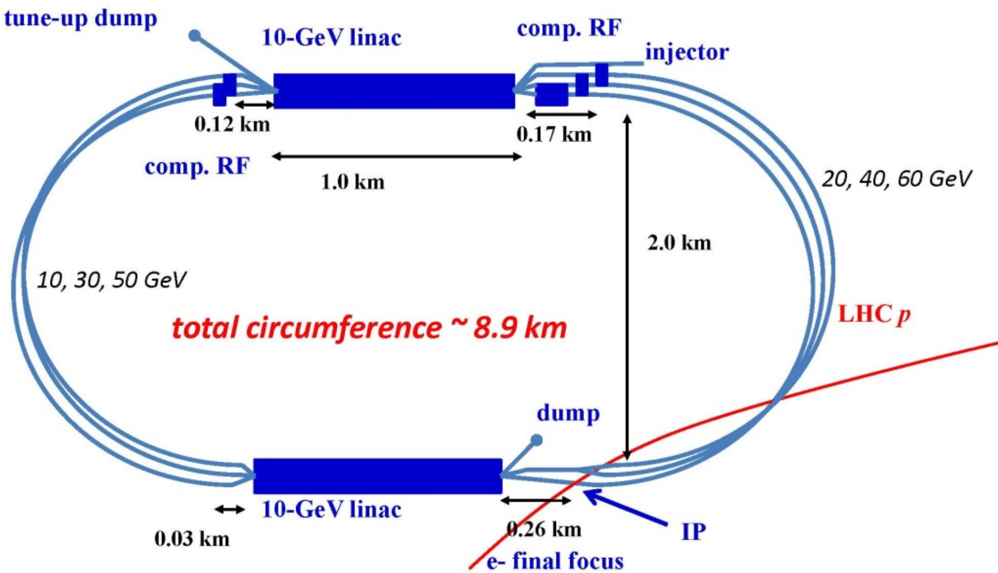
Potential of Higgs studies, BSM searches and more at the LHeC

Uta Klein
on behalf of
the LHeC/FCC-eh Study Group

HL-LHC Workshop, CERN, October, 2017

Baseline : Electron Linac - LHC Ring

- Design constraint: power consumption < 100 MW, E_e = 60 GeV
- Two 10 GeV electron Linacs with I_e>6 mA and high electron polarisation of 80-90%
- 3 return arcs, 20 MV/m
- Energy recovery in same structure
- Installation fully decoupled from LHC operation! ~ 7 years for civil engineering

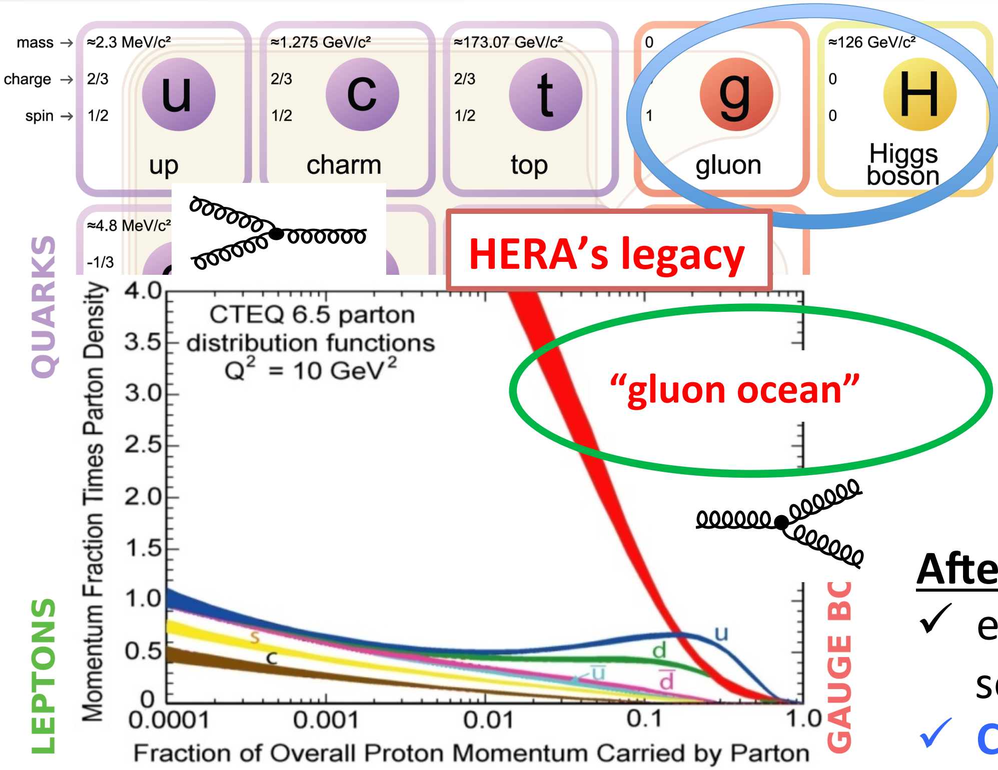


- ep Lumi 10^{34} cm s^{-2} s^{-1} **
- 100 fb^{-1} per year
- 1000 fb^{-1} total collected in 10 years
- eD and eA collisions have always been integral to programme
- eA luminosity estimates ~ 10^{32} cm s^{-2} s^{-1} for eD (ePb)

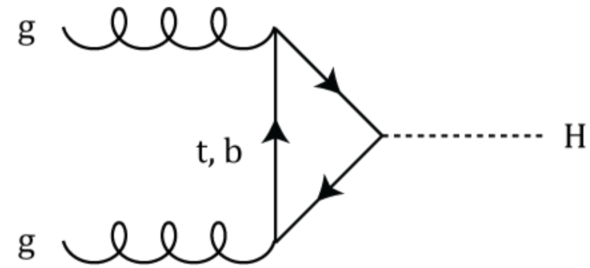
** based on existing HL-LHC proposal

Using material from Oliver Bruning, FCC kickoff, Geneva 2014, https://indico.cern.ch/event/282344/session/15/contribution/96/material/slides/1.pdf

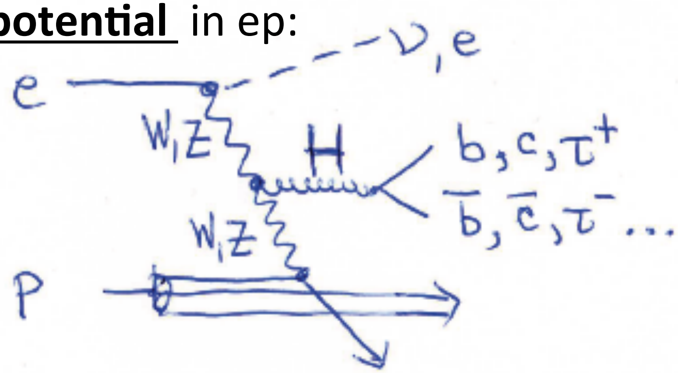
SM, Higgs and QCD



Higgs discovery at LHC via gluon-gluon fusion



Higgs potential in ep:



After the Higgs discovery:

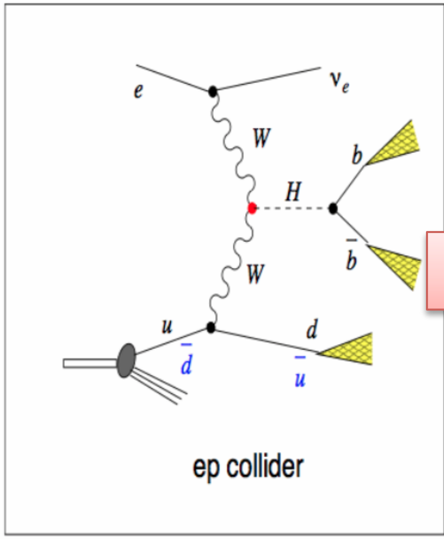
- ✓ ep : High precision quark-gluon dynamics for sensitive searches; top & Higgs physics
- ✓ **Concurrent running of pp and ep : Compelling synergy for exploring the EW and QCD sector to unprecedented precision.**

Higgs physics & EW symmetry breaking:

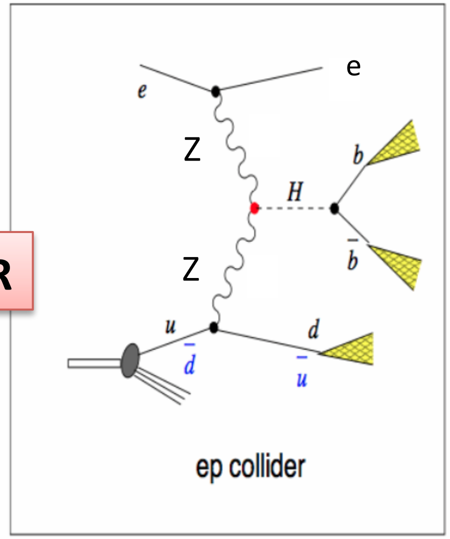
① **High precision coupling measurements**

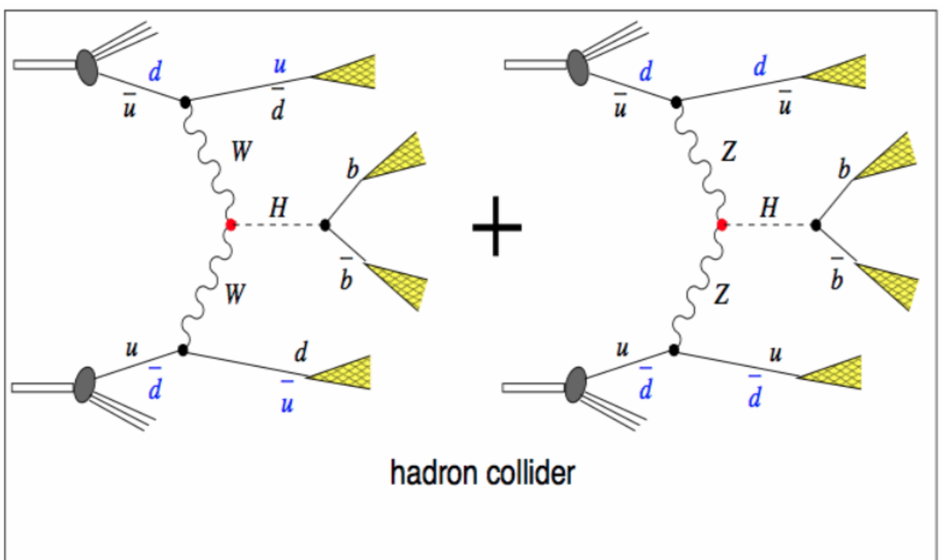
② **Higgs as the portal for new physics, DM etc.**

VBF Higgs Production in ep (top) and pp (bottom)



OR





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

Clean bb final state, S/B >1
e-h Cross Calibration for Precision ep

Clean, precise reconstruction and easy distinction of ZZH and WWH without pile-up:
<0.1@LHeC up to 1@FCCeh events
VBF: Small theoretical uncertainties!

pp: Higgs production in pp comes predominantly from gg→ H :
high rates crucial for rare decays

VBF cross section about 200 fb
(about as large as at the LHeC).

Pile-up in pp at 5 10^{34} cm^{-2} s^{-1} is 150@25ns
S/B very small for bb
Final Precision in pp needs accurate N^3LO PDFs & αS

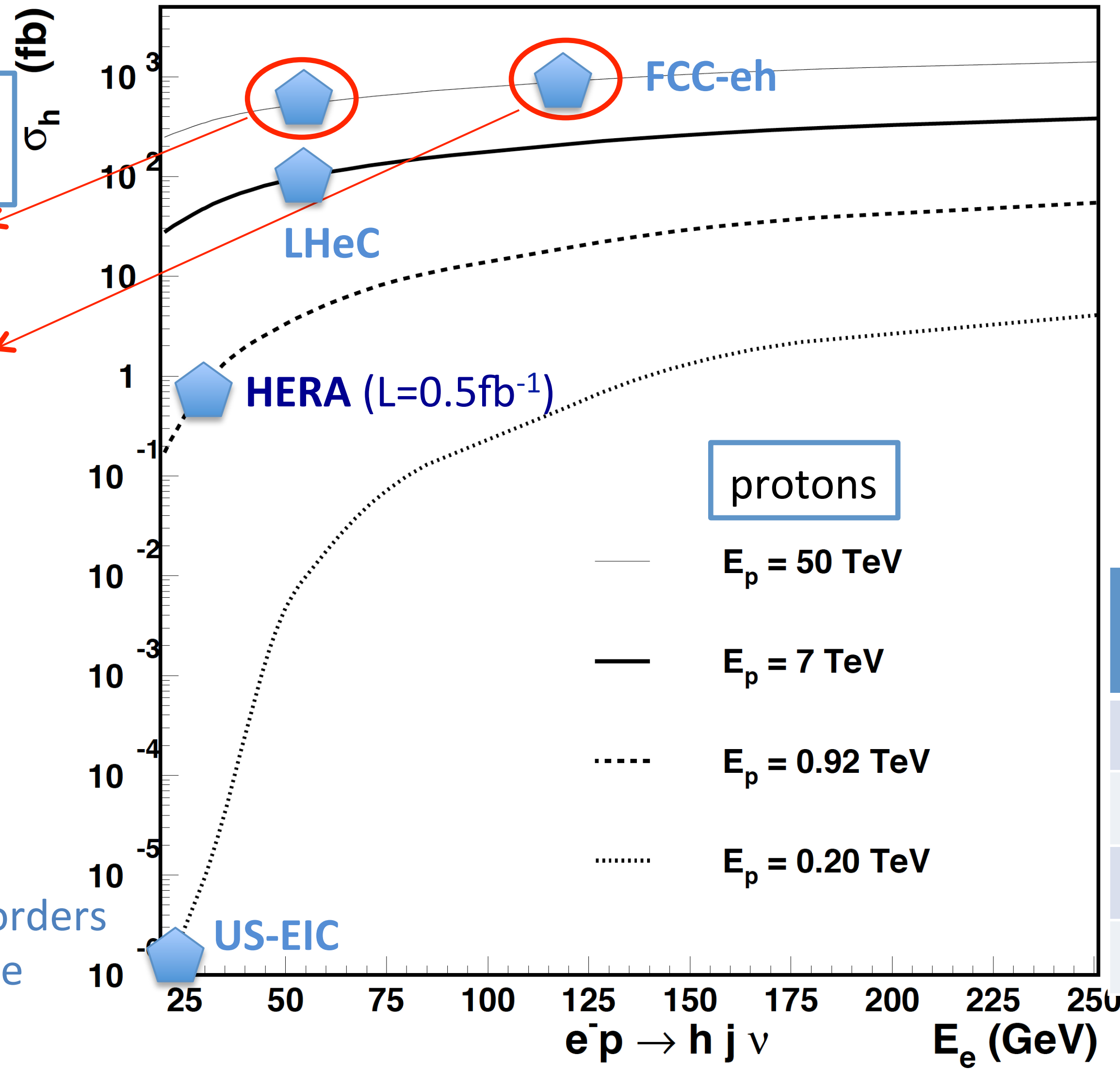
SM Higgs in ep

U. Klein,
@DIS2015

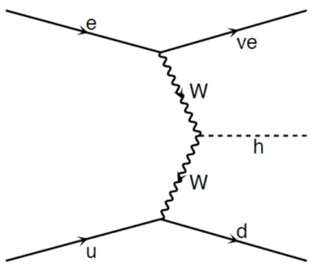
unpolarised electrons

E_e=60 GeV

E_e=120 GeV



σ @ EIC: 7 orders of magnitude lower



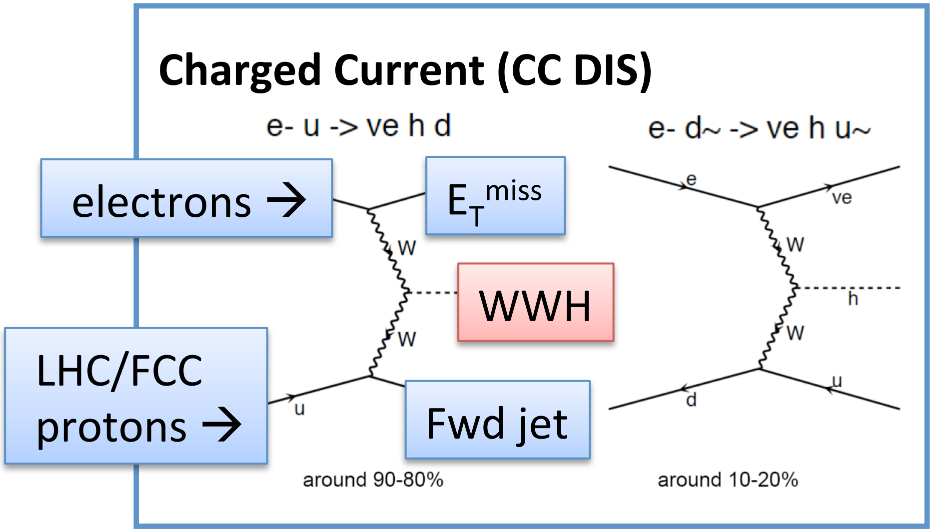
Note:

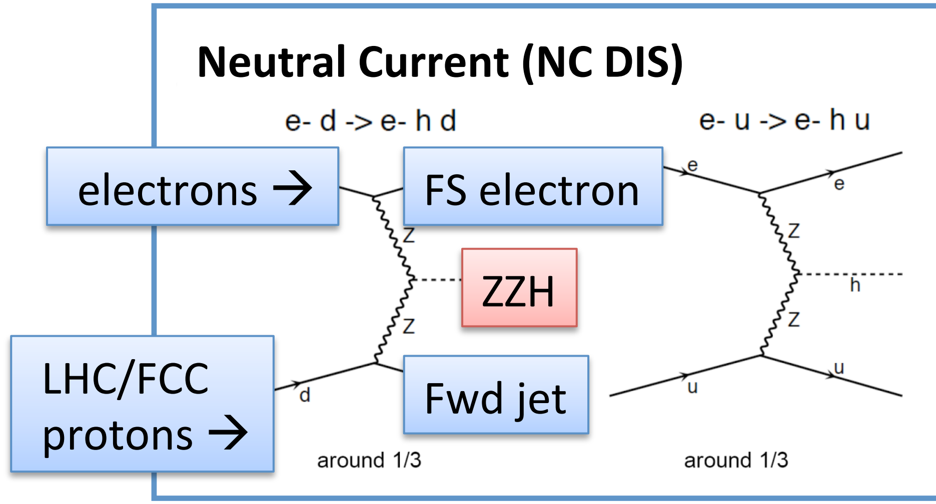
σ_{Higgs} @FCC-ePb [fb]
eff. 'Ep'=19.7 TeV

E_e [GeV]	P_e = 0	-0.8
20	105	190
30	153	276
50	242	436
60	282	507

LHeC / FCC-he: Sizeable Higgs rates in charged current (CC) DIS for L=100-1000 fb^{-1}

SM Higgs Production in ep





σ (LO QCD CTEQ6L1 M_H=125 GeV)

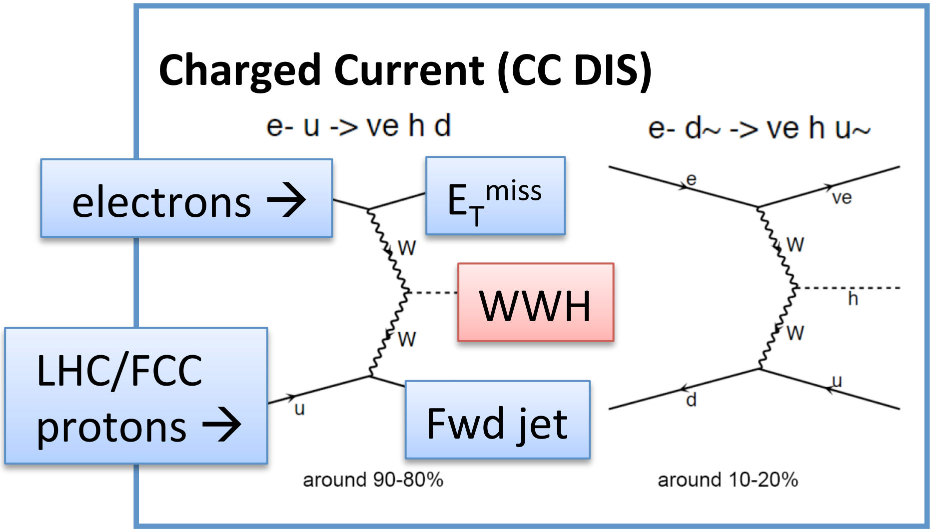
c.m.s. energy	1.3 TeV @LHC	3.5 TeV @FCC
cross section [fb] NC DIS CC DIS	 21 109	 127 560
CC DIS polarised cross section [fb] P=-80%	**196**	**1008**

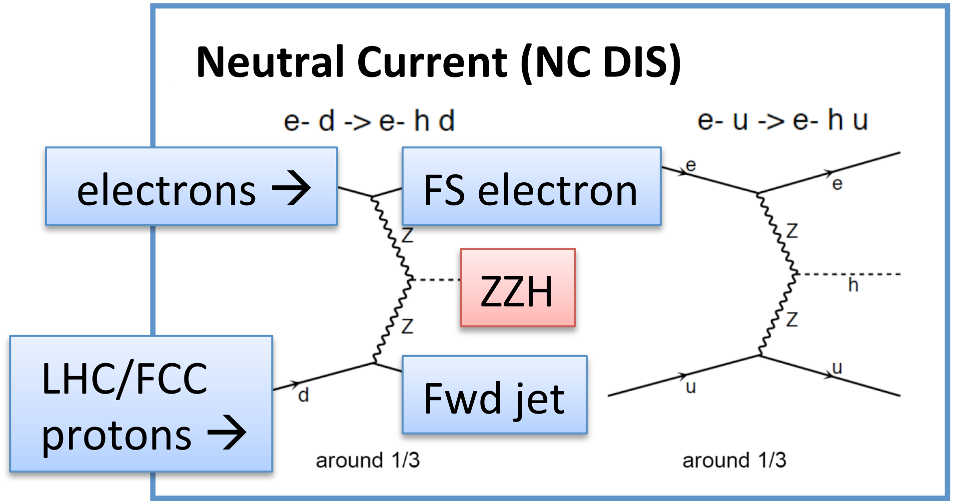
→ In ep, direction of quark (FS) is well defined.

