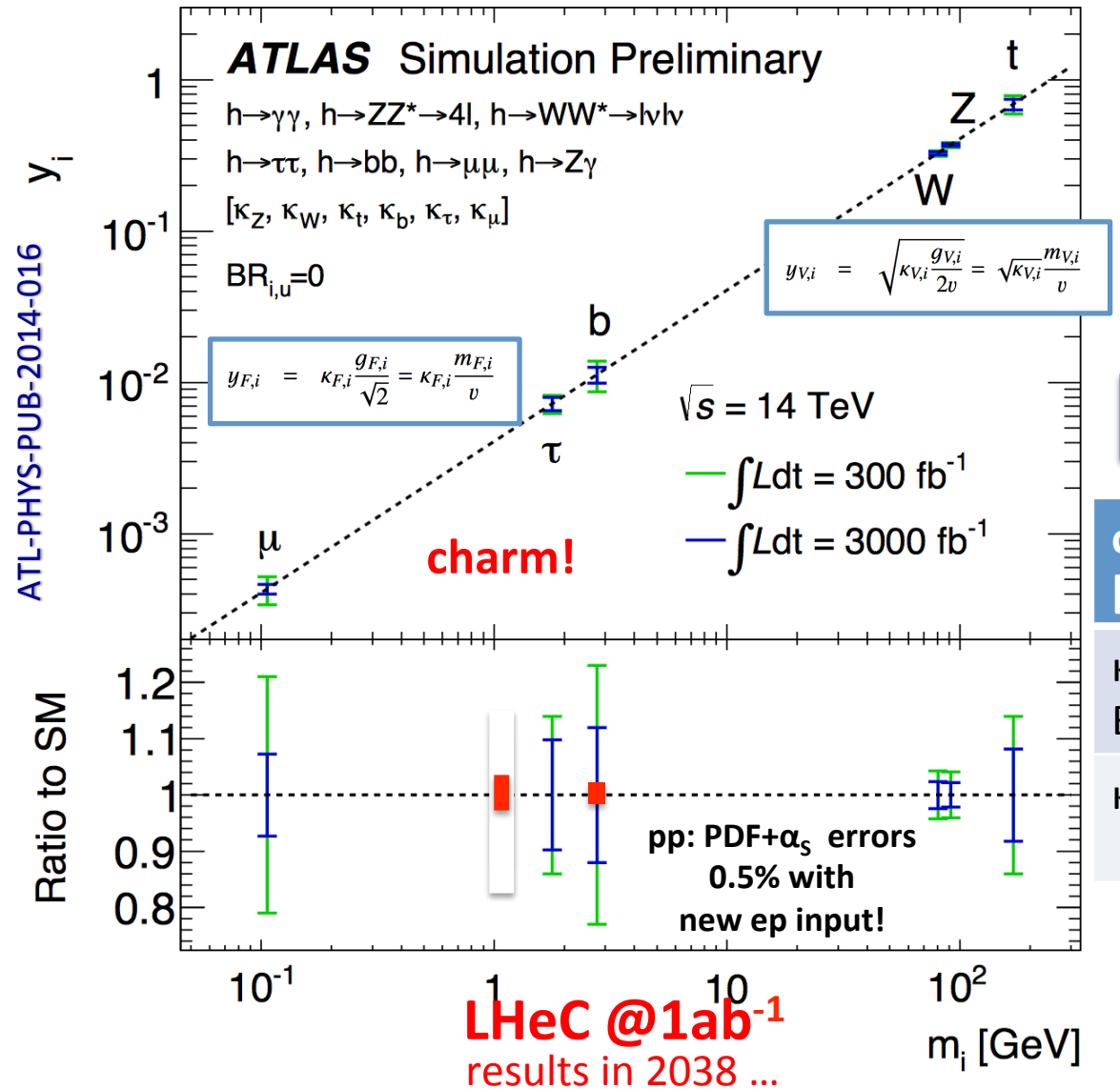
FCC-eh
Progress on BSM Higgs Studies

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

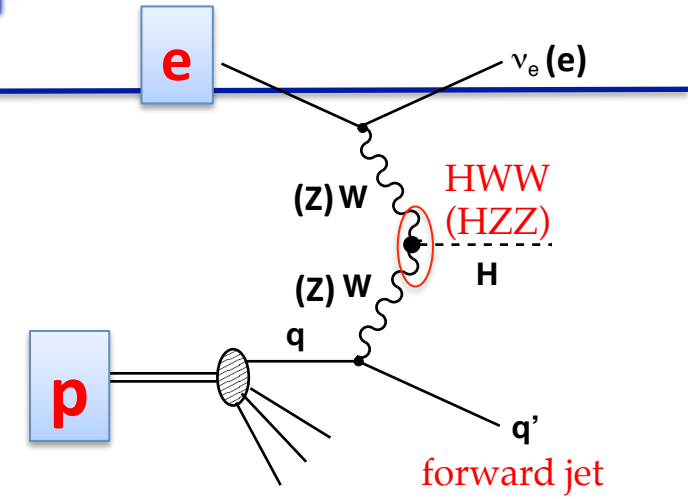
FCC Week 2017 CERN, January 18th, 2017

Higgs Couplings at pp + ep

running concurrently



LHeC @1ab^{-1}
results in 2038 …
concurrent with HL-LHC end



E_p = 7 TeV 14 TeV 50 TeV

c.m.s. [TeV]	LHeC 1.3	DLeHC 1.8	FCC –eh 3.5
κ(H→bb) BR=57%	**0.5%**	0.3%	**0.2%**
κ(H→cc) BR=3%	**4%**	2.8%	**1.8%**

→ to be improved further
→ more couplings to come
→ turn pp into ONE powerful Higgs facility by adding an electron beam

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

Analysis Framework

Event generation

- **BSM Higgs 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 → BDT

- Calculate cross section with tree-level Feynman diagrams (any UFO) using pT of scattered quark as scale (CDR ŝ) for ep processes like single t, Z, W, H

→ Standard HERA tools can NOT to be used !

→ **MadgGraph5**

- **Higgs mass 125 GeV as default**
- Fragmentation & hadronisation uses **ep-customised** Pythia.
- **Delphes 'detector' →displaced vertices and signed impact parameter distributions → studied for LHeC, and used for 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

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]

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

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

SM

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

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

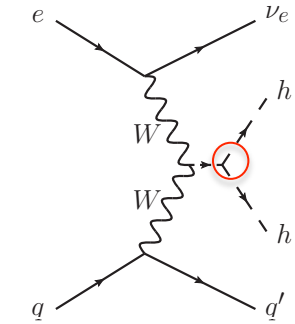
$$\mathcal{L}^{(4)}_{hhWW} = -g^2\left[\frac{g^{(1)}_{hhWW}}{4m_W^2} W^{\mu\nu} W^\dagger_{\mu\nu} h^2 + \frac{g^{(2)}_{hhWW}}{2m_W^2}(W^\nu \partial^\mu W^\dagger_{\mu\nu} h^2 + \text{h.c}) + \frac{\tilde{g}_{hhWW}}{4m_W^2} W^{\mu\nu} \widetilde{W}^\dagger_{\mu\nu} h^2\right]. \quad (4)$$

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

[arXiv:1509.04016]

