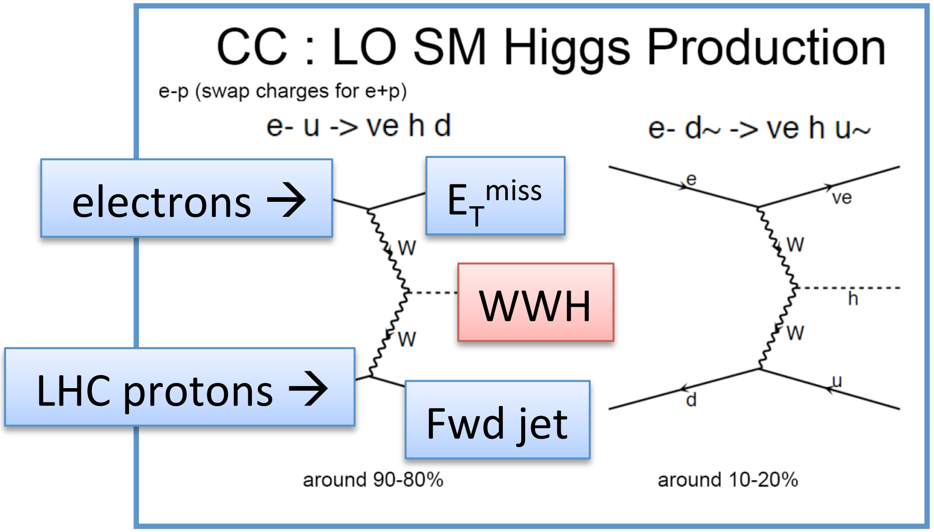
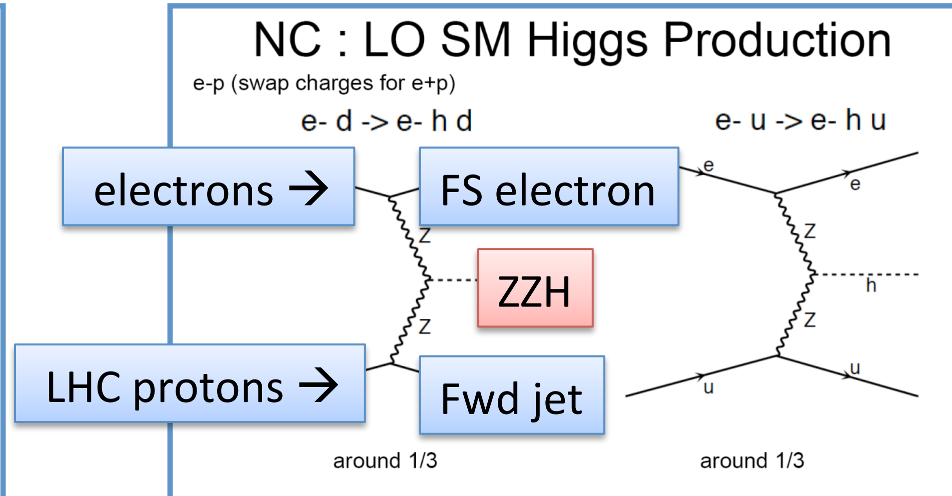
FCC-eh
SM and BSM Higgs Studies

Uta Klein
on behalf of
the LHeC/FCC-eh Higgs Group

FCC Week 2017 Berlin, June 1th, 2017

SM Higgs Production in ep





➔ In ep, direction of quark (FS) is well defined.

σ (LO QCD CTEQ6L1 M_H=125 GeV)

c.m.s. energy	1.3 TeV	3.5 TeV
cross section [fb] NC DIS CC DIS	 21 109	 127 560
CC DIS polarised cross section [fb] P=-80%	**196**	**1008**

•Scale dependencies of the LO calculations are in the range of 5-10%.

• NLO QCD corrections are small, but shape distortions of kinematic distributions up to 20%. QED corrections up to -5%.

[J. Blumlein, G.J. van Oldenborgh , R. Ruckl, Nucl.Phys.B395:35-59,1993]
[B.Jager, arXiv:1001.3789]

Analysis Framework

Event generation

- **SM or BSM production**
- **CC & NC DIS background**

by MadGraph5/MadEvent

↓

- **Fragmentation**
- **Hadronization**

by PYTHIA (modified for ep)

↓

Fast detector simulation

by Delphes

→ test of FCCeh detector

↓

S/B analysis → cuts or BDT

- Calculate cross section with tree-level Feynman diagrams (any UFO) using <u>pT of scattered quark as scale (CDR $\hat{s}$)</u> for ep processes with **MadGraph5**
- Standard HERA tools can NOT to be used !
- **Higgs mass 125 GeV as default**
- Fragmentation & hadronisation uses <u>**ep-customised** Pythia</u>.
- **Delphes 'detector' →displaced vertices and signed impact parameter distributions → studied for LHeC, and used for FCC-eh SM Higgs extrapolations**

→ powerful method to optimise detector tuning and S/N for various Higgs, top and BSM decays

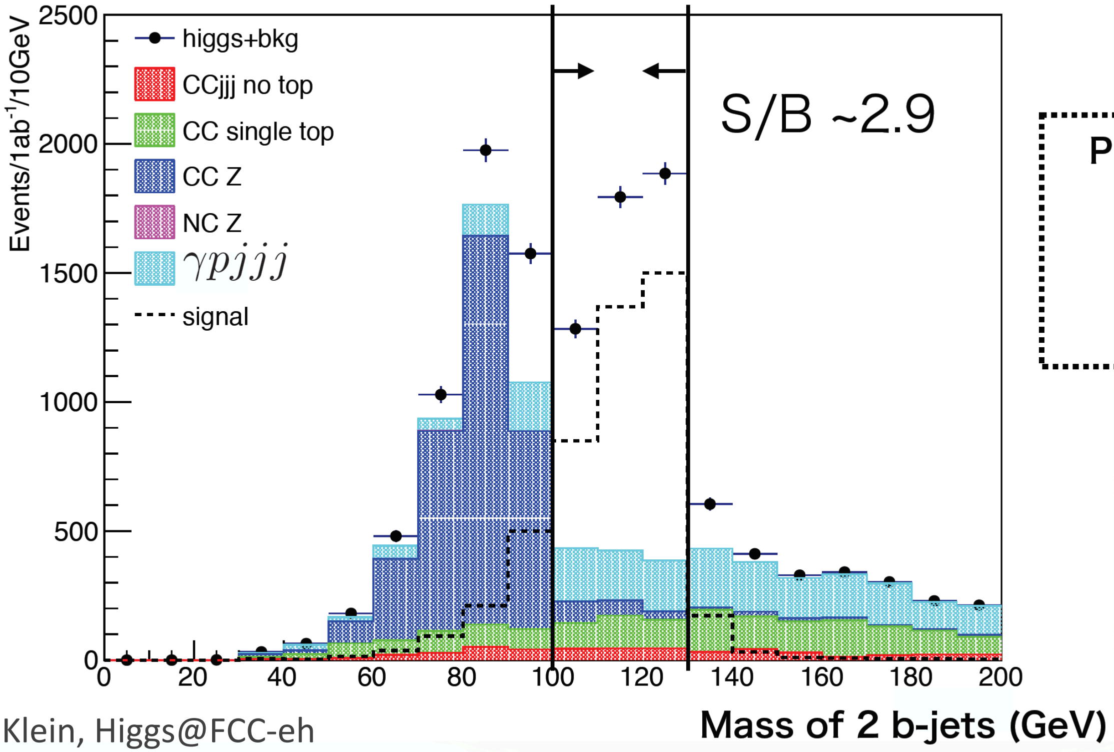
→ Ongoing : Integration of FCCeh into FCC simulation framework

Cut-based Results for Hbb @ LHeC

Masahiro Tanaka, Masahiro Kuze

Various studies pursued since the LHeC CDR [before the Higgs discovery, see http://cern.ch/lhec] focusing on SM 125 GeV Higgs decay into b-quarks

- Assumed 1000 fb^{-1} of statistics. (~10 years running for LHeC.)
- Veto efficiency of 90% for photo-production background is assumed, using forward electron tagging.



b-tag performance (cut based)
- b-jet: 75%
- c-jet mis-tagging rate: 5%
- Light-jet mis-tagging rate: 1%

Precision of coupling constant (Statistics error only)

