

# Electrons for the LHC

Future Deep Inelastic Lepton-Hadron Scattering at the Energy Frontier

Max Klein



DIS

CDR

LHC

Physics

PERLE

Detector+

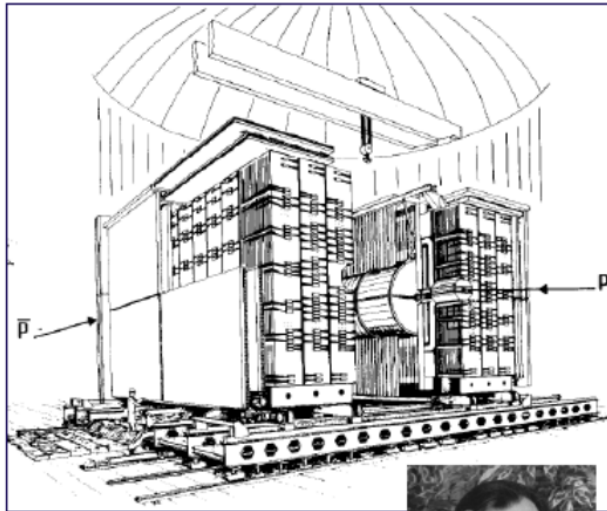


<http://lhec.web.cern.ch>  
CDR 2012, Update 2018  
ep (and eA) at the LHC

Seminar at Saclay, 26.03.2018

# DIS and pp at CERN some 30-40 years ago

## Charged Currents



UA1



“ We have two tasks: kill Weinberg Salam, kill QCD”  
Carlo Rubbia: 1978 BCDMS meeting at Dubna.  
The failure to fulfill his task made Carlo famous...



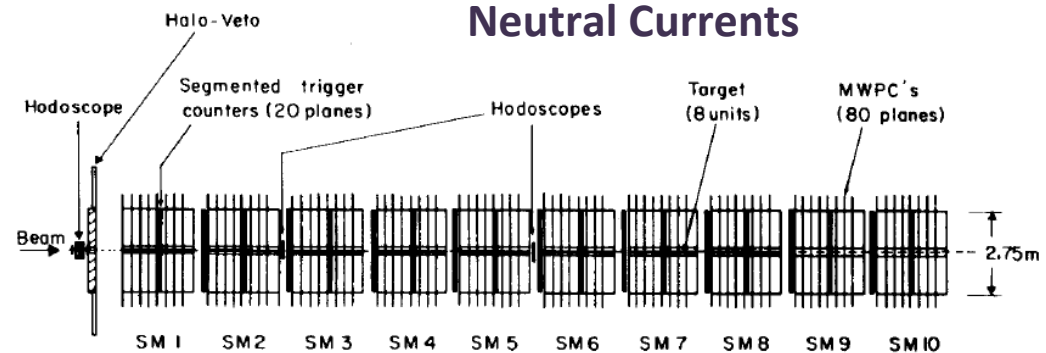
UA2

Pierre Darriulat



BEBC, CDHS(W), CHARM, CHORUS

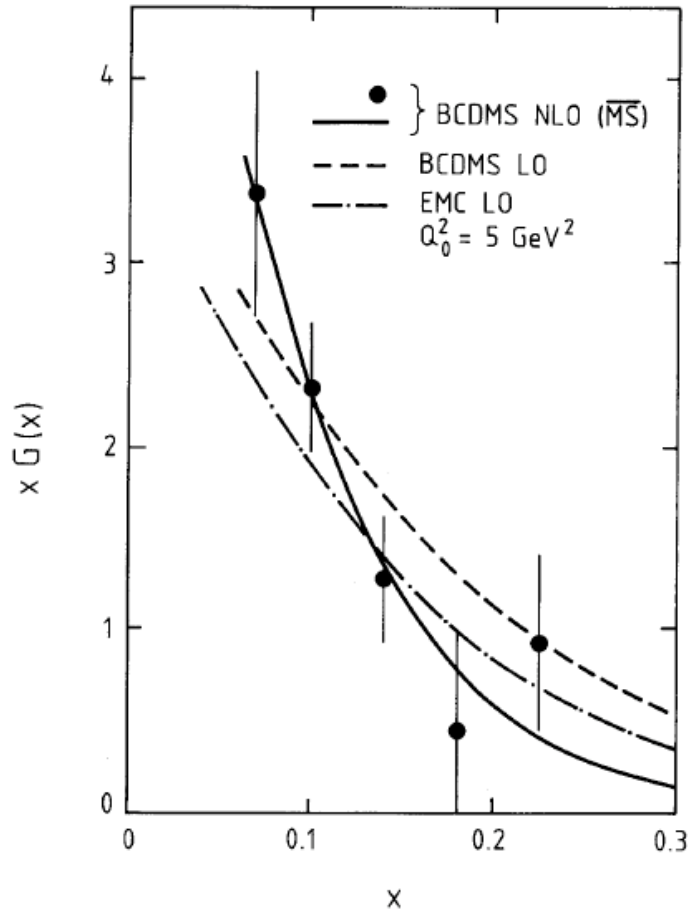
## Neutral Currents



BCDMS, EMC, SMC, COMPASS

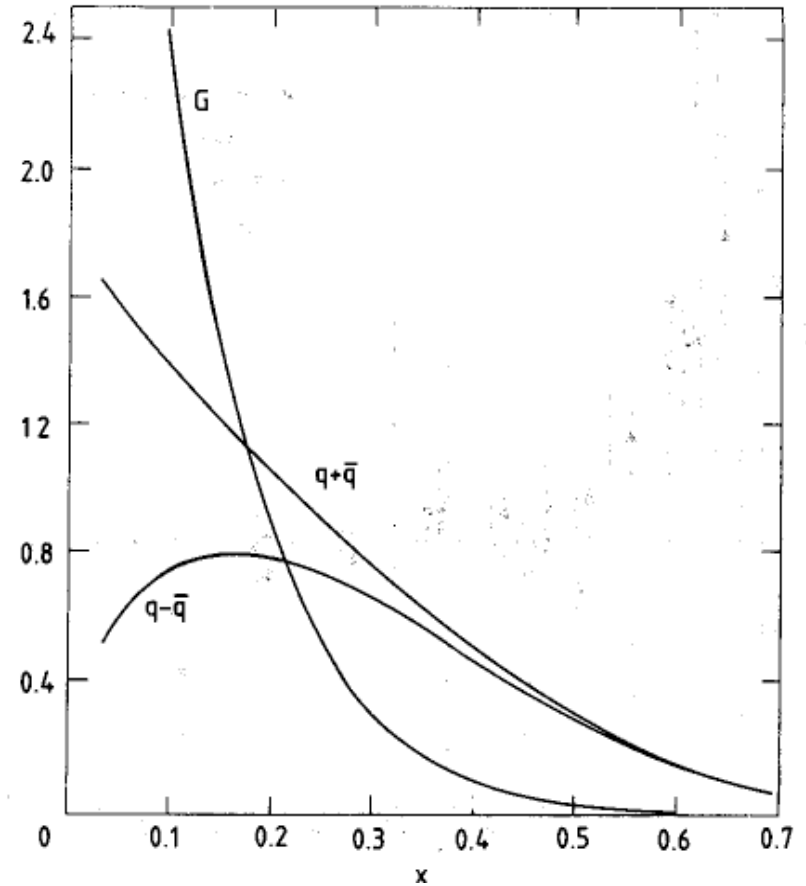
# PDFs before HERA - Gluon - $xg(x, Q^2)$

BCDMS



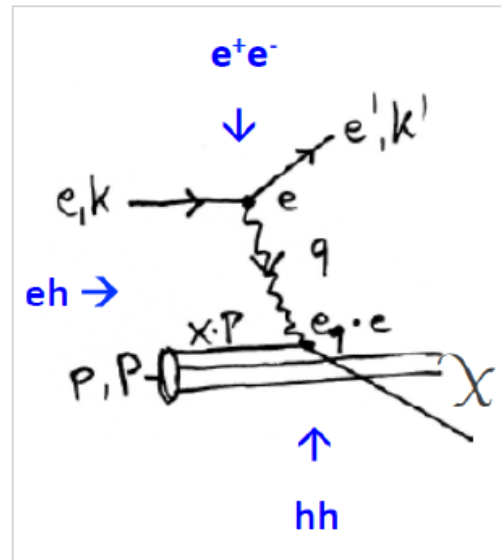
CERN-EP/89-07  
January 17th, 1989

CDHS



CERN-EP/89-103  
15 August 1989

# Deep Inelastic Lepton-Hadron Scattering



ep Colliders:

Calculated to N<sup>2</sup>LO  
J Vermaseren et al,  
and N<sup>3</sup>LO to come

Redundant determination of the scattering kinematics:  $x, Q^2 \leq 4E_e E_p = s \rightarrow$  high precision

Resolution of substructure  $d=1/\sqrt{Q^2}$  (protons and nuclei: the 'forgotten' task of HERA)

Proton, neutron, diffractive, nuclear, generalised, unintegrated partons. Much more than 'PDFs'.

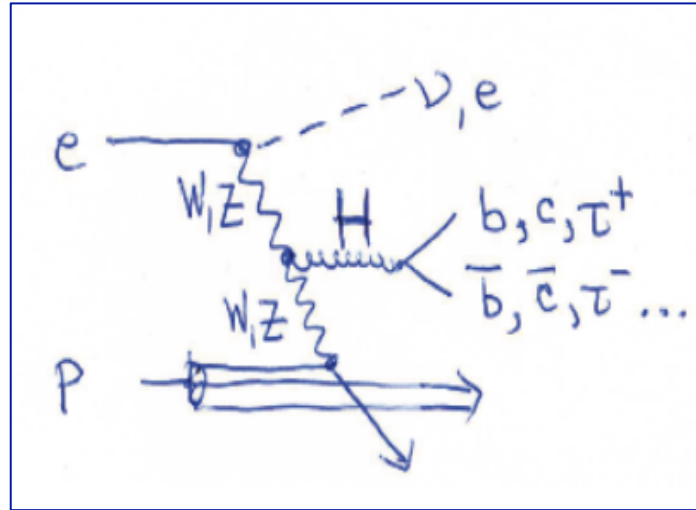
$Q^2=sxy$  varies by 7(8) orders of magnitude,  $0.1-10^{6(7)}$  GeV<sup>2</sup> for LHeC (FCCeh)

Small  $x > 1/s$  ( $Q^2 > M_p^2$ ): new parton dynamics, confinement, UHE neutrino scattering...

Electroweak  $\gamma, W, Z$ -parton scattering: clean final state, no pile-up ( $\mu=0.1$  at the LHeC), tag  $\gamma^*p$

**The LHeC and the FCC-eh are the cleanest high resolution microscopes the world can build.**

# Deep Inelastic Lepton-Hadron Scattering

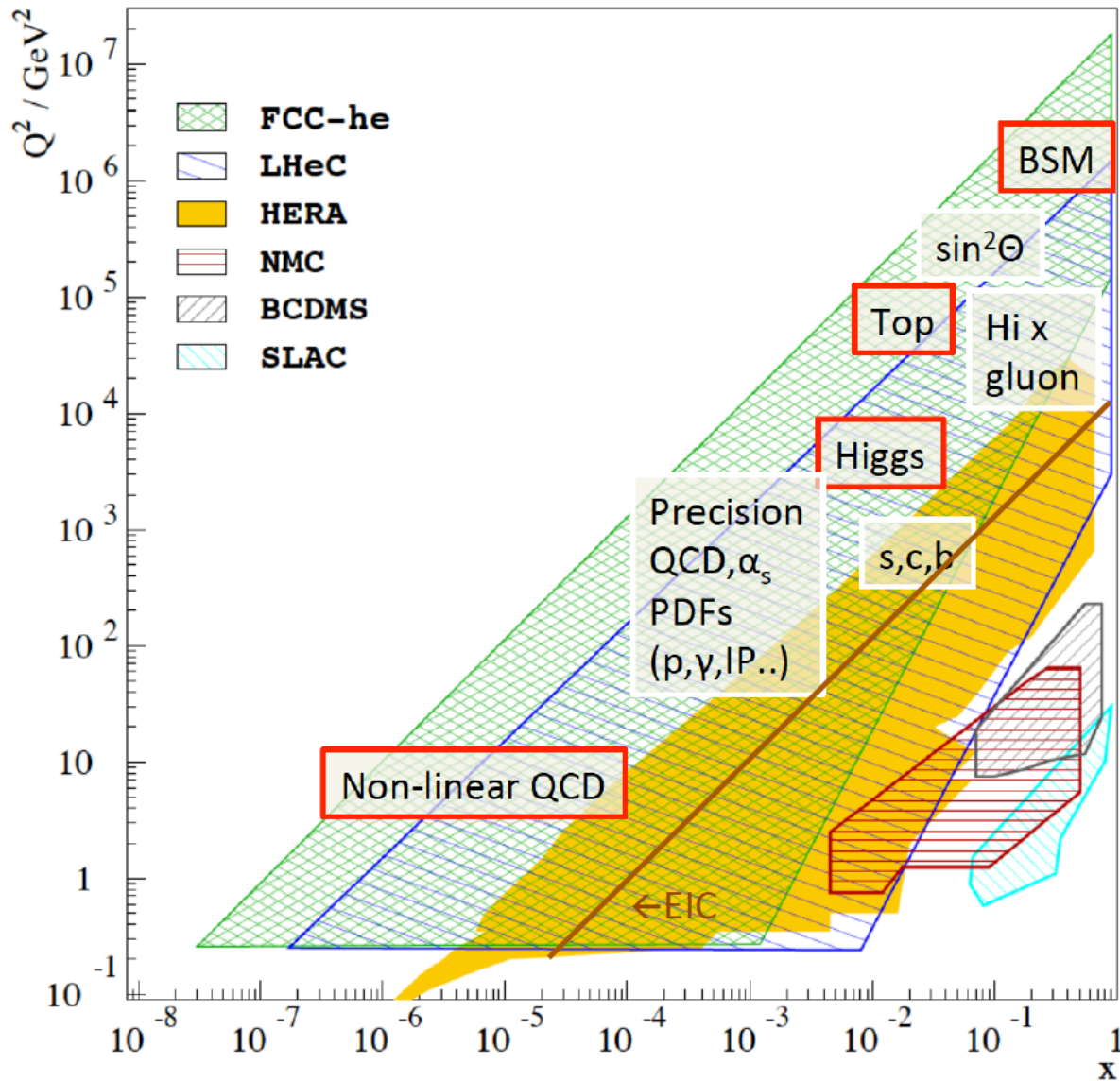


**Can produce heavy new states (Higgs, 750 GeV ghost..) and reach to O(200) TeV by indirect constraints, such as high precision contact interaction measurements**

pp, ep and ee are ordered in energy reach:  $2E_p \gg 2\sqrt{E_p E_e} \gg 2E_e$   
 For the LH(e)C this translates to 14 TeV vs 1.3 TeV vs 0.25-0.35 TeV.

Drell-Yan production in pp of new states with mass M in pp:  $M^2 = s x_1 x_2$   
 Resolving high mass physics needs PDFs at high x. Note: Higgs at FCC will be low x physics  
 For pp need to separate new physics from QCD dynamics in the proton

# Pursue New Physics of Deep Inelastic Scattering



.. and yet, ep is usually treated like the early Cinderella



→ Needs radiant appearance (lumi, physics, technology), readiness to work and a bit of luck..

# II The LHeC Conceptual Design Report

ep@LHC: Lausanne 1984

Aachen 1990

Rubbia: ICHEP Singapore 1990: pp in 1996 and ep in 1998

In 2007: the CERN SPC asks about ep: (r)ECFA+CERN Mandate

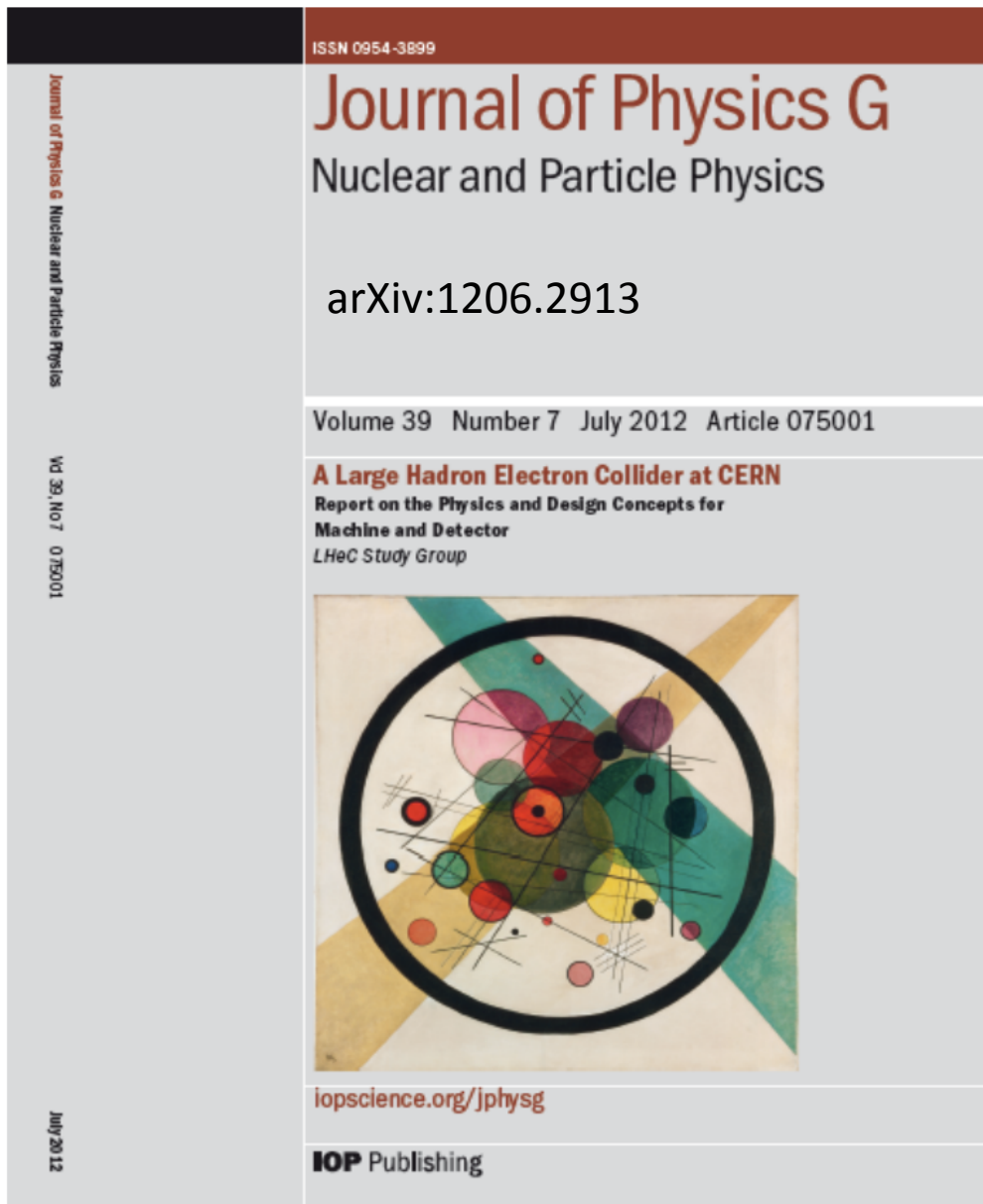
→ CDR in 2012



**W.Kandinsky: "Circles in a circle" (1923) Philadelphia (USA) Museum of Art**

First shown in LHeC context in a talk by A.S.Vera Workshop 2008





## 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**

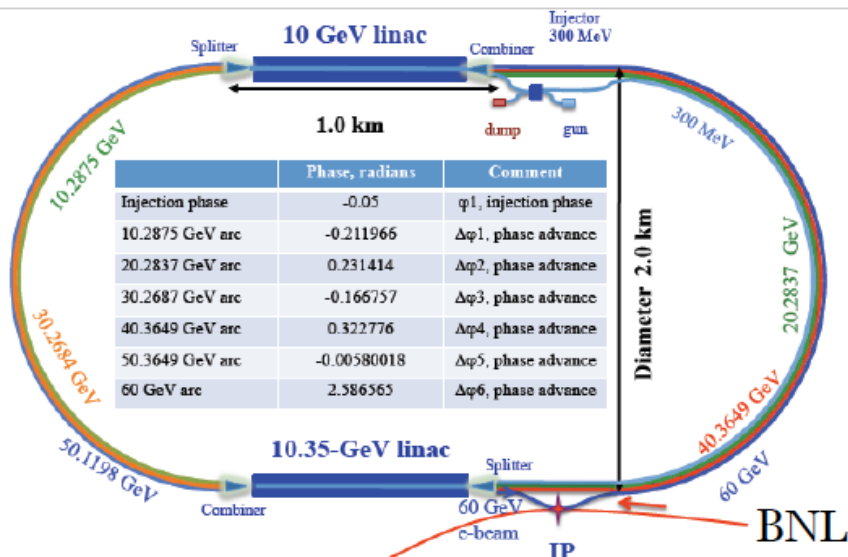
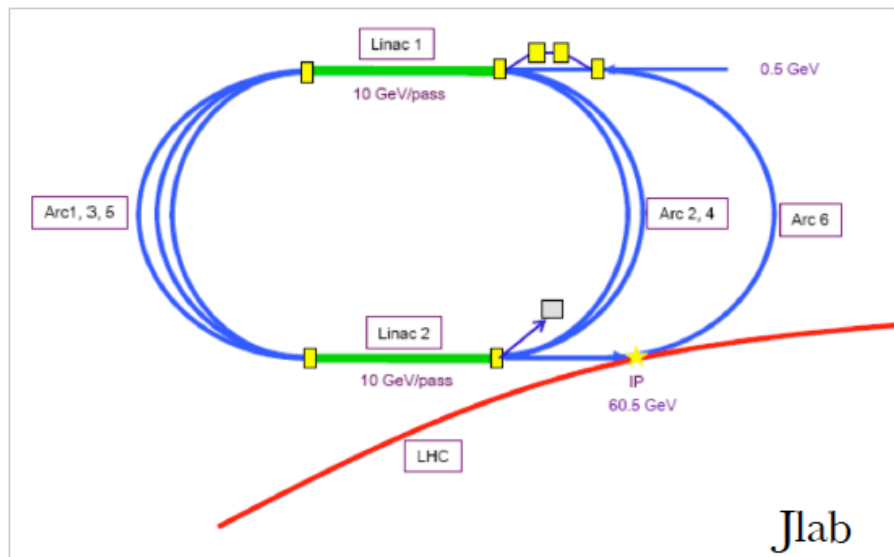
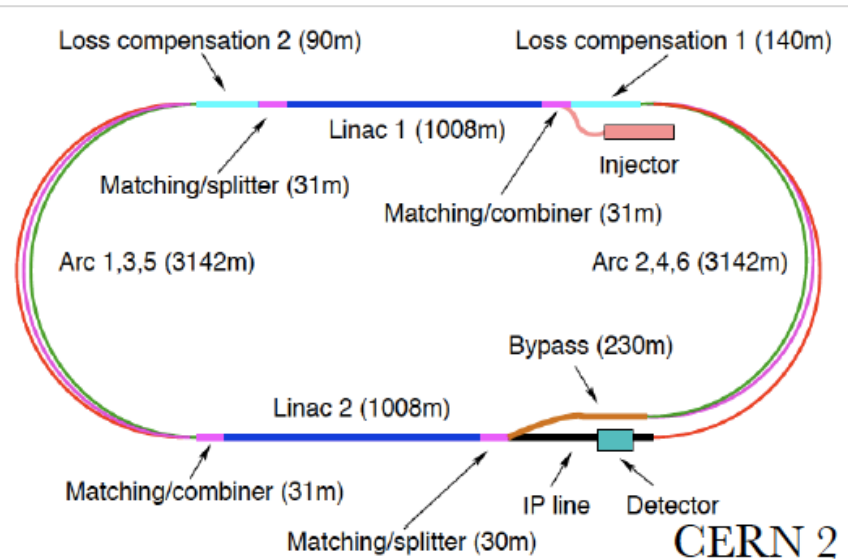
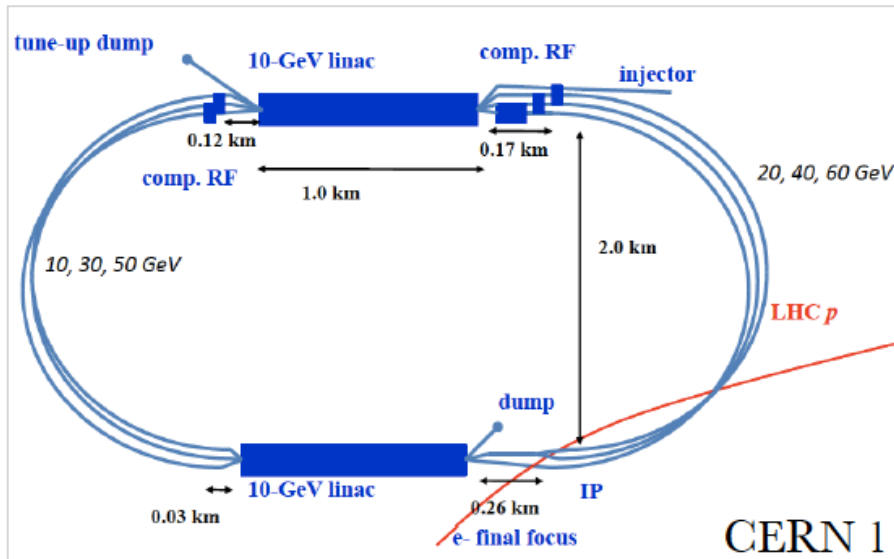
Guido Altarelli (Roma)  
Vladimir Chekelian (MPI Munich)  
Alan Martin (Durham)

### **Physics at High Parton Densities**

Alfred Mueller (Columbia)  
Raju Venugopalan (BNL)  
Michele Arneodo (INFN Torino)

Published 600 pages conceptual design report (CDR) written by 200 authors from 60 Institutes and refereed by 24 world experts on physics, accelerator and detector, which CERN had invited.

# 60 GeV Energy Recovery Linac



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

<b>7</b>	<b>Linac-Ring Collider</b>		<b>317</b>
7.1	Basic parameters and configurations		317
7.1.1	General considerations		317
7.1.2	ERL performance and layout		318
7.1.3	Polarisation	<b>Performance</b>	327
7.1.4	Pulsed linacs		329
7.1.5	Higher-energy LHeC ERL option		329
7.1.6	$\gamma$ -p/A Option		330
7.1.7	Summary of basic parameters and configurations		331
7.2	Interaction region		332
7.2.1	Layout		333
7.2.2	Optics	<b>Interaction Region</b>	334
7.2.3	Modifications for $\gamma$ p or $\gamma$ -A		340
7.2.4	Synchrotron radiation and absorbers		340
7.3	Linac lattice and impedance		348
7.3.1	Overall layout		348
7.3.2	Linac layout and lattice	<b>Optics</b>	350
7.3.3	Beam break-up		356
7.3.4	Imperfections		368
7.3.5	Touschek scattering		369
7.4	Performance as a Linac-Ring electron-ion collider		369
7.4.1	Heavy nuclei, e-Pb collisions		370
7.4.2	Electron-deuteron collisions	<b>Ions</b>	370
7.5	Polarised-electron injector for the Linac-Ring LHeC		370
7.6	Spin Rotator		372
7.6.1	Introduction		372
7.6.2	LHeC spin rotator options		373
7.6.3	Polarimetry	<b>Polarisation (80-90%)</b>	376
7.6.4	Conclusions and Outlook		377
7.7	Positron options for the Linac-Ring LHeC		379
7.7.1	Motivation		379
7.7.2	LHeC Linac-Ring $e^+$ requirements	<b>Positrons</b>	380
7.7.3	Mitigation schemes		380
7.7.4	Cooling of positrons		381
7.7.5	Production schemes		382
7.7.6	Conclusions on positron options for the Linac-Ring LHeC		388

**CDR: VERY detailed design of the LHeC Linac (and Ring) – Ring Collider, + components, CE..**

J.L.Abelleira Fernandez<sup>16,23</sup>, C.Adolphsen<sup>57</sup>, P.Adzic<sup>74</sup>, A.N.Akay<sup>03</sup>, H.Aksakal<sup>39</sup>, J.L.Albacete<sup>52</sup>, B.Allanach<sup>73</sup>, S.Alekhin<sup>17,54</sup>, P.Allport<sup>24</sup>, V.Andreev<sup>34</sup>, R.B.Appleby<sup>14,30</sup>, E.Arikan<sup>39</sup>, N.Armento<sup>53,a</sup>, G.Azuelos<sup>33,64</sup>, M.Bai<sup>37</sup>, D.Barber<sup>14,17,24</sup>, J.Bartels<sup>18</sup>, O.Behnke<sup>17</sup>, J.Behr<sup>17</sup>, A.S.Belyaev<sup>15,56</sup>, I.Ben-Zvi<sup>37</sup>, N.Bernard<sup>25</sup>, S.Bertolucci<sup>16</sup>, S.Bettoni<sup>16</sup>, S.Biswal<sup>41</sup>, J.Blümlein<sup>17</sup>, H.Böttcher<sup>17</sup>, A.Bogacz<sup>36</sup>, C.Bracco<sup>16</sup>, J.Bracinik<sup>06</sup>, G.Brandt<sup>44</sup>, H.Braun<sup>65</sup>, S.Brodsky<sup>57,b</sup>, O.Brüning<sup>16</sup>, E.Bulyak<sup>12</sup>, A.Buniatyan<sup>17</sup>, H.Burkhardt<sup>16</sup>, I.T.Cakir<sup>02</sup>, O.Cakir<sup>01</sup>, R.Calaga<sup>16</sup>, 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M.Ishitsuka<sup>58</sup>, M.Jacquet<sup>42</sup>, B.Jeaneret<sup>16</sup>, E.Jensen<sup>16</sup>, J.M.Jimenez<sup>16</sup>, J.M.Jowett<sup>16</sup>, H.Jung<sup>17</sup>, H.Karadeniz<sup>02</sup>, D.Kayran<sup>37</sup>, A.Kilic<sup>62</sup>, K.Kimura<sup>58</sup>, R.Klees<sup>75</sup>, M.Klein<sup>24</sup>, U.Klein<sup>24</sup>, T.Kluge<sup>24</sup>, F.Kocak<sup>62</sup>, M.Korostelev<sup>24</sup>, A.Kosmicki<sup>16</sup>, P.Kostka<sup>17</sup>, H.Kowalski<sup>17</sup>, M.Kraemer<sup>75</sup>, G.Kramer<sup>18</sup>, D.Kuchler<sup>16</sup>, M.Kuze<sup>58</sup>, T.Lappi<sup>21,c</sup>, P.Laycock<sup>24</sup>, E.Levichev<sup>40</sup>, S.Levonian<sup>17</sup>, V.N.Litvinenko<sup>37</sup>, A.Lombardi<sup>16</sup>, J.Maeda<sup>58</sup>, C.Marquet<sup>16</sup>, B.Mellado<sup>27</sup>, K.H.Mess<sup>16</sup>, A.Milanese<sup>16</sup>, J.G.Milhano<sup>76</sup>, S.Moch<sup>17</sup>, I.I.Morozov<sup>40</sup>, Y.Muttoni<sup>16</sup>, S.Myers<sup>16</sup>, S.Nandi<sup>55</sup>, Z.Nergiz<sup>39</sup>, P.R.Newman<sup>06</sup>, T.Omori<sup>61</sup>, J.Osborne<sup>16</sup>, E.Paoloni<sup>49</sup>, Y.Papaphilippou<sup>16</sup>, C.Pascaud<sup>42</sup>, H.Paukkunen<sup>53</sup>, E.Perez<sup>16</sup>, T.Pieloni<sup>23</sup>, E.Pilicer<sup>62</sup>, B.Pire<sup>45</sup>, R.Placakyte<sup>17</sup>, A.Polini<sup>07</sup>, V.Ptitsyn<sup>37</sup>, Y.Pupkov<sup>40</sup>, V.Radescu<sup>17</sup>, S.Raychaudhuri<sup>35</sup>, L.Rinolfi<sup>16</sup>, E.Rizvi<sup>71</sup>, R.Rohini<sup>35</sup>, J.Rojo<sup>16,31</sup>, S.Russenschuck<sup>16</sup>, M.Sahin<sup>03</sup>, C.A.Salgado<sup>53,a</sup>, K.Sampej<sup>58</sup>, R.Sassot<sup>09</sup>, E.Sauvan<sup>04</sup>, M.Schaefer<sup>75</sup>, U.Schneekloth<sup>17</sup>, T.Schörner-Sadenius<sup>17</sup>, D.Schulte<sup>16</sup>, A.Senol<sup>22</sup>, A.Seryi<sup>44</sup>, P.Sievers<sup>16</sup>, A.N.Skrinsky<sup>40</sup>, W.Smith<sup>27</sup>, D.South<sup>17</sup>, H.Spiesberger<sup>29</sup>, A.M.Stasto<sup>48,d</sup>, M.Strikman<sup>48</sup>, 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V.Yakimenko<sup>37</sup>, A.F.Zarnecki<sup>67</sup>, Z.Zhang<sup>42</sup>, F.Zimmermann<sup>16</sup>, R.Zlebcik<sup>51</sup>, F.Zomer<sup>42</sup>

LHeC Study group and CDR authors 2014

“you never walk alone”

# Physics Overview - CDR

LHeC Note 2012-004, arXiv:1211.5102

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 <sup>3</sup> LO, 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, ..

