Higgs @ LHeC

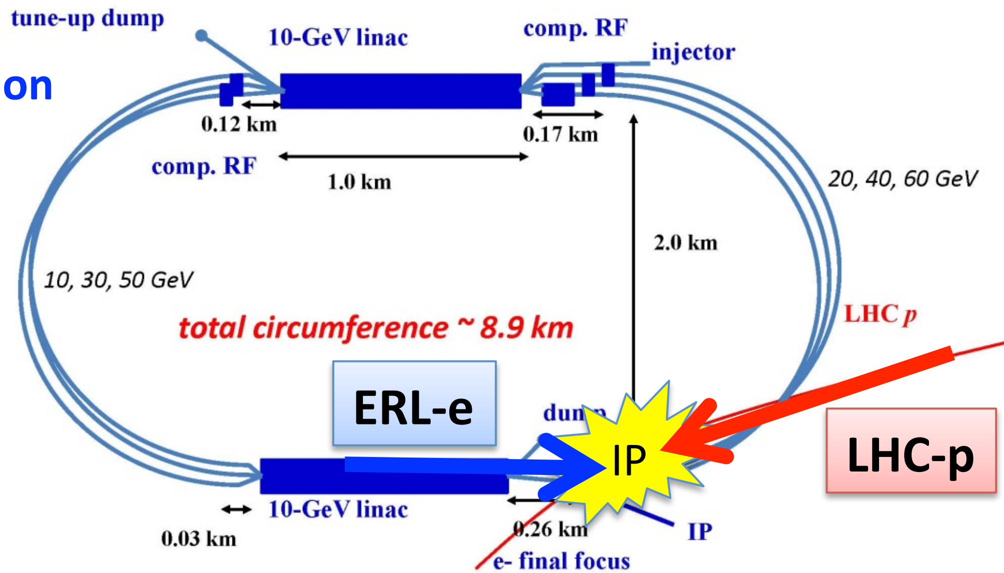
Uta Klein
on behalf of
the LHeC/FCC-eh Higgs Group

HL/HE-LHC Meeting, Fermilab, April 4th, 2018

electrons for LHC : ERL + LHC

- Two Electron LINACs + 3 return arcs: using energy recovery in same structure: 'green' technology with power consumption < 100 MW : nominal E_e = 60 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



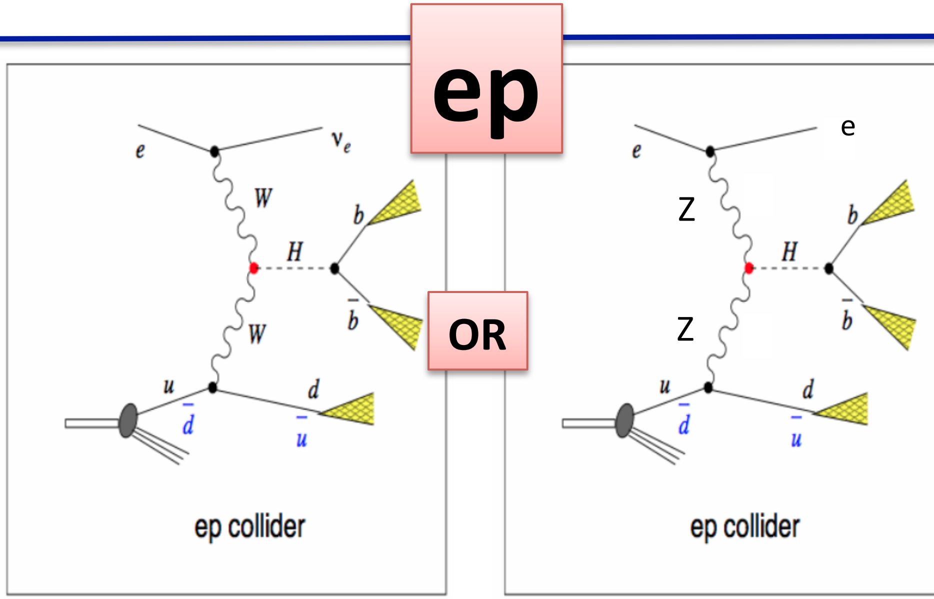
- ep Lumi 10^{34} cm s^{-2} s^{-1} **
- 100 fb^{-1} per year, e.g. ~2030-2040 (HL-LHC)
- L= 1000 fb^{-1} total collected in 10 years
- eA luminosity estimates ~ 10^{33} cm s^{-2} s^{-1} eA

** 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

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



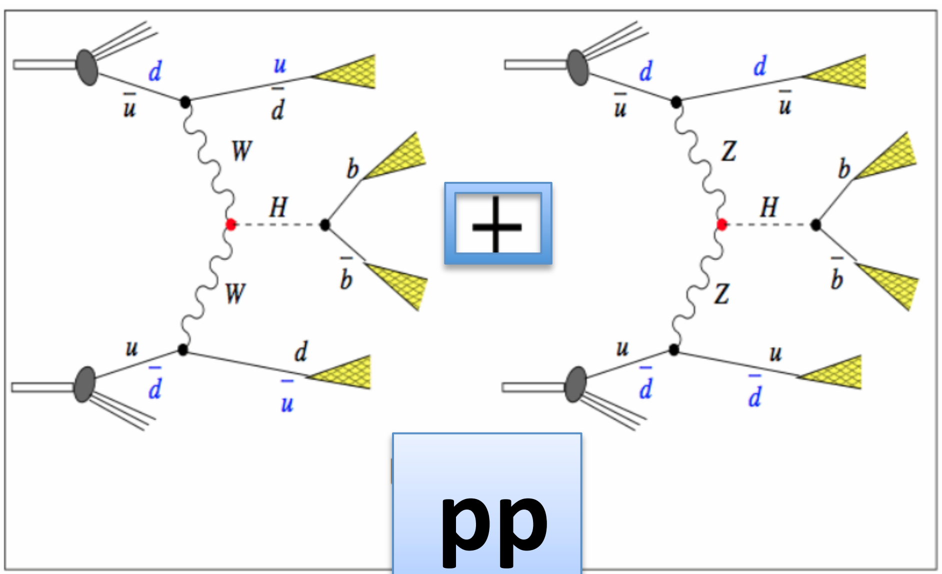
ep: Higgs production in ep comes uniquely from either CC or NC DIS via VBF

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: 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

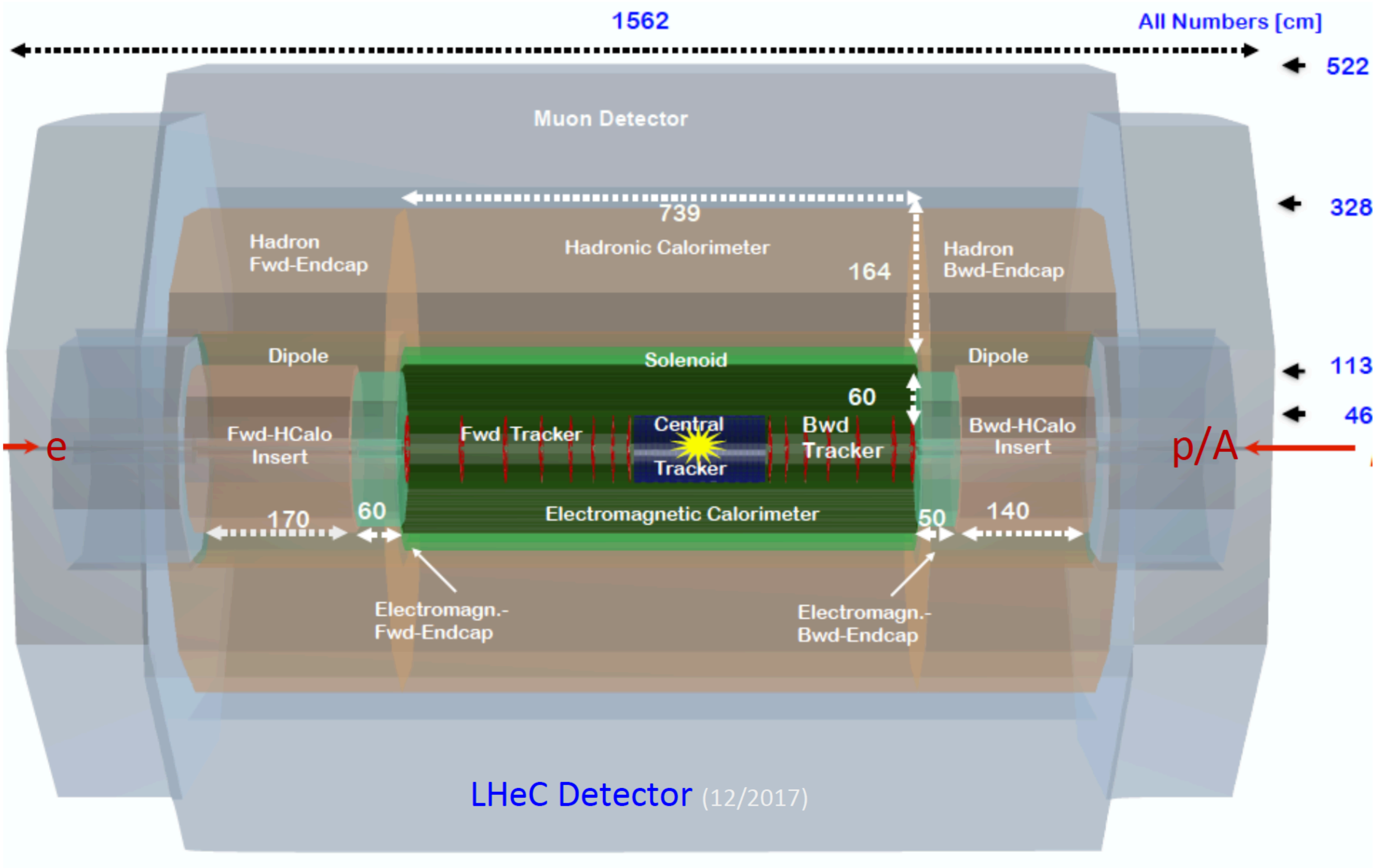
→ test of LHeC detector

↓

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 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]

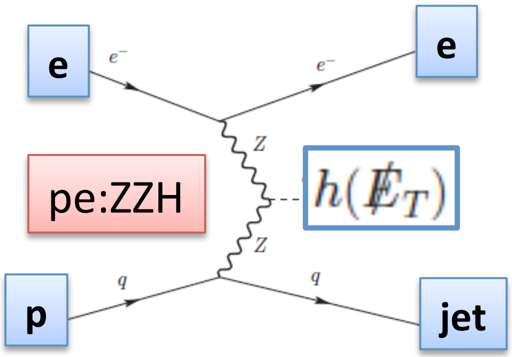
If CERN decides that the HE LHC comes, the LHeC detector should anticipate that

Branching for invisible Higgs

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

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

Delphes detectors	LHeC 1.3 TeV	HE-LHC 1.8 TeV
LHC-style	4.7%	3.2%
First 'ep-style'	5.7%	
+BDT Optimisation	5.5% (4.5%*)	3.4% (2.9%*)



- ✓ **Uses ZZH fusion process to estimate prospects of Higgs to invisible decay using *standard cut and BDT analysis techniques***
- ✓ **Results for full MG5+Delphes analyses look very encouraging for a measurement of the branching of Higgs to invisible in ep down to 5-3%** (1.2% for 2 ab^{-1} for FCC-he @ 3.5 TeV)

- ✓ We also checked LHeC ←→ FCC-he scaling with the corresponding cross sections (* results in table from down scaled FCC-he simulation) → all well within uncertainties of projections of ~25%
- employ further synergies within LHC and HL-LHC&FCC (HE) community → **further detector and analysis details have certainly an impact on results**

