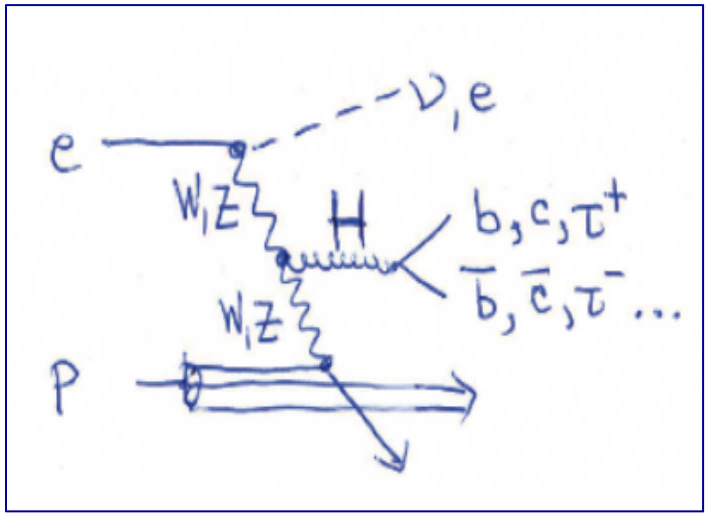
Prospects for Higgs Physics with Electron-Proton Colliders



Max Klein

UNIVERSITY OF LIVERPOOL

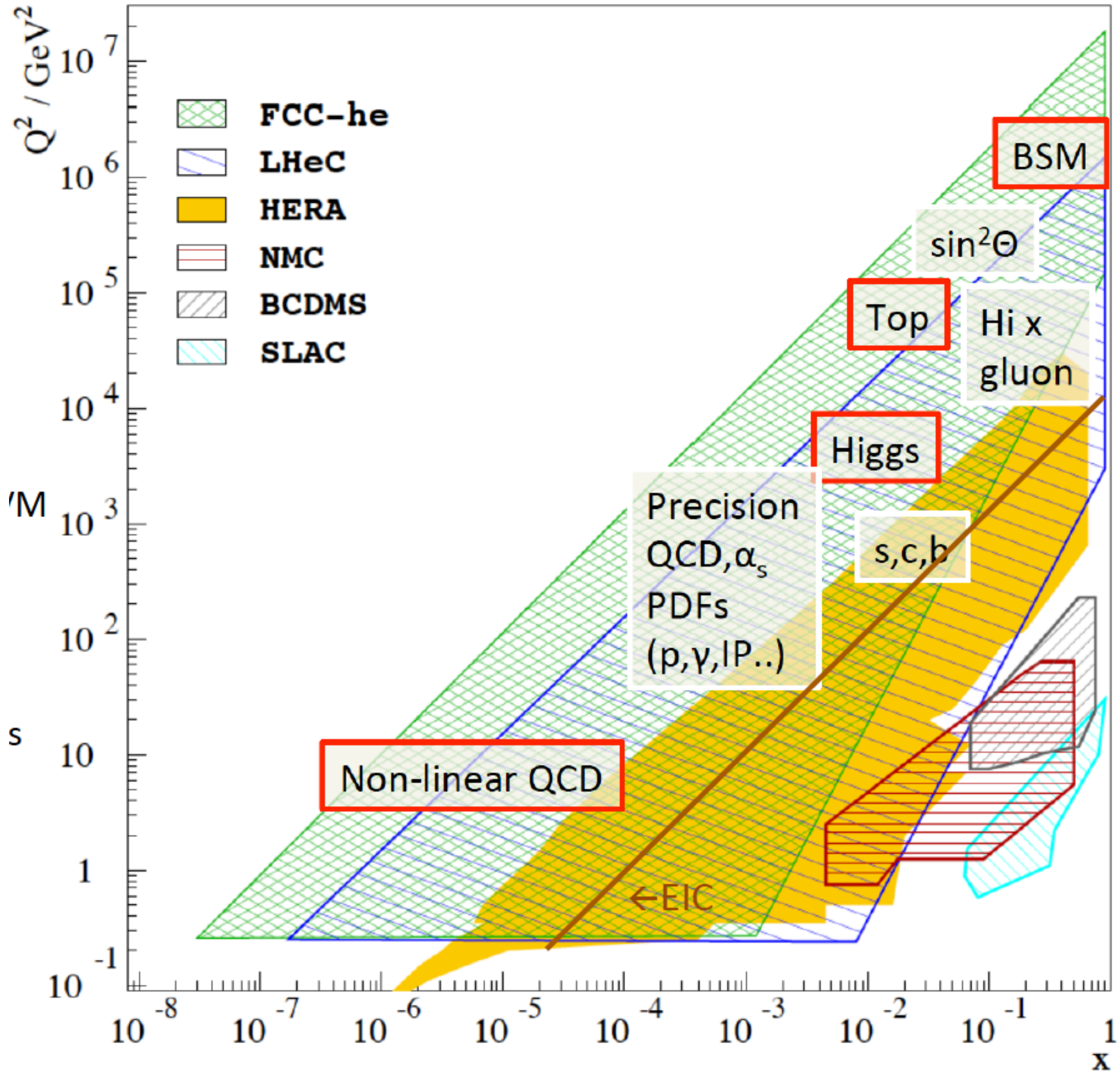
on behalf of

the LHeC/FCC-eh Higgs Group

Based on Uta Klein, Talk at FCC CDR 4.3.2019 at CERN and Higgs in ep paper, in preparation

DIS19, Torino, April 11th, 2019

Physics with Energy Frontier DIS



Raison(s) d'etre of the LHeC

Cleanest High Resolution Microscope: QCD Discovery

Empowering the LHC Search Programme

Transformation of LHC into high precision Higgs facility

Discovery (top, H, heavy ν's..) Beyond the Standard Model

A Unique Nuclear Physics Facility

Organisation*)

LHeC + FCC-he

International Advisory Committee with CERN mandate to provide "..Direction for ep/eA both at LHC+FCC"

Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Eckhard Elsen (CERN)
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Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – Chair
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (ESS)

*) 2018

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Accelerator+Detector+Physics

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Max Klein – Co-Chair
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5(11) are members of the FCC coordination team

OB+MK: FCC-eh coordinators

FCC IAC: Guenter Dissertori +

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Paul Newman,
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Detector
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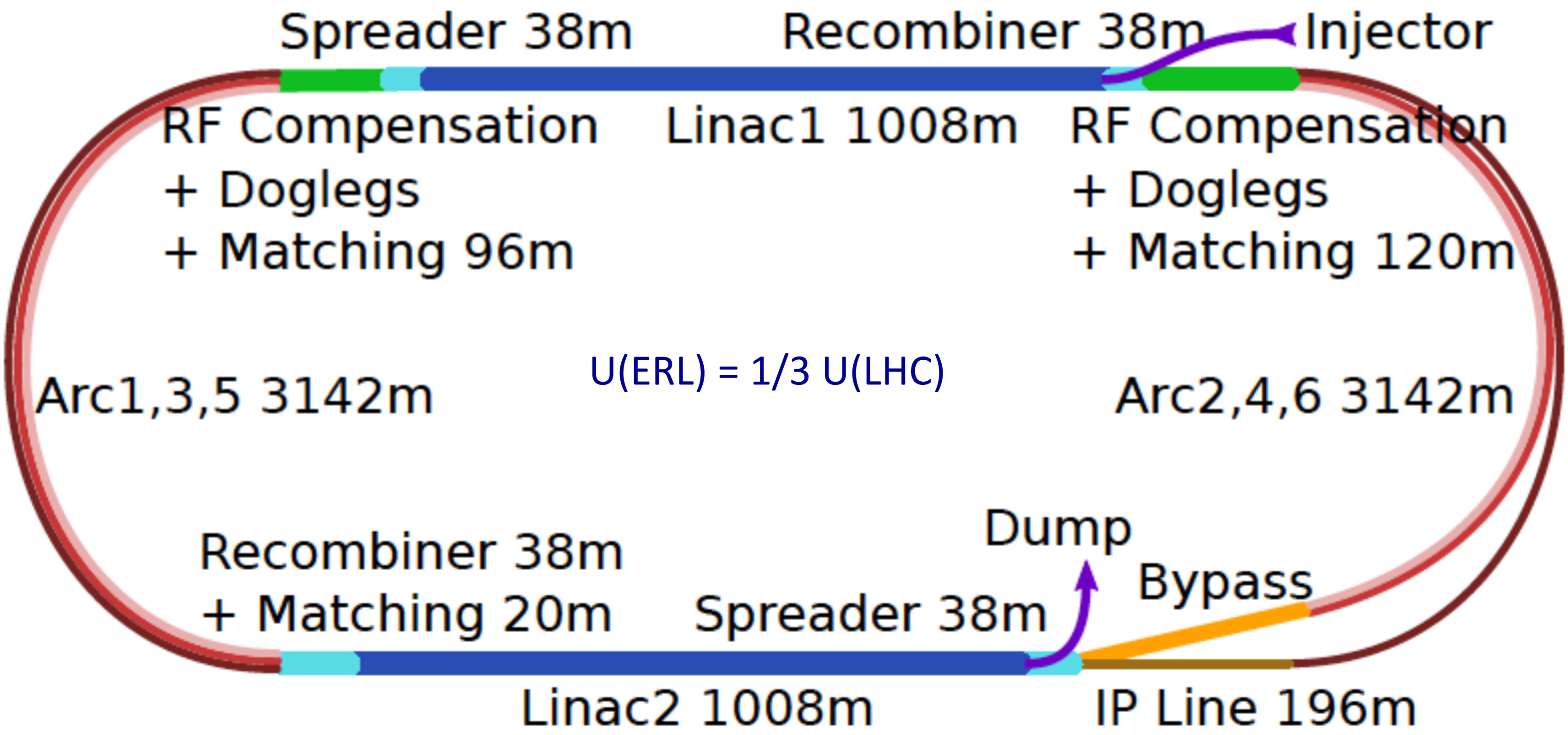
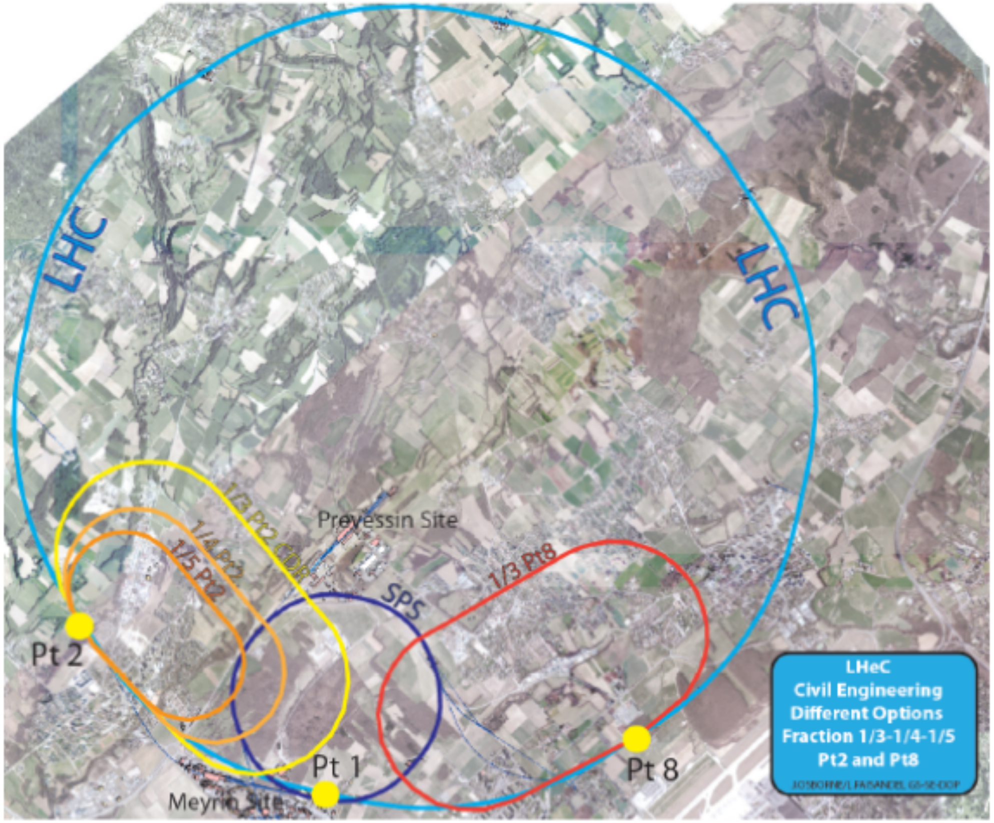
Energy Recovery Linac for LHeC/FCCeh



Concurrent operation to pp, LHC/FCC become 3 beam facilities. Power limit: 100 MW
10^{34} cm^{-2} s^{-1} luminosity and factor of 15/120 (LHC/FCCeh) extension of Q^2, 1/x reach
1000 times HERA luminosity. It therefore extends up to x~1.
Four orders of magnitude extension in deep inelastic lepton-nucleus (ion) scattering.

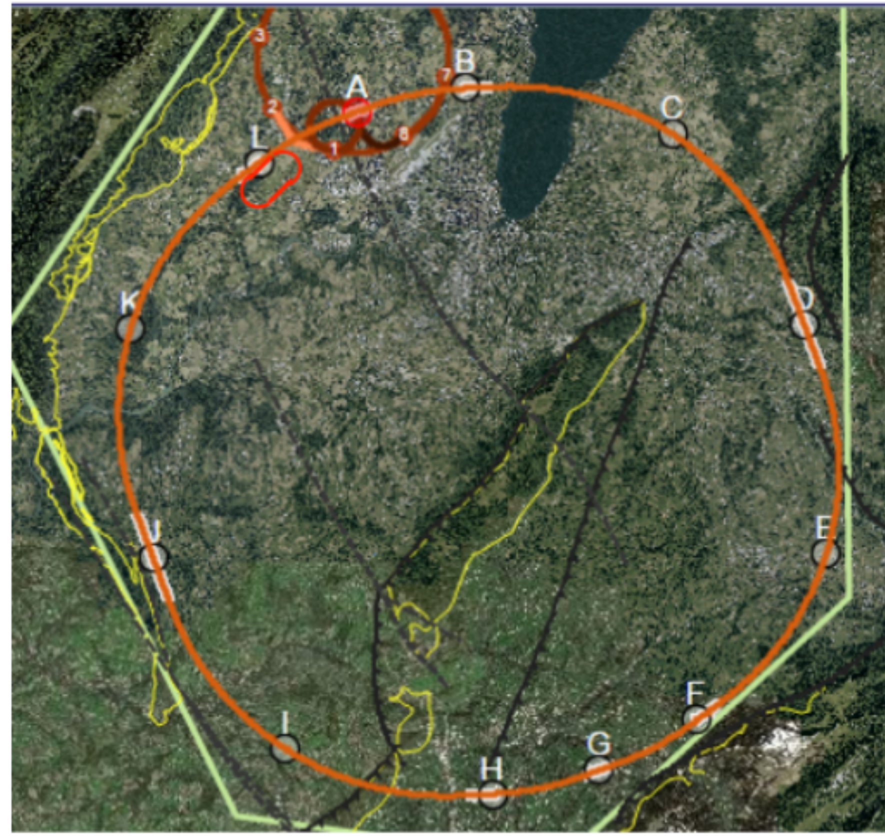
Future ep Colliders at CERN with electron ERL

LHC (HL and HE)



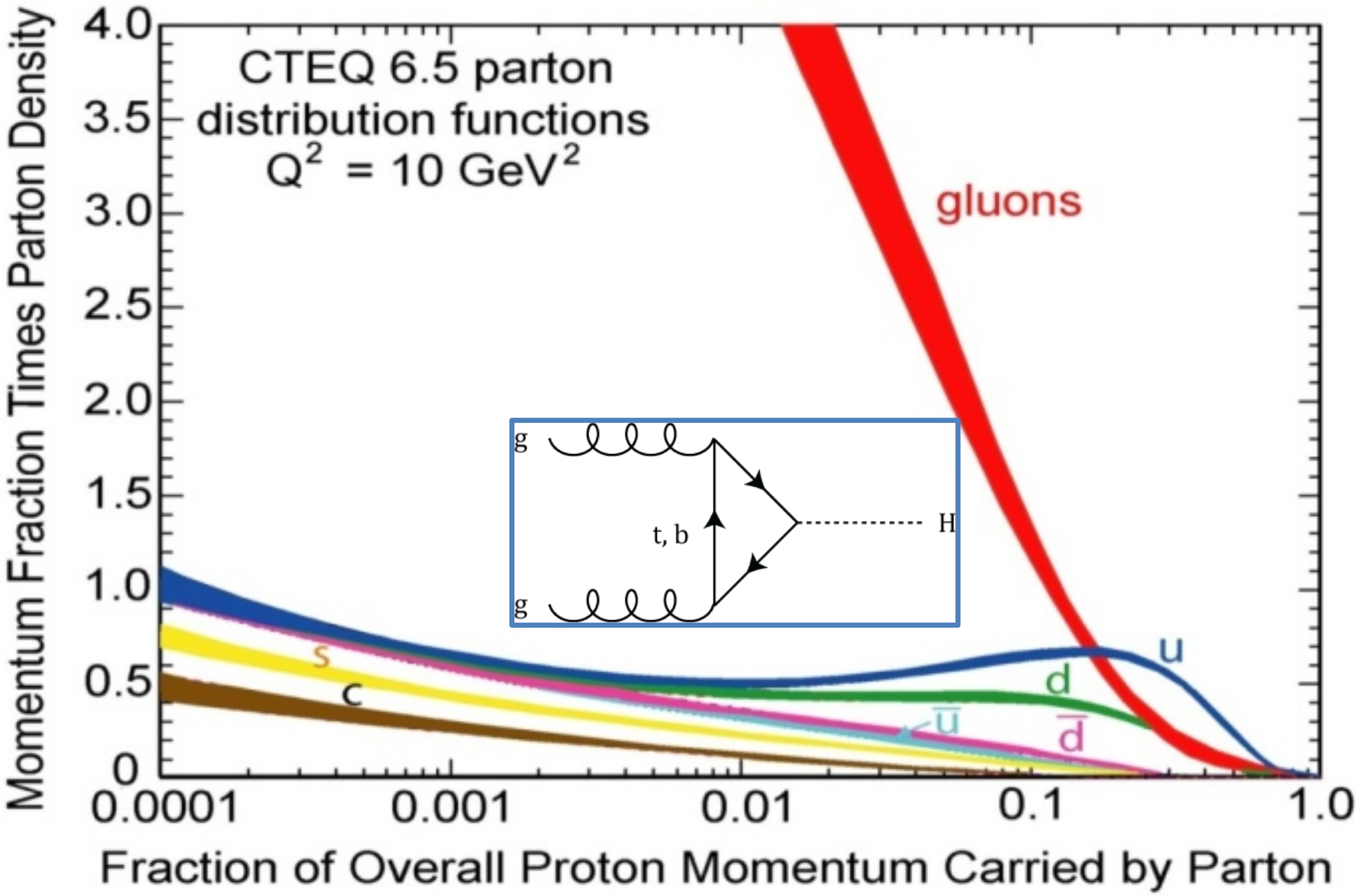
1.2-1.3 TeV cms energy
10^{34} luminosity: 1ab^{-1} in 10 years.]
2 ab^{-1} with HE LHC [interesting ERL Programme standalone in transition!]
WW→H Cross section similar to Z*→ ZH
Note: gg→H is about 50pb at LHC