$$\kappa = \frac{\sqrt{N_s + N_b}}{2N_s}$$

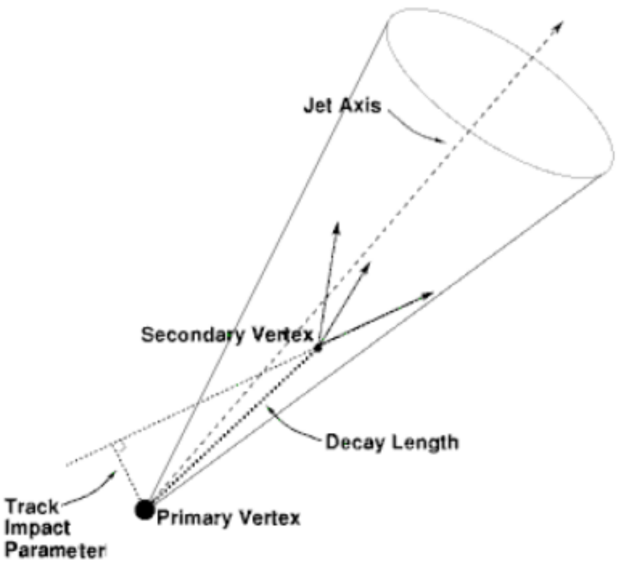
Signal: 3600

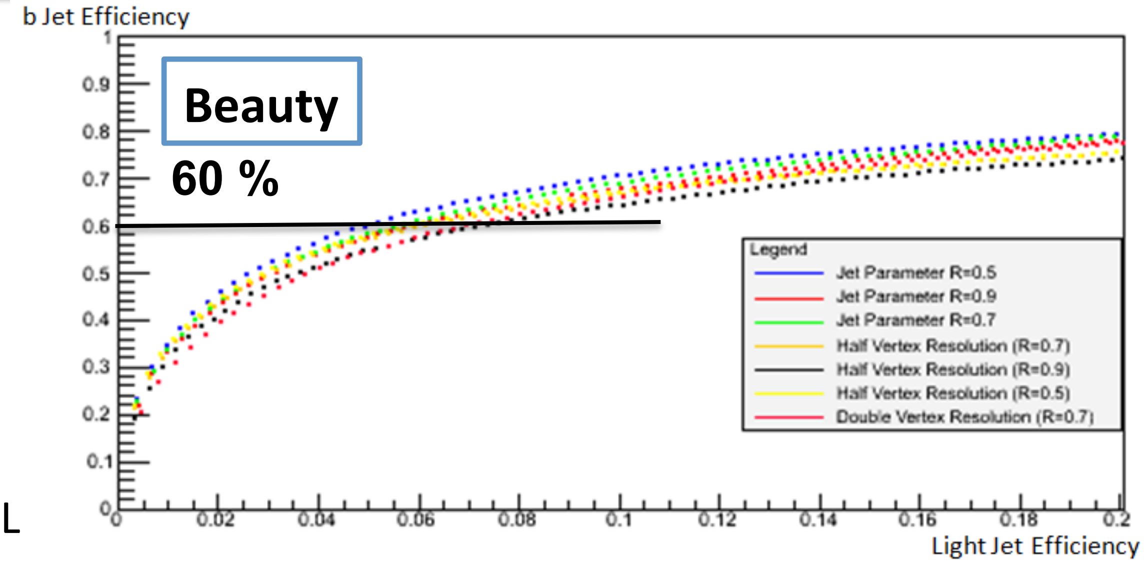
Bkg: 1250

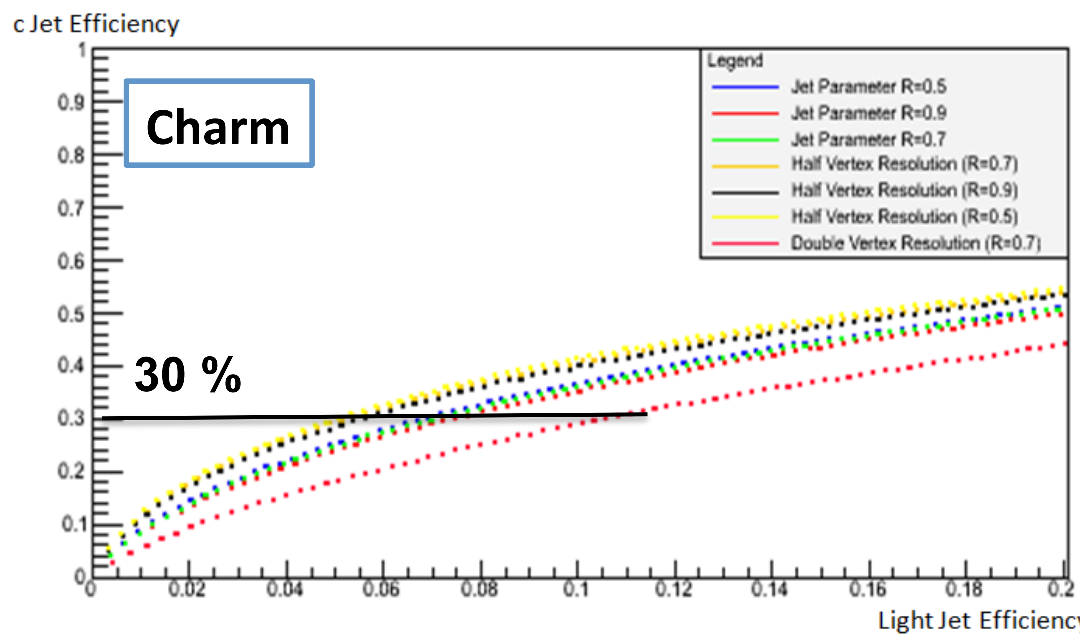
κ (Hbb) ~ 0.97%

HFL Tagging

Uta Klein &
Daniel Hampson





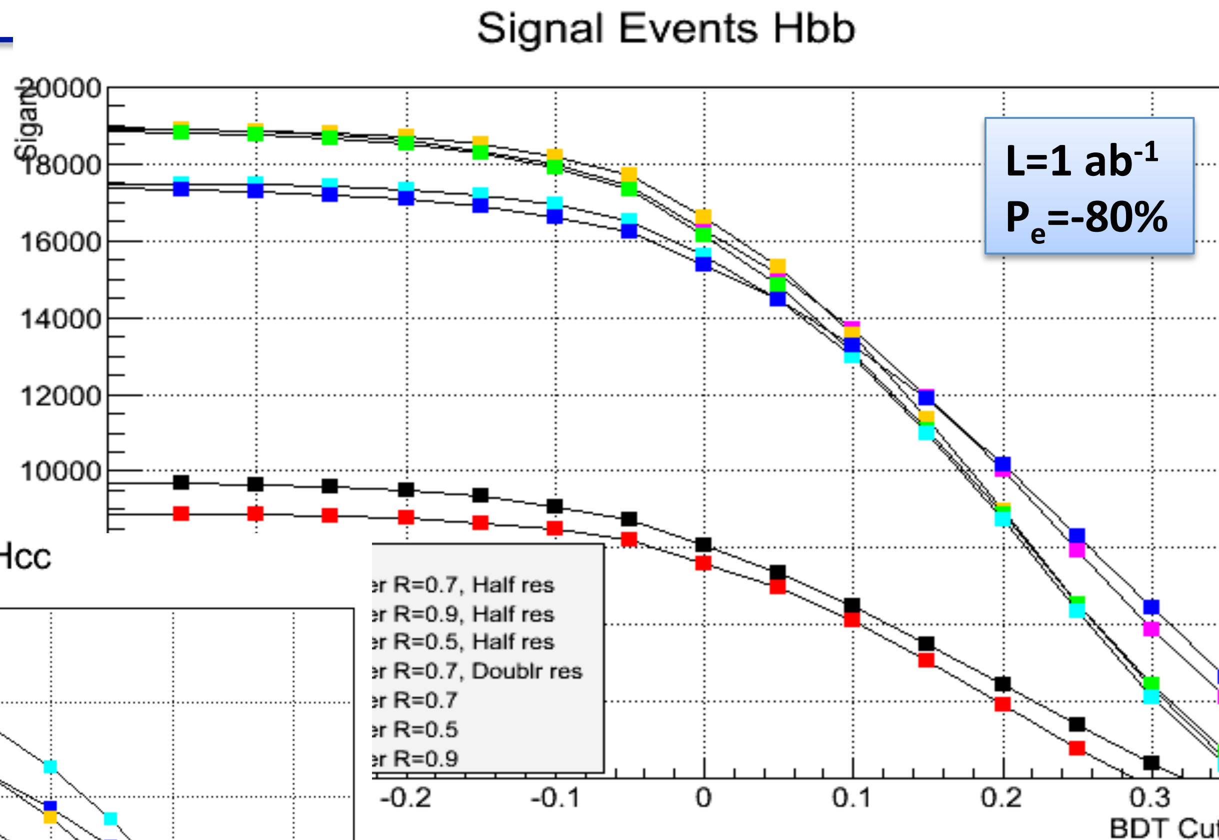


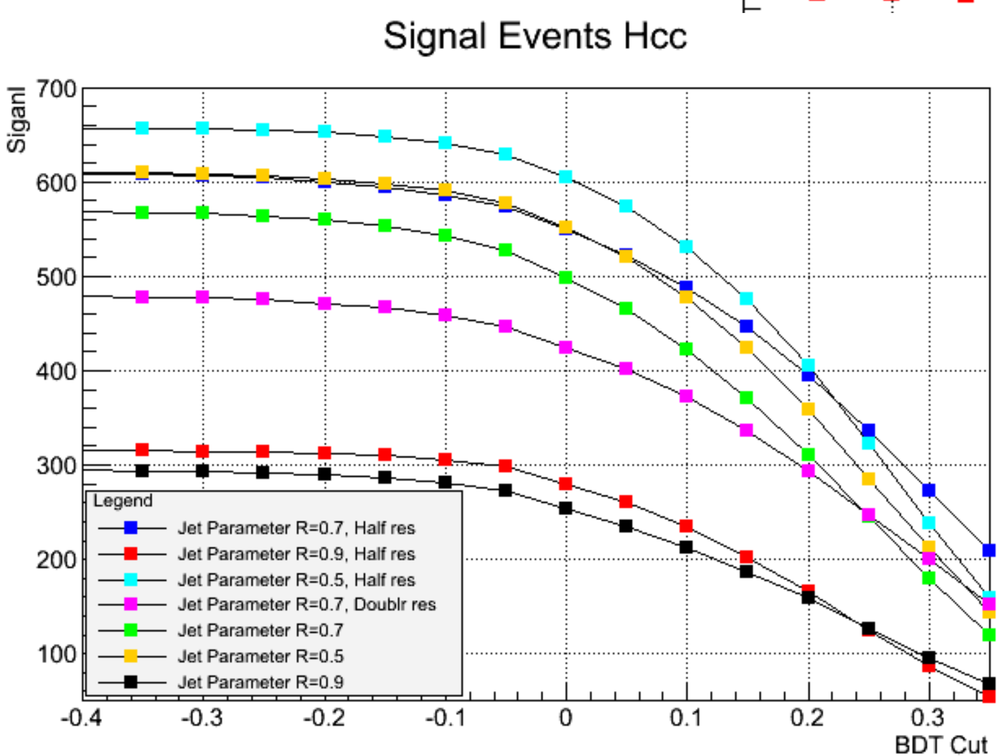
- → Realistic and conservative HFL tagging within Delphes realised, and dependence on vertex resolution (nominal 10 µm) and anti-kt jet radius studied
- → Light jet rejection very conservative, i.e. factor 10 worse than ATLAS
- → **used in full LHeC analysis and for FCC-eh extrapolations**

BDT Results for Higgs @ LHeC

Uta Klein &
Daniel Hampson

Hbb : Using same background assumptions as for cut-based analysis, we get factor 5 more Hbb candidates (~15000) and a coupling error of 0.6%.





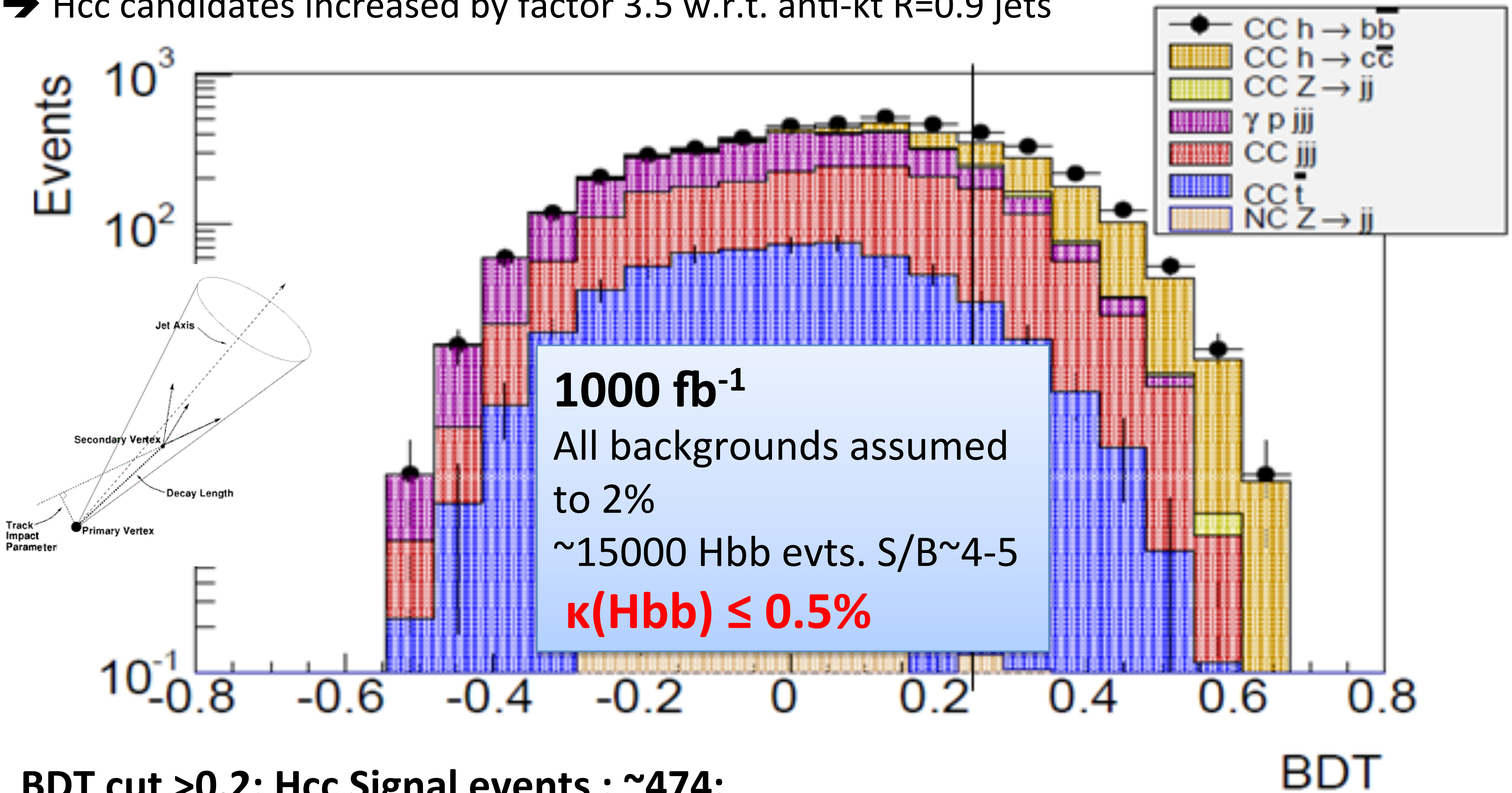
Hcc : High sensitivity to vertex resolution (nominal 10 μm) and jet radius

→ expect about 400-600 Hcc candidates

BDT Result for H→cc

Uta Klein &
Daniel Hampson

NEW : Using R = 0.5 anti-kt jets and ATLAS IBL vertex resolution (5 μm)
➔ Hcc candidates increased by factor 3.5 w.r.t. anti-kt R=0.9 jets



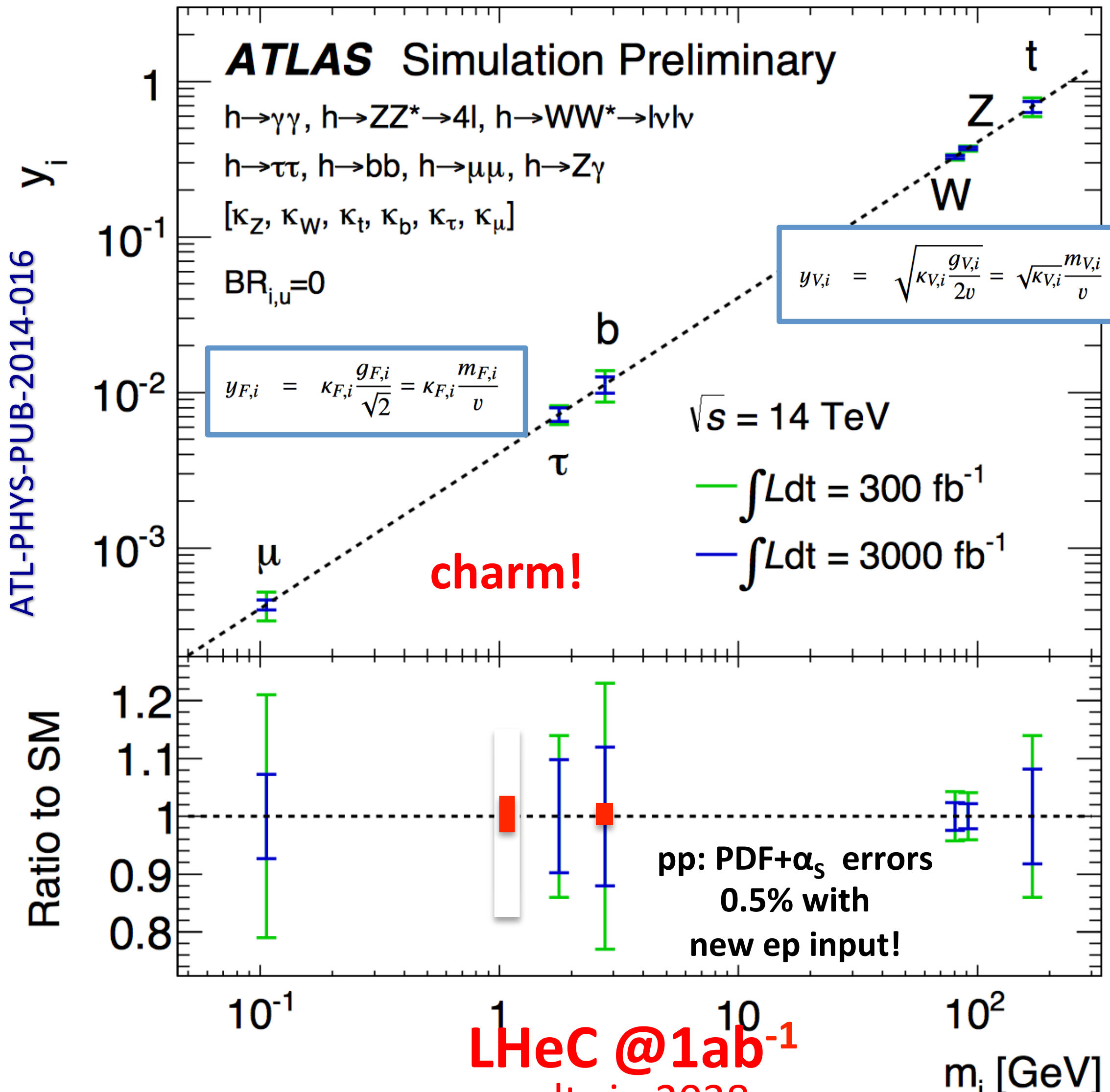
1000 fb^{-1}
All backgrounds assumed to 2%
~15000 Hbb evts. S/B~4-5
κ(Hbb) ≤ 0.5%

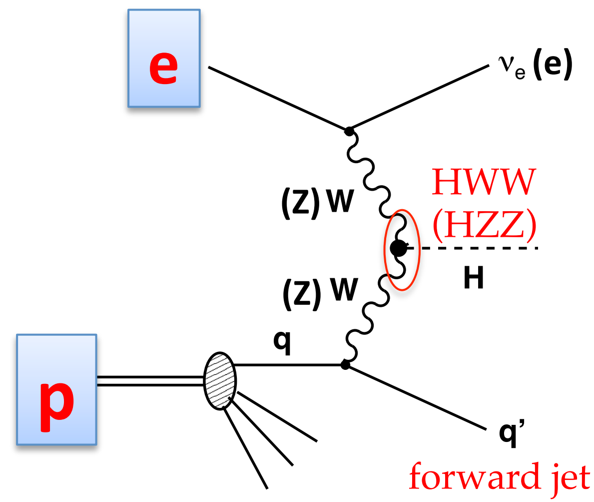
BDT cut >0.2: Hcc Signal events : ~474;
S/√S+B=12.8 → κ(Hcc) = 4% for 1000 fb^{-1}

Clear potential to access the Higgs to charm decay channel in ep.

