

Higgs Physics at the LHeC and FCC-eh

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LIVERPOOL

on behalf of
the LHeC/FCC-eh Study Group



ICHEP 2020, with Zoom in Prague, July 29th, 2020

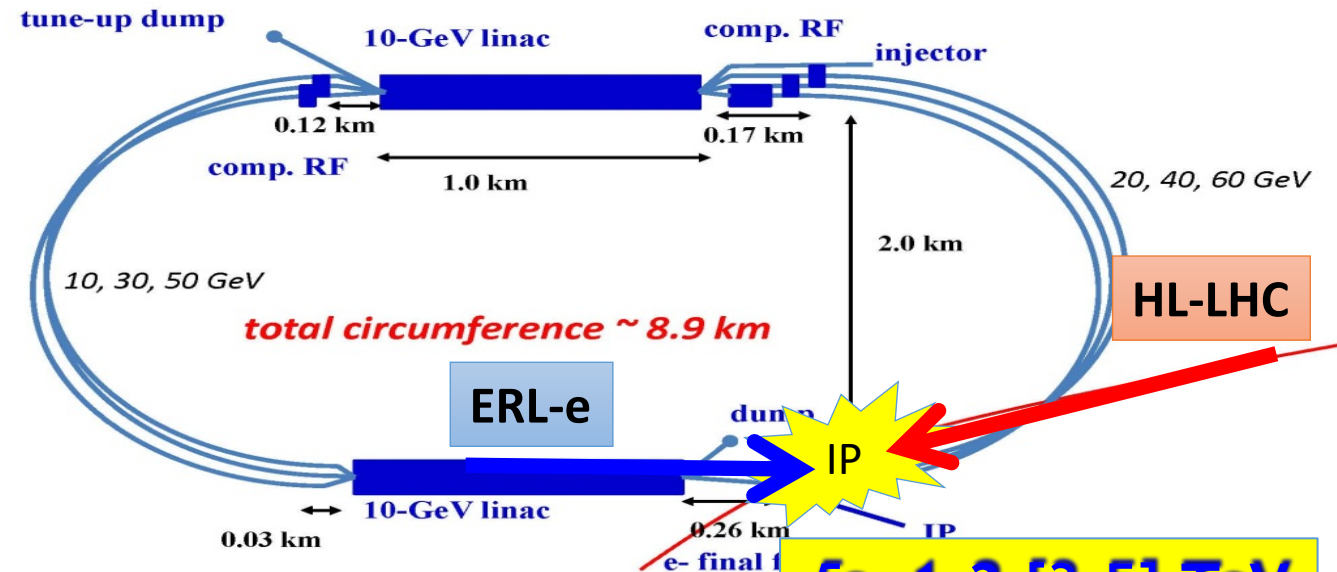


electrons for eh : ERL-e + FCC-hh [LHC]

- 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 hh operation with same running time!

Genuine *Twin Collider* idea holds for LHC and FCC-hh.



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

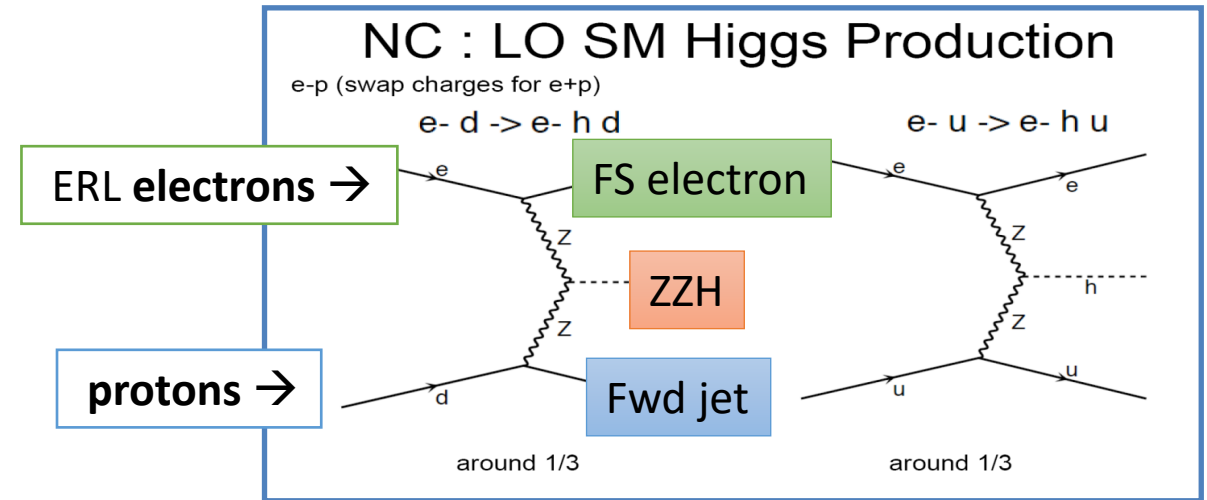
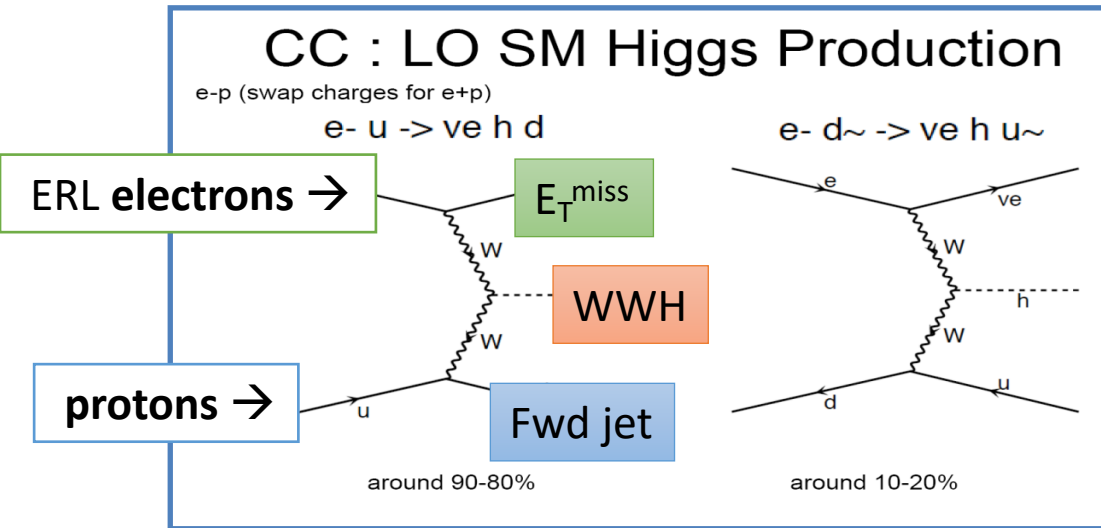
$E_e = 60 \text{ GeV}$

$E_p = 7 [50] \text{ TeV}$

- ep peak lumi $10^{34} \text{ cm s}^{-2} \text{ s}^{-1}$ (based on existing HL-LHC design)
- Operation scenario: F. Bodry et al. CERN-ACC-2018-0037 [arXiv:1810.13022]
- LHeC [FCC-eh] $L = 1000 [2000] \text{ fb}^{-1}$ 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 CDR update CERN-ACC-Note-2020-0002 [arXiv:2007.14491] and submitted to J. Phys. G → see Talk #729 by B Holzer & Talk #730 about ERL Facility at Orsay

SM Higgs Production in ep



\rightarrow 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	109	560
NC DIS	21	127
P=-80%		
CC DIS	196	1008
NC DIS	25	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

CC : LO SM Higgs Production

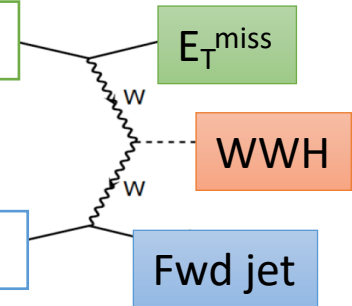
e-p (swap charges for e+p)

e- u -> ve h d

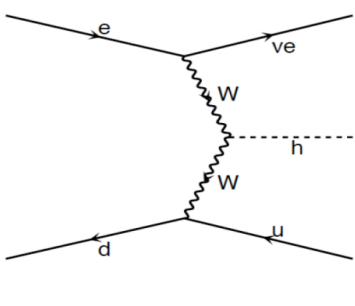
e- d~ -> ve h u~

ERL electrons →

FCC protons →



around 90-80%



around 10-20%

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	109	560
NC DIS	21	127
P=-80%		
CC DIS	196	1008
NC DIS	25	148

NC : LO SM Higgs Production

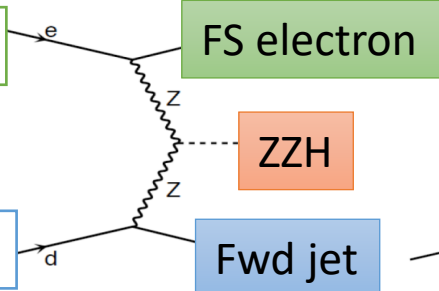
e-p (swap charges for e+p)

e- d -> e- h d

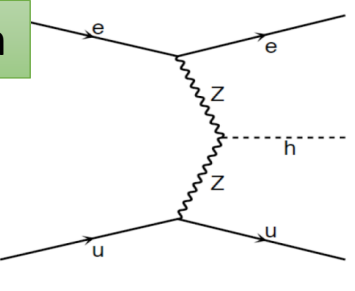
e- u -> e- h u

ERL electrons →

FCC protons →



around 1/3



around 1/3

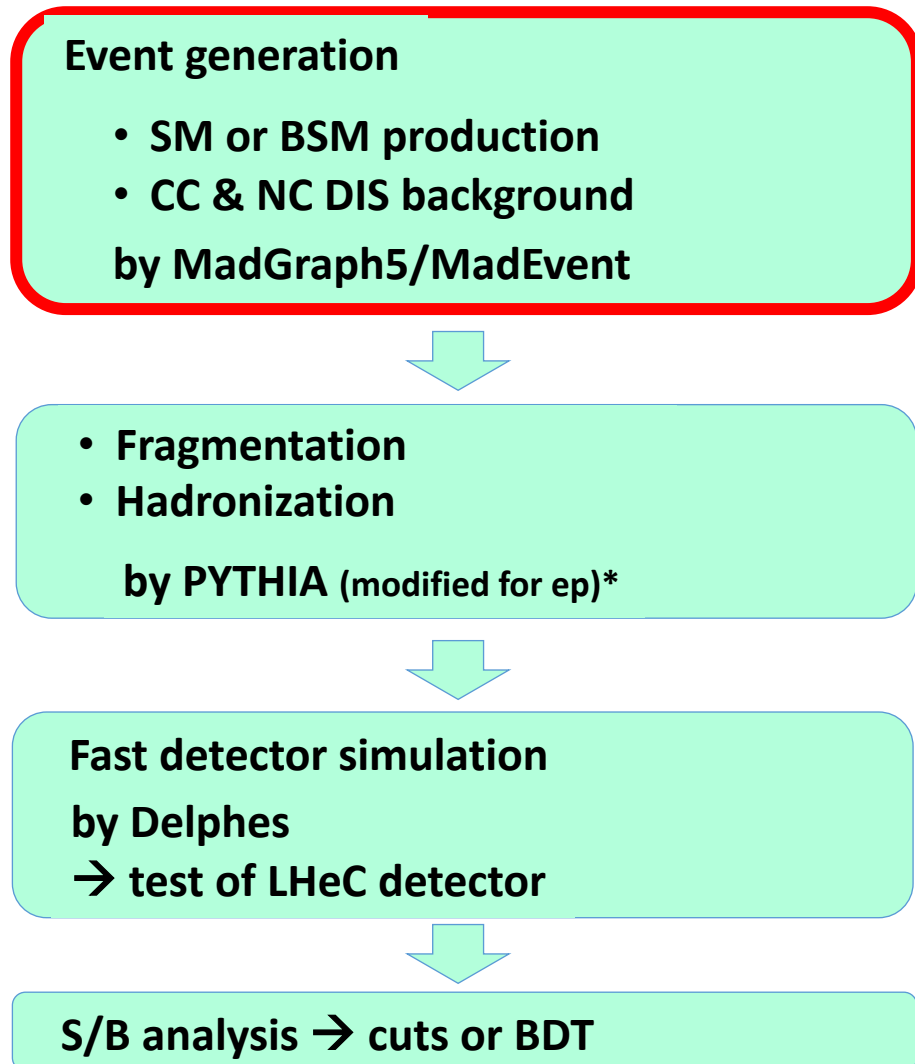
→ In ep, direction of quark (FS) is well defined

- Scale dependencies of the cross section are small, of order 5-10%. Tests of the Higgs boson production cross section at the LHeC will deliver N³LO PDFs, m_c to 3 MeV, m_b to 10 MeV and α_s to ~0.1-0.2%
- NLO QCD corrections to the Higgs boson production cross section at the LHeC will deliver N³LO PDFs, m_c to 3 MeV, m_b to 10 MeV and α_s to ~0.1-0.2%

Theory well under control in ep!
LHeC will deliver N³LO PDFs,
m_c to 3 MeV, m_b to 10 MeV and
α_s to ~0.1-0.2%

[B. R. Webber, R. Ruckl, Nucl.Phys.B395:35-44, 1993]
[B. R. Webber, R. Ruckl, Nucl.Phys.B395:35-44, 1993]

Analysis Framework and *Detector**



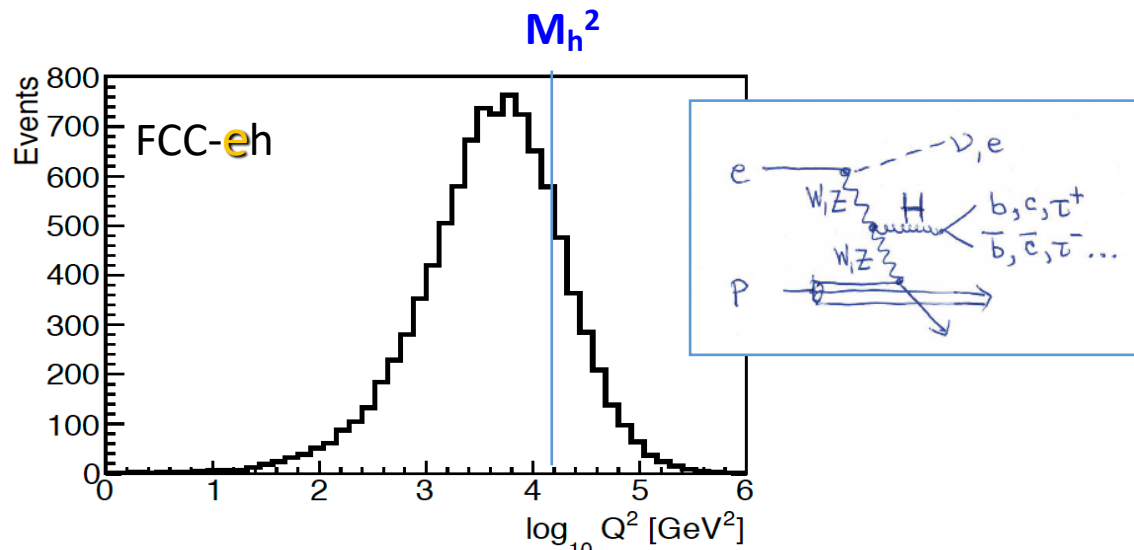
- Calculate cross section with tree-level Feynman diagrams (any UFO) using pT of scattered quark as scale (CDR \hat{s}) for ep processes with **MadGraph5** ; parton-level x-check CompHep
- Fragmentation & hadronisation uses **ep-customised Pythia**.
- **Delphes 'detector'**
→ **displaced vertices and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