FCC



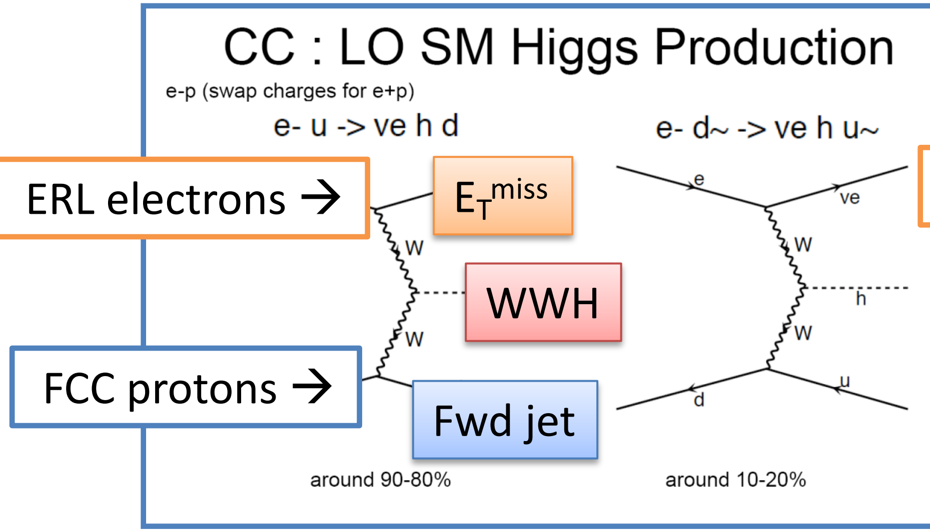
3.5 TeV cms energy
1.5 10^{34} luminosity: 2-3 ab^{-1} in 20 years
CC Higgs cross section ~ 1pb
This is 4 times higher than FCC-ee
Expect similar precision for both eh and ee

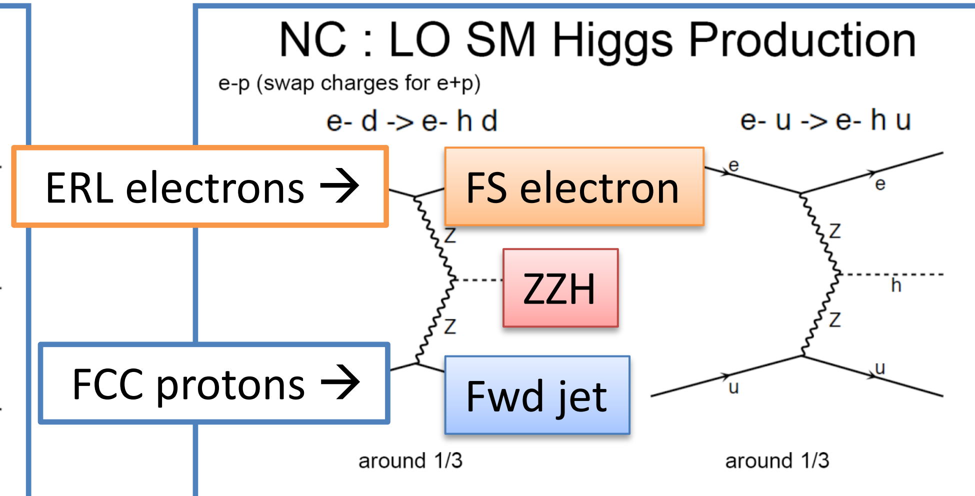
HERA's legacy: the gluon dominated proton



Rapidity plateau at $x=M_H/2E_p=0.01$: Precise knowledge of xg is a base for LHC Higgs physics
Prospect: very high precision PDFs and coupling from LHeC: to N^{3}LO → precision in pp (+ep)

SM Higgs Production in ep well understood





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

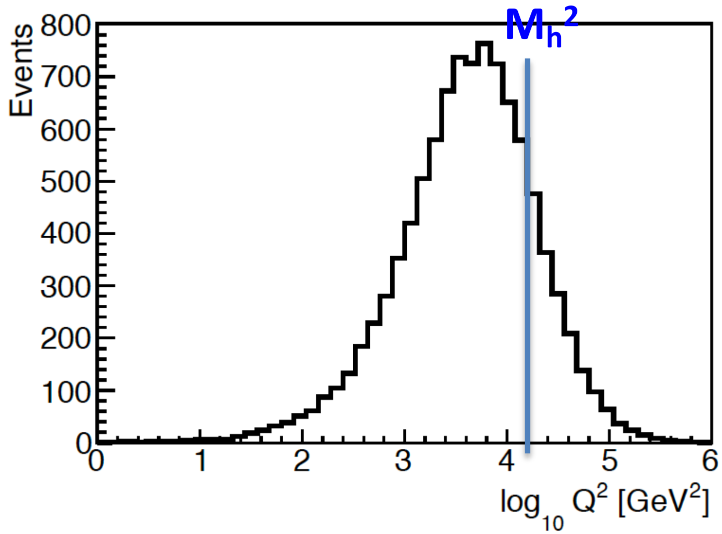
- Scale dependencies of the LO calculations are in the range of 5-10%. Tests done with MG5 and CompHep.
- **NLO QCD corrections are small**, but shape distortions of kinematic distributions up to 20%. QED corrections up to -5%.

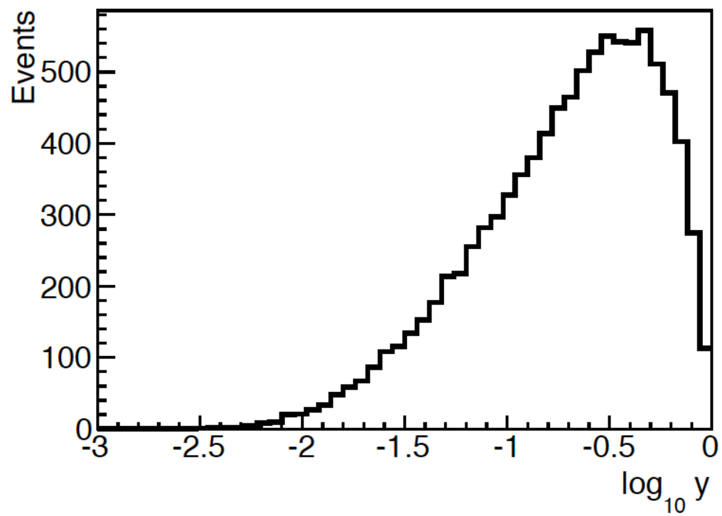
[J. Bluemlein, G.J. van Oldenborgh , R. Rueckl, Nucl.Phys.B395:35-59,1993]
[B.Jaeger, arXiv:1001.3789]

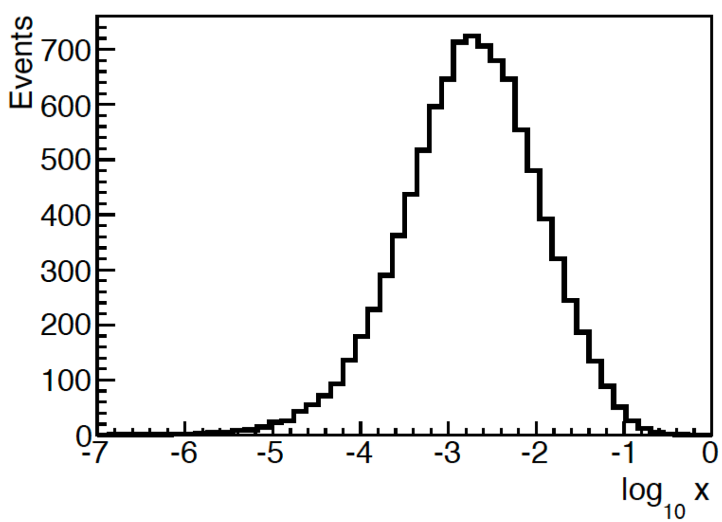
DIS Kinematics at FCC-eh @ √s=3.5 TeV

MadGraph scale: p_T of leading jet

Parton-level







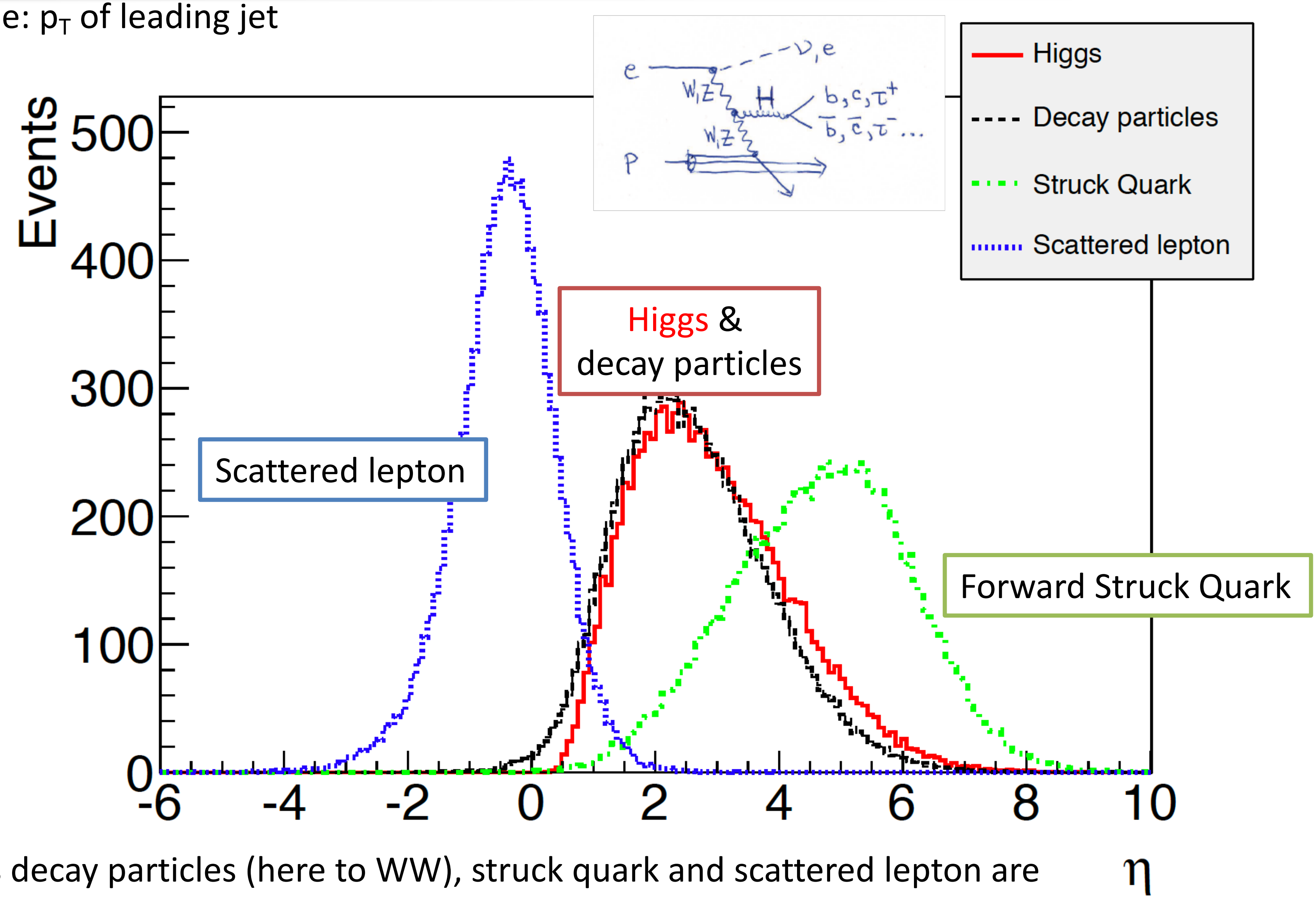
DIS kinematics very well behaved

[btw also at HERA, but the cross section was 0.7 (0.1) fb in CC (NC) while H1 and ZEUS each collected only about 0.5 fb^{-1} of luminosity.
LHeC: cross section 200 times larger and luminosity 500 times larger:
→ ep becomes a Higgs laboratory]

η Distributions in Higgs events at FCC-eh

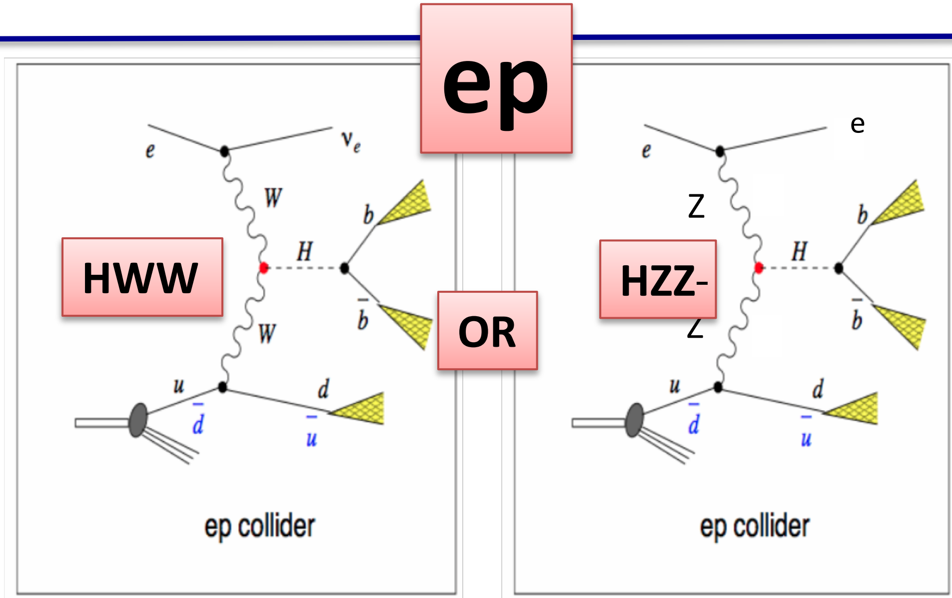
Parton-level

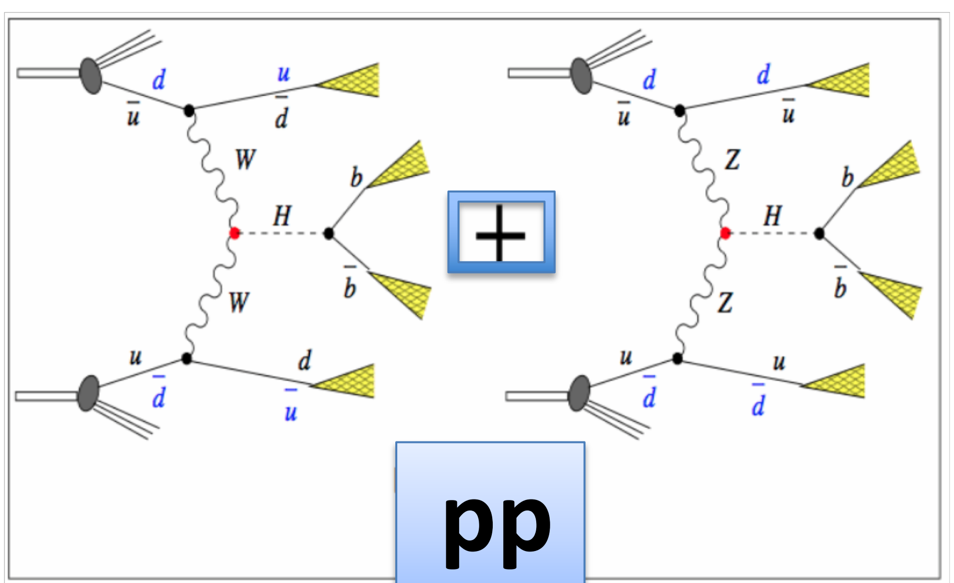
MG5 scale: p_T of leading jet



Higgs decay particles (here to WW), struck quark and scattered lepton are well separated in polar angle and in detector acceptance. Very fwd jet at FCC.

VBF Higgs Production and experimental conditions

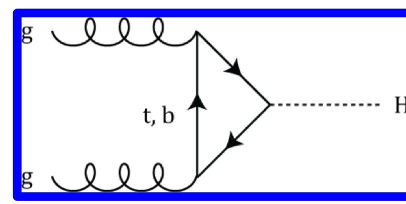




ep: Higgs production in ep comes uniquely from either CC or NC DIS via VBF

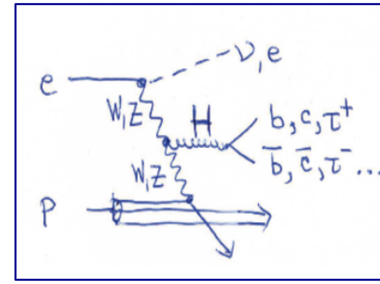
Clean bb final state, S/B >1
e-h Cross Calibration for Precision ep
Clean, precise reconstruction and easy distinction of ZZH and WWH
pile-up in ep:
<0.1@LHeC up to 1@FCCeh events

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, too harsh for cc
Final precision in pp needs
accurate N^3LO PDFs & α_S

Rates of Higgs production at LHeC



LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	$\text{N}^H_{CC}\ e^-p$	$\text{N}^H_{NC}\ e^-p$	$\text{N}^H_{CC}\ e^+p$
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

Approximately

x4 at HE LHC

x10 at FCC-eh
a million bb ..

Due to longer operation, higher luminosity and higher cross sections

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
- **Higgs mass 125 GeV as default**
- Fragmentation & hadronisation uses **ep-customised** Pythia.

