Status of FCC-eh and LHeC

B.Mellado

Wits Institute for Collider Particle Physics & iThemba LABS

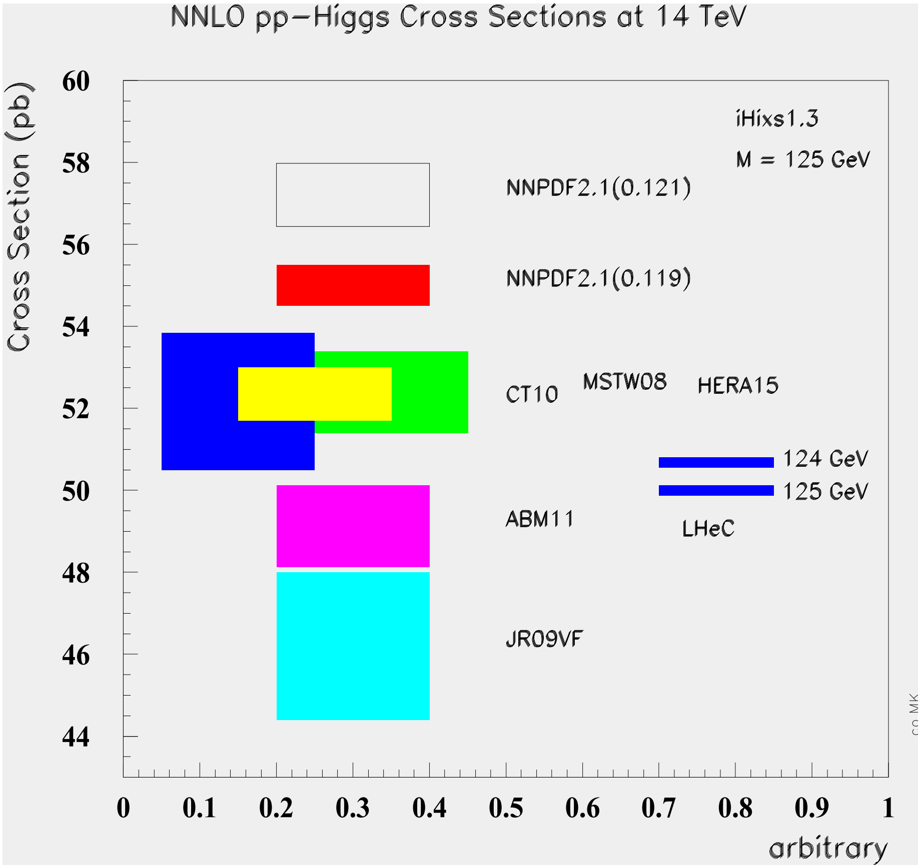
On behalf of the LHeC/FCC-eh Study Group

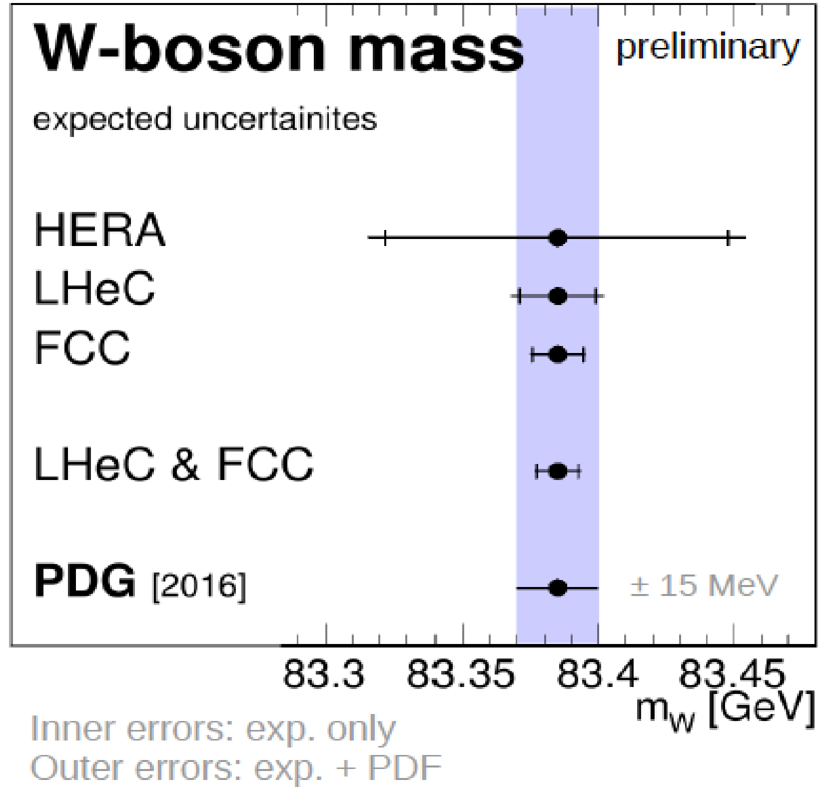
Many thanks to M.Klein, U.Klein and M.Kuze for slides

Electrons for the LHC, Chavannes de Bogis, 24/10/19

High Precision for pp

M.Klein





Can achieve <0.5% precision in pdf uncertainty, thus removing this uncertainty from the prediction of the Higgs cross-section.

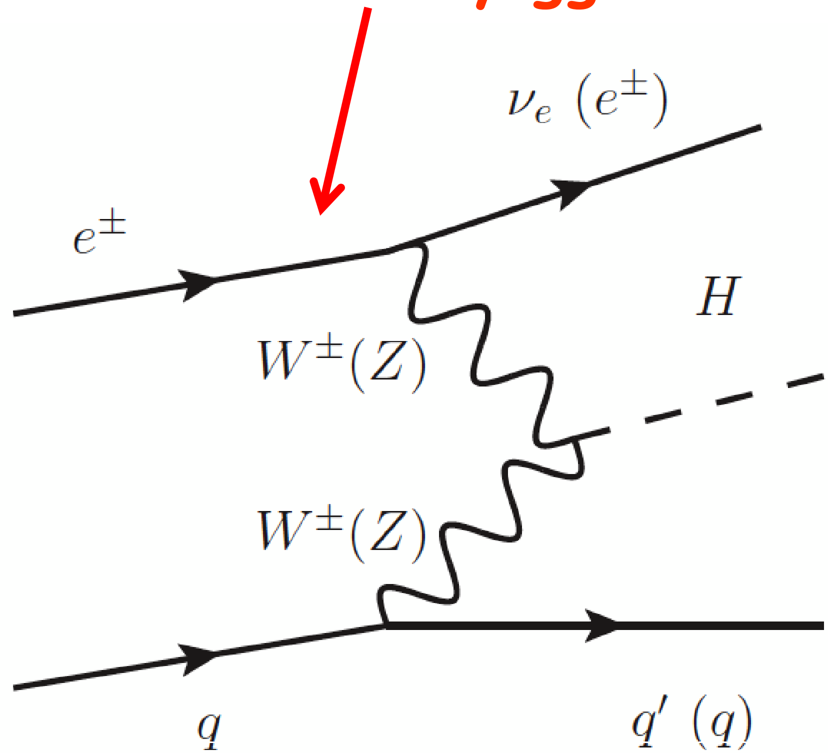
Reduce pdf error 2.8 MeV →
Remove PDF uncertainty on M_W LHC

Spacelike M_W to 10 MeV from ep
→ Electroweak test at 0.01% !