- **Scale dependencies of the LO calculations are in the range of 5-10%.**
- **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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Theory well under control in ep!

[...lein, G.J. van Oldenborgh , R. Ruckl, Nucl.Phys.B395:35-59,1993]
[B.Jager, arXiv:1001.3789]

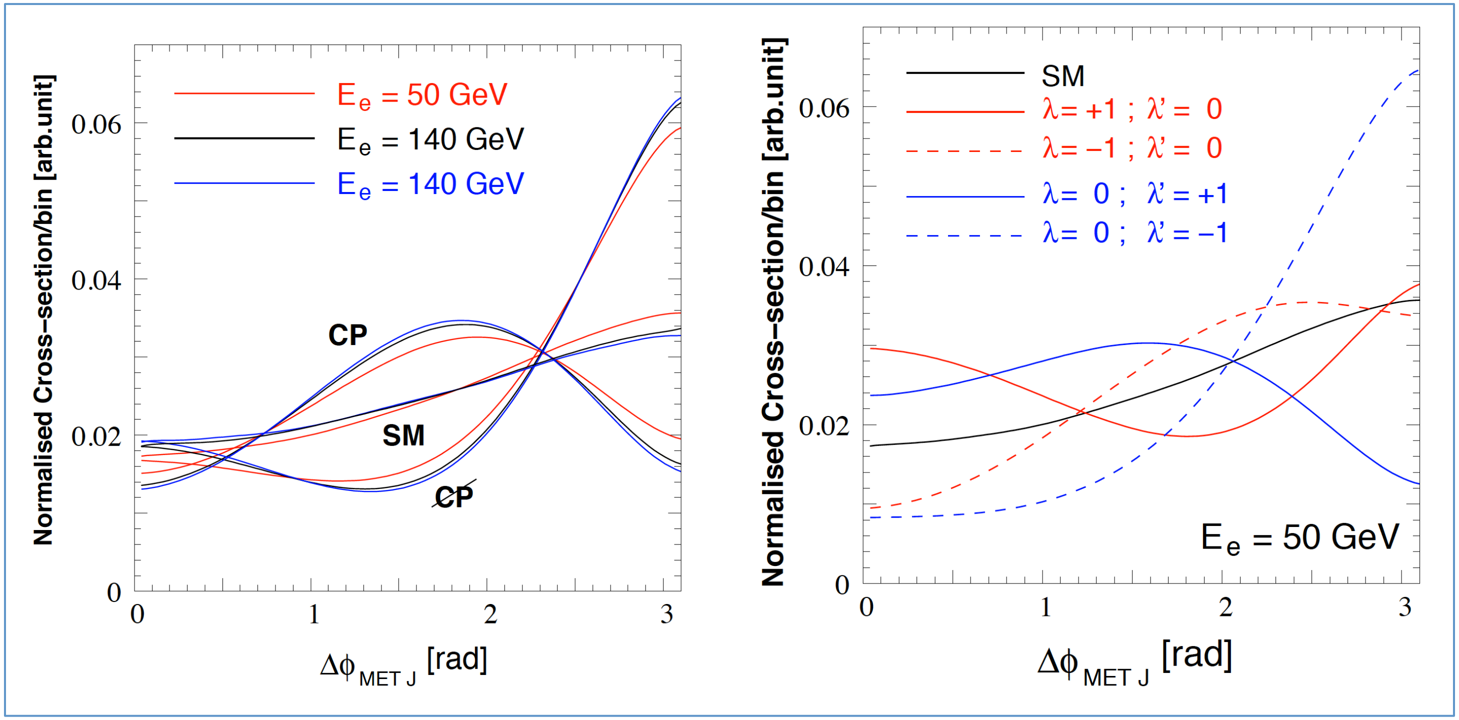
Measure CP Properties of Higgs

[CDR before Higgs discovery M_H=120 GeV, E_p=7 TeV]

- Higgs couplings with a pair of gauge bosons (WW/ZZ) and a pair of heavy fermions (t/b/τ) are largest.
- Higgs@LHeC allows uniquely to access HWW vertex ➔ explore the CP properties of HVV couplings: BSM will modify CP-even (λ) and CP-odd (λ') states differently

$$\Gamma^{\mu\nu}_{(\mathrm{SM})}(p,q) = g M_W\, g^{\mu\nu} \quad \rightarrow \quad \Gamma^{(\mathrm{BSM})}_{\mu\nu}(p,q) = \frac{-g}{M_W}\left[\lambda\,(p.q\, g_{\mu\nu} - p_\nu q_\mu) + i\,\lambda'\, \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma\right]$$

- Study ***shape changes*** in DIS normalised CC Higgs→ bb cross section versus the azimuthal angle, $\Delta\phi_{MET,J}$, between $E_{T,miss}$ and forward jet.



CDR initial study of HWW vertex:

CP couplings probed to

λ~0.05

λ'~0.2

based on 50 fb^{-1}

LHeC: Higgs "Facility" @ 1 ab^{-1}

Post-CDR: **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)

➔ **full MG5 + Pythia + Delphes feasibility studies**

√s= **1.3 TeV**

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

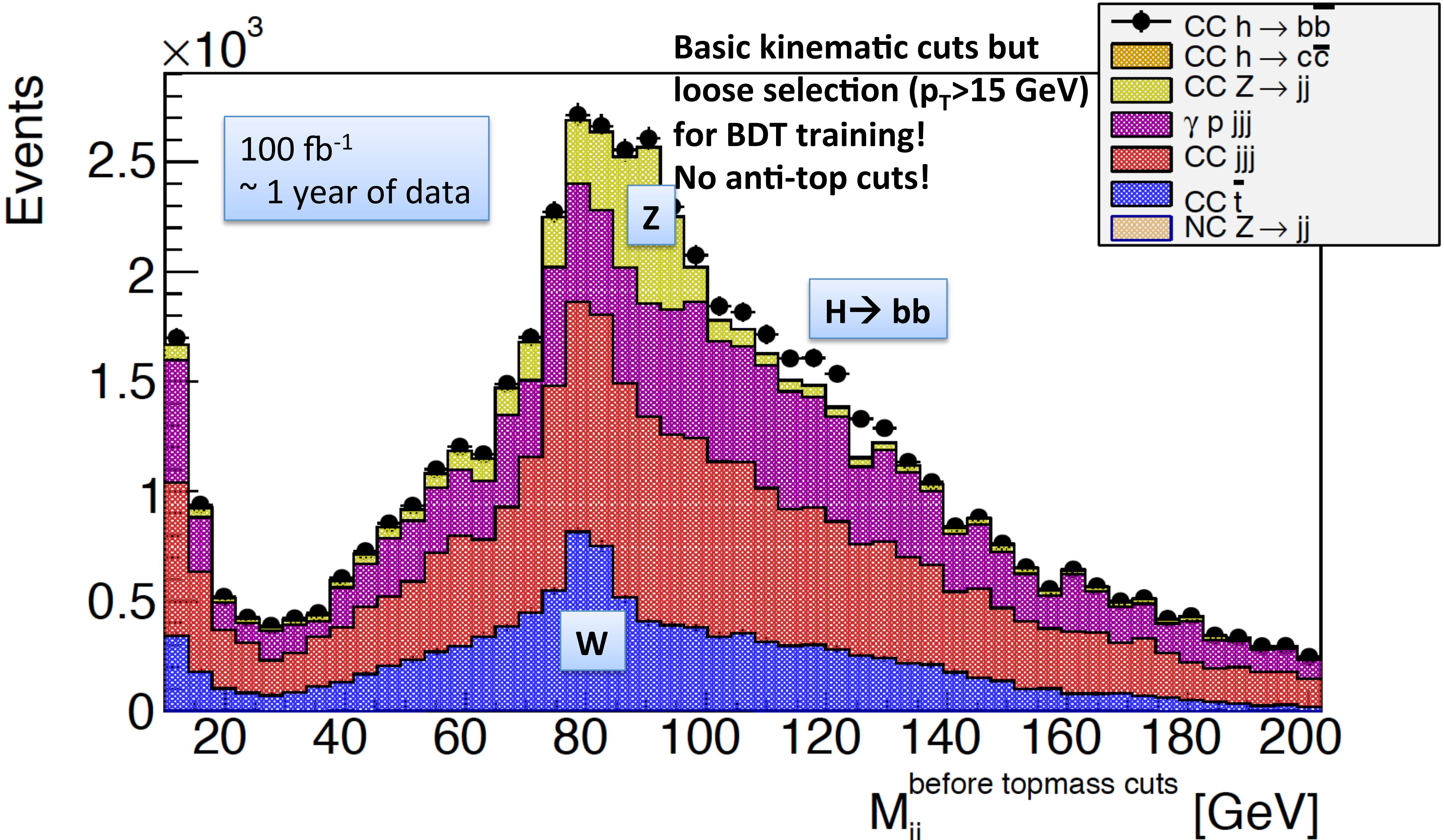
Ultimate polarised e-beam of 60 GeV and LHC 7 TeV p-beams, 10 years of operation

➔ **Decay to bb is dominating decay mode : 58%**

Higgs decay to charm is factor 20 less likely than Hbb

LHC: perfect Higgs factory for gluon-induced rare decays

Dijet Mass : two lowest eta Jets - *HFL untagged*



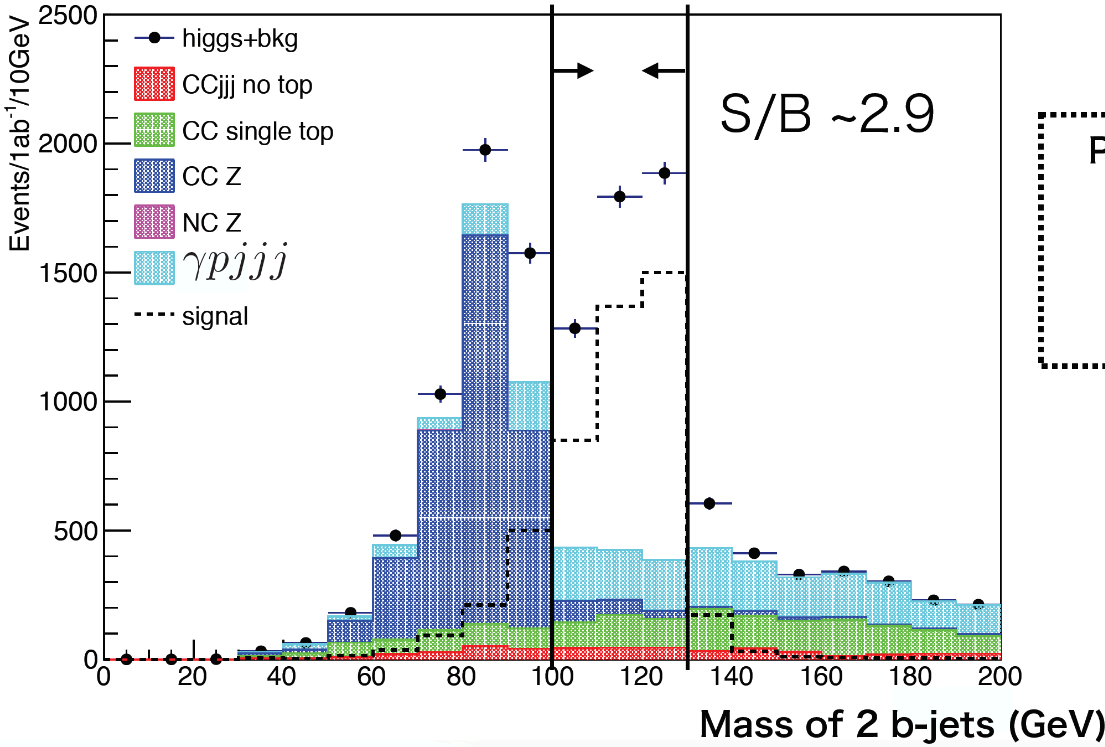
Note : Photoproduction background is assumed to be untagged ('worst' scenario)!
→ addition of small angle electron taggers will reduce the PHP ~1-2%

Cut-based Results for Hbb @ LHeC

Masahiro Tanaka, Masahiro Kuze

Various studies pursued since the LHeC CDR [before the Higgs discovery, see http://cern.ch/lhec] focusing on SM 125 GeV Higgs decay into b-quarks

- Assumed 1000 fb^{-1} of statistics. (~10 years running for LHeC.)
- Veto efficiency of 90% for photo-production background is assumed, using forward electron tagging.



b-tag performance (cut based)
- b-jet: 75%
- c-jet mis-tagging rate: 5%
- Light-jet mis-tagging rate: 1%

Precision of coupling constant (Statistics error only)

$$\kappa = \frac{\sqrt{N_s + N_b}}{2N_s}$$

Signal: 3600

Bkg: 1250

κ (Hbb) ~ 0.97%

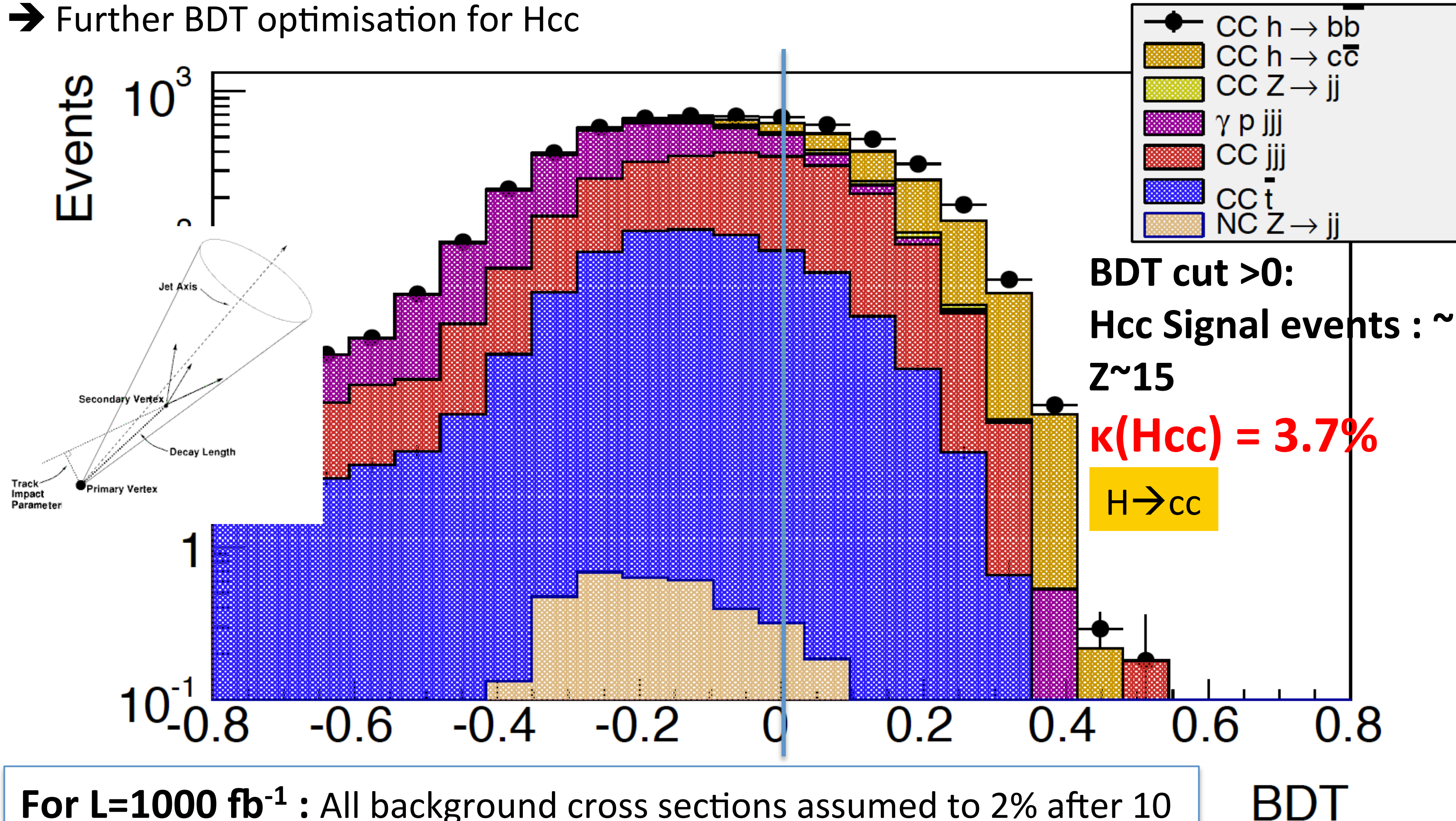
LHeC: BDT Result for H→cc

Uta Klein &
Daniel Hampson
& Izzy Harris

NEW : Using R = 0.5 anti-kt jets and ATLAS IBL vertex resolution (5 μm)

➔ Hbb and Hcc candidates increased by factor 3.5 w.r.t. anti-kt R=0.9 jets

➔ Further BDT optimisation for Hcc



BDT cut >0:

Hcc Signal events : ~600;

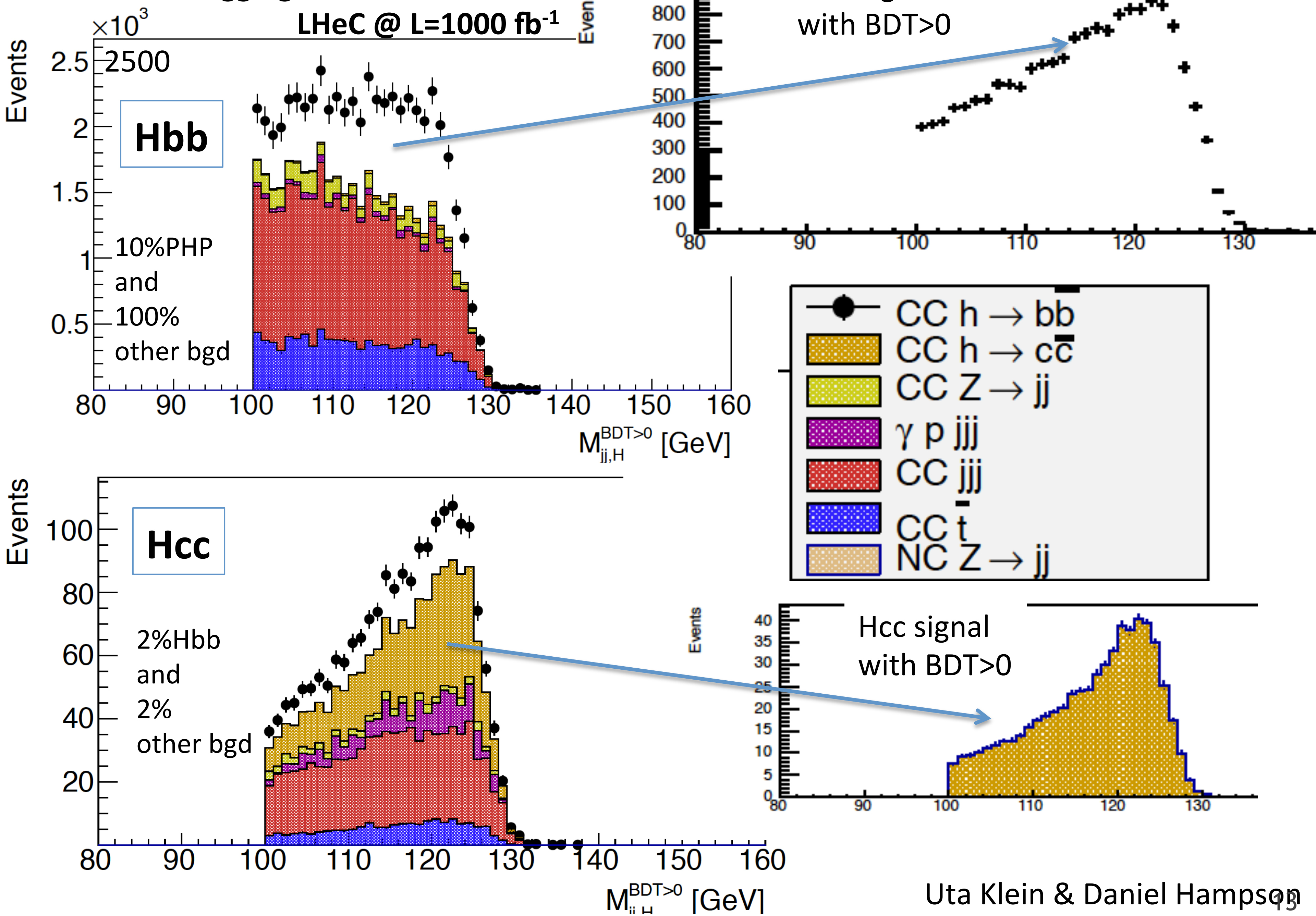
Z~15

κ(Hcc) = 3.7%

H→cc

For L=1000 fb^{-1} : All background cross sections assumed to 2% after 10 years of running; ~15000 Hbb evts means δμ(Hbb) ≤ 1 … 2 %

