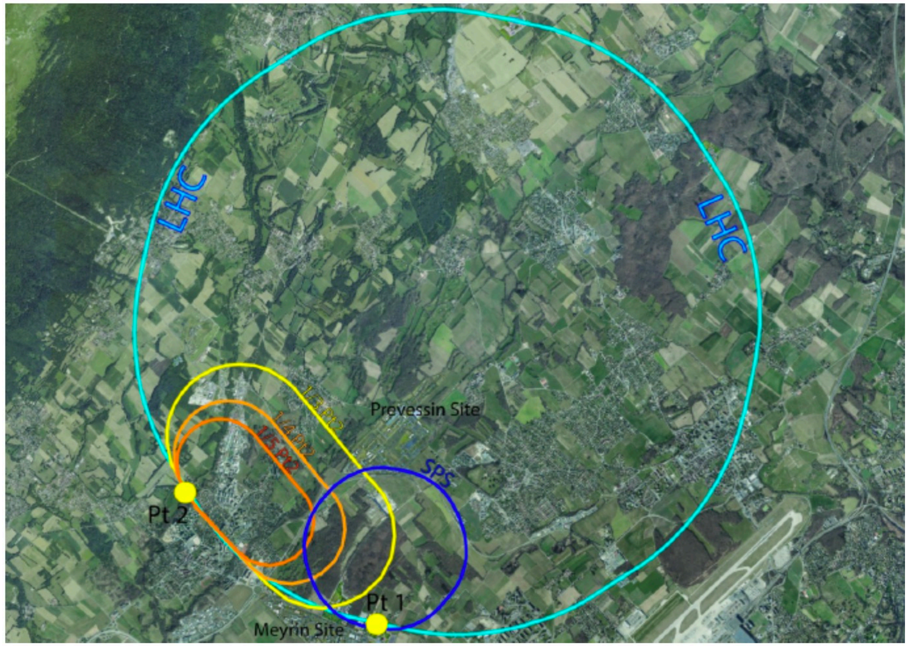
Higgs Physics at the LHeC and FCC-eh

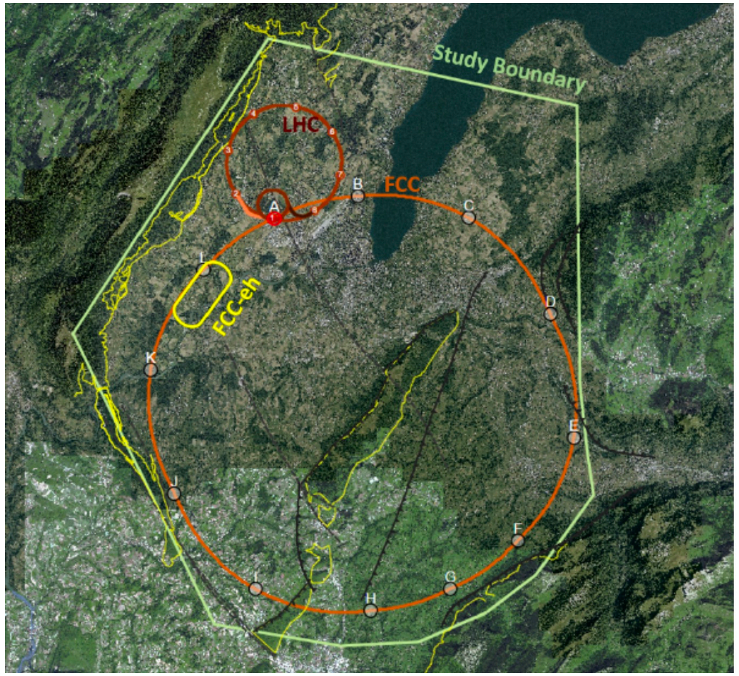
Uta Klein

UNIVERSITY OF LIVERPOOL

on behalf of

the LHeC & FCC-eh Study Group





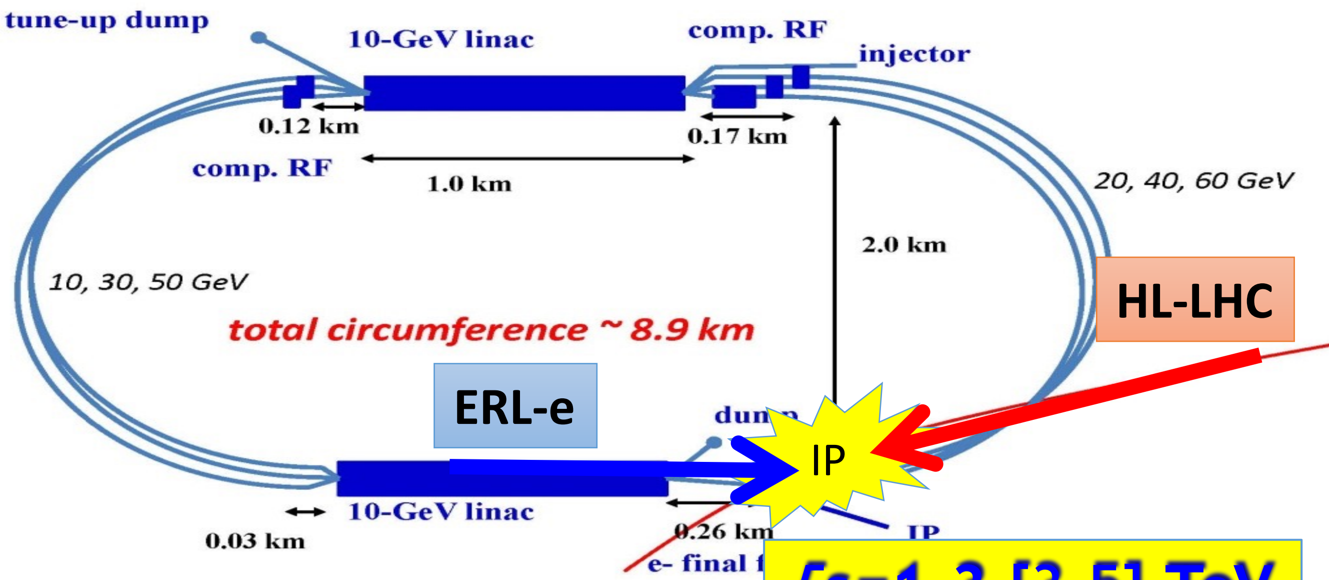
EPS HEP2021 VIRTUAL EDITION

electrons for eh : ERL-e + 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 hh operation with same running time!

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



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

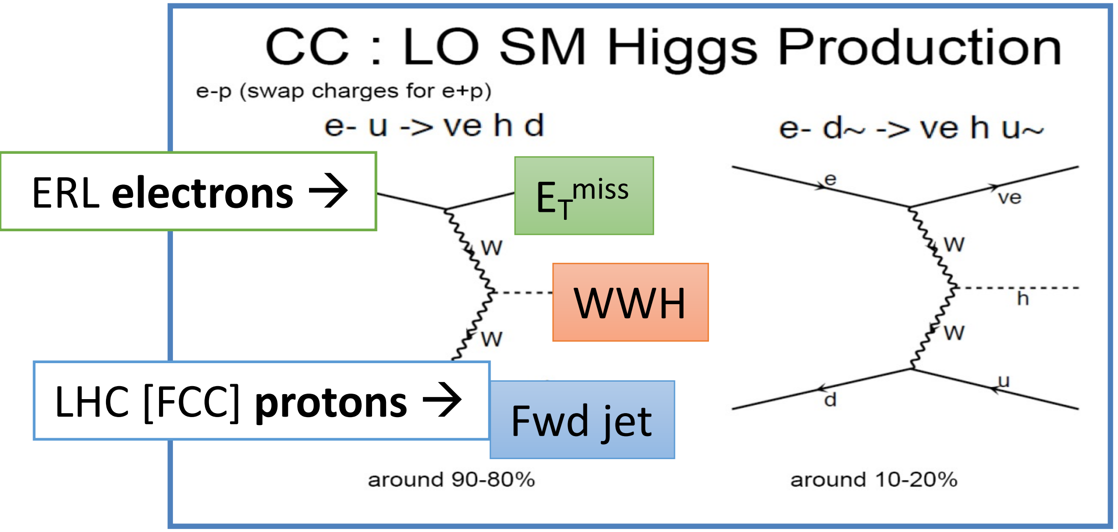
E_e = 60 GeV

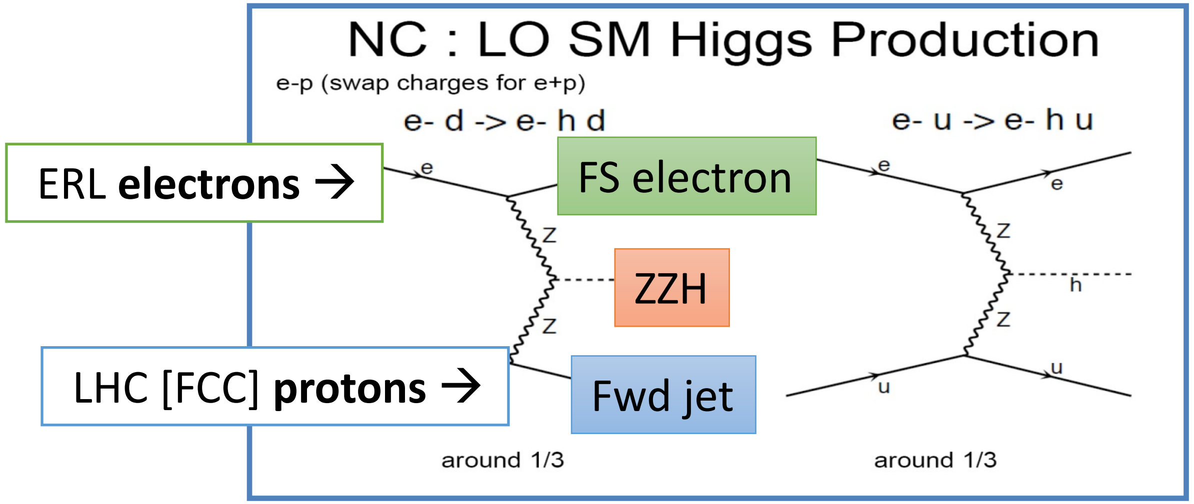
E_p = 7 [50] TeV

- **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 CDR update CERN-ACC-Note-2020-0002 [arXiv:2007.14491] accepted by J. Phys. G. **See FCC Week 2021 for project news.**

