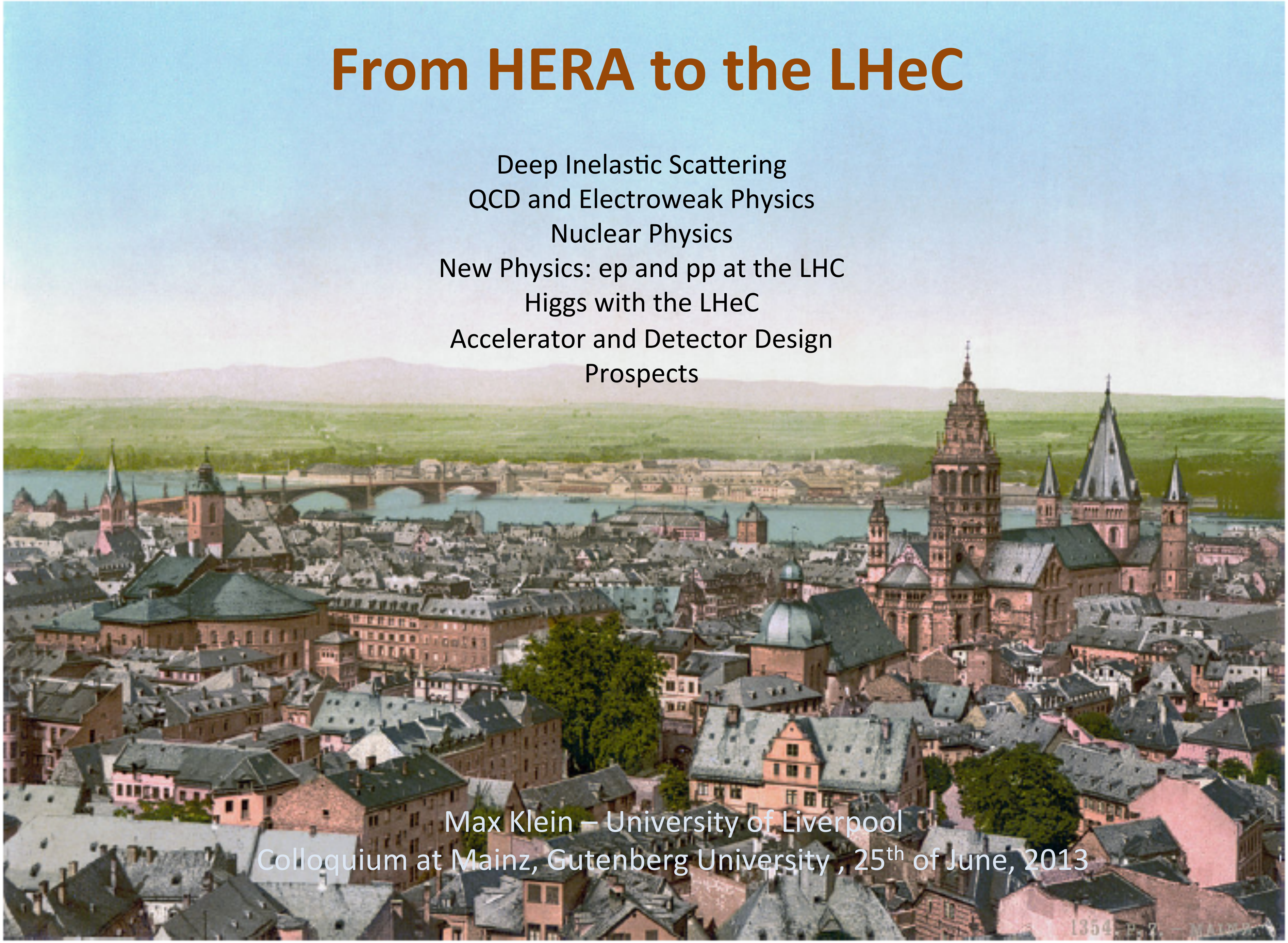
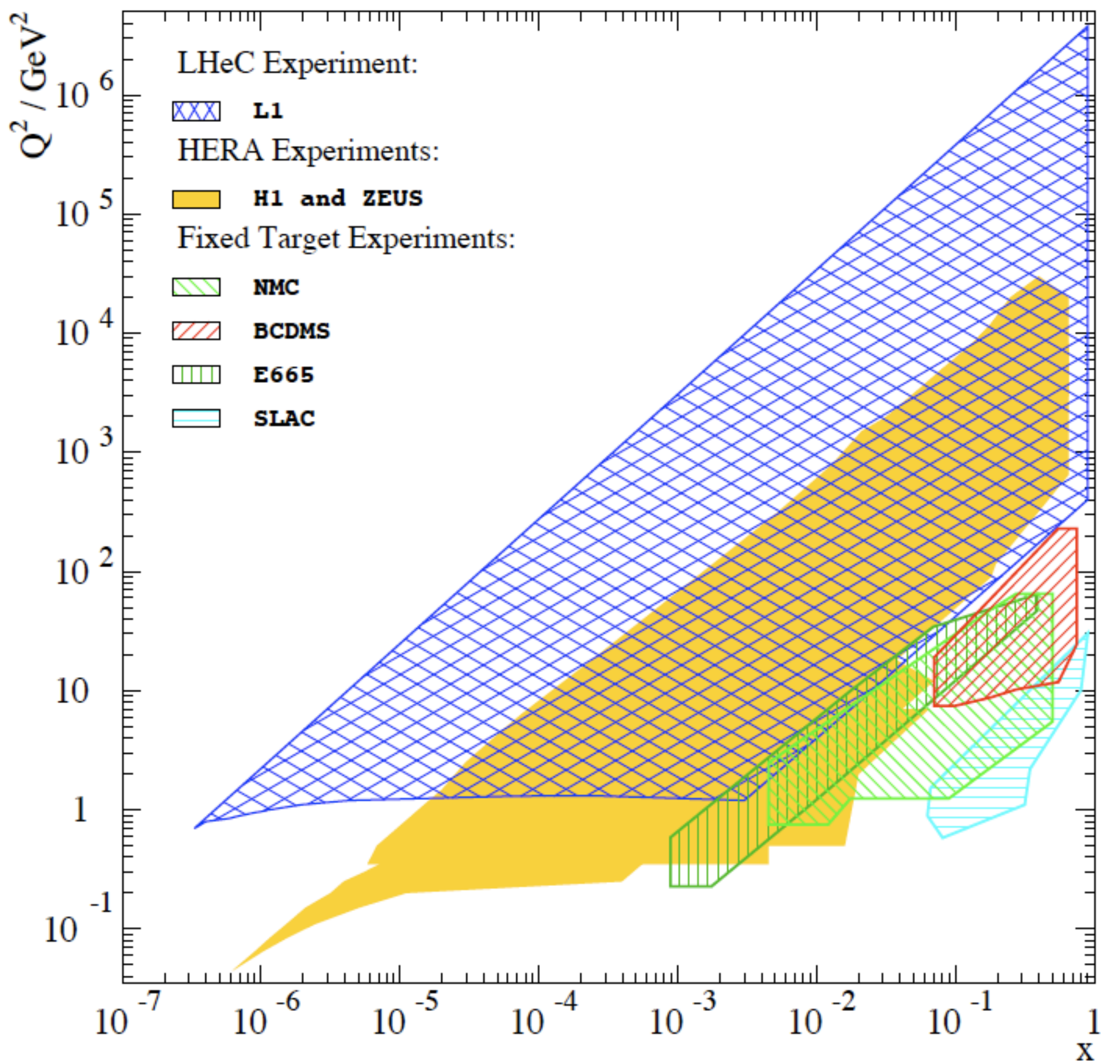
From HERA to the LHeC

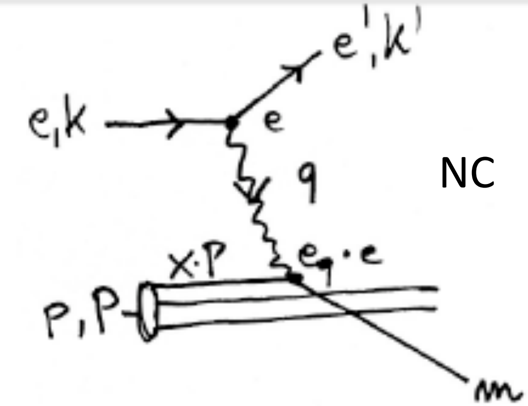
Deep Inelastic Scattering
QCD and Electroweak Physics
Nuclear Physics
New Physics: ep and pp at the LHC
Higgs with the LHeC
Accelerator and Detector Design
Prospects



Max Klein – University of Liverpool
Colloquium at Mainz, Gutenberg University , 25th of June, 2013

Deep Inelastic e/μp Scattering





$$q = (k - k'), q^2 = -Q^2$$

$$s = (k + P)^2$$

$$(xP + q)^2 = m^2, P^2 = M_p^2$$

$$if\,(Q^2 >> x^2 M_p^2, m^2):$$

$$q^2 + 2xPq = 0$$

$$x = \frac{Q^2}{2Pq}$$

$$Q^2 = sxy$$

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{e^4 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)} \left[W_2(q^2, W) + 2W_1(q^2, W)\tan^2(\theta/2)\right]$$

SLAC-PUB-642
August 1969

The birth of DIS, 45 years ago..

Neutral (NC) and Charged Current (CC) DIS Cross Sections

$$\sigma_{r,NC} = \frac{d^2\sigma_{NC}}{dxdQ^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \mathbf{F_2} + \frac{Y_-}{Y_+}\mathbf{xF_3} - \frac{y^2}{Y_-}\mathbf{F_L}$$

$$\begin{aligned}\mathbf{F}_2^{\pm} &= F_2 + \kappa_Z(-v_e \mp P a_e) \cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2P v_e a_e) \cdot F_2^Z \\ \mathbf{xF}_3^{\pm} &= \kappa_Z(\pm a_e + P v_e) \cdot xF_3^{\gamma Z} + \kappa_Z^2(\mp 2 v_e a_e - P(v_e^2 + a_e^2)) \cdot xF_3^Z\end{aligned}$$

$$\kappa_Z(Q^2) = Q^2/[(Q^2 + M_Z^2)(4\sin^2\Theta\cos^2\Theta)]$$

$$\begin{aligned}(F_2, F_2^{\gamma Z}, F_2^Z) &= x\sum(e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q}) \\ (xF_3^{\gamma Z}, xF_3^Z) &= 2x\sum(e_q a_q, v_q a_q)(q - \bar{q}),\end{aligned}$$

$$\sigma_{r,CC} = \frac{2\pi x}{Y_+ G_F^2}\left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 \frac{\mathrm{d}^2\sigma_{CC}}{\mathrm{d}x\mathrm{d}Q^2}$$

$$\sigma_{r,CC}^{\pm} = \frac{1 \pm P}{2}(W_2^{\pm} \mp \frac{Y_-}{Y_+} x W_3^{\pm} - \frac{y^2}{Y_+} W_L^{\pm})$$

$$W_2^+ = x(\overline{U} + D)\,,\, xW_3^+ = x(D - \overline{U})$$

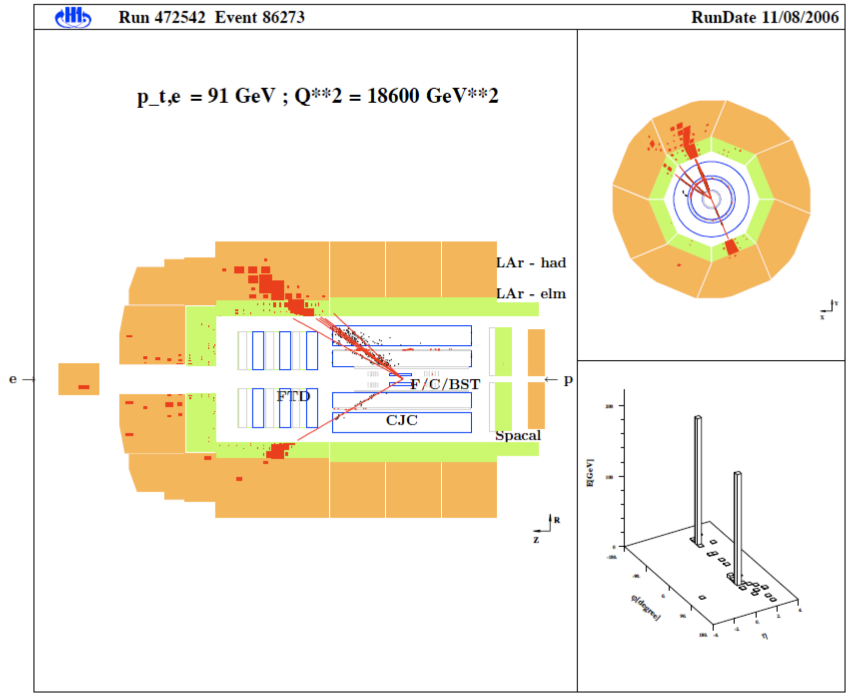
$$W_2^- = x(U + \overline{D})\,,\, xW_3^- = x(U - \overline{D})$$

$Y_\pm = 1 \pm (1-y)^2$

Sensitive to sum or difference of q and anti-q
Electroweak effects appear $O(10^{-4}Q^2/\mathrm{GeV}^2)$.
Charge and polarisation asymmetry effects.

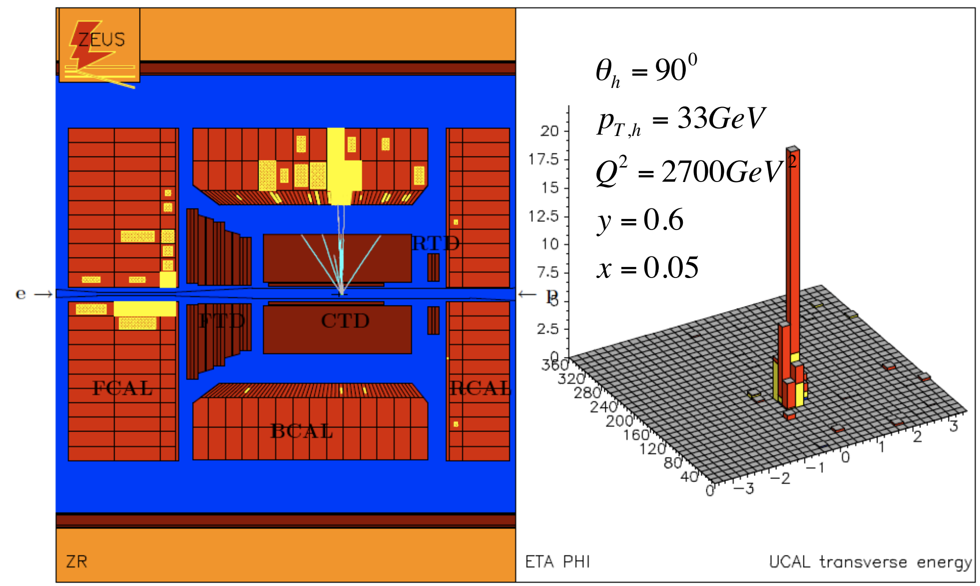
CC on protons are charge dependent.
Flavour separation but of sums of up and down quarks. Propto $(1 \pm P_e)$.

Neutral (NC) and Charged Current (CC) HERA Events

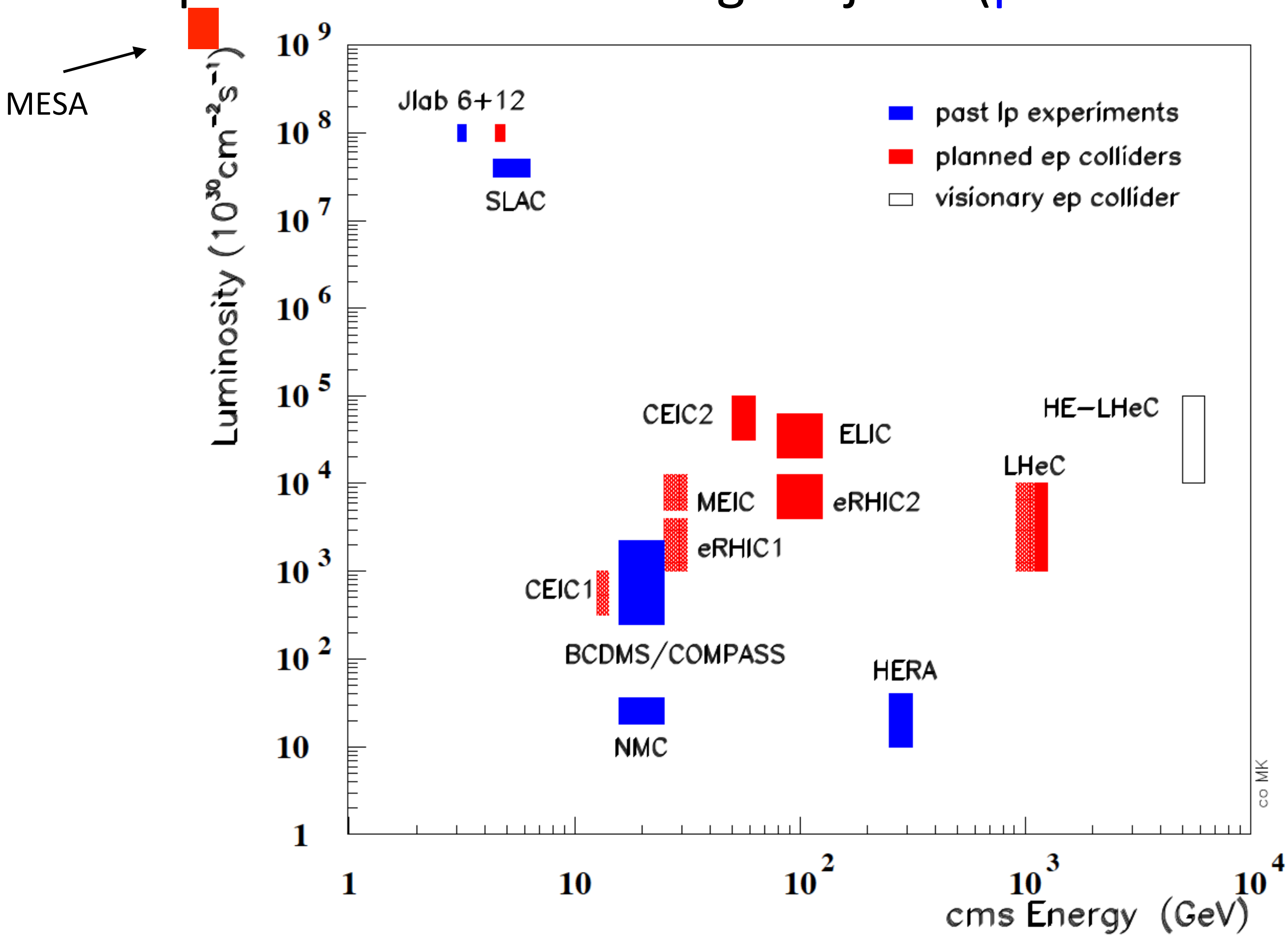


H1 Collaboration

ZEUS Collaboration



Lepton-Proton Scattering Projects (past and future)



High Intensity (low Q^2) -- Medium Energies (polarised) -- Energy Frontier DIS

Deep Inelastic Lepton-Hadron Scattering

Early and Recent ep Scattering
HERA
HERA's Legacy I - Achievements
HERA's Legacy II - Open Questions
The LHeC - One Slide
x,Q^2 Ranges
Physics Overview on the LHeC

Early ep Scattering

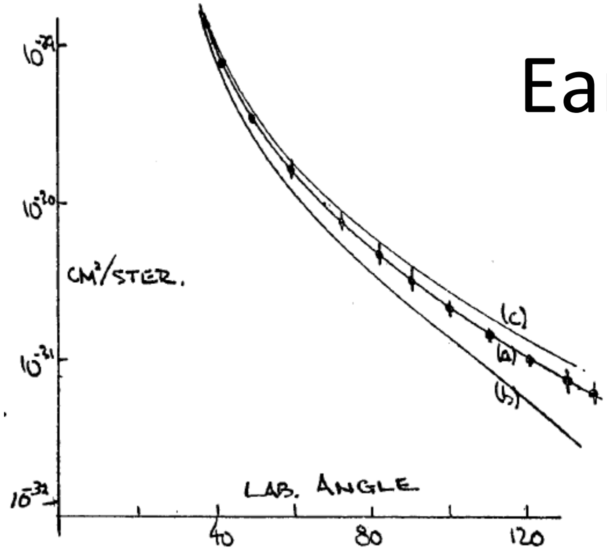
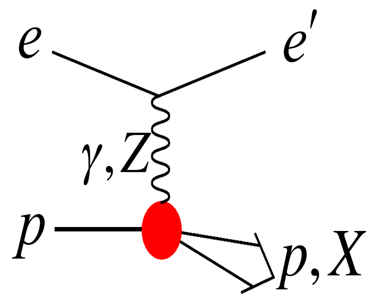
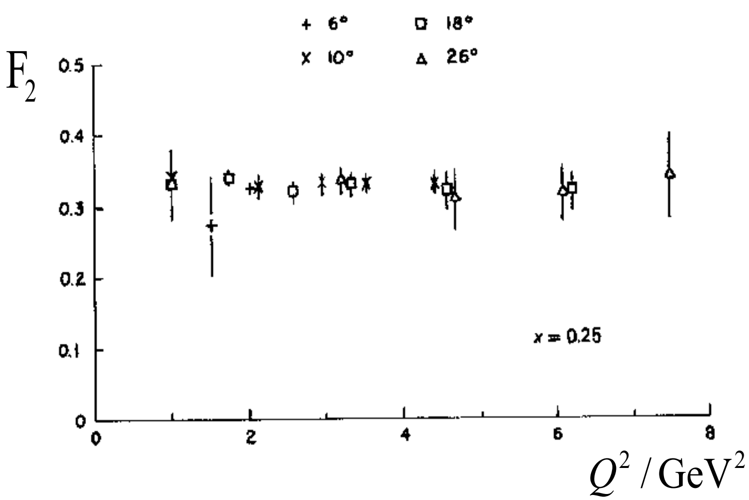


Fig. 2

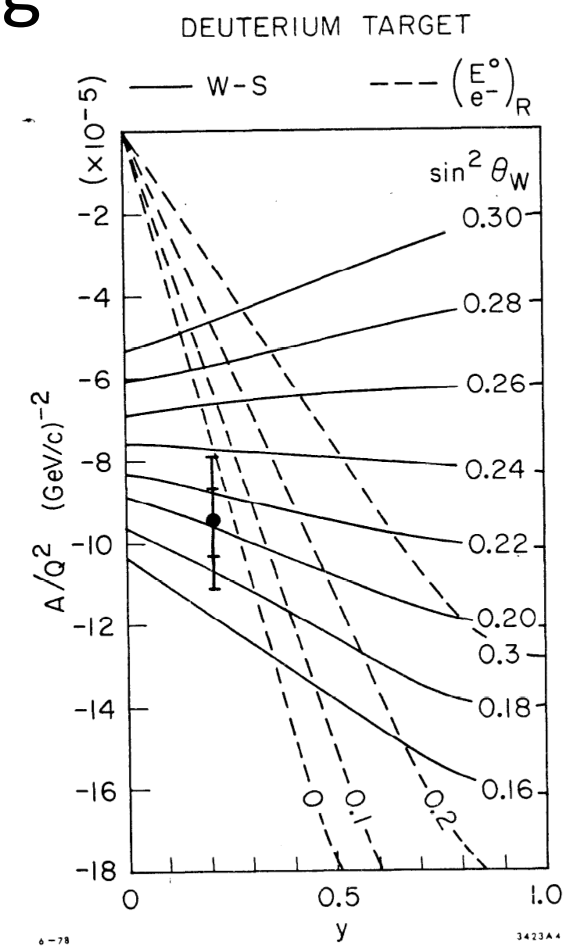
Hofstadter et al, 1955, r_p=0.74±0.20fm





SLAC-MIT 1968 Bj Scaling → Partons

In DIS the x and Q^2 scales are prescribed by the electron kinematics



$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

SLAC-PUB-2148
July 1978

Prescott et al, 1978, $I_{3,R}^{e}$=0

Recent/Future ep Scattering

M.Vanderhaeghen 2009

ep-scattering (MAMI)

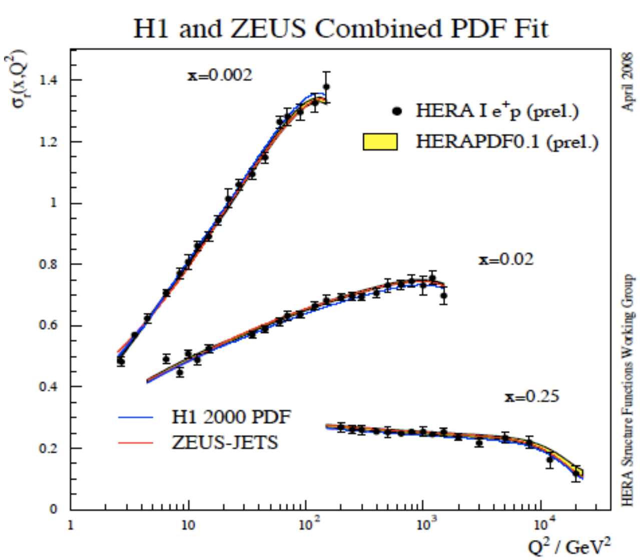
Bernauer et al.

