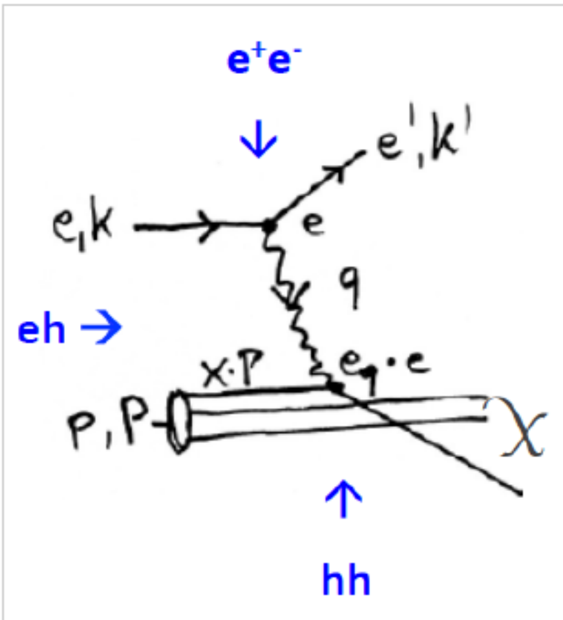
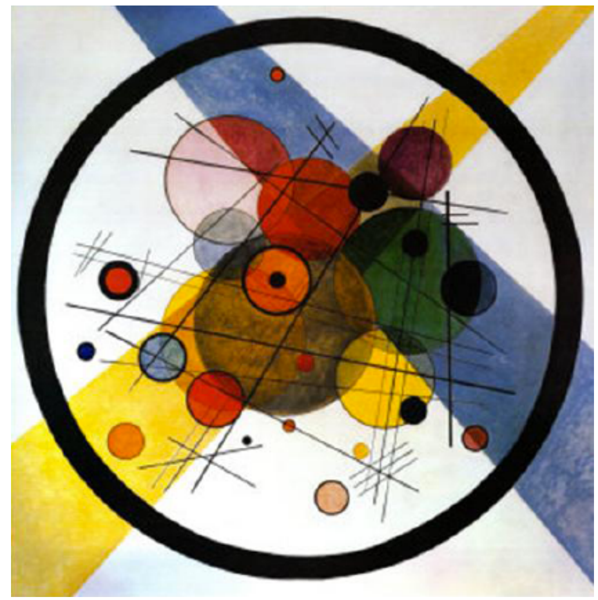
Physics and Prospects with LHeC

Large Hadron Electron Collider: add 60 GeV electron accelerator to LHC in the 30ies
Transform the HL and HE LHC to Twin pp+ep (AA+eA) Colliders, and FCC later as well



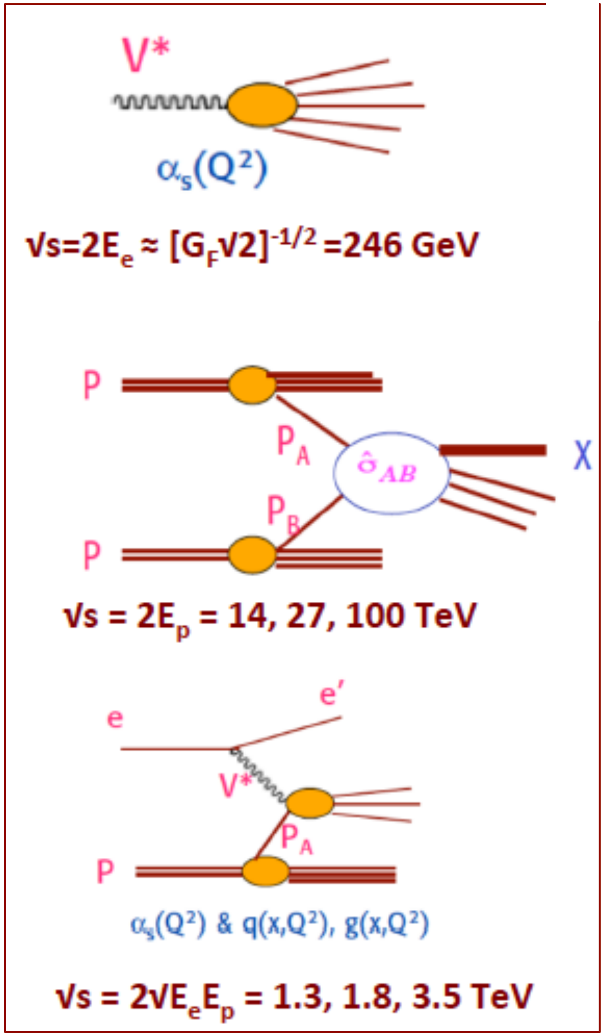


W Kandinsky, Circles in a Circle,
1923, Philadelphia Art Museum

Note that LHeC has had a 600 pages CDR on physics, accelerator, detector arXiv:1206.2913

Max Klein, for the LHeC/FCCeh/PERLE Collaborations. Shanghai, TDLI 2.7.2018

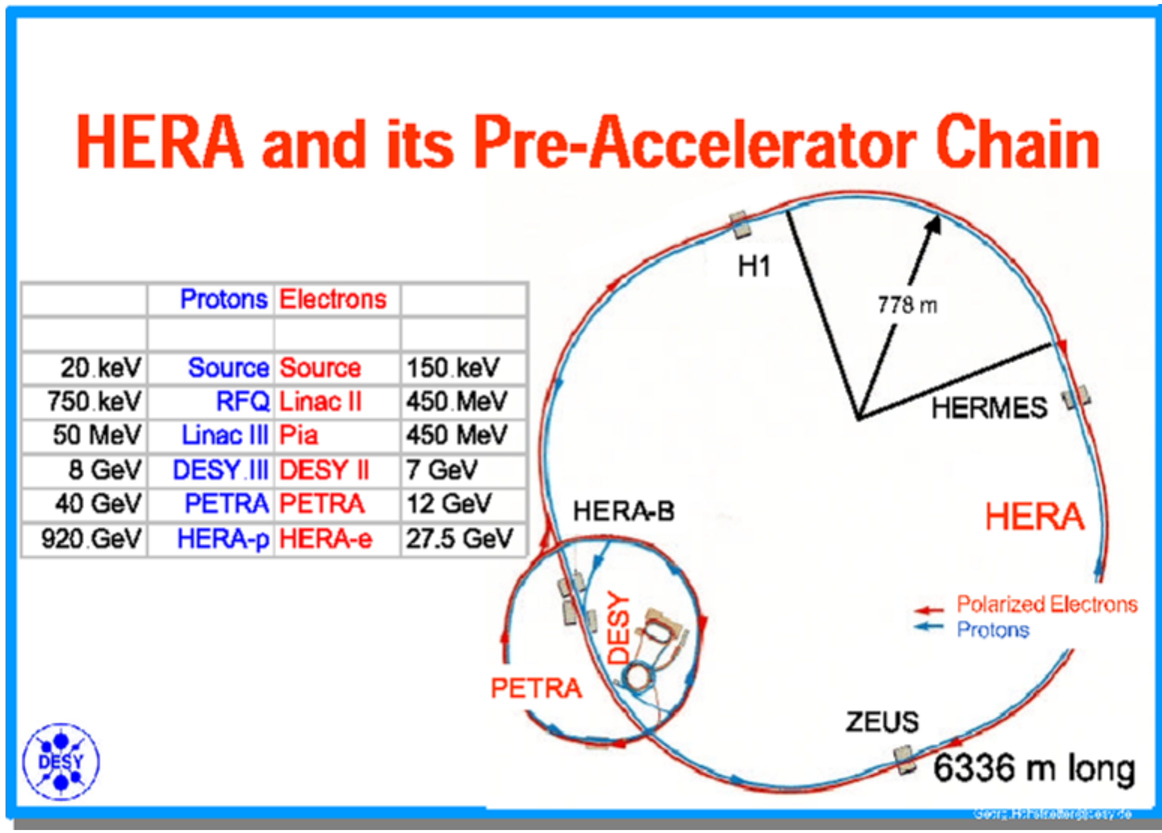
Electron-Hadron, or Deep Inelastic Scattering



ee, pp, ep belong together

HERA: first ep collider: E_e=27.6 GeV, E_p=920 GeV, L=3 10^{31}

Parton Structure, Electroweak Unification, Diffractive DIS
No Leptoquarks, no SUSY up to 300 GeV. Crucial for LHC



	Protons	Electrons	
20 keV	Source	Source	150 keV
750 keV	RFQ	Linac II	450 MeV
50 MeV	Linac III	Pia	450 MeV
8 GeV	DESY III	DESY II	7 GeV
40 GeV	PETRA	PETRA	12 GeV
920 GeV	HERA-p	HERA-e	27.5 GeV

HERA operated in parallel with Tevatron and LEP
Unification of ee-ep-pp also recognised in FCC study

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

*) April 2018

Working Groups

PDFs, QCD
Fred Olness,
Claire Gwenlan

Higgs
Uta Klein,
Masahiro Kuze

BSM
Georges Azuelos,
Monica D'Onofrio
Oliver Fischer

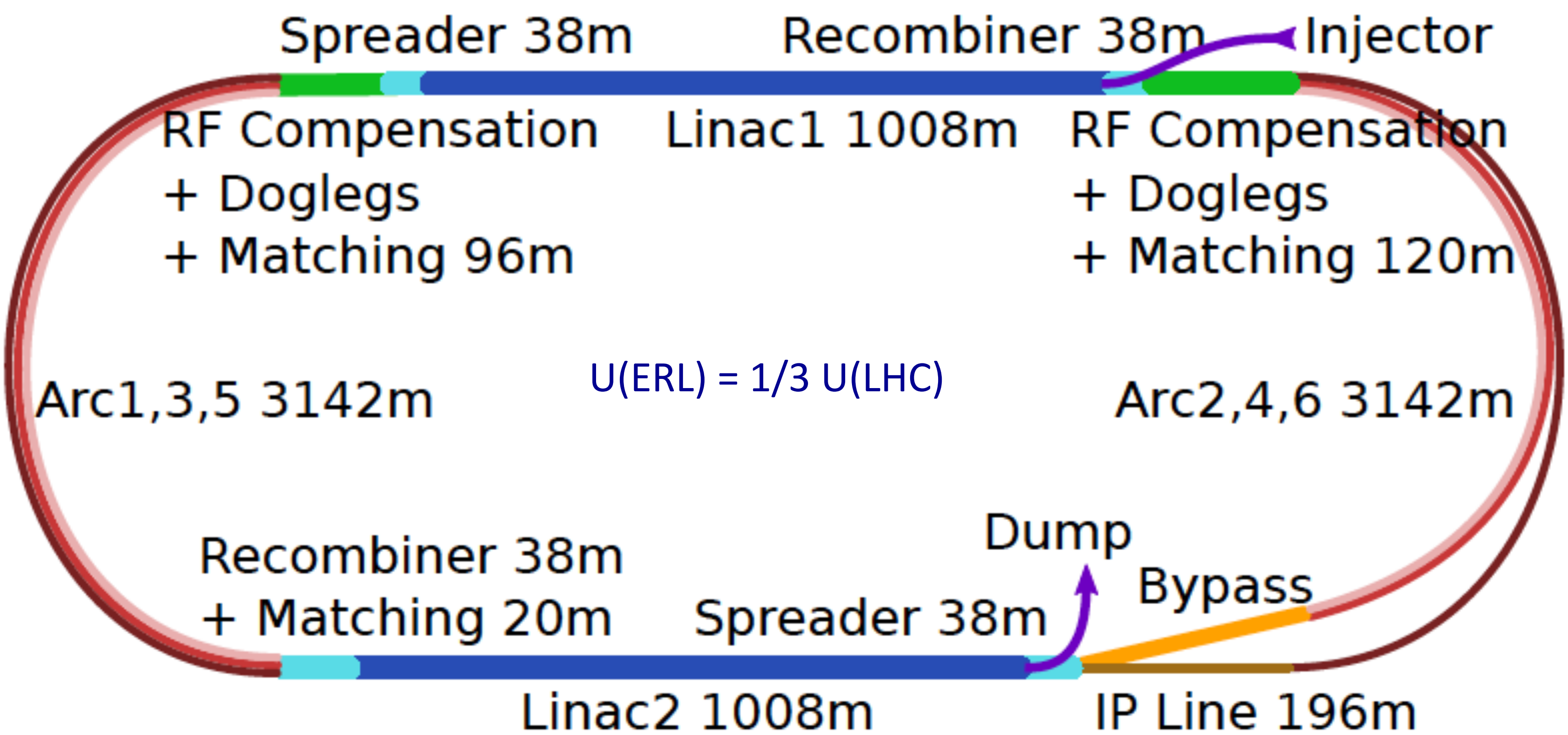
Top
Olaf Behnke,
Christian
Schwanenberger

eA Physics
Nestor Armesto

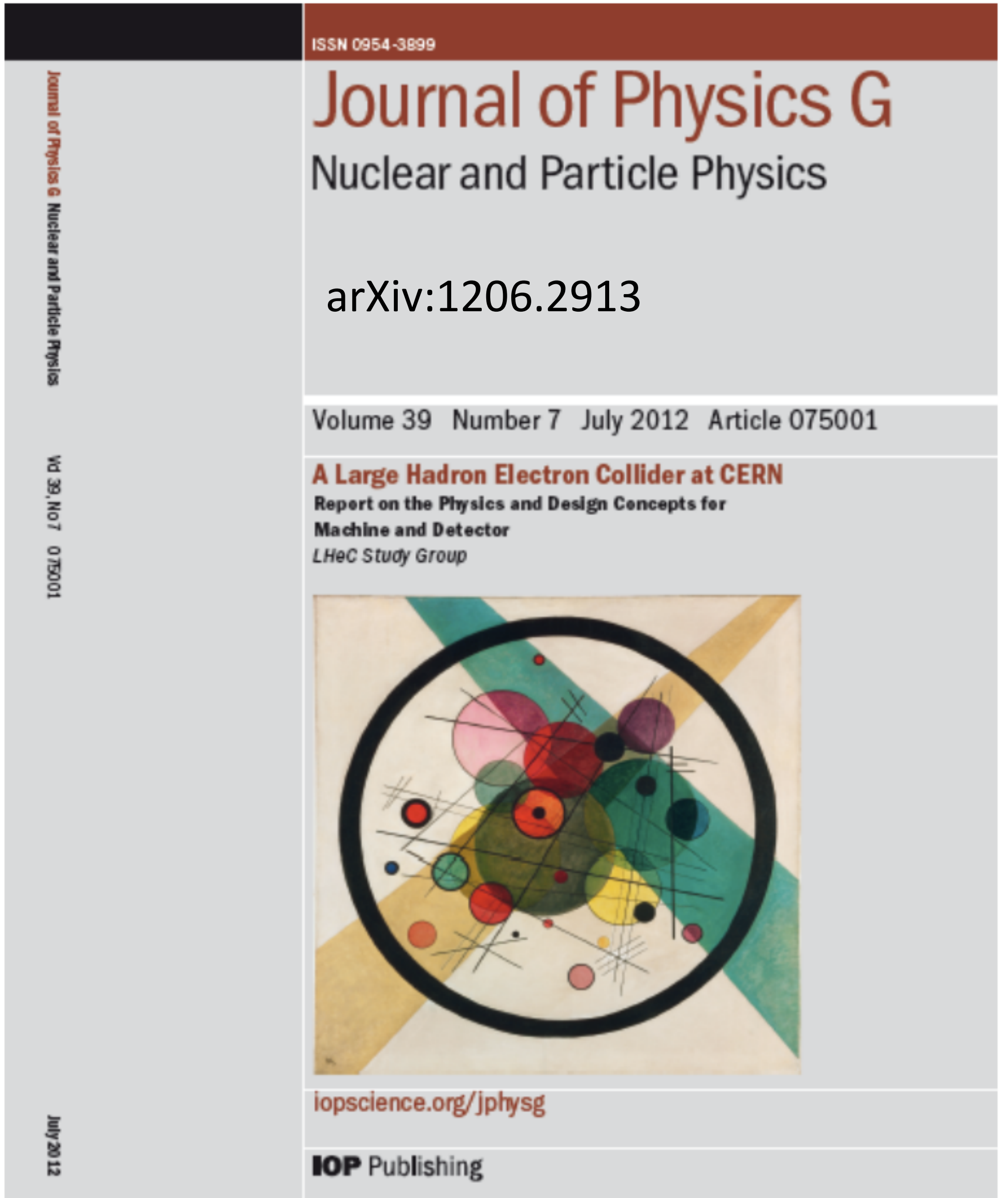
Small x
Paul Newman,
Anna Stasto

Detector
Alessandro Polini
Peter Kostka

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.

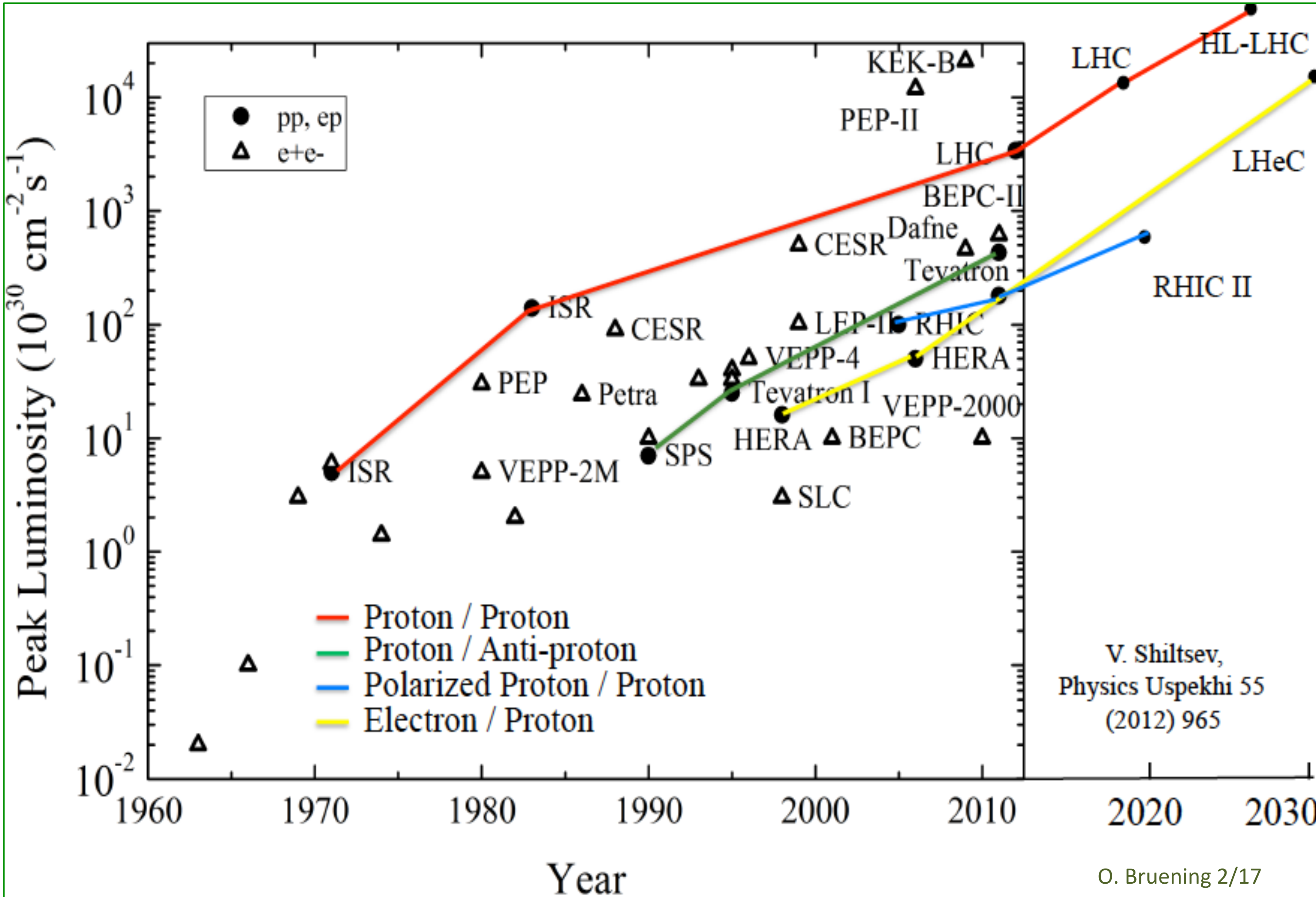


CERN Referees

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.

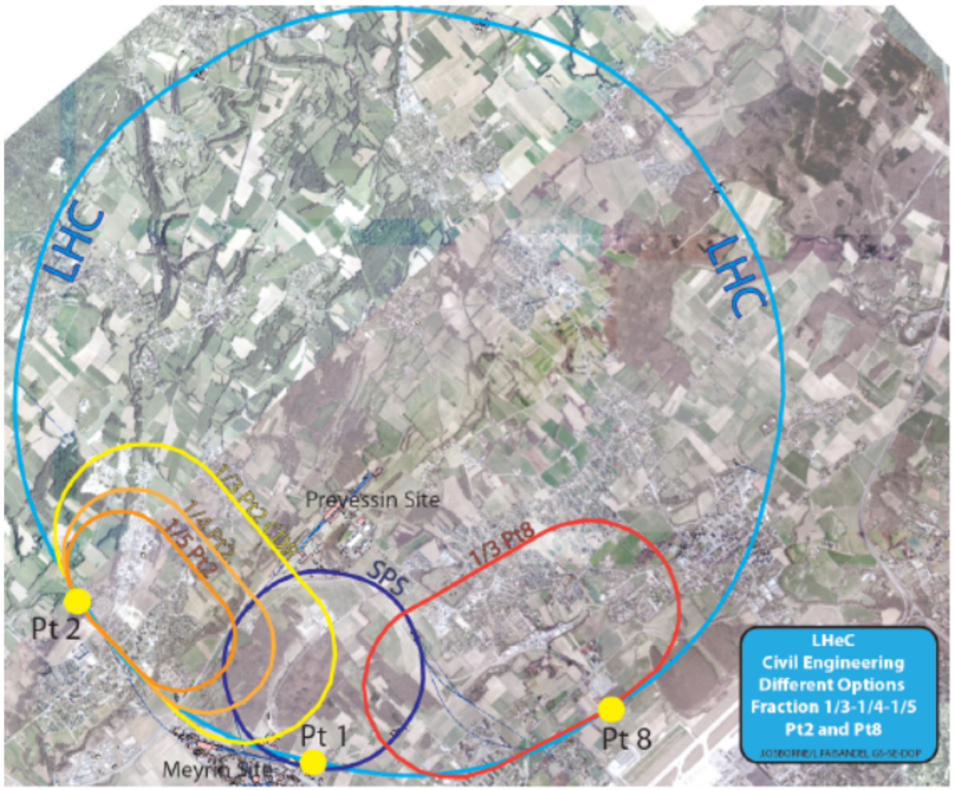
Collider Luminosities vs Year (pp and ep)

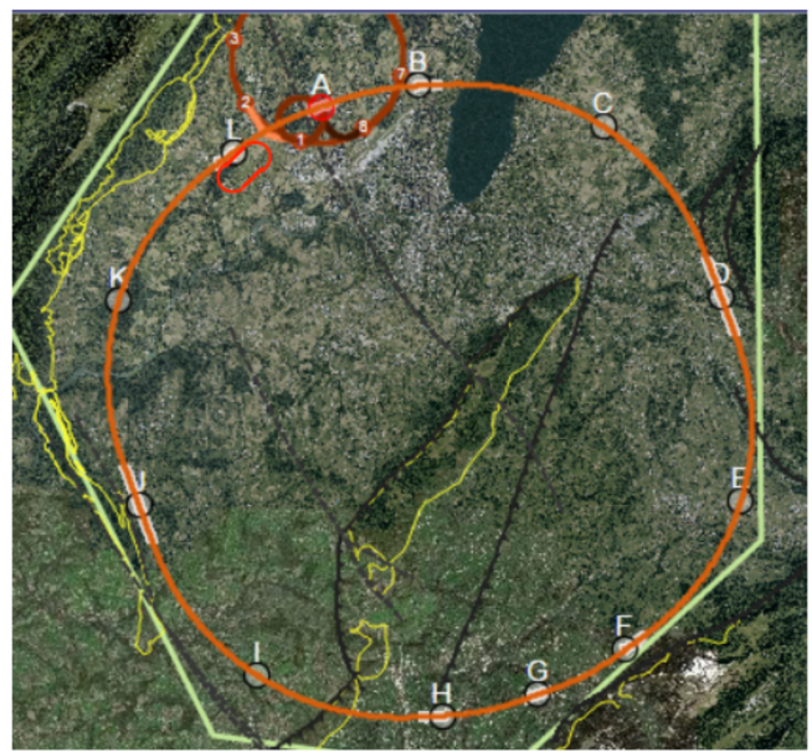


O. Bruening 2/17

Location, Footprint, Use of the Electron Racetrack

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



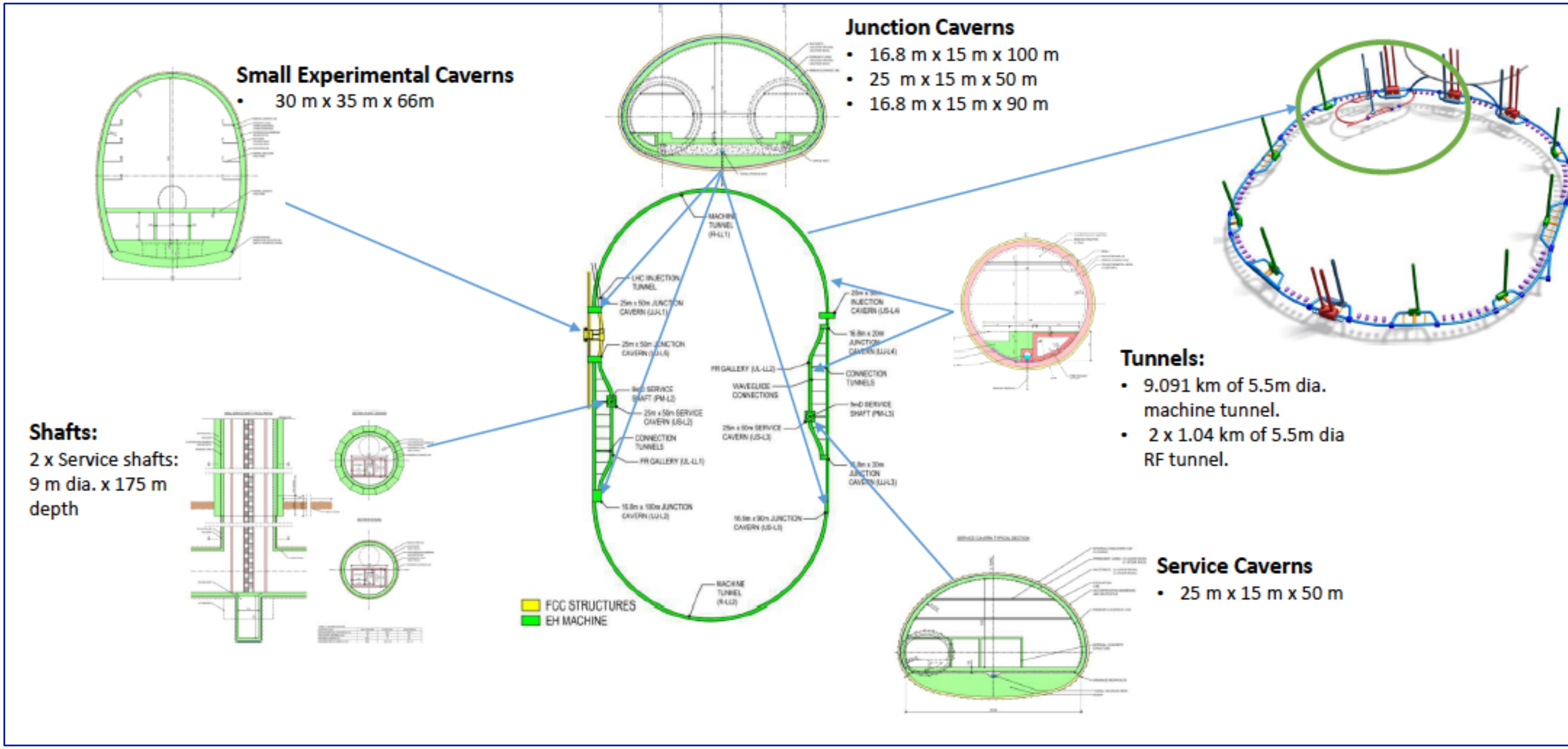


- U(ERL) = 1/n U(LHC): 60 GeV: 1/3
- BSM, top, Higgs, Low x all want maximum E_e
- Cost goes almost linearly down with E_e

For FCC can realise ep/A collisions
With IR at point L, not far from CERN
U(ERL) = 1/11 U(FCC)

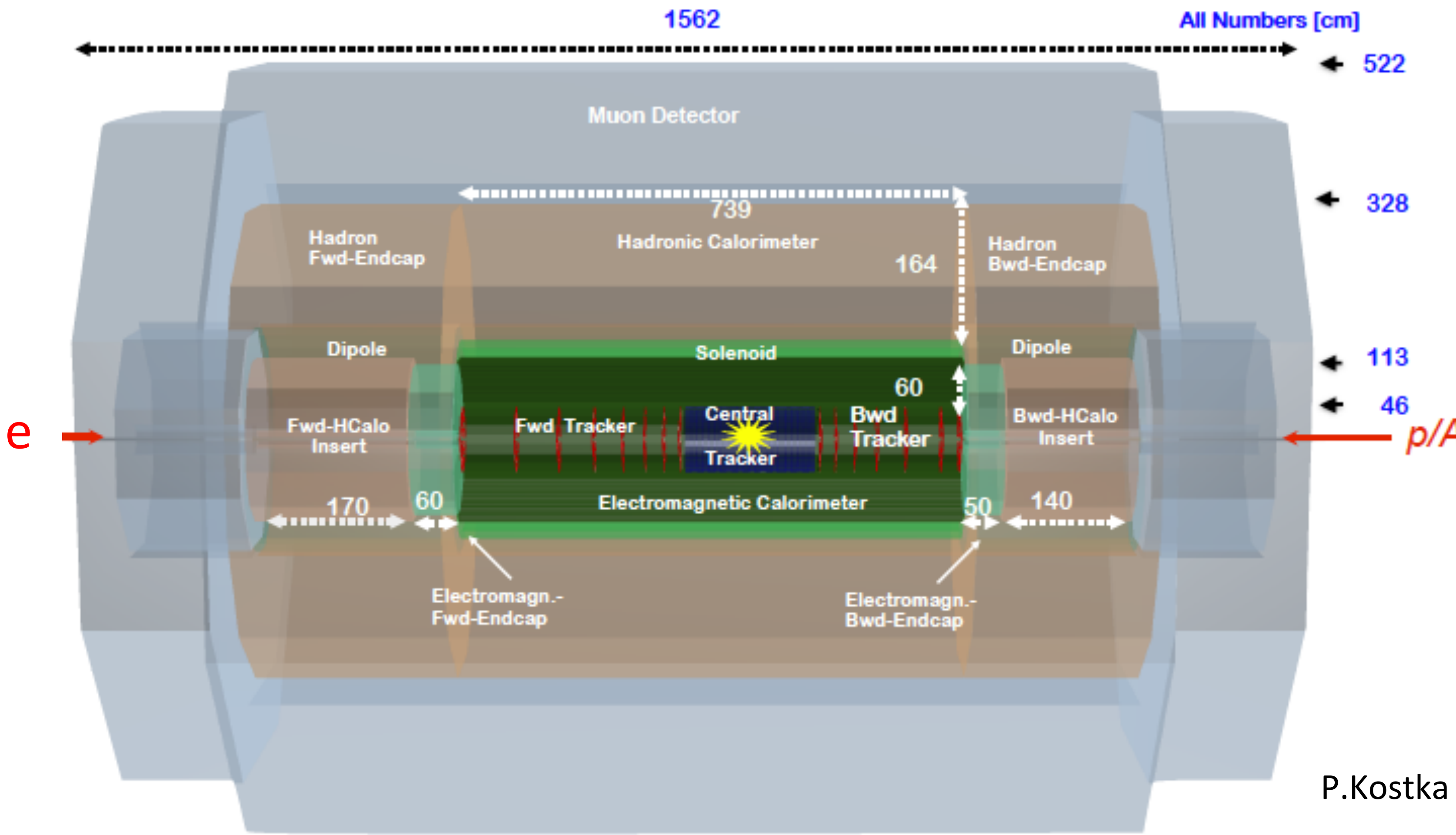
Energy – Cost – Physics – Footprint are being reinvestigated for EU strategy

Civil Engineering for ERL



For LHC: re-use IP2. For FCC: deeper shafts, new IP cavern
Refinement of CE study, see J Osborne Amsterdam FCC week
and see Matt Stuart at LHeC Workshop, last week

LHeC Detector for the HL/HE LHC



P.Kostka et al

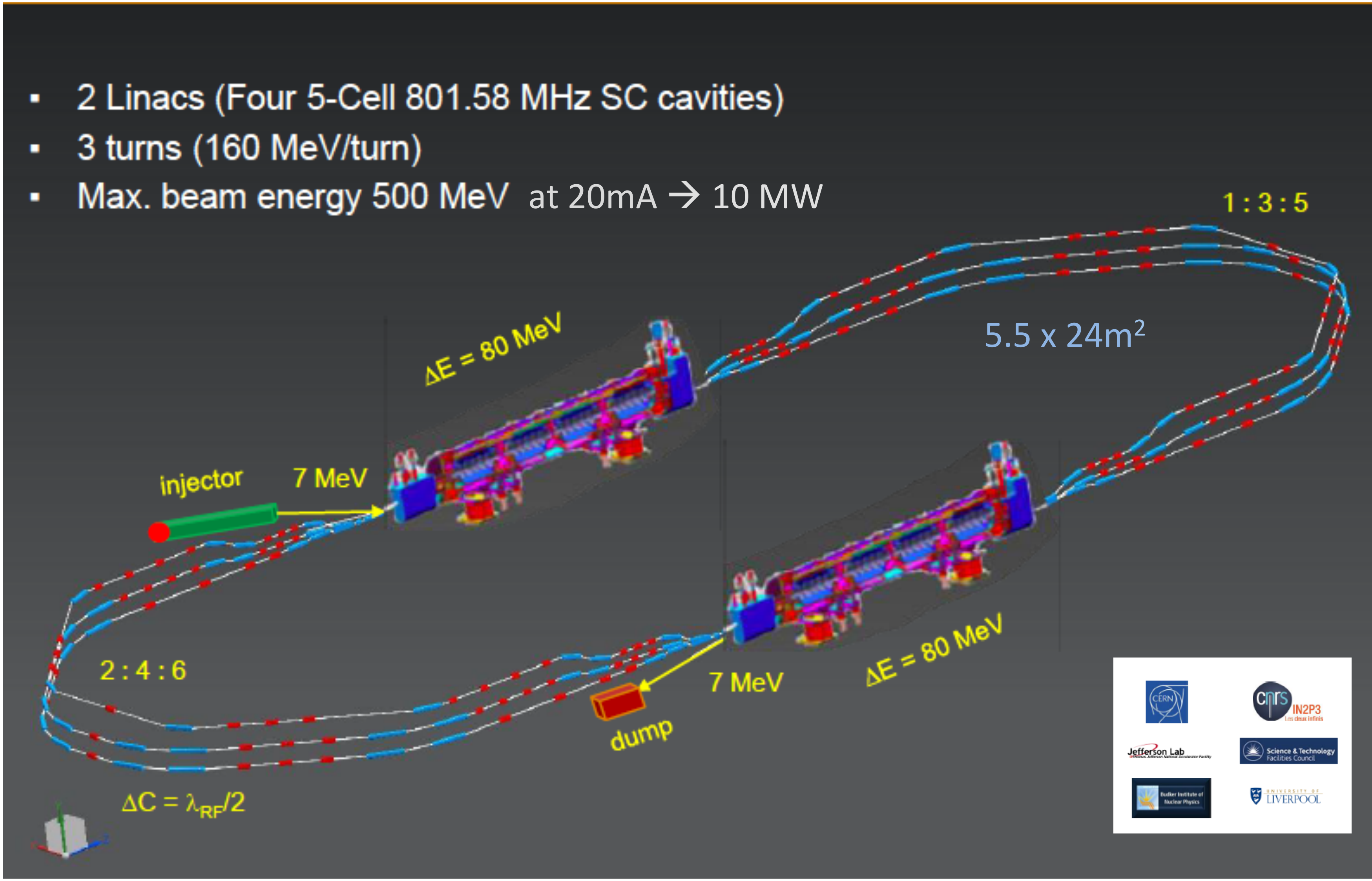
Length x Diameter: LHeC (13.3 x 9 m^2) HE-LHC (15.6 x 10.4) FCCeh (19 x 12)

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

Forward taggers for p,n, d?. Backward for photons and electrons (Lumi and low Q^2)

Powerful ERL for Experiments at Orsay

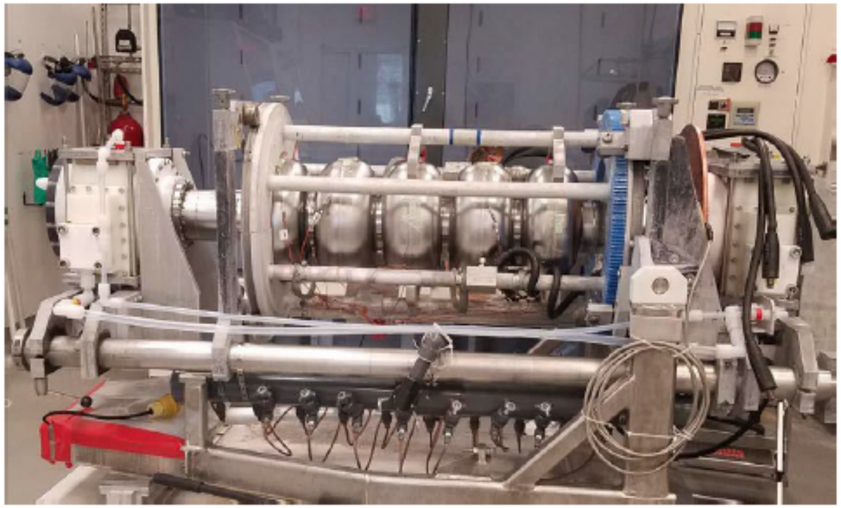


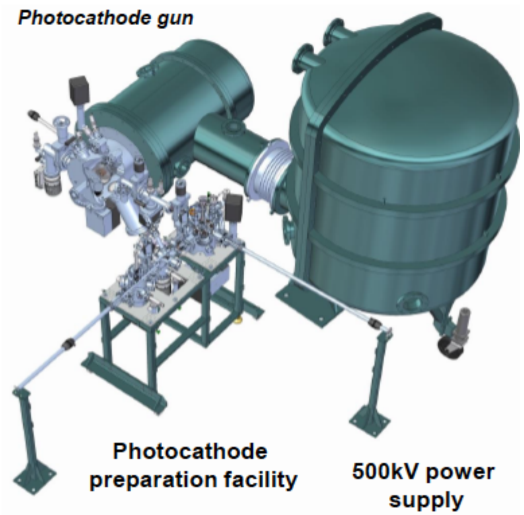
cf Walid Kaabi at Amsterdam FCC

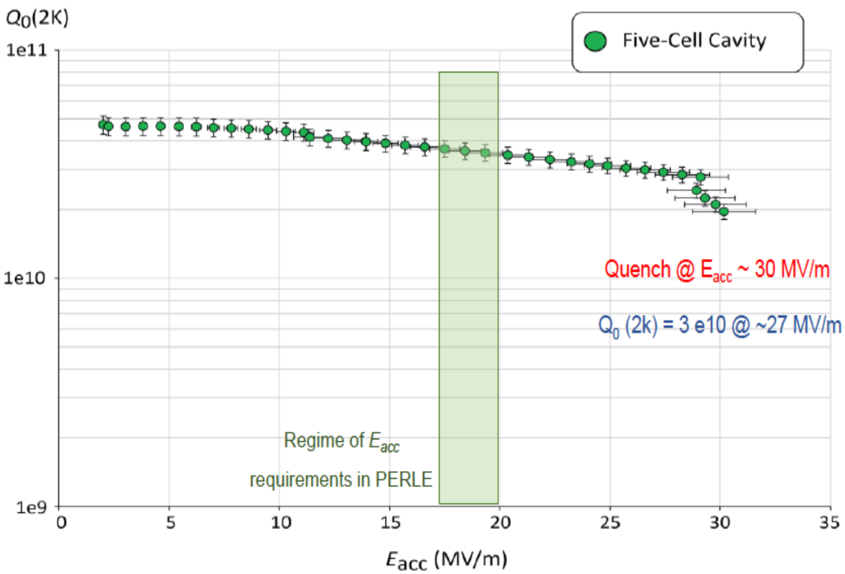
New SCRF, High Intensity (100 x ELI) ERL Development Facility with unique low E Physics

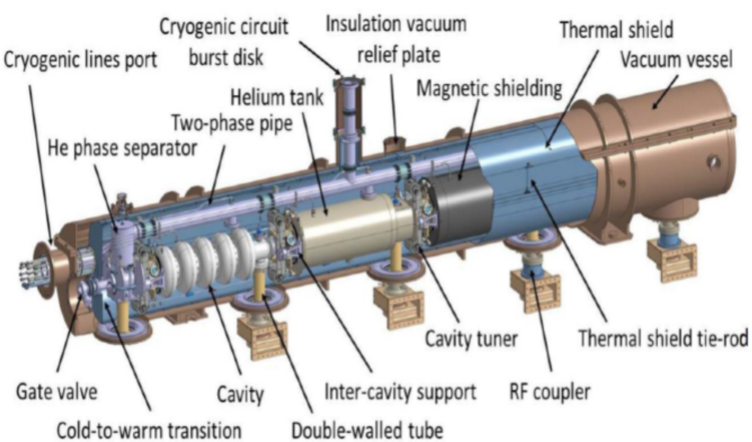
Towards PERLE: 802 MHz cavity, Source, Cryomodule, Magnets

First 802 MHz cavity successfully built (Jlab)





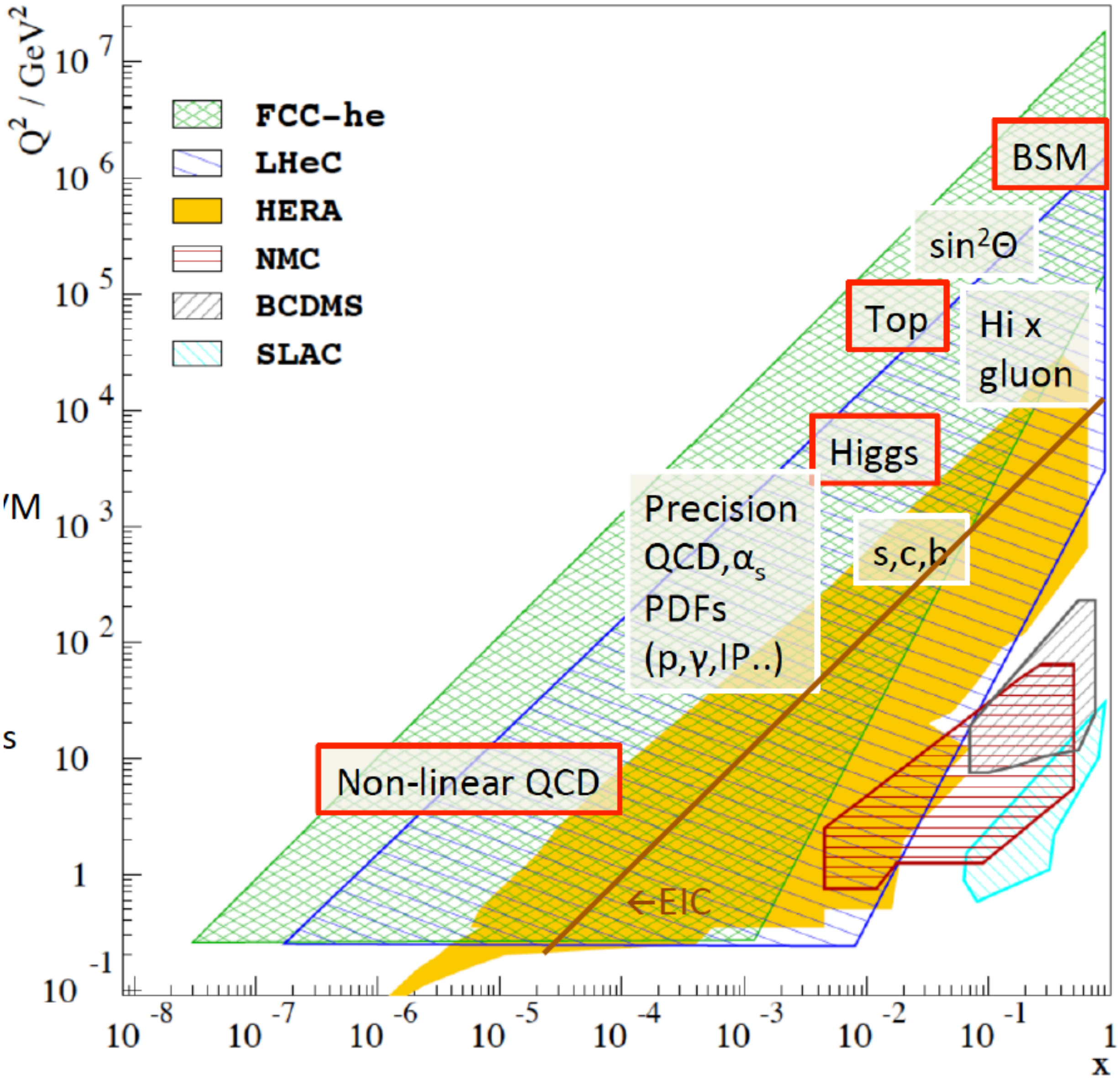




BINP, CERN, Daresbury/Liverpool, Jlab, Orsay, +

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

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 + DIS physics

The **Classic DIS Programme** with the LHeC: $0 < Q^2 < 10^6$ GeV^2, $1 > x > 10^{-6}$
besides collinear PDFs and strong coupling

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

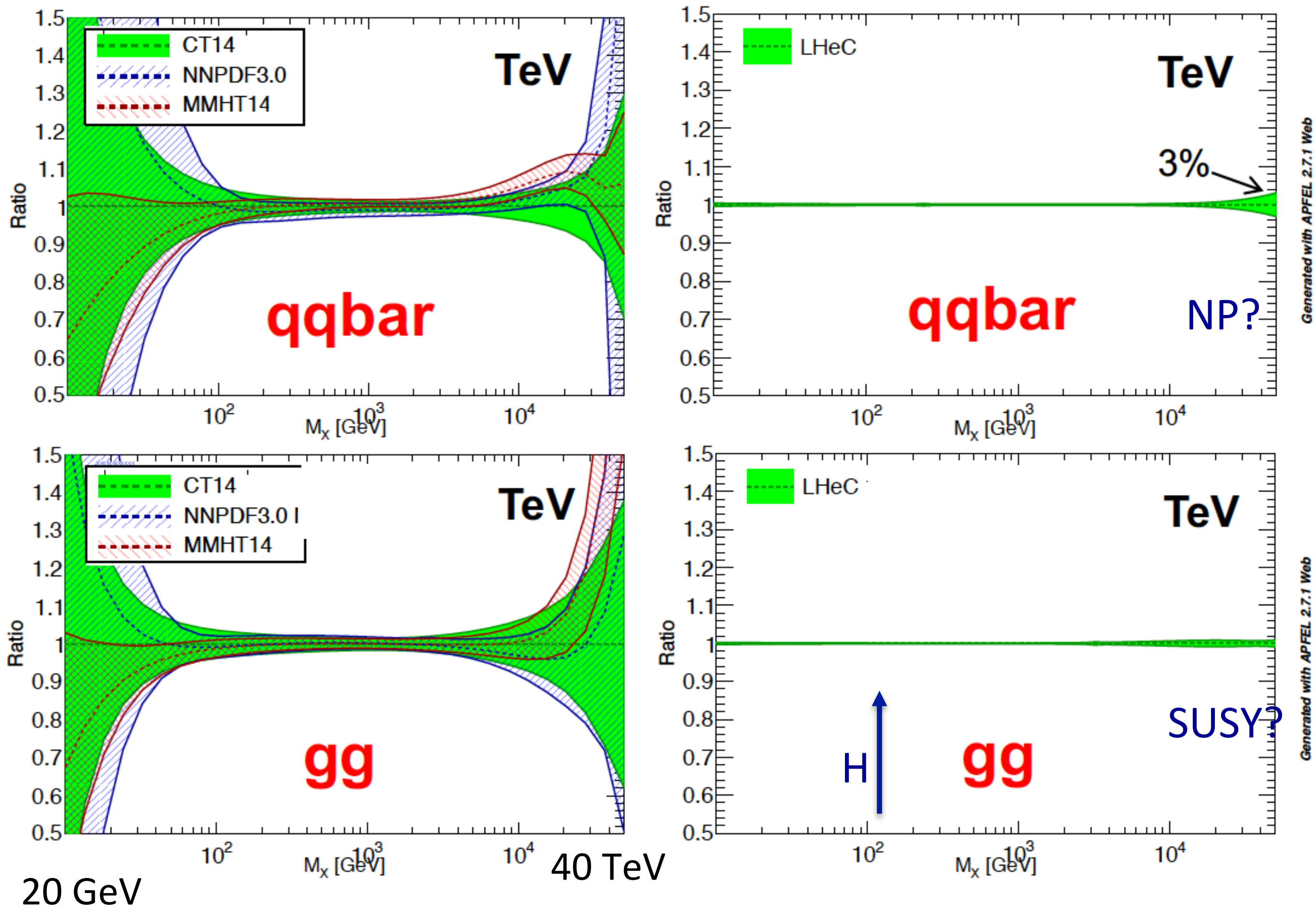
see the CDR 1206.2913 + updates

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…

No
higher twist
No
Nuclear
Corrections
No
Jet or pp data
→ Test QCD

**Alpha_s
to
0.1-0.2%
total
uncertainty**

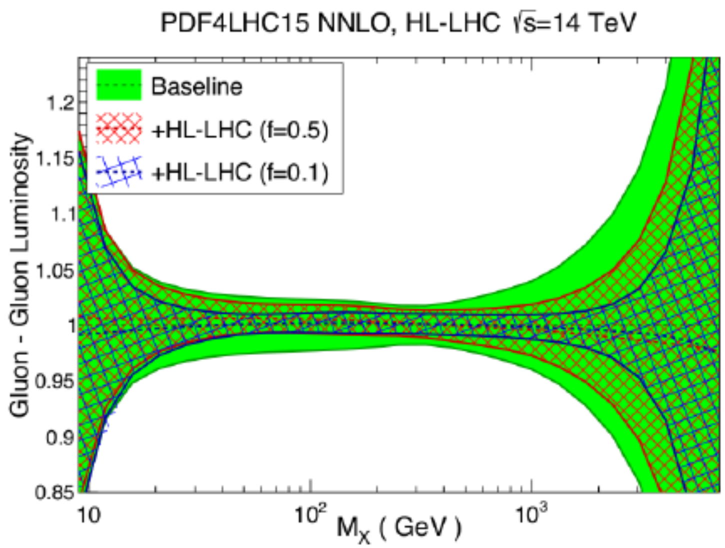


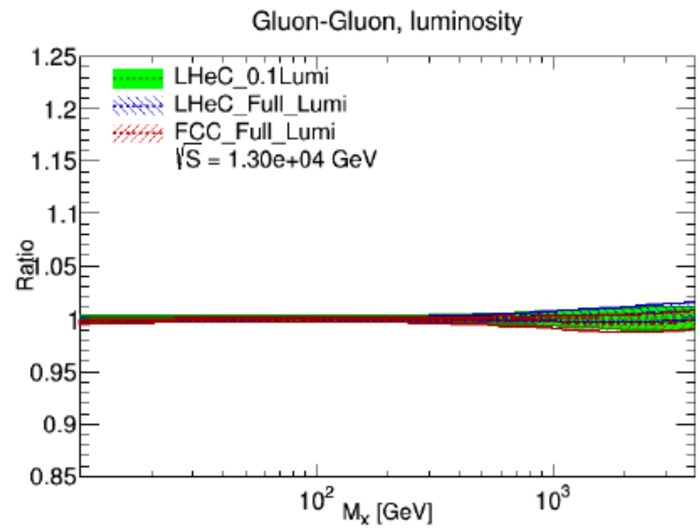
Empowers the LHC H, BSM + SM Physics

Parton Distributions from pp and ep

all preliminary

L_{gg}

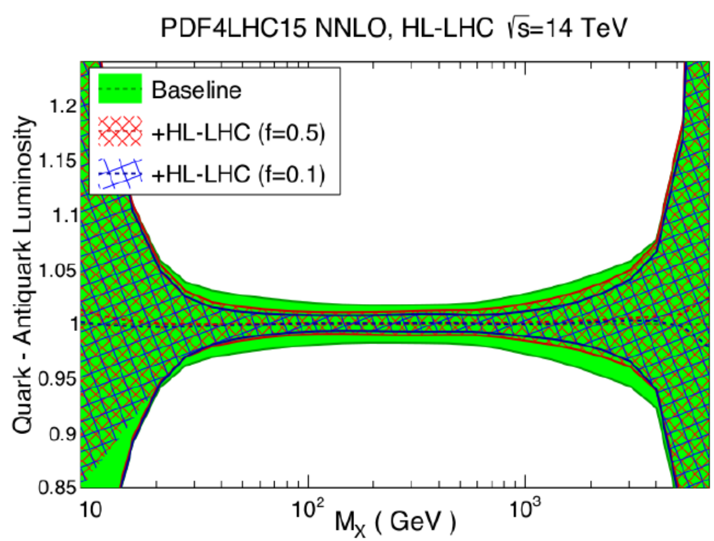


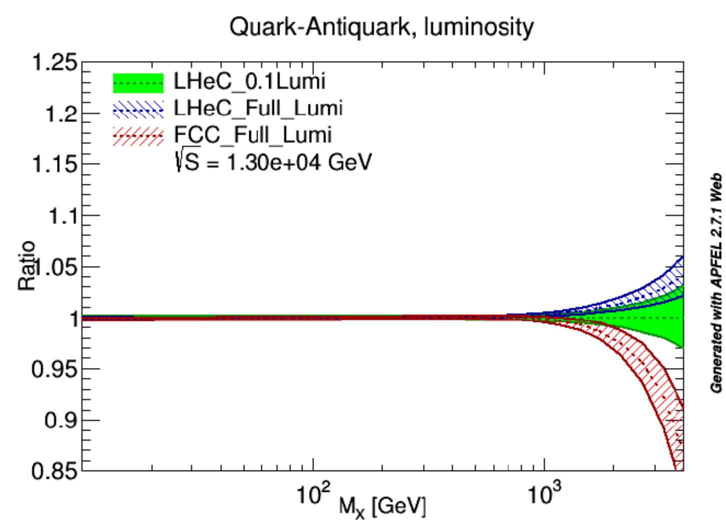


New/First Analysis of Full HL LHC Potential

New, Consistent Study of LHeC PDFs (NC,CC)

L_{qqb}





L Harlang, presented at HL LHC WS, last week

Gavin Pownall, Claire Gwenlan, MK, LHeC WS last week

QCD is far from fully developed and it will evolve and may break:

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

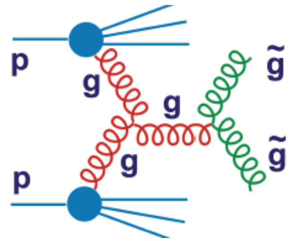
C. Quigg, arXiv1308.6637

Empowering pp Discoveries

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

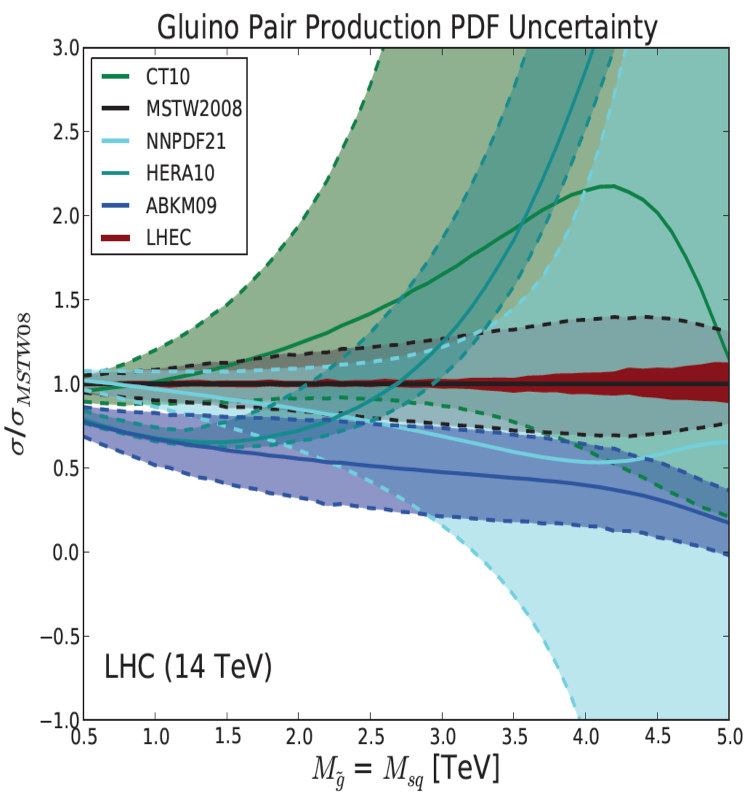
GLUON

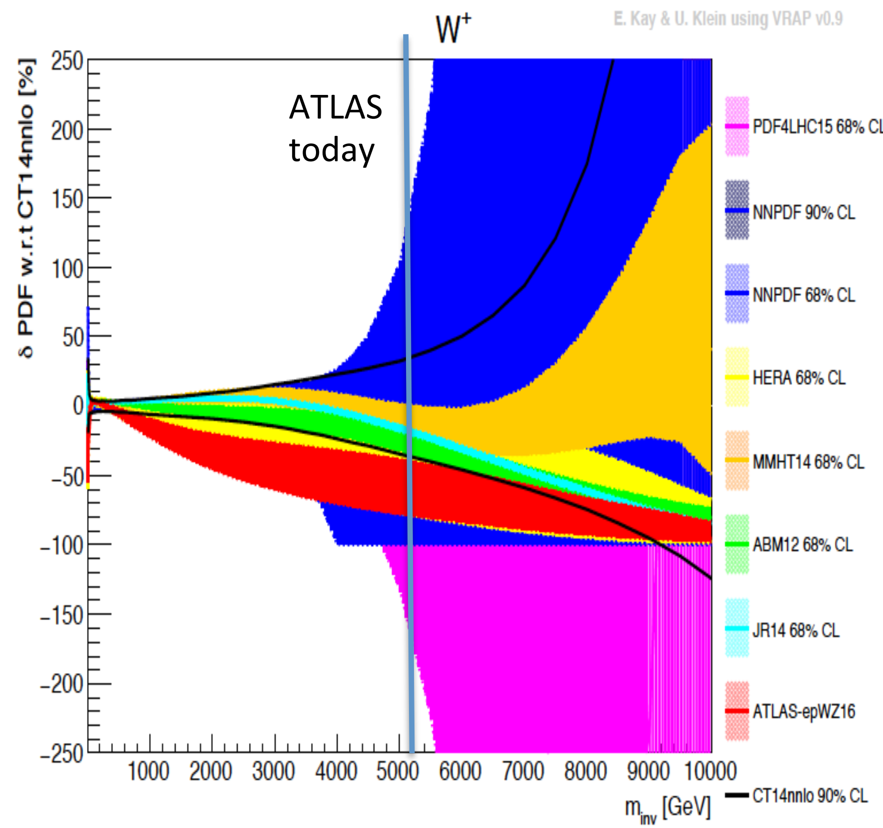
SUSY, RPC, RPV, LQS..



QUARKS

Exotic+ Extra boson searches at high mass





Higgs - Signal Strengths and Couplings in ep

$$\mu_i^k = \frac{\sigma_{i,\exp}^k}{\sigma_{i,SM}^k}$$

$$\sigma_i^k = \sigma_{prod}^k \cdot br_i^k$$

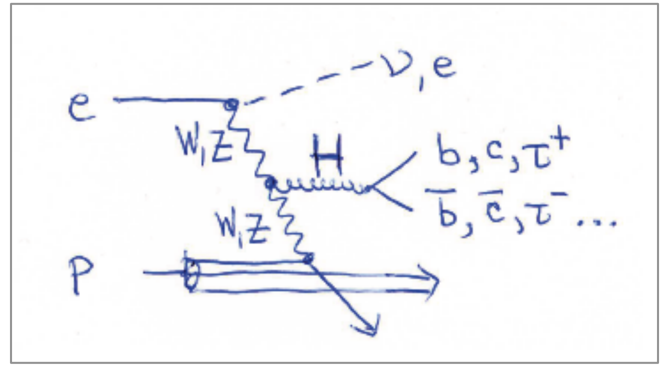
$$\frac{\sigma_{prod}^{k,\exp}}{\sigma_{prod}^{k,SM}} = \kappa_k^2$$

$$\frac{br_i^{\exp}}{br_i^{SM}} = \frac{\Gamma_i^{\exp}}{\Gamma_i^{SM}} \cdot \frac{\Gamma_{tot}^{SM}}{\Gamma_{tot}^{\exp}} = \kappa_i^2 \cdot \frac{1}{\sum_j \kappa_j^2 br_j^{SM}}$$

$$\mu_i^k = \kappa_k^2 \cdot \kappa_i^2 \cdot \frac{1}{\sum_j \kappa_j^2 br_j^{SM}}$$

Jorge de Blas, M+U.Klein 4/18

Reconstruct the full cross section as Σ_j
In e^+e^- use Z recoil for the total width.
In ep, the kinematics constrained also (under study, needs x..)



k=1: CC: WW, $\sigma_{tot}^{SM} \approx 200$ fb
k=2: NC: ZZ, $\sigma_{tot}^{SM} \approx 25$ fb

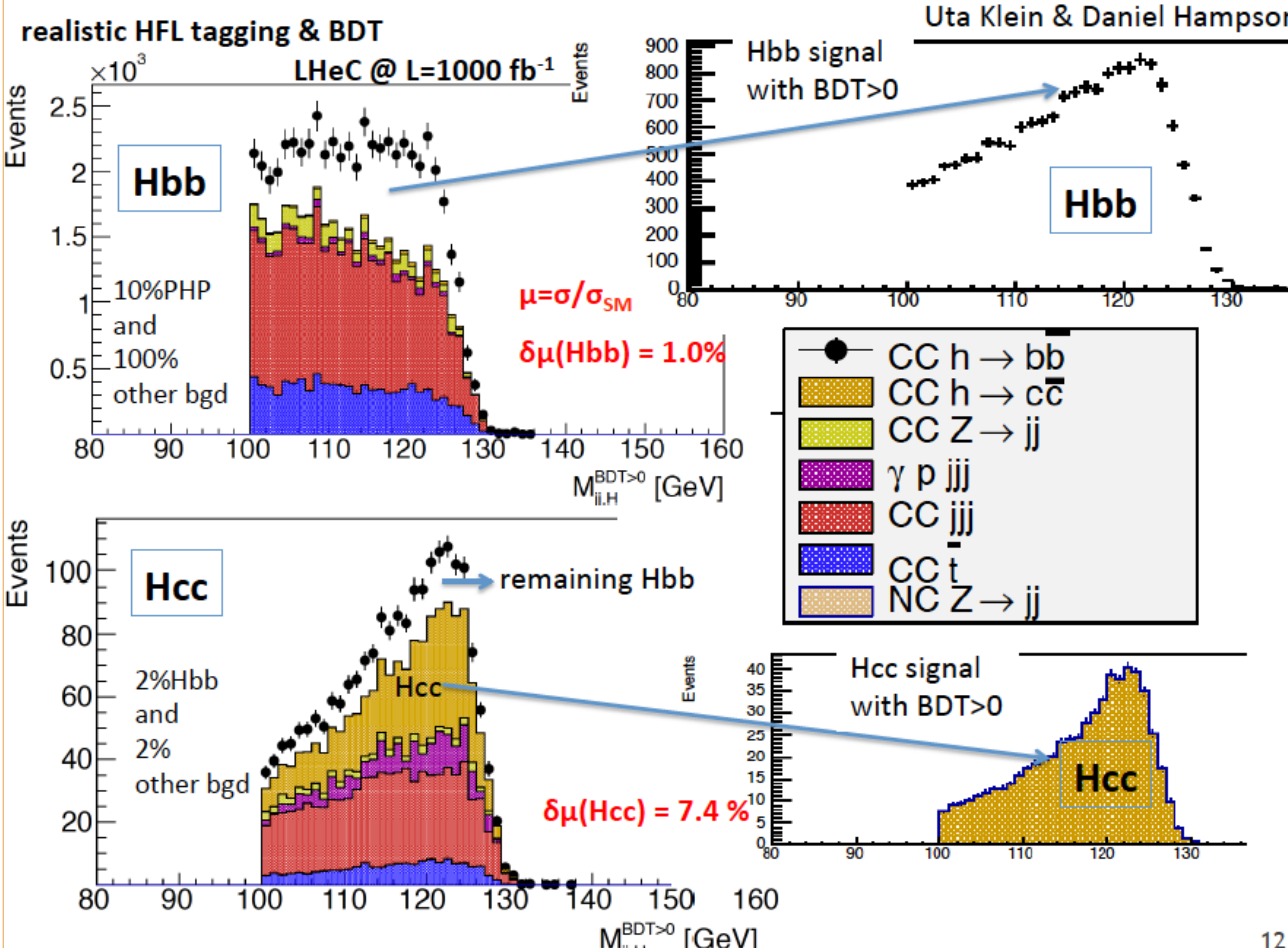
So far we considered 7 most abundant SM Higgs decay channels, i=1..7

bb, WW, gg, ττ, cc, ZZ, γγ

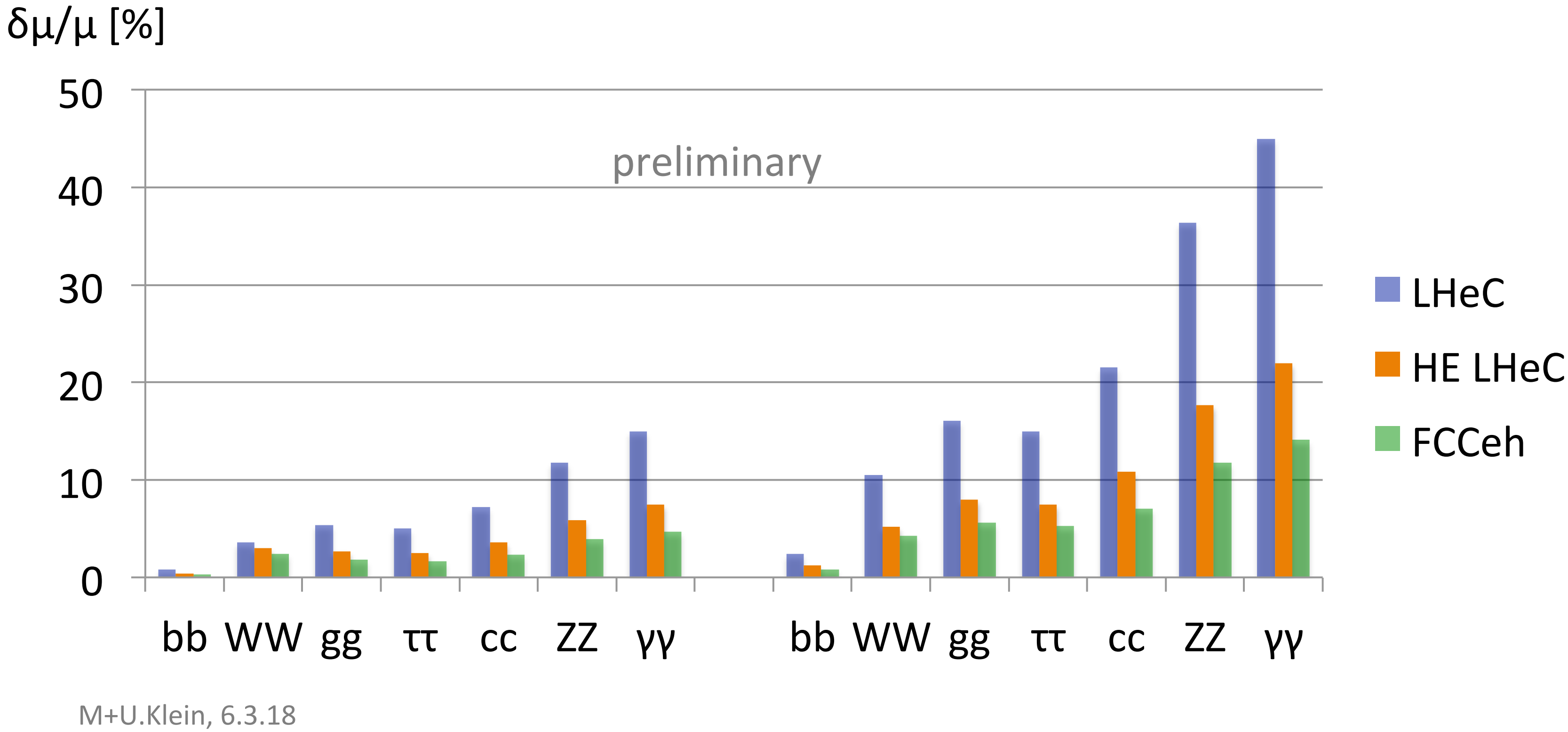
ttH will be added. (ep: 1.3 TeV cms!)

→ Nine measurements of κ_W and κ_Z
→ Two simultaneous measurements of the other couplings (in CC and NC)

Note: FCCeh: CC: $\sigma_{tot}^{SM} \approx 1$ pb. L=2ab^{-1}


realistic HFL tagging & BDT
Uta Klein & Daniel Hampson
LHeC @ L=1000 fb^-1
Hbb
10%PHP
and
100%
other bgd
μ=σ/σ_SM
δμ(Hbb) = 1.0%
Hbb signal
with BDT>0
Hbb
CC h → bb̄
CC h → cc̄
CC Z → jj
γ p jjj
CC jjj
CC t̄
NC Z → jj
Hcc
2%Hbb
and
2%
other bgd
remaining Hbb
Hcc
δμ(Hcc) = 7.4 %
Hcc signal
with BDT>0
Hcc
Events
M_jj,H^BDT>0 [GeV]

Signal Strength of SM Higgs Decays in ep [LHeC and FCCeh]

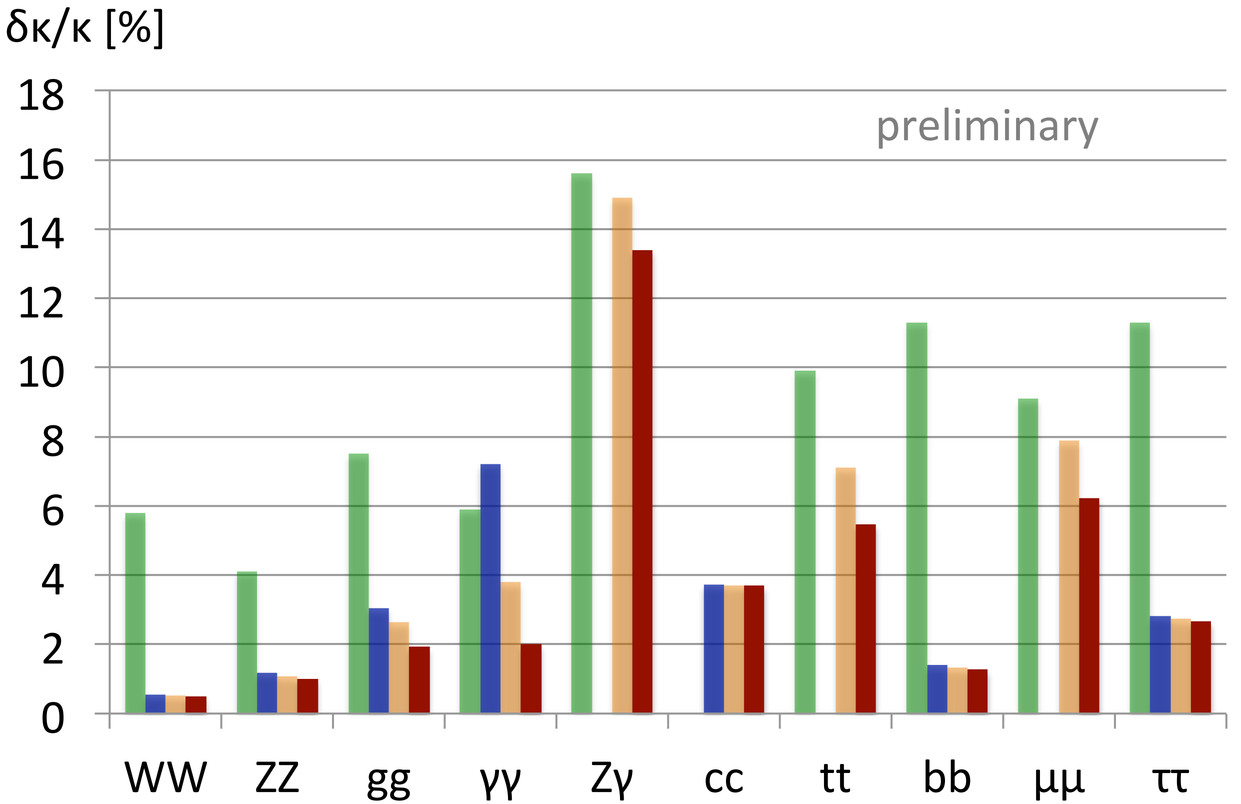


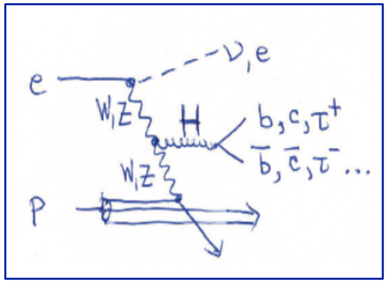
Charged Currents: ep → νHX   Neutral Currents: ep → eHX

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

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

Transformation of the LHC into a High Precision Higgs Facility





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

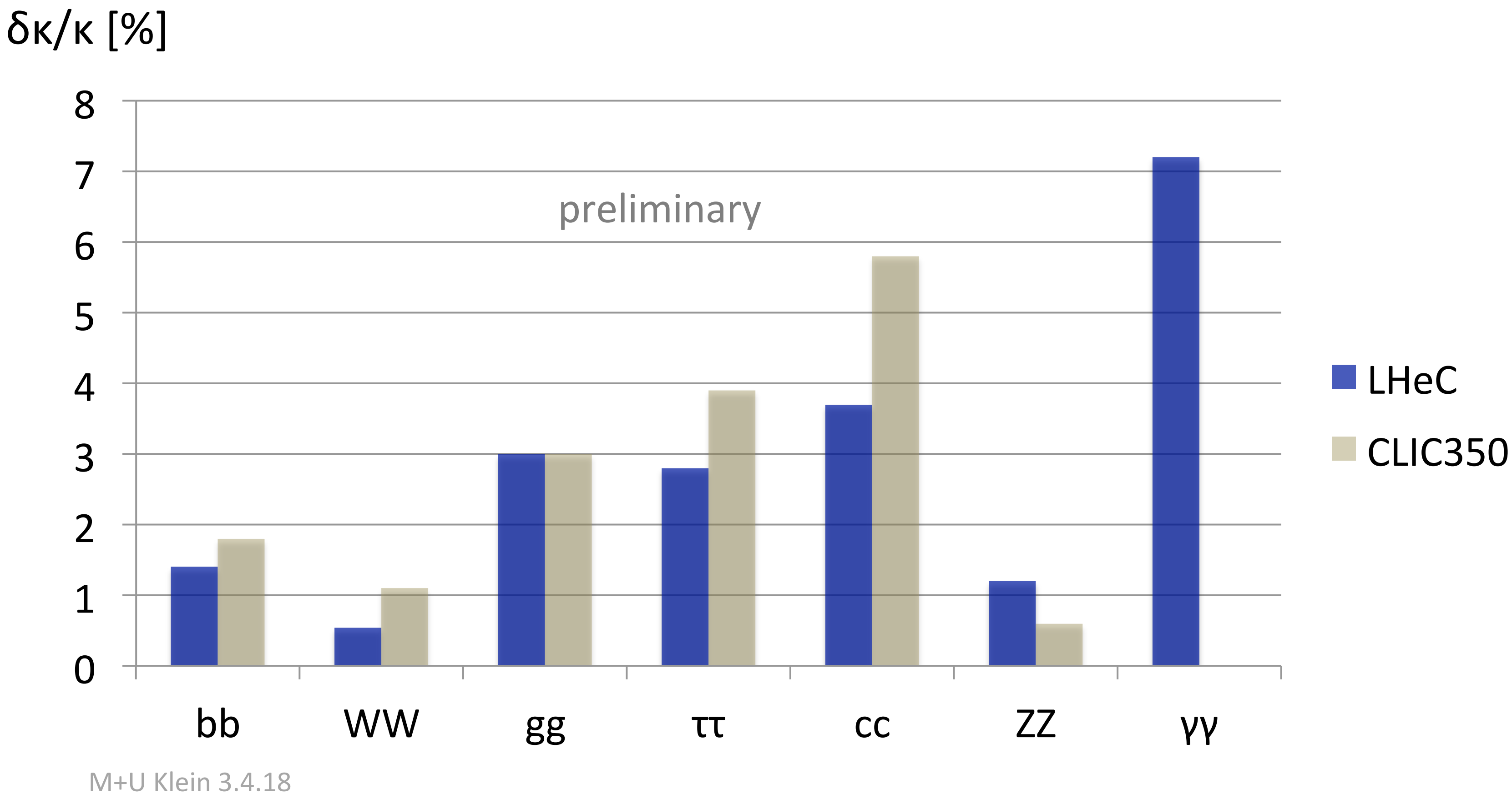
LHC: ATLAS prospects PUB Note 2014-016

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).

Comparison of LHeC and CLIC Prospects



LHeC: 60 GeV x 7 TeV. **CLIC: 350 GeV** [arXiv:1608.07538, "model dependent fit", 0.5ab^{-1}]

Ultimate: Combine pp-ee-ee to test the Higgs Sector as stringent as possible, SM, HH, BSM
Note: Demanding level of precision, width from Z recoil, rare channels in pp, low cost ep

Higgs precision observables at FCC ee and eh

Talk by J deBlas @ FCC Week

- Fit to modified Higgs couplings (assuming no extra invisible decays)

NEW

FCC-ee	
Coupling	Relative precision
κ_b	0.58%
κ_t	–
κ_τ	0.78%
κ_c	1.05%
κ_μ	9.6%
κ_Z	0.16%
κ_W	0.41%
κ_g	1.23%
κ_γ	2.18%
$\kappa_{Z\gamma}$	–

FCC-eh	
Coupling	Relative precision
κ_b	0.74%
κ_t	–
κ_τ	1.10%
κ_c	1.35%
κ_μ	–
κ_Z	0.43%
κ_W	0.26%
κ_g	1.17%
κ_γ	2.35%
$\kappa_{Z\gamma}$	–

Summary by J deBlas@FCC-Amsterdam2018 $\equiv g_{hi}/g_{hi}^{SM}$

Higgs→ invisible: 1.2%
ttH: 1.85%

- **All three FCC options complement each other very well:**
  - **FCC-ee allows not only very precise measurements of the Higgs and EWPO but also provides the normalization for more precise measurements at the FCC-eh and FCC-hh**
  - **FCC-eh complements FCC-ee providing information about light quark EW couplings. Similar precision in the Higgs sector**
  - **FCC-hh fills gaps in precision Higgs measurements for rare decays, top and the Higgs self-coupling**

NEW
ee+ep+pp

Talk by J deBlas@FCC-Week2018

Higgs complementarities: Global fit to Higgs couplings at FCC

- All single Higgs couplings can be determined below the 1%

FCC-ee/FCC-eh
Precise determinations for the leading couplings

HZZ Crucial for normalization of FCC-hh results

FCC-hh
Completes the picture with precise determinations of Top and coupling associated to rare decays

NOT MODEL-INDEPENDENT:
Results assume that, if there is New physics, it can only be in the Higgs couplings

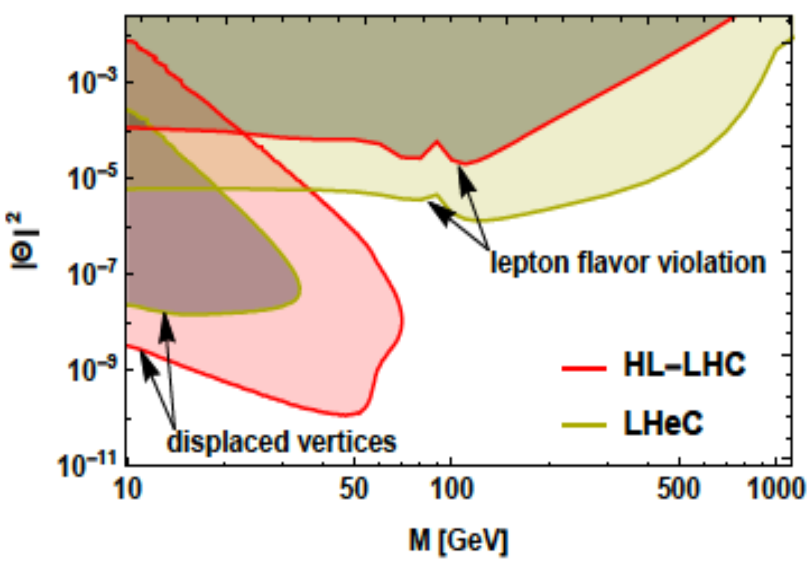
HLLHC + FCC	
Coupling	Relative precision
κ_b	0.38%
κ_t	0.51%
κ_τ	0.58%
κ_c	0.79%
κ_μ	0.42%
κ_Z	0.14%
κ_W	0.17%
κ_g	0.74%
κ_γ	0.40%
$\kappa_{Z\gamma}$	0.52%

$$\kappa_i \equiv g_{hi}/g_{hi}^{SM}$$

→ Combine the complementary measurements for best physics outcome!
→ Next: joint EFT fits

New Physics through High Precision (LHC: ep& pp)

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**



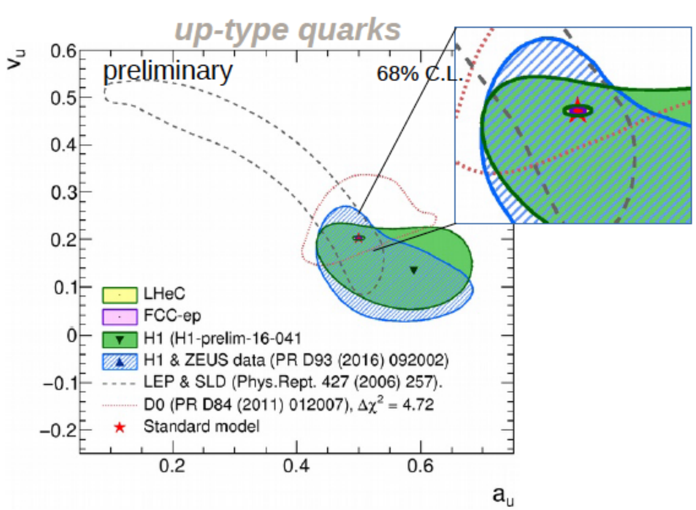
Antusch, Cazzato, Fischer – work still in progress
Int. J. Mod. Phys., A32(14):1750078, 2017.

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



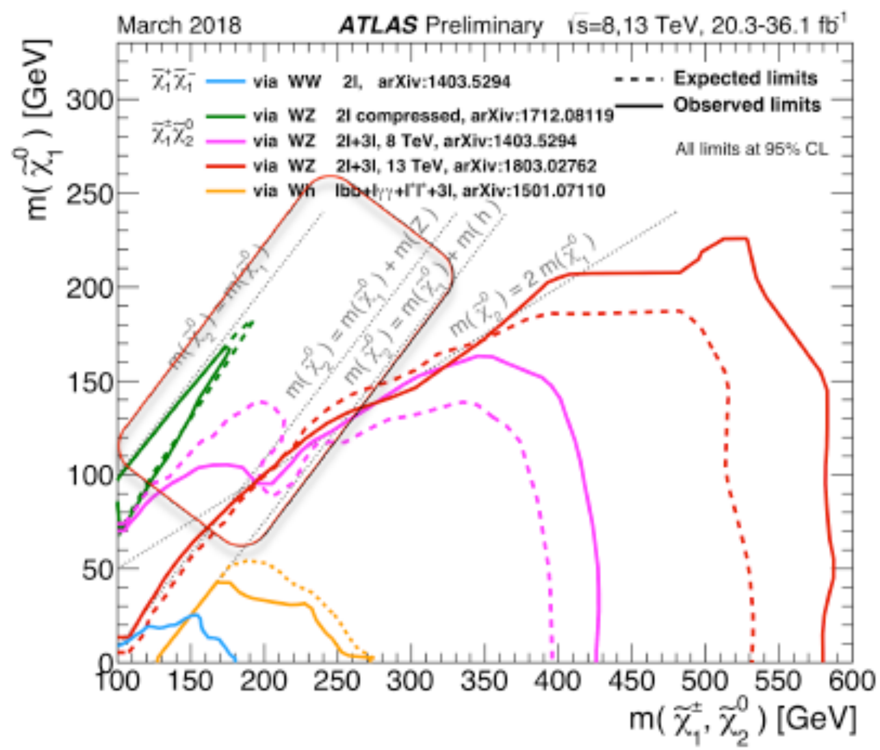
Britzger, MK, Spiessberger, Zhang – work still in progress

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



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

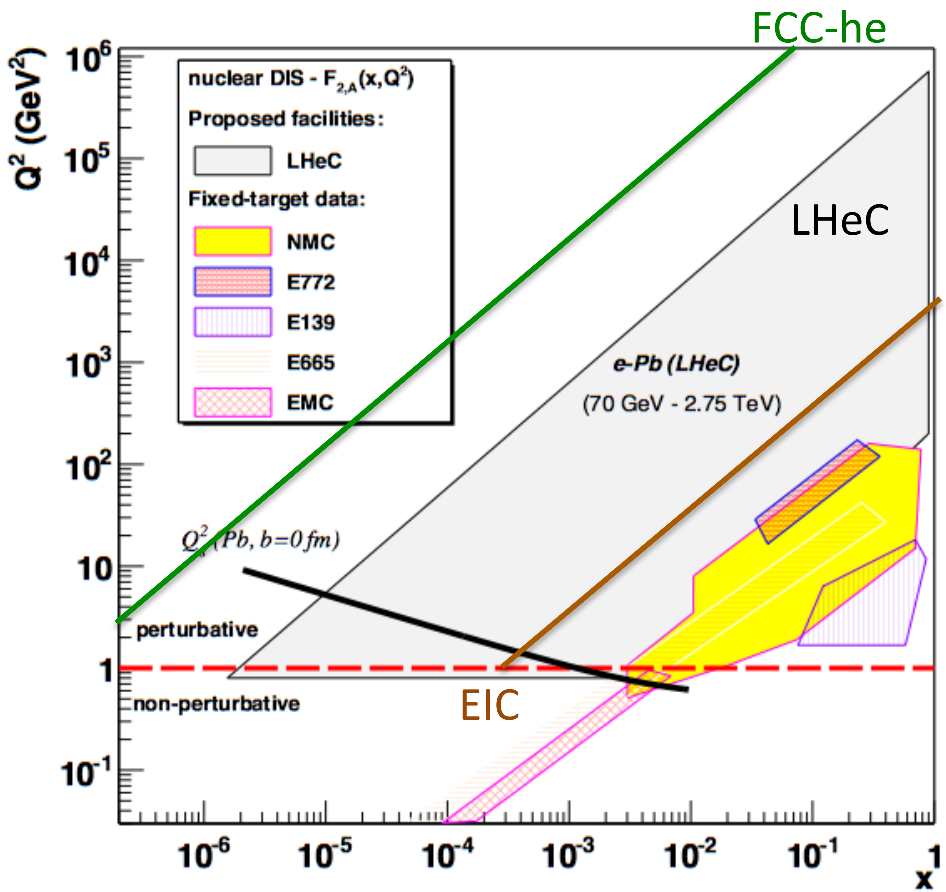
→ SUSY ewk sector most challenging for pp colliders

cf U Klein + M Donofrio at Amsterdam FCC

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.

LHeC as Electron Ion Collider



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 (anti)shadowing ?

- Safely can expect
nuclear PDFs like at HERA
→ $R(x,Q^2)$ flavour dependent

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

Precision QCD study of parton dynamics in nuclei
Investigation of high density matter and QGP
DGLAP to BFKL – vital for LHC and FCCpp physics
Note Change of Paradigm: pPb shows collective behaviour. Ridge – correlations.. **Discovery with eA**

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.

1802.04317

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

http://lhec.web.cern.ch

Challenges: Demonstration 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.

LHeC Prospects

- The ep interaction does not disturb pp, i.e. the LHC may become a twin collider, ep and pp operate concurrently and no luminosity loss is planned for pp. This requires a premounted eh detector which may then be inserted in 2 years.

- At LS4 (~2030) the heavy ion LHC operation ends and one may propose a different use of IP2 which currently houses ALICE.

- The electron beam energy (> 50 GeV) and luminosity ($O(10^{34})$ cm^{-2} s^{-1}) goals are derived from Higgs, top and BSM physics, also DIS itself (F_L, low x~1/s).

- The cost of the O(1) TeV ep collider is a small fraction of any other big project currently under discussion. The LHC determines the time frame. This may extend considerably if CERN moves to HE LHC in the fourties.

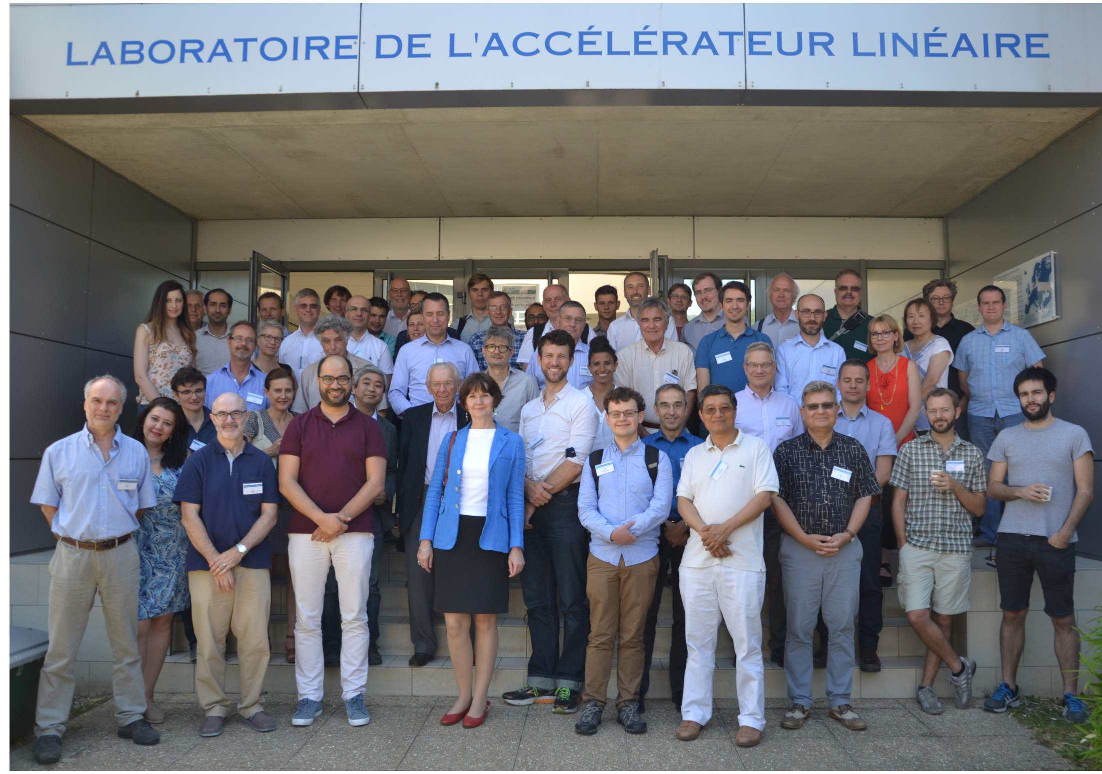
- The ERL technology is being developed worldwide (Darmstadt, Cornell, Berlin, Novosibirsk, Jefferson Lab). PERLE would be a multi-turn 802 MHZ ERL technology development and test facility which would timely accompany the LHeC progress.

- We celebrate this year the 50th anniversary of the discovery of quarks. This was not planned and achieved by a step in energy with a linac SHORTER than LHeC's

- There is a very long term future for eh as part of hh in the FCC vision

Most up-to-date Information: https://indico.cern.ch/event/698368/

Workshop: LHeC/FCCeh and PERLE
Last week at Orsay near Paris



http://lhec.web.cern.ch

New and Updates on

Physics: PDFs, QCD, H, t, BSM, eA + Relation eh-hh..
Accelerator: IR, Optics, Lattice, Cost-Energy, CE..
Detector: the GPD and its fwd and bwd detectors
PERLE: Source, Injector, Cavity, Cryomodule,.. Physics
Project Development towards the ES2020:
LHeC + FCCeh+ PERLE input 12/18. PERLE TDR in 2019.

CERN-OPEN-2019-nnn
LHeC-Note-2019-001 GEN
Geneva, June 25, 2018

A Higgs Facility Resolving the Substructure of Matter

Update on the 2012 LHeC Report
on the Physics and Design Concepts for Machine and Detector

LHeC Collaboration

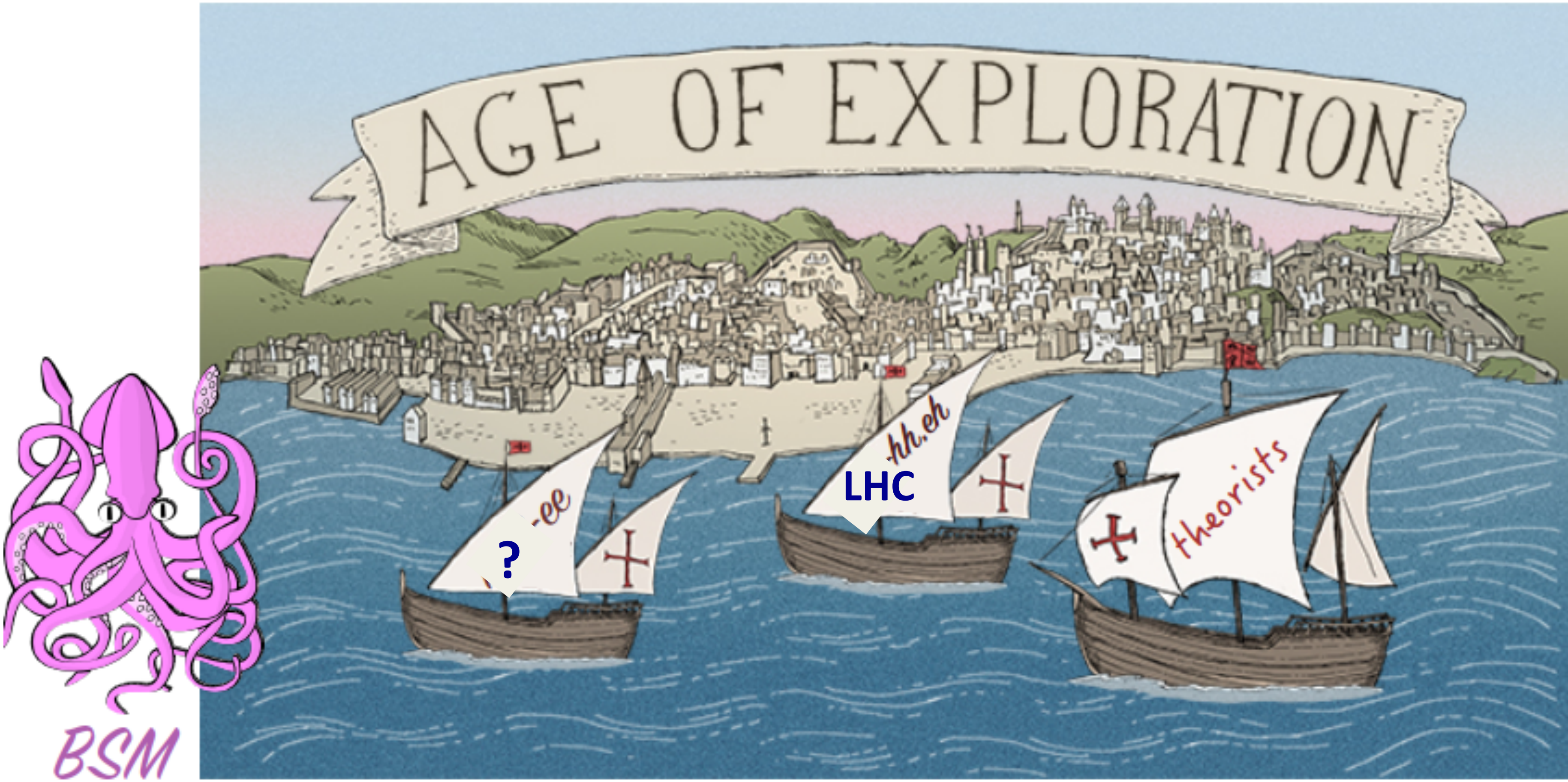
Submitted to J.Phys. G

← "Implementation Plan" or "Expression of Interest" … will be written in early 2019

Submissions of Papers to the European Strategy 12/18:

- PERLE Acc/ERL Development
- LHeC for HL and HE LHC
- FCCeh as part of FCC
- Generic DIS 10 page Paper

Time comes to unite pp with ep and ee at TeV scale



Jo Ruderman, modified

By adding ep to HL and HE LHC and building one new e^+e^- collider, a realistic program emerges for exploring the SM deeper and leading beyond, for the next 40 years ahead.

Shanghai backup

Physics and Prospects with LHeC

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

Project Design and Developments

Accelerator: ERL: 10-60 GeV Ee

Luminosity O(1000) HERA

ERL Technology Development: PERLE

Detector and its Installation

Project Features + Prospects

Outlook to HE LHC and FCCeh pp and ee

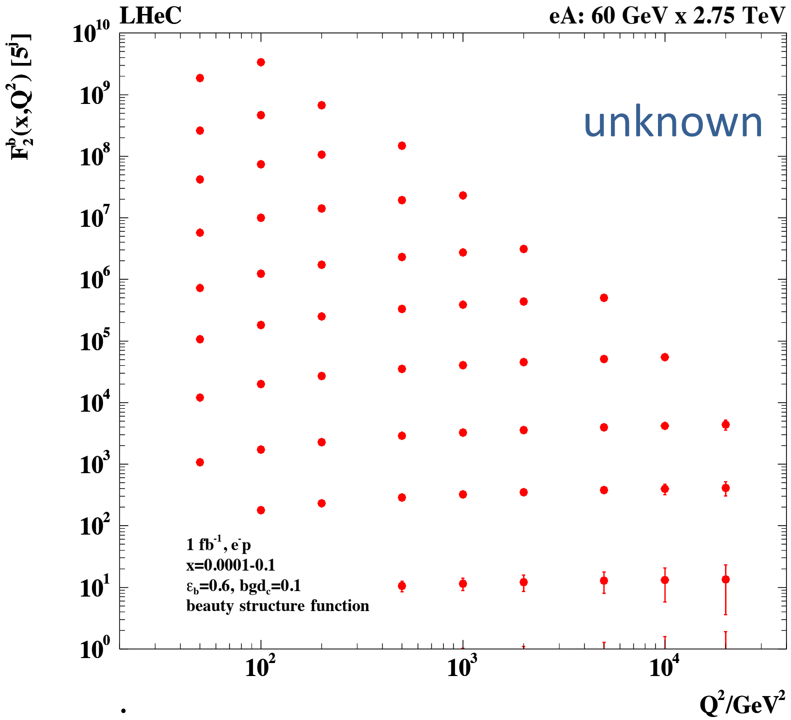
Towards the European Strategy

Note that LHeC has had a 600 pages CDR on physics, accelerator, detector arXiv:1206.2913

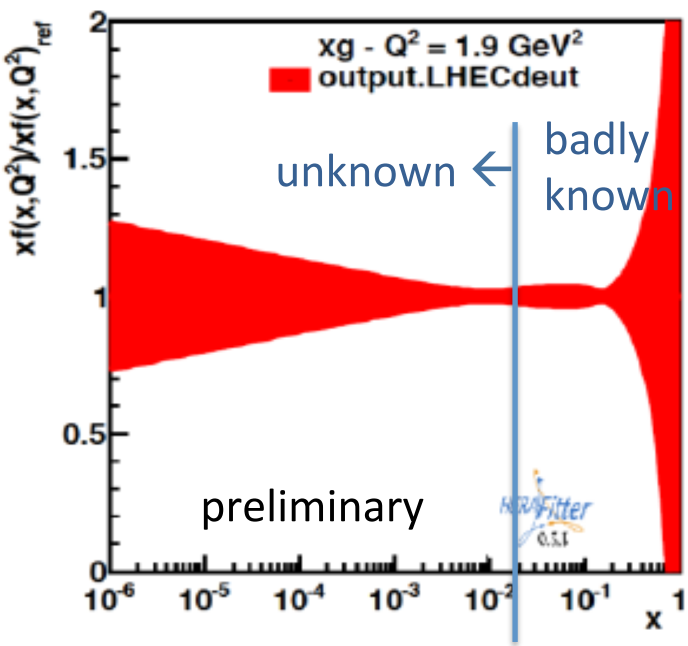
Max Klein, for the LHeC/FCCeh/PERLE Collabrations. Shanghai, TDLI 2.7.2018

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)

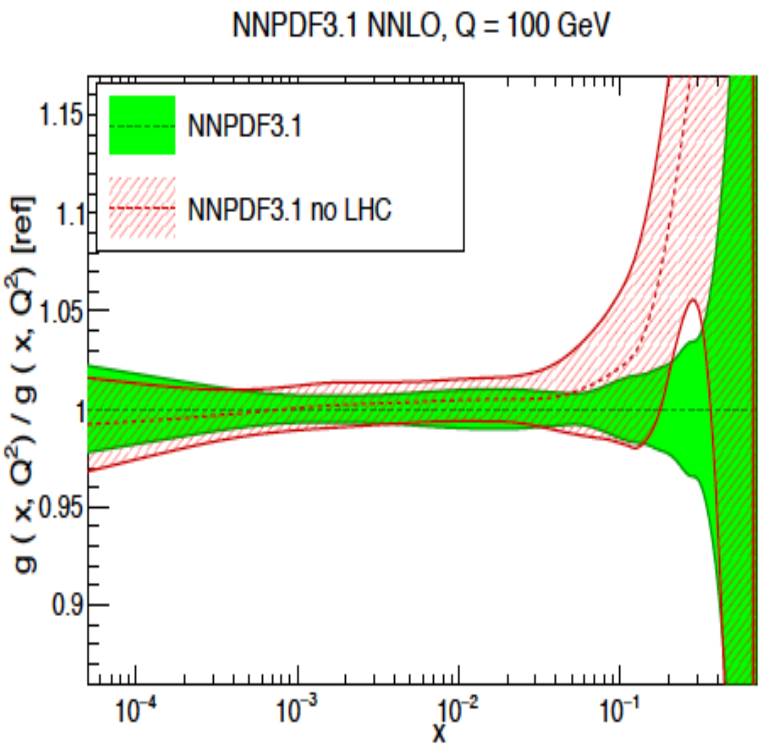
Measure nPDFs as in ep scattering and determine then the ratio $R(x,Q^2)$=nPDF/PDF

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

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. …

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.

Powerful Energy Recovery Linac for Experiments

PERLE

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

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

Extended H Decay Channel Prospect Study

Presented by Uta Klein to FCC and DIS workshops in 2018 - preliminary

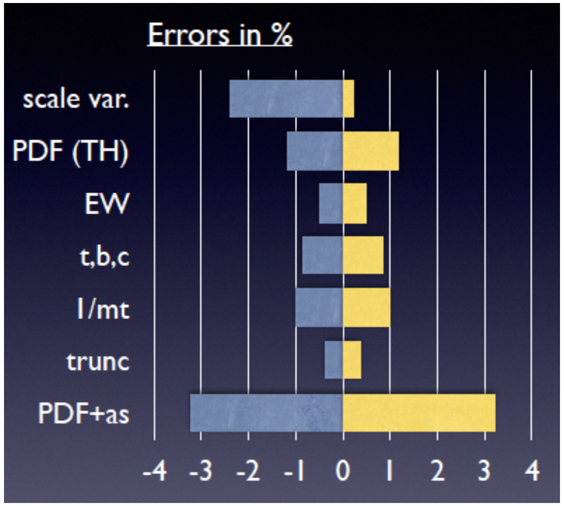
- Use LO Higgs cross sections **σ_H for M_H=125 GeV, in [fb],** and branching fractions BR(H→XX from Higgs Cross Section Handbook (c.f. appendix)
- Apply further branching, BR(X→FS) in case e.g. of W→ 2 jets and use acceptance, Acc, estimates based on MG5, for further decay
- Use reconstruction efficiencies, ε, achieved at LHC Run-1, see e.g. prospect calculations explored in arXiV:1511.05170
- Use fully simulated LHeC Hbb and Hcc results as baseline for S/B ranges
- Use fully simulated Higgs to invisible for 3 ep c.m.s. scenarios as guidance for extrapolation uncertainty (~25%)
- Estimate HIggs events per decay channel for certain Luminosity in [fb^{-1}]

$$N = \sigma_H \bullet BR(H \to XX) \bullet BR(X \to FS) \bullet L$$

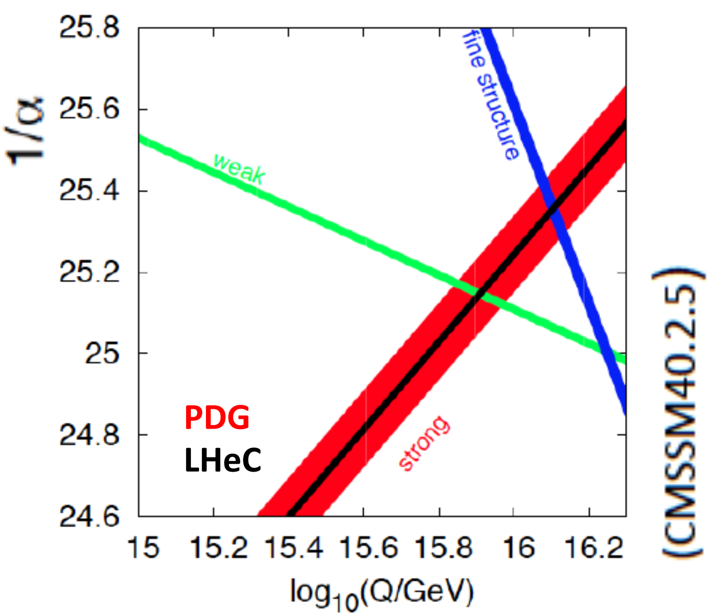
- Calculate uncertainties of signal strengths w.r.t. SM expectation $\mu = \frac{\sigma}{\sigma_{SM}}$

$$\frac{\delta\mu}{\mu} = \frac{1}{\sqrt{N}} \bullet f \quad \text{with} \quad f = \sqrt{\frac{1+1/(S/B)}{Acc \bullet \varepsilon}}$$

Strong Coupling Constant



Uncertainty on Higgs cross section
Giulia Zanderighi, Vietnam 9/16,
from C.Anastasiou et al, 1602.00695
who also discuss the ABM alpha_s..



- α_s least known of coupling constants
  Grand Unification predictions need smaller $\delta\alpha_s$
- Is α_s(DIS) lower than world average (?)
- LHeC: per mille - independent of BCDMS!
- High precision from inclusive data – α_s(jets)??
- Challenge lattice QCD

LHeC simulation, NC+CC inclusive, total exp error

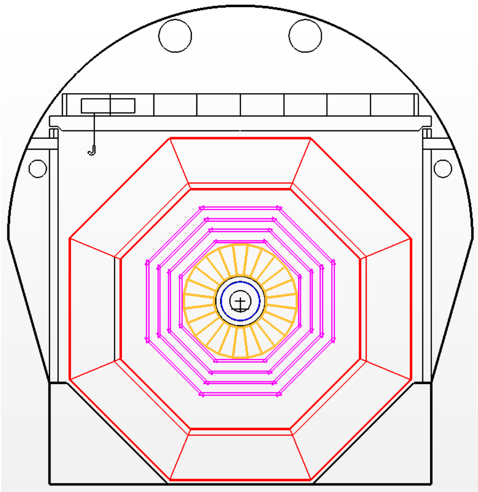
case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 >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

Two independent QCD analyses using LHeC+HERA/BCDMS

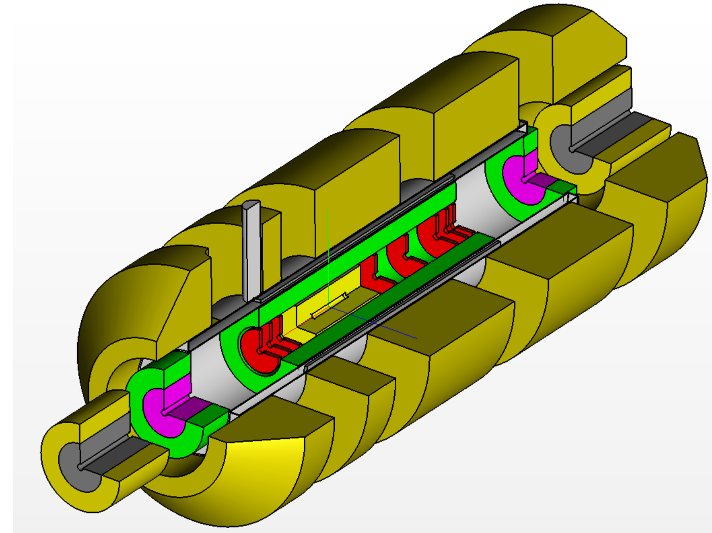
Installation Study

to fit into LHC shutdown needs, directed to IP2

Andrea Gaddi et al



Detector fits in L3 magnet support



Modular structure

LHeC INSTALLATION SCHEDULE