- **Delphes 'detector'**

→displaced vertices and signed impact parameter distributions → studied for LHeC, and used for FCC-eh SM Higgs 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')

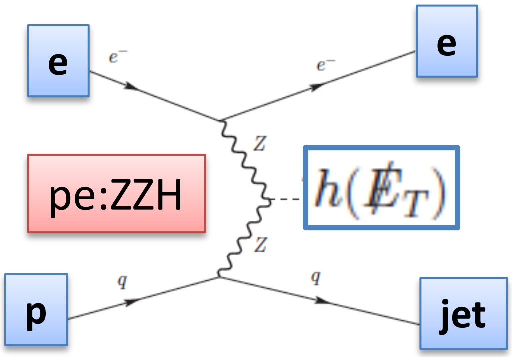
Branching for invisible Higgs

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-he 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% [arXiv: 1508.01095]
HL-LHC @ 3 ab^{-1} < 3.5% [arXiv:1411. 7699]



PORTAL to Dark Matter ?

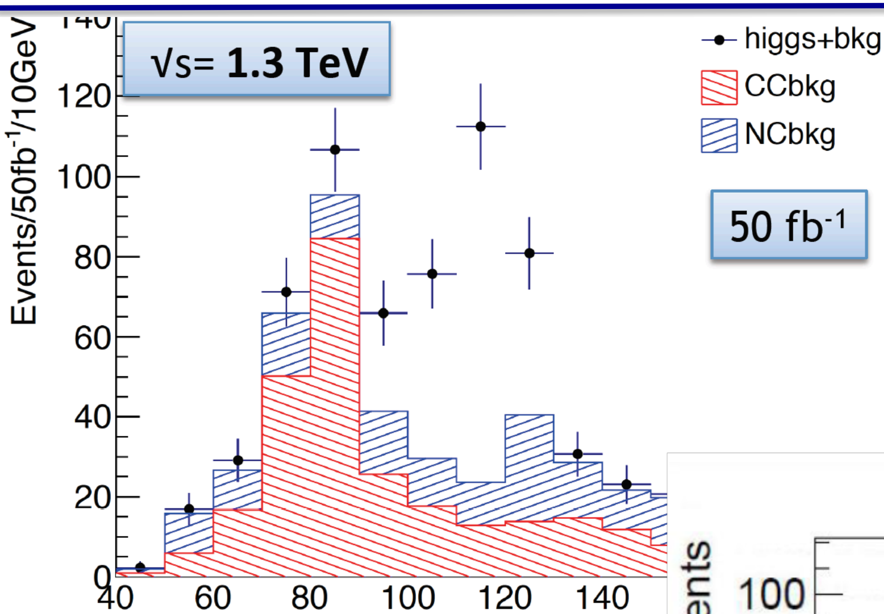
- ✓ **Uses ZZH fusion process to estimate prospects of Higgs to invisible decay using *standard cut/BDT analysis techniques***
- ✓ **Results for full MG5+Delphes analyses, done for 3 c.m.s. energies → very encouraging for a measurement of the branching of Higgs to invisible in ep down to 1.2% (1.7%) for 2 (1) ab^{-1}**

- ✓ 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**

CDR Updates: Two independent analyses

[after Higgs discovery M_H=125 GeV, E_p=7 TeV, E_e=60 GeV; cut-based & conservative]

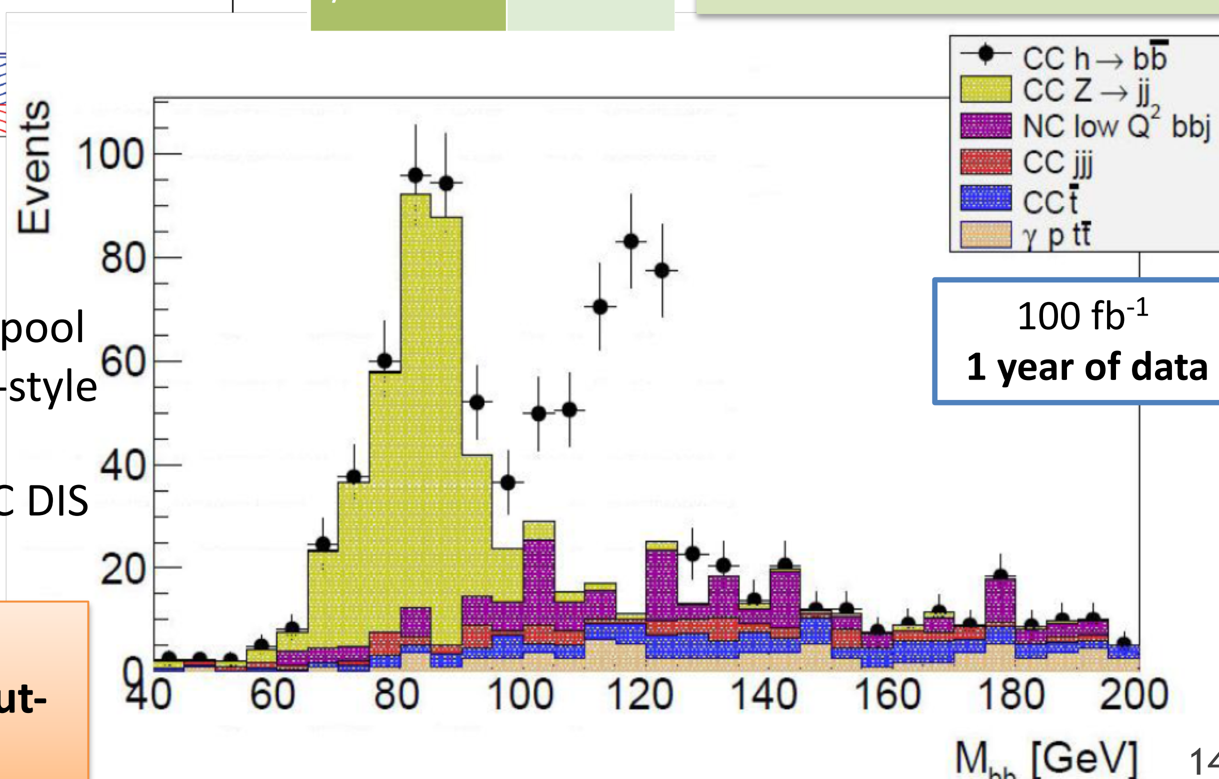


Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

M_H selection [100-130 GeV]	E_e = 60 GeV ($50\ fb^{-1}$, P=0)
H → bb signal	175
S/N	1.9
S/√N	18.1

PGS of LHC detector
+ flat parton-level b-tagging for |η|<3.0
b: 60%, c: 10%, **udsg: 1%**
CAL coverage |η|<5.0

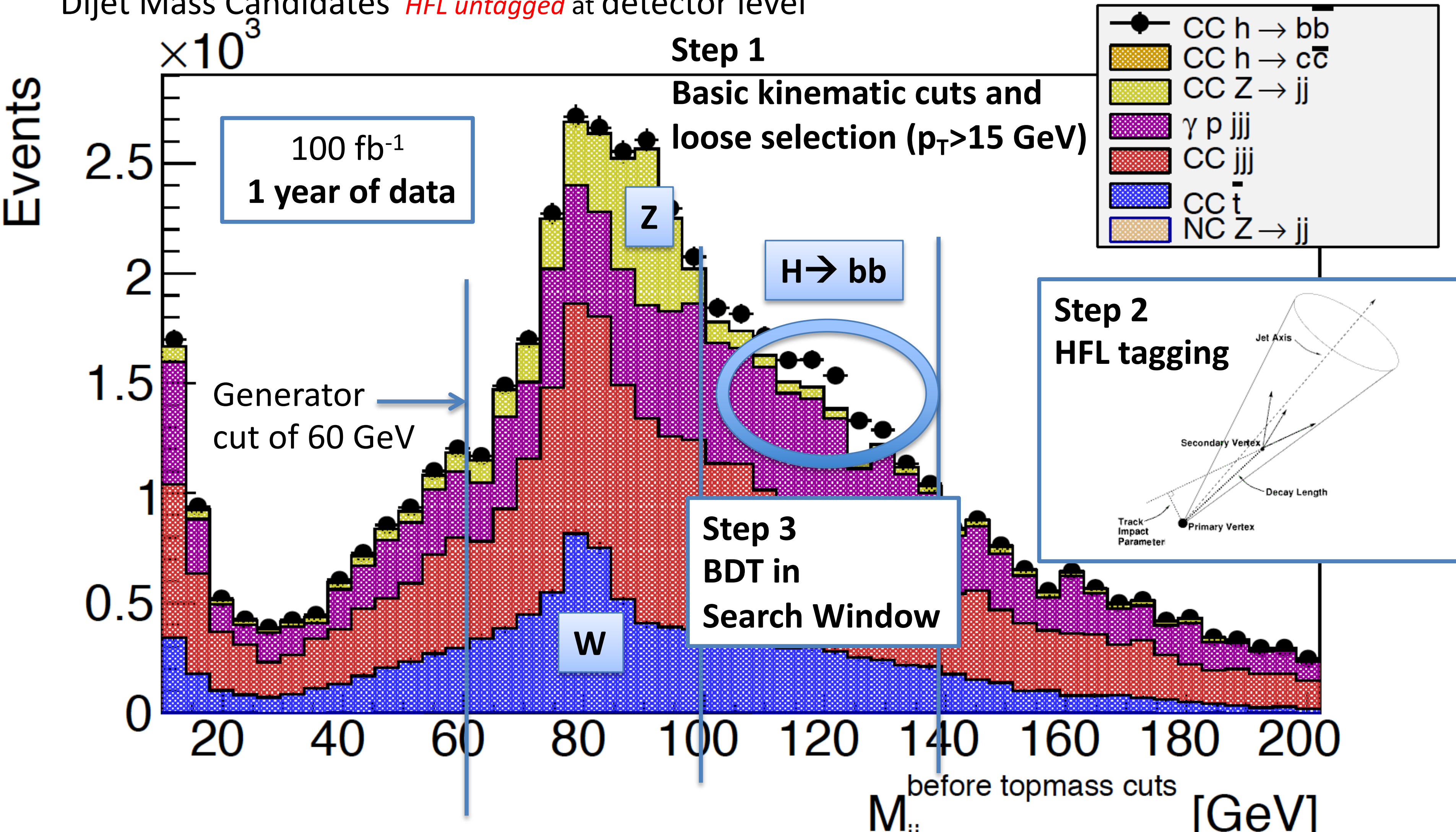
ICHEP 2014
Master Thesis Ellis Kay, Liverpool 2014, PGS "detector" ATLAS-style and & modeling of PHP background using low Q^2 NC DIS



Confirmed CDR: S/N>1 using conservative light misID and cut-based δμ=2% for 1 ab⁻¹

Hunting for Precision Hbb

Dijet Mass Candidates *HFL untagged* at detector level



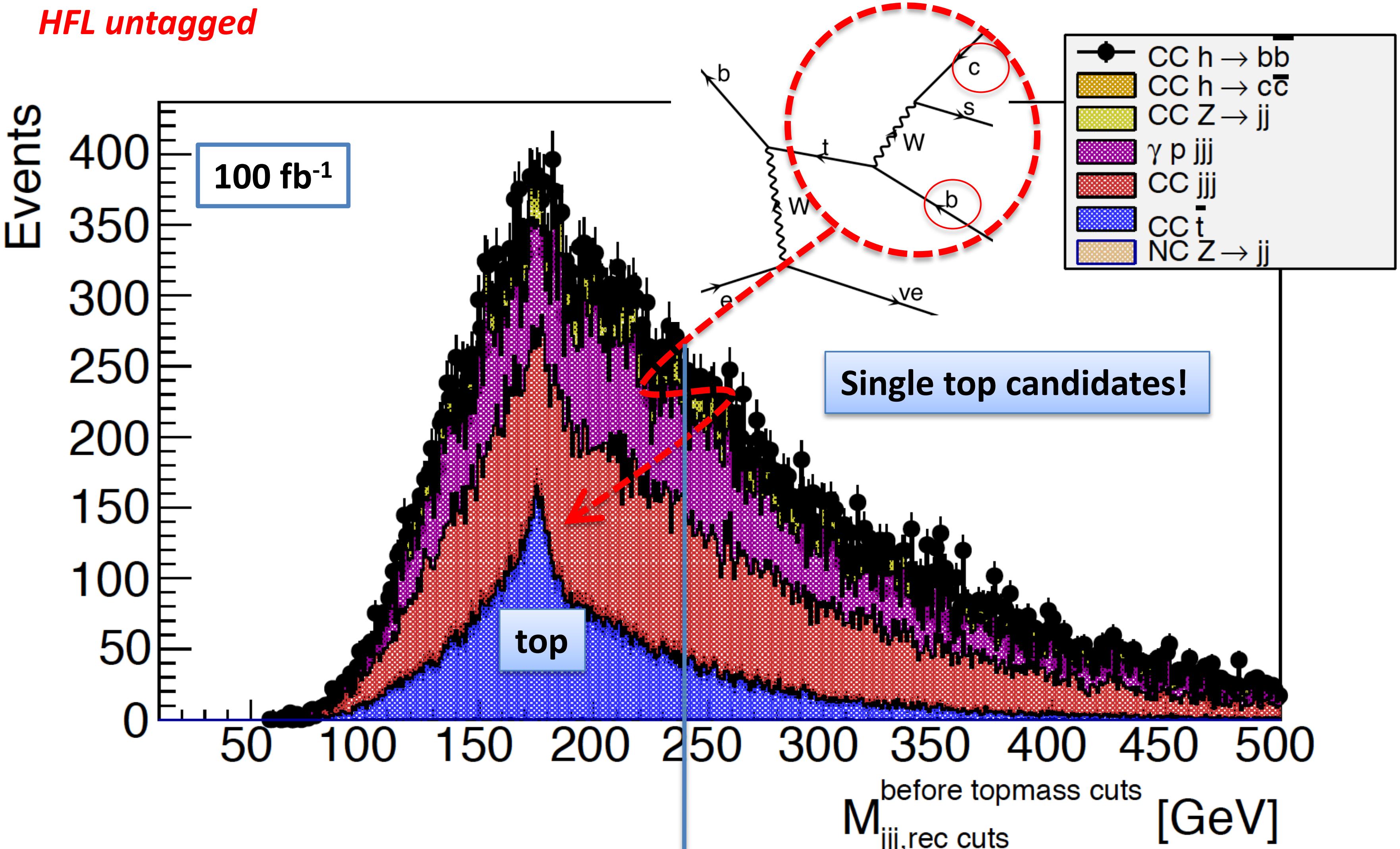
'Worst' case scenario plot : Photoproduction background (PHP) is assumed to be 100%!

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

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

Top: Mass of three highest p_T Jets

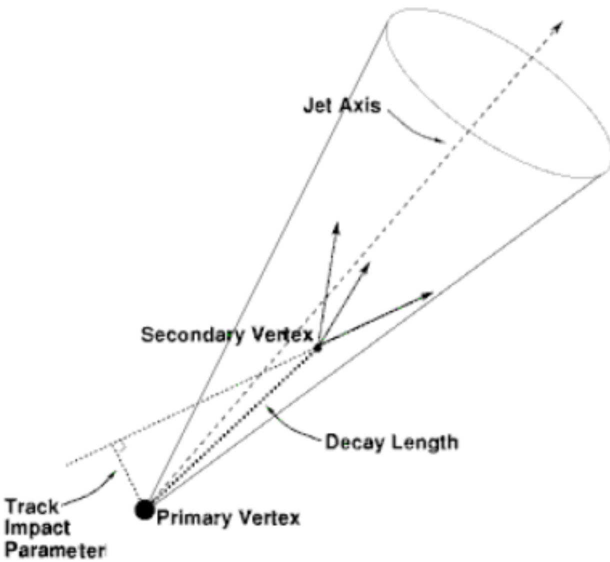
HFL untagged



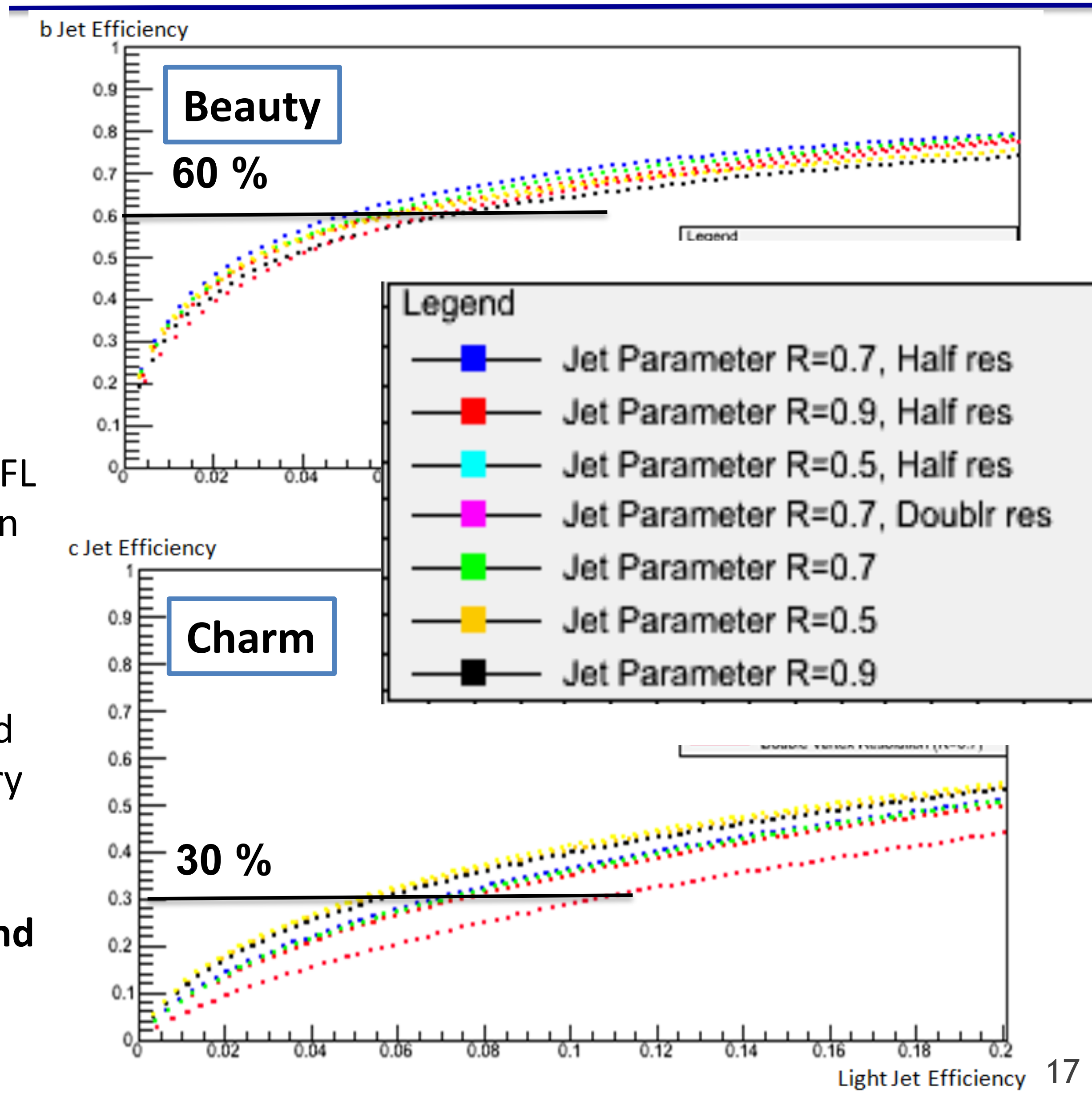
➔ <u>cut-based</u> analysis: usual cut to accept Higgs candidates on cost of signal efficiency