* See page 11 for ep Pythia checks

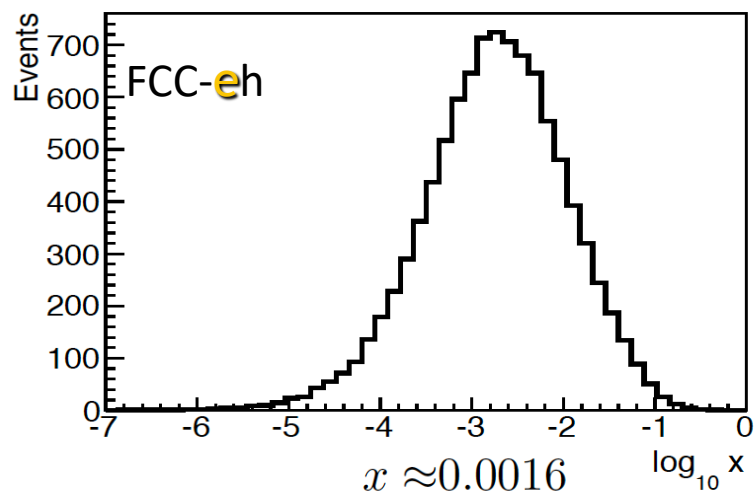
https://indico.cern.ch/event/278903/contributions/631181/attachments/510303/704309/Chavannes_UKLein_20.01.2014.pdf

DIS Kinematics

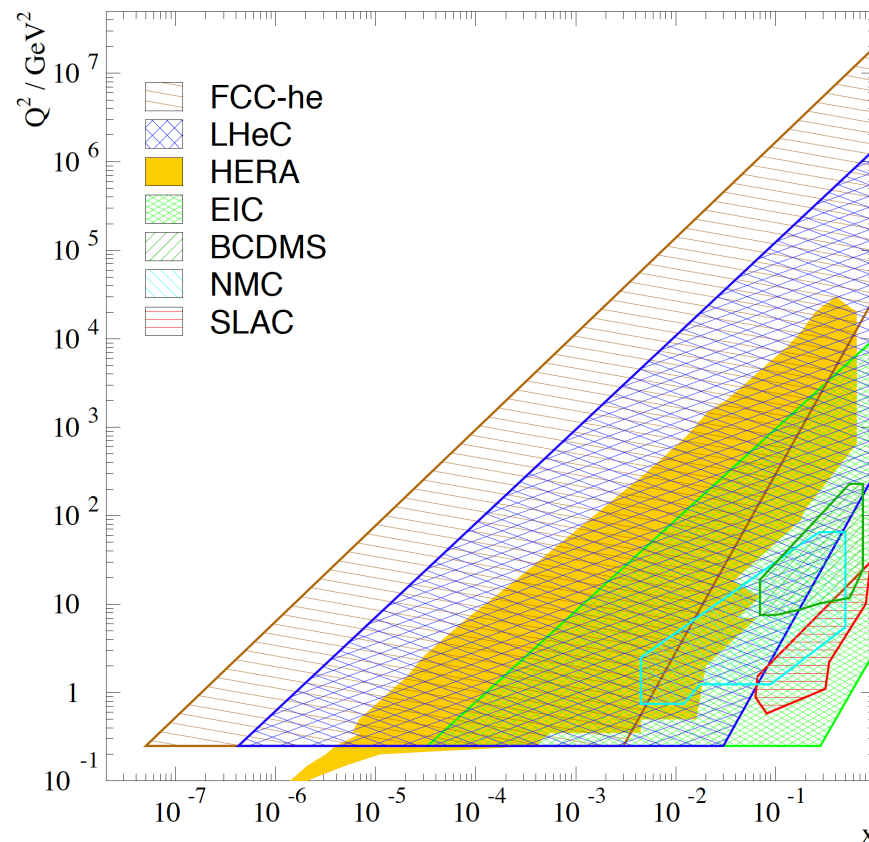
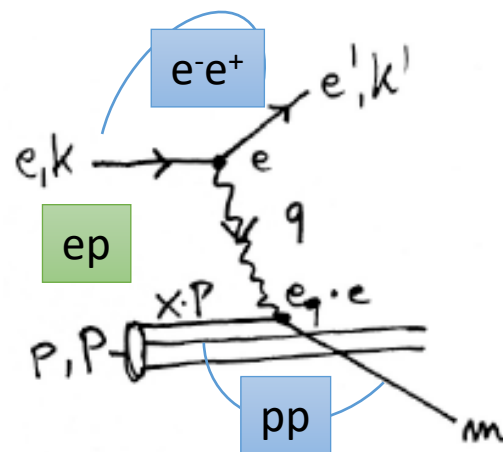
MadGraph scale: p_T of leading jet
-Parton-level-



$$Q^2 \approx 6500 \text{ GeV}^2$$



$$x \approx 0.0016$$



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

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

$$\text{if } (Q^2 \gg x^2 M_p^2, m^2):$$

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

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

$$Q^2 = sxy$$

relation to pp LO QCD

$$x_{1,2} = (M/\sqrt{s}) \exp(\pm y)$$

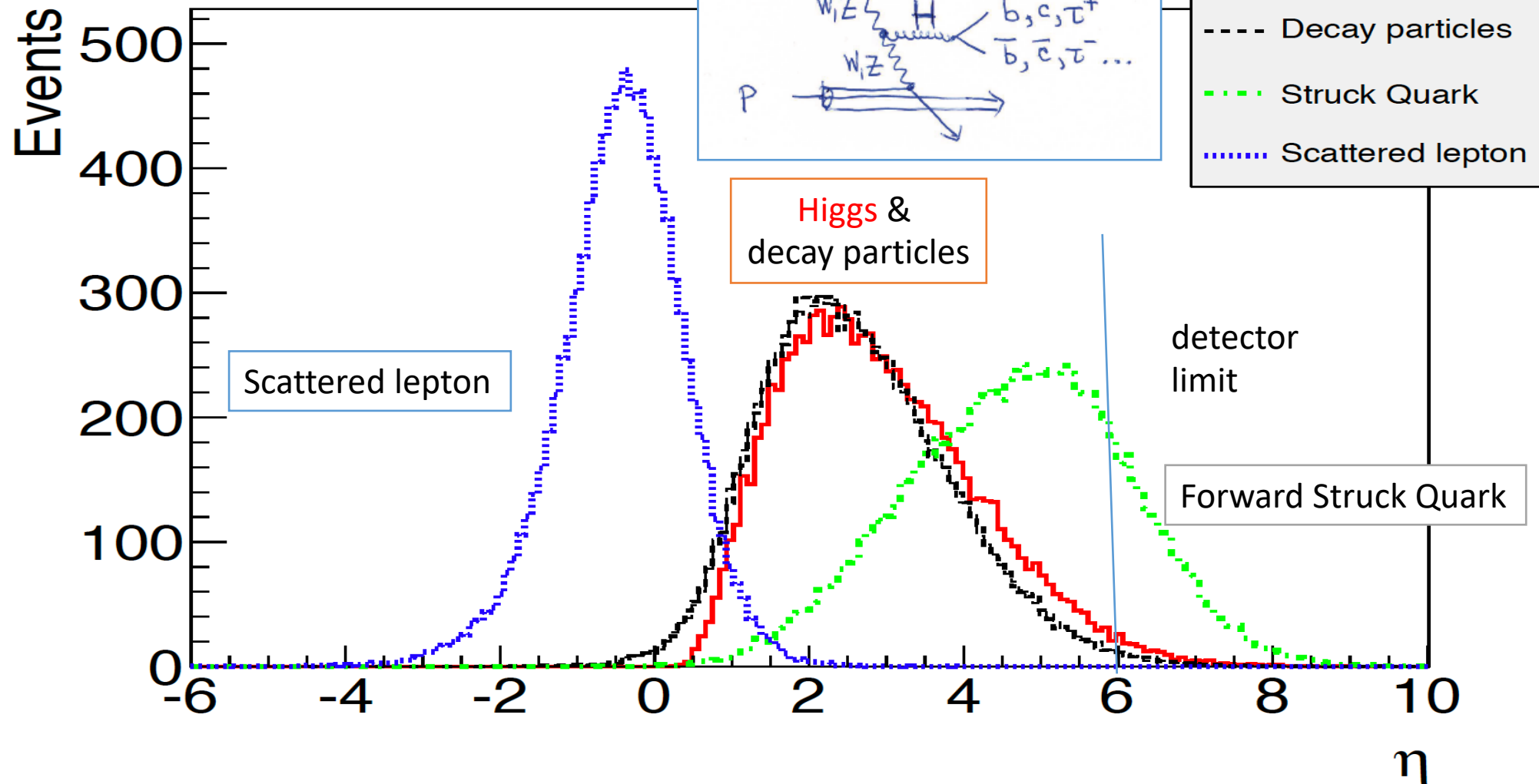
$$Q^2 \sim M^2$$

η Distributions at FCC-eh

Most *asymmetric*
ep configuration

MadGraph scale: p_T of leading jet

-Parton-level-



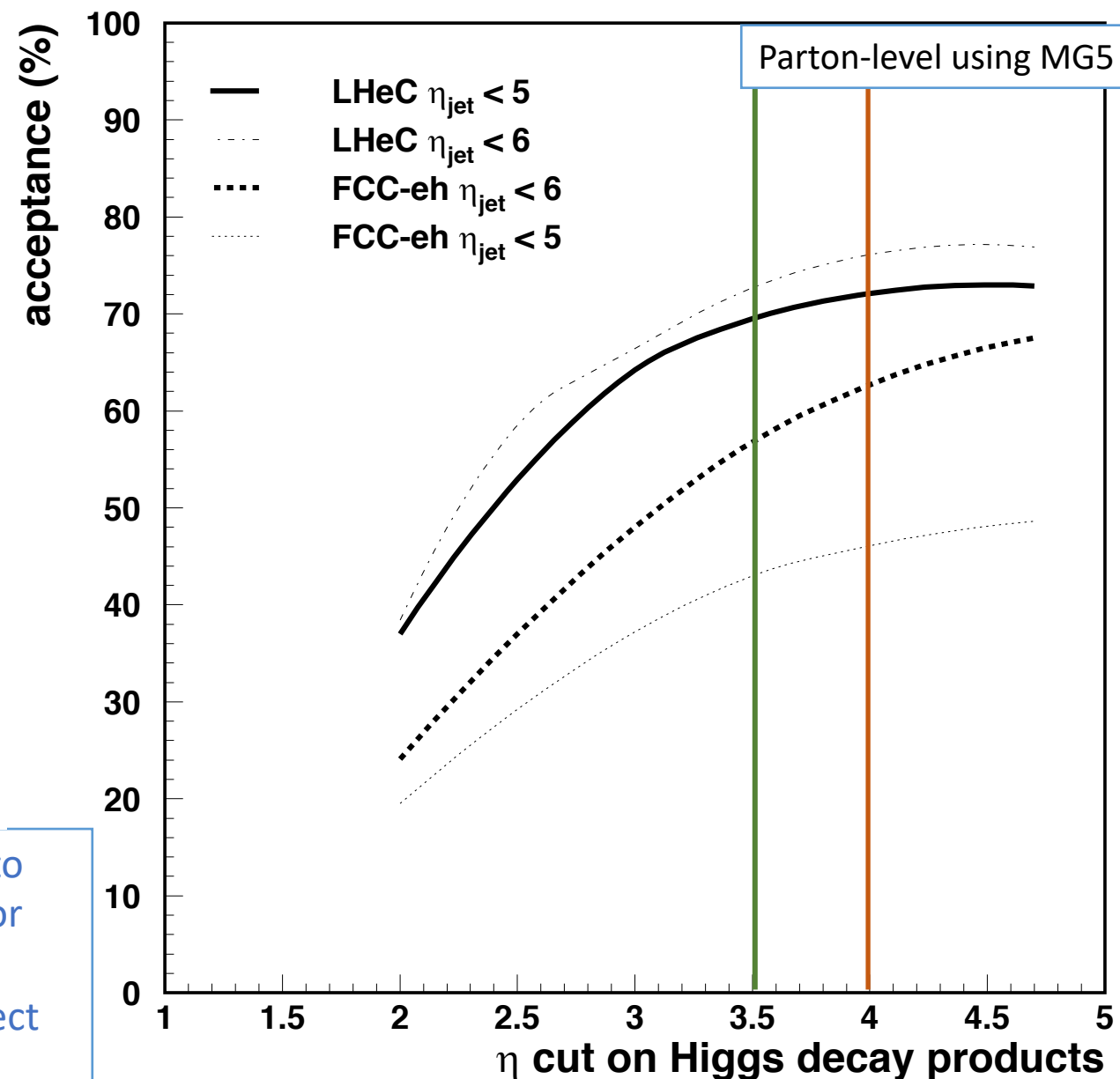
Higgs decay particles (here to W^*W), struck quark and scattered lepton are well separated in detector acceptance.