PRL 105 (2010) 242001

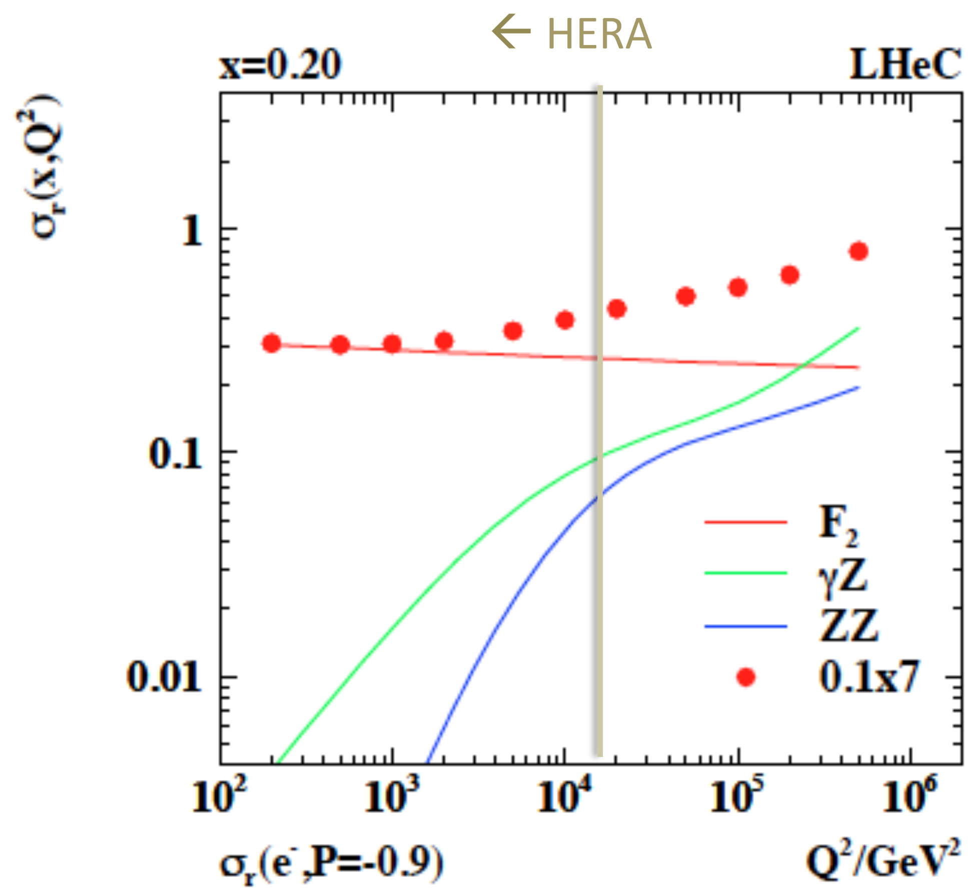
R_E = 0.879 (8) fm

R_E = 0.84184 (67) fm ?

Nature 466 (2010) 213

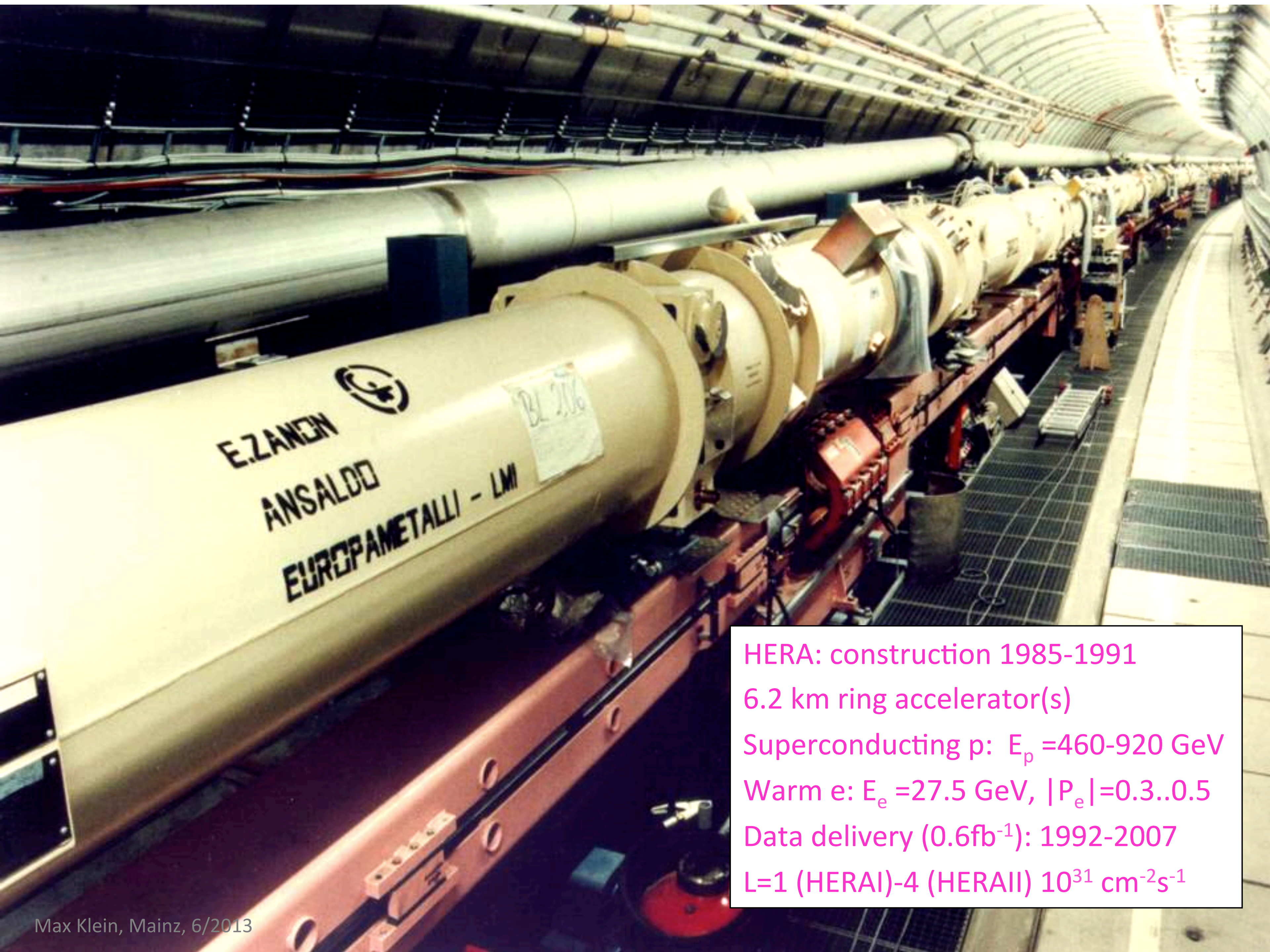


HERA Violation of Bj Scaling → Gluon



$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

MESA, Jlab, LHeC: $\sin^2\Theta(\mu)$



HERA: construction 1985-1991

6.2 km ring accelerator(s)

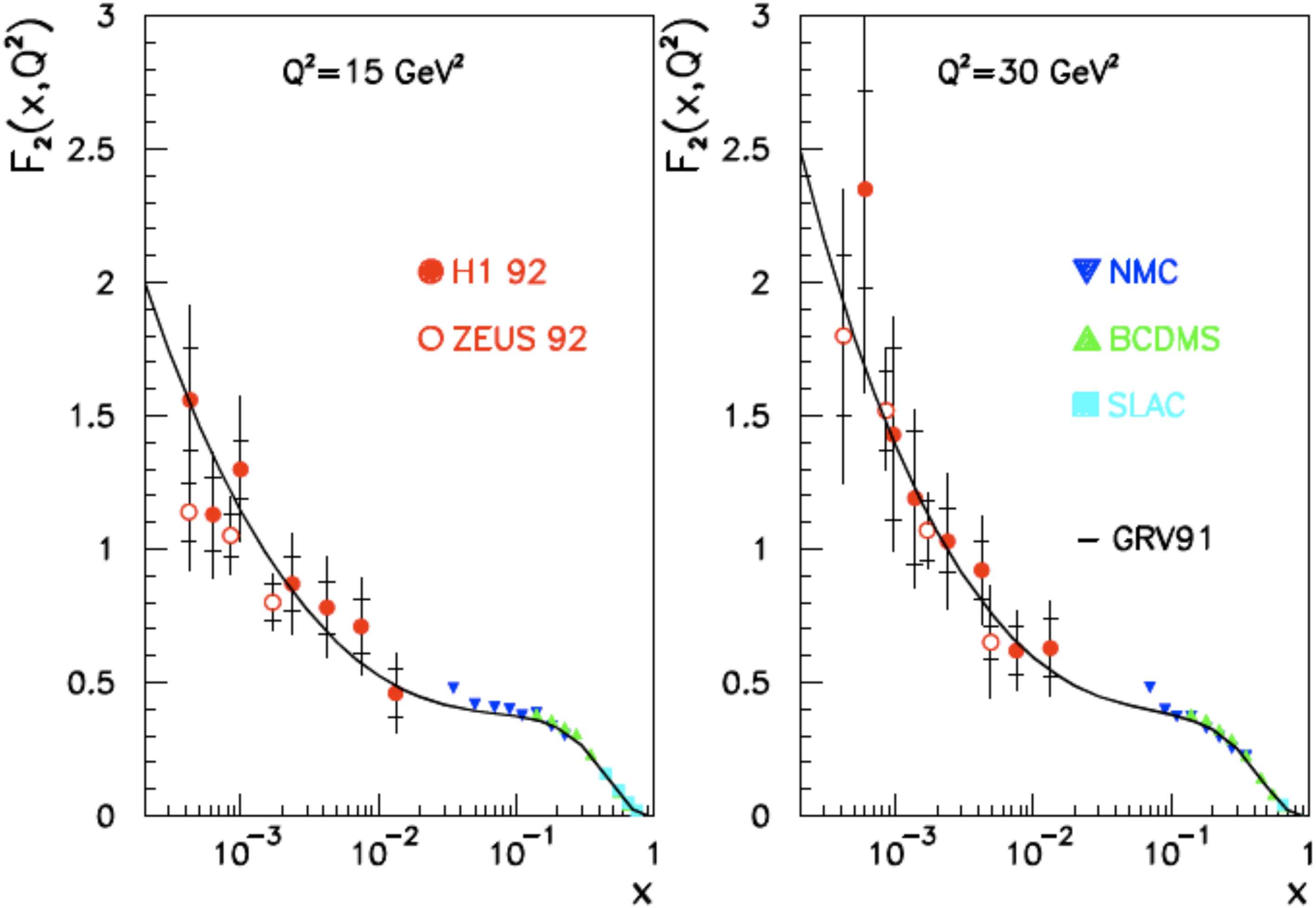
Superconducting p: E_p =460-920 GeV

Warm e: E_e =27.5 GeV, $|P_e|$=0.3..0.5

Data delivery (0.6fb^{-1}): 1992-2007

L=1 (HERAI)-4 (HERAII) 10^{31} $cm^{-2}s^{-1}$

HERA: Discovery of the Rise of F_2 Towards Low x

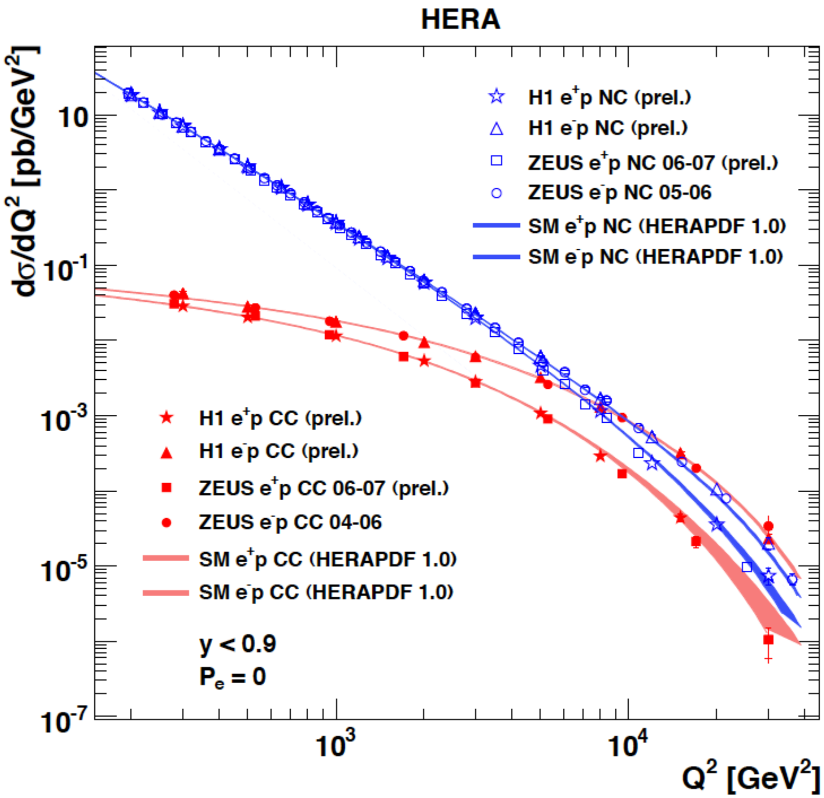


H1 Collaboration, Nucl. Phys. B407 (1993) 515
ZEUS Collaboration, Phys. Lett. B316(1993) 412

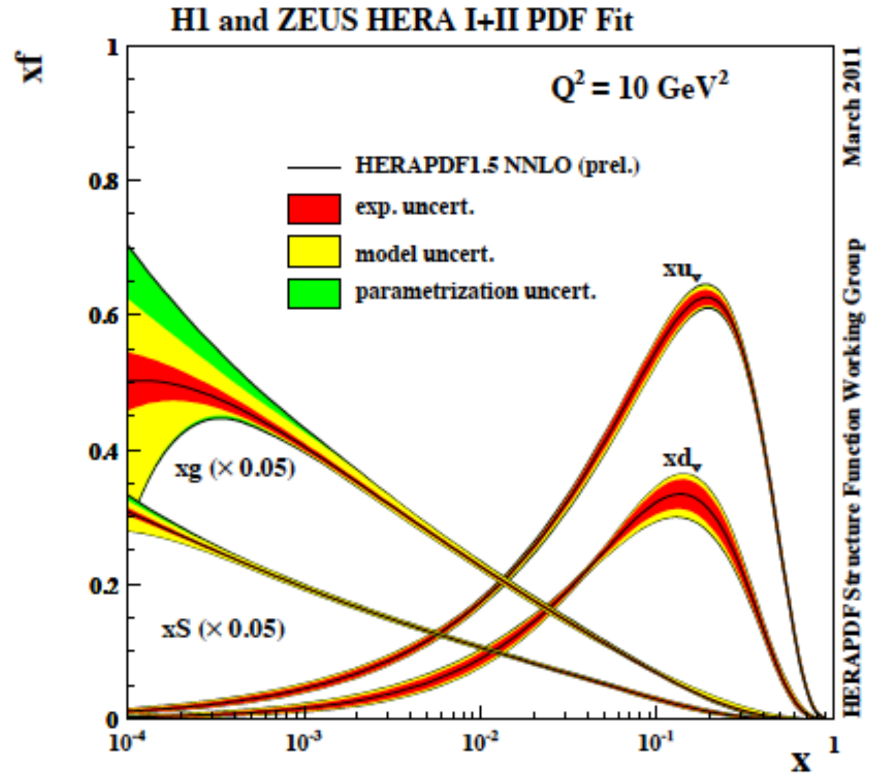
Not too steep, not flat (Regge)
in accord with 1974 expectation
hidden in pioneering pQCD paper

20 years ago..

HERA's Legacy I - Achievements



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), PDFs
New limits for leptoquarks, excited electrons and neutrinos, quark substructure, RPV SUSY
Interpretation of Tevatron+LHC measurements (high Et jet excess, M_W, searches, **Higgs**, ..)

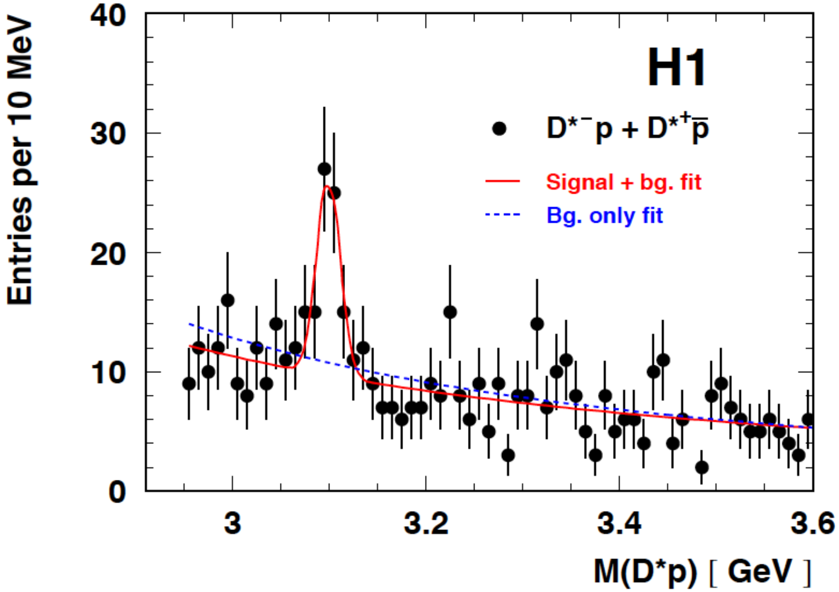
M.Klein, R.Yoshida: **Collider Physics at HERA** Prog.Part.Nucl.Phys. 61 (2008) 343-393 and recent H1,ZEUS results
A Recent review of **The Theory of Deep Inelastic Scattering**: J.Bluemlein arXiv:1208.6087 ProgPartNuclPhys 69(2013)28

HERA's Legacy II – Open Questions

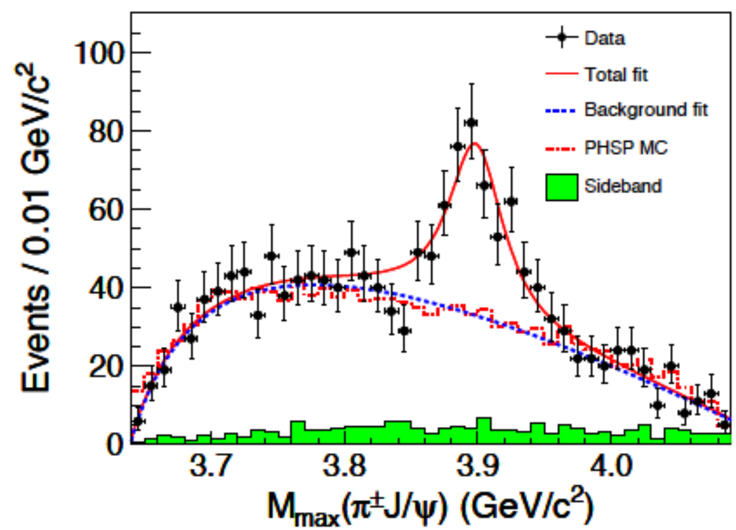
Test of the isospin symmetry (u-d) with eD	- no deuterons
Investigation of the q-g dynamics in nuclei	- no time for eA
Verification of saturation prediction at low x	- too low s
Measurement of the strange quark distribution	- too low L
Discovery of Higgs in WW fusion in CC	- cross section ~0.5fb
Study of top quark distribution in the proton	- too low energy
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
…	

→ Need: much higher luminosity, higher energy, nuclear targets

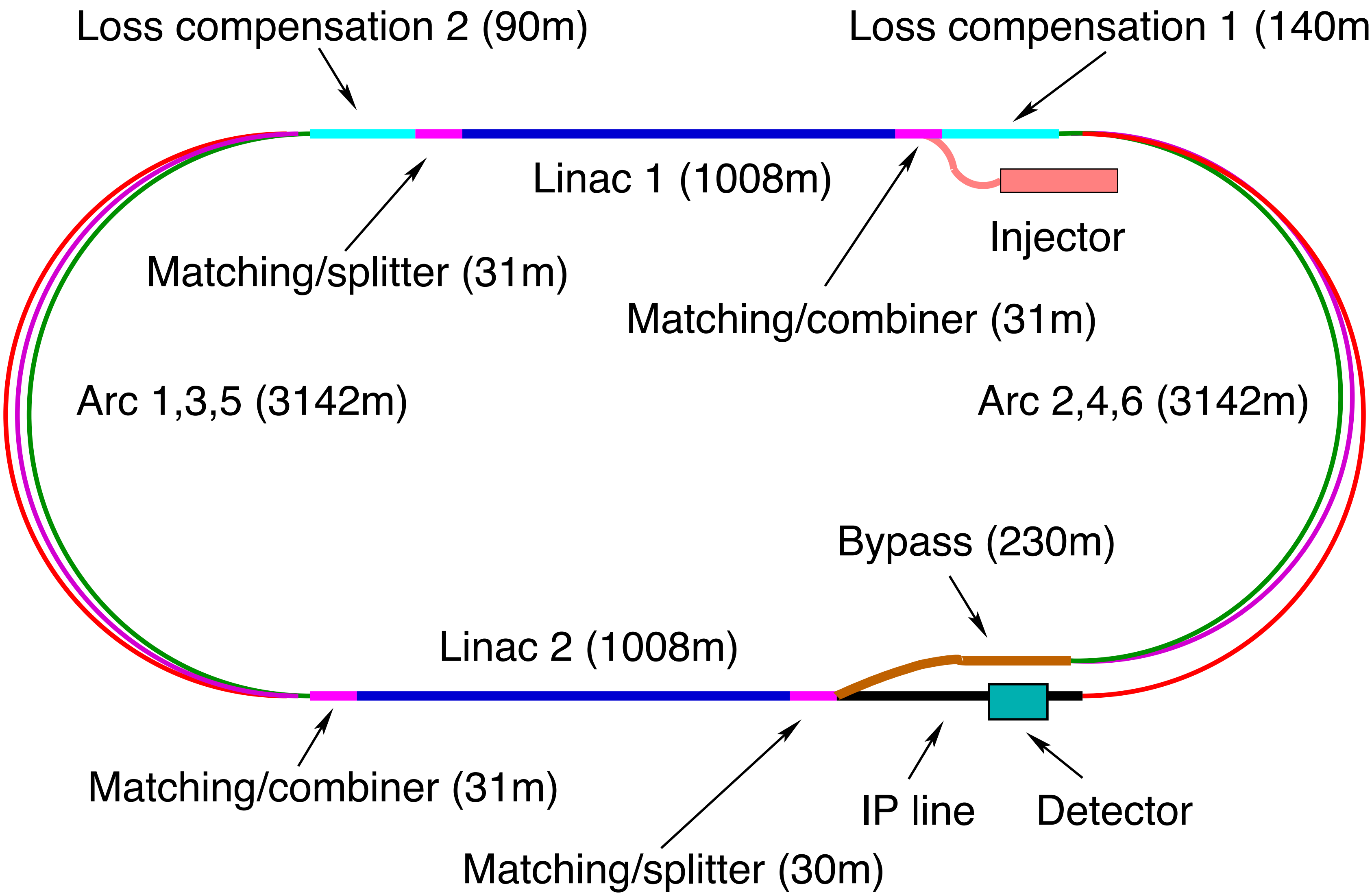
Puzzle – charm multi-quark states



uuddcbar
DESY 04-038 (2004)
Not seen by ZEUS..