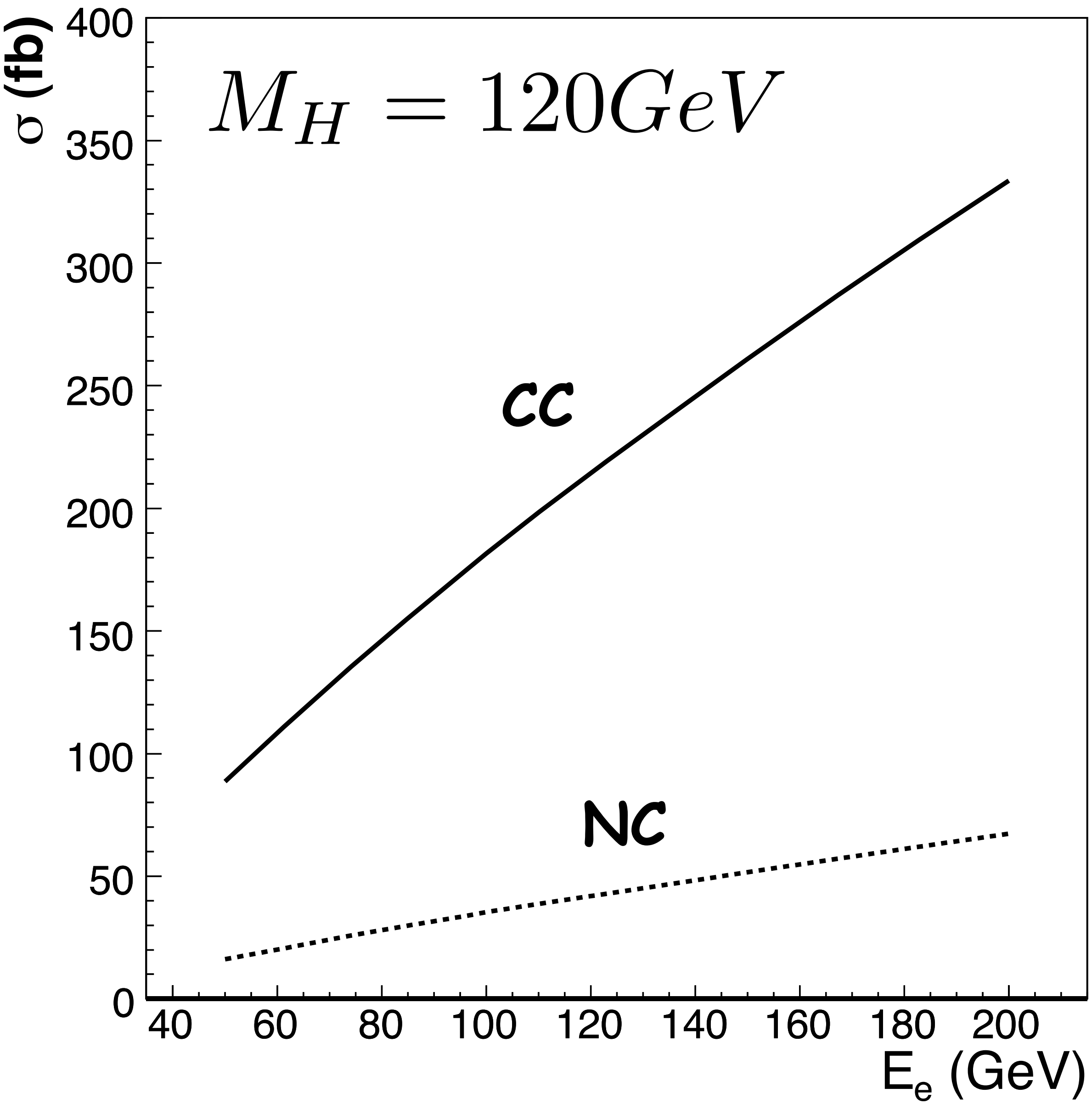
Higgs in ep

- It is remarkable that VBF diagrams were calculated for lepton nucleon collisions before for pp!
- Small theoretical uncertainties
- Topological requirements effective in background suppression
- Large S/B w.r.t. pp, e.g. in h→bb expect S/B=3

At LHC replace lepton lines by quark lines but dominantly gg → H



Cross-Sections



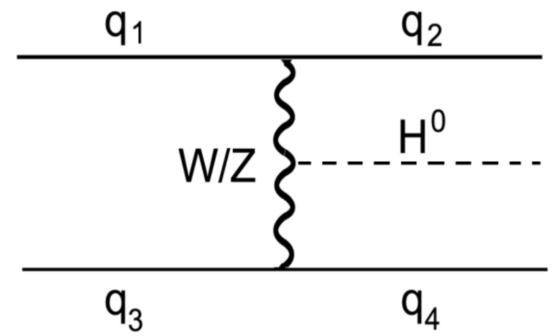
Cross-sections given for unpolarized electrons

Cross-sections comparable to e^+e^- case

Higher Order corrections known to be very small

Tool for precision Higgs physics

Higgs via VBF
Qualitative remarks



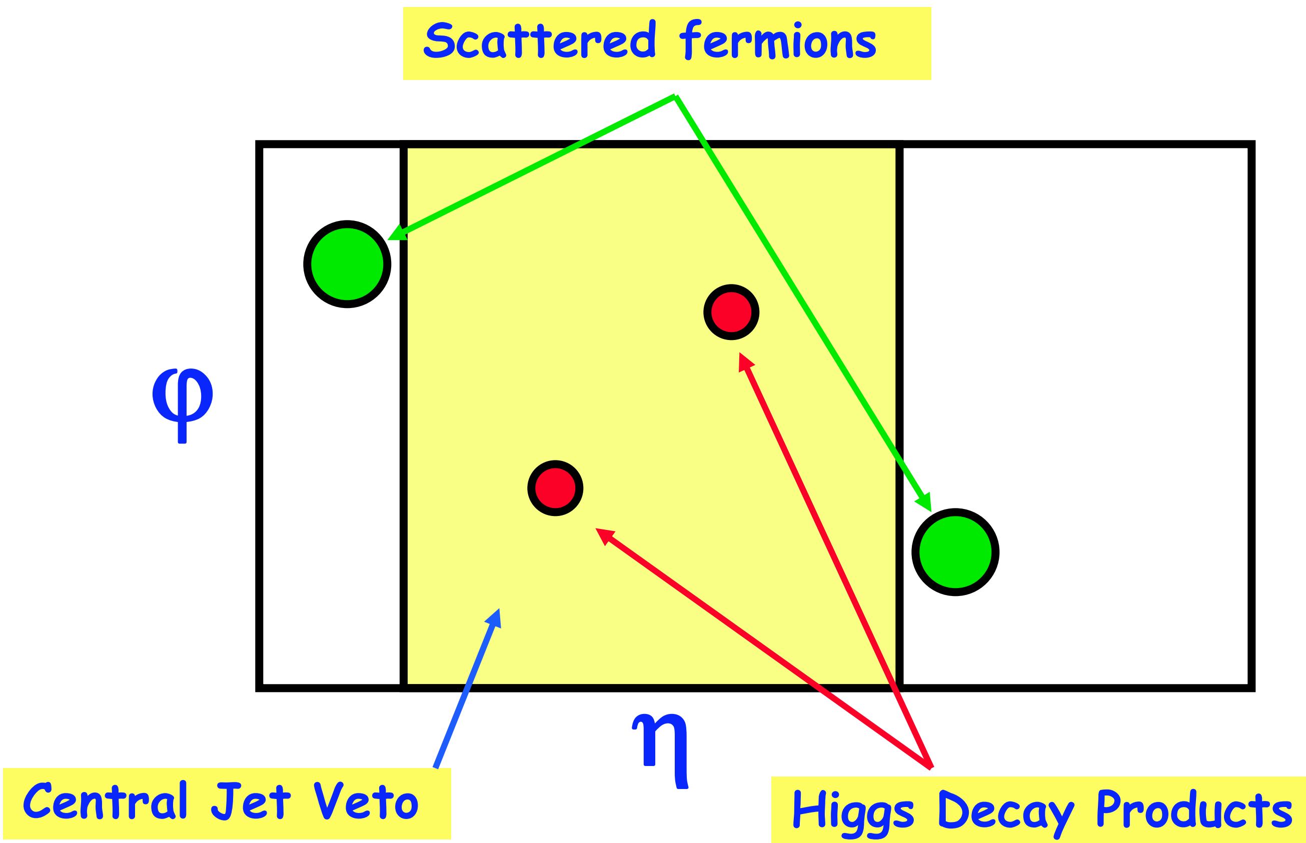
$$\sigma(fa \to f'X) \approx \int dx dp_T^2 P_{V/f}(x, p_T^2)\sigma(Va \to X)$$

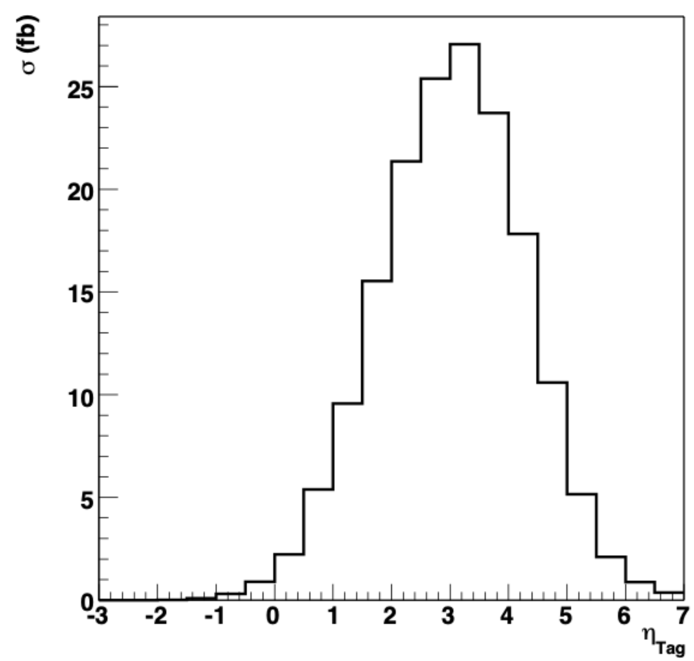
$$P_{V/f}^T(x, p_T^2) = \frac{g_V^2 + g_V^2}{8\pi^2} \frac{1+(1-x)^2}{x} \frac{p_T^2}{(p_T^2 + (1-x)M_V^2)^2}$$

$$P_{V/f}^L(x, p_T^2) = \frac{g_V^2 + g_V^2}{4\pi^2} \frac{1-x}{x} \frac{(1-x)M_V^2}{(p_T^2 + (1-x)M_V^2)^2}.$$