Table 3: Schematic overview on key physics topics for investigation with the LHeC.

LHeC: 20 times  $1/x$  and  $Q^2$  and 100-1000 times luminosity as compared to HERA  
**→ Very rich programme on DIS, ions, Higgs and new physics in much extended range**

# Strong Coupling Constant

-  $\alpha_s$  least known of coupling constants

Grand Unification predictions need smaller  $\delta\alpha_s$

- Is  $\alpha_s(\text{DIS})$  lower than world average (?)

- LHeC: per mille - independent of BCDMS!

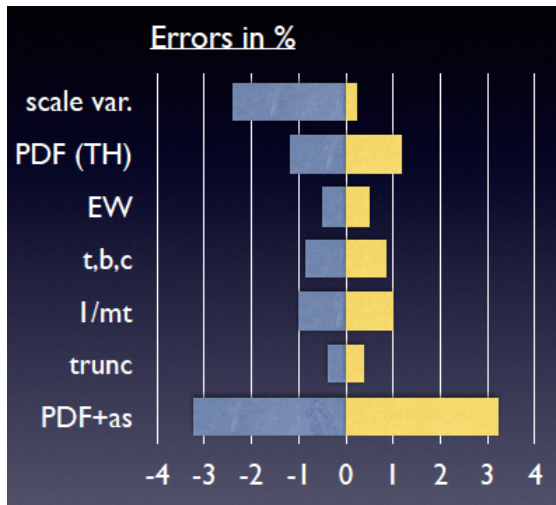
- High precision from inclusive data –  $\alpha_s(\text{jets})$ ??

- Challenge lattice QCD

LHeC simulation, NC+CC inclusive, total exp error

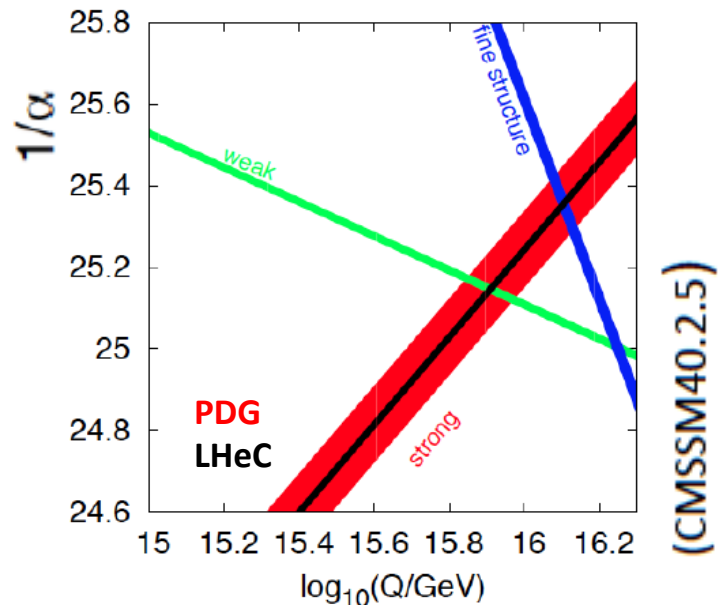
case	cut [ $Q^2$ in $\text{GeV}^2$ ]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

Two independent QCD analyses using LHeC+HERA/BCDMS



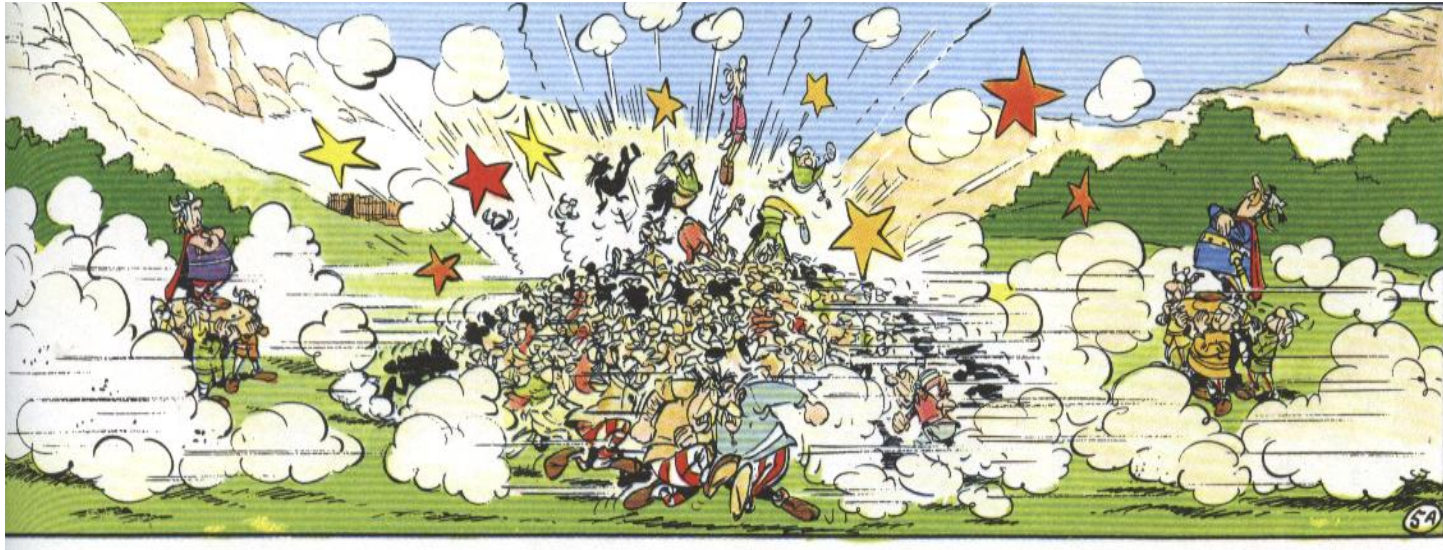
## Uncertainty on Higgs cross section

Giulia Zanderighi, Vietnam 9/16,  
from C.Anastasiou et al, 1602.00695  
who also discuss the ABM  $\alpha_s$ ..



# III LHC Physics

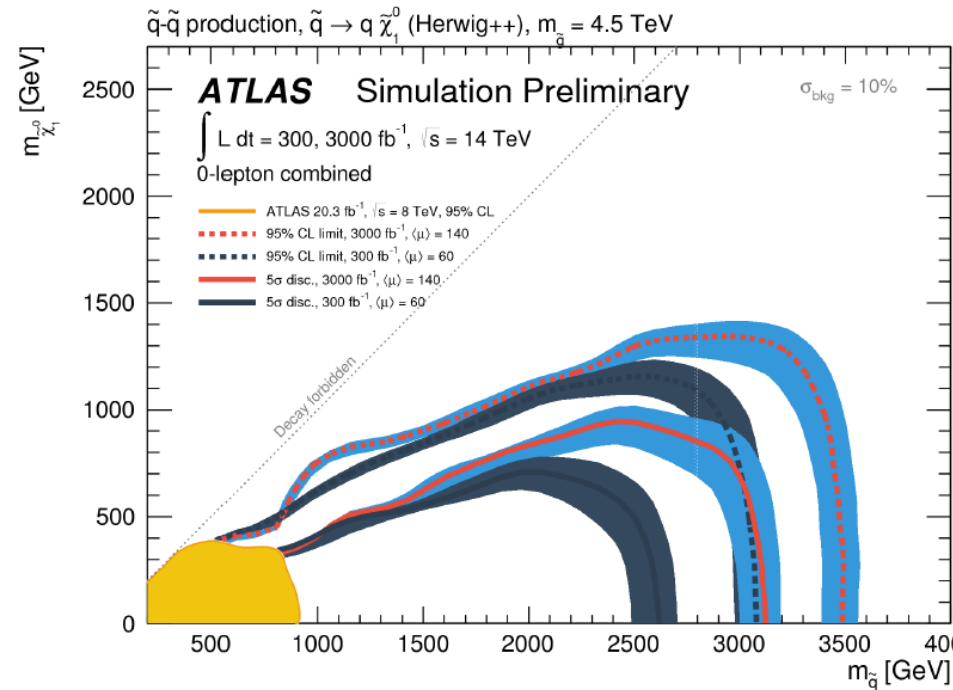
Superb LHC performance, reliable detectors and great experimental art



French artist's view on LHC physics – pileup at HL LHC 140-200

- 2000 LHC papers published (ATLAS 100/year). No BSM Physics observed
- Discovery of the Higgs Boson (Mass to W,Z,fermions + portal to BSM??)
- Surprisingly high precision (e.g. ATLAS  $W_{\text{mass}}$  to 19 MeV  $\rightarrow$  0.02%)
- The LHC exploits the large majority of HEP physicists, ATLAS: 1200 PhD's
- Programme HL LHC to operate until about/almost 2040

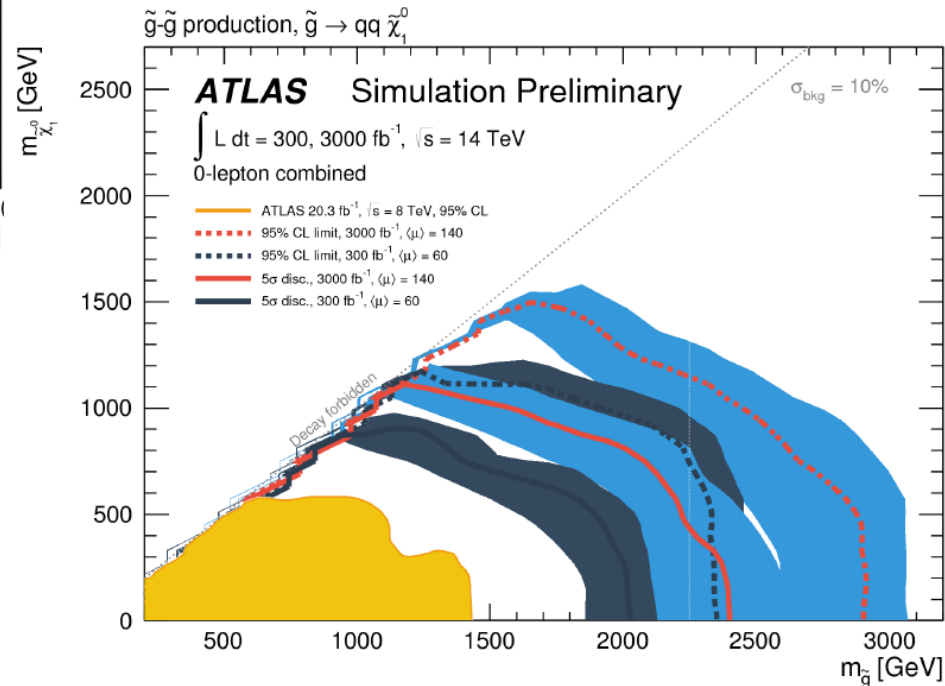
# Extended Search Programme (SUSY?)



5 $\sigma$  up to  $\sim 2.5 \text{ TeV}$  gluinos  
@ HL-LHC

ATLAS-PUB-2014-10

5 $\sigma$  up to  $\sim 3 \text{ TeV}$  squarks  
5 $\sigma$  up to  $\sim 1.2 \text{ TeV}$  stops  
5 $\sigma$  up to  $\sim 1.3 \text{ TeV}$  sbottoms  
@ HL-LHC



SUSY is too beautiful to not exist but it is broken “heavier and heavier”

Physics studies of the HL LHC Potential: ongoing  $\rightarrow$  **HL/HE LHC Workshop 17/18**



## IV Recent LHeC Developments (mostly) past CDR

## Particle Physics - a Sequence of Spectroscopies

- "Excitation of the 2536 Å Resonance Line of Mercury"  
Franck /Hertz 1914  
Bohr → ATOMIC SPECTROSCOPY
- "Disintegration of Elements by High Velocity Protons"  
Cockcroft / Walton 1932  
 $p\text{Li} \rightarrow \alpha\alpha$  : NUCLEAR SPECTROSCOPY
- "Total Cross-Sections of Positive Pions in Hydrogen"  
Anderson/Fermi/Long/Nagle 1952  
 $\Delta^{++} \rightarrow p\pi$  : HADRON SPECTROSCOPY
- The charming "November Revolution"  
Ting et al., Richter et al. 11.11.1974  
 $\mathcal{J}/\Psi \rightarrow c\bar{c}$ : QUARK SPECTROSCOPY



Gustav Hertz: Nobel 1925



John Cockcroft and Ernest Walton: Nobel 1951



Enrico Fermi: Nobel 1935



Sam Ting and Burt Richter: Nobel 1976

**No new spectroscopy appeared – neither 1992 (LEP) nor 2012 (LHC),  
No SUSY, neither at 100 GeV nor at 1000 GeV → a major surprise**



# 50 years ago

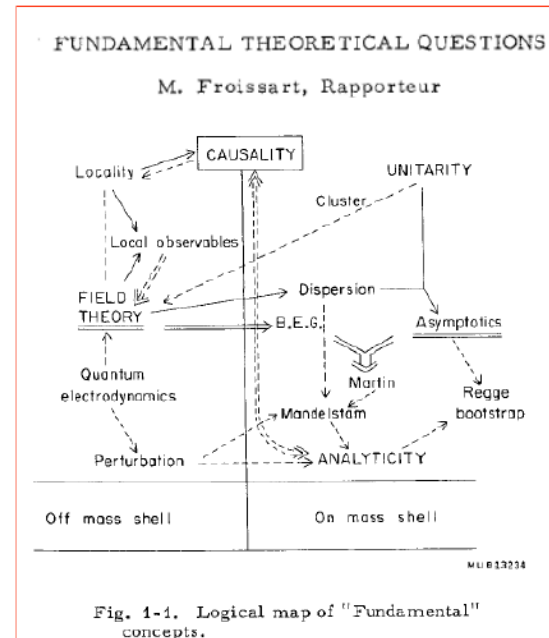
**Robert Jungk (1966)**

Die grosse Maschine  
auf dem Weg in eine andere Welt  
**The big machine**  
on the road into a new world  
A book on the Proton Synchrotron ..



Niels Bohr at 1<sup>st</sup> Council 1952  
Council: highest level committee

ICHEP 1966



**No Standard Model, Theory confused,  
ECFA, Amaldi: SPS for CERN  
Experiment paved the way:  
Quarks (ep) → QCD, SU<sub>L</sub>(2)xU(1)**

Today in various aspects resembles 50 years ago:

- Some think our dreams are too ambitious
- Our scientific standards are kept maximally high
- and the theory is pointing to every- or nowhere

**Our science is experiment driven, it can't be realised with pp alone**

# Framework of the Development

Following the CDR in 2012: Mandate issued by CERN:2014 (RH), confirmed in 2016 (FG)

## **Mandate to the International Advisory Committee**

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

Chair: Herwig Schopper, em. DG of CERN. IAC+CERN have invited four of its members to follow the study with special attention (Stefano Forte, Andrew Hutton, Leandro Nisati and Lenny Rifkin). Collaboration also with the FCC Review Committee chaired by Guenther Dissertori.

LHeC has been a development for and initiated by CERN, ECFA and NuPECC, so far, it's formal status is that of a community study, not a proposal, which holds for the FCC also, of which 'eh' is a part.

# Organisation<sup>\*)</sup>

## International Advisory Committee

“..Direction for ep/A both at LHC+FCC”

Sergio Bertolucci (CERN/Bologna)  
Nichola Bianchi (Frascati)  
Frederick Bordry (CERN)  
Stan Brodsky (SLAC)  
Hesheng Chen (IHEP Beijing)  
Eckhard Elsen (CERN)  
Stefano Forte (Milano)  
Andrew Hutton (Jefferson Lab)  
Young-Kee Kim (Chicago)  
Victor A Matveev (JINR Dubna)  
Shin-Ichi Kurokawa (Tsukuba)  
Leandro Nisati (Rome)  
Leonid Rivkin (Lausanne)  
Herwig Schopper (CERN) – Chair  
Jurgen Schukraft (CERN)  
Achille Stocchi (LAL Orsay)  
John Womersley (ESS)

**We miss Guido Altarelli.**

## Coordination Group

### Accelerator+Detector+Physics

Nestor Armesto  
Oliver Brüning – Co-Chair  
Andrea Gaddi  
Erk Jensen  
Walid Kaabi  
Max Klein – Co-Chair  
Peter Kostka  
Bruce Mellado  
Paul Newman  
Daniel Schulte  
Frank Zimmermann

5(11) are members of the  
FCC coordination team

OB+MK: FCC-eh responsables  
MDO: physics co-convenor

## Working Groups

### PDFs, QCD

Fred Olness,  
Claire Gwenlan

### Higgs

Uta Klein,  
Masahiro Kuze

### BSM

Georges Azuelos,  
Monica D’Onofrio

### Top

Olaf Behnke,  
Christian  
Schwanenberger

### eA Physics

Nestor Armesto

### Small x

Paul Newman,  
Anna Stasto

### Detector

Alessandro Polini  
Peter Kostka

<sup>\*)</sup>September 2017

# Luminosity for LHeC, HE-LHeC and FCC-ep

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

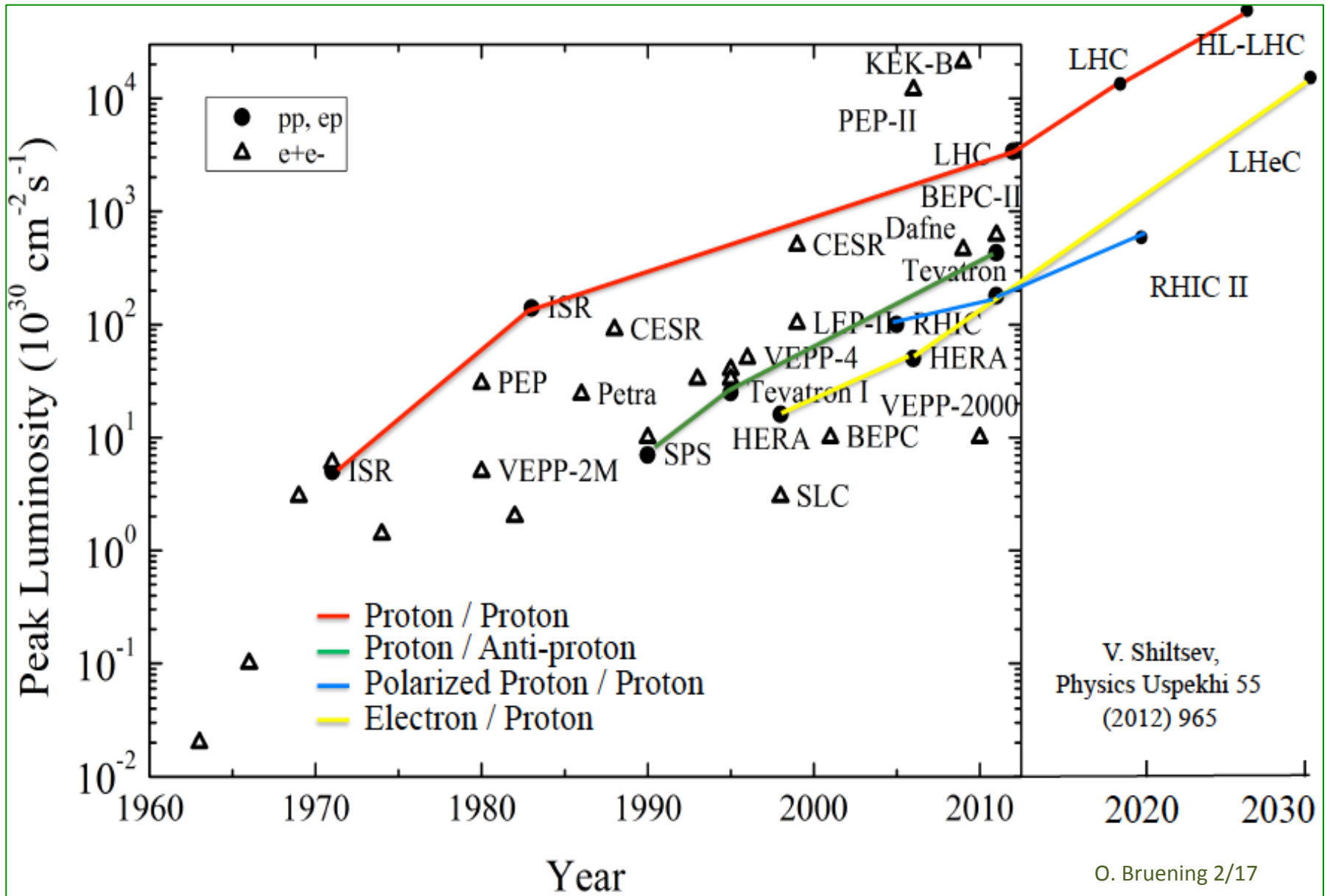
Oliver Brüning<sup>1</sup>, John Jowett<sup>1</sup>, Max Klein<sup>2</sup>,

Dario Pellegrini<sup>1</sup>, Daniel Schulte<sup>1</sup>, Frank Zimmermann<sup>1</sup>

EDMS 17979910 | FCC-ACC-RPT-0012

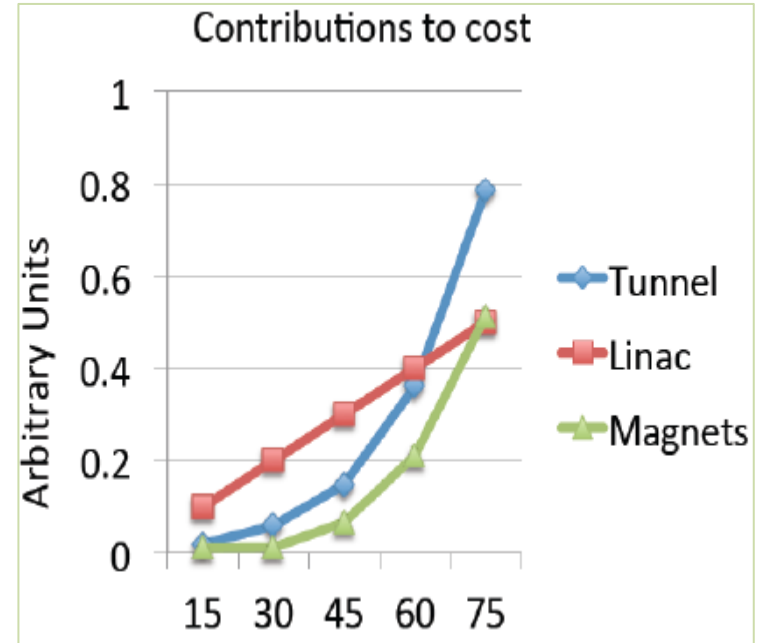
Contains update on eA:  
6  $10^{32}$  in e-Pb for LHeC.

# Collider Luminosities vs Year (pp and ep)



# Location, Footprint, Use of the Electron Racetrack

**e beam external to LHC. Location suitable for both HL and HE LHC.**



MK, F Zimmermann

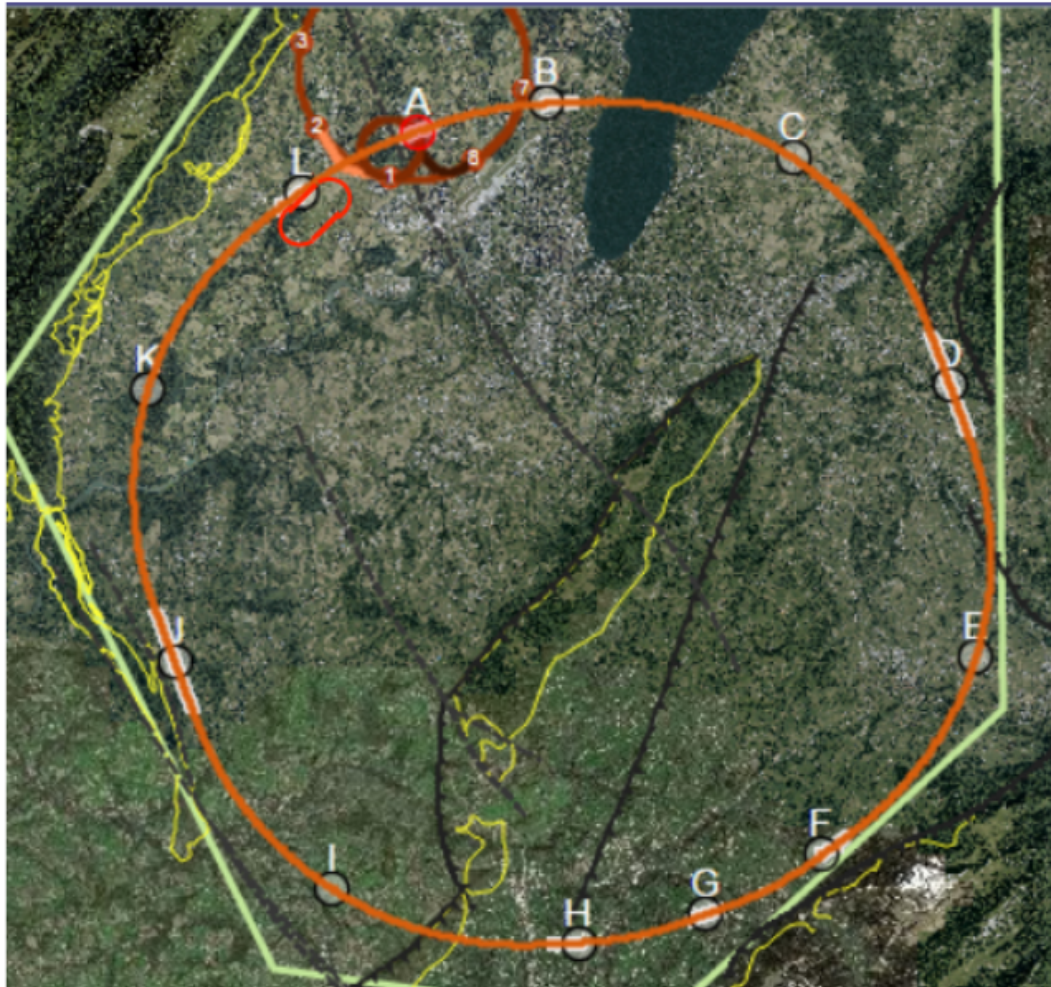
- $U(\text{ERL}) = 1/n U(\text{LHC})$ : 60 GeV: 1/3
- BSM, top, Higgs, Low x all want maximum  $E_e$

Initial, **tentative**, rough scaling estimate of basic cost (tunnel, linac (XFEL), magnets)

**Energy – Cost – Physics – Footprint** are being reinvestigated for EU strategy

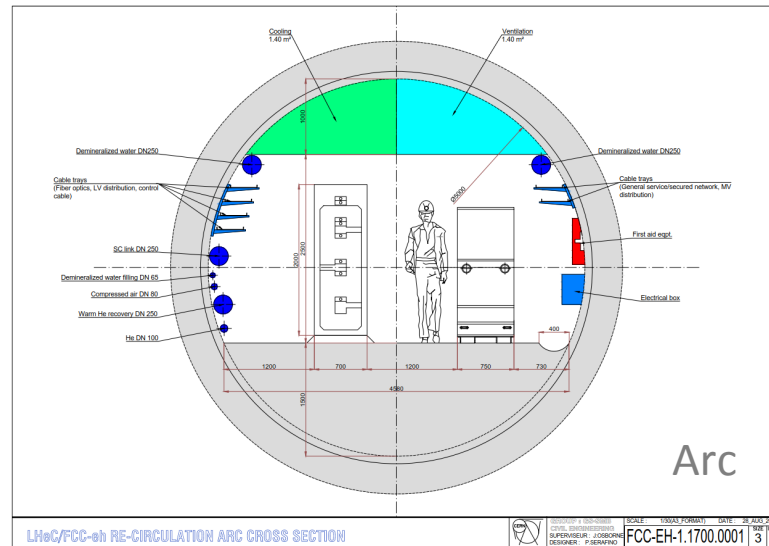


# FCC-eh

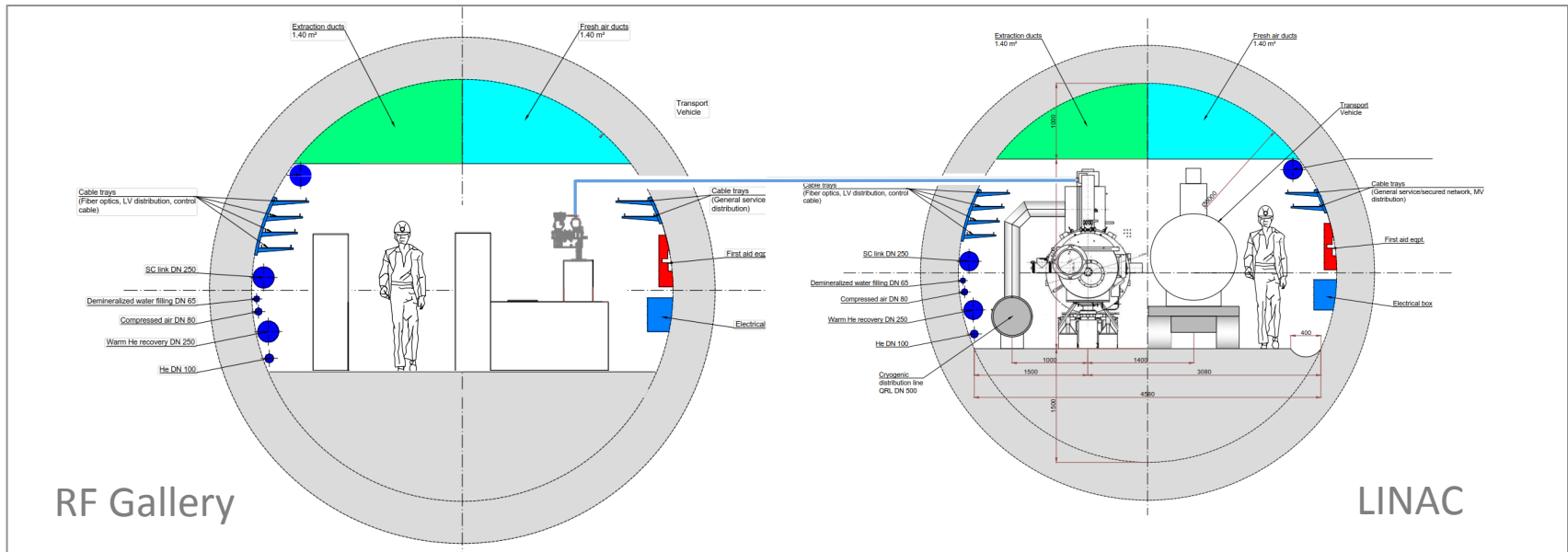


60 GeV ERL tangential to FCC-hh. IP: L for geological reasons.  $L = 1.5 \cdot 10^{34}$  Higher  $s$ ,  $Q^2$ ,  $1/x$

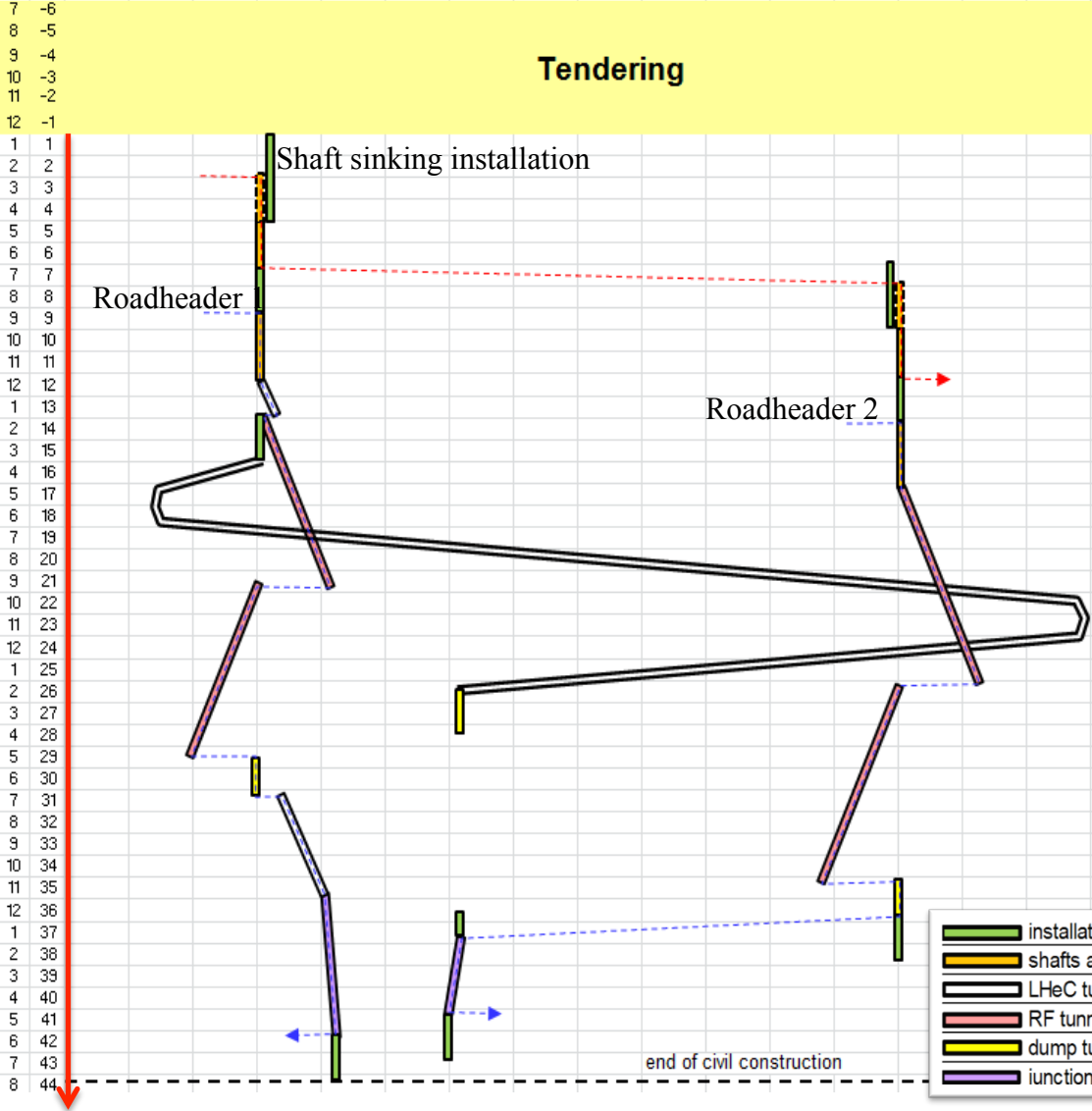
# Tunnels: Triple Arc and LINACs



**DRAFT: for ERL in any pp combi.**  
 cf Matt Stewart et al. 12.9.17



# Civil Engineering – full design made



CDR: Evaluation of CE, analysis of ring and linac by Amber Zurich. Detailed estimate of cost and time: **3.5 years for underground works** using 2 roadheaders and 1 TBM