udccbar
BESIII, arXiv:1303.5949
also seen by BELLE

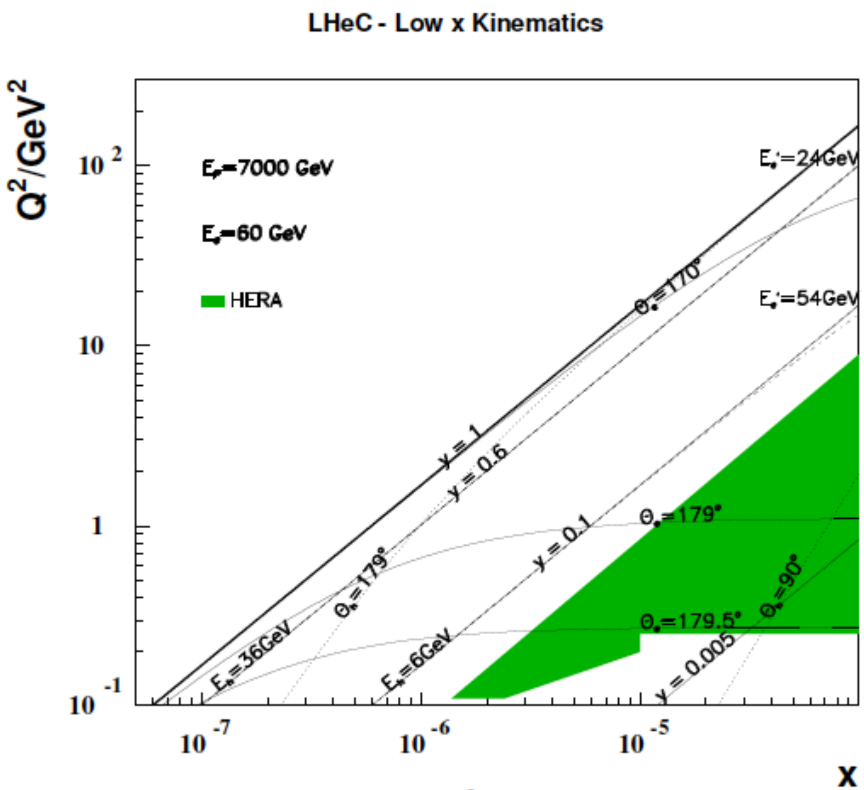


Max Klein, Mainz, 6/2013

60 GeV electron beam energy, L= 10^{33} cm^{-2}s^{-1}, √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

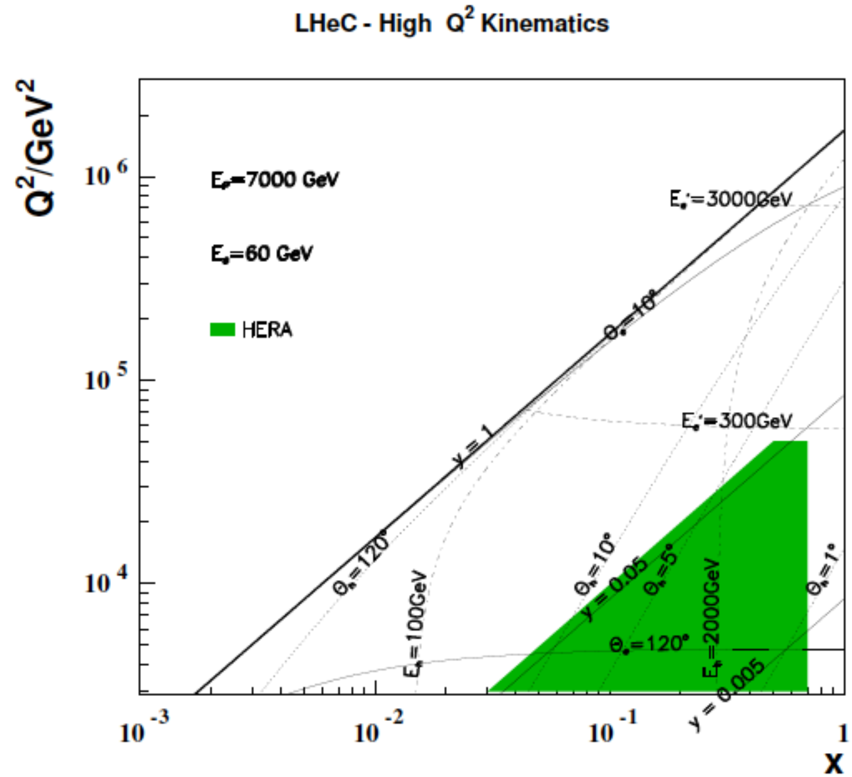
Kinematics - LHeC and HERA

Access to "saturation" (?) region in DIS ($Q^2 > 1$ GeV^2) and ep



Forward/backward acceptance to 1/179°

Luminosity 100-1000 times higher



Extending beyond the Fermi scale with precision Z and W exchange data → high x, top PDF, flavour & new physics,

Summary of the LHeC Physics Programme

CDR, arXiv:1211.4831 and 1211.5102 http://cern.ch/lhec

QCD Discoveries Higgs Substructure New and BSM Physics Top Quark	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$ WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate electromagnetic quark radius, e^*, ν^*, $W?$, $Z?$, top?, $H?$ leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s 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 Precision DIS	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c $\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure Quark Distributions QCD	Proton, Deuteron, Neutron, Ions, Photon valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron Heavy Ions Modified Partons	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing initial QGP, nPDFs, hadronization inside media, black limit, saturation 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, ..

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

QCD and Electroweak Physics

Mapping the Gluon Distribution
Proton Quark Distributions
Neutron Structure and Electron-Deuteron Scattering
Vector Meson Production and Diffraction
Weak Structure Functions and Asymmetries
x,Q^2 Range in Lepton-Nucleus Scattering
Nuclear Parton Distributions

LHeC

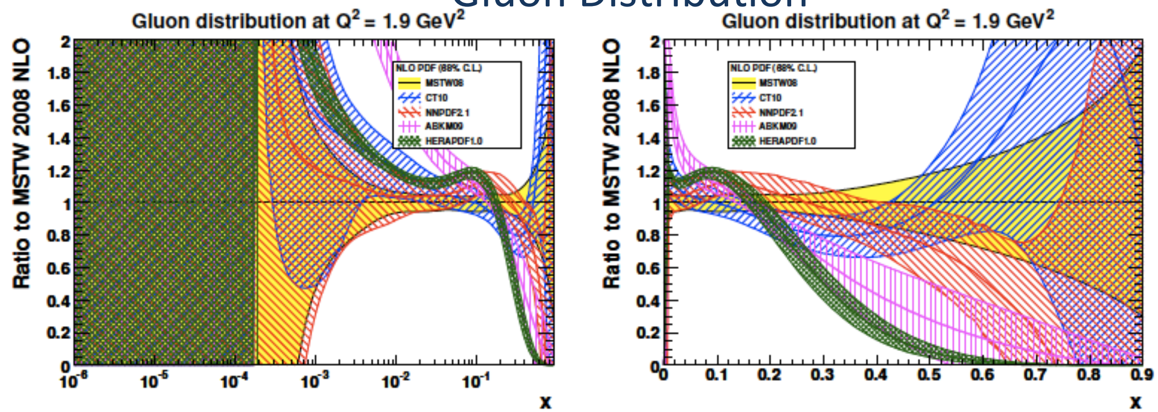
CDR

153 pages

now

then

Gluon Distribution



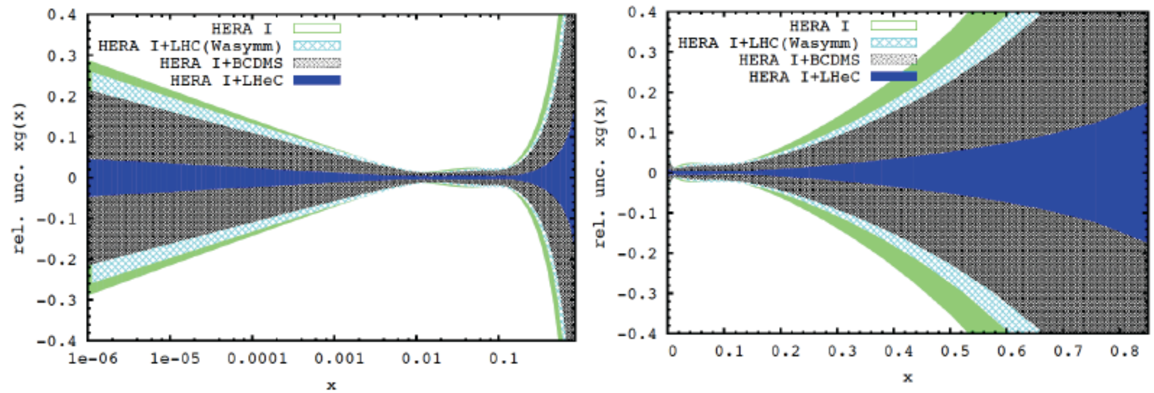
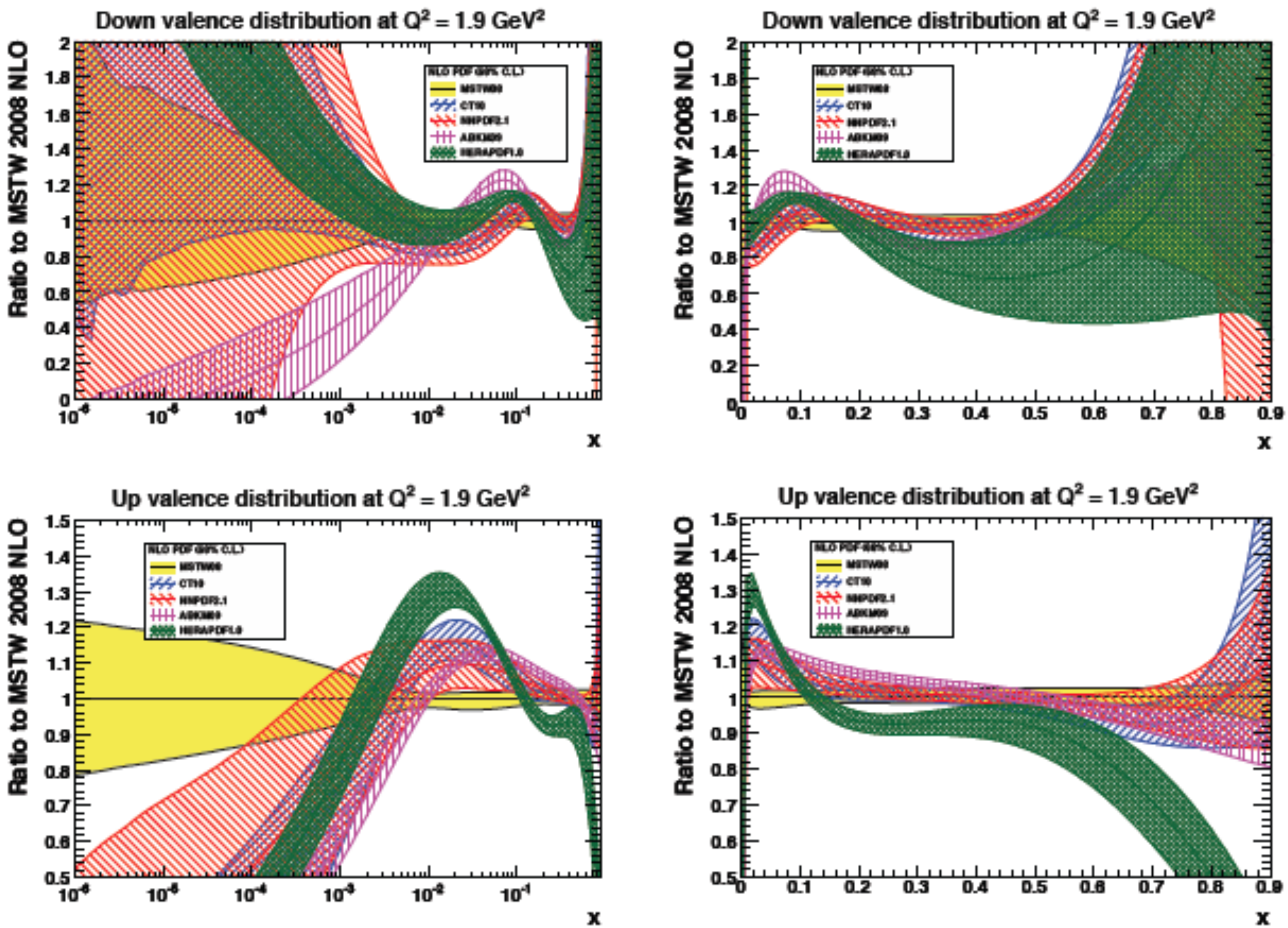


Figure 4.17: Relative uncertainty of the gluon distribution at $Q^2 = 1.9$ GeV^2, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x, right: linear x.

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?

Valence Quarks - now



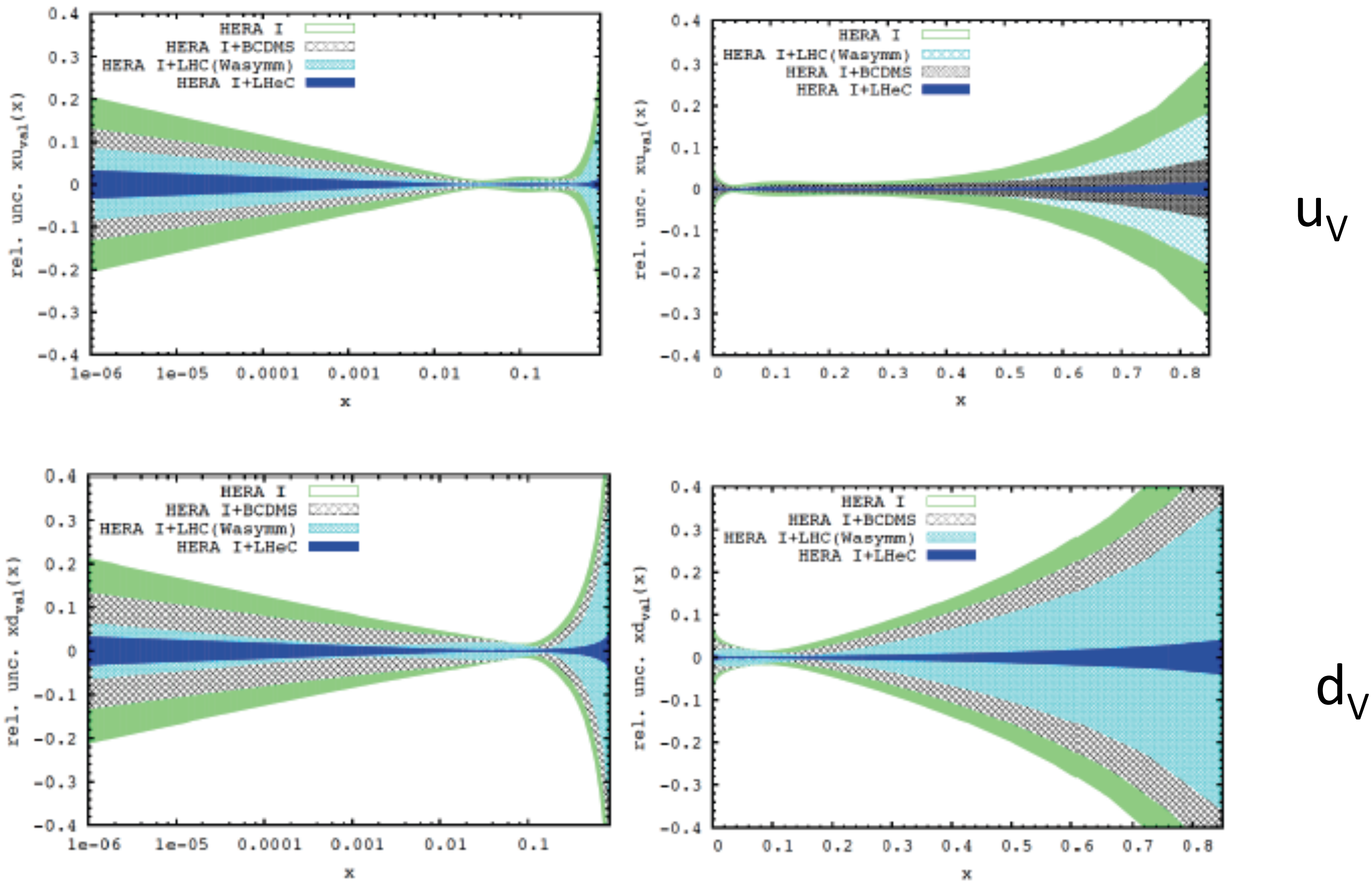
d_V

u_V

logarithm x Bjorken

linear x Bjorken

Valence Quarks - then

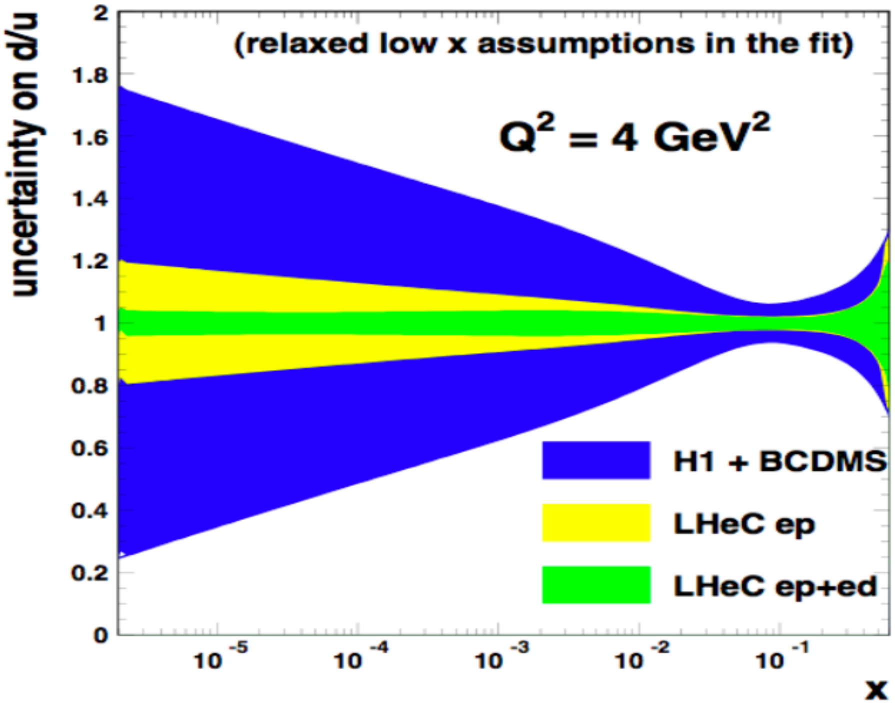


logarithm x Bjorken

linear x Bjorken

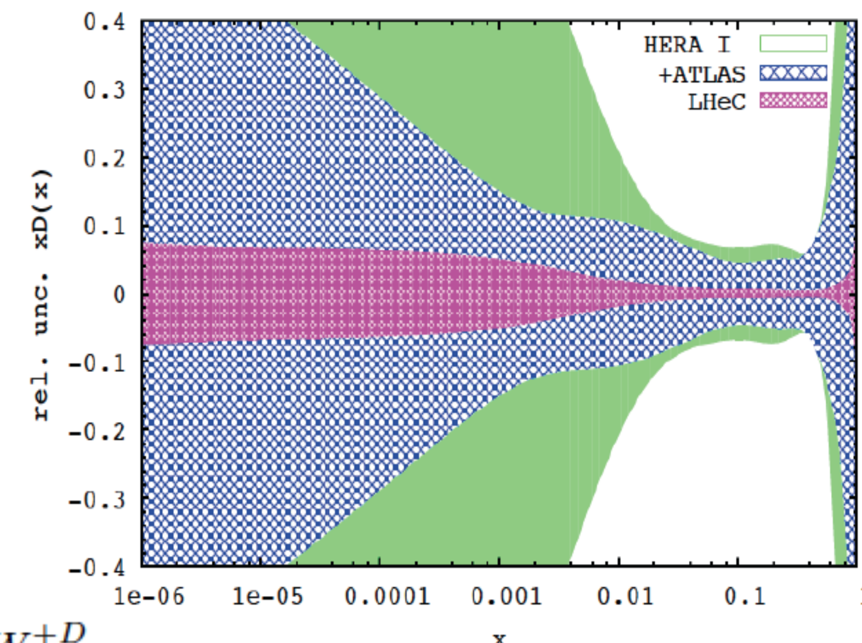
Deuterons and Light Sea Quark Asymmetry

d/u at low x from deuterons



D="total down" from LHeC (ep) fit with FREE d-u difference, including simulated high precision LHC W,Z

CDR



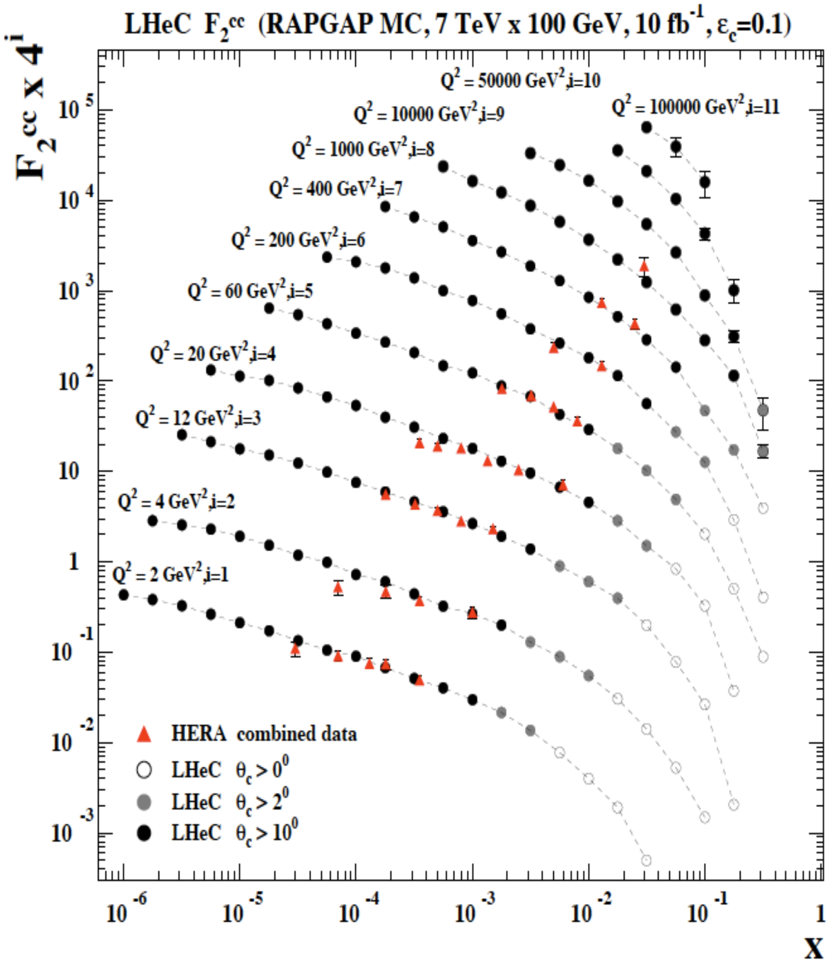
Deuterons: Crucial for

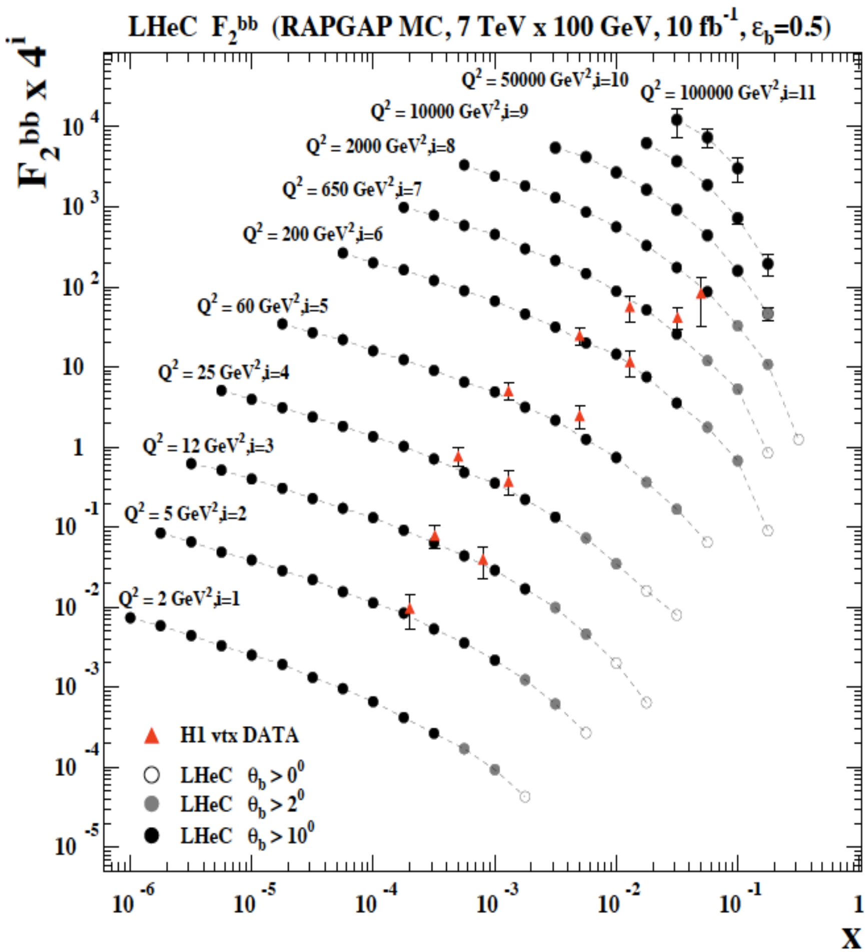
- NS-S decomposition
- Neutron structure
- Flavour separation

$$R^{-} = 2\frac{W_2^{-D} - W_2^{+D}}{W_2^{-p} + W_2^{+p}}$$

Nice: Gribov relation and spectator tagging to get rid off shadowing and Fermi motion!!