HFL Tagging

Uta Klein & Alan Chan & Jonas Waldendorf MPHYS 2015; Daniel Hampson MPHYS 2016



- → Realistic and conservative HFL tagging (a la Tevatron) within Delphes realised and dependence on vertex resolution (nominal 10 μm) and anti-kt jet radius studied
- → Light jet misID efficiency very conservative, worse than ATLAS-BDT-based
- → **used in full LHeC analysis and for FCC-eh extrapolations**

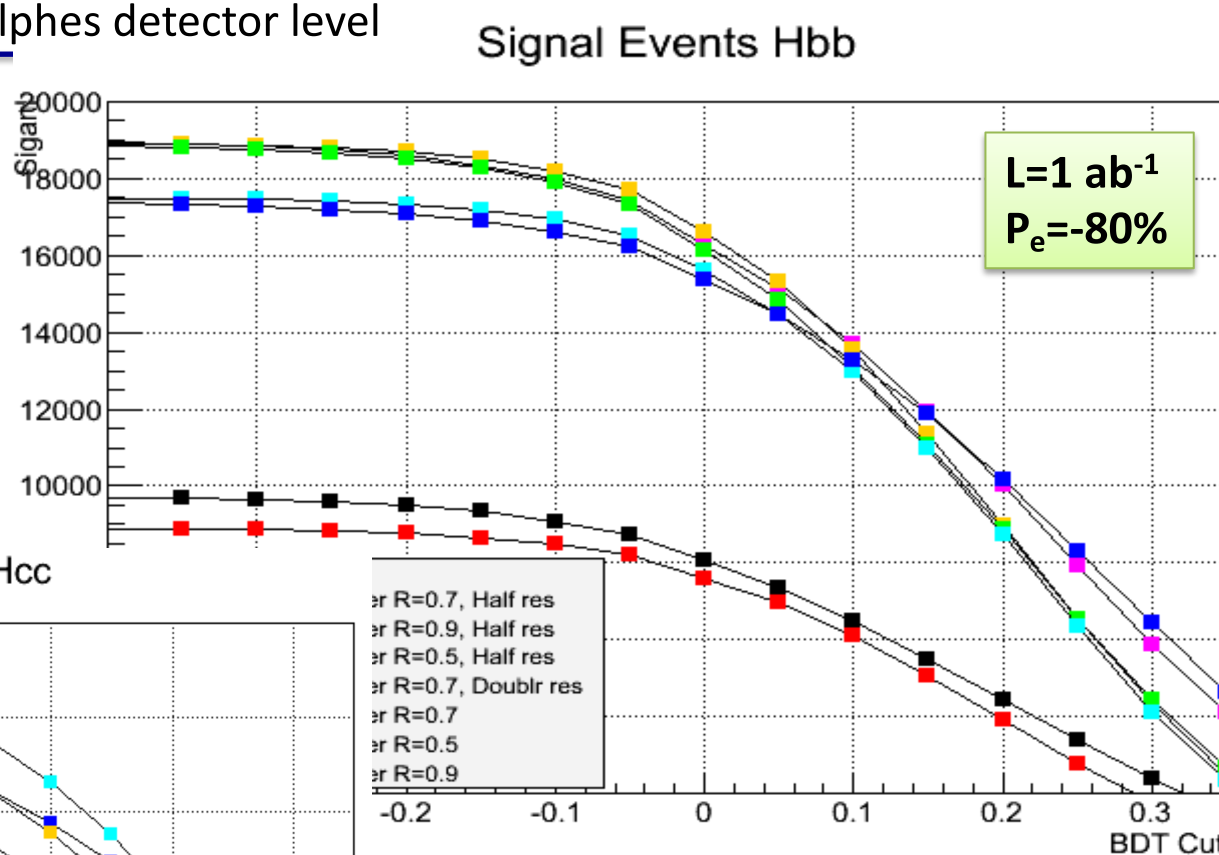


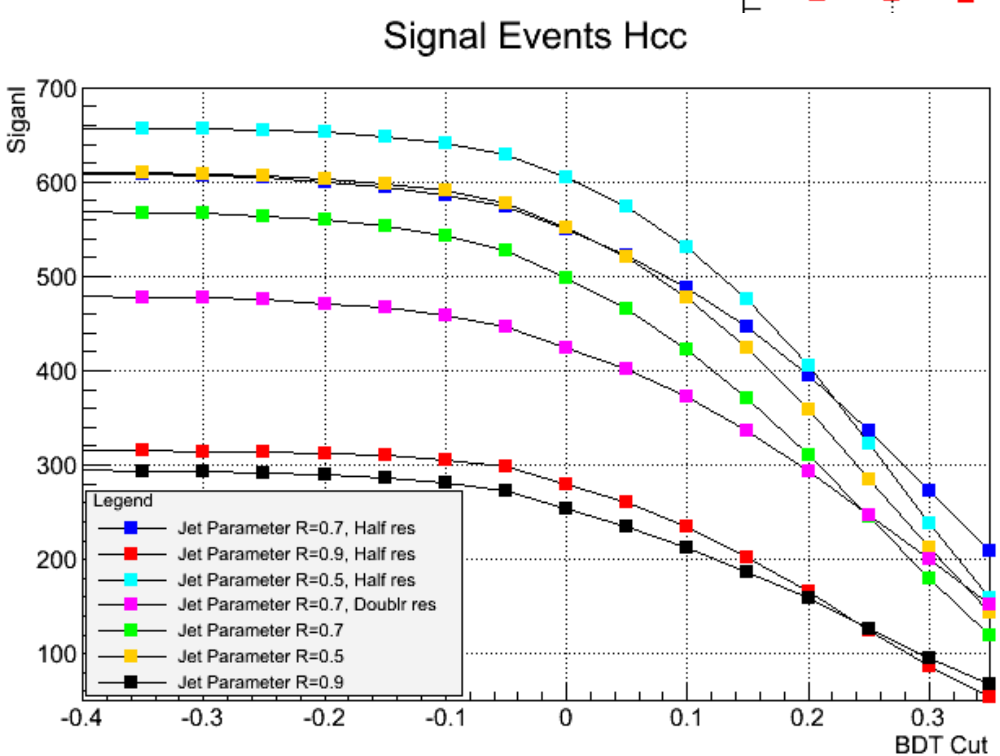
BDT Results for Higgs @ LHeC

using realistic HFL tagging at Delphes detector level

Daniel Hampson,
MPHYS 2016

Hbb : Clear sensitivity to chosen jet radius; rather robust w.r.t. vertex resolution in range of 5 to 20 μm

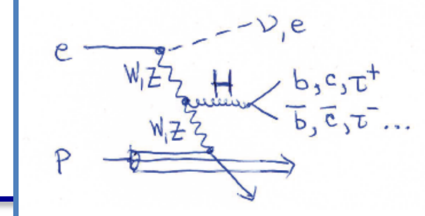




Hcc : High sensitivity to vertex resolution (nominal 10 μm) and jet radius

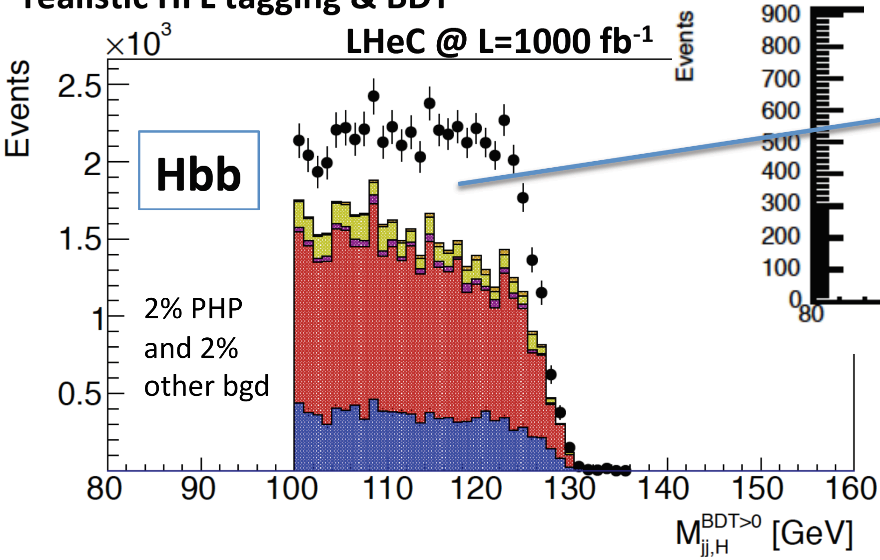
→ expect about 400-600 Hcc candidates

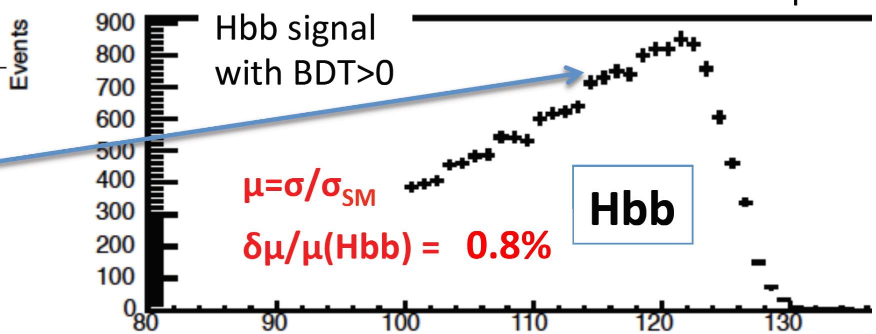
Higgs in ep – clean S/B, no pile-up

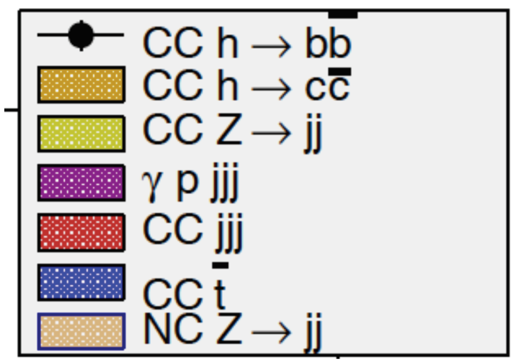


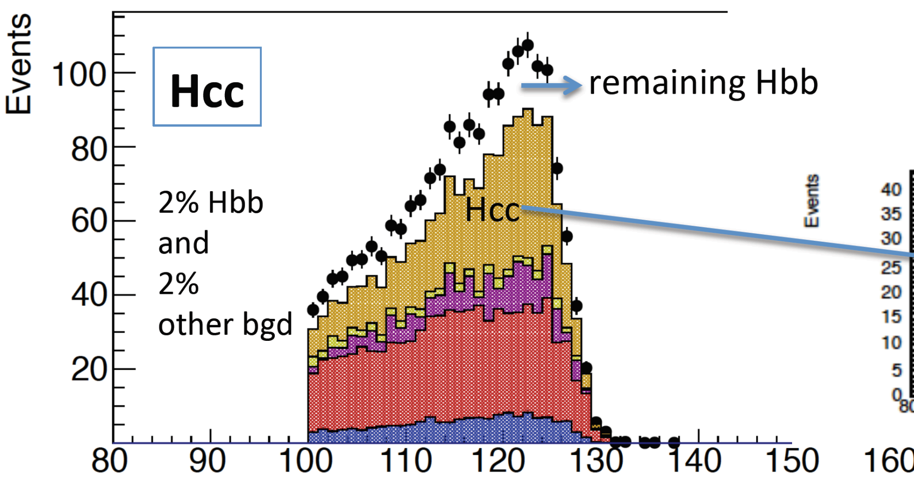
Uta Klein & Daniel Hampson

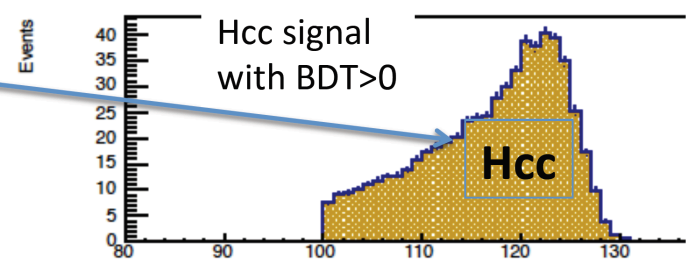
& Izzy Harris
BSc 2017











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

Assuming
ATLAS
light
jet misID
efficiencies

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

Further Estimates of Higgs Prospects

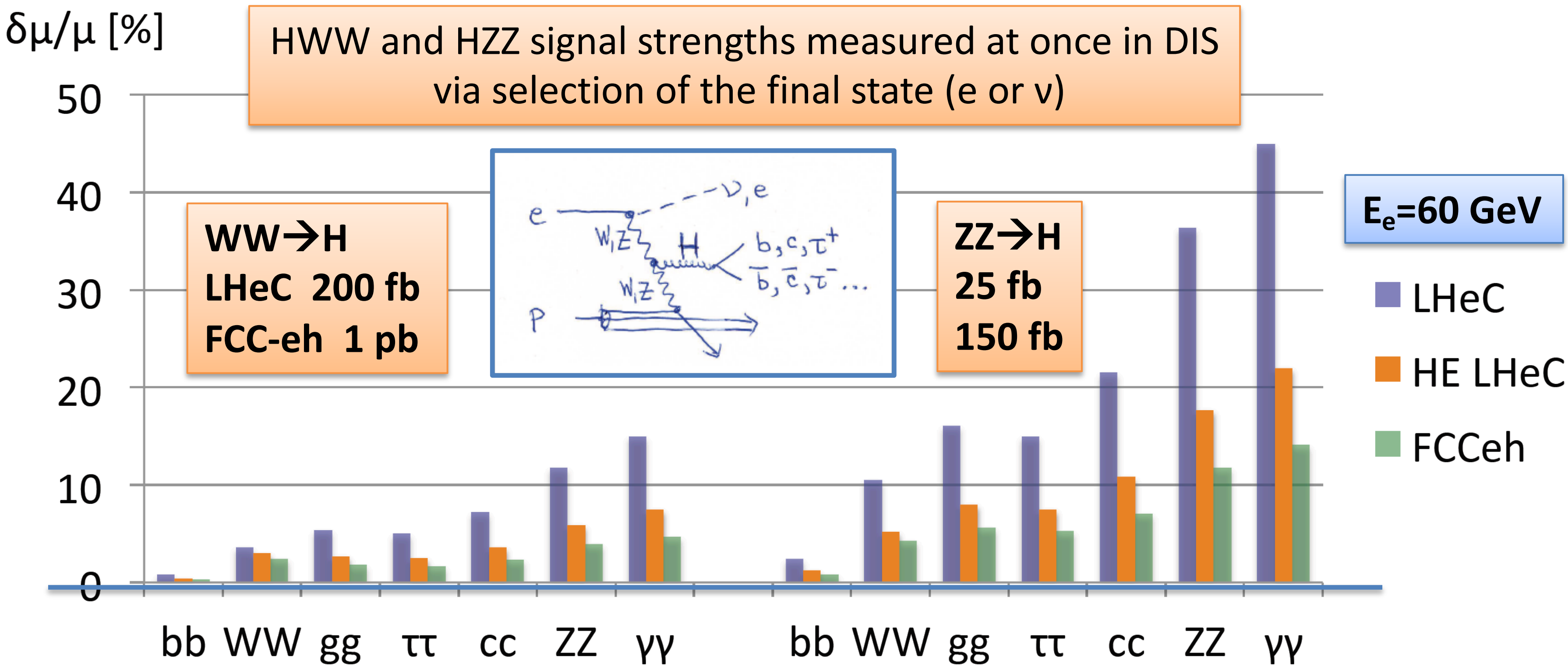
- Use LO Higgs cross sections **σ_H for M_H=125 GeV, in [fb],** and branching fractions BR(H→XX from Higgs Cross Section Handbook (c.f. appendix)
- Apply further branching, BR(X→FS) in case e.g. of W→ 2 jets and use acceptance, Acc, estimates based on MG5, for further decay
- Use reconstruction efficiencies, ε, achieved at LHC Run-1, see e.g. prospect calculations explored in arXiV:1511.05170
- Use fully simulated LHeC Hbb and Hcc results as baseline for S/B ranges
- Use fully simulated Higgs to invisible for 3 ep c.m.s. scenarios as guidance for extrapolation uncertainty (~25%)
- Estimate HIggs events per decay channel for certain Luminosity in [fb^{-1}]

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

- Calculate uncertainties of signal strengths w.r.t. SM expectation $\mu = \frac{\sigma}{\sigma_{SM}}$

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

SM Higgs Signal Strengths in ep



submitted to EU strategy CERN-ACC-Note-2018-0084

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}

Systematic errors of μ for bb

work in progress

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

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

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

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

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

Jorge de Blas, M+U.Klein 4/18

$$\frac{\delta\mu}{\mu} = \frac{1}{\sqrt{N}} \bullet f$$

$$f = \sqrt{\frac{1+1/(S/B)}{Acc \bullet \varepsilon}}$$

$N \approx 10^5$

Dominant HFL tagging: light jet misID [ATLAS vs 3 ATLAS]
Photoproduction: reduced down to 10% vs 2%
Acceptance x Efficiency: ±5%
→ Estimated effects on f

Variation of hadronic energy resolution
(M Tanaka, 2017): 7% on cross section
Luminosity 0.5 to 1%: negligible

Prediction of ep CC SM H→bb cross section: 2%
Based on LHeC measurements and PDFs

→ δμ/μ = (0.80 ± 0.10 light q ± 0.02 Acc ± 0.02 γp ±0.06 hadr cal ± 0.02 σ_{SM})%
= (0.80 ± 0.12) % [***preliminary***]

→ δκ (bb) = (1.40 ± 0.03)%
→ δκ (WW) = (0.54 ± 0.03)%

Note:
Doubling the WW signal strength uncertainty increases δκ (bb) from 1.4 to 1.9% and δκ (WW) from .54 to .74%

κ Coupling Fit Comparison

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

So far we considered 7 most abundant SM Higgs decay channels, i=1..7

- ✧ bb, WW, gg, ττ, cc, ZZ, γγ
- ✧ ttH may be added. (ep: 1.3 TeV cms!)

