Higgs Physics in Energy Frontier DIS

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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

Institute for Collider Particle Physics

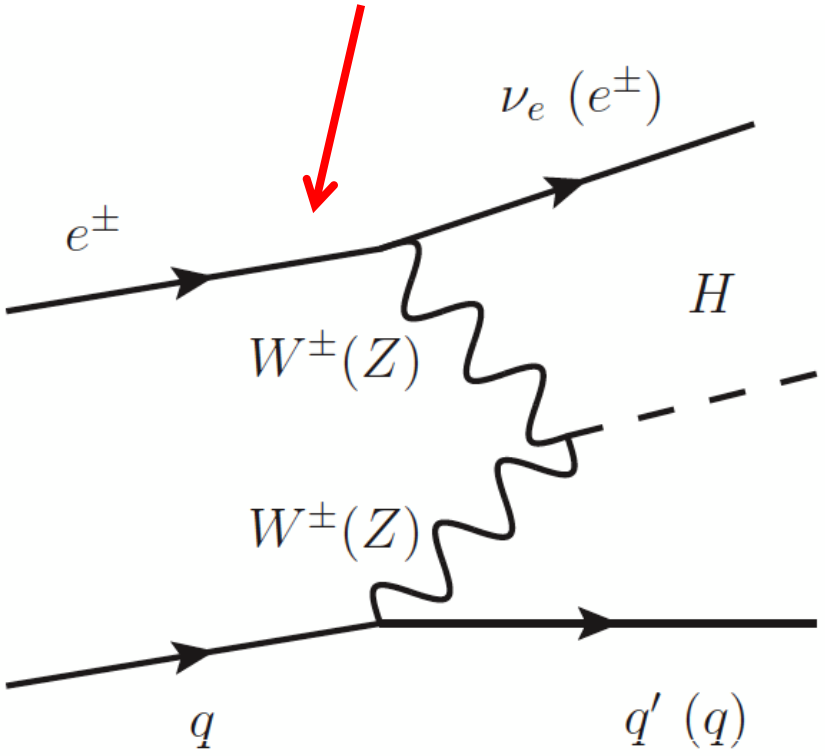
University of the Witwatersrand

IAS High Energy Physics, Hong Kong, 19/01/21

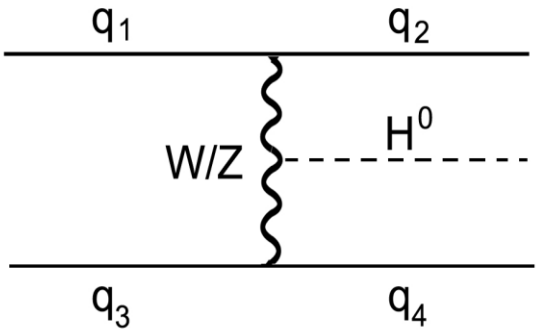
Higgs in ep

- 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



Higgs via VBF
Qualitative remarks



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

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

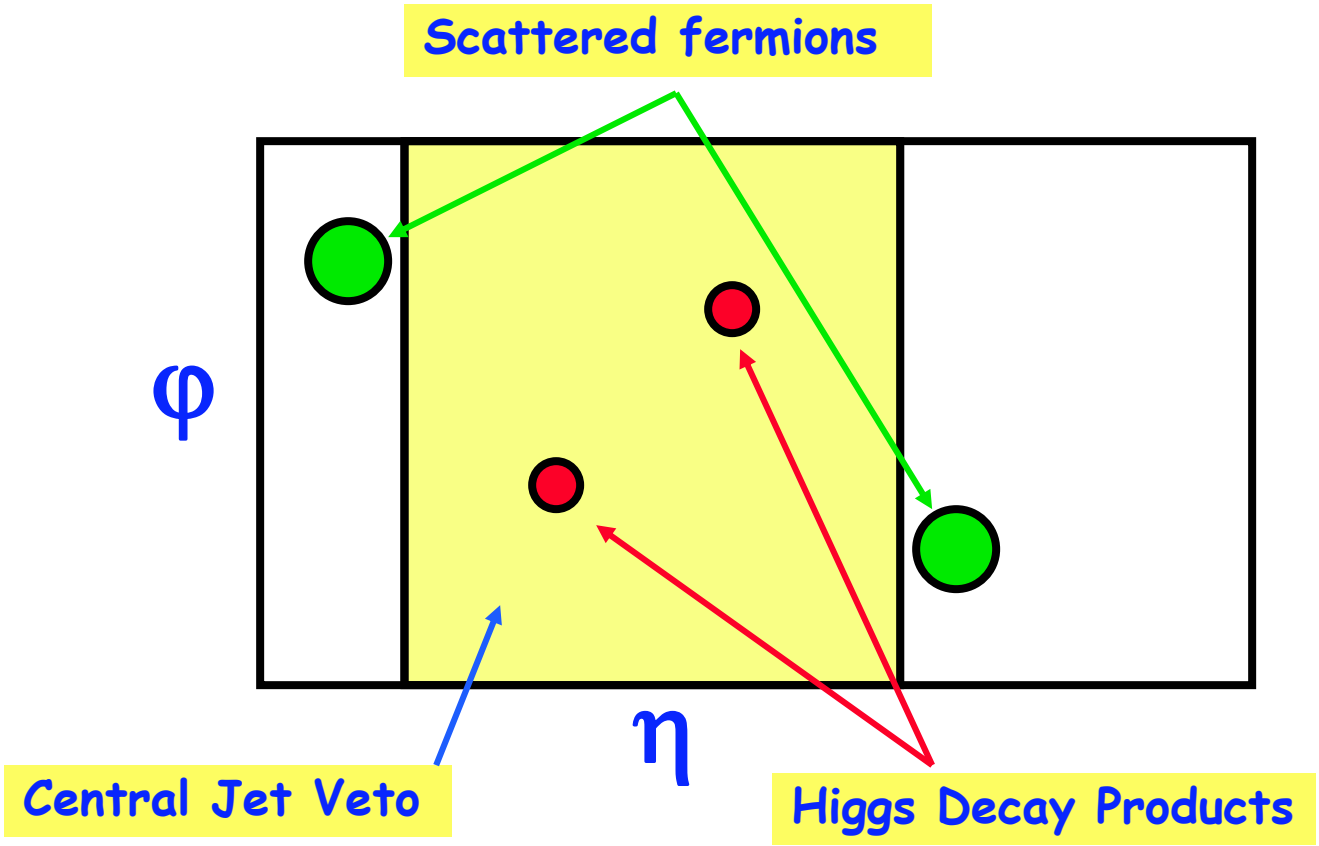
$$P_{V/f}^L(x, p_T^2) = \frac{g_V^2 + g_V^2}{4\pi^2}\frac{1-x}{x}\frac{(1-x)M_V^2}{(p_T^2 + (1-x)M_V^2)^2}.$$

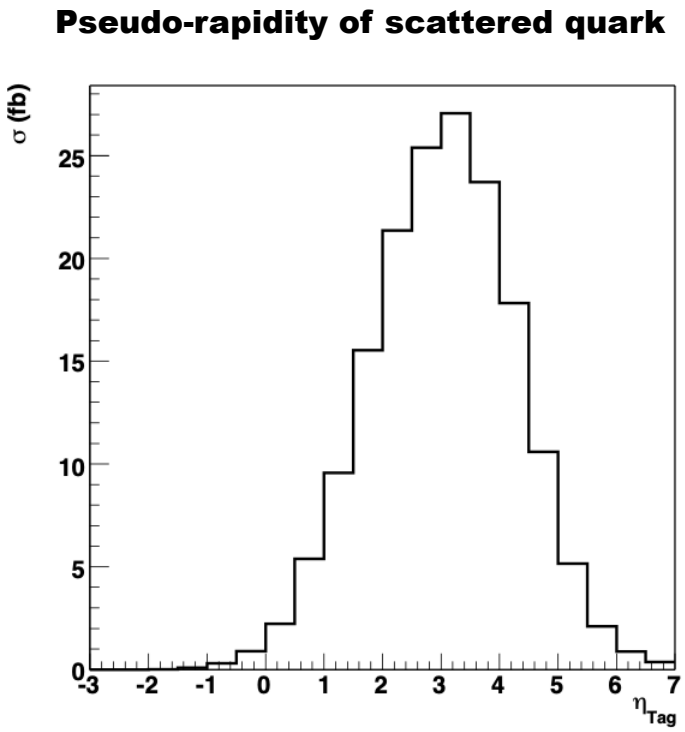
- **Unlike QCD partons that scale like $1/P_T^2$, here $P_T \sim \sqrt{(1-x)}M_W$**

- **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 !

