Physics at the LHeC

B.Mellado

University of the Witwatersrand

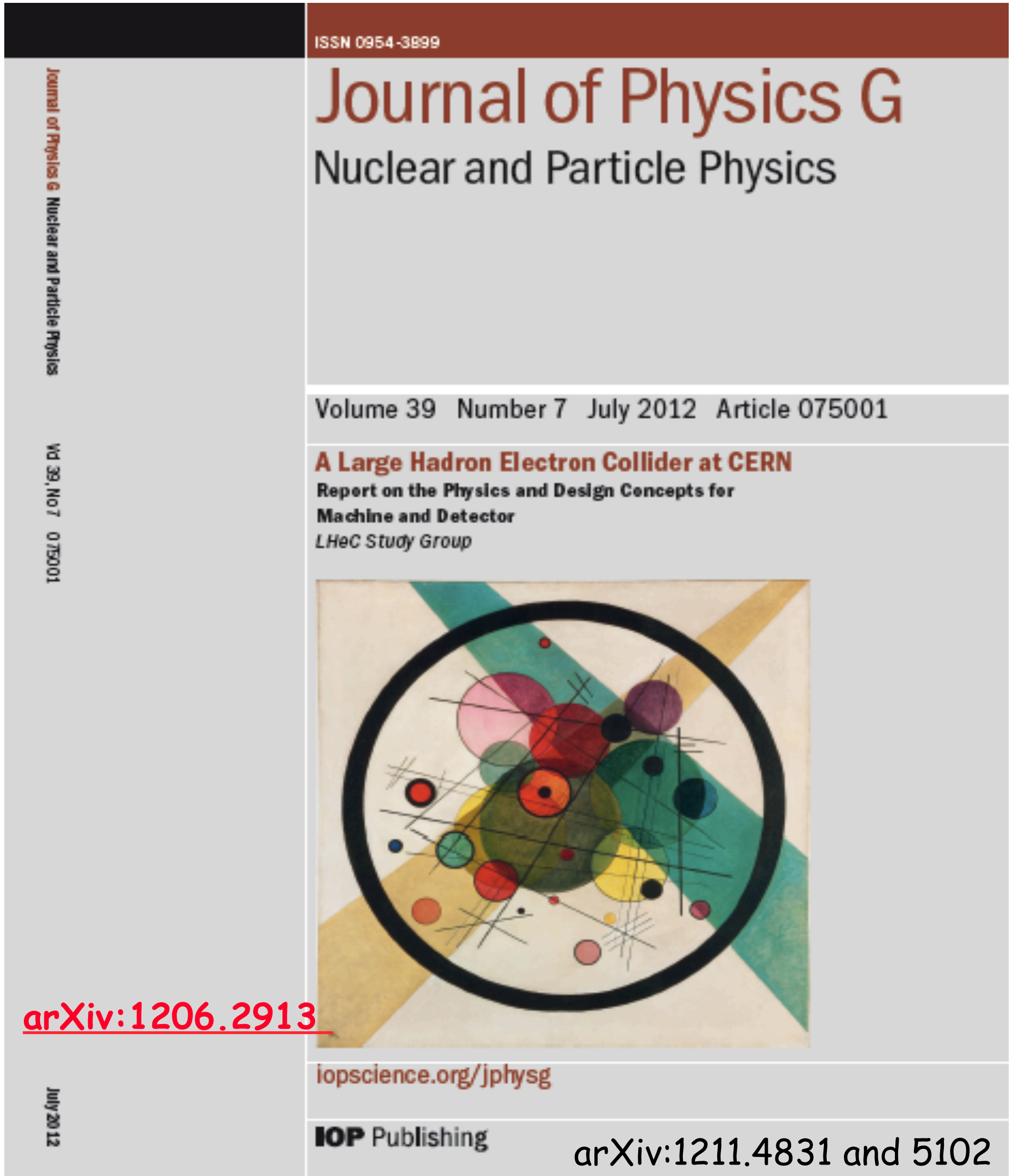
On behalf of the LHeC Study Group

Many thanks to N.Armesto, S.Forte, M.Klein, U.Klein, M.Kumar, M.Kuze and H.Sun for slides

LHCP, Shanghai Jiao Tong University, 19/05/17

Outline

- The LHeC project
- The LHeC Physics Program
  - The proton PDF
  - High precision for the LHC
  - Top physics, etc…
- The LHeC, a Higgs facility
  - Sensitivity to coupling strength
  - Sensitivity to HVV coupling structure
  - Invisible decays
  - Top Yukawa coupling
- Outlook and conclusions



arXiv:1206.2913

arXiv:1211.4831 and 5102

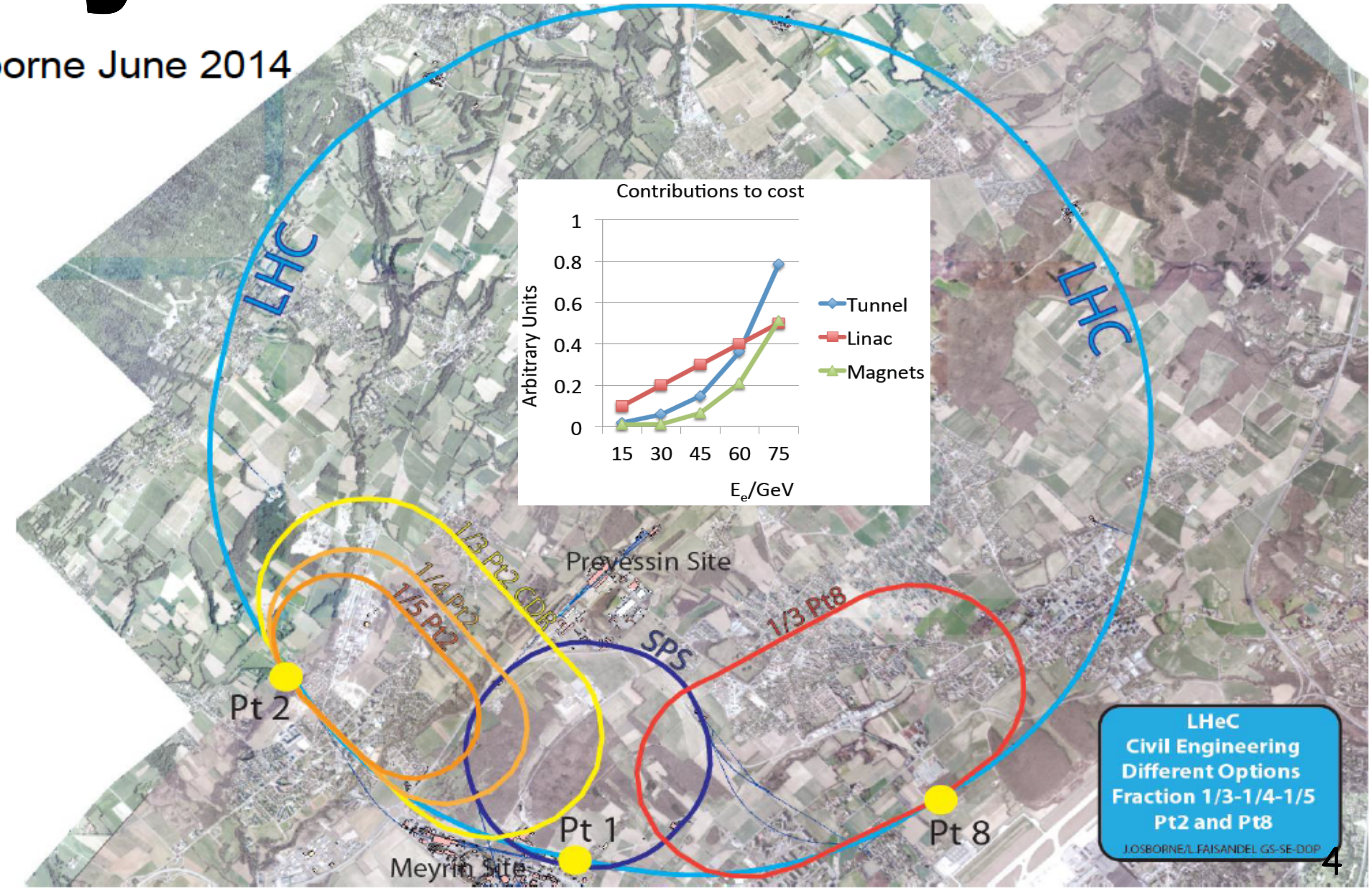
CERN Referees

Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)
Interaction Region
Daniel Pitzl (DESY)
Mike Sullivan (SLAC)
Detector Design
Philippe Bloch (CERN)
Roland Horisberger (PSI)
Installation and Infrastructure
Sylvain Weisz (CERN)
New Physics at Large Scales
Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)
Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)
Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

Published 600 pages conceptual design report (CDR) written by 150 authors from 60 Institutes.
Reviewed by ECFA, NuPECC (long range plan), Referees invited by CERN. Published June 2012.

