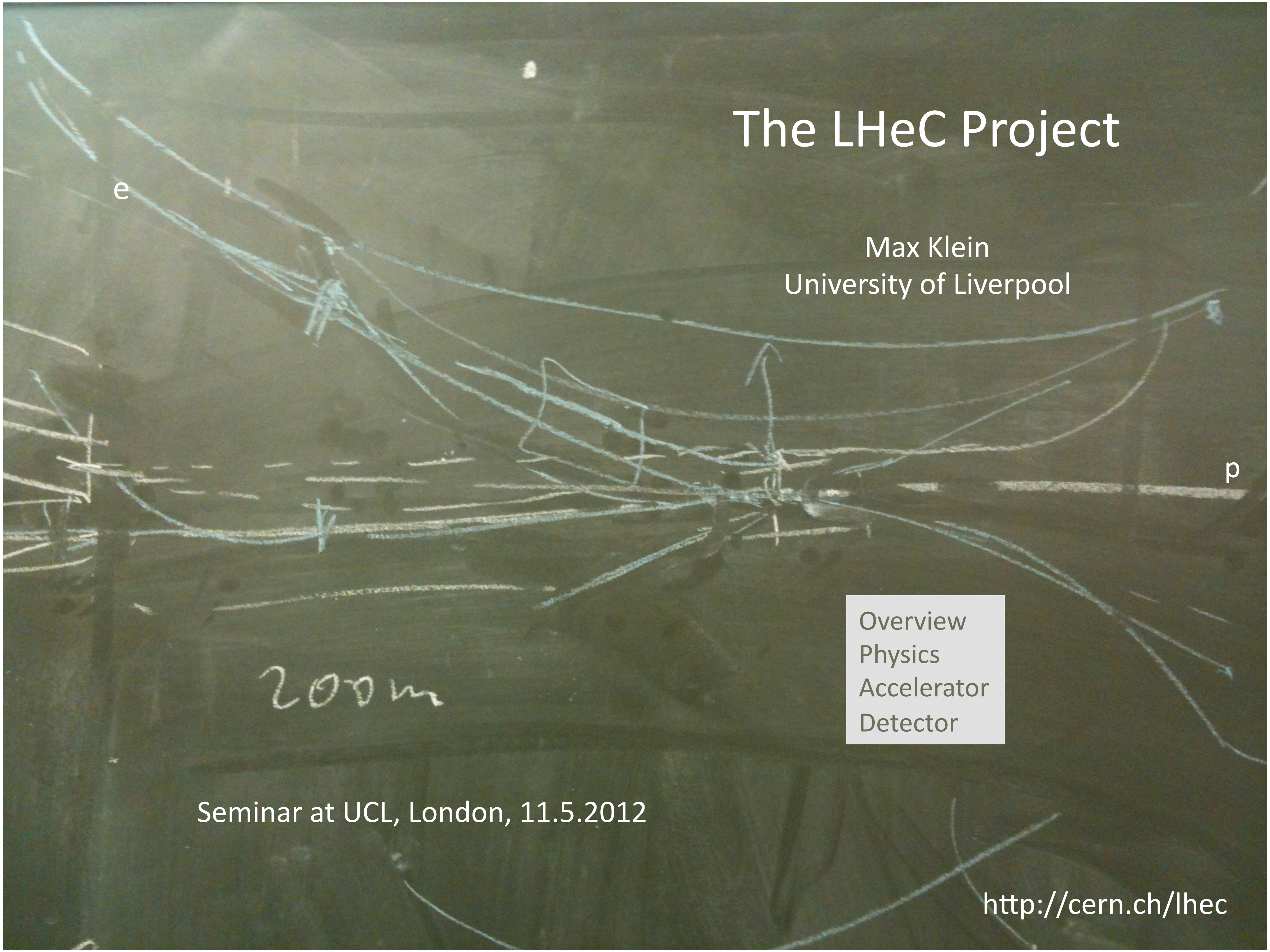
The LHeC Project

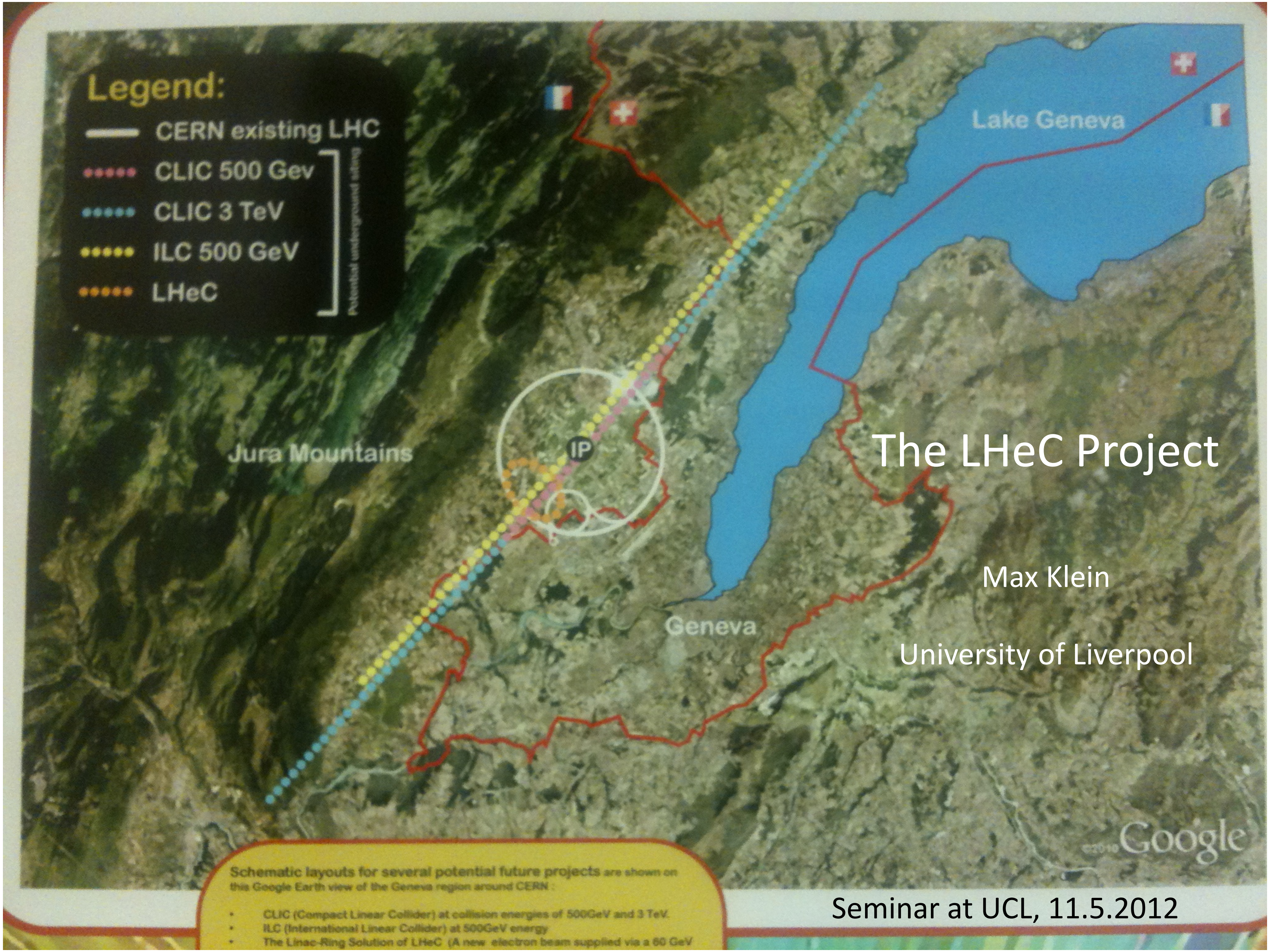
Max Klein
University of Liverpool



Overview
Physics
Accelerator
Detector

Seminar at UCL, London, 11.5.2012

http://cern.ch/lhec



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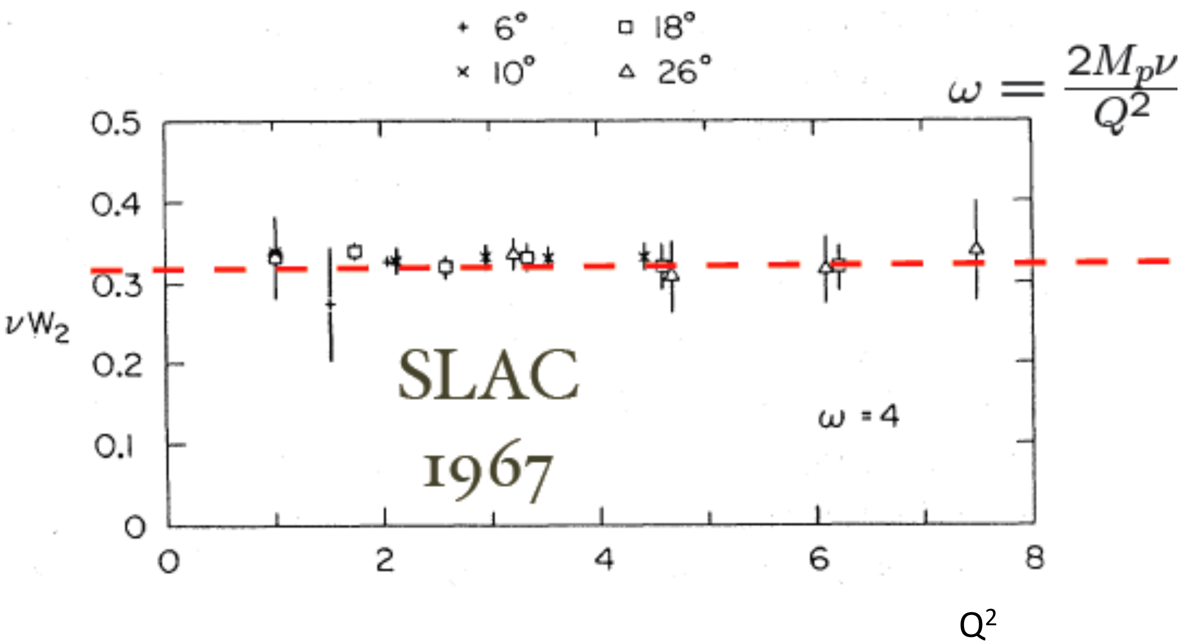
Seminar at UCL, 11.5.2012

Foundation of DIS



2 mile electron linac

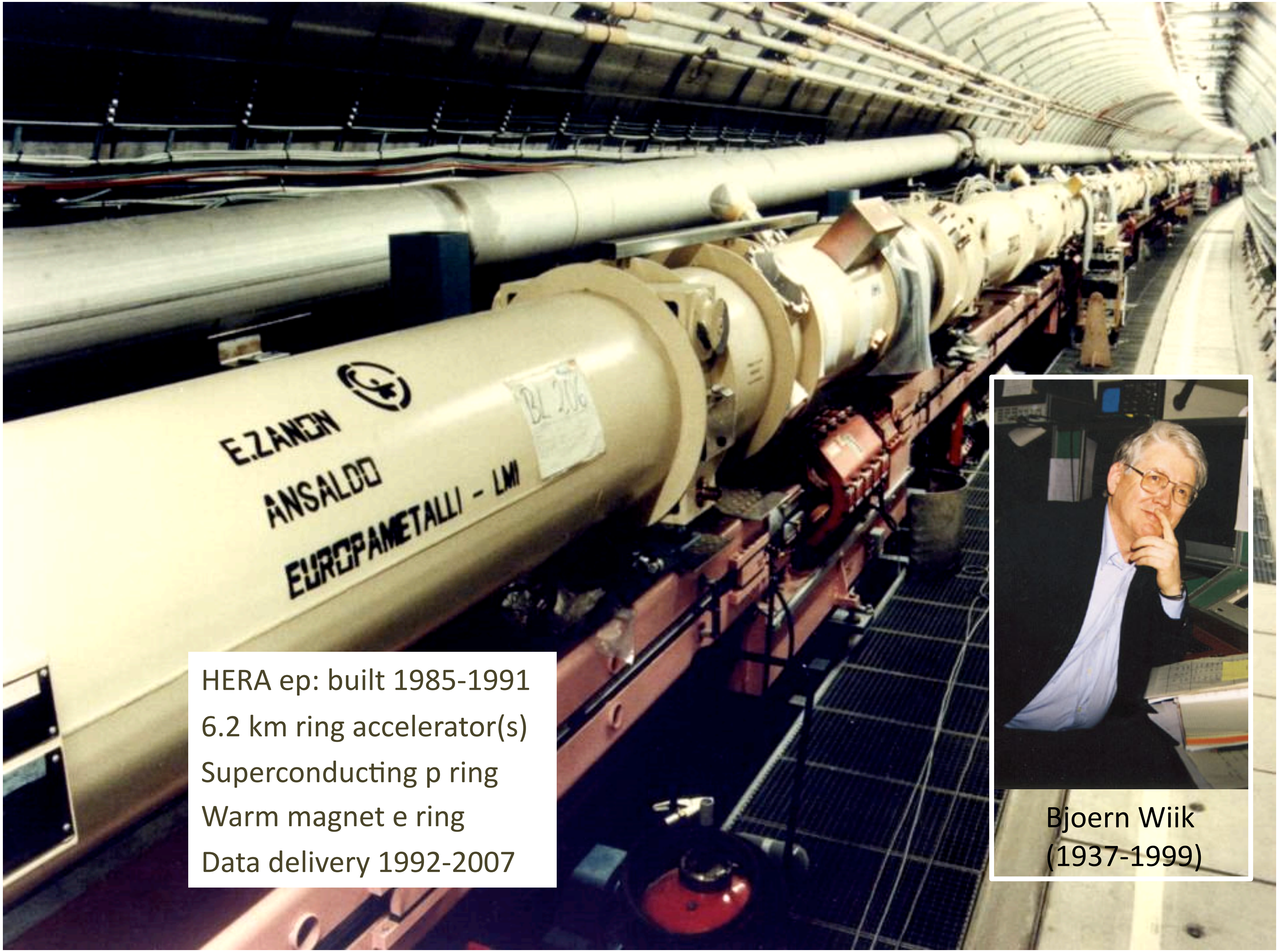
Bjorken scaling → Partons → Quark-Parton Model → QCD

SLAC 1967 $s = 2M_pE_e \approx 20GeV^2$

LHeC 2024 $s = 4E_pE_e \approx 2 \cdot 10^6 GeV^2$

With 2m (2*1km) linac, but off p at rest or the LHC

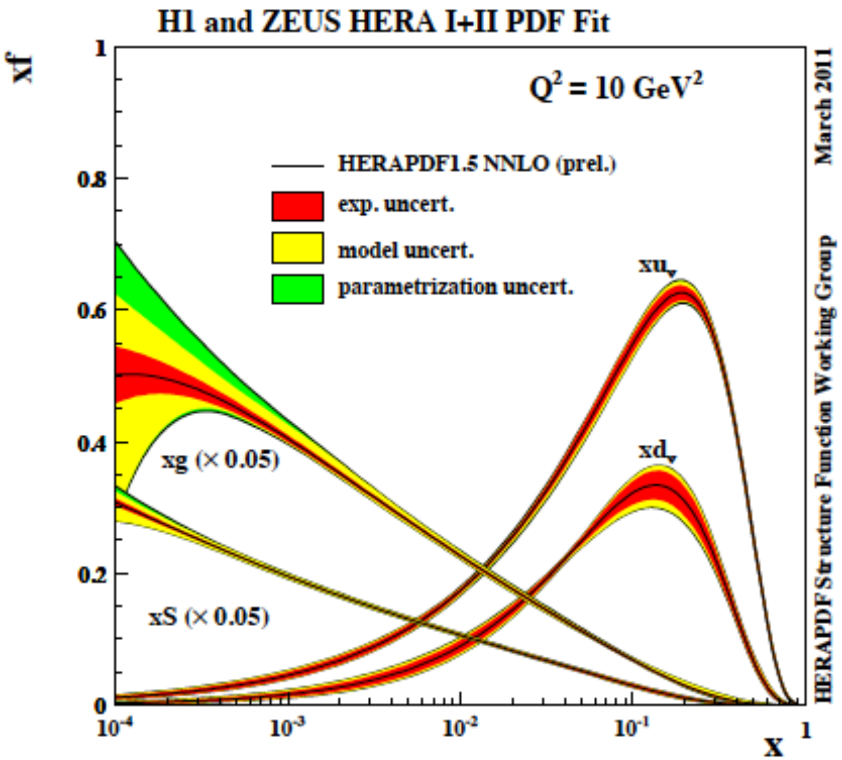
“Pief” Panowsky (1919-2007)



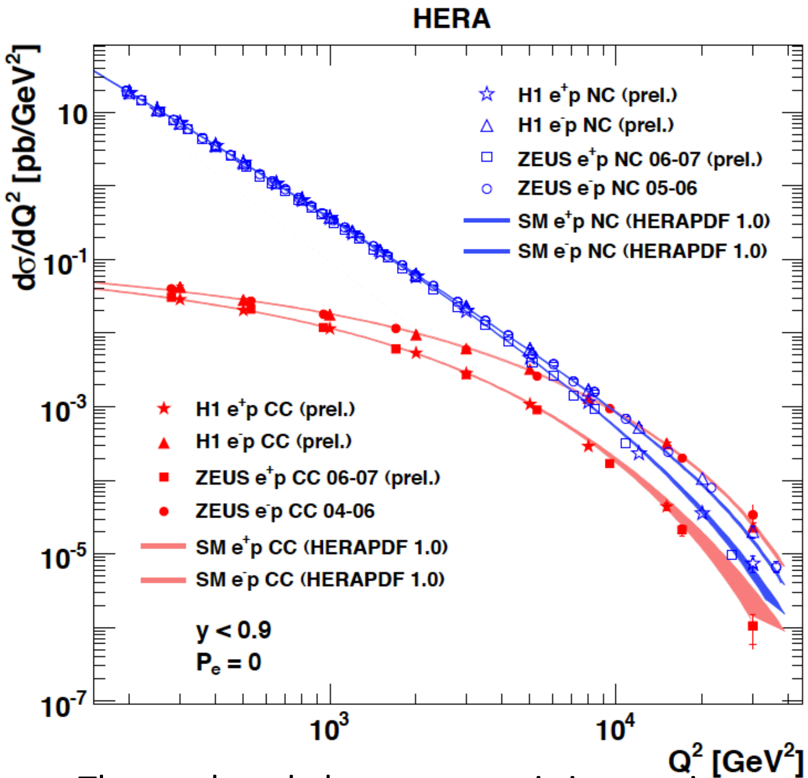
HERA ep: built 1985-1991
6.2 km ring accelerator(s)
Superconducting p ring
Warm magnet e ring
Data delivery 1992-2007

Bjoern Wiik
(1937-1999)

Results from HERA



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

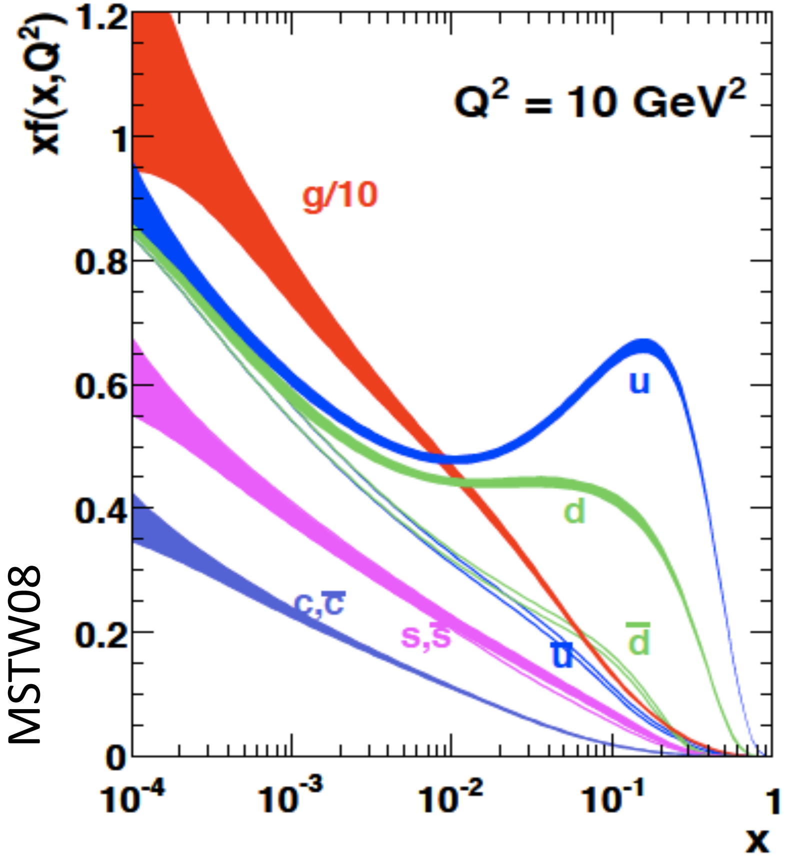


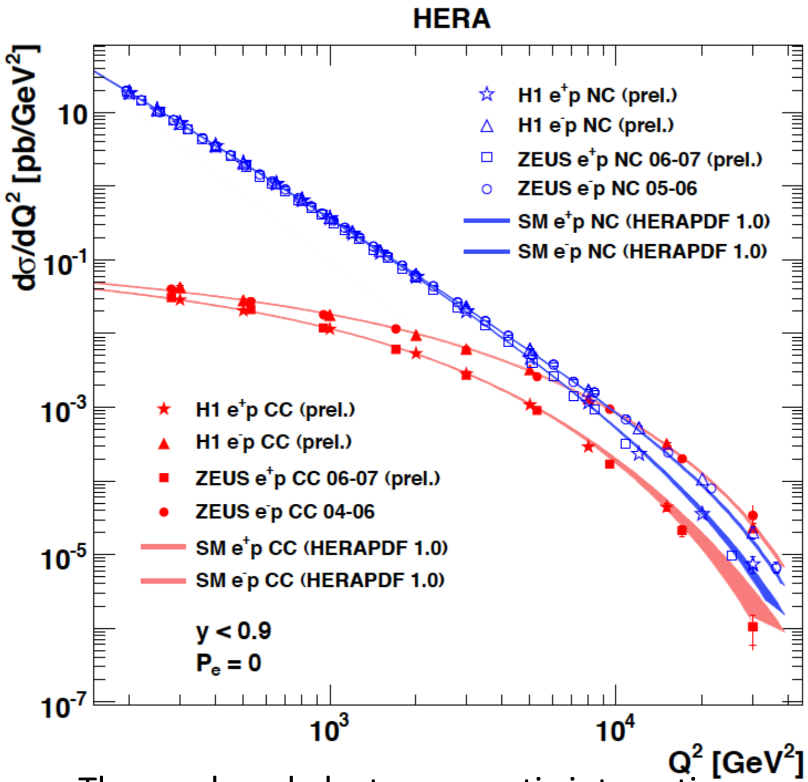
The weak and electromagnetic interactions reach similar strength when $Q^2 \geq M^2_{W,Z}$

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..)

M.Klein, R.Yoshida: Collider Physics at HERA Prog.Part.Nucl.Phys. 61 (2008) 343-393 and recent H1,ZEUS results

Results from HERA





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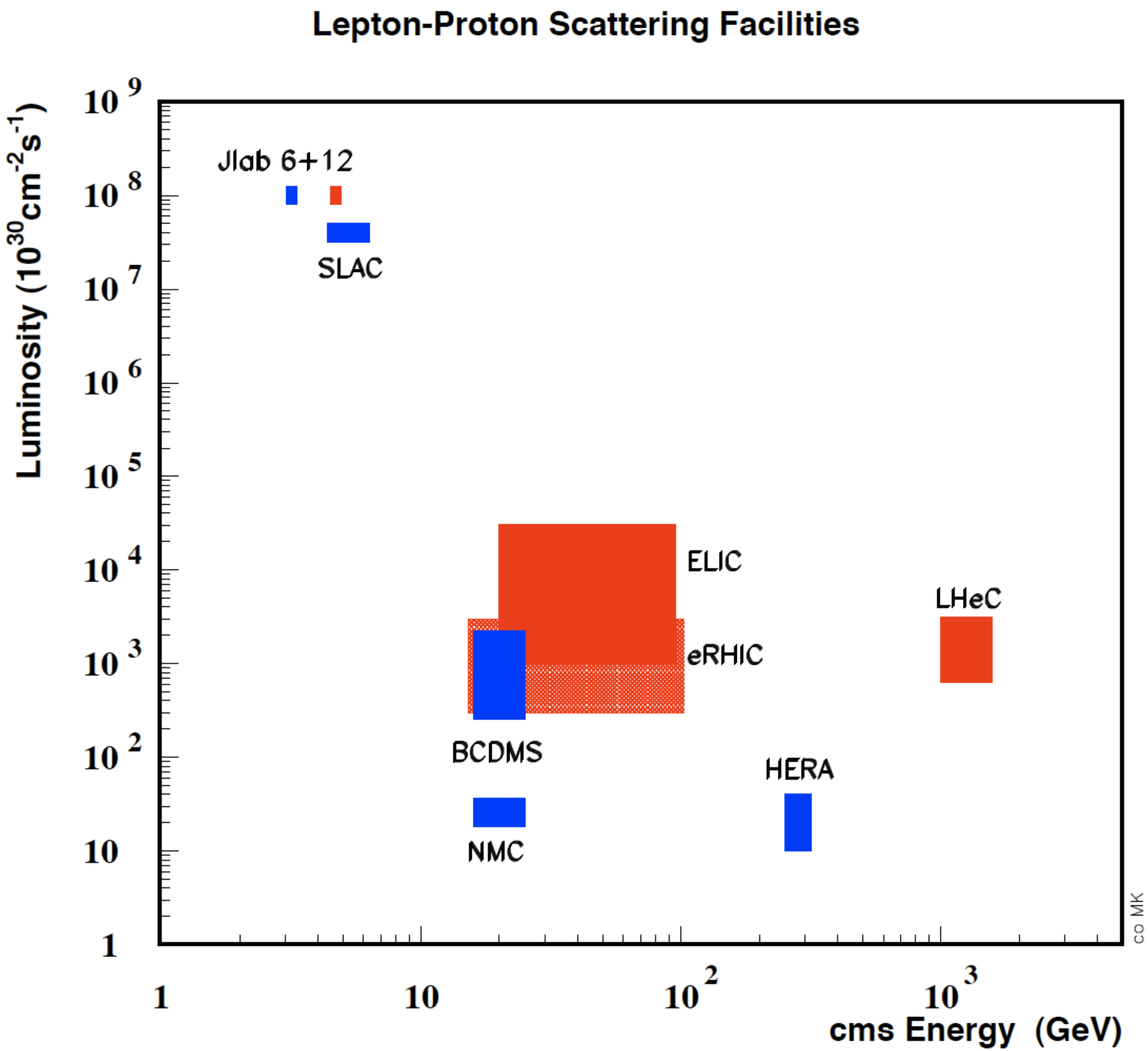
DIS beyond HERA



Built

Proposed

The LHeC is the only proposal and possibility to exceed HERA energy (and luminosity).

L vs E_e

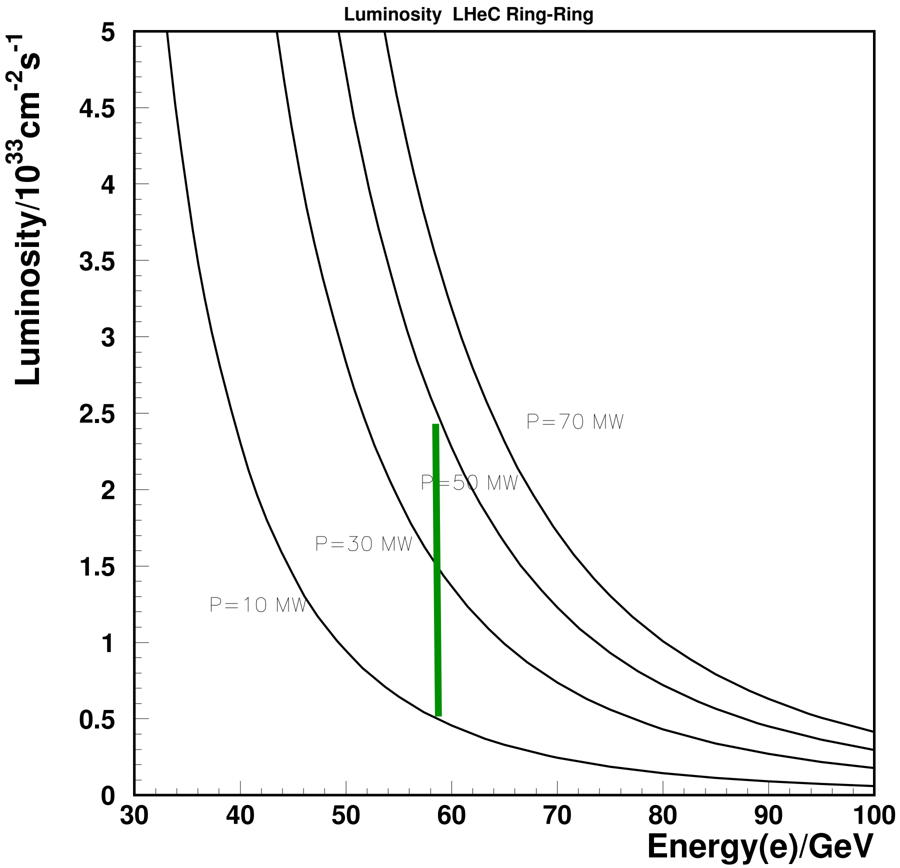
Storage Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}}$$

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8\mu m, \beta_{px(y)} = 1.8(0.5)m, \gamma = \frac{E_p}{M_p}$$

$$L = 8.2 \cdot 10^{32} cm^{-2} s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{m}{\sqrt{\beta_{px}\beta_{py}}} \cdot \frac{I_e}{50mA}$$

$$I_e = 0.35mA \cdot P[MW] \cdot (100/E_e[GeV])^4$$



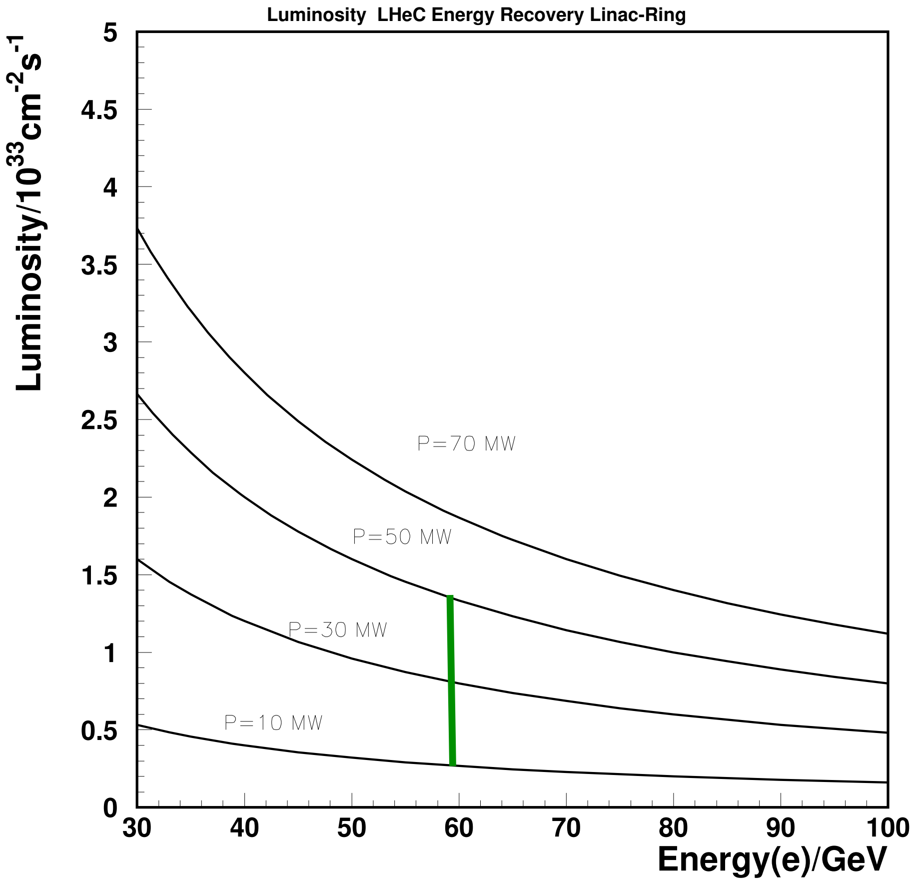
Energy Recovery Linac

$$L = \frac{1}{4\pi} \cdot \frac{N_p}{\varepsilon_p} \cdot \frac{1}{\beta^*} \cdot \gamma \cdot \frac{I_e}{e}$$

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8\mu m, \beta^* = 0.2m, \gamma = 7000/0.94$$

$$L = 8 \cdot 10^{31} cm^{-2} s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{0.2}{\beta^*/m} \cdot \frac{I_e/mA}{1}$$

$$I_e = mA \frac{P_E/MW}{E_e/GeV}, P_E = P/(1-\eta), \eta \approx 0.95$$



Project Milestones

2007: Invitation by SPC to ECFA and by (r)ECFA to work out a design concept

2008: First CERN-ECFA Workshop in Divonne (1.-3.9.08)

2009: 2nd CERN-ECFA-NuPECC Workshop at Divonne (1.-3.9.09)

2010: Report to CERN SPC (June)
3rd CERN-ECFA-NuPECC Workshop at Chavannes-de-Bogis (12.-13.11.10)
NuPECC puts LHeC to its Longe Range Plan for Nuclear Physics (12/10)

2011: Draft CDR (530 pages on Physics, Detector and Accelerator) (5.8.11)
being refereed and updated

2012: Publication of CDR – European Strategy
New workshop (Chavannes, June 14-15, 2012)

Goal: TDR by 2015
Perspective: Operation by 2023 (synchronous with pp)

Organisation for CDR

Scientific Advisory Committee

Guido Altarelli (Roma)
Sergio Bertolucci (CERN)
Stan Brodsky (SLAC)
Allen Caldwell (MPI Muenchen) - Chair
Swapan Chattopadhyay (Cockcroft Institute)
John Dainton (Liverpool)
John Ellis (CERN)
Jos Engelen (NWO)
Joel Feltesse (Saclay)
Roland Garoby (CERN)
Rolf Heuer (CERN)
Roland Horisberger (PSI)
Young-Kee Kim (Fermilab)
Aharon Levy (Tel Aviv)
Lev Lipatov (St. Petersburg)
Karlheinz Meier (Heidelberg)
Richard Milner (MIT)
Joachim Mnich (DESY)
Steve Myers (CERN)
Guenther Rosner (Glasgow)
Alexander N. Skrinsky (INP Novosibirsk)
Anthony Thomas (JLab)
Steve Vigdor (Brookhaven)
Ferdinand Willeke (Brookhaven)
Frank Wilczek (MIT)

LHeC

Steering Committee

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John Dainton (Liverpool)
Albert De Roeck (CERN)
Stefano Forte (Milano)
Max Klein (Liverpool) - Chair
Paul Laycock (Liverpool)
Paul Newman (Birmingham)
Emmanuelle Perez (CERN)
Wesley Smith (Wisconsin)
Bernd Surrow (MIT)
Katsuo Tokushuku (KEK)
Urs Wiedemann (CERN)
Frank Zimmermann (CERN)

Working Group Convenors

Accelerator Design

Oliver Bruening (CERN)
John Dainton (Liverpool)

Interaction Region

Bernhard Holzer(CERN)
Uwe Schneekloth (DESY)
Pierre van Mechelen (Antwerpen)

Detector Design

Peter Kostka (DESY)
Alessandro Polini (Bologna)
Rainer Wallny (Zurich)

New Physics at Large Scales

Georges Azuelos (Montreal)
Emmanuelle Perez (CERN)
Georg Weiglein (Hamburg)

Precision QCD and Electroweak

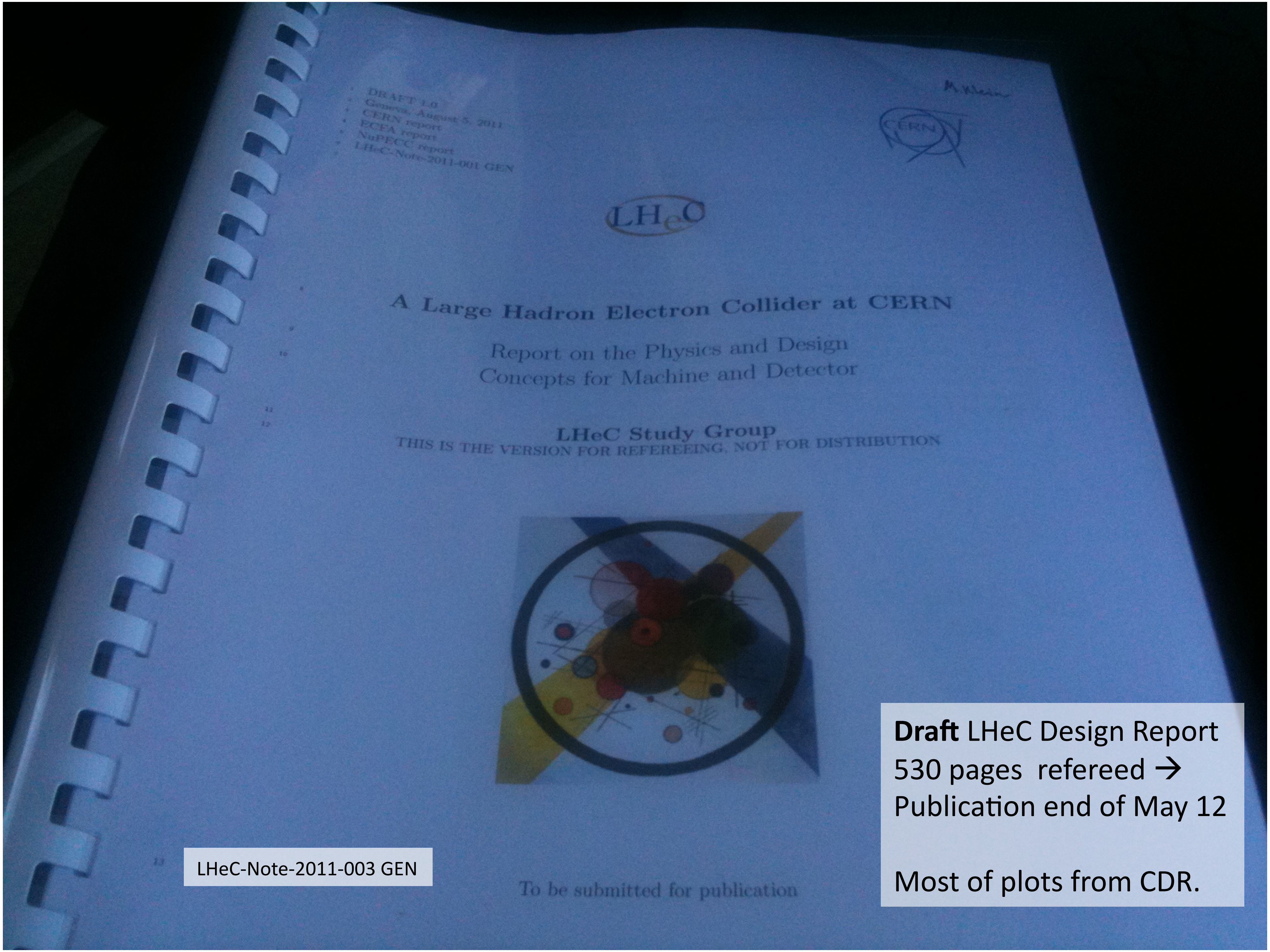
Olaf Behnke (DESY)
Paolo Gambino (Torino)
Thomas Gehrmann (Zurich)
Claire Gwenlan (Oxford)

Physics at High Parton Densities

Néstor Armesto (Santiago de Compostela)
Brian A. Cole (Columbia)
Paul R. Newman (Birmingham)
Anna M. Stasto (PennState)

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)



Draft LHeC Design Report
530 pages refereed →
Publication end of May 12

Most of plots from CDR.

LHeC-Note-2011-003 GEN

http://cern.ch/lhec

LHeC Study Group

J.L. Abelleira Fernandez[10,15], C.Adolphsen[39], S.Alekhin[40,11], A.N.Akai[01], H.Aksakal[30], P.Allport[17], J.L.Albacete[37], V.Andreev[25], R.B.Appleby[23], E.Arikan[30], N.Armesto[38], G.Azuelos[26], M.Bai[47], D.Barber[11,17,23], J.Bartels[12], J.Behr[11], O.Behnke[11], S.Belyaev[10], I.BenZvi[47], N.Bernard[16], S.Bertolucci[10], S.Bettoni[10], S.Biswal[32], J.Bluemlein[11], H.Boettcher[11], H.Braun[48], S.Brodsky[39], A.Bogacz[28], C.Bracco[10], O.Bruening[10], E.Bulyak[08], A.Bunyatian[11], H.Burkhardt[10], I.T.Cakir[54], O.Cakir[53], R.Calaga[47], E.Ciapala[10], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[29], J.C.Collins[46], J.Dainton[17], A.De.Roeck[10], D.d'Enterria[10], A.Dudarev[10], A.Eide[43], R.Enberg[58], E.Eroglu[45], K.J.Eskola[14], L.Favart[06], M.Fitterer[10], S.Forte[24], P.Gambino[42], H. García Morales[10], T.Gehrmann[50], C.Glasman[22], R.Godbole[27], B.Goddard[10], T.Greenshaw[17], A.Guffanti[09], V.Guzey[28], C.Gwenlan[34], T.Han[36], Y.Hao[47], F.Haug[10], W.Herr[10], B.Holzer[10], M.Ishitsuka[41], M.Jacquet[33], B.Jeanneret[10], J.M.Jimenez[10], H.Jung[11], J.M.Jowett[10], H.Karadeniz[54], D.Kayran[47], F.Kocac[45], A.Kilic[45], K.Kimura[41], M.Klein[17], U.Klein[17], T.Kluge[17], G.Kramer[12], M.Korostelev[23], A.Kosmicki[10], P.Kostka[11], H.Kowalski[11], D.Kuchler[10], M.Kuze[41], T.Lappi[14], P.Laycock[17], E.Levichev[31], S.Levonian[11], V.N.Litvinenko[47], A.Lombardi[10], C.Marquet[10], B.Mellado[07], K.H.Mess[10], A.Milanese[10], S.Moch[11], I.I.Morozov[31], Y.Muttoni[10], S.Myers[10], S.Nandi[26], P.R.Newman[03], T.Omori[44], J.Osborne[10], Y.Papaphilippou[10], E.Paoloni[35], C.Pascaud[33], H.Paukkunen[38], E.Perez[10], T.Pieloni[15], E.Pilicer[45], B.Pire[55], A.Polini[04], V.Ptitsyn[47], Y.Pupkov[31], V.Radescu[13], S.Raychaudhuri[27], L.Rinolfi[10], R.Rohini[27], J.Rojo[24], S.Russenschuck[10], C.A.Salgado[38], K.Sampei[41], R.Sassot[57], E.Sauvan[19], M.Sahin[01], U.Schneekloth[11], T.Schoerner Sadenius[11], D.Schulte[10], A.N.Skrinsky[31], W.Smith[20], H.Spiesberger[21], A.M.Stasto[46], M.Strikman[46], M.Sullivan[39], B.Surrow[05], S.Sultansoy[01], Y.P.Sun[39], L.Szymanowski[56], I.Tapan[45], P.Taels[02], E.Tassi[52], H.Ten.Kate[10], J.Terron[22], H.Thiesen[10], L.Thompson[23], K.Tokushuku[44], R.Tomás García[10], D.Tommasini[10], D.Trbojevic[47], N.Tsoupas[47], J.Tuckmantel[10], S.Turkoz[53], K.Tywoniuk[18], G.Unel[10], J.Urakawa[44], P.VanMechelen[02], A.Variola[37], R.Veness[10], A.Vivoli[10], P.Vobly[31], R.Wallny[51], S.Wallon[59], G.Watt[10], G.Weiglein[12], C.Weiss[28], U.A.Wiedemann[10], U.Wienands[39], F.Willeke[47], B.-W.Xiao[46], V.Yakimenko[47], A.F.Zarnecki[49], F.Zimmermann[10], R.Zlebcik[60], F.Zomer[33]

About 180 Experimentalists and Theorists from 60 Institutes

Tentative **list of those who contributed to the CDR [11. May 12]**

Supported by
CERN, ECFA, NuPECC

Why an ep/A Experiment at TeV Energies?

1. For resolving the quark structure of the nucleon with p, d and ion beams

   QPM symmetries, quark distributions (complete set from data!), GPDs, nuclear PDFs ..

2. For the development of perturbative QCD

   N^kLO ($k \geq 2$) and h.o. eweak, HQs, jets, resummation, factorisation, diffraction

3. For mapping the gluon field

   Gluon for $\sim 10^{-5} < x < 1$, is unitarity violated? J/ψ, F_2^c, … unintegrated gluon

4. For searches and the understanding of new physics

   GUT (α_s to 0.1%), LQs RPV, Higgs (bb, HWW) … PDFs4LHC… instanton, odderon,..?

5. For investigating the physics of parton saturation

   Non-pQCD (chiral symm breaking, strings), black disc limit, saturation border..

..For providing data which could be of use for future experiments [Proposal for SLAC ep 1967]

Candidates for Surprises and Discoveries

PDFs (t, s, $q-\bar{q}$, val, xg)
Odderon
Instanton
(no) saturation, QCD
QGP initial state

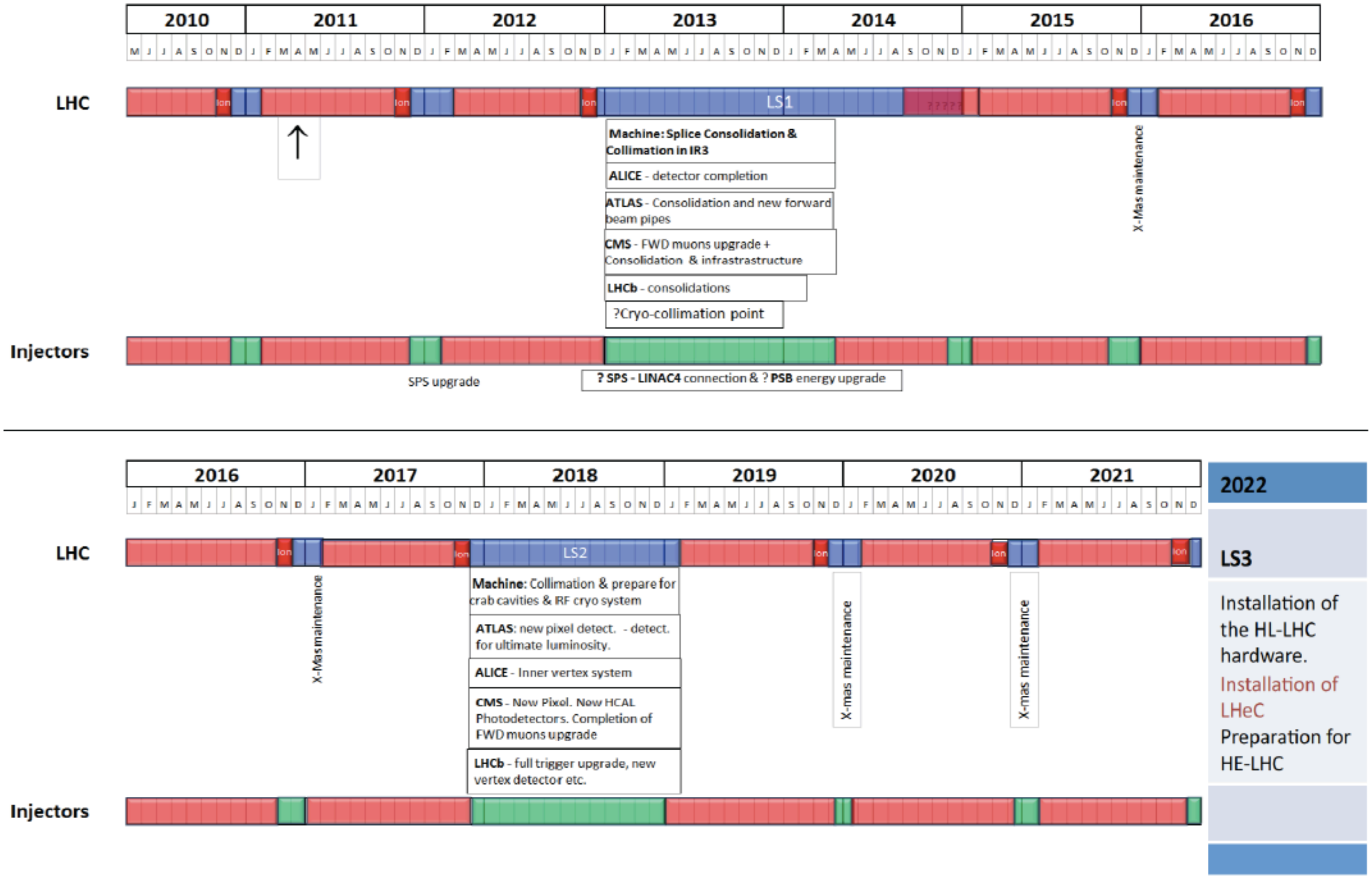
The study of deep inelastic *ep* scattering is important for the investigation of the nature of the Pomeron and Odderon, which are Regge singularities of the t-channel partial waves $f_j(t)$ in the complex plane of the angular momentum j. The Pomeron is responsible for a growth of total cross sections with energy. The Odderon describes the behaviour of the difference of the cross sections for particle-particle and particle-antiparticle scattering which obey the Pomeranchuck theorem. In perturbative QCD, the Pomeron and Odderon are the simplest colorless reggeons (families of glueballs) constructed from two and three reggeized gluons, respectively. Their wave functions satisfy the generalized BFKL equation. In the next-to-leading approximation the solution of the BFKL equation contains an infinite number of Pomerons and to verify this prediction of QCD one needs to increase the energy of colliding particles. In the N=4 supersymmetric generalization of QCD, in the t'Hooft limit of large N_c, the BFKL Pomeron is equivalent to the reggeized graviton living in the 10-dimensional anti-de-Sitter space. Therefore, the Pomeron interaction describing the screening corrections to the BFKL predictions, at least in this model, should be based on a general covariant effective theory being a generalization of the Einstein-Hilbert action for general relativity. Thus, the investigation of high energy *ep* scattering could be interesting for the construction of a non-perturbative approach to QCD based on an effective string model in high dimensional spaces.

Lev Lipatov in the CDR…

Factorization pp-ep
LQs, RPV SUSY
e^*
Higgs CP
α_s indeed small (GUT)

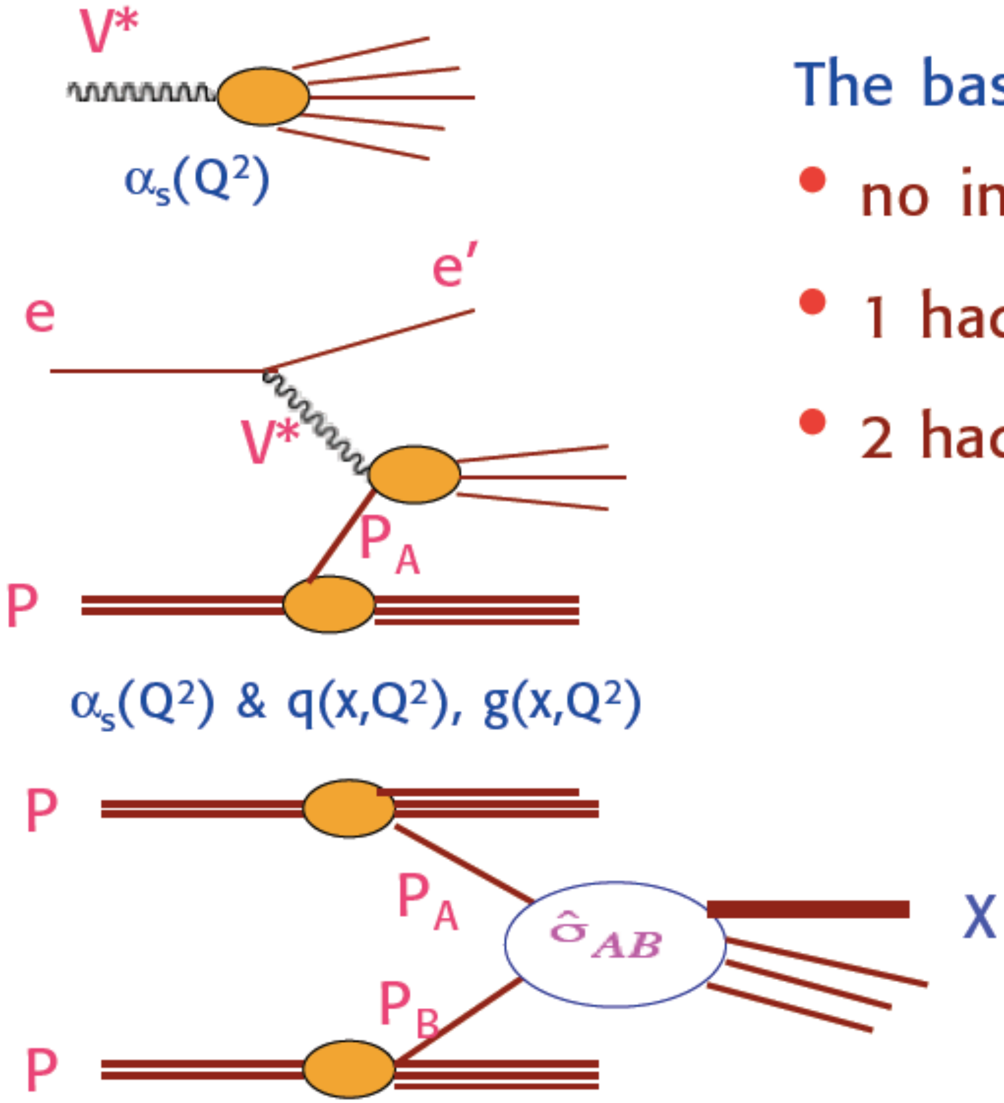
Ultra high precision (detector, e-h redundancy) - new insight
Maximum luminosity and much extended range - rare, new effects
Deep relation to (HL-) LHC (precision+range) - complementarity
→ **LHeC brings a substantial enrichment of LHC physics**

Draft LHC Schedule for the coming decade



as shown by S. Myers at EPS 2011 Grenoble

Physics with the LHeC

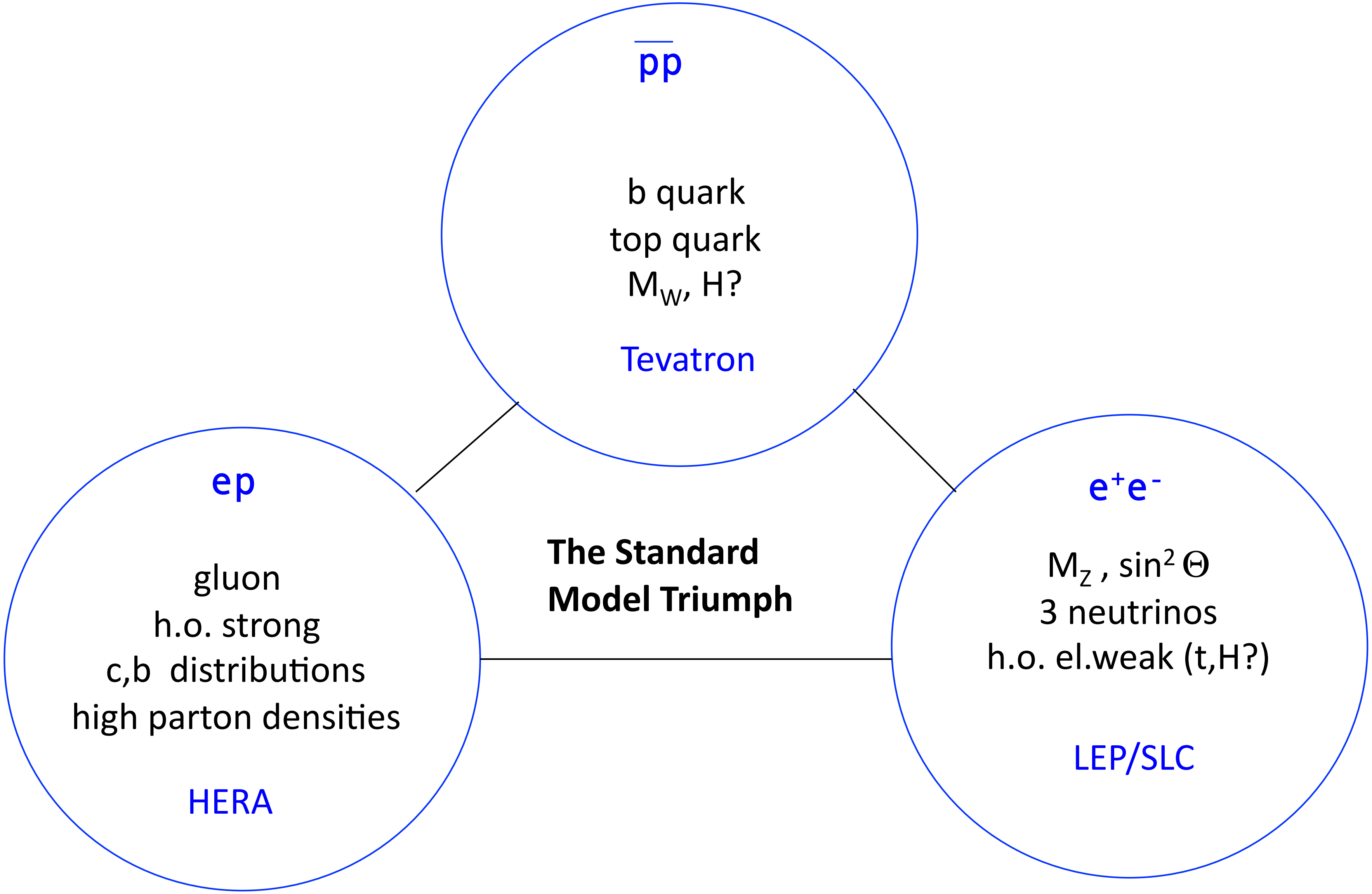


The basic experimental set ups:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (....SppS, Tevatron, LHC)

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

The Fermi Scale [1985-2012]



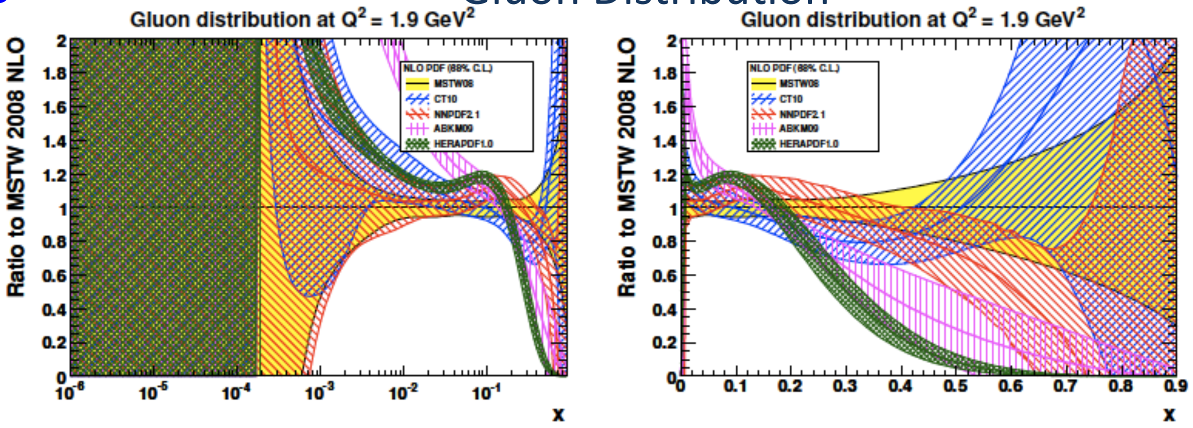
CDR Physics

153 pages

now

then

Gluon Distribution



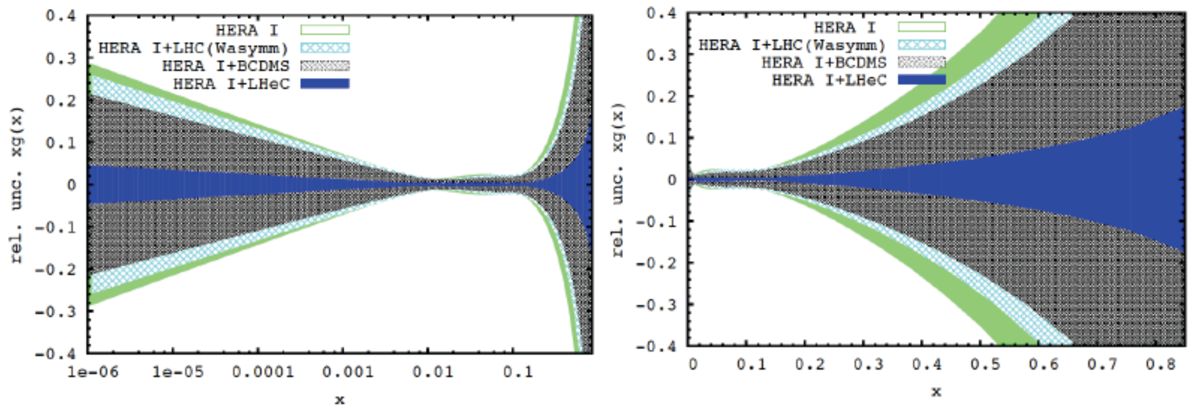


Figure 4.17: Relative uncertainty of the gluon distribution at $Q^2 = 1.9\,\mathrm{GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x, right: linear x.

Precision measurement of gluon density to extreme x → α_s
Low x: saturation in ep? Crucial for QCD, LHC, UHE neutrinos!
High x: xg and valence quarks: resolving new high mass states!
Gluon in Pomeron, odderon, photon, nuclei.. Local spots in p?
Heavy quarks intrinsic or only gluonic?

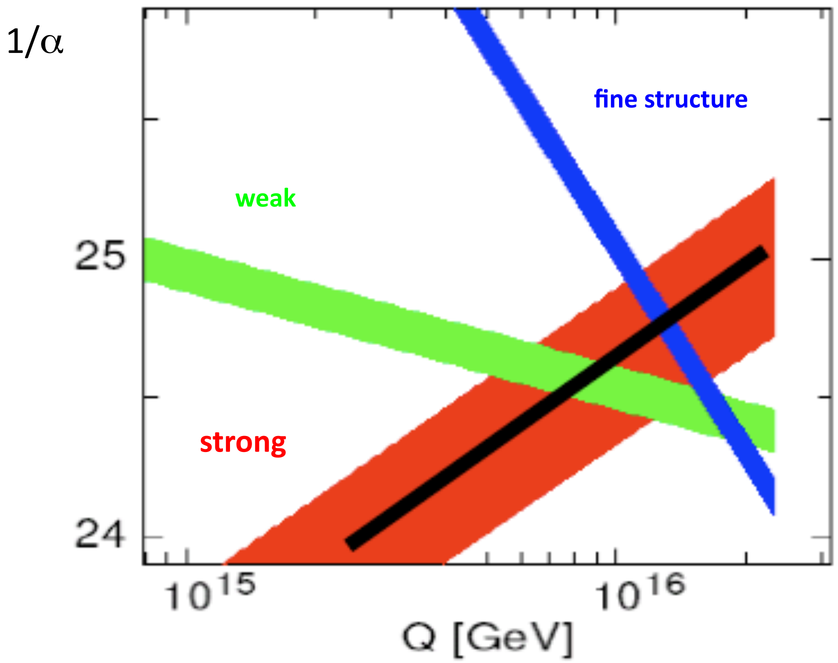
Strong Coupling Constant

α_s least known of coupling constants
Grand Unification predictions suffer from $\delta\alpha_s$

DIS tends to be lower than world average
Recently challenged by MSTW and NNPDF – jets??

LHeC: per mille - independent of BCDMS.

Challenge to experiment and to h.o. QCD →
A genuine DIS research programme rather than one outstanding measurement only.