SM Higgs Production in ep





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

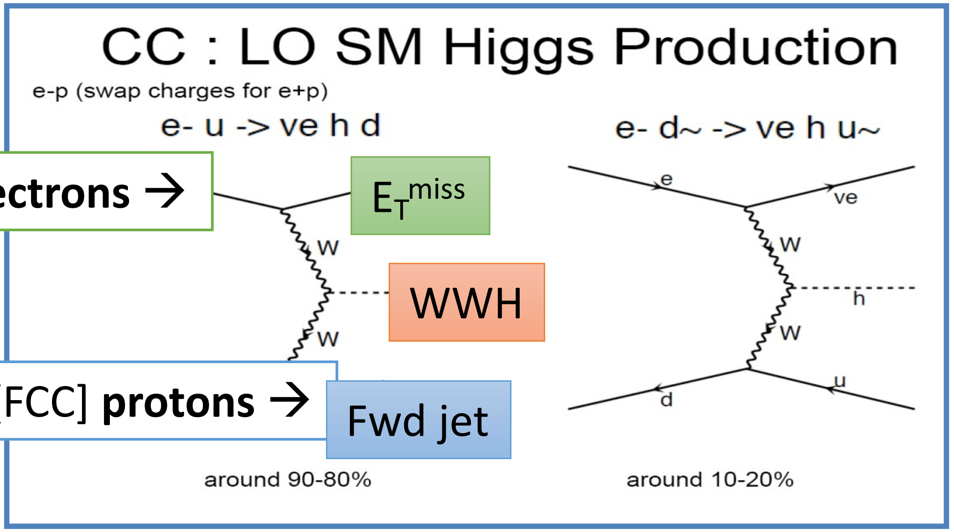
Total cross section [fb]
(LO QCD CTEQ6L1 M_H=125 GeV)

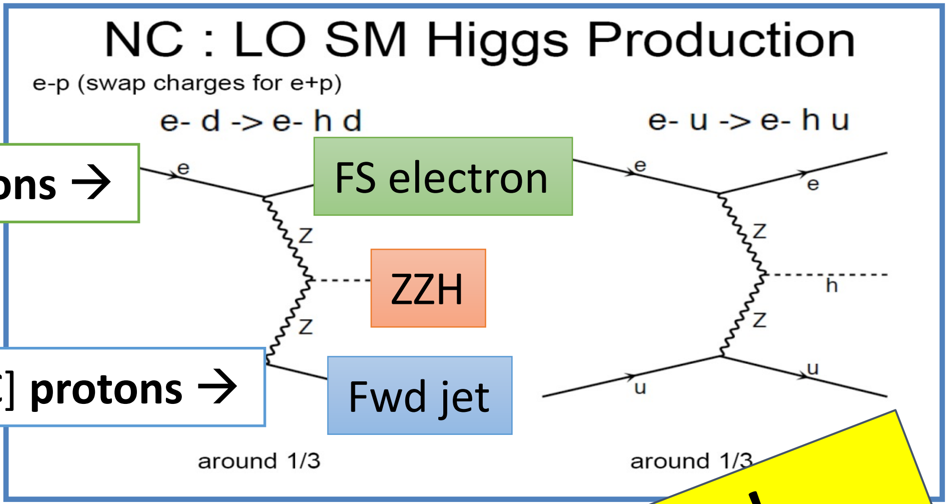
c.m.s. energy	1.3 TeV LHeC	3.5 TeV FCC-eh
CC DIS NC DIS	109 21	560 127
P=-80% CC DIS NC DIS	 **196** **25**	 **1008** **148**

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

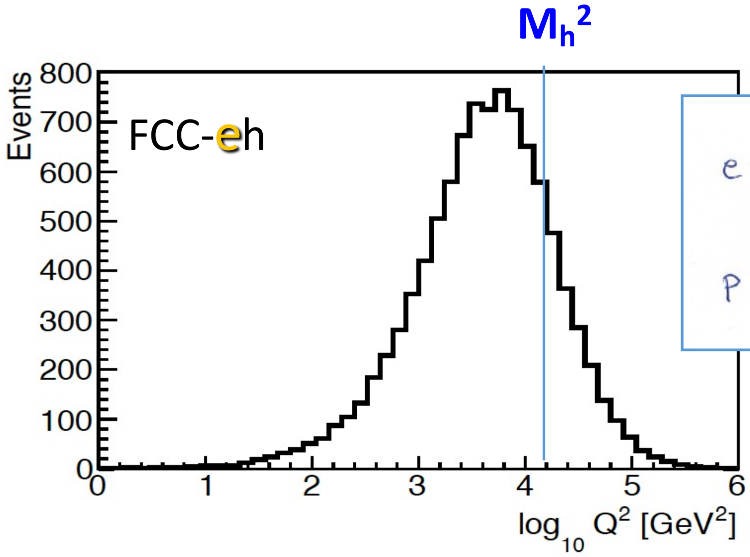
•Scale depende... ge
of 5-10% ...
... r
... ns up to -
... , R. Ruckl, Nucl.Phys.B395:35-
5...
[B... 1.3789]