Higgs Couplings at pp + ep

running concurrently





→ use ep as the 'near' detector for pp to beat α_s and PDF uncertainties to <~0.5%, δm_b to 10 MeV, δm_{charm} to 3 MeV

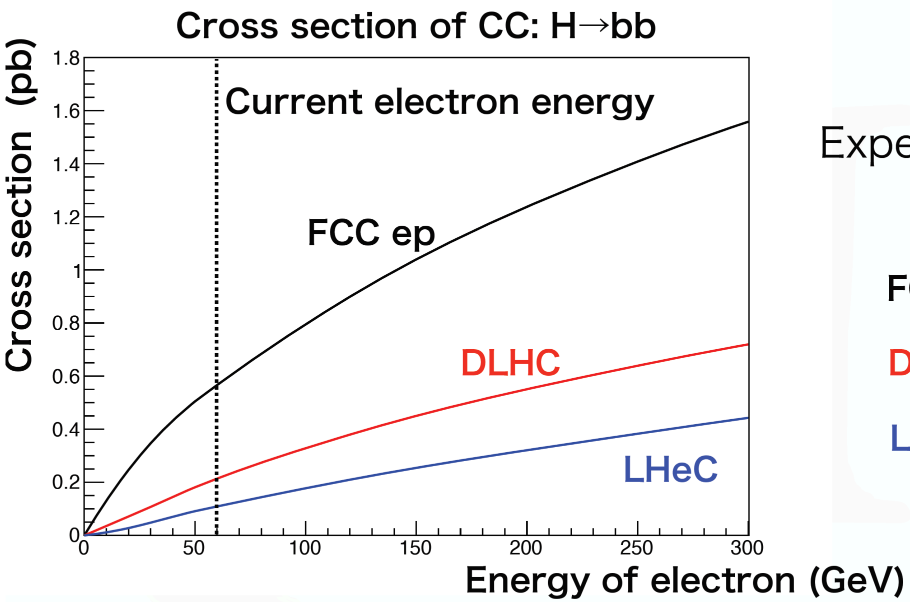
LHeC @1ab^{-1}

results in 2038 …

concurrent with HL-LHC end

SM Higgs into HFL Summary

- Assume a 60 GeV polarized electron beam and 1000 fb^{-1} (~10 years running)
- Expected number of signal events and error of coupling constant from BDT results.
- Background assumed to be known to ~2%



U Klein (Liverpool)

Expected number of signal events
(E_e = 60 GeV)

FCC ep (~85,000 H→bb events)

DLHC (~35,000 H→bb events)

LHeC (~15,000 H→bb events)

	LHeC (E_p = 7 TeV $\sqrt{s}$ ~1.3 TeV)	DLHC (E_p = 14 TeV $\sqrt{s}$ ~1.8 TeV)	FCC ep (E_p = 50 TeV $\sqrt{s}$ ~ 3.5 TeV)
κ (Hbb)	0.5%	0.3%	0.2%
κ (Hcc)	4%	2.8%	1.8%

Exploring SM EFT & New Physics

M. Trott @ LHeC Workshop 2014
http://lhec.web.cern.ch

In the absence of any explicit new states, or overwhelming theory prejudice, the goal is to systematically study the SM EFT for hints of NP, using all possible future facilities to maximize physics conclusions.

What is the SM EFT? A linear realization of gauge symmetry and the new state is a 0+ scalar:

Four fermion operators with leptons and quark fields:

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

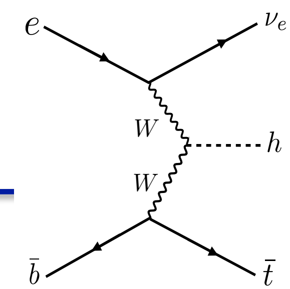
$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

- ➔ 59 operators or 2499 parameters experimentally to constraint!
- ➔ where nearly 50% of the parameters (1053) are sensitive to lepton-quark interactions – not just about lepto-quarks

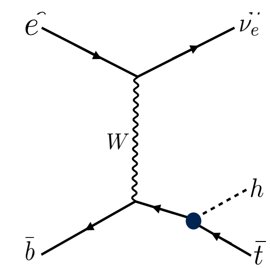
Top Yukawa Coupling @ LHeC

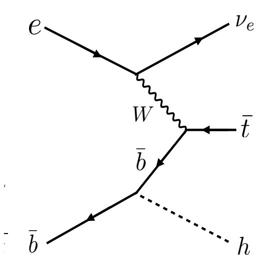
B.Coleppa, M.Kumar, S.Kumar, B.Mellado, Phys. Lett. B770 (2017) 335



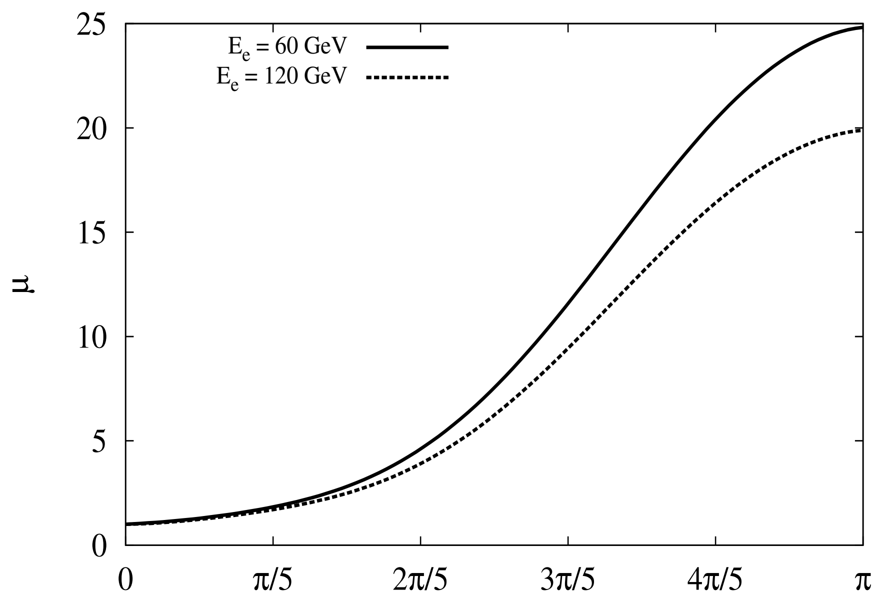
Introduce phase dependent top Yukawa coupling

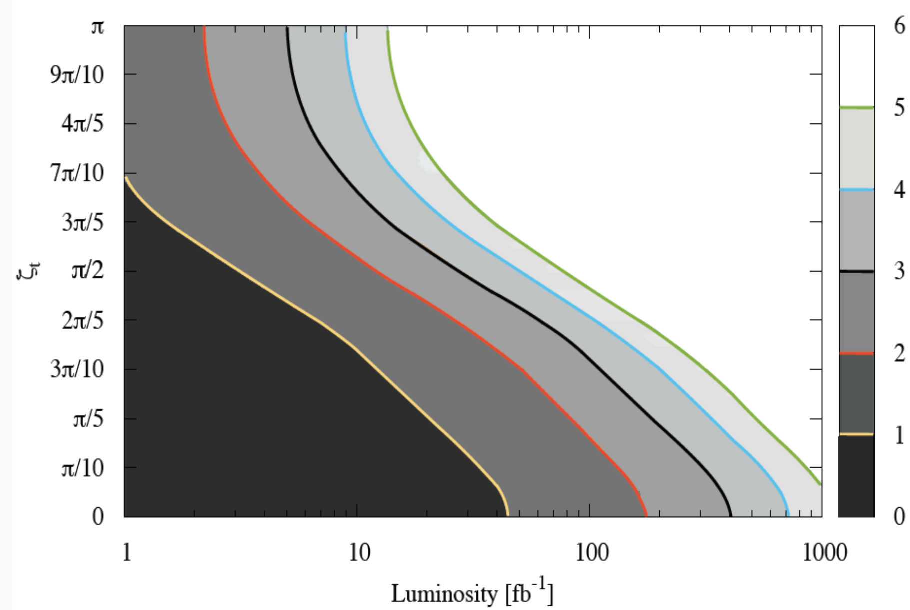
$$\mathcal{L} = -i\frac{m_t}{v}\bar{t}\,[\cos\zeta_t + i\gamma_5\sin\zeta_t]\;t\;h$$





Enhancement of the cross-section as a function of phase





Observe/Exclude non-zero phase to better than 4σ ➔ With Zeor Phase: Measure coupling with 17% accuracy ➔ work ongoing on FCC-eh prospects

Double Higgs Production at FCC-eh

"Probing anomalous couplings using di-Higgs production in electron-proton collisions" by Mukesh Kumar, Xifeng Ruan, Rashidul Islam, Alan S. Cornell, Max Klein, Uta Klein, Bruce Mellado,

Physics Letters B 764 (2017) 247-253 [arXiv:1509.04016]

$$\boxed{\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^{(3)}_{hhh} + \mathcal{L}^{(3)}_{hWW} + \mathcal{L}^{(4)}_{hhWW}.}$$

FCC-eh SM(P=-0.8) σ(HH)=430 ab in VBF!

SM

$$\mathcal{L}^{(3)}_{hhh} = \frac{m_h^2}{2v}(1 - g^{(1)}_{hhh})h^3 + \frac{1}{2v} g^{(2)}_{hhh} h\partial_\mu h \partial^\mu h, \quad (2)$$

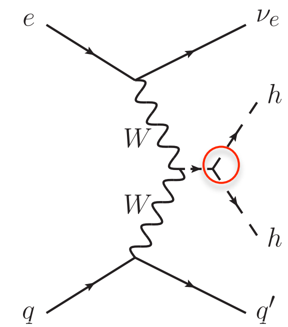
$$\mathcal{L}^{(3)}_{hWW} = -g\Big[\frac{g^{(1)}_{hWW}}{2m_W} W^{\mu\nu}W^\dagger_{\mu\nu}h + \frac{g^{(2)}_{hWW}}{m_W}(W^\nu\partial^\mu W^\dagger_{\mu\nu}h + \mathrm{h.c}) + \frac{\tilde{g}_{hWW}}{2m_W} W^{\mu\nu}\widetilde{W}^\dagger_{\mu\nu}h\Big], \quad (3)$$

$$\mathcal{L}^{(4)}_{hhWW} = -g^2\Big[\frac{g^{(1)}_{hhWW}}{4m_W^2} W^{\mu\nu}W^\dagger_{\mu\nu}h^2 + \frac{g^{(2)}_{hhWW}}{2m_W^2}(W^\nu\partial^\mu W^\dagger_{\mu\nu}h^2 + \mathrm{h.c}) + \frac{\tilde{g}_{hhWW}}{4m_W^2} W^{\mu\nu}\widetilde{W}^\dagger_{\mu\nu}h^2\Big]. \quad (4)$$

→ All other g coefficients are anomalous couplings to the hhh, hWW and hhWW anomalous vertices
→ those are 0 in SM

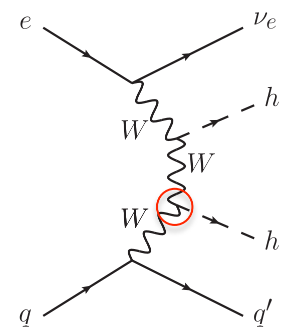
Effective Vertices

$$\Gamma_{hhh} = -6\lambda v\left[g^{(1)}_{hhh} + \frac{g^{(2)}_{hhh}}{3m_h^2}(p_1\cdot p_2 + p_2\cdot p_3 + p_3\cdot p_1)\right], \qquad (6)$$



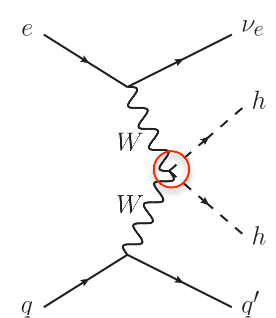
1,2,3=
h,h,h

$$\begin{aligned}\Gamma_{hW^-W^+} = g m_W\Bigg[&\left\{1 + \frac{g^{(1)}_{hWW}}{m_W^2} p_2\cdot p_3 + \frac{g^{(2)}_{hWW}}{m_W^2}(p_2^2 + p_3^2)\right\}\eta^{\mu_2\mu_3} \\ &- \frac{g^{(1)}_{hWW}}{m_W^2} p_2^{\mu_3} p_3^{\mu_2} - \frac{g^{(2)}_{hWW}}{m_W^2}(p_2^{\mu_2} p_2^{\mu_3} + p_3^{\mu_2} p_3^{\mu_3}) \\ &- \mathrm{i}\frac{\tilde{g}_{hWW}}{m_W^2}\epsilon_{\mu_2\mu_3\mu\nu} p_2^{\mu} p_3^{\nu}\Bigg], \qquad (7)\end{aligned}$$



1,2,3 =
h,W-,W+

$$\begin{aligned}\Gamma_{hhW^-W^+} = g^2\Bigg[&\left\{\frac{1}{2} + \frac{g^{(1)}_{hhWW}}{m_W^2} p_3\cdot p_4 + \frac{g^{(2)}_{hhWW}}{m_W^2}(p_3^2 + p_4^2)\right\}\eta^{\mu_3\mu_4} \\ &- \frac{g^{(1)}_{hhWW}}{m_W^2} p_3^{\mu_4} p_4^{\mu_3} - \frac{g^{(2)}_{hhWW}}{m_W^2}(p_3^{\mu_3} p_3^{\mu_4} + p_4^{\mu_3} p_4^{\mu_4}) \\ &- \mathrm{i}\frac{\tilde{g}_{hhWW}}{m_W^2}\epsilon_{\mu_3\mu_4\mu\nu} p_3^{\mu} p_4^{\nu}\Bigg]. \qquad (8)\end{aligned}$$



1,2,3,4 =
h,h,W-,W+

Note the dependence on momenta in non-SM vertices. This induces significant impact on scattering kinematics.

