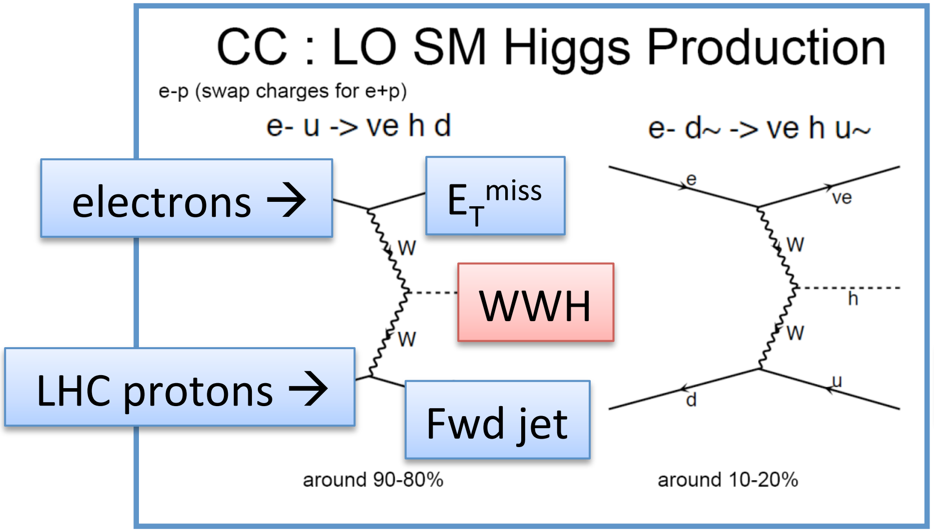
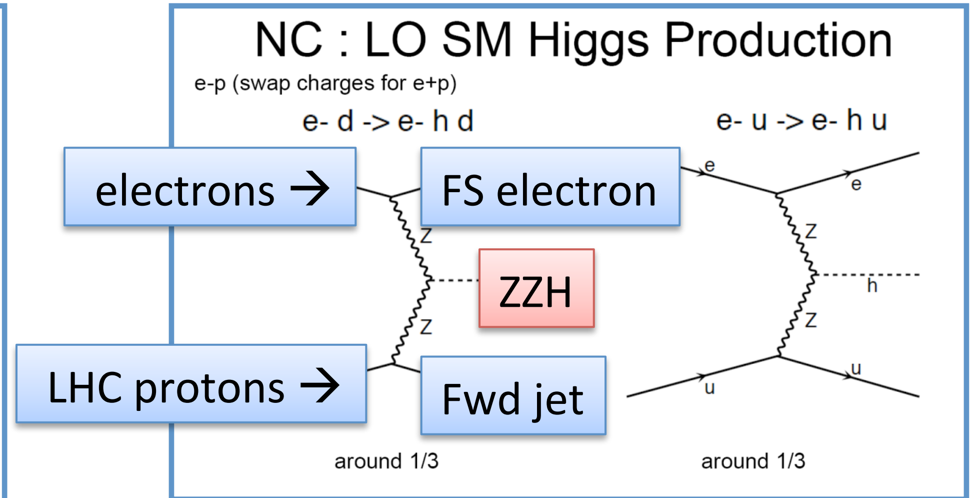
Higgs physics at the LHeC and the FCC-he

Uta Klein
on behalf of
the LHeC/FCC-he Higgs Group

DIS 2018, Kobe, April 19th, 2018

SM Higgs Production in ep





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

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

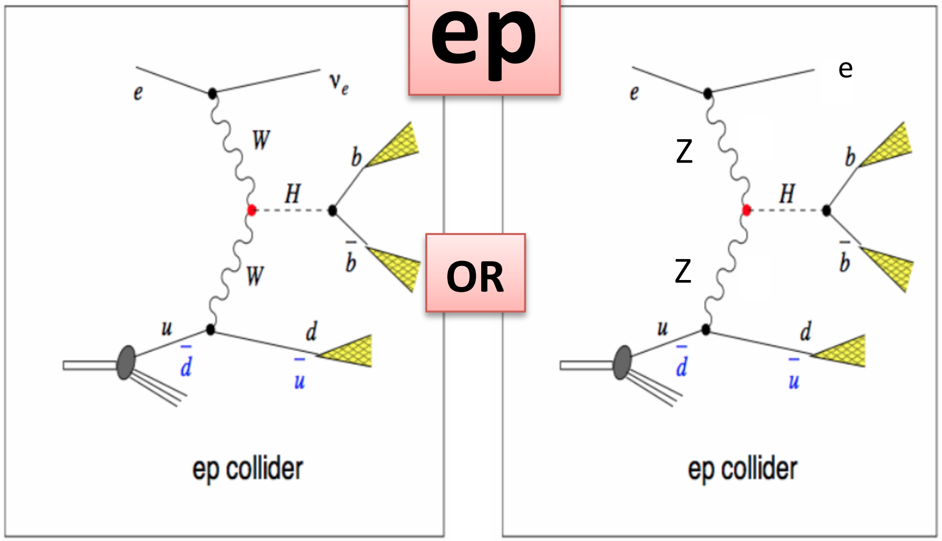
c.m.s. energy	1.3 TeV LHeC	3.5 TeV FCC-he
CC DIS	109	560
NC DIS	21	127
P=-80%		
CC DIS	**196**	**1008**
NC DIS	**25**	**148**

•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]

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

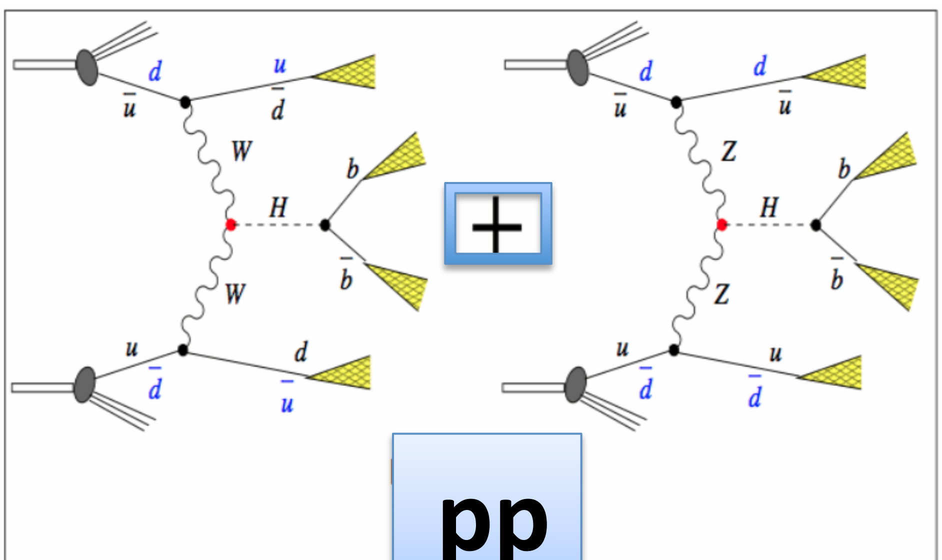
ep



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

Clean final states, e.g. Hbb with S/B >1
e-h Cross Calibration for Precision ep
Clean, precise reconstruction and easy distinction of ZZH and WWH <u>**without pile-up**</u>:
<0.1@LHeC up to 1@FCCeh events

<u>**VBF: Small theoretical uncertainties!**</u>



pp

pp: Higgs production in pp comes **predominantly from gg→ H :**
high rates crucial for rare decays
LHC 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
FCC-hh: pile-up 500-1000
S/B very small for bb
Final Precision in pp needs accurate N^3LO PDFs & α_s

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 <u>pT of scattered quark as scale (CDR $\hat{s}$)</u> for ep processes with **MadGraph5**
- **Higgs mass 125 GeV as default**
- Fragmentation & hadronisation uses <u>**ep-customised** Pythia</u>.
- **Delphes 'detector' →displaced vertices and signed impact parameter distributions → studied for LHeC, and used for FCC-eh SM Higgs extrapolations**
- 'Standard' GPD LHC-style detectors used and further studied based on optimising Higgs measurements, i.e. vertex resolution a la ATLAS IBL of ~ 5 μm, excellent hadronic and elmag resolutions using 'best' state-of-the art detector technologies (no R&D 'needed')

LHeC@HL-LHC: SM Higgs rates @ 1 ab^{-1}

Baseline: **Realistic option of an 1000 fb^{-1} ep collider – 1000 times HERA Lumi** (stronger e-source, stronger focussing magnets) and **excellent performance of LHC** (higher brightness of proton beam) ➔ **full MG5 + Pythia + Delphes feasibility studies**

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

√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

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

Higgs decay to charm is factor 20 less likely than Hbb

pp: **perfect Higgs factory for gluon-induced rare decays**

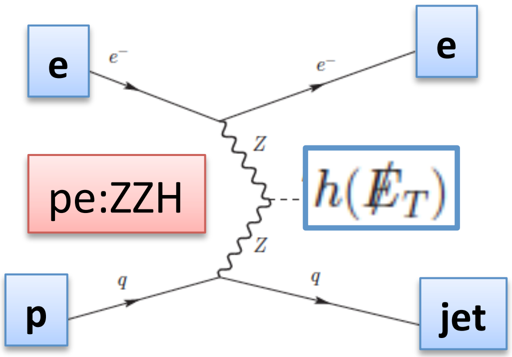
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR2014

Branching for invisible Higgs

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

Values given in case of 2σ and L=1 ab^{-1}

Delphes detectors	LHeC 1.3 TeV	FCC-he 3.5 TeV
LHC-style	4.7%	1.9%
First 'ep-style'	5.7	2.6%
+BDT Optimisation	5.5% (4.5%*)	1.7% (2.1%*)



- ✓ **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 cms energies, look 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}**

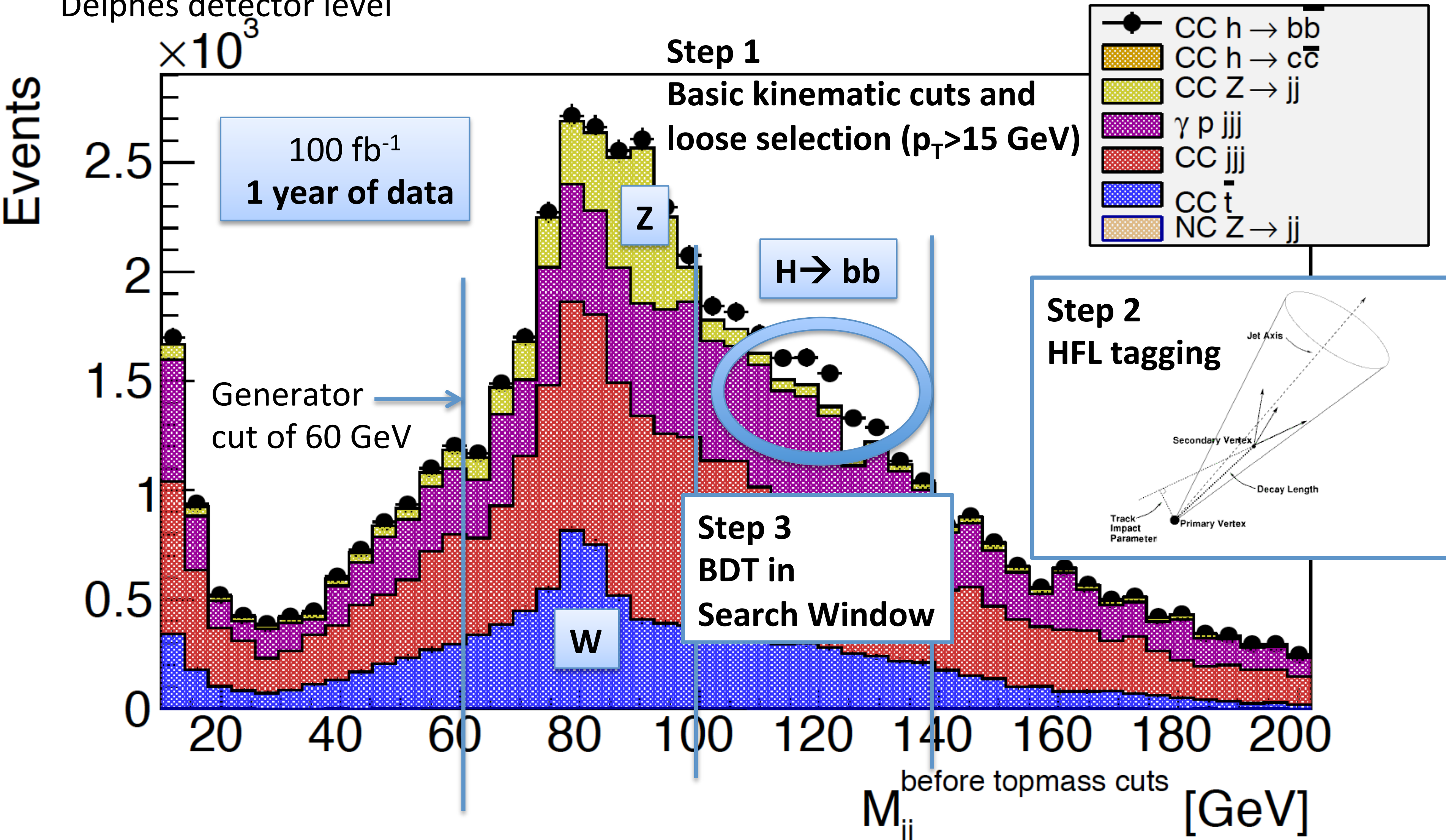
- ✓ We also checked LHeC ←→ FCC-he scaling with the corresponding cross sections (* results in table) : Downscaling FCC-he simulation results to LHeC would give 4.5%, while up-scaling of LHeC simulation to FCC-he would result in 2.1% ➔ all well within uncertainties of projections of ~25%

- employ further synergies within LHC community and HL-LHC&FCC study group
  ➔ **further detector and analysis details have certainly an impact on results**