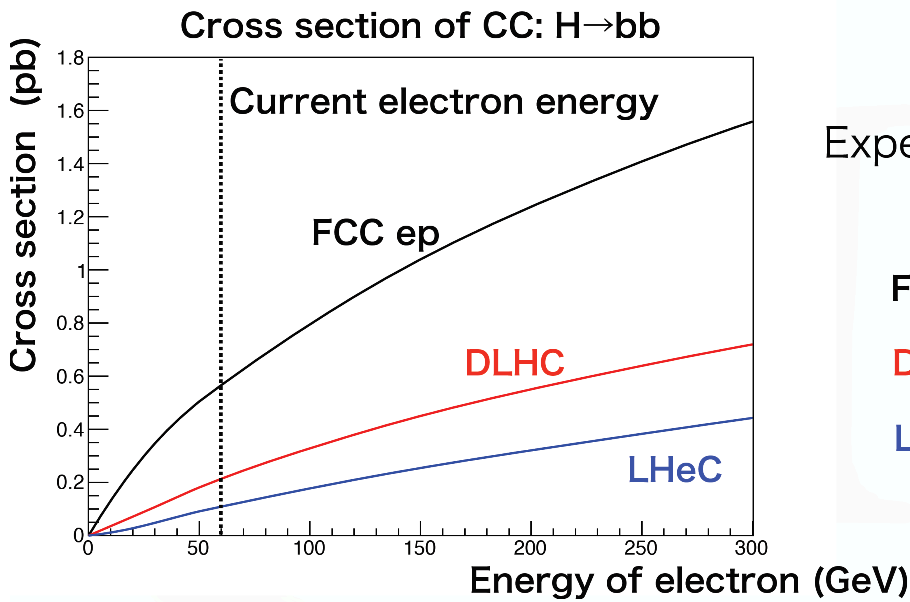
realistic HFL tagging & BDT for



Uta Klein & Daniel Hampson

SM Higgs into HFL Summary

- Assume a 60 GeV polarized electron beam and 1000 fb^{-1} (~10 years running)
- Expected number of signal events and error of coupling constant from BDT results.
- Background assumed to be known to ~2%



U Klein (Liverpool)

Expected number of signal events
(E_e = 60 GeV)

FCC ep (~85,000 H→bb events)

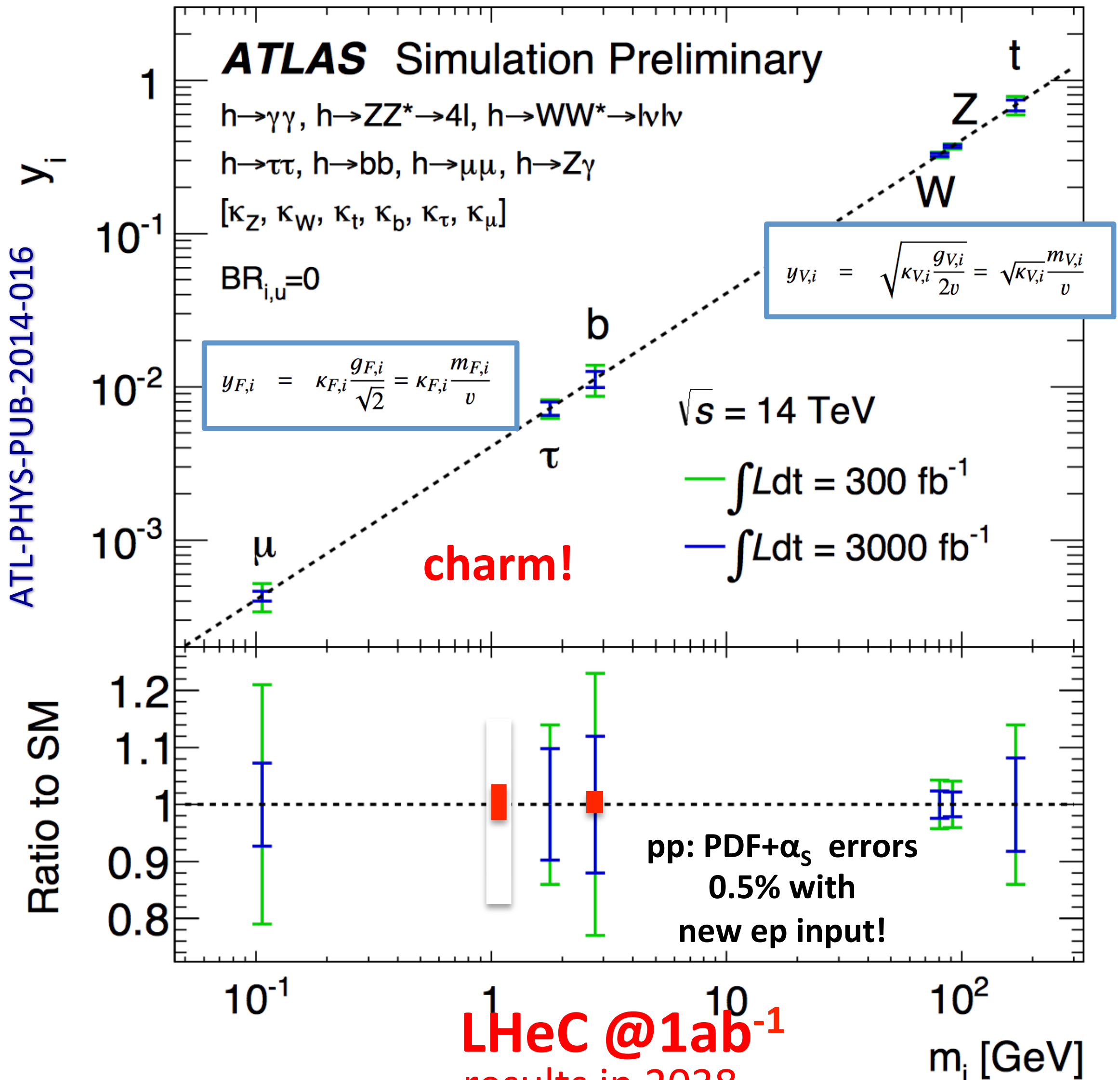
DLHC (~35,000 H→bb events)

LHeC (~15,000 H→bb events)

	LHeC (E_p = 7 TeV $\sqrt{s}$ ~1.3 TeV)	**DLHC** (E_p = 14 TeV $\sqrt{s}$ ~1.8 TeV)	**FCC ep** (E_p = 50 TeV $\sqrt{s}$ ~ 3.5 TeV)
κ (Hbb)	0.5%	0.3%	0.2%
κ (Hcc)	4%	2.8%	1.8%

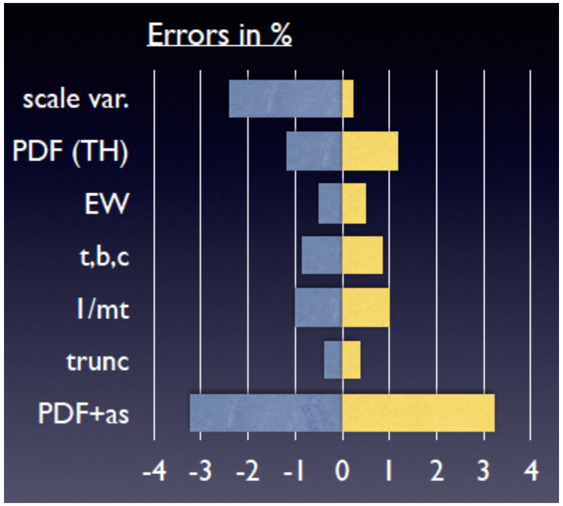
In ~2040: Higgs Couplings at pp + ep

After HL-LHC and LHeC running concurrently for 10 years



LHeC @1ab^{-1}
results in 2038 …
concurrent with HL-LHC end

Uncertainty on pp Higgs cross section
Giulia Zanderighi, Vietnam 9/16,
from C.Anastasiou et al, 1602.00695
who also discuss the ABM alpha_s..



→ use **ep** as the 'near' detector for pp to beat those α_s and PDF uncertainties to <~0.5%, δm_b to 10 MeV; δm_{charm} to 3 MeV

Exploring SM EFT & New Physics

M. Trott @ LHeC Workshop 2014
http://lhec.web.cern.ch

In the absence of any explicit new states, or overwhelming theory prejudice, the goal is to systematically study the SM EFT for hints of NP, using all possible future facilities to maximize physics conclusions.

What is the SM EFT? A linear realization of gauge symmetry and the new state is a 0+ scalar:

Four fermion operators with leptons and quark fields:

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

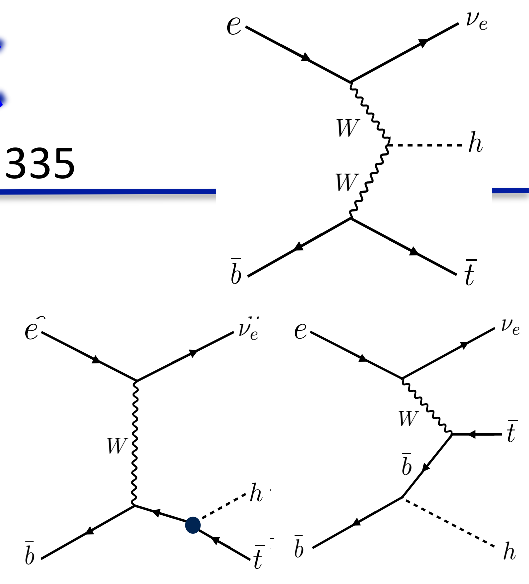
$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

- ➔ 59 operators or 2499 parameters experimentally to constraint!
- ➔ where nearly 50% of the parameters (1053) are sensitive to lepton-quark interactions – not just about lepto-quarks

Top Yukawa Coupling @ LHeC

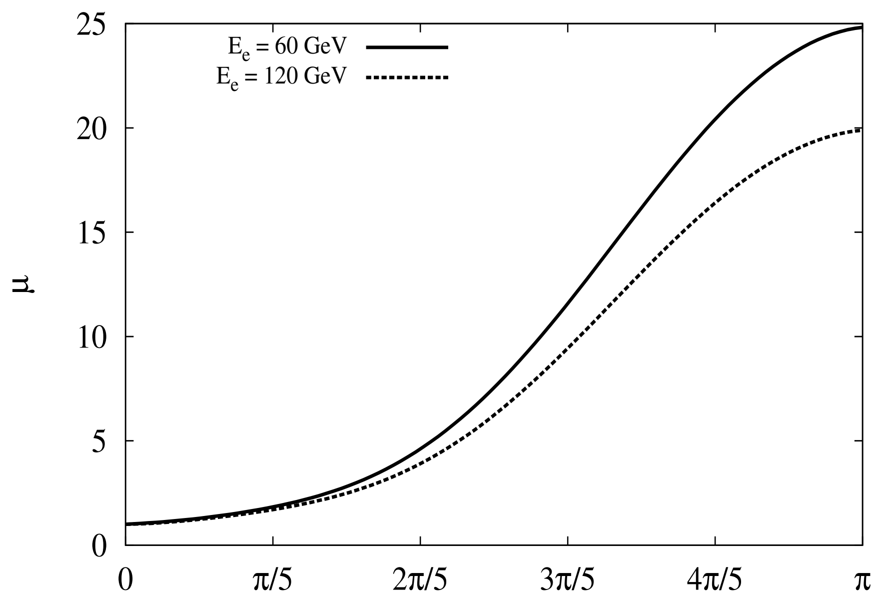
B.Coleppa, M.Kumar, S.Kumar, B.Mellado, Phys. Lett. B770 (2017) 335

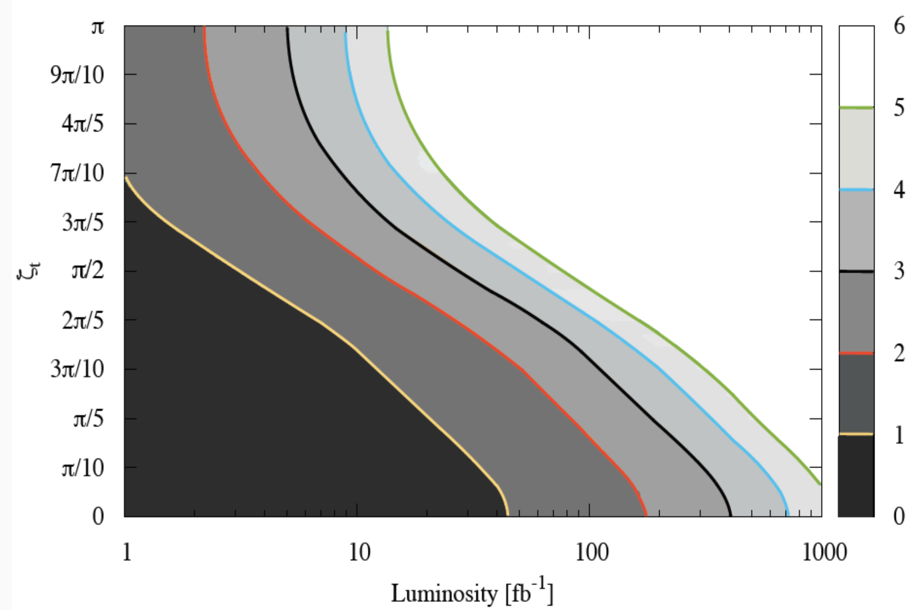


Introduce phase dependent top Yukawa coupling

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

Enhancement of the cross-section as a function of phase





Observe/Exclude non-zero phase to better than 4σ ➔ With Zero Phase: Measure coupling with 17% accuracy ➔ work ongoing on FCC-eh prospects

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

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

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

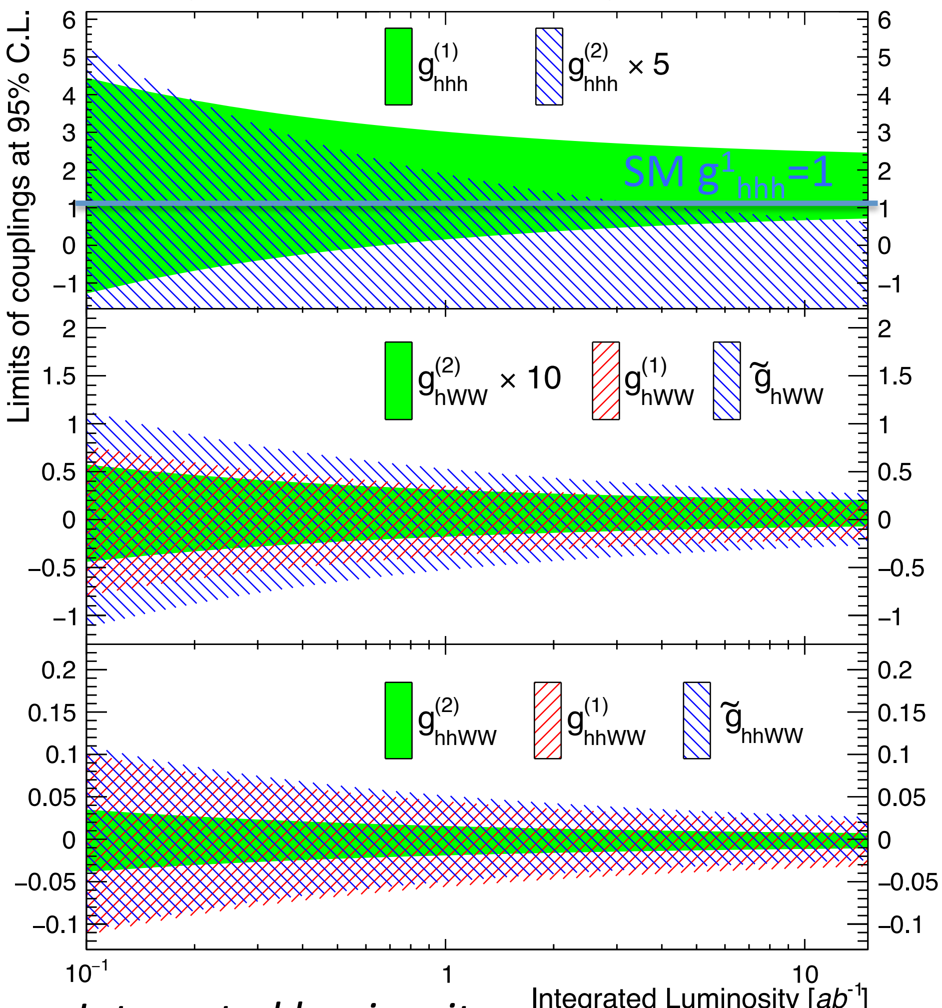
$$\mathcal{L}^{(4)}_{hhWW} = -g^2\Big[\frac{g^{(1)}_{hhWW}}{4m_W^2} W^{\mu\nu} W^\dagger_{\mu\nu} h^2 + \frac{g^{(2)}_{hhWW}}{2m_W^2}(W^\nu \partial^\mu W^\dagger_{\mu\nu} h^2 + \text{h.c}) + \frac{\tilde{g}_{hhWW}}{4m_W^2} W^{\mu\nu} \widetilde{W}^\dagger_{\mu\nu} h^2\Big]. \quad (4)$$

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

95% C.L. Exclusion Limits from $\sigma_{fiducial}$

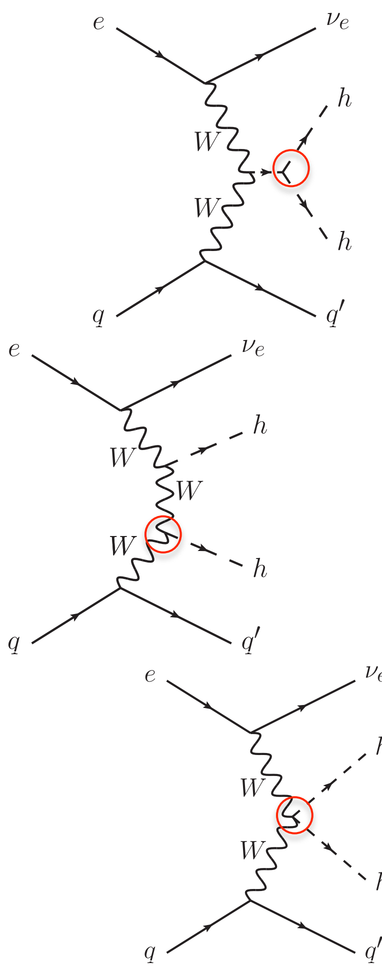
[1509.04016]

5% systemtatic uncertainty included



Integrated luminosity

100 *1000* *10000 fb^{-1}*



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 LHeC and DLHeC potential!

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.

Invisible Higgs@LHeC

relating the Higgs and 'dark' matter

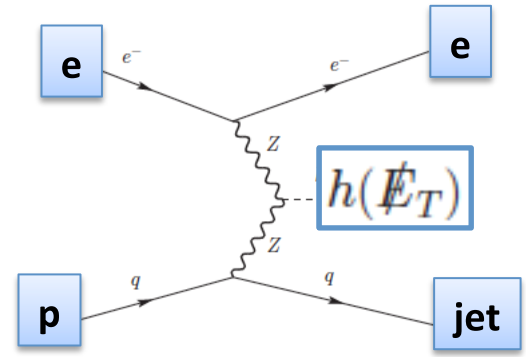
Y.-L. Tang et al.,
arXiv: 1508.01095

HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

$\mathrm{Br}(h \to \not{E}_T)$ < 3.5% @95% C.L., MVA based

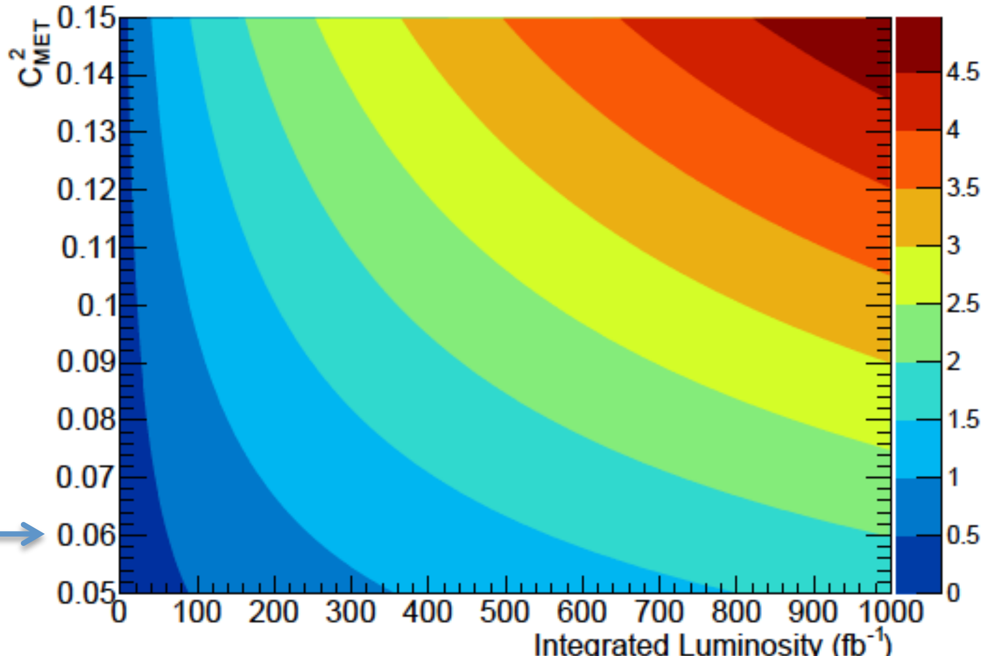
For **LHeC**, assume : $1ab^{-1}$, P_e=-0.9, cut based

$\mathrm{Br}(h \to \not{E}_T)$ < 6% @ 95 % C.L.



$$C^2_{\mathrm{MET}} = \kappa^2_Z \times \mathrm{Br}(h \to \not{E}_T)$$

κ_Z : BSM w.r.t. SM HZZ coupling



Colours:
expected statistical significance

→ **potential much enhanced for FCC-eh @ 3.5 TeV and HE-LHC-eh @ 1.8 TeV**

→ **NEW studies performed on Delphes detector-level using our Madevent framework**

Branching for invisible Higgs

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

Values given in case of 2σ

Delphes detectors	LHeC 1.3 TeV	DLHeC 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%*)

- ✓ **Results for full MG5+Delphes analyses look very encouraging for a measurement of the branching of Higgs to invisible in ep down to 2%.**
- ✓ For 2 different detector options we get similar results
- ✓ We also checked LHeC ←→ FCC-eh scaling with the corresponding cross sections (* results in table) : Downscaling FCC-eh simulation results to LHeC would give 4.5%, while upscaling of LHeC simulation to FCC-eh would result in 2.1% → all well within uncertainties of projections
- employ further synergies within LHC community and FCC study group → further detector and analysis details has certainly an impact on results

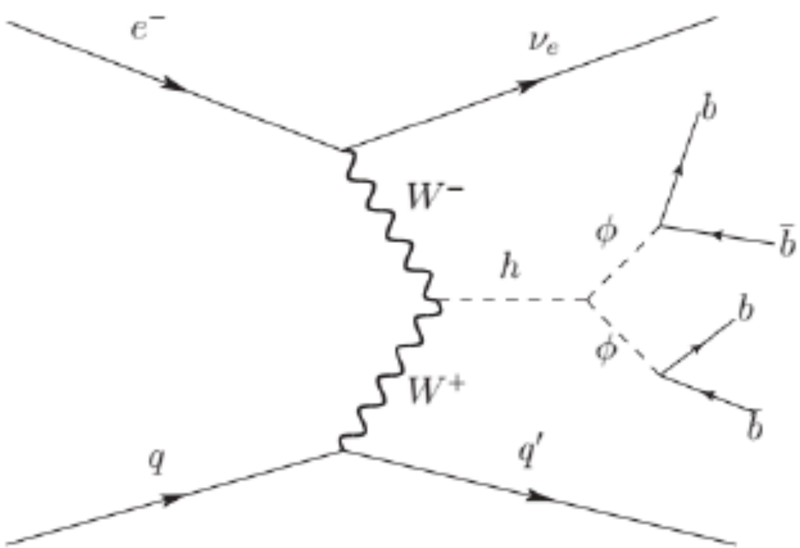
Exotic Higgs Decays

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

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

ϕ: a spin-0 particle from new physics.

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



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

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.

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

Exotic Higgs at LHeC@1ab^{-1}

[arXiv:1608.08458]

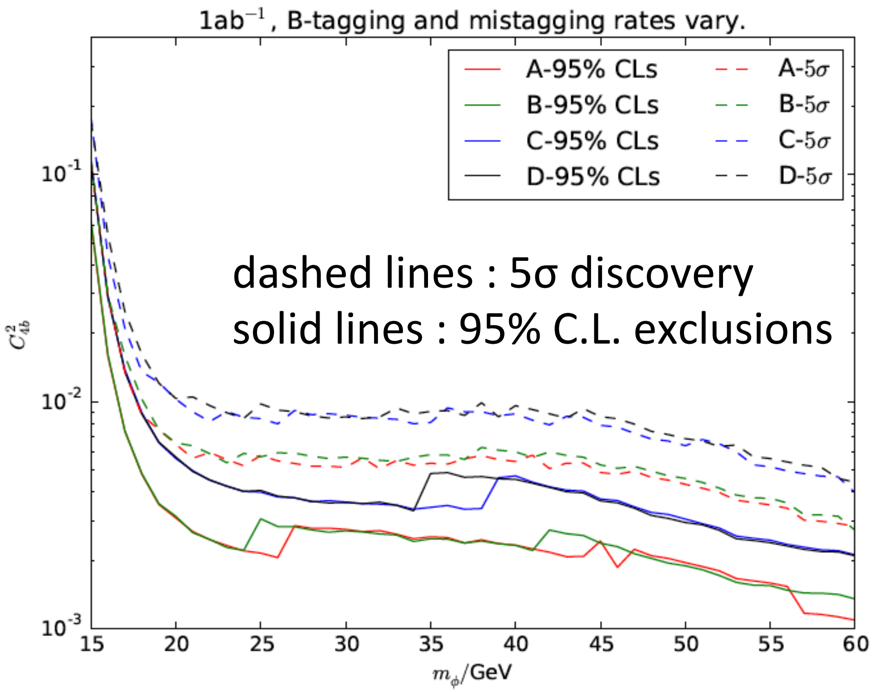
Btag scenarios

(A) $\epsilon_b = 70\%, \epsilon_c = 10\%, \epsilon_{g,u,d,s} = 1\%$

(B) $\epsilon_b = 70\%, \epsilon_c = 20\%, \epsilon_{g,u,d,s} = 1\%$

(C) $\epsilon_b = 60\%, \epsilon_c = 10\%, \epsilon_{g,u,d,s} = 1\%$

(D) $\epsilon_b = 60\%, \epsilon_c = 20\%, \epsilon_{g,u,d,s} = 1\%$

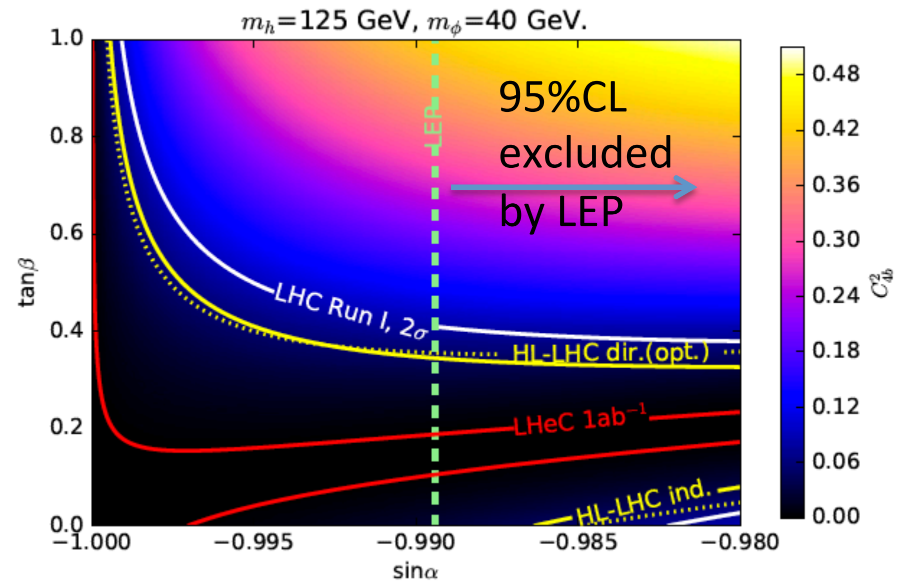


95% C.L. for m_ϕ of 20, 40, 60 GeV for

$$C^2_{4b} = \kappa_V^2 \times \mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}^2(\phi \to b\bar{b})$$

is 0.3%, 0.2% and 0.1%

Sensitivity comparison in Higgs Singlet Model



$$\Phi \equiv \begin{pmatrix} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix}, S \equiv \frac{h' + x}{\sqrt{2}} \qquad (12)$$

Here v = 246 GeV ensures the correct mass generation for W, Z bosons and SM fermions. The gauge eigenstates $\tilde{h}, h'$ can be related to mass eigenstates ϕ, h via an orthogonal rotation

$$\begin{pmatrix} \phi \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix} \qquad (13)$$

Now it is convenient to parameterize the model in terms of five more physical quantities: (m_ϕ, m_h are masses of ϕ and h respectively)

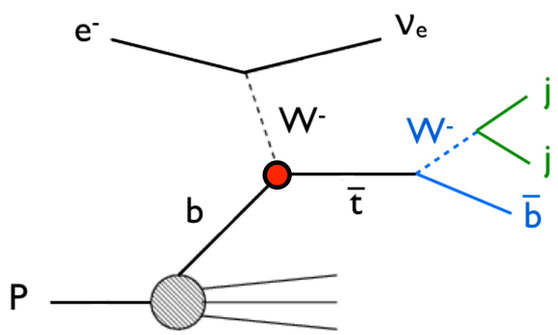
$$m_\phi, m_h, \alpha, v, \tan\beta \equiv \frac{v}{x} \qquad (14)$$

Top Quark & EW in ep

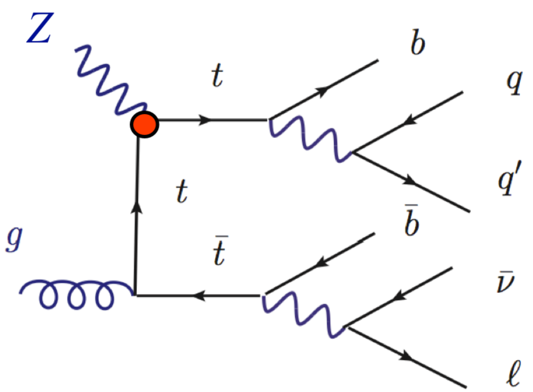
…. a few examples only

C. Schwanenberger, @DIS2015

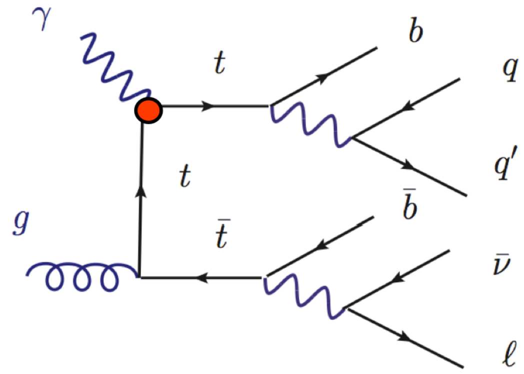
precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations) : **top quark expected to be most sensitive to BSM physics, due to large mass**



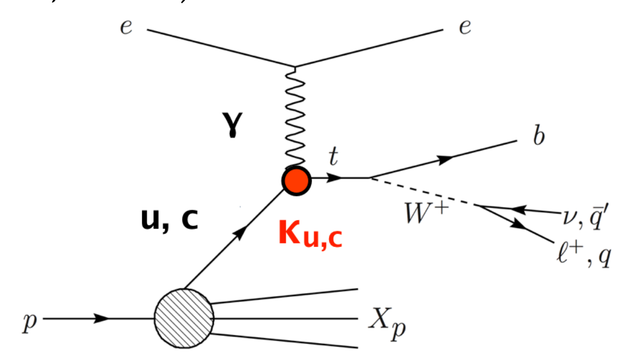
- high precision measurements of Vtb and search for **anomalous Wtb** couplings



- measurement of top isospin and search for **anomalous ttbarZ** couplings (eg. EDM, MDM)



- direct measurement of top quark charge and search for **anomalous ttbarγ** couplings (eg. EDM, MDM)

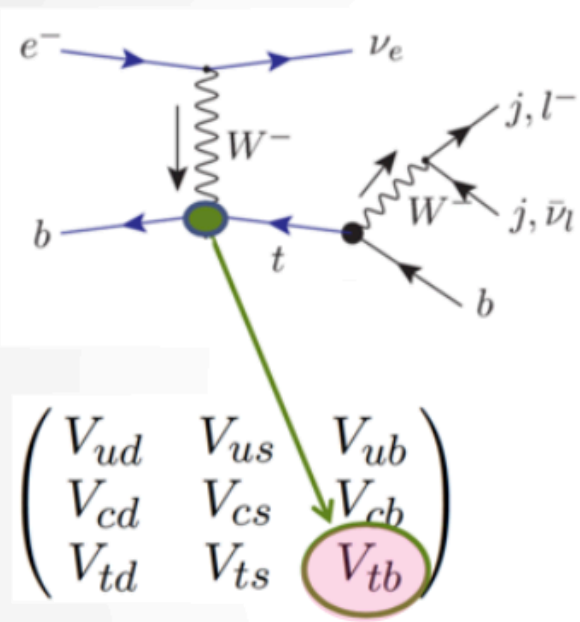


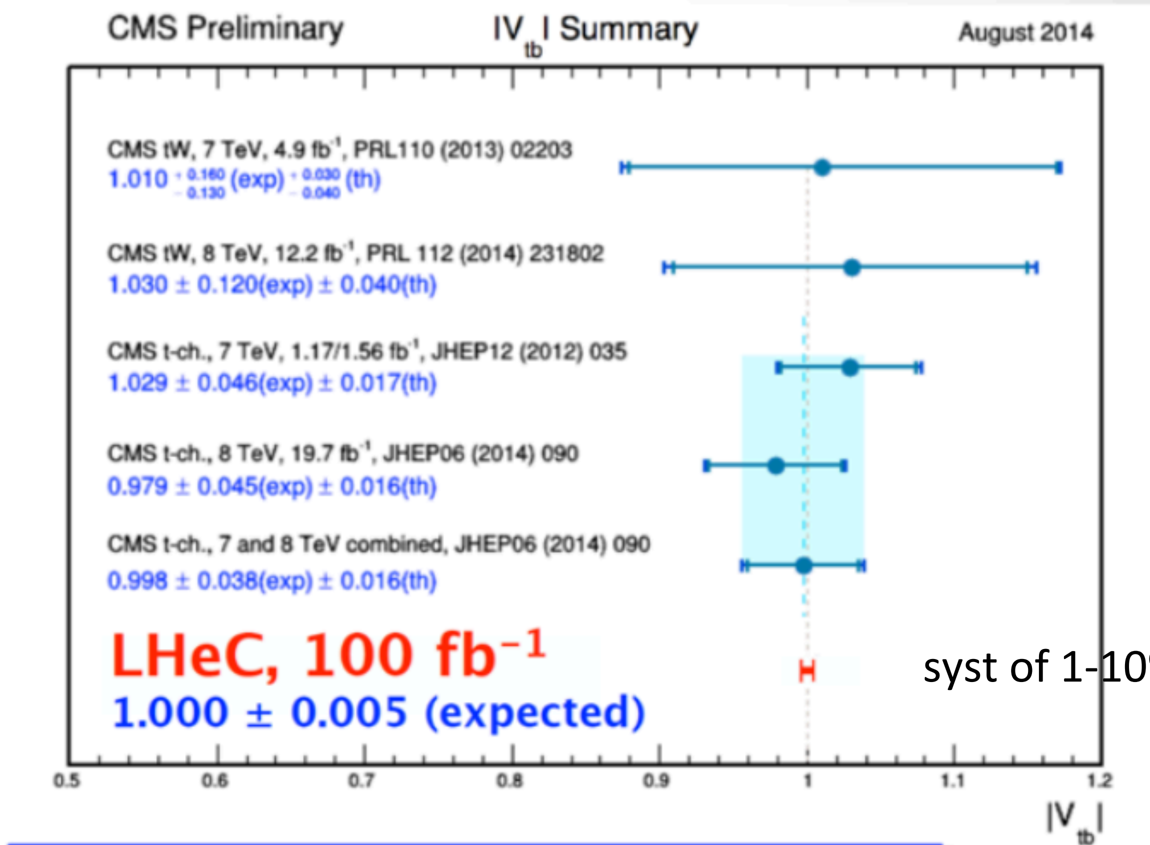
- sensitive search **for FCNC couplings** will constrain BSM models that predict FCNC (eg. SUSY, little Higgs, technicolour)

MEASUREMENT OF Vtb

➤ the results can also be applied conservatively to the FCC-ep.

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688 [hep-ph]





e beam: 60 GeV

L_{int} = 100 fb^{-1} and simple cuts:

HAD: N_t = 22000, S/B=1.2

LEP: N_t = 11000, S/B=11

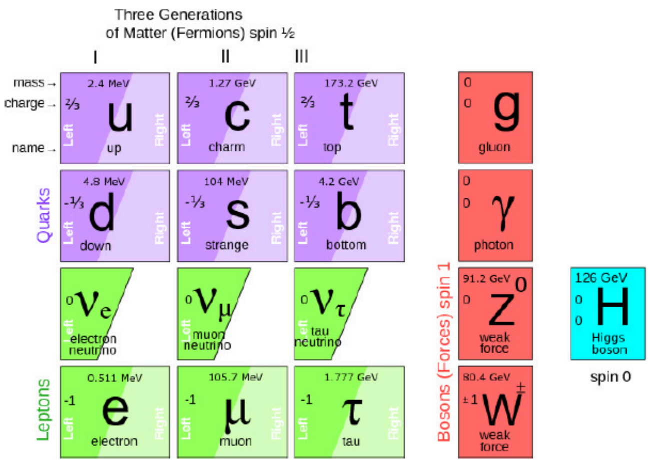
LHeC: very high precision measurement

current LHC+Tevatron average: $|V_{tb}|$=1.009 ±0.031

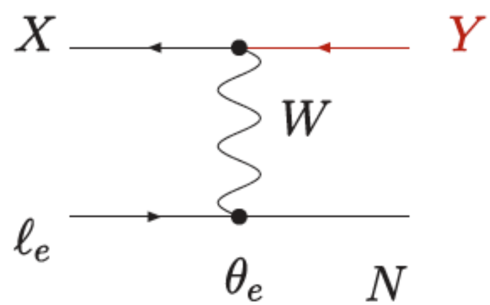
Oliver Fischer

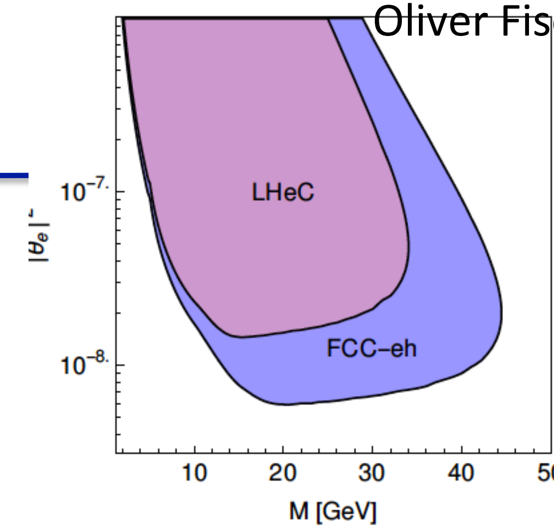
Sterile Neutrino Searches

$$\mathscr{L}_N = -\underbrace{(Y_\nu)_{i\alpha}}_{\nu\text{ Yukawa matrix}} \overline{\nu_R^i}\widetilde{\phi}^\dagger L^\alpha - \frac{1}{2}\overline{\nu_R^i}\underbrace{M_{ij}}_{\text{sterile }\nu\text{ mass matrix}}(\nu_R^j)^c + \text{H.c.}$$

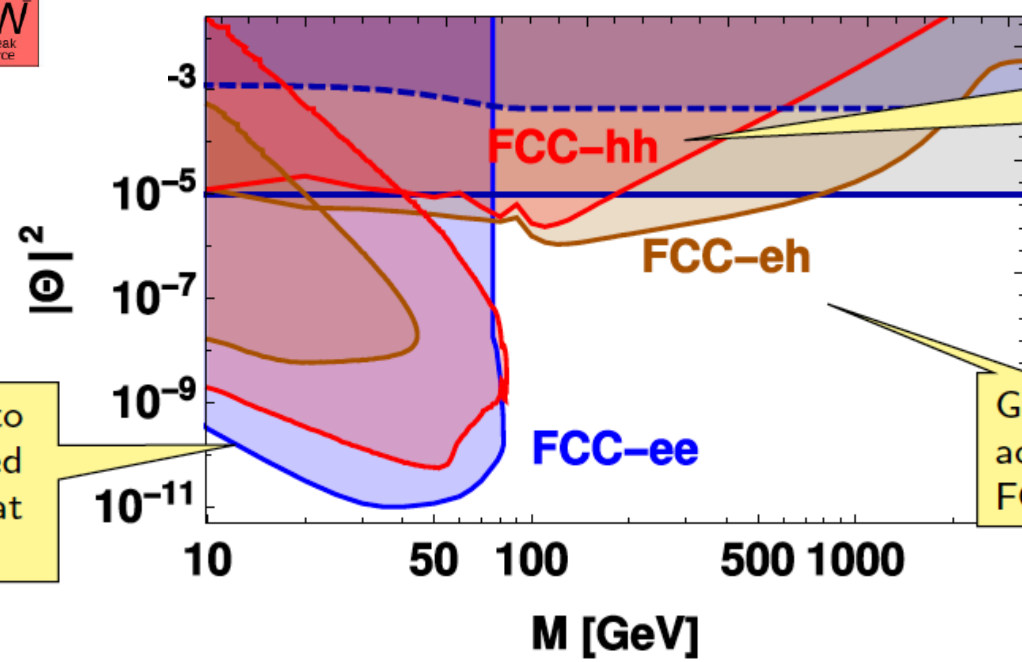


Shaposhnikov et al.





Non-unitarity parameters: $\varepsilon_{\alpha\alpha} = -\theta^*_\alpha\theta_\alpha$



FCC-hh able to test all flavour combinations.

Good sensitivity reach from FCC-hh & FCC-eh.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

… to take home

- **We have a fantastic machine at work – the LHC – let's use it as best as we can**

➔ we can turn the LHC into ONE powerful Higgs and search facility adding ep precision measurements: Higgs, top and BSM!

- An **upgrade** of the HL-LHC complex at CERN **with an electron beam** will **challenge the QCD and electroweak sector of the SM to a state-of-the art level with an extremely rich physics programme**– all this at moderate cost and **within the next 10 to 25 years.**

- There is plenty of new opportunities, also in the context of exciting new theoretical developments for HE-LHC/FCC physics and accelerator developments ➔ LHeC design (1000* HERA Luminosity) rests on high current, multi-turn energy recovery e Linac. ERL test facility: CDR to be published soon. TDR for demonstrator ("PERLE at Orsay")

Additional Sources & Thanks to

- LHeC and FCC-eh Workshop, September 2017, CERN

https://indico.cern.ch/event/639067/

Additional Sources & Thanks to

The LHeC/FCC-eh study group, http://cern.ch/lhec.

"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]

Poetic 2016 Workshop, 14.-18.11.2016, Temple University (USA)

https://phys.cst.temple.edu/poetic-cteq-2016/scientific_program.html

1st FCC Physics Workshop, 16.1.-20.1.2017, CERN

https://indico.cern.ch/event/550509/

→ see M. Benedikt's and F. Zimmermann's and further eh talks given at this workshop

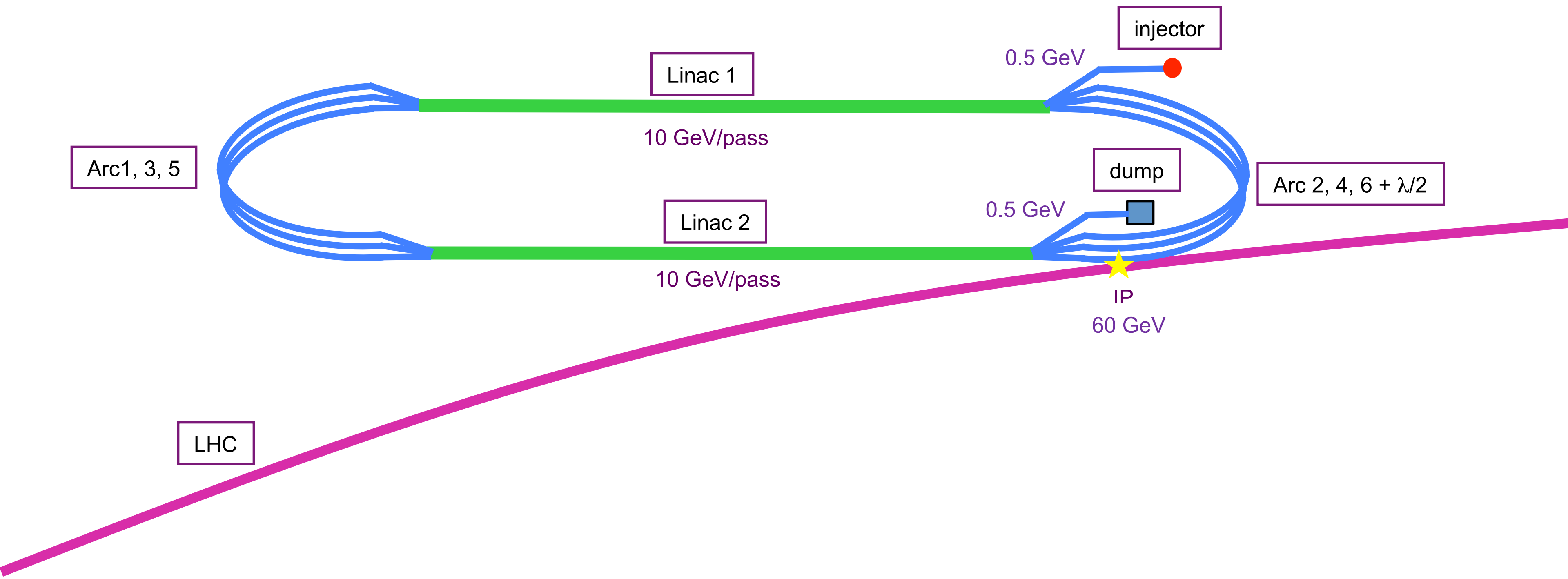
Special thanks to my colleagues in the LHeC/FCC-eh Higgs group, the project leader Max Klein, our detector expert Peter Kostka, and our bi-weekly Higgs-top working group discussions.

More New Studies Ongoing

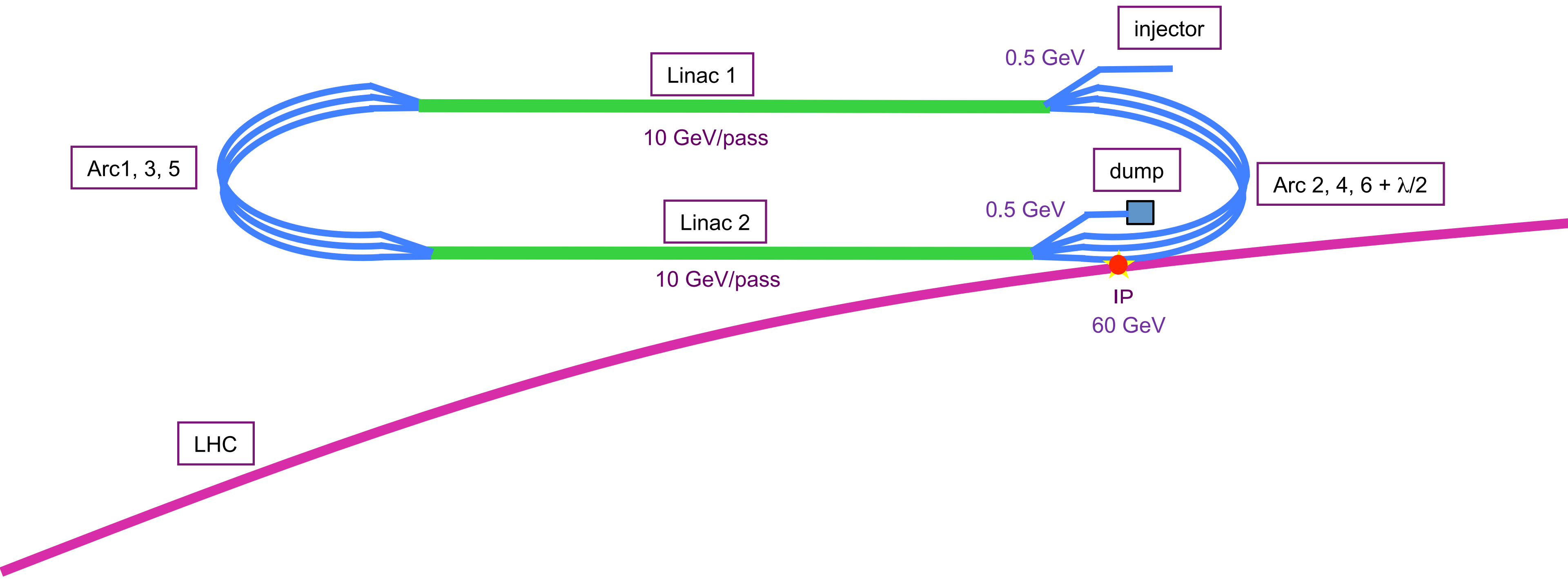
… and publications in preparation

- "Search for Anomalous HVV couplings at the LHeC and the FCC-ep" by M. Altinli et al.
- "Probing FCNC couplings of Higgs-top at FCC-ep and LHeC" by B. Hacisahinoglu et al.
- "Searching for doubly-charged Higgs bosons in the Georgi-Machacek model at ep colliders " by H. Sun et al. (see also presentation at DIS2017)

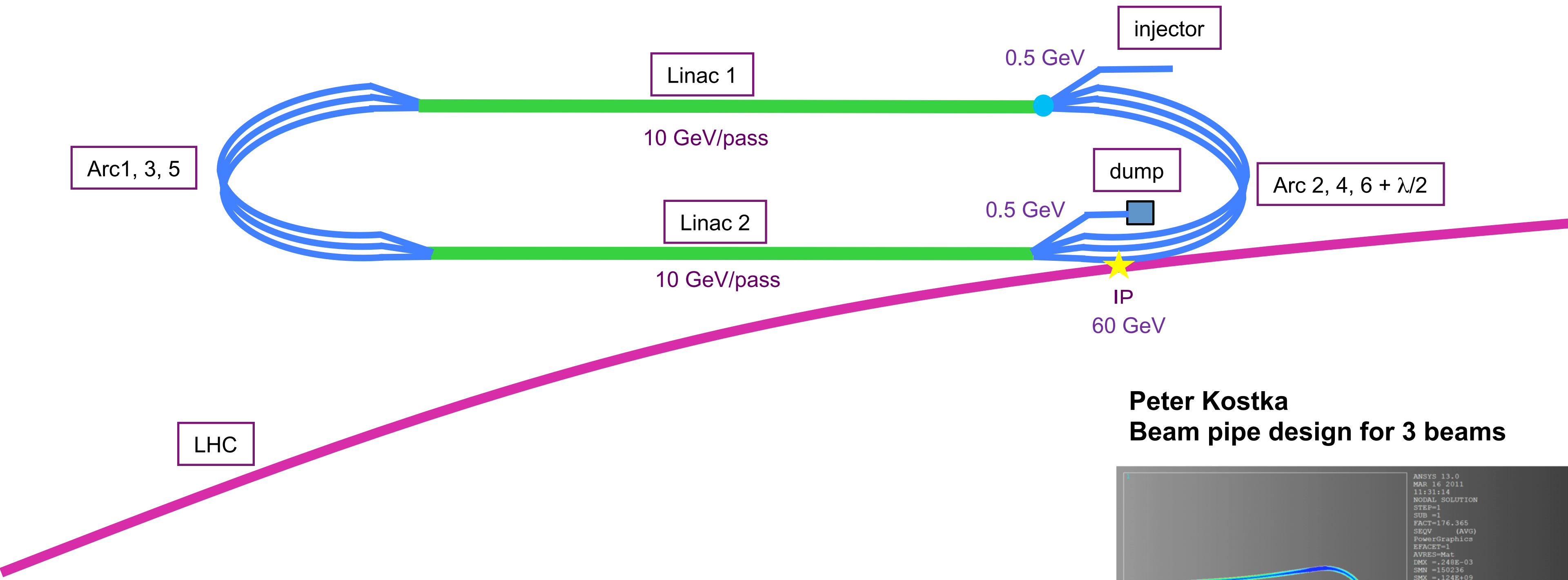
LHeC Recirculator with Energy Recovery



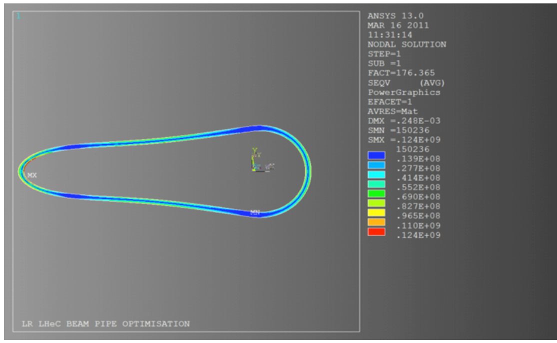
LHeC Recirculator with Energy Recovery



LHeC Recirculator with Energy Recovery

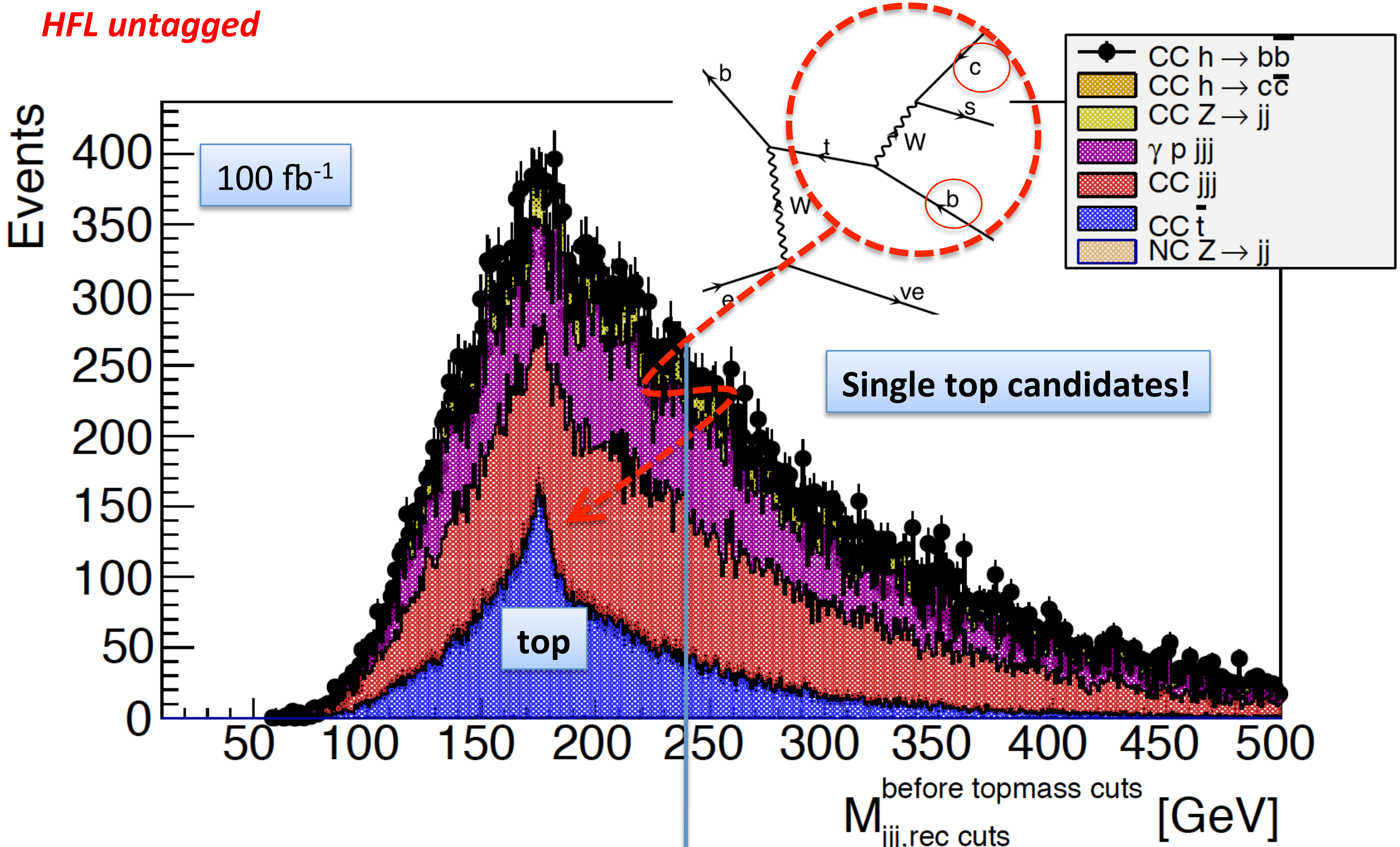


Peter Kostka
Beam pipe design for 3 beams



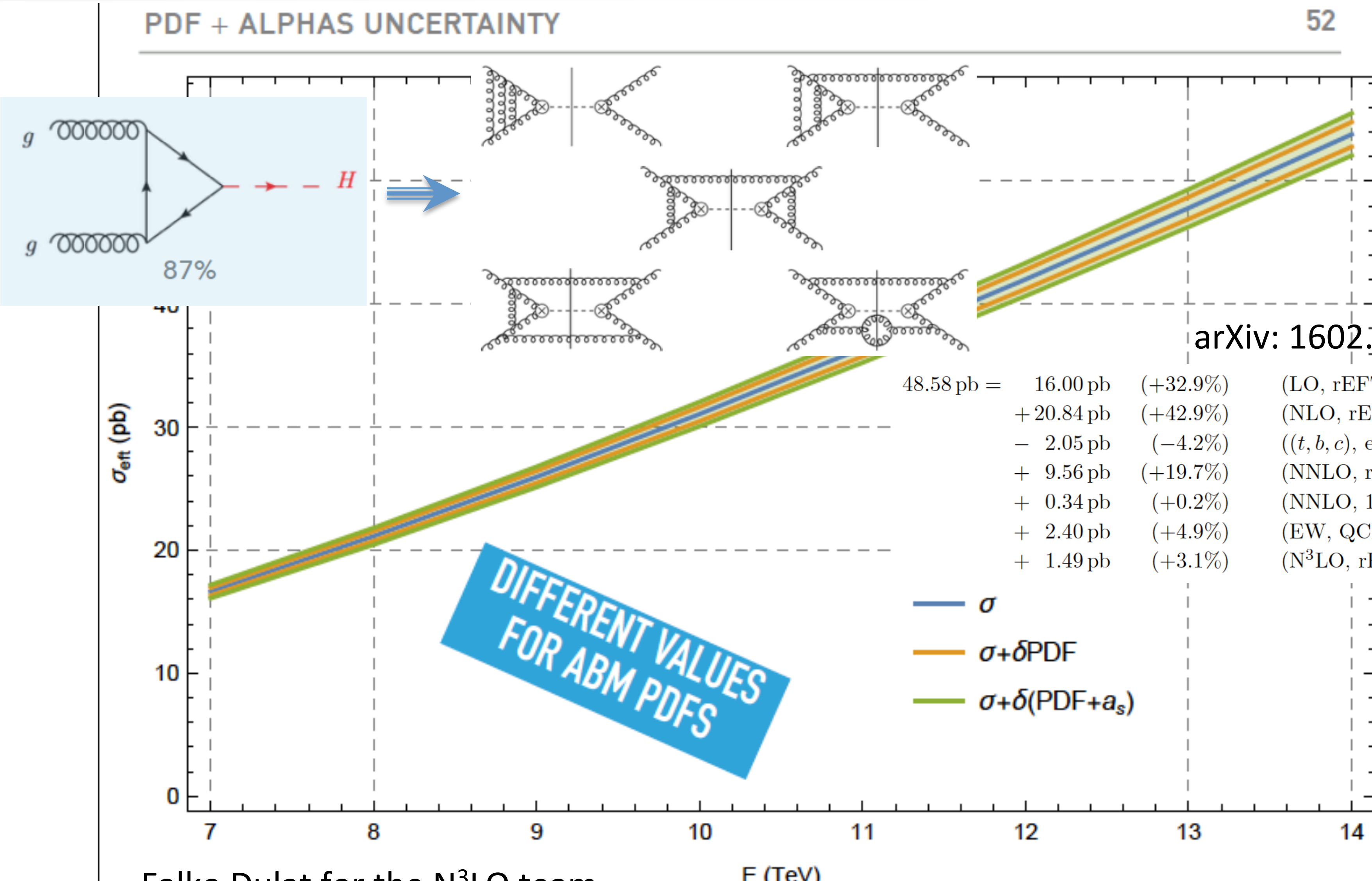
Top: Mass of three highest p_T Jets

HFL untagged



➔ usual cut to accept Higgs candidates
BUT on high cost of signal efficiency

LHC : Total Higgs Cross Sections @ N^3LO

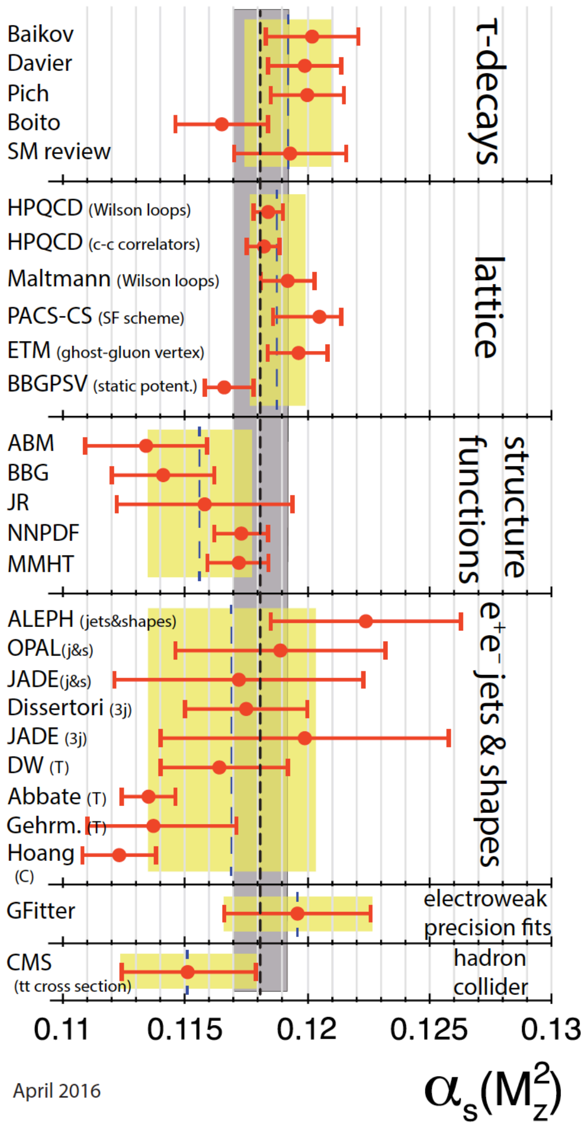


arXiv: 1602.00695

$48.58\,\text{pb} =$	$16.00\,\text{pb}$	$(+32.9\%)$	(LO, rEFT)
	$+\,20.84\,\text{pb}$	$(+42.9\%)$	(NLO, rEFT)
	$-\,2.05\,\text{pb}$	(-4.2%)	$((t,b,c)$, exact NLO)
	$+\,9.56\,\text{pb}$	$(+19.7\%)$	(NNLO, rEFT)
	$+\,0.34\,\text{pb}$	$(+0.2\%)$	(NNLO, $1/m_t$)
	$+\,2.40\,\text{pb}$	$(+4.9\%)$	(EW, QCD-EW)
	$+\,1.49\,\text{pb}$	$(+3.1\%)$	(N^3LO, rEFT)

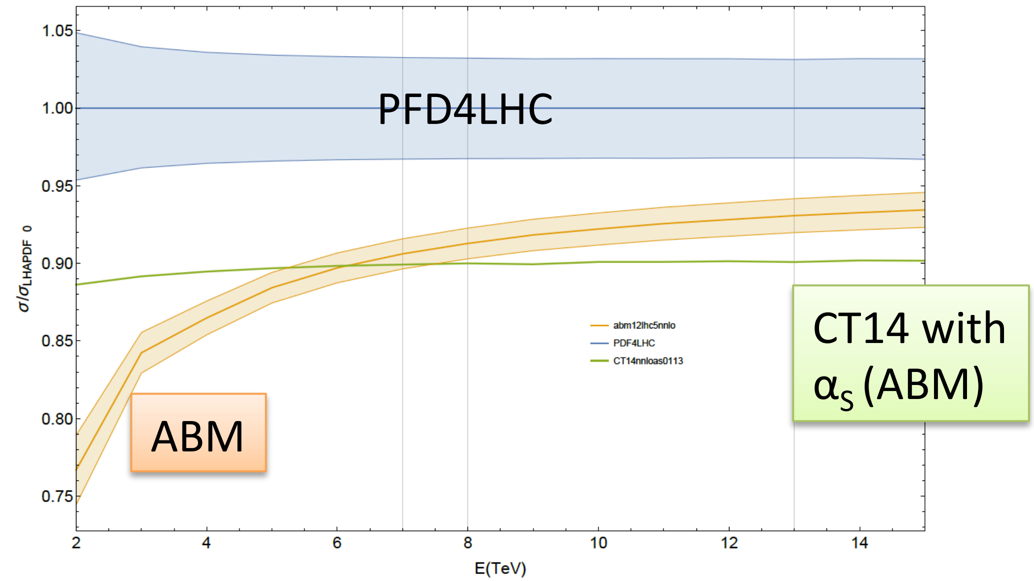
Falko Dulat for the N^3LO team.
CERN seminar 11.12.2015 https://indico.cern.ch/event/462111/

Tensions : α_s and σ^{tot}_{Higgs} @ 13 TeV



PDG 2016

C.Anastasiou et al, arXiv: 1602.00695



Recommendation using PDF4LHC and 68% CL

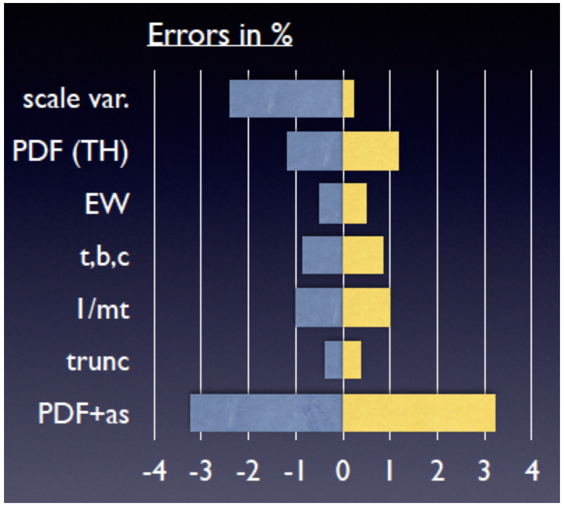
$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)\,.$$

ABM prediction

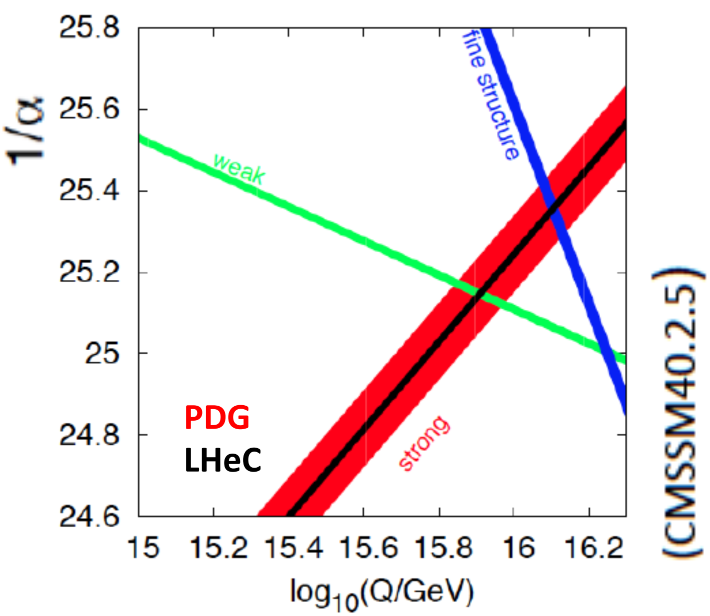
$$\sigma_{\text{ABM12}} = 45.07\,\text{pb}^{+2.00\,\text{pb}\,(+4.43\%)}_{-2.88\,\text{pb}\,(-6.39\%)}\ (\text{theory}) \pm 0.52\,\text{pb}\,(1.17\%)\ (\text{PDF}+\alpha_s)\,. \quad (8.3)$$

The significantly lower central value is mostly due to the smaller value of α_s, which however is also smaller than the world average.