- **Unlike QCD partons that scale like $1/P_T^2$, here $P_T \sim \mathrm{sqrt}(1-x)M_W$**
- **Due to the 1/x behavior of the Weak boson the outgoing parton energy (1-x)E is large <u>forward jets</u>**
- **At high P_T** $P_{V/f}^T \sim 1/p_T^2$ and $P_{V/f}^L \sim 1/p_T^4$
- **Contribution from longitudinally polarized Weak Bosons is suppressed in favor of transversely polarized WB at high p_T**

Well-defined prediction of the SM. Kinematics of scattered quarks, sensitive to new physics





LHeC, a Higgs Facility

→ **for first time a realistic option of an 1 ab^{-1} ep collider** (stronger e-source, stronger focussing magnets) and **excellent performance of LHC** (higher brightness of proton beam); ERL : 960 superconducting cavities (20 MV/m) and 9 km tunnel [arXiv:1211.5102, arXiv:1305.2090; EPS2013 talk by D. Schulte]

√s= 1.3 TeV

→ need of different models :
cc: 'sm-full'
gg, γγ: 'heft'

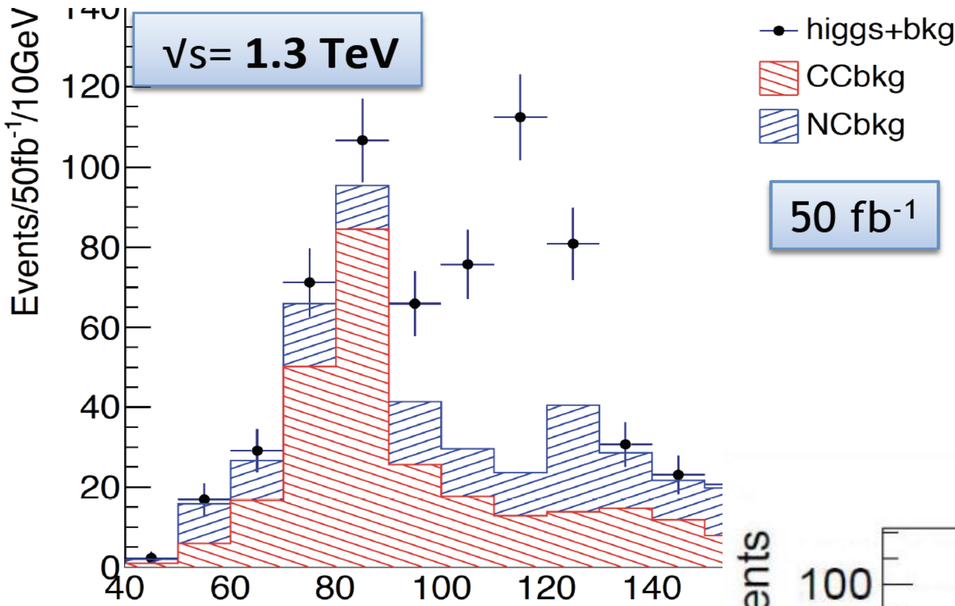
LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	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

Ultimate polarised e-beam of 60 GeV and LHC-p beams, 10 years of operation

→ **Decay to bb is dominating HFL decay modes :**
Higgs decay to cc is factor 20 less likely than Hbb
times the ratio of detection efficiencies-squared !