F_2^{charm} and F_2^{beauty} at HERA and the LHeC



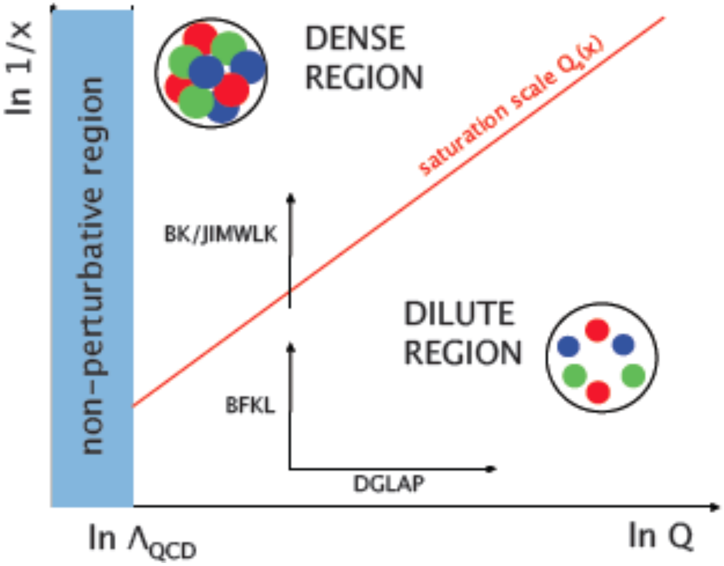


Hugely extended range and much improved precision **(δM_c=60 HERA → 3 MeV)**

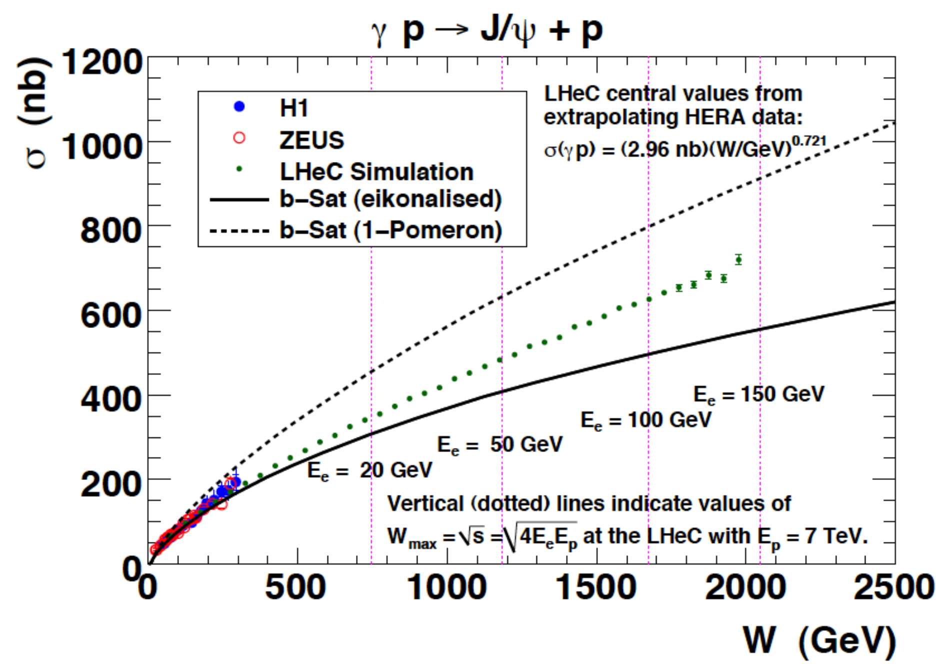
will pin down heavy quark behaviour at and far away from thresholds, crucial for precision t,H..

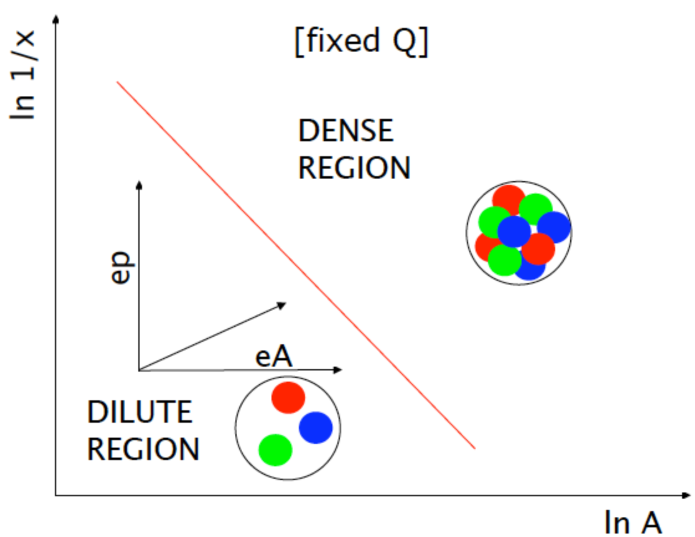
Intrinsic Charm? In MSSM, Higgs is produced dominantly via bb → H , but where is the MSSM..

Low x Physics



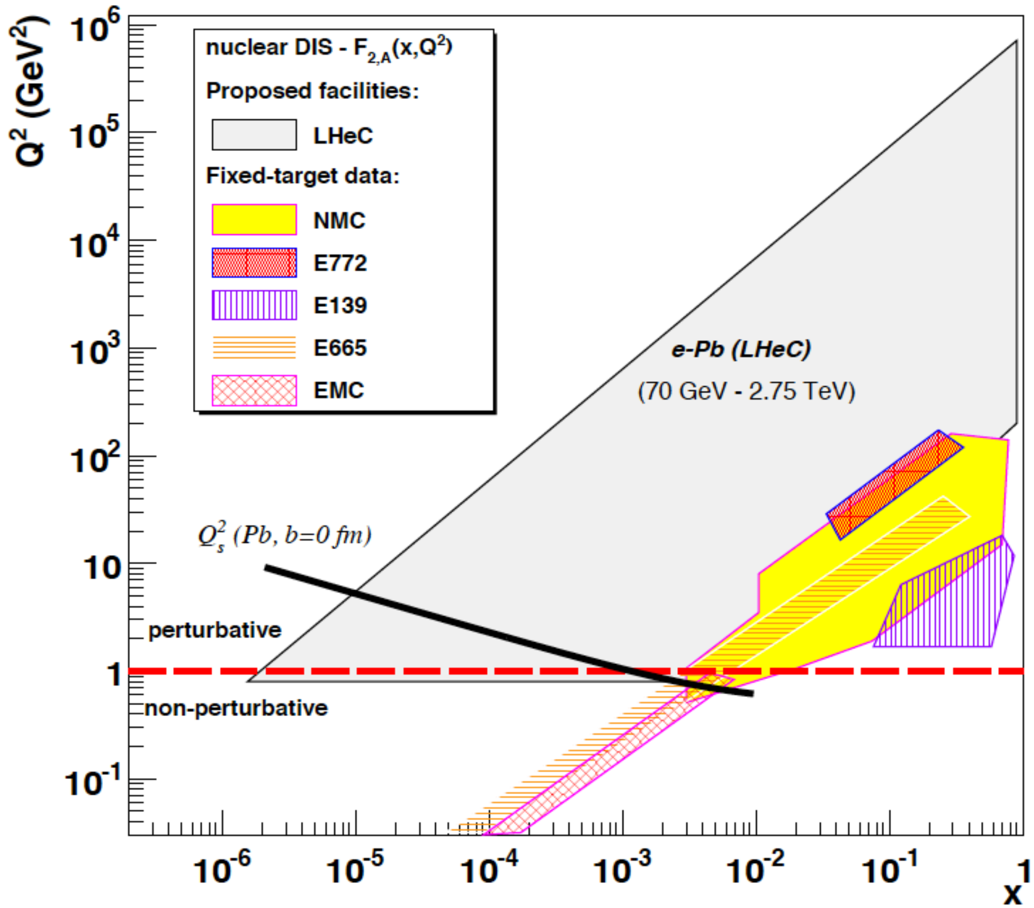
Precision Measurements of various crucial observables (F_2, F_L, J/ψ, diffraction

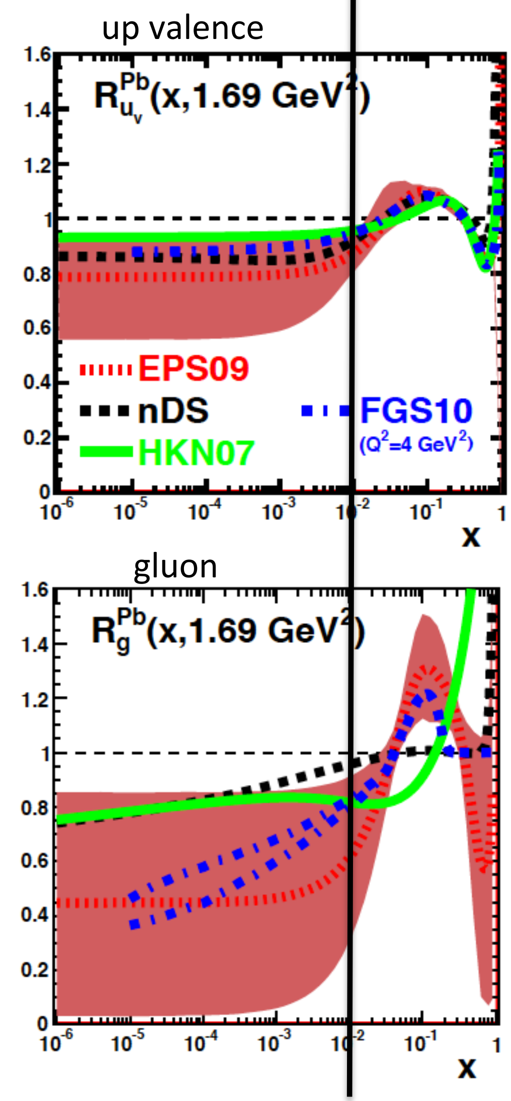




DGLAP → nonlinear evolution
Saturation of the gluon density??

Nuclear Parton Distributions from eA





3-4 orders of magnitude extension of lA kinematic range

unmeasured | known?

→ LHeC has huge discovery potential for new HI physics

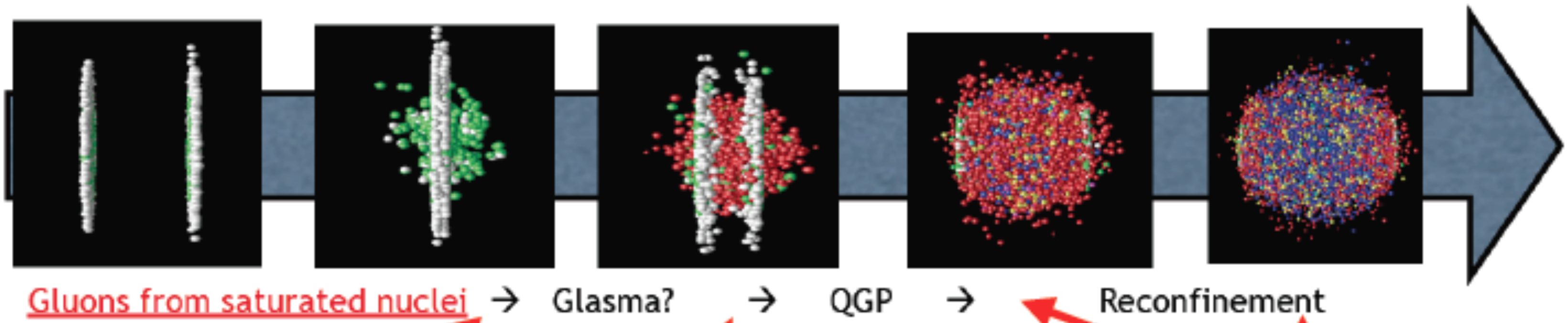
(bb limit, saturation.. will put nPDFs on completely new ground

New Physics: LHeC and LHC

Physics of the Quark-Gluon Plasma
Grand Unification and the Strong Coupling Constant
PDFs, xg and the Higgs Production in pp at the LHC
PDFs, xg and the HL-LHC Discovery Reach
The strange quark distribution in ep and pp
Top Physics and Lepto-Quarks

Cf most recent: M.D'Onofrio New Physics with the LHeC, LPCC Workshop on LHeC 3/2013

Relation of the LHeC and the LHC HI Program



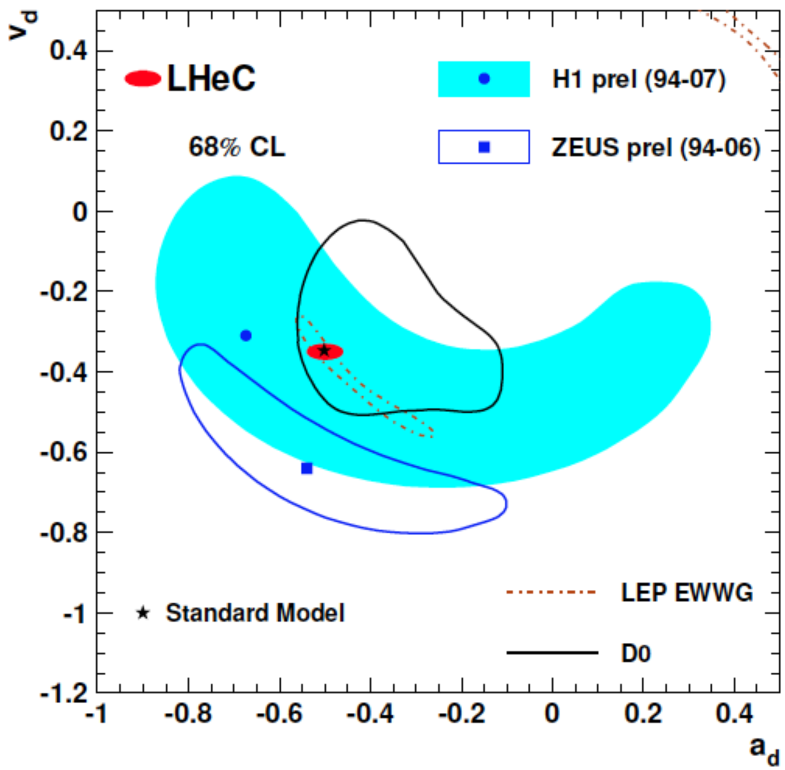
- Nuclear wave function at small x: nuclear structure functions.

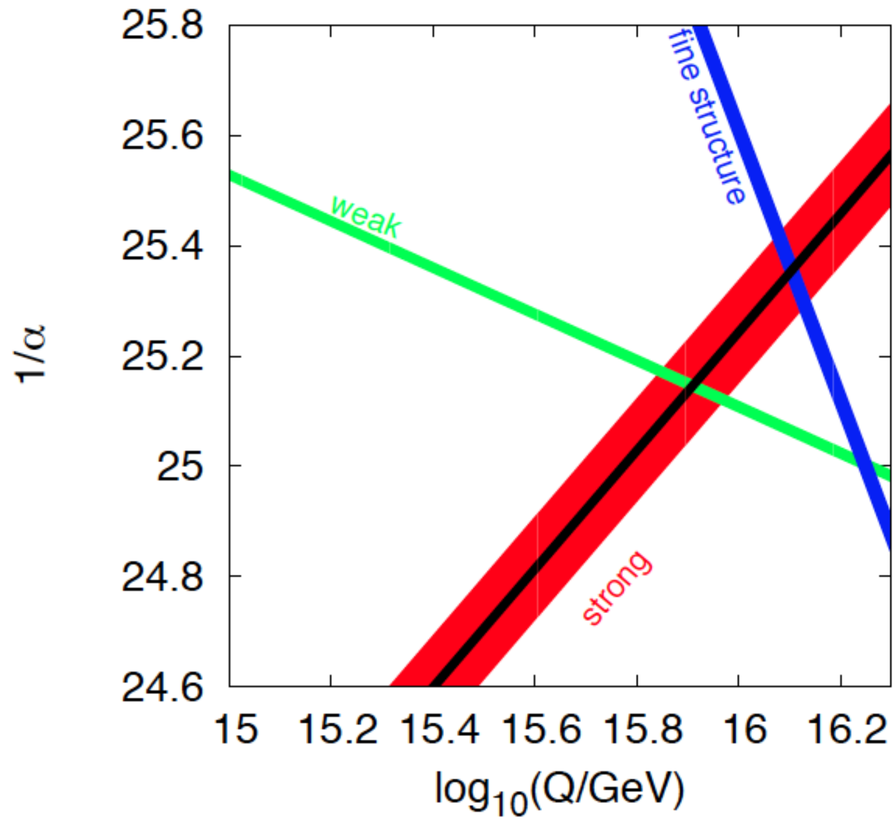
- Particle production at the very beginning: which factorisation in eA?

- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

High Precision DIS

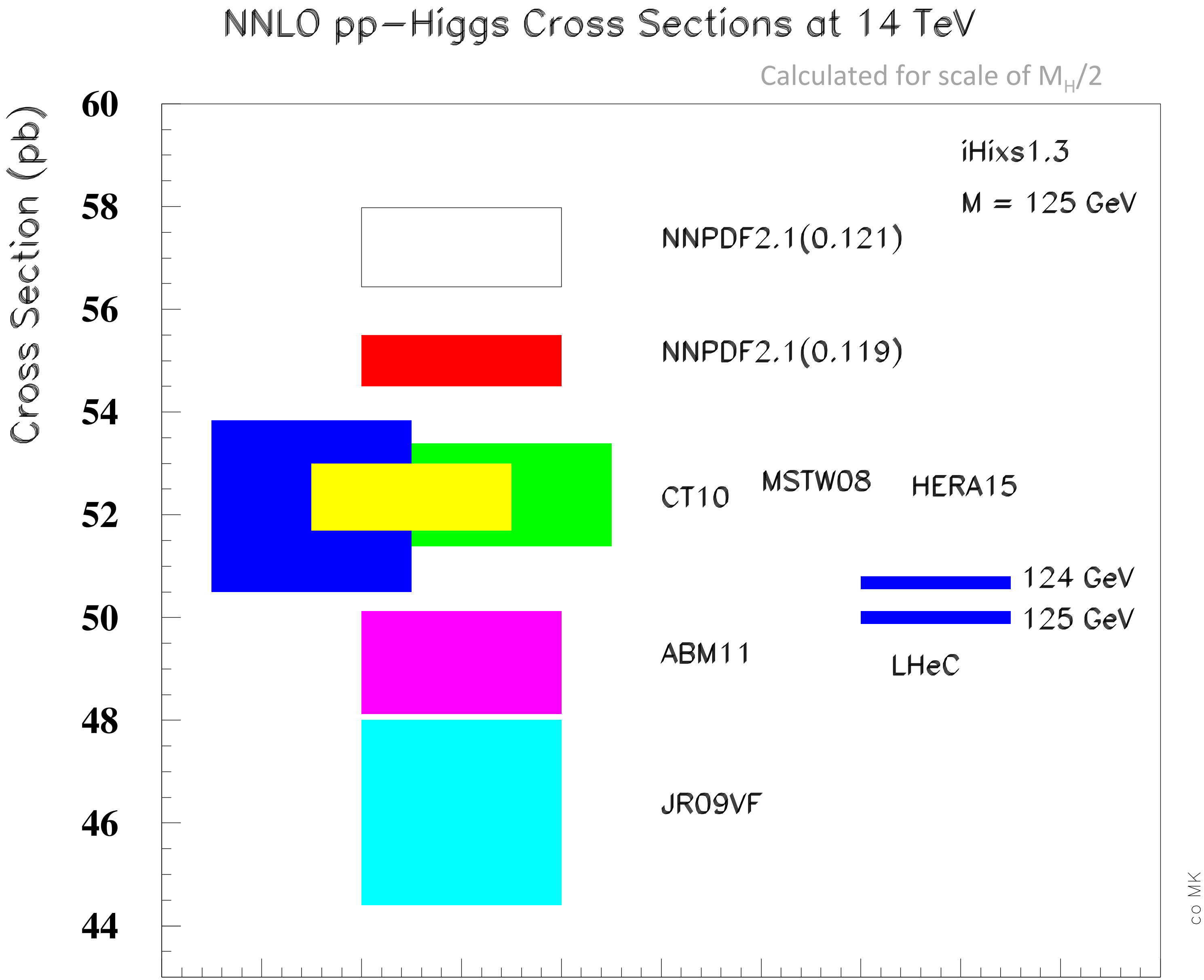




$Q^2 >> M_{Z,W}^2$, high luminosity, large acceptance
Unprecedented precision in NC and CC
Contact interactions probed to 50 TeV
Scale dependence of $\sin^2\theta$ left and right to LEP

→ 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



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

Leads to H mass sensitivity.

