

# FCC-eh and LHeC Overview

**B.Mellado**

**Univ. of the Witwatersrand & iThemba LABS  
On behalf of the LHeC Study Group**

**Many thanks to N.Armesto, G.Azuelos, O.Bruening, M.D'ONofrio,  
O.Fischer, S.Forte, M.Klein, U.Klein, P.Kostka, M.Kumar, M.Kuze,  
C.Schwanenberger and M.Tanaka for slides**



**iThemba  
LABS**

National Research  
Foundation

Laboratory for Accelerator  
Based Sciences



**FCC week, Amsterdam, 09/04/18**

# **EP Collisions @ FCC Week 2018**

**Jorge de Blas, Higgs in hh-eh-ee**

**Uta Klein, FCC-eh as a Higgs Facility**

**Monica D'Onofrio, BSM Physics in eh**

**Orhan Cakir, Top Quark Physics in eh**

**Christian Schwanenberger, Top in hh-eh-ee**

**Peter Kostka, A Detector for eh**

**Max Klein, QCD measurements at FCC**

**Oliver Bruening, Overview on FCC-eh design**

**John Osborne, Civil engineering**

**Roman Martin, Interaction region**

**Walid Kaabi, PERLE facility**

**Uta Klein, FCC-eh Summary**

ISSN 0954-3899

# Journal of Physics G

## Nuclear and Particle Physics

Volume 39 Number 7 July 2012 Article 075001

### A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for  
Machine and Detector  
*LHeC Study Group*



[arXiv:1206.2913](https://arxiv.org/abs/1206.2913)

iopscience.org/jphysg

IOP Publishing

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)

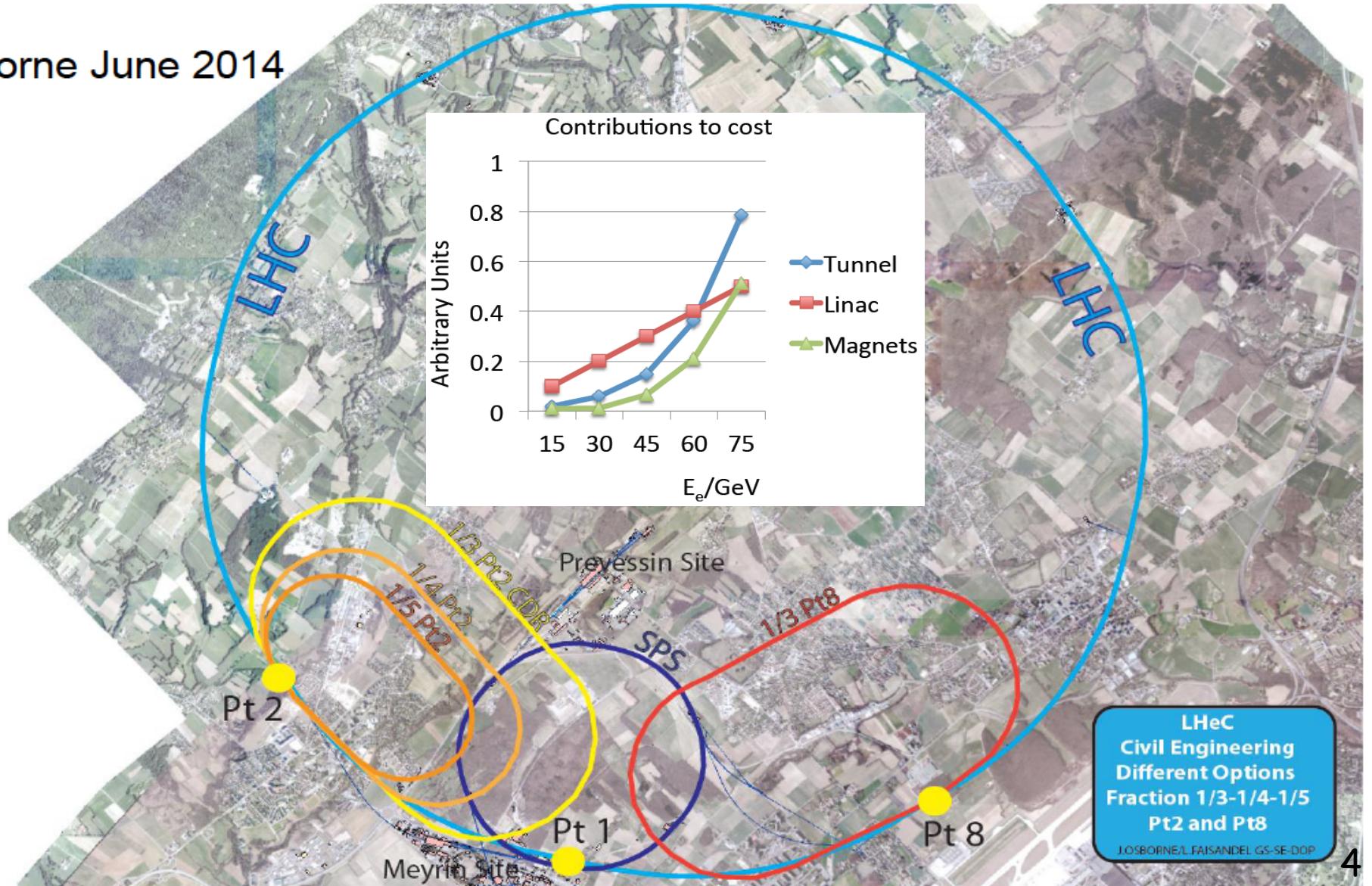
Raju Venugopalan (BNL)

Michele Arneodo (INFN Torino)

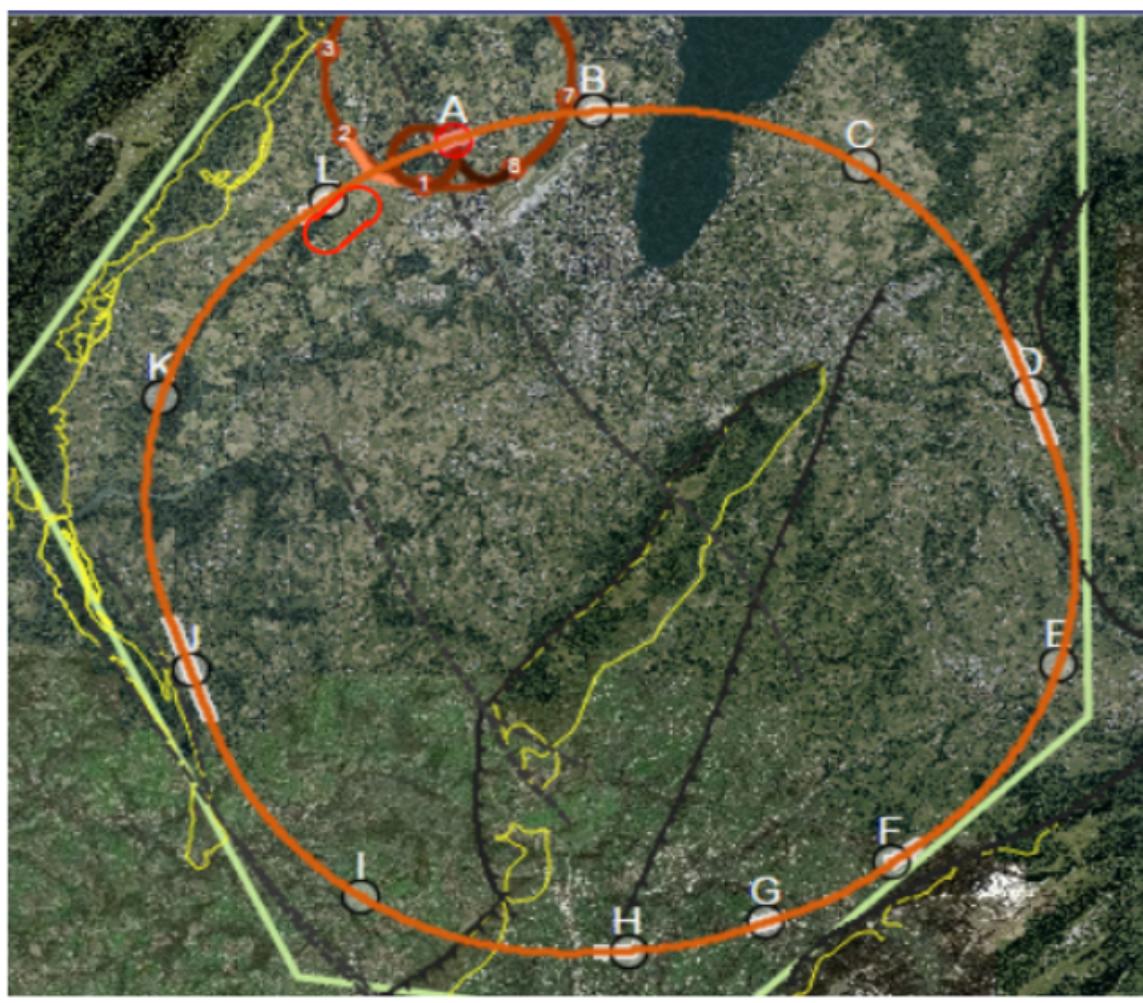
Published 600 pages conceptual design report (CDR) written by 150 authors from 60 Institutes.  
Reviewed by ECFA, NuPECC (long range plan), Referees invited by CERN. Published June 2012.

# Layout

John Osborne June 2014

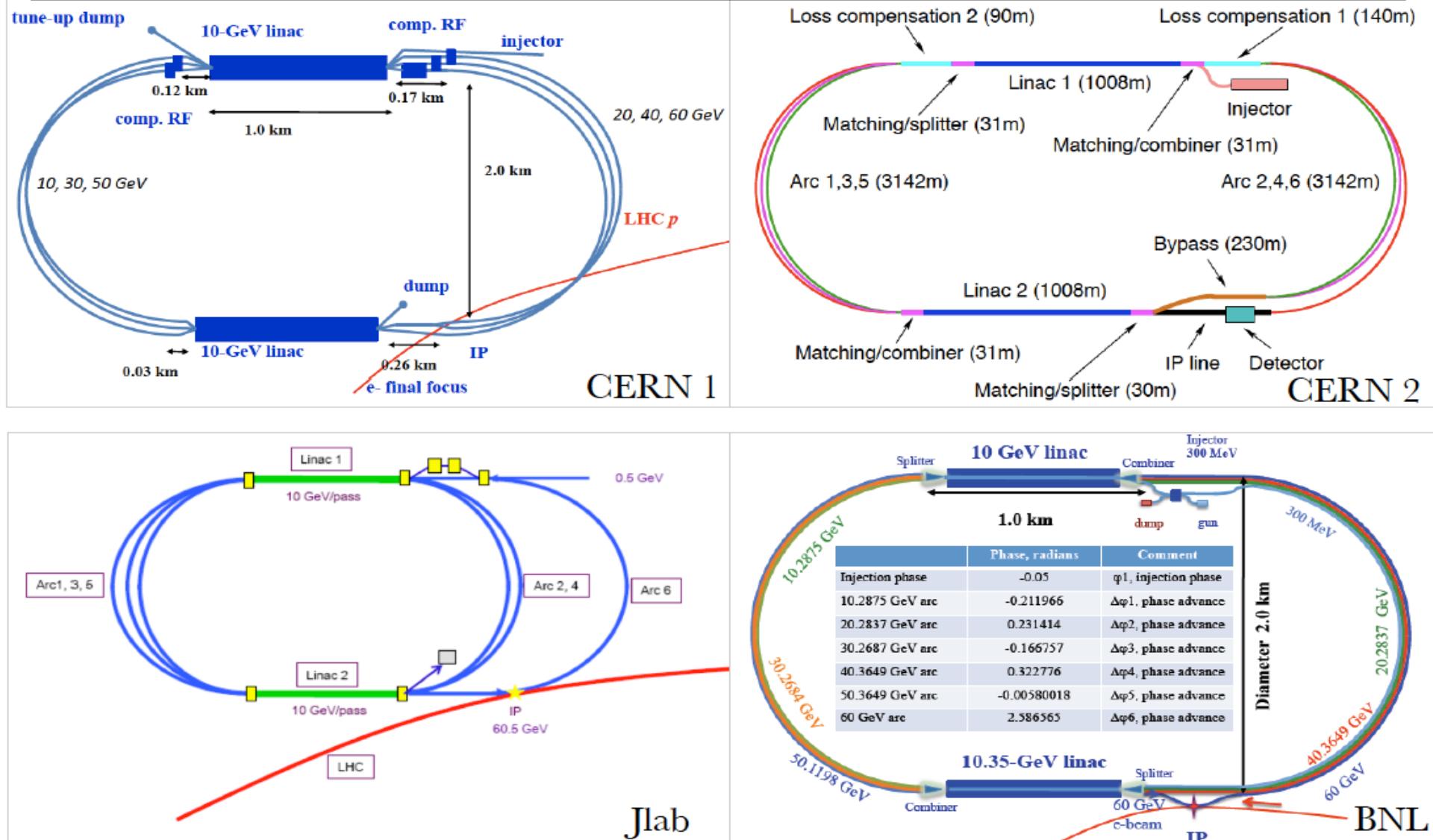


# FCC-eh



**60 GeV ERL tangential to FCC-hh. IP: L for geological reasons.**  
**L =  $1.5 \cdot 10^{34}$  Higher s, Q<sup>2</sup>, 1/x**

# 60 GeV Recovery Linac



**CDR: Default configuration, 60 GeV, 3 passes, 720 MHz, synchronous ep+pp,  $L_{ep} = 10^{33}$**

# Luminosity for LHeC, HE-LHeC and FCC

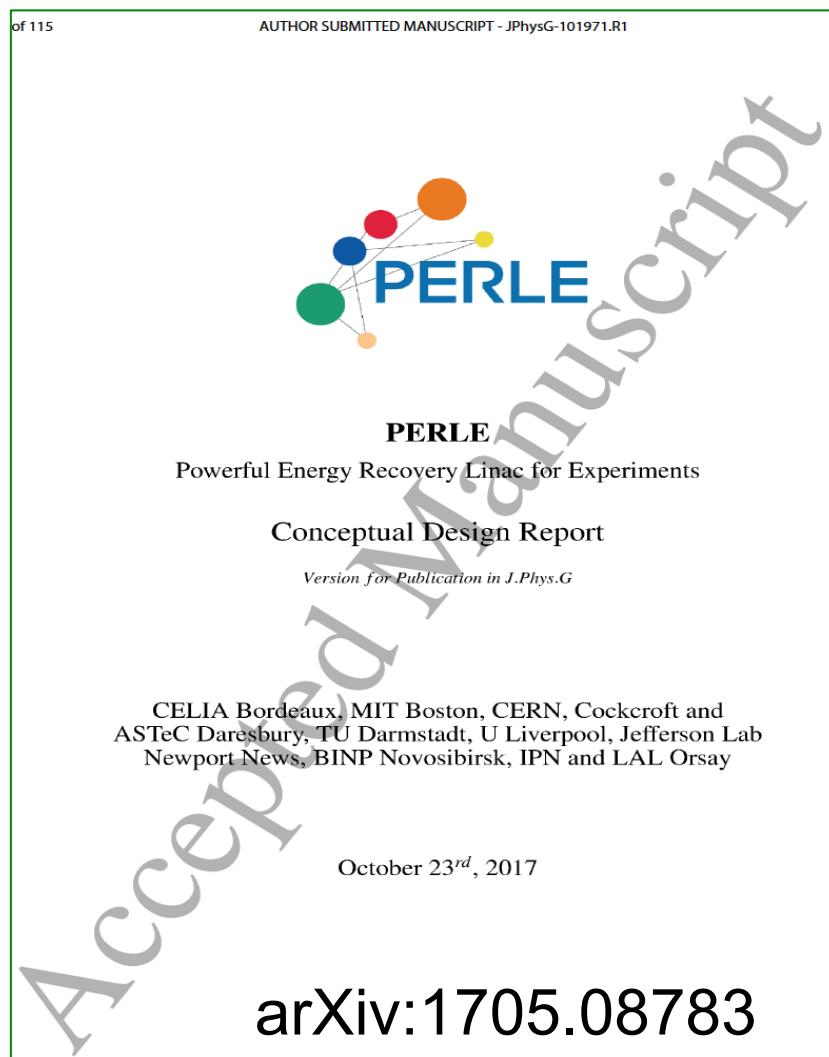
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
$E_p$ [TeV]	7	7	12.5	50
$E_e$ [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [ $10^{11}$ ]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [ $\mu\text{m}$ ]	3.7	2	2.5	2.2
electrons per bunch [ $10^9$ ]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function $\beta_p^*$ [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 [ $10^{33}\text{cm}^{-2}\text{s}^{-1}$ ]	1	8	12	15

Oliver Brüning<sup>1</sup>, John Jowett<sup>1</sup>, Max Klein<sup>2</sup>,  
Dario Pellegrini<sup>1</sup>, Daniel Schulte<sup>1</sup>, Frank Zimmermann<sup>1</sup>

**Contains update on eA:  
 $6 \times 10^{32}$  in e-Pb for LHeC.**

# Powerful ERL for Experiments

**Collaboration of BINP, CERN, Daresbury/Liverpool, Jlab, Orsay INP+LAL  
CDR 2016/17, TDR 2018/19 ..**



## WHY PERLE?

An Accelerator Test Facility  
Supporting the LHeC

University of Liverpool, November 2017

Steve Benson, Alex Bogacz, David Douglas,  
and Chris Tennant

for the Jlab PERLE Study Group

Saturday, November 11, 2017

 Jefferson Lab

<https://indico.cern.ch/event/680603/>

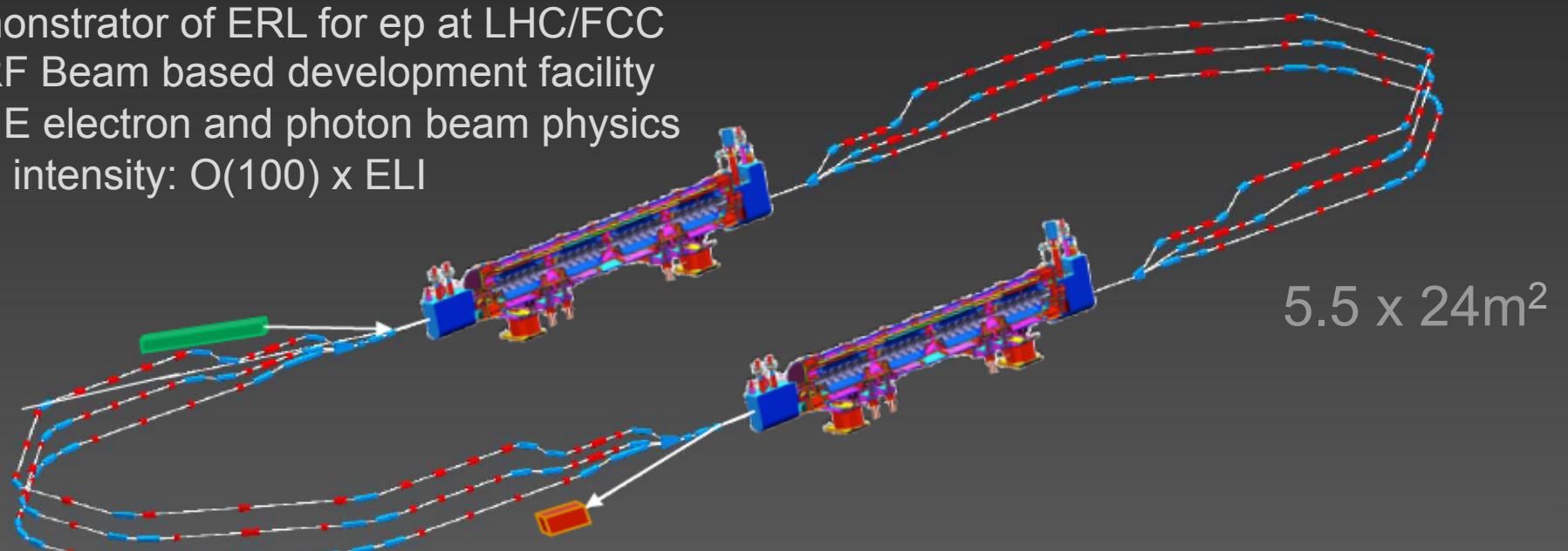
**ERL facility: high current and energy  
low energy nuclear, particle and astro-physics**

# PERLE at Orsay

PERLE at Orsay (LAL/INP) Collaboration: BINP, CERN, Daresbury/Liverpool, Jlab, Orsay

3 turns, 2 Linacs, 500 MeV, 20mA, 802 MHz, Energy Recovery Linac facility

- Demonstrator of ERL for ep at LHC/FCC
- SCRF Beam based development facility
- Low E electron and photon beam physics
- High intensity:  $O(100) \times$  ELI



CDR to appear in J Phys G [arXiv:1705. 08783]



A.Bogacz

Strong low energy physics program

<https://indico.cern.ch/event/698368/>

# Why PERLE [as seen from LHeC]?

## FUNDAMENTAL MOTIVATION:

- **Validation of key LHeC Design Choices**
- **Build up expertise in the design and operation for a facility with a fundamentally new operation mode:**  
ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no ‘automatic’ longitudinal phase stability, etc.)
- **Proof validity of fundamental design choices:**  
Multi-turn recirculation (other existing ERLs have only 1-2 passages)  
Implications of high current operation ( $2 * 3 * [6\text{mA} - 25\text{mA}] \rightarrow 30\text{-}150\text{mA}!!$ )
- **Verify and test machine and operation tolerances before designing a large scale facility**  
Tolerances in terms of field quality of the arc magnets and cavity alignment  
Required RF phase stability (RF power) and LLRF requirements  
Halo and beam loss tolerances

# PERLE Magnets

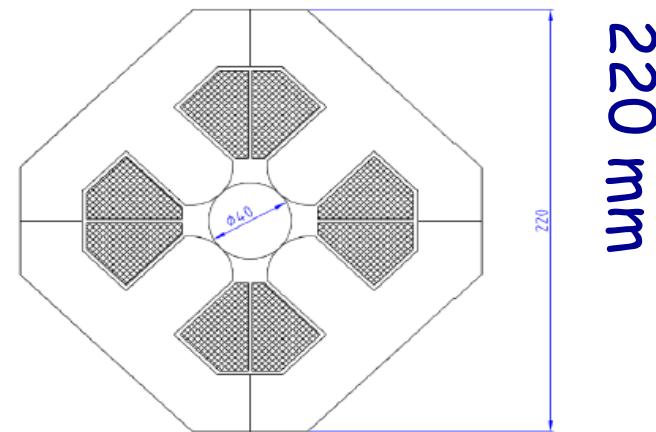
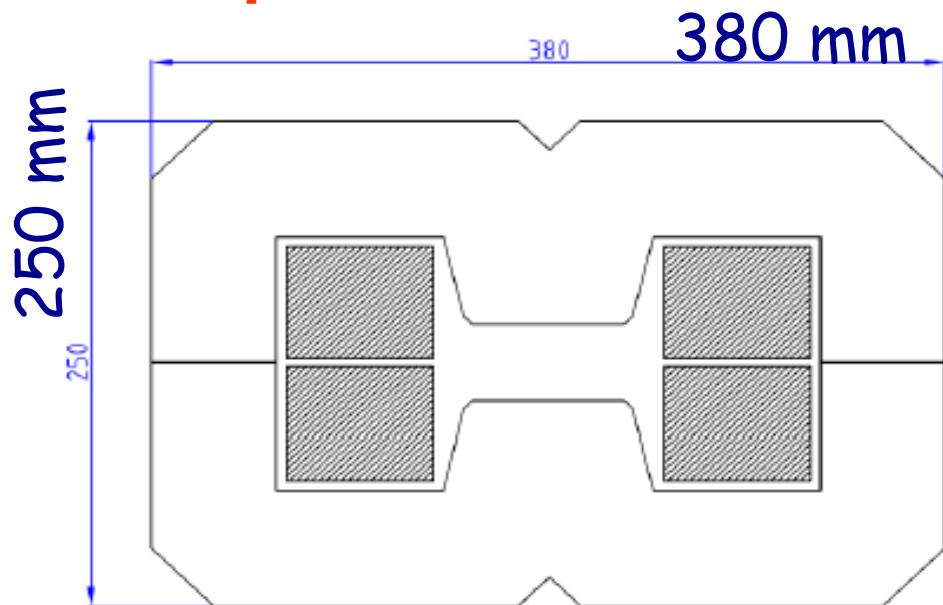
**70 dipoles 0.45-1.29 T**

**±20 mm aperture, l=200,300,400 mm**

**May be identical for hor+vert bend**

**7A/mm<sup>2</sup> (in grey area) water cooled**

**DC operated**



**114 quadrupoles max 28T/m**

**Common aperture of 40mm all arcs**

**Two lengths: 100 and 150mm**

**DC operated**

# 1st 802 MHz Cavity



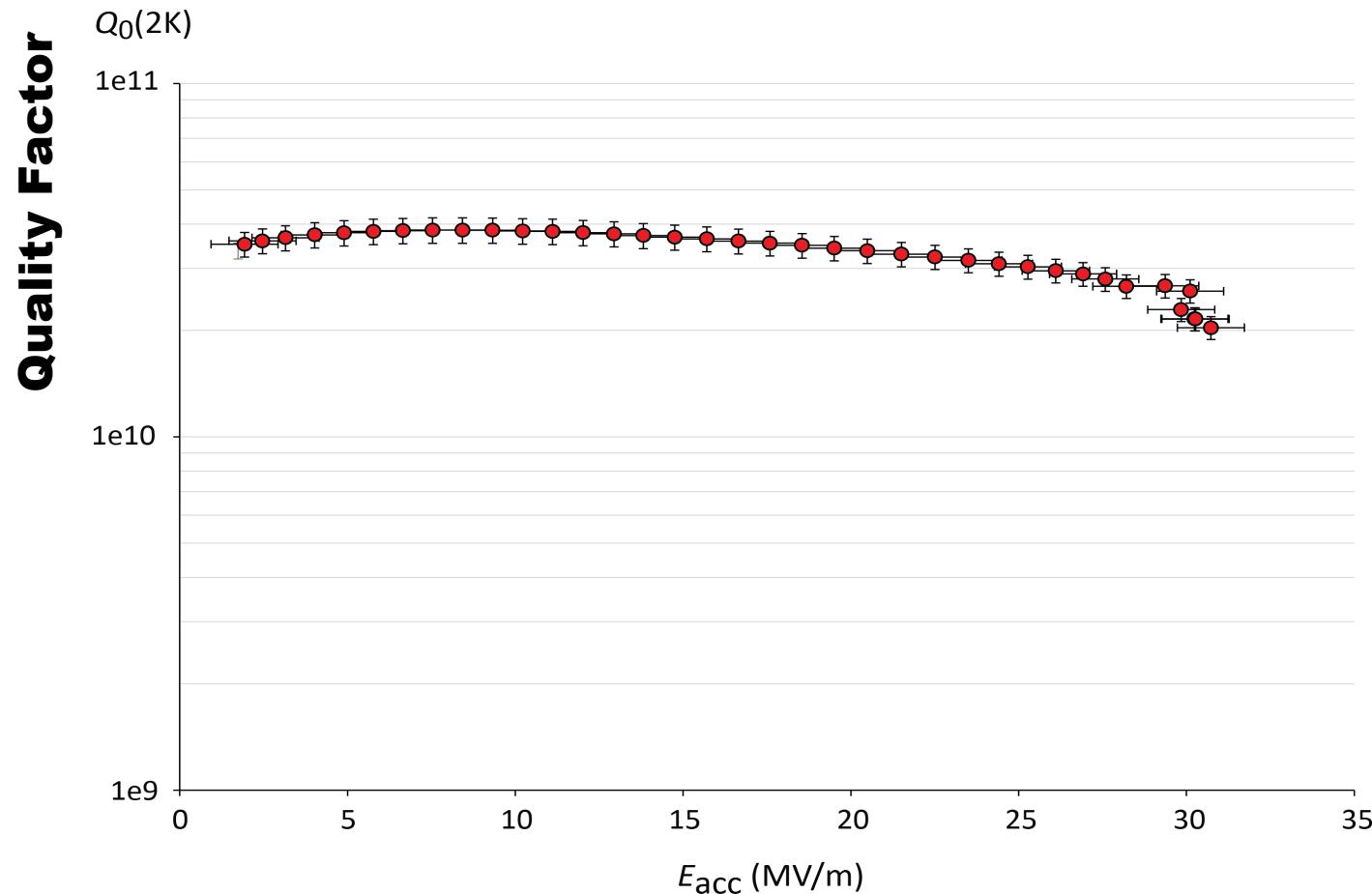
CERN-Jlab design, produced at Jefferson Laboratory November 2017

12

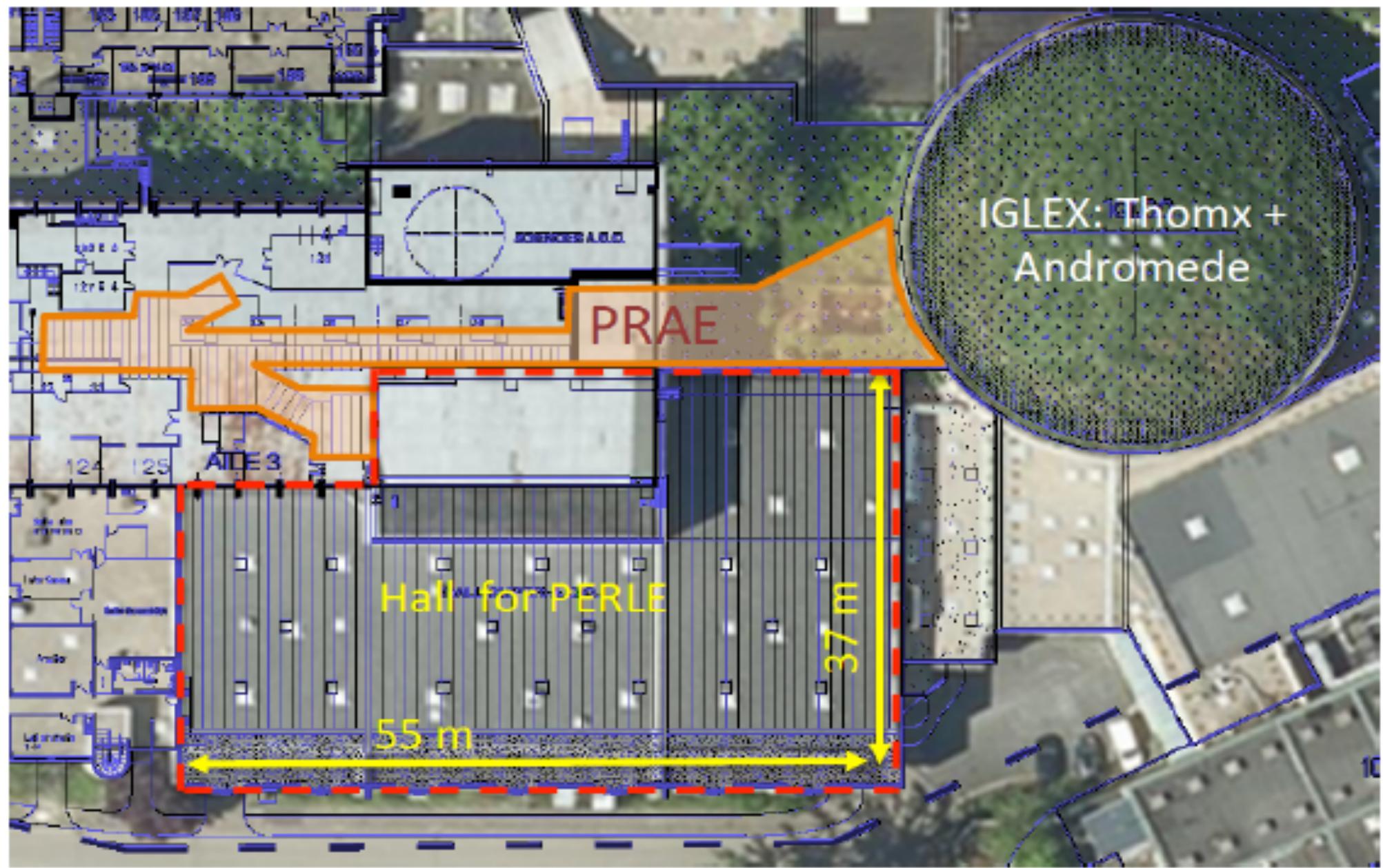
Goal: 16 MV/m,  $Q_0 > 10^{10}$  operated in CW in the PERLE+LHeC ERLs, prototype also for FCC-ee

# Initial 2K Test of 802 MHz Nb Cavity

December 2017

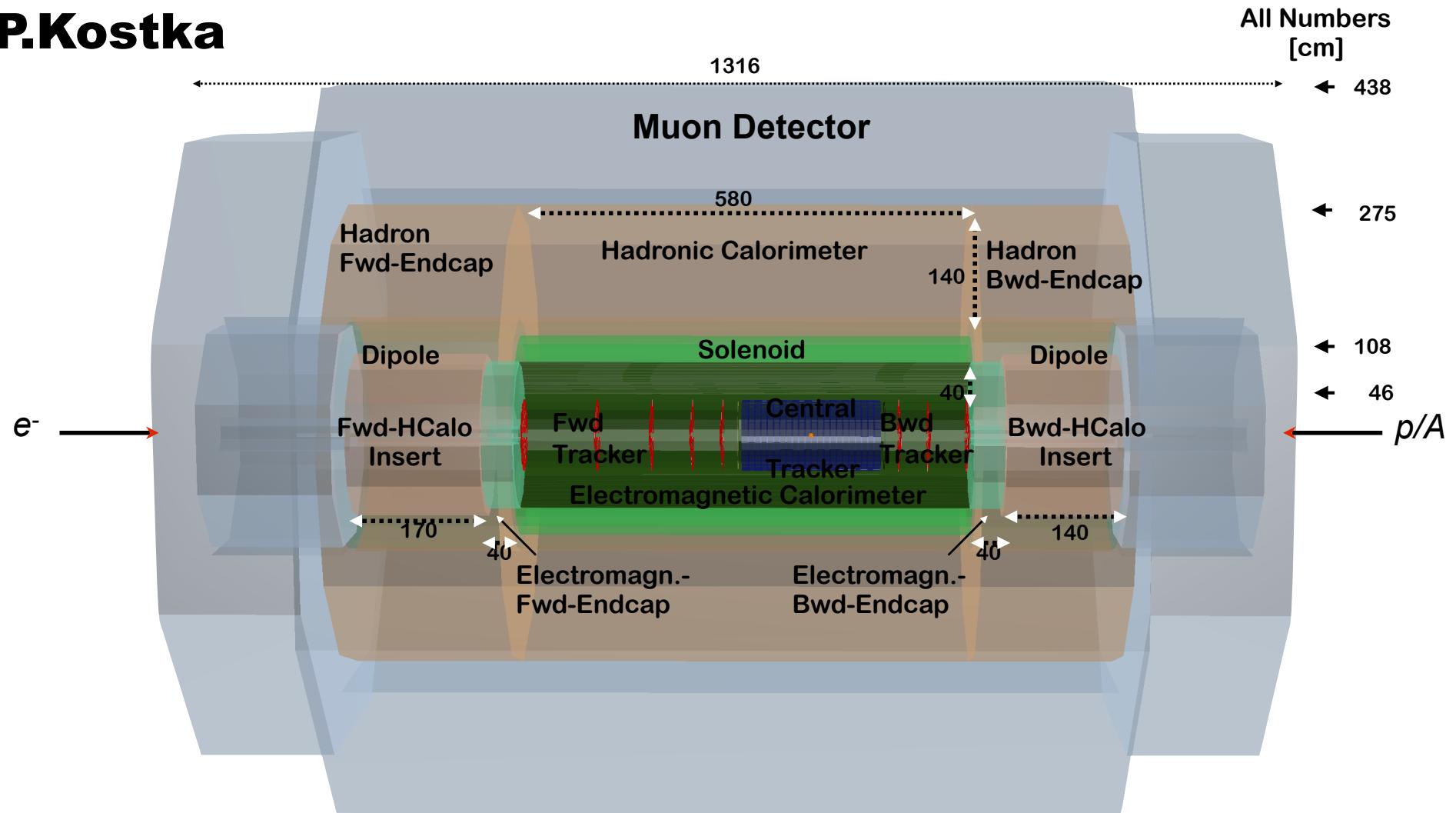


**High quality, CW: operation point at about 18 MV/m. Quench at 31 MV/m  
Rerinsing for field emission suppression, observed at higher gradients.  
Next: HOM adapter and cryomodule design – cavity production to proceed.**



# LHeC Detector Basic Layout

P.Kostka

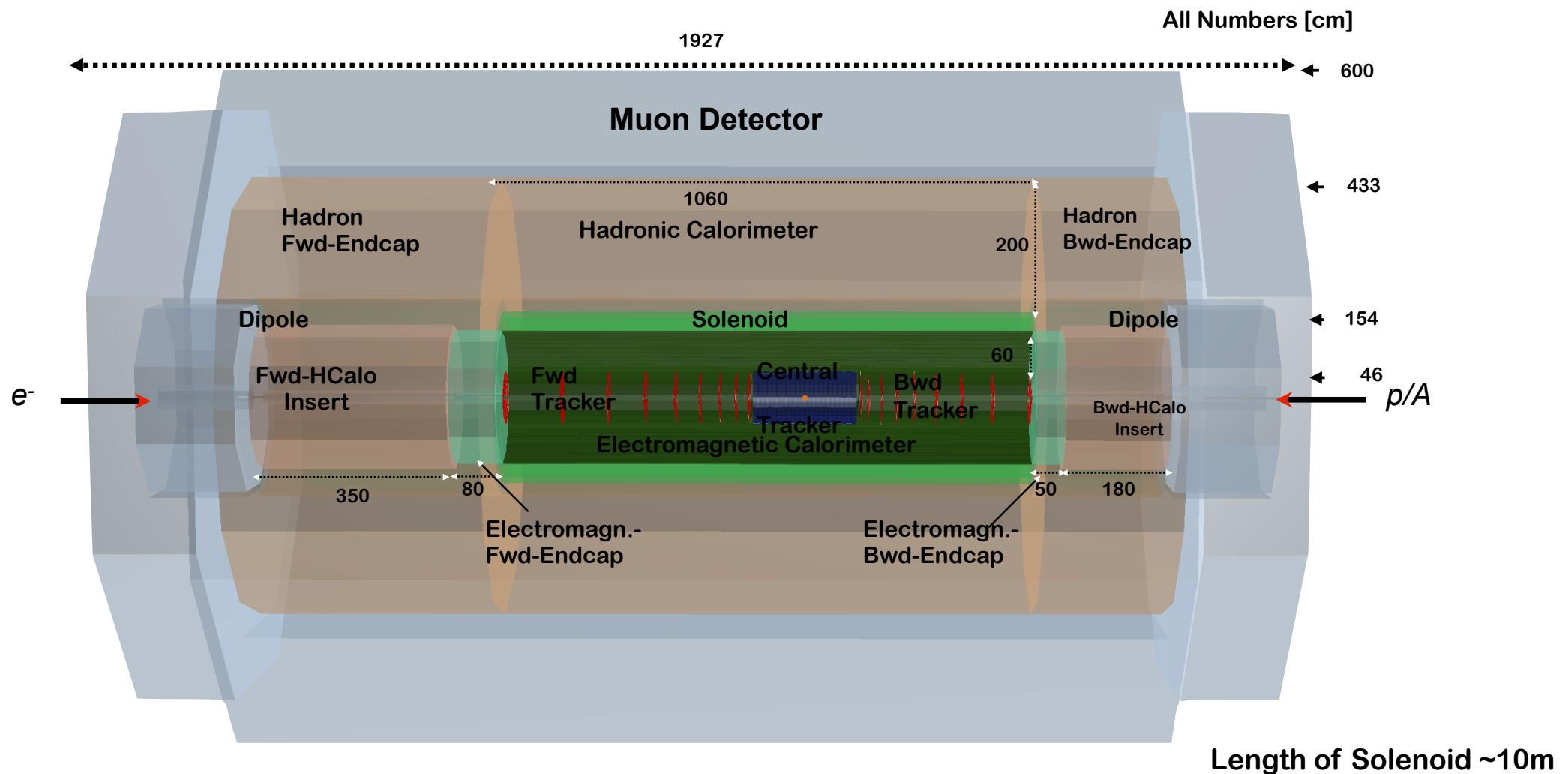


<http://cern.ch/lhec>  
CDR: “A Large Hadron Electron Collider at CERN”,  
LHeC Study Group, [arXiv:1206.2913],  
J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001

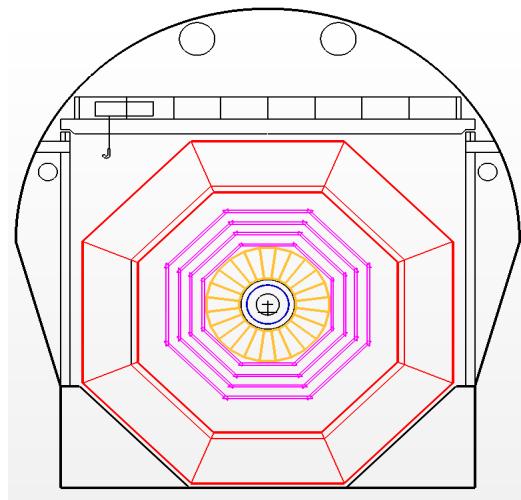
“On the Relation of the LHeC and the LHC” [arXiv:1211.5102]

# FCC-he Detector Basic Layout

P.Kostka

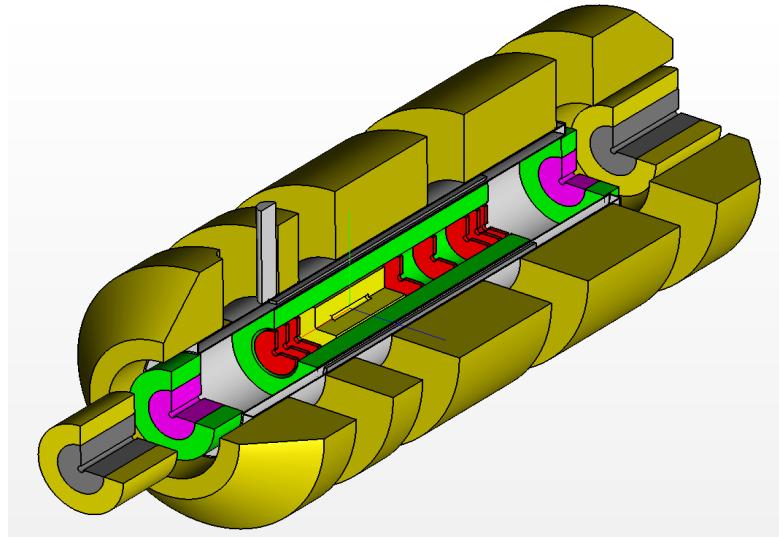


Based on the LHeC design; Solenoid&Dipoles between Electromagnetic Calorimeter and Hadronic Calorimeter.



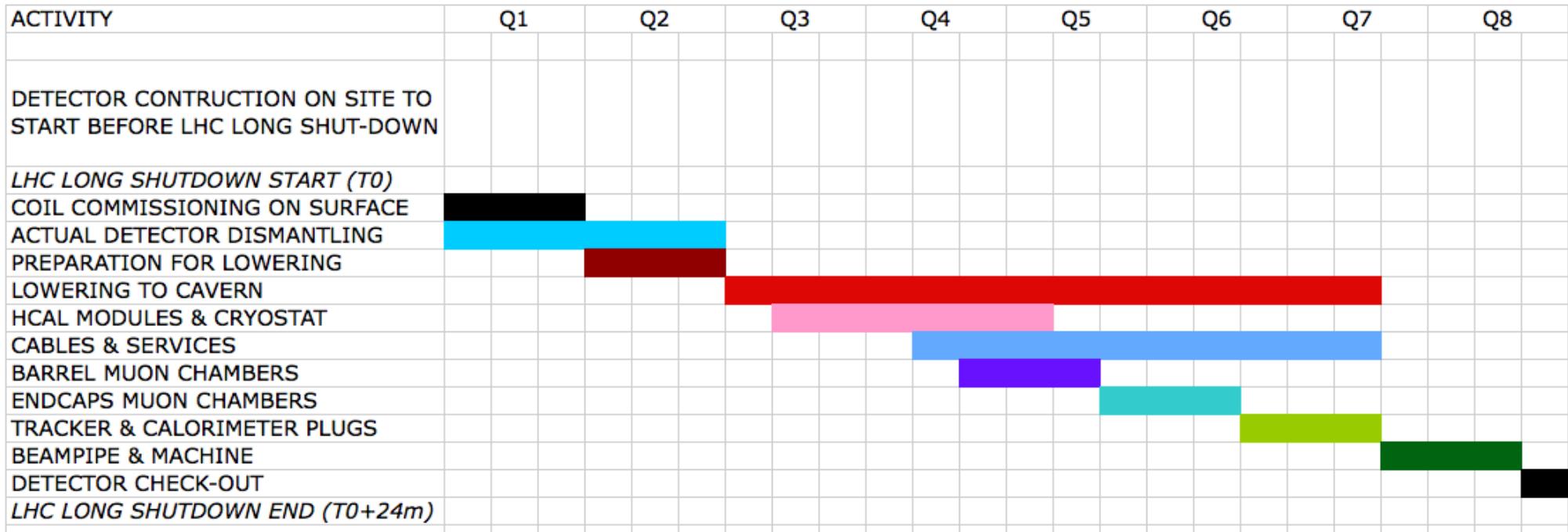
Detector fits in L3 magnet support

# Installation Study to fit into LHC shutdown needs directed to IP2 Andrea Gaddi *et al*



Modular structure

## LHeC INSTALLATION SCHEDULE



# **Physics Highlights**

# LHeC Physics Programme

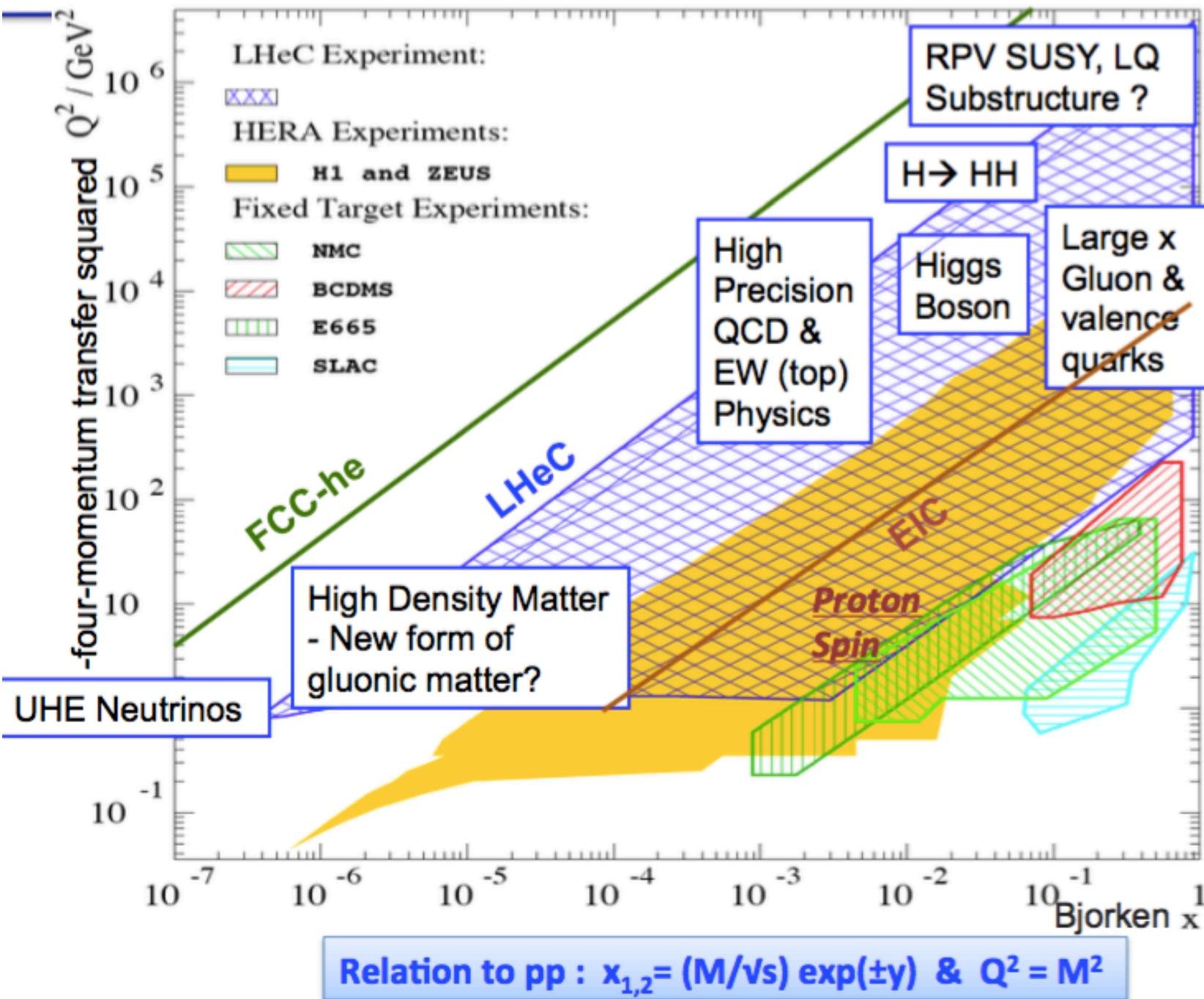
CDR, arXiv:1211.4831 and 5102

<http://cern.ch/lhec>

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

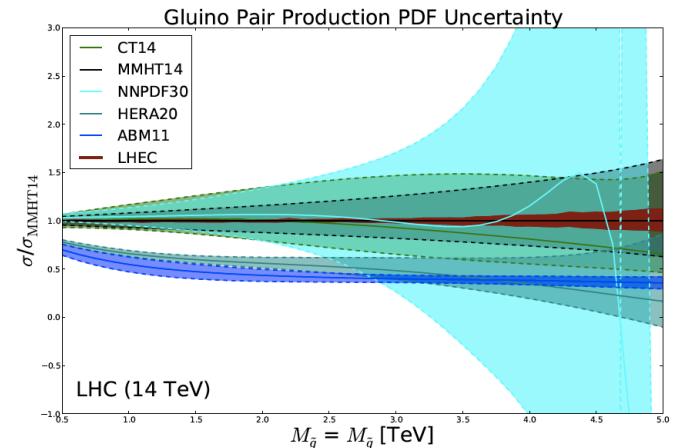
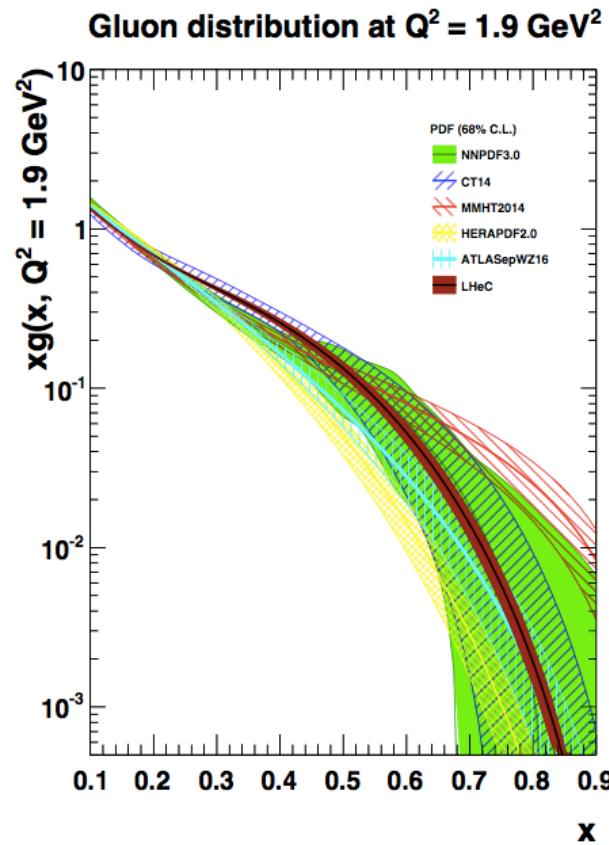
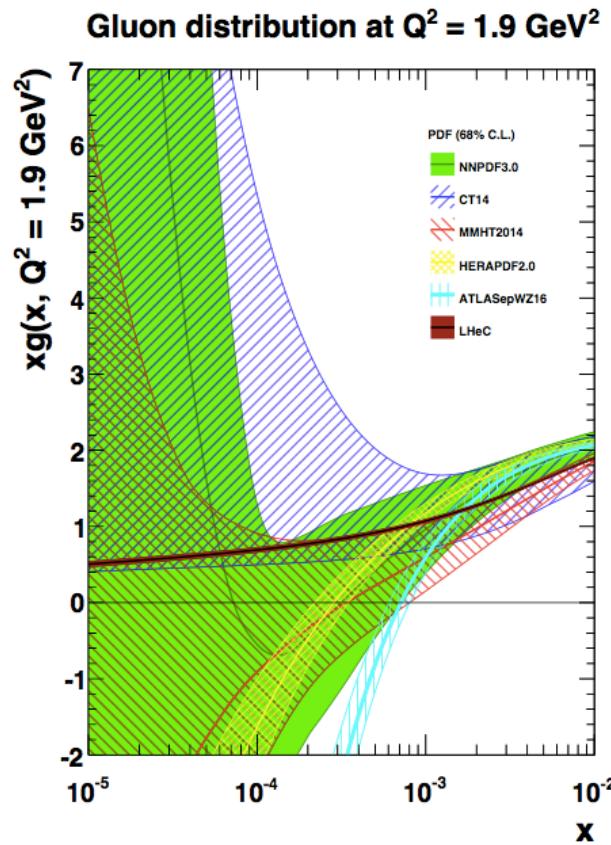
**Ultra high precision (detector, e-h redundancy)** - new insight  
**Maximum luminosity and much extended range** - rare, new effects  
**Deep relation to (HL-) LHC (precision+range)** - complementarity

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



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!

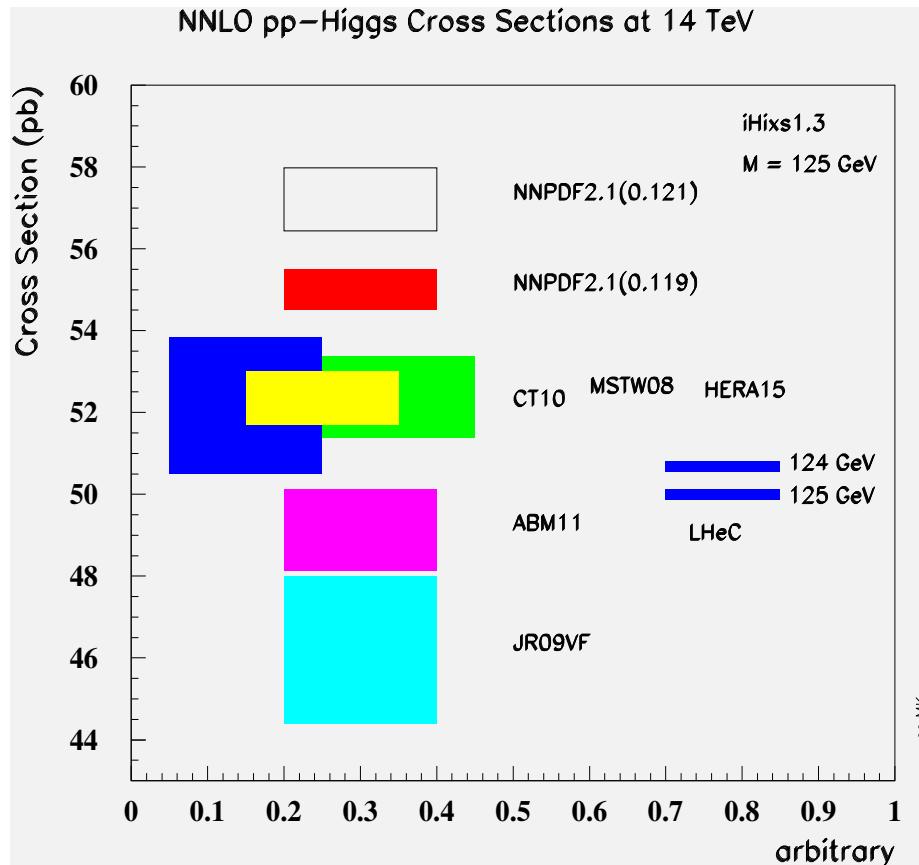


**Strong reduction of parton pdf uncertainties, with large impact on high- $x$  physics in pp**

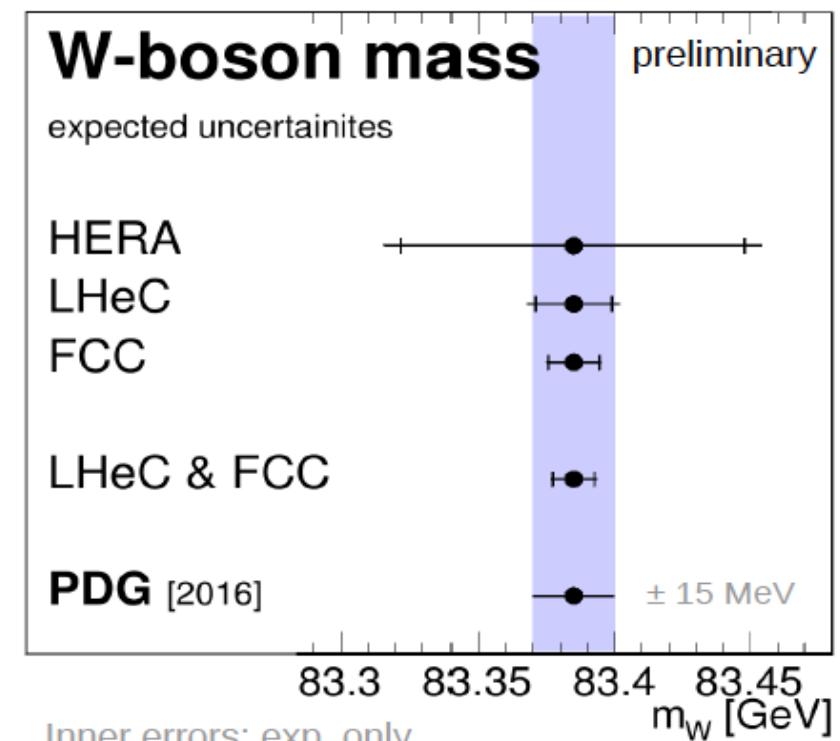
case	cut [ $Q^2$ ( $\text{GeV}^2$ )]	uncertainty	relative precision (%)
HERA only	$Q^2 > 3.5$	0.00224	1.94
HERA+jets	$Q^2 > 3.5$	0.00099	0.82
LHeC only	$Q^2 > 3.5$	0.00020	0.17
LHeC+HERA	$Q^2 > 3.5$	0.00013	0.11
LHeC+HERA	$Q^2 > 7.0$	0.00024	0.20
LHeC+HERA	$Q^2 > 10.$	0.00030	0.26

**Achieve down to 0.1% error in  $\alpha_s$**

# High Precision for pp



**Can achieve <0.5% precision in pdf uncertainty, thus removing this uncertainty from the prediction of the Higgs cross-section.**



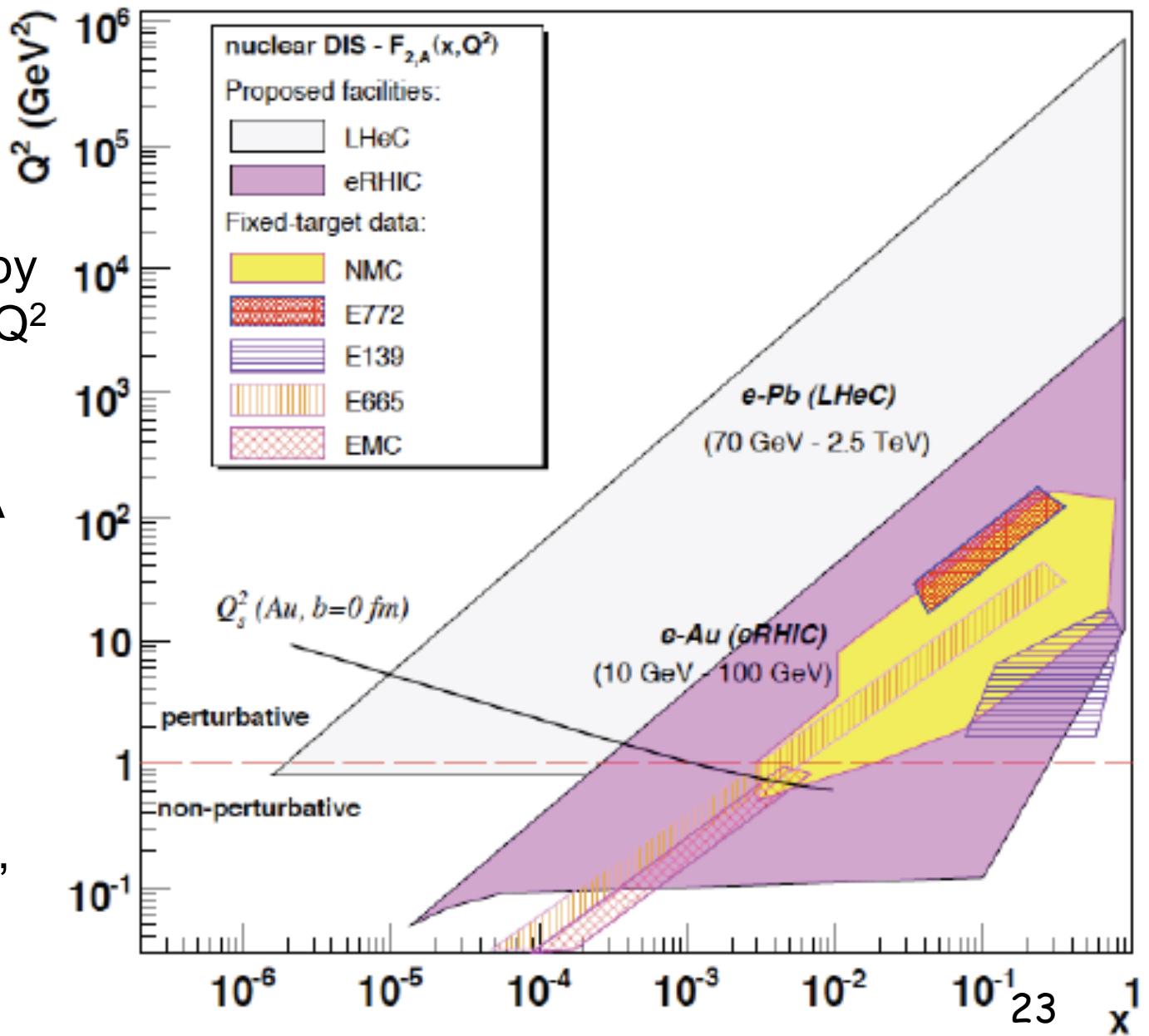
**Reduce pdf error 2.8 MeV → Remove PDF uncertainty on  $M_W$  LHC**

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

# eA Collisions

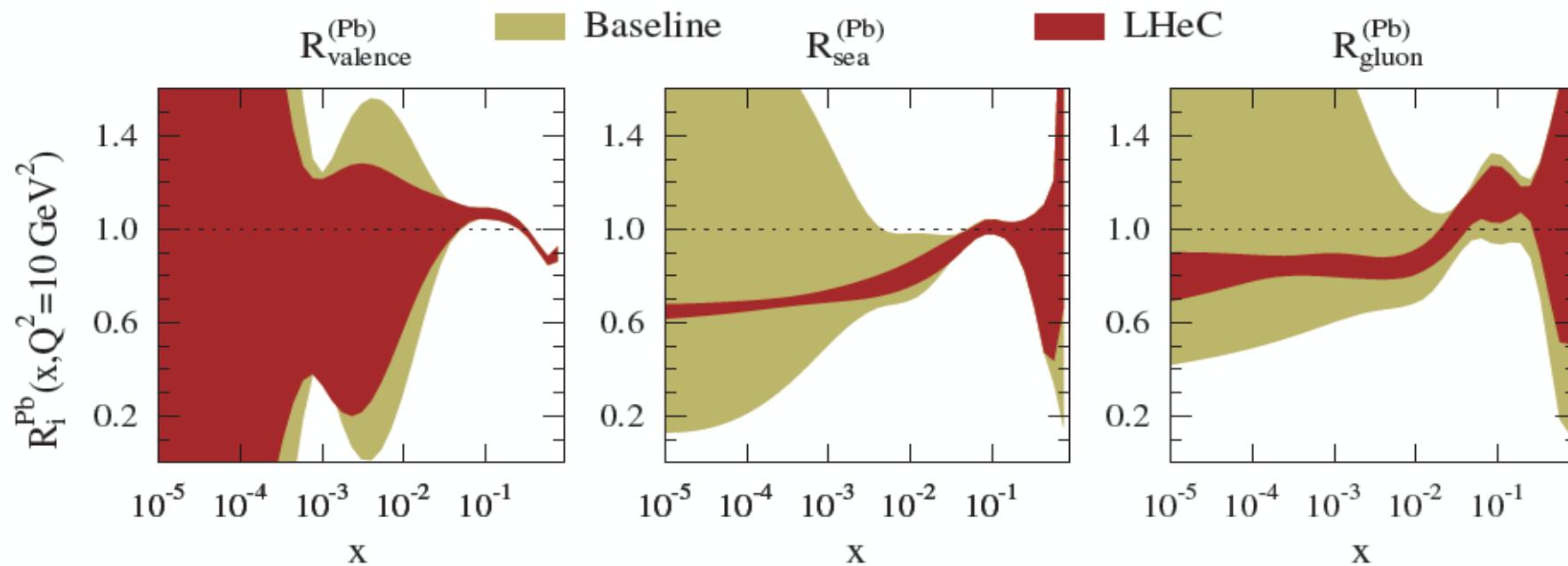
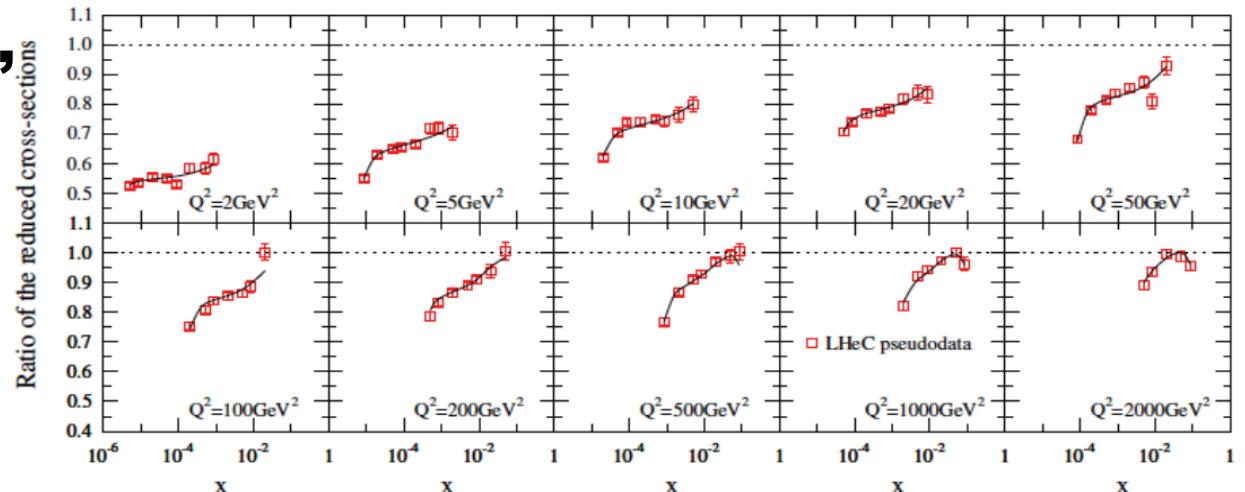
Extension of kinematic range of eN scattering by orders of magnitude in  $Q^2$  and  $1/x$

Complementarity to AA and pA physics: initial state of QGP, hadronisation and mechanism of confinement, collective phenomena seen in AA, pA and pp



# eA: inclusive

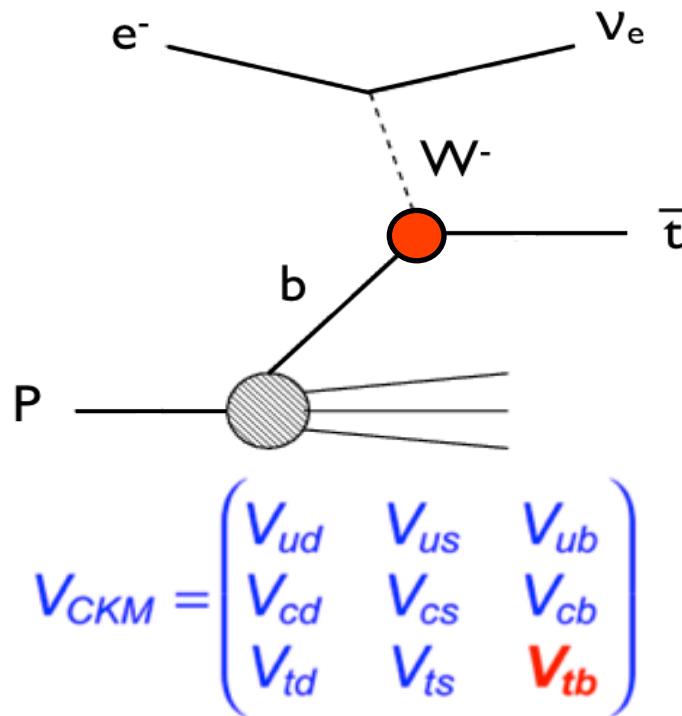
- Large impact on nPDFs, possible to make a Pb fit without proton PDFs
- Large room for improvements: NC+CC at several energies, flavour decomposition,...



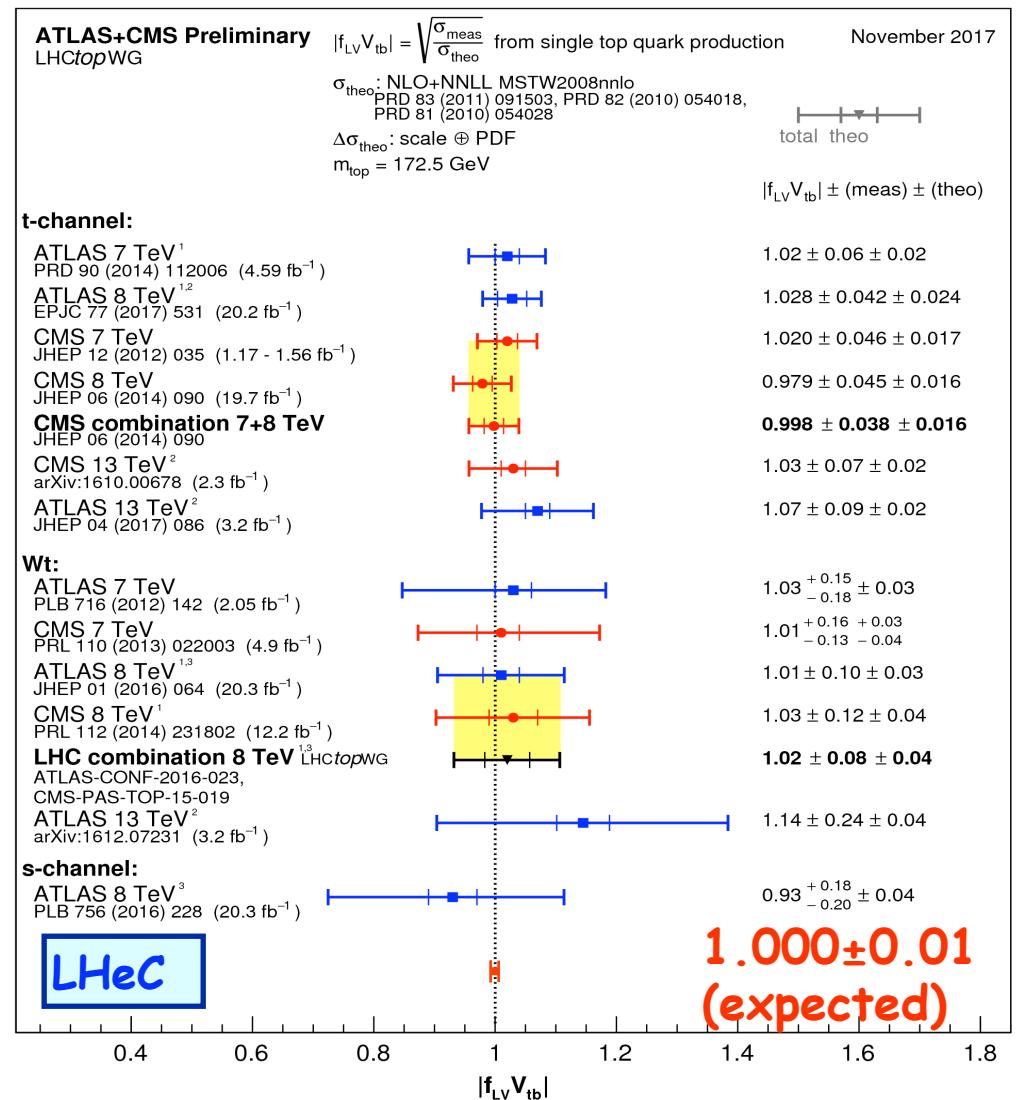
# Direct Measurement of $|V_{tb}|$

C.Schwanenberger

- <sup>1</sup> including top-quark mass uncertainty
- <sup>2</sup>  $\sigma_{\text{theo}}$ : NLO PDF4LHC11
- <sup>3</sup> NPPS205 (2010) 10, CPC191 (2015) 74 including beam energy uncertainty



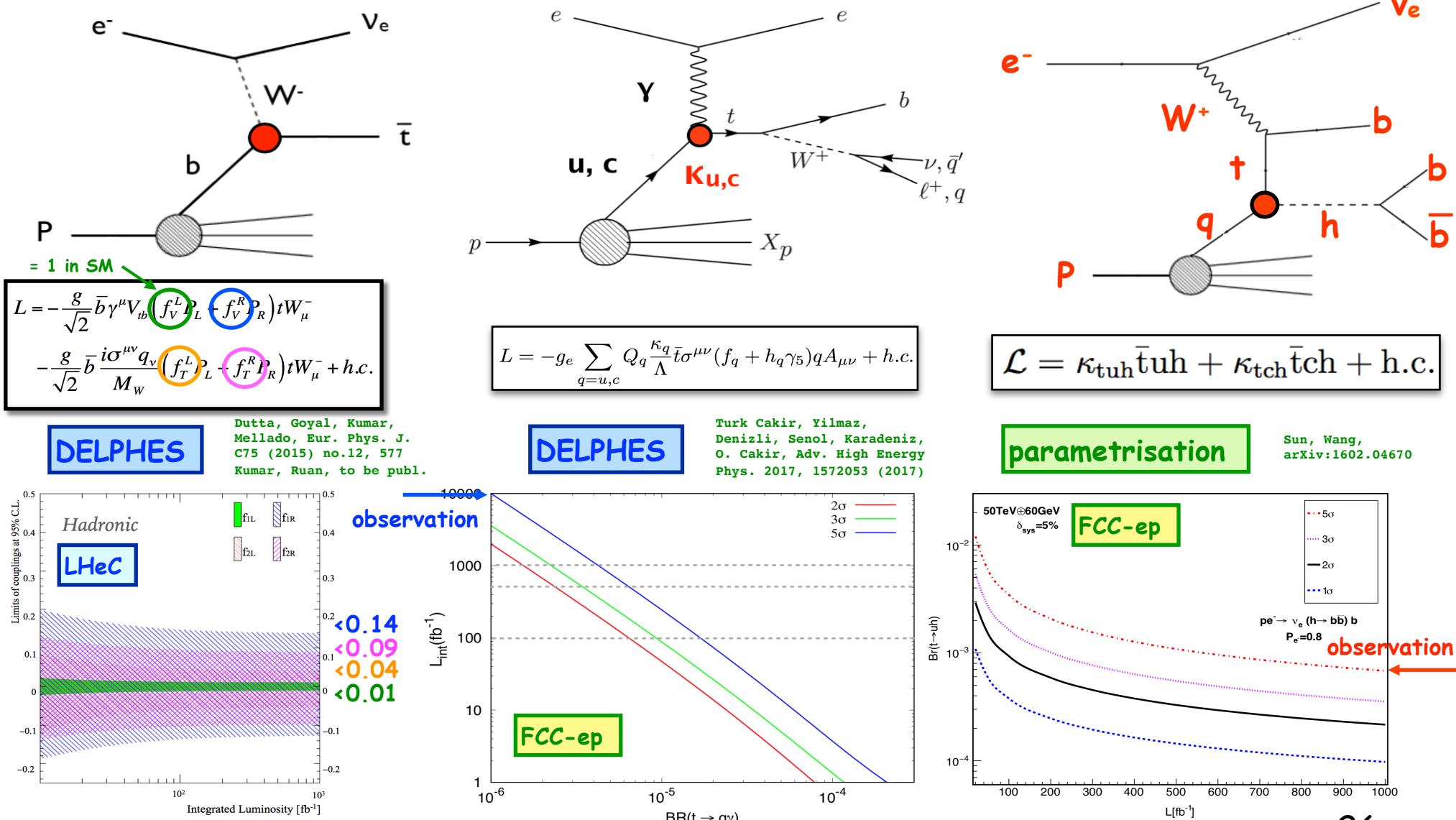
Takes advantage that  $t\bar{t}$  production is suppressed in ep.  
FCC-eh with  $2 \text{ ab}^{-1}$  would further improve the result significantly.



**LHeC,  $100 \text{ fb}^{-1}$**

# Top Quark Anomalous Couplings

c.Schwanenberger



# Higgs in ep

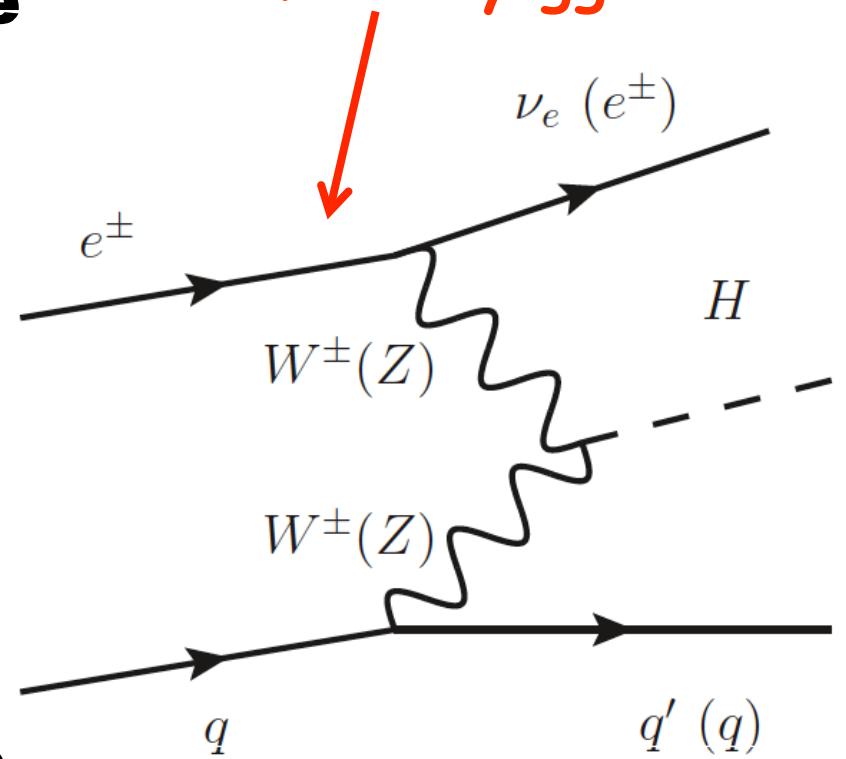
□ It is remarkable that VBF diagrams were calculated for lepton nucleon collisions before for pp!

□ Small theoretical uncertainties

□ Topological requirements effective in background suppression

□ Large S/B w.r.t. pp, e.g. in  $h \rightarrow bb$  expect S/B=3

At LHC replace lepton lines by quark lines but dominantly  $gg \rightarrow H$



# LHeC, a Higgs Facility

→ for first time a realistic option of an  $1 \text{ ab}^{-1}$  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]

$\sqrt{s} = 1.3 \text{ TeV}$

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

gg,  $\gamma\gamma$ : 'heft'

LHeC Higgs		CC ( $e^- p$ )	NC ( $e^- p$ )	CC ( $e^+ p$ )
Polarisation		-0.8	-0.8	0
Luminosity [ $\text{ab}^{-1}$ ]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	$N_{CC}^H e^- p$	$N_{NC}^H e^- p$	$N_{CC}^H e^+ p$
$H \rightarrow b\bar{b}$	0.577	113 100	13 900	3 350
$H \rightarrow c\bar{c}$	0.029	5 700	700	170
$H \rightarrow \tau^+\tau^-$	0.063	12 350	1 600	370
$H \rightarrow \mu\mu$	0.00022	50	5	—
$H \rightarrow 4l$	0.00013	30	3	—
$H \rightarrow 2l2\nu$	0.0106	2 080	250	60
$H \rightarrow gg$	0.086	16 850	2 050	500
$H \rightarrow WW$	0.215	42 100	5 150	1 250
$H \rightarrow ZZ$	0.0264	5 200	600	150
$H \rightarrow \gamma\gamma$	0.00228	450	60	15
$H \rightarrow Z\gamma$	0.00154	300	40	10

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

→ Decay to  $b\bar{b}$  is dominating HFL decay modes :

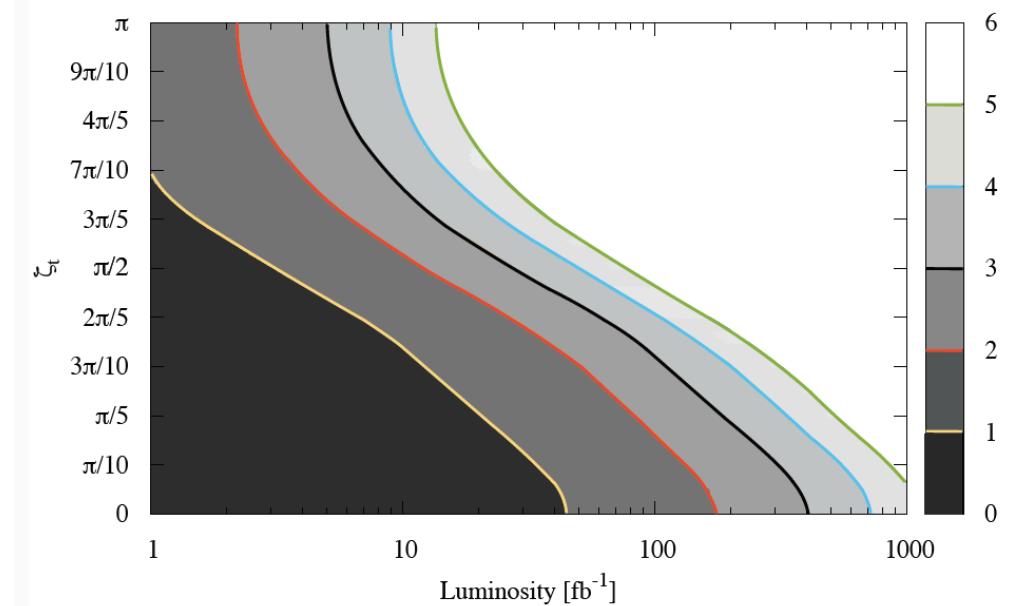
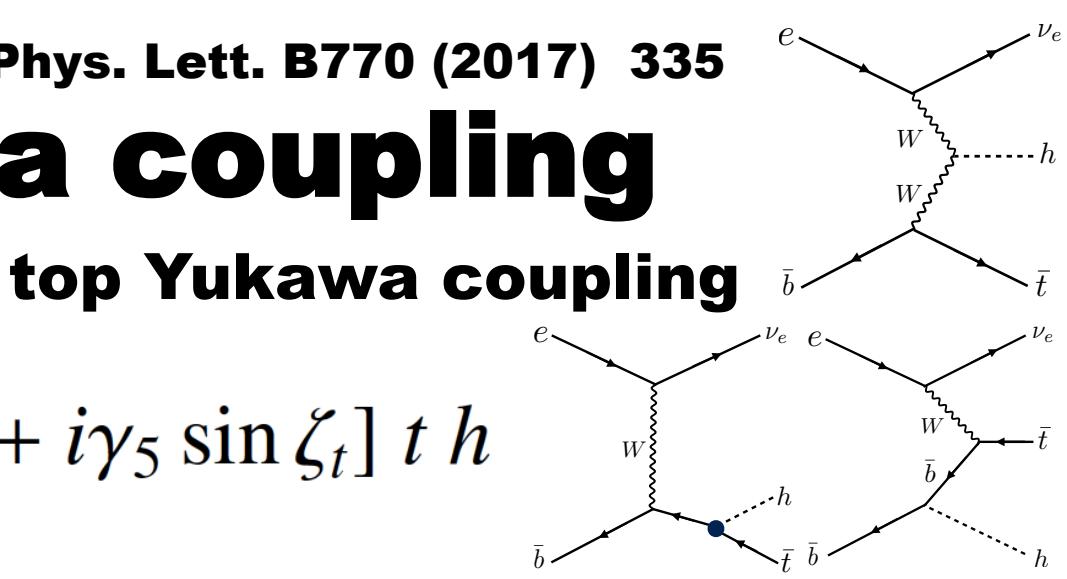
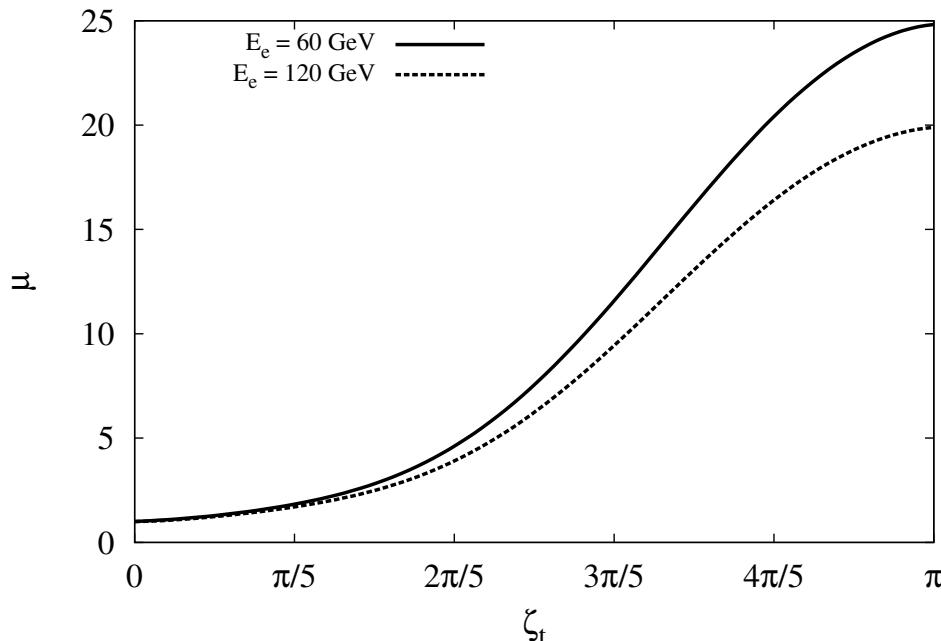
Higgs decay to cc is factor 20 less likely than Hbb times the ratio of detection efficiencies-squared !

# Top Yukawa coupling

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 cross-section as a function of phase

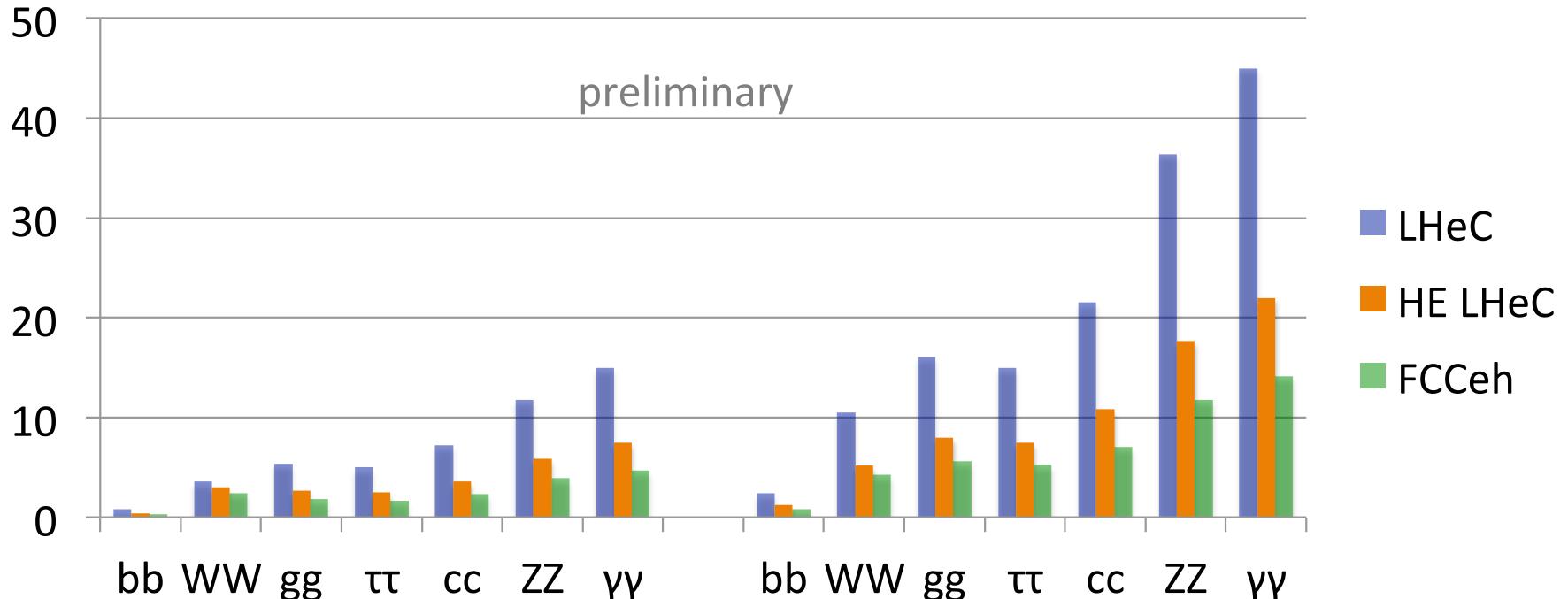


Observe/Exclude non-zero phase to better than  $4\sigma$ .  
Measure coupling with 17% accuracy with zero phase <sup>29</sup>

# Signal Strength of SM Higgs decay in ep

$\delta\mu/\mu [\%]$

See U.Klein's talk



M+U.Klein, 6.3.18

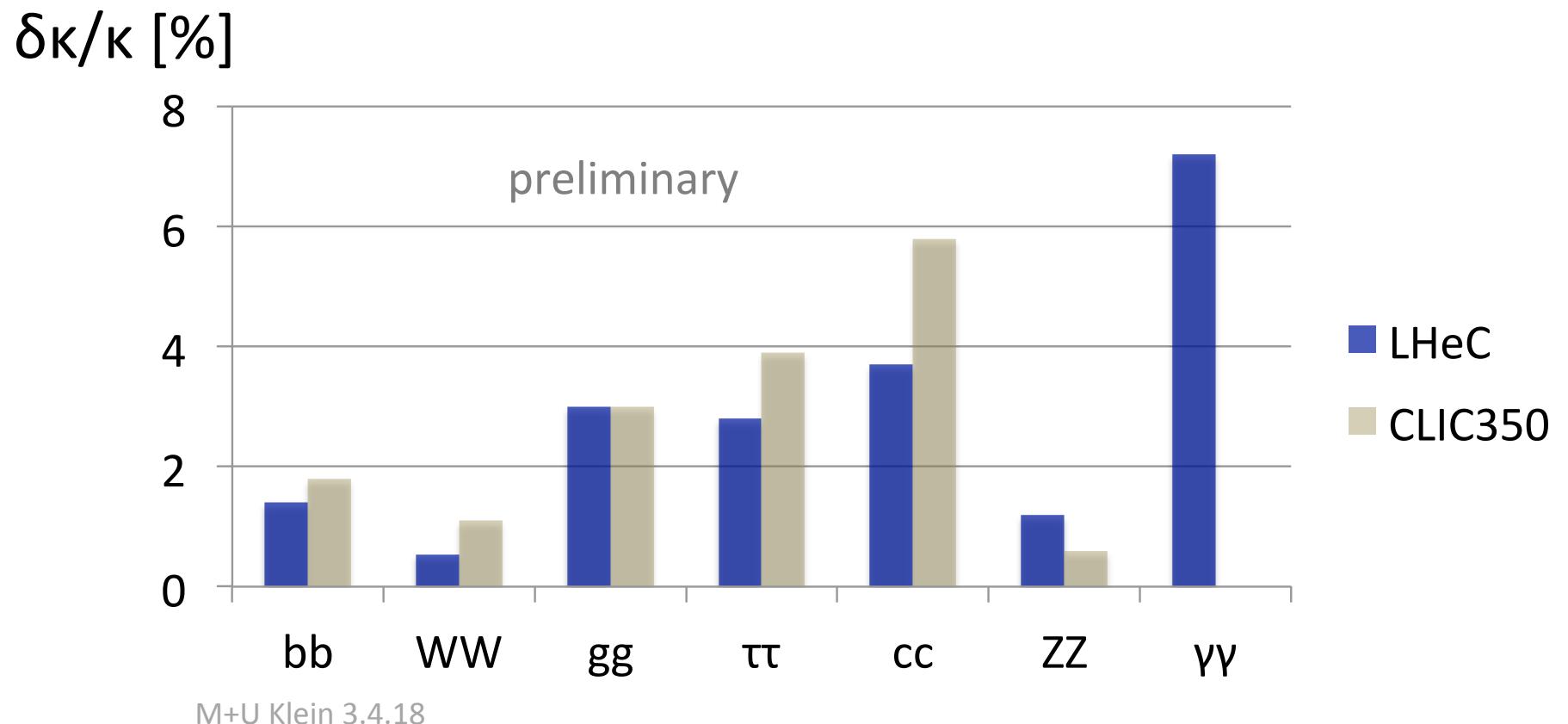
Charged Currents:  $ep \rightarrow vHX$

Neutral Currents:  $ep \rightarrow eHX$

$\Sigma br_i = 0.99 \pm 0.01$  precise reconstruction of full width from 7 most frequent decays  
(2% at LHeC, and 1% at LHeC+LHC). Charged currents only

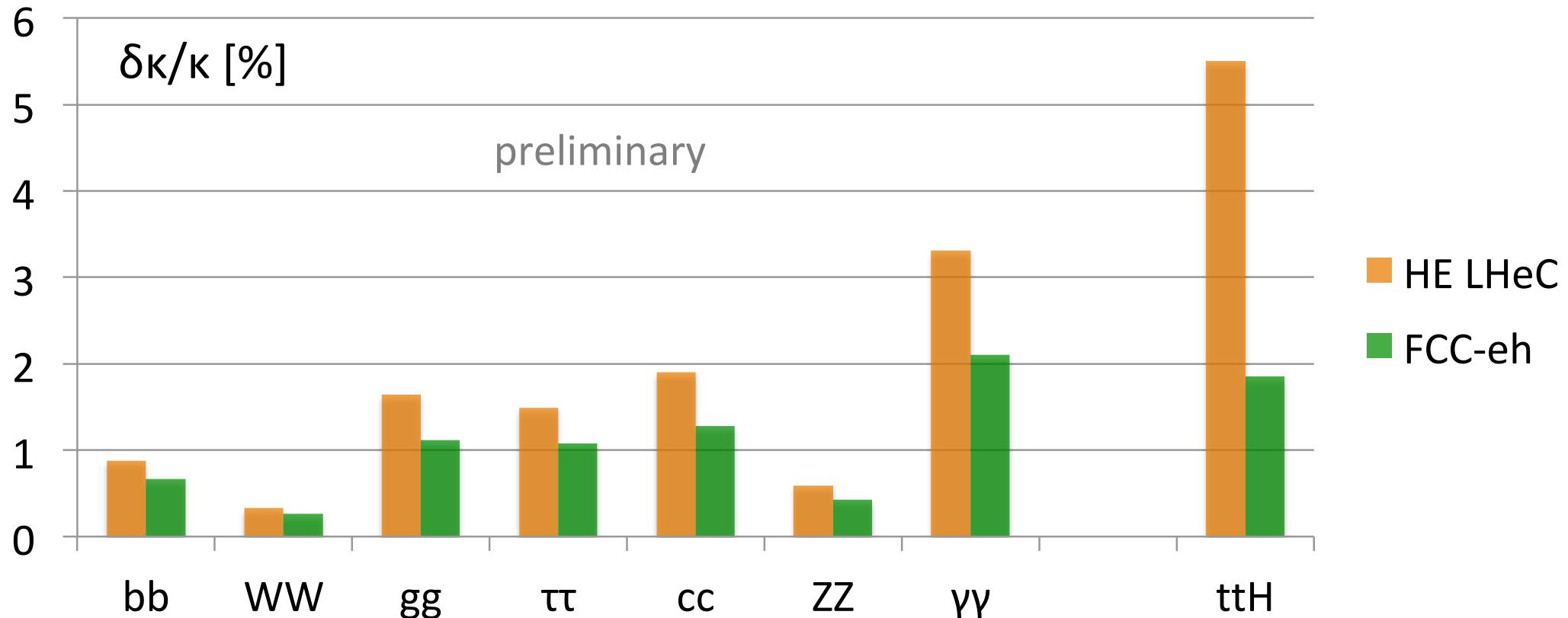
$E_e = 60 \text{ GeV}$  LHeC  $E_p = 7 \text{ TeV} L=1\text{ab}^{-1}$  HE-LHC  $E_p = 14 \text{ TeV} L=2\text{ab}^{-1}$  FCC:  $E_p = 50 \text{ TeV} L=2\text{ab}^{-1}$

# SM Higgs Couplings, $\kappa$ , with LHeC



**LHeC: 60 GeV x 7 TeV. CLIC: 350 GeV** [arXiv:1608.07538, “model dependent fit”]

# SM Higgs Couplings, $\kappa$ , with FCC-eh



M+U.Klein, 5.4.18

NC+CC Analysis using overconstrained system of couplings

arXiv:1702.03426

Coleppa, Kumar<sup>2</sup>, Mellado

$E_e = 60 \text{ GeV}$   $L = 2ab^{-1}$

HE-LHC  $E_p = 14 \text{ TeV}$

FCC:  $E_p = 50 \text{ TeV}$

# Growing interest in BSM physics with ep

See talk by M.D'Onofrio

## number general

1 [Acar, Y. C., Akay, A. N., Beser, S., Karadeniz, H., Kaya, U., Oner, B. B., & Sultansoy, S., FCC Based Lepton-Hadron and Photon-Hadron Colliders: Luminosity and Physics., http://arxiv.org/abs/1608.02190](http://arxiv.org/abs/1608.02190)

## SUSY (general)

2 [Han, C., Li, R., Pan, R.-Q., & Wang, K., Searching for the light Higgsinos at the CERN LHeC., http://arxiv.org/abs/1802.03679](http://arxiv.org/abs/1802.03679)

3 [S. Kuday, Resonant Production of sbottom via RPV Couplings at the LHeC https://arxiv.org/abs/1304.2124](https://arxiv.org/abs/1304.2124)

4 [Hong-Tang, W., Ren-You, Z., Lei, G., Liang, H., Wen-Gan, M., Xiao-Peng, L., & Ting-Ting, W., Probe R-parity violating stop resonance at the LHeC, http://lanl.arxiv.org/abs/1107.4461](http://lanl.arxiv.org/abs/1107.4461)

## Long-lived particles - SUSY and beyond

5 [Curtin, D., Deshpande, K., Fischer, O., & Zurita, J., New Physics Opportunities for Long-Lived Particles at Electron-Proton Colliders. http://arxiv.org/abs/1712.07135](http://arxiv.org/abs/1712.07135)

## heavy/sterile neutrinos

6 [Duarte, L., Zapata, G., & Sampayo, O. A., Angular and polarization traits from effective interactions of Majorana neutrinos at the LHeC., http://arxiv.org/abs/1802.07620](http://arxiv.org/abs/1802.07620)

7 [Antusch, S., Cazzato, E., & Fischer, O. Sterile neutrino searches at future  \$e^-e^+\$ ,  \$p\bar{p}\$ , and  \$e^-p\$  colliders., http://arxiv.org/abs/1612.02728](http://arxiv.org/abs/1612.02728)

8 [Duarte, L., González-Sprinberg, G. A., & Sampayo, O. A., Majorana Neutrinos Production at LHeC in an Effective Approach, http://xxx.lanl.gov/abs/1412.1433](http://xxx.lanl.gov/abs/1412.1433)

## anomalous couplings, Effective Lagrangian

9 [Kuday, S., Saygin, H., Hos, I., & Cetin, F., Limits on Neutral Di-Boson and Di-Higgs Interactions for FCC-he Collider., http://arxiv.org/abs/1702.00185](http://arxiv.org/abs/1702.00185)

10 [Cakir, I. T., Cakir, O., Senol, A., & Tasci, A. T., Search for Anomalous WW \$\gamma\$  and WWZ Couplings with Polarized  \$e^-\$ -Beam at the LHeC, Acta Physica Polonica B, 45\(10\), 1947 \(2014\) https://doi.org/10.55](https://doi.org/10.55)

## BSM Higgs:

11 [Azuelos, G., Sun, H., & Wang, K., Search for Singly Charged Higgs in Vector Boson Scattering at the ep Colliders., http://arxiv.org/abs/1712.07505, see also K. Wang and H Sun: talk at Sept. 2017 workshop](http://arxiv.org/abs/1712.07505)

12 [Sun H, Luo X, Wei W, Liu T., Searching for the doubly-charged Higgs bosons in the Georgi-Machacek model at the ep colliders, Phys. Rev. D 96, 095003](https://doi.org/10.1103/PhysRevD.96.095003)

## compositeness, contact interactions, excited/heavy fermions,GUT

13 [Zarnecki: arXiv:0809.2917, hep-ph/0104107](http://arxiv.org/abs/0809.2917)

14 [see also new limits from HERA: Zeus Collaboration, 1604.01280 and Zarnecki, 1611.03825](#)

15 [Liu, Y.-B., Search for single production of vector-like top partners at the Large Hadron Electron Collider., http://arxiv.org/abs/1704.02059](http://arxiv.org/abs/1704.02059)

16 [Lindner, M., Queiroz, F. S., Rodejohann, W., & Yaguna, C. E., Left-right symmetry and lepton number violation at the Large Hadron electron Collider., Journal of High Energy Physics, 2016\(6\), 140., https://doi.org/10.1007/JHEP06\(2016\)140](https://doi.org/10.1007/JHEP06(2016)140)

17 [Mondal, S., & Rai, S. K., Polarized window for left-right symmetry and a right-handed neutrino at the Large Hadron-Electron Collider, Physical Review D, 93\(1\), 11702. \(2016\) https://doi.org/10.1103/PhysRevD.93.11702](https://doi.org/10.1103/PhysRevD.93.11702)

## top quark FCNC and anomalous couplings (top group)

18 [http://arxiv.org/abs/1701.06932, Denizli H, Senol A, Yilmaz A, Cakir IT, Karadeniz H, Cakir O., Top quark FCNC couplings at future circular hadron electron colliders](http://arxiv.org/abs/1701.06932)

19 [http://arxiv.org/abs/1703.02691, Wang X, Sun H, Luo X., Searches for the Anomalous FCNC Top-Higgs Couplings with Polarized Electron Beam at the LHeC](http://arxiv.org/abs/1703.02691)

20 [http://arxiv.org/abs/1705.05419, Cakir IT, Yilmaz A, Denizli H, Senol A, Karadeniz H, Cakir O., Probing the Anomalous FCNC  \$t\bar{t}\gamma\$  Couplings at Large Hadron electron Collider](http://arxiv.org/abs/1705.05419)

21 [Sarmiento-Alvarado, I. A., Bouzas, A. O., & Larios, F., Analysis of the top-quark charged-current coupling at the LHeC, http://arxiv.org/abs/1412.6679](http://arxiv.org/abs/1412.6679)

22 [Dutta, S., Goyal, A., Kumar, M., & Mellado, B., Measuring anomalous  \$Wtb\$  couplings at  \$e^-p\$  collider, http://arxiv.org/abs/1307.1688](http://arxiv.org/abs/1307.1688)

## exotic and miscellaneous

23 [Acar, Y. C., Kaya, U., Oner, B. B., & Sultansoy, S., Color Octet Electron Search Potential of the FCC Based e-p Colliders, http://arxiv.org/abs/1605.08028](http://arxiv.org/abs/1605.08028)

24 [Hernandez-Sanchez, J., Das, S. P., Moretti, S., Rosado, A., & Xoxocotzi, R., Flavor violating signatures of neutral Higgs bosons at the LHeC, http://arxiv.org/abs/1509.05491](http://arxiv.org/abs/1509.05491)

25 [Das, S. P., Hernández-Sánchez, J., Rosado, A., & Xoxocotzi, R., Flavor signatures of lighter and heavier Higgs bosons within Two Higgs Doublet Model type III at the LHeC, http://arxiv.org/abs/1503.01464](http://arxiv.org/abs/1503.01464)

26 [Sahin, M., Resonant Production of Spin-3/2 Color Octet Electron at the LHeC. Acta Physica Polonica B, 45\(9\), 1811 \(2014\), https://doi.org/10.5506/APhysPolB.45.1811](https://doi.org/10.5506/APhysPolB.45.1811)

