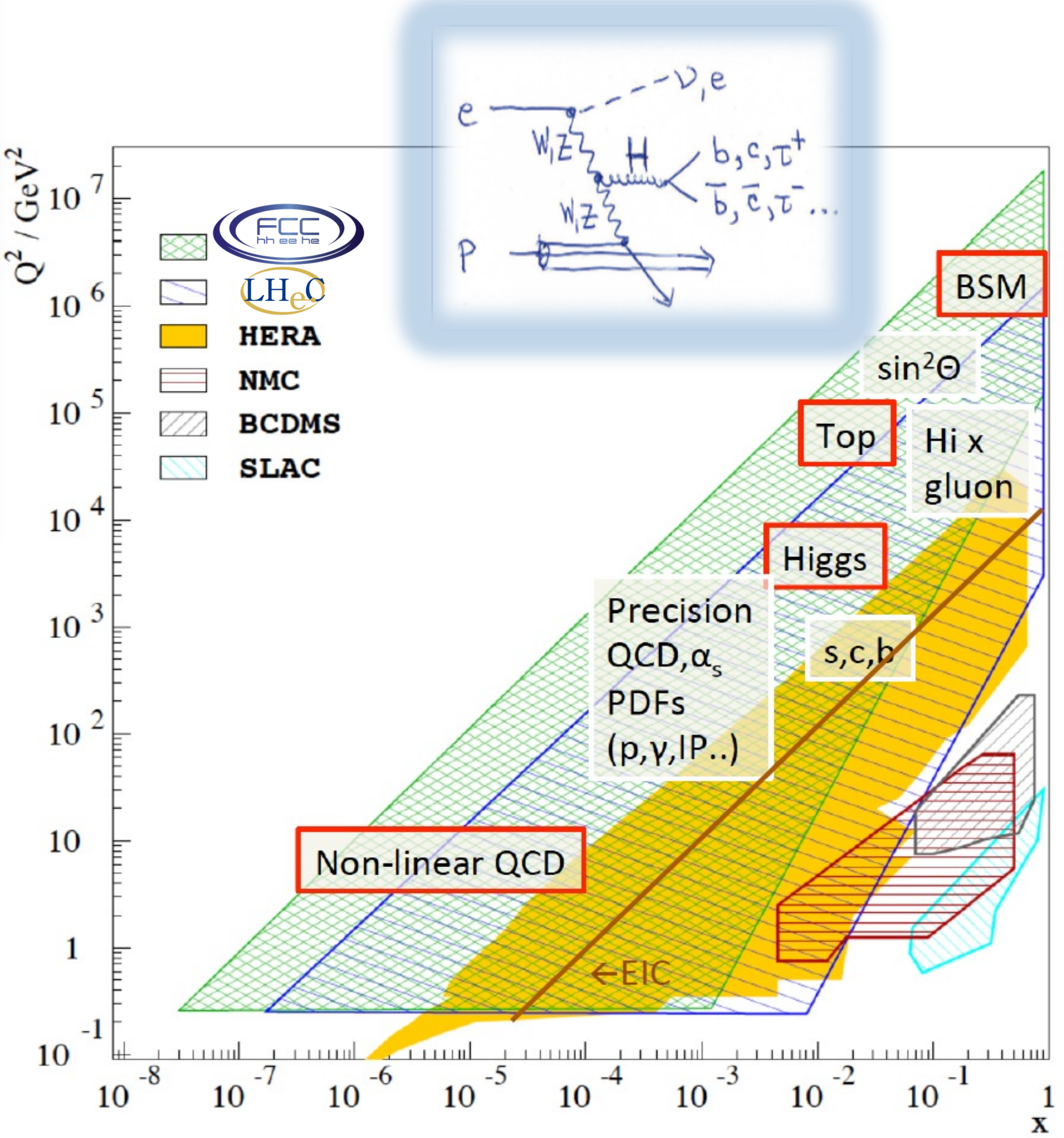
Higgs precision physics in electron–proton scattering at CERN

Uta Klein

UNIVERSITY OF LIVERPOOL

on behalf of

the LHeC & FCC-eh Study Group

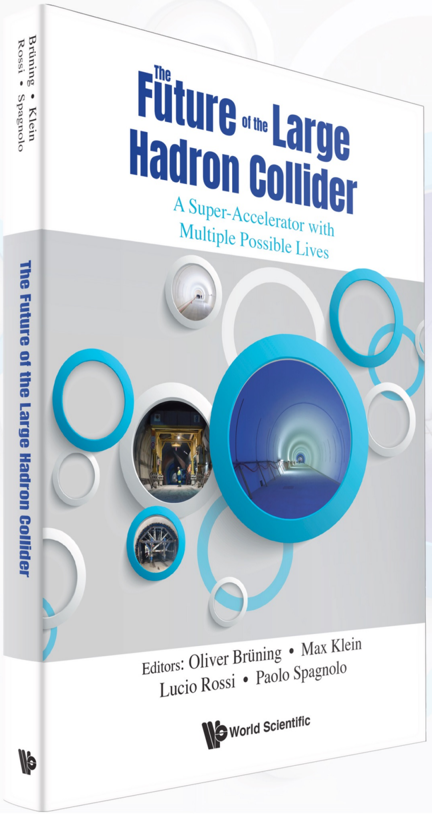


Prague, July 18th, 2024

ICHEP 2024

The Future of the Large Hadron Collider

A Super-Accelerator with Multiple Possible Lives



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Proton and nuclear structure from EIC and HERA to LHeC and FCC-eh

The general-purpose LHeC and FCC-eh high-energy precision programme: Top and EW measurements

High energy gamma-gamma interactions at the LHeC

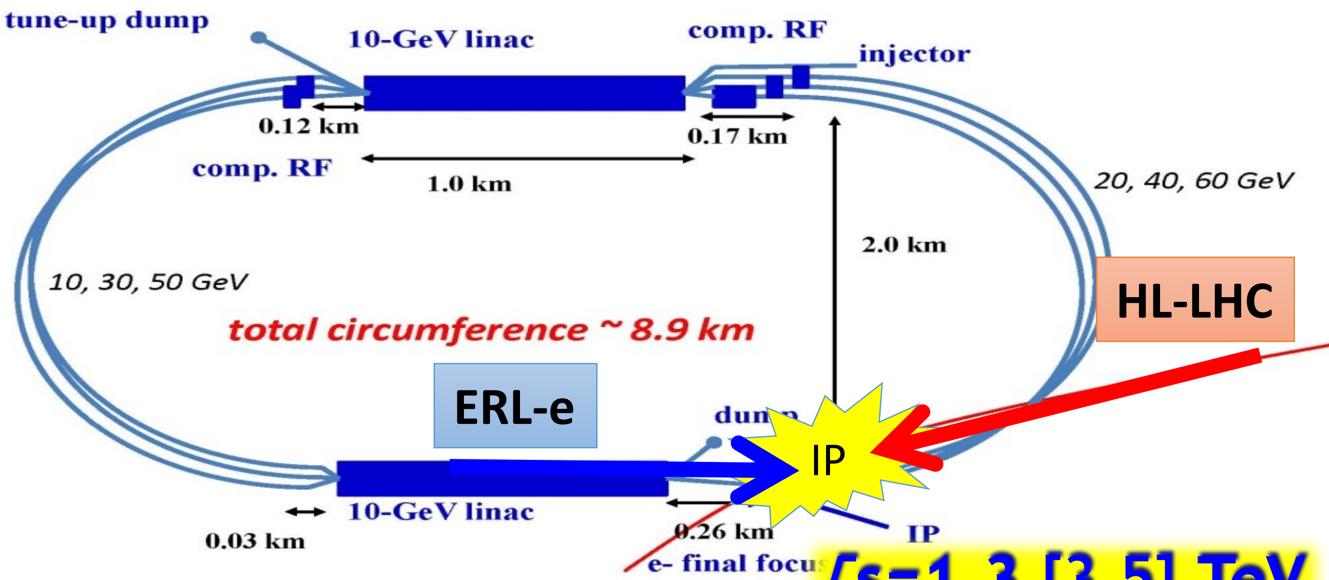
Higgs precision Higgs physics in electron–proton scattering at CERN

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

- 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!

Concurrent eh and hh operation with same running time!

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



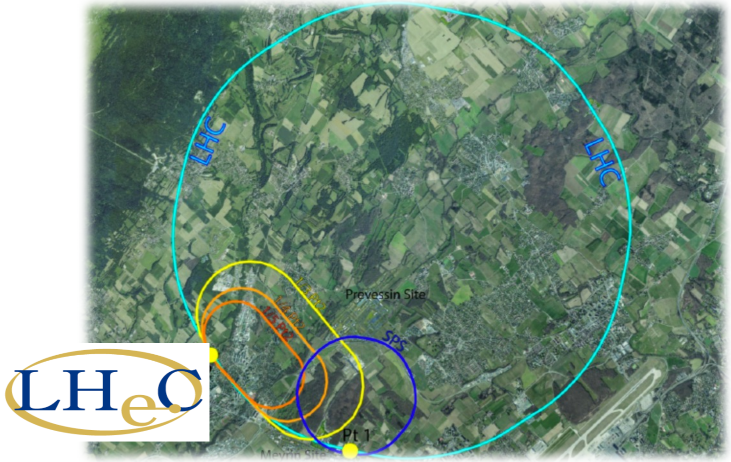
$\sqrt{s}$=1.3 [3.5] TeV

E_e = 60 GeV

E_p = 7 [50] TeV

- **LHeC** [FCC-eh] **L= 1000** [2000] **fb^{-1} in 10** [20] **years**
- **'No' pile-up**: <0.1@LHeC; ~1@FCCeh

CDR update J. Phys. G 48 (2021) 11, 110501 [arXiv:2007.14491]; see talk by J D' Hondt



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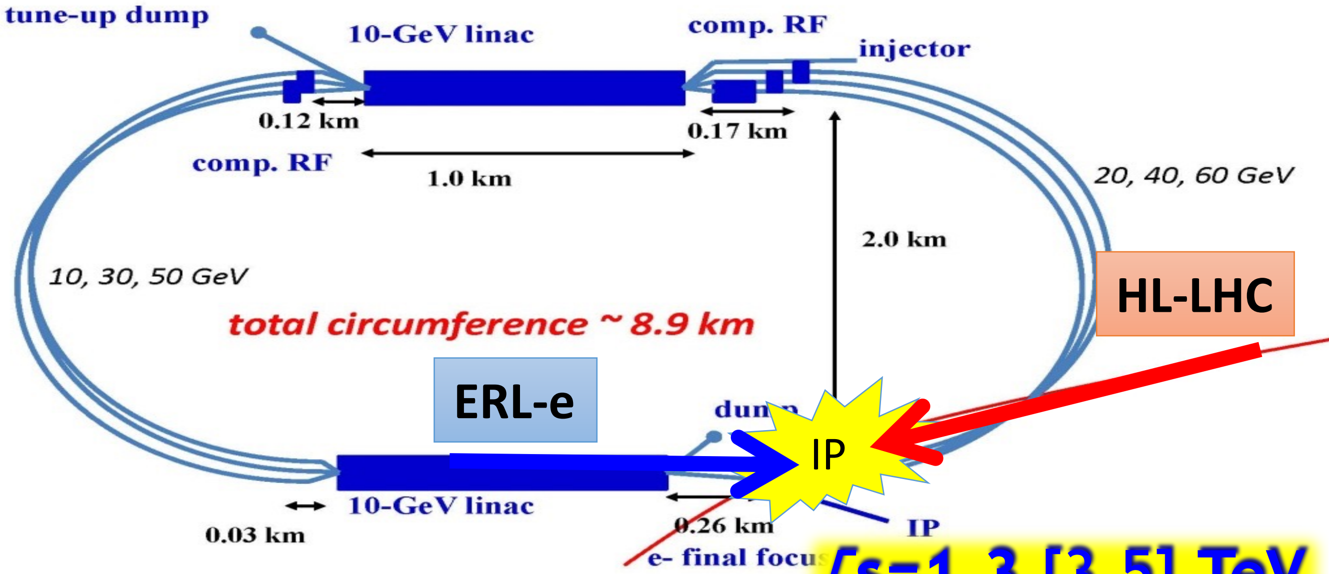