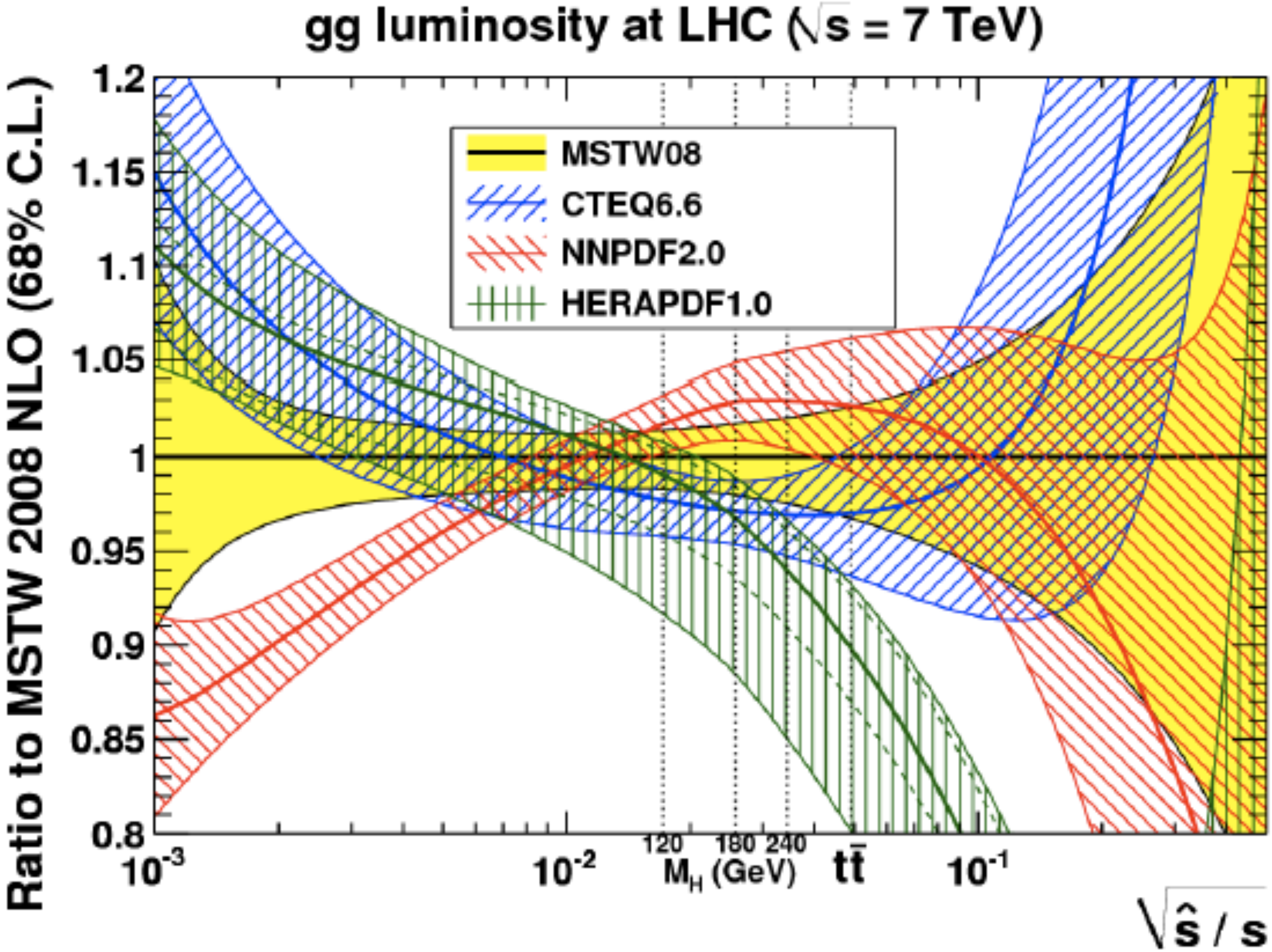
Strong coupling underlying parameter (0.005 – 10%). LHeC: 0.0002

Needs N^3LO

HQ treatment important

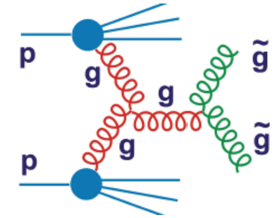
PRECISION σ(H)

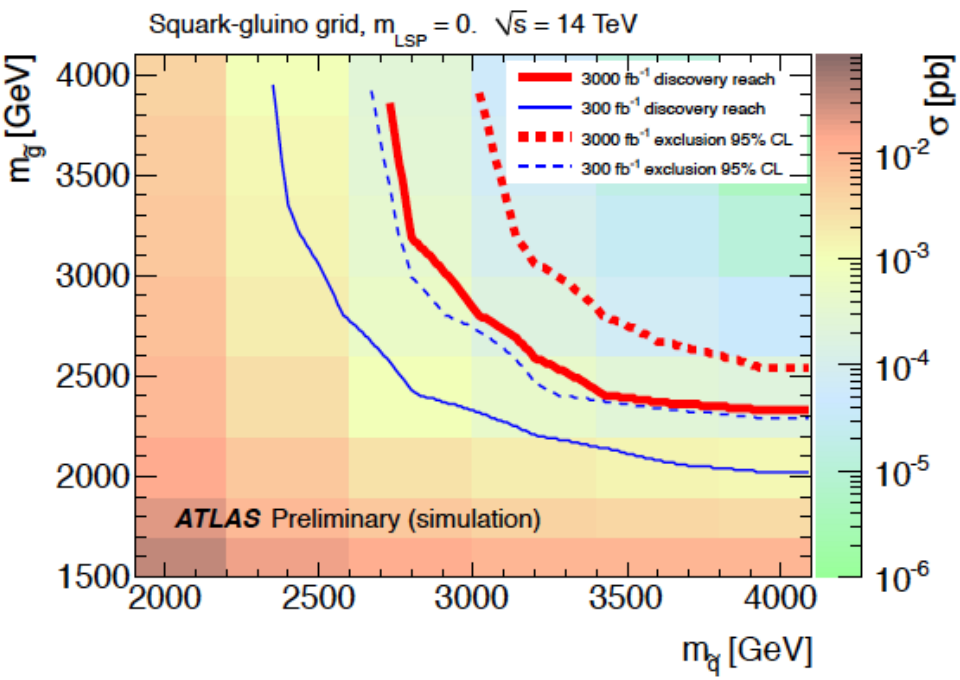
Bandurin (ICHEP12) Higgs physics at the LHC is limited by the PDF knowledge



gg luminosity at LHC (√s = 7 TeV)
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
MSTW08
CTEQ6.6
NNPDF2.0
HERAPDF1.0
10^-3
10^-2
120
180
240
M_H (GeV)
tt̄
10^-1
√ŝ / s

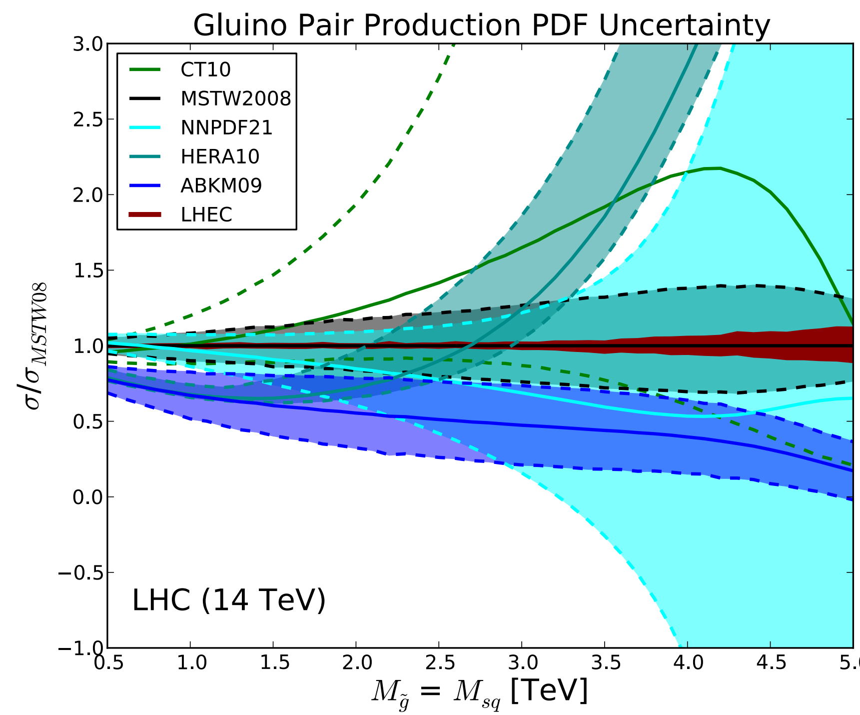
Link to HL LHC, e.g. High Mass SUSY





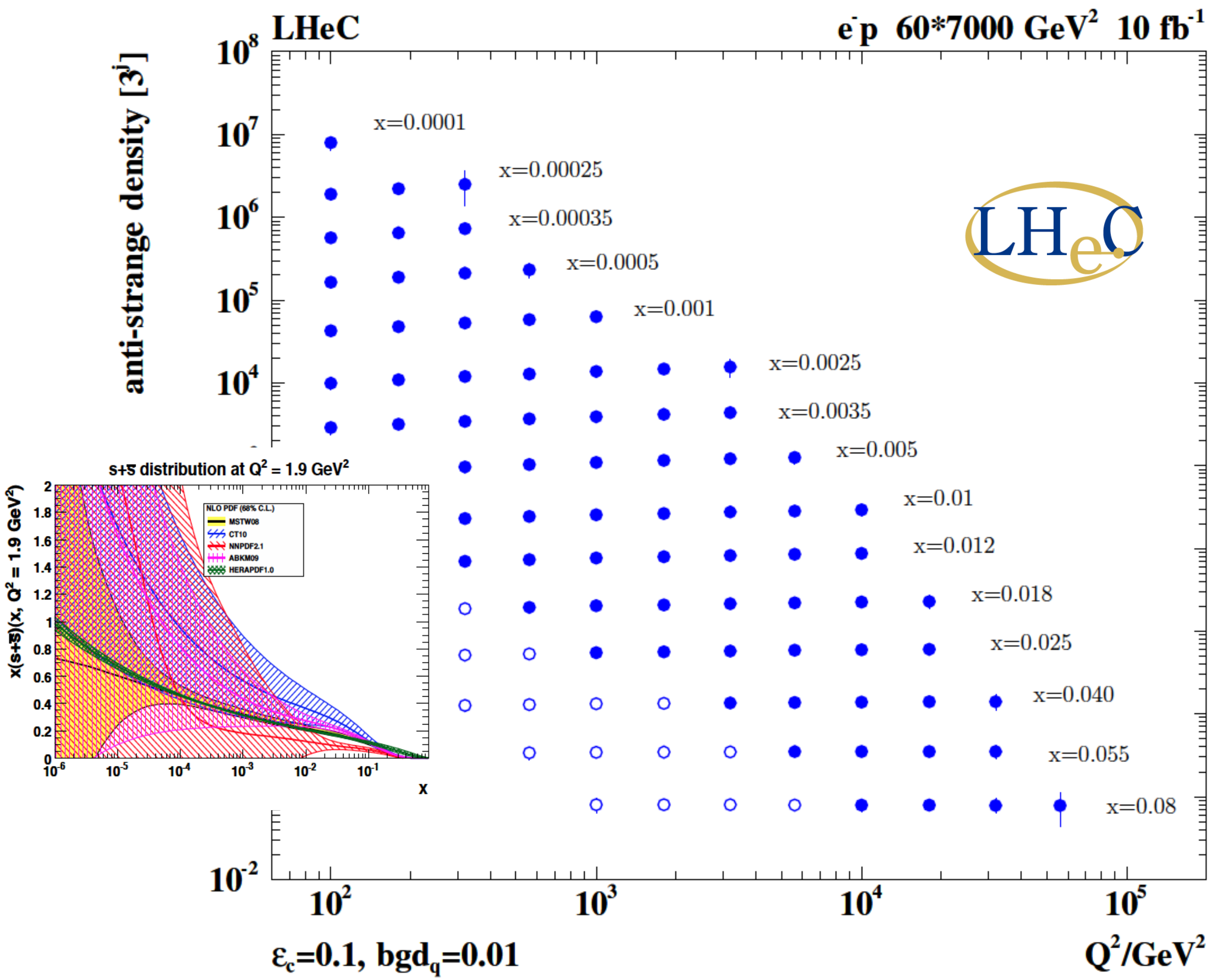
ATLAS October 2012 “Physics at High Luminosity”

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), CI effects?

Strange Quark Distribution



High luminosity

High Q^2

Small beam spot

Modern Silicon

NO pile-up..

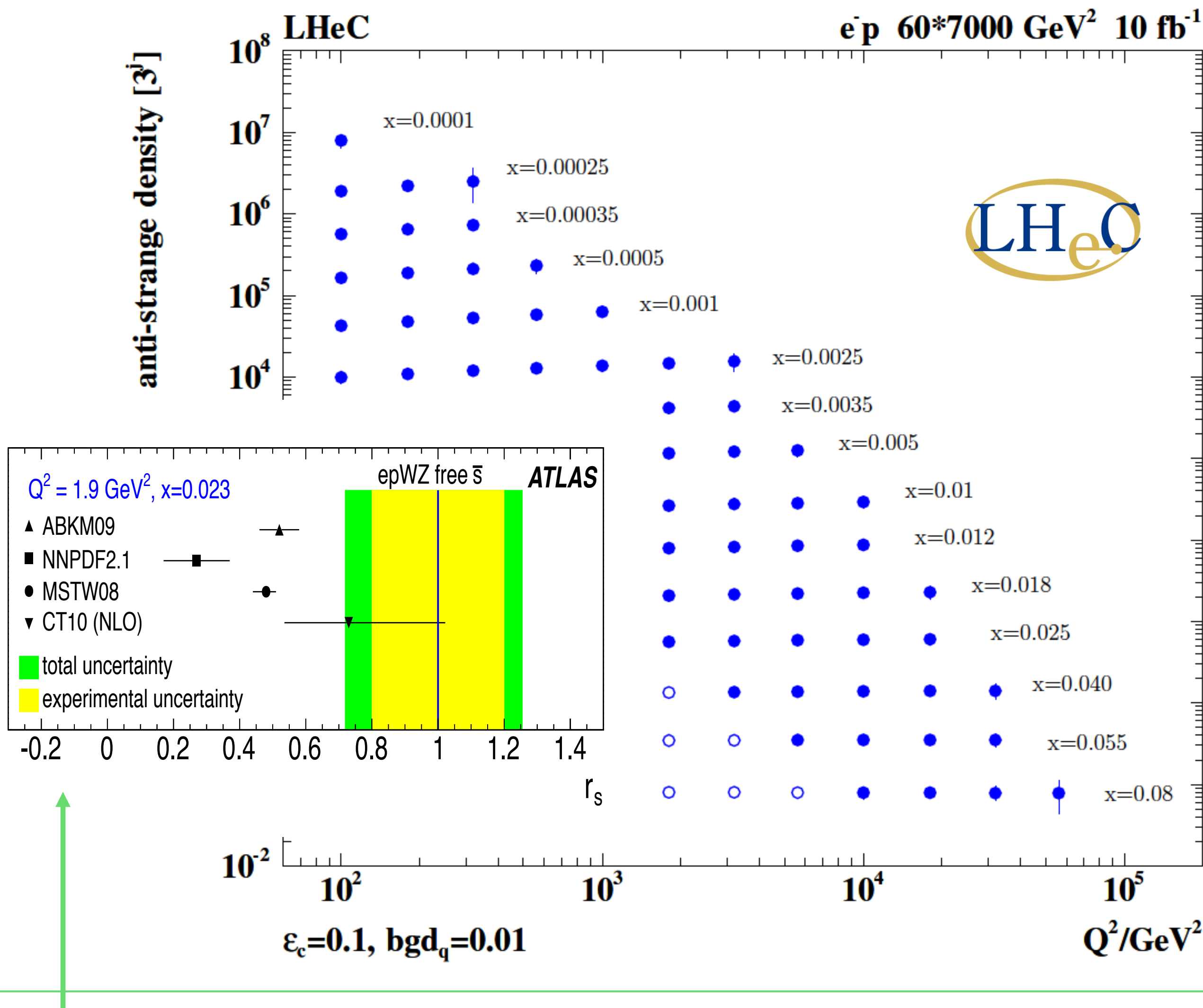
→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

$x = 10^{-4}$ .. 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

Strange Quark Distribution



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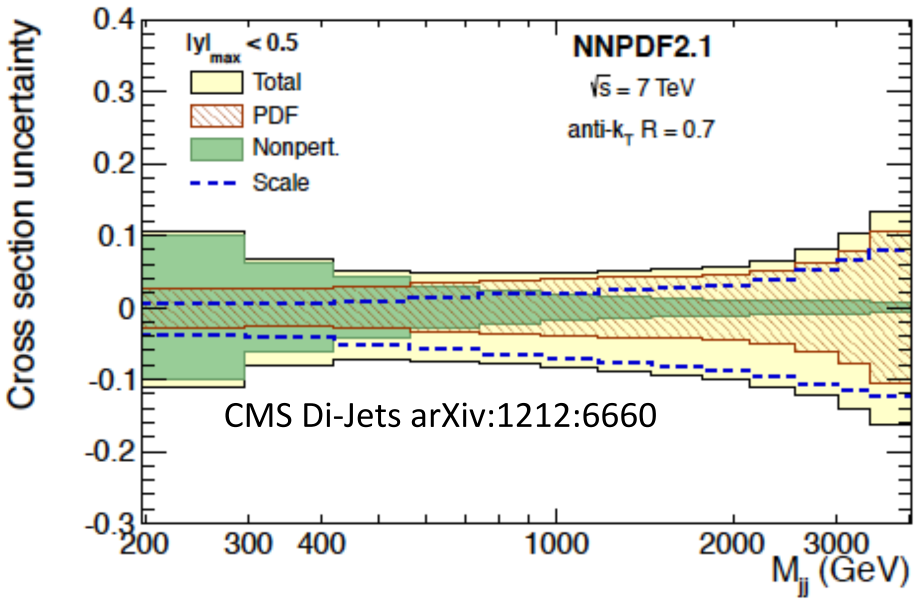
$x = 10^{-4} .. 0.05$
$Q^2 = 100 – 10^5 \, GeV^2$

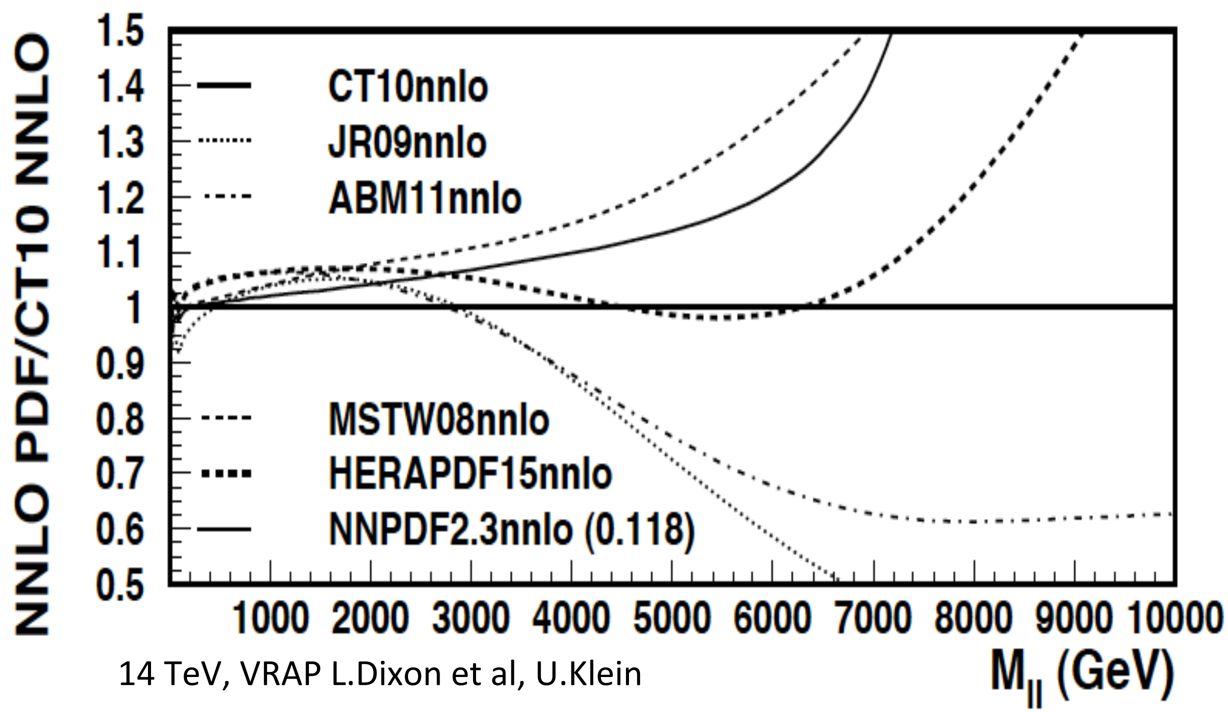
HERA+ATLAS (W,Z data from 2010): Determination of strange/anti-down quark ratio: symmetric light sea?
Obtain PDF constraints from LHC, but: no direct determinations (Q2,x), less precision, factorisation, BSM?

High Mass Drell Yan



Towards high mass the PDF uncertainties rise, strongly towards the edge (√s) x → 1…

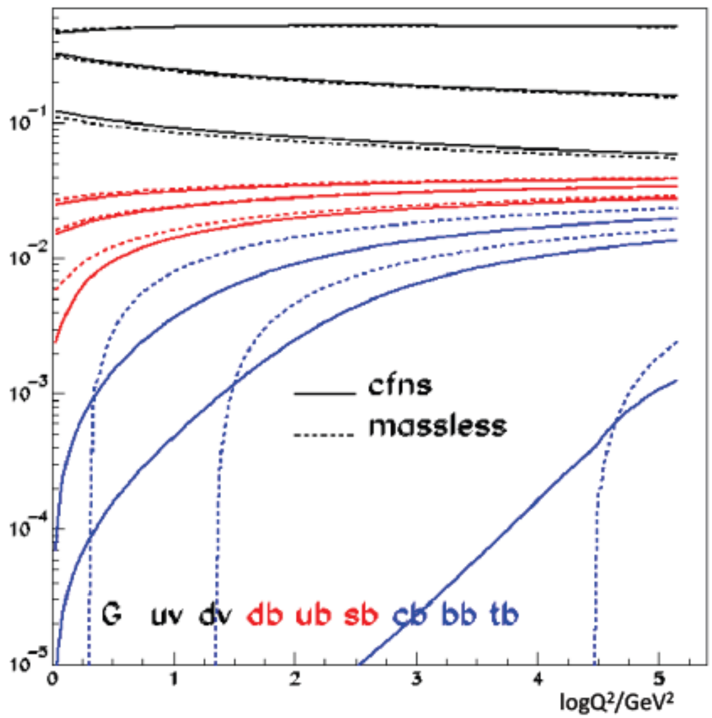
For HL-LHC:
Need to study limits and interferences (ED?) in context with energy calibrations, and thy uncertainties, + PDFs vs BSM expectations

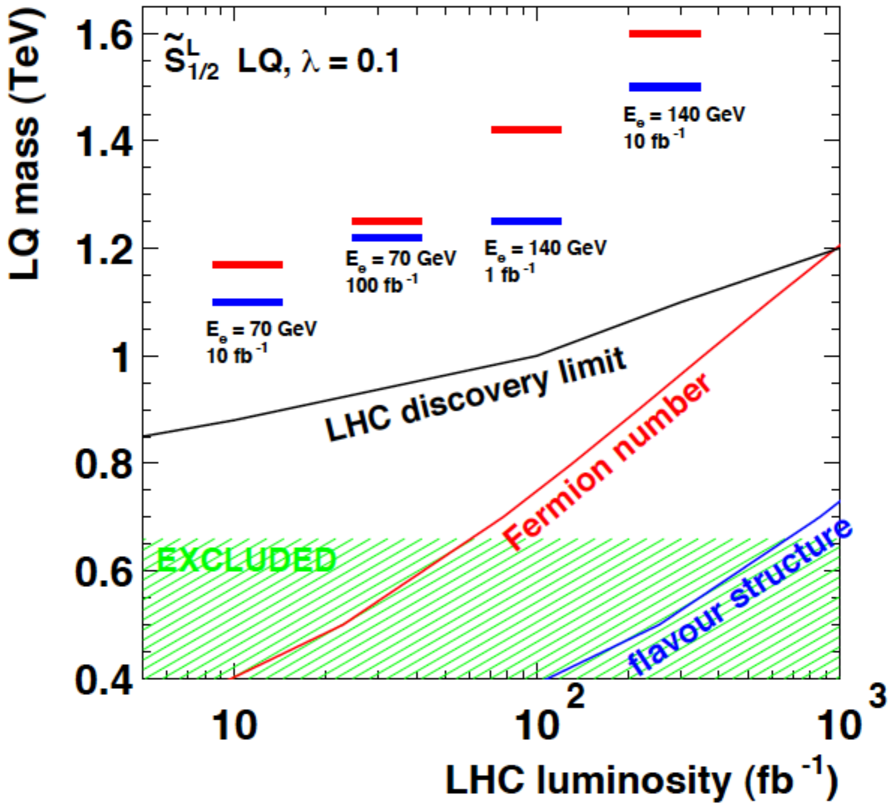


14 TeV, VRAP L.Dixon et al, U.Klein

Top Quark and Leptoquarks

The LHeC is a (single) top quark production factory, via Wb → t. Top was never observed in DIS. With ep: top-PDF → 6 flavour VFNS, precision M_t direct and from cross section, anomalous couplings [to be studied]





Leptoquarks (-gluons) are predicted in RPV SUSY, E6, extended technicolour theories or Pati-Salam.

The LHeC is the appropriate configuration to do their spectroscopy, should they be discovered at the LHC.