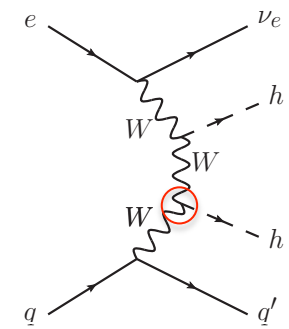
Effective Vertices

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



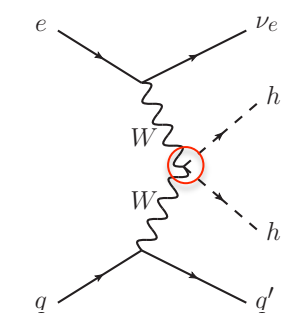
1,2,3= h,h,h

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



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

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



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

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

[1509.04016]

Event Selection using h→bb

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

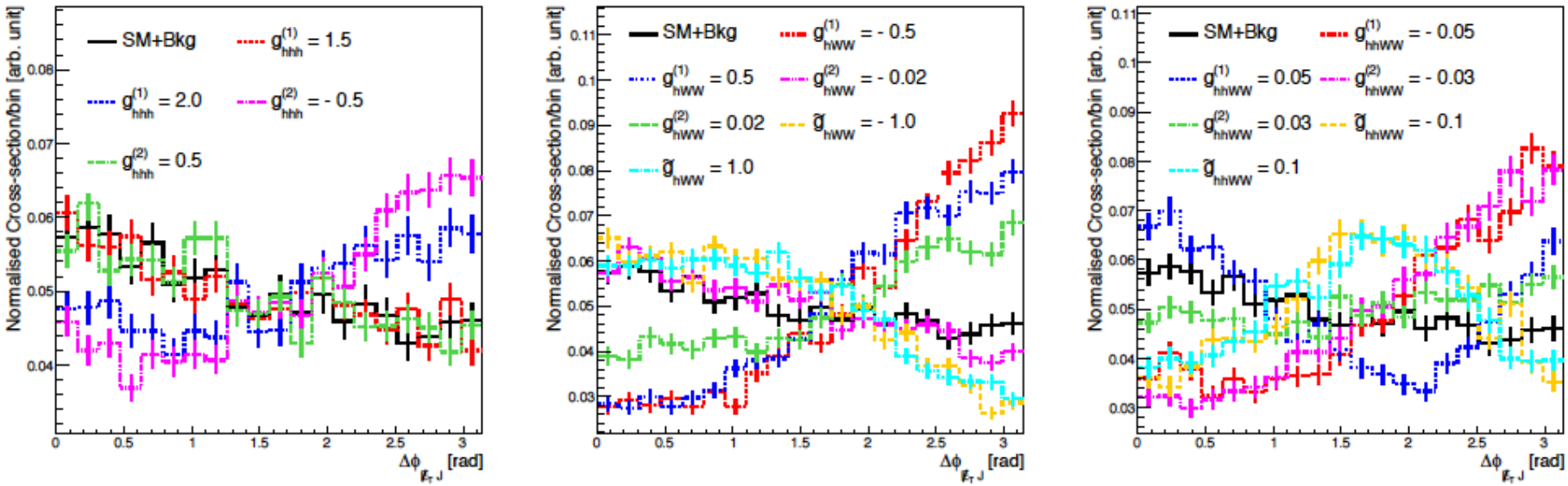
$$\mathcal{S} = \sqrt{2[(S+B)\log(1+S/B) - S]}$$

[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

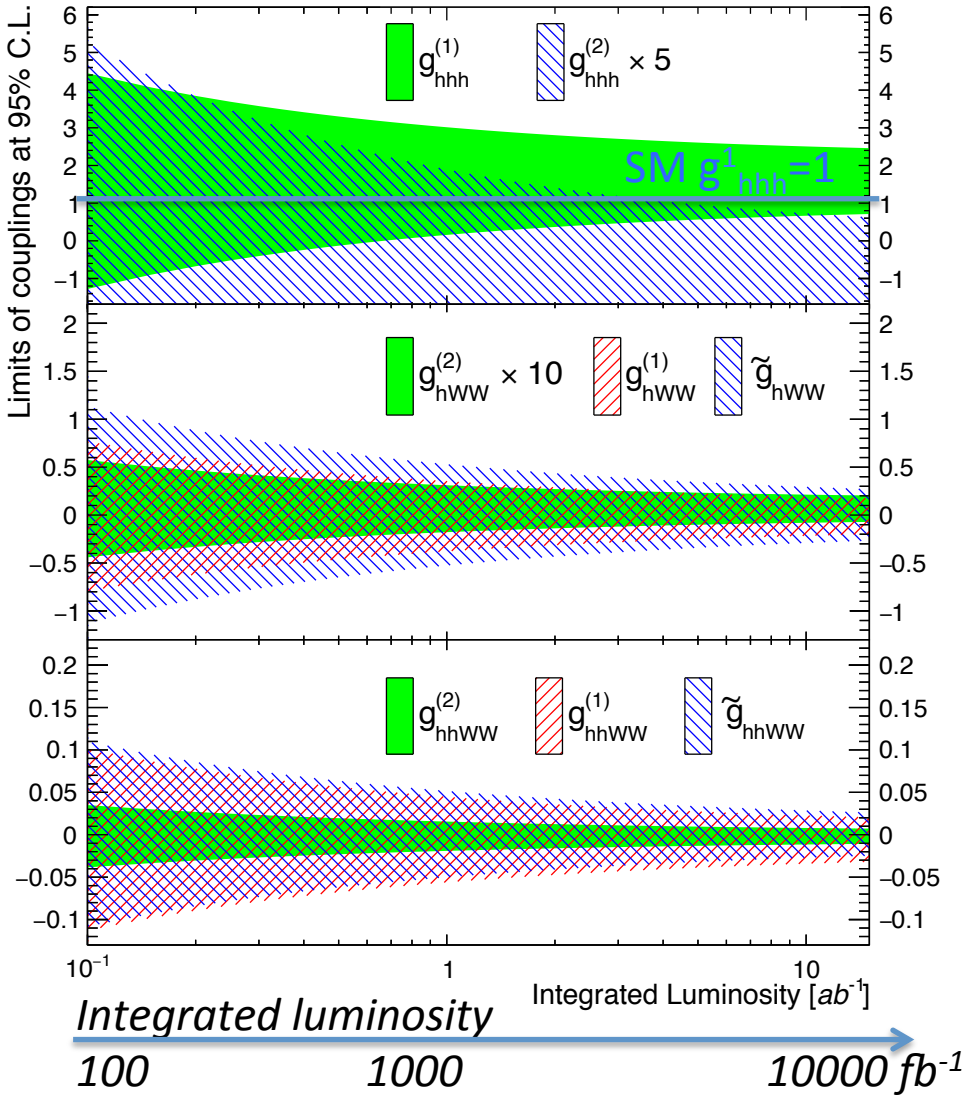
➔initial study published for this novel variable

➔potential for a deeper analysis and interpretation

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

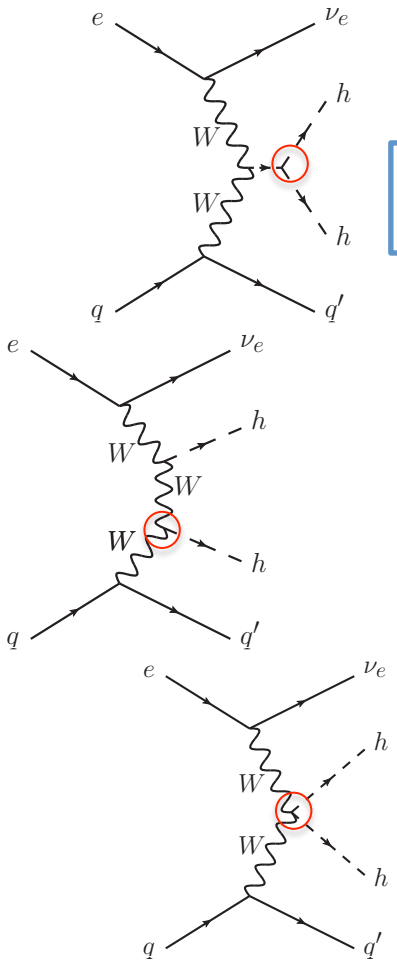
[1509.04016]

5% systemtatic uncertainty included



Integrated luminosity

100 *1000* *10000 fb^{-1}*



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

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

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

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

Invisible Higgs@LHeC

relating the Higgs and the 'dark' sectors

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

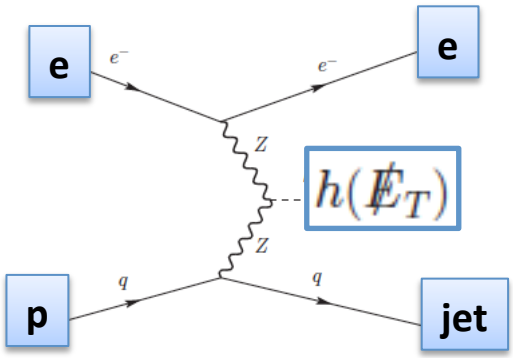
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

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

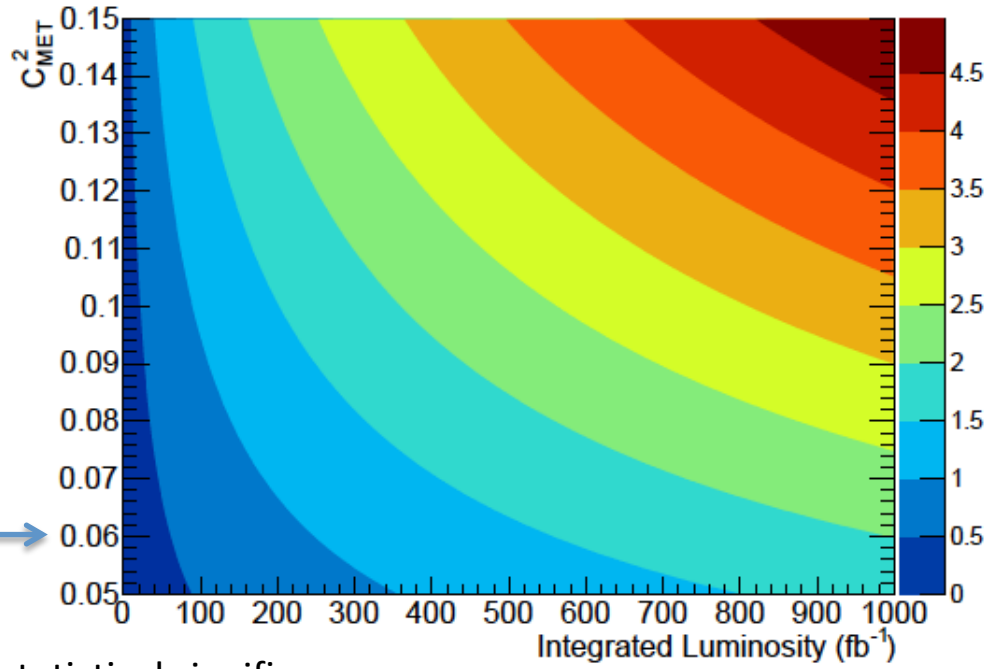
For **LHeC**, assume : 1ab^{-1}, P_e=-0.9, <u>cut based</u>

$\mathrm{Br}(h \to \not{E}_T)$ < 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



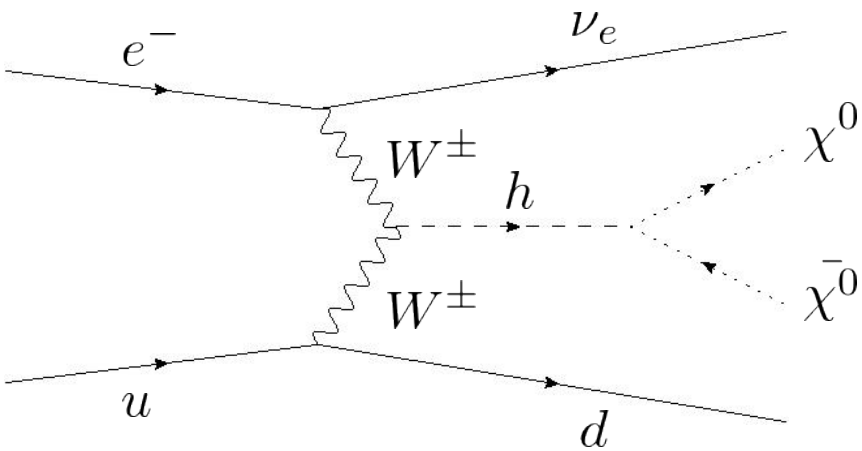
Colours: expected statistical significance

- ➔ **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**

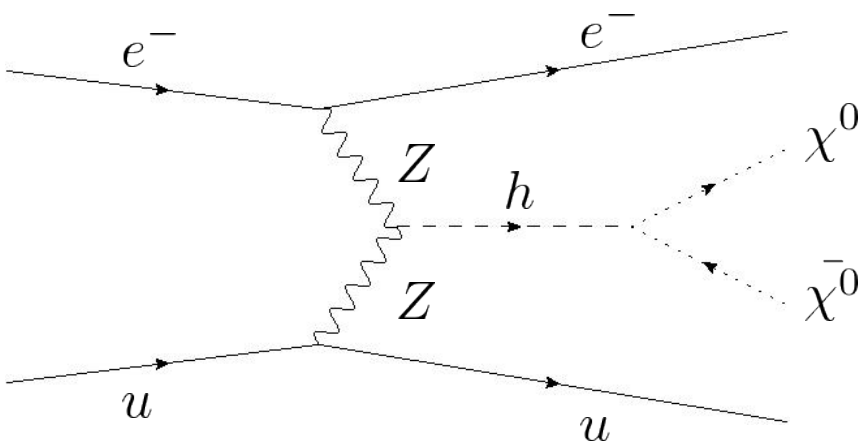
Invisible Higgs Decay in ep

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 (1)

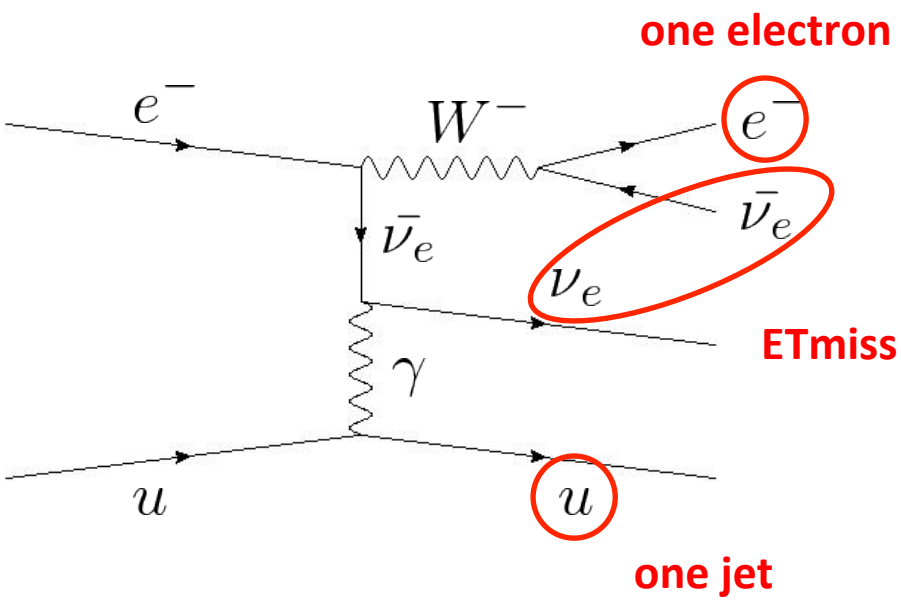
Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

for faking our signal feature :
one electron, one jet, and missing transverse energy (Etmiss)

Wjν background

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

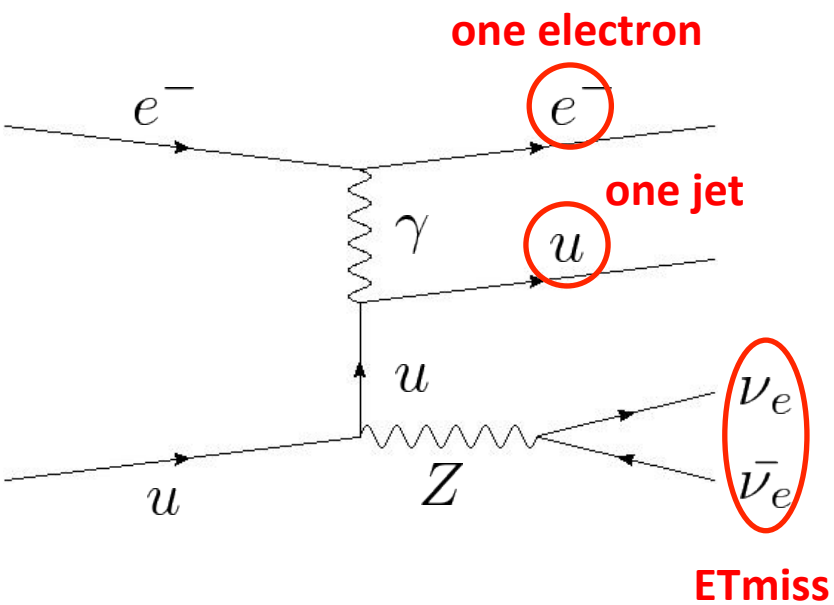
$$W^- \to e^- + \nu_e$$



Zje background

$$p + e^- \to Z + j + e^-$$

$$Z \to \nu + \bar{\nu}$$



Dominant Background (2)

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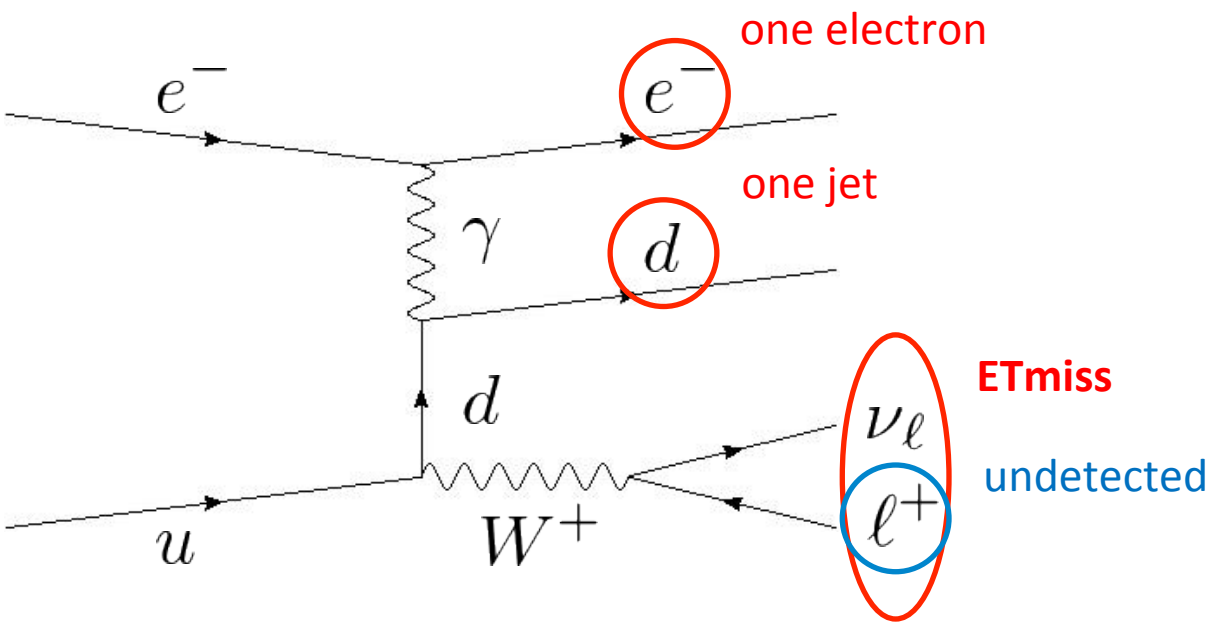
Masahiro Kuze
Tokyo Tech

Wje background

$p + e^- \to W + j + e^-$ $\quad W \to \ell + \nu_\ell$

undetected



W+ and W- separately generated

Selection Requirements

Satoshi Kawaguchi,
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

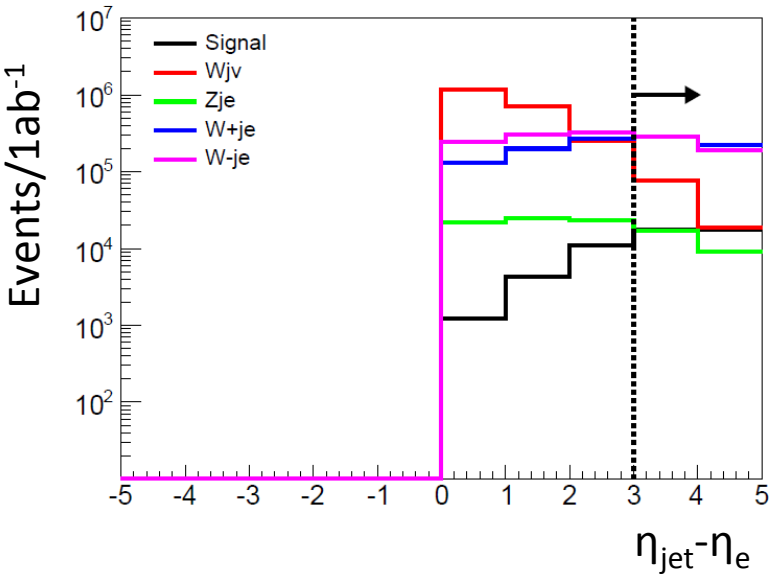
Cut 3 : $\eta_{jet}-\eta_e > 3$

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



Results for FCC-eh - Using Cuts

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

We analyzed the signal and the backgrounds by cut-based analysis

Event	cut0	cut1	cut2	cut3	cut4	cut5	cut6	cut7
Signal (Br=100%)	79626	53263	40134	30299	24558	23640	18774	10862
	2801080	1823611	1009497	45034	30154	26767	5292	3062
	127927	78521	39227	11837	8005	6729	3498	1701
	1599622	875306	395383	216470	118524	106884	72068	4320
	1815491	878388	259793	124438	71995	64375	44522	2706
…								
Total background	9842523	5849216	2562766	426915	246905	221774	126320	12129

The number of events of the signal and the main backgrounds after application of each cut, assuming an integrated luminosity of $1ab^{-1}$

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

$$Z = 10862 \times \mathrm{Br}(h \to \not{E}\downarrow T)/\sqrt{10862 \times \mathrm{Br}(h \to \not{E}\downarrow T) + 12129}$$

In the case of 2σ

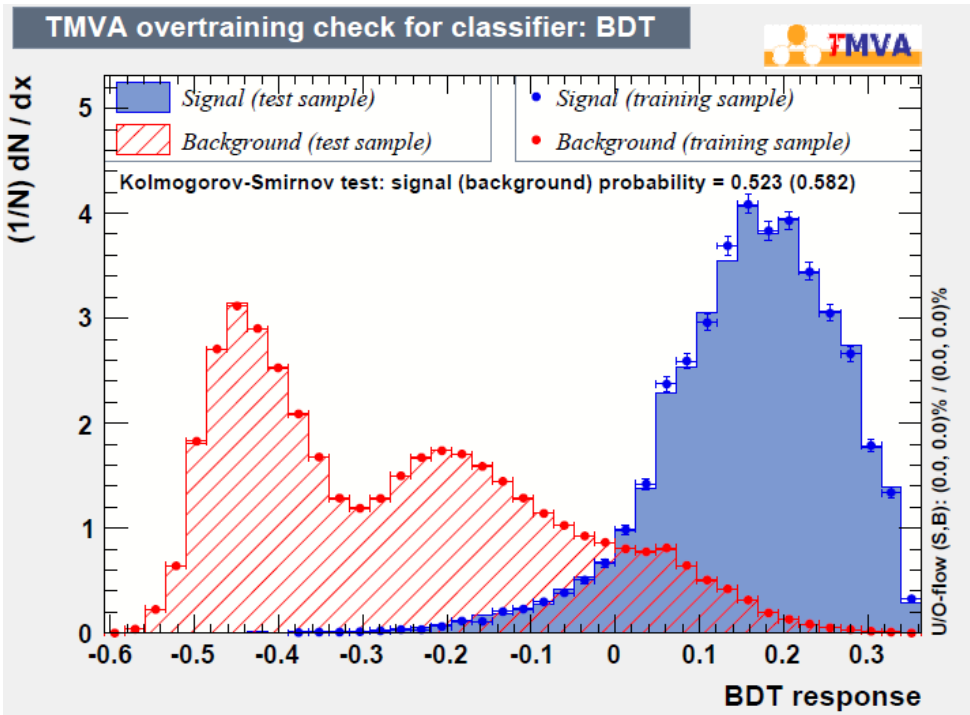
$$\mathrm{Br}(h \to \not{E}\downarrow T) \sim 2.05\%$$

Results for FCC-eh - Using BDT

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

MVA (BDT) using samples after cut 0 and cut 7, and use other variables as a BDT input.

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 $S/\sqrt{S+B}$:

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

In the case of 2σ

$$\mathrm{Br}(h \to \not{E}\downarrow T) \sim 1.93\%$$

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 has certainly a significant impact on results

Exotic Higgs Decays

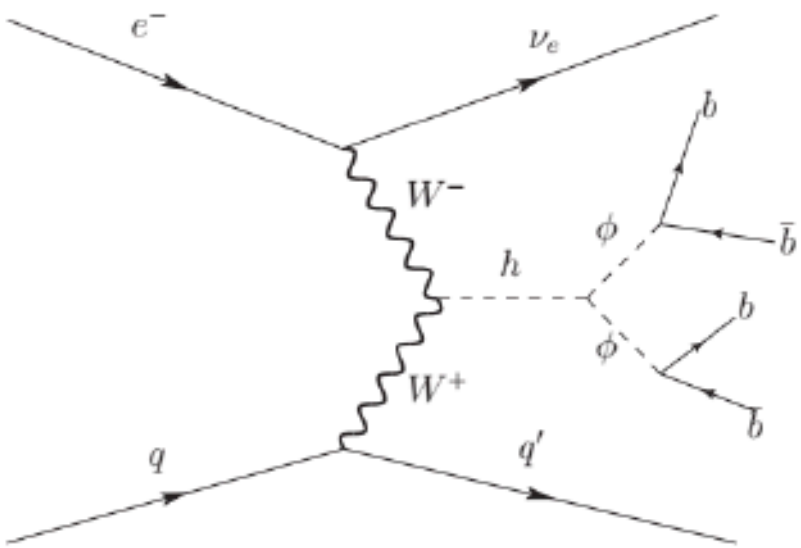
$$\mathcal{L}_{eff} = \lambda_h v h \phi^2 + \lambda_b \phi \bar{b} b + \mathcal{L}_{\phi\,\mathrm{decay,other}}$$

$$h \to \phi\phi \to 4b$$

ϕ: a spin-0 particle from new physics.

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

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



- 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.

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

ϕ mass range targeted in this study: [20,60]GeV, scanned in 1 GeV step.

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

[arXiv:1608.08458]