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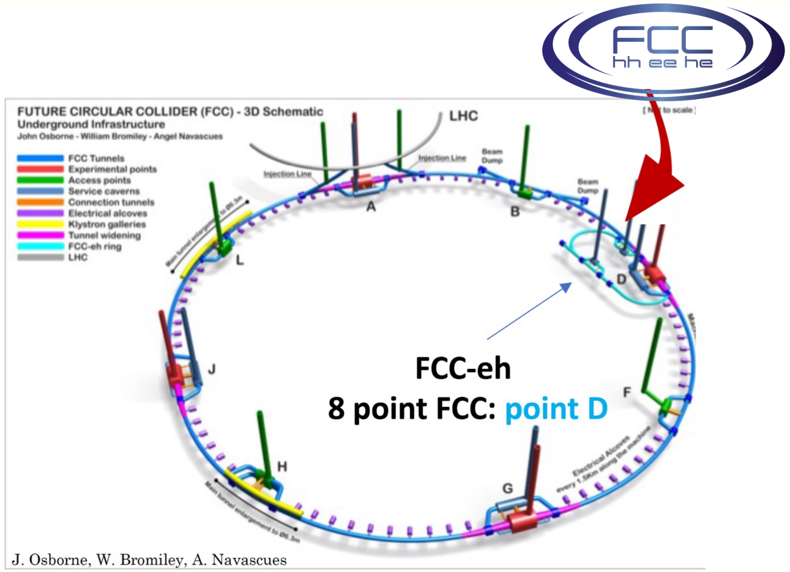

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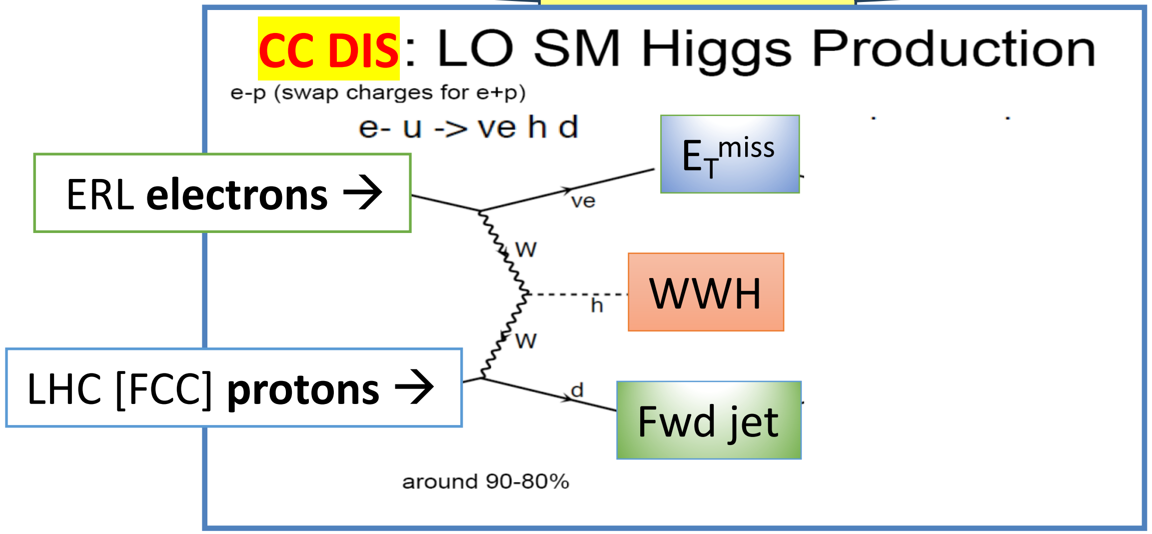
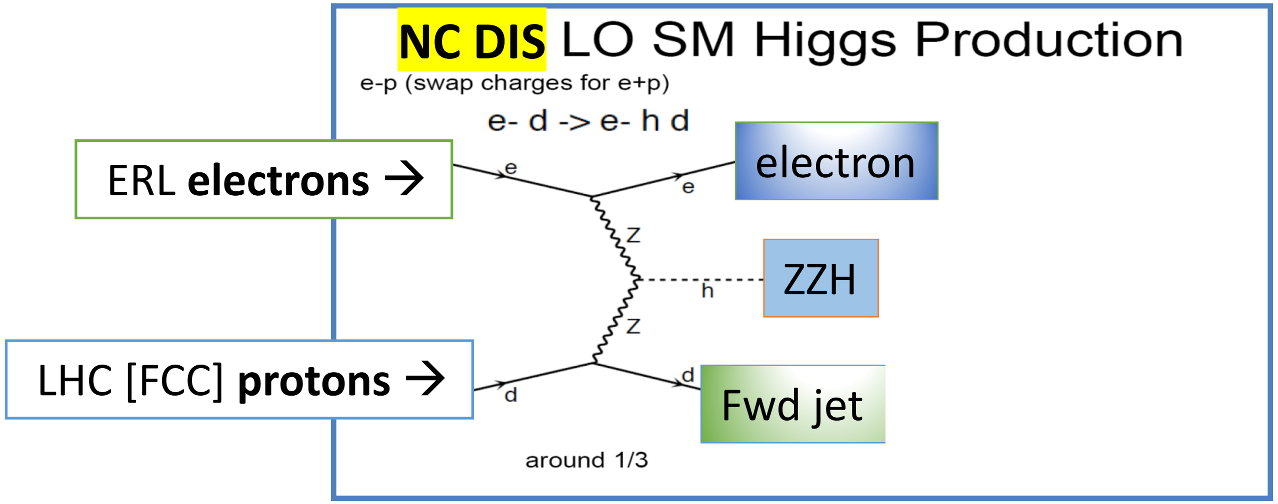
SM Higgs Production in DIS ep

- dominant -





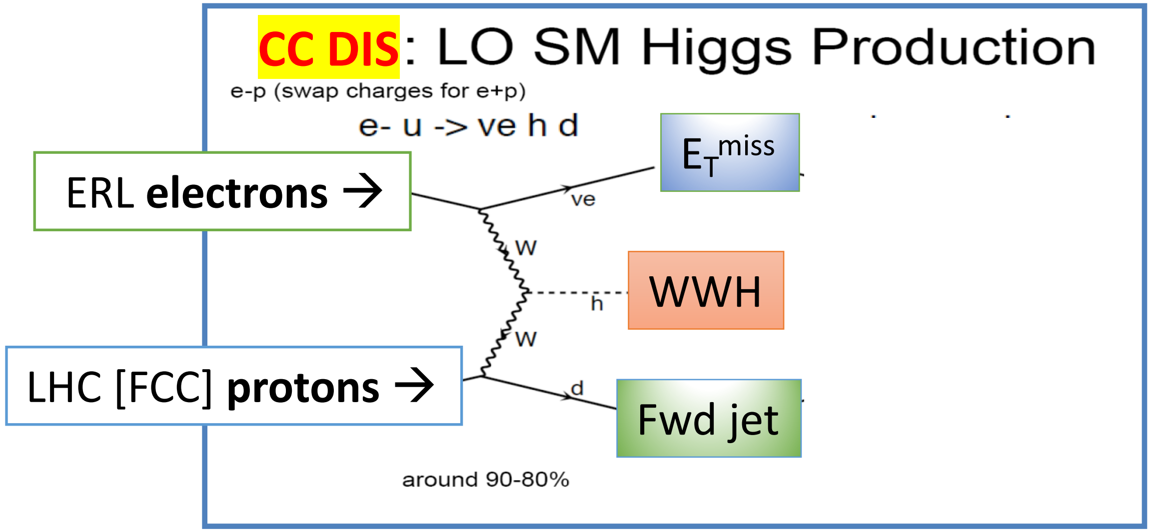
➔ In ep, direction of quark (Fwd jet) is well defined.

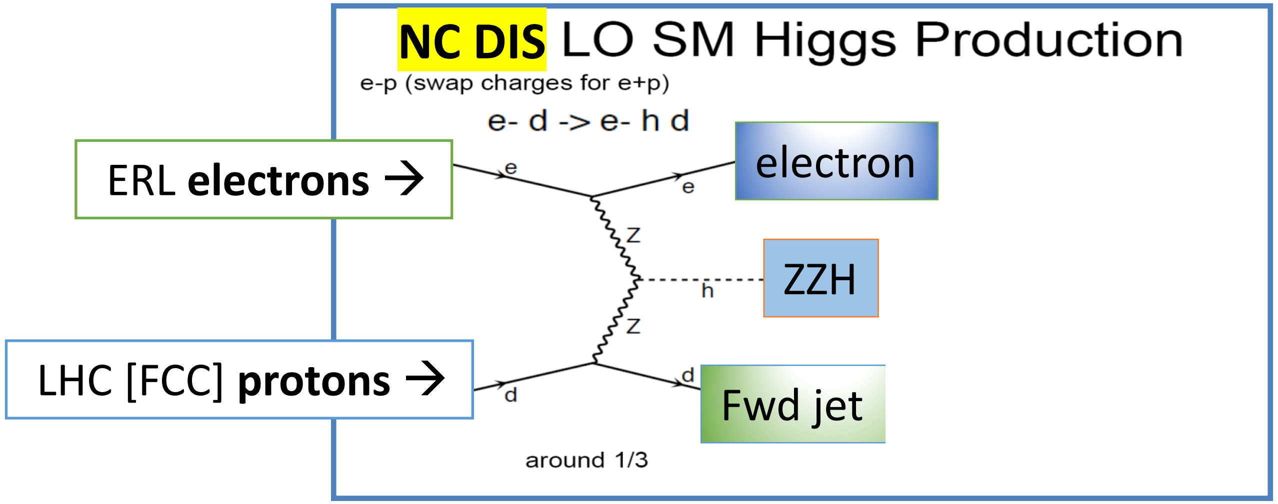
Total cross sections
(LO QCD CTEQ6L1 M_H=125 GeV)

c.m.s. energy	1.3 TeV LHeC	3.5 TeV FCC-eh
P_e=-80% CC DIS : HWW NC DIS : HZZ	 197 fb 24 fb	 1004 fb* 150 fb*

** larger than HWW&HZZ xsecs at ee@3.5TeV, see backup

SM Higgs Production in DIS ep





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- ***Scale*** dependencies of the LO calculations are about 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]

Theory well under control in ep!
LHeC will deliver N³LO PDFs,
δm_c to 3 MeV, δm_b to 10 MeV and
$\delta \alpha_s$ to ~0.1-0.2%

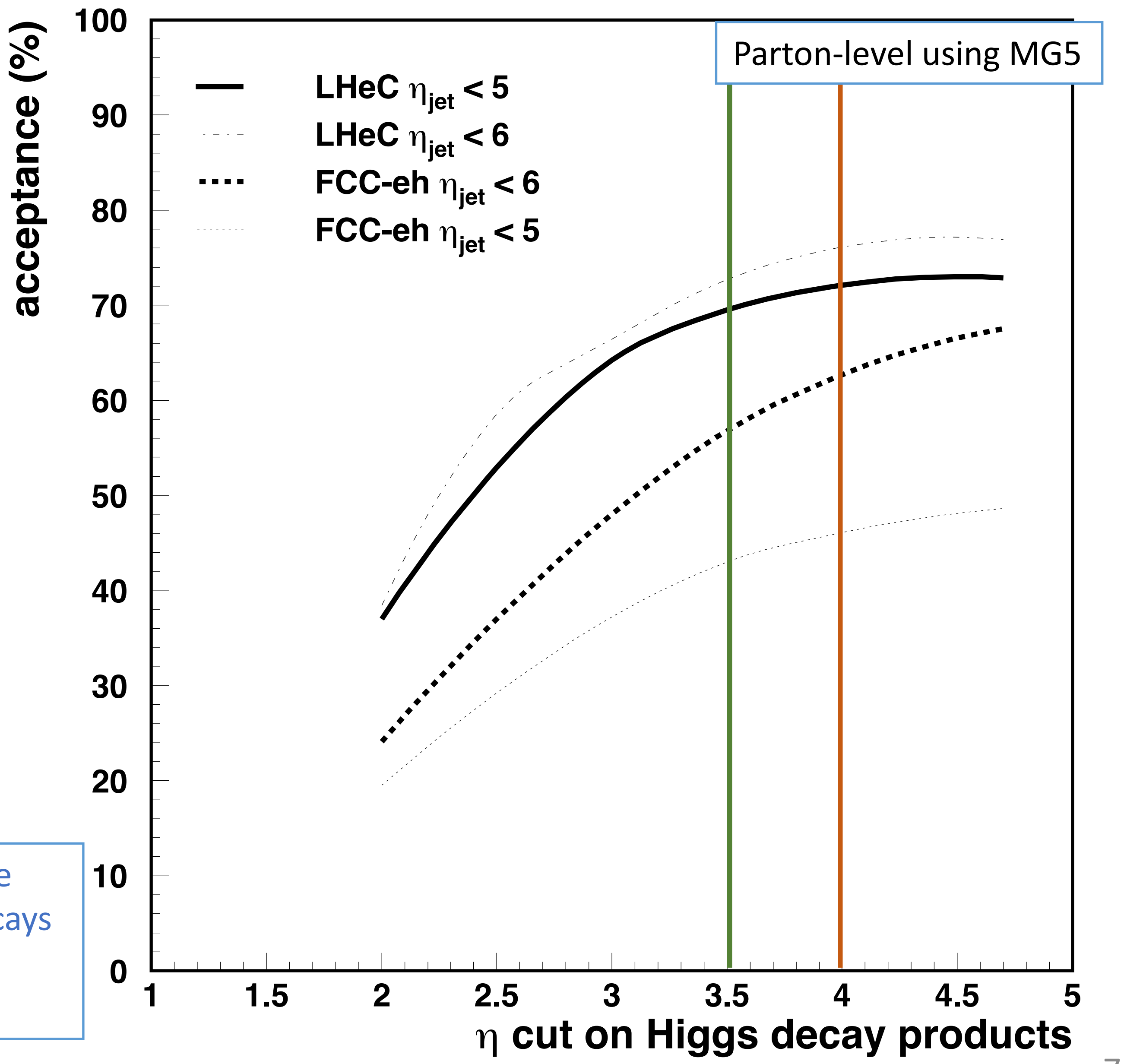
[arXiv:2007.14491]

Rates and Geometric acceptances

P_e=-80%

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

		Number of Events			
		Charged Current		Neutral Current	
Channel	Fraction	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
σ [pb]		0.197	1.04	0.024	0.15



- ➔ Tracking acceptance up to **η**=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 **η**=4 opens prospect to measure H➔ **μμ** signal strength to ~6% at FCC-eh

Higgs in eh: *cut* based results

Masahiro Tanaka, Masahiro Kuze, Tokyo Tech 2017/2018
See also M Schott@Off-shell 2021, Hbb in ep using ATLAS software

Unpolarised (P_e=0) samples for 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

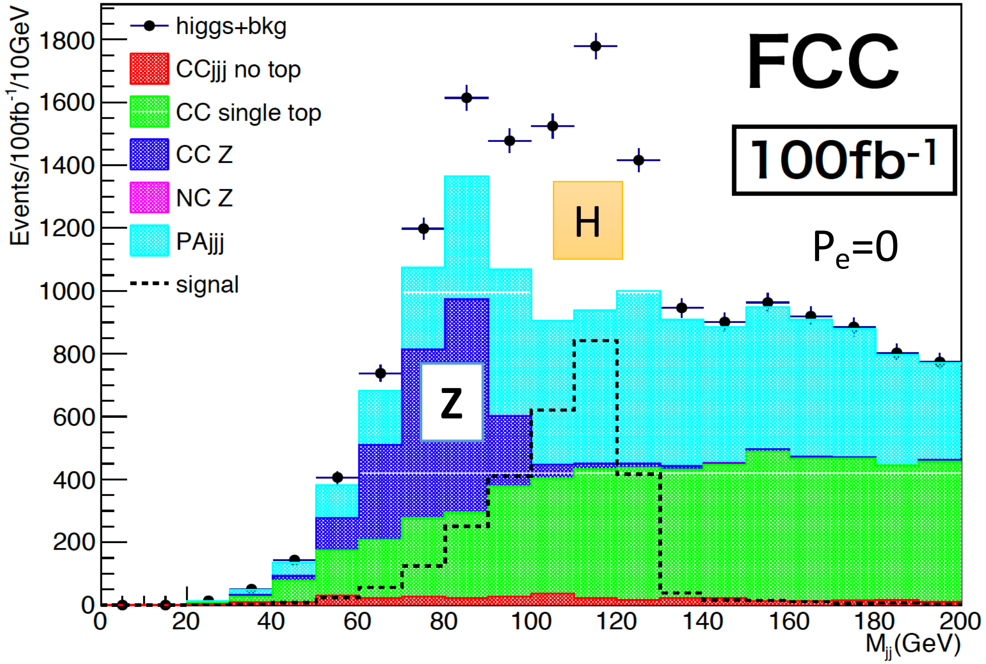
MadGraph and
Delphes ep-style detector
+ flat parton-level b-tagging
for |η|<3.0
conservative HFL tagging:
b: 60%, c: 10%, **udsg: 1%**
CAL coverage |η|<5 LHeC [<6 FCC-eh]

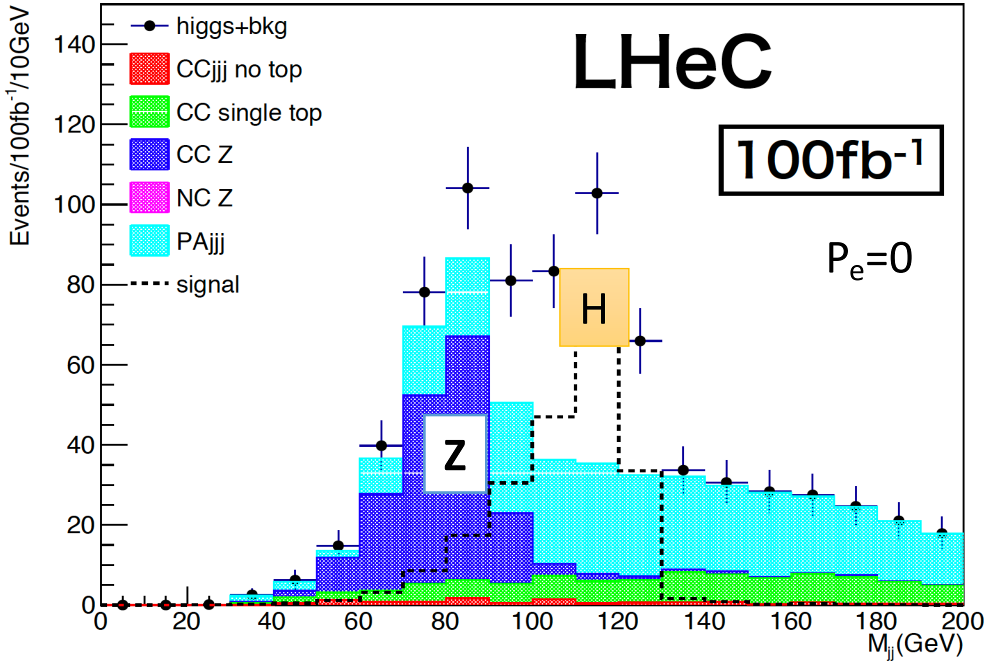
H→bb: S/N>1
using *simple* cuts
and *conservative*
HFL tagging

✓ **confirmed in multiple post CDR studies**

Plots are for 100 fb^{-1}
~ 1 year of data w/o electron polarisation

Mass of 2 b-jets after event selection



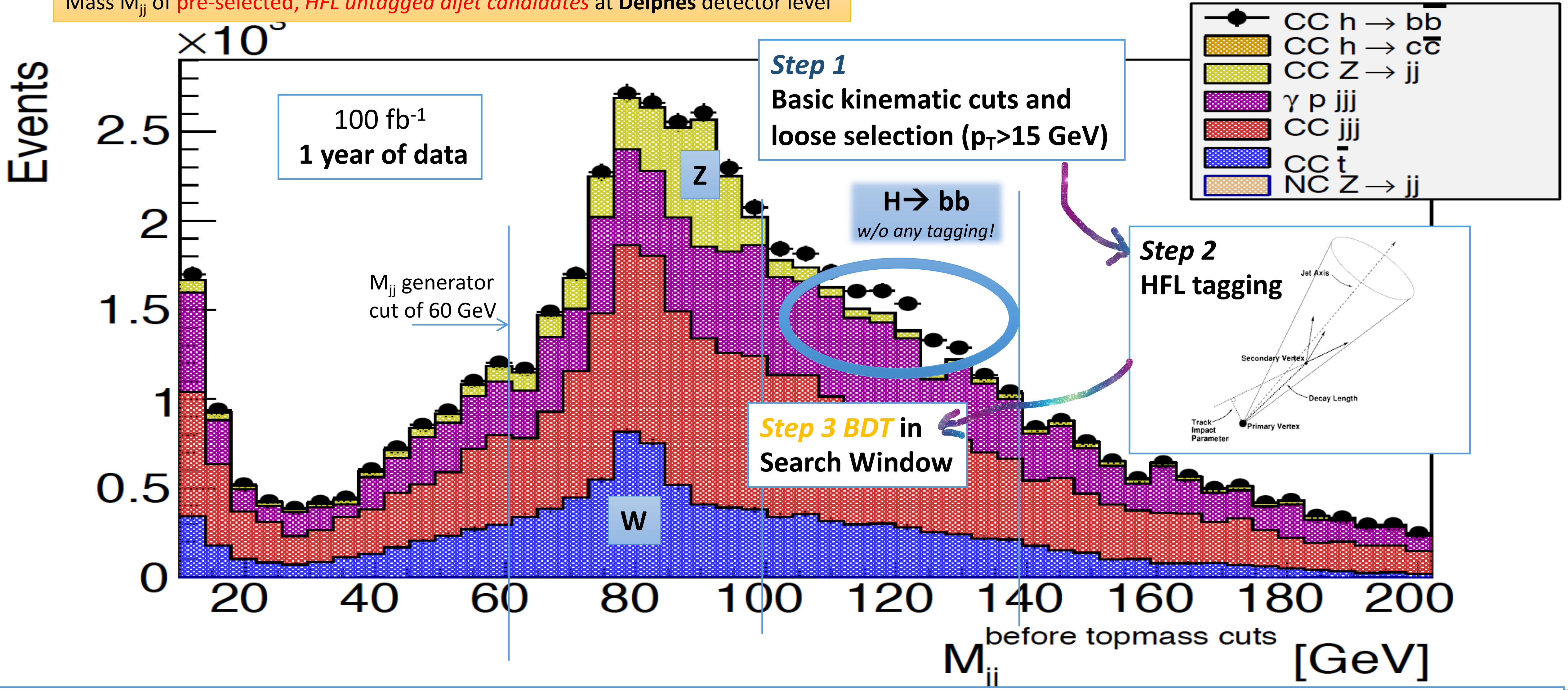


Note: plenty of single Z, W and top in ep

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

Hunting for Precision Hbb : *BDT* based

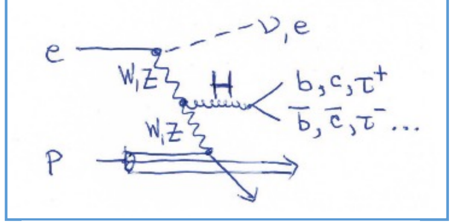
Mass M_{jj} of pre-selected, *HFL untagged dijet candidates* at **Delphes** detector level



'Worst' case scenario plot : Photoproduction multijet background ('**γ**p jjj' in purple) is assumed to be 100%!
It has been modelled using the Weizsäcker-Williams approximation and alternatively with PYTHIA.

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

Higgs in ep – clean S/B, no pile-up

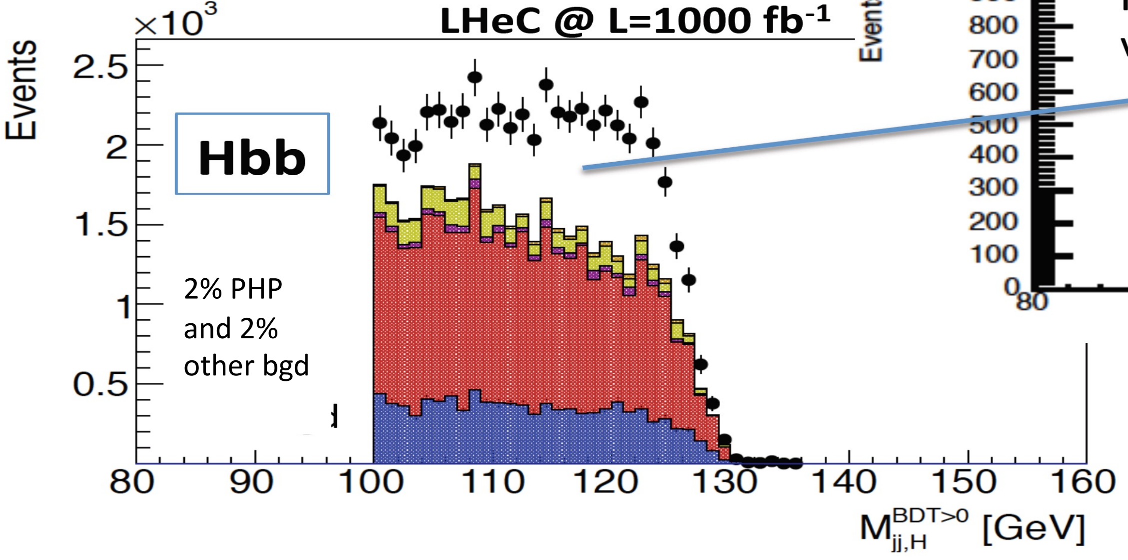


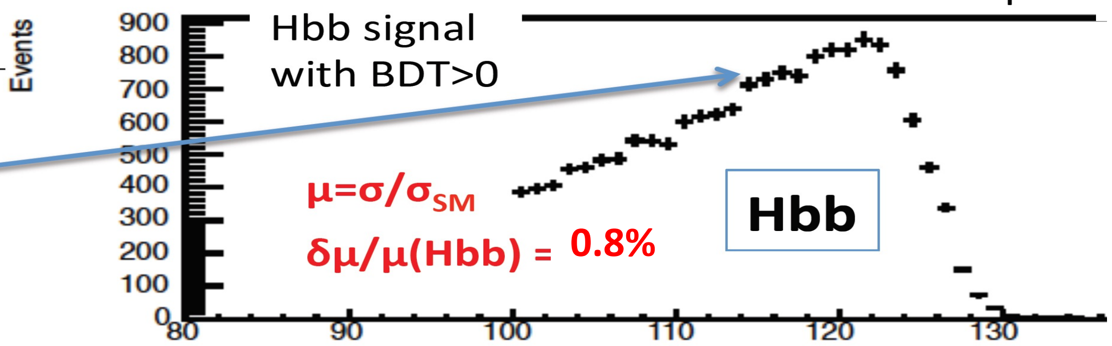
Neural networks/BDT is crucial for precision

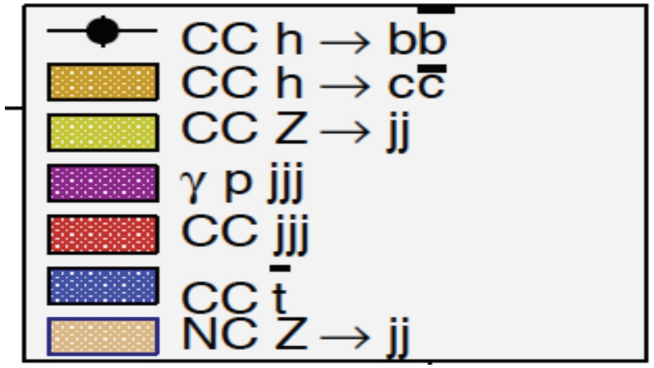
realistic HFL tagging & BDT

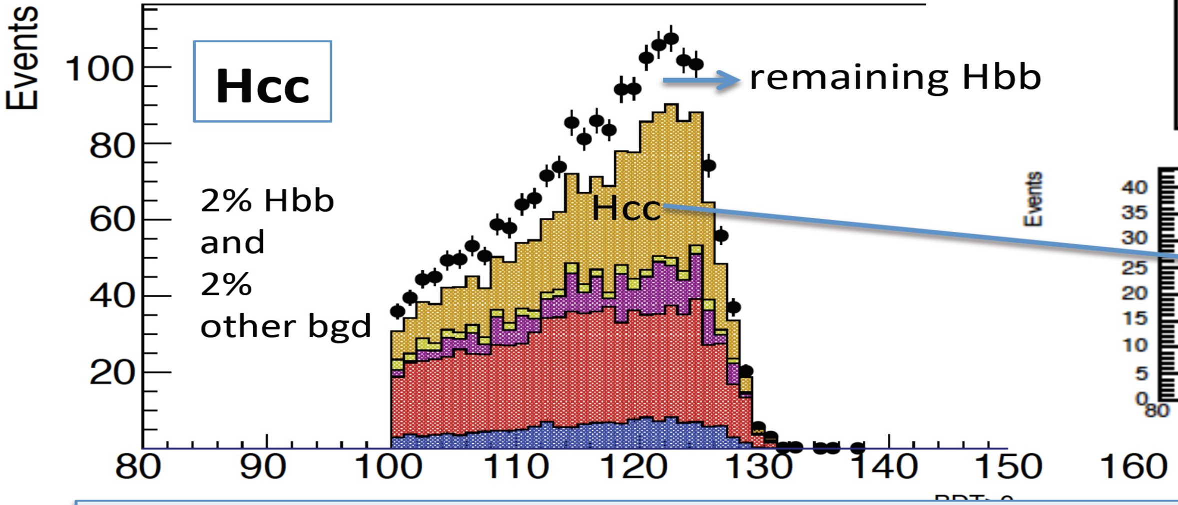
Uta Klein & Daniel Hampson & Izzy Harris BSc 2017

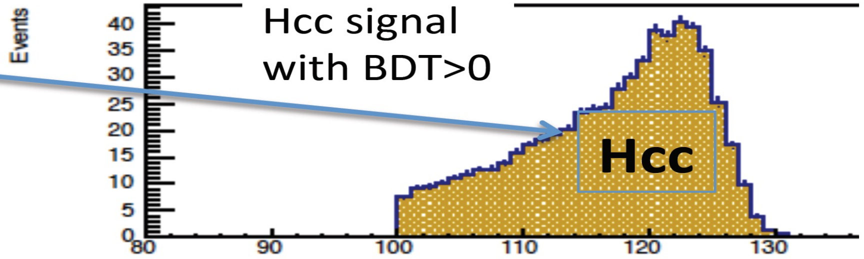
[arXiv:2007.14491]











δμ/μ(Hcc) = 7.4 %

Assuming background in control regions understood to 2% and negligible MC statistics for background in signal region; SM Higgs bb contribution in cc can be further controlled by genuine Hbb measurement and b and c-jet correlation,

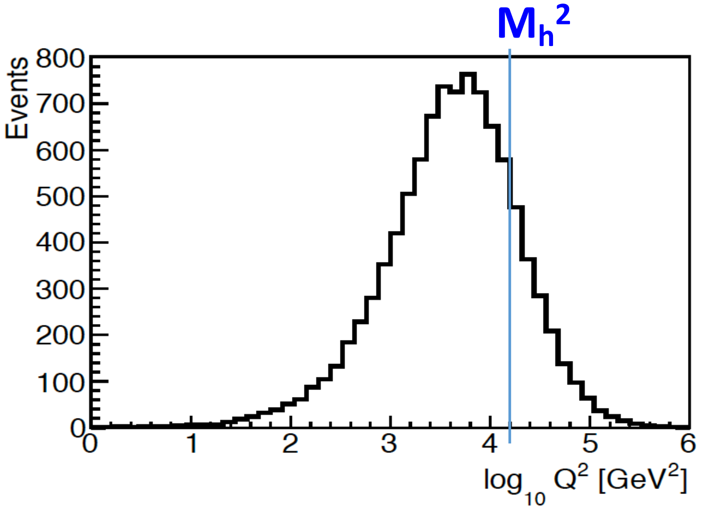
see, e.g., methodology ILC Hcc study arXiv: 0909.1052

[ILC Zqq-Hcc study got 8.8% for Hcc signal strength for M_H=120 GeV σ_{pol}(Hcc)=6.9 fb with similar Hcc, Hbb event numbers but factor 6.8 higher SM background than LHeC]

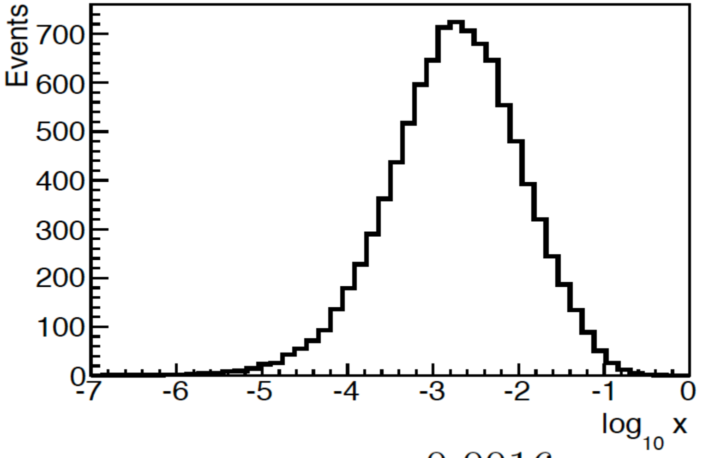
➔ **Main systematic checks: variations of background contribution and tagging efficiencies**

