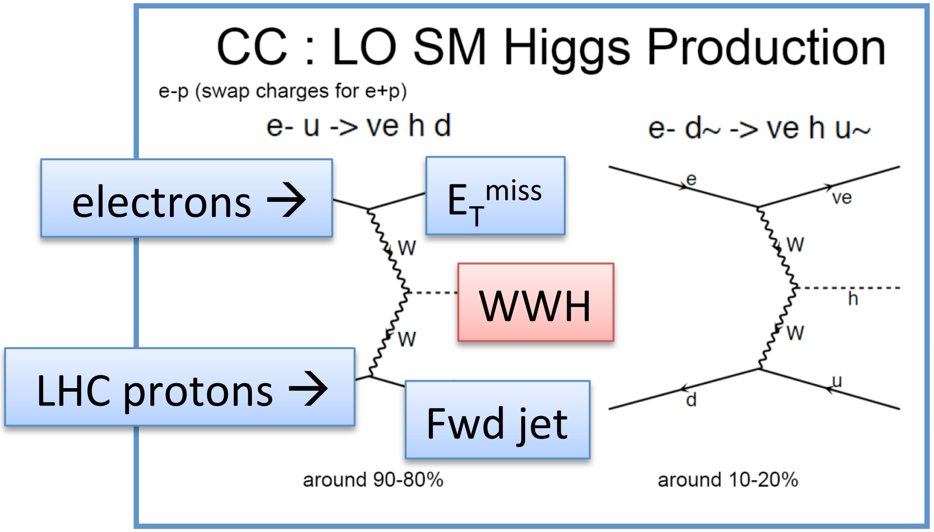
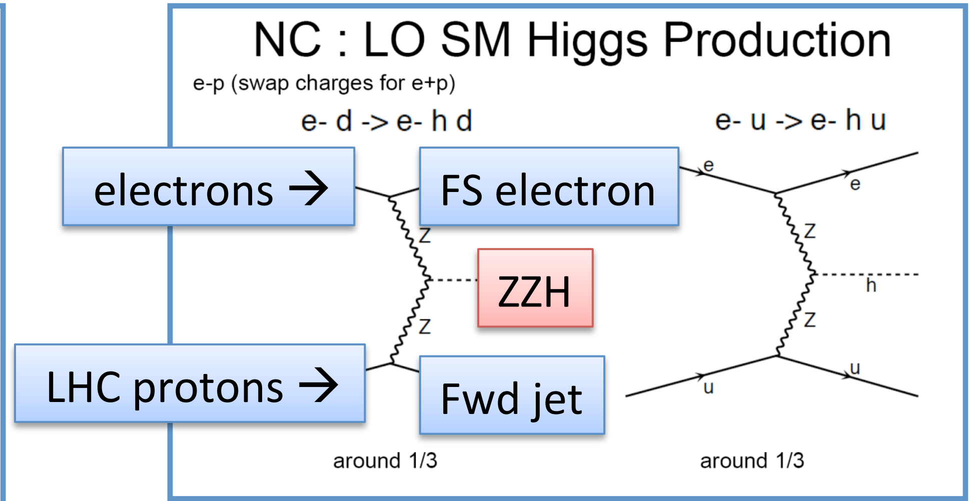
FCC-he
Update on SM Higgs Studies

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

2nd FCC Physics Week 2018, CERN, January 16th, 2018

SM Higgs Production in ep





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

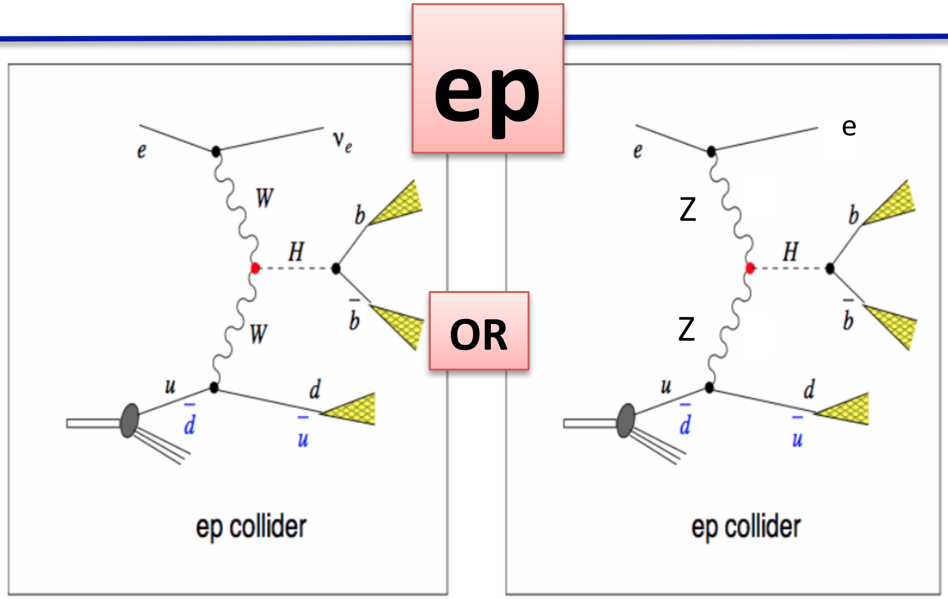
Total cross section [fb]
(LO QCD CTEQ6L1 M_H=125 GeV)

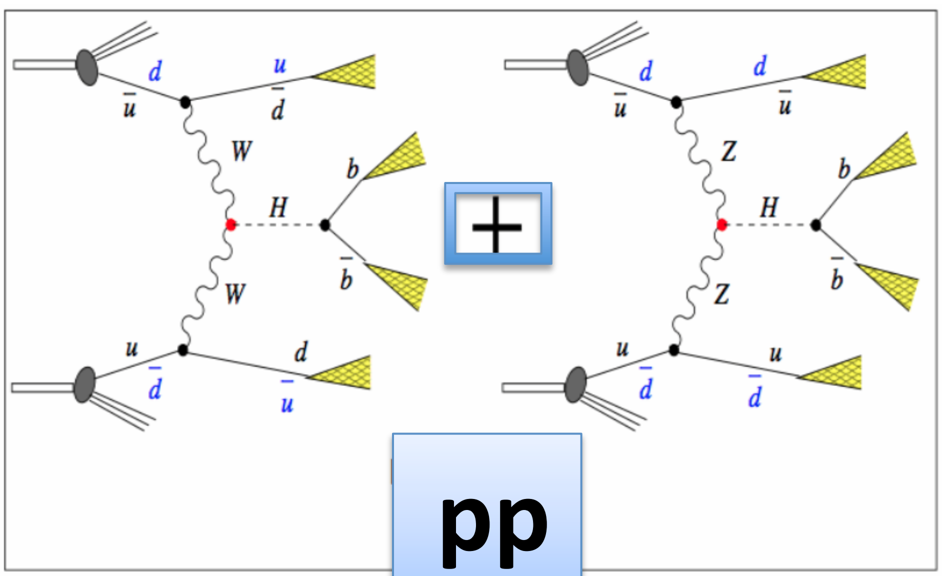
c.m.s. energy	1.3 TeV LHeC	3.5 TeV FCC-he
CC DIS NC DIS	109 21	560 127
P=-80% CC DIS NC DIS	 **196** **25**	 **1008** **148**

- **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]

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 bb final state, 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

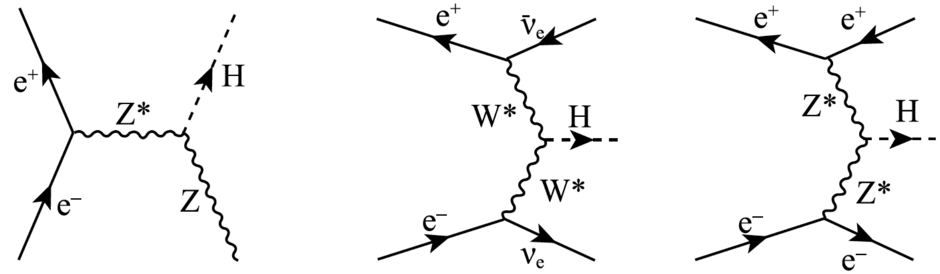
<u>VBF: Small theoretical uncertainties!</u>

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).

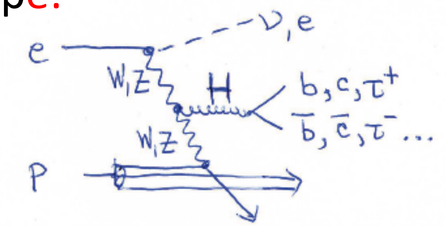
Pile-up in pp at 5 10^{34} cm^{-2} s^{-1} is 150@25ns
FCC-hh: pile-up 500-1000
S/B very small for bb
Final Precision in pp needs accurate N^3LO PDFs & α_s

Higgs in ee vs pe

ee: Dominant Higgs productions



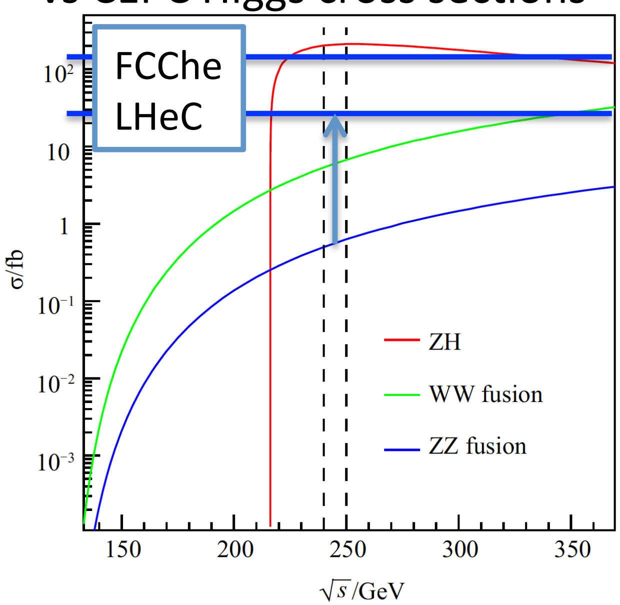
pe:

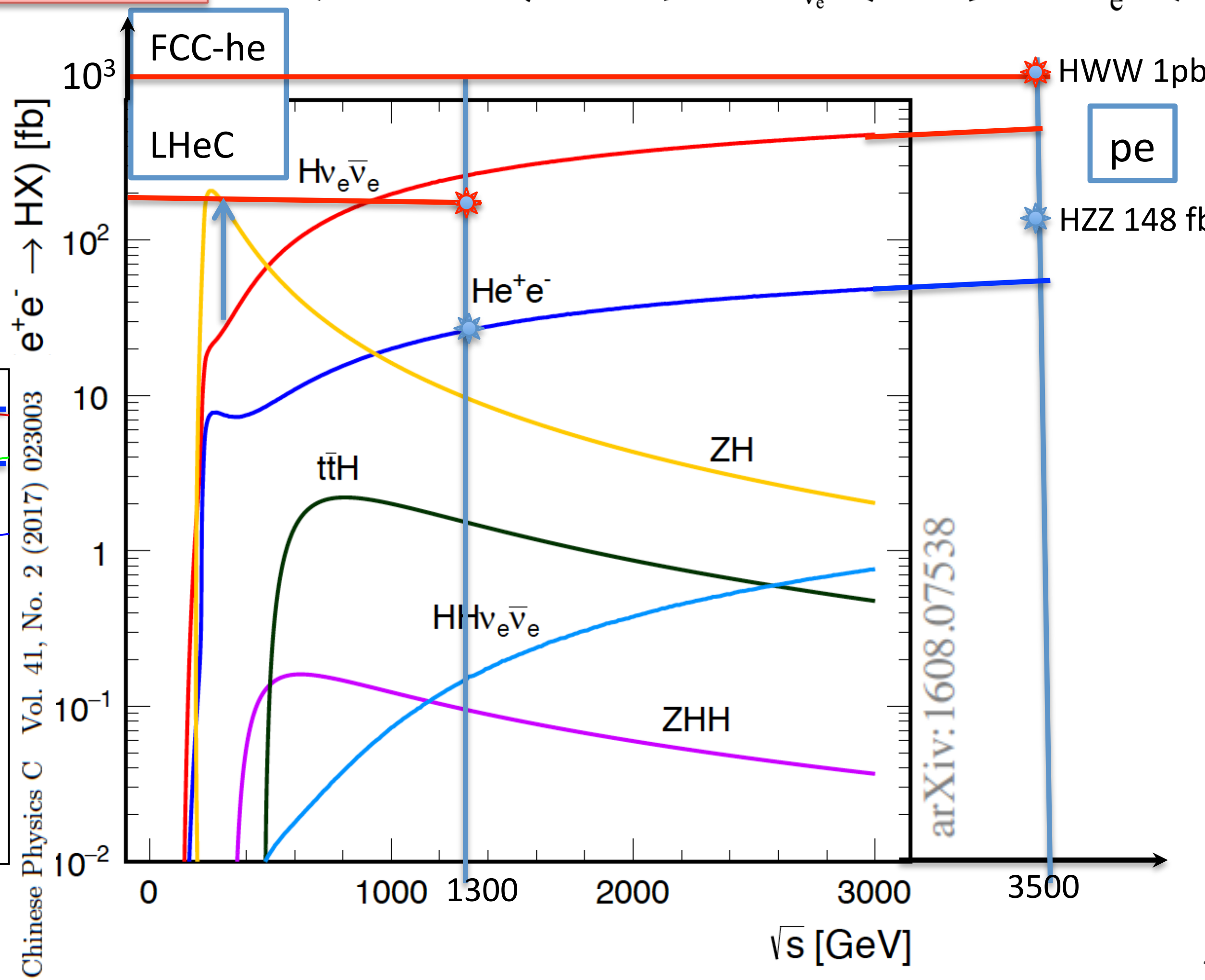


pe:WW Fusion

pe: ZZ Fusion

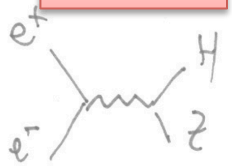
vs CEPC Higgs cross sections





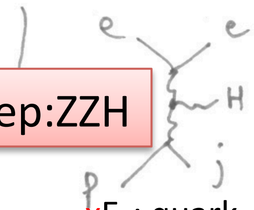
Kinematics and M_H : ee vs pe

ee: ZZH



e^+e^-

ep:ZZH



ep

$J_e := (e+j)$

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

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

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

$$\leadsto\ 2E_e = E_H + E_Z$$

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

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

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

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

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

ee: x=1 no PDF or form factor involved

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

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

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

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

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

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

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 LESSONs:

It was found very important to use sophisticated tools like various Neural Networks and kinematic fitting of the Higgs mass;

And: it is crucial to reach high luminosity and excellent detector performance!

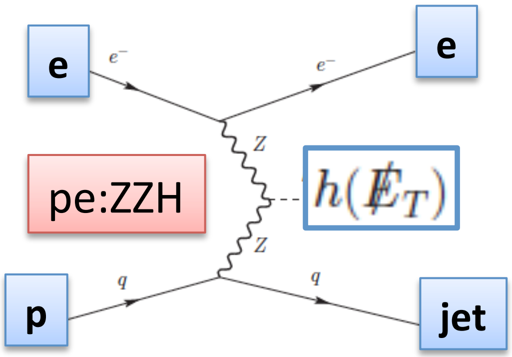
→ certainly very interesting to follow up for pe as well, but obviously non-trivial

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	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 look very encouraging for a measurement of the branching of Higgs to invisible in ep down to 1.7% to 1.2% for 1 to 2 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**

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

Baseline: **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**

➔ **used for extrapolations to FCC-he**

√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%**

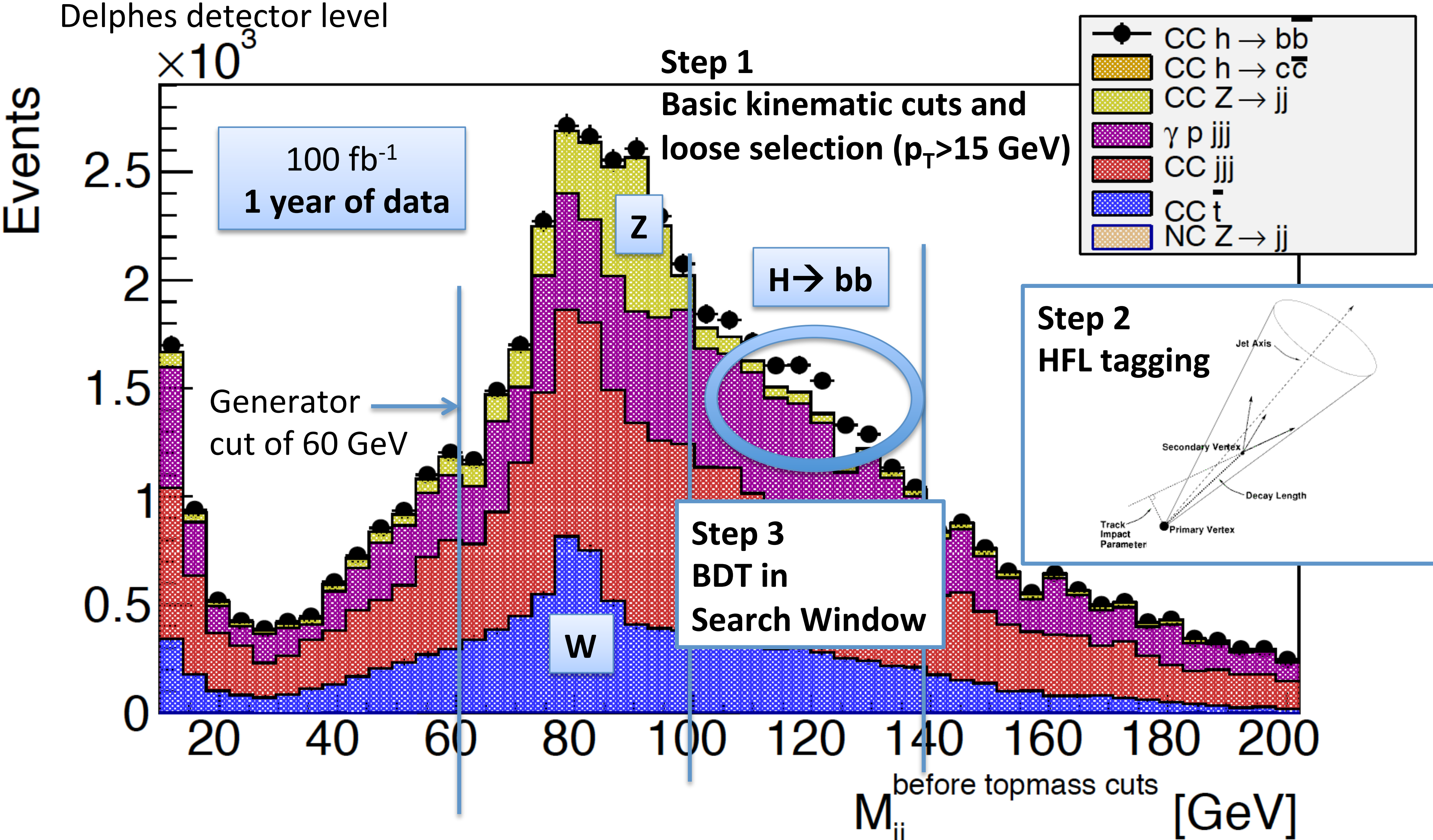
Higgs decay to charm is factor 20 less likely than Hbb

pp: perfect Higgs factory for gluon-induced rare decays

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

Dijet Mass Candidates *HFL untagged*

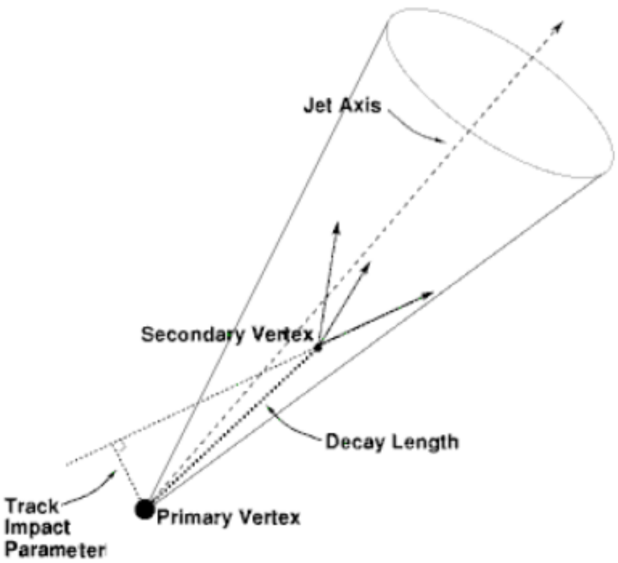
Delphes detector level

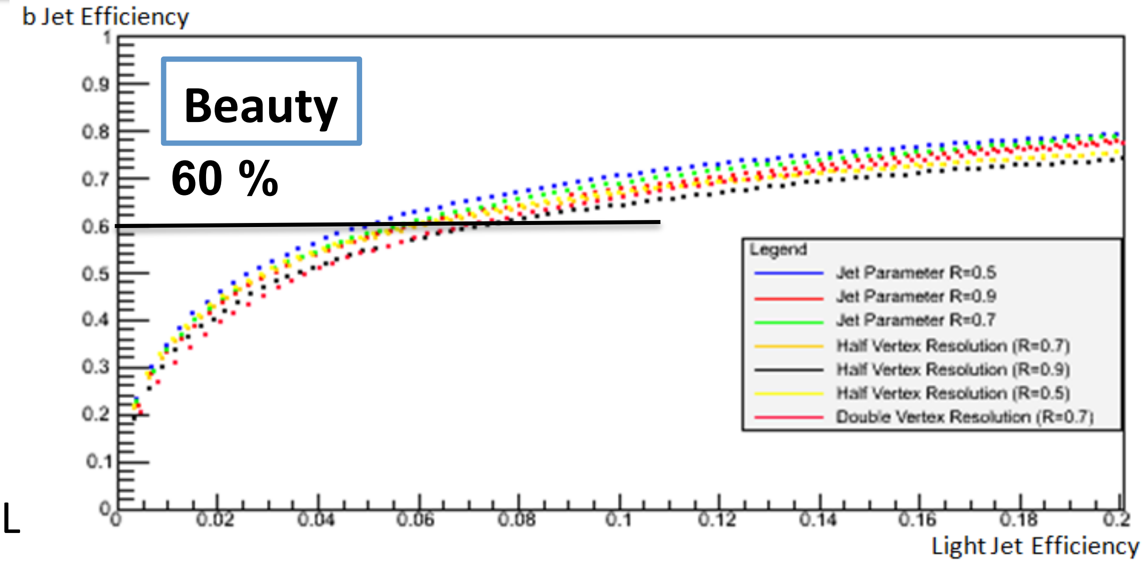


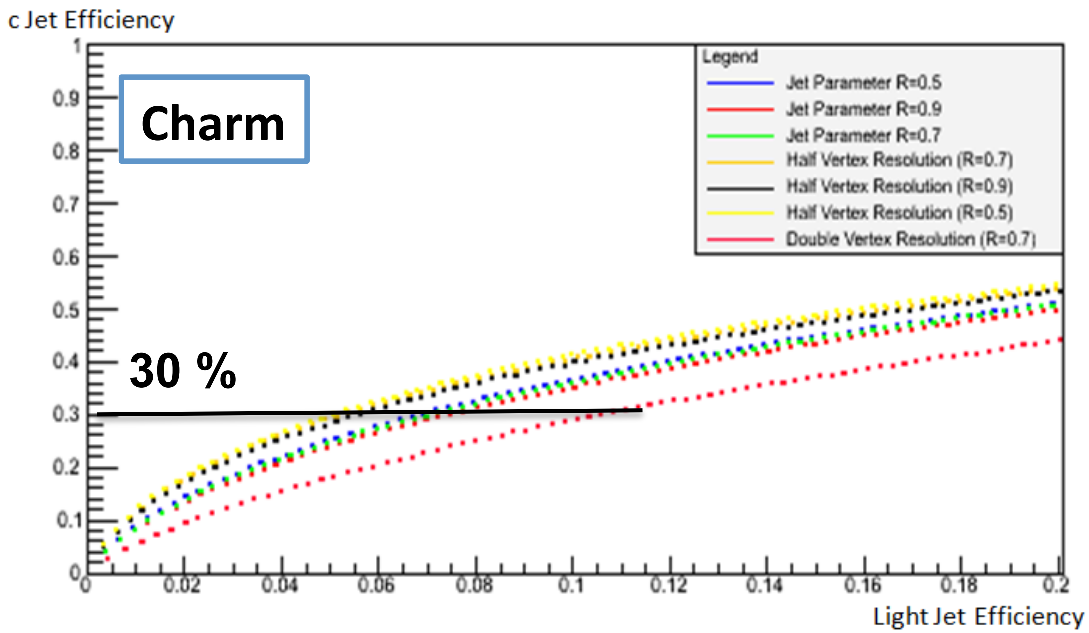
'Worst' case scenario plot : Photoproduction background (PHP) is assumed to be 100%!
→ However, addition of small angle electron taggers will reduce PHP to ~1-2%

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

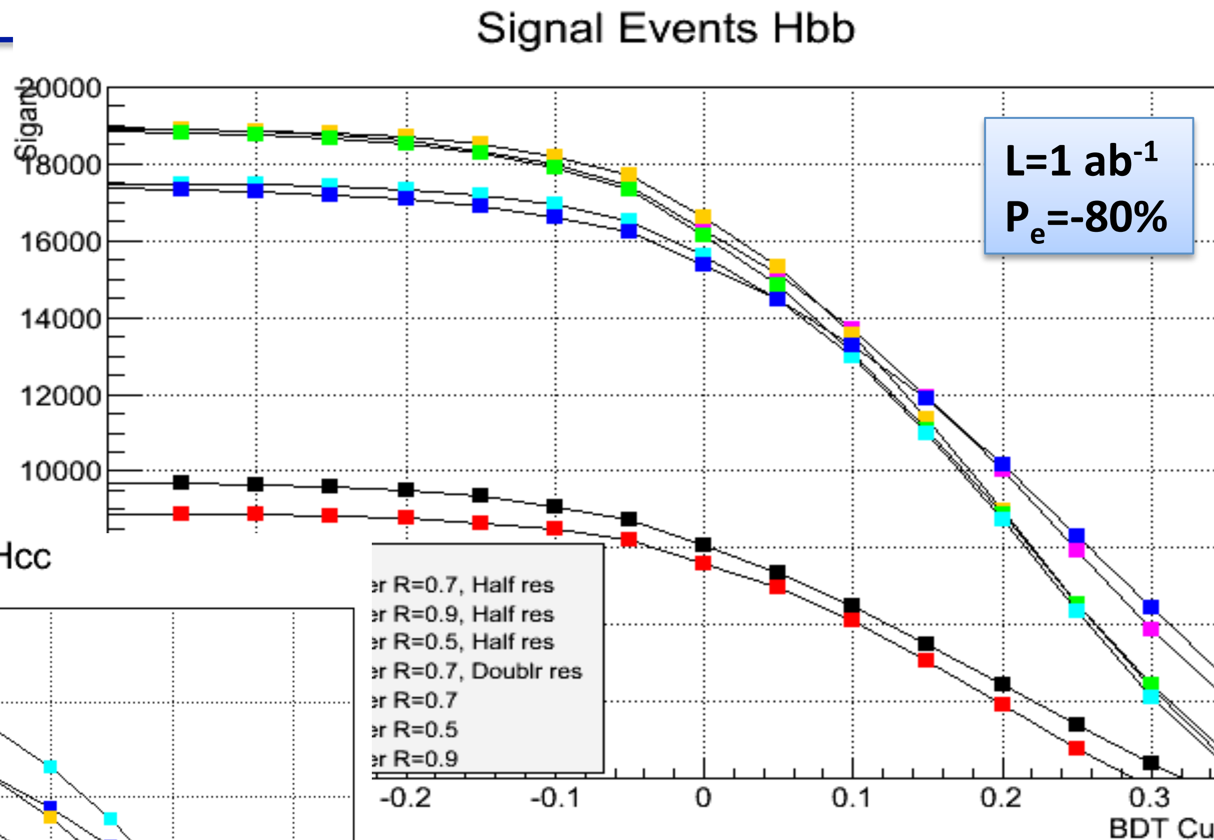
→ Light jet rejection very conservative, i.e. factor 10 worse than ATLAS

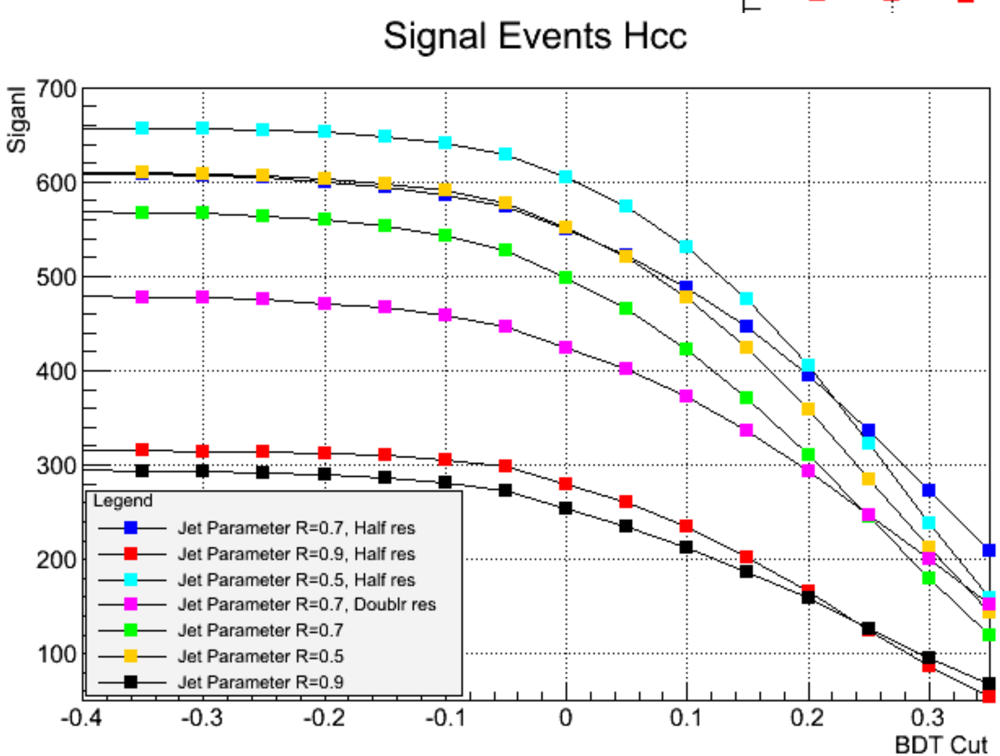
→ **used in full LHeC analysis and for FCC-eh extrapolations**

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



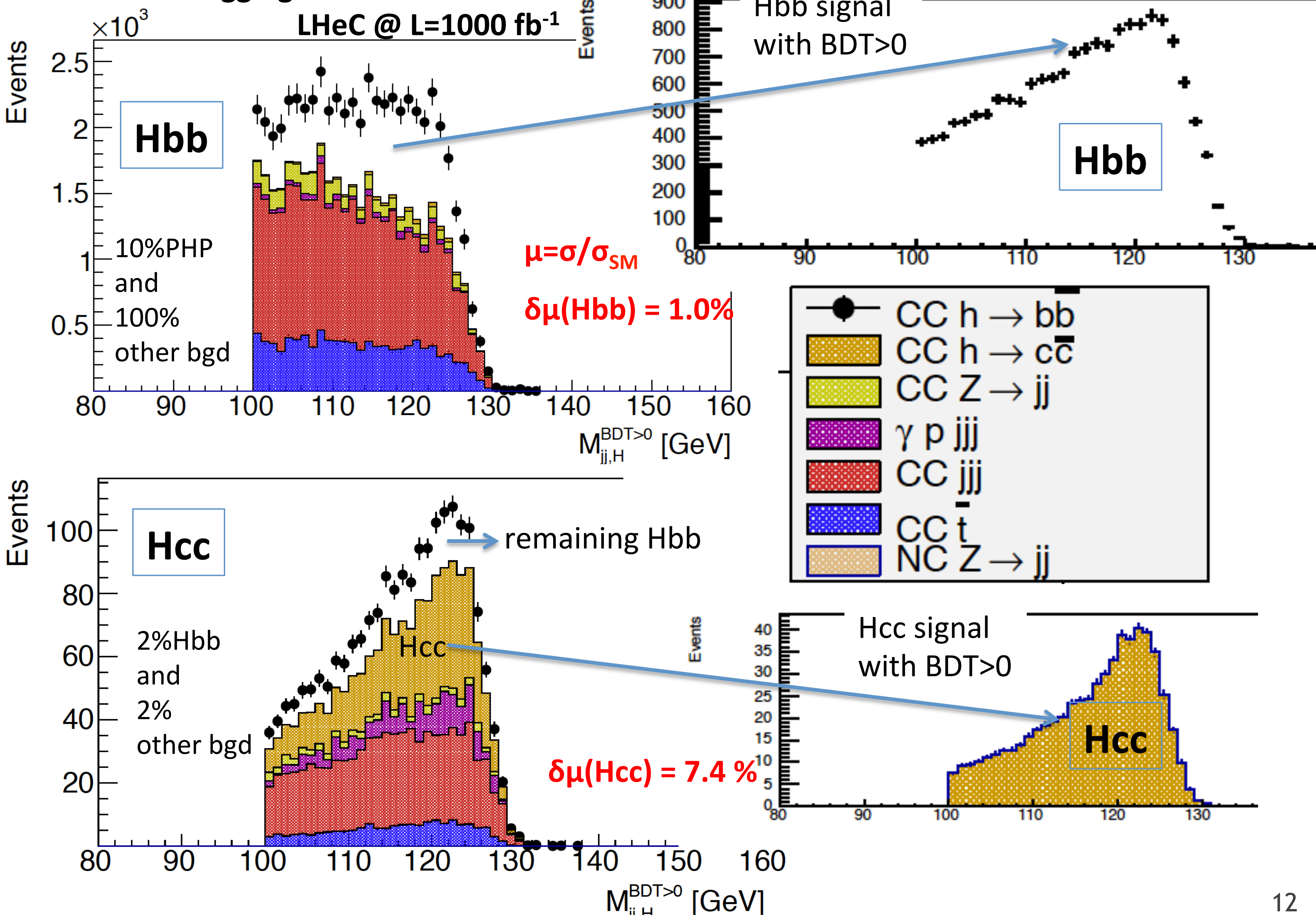


Hcc : High sensitivity to vertex resolution (nominal 10 μm) and jet radius

→ expect about 400-600 Hcc candidates

realistic HFL tagging & BDT

Uta Klein & Daniel Hampson

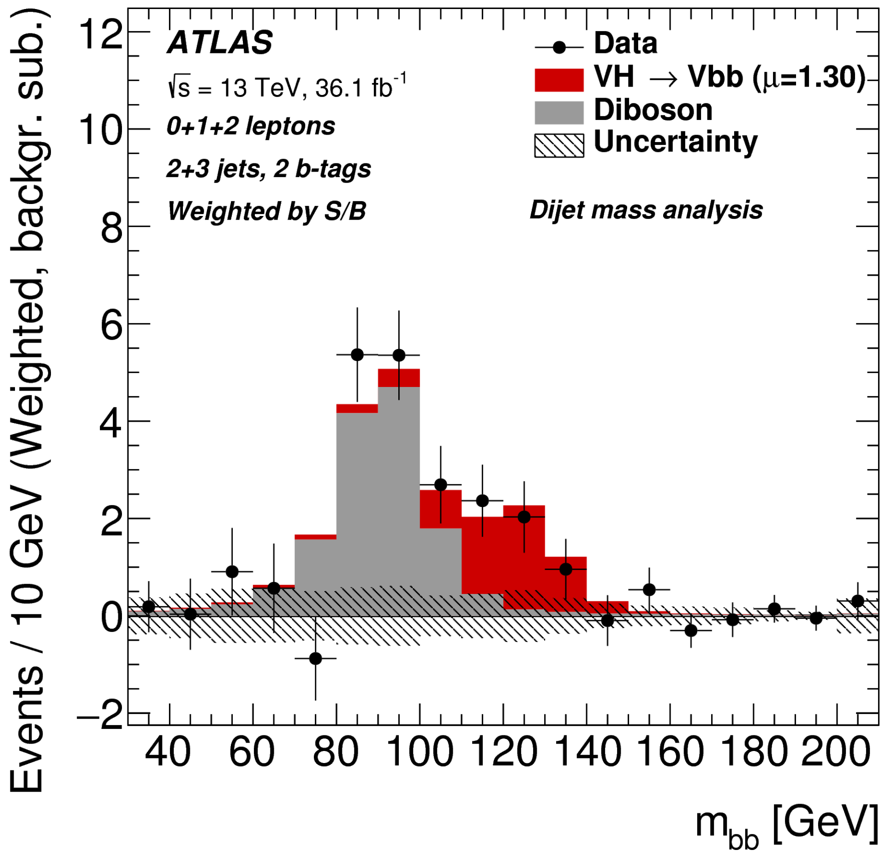


LHC: First 3σ Hbb Evidence!

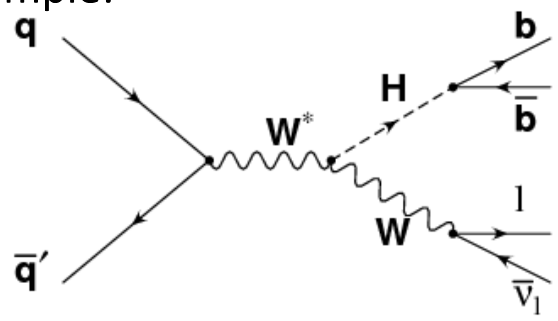
ATLAS, Aug 2017, sub. to JHEP

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:



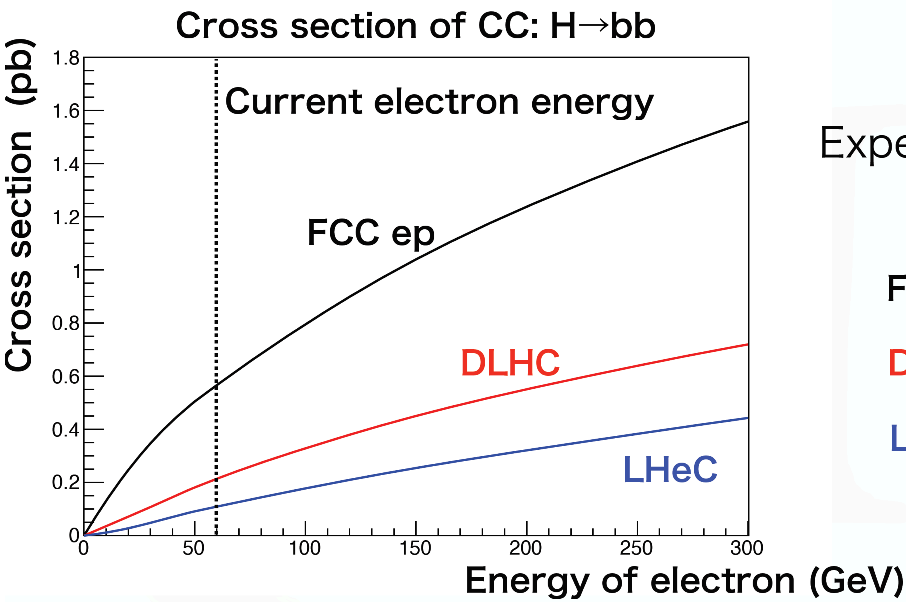
- ✓ Encouraging result for HL-LHC prospects
- ✓ **Very encouraging for prospects in ep that we can handle S/B ~10^{-3} processes with sophisticated analysis techniques**

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

SM Higgs into HFL Summary

Uta Klein et al.

- 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 $\sqrt{s}$ ~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%

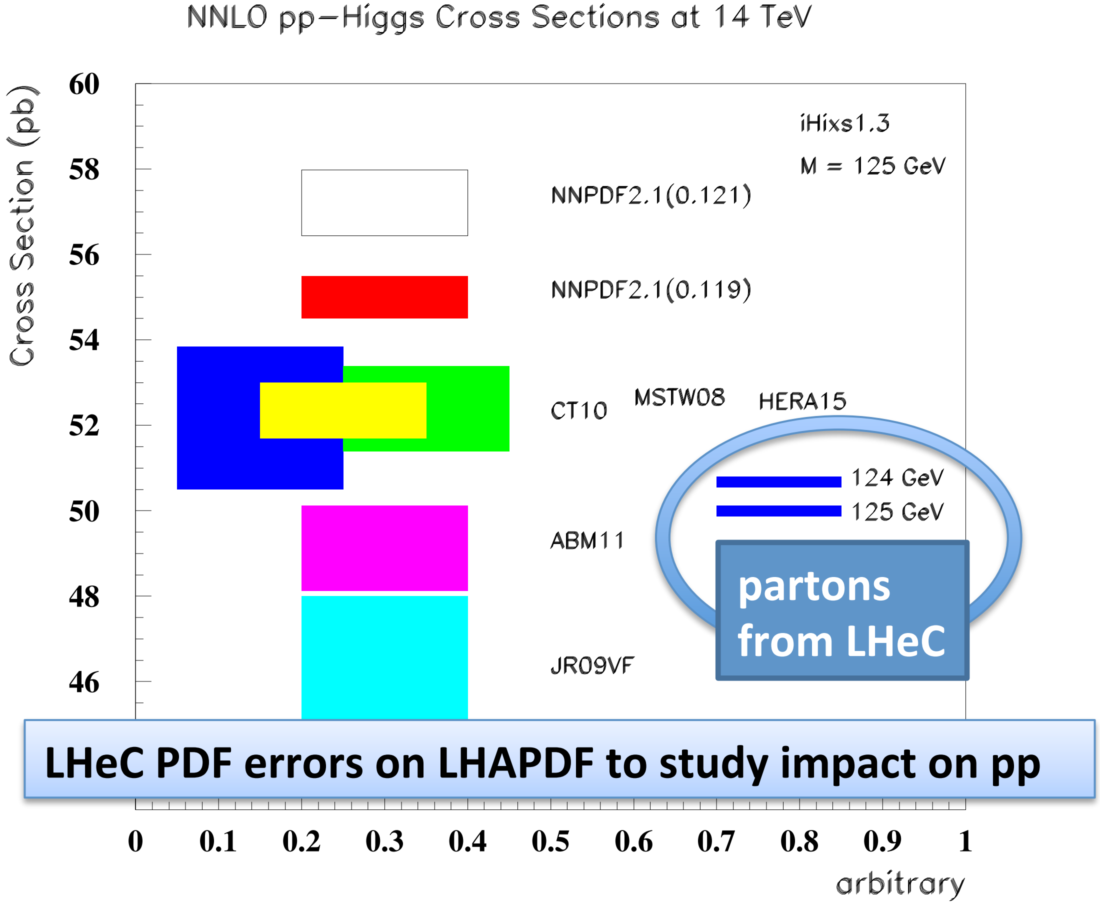
See also talk by C Gwenlan

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%**

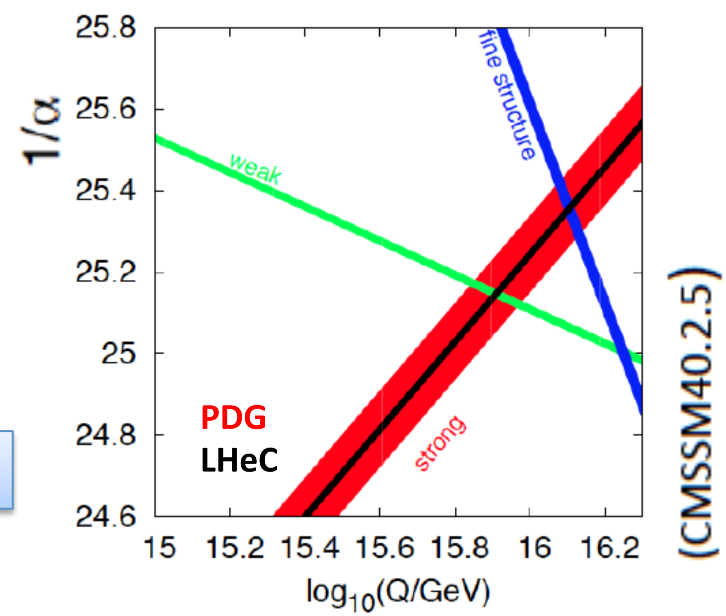
→ ***theoretically clean path to determine N³LO PDFs*** using ep DIS

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



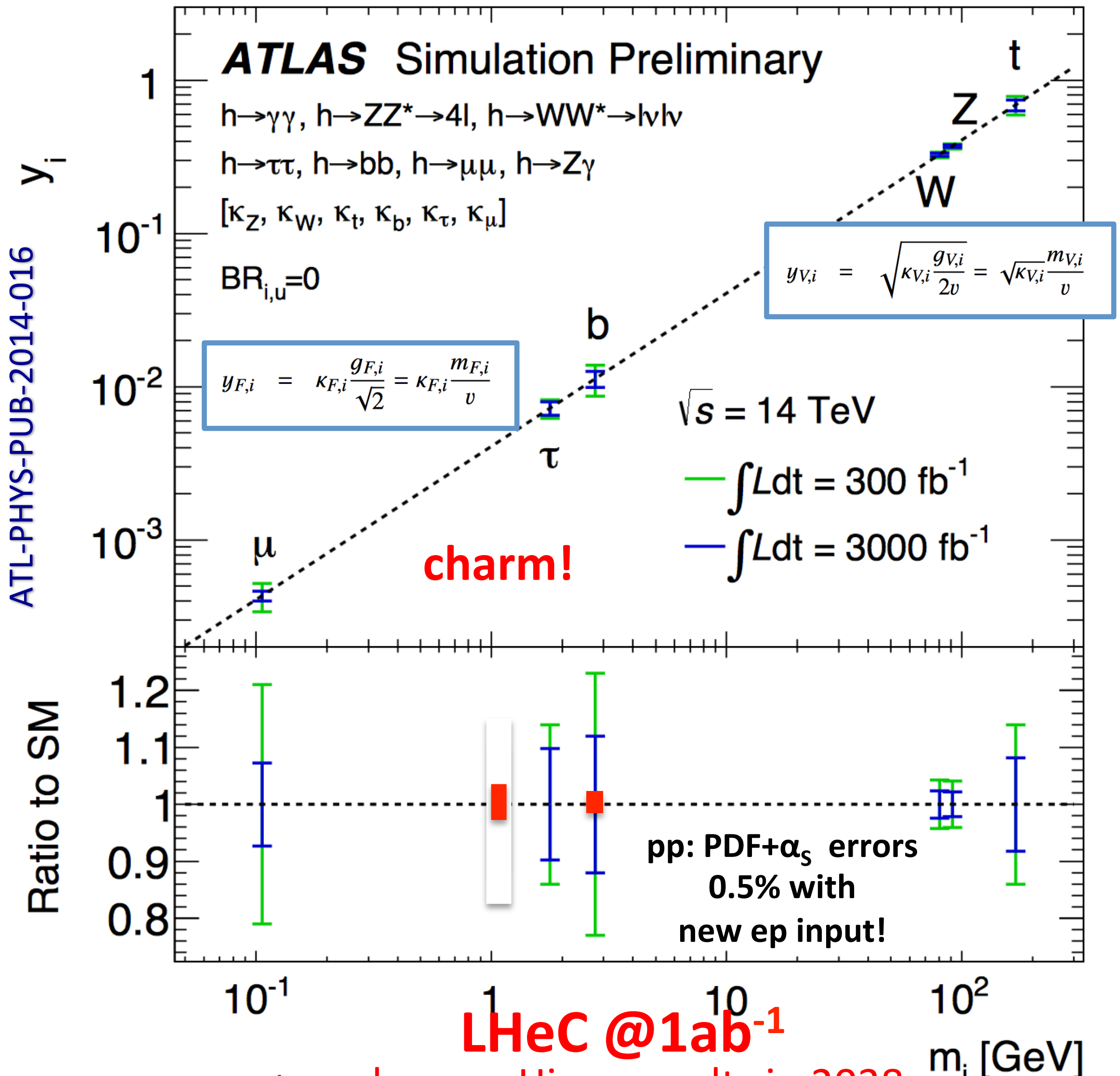
LHeC PDF errors on LHAPDF to study impact on pp

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



Higgs Couplings at pp + ep

After HL-LHC and LHeC running in parallel for 10 years

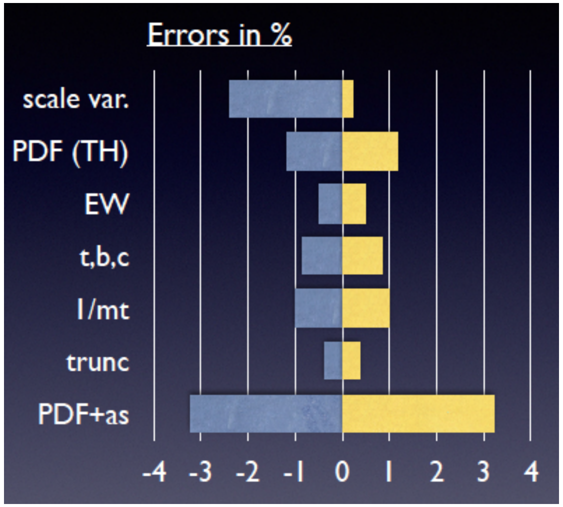


+much more Higgs results in 2038 …

top, W, Z , τ , …under study

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..



Already with the first ~100 fb^{-1}

→ use ep as the 'near' detector for pp to beat the α_s and PDF uncertainties from ~3% to <~0.5%,

→ δm_b to 10 MeV; δm_{charm} to 3 MeV

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}]

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

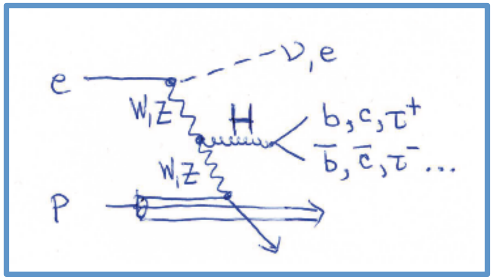
- Calculate uncertainties of signal strengths w.r.t. SM expectation $\mu = \frac{\sigma}{\sigma_{SM}}$

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

CC DIS WWH → H

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

	bb	WW	gg	ττ	cc	ZZ	γγ
BR	**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**	**3.23**
$\delta\kappa = \frac{1}{2}\frac{\delta\mu}{\mu}$	0.14	0.61*	0.89	0.83	1.18	1.97	2.37



→ Sum of first 6 branching fractions that could be measured

LHeC : 0.9964 +- 0.02

FCChe: 0.9964 +- 0.01

pp: < 0.99 → cc? gg?

Further coupling constraints to be explored:

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

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

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

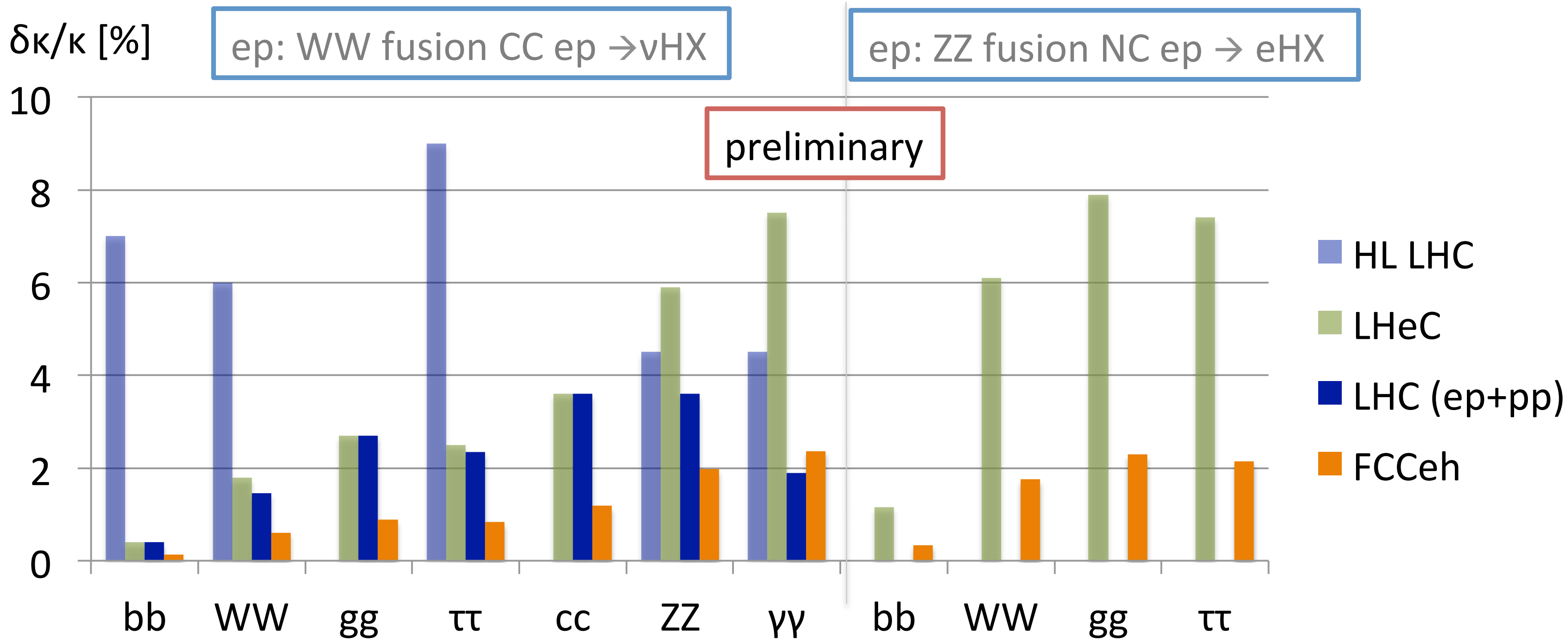
$$\sigma(WW \to H \to gg) \propto \kappa^2(HWW) \bullet \kappa^2(Hgg)$$

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

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

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

Higgs SM Coupling Prospects: pe+pp



HL LHC: ATLAS-PUB-2014-016 14 TeV 3ab^{-1} – LHC has no gg, no cc, and poor bb, but rare channels as γγ
LHeC: 1ab^{-1}, 60 GeV x 7 TeV - Work in progress. ep also provides precise: xg, α_s and PDFs to N^{3}LO..
LHC (ep+pp): HL LHC with reduced theory uncertainty combined with LHeC –**running in parallel**
FCCeh: 2ab^{-1}, 60 GeV x 50 TeV - Work in progress. ep also provides precise: xg, α_s and PDFs to N^{3}LO..

Improvements: ATLAS 2014 conservative, no CMS. ep (LHeC/FCCeh) are overconstrained:
CC+NC, ratios, sum(br)=1.. → joint coupling determination: especially WW and ZZ should improve

Please take home:

- **We just got a first glance on the exciting combined ep+pp Higgs potential to constrain the sum of most important SM Higgs branching fractions to 1+-1%, i.e. with a precision of the dominant couplings to sub-percent level.**
- **An ep collider would complement the most powerful pp machines by providing invaluable high precision proton structure data required for high precision PDF, α_S and N^3LO.**

- **For the FCC CDR : Quantify in a consistent way the joint Higgs coupling measurement potential**

→ **fix the assumptions and benchmark**, e.g. add also ttH and HH

→ **pp: use ep PDFs and α_S to estimate error reduction**

→ **combined analysis of pp and ep cross sections to constrain SM (and BSM) Higgs scenario's and to design the *most powerful and sustainable* search complex at the energy frontier.**

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/
- Higgs branching fractions and uncertainties taken from : https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR2014

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.

Additional material

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 FCCeh detector

↓

S/B analysis → cuts or BDT

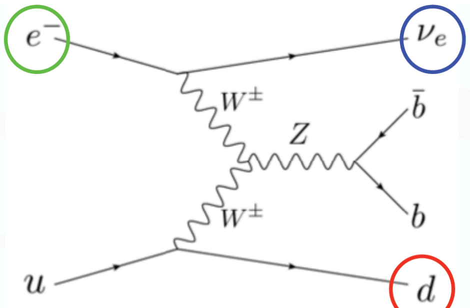
- Calculate cross section with tree-level Feynman diagrams (any UFO) using pT of scattered quark as scale (CDR ŝ) for ep processes with **MadGraph5**
- Standard HERA tools can NOT to be used !
- **Higgs mass 125 GeV as default**
- Fragmentation & hadronisation uses **ep-customised** Pythia.
- **Delphes '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

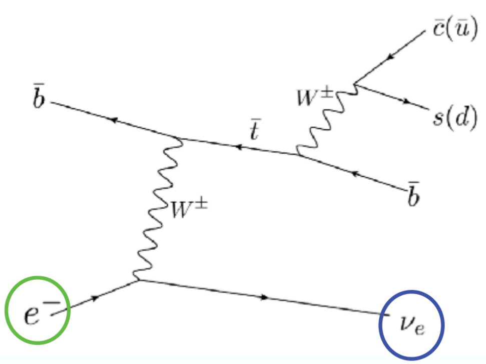
→ Ongoing : Integration of FCCeh into FCC simulation framework

SM Higgs Decay into b-quarks

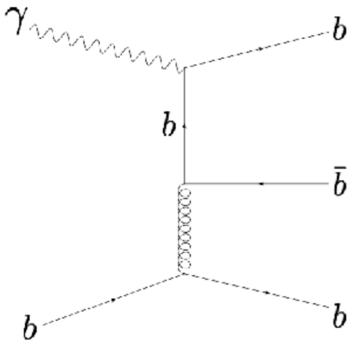
- Typical background processes



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

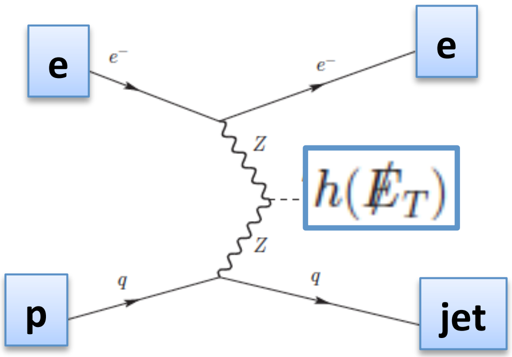
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

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

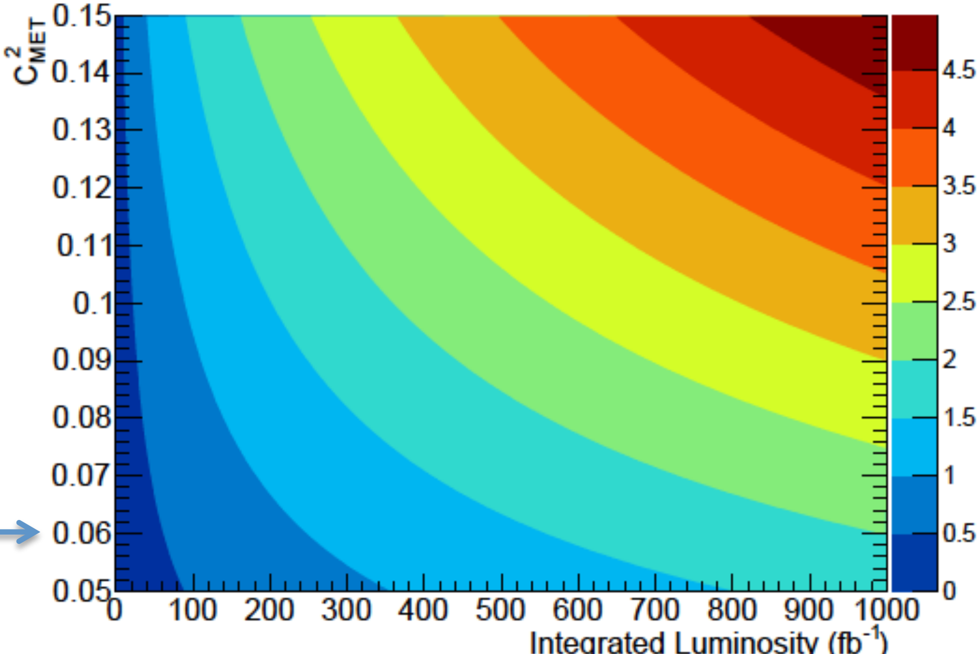
For **LHeC**, assume : 1ab^{-1}, P_e=-0.9, cut based

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

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



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**