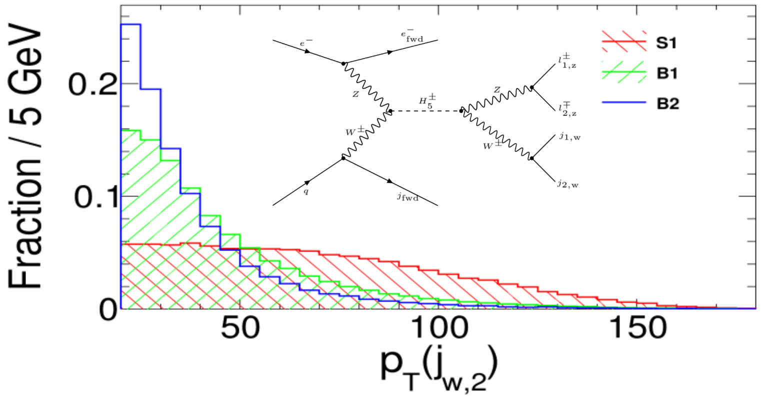
Input Observables

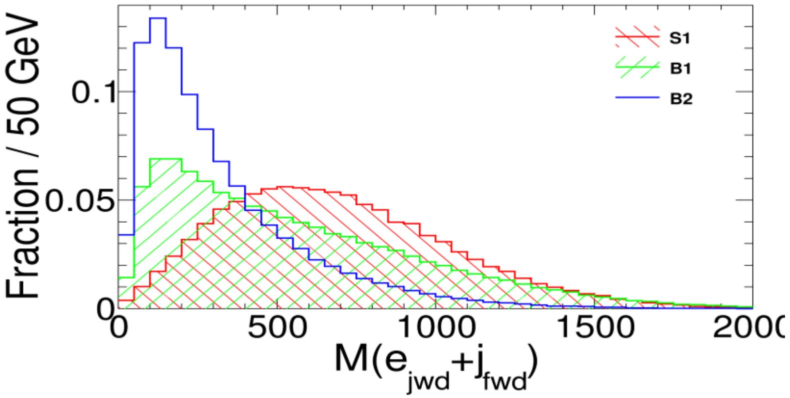


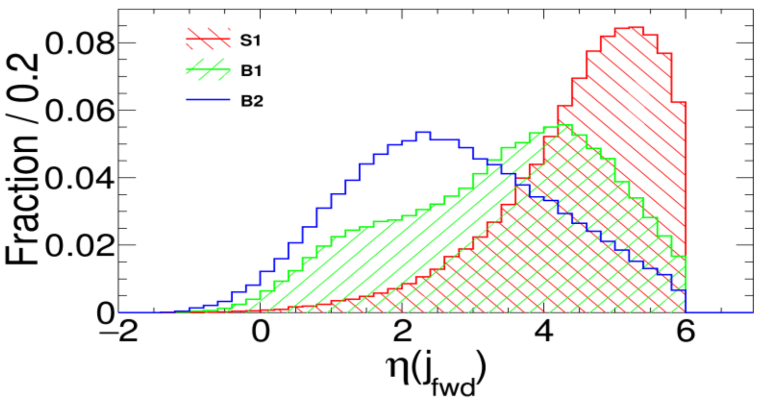


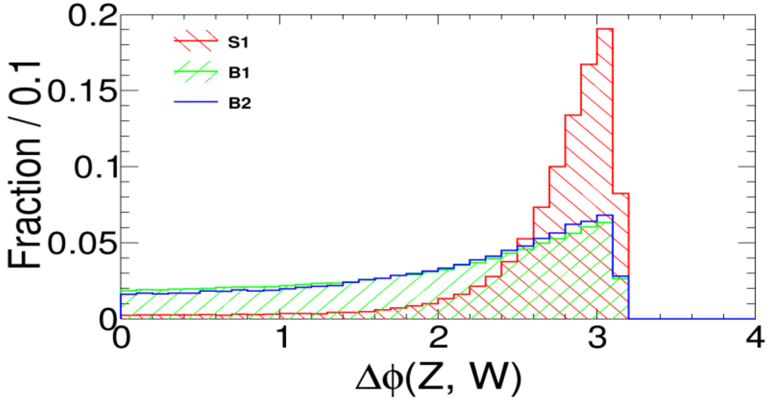


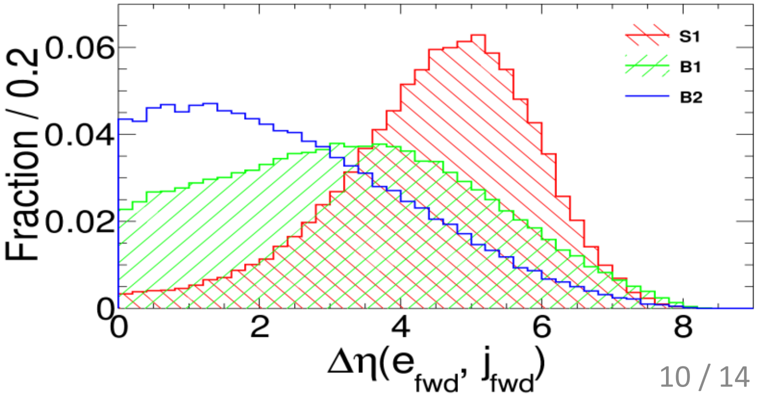






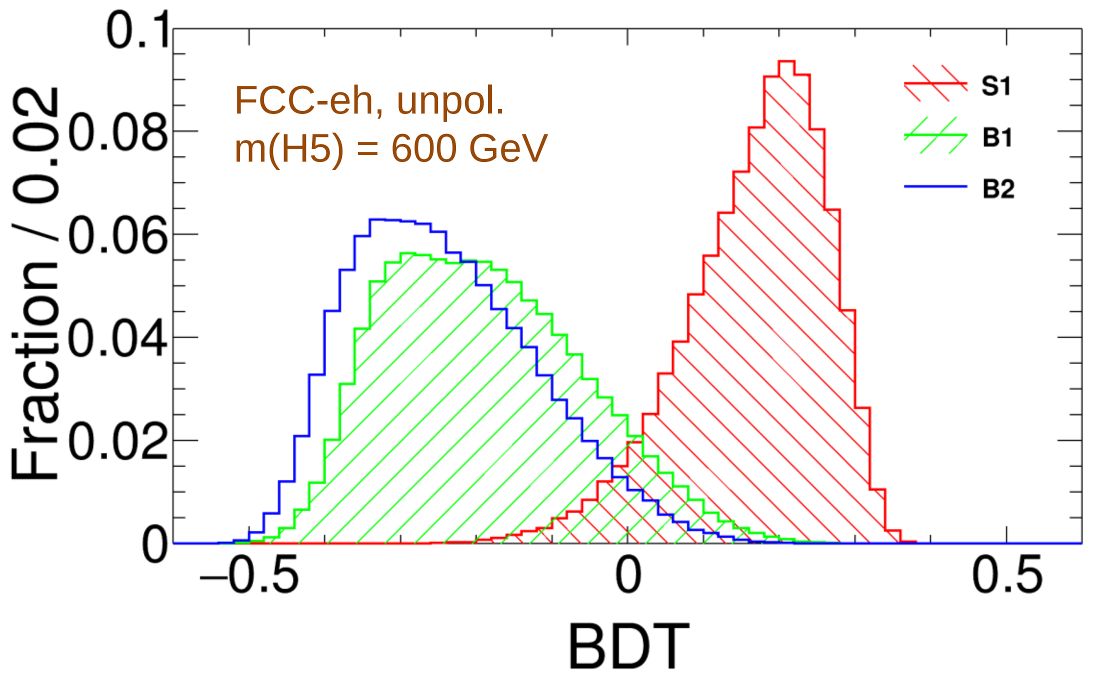






Significances for $H_5^{\pm}$ Search

BDT Distribution



$$SS = \sqrt{2[(N_s + N_b)\ln(1 + \frac{N_s}{N_b}) - N_s]}$$ = Significance1

with sys. unc. $\sigma_b = 10\% \, N_b$

$$SS = \left[2\left((N_s + N_b)\ln\frac{(N_s + N_b)(N_b + \sigma_b^2)}{N_b^2 + (N_s + N_b)\sigma_b^2} - \frac{N_b^2}{\sigma_b^2}\ln(1 + \frac{\sigma_b^2 N_s}{N_b(N_b + \sigma_b^2)})\right)\right]^{1/2}$$ = Significance2

@FCC-eh, unpol., 1 ab^{-1}
Cut-flow table for m(H5) = 600 GeV & sinθ = 0.5

# of events	Signal	Background1	Background2
inital production	260	1.09×10^4	1.52×10^5
pre-selection	102	751	6442
BDT > 0.189	48	1.7	1.7
Significance1	13.5		
Significance2	12.7		

@ **LHeC**, unpol., 1 ab^{-1}
Cut-flow table for m(H5) = 200 GeV & sinθ = 0.5

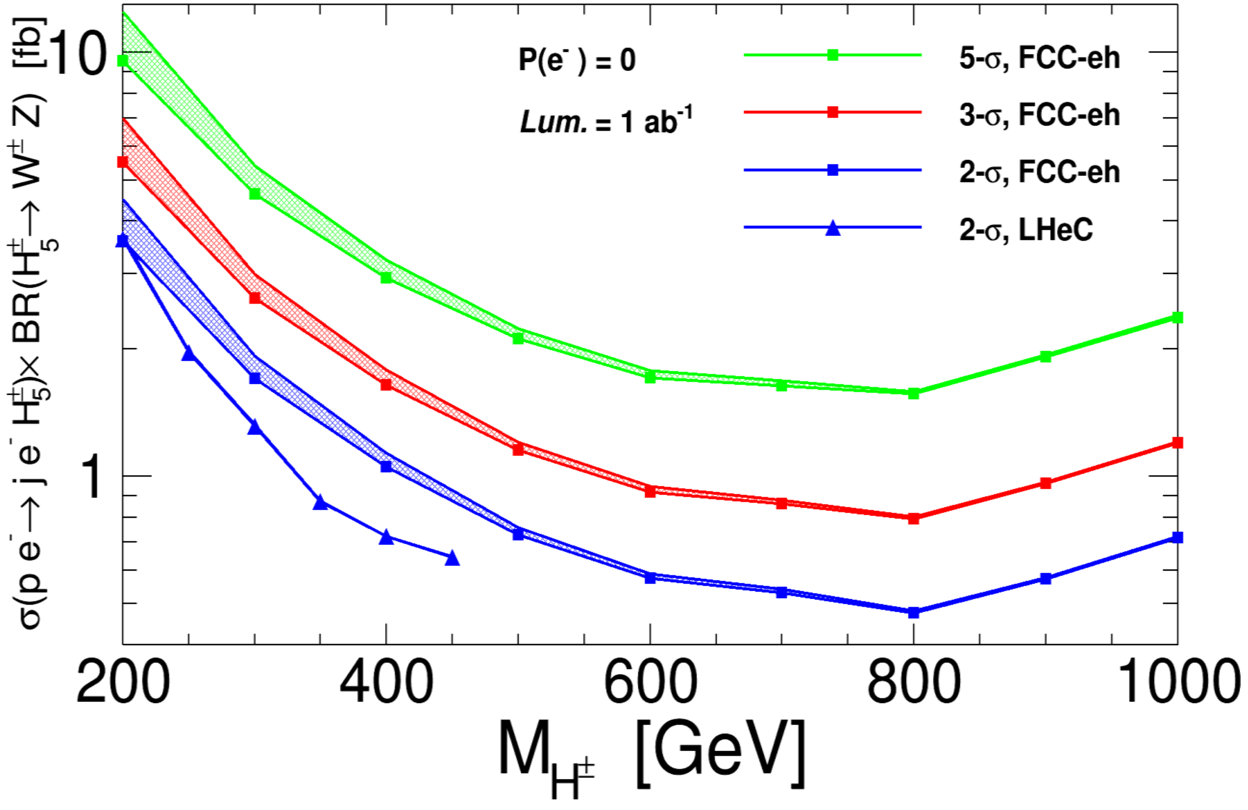
# of events	Signal	Background1	Background2
inital production	220	531	3.19×10^4
pre-selection	13	11	148
BDT > 0.119	4.9	0.2	0.8
Significance1	3.35		
Significance2	3.32		

Limits for $H_5^\pm$ Search

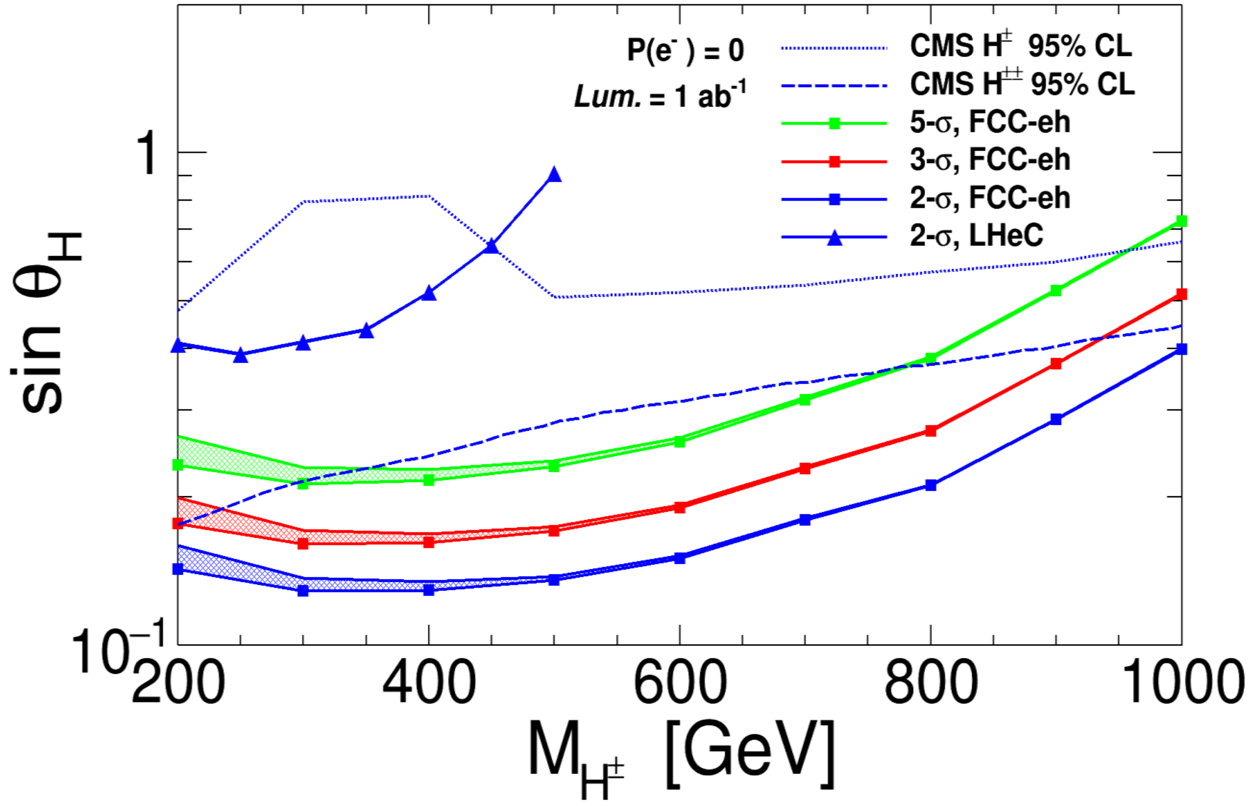
Limits at LHeC & FCC-eh

→ 10% systematic uncertainty on background included

"production cross section vs. Mass" contour curve



"sinθ vs. Mass" contour curve



Effects of Electron Beam Polarization

@FCC-eh, **P(e$^-$) = +80%**, 1 ab^{-1}
Cut-flow table for m(H5) = 600 GeV & sinθ = 0.5

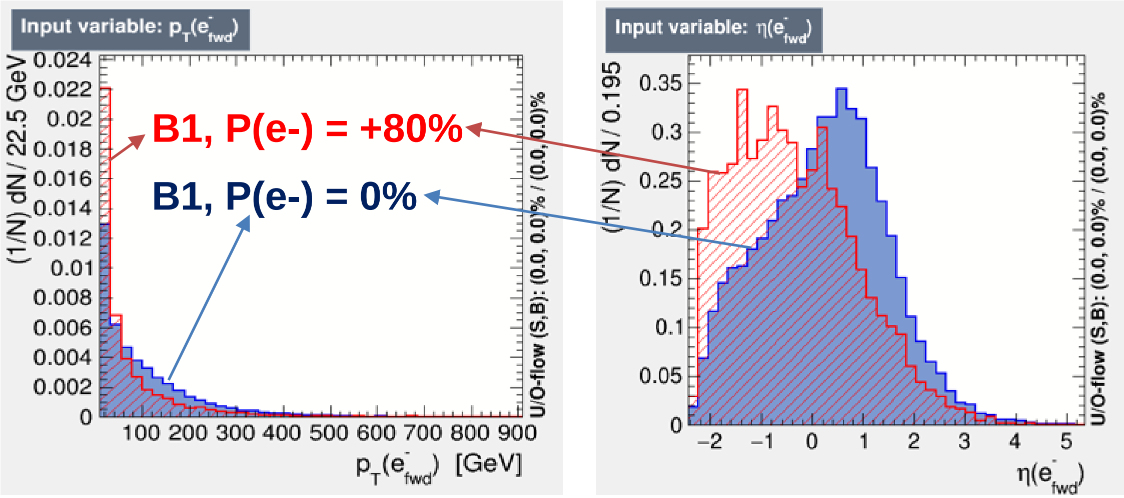
# of events	Signal	Background1	Background2
inital production	232	9615	1.16×10^5
pre-selection	91	330	3700
BDT > 0.186	43	0.8	1.5
Significance2	13.4		
Significance3	12.8		

@FCC-eh, **P(e$^-$) = -80%**, 1 ab^{-1}
Cut-flow table for m(H5) = 600 GeV & sinθ = 0.5

# of events	Signal	Background1	Background2
inital production	288	1.23×10^4	1.90×10^5
pre-selection	112	1191	9265
BDT > 0.188	49	2.2	1.8
Significance2	13.2		
Significance3	12.4		

@FCC-eh, **unpolarized**, 1 ab^{-1}
Cut-flow table for m(H5) = 600 GeV & sinθ = 0.5

# of events	Signal	Background1	Background2
inital production	260	1.09×10^4	1.52×10^5
pre-selection	102	751	6442
BDT > 0.189	48	1.7	1.7
Significance1	13.5		
Significance2	12.7		



Summary

★ ep colliders: LHeC, HE-LHeC, FCC-eh
→ Could be done in parallel to HL-LHC by adding an electron beam to the pp machines, and later also to a High-energy LHC, and FCC-hh

★ ep offers a variety of opportunities for BSM searches
→ Improving pp limits indirectly by improved PDF (@ high and low x)
→ Direct searches:
Leptoquarks, Contact interactions, Anomalous gauge couplings, Vector boson scattering, BSM top physics, SUSY (RPV & RPC), BSM Higgs, Sterile neutrinos...

★ Search for $H_5^{\pm}$ in the GM model at the LHeC & FCC-eh
→ 2 free model parameters M(H_5), $\sin\theta_H$;
→ Production via VBF ;
→ Final state: 1 e^- + 1 j + 1 Z(-> l^+ l^-) + 1 W(-> j j) ;
→ Detector-level analysis using the BDT method ;
→ limits on $\sin\theta_H$ @FCC-eh & LHeC, 1 ab^{-1} , unpol. e^- beam
→ Increasement from electron beam polarization is limited.

Backup Slide

Georgi – Machacek (GM) Model

Scalar sector of the GM model:

complex isospin doublet (ϕ^+, ϕ^0) with hypercharge Y=1 ;
real triplet $(\xi^+,\ \xi^0,\ \xi^-)$ with Y=0;
complex triplet $(\chi^{++},\ \chi^+,\ \chi^0)$ with Y = 2;

→ Scalar potential is chosen to preserve a global $SU(2)_L \times SU(2)_R$ symmetry

Using $SU(2)_L \times SU(2)_R$ covariant forms of the fields:

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix} \qquad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}$$

Signatures of the five-plet in GM model:
[H. Logan, M. Zaro, LHCHXSWG-2015-001]

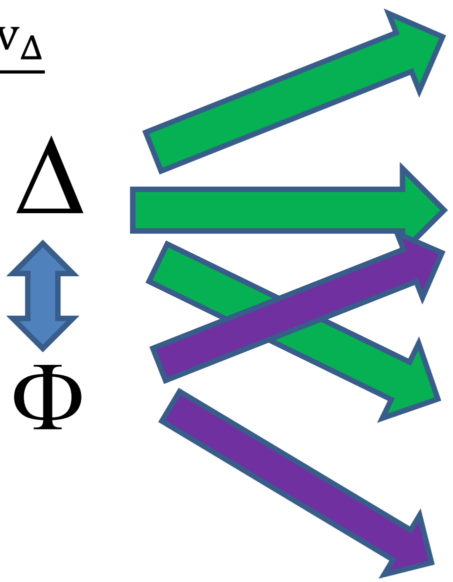
$$v^2 = v_\Phi^2 + 8 v_\Delta^2$$

$$\sin\theta_H = \frac{2\sqrt{2}\, v_\Delta}{v}$$

$$\cos\theta_H = \frac{v_\Phi}{v}$$

mixing : θ_H

Physical fields under the custodial SU(2) symmetry



5 - plet $H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--}$

3 - plet H_3^+, H_3^0, H_3^-

singlet $H_1^{'0}$

mixing : α → H, h

singlet H_1^0

h ⇒ **125GeV Higgs**

- Have a common mass $M(H_5)$;
- Do not couple to fermions;
- Tree-level H_5VV interaction;
- Production via VBF;
- $g(H_5VV) \propto \sin\theta_H$
  => $\sigma(VBF \to H_5) \propto \sin^2\theta_H$;
- $BR(H_5^\pm \to W^\pm Z) \approx 100\ \%$;
  $BR(H_5^{\pm\pm} \to W^\pm W^\pm) \approx 100\ \%$;
- 2 free pars. $M(H_5)$, $\sin\theta_H$.