Event Selection using h→bb

[1509.04016]

Pe=-0.8, Anti-kt jets R=0.4, Etmiss>40 GeV, η(fwd jet)>5,
90< mbb(1) , mbb(2)<125 GeV, m(4b)>290 GeV
b-tagging for |η|<5 assumed to be 70% with misidentifications of 10% for charm and 1% for light quarks /gluons

Delphes detector-level

Cuts / Samples	Signal	$4b$+jets	$2b$+jets	Top	ZZ	$b\bar{b}H$	ZH	Total Bkg	Significance
Initial	2.00×10^3	3.21×10^7	2.32×10^9	7.42×10^6	7.70×10^3	1.94×10^4	6.97×10^3	2.36×10^9	0.04
At least $4b + 1j$	3.11×10^2	7.08×10^4	2.56×10^4	9.87×10^3	7.00×10^2	6.32×10^2	7.23×10^2	1.08×10^5	0.94
Lepton rejection $p_T^\ell > 10$ GeV	3.11×10^2	5.95×10^4	9.94×10^3	6.44×10^3	6.92×10^2	2.26×10^2	7.16×10^2	7.75×10^4	1.12
Forward jet $\eta_J > 4.0$	233	13007.30	2151.15	307.67	381.04	46.82	503.22	16397.19	1.82
$\not{E}_T > 40$ GeV	155	963.20	129.38	85.81	342.18	19.11	388.25	1927.93	3.48
$\Delta\phi_{\not{E}_T j} > 0.4$	133	439.79	61.80	63.99	287.10	14.53	337.14	1204.35	3.76
$m_{bb}^1 \in [95, 125]$, $m_{bb}^2 \in [90, 125]$	54.5	28.69	5.89	6.68	5.14	1.42	17.41	65.23	6.04
$m_{4b} > 290$ GeV	49.2	10.98	1.74	2.90	1.39	1.21	11.01	29.23	7.51

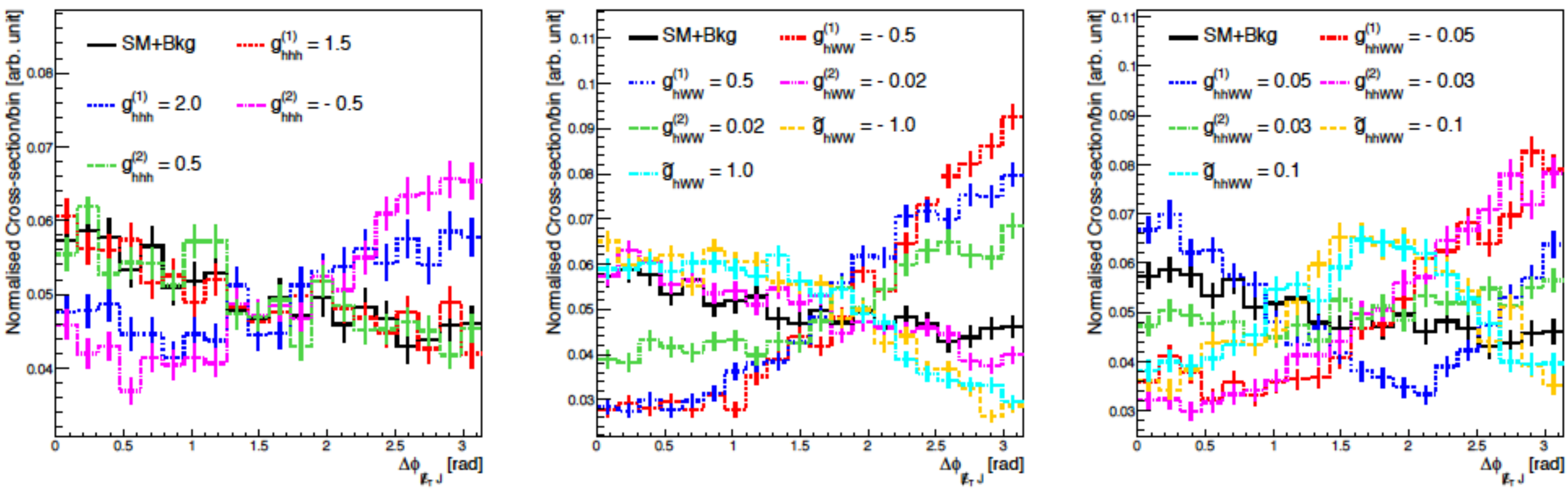
Table 2: A summary table of event selections to optimise the signal with respect to the backgrounds in terms of the weights at 10 ab^{-1}. In the first column the selection criteria are given as described in the text. The second column contains the weights of the signal process $p\,e^- \to hh\,j\nu_e$, where both the Higgs bosons decay to $b\bar{b}$ pair. In the next columns the sum of weights of all individual prominent backgrounds in charged current, neutral current and photo-production are given with each selection, whereas in the penultimate column all backgrounds' weights are added. The significance is calculated at each stage of the optimised selection criteria using the formula $S = \sqrt{2[(S+B)\log(1+S/B) - S]}$, where S and B are the expected signal and background yields at a luminosity of 10 ab^{-1}respectively. This optimisation has been performed for $E_e = 60$ GeV and $E_p = 50$ TeV.

$$\boxed{S = \sqrt{2[(S+B)\log(1+S/B) - S]},}$$

[arXiv:1509.04016]

Azimuthal Angle Distributions

between missing transverse energy and forward jet, at Delphes detector-level, including background : bbbbj, bbjjj, Z(bb)h(bb)j, ttj, h(bb)bbj
→ For signal, we consider hh→ bbbb decays motivated by h→bb studies.

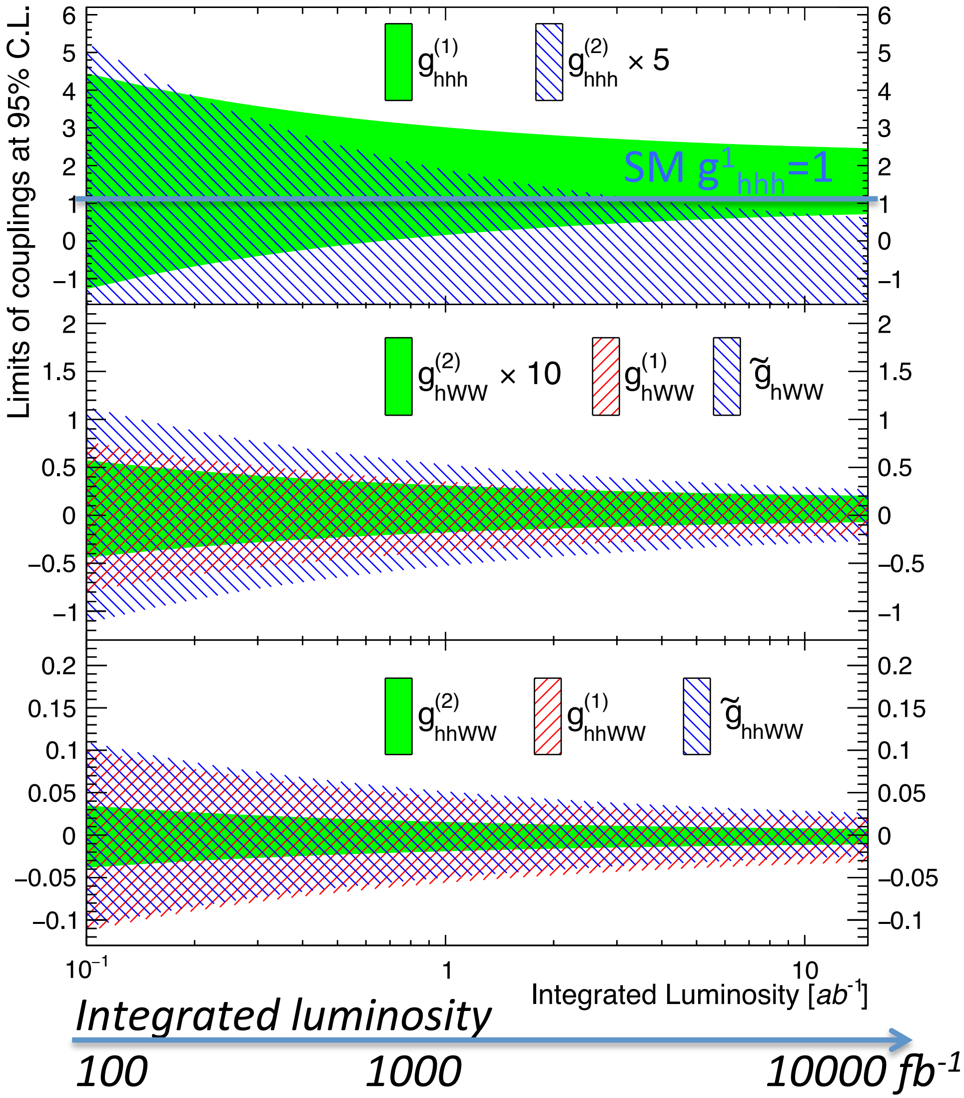


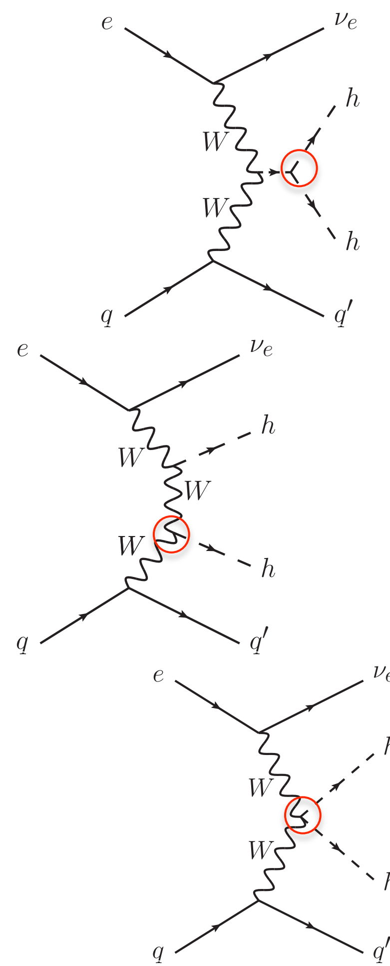
→ normalised DIS cross sections are sensitive to non-BSM vertices
→ initial study published for this novel variable
→ potential for a deeper analysis and interpretation

95% C.L.Exclusion Limits from $\sigma_{fiducial}$

[1509.04016]

5% systemtatic uncertainty included





1σ for SM hhh for E_e 60 (120)GeV and 10ab^{-1}

$$\boxed{g^{(1)}_{hhh} = 1.00^{+0.24(0.14)}_{-0.17(0.12)}}$$

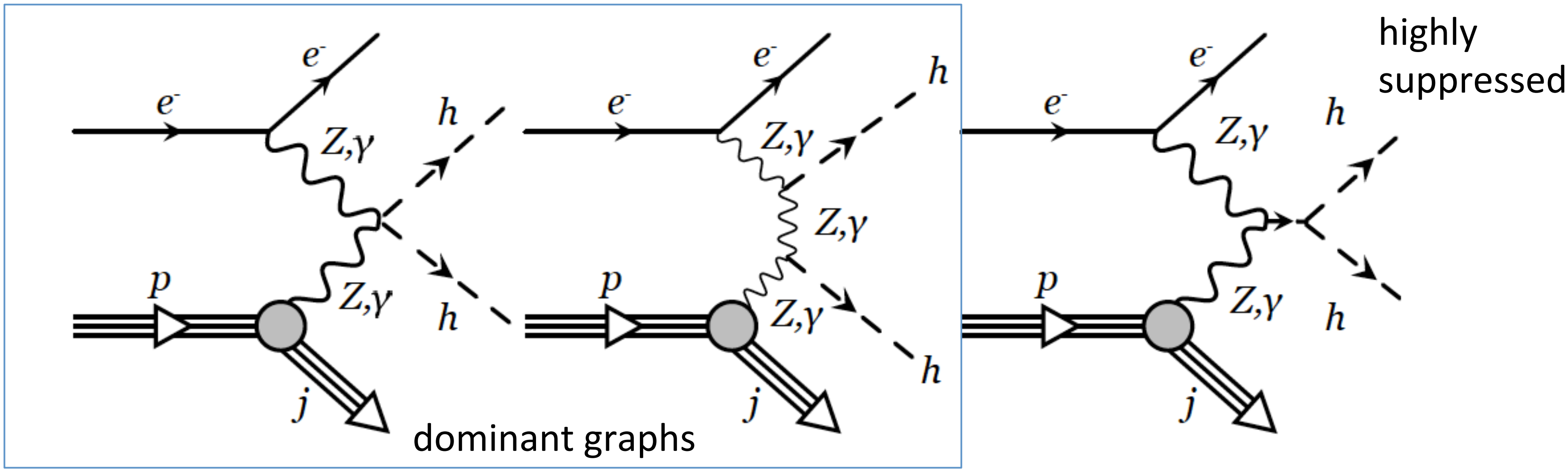
Probing anomalous couplings: limits are obtained by scanning one of the non-BSM coupling while keeping other couplings to their SM values.

Here $g^{(i)}_{(\dots)}, i = 1, 2,$ and $\tilde{g}_{(\dots)}$ are real coefficients corresponding to the CP-even and CP-odd couplings respectively, of the hhh, hWW and $hhWW$ anomalous vertices.