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

Baseline: **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

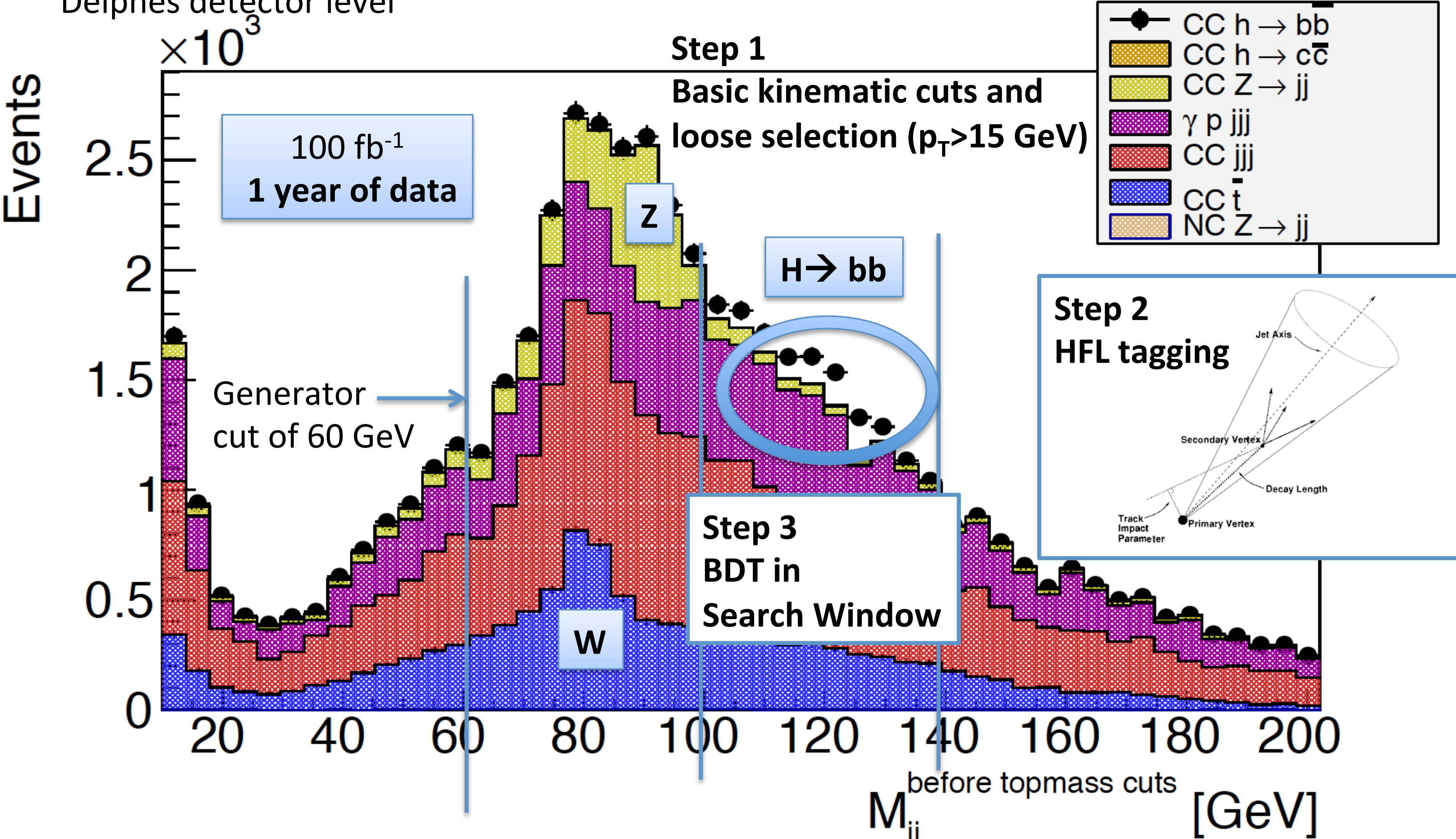
pp: **perfect Higgs factory for gluon-induced rare decays**

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

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

Dijet Mass Candidates *HFL untagged*

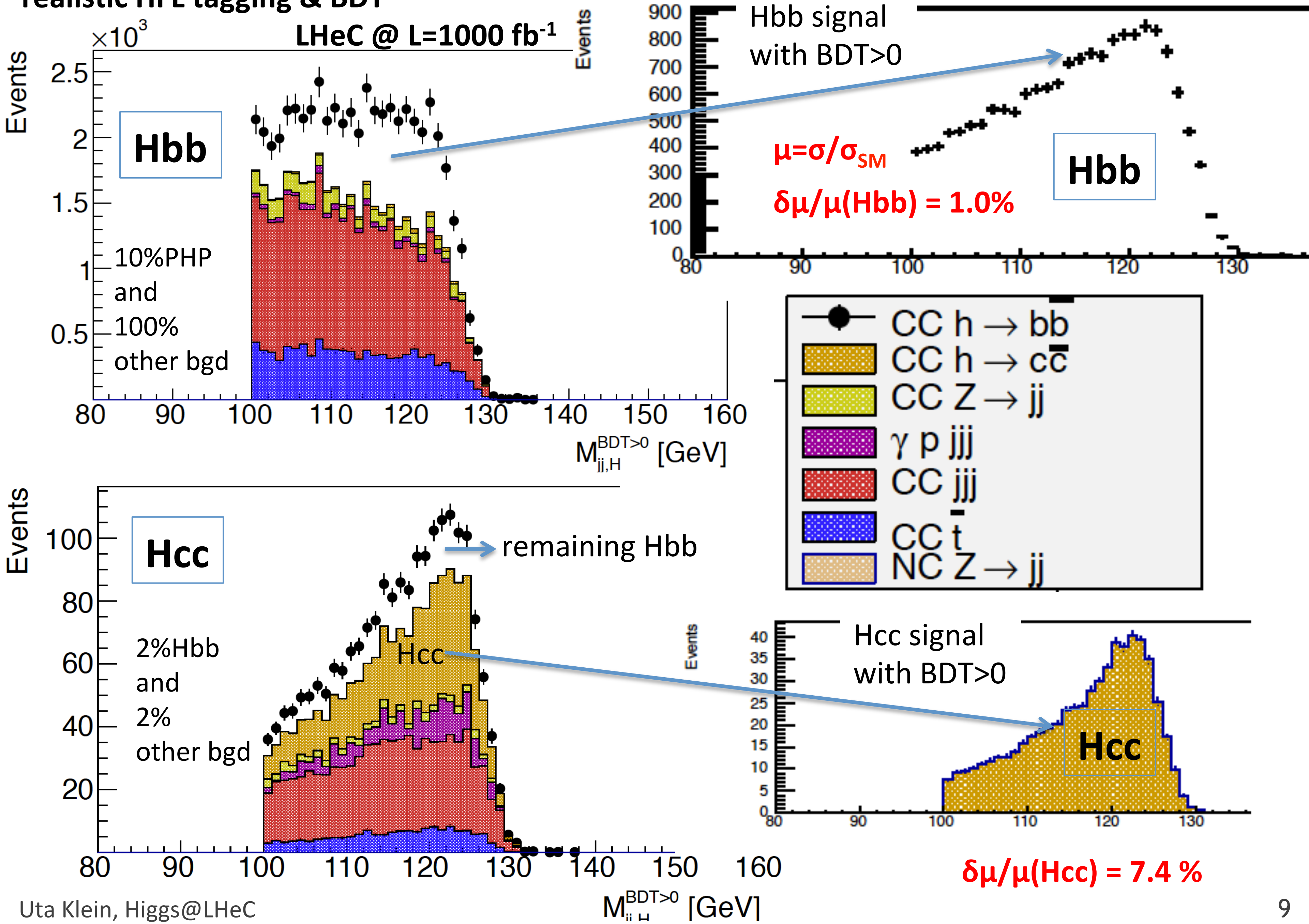
Delphes detector level



'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%

realistic HFL tagging & BDT

Uta Klein & Daniel Hampson



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}]

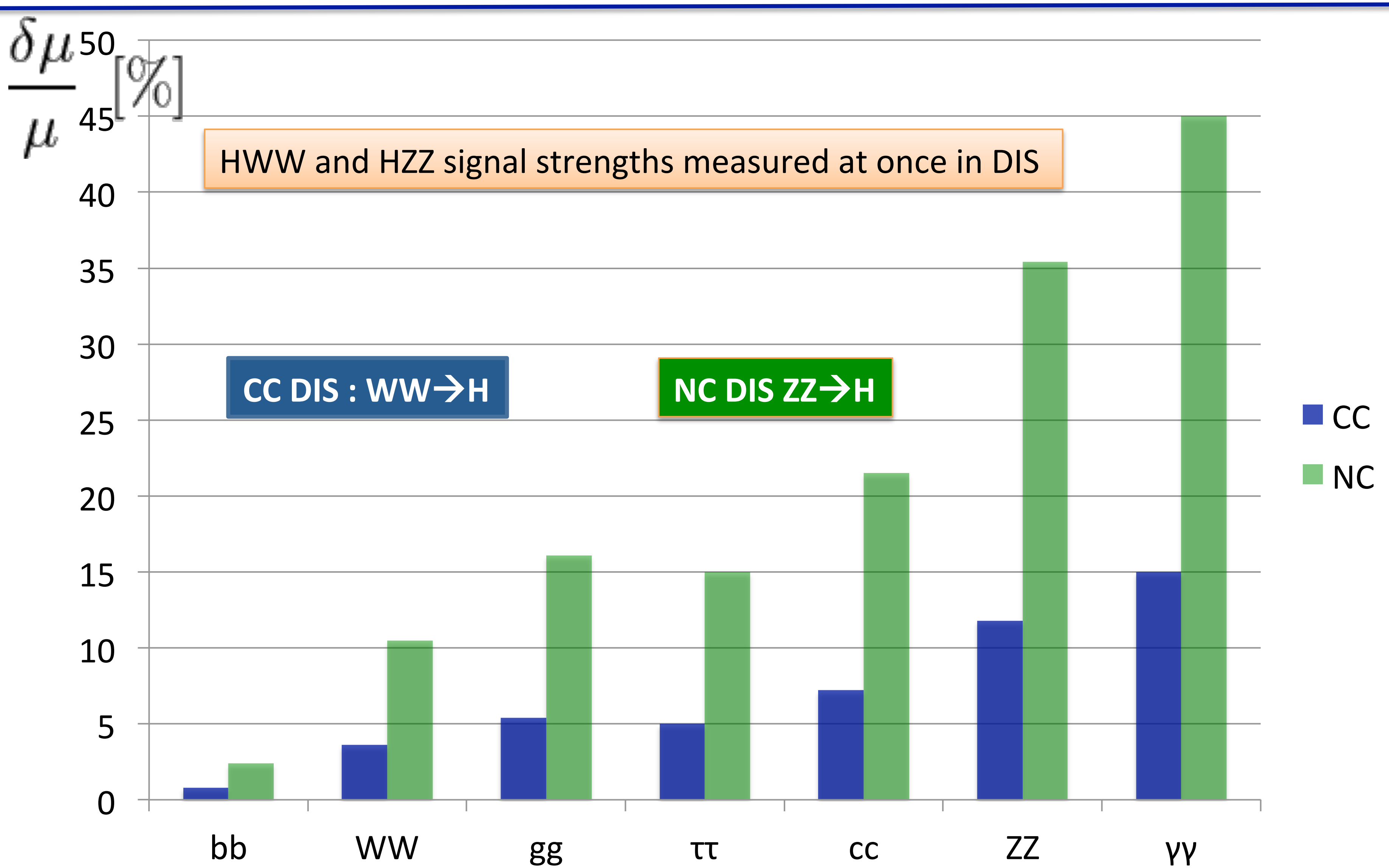
$$N = \sigma_H \bullet BR(H \rightarrow XX) \bullet BR(X \rightarrow FS) \bullet L$$