BDT:U Klein; Cut-based: M Kuze, M Tanaka

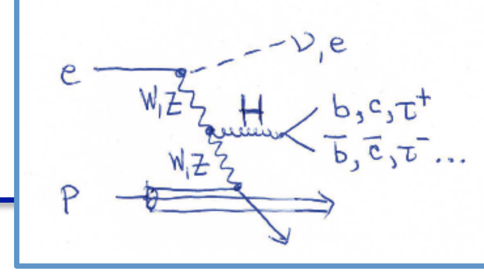
Dijet Mass Candidates *HFL untagged*

Delphes detector level



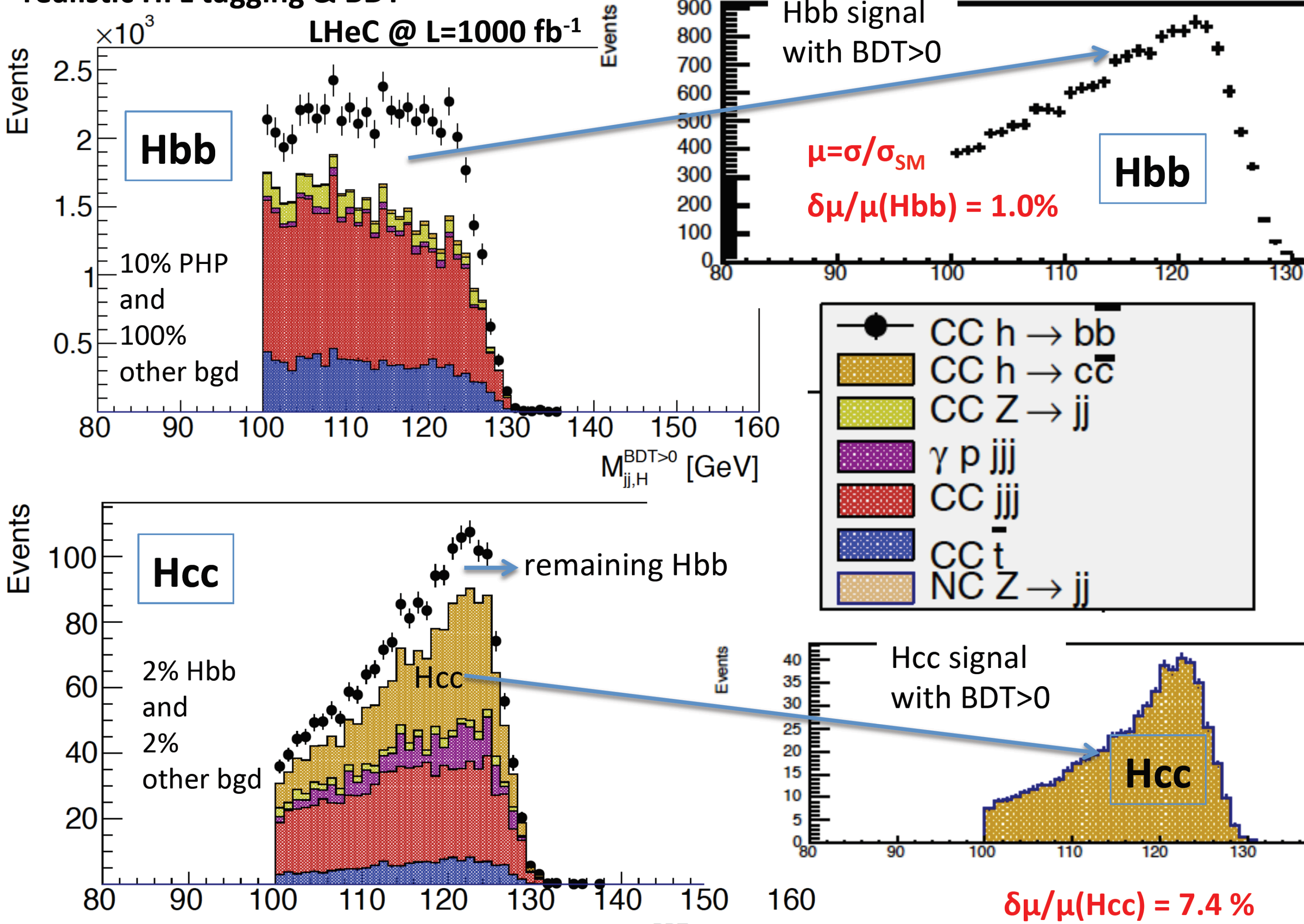
'Worst' case scenario plot : Photoproduction background (PHP) is assumed to be 100%!
→ However, addition of small angle electron taggers will reduce PHP to ~1-2%

Higgs in ep – clean S/B, no pile-up



Uta Klein & Daniel Hampson

realistic HFL tagging & BDT



→ Hcc signal strength given for assumptions with Hbb background enhanced by factor 2!

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

New: 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}]

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

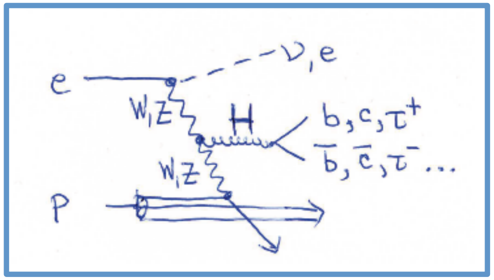
- Calculate uncertainties of signal strengths w.r.t. SM expectation $\mu = \frac{\sigma}{\sigma_{SM}}$

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

CC DIS WWH → H

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

	bb	WW	gg	ττ	cc	ZZ	γγ
BR2014	**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**	**4.74**



Further coupling constraints to be explored (simplified for illustration only!):

$$\sigma(WW \to H \to WW) \propto \kappa^4(HWW)$$

$$\sigma(WW \to H \to bb) \quad \propto \kappa^2(HWW) \bullet \kappa^2(Hbb)$$

$$\sigma(WW \to H \to \tau\tau) \quad \propto \kappa^2(HWW) \bullet \kappa^2(H\tau\tau)$$

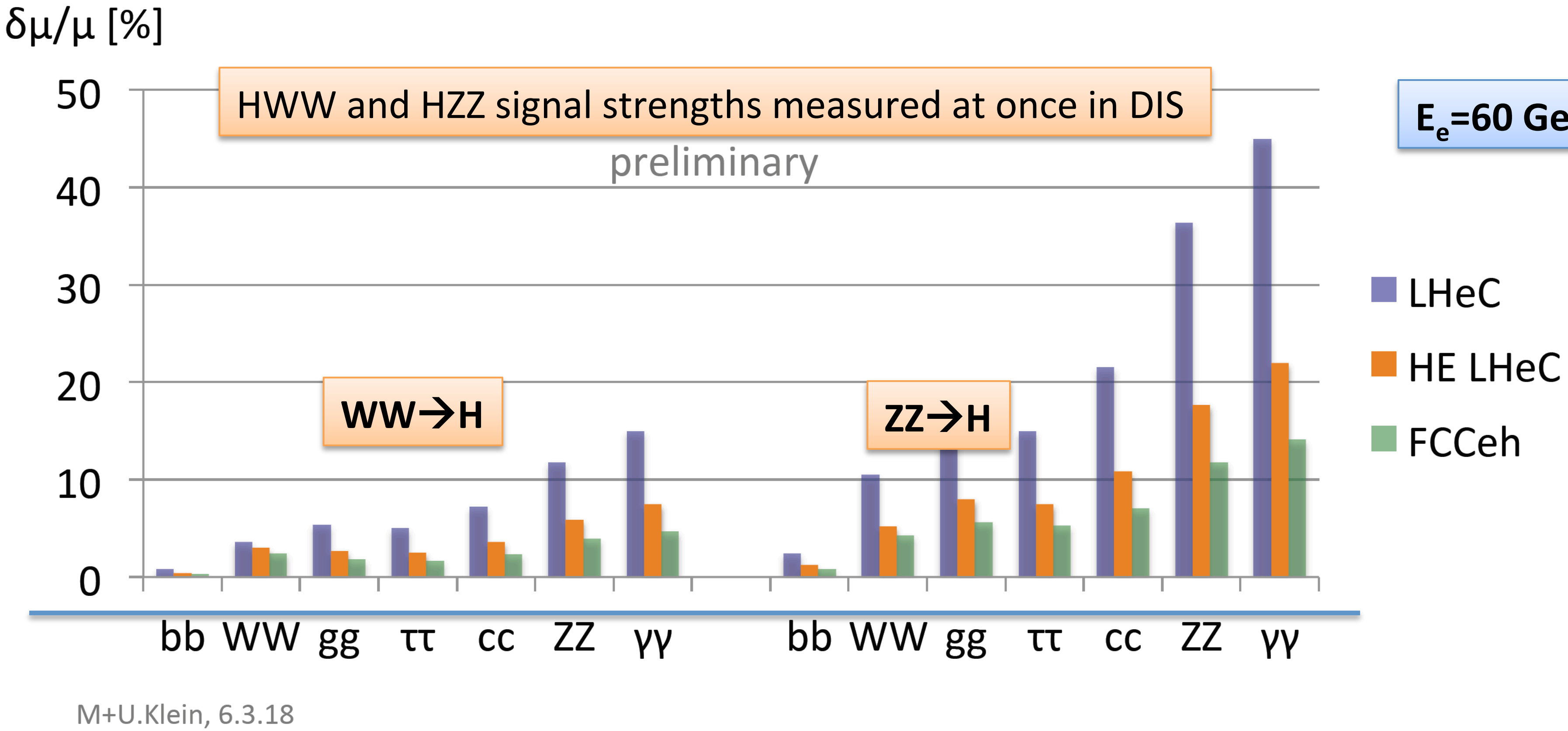
$$\sigma(WW \to H \to gg) \quad \propto \kappa^2(HWW) \bullet \kappa^2(Hgg)$$

$$\sigma(WW \to H \to cc) \quad \propto \kappa^2(HWW) \bullet \kappa^2(Hcc)$$

$$\sigma(WW \to H \to ZZ) \quad \propto \kappa^2(HWW) \bullet \kappa^2(HZZ)$$

$$Note: \sigma(ZZ \to H \to WW) \quad \propto \kappa^2(HZZ) \bullet \kappa^2(HWW)$$

Signal Strengths @ LHeC - HE-LHeC - FCCeh



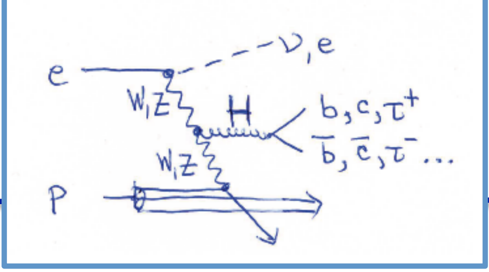
E_e=60 GeV

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

Note: HWW and HZZ requires different e+e- machine settings / c.m.s. energies for high precision
→NC and CC DIS together over-constrain Higgs couplings in a combined 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}

Higgs Couplings



M_H=125 GeV
Γ_H=4.088 MeV

	bb	WW	gg	ττ	cc	ZZ	γγ
BR 2016 (BR2014)	**0.5824 (0.577)**	**0.2137 (0.215)**	**0.08187 (0.086)**	**0.06272 (0.0632)**	**0.02891 (0.0291)**	**0.02619 (0.0264)**	**0.00227 (0.00228)**

CC DIS: ***WW→H → i i*** (decay into FS i as listed in the table)

$$\sigma_{WW\to H\to ii} = \sigma_{WW\to H}\cdot br_i \propto \sigma_H^{SM}\cdot br_i^{SM}\cdot \kappa_W^2\cdot\kappa_i^2\cdot\frac{\Gamma^{SM}}{\sum_j \kappa_j^2\Gamma_j}$$

NC DIS: ***ZZ→H → i i*** (decay into FS i as listed in the table)

$$\sigma_{ZZ\to H\to ii} = \sigma_{ZZ\to H}\cdot br_i \propto \sigma_H^{SM}\cdot br_i^{SM}\cdot \kappa_Z^2\cdot\kappa_i^2\cdot\frac{\Gamma^{SM}}{\sum_j \kappa_j^2\Gamma_j}$$

$$\sum_i \kappa_i^2 br_i = \frac{\Gamma_{H,md}}{\Gamma_H^{SM}}$$ =1 ?

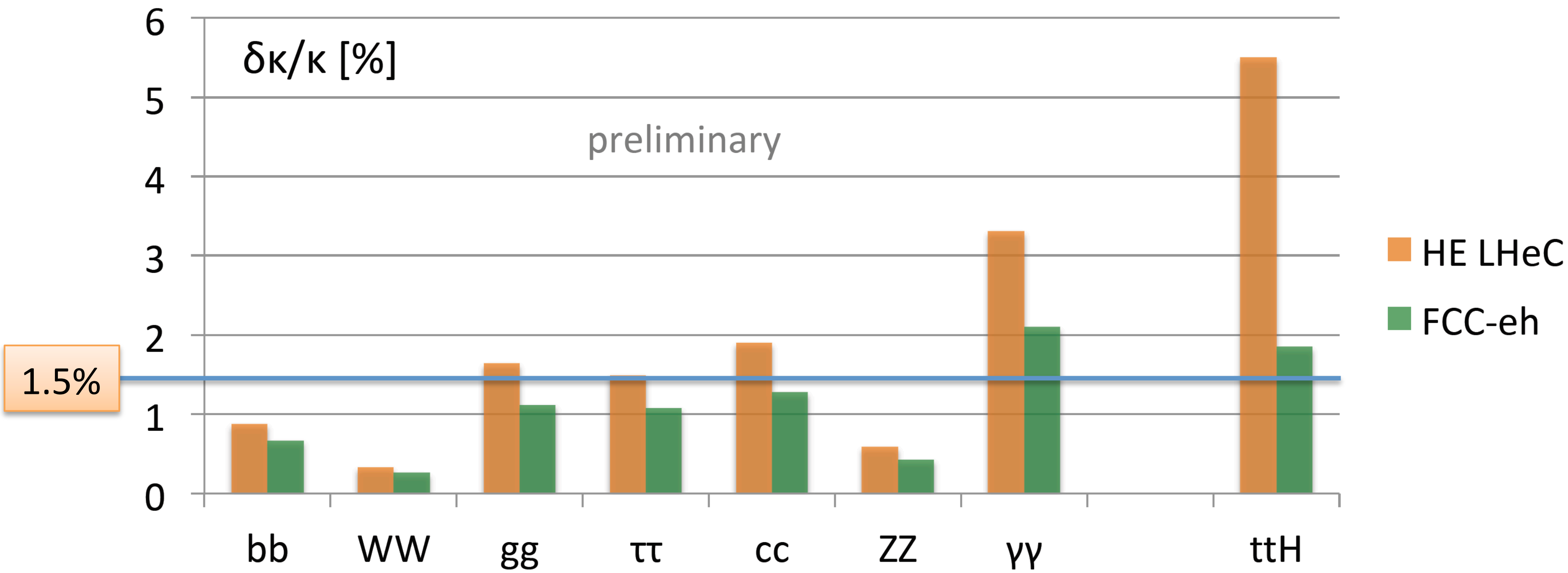
➔ allows a model-dependent fit of coupling uncertainties, see next slide

→ assuming SM or combination with ee absolute Higgs cross section would enable to measure sum of the 7 branching fractions to

LHeC : 0.99 +- 0.02 **FCC-he : 0.998 +- 0.010**

Model-dependent Coupling Fit

→ 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

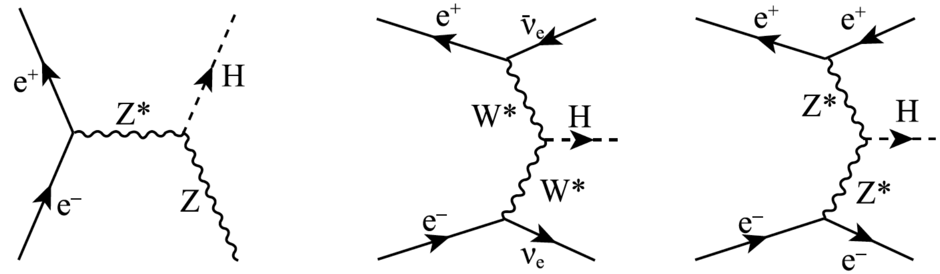
arXiv:1702.03426
Coleppa, Kumar^2, Mellado

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 at this workshop for further fits and ep+ee combinations.