Kinematic Distributions at FCC-eh

Most ***asymmetric*** **ep** configuration



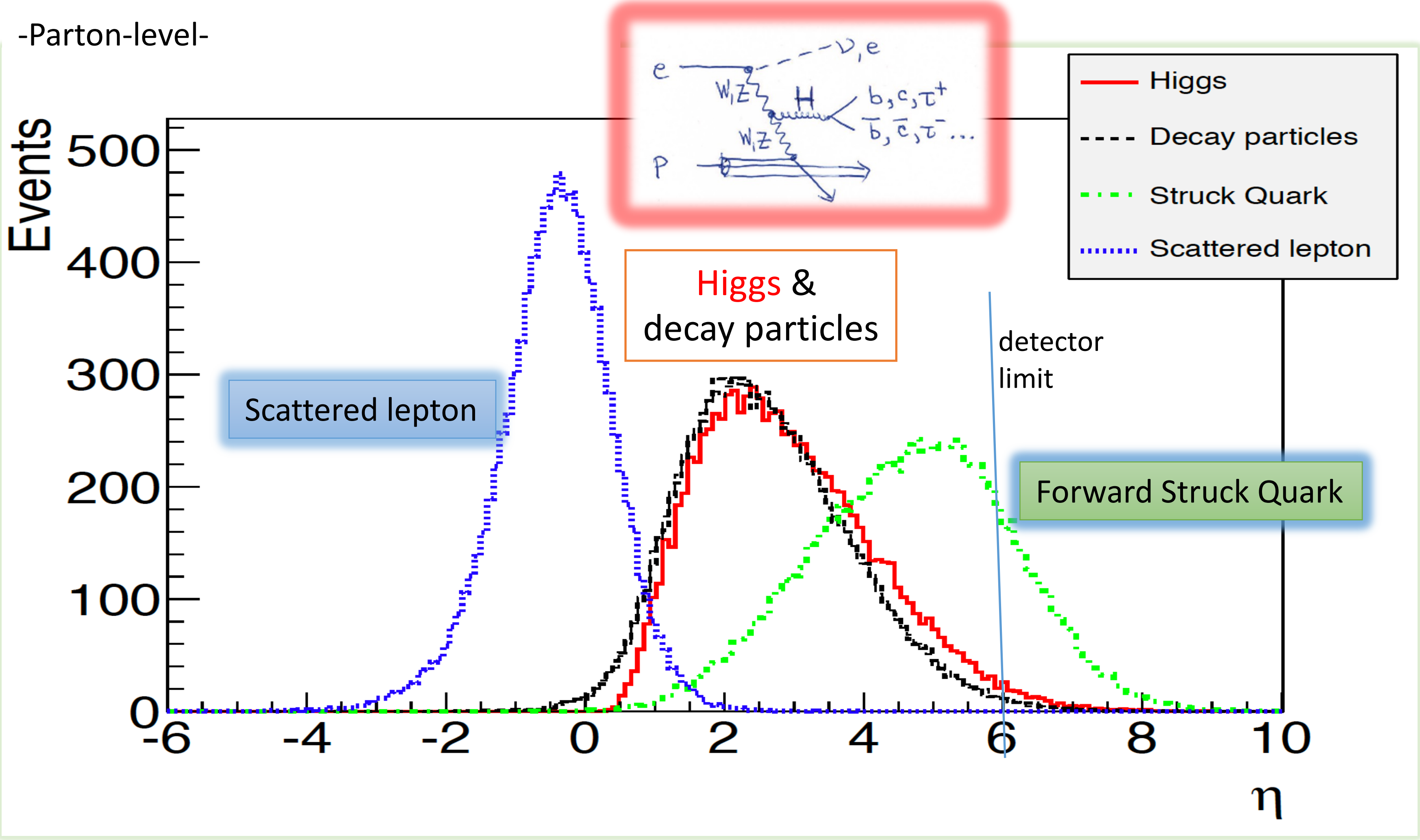
$Q^2 \approx 6500\,\mathrm{GeV}^2$



$x \approx 0.0016$

MadGraph scale: p_T of leading jet

-Parton-level-

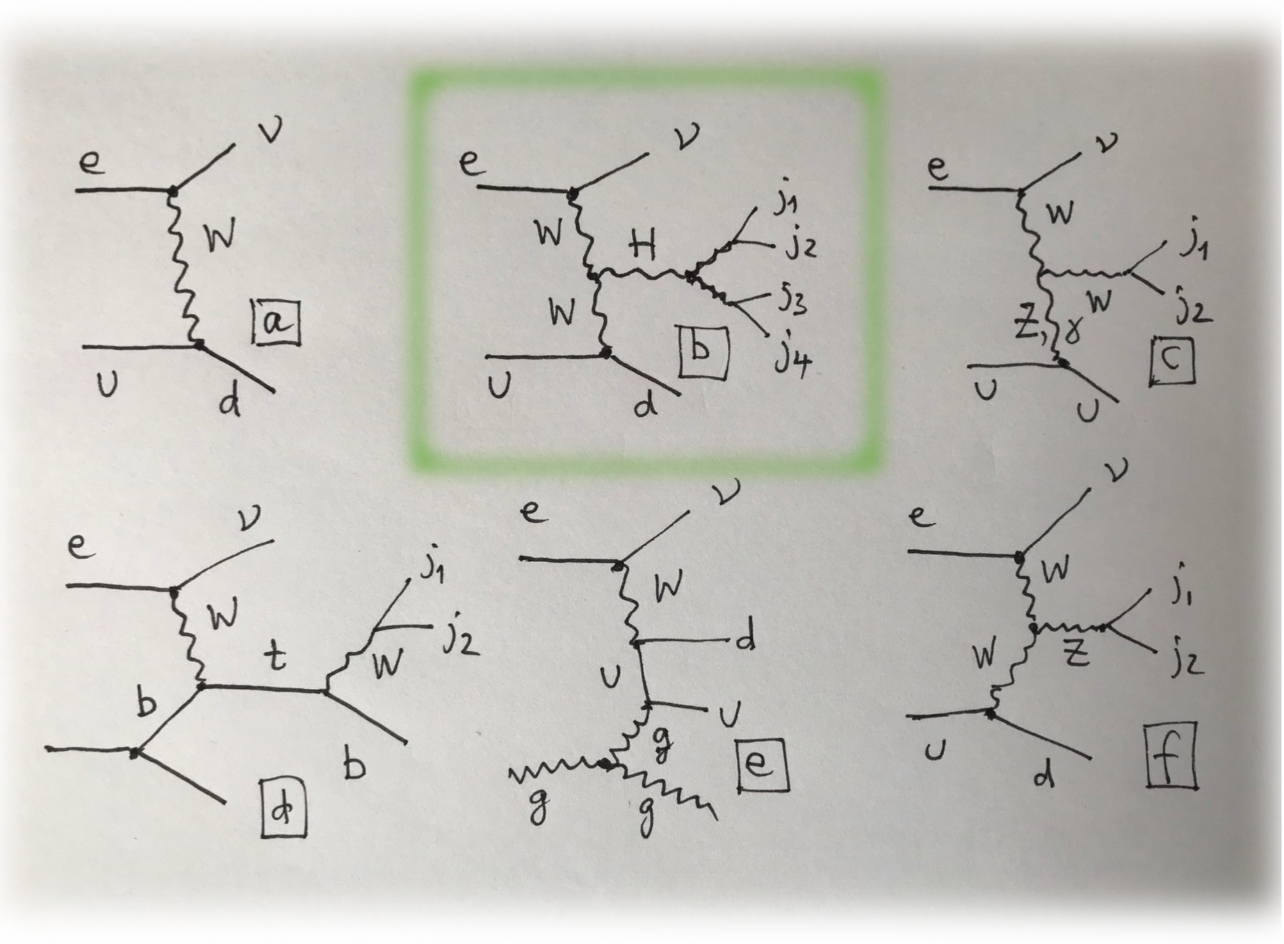


Higgs decay particles (here to W*W), struck quark and scattered lepton are well separated in detector acceptance.

WW to Higgs to W*W to 4 jets

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

→ g_{HWW} with $\delta g_{HWW} = ¼\ \delta\mu/\mu$ (H→W*W)



Study for **FCC-eh** at 3.5 TeV: [arXiv:2007.14491]

Signal and Background generated by MG5+PYTHIA using BR(H→WW)=21.5% and 67% for W→jj decay:

σ=100 fb ~45% of **σ**(HWW)

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

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

→ optimal choice R=0.7

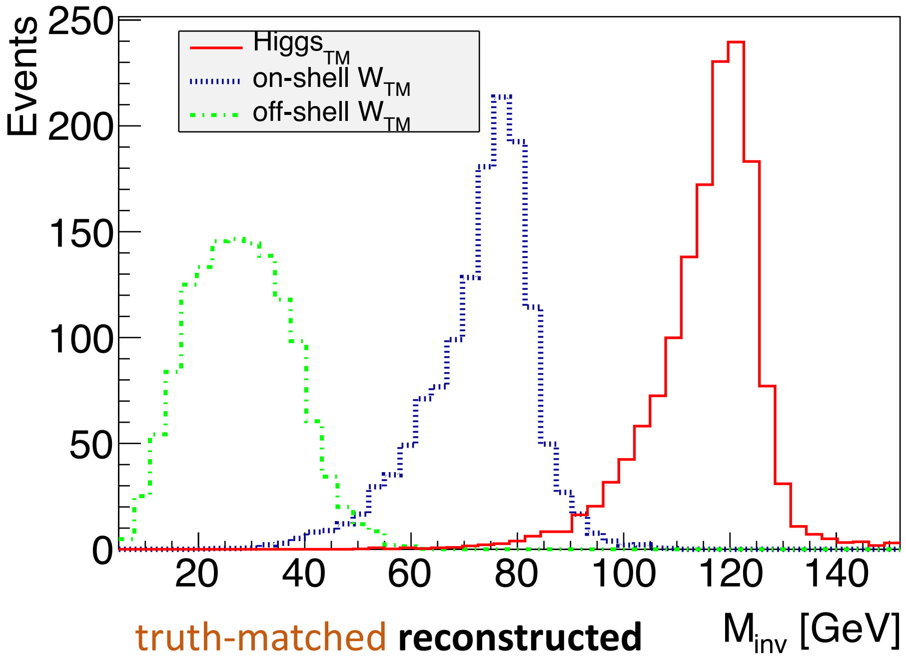
Note: more event categories and decay modes could be added *a la* LHC-style studies

[arXiv:2007.14491]

H→ WW* analysis strategy & results

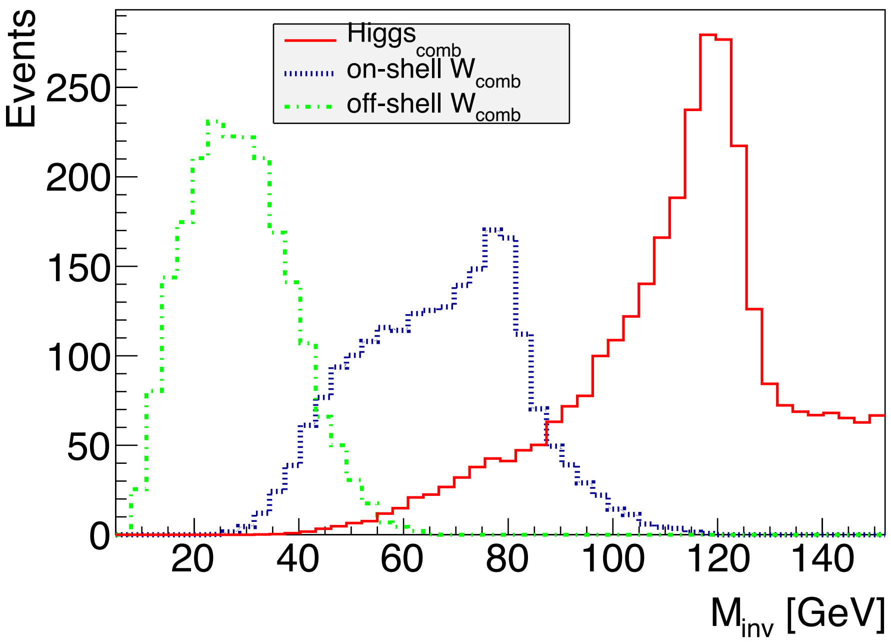
Very precise results expected from this channel only : **δg_{HWW} ≃ 0.5% to 0.6%**

NO mass requirements in combinatorics!



truth-matched **reconstructed**
W*, W and Higgs candidates

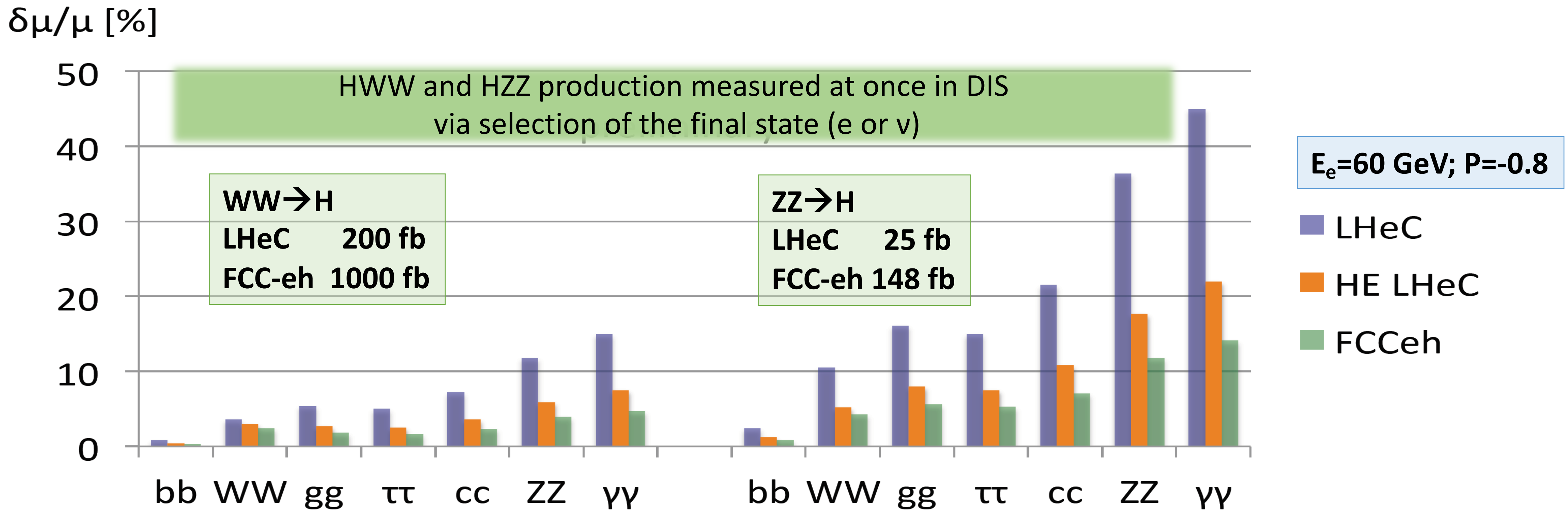
At Delphes detector level



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 **$\Delta\eta$**; max **$\Delta\eta$** between Higgs candidate and fwd jet; max **$\Delta\phi$** between Higgs candidate and E_T^{miss} or Higgs candidate and fwd jet ➔ then *passed to BDT for S/N optimisation*

- ✓ Acceptance ✕ efficiency of 20% ;
- ✓ 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.