27 [Ren-You, Z., Hua, W., Liang, H., & Wen-Gan, M., Probing  \$L\bar{L}\$ -violating coupling via sbottom resonance production at the LHeC, http://lanl.arxiv.org/abs/1401.4266](http://lanl.arxiv.org/abs/1401.4266)

# Sterile Neutrinos at ep colliders

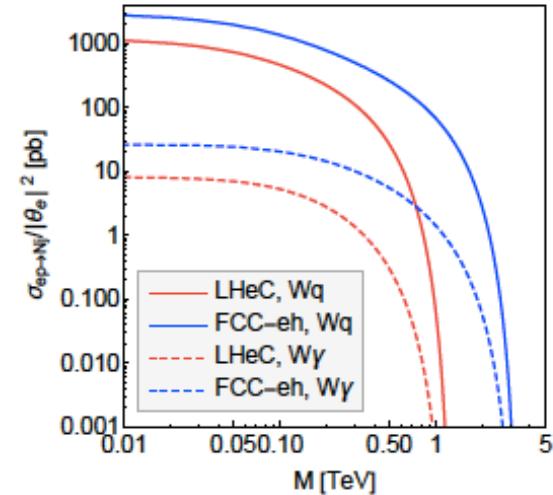
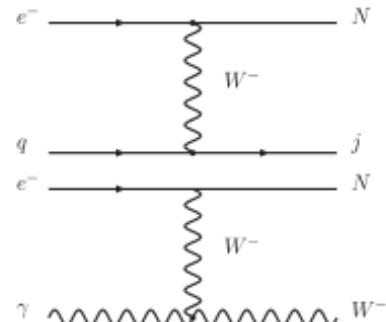
O.Fischer

Antusch et al. Int. J. Mod. Phys. A 32 (2017) no.14, 1750078

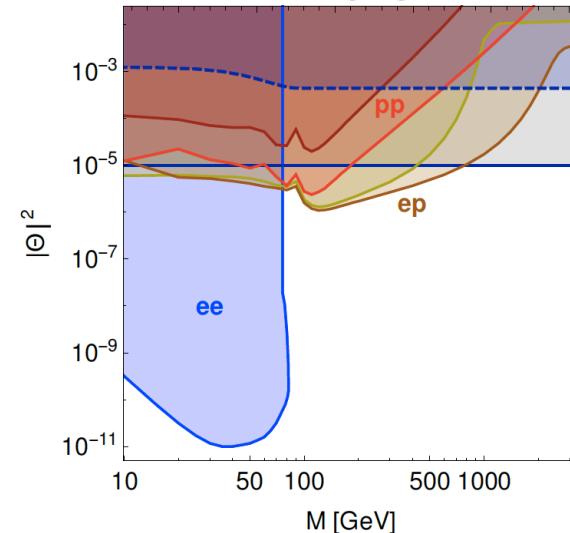
Three Generations of Matter (Fermions) spin $\frac{1}{2}$					
	I	II	III		
mass -	2.4 MeV	1.27 GeV	173.2 GeV		
charge -	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{1}{3}$		
name -	u	c	t		
Quarks	up	charm	top		
mass -	0.0 MeV	104 MeV	4.2 GeV		
charge -	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$		
name -	d	s	b		
Quarks	down	strange	bottom		
mass -	0 $\nu_e$	0 $\nu_\mu$	0 $\nu_\tau$		
charge -	0	0	0		
name -	e neutrino	muon neutrino	tau neutrino		
Leptons					
mass -	0.511 MeV	105.7 MeV	1.777 GeV		
charge -	-1	-1	-1		
name -	e	mu	tau		
Leptons	electron	muon	tau		

Bosons (Forces) spin 1					
g	gluon	q	j	$\nu_N \rightarrow N$	
$\gamma$	photon	$e^-$	$N$		
$Z^0$	weak force	$W^-$	$W^-$		
H	Higgs boson	$\gamma$	$W^-$		
$W^\pm$	weak force				

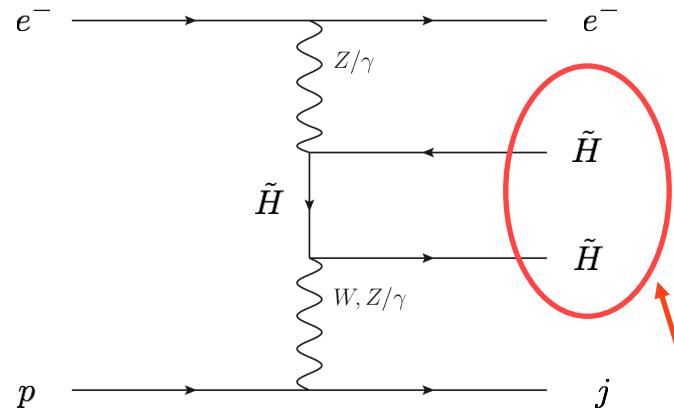


- ▶ Neutrino oscillations  $\rightarrow$  type I seesaw
- ▶ Lowscale seesaw models allow large production xsections at colliders
- ▶ Present constraints:  $|\theta_e| \leq 10^{-3}$
- ▶ Searches via lepton-flavor violating final states:  $\mu + \text{jets}$ ,  $\mu\tau + \text{jets}$
- ▶ Displaced vertex searches for heavy neutrino masses  $< m_W$



# Higgsino search at FCC-eh

Higgsino: Higgs partner in supersymmetry,  
difficult to probe at the LHC(C. Han *et al*, JHEP 1402 (2014) 049)



Higgsino production

Typical signal: electron + jet + missing energy

$$E_T^{miss} > 70 \text{ GeV}$$

$$5 \text{ GeV} < p_T^e < 25 \text{ GeV}, 1.0 < \eta^e < 5.0$$

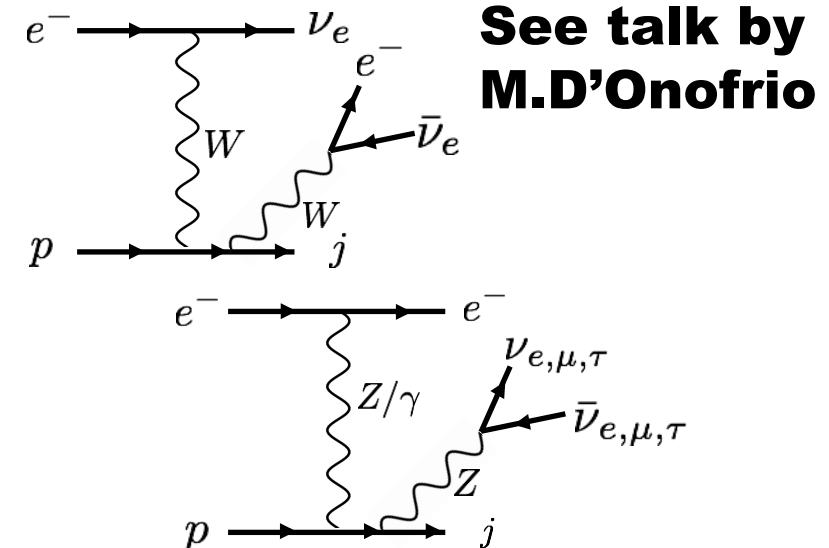
$$p_T^j > 20 \text{ GeV}, -5.0 < \eta^j < -3.0$$

$$m_{ej} > 400 \text{ GeV}$$

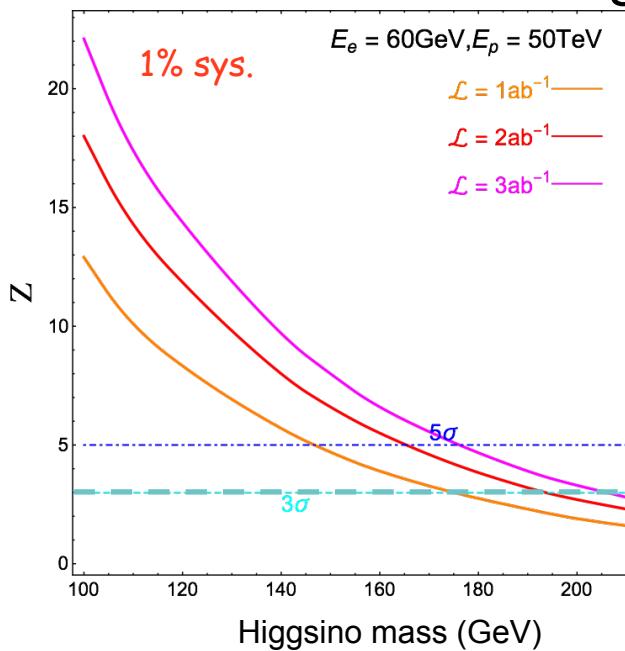
$$y = \frac{k_p \cdot (k_e^{in} - k_e^{out})}{k_e^{in} \cdot k_p} > 0.2$$

preliminary  
result

C. Han, R. Li, R. Pan, K. Wang, arXiv:1802.03679



Standard model main backgrounds



# Outlook and Conclusions

- **Progress in devising concurrent ep/pp running**
  - **Unique DIS facility at CERN with  $10^{34}$  instantaneous luminosity, opens new horizon for particle physics**
- **PERLE collaboration formed, conceptual design**
  - **Demonstrator for ERL; envisioned at Orsay**
- **First 802 MHz cavity produced**
  - **Passed tests and quality factors requirements**
- **Complete design of FCC-eh detector**
- **Complementarities of the ep/pp programs strongly benefits HL(HE)-LHC, FCC prospects:**
  - **Precise measurements and discoveries in QCD**
  - **Exploration of new nuclear substructure in new domains**
  - **Precise/complete determination of SM Higgs couplings**
  - **Unprecedented precision in top physics topics**
  - **Additional sensitivity to physics BSM**

# **Additional slides**

# Why PERLE [as seen from LHeC]?

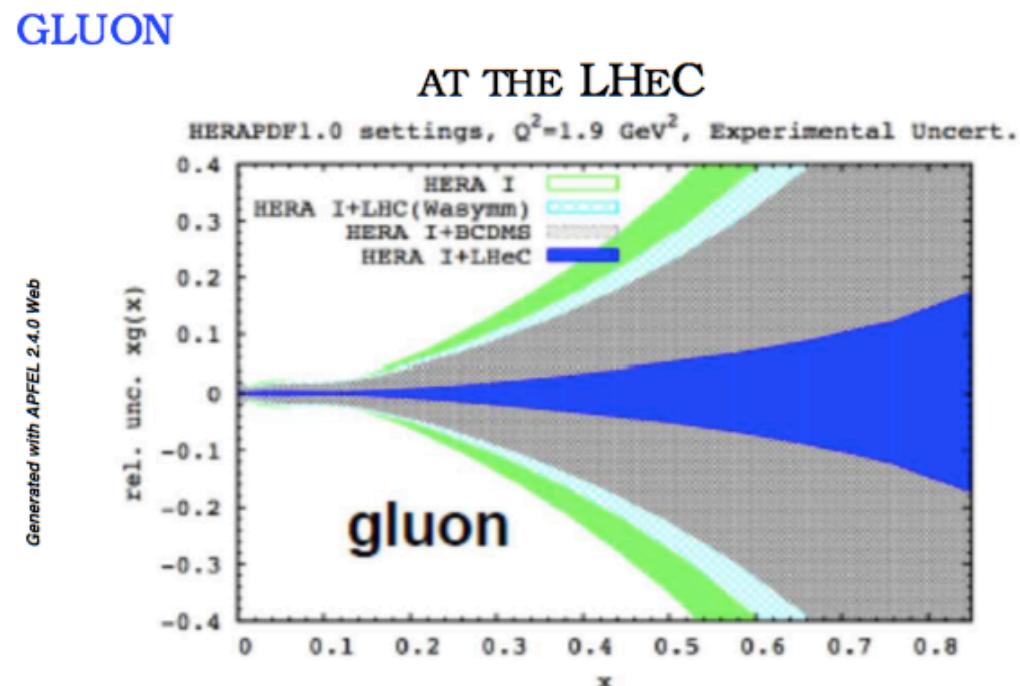
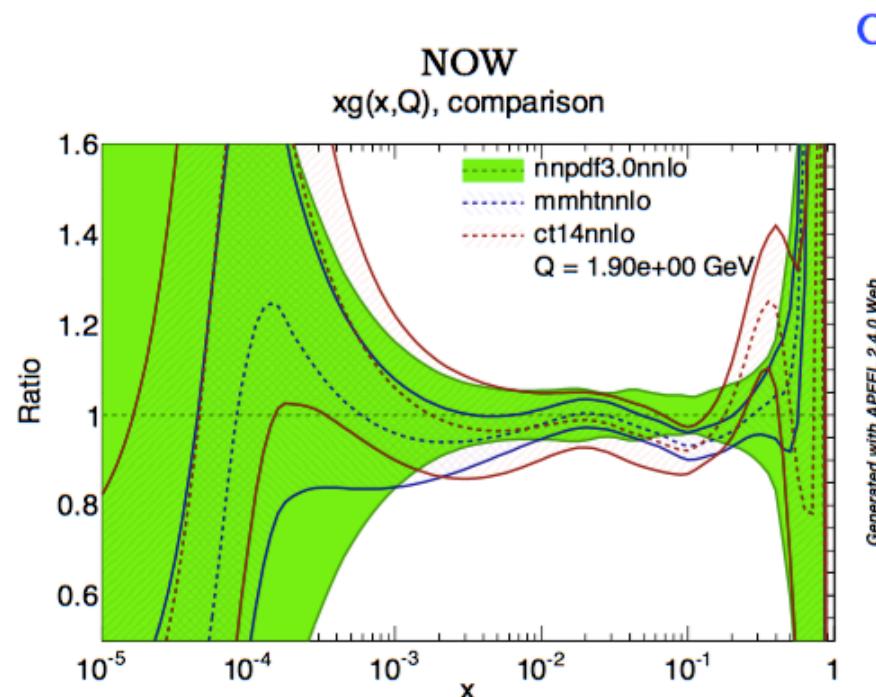
## FUNDAMENTAL MOTIVATION:

- **Validation of key LHeC Design Choices**
- **Build up expertise in the design and operation for a facility with a fundamentally new operation mode:**  
ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no ‘automatic’ longitudinal phase stability, etc.)
- **Proof validity of fundamental design choices:**  
Multi-turn recirculation (other existing ERLs have only 1-2 passages)  
Implications of high current operation ( $2 * 3 * [6\text{mA} - 25\text{mA}] \rightarrow 30\text{-}150\text{mA}!!$ )
- **Verify and test machine and operation tolerances before designing a large scale facility**  
Tolerances in terms of field quality of the arc magnets and cavity alignment  
Required RF phase stability (RF power) and LLRF requirements  
Halo and beam loss tolerances

# PDFS AT THE LHeC

**S.Forte**

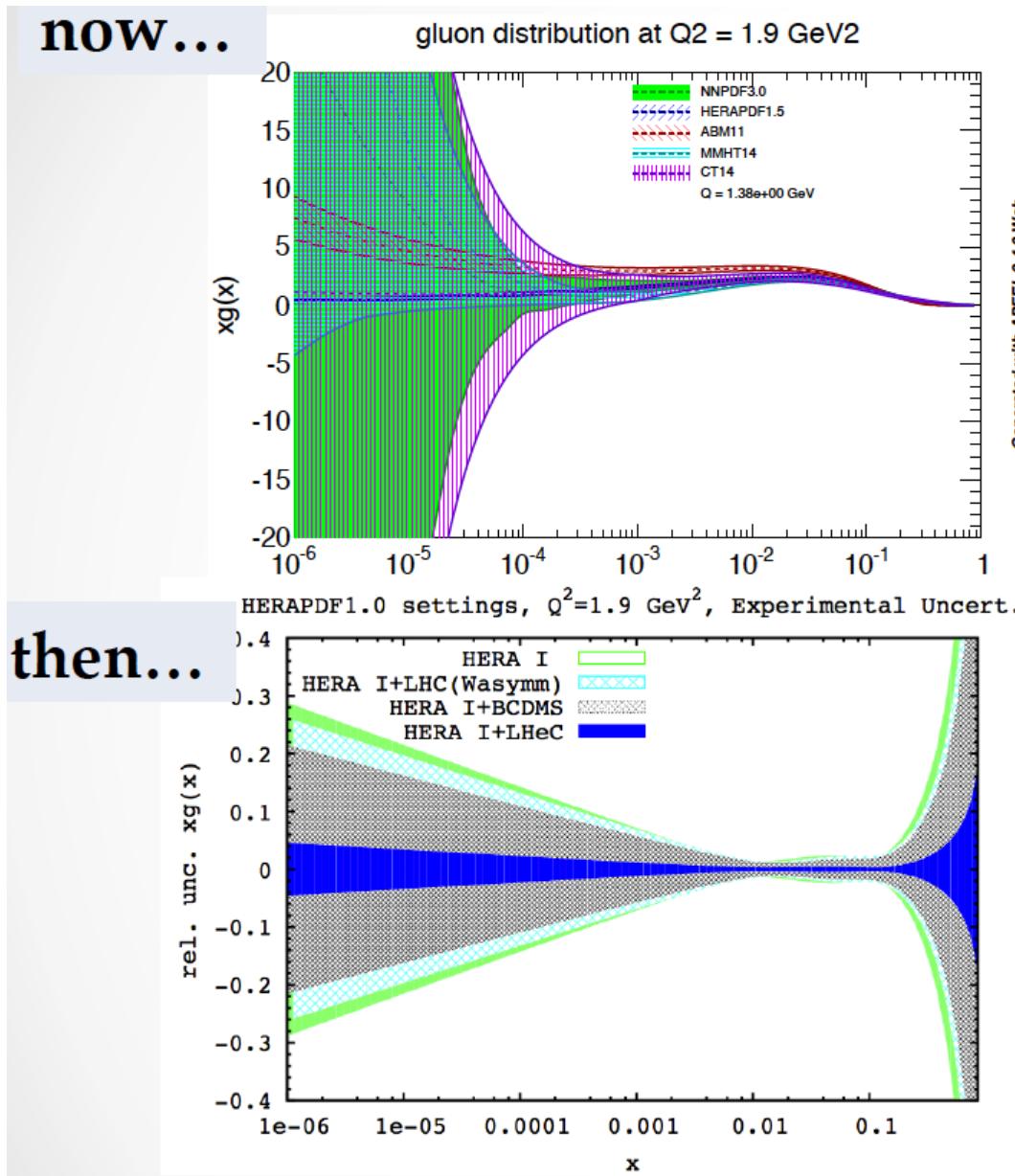
- UNCERTAINTIES DOWN TO PERCENT LEVEL IN WIDE KINEMATIC REGION
- WITH DEUTERON BEAMS, **FULL LIGHT FLAVOR DECOMPOSITION**
- THANKS TO HIGH ENERGY, NC+CC  $\Rightarrow$  PRECISION STRANGENESS DETERMINATION



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

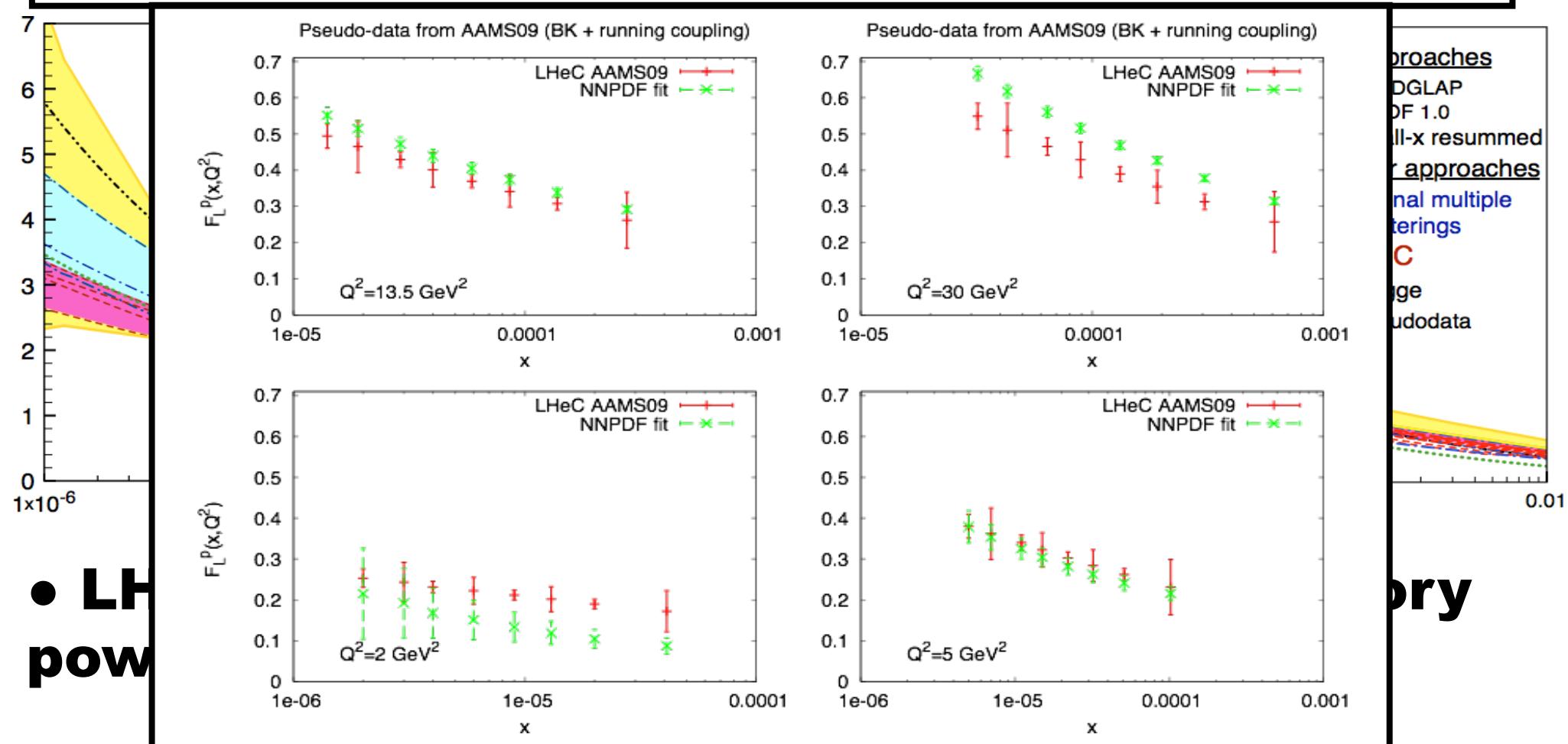
**PDF uncertainty on Higgs production at LHC will become negligible due to measurements at the LHeC<sub>39</sub>**