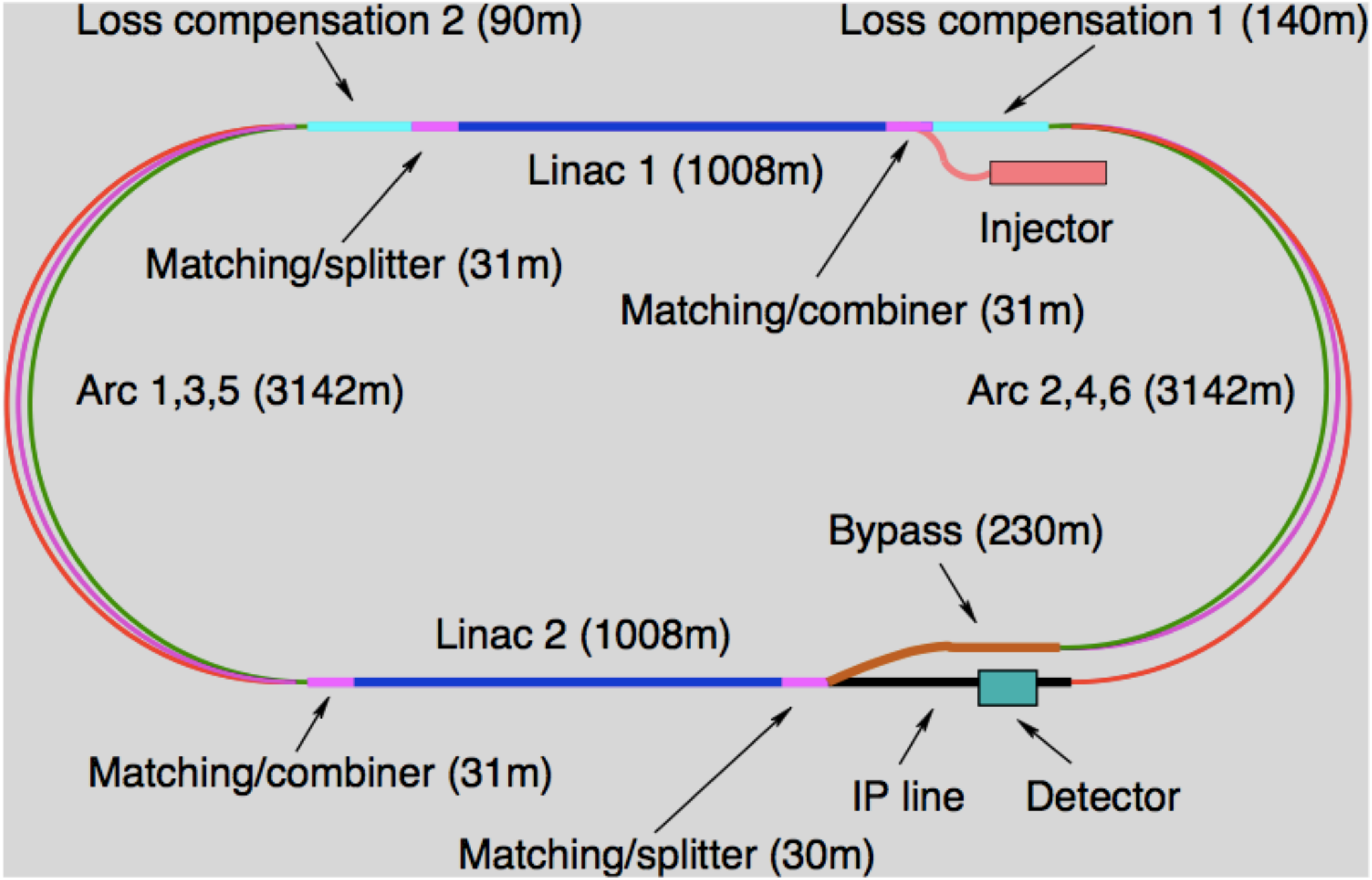
Layout

John Osborne June 2014



CDR: Physics, Accelerator, Detector

M.Klein



JPhysG:39(2012)075001, arXiv:1206.2913 http://cern.ch/lhec

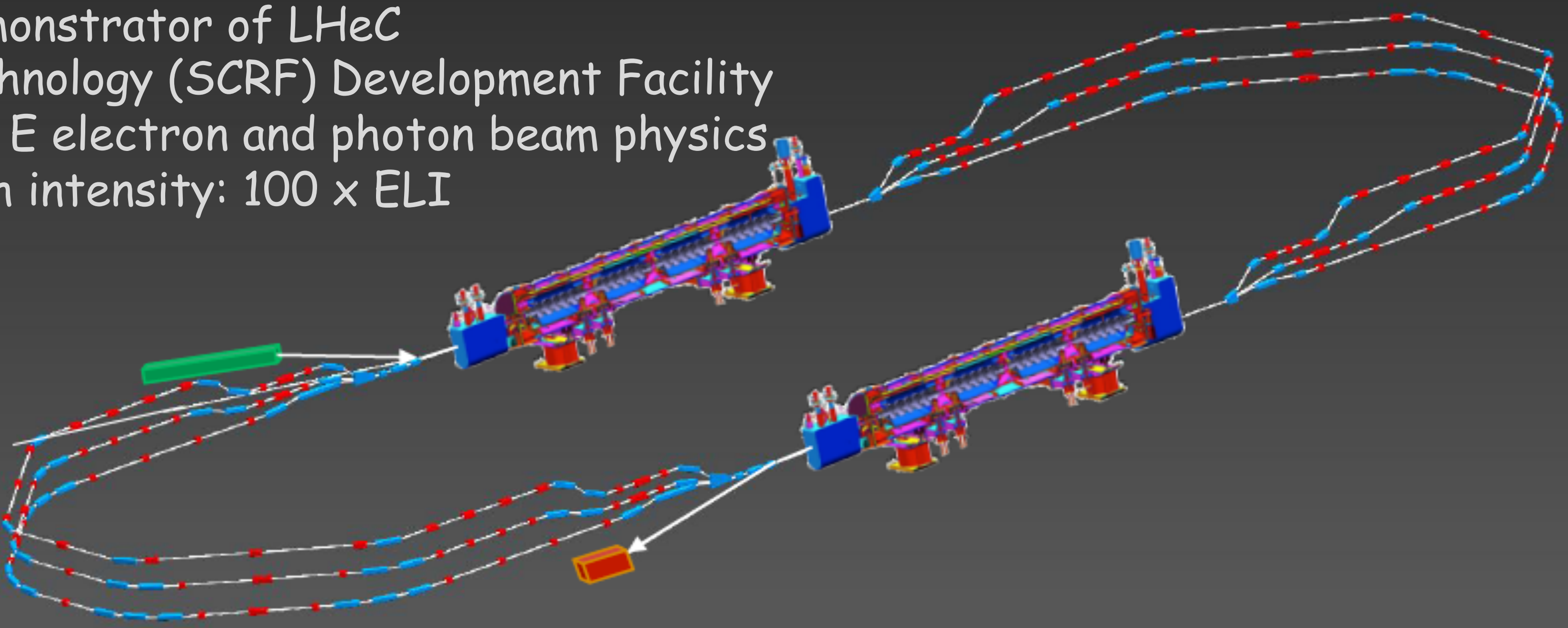
CDR: default design. 60 GeV. L=10^{33}cm^{-2}s^{-1}, P< 100 MW → ERL, synchronous ep/pp

Powerful ERL for Experiments (ep.yp): PERLE at Orsay

M.Klein

PERLE at Orsay: New Collaboration: BINP, CERN, Daresbury/Liverpool, Jlab, Orsay

CDR publication imminent.
3 turns, 2 Linacs, 15mA, 802 MHz ERL facility
-Demonstrator of LHeC
-Technology (SCRF) Development Facility
-Low E electron and photon beam physics
-High intensity: 100 x ELI



