Higgs Physics at the LHeC & FCC-eh

Uta Klein

University of Liverpool

on behalf of

the LHeC/FCC-eh Study Group

European Physical Society HEP2019

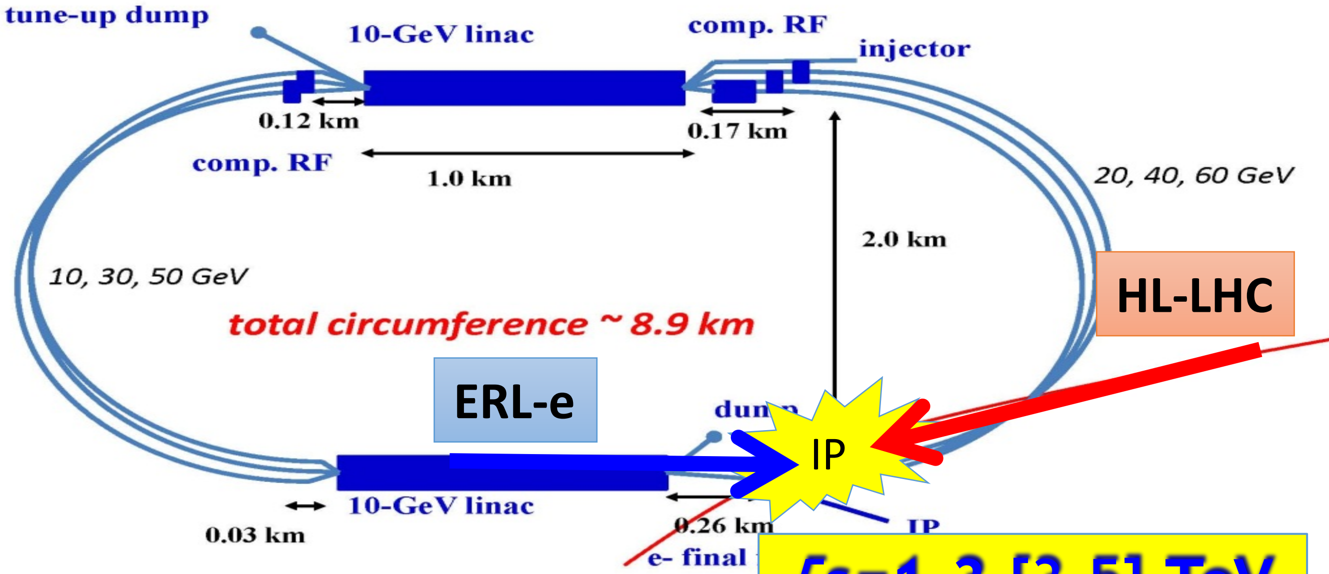
July 12th, 2019

electrons for eh : ERL-e + HL-LHC [FCC-hh]

- **Two 802 MHz Electron LINACs + 2x3 return arcs: using energy recovery in same structure: *sustainable* technology with power consumption < 100 MW** *instead of 1 GW for a conventional LINAC.*
- **Beam dump: no radioactive waste!**
- **high electron polarisation of 80-90%**

Concurrent eh and HL-LHC operation!

Same *Twin Collider* idea holds for HE-LHC and FCC-hh



$\sqrt{s}$=1.3 [3.5] TeV

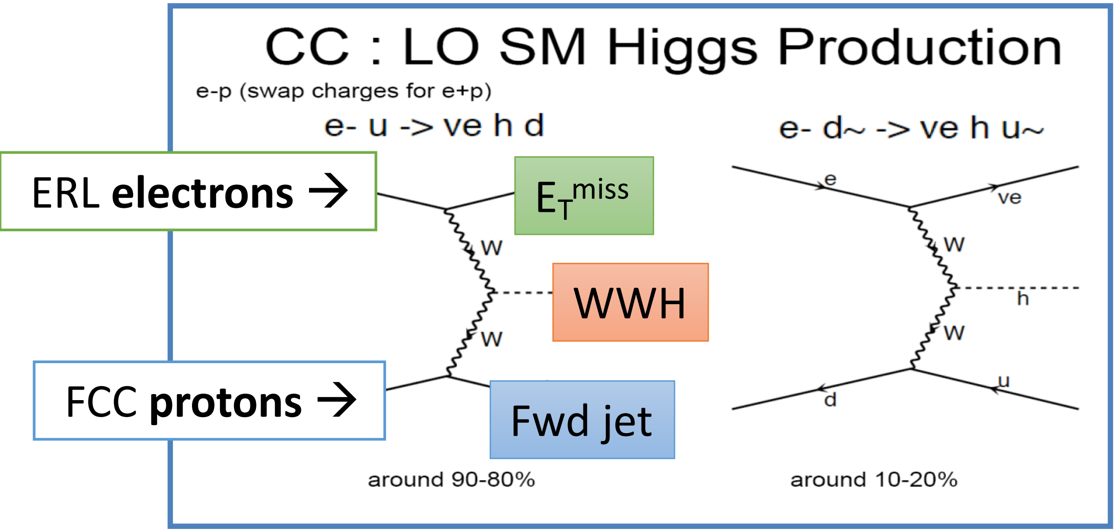
E_e = 60 GeV

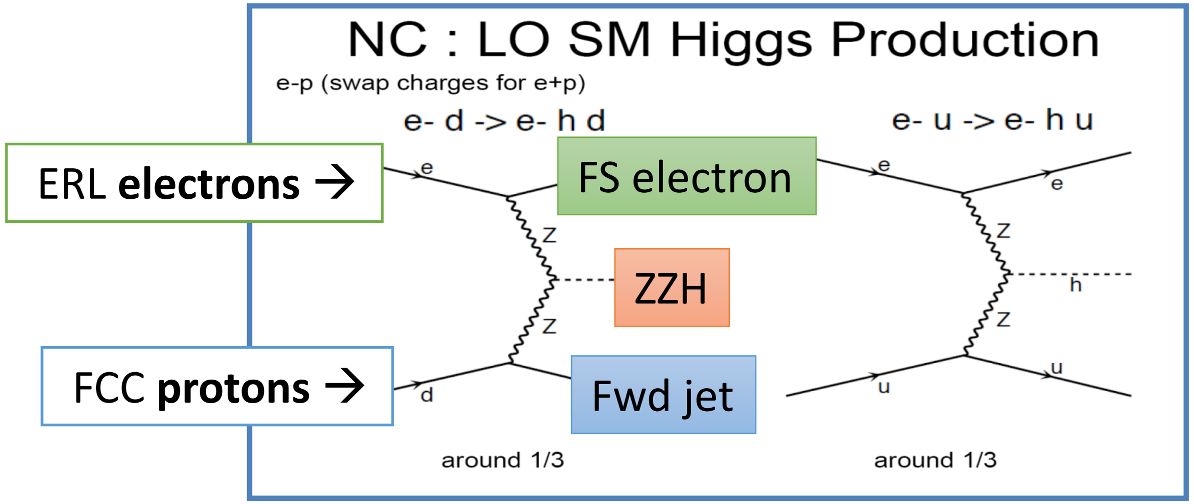
E_p = 7 [50] TeV

- **ep peak lumi 10^{34} cm s^{-2} s^{-1}** (based on existing HL-LHC design)
- **Operation scenario: F. Bodry et al.** CERN-ACC-2018-0037 [arXiv:1810.13022]
- **LHeC** [FCC-eh] **L= 1000** [2000] **fb^{-1} total collected in 10** [20] **years**
- **'No' pile-up**: <0.1@LHeC; ~1@FCCeh

ERL design detailed in LHeC CDR: J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001 [arXiv:1206.2913] and updates at recent LHeC/FCC-eh workshops Sep-17@CERN and June-18@Orsay.

SM Higgs Production in ep





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

Total cross section [fb]
(LO QCD CTEQ6L1 M_H=125 GeV)

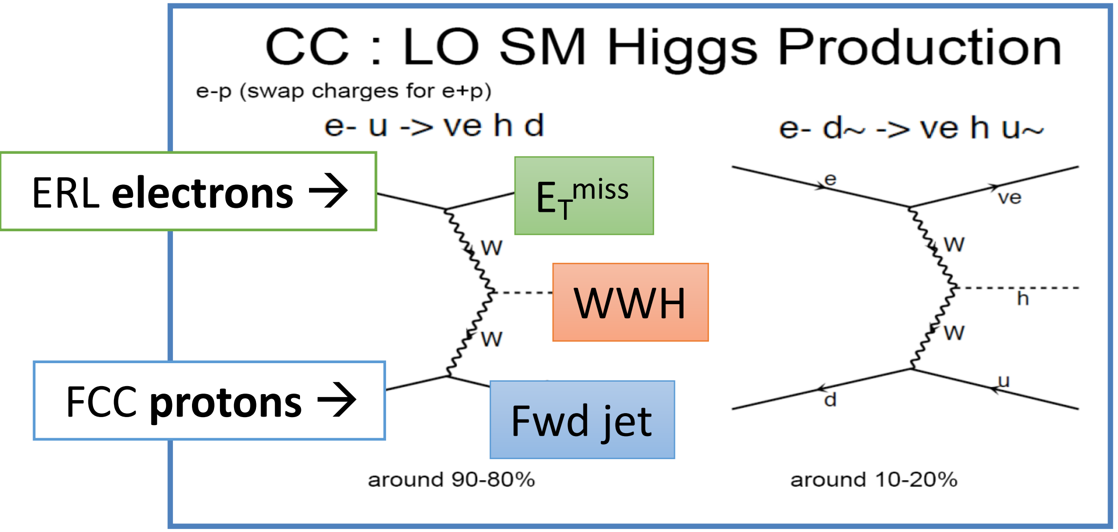
c.m.s. energy	1.3 TeV LHeC	3.5 TeV FCC-eh
CC DIS NC DIS	109 21	560 127
P=-80% CC DIS NC DIS	 **196** **25**	 **1008** **148**

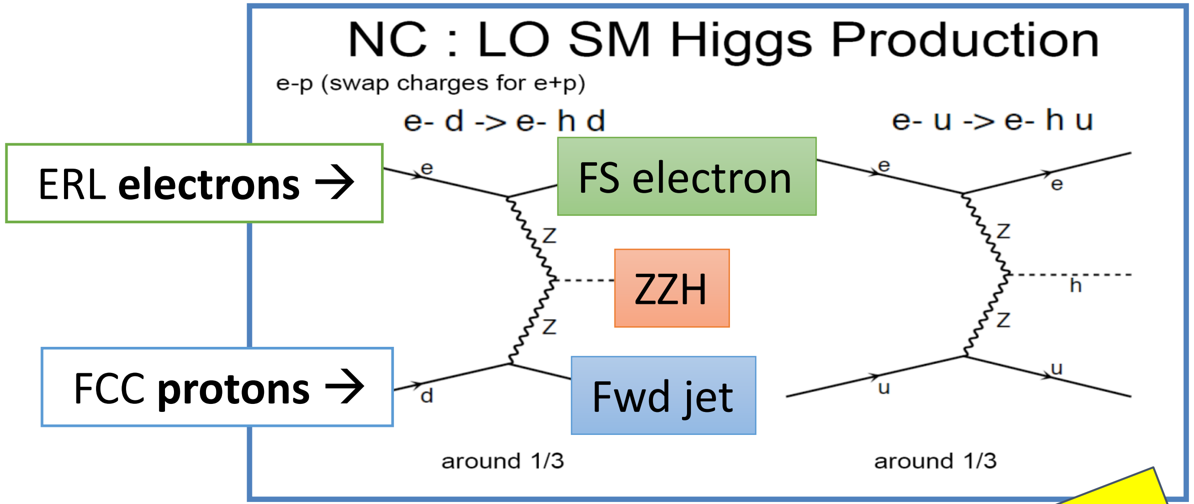
•Scale dependencies of the LO calculations are in the range of 5-10%. Tests done with MG5 and CompHep.

• **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]

SM Higgs Production in ep





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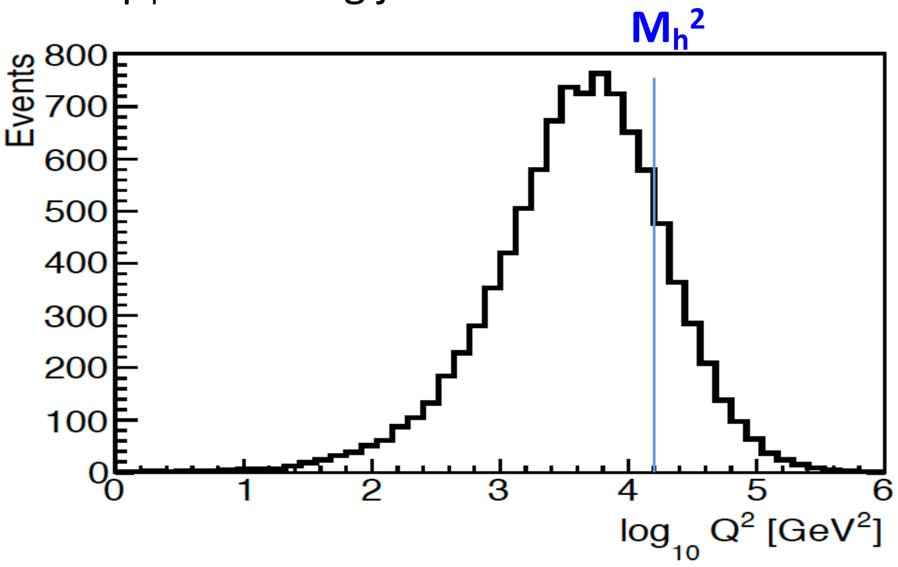
…gh , R. Ruckl, Nucl.Phys.B395:35-
[E… …001.3789]

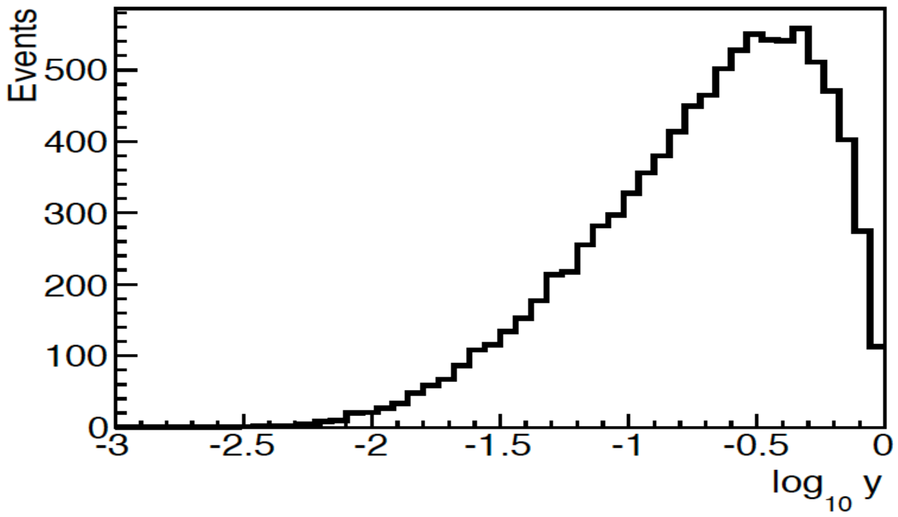
Theory well under control in ep!
LHeC will deliver N^3LO PDFs,
m_c to 3 MeV, m_b to 10 MeV and
α_s to ~0.1-0.2%