Rates and Geometric acceptances

$P_e = -80\%$

LHeC: 1.3 TeV, 1 ab^{-1}
FCC-eh: 3.5 TeV, 2 ab^{-1}

Channel	Fraction	Number of Events			
		Charged Current		Neutral Current	
		LHeC	FCC-eh	LHeC	FCC-eh
$b\bar{b}$	0.581	114 500	1 208 000	14 000	175 000
W^+W^-	0.215	42 300	447 000	5 160	64 000
gg	0.082	16 150	171 000	2000	25 000
$\tau^+\tau^-$	0.063	12 400	131 000	1 500	20 000
$c\bar{c}$	0.029	5700	60 000	700	9 000
ZZ	0.026	5 100	54 000	620	7 900
$\gamma\gamma$	0.0023	450	5 000	55	700
$Z\gamma$	0.0015	300	3 100	35	450
$\mu^+\mu^-$	0.0002	40	410	5	70
$\sigma [\text{pb}]$		0.197	1.04	0.024	0.15



→ Tracking acceptance up to $\eta=3.5$ for Higgs decay products to ensure high acceptances of 57% at FCC-eh [70% at LHeC] for dominant decays

→ Acceptance of muon spectrometer up to $\eta=4$ opens prospect to measure $H \rightarrow \mu\mu$ signal strength to $\sim 6\%$ at FCC-eh

Higgs in eh: *cut* based results

Masahiro Tanaka, Masahiro Kuze,
Tokyo Tech 2017/2018

Example of samples:

Unpolarised ($P=0$) samples $E_e=60$ GeV

$E_p=7$ TeV	LHeC			$E_p=50$ TeV	FCC		
	σ (pb)	Nsample	N/ σ (fb $^{-1}$)		σ (pb)	Nsample	N/ σ (fb $^{-1}$)
Signal CC:H \rightarrow bb	0.113	0.2M	1760	Signal CC:H \rightarrow bb	0.467	0.15M	321
CCjjj no top	4.5	2.6M	570	CCjjj no top	21.2	1.95M	92
CC single top	0.77	0.9M	1160	CC single top	9.75	1.05M	108
CC Z	0.52	0.6M	1160	CC Z	1.6	0.15M	94
NC Z	0.13	0.15M	1140	NC Z	0.33	0.15M	455
PAjjj	41	14M	350	PAjjj	262	12.9M	49

Delphes ep-style detector
+ flat parton-level b-tagging
for $|\eta| < 3.0$

conservative HFL tagging:
b: 60%, c: 10%, udsg: 1%

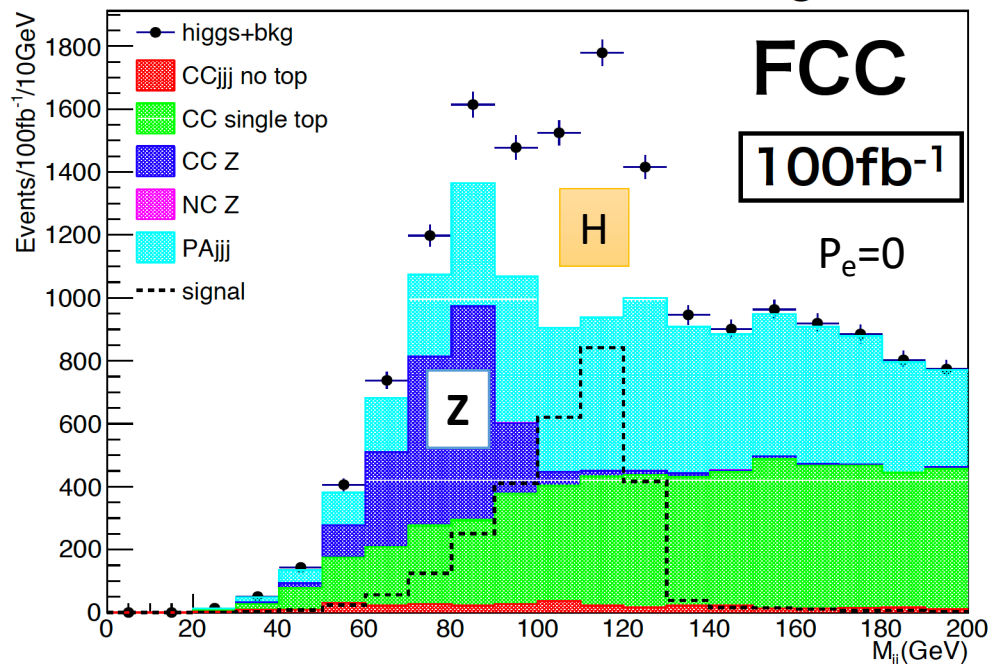
CAL coverage $|\eta| < 5$ LHeC [< 6 FCC-eh]

Mass of 2 b-jets after event selection

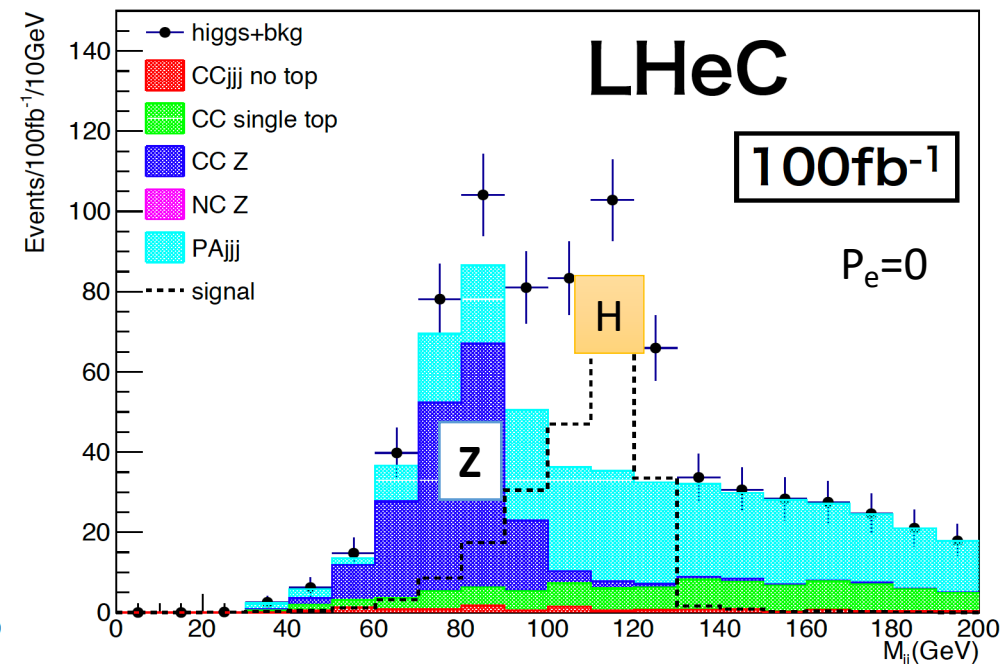
H \rightarrow bb: S/N>1
using *conservative*
light quark misID
and *simple* cuts

**\rightarrow confirmed
earlier & post CDR
studies**

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



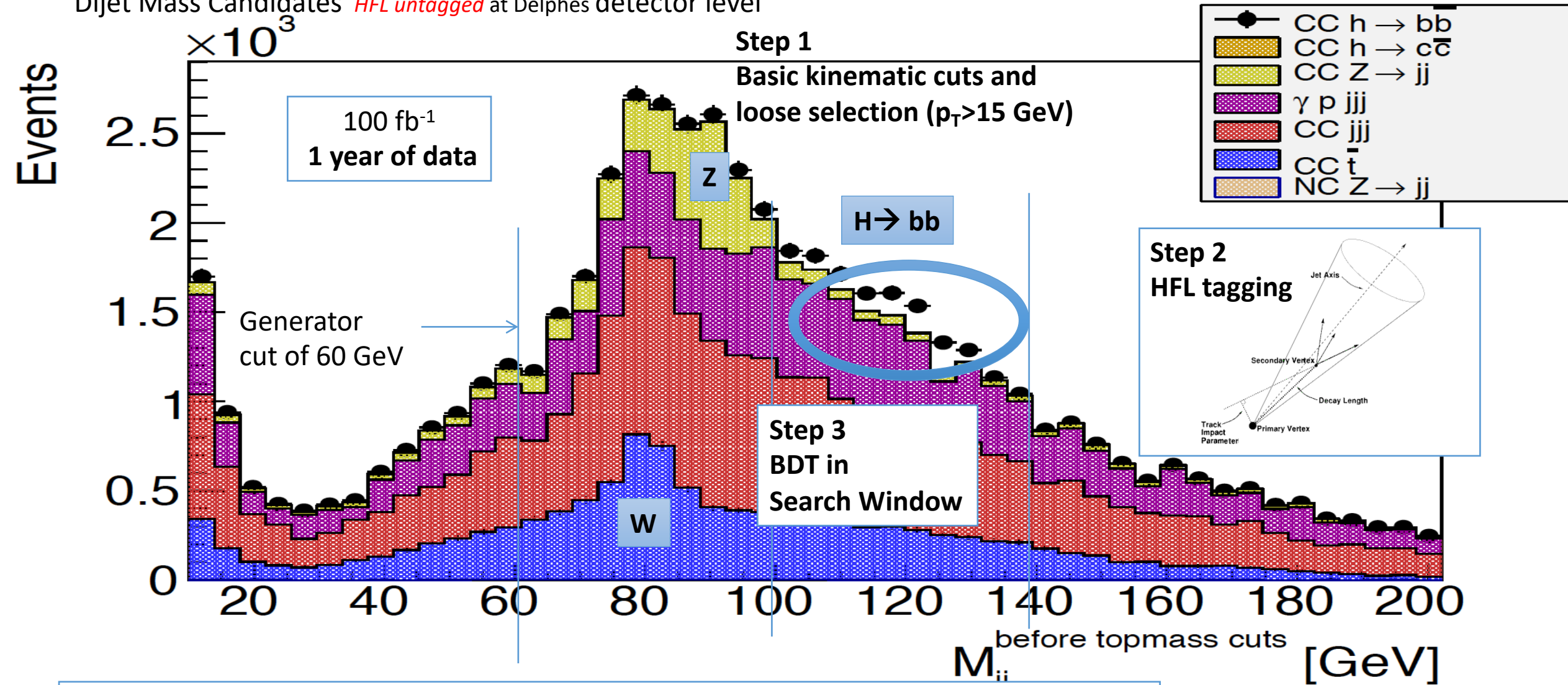
Note: plenty of single Z, W and top in ep



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.

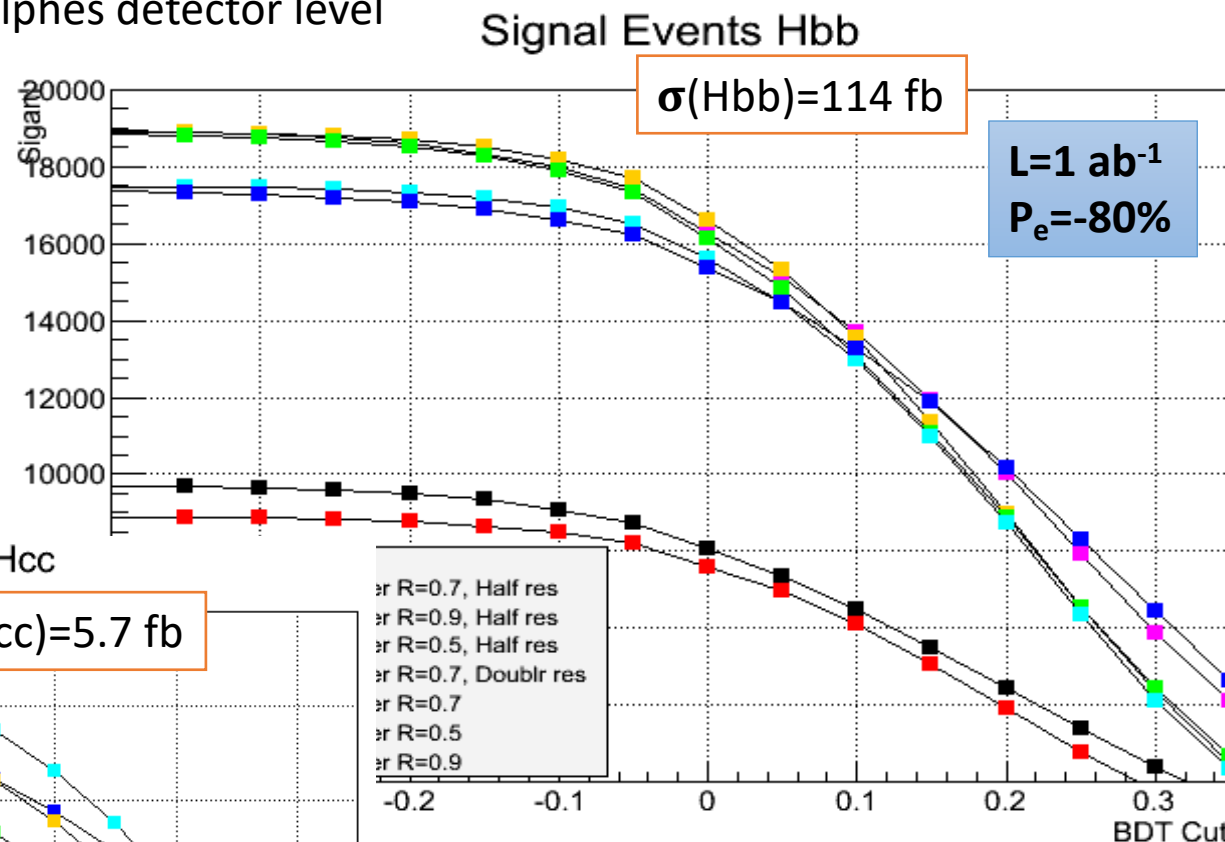
→ addition of small angle electron taggers will reduce PHP to ~1-2%

BDT Results for Higgs @ LHeC

Uta Klein &
Daniel Hampson

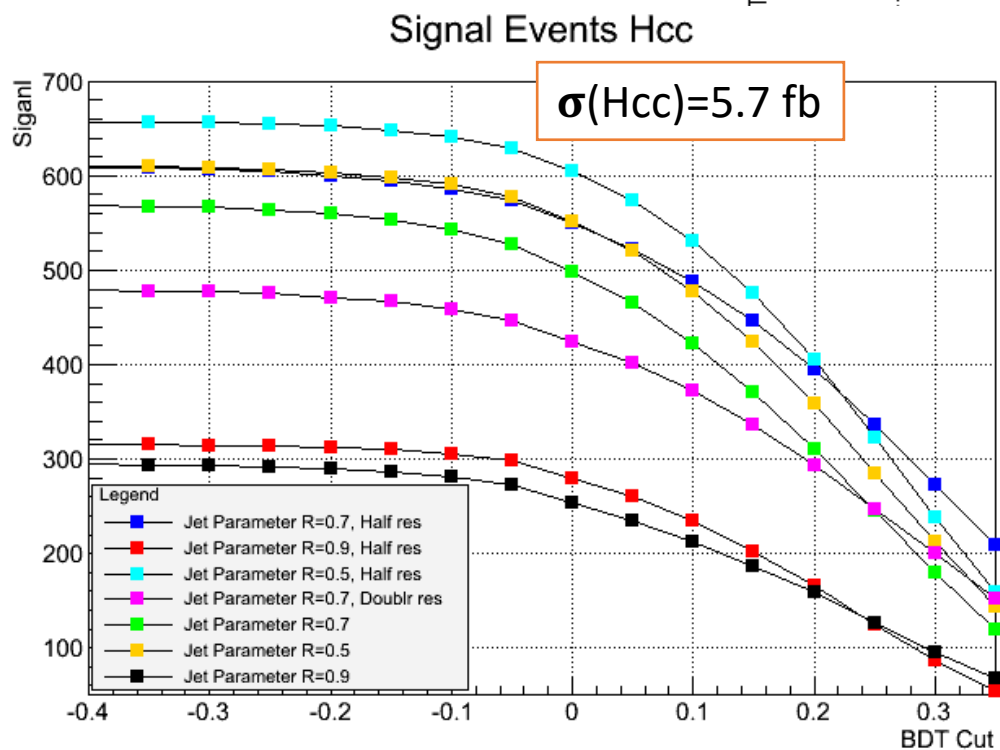
using realistic HFL tagging at Delphes detector level

Hbb : Clear sensitivity to
chosen jet radius; rather
robust w.r.t. vertex
resolution in range of 5 to
20 μm for $0.5 < p_T < 5$ GeV