SM Higgs *Signal Strength uncertainties* $\delta\mu/\mu$ in ep



Charged Currents: ep → νHX Neutral Currents: ep → eHX

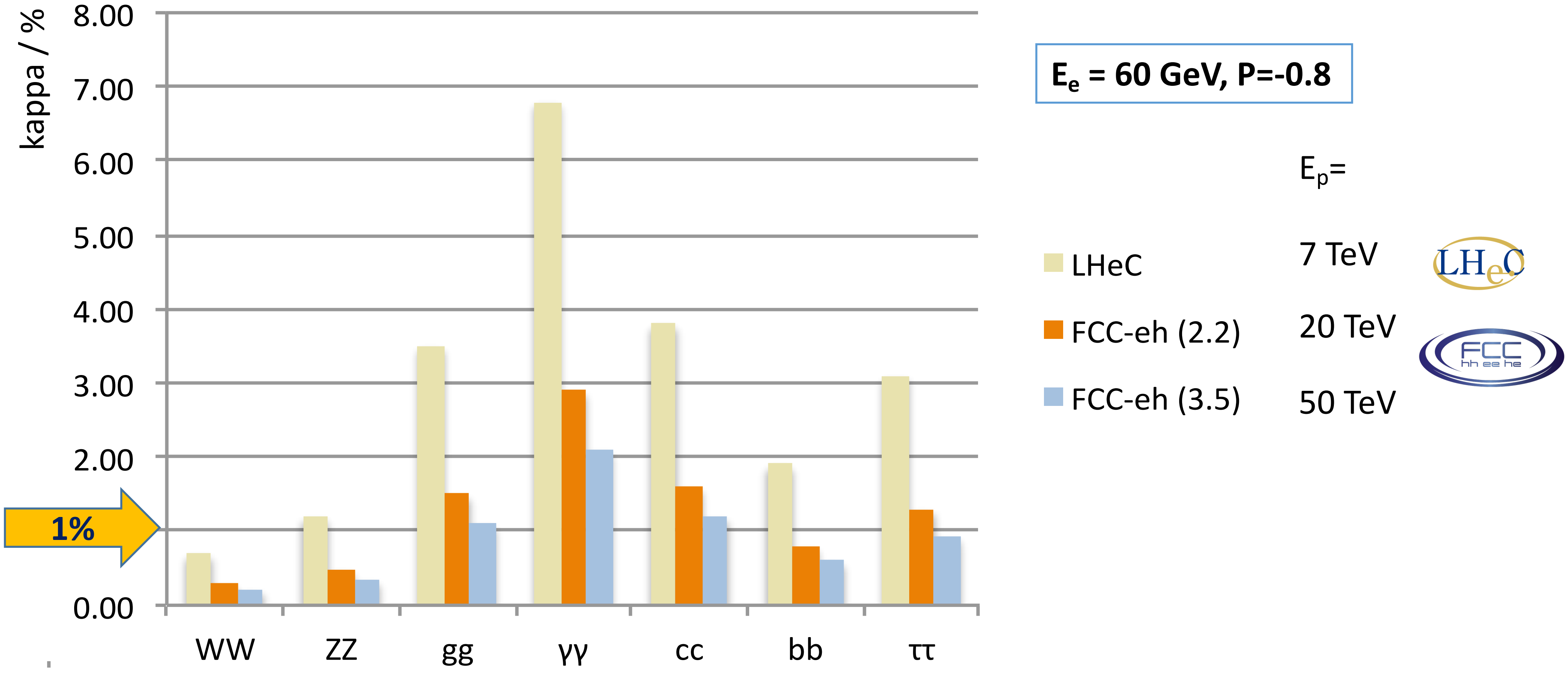
NC and CC DIS together over-constrain Higgs couplings in a combined SM fit.

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}

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]

Note: Higgs in ePb for FCC-eh



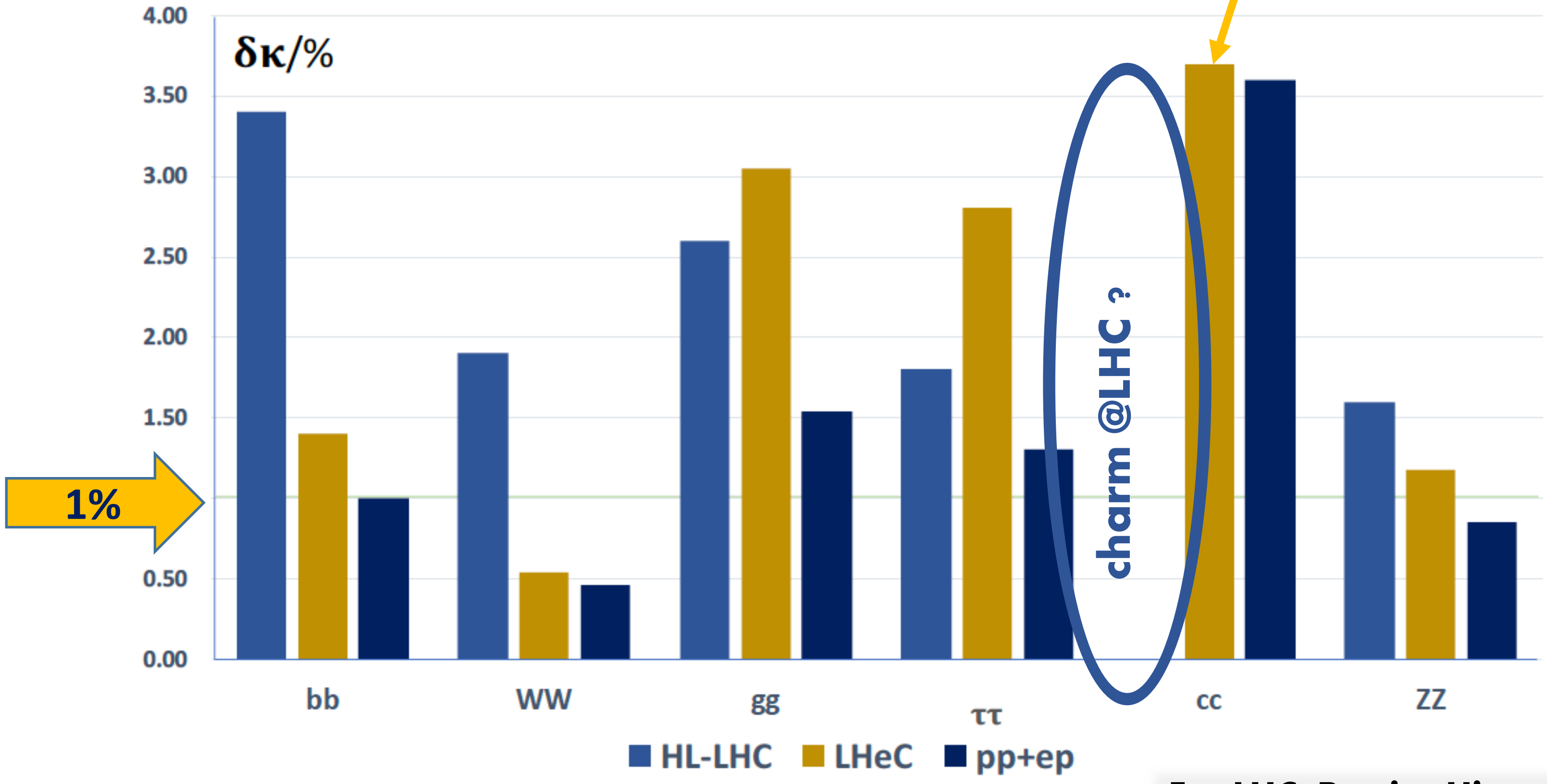
Very high precision due to CC+NC DIS in clean environment in luminous, energy frontier ep scattering

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

LHeC ES submission CERN-ACC-2018-0084 & CDR update [arXiv:2007.14491]

LHeC and HL-LHC prospects

LHeC adds charm



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

For LHC: Precise Higgs in pp cross section prediction with LHeC input:

$\delta\sigma(pp \rightarrow Higgs) = [0.3\ (pdf) + 0.2\ (\alpha_s)]\%$

* see also backup slides & more on PDFs in F Giuli talk

CERN-ACC-2018-0056

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
$\delta\Gamma_H/\Gamma_H$ (%)	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!
➔ *Only* FCC-hh will be the machine to pin down HH and all rare decays!