Higgs in eh: *cut* based results

Masahiro Tanaka, Masahiro Kuze,
Tokyo Tech 2017/2018

Example of samples: Unpolarised (P=0) samples E_e=60 GeV

E_p=7 TeV **LHeC**

	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

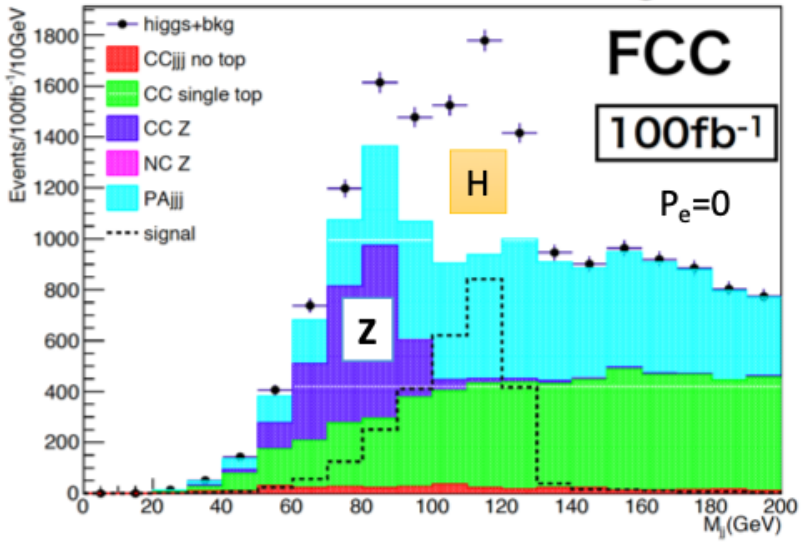
Delphes ep-style detector
+ flat parton-level b-tagging
for |η|<3.0
conservative HFL tagging:
b: 60%, c: 10%, **udsg: 1%**
CAL coverage |η|<5 LHeC [<6 FCC-eh]