The LHeC Design and the Higgs

Ring-Ring and Linac-Ring Choice
A Simulation of WW→H→bbar
Higgs on ATLAS
LHeC as a Higgs "Factory"
Rates for LHeC and ILC
CP Properties at the WW and ZZ Vertices

LHeC

L vs E_e

Storage Ring

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

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

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

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

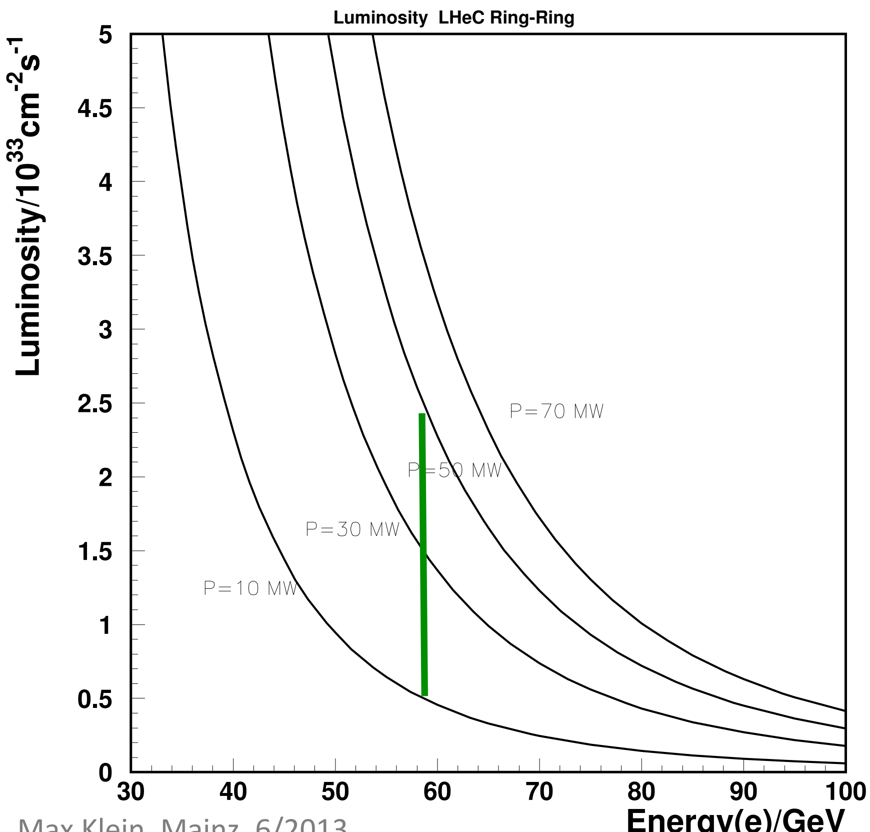
Energy Recovery Linac

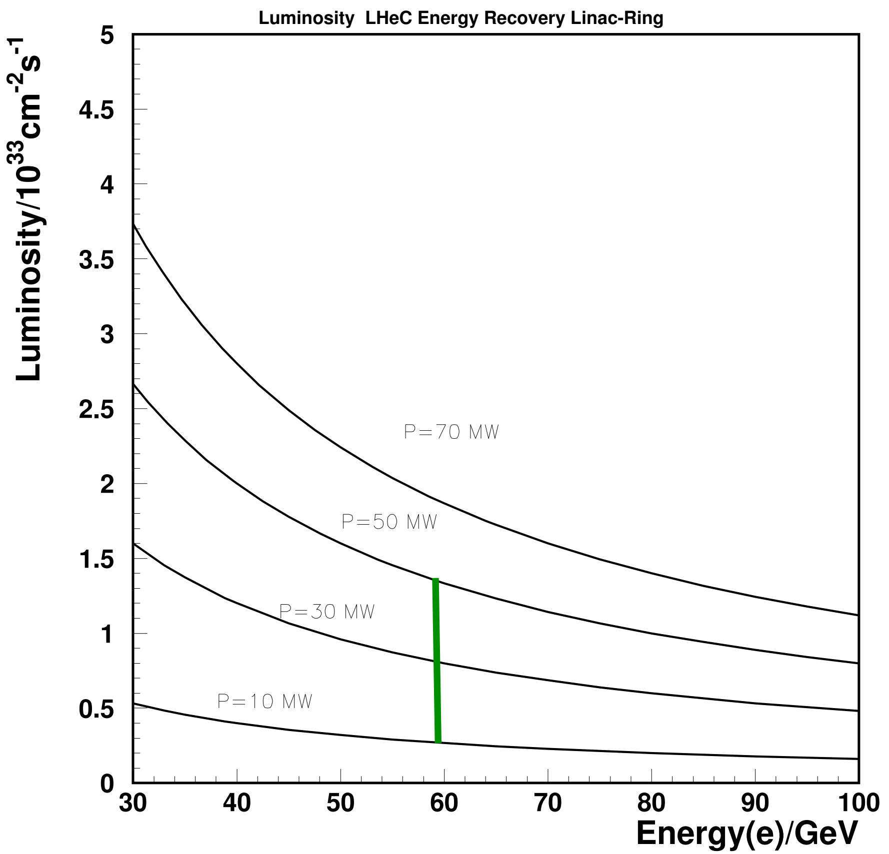
$$L = \frac{1}{4\pi} \cdot \frac{N_p}{\varepsilon_p} \cdot \frac{1}{\beta^*} \cdot \gamma \cdot \frac{I_e}{e}$$

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

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

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

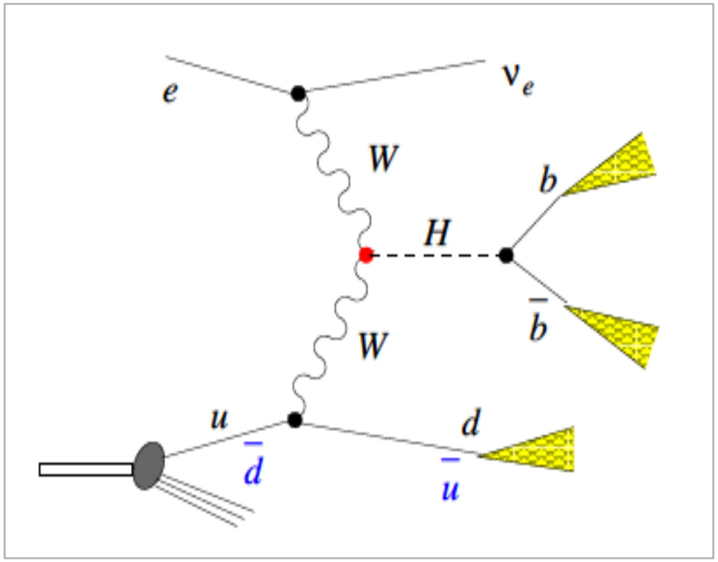




Higgs at the LHeC

Clean final state, no pile-up, low QCD bgd, uniquely WW and ZZ, small theory unc.ties

Default



	E_e = 150 GeV (10 fb^{-1})	E_e = 60 GeV (100 fb^{-1})
H → bb signal	84.6	248
S/N	1.79	1.05
S/√N	12.3	16.1

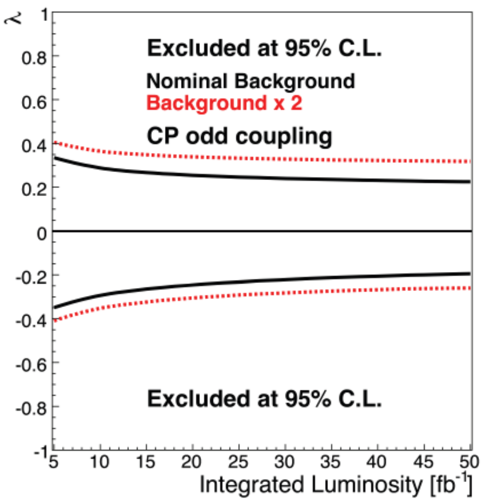
U. Klein, ICHEP12, Melbourne for the LHeC

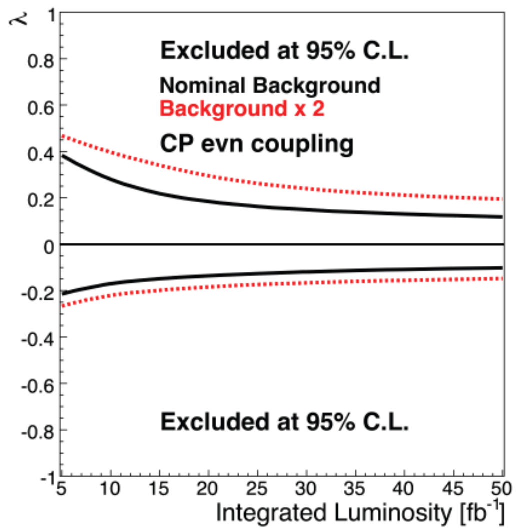
Full simulation of ep → nu H X → nu bbar X: reconstruction efficiency of 2.5%

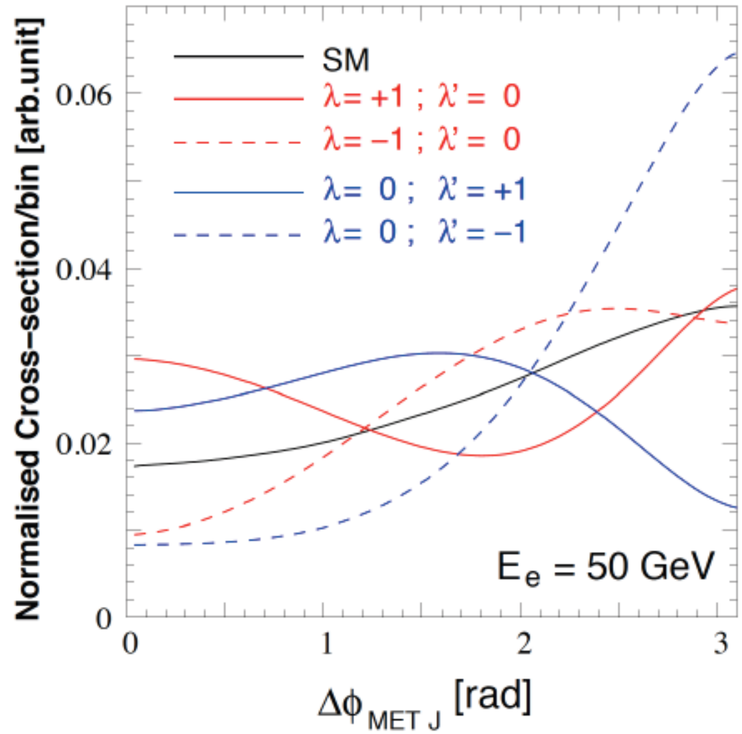
With **polarised** electrons, 100fb^{-1} - bb coupling measurement precision of 2-3%.

CP Higgs at the LHeC

In the SM the Higgs is a $J^{PC}=0^{++}$ state.
One needs to measure the EV if CP
is conserved, and the mixture of even
and odd states if it is not.







λ (λ') anomalous CP (non) conserving terms

$$\mathcal{L}_{\rm int} = -gM_W \left(W_\mu W^\mu + \frac{1}{2\cos\theta_W} Z_\mu Z^\mu \right) H$$

$$\Gamma^{\mu\nu}_{\rm (SM)}(p,q) = \; -gM_W \, g^{\mu\nu}$$

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

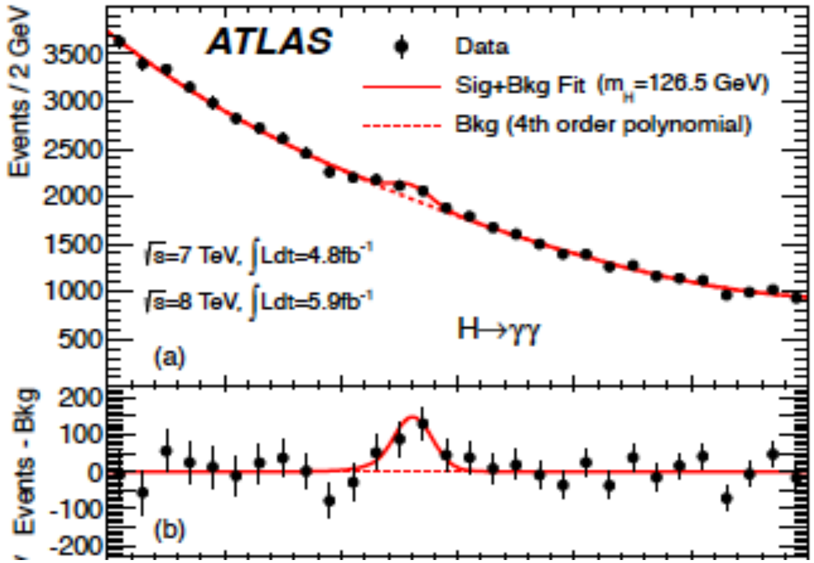
S.Biswal et al, PhysRevLett.109.261801

Discovery of H

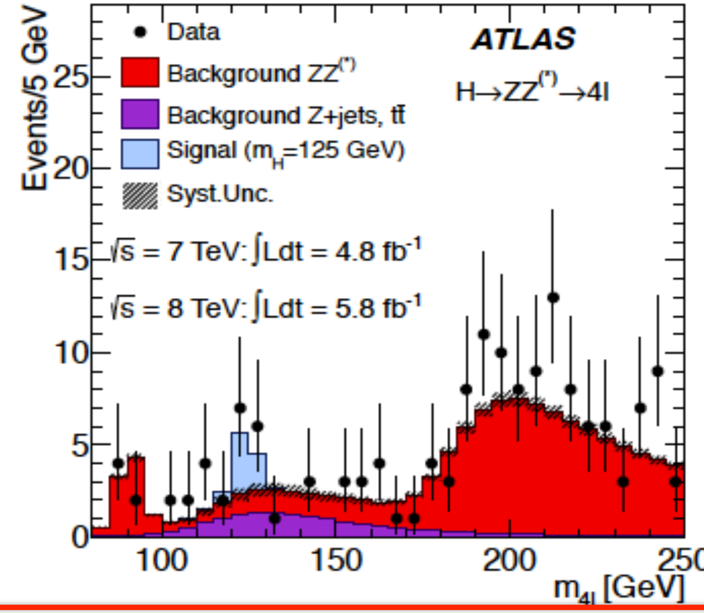
$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ^* \rightarrow 4l$

4.7.2012 ICHEP Melbourne

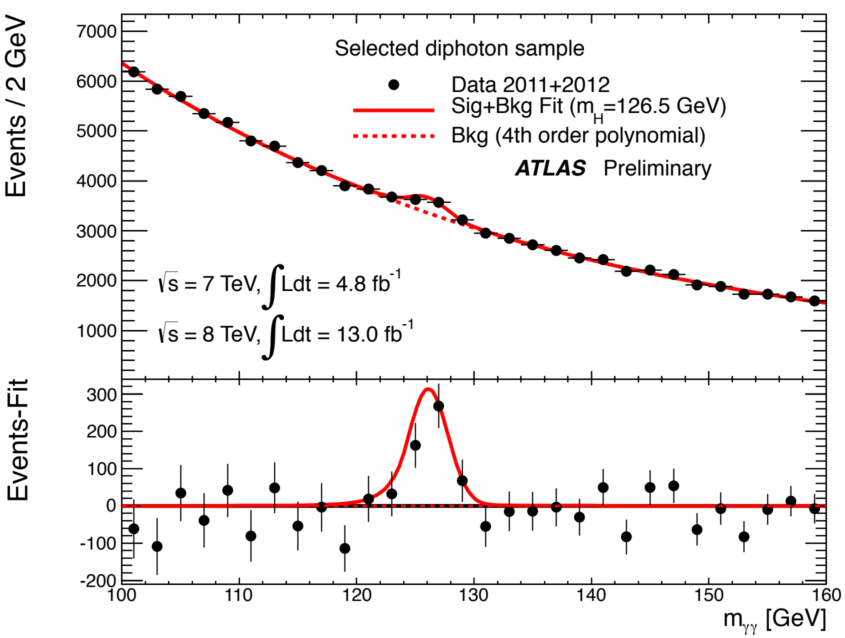


arXiv:1207.7214

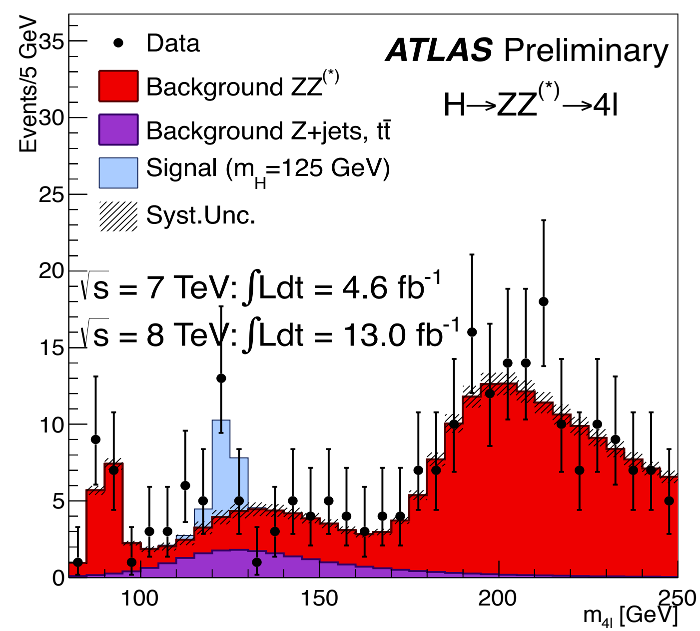


arXiv:1207.7214

13.12.2012 CERN Council



ATLAS CONF 2012-168



ATLAS CONF 2012-169

LHeC at 10^{34} Luminosity

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

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

LHeC Collaboration arXiv:1211:5102, see also O.Bruening and M.Klein arXiv:1305.2090, MPLA 2013

LHeC Higgs Rates

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

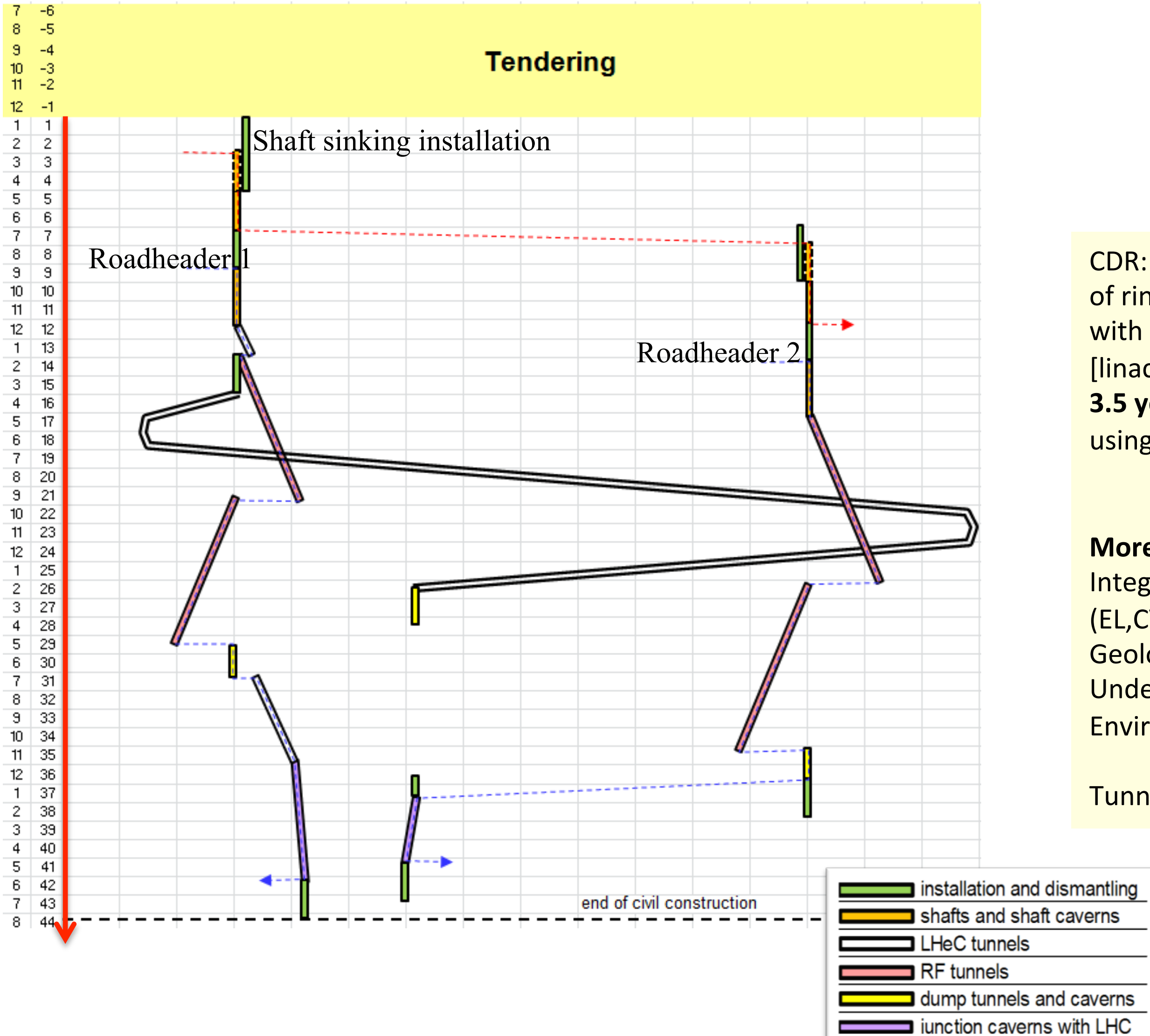
H-bbar coupling to 0.7% precision with 1ab-1, at an S/B of 1 – studies of t, c, .. to come
The LHeC WW → H cross section is as large as the ILC Z*→ZH cross section (300fb)…

50pb LHC, HL-LHC + ep H and PDFs : transform the LHC facility into a genuine H factory

Technical Design of the LHeC and a Detector

Civil Engineering
Components
Interaction Region and Q1
A Detector for Precision DIS Physics
Installation Study

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

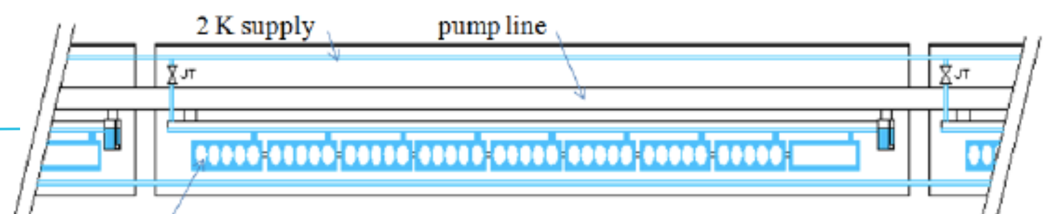
J.Osborne, Chavannes

Chapter 9 of CDR

Components and Cryogenics

	Ring	Linac
magnets		
number of dipoles	3080	3504
dipole field [T]	0.013 – 0.076	0.046 – 0.264
number of quadrupoles	968	1514
RF and cryogenics		
number of cavities	112	960
gradient [MV/m]	11.9	20
linac grid power [MW]	–	24
synchrotron loss compensation [MW]	49	23
cavity voltage [MV]	5	20.8
cavity R/Q [Ω]	114	285
cavity Q_0	–	$2.5\ 10^{10}$
cooling power [kW]	5.4@4.2 K	30@2 K

Jlab: $4\ 10^{11}$

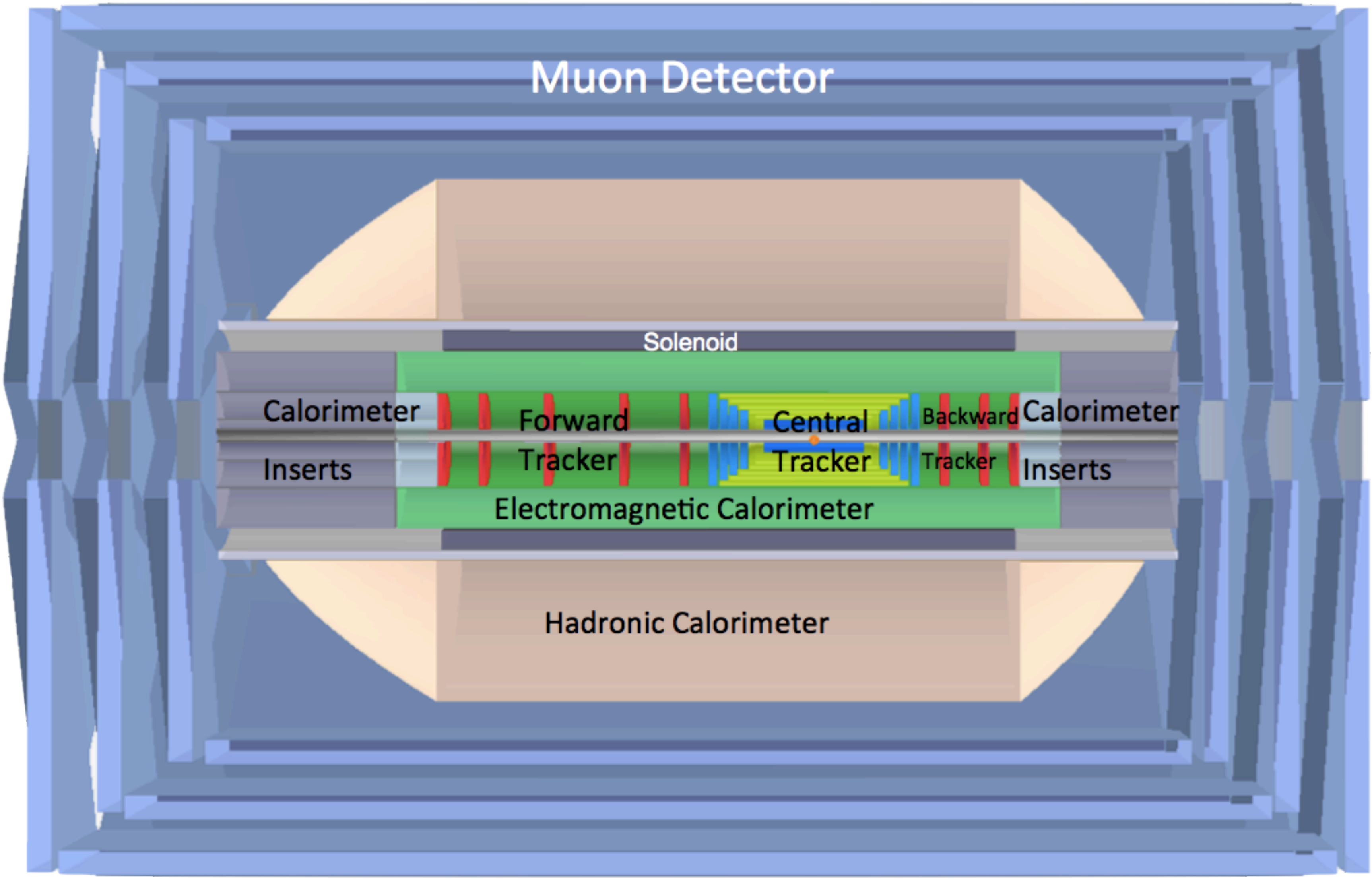


Need to develop LHeC cavity (cryo-module)