CDR Updates: Two independent analyses

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

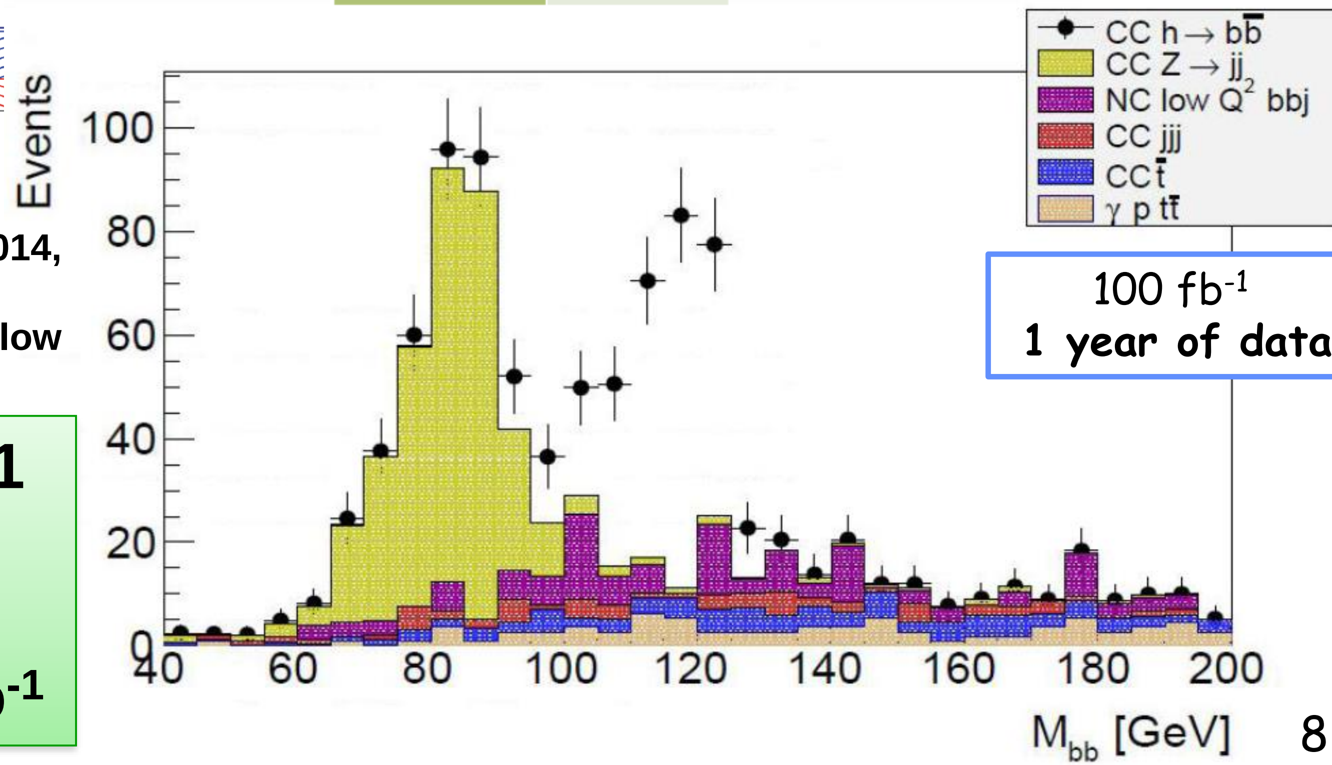


Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

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



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

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

BDT Results for Higgs @ LHeC

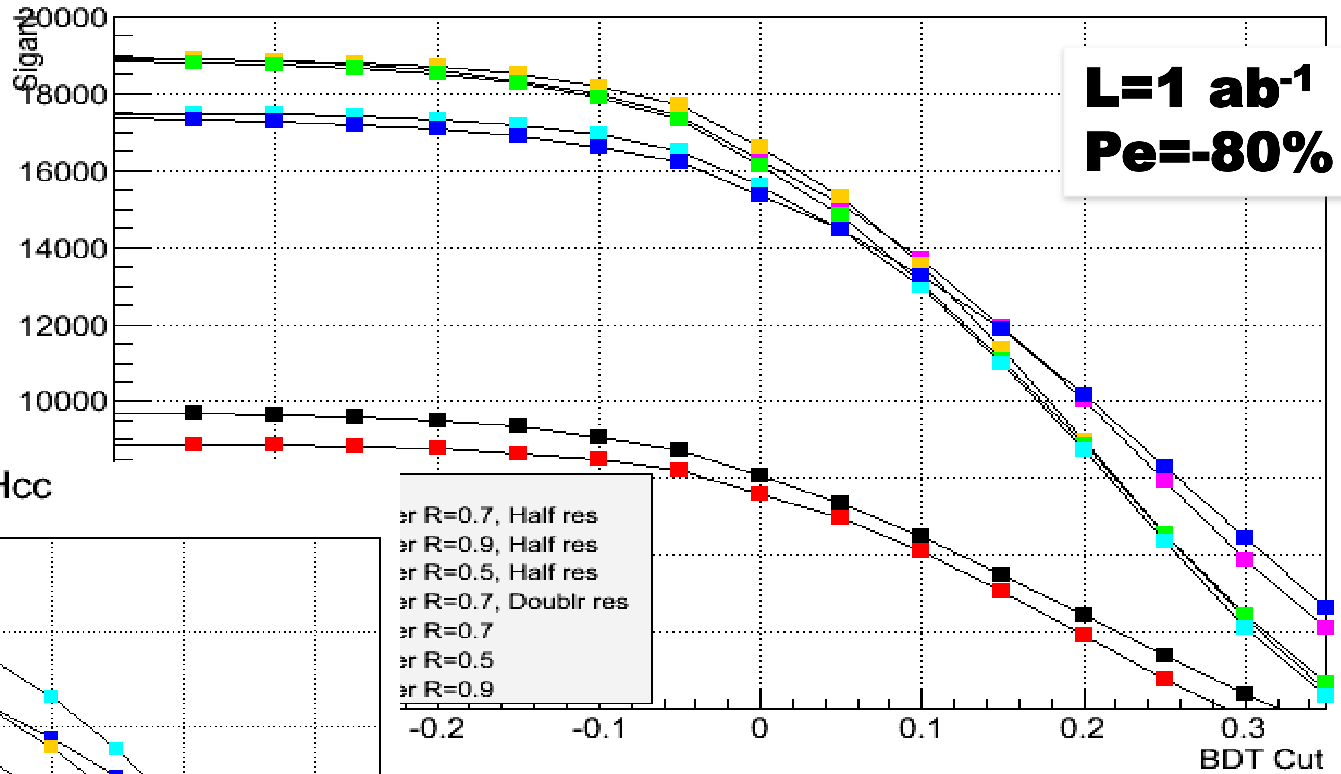
Daniel Hampson, MPHYS 2016

U.Klein

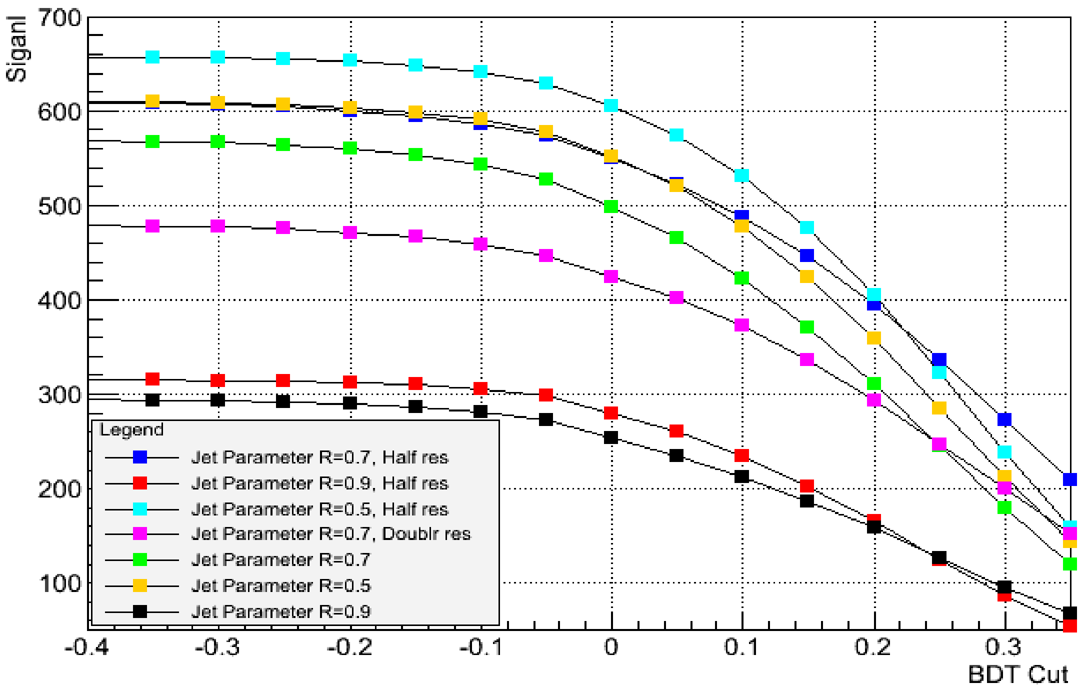
using realistic HFL tagging at Delphes detector level