→ eight measurements of κ_W and κ_Z

→ two simultaneous measurements of the other couplings (in CC and NC)

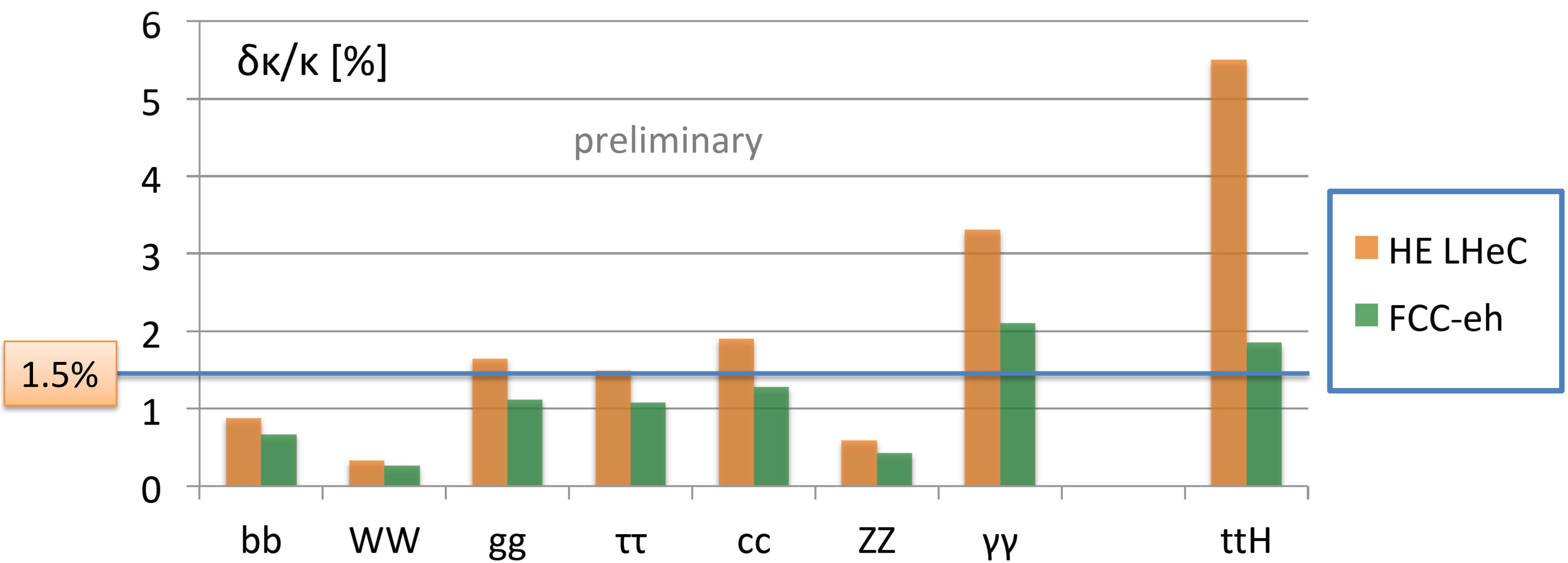
For LHeC nominal

0) Parameter "Kw" : 1 +- 0.0054	xww 1. 0.54536E-02
1) Parameter "Kz" : 1 +- 0.012	xzz 1. 0.11857E-01
2) Parameter "Kg" : 1 +- 0.030	xgg 1. 0.30503E-01
3) Parameter "Kga" : 1 +- 0.072	xyy 1. 0.72375E-01
4) Parameter "Kc" : 1 +- 0.037	xcc 1. 0.37344E-01
5) Parameter "Kb" : 1 +- 0.014	xbb 1. 0.13978E-01
6) Parameter "Ktau" : 1 +- 0.028	xttau 1. 0.28223E-01
J de Blas	M Klein

Two independent fit programs: results are in very good agreement.

Model-dependent Coupling Fit HE LHeC & FCC-eh

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



M+U.Klein, 5.4.18

NC+CC Analysis using overconstrained system of couplings

arXiv:1702.03426
Coleppa, Kumar^2, Mellado

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

See also talk by Jorge de Blas@FCC-Week2018 for further fits and ep+ee combinations.

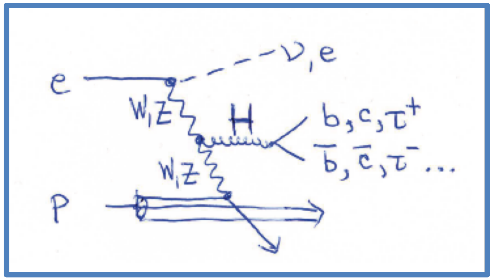
… and Consistency Checks of EW Theory

→ 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 cos²Θ 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-he	**± 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

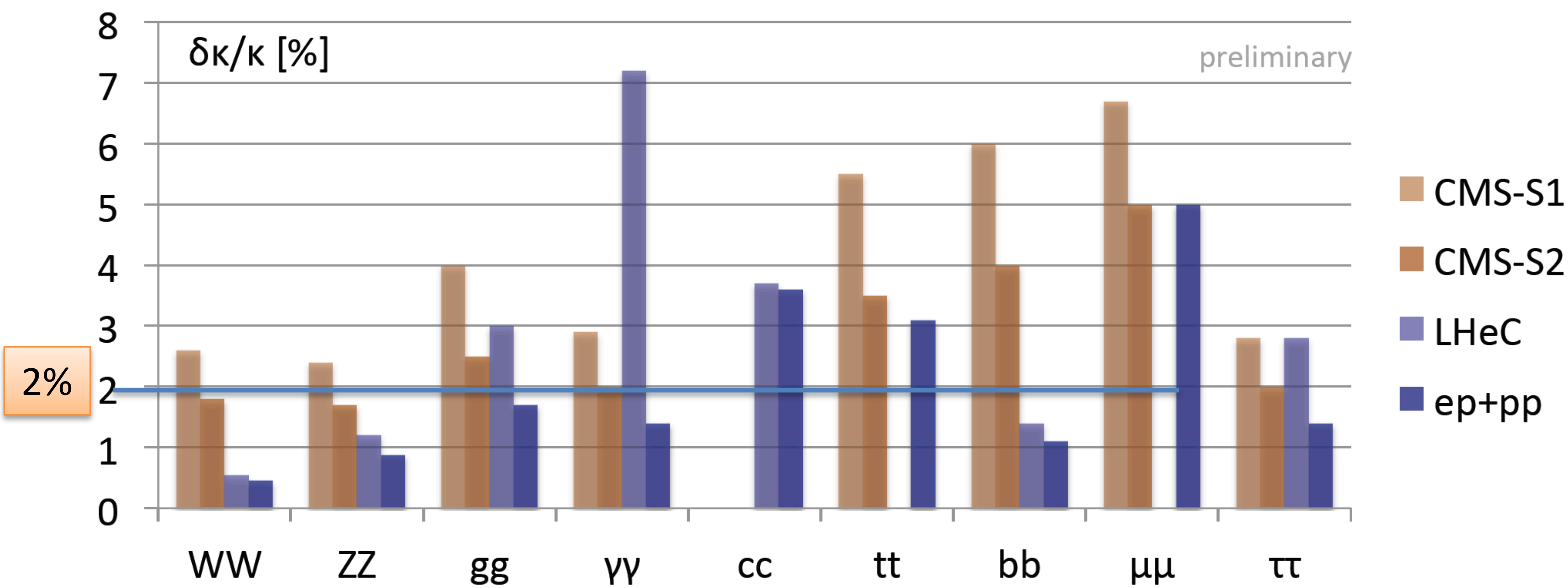
$$\frac{\sigma_{WW\to H\to c\bar{c}}}{\sigma_{WW\to H\to b\bar{b}}} = \frac{\kappa_c^2}{\kappa_b^2}$$

LHeC and HL-LHC Higgs Prospects

Hcc@pp: ~2.0-5.5 σ_{SM}@HL-LHC
[HL-LHC Oct 2017]

submitted to ECFA:

preliminary



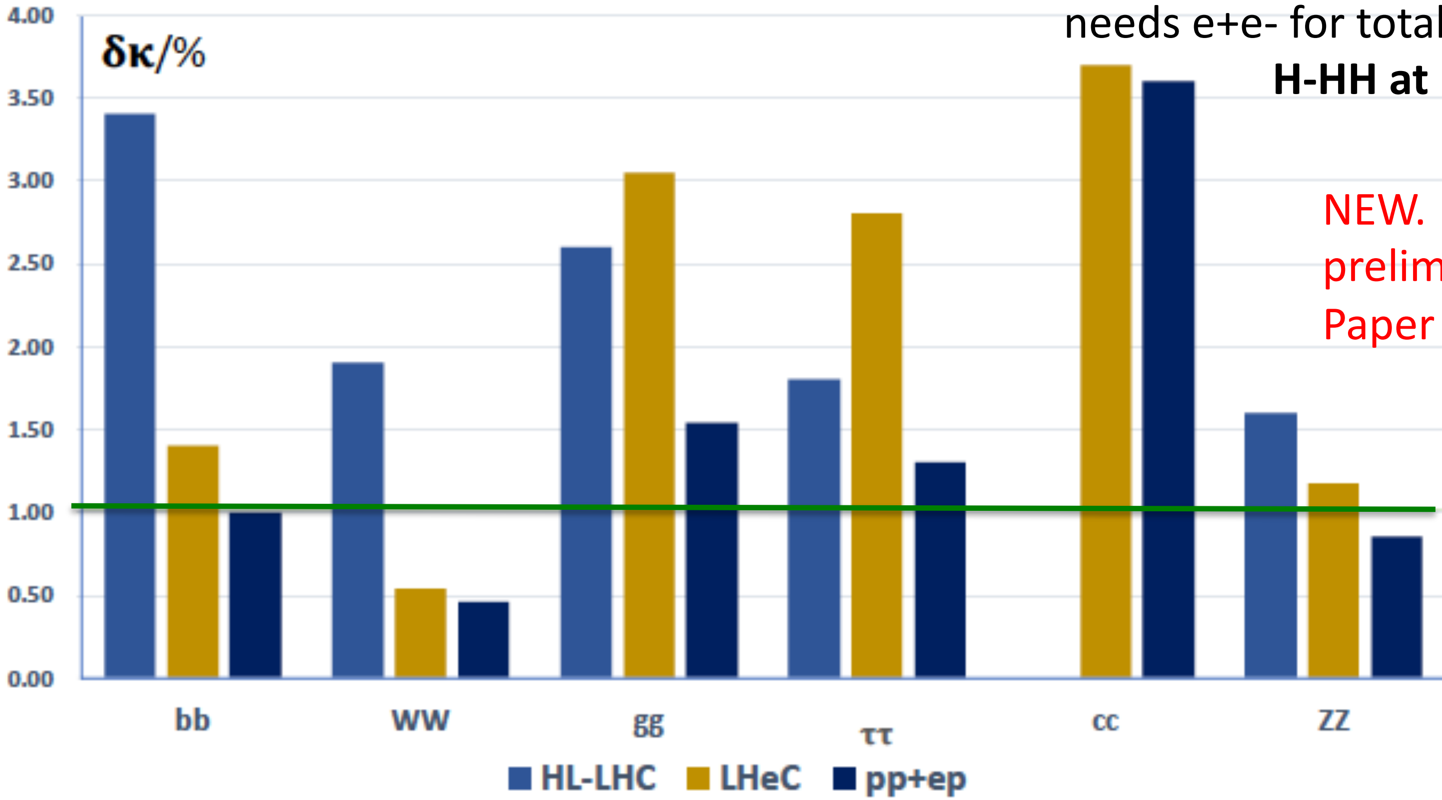
→ **Amazing prospect for measuring fundamental Higgs couplings to high precision (dark blue) at LHC with pp + ep using SM assumptions.**

HL-LHC prospects using new CMS projections ($3ab^{-1}$) with two scenarios, S1 and S2, in a SM coupling fit

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).

Higgs precision observables at FCC ee and eh

- **Fit to modified Higgs couplings (assuming no extra invisible decays)**

FCC-ee	
Coupling	Relative precision
κ_b	0.58%
κ_t	–
κ_τ	0.78%
κ_c	1.05%
κ_μ	9.6%
κ_Z	0.16%
κ_W	0.41%
κ_g	1.23%
κ_γ	2.18%
$\kappa_{Z\gamma}$	–

FCC-eh	
Coupling	Relative precision
κ_b	0.74%
κ_t	–
κ_τ	1.10%
κ_c	1.35%
κ_μ	–
κ_Z	0.43%
κ_W	0.26%
κ_g	1.17%
κ_γ	2.35%
$\kappa_{Z\gamma}$	–

$$\kappa_i \equiv g_{hi}/g_{hi}^{SM}$$

Published in book 1 of FCC

Higgs coupling prospects in kappa framework

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	8	3	+4	—	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.30	0.60	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.3	**0.61**	0.56	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	1.6	**1.01**	0.90	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.4	**0.74**	0.67	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	10.1	**9.0**	3.8	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	4.8	**3.9**	1.3	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	3.1	1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	< 1.0	< 1.0	n.a.

Table from Book1 of FCC. (w/o LHeC and CepC)

Synergetic evaluation under way by ECFA Higgs working group → preparation for Granada.
Note: rare channels are for pp. Muon has 0.02% branching fraction – 10% error in e+e-

Higgs complementarities: Global fit to Higgs couplings at FCC

- **All single Higgs couplings can be determined below the 1%**

FCC-ee/FCC-eh
Precise determinations for the leading couplings

HZZ Crucial for normalization of FCC-hh results

FCC-hh
Completes the picture with precise determinations of Top and coupling associated to rare decays

NOT MODEL-INDEPENDENT:
Results assume that, if there is New physics, it can only be in the Higgs couplings

HLLHC + FCC	
Coupling	Relative precision
κ_b	0.38%
κ_t	0.51%
κ_τ	0.58%
κ_c	0.79%
κ_μ	0.42%
κ_Z	0.14%
κ_W	0.17%
κ_g	0.74%
κ_γ	0.40%
$\kappa_{Z\gamma}$	0.52%

$$\kappa_i \equiv g_{hi}/g_{hi}^{SM}$$

what Higgs precision do we need?

- If new particles with TeV mass, effects on Higgs couplings are small, need ILC precision to confirm and decipher them
  - Little Higgs models with TeV scale partners

$$\frac{g_{hgg}}{g_{h_{SM}gg}} = 1 - (5\% \sim 9\%)$$
$$\frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} = 1 - (5\% \sim 6\%)$$

  - Heavy Higgs effects

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$$

  - Scalar top partner effects

$$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 1.4\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2, \qquad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.4\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2$$

ILC TDR Volume 2

It is not enough to celebrate super-high precision, and it will be very hard to indeed achieve that

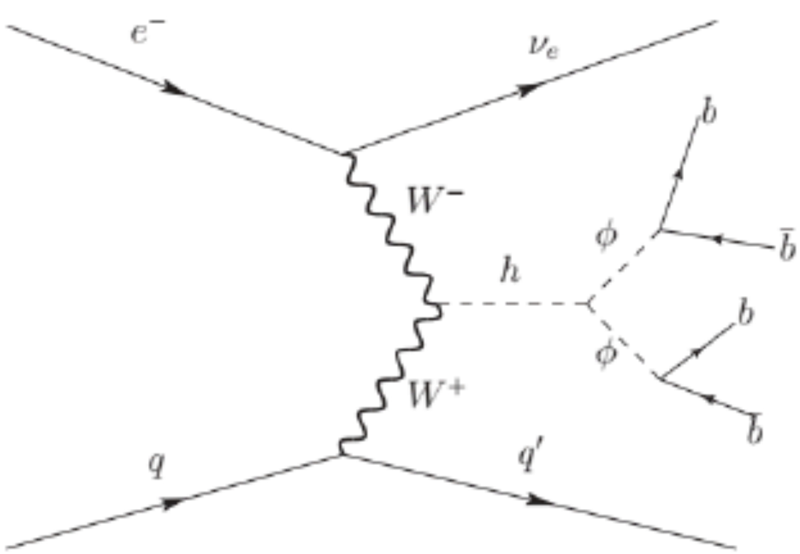
Exotic Higgs Decays

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

ϕ: a spin-0 particle from new physics.

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

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



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

- Well motivated signature in extended Higgs sector.
- Difficult to probe at hadron colliders.
- LHeC signal: here using CC channel.
- Backgrounds: CC multijet, CC t/h/W/Z+jets, PHP multijet.
- PHP backgrounds assumed to be negligible after MET requirements and electron tagging.
- Current analysis is done at parton level.