Higgs-inv.: 1.2%
HH ~20%

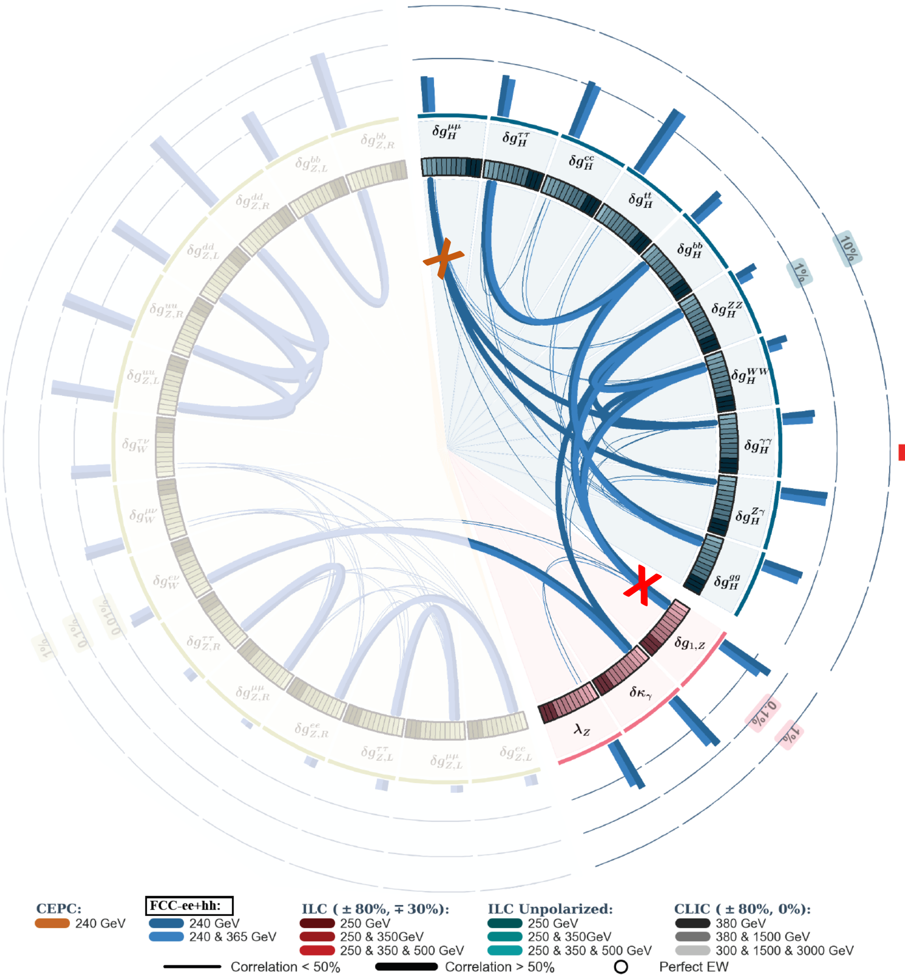
Interplay EW/Higgs at future colliders

J de Blas at FCC WS 2020

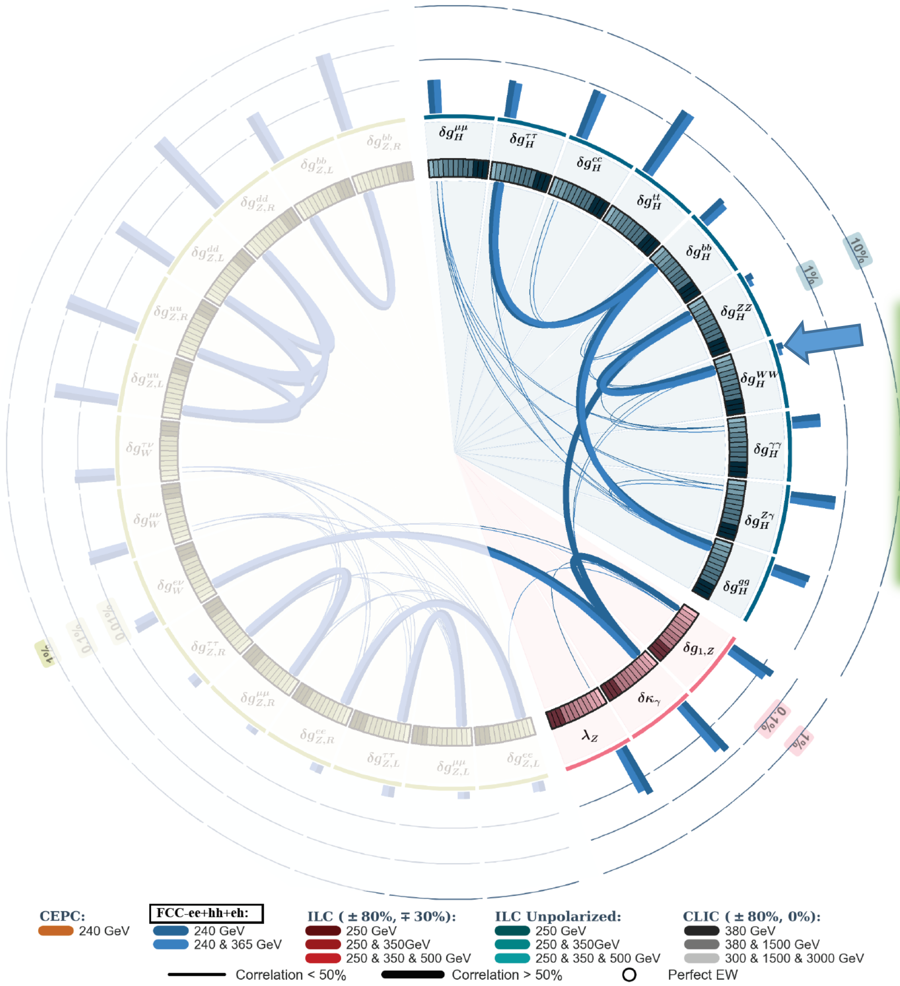
See also Talk by Sally Dawson@DIS21, p13 Higgs at future colliders; Tables in backup & [arXiV: 1905.03764]

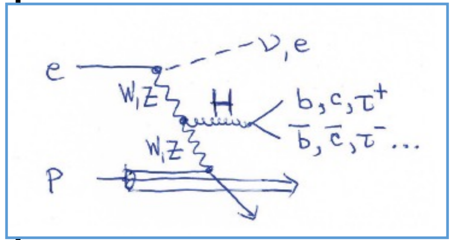
Couplings and correlations

FCCee+hh



FCCee+eh+hh





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

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

PRELIMINARY

Please take home … that …

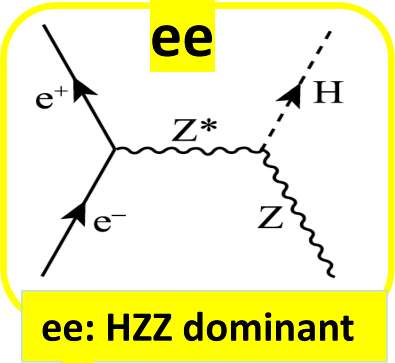
- ***A high energy ep collider like LHeC and FCC-eh* could measure the dominant** (Hbb, HWW, Hgg, HZZ, Hcc, H$\tau\tau$) **Higgs couplings**, and ttH, **to high precision** [CC+NC DIS, no pile-up, clean final state..]
- **Higgs measurements in ep are *selfconsistent,* experimentally and theoretically, based on DIS cross sections with very small systematic uncertainties.**
- **Striking synergy of ep** (*HWW* and √s >~1 TeV) **and ee** (*HZZ* and √s of 250 to 350 GeV) **and pp for Higgs coupling measurements**, and to remove HZZ and HWW and further correlations!
- ***Energy frontier* ep would empower the physics potential of highest energy proton-proton colliders** (LHC, FCC-hh) **for Higgs *(differential distributions!)* through high precision QCD measurements: flavour separated PDFs at N^{3}LO, α_S to per mille accuracy…**

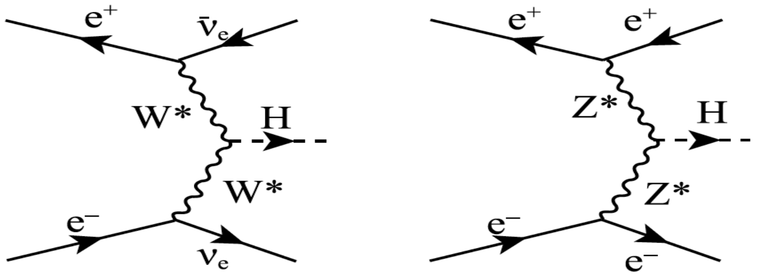
Combining pp with ep,
a very powerful Higgs facility can be established
at the HL-LHC already in the 30ties
and, later, at the FCC eh+hh.

Additional material

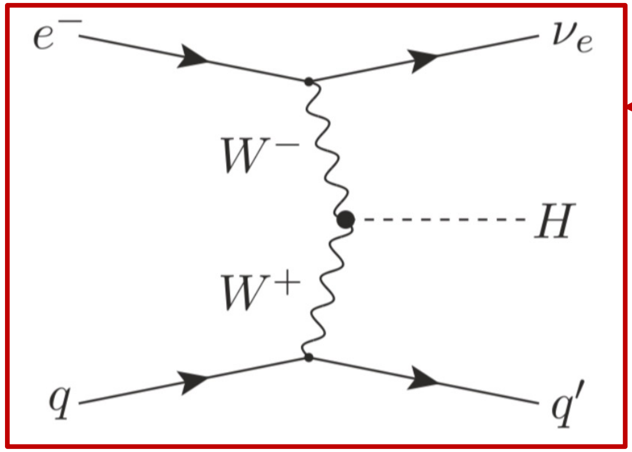
Higgs in ep and ee

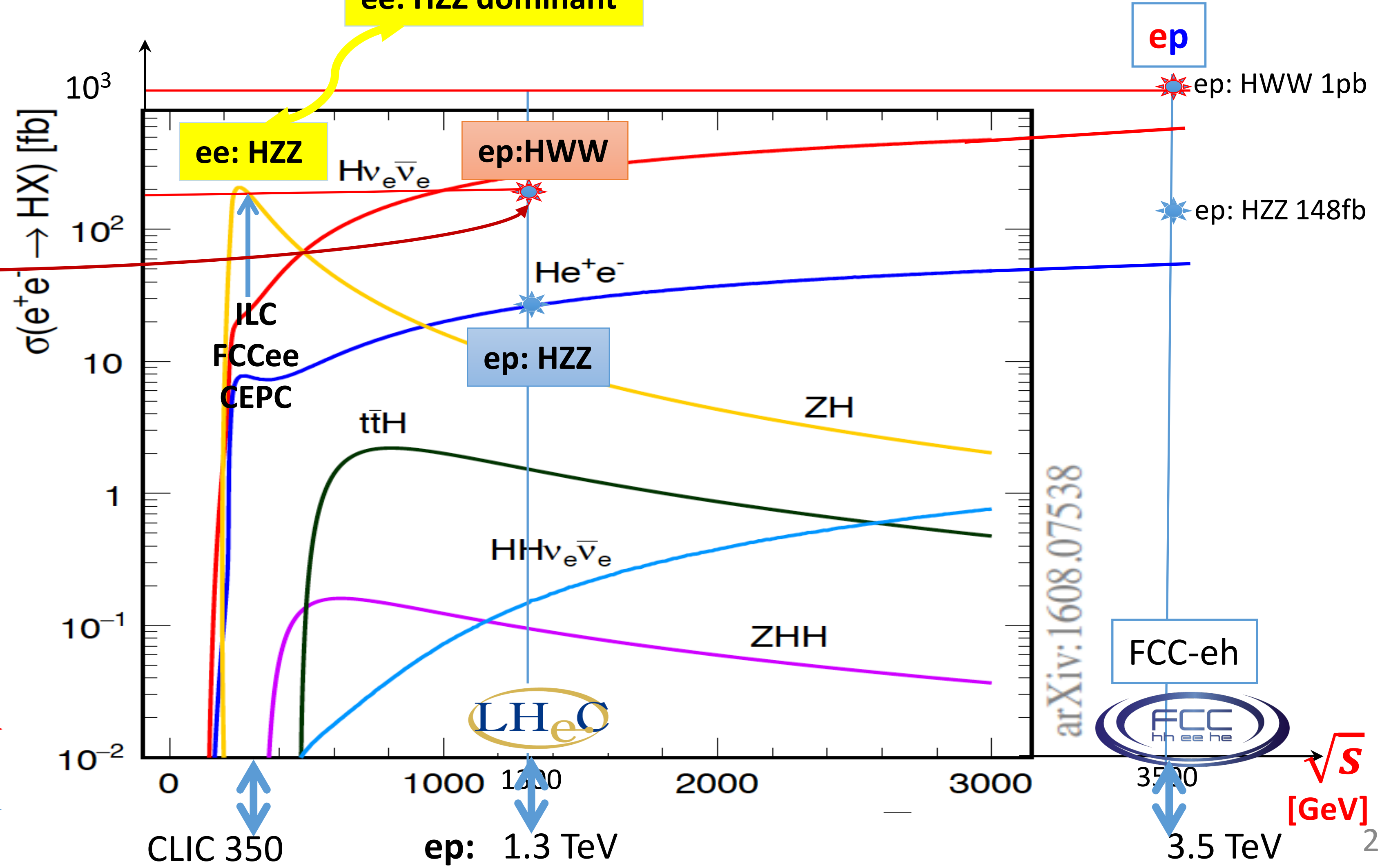
Higgs cross sections for ee and ep





ep : HWW dominant





ep:CC DIS WW Fusion

ep: NC DIS ZZ Fusion

HL-LHC and LHeC
- *Combined* -

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 %
$pp \to WH$	1.5	0.5 %	1.4 %	0.2 %
$pp \to ZH$	1.0	3.5 %	1.9 %	0.3 %
$pp \to t\bar{t}H$	0.6	7.5 %	3.5 %	0.4 %

Table 9.4: Predictions for Higgs boson production cross sections at the HL-LHC at $\sqrt{s} = 14\,\text{TeV}$ 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.