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

Signal Events Hbb



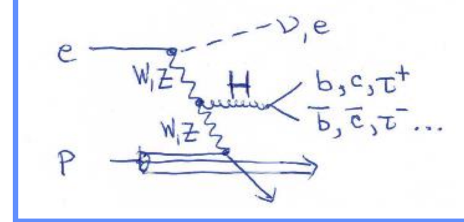
Signal Events Hcc



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

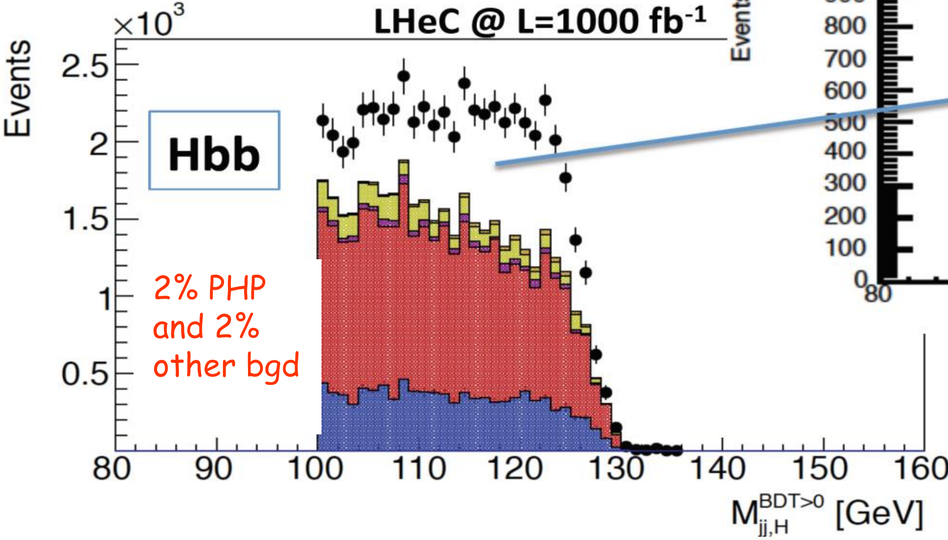


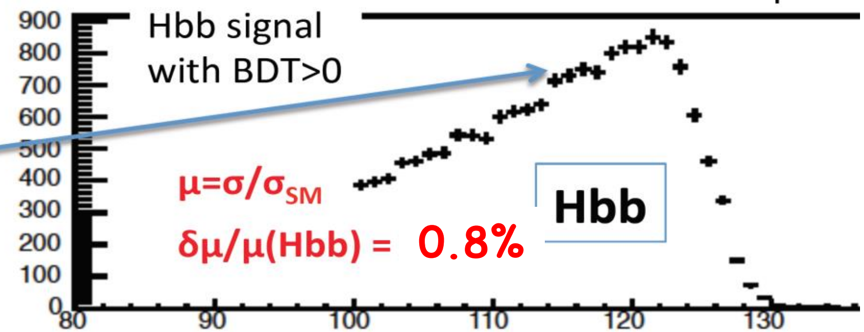
Uta Klein & Daniel Hampson

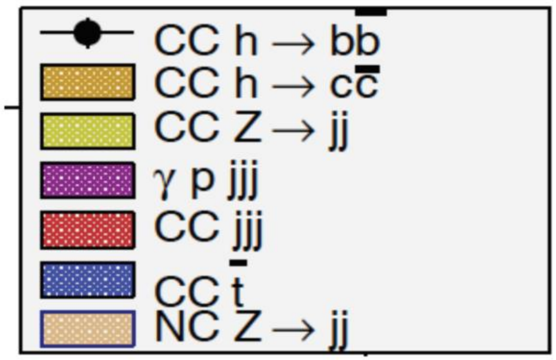
& Izzy Harris BSc 2017

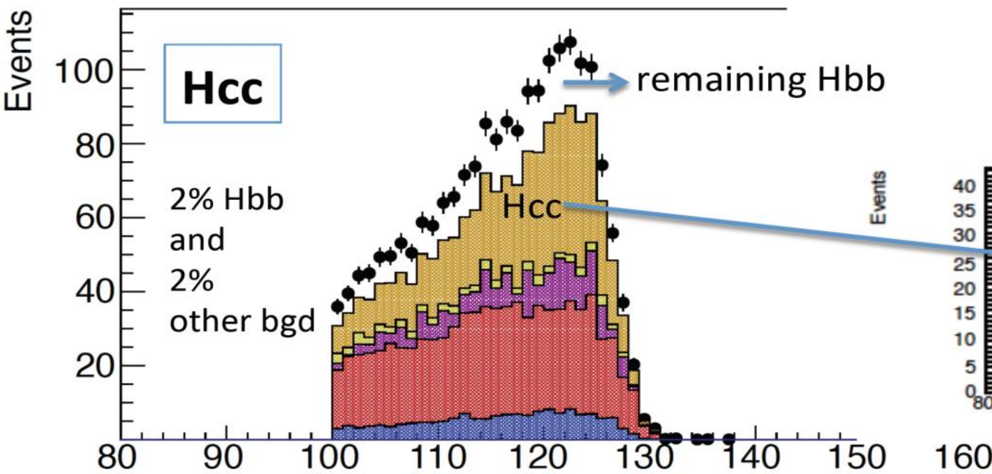
U.Klein

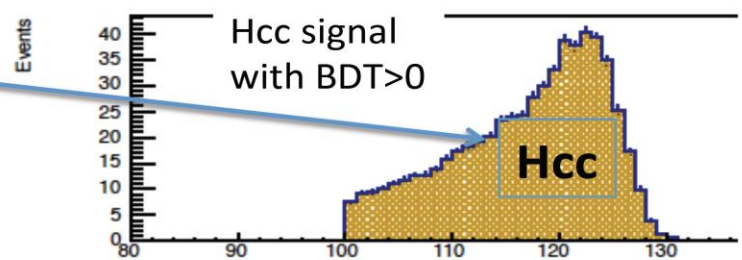
realistic HFL tagging & BDT











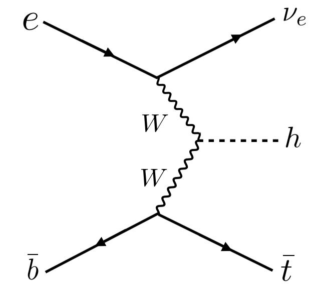
$\delta\mu/\mu(Hcc) = 7.4\ \%$

Assuming ATLAS light jet misID efficiencies

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

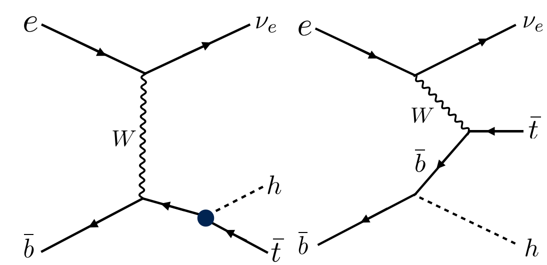
B.Coleppa, M.Kumar, S.Kumar, B.M., Phys. Lett. B770 (2017) 335

Top Yukawa coupling

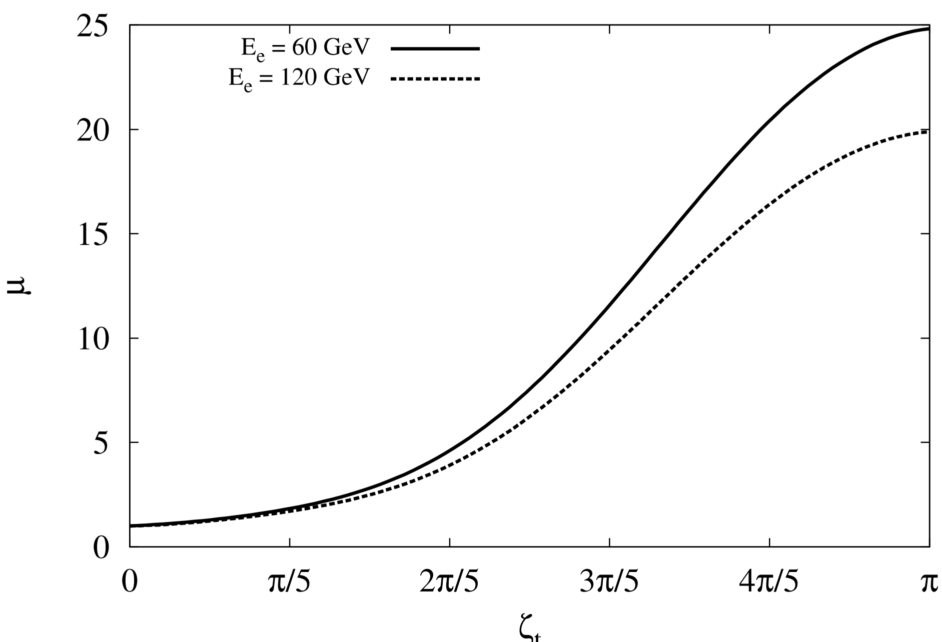


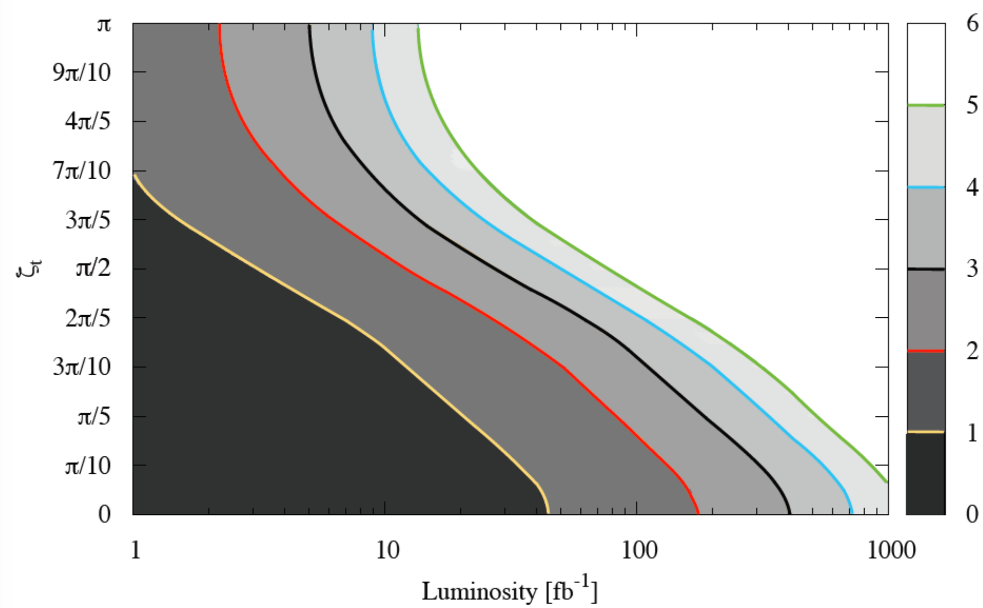
Introduce phase dependent top Yukawa coupling

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



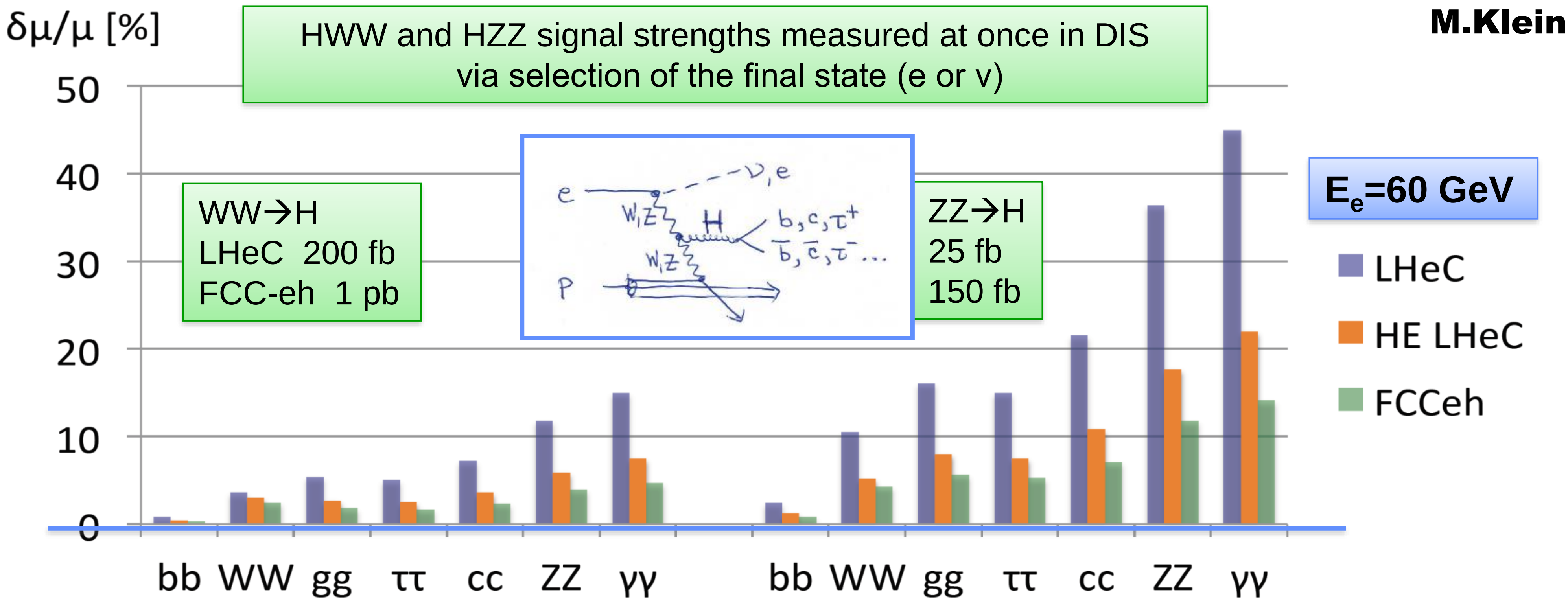
Enhancement of the cross-section as a function of phase





Observe/Exclude non-zero phase to better than 4σ at LHeC. Achieve <2% error on k_t at the FCC-eh.