Strong Coupling Constant



Uncertainty on Higgs cross section
Giulia Zanderighi, Vietnam 9/16,
from C.Anastasiou et al, 1602.00695
who also discuss the ABM alpha_s..



- **α_s least known of coupling constants**
  Grand Unification predictions need smaller $\delta\alpha_s$

- **Is α_s(DIS) lower than world average (?)**

- **LHeC: per mille - independent of BCDMS!**

- **High precision from inclusive data – α_s(jets)**
  → for HERA : now NNLO calculations available

- **Challenge lattice QCD**

LHeC simulation, NC+CC inclusive, total exp error

case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

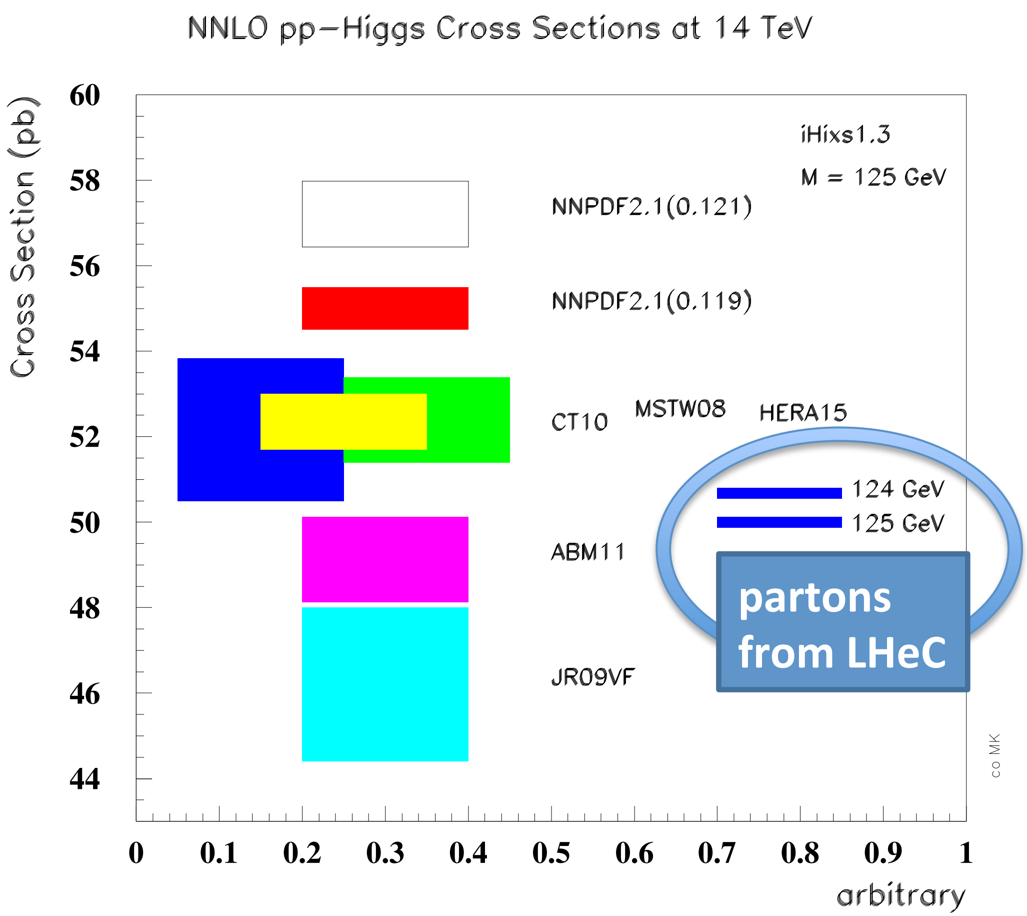
Two independent QCD analyses using LHeC+HERA/BCDMS

LHeC Precision Partons for Higgs@LHC

→ **<u>Using LHeC input</u>**: experimental uncertainty of predicted **LHC Higgs cross section due to PDFs and α_s** is strongly **reduced to ~0.4%**

→ ***clear theoretical path to determine N³LO PDFs***

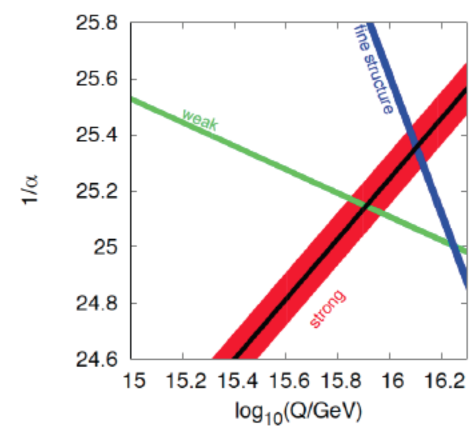
→ Similar conclusions and relations expected for FCC-hh and LHeC/FCC-he



α_s = underlying parameter relevant for uncertainty (0.0015 → 2.6%) @ LHeC: measure to permille accuracy (0.0002)

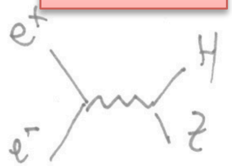
→ precision from LHeC can add a very significant constraint on the Higgs mass *but also:*

Study unification of couplings



Kinematics and M_H : ee vs ep

ee: ZZH



e^+e^-

ee: Z→ νν contribution!

$$(p_{e^-}+p_{e^+})^2 = s = (p_H+p_Z)^2 = M_H^2+M_Z^2+2(E_H E_Z - \vec{p}_H\vec{p}_Z)$$

$$p_e^+ = (E_e, -E_e, \vec{0}_\perp),\ p_e^- = (E_e, E_e, \vec{0}_\perp)$$

$$\curvearrowright\ 2E_e = E_H + E_Z$$
$$\vec{p}_H = -\vec{p}_Z$$

$$s = M_H^2 + M_Z^2 + 2(E_Z\cdot(2E_e - E_Z)) + 2p_Z^2$$

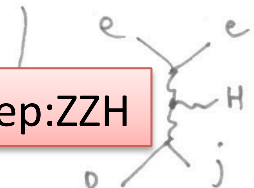
$$s = M_H^2 + M_Z^2 - 2M_Z^2 + 4E_Z\cdot E_e$$

$$s = M_H^2 - M_Z^2 + 2\sqrt{s}\cdot E_Z$$

$$\rightarrow M_H^2 = s + M_Z^2 - 2\sqrt{s}\cdot E_Z$$

ee: x=1 no PDF or from factor involved

ep:ZZH



ep

$J_e := (e+j)$

ep: no Z→ νν contribution!

xE_p: quark in DIS carries fraction x of initial proton energy

$$(p_e+p_p)^2 = s = 4E_eE_p x = M_H^2 + M_{J_e}^2 + 2(E_H\cdot E_{J_e} - \vec{p}_H\cdot\vec{p}_{J_e})$$

$$p_e = (E_e, -E_e, \vec{0}),\quad p_p = (xE_p, xE_p, \vec{0})$$

$$E_e + xE_p = E_H + E_{J_e};\quad (\vec{p}_H + \vec{p}_{J_e})_z = xE_p - E_e$$

$$s = M_H^2 + M_{J_e}^2 + 2E_{J_e}\cdot(E_e + xE_p - E_{J_e}) - 2\vec{p}_{J_e,z}[(xE_p - E_e) - \vec{p}_{J_e,z}]$$

$$= M_H^2 + M_{J_e}^2 - 2M_{J_e}^2 + 2E_{J_e}(E_e + E_p) - 2\vec{p}_{J_e,z}(E_p - E_e)$$

$$\rightarrow M_H^2 = s + M_{J_e}^2 - 2(E_e + xE_p)\cdot E_{J_e} + 2(xE_p - E_e)\cdot\vec{p}_{J_e,z}$$

for $xE_p = E_e$, $J_e = Z$ this is equivalent to M_H in e^+e^-

12.8.17.

→ x in DIS can be determined via electron angle and energy or inclusive hadron kinematics or combinations of it

Some ILC Results

$\sqrt{s} = 500$ GeV

https://arxiv.org/abs/hep-ex/9912041v1
see also ILC reference design report :
https://arxiv.org/pdf/0709.1893.pdf

4-jet channel:
Signal eff.~67%
and sample purity 4%
→ pre-selection
required trained NN

Process	ϵ (%)	σ_{eff} (fb)
$ZH \to q\bar{q}H$	67.27	31.08
$ZH \to \ell^+\ell^- H$	1.48	0.10
$q\bar{q}$ (5 flavors)	6.76	290.96
$t\bar{t}$	4.26	24.79
W^+W^-	5.00	391.07
ZZ	12.30	70.11
Total Bckg		747.03

Table 2: Hadronic channel preselection efficiencies and effective cross-sections.

SMALL signal cross sections similar like in ep!

$$ZH \to \ell^+\ell^- H,\ \ell = e, \mu : \quad (\Delta M_H)_{stat} \simeq 160 \text{ MeV}, \quad \left(\frac{\Delta g_{ZZH}}{g_{ZZH}}\right)_{stat} \simeq 3.8\%,$$

hadronic: $$ZH \to q\bar{q}H : \quad (\Delta M_H)_{stat} \simeq 50 \text{ MeV}, \quad \left(\frac{\Delta g_{ZZH}}{g_{ZZH}}\right)_{stat} \simeq 0.7\%,$$

assuming $\int \mathcal{L}dt = 500$ fb^{-1} of integrated luminosity.

IMPORTANT LESSON:

It was found very important to use sophisticated tools like Neural Networks and kinematic fitting of the Higgs mass;
And: it is crucial to reach high luminosity and excellent detector performance!

Analysis Framework

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 detectors

↓

S/B analysis → cuts or BDT

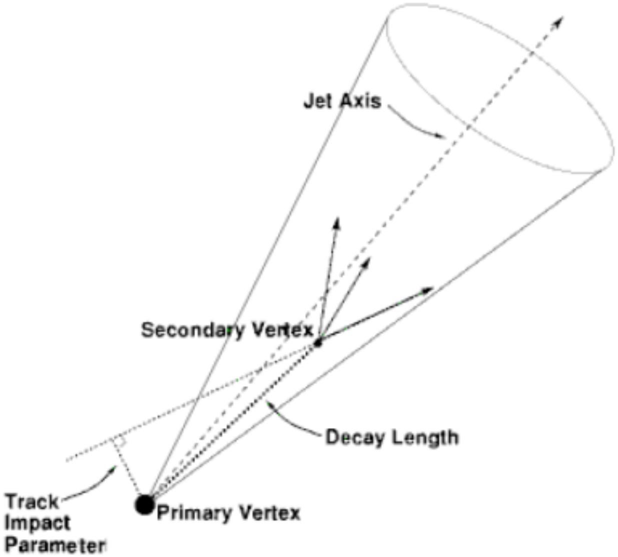
- Calculate cross section with tree-level Feynman diagrams (any UFO) using pT of scattered quark as scale (CDR ŝ) for ep processes with **MadGraph5**
- Standard HERA tools can NOT to be used !
- **Higgs mass 125 GeV as default**
- Fragmentation & hadronisation uses **ep-customised** Pythia.
- **Delphes 'detector' →displaced vertices and signed impact parameter distributions → studied for LHeC, and used for FCC-eh SM Higgs extrapolations**

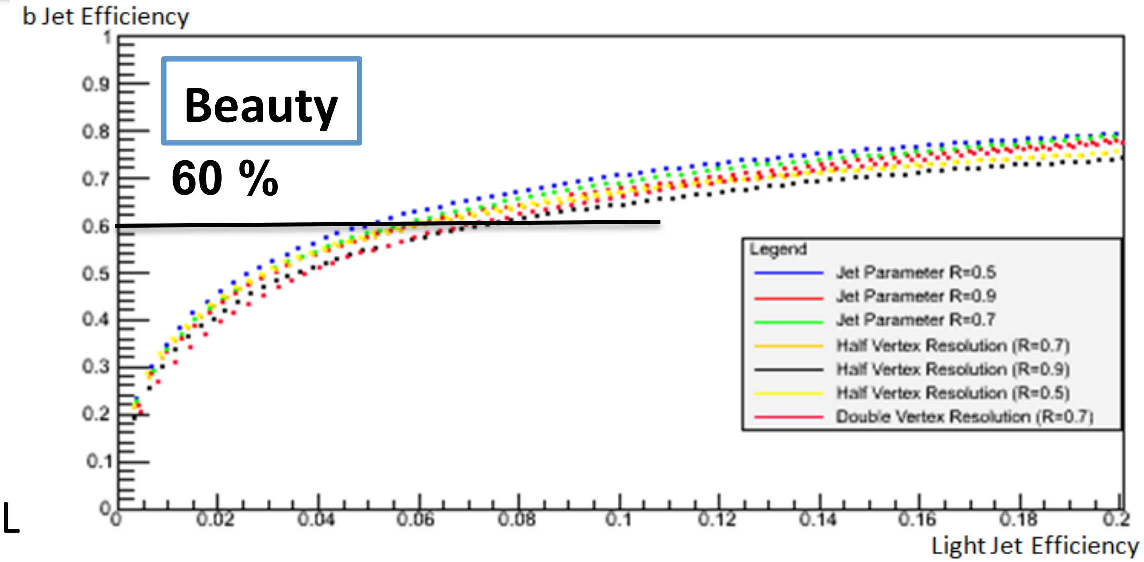
→ powerful method to optimise detector tuning and S/N for various Higgs, top and BSM decays

→ Ongoing : Integration of eh into FCC simulation framework

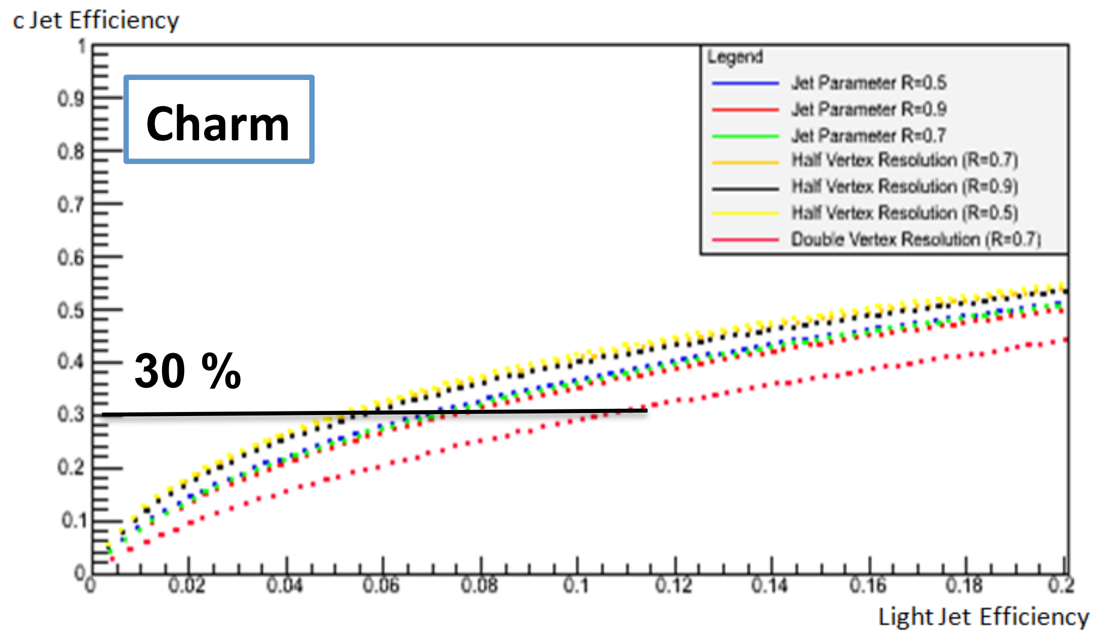
HFL Tagging

Uta Klein &
Daniel Hampson



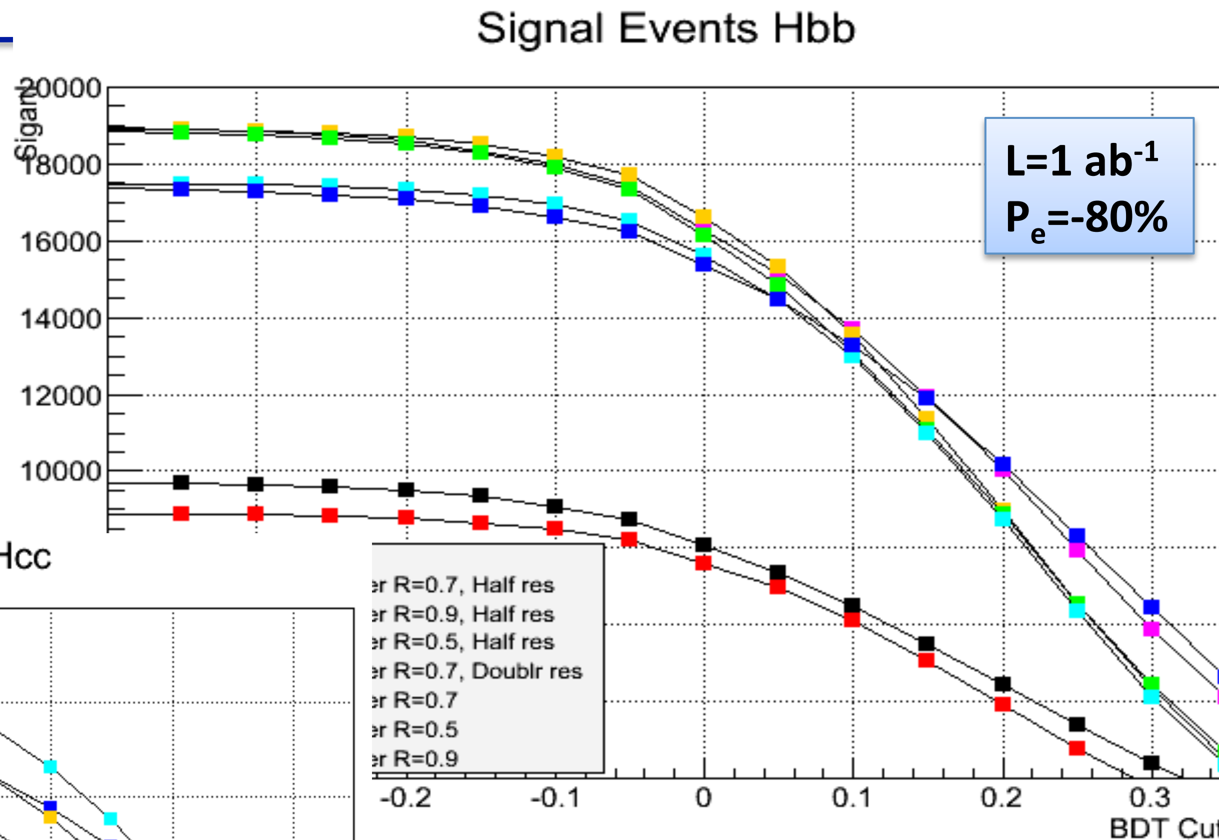


- → Realistic and conservative HFL tagging within Delphes realised, and dependence on vertex resolution (nominal 10 μm) and anti-kt jet radius studied
- → Light jet rejection very conservative, i.e. factor 10 worse than ATLAS
- → **used in full LHeC analysis and for FCC-eh extrapolations**

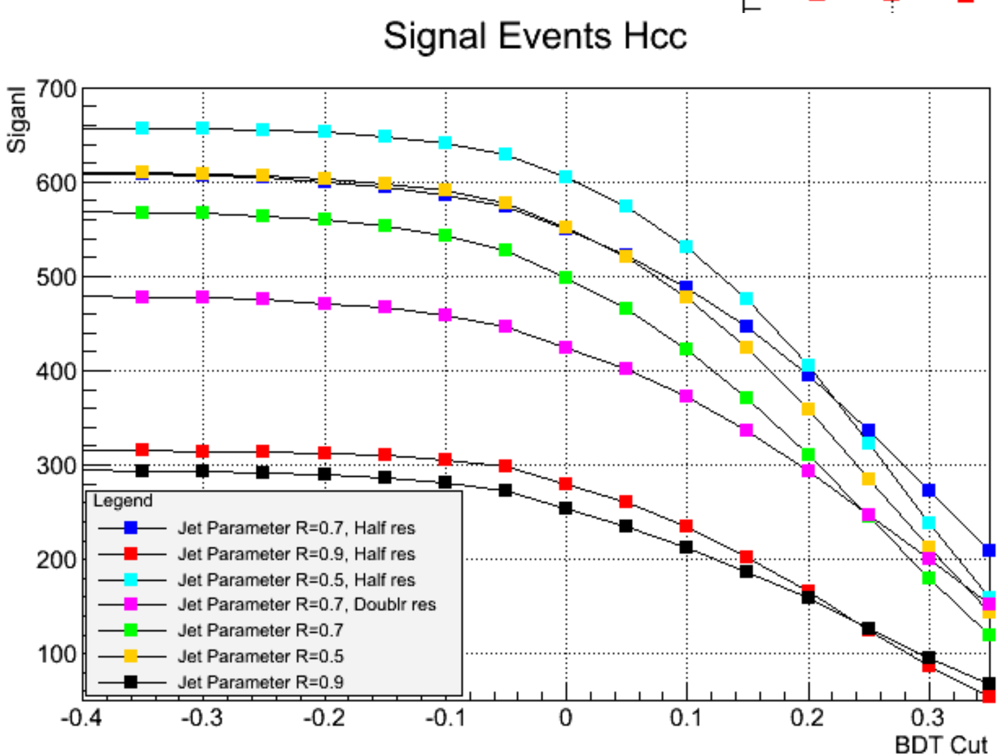


BDT Results for Higgs @ LHeC

Uta Klein &
Daniel Hampson



Hbb : Using same background assumptions as for cut-based analysis, we **get factor 5 more Hbb candidates (~15000)** and a coupling error of 0.6%.



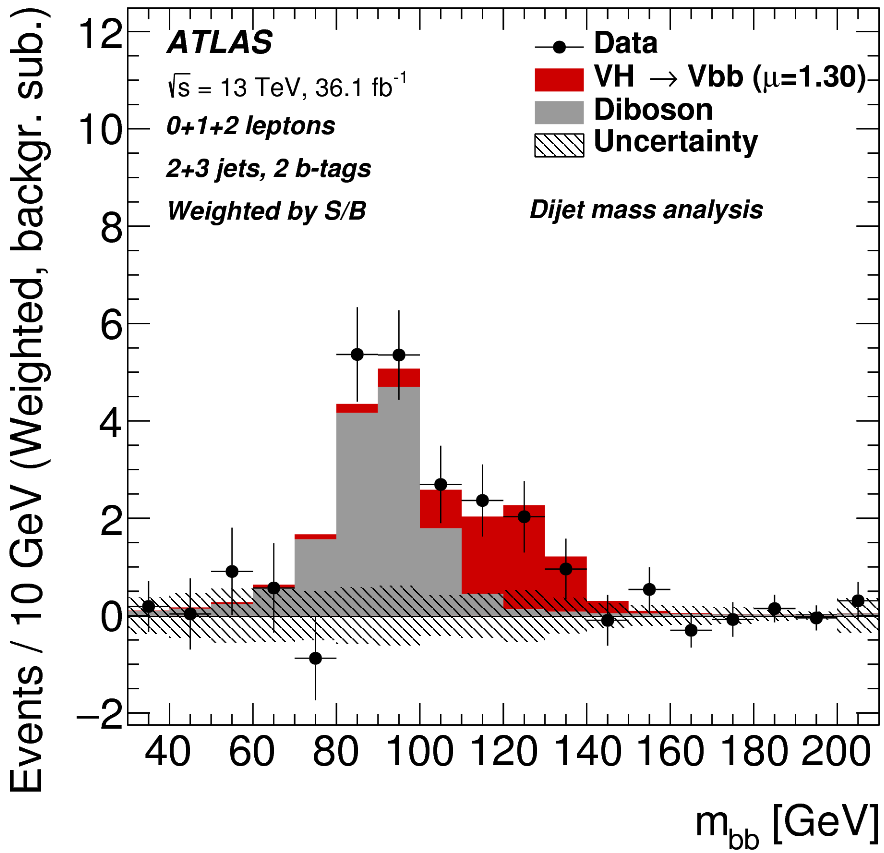
Hcc : High sensitivity to vertex resolution (Half res= 5 µm best) and jet radius (R=0.5 best)

→ **expect about 500-600 Hcc candidates**

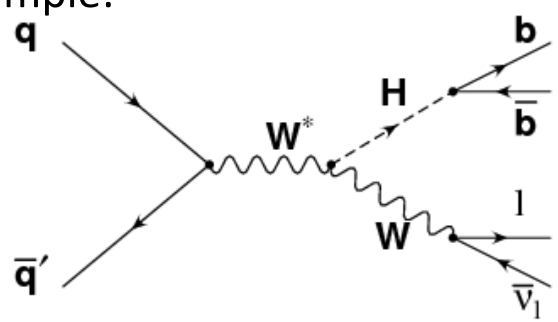
First 3σ Hbb Evidence!

ATLAS, August 2017, sub. to JHEP
https://arxiv.org/abs/1708.03299

- use Higgs→bb in associated production with a W or Z boson
- explore various final states (e.g. Z→νν, W→lν, Z→ll categories)
- Run-I and II combined, S/B-weighted categories : μ=0.9±0.28(stat+syst)



Example:



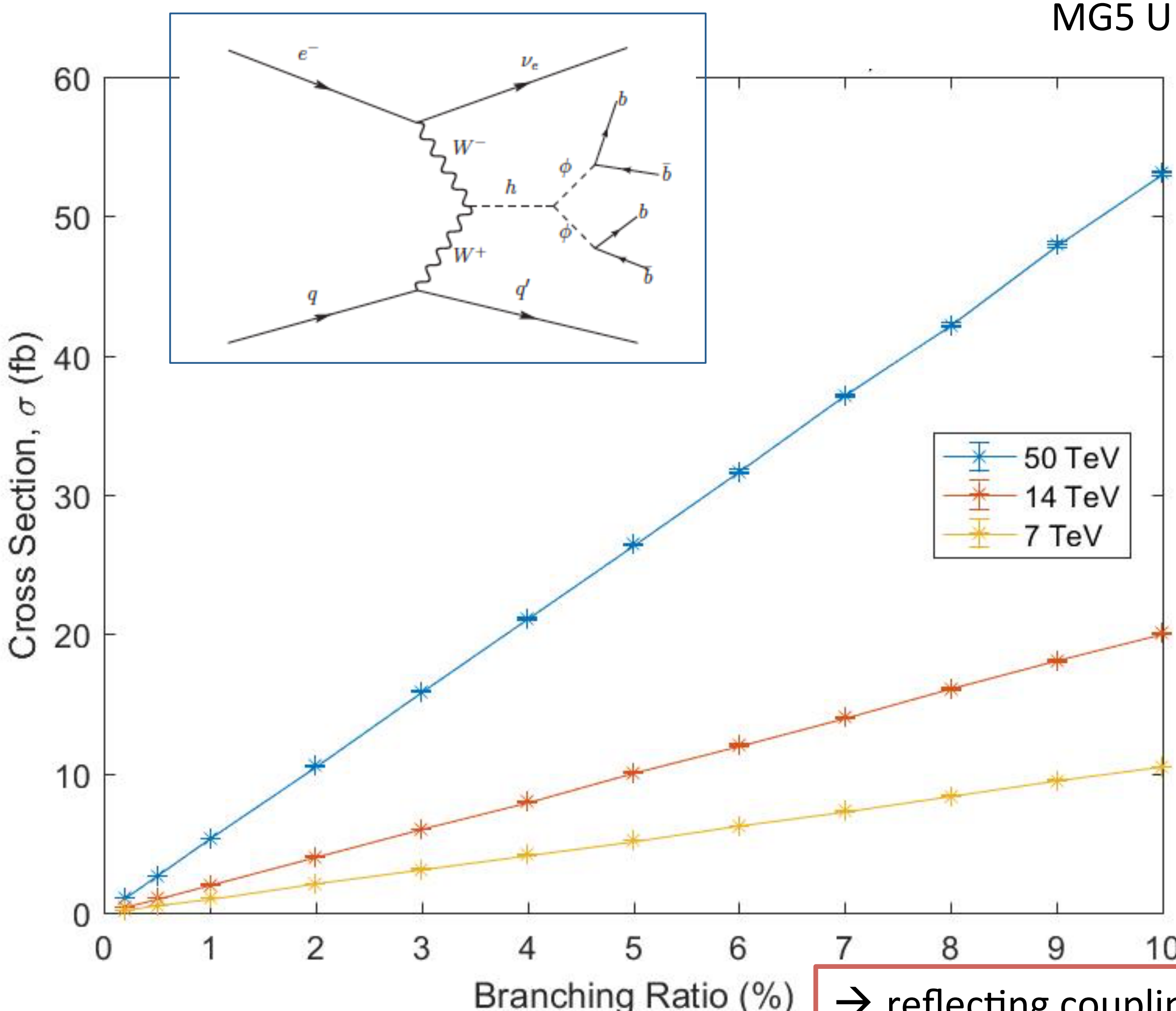
- ✓ Very encouraging result for HL-LHC prospects
- ✓ Also encouraging for prospects in ep that we can handle S/B ~10^{-3} processes with sophisticated analysis techniques

Hbb expectation @ LHeC for 36 fb^{-1} (½ year data)**: δμ~7-8% with significance of ~14**

Exotic Higgs@FCC-eh

Uta Klein
Michael o'Keefe
Liverpool

MG5 UFO [arXiv:1608.08458]



FCC-eh @ 3.5TeV

DLHeC @ 1.8 TeV

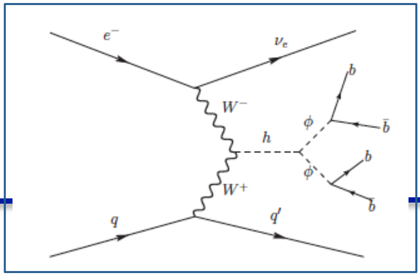
LHeC @ 1.3 TeV

Values for P_e=0

→ reflecting coupling of new scalar to 125 GeV higgs

Samples

Focusing on dominant backgrounds



Uta Klein
Michael o'Keefe
Liverpool

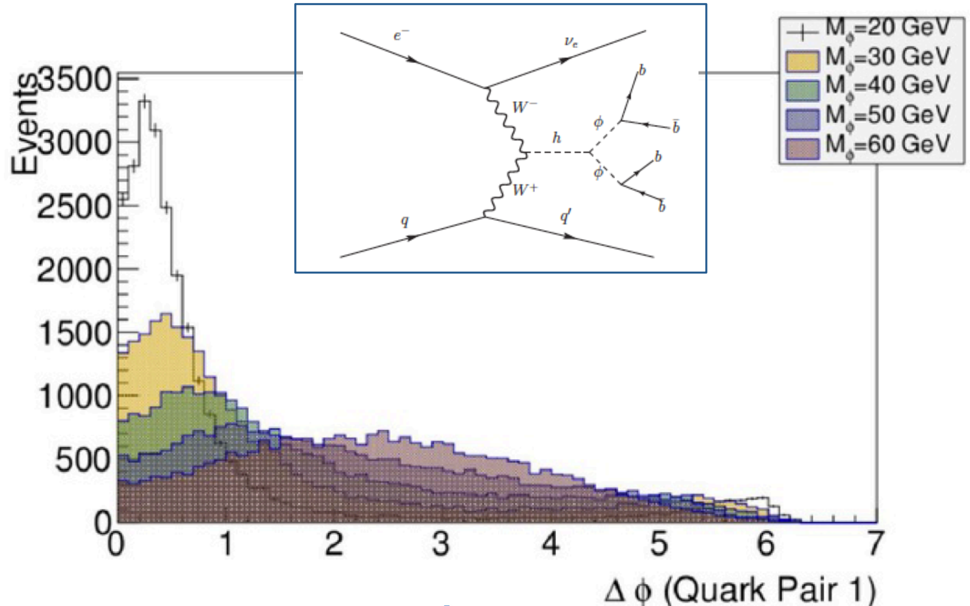
Sample	Process	Generator Level Constraints	Cross Section (fb)
Signal[1]	h→φφ→b b~ b b~	PT of Jets/b's/photons/charged leptons > 6.5 GeV η of Jets/b's/photons/charged leptons < 6.1 Min. ΔR between jets = 0.2 Min. Inv. Mass of Jet/bb~ pair = 8 GeV	51.34
CC Single Top Production	pe-→j t~ vl all /h (t~ → W- b~, W- → all all	PT of Jets/b's/photons/charged leptons > 6.5 GeV η of Jets/b's/photons/charged leptons < 6.1 Min. ΔR between jets = 0.2 Min. Inv. Mass of Jet/bb~ pair = 8 GeV	11,347
CC Top+Multijet Sample	all = g u c d s u~ c~ d~ s~ , ve vm vt ve~ vm~ vt~ ta- ta+ b b, ~ z w+ w- h t t~ pe- → b~ all all vl pe- → b all all vl	PT of Jets/b's/photons/charged leptons > 6.5 GeV η of Jets/b's/photons/charged leptons < 6.1 Min. ΔR between jets = 0.2 Min. Inv. Mass of Jet/bb~ pair = 8 GeV Beam Polarisation = 0	9683
CC Inclusive Single W/Z/h Production	p e- → vl w- j j / t~ t , w- → j j p e- → vl h j j , h → j j p e- → vl z j j , z → j j	η of Jets/b's/photons/charged leptons < 6.1 Min. ΔR between jets = 0.2 Min. Inv. Mass of Jet/bb~ pair = 8 GeV Beam Polarisation = 0	3566
CC b b~ + 2j Production	all = g u c d s u~ c~ d~ s~ ve vm vt ve~ vm~ vt~ ta- ta+ b b~ p e- > b~ b all all vl	PT of Jets/b's/photons/charged leptons > 6.5 GeV η of Jets/b's/photons/charged leptons < 6.1 Min. ΔR between jets = 0.2 Min. Inv. Mass of Jet/bb~ pair = 8 GeV Beam Polarisation = 0	1120

➔ low pT and low dijet mass generation to retain sensitivity for 20 GeV scalar

Kinematics @ Quark-Level

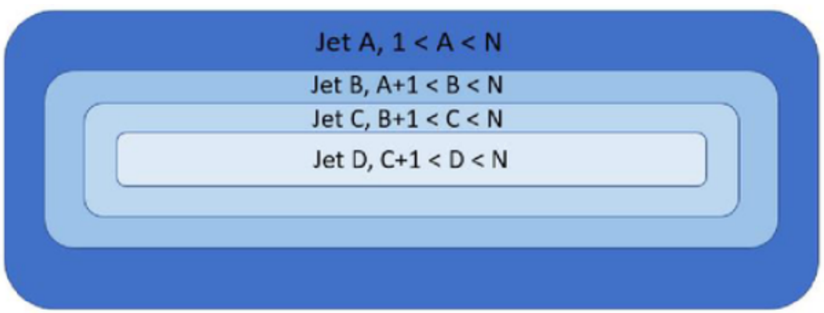
Uta Klein
Michael o'Keefe
Liverpool

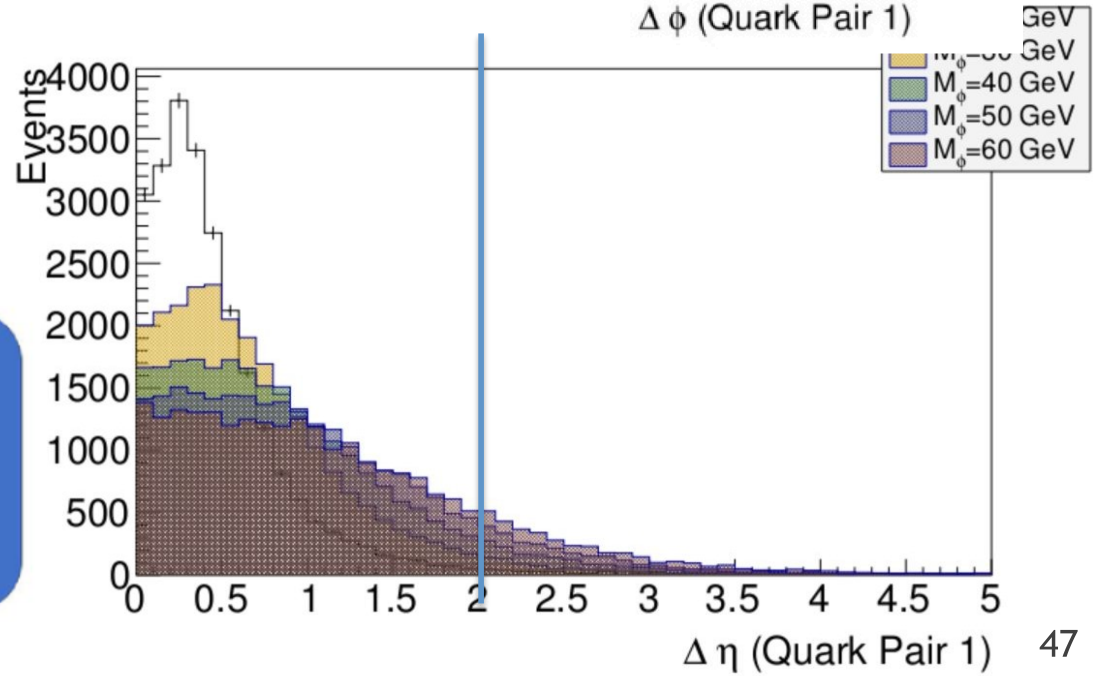
$\Delta\varphi$ between b quarks in the scalar (parton level)



$\Delta\eta$ between b quarks in the scalar (parton level)

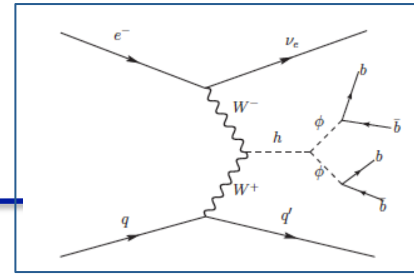
➔ use $\Delta\eta<2$ for finding two scalars with mass within $2m_b$ and $m_H/2$ looping over N jets minimising Δm





BDT Analysis @ BR=10%

Delphes-detctor level with b-tag |η|<2.5



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Michael o'Keefe
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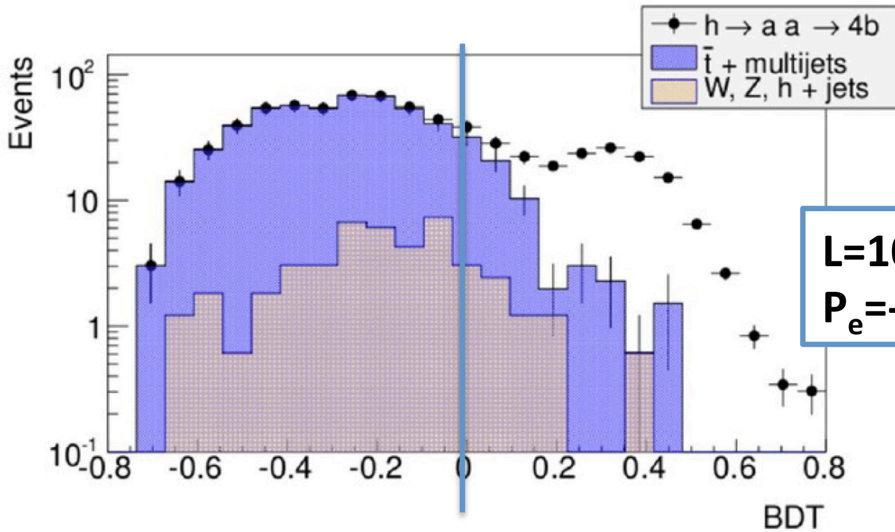
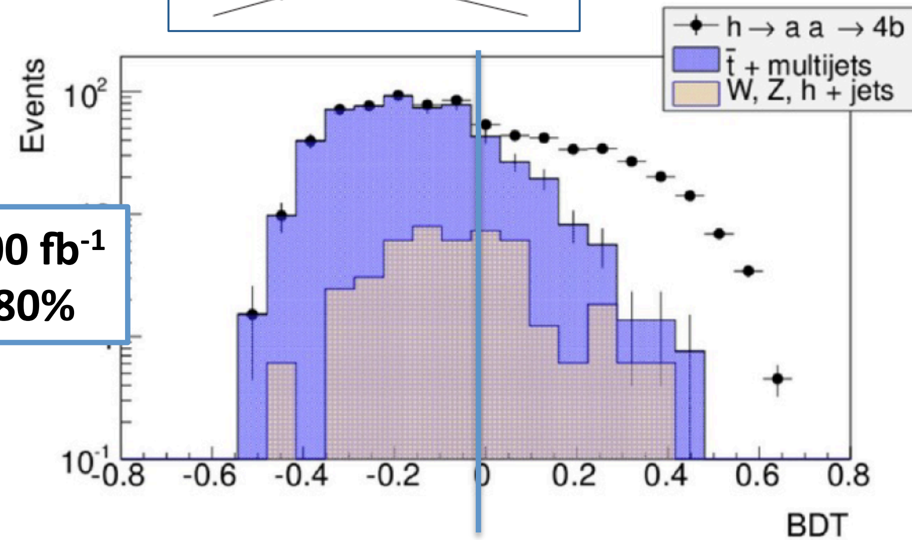
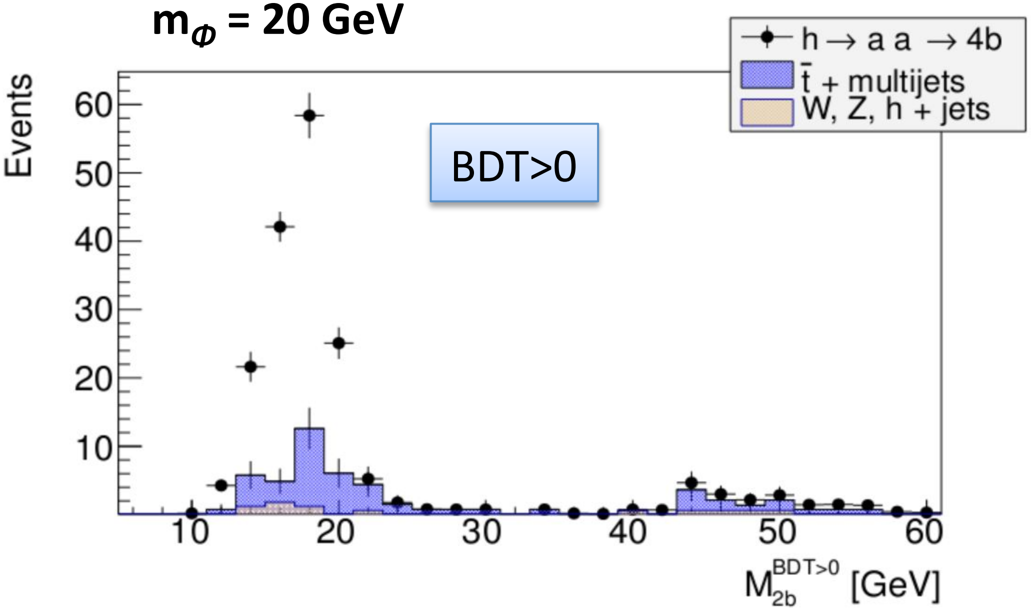


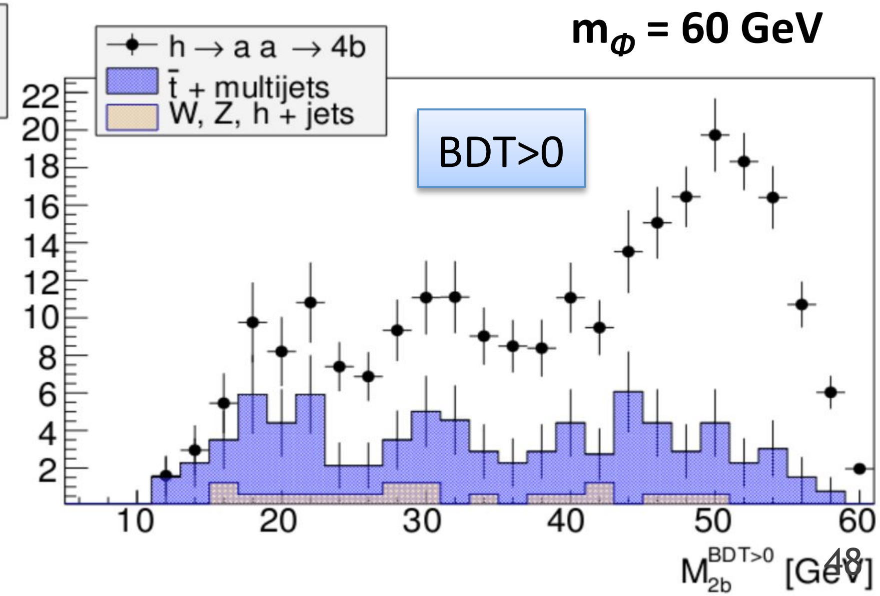
L=100 fb^{-1}
P_e=-80%



m_Φ = 20 GeV



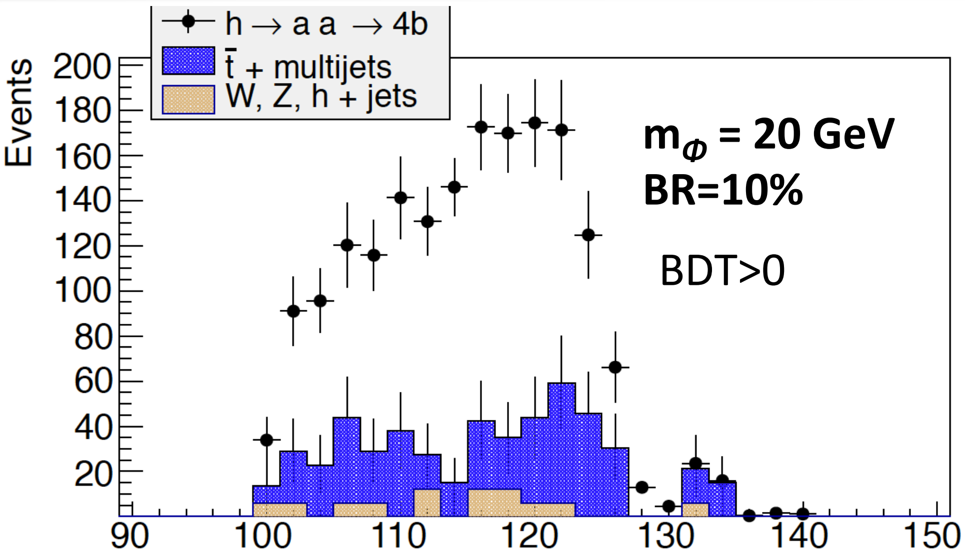
m_Φ = 60 GeV



First Results @ FCC-eh

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

Uta Klein
Michael o'Keefe
Liverpool



Very promising first results to discover an exotic Higgs decay into two new light scalars at FCC-eh 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

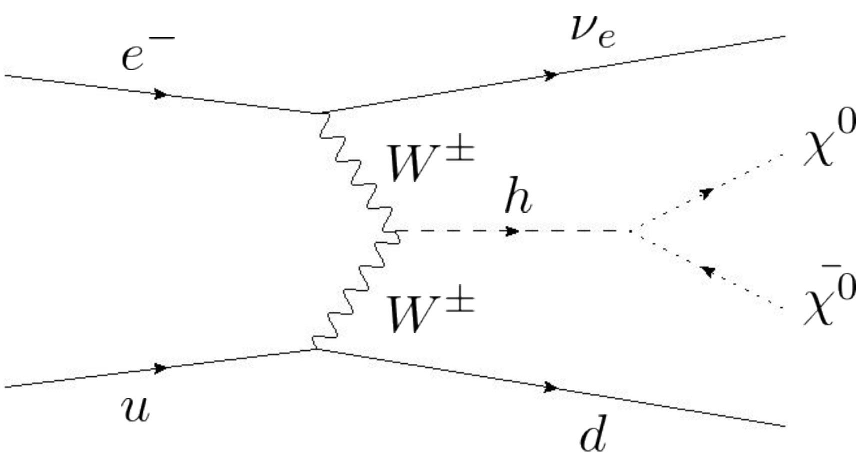
$$Z = \sqrt{2\left[(S+B)\ln\left(1+\frac{S}{B}\right)-S\right]}$$

	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

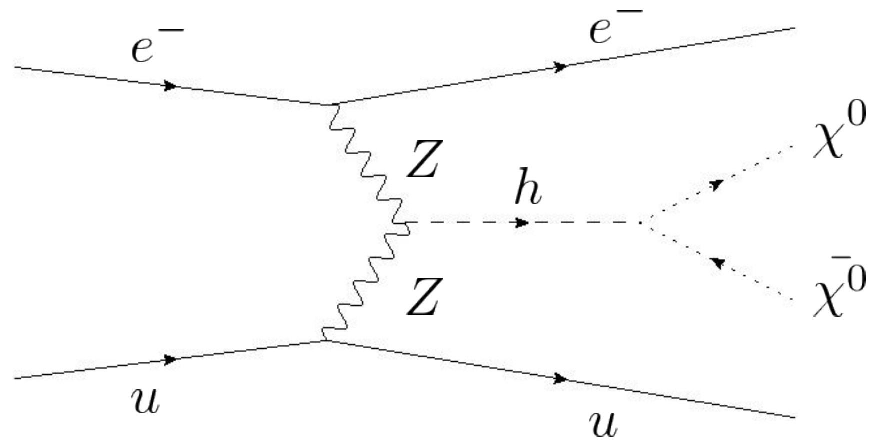
Invisible Higgs Decay in ep

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

CC production of an invisible Higgs



NC production of an invisible Higgs



→ We focus currently on NC DIS channel: employ that kinematic is over constrained using jet and electron information in the final state

→ We use the idea from C. Zhang and Y.-L. Tang : We emulate Higgs to invisible by assuming a branching of 100% for H→ ZZ → 4ν

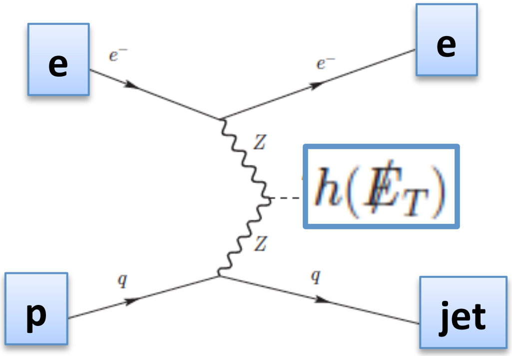
→ We started to study signals and backgrounds using CMS-style and FCC-eh-style ‘Delphes’ detectors, using same analysis strategies as developed for LHeC (C. Zhang and BSc thesis S. Kawaguchi)

Selection Requirements

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

Basic cuts (Cut 0)

- N(jets) for the jet and the electron
- pT for the leading jet and the leading electron
- for the leading jet and the leading electron
- for the leading jet and the leading electron



Cut 1 : $|\Delta\phi_{jet,Etmiss}| > 1$ rad

Cut 2 : Etmiss > 50 GeV

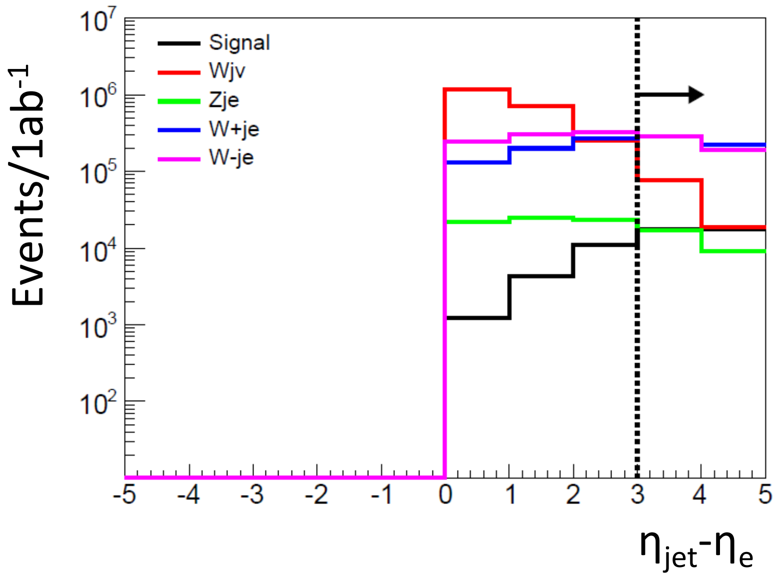
Cut 3 : $\eta_{jet}-\eta_e > 3$

Cut 4 : $\phi_{jet} - \phi_e < 2.4$

Cut 5 : $-1.3 < \eta_e < 1.1$

Cut 6 : $0.08 < y_e < 0.55$

Cut 7 : require 1 electron, 1 jet,
and veto tau's and muons

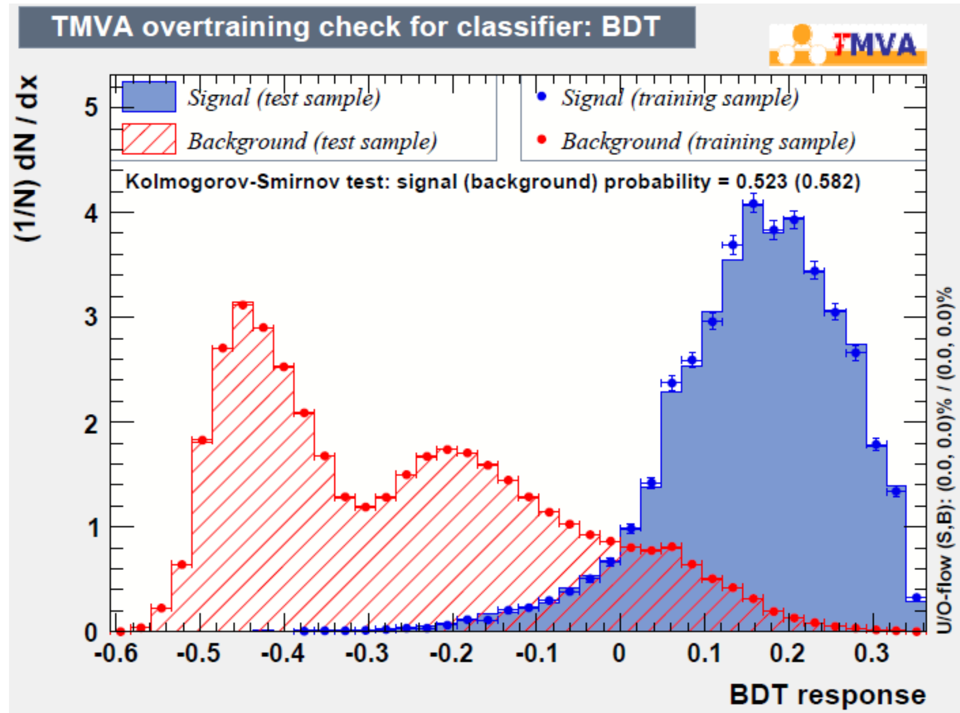


Results for FCC-eh - Using BDT

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

MVA using samples with 1 jet and 1e- with high pT, and other variables as a BDT input.

BDT >	Signal		Z[%]
0	31961	267904	3.25
0.05	29932	176439	2.81
0.1	25686	94138	2.40
0.15	19898	42439	2.08
0.2	13020	15562	1.93
0.25	6998	4969	2.04
0.3	2320	1003	2.82



Branching ratio calculated by $S/\sqrt{S+B}$:

$$Z=13020\times \mathrm{Br}(h\to \not{E}_T)/\sqrt{13020\times \mathrm{Br}(h\to \not{E}_T)+15562}$$

In the case of 2σ

$\mathrm{Br}(h\to \not{E}_T)\sim 1.93\%$

Dominant Background

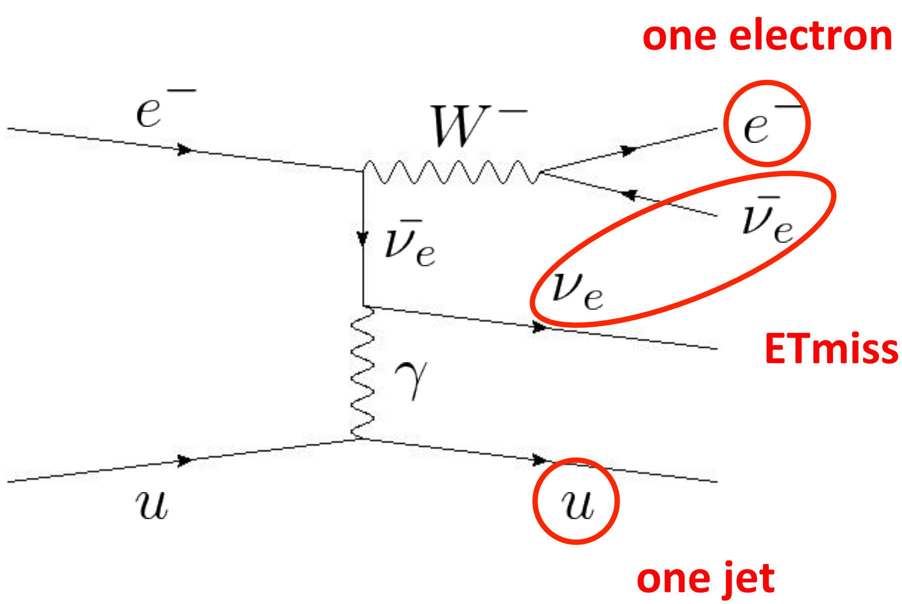
Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

for faking our signal feature :
one electron, one jet, and missing transverse energy (E_T^{miss})
W^+je^- and W^-je^- backgrounds and

$Wj\nu$ background

$$p + e^- \to W^- + j + \nu_e$$

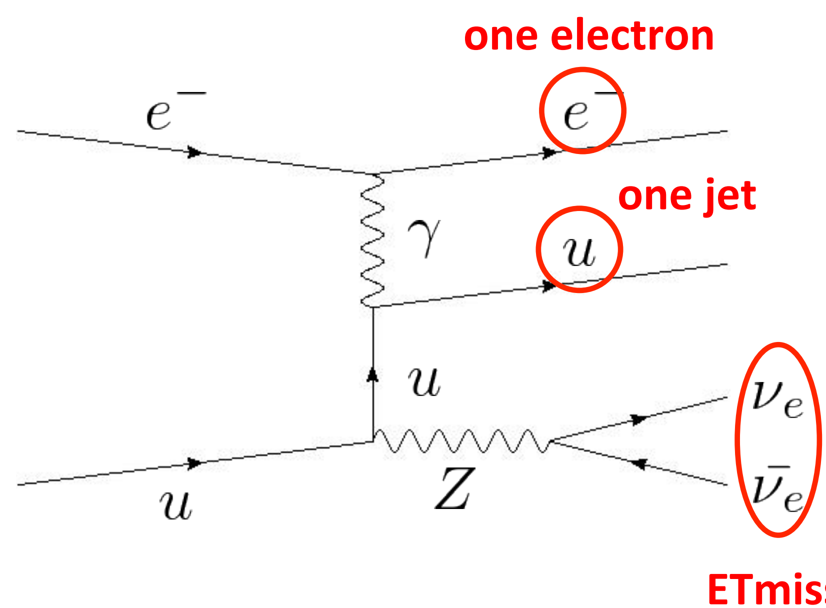
$$W^- \to e^- + \nu_e$$



Zje background

$$p + e^- \to Z + j + e^-$$

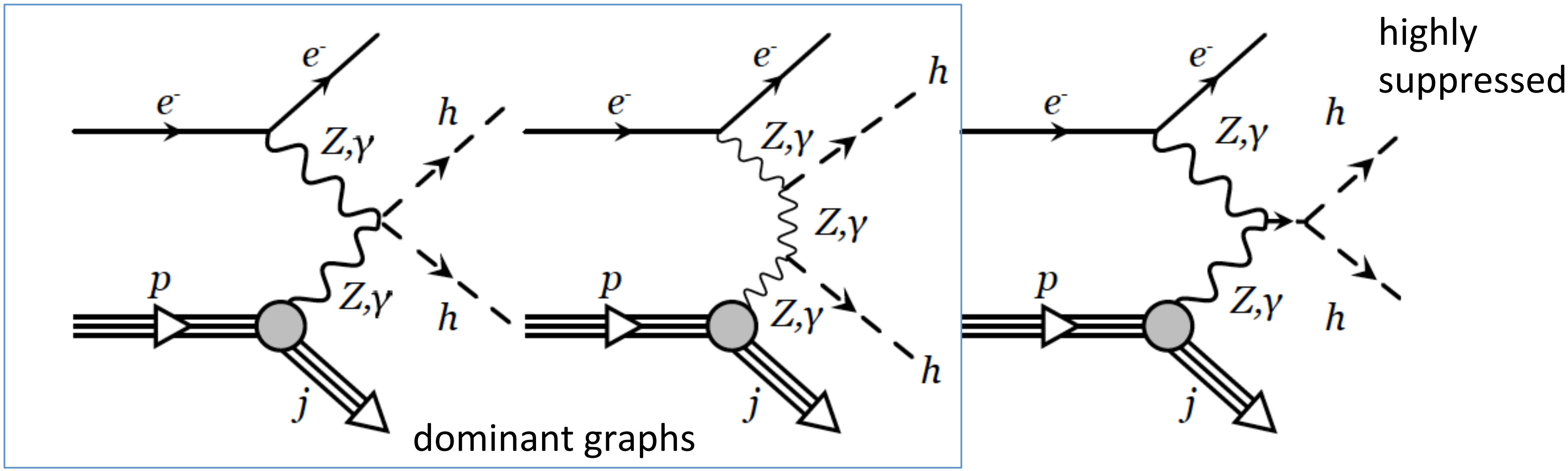
$$Z \to \nu + \bar{\nu}$$



Limits on Neutral Di-Boson and Di-Higgs Interactions for FCC-he Collider

[1702.00185]

S. Kuday,* H. Saygın,† İ. Hoş,‡ and F. Çetin§



- Vertices for Neutral Current DIS (Z, γ) and Photoproduction (γ) studied in Higgs Effective Langrangian Model : parametrise hhZZ and hhγγ in 4-point interactions in terms of CP-even and CP-odd Wilson coefficients (and Higgs self coupling and Yukawa coupling)
- Study at Delphes-detector level (FCC-hh) azimuthal dependencies between scattered lepton and forward jet
- hh : 4b final states investigated using a very first version of FCC-hh detector
- Promising sensitivity found while scanning parameter space for Wilson coefficients