Higgs in ee vs ep

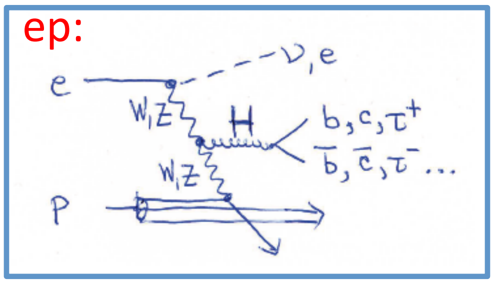
ee: Dominant Higgs productions

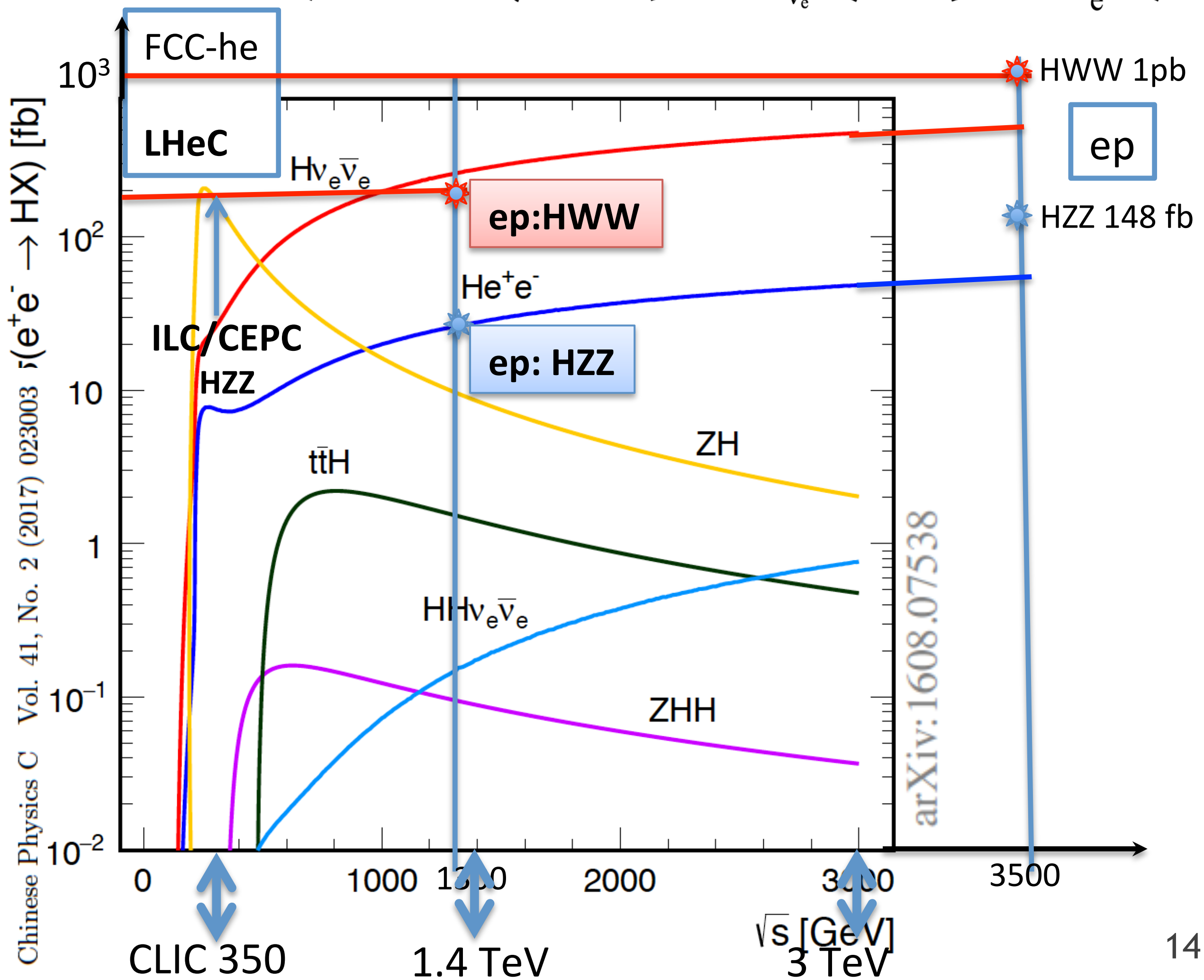


pe vs e+e- Higgs cross sections

ep:CC DIS WW Fusion

ep: NC DIS ZZ Fusion

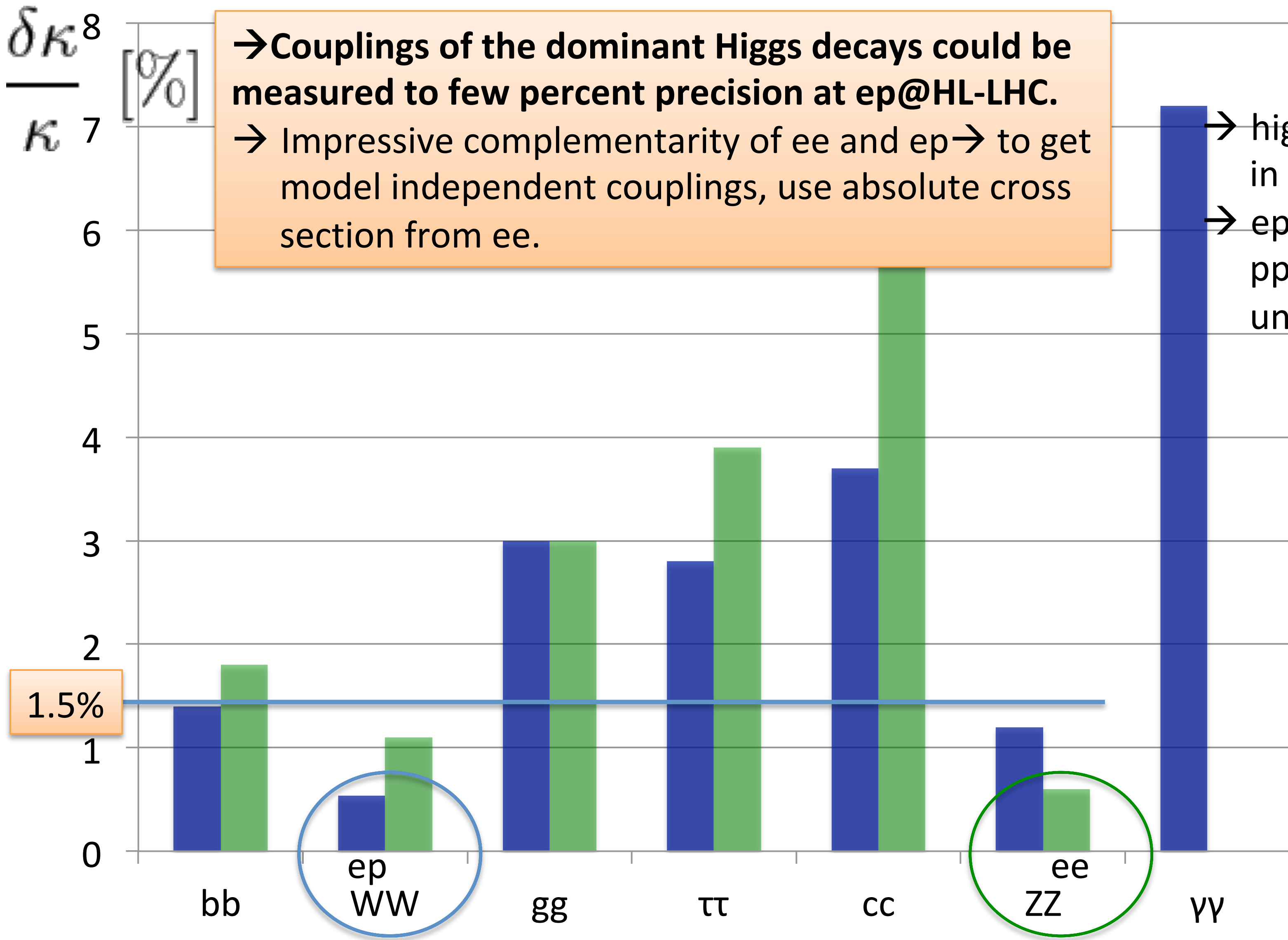




Model-dependent Coupling Fit @ LHeC

→**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 cross section from ee.



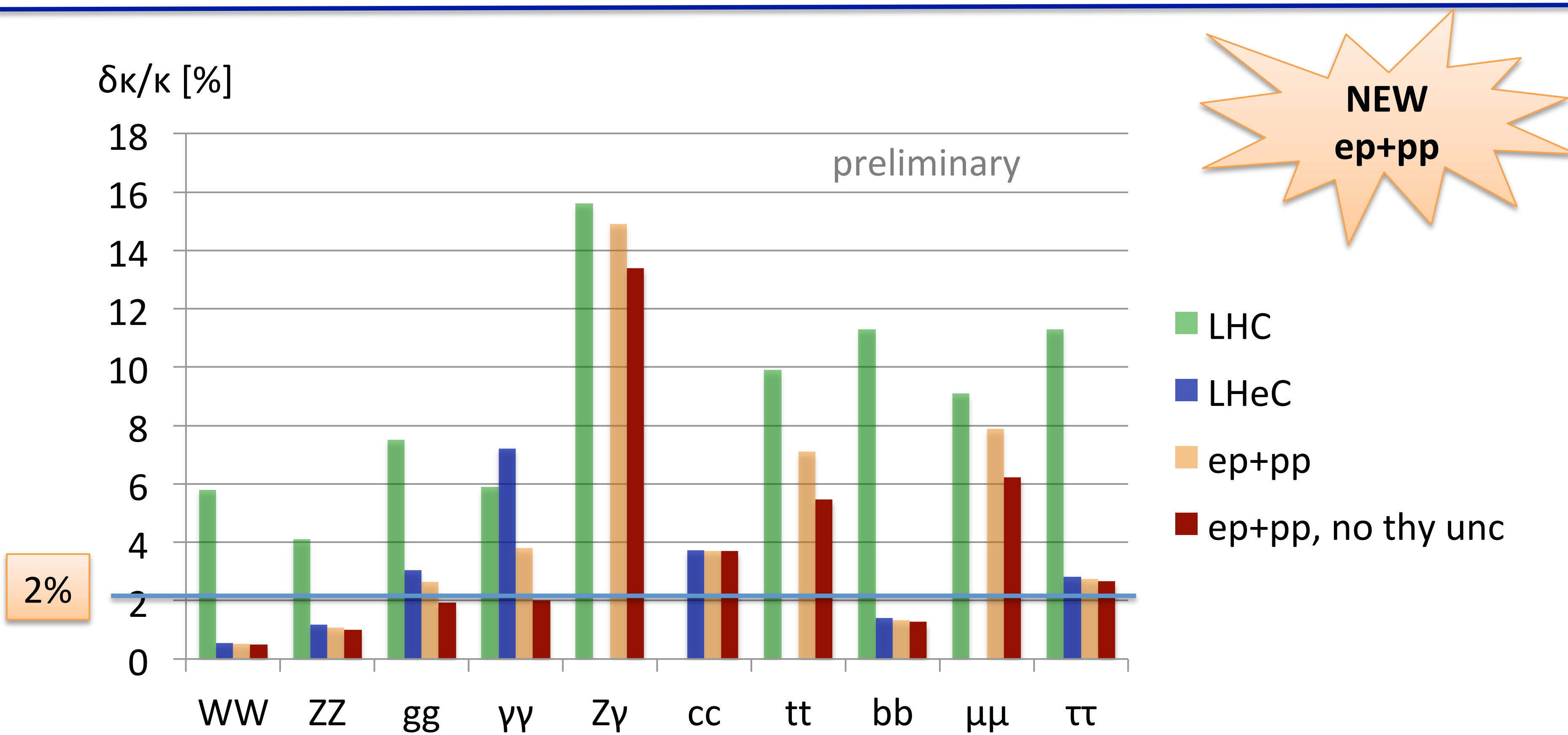
→ high impact for γγ in pp expected!

→ ep will also reduce pp Higgs uncertainties!

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

→ **For 2030-2040: Excellent prospects of combining further Higgs from pp@HL-LHC and LHeC [ep@HL-LHC].**

LHeC and HL-LHC Higgs Prospects



J. De Blas, M.+U. Klein, 16.4.2018

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

HL-LHC prospects using ATLAS 2014 projections (3ab^{-1}) w and w/o theoretical uncertainties (‘no thy unc’) in a SM coupling fit → to be updated with HL-LHC yellow report in preparation

Higgs precision observables at FCC ee and eh

Talk by J deBlas @ FCC Week

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

NEW

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%
$\kappa_{Z\gamma}$	–

Summary by J deBlas

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

Higgs→ invisible: 1.2%
ttH: 1.85%

- **All three FCC options complement each other very well:**
  - **FCC-ee allows not only very precise measurements of the Higgs and EWPO but also provides the normalization for more precise measurements at the FCC-eh and FCC-hh**
  - **FCC-eh complements FCC-ee providing information about light quark EW couplings. Similar precision in the Higgs sector**
  - **FCC-hh fills gaps in precision Higgs measurements for rare decays, top and the Higgs self-coupling**

NEW
ee+ep+pp

Talk by J deBlas@FCC Week

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%

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

FCC Week 2018
Amsterdam, April 11, 2018

Jorge de Blas
INFN - University

➔ Combine the complementary measurements fo rbest physics outcome!

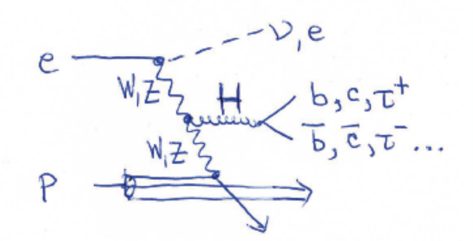
… and Consistency Checks of EW Theory

→ 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 $\cos^2\Theta$ given here are the PDG value as central value **0.777** and uncertainty from ep Higgs measurement prospects

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

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

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

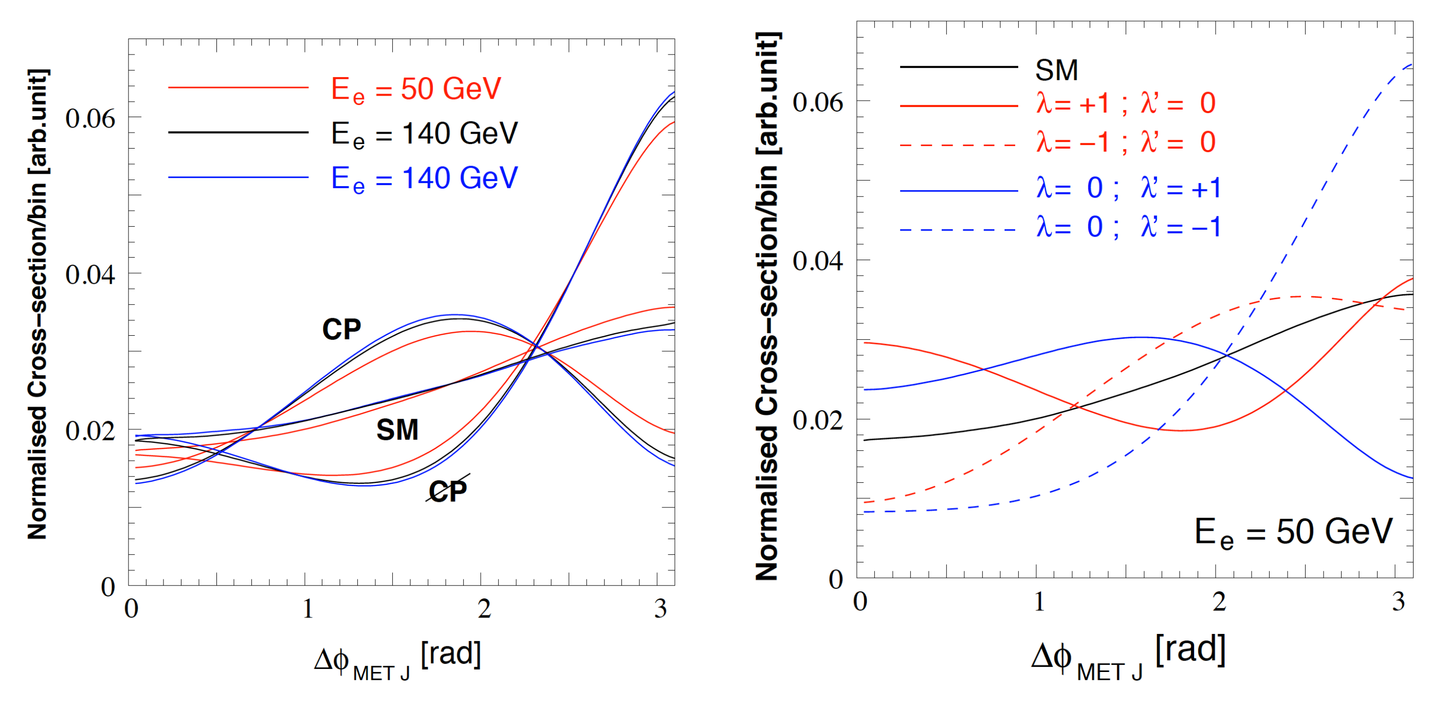
Measure CP Properties of Higgs

[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

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

- 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

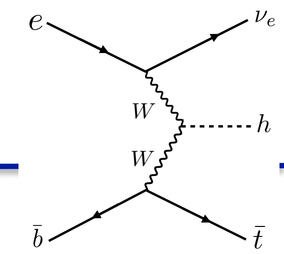
λ′~0.2

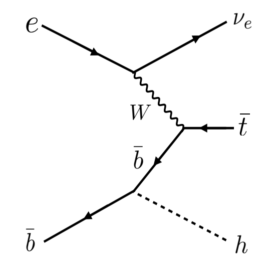
based on 50 fb^{-1}

→ Todo: full detector, 125 GeV Higgs study

Top Yukawa Coupling @ LHeC

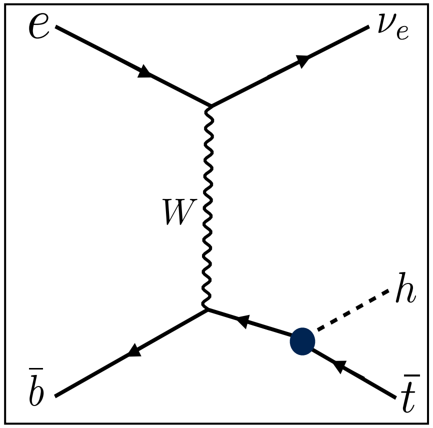
B.Coleppa, M.Kumar, S.Kumar, B.Mellado, Phys. Lett. B770 (2017) 335