Hbb:
At BDT=0
acceptance x
efficiency 28%

Hcc:
At BDT=0:
acceptance x
efficiency 11%

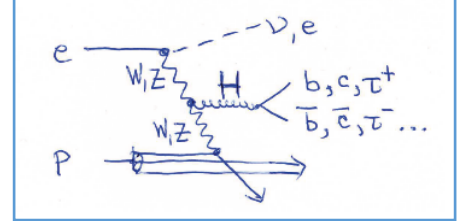


Hcc : High sensitivity to vertex resolution
(nominal 10 μm) and jet radius choice

→ expect about 400-600 Hcc candidates

[similar event numbers for ILC Zqq-Hcc study arXiv:
0909.1052]

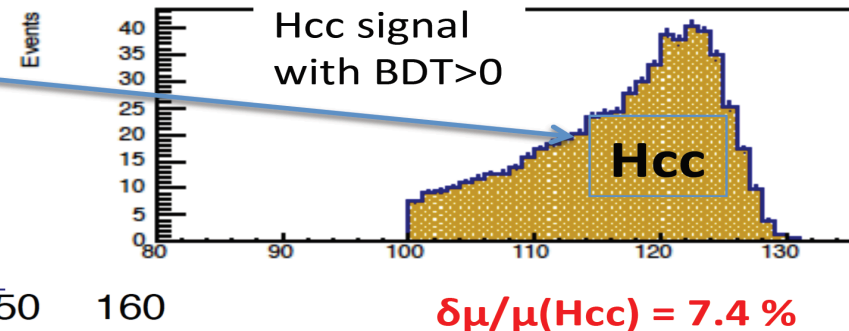
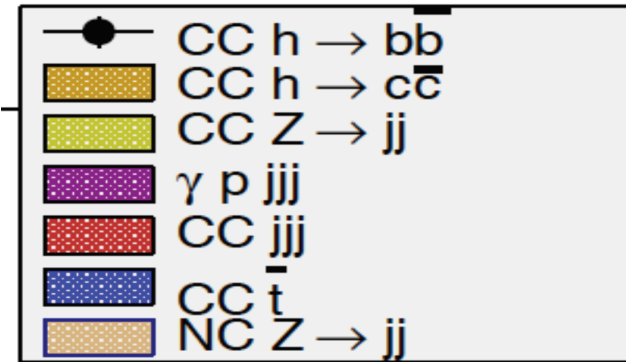
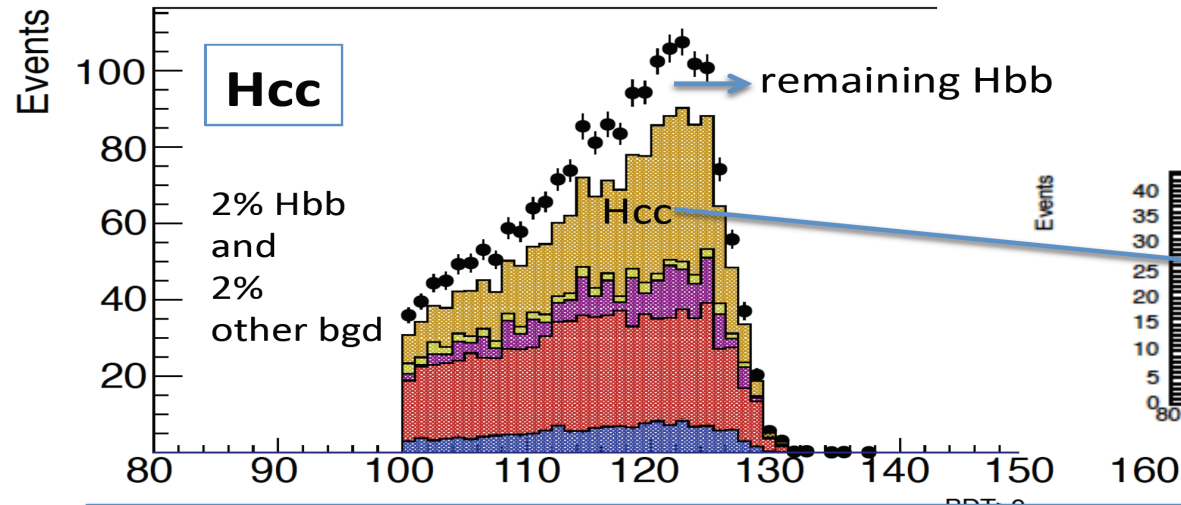
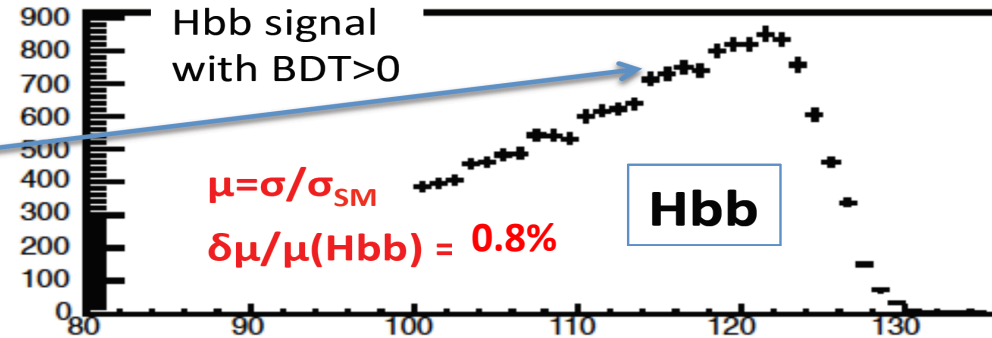
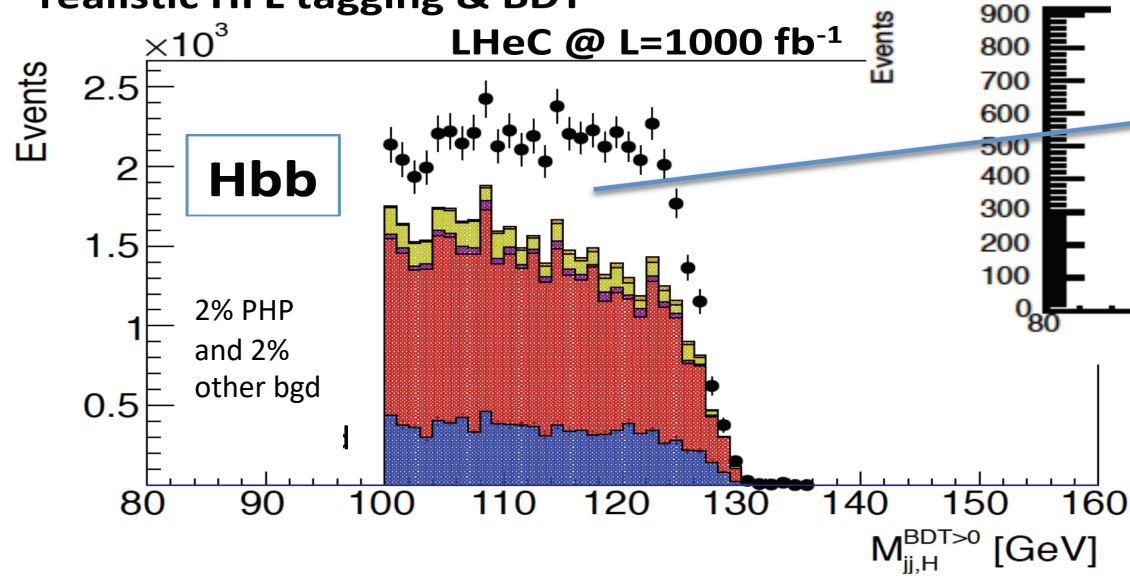
Higgs in ep – clean S/B, no pile-up



→ further improvements using BDT

realistic HFL tagging & BDT

Uta Klein & Daniel Hampson & Izzy Harris BSc 2017



Assuming background in control regions understood to 2% and negligible MC statistics for background in signal region; SM Higgs bb contribution in cc controlled by genuine Hbb measurement and b and c-jet correlation, see e.g. methodology ILC Hcc study arXiv: 0909.1052 [ILC Zqq-Hcc study got 8.8% for Hcc signal strength for $M_H=120 \text{ GeV}$ $\sigma_{\text{pol}}(\text{Hcc})=6.9 \text{ fb}$ with similar Hcc, Hbb event numbers but factor 6.8 higher SM background than LHeC]

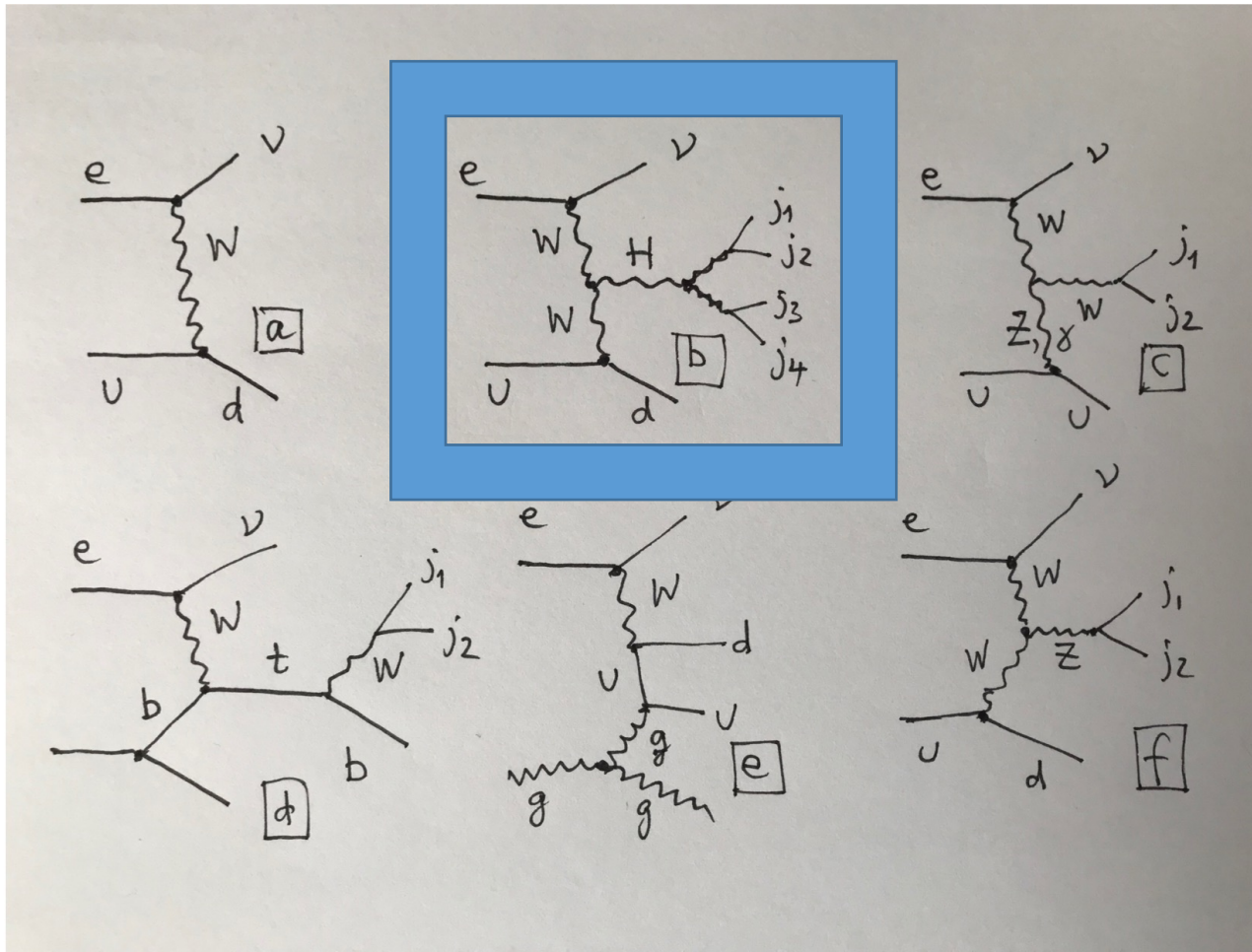
→ Main systematic checks: variations of background contribution and tagging efficiencies

WW to Higgs to W*W to 4 jets



- CC DIS Higgs production and decay to W*W gives direct access to g_{HWW}^4 assuming no NP in production and decay

→ important process: allows *nearly direct* access to g_{HWW} and $\delta g_{HWW} = 1/4 \delta \mu / \mu$ ($H \rightarrow W^*W$)



New study for FCC-eh at 3.5 TeV:

Signal and Background generated by MG5+Pythia using $BR(H \rightarrow WW) = 21.5\%$ and 67% for $W \rightarrow jj$ decay:

$\sigma = 100 \text{ fb} \sim 45\%$ of $\sigma(HWW)$

- passed thru FCC-eh Delphes detector
- background processes dominated by CC multijets, top and single H, W, Z + jets (4^{th} + more jets from shower)

→ various anti-kt R choices studied for the resolved case: all 4 jets reconstructed

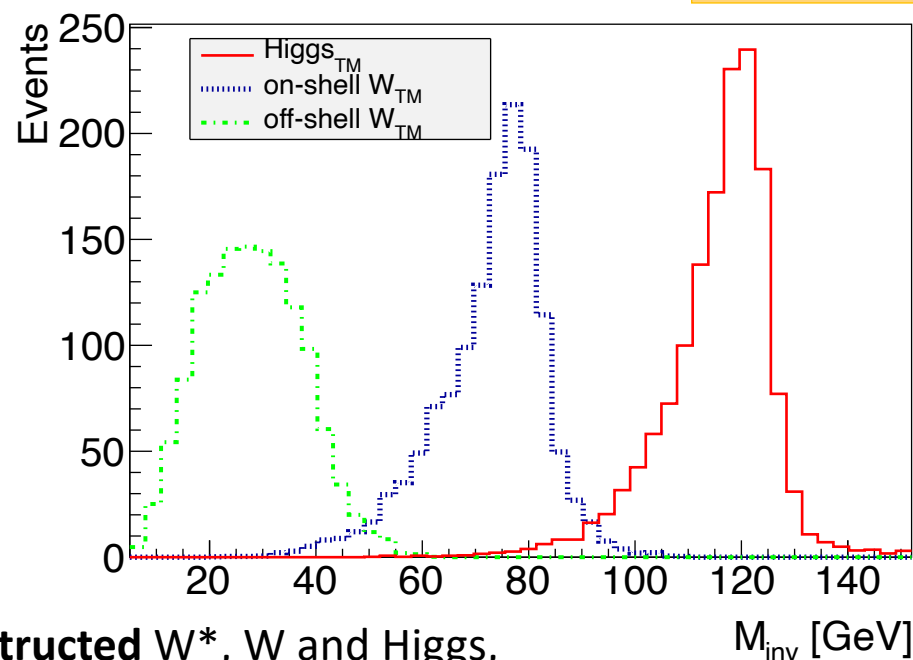
→ optimal choice $R = 0.7$

Note: more event categories and decay modes could be added a la LHC-style studies

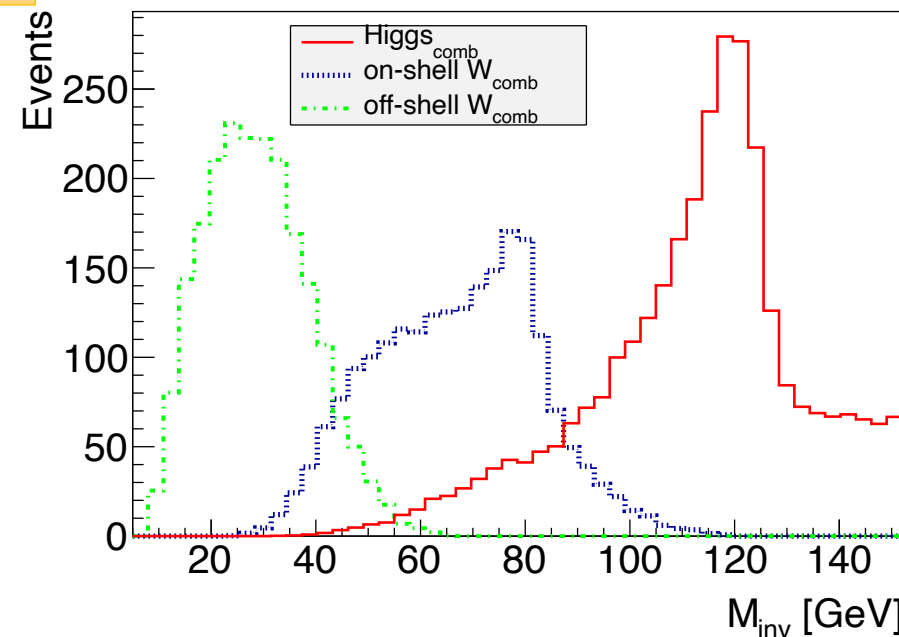
$H \rightarrow WW^*$ analysis strategy & results

At Delphes detector level

NO mass requirements in combinatorics!