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

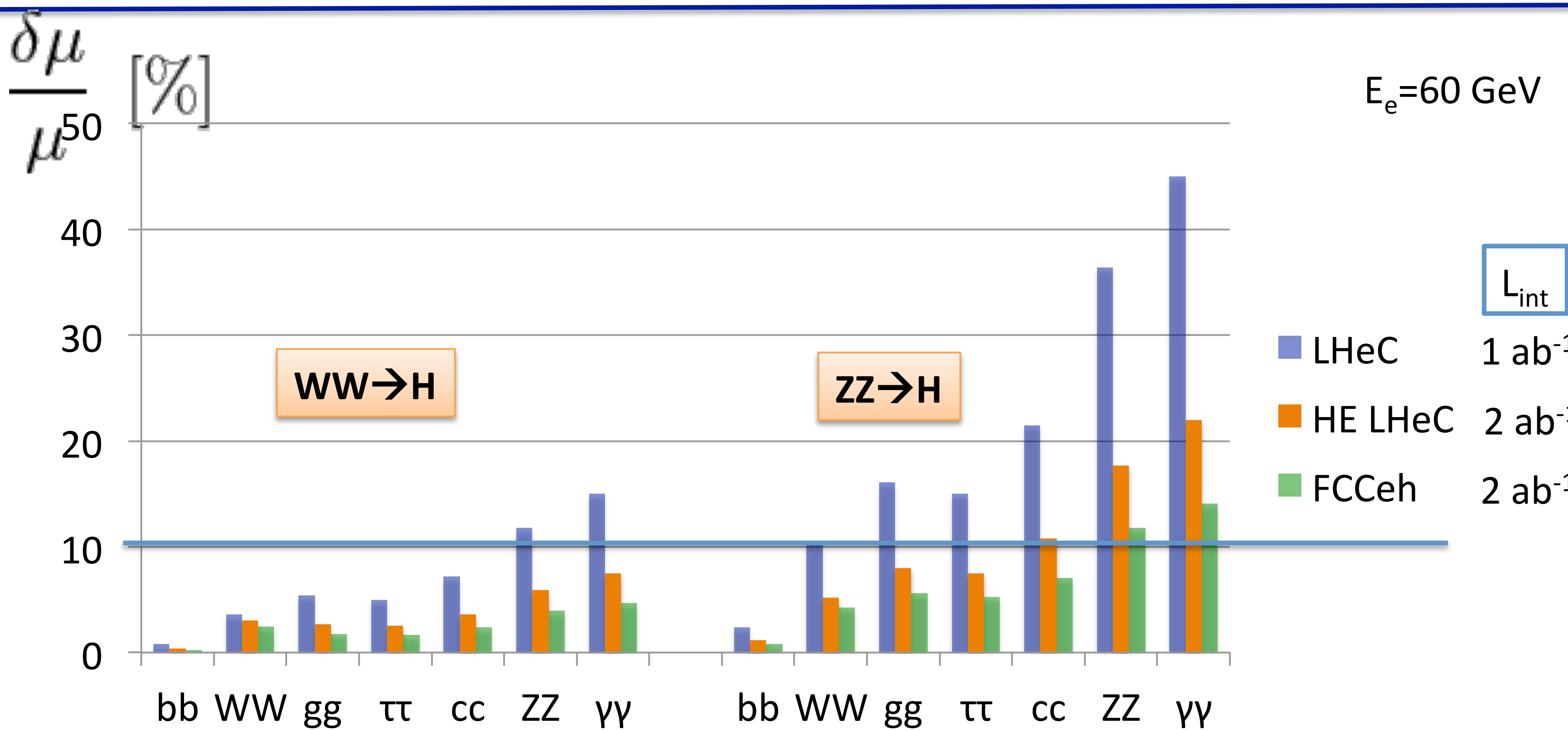
$$\frac{\delta\mu}{\mu} = \frac{1}{\sqrt{N}} \bullet f \quad \text{with} \quad f = \sqrt{\frac{1 + 1/(S/B)}{Acc \bullet \varepsilon}}$$

LHeC: Signal Strengths

L=1 ab^{-1}, running in parallel to HL-LHC



Signal Strengths @ LHeC - HE-LHeC - FCCeh

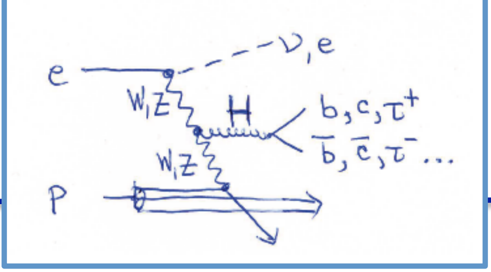


Charged Currents: ep → νHX **Neutral Currents**: ep → eHX

Note: CC (HWW)and NC (HZZ) data are taken at once in DIS (requires different e+e- machine settings for high precision)

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

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)

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

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

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

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$

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

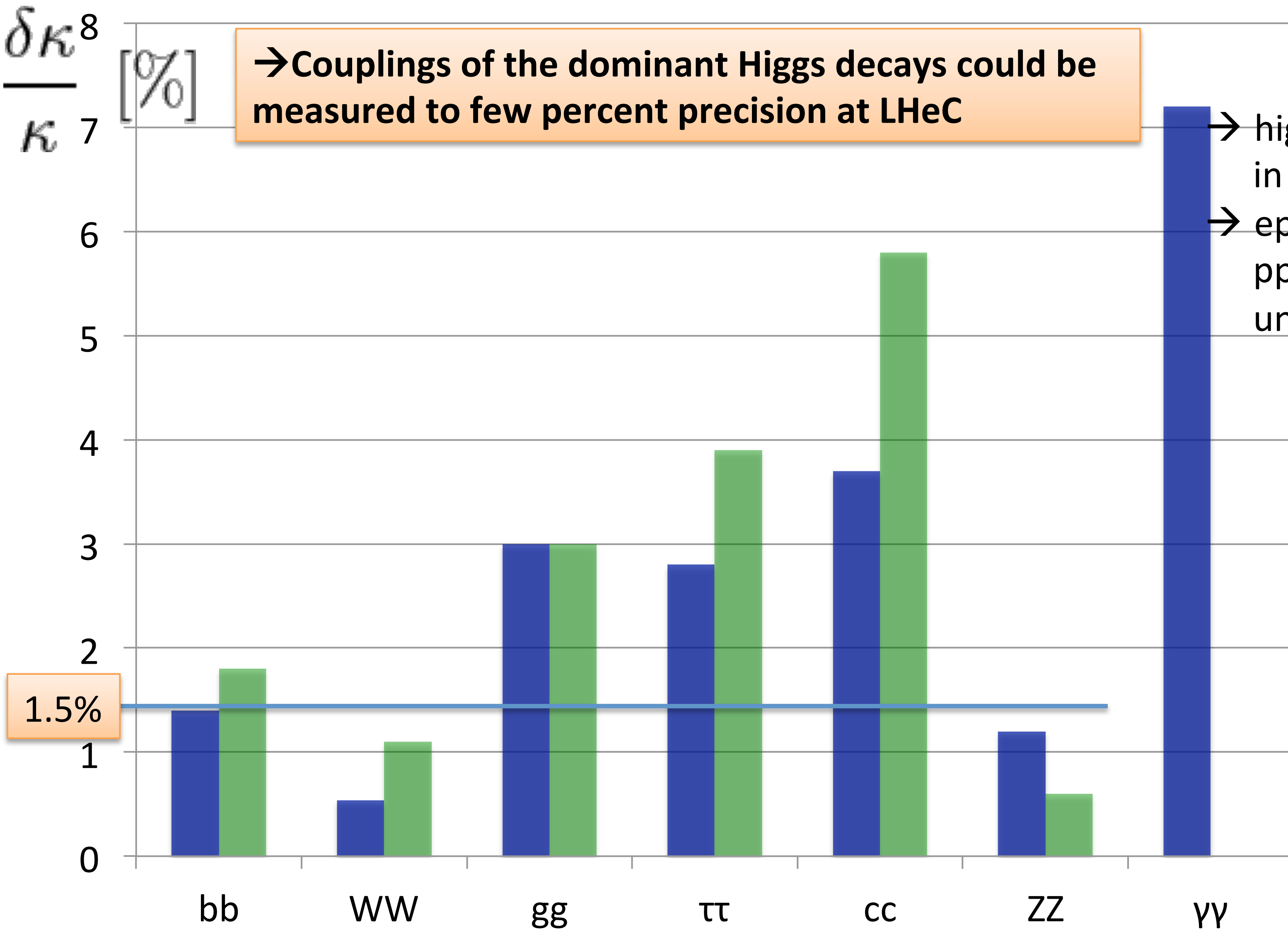
→ **Sum of first 6 branching fractions as listed in table above that could be measured**

LHeC : 0.996 +- 0.020 [pp: < 0.99 → cc? gg?]

→ gives model-dependent width ('md') uncertainty using SM branching fractions

➔ **allows a model-dependent fit of coupling uncertainties**

Model-dependent Coupling Fit



→Couplings of the dominant Higgs decays could be measured to few percent precision at LHeC

→ high impact for γγ in pp expected!

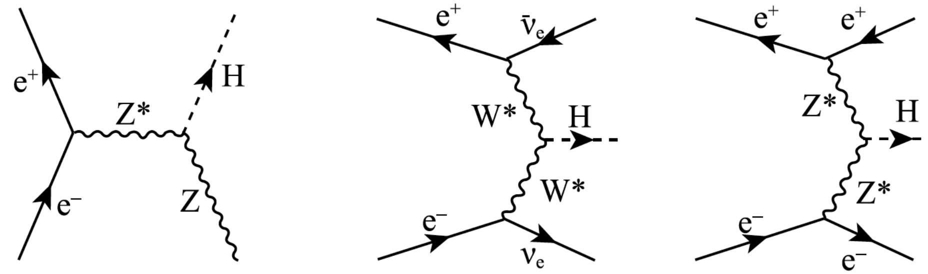
→ ep will also reduce pp Higgs uncertainties!