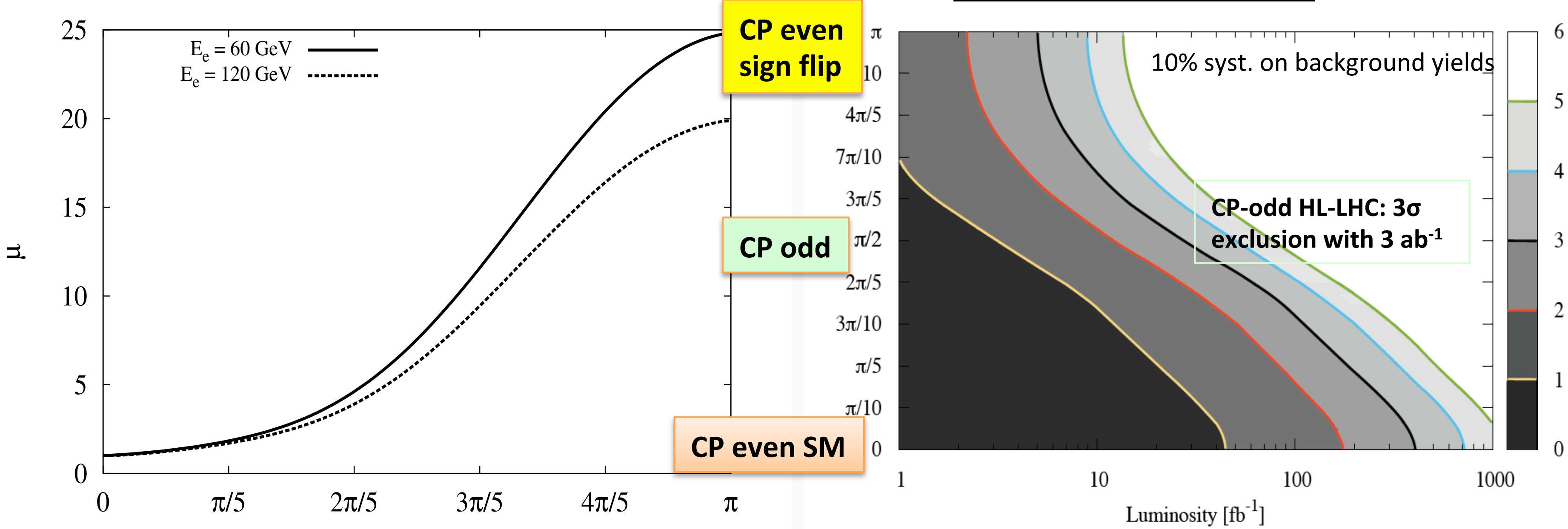


Introduce phase dependent top Yukawa coupling

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



Enhancement of the DIS cross-section as a function of phase



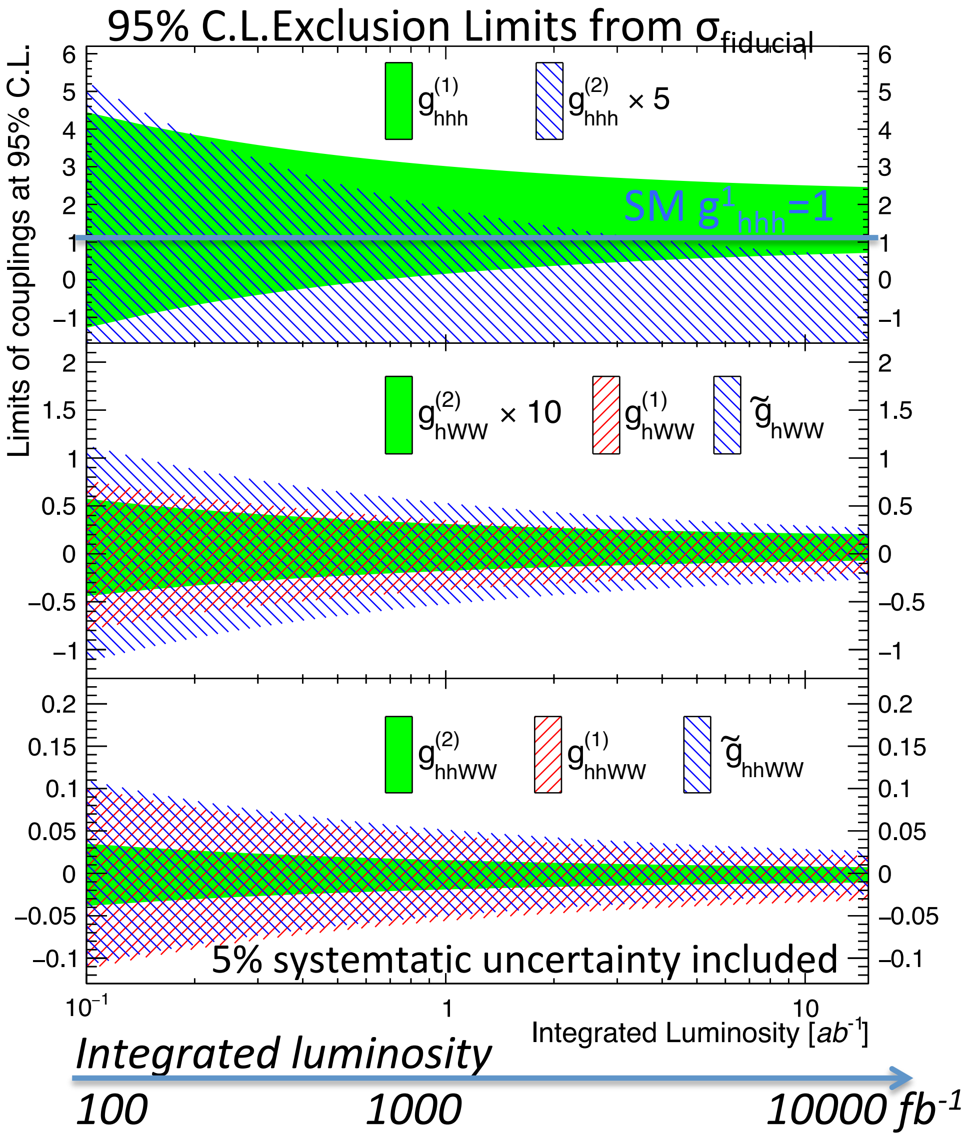
Observe/Exclude non-zero phase to better than 4σ ➔ With Zero Phase: Measure **ttH** coupling with **17% accuracy at LHeC** ➔ **extrapolation to FCCeh: ttH to 1.85%**

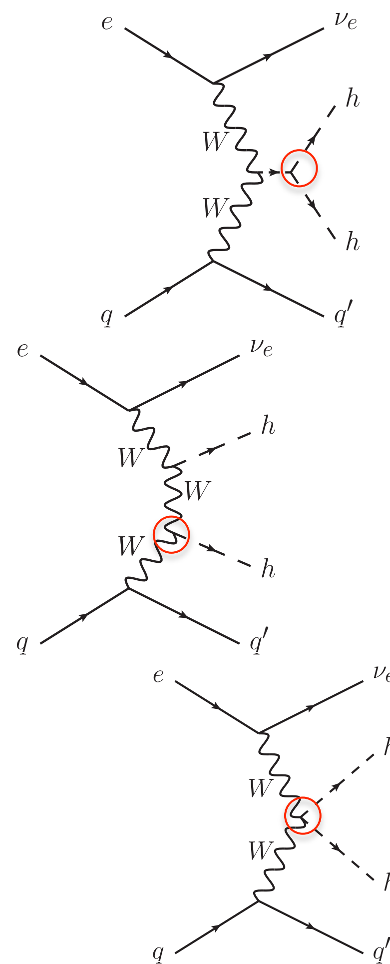
Double Higgs Production

FCC-he study

[1509.04016]

FCCe 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!

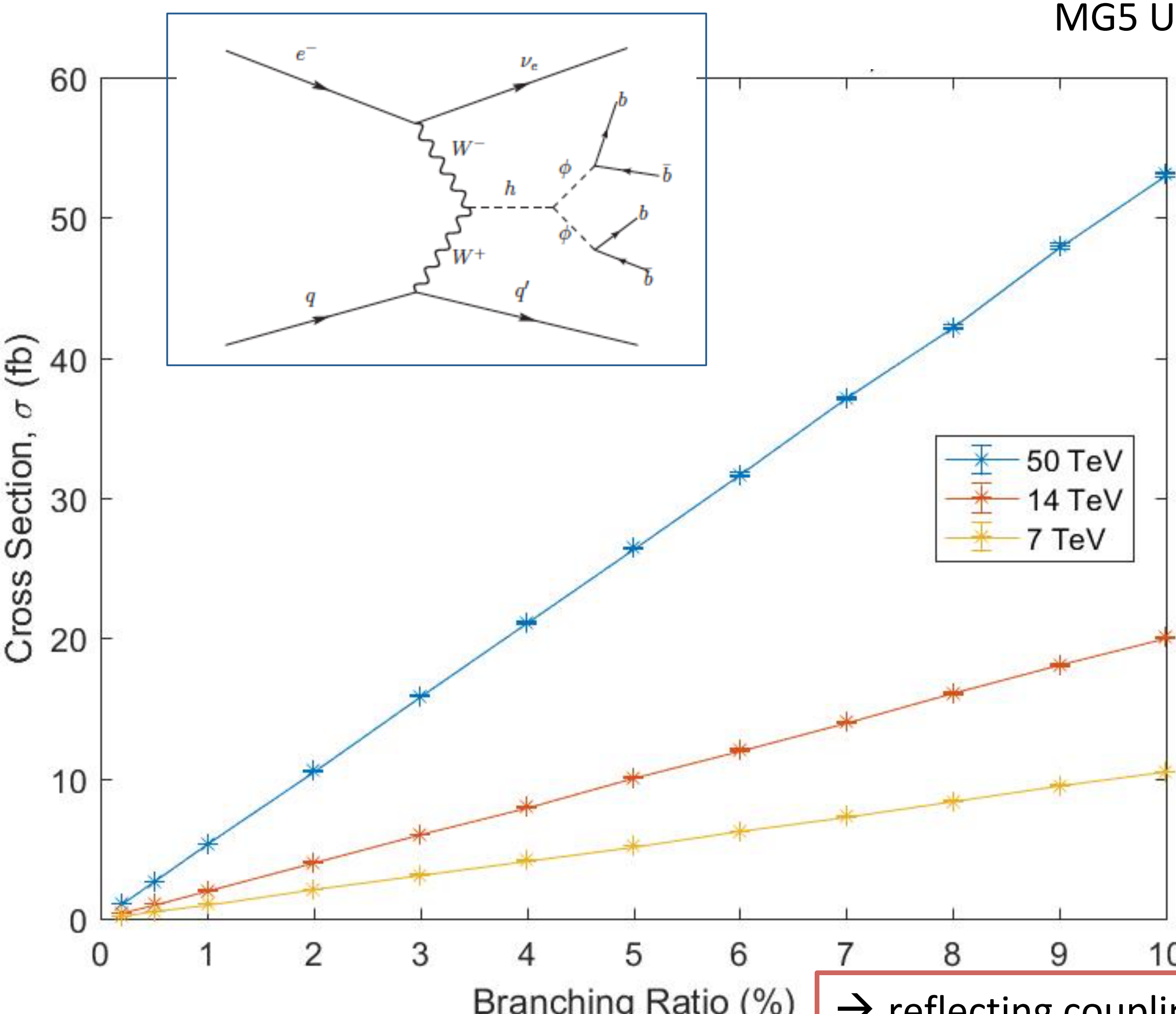
CLIC-1.4TeV: δg_{HHH} ~40-50%

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.

Exotic Higgs@FCC-he

Uta Klein
Michael o'Keefe
Liverpool

MG5 UFO [arXiv:1608.08458]



FCC-he @ 3.5TeV

DLHeC @ 1.8 TeV

LHeC @ 1.3 TeV

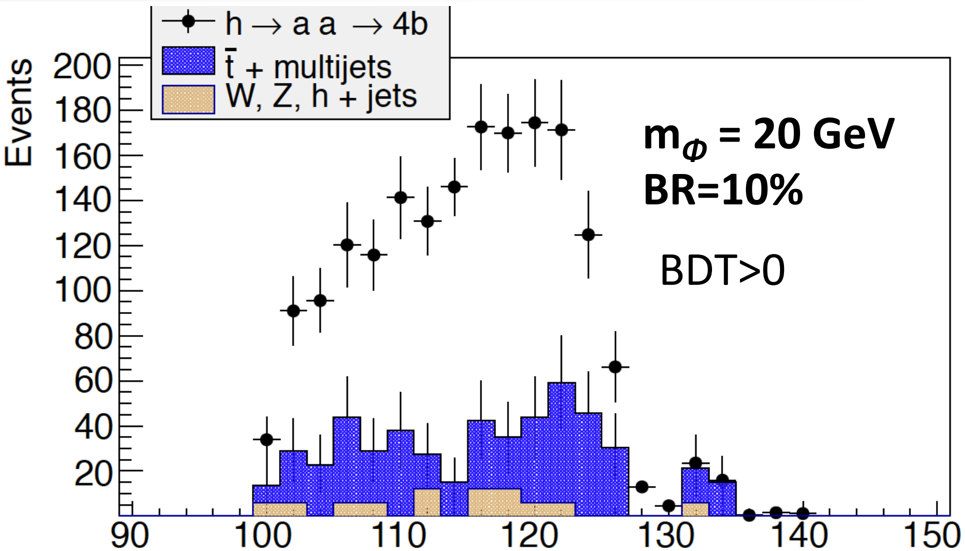
Values for P_e=0

→ reflecting coupling of new scalar to 125 GeV higgs

First Results @ FCC-he

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

Uta Klein
Michael o'Keefe
Liverpool



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

Further BSM Higgs Studies

Example: Charged Higgs

- $H\pm$, in Vector Boson Scattering

  [Georges Azuelos, Hao Sun, and Kechen Wang, 1712.07505]

- $H\pm\pm$, in Vector Boson Scattering

  [H. Sun, X. Luo, W. Wei and T. Liu, Phys. Rev. D 96, 095003 (2017)]

- $H+$, in 2HDM type III, $p\ e \rightarrow \nu j H \rightarrow \nu j\ cb$

  [J. Hernández-Sánchez et al., 1612.06316]

(see also talk by K. Wang at 2nd FCC Physics Week, Jan 2018)

…to take home: ep+pp >~ 2030

- LHeC (FCC-he) could measure the dominant Higgs couplings including ttH to 0.6-4% (0.2-2%) precision [CC+NC, no pile-up, clean final state..]
- ep (>~1 TeV) complement with HWW the ee (250-350 GeV) HZZ coupling measurements: HIGH luminosity is KEY!
- eh has a strong Higgs program, that turns the LHC (FCC-pp) machine (ep+pp) into very powerful Higgs facilities, including a strong Higgs BSM ep potential (H→ invisible, HH, CP nature,…)
- ep would empower the physics potential of pp (searches, Higgs..) through high precision QCD measurements: flavour separated PDFs at N^3LO, α_S to per mille …

Already with the first ~100 fb^{-1} ep data (first few years)

→ use ep as the 'near' detector for pp to beat the α_s and PDF uncertainties for Higgs@HL-LHC from ~3% to <~0.5%,
→ δm_b to 10 MeV;
δm_{charm} to 3 MeV

Additional Sources & Thanks to

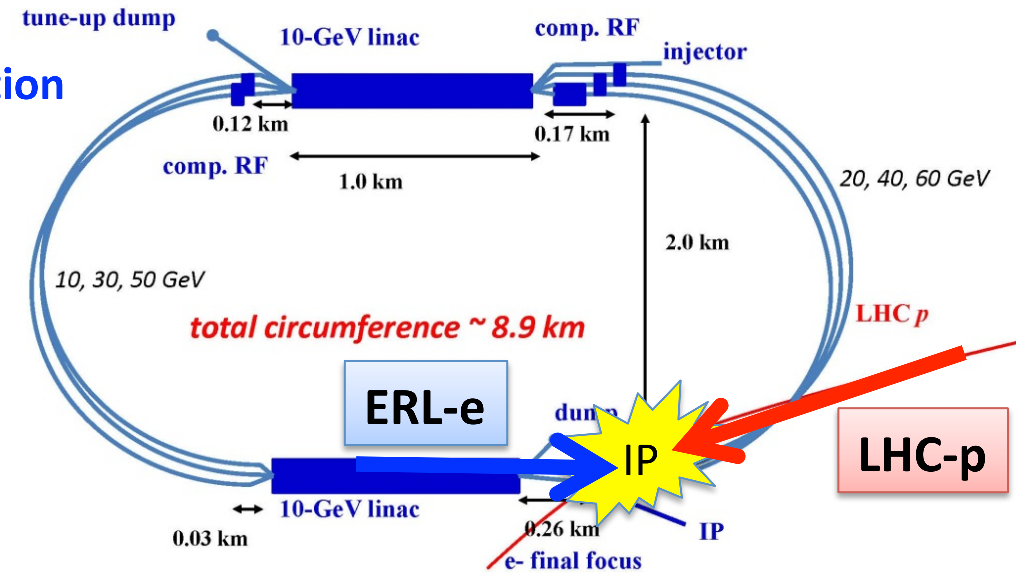
- Much more material can be found here: LHeC and FCC-eh Workshop, September 2017, CERN https://indico.cern.ch/event/639067/
- **The LHeC/FCC-eh study group, http://cern.ch/lhec.**
- "On the Relation of the LHeC and the LHC" [arXiv:1211.5102]
- 1^{st} FCC Physics Workshop, 16.1.-20.1.2017, CERN https://indico.cern.ch/event/550509/
- Before April 2018: Higgs branching fractions and uncertainties taken from https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR2014
- Update used from April 2018 https://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.

Additional material

electrons for pp : ERL + LHC

- Two Electron LINACs + 3 return arcs: using energy recovery in same structure: 'green' technology with power consumption < 100 MW : nominal $\underline{E_e = 60\ \text{GeV}}$
- Beam dump: no radioactive waste!
- high electron polarisation of 80-90%
- Installation decoupled from LHC operation



Concurrent ep and HL-LHC operation!
Same idea holds for HE-LHC and FCC-hh

- ep Lumi 10^{34} cm s^{-2} s^{-1} **
- 100 fb^{-1} per year, e.g. ~2030-2040 (HL-LHC)
- L= 1000 fb^{-1} total collected in 10 years
- eA luminosity estimates ~ 10^{33} cm s^{-2} s^{-1} eA

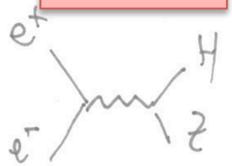
** based on existing HL-LHC proposal

Detector Design
for HL+HE+FCC ep
Peter Kostka et al.
→ installation in 2 years,
e.g. during LS4

LHeC CDR: arXiv:1206.2913 and updates at LheC/FCC-eh WS@CERN, 9/17

Kinematics and M_H : ee vs ep

ee: ZZH



e^+e^-

ee: Z→ νν contribution!

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

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

$\curvearrowright 2E_e = E_H + E_Z$

$\vec{p}_H = -\vec{p}_Z$

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

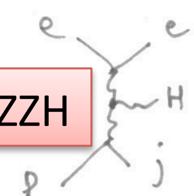
$s = M_H^2 + M_Z^2 - 2M_Z^2 + 4E_Z\cdot E_e$

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

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

ee: x=1 no PDF or form 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

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

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

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

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

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

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

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

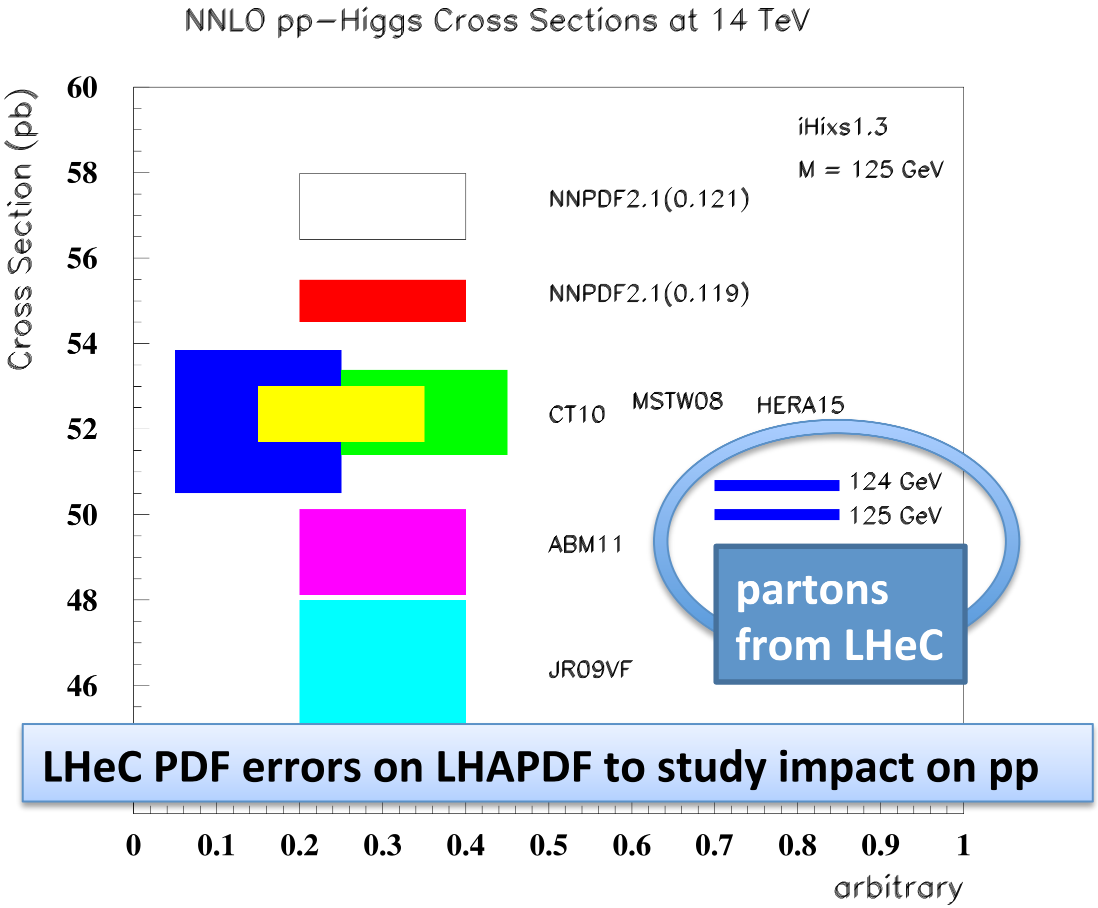
See also talk by C Gwenlan

LHeC Precision Partons for Higgs@pp

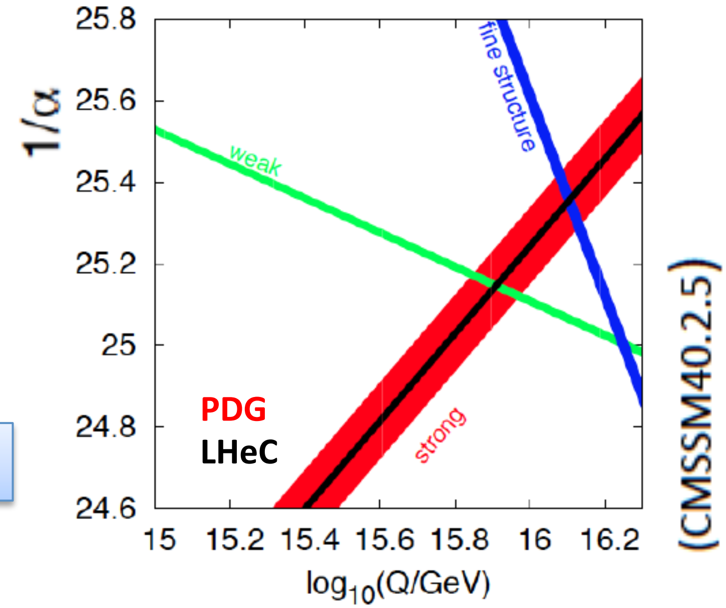
→ **Using LHeC input**: experimental uncertainty of predicted **LHC Higgs cross section due to PDFs and α_S** is strongly **reduced to <~0.5%**

→ ***theoretically clean path to determine N³LO PDFs*** using ep DIS

→ ***ALL those 'benefits' for pp within the first few years, using ~100 fb^{-1} ep data***



→ **precision from LHeC can add a very significant constraint on the Higgs mass** *and challenge Lattice QCD calculations for α_S:*



Invisible Higgs@LHeC

relating the Higgs and the 'dark' sectors

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

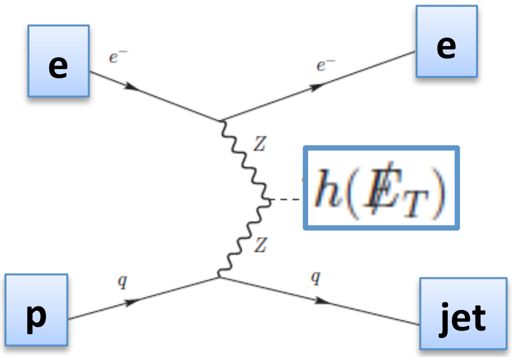
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

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

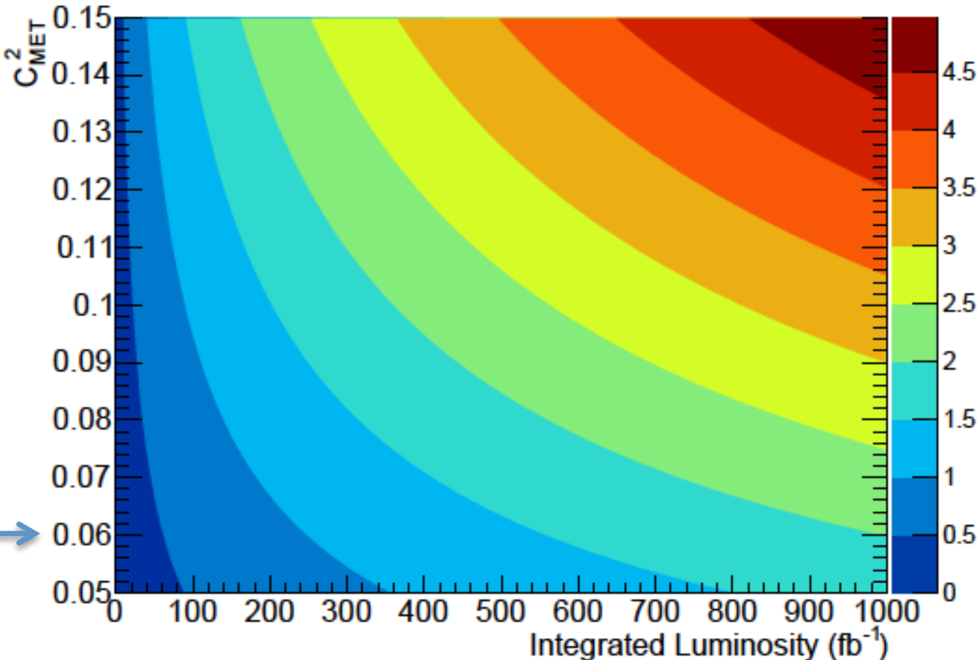
For **LHeC**, assume : 1ab^{-1}, P_e=-0.9, <u>cut based</u>

$\mathrm{Br}(h \to \not{E}_T)$ < 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

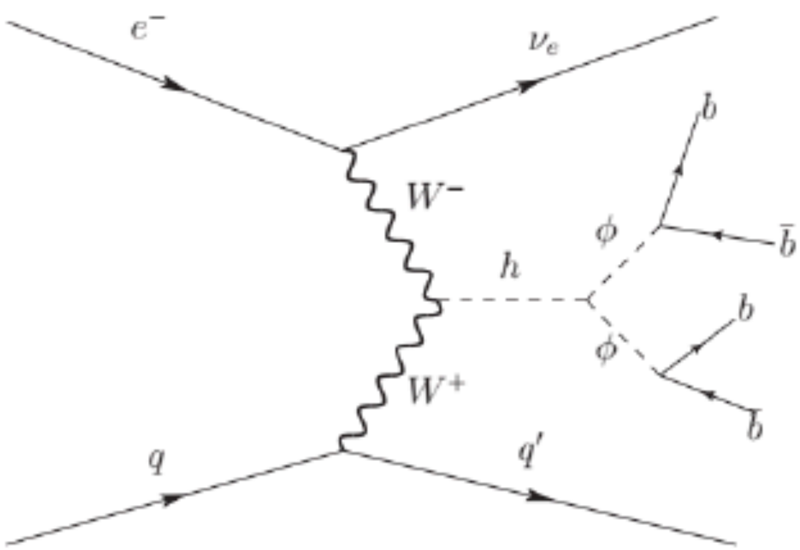
- → **potential much enhanced for FCC-eh @ 3.5 TeV and HE-LHC-eh @ 1.8 TeV**
- → **NEW studies performed on Delphes detector-level using our Madevent framework**

Exotic Higgs Decays

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

ϕ: a spin-0 particle from new physics.

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



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

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

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

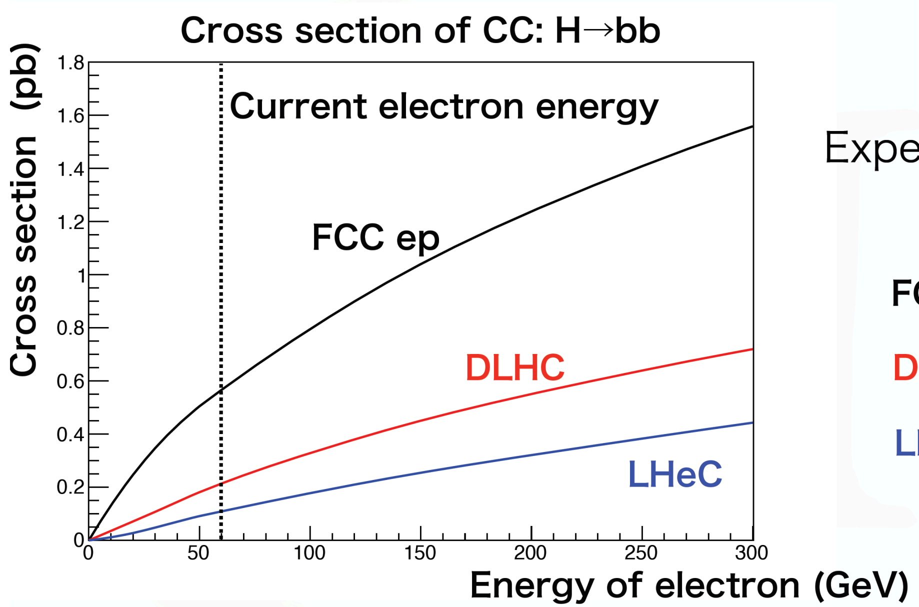
- Well motivated signature in extended Higgs sector.
- Difficult to probe at hadron colliders.
- LHeC signal: here using CC channel.
- Backgrounds: CC multijet, CC t/h/W/Z+jets, PHP multijet.
- PHP backgrounds assumed to be negligible after MET requirements and electron tagging.
- Current analysis is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

Uta Klein et al.

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%



Expected number of signal events
(E_e = 60 GeV)

FCC ep (~85,000 H→bb events)

DLHC (~35,000 H→bb events)

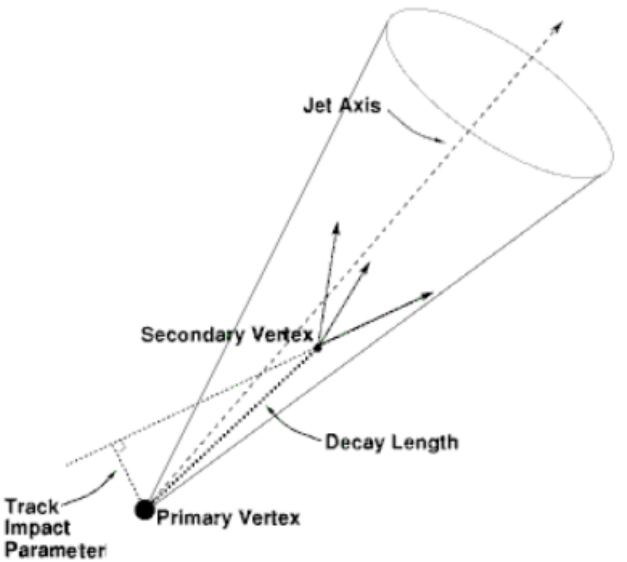
LHeC (~15,000 H→bb events)

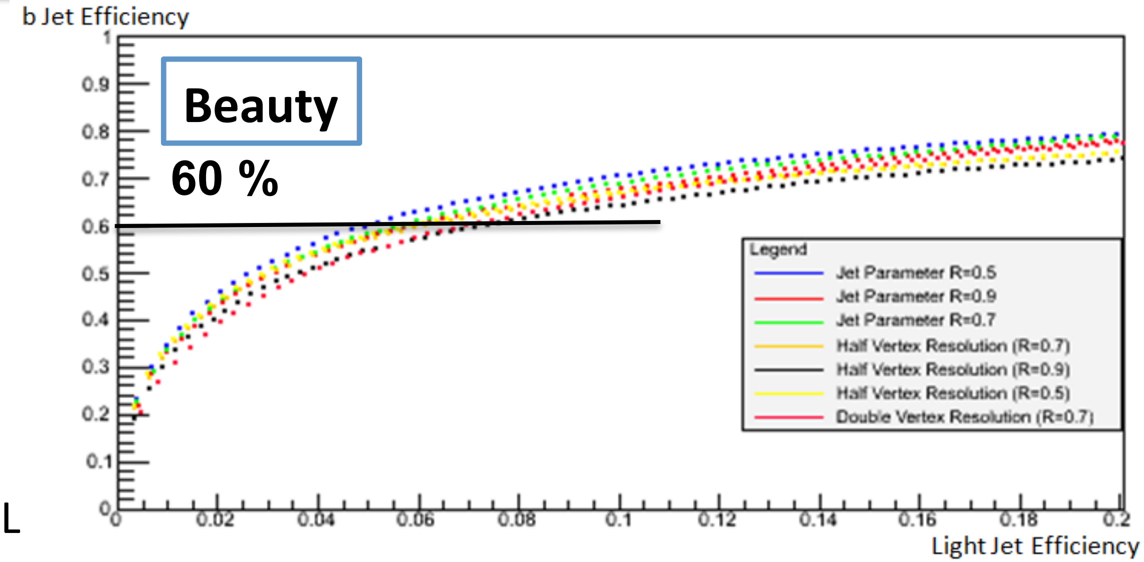
$$\delta\kappa = \frac{1}{2}\frac{\delta\mu}{\mu}$$

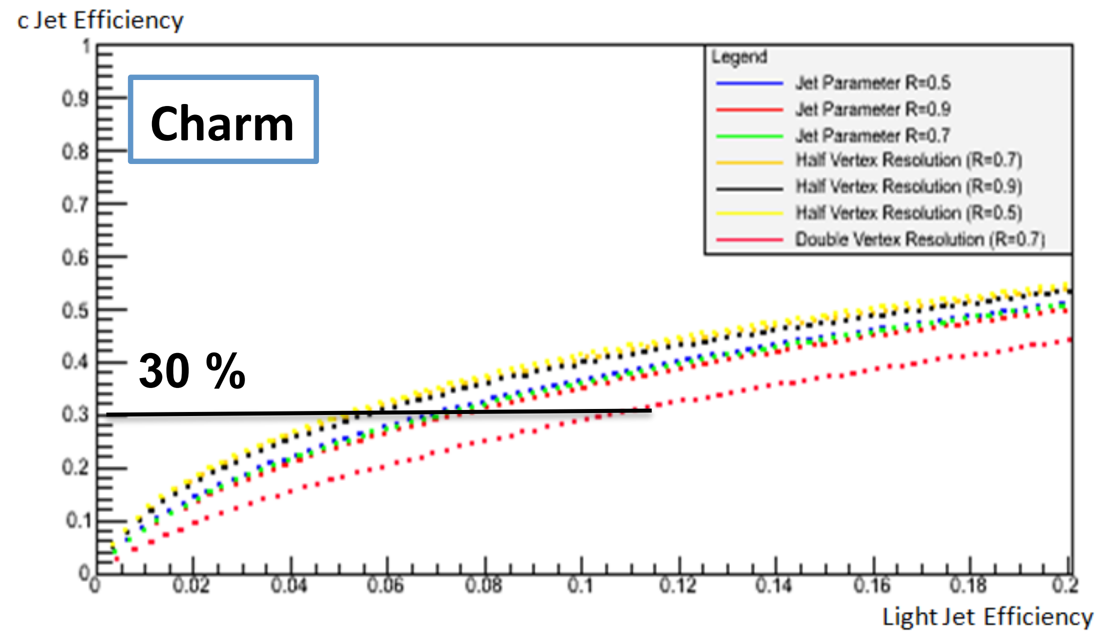
	LHeC (E_p = 7 TeV √s ~1.3 TeV)	**DLHC** (E_p = 14 TeV √s ~1.8 TeV)	**FCC ep** (E_p = 50 TeV √s ~ 3.5 TeV)
κ (Hbb)	0.5%	0.3%	0.2%
κ (Hcc)	4%	2.8%	1.8%

HFL Tagging

Uta Klein &
Daniel Hampson





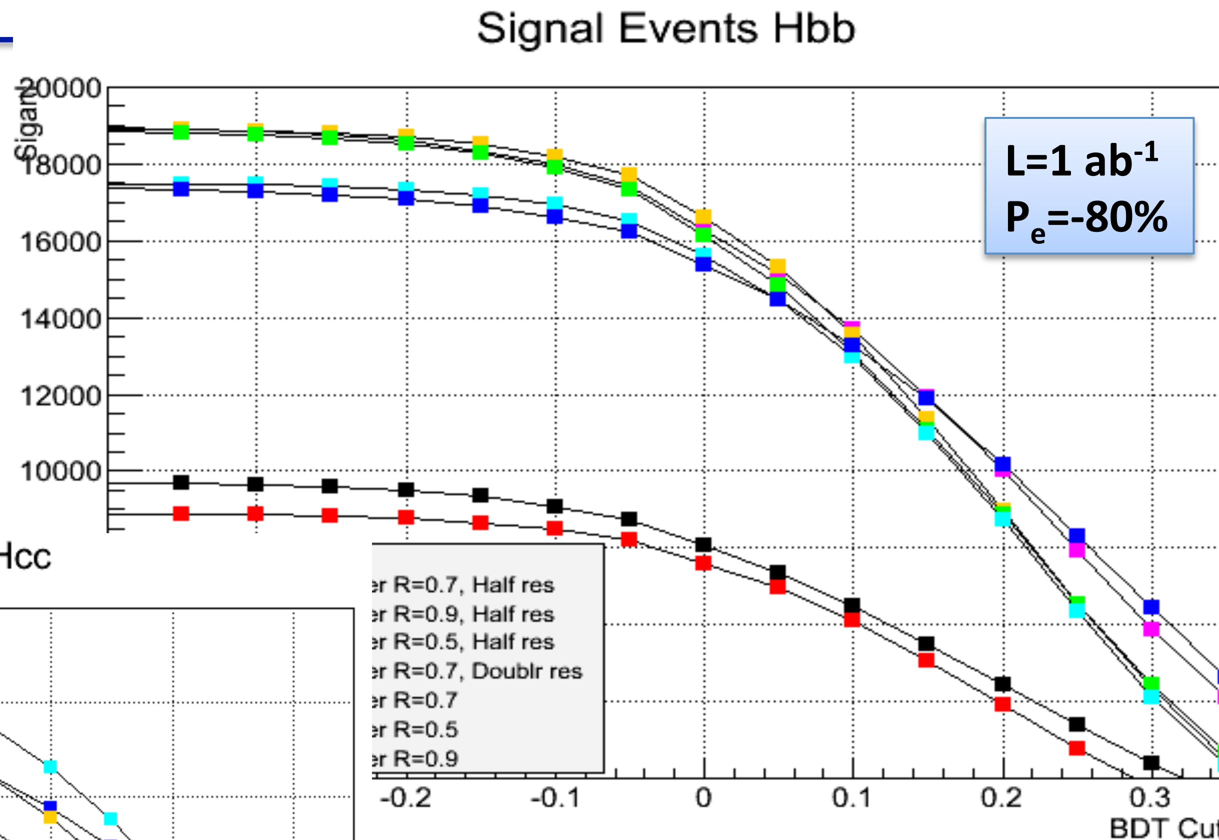


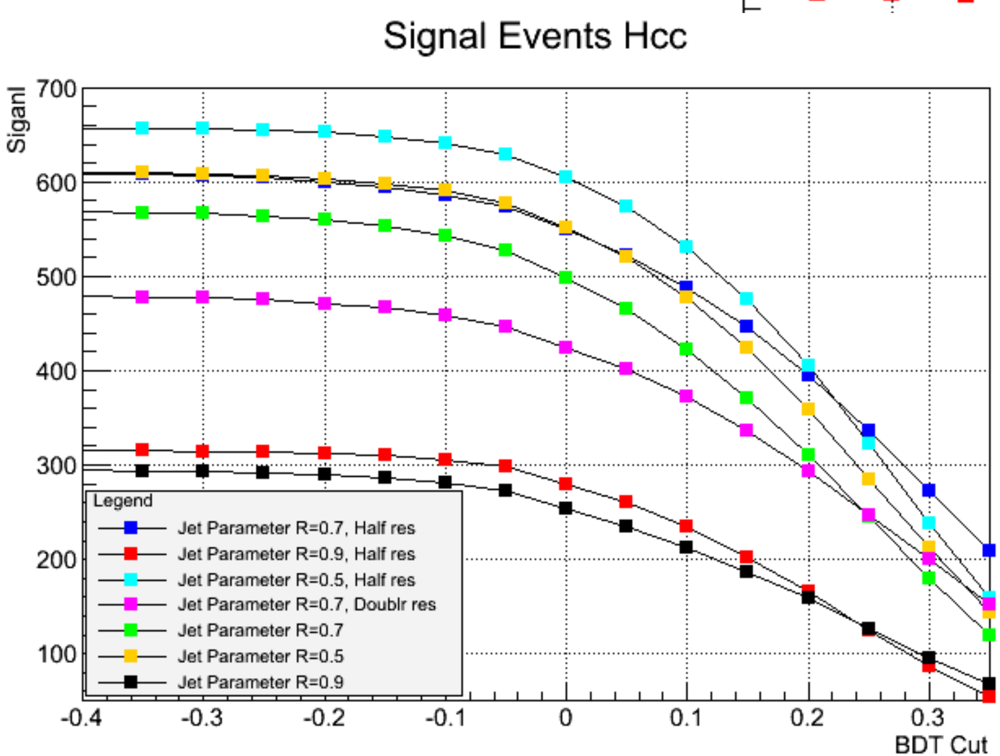
- → Realistic and conservative HFL tagging within Delphes realised, and dependence on vertex resolution (nominal 10 μm) and anti-kt jet radius studied
- → Light jet rejection very conservative, i.e. factor 10 worse than ATLAS
- → **used in full LHeC analysis and for FCC-eh extrapolations**

BDT Results for Higgs @ LHeC

Uta Klein &
Daniel Hampson

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



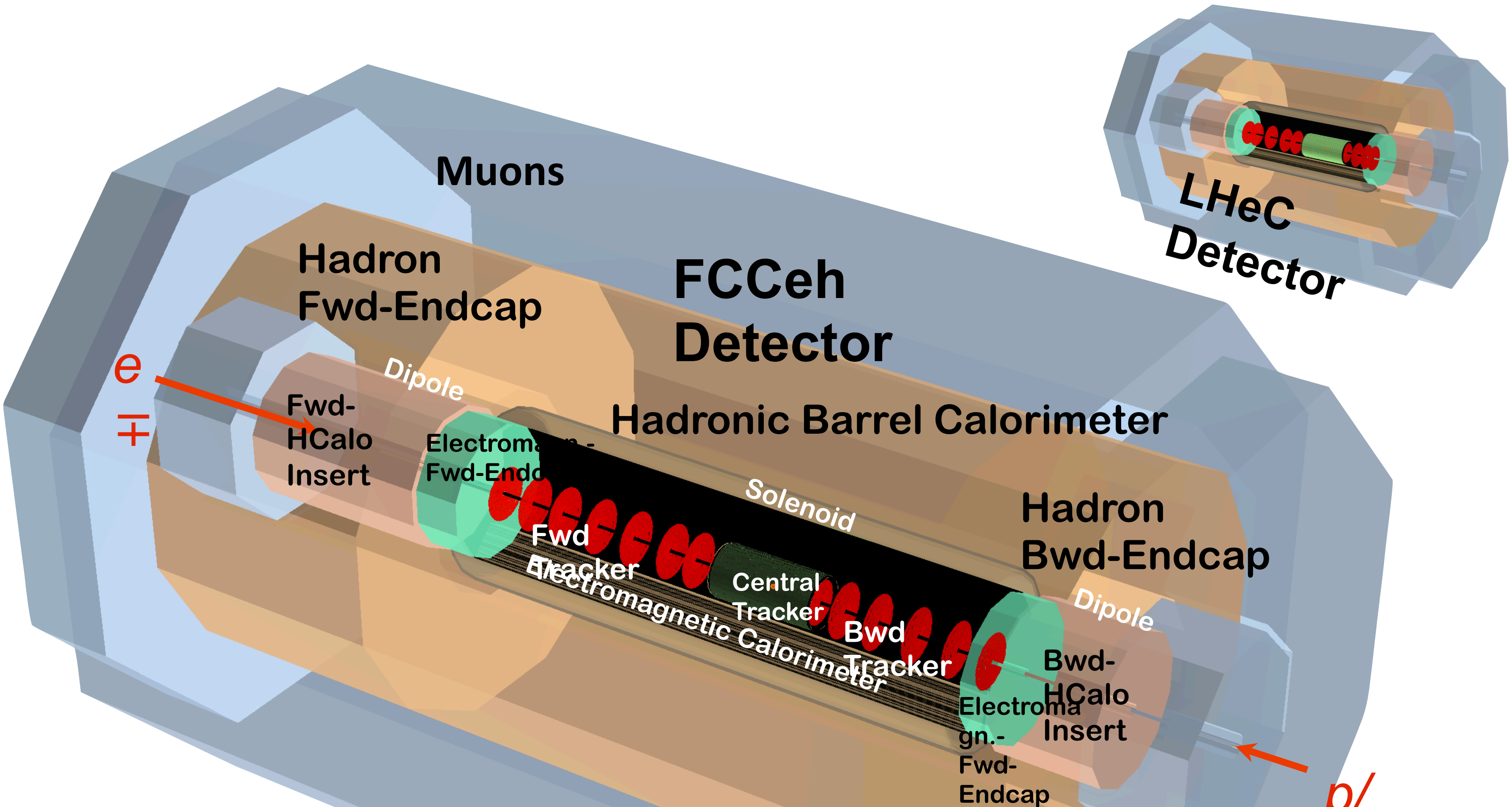


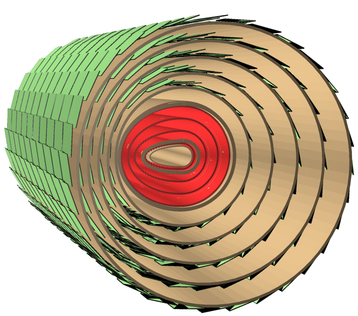
Hcc : High sensitivity to vertex resolution (nominal 10 μm) and jet radius

→ expect about 400-600 Hcc candidates

LHeC/FCC ep/eA detector

P Kostka et al.





Central Tracker
circular-elliptical beam pipe
4 layers Si-pixel
5 layers Si-strixel

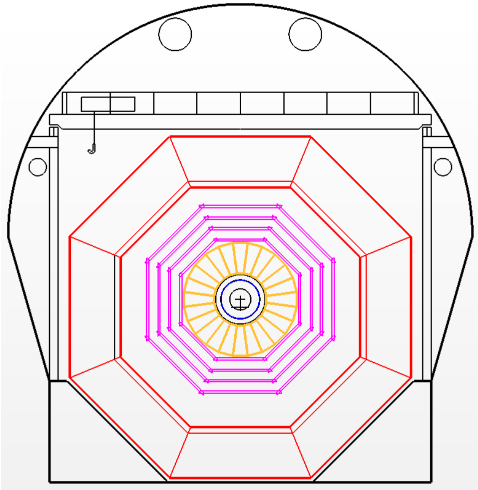
(see Table of Detector Dimensions/ Parameters in backup)

Length of Inner Solenoid ~12m

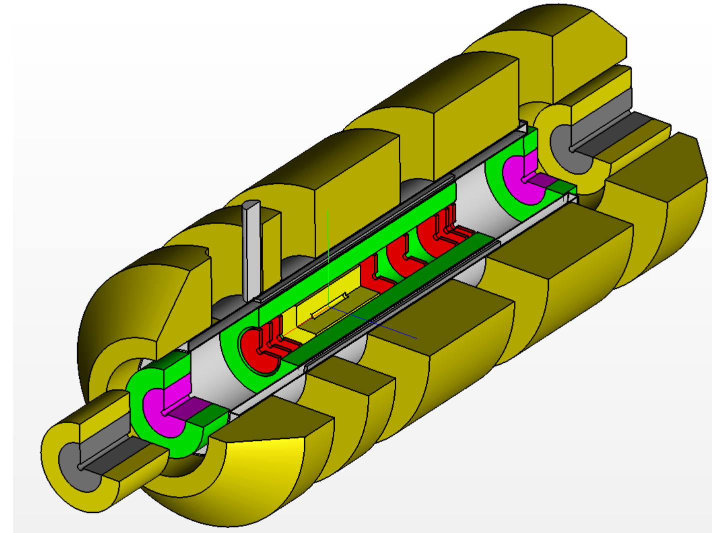
Installation Study

to fit into LHC shutdown needs directed to IP2

Andrea Gaddi et al

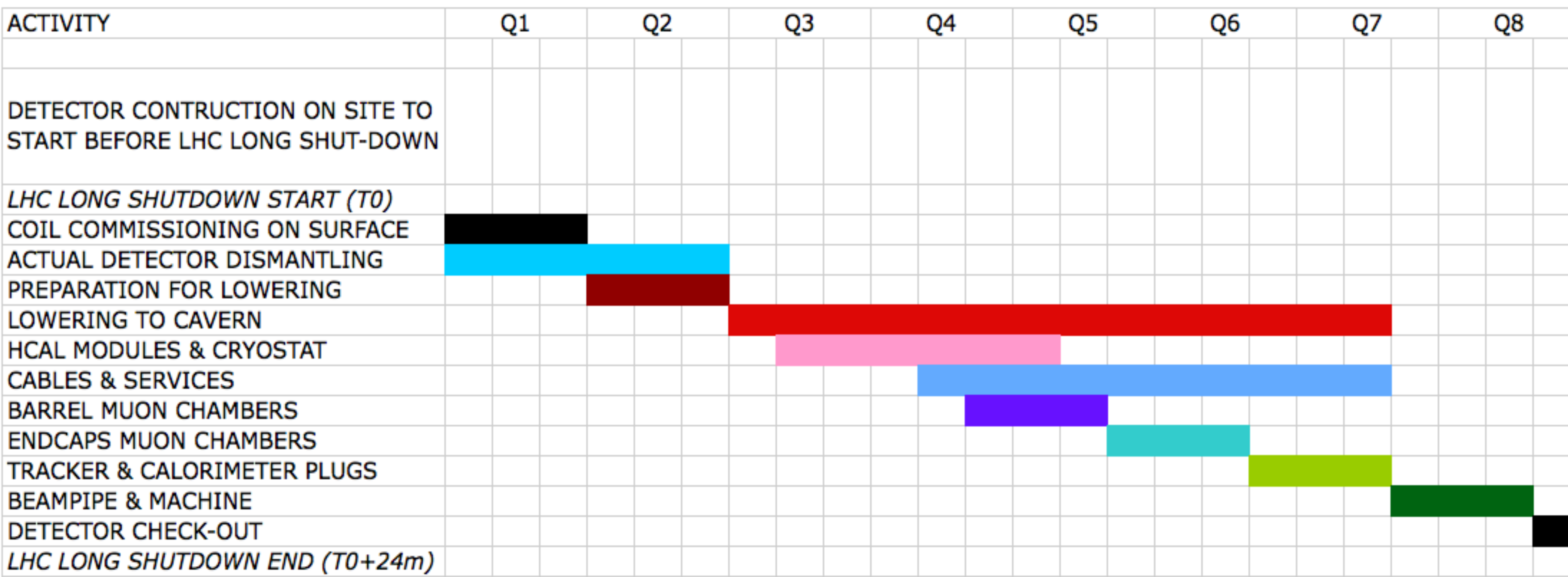


Detector fits in L3 magnet support



Modular structure

LHeC INSTALLATION SCHEDULE

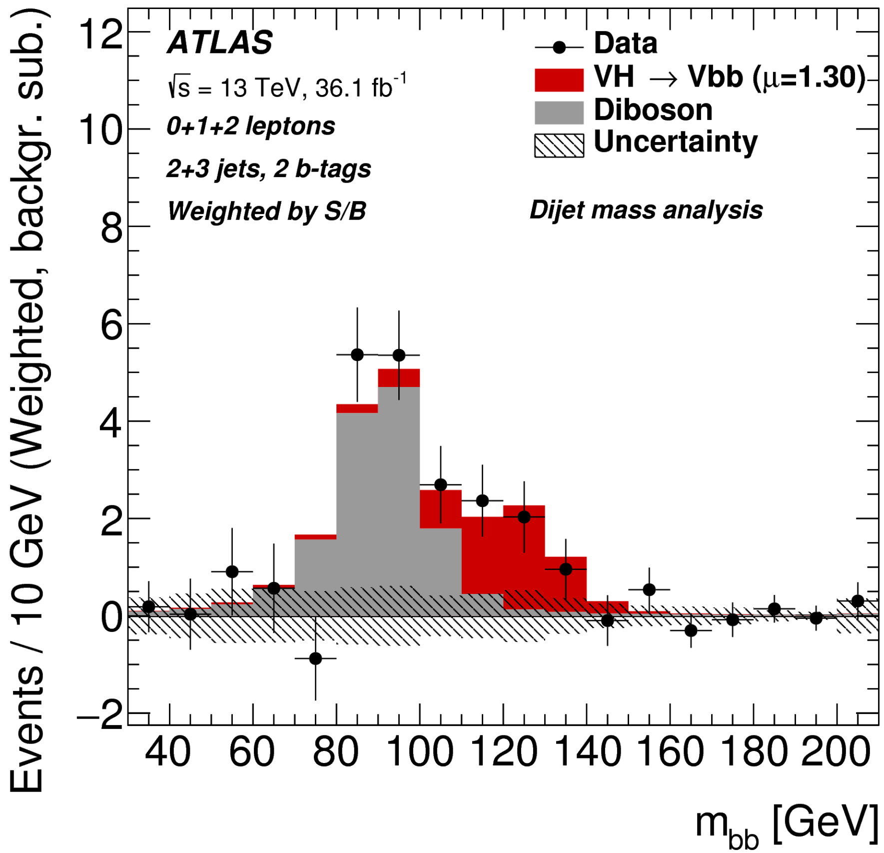


LHC: First 3σ Hbb Evidence!

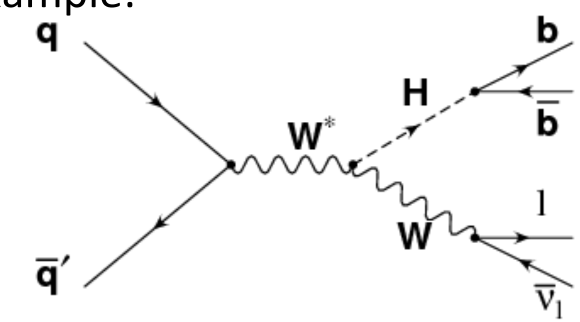
ATLAS, Aug 2017, sub. to JHEP

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)



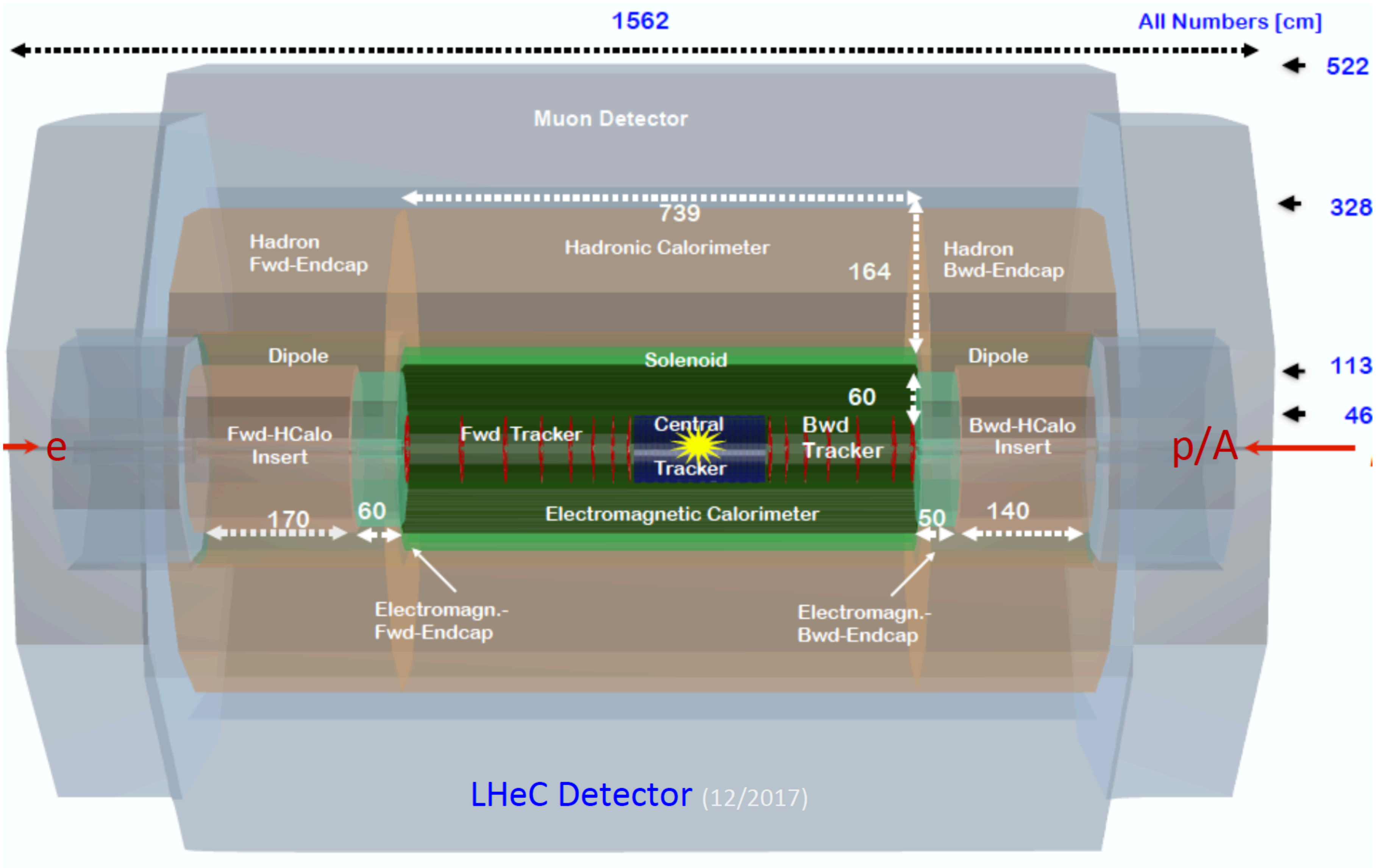
Example:



- ✓ Encouraging result for HL-LHC prospects
- ✓ **Very 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**

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

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]

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}^{(3)}_{hhh} + \mathcal{L}^{(3)}_{hWW} + \mathcal{L}^{(4)}_{hhWW}\,.$$

FCC-eh
SM(P=-0.8)
σ(HH)=430 ab
in VBF!

