The LHeC – from Bonn to Marseille and Beyond

Chavannes Workshop
Conceptual Design Report
Higgs Discovery
ECFA Review
LHC and LHeC Relation
Daresbury Workshop
LPCC Review of LHeC Programme
Outlook

Max Klein

LHeC last week at LPCC

PDFs – V.Radescu
Heavy PDFs – R.Pacakyte
Accelerator – O.Brüning
Higgs – B. Mellado
BSM LH(e)C – M.D'Onofrio
QCD at low x – A.Stasto
eA Physics – N.Armesto

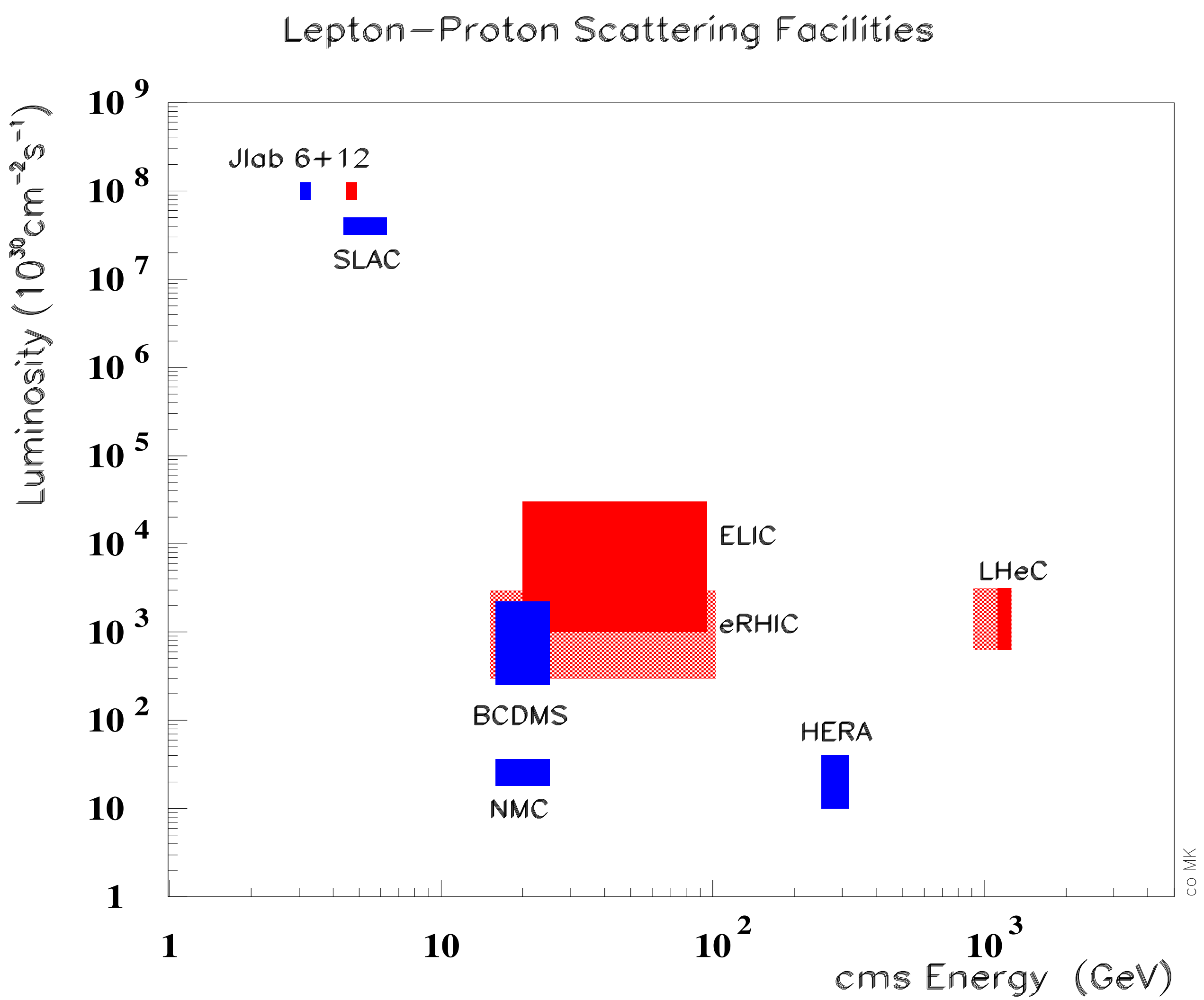
http://cern.ch/lhec

LHeC at this Conference

Accelerator – O. Brüning
Detector – D. South
Higgs in ep – B. Mellado
Low x physics – N. Armesto
Nuclear PDFs – H. Paukkunen

Workshop on Deep Inelastic Scattering, Marseille, April 24sth, 2013

From Doubts to Faith (Franciscus de Assisi)



High energy frontier DIS: Higgs, RPV SUSY/LQ, ewk + QCD precision physics, low x
With the LHC: ~$10^{34}cm^{-2}s^{-1}$ in ep, 4 orders of magnitude in 1/x in eA, half ep exists.

1. Chavannes Workshop

4th in the series of LHeC Workshops
(2008,2009, 2010,2012)

Next workshop tentatively 14/15.10.2013

Four main results of a sunny workshop:

- **Higgs** close to be discovered
  [WW→ H re-emphasised
  and LHeC physics reviewed]

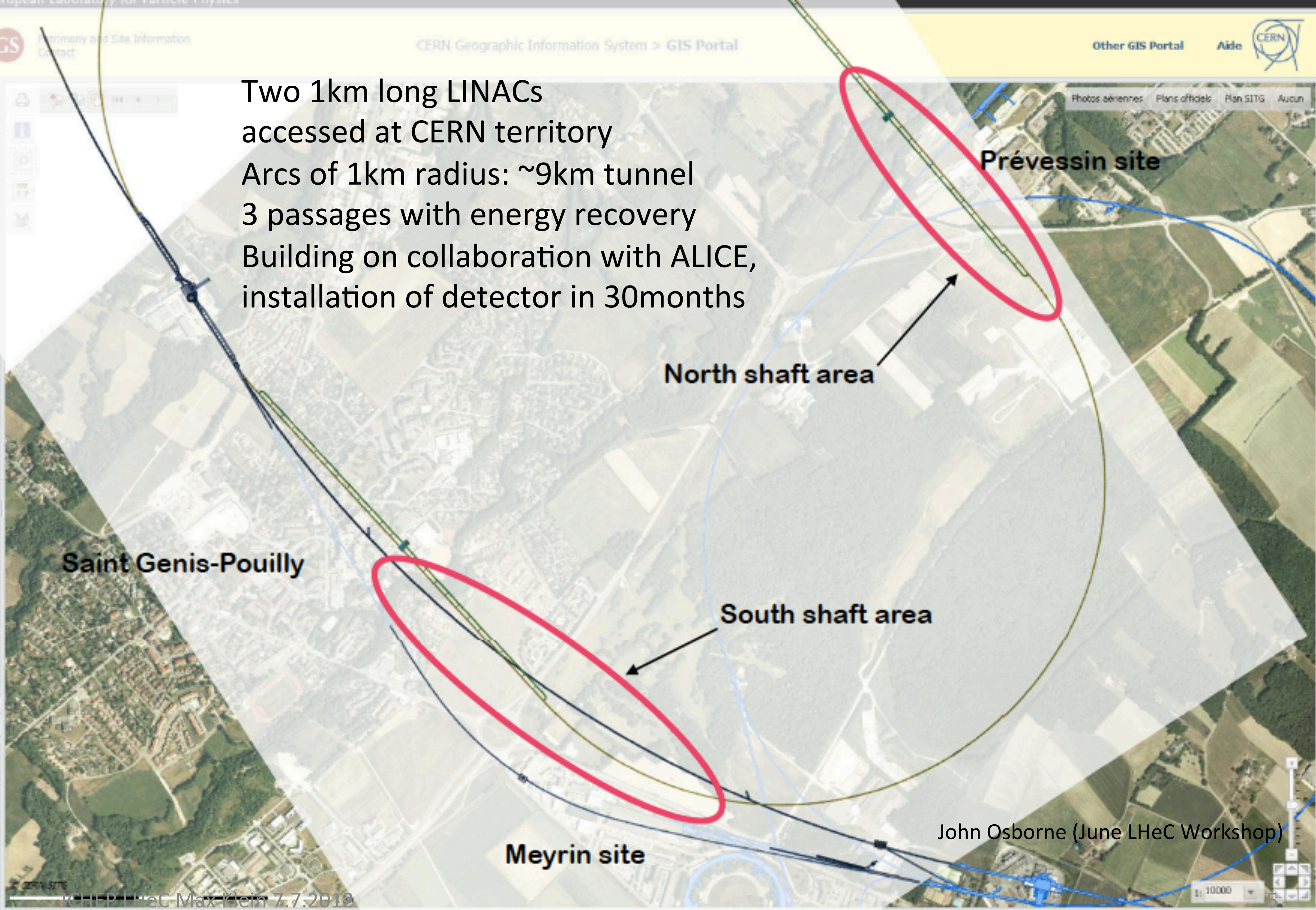
- Decision for **Linac-Ring**
  [Ring-Ring as backup, doable
  but challenging installation]

- Confirmation of **Detector Concept**
  [detailed reviews of tracking,
  magnets, IR and calorimetry]

- **Mandate of CERN to proceed**
  [preparations of key technologies
  for project decision in ~2017]

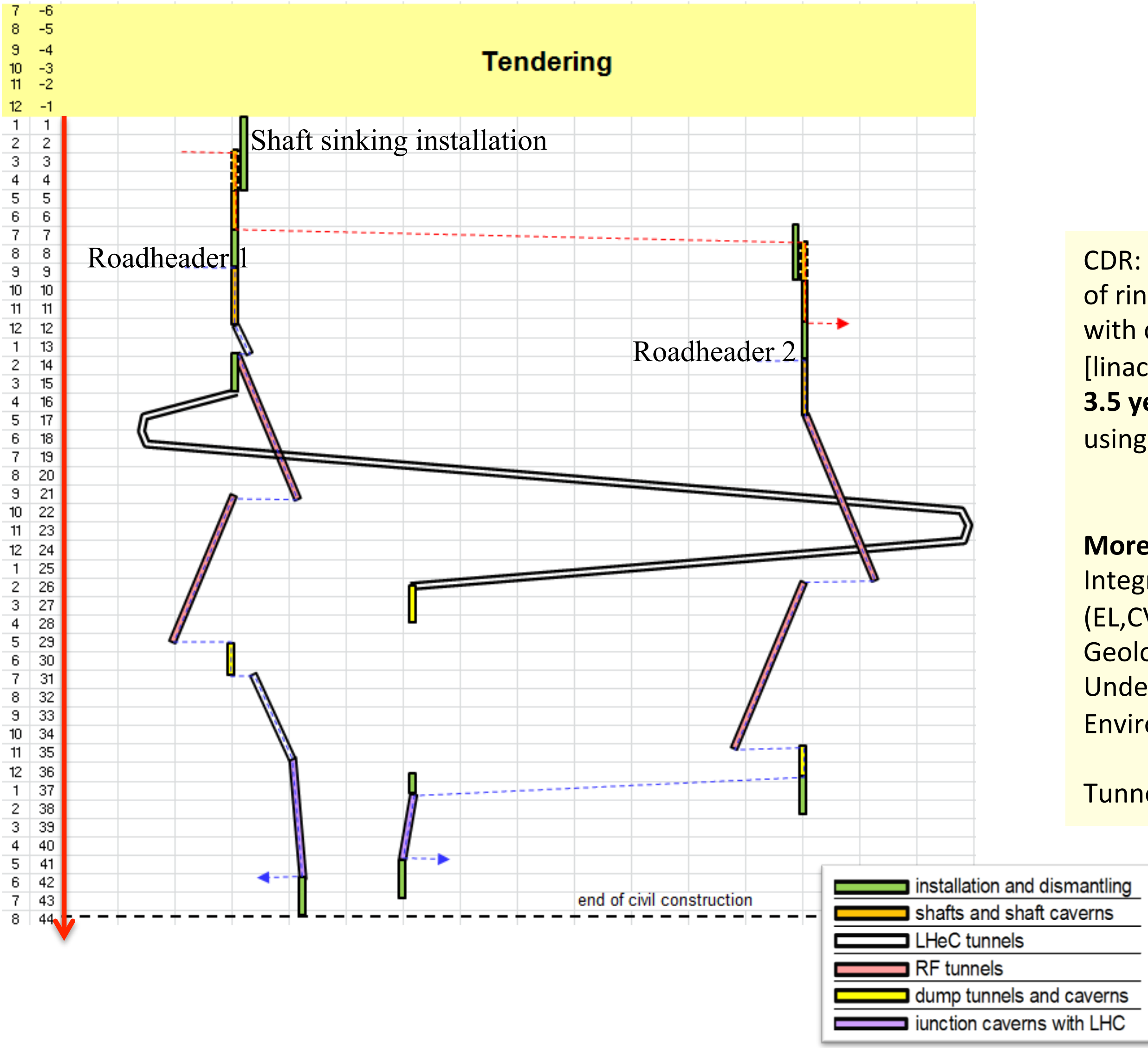
60 GeV Electron Accelerator with wall-plug power < 100MW

Two 1km long LINACs
accessed at CERN territory
Arcs of 1km radius: ~9km tunnel
3 passages with energy recovery
Building on collaboration with ALICE,
installation of detector in 30months



John Osborne (June LHeC Workshop)

Civil Engineering



CDR: Evaluation of CE, analysis of ring and linac by Amber Zurich with detailed cost estimate [linac CE: 249,928 kSF..] and time: **3.5 years for underground works** using 2 roadheaders and 1 TBM

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

Tunnel connection in IP2

J.Osborne, Chavannes

ISSN 0954-3899

Journal of Physics G

Nuclear and Particle Physics

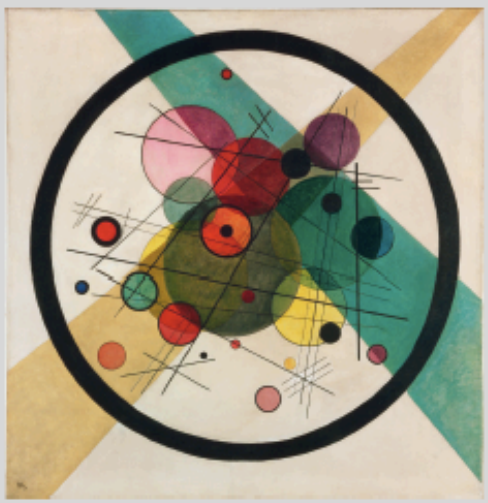
Journal of Physics G Nuclear and Particle Physics   Vol 39, No 7   075001   July 2012

Volume 39   Number 7   July 2012   Article 075001

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group



iopscience.org/jphysg

IOP Publishing

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.

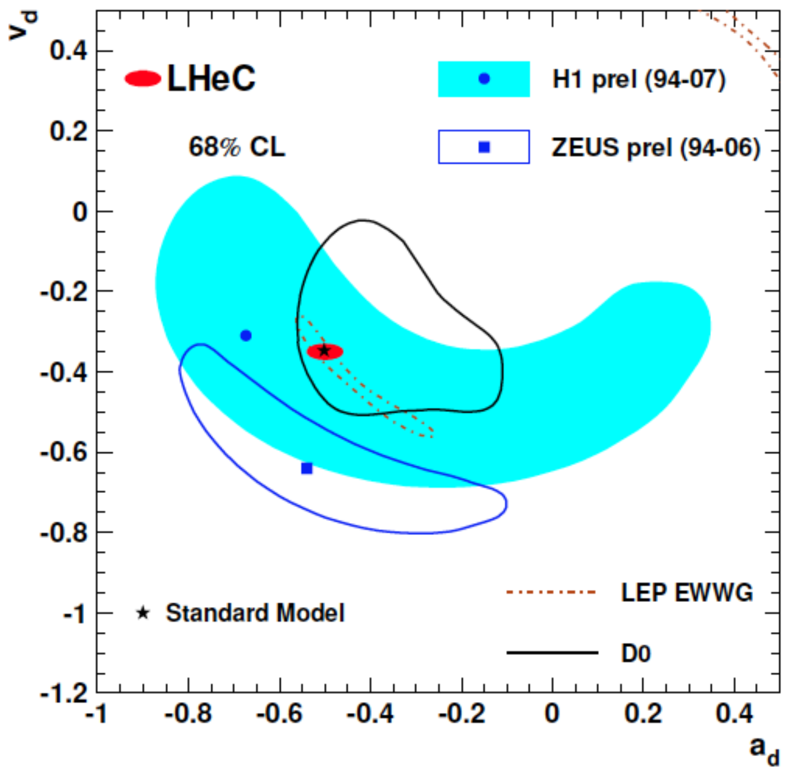
“BFKL evolution and Saturation in DIS”

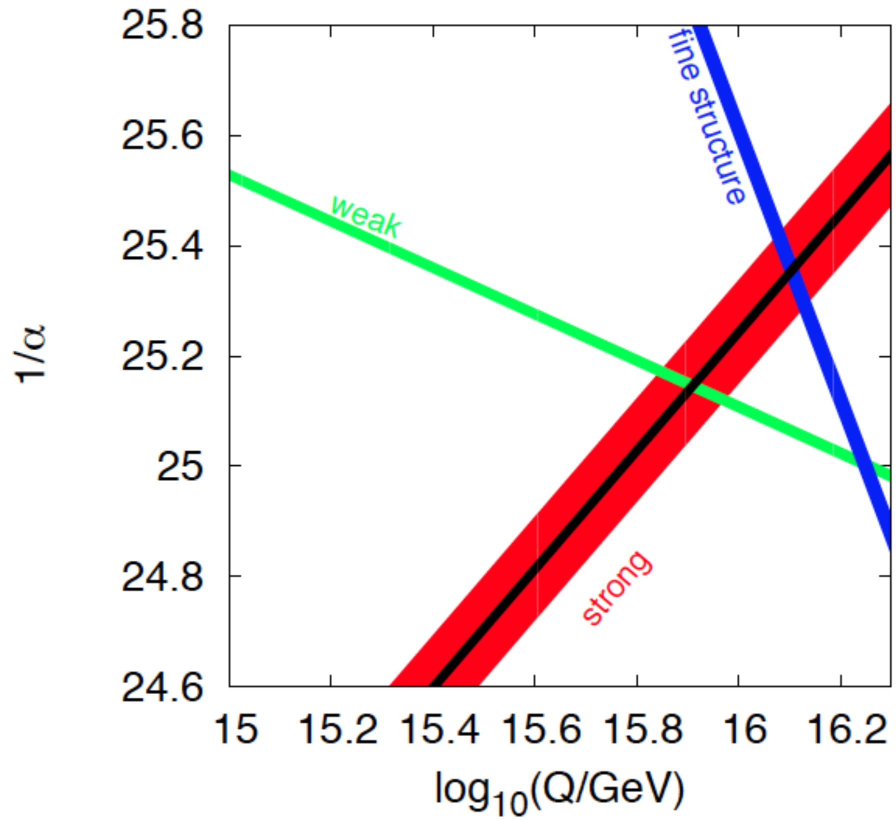
Circles in a circle
V. Kandinsky, 1923
Philadelphia Museum of Art

“Critical gravitational collapse”

5d tiny black holes and perturbative saturation
Talk by A.S.Vera at LHeC Workshop 2008

High Precision DIS



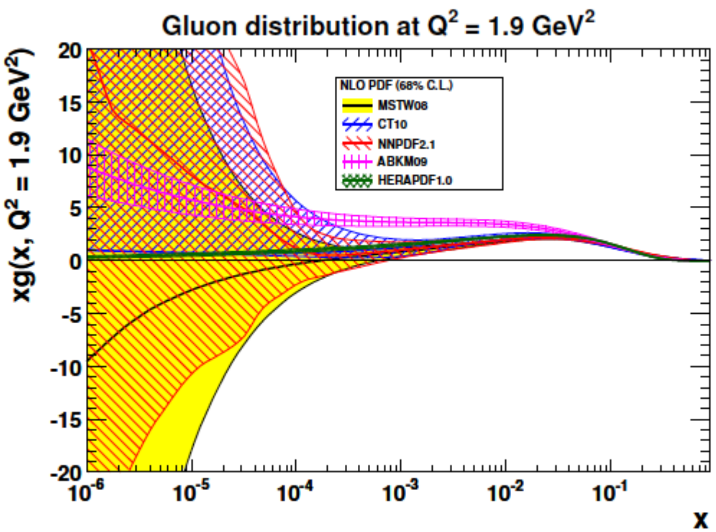


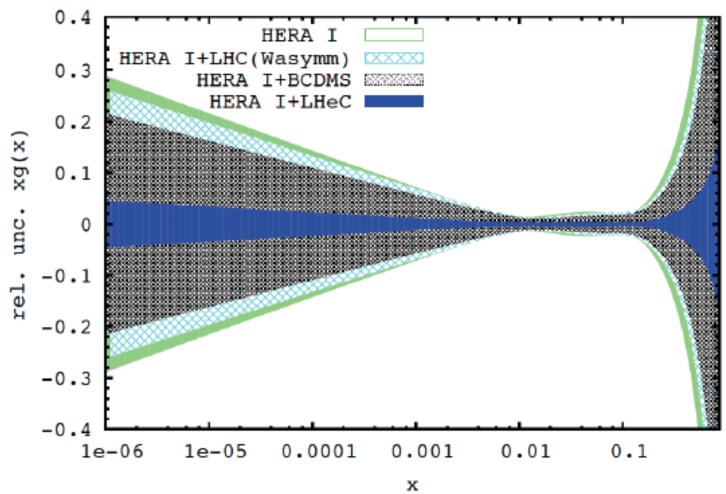
$Q^2 >> M_{Z,W}^2$, high luminosity, large acceptance
Unprecedented precision in NC and CC
Contact interactions probed to 50 TeV
Scale dependence of $\sin^2\theta$ left and right to LEP

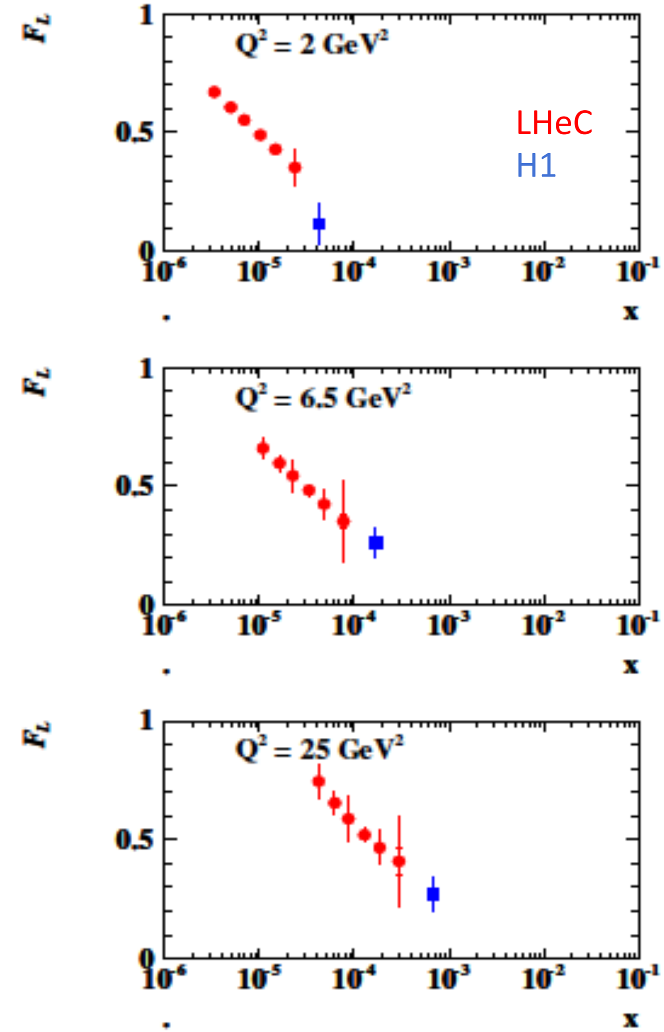
→ A renaissance of deep inelastic scattering ←

Solving a 30 year old puzzle:
α_s small in DIS or high with jets?
Per mille measurement accuracy
Testing QCD lattice calculations
Constraining GUT (CMSSM40.2.5)
Charm mass to 3MeV, N^3LO

Gluon Saturation at Low x?



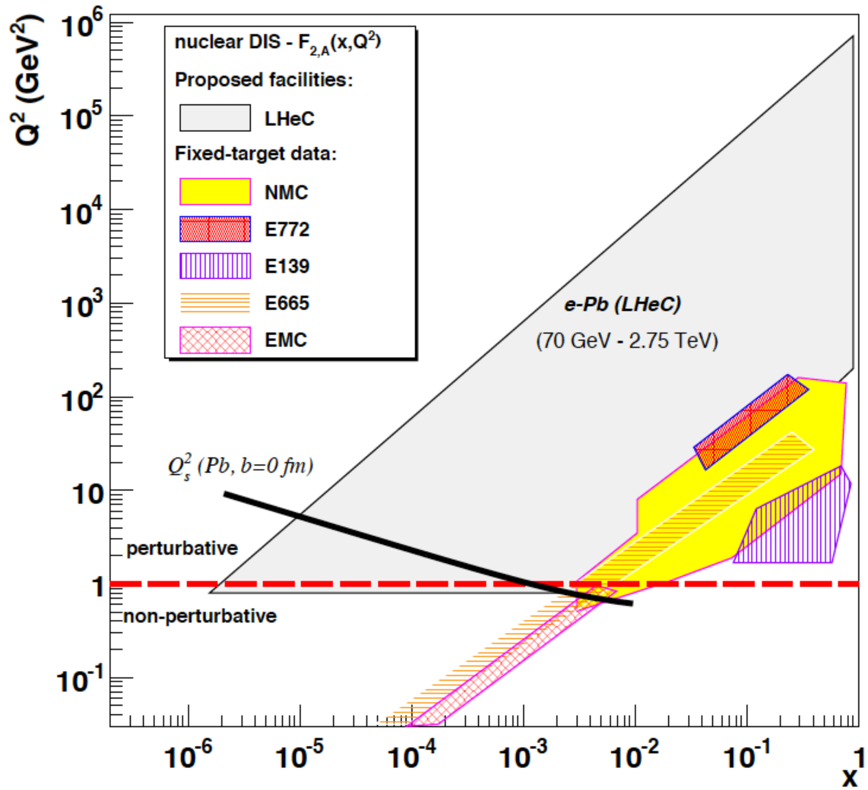




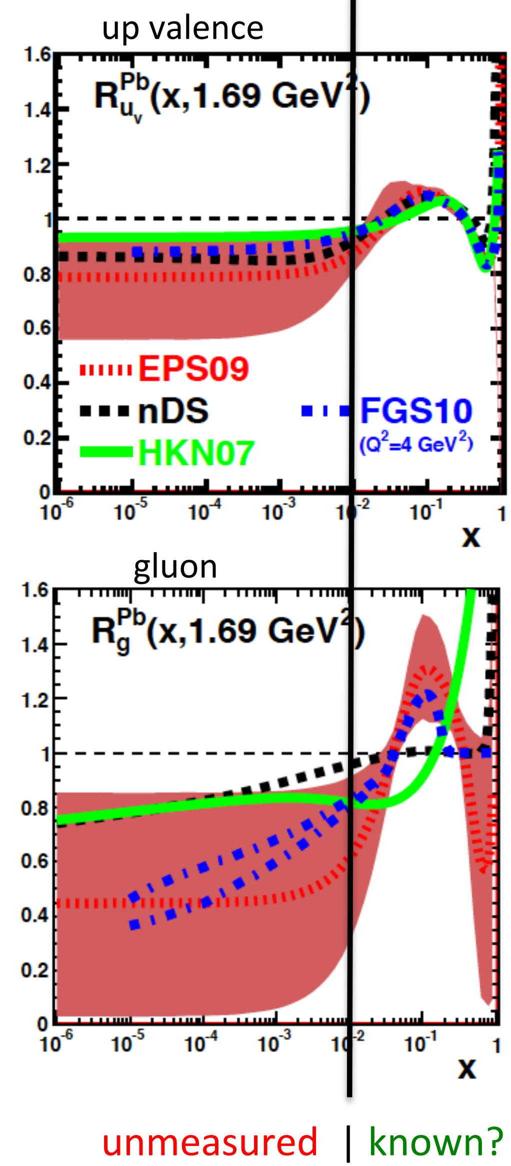
Gluon measurement down to $x=10^{-5}$, **Saturation or no saturation** (F_2 and precise F_L)
Non-linear evolution equations? Relations to string theory, and **SUSY at ~10 TeV**?

cf H.Kowalski, L.Lipatov, D.Ross, arXiv:1205.6713

Heavy Ion Physics



eA physics is essentially not done yet (no eA at HERA)
LHeC has huge discovery potential for new HI physics
(bb limit, saturation, deconfinement, hadronisation..)
It will put nPDFs on completely new ground and constrain the initial conditions of the Quark-Gluon Plasma



Summary of LHeC Physics [arXiv:1211:4831+5102]

The LHeC represents a new laboratory for exploring a hugely extended region of phase space with an unprecedented high luminosity in high energy DIS. It builds the link to the LHC and a future pure lepton collider, similar to the complementarity between HERA and the Tevatron and LEP, yet with much higher precision in an extended energy range. Its physics is fundamentally new, and it also is complementary especially to the LHC, for which the electron beam is an upgrade. Given the broad range of physics questions, there are various ways to classify these, partially overlapping. An attempt for a schematic overview on the LHeC physics programme as seen from today is presented in Tab. 3. The conquest of new regions of phase space and intensity has often lead to surprises, which tend to be difficult to tabulate.

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^*, ν^*, W?, Z?, top?, H?
New and BSM Physics	leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_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, $x \simeq 1$, J/ψ, Υ, 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^3LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing
Heavy Ions	initial QGP, nPDFs, hadronization inside media, black limit, saturation
Modified Partons	PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

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

3. Higgs Discovery

$$L = (D_\mu \phi)^+ (D_\mu \phi) - V(\phi^+ \phi) - \frac{1}{4} F^a_{\mu\nu} (F^a)^{\mu\nu} - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}$$

$$D_\mu = (\partial_\mu + igA^a_\mu \frac{\varepsilon_a}{2} + ig' B_\mu \frac{1}{2}), \phi = \begin{pmatrix} 0 \\ \eta + \sigma(x)/\sqrt{2} \end{pmatrix}$$

$$M_{W^+} = M_{W^-} = \frac{g\eta}{\sqrt{2}}$$

$$M_Z = \frac{M_W}{\cos\theta}$$

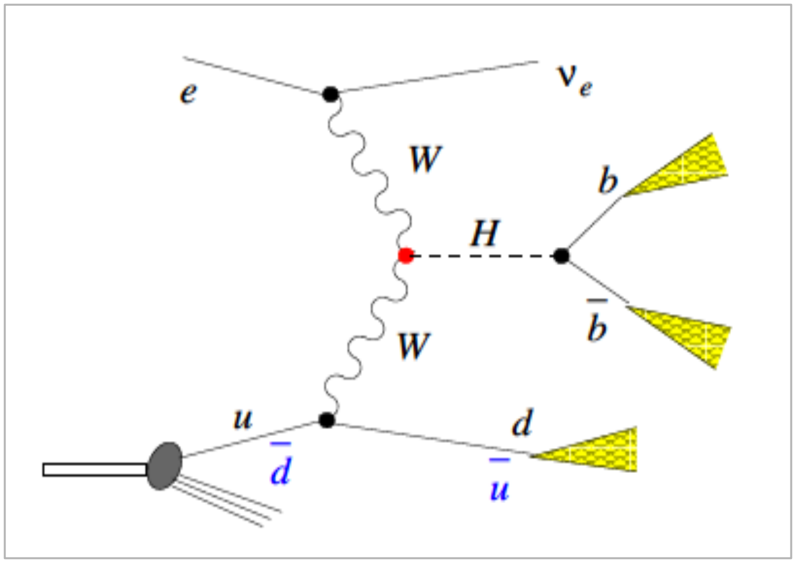
$$M_\gamma = 0$$

$$M_H = \sqrt{-2\mu^2} = 2\eta \cdot \sqrt{\lambda}$$

Higgs was studied in CDR
especially the H → bb decay
using a (PGS) detector simulation.
The discovery of the Higgs particle
introduced a new benchmark
for particle physics projects.
LHeC: consider raising L by 10

Higgs at the LHeC

LHeC is a Higgs "Factory": 200 fb cross section in CC e^-p: L= 1 ab^{-1}: 2 10^5 Higgs events
Clean final state, no pile-up, low QCD bgd, uniquely WW and ZZ, small theory unc.ties



LHeC Higgs	CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation	-0.8	0	0
Luminosity [ab^{-1}]	1	1	0.1
Cross Section [fb]	196	20	58
Acceptance	0.92	0.93	0.94
Decay Channel	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	97 500	12 000	3500
$H \to c\bar{c}$	5 900	600	180
$H \to gg$	16 200	1 600	480
$H \to WW$	25 200	2 600	760
$H \to ZZ$	2 880	1900	560
$H \to \tau^+\tau^-$	10 260	1 000	310
$H \to \gamma\gamma$	360	40	12

Ultimate e and p beams, 10 years of operation

Table 1: Cross sections and rates of Higgs production in ep scattering with the LHeC. The cross sections are obtained with MADGRAPH5 (v1.5.4) using the p_T of the scattered quark as scale, CTEQ6L1 partons and $M_H = 125\,\text{GeV}$. The acceptance is obtained with kinematic cuts on final state particles ($|\eta_{jet}| < 5$, $|\eta_{e,\gamma}| < 4.7$, $p_{T,jet} > 1\,\text{GeV}$, $E_{jet} > 15\,\text{GeV}$, $E'_e > 10\,\text{GeV}$, $E_\gamma > 5\,\text{GeV}$) but excludes the tagging probabilities for b, c, τ and further g, W, Z reconstruction efficiencies. In an initial study (CDR) the $b\bar{b}$ final state is reconstructed with an efficiency of about 5 %. This leads to $\simeq$ 5000 events in this channel, at an S/N of 1.

cf CDR, **Talk of Bruce Mellado**, also Uta Klein ICHEP12

ILC: 10^{34} $cm^{-2}s^{-1}$, 280fb, 15000 cavities, width - LHeC: 10^{34} 200fb 960 cavities, no width

4. ECFA Review 2007-2012

CERN SPC, [r]ECFA Mandate given in 2007 to work out the LHeC physics, detector and accelerator design(s) – looking back to 1994 CDR and referee process carefully evaluated by ECFA committee

… We believe that such a comparison is desirable to promote the LHeC physics case by highlighting the uniqueness of its physics programme, and by viewing it in a larger context of physics at the frontiers of highest energy, highest precision and highest densities.

Stressed: Link to LHC physics and operation, link to HEP, cost estimates, R&D, DIS community

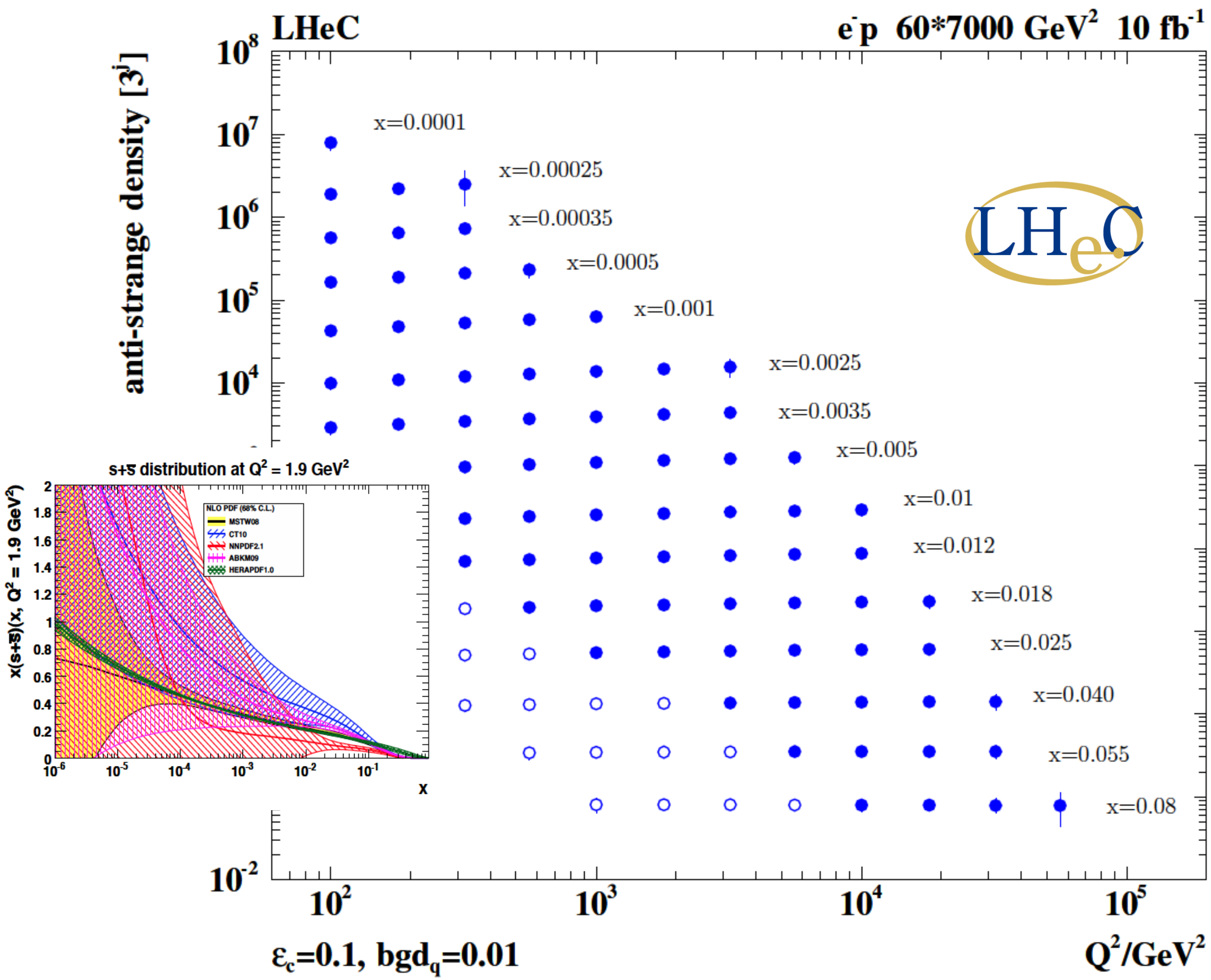
It is our opinion that only the linac-ring option is viable. We point out that there are still important issues to be addressed concerning the physics potential, the accelerator and the detector.

We regard the design effort carried out on the machine as very valuable also for other projects.

Most important is to assemble a strong community in particle and nuclear physics to push further this challenging project, and to secure resources for the ensuing R&D projects towards the formulation of a TDR.

ECFA Statement ECFA/12/279 December 2012

Strange Quark Distribution



High luminosity

High Q^2

Small beam spot

Modern Silicon

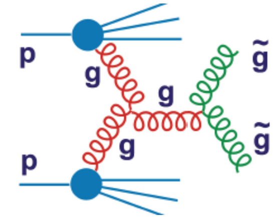
NO pile-up..

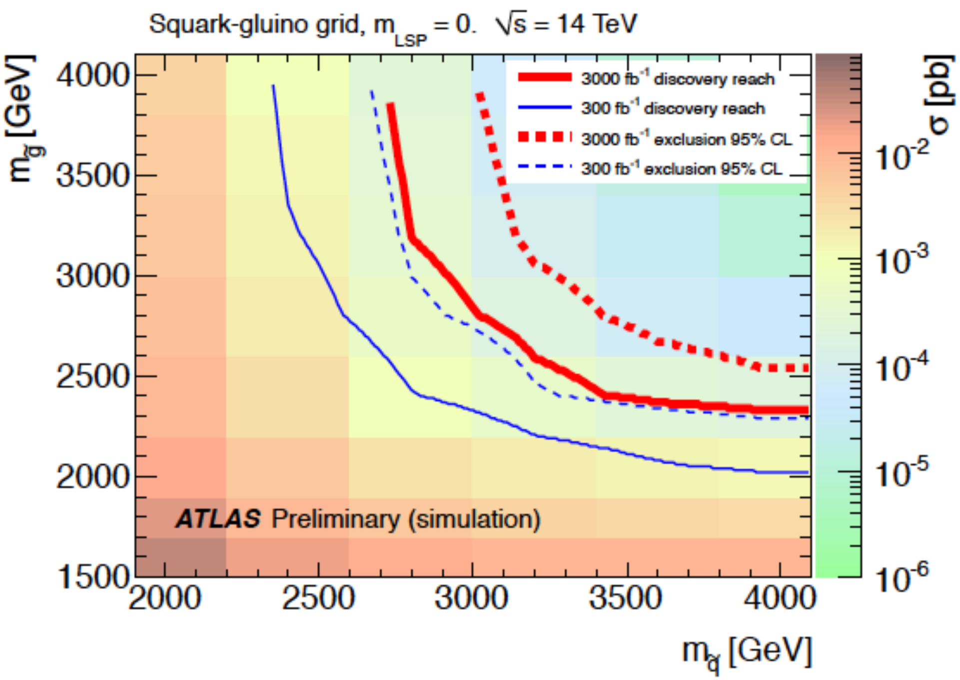
→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

$x = 10^{-4} .. 0.05$
$Q^2 = 100 – 10^5$ GeV^2

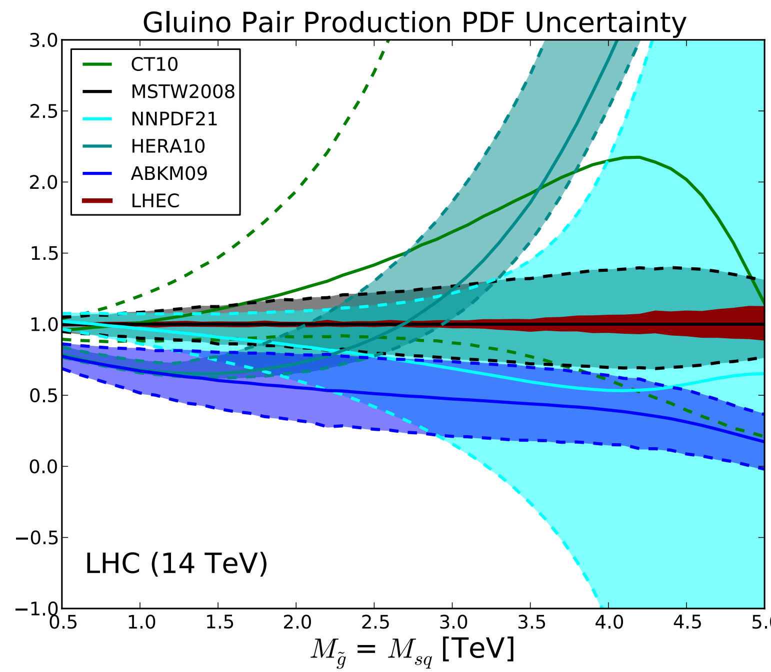
Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter

Searching for High Mass SUSY



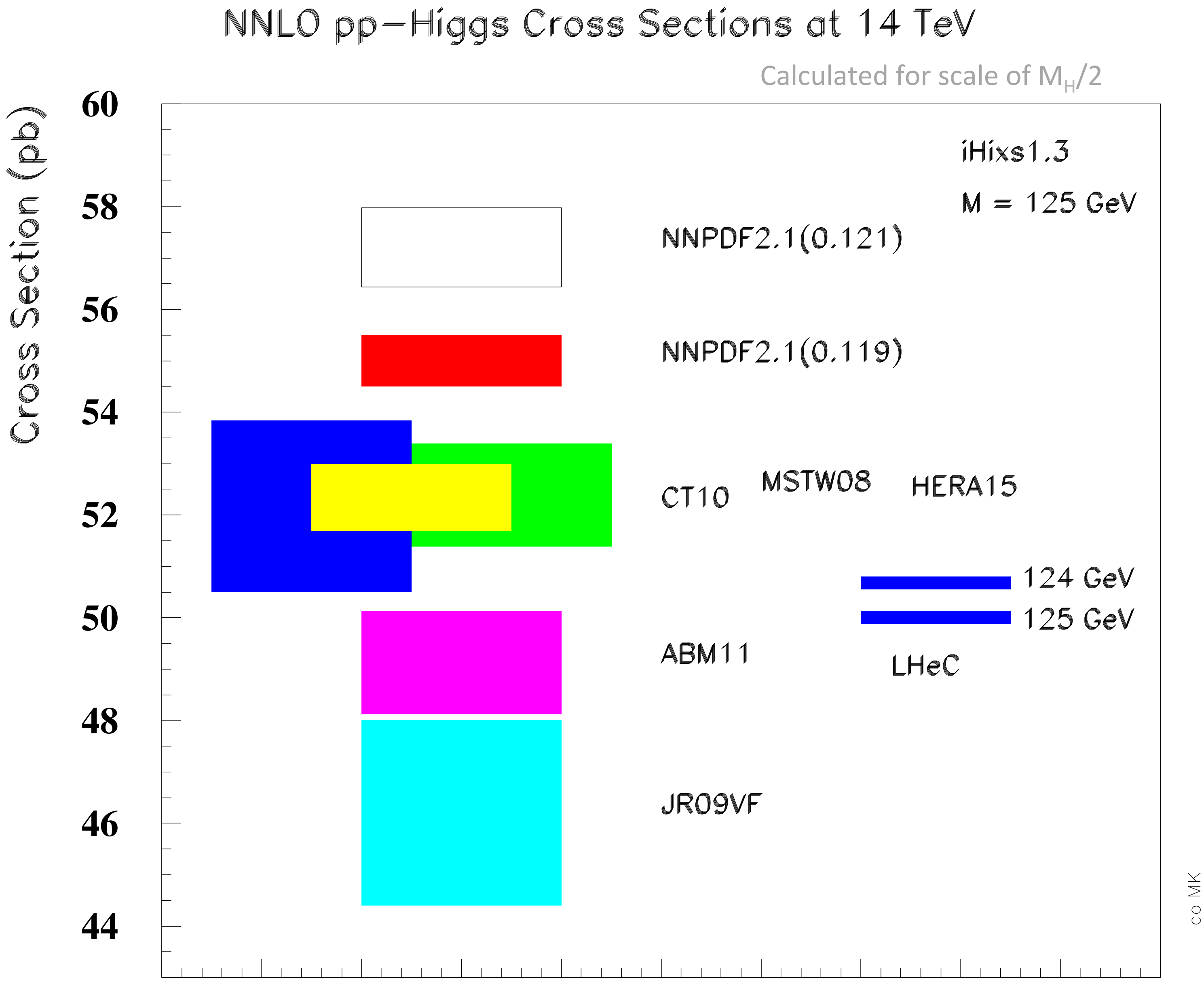


ATLAS October 2012 “Physics at High Luminosity”



LHeC: arXiv:1211.5102

With high energy and luminosity, the LHC search range will be extended to high masses, up to 4-5 TeV in pair production, and PDF uncertainties come in ~ 1/(1-x).



Exp uncertainty of LHeC Higgs cross section is 0.25% (sys+sta), using LHeC only.

Leads to mass sensitivity..

Strong coupling underlying parameter (0.005 – 10%). LHeC: 0.0002

Needs N^3LO

HQ treatment important

PRECISION σ(H)

Higgs production (gg) at the LHC is $\propto \alpha_s^2(M_H^2) xG(x, M_H^2) \otimes xG(x, M_H^2)$

Bandurin (ICHEP12) Higgs physics at the LHC is limited by the PDF knowledge

5. Workshop on LHeC ERL Test Facility at CERN

Contribution to IPAC13

STRAWMAN OPTICS DESIGN FOR THE LHeC ERL TEST FACILITY

A. Valloni[*], O. Bruning, R. Calaga, E. Jensen, M. Klein, R.Tomas, F. Zimmermann,
CERN, Geneva, Switzerland
A. Bogacz, D. Douglas, Jefferson Lab, Newport News Virginia

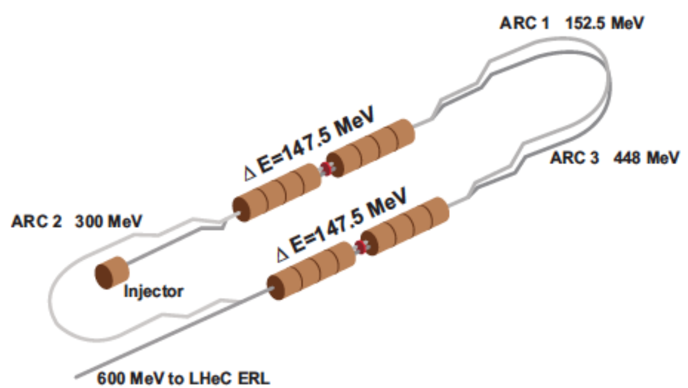


Figure 2: Consequent upgrade to LHeC pre-accelerator. By modifying the machine backleg to include a second full cryomodule, the recirculator can deliver higher beam energy of 600 MeV.

Proposal for an LHeC ERL Test Facility at CERN

R. Calaga, E. Ciapala, E. Jensen
CERN, Geneva, Switzerland

CERN-LHeC-Note-2012-001 ACC

October 17, 2012

Rama.Calaga@cern.ch

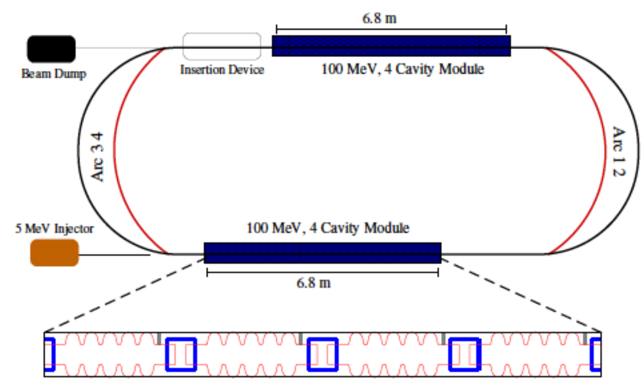


Table 3: Future ERLs for electron-hadron colliders

Parameter	JLab MEIC	BNL eRHIC	CERN LHeC
Energy [GeV]	5-10	20	60
Frequency [MHz]	750	704	$n\times40$
# of passes	-	6	3
Current/pass [mA]	3	50	6.6
Charge [nC]	4	3.5	0.3
Bunch Length [mm]	7.5	2.0	0.3

Workshop:

- Collaboration: CERN, AsTEC, CI, JeffersonLab, U Mainz, +
- LHeC Parameters (C,Q,source,I) rather conservative
- Test Facility to develop full technology, key: cavity
- RF frequency chosen

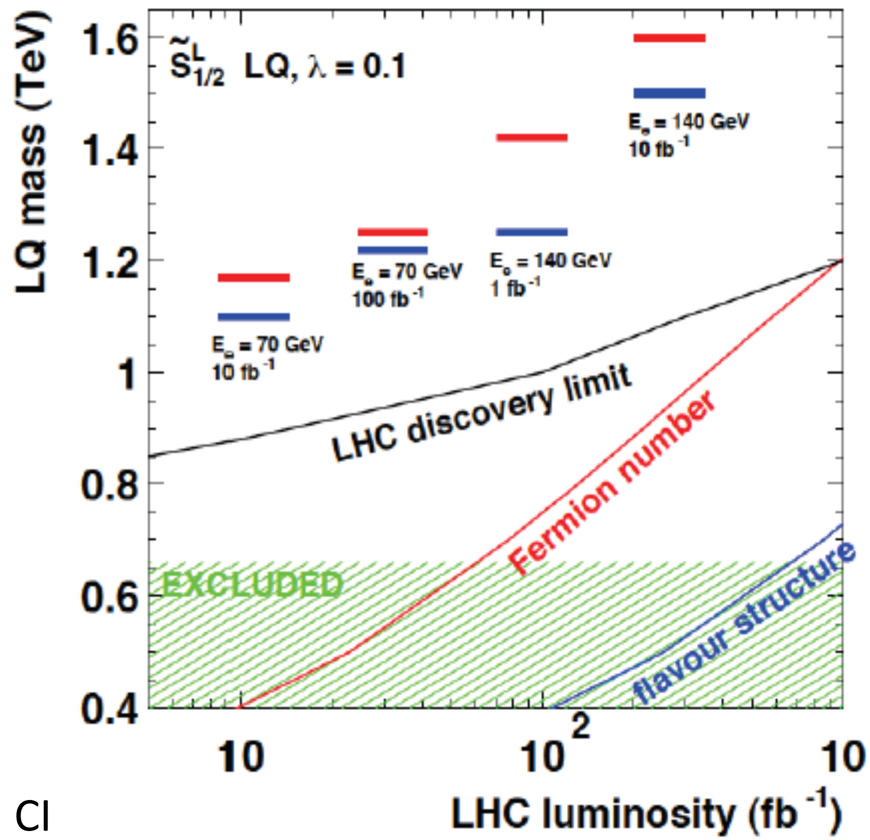
6. LPCC miniworkshop on LHeC 17/18.4.2013 at CERN

Review of CDR
Updates and discussion with LHC

LHeC last week at LPCC

PDFs – V.Radescu
Heavy PDFs – R.Pacakyte
Accelerator – O.Brüning
Higgs – B. Mellado
BSM LH(e)C – M.D'Onofrio
QCD at low x – A.Stasto
eA Physics – N.Armesto

http://cern.ch/lhec



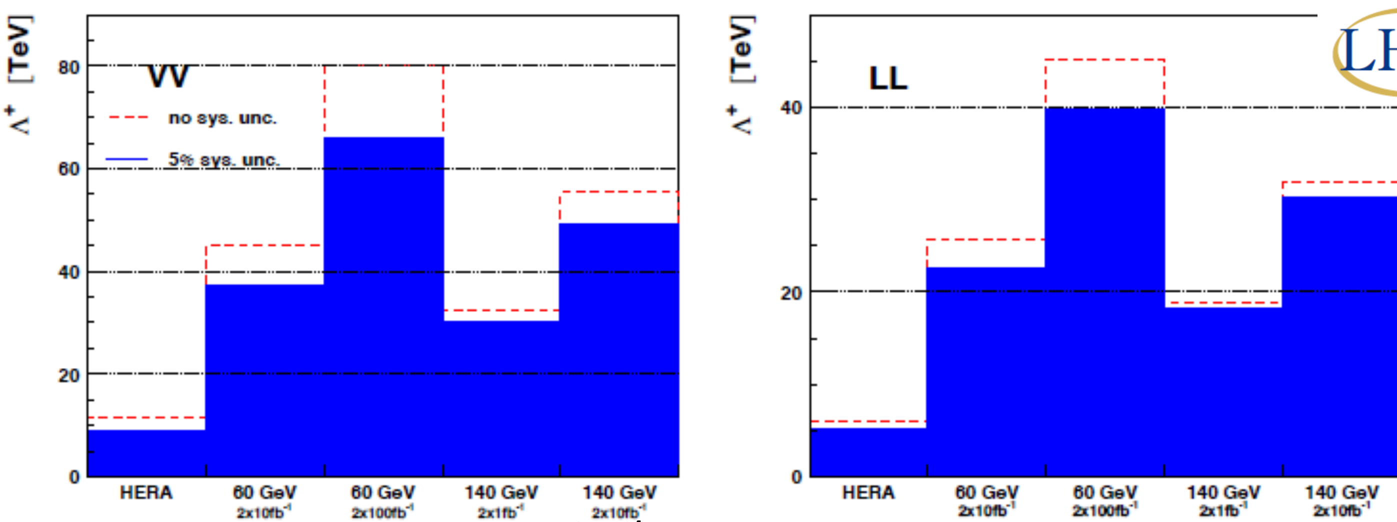
From CDR 6/12

BSM with LHeC:
RPV SUSY,LQs, r_{quark}, excited leptons, CI

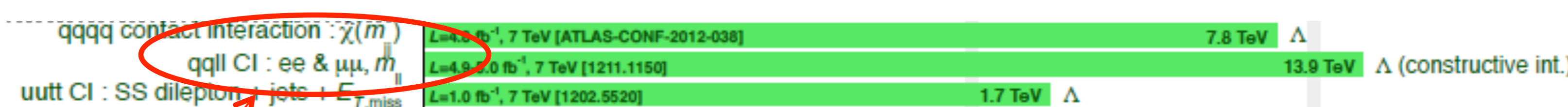
" The LHC is the primary machine to search for physics beyond the SM at the TeV scale.
The role of the LHeC is to complement and possibly resolve the observation of new phenomena…"
LHeC CDR

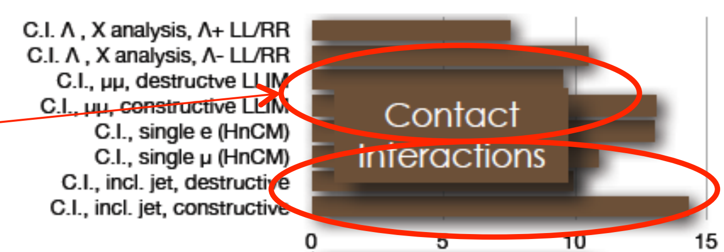
Contact interactions (eeqq)

- New currents or heavy bosons may produce indirect effect via new particle exchange interfering with γ/Z fields.
- Reach for Λ (CI eeqq): 25-45 TeV with 10 fb^{-1} of data depending on the model



Similar to LHC





ATLAS and CMS constraints on eeqq CI (expected up to 30-40 TeV at c.o.m. 14 TeV LHC)

Concluding Remarks

From HERA to the LHeC

LHeC Summary Spring 2013

1. The LHeC is the natural (and the only possible) successor of the energy frontier exploration of deep inelastic scattering with fixed target experiments and HERA at 10, 100 and then 1000 GeV of cms energy.

2. Its physics programme has key topics (WW→ H, RPV SUSY, α_s , gluon mapping, PDFs, saturation, eA…) which ALL are closely linked to the LHC (Higgs, searches for LQ and at high masses, QGP ..). With the upgrade of the LHC by adding an electron beam, the LHC can be transformed to a high precision energy frontier facility which is crucial for understanding new+"old" physics and its sustainability.

3. The LHeC will deliver vital information to future QCD developments (N3LO, resummation, factorisation, non-standard partons, neutron and nuclear structure, AdS/CFT, non-pQCD, SUSY..) and as a gigantic next step into DIS physics it promises to find new phenomena (no saturation, instantons, substructure of heavy elementary particles ??).

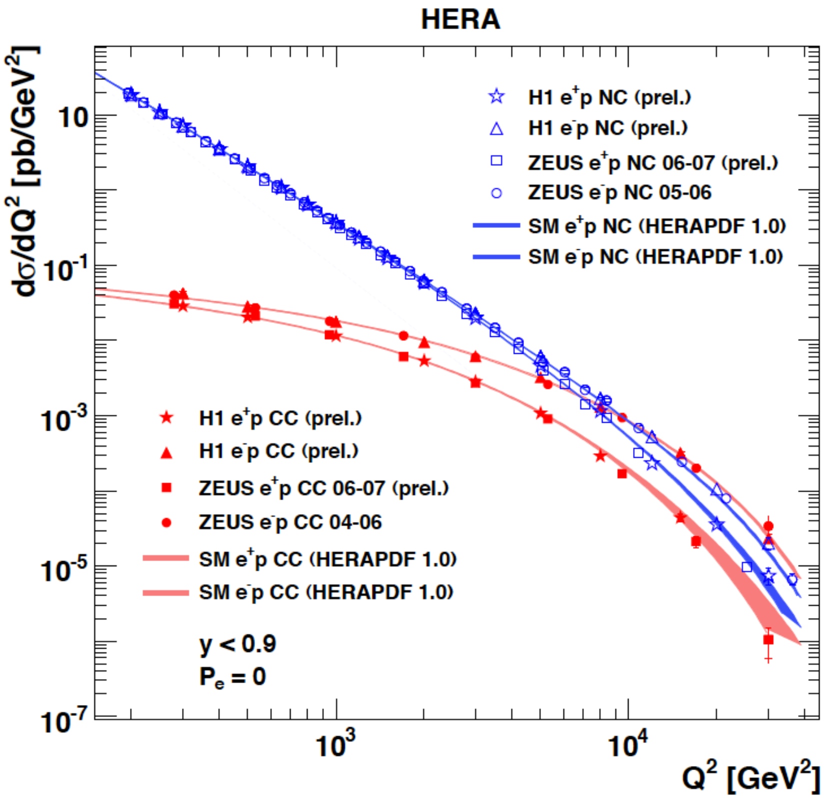
4. The default LHeC configuration is a novel ERL (with < 100MW power demand) in racetrack shape which is built inside the LHC ring and tangential to IP2. This delivers multi-100fb^{-1} (> 100 * HERA) and a factor of larger than 10^3 increased kinematic range in lN DIS, accessing the range of saturation at small α_s in ep+eA.

5. The LHeC is designed for synchronous operation with the LHC (3 beams) and has to be operational for the final decade of its lifetime. This gives 10-12 years for its realisation, as for HERA or CMS.

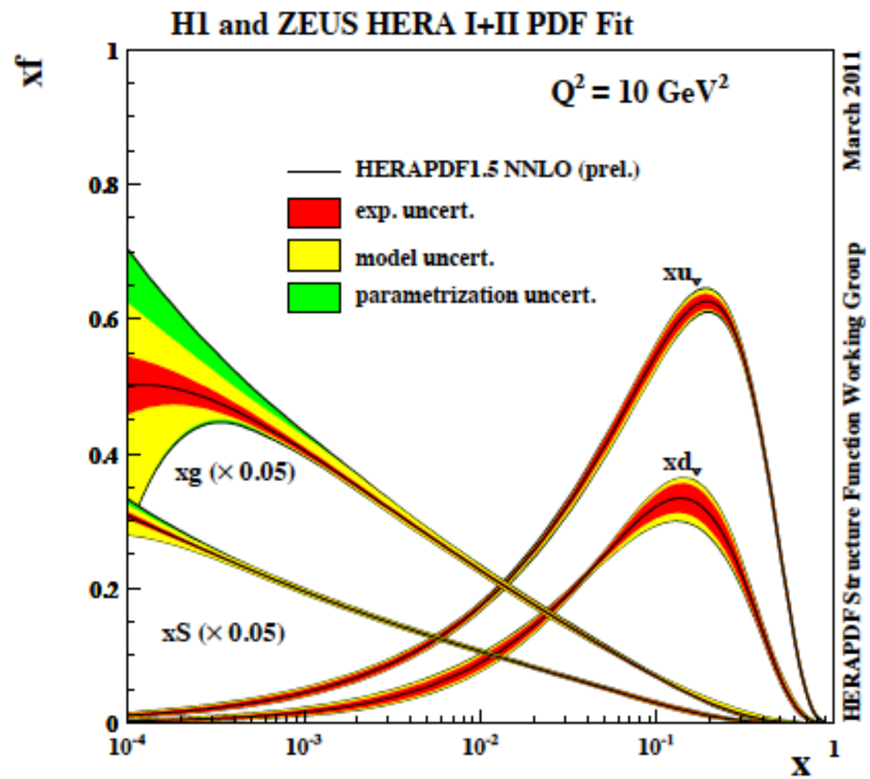
6. A detector concept is described in the CDR suitable for the Linac-Ring IR and to obtain full coverage and ultimate precision. This can be realised with a collaboration of ~500 physicists.

7. Half of the LHeC is operational. The other half requires next: an ERL test facility at CERN, IR related proto-typing (Q1, pipe), to develop the LHC-LHeC physics links, to simulate and preparing for building the detector.

Unique DIS Physics - Results from HERA



The weak and electromagnetic interactions reach similar strength when $Q^2 \geq M^2_{W,Z}$



F_2 rises towards low x, and xg too.
Parton evolution - QCD to NNLO

Measurements on α_s, Basic tests of QCD: longitudinal structure function, jet production, γ structure
Some 10% of the cross section is diffractive (ep → eXp) : **diffractive partons; c,b quark distributions**
New concepts: unintegrated parton distributions (k_T) , generalised parton distributions (DVCS)
New limits for leptoquarks, excited electrons and neutrinos, quark substructure, RPV SUSY
Interpretation of the Tevatron measurements (high Et jet excess, M_W, searches..), + **base for PDF fits**..

M.Klein, R.Yoshida: **Collider Physics at HERA** Prog.Part.Nucl.Phys. 61 (2008) 343-393 and recent H1,ZEUS results
A Recent review of **The Theory of Deep Inelastic Scattering**: J.Bluemlein arXiv:1208.6087 ProgPartNuclPhys 69(2013)28

What HERA could not do or has not done

Test of the isospin symmetry (u-d) with eD - no deuterons
Investigation of the q-g dynamics in nuclei - no time for eA
Verification of saturation prediction at low x – too low s
Measurement of the strange quark distribution – too low L
Discovery of Higgs in WW fusion in CC – too low cross section
Study of top quark distribution in the proton – too low s
Precise measurement of F_L – too short running time left
Resolving d/u question at large Bjorken x – too low L
Determination of gluon distribution at hi/lo x – too small range
High precision measurement of α_s – overall not precise enough
Discovering instantons, odderons – don't know why not
Finding RPV SUSY and/or leptoquarks – may reside higher up
…

M.Froissart ICHEP ("Rochester") 1966

THEORY

H.Murayama – ICFA11

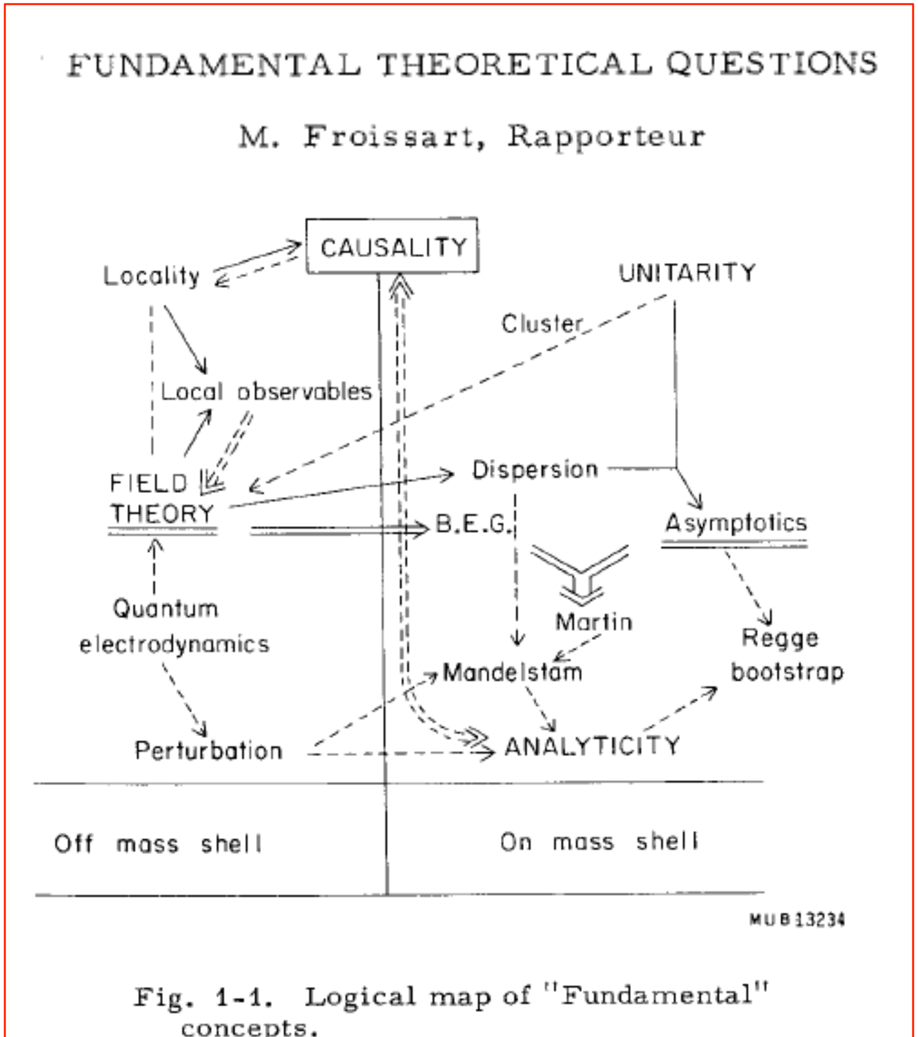
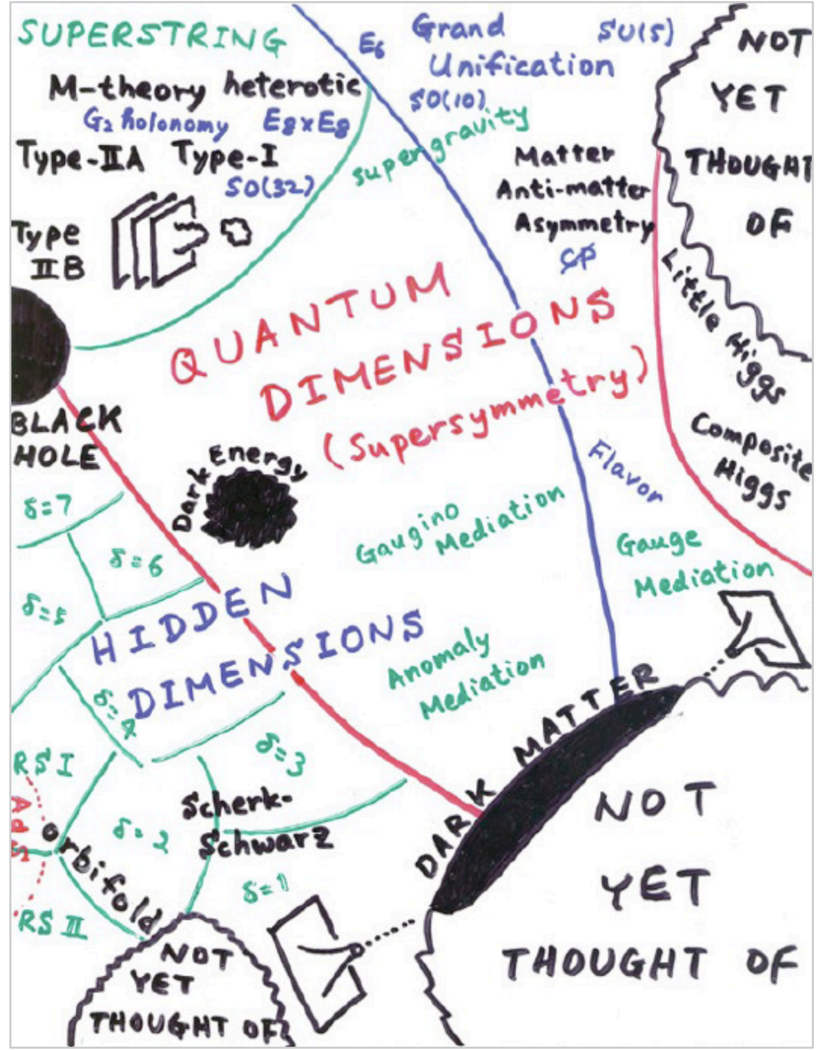


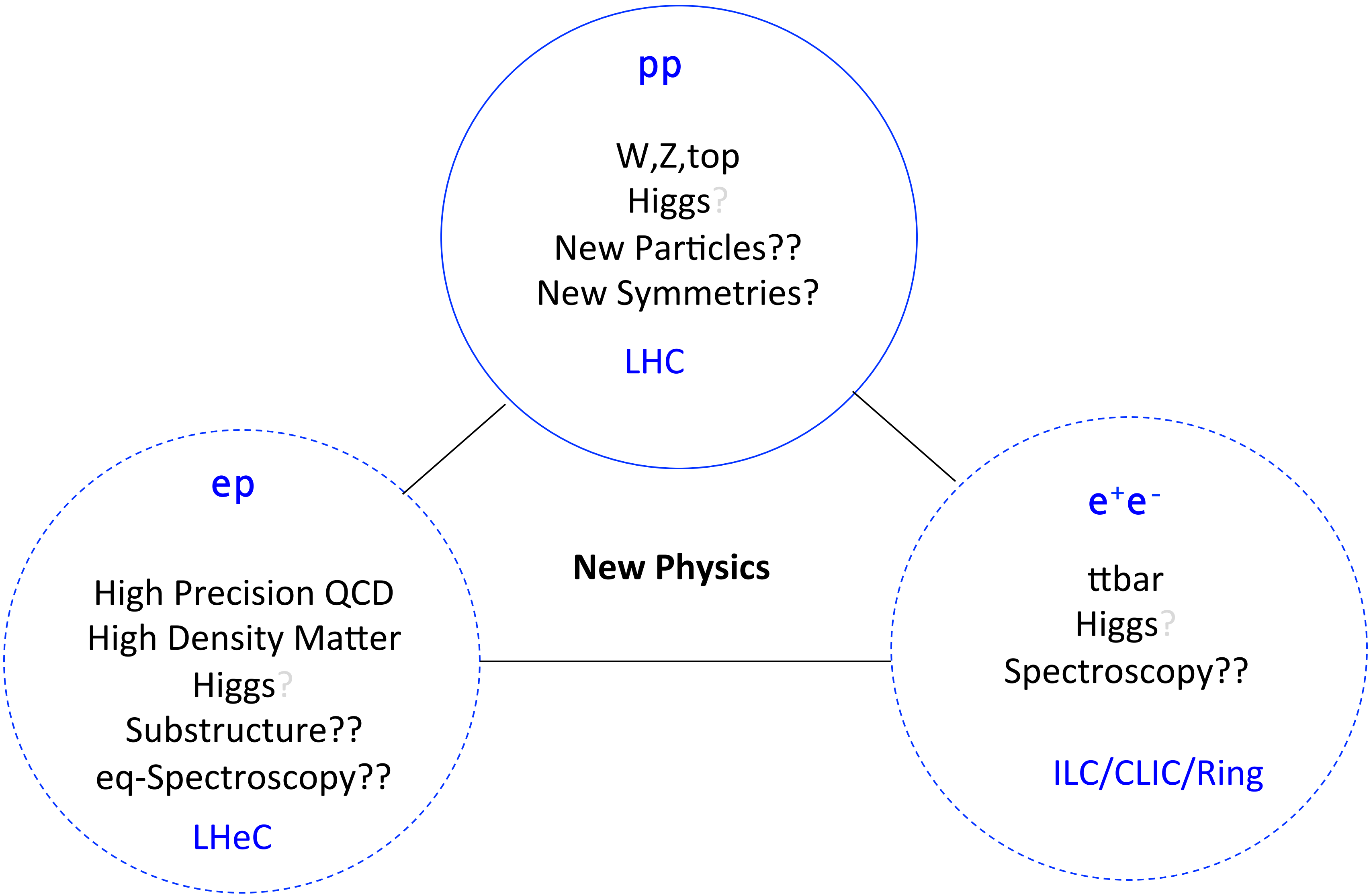
Fig. 1-1. Logical map of "Fundamental" concepts.



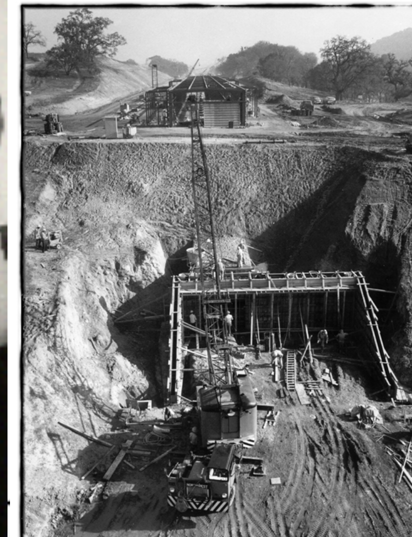
→ Quarks in 1969

→ ?in 2014?

The TeV Scale [2012-2035..]



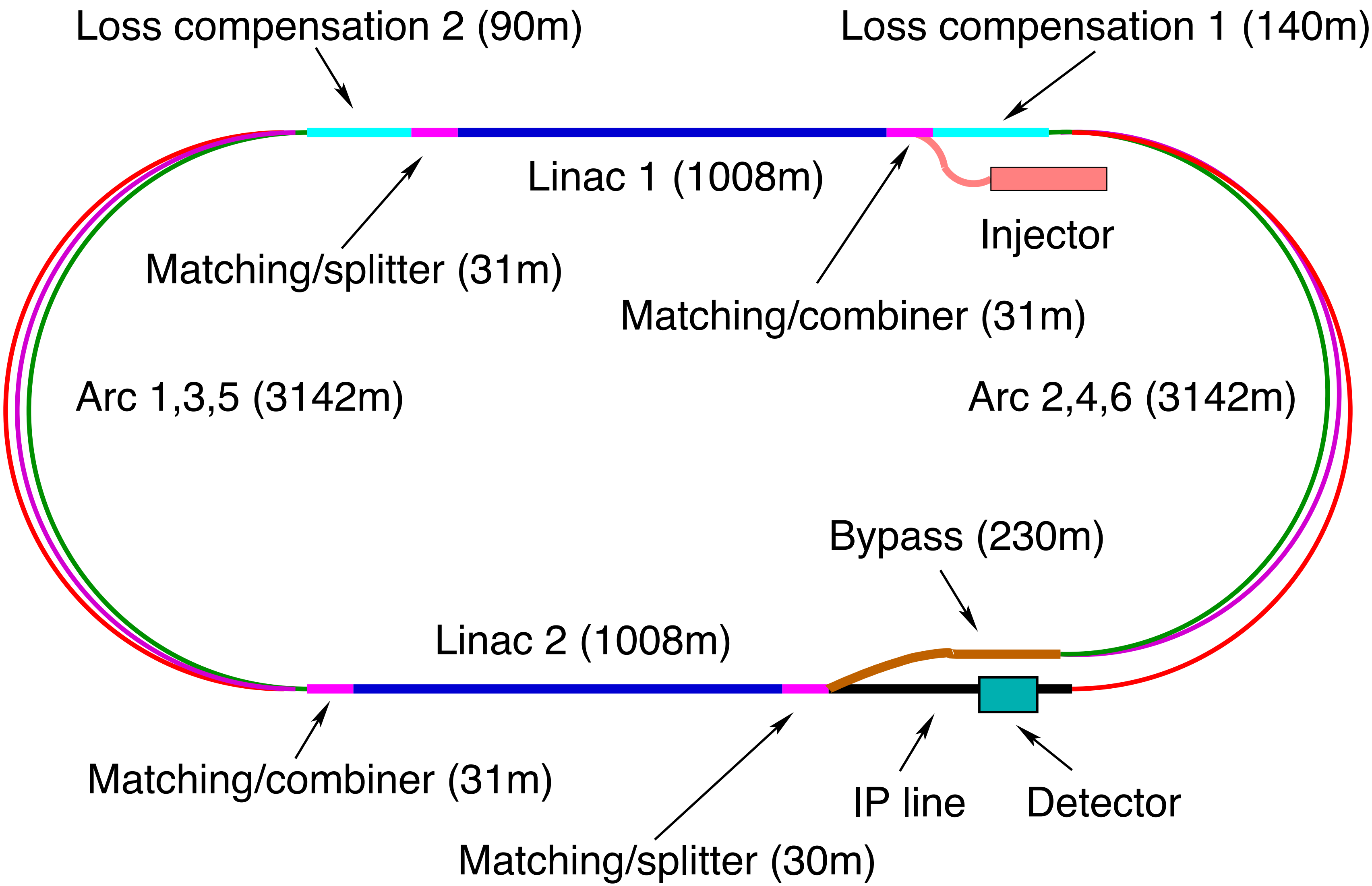
can one build a 2-3-km long linac?



it has been done before

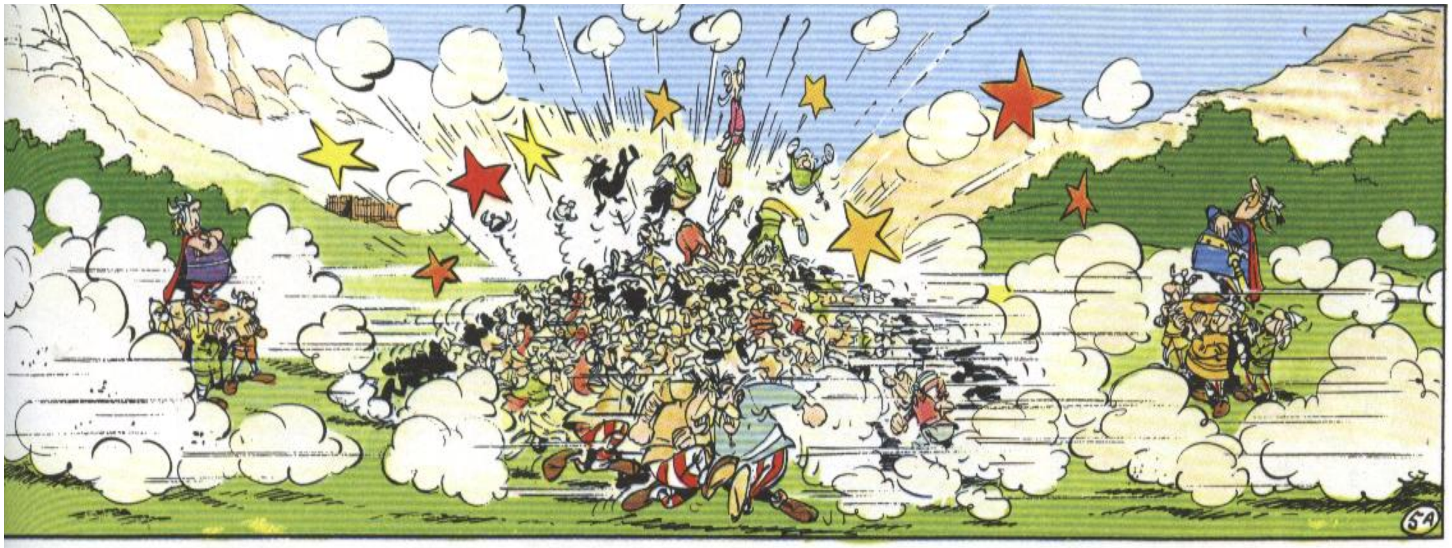
Courtesy F.Zimmermann

Backup



60 GeV electron beam energy, L= 10^{33} $cm^{-2}s^{-1}$, $\sqrt{s}$=1.3 TeV: Q^2_{max}= 10^6 GeV^2, 10^{-6} < x< 1
Recirculating linac (2 * 1km, 2*60 cavity cryo modules, 3 passes, energy recovery)
Ring-ring as fall back. “SAPHIRE” 4 pass 80 GeV option to do mainly: γγ→ H

LHC forward look



Mean pileup about 10 at L ~ $10^{33} cm^{-2} s^{-1}$

Upgrades as of the ATLAS tracker for 5 10^{34} are major undertaking of HEP

ep/eA will provide possibly crucial information for new physics and high precision.