See https://indico.lal.in2p3.fr/event/3428/

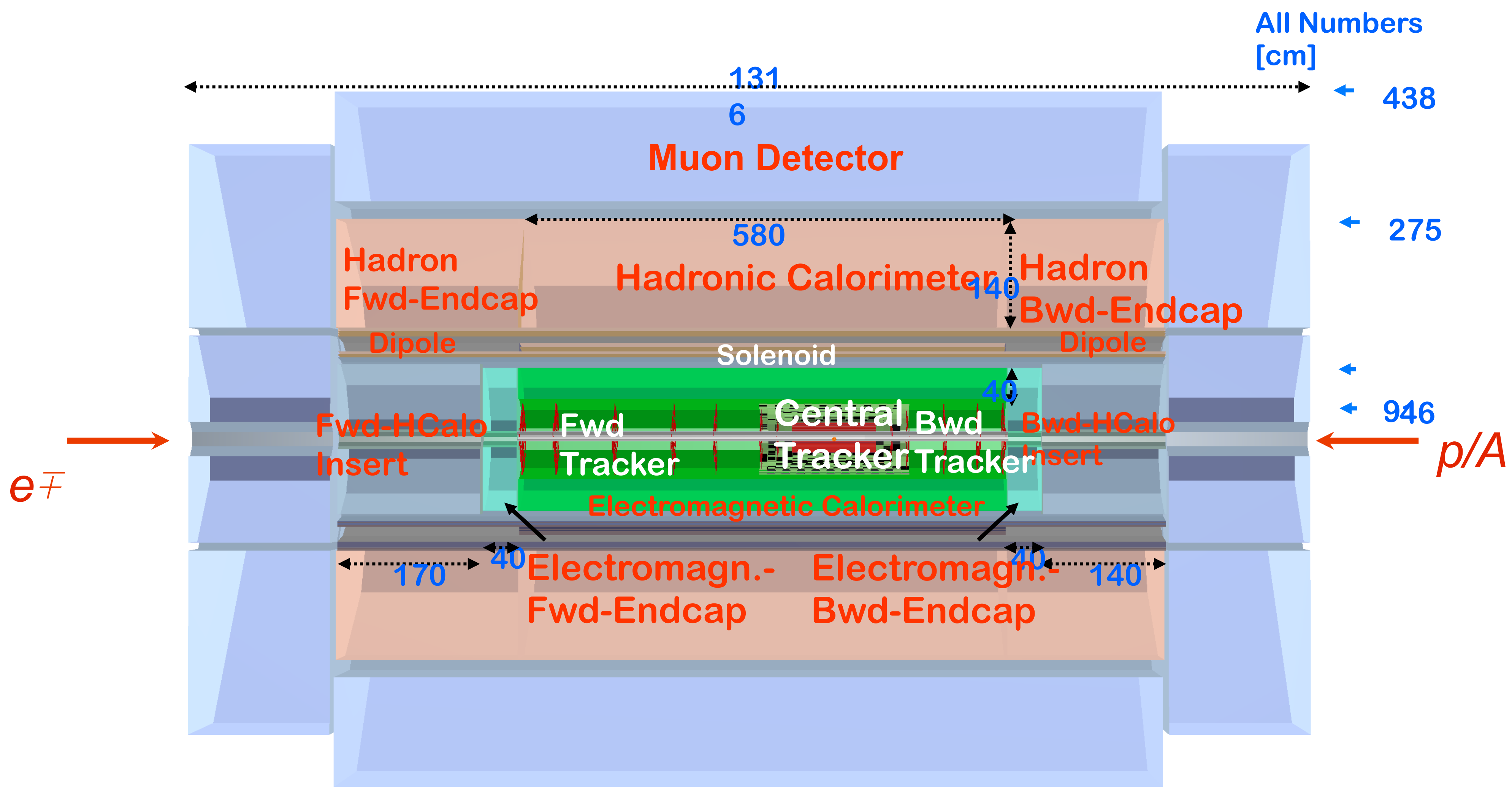
Luminosity for LHeC, HE-LHeC and FCC

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

Oliver Brüning[1], John Jowett[1], Max Klein[1,2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool
April 6^{th}, 2017

The LHeC Detector

P. Kostka



Physics Highlights

LHeC Physics Programme

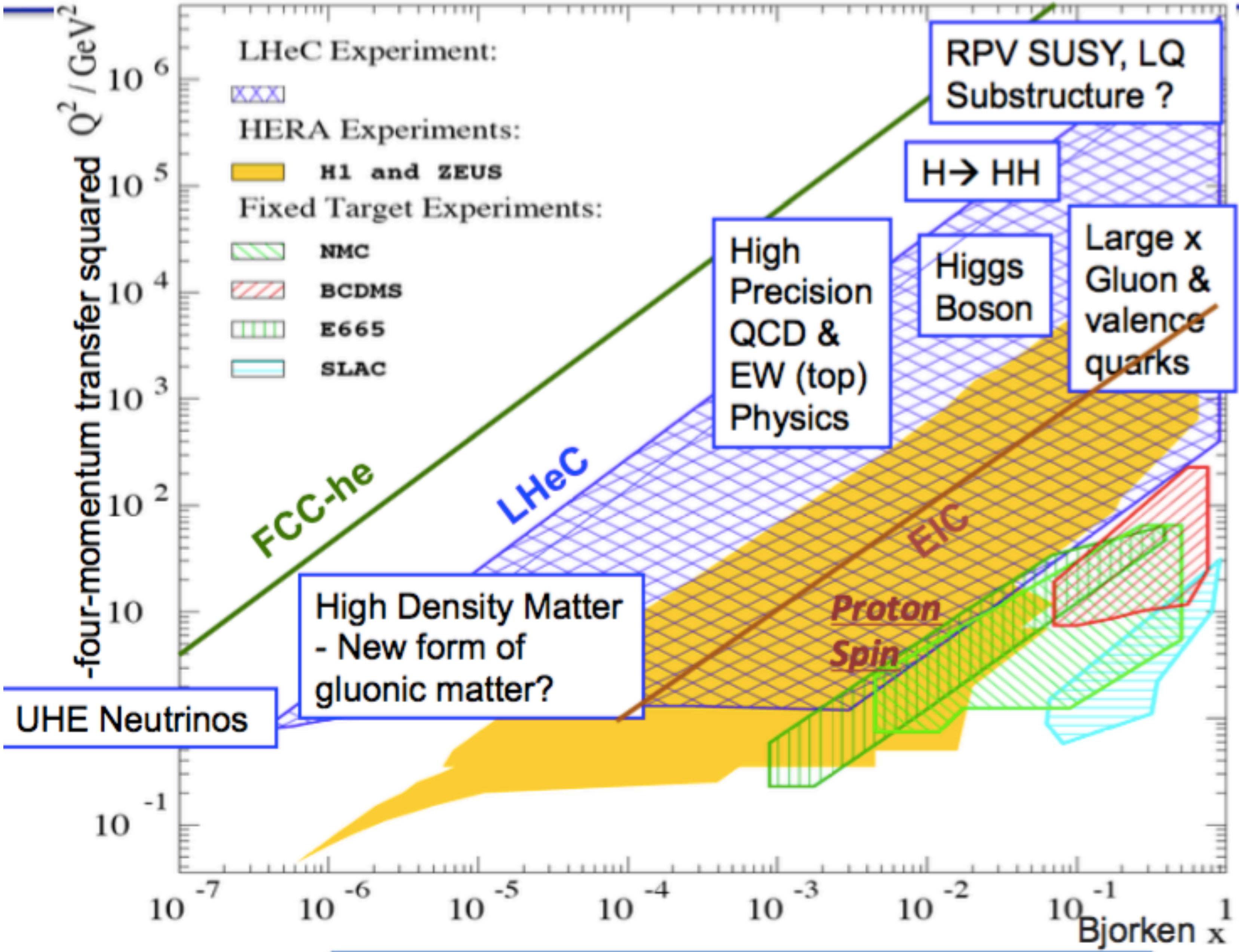
CDR, arXiv:1211.4831 and 5102
http://cern.ch/lhec

QCD Discoveries Higgs Substructure New and BSM Physics Top Quark	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$ WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H? leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s top PDF, $xt = x\overline{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution Precision DIS	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c $\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure Quark Distributions QCD	Proton, Deuteron, Neutron, Ions, Photon valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron Heavy Ions Modified Partons	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing initial QGP, nPDFs, hadronization inside media, black limit, saturation PDFs “independent” of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

Ultra high precision (detector, e-h redundancy) - new insight
Maximum luminosity and much extended range - rare, new effects
Deep relation to (HL-) LHC (precision+range) - complementarity

Strong coupling 0.1%; Full unfolding of PDFs; Gluon: low x: saturation?, high x: HL LHC searches…

U. Klein



HERA established the validity of pQCD down to $x>10^{-4}$ (DGLAP) due to a very high lever arm in Q^2.

Extensions of both x and Q^2 ranges are crucial for new experiments and HEP theory developments!