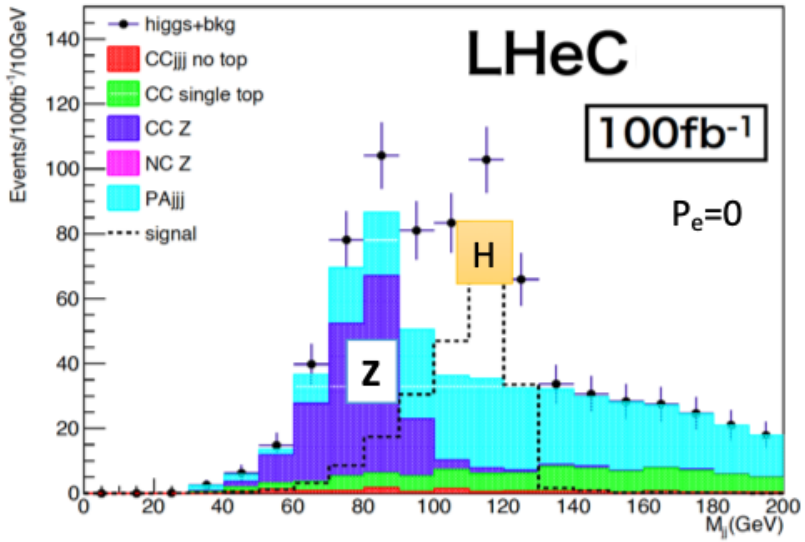
Mass of 2 b-jets after event selection

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

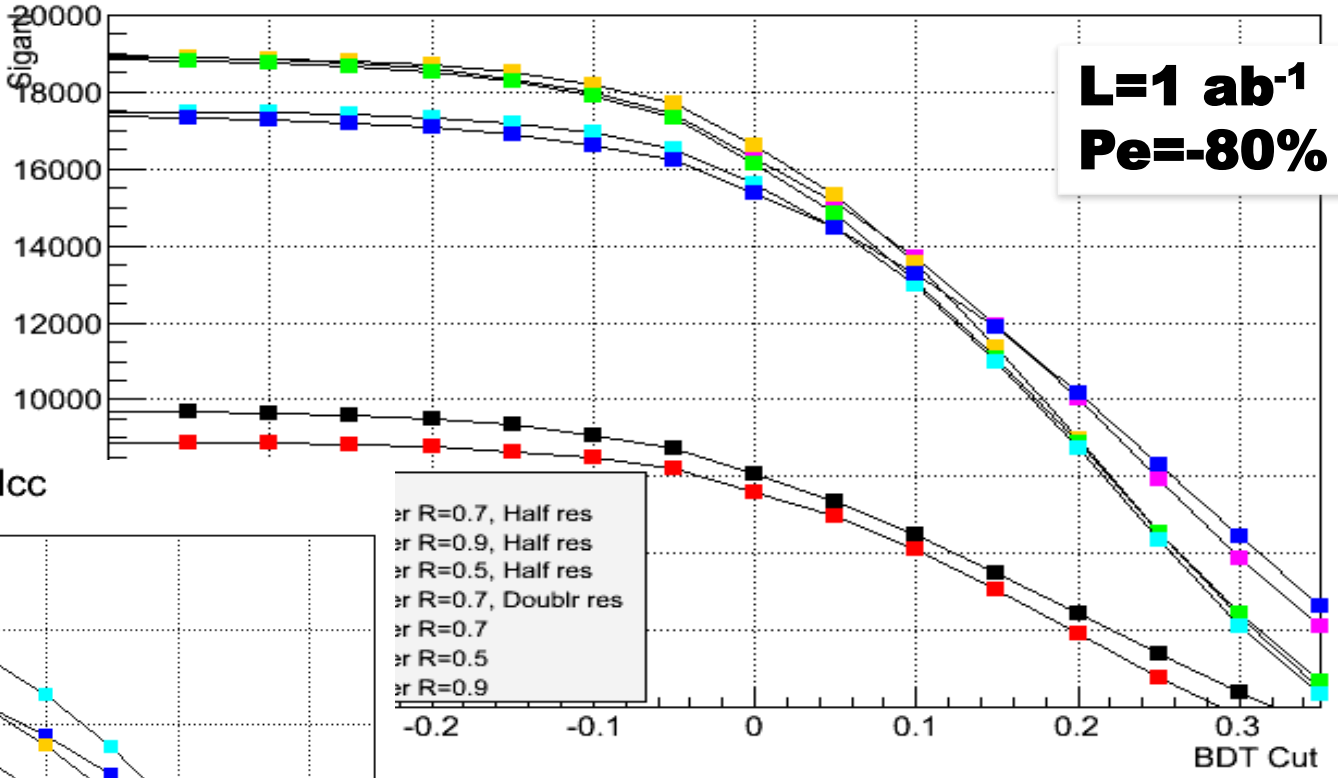
BDT Results for Higgs @ LHeC

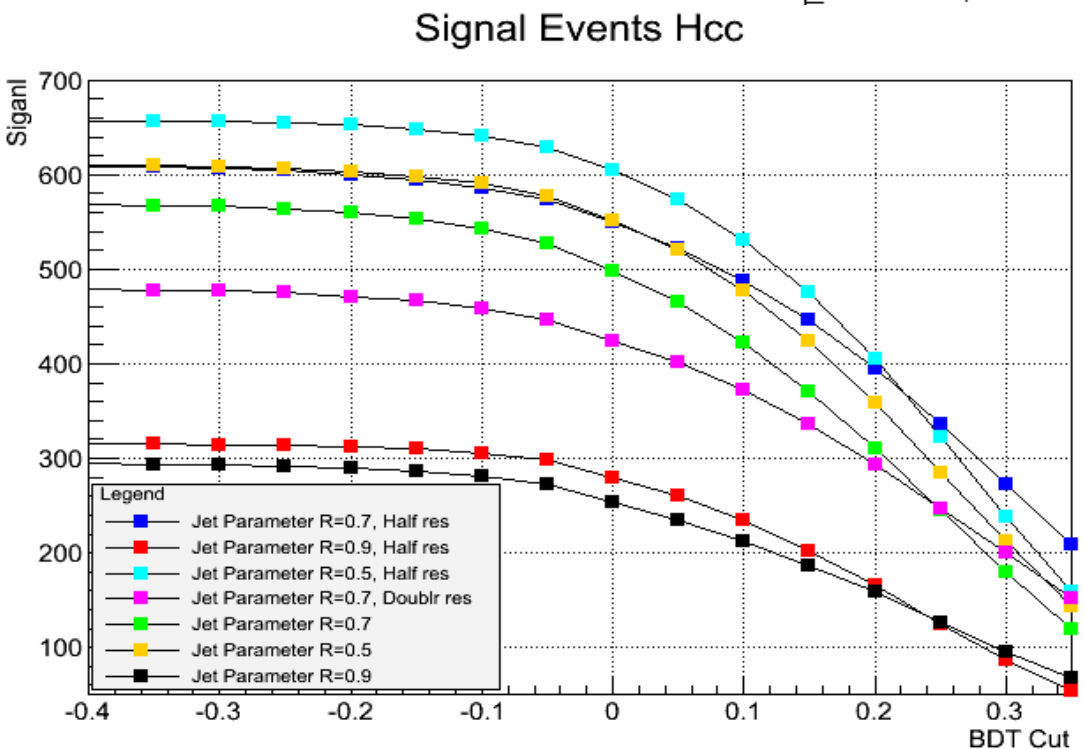
Daniel Hampson, MPHYS 2016

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

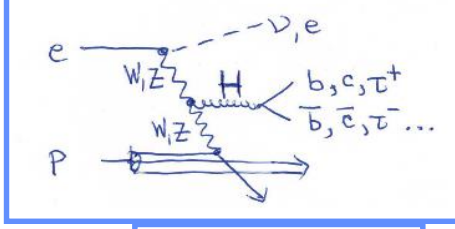




Hcc : High sensitivity to vertex resolution (nominal 10 µm) and jet radius

→ 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

LHeC @ L=1000 fb^{-1}

Hbb

2% PHP and 2% other bgd

Events

$M_{jj,H}^{BDT>0}$ [GeV]

Hbb signal with BDT>0

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

$\delta\mu/\mu$(Hbb) = 0.8%

Hbb

CC h → bb
CC h → cc̄
CC Z → jj
γ p jjj
CC jjj
CC t
NC Z → jj

Hcc

remaining Hbb

2% Hbb and 2% other bgd

Hcc

Hcc signal with BDT>0

Hcc

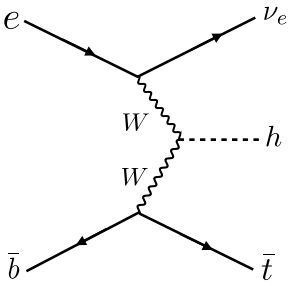
$\delta\mu/\mu$(Hcc) = 7.4 %

Assuming ATLAS light jet misID efficiencies

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

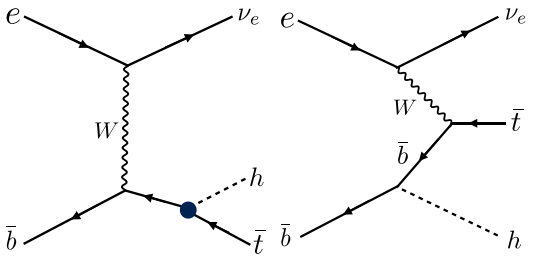
B.Coleppa, M.Kumar, S.Kumar, B.M., Phys. Lett. B770 (2017) 335

Top Yukawa coupling

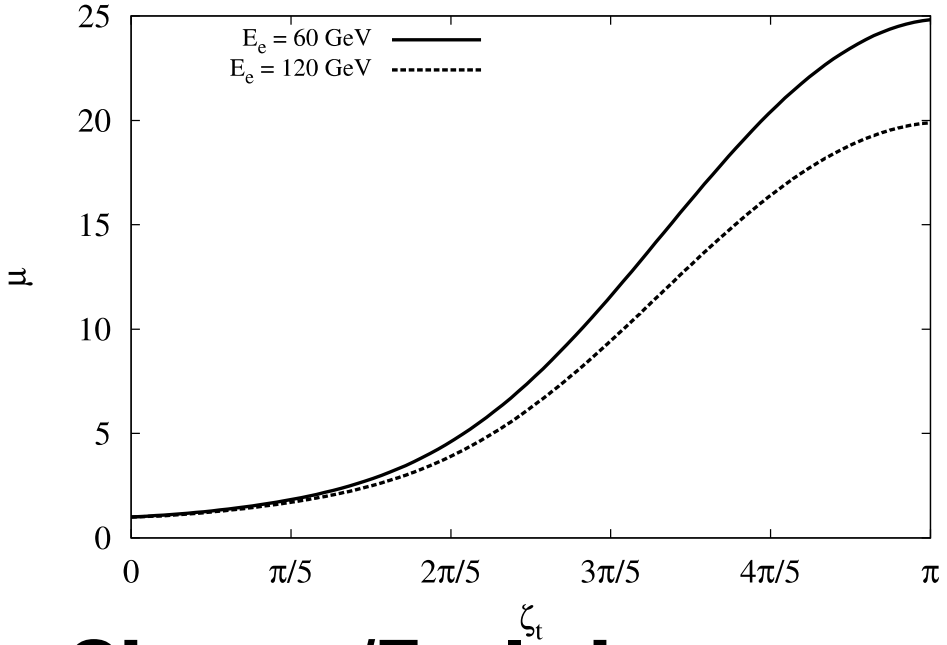


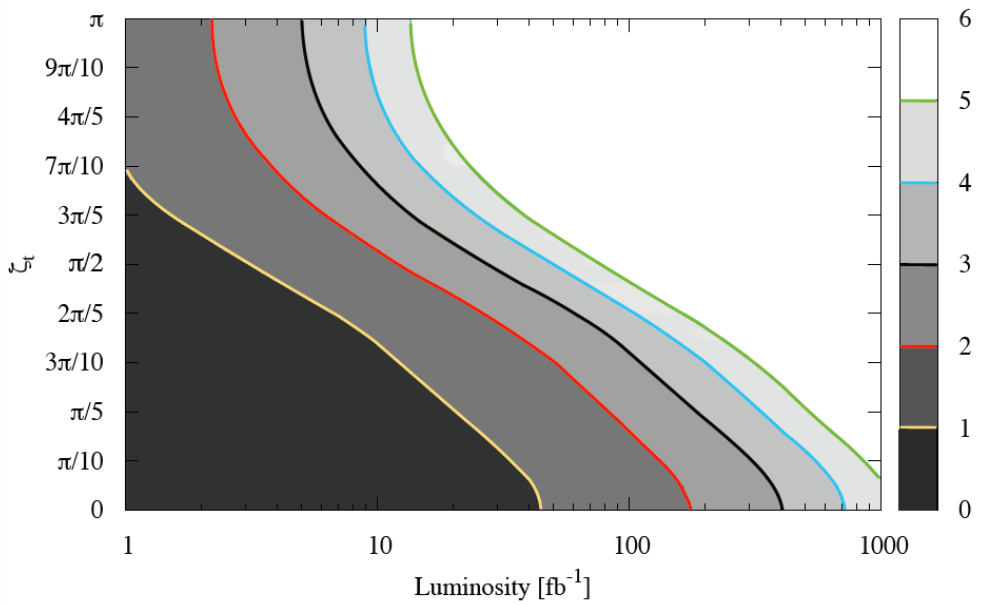
Introduce phase dependent top Yukawa coupling

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



Enhancement of the cross-section as a function of phase

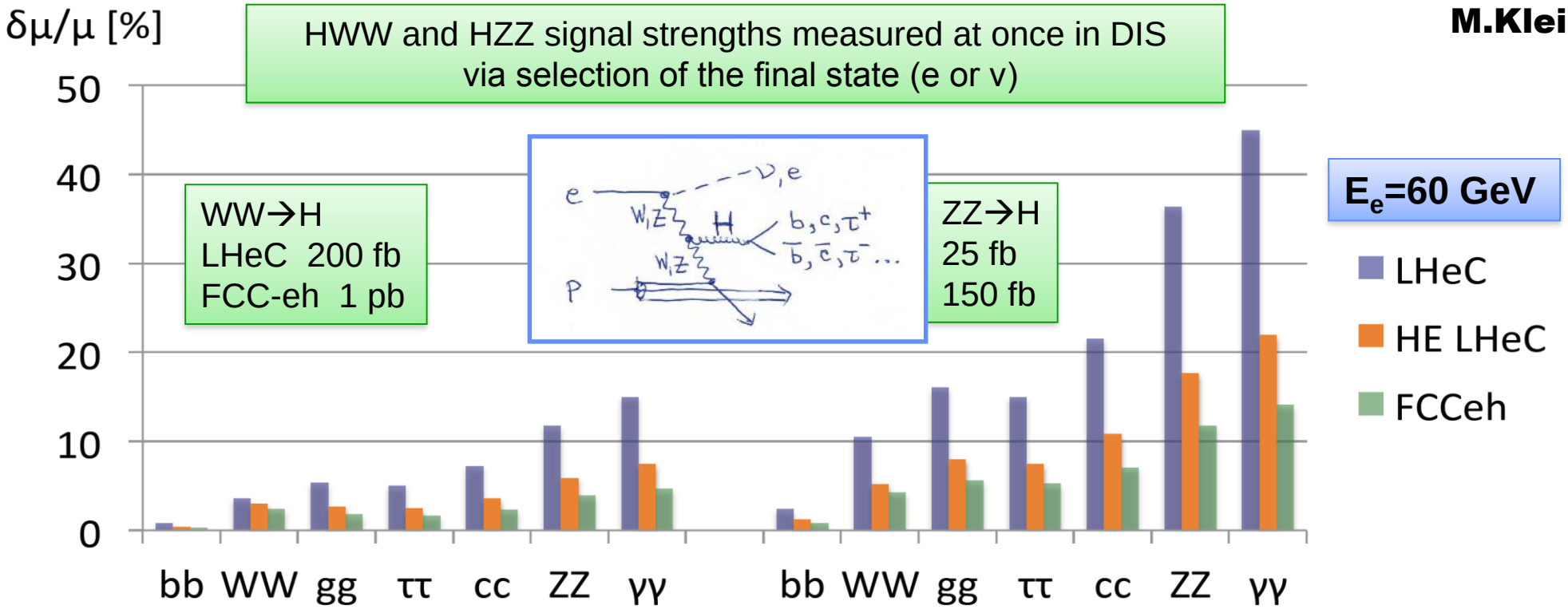




Observe/Exclude non-zero phase to better than 4σ at LHeC. Achieve <2% error on k_t at the FCC-eh.

SM Higgs Signal Strengths in ep

M.Klein



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

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

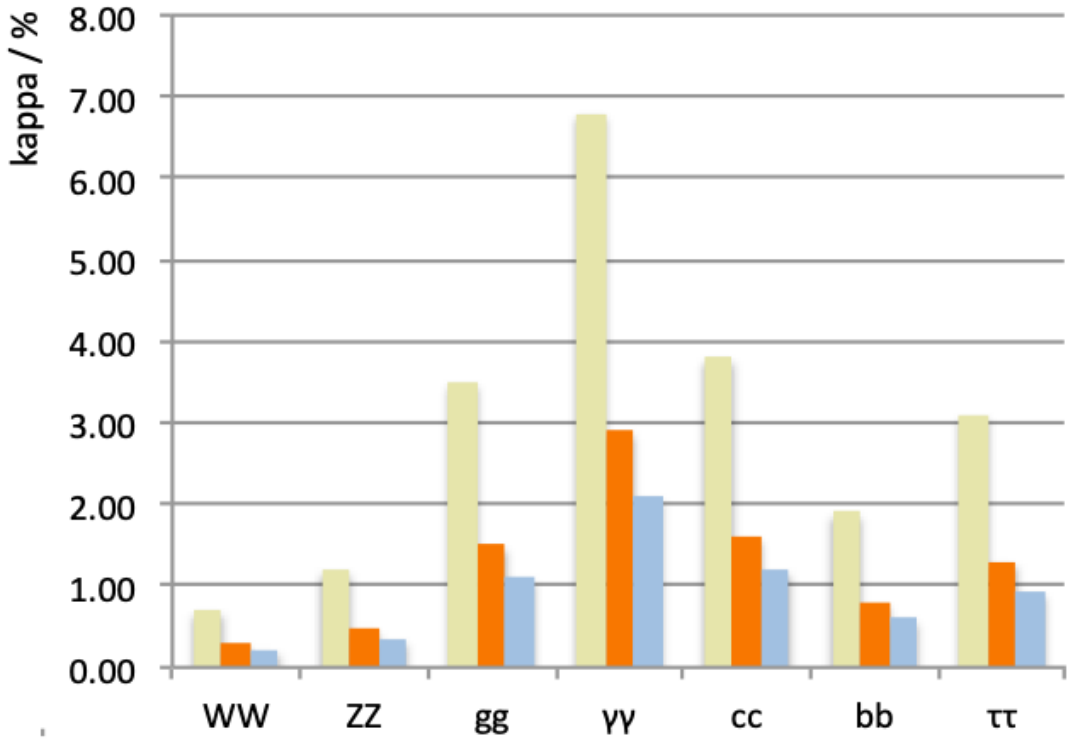
→NC and CC DIS together over-constrain Higgs couplings in a combined SM fit.

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}

[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]



E_e = 60 GeV, P=-0.8

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

Note: also
H in ePb

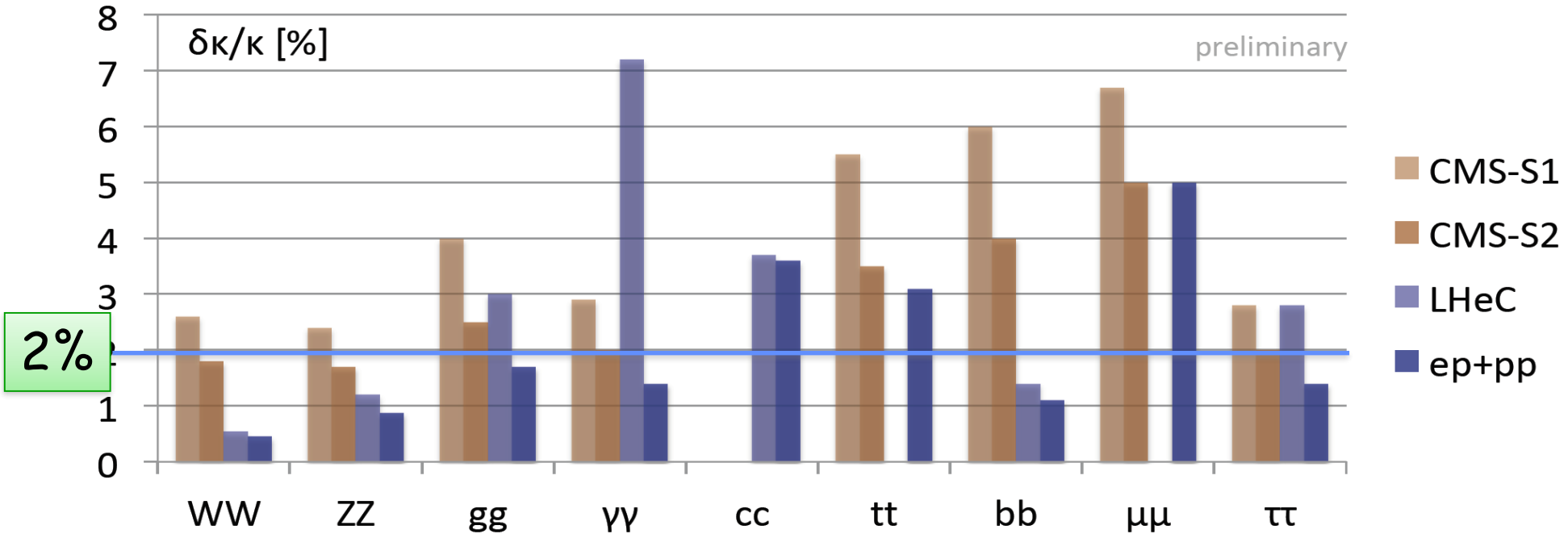
Very high precision due to CC+NC DIS in clean environment in luminous, energy frontier ep scattering

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:



→ 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%
$\kappa_{Z\gamma}$	–

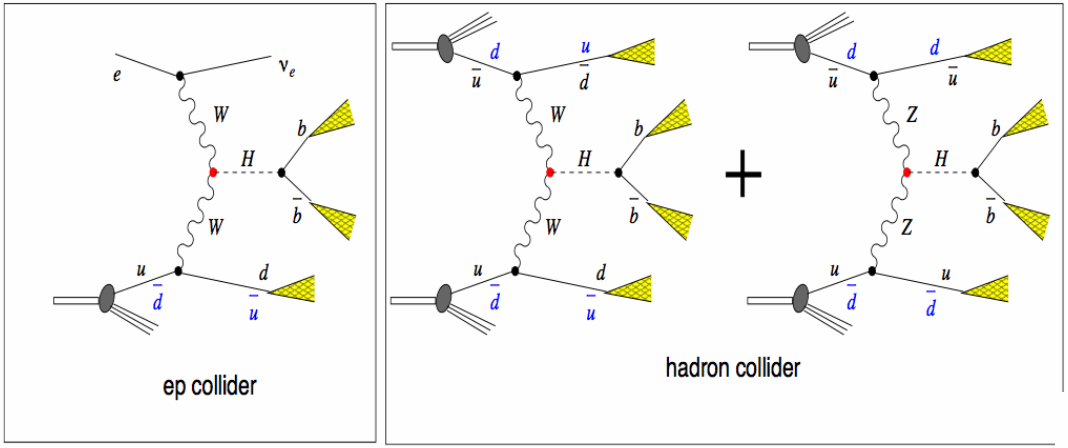
FCC-eh	
Coupling	Relative precision
κ_b	0.74%
κ_t	–
κ_τ	1.10%
κ_c	1.35%
κ_μ	–
κ_Z	0.43%
κ_W	0.26%
κ_g	1.17%
κ_γ	2.35%
$\kappa_{Z\gamma}$	–

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

Published in book 1 of FCC

Structure of HVV couplings

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



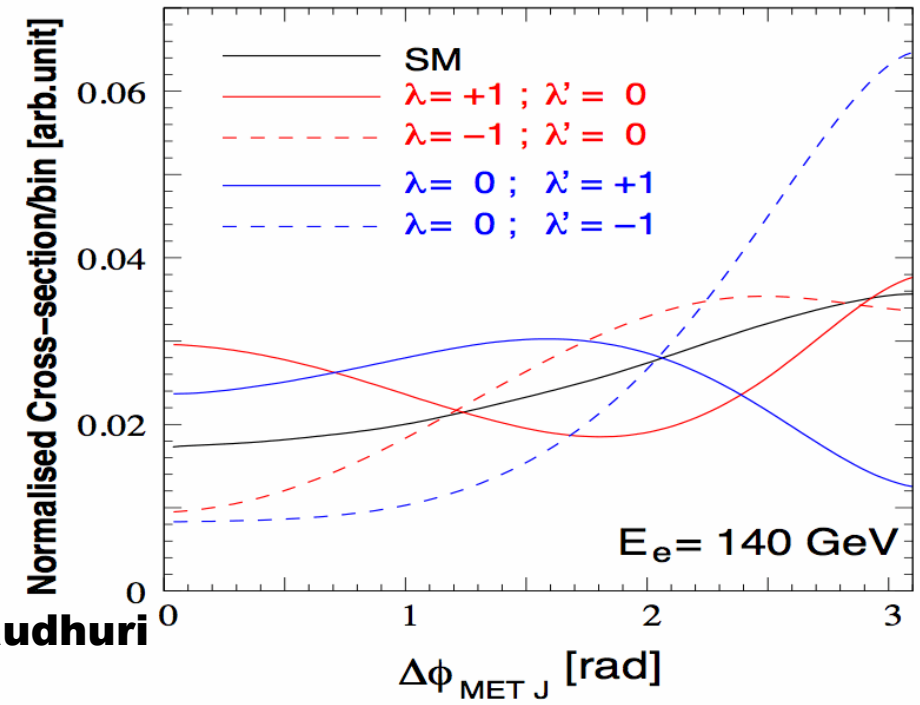
$$\Gamma^{\rm SM}_{\mu\nu} = -gM_V\, g_{\mu\nu}$$

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

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

ep **process uniquely addresses the** HWW **vertex.**

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

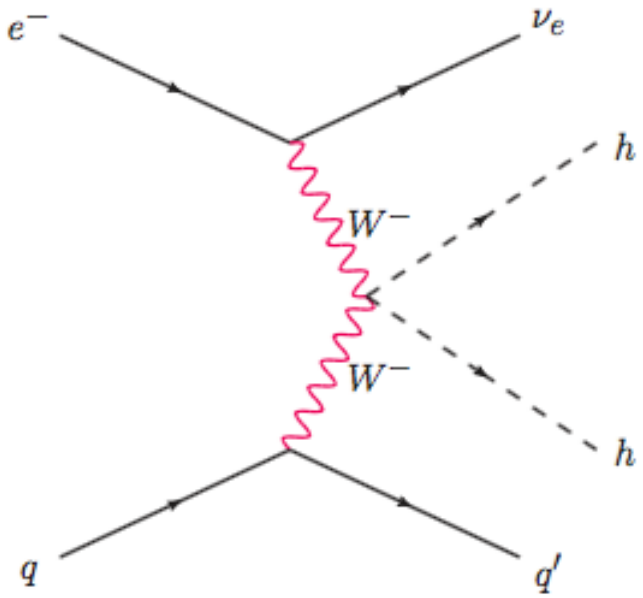


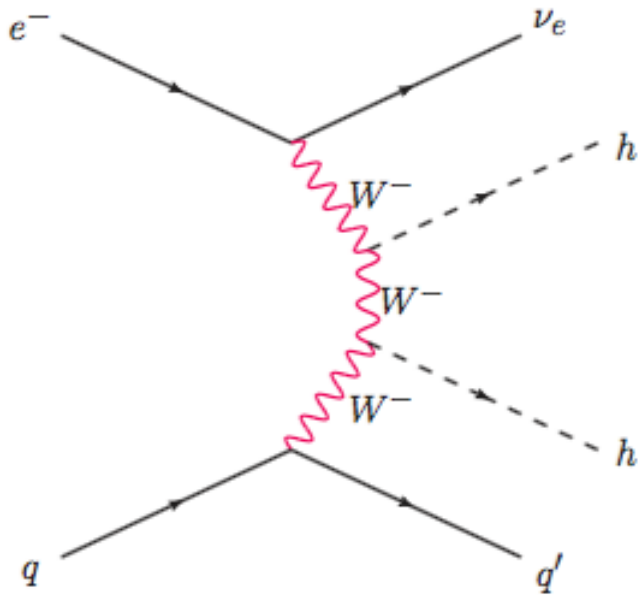
B.Biswal, R.Godbole, S.Kumar, B.M., S.Raychaudhuri Phys.Rev.Lett. 109 (2012) 261801