Limits on Neutral Di-Boson and Di-Higgs Interactions for FCC-he Collider

[1702.00185]

S. Kuday,* H. Saygın,† İ. Hoş,‡ and F. Çetin§



- Vertices for Neutral Current DIS (Z, γ) and Photoproduction (γ) studied in Higgs Effective Langrangian Model : parametrise hhZZ and hhγγ in 4-point interactions in terms of CP-even and CP-odd Wilson coefficients (and Higgs self coupling and Yukawa coupling)
- Study at Delphes-detector level (FCC-hh) azimuthal dependencies between scattered lepton and forward jet
- hh : 4b final states investigated using a very first version of FCC-hh detector
- Promising sensitivity found while scanning parameter space for Wilson coefficients

Invisible Higgs@LHeC

relating the Higgs and the 'dark' sectors

Y.-L. Tang et al.,
arXiv: 1508.01095

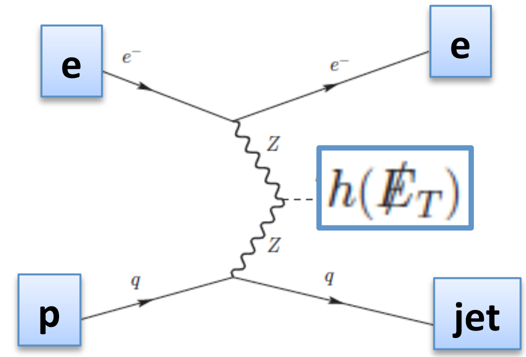
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

$\mathrm{Br}(h \to \not{E}_T)$ < 3.5% @95% C.L., MVA based

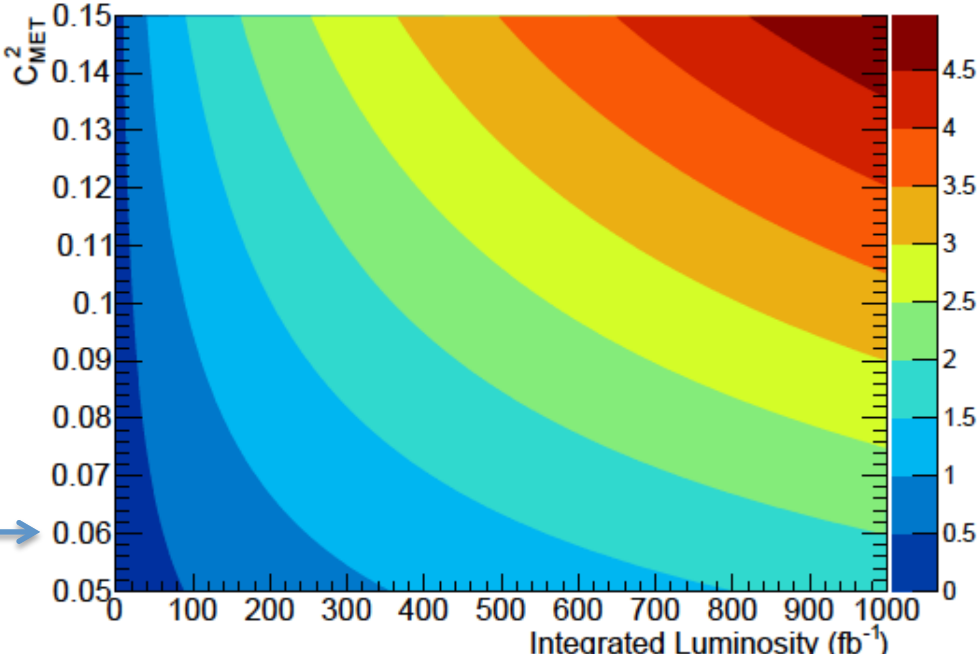
For **LHeC**, assume : 1ab^{-1}, P_e=-0.9, <u>cut based</u>

$\mathrm{Br}(h \to \not{E}_T)$ < 6% @ 95 % C.L.

$$C^2_{\mathrm{MET}} = \kappa_Z^2 \times \mathrm{Br}(h \to \not{E}_T)$$



κ_Z : BSM w.r.t. SM HZZ coupling



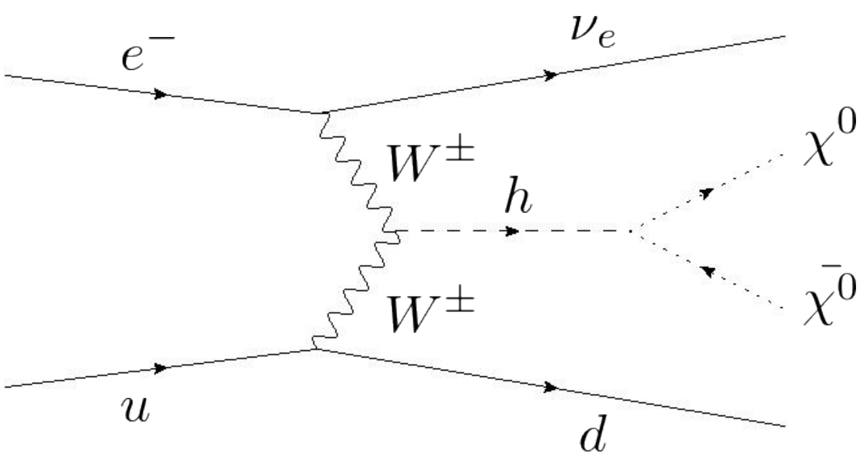
Colours:
expected statistical significance

- ➔ **potential much enhanced for FCC-eh @ 3.5 TeV and HE-LHC-eh @ 1.8 TeV**
- ➔ **NEW studies performed on Delphes detector-level using our Madevent framework**

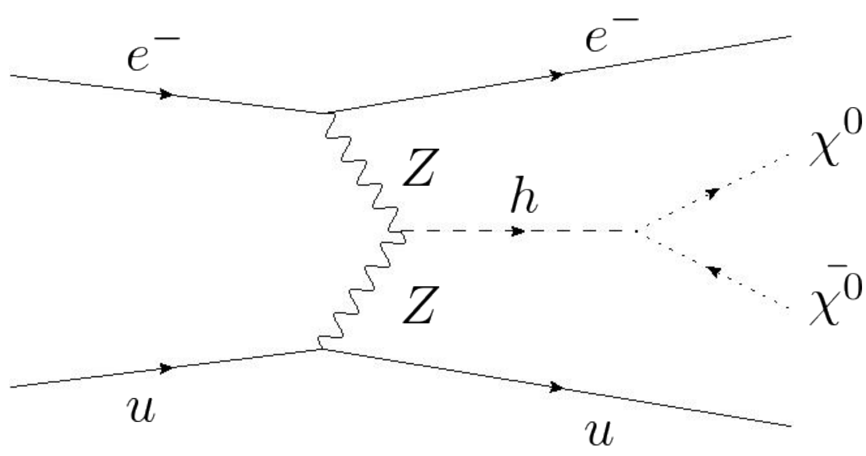
Invisible Higgs Decay in ep

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

CC production of an invisible Higgs



NC production of an invisible Higgs



→ We focus currently on NC DIS channel: employ that kinematic is over constrained using jet and electron information in the final state

→ We use the idea from C. Zhang and Y.-L. Tang : We emulate Higgs to invisible by assuming a branching of 100% for H→ ZZ → 4ν

→ We started to study signals and backgrounds using CMS-style and FCC-eh-style 'Delphes' detectors, using same analysis strategies as developed for LHeC (C. Zhang and BSc thesis S. Kawaguchi)

Dominant Background

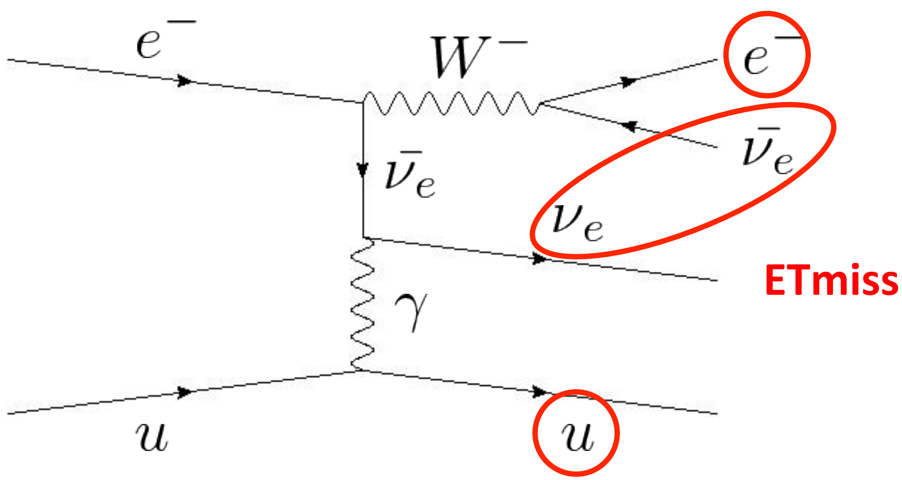
Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

for faking our signal feature :
one electron, one jet, and missing transverse energy (E_T^{miss})

W^+je^- and W^-je^- backgrounds and

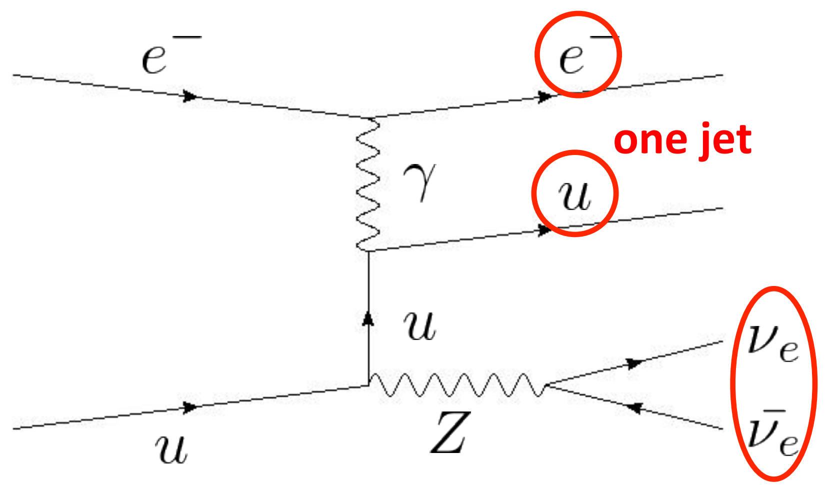
$Wj\nu$ background

$$p + e^- \to W^- + j + \nu_e$$
$$W^- \to e^- + \nu_e$$



Zje background

$$p + e^- \to Z + j + e^-$$
$$Z \to \nu + \bar{\nu}$$

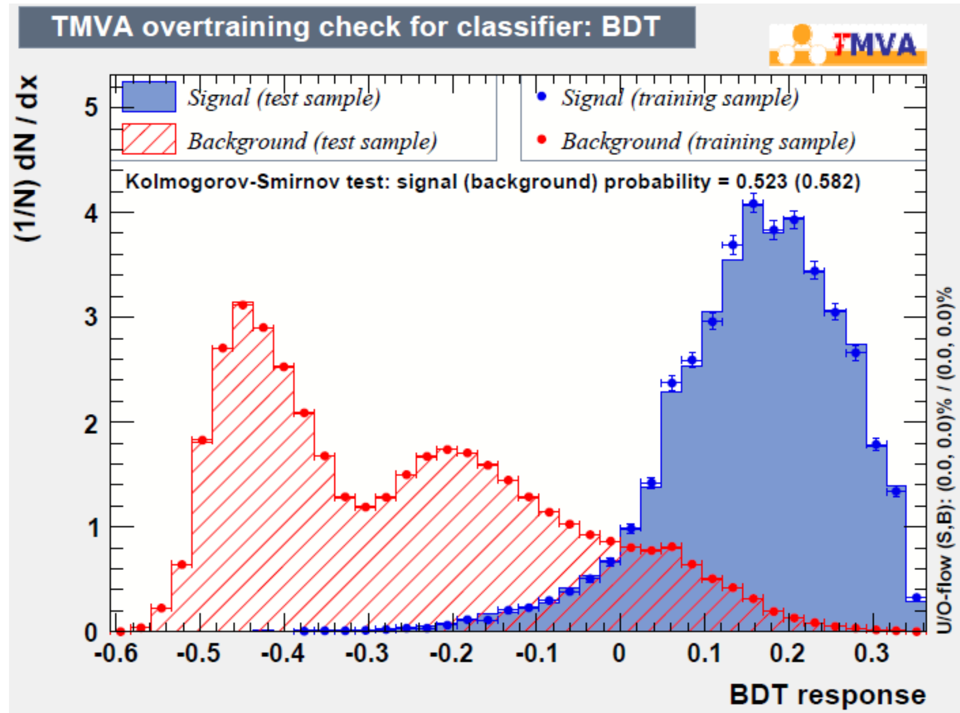


Results for FCC-eh - Using BDT

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

MVA (BDT) using samples with 1 jet and 1e- with high pT, and other variables as a BDT

BDT >	Signal		Z[%]
0	31961	267904	3.25
0.05	29932	176439	2.81
0.1	25686	94138	2.40
0.15	19898	42439	2.08
0.2	13020	15562	1.93
0.25	6998	4969	2.04
0.3	2320	1003	2.82



Branching ratio calculated by $S/\sqrt{S+B}$:

$$Z=13020\times \mathrm{Br}(h\to \not{E}_T)/\sqrt{13020\times \mathrm{Br}(h\to \not{E}_T)+15562}$$

In the case of 2σ

$$\boxed{\mathrm{Br}(h\to \not{E}_T)\sim 1.93\%}$$

Branching for invisible Higgs

Values given in case of 2σ

Delphes detectors	LHeC	DLHeC	FCC-eh
	1.3 TeV	1.8 TeV	3.5 TeV
LHC-style	4.7%	3.2%	1.9%
First 'ep-style'	5.7%		2.6%

- ✓ **Results look very encouraging for a measurement of the branching of Higgs to invisible in ep down to 2%.**
- ✓ For 2 different detector options we get similar results.

- Certainly : we will use this channel to further optimize analysis strategies (used methods and requirements, e.g. size of jets and electron reconstructions) and to modify our ep-detector
- employ synergies within FCC study group → detector and analysis details (BDT optimisation) has certainly an impact on results

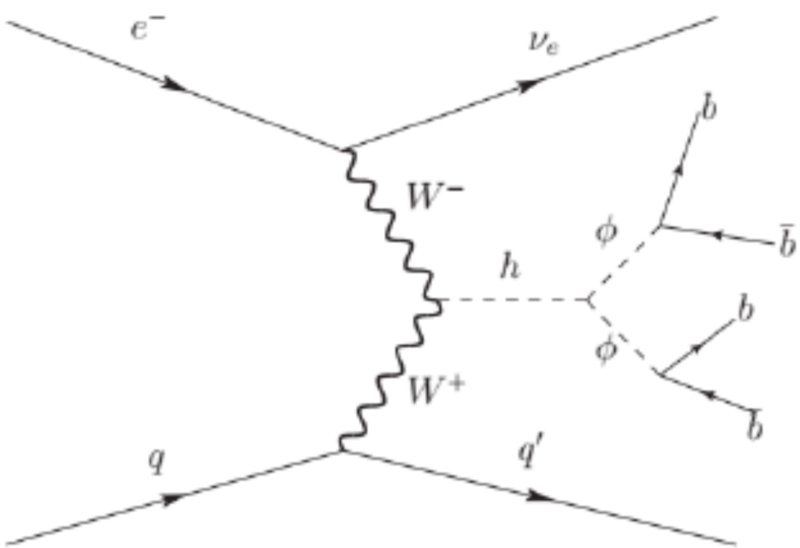
Exotic Higgs Decays

$$\mathcal{L}_{eff} = \lambda_h v h \phi^2 + \lambda_b \phi \bar{b} b + \mathcal{L}_{\phi\,\text{decay,other}}$$

$$\boxed{h \to \phi\phi \to 4b}$$

ϕ: a spin-0 particle from new physics.

