SM & BSM Higgs Physics at the LHeC and FCC-eh

Chen Zhang (张宸) (NCTS)

On Behalf of the LHeC Higgs Group

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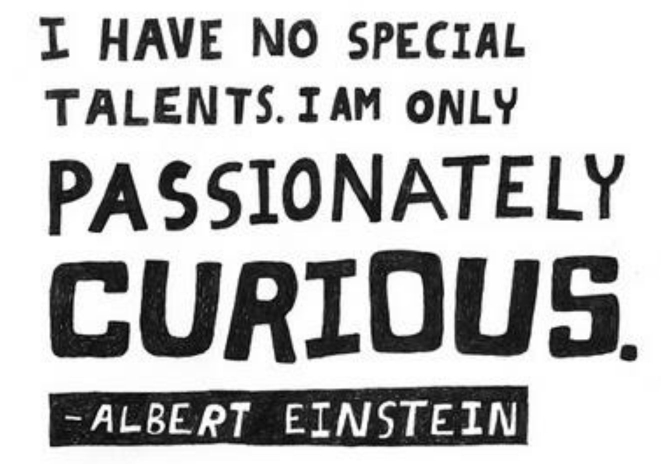
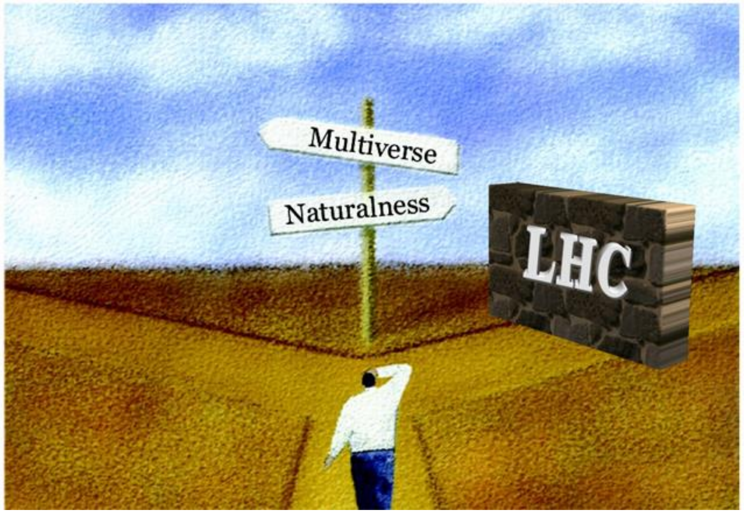
Motivation for Higgs Physics

- A most precise determination of the Higgs properties will be a glorious landmark of human civilization that undoubtedly exhibits the meaning of human existence.
- =>**Fundamental Curiosity**



Collider

- A most precise determination of the Higgs properties will shape our understanding of the universe in a deepest possible manner.
- =>**Fundamental Paradigm**

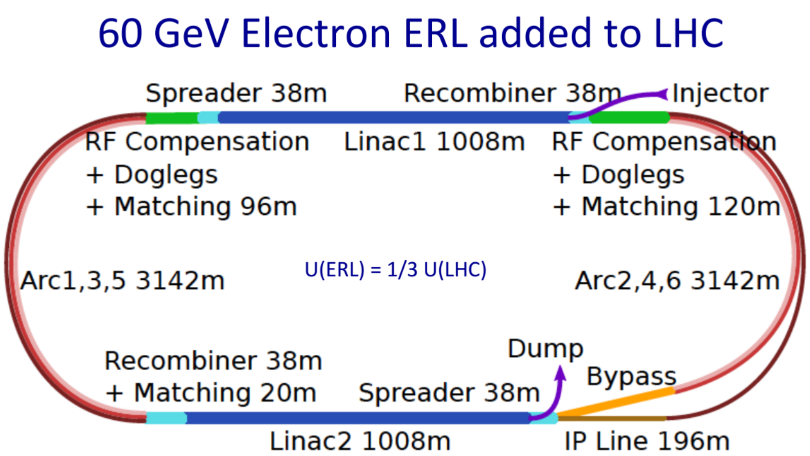


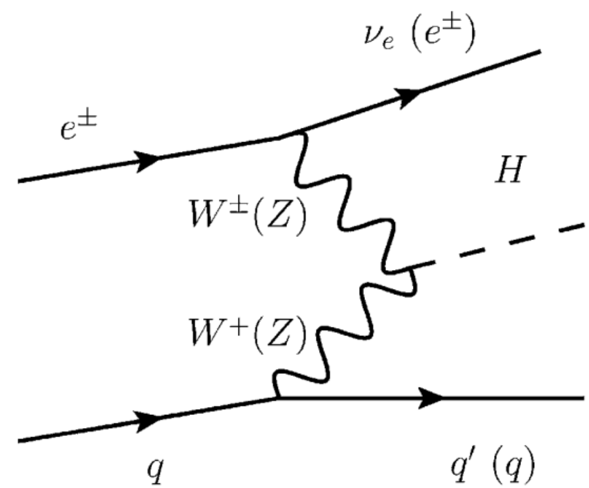
Collider Type Consideration

- Hadron Colliders: (HL-)LHC, FCC-hh
  - Large signal cross sections but not-so-clean environment
- Electron-Positron Colliders: FCC-ee, CEPC, ILC, CLIC
  - Small signal cross sections but clean environment
  - Ideal for Higgs studies in many channels
  - Project schedule/availability is subject to large uncertainties
- Lepton-Hadron Colliders: LHeC (Large Hadron Electron Collider), FCC-eh
  - Signal cross sections comparable to lepton colliders
  - Much cleaner than pp => suited for improving dirty channels at pp
  - Expected to run synchronously with the corresponding pp machine
  - Cost much less than a fully new lepton collider

LHeC and FCC-eh

- LHeC:
  - 60 GeV electron (with -0.8 polarization) times 7 TeV proton (√s=1.3TeV)
  - Expected to run synchronously with the HL-LHC, integrated luminosity ~1ab^{-1}(default)
  - Higgs production: **WW fusion~200fb, ZZ fusion~25fb**

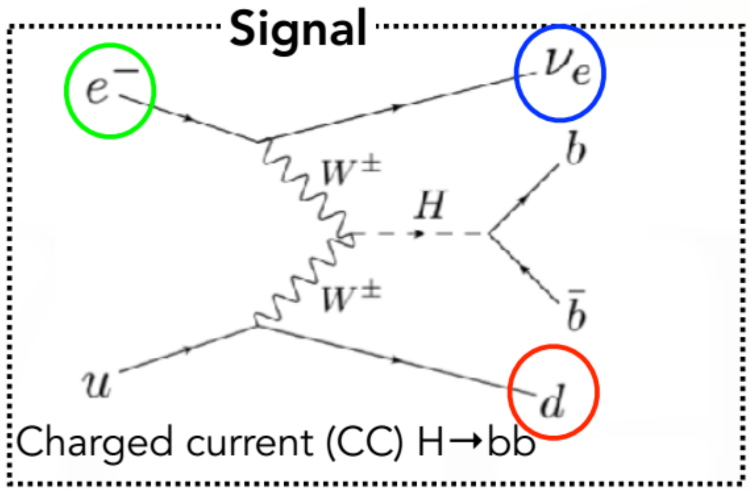


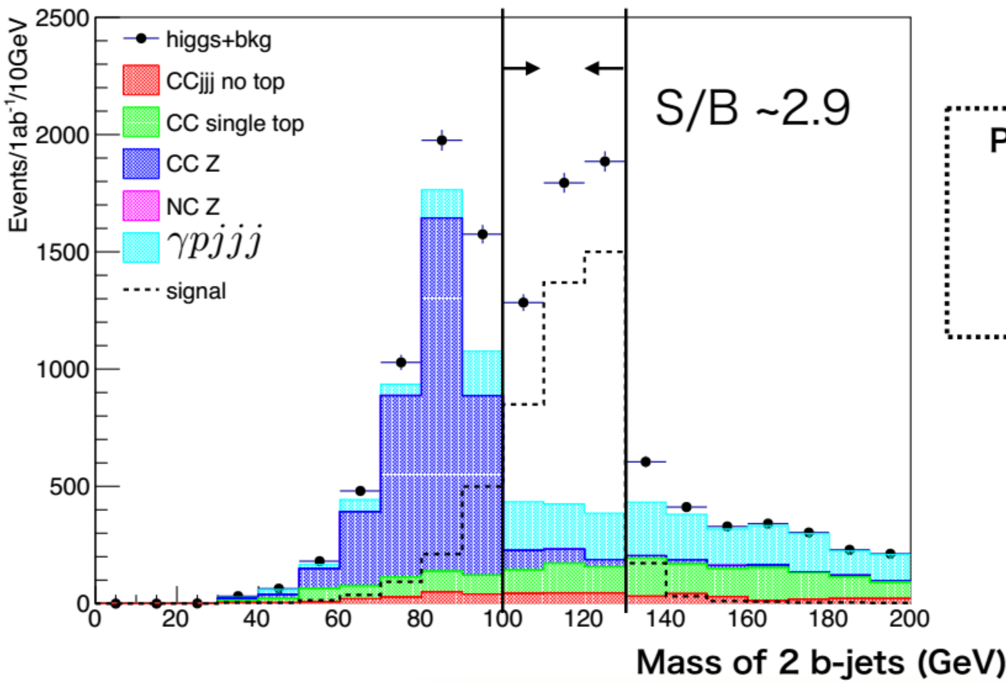


- FCC-eh:
  - 60 GeV electron (with -0.8 polarization) times 50TeV proton (√s=3.5TeV)
  - Expected to run synchronously with the FCC-hh, integrated luminosity ~O(1)ab^{-1}
  - Higgs production: **WW fusion~1000fb, ZZ fusion~150fb**

Higgs to bb at the LHeC: Cut-Based Results

- Higgs to bb at the LHeC: using CC channel, detector-level cut-based study performed by M. Kuze & M. Tanaka.
- Forward electron tagging vetoes 90% of PHP backgrounds.





Precision of coupling constant (Statistics error only)

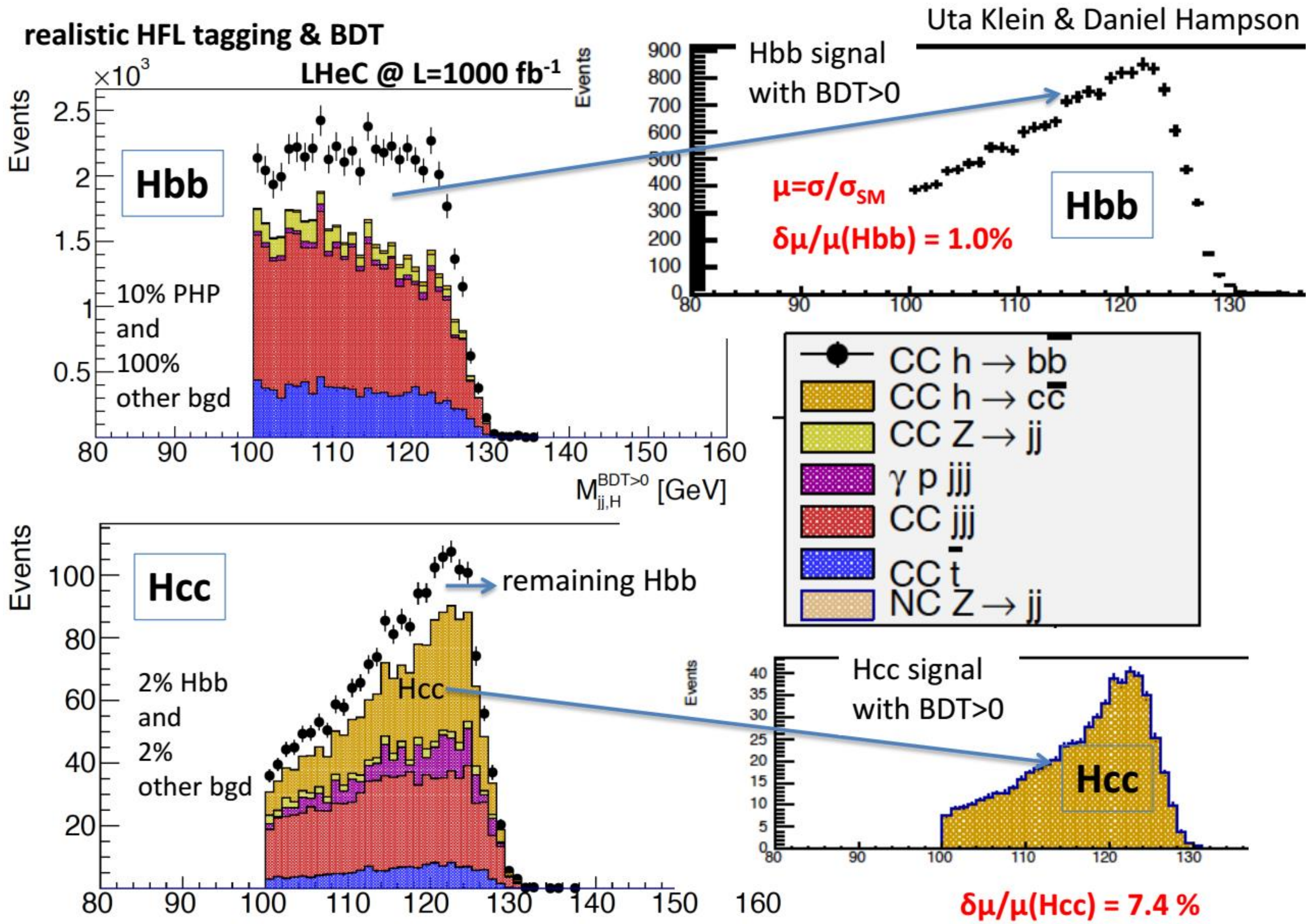
$$\kappa = \frac{\sqrt{N_s + N_b}}{2N_s}$$

Signal: 3600

Bkg: 1250

κ (Hbb) ~ 0.97%

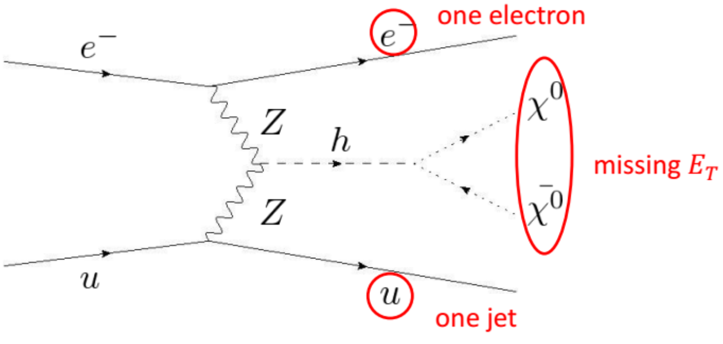
Higgs to bb/cc at the LHeC: BDT Analysis



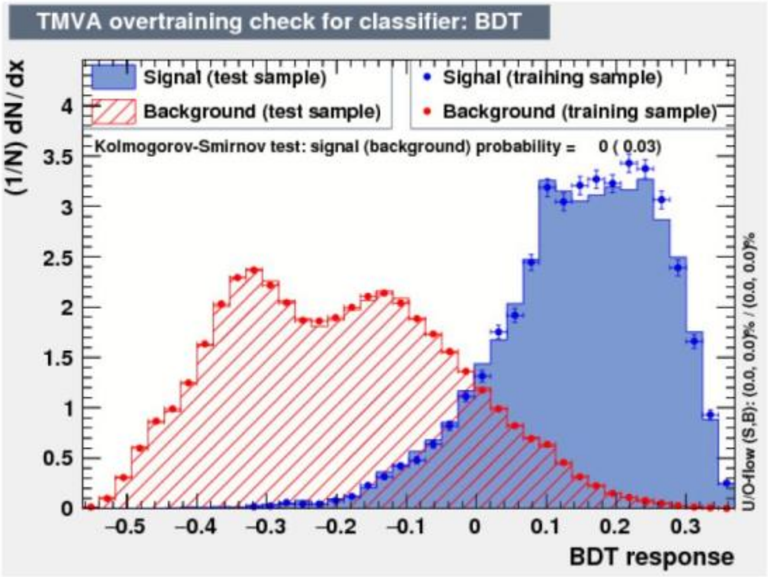
➔ Main systematic checks: variations of background contribution and tagging efficiencies

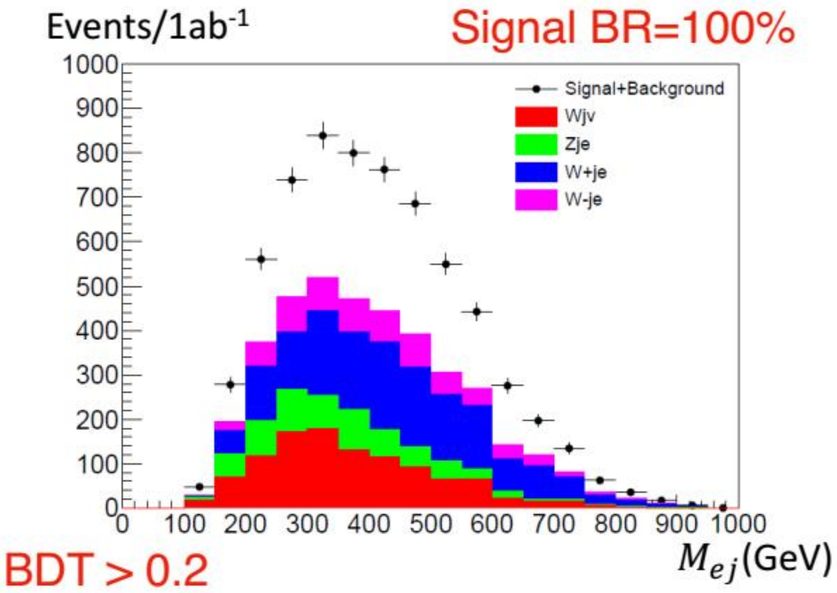
Invisible Higgs Decay at the LHeC & FCC-eh

- Invisible Higgs Decay: Important constraint on DM
  - Using ZZ fusion channel, signature: electron+jet+MET
  - No counterpart of QCD Vjj backgrounds
  - 2σ upper limit at LHeC: BR~5.5% (BDT Analysis)
  - 2σ upper limit at FCC-eh: BR~1.7% (BDT Analysis)



Parton level study: Tang, Zhang and Zhu, PRD94, 011702(R)(2016) BDT study: M. Kuze, S. Kawaguchi, T. Sekine

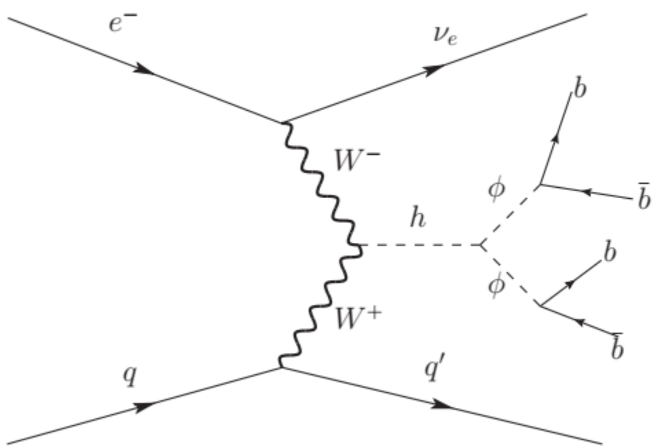


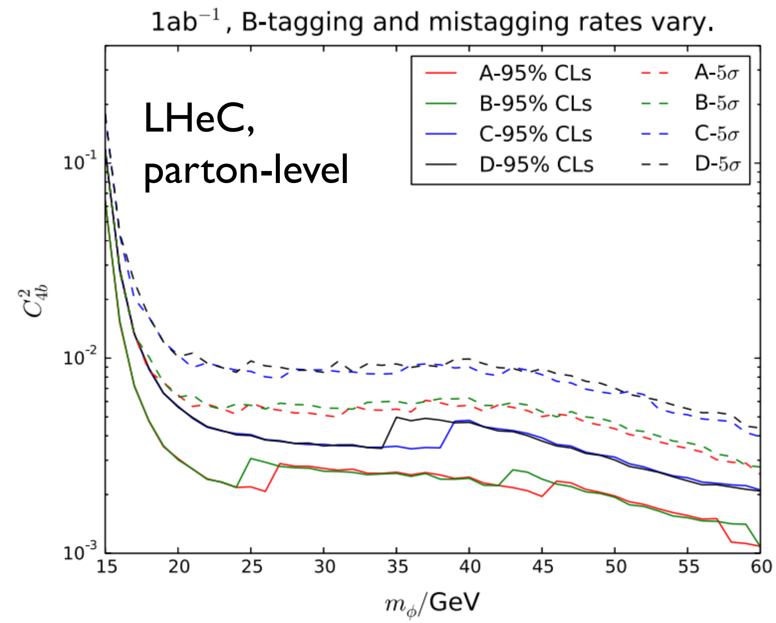


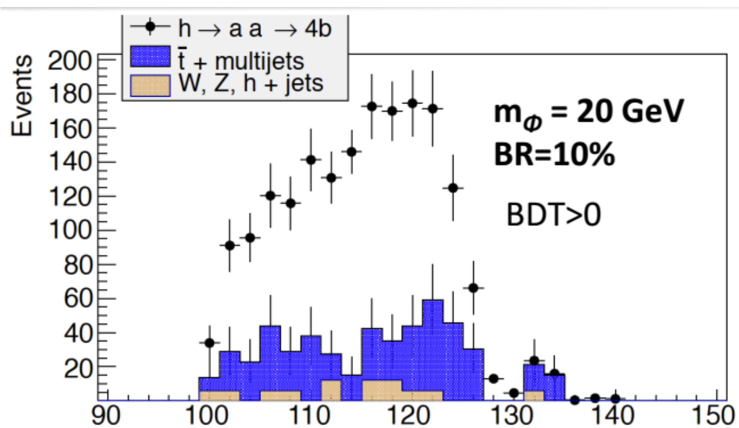
Exotic Higgs Decay h→2φ → 4b at the LHeC and FCC-eh

- Exotic Higgs Decay h→2ϕ → 4b: Well-motivated, Difficult at (HL-)LHC

LHeC parton level study: Liu, Tang, Zhang, Zhu, EPJC(2017)77:457







$1ab^{-1}$, FCC-eh, detector level study: U. Klein, M. o'Keefe

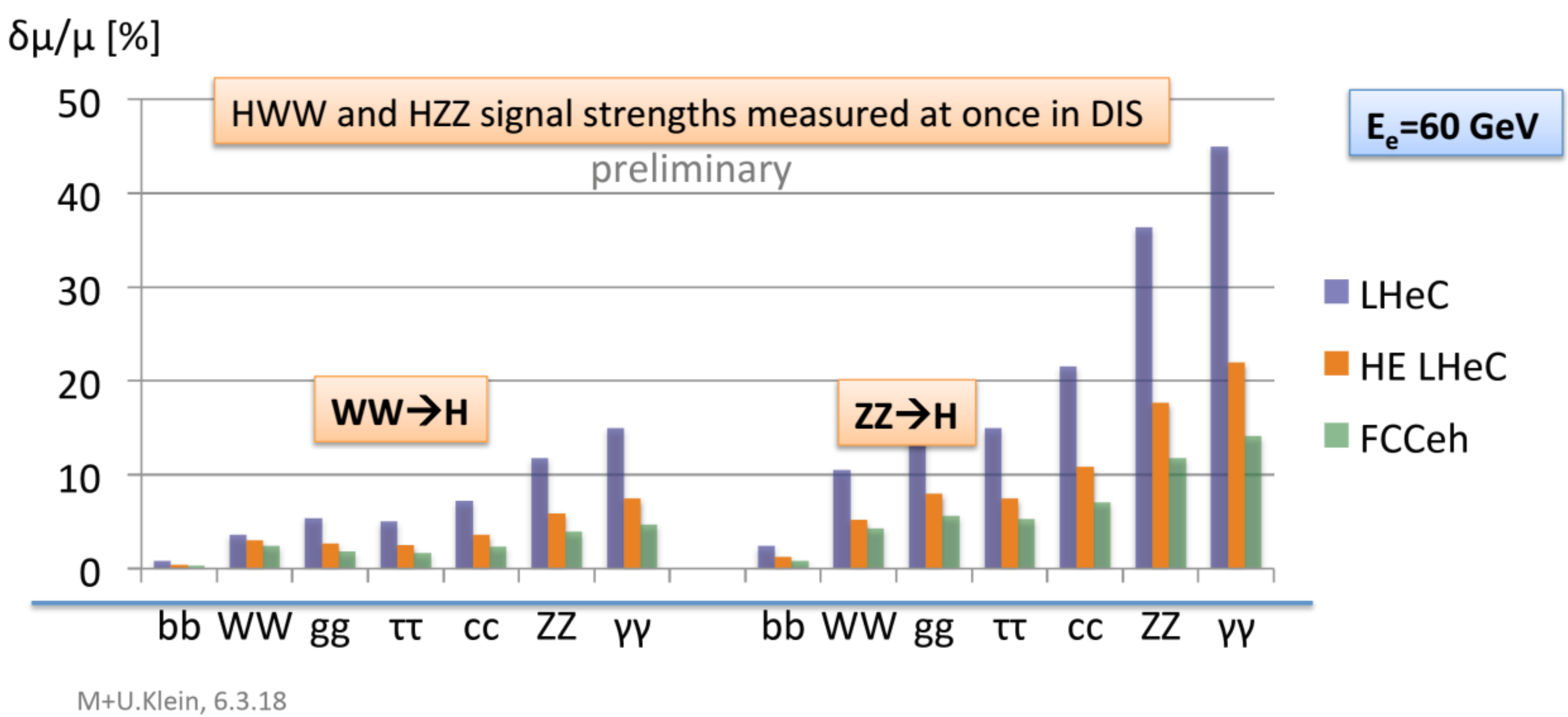
for BDT>0

	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

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

Precision of Signal Strengths at the LHeC/FCC-eh

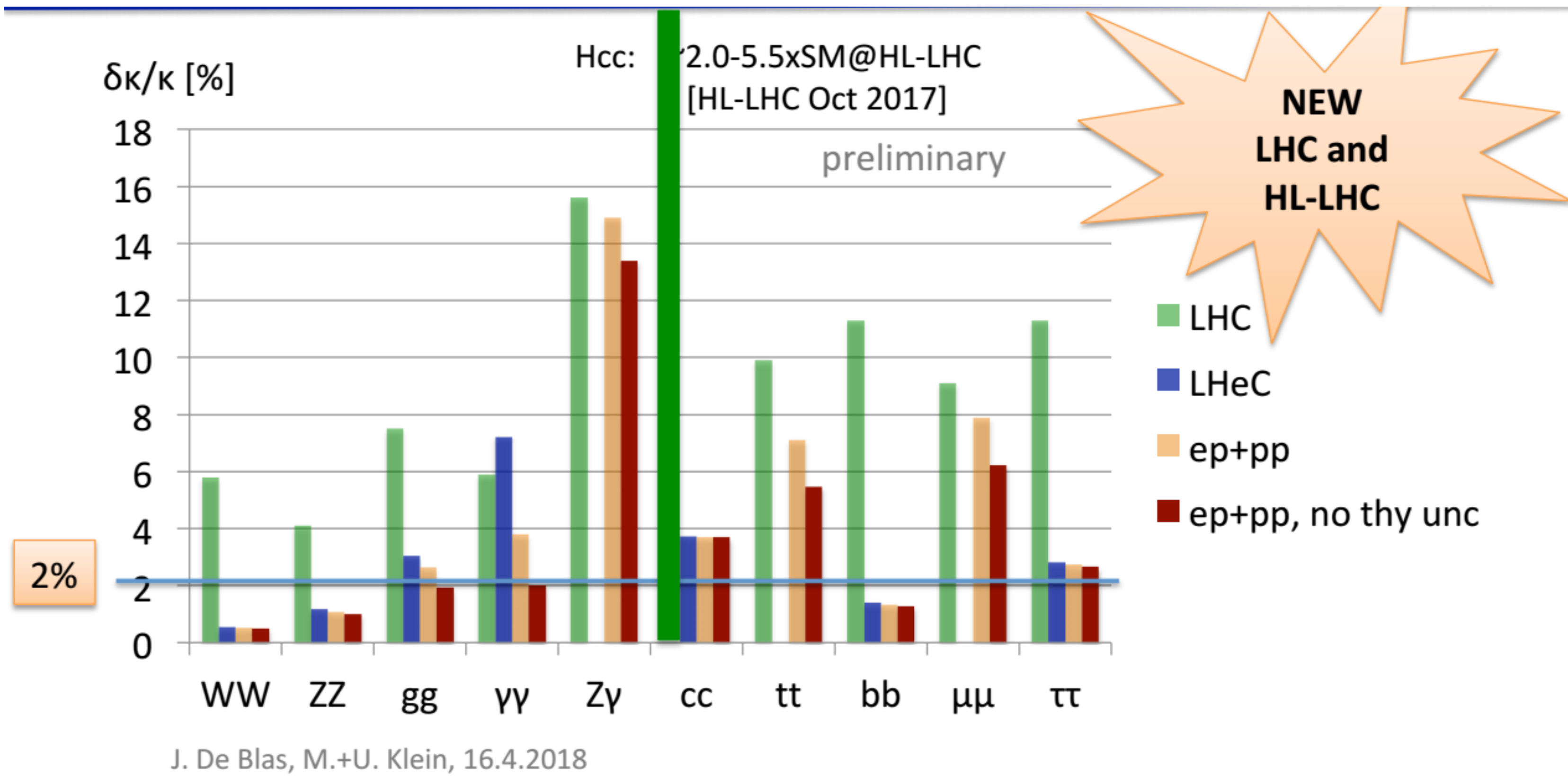
Note: Very preliminary results



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}

Prospects of Higgs Couplings at the LHeC

Note: Very preliminary results

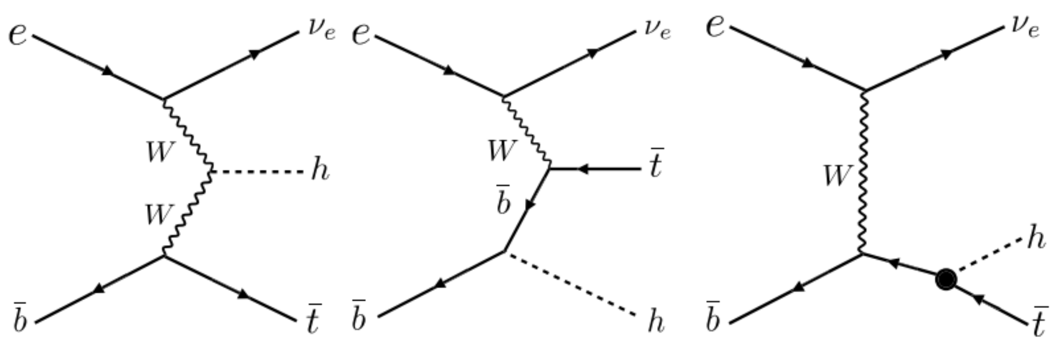


→ **Amazing prospect for measuring fundamental Higgs couplings to high precision (dark red) at LHC with pp + ep using SM assumptions.**

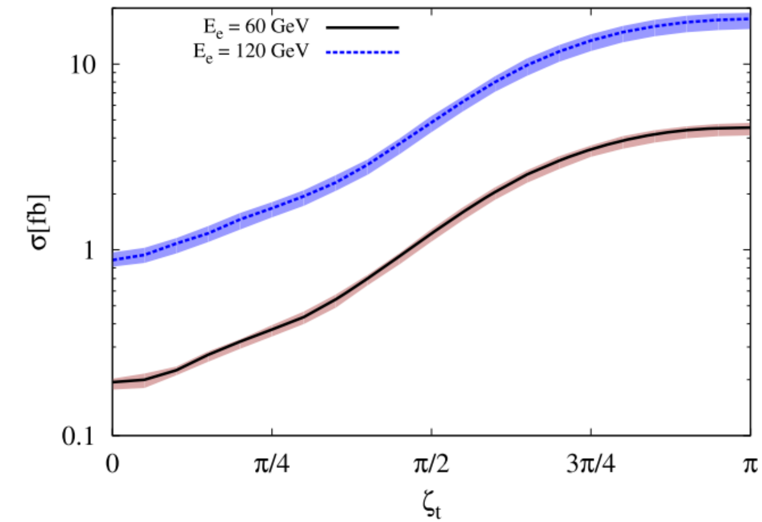
HL-LHC prospects using ATLAS 2014 projections (3ab^{-1}) w and w/o theoretical uncertainties ('no thy unc') in a SM coupling fit → will be updated with HL-LHC yellow report in preparation

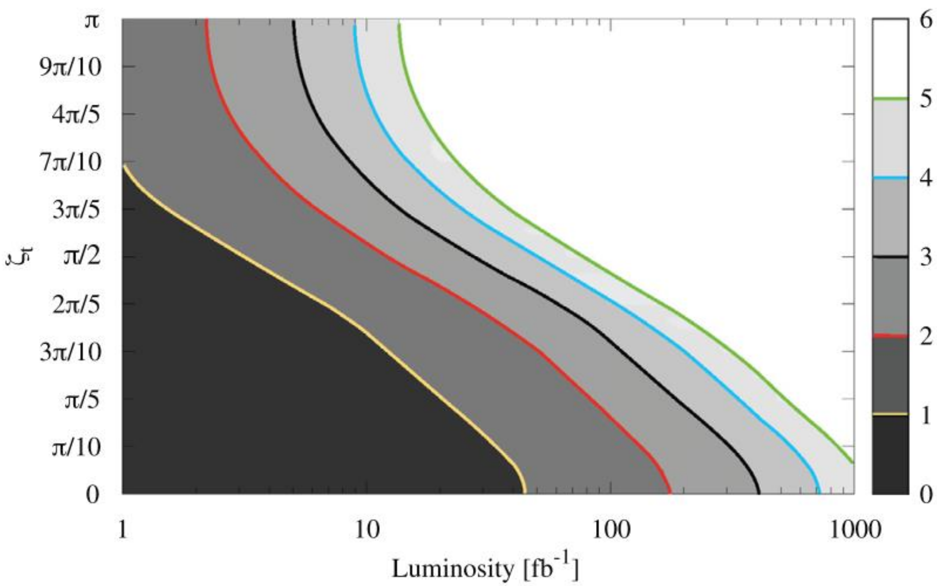
Top-Higgs Coupling at the LHeC

- Top-Higgs associated production: sensitive to relative phase and magnitude of htt and hWW couplings $\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]t\,h$



(a) (b) (c)





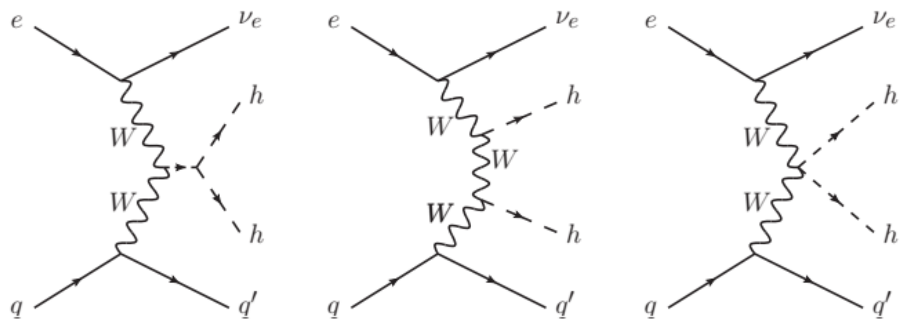
Precision on tth coupling using t+h production at ep colliders:

17% at LHeC and ~2% at FCC-eh

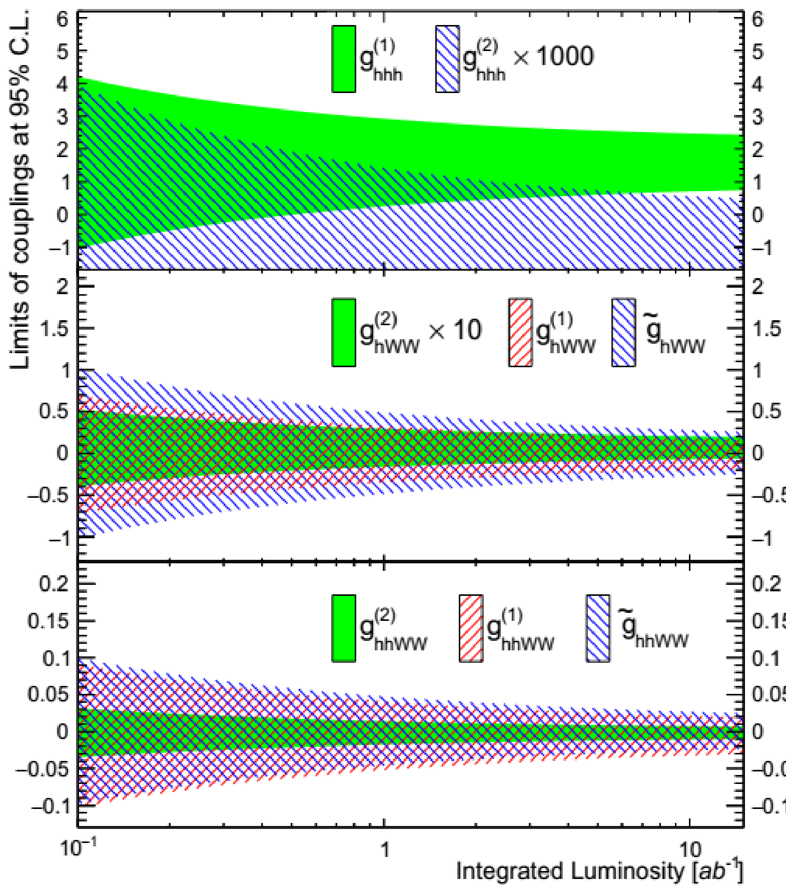
B. Coleppa et al., PLB 770(2017)335

Di-Higgs Production at the FCC-eh

- Di-Higgs production: probing h^3 and hhVV couplings (M. Kumar, X. Ruan, R. Islam, A. S. Cornell, M. Klein, U. Klein & B. Mellado, PLB 764(2017)247). Anomalous hWW couplings can also be probed at the LHeC using azimuthal angle correlations (S. S. Biswal, R. M. Godbole, B. Mellado, & S. Raychaudhuri et al., PRL 109, 261801(2012)).



$$\begin{aligned}
\mathcal{L}^{(3)}_{hhh} &= \frac{m_h^2}{2v}(1-g^{(1)}_{hhh})h^3 + \frac{1}{2}g^{(2)}_{hhh}\, h\partial_\mu h \partial^\mu h, \\
\mathcal{L}^{(3)}_{hWW} &= -\frac{g}{2m_W} g^{(1)}_{hWW} W^{\mu\nu}W^\dagger_{\mu\nu}h \\
&\quad - \frac{g}{m_W}\left[g^{(2)}_{hWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} h + \text{h.c.}\right] \\
&\quad - \frac{g}{2m_W}\tilde{g}_{hWW} W^{\mu\nu}\tilde{W}^\dagger_{\mu\nu}h, \\
\mathcal{L}^{(4)}_{hhWW} &= -\frac{g^2}{4m_W^2} g^{(1)}_{hhWW} W^{\mu\nu}W^\dagger_{\mu\nu}h^2 \\
&\quad - \frac{g^2}{2m_W^2}\left[g^{(2)}_{hhWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} h^2 + \text{h.c.}\right] \\
&\quad - \frac{g^2}{4m_W^2}\tilde{g}_{hhWW} W^{\mu\nu}\tilde{W}^\dagger_{\mu\nu}h^2.
\end{aligned}$$



Probing Extended Higgs Sector at the LHeC & FCC-eh

- NMSSM:
  - Light neutral CP-even Higgs @LHeC: e+2b+j or 2b+j+MET. (S. P. Das & M. Nowakowski, PRD 96, 055014(2017))
  - Light charged Higgs @FCC-eh: b+2j+MET. (S. P. Das, J. Hernández-Sánchez, S. Moretti & A. Rosado, 1806.08361)
- Two Higgs Doublet Model:
  - Type I CP-even Higgs @LHeC & FCC-eh. (C. Mosomane, M. Kumar, A. S. Cornell & B. Mellado, 1707.05997)
  - Type III Flavor-violating Higgs @LHeC: b+2j+MET. (S. P. Das, J. Hernández-Sánchez, S. Moretti, A. Rosado, R. Xoxocotzi, PRD 94, 055003 (2016))
- Georgi-Machacek Model:
  - Doubly charged Higgs @LHeC & FCC-eh: same-sign dimuon+j+MET. (H. Sun, X. Luo, W. Wei & T. Liu, PRD 96, 095003 (2017)).
  - Singly charged Higgs @LHeC & FCC-eh: 3l+3j. (G. Azuelos, H. Sun & K. Wang., PRD 97, 116005 (2018)).

Most up-to-date Information: https://indico.cern.ch/event/698368/

Workshop: LHeC/FCCeh and PERLE
Last week at Orsay near Paris

http://lhec.web.cern.ch

New and Updates on

Physics: PDFs, QCD, H, t, BSM, eA + Relation eh-hh..
Accelerator: IR, Optics, Lattice, Cost-Energy, CE..
Detector: the GPD and its fwd and bwd detectors
PERLE: Source, Injector, Cavity, Cryomodule,.. Physics
Project Development towards the ES2020:
LHeC + FCCeh+ PERLE input 12/18. PERLE TDR in 2019.

Summary

- The LHeC & FCC-eh project
  - LHeC: 60 GeV electron times 7TeV proton ($\sqrt{s}$=1.3TeV), synchronous with HL-LHC
  - FCC-eh: 60 GeV electron times 50TeV proton ($\sqrt{s}$=3.5TeV), synchronous with FCC-hh
- Highlights of Higgs physics at the LHeC and FCC-eh

	LHeC ($1 ab^{-1}$)	FCC-eh ($1 ab^{-1}$)
Bottom Yukawa	0.5%	0.2%
Charm Yukawa	4%	1.8%
Other Interesting Measurements	Invisible & exotic Higgs decays, tth, hVV, hhVV, di-Higgs, extended Higgs sector, etc.	

- *The LHeC & FCC-eh offer an excellent opportunity to improve Higgs-related measurements by maximally exploiting the infrastructure of future high-energy hadron colliders. If a lepton collider is not available, then the ep machine will be our best imaginable (perhaps only) option to boost Higgs-related measurements beyond what can be achieved at the corresponding hadron collider.*

Backup

LHeC Prospects

- The ep interaction does not disturb pp, i.e. the LHC may become a twin collider, ep and pp operate concurrently and no luminosity loss is planned for pp. This requires a premounted eh detector which may then be inserted in 2 years.

- At LS4 (~2030) the heavy ion LHC operation ends and one may propose a different use of IP2 which currently houses ALICE.

- The electron beam energy (> 50 GeV) and luminosity ($O(10^{34})$ cm^{-2} s^{-1}) goals are derived from Higgs, top and BSM physics, also DIS itself (F_L, low x~1/s).

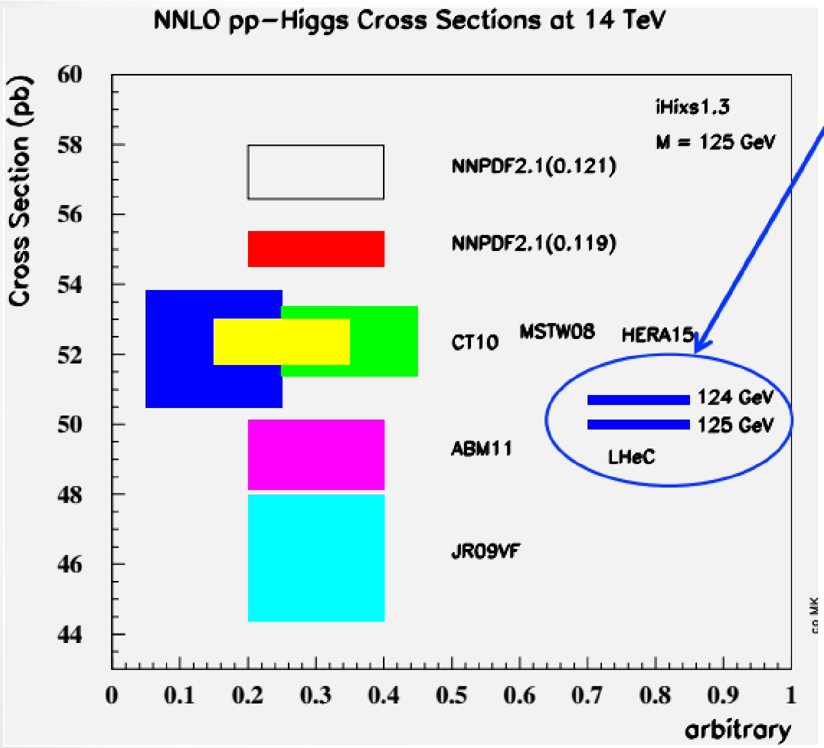
- The cost of the O(1) TeV ep collider is a small fraction of any other big project currently under discussion. The LHC determines the time frame. This may extend considerably if CERN moves to HE LHC in the fourties.

- The ERL technology is being developed worldwide (Darmstadt, Cornell, Berlin, Novosibirsk, Jefferson Lab). PERLE would be a multi-turn 802 MHZ ERL technology development and test facility which would timely accompany the LHeC progress.

- We celebrate this year the 50th anniversary of the discovery of quarks. This was not planned and achieved by a step in energy with a linac SHORTER than LHeC's

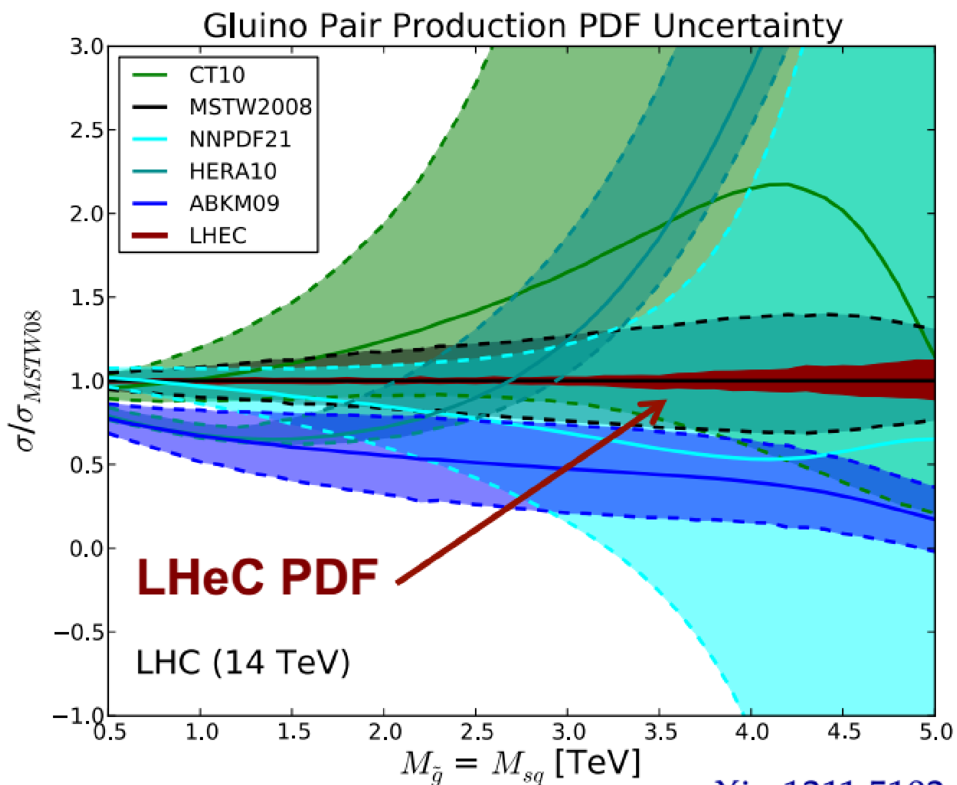
- There is a very long term future for eh as part of hh in the FCC vision

Relevance of ultra-precise PDF



arXiv:1305.2090

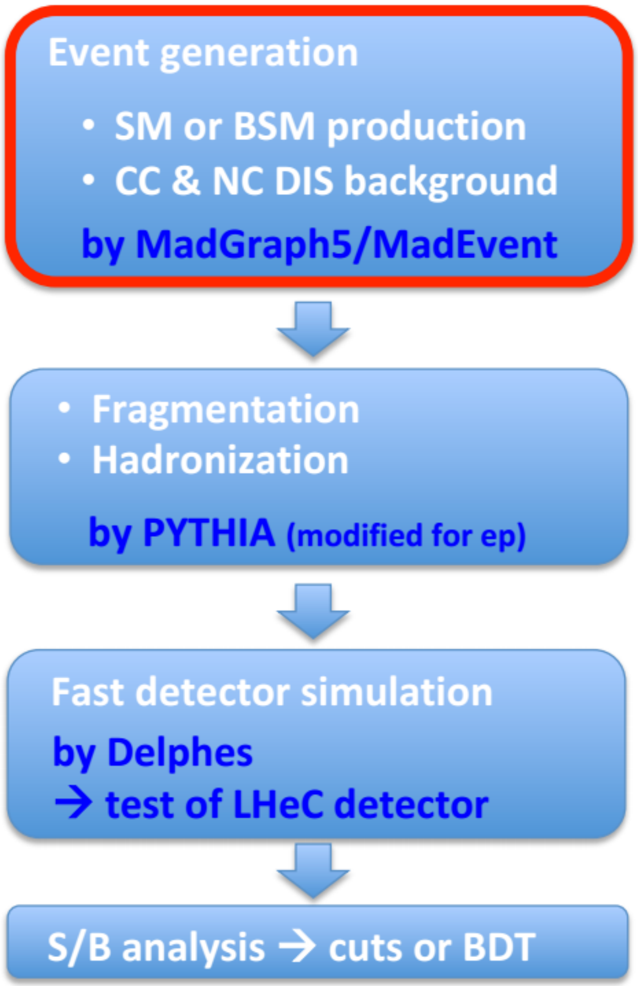
- PDF-uncertainty of Higgs cross section squeezes to be sensitive to m_H



arXiv:1211.5102

- High-mass gluino xsec uncertainty >> 100% → squeezes to < 10%

Analysis Framework and ‘Detector’



- Calculate cross section with tree-level Feynman diagrams (any UFO) using <u>pT of scattered quark as scale (CDR ŝ)</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’)

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}]

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

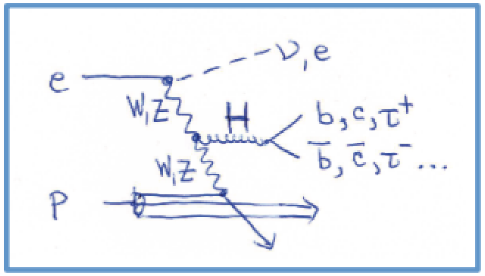
- Calculate uncertainties of signal strengths w.r.t. SM expectation $\mu = \frac{\sigma}{\sigma_{SM}}$

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

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!):

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

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

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

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

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

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

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