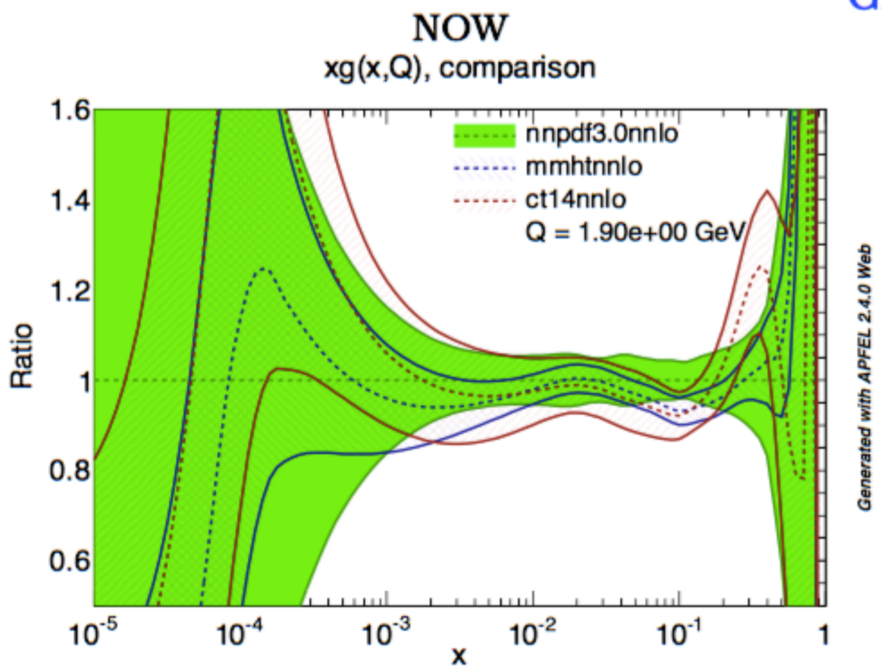
Relation to pp : $x_{1,2} = (M/\sqrt{s}) \exp(\pm y)$ & $Q^2 = M^2$

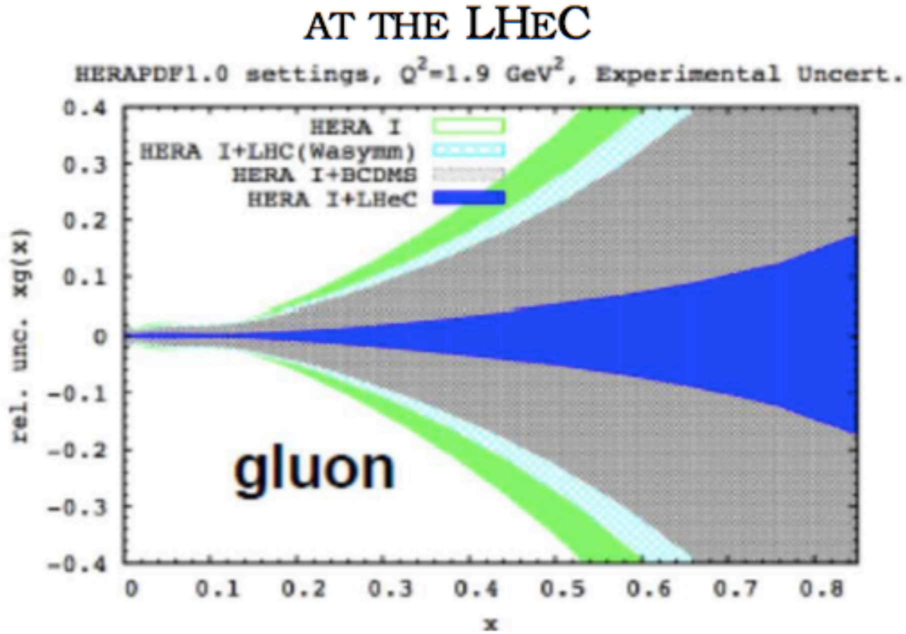
PDFS AT THE LHEC

S. Forte

- UNCERTAINTIES DOWN TO PERCENT LEVEL IN WIDE KINEMATIC REGION
- WITH DEUTERON BEAMS, FULL LIGHT FLAVOR DECOMPOSITION
- THANKS TO HIGH ENERGY, NC+CC ⇒ PRECISION STRANGENESS DETERMINATION

GLUON



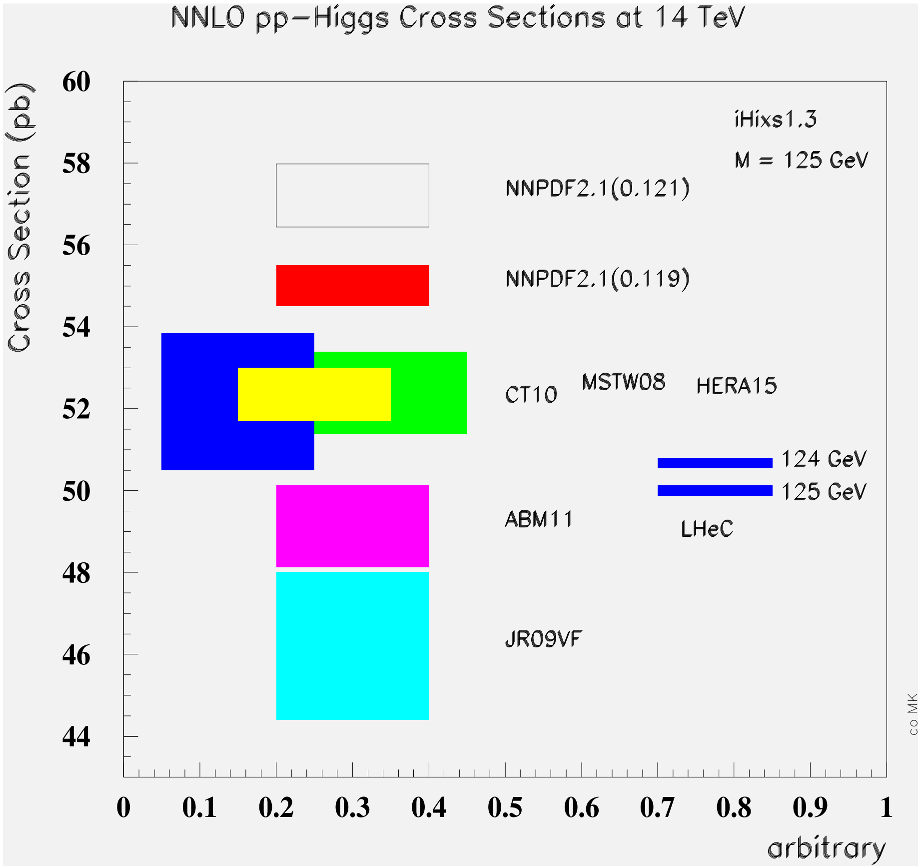


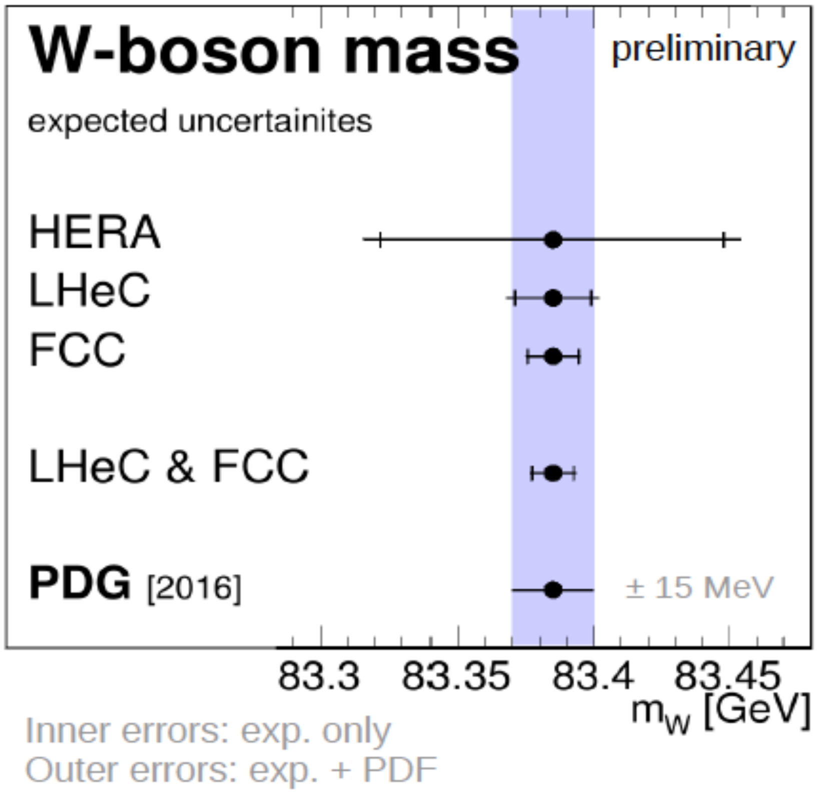
(A. Cooper-Sarkar & Voica Radescu, 2015)

PDF uncertainty on Higgs production at LHC will become negligible due to measurements a the LHeC

High Precision for the LHC

M.Klein





Can achieve 0.2% precision in pdf uncertainty, thus removing this uncertainty from the prediction of the Higgs cross-section.

Spacelike M_W to 10 MeV from ep
→ Electroweak thy test at 0.01% !