- More studies will be needed for**
- Integration with all services
  - (EL,CV, transport, survey etc).
  - Geology
  - Understanding vibration risks
  - Environmental impact assessment

Tunnel connection in IP2

Tentative

# Physics Considerations on the Choice of $E_e$

## SM Higgs Couplings

$H \rightarrow bb$  ( $cc$ ): 0.5 (4)% coupling uncertainty, for  $1ab^{-1}$ , 60 GeV, polarised  
This becomes 2(15)% for  $0.5ab^{-1}$  and 30 GeV: **Under these conditions one loses high H precision and the ep portal to new physics potential and the neutral current Higgs programme disappears**

## New Higgs+top Physics

**Heavy new objects:**  $Htt$  coupling: 17  $\rightarrow$  31 % for 60  $\rightarrow$  40 GeV (M Kumar)  
Discovery potential for anomalous  $tqH$ : 0.5 – 3.2 -22% precision for  
60  $\rightarrow$  50  $\rightarrow$  40 GeV (H Sun). **At 40 GeV the discovery potential is gone.**

## Longitudinal Structure Function – THE path to saturation

Low  $x$  physics: **Saturation** requires 1% measurement of  $F_L$ . That needs  $y=0.9=1-E'/E_e$ . HERA: big complication:  $E'$  at high  $y$  too small for precision (eID, background, charge symmetry): needs  $\sim$ twice  $E_e$  to be safe.

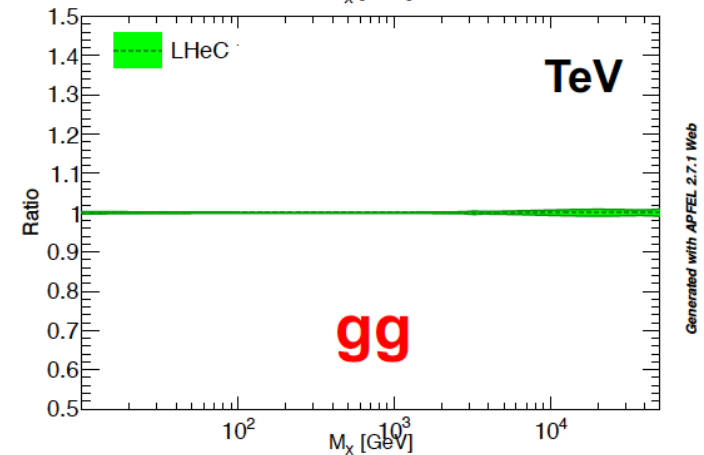
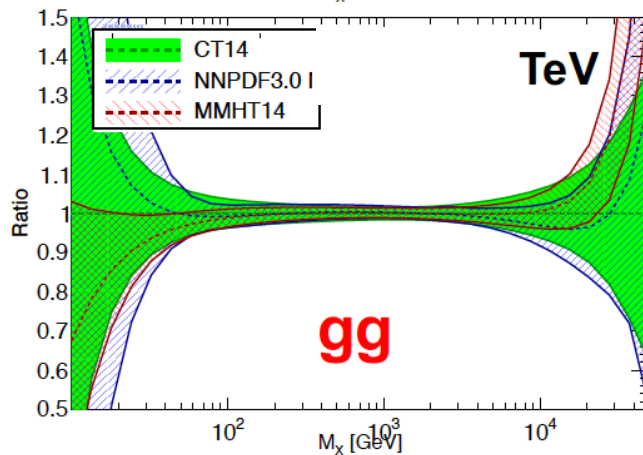
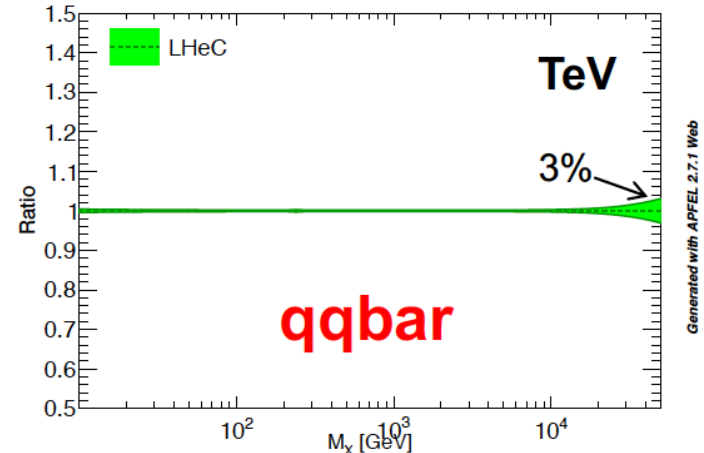
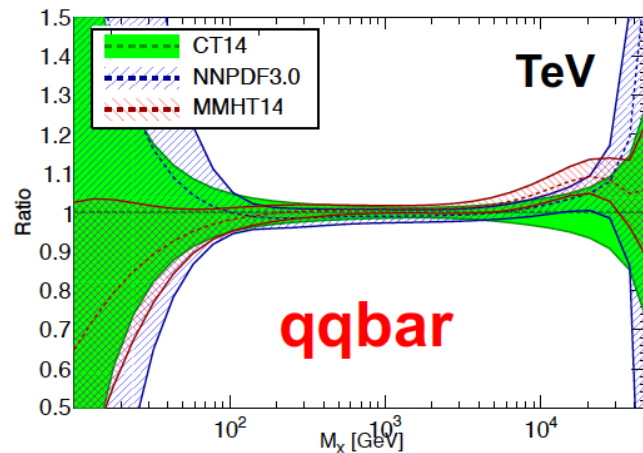
- $\rightarrow$  50 GeV the programme stands, 40 GeV it loses BSM,  $t$ , 30 GeV: precision gone
- $\rightarrow$  Keep the electron energy as high as it can be afforded, and not lower than 50 GeV

# The LHeC PDF Programme

Resolve parton structure of the proton completely:  $u_v, d_v, s_v, u, d, s, c, b, t$  and  $xg$   
 Unprecedented range, sub% precision, free of parameterisation assumptions,  
 Resolve  $p$  structure, solve non linear and saturation issues, test QCD,  $N^3LO$ ...

Strong  
 Coupling in  
 inclusive  
 DIS at LHeC  
 to 0.1%

Lattice??  
 Jets??  
 BCDMS??  
 GUTs?  
 Higgs in pp



Solve the PDF issues for pp and test QCD with permille measurement of strong coupling

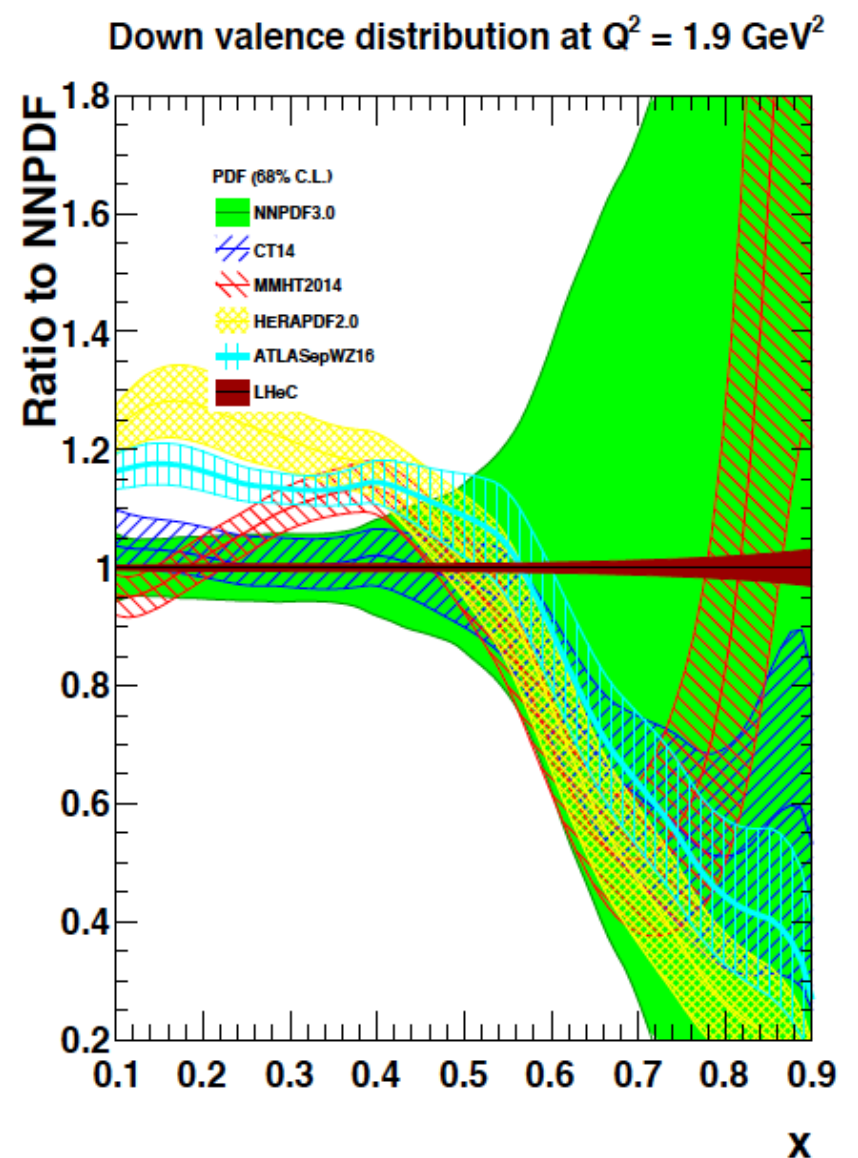
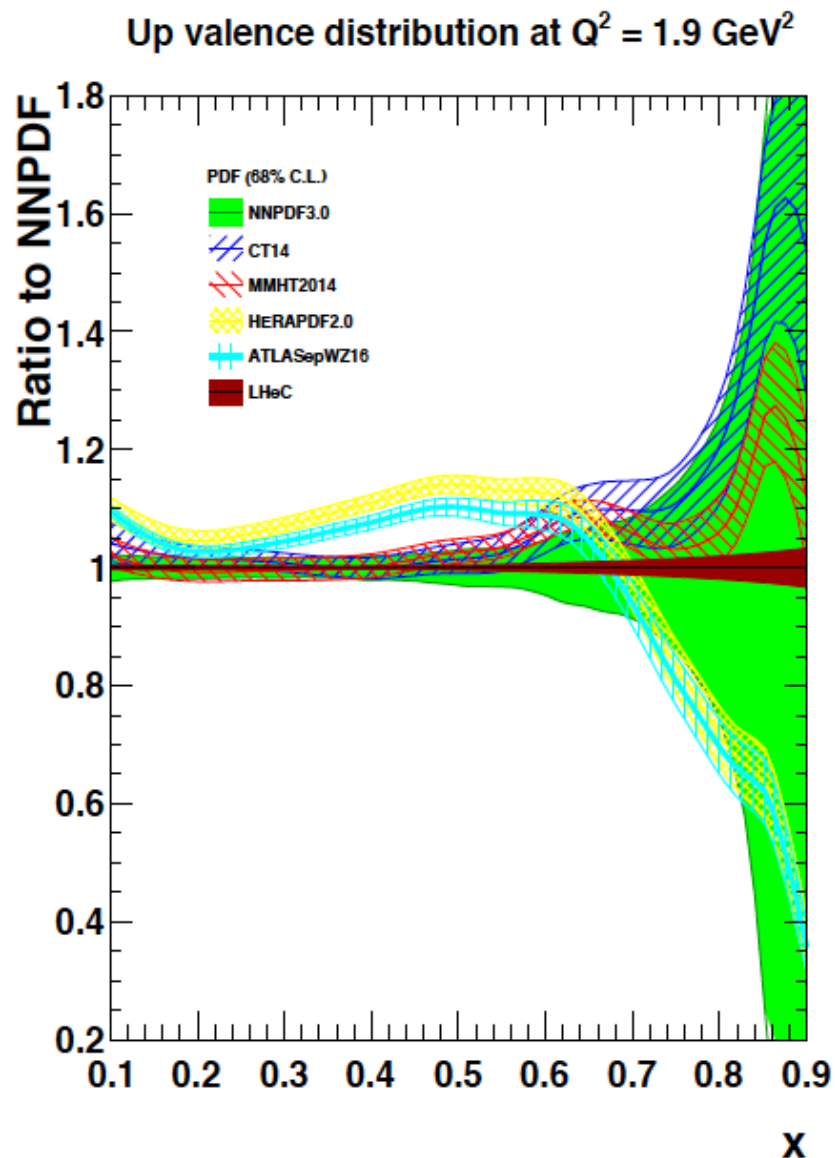


Figure 2: Determination of the valence quark distributions as functions of Bjorken  $x$ . Plotted are the ratios to the NNPDF result with uncertainties displayed as are provided by the individual sets, left for the up-valence quark and right the down-valence quark distribution. For the LHeC the total uncertainty is plotted and the central value assumed to agree with NNPDF. As non-singlet quantities, the valence quark distributions are approximately the same with varying  $Q^2$ .

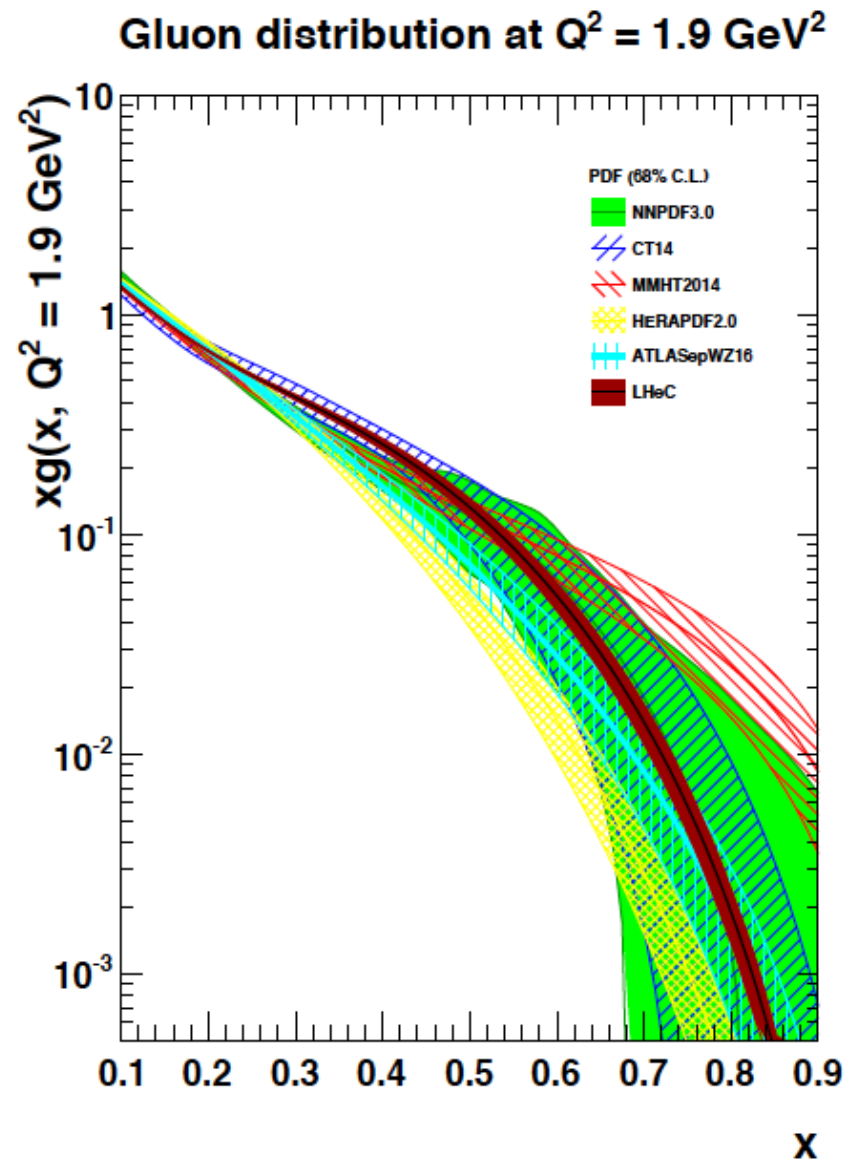
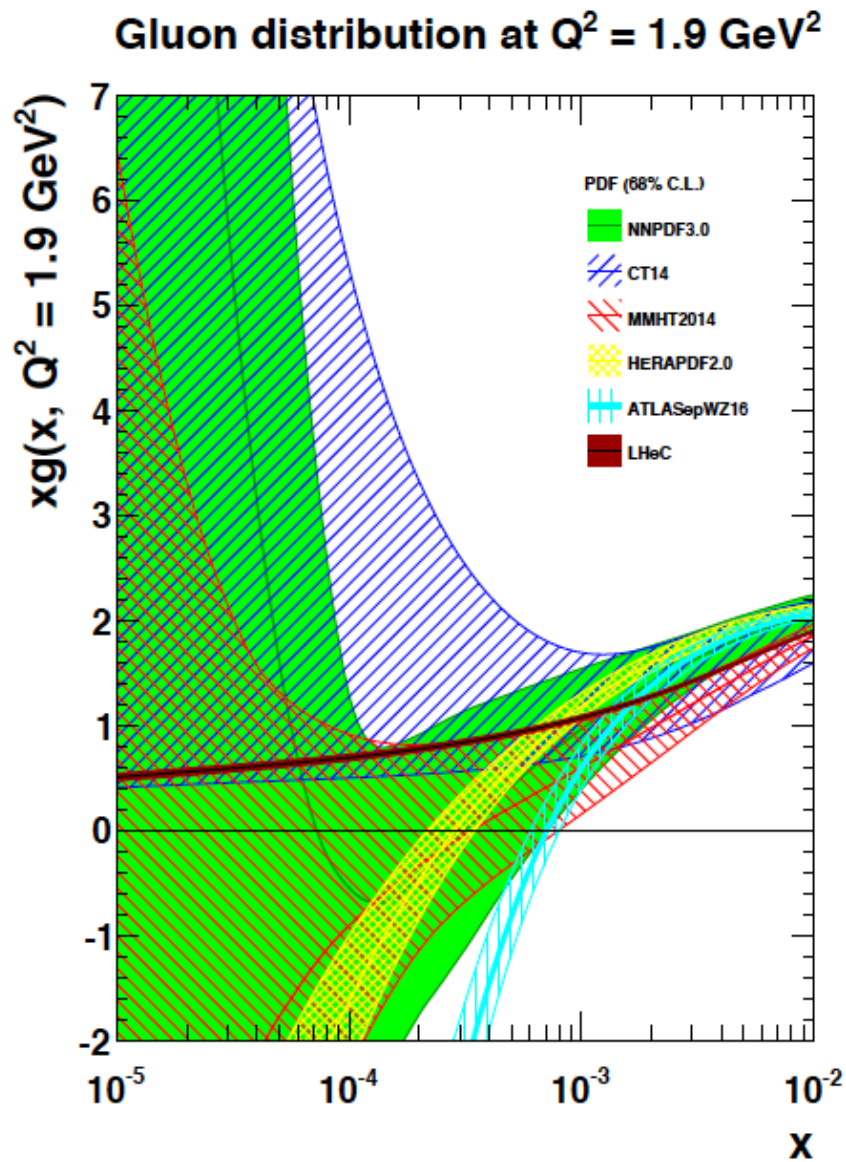
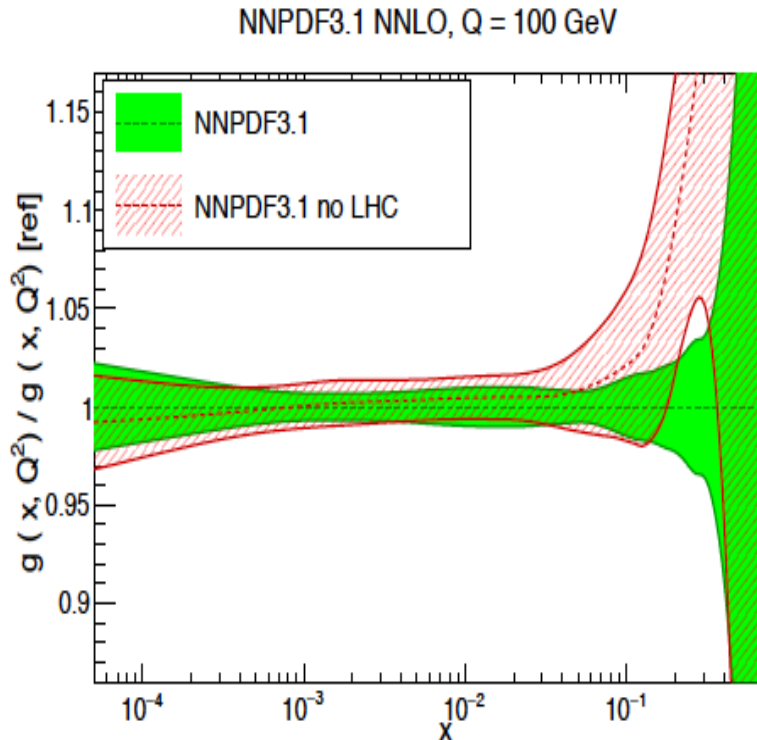


Figure 3: Determination of the gluon momentum distribution in the proton. The expected total experimental uncertainty on  $xg$  from the LHeC (dark purple bands) is compared with the most recent global PDF determinations which include the final HERA data, covering for  $xg$  a range from  $x \simeq 5 \cdot 10^{-4}$  to  $x \simeq 0.6$ , and much of the LHC data from Run I. Left:  $xg$  at small  $x$ ; Right at large  $x$ .

# LHC Folklore: PDFs come from pp



NNPDF3.1 arXiv:1706.00428

LHC data constrain PDFs, BUT do not determine them:

- Needs complete  $q, g$  unfolding (miss variety) at all  $x$ , as there are sum-rules
- Needs strong coupling to per mille precision, not in pp
- Needs stronger effects (miss  $Q^2$  variation) cannot come from  $W, Z$  at  $Q^2 = 10^4 \text{ GeV}^2$
- Needs clear theory (hadronisation, one scale)
- Needs heavy flavour  $s, c, b, t$  measured and VFNS fixed
- Needs verification of BFKL at low  $x$  (only  $F_2 - F_L$ )
- Needs  $N^3\text{LO}$  (as for Higgs)
- Needs external input to find QCD subtleties such as factorisation, resummation...to not go wrong
- Needs external precise input for subtle discoveries
- Needs data which yet ( $W, Z$ ) will hardly be better
- Needs agreement between the PDFs and  $\chi^2 + 1$  ..

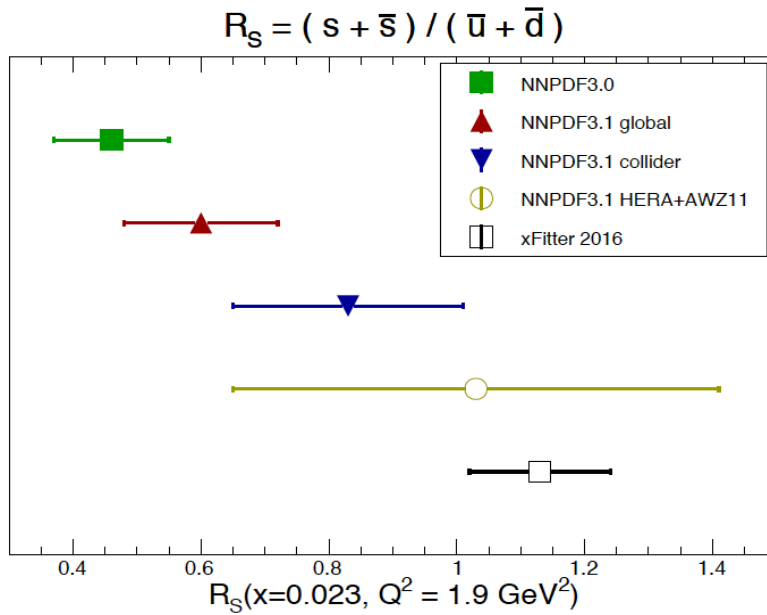
PDFs are not derived from pp scattering. And yet we try, as there is nothing else.., sometimes with interesting results as on the light flavour democracy at  $x \sim 0.01$  (nonsuppressed  $s/\bar{d}$ ). Can take low pileup runs, mitigate PDF influence .. – but can't do what is sometimes stated.

**LHeC vs HERA: Higher  $Q^2$ : CC; higher  $s$ : small  $x/g$  saturation?; high lumi:  $x \rightarrow 1$ ;  $s, c, b, t$ . ...**

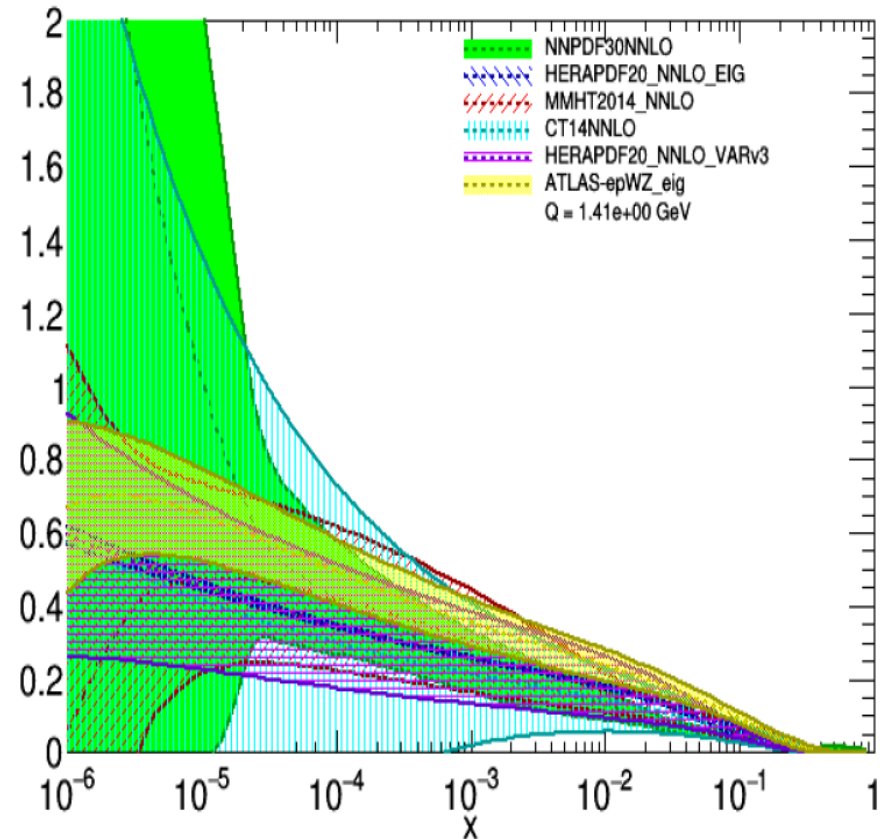


# Strange Strange

Strange quark suppression [dimuons in neutrino data] vs light flavour democracy [W,Z LHC]



$x_s(x, Q)$ , comparison



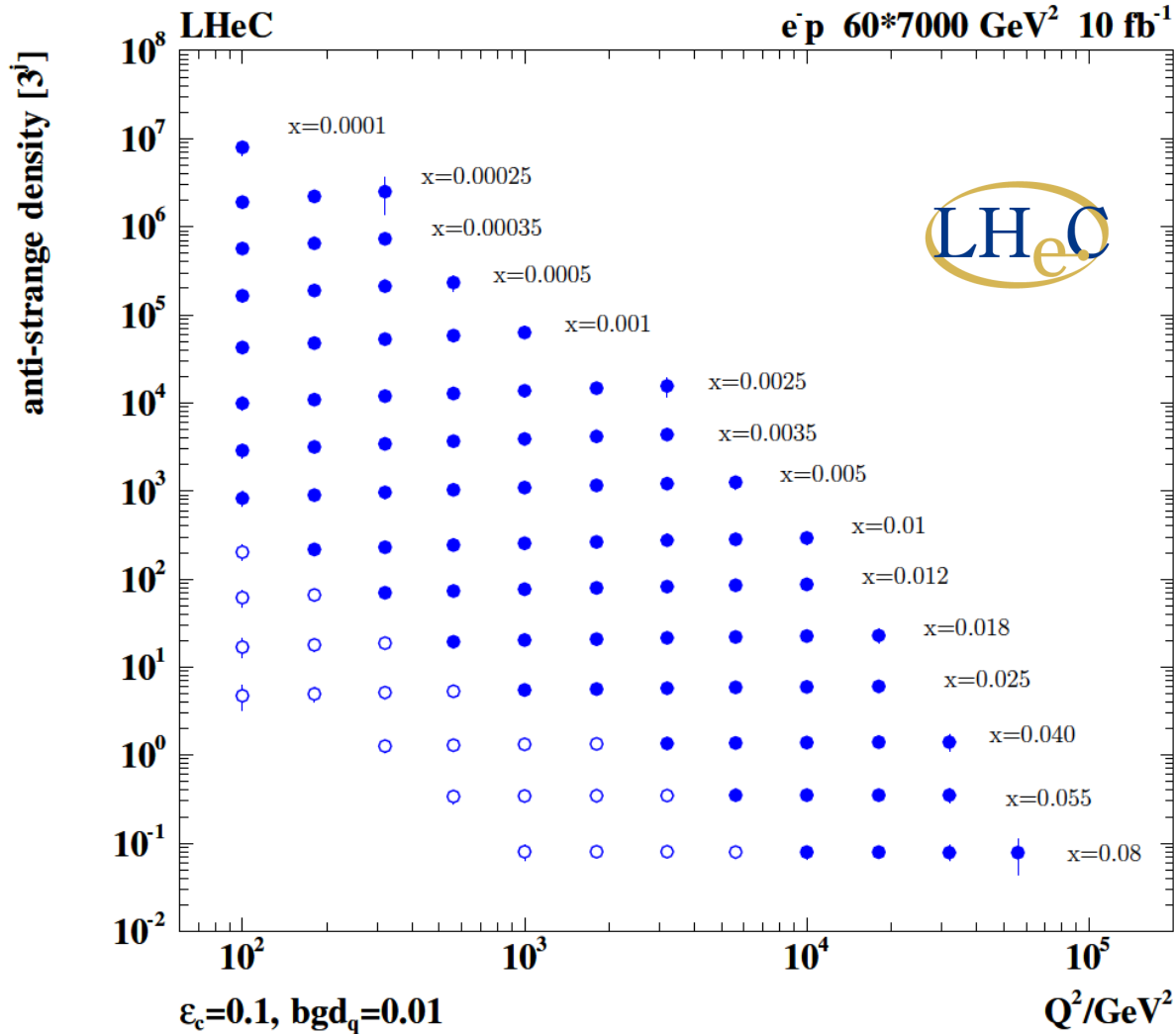
Generated with APFEL 2.7.1 Web

NNPDF3.1 arXiv:1706.00428, note:  
 “xFITTER16” = ATLAS: 1612.0301  
 Also look at MMHT and other results

A Cooper-Sarkar, DIS17

**The strange quark density, after 60 years of DIS, has remained unknown. Is there a valence s?**

# Strange Quark Distribution from LHeC



High luminosity

High  $Q^2$

Small beam spot

Modern Silicon

NO pile-up..

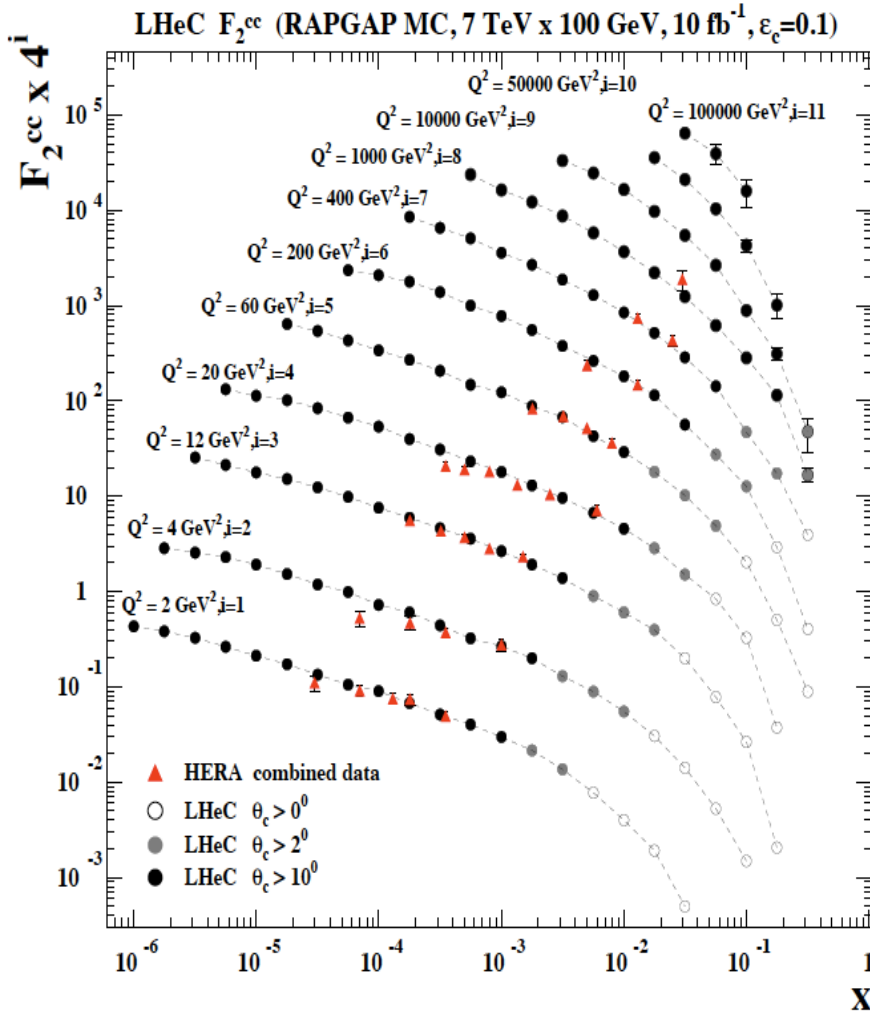
→ First ( $x, Q^2$ )  
 measurement of  
 the (anti-)strange  
 density, HQ valence?

$x = 10^{-4} \dots 0.1$   
 $Q^2 = 100 - 10^5 \text{ GeV}^2$

Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter

# Charm $F_2^{cc}$ and Mass

LHeC CDR arXiv:1206.2913



HERA 0.0005/2.5 .. 0.05/2000 GeV<sup>2</sup>  
 LHeC 0.00001/1 .. 0.2/200000 GeV<sup>2</sup>

$\epsilon(c)$  assumed 10%, 1% light background, ~3%  $\delta(\text{syst})$

**Heavy Flavour with LHeC**

Beam spot (in xy): 7 $\mu\text{m}$   
 Impact parameter: better than 10 $\mu\text{m}$   
 Modern Silicon detectors, no pile-up  
 Higher E, L, Acceptance,  $\epsilon$ , than at HERA  
 → Huge improvements predicted

	<b>HERA</b>	<b>LHeC</b>
$m_c(m_c)/\text{GeV}$	1.26	?
$\delta(\text{exp})$	0.05	0.003
$\delta(\text{mod})$	0.03	~0.002
$\delta(\text{par})$	0.02	~0.002
$\delta(\alpha_s)$	0.02	0.001

**LHeC determines strong coupling to 0.1%**  
 High precision PDF data will reduce the mod and par errors by a very large amount.

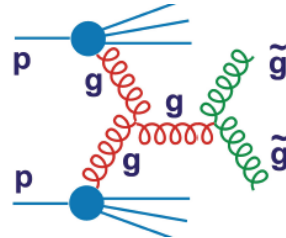
**Determination of charm mass to 3 MeV:**  
 crucial for  $M_W$  in pp or  $H \rightarrow cc$  in ep  
 cf also NNPDF3.1 (arXiv:1706.00428) and refs

# Empowering pp Discoveries

External, reliable input (PDFs, factorisation..) is crucial for range extension + CI interpretation

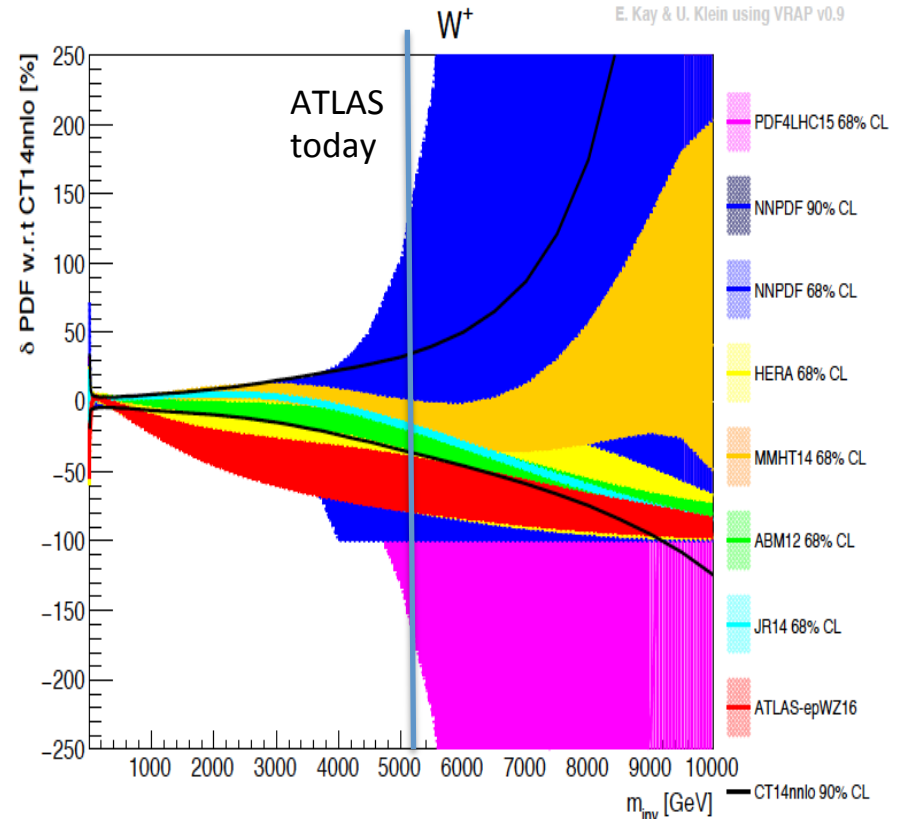
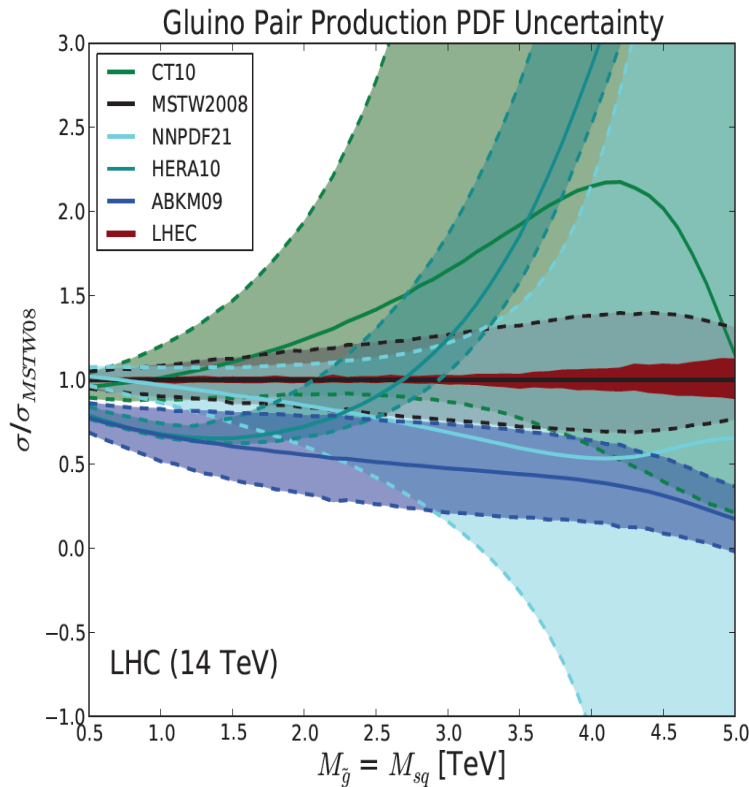
GLUON

SUSY, RPC, RPV, LQS..

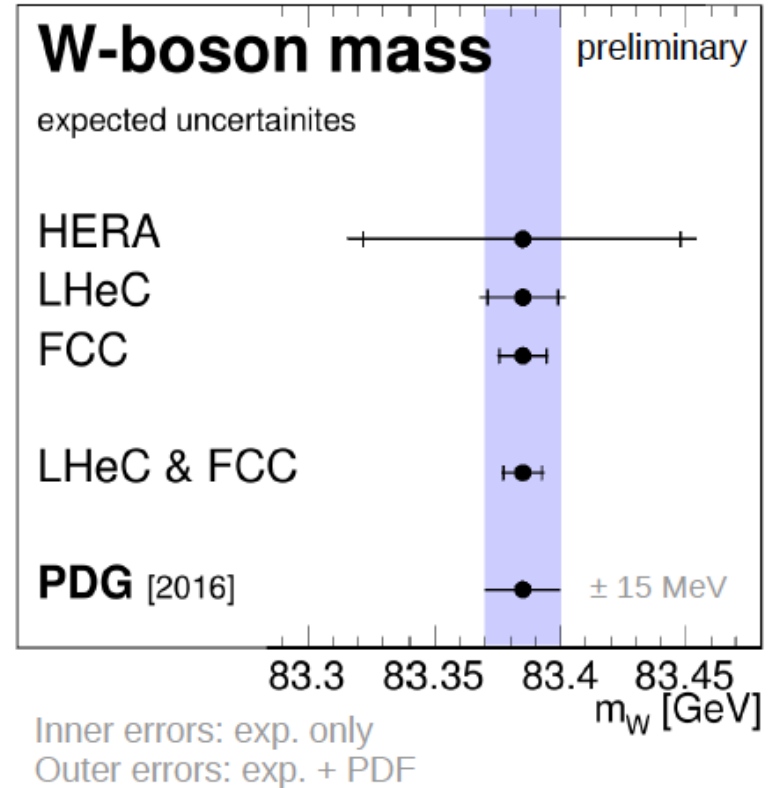
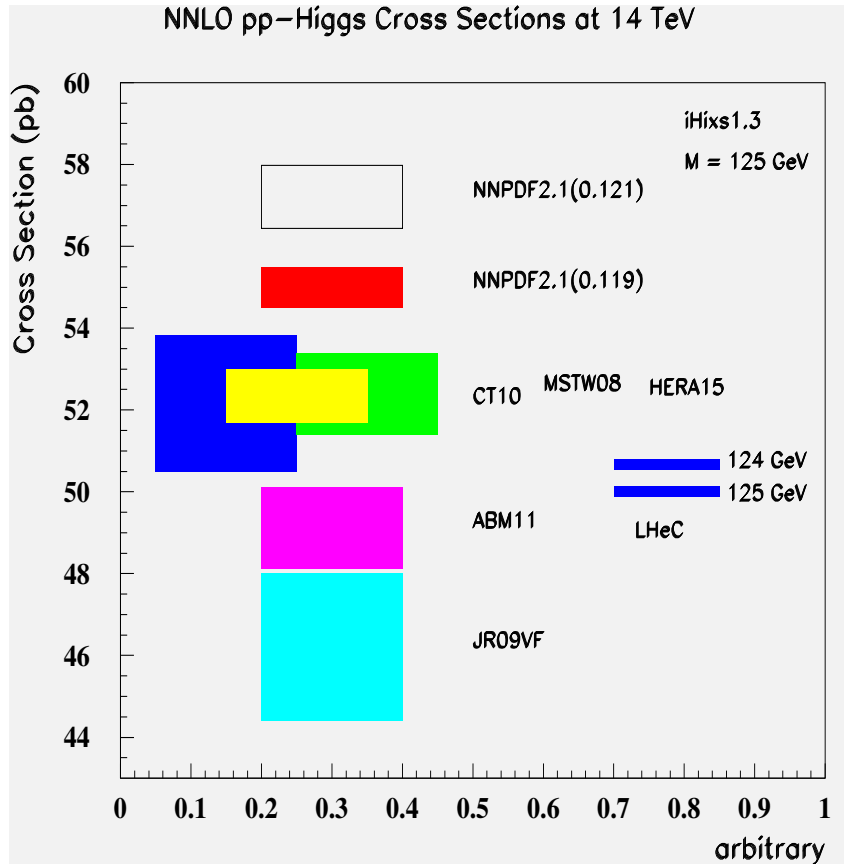


QUARKS

Exotic+ Extra boson searches at high mass



# High Precision for the LHC



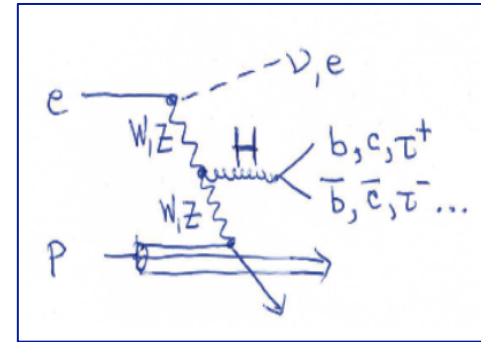
Predict the Higgs cross section in pp to 0.2% precision which matches the  $M_H$  measurement and removes the PDF error

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

Predict  $M_W$  in pp to 2.8 MeV →  
Remove PDF uncertainty on  $M_W$  LHC

# LHeC Higgs Physics

## High precision coupling measurements



## Higgs as portal to new physics (in decay and production of non SM Higgses)

CC cross section: 200 fb. That is the 'same' value as for  $Z^* \rightarrow HZ$  in  $e^+e^-$   
NC cross section: 25 fb.  $ZZ \rightarrow H$  ( $\rightarrow WW$ ) and  $WW \rightarrow H$  ( $\rightarrow ZZ$ ) uniquely distinguishable.  
VBF cross sections in pp at LHC are  $O(100)$  fb also.

Final state in ep clean. Pileup 0.1 at LHeC. Theory clear. Luminosity to 0.5-1%.  
Detector: full acceptance to  $\eta = 4.7$  Requirement for high resolution hadron calorimeter

First studies: complete detector, S and B simulation and BDT for  $H \rightarrow bb$  and  $cc$

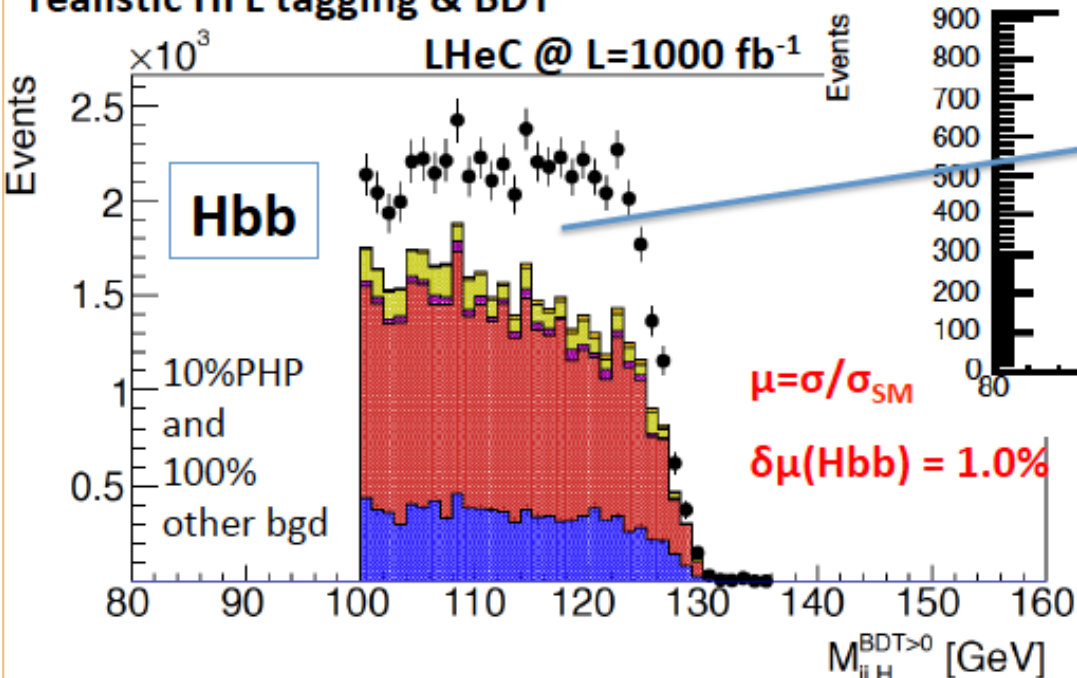
New: MADGRAPH based extension to other channels using  $bb$  and  $cc$  experience

New also: various, often Chinese publications on exotic Higgs physics in ep, cf below  
and talks by Uta Klein and Kechen Wang in January at FCC Physics at CERN

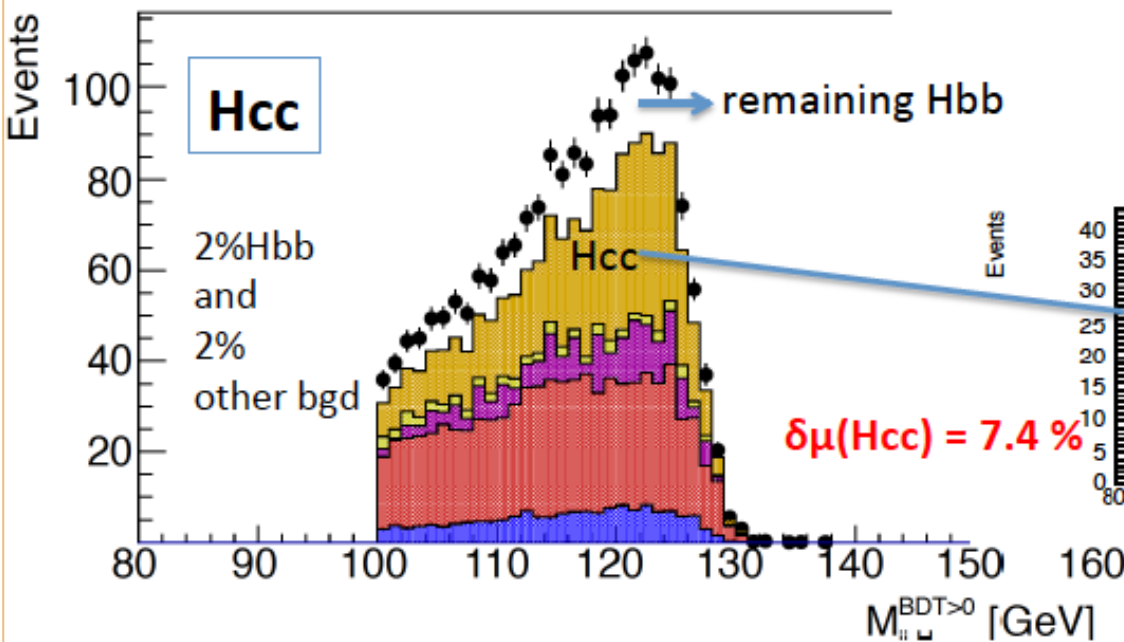
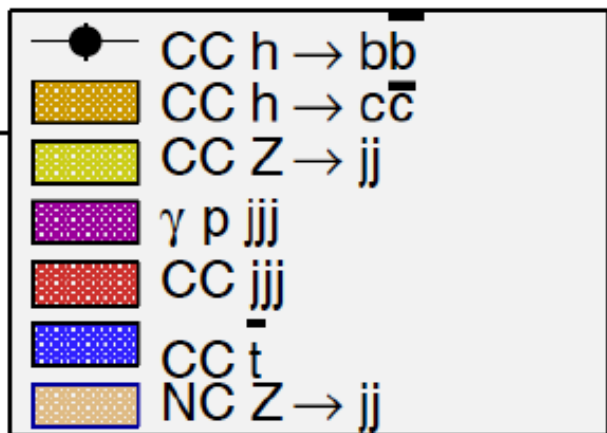
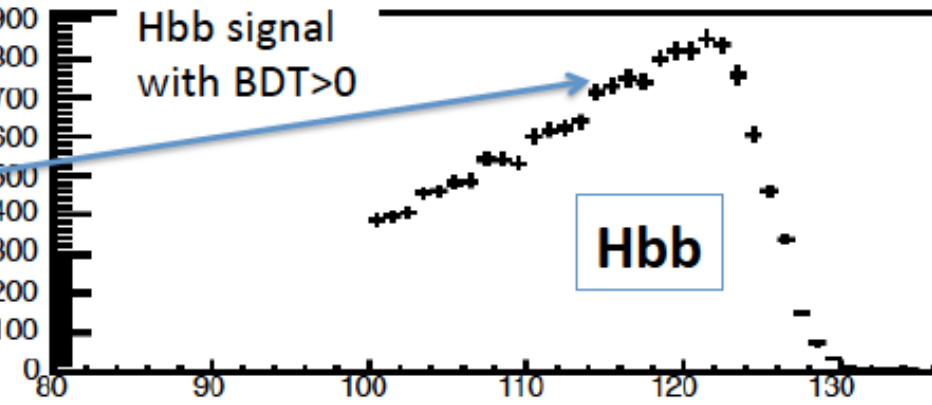
H-HH: very hard at LHeC, possible to  $\sim 30\%$  at FCC-eh: see arXiv:1509.04016 M Kumar et al

realistic HFL tagging & BDT

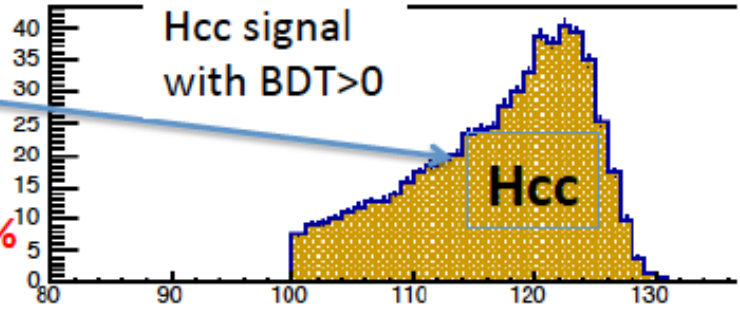
LHeC @  $L=1000 \text{ fb}^{-1}$



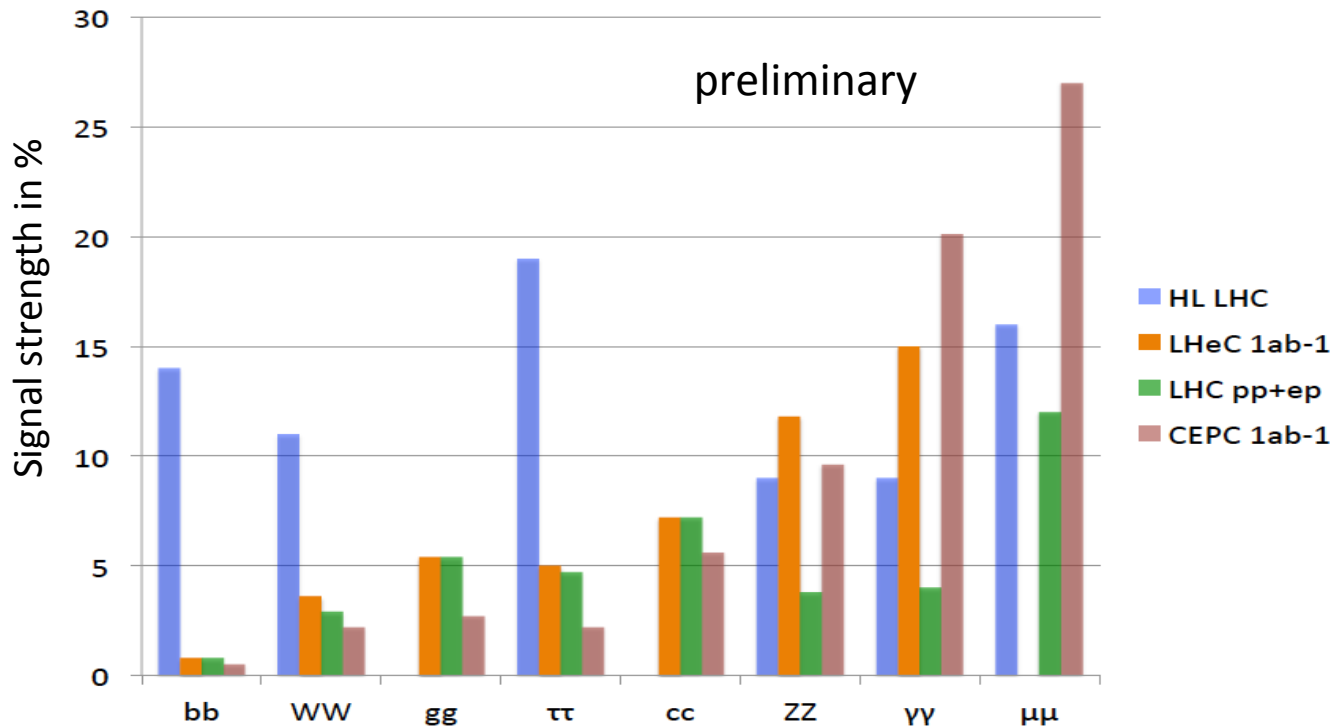
Hbb signal  
with BDT>0



Hcc signal  
with BDT>0



# Comparison LH(e)C and CEPC



**LHC:** ATLAS 2014  
(will be better)

**LHeC:** MK+UK  
FCC WS1/18

**LHC:** pp (no thy) + ep

**CEPC:** M Ruan, 14.1.17  
scaled to  $1ab^{-1}$

The **ep** and the **e<sup>+</sup>e<sup>-</sup>** prospects of measuring Higgs decays are (about) the same for same L. Note that  $1ab^{-1}$  is 10 years of operation at  $10^{34}$ , at high reliability.

J Gao: CEPC wants  $3 \cdot 10^{34}$  and hopes for  $5 ab^{-1}$ . Theorists write about a 350 GeV operation. LHeC NC:  $ZZ \rightarrow H \rightarrow bb$  at high precision which should fix the H-ZZ coupling to 2%..  $\Gamma$  ??

**Sum of all major decay channels: LHC 0.89+-0.12, LHeC 0.99 +- 0.02, LHcep+pp: 1.00+-0.01**

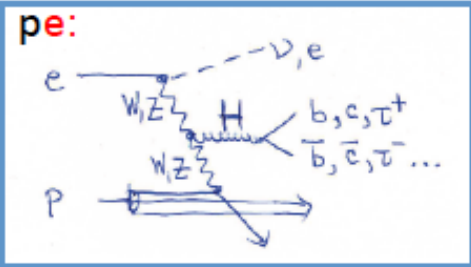
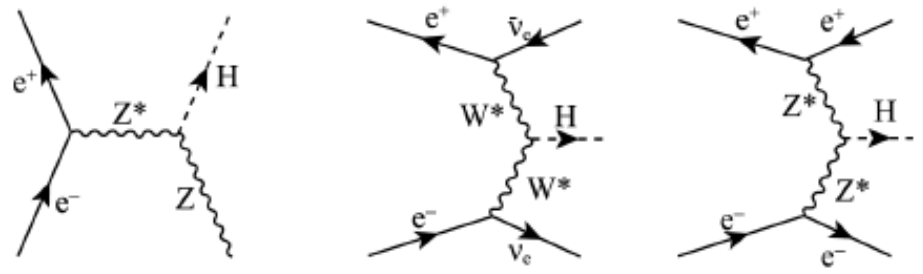
In ep couplings are overconstrained. Fit to do. EFT analyses may then include ep.

**The addition of the LHeC to the HL LHC transforms that into a high precision Higgs facility**



# Higgs in ee vs pe

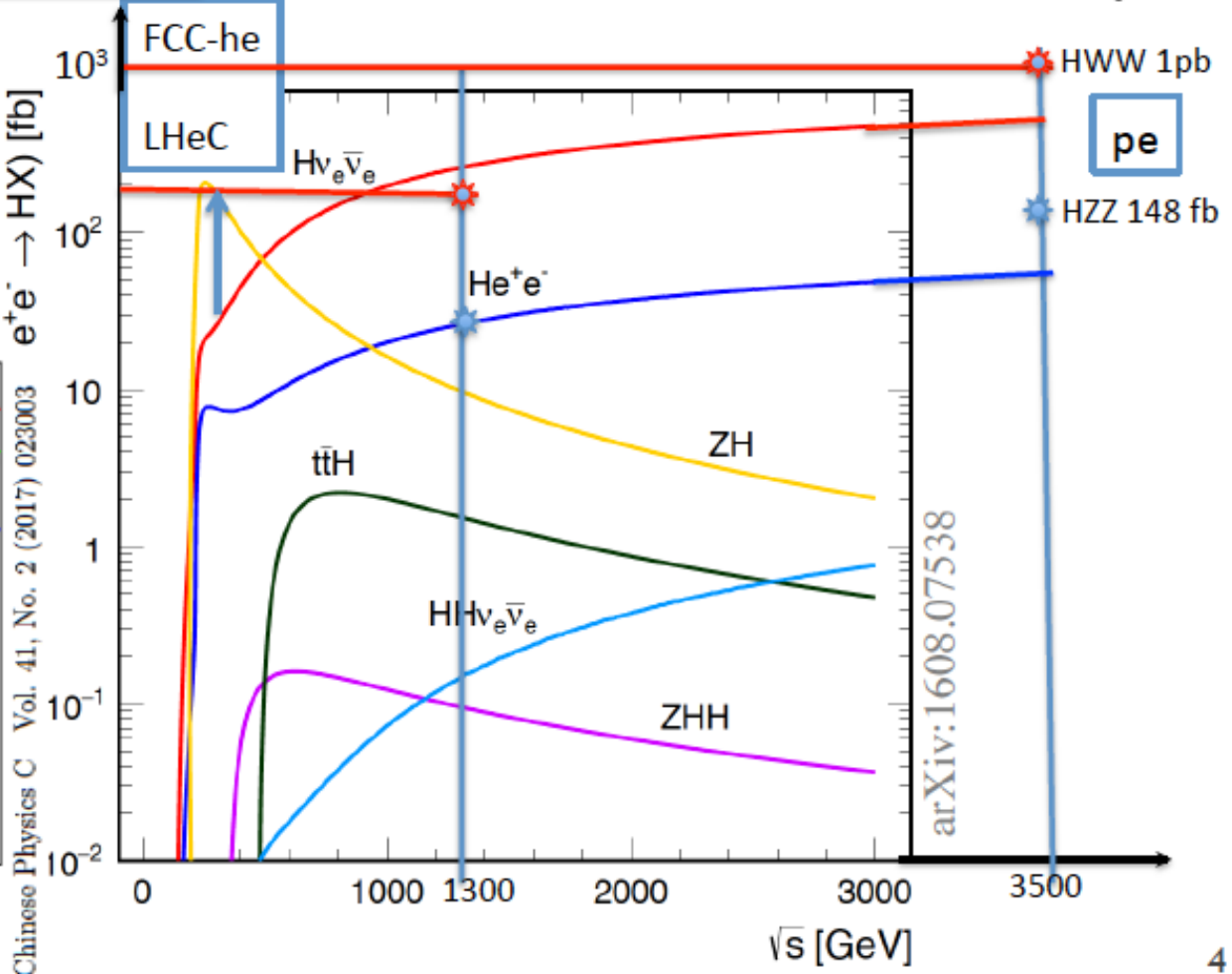
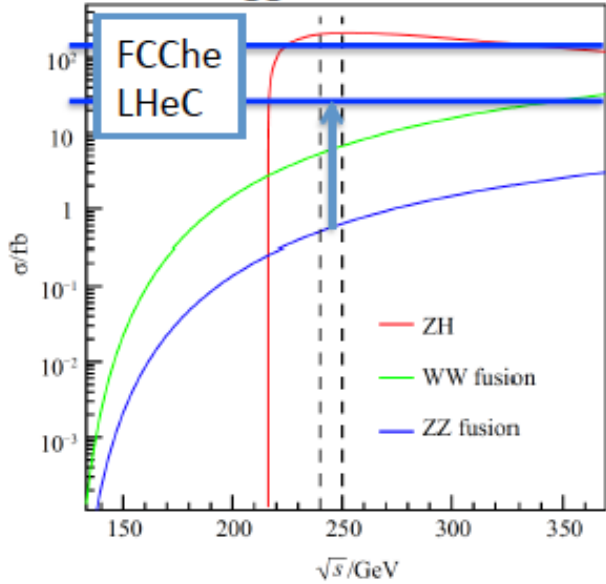
**ee:** Dominant Higgs productions



**pe:WW Fusion**

**pe: ZZ Fusion**

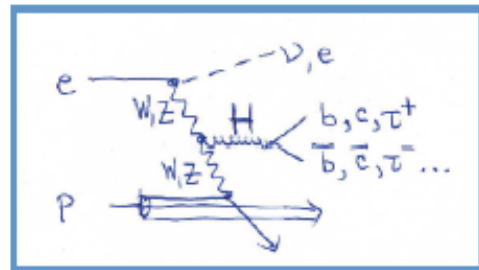
vs CEPC Higgs cross sections



# CC DIS WWH $\rightarrow$ H

FCC-he L=2 ab<sup>-1</sup>

	bb	WW	gg	$\tau\tau$	cc	ZZ	$\gamma\gamma$
BR	0.577	0.215	0.086	0.0632	0.0291	0.0264	0.00228
$\delta BR_{\text{theory}}$	3.2%	4.2%	10.1%	5.7%	12.2%	4.2%	5.0%
N	1.15 10 <sup>6</sup>	4.3 10 <sup>5</sup>	1.72 10 <sup>5</sup>	1.26 10 <sup>5</sup>	5.8 10 <sup>4</sup>	5.2 10 <sup>4</sup>	4600
f	2.86 <sub>BDT</sub>	16	7.4	5.9	5.6 <sub>BDT</sub>	8.9	3.23
$\delta\mu/\mu$ [%]	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



Further coupling constraints to be explored:

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

$$\sigma(WW \rightarrow H \rightarrow bb) \propto \kappa^2(HWW) \cdot \kappa^2(Hbb)$$

$$\sigma(WW \rightarrow H \rightarrow \tau\tau) \propto \kappa^2(HWW) \cdot \kappa^2(H\tau\tau)$$

$$\sigma(WW \rightarrow H \rightarrow gg) \propto \kappa^2(HWW) \cdot \kappa^2(Hgg)$$

$$\sigma(WW \rightarrow H \rightarrow cc) \propto \kappa^2(HWW) \cdot \kappa^2(Hcc)$$

$$\sigma(WW \rightarrow H \rightarrow ZZ) \propto \kappa^2(HWW) \cdot \kappa^2(HZZ)$$

$$\text{Note: } \sigma(ZZ \rightarrow H \rightarrow WW) \propto \kappa^2(HZZ) \cdot \kappa^2(HWW)$$

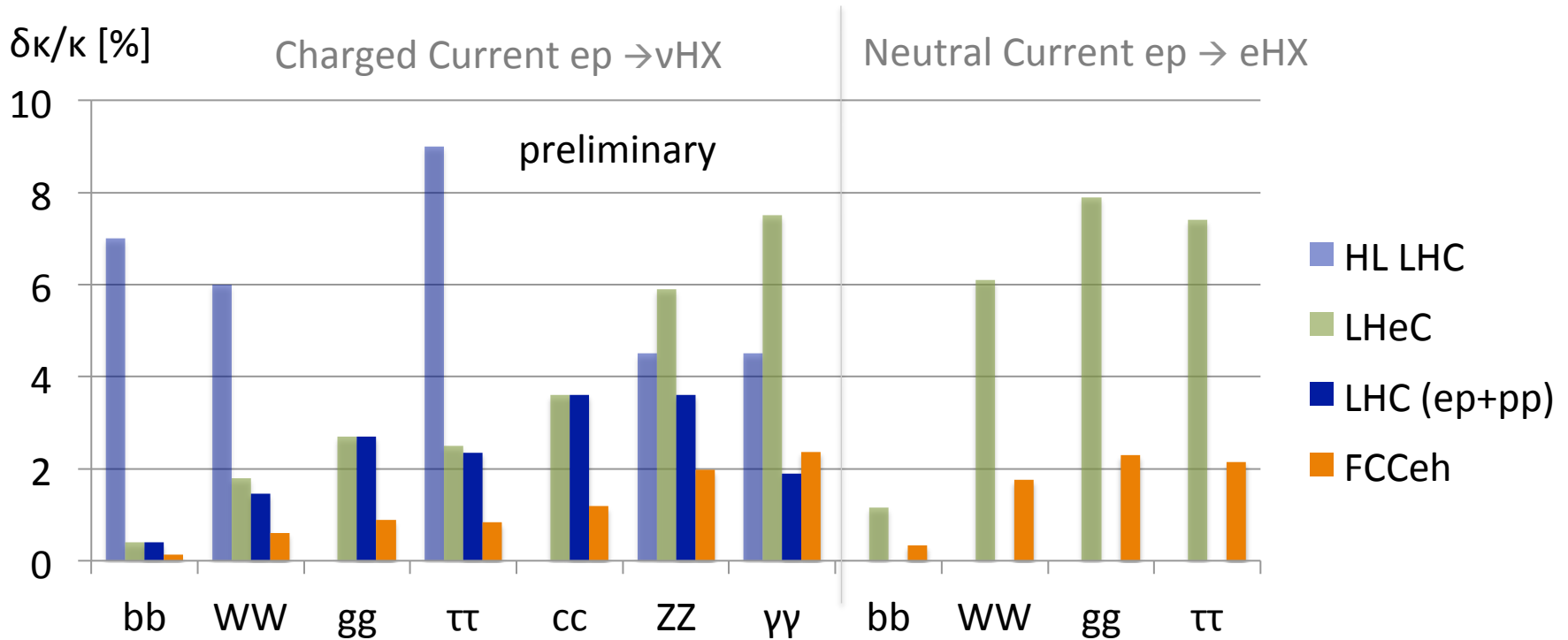
$\rightarrow$  Sum of first 6 branching fractions that could be measured

LHeC : 0.9964 +- 0.02

**FCChe: 0.9964 +- 0.01**

pp: < 0.99  $\rightarrow$  cc? gg?

# FCCeh: Higgs SM Coupling Prospects



**HL LHC:** ATLAS-PUB-2014-016 14 TeV  $3ab^{-1}$  – LHC has no  $gg$ , no  $cc$ , and poor  $bb$ , but rare channels as  $\gamma\gamma$

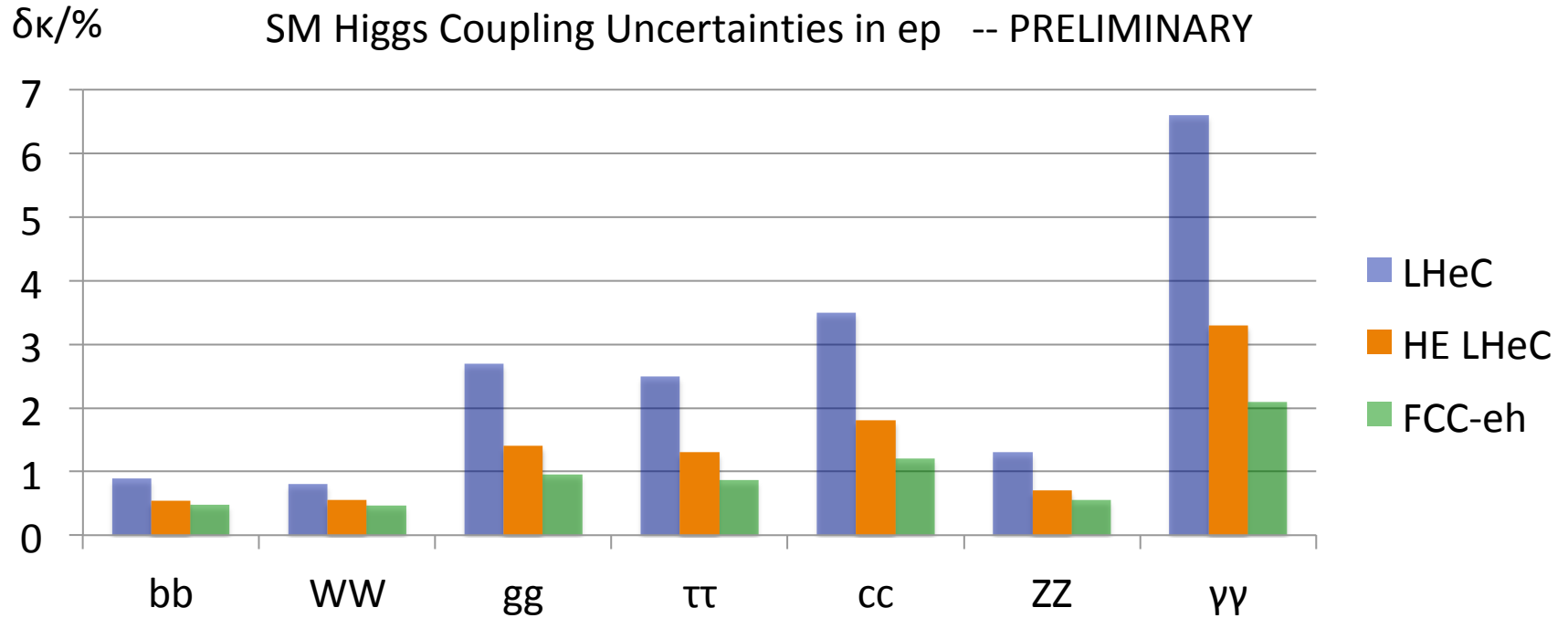
**LHeC:**  $1ab^{-1}$ , 60 GeV x 7 TeV - Work in progress. ep also provides precise:  $xg$ ,  $\alpha_s$  and PDFs to  $N^3LO$ .

**LHC (ep+pp):** HL LHC with reduced theory uncertainty combined with LHeC

**FCCeh:**  $2ab^{-1}$ , 60 GeV x 50 TeV - Work in progress. ep also provides precise:  $xg$ ,  $\alpha_s$  and PDFs to  $N^3LO$ .

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

# Couplings from Joint Fit to NC and CC Input



# BSM Higgs

## ➤ Higgs invisible decays

❖  $h \rightarrow \text{invisible}$ , see [Uta Klein's talk "Higgs SM Couplings at FCC-ep" ]

## ➤ Higgs exotic decays

❖  $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (3j)(3j)$  in RPV SUSY

❖  $h \rightarrow 2\phi \rightarrow (b\bar{b})(b\bar{b})$  [ S. Liu, Y. Tang, C. Zhang, S. Zhu, 1608.08458 ]

## ➤ Charged Higgs

❖  $H^{\pm\pm}$ , in Vector Boson Scattering

[H. Sun, X. Luo, W. Wei and T. Liu, Phys. Rev. D 96, 095003 (2017) ]

❖  $H^\pm$ , in Vector Boson Scattering

[Georges Azuelos, Hao Sun, and Kechen Wang, 1712.07505 ]

❖  $H^+$ , in 2HDM type III,  $p e^- \rightarrow vjH^+ \rightarrow vj (c\bar{b})$ ,

[J. Hernández-Sánchez, etc. 1612.06316]

## Triple Gauge Couplings (WWV, $V = \gamma, Z$ )

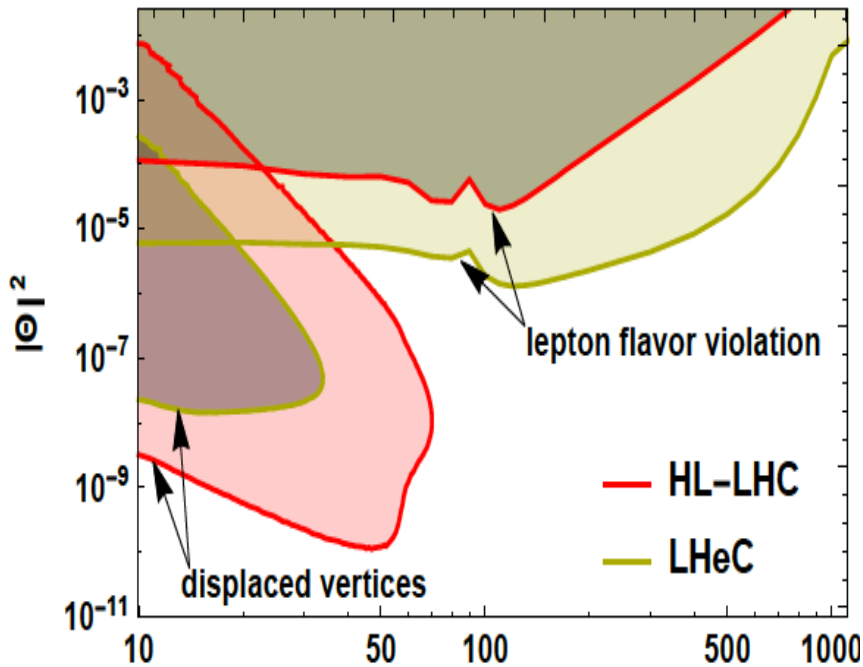
[R. Li, X. Shen, K. Wang, T. Xu, L. Zhang and G. Zhu, 1711.05607 ]

**Impressive flow of new physics in ep studies is being digested for 2018**

# Lots of important new papers on BSM in ep

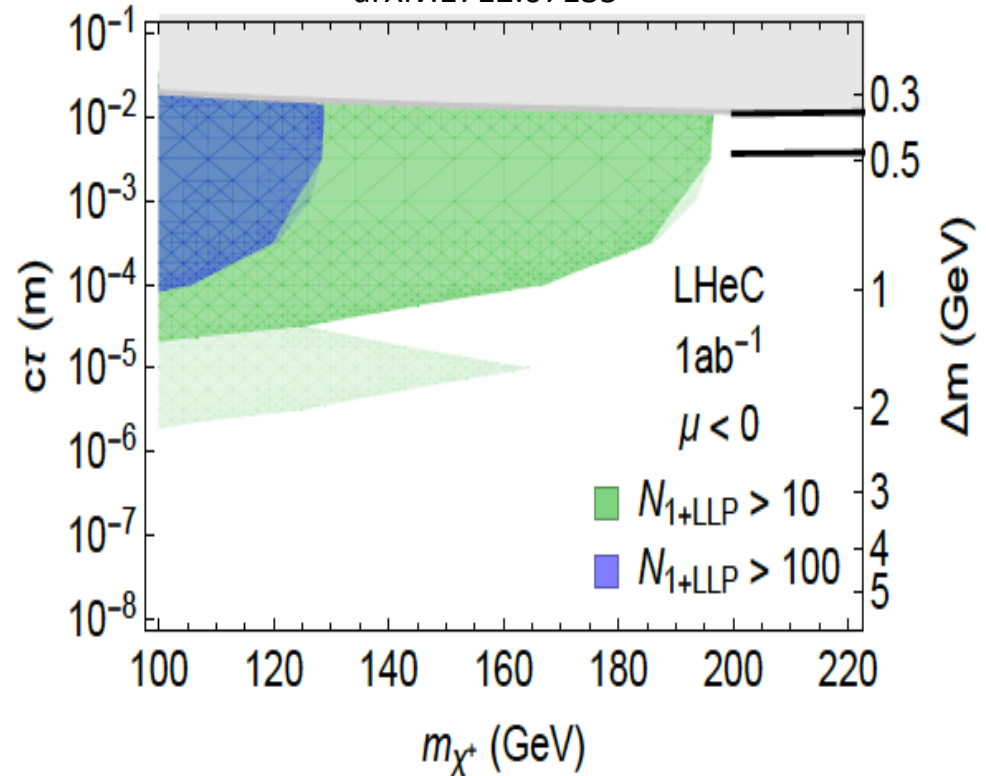
Sterile (heavy) Neutrinos in ep  $\rightarrow$  NX

arXiv:1612.02728

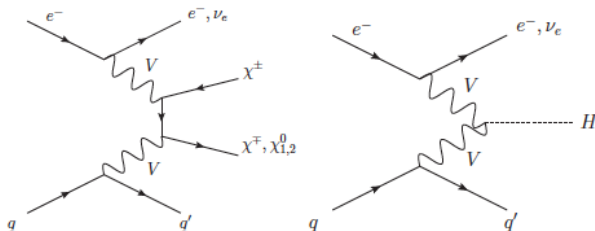


Search for Higgsino at LHeC

arXiv:1712.07135



Joint study on pp/pe/ee M [GeV]



This adds significant motivation for the construction of future  $e^-p$  colliders. Together with the invaluable proton PDF data, as well as precision measurements of EW parameters, top quark couplings and Higgs couplings, our results make clear that adding a DIS program to a  $pp$  collider is necessary to fully exploit its discovery potential for new physics.

# QCD - Developments and Discoveries

AdS/CFT

Instantons

Odderons

Non pQCD

QGP

$N^k$ LO

Resummation

Saturation and BFKL

Non-conventional PDFs ...

Breaking of Factorisation

Free Quarks

Unconfined Color

New kind of coloured matter

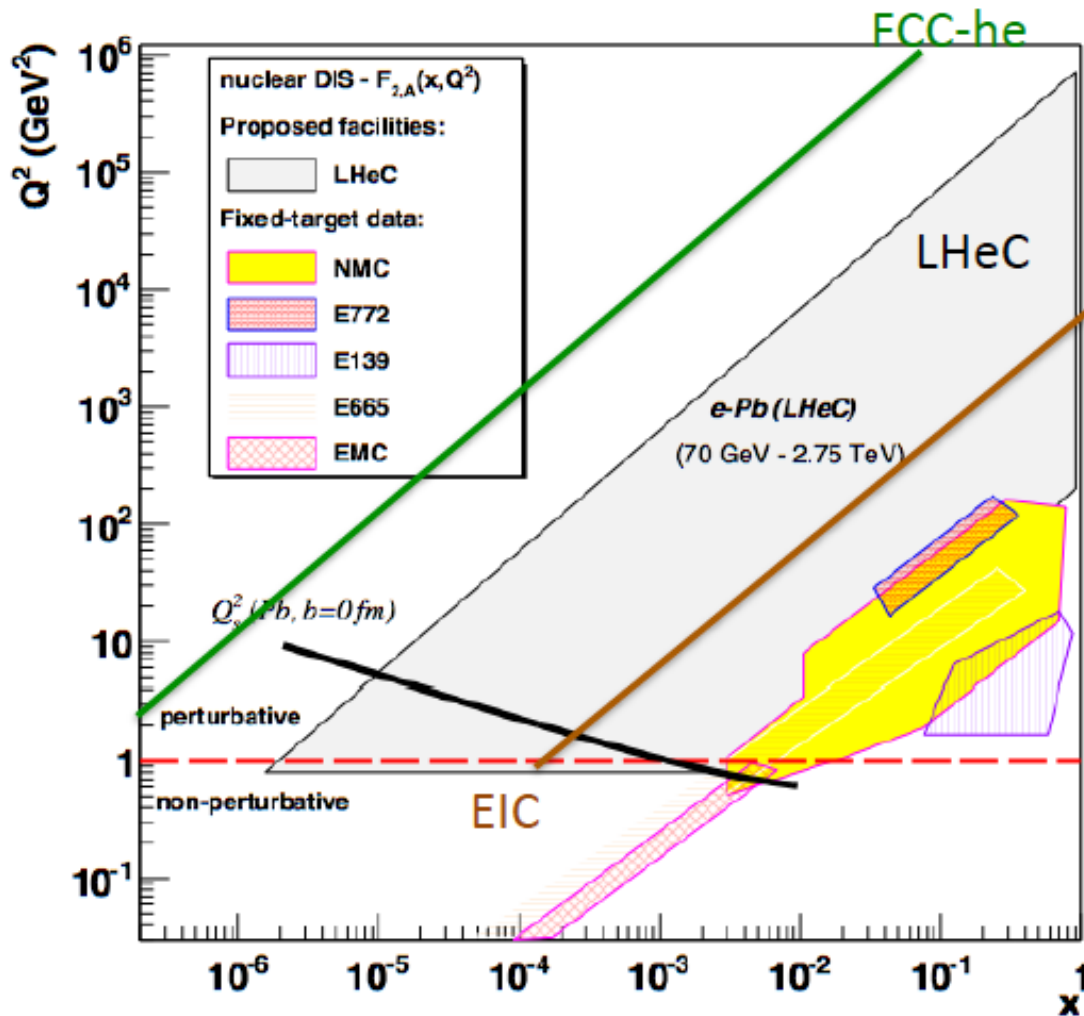
Quark substructure

New symmetry embedding QCD

QCD may break .. (Quigg DIS13)

QCD is the richest part of the Standard Model Gauge Field Theory and will (have to) be developed much further, on its own and as background.

# Electron-Ion Nuclear and Particle Physics



**Extension of kinematic range in IA by 4 orders of magnitude:**

will change QCD view on nuclear structure and parton dynamics

**May lead to genuine surprises...**

- No saturation of  $xg(x, Q^2)$  ?
- Small fraction of diffraction ?
- Broken isospin invariance ?
- Flavour dependent shadowing ?

**Relates to LHC Heavy Ion Physics**

- Quark Gluon Plasma
- Collectivity of small nuclei (p)?
- ..

**Saturation:** needs large  $xg$  at small  $x$  ep and eA



# Powerful Energy Recovery Linac for Experiments



$$I_e = eN_e f = \frac{P}{E_e}$$

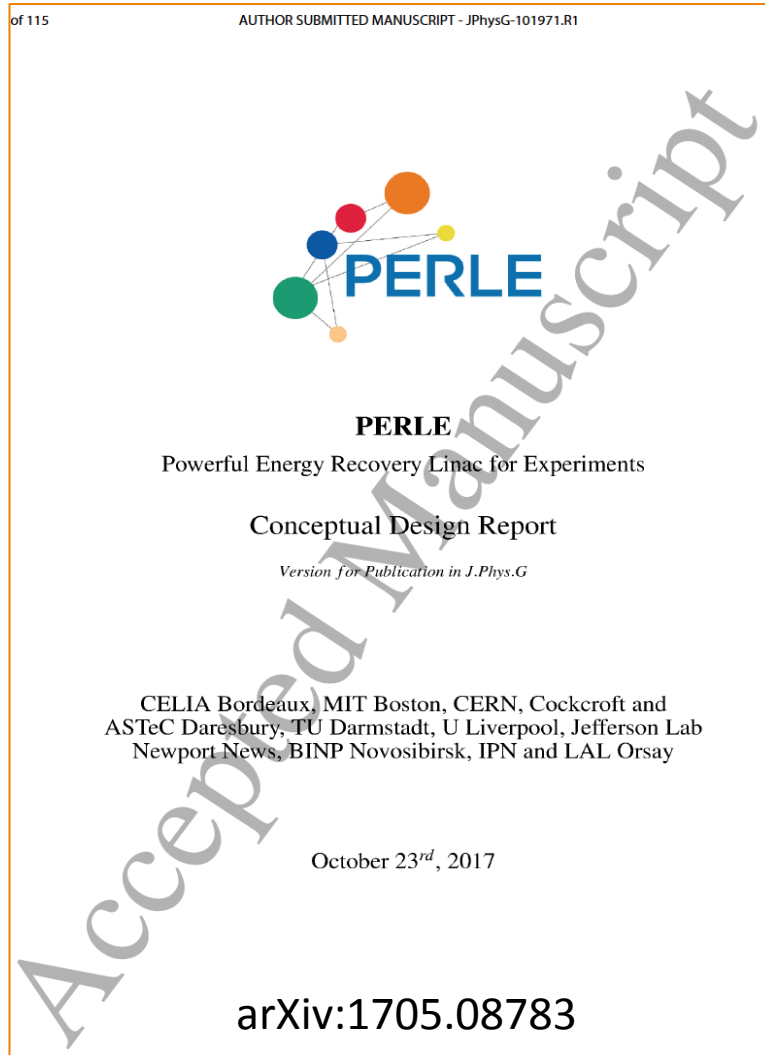
15mA and 60 GeV correspond to 900 MW power  
This can only be realised using energy recovery.