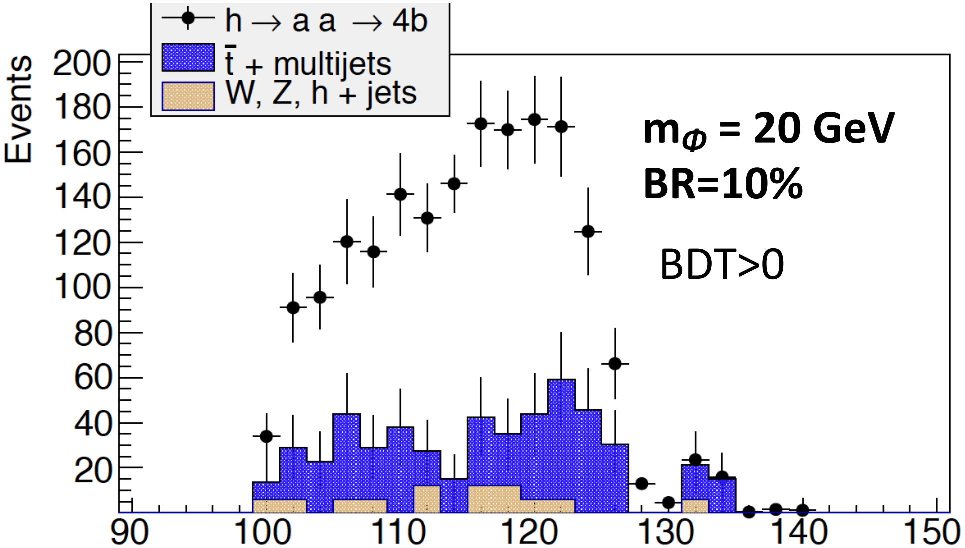
$$C_{4b}^2 = \kappa_V^2 \times \text{Br}(h \to \phi\phi) \times \text{Br}^2(\phi \to b\bar{b})$$

@LHeC: 95% C.L. for m_ϕ of 20, 40, 60 GeV is 0.3%, 0.2% and 0.1% for C_{4b}^2

First Results @ FCC-eh

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

Uta Klein &
Michael O'Keefe
MPHYS 2017



Very promising first results to discover an exotic Higgs decay into two new light scalars at FCC-he down to a BR of 1% for 1 ab^{-1}. A BR of 10% could be discovered within 1 year (100 fb^{-1}).

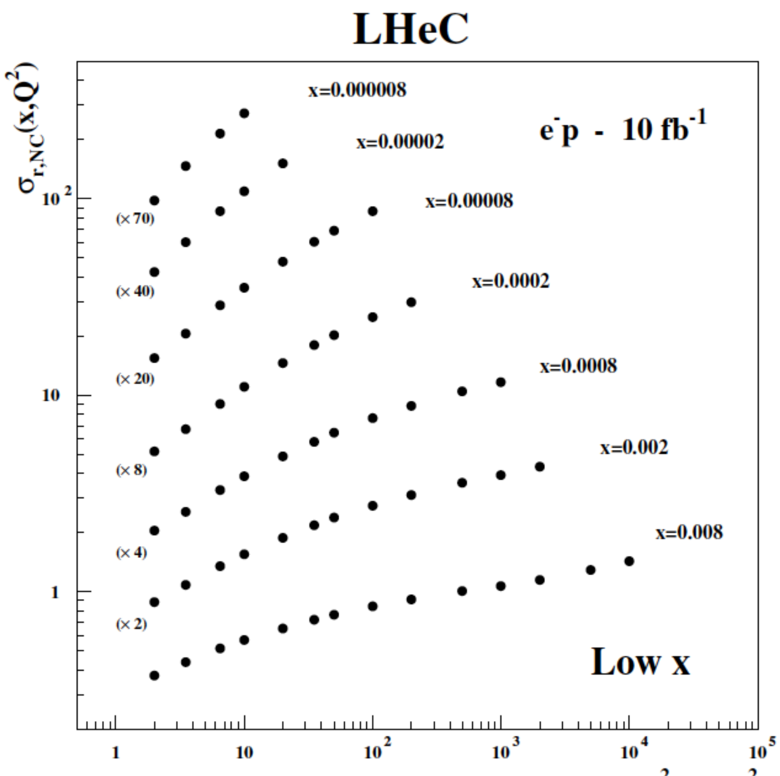
Values for BDT>0

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

	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

Full simulation of DIS [EM,had calibration, tracking, backgrounds, ..]

$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 dz \left[F_2(\frac{x}{z})P_{qq}(z) + 2\sum_{i=1}^{N_f} e_i^2 \cdot G(\frac{x}{z})P_{qG}(z)\right]$$



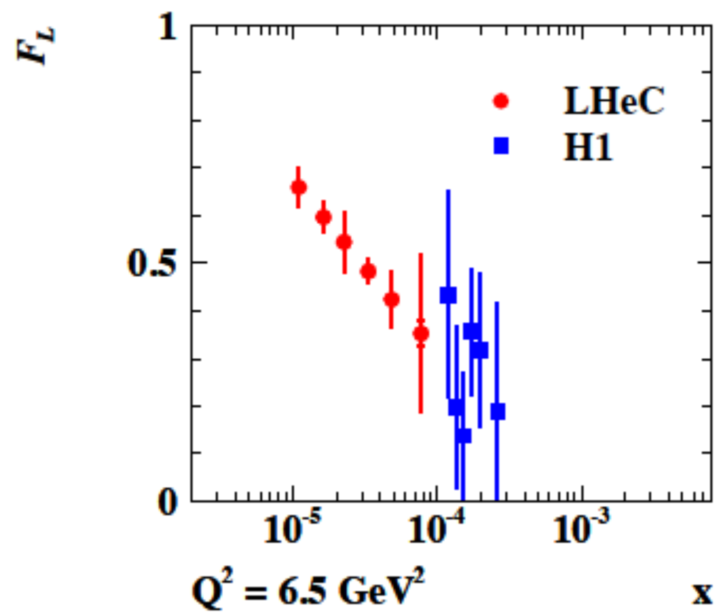
LHeC CDR: 1206.2913 J Phys G

High precision $F_2(x,Q^2)$ from few days of nominal ep running. Needs large Q^2 and low $x \sim 1/s$:
Impossible at EIC

Unravelling proton structure needs cleanest DIS constraints, proton
cf Claire Gwenlan, at this workshop

$$F_L(x,Q^2) = \frac{\alpha_s}{\pi}x^2\int_x^1 \frac{dz}{z^3}\left[\frac{4}{3}F_2(z,Q^2) + 2\sum_i^{N_f} e_i^2 \cdot G(z,Q^2)\left(1-\frac{x}{z}\right)\right]$$

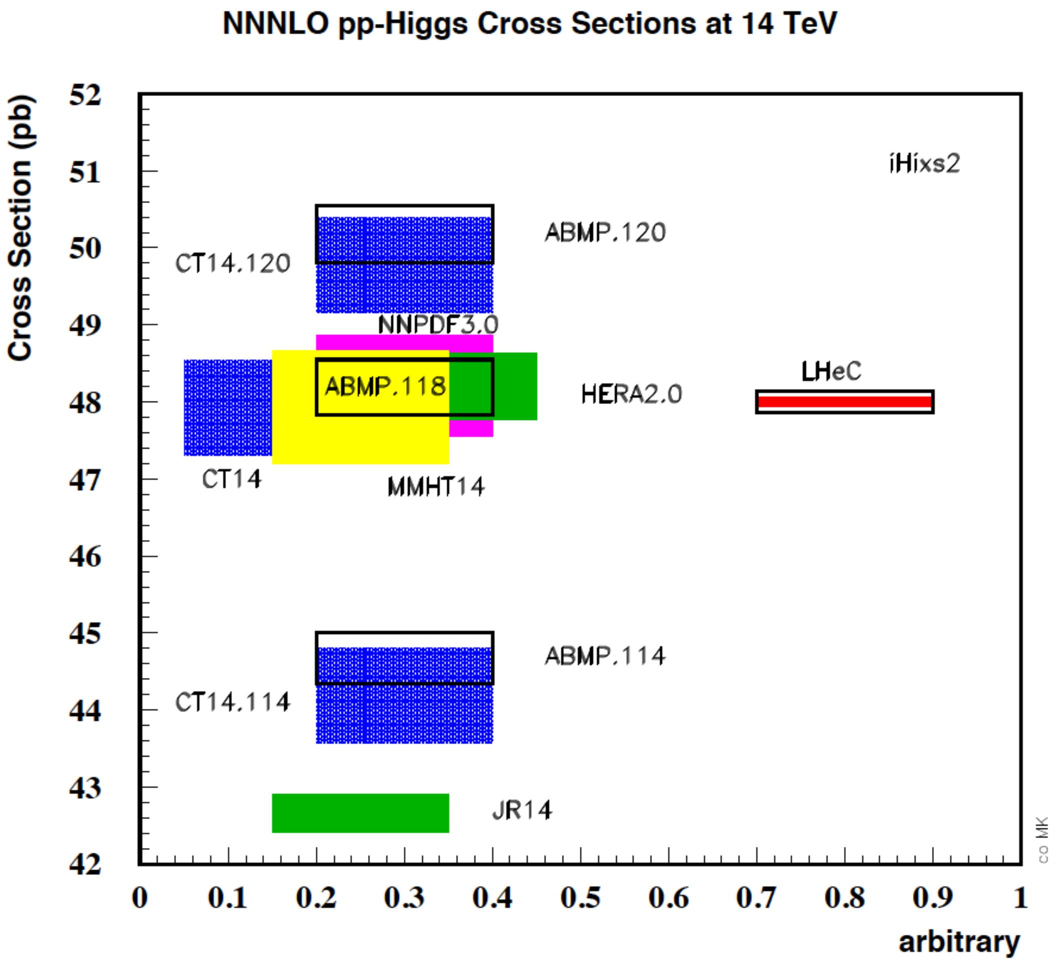
High precision F_L from variation of E_e independently of LHC/FCC



MK: 1802.04317

Full set of PDFs and strong coupling: self consistent system!
Discovery of Saturation @ low x; Test of Factorisation; high x

Precision PDFs and LHC Higgs physics



Cross section to N^3LO needs PDFs to N^3LO and strong coupling to per mile precision

LHeC with $50fb^{-1}$

$$\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\ (\mathrm{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\ (\mathrm{PDF}+\alpha_s)$$

ep Higgs paper, to appear.

C Anastasiou et al, arXiv:1602.00695 → iHixs programe

Precision Higgs Physics at High-Energy Electron-Proton Colliders

Draft 9.4. – in preparation

LHeC Higgs Study Group

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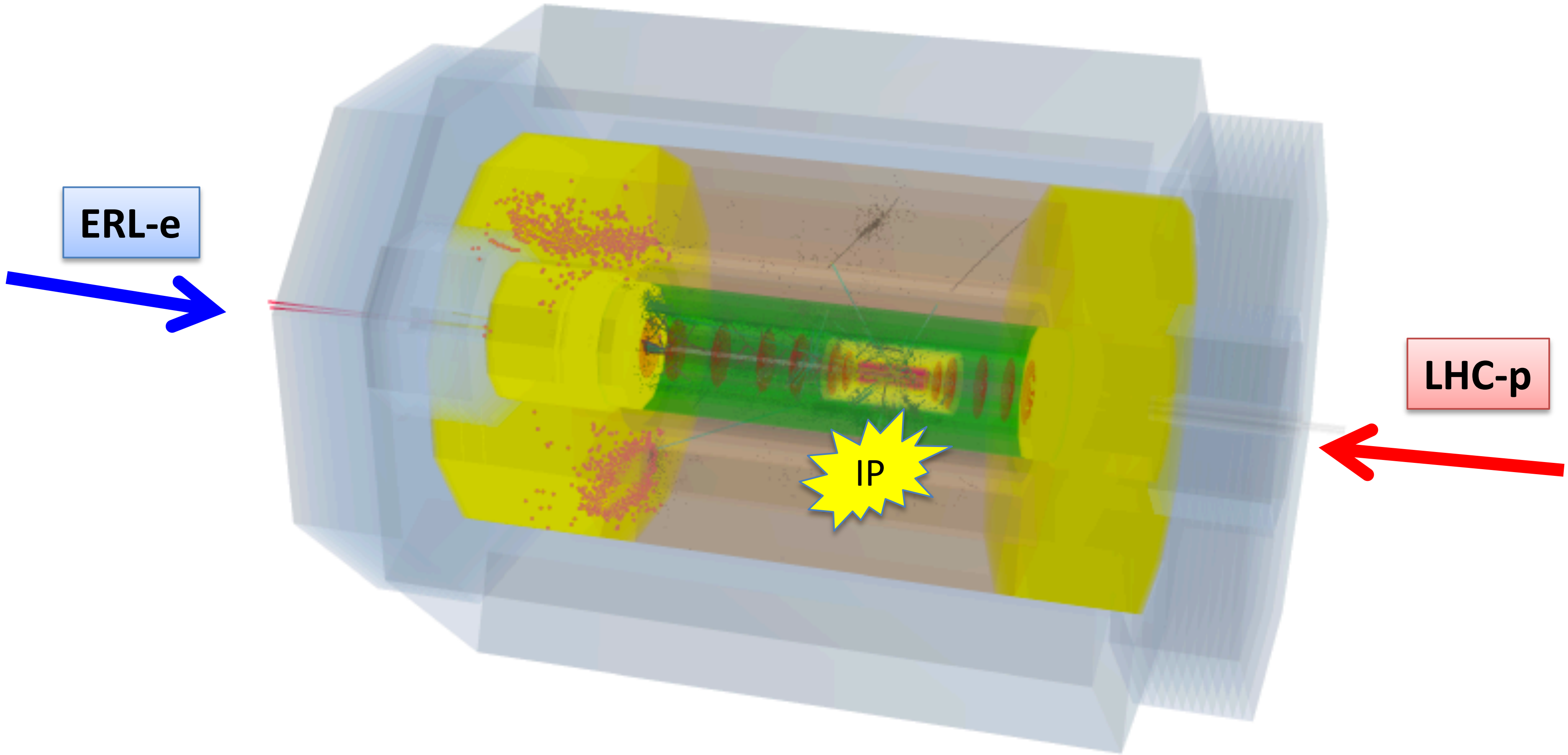
Tentative authorlist - TO BE UPDATED

Abstract. The Higgs boson and its physics have become a central topic of modern particle physics and a key parameter in the evaluation of future high energy collider projects. This paper provides a summary and overview on the potential of future luminous, energy frontier electron-proton colliders, especially the LHeC, the HE-LHC and the FCC-eh, for precision Standard Model measurements of the properties of the Higgs boson in deep inelastic scattering. Detailed analyses are presented on the prospects for accurate measurements of the Higgs boson decays into pairs of bottom and charm quarks. An extended study is performed for estimating the precision on the Higgs couplings in the most abundant decay channels, based on measurements in the charged and weak neutral current DIS reactions. The addition of *ep* information to the expected HL-LHC Higgs coupling measurements is demonstrated to lead to major improvements on the Higgs results one can expect to come from the LHC facility at large.

We hope to see H→ bb in the LHeC Detector



P. Kostka et al., Orsay WS 2018

Wrap Up [Uta Klein at FCC CDR Meeting]

- LHeC (FCC-he) could measure the dominant Higgs couplings, including ttH, to 0.6-17% (0.2-2%) precision [CC+NC DIS, no pile-up, clean final state..]
- 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^3LO, 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 LHC and subsequently at higher energy hadron colliders.

Additional material

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Thanks to Hao Sun

50 journal papers on BSM with LHeC in recent years

LHeC / HE-LHeC / FCCeh Calorimeter Characteristic

LHeC

$Calo_{LHeC}$	FHC Plug[SiW]	FEC Plug[SiW]	EMC Bar[SciPb]	HC Bar/Ecap[SciFe]	BEC Plug[SiPb]	BHC Plug[SiCu]
$\eta_{max/min}$	5.2	5.1	2.7/-2.1	2.1/-1.7	-4.5	-4.7
σ_E/E [%] $= a/\sqrt{E} \oplus b$	1) 2)		13.5 1.7	31.8 2.4		
E-Flow	$\sigma_{E_{jet}}/E_{jet} = 0.03$ (at lower energies $25\%/\sqrt{E}$; sampling ~50 ; $\sigma_{jet} \sim 3\%$)					
Λ_I / X_0	$\Lambda_I \geq 12$	$X_0 \geq 28$	$X_0 \geq 28$	$\Lambda_I \geq 12$	$X_0 \geq 25$	$\Lambda_I \geq 10$
Volume [m^3]	6.7	1.6	15.1	165.	1.6	5.8
Sum-Si [m^2]	197.4					

HE-LHeC

$Calo_{HE-LHeC}$	FHC Plug[SiW]	FEC Plug[SiW]	EMC Bar[SciPb]	HC Bar/Ecap[SciFe]	BEC Plug[SiPb]	BHC Plug[SiCu]
$\eta_{max/min}$	5.7	5.3	2.8/-2.5	2.1/-1.8	-5.1	-5.4
σ_E/E [%] $= a/\sqrt{E} \oplus b$	1) 2) 62.7 1.8	17.7 0.2	17.0 0.8	28.0 2.2	13.9 0.6	52.3 3.1
E-Flow	$\sigma_{E_{jet}}/E_{jet} = 0.03$ (at lower energies $25\%/\sqrt{E}$; sampling ~55 ; $\sigma_{jet} \sim 3\%$)					
Λ_I / X_0	$\Lambda_I \geq 12$	$X_0 \geq 28$	$X_0 \geq 28$	$\Lambda_I \geq 12$	$X_0 \geq 25$	$\Lambda_I \geq 10$
Volume [m^3]	13.2	3.1	28.8	407	1.98	7.0
Sum-Si [m^2]	461					

FCCeh

$Calo_{FCCeh}$	FHC Plug[SiW]	FEC Plug[SiW]	EMC Bar[SciPb]	HC Bar/Ecap[SciFe]	BEC Plug[SiPb]	BHC Plug[SiCu]
$\eta_{max/min}$	6.0	5.6	3.0/-2.7	2.5/-2.2	-5.3	-5.6
σ_E/E [%] $= a/\sqrt{E} \oplus b$	1) 58. 2. 2) 66. 2.	19. 0.01 18. 0.01	17. 1. 17. 1.	28. 1.9 28. 2.	14. 0.8 14. 1.	48. 3. 54 2.
E-Flow	$\sigma_{E_{jet}}/E_{jet} = 0.03$ (at lower energies $25\%/\sqrt{E}$; sampling ~55 ; $\sigma_{jet} \sim 3\%$)					
Λ_I / X_0	$\Lambda_I \geq 12$	$X_0 \geq 28$	$X_0 \geq 28$	$\Lambda_I \geq 12$	$X_0 \geq 25$	$\Lambda_I \geq 10$
Volume [m^3]	13.2	3.1	28.8	407	1.98	7.0
Sum-Si [m^2]	461					