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.

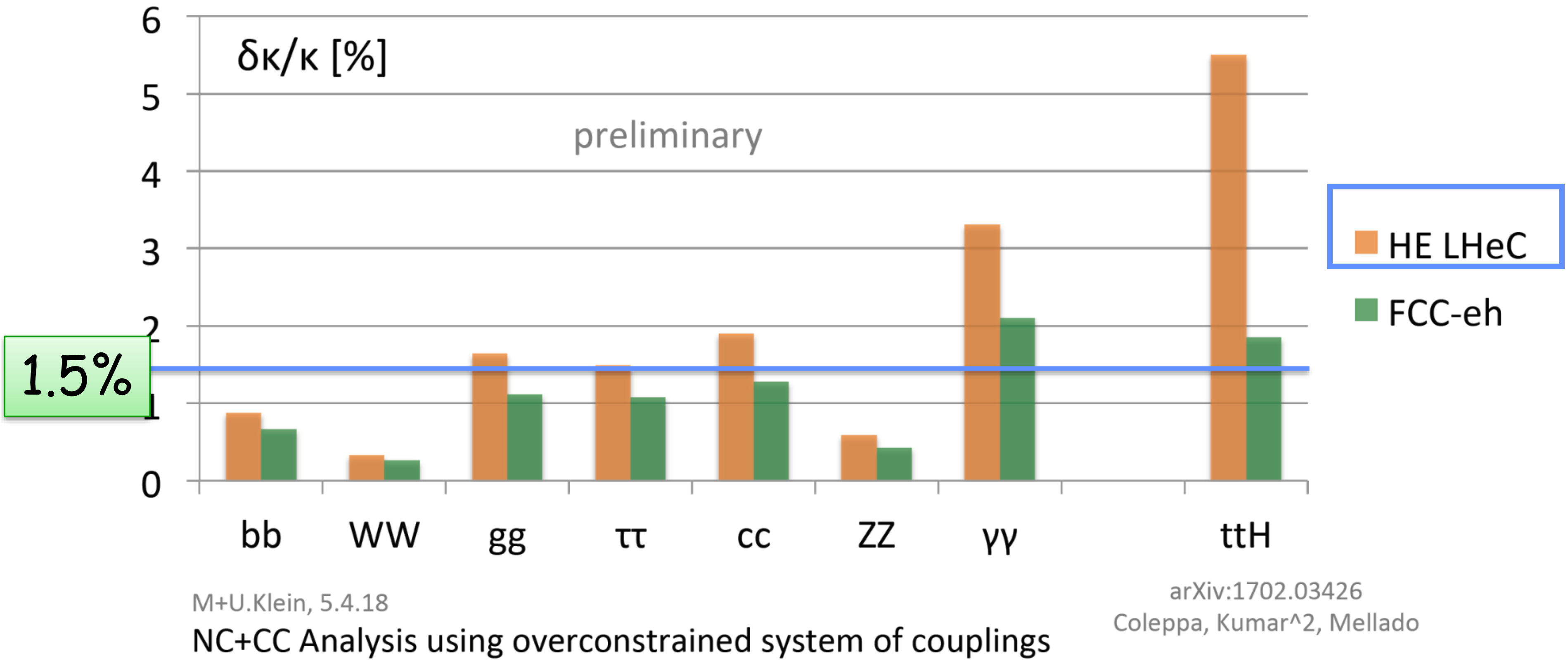
E_e = 60 GeV **LHeC E_p = 7 TeV L=1ab^{-1}** **HE-LHC E_p = 14 TeV L=2ab^{-1}** **FCC: E_p = 50 TeV L=2ab^{-1}**

Model-dependent Coupling Fit

HE LHeC & FCC-eh

M.Klein

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



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

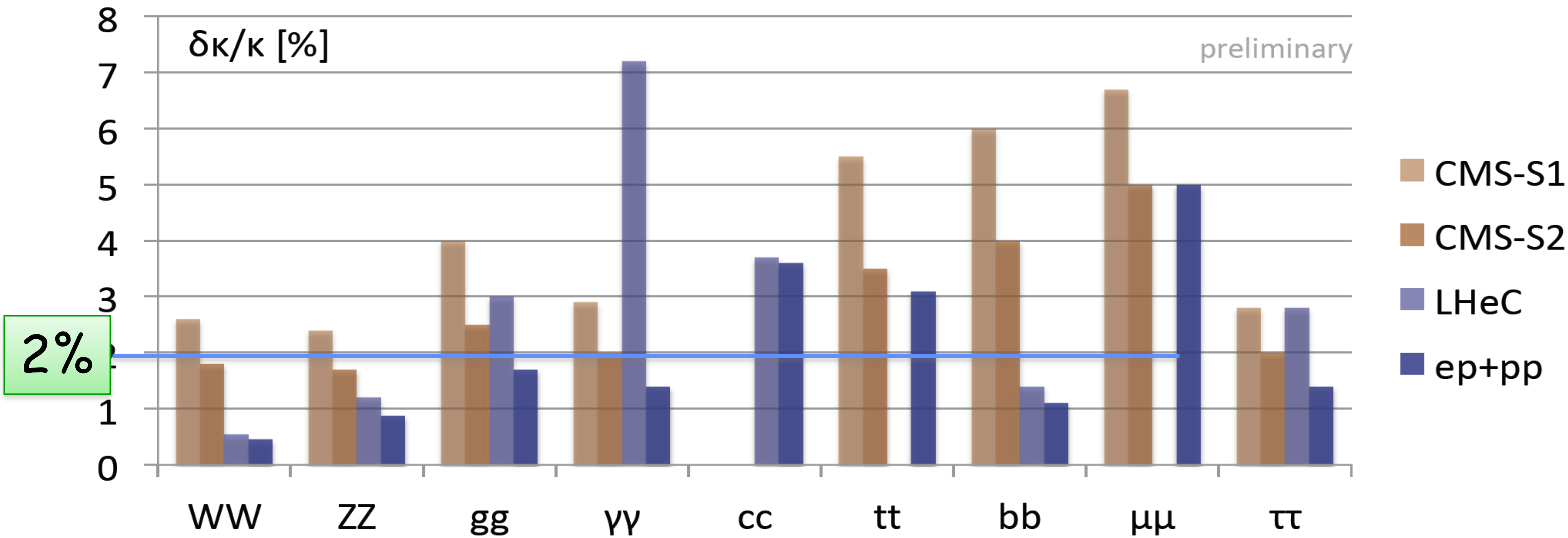
LHeC and HL-LHC Higgs Prospects

M.Klein

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

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%
$\kappa_{Z\gamma}$	–

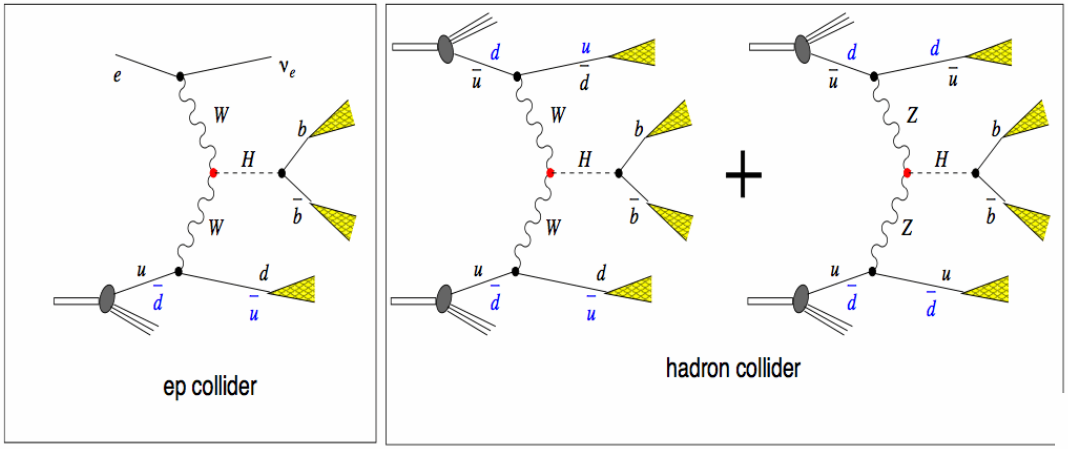
FCC-eh	
Coupling	Relative precision
κ_b	0.74%
κ_t	–
κ_τ	1.10%
κ_c	1.35%
κ_μ	–
κ_Z	0.43%
κ_W	0.26%
κ_g	1.17%
κ_γ	2.35%
$\kappa_{Z\gamma}$	–

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

Published in book 1 of FCC

Structure of HVV couplings

higgs + 2jets: VBF (LHC), higgs + jet + missing E_T (LHeC)