Reconstructed W^* , W and Higgs,
truth-matched

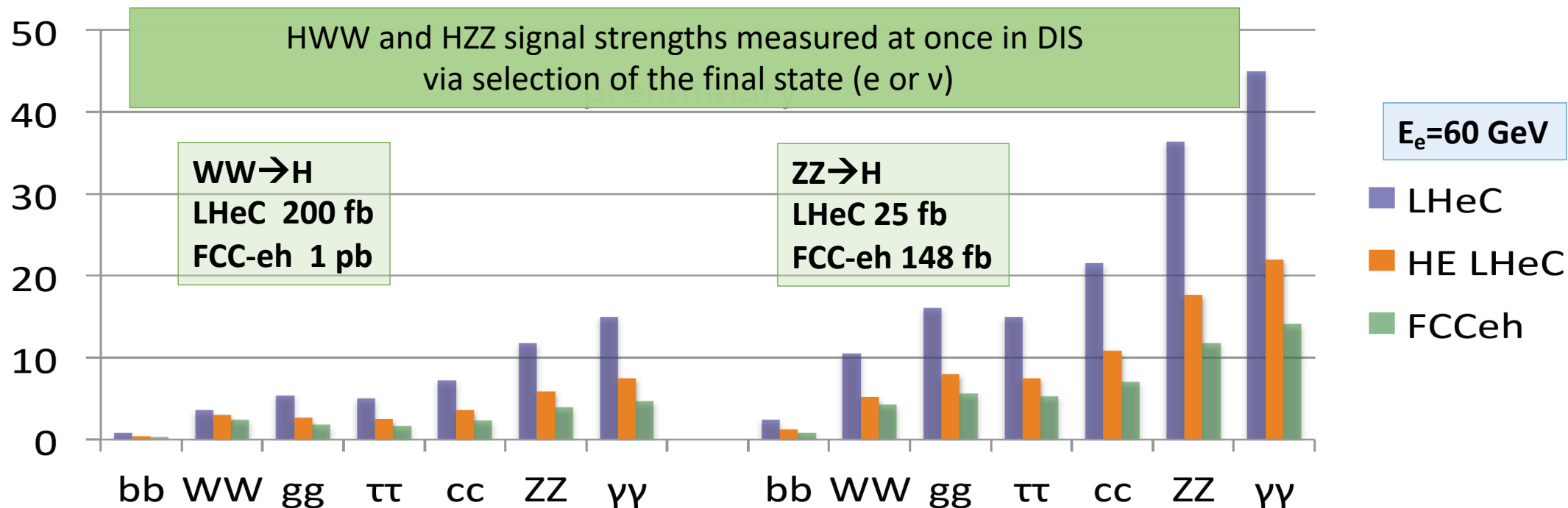


Reconstructed W^* , W and Higgs, after jet combinatorics based on selecting at least 5 jets with $p_T > 6$ GeV and finding the higgs candidate which has two jet pairs with min $\Delta\eta$, and max $\Delta\eta$ between Higgs and fwd jet, and max $\Delta\phi$ between Higgs and ETmiss or Higgs and fwd jet → passed to BDT

- Acceptance x efficiency of 20% and purity of 68% that true forward jet is identified for pre-selected events
- **HWW signal strengths of 1.9 to 2.5%** reached depending on background assumptions and pre-selection & BDT details
- very nice results expected for **δg_{HWW} of 0.5 to 0.6% from this channel only**

SM Higgs Signal Strengths in ep

$\delta\mu/\mu$ [%]



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

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

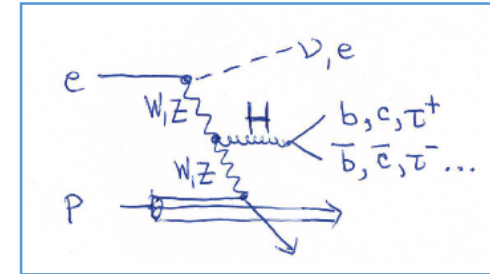
... and Consistency Checks of EW Theory

→ similar tests possible using various cms energy CLIC machines, see e.g. [arXiv:1608.07538], however, in ep, we could perform them with one machine

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

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

- ➔ Dominated by $H \rightarrow b\bar{b}$ 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

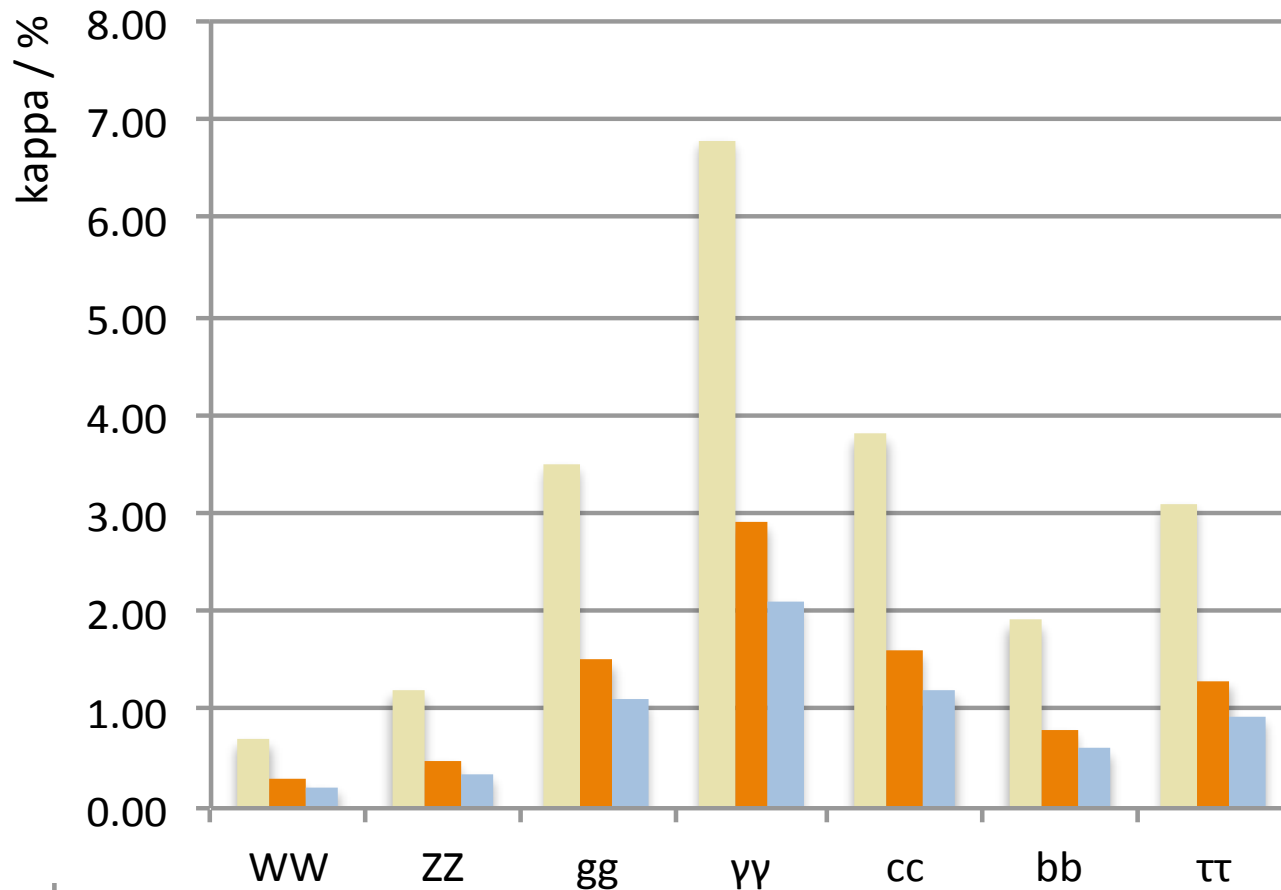
- ➔ Another nice test: **How does the Higgs couple to 3rd and 2nd generation quark?**

b is down-type and c is up-type

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

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)
see e.g. [arXiv:1608.07538]



$E_e = 60 \text{ GeV}, P = -0.8$

$E_p =$

LHeC

7 TeV



FCC-eh (2.2)

20 TeV



FCC-eh (3.5)

50 TeV

Note: also
H in ePb

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

... to explore the synergy fully

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
$\delta\Gamma_{\text{H}}/\Gamma_{\text{H}}$ (%)	SM	3.8	6.3	2.7	1.3	1.1	SM
$\delta g_{\text{HZZ}}/g_{\text{HZZ}}$ (%)	1.3	0.35	0.80	0.2	0.17	0.16	0.43
$\delta g_{\text{HWW}}/g_{\text{HWW}}$ (%)	1.4	1.7	1.3	1.3	0.43	0.40	0.26
$\delta g_{\text{Hbb}}/g_{\text{Hbb}}$ (%)	2.9	1.8	2.8	1.3	0.61	0.55	0.74
$\delta g_{\text{Hcc}}/g_{\text{Hcc}}$ (%)	SM	2.3	6.8	1.7	1.21	1.18	1.35
$\delta g_{\text{Hgg}}/g_{\text{Hgg}}$ (%)	1.8	2.2	3.8	1.6	1.01	0.83	1.17
$\delta g_{\text{H}\tau\tau}/g_{\text{H}\tau\tau}$ (%)	1.7	1.9	4.2	1.4	0.74	0.64	1.10
$\delta g_{\text{H}\mu\mu}/g_{\text{H}\mu\mu}$ (%)	4.4	13	n.a.	10.1	9.0	3.9	n.a.
$\delta g_{\text{H}\gamma\gamma}/g_{\text{H}\gamma\gamma}$ (%)	1.6	6.4	n.a.	4.8	3.9	1.1	2.3
$\delta g_{\text{H}t\bar{t}}/g_{\text{H}t\bar{t}}$ (%)	2.5	—	—	—	—	2.4	ttH 1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	< 1.0	< 1.0	n.a.

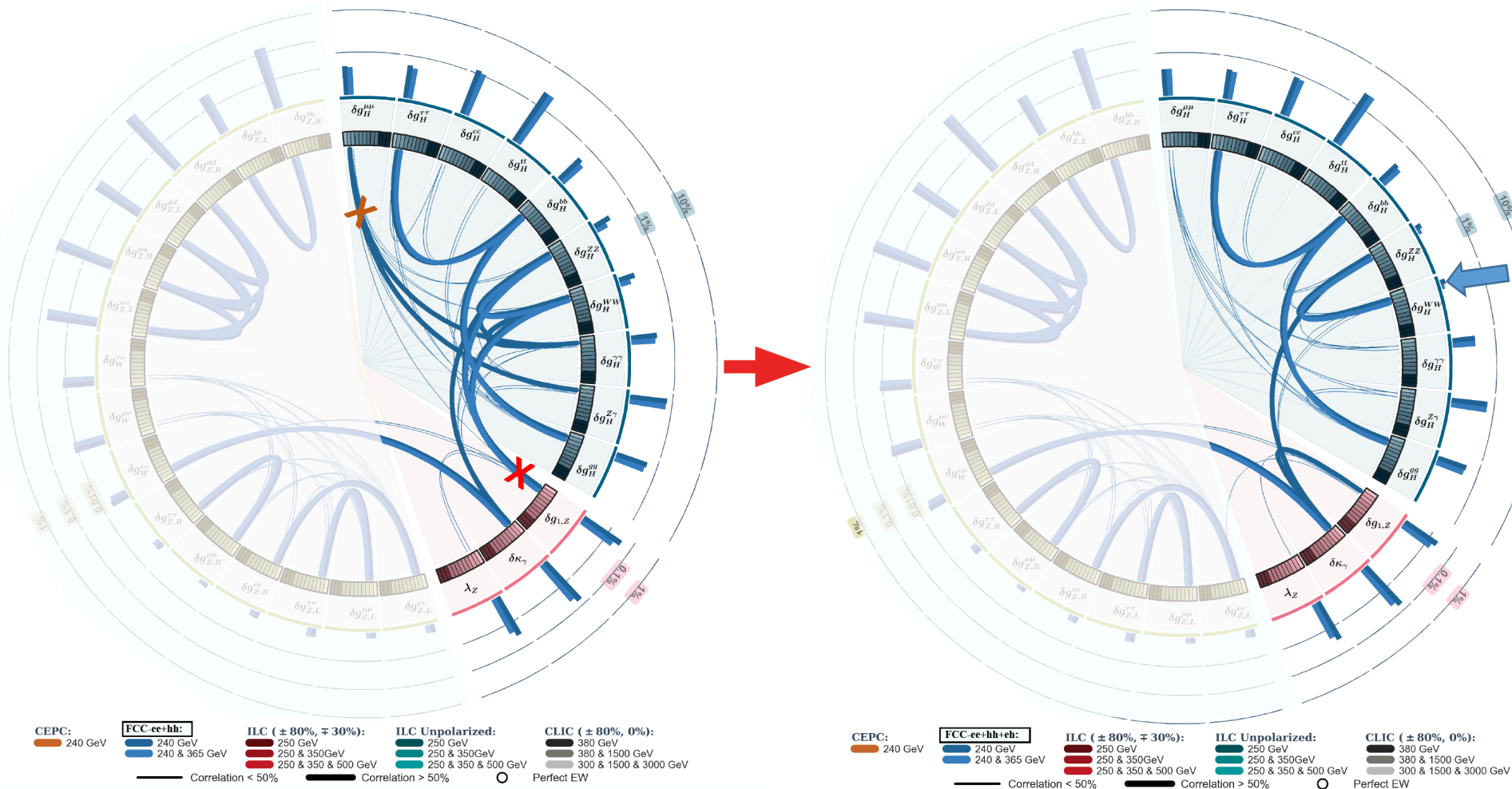
- Combine the complementary measurements for best physics outcome!
- FCC-hh will be the machine to pin down HH and all rare decays!

Higgs-inv.: 1.2%
HH ~20%

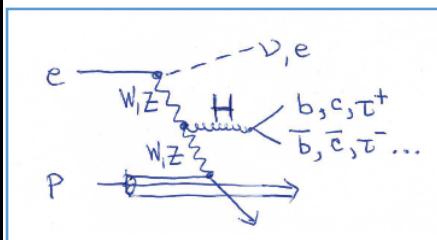
Couplings and correlations

FCCee+hh

FCCee+eh+hh



PRELIMINARY



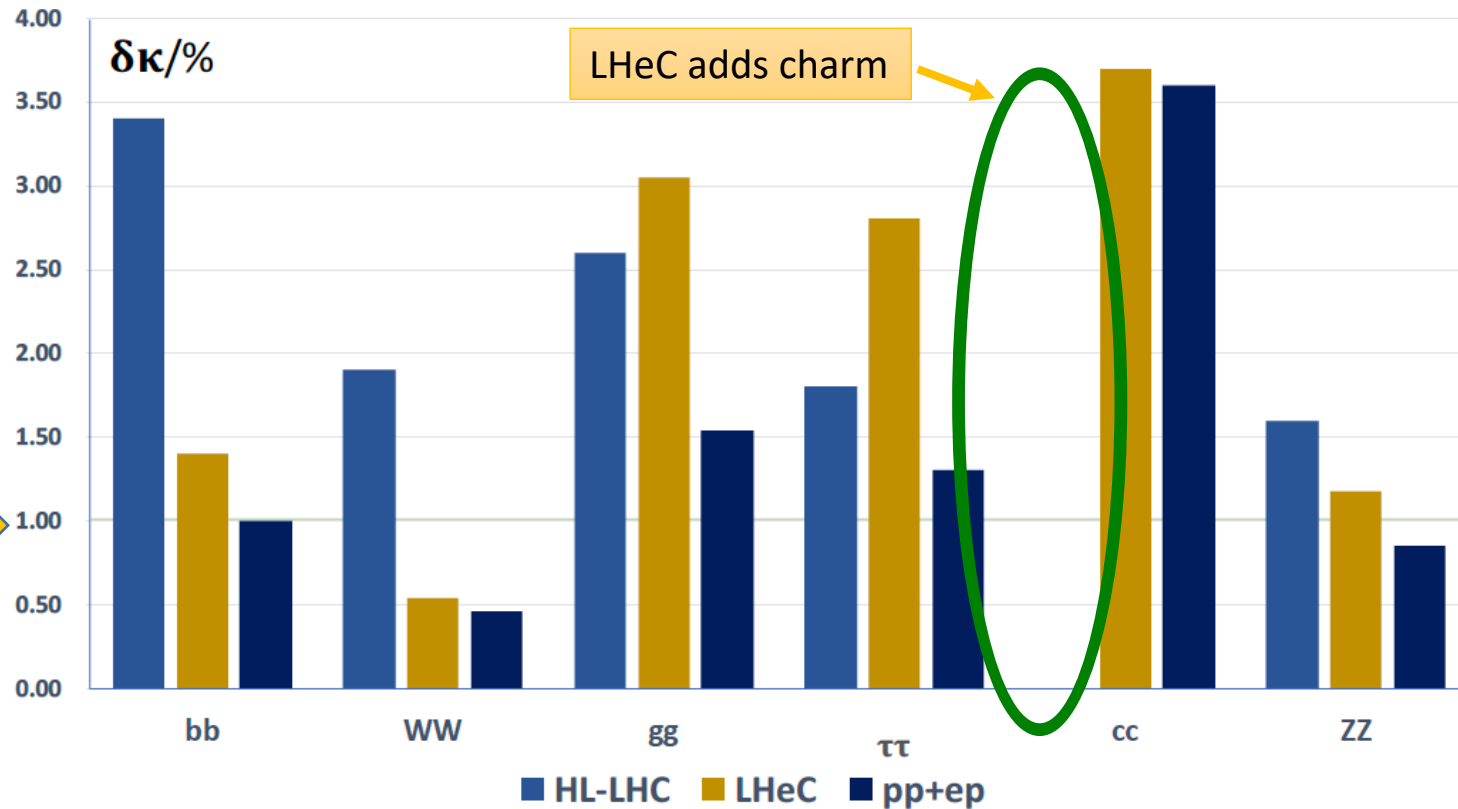
eh resolves HWW-HZZ correlation, see line marked with **X** on left plot, and reduces further correlations **X**

Higgs production in the three collider modes ee, ep, pp are also important for theory development



For the near future*: SM Higgs Couplings & $\delta\sigma_{\text{Higgs}}$ (pp)

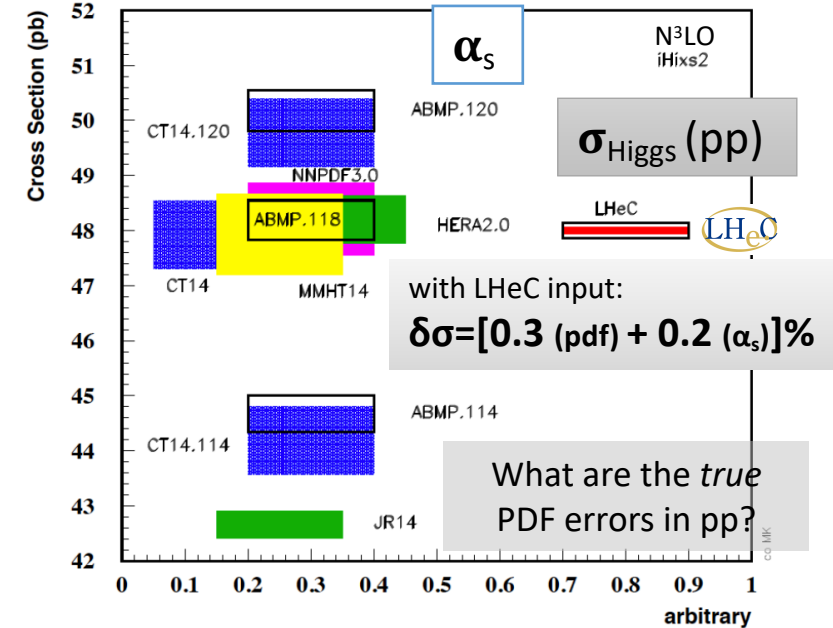
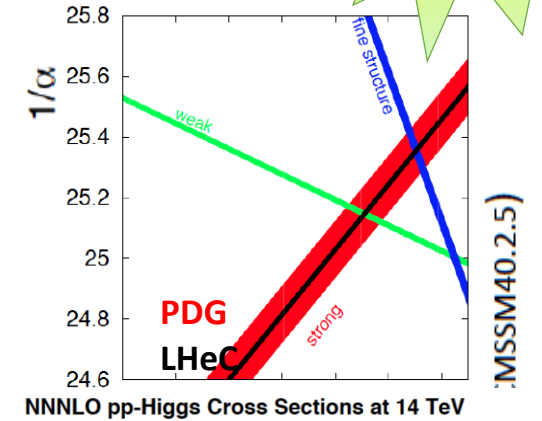
Update of LHeC ES submission CERN-ACC-2018-0084 & CDR update submitted to arXiv



[arXiv:2007.14491]

LHeC and
HL-LHC
prospects

See talk #731 by C Gwenlan



* see also backup slide

Wrap Up

- *LHeC and FCC-eh* could measure the dominant Higgs couplings, including ttH, to high precision [CC+NC DIS, no pile-up, clean final state..]
- Higgs measurements in ep are *self consistent* experimentally and theoretically based on DIS cross sections with very small systematic uncertainties.
- Striking synergy of ep ($>\sim 1$ TeV) and ee (250-350 GeV) and pp for Higgs coupling measurements, also to remove HZZ and HWW and further correlations!
- *Energy frontier ep* would empower the physics potential of pp (non-resonant searches, EW, Higgs..) through **high precision QCD measurements: flavour separated PDFs at N³LO, α_s to per mille ...**

Combining pp with ep,
a very powerful Higgs facility can be established
at the HL-LHC already in the 30ties
and later at the FCC eh+hh.

Additional Sources & Thanks to

- **LHeC & FCC-eh Talks at this conference: #731 Precision QCD, #733 Top and EW, #736 BSM Physics, #735 eA Collisions, #729 Accelerator, #737 Detector, #730 Perle: ERL at Orsay**
- **CDR Update** [arXiv:2007.14491]
- **The LHeC/FCC-eh study group, <http://lhec.web.cern.ch>**
- “On the Relation of the LHeC and the LHC” [arXiv:1211.5102]
- FCC to EU Strategy CERN-ACC-2018-0056
- LHeC to EU Strategy CERN-ACC-2018-0084
- Higgs branching fractions and uncertainties taken from <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR>
- 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.

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

Thanks to Hao Sun

Additional material

Combined HL-LHC and LHeC

Parameter	Uncertainty		
	HL-LHC	LHeC	HL-LHC+LHeC
κ_W	1.7	0.75	0.50
κ_Z	1.5	1.2	0.82
κ_g	2.3	3.6	1.6
κ_γ	1.9	7.6	1.4
$\kappa_{Z\gamma}$	10	–	10
κ_c	–	4.1	3.6
κ_t	3.3	–	3.1
κ_b	3.6	2.1	1.1
κ_μ	4.6	–	4.4
κ_τ	1.9	3.3	1.3

Table 9.5: Results of the combined HL-LHC + LHeC κ fit. The output of the fit is compared with the results of the HL-LHC and LHeC stand-alone fits. The uncertainties of the κ values are given in per cent.

Process	σ_H [pb]	$\Delta\sigma_{\text{scales}}$	$\Delta\sigma_{\text{PDF}+\alpha_s}$	
			HL-LHC PDF	LHeC PDF
Gluon-fusion	54.7	5.4 %	3.1 %	0.4 %
Vector-boson-fusion	4.3	2.1 %	0.4 %	0.3 %
$pp \rightarrow WH$	1.5	0.5 %	1.4 %	0.2 %
$pp \rightarrow ZH$	1.0	3.5 %	1.9 %	0.3 %
$pp \rightarrow t\bar{t}H$	0.6	7.5 %	3.5 %	0.4 %

Table 9.4: Predictions for Higgs boson production cross sections at the HL-LHC at $\sqrt{s} = 14$ TeV and its associated relative uncertainties from scale variations and two PDF projections, HL-LHC and LHeC PDFs, $\Delta\sigma$. The PDF uncertainties include uncertainties of α_s .

Higgs Boson studies at future particle colliders

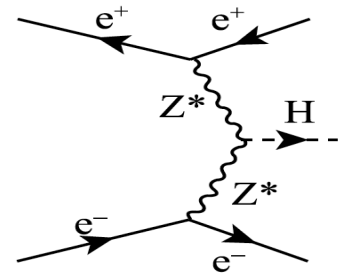
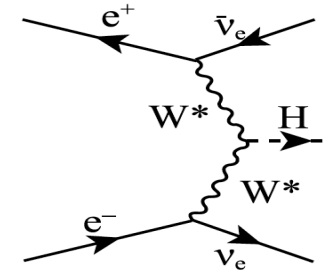
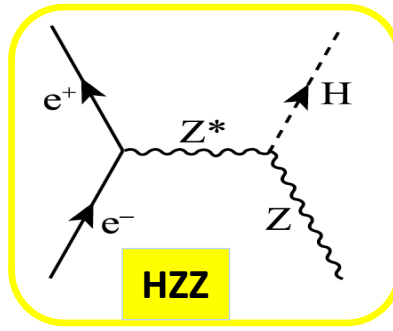
Table 3. Expected relative precision (%) of the κ parameters in the kappa-0 scenario described in Section 2 for future accelerators. Colliders are considered independently, not in combination with the HL-LHC. No BSM width is allowed in the fit: both BR_{unt} and BR_{inv} are set to 0, and therefore κ_V is not constrained. Cases in which a particular parameter has been fixed to the SM value due to lack of sensitivity are shown with a dash (-). A star (★) indicates the cases in which a parameter has been left free in the fit due to lack of input in the reference documentation. The integrated luminosity and running conditions considered for each collider in this comparison are described in Table 1. FCC-ee/eh/hh corresponds to the combined performance of FCC-ee₂₄₀+FCC-ee₃₆₅, FCC-eh and FCC-hh. In the case of HE-LHC, two theoretical uncertainty scenarios (S2 and S2') [13] are given for comparison.

kappa-0	FCC-ee/eh/hh													
	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2'	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98★	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	—	5.7	3.8	99★	86★	85★	120★	15	6.9	8.2	81★	75★	0.69
κ_c [%]	—	4.1	—	—	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	—	2.8	1.7	—	6.9	1.6	—	—	2.7	—	—	—	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	—	2.5	1.7	15	9.4	6.2	320★	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

... gives the complete picture
→ check consistency at sub-percent level of different Higgs production & background compositions!