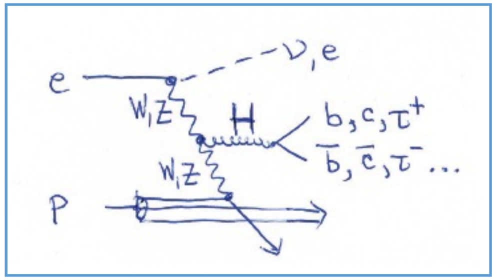
Consistency Checks of EW Theory

→ 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

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

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

- ➔ 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

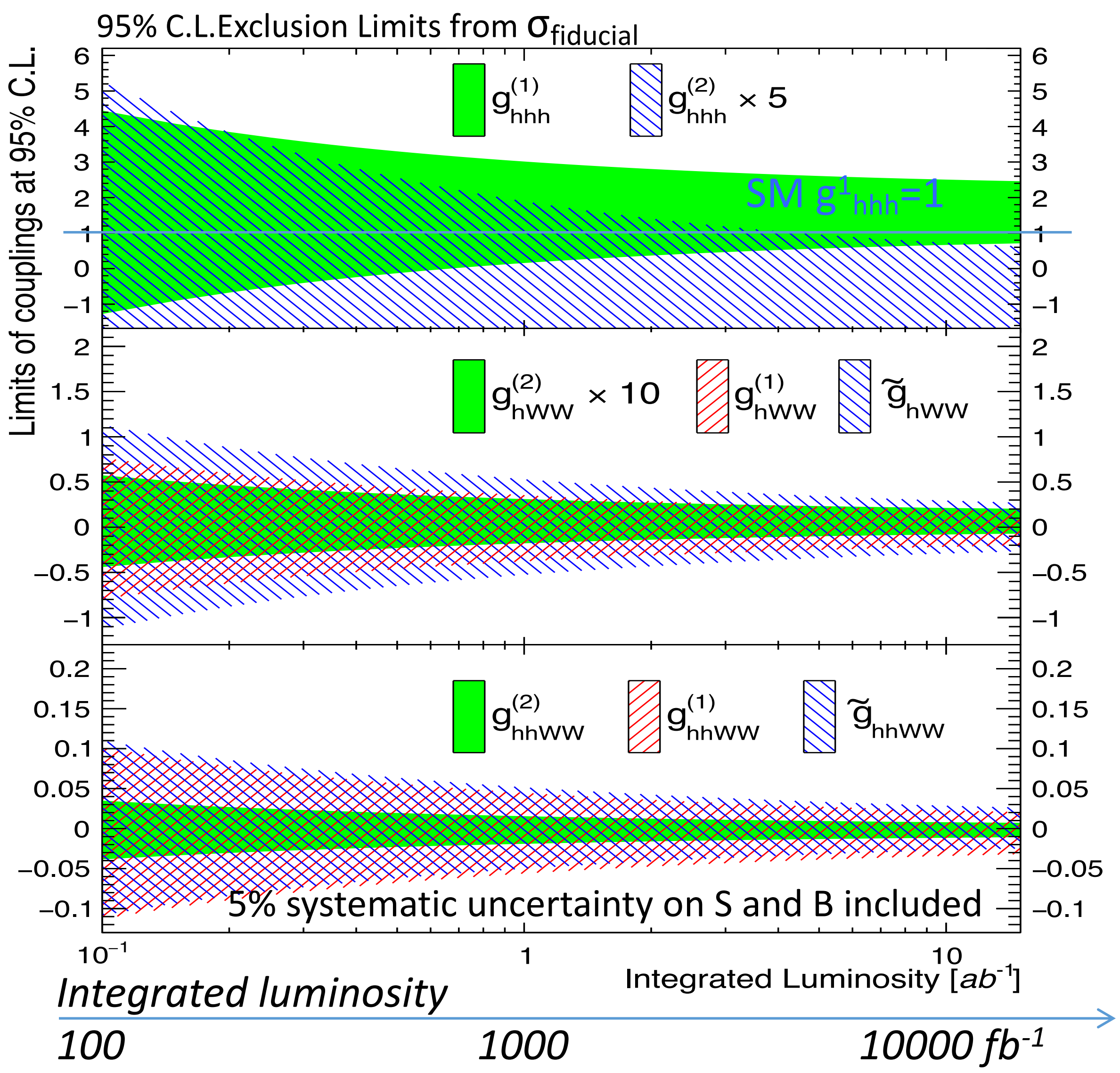
$$\frac{\sigma_{WW\to H\to c\bar{c}}}{\sigma_{WW\to H\to b\bar{b}}} = \frac{\kappa_c^2}{\kappa_b^2}$$

Double Higgs Production

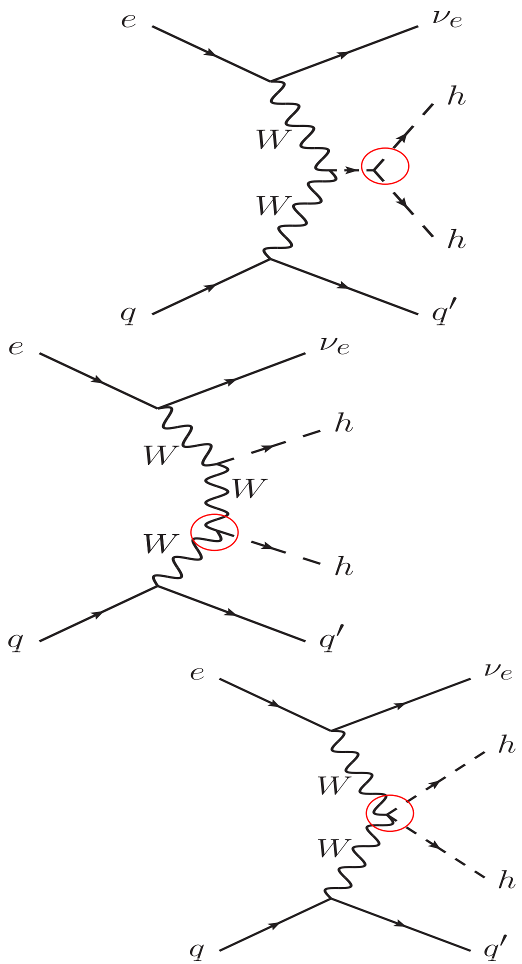
[arXiv:1509.04016]

Encouraging FCC-eh cut-based study; full Delphes-detector simulation; conservative HFL tagging → full potential to be explored yet

FCC-eh g_{HHH} ~ 20% in ep only
→ go for ep+pp Higgs physics combination!



Note: Bands show the still allowed regions



cut-based 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.

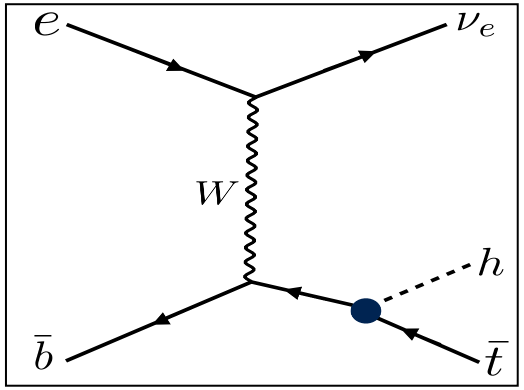
Top Yukawa Coupling @ LHeC

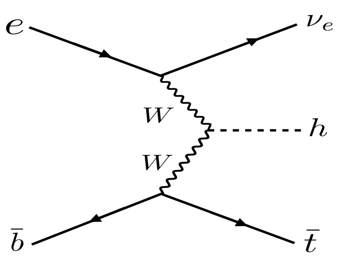
B.Coleppa, M.Kumar, S.Kumar, B.Mellado, PLB770 (2017) 335

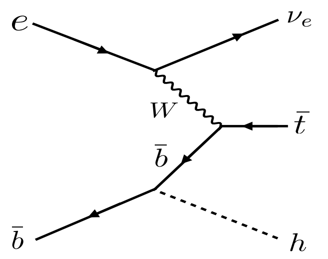
SM: $$\mathcal{L}_{\text{Yukawa}} = -\frac{m_t}{v}\bar{t}th - \frac{m_b}{v}\bar{b}bh,$$

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

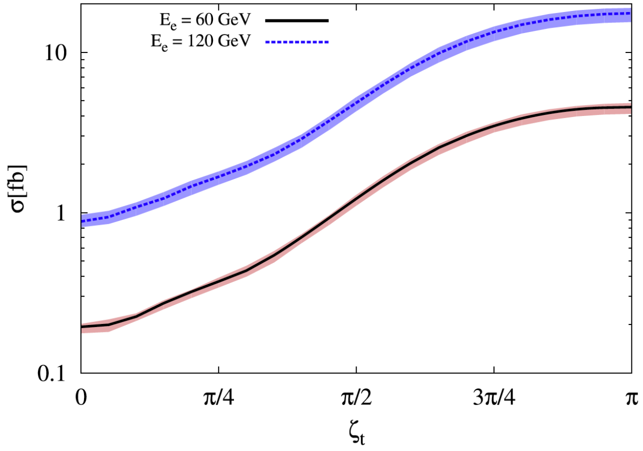
$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]t\,h$$
$$-\frac{m_b}{v}\bar{b}\,[\cos\zeta_b + i\gamma_5\sin\zeta_b]b\,h.$$







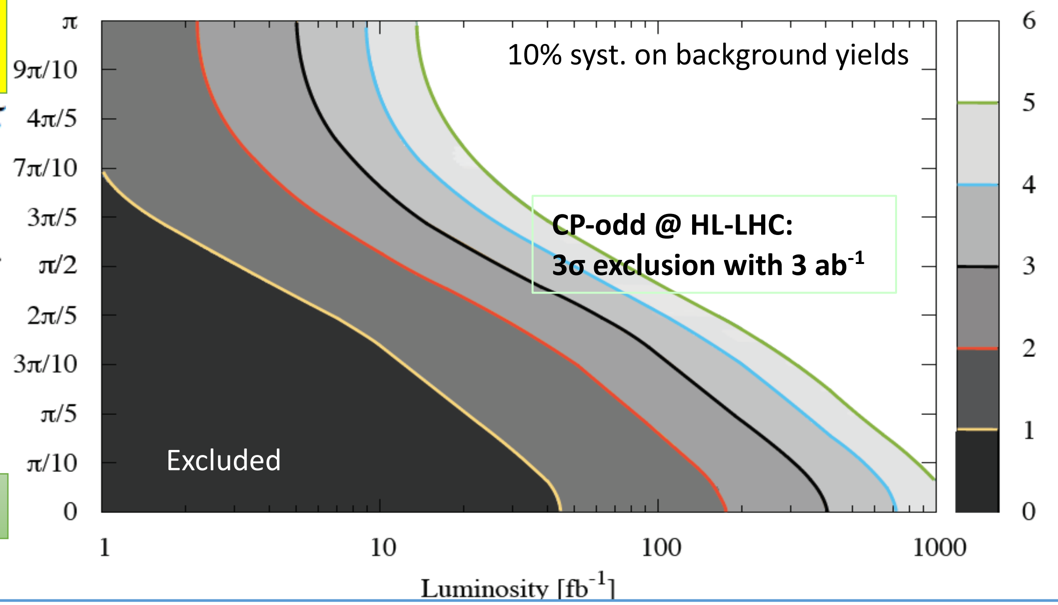
Enhancement of the DIS cross-section as a function of phase



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%**

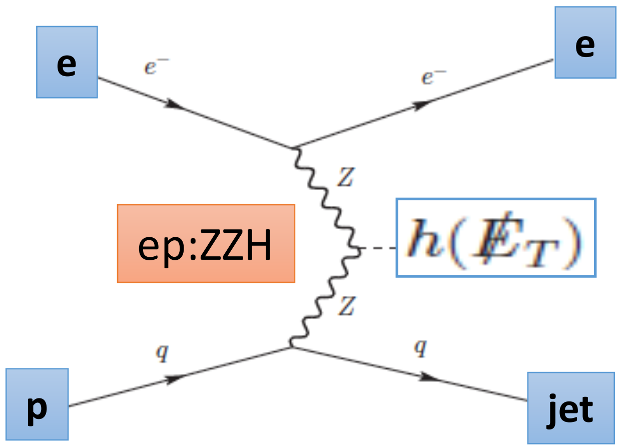
Stand alone Branching for invisible Higgs

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%
'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 focused on a stand alone determination***
- ✓ **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-eh 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 to enhance potential further**