1) GEANT4 simulation based fits; 2) DDG4 simulation based fits

LHeC / HE-LHeC / FCCeh Tracker Characteristic

$Tracker_{LHeC}$ Part	Inner Barrel Pix	Inner Barrel Strix	ECAP Barrel Pix	Forward Tracker Pix	Forward Tracker Strix	Backward Tracker Pix	Backward Tracker Strix
#Layers/Wheels	4_{inner}	3_{outer}	4	3		2	
#Mods/Ring/Wheel	max $12/^{lat}$	max 24^{tilt}	2	2_{inner}	2_{outer}	2_{inner}	2_{outer}
#Modules	6010			648		432	
$\eta_{max/min}$	±1.5		±2.5	$2.5 - 5.1$		-2.5 – -4.8	
$\sigma^{r-\phi}$ [μm]	5-7.5	7-9.5	5-7.5	5-7.5	7-9.5	5-7.5	7-9.5
σ^{z} [μm]	15	15	15	15	30	15	30
X_0/Λ_I [%]	9.42 / 2.92			2.27 / 0.71		1.52 / 0.47	
Sum-Si [m²]	17.			3.3		2.2	

LHeC

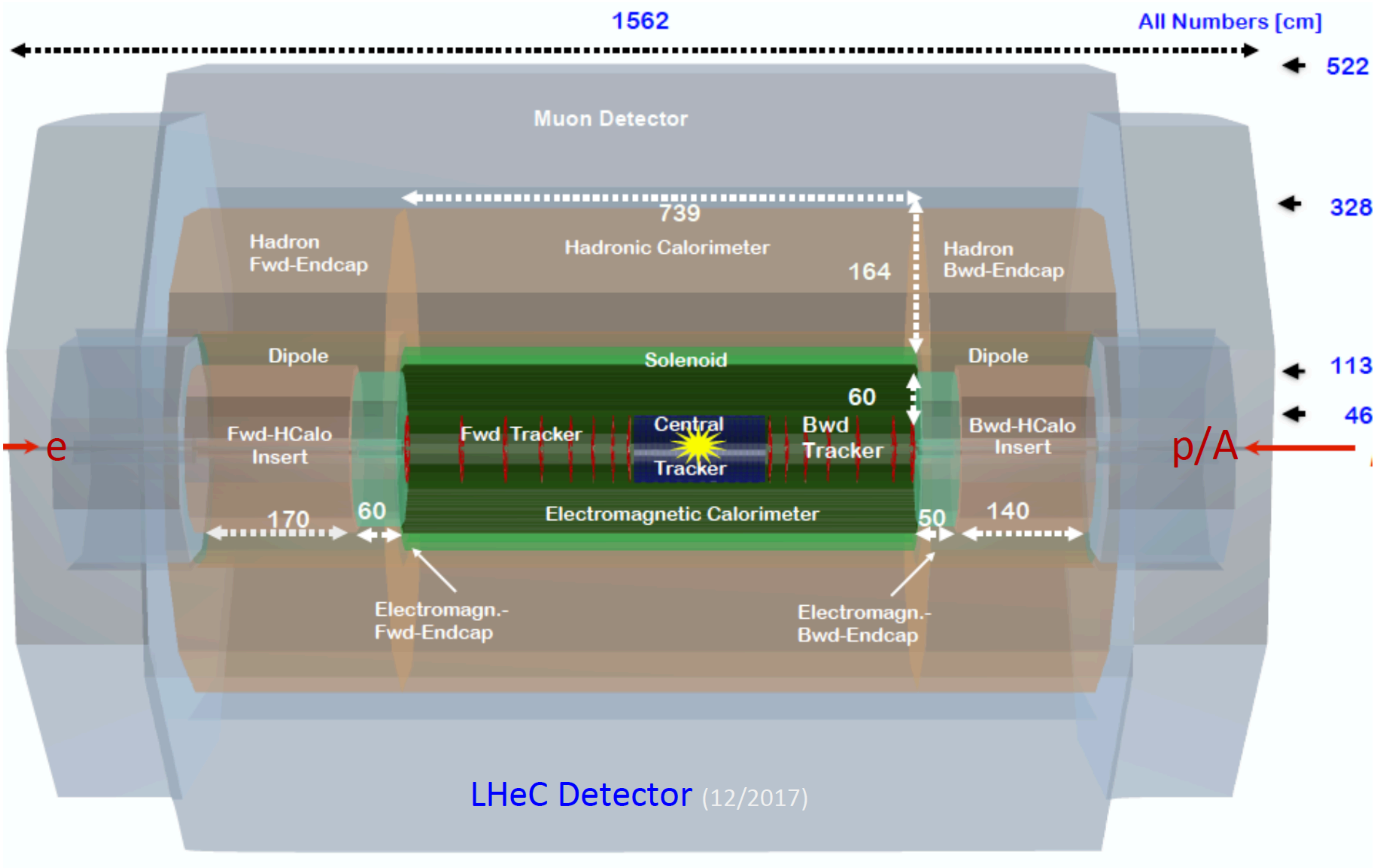
$Tracker_{HE-LHeC}$ Part	Inner Barrel Pix	Inner Barrel Strix	ECAP Barrel Pix	Forward Tracker Pix	Forward Tracker Strix	Backward Tracker Pix	Backward Tracker Strix
#Layers/Wheels	4_{inner}	3_{outer}	4	6		4	
#Mods/Ring/Wheel	max $12/^{lat}$	max 24^{tilt}	2	2_{inner}	2_{outer}	2_{inner}	2_{outer}
#Modules	5794			1296		864	
$\eta_{max/min}$	±1.5		±2.5	$2.5 - 5.5$		-2.5 – -5.3	
$\sigma^{r-\phi}$ [μm]	5-7.5	7-9.5	5-7.5	5-7.5	7-9.5	5-7.5	7-9.5
σ^{z} [μm]	15	15	15	15	30	15	30
X_0/Λ_I [%]	9.51 / 2.95			4.55 / 1.41		3.03 / 0.94	
Sum-Si [m²]	15.8			6.6		4.4	

HE-LHeC

$Tracker_{FCCeh}$ Part	Inner Barrel Pix	Inner Barrel Strix	ECAP Barrel Pix	Forward Tracker Pix	Forward Tracker Strix	Backward Tracker Pix	Backward Tracker Strix
#Layers/Wheels	4_{inner}	3_{outer}	4	7		5	
#Mods/Ring/Wheel	max $12/^{lat}$	max 24^{tilt}	2	2_{inner}	2_{outer}	2_{inner}	2_{outer}
#Modules	5794			1512		1080	
$\eta_{max/min}$	±1.5		±2.5	$2.5 - 6.0$		-2.5 – -6.0	
$\sigma^{r-\phi}$ [μm]	5-7.5	7-9.5	5-7.5	5-7.5	7-9.5	5-7.5	7-9.5
σ^{z} [μm]	15	15	15	15	30	15	30
X_0/Λ_I [%]	9.51 / 2.95			5.31 / 1.65		3.79 / 1.18	
Sum-Si [m²]	15.8			7.7		5.5	

FCCeh

LHeC Detector for the HL/HE-LHC [arXiv:1802.04317]



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

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

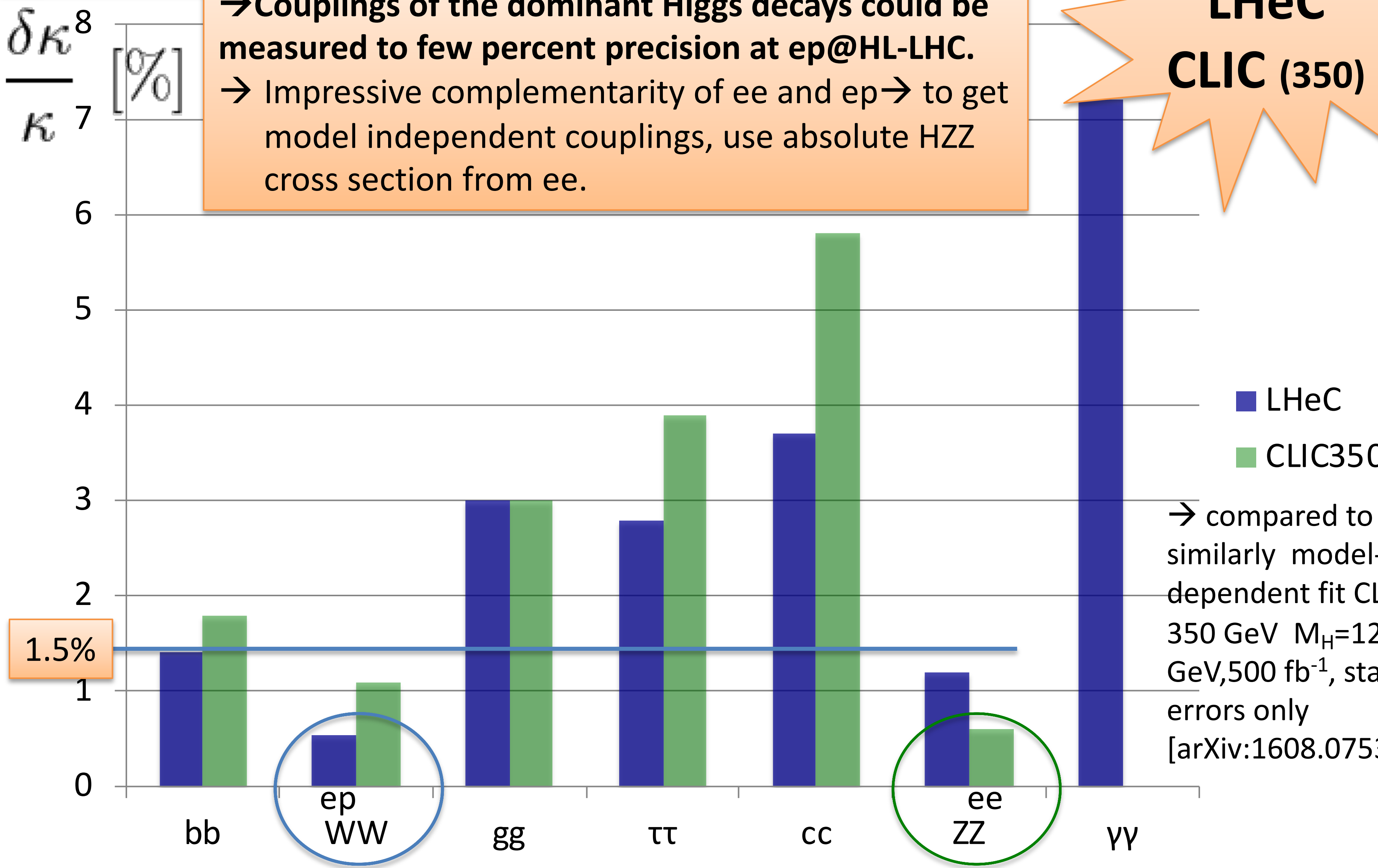
If CERN decides that the HE LHC comes, the LHeC detector should anticipate that

Model-dependent Coupling Fit

→**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.

LHeC
CLIC (350)



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

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://cern.ch/lhec.**
- “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/

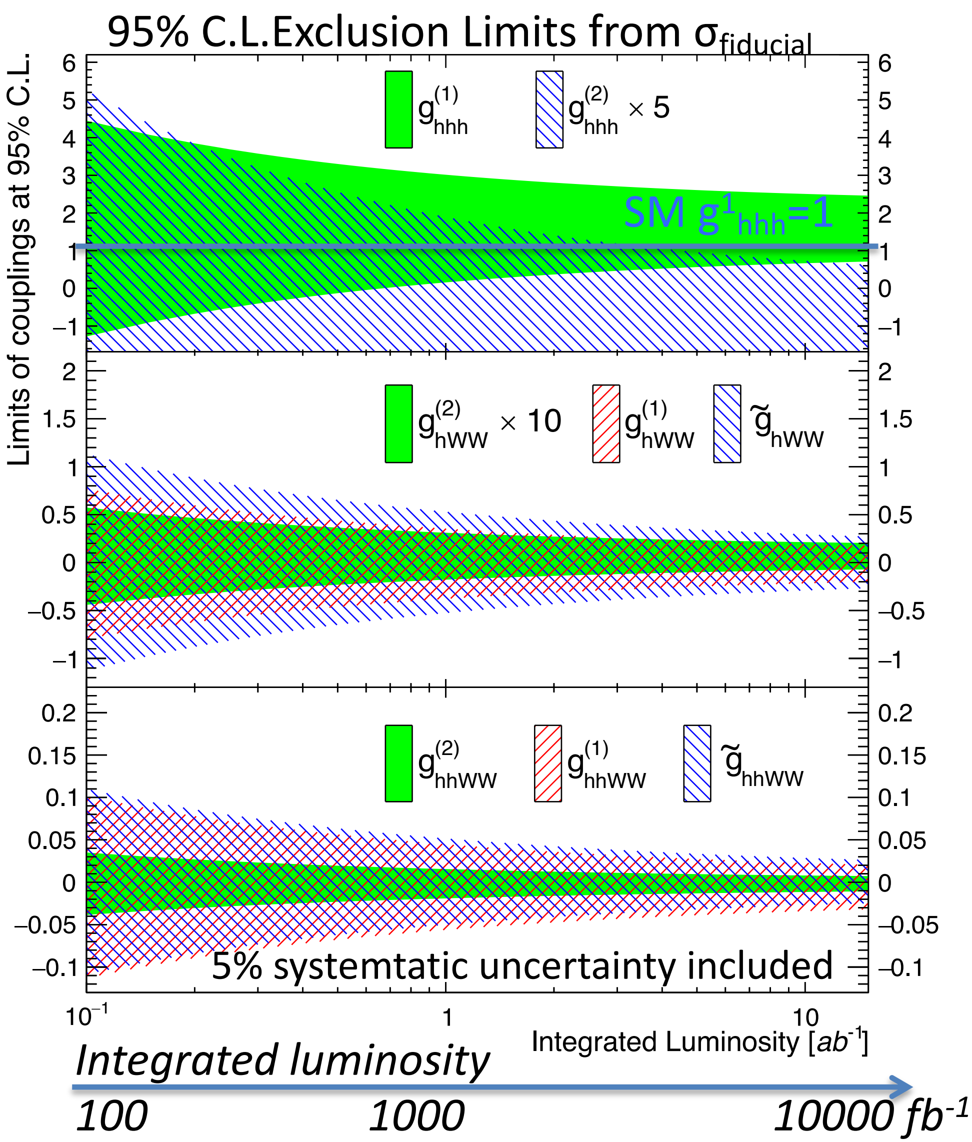
Special thanks to my colleagues in the LHeC/FCC-he Higgs group and to Jorge de Blas for the discussion of model-dependent coupling fits.

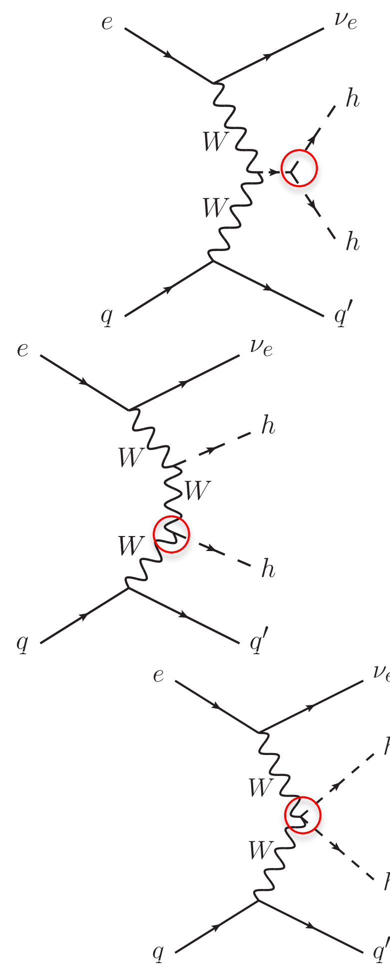
Double Higgs Production

FCC-eh cut-based study

[1509.04016]

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

➔ explore He-LHeC/LHeC ep prospects!

CLIC-1.4TeV: δg_{HHH} ~40-50%

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.