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

LHeC Detector Overview



Max Klein, Mainz, 6/2013

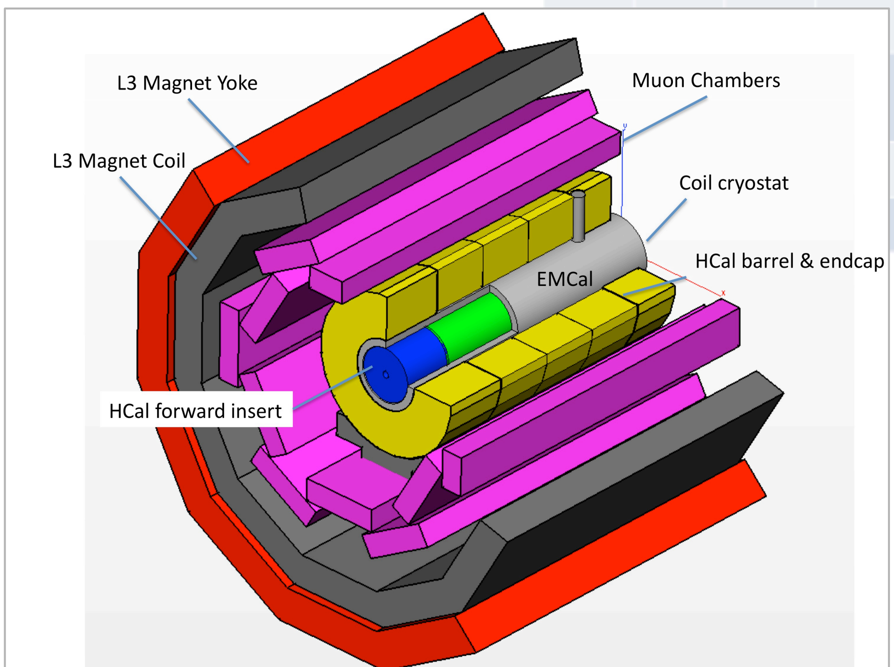
Detector option 1 for LR and full acceptance coverage

Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =14x9m^2 [CMS 21 x 15m^2, ATLAS 45 x 25 m^2]
Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

Time Schedule*)

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
	RF Proto Type Development												
				RF Production and Test Stand Operation									
			Magnet Preseries										
					Magnet Production and Testing								
				Legal Preparation									
						Civil Engineering							
									Infra-structure				
										Installation			
												Operation	

Detector installation study for IP2, reuse of L3 magnet as support for LHeC. Estimated 30 months



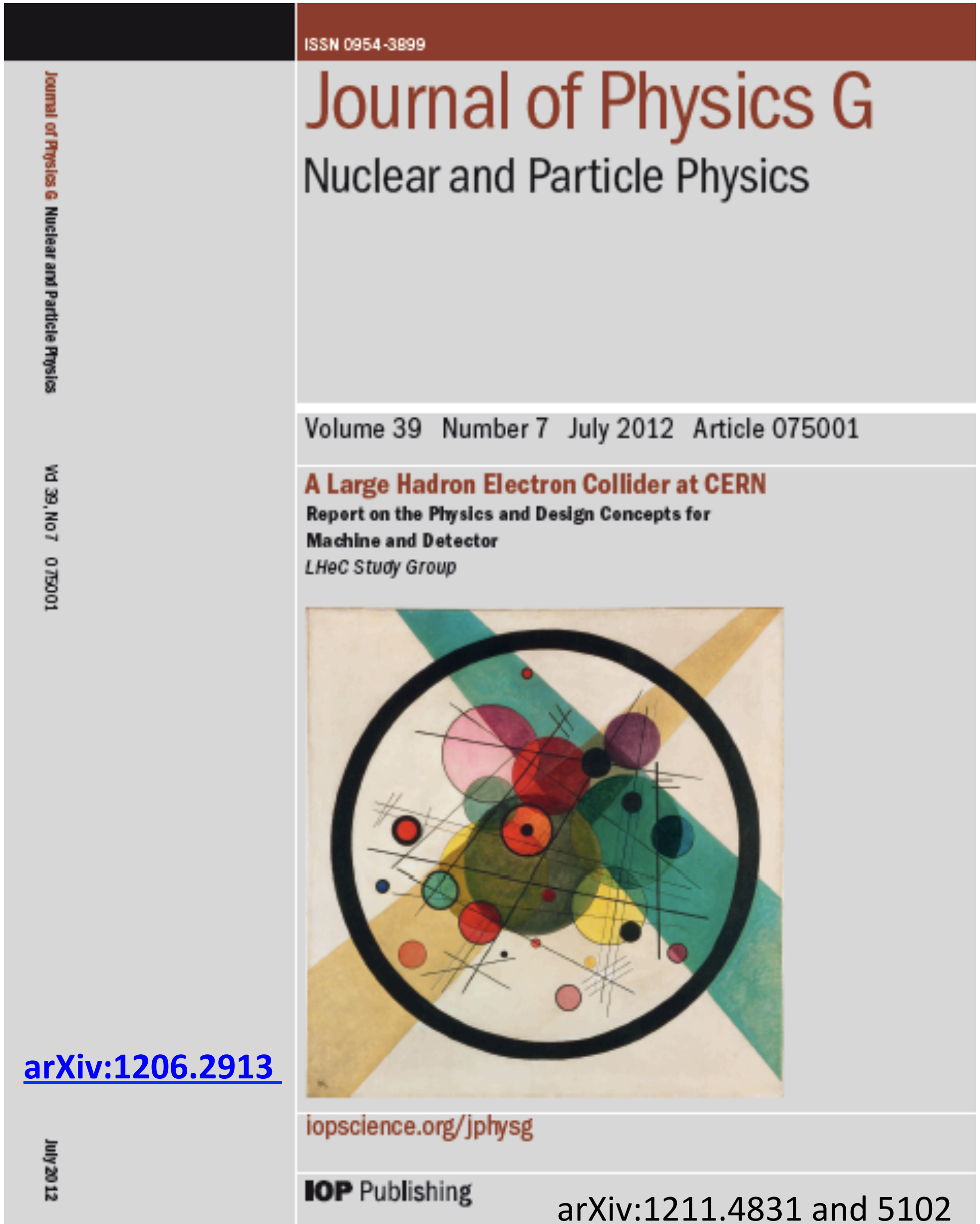
LHeC is to operate synchronous with HL-LHC

LS3 requires 2-3 years for ATLAS+. It is the one extended time period, which will allow installation and connection of LHeC

*) LS3 → schedule most likely shifted by +2 years

Prospects and Next Steps

The Conceptual Design Report
LHeC Collaboration
ECFA's Evaluation
An ERL Test Facility for the LHeC
Magnet Prototypes and Design
Interaction Region and Beam Pipe



arXiv:1206.2913

arXiv:1211.4831 and 5102

CERN Referees

Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)
Interaction Region
Daniel Pitzl (DESY)
Mike Sullivan (SLAC)
Detector Design
Philippe Bloch (CERN)
Roland Horisberger (PSI)
Installation and Infrastructure
Sylvain Weisz (CERN)
New Physics at Large Scales
Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)
Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)
Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

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

http://cern.ch/lhec

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], P.Adzic[74], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], B.Allanach[73], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], J.Bracinik[06], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], A.Caldwell[70], V.Cetinkaya[01], V.Chekelian[70], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], P.DiNezza[72], M.D'Onofrio[24], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], A.Glazov[17], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], E.Jensen[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], R.Klees[75], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], M.Kraemer[75], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], J.G.Milhano[76], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], E.Rizvi[71], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], M.Schaefer[75], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], D.South[17], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], P.Thompson[06], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], T.Ullrich[37], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[69], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]

LHeC Study group and CDR authors (Dec.2012)

About 200 Experimentalists and Theorists from 76 (+3) Institutes

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

Towards an 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

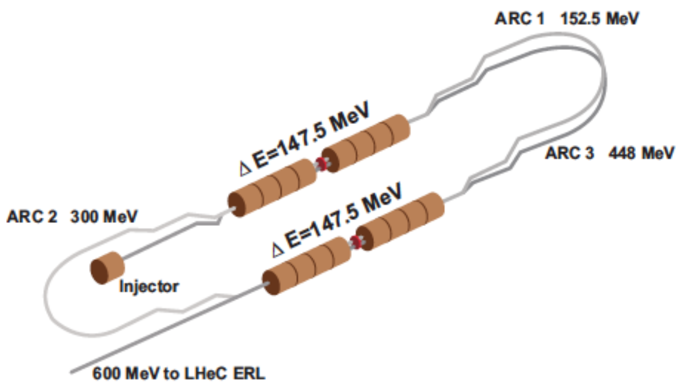


Figure 2: Consequent upgrade to LHeC pre-accelerator. By modifying the machine backleg to include a second full cryomodule, the recirculator can deliver higher beam energy of 600 MeV.

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

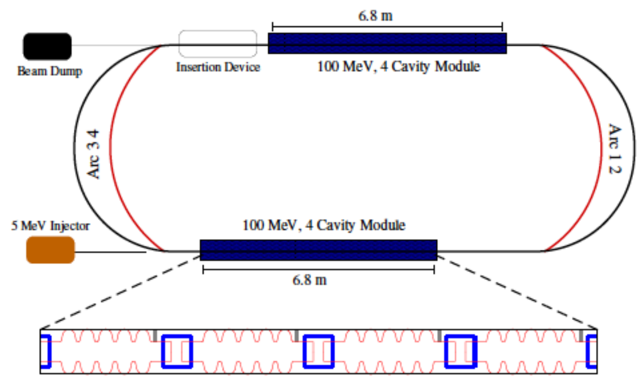


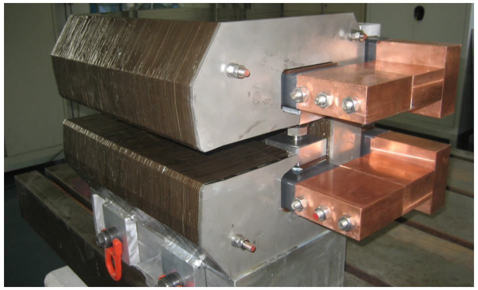
Table 3: Future ERLs for electron-hadron colliders

Parameter	JLab MEIC	BNL eRHIC	CERN LHeC
Energy [GeV]	5-10	20	60
Frequency [MHz]	750	704	n×40
# 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

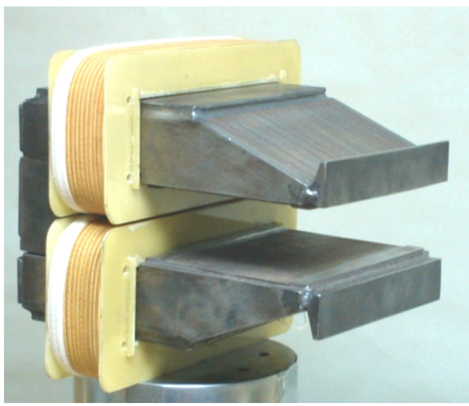
Daresbury Workshop 22/23.1.:

- 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

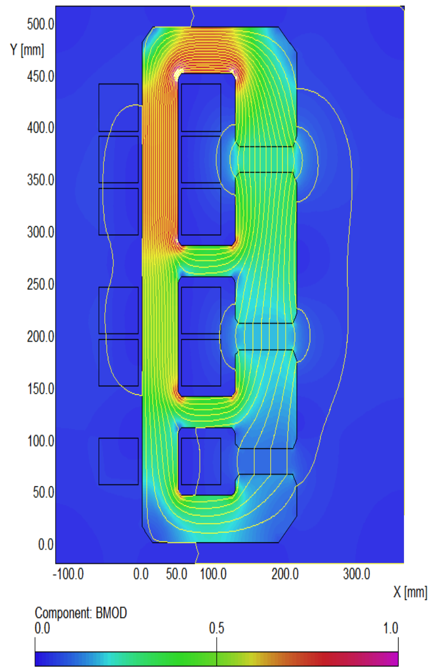
Magnet Developments



Prototypes for Ring dipoles
Fabricated and tested by
CERN (top) and Novosibirsk



LR recirculator dipoles and quadrupoles
New requirements (aperture, field)?
Combined apertures?
Combined functions (for example, dipole + quad)?
LR linac quadrupoles and correctors
New requirements (aperture, field)?
More compact magnets, maybe with at least two families for quadrupoles?
Permanent magnets / superconducting for quads?
A.Milanese, Chavannes workshop



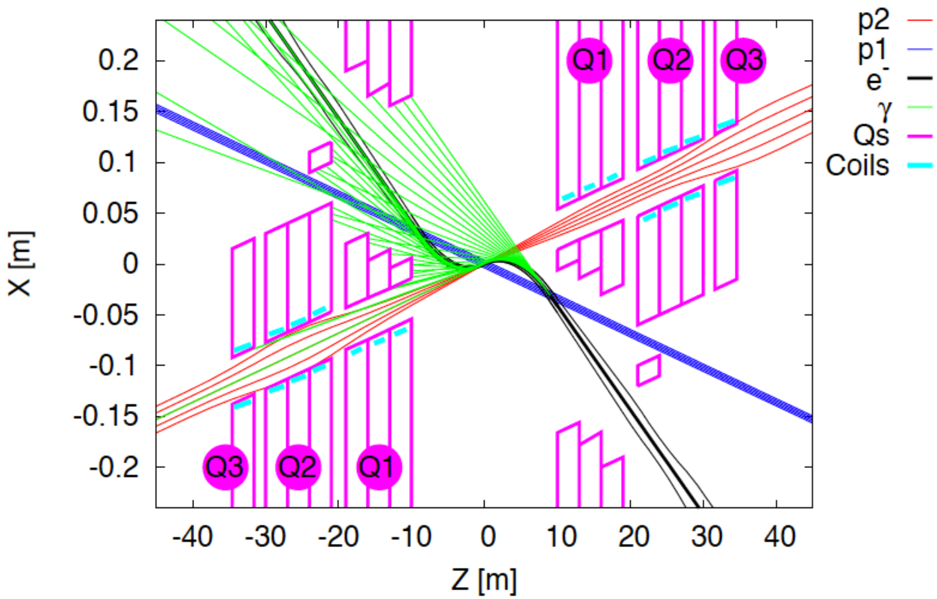
1/2m dipole model
Full scale prototype
Quadrupole for Linac

Magnets for ERL test stand

Collaboration of CERN, Beijing, Daresbury, Novosibirsk)

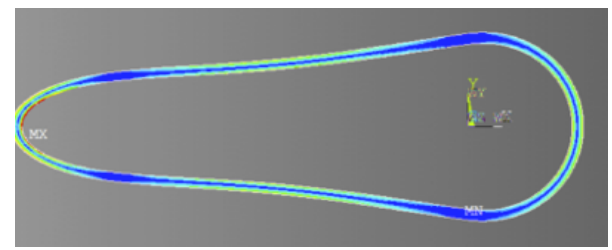
flux density in the gaps	0.264 T 0.176 T 0.088 T
magnetic length	4.0 m
vertical aperture	25 mm
pole width	85 mm
number of magnets	584
current	1750 A
number of turns per aperture	1 / 2 / 3
current density	0.7 A/ mm^2
conductor material	copper
resistance	0.36 mΩ
power	1.1 kW
total power 20 / 40 / 60 GeV	642 kW
cooling	air

Interaction Region Developments



Beam pipe: in CDR 6m, Be, ANSYS calculations

Composite material R+D, prototype, support..
→ Essential for tracking, acceptance and Higgs



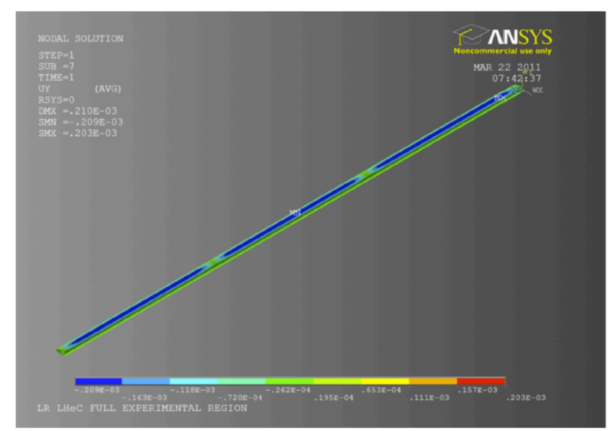


Figure 9.32: 3-D view of the LR geometry showing contours of bending displacement [m].

Have optics compatible with LHC and β*=0.1m
Head-on collisions mandatory →
High synchrotron radiation load, dipole in detector

Specification of Q1 – NbTi prototype (with KEK?)
Revisiting SR (direct and backscattered),
Masks+collimators
Beam-beam dynamics and 3 beam operation studies

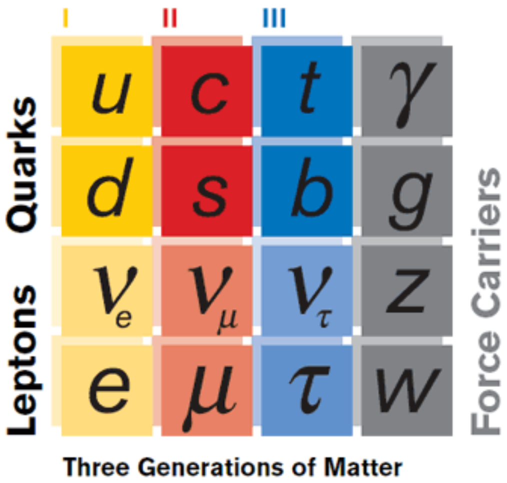
Optimisation: HL-LHC uses IR2 quads to squeeze IR1
(“ATS” achromatic telescopic squeeze) Start in IR3 – 10cm ok.

Final Remarks

Searches for New Physics
Theory and Experiment
LHeC Physics in Q^2,x
Higgs with the LHeC
Project Development
A Summary Slide
SLAC

Searching for new physics

Standard Model: remarkably successful description of known phenomena, **but** requires new physics at the (multi)TeV scale.



Extra Dimensions

- Large, warped, or universal extra dimensions
- Might provide:
  - Dark Matter candidate
  - Solution to Hierarchy problem
  - Unification of forces
- Searches for new heavy particles, black holes..

Strong EW symmetry breaking

- Modern variants of Technicolor
- Might provide:
  - Dark Matter
  - Hierarchy problem
- Possibly search for composite Higgs, new heavy vector bosons (Z', W'…), 4th generation of quarks

Composite (SUSY) theories

- Composite Higgs and top

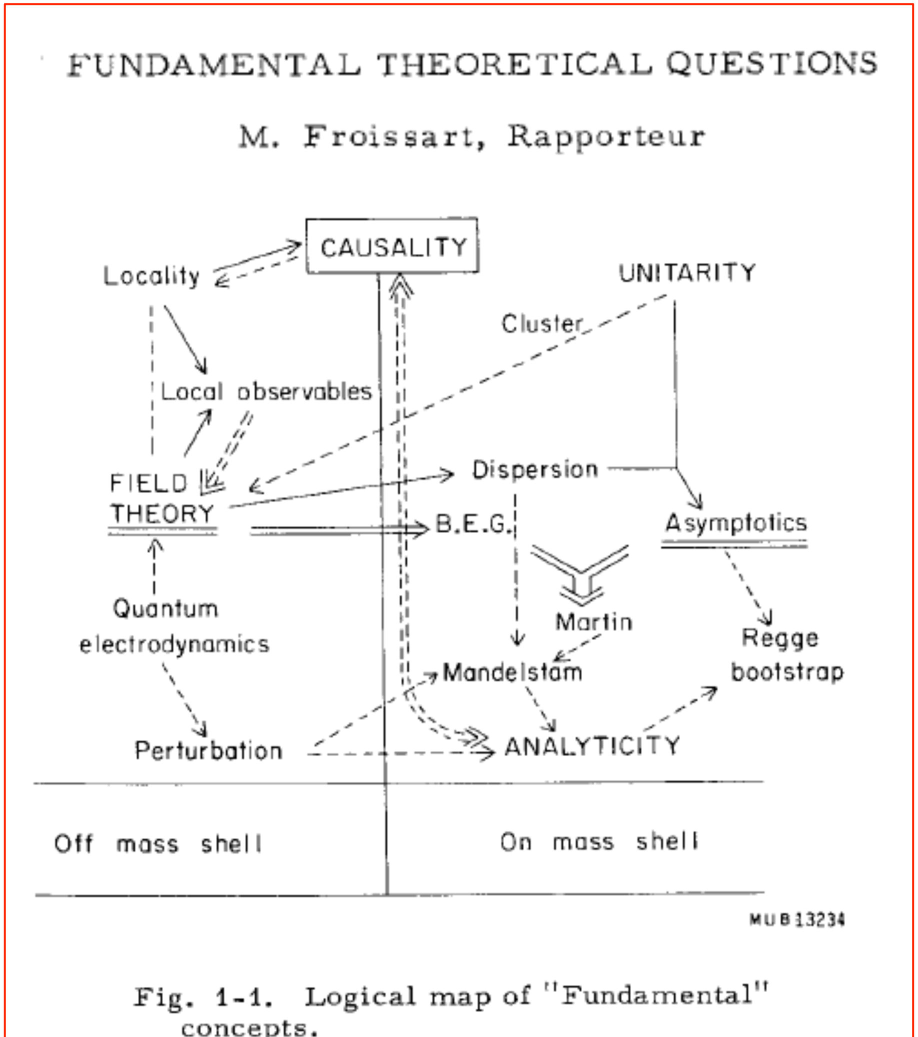
Supersymmetry

- Introduce heavy superpartners, scalar particles, light neutral Higgs
- More than100 parameters even in MSSM