# Impact of LHeC at small x



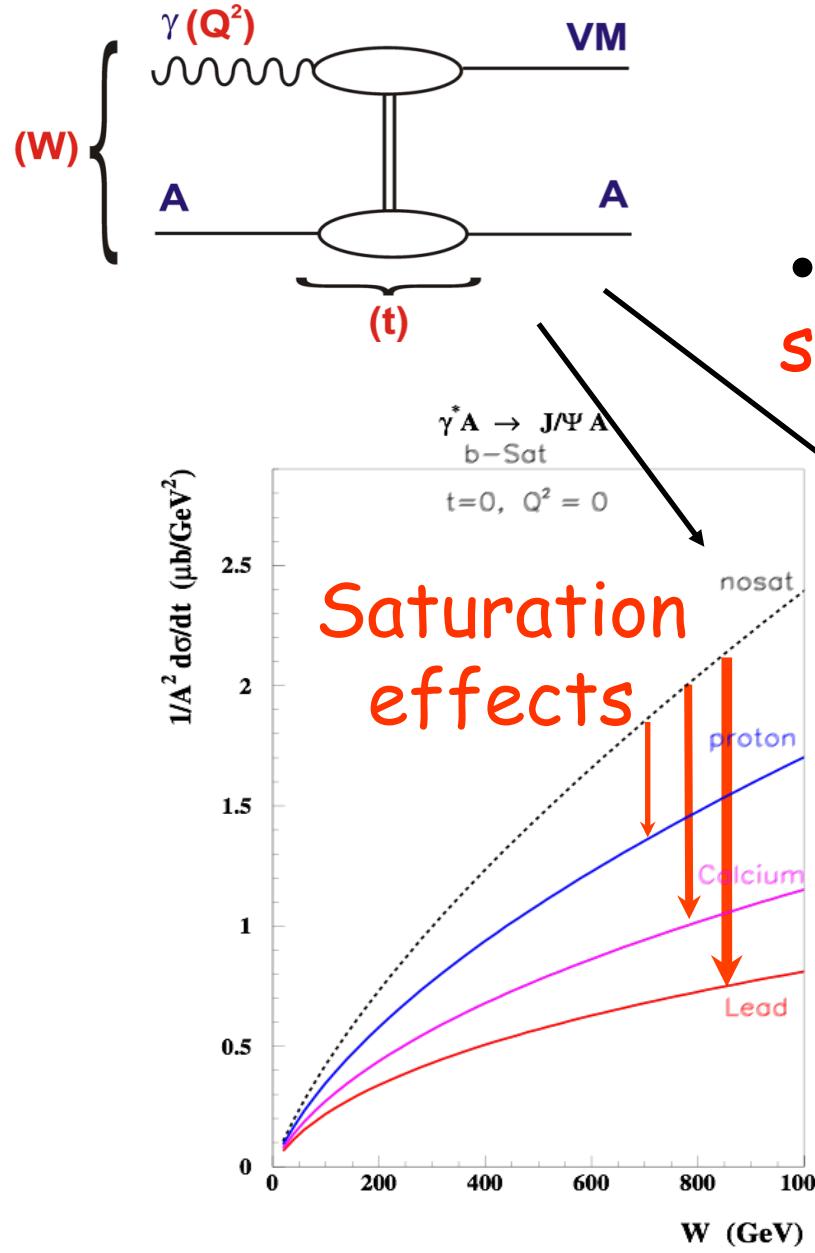
# Small-x: inclusive

# **NLO DGLAP cannot accommodate $F_2$ and $F_L$ in presence of saturation**

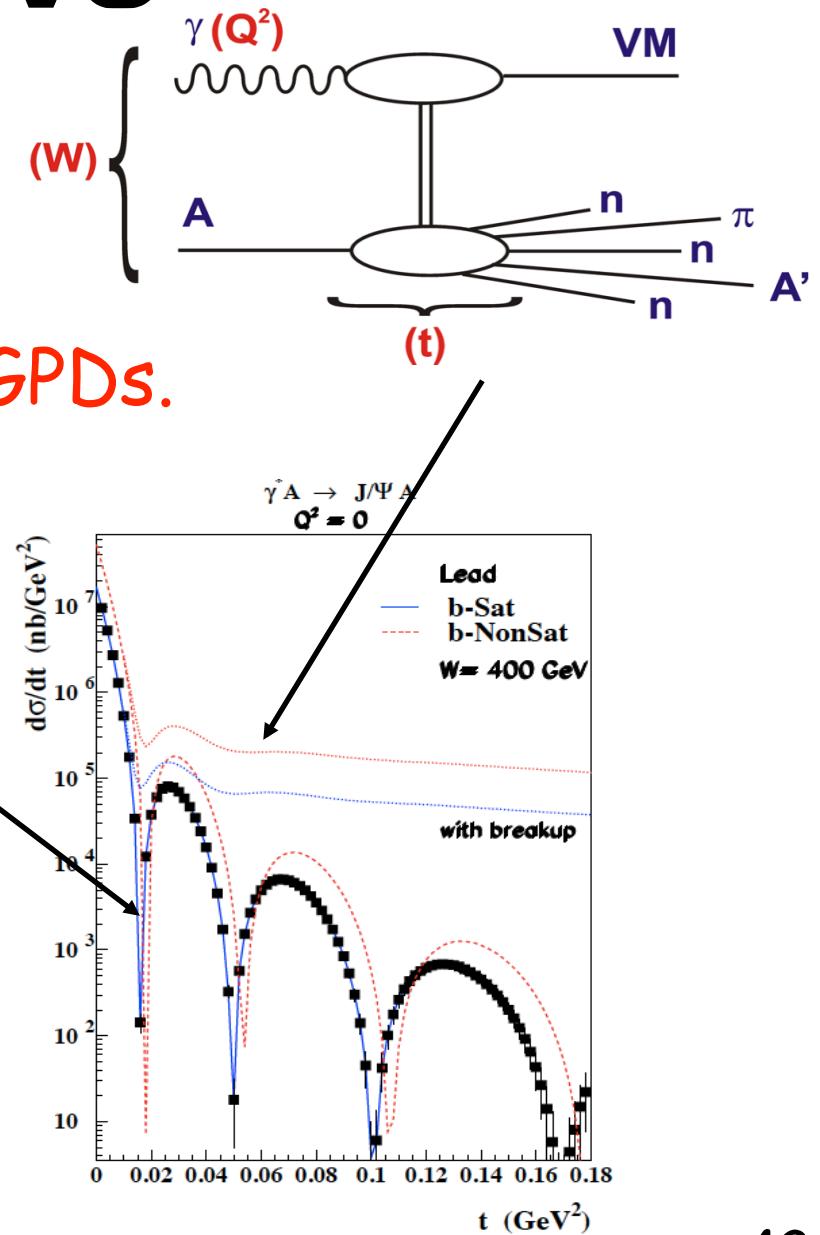


**N. Armesto**

# eA: diffractive



- Elastic VM:  
saturation, nGPDs.



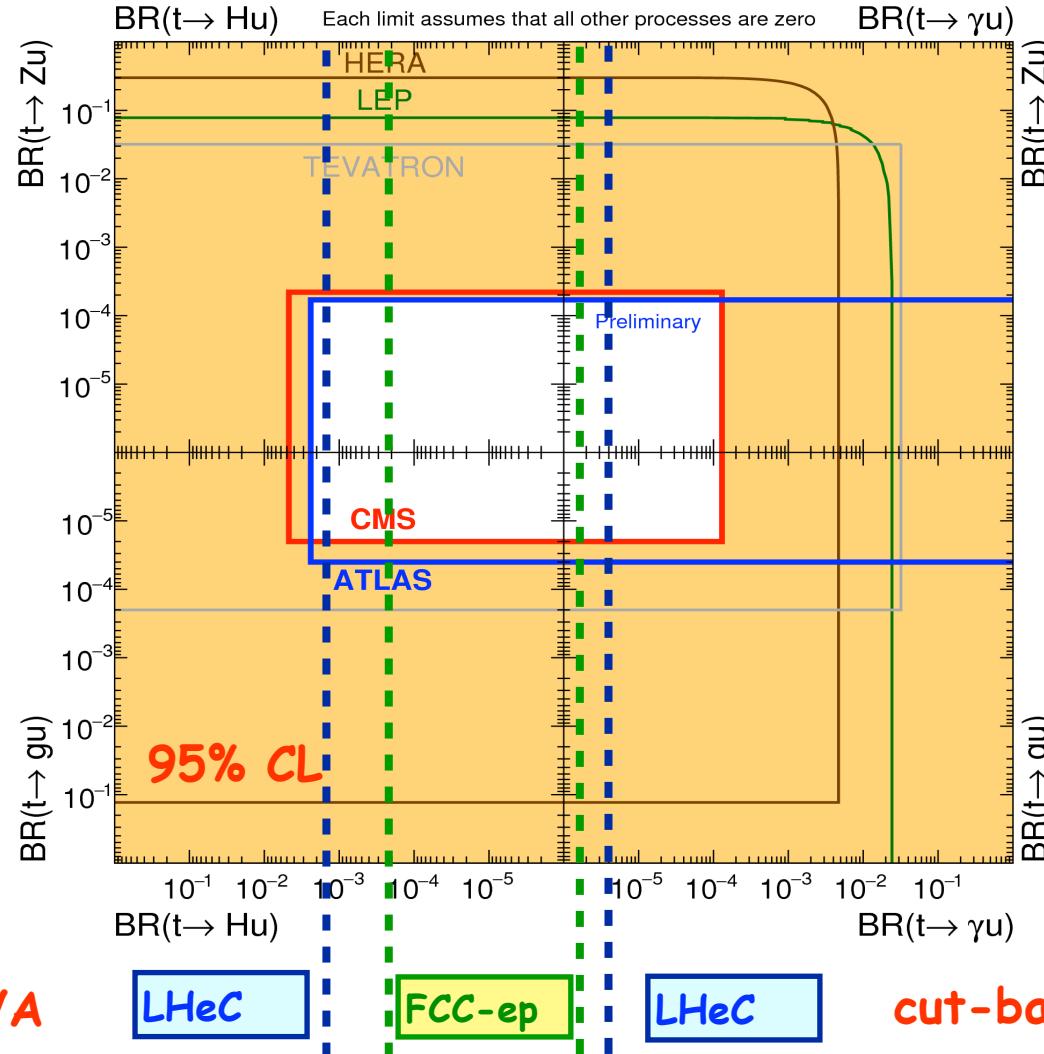
N. Armesto

# FCNC Branching Ratios at Colliders

C.Schwanenberger

ATLAS+CMS Preliminary  
LHCtopWG

November 2017

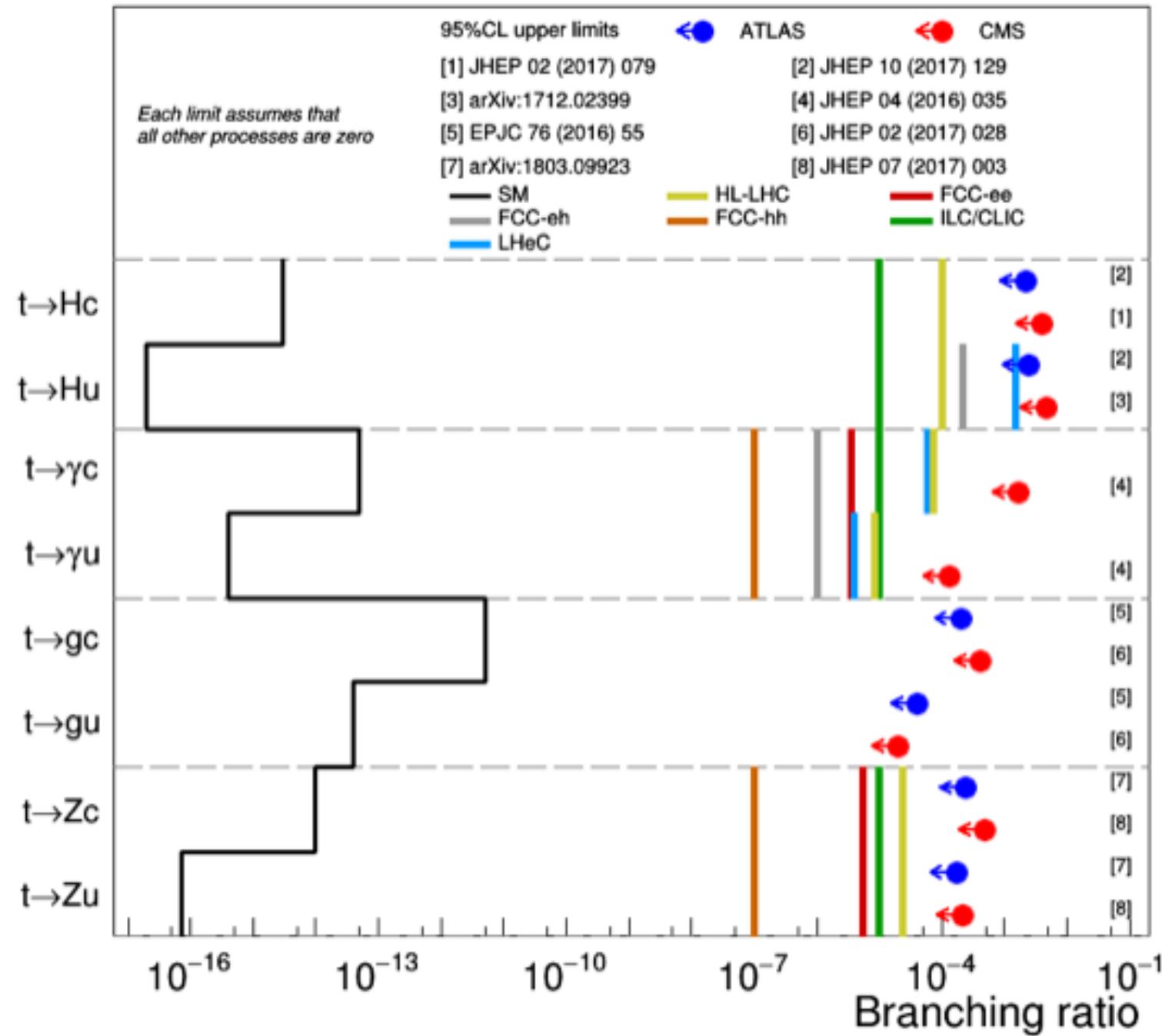


- improve limits on  $\text{BR}(t \rightarrow \gamma u)$ ,  $\text{BR}(t \rightarrow Hu)$  considerably

→ test SUSY, little Higgs, technicolor...

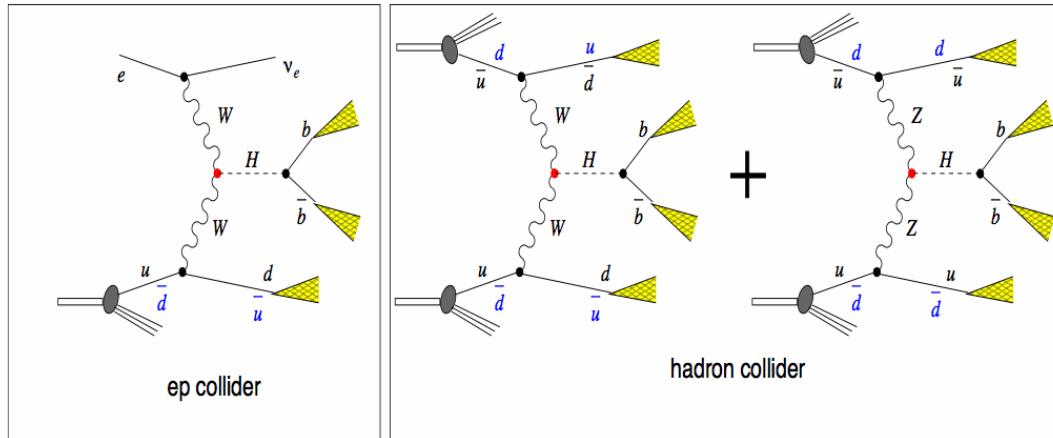
$E_e = 60 \text{ GeV}$   
 $1000 \text{ fb}^{-1}$

# C.Schwanenberger



# Structure of HVV couplings

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

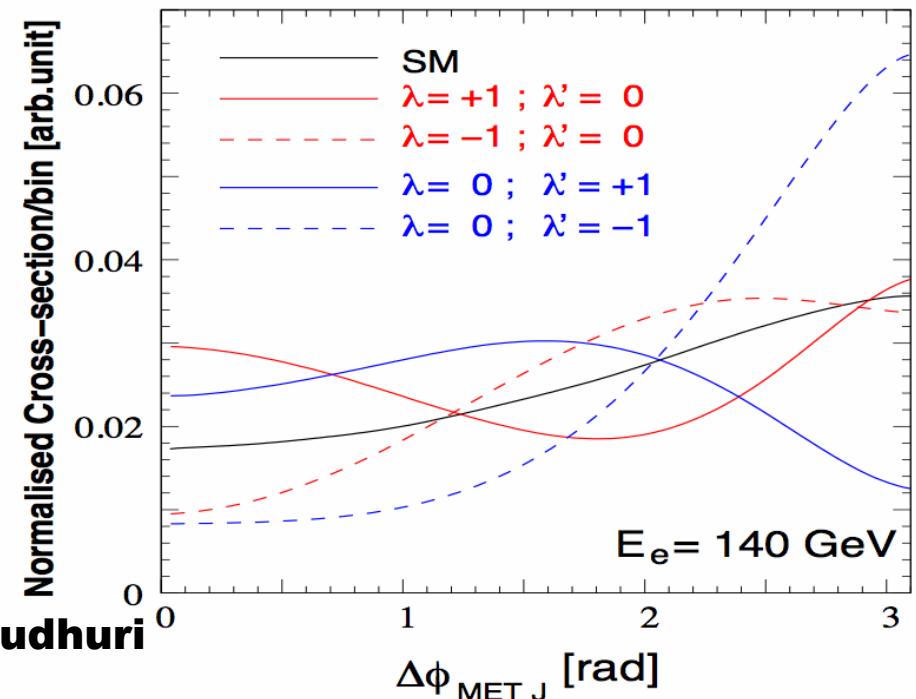


*ep* process uniquely addresses the  $HWW$  vertex.

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

$$\begin{aligned}\Gamma_{\mu\nu}^{\text{SM}} &= -gM_V g_{\mu\nu} \\ \Gamma_{\mu\nu}^{\text{BSM}}(p, q) &= \frac{g}{M_V} [\lambda(p \cdot q g_{\mu\nu} - p_\nu q_\mu) + \lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma]\end{aligned}$$

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

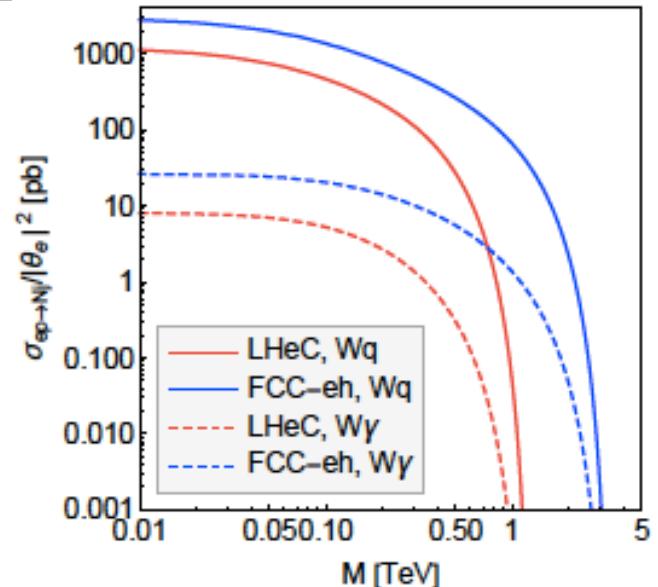
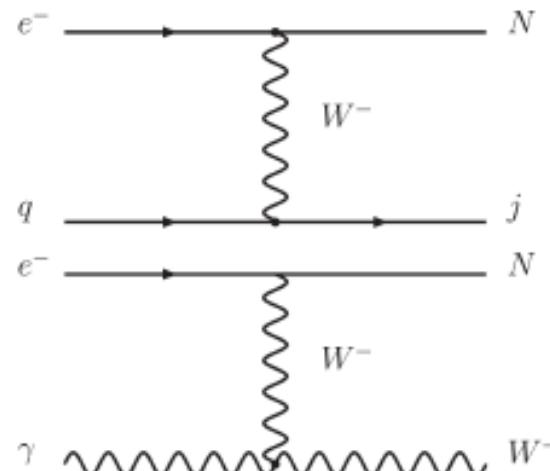


<b>Compositeness</b>	<ul style="list-style-type: none"> <li>• <i>4-fermion EFT: Lepton-quark compositeness scale</i></li> <li>• <b>Quark radius</b></li> </ul>
<b>Leptoquarks and RPV squark decay</b>	<ul style="list-style-type: none"> <li>• <i>Accessible range largely excluded, but not completely</i></li> <li>• <b>Better measure of LQ characteristics, if they exist</b></li> </ul>
Anomalous Triple Gauge Couplings	<ul style="list-style-type: none"> <li>• <i>Comparable to LHC</i></li> </ul>
<b>Top FCNC couplings</b>	<ul style="list-style-type: none"> <li>• <b><i>couplings – great potential wrt HL-LHC</i></b></li> </ul>
Vector-like leptons, heavy/excited leptons, bileptons, higher isospin lepton multiplets	<ul style="list-style-type: none"> <li>• <i>No constraints on VLL, so far, at LHC</i></li> <li>• <i>Extend sensitivity to for lower masses</i></li> </ul>
<b>Heavy neutrinos, Majorana neutrinos, sterile neutrinos</b>	<ul style="list-style-type: none"> <li>• <i>Symmetry-protected see-saw model</i></li> <li>• <b><i>LHeC reach similar or better than HL-LHC</i></b></li> </ul>
<b>SUSY EW:</b> compressed scenario, <b>Higgsino,</b> (dark sector)	<ul style="list-style-type: none"> <li>• <i>Long-lived neutral particles</i></li> <li>• <b><i>Disappearing tracks – low background, compensate the low signal production rate</i></b></li> </ul>
Anomalous Quartic Gauge Couplings	<ul style="list-style-type: none"> <li>• <i>Better control on background: no gluon exchange diagrams (mostly FCC?)</i></li> </ul>
extended Higgs sector: higher isospin multiplet	<ul style="list-style-type: none"> <li>• <i>Singly- and doubly- charged higgs by VBF (mostly FCC)</i></li> </ul>

# Sterile Neutrinos at ep colliders

Three Generations of Matter (Fermions) spin $\frac{1}{2}$		
mass →	2.4 MeV	1.27 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$
name →	u	c
Quarks	Left up	Right charm
mass →	4.8 MeV	104 MeV
charge →	$-\frac{1}{3}$	$-\frac{1}{3}$
name →	d	s
Leptons	Left down	Right strange
mass →	10.8 MeV	42.0 GeV
charge →	$-1$	$-\frac{1}{3}$
name →	e	b
Leptons	Left electron	Right muon
mass →	0.511 MeV	105.7 MeV
charge →	$-1$	$-1$
name →	$\nu_e$	$\nu_\mu$
Leptons	Left tau	Right tau
mass →	1.777 GeV	1.777 GeV
charge →	$-1$	$-1$
name →	$\tau$	$\tau$

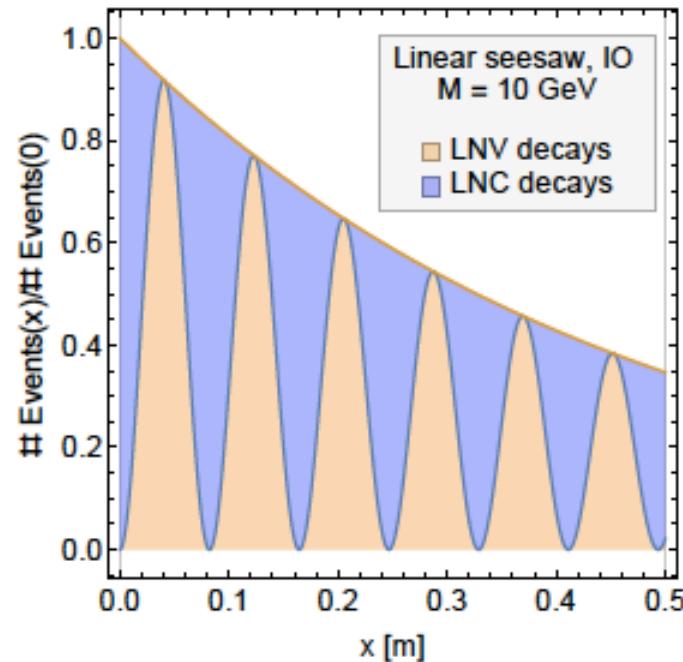
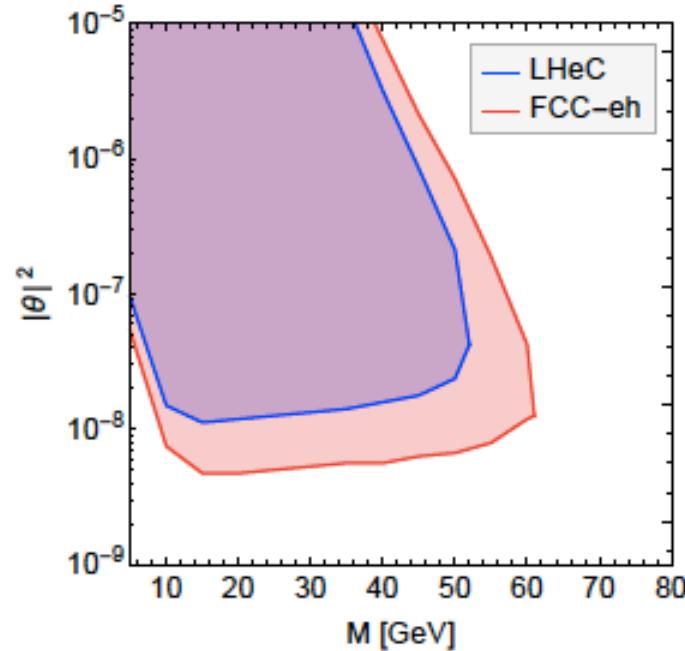
Bosons (Forces) spin 1		
0	g	gluon
0	$\gamma$	photon
91.2 GeV	0	Z
126 GeV	0	H
90.4 GeV	$\pm 1$	W
		weak force
		spin 0



Antusch *et al.*; Int. J. Mod. Phys. A 32 (2017) no.14, 1750078

- ▶ Neutrino oscillations are evidence for non-zero  $m_\nu$ .
- ▶ Lowscale type I seesaw with sterile neutrinos  
→ heavy neutrino mass eigenstates with  $M \sim v_{EW}$
- ▶ Neutrino mixing  $|\theta_\alpha|$ ,  $\alpha = e, \mu, \tau \Rightarrow$  Weak current production.
- ▶ Present constraints:  $|\theta_e| \leq 10^{-3} \Rightarrow$  sizable cross sections at ep.

Antusch, Fischer; JHEP 1410 (2014) 094



## Displaced vertices:

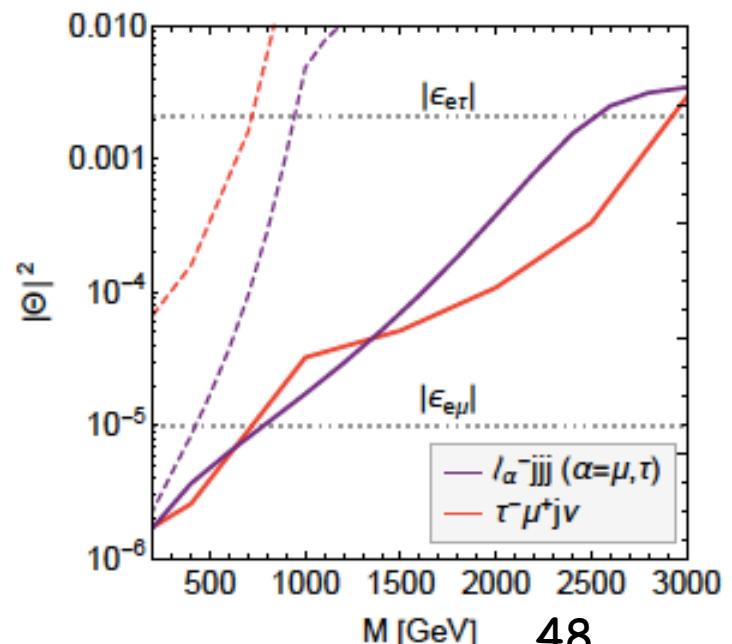
- ▶ Heavy neutrino-antineutrino oscillations
- ▶ Oscillation from  $\Delta m_\nu^2$ , can be  $\sim \text{mm}$ .

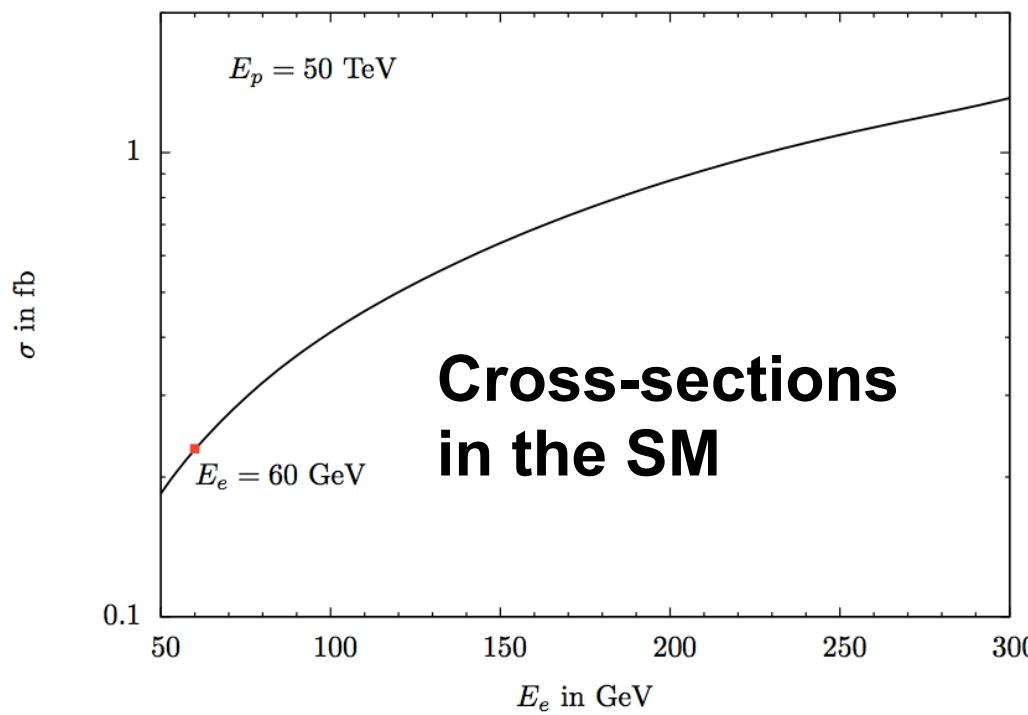
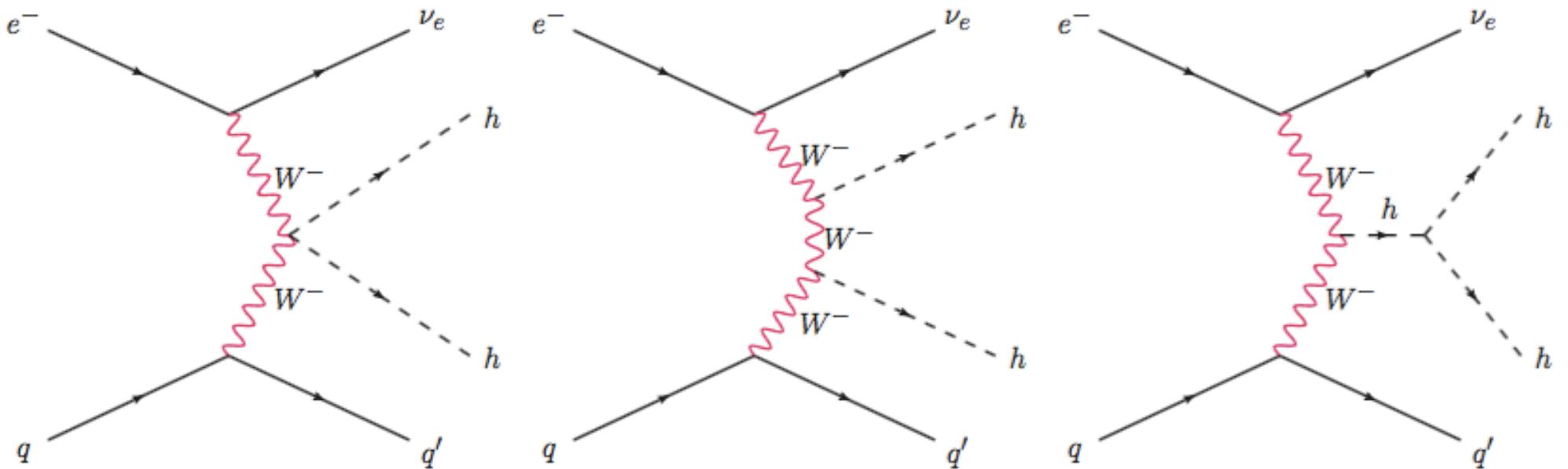
## Lepton flavor violation:

[Antusch et al.; \[1709.03797\]](#)

- ▶ Unambiguous:  $\mu + \text{jets}$ ,  $\tau + \text{jets}$ ,  $\mu\tau + \text{jets}$
- ▶ Highest sensitivity to  $|\theta_e \theta_\alpha|^2$ ,  $\alpha = \mu, \tau$

[Antusch et al.; Int. J. Mod. Phys. A 32 \(2017\) no.14, 1750078](#)





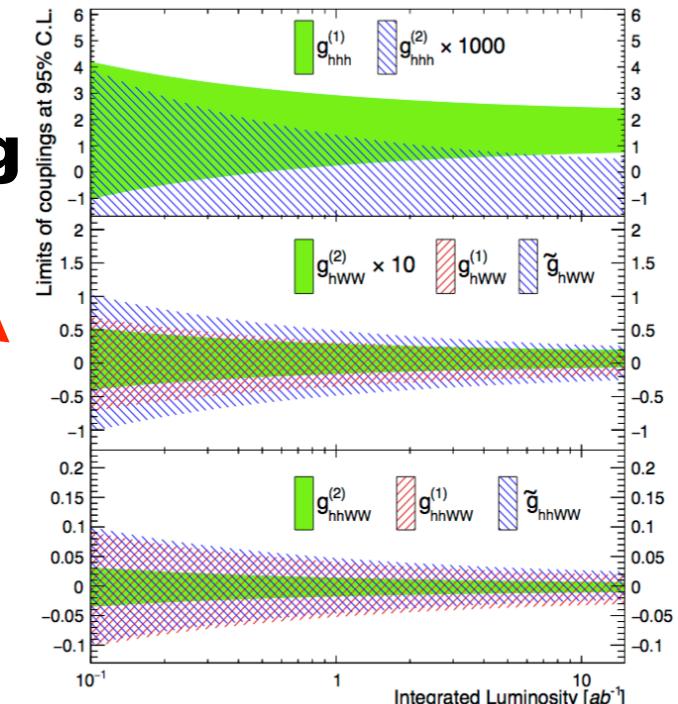
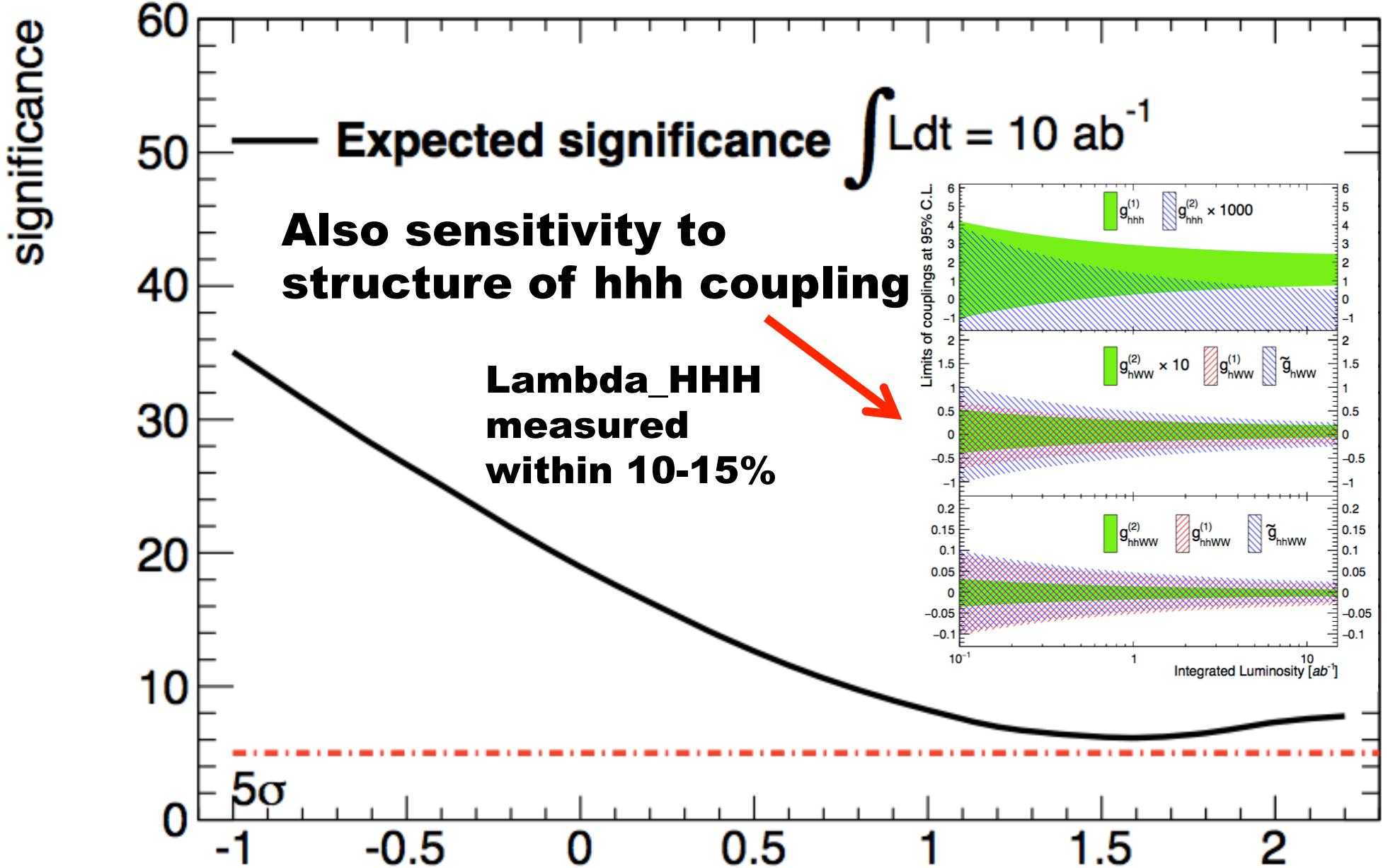
**Considering highly  
asymmetric  
collisions**

**Effective vertices. Note the dependence on momenta in non-SM vertices. This induces significant impact on scattering kinematics.**

$$i\Gamma_{hhh} = -6iv\lambda g_{hhh}^{(1)} - ig_{hhh}^{(2)}(p_1 \cdot p_2 + p_2 \cdot p_3 + p_3 \cdot p_1),$$

$$\begin{aligned} i\Gamma_{hW-W^+} = & i \left[ \left\{ \frac{g^2}{2}v + \frac{g}{m_W}g_{hWW}^{(1)}p_2 \cdot p_3 + \frac{g}{m_W}g_{hWW}^{(2)}(p_2^2 + p_3^2) \right\} \eta^{\mu_2\mu_3} \right. \\ & - \frac{g}{m_W}g_{hWW}^{(1)}p_2^{\mu_3}p_3^{\mu_2} - \frac{g}{m_W}g_{hWW}^{(2)}(p_2^{\mu_2}p_2^{\mu_3} + p_3^{\mu_2}p_3^{\mu_3}) \\ & \left. - i\frac{g}{m_W}\tilde{g}_{hWW}\epsilon_{\mu_2\mu_3\mu\nu}p_2^\mu p_3^\nu \right], \end{aligned}$$

$$\begin{aligned} i\Gamma_{hhW-W^+} = & i \left[ \left\{ \frac{g^2}{2} + \frac{g^2}{m_W^2}g_{hhWW}^{(1)}p_3 \cdot p_4 + \frac{g^2}{m_W^2}g_{hhWW}^{(2)}(p_3^2 + p_4^2) \right\} \eta^{\mu_3\mu_4} \right. \\ & - \frac{g^2}{m_W^2}g_{hhWW}^{(1)}p_3^{\mu_4}p_4^{\mu_3} - \frac{g^2}{m_W^2}g_{hhWW}^{(2)}(p_3^{\mu_3}p_3^{\mu_4} + p_4^{\mu_3}p_4^{\mu_4}) \\ & \left. - i\frac{g^2}{m_W^2}\tilde{g}_{hhWW}\epsilon_{\mu_3\mu_4\mu\nu}p_3^\mu p_4^\nu \right] \cdot \textbf{M. Kumar et al. [1509.04016]} \end{aligned}$$



$g_{hhh}^{(1)}$