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

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

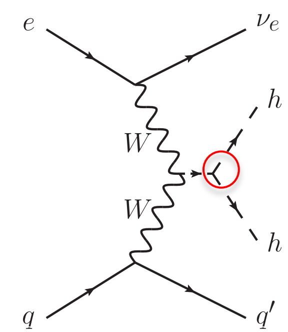
$$\mathcal{L}^{(3)}_{hww} = -g\Big[\frac{g^{(1)}_{hww}}{2m_W} W^{\mu\nu}W^\dagger_{\mu\nu}h + \frac{g^{(2)}_{hww}}{m_W}(W^\nu\partial^\mu W^\dagger_{\mu\nu}h + \mathrm{h.c}) + \frac{\tilde{g}_{hww}}{2m_W} W^{\mu\nu}\widetilde{W}^\dagger_{\mu\nu}h\Big], \quad (3)$$

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

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

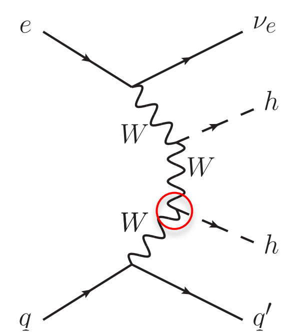
Effective Vertices

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



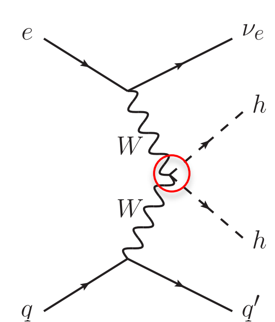
1,2,3= h,h,h

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



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

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

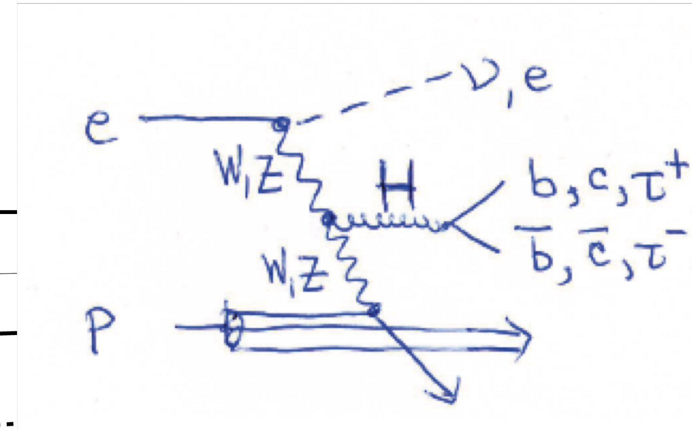


1,2,3,4 = h,h,W-,W+

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

SM Higgs in ep

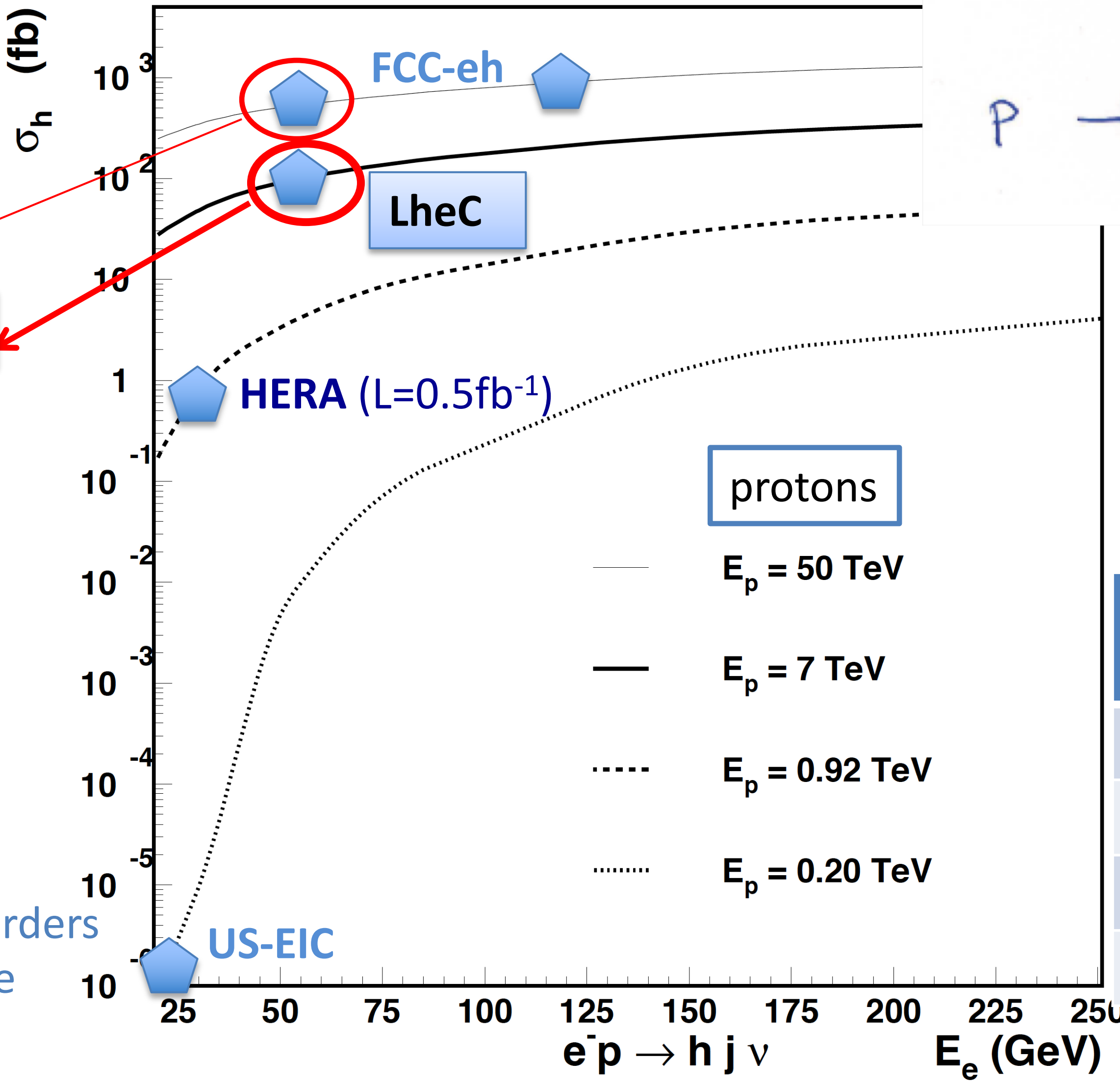
U. Klein, @DIS2015



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}

FCC-eh cut based results

Masahiro Tanaka, Masahiro Kuze, Tokyo Tech 2017

- unpolarised samples using E_e=60 GeV and Ep of 7 and 50 TeV

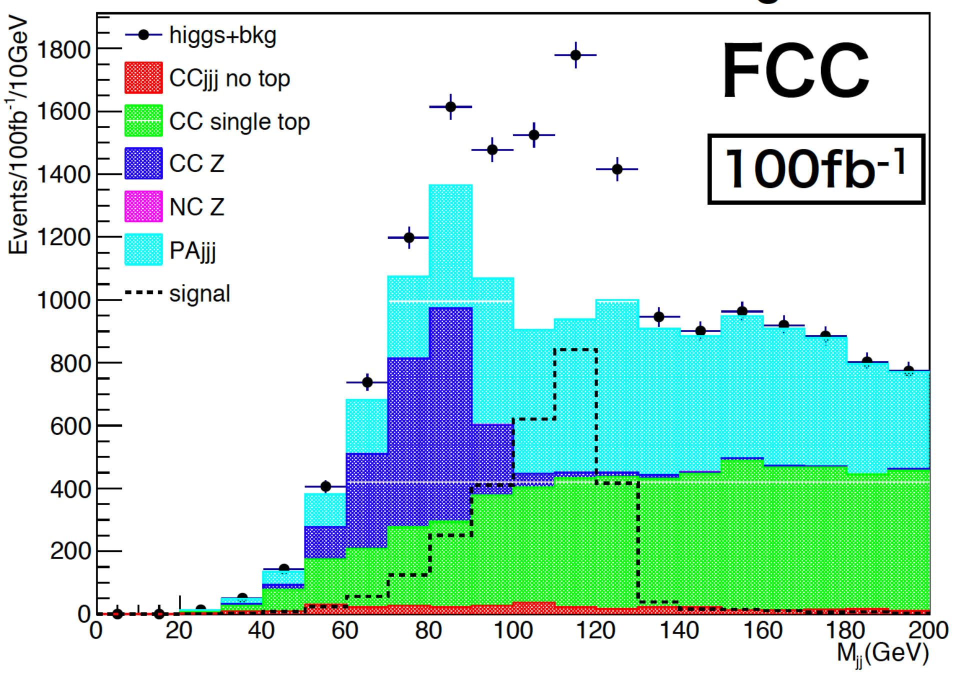
LHeC

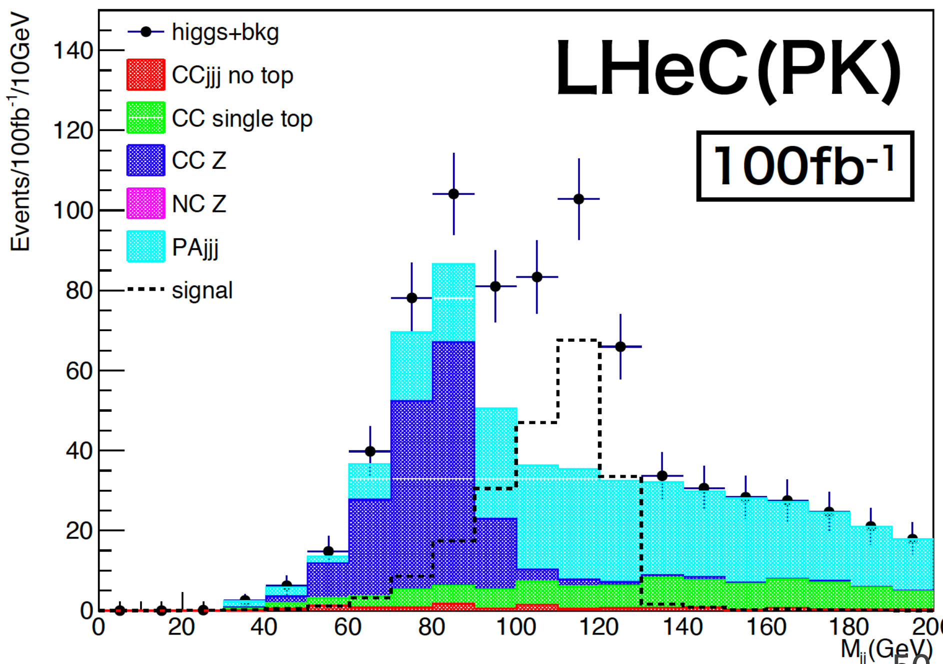
	σ (pb)	Nsample	N/σ (fb^{-1})
Signal CC:H->bb	0.113	0.2M	1760
CCjjj no top	4.5	2.6M	570
CC single top	0.77	0.9M	1160
CC Z	0.52	0.6M	1160
NC Z	0.13	0.15M	1140
PAjjj	41	14M	350

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

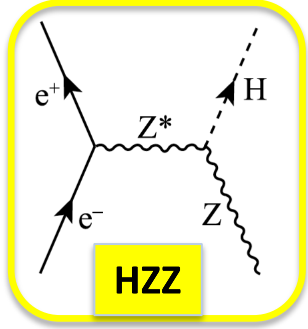
Mass of 2 b-jets after event selection



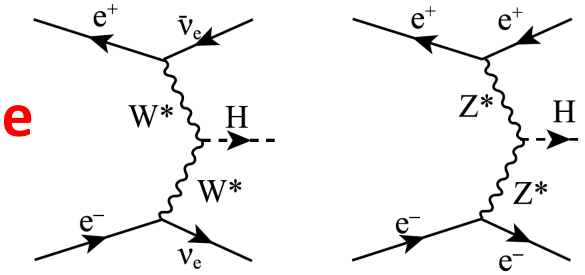


Higgs in ee vs ep

ee: Dominant Higgs productions



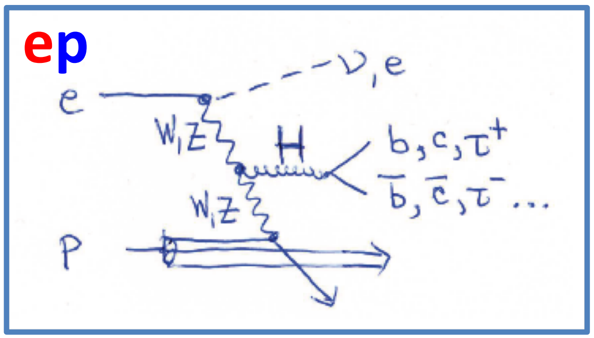
ee

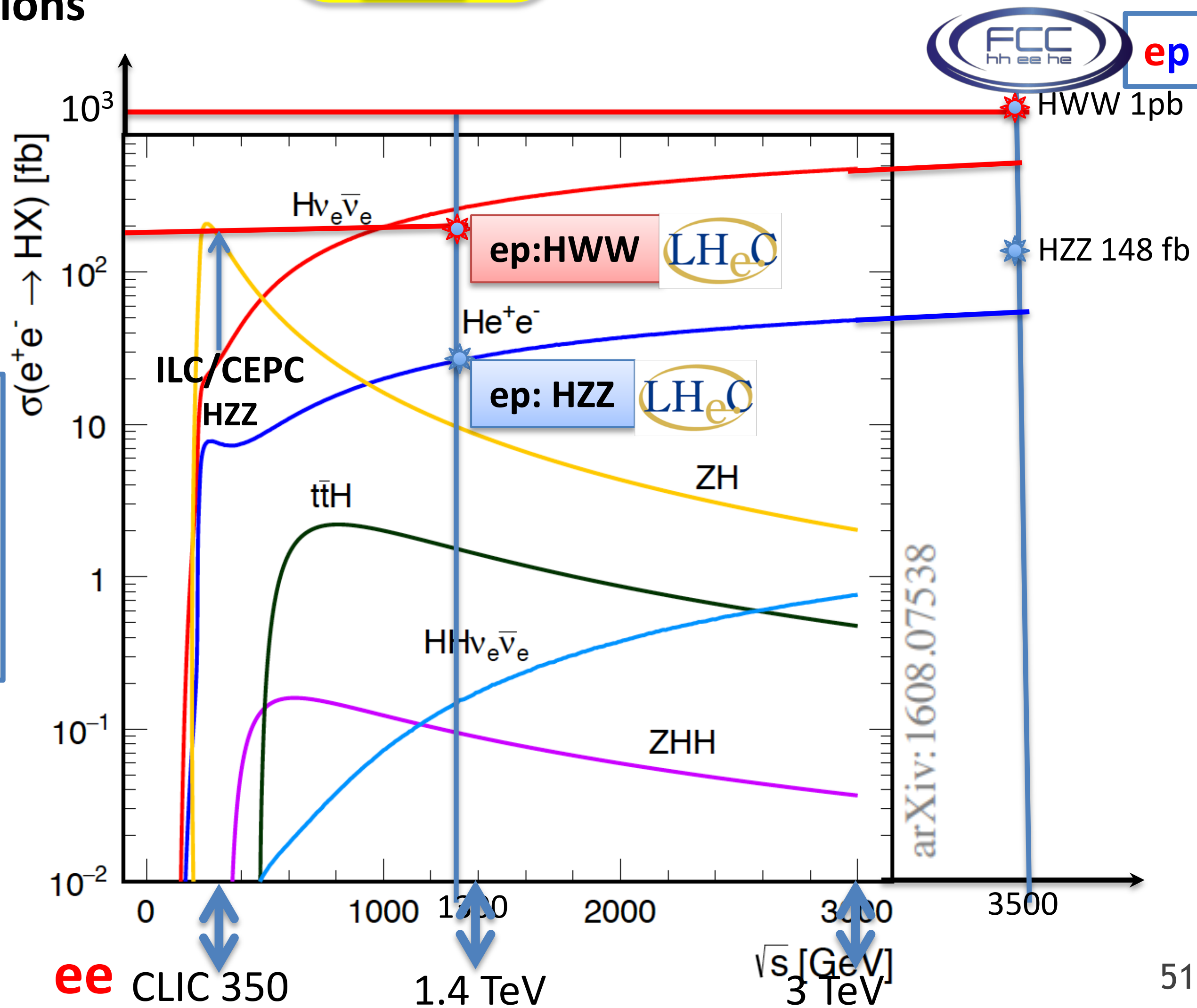


pe vs e+e- Higgs cross sections

ep:CC DIS WW Fusion

ep: NC DIS ZZ Fusion

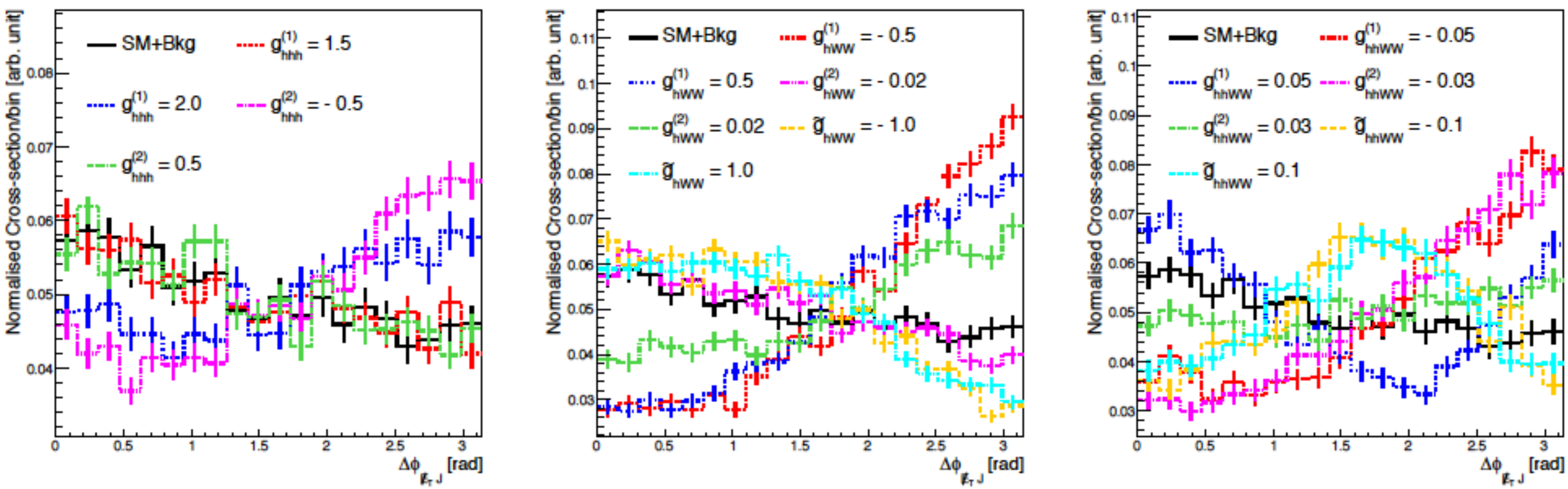




Azimuthal Angle Distributions

between missing transverse energy and forward jet, at Delphes detector-level, including background : bbbbj, bbjjj, Z(bb)h(bb)j, ttj, h(bb)bbj

→ For signal, we consider hh→ bbbb decays motivated by h→bb studies.



→ normalised DIS cross sections are sensitive to non-BSM vertices

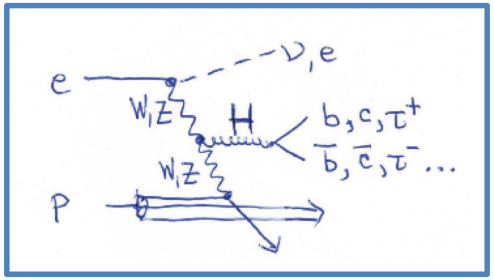
→ initial study published for this novel variable

→ potential for a deeper analysis and interpretation

CC DIS WWH → H

FCC-eh L=2 ab^{-1}

	bb	WW	gg	ττ	cc	ZZ	γγ
BR	**0.577**	**0.215**	**0.086**	**0.0632**	**0.0291**	**0.0264**	**0.00228**
δBR_{theory}	3.2%	4.2%	10.1%	5.7%	12.2%	4.2%	5.0%
N	**$1.15\ 10^6$**	**$4.3\ 10^5$**	**$1.72\ 10^5$**	**$1.26\ 10^5$**	**$5.8\ 10^4$**	**$5.2\ 10^4$**	**4600**
f	2.86 BDT	16	7.4	5.9	5.6 BDT	8.9	3.23
δμ/μ [%]	**0.27**	**2.45**	**1.78**	**1.65**	**2.36**	**3.94**	**3.23**



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

→ Sum of first 6 branching fractions that could be measured

LHeC : 0.9964 +- 0.02

FCC-eh: 0.9964 +- 0.01