SM

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

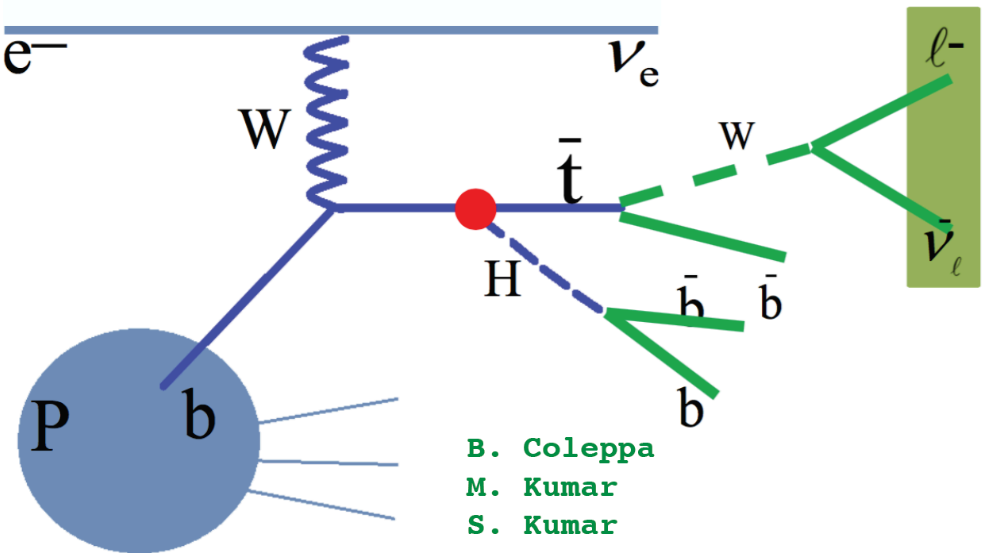
$$\mathcal{L}^{(3)}_{hWW} = -g\Big[\frac{g^{(1)}_{hWW}}{2m_W} W^{\mu\nu}W^{\dagger}_{\mu\nu}h + \frac{g^{(2)}_{hWW}}{m_W}(W^{\nu}\partial^{\mu}W^{\dagger}_{\mu\nu}h + \mathrm{h.c}) + \frac{\tilde{g}_{hWW}}{2m_W} W^{\mu\nu}\widetilde{W}^{\dagger}_{\mu\nu}h\Big], \tag{3}$$

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

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

→ see talk by Mukesh Kumar

CP Nature of Top-Higgs Coupling

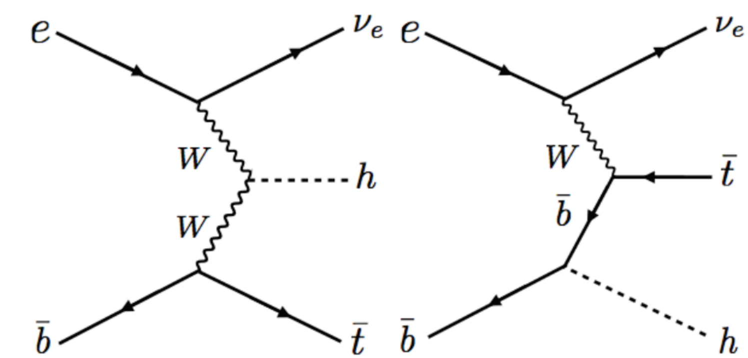


B. Coleppa
M. Kumar
S. Kumar
B. Mellado

parton level

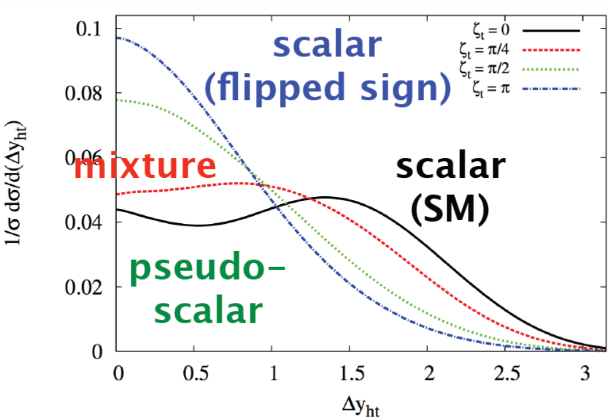
Phys. Lett. B770 (2017) 335

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

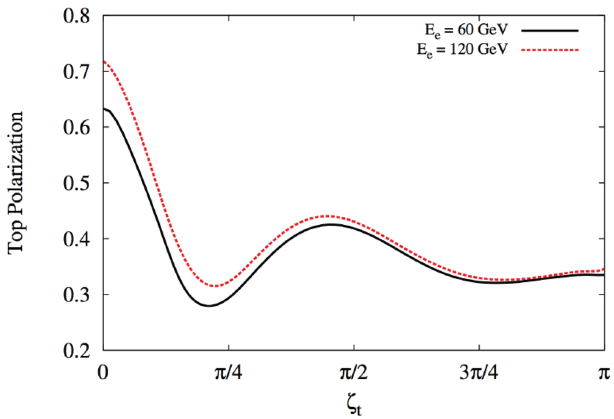


LHeC

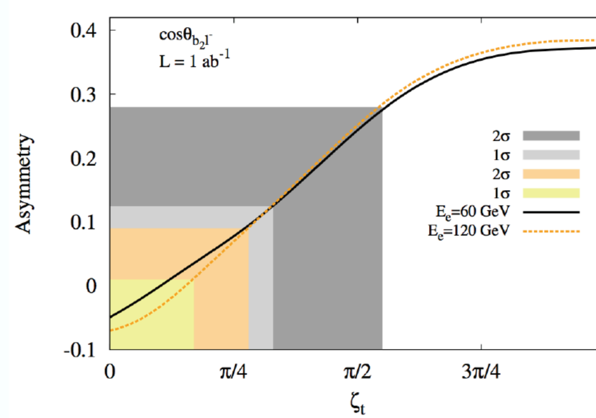
rapidity difference (H,$\bar{t}$)



top polarisation



angular asymmetries (b_2,l^-)



Exclusion Contours (fiducial cross section)

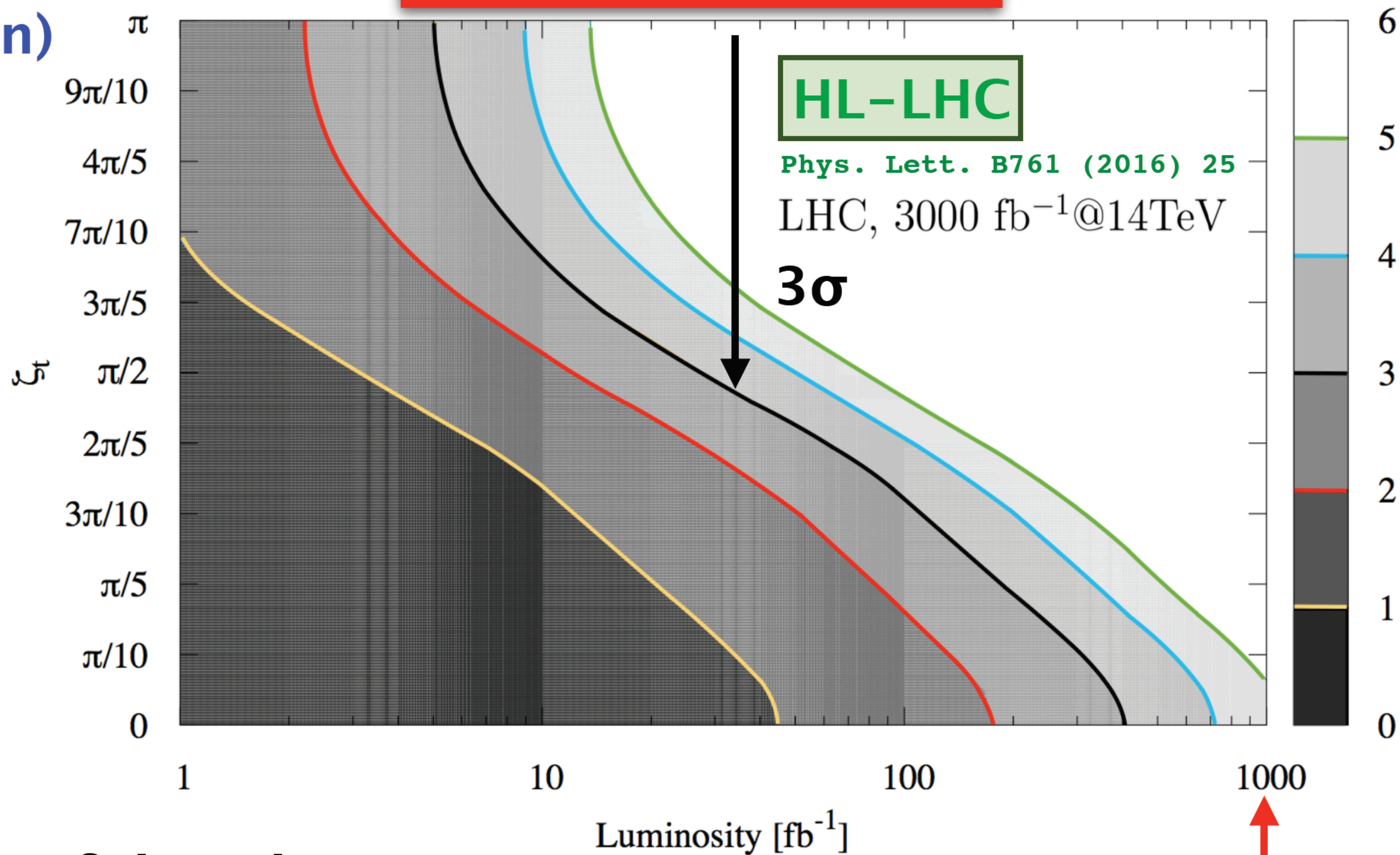
LHeC

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

CP-even (flipped sign)

CP-odd

CP-even (SM)



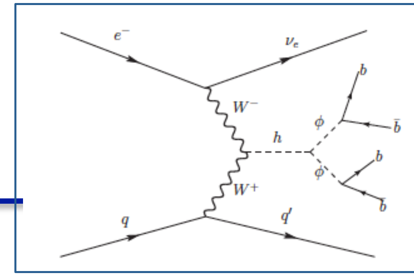
→ **powerful probe of ttH coupling**

10% uncertainty on background yields

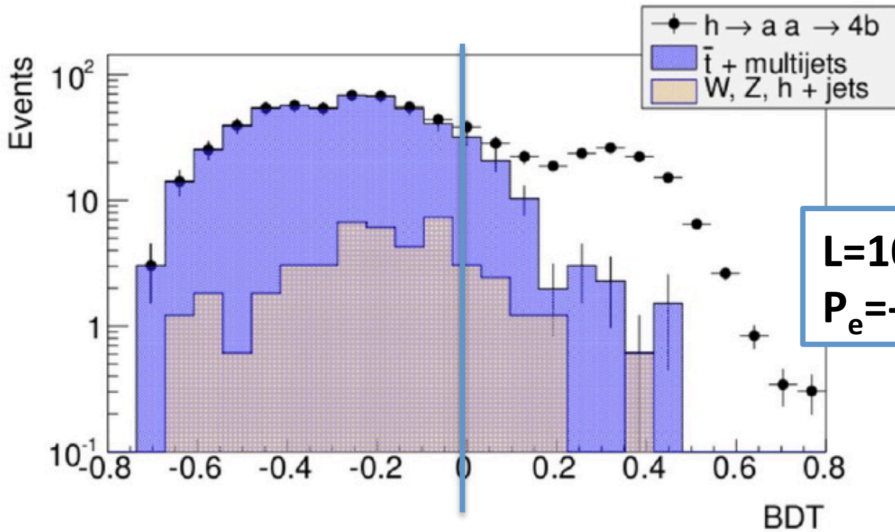
$\kappa = 1.00 \pm 0.17$

BDT Analysis @ BR=10%

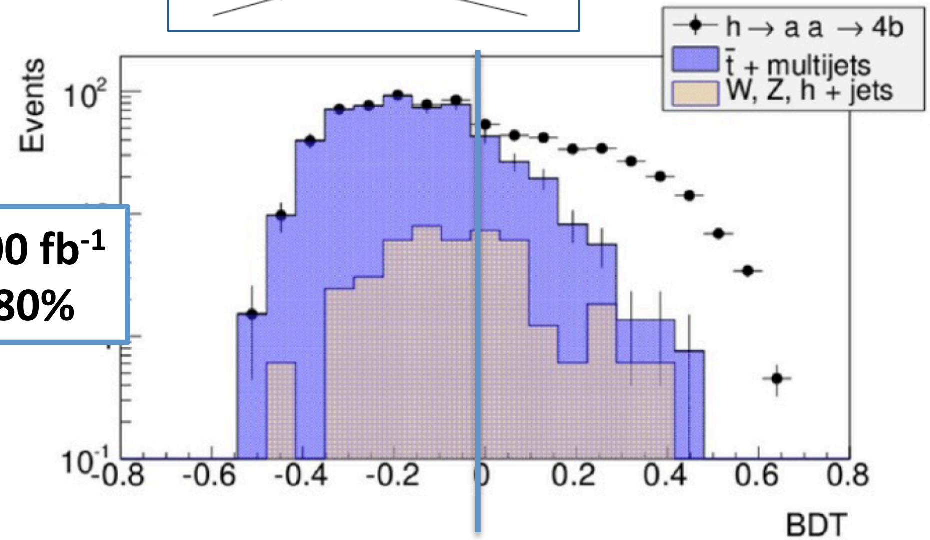
Delphes-detctor level with b-tag |η|<2.5



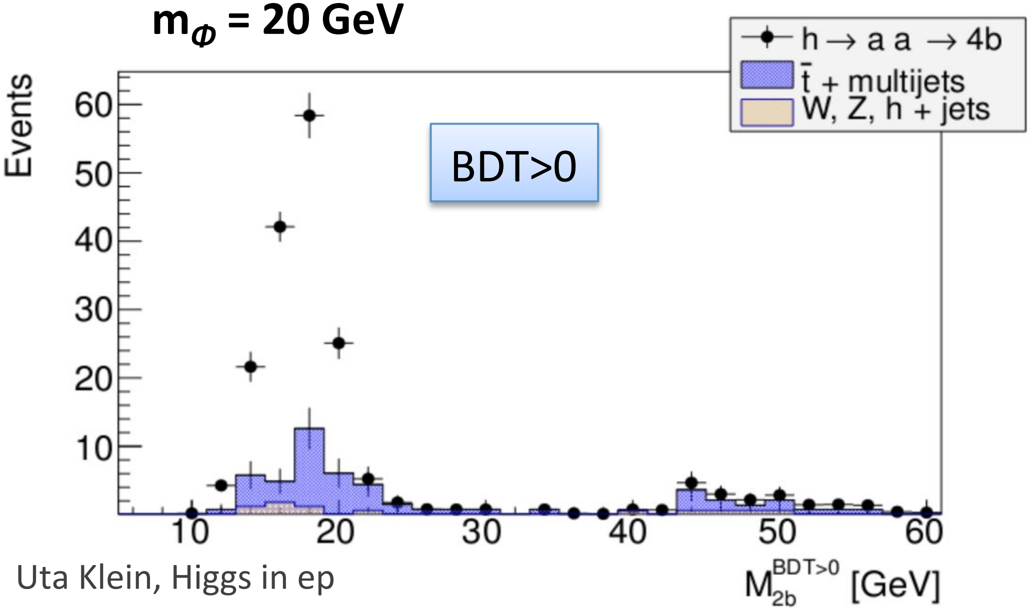
Uta Klein
Michael o'Keefe
Liverpool



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



m_Φ = 20 GeV



m_Φ = 60 GeV