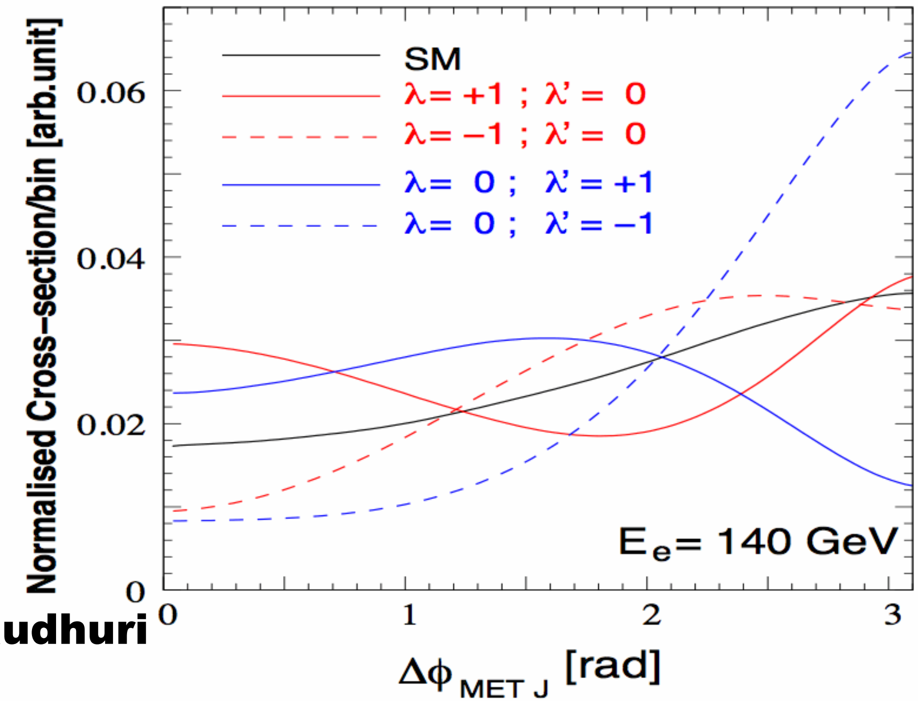


ep process uniquely addresses the HWW vertex.

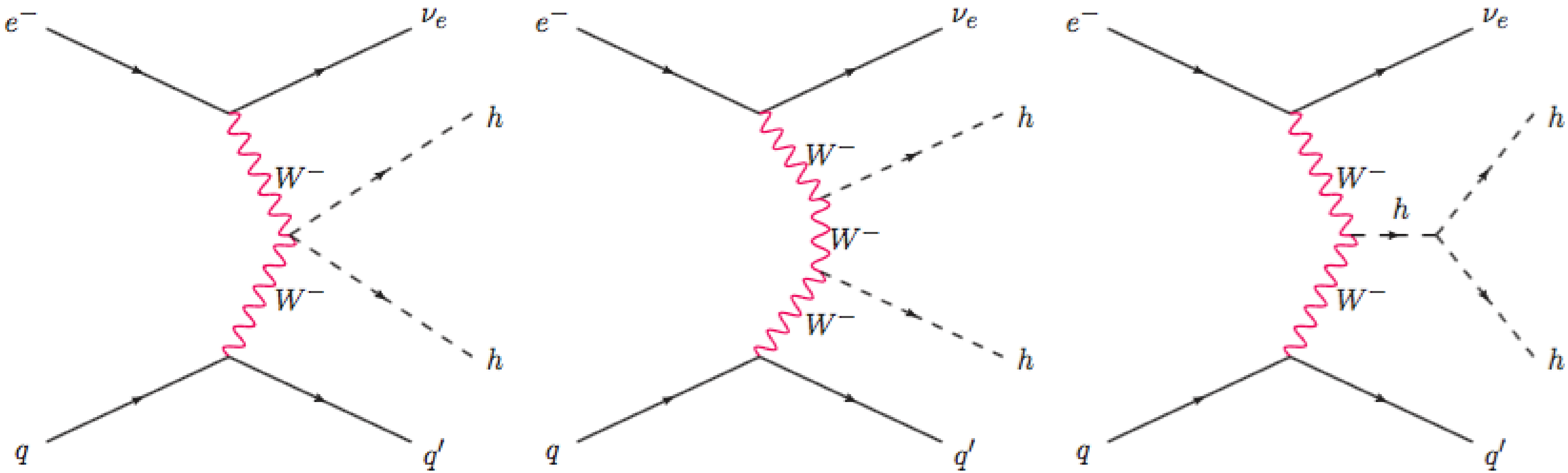
$$\Gamma^{\rm SM}_{\mu\nu} = -gM_V\, g_{\mu\nu}$$
$$\Gamma^{\rm BSM}_{\mu\nu}(p,q) = \frac{g}{M_V}\left[\lambda\left(p\cdot q\, g_{\mu\nu} - p_\nu q_\mu\right) + \lambda'\, \epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

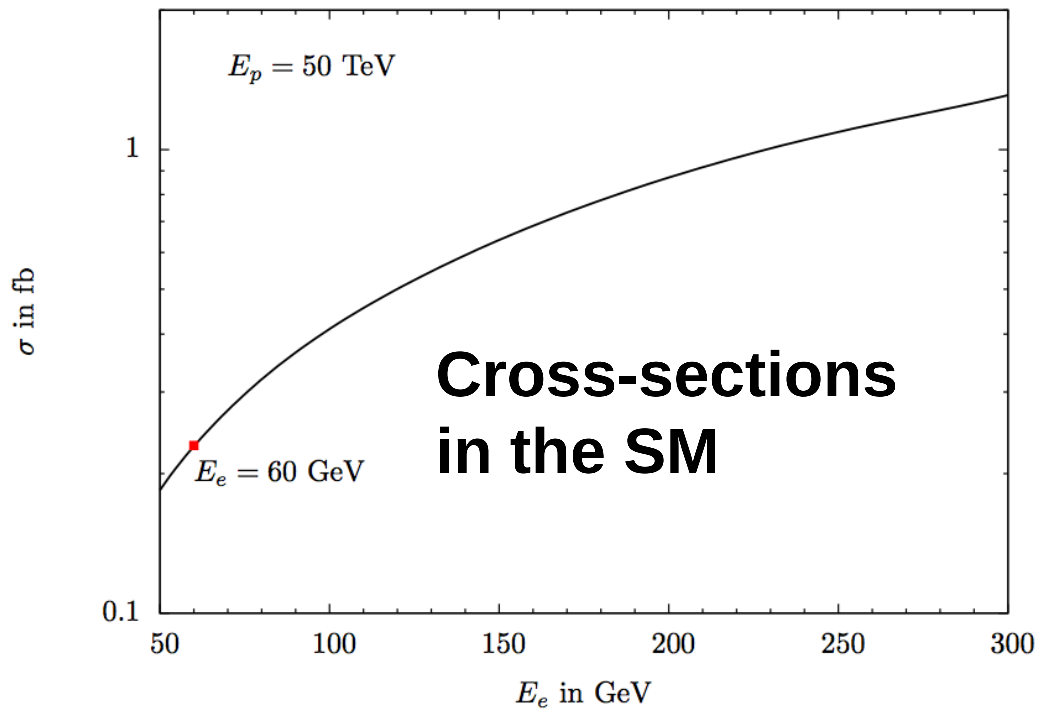
Can consider azimuthal angle correlation between scattered neutrino and quark. Other observables can be used too.

Model independent separation of HWW and HZZ coupling, unique capability of ep collisions, not available in pp and e^+e^- collisions



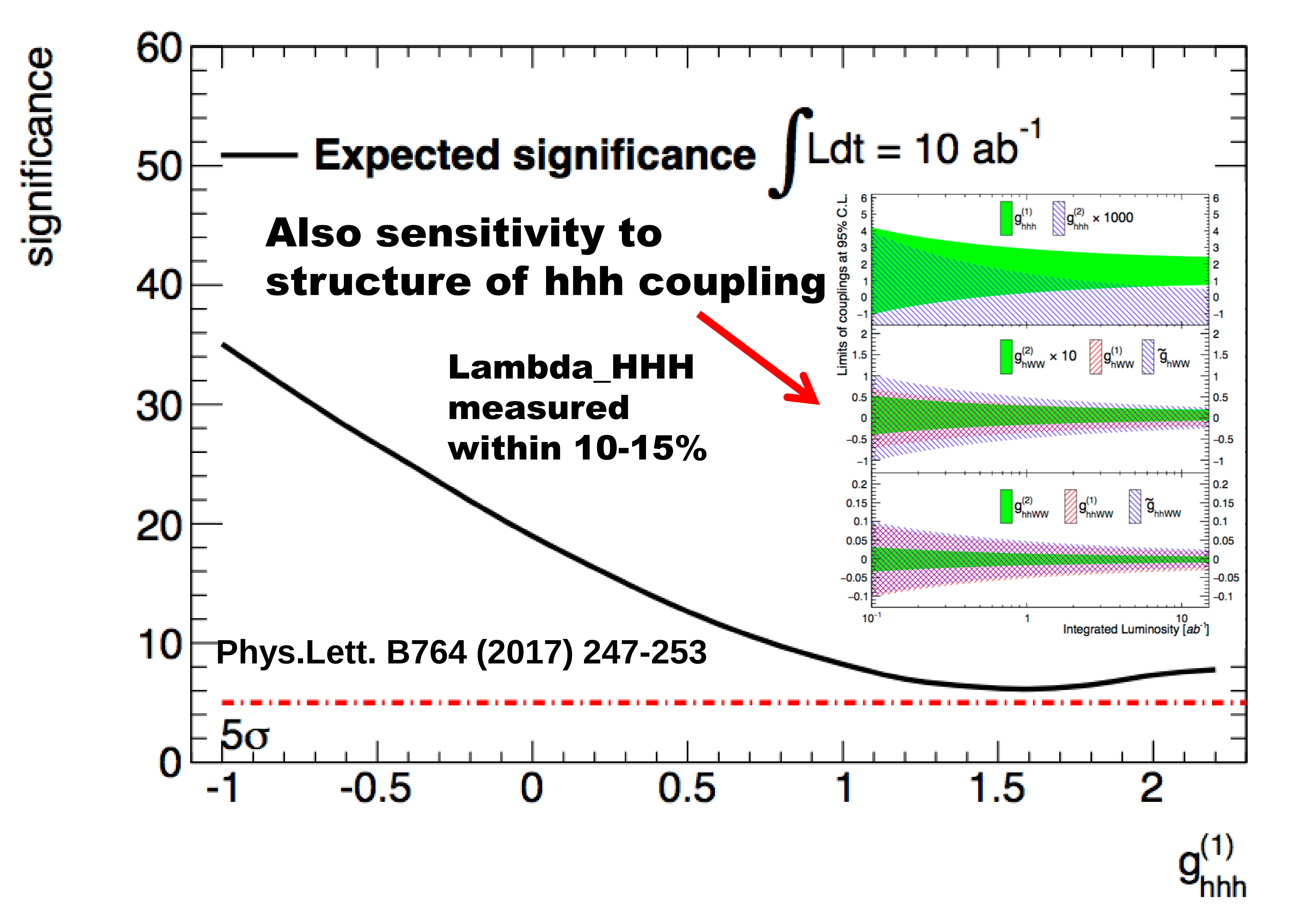
B.Biswal, R.Godbole, S.Kumar, B.M., S.Raychaudhuri
Phys.Rev.Lett. 109 (2012) 261801





Cross-sections in the SM

Considering highly asymmetric collisions

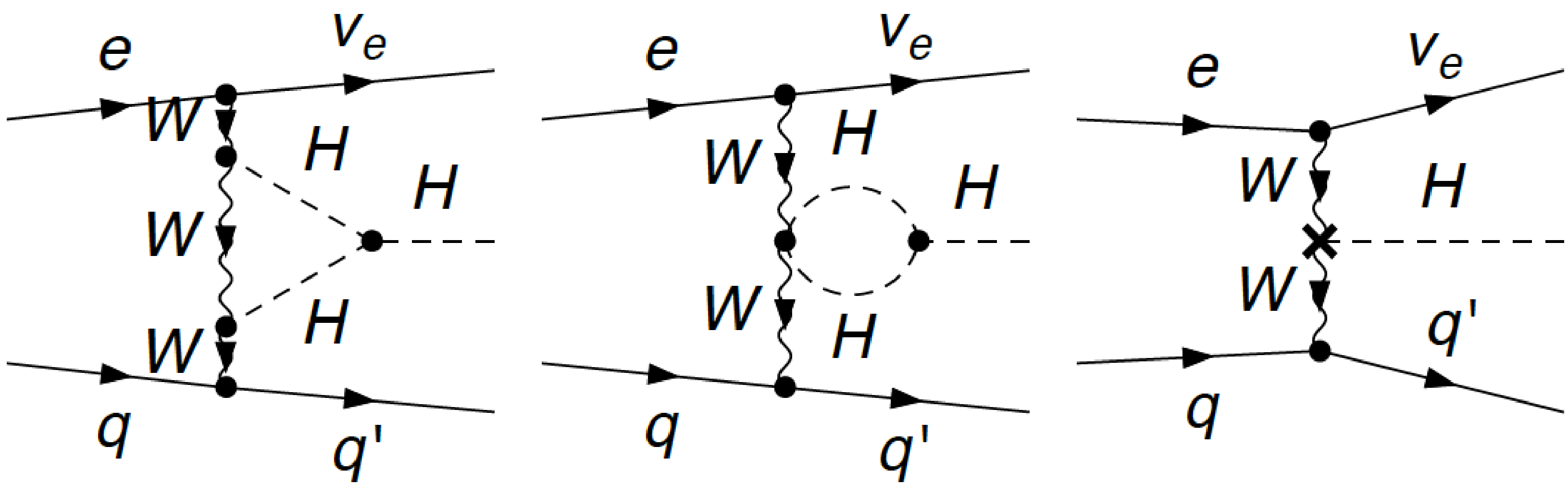


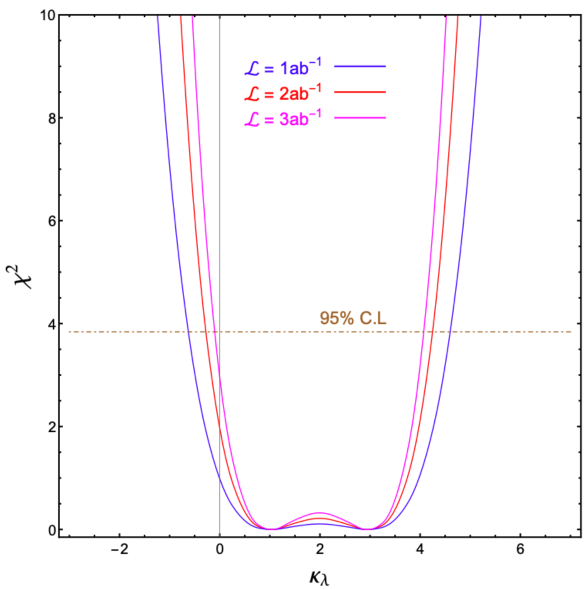
significance
Expected significance $\int Ldt = 10\ ab^{-1}$
Also sensitivity to
structure of hhh coupling
Lambda_HHH
measured
within 10-15%
Phys.Lett. B764 (2017) 247-253
5σ
60
50
40
30
20
10
0
-1
-0.5
0
0.5
1
1.5
2
$g^{(1)}_{hhh}$
Limits of couplings at 95% C.L.
$g^{(1)}_{hhh}$
$g^{(2)}_{hhh}$ × 1000
$g^{(2)}_{hWW}$ × 10
$g^{(1)}_{hWW}$
$\tilde{g}_{hWW}$
$g^{(2)}_{hhWW}$
$g^{(1)}_{hhWW}$
$\tilde{g}_{hhWW}$
Integrated Luminosity [ab^{-1}]

Probing Trilinear coupling via single h prod. (LHeC)

Diagrams sensitive to λ_{hhh}

K.Wang et al. 1910.09424





No cuts

The integrated luminosity	Bounds of the κ_λ	10% h acceptance
$\mathcal{L} = 1\ \text{ab}^{-1}$	[-0.63, 4.61]	[-2.65, 6.62]
$\mathcal{L} = 2\ \text{ab}^{-1}$	[-0.28, 4.25]	[-1.95, 5.93]
$\mathcal{L} = 3\ \text{ab}^{-1}$	[-0.11, 4.08]	[-1.59, 5.57]

Results can be significantly improved. Sensitivity will help the HL-LHC:

$$0.5 < k_\lambda < 1.5$$

Precision Higgs Physics at High-Energy Electron-Proton Colliders

Draft – in preparation

LHeC Higgs Study Group

G. Azuelos, S. Behera, J. De Blas, D. Hampson, R. Islam, S. Kawaguchi, E. Kay, U. Klein, M. Klein, P. Kostka, M. Kumar, M. Kuze, B. Mellado, M. O'Keefe, R. Li, C. Gwenlan, R. Ruan, T. Sekine, A. Senol, H. Sun, M. Tanaka, K. Wang, C. Zhang

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.

Outlook and Conclusions

- Progress in devising concurrent ep/pp running
  - Unique DIS facility at CERN with 10^{34} instantaneous luminosity, opens new horizon for particle physics, in particular in the space of precision measurements
- Combining pp with ep, turns the LHC into a precision machine
  - Reach <1%-<2% precision for HL-LHC/LHeC, depending on coupling
  - Competitive and complementary to e^+e^-
- Unique access to structure of hVV coupling
- Measurement of trilinear self-coupling
  - FCC-eh yields ~10% precision and unique access to coupling structure
  - Preliminary studies shows sensitivity to self-coupling via single h production, can contribute to HL-LHC

Additional slides

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

$$i\Gamma_{hhh} = -6iv\lambda g^{(1)}_{hhh} - ig^{(2)}_{hhh}(p_1 \cdot p_2 + p_2 \cdot p_3 + p_3 \cdot p_1),$$

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

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

M. Kumar et al.[1509.04016]