**New: high current, high energy, multi-pass: study!**

BINP, CERN, Daresbury, Jefferson Laboratory, U Liverpool, Orsay (LAL+INP), + Collaboration

# Powerful ERL for Experiments

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



J Phys G in print



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

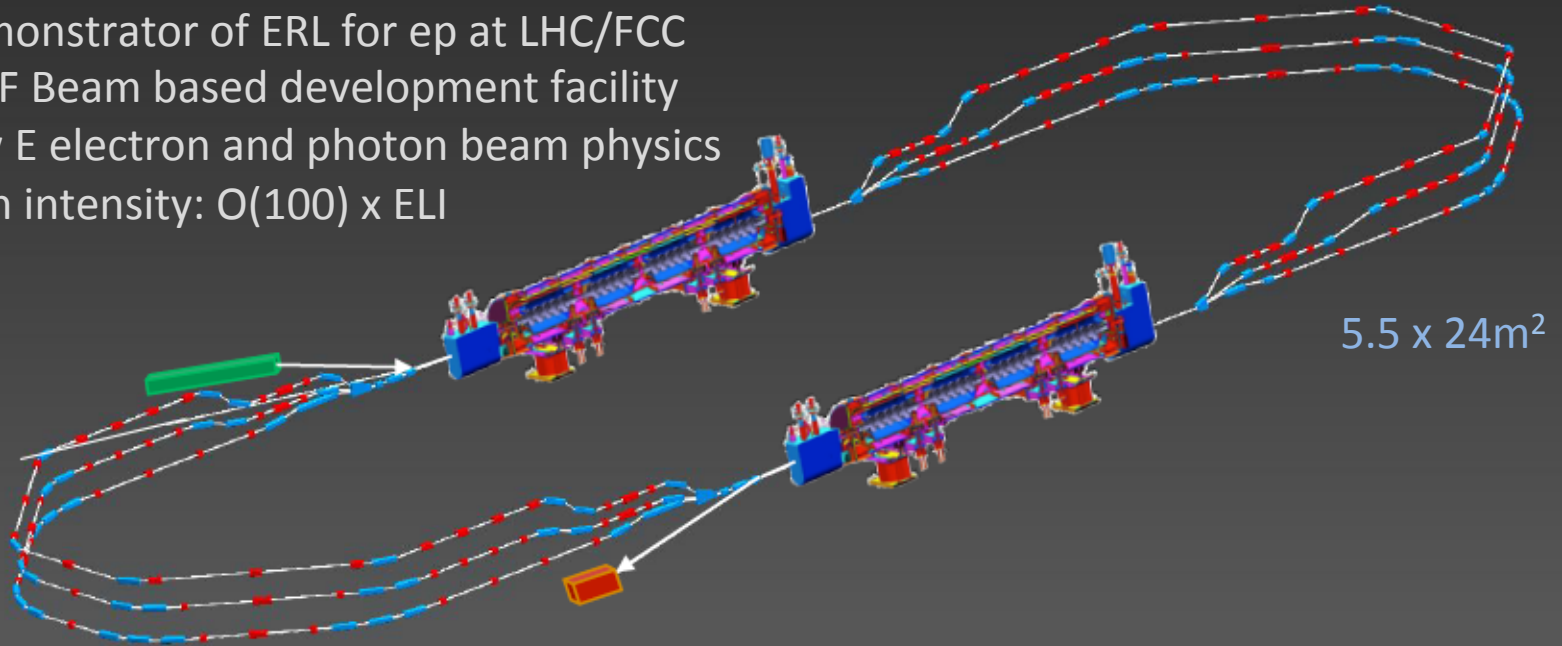
ERL facility: high current and energy  
low energy nuclear, particle and astro physics

# PERLE at Orsay

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

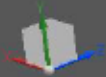
3 turns, 2 Linacs, 500 MeV, 20mA, 802 MHz, Energy Recovery Linac facility

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

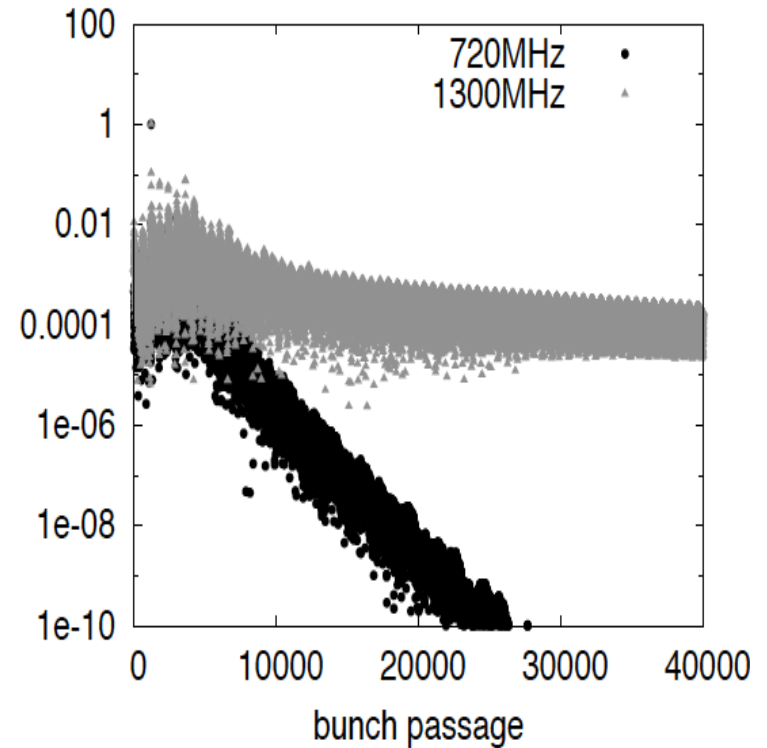
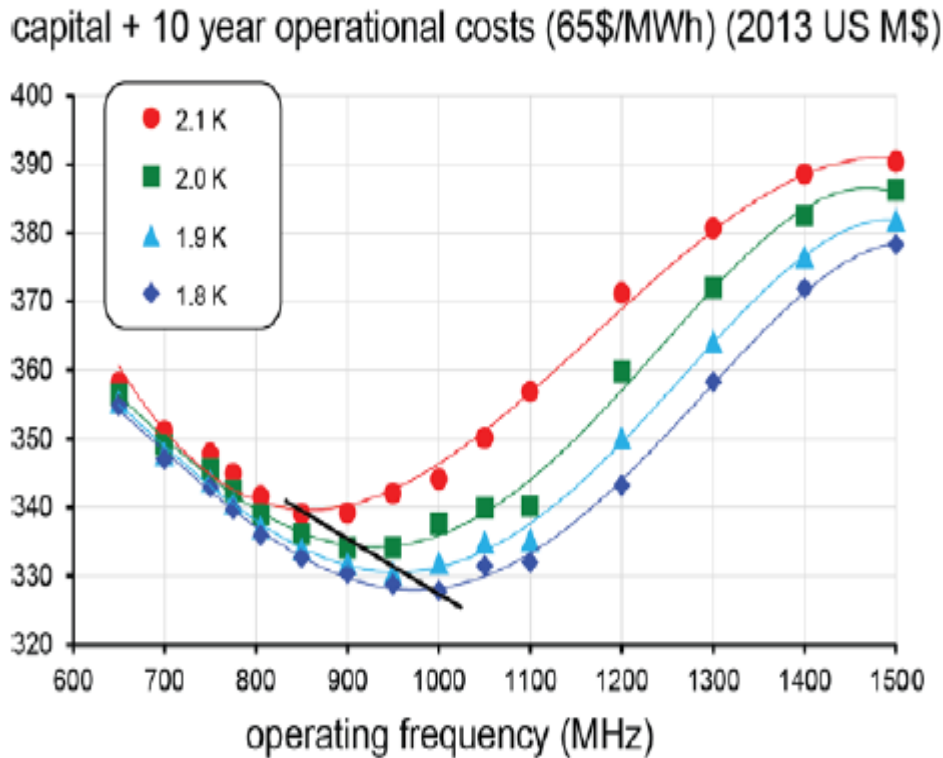


CDR to appear in J Phys G [arXiv:1705.08783]

**Strong low energy physics program:**  
p radius,  $\sin^2\theta$ , dark photons, photon-nuclear physics, ..



# Frequency Choice



Cost, dynamic heat losses, resistance,  $Q_0$ ... point to  $f < 1$  GHz (F Marhauser, Orsay 2/17)

Beam beam interactions unstable for  $f > 1$  GHz (D Schulte, D Pellegrini March 2013)

Compatibility with LHC: **Decision for 802 MHz** ( E Jensen CI Workshop 1/2015, FM input)

# 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

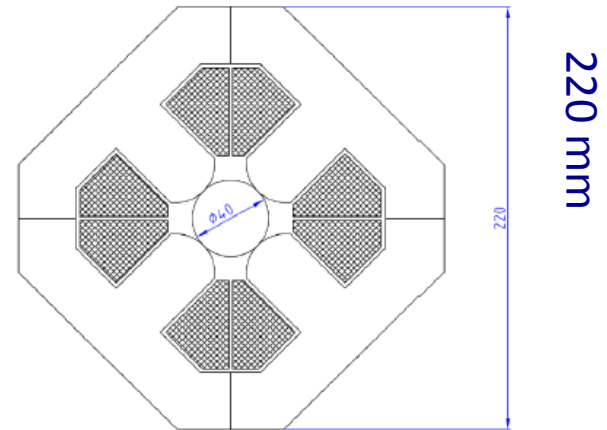
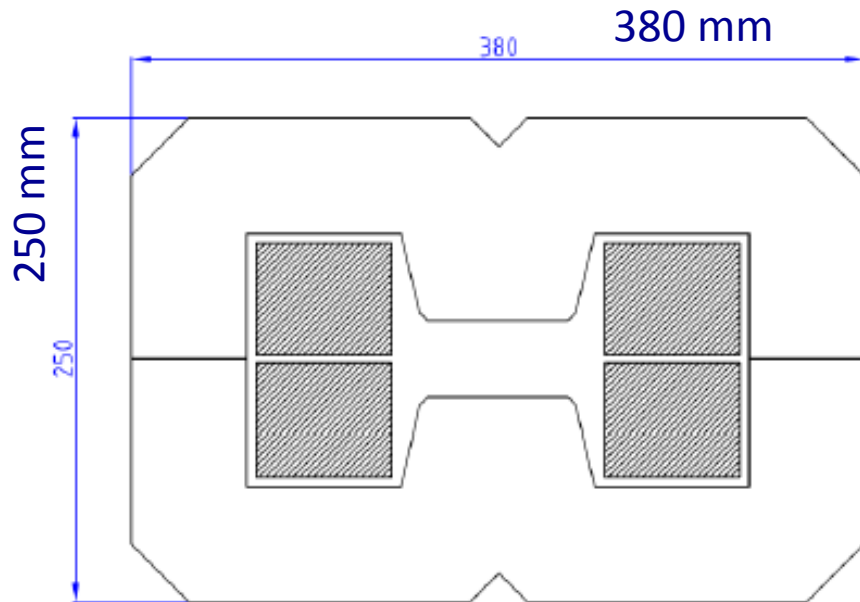
**70 dipoles 0.45-1.29 T**

+/- 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

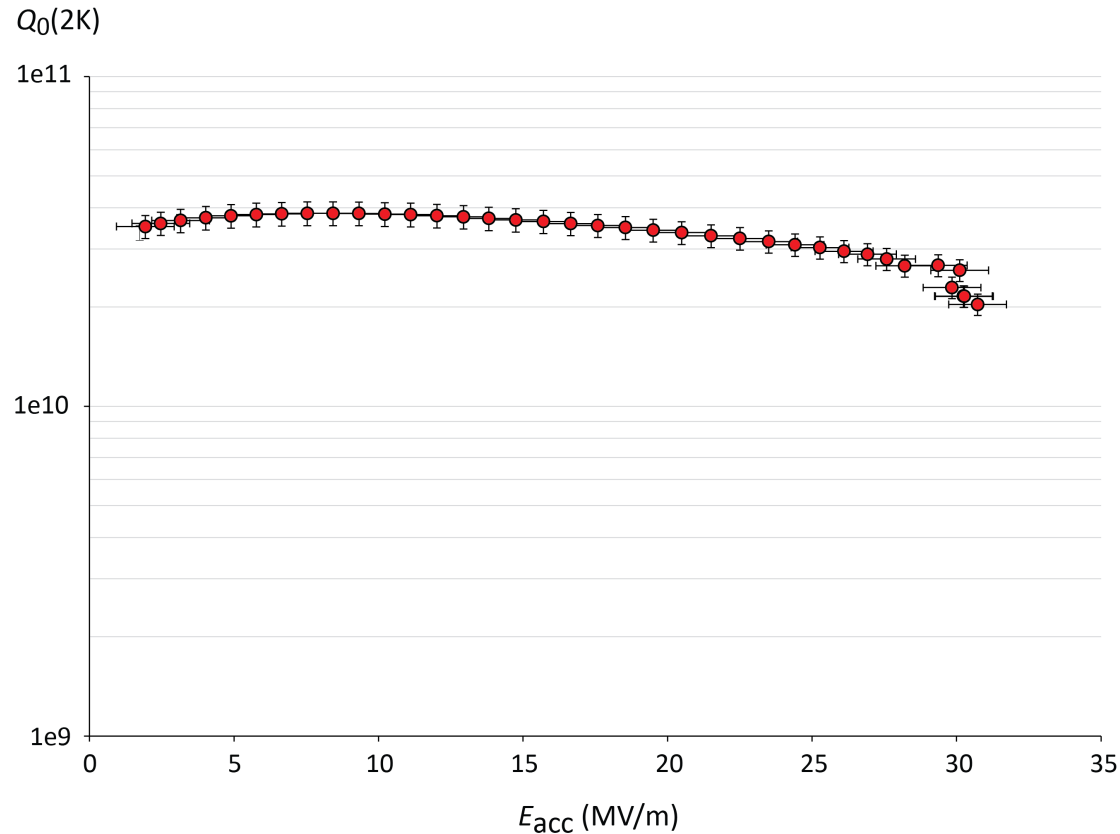
# 1<sup>st</sup> 802 MHz Cavity



Tests ongoing. CERN-Jlab design, produced at Jefferson Laboratory **November 2017**

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 17



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.

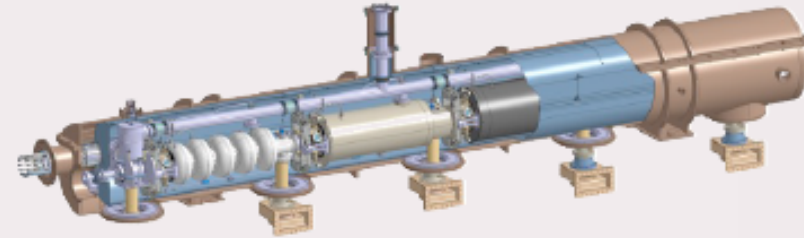


# Next Step: Cryomodule

**SPL**  
« Short  
cryomodule »

5-cells Elliptical  
700 MHz,  $\beta = 1.0$   
**X 4**

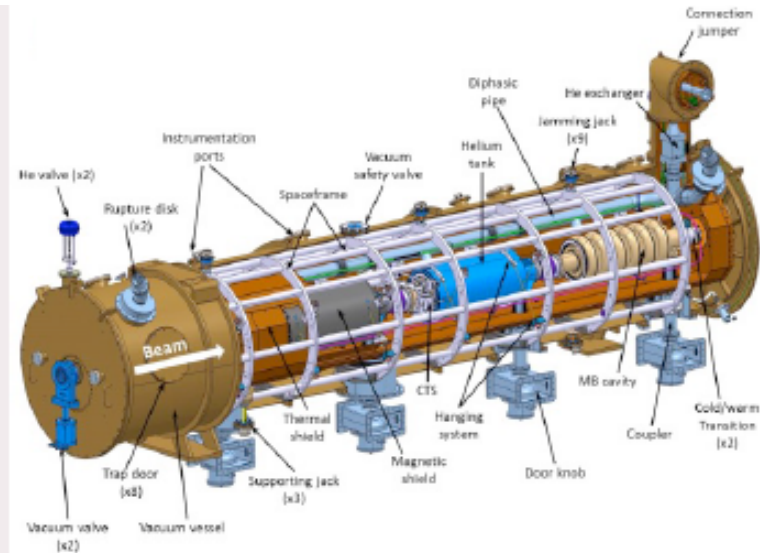
Full length top lid closure  
Cold mass supported by  
power couplers



**ESS**  
Elliptical  
cryomodule(s)

5&6-cells  
Elliptical  
700 MHz  
 $\beta = 0.67$  &  $0.86$   
**X 4**

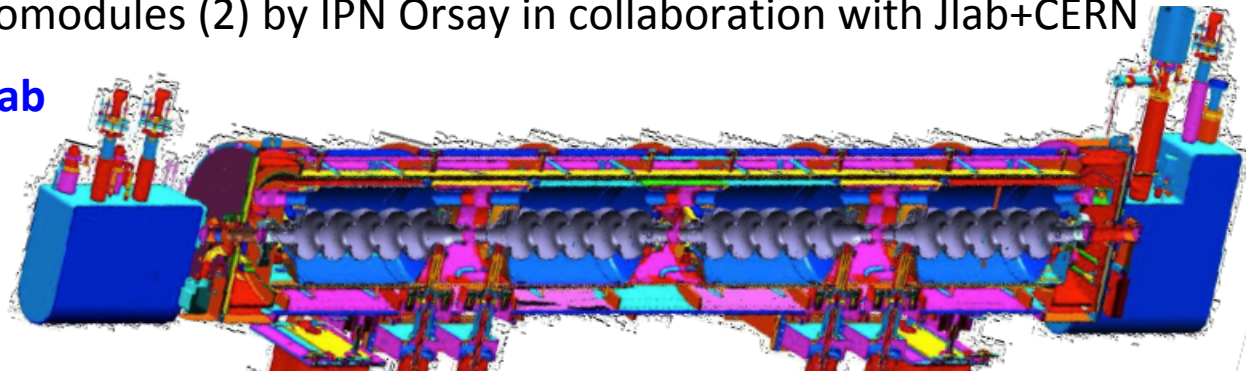
Side loading  
Space frame

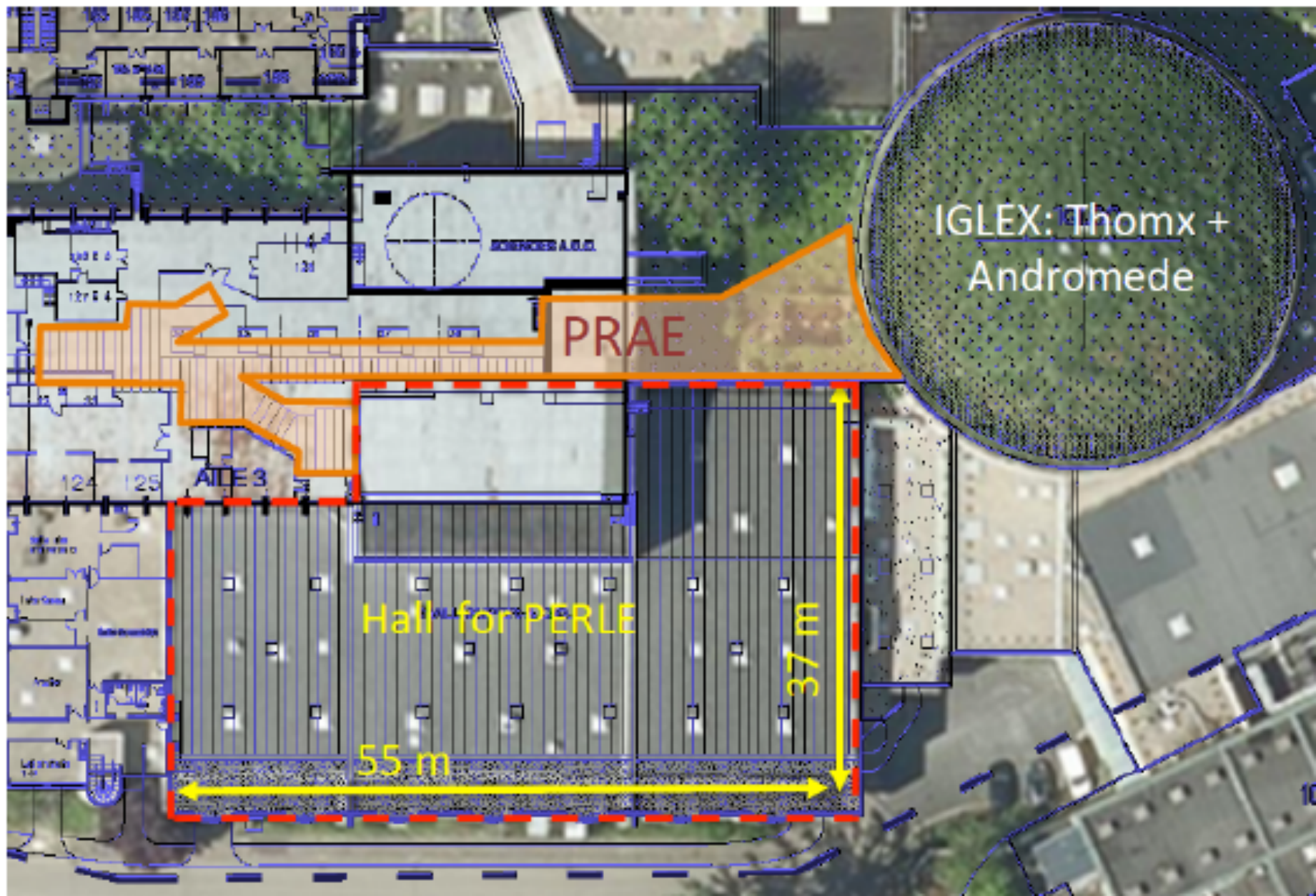


Plan for production of PERLE cryomodules (2) by IPN Orsay in collaboration with Jlab+CERN

SNS 805 MHz cryomodule

Jlab

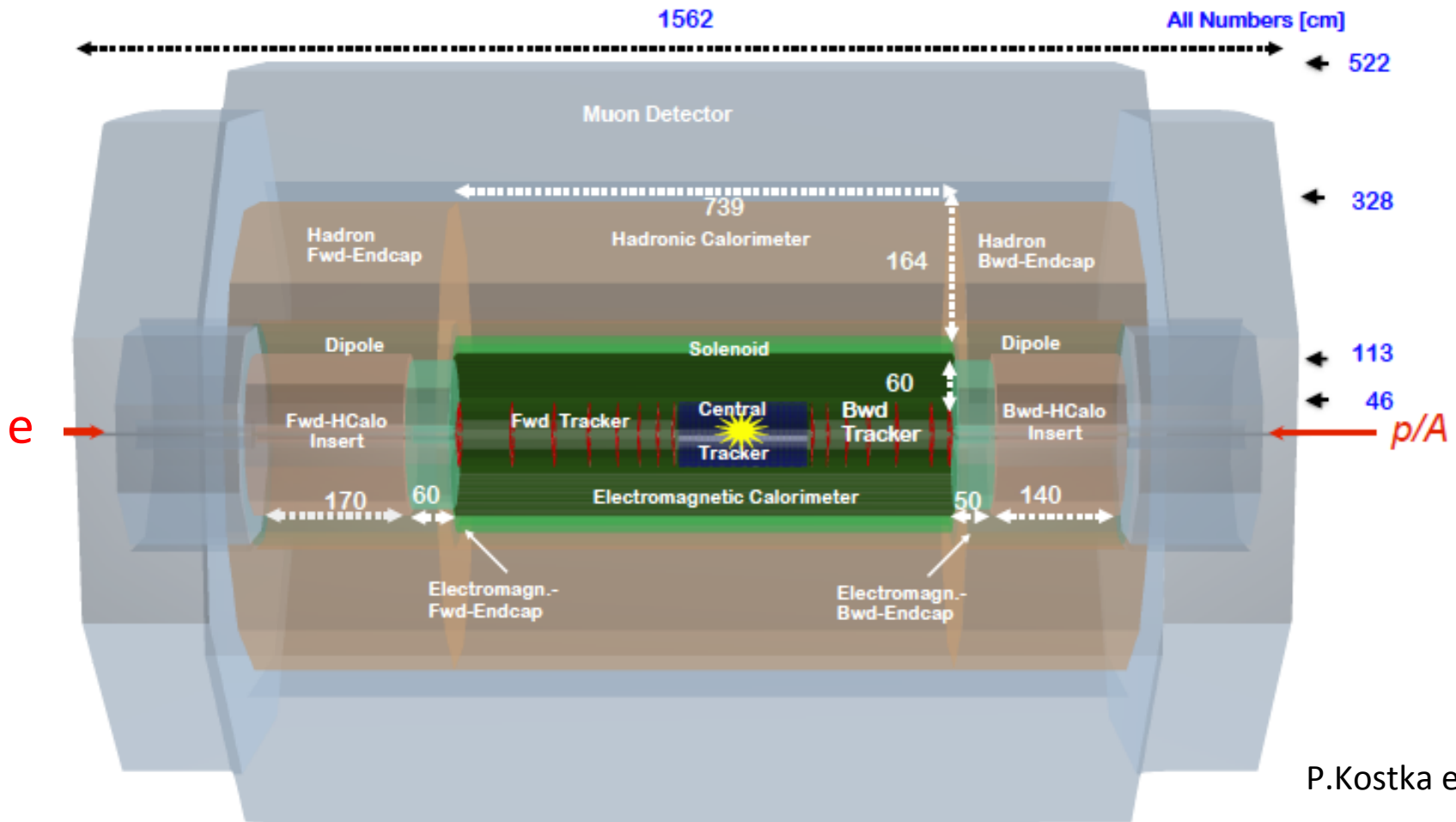






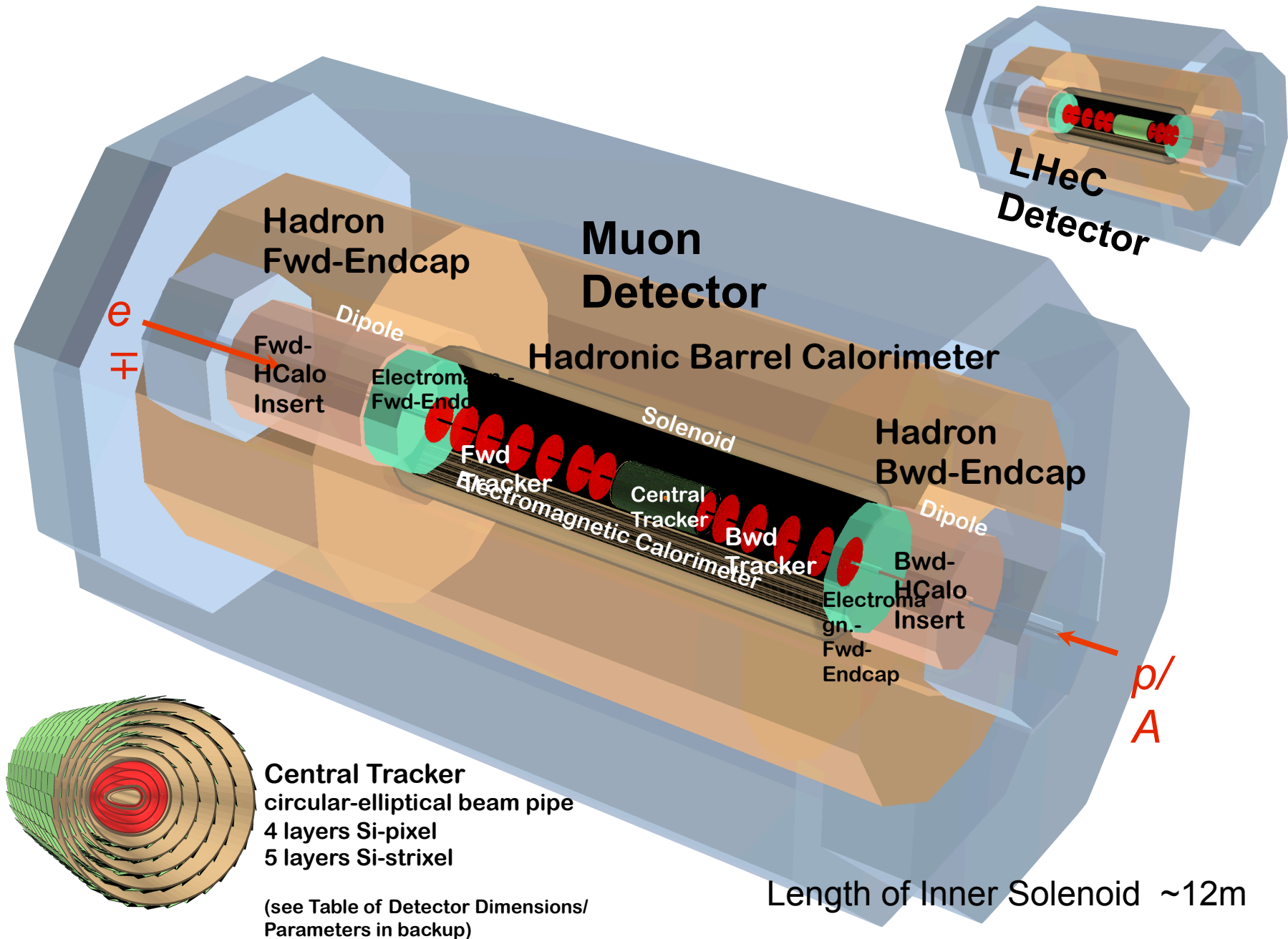
## VI Towards $e$ for the LHC

# LHeC Detector for the HL/HE LHC

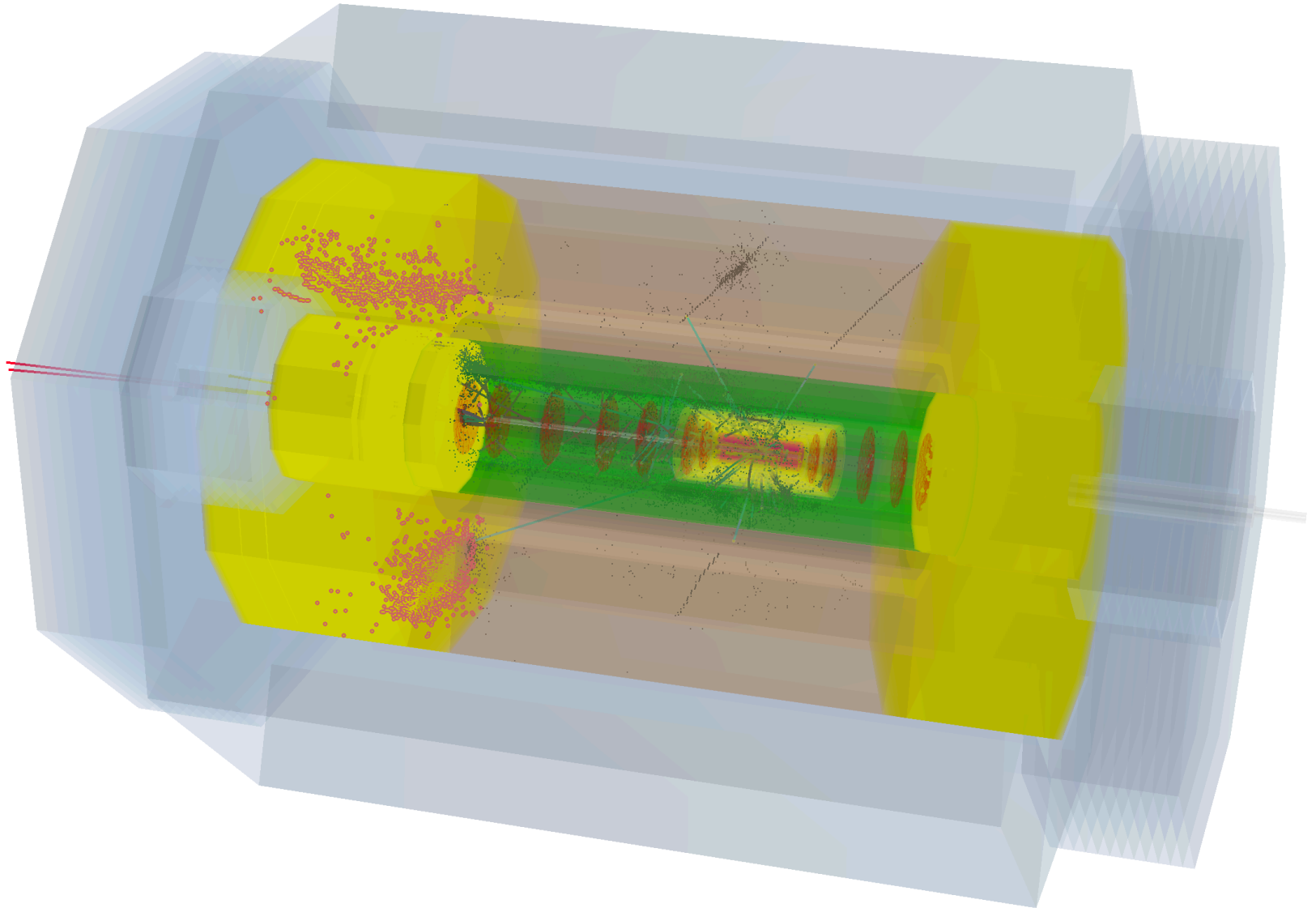


Length x Diameter: LHeC (13.3 x 9 m<sup>2</sup>) HE-LHC (15.6 x 10.4) FCCeh (19 x 12)  
 ATLAS (45 x 25) CMS (21 x 15): [LHeC < CMS, FCC-eh ~ CMS size]  
 If CERN decides that the HE LHC comes, the LHeC detector should anticipate that

# LHeC/FCC ep/eA detector - a test bed for new technology in the twenties



# $H \rightarrow b\bar{b}$ in LHeC Detector

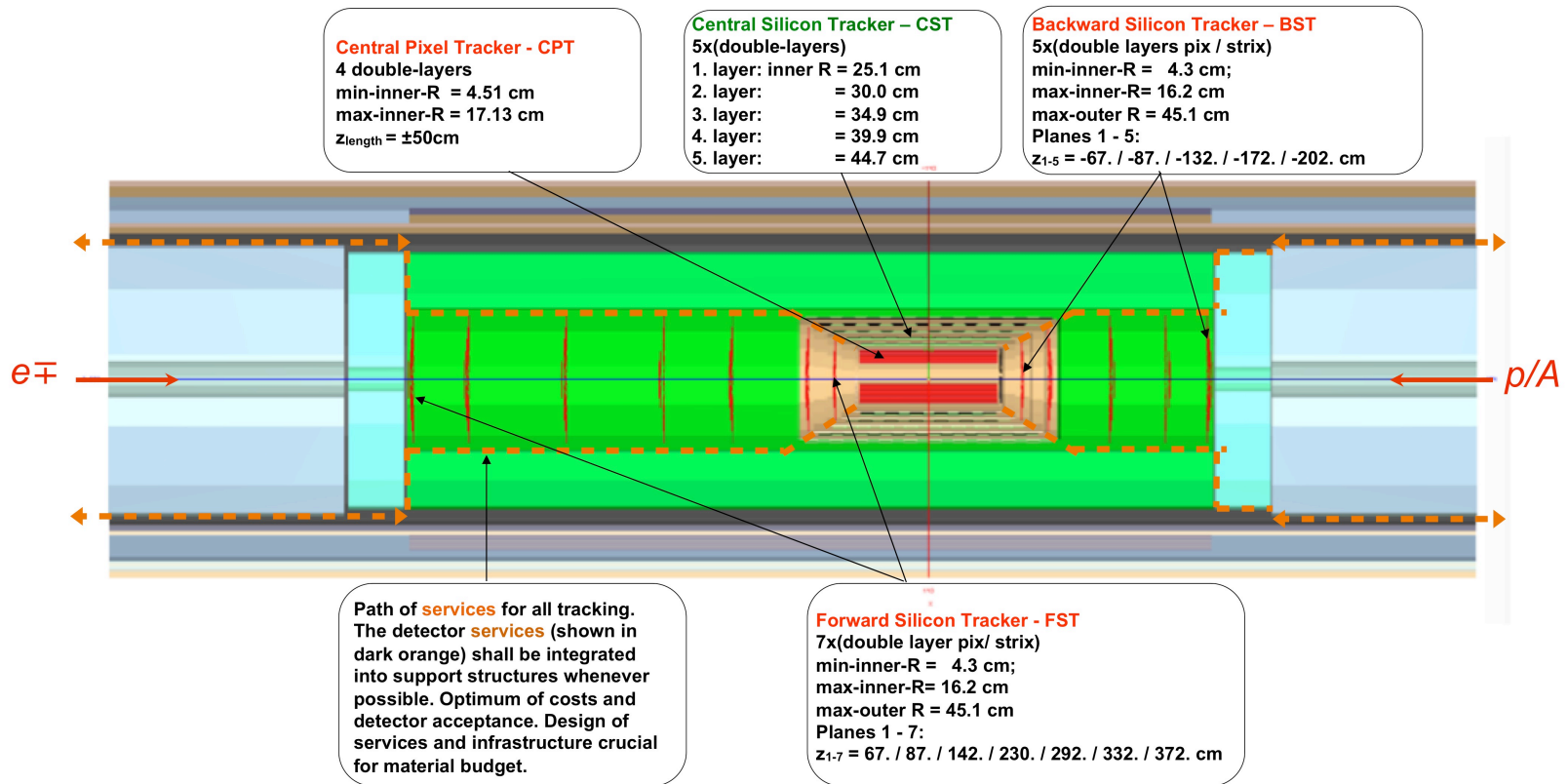


# Dimensions and Multitudes - LHeC

Tracker	FST <sub>pix</sub>	FST <sub>striz</sub>	CFT <sub>pix</sub>	CPT <sub>pix</sub>	CST <sub>striz</sub>	CBT <sub>pix</sub>	BST <sub>striz</sub>	BST <sub>pix</sub>
#Wheels	5		2	—	—	2	3	
#Rings/Wheel	2 <sub>inner</sub>	3 <sub>outer</sub>	3/4	—	—	3/4	3 <sub>outer</sub>	2 <sub>inner</sub>
#Layers	—	—	—	4	5	—	—	—
$\theta_{min/max}$ [°]	0.7	3.8	3.0	5.1	24/155	177.8	173.1	178.7
$\eta_{max/min}$	5.1	3.4	3.6	±3.1	±1.4	-3.6	-2.8	-4.5
Si <sub>pix/striz</sub> [m <sup>2</sup> ]	6.9	9.5	2.8	5.4	33.7	2.8	5.7	4.1
Sum-Si [m <sup>2</sup> ]	70.9 double layers taken into account							
Calo	FHC <sub>SiW</sub>	FEC <sub>SiW</sub>	EMC <sub>SciPb/LAr</sub>		HAC <sub>SciFe</sub>		BEC <sub>SiPb</sub>	BHC <sub>SiFe</sub>
$\theta_{min/max}$ [°]	0.61	0.68	8/166		14.2/160		178.7	178.9
$\eta_{max/min}$	5.2	5.1	2.7/-2.1		2.1/-1.7		-4.5	-4.7
Volume [m <sup>3</sup> ]	6.7	1.6	15.1		165		1.6	5.8
Sum-Si [m <sup>2</sup> ]	197.4							