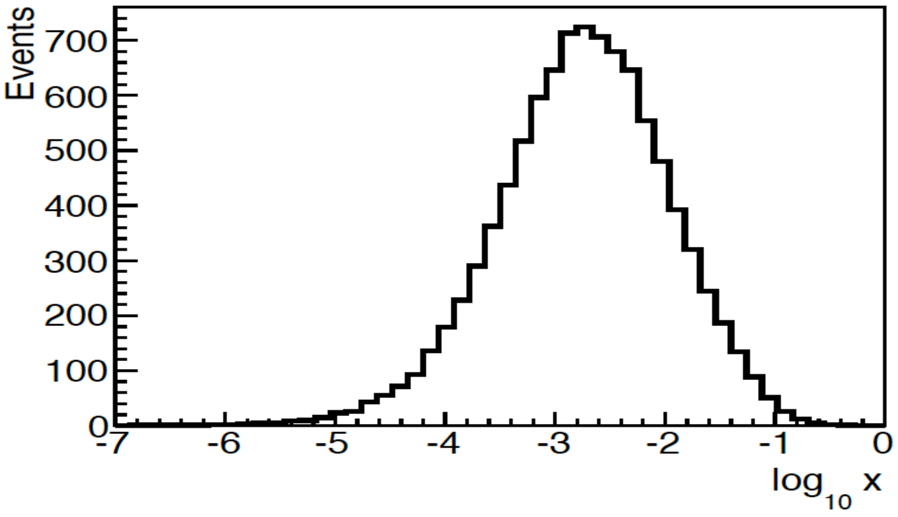
DIS Kinematics at FCC-eh @ √s=3.5 TeV

MadGraph scale: p_T of leading jet

Parton-level







$$q = (k - k'), q^2 = -Q^2$$

$$s = (k + P)^2$$

$$(xP + q)^2 = m^2, P^2 = M_p^2$$

$$if\,(Q^2 >> x^2 M_p^2, m^2):$$

$$q^2 + 2xPq = 0$$

$$x = \frac{Q^2}{2Pq}$$

$$Q^2 = sxy$$

relation to pp LO QCD

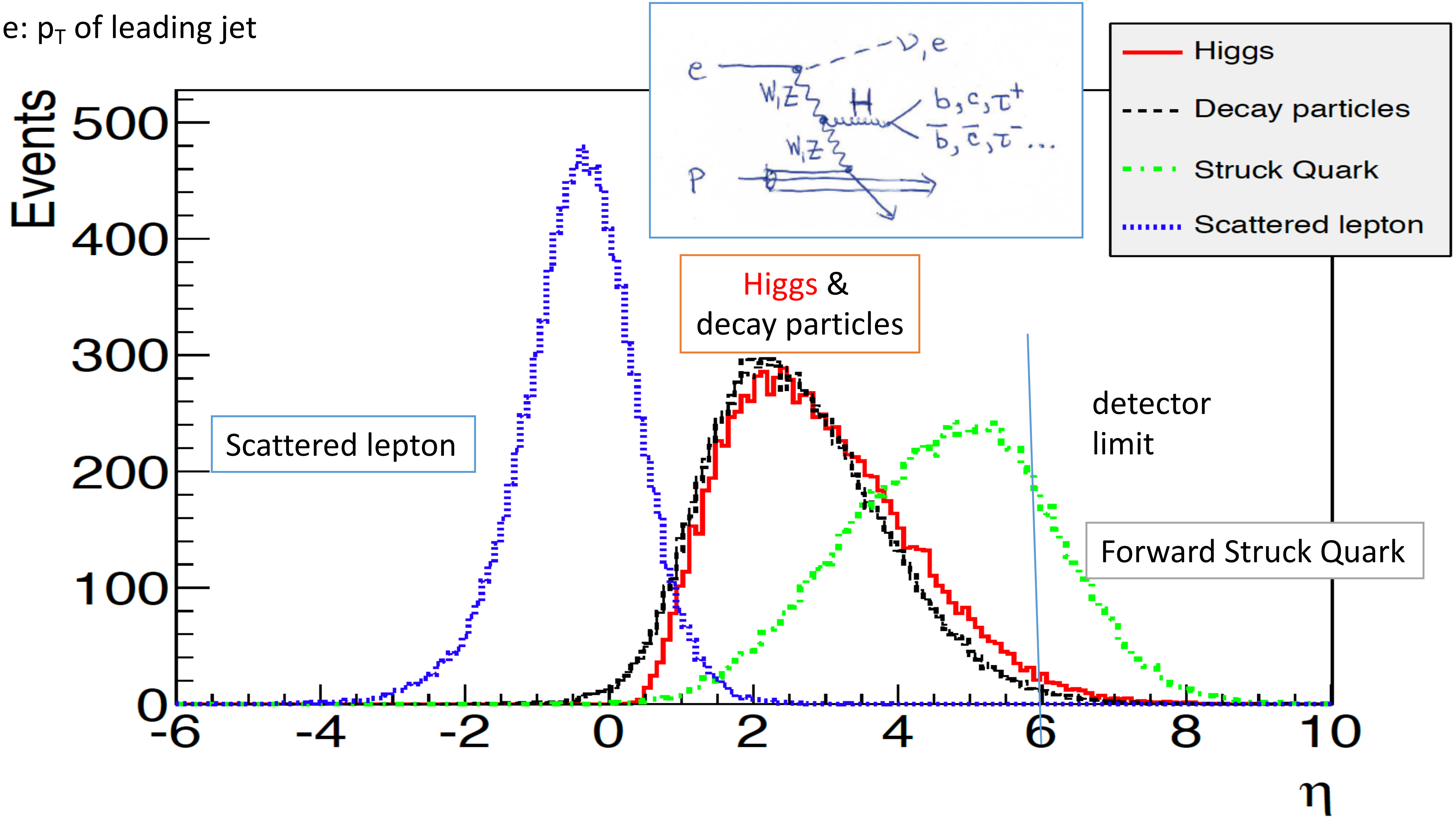
$x_{1,2}$= (M/√s) exp(±y)

Q^2 ~ M^2

η Distributions at FCC-eh

Parton-level

MadGraph scale: p_T of leading jet



Higgs decay particles (here to WW), struck quark and scattered lepton are well separated in detector acceptance.

Analysis Framework and Detector

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 LHeC detector

↓

S/B analysis → cuts or BDT

- Calculate cross section with tree-level Feynman diagrams (any UFO) using pT of scattered quark as scale (CDR $\hat{s}$) for ep processes with **MadGraph5** ; parton-level x-check CompHep
- Fragmentation & hadronisation uses **ep-customised** Pythia.

- **Delphes 'detector'**

→displaced vertices and signed impact parameter distributions → studied for LHeC and FCC-eh SM Higgs; and for extrapolations [PGS for CDR and until 2014]

- 'Standard' GPD LHC-style detectors used and further studied based on optimising Higgs measurements, i.e. vertex resolution a la ATLAS IBL, excellent hadronic and elmag resolutions using 'best' state-of-the art detector technologies (no R&D 'needed')
- Analysis requirements fed back to ep detector design →

Higgs in eh: *cut* based results

Masahiro Tanaka, Masahiro Kuze,
Tokyo Tech 2017

Example of samples: Unpolarised (P=0) samples E_e=60 GeV

E_p=7 TeV **LHeC**

	σ (pb)	Nsample	N/σ (fb⁻¹)
Signal CC:H->bb	0.113	0.2M	1760
CCjjj no top	4.5	2.6M	570
CC single top	0.77	0.9M	1160
CC Z	0.52	0.6M	1160
NC Z	0.13	0.15M	1140
PAjjj	41	14M	350

E_p=50 TeV **FCC**

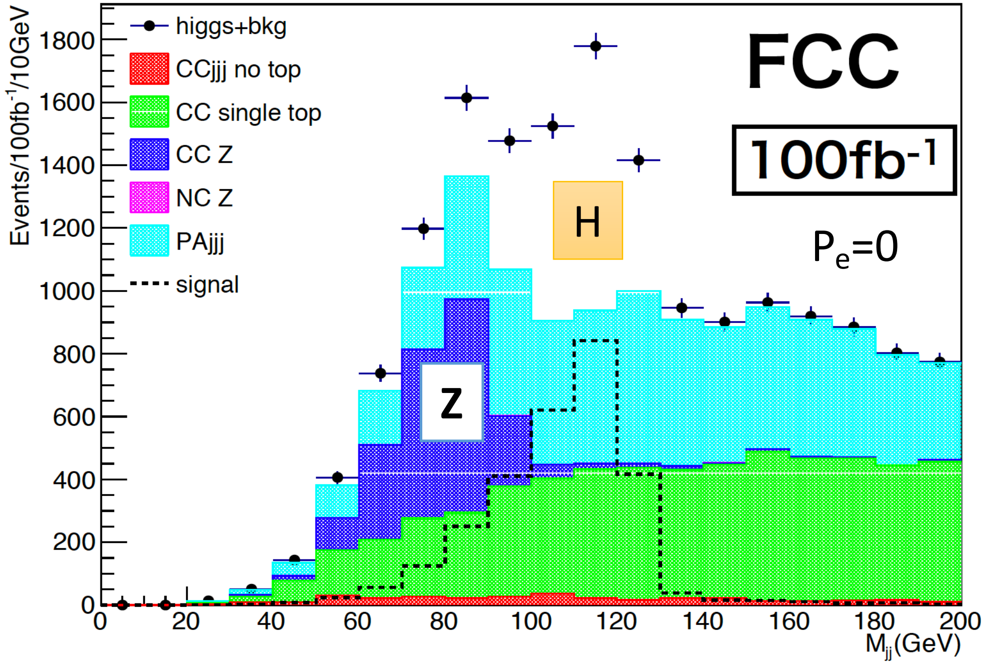
	σ (pb)	Nsample	N/σ (fb⁻¹)
Signal CC:H->bb	0.467	0.15M	321
CCjjj no top	21.2	1.95M	92
CC single top	9.75	1.05M	108
CC Z	1.6	0.15M	94
NC Z	0.33	0.15M	455
PAjjj	262	12.9M	49

Delphes ep-style detector
+ flat parton-level b-tagging
for |η|<3.0
conservative HFL tagging:
b: 60%, c: 10%, **udsg: 1%**
CAL coverage |η|<5 LHeC [<6 FCC-eh]

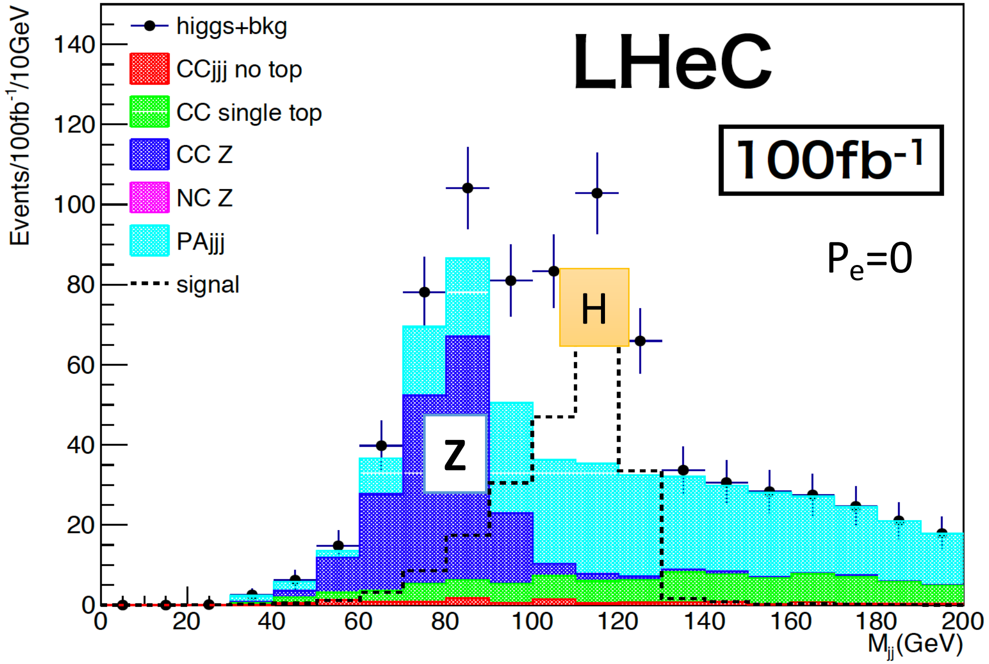
H→bb:
S/N>1 using
conservative **light misID and**
simple **cuts**
→ confirmed earlier & post CDR studies

100 fb^{-1}
~ 1 year of data

Mass of 2 b-jets after event selection



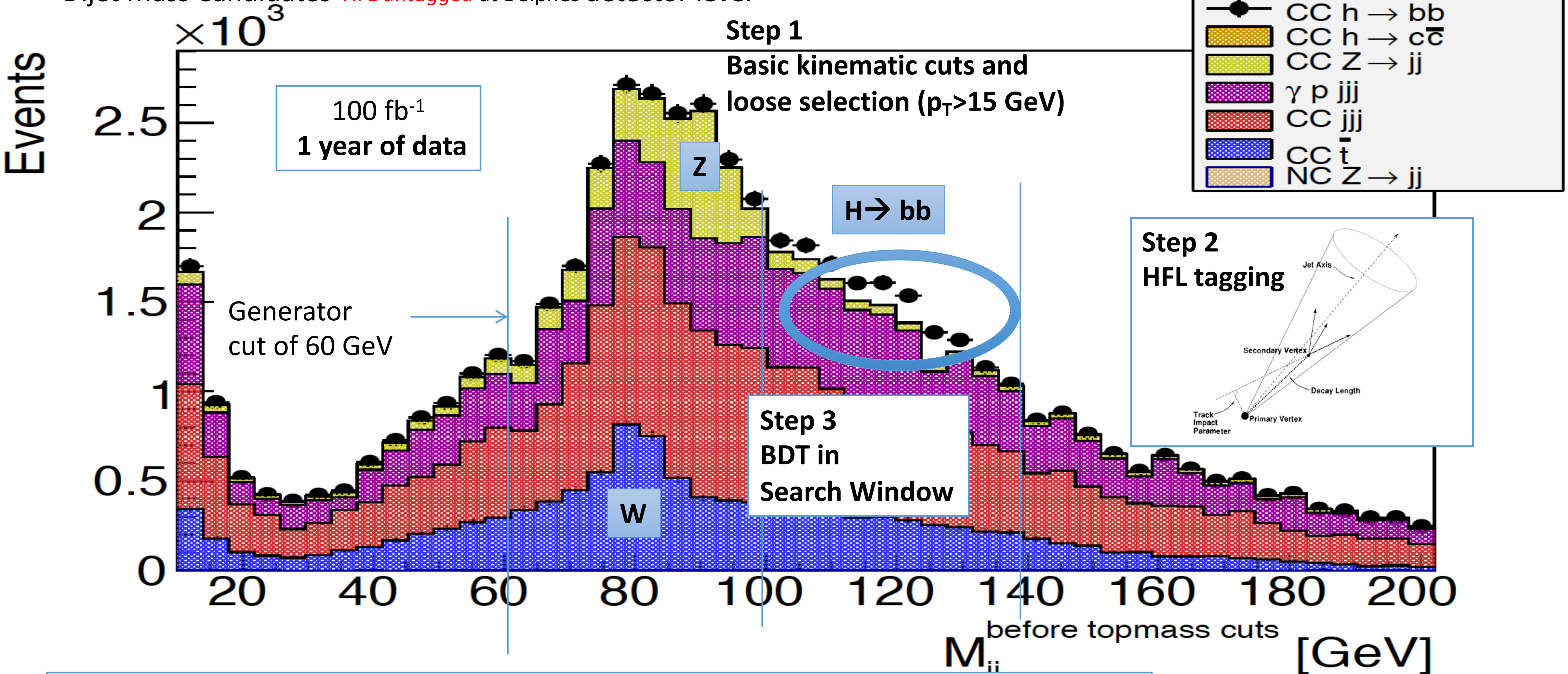
Note: plenty of single Z, W and top in ep



Higgs@LHeC: see also CDR & PRD.D82:016009,2010

Hunting for Precision Hbb

Dijet Mass Candidates *HFL untagged* at Delphes detector level



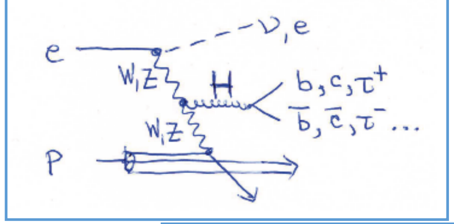
'Worst' case scenario plot : Photoproduction background (PHP) is assumed to be 100%!

PHP update: Modelled via Weiszaecker-Williams and cross-checked with Pythia.