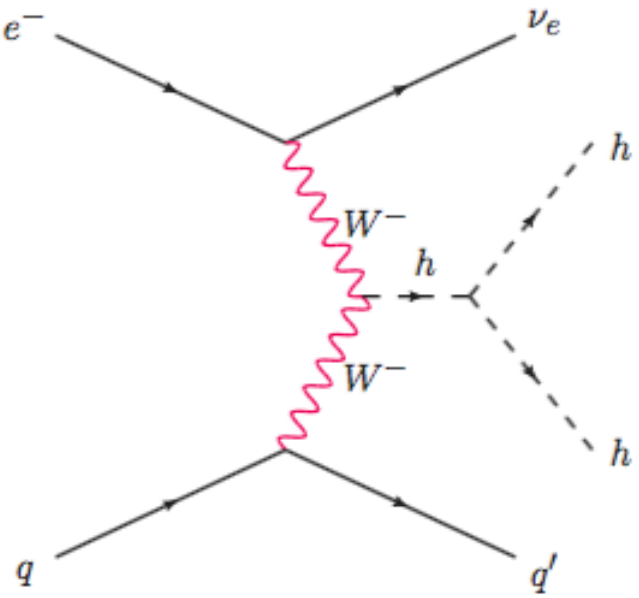
Outlook and Conclusions

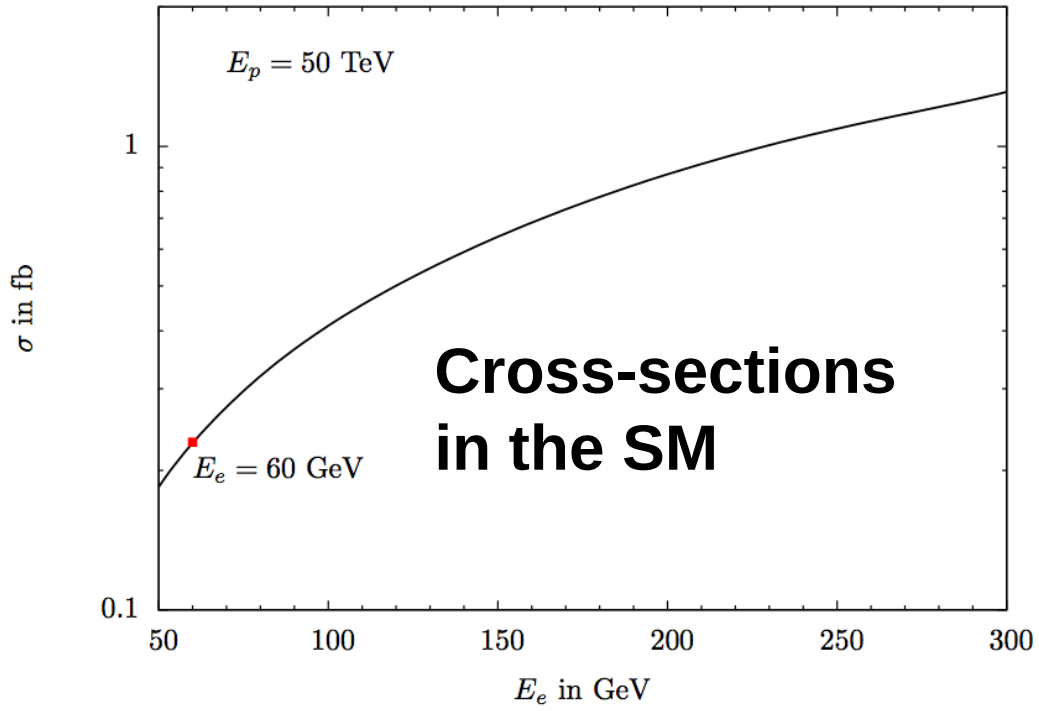
- Progress in devising concurrent ep/pp running
  - Unique DIS facility at CERN with 10^{34} instantaneous luminosity, opens new horizon for particle physics, in particular in the space of precision measurements
- Combining pp with ep, turns the LHC into a precision machine
  - Reach <1%-<2% precision for HL-LHC/LHeC, depending on coupling
  - Competitive and complementary to e^+e^-
- Direct measurement of top Yukawa coupling down to <2% in k_t at the FCC-eh
- Unique access to structure of hWW coupling

Additional slides



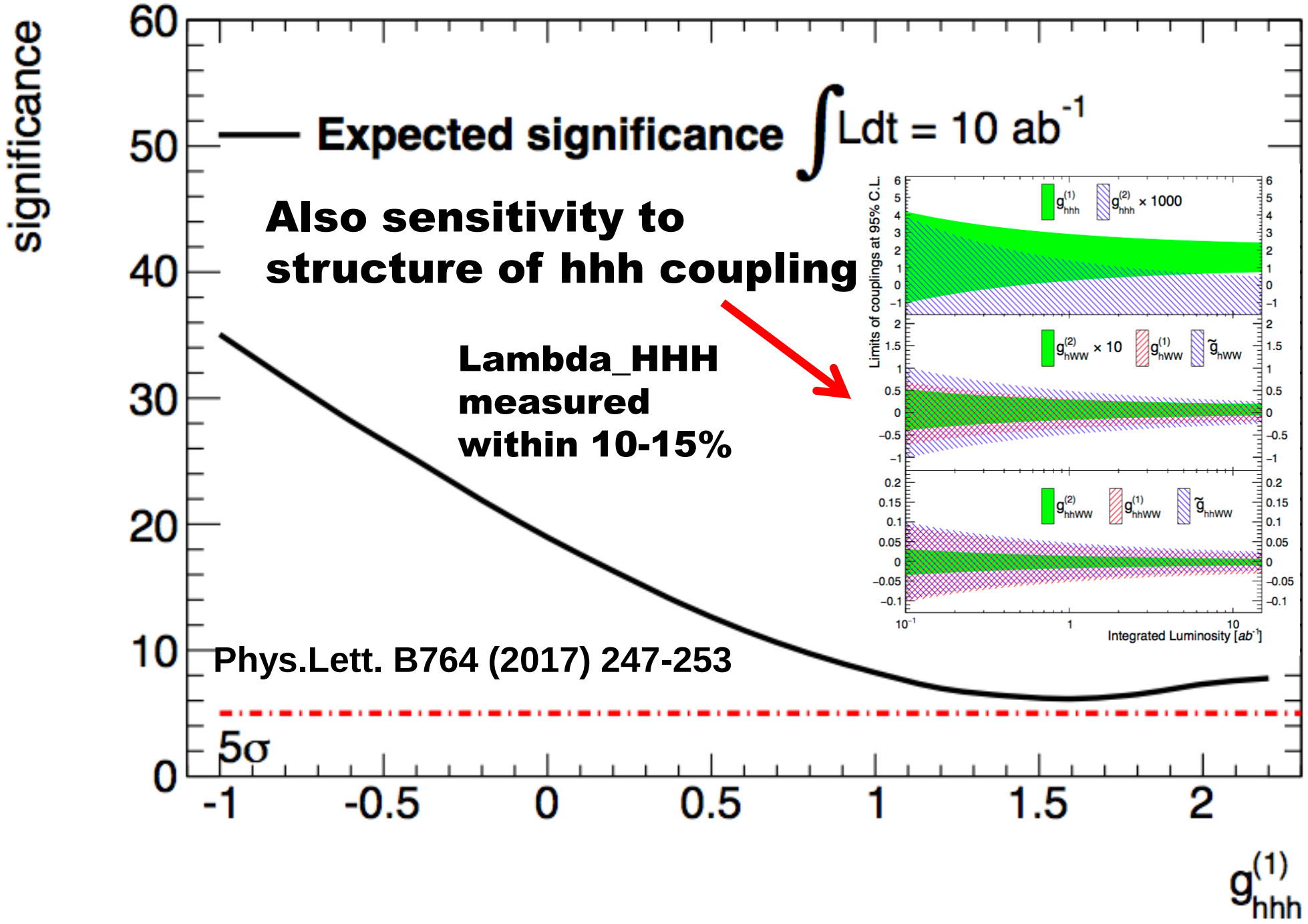






Cross-sections in the SM

Considering highly asymmetric collisions


significance
60
50
40
30
20
10
0
Expected significance ∫Ldt = 10 ab-1
Also sensitivity to structure of hhh coupling
Lambda_HHH measured within 10-15%
Phys.Lett. B764 (2017) 247-253
5σ
-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
g̃hww
g(2)hhww
g(1)hhww
g̃hhww
10-1
1
10
Integrated Luminosity [ab-1]

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

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

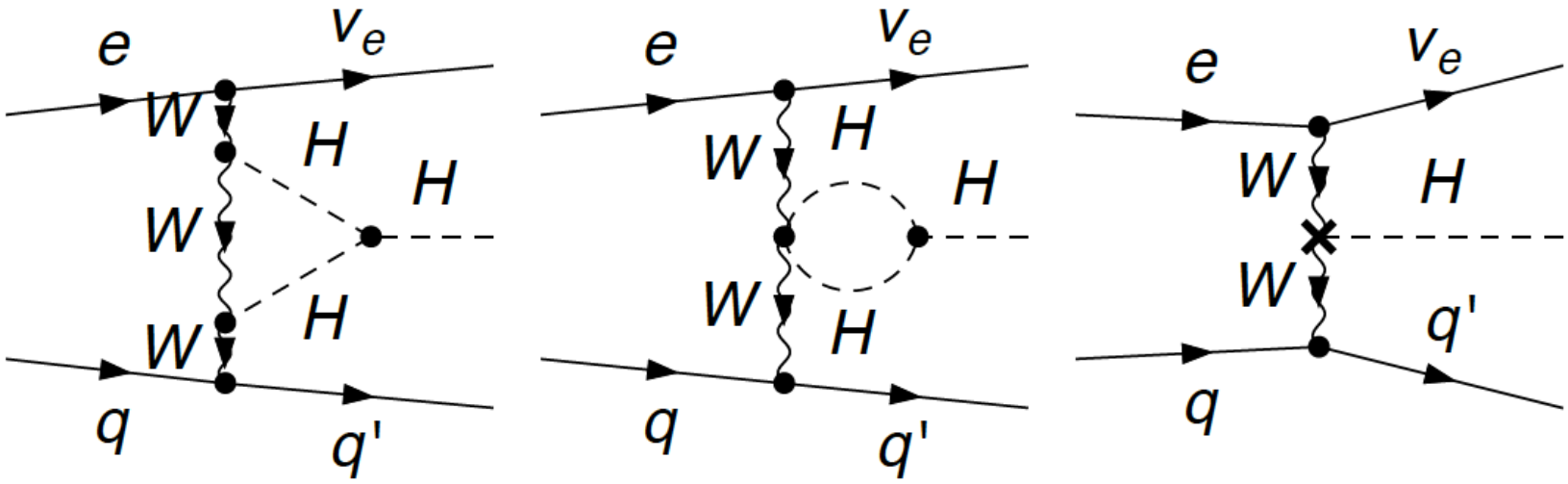
$$\begin{aligned} i\Gamma_{hW^-W^+} =& i\left[\left\{\frac{g^2}{2}v + \frac{g}{m_W}g^{(1)}_{hWW}p_2\cdot p_3 + \frac{g}{m_W}g^{(2)}_{hWW}(p_2^2+p_3^2)\right\}\eta^{\mu_2\mu_3}\right. \\ & -\frac{g}{m_W}g^{(1)}_{hWW}p_2^{\mu_3}p_3^{\mu_2} - \frac{g}{m_W}g^{(2)}_{hWW}(p_2^{\mu_2}p_2^{\mu_3} + p_3^{\mu_2}p_3^{\mu_3})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