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

→ Very nice prospects of combining further Higgs from pp@HL-LHC and ep@HL-LHC

Higgs in ee vs ep

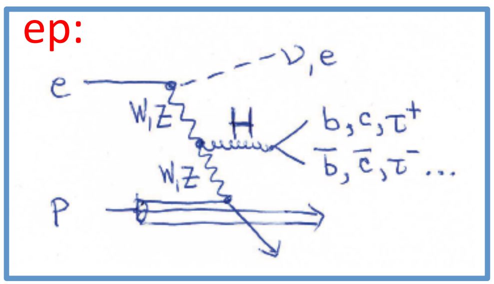
ee: Dominant Higgs productions

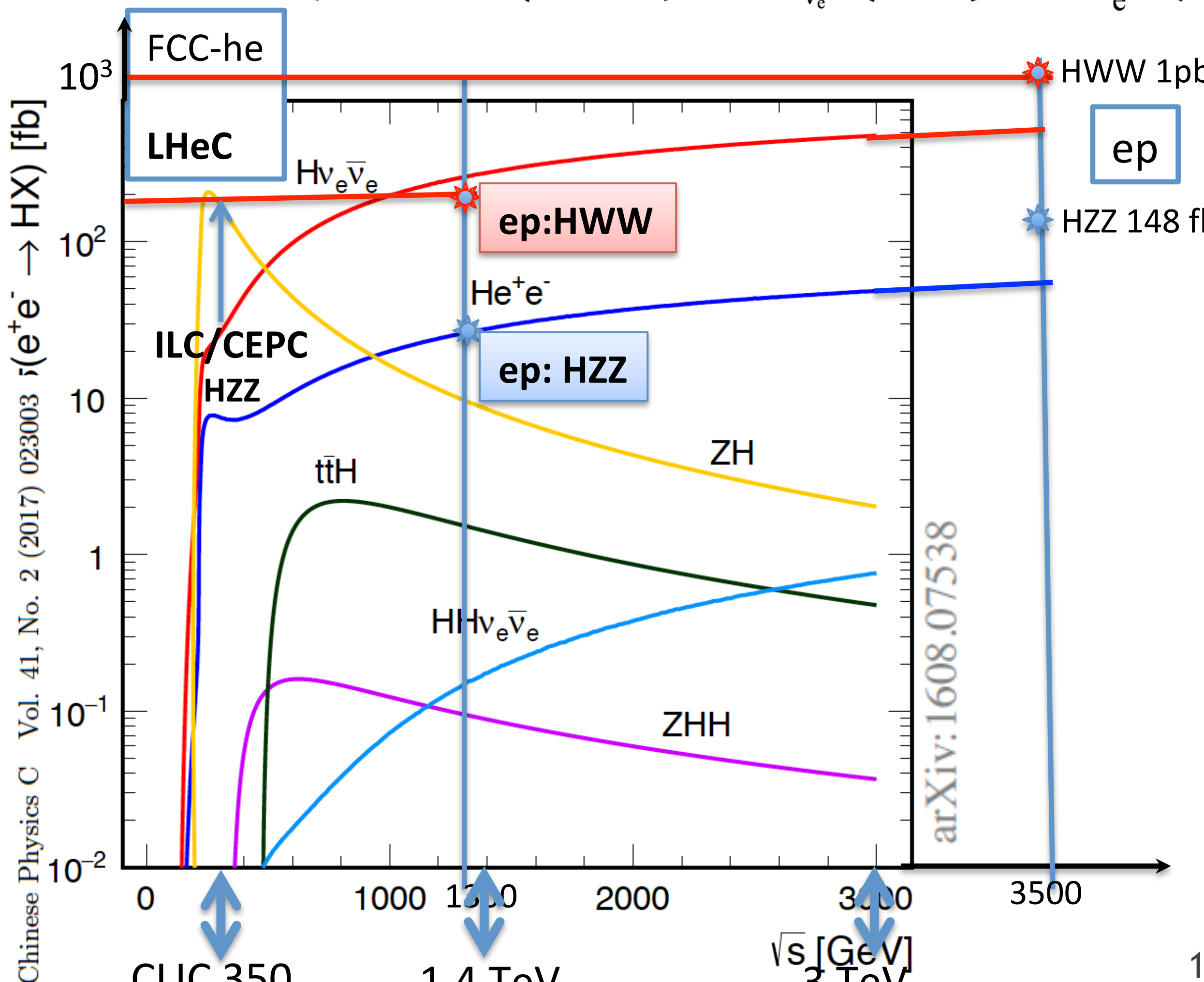


pe vs e+e- Higgs cross sections

ep:CC DIS WW Fusion

ep: NC DIS ZZ Fusion



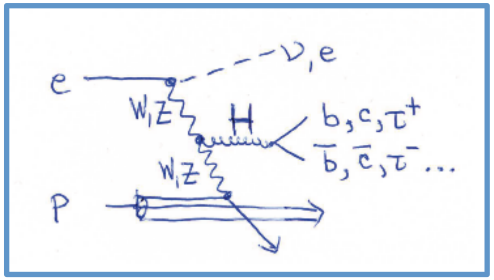


… and Consistency Checks of EW Theory

→ 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

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

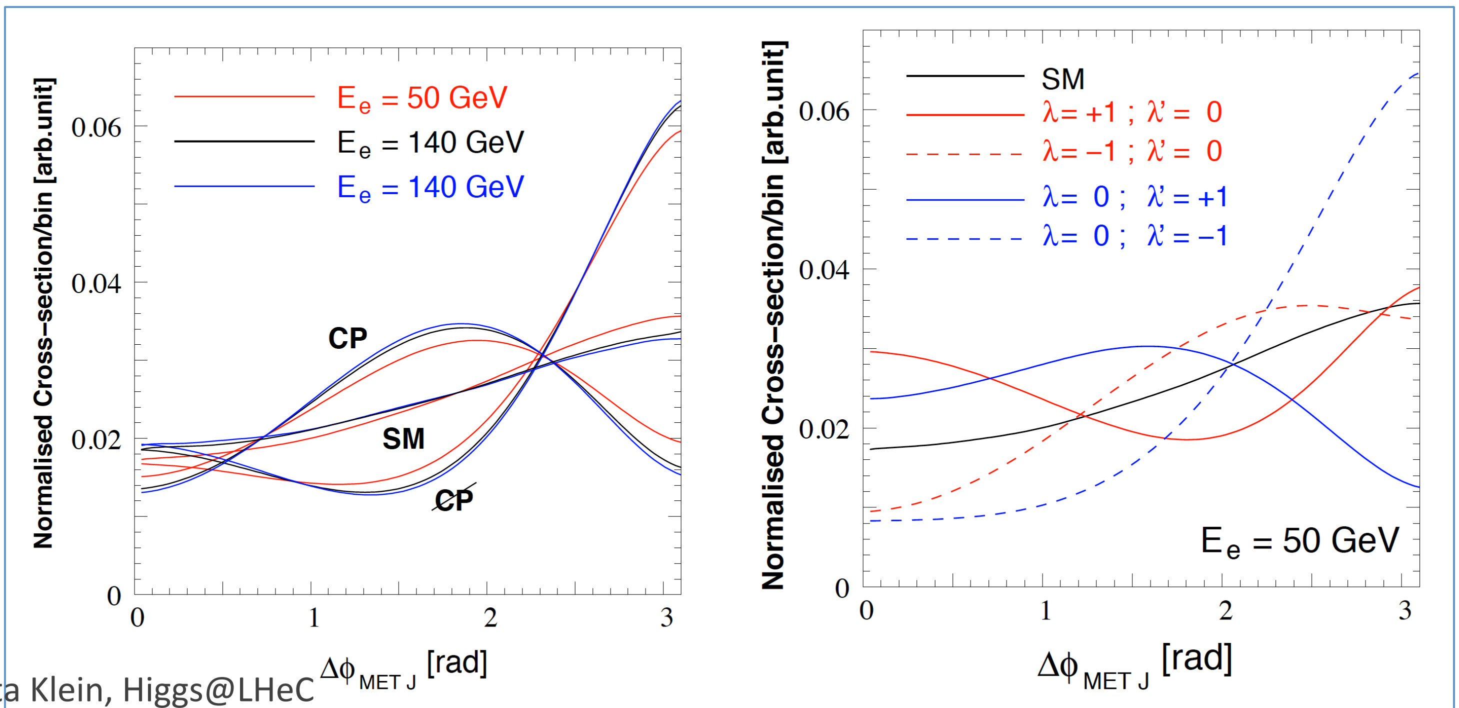
Measure CP Properties of Higgs

[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

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

- 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

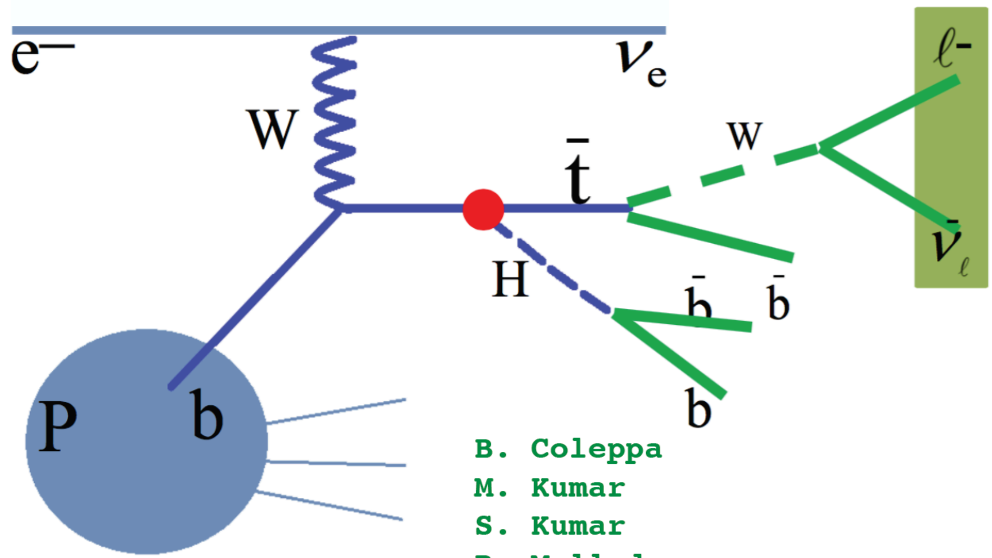
λ~0.05

λ'~0.2

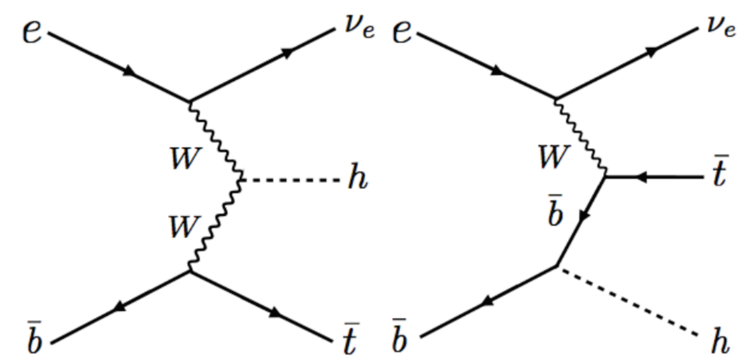
based on 50 fb^{-1}

→ Todo: full detector, 125 GeV Higgs study

CP Nature of Top-Higgs Coupling



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



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

parton level

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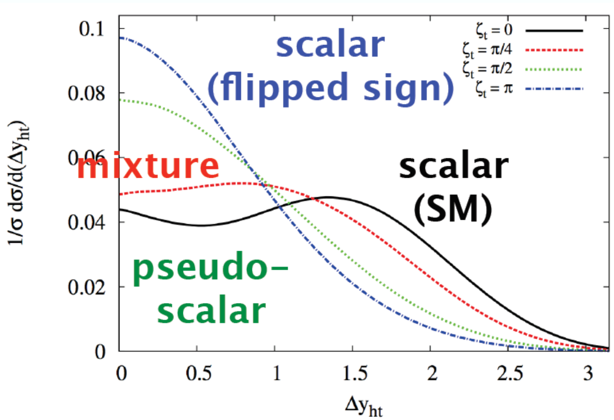
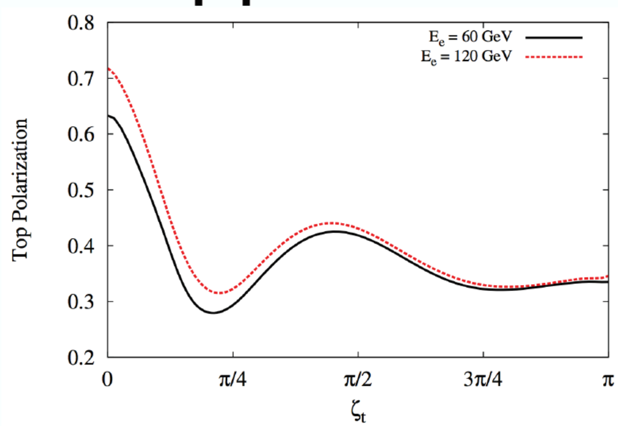
LHeC

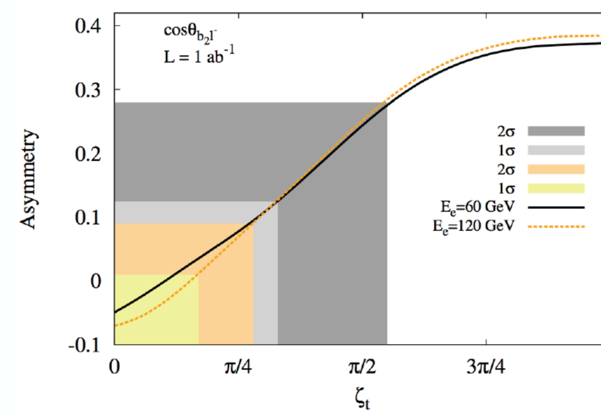
rapidity difference (H,$\bar{t}$)



top polarisation



angular asymmetries (b_2,l^-)



Exclusion Contours (fiducial cross section)