→ addition of small angle electron taggers will reduce PHP to ~1-2%

Higgs in ep – clean S/B, no pile-up

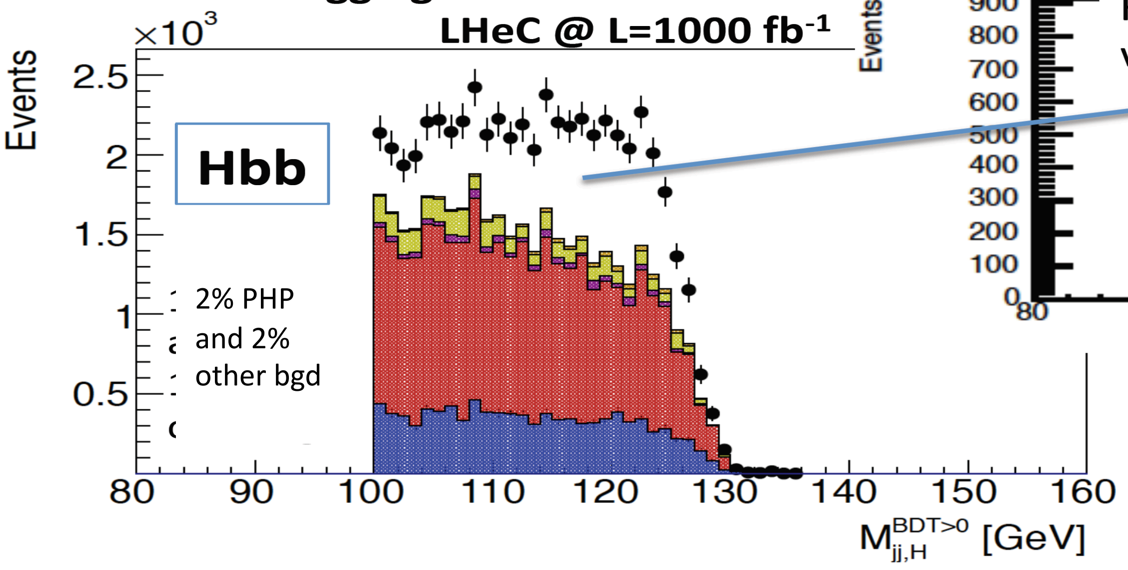
→ further improvements using BDT

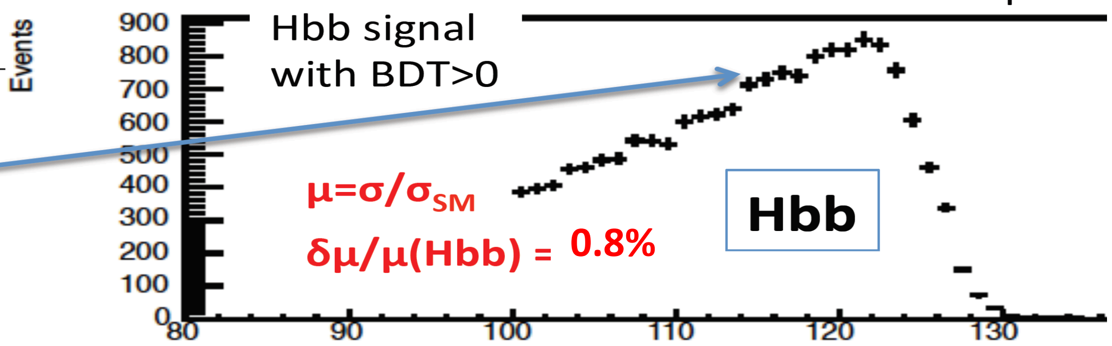


Uta Klein & Daniel Hampson

& Izzy Harris BSc 2017

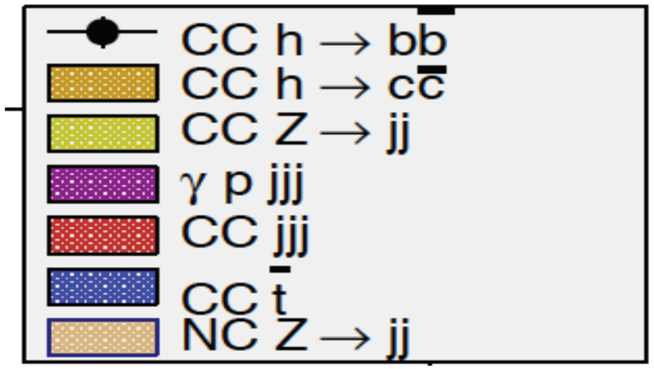
realistic HFL tagging & BDT

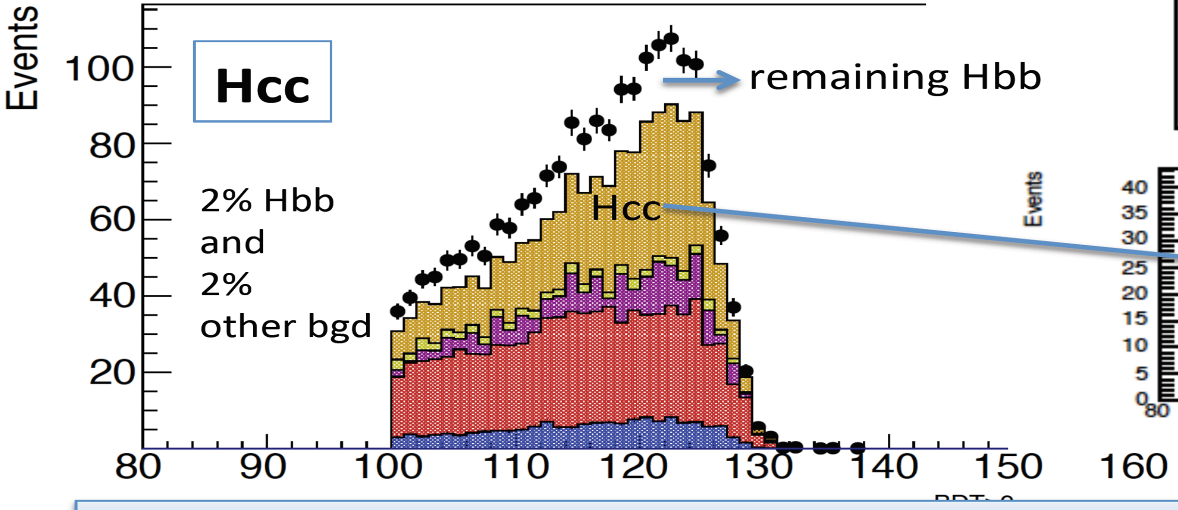


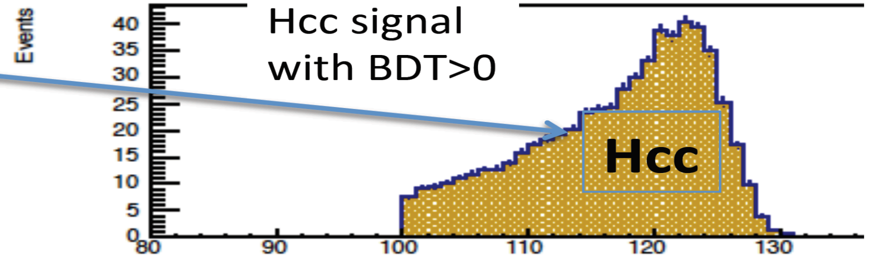


$\mu=\sigma/\sigma_{SM}$

$\delta\mu/\mu(Hbb)$ = 0.8%







$\delta\mu/\mu(Hcc)$ = 7.4 %

Assuming ATLAS light jet misID efficiencies

➔ **Main systematic checks: variations of background contribution and tagging efficiencies**

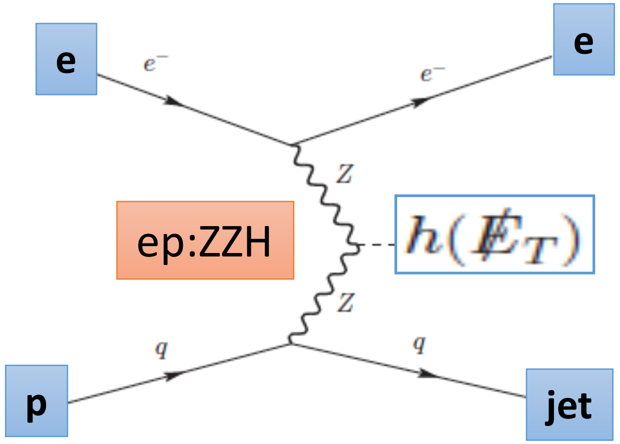
Branching for invisible Higgs

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

Values given in case of 2σ and L=1 ab^{-1}

Delphes detectors	LHeC [HE-LHeC] 1.3 [1.8 TeV]	FCC-eh 3.5 TeV
LHC-style	4.7% [3.2%]	1.9%
First 'ep-style'	5.7%	2.6%
+BDT Optimisation	5.5% (4.5%*)	1.7% (2.1%*)

LHeC parton-level, cut based <6% [Y.-L.Tang et al. arXiv: 1508.01095]



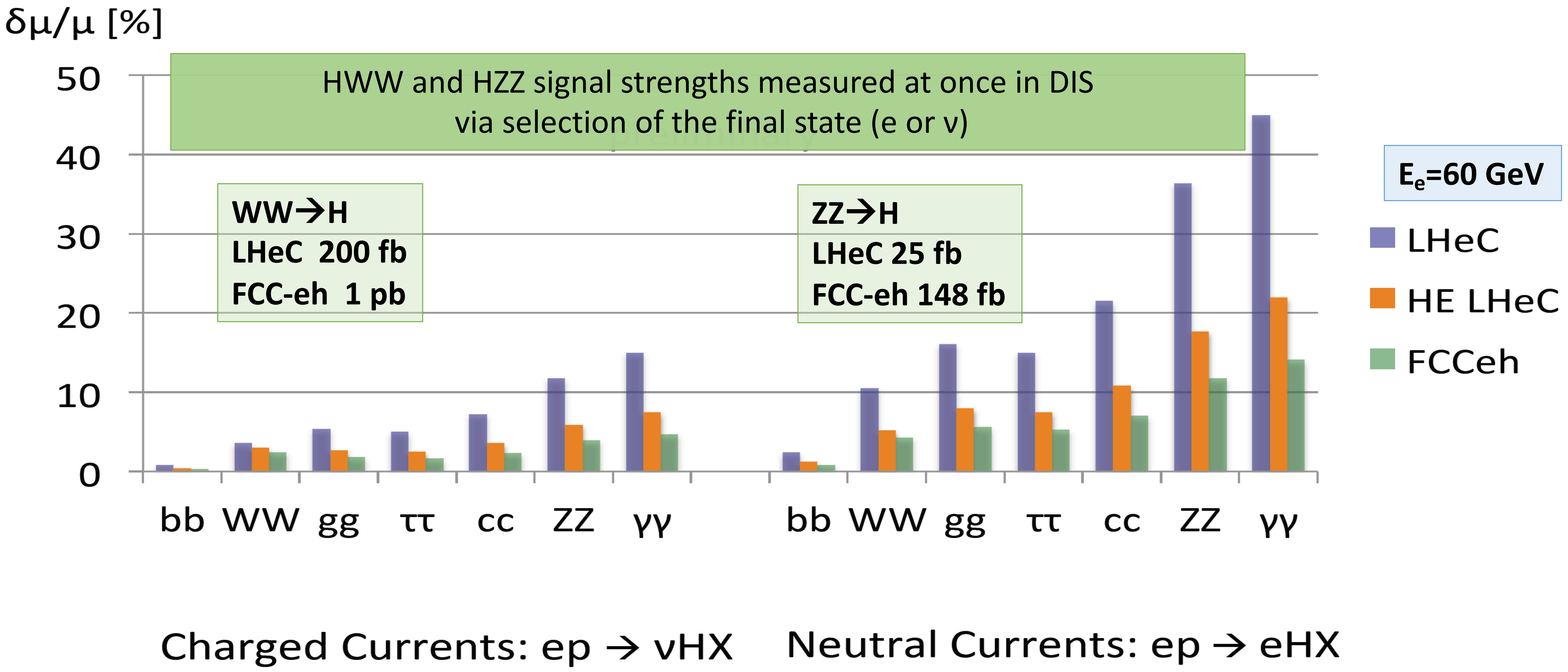
PORTAL to Dark Matter ?

- ✓ **Uses ZZH fusion process to estimate prospects of Higgs to invisible decay using *standard cut/BDT analysis techniques***
- ✓ **Full MG5+Delphes analyses, done for 3 c.m.s. energies → very encouraging for a measurement of the branching of Higgs to invisible in ep down to 5%** [1.2%] **for 1** [2] **ab^{-1} for LHeC** [FCC-eh]

- ✓ A lot of checks done: We also checked LHeC ←→ FCC-he scaling with the corresponding cross sections (* results in table) : Downscaling FCC-he simulation results to LHeC would give 4.5%, while up-scaling of LHeC simulation to FCC-he would result in 2.1% → all well within uncertainties of projections of ~25%

→ ***further detector and analysis details have certainly an impact on results → enhance potential further***

SM Higgs Signal Strengths in ep



→NC and CC DIS together over-constrain Higgs couplings in a combined SM fit.

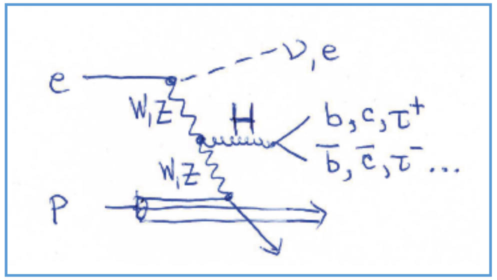
E_e = 60 GeV LHeC E_p = 7 TeV L=1ab^{-1} HE-LHC E_p = 14 TeV L=2ab^{-1} FCC: E_p = 50 TeV L=2ab^{-1}

... and Consistency Checks of EW Theory

→ similar tests possible using various cms energy CLIC machines, however, in ep, we could perform them with one machine

$$\frac{\sigma_{WW\to H\to ii}}{\sigma_{ZZ\to H\to ii}} = \frac{\kappa_W^2}{\kappa_Z^2}$$

$$\frac{\kappa_W}{\kappa_Z} = \cos^2\theta_W = 1 - \sin^2\theta_W$$



➔ Dominated by H→bb decay channel precision

➢ Very interesting consistency check of EW theory

➢ Values for $\cos^2\Theta$ given here are the PDG value as central value **0.777** and uncertainty from ep Higgs measurement prospects

LHeC:	**± 0.010**
HE-LHeC	± 0.006
FCC-eh	**± 0.004**

➔ Another nice test: **How does the Higgs couple to 3rd and 2nd generation quark?**
b is down-type and c is up-type

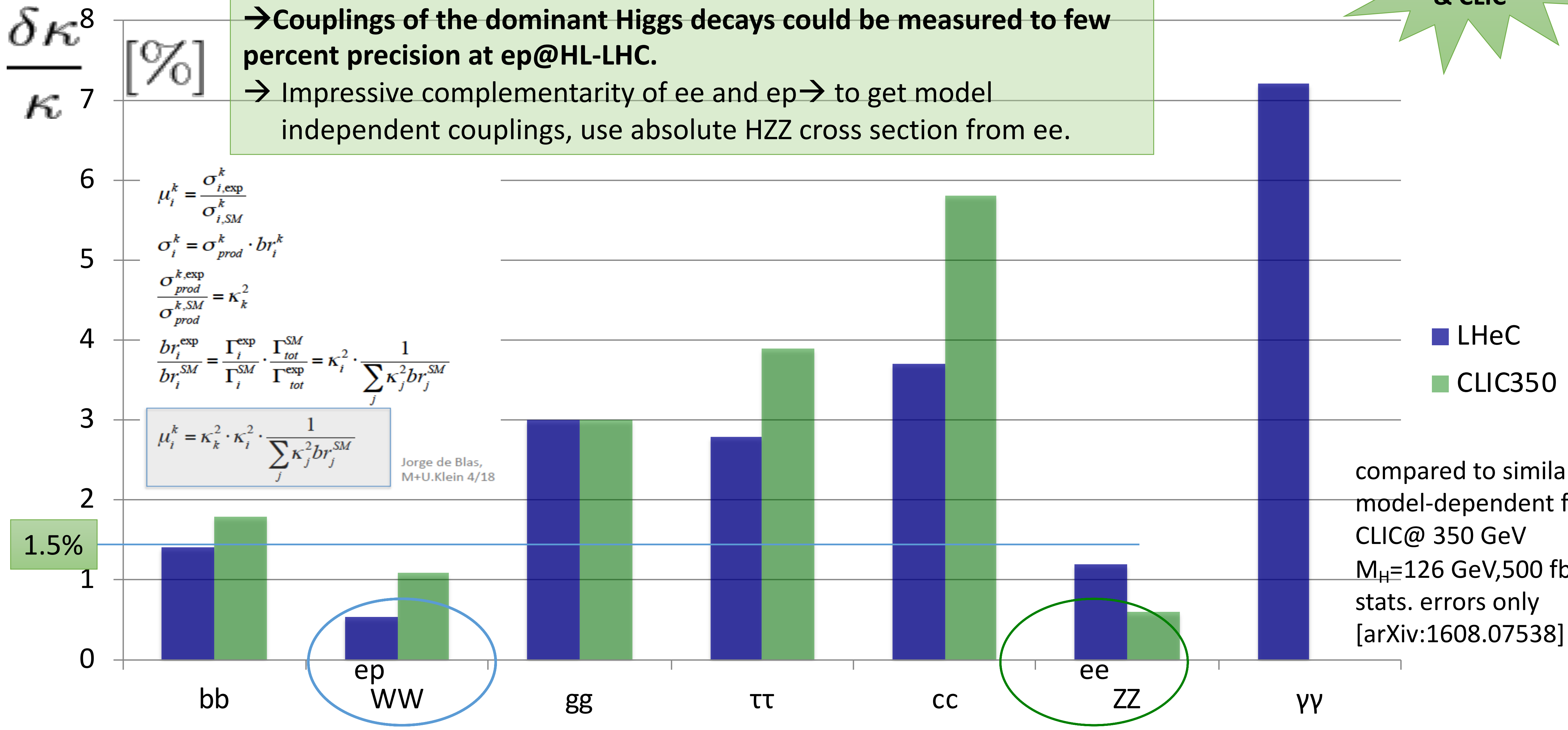
$$\frac{\sigma_{WW\to H\to c\bar{c}}}{\sigma_{WW\to H\to b\bar{b}}} = \frac{\kappa_c^2}{\kappa_b^2}$$

Model-dependent Coupling Fit

LHeC & CLIC

→Couplings of the dominant Higgs decays could be measured to few percent precision at ep@HL-LHC.

