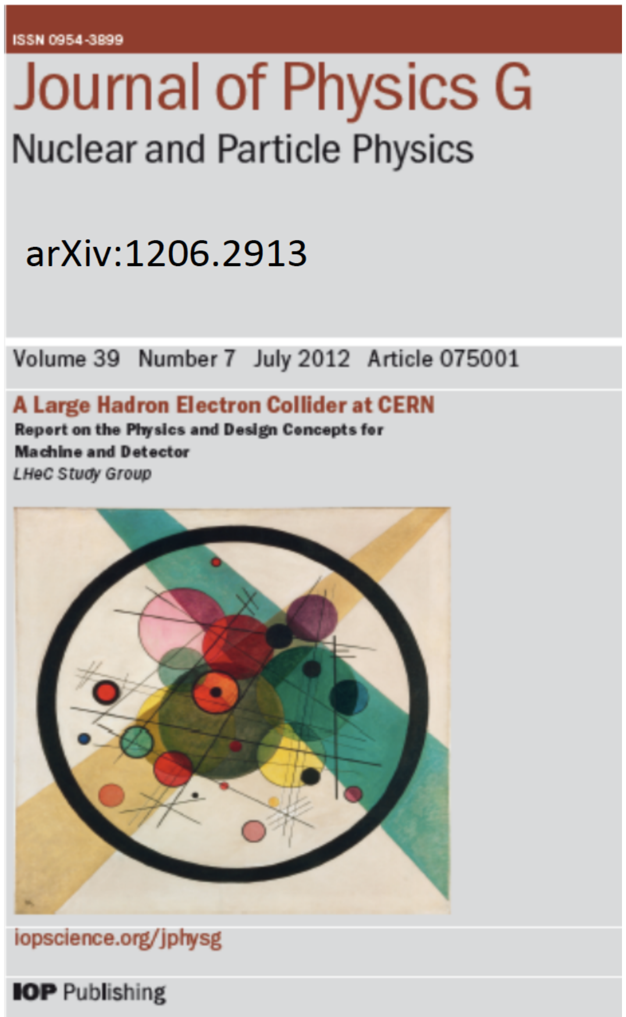
The Case for the LHeC

From the CDR 2012 to the time ahead 2018+



Particle Physics

Physics Case

Preparations

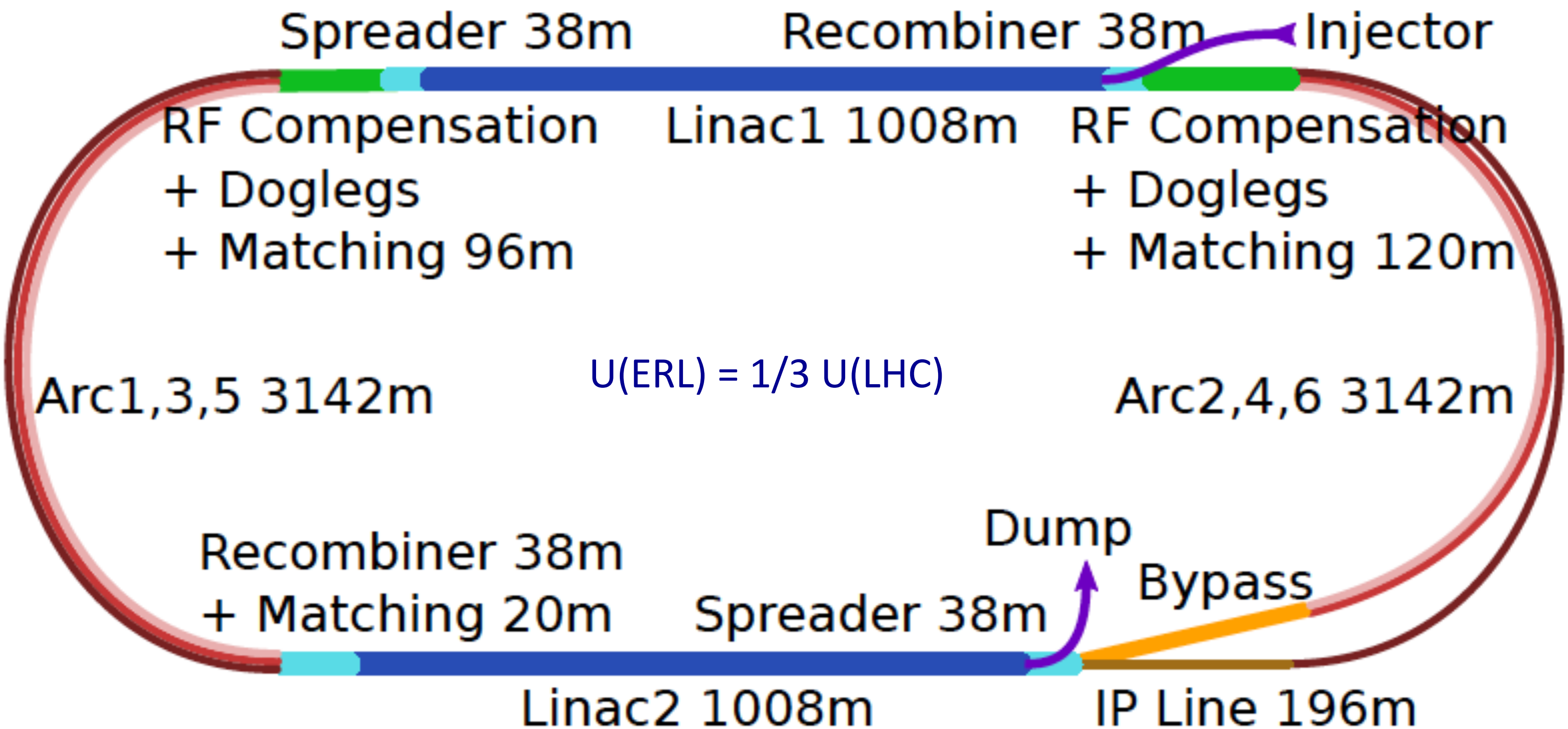
Max Klein

UNIVERSITY OF LIVERPOOL

Contribution to a Panel on Future DIS, 17.4.2018, Kobe, for the LHeC/FCCeh Study Group

http://lhec.web.cern.ch

60 GeV Electron ERL added to LHC



Concurrent operation to pp, LHC/FCC become 3 beam facilities. Power limit: 100 MW
10^{34} cm^{-2} s^{-1} luminosity and factor of 15/120 (LHC/FCCeh) extension of Q^2, 1/x reach
1000 times HERA luminosity. It therefore extends up to x~1.
Four orders of magnitude extension in deep inelastic lepton-nucleus (ion) scattering.

Towards a strategy for European Particle Physics

"Two Problems" of HEP

1980: Leon Lederman at ICHEP in Madison:
"Shortage of Money and Overconfidence of Theorists" [SU(5)/SUSY ahead times..]

Today:
Shortage of Money and Missing Confidence of Theory [EFT/ SUSY passed times?]

Reminiscent of the situation as experienced 50 years ago:
before the SM and **discovery of partons in ep at Stanford**

↓

Time for high precision,
high energy,
high luminosity
collider experiments
ee, pp and ep:

Progress in particle physics needs their continuous interplay to take full advantage of their complementarity

Guido Altarelli, DIS 2009, Madrid

→

In 2014 CERN decided to set up a new LHeC organisation and an IAC to "assist building the international case of an ep/A collider" at CERN

IAC: Two main tasks:
Update CDR + Testfacility

Organisation*)

International Advisory Committee

Mandate by CERN to define
"..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

Gianluigi Arduini
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(12) are members of the FCC coordination team

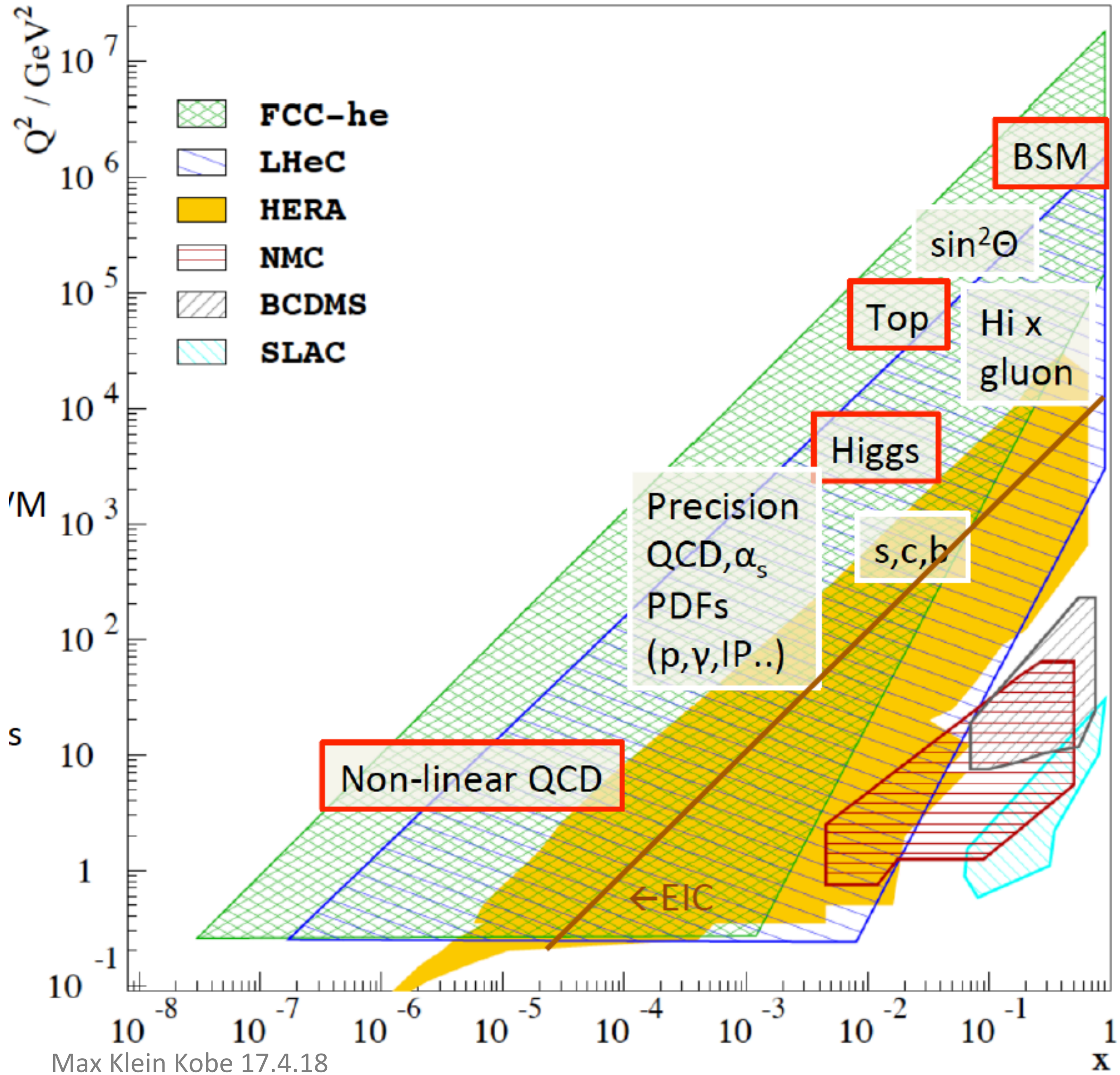
OB+MK: co-coordinate FCCeh

Working Groups

PDFs, QCD
Fred Olness,
Claire Gwenlan
Higgs
Uta Klein,
Masahiro Kuze
BSM
Georges Azuelos,
Monica D'Onofrio
Oliver Fischer
Top
Olaf Behnke,
Christian Schwanenberger
eA Physics
Nestor Armesto
Small x
Paul Newman,
Anna Stasto
Detector
Alessandro Polini
Peter Kostka

*) April 2018

Physics with Energy Frontier DIS



Raison(s) d'etre of the LHeC

Cleanest High Resolution Microscope: QCD Discovery

Empowering the LHC Search Programme

Transformation of LHC into high precision Higgs facility

Discovery (top, H, heavy ν's..) Beyond the Standard Model

A Unique Nuclear Physics Facility

Huge increase in energy and luminosity enables unique development of particle physics

The Classic DIS Programme with the LHeC: $0 < Q^2 < 10^6$ GeV2, $1 < x < 10^{-6}$

Generalised Parton Distributions [DVCS] – “proton in 3D - tomography”

Unintegrated Parton Distributions [Final State] – DGLAP/BFKL?

Diffractive Parton Distributions [Diffraction] – pomeron, confinement??

Photon Parton Distribution [Photoproduction Dijets,QQ; $F_{2,L}$] - fashionable..

Neutron Parton Distributions [Tagged en (eD) Scattering] – ignored at HERA

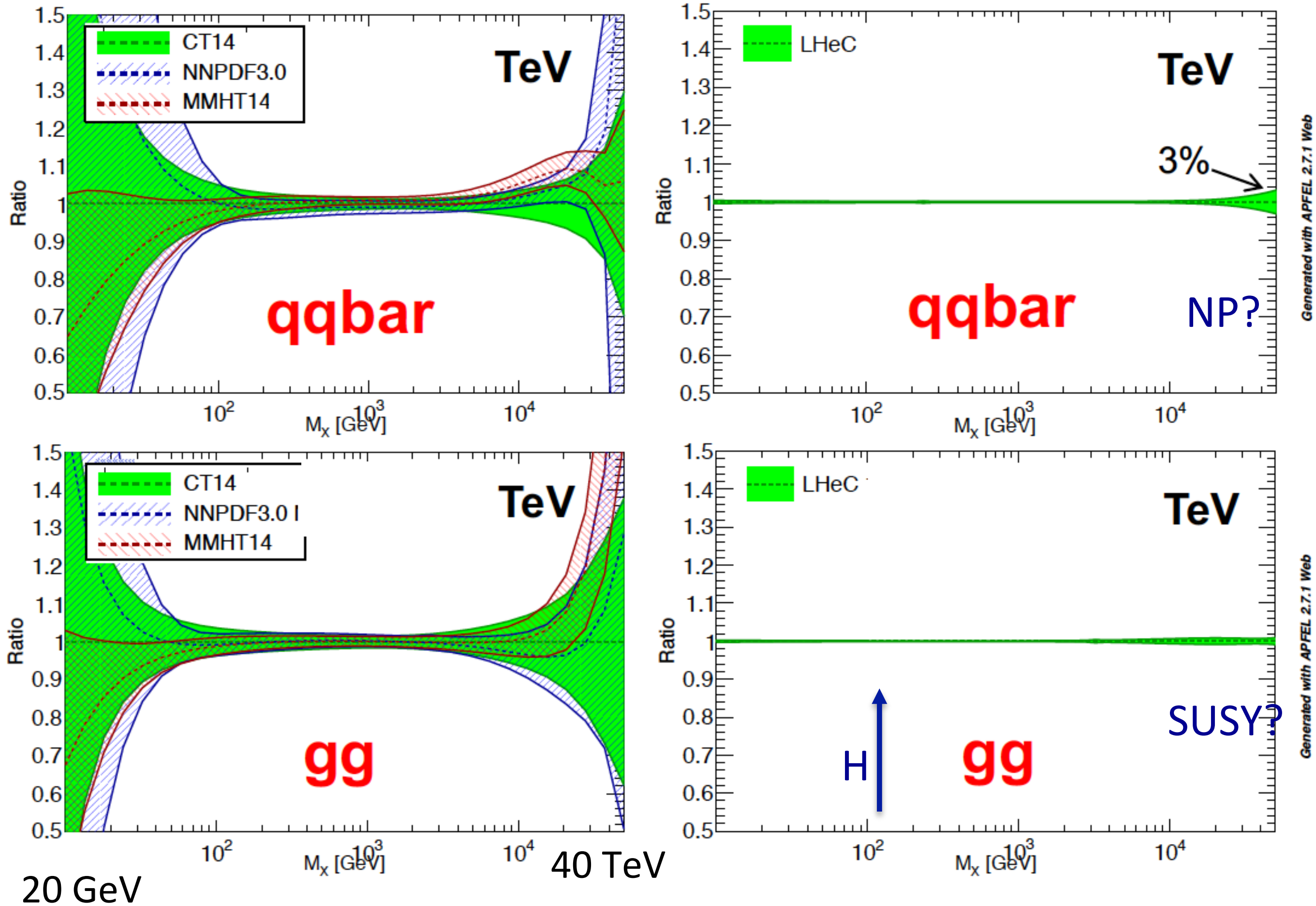
see the CDR 1206.2913 + updates

The LHeC collinear proton (and nuclear) 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…

PDFs are NOT determined in pp but in ep

cf backup



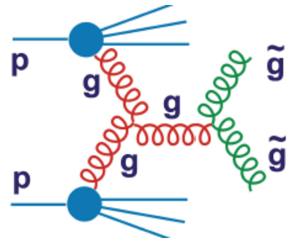
Empowers the LHC H, BSM + SM Physics

Empowering pp Discoveries

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

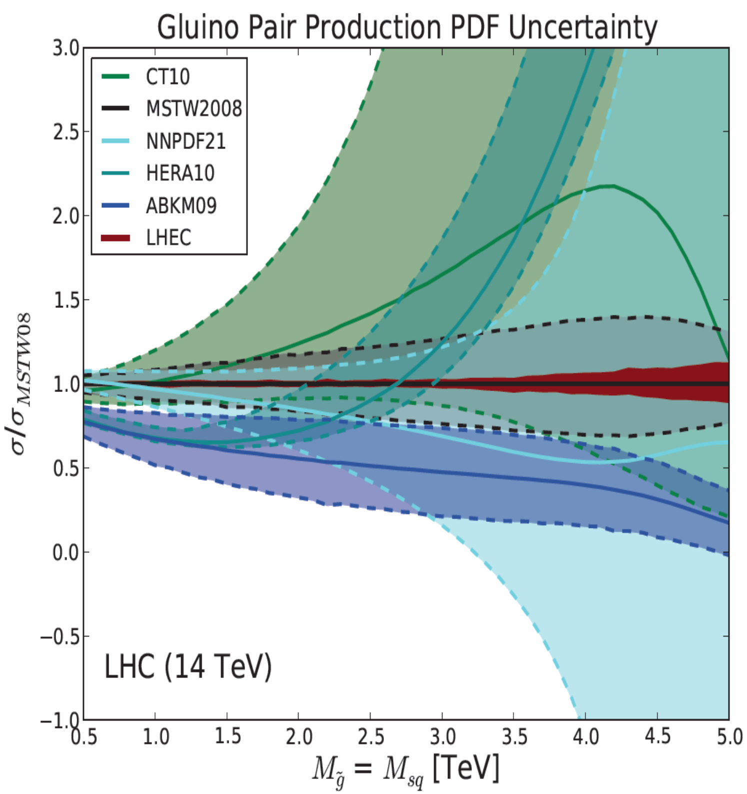
GLUON

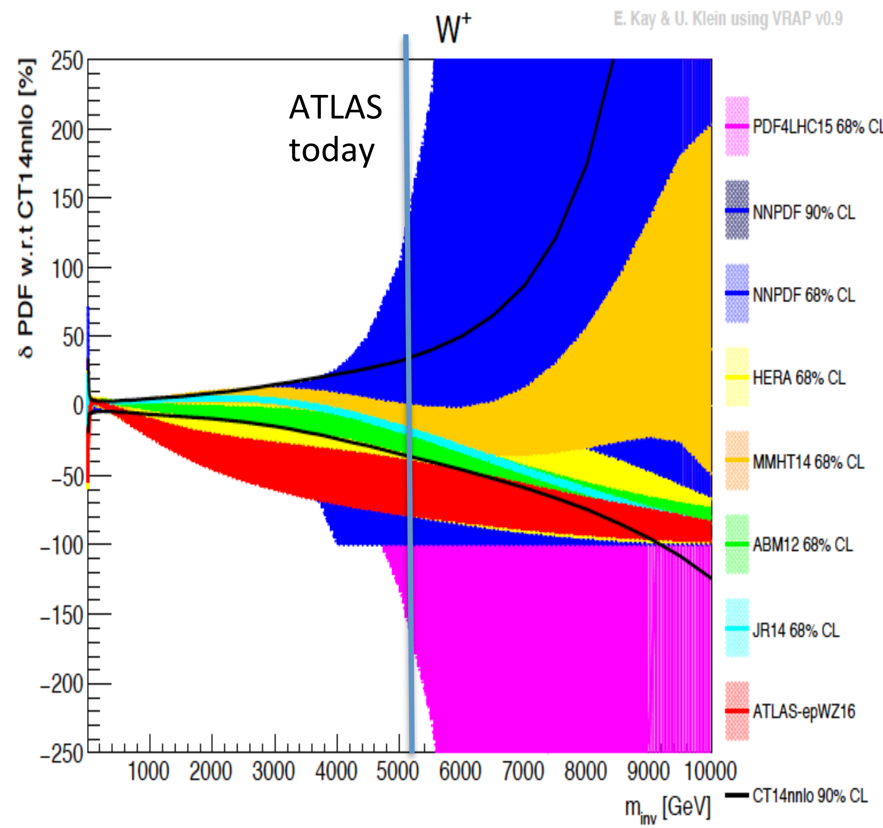
SUSY, RPC, RPV, LQS..



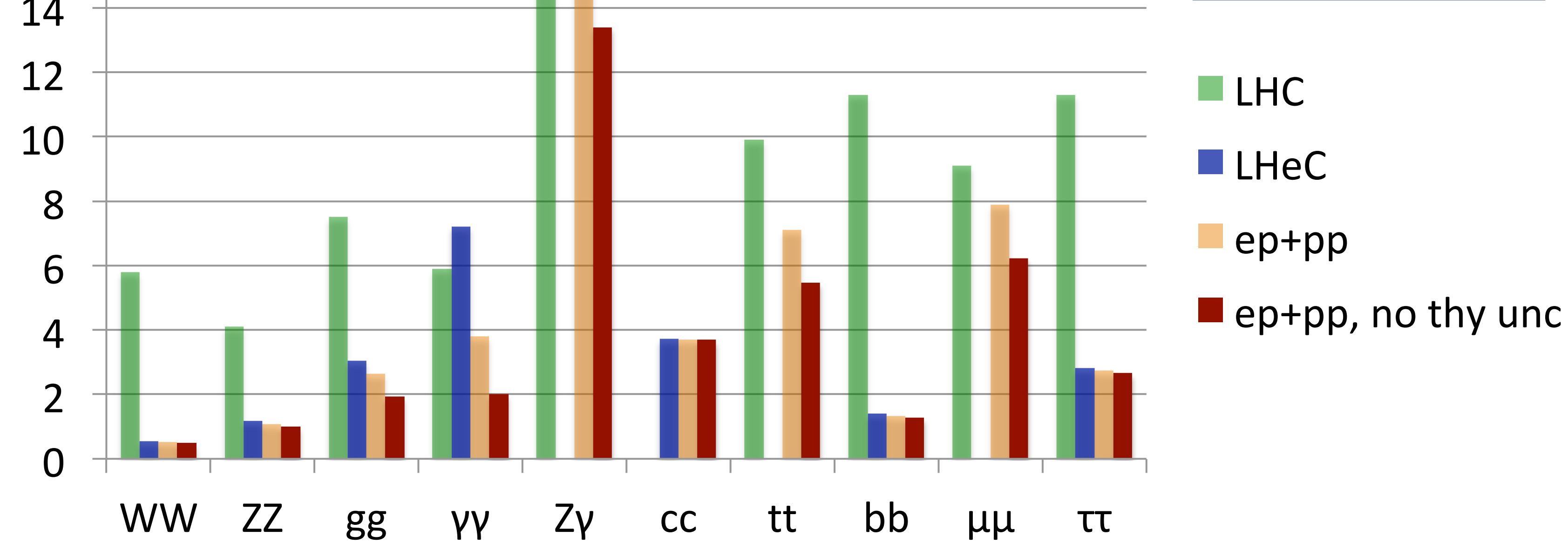
QUARKS

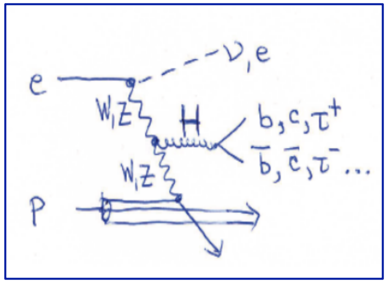
Exotic+ Extra boson searches at high mass





Determination of SM Higgs Couplings, HL-LHC and LHeC → LHC





J. De Blas, M.+U. Klein, 16.4.2018

LHC: ATLAS prospects PUB Note 2014-016

ttH at LHeC to 15%

The addition of ep to pp (LHeC to LHC (HL,HE) and FCC-eh to FCC-pp) **transforms these machines into precision Higgs facilities. Vital complementarity with e^+e^-** (JdB Amsterdam)

Note that the HL LHC prospects are being updated (HL/HE LHC Physics workshop).

New Physics through High Precision

Masses:

Charm HERA 40 MeV LHeC 3 MeV

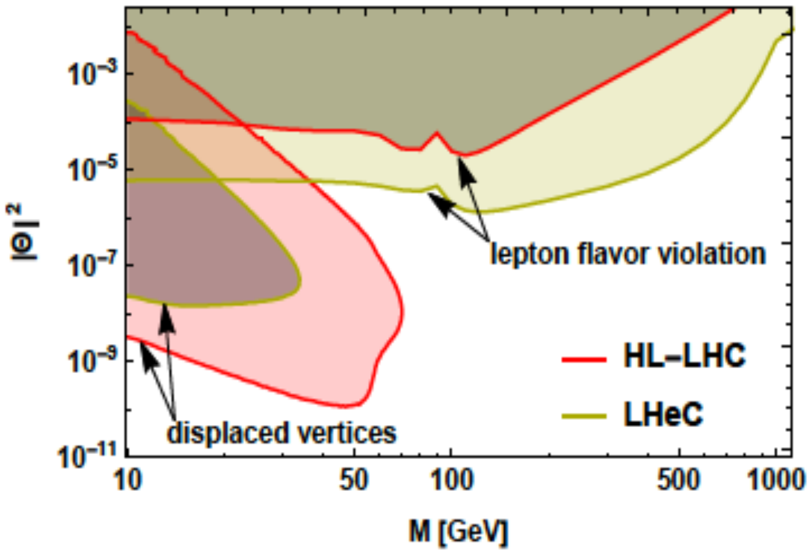
W LHC 19→ 10 MeV LHeC 15 MeV
and prediction to ±2.8 MeV for pp

Top: to be studied

Proton: gluon we are made of…

Higgs: Cross section to 0.3%: Mass dependent. OB, MK 1305.2090

Neutrinos: **Heavy "sterile" Neutrinos**



Antusch, Cazzato, Fischer – work still in progress

Int. J. Mod. Phys., A32(14):1750078, 2017.

CKM, electroweak, alpha_s, …

V_{tb}: to 0.01

V_{cs}: to 0.02 [LHC+LHeC, like ATLAS+HERA]

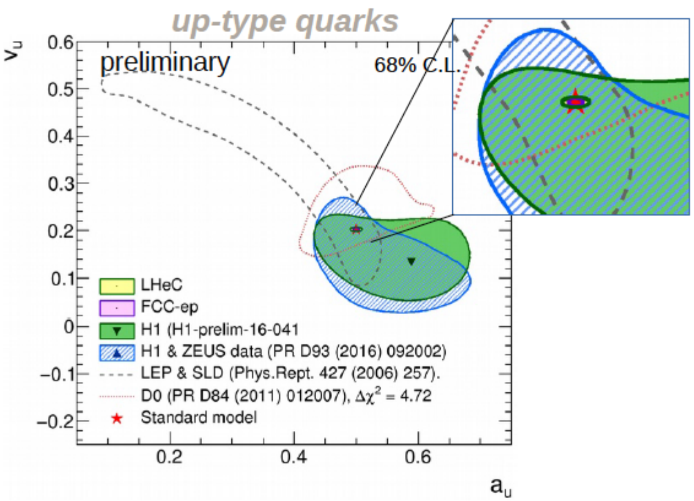
α_s to 0.2% [0.1% with HERA] – GUT?

$\sin^2\theta_W$ (μ)

LHC: better than LEP with LHeC PDFs

LHeC: scale dependence from 0.4 GeV (PERLE) to 1 TeV (LHeC)

NC couplings



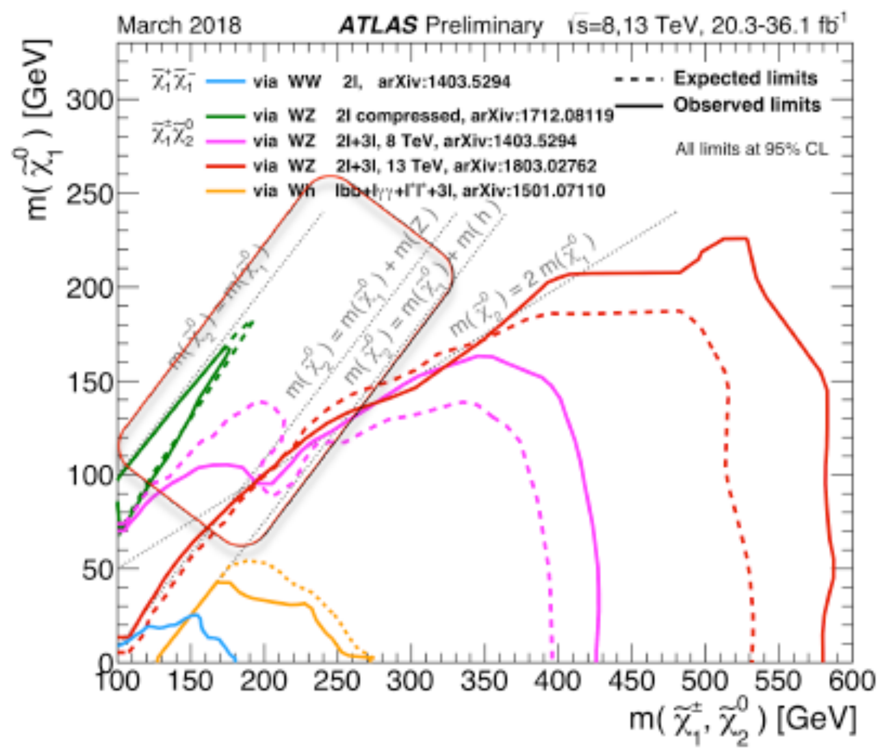
Britzger, MK, Spiessberger, Zhang – work still in progress

Beyond the Standard Model

Higgs into Dark Matter
Higgs into Neutralinos (RPV SUSY)
Higgs into Scalars → 4b

$H^{\pm\pm}$ in Vector Boson Scattering
$H^{\pm}$ in Vector Boson Scattering
H^{+} in 2HDM

Triple Gauge Couplings
Top FCNC
Contact Interactions
Empower LHC Discoveries



D Curtin et al arXiv:1712.07135

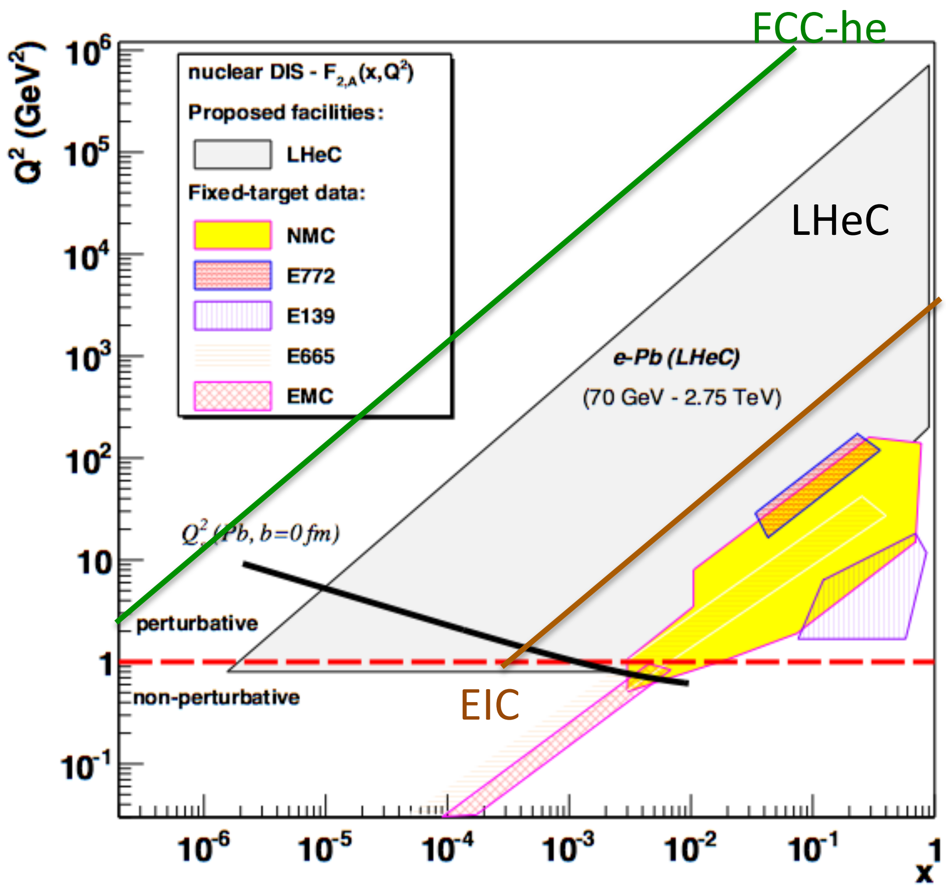
> This adds significant motivation for the construction of future $e^- p$ colliders. Together with the invaluable proton PDF data, as well as precision measurements of EW parameters, top quark couplings and Higgs couplings, our results make clear that adding a DIS program to a *pp* collider is necessary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

Higgsinos: mass degenerate
Wino/bino compressed
Prompt decays or long lifetimes

→ SUSY ewk sector most challenging for pp colliders

cf U Klein + M Donofrio at Amsterdam FCC

LHeC as Electron Ion Collider



Precision QCD study of parton dynamics in nuclei
Investigation of high density matter and QGP
DGLAP to BFKL – vital for LHC and FCCpp physics

Extension of kinematic range in lA by 4-5 orders of magnitude will change QCD view on nuclear structure and parton dynamics

May lead to genuine surprises…

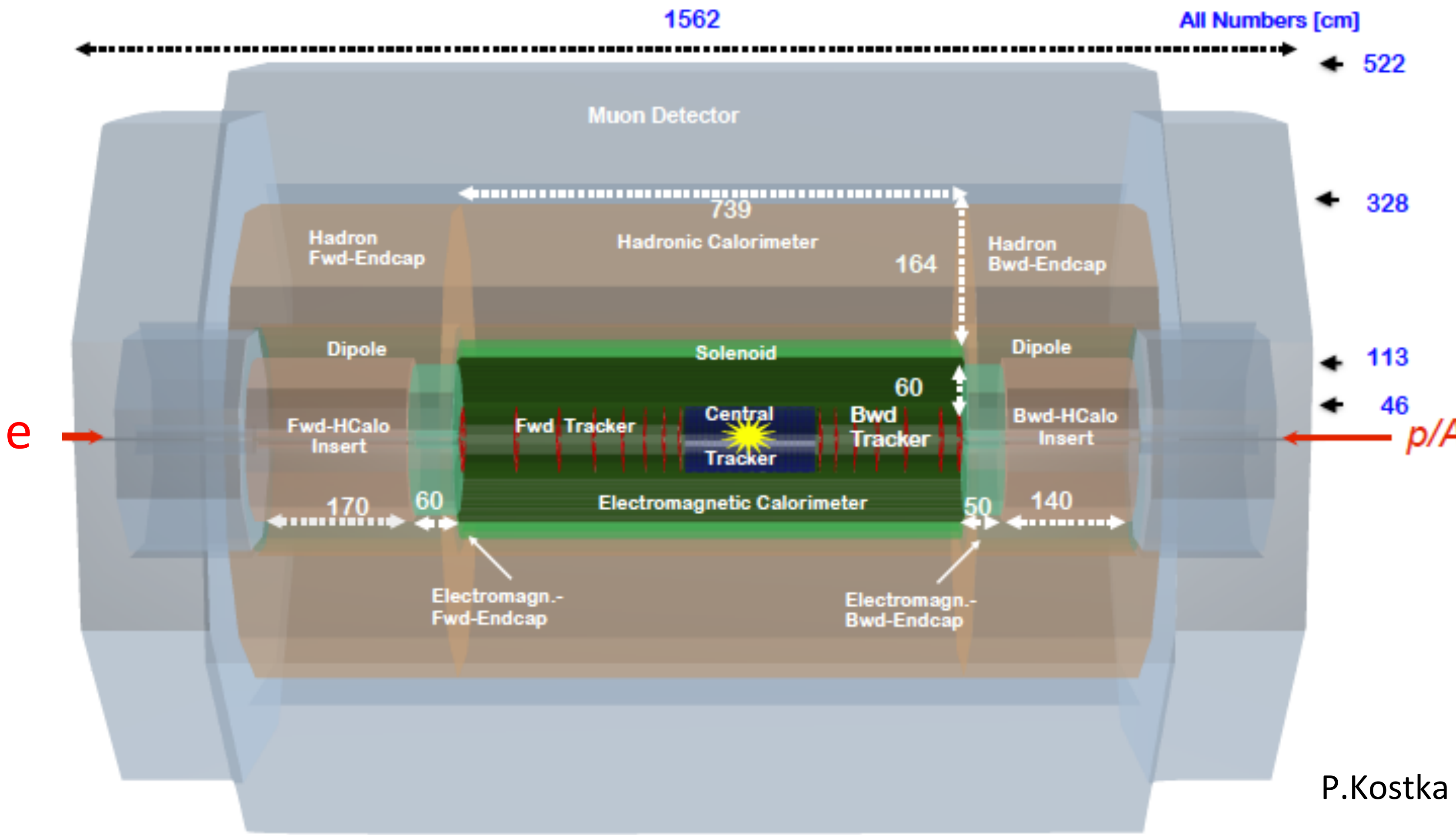
- No saturation of xg (x,Q^2) ?
  [discover saturation in ep
  THEN analyse eA −separate
  nonlinear g from nuclear effects]
- Small fraction of diffraction ?
- Broken isospin invariance ?
- Flavour dependent shadowing ?

- Safe: nuclear PDFs like at HERA

→ $R(x,Q^2)$ flavour dependent

$L_{eN} = 6\ 10^{32}\ cm^{-2}\ s^{-1}$

LHeC Detector for the HL/HE LHC



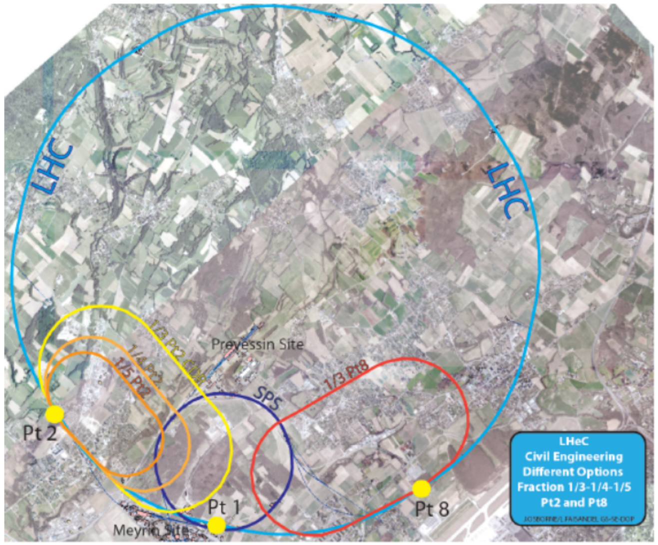
P.Kostka et al

Length x Diameter: LHeC (13.3 x 9 m^2)   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

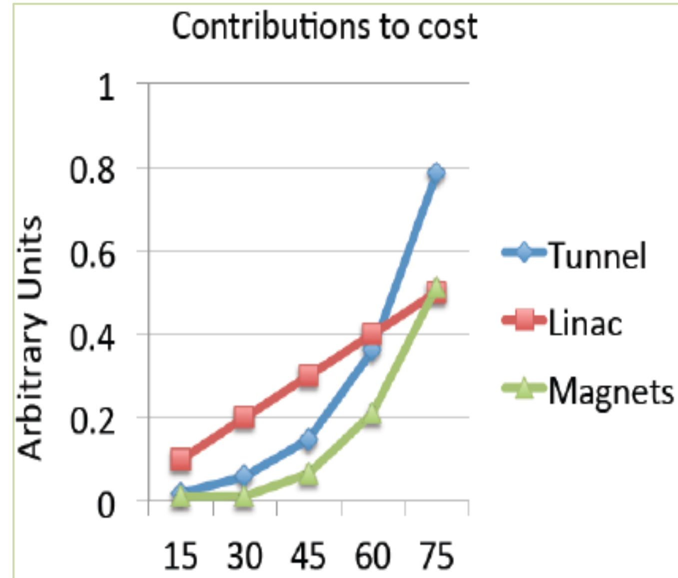
Civil Engineering and Cost Optimisation

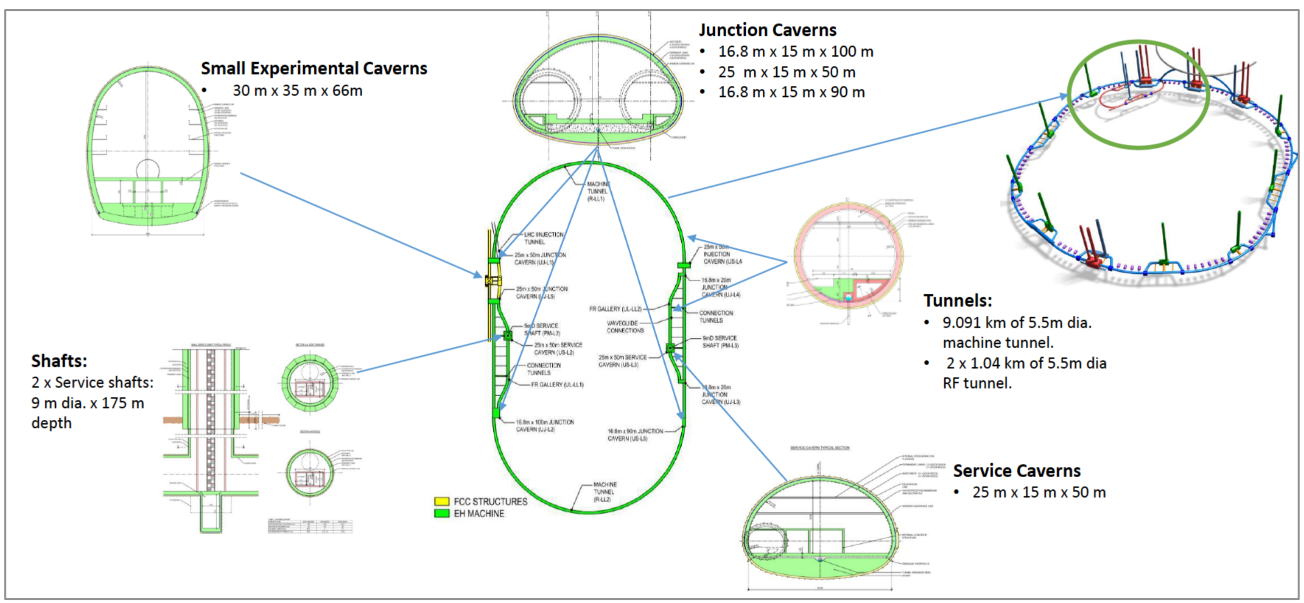


Linac cost driver

E_e- physics – cost for Halina to come

Staging? HL→ HE





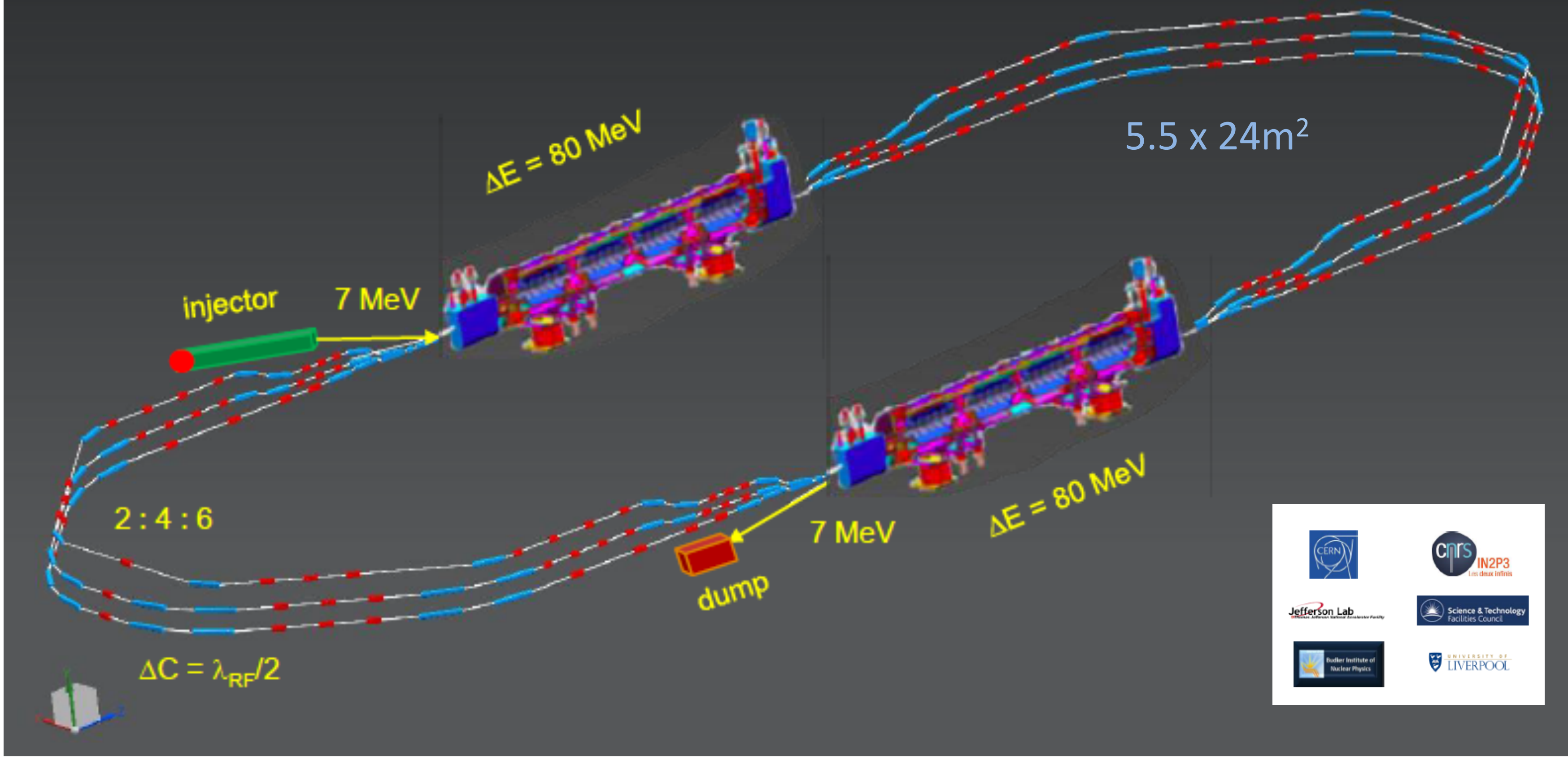
2nd full civil engineering study

Amberg + ILF consult

John Osborne et al
Amsterdam FCC 12.4.

Powerful ERL for Experiments at Orsay

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA → 10 MW

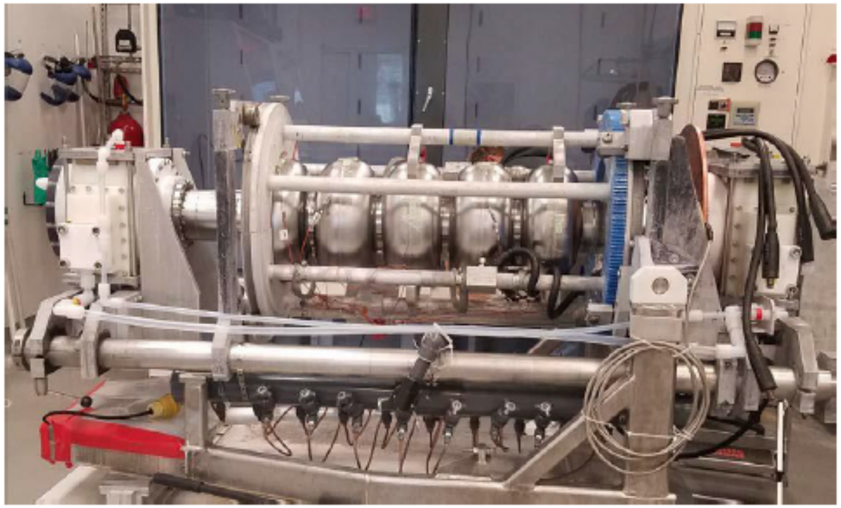


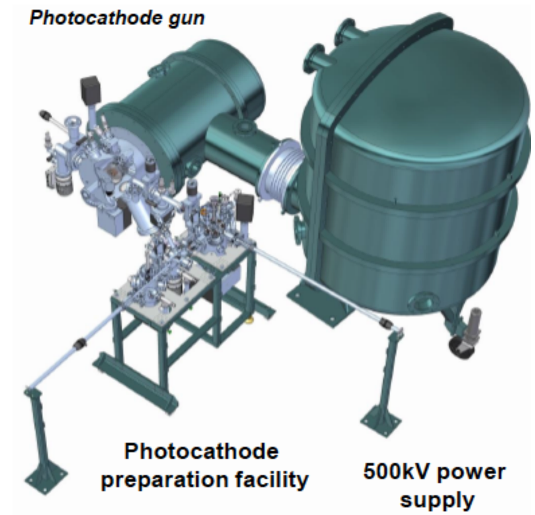
cf Walid Kaabi at Amsterdam FCC

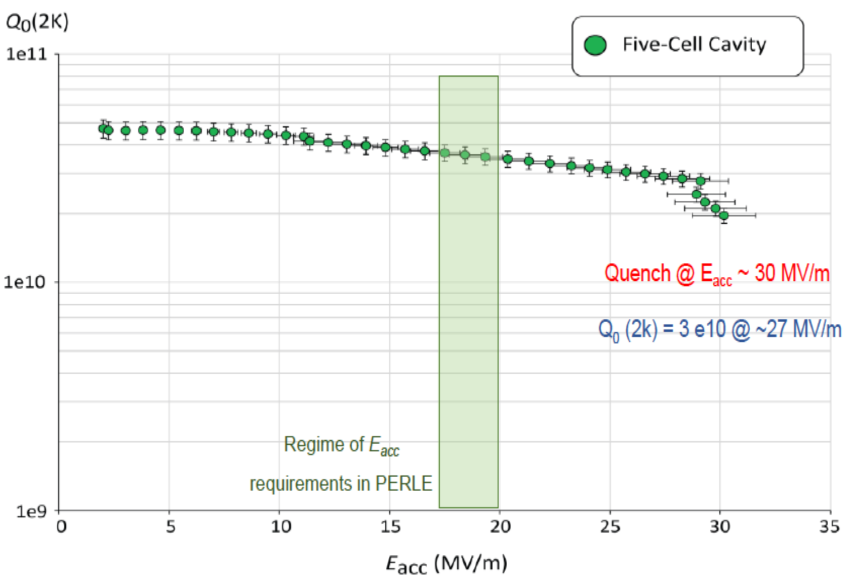
New SCRF, High Intensity (100 x ELI) ERL Development Facility with unique low E Physics

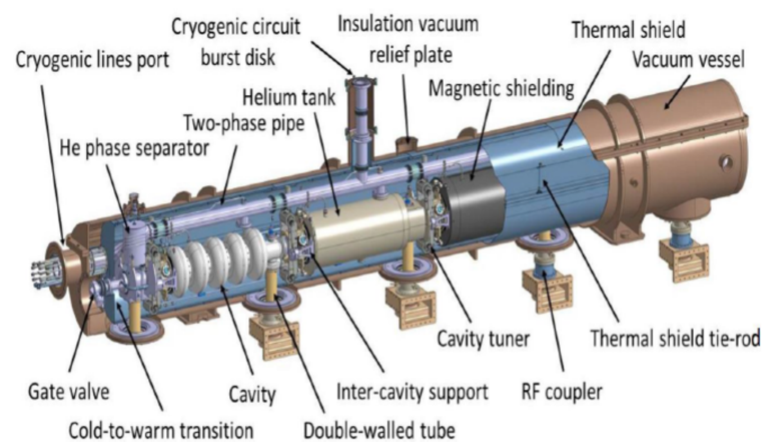
Towards PERLE: 802 MHz cavity, Source, Cryomodule, Magnets

First 802 MHz cavity successfully built (Jlab)









BINP, CERN, Daresbury/Liverpool, Jlab, Orsay, +

CDR 1705.08783 [J.Phys G] → TDR in 2019

Recent Presentations on LHeC and FCCeh

http://lhec.web.cern.ch

FCC Week Amsterdam 9-13.4.18

Theory
Jo Rudermann, Jorge de Blas
Overviews
Bruce Mellado, Uta Klein

QCD Max Klein
Top Christian Schwanenberger
and Orhan Cakir
Higgs Uta Klein
BSM Monica D'Onofrio
Detector Peter Kostka

Machine Oliver Bruening
Civil Engineering John Osborne
Cavity Frank Marhauser
IR Roman Martin
PERLE Walid Kaabi

DIS Workshop Kobe 16.4.-18.4.

Machine+PERLE Gianluigi Arduini

PDFs Claire Gwenlan
Low x+Diffraction Paul Newman
Nuclear PDFs Nestor Armesto
Higgs Uta Klein
Top Hao Sun
Electroweak Max Klein
New and BSM Jose Zurita

Project Max Klein
Structure of the Proton Uta Klein

FCC David D'Enterria

Large Hadron Electron Collider on one page

E_e = 10-60 GeV, E_p =1-7 TeV: √s = 200 − 1300 GeV. **Kinematics**: $0 < Q^2 < s$, $1 > x \geq 10^{-6}$ (DIS)
Electron Polarisation P=±80%. Positrons: significantly lower intensity, unpolarised
Luminosity: $O(10^{34})$ $cm^{-2} s^{-1}$. integrated O(1) ab^{-1} for HL LHC and 2 ab^{-1} for HE LHC/FCCeh
e-ions 6 10^{32} $cm^{-2} s^{-1}$ O(10)fb^{-1} in ePb . O(1)fb^{-1} for ep F_L measurements

Physics: QCD: develop+break? The worlds best microscope. BSM (H, top, ν, SUSY..)
Transformations: Searches at LHC, LHC as Higgs Precision Facility, QCD of Nuclear Dynamics
The LHeC has a deep, unique QCD, H and BSM precision and discovery physics programme.

Time: Determined by the Large Hadron Collider (HL LHC needs till ~2040 for 3 ab^{-1})
LHeC: Detector Installation in 2 years, earliest in LS4 (2030/31).
HE LHC: re-use ERL. In between HL-HE, 10 years time of ERL Physics (laser, γγ..)
Very long term: FCC-eh

Challenges: Development of ERL Technology (high electron current, multi-turn)
Design 3-beam IR for concurrent ep+pp operation, New Detector with Taggers - in 10 years.

The LHeC is a great opportunity to sustain deep inelastic physics within future HEP.
The cost of an ep Higgs event is O(1/10) of that at any of the 4 e^+e^- machines under consideration
It can be done: the Linac is shorter than 2 miles and the time we have longer than HERA had.

CERN and world HEP: Vital to make the High Luminosity LHC programme a success.

backup

- 7×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;

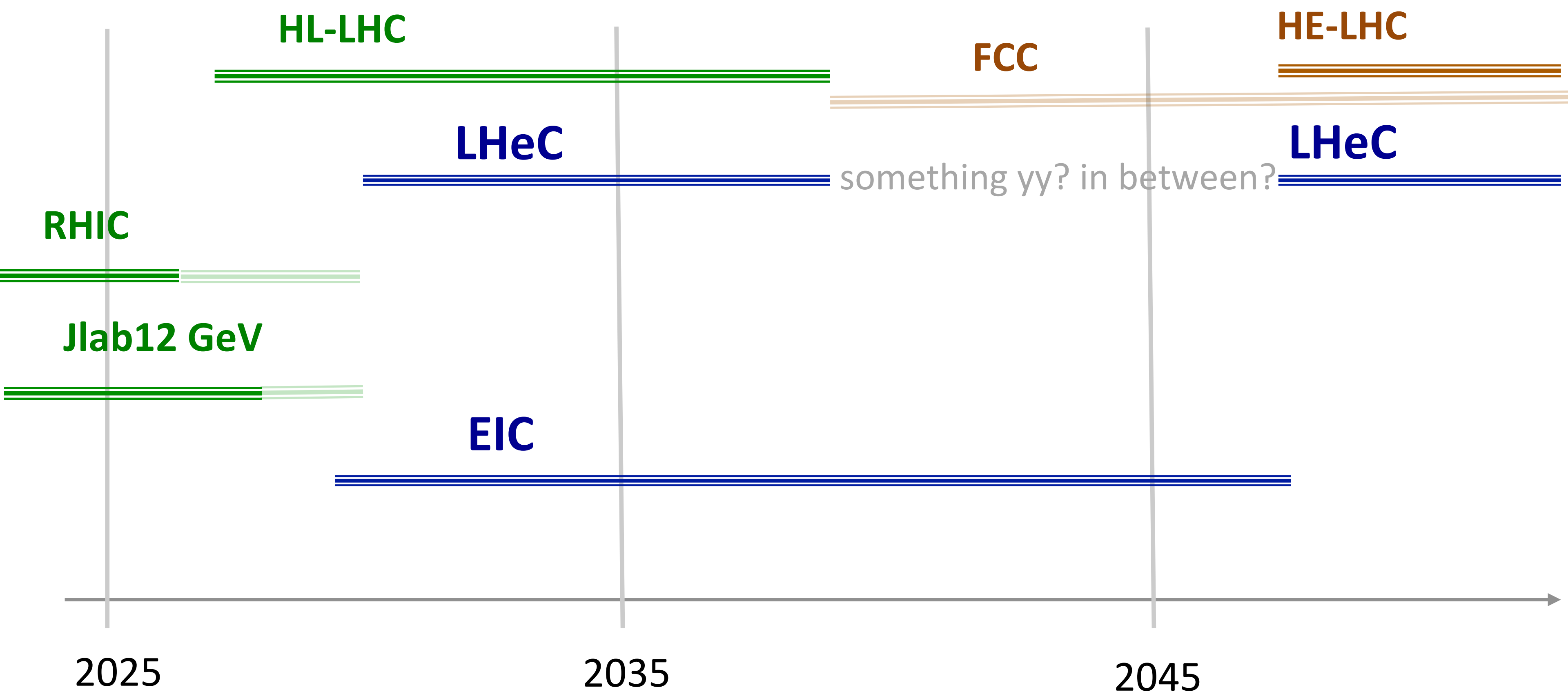
iv) the necessary addendum for pp in resolving the largely unknown region of high mass (corresponding to large x_bj) where new particles or interactions may reside;

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.

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

Dislaimer: For discussion and illustration at DIS17 only MK+RY, April 7th, 2017, DIS at Birmingham

Luminosity for LHeC, HE-LHeC and FCC-ep

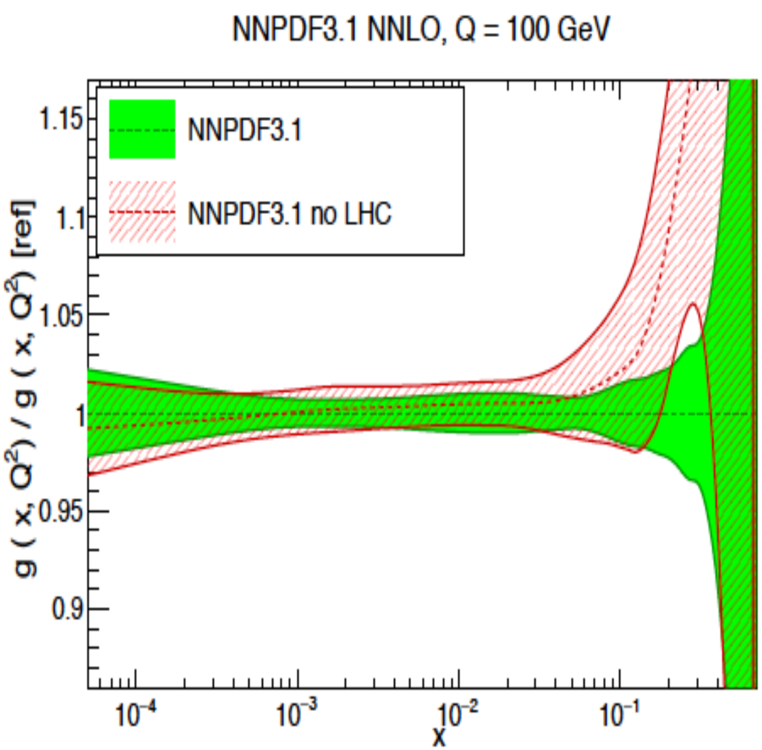
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current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

Oliver Brüning[1], John Jowett[1], Max Klein[2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]

EDMS 17979910 | FCC-ACC-RPT-0012

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

LHC Folklore: PDFs come from pp



NNPDF3.1 arXiv:1706.00428

LHC data constrain PDFs, BUT do not determine them:

- Needs complete q_i,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 $Q^2=10^4$ 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^3LO (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 χ^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 ~ 0.01 (nonsuppressed s/dbar). 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→ 1; s, c,b,t. …

That's it?? That may not be it..

Developments

AdS/CFT
Instantons
Odderons
TOTEM ? CERN EP 2017-335

Non pQCD, Spin
Quark Gluon Plasma

QCD of Higgs boson

N^kLO, Monte Carlos..
Resummation
Saturation and BFKL

Photon, Pomeron, n PDFs
Non-conventional partons
(unintegrated, generalised)
Vector Mesons
The 3 D view on hadrons..

Discoveries

CP violation in QCD?
Massless quarks?? Would solve it..
Electric dipole moment of the neutron?
Axions, candidates for Dark Matter

Breaking of Factorisation [ep-pp]

Free Quarks

Unconfined Color

New kind of coloured matter

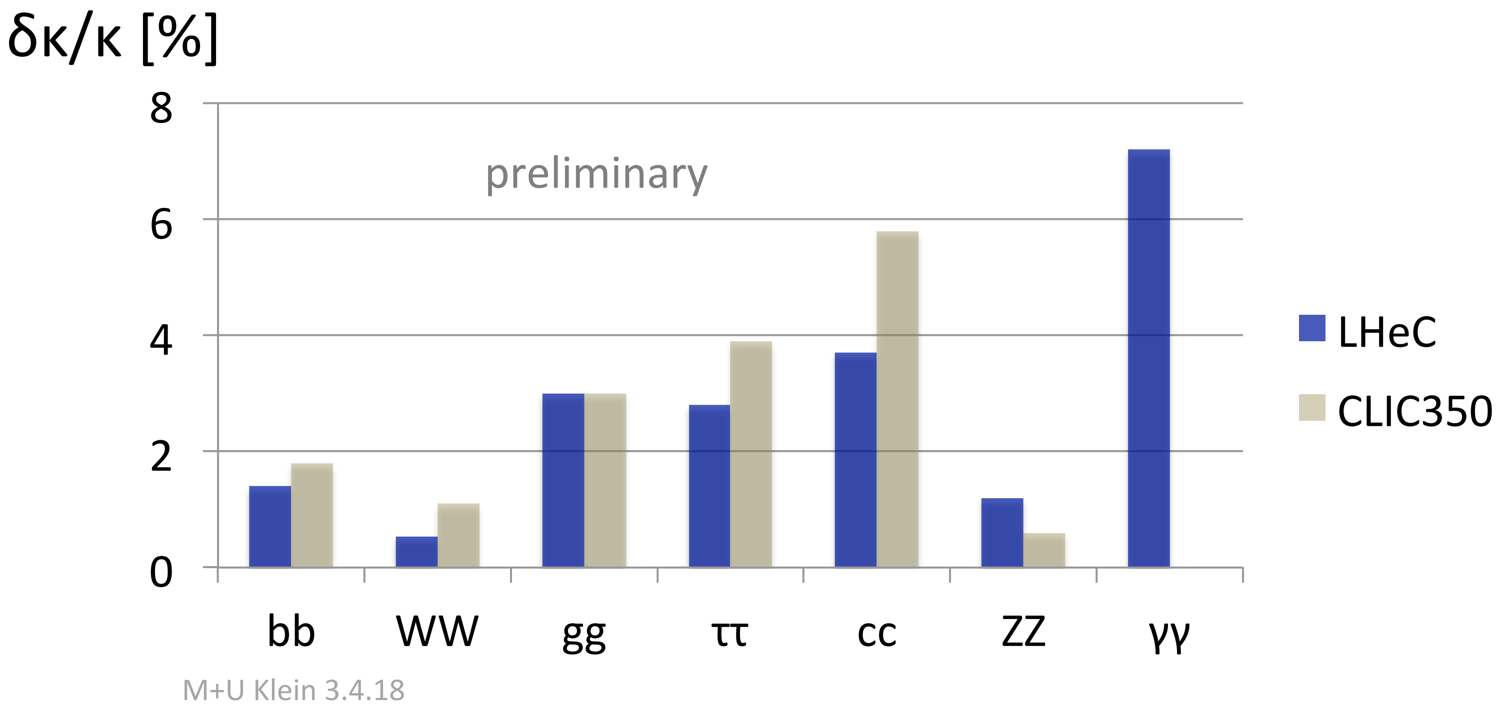
Quark substructure

New symmetry embedding QCD

C. Quigg, arXiv1308.6637

QCD has an exciting future with the FCC

SM Higgs Couplings from the LHeC

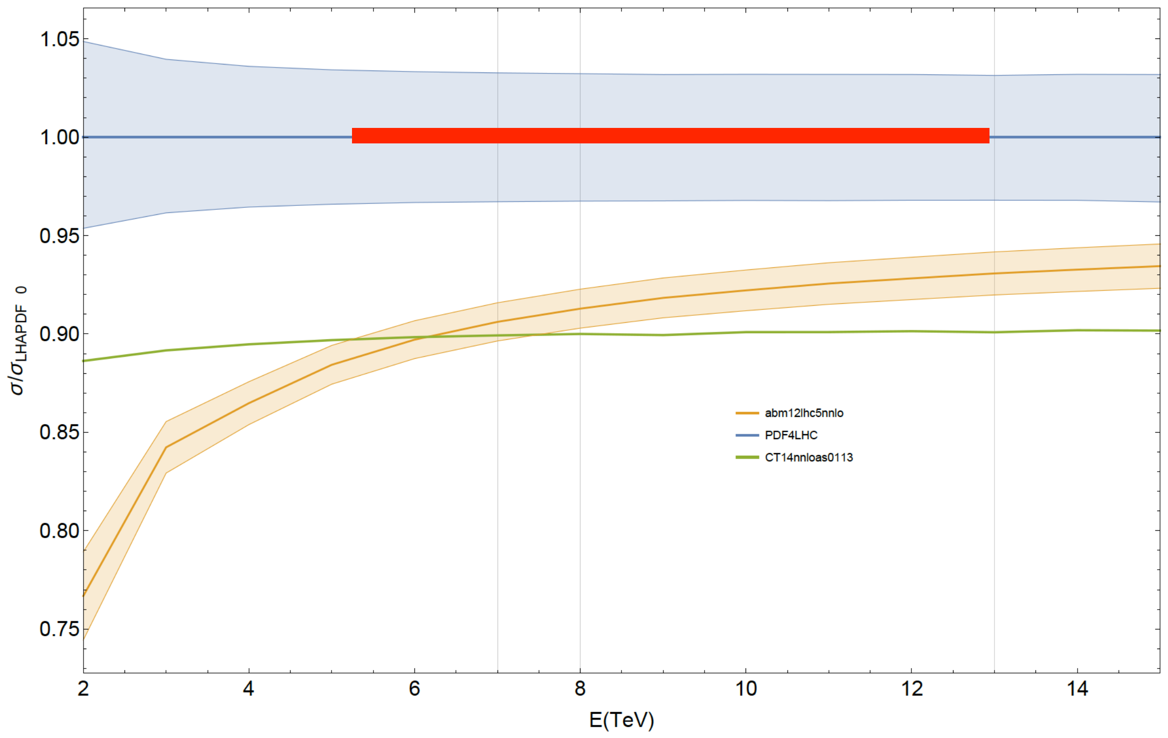


LHeC: 60 GeV x 7 TeV. **CLIC: 350 GeV** [arXiv:1608.07538, "model dependent fit"]

The principal advantage of e^+e^- is the measurement of the inclusive ZH production cross section.

For a joint ee/ep/pp FCC Higgs analysis see Jorge De Blas Amsterdam FCC week.

QCD of the Higgs Boson



← LHeC
1305.2090

Figure 18: Higgs production cross-section and 68% C.L. PDF+α_s uncertainty from the ABM12 fit and from the CT14 set computed at $\alpha_s = \alpha_s^{ABM}$, normalized by the central value obtained with the PDF4LHC combination.

$$\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\ (\mathrm{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\ (\mathrm{PDF}+\alpha_s)$$

C Anastasiou et al, arXiv:1602.00695

True PDF errors?

[LHeC/FCCeh at per-mille level, mass and xsection]

PDFs to N^{3}LO → DIS to N^{3}LO [10 years program]

$\sigma \sim (\alpha_s\, xg)^2$

High precision pp Higgs physics requires high precision for PDFs and α_s

Observations post CDR/EUSPP - 2012+ affecting ep at CERN:

LHC lifetime now extended to ~2040 to collect 3 [4] ab^{-1} . LS3 2024-2026+..

Discovery of the Higgs: L(ep): $10^{33} \rightarrow 10^{34}$ cm^{-2} s^{-1} [HERA in days]
LHC brightness N_p/ε about 3 times higher than "ultimately" expected

No further discovery at the LHC, so far

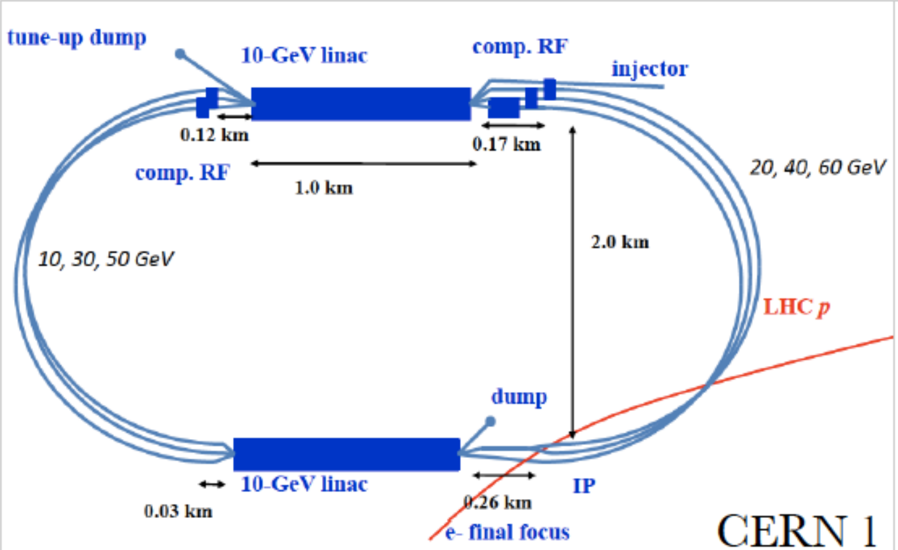
Detector technology developments (LHC Det. Upgrades)

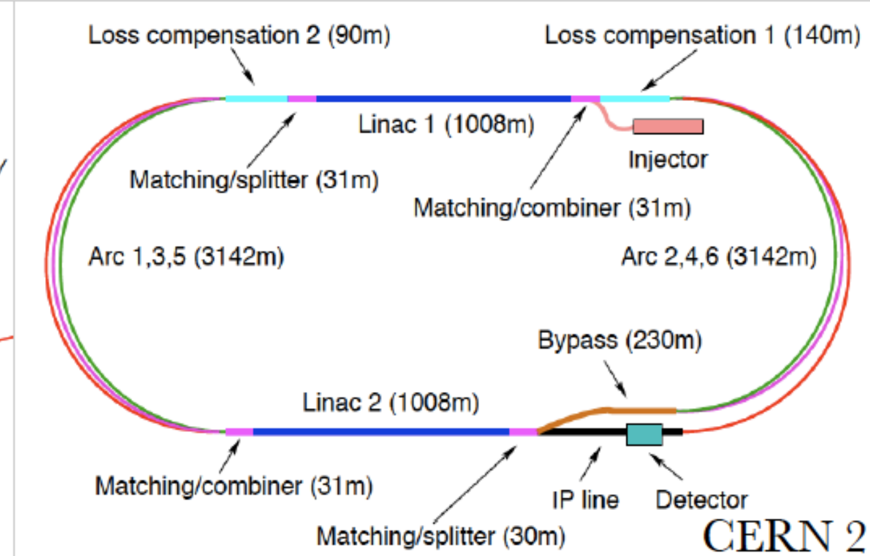
Strong **accelerator technology** developments, notably SCRF
ERL. LHeC: 720 $\rightarrow$ 802 MHz. enhanced $Q_0 > 10^{10}$

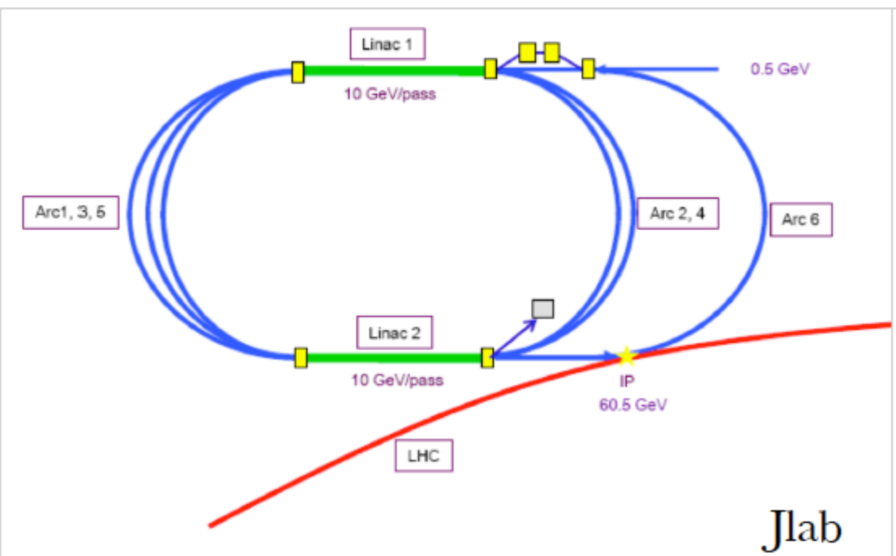
EU strategy 13: exploit LHC, study Higgs, develop SCRF+,
CERN: new accelerators "with emphasis on pp and ee"
Fine with the LHeC cost being a small fraction of ILC,CLIC,FCC

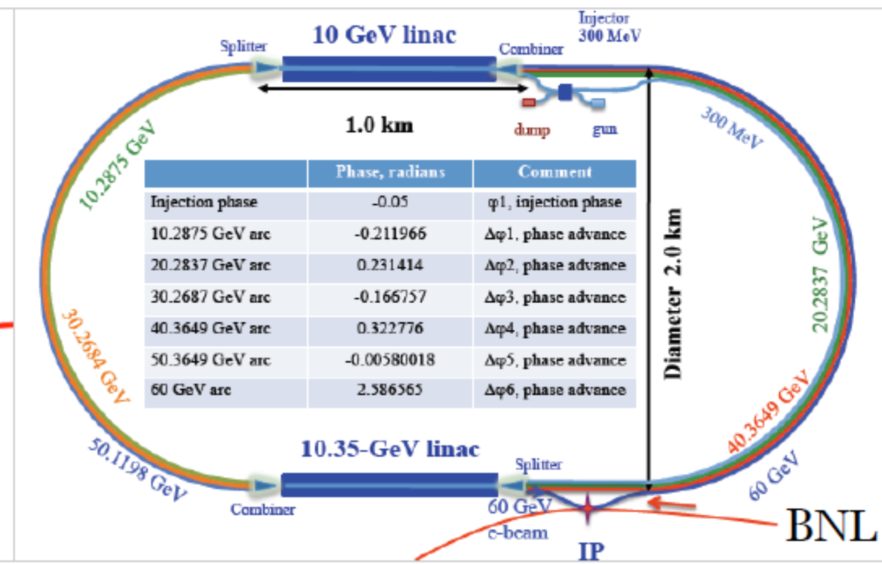
$\rightarrow$ CERN in 14 set up a new LHeC organisation with a new mandate
and IAC (H.Schopper et al) to prepare for the next EU strategy 2019+
Two main tasks (IAC): Update of CDR for HL-LHeC/FCCeh + Testfacility

60 GeV Energy Recovery Linac



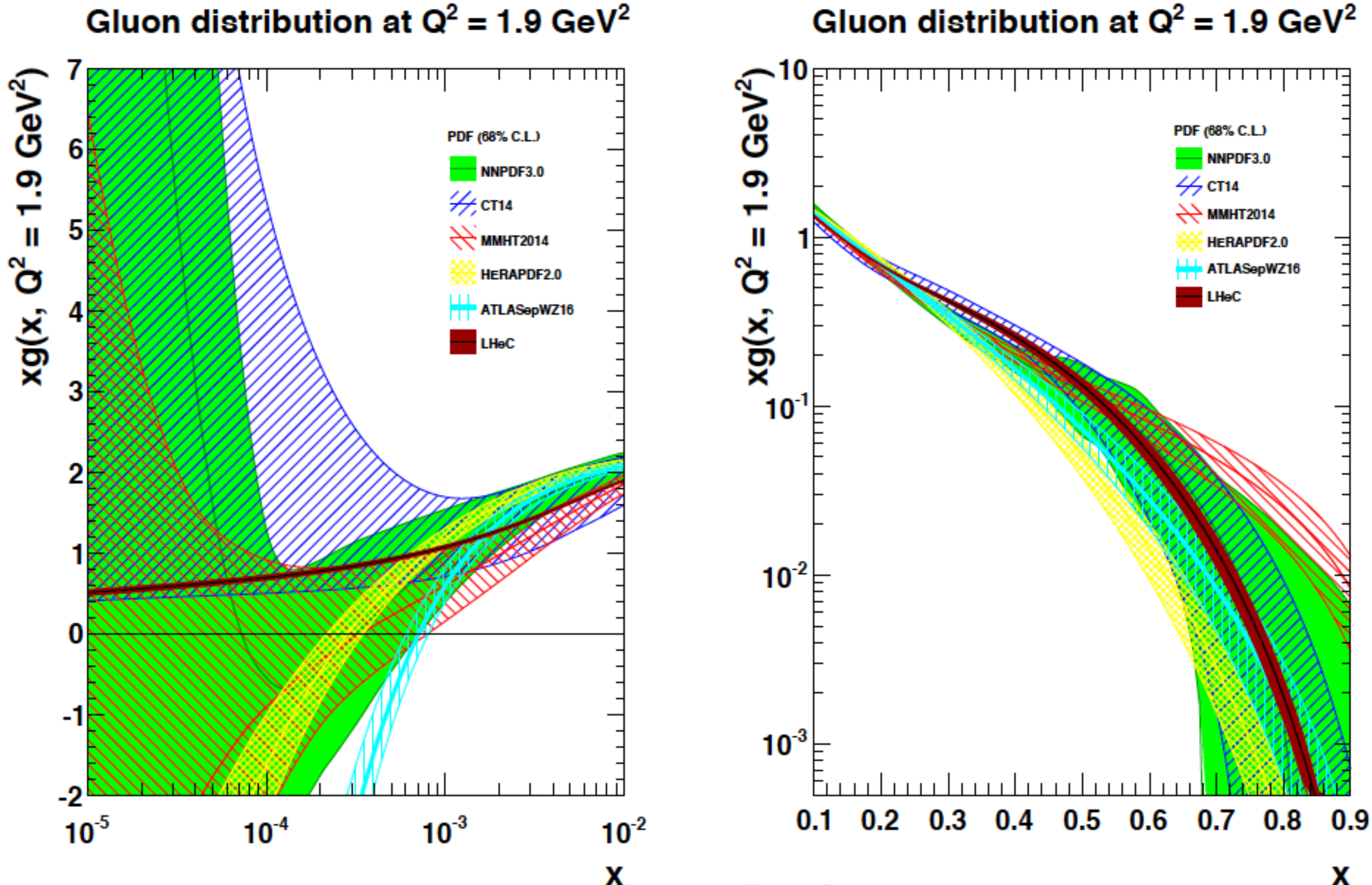






	Phase, radians	Comment
Injection phase	-0.05	φ1, injection phase
10.2875 GeV arc	-0.211966	Δφ1, phase advance
20.2837 GeV arc	0.231414	Δφ2, phase advance
30.2687 GeV arc	-0.166757	Δφ3, phase advance
40.3649 GeV arc	0.322776	Δφ4, phase advance
50.3649 GeV arc	-0.00580018	Δφ5, phase advance
60 GeV arc	2.586565	Δφ6, phase advance

CDR+: Default configuration, 60 GeV, 3 passes, 802 MHz, synchronous ep+pp, $L_{ep}=10^{34}$



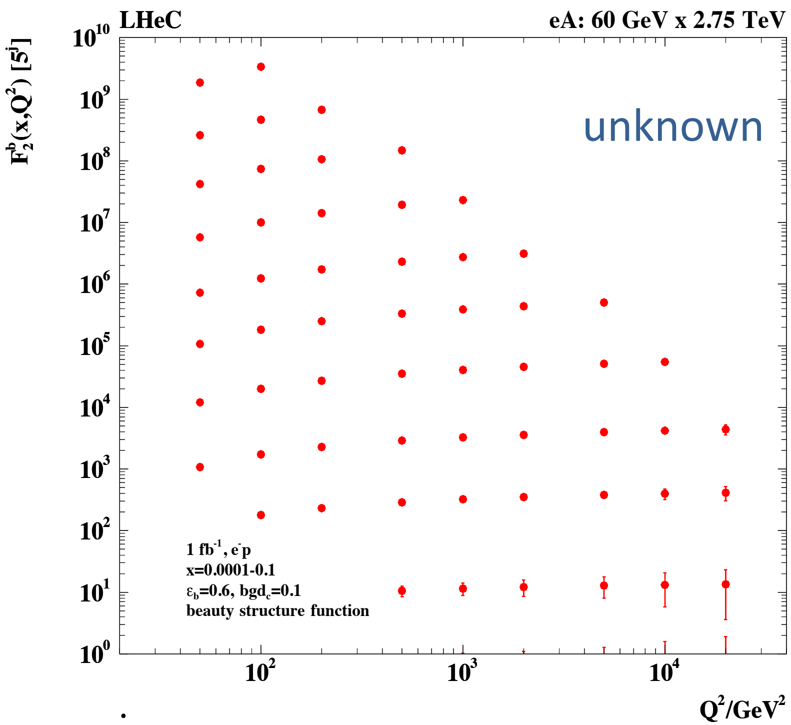
LHeC: High Precision F_2 and F_L to discover BFKL (CDR)

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 $x \simeq 5\ 10^{-4}$ to $x \simeq 0.6$, and much of the LHC data from Run I. Left: xg at small x; Right at large x.

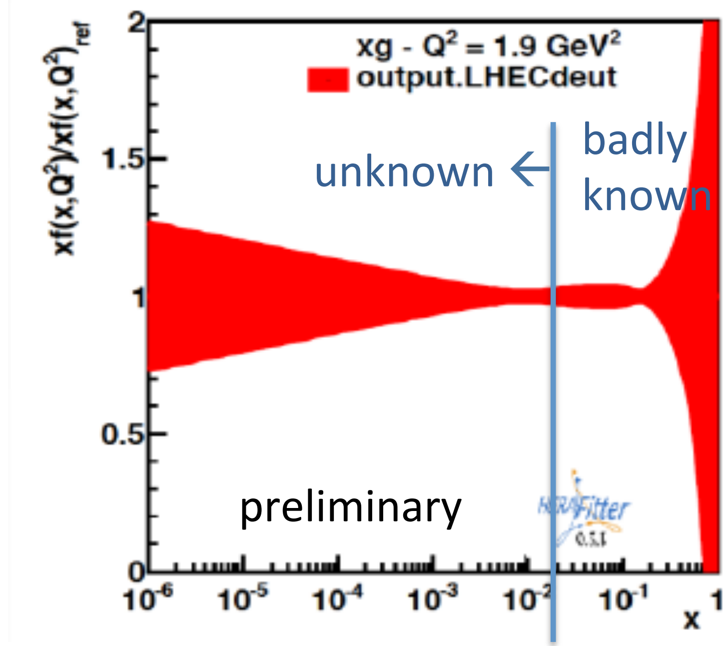
C Gwenlan, V Radescu, MK

Nuclear QCD through eA at FCCeh/LHeC

Beauty in Lead



δGluon in Lead



eA: extends kinematic range in Q^2, 1/x by 3-4 orders of magnitude. Lumi 6 10^{32} (J.Jowett)

Measure nPDFs as in ep scattering and determine then the ratio $R(x,Q^2)$=nPDF/PDF

Shadowing? A1/3 amplification? Saturation? Colour Flow? QGP initial state, collective effects

LHeC has been co-initiated and supported by NuPECC

see: Nestor Armesto FCC week 1/2018, CDR (LHeC) M.K. DOI: 10.1051/epjconf/201611203002