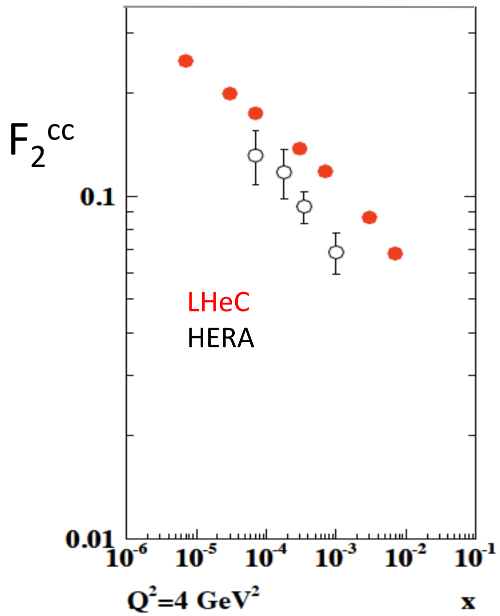


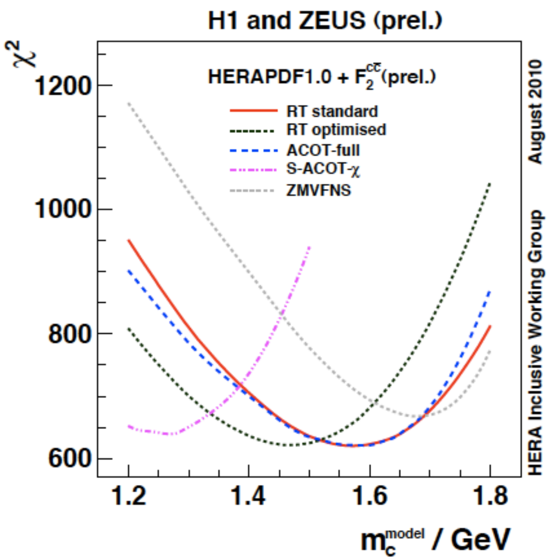
case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 >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

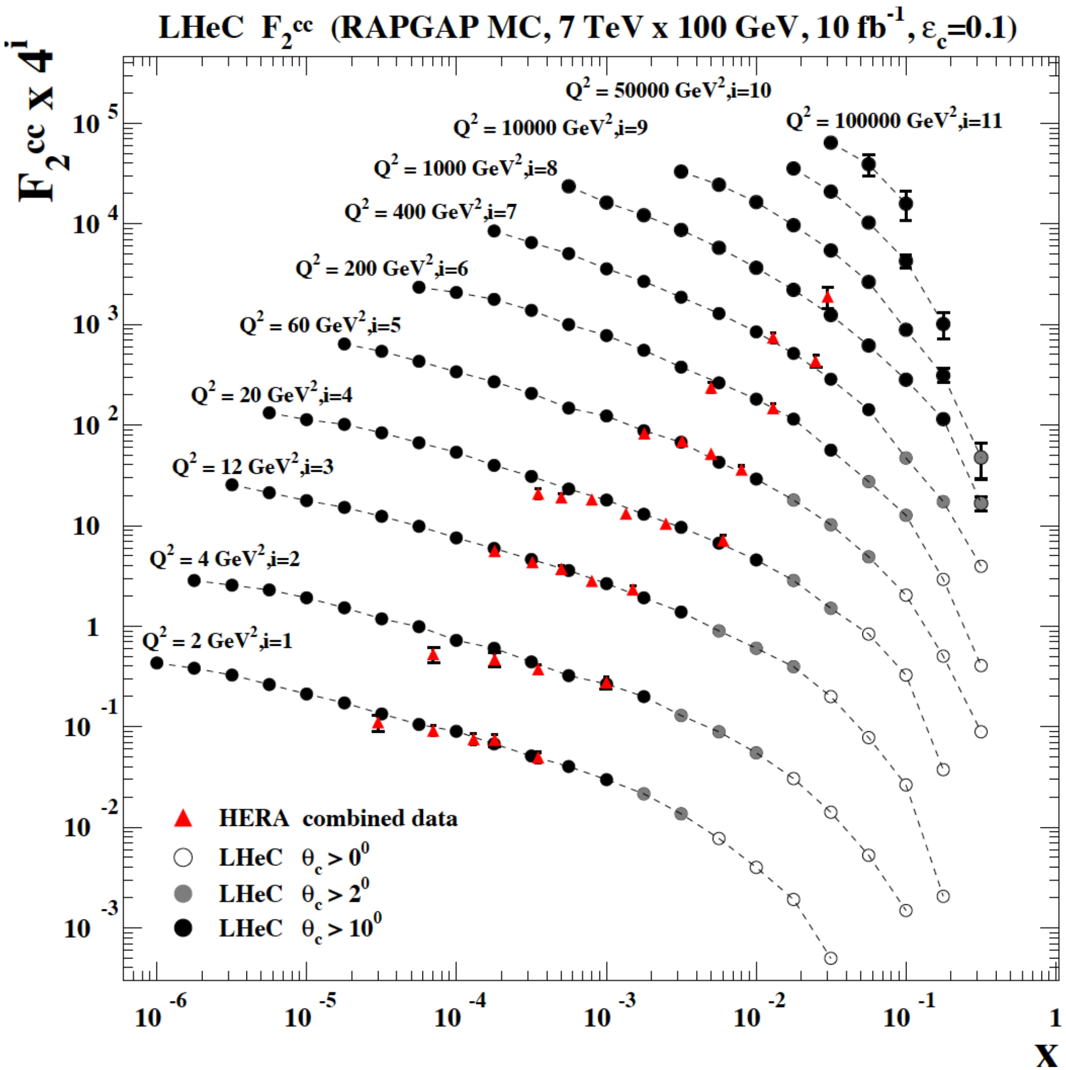
Two independent QCD analyses using LHeC+HERA/BCDMS
Full experimental uncertainties (unc+corr systematics)

DATA	exp. error on α_s
NC e^+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=(1)**
(1) $\gamma_h > 5°$	0.36% :=(2)
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%

Treatment of charm influences α_s







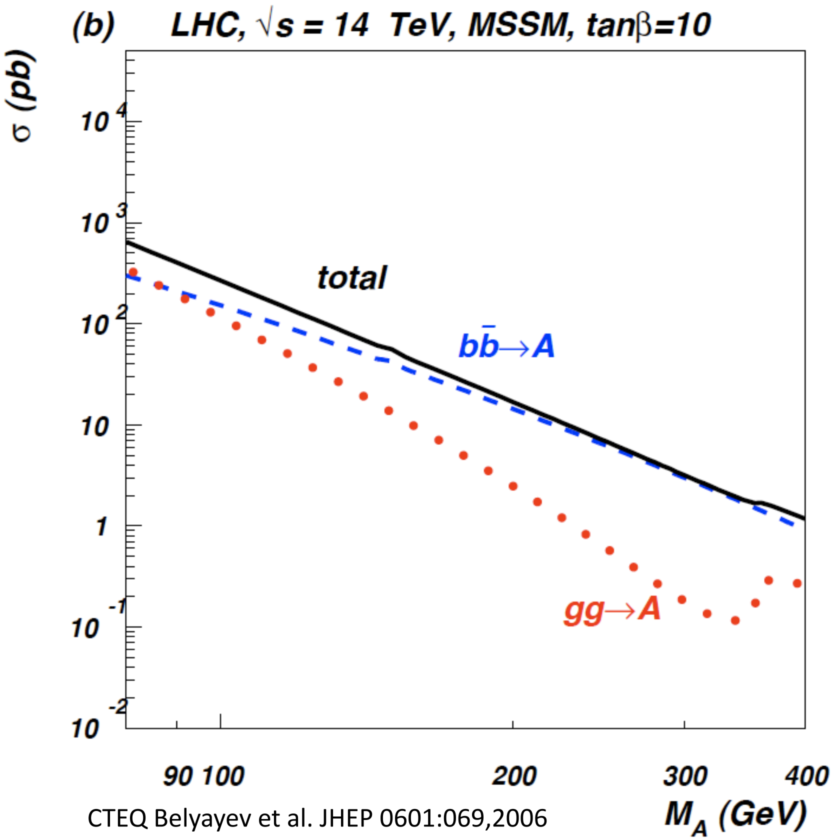
LHeC vs HERA: higher fraction of c, larger range, smaller beam spot, better Silicon detectors

note: 100 MeV of m_c is about 1% on α_s

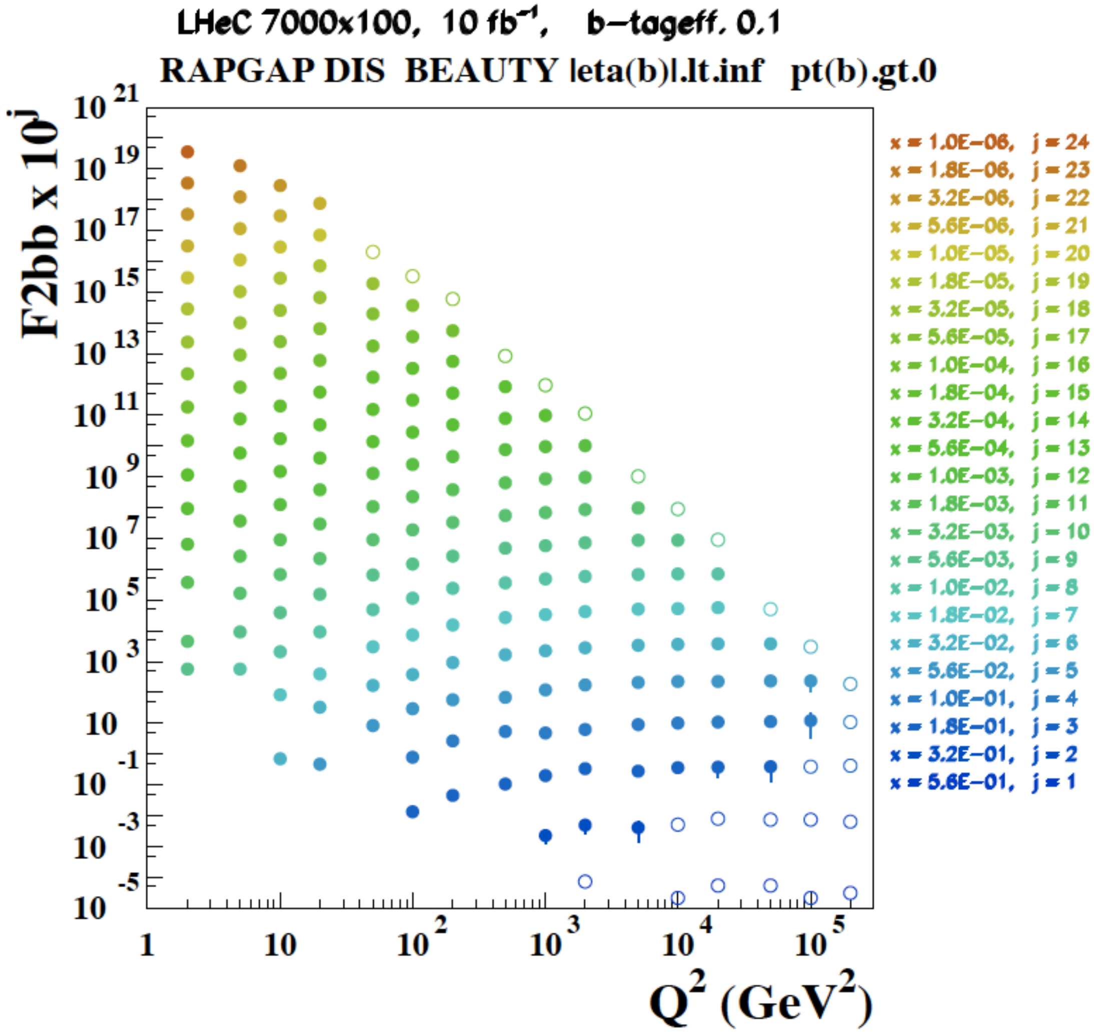
Intrinsic charm at large x?

CDR

Beauty - MSSM Higgs



CTEQ Belyayev et al. JHEP 0601:069,2006

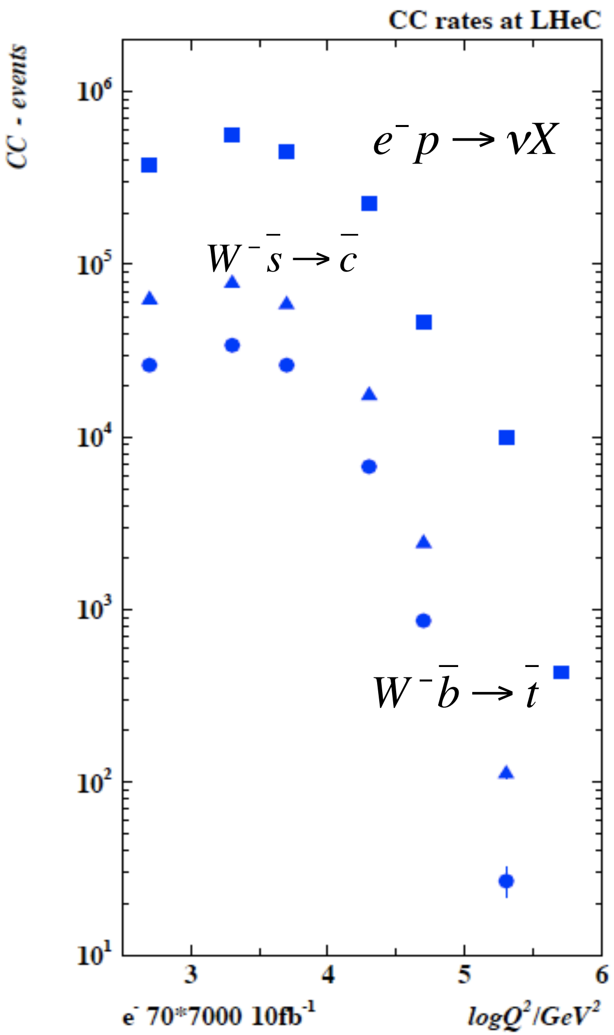


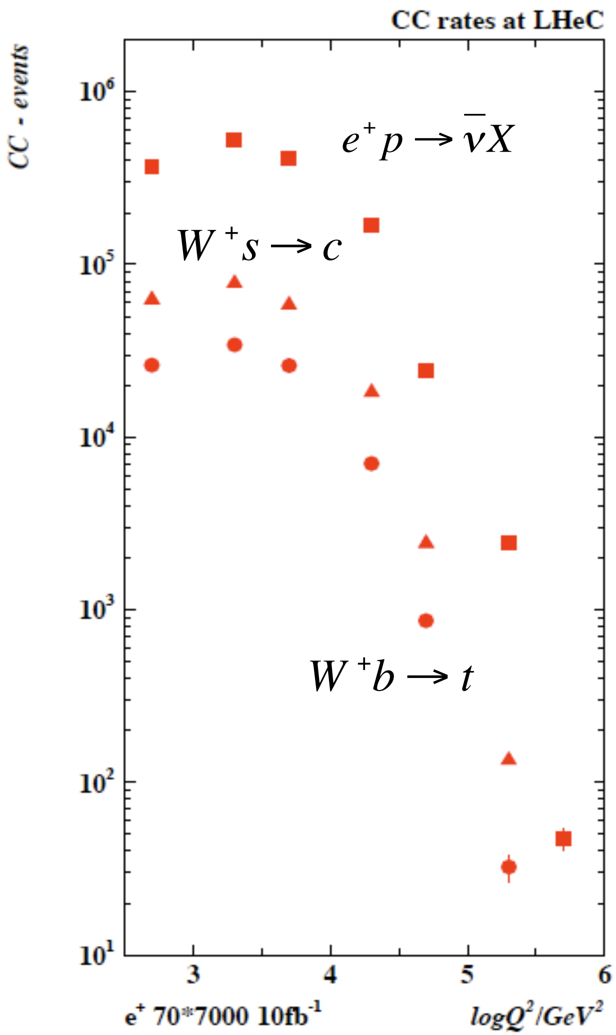
In MSSM Higgs production is b dominated

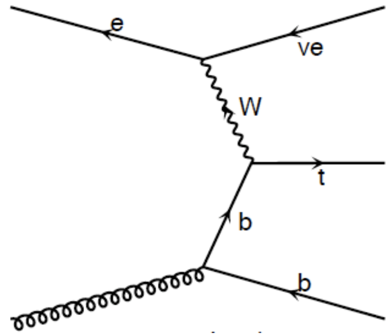
LHeC: higher fraction of b, larger range, smaller beam spot, better Si detectors

HERA: First measurements of b to ~20%
LHeC: precision measurement of b-df

$\overline{\text{Top}}$ and Top Production in Charged Currents







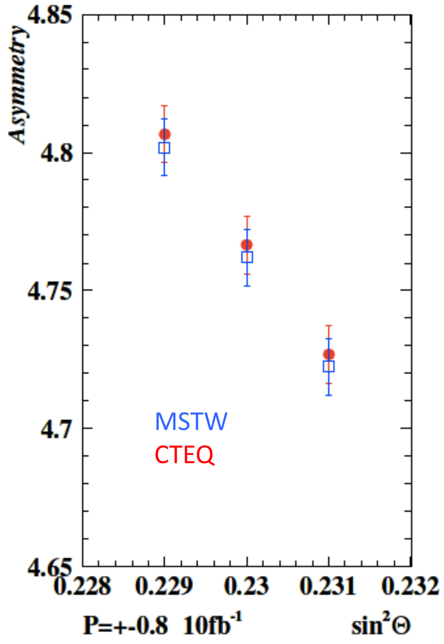
LHeC copious single top and anti-top quark production

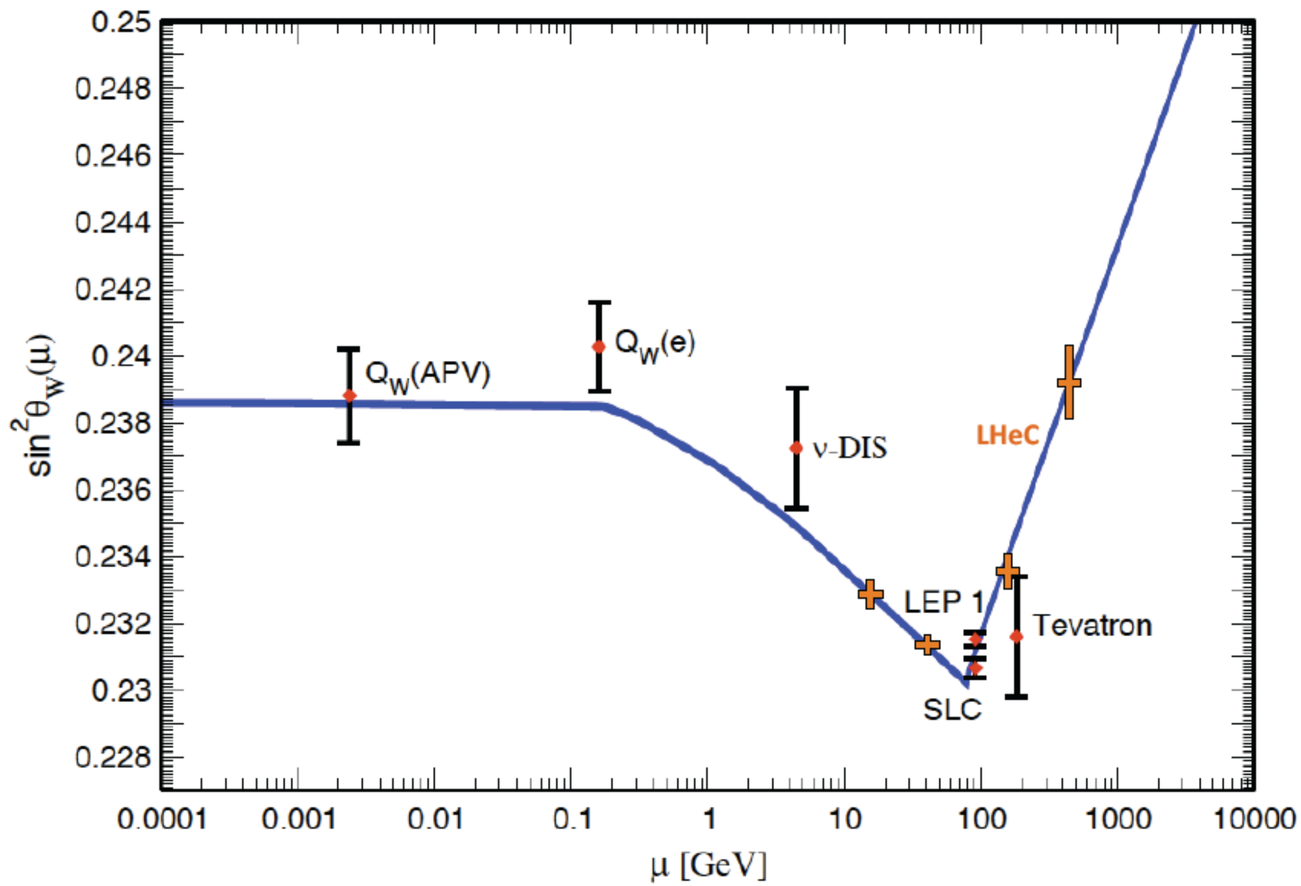
with a CC cross section of O(10) pb

Study Q^2 evolution of top quark onset – 6 quark CFNS
(Pascaud at DIS11)

m_{top}
Not yet simulated..

Weak Neutral Currents – Polarisation Asymmetry



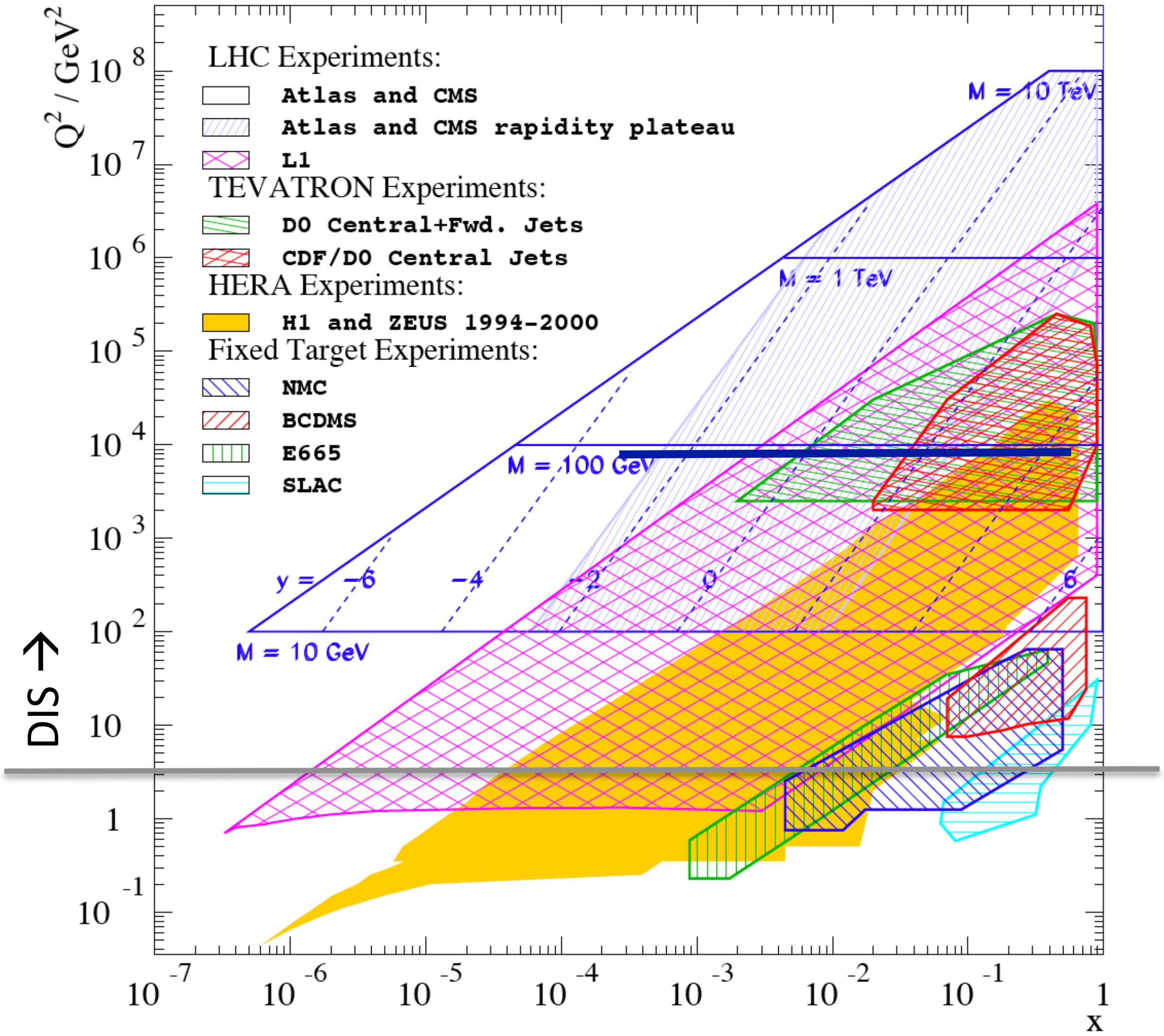


$$A^{\pm} = \frac{\sigma^{\pm}_{NC}(P_R) - \sigma^{\pm}_{NC}(P_L)}{\sigma^{\pm}_{NC}(P_R) + \sigma^{\pm}_{NC}(P_L)}$$

$$A^{\pm} \simeq \mp\kappa_Z a_e \frac{F_2^{\gamma Z}}{(F_2 + \kappa_Z a_e Y_- x F_3^{\gamma Z}/Y_+)} \simeq \mp\kappa_Z a_e \frac{F_2^{\gamma Z}}{F_2}.$$

Measure running of the weak mixing angle to high precision with polarised e^-. [stat. errors, much of syst cancels, pdfs from LHeC itself]

Complementing the LHC with ep/A



In Drell-Yan kinematics: mass and rapidity relate to Q^2 and x

LHC partons: W,Z +c,b new constraints but severely limited in x,Q^2 range

Discoveries at the LHC will be at high masses: large x and very high Q^2 which require high s, lumi of LHeC for precision PDFs (u,d,xg mainly)

If the Higgs exists, its study will become a major field of research: ep: WW→ H → bbar (CP odd/even?)

top distribution in the proton TDF

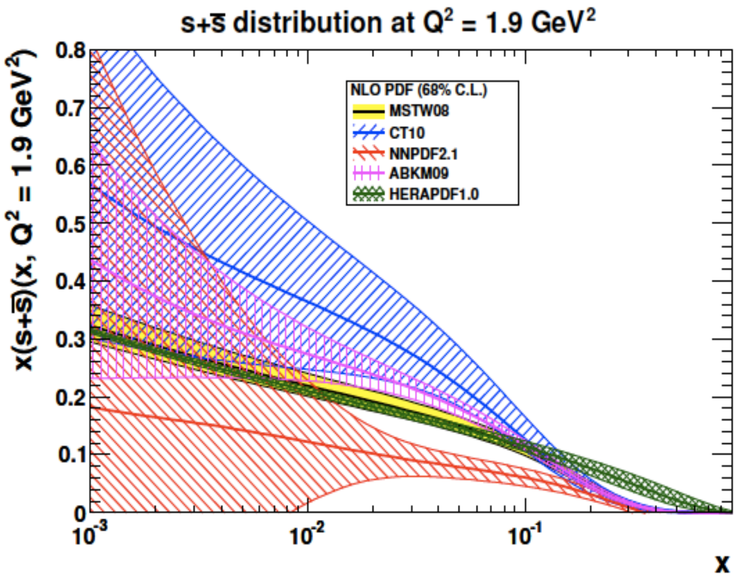
IF RP is violated and LQ or RPV SUSY discovered: LHeC is uniquely suited

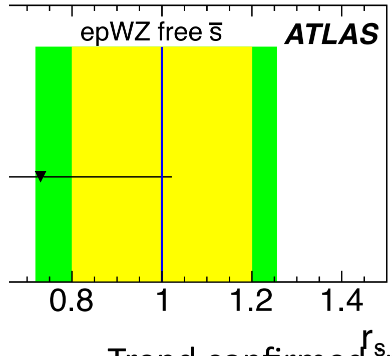
AA: QGP: study initial state in eA
Resolve parton distributions in nuclei

LHeC is unique in various areas, e.g.:
Low x and saturation physics
Strong coupling constant to 0.1% level

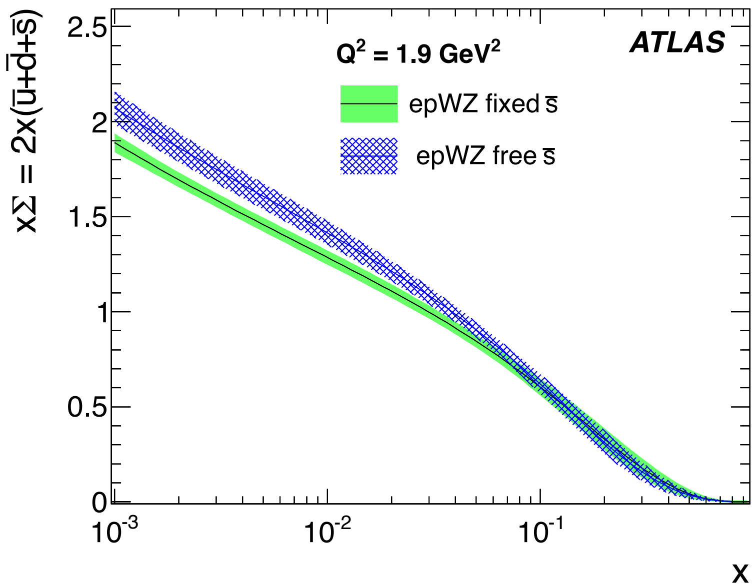
LHC and LHeC - Strange Quark Distribution

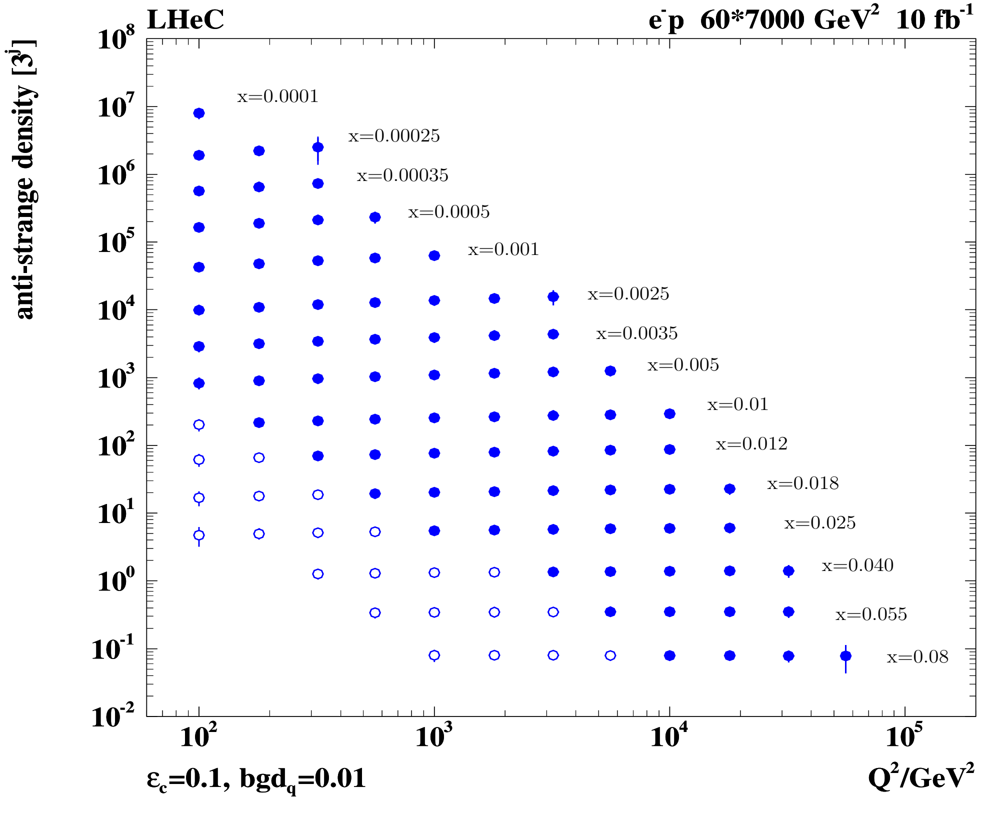
ATLAS → PRL





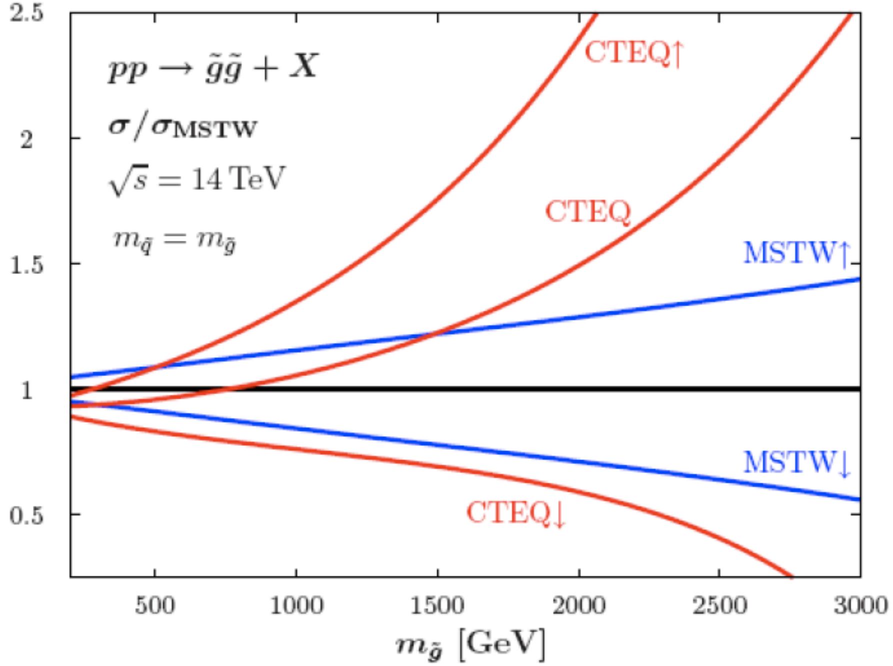
Trend confirmed in NNPDF collider only fit



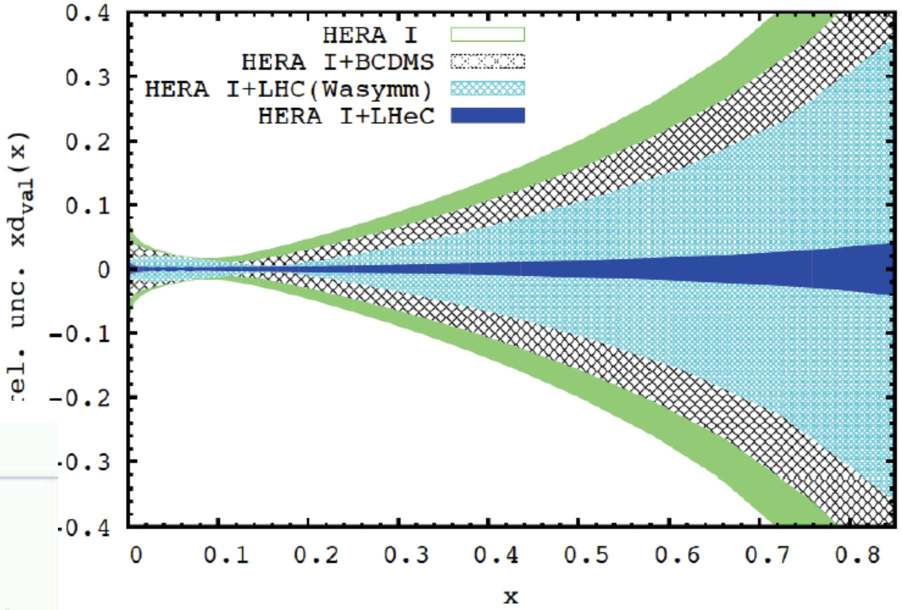


Change of strange affects sea - UHE ν

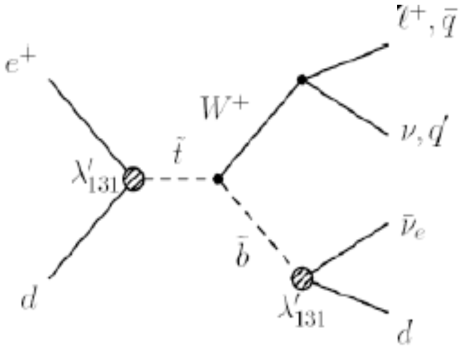
SUSY

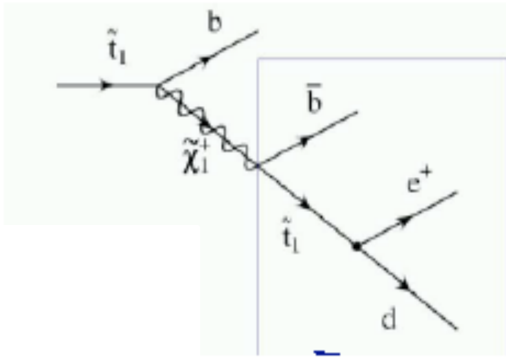


HL-LHC will explore highest mass range. This requires to control very high Bj x, where LHeC pins down partons such that resummation and factorisation effects can be controlled.



RPV SUSY in 3rd generation?

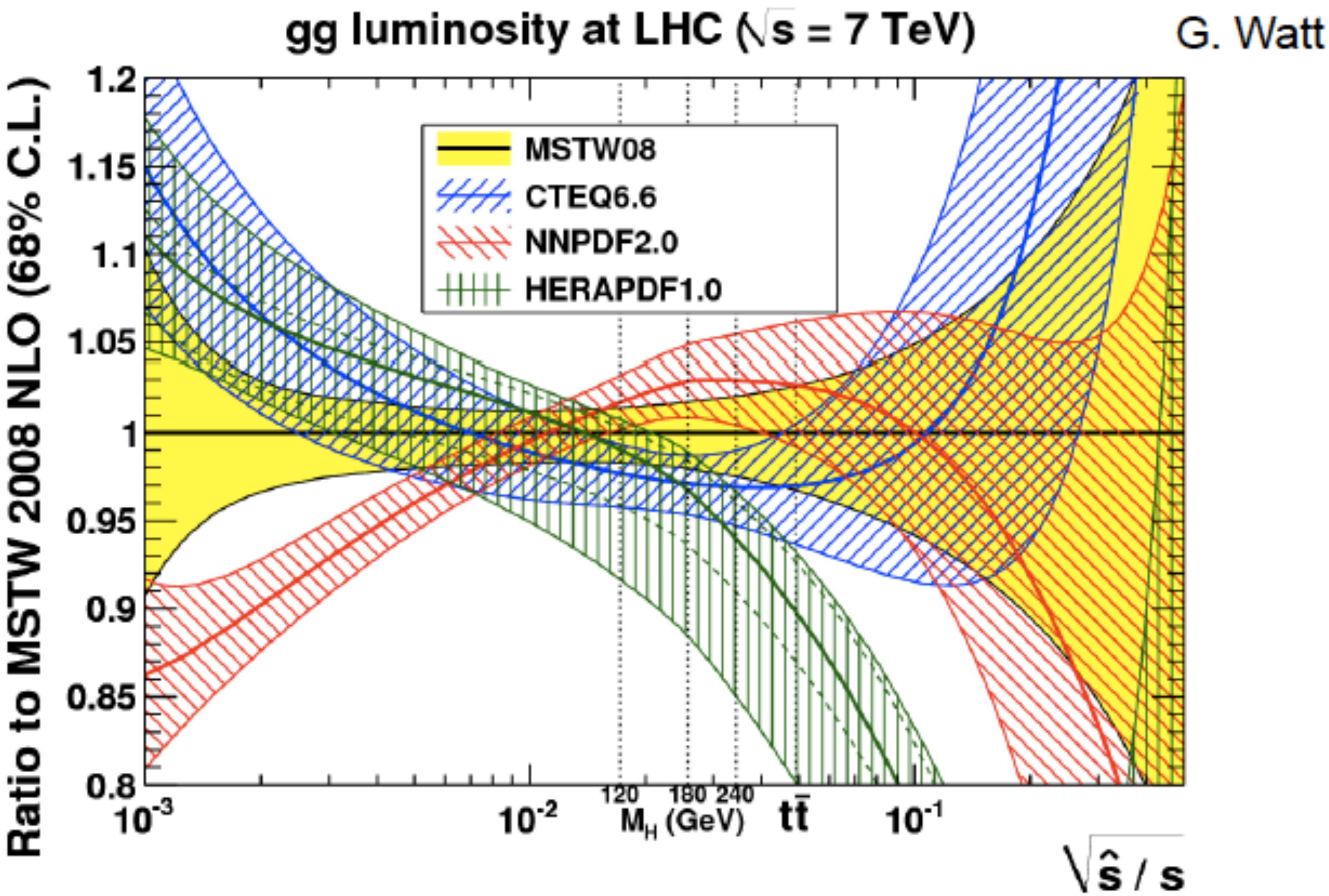




$$W_R = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$$

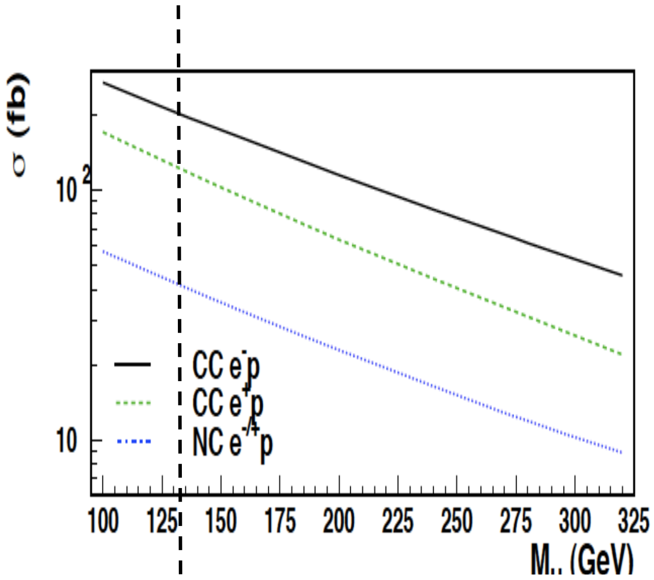
L: LH (s)leptons, Q: LH (s)quarks, D: RH down-type (s)quarks

i,j,k generation indices (27 couplings)

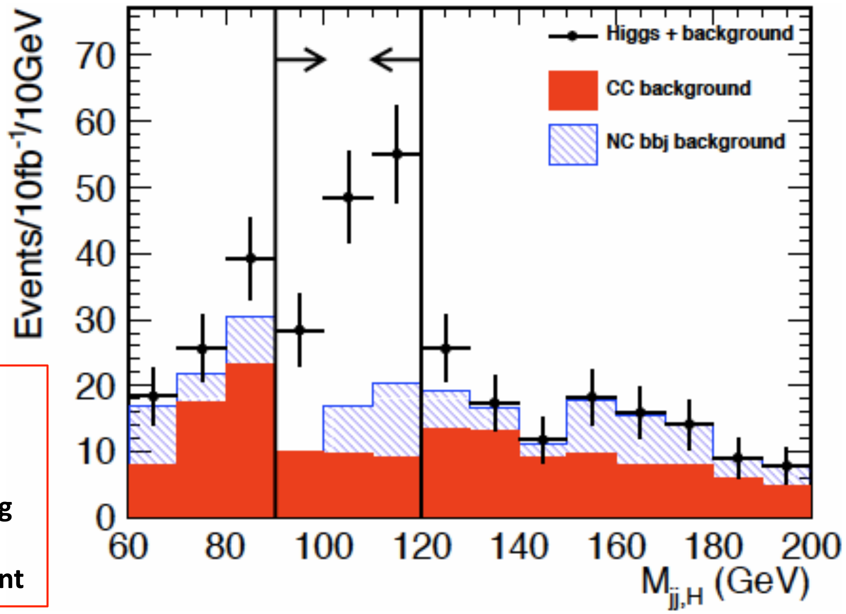


gg luminosity at LHC ($\sqrt{s}$ = 7 TeV)
G. Watt
MSTW08
CTEQ6.6
NNPDF2.0
HERAPDF1.0
Ratio to MSTW 2008 NLO (68% C.L.)
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
10^{-3}
10^{-2}
10^{-1}
120
180
240
M_H (GeV)
$t\bar{t}$
$\sqrt{\hat{s}/s}$

Higgs

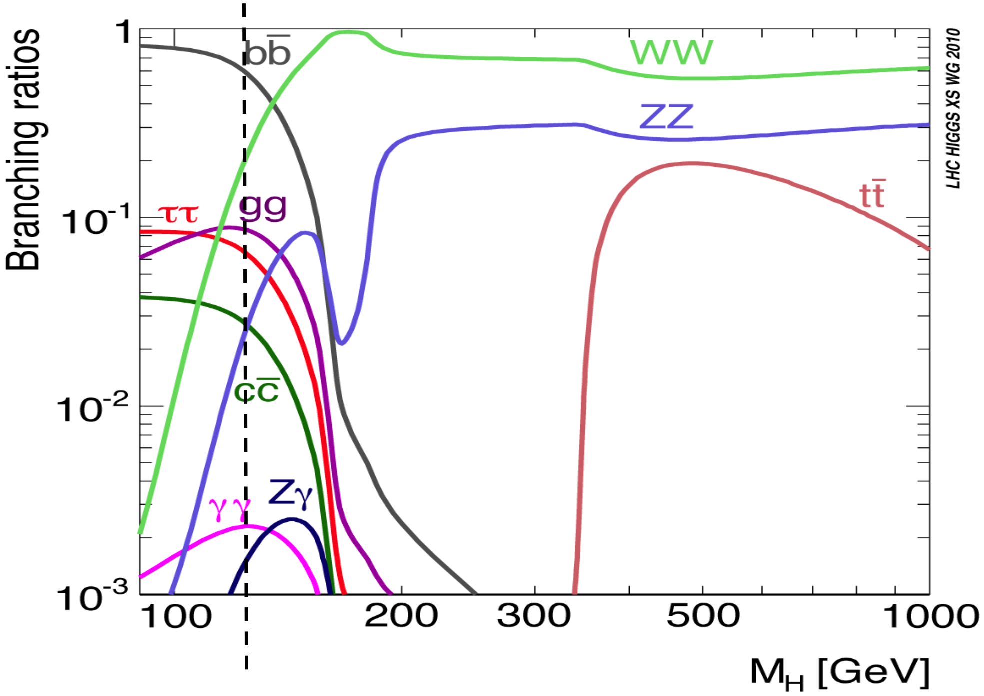


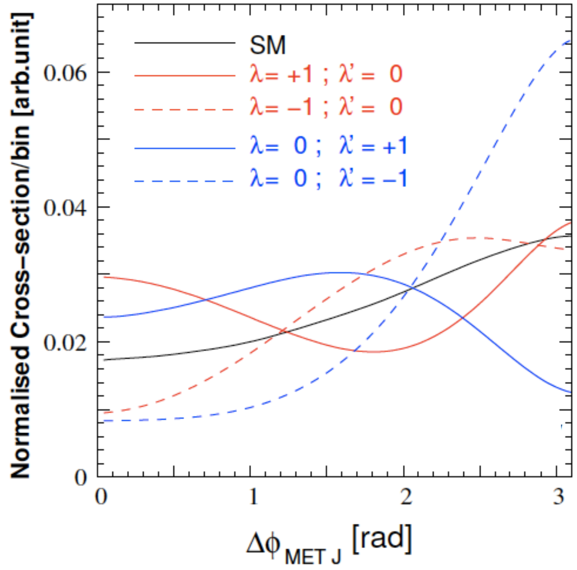
Process determines much of detector acceptance and calibration and b tag (also single top) and L/E_e requirement



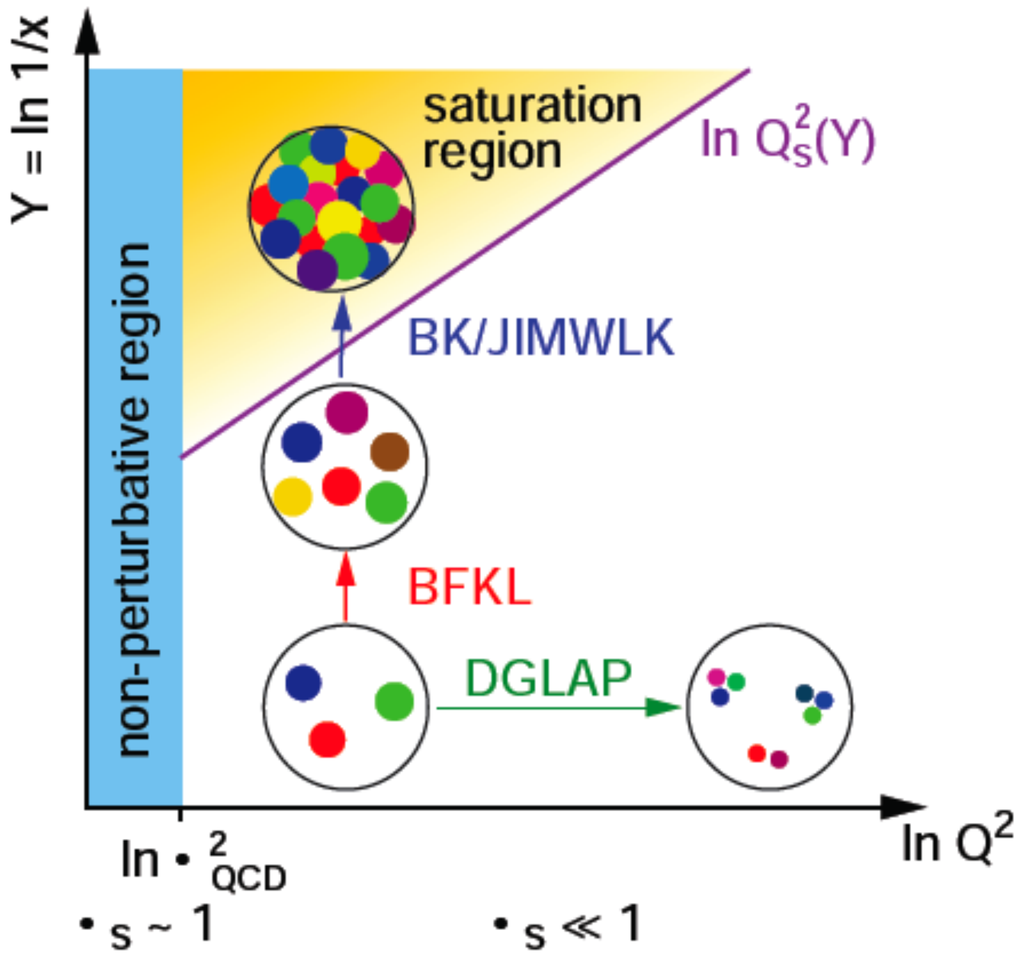
Higgs is light (or absent), CC: WW→H→bb

CP even: SM, CP odd: nonSM, mixture?





High Parton Densities



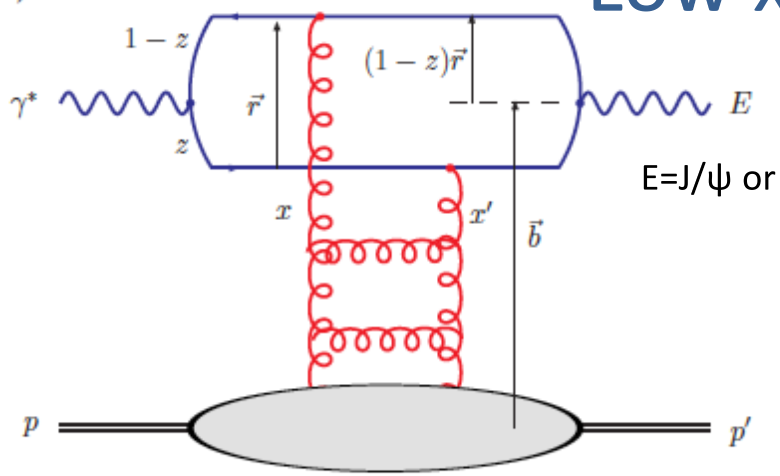
Should lead to non-linear evolution theory and eventually discover saturation of rise of gluon density (unitarity limit?)

Needs highest energy to be studied in both ep and eA.

CDR $L_{eN} \cong 3\text{-}10 * 10^{31}\ cm^{-2}s^{-1}$ for D,A - not optimised

Low x physics - J/ψ in γ*p/A

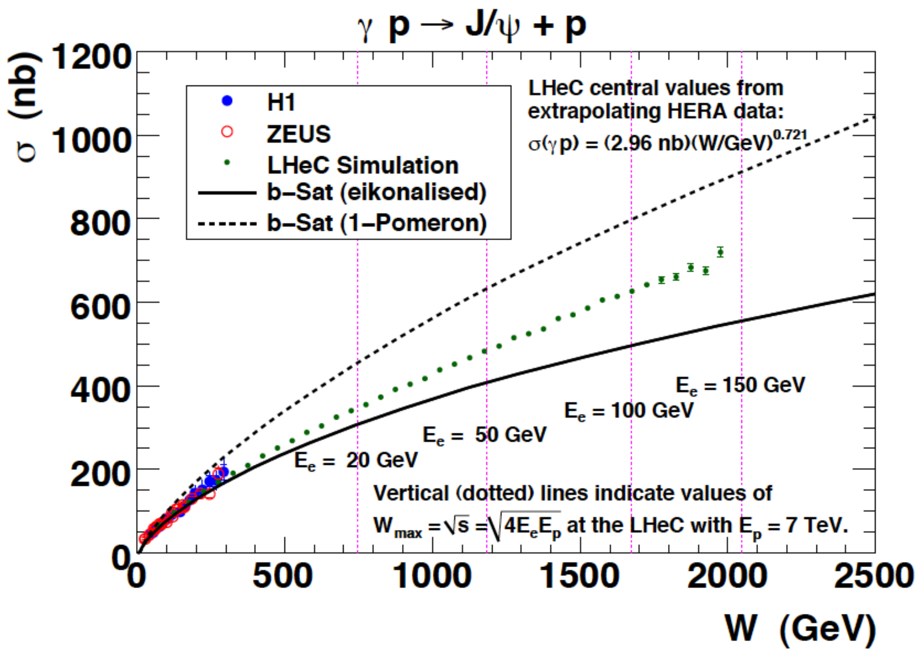
(a)



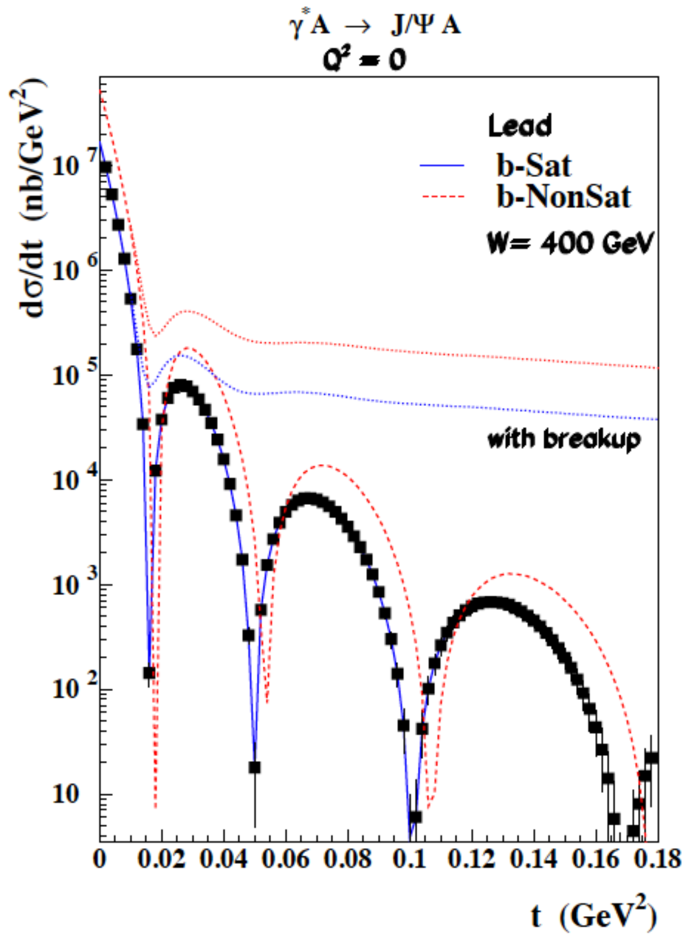
E=J/ψ or photon (DVCS)

$$\sigma_{T,L}^{\gamma^* p}(x,Q) = \mathrm{Im}\,\mathcal{A}_{T,L}^{\gamma^* p\to\gamma^* p}(x,Q,\Delta=0) = \sum_f \int \mathrm{d}^2\boldsymbol{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} (\Psi^*\Psi)_{T,L}^f \int \mathrm{d}^2\boldsymbol{b}\, \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}$$

Optical theorem relates J/ψ to $F_T=F_2-F_L$



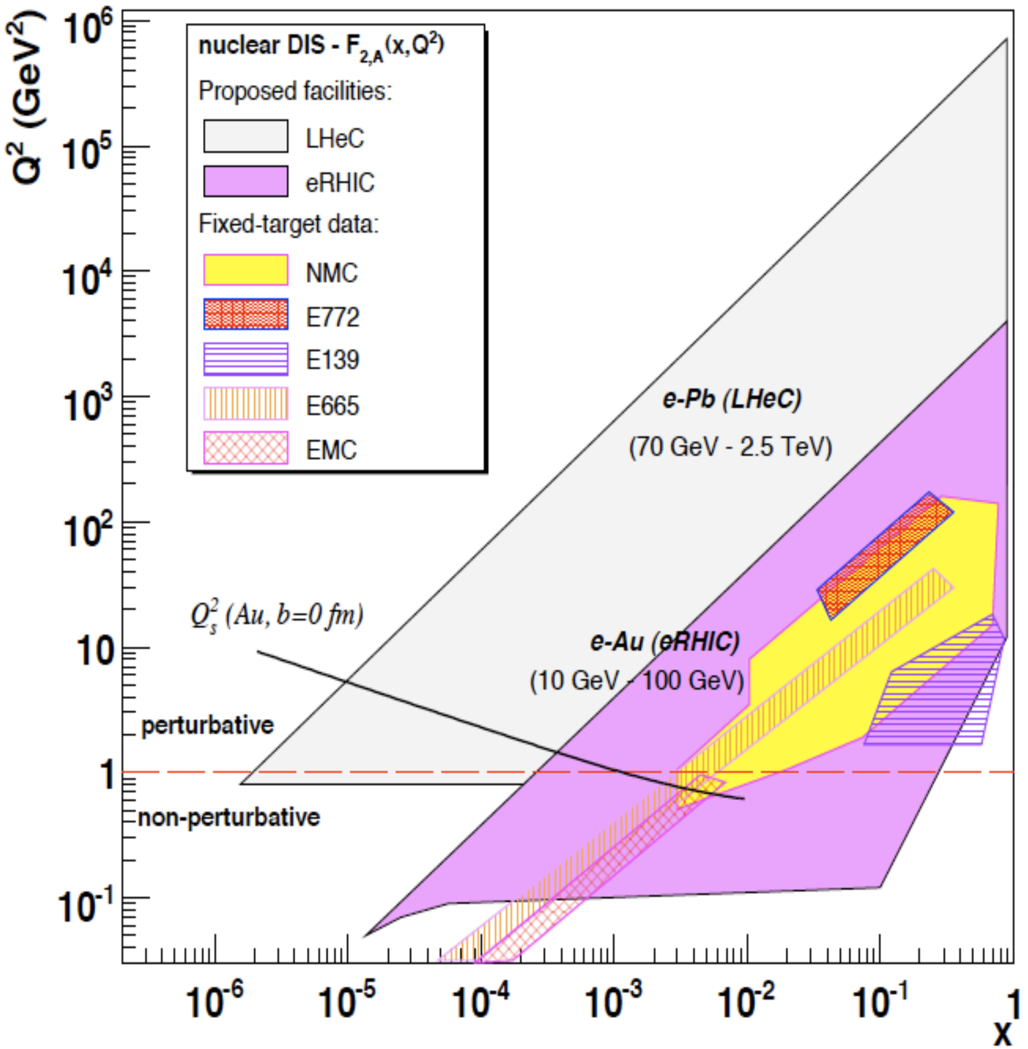
Test of saturation



Coherent production in γ*A

Probing of nuclear matter

Electron-Ion Scattering



EIC programme:
see recent workshop arXiv:1108.1713 [nucl-th]

Dipole models predict **saturation** which resummation in pQCD moves to lower x..
It requires highest energy, low x, $Q^2 > M_p^2$

Saturation at the LHeC is predicted to be observed both in ep AND in eA.
This combination is crucial to disentangle nuclear from unitarity effects.

Expect **qualitative changes of behaviour**

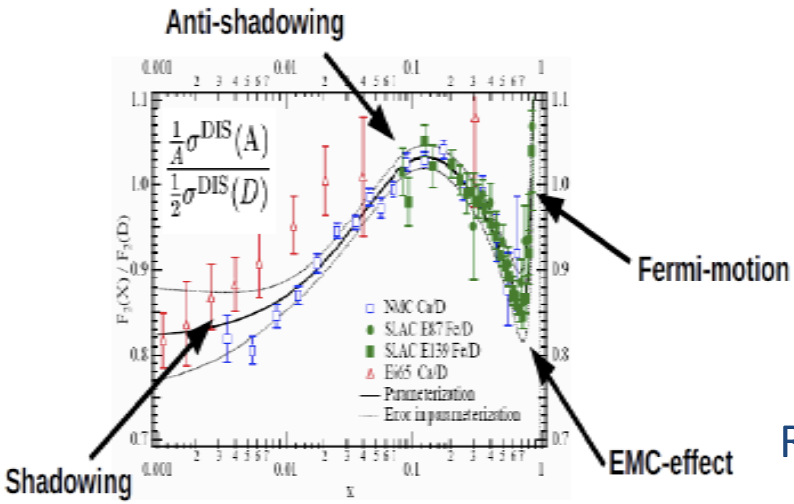
- Black body limit of F_2
- Saturation amplified with $A^{1/3}$
- Rise of diffraction to 50%? ….

Below x ~ 10^{-2}: DIS data end. NO flavour separation yet. However indications are that e.g. shadowing is flavour dependent.

Deuterons: tag spectator,
relate shadowing-diffraction (Gribov)!
stabilise QCD evolution (singlet!)

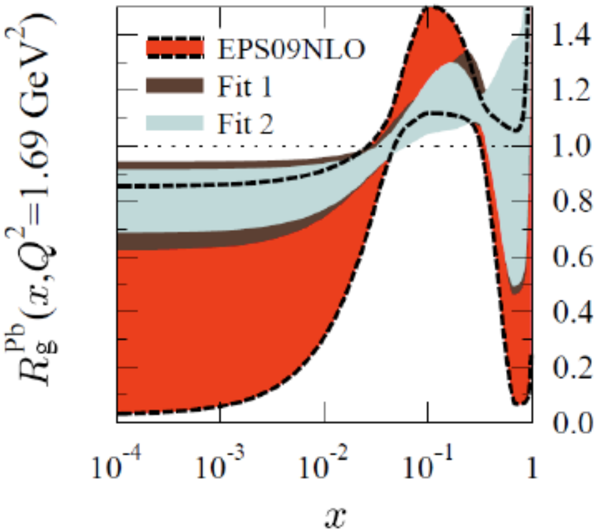
Neutron (light sea, UHE neutrinos, QPM)

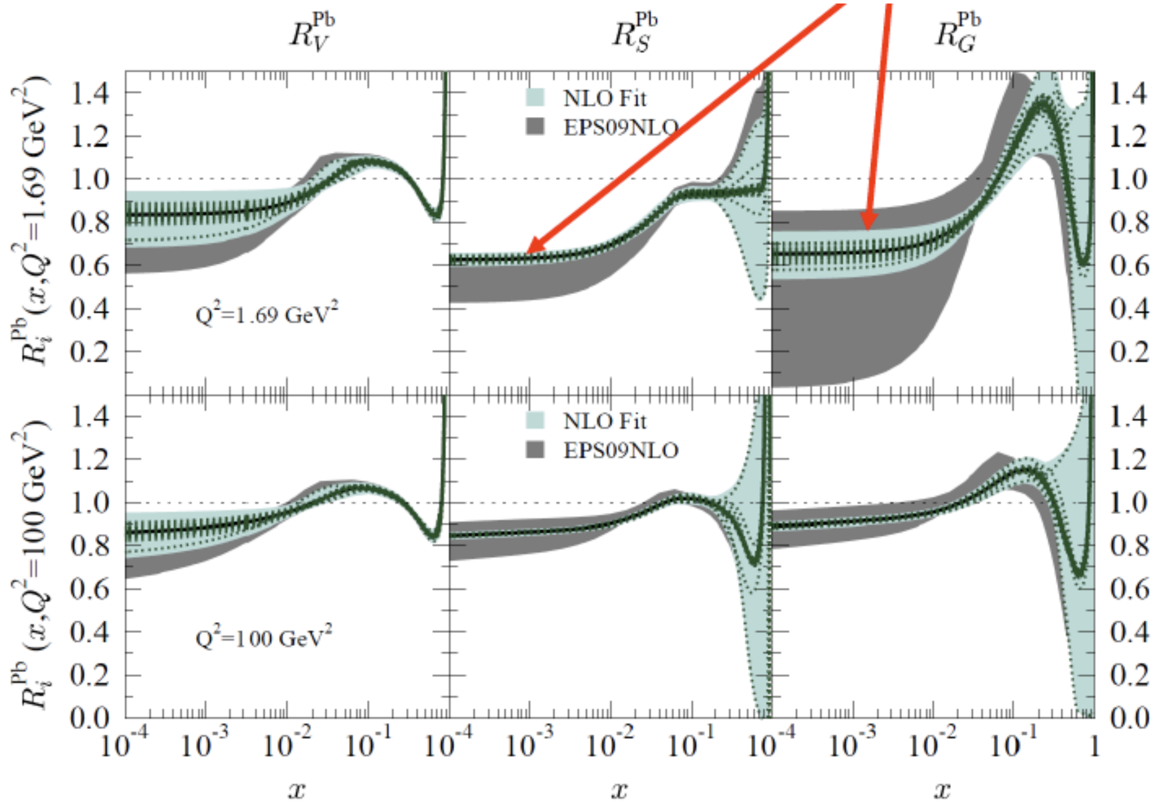
Nuclear Parton Distributions



Study using eA LHeC pseudodata

$R = q^{Pb}/q^{p}$





K.Eskola, H.Paukkunen, C.Salgado, Divonne09

→A complete determination of nPDFs in grossly extended range, into nonlinear regime nPDFs - certainly more diverse than in V,S,G terms and cleaner than pA at the LHC

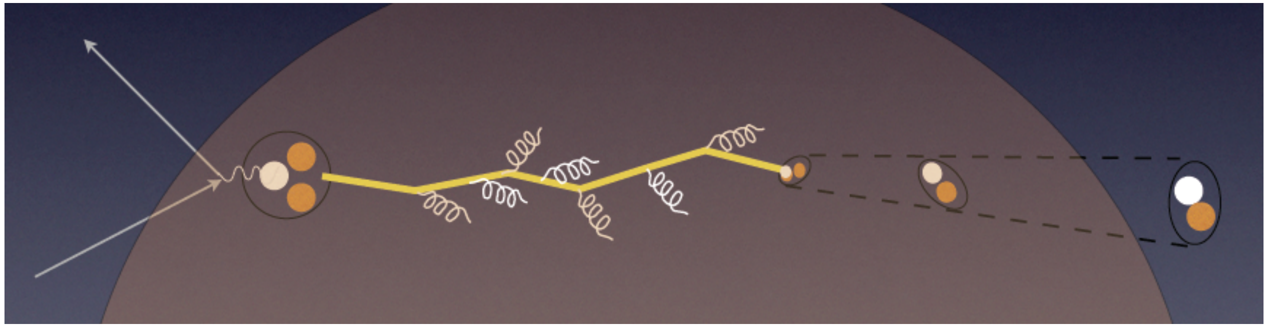
In-medium Hadronisation

The study of particle production in eA (fragmentation functions and hadrochemistry) allows the study of the space-time picture of hadronisation (the final phase of QGP).

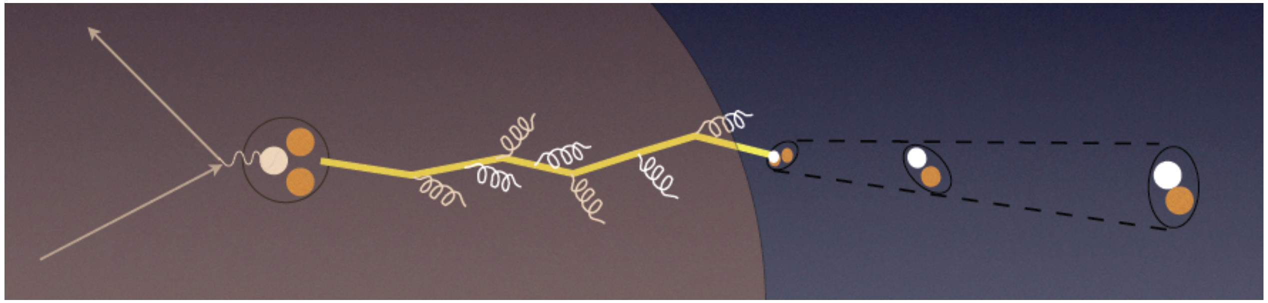
Low energy (ν): need of hadronization inside.

Parton propagation: pt broadening

Hadron formation: attenuation



High energy (ν): partonic evolution altered in the nuclear medium.



W.Brooks, Divonne09

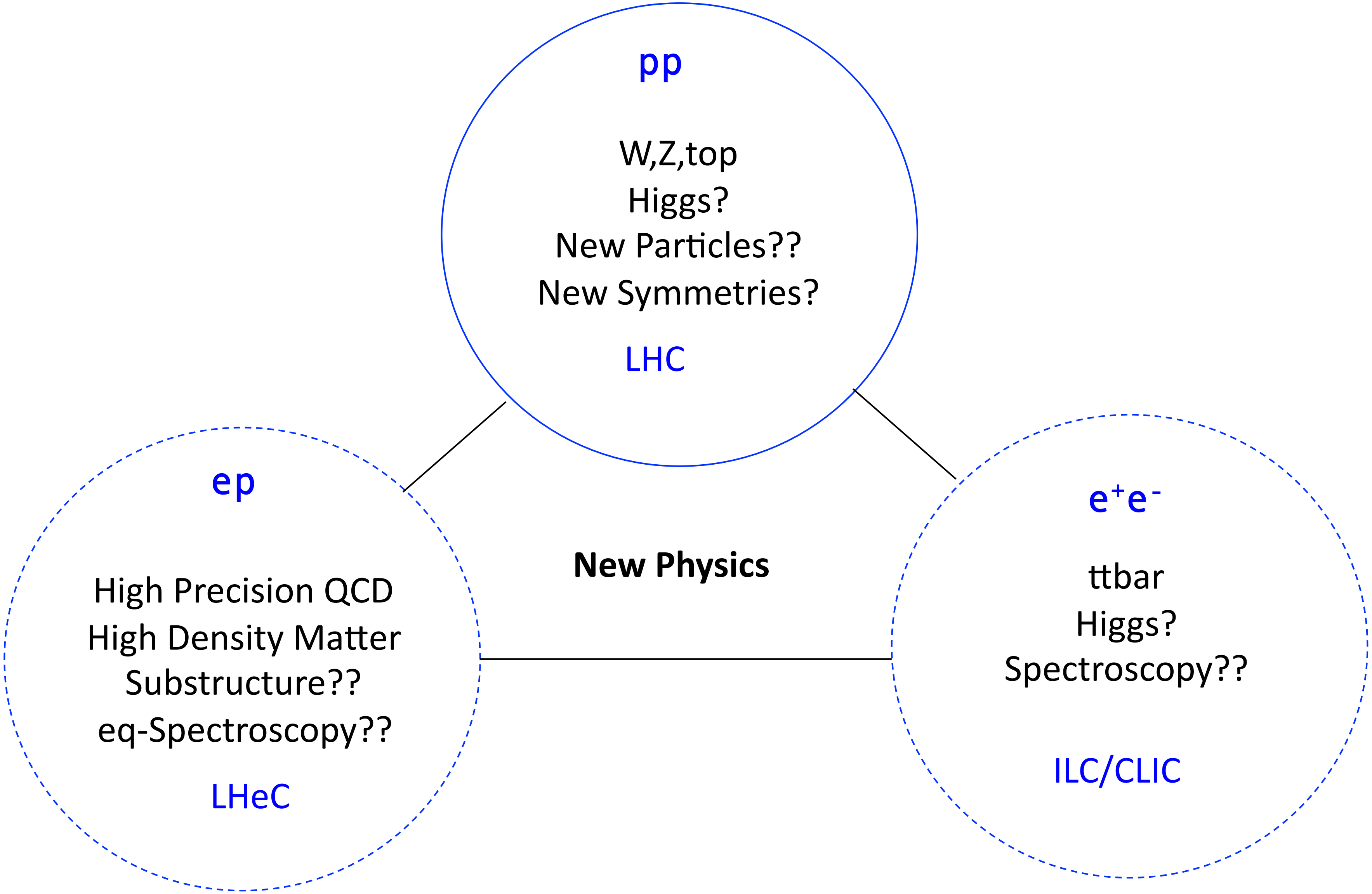
LHeC :

+ study the transition from small to high energies in hugely extended range wrt. fixed target data

+ test of the energy loss mechanism crucial for understanding of the medium produced in HIC

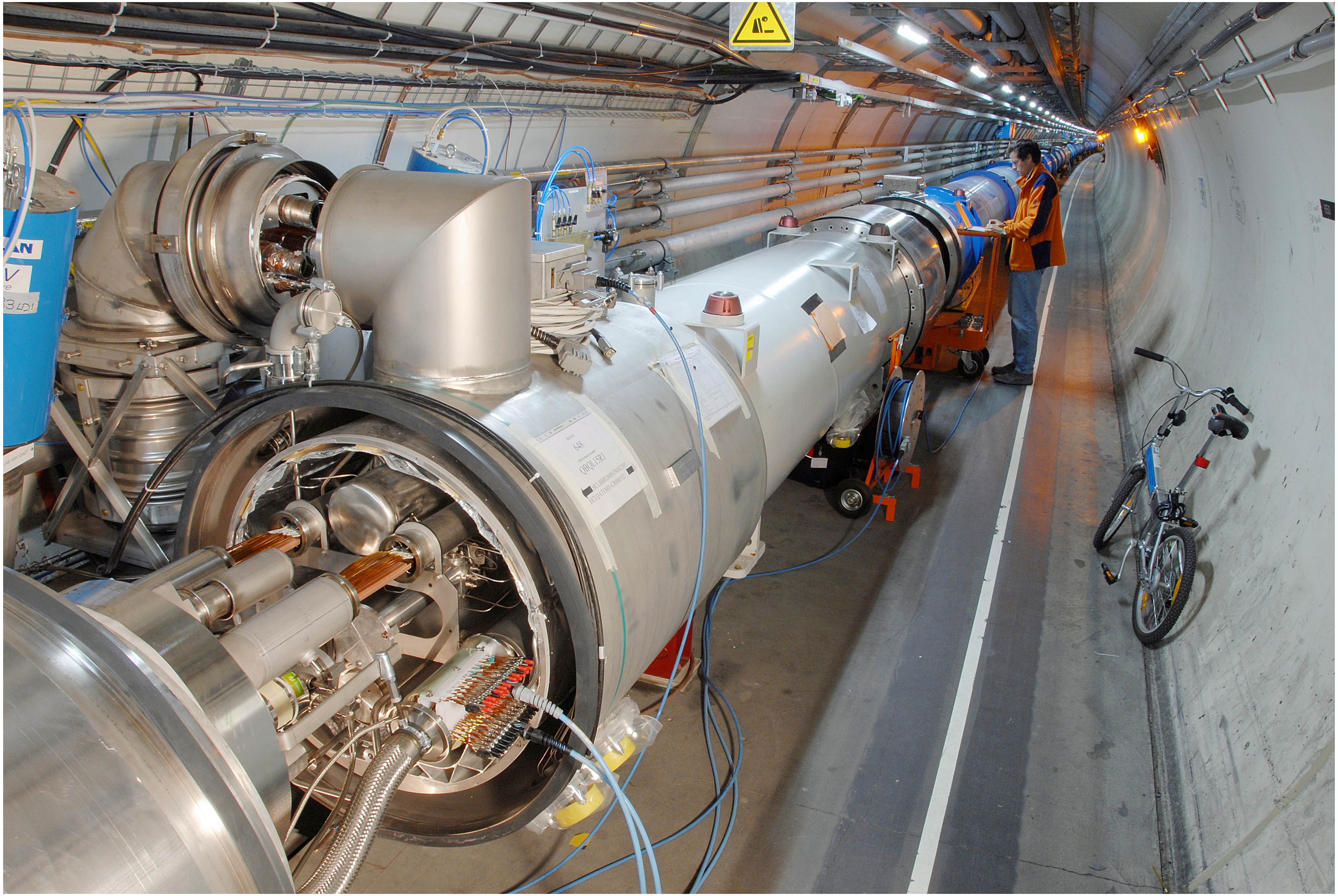
+ detailed study of heavy quark hadronisation …

The TeV Scale [2010-2035..]



Accelerator and Detector

How can we use the LHC for ep/A?



S.Russenschuck

e Ring- p/A Ring – “RR”

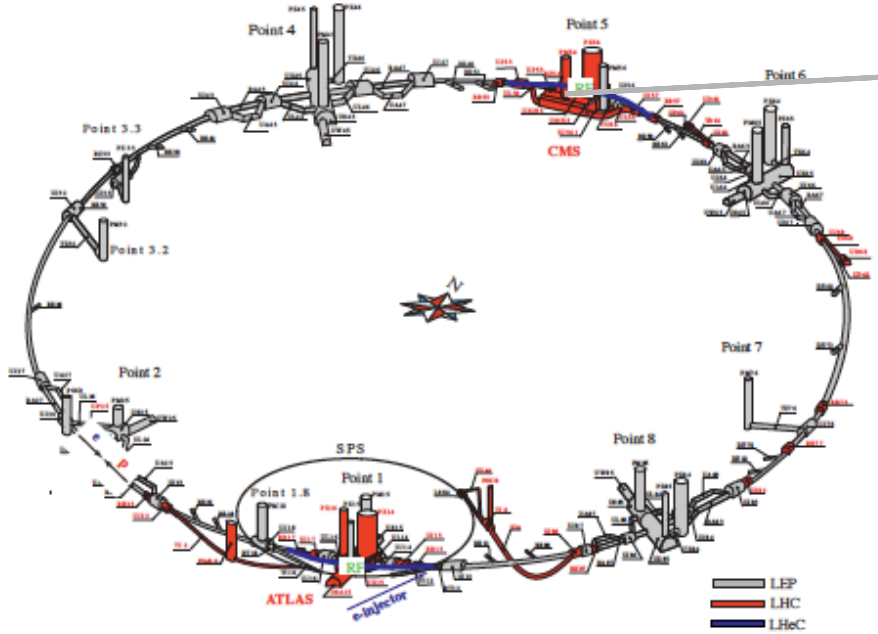
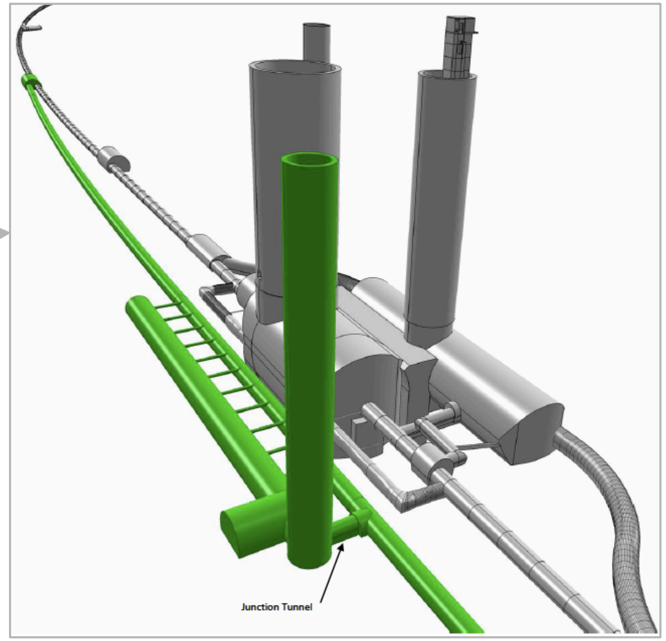
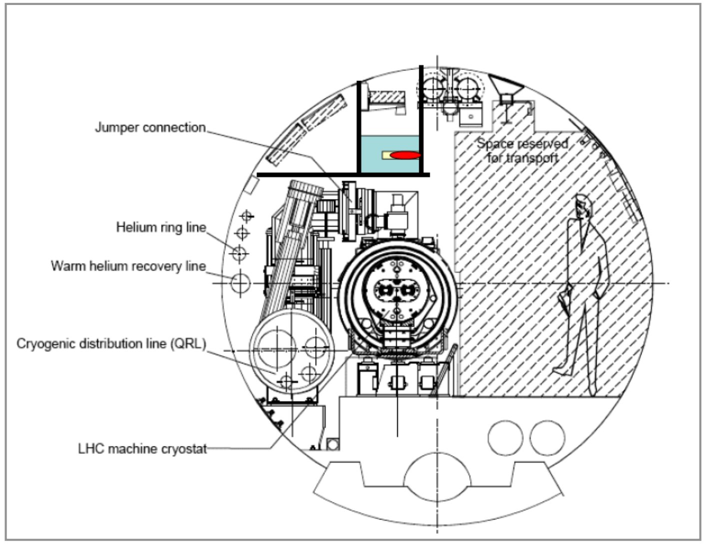
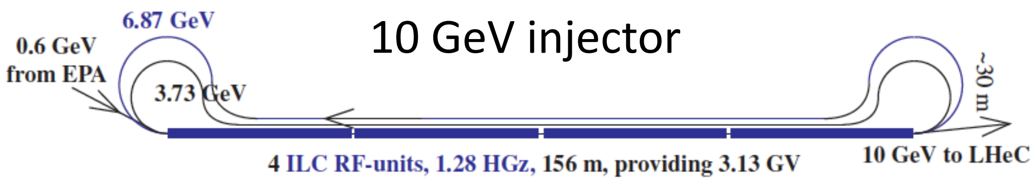


Figure 1: Schematic Layout of the LHC (grey/red) with the bypasses of CMS and ATLAS for the ring electron beam (blue) in the RR version. The e injector is a 10 GeV super-conducting linac in triple racetrack configuration which is considered to reach the ring via the bypass around ATLAS.





10 GeV injector



10 GeV injection: dipoles with low field and 10^{-4} reproducability

Magnets

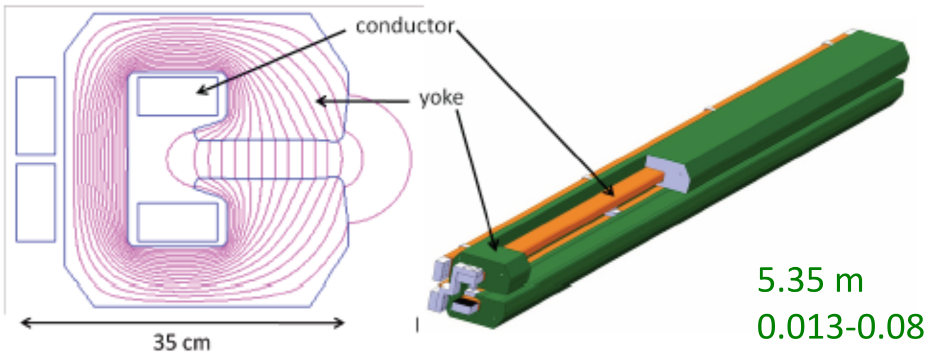
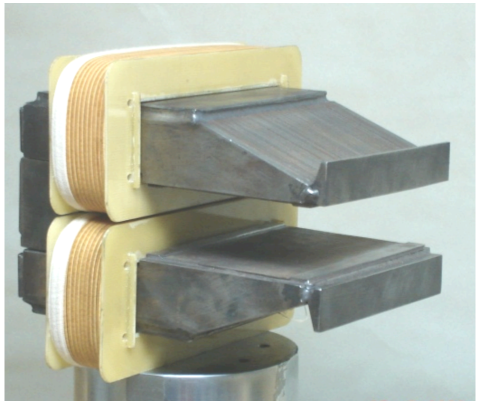


Fig. 2. Field lines and artistic view of a LHeC arc dipole.

5.35 m
0.013-0.08 T
~200kg/m



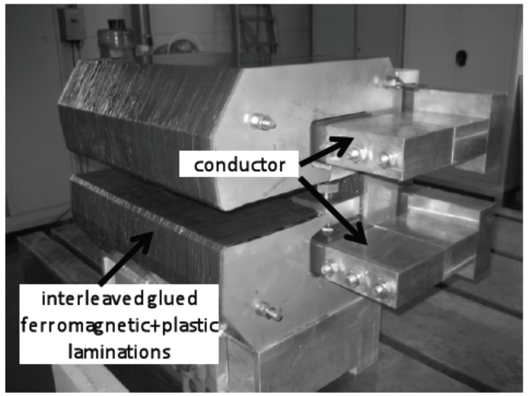
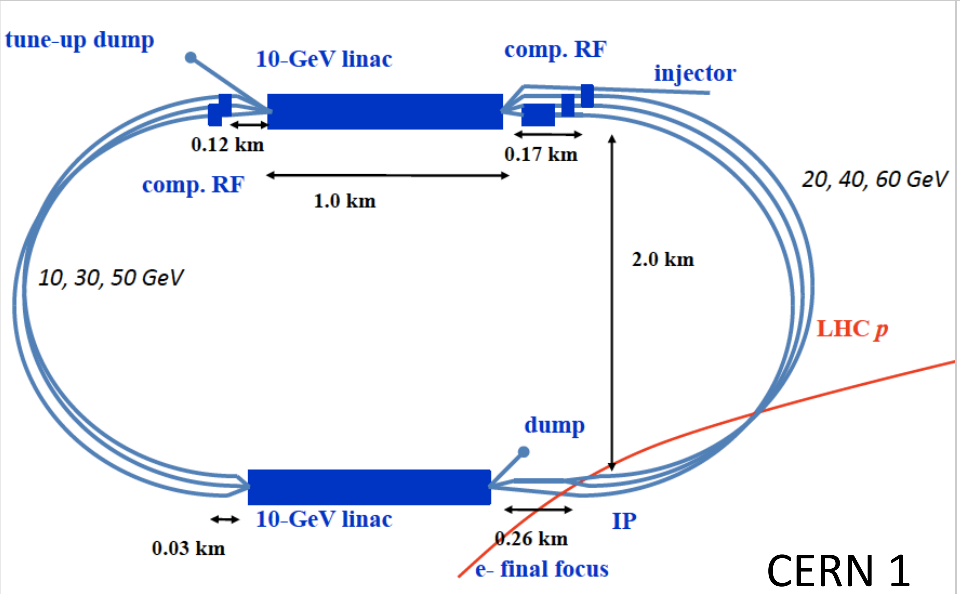


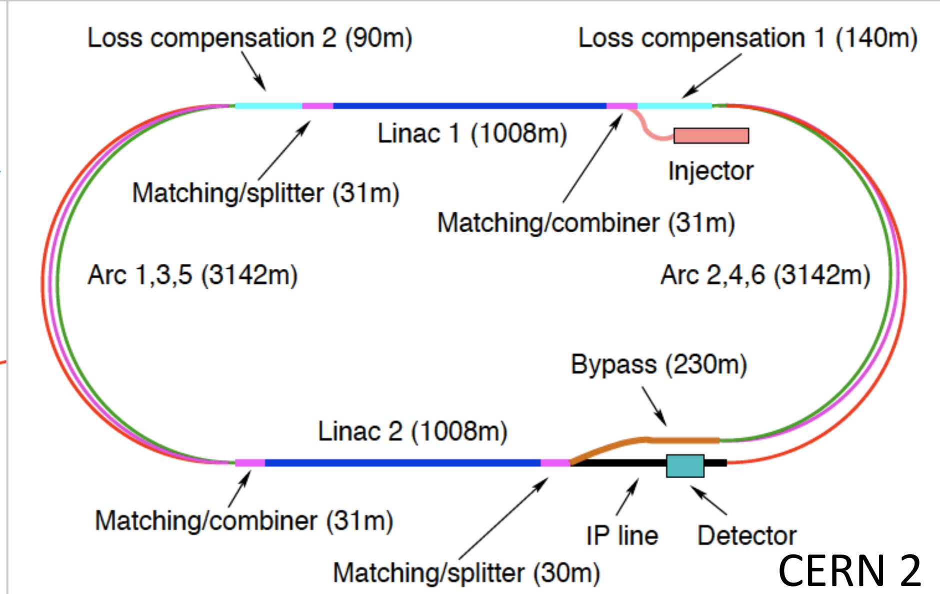
TABLE II REPRODUCIBILITY OF MAGNETIC FIELD OVER 8 CYCLES

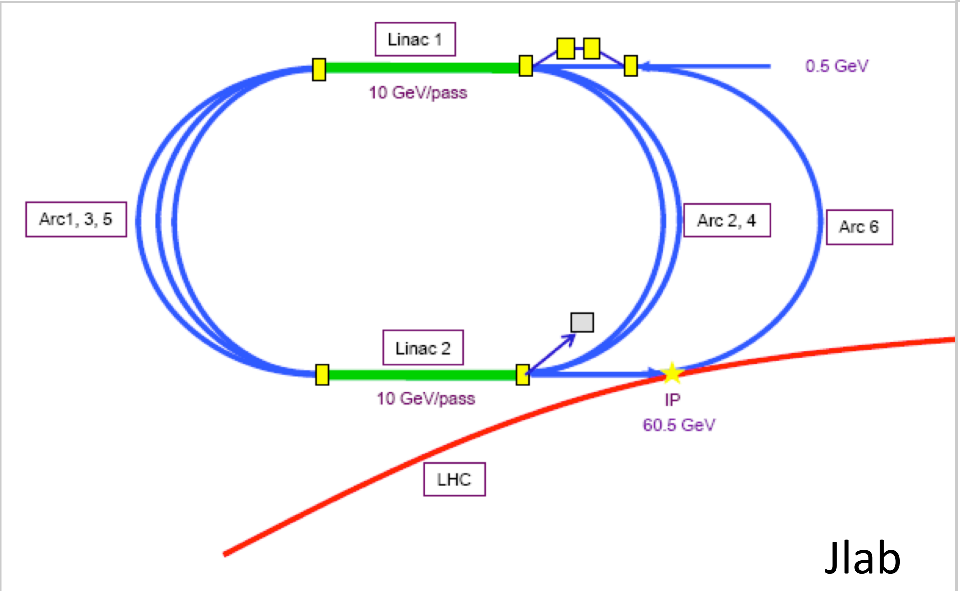
Model	Low field	High fields
Maximum Relative Deviation from Average		
Model 1 (NiFe steel)	$5\cdot10^{-5}$	$4\cdot10^{-5}$
Model 2 (Low carbon steel)	$6\cdot10^{-5}$	$6\cdot10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$4\cdot10^{-5}$	$6\cdot10^{-5}$
Standard Deviation from Average		
Model 1 (NiFe steel)	$3\cdot10^{-5}$	$3\cdot10^{-5}$
Model 2 (Low carbon steel)	$4\cdot10^{-5}$	$5\cdot10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$2\cdot10^{-5}$	$4\cdot10^{-5}$

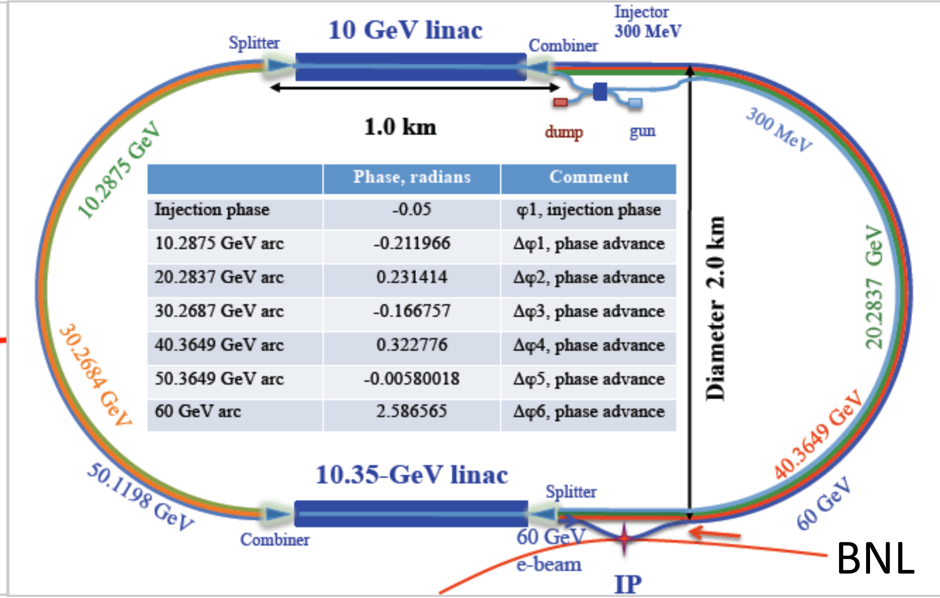
Prototypes from BINP and CERN: function to spec's

60 GeV Energy Recovery Linac









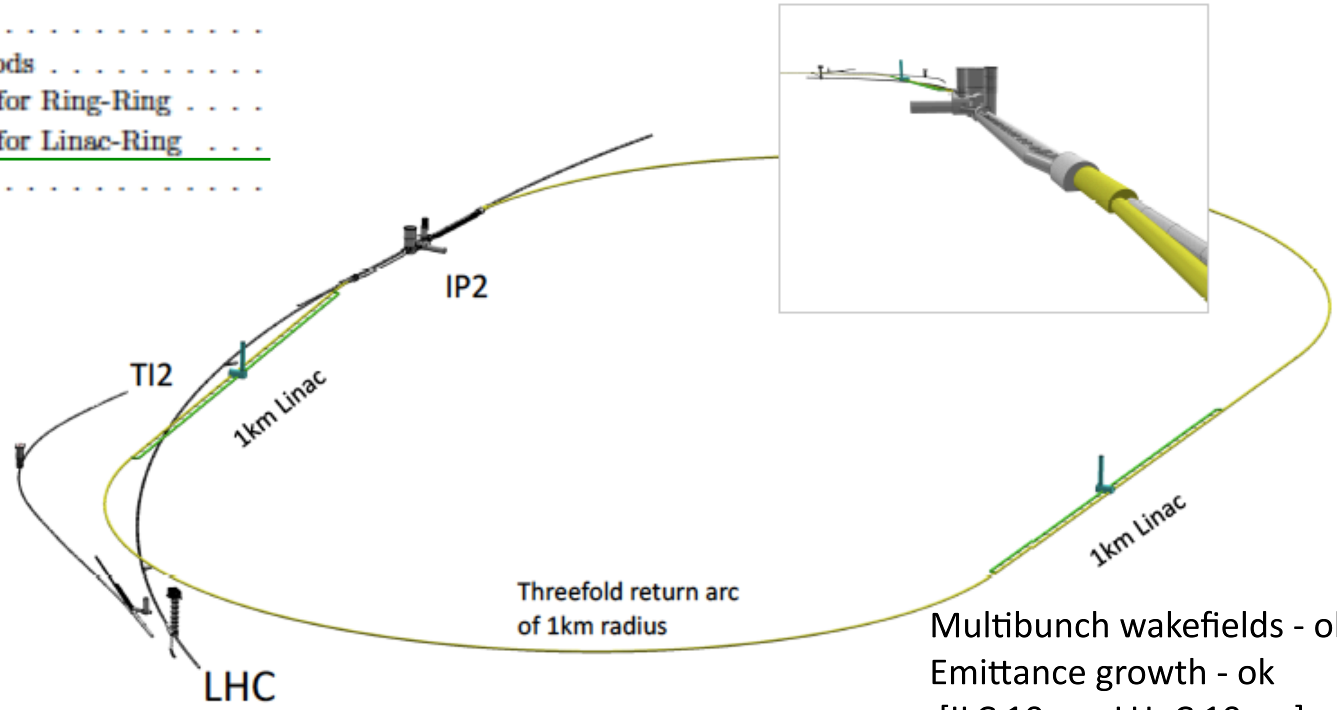
	Phase, radians	Comment
Injection phase	-0.05	φ1, injection phase
10.2875 GeV arc	-0.211966	Δφ1, phase advance
20.2837 GeV arc	0.231414	Δφ2, phase advance
30.2687 GeV arc	-0.166757	Δφ3, phase advance
40.3649 GeV arc	0.322776	Δφ4, phase advance
50.3649 GeV arc	-0.00580018	Δφ5, phase advance
60 GeV arc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

Two 10 GeV energy recovery Linacs, 3 returns, 720 MHz cavities

Linac Infrastructure

10 Civil Engineering and Services

$U_{LHeC}=U_{LHC}/3$: 1.5 x HERA



944 cavities
59 cryo modules per linac
721 MHz
20 MV/m CW

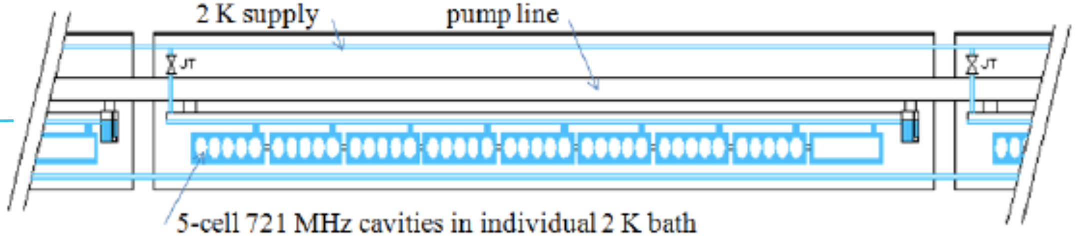
Multibunch wakefields - ok
Emittance growth - ok
[ILC 10nm, LHeC 10µm]
36σ separation at 3.5m - ok
Fast ion instability - probably ok
with clearing gap (1/3)

Figure 10.11: View on the ERL placed inside the LHC ring and tangential to IP2. TI2 is the injection line into the LHC. The insert shows the view towards IP2, which currently houses the ALICE experiment, from the direction of the protons colliding with the electron beam incoming from behind.

Cryogenics

Table 2: Components of the Electron Accelerators

	Ring	Linac
magnets		
beam energy	60 GeV	
number of dipoles	3080	3600
dipole field [T]	0.013 – 0.076	0.046 – 0.264
total nr of quads	866	1588
RF and cryogenics		
number of cavities	112	944
gradient [MV/m]	11.9	20
RF power [MW]	49	39
cavity voltage [MV]	5	21.2
cavity R/Q [Ω]	114	285
cavity Q_0	–	$2.5\ 10^{10}$
cooling power [kW]	5.4@4.2 K	30@2 K



systems will consist of a complex task. Further cavities and cryomodules will require a limited R&D program. From this we expect improved quality factors with respect to today's state of the art. The cryogenics of the L-R version consists of a formidable engineering challenge, however, it is feasible and, CERN disposes of the respective know-how.

from CDR LHeC

Table 1: Parameters of the RR and RL configurations.

	Ring	**Linac**
electron beam		
beam energy E_e	60 GeV	
e^- (e^+) per bunch N_e [10^9]	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	10	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.58, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	131	6.6
energy recovery intensity gain	–	17
total wall plug power	100 MW	
syn rad power [kW]	51	49
critical energy [keV]	163	718
proton beam		
beam energy E_p	7 TeV	
protons per bunch N_p	$1.7 \cdot 10^{11}$	
transverse emittance $\gamma\epsilon^p_{x,y}$	3.75 μm	
collider		
Lum e^-p (e^+p) [10^{32}cm^{-2}s^{-1}]	9 (9)	10 (1)
bunch spacing	25 ns	
rms beam spot size $\sigma_{x,y}$ [μm]	30, 16	7
crossing angle θ [mrad]	1	0
$L_{eN} = A\, L_{eA}$ [10^{32}cm^{-2}s^{-1}]	0.3	1

M.Klein at IPAC11

Linac has real
γ beam option

Proton beam parameters:
E_p perhaps 6.5 TeV
N_p almost achieved
ε_p already lower in 2011

Both the ring and the linac are feasible and both come very close to the desired performance.
The decision is essentially taken for the linac.

LHeC Accelerator Design: Participating Institutes

CERN

SLAC
NATIONAL ACCELERATOR LABORATORY

NTNU
Norwegian University of Science and Technology

CLIC

The Cockcroft Institute
of Accelerator Science and Technology

Jefferson Lab
Thomas Jefferson National Accelerator Facility

ANKARA ÜNİVERSİTESİ

NİĞDE ÜNİVERSİTESİ 1992

ULUDAĞ ÜNİVERSİTESİ 1975

TOBB ETU

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

DESY

LAL Physique des accélérateurs

ECFA

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

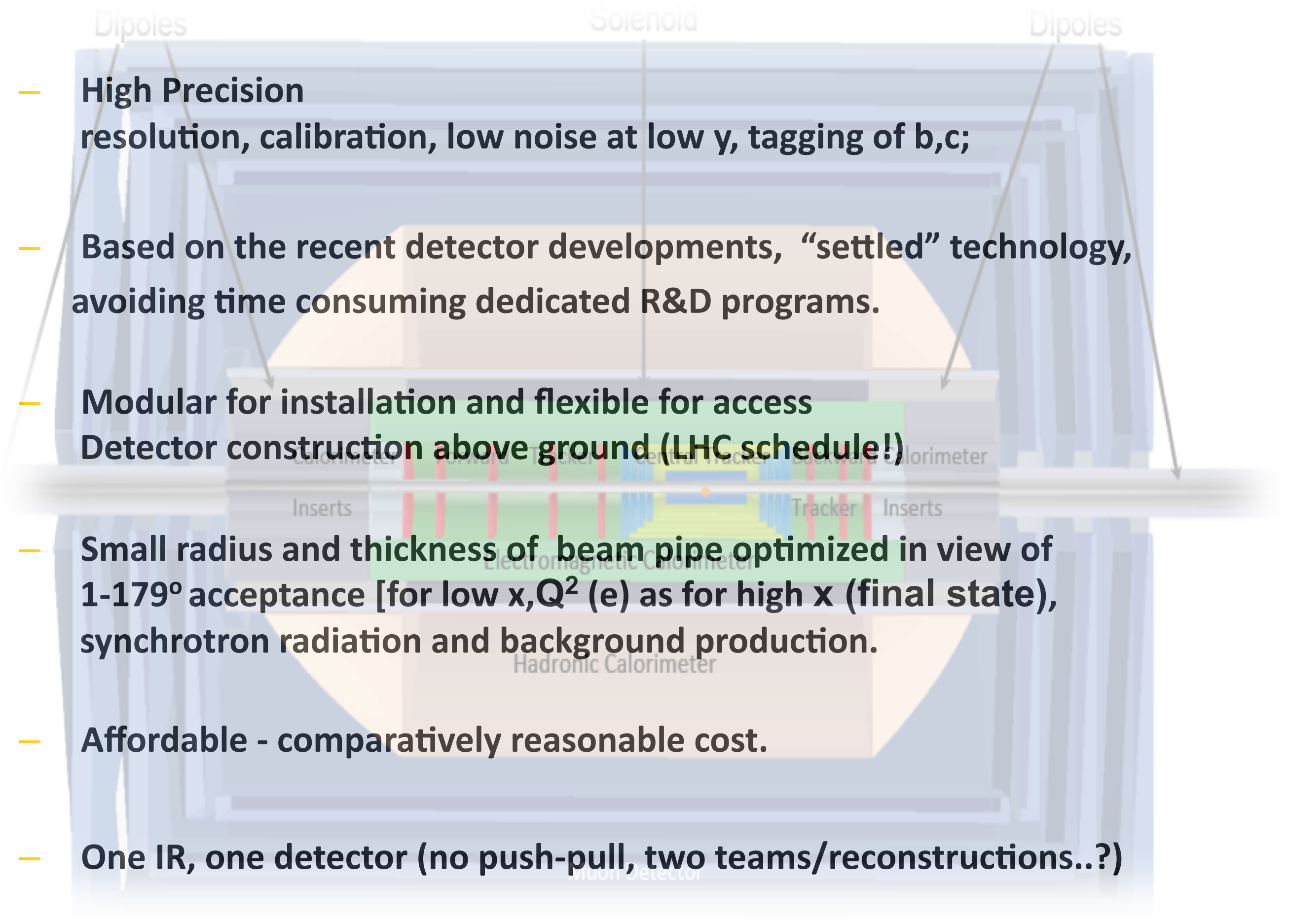
UNIVERSITY OF LIVERPOOL

BROOKHAVEN
NATIONAL LABORATORY

СИБИРСКОЕ ОТДЕЛЕНИЕ РАН
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
им. Г.И.Будкера
630090 Новосибирск

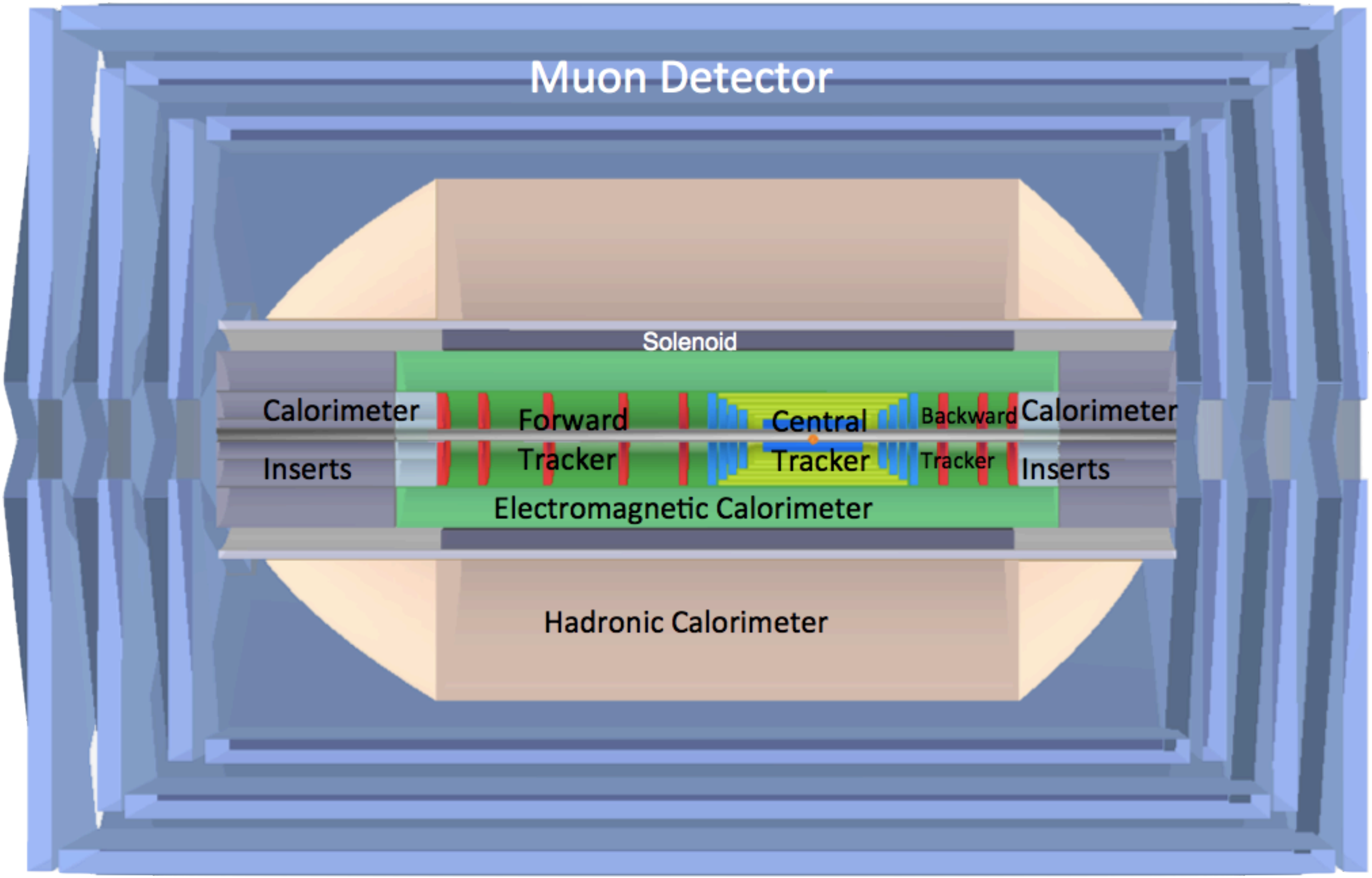
KEK

Detector Requirements



- **High Precision**
  resolution, calibration, low noise at low y, tagging of b,c;
- **Based on the recent detector developments, "settled" technology, avoiding time consuming dedicated R&D programs.**
- **Modular for installation and flexible for access**
  Detector construction above ground (LHC schedule!)
- **Small radius and thickness of beam pipe optimized in view of 1-179° acceptance [for low x,Q^2 (e) as for high x (final state), synchrotron radiation and background production.**
- **Affordable - comparatively reasonable cost.**
- **One IR, one detector (no push-pull, two teams/reconstructions..?)**

LHeC Detector Overview



Detector option 1 for LR and full acceptance coverage

Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =14x9m² [CMS 21 x 15m², ATLAS 45 x 25 m²]
Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

Silicon Tracker and EM Calorimeter

Transverse momentum
$\Delta p_t/p^2_t \rightarrow 6\ 10^{-4}\ GeV^{-1}$
transverse
impact parameter
$\rightarrow$ 10μm

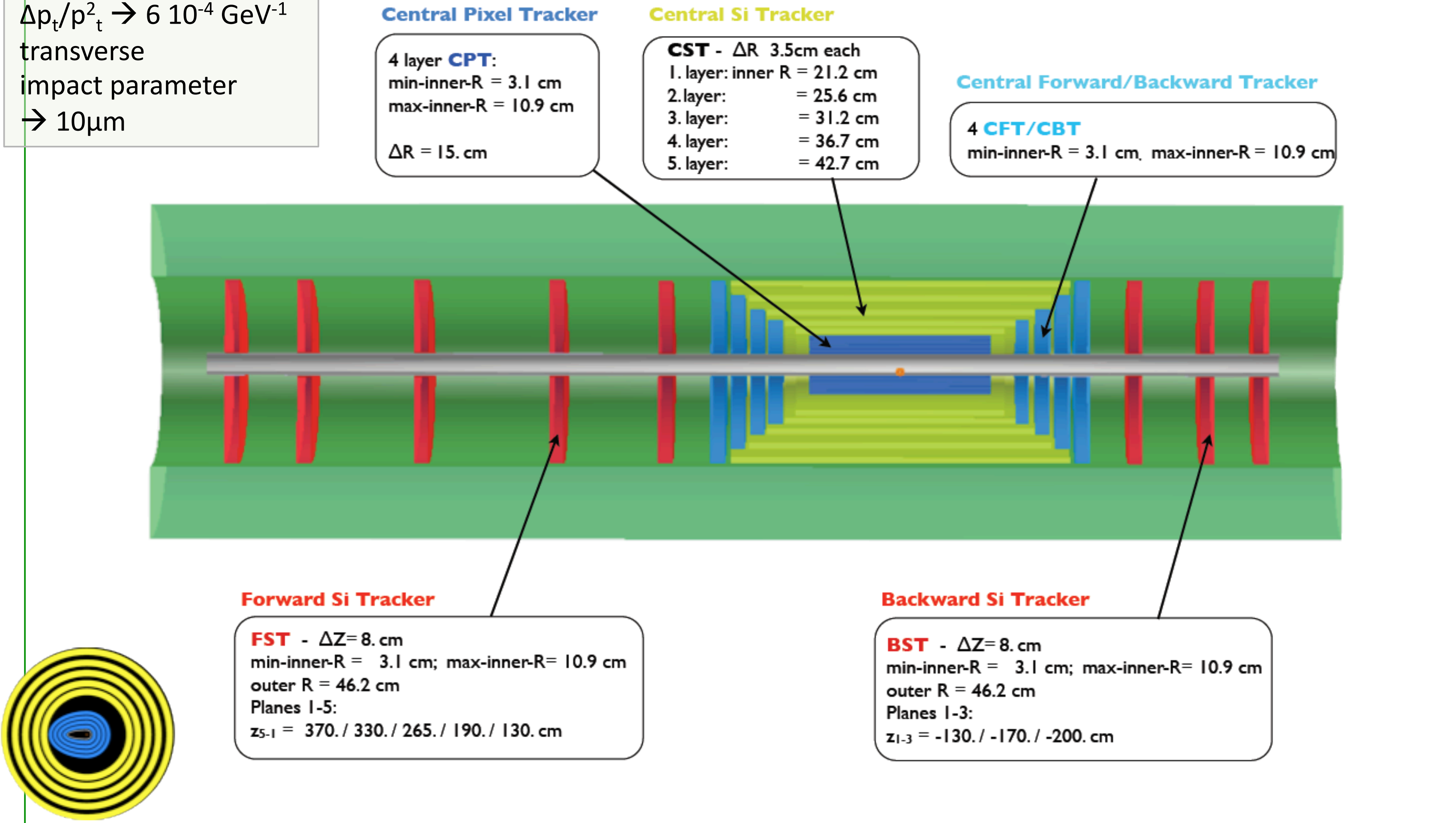


Figure 13.18: Tracker and barrel Electromagnetic-Calorimeter rz view of the baseline detector (Linac-Ring case).

Liquid Argon Electromagnetic Calorimeter

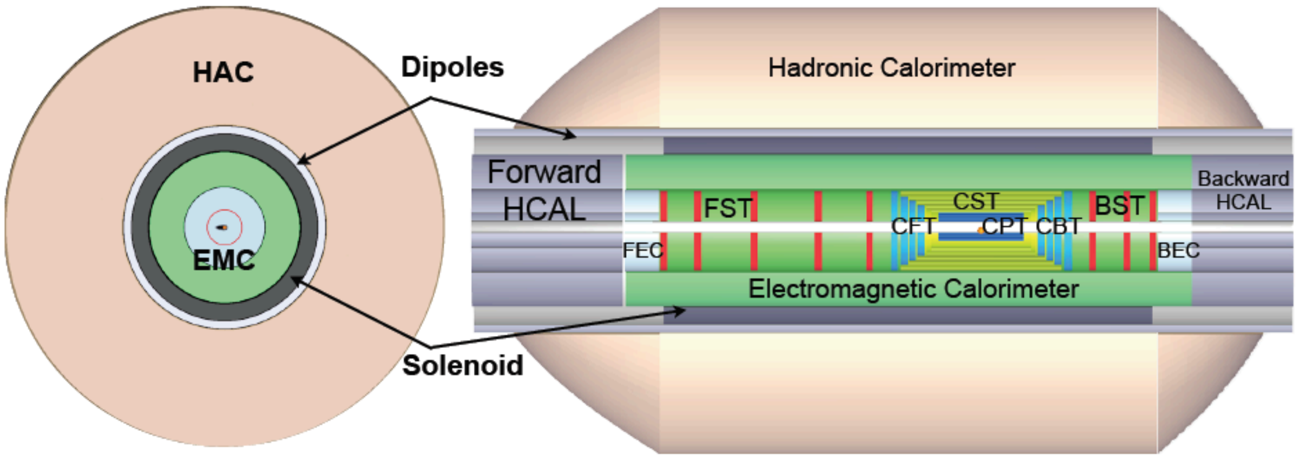


Figure 13.30: x-y and r-z view of the LHeC Barrel EM calorimeter (green).

Inside Coil
H1, ATLAS experience.

Barrel: Pb, 20 X_0 , 11m^3

fwd/bwd inserts:

FEC: Si -W, 30 X_0 ,0.3m^3

BEC: Si -Pb, 25 X_0,0.3m^3

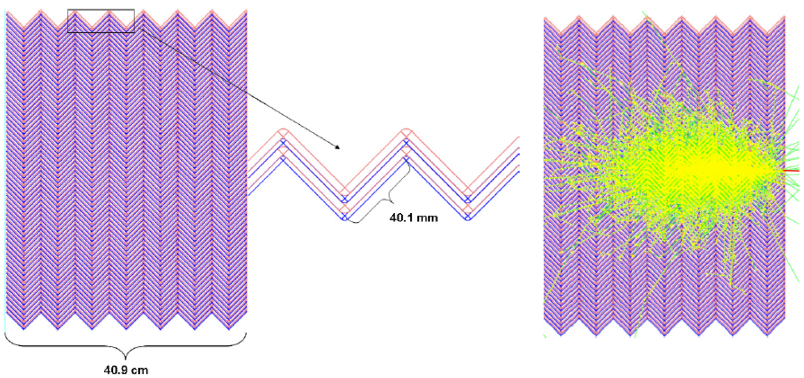


Figure 13.35: View of the parallel geometry accordion calorimeter (left) and simulation of a single electron shower with initial energy of 20 GeV (right).

GEANT4 Simulation

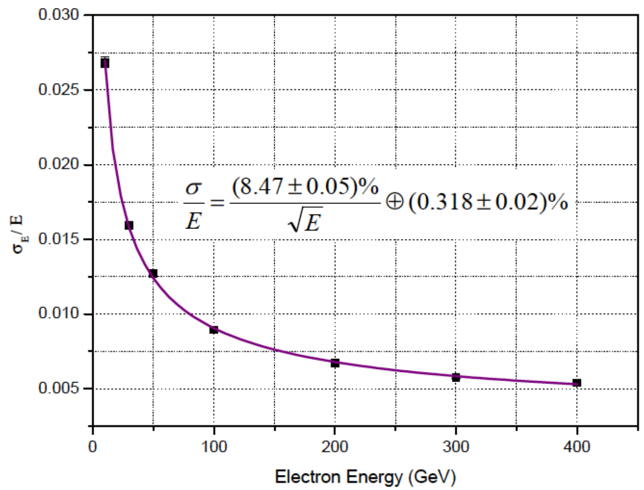
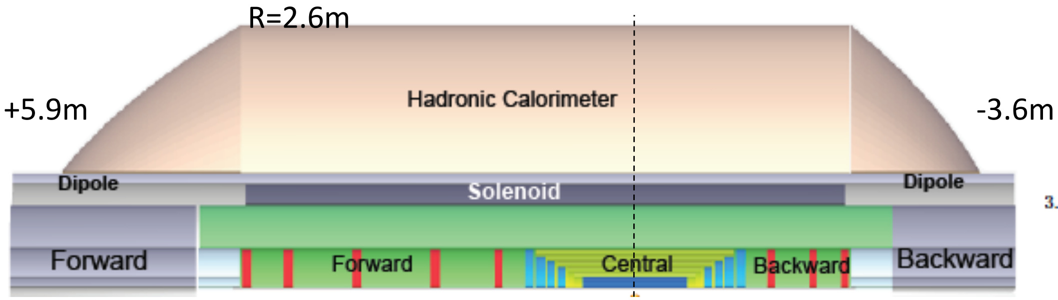


Figure 13.36: LAr accordion calorimeter energy resolution for electrons between 10 and 400 GeV.

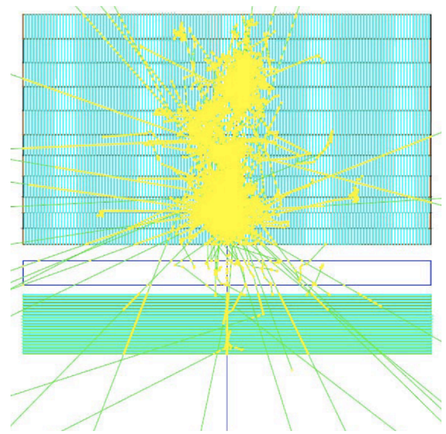
Hadronic Tile Calorimeter

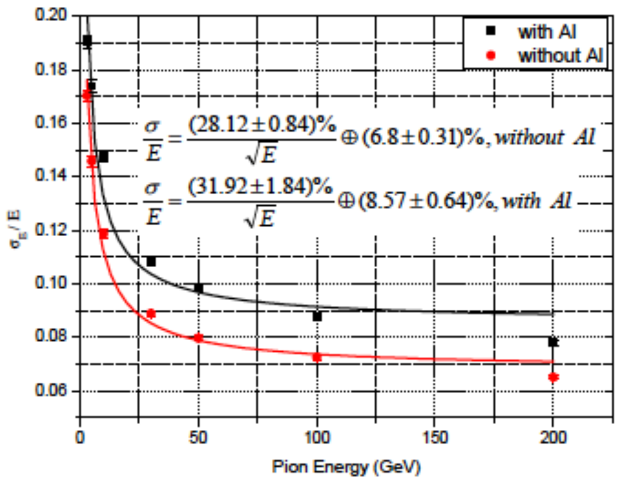
E-Calo Parts	FEC1	FEC2		EMC		BEC2	BEC1
Min. Inner radius R [cm]	3.1	21		48		21	3.1
Min. polar angle θ [°]	0.48	3.2		6.6/168.9		174.2	179.1
Max. pseudorapidity η	5.5	3.6		2.8/-2.3		-3.	-4.8
Outer radius [cm]	20	46		88		46	20
z-length [cm]	40	40		660		40	40
Volume [m^3]	0.3			11.3		0.3	
H-Calo Parts barrel			FHC4	HAC	BHC4		
Inner radius [cm]			120	120	120		
Outer radius [cm]			260	260	260		
z-length [cm]			217	580	157		
Volume [m^3]				121.2			
H-Calo Parts Inserts	FHC1	FHC2	FHC3		BHC3	BHC2	BHC1
Min. inner radius R [cm]	11	21	48		48	21	11
Min. polar angle θ [°]	0.43	2.9	6.6		169.	175.2	179.3
Max/min pseudorapidity η	5.6	3.7	2.9		-2.4	-3.2	-5.
Outer radius [cm]	20	46	88		88	46	20
z-length [cm]	177	177	177		117	117	117
Volume [m^3]		4.2				2.8	

Table 13.6: Summary of calorimeter dimensions.
The electromagnetic barrel calorimeter is currently represented by the barrel part EMC (LAr-Pb module); the setup reaches $X_0 \approx 25$ radiation length) and the movable inserts forward FEC1, FEC2 (Si-W modules ($X_0 \approx 30$) and the backward BEC1, BEC2 (Si-Pb modules; $X_0 \approx 25$).
The hadronic barrel parts are represented by FHC4, HAC, BHC4 (forward, central and backward - Scintillator-Fe Tile modules; $\lambda_I \approx 8$ interaction length) and the movable inserts FHC1, FHC2, FHC3 (Si-W modules; $\lambda_I \approx 10$), BHC1, BHC2, BHC3 (Si-Cu modules, $\lambda_I \approx 8$) see Fig. 13.9.



Outside Coil: flux return
Modular. ATLAS experience.



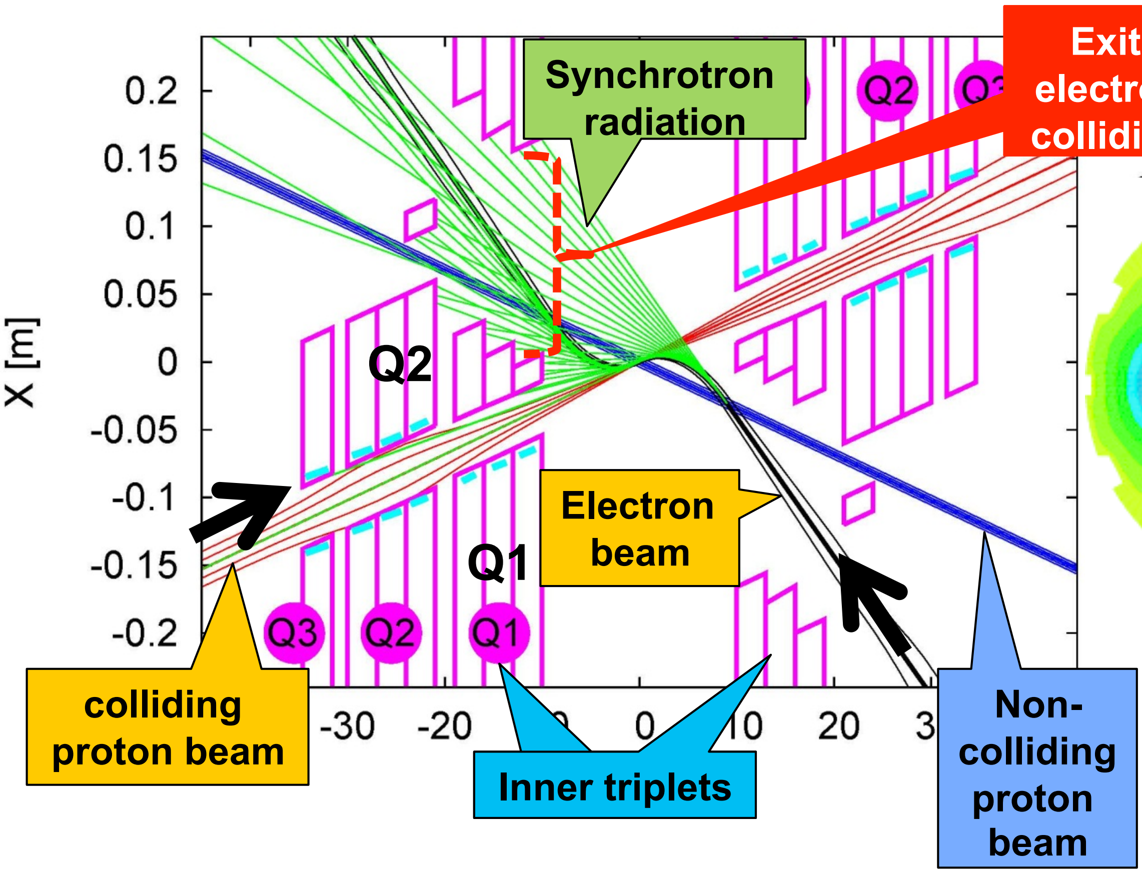


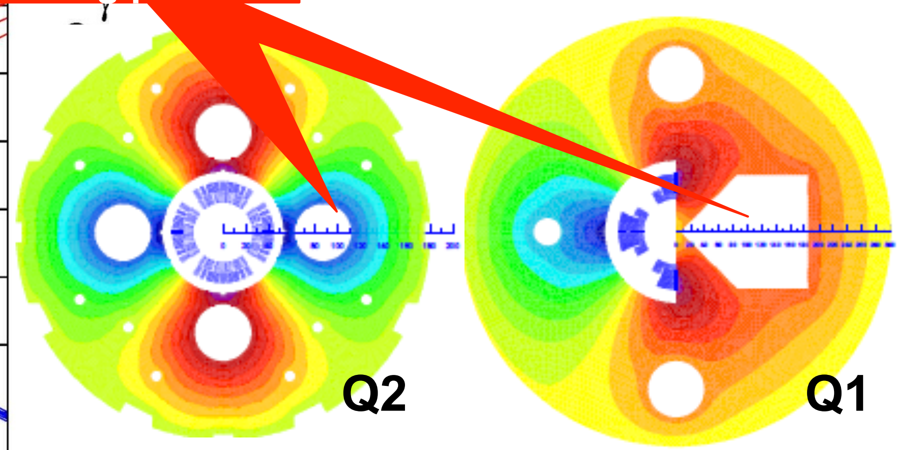
3.37: Accordion and Tile Calorimeter energy resolution for pions with and without 14cm Al block.

Combined GEANT4 Calorimeter Simulation

Some current+next steps

LR LHeC IR layout & SC IR quadrupoles





Nb_3Sn (HFM46): 5700 A, 175 T/m, 4.7 T at 82% on LL (4 layers), 4.2 K	Nb_3Sn (HFM46): 8600 A, 311 T/m, at 83% LL, 4.2 K
46 mm (half) ap., 63 mm beam sep.	23 mm ap.. 87 mm beam sep.
0.5 T, 25 T/m	0.09 T, 9 T/m

High-gradient SC IR quadrupoles based on Nb_3Sn for colliding proton beam with common low-field

As shown by F. Zimmermann at Chamonix12

L.Bottura
Chamonix 2/12
on Magnet R+D
for LHeC + HE-LHC

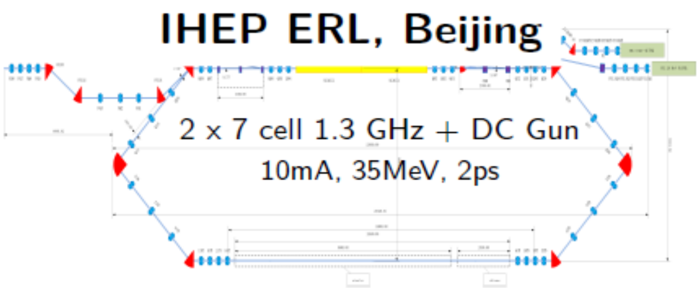
Magnet Development at CERN

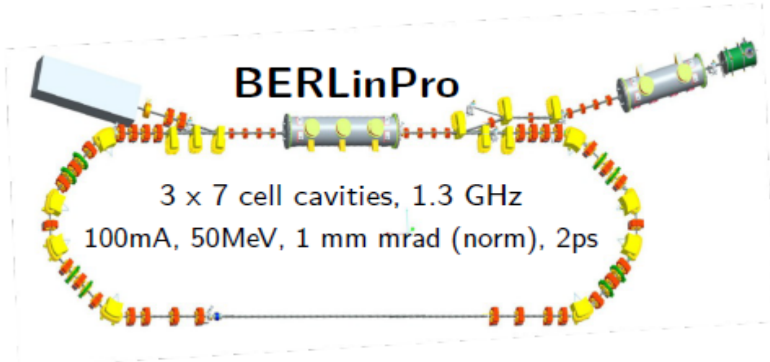
			LHeC RR dipole prototype	CRISP and fast cycled SC magnets	MQXC R&D	EuCARD FReSCa-II	DS 11 T MB program	US-LARP IR quadrupole program	EuCARD HTS insert	EuCARD2 HTS model	activated SC magnets handling for	Comments
LHeC	Low field resistive magnets	field quality and reproducibility	X									demonstrated
LHeC	Low field resistive magnets	operating cost		x								tests planned in 2012
LHeC	Low field resistive magnets	integration in the LHC tunnel									x	study launched in 2012 (LS1)
LHeC	IR magnets	large aperture			X			X				results in 2012…2014
LHeC	IR magnets	large gradient						X				
LHeC	IR magnets	heat removal		x	X							results in 2012
LHeC	co-activities and tunnel works										x	integration study and models (BINP); schedule revision
HE-LHC	Very high field magnets	15 T dipole outsert				X						deliverable Q1 2014
HE-LHC	Very high field magnets	5 T dipole insert							X	X		EuCARD2 proposal
HE-LHC	Very high field magnets	high gradient quadrupoles						X				US-LARP technology demonstration by 2014
HE-LHC	Very high field magnets	magnet protection				X	X	X				
HE-LHC	Very high field magnets	heat loads and removal			x	X						dedicated model tests
HE-LHC	Very high field magnets	field quality					X	X		X		
HE-LHC	Pulsed SC magnets	quench performance and margin		X								
HE-LHC	Pulsed SC magnets	low-loss cables		X								
HE-LHC	Transfer lines											options reviewed at HE-LHC workshop in Malta, 2010
HE-LHC	Material availability and cost					X	X	X	x	x		
HE-LHC	Installation in 2030										X	study launched in 2012 (LS1)

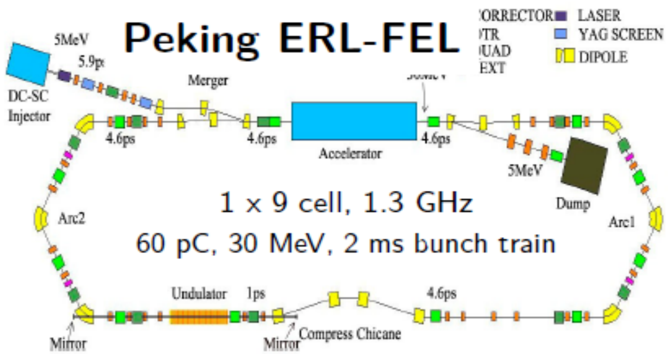
ERL Choice of frequency (Erk Jensen - Chamonix12)

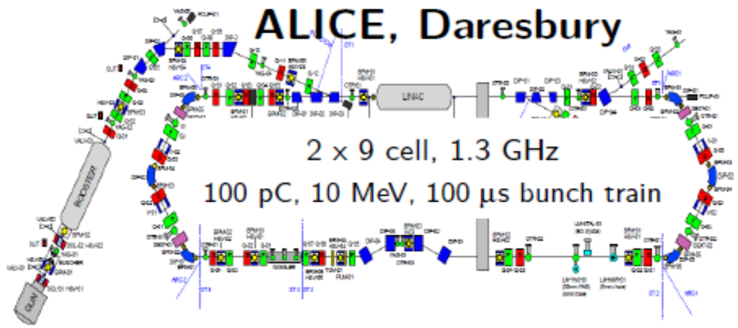
- The frequency has to be a harmonic of 20.04 MHz!
- LHeC baseline: 721.42 MHz, alternative 1322.6 MHz.
- **Advantages of lower frequency:**
  - Less cryo-power
  - High-power couplers easier
  - Less cells per cavity – less trapped modes
  - Less beam loading and transverse wake – better beam stability
  - Less HOM power
  - Synergy with SPL, e-RHIC and ESS.
- **Advantages of higher frequency:**
  - Larger R/Q → with same Q_{ext} less RF power (but Q_{ext} must be reduced!)
  - Synergy with ILC/X-FEL

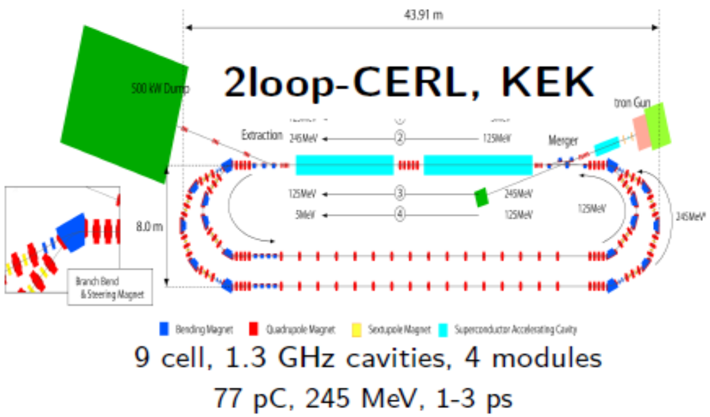
Collaboration on ERL

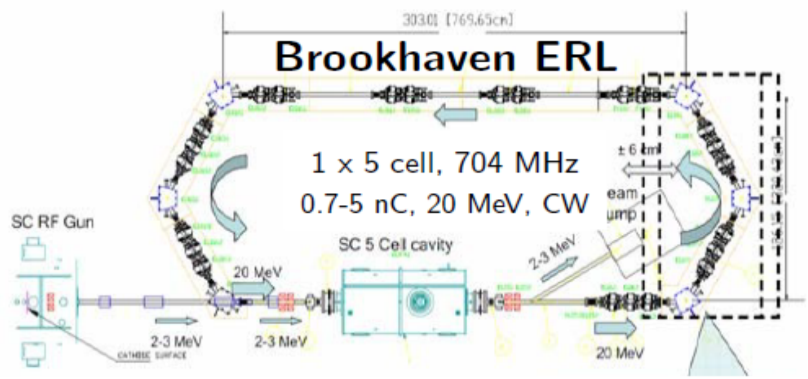






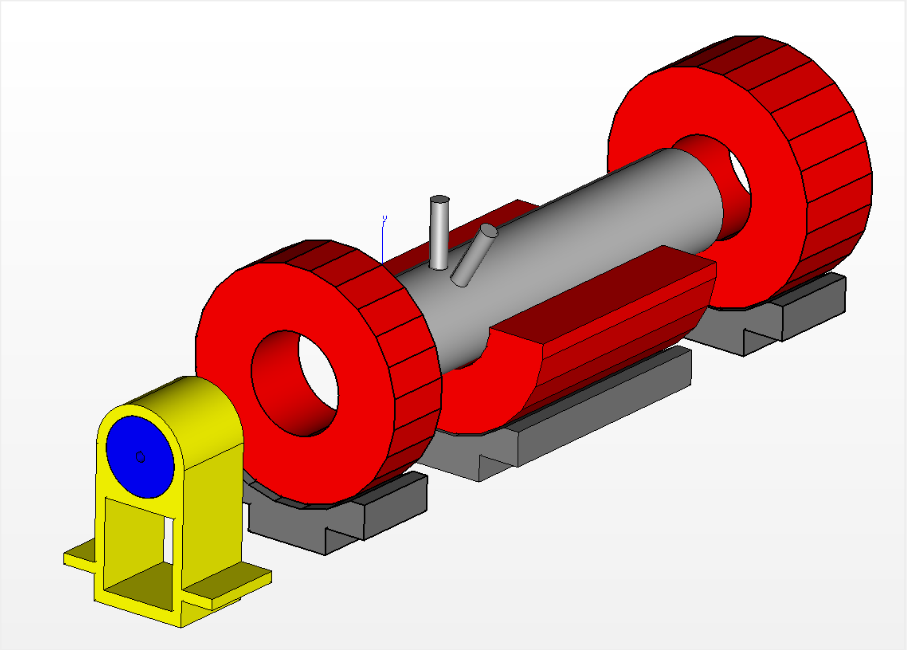


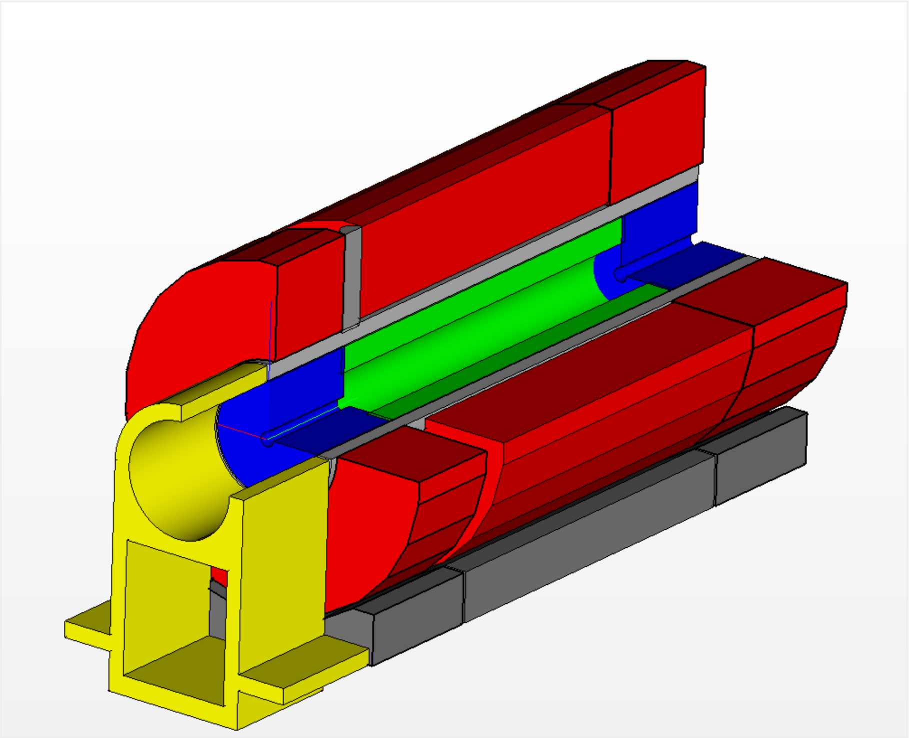


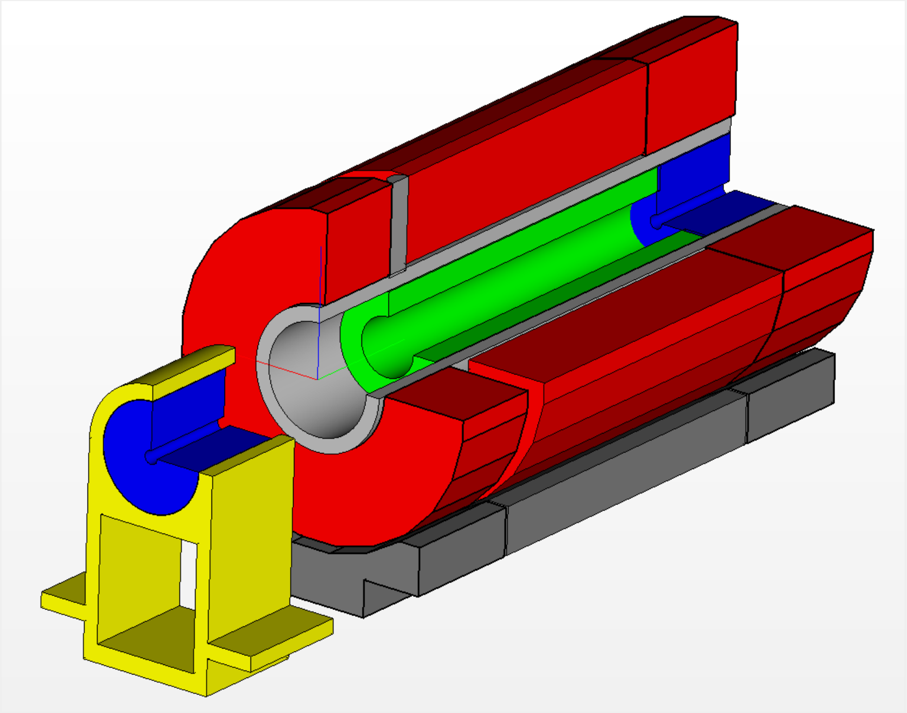


Budker Institute

Detector has to be pre-mounted on top of IP2, the hall be emptied, the detector lowered and to be mounted inside the L3 magnet barrel during the 2-3 years shutdown LS3







Study of Installation of the LHeC Detector [ongoing]   A.Gaddi, 7.5.2012

Concluding Remarks

The physics of deep inelastic scattering has been an essential part of HEP.

Major breakthroughs in (particle) physics are difficult to plan, despite certain "overconfidence of theorists" [Ledermann ICHEP 1980] in the past.

The LHeC has passed a major milestone with a refereed CDR, supported and monitored by CERN, ECFA and NuPECC, soon to be published.

The time schedule of the LHC is such that there is not more time than a decade+ for realising the LHeC. This requires to continue to be realistic.

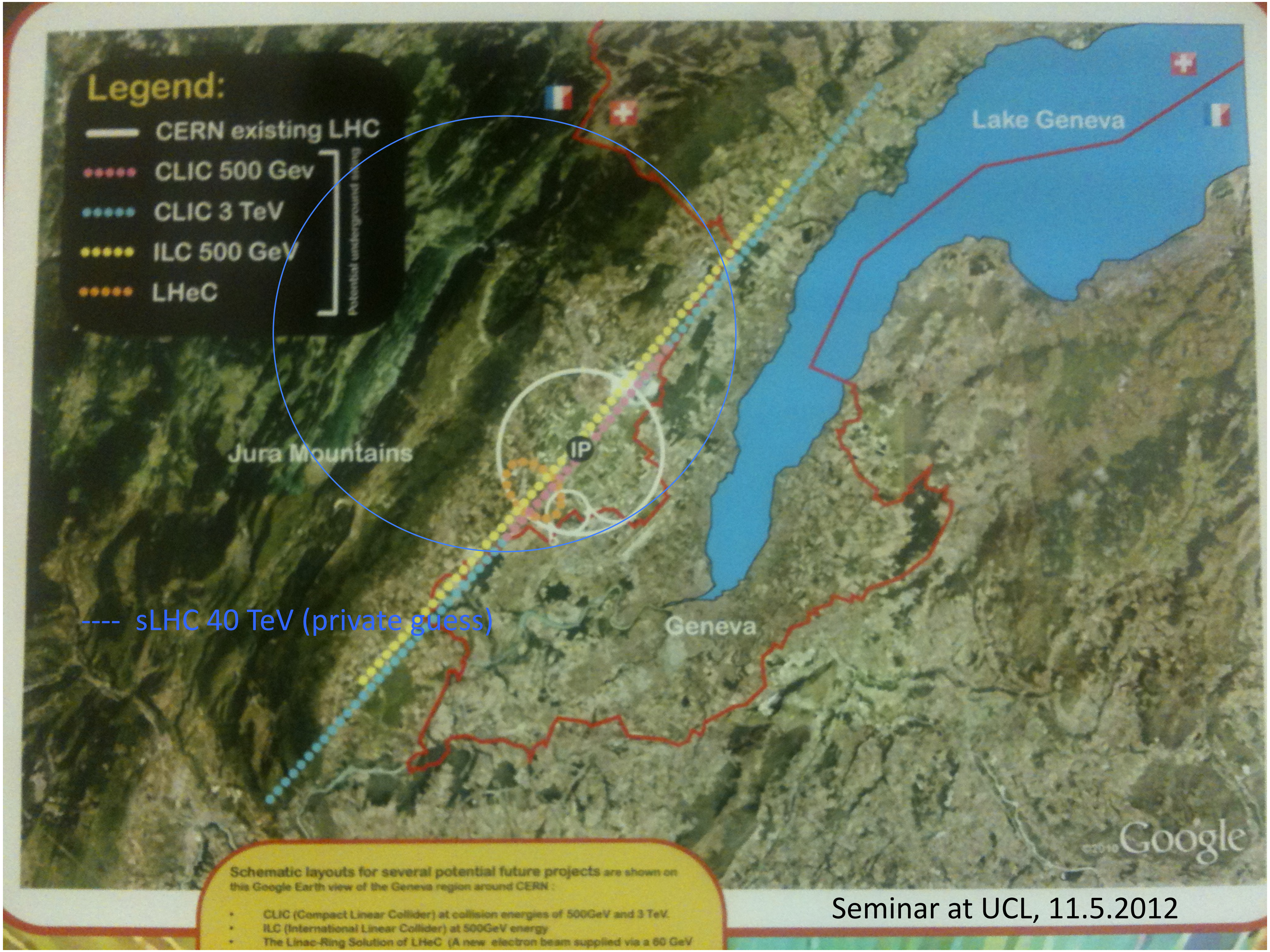
Collaborations are soon to be built for further design, of the machine and the detector. The experimental prospect challenges theory and requires to continue our intimate interaction with our thy colleagues.

A programme of technical and physics developments and a corresponding project structure are being developed, with the goal to enable a project decision by 2015 based on a technical design.

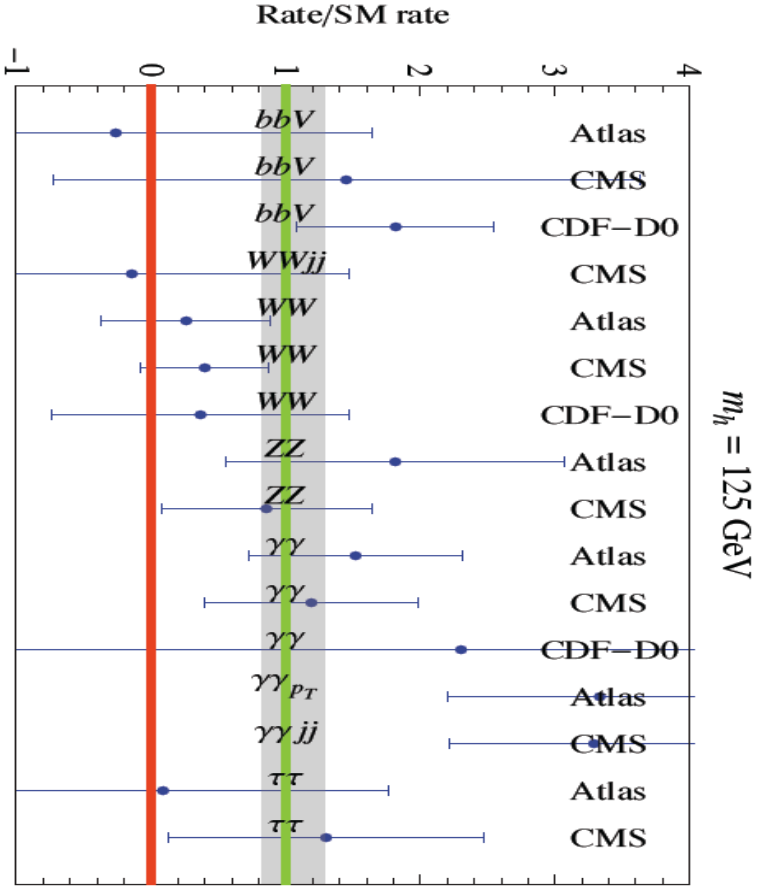
You are invited to join the workshop and so you wish the project too.

Next Workshop - Chavannes 14/15.6.2012

backup



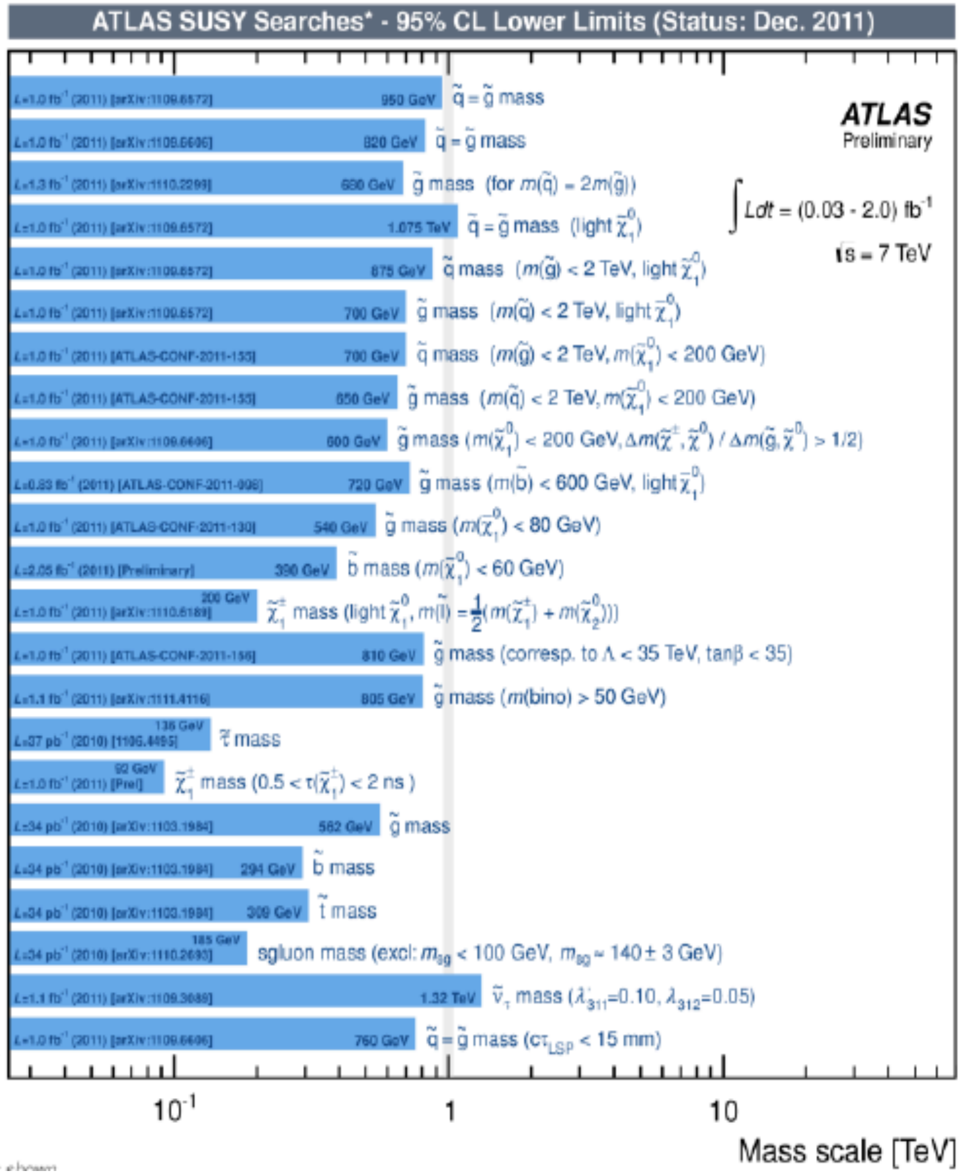
Legend:
CERN existing LHC
CLIC 500 Gev
CLIC 3 TeV
ILC 500 GeV
LHeC
Potential underground siting
Lake Geneva
Jura Mountains
IP
Geneva
---- sLHC 40 TeV (private guess)
©2010 Google
Schematic layouts for several potential future projects are shown on this Google Earth view of the Geneva region around CERN :
• CLIC (Compact Linear Collider) at collision energies of 500GeV and 3 TeV.
• ILC (International Linear Collider) at 500GeV energy
• The Linac-Ring Solution of LHeC (A new electron beam supplied via a 60 GeV



J.Gunion (CERN 27.3.2012)

LHC

Selected SUSY Search Results → 3rd generation?



CMS similar results

LHCb: $B_s \to \mu\ \mu\ < 4.5\ 10^{-9}$ SM$(3.2\pm0.2)\ 10^{-9}$

Technicolor ??

"We argue that the existence of fundamental scalar fields constitutes a serious flaw of the Weinberg-Salam theory…

L.Susskind, Dynamics of Spontaneous Symmetry Breaking in the Weinberg Salam Theory. Phys D20 (1979) 2619-2625

Dimopoulos,Susskind: Mass Without Scalars NP. B155 (1979) 237

What HERA could not do or has not done

HERA in one box
the first ep collider

$E_p * E_e =$
$920 * 27.6 GeV^2$
$\sqrt{s} = 2\sqrt{E_e E_p} = 320$ GeV

$L = 1..4\ 10^{31} cm^{-2} s^{-1}$
→ $\Sigma L = 0.5 fb^{-1}$
1992-2000 & 2003-2007

$Q^2 = [0.1 -- 3 * 10^4]\ GeV^2$
-4-momentum transfer^2

$x = Q^2/(sy) \cong 10^{-4}$ .. 0.7
Bjorken x

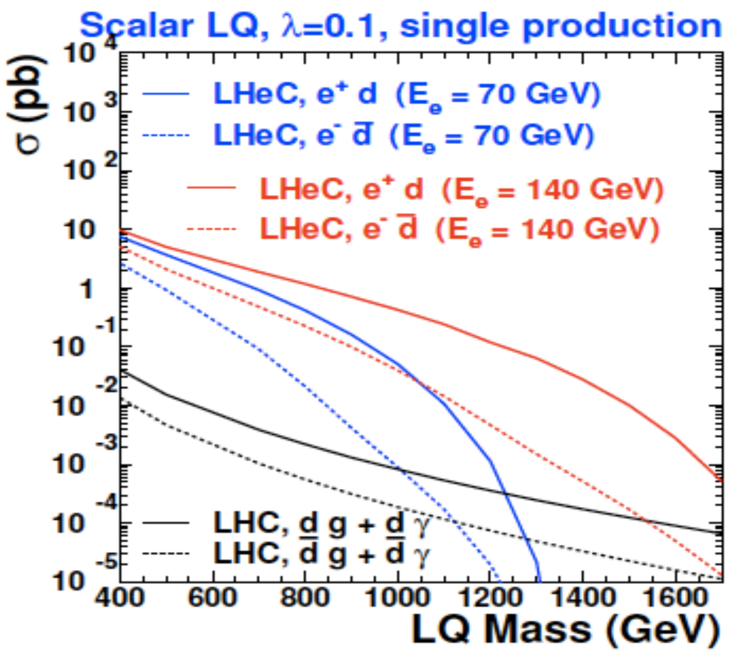
$y \cong 0.005$ .. 0.9
inelasticity

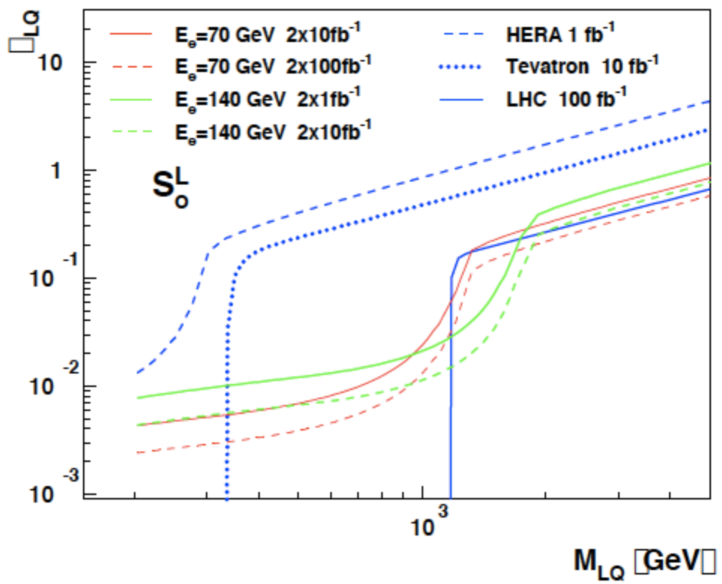
Test of **the isospin symmetry** (u-d) with eD - no deuterons
Investigation of the q-g dynamics in **nuclei** - no time for eA
Verification of **saturation** prediction at low x – too low s
Measurement of the **strange** quark distribution – too low L
Discovery of **Higgs** in WW fusion in CC – too low cross section
Study of **top** quark distribution in the proton – too low s
Precise measurement of $\mathbf{F_L}$ – 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 $\boldsymbol{\alpha_s}$ – overall not precise enough
Discovering **instantons, odderons** – don't know why not
Finding **RPV SUSY** and/or leptoquarks – may reside higher up
…

The H1 and ZEUS apparatus were basically well suited
The machine had too low luminosity and running time

HEP needs a TeV energy scale machine with 100 times higher luminosity than HERA to develop DIS physics further and to complement the physics at the LHC. The **Large Hadron Collider p and A beams offer a unique opportunity to build a second ep and first eA collider** at the energy frontier [discussed at DIS since Madison 2005]

Leptoquark Sensitivity





E6 new fields
TC bound states of technifermions
PS 4th colour of quarks
l,q composite models

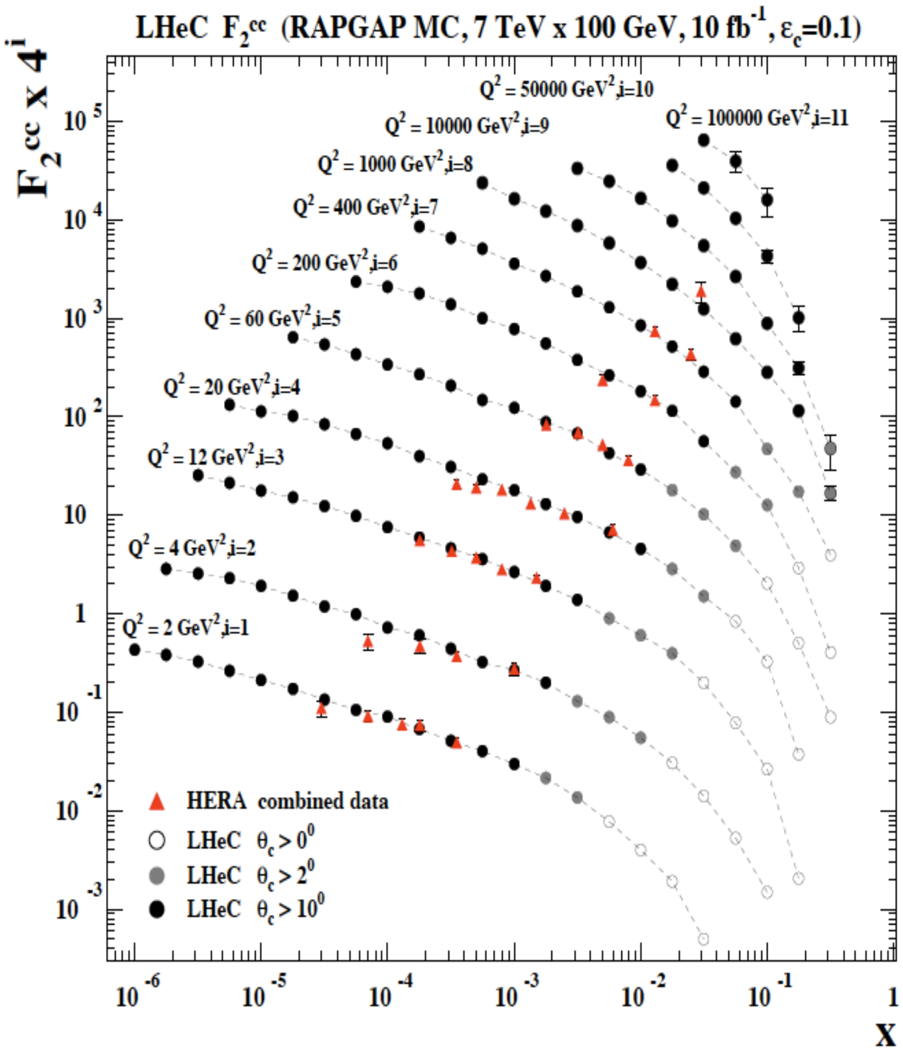
The cross section in ep is (depending on couplings) 100 times higher than in pp, but LHC is there, has pair production and higher energy

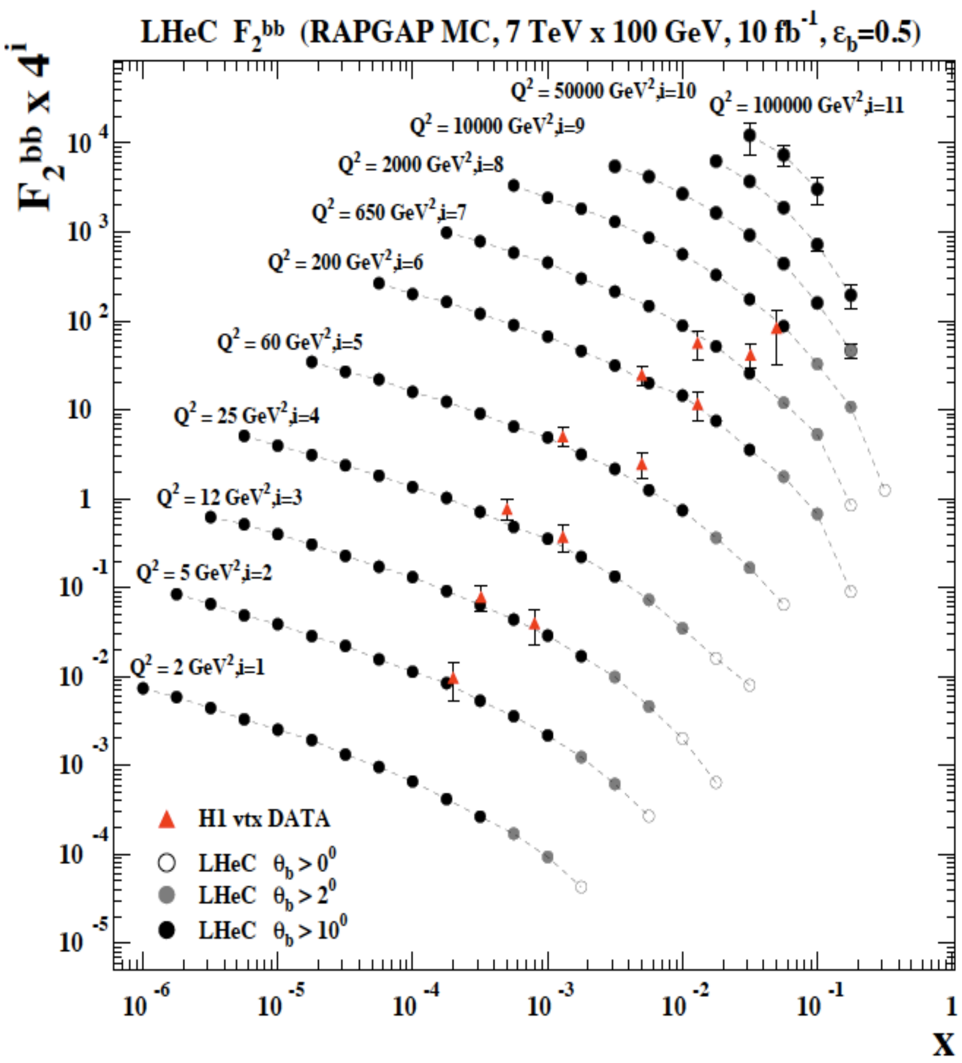
LHeC has mass reach up to about the cms energy (M < sqrt(s) = 1.3 .. 2 TeV for 60 .. 140 GeV electron beam energy)

→IF LQs are discovered at the LHC the electron beam energy would possibly be adjusted

→The role of ep would be to determine the quantum numbers

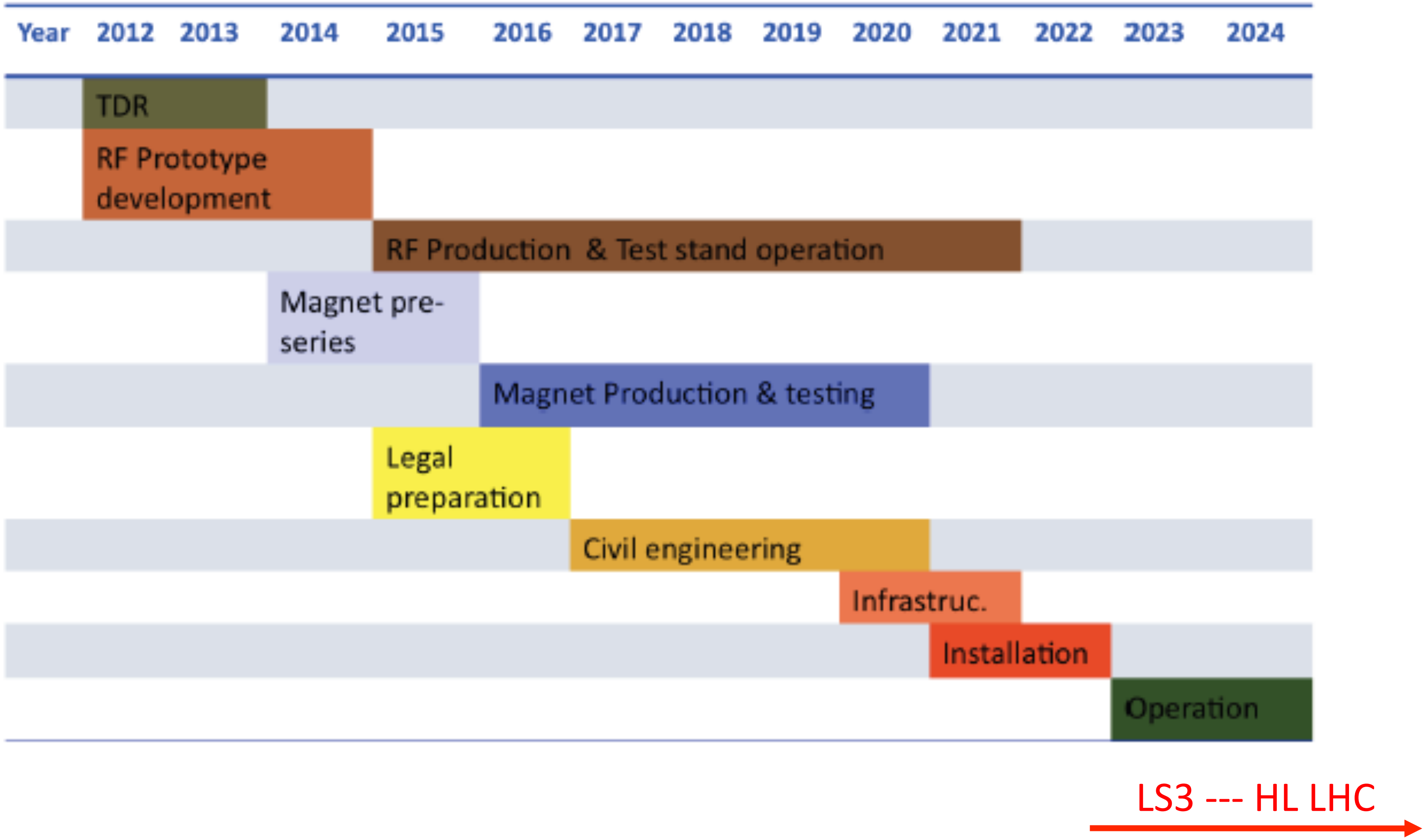
F_2^{charm} and F_2^{beauty} from LHeC





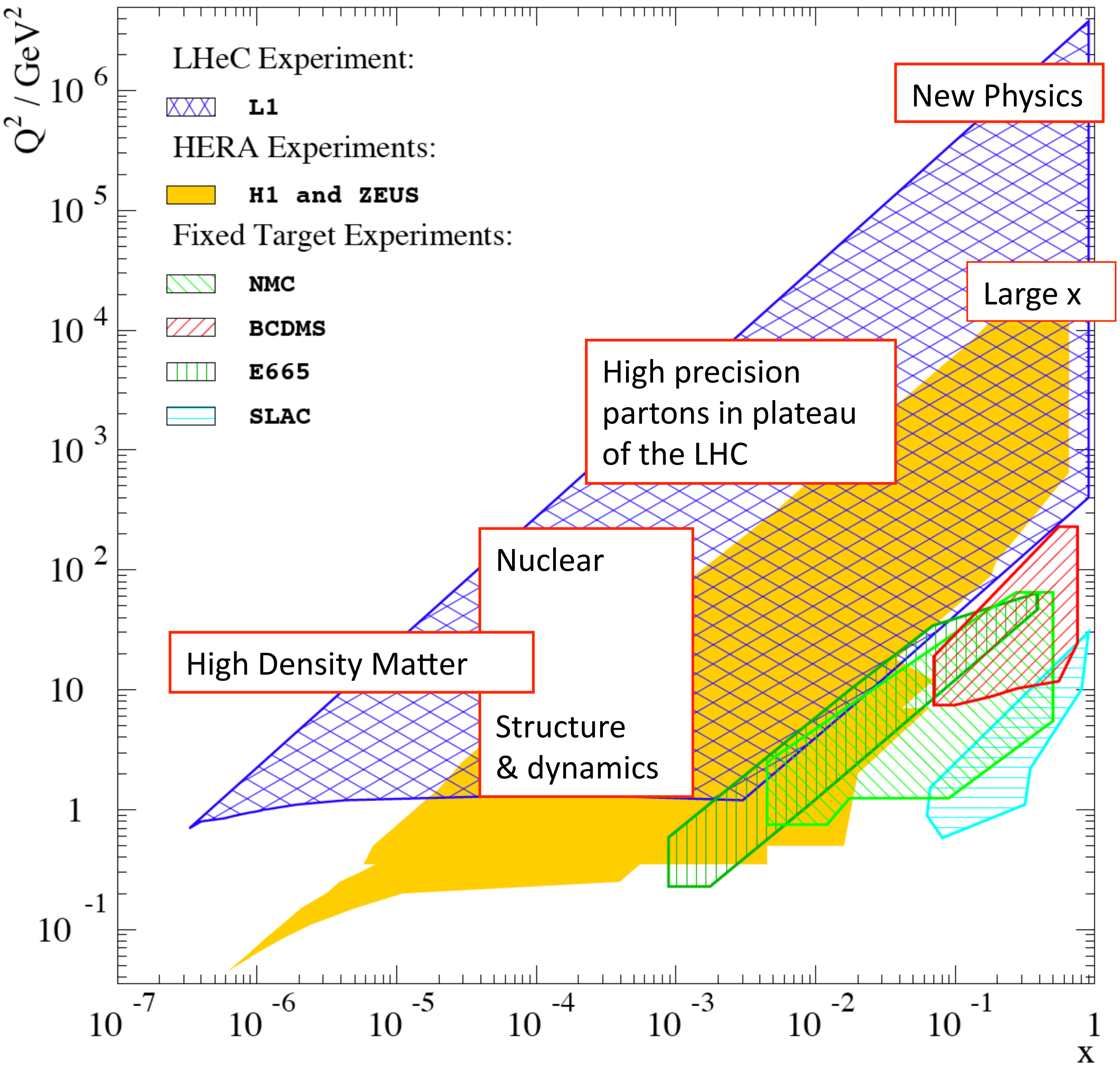
Hugely extended range and much improved precision
will pin down heavy quark behaviour at and away from thresholds

Tentative Time Schedule



We base our estimates for the project time line on the experience of other projects, such as (LEP, LHC and LINAC4 at CERN and the European XFEL at DESY and the PSI XFEL)

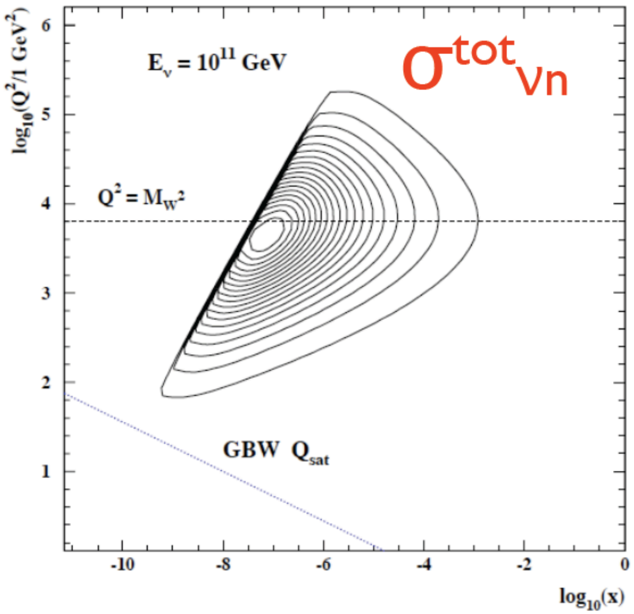
from draft CDR



Q^2 = 4momentum transfer^2

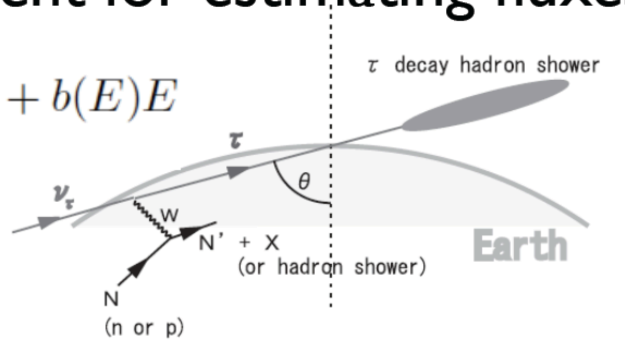
x = Bjorken x: fraction of p's momentum

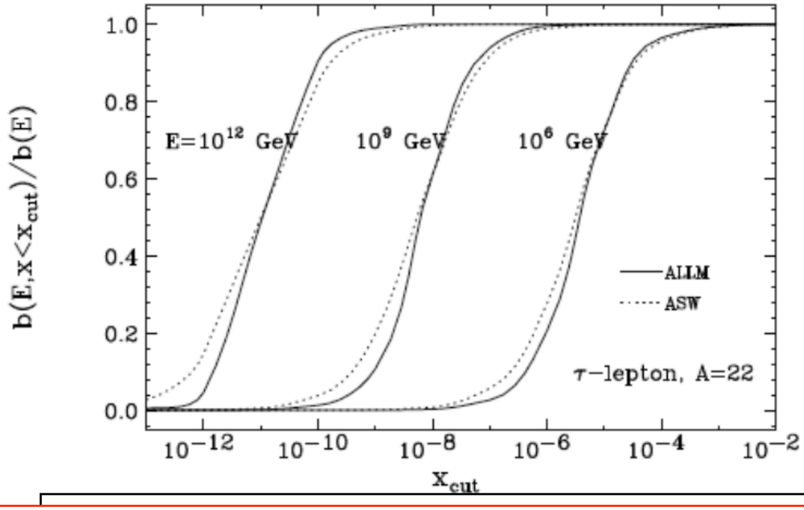
Neutrino Scattering

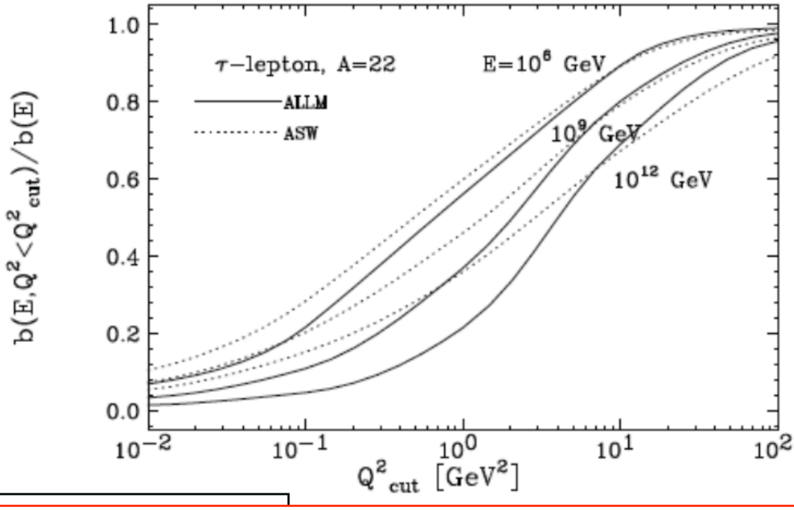


- ν-n/A cross section (τ energy loss) dominated by DIS structure functions / (n)pdfs at small-x and large (small) Q^2.
- Key ingredient for estimating fluxes.

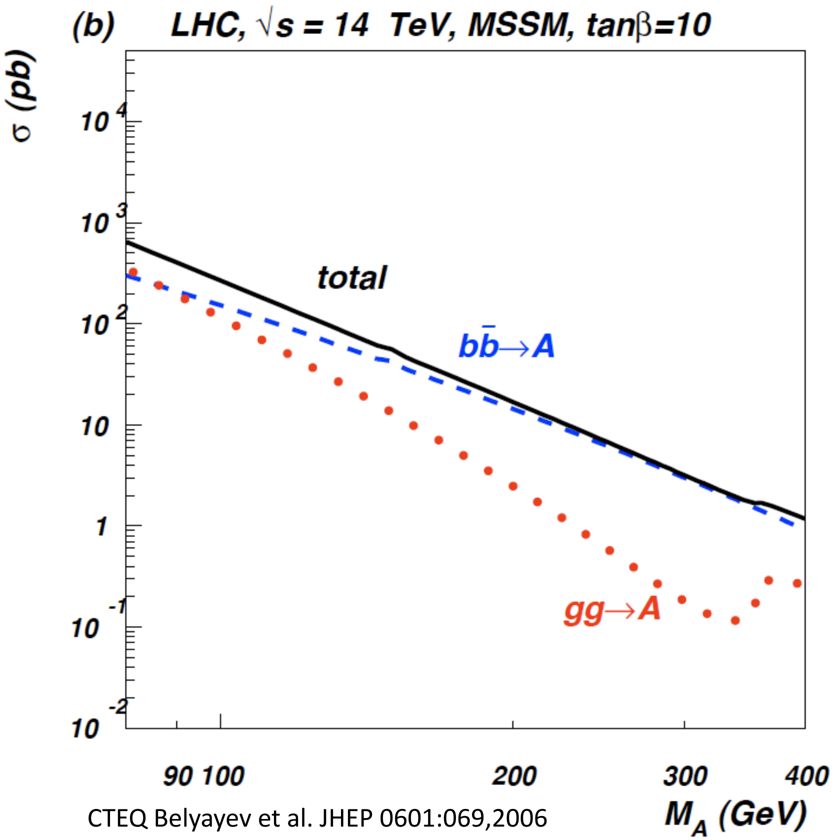
$$-\left\langle \frac{dE}{dX} \right\rangle = a(E) + b(E)E$$





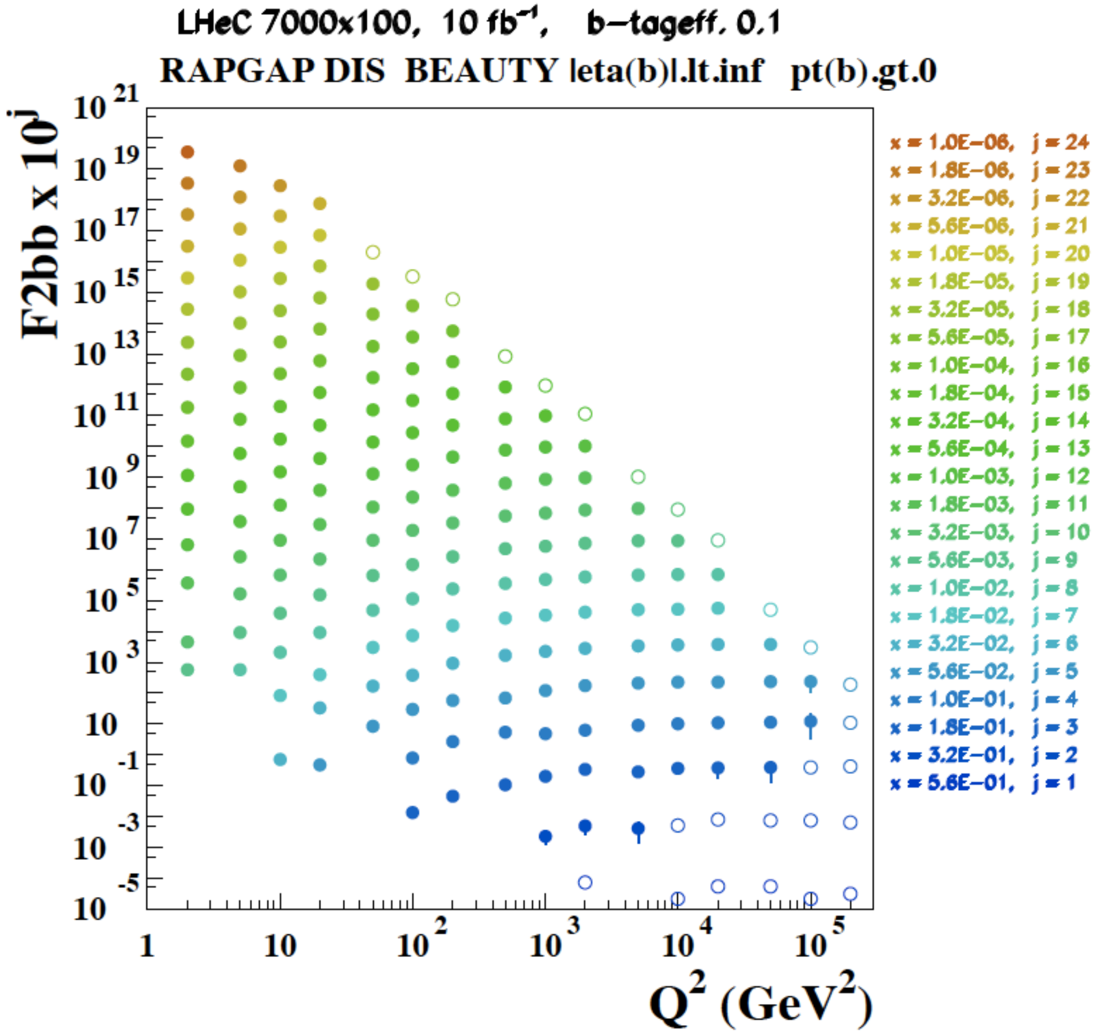


Beauty – MSSM ?? Higgs



CTEQ Belyayev et al. JHEP 0601:069,2006

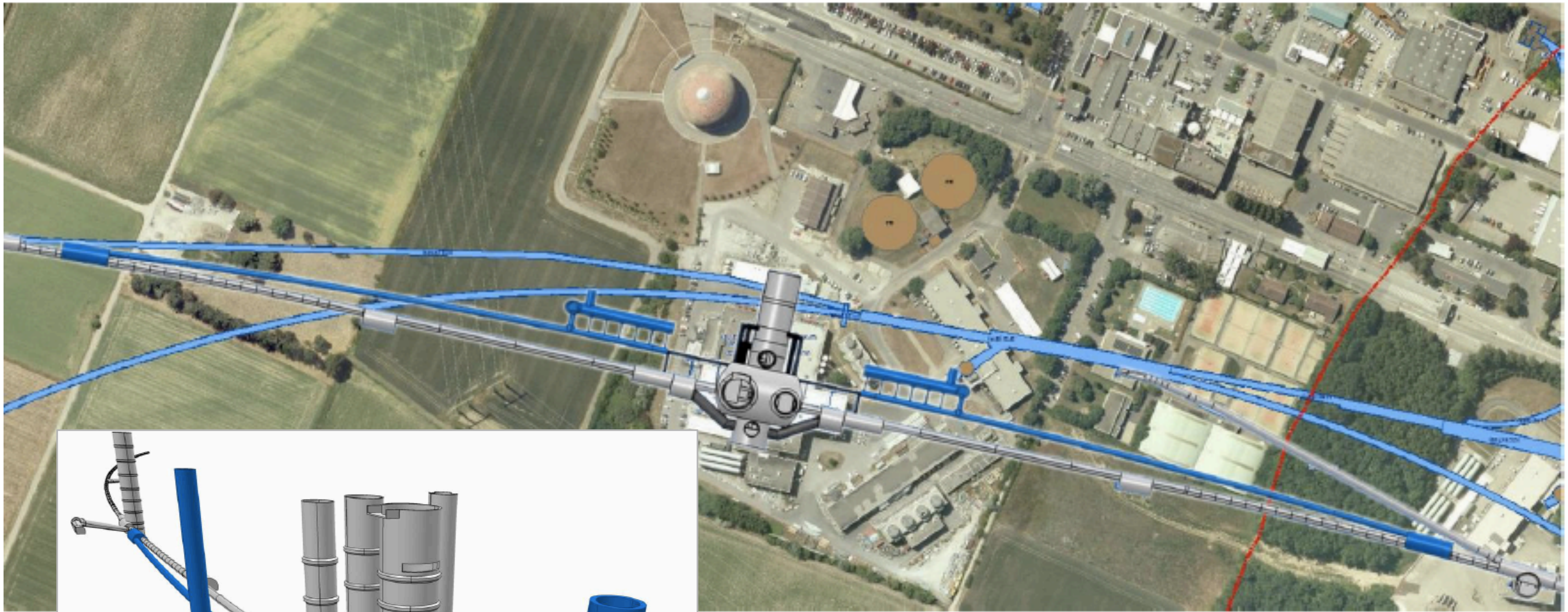
In MSSM Higgs production is b dominated

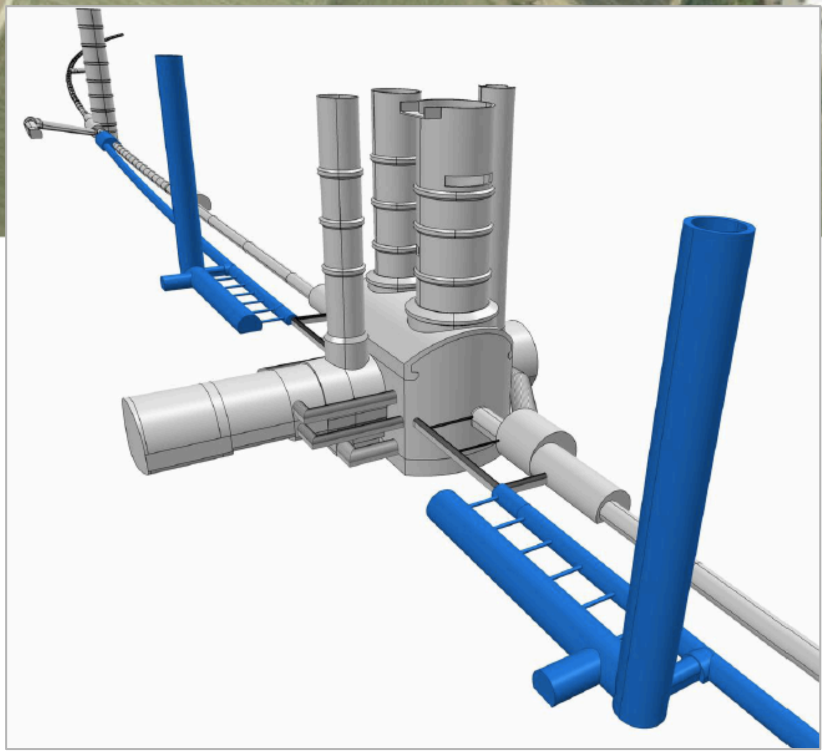


HERA: First measurements of b to ~20%
LHeC: precision measurement of b-df

LHeC: higher fraction of b, larger range, smaller beam spot, better Si detectors

Bypassing ATLAS





For the CDR the bypass concepts were decided to be confined to ATLAS and CMS

Detector Magnets

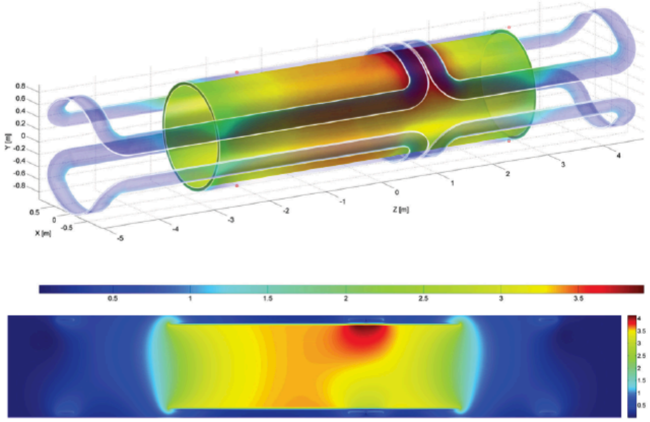


Figure 13.13: Magnetic field of the magnet system of solenoid and the two internal superconducting dipoles at nominal currents (effect of iron ignored). The position of the peak magnetic field of 3.9 T is local due to the adjacent current return heads on top of the solenoid where all magnetic fields add up.

Dipole (for head on LR) and solenoid in common cryostat, perhaps with electromagnetic LAr

3.5T field at ~1m radius to house a Silicon tracker

Based on ATLAS+CMS experience

Property	Parameter	value	unit
Dimensions	Cryostat inner radius	0.900	m
	Length	10.000	m
	Outer radius	1.140	m
	Coil windings inner radius	0.960	m
	Length	5.700	m
	Thickness	60.0	mm
	Support cylinder thickness	0.030	m
	Conductor section, Al-stabilized NbTi/Cu + insulation	30.0×6.8	mm^2
	Length	10.8	km
	Superconducting cable section, 20 strands	12.4×2.4	mm^2
	Superconducting strand diameter Cu/NbTi ratio = 1.25	1.24	mm
Masses	Conductor windings	5.7	t
	Support cylinder, solenoid section + dipole sections	5.6	t
	Total cold mass	12.8	t
	Cryostat including thermal shield	11.2	t
	Total mass of cryostat, solenoid and small parts	24	t
Electro-magnetics	Central magnetic field	3.50	T
	Peak magnetic field in windings (dipoles off)	3.53	T
	Peak magnetic field in solenoid windings (dipoles on)	3.9	T
	Nominal current	10.0	kA
	Number of turns, 2 layers	1683	
	Self-inductance	1.7	H
	Stored energy	82	MJ
	E/m, energy-to-mass ratio of windings	14.2	kJ/kg
	E/m, energy-to-mass ratio of cold mass	9.2	kJ/kg
	Charging time	1.0	hour
	Current rate	2.8	A/s
	Inductive charging voltage	2.3	V
Margins	Coil operating point, nominal / critical current	0.3	
	Temperature margin at 4.6 K operating temperature	2.0	K
	Cold mass temperature at quench (no extraction)	~ 80	K
Mechanics	Mean hoop stress	~ 55	MPa
	Peak stress	~ 85	MPa
Cryogenics	Thermal load at 4.6 K, coil with 50% margin	~ 110	W
	Radiation shield load width 50% margin	~ 650	W
	Cooling down time / quench recovery time	4 and 1	day
	Use of liquid helium	~ 1.5	g/s

Table 13.1: Main parameters of the baseline LHeC Solenoid providing 3.5 T in a free bore of 1.8 m.

Summary of Design Parameters

electron beam	RR	LR	LR
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	17	10	0.44
polarization [%]	40	90	90
bunch population [10^9]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

High E_e Linac option (ERL?) if physics demands HE-LHC?

proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit.$\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1
bunch spacing [ns]	25	25

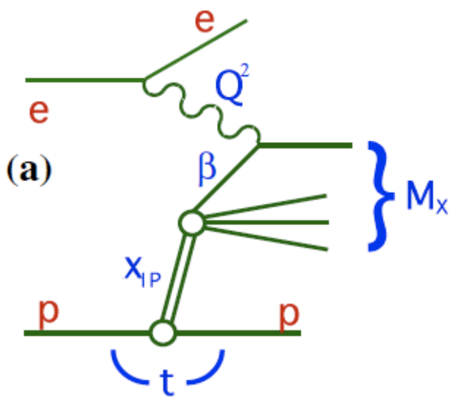
"ultimate p beam"
1.7 probably conservative
and emittance too

CDR has design also for
D and A ($L_{eN} \cong 3 * 10^{31}$ $cm^{-2}s^{-1}$)

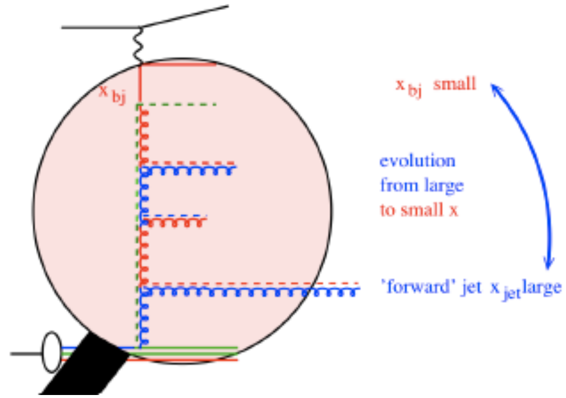
RR= Ring – Ring
LR =Linac –Ring

Ring: use 1° as baseline : L/2
Linac: clearing gap: L*2/3

Quark-Gluon Dynamics - Diffraction and HFS (fwd jets)

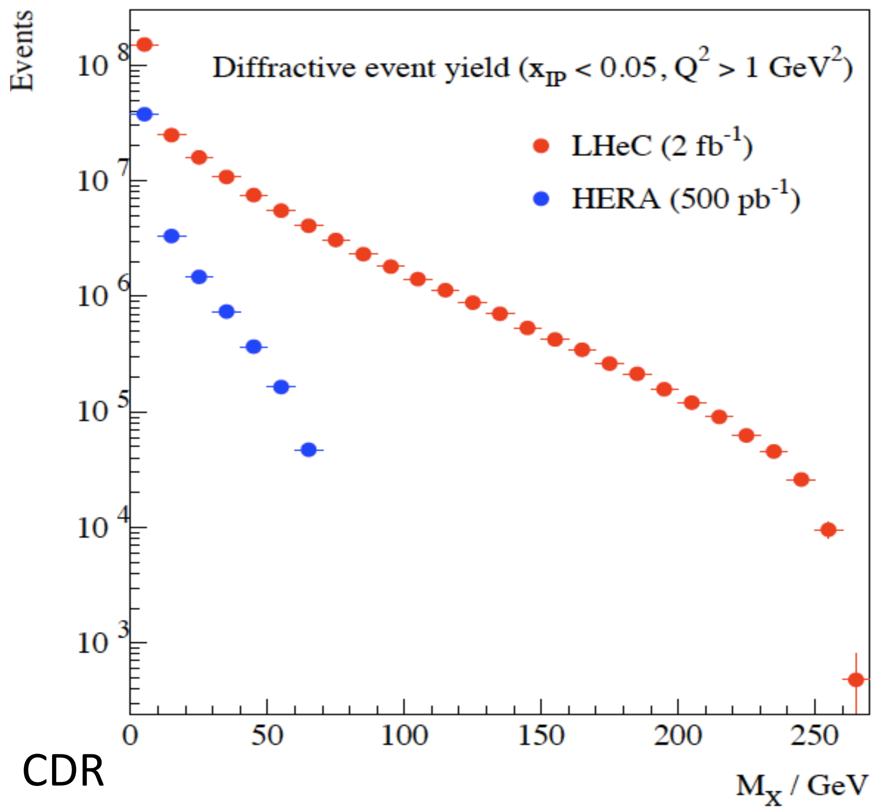


Factorisation broken
(LHC fwd – LHeC diff)

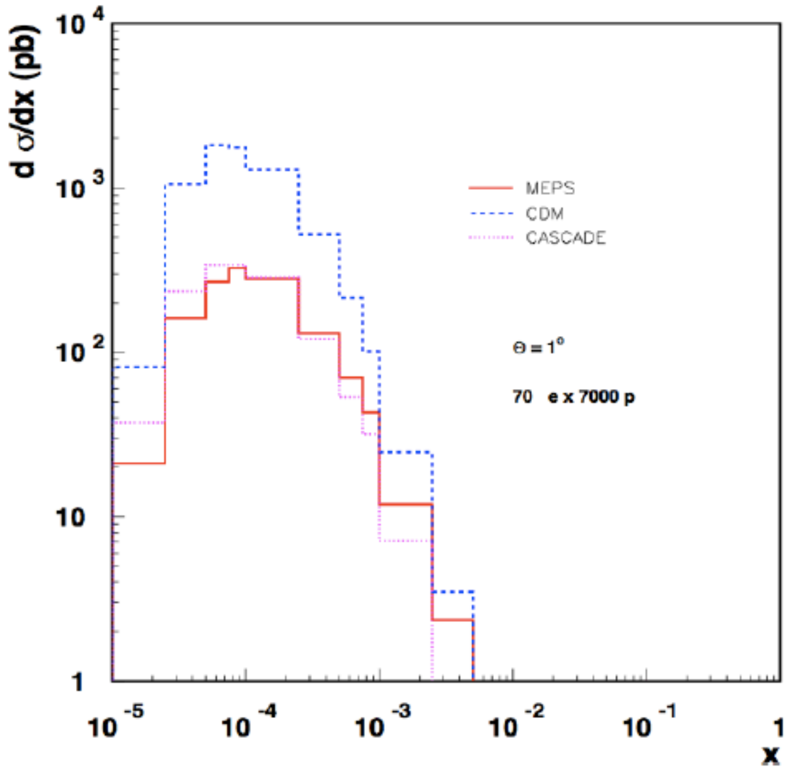


Understand multi-jet emission (unintegr. pdf's), tune MC's

Production of high mass 1⁻ states

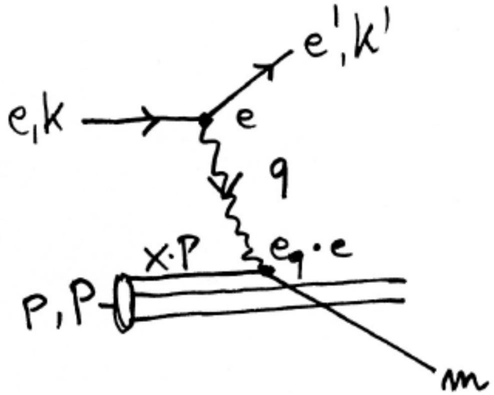


CDR



At HERA resolved γ effects mimic non-kt ordered emission

Deep Inelastic Scattering ("DIS")



"fixed target":

$$P = (M_p, 0,0,0)$$
$$2Pq = 2M_p(E - E')$$
$$= 2M_p E \cdot \frac{\nu}{E} \equiv s \cdot y$$
$$Q^2 = sxy \le s$$
$$s = 2M_p E$$
$$s = 4E_e E_p$$ - ep collider
$$x = \frac{Q^2}{sy}$$

$$q = (k - k')$$
$$(xP + q)^2 = m^2, P^2 = M_p^2$$
$$Q^2 = -q^2 > 0$$
$$if: Q^2 >> x^2 M_p^2, m^2:$$
$$q^2 + 2xPq = 0:$$
$$x = \frac{Q^2}{2Pq}$$

$$\sigma(ep \to eX) = \frac{d^2\sigma}{dxdQ^2} \approx \frac{2\pi\alpha^2}{Q^4}(1 + (1-y)^2) \cdot F_2$$
$$F_2(x, Q^2) = x \sum_q e_q^2 (q + \bar{q}), q = u,d,s,c,b,t$$
$$q = q(x, Q^2)$$

In DIS the inclusive cross section depends on two variables, the negative 4-momentum transfer squared (Q^2), which determines the resolving power of the exchanged particle in terms of p substructure, and the variable Bjorken x, which Feynman could relate to the fraction of momentum of the proton carried by a parton [in what he called the 'infinite momentum frame' in which the transverse momenta are neglected].

Deep inelastic scattering resolves the nucleon structure. If s is high: produce new states
Kinematics is determined with scattered electron or with HFS → high precision due to redundancy