→ Impressive complementarity of ee and ep→ to get model independent couplings, use absolute HZZ cross section from ee.



$$\mu_i^k = \frac{\sigma_{i,\exp}^k}{\sigma_{i,SM}^k}$$

$$\sigma_i^k = \sigma_{prod}^k \cdot br_i^k$$

$$\frac{\sigma_{prod}^{k,\exp}}{\sigma_{prod}^{k,SM}} = \kappa_k^2$$

$$\frac{br_i^{\exp}}{br_i^{SM}} = \frac{\Gamma_i^{\exp}}{\Gamma_i^{SM}} \cdot \frac{\Gamma_{tot}^{SM}}{\Gamma_{tot}^{\exp}} = \kappa_i^2 \cdot \frac{1}{\sum_j \kappa_j^2 br_j^{SM}}$$

$$\mu_i^k = \kappa_k^2 \cdot \kappa_i^2 \cdot \frac{1}{\sum_j \kappa_j^2 br_j^{SM}}$$

compared to similarly model-dependent fit CLIC@ 350 GeV M_H=126 GeV,500 fb^{-1}, stats. errors only [arXiv:1608.07538]

SM Higgs Couplings & $\delta\sigma_{Higgs}$ (pp)

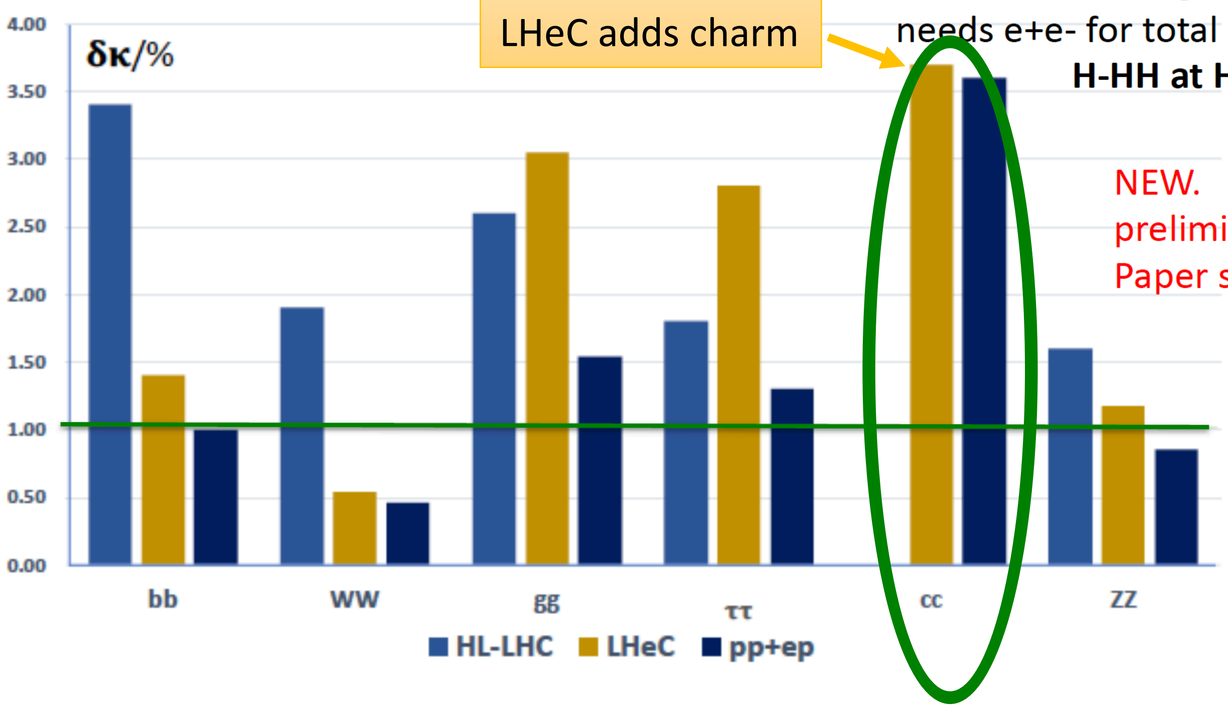
LHeC and HL-LHC prospects

Update of LHeC ES submission CERN-ACC-2018-0084

4.2. Determination of Higgs Couplings in pp and ep

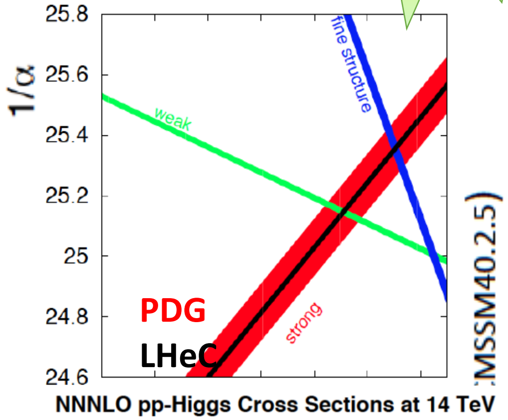
HL-LH(e)C ensures centre of Higgs physics stays at CERN in the thirties. High precision needs e+e- for total width.

H-HH at HL-LHC!

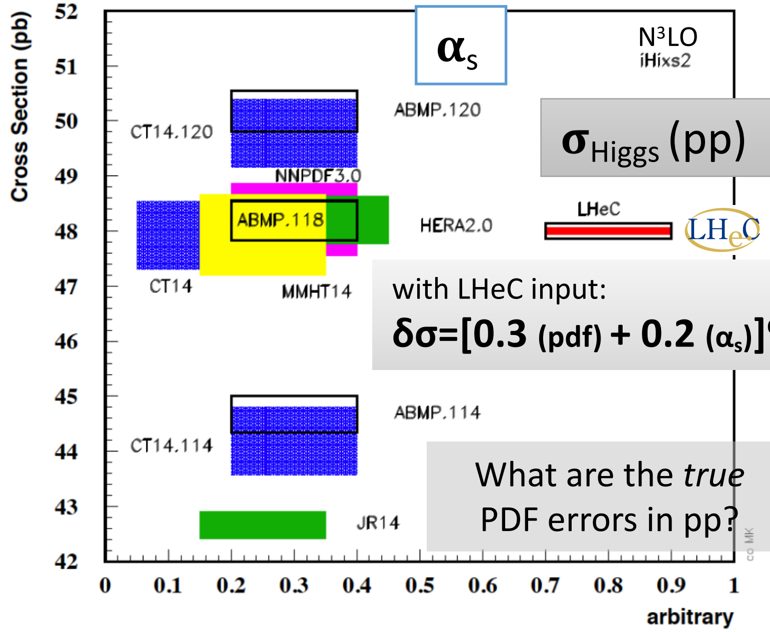


NEW. preliminary Paper soon

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, $3\,\mathrm{ab}^{-1}$), the LHeC (gold, $1\,\mathrm{ab}^{-1}$) and the combination of pp and ee (dark blue).



NNNLO pp-Higgs Cross Sections at 14 TeV



σ_{Higgs} (pp)

with LHeC input:
$\delta\sigma$=[0.3 (pdf) + 0.2 (α_s)]%

What are the *true* PDF errors in pp?

Plot from M Klein, DIS2019

Stand-alone ep κ Coupling Fits

→ Assuming SM branching fractions weighted by the measured κ values, and Γ_{md} (c.f. CLIC model-dependent method)

Note: also H in ePb

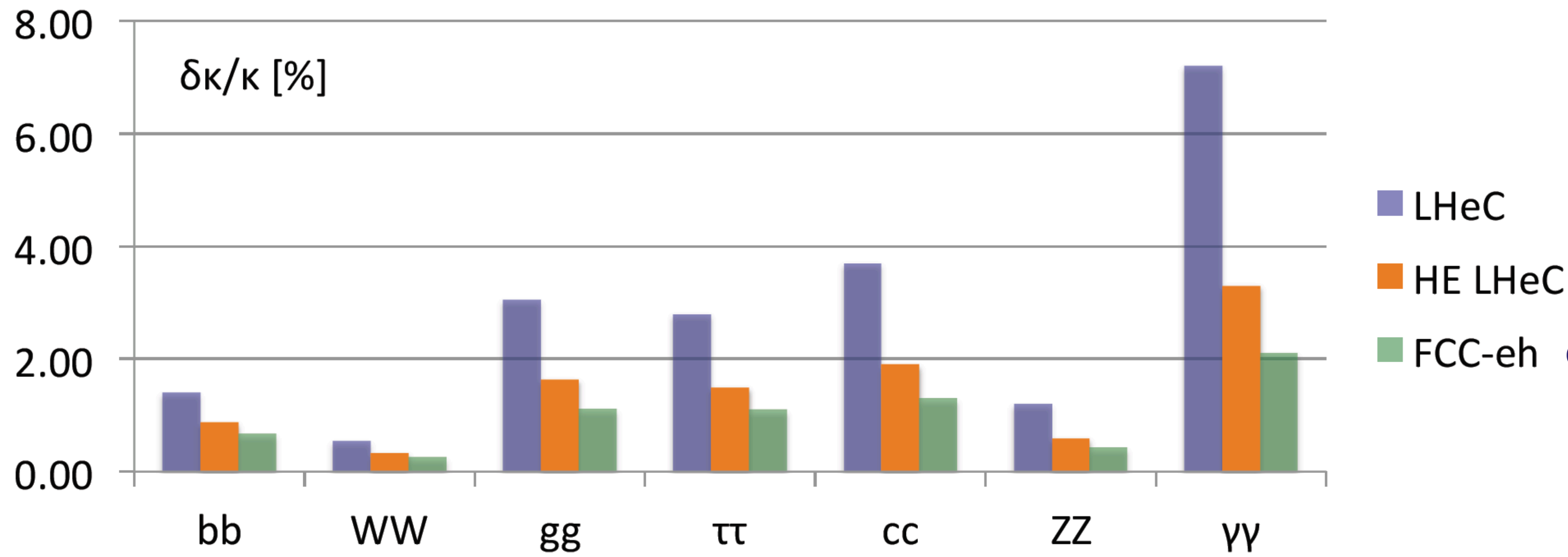


Figure 4.12: Determination of the κ scaling parameter uncertainties, from a joint SM fit of CC and NC signal strength results for the FCC-eh (green, $2\,\text{ab}^{-1}$), the HE LHeC (brown, $2\,\text{ab}^{-1}$) and LHeC (blue, $1\,\text{ab}^{-1}$).

Very high precision due to CC+NC DIS in clean environment in luminous, energy frontier ep scattering

Higgs @ HL-LHC, ee and FCC-eh

within kappa framework; statistical errors only

FCC-eh

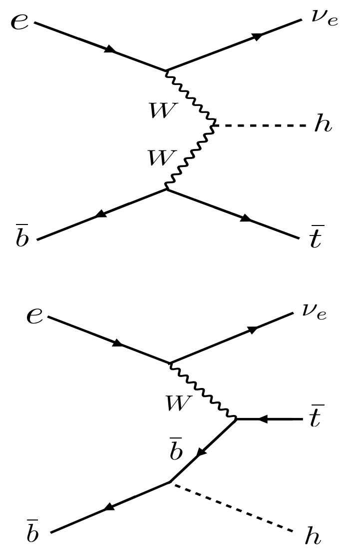
Collider	HL-LHC	ILC_{250}	CLIC_{380}	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	7	3	+4	—	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.8	6.3	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.35	0.80	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.7	1.3	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.8	2.8	1.3	**0.61**	0.55	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	6.8	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	2.2	3.8	1.6	**1.01**	0.83	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.9	4.2	1.4	**0.74**	0.64	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	13	n.a.	10.1	**9.0**	3.9	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	6.4	n.a.	4.8	**3.9**	1.1	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	–	–	2.4	ttH 1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	$< \mathbf{1.0}$	< 1.0	n.a.

➔ Combine the complementary measurements for best physics outcome!

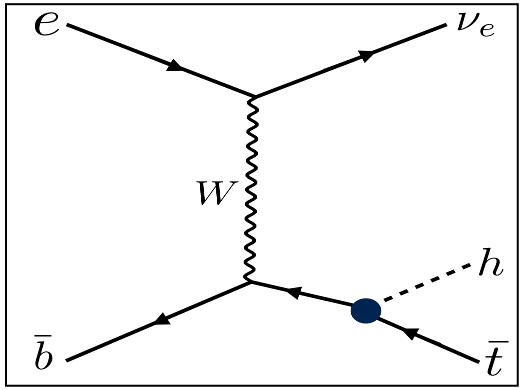
Higgs-inv.: 1.2%
HH ~20%

Top Yukawa Coupling @ LHeC

B.Coleppa, M.Kumar, S.Kumar, B.Mellado, PLB770 (2017) 335



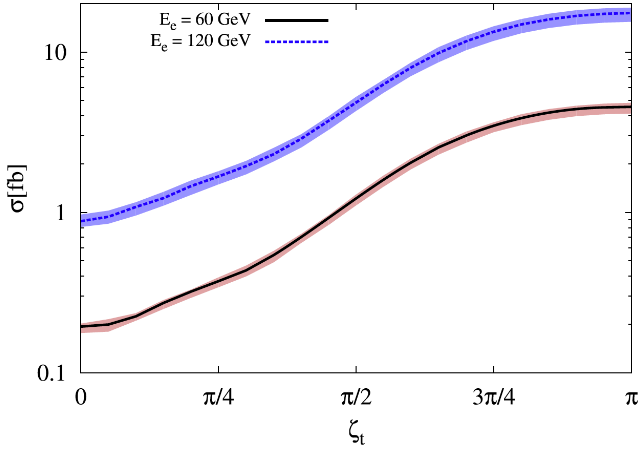
SM: $$\mathcal{L}_{\rm Yukawa} = -\frac{m_t}{v}\bar{t}th - \frac{m_b}{v}\bar{b}bh,$$

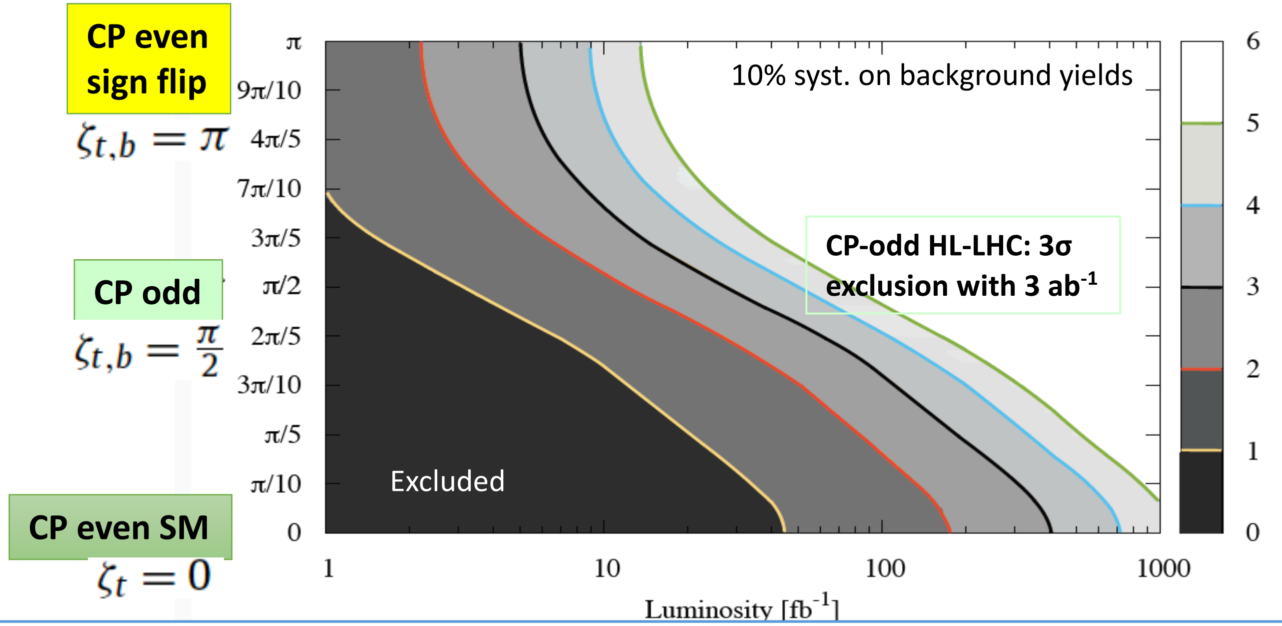


BSM: Introduce phases of top-Higgs and bottom-Higgs couplings

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]t\,h - \frac{m_b}{v}\bar{b}\,[\cos\zeta_b + i\gamma_5\sin\zeta_b]b\,h.$$