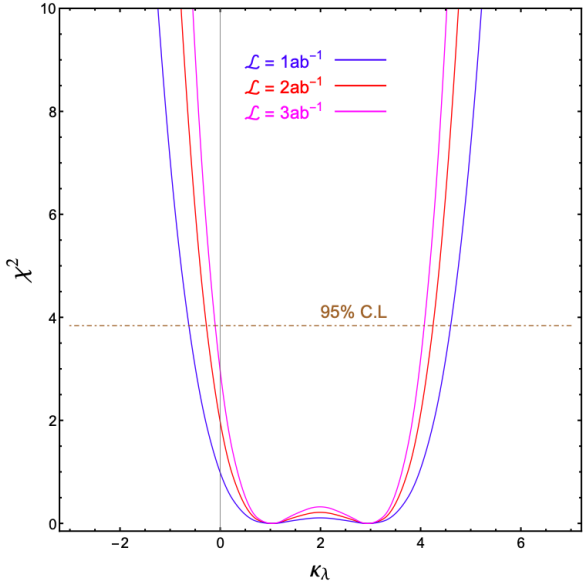
$$\begin{aligned} i\Gamma_{hhW^-W^+} =& i\left[\left\{\frac{g^2}{2} + \frac{g^2}{m_W^2}g^{(1)}_{hhWW}p_3\cdot p_4 + \frac{g^2}{m_W^2}g^{(2)}_{hhWW}(p_3^2+p_4^2)\right\}\eta^{\mu_3\mu_4}\right. \\ & -\frac{g^2}{m_W^2}g^{(1)}_{hhWW}p_3^{\mu_4}p_4^{\mu_3} - \frac{g^2}{m_W^2}g^{(2)}_{hhWW}(p_3^{\mu_3}p_3^{\mu_4} + p_4^{\mu_3}p_4^{\mu_4}) \\ & \left. -i\frac{g^2}{m_W^2}\tilde{g}_{hhWW}\epsilon_{\mu_3\mu_4\mu\nu}p_3^{\mu}p_4^{\nu}\right] \cdot \end{aligned}$$ **M. Kumar et al.[1509.04016]**

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
$\mathcal{L} = 1$ ab^{-1}	[-0.63, 4.61]
$\mathcal{L} = 2$ ab^{-1}	[-0.28, 4.25]
$\mathcal{L} = 3$ ab^{-1}	[-0.11, 4.08]

10% h acceptance

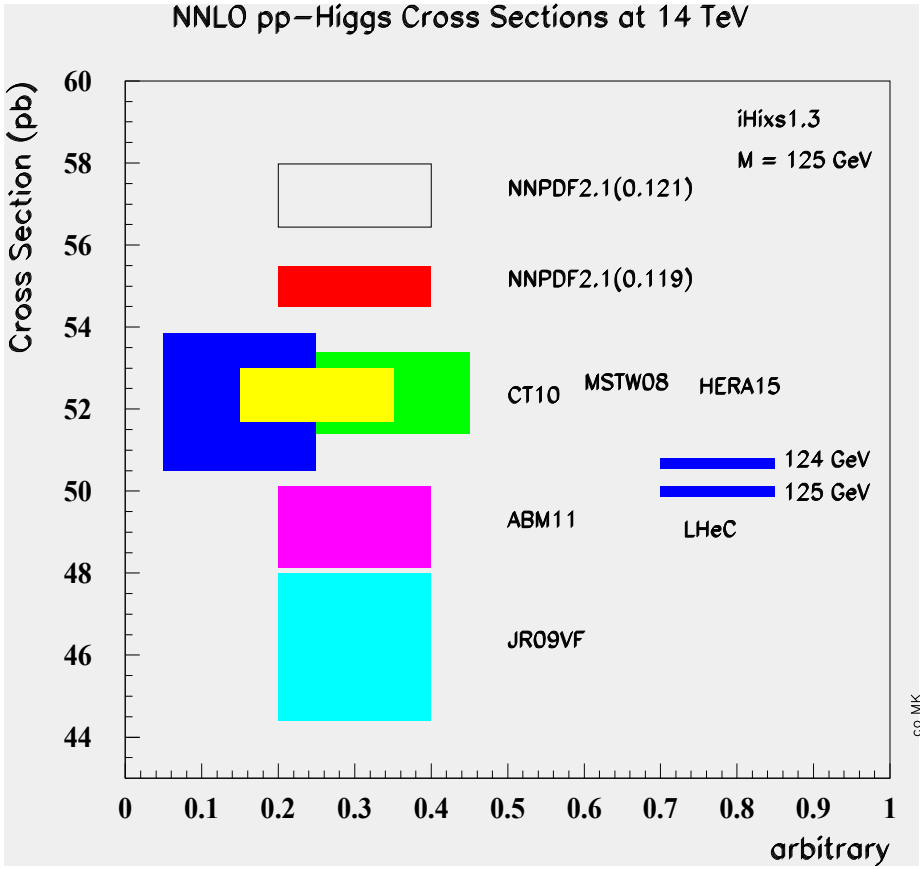
[-2.65, 6.62]
[-1.95, 5.93]
[-1.59, 5.57]

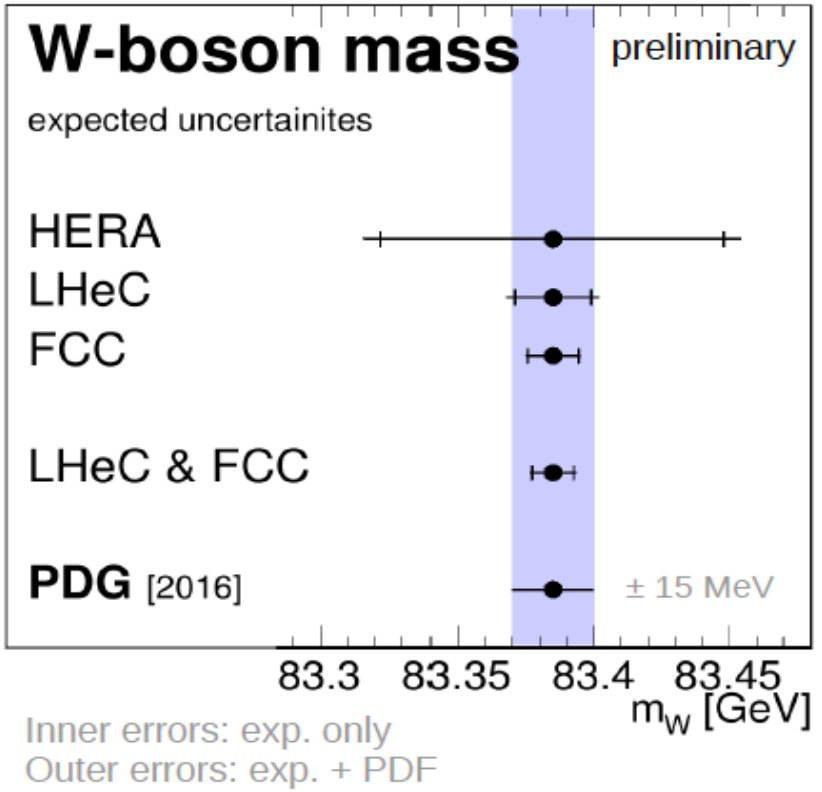
Results can be significantly improved. Sensitivity will help the HL-LHC:

$$0.5 < k_\lambda < 1.5$$

High Precision for pp

M.Klein





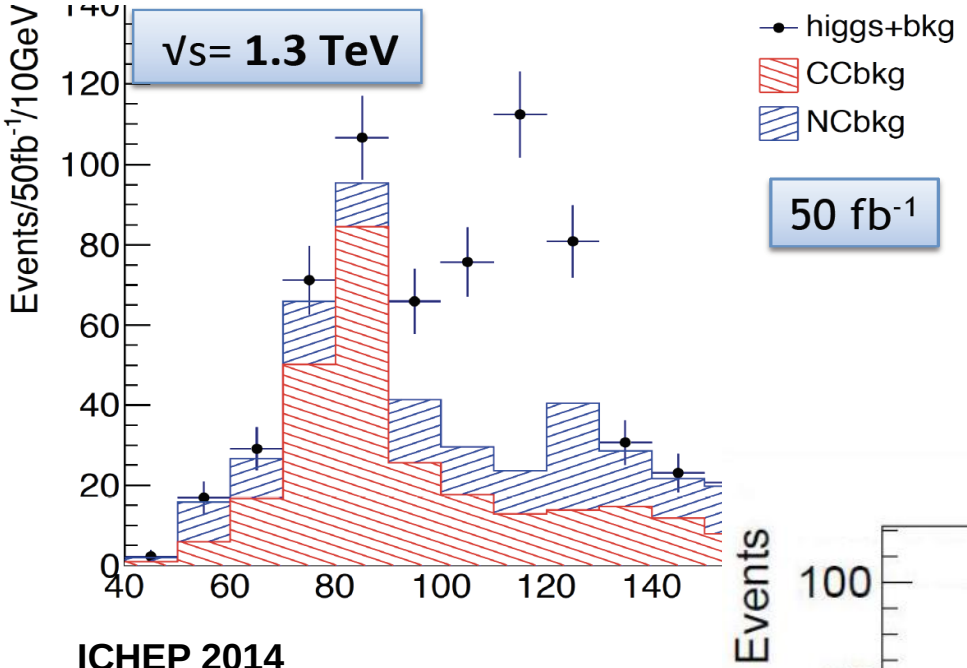
Can achieve <0.5% precision in pdf uncertainty, thus removing this uncertainty from the prediction of the Higgs cross-section.

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% !

CDR Updates: Two independent analyses

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

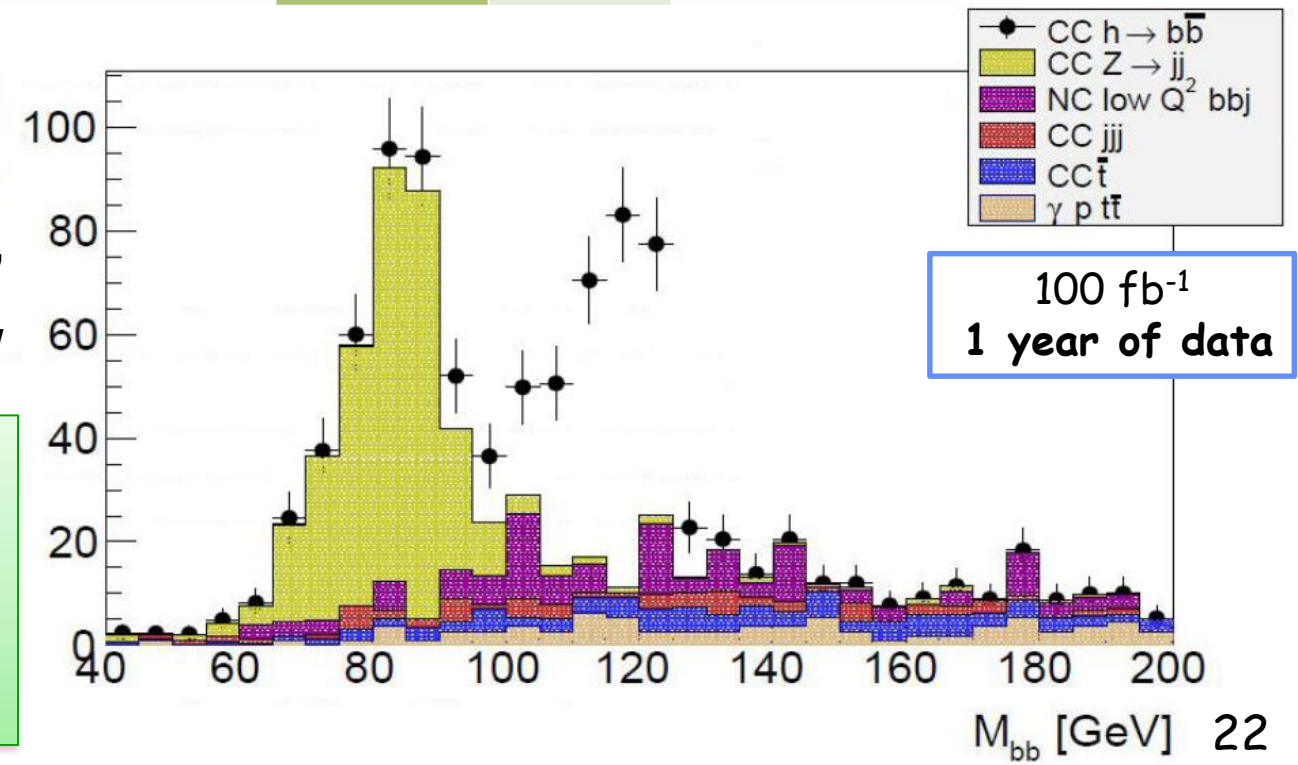


Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

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

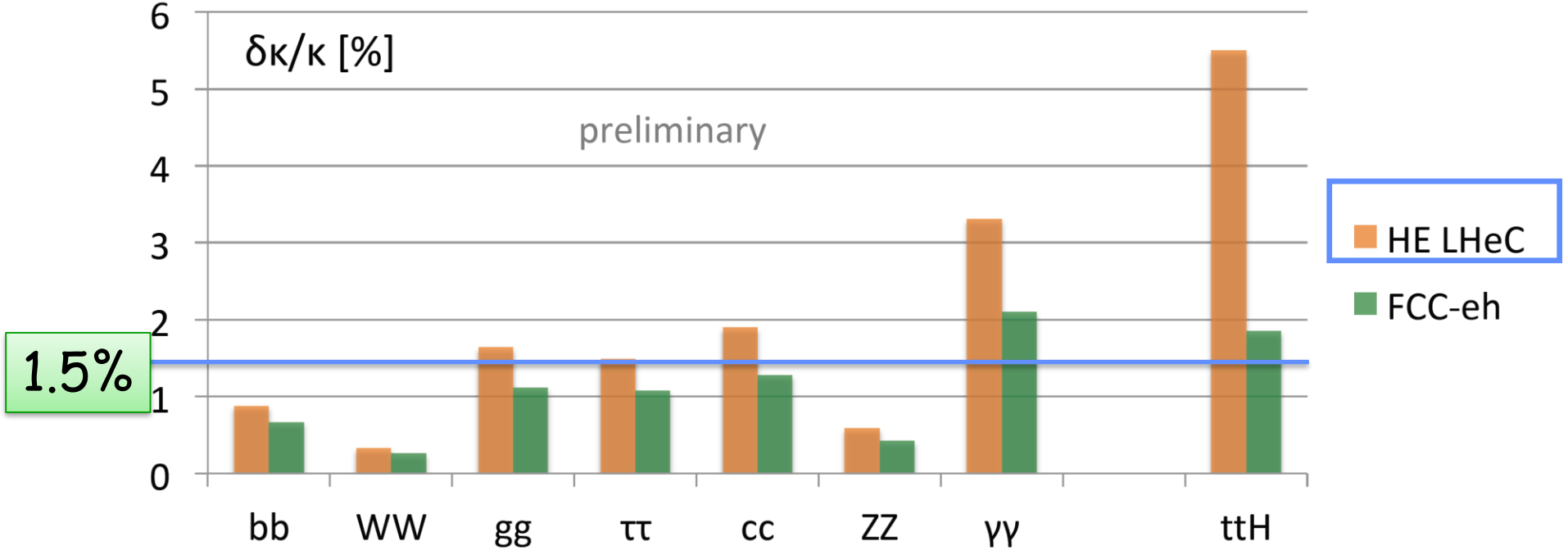
Confirmed CDR: S/N>1 using conservative light misID and cut-based δμ=2% for 1 ab^{-1}

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)



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**