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%
see talk by C Gwenlan

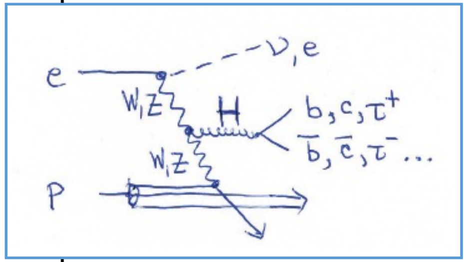
DIS Kinematics

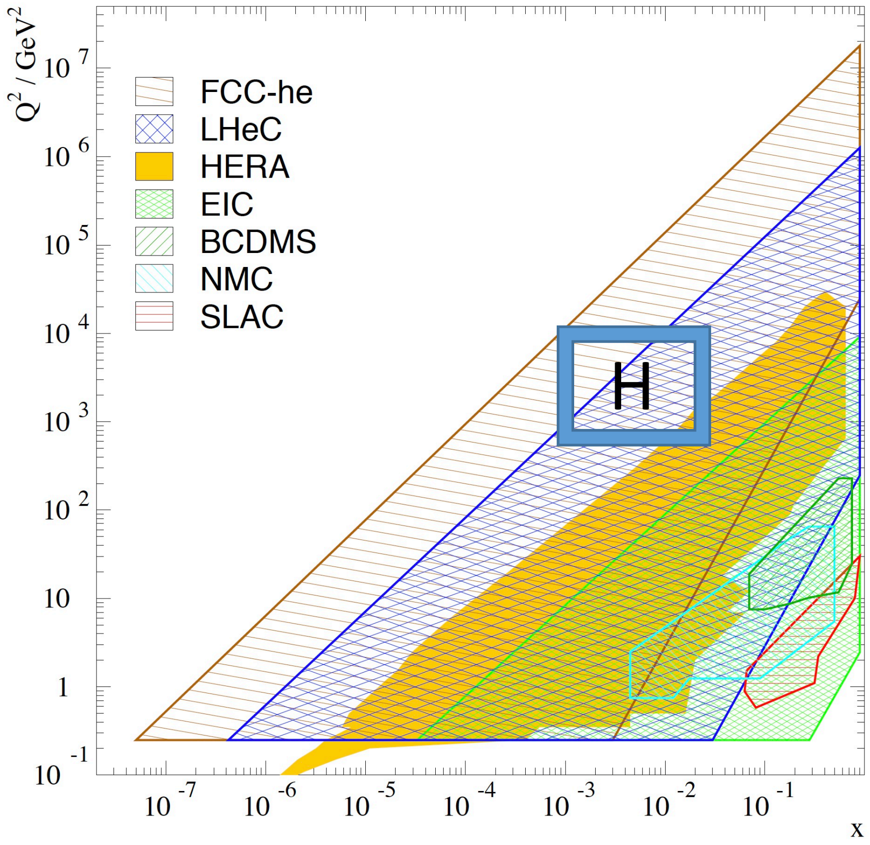
MadGraph scale: p_T of leading jet

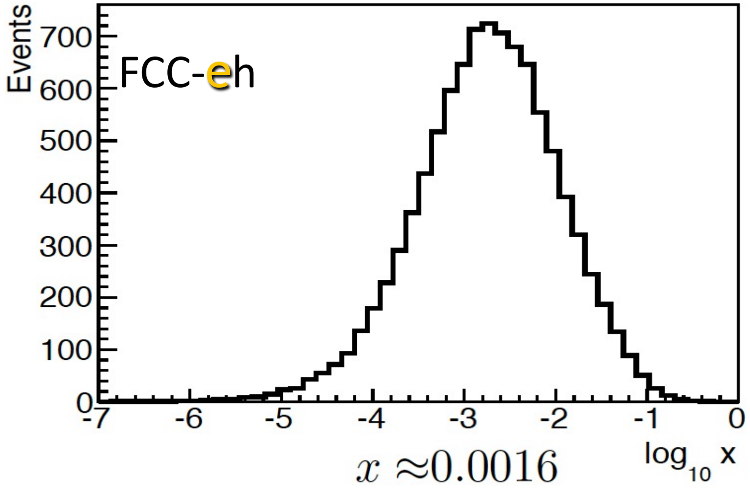
-Parton-level-



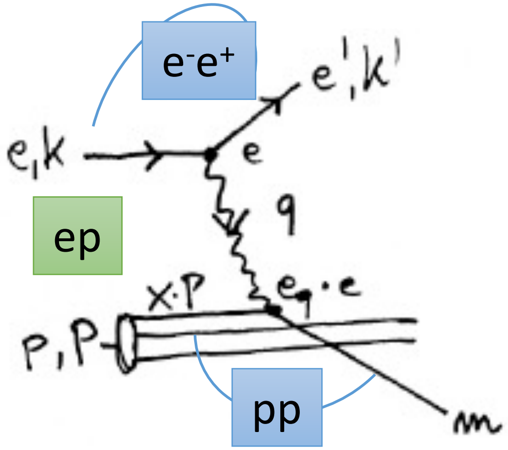
$Q^2 \approx 6500\,\mathrm{GeV}^2$







$x \approx 0.0016$



$s = (k + P)^2$

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

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

$q^2 + 2xPq = 0$

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

$Q^2 = sxy$

relation to pp LO QCD

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

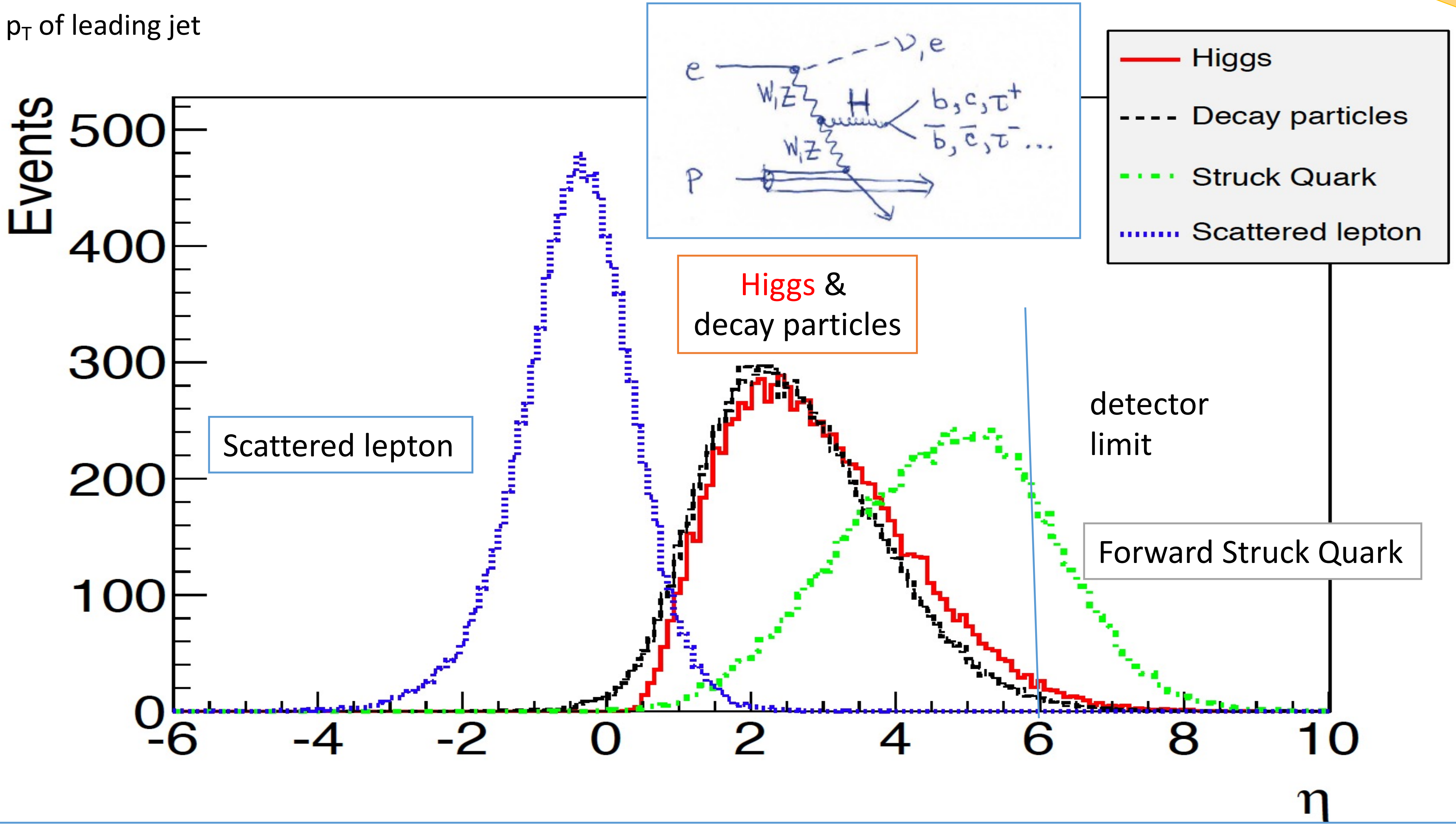
$Q^2 \sim M^2$

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.

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

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

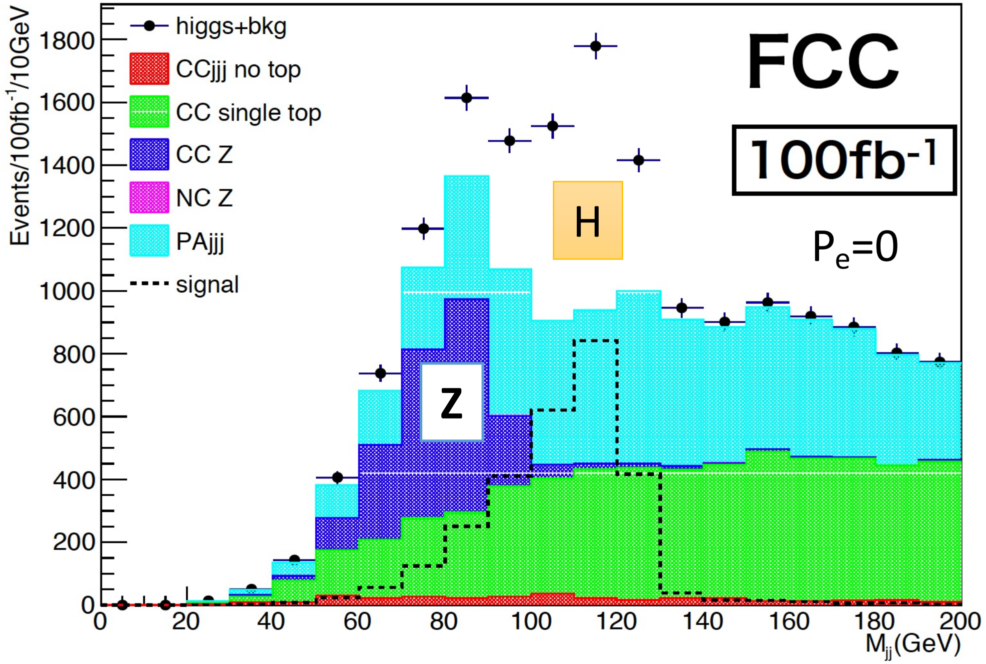
MadGraph and Delphes ep-style detector
+ flat parton-level b-tagging for |η|<3.0
conservative HFL tagging:
b: 60%, c: 10%, **udsg: 1%**
CAL coverage |η|<5 LHeC [<6 FCC-eh]