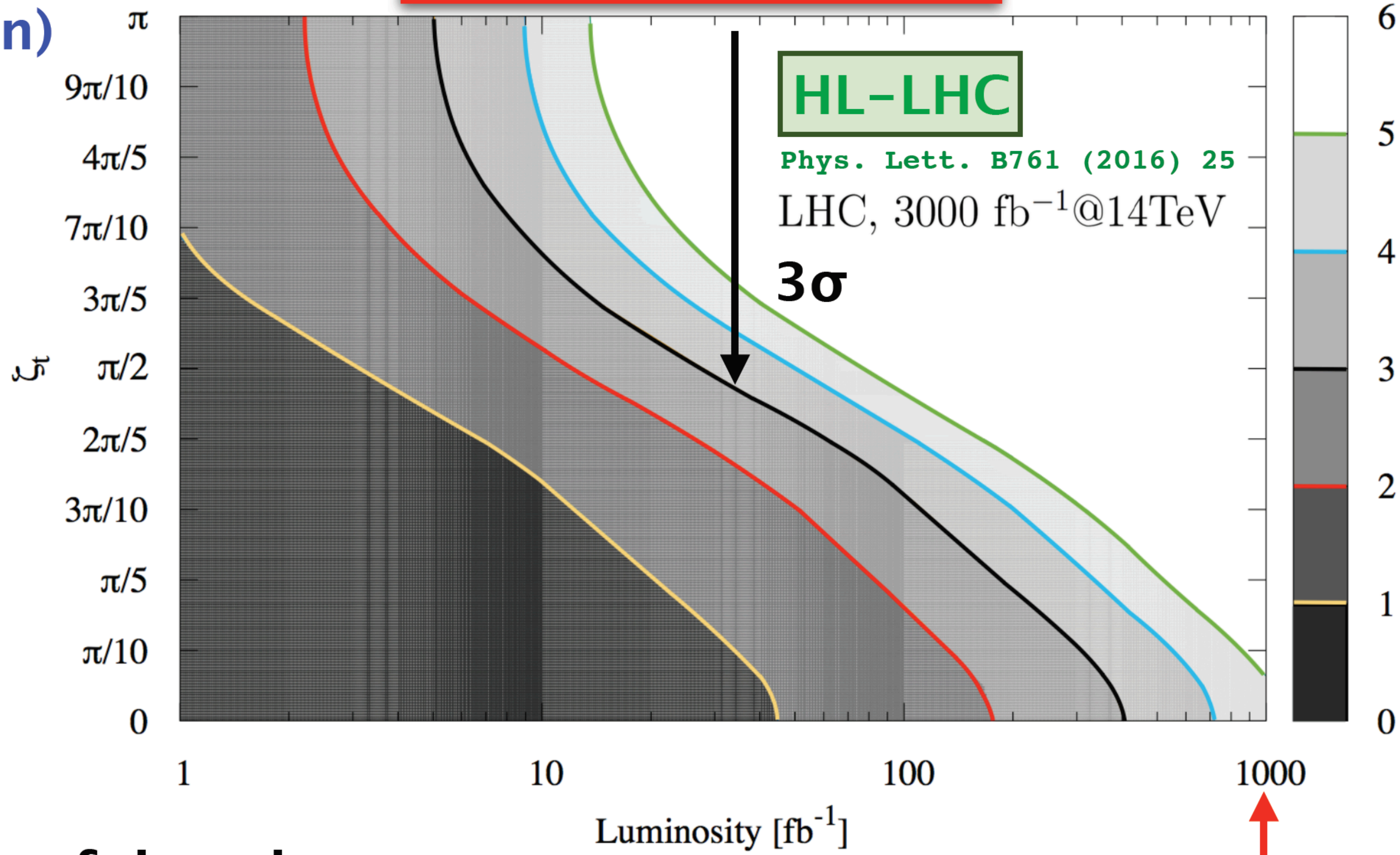
LHeC

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

CP-even (flipped sign)

CP-odd

CP-even (SM)



→ **powerful probe of ttH coupling**

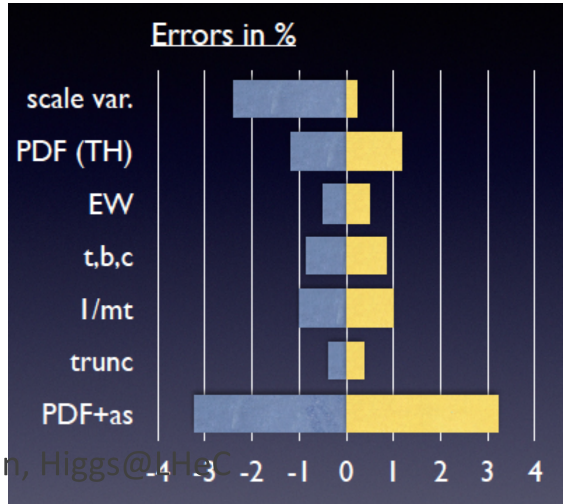
10% uncertainty on background yields

$\kappa = 1.00 \pm 0.17$

...to take home: ep+pp in 2030-40

- LHeC could measure the dominant Higgs couplings to 0.5-3% precision [CC+NC, no pile-up, clean final state..].
- This turns the LHC (ep+pp) into a very powerful Higgs facility, including a strong Higgs BSM potential (H→ invisible, ttH..)
- The LHeC would empower the physics potential of the HL LHC (searches, Higgs..) through high precision QCD measurements: flavour separated PDFs at N^3LO, α_s to per mille ...

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



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

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

Workshops

Recent: September 2017
https://indico.cern.ch/event/639067/

Next: 27-29 June 2018 Orsay
https://indico.cern.ch/event/698368/
Preparation for strategy:
Physics, Accelerator, Detector, PERLE

Many eh related workshops
FCC: Physics week (CERN Jan 2018)
and in April 2018 (Amsterdam)
POETIC in March (Regensburg)
DIS 2018 in April (Kobe)
HL-HE LHC Physics June 2018 (CERN)
which includes ep/eA

https://lhec.web.cern.ch

Additional Sources & Thanks to

- Much more material can be found here: LHeC and FCC-eh Workshop, September 2017, CERN https://indico.cern.ch/event/639067/
- **The LHeC/FCC-eh study group, http://cern.ch/lhec.**
- "On the Relation of the LHeC and the LHC" [arXiv:1211.5102]
- 1st FCC Physics Workshop, 16.1.-20.1.2017, 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

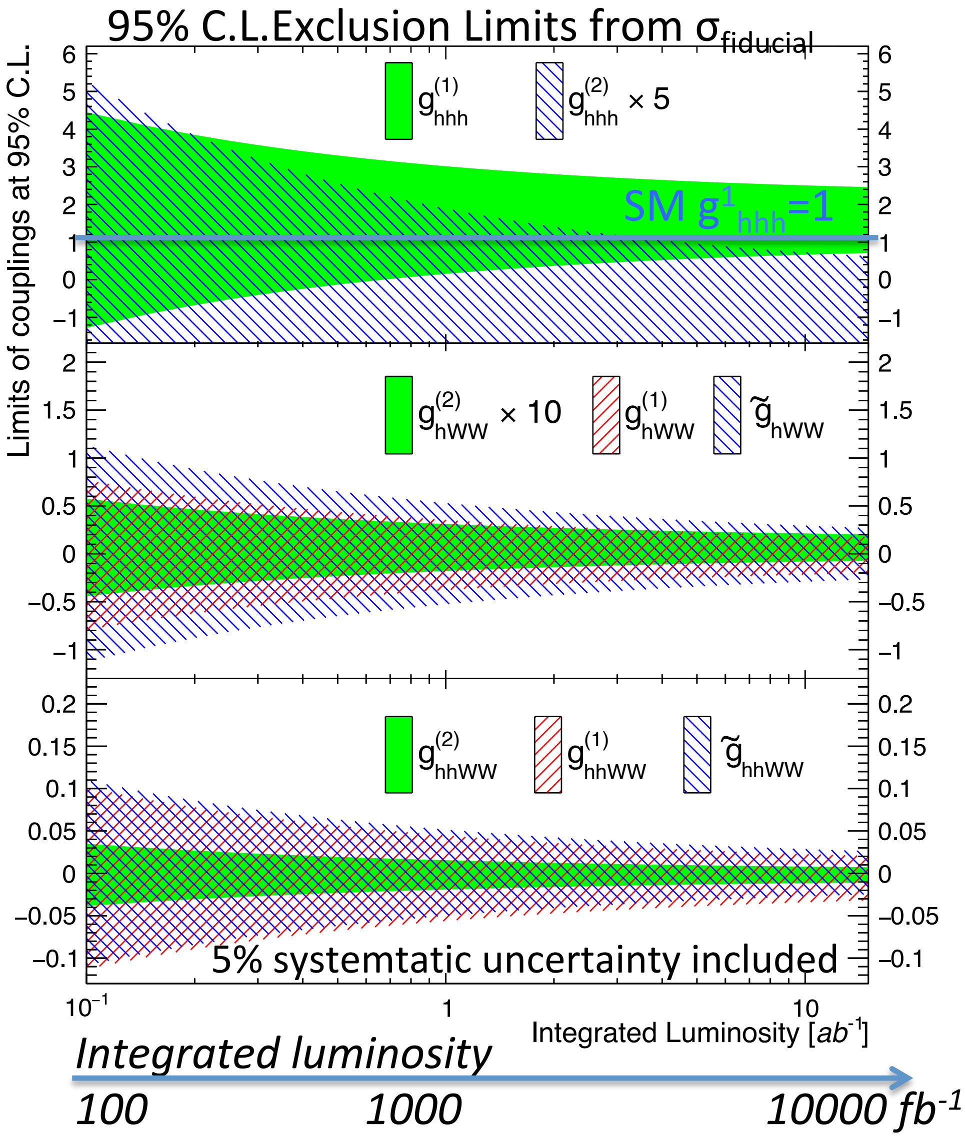
Special thanks to my colleagues in the LHeC/FCC-eh Higgs group and to Jorge de Blas for the discussion of model-dependent coupling fits.

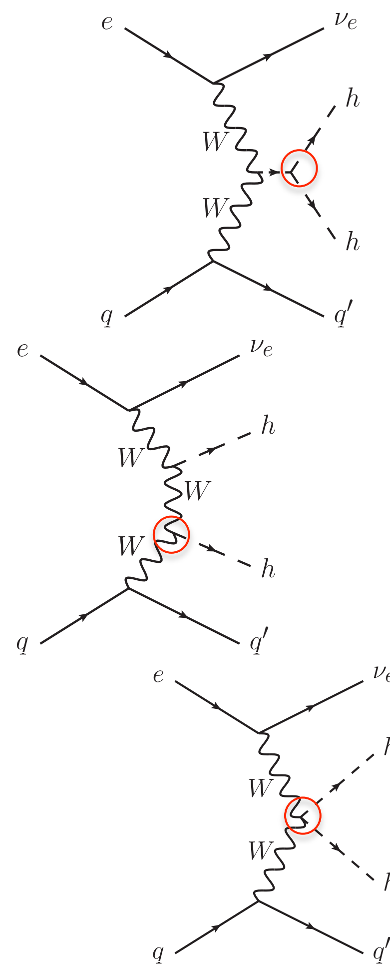
Additional material

Double Higgs Production

[1509.04016]

FCC-eh study





1σ for SM hhh for E_e 60 (120)GeV and 10ab^{-1}

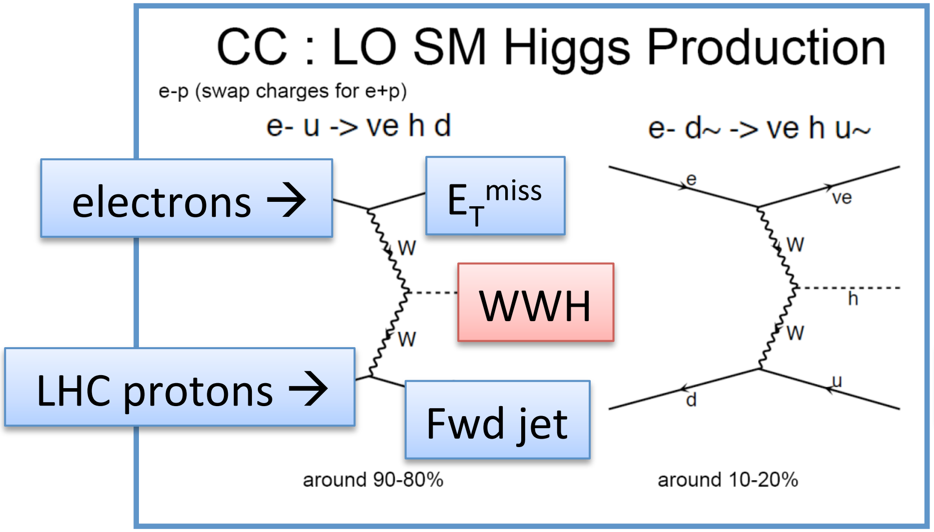
$$g^{(1)}_{hhh} = 1.00^{+0.24(0.14)}_{-0.17(0.12)}$$

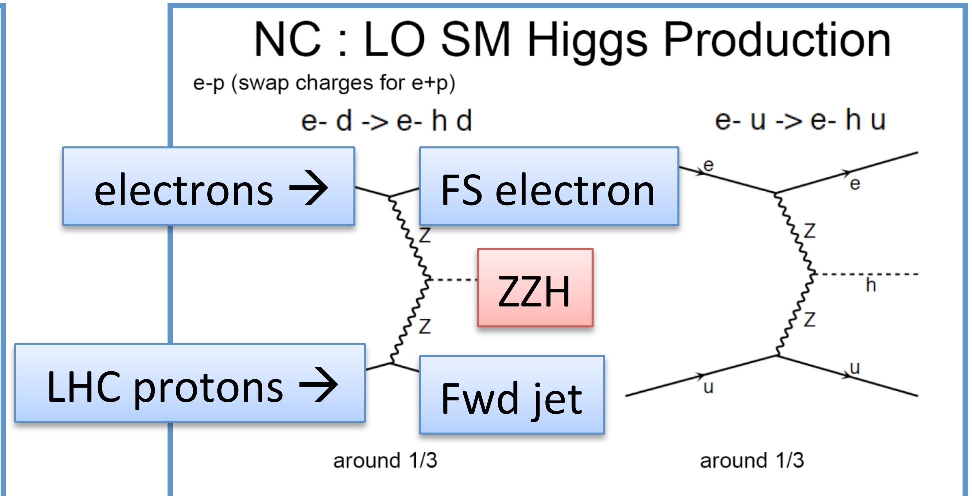
Probing anomalous couplings: limits are obtained by scanning one of the non-BSM coupling while keeping other couplings to their SM values.

➔ explore LHeC/HL-LHC 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.

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)

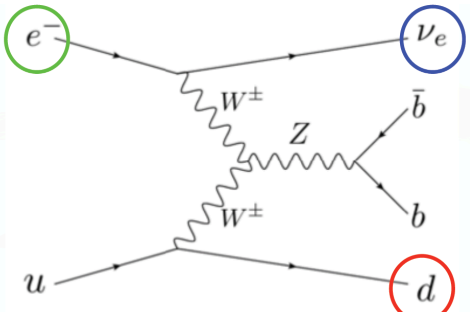
c.m.s. energy	1.3 TeV LHeC	3.5 TeV FCC-he
CC DIS NC DIS	109 21	560 127
P=-80% CC DIS NC DIS	 **196** **25**	 **1008** **148**

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

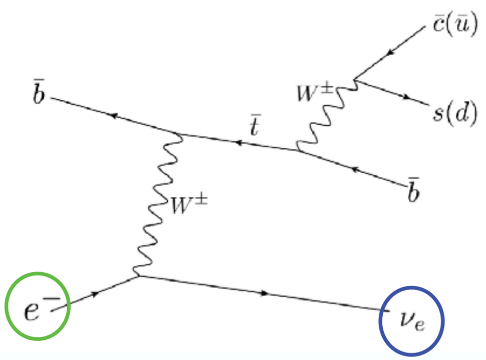
[J. Blumlein, G.J. van Oldenborgh , R. Ruckl, Nucl.Phys.B395:35-59,1993]
[B.Jager, arXiv:1001.3789]

SM Higgs Decay into b-quarks

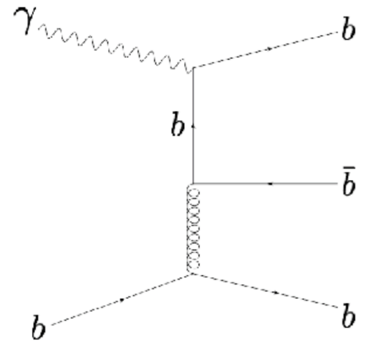
- Typical background processes



CC Z production



Single top production



Multi jets

Invisible Higgs@LHeC

relating the Higgs and the 'dark' sectors

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

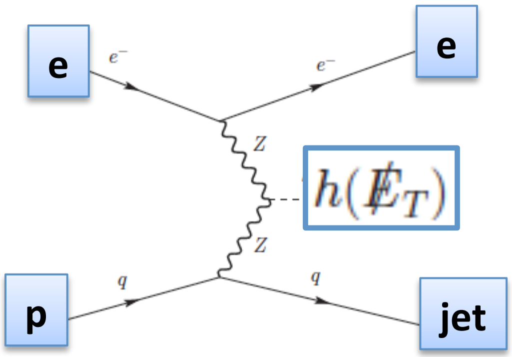
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

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

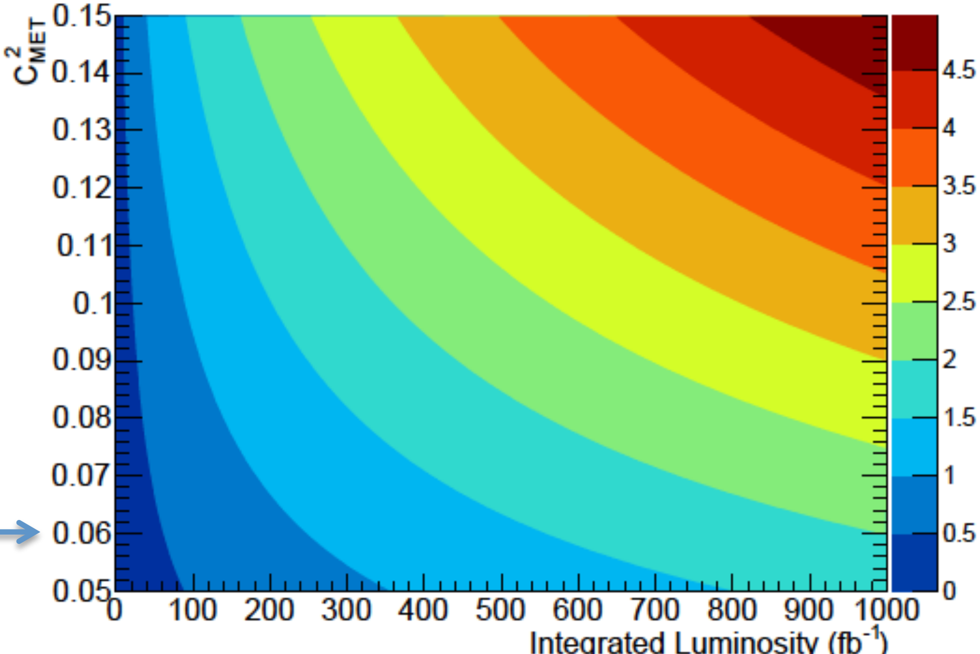
For **LHeC**, assume : 1ab^{-1}, P_e=-0.9, cut based

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

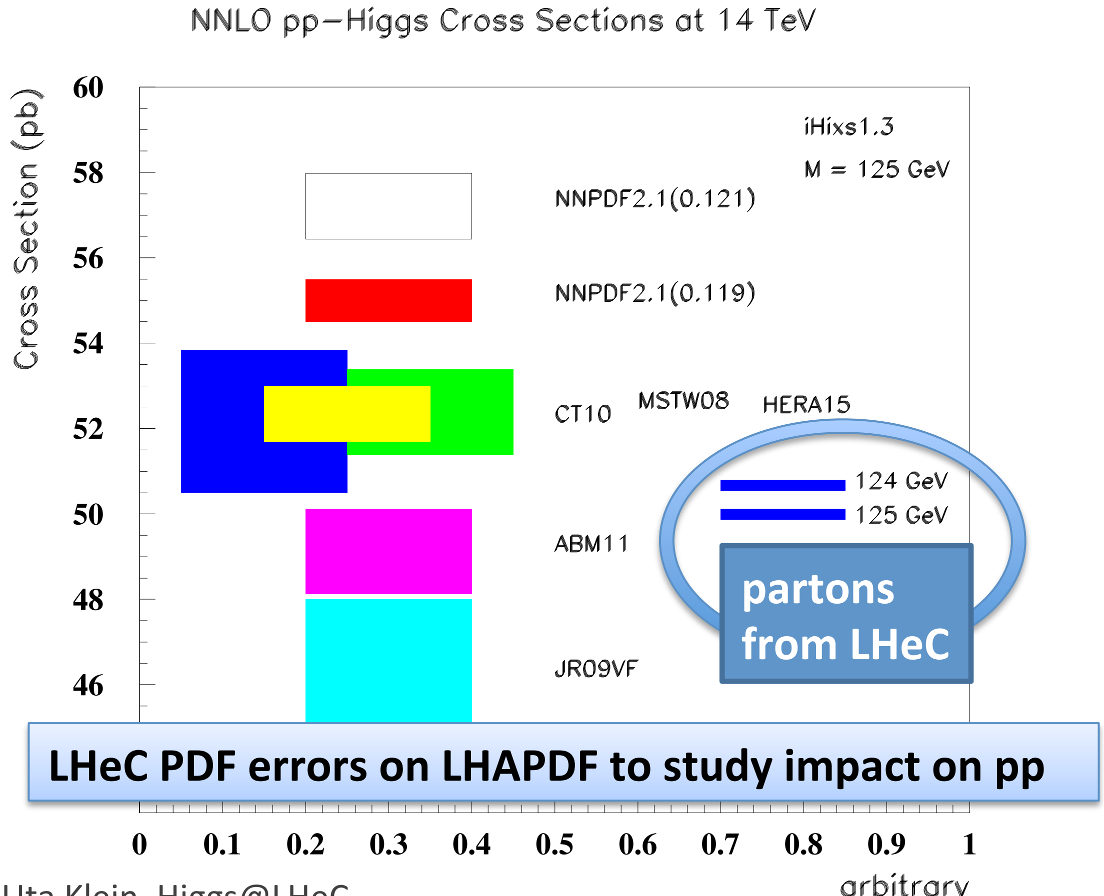
See also talk by C Gwenlan

LHeC Precision Partons for Higgs@pp

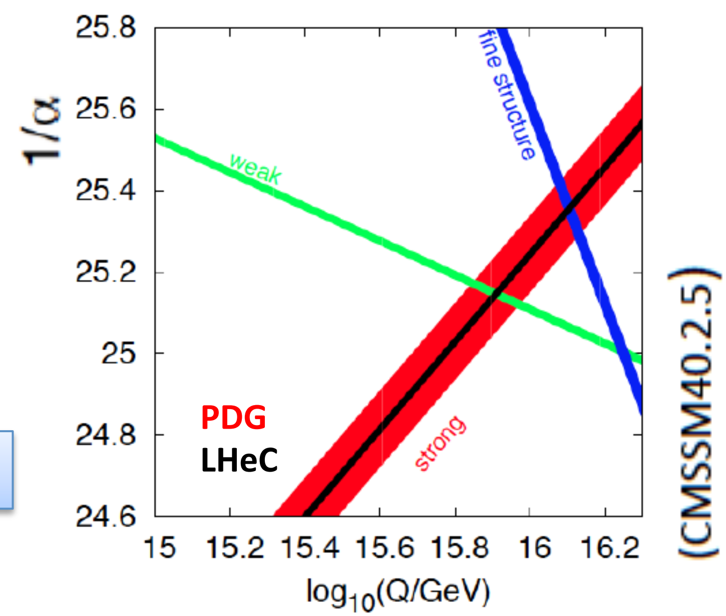
→ **Using LHeC input**: experimental uncertainty of predicted **LHC Higgs cross section due to PDFs and α_s** is strongly **reduced to <~0.5%**

→ ***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***

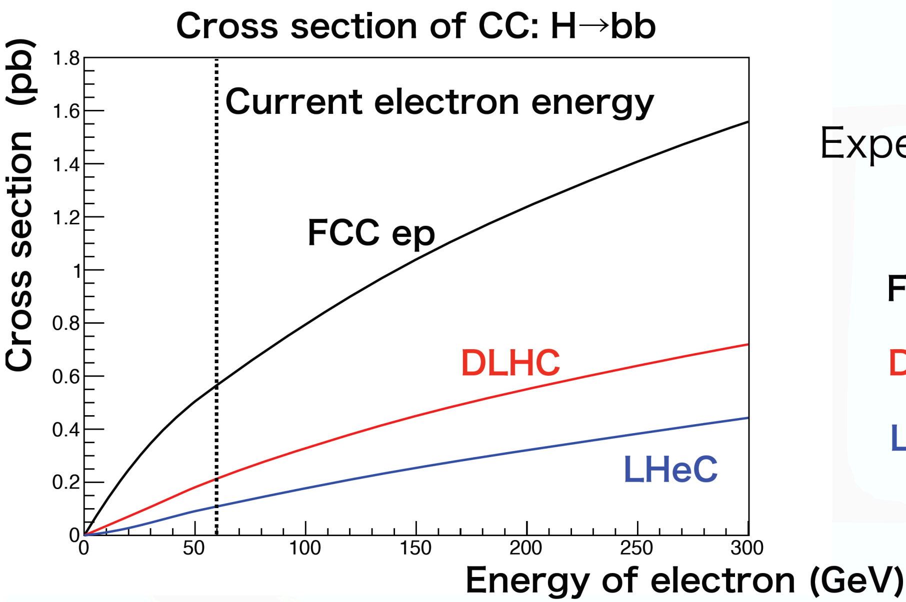


→ **precision from LHeC can add a very significant constraint on the Higgs mass** *and challenge Lattice QCD calculations for α_S:*



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)

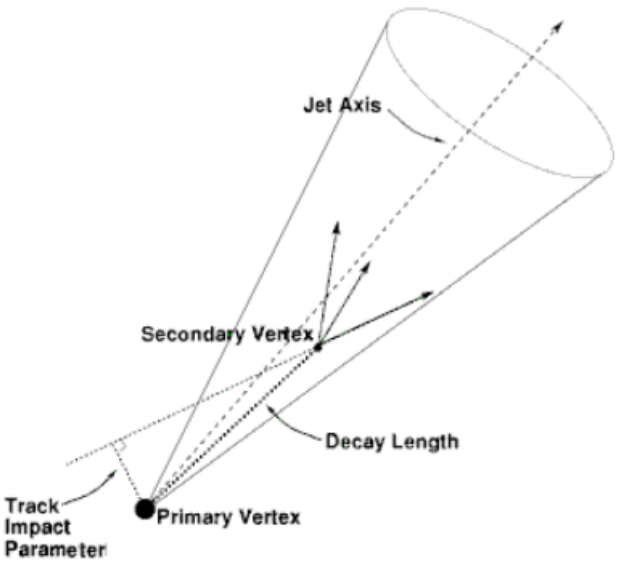
LHeC (~15,000 H→bb events)

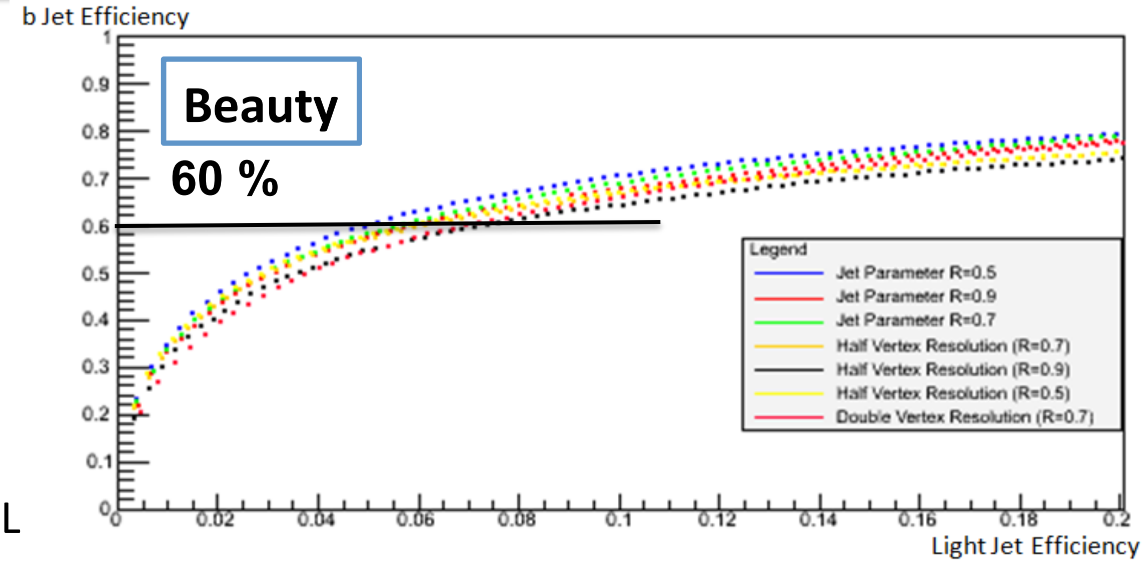
$$\delta\kappa = \frac{1}{2}\frac{\delta\mu}{\mu}$$

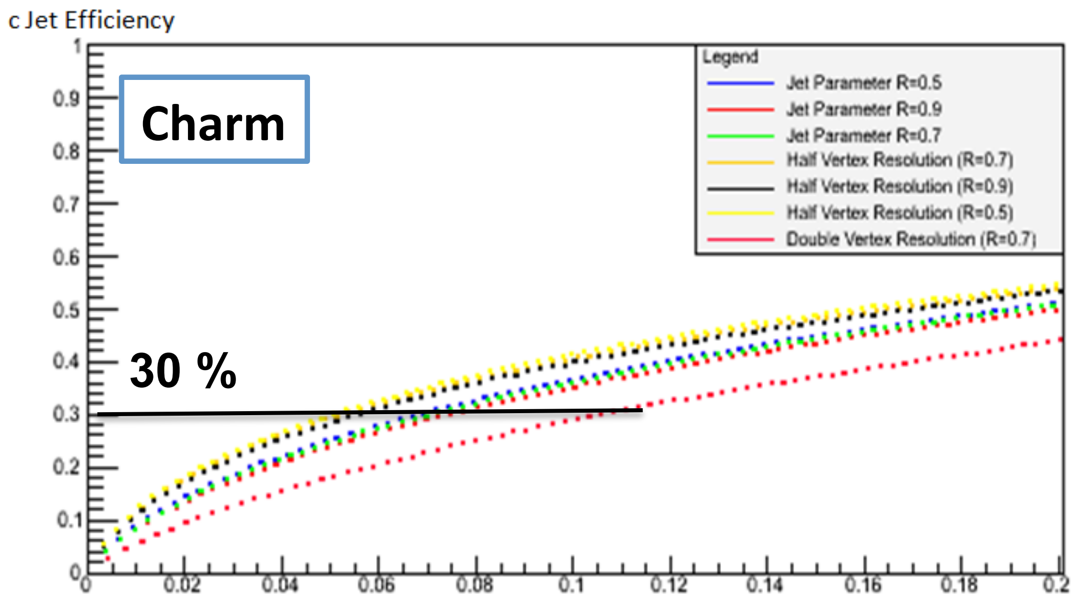
	LHeC (E_p = 7 TeV √s ~1.3 TeV)	DLHC (E_p = 14 TeV √s ~1.8 TeV)	FCC ep (E_p = 50 TeV √s ~ 3.5 TeV)
κ (Hbb)	0.5%	0.3%	0.2%
κ (Hcc)	4%	2.8%	1.8%

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

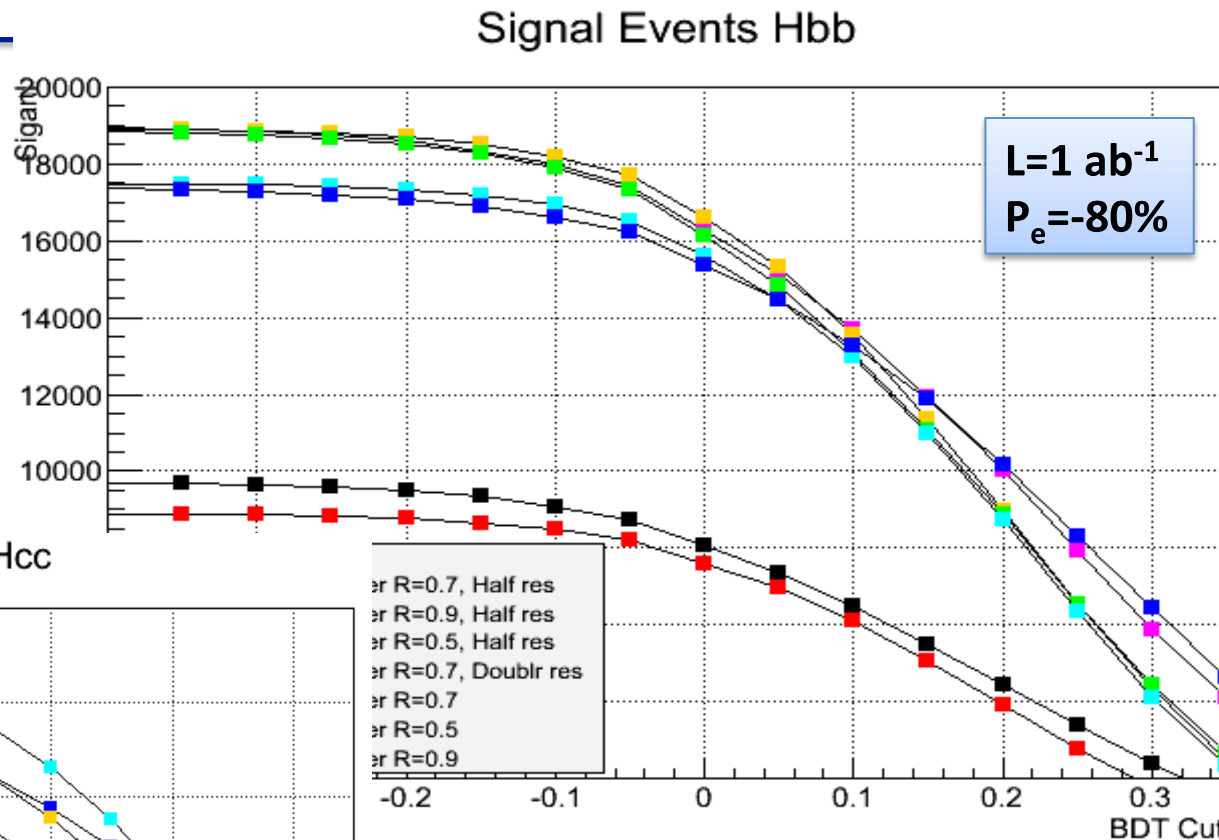
→ Light jet rejection very conservative, i.e. factor 10 worse than ATLAS

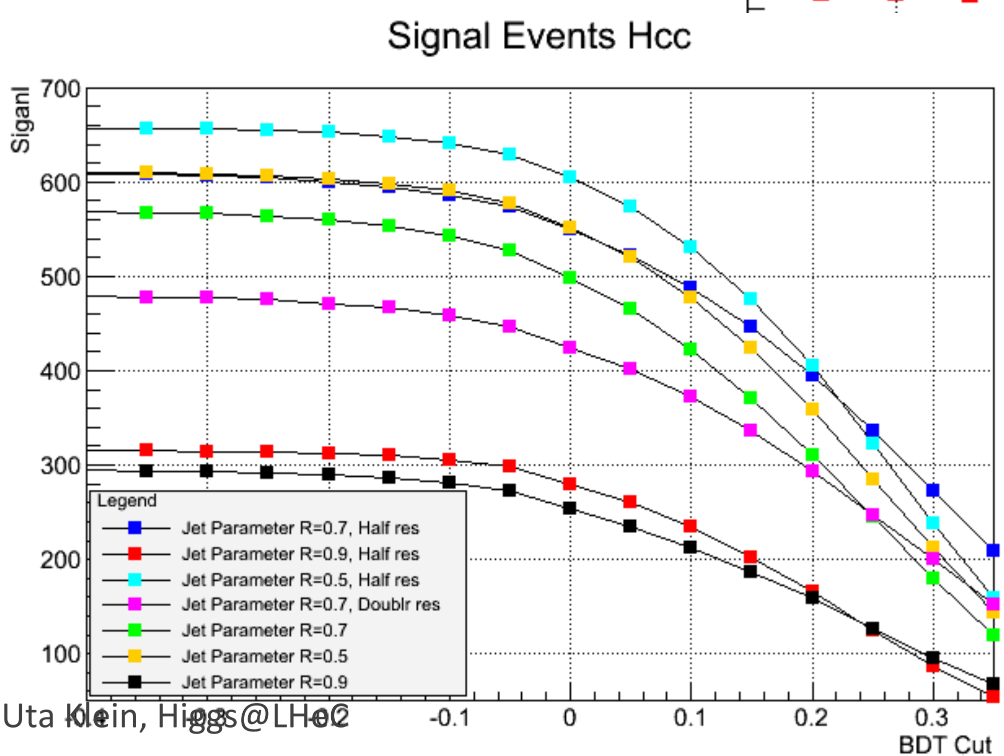
→ **used in full LHeC analysis and for FCC-eh extrapolations**