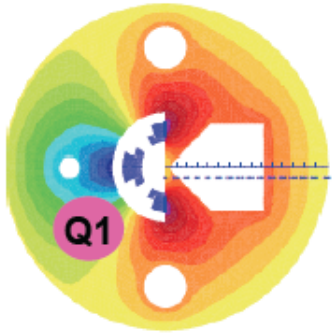


# Detector design: Inner Silicon Tracker (status 3/16)

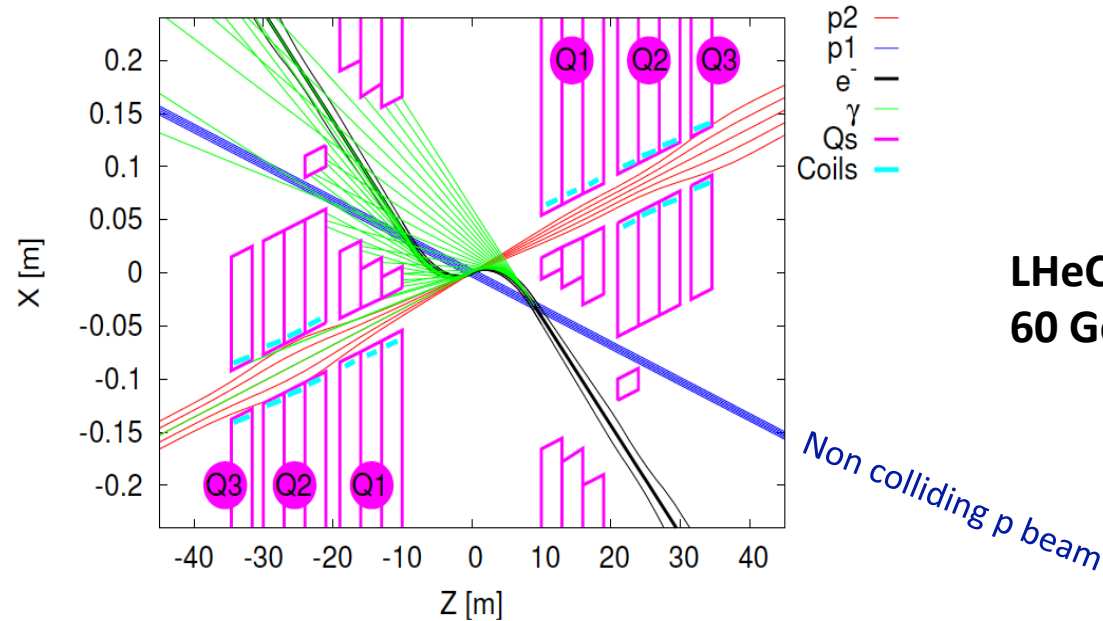


More detailed designs for other components too. DD4HEP software developments..  
 An opportunity for R+D and building a novel, challenging  $4\pi$  detector in the twenties.  
**Profit from HL LHC detector upgrades, also ILC, with no pileup and small radiation load**

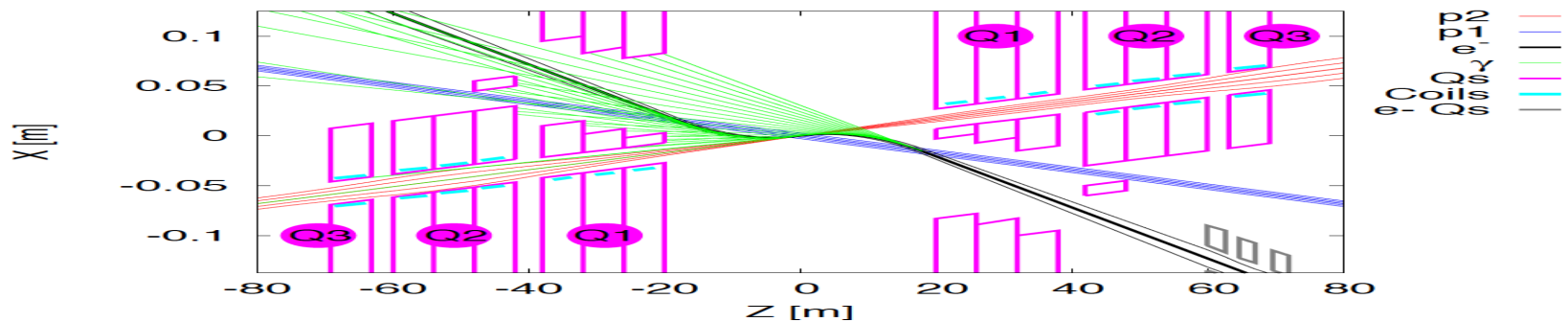
# Interaction Regions for ep with Synchronous pp Operation



Still work in progress:  
 may not need half  
 quad if  $L^*(e) < L^*(p)$



**LHeC (CDR)**  
**60 GeV \* 7 TeV**

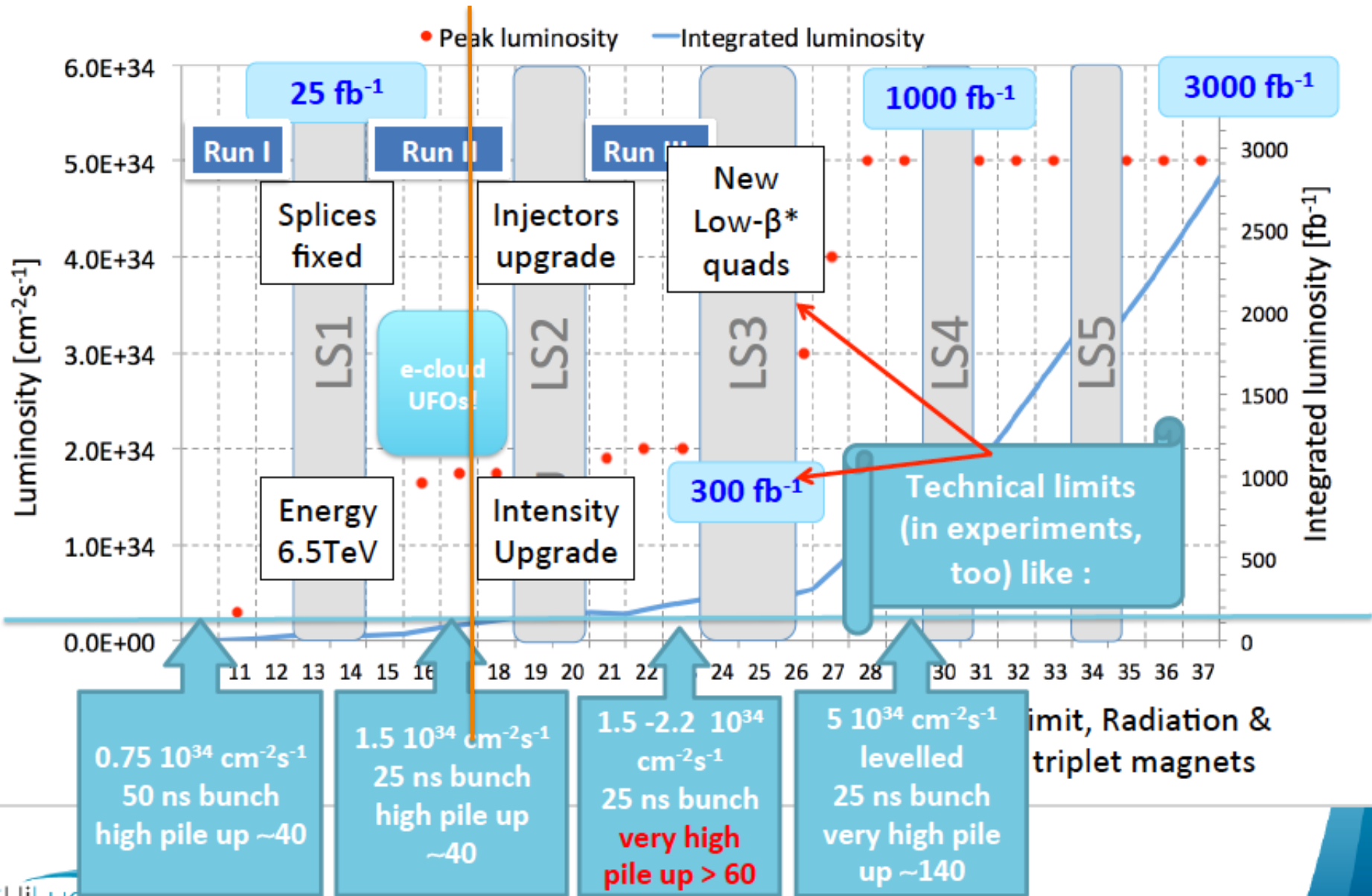


**FCC-he (ERL)**  
**60 GeV \* 50 TeV**

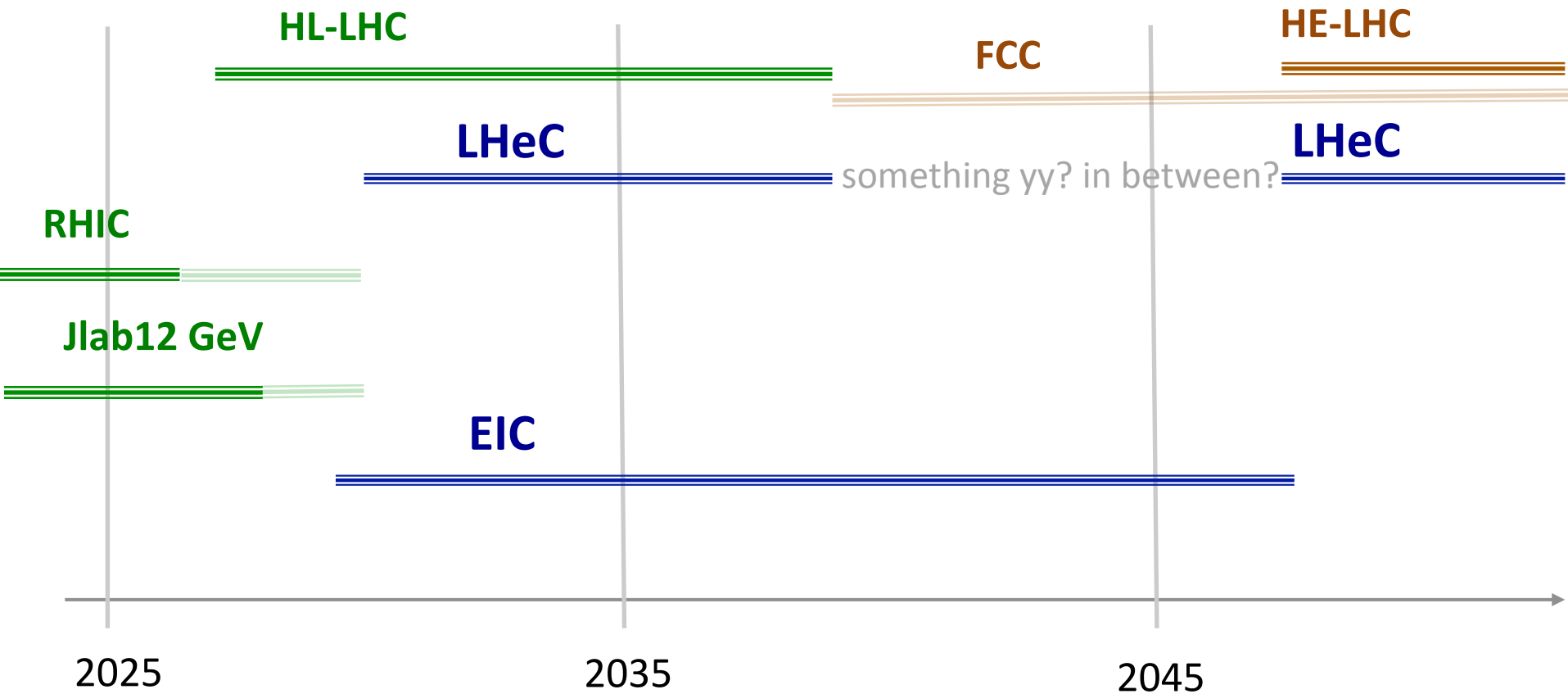
Tentative:  $\epsilon_p = 2\mu\text{m}$ ,  $\beta^* = 20\text{cm} \rightarrow \sigma_p = 3\mu\text{m} \approx \sigma_e$  matched!  $\epsilon_e = 5\mu\text{m}$  ..



# HL LHC offers unique opportunity for ep and eA detector in the 30ies



# Projected Timelines for Future ep/eA Colliders



**HERA:** Proposal 1984, Data 1992-2007, Publications 1993-2018

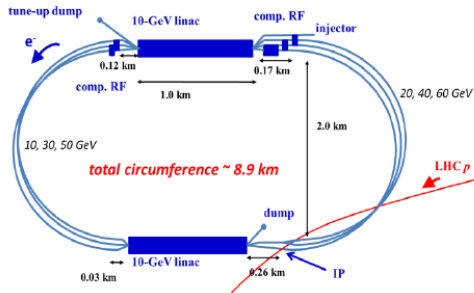
**VHEep:** Plasma e – LHC. **Chinese ep/A** projects: Lanzhou (low E) and CEPC/SPPC

**Disclaimer:** For discussion and illustration at DIS17 only MK+RY, April 7<sup>th</sup>, 2017, DIS at Birmingham

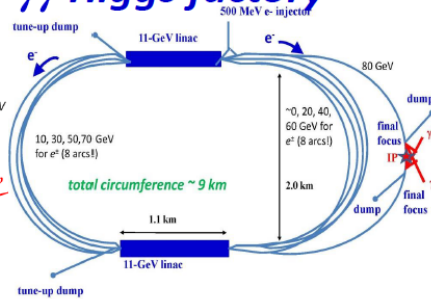
# Further use of ERL in between HL and HE LHC

## Reconfiguring LHeC $\rightarrow$ SAPPHiRE

### LHeC-ERL



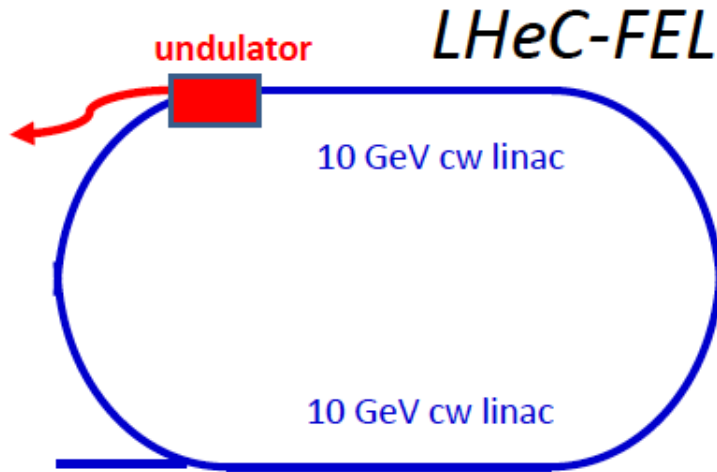
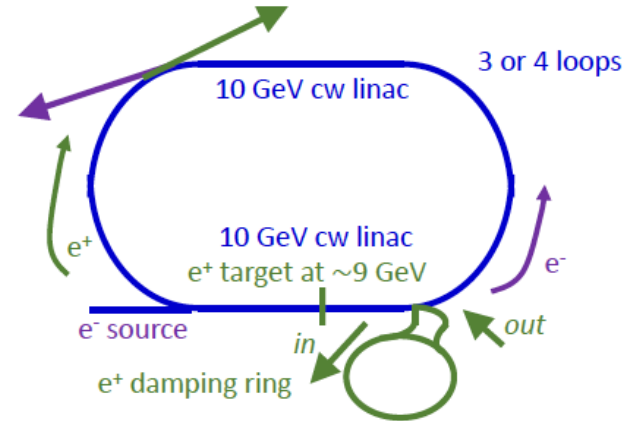
### SAPPHiRE\* $\gamma\gamma$ Higgs factory



\*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons  
S. A. Bogacz, J. Ellis, L. Lusito, D. Schulte, T. Takahashi, M. Velasco, M. Zanetti, F. Zimmermann,  
'SAPPHiRE: a Small Gamma-Gamma Higgs Factory,' arXiv:1208.2827

F.Zimmermann at LHeC WS 9/17

## LHeC: perfect FCC-ee injector!



up to 60 GeV,  
~25 mA,  
1 MeV photons?

3-15x higher beam energy  
(10-200x higher  $\gamma$  energies),  
300-600x higher current

XFEL: 20GeV e, 0.03mA, 24keV photons. LCLSII: 4 GeV e, 0.06mA, 5 keV photons

# Time Projections

## *Scientific activities*

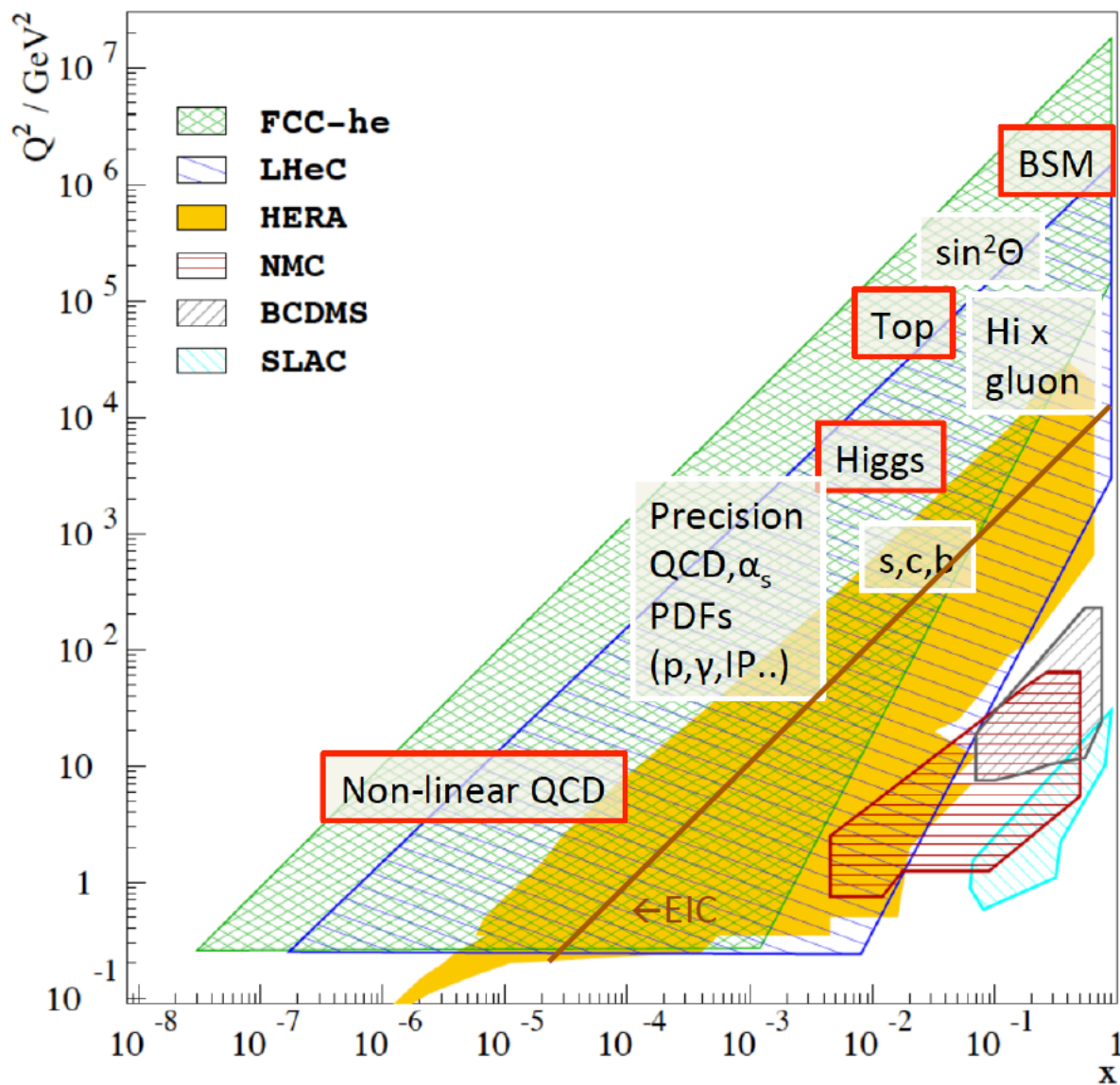
*European Strategy 2006*

3. The LHC will be the energy frontier machine for the foreseeable future, maintaining European leadership in the field; *the highest priority is to fully exploit the physics potential of the LHC, resources for completion of the initial programme have to be secured such that machine and experiments can operate optimally at their design performance. A subsequent major luminosity upgrade (SLHC), motivated by physics results and operation experience, will be enabled by focussed R&D; to this end, R&D for machine and detectors has to be vigorously pursued now and centrally organized towards a luminosity upgrade by around 2015.*

Most likely, the LHC will have been the main base for HEP for ~50 years...

**Apparently we are unable to deliver reliable time projections  
... and yet we need optimism in order to progress ...**

# Pursue New Physics of Deep Inelastic Scattering





# Five Major Themes of Electron-Hadron Physics

at the energy frontier

Cleanest High Resolution Microscope

Joint ep and pp Physics at LHC and FCC

High Precision Higgs Exploration

Discovery Beyond the Standard Model

A Unique Nuclear Physics Facility

CERN has the obligation to utilize its potential fully: the HL LHC programme can and should not “fade away”, new discoveries have to be correctly interpreted, and the world’s Collider future is with CERN. DIS has to be part of it, as Guido Altarelli and Lev Lipatov had taught us.

# Electrons for the LHC

## LHeC/FCCeh and PERLE Workshop

June 27-29, 2018  
LAL-Orsay, France

### Organising Committee:

Nestor Armesto (USC)  
Oliver Brüning (CERN)  
Walid Kaabi (LAL)  
Uta Klein (Liverpool)  
Zhiqing Zhang (LAL)



### Advisory Committee:

Sergio Bertolucci (Bologna)  
Nicola Bianchi (INFN)  
Frédéric Bordry (CERN)  
Oliver Brüning (CERN)  
Stanley Brodsky (SLAC)  
Hesheng Chen (IHEP Beijing)  
Eckhard Eisen (CERN)  
Stefano Forte (Milano)  
Andrew Hutton (Jefferson Lab)

Young-Kee Kim (Chicago)  
Max Klein (U Liverpool)  
Shin-ichi Kurokawa (Tsukuba)  
Victor Matveev (JINR Dubna)  
Alessandro Nisati (Rome)  
Leonid Rivkin (PSI Villigen)  
Herwig Schopper (CERN) - Chair  
Jürgen Schukraft (CERN)  
Achille Stocchi (LAL Orsay)  
John Womersley (ESS/Lund)

### Coordination Group:

Nestor Armesto (Santiago de Compostela)  
Gianluigi Arduini (CERN)  
Oliver Brüning (CERN)  
Andrea Gaddi (CERN)  
Erk Jensen (CERN)  
Walid Kaabi (LAL Orsay)  
Max Klein (Liverpool)  
Peter Kostka (Liverpool)

Bruce Mellado (Wits)  
Paul Newman (Birmingham)  
Daniel Schulte (CERN)  
Frank Zimmermann (CERN)

### Physics Convenors:

Nestor Armesto (Santiago de Compostela)  
George Asakaha (Montreal)  
Olivier Estora (DSY)  
Monica D'Onofrio (Liverpool)  
Claire Flecker (Marseille)  
Claire Gwinn (Oxford)  
Uta Klein (Liverpool)  
Peter Kostka (Liverpool)  
Masahiko Kurokawa (Tsukuba)  
Paul Newman (Birmingham)  
Alessandro Nisati (Rome)  
Frédéric Bordry (CERN)  
Zhiqing Zhang (LAL Orsay)  
Wolfgang Steninger (DESY)  
Anna Schäfer (Potsdam)

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

An electron-proton collider could bridge the gap between the LHC and its successor

Frédéric Bordry, CERN's director for accelerators and technology. The project needs more support from the particle-physics community, he notes. "The next European strategy for particle physics will be very important for the LHeC." The strategy recommendations are slated to come out in 2020, and decisions may be delayed beyond that.

**Toni Feder**

MAY 2017 | PHYSICS TODAY 31

- 7x why -

- i) a huge step (in energy and luminosity) into the unknown of the space-like lepton-parton interaction which only CERN can make, a unique test bed for new physics, certainly in QCD;
- ii) the continuation of a seminal tradition of particle physics in building high resolution microscopes, from Hofstadter to Wiik, for searching deeper into the substructure of matter;
- iii) the next realistic option to study the Higgs boson and shed more light on its properties, by also making the LHC facility at large the first precision H factory;
- iv) the necessary addendum for pp in resolving the largely unknown region of high mass (corresponding to large  $x_b$ ) where new particles or interactions may reside;
- v) the real (QCD) base for physics of nuclear interactions (which is not just hydrodynamics but parton interactions, non-linear) - ways better than any low energy EIC;
- vi) the next energy frontier collider which CERN could build in the twenties, boosting not only SCRF but also the arts of civil engineering, cryogenics, magnet or IR design to a new level, electrons back at CERN, prior to when the time will come for an even bigger enterprise;
- vii) a convincing answer to the question as to which detector could one build next, which is becoming formulated more and more pressing, when one listens to detector builders we join in the ATLAS upgrade and elsewhere.

*“The future belongs to those who believe  
in the beauty of their dreams.”*

Anna Eleanor Roosevelt  
(1884-1962)



Universal Declaration of Human Rights (1948)

cited by Frank Zimmermann at the FCC Meeting at Washington DC, March 2015

title

# Particle Physics with pp-ee-ep

**SM was completed with a series of pp, ee and ep machines** exploring the 10 GeV scale (ISR, SppS – PETRA, Tristan – electron, muon and neutrino experiments) and the Fermi scale (Tevatron – LEP, SLC – HERA), **besides further dedicated experiments [ep SLAC78..].**

All three types of colliding experiments were instrumental in the SM establishment:  
For example: LEP predicted the top mass and Tevatron found the top quark;  
HERA measured the gluon distribution and LHC discovered  $gg \rightarrow \text{Higgs} \rightarrow 4l, \gamma\gamma$ .  
Tevatron saw excess in high pt jets, yet attributed to PDFs with DIS etc

For the first time since decades we have NO definite guidance, no SM particle to find. Note, however, that the Tevatron, LEP and HERA proposals largely emphasised NOT the SM but the BSM (SUSY, LQ) physics. Rarely the SM was a funding argument before either and the theory was no less speculative. Theory only guides: e.g. Weinberg 1980 SU(5): end of colliders, go underground to see proton decay ... to find neutrino oscillations ..

The LHC stands alone, it has no ep partner to explore the 1 TeV scale and it has no ee partner to study the Higgs boson. Can we build in time a 1 TeV ep collider (yes we could) and can we build a higher (than LEP) energy ee collider (for others to discuss)

**The FCC study has hh, ee and eh: yet 5?: time, cost, technology, theory, detectors**  
+ the public acceptance of such a major step into the unknown and below Lac Lemans

# Three Lessons from HERA

HERA kept electron-proton scattering as an integral part of high energy particle physics. It demonstrated the richness of DIS physics and the feasibility of constructing and operating energy frontier  $ep$  colliders. It is a testimony of the vision and authority of Bjoern Wiik. What did we learn to take into a next higher energy  $ep$  collider design? Perhaps there were three lessons about i) the need for higher energy, for three reasons: to make charged currents a real, precision part of  $ep$  physics, for instance for the complete unfolding of the flavour composition of the sea and valence quarks, to produce heavier mass particles (Higgs, top, exotics) with favourable cross sections and, a third reason, to discover or disprove the existence of gluon saturation for which one needs to measure at lower  $x \propto Q^2/s$  than HERA could; ii) the need for much, much higher luminosity: the first almost ten years of HERA provided just a hundred  $\text{pb}^{-1}$ . As a consequence, HERA could not accurately access the high  $x$  region, and it was inefficient and short of statistics in resolving puzzling event fluctuations; iii) the complexity of the interaction region design when a bent electron beam caused synchrotron radiation while the opposite proton beam generated quite some halo background through beam-gas and beam-wall proton-ion interactions. This we had not seen clearly enough prior to and during the initial phase of the HERA luminosity upgrade.

Need higher energy, higher luminosity and to carefully design the IR

# The strong coupling constant in DIS (today)

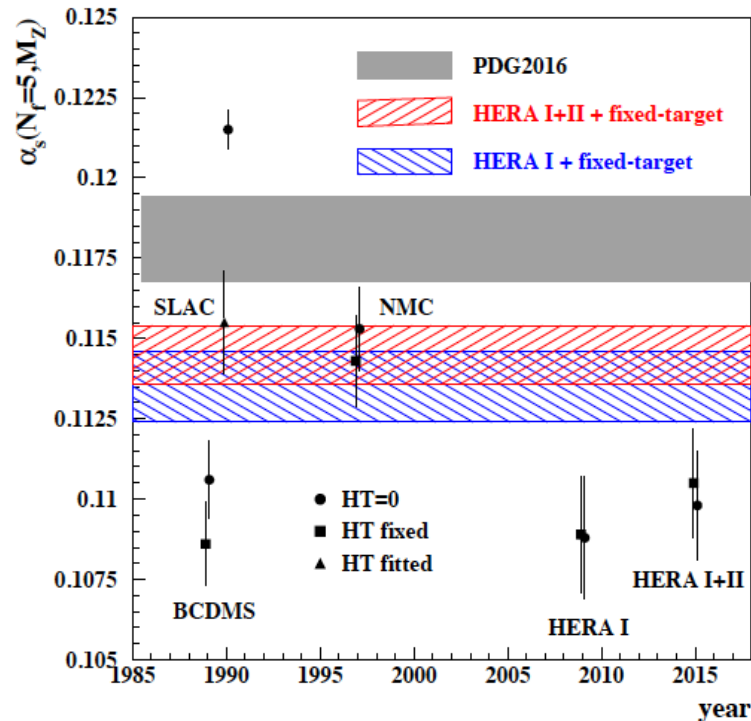


Figure 12: Determinations of  $\alpha_s$  by the ABMP group [85]. One observes quite some spread and a final result (red dashed) below the PDG average value, which includes DIS. Results are shown with the higher twist terms set to zero (circles), HT terms fixed to the values obtained in the ABMP16 fit from considering all data sets (squares) and when fitting the HT terms to the individual data sets (triangles). The bands are obtained by using the combination of the SLAC, BCDMS and NMC samples together with the combined H1 and ZEUS data from HERA I (left-tilted hatches, blue) and from HERA I+II (right-tilted hatches, red).