M.Froissart ICHEP ("Rochester") 1966

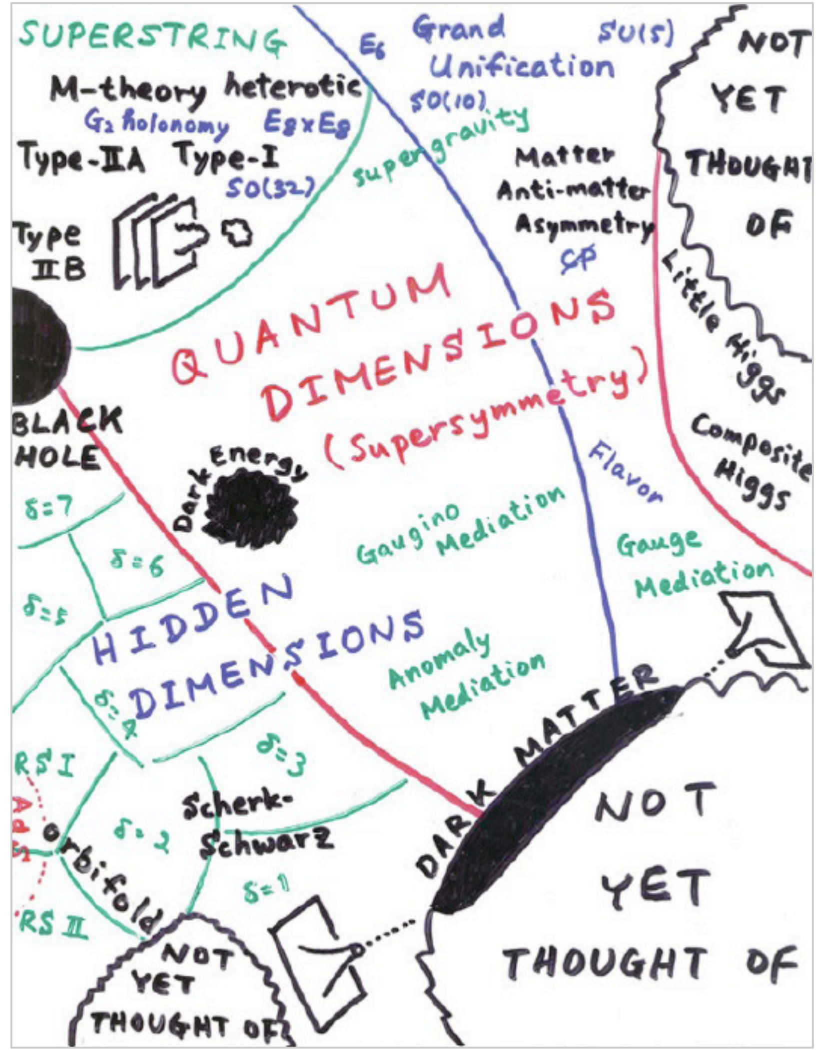
THEORY

H.Murayama – ICFA11


FUNDAMENTAL THEORETICAL QUESTIONS

M. Froissart, Rapporteur

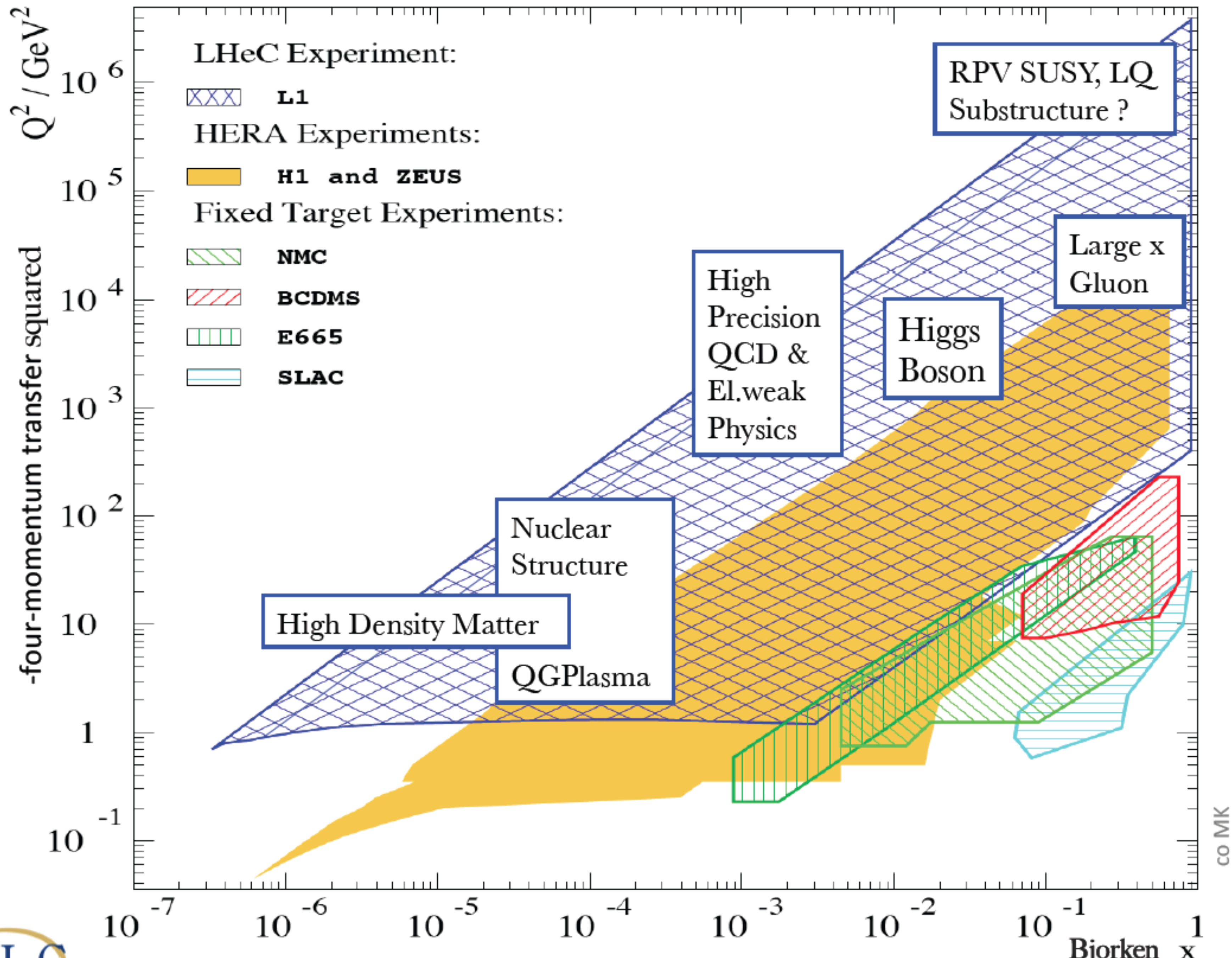
Fig. 1-1. Logical map of "Fundamental" concepts.



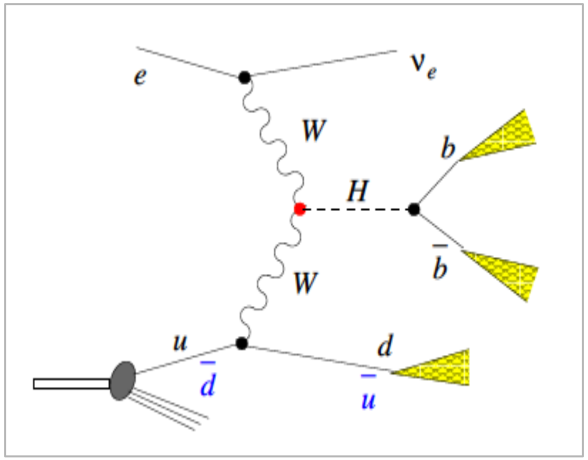
→ Quarks in 1969

→ ?in 2015+?

We like to see particle physics as driven by experiment … Burt Richter


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

Higgs with the LHeC



ZZ → H ~10 times lower rate

Unique production mechanism (WW,ZZ)
Clean experimental conditions:
No pileup, simpler final state …

LHeC at $10^{34}cm^{-2}s^{-1}$: arXiv:1211:5102
Nb: Cross section and luminosity as large as are projected for the ILC. Access to difficult channels (ττ, cc – under study)

With its unique Higgs measurements and precision N^3LO PDFs and $\delta\alpha_s$,
ep upgrade transforms the LHC facility into a precision Higgs factory.
[cf arXiv:1211:5102 + OB, MK: arXiv:1305:2090]

LHeC Higgs		CC (e^-p)
Polarisation		-0.8
Luminosity [ab^{-1}]		1
Cross Section [fb]		196
Decay	BrFraction	N^H_{CC} e^-p
$H \to b\bar{b}$	0.577	113 100
$H \to c\bar{c}$	0.029	5 700
$H \to \tau^+\tau^-$	0.063	12 350
$H \to \mu\mu$	0.00022	50
$H \to 4l$	0.00013	30
$H \to 2l2\nu$	0.0106	2 080
$H \to gg$	0.086	16 850
$H \to WW$	0.215	42 100
$H \to ZZ$	0.0264	5 200
$H \to \gamma\gamma$	0.00228	450
$H \to Z\gamma$	0.00154	300

Rates for E_e=60 GeV, proportional to E_e
Initial study for CDR:
H →bbar: selection efficiency: ~2.5%
which gives 5000 events with S/B=1.
corresponding to 0.7% coupling precision.
[cf: CDR, U.Klein ICHEP12, B.Mellado LPCC]

Project Development

CERN Mandate

LHeC three years programme

Accelerator

SC RF, LTF, Q1, Optimisation, Lumi,

Detector

IR, Technical Design, Installations

Physics

Higgs, RPV SUSY, top, ..LHC

Project

Workshops, Collaboration..

The LHeC is a challenge worth developing for the future of HEP

The mandate for the technology development **includes studies and prototyping of the following key technical components:**

- Superconducting RF system for CW operation in an Energy Recovery Linac, (high Q0 for efficient energy recovery). The studies require design and prototyping of the cavity, couplers and cryostat.
- Superconducting magnet development of the insertion regions of the LHeC with three beams. The studies require the design and construction of short magnet models.
- Studies related to the experimental beam pipes with large beam acceptance in a high synchrotron radiation environment.
- The design and specification of an ERL test facility for the LHeC.
- The finalization of the ERL design for the LHeC including a finalization of the optics design, beam dynamic studies and identification of potential performance limitations.

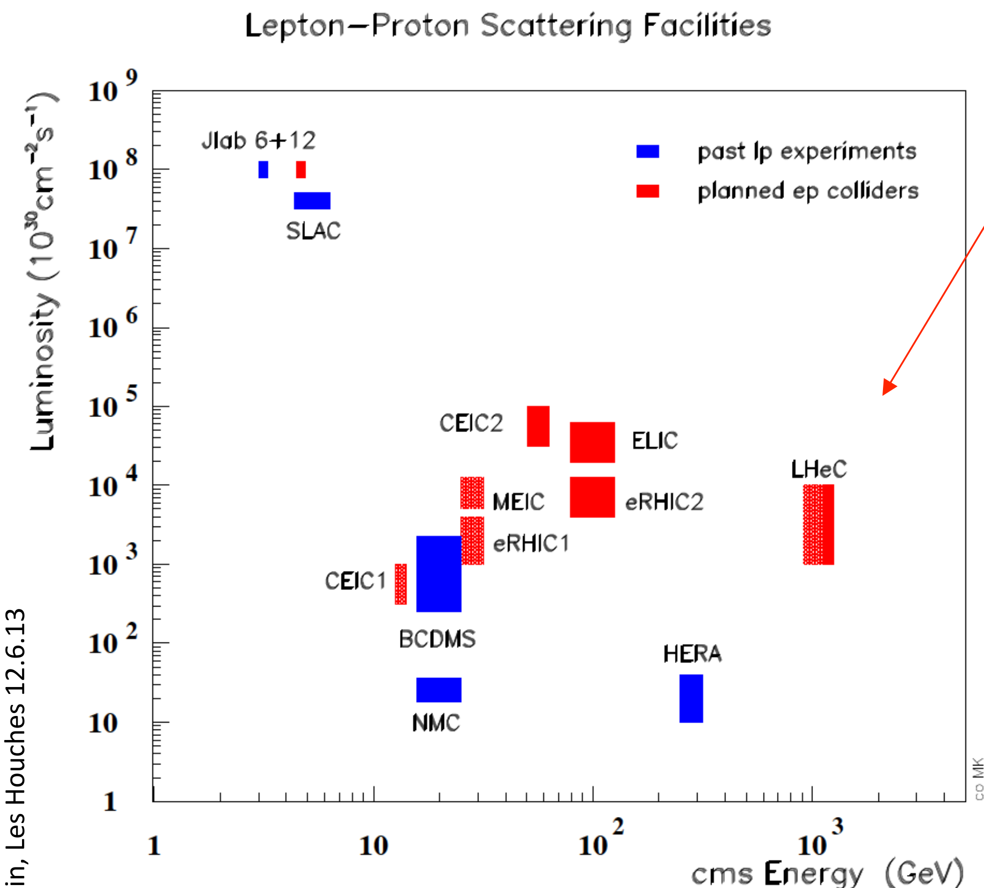
The above technological developments require close collaboration between the relevant technical groups at CERN and external collaborators.

Given the rather tight personnel resource conditions at CERN **the above studies should exploit where possible synergies within existing CERN studies** (e.g. SPL and ESS SC RF, HL-LHC triplet magnet development and collaboration with ERL test facility outside CERN).

S.Bertolucci at Chavannes workshop 6/12 based on
CERN directorate's decision to include LHeC in the MTP

Large Hadron Electron Collider - LHeC

Information on http://cern.ch/lhec



ep/A synchronous to pp/AA

- LHC is the only place for TeV energy DIS
- ~60 GeV electron beam upgrade to the LHC
- DIS at TeV energies: $Q^2_{max} 10^6$, $x > 10^{-6}$
- **A new Higgs facility** – new detector

Noteable:

- Unprecedent precision (α_s to per mille)
- Complete unfolding of PDFs (1^{st} time)
- Precision electroweak measurements
- Novel precision input for LHC physics
- BSM (RPV SUSY, e*, CI, lq resonances?)
- Quark Gluon Plasma – initial formation

QCD

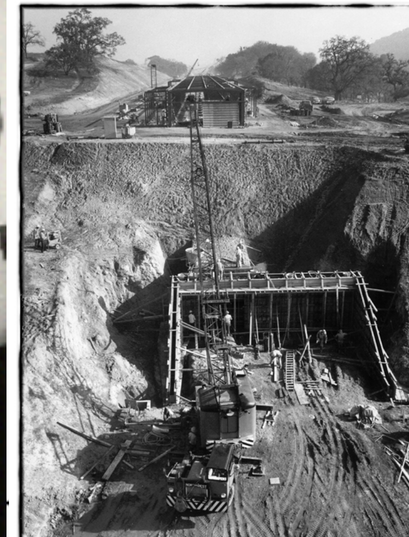
- Discovery/disproval of saturation at low x
- Less conventional partons (kt, diff., GPDs)
- Nuclear structure in huge kinematic range
- Top with 10pb cross section in DIS, tPDF

The LHeC is a new laboratory for energy frontier particle physics of unique character.

Ref's: CDR arXiv:1205:2913, summary: arXiv:1211.4831, relation to LHC: arXiv:1211:5102

Max Klein, Les Houches 12.6.13

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

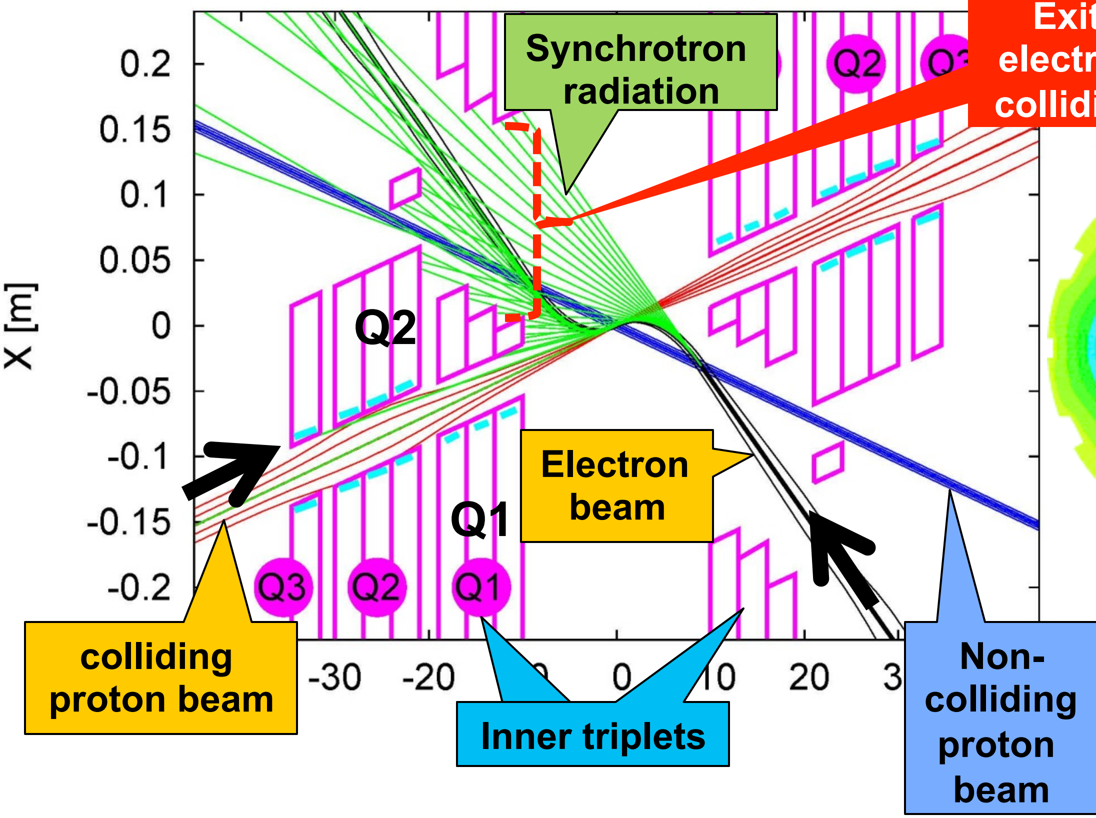


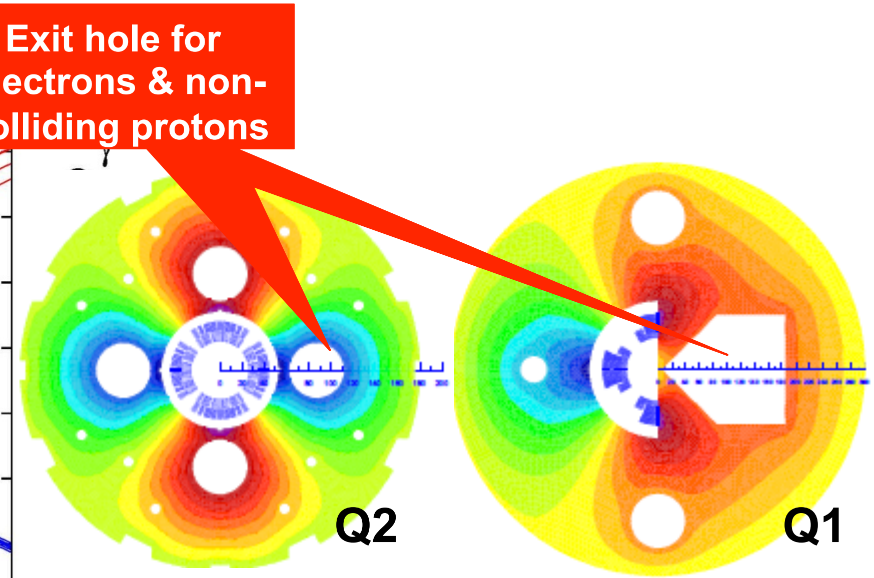
it has been done before

Courtesy F.Zimmermann

Backup

LR LHeC IR layout & SC IR quadrupoles





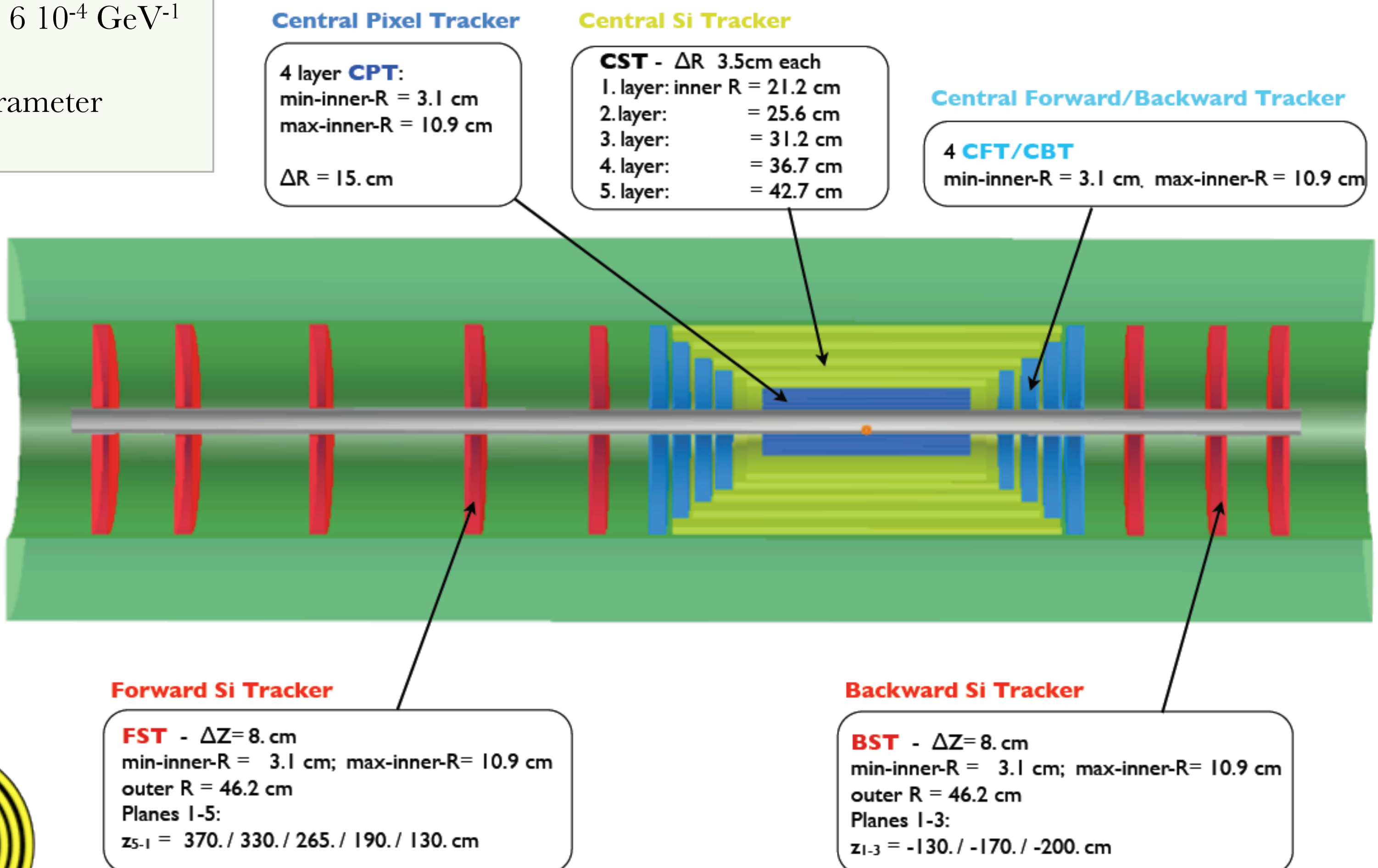
Nb_3Sn (HFM46): 5700 A, 175 T/m, 4.7 T at 82% on LL (4 layers), 4.2 K	Nb_3Sn (HFM46): 8600 A, 311 T/m, at 83% LL, 4.2 K
46 mm (half) ap., 63 mm beam sep.	23 mm ap.. 87 mm beam sep.
0.5 T, 25 T/m	0.09 T, 9 T/m

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

As shown by F. Zimmermann at Chamonix12

Silicon Tracker and EM Calorimeter

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



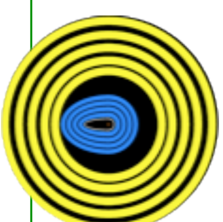


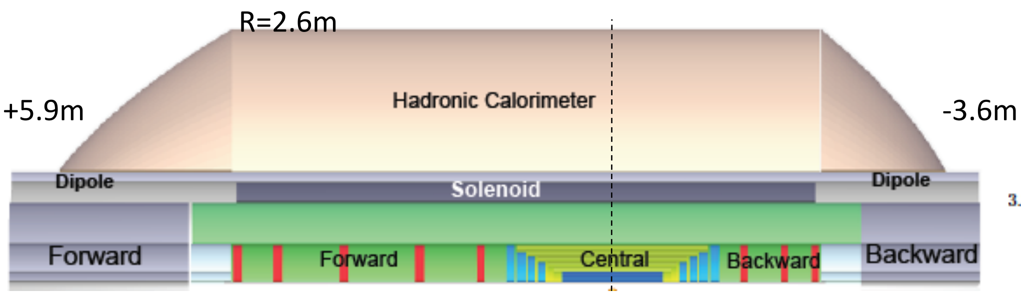
Figure 13.18: Tracker and barrel Electromagnetic-Calorimeter rz view of the baseline detector (Linac-Ring case).

LHeC-LHC: no pile-up, less radiation, smaller momenta apart from forward region

Hadronic Tile Calorimