# Physics and the Large Hadron Electron Collider


**B.Mellado**

**University of the Witwatersrand**

**On behalf of the LHeC Study Group**



**Many thanks to N.Armesto, S.Forte and M.Klein, P. Kostka for slides**


**Initial Stages 2016, Lisbon, 26/05/16**

# DIS at the LHC:

## Guido Altarelli (1941-2015)

CERN-ECFA workshop, Lausanne, March 1984:
a Large Hadron Collider in the LEP tunnel

PHYSICS OF ep COLLISIONS IN THE TeV ENERGY RANGE

G. Altarelli*), B. Mele*) and R. Rückl,
CERN, Geneva, Switzerland
*(Presented by G. Altarelli)*

ABSTRACT

We study the physics of electron-proton collisions in the range of centre-of-mass energies between $\sqrt{s} \simeq 0.3$ TeV (HERA) and $\sqrt{s} \simeq (1-2)$ TeV. The latter energies would be achieved if the electron or positron beam of LEP [$E_e \simeq (50-100)$ GeV] is made to collide with the proton beam of LHC [$E_p \simeq (5-10)$ TeV].

**Proposal of the Large Hadron Electron Collider in 2006 (hep-ex/063016) taken up to CERN, ECFA and NuPECC**

**Study group formed in 2008 with regular workshops, groups meetings and publications**


arXiv:1206.2913

arXiv:1211.4831 and 5102

## CERN Referees

**Ring Ring Design**
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)

**Linac Ring Design**
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)

**Energy Recovery**
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)

**Magnets**
Neil Marks (Cockcroft)
Martin Wilson (CERN)

**Interaction Region**
Daniel Pitzl (DESY)
Mike Sullivan (SLAC)

**Detector Design**
Philippe Bloch (CERN)
Roland Horisberger (PSI)

**Installation and Infrastructure**
Sylvain Weisz (CERN)

**New Physics at Large Scales**
Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)

**Precision QCD and Electroweak**
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)

**Physics at High Parton Densities**
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

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

http://cern.ch/lhec

LHeC

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Present LHeC Study group and CDR authors

About 200 Experimentalists and Theorists from 76 Institutes

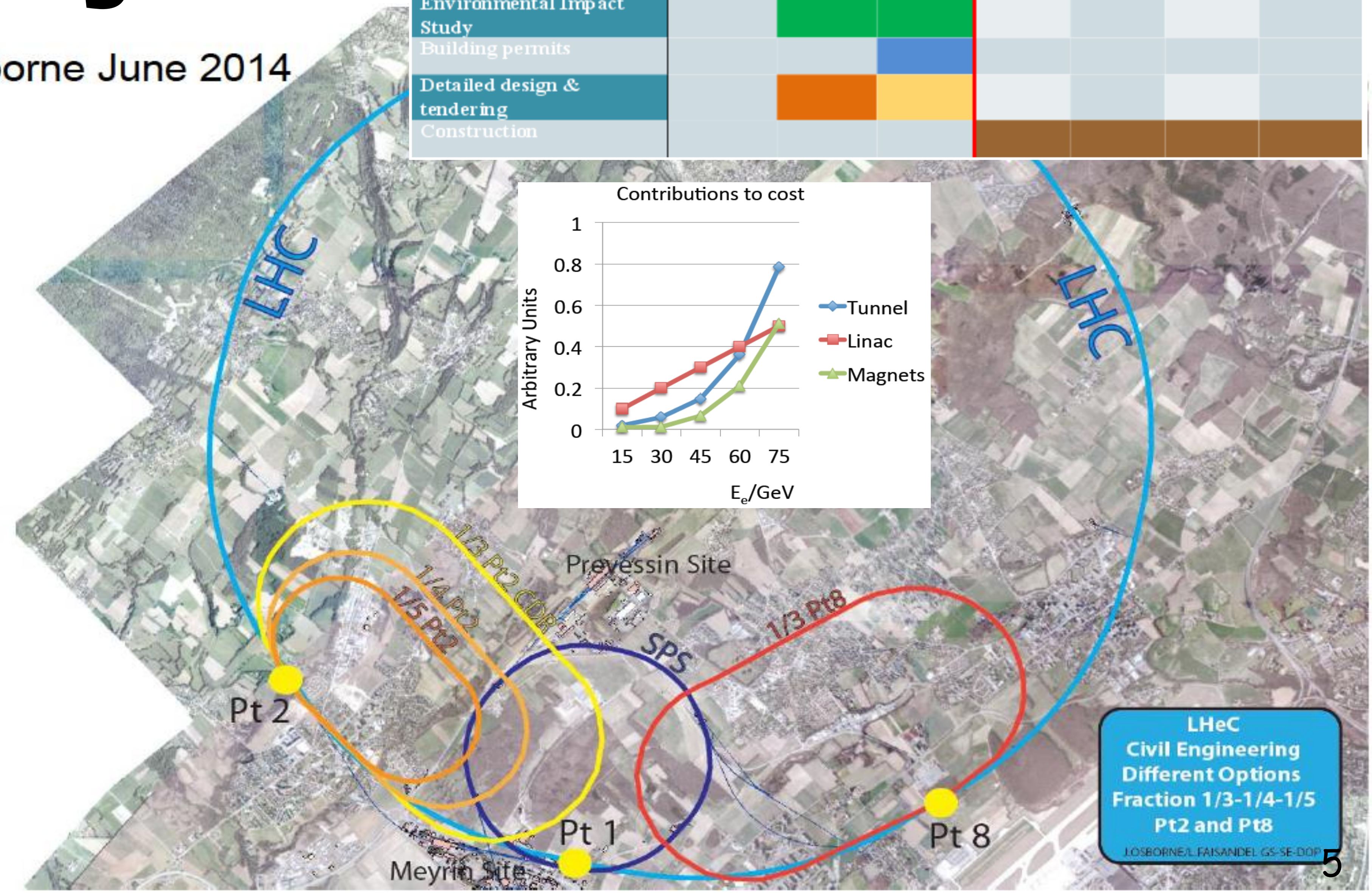
Supported by
CERN, ECFA, NuPECC

N. Armesto

# Layout

John Osborne June 2014

| LHeC construction planning | YEAR 1 | YEAR 2 | YEAR 3 | YEAR 4 | YEAR 5 | YEAR 6 | YEAR 7 |
|---|---|---|---|---|---|---|---|
| Land negotiations | | | | | | | |
| Environmental Impact Study | | | | | | | |
| Building permits | | | | | | | |
| Detailed design & tendering | | | | | | | |
| Construction | | | | | | | |



# After the Higgs discovery: LHeC $10^{33 \rightarrow 34}$ Luminosity

## (parameters in parenthesis) Turn the LHeC into a Higgs factory

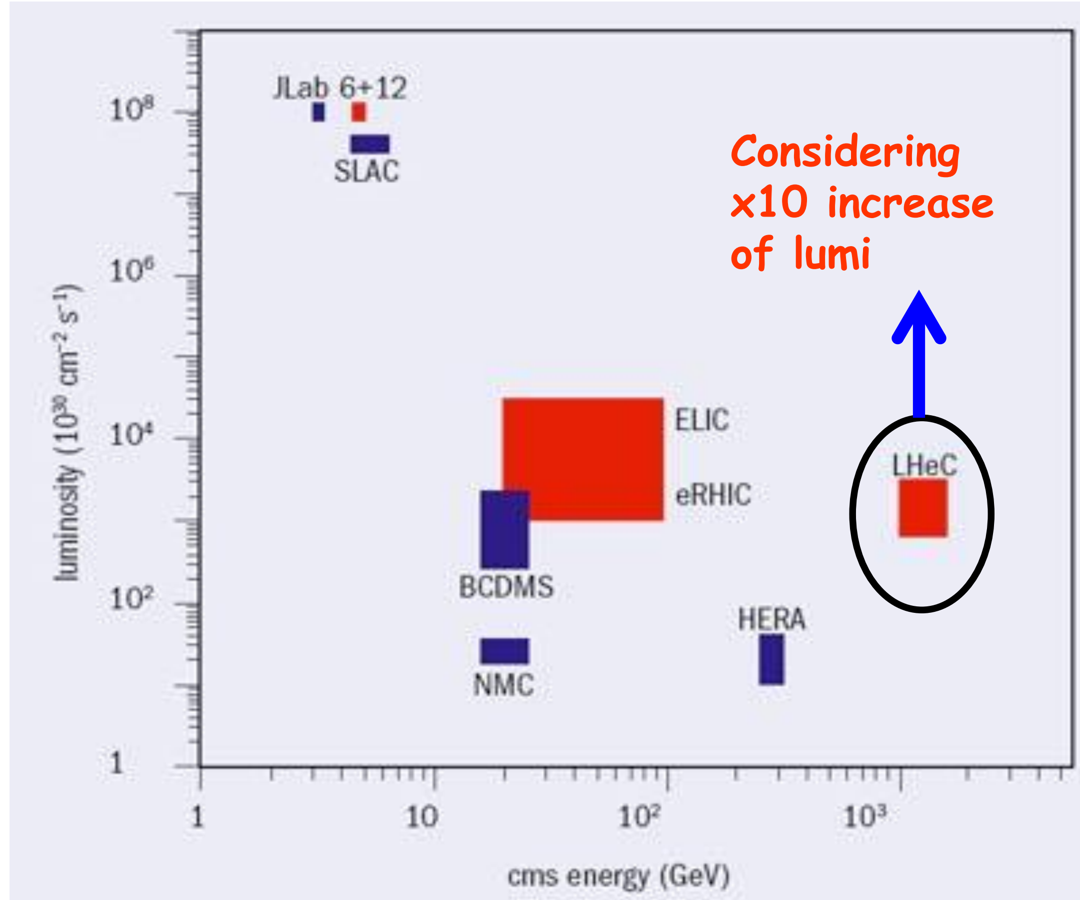
| parameter [unit] | LHeC | |
|---|---|---|
| species | $e^-$ | $p$, $^{208}Pb^{82+}$ |
| beam energy (/nucleon) [GeV] | 60 | 7000, 2760 |
| bunch spacing [ns] | 25, 100 | 25, 100 |
| bunch intensity (nucleon) [$10^{10}$] | 0.1 (0.2), 0.4 | 17 (22), 2.5 |
| beam current [mA] | 6.4 (12.8) | 860 (1110), 6 |
| rms bunch length [mm] | 0.6 | 75.5 |
| polarization [%] | 90 | none, none |
| normalized rms emittance [$\mu$m] | 50 | 3.75 (2.0), 1.5 |
| geometric rms emittance [nm] | 0.43 | 0.50 (0.31) |
| IP beta function $\beta^*_{x,y}$ [m] | 0.12 (0.032) | 0.1 (0.05) |
| IP spot size [$\mu$m] | 7.2 (3.7) | 7.2 (3.7) |
| synchrotron tune $Q_s$ | — | $1.9 \times 10^{-3}$ |
| hadron beam-beam parameter | 0.0001 (0.0002) | |
| lepton disruption parameter $D$ | 6 (30) | |
| crossing angle | 0 (detector-integrated dipole) | |
| hourglass reduction factor $H_{hg}$ | 0.91 (0.67) | |
| pinch enhancement factor $H_D$ | 1.35 | |
| CM energy [TeV] | 1300, 810 | |
| luminosity / nucleon [$10^{33}$ cm$^{-2}$s$^{-1}$] | 1 (10), 0.2 | |

Table 1: LHeC *ep* and *eA* collider parameters. The numbers give the default CDR values, with optimum values for maximum *ep* luminosity in parentheses and values for the *ePb* configuration separated by a comma.

**LHeC Collaboration arXiv:1211:5102, see also O.Bruening and M.Klein arXiv:1305.2090**

# Some LHeC Context

The LHeC is not the first proposal for TeV scale DIS, but it is the first with the potential for significantly higher luminosity than HERA …





DESY 06-006
Cockcroft-06-05


## Deep Inelastic Electron-Nucleon Scattering at the LHC*


J. B. Dainton[1], M. Klein[2], P. Newman[3], E. Perez[4], F. Willeke[2]

[1] Cockcroft Institute of Accelerator Science and Technology, Daresbury International Science Park, UK
[2] DESY, Hamburg and Zeuthen, Germany
[3] School of Physics and Astronomy, University of Birmingham, UK
[4] CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France


… achievable with a new electron accelerator at the LHC …

[JINST 1 (2006) P10001]

# Future Circular Collider

N. Armesto

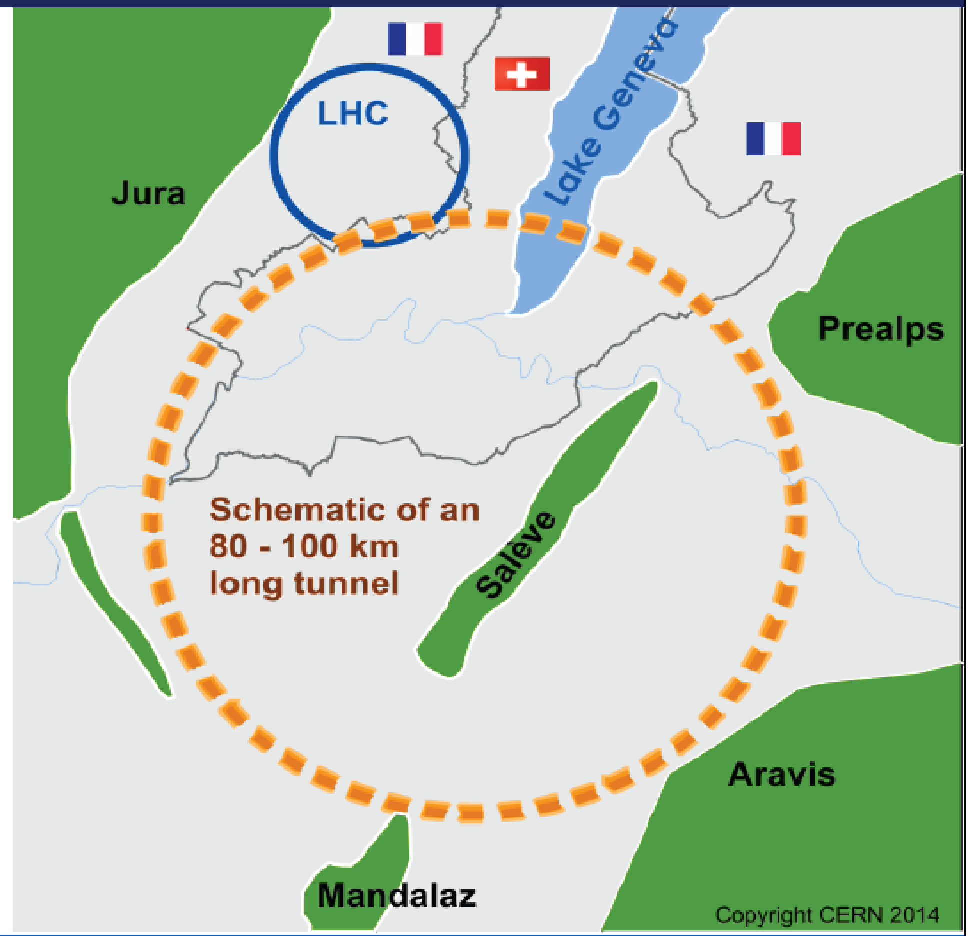
## Future Circular Collider Study - SCOPE
## CDR and cost review for the next ESU (2018)

**Forming an international collaboration to study:**

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

| |
|---|
| ~16 T ⇒ 100 TeV *pp* in 100 km |
| ~20 T ⇒ 100 TeV *pp* in 80 km |

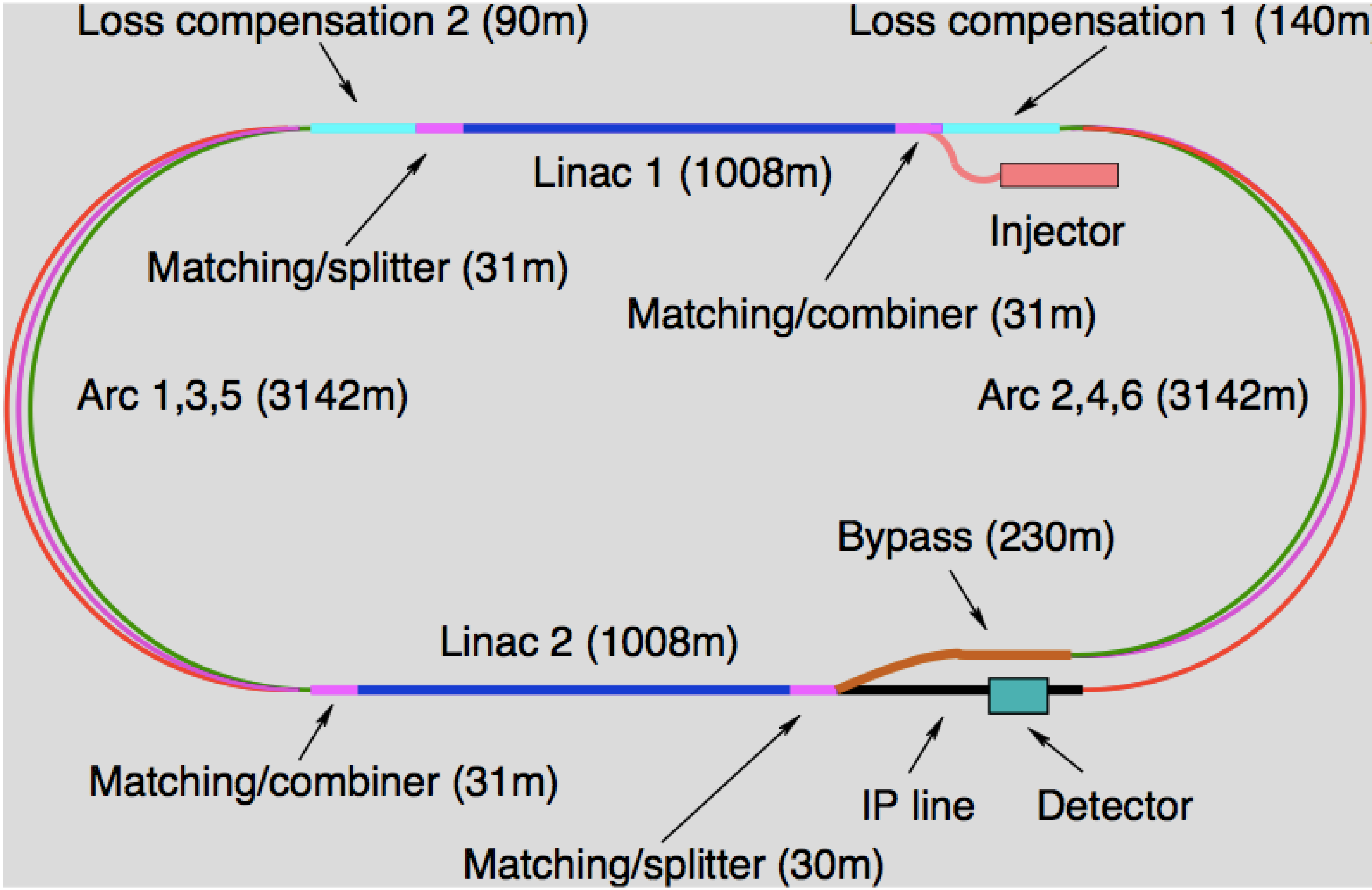
- ***e⁺e⁻* collider (*FCC-ee*) as** potential intermediate step
  **120-350 GeV**
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area




Future Circular Collider Study
Michael Benedikt
FCC Kick-Off 2014
5

# CDR: Physics, Accelerator, Detector

**M.Klein**




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

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

# ERL Demonstrator

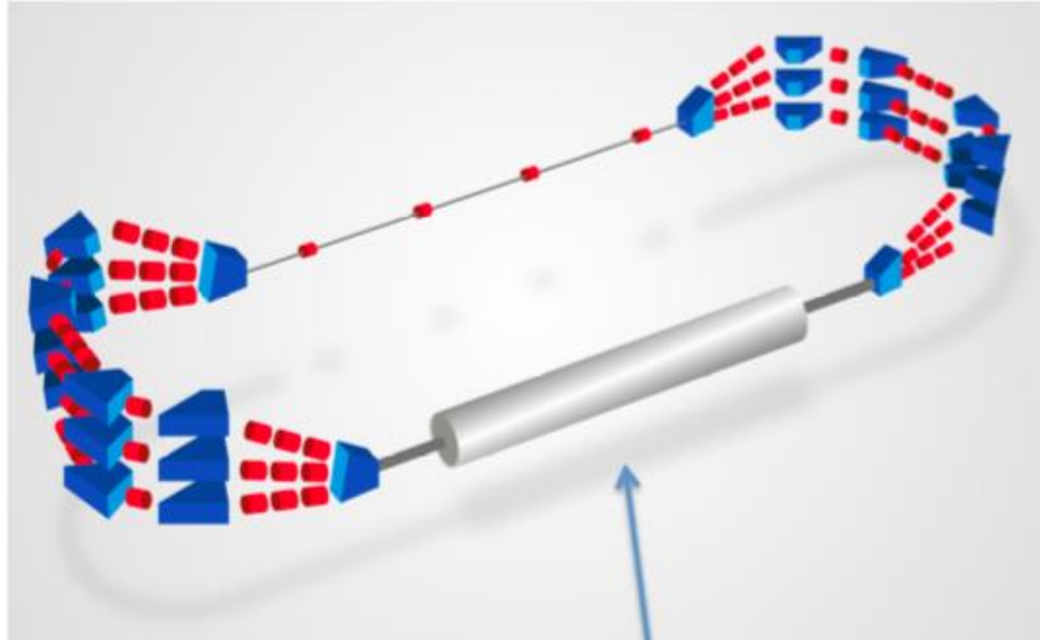
M.Klein

Demonstration of high current (10mA), multi(3)turn ERL

Test and development of 802MHz SCRF technology

$E_e$ = 200 (400) MeV with 1(2) module

A.Valloni 2/16



| Parameter | Value |
|---|---|
| Dipoles per arc<br>Dipole length<br>Max B Field | 3/4<br>50 cm<br>1.1 T |
| Quadrupoles per arc<br>Quadrupoles in straight lines | 5<br>4 |
| Dipoles in Spreader/Combiner<br>Quads in Spreader/Combiner | 1-3<br>3 |
| Dipoles for Injection-Extraction | 6 |

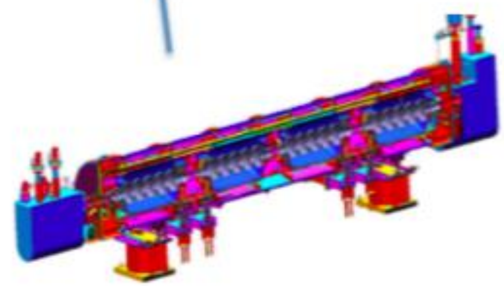


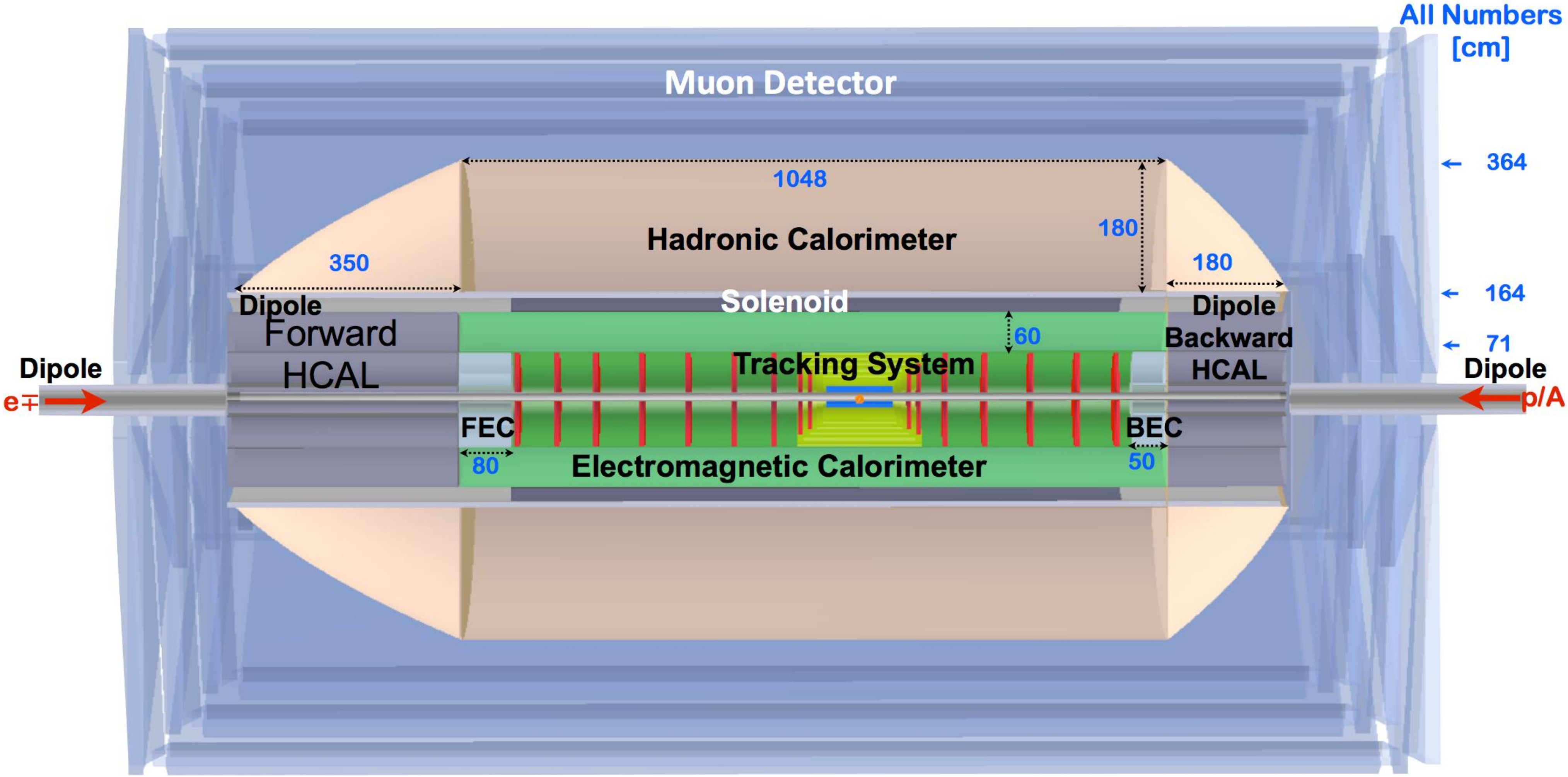
Figure 3.9: SNS high β module adapted to house β =1 5-cell cavities for LHeC.

**Discussions with Orsay encouraging**

Work in progress

# The LHeC Detector

P. Kostka



# Physics Highlights

# LHeC Physics Programme

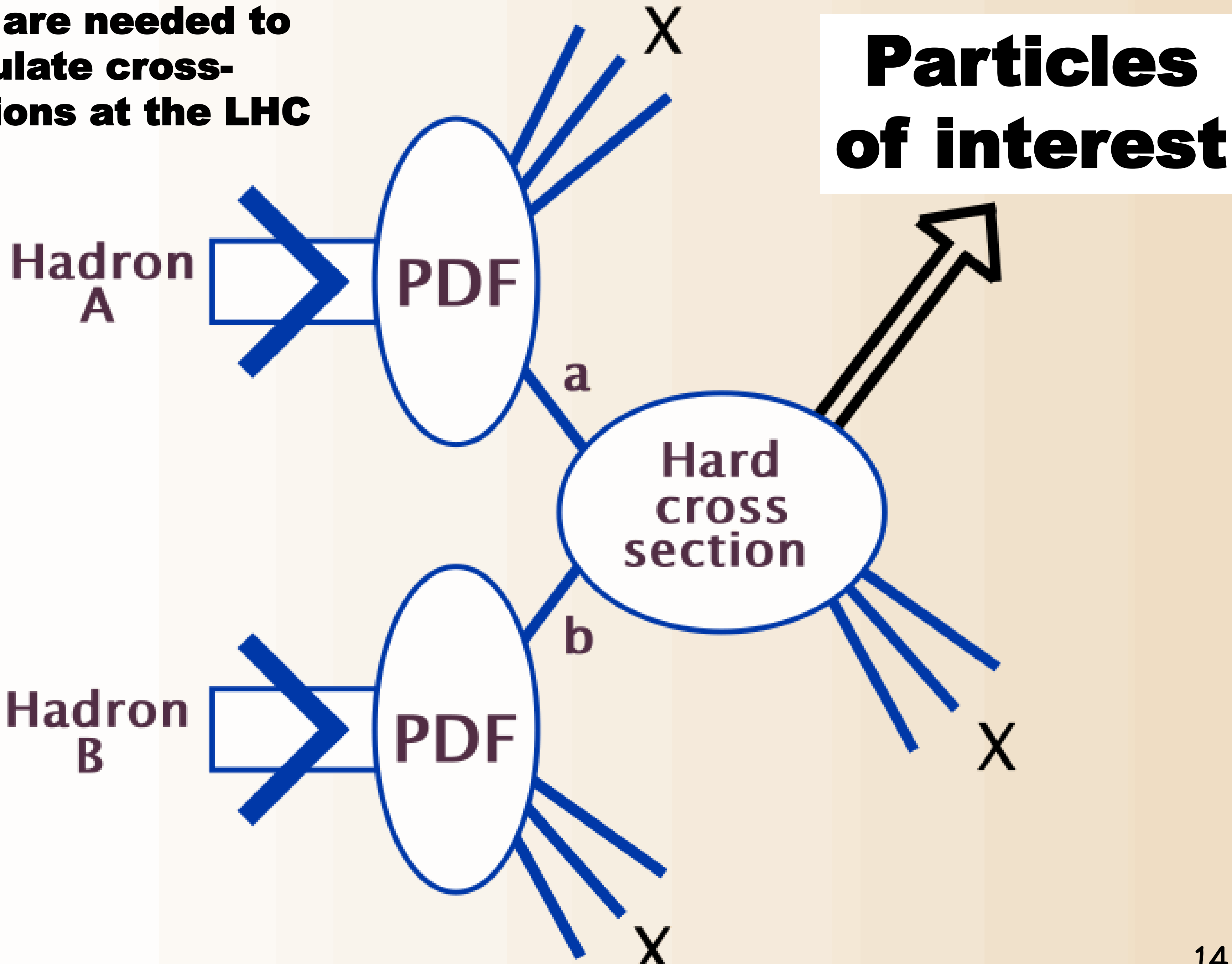
**CDR, arXiv:1211.4831 and 5102**
http://cern.ch/lhec

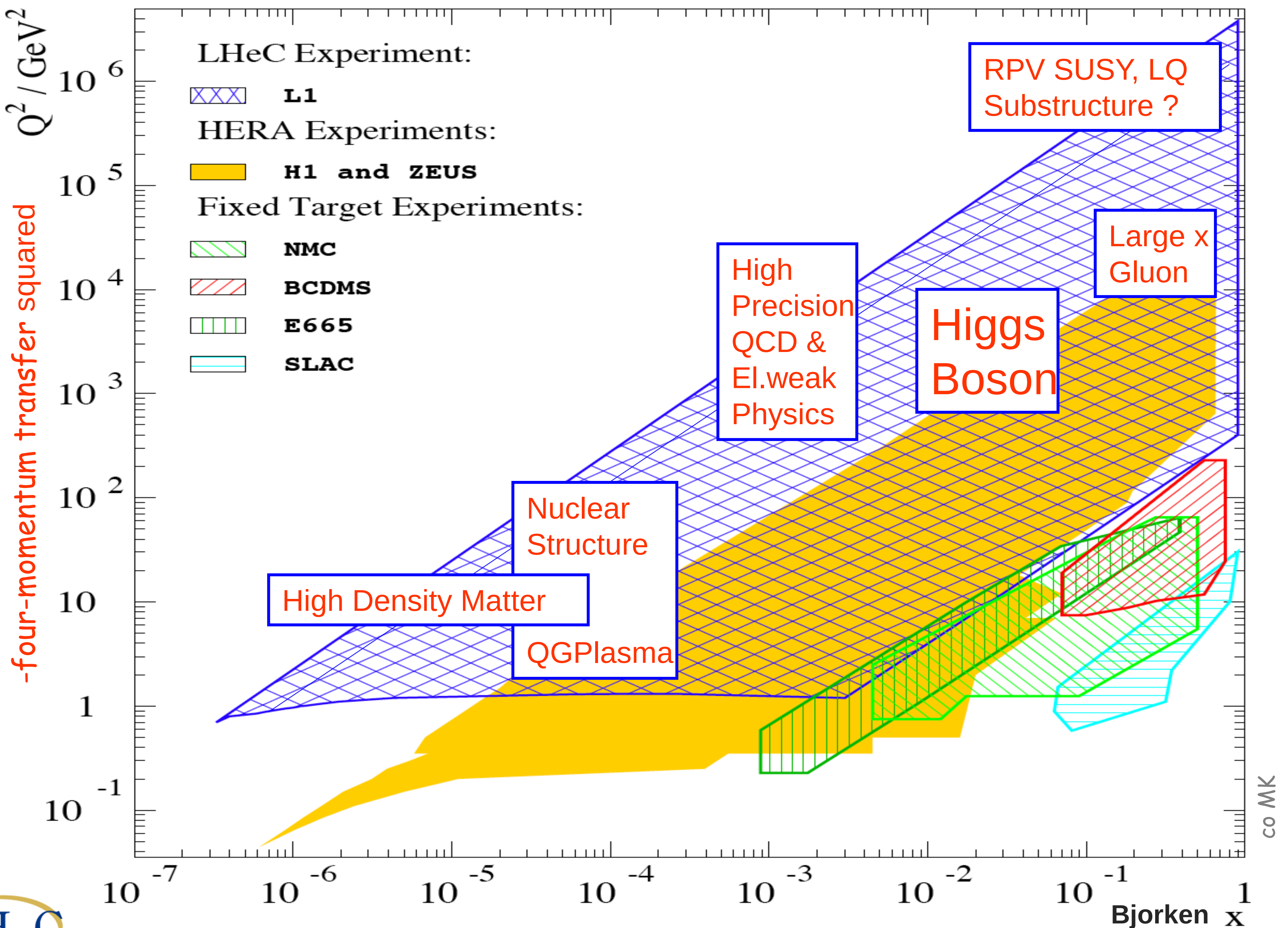
| | |
|---|---|
| QCD Discoveries | $\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low $x$: (n0) saturation, $\overline{u} \neq \overline{d}$ |
| Higgs | $WW$ and $ZZ$ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate |
| Substructure | electromagnetic quark radius, $e^*$, $\nu^*$, $W$?, $Z$?, top?, $H$? |
| New and BSM Physics | leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through $\alpha_s$ |
| Top Quark | top PDF, $xt = x\overline{t}$?, single top in DIS, anomalous top |
| Relations to LHC | SUSY, high $x$ partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs |
| Gluon Distribution | saturation, $x \approx 1$, $J/\psi$, $\Upsilon$, Pomeron, local spots?, $F_L$, $F_2^c$ |
| Precision DIS | $\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ 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, $d/u$, $s = \overline{s}$?, charm, beauty, top |
| QCD | N$^3$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, .. |

**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…**

**Pdfs are needed to calculate cross-sections at the LHC**





$Q^2$ / GeV$^2$
-four-momentum transfer squared
LHeC Experiment:
L1
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
RPV SUSY, LQ
Substructure ?
Large x
Gluon
High
Precision
QCD &
El.weak
Physics
Higgs
Boson
Nuclear
Structure
High Density Matter
QGPlasma
$10^{-1}$ 1 10 $10^2$ $10^3$ $10^4$ $10^5$ $10^6$
$10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ 1
Bjorken x
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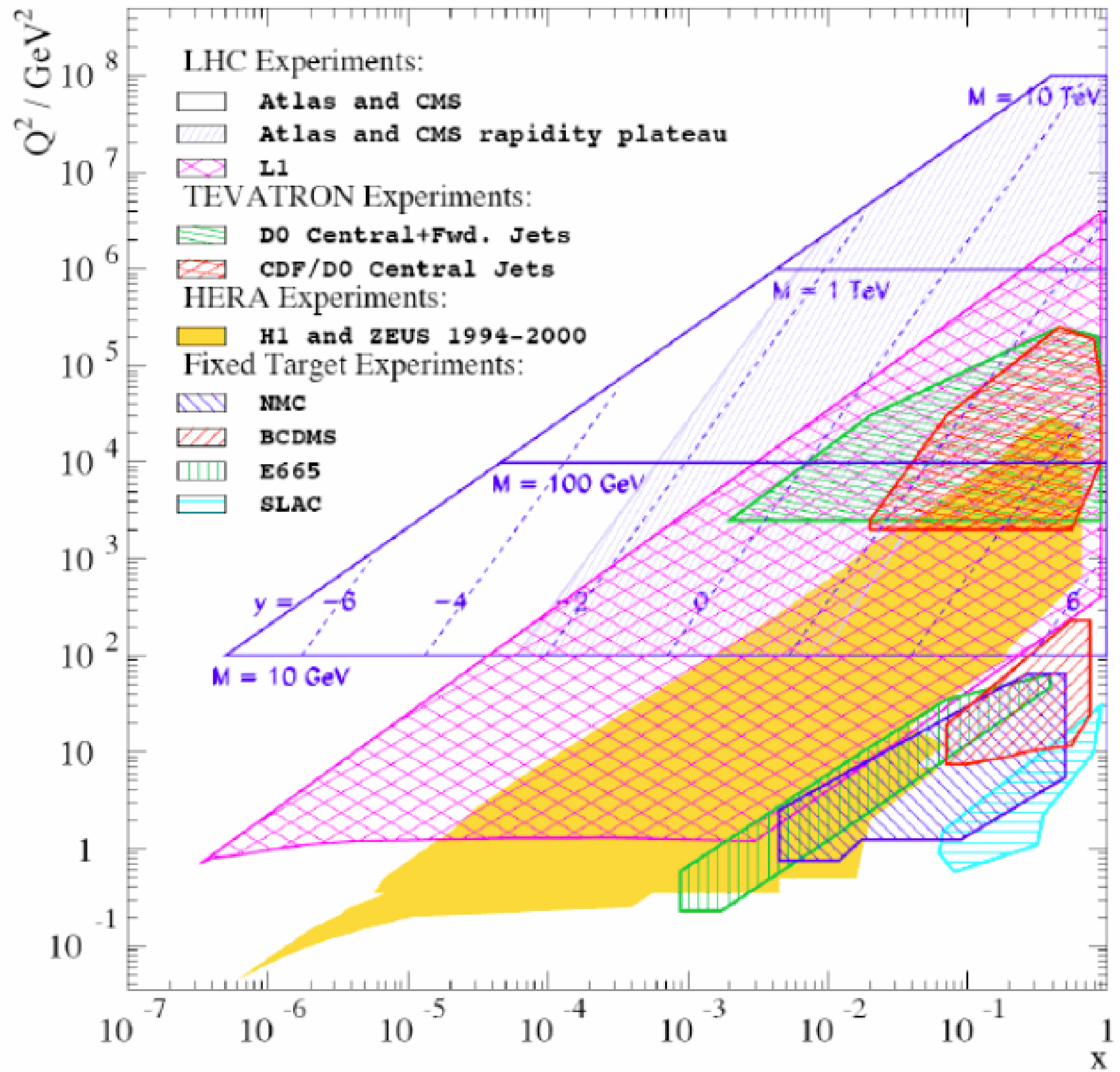
LHeC

# LHeC Kinematics and the LHC

Extension of parton density measurements at the LHeC very important for upgraded LHC




Luminosity

# HERA AND LHC DATA: WHAT IS THE RELATIVE IMPACT?

**S. Forte**

- OVERALL MEASURE OF IMPACT:
  $\varphi \Rightarrow$ FIT UNCERTAINTY/DATA UNCERTAINTY
- HERA-II IMPACT SIZABLE
- IMPACT OF LHC DATA MODERATE BUT VISIBLE
- IMPACT OF CMS OR ATLAS COMPARABLE TO (MODERATE) IMPACT OF NON-LHC, NON-HERA DATA

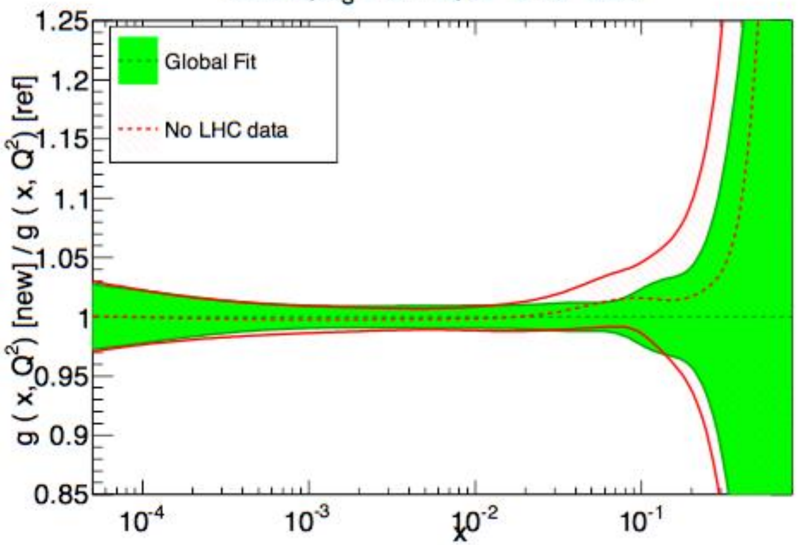
FRACTIONAL UNCERTAINTY

| Dataset | $\varphi$ NLO | $\varphi$ NNLO |
|---|---|---|
| Global | 0.291 | 0.302 |
| HERA-I | 0.453 | 0.439 |
| HERA all | 0.375 | 0.343 |
| HERA+ATLAS | 0.391 | 0.318 |
| HERA+CMS | 0.315 | 0.345 |
| no LHC | 0.312 | 0.316 |

THE GLUON

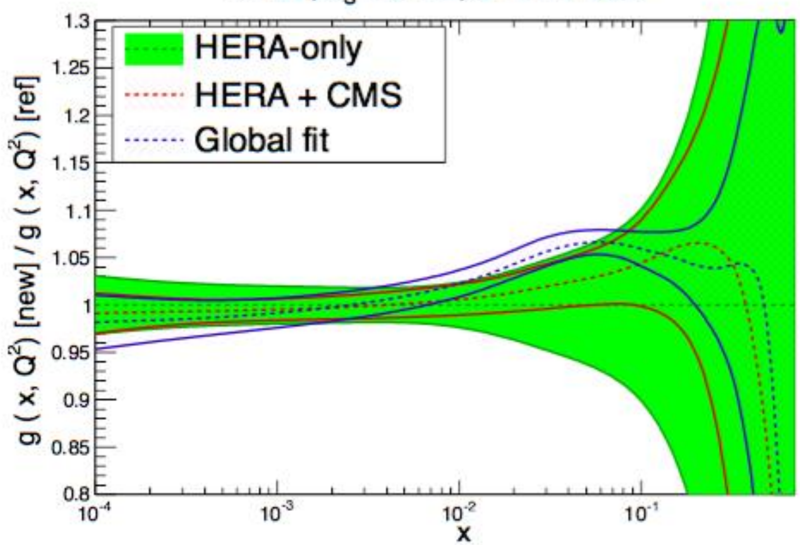
GLOBAL VS NO LHC

NNLO, $\alpha_S = 0.118$, $Q^2 = 10^4$ GeV$^2$




GLOBAL VS HERA+CMS

NNLO, $\alpha_S = 0.118$, $Q^2 = 10^4$ GeV$^2$




**Very difficult to reduce uncertainty below 3-4% with hadron-hadron collisions. Need ep collisions**

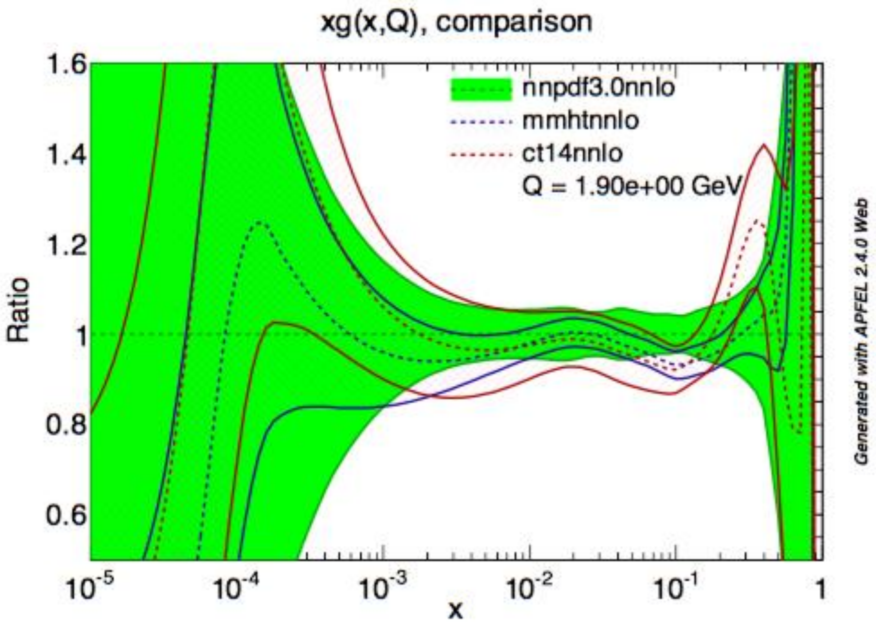
# PDFS AT THE LHEC

S. Forte

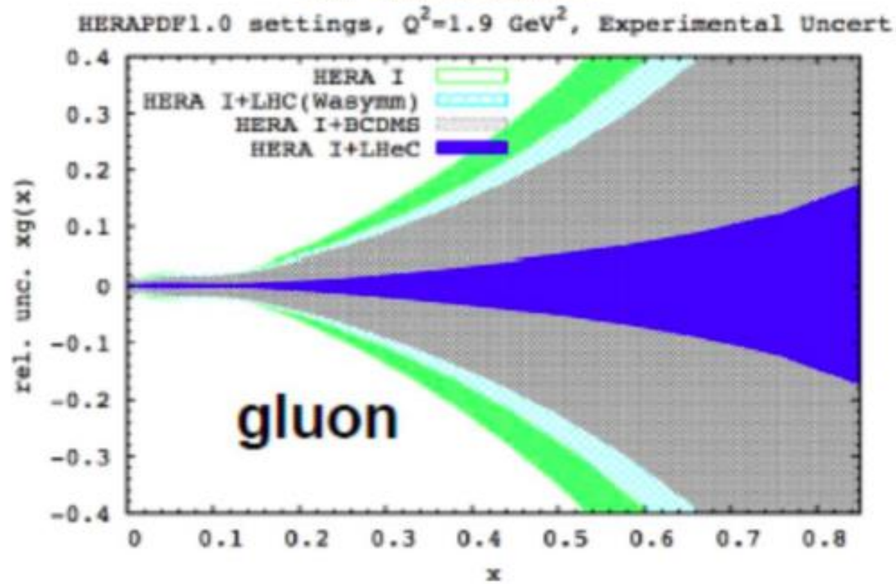
- UNCERTAINTIES DOWN TO PERCENT LEVEL IN WIDE KINEMATIC REGION
- WITH DEUTERON BEAMS, FULL LIGHT FLAVOR DECOMPOSITION
- THANKS TO HIGH ENERGY, NC+CC ⇒ PRECISION STRANGENESS DETERMINATION

GLUON

NOW




AT THE LHEC

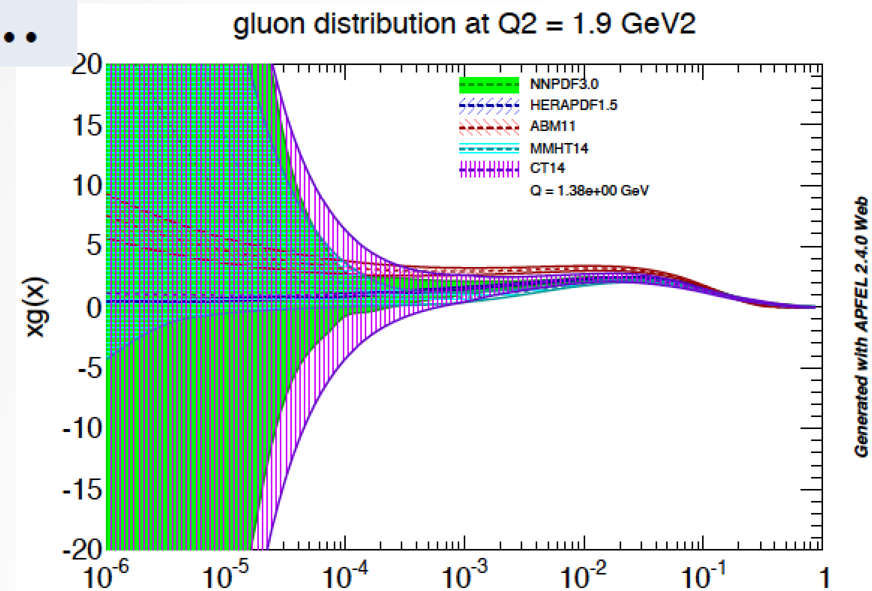



(A. Cooper-Sarkar & Voica Radescu, 2015)

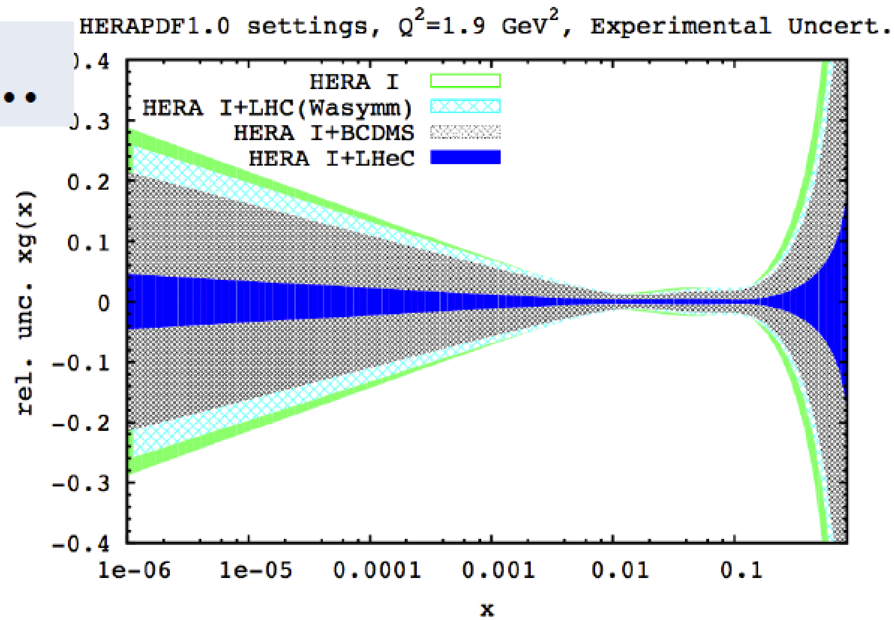
**PDF uncertainty on Higgs production at LHC will become negligible due to measurements a the LHeC**

# Impact of LHeC at small x

now...

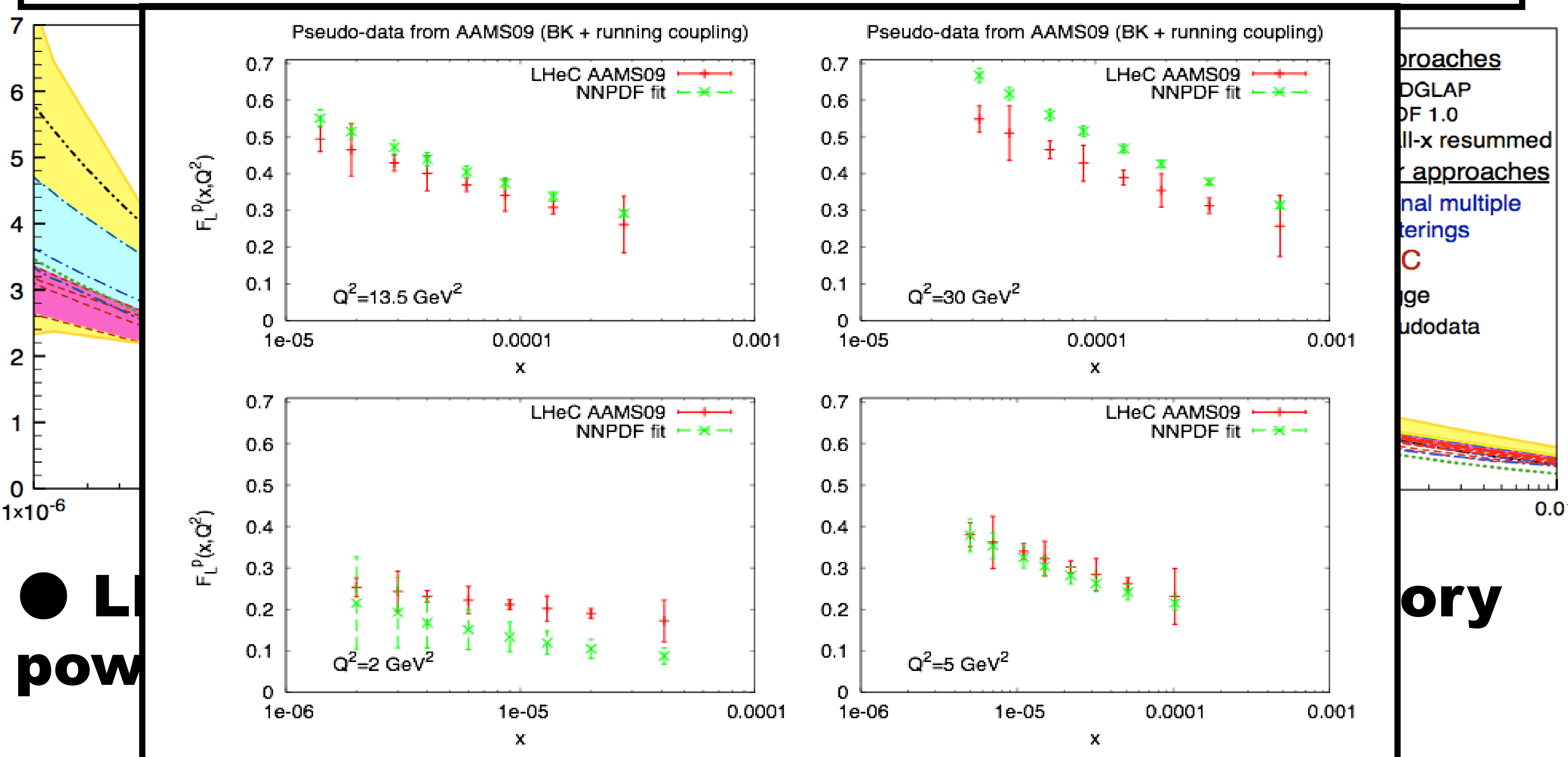



then...



# Small-x: inclusive

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




● LH ... ory pow

# LHeC, a Higgs Factory

M.Klein

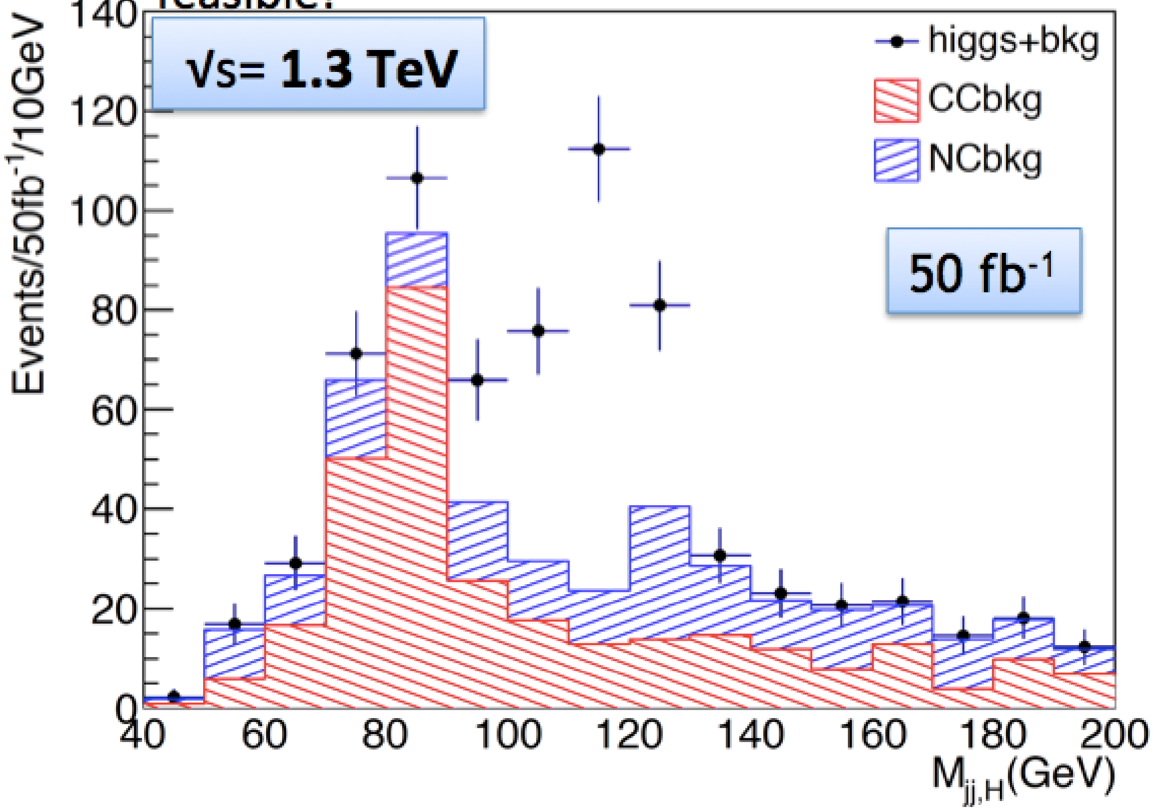
| LHeC Higgs | | CC ($e^-p$) | NC ($e^-p$) | CC ($e^+p$) |
|---|---|---|---|---|
| Polarisation | | -0.8 | -0.8 | 0 |
| Luminosity [$ab^{-1}$] | | 1 | 1 | 0.1 |
| Cross Section [fb] | | 196 | 25 | 58 |
| Decay | BrFraction | $N^H_{CC}$ $e^-p$ | $N^H_{NC}$ $e^-p$ | $N^H_{CC}$ $e^+p$ |
| $H \to b\bar{b}$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

# H→$b\bar{b}$ results updated

[ after Higgs discovery $M_H$=125 GeV, $E_p$=7 TeV]

U.Klein

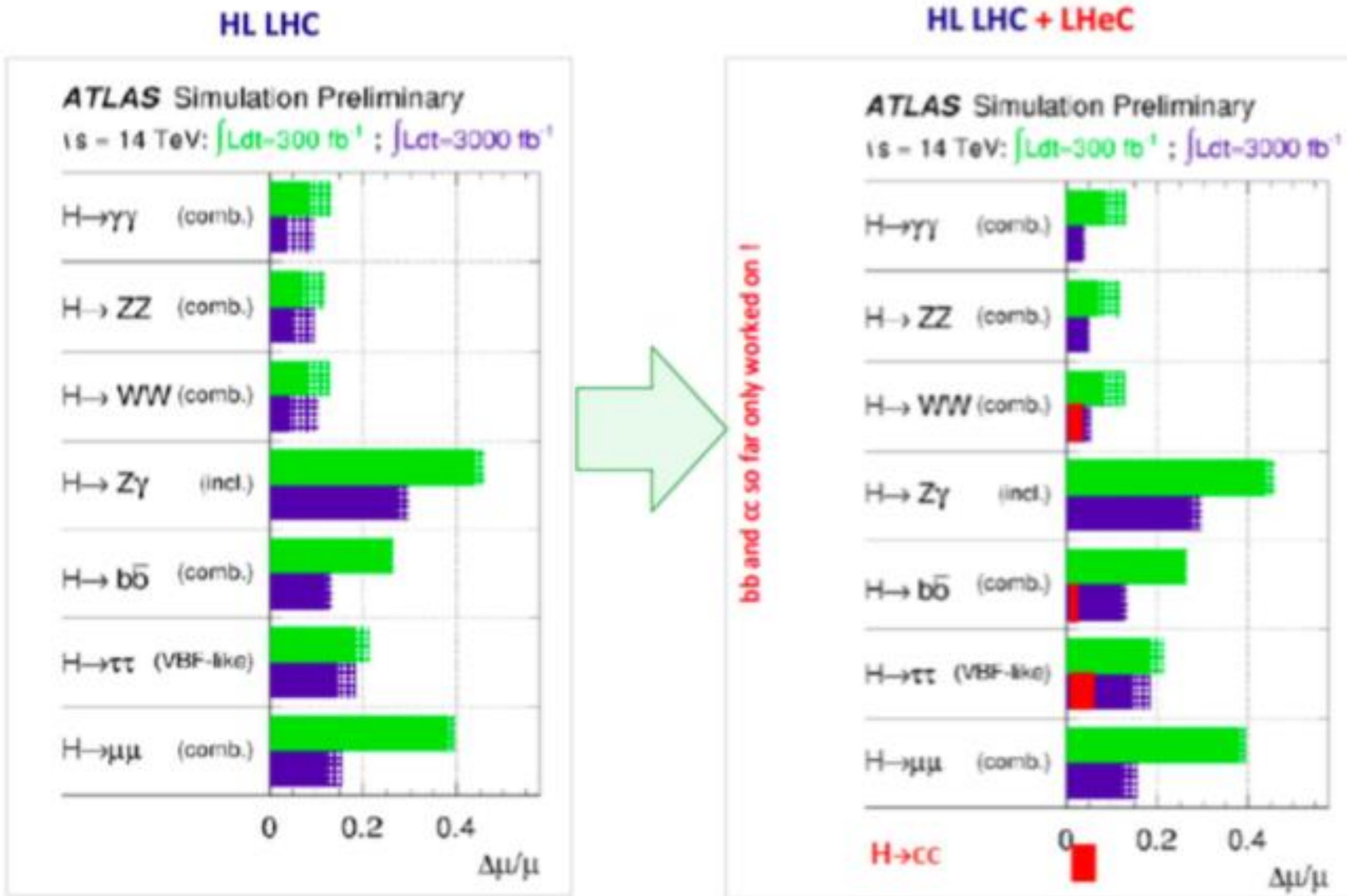
- Case study for electron beam energy of 60 GeV using same analysis strategy
  - luminosity values of 50 $fb^{-1}$ → with high luminosity LHeC 100 $fb^{-1}$/year would be feasible!




Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

| $M_H$ selection [100-130 GeV] | $E_e$ = 60 GeV (50 $fb^{-1}$, P=0) |
|---|---|
| H → bb signal | 175 |
| S/N | 1.9 |
| S/√N | 18.1 |

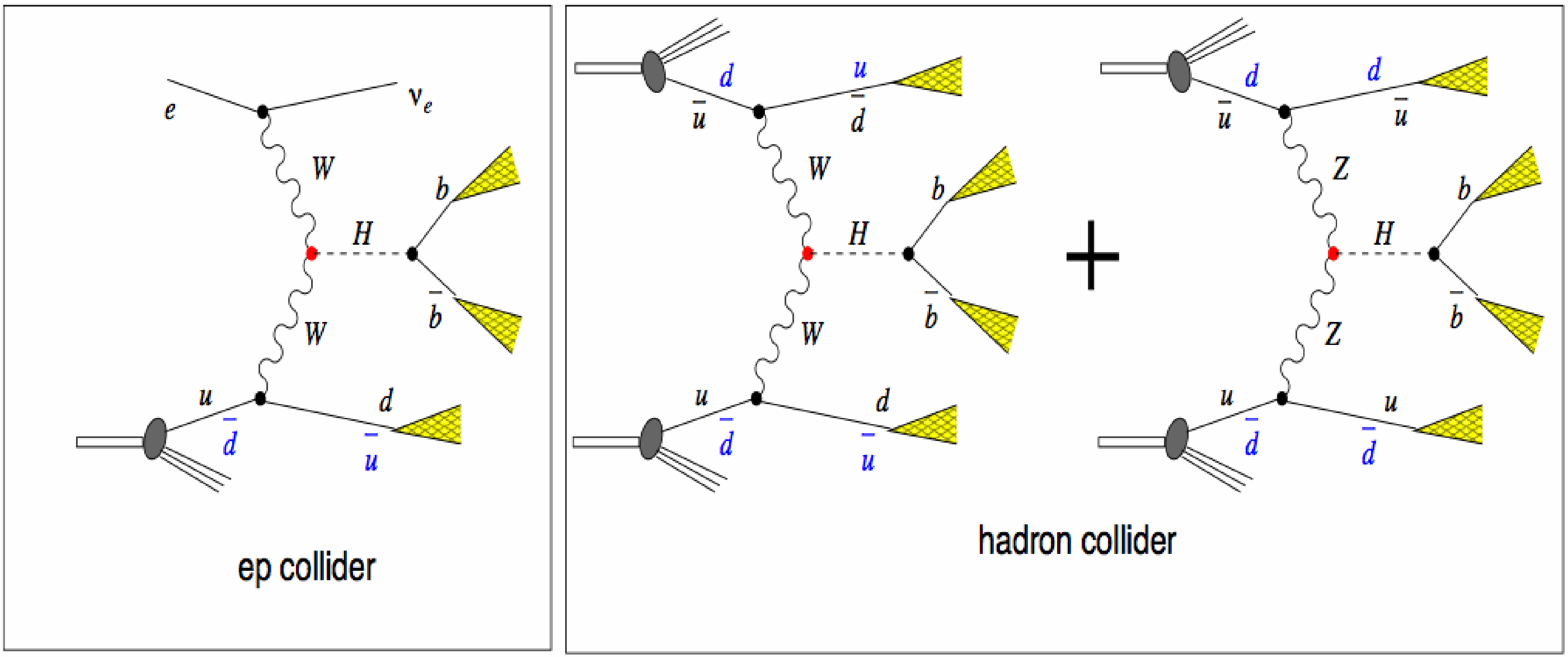
- Electron energy recovery LINAC with **high electron polarisation of 80% and $10^{34}$ $cm^{-2}$ $s^{-1}$** ➔ enhancement by factor 20*1.8 feasible, i.e. around 6300 Higgs candidates for $E_e$=60 GeV allowing to measure Hbb coupling with ~ **0.5 % - 1%** statistical precision.




- GLUON FUSION AND $W$ FUSION $\Rightarrow$ PDF+$\alpha_s$ UNCERTAINTY REMOVED (hatched bands)
- $H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION;
- $\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE

**S. Forte**

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

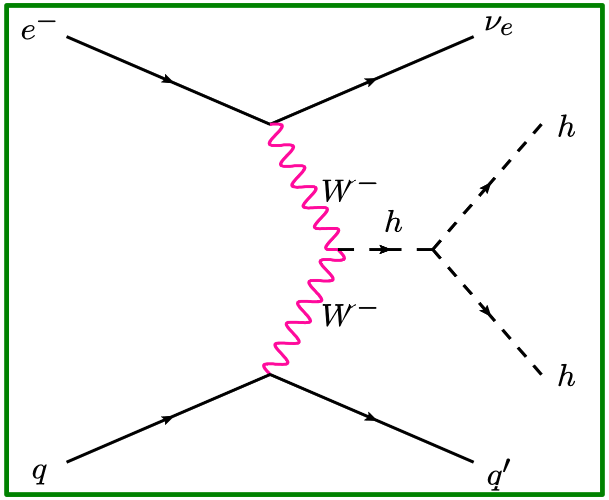



**$ep$ process uniquely addresses the $HWW$ vertex.**

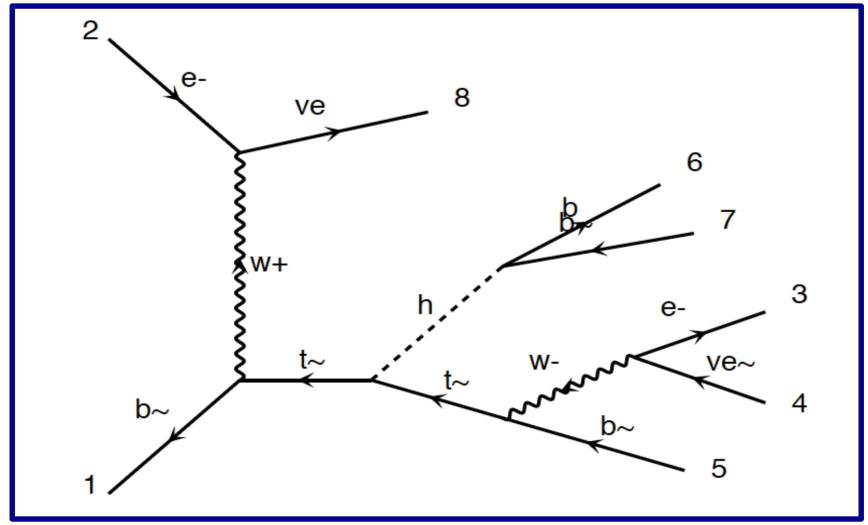
$$\Gamma^{\mathrm{SM}}_{\mu\nu} = -g M_V \, g_{\mu\nu}$$

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

# FCC: HH and tHt in ep




New Studies



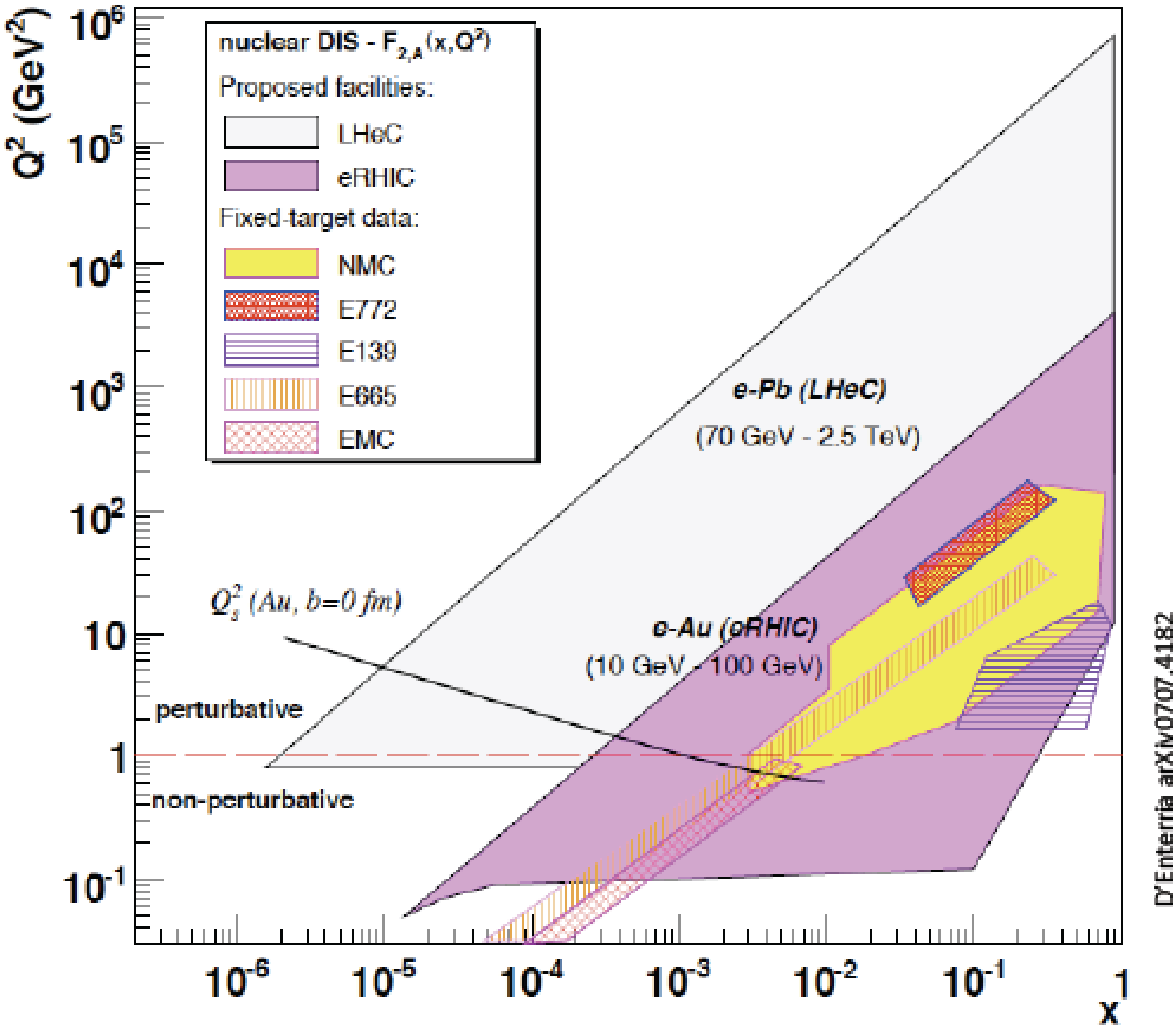

FCC-he unpolarised
Cross section at 3.5 TeV:

total : 0.7 fb
fiducial : 0.2 fb
using pt(b,j)>20 GeV
ΔR(j.b)>0.4
n(j) <5
n(b) < 3

| Processes | $E_e$ (GeV) | $\sigma$(fb) | $\sigma_{eff}$(fb) |
|---|---|---|---|
| $e^-p \to \nu_e hhj, h \to b\bar{b}$ | 60 | 0.04 | 0.01 |
| | 120 | 0.10 | 0.024 |
| | 150 | 0.14 | 0.034 |

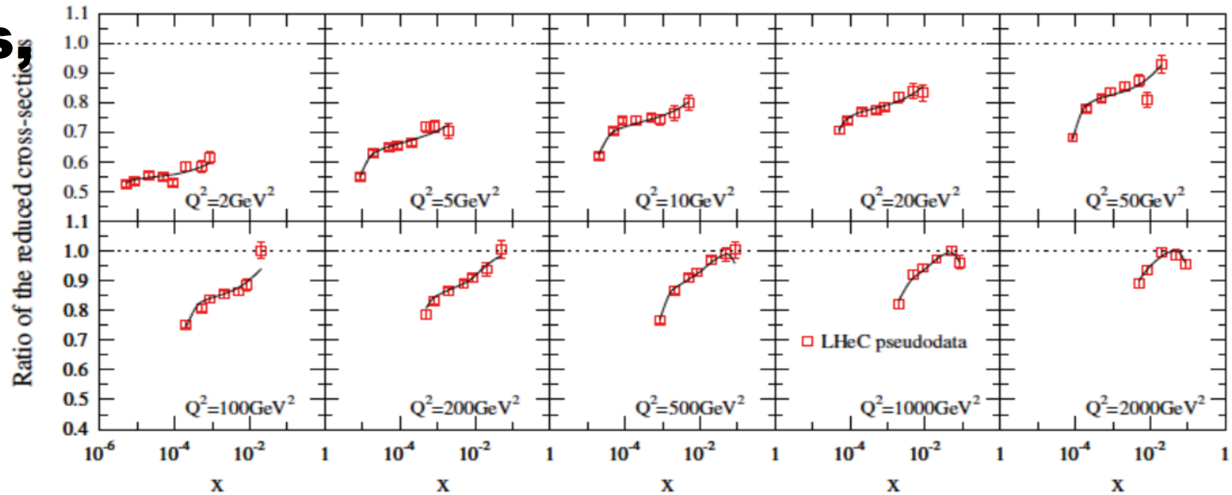
Polarisation, max lumi, tuning cuts, bb and WW decays may provide O(10%) precision. Exploration of anomalous couplings possible

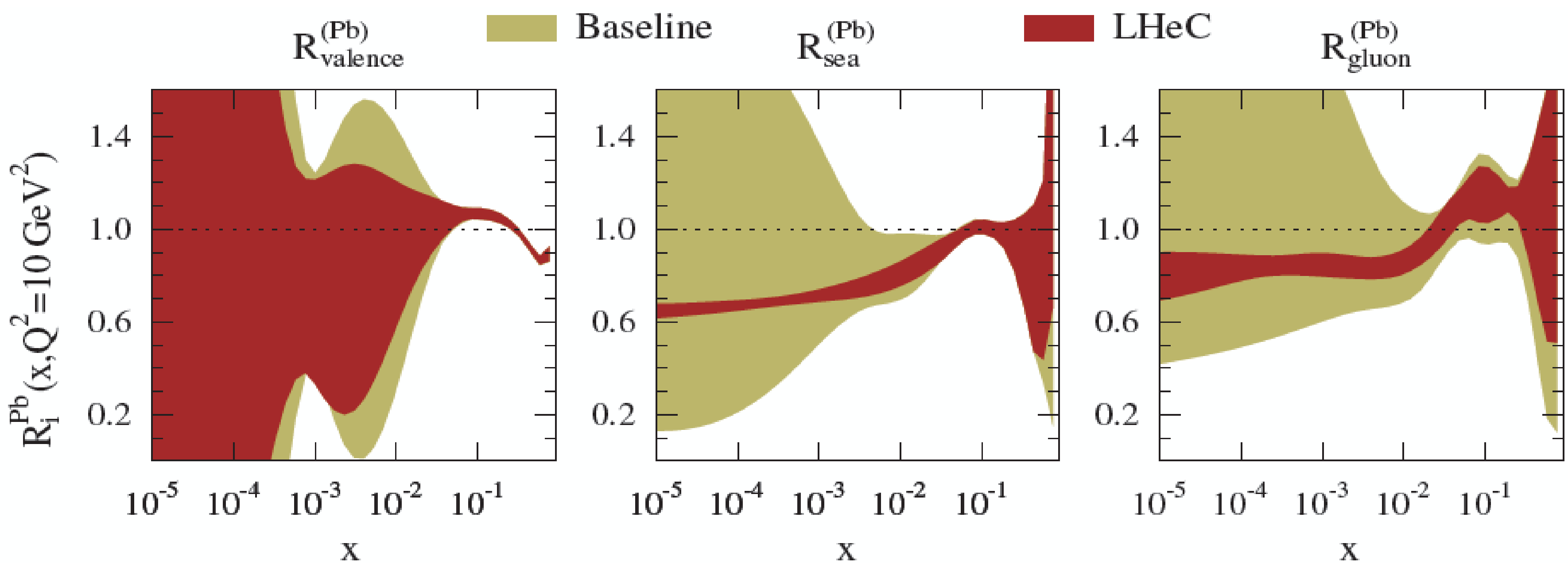
# eA Collisions



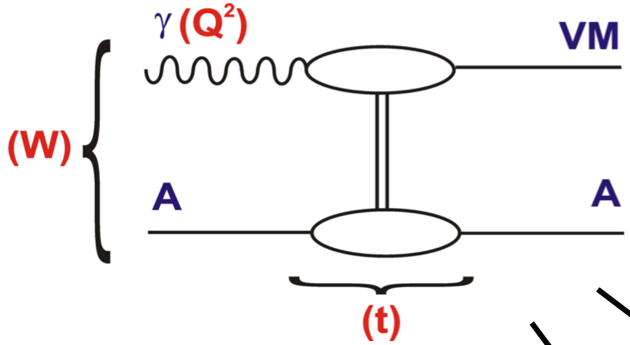
# eA: inclusive

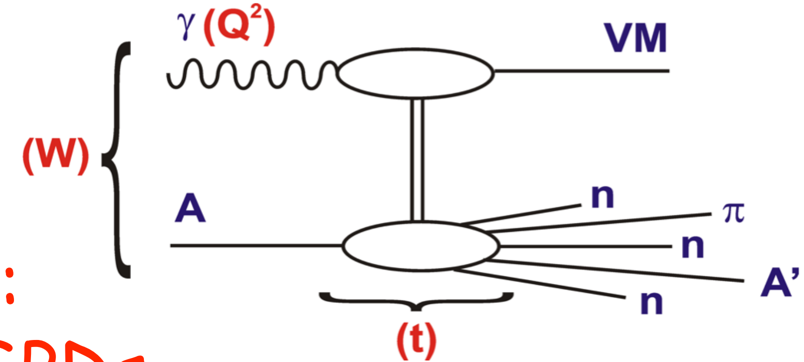
- Large impact on nPDFs, possible to make a Pb fit without proton PDFs!!!
- Large room for improvements: NC+CC at several energies, flavour decomposition,...



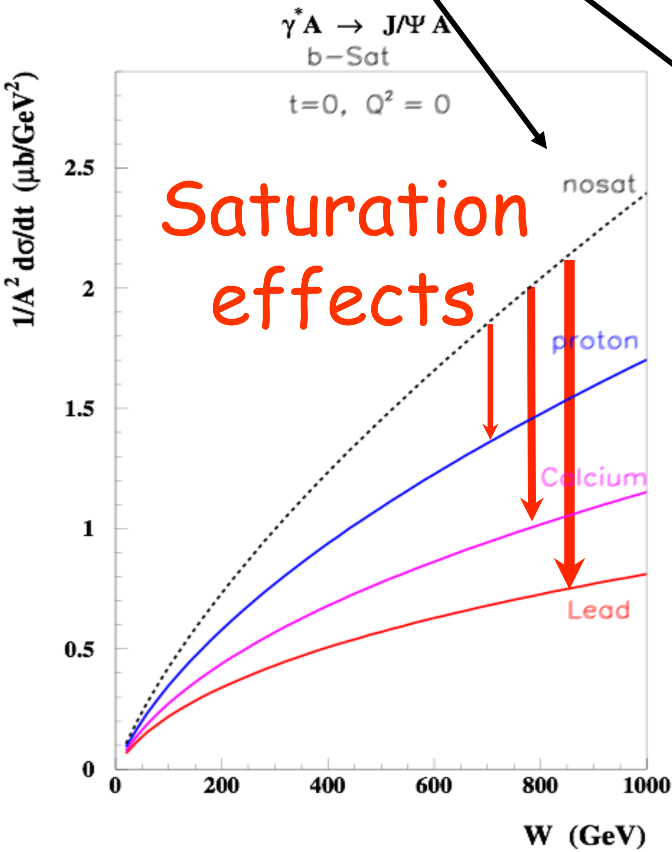



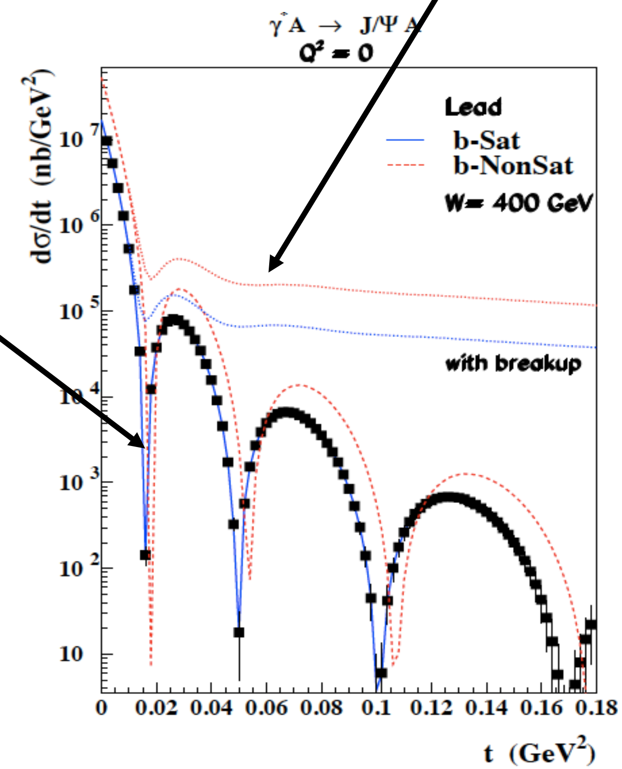
# eA: diffractive




- Elastic VM: saturation, nGPDs.




N. Armesto

# Further Path Determined with IAC Mandate

**M.Klein**

Guido Altarelli (Rome) *)
Sergio Bertolucci (CERN)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
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)

The IAC was invited in 12/13 by the DG with the following

**Mandate 2014-2017**

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.

*) IAC Composition End of January 2014 +
Oliver Brüning Max Klein ex officio

# Coordination Group for Future DIS at CERN

**M.Klein**

LCG (2014-2017) *)

Nestor Armesto
Oliver Brüning
Stefano Forte
Andrea Gaddi
Bruce Mellado
Max Klein
Peter Kostka
Daniel Schulte
Frank Zimmermann

Directors (ex-officio)
Sergio Bertolucci, Frederick Bordry

The coordination group was invited end of December 2013 by the CERN directorate with the following mandate (2014-2017)

The group has the task to coordinate the study of the scientific potential and possible technical realisation of an ep/eA collider and the associated detectors at CERN, with the LHC and the FCC, over the next four years. It also should coordinate the design of an ERL test facility at CERN as part of the preparations for a larger energy electron accelerator employing ERL techniques.

The group will cooperate with CERN and an International Advisory Committee, chaired by the emeritus DG of CERN, Professor Herwig Schopper, who also advises the CERN directorate. The Coordination Group is asked to represent the ep/eA collider development towards CERN, its committees and the international community. The currently tentative composition is listed *left*. CERN has asked Max Klein to chair and Oliver Brüning to co-chair this activity

*) LCG Composition early January 14

# Outlook and Conclusions

- The importance of ep/eA collisions for high energy pp/pA/AA collider is well known
- The LHeC would provide precise determination of parton distribution functions necessary to fully exploit the discovery potential of the LHC
- The physics program of the LHeC is broad
  - From “standard’ QCD to discovery physics
- With enhanced luminosity the LHeC would be turned into a Higgs and single top factory
  - Unique capabilities and complementarities
- With FCC-eh the production of double Higgs and ttH possible with unique capabilities