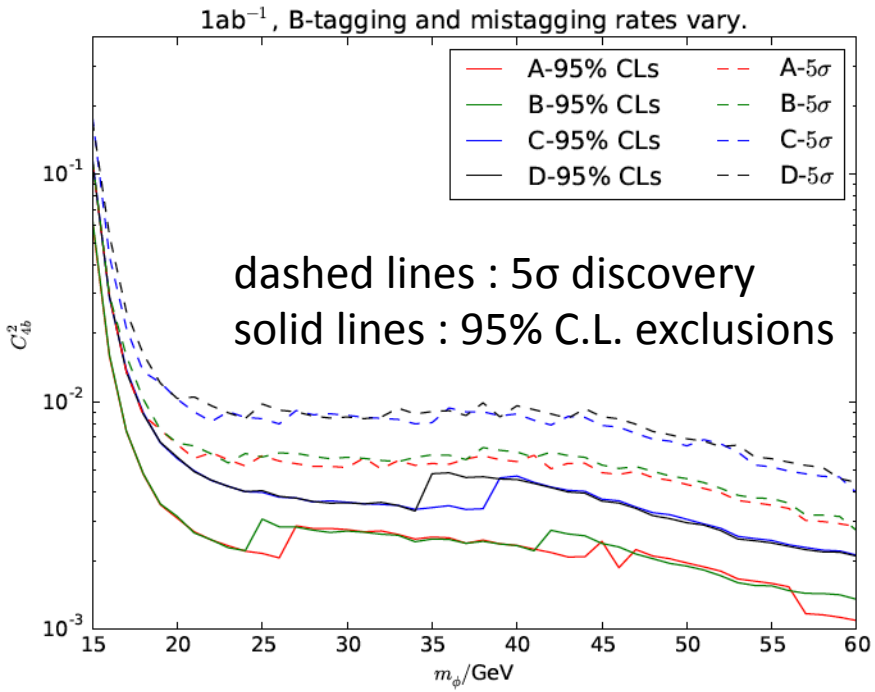
Btag scenarios

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

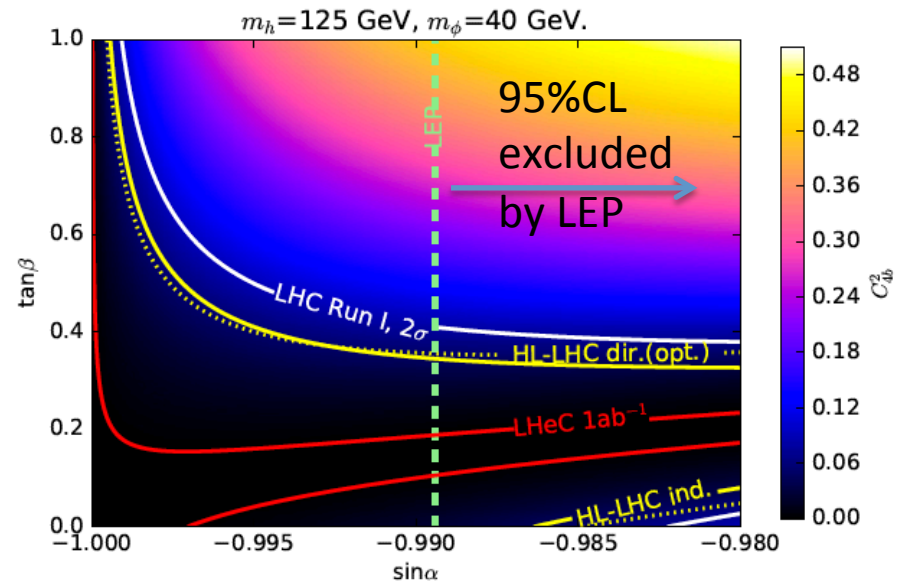


95% C.L. for m_ϕ of 20, 40, 60 GeV for

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

is 0.3%, 0.2% and 0.1%

Sensitivity comparison in Higgs Singlet Model



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

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

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

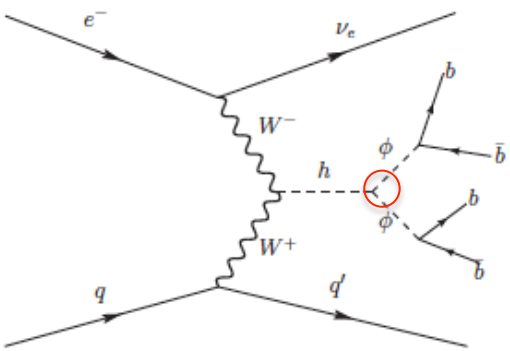
Now it is convenient to parameterize the model in terms of five more physical quantities: (m_ϕ, m_h are masses of ϕ and h respectively)

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

FCC-eh Cross Sections BR to bb 100%

Uta Klein
Michael o'Keefe
Liverpool

AhSS



Ahss	BR (%)	σ (fb)	Δσ (fb)
0.1643	0.2	1.06	0.01
0.2598	0.5	2.65	0.01
0.3674	1	5.32	0.02
0.5195	2	10.53	0.04
0.6363	3	15.86	0.07
0.7347	4	21.1	0.1
0.8215	5	26.4	0.1
0.8999	6	31.6	0.2
0.9720	7	37.1	0.1
1.0391	8	42.2	0.2
1.1021	9	47.9	0.2
1.1617	10	53.1	0.2

We use as our baseline model (from Sep 2016) :

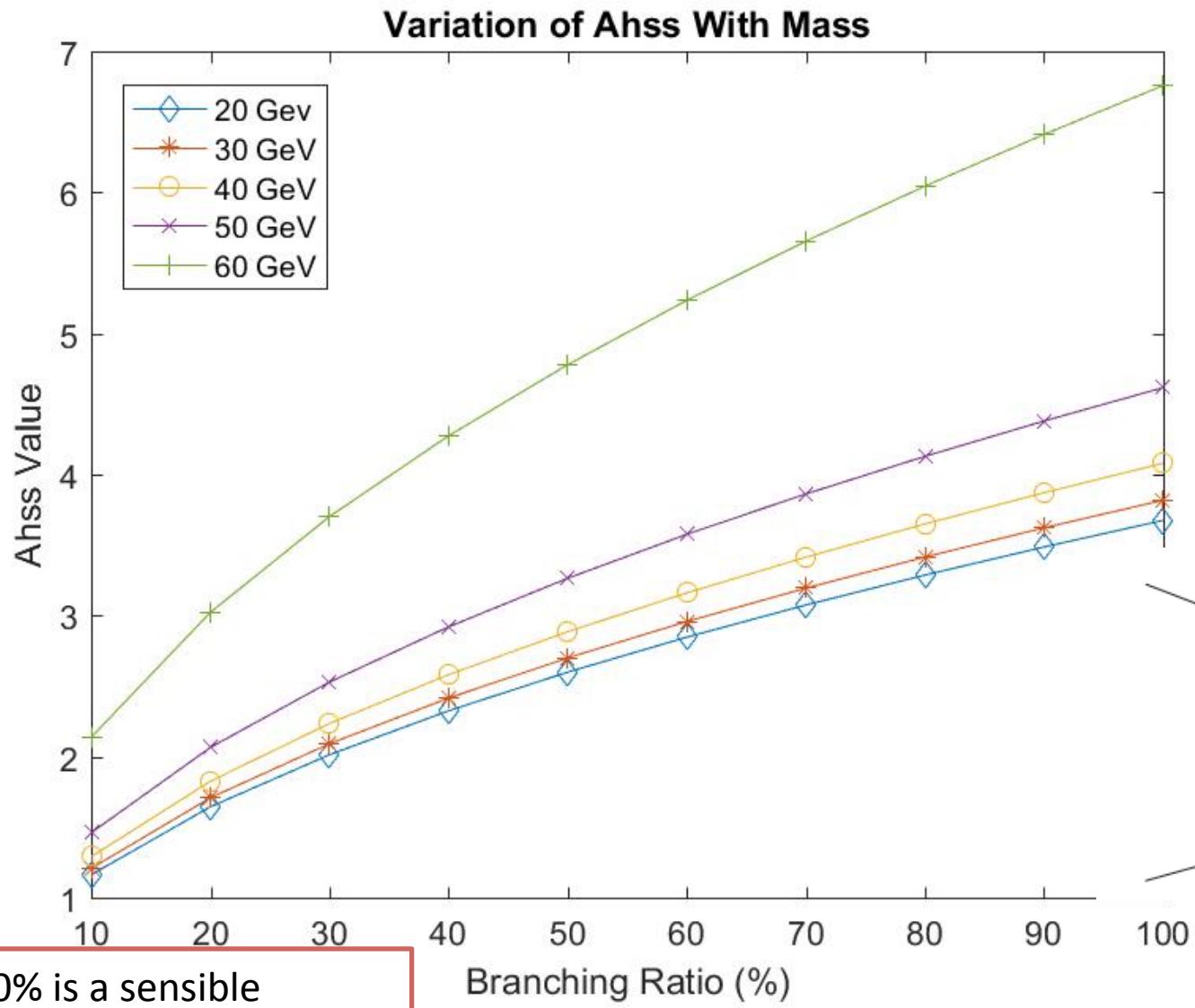
[arXiv:1608.08458]
in close collaboration with C. Zhang & Y.L. Tang

The model assumes same narrow width for higgs and new scalar.

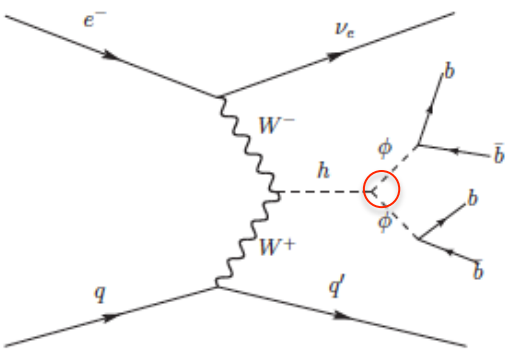
AhSS is the coupling set in MG5 model.

Coupling of new scalar to 125 GeV-Higgs

Uta Klein
Michael o'Keefe
Liverpool



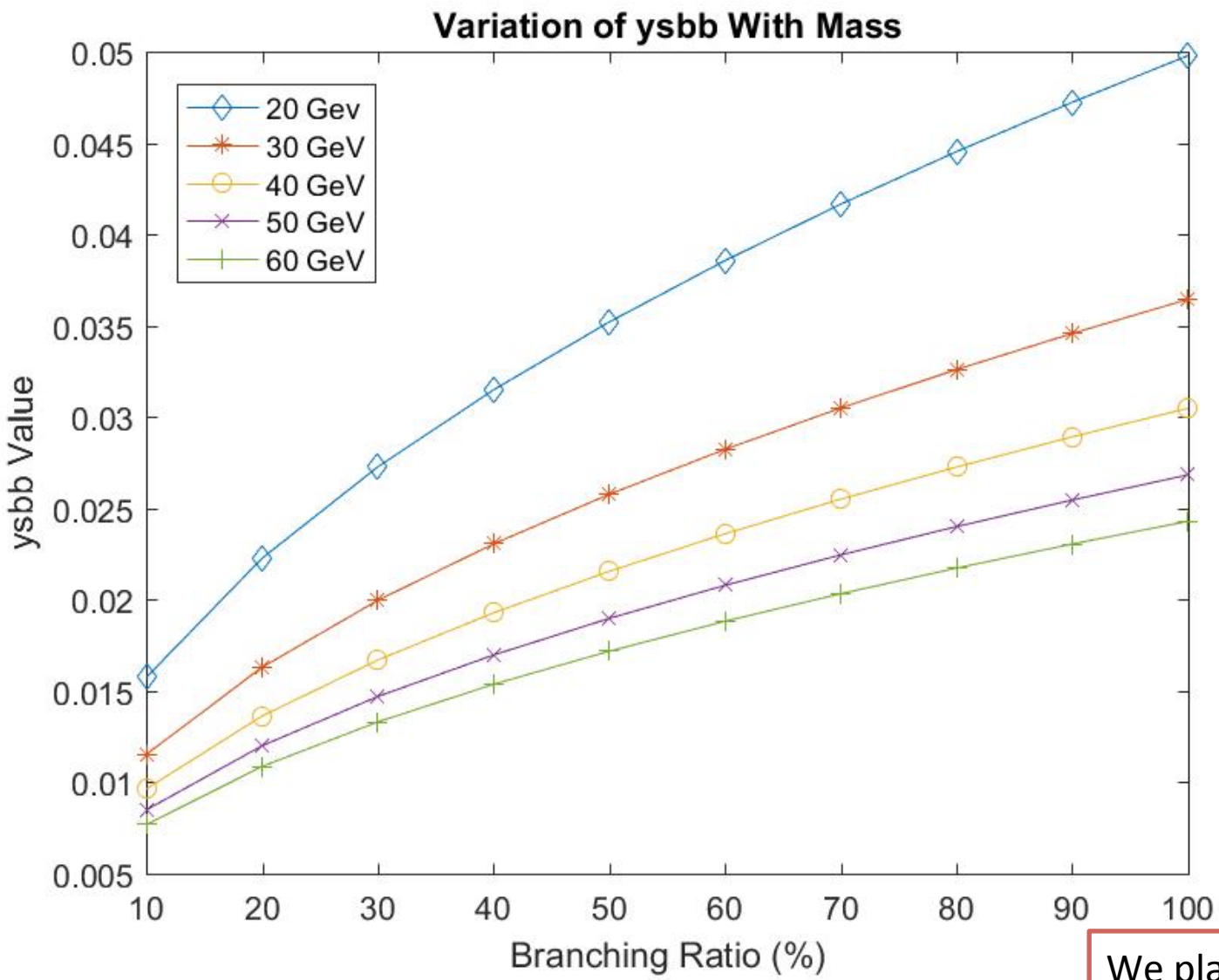
AhSS



10% is a sensible nominal value to study

Coupling of new scalar to b-quarks

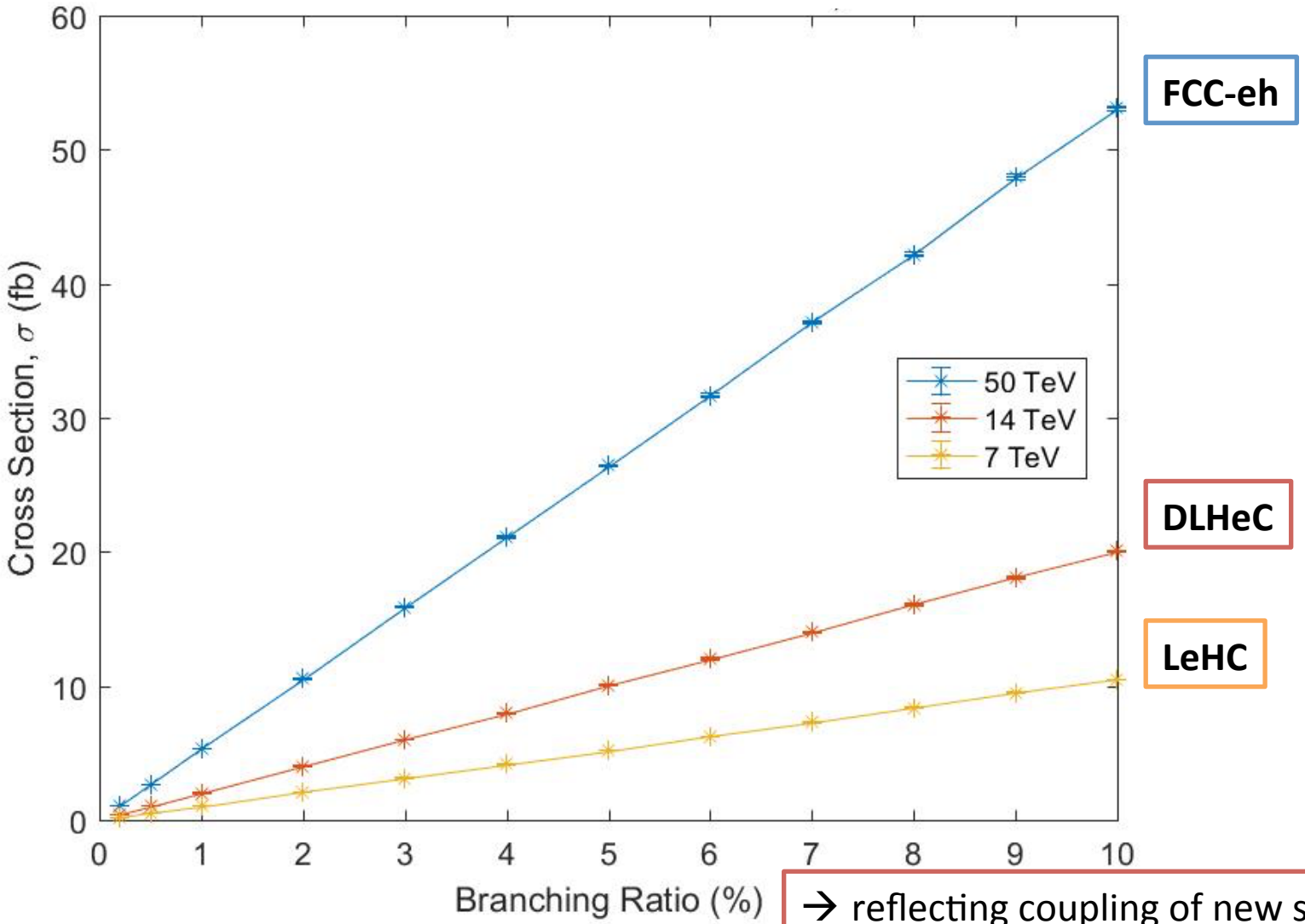
Uta Klein
Michael o'Keefe
Liverpool



We plan to use 100% as our nominal value

Variation of Cross Sections

Uta Klein
Michael o'Keefe
Liverpool

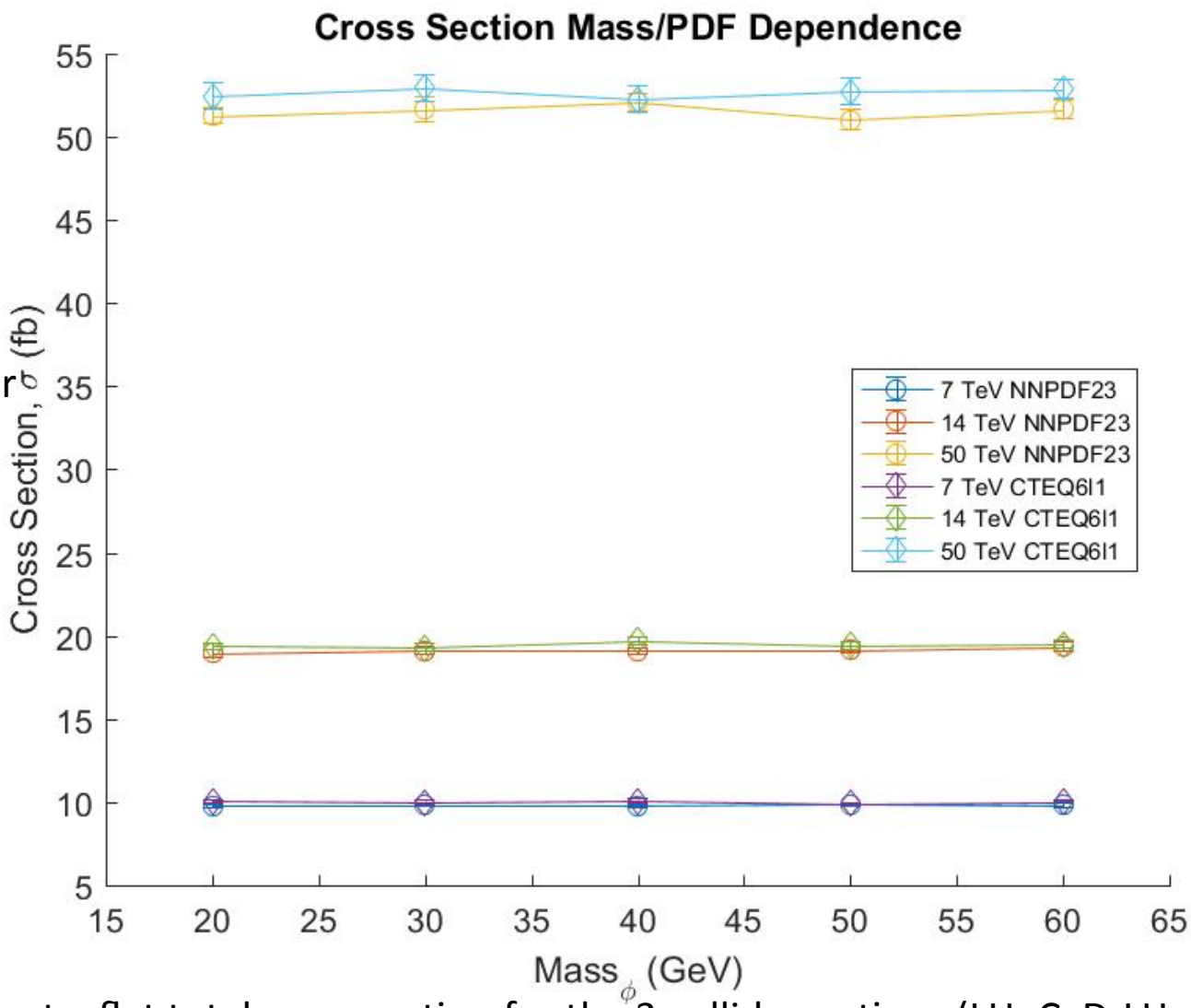


→ reflecting coupling of new scalar to 125 GeV higgs

Total Cross Sections vs Masses

Uta Klein
Michael o'Keefe
Liverpool

BR=10% for h to new scalar and 100% for BR of new scalar to bb



FCC-eh

DLeHC

LeHC

→ We expect a flat total cross section for the 3 collider options (LHeC, D-LHeC and FCC-he)

→ Next : Study effect of pT and eta acceptances using our MG5/Madevent simulation

More New Studies

Please see the posters at this workshop

- "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.
- "Limits on Neutral Diboson and Di-Higgs Interactions for FCC-he Collider" by S. Kuday et al.

➔ we will discuss those in our bi-weekly Higgs-top LHeC/FCC-eh meetings in preparation of FCC week in Berlin.

Conclusions

- **We just started to explore the potential of complementary 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 BSM physics scenario's and to design the *most powerful and sustainable* BSM 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 and our detector expert Peter Kostka.

Additional material

Asymmetries

$$\mathcal{A}_{\Delta\phi_{\not{E}_T J}} = \frac{|A_{\Delta\phi>\pi/2}| - |A_{\Delta\phi<\pi/2}|}{|A_{\Delta\phi>\pi/2}| + |A_{\Delta\phi<\pi/2}|},$$

[1509.04016]

Samples		$\mathcal{A}_{\Delta\phi_{\not{E}_T J}}$	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.