Reduce pdf error 2.8 MeV →
Remove PDF uncertainty on M_W LHC

M.Klein

Top Physics

Top electric charge

EDM and MDM

Anomalous t-q-y and t-g-Z

V_{tb}

Top spin

W-t-b

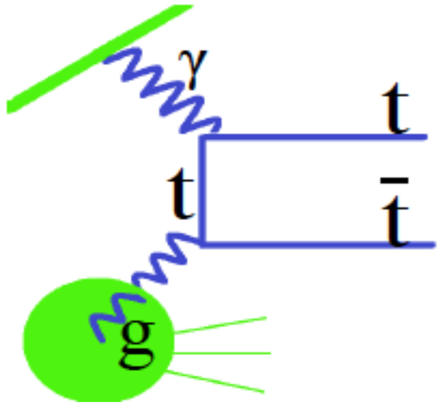
Top PDF

Top mass

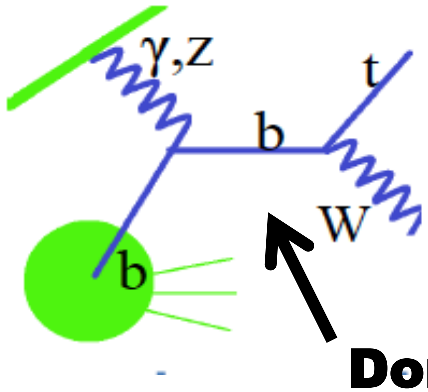
Top-Higgs (1602.04670)

CP nature of ttH (1702.03426)

Pair production

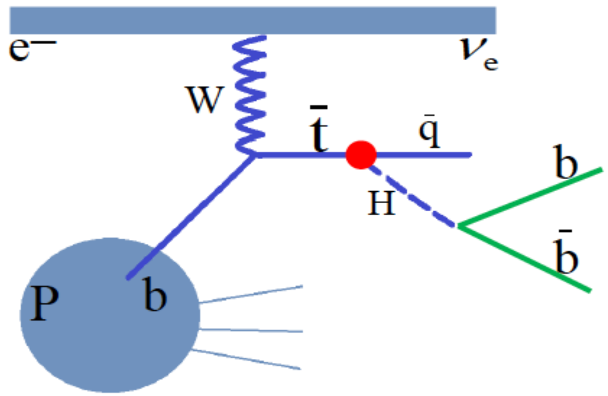


Single production



Dominant

FCNC top Higgs CC interaction



Just started to fully see the huge potential of top physics in ep at high energies

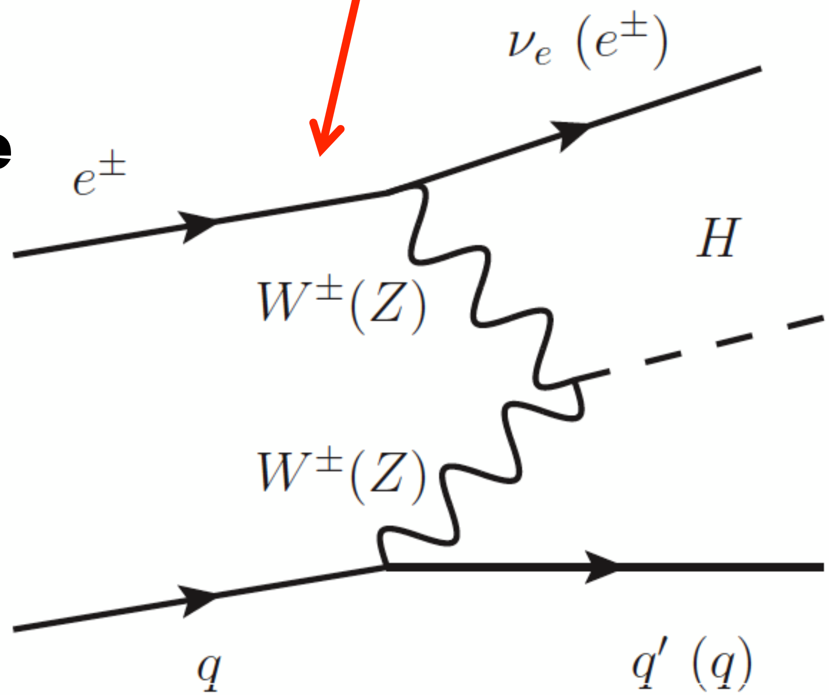
LHeC, a Higgs facility

Higgs at LHeC

At LHC replace lepton lines by quark lines but dominantly gg → H

- It is remarkable that VBF diagrams were calculated for lepton nucleon collisions before for pp!

- Consider feasibility for the following LHeC point:



$$E_p = 7\,TeV, \quad E_e = 60\,GeV, \quad m_H = 125\,GeV$$

LHeC, a Higgs Facility

→ **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); ERL : 960 superconducting cavities (20 MV/m) and 9 km tunnel [arXiv:1211.5102, arXiv:1305.2090; EPS2013 talk by D. Schulte]

√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

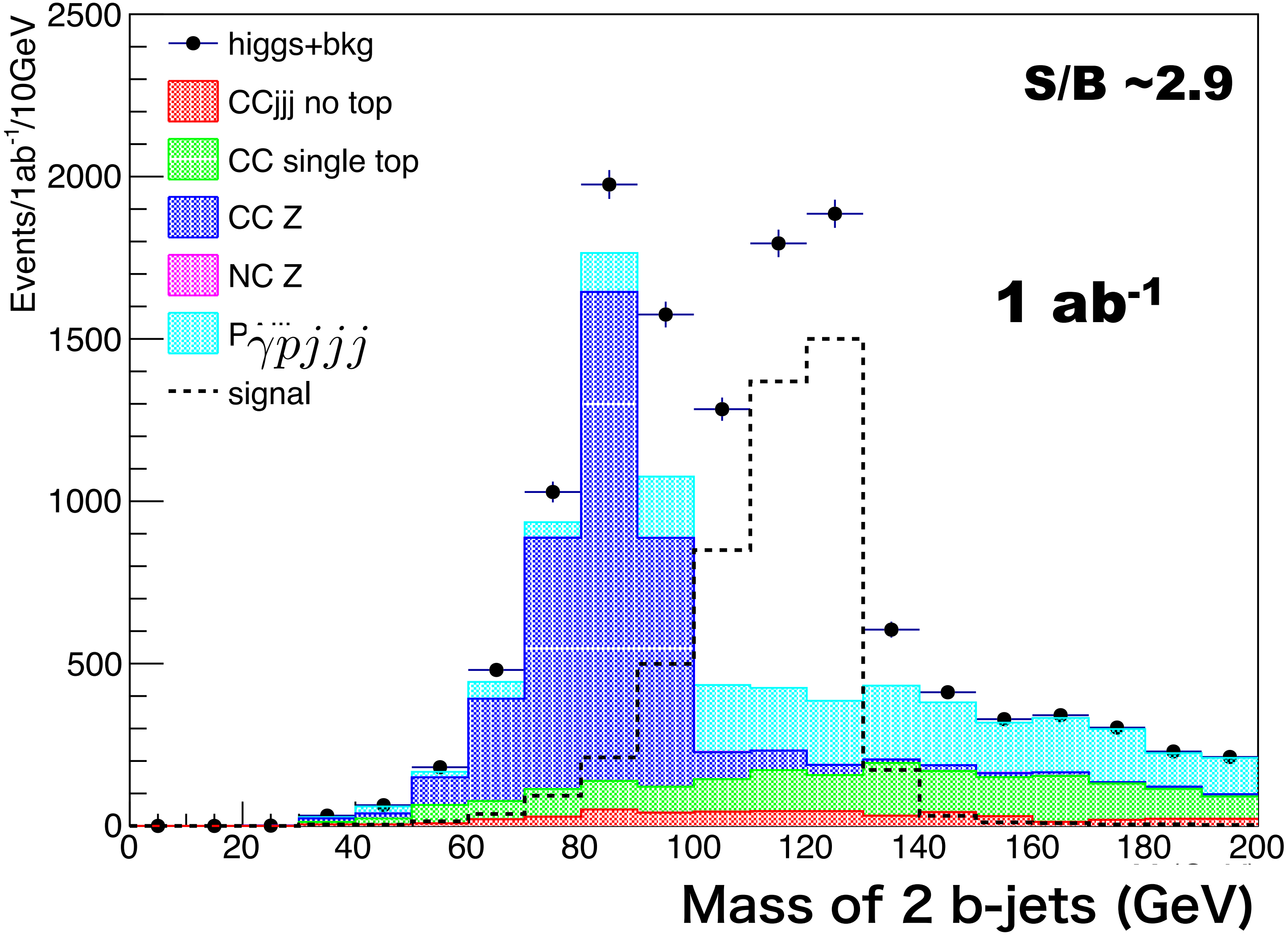
→ need of different models :
cc: 'sm-full'

gg, γγ: **'heft'**

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

➔ **Decay to bb is dominating HFL decay modes :**
Higgs decay to cc is factor 20 less likely than Hbb
times the ratio of detection efficiencies-squared !

H→bb coupling, cut based analysis



M.Kuze
M.Tanaka

Veto efficiency of 90% for photo-production background is assumed, using forward electron tagging

Large signal to background achieved

κ(Hbb) ~ 1% for 1 ab^{-1}

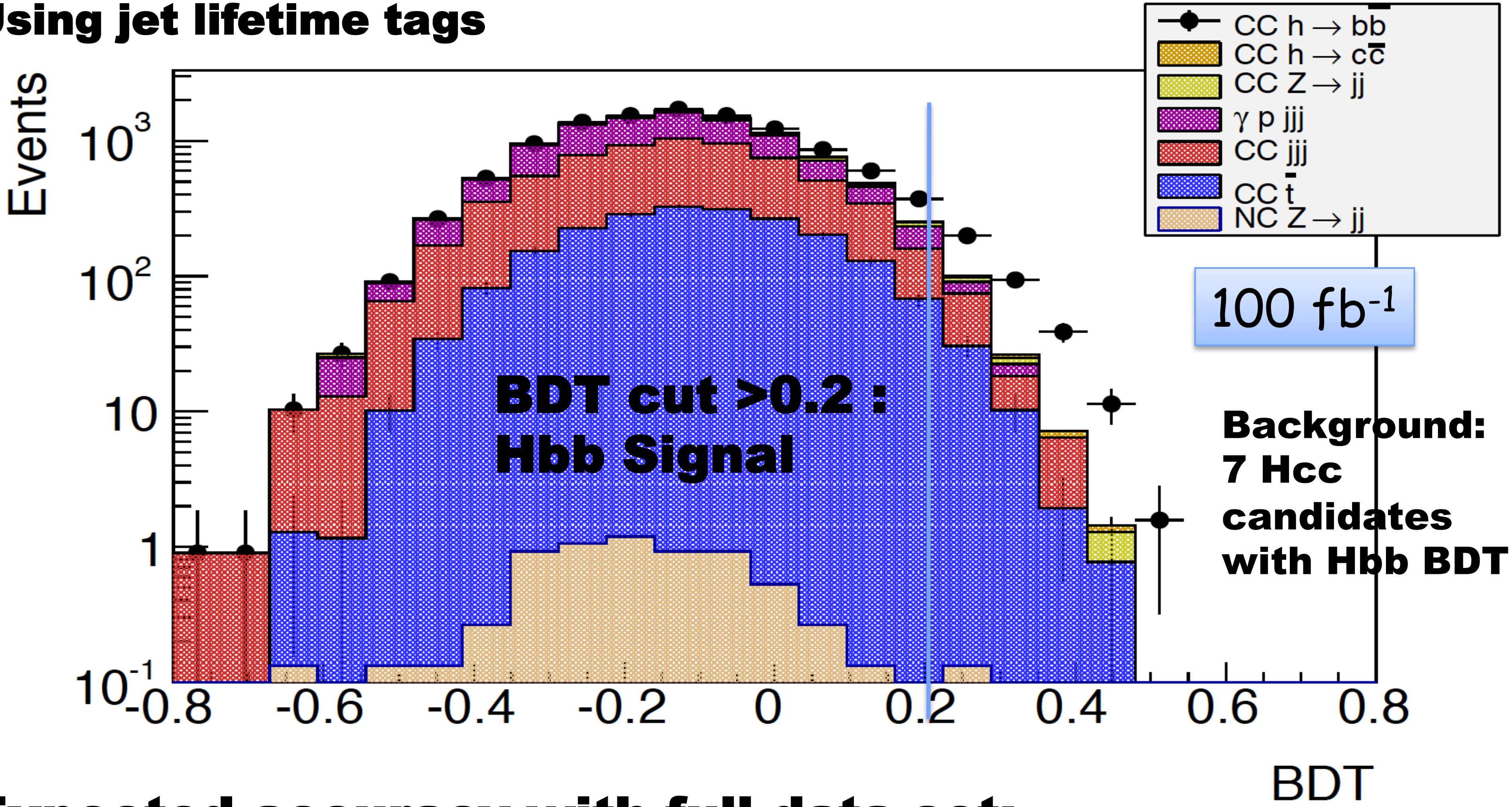
Results obtained with Delphes output

U. Klein

[P=-0.8, BR=0.577]

First BDT results: Higgs→ bb

Using jet lifetime tags



Expected accuracy with full data set:

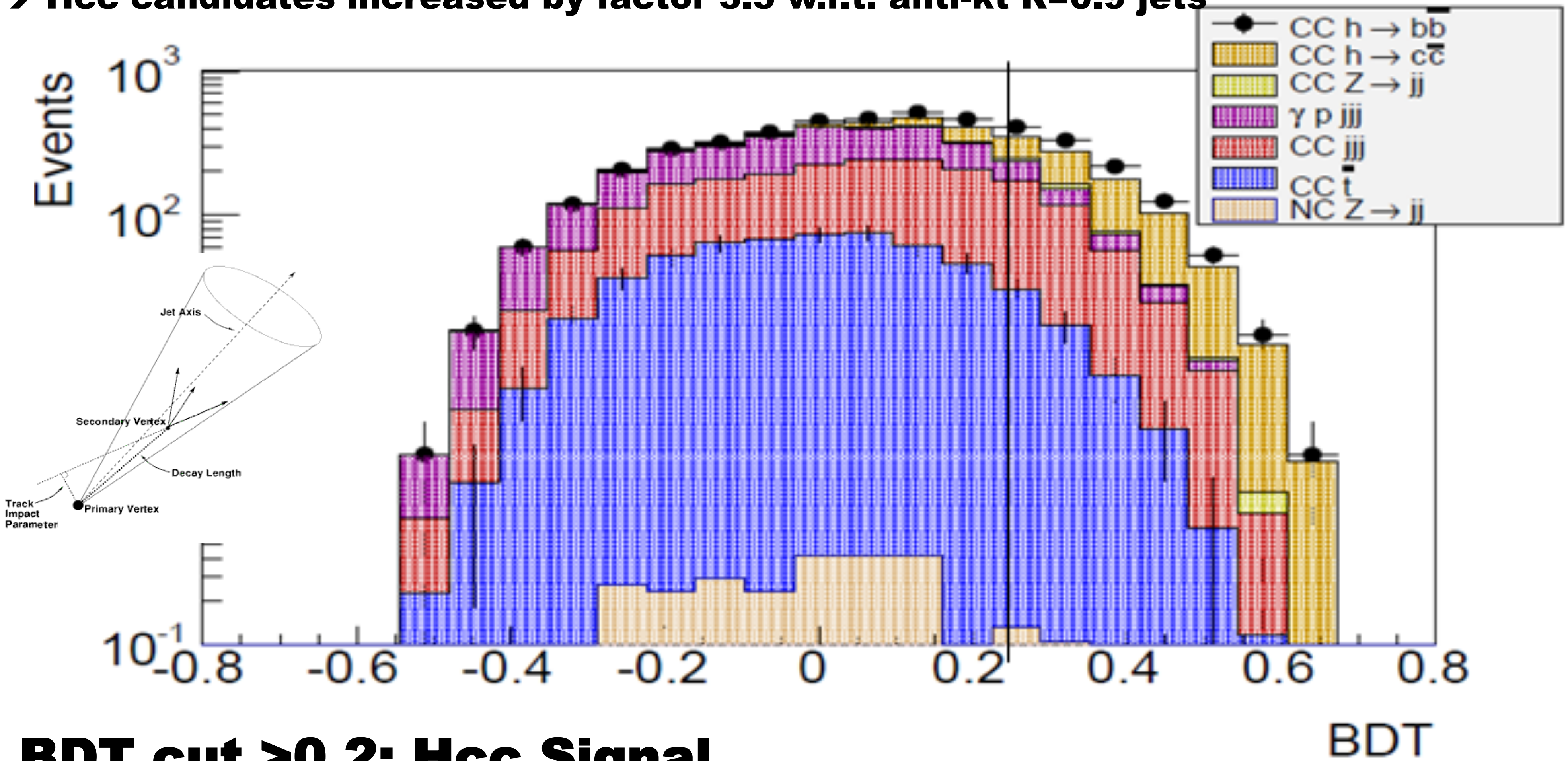
κ(Hbb) ~ 0.5% for 1000 fb^{-1}

Conservative light jet rejection factor of 10 is used

U Klein and D Hampson.

BDT Results Higgs→ cc

NEW : Using R = 0.5 anti-kt jets and ATLAS IBL vertex resolution (5 μm)
→ Hcc candidates increased by factor 3.5 w.r.t. anti-kt R=0.9 jets

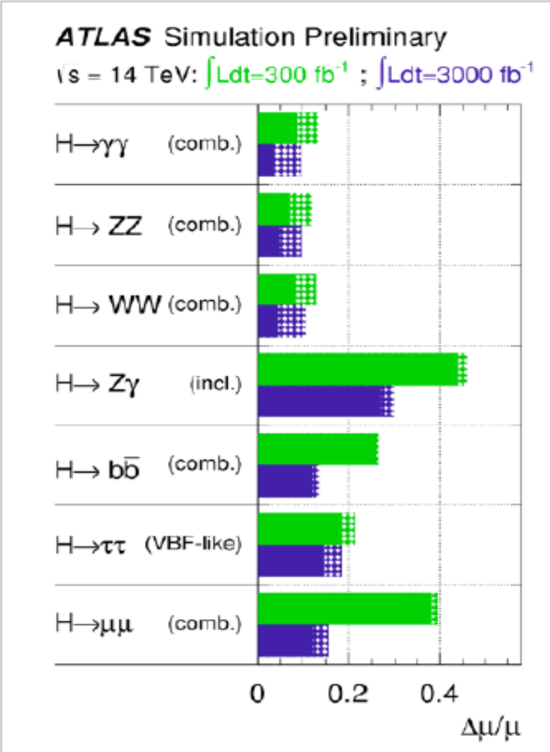


BDT cut >0.2: Hcc Signal events : 474; $S/\sqrt{S+B}$=12.8
→ κ(Hcc) = 4% for 1000 fb^{-1}

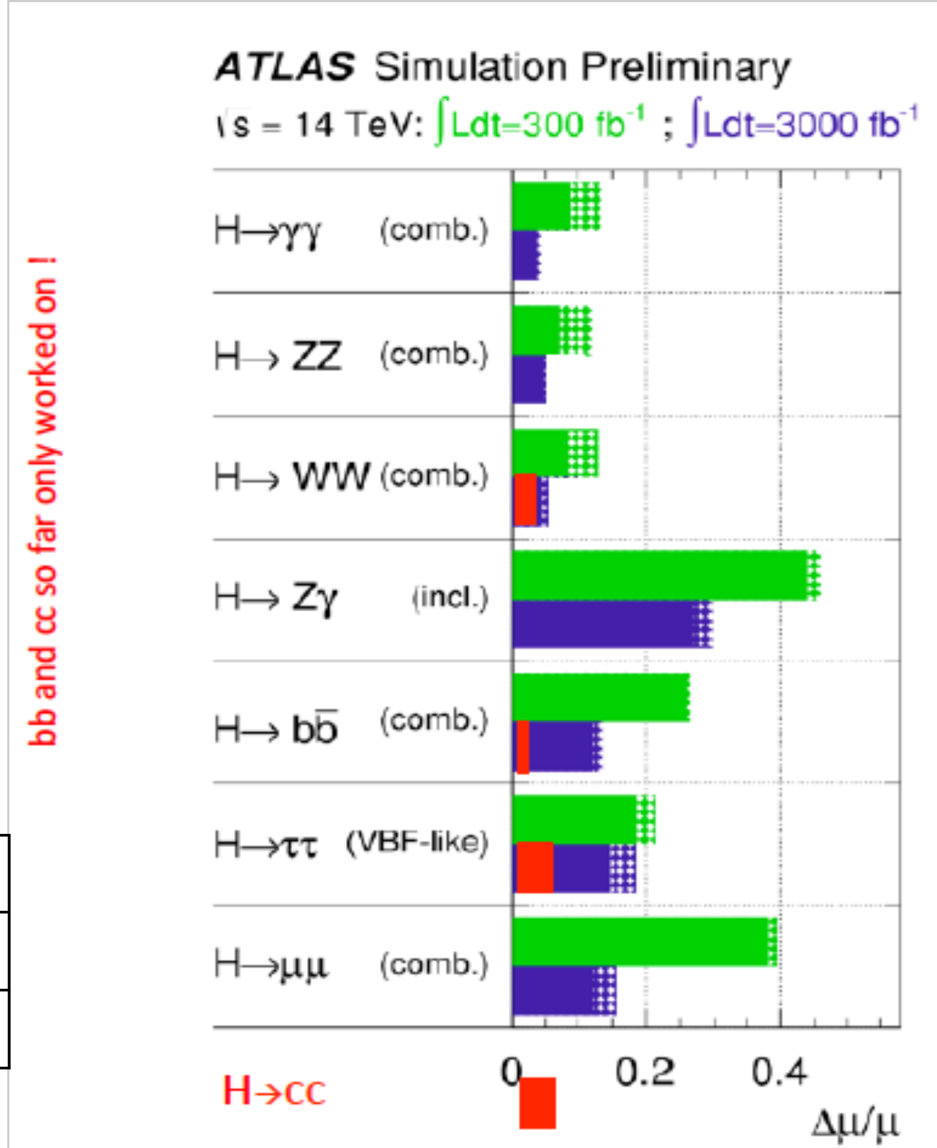
Clear potential to access the Higgs to charm decay channel at the LHeC.

Couplings: HL-LHC+LHeC

HL-LHC



HL-LHC + LHeC



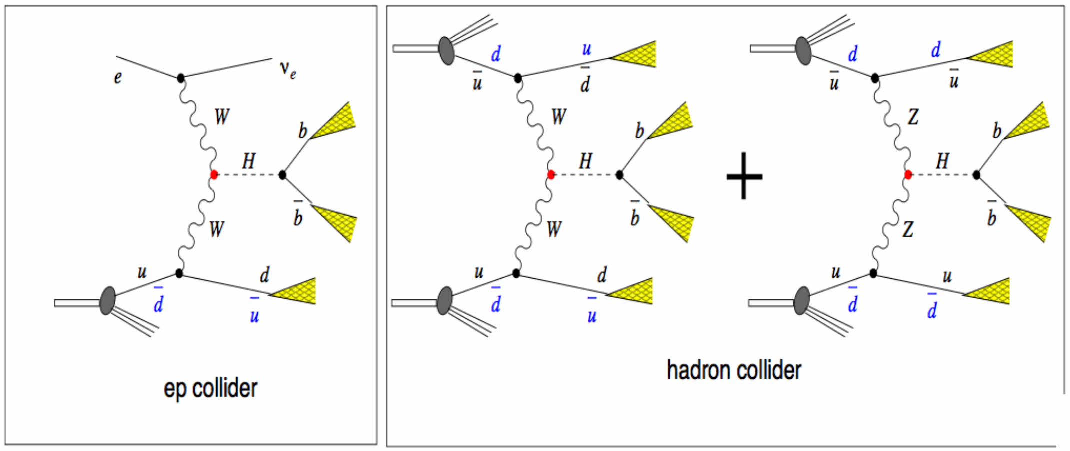
κ in %	HL LHC	LHeC HL	LHeC HE	FCC-eh
H → bb	10	0.5	0.3	0.2
H → cc	50?	4	2.8	1.8

Structure of HVV couplings

$$\Gamma^{\rm SM}_{\mu\nu} = -gM_V\, g_{\mu\nu}$$

$$\Gamma^{\rm BSM}_{\mu\nu}(p,q) = \frac{g}{M_V}\left[\lambda\left(p\cdot q\, g_{\mu\nu} - p_\nu q_\mu\right) + \lambda'\, \epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

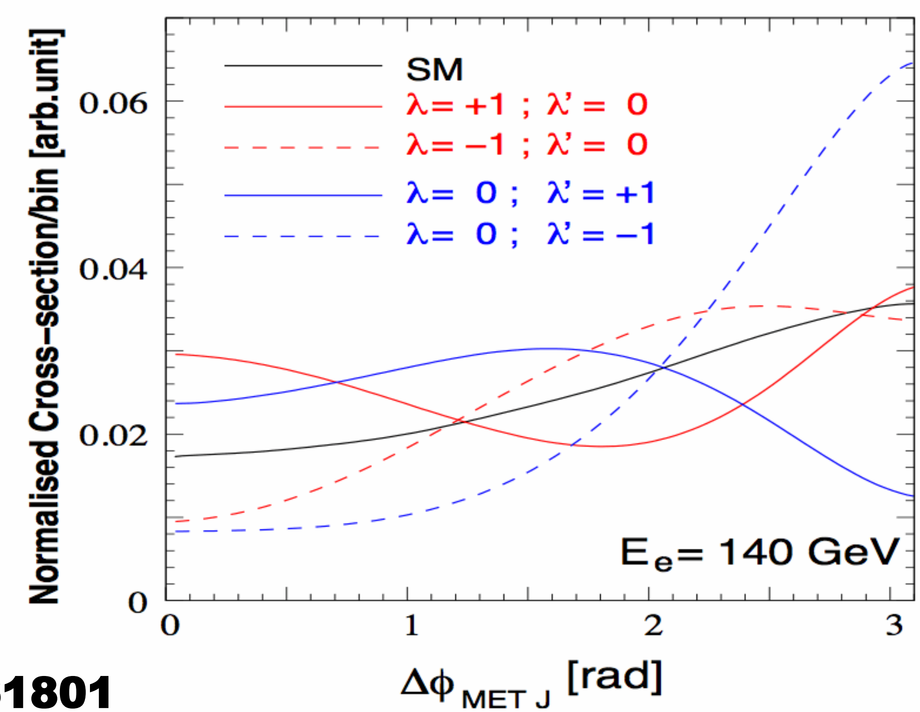
higgs + 2jets: VBF (LHC), higgs + jet + missing E_T (LHeC)



ep process uniquely addresses the HWW vertex.

Can consider azimuthal angle correlation between scattered neutrino and quark. Other observables can be used too.

Model independent separation of HWW and HZZ coupling, unique capability of ep collisions, not available in pp and e^+e^- collisions



B.Biswal, R.Godbole, S.Kumar, B.M., S.Raychaudhuri , Phys.Rev.Lett. 109 (2012) 261801

Invisible Higgs

Y.-L. Tang et al., Phys. Rev. D 94, 011702 (2016)

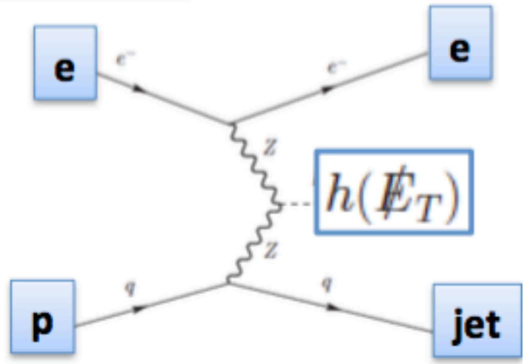
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

$\mathrm{Br}(h \to \not{E}_T)$ < 3.5% @90% C.L., MVA based

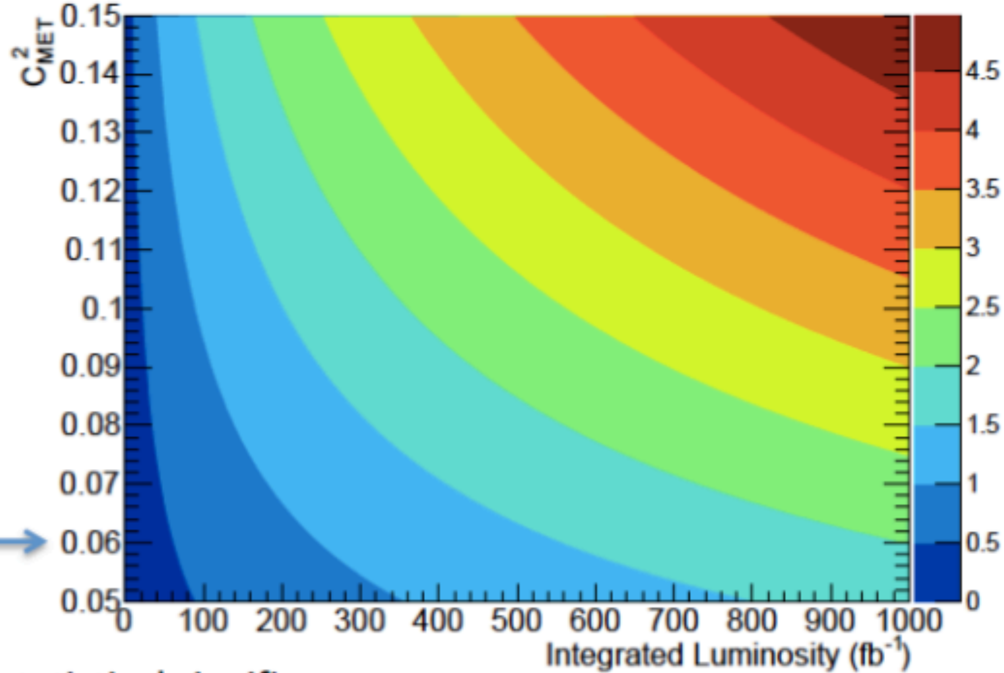
For **LHeC**, assume : 1ab^{-1}, P_e=-0.9, <u>cut based</u>

$\mathrm{Br}(h \to \not{E}_T)$ < 6% @ 2σ level

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



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**

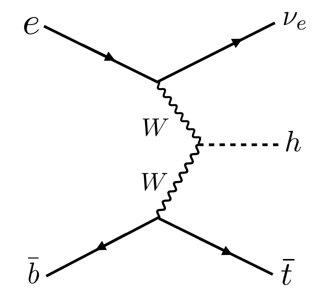
FCNC Top and Higgs couplings :
H. Sun [arXiv:1602.04670]
New study for HE-LHC 14 TeV p x 150 GeV e

BR(t→ qh) < 0.23%
@ 95% C.L. and 100 fb^{-1}

See Chen Zhang's poster on exotic decays

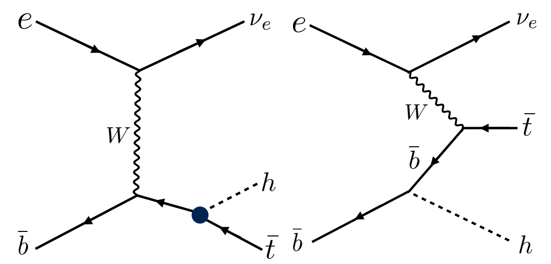
B.Coleppa, M.Kumar, S.Kumar, B.M., Phys. Lett. B770 (2017) 335

Top Yukawa coupling

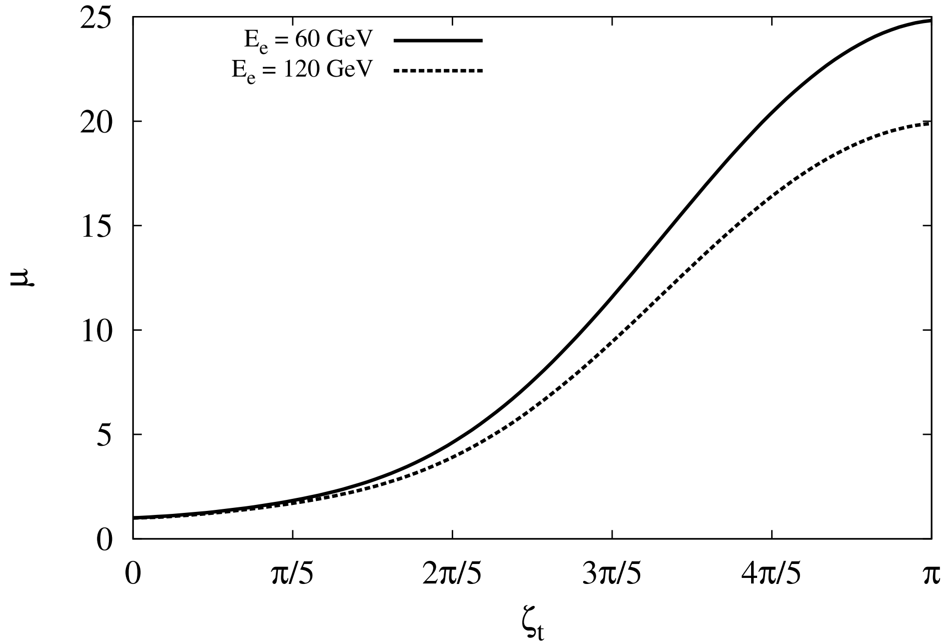


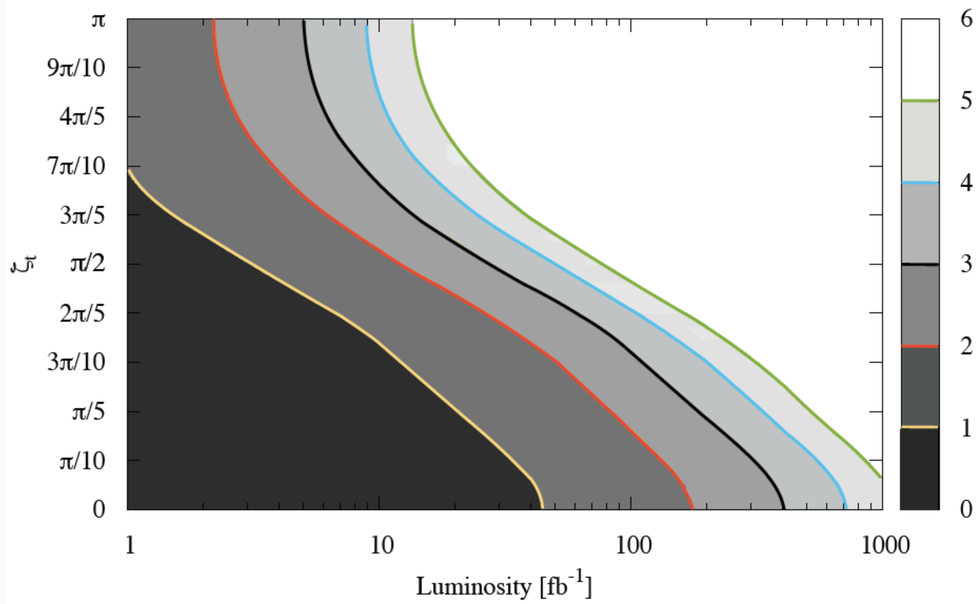
Introduce phase dependent top Yukawa coupling

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



Enhancement of the cross-section as a function of phase





Observe/Exclude non-zero phase to better than 4σ.
Measure coupling with 17% accuracy with zero phase

Outlook and Conclusions

- The LHeC has a vast physics program, further boosting the physics potential of the LHC
  - Unique capability to measure proton PDFs+α_S, etc…
  - Critical to the LHC in the long term
  - Rich top physics, etc…
- The LHeC is also a Higgs facility
  - Higgs produced via EW process
    - Good theoretical control of the cross-section
  - No contamination from ggF and no pile-up
  - Strengths ep with respect to pp:
    - h→bb(0.5%), cc(4%), tautau couplings
    - Structure of hVV and top/bottom Yukawa couplings
  - Combination of ep/pp boosts precision of LHC