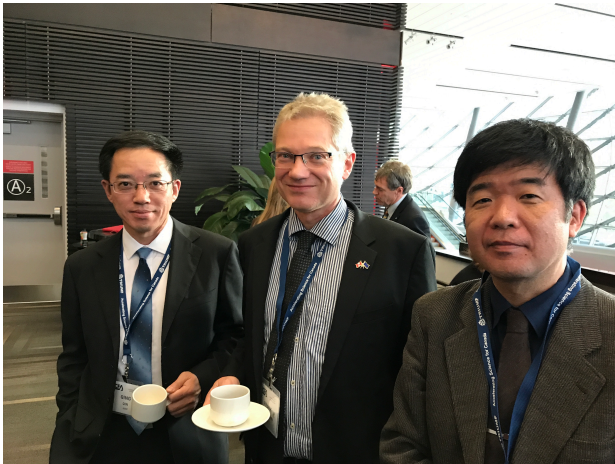
# on “the strategy”

The next European strategy will hardly decide anything as it is five years before the 2 BSF HL upgrade takes place, and no one knows how to reach out to O(10)BSF. The demand to make HL LHC a success will be overriding, adding ep and eA is a golden key to this.

Directions may become visible in a global context (an asiatic e+e- machine decision would be important). HEP is remarkably in the hands of the J+Ch governments.

The ERL development and the detector+physics study has a long term future with CERN as we consider this accelerator as a modular addition to HL/HE LHC and the FCC hh.

MK remarks made in the LHeC Coordination June 2017



At ICFA Seminar in Canada 11/17

Quin Qin, Frank Zimmermann  
and Shinichiro Michizono

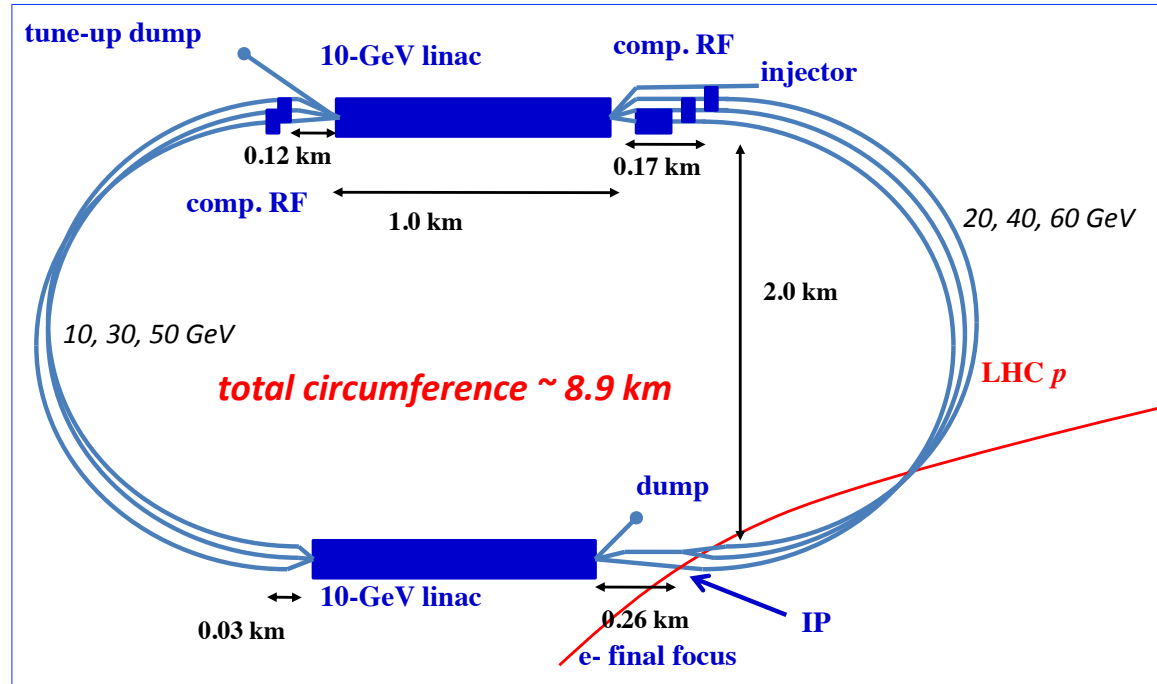
# Summary and Complementary between ep and pp

slide based on [Georges Azuelos and Monica D'Onofrio ]

Compositeness	<ul style="list-style-type: none"> <li>• <i>4-fermion EFT: Lepton-quark compositeness scale</i></li> <li>• <i>Quark radius</i></li> </ul>
Leptoquarks and RPV squark decay	<ul style="list-style-type: none"> <li>• <i>Accessible range largely excluded, but not completely</i></li> <li>• <i>Better measure of LQ characteristics, if they exist</i></li> </ul>
Anomalous Triple Gauge Couplings	<ul style="list-style-type: none"> <li>• <i>Comparable to LHC</i></li> </ul>
Top FCNC couplings	<ul style="list-style-type: none"> <li>• <i><math>t_{uy}, t_{cy}, t_{uH}</math> couplings</i></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 <math>e\gamma</math> for lower masses</i></li> </ul>
Heavy neutrinos, Majorana neutrinos, sterile neutrinos	<ul style="list-style-type: none"> <li>• <i>Symmetry-protected see-saw model</i></li> </ul>
SUSY EW: sleptons, Higgsino, (dark sector)	<ul style="list-style-type: none"> <li>• <i>kinematical observables for compressed scenario</i></li> <li>• <i>Long-lived neutral particles</i></li> <li>• <i>Disappearing tracks</i></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>

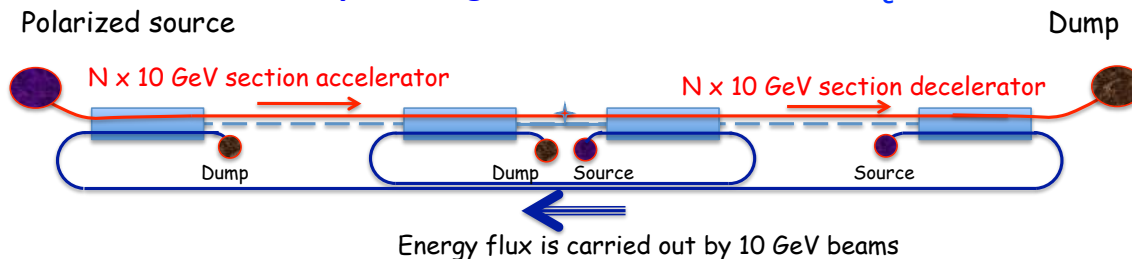
# ep/A with the LHC

Conceptual Design Report: arXiv:1206.2913, published in JPhysG



LHeC: 60 GeV off 7 TeV,  $L(ep) = 10^{33 \rightarrow 34} \text{ cm}^{-2} \text{ s}^{-1}$  (1000 x HERA) **in synchronous ep+pp operation**

**Non default: An expensive generalisation to achieve  $E_e = 500 \text{ GeV}$  or more**



# III LHC

1000 papers:

Higgs Discovery

No BSM up to  $O(\text{TeV})$  SUSY RPV/RPC,  $W'$ ,  $Z'$ , Kaluza Klein gravitons, DarkMatter...

QCD to high orders well established in new range

Precision Measurements:  $W, Z$  to 1/2 %,  $M_W$  to  $2 \cdot 10^{-4}$

Some fluctuations

The LHC delivered now  $100 \text{ fb}^{-1}$  and is scheduled to deliver 3-4  $\text{ab}^{-1}$  by 2040

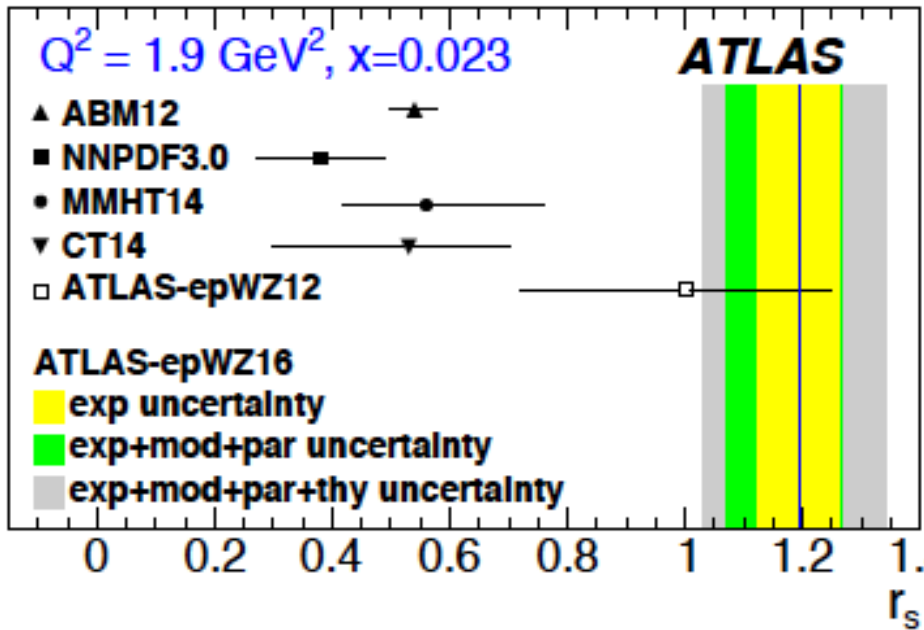
Amazing detector performances and innovative analyses by few 1000 people.

30 times more luminosity, slight energy increase. Pileup from 40 to 150, radiation ..

Major detector upgrades (completely new tracker for ATLAS. ITK, perhaps with HGTD)

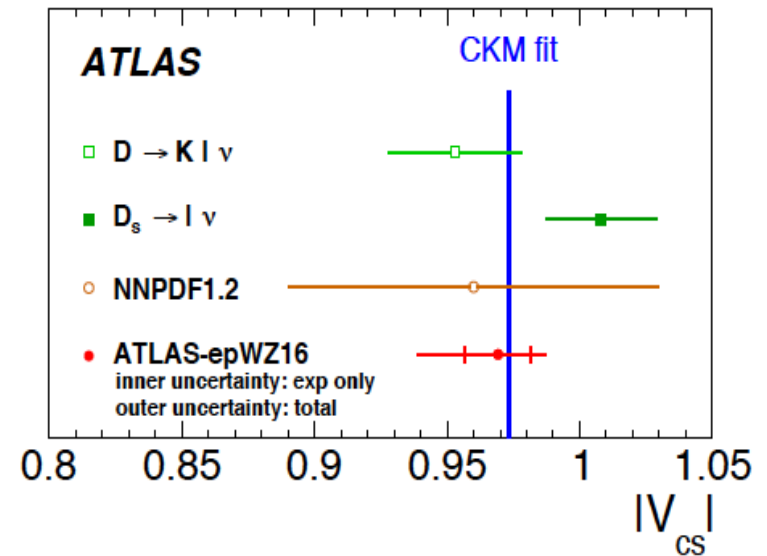
# Strange Strange

Strange quark suppression [dimuons in neutrino data] vs light flavour democracy [W,Z LHC]



Confirmed with much higher precision

ATLAS: 1612.0301, PRD



HERA+ATLAS  $\rightarrow V_{CS}$

Expect LHeC+HL LHC to be 10 x better from +2-3% to surely 0.5% or below

# Source: DC Photocathode

Material	Typical oper. $\lambda$	Work function	Observed Q.E.	Laser power for 20 mA	Observed max current	Obs. lifetime
Sb-based unpolarised	532 nm	1.5-1.9 eV	4-5%	4.7 W at Q.E.=1%	65 mA [Cornell]	Days rep.
GaAs-based polarised	780 nm	1.2 eV at NEA state	0.1-1.0%	31.8 W at Q.E.=0.1%	5-6 mA [JLAB]	Hours

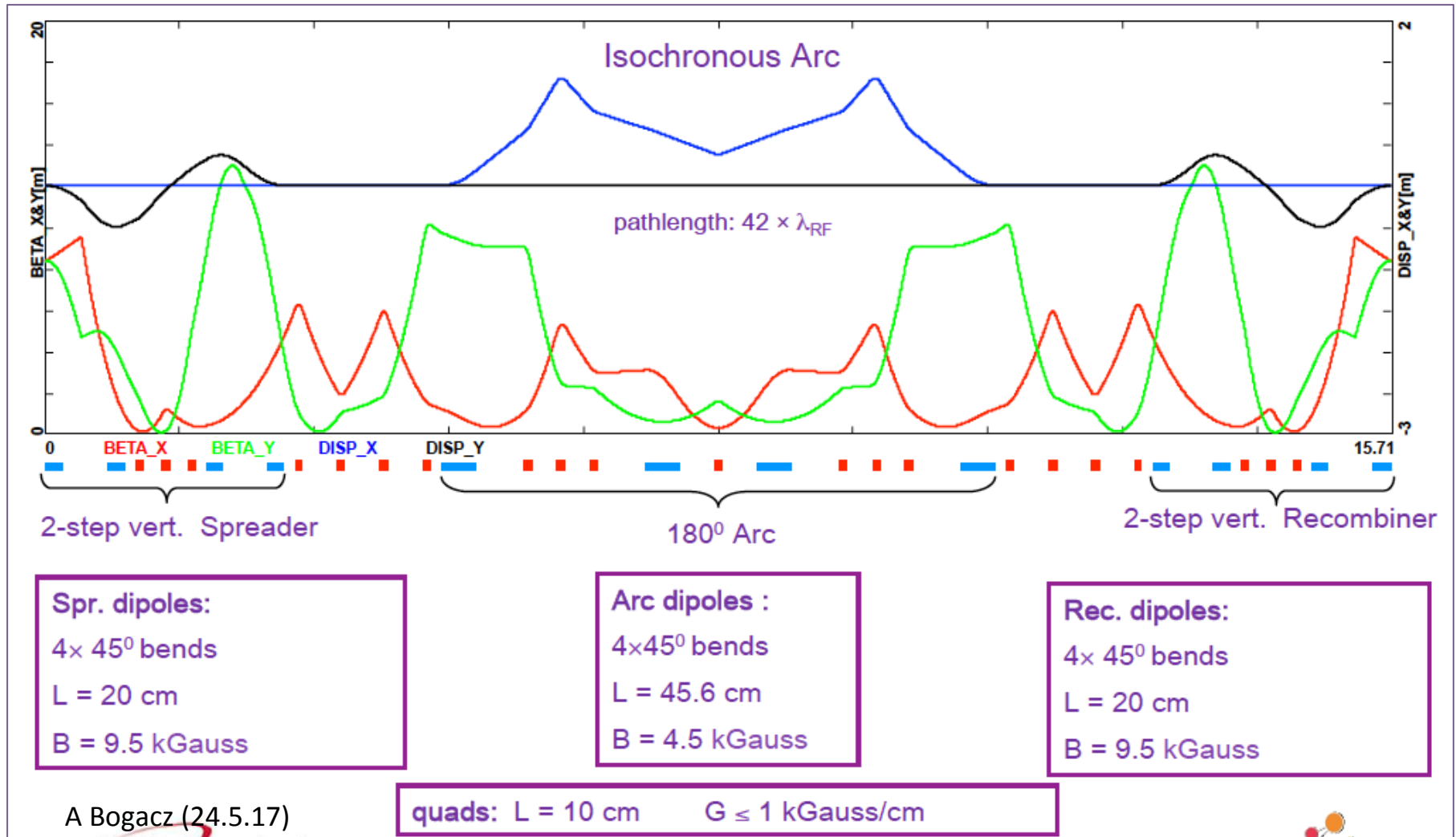
Table 4.1: Characteristics of photocathode materials available for PERLE



← Boris Militsyn's kukhnja at Daresbury

GaAs photocathode preparation facility designed for 4GLS and ALICE gun upgrade.

# PERLE 3 turn optics (80 MeV Arc)

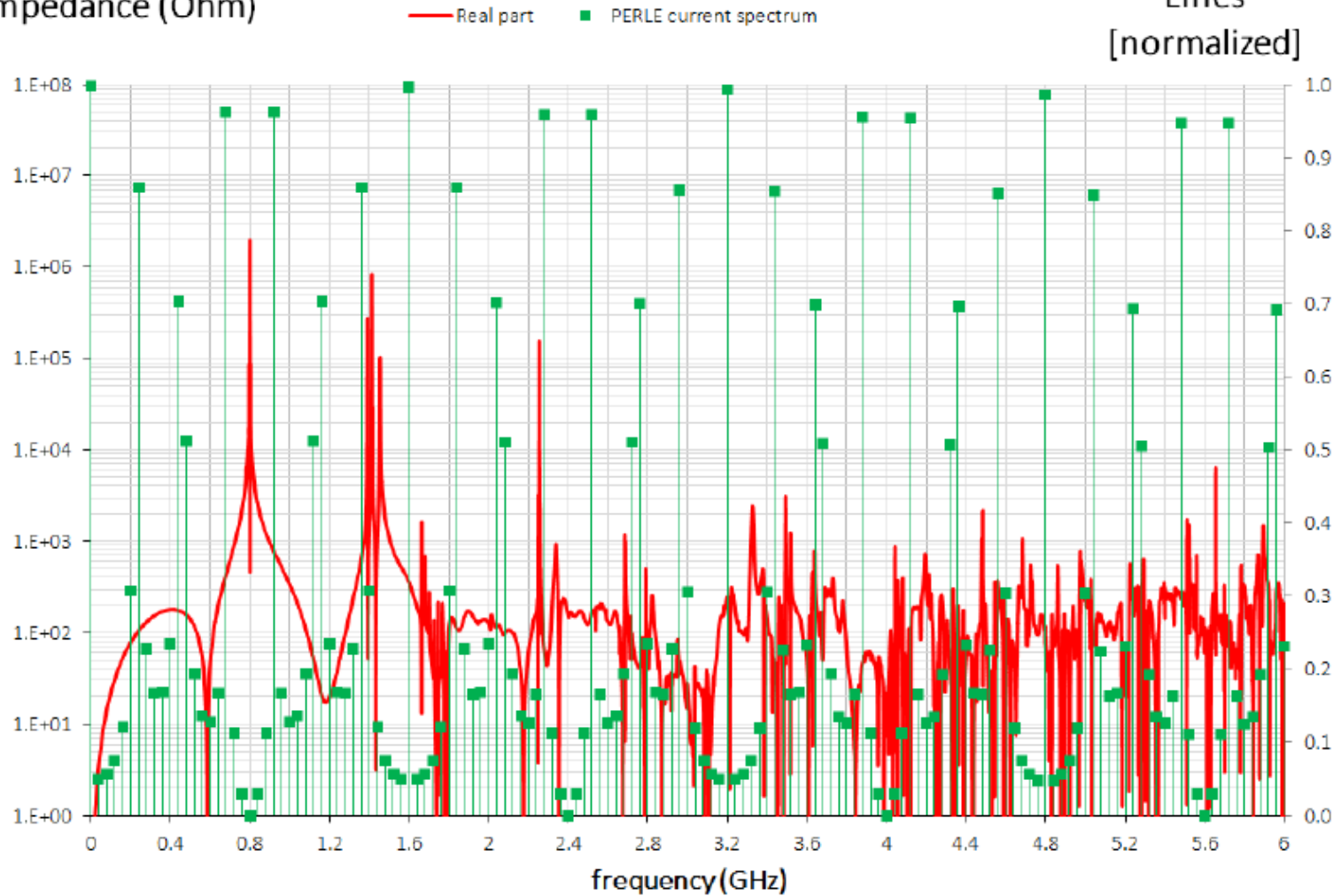


**70 Dipoles** and **114 Quadrupoles** footprint 22 x 5.5 m<sup>2</sup>

# HOM Assessment

real part of  
impedance (Ohm)

Current Spectral  
Lines  
[normalized]



Impedance of cavities + oscillating modes (F Marhauser)  $\neq$  Spectral content of PERLE beam (D Pellegrini)



# Electrons for the LHC

There are various reasons to indeed build the LHeC

Physics (cf slide before)

The uncertainty of HEP and its experience demand pp+ep+ee

The LHC HL Phase physics program would be transformed with ep/eA

CERN needs to build a new machine 20 years after LHC was built and 20 years before a next big machine may indeed be realised.

An ep detector would be a welcome task following the HL LHC.

There is a window of opportunity with the LHC lifetime, AA ending etc.

The ERL is green, high tech, innovative accelerator technology, in line with XFEL..

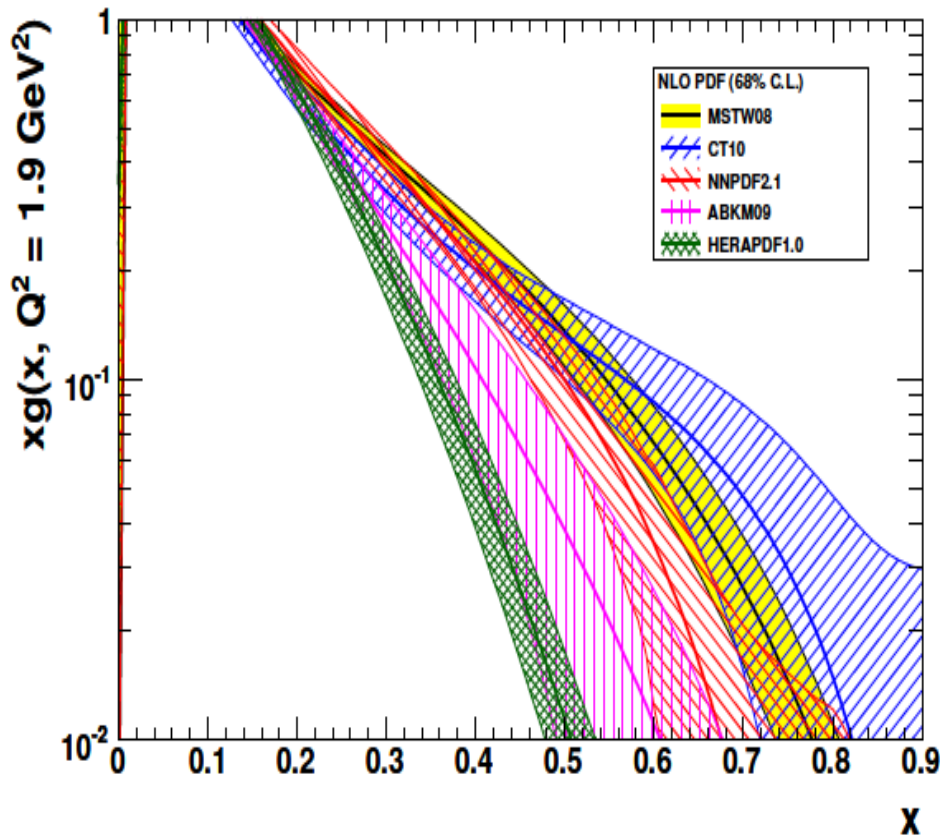
Veksler wanted one reason:

ep is the most precise and versatile microscope the world can build and CERN its place

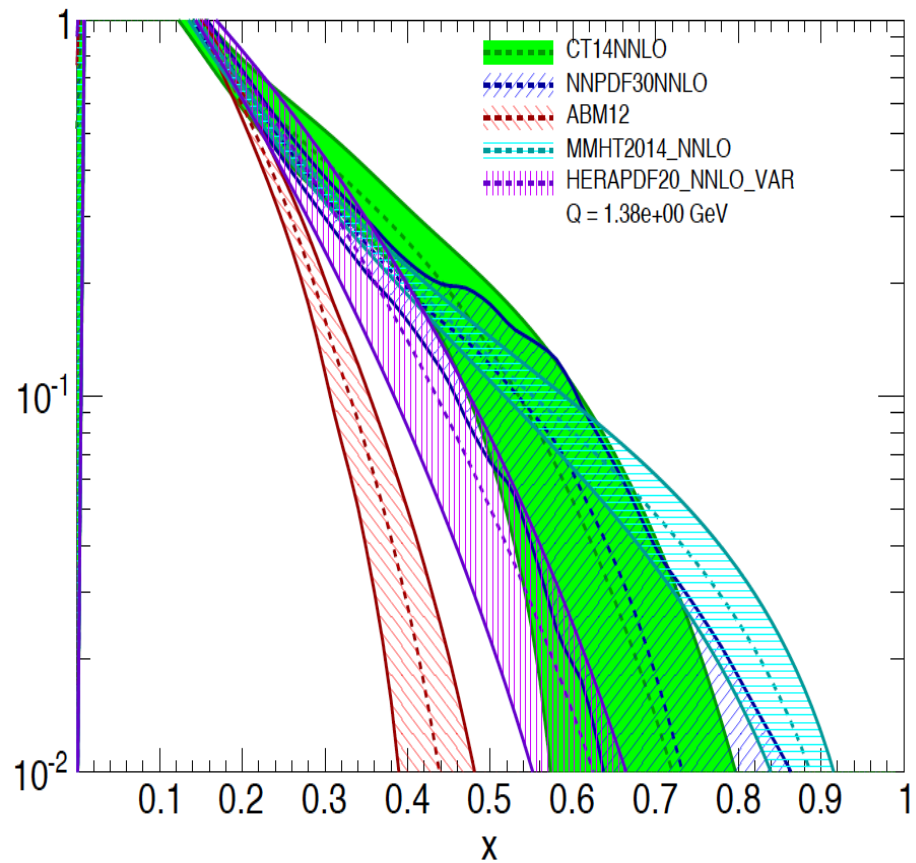
# High x Gluon Density Now

High x

Gluon distribution at  $Q^2 = 1.9 \text{ GeV}^2$



Gluon prior to LHC data (2011)



Gluon with (first) LHC data (2015)  
used by CT14, NNPDF, MMHT

# Top Physics

Top electric charge

EDM and MDM

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

$V_{tb}$  and W-t-b

Top spin

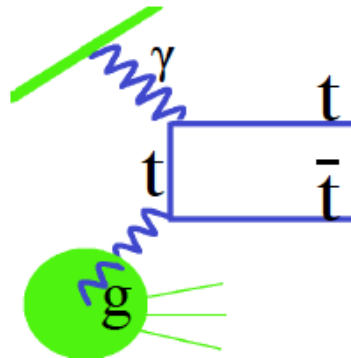
Top PDF

Top mass

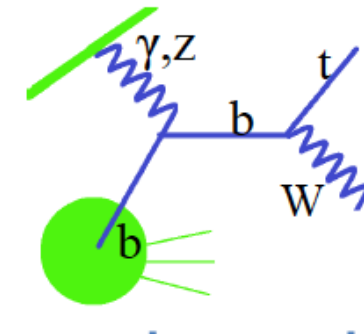
Top-Higgs (1602.04670)

CP nature of ttH (1702.03426)

Pair production



Single production



$$\sigma = 0.05 \text{ pb @ LHeC}$$

$$\sigma = 1.14 \text{ pb @ FCC-ep}$$

$$\sigma = 1.73 \text{ pb @ LHeC}$$

$$\sigma = 15.3 \text{ pb @ FCC-ep}$$

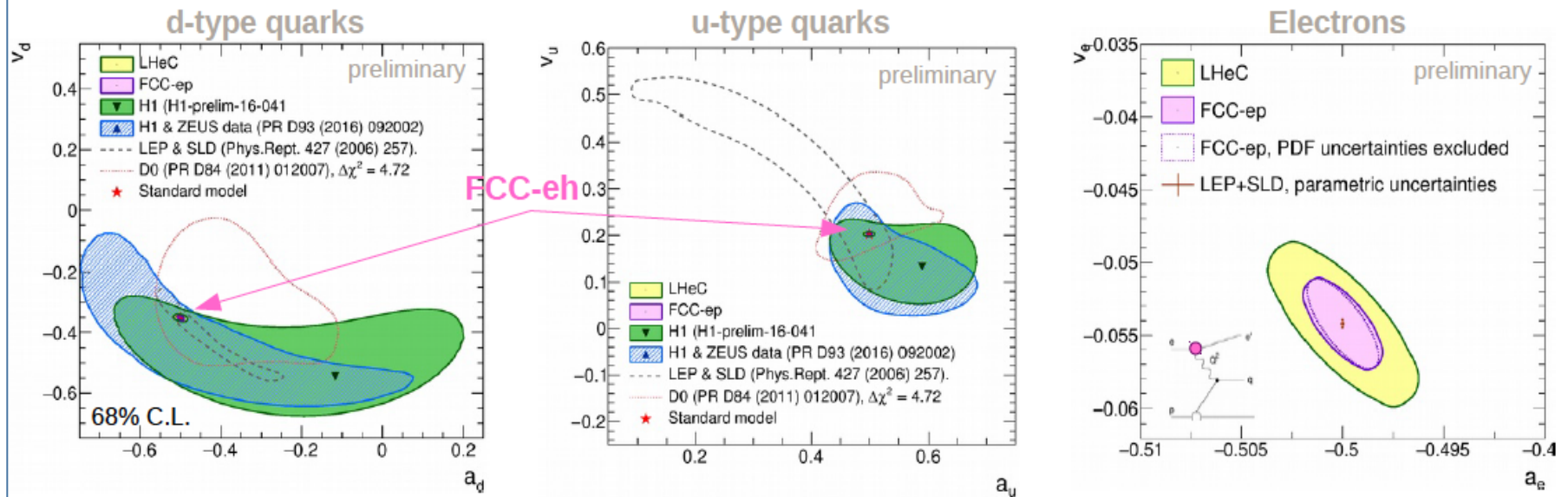
**LHeC and even more FCC-eh are top factories with huge BSM potential**

For top itself: maximise Ee. For t as background for Higgs: not too much

cf Christian Schwanenberger, Top in ep, Talk at FCC Physics Week 17.1.18

# Electroweak Physics: LHeC and FCCeh

## Weak neutral couplings: quarks, electrons



### Weak neutral quark couplings

- u- and d-quark couplings determined simultaneously
- Very precise measurements feasible

$$\begin{aligned}
 a_u &= 0.5 \quad \pm 0.003 \\
 a_d &= -0.5 \quad \pm 0.005 \\
 v_u &= 0.20 \quad \pm 0.002 \\
 v_d &= -0.35 \quad \pm 0.005
 \end{aligned}$$

High precision test of electroweak sector of Standard Model

### Electron couplings

- High precision
- Though: LEP with 'ultimate' precision

Complementary test

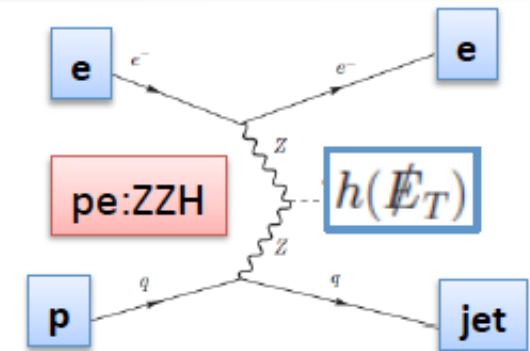
title

# Branching for invisible Higgs

Update of values given in case of  $2\sigma$  and  $L=1 \text{ ab}^{-1}$

Satoshi Kawaguchi,  
Masahiro Kuze  
Tokyo Tech

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  $\text{ab}^{-1}$
- ✓ We also checked LHeC  $\leftrightarrow$  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%  $\rightarrow$  all well within uncertainties of projections of  $\sim 25\%$
- employ further synergies within LHC community and HL-LHC&FCC study group  $\rightarrow$  further detector and analysis details have certainly an impact on results