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



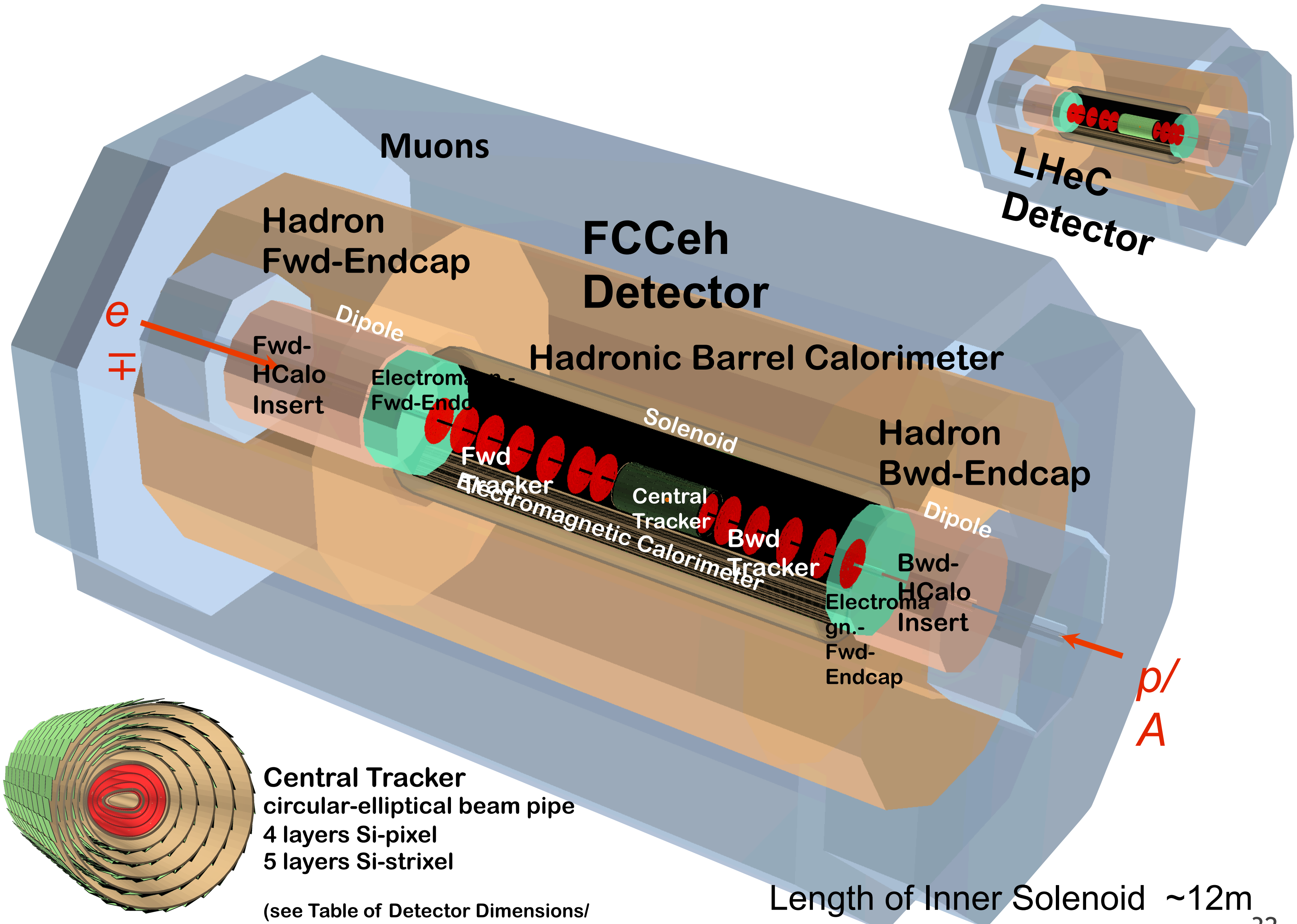


Hcc : High sensitivity to vertex resolution (nominal 10 μm) and jet radius

→ 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

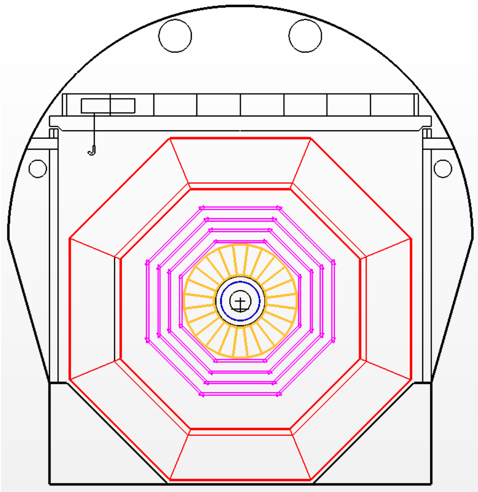
(see Table of Detector Dimensions/ Parameters in backup)

Length of Inner Solenoid ~12m

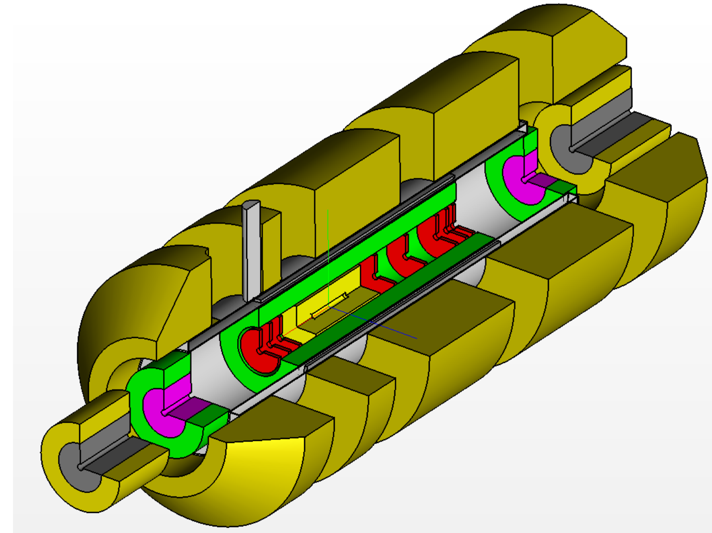
Installation Study

to fit into LHC shutdown needs directed to IP2

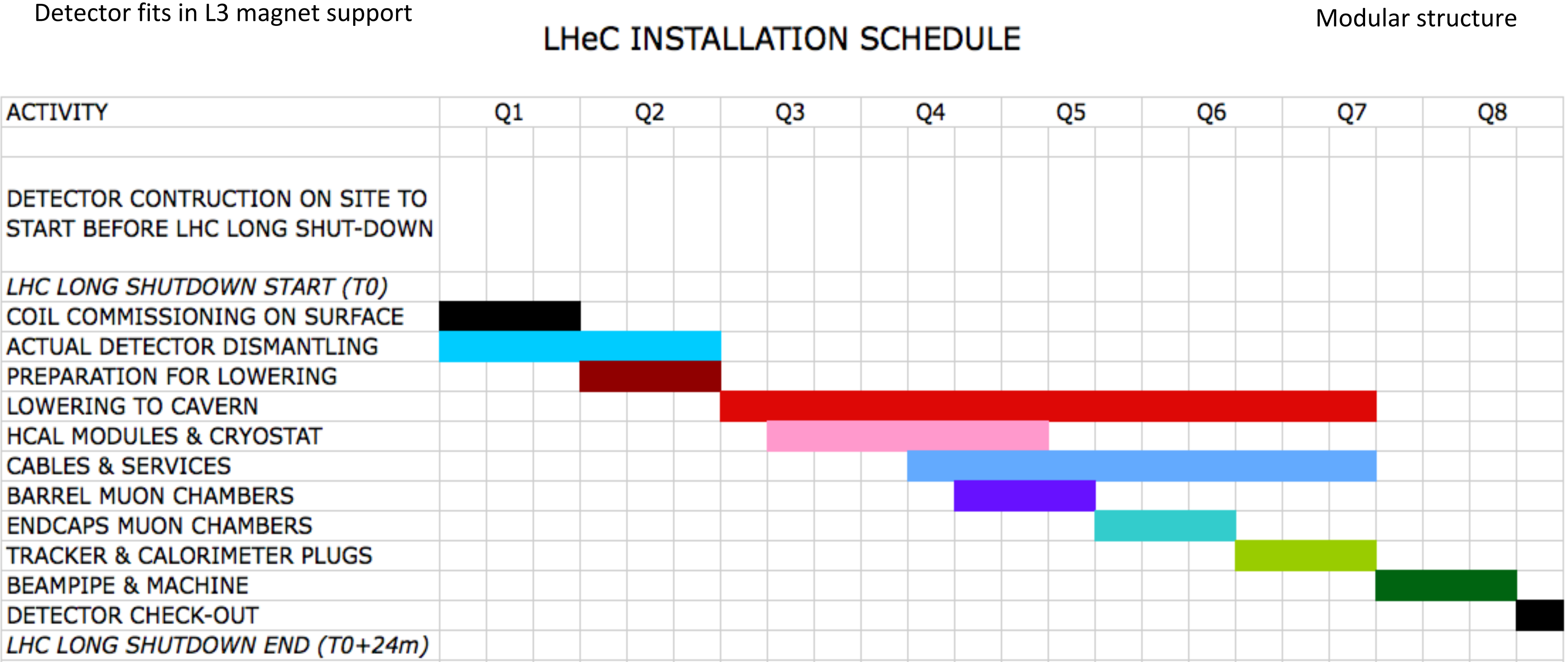
Andrea Gaddi et al



Detector fits in L3 magnet support



Modular structure

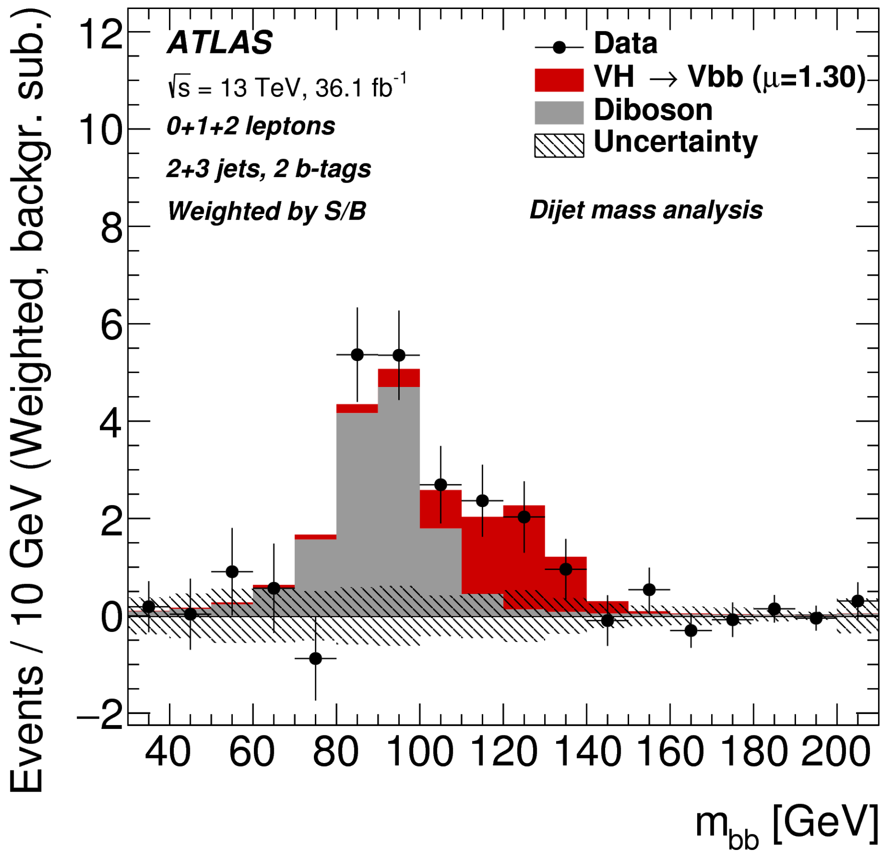


LHC: First 3σ Hbb Evidence!

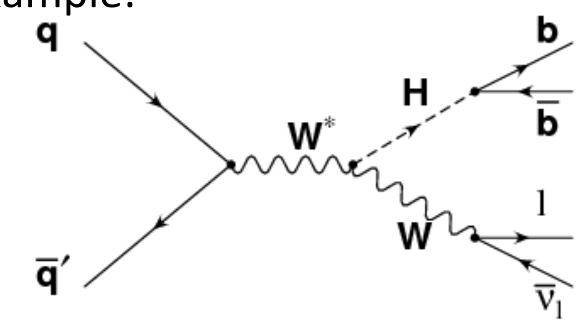
ATLAS, Aug 2017, sub. to JHEP

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**