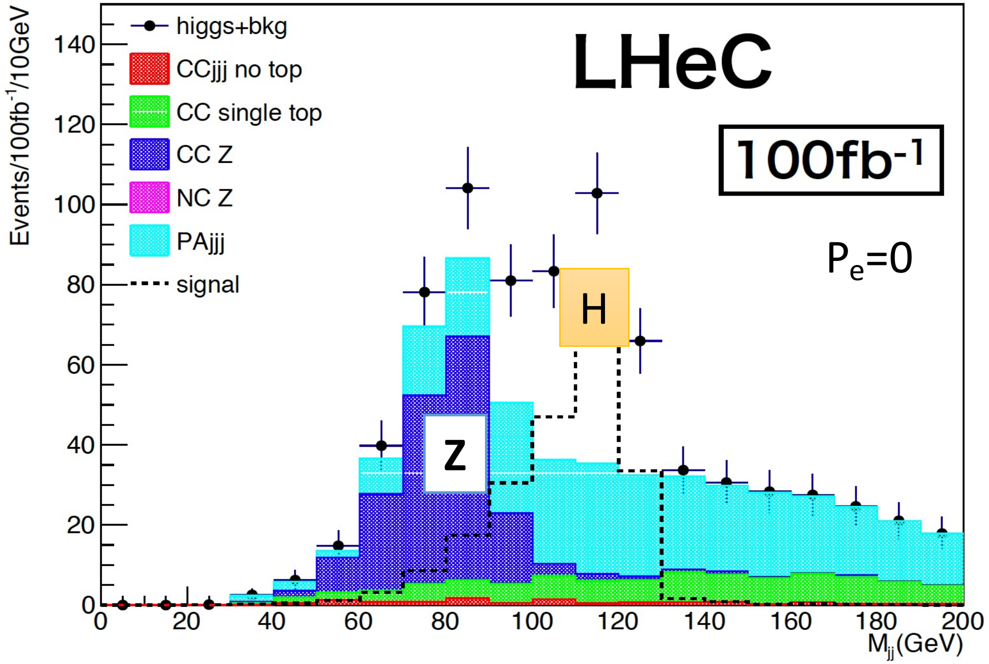
Mass of 2 b-jets after event selection

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

→ confirmed earlier & post CDR studies

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



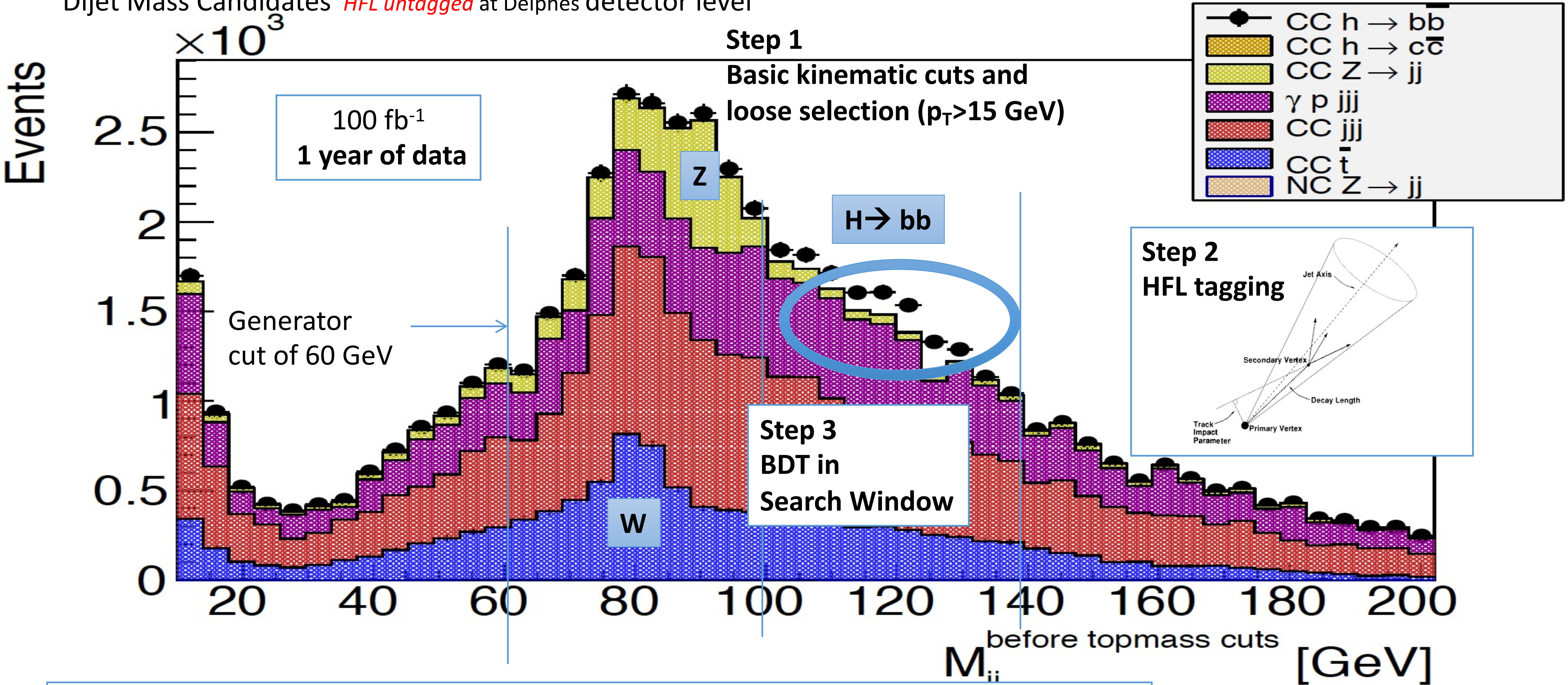


Note: plenty of single Z, W and top in ep

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

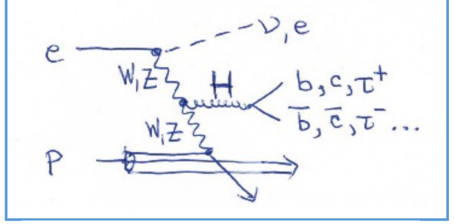
Hunting for Precision Hbb

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%

Higgs in ep – clean S/B, no pile-up

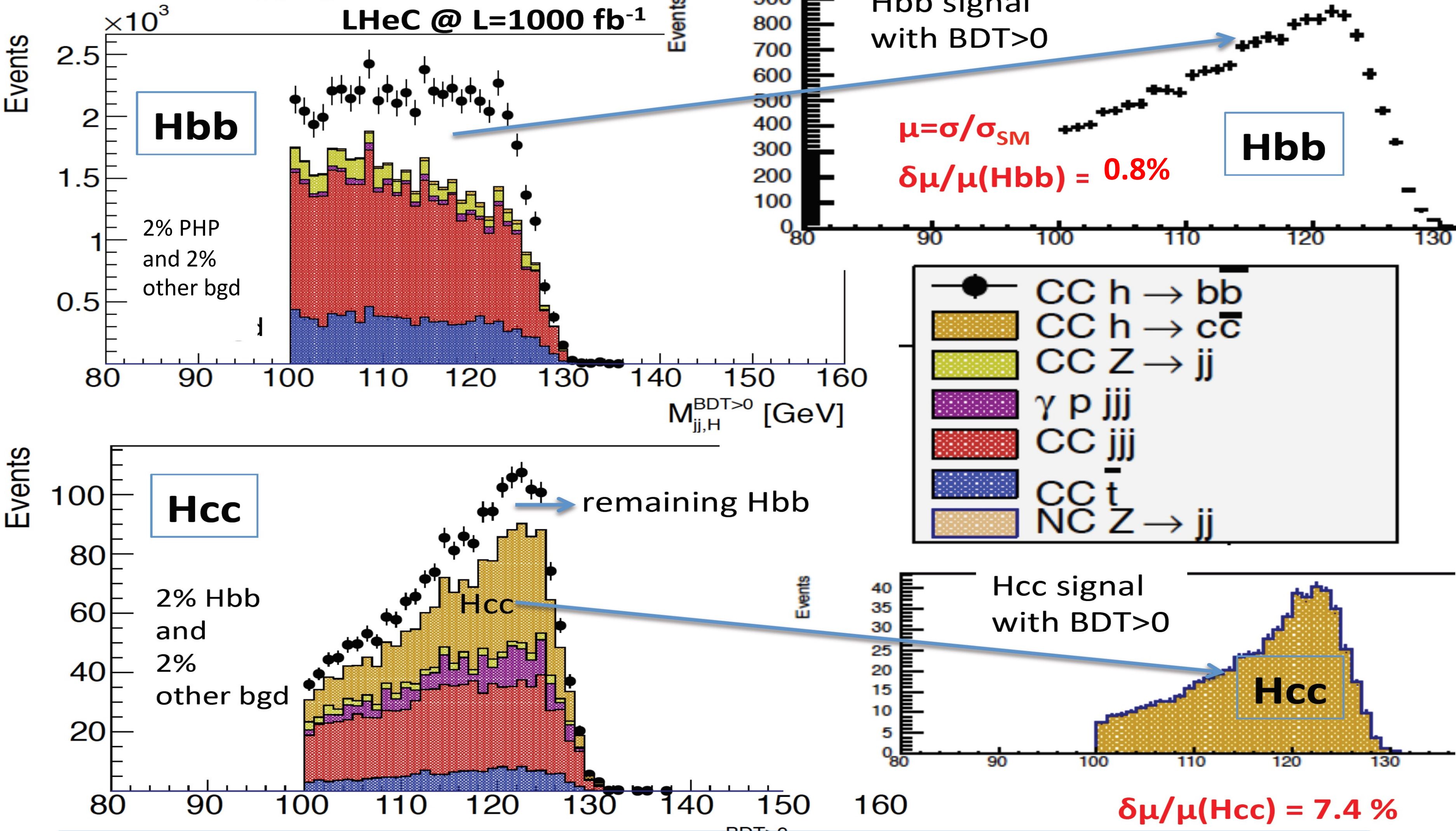


→ further improvements using BDT

realistic HFL tagging & BDT

Uta Klein & Daniel Hampson & Izzy Harris BSc 2017

[arXiv:2007.14491]



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

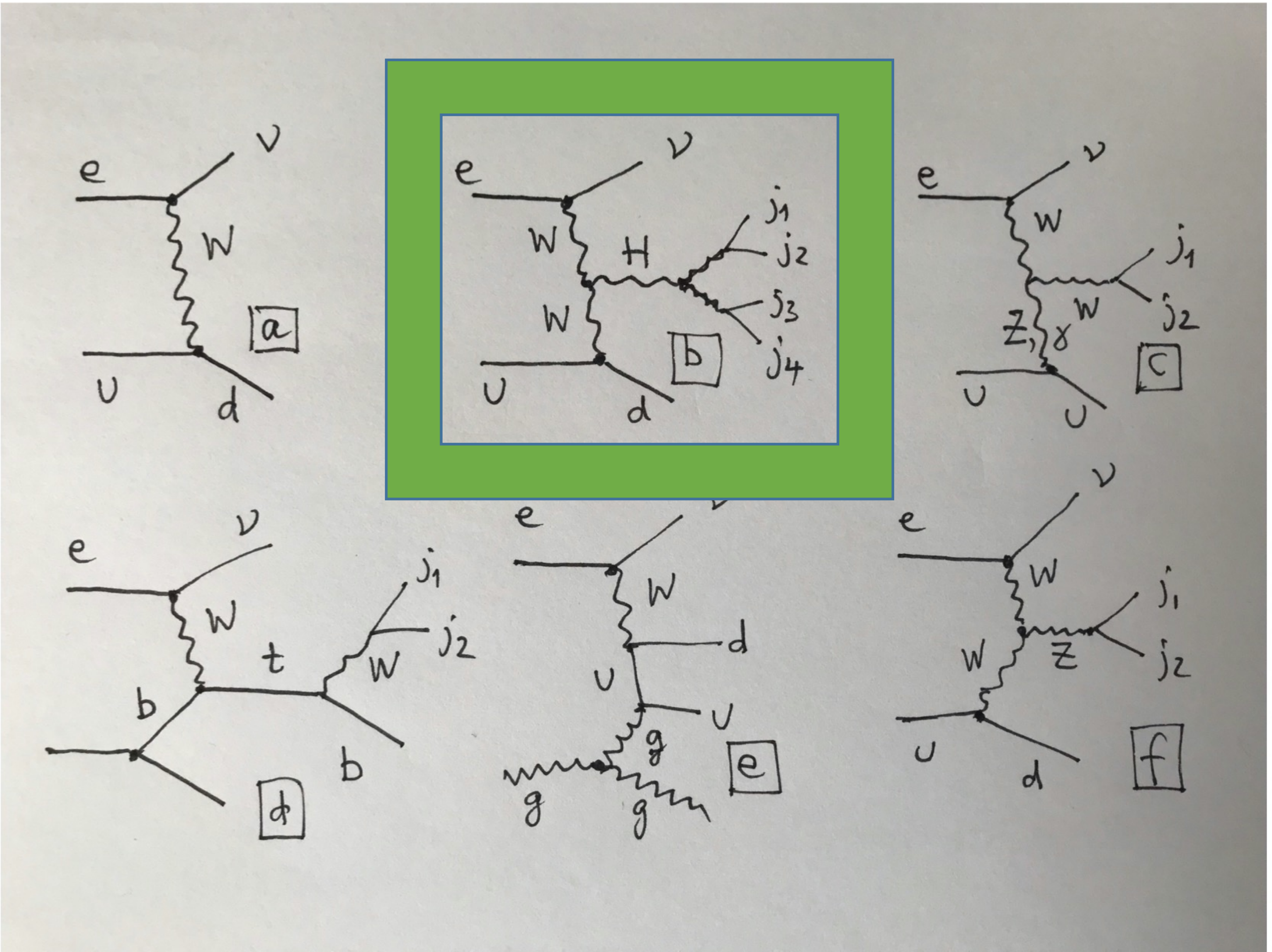
[ILC Zqq-Hcc study got 8.8% for Hcc signal strength for M_H=120 GeV $\boldsymbol{\sigma}_{pol}$(Hcc)=6.9 fb with similar Hcc, Hbb event numbers but factor 6.8 higher SM background than LHeC]

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

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

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



New 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 multijets, top and single H,W, Z + jets (4^{th} + more jets from shower)

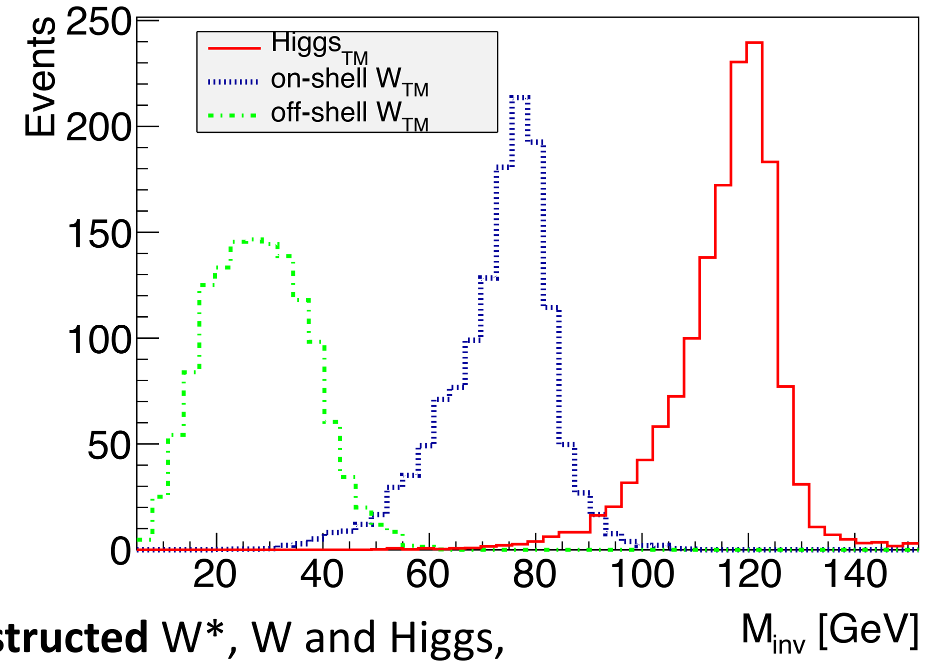
→ various anti-kt R choices studied for the resolved case: all 4 jets reconstructed
→ optimal choice R=0.7

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

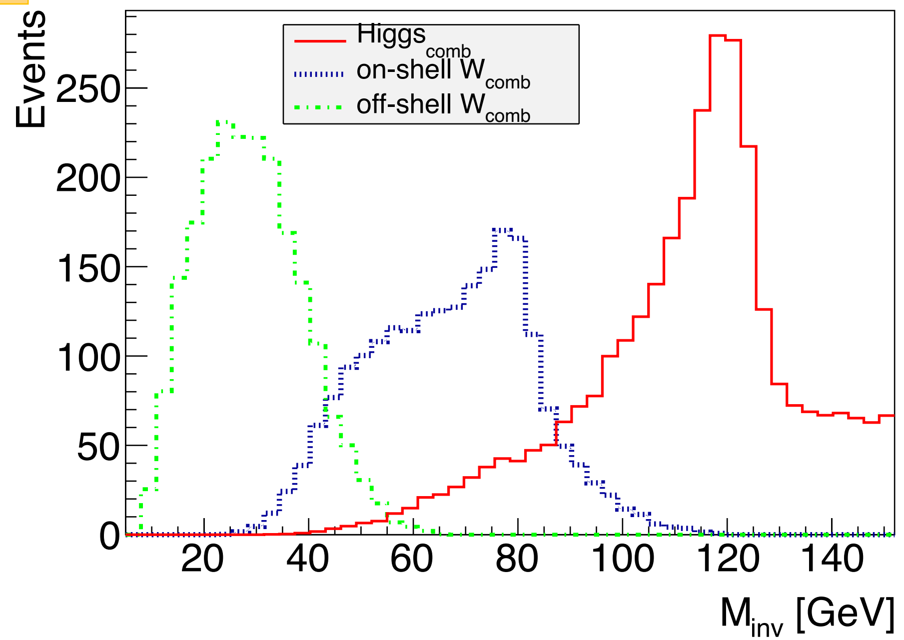
H→ WW* analysis strategy & results

At Delphes detector level

NO mass requirements in combinatorics!



Reconstructed W*, W and Higgs, truth-matched



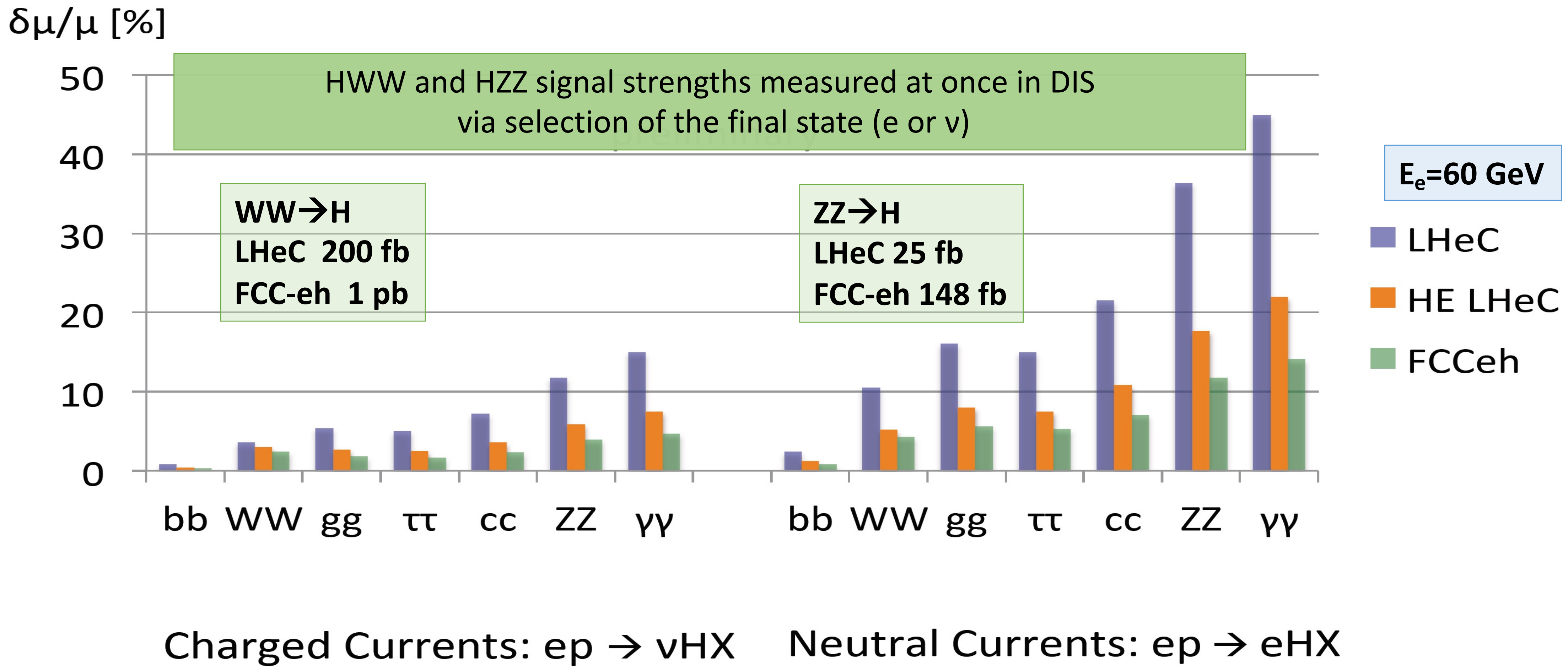
Reconstructed W*, W and Higgs, after jet combinatorics based on selecting at **least 5 jets** with $\mathbf{p_T}$**> 6 GeV** and finding the higgs candidate which has two jet pairs with min $\Delta\eta$, and max $\Delta\eta$ between Higgs and fwd jet, and max $\Delta\phi$ between Higgs and ETmiss or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



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

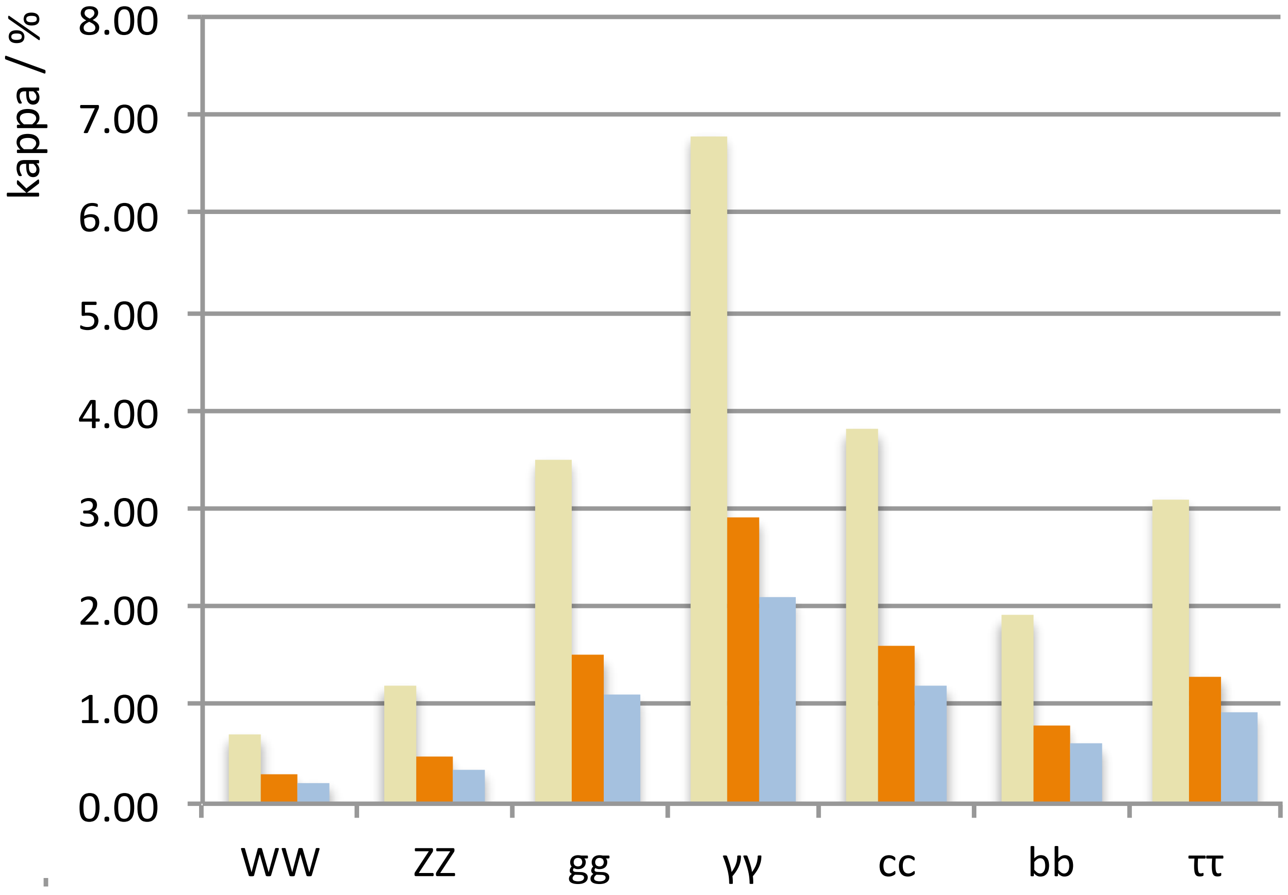
E_e = 60 GeV LHeC E_p = 7 TeV L=1ab^{-1} HE-LHC E_p = 14 TeV L=2ab^{-1} FCC: E_p = 50 TeV L=2ab^{-1}

[arXiv:2007.14491]

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



E_e = 60 GeV, P=-0.8

	E_p=
LHeC	7 TeV
FCC-eh (2.2)	20 TeV
FCC-eh (3.5)	50 TeV

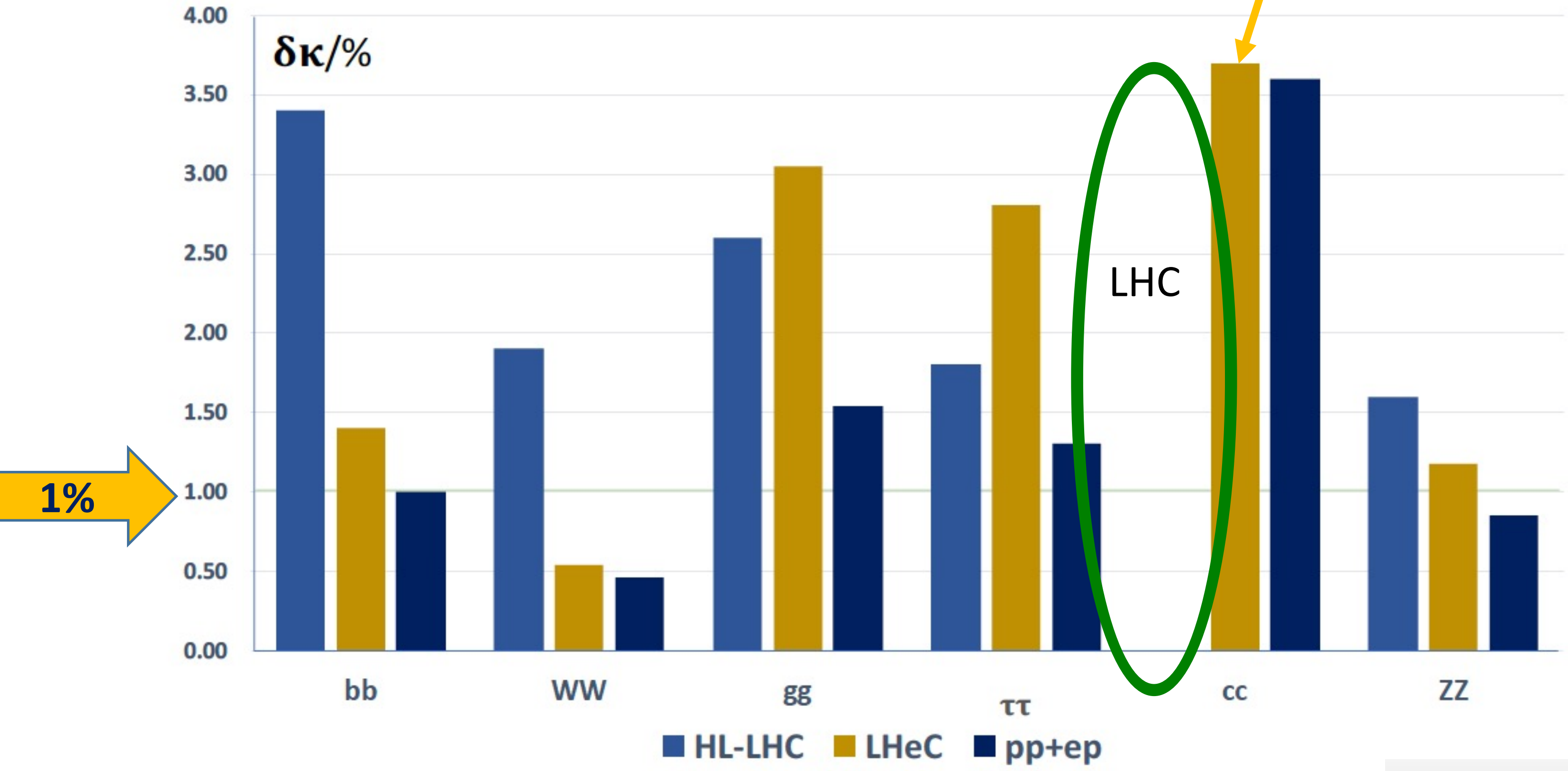
Very high precision due to CC+NC DIS in clean environment in luminous, energy frontier ep scattering

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

Update of 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

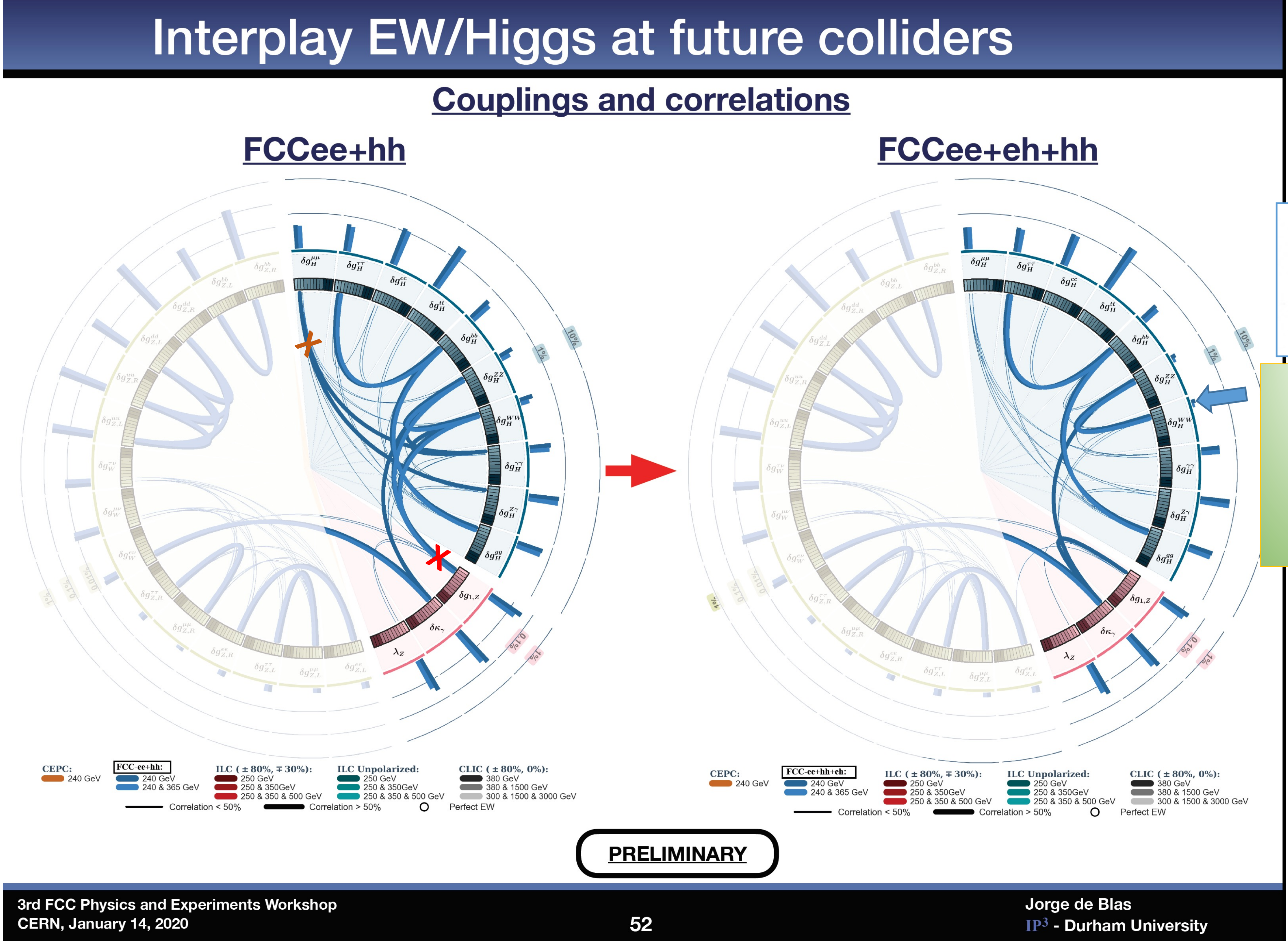
For LHC: Precise Higgs cross section prediction with LHeC input:

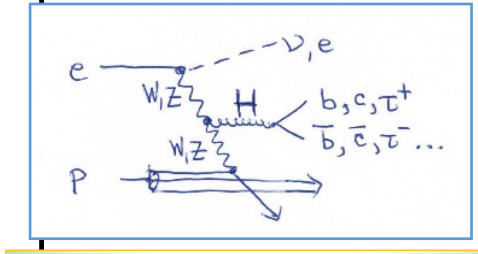
$\delta\sigma$(pp→ Higgs)=[0.3 (pdf) + 0.2 (α_s)]%

* see also backup slide

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]





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

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 (>~1 TeV) and ee (250-350 GeV) and pp for Higgs coupling measurements**,

  to remove also 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 N^3LO, 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

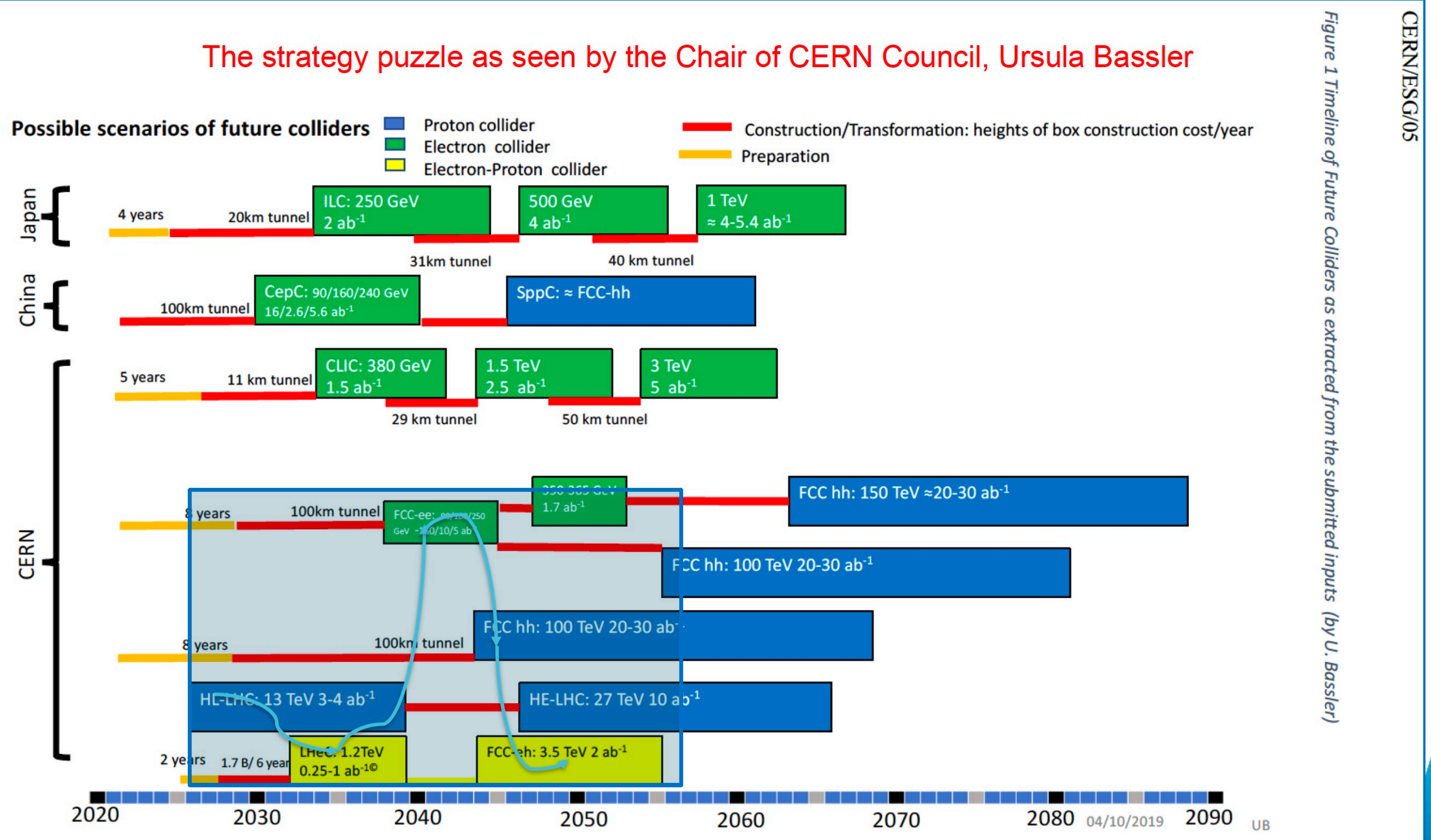
- **@ EPS2021 Talks/Abstracts:**
  1005.BSM Physics at the LHeC and the FCC-he : Oliver Fischer
  1012.Precision QCD in ep collisions at the LHeC, merged with
  1018.Small-x Physics at the LHeC and FCC-he : Claire Gwenlan
  1015.Electron-Ion Collisions at the LHeC and FCC-he : Guilherme Milhano
  1017.Higgs physics at the LHeC and the FCC-he : Uta Klein
  1021.The ERL Facility PERLE at Orsay (poster) : Ben Hounsell
  1022.The Large Hadron-electron Collider at CERN: Status and Plans (poster) : Kevin Andre
  1024.The LHeC as Part of the HL-LHC Programme, merged with
  1032.Precision electroweak measurements at the LHeC and the FCC-he : Daniel Britzger
  1026.Top physics at the LHeC and the FCC-he : Subhasish Behera
- **@FCC Week 2021:** https://indico.cern.ch/event/995850/
  Project status, LHeC and FCC-eh Detector Status [https://indico.cern.ch/event/995850/contributions/4420316/**], physics news**
- **@IAS HL-LHC Upgrade and LHeC Option by O Bruening:** https://indico.cern.ch/event/971970/contributions/4174477/
- **CDR Update** [arXiv:2007.14491]
- "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.