Higgs in ee vs $e p$

ee Dominant Higgs productions:

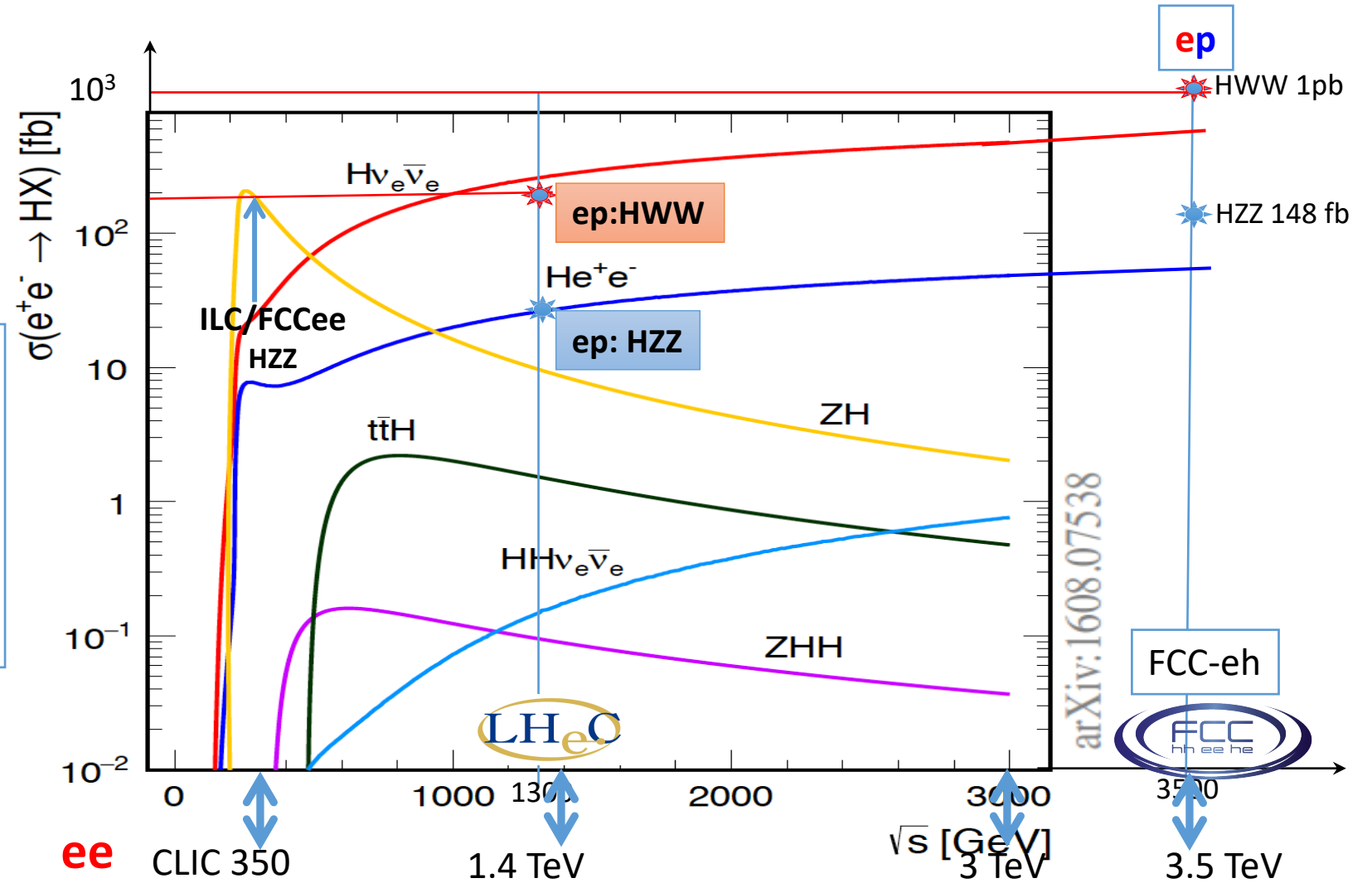
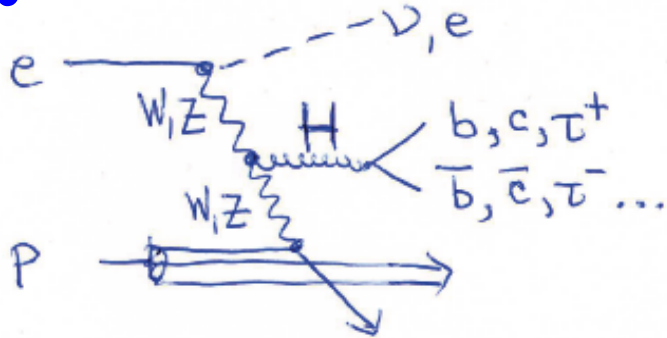


ep vs ee- Higgs cross sections

ep:CC DIS WW Fusion



ep: NC DIS ZZ Fusion



Top Yukawa Coupling @ LHeC

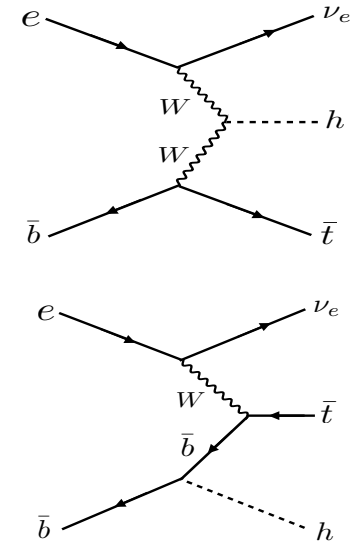
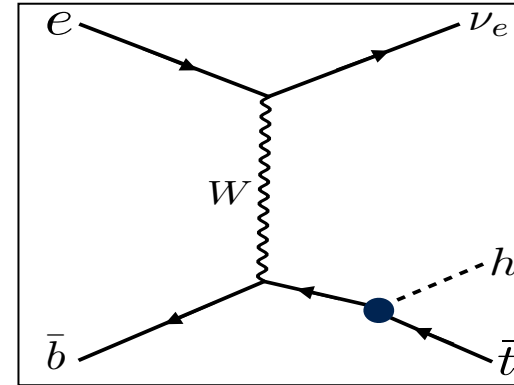
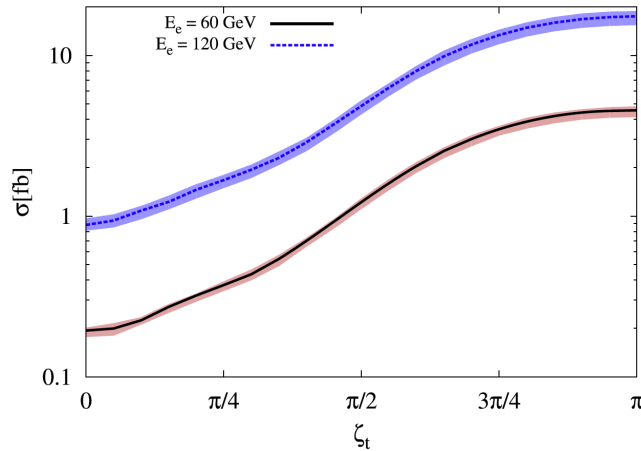
B.Coleppa, M.Kumar, S.Kumar, B.Mellado, PLB770 (2017) 335

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

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



**CP even
sign flip**

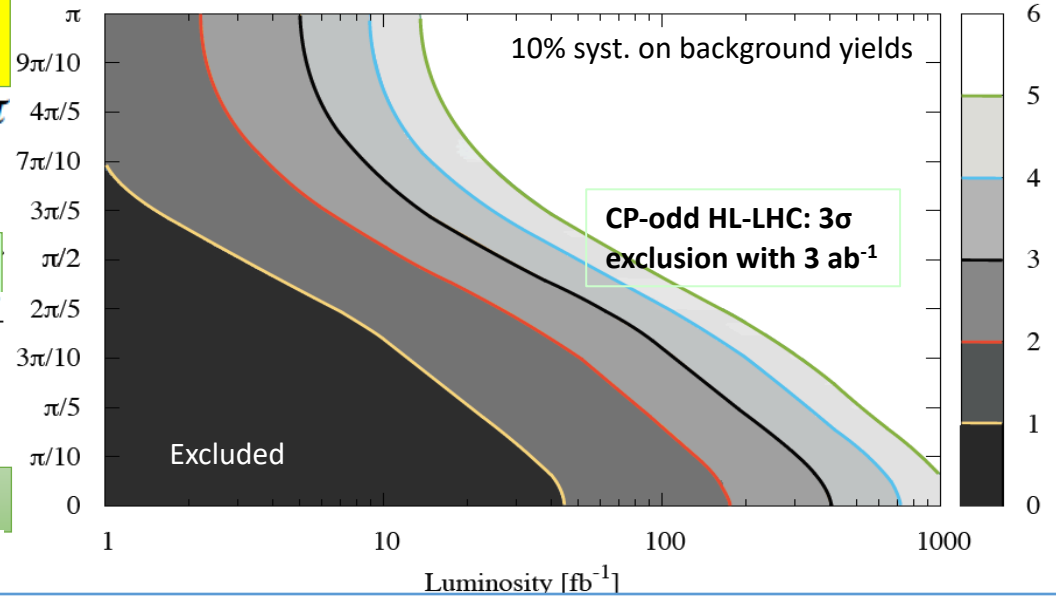
$$\zeta_{t,b} = \pi$$

CP odd

$$\zeta_{t,b} = \frac{\pi}{2}$$

CP even SM

$$\zeta_t = 0$$



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

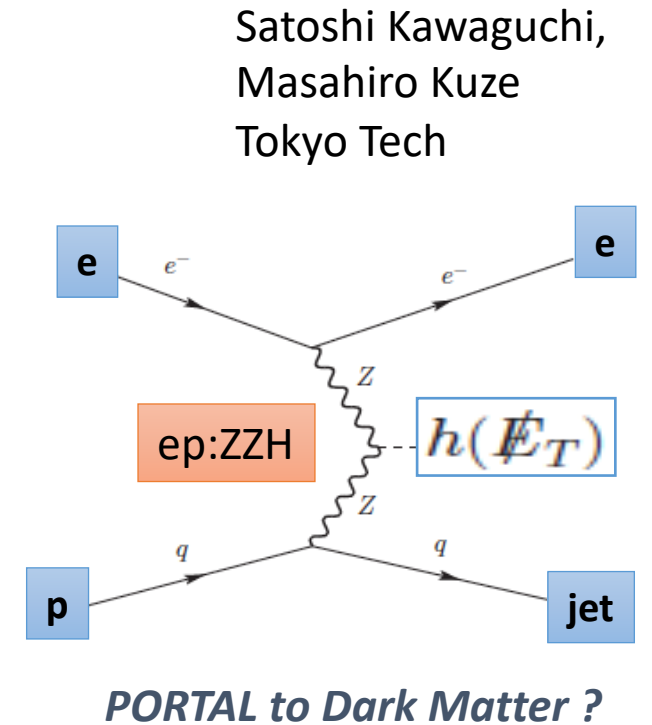
➔ With Zero Phase: Measure **ttH** coupling with **17% accuracy at LHeC** ➔ **extrapolation to FCC-eh: ttH to 1.7%**

Branching for invisible Higgs

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

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]



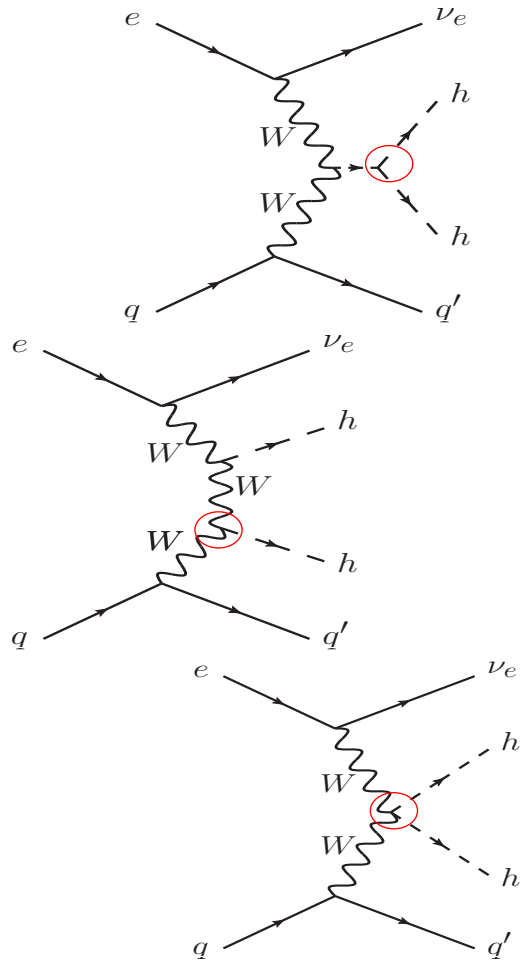
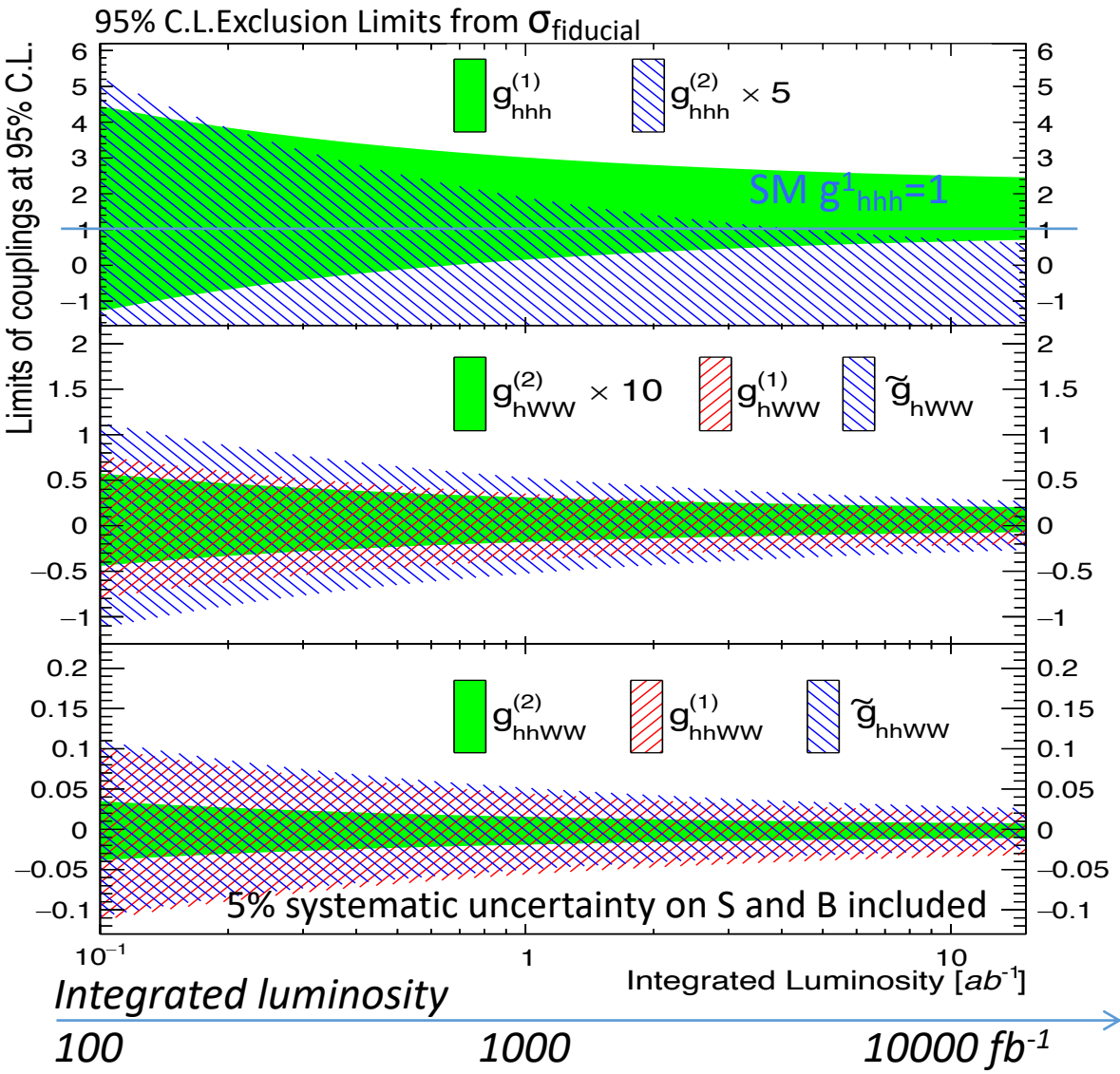
- ✓ Uses ZZH fusion process to estimate prospects of Higgs to invisible decay using *standard cut/BDT analysis techniques*
- ✓ Full MG5+Delphes analyses, done for 3 c.m.s. energies → very encouraging for a measurement of the **branching of Higgs to invisible in ep down to 5% [1.2%] for 1 [2] ab^{-1} for LHeC [FCC-eh]**
- ✓ A lot of checks done: We also checked LHeC \leftrightarrow 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 $\sim 25\%$

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

Double Higgs Production

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

FCC-eh $g_{HHH} \sim 20\%$ in ep



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

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

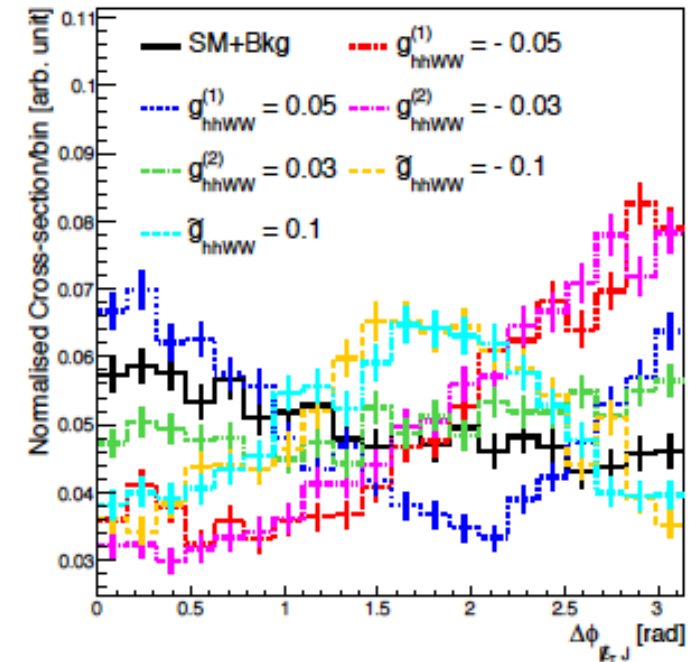
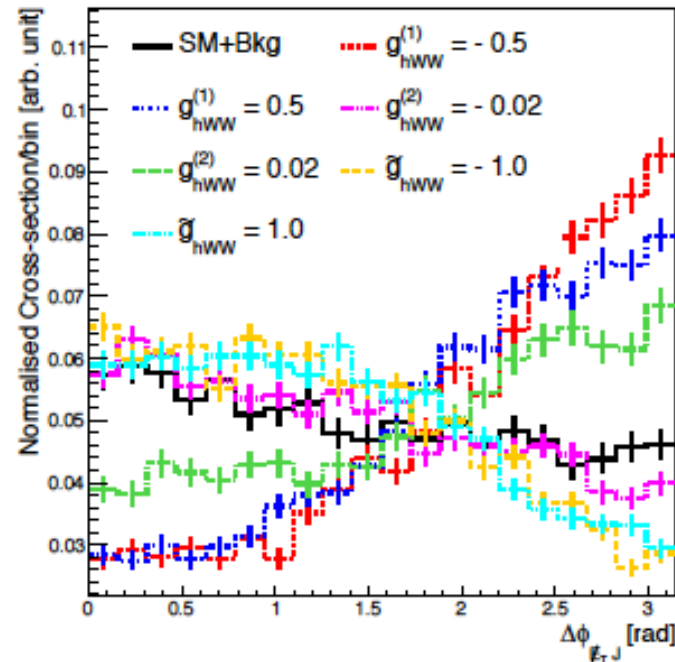
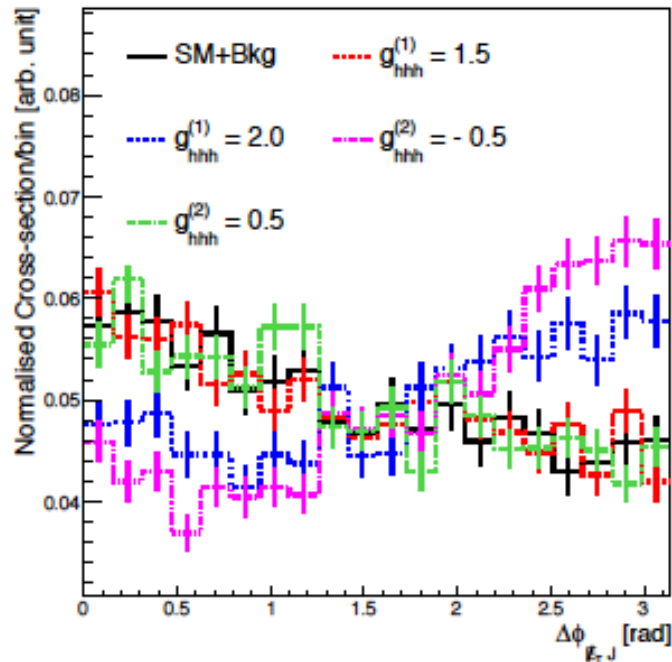
Probing anomalous couplings within Higgs EFT: limits are obtained by scanning one of the non-BSM coupling while keeping other couplings to their SM values.

Here $g_{(\dots)}^{(i)}$, $i = 1, 2$, 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.

HH@FCC-eh: Azimuthal Angle Distributions

- $\Delta\Phi_{\text{Emiss,jet}}$ 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.

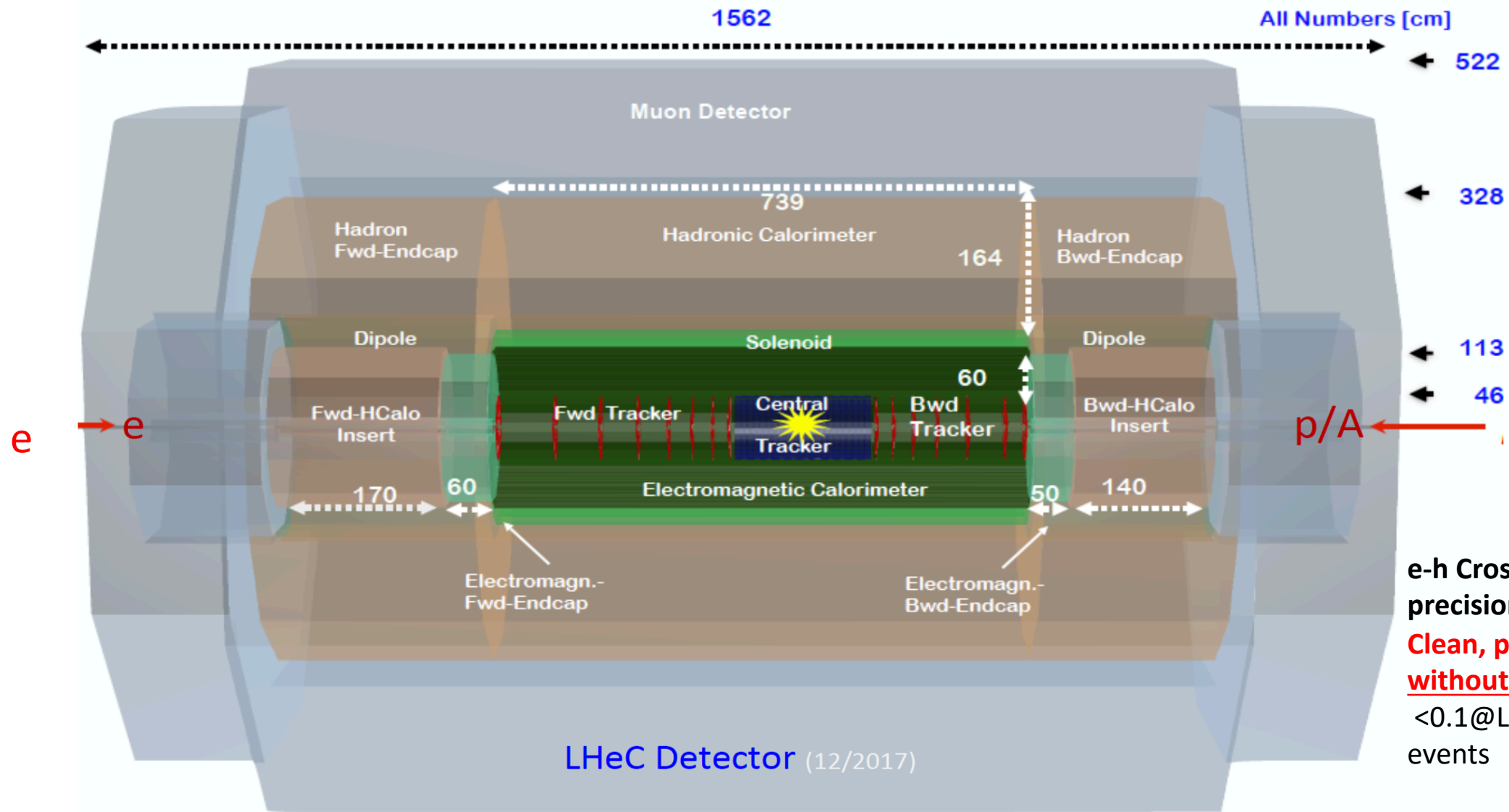


- normalised DIS cross sections are sensitive to non-BSM vertices
- initial study published for this novel $\Delta\Phi_{\text{Emiss,jet}}$ variable
- potential for a deeper analysis and interpretation

Detector for LHeC/HE-LHC/FCC-eh

[arXiv:1802.04317]

& P.Kostka et al



e-h Cross Calibration for precision $e p$

Clean, precise reconstruction without pile-up:

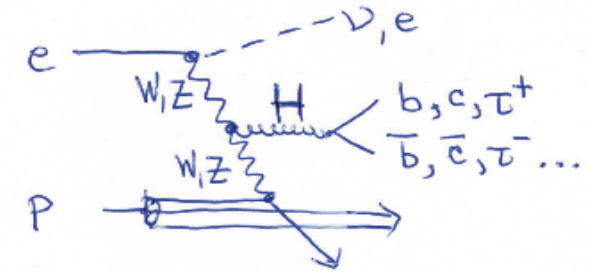
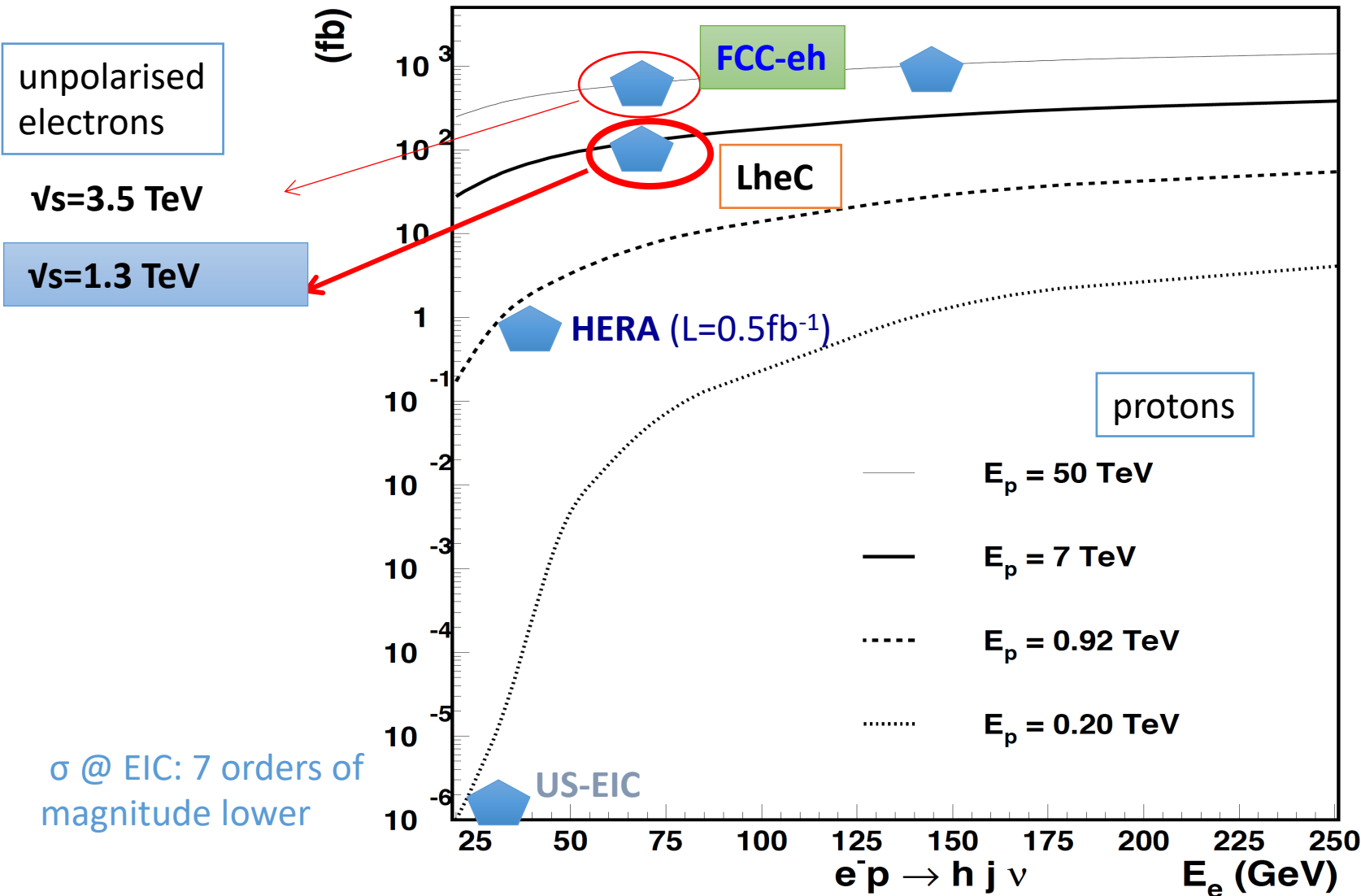
<0.1 @LHeC up to 1 @FCCeh events

Length x Diameter: LHeC ($13.3 \times 9 \text{ m}^2$) HE-LHC (15.6×10.4) FCCeh (19×12) m^2

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

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

SM Higgs in ep



Higgs in eA @FCC-ePb

σ_{Higgs} [fb]

eff. ' E_p '=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 $L=100\text{-}1000\text{ fb}^{-1}$

Further Estimates of Higgs Prospects

- Use LO Higgs cross sections σ_H for $M_H=125$ GeV, in [fb], and branching fractions $BR(H \rightarrow XX)$ from Higgs Cross Section Handbook
- Apply further branching, $BR(X \rightarrow FS)$ in case e.g. of $W \rightarrow 2$ 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 $H \rightarrow bb$ and $H \rightarrow cc$ & FCC-eh $H \rightarrow WW^*$ and exotic Higgs search results as baseline for S/B ranges; use fully simulated cut-based FCC-eh & LHeC $H \rightarrow bb$ 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]

$$N = \sigma_H \cdot BR(H \rightarrow XX) \cdot BR(X \rightarrow FS) \cdot L$$

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

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

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