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



$$C^2_{4b} = \kappa^2_V \times \text{Br}(h \to \phi\phi) \times \text{Br}^2(\phi \to b\bar{b})$$

S. Liu, Y. L. Tang, C. Zhang, S. Zhu, 1608.08458

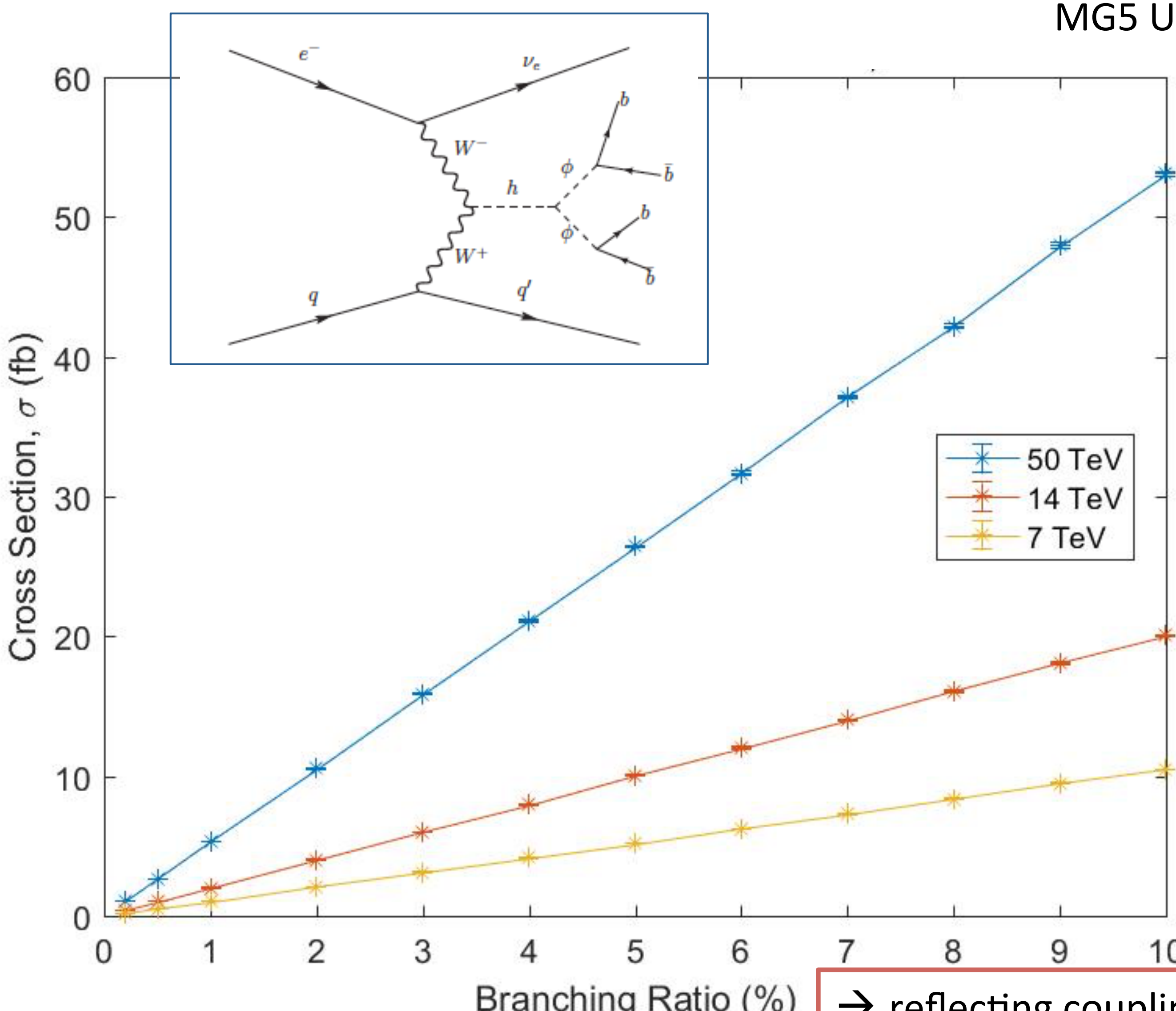
- Well motivated signature in extended Higgs sector.
- Difficult to probe at hadron colliders.
- LHeC signal: here using CC channel.
- Backgrounds: CC multijet, CC t/h/W/Z+jets, PHP multijet.
- PHP backgrounds assumed to be negligible after MET requirements and electron tagging.
- Current analysis is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

@LHeC: 95% C.L. for m_ϕ of 20, 40, 60 GeV is 0.3%, 0.2% and 0.1% for C_{4b}^2

Exotic Higgs@FCC-eh

Uta Klein
Michael o'Keefe
Liverpool

MG5 UFO [arXiv:1608.08458]



FCC-eh @ 3.5TeV

DLHeC @ 1.8 TeV

LHeC @ 1.3 TeV

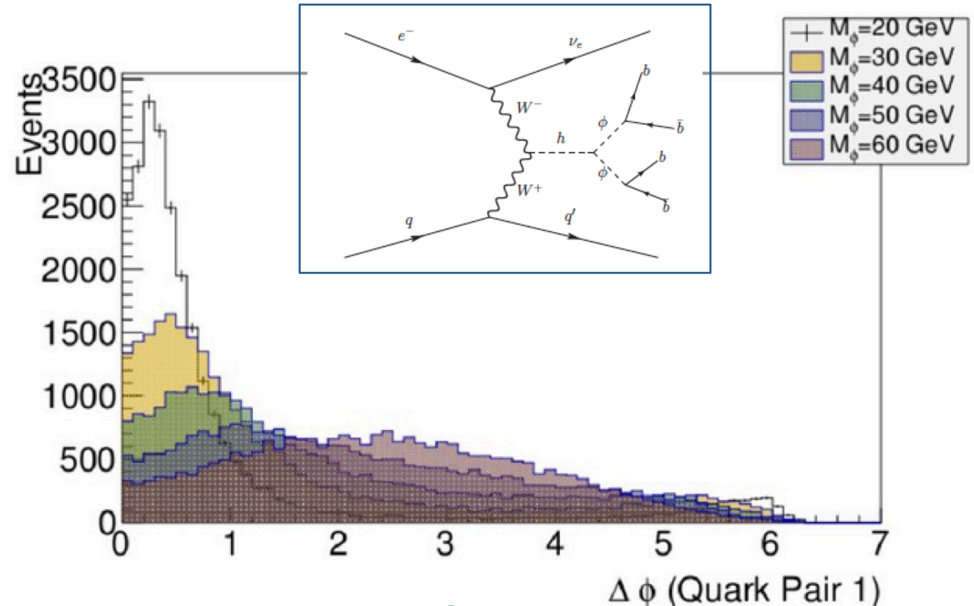
Values for P_e=0

→ reflecting coupling of new scalar to 125 GeV higgs

Kinematics @ Quark-Level

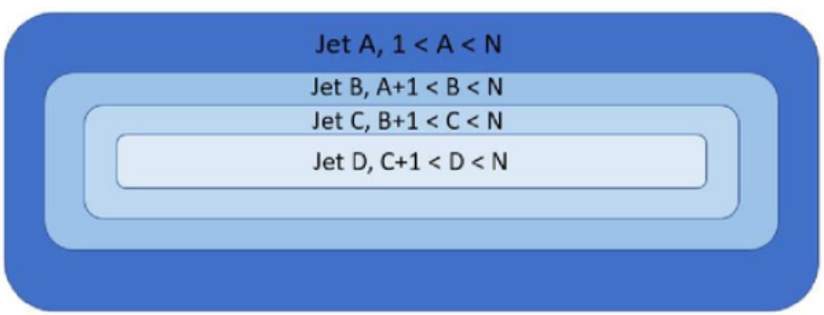
Uta Klein
Michael o'Keefe
Liverpool

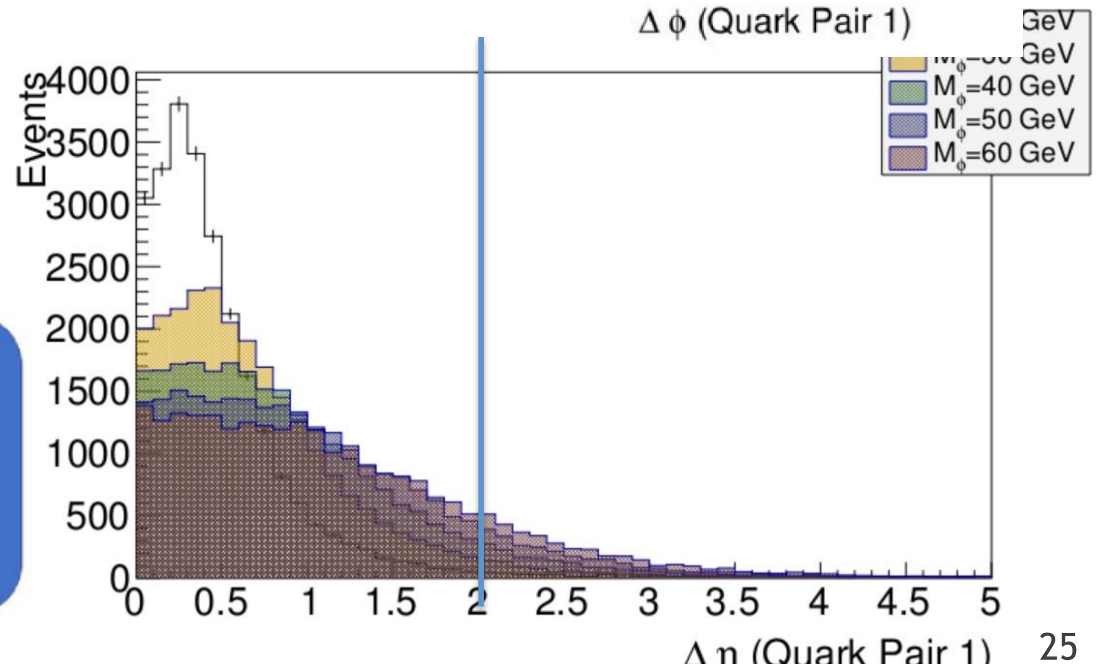
Δφ between b quarks in the scalar (parton level)



Δη between b quarks in the scalar (parton level)

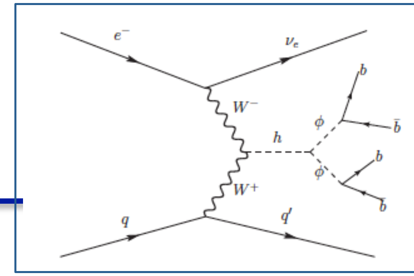
➔ use Δη<2 for finding two scalars with mass within $2m_b$ and $m_H/2$ looping over N jets minimising Δm





BDT Analysis @ BR=10%

Delphes-detctor level with b-tag |η|<2.5



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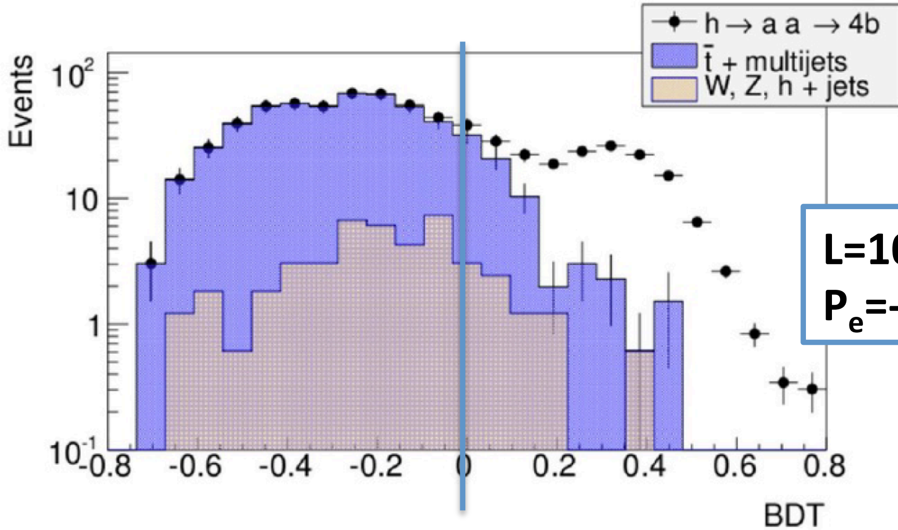
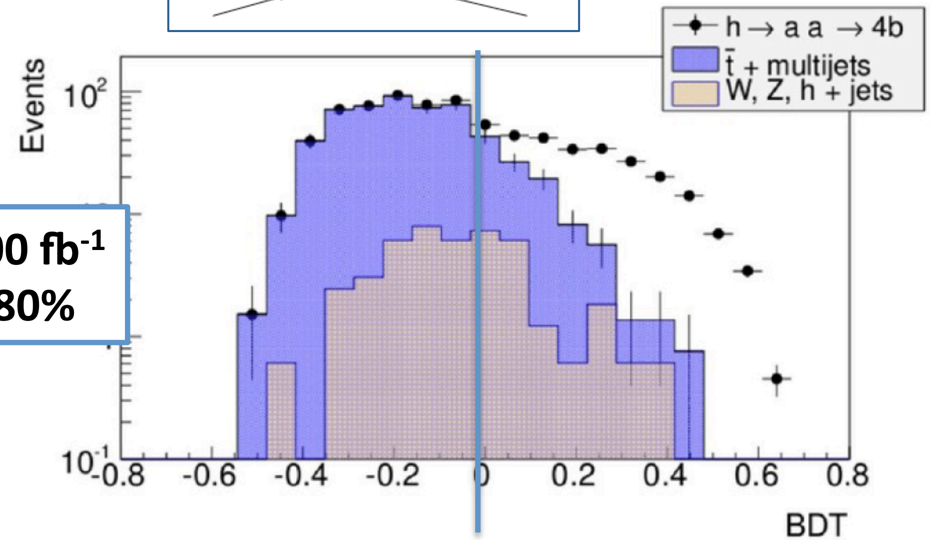
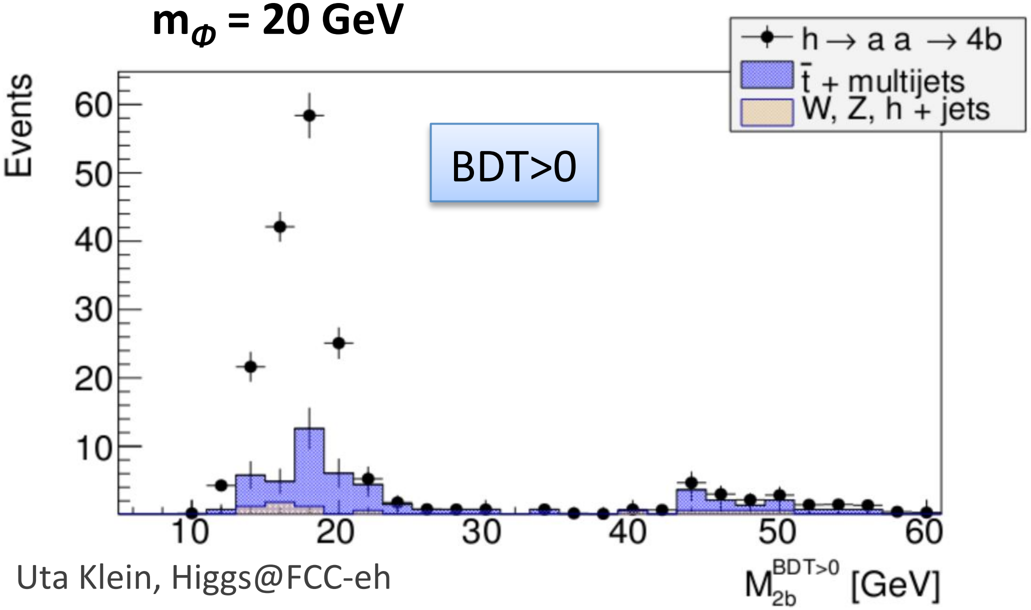
Liverpool



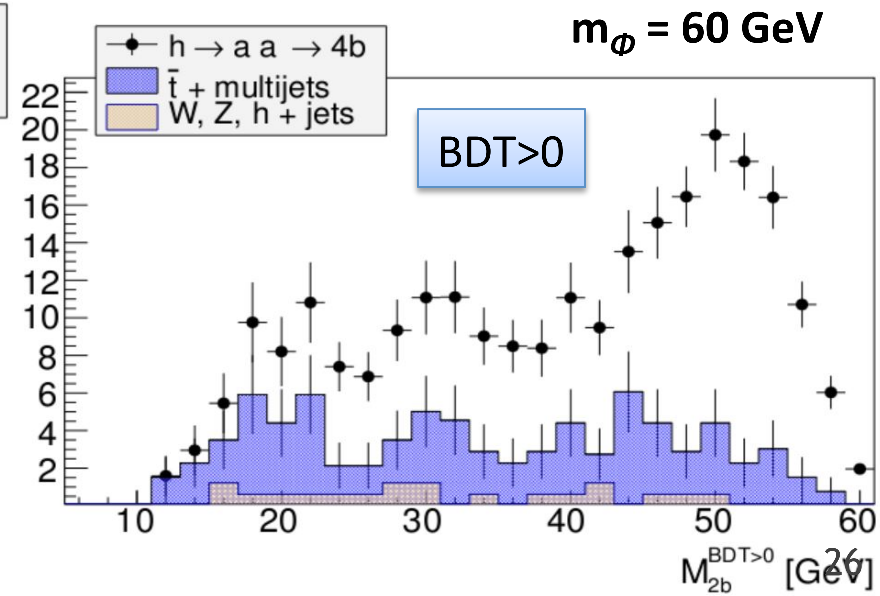
L=100 fb^{-1}
P$_e$=-80%



m$_\Phi$ = 20 GeV



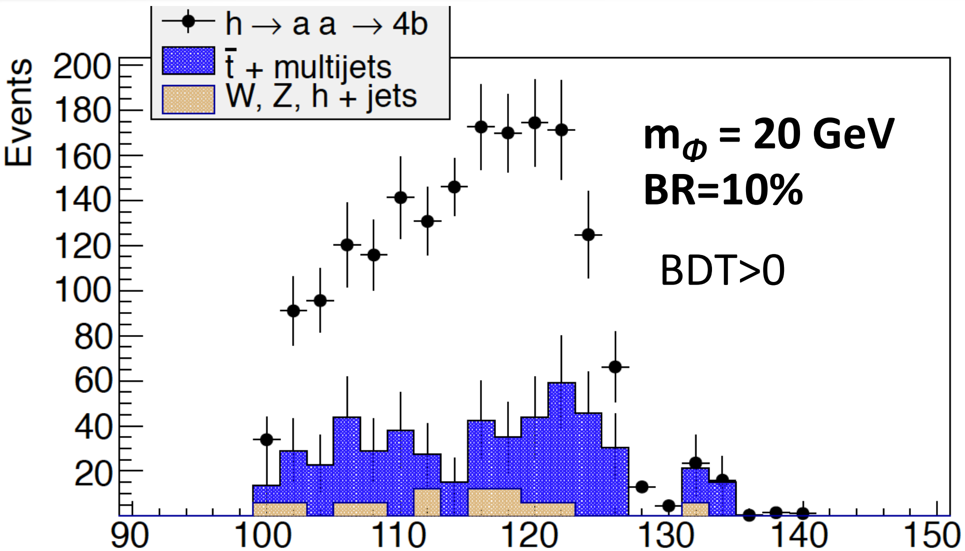
m$_\Phi$ = 60 GeV



First Results @ FCC-eh

L=1 ab^{-1}
P_e=-80%

Uta Klein
Michael o'Keefe
Liverpool



Very promising first results to discover an exotic Higgs decay into two new light scalars at FCC-eh down to a BR of 1% for 1 ab^{-1}. A BR of 10% could be discovered within 1 year (100 fb^{-1}).

Values for BDT>0

$$Z = \sqrt{2\left[(S+B)\ln\left(1+\frac{S}{B}\right)-S\right]}$$

	M_φ (GeV)					
	20			60		
BR (%)	σ (fb)	Δσ (fb)	Z	σ (fb)	Δσ (fb)	Z
0.2	0.03	0.02	1.14	0.03	0.03	1.17
0.4	0.05	0.02	2.27	0.07	0.03	2.33
0.6	0.08	0.02	3.37	0.10	0.03	3.47
0.8	0.10	0.02	4.46	0.13	0.03	4.59
1	0.13	0.03	5.54	0.17	0.03	5.71

More New Studies Ongoing

… and publications in preparation

- "Search for Anomalous HVV couplings at the LHeC and the FCC-ep" by M. Altinli et al.
- "Probing FCNC couplings of Higgs-top at FCC-ep and LHeC" by B. Hacisahinoglu et al.
- "Searching for doubly-charged Higgs bosons in the Georgi-Machacek model at ep colliders " by H. Sun et al. (see also presentation at DIS2017)

Conclusions

- We just started to explore the potential of complementary Sm and BSM Higgs searches using concurrent ep collisions at FCC-pp in particular for HH and Hϕ couplings

→ many more studies ongoing (e.g. anomalous htt coupling) and possible! You are welcome!

- Enhance ep potential further by strengthen analysis techniques and detector developments between p, ep and ee : extended beauty and charm tagging using BDT, jet-substructure, boosted pairs …

- For the FCC CDR : Quantify the joint potential → combined analysis of pp, ep and ee cross sections to constrain SM/BSM physics scenario's and to design the ***most powerful and sustainable*** search complex at the energy frontier.

Additional Sources & Thanks to

The LHeC/FCC-eh study group, http://cern.ch/lhec.

"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]

Poetic 2016 Workshop, 14.-18.11.2016, Temple University (USA)

https://phys.cst.temple.edu/poetic-cteq-2016/scientific_program.html

1st FCC Physics Workshop, 16.1.-20.1.2017, CERN

https://indico.cern.ch/event/550509/

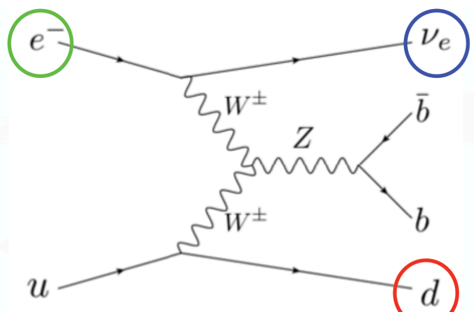
→ see M. Benedikt's and F. Zimmermann's and further eh talks given at this workshop

Special thanks to my colleagues in the LHeC/FCC-eh Higgs group, the project leader Max Klein, our detector expert Peter Kostka, and our bi-weekly Higgs-top working group discussions.

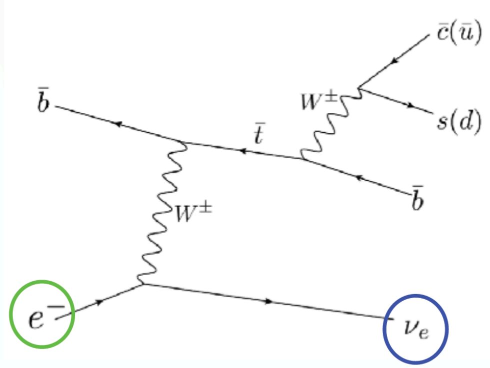
Additional material

SM Higgs Decay into b-quarks

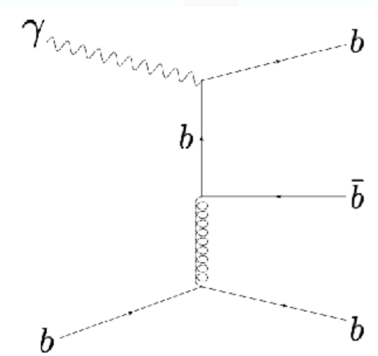
- Typical background processes and assumptions about b-tagging for cut-based study



CC Z production

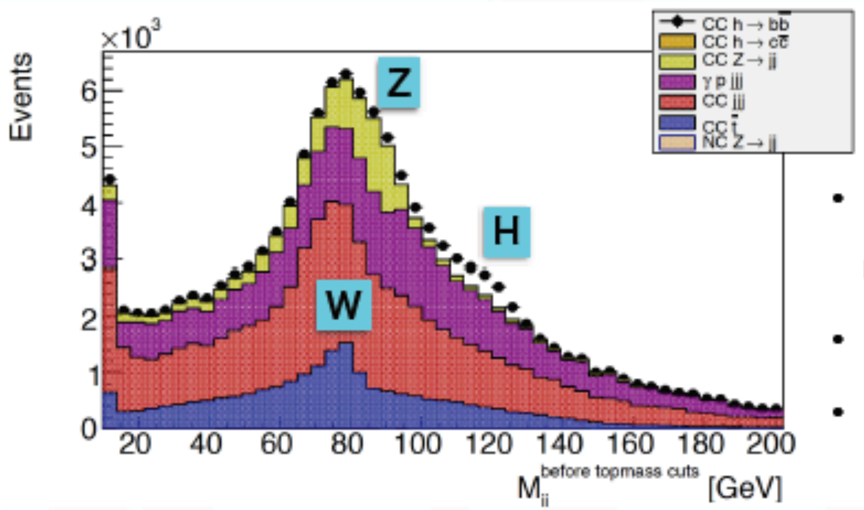


Single top production

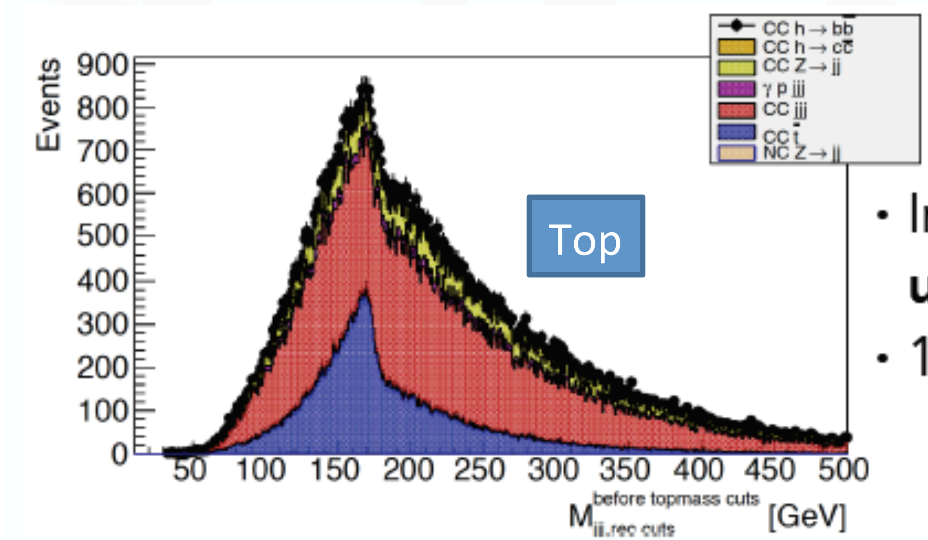


Multi jets

Higgs w/o HFL tagging



- Invariant Di-jet Mass using 2 lowest eta **un-tagged** jets.
- 100% photo production background.
- No anti top cut.



- Invariant Mass of 3 highest p_T **un-tagged** jets.
- 10% photo production background.

Asymmetries

$$\mathcal{A}_{\Delta\phi_{E_T J}} = \frac{|A_{\Delta\phi>\pi/2}| - |A_{\Delta\phi<\pi/2}|}{|A_{\Delta\phi>\pi/2}| + |A_{\Delta\phi<\pi/2}|},$$

[1509.04016]

Samples		$\mathcal{A}_{\Delta\phi_{E_T J}}$	σ(fb)
SM+Bkg		0.277 ± 0.088	
$g^{(1)}_{hhh}$	= 1.5	0.279 ± 0.052	0.18
	= 2.0	0.350 ± 0.053	0.21
$g^{(2)}_{hhh}$	= - 0.5	0.381 ± 0.050	0.19
	= 0.5	0.274 ± 0.024	0.74
$g^{(1)}_{hWW}$	= - 0.5	0.506 ± 0.022	0.88
	= 0.5	0.493 ± 0.020	0.94
$g^{(2)}_{hWW}$	= - 0.02	0.257 ± 0.025	0.67
	= 0.02	0.399 ± 0.040	0.33
$\tilde{g}_{hWW}$	= - 1.0	0.219 ± 0.016	1.53
	= 1.0	0.228 ± 0.016	1.53
$g^{(1)}_{hhWW}$	= - 0.05	0.450 ± 0.033	0.52
	= 0.05	0.254 ± 0.029	0.68
$g^{(2)}_{hhWW}$	= - 0.03	0.462 ± 0.022	1.22
	= 0.03	0.333 ± 0.018	1.46
$\tilde{g}_{hhWW}$	= - 0.1	0.351 ± 0.020	1.60
	= 0.1	0.345 ± 0.020	1.61

Table 3: Estimation of the asymmetry, defined in Eq. (9), and statistical error associated with the kinematic distributions in Fig. 2 at an integrated luminosity of 10 ab^{-1}. The cross section (σ) for the corresponding coupling choice is given in the last column with same parameters as in Table 1.

Wilson Coefficients in NC DIS

[1702.00185]

Mass Basis	$g_{hh\gamma\gamma}$	$\tilde{g}_{hh\gamma\gamma}, \tilde{g}_{hhzz}$	$g^{(1)}_{hhzz}, g^{(2)}_{hhzz}$	$g^{(3)}_{hhzz}$
Gauge Basis	$-\frac{4\bar{c}_\gamma g^2 s_W^2}{m_W^2}$	$\frac{g}{2m_W}\{\tilde{g}_{h\gamma\gamma}, \tilde{g}_{hzz}\}$	$\frac{g}{2m_W}\{g^{(1)}_{hzz}, g^{(2)}_{hzz}\}$	$\frac{g^2}{2c_W^2}[1 - 6\bar{c}_T - \bar{c}_H + 8\bar{c}_\gamma \frac{s_W^4}{c_W^2}]$

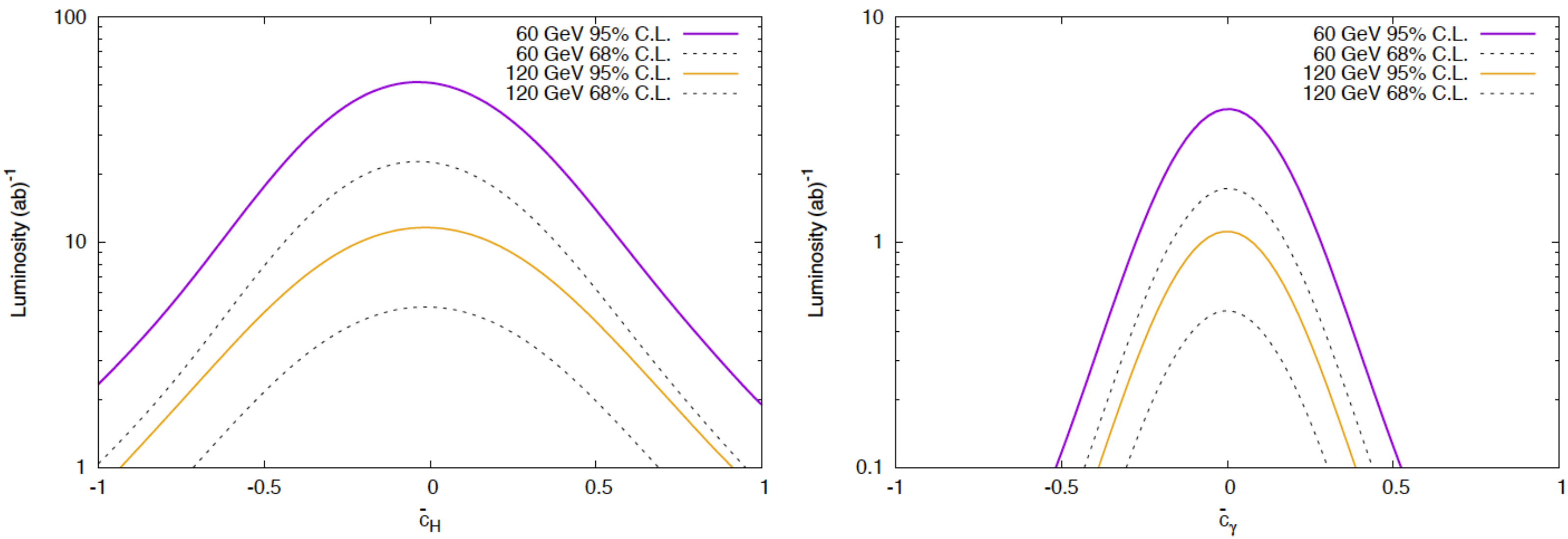


Figure 9: Required integrated luminosities to obtain corresdonding Wilson coefficients for FCC-he energy options.

Selection Requirements

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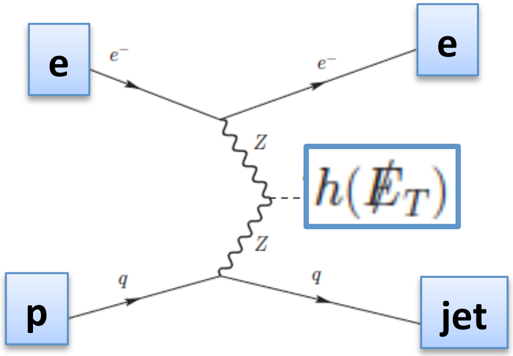
Masahiro Kuze
Tokyo Tech

Basic cuts (Cut 0)

- N(jets) for the jet and the electron
- pT for the leading jet and the leading electron
- for the leading jet and the leading electron
- for the leading jet and the leading electron



Cut 1 : $|\Delta\phi_{jet,Etmiss}| > 1$ rad

Cut 2 : Etmiss > 50 GeV

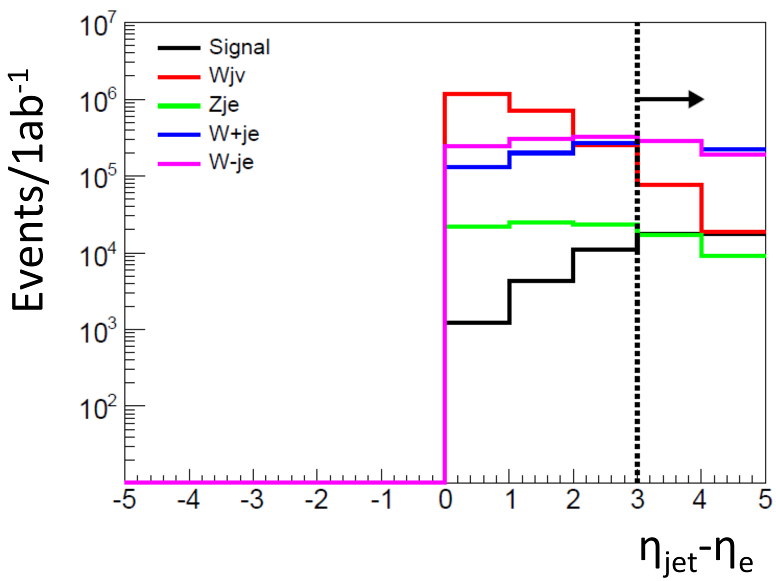
Cut 3 : $\eta_{jet}-\eta_e > 3$

Cut 4 : $\phi_{jet} - \phi_e < 2.4$

Cut 5 : $-1.3 < \eta_e < 1.1$

Cut 6 : $0.08 < y_e < 0.55$

Cut 7 : require 1 electron, 1 jet, and veto tau's and muons



Exotic Higgs at LHeC@1ab^{-1}

[arXiv:1608.08458]

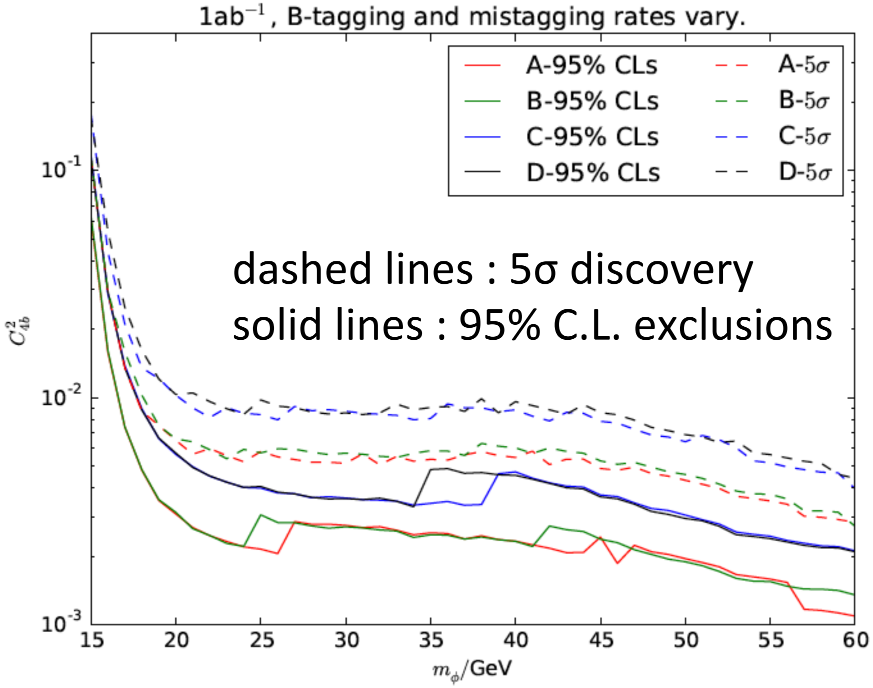
b-tag scenarios $|\eta|<5$

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

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

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

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

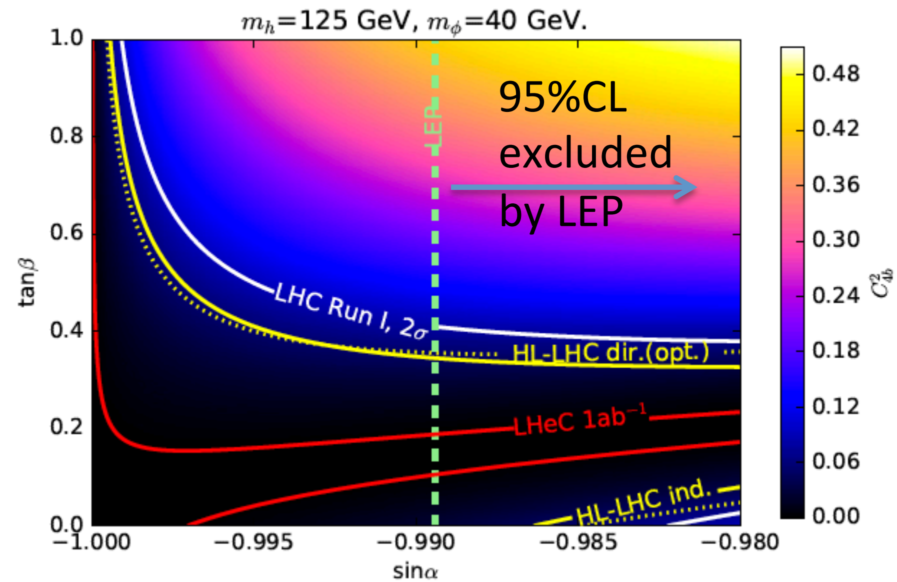


95% C.L. for m_ϕ of 20, 40, 60 GeV for

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

is 0.3%, 0.2% and 0.1%

Sensitivity comparison in Higgs Singlet Model



$$\Phi \equiv \begin{pmatrix} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix}, S \equiv \frac{h'+x}{\sqrt{2}} \quad (12)$$

Here $v = 246$ GeV ensures the correct mass generation for W, Z bosons and SM fermions. The gauge eigenstates $\tilde{h}, h'$ can be related to mass eigenstates ϕ, h via an orthogonal rotation

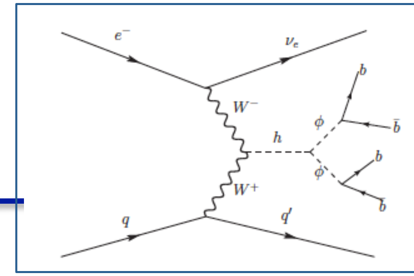
$$\begin{pmatrix} \phi \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix} \quad (13)$$

Now it is convenient to parameterize the model in terms of five more physical quantities: (m_ϕ, m_h are masses of ϕ and h respectively)

$$m_\phi, m_h, \alpha, v, \tan\beta \equiv \frac{v}{x} \quad (14)$$

Samples

Focusing on dominant backgrounds



Uta Klein
Michael o'Keefe
Liverpool

Sample	Process	Generator Level Constraints	Cross Section (fb)
Signal[1]	h→φφ→b b~ b b~	PT of Jets/b's/photons/charged leptons > 6.5 GeV η of Jets/b's/photons/charged leptons < 6.1 Min. ΔR between jets = 0.2 Min. Inv. Mass of Jet/bb~ pair = 8 GeV	51.34
CC Single Top Production	pe-→j t~ vl all /h (t~ → W- b~, W- → all all	PT of Jets/b's/photons/charged leptons > 6.5 GeV η of Jets/b's/photons/charged leptons < 6.1 Min. ΔR between jets = 0.2 Min. Inv. Mass of Jet/bb~ pair = 8 GeV	11,347
CC Top+Multijet Sample	all = g u c d s u~ c~ d~ s~ , ve vm vt ve~ vm~ vt~ ta- ta+ b b, ~ z w+ w- h t t~ pe- → b~ all all vl pe- → b all all vl	PT of Jets/b's/photons/charged leptons > 6.5 GeV η of Jets/b's/photons/charged leptons < 6.1 Min. ΔR between jets = 0.2 Min. Inv. Mass of Jet/bb~ pair = 8 GeV Beam Polarisation = 0	9683
CC Inclusive Single W/Z/h Production	p e- → vl w- j j / t~ t , w- → j j p e- → vl h j j , h → j j p e- → vl z j j , z → j j	η of Jets/b's/photons/charged leptons < 6.1 Min. ΔR between jets = 0.2 Min. Inv. Mass of Jet/bb~ pair = 8 GeV Beam Polarisation = 0	3566
CC b b~ + 2j Production	all = g u c d s u~ c~ d~ s~ ve vm vt ve~ vm~ vt~ ta- ta+ b b~ p e- > b~ b all all vl	PT of Jets/b's/photons/charged leptons > 6.5 GeV η of Jets/b's/photons/charged leptons < 6.1 Min. ΔR between jets = 0.2 Min. Inv. Mass of Jet/bb~ pair = 8 GeV Beam Polarisation = 0	1120

➔ low pT and low dijet mass generation to retain sensitivity for 20 GeV scalar