Additional material

The strategy puzzle as seen by the Chair of CERN Council, Ursula Bassler



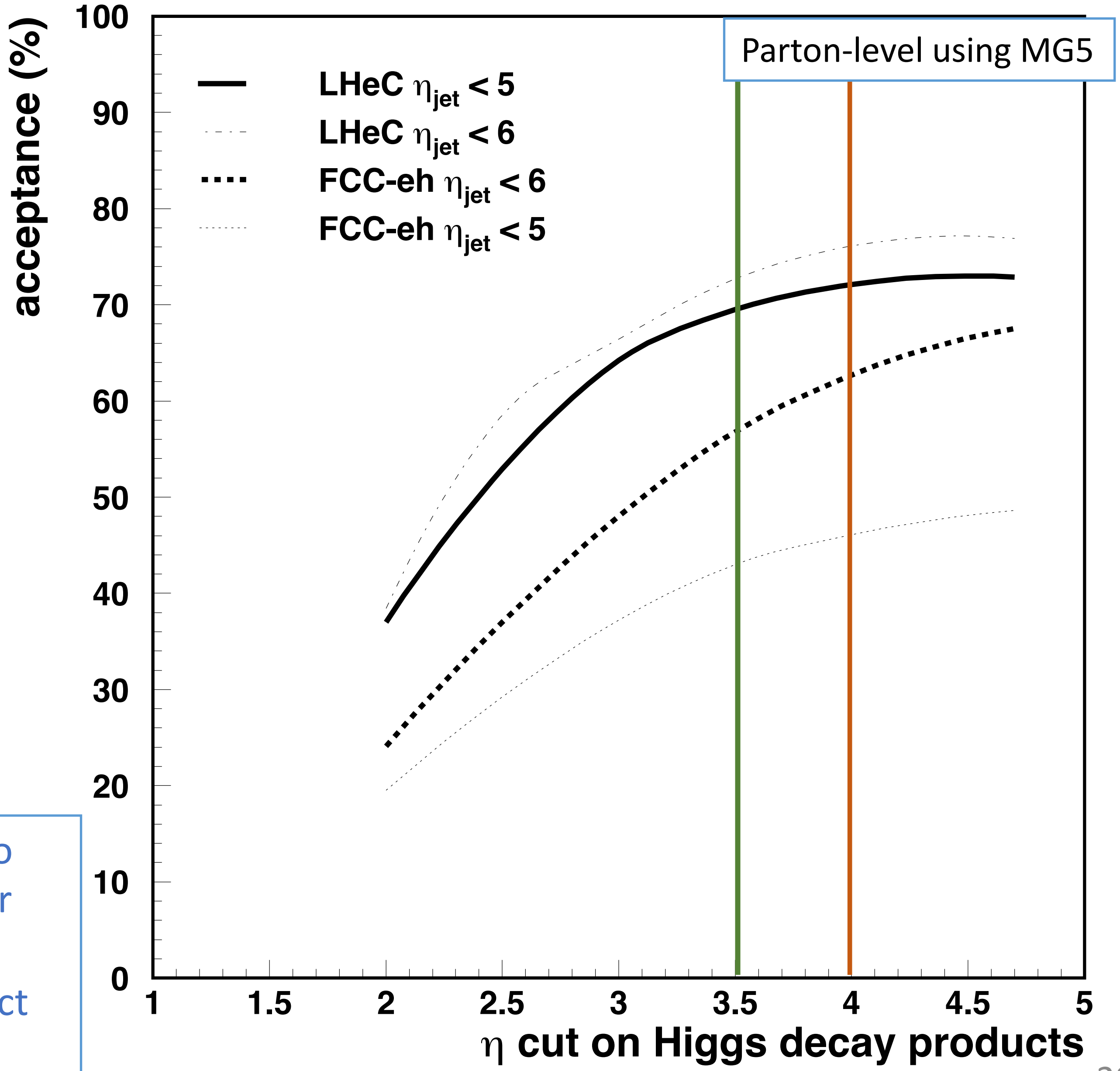
Rates and Geometric acceptances

[arXiv:2007.14491]

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

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
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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 $\sqrt{s} = 14$ 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 ($\star$) 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-ee$_{240}$+FCC-ee$_{365}$, FCC-eh and FCC-hh. In the case of HE-LHC, two theoretical uncertainty scenarios (S2 and S2′) [13] are given for comparison.

FCC-ee/eh/hh

kappa-0	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$\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	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$\star$	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 @ 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	$<$ **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%

Analysis Framework and *Detector**

*see FCC Week 2021

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

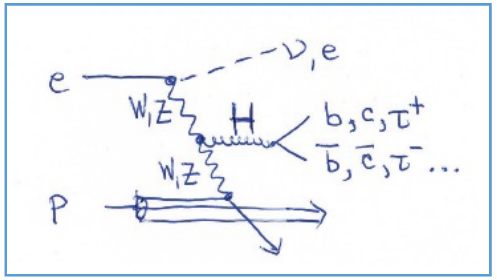
**See page 11 for ep Pythia checks: https://indico.cern.ch/event/278903/contributions/631181/attachments/510303/704309/Chavannes_UKLein_20.01.2014.pdf

... 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

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

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



- ➔ 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

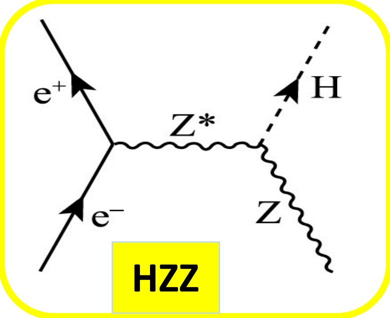
LHeC:	**± 0.010**
HE-LHeC	± 0.006
FCC-eh	± 0.004

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

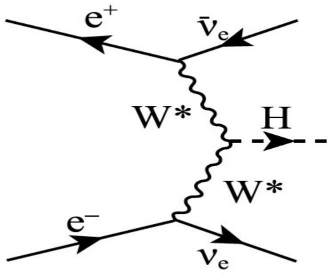
$$\frac{\sigma_{WW\to H\to c\bar{c}}}{\sigma_{WW\to H\to b\bar{b}}} = \frac{\kappa_c^2}{\kappa_b^2}$$

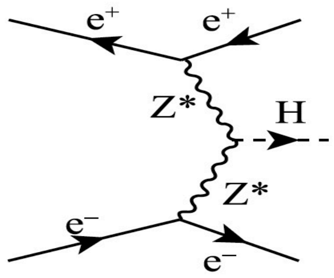
Higgs in ee vs ep

ee Dominant Higgs productions:



ee



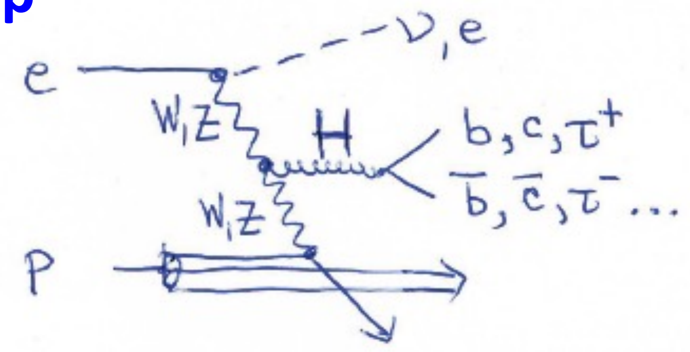


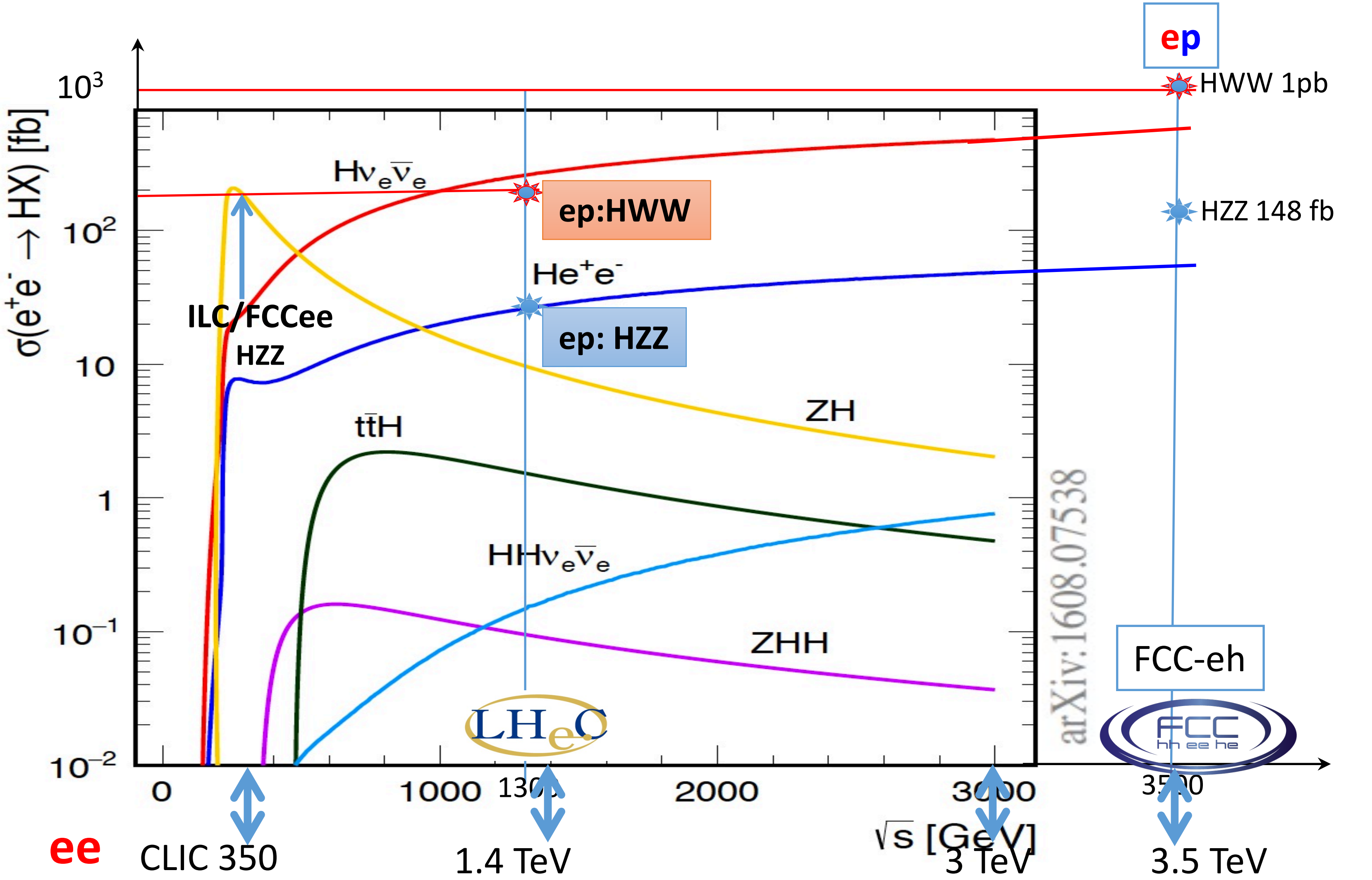
ep vs ee- Higgs cross sections

ep:CC DIS WW Fusion

ep: NC DIS ZZ Fusion

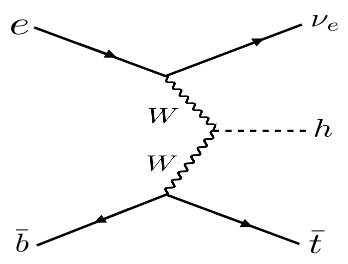
ep

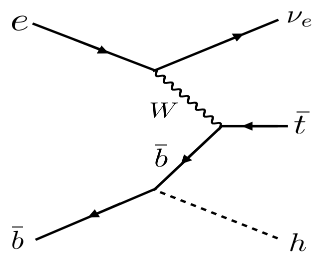


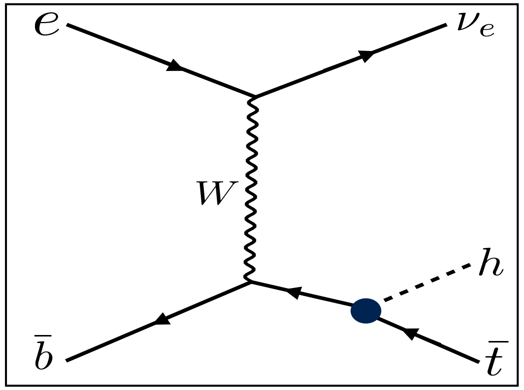


Top Yukawa Coupling @ LHeC

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





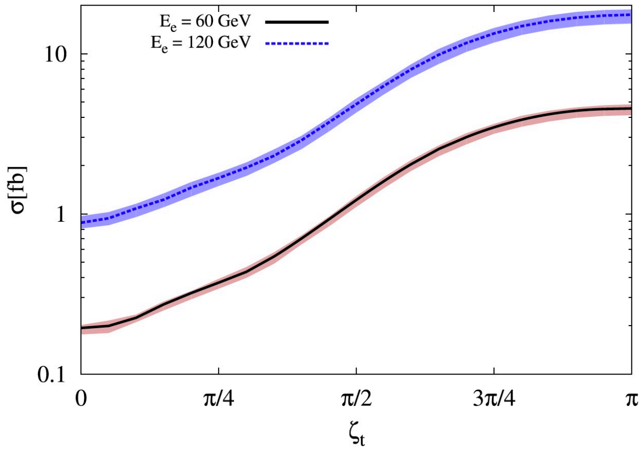


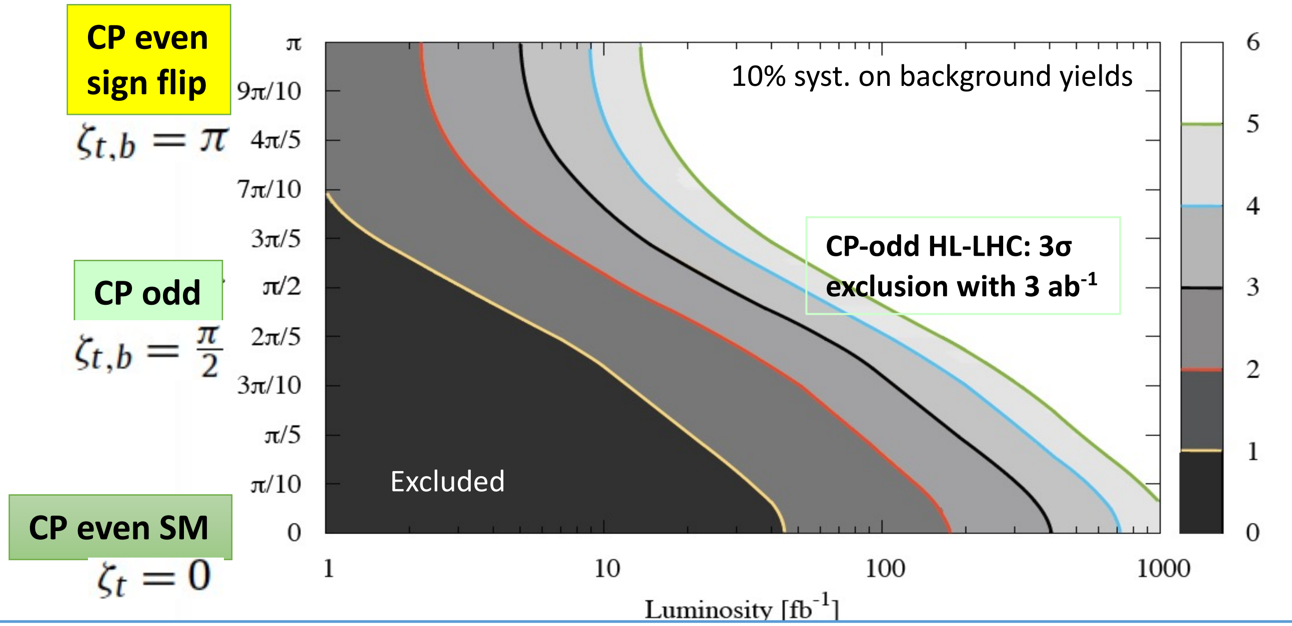
SM: $$\mathcal{L}_{\text{Yukawa}} = -\frac{m_t}{v}\bar{t}th - \frac{m_b}{v}\bar{b}bh,$$

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





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%**

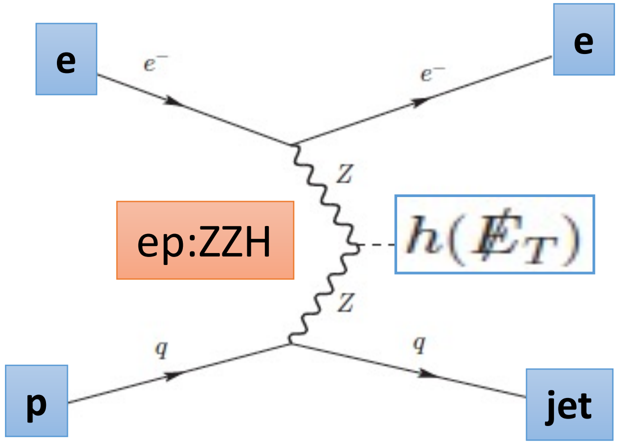
Branching for invisible Higgs

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%

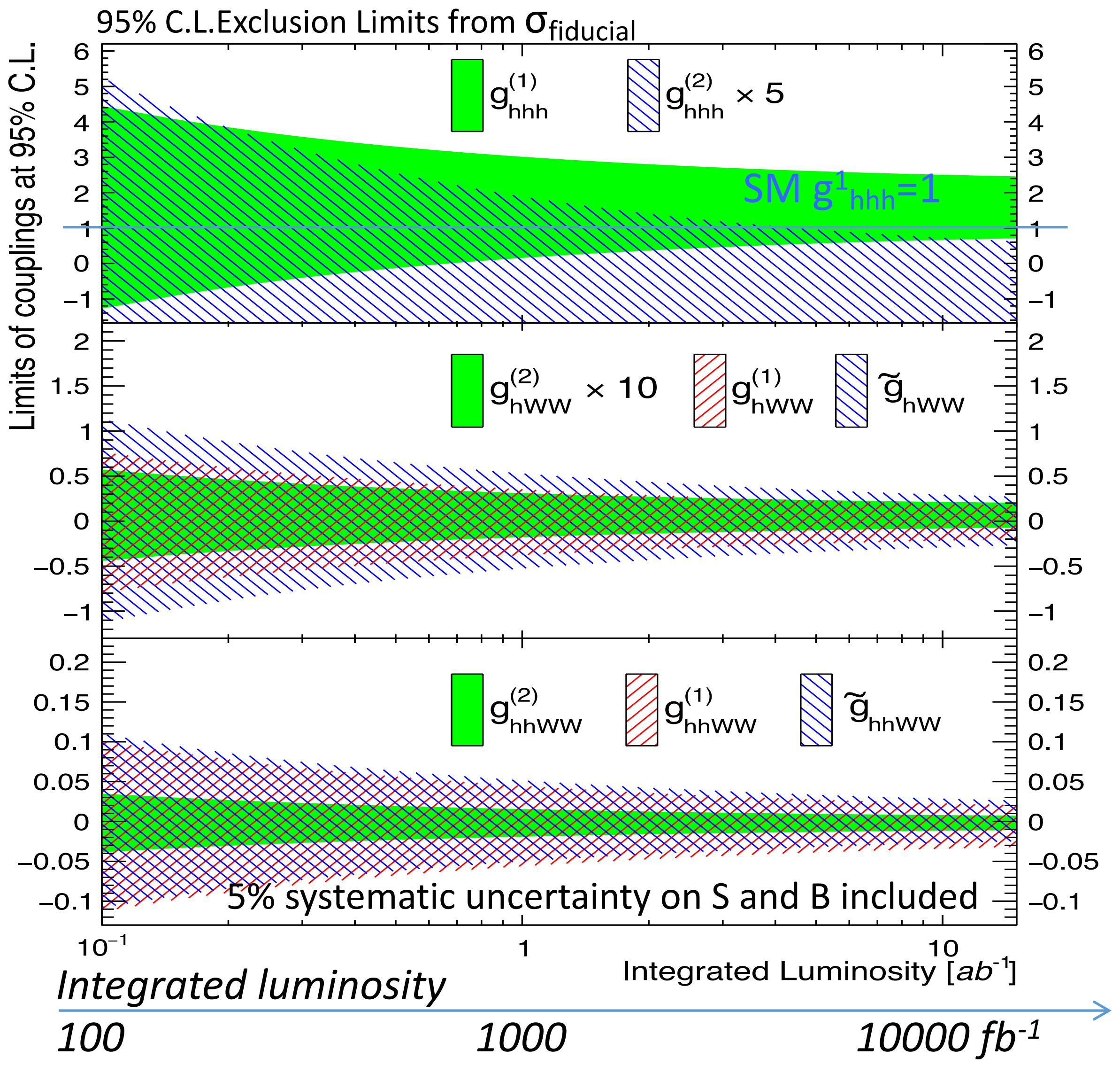
→ further detector and analysis details have certainly an impact on results → enhance potential further

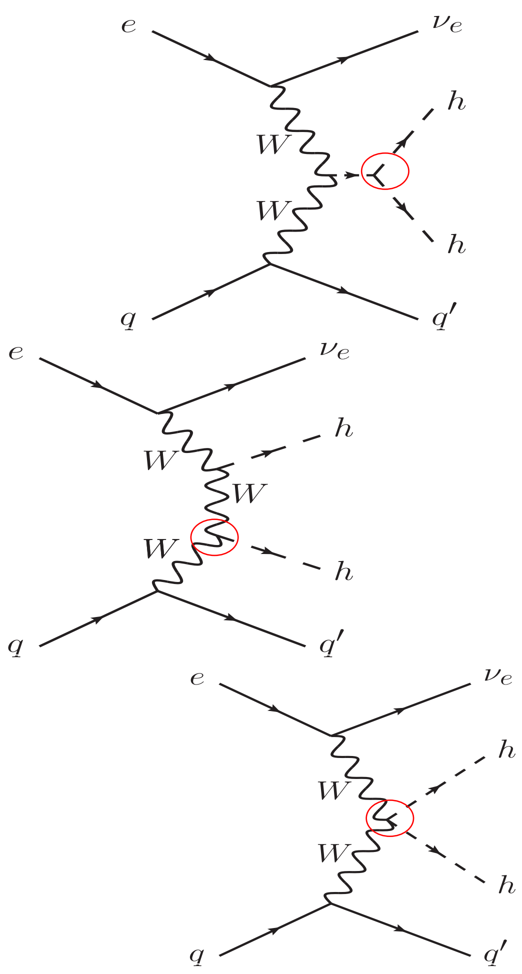
Double Higgs Production

[arXiv:1509.04016]

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.