Enhancement of the DIS cross-section as a function of phase





Observe/Exclude non-zero phase to better than 4σ

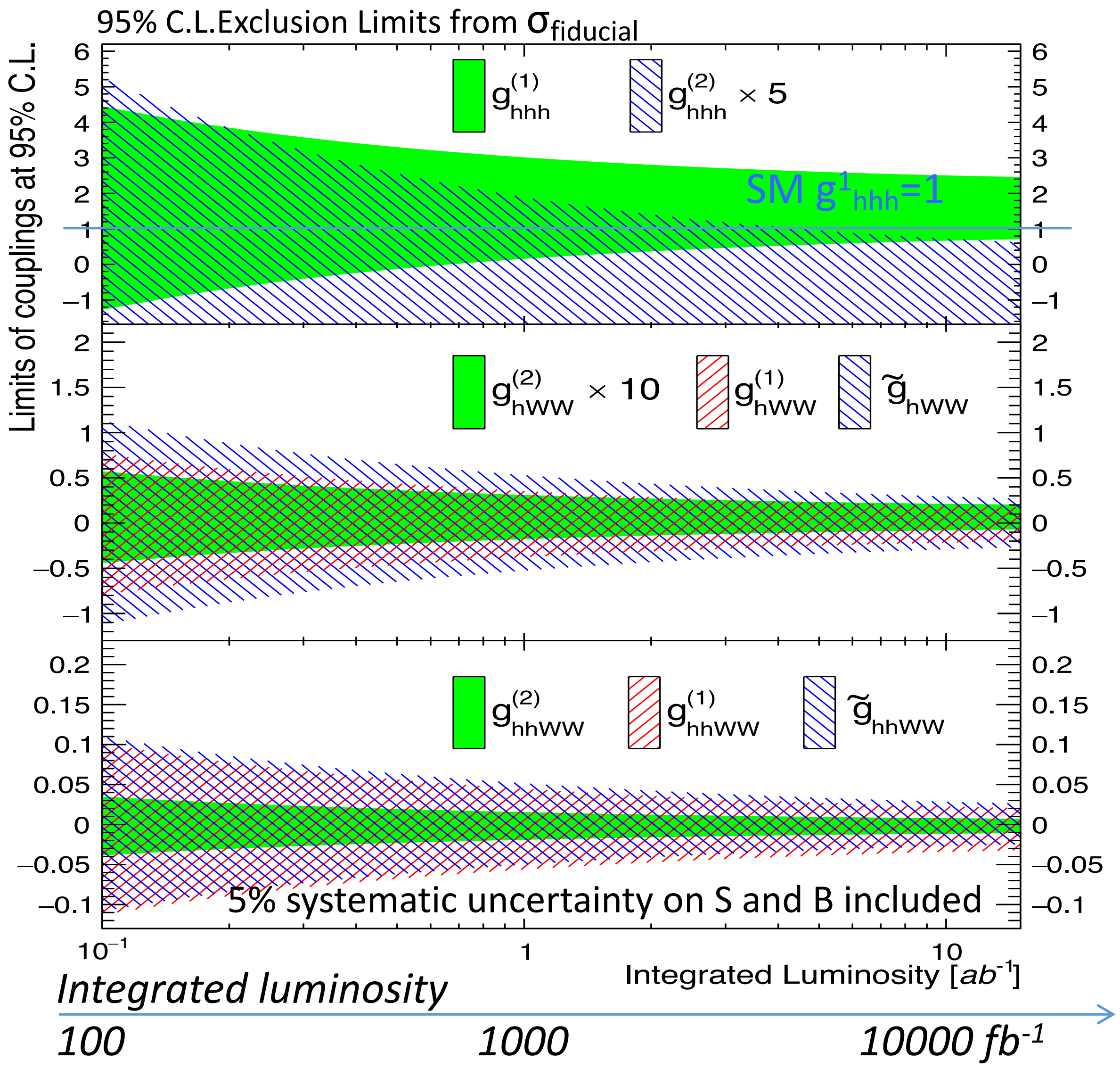
➔ With Zero Phase: Measure **ttH** coupling with **17% accuracy at LHeC** ➔ **extrapolation to FCC-eh: ttH to 1.7%**

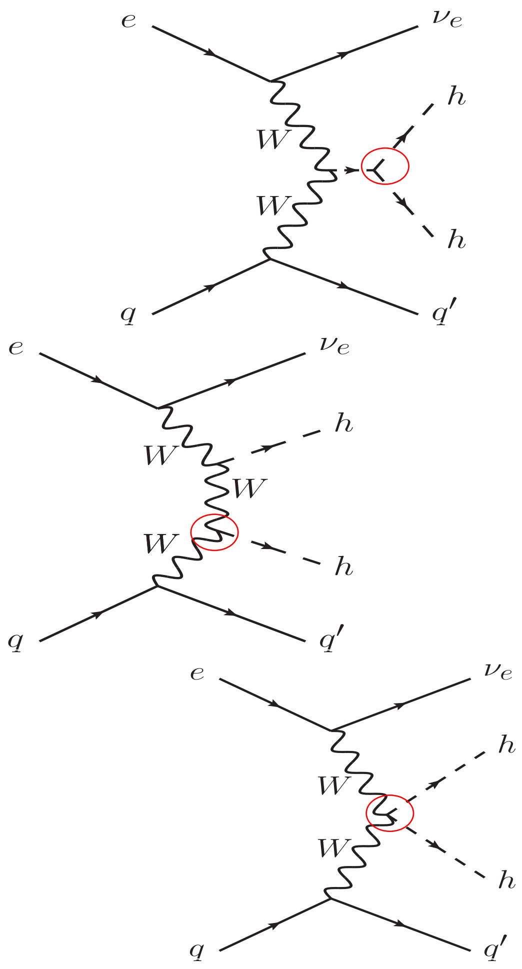
[arXiv:1509.04016]

Double Higgs Production

Encouraging FCC-eh cut-based study; full Delphes-detector simulation; conservative HFL tagging

FCC-eh g_{HHH} ~ 20% in ep





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 within Higgs EFT: 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.

Bands show the still allowed regions.

Wrap Up

- **LHeC** [FCC-eh] **could measure the dominant Higgs couplings, including ttH, to 0.6-17** [0.2-1.7] **% precision [CC+NC DIS, no pile-up, clean final state..]**

➔ ***LHeC would add charm to HL-LHC***

- **Striking synergy of ep (>~1 TeV) and ee (250-350 GeV) and pp for Higgs coupling measurements!**
- **ep would empower the physics potential of pp (non-resonant searches, EW, Higgs..) through high precision QCD measurements: flavour separated PDFs at N^{3}LO, α_S to per mille …**
- **Higgs measurements in ep are self consistent experimentally and theoretically based on DIS cross sections with very small systematic uncertainties**
- **Combining pp with ep, a very powerful Higgs facility can be established at the HL-LHC already in the 30ties or later at the FCC-hh.**

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Thanks to Hao Sun

50 journal papers on BSM with LHeC/Fcc-eh in recent years

Additional Sources & Thanks to

- Much more material can be found here: LHeC and FCC-eh Workshop, September 2017, CERN https://indico.cern.ch/event/639067/
- **The LHeC/FCC-eh study group, http://lhec.web.cern.ch**
- “On the Relation of the LHeC and the LHC” [arXiv:1211.5102]
- 1st FCC Physics Workshop, 16.1.-20.1.2017, CERNhttps://indico.cern.ch/event/550509/
- Before April 2018: Higgs branching fractions and uncertainties taken from https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR2014
- Update used from April 2018https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR
- FCC Week 2018, Amsterdam, https://indico.cern.ch/event/656491/
- FCC to EU Strategy CERN-ACC-2018-0056
- LHeC to EU Strategy CERN-ACC-2018-0084

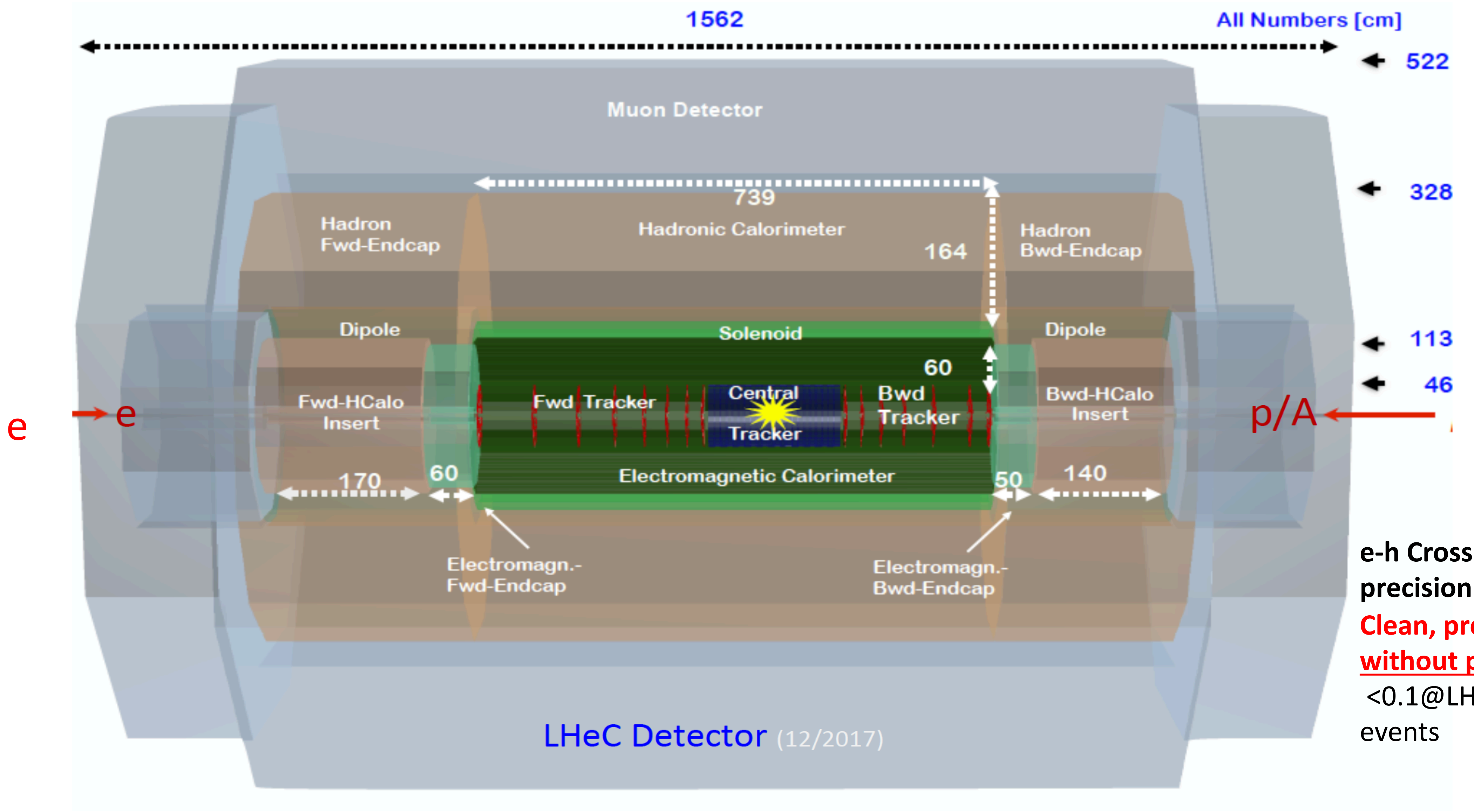
Special thanks to my colleagues in the LHeC/FCC-eh study group and to Jorge de Blas for the discussion of model-dependent coupling fits.

Additional material

Detector for LHeC/HE-LHC/FCC-eh

[arXiv:1802.04317]

& P.Kostka et al



e-h Cross Calibration for precision ep

Clean, precise reconstruction without pile-up:
<0.1@LHeC up to 1@FCCeh events

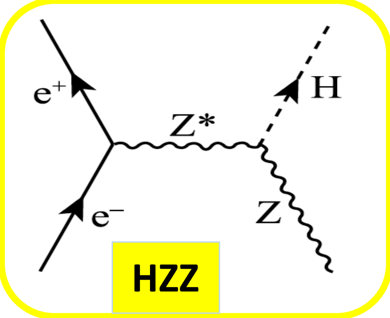
Length x Diameter: LHeC (13.3 x 9 m^2) HE-LHC (15.6 x 10.4) FCCeh (19 x 12) m^2

ATLAS (45 x 25) CMS (21 x 15): [LHeC < CMS, FCC-eh ~ CMS size]

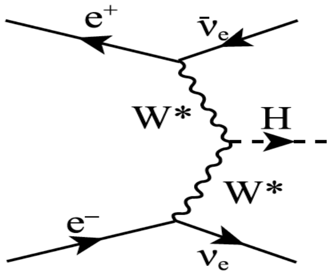
If CERN decides that the HE LHC comes, the LHeC detector should anticipate that

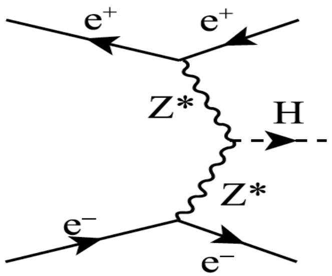
Higgs in ee vs ep

ee Dominant Higgs productions:



ee

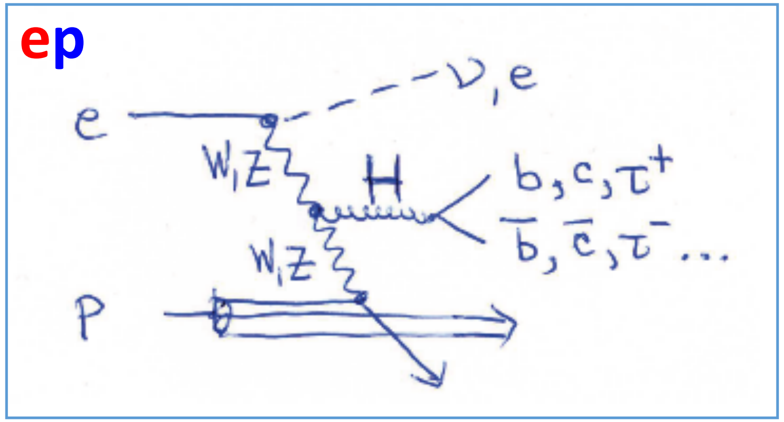


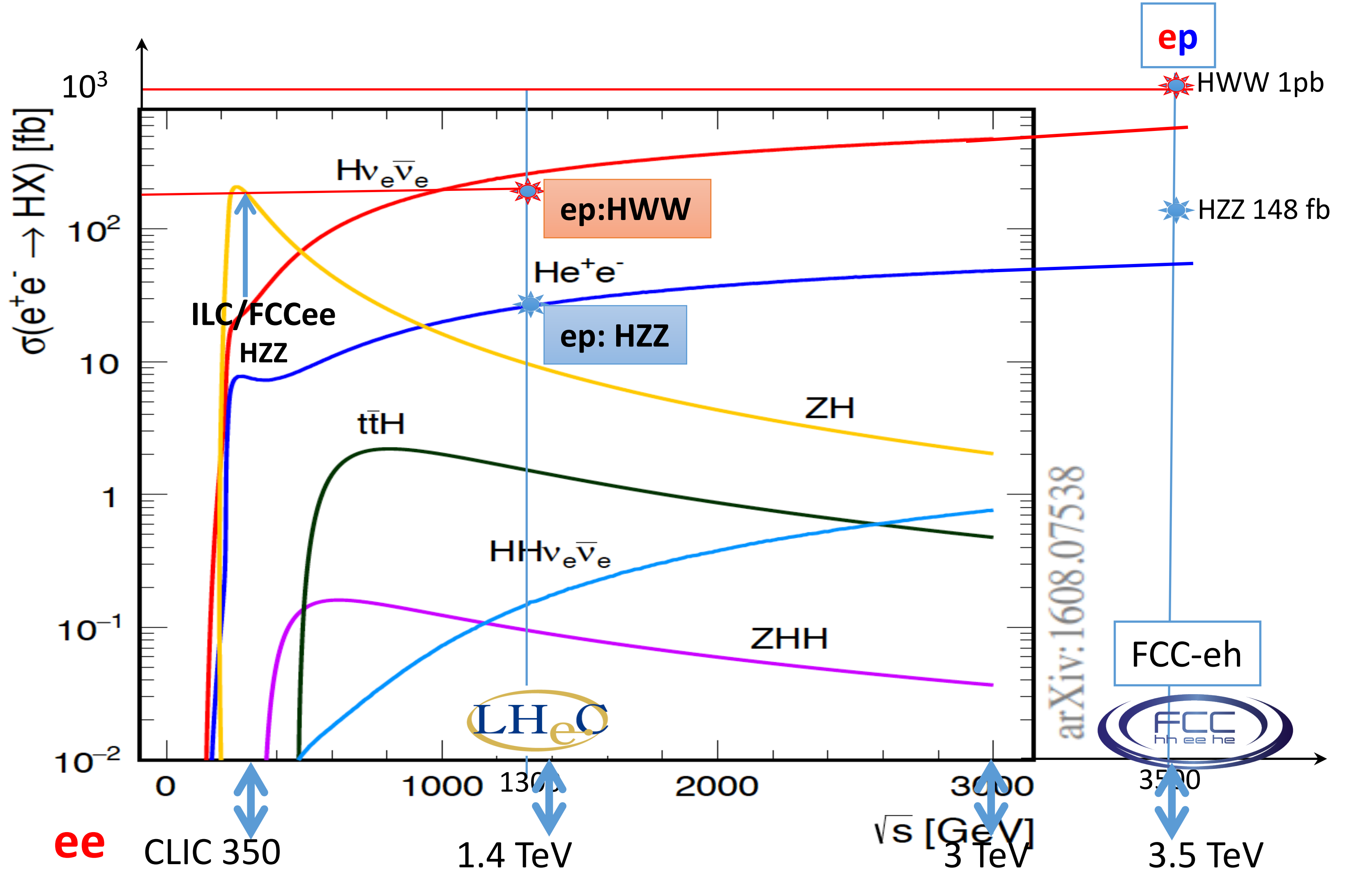


ep vs ee- Higgs cross sections

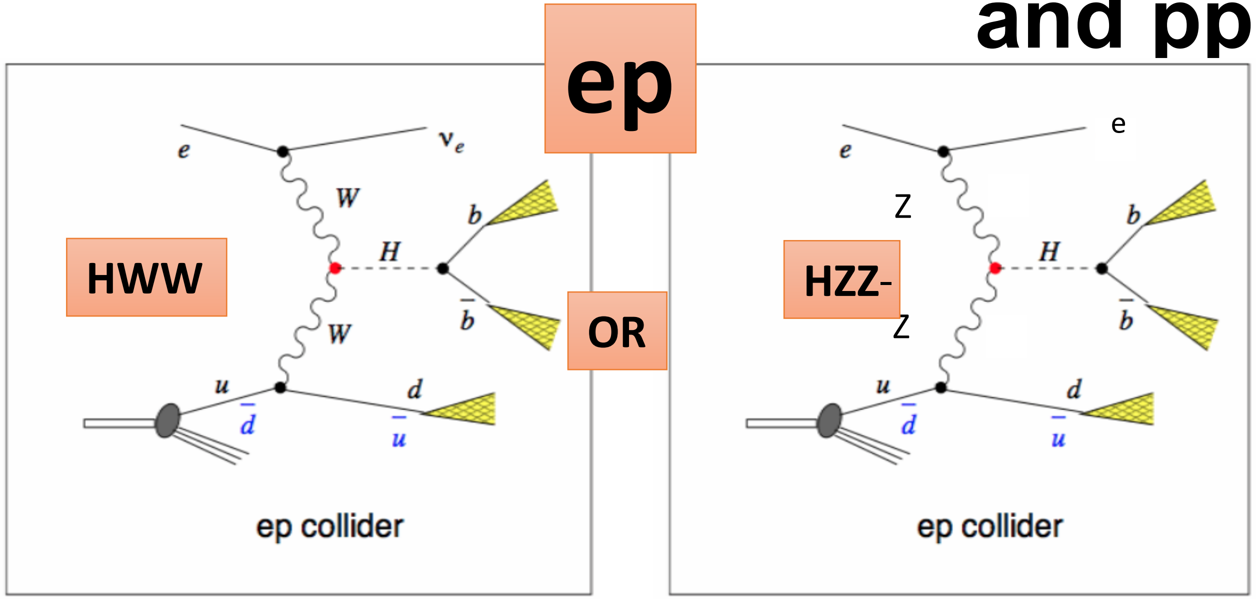
ep:CC DIS WW Fusion

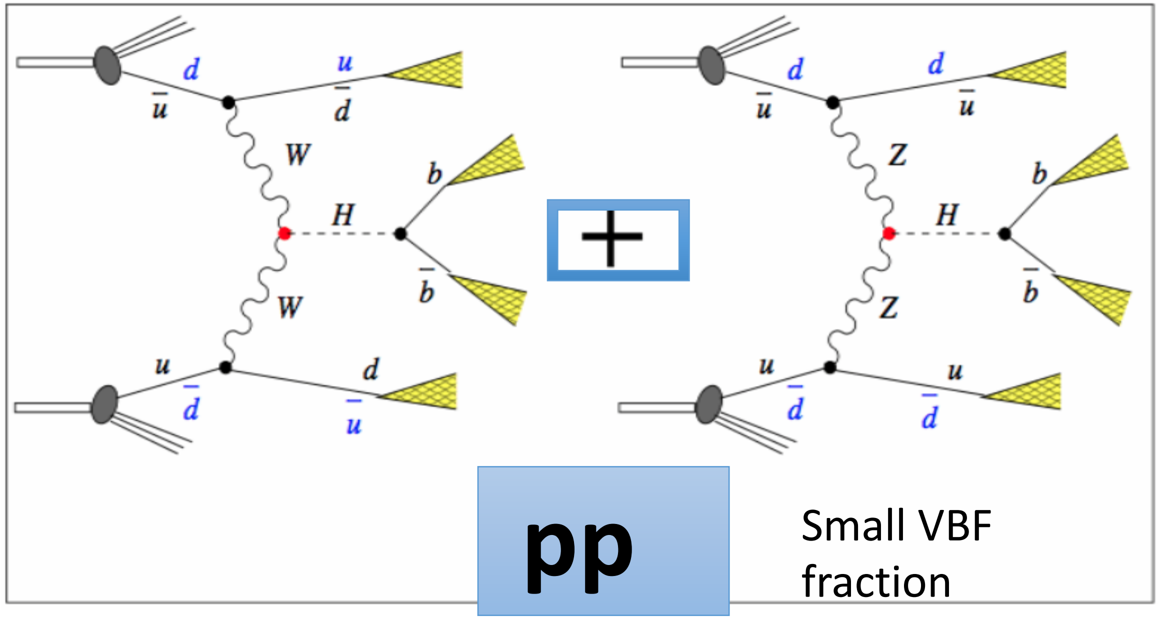
ep: NC DIS ZZ Fusion





VBF Higgs Production in ep (top) and pp (bottom)

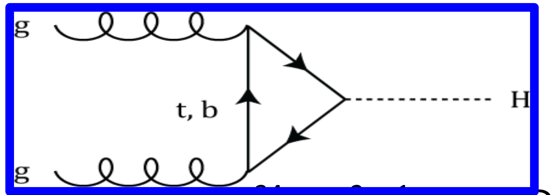




ep: Higgs production in ep comes uniquely from either CC or NC DIS via VBF

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

pp: Higgs production in pp comes predominantly (~80%) from gg→ H :
high rates crucial for rare decays



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

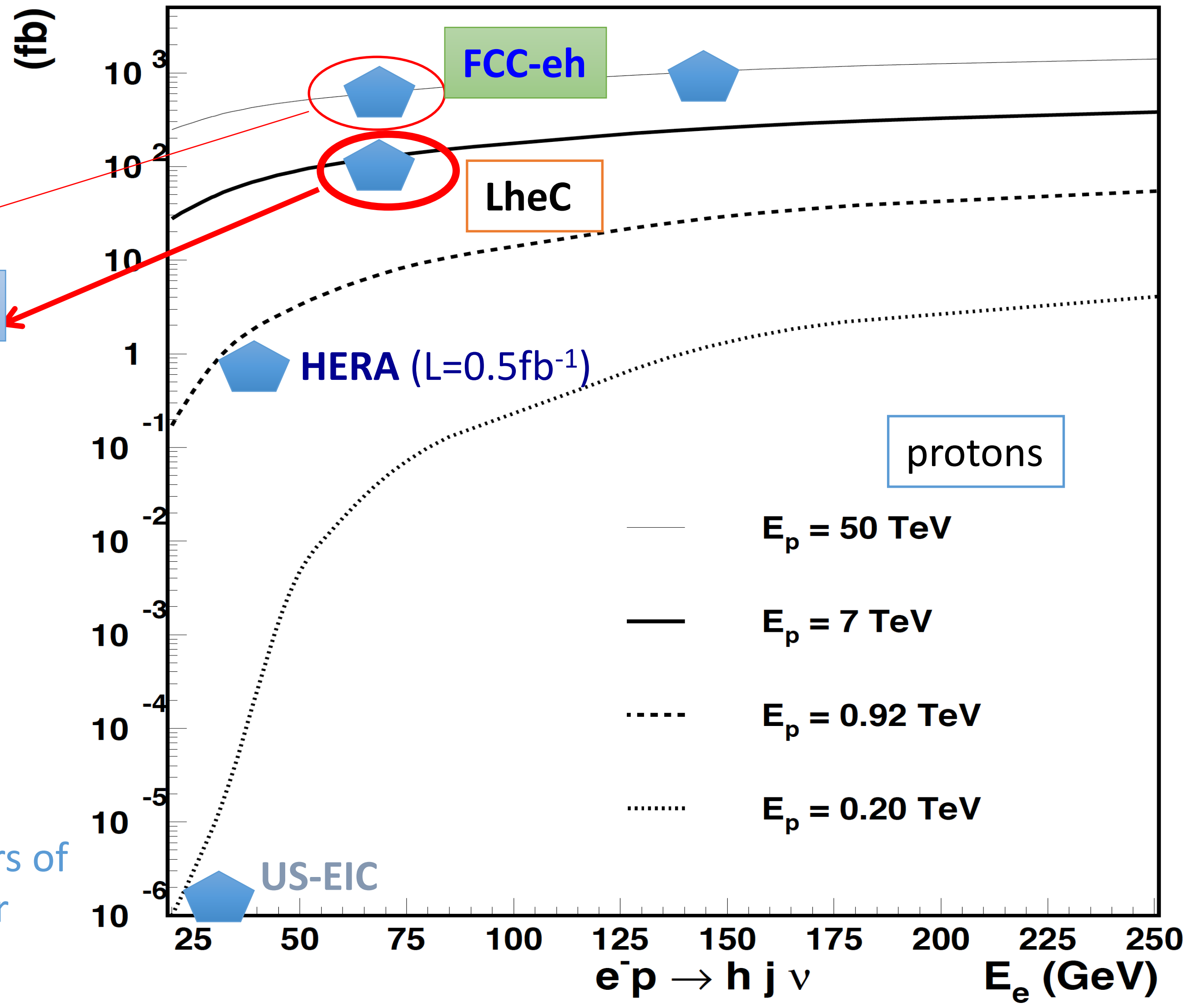
U. Klein,
@DIS2015

SM Higgs in ep

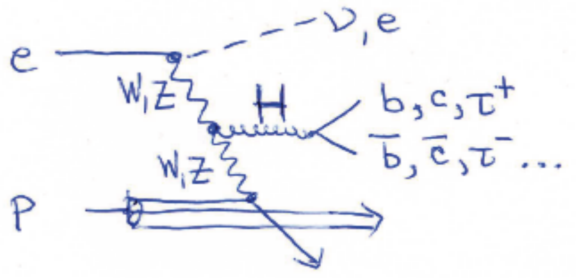
unpolarised electrons

√s=3.5 TeV

√s=1.3 TeV



σ @ EIC: 7 orders of magnitude lower



Higgs in eA @FCC-ePb

σ_{Higgs} [fb]

eff. 'Ep'=19.7 TeV

E_e [GeV]	P_e = 0	-0.8
20	105	190
30	153	276
50	242	436
60	282	507

LHeC / FCC-eh: Sizeable Higgs rates in charged current (CC) DIS for L=100-1000 fb^{-1}

Further Estimates of Higgs Prospects

- Use LO Higgs cross sections **σ_H for M_H=125 GeV, in [fb],** and branching fractions BR(H→XX) from Higgs Cross Section Handbook
- Apply further branching, BR(X→FS) in case e.g. of W→ 2 jets and use acceptance (Acc) estimates based on MG5, for further decay
- Use reconstruction efficiencies, ε, achieved at LHC Run-1, see e.g. prospect calculations explored in arXiv:1511.05170
- Use fully simulated LHeC BDT H→bb and H→cc & FCC-eh H→WW* and exotic Higgs search results as baseline for S/B ranges; use fully simulated cut-based FCC-eh & LHeC H→bb results for further bench-marking
- Use fully simulated Higgs to invisible for 3 c.m.s. scenarios as guidance for extrapolation uncertainty
- Estimate HIggs events per decay channel for certain Luminosity in [fb^{-1}] and cross section in [fb]

$$N = \sigma_H \bullet BR(H \to XX) \bullet BR(X \to FS) \bullet L$$

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

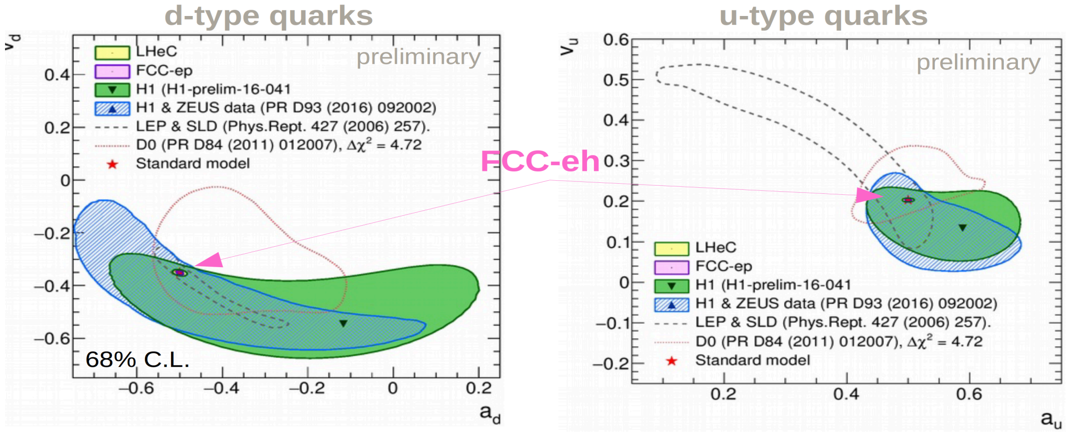
- Calculate uncertainties of signal strengths w.r.t. SM expectation

$$\frac{\delta\mu}{\mu} = \frac{1}{\sqrt{N}} \bullet f \qquad \text{with} \qquad f = \sqrt{\frac{1 + 1/(S/B)}{Acc \bullet \varepsilon}}$$

Electroweak precision observables at FCC eh

- **Electroweak precision measurements at FCC-eh**

Precision measurements of couplings to light quark families

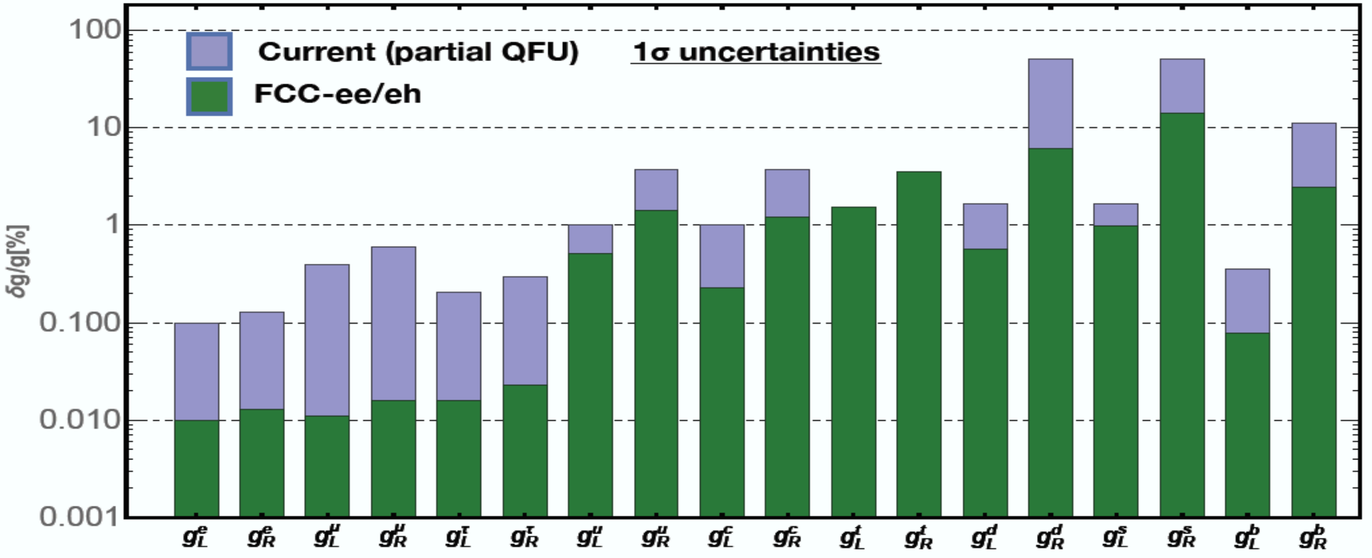


Talk by D Britzger, FCC Physics Week 2018

Observable	Uncertainty	(Relative uncertainty)
g_V^u	0.0022	(1.1%)
g_A^u	0.0031	(0.6%)
g_V^d	0.0049	(1.4%)
g_A^d	0.0049	(0.97%)

- **Global fit to electroweak precision measurements at FCC-ee + FCC-eh**

NEW
ee + ep



Talk by J deBlas
FCC Week 2018

No Fermion flavour universality assumed

Independent info about all 3 SM fermion families

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

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

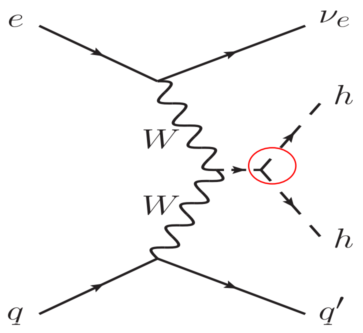
$$\mathcal{L}^{(3)}_{hWW} = -g\Big[\frac{g^{(1)}_{hWW}}{2m_W} W^{\mu\nu}W^\dagger_{\mu\nu}h + \frac{g^{(2)}_{hWW}}{m_W}(W^\nu\partial^\mu W^\dagger_{\mu\nu}h + \text{h.c}) + \frac{\tilde{g}_{hWW}}{2m_W} W^{\mu\nu}\widetilde{W}^\dagger_{\mu\nu}h\Big], \quad (3)$$

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

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

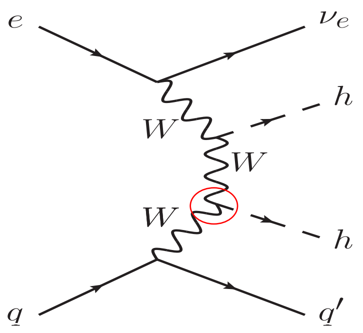
Effective Vertices

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



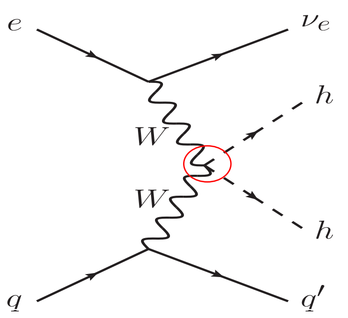
1,2,3= h,h,h

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



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

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



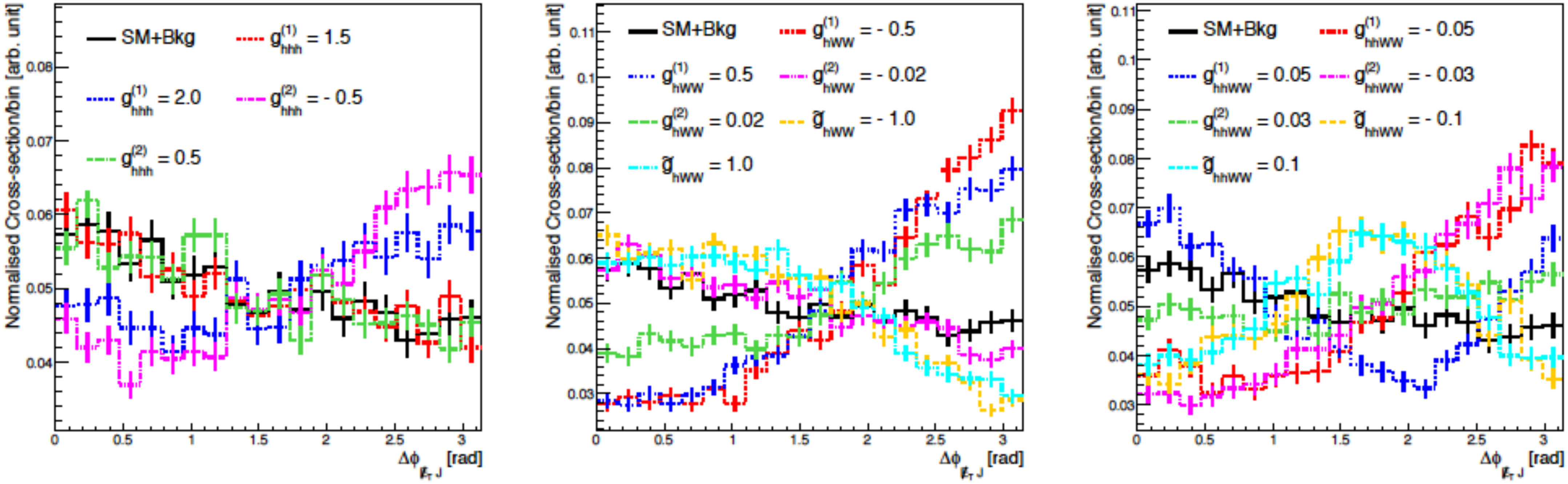
1,2,3,4 = h,h,W-,W+

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

[arXiv:1509.04016]

HH@FCC-eh: Azimuthal Angle Distributions

→ $\Delta\Phi_{Etmiss,jet}$ between missing transverse energy and forward jet, at Delphes detector-level, including background : bbbbj, bbjjj, Z(bb)h(bb)j, ttj, h(bb)bbj
→ Signal: hh→ bbbb decays motivated by h→bb studies.



→ normalised DIS cross sections are sensitive to non-BSM vertices
→ initial study published for this novel $\Delta\Phi_{Etmiss,jet}$ variable
→ potential for a deeper analysis and interpretation

[1509.04016]

Event Selection using h→bb

Pe=-0.8, Anti-kt jets R=0.4, Etmiss>40 GeV, η(fwd jet)>5,
90< m_{bb}(1) , m_{bb}(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

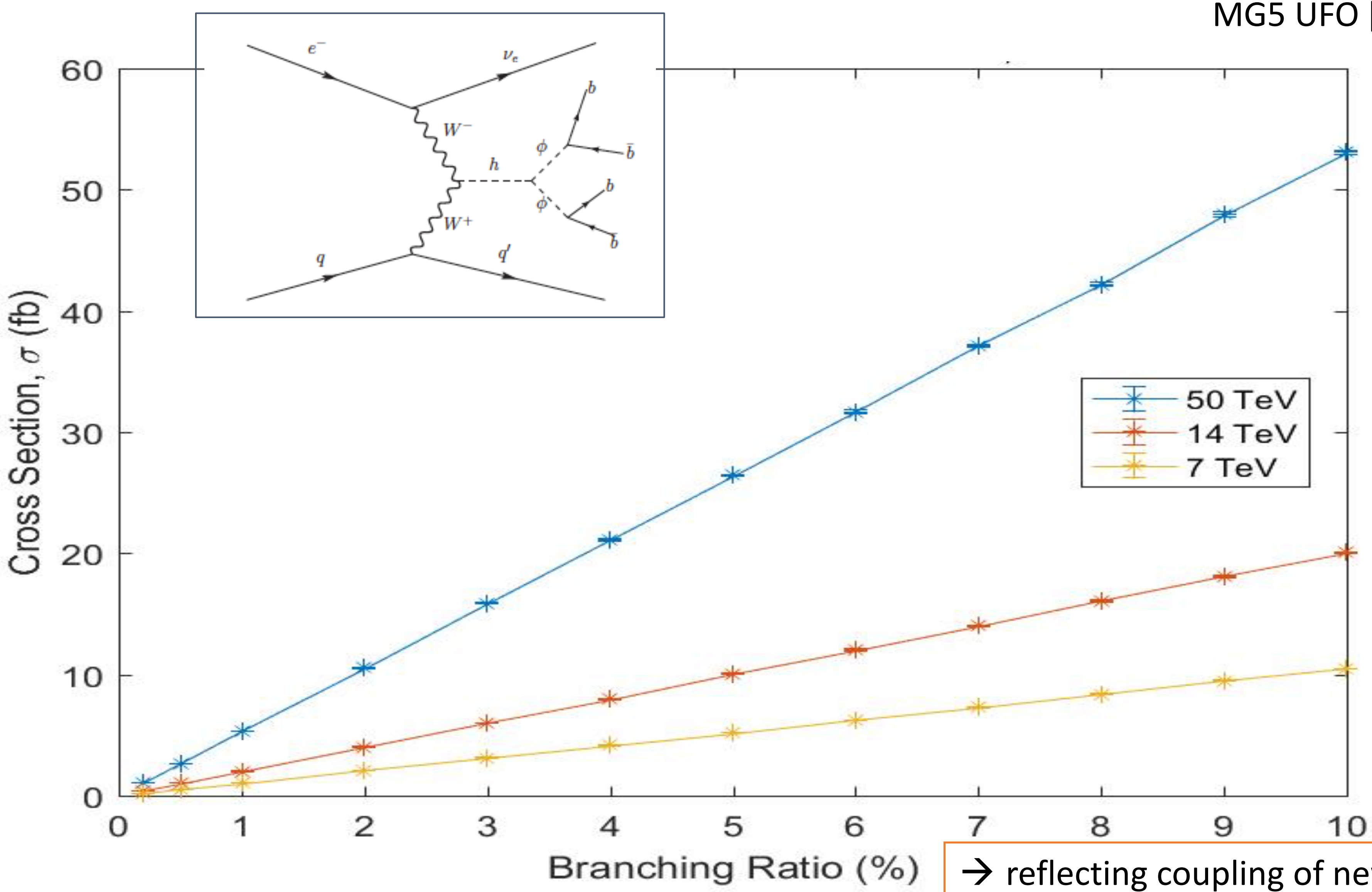
Table 2: A summary table of event selections to optimise the signal with respect to the backgrounds in terms of the weights at 10 ab^{-1}. In the first column the selection criteria are given as described in the text. The second column contains the weights of the signal process $p\,e^- \to hh\,j\nu_e$, 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.

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

Exotic Higgs Searches in ep

Uta Klein &
Michael O'Keefe
MPHYS 2017

MG5 UFO [arXiv:1608.08458]



FCC-eh @ 3.5TeV

LHeC HE-LHC @ 1.8 TeV

LHeC @ 1.3 TeV

Values for P_e=0

→ reflecting coupling of new scalar to 125 GeV Higgs

Exotic Higgs @ FCC-eh

Uta Klein &
Michael O'Keefe
MPHYS 2017

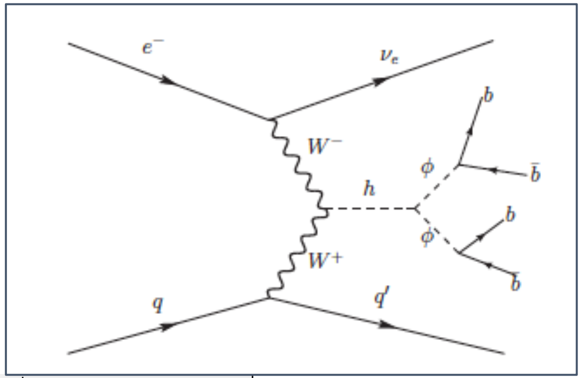
MG5 model and LHeC results [arXiv:1608.08458]

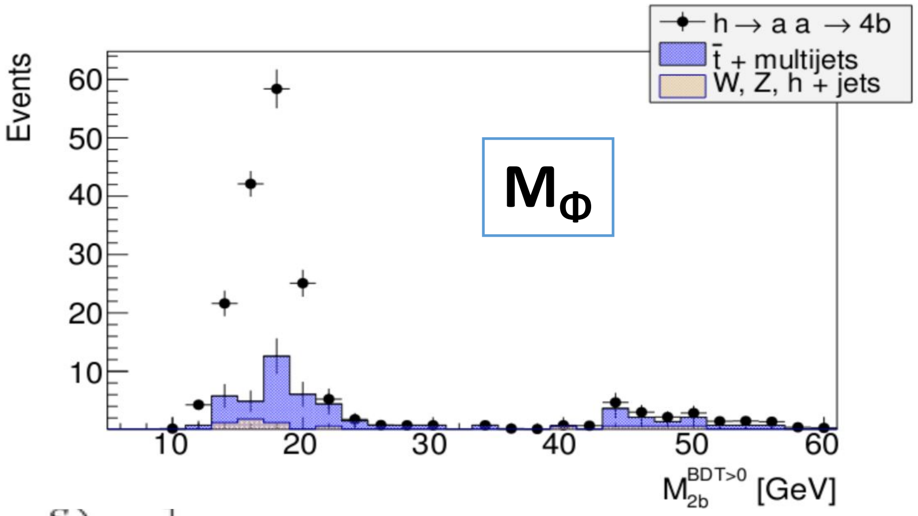
Example: $h \to \phi\phi \to 4b$

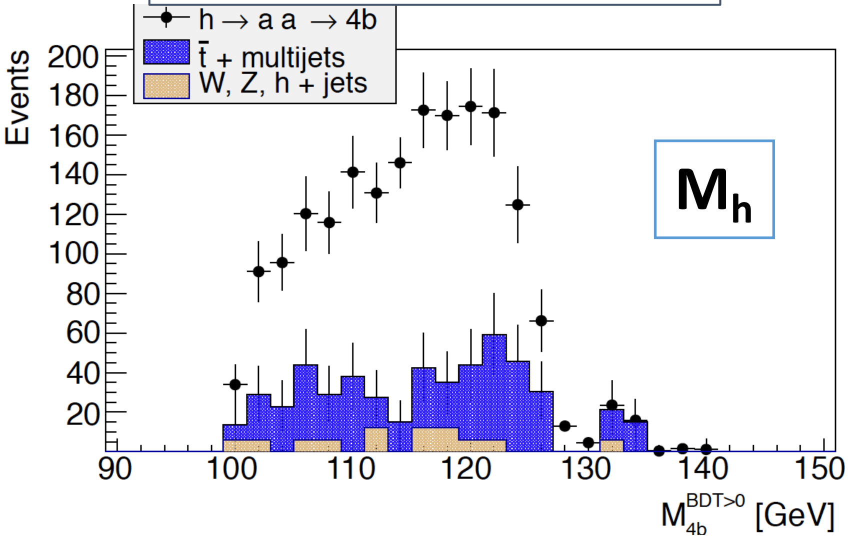
L=1 ab^{-1}
P_e=-80%

Values for BDT>0

m_Φ = 20 GeV
BR=10%







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

	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

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}).

BDT Analysis @ BR=10%

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

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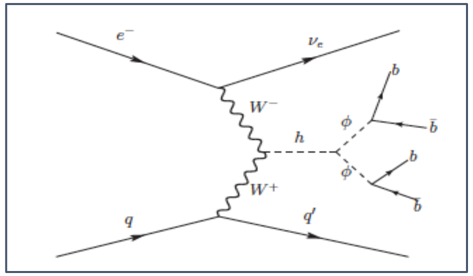
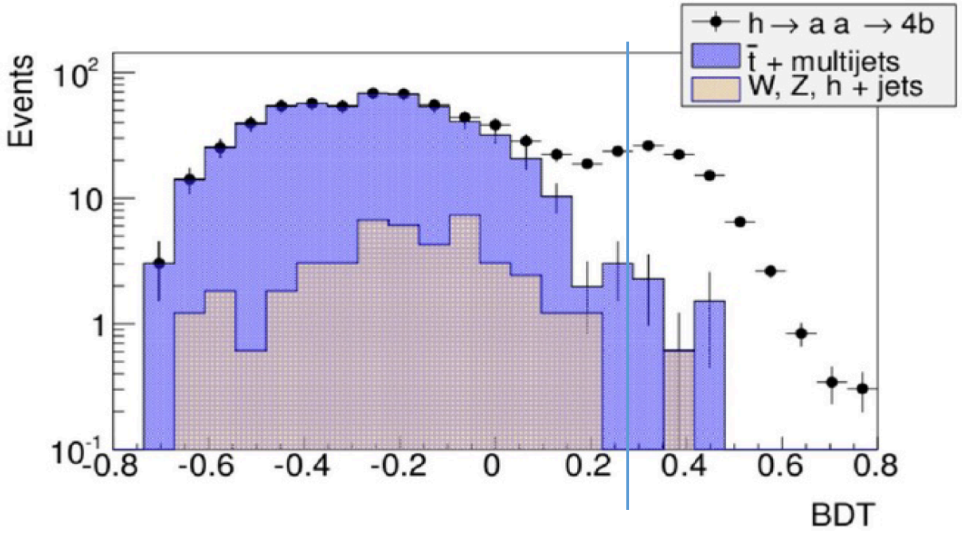
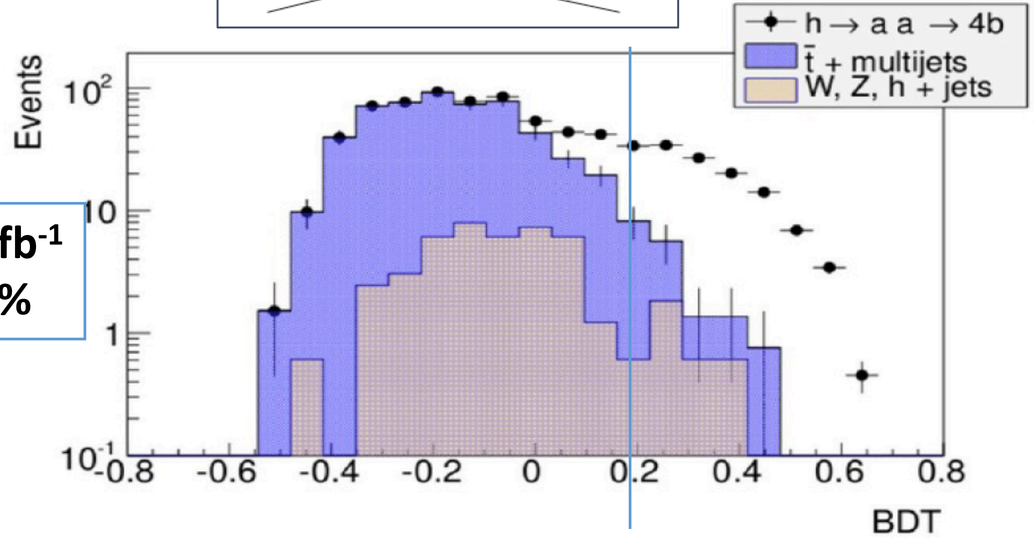
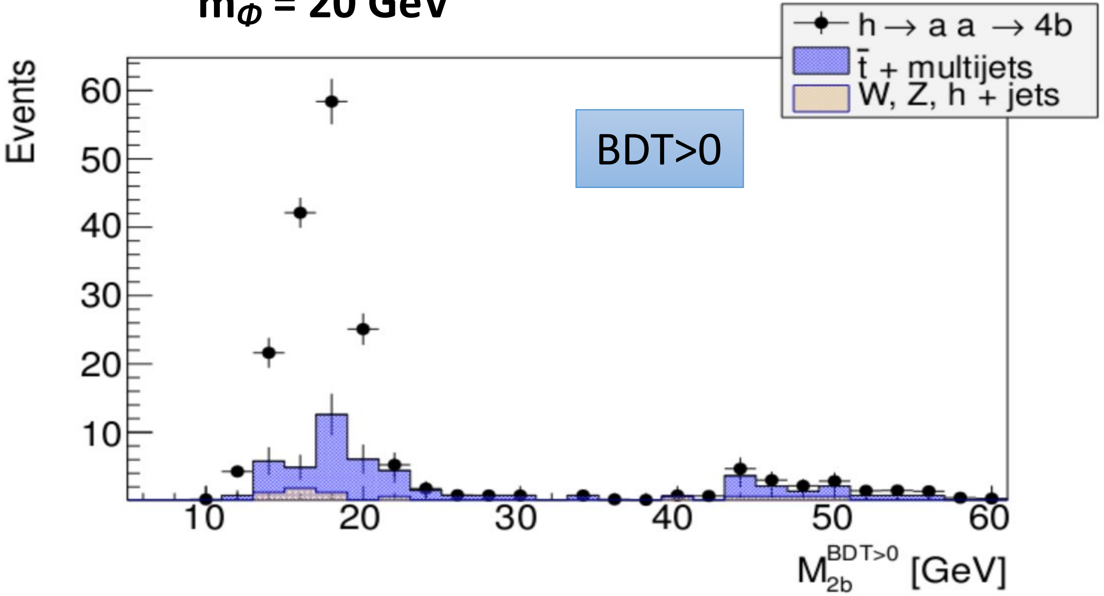




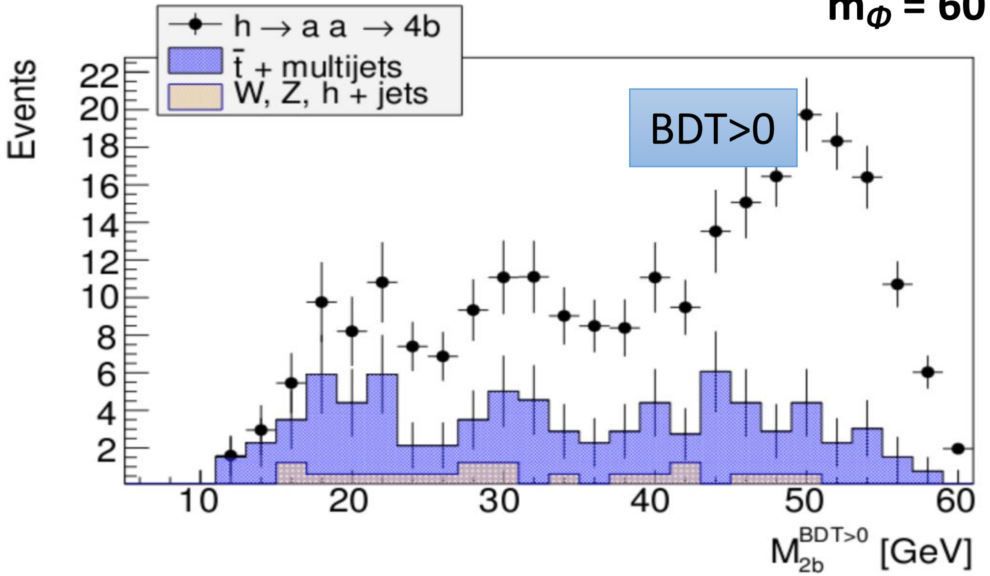


L=100 fb^{-1}
P$_e$=-80%

m_Φ = 20 GeV



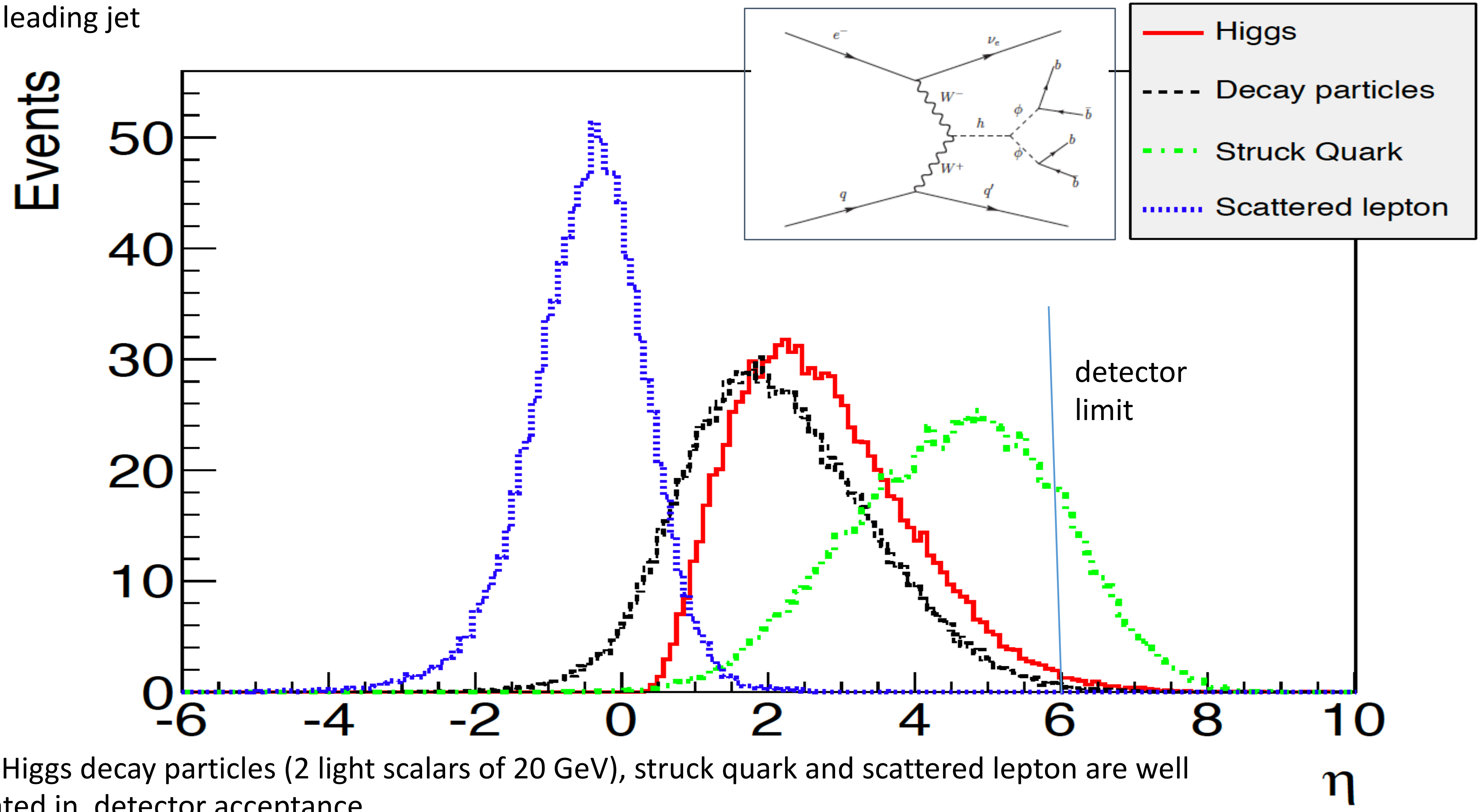
m_Φ = 60 GeV



η Distributions at FCC-eh

Parton-level

Scale: p_T of leading jet

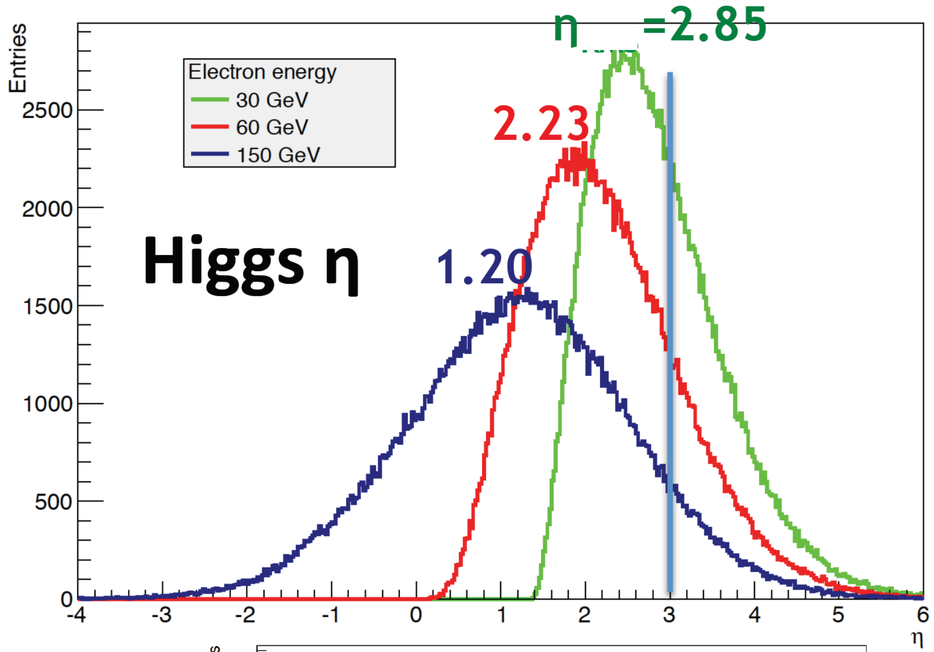


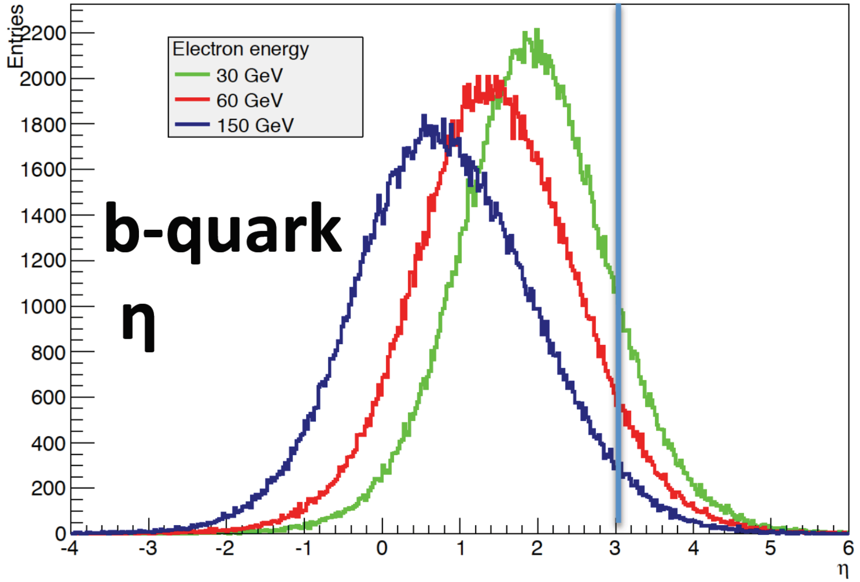
Exotic Higgs decay particles (2 light scalars of 20 GeV), struck quark and scattered lepton are well separated in detector acceptance

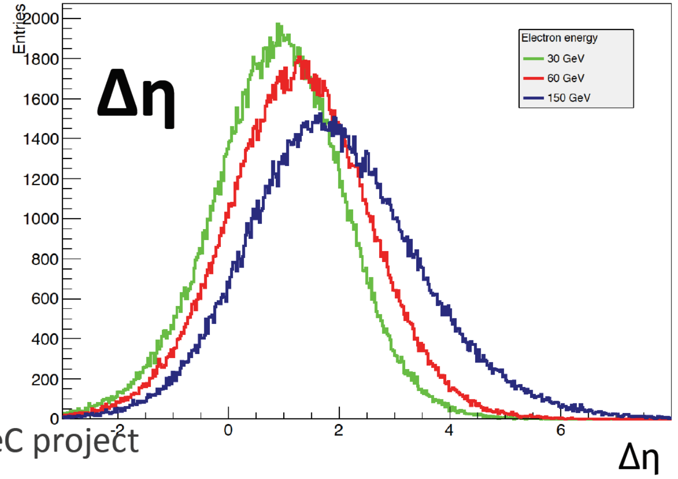
Higgs acceptance vs E_e

[after Higgs discovery M_H=125 GeV, E_p=7 TeV]

[Master thesis by Sergio Mandelli, Liverpool 2013]







➔ lowering of electron beam energy (more cost efficient) will challenge more detector design: worse separation between higgs and forward jet (Δη shrinks by 1 unit) and b-quarks from Higgs decay are more forward

➔ **stick with 60 GeV** E_e : decay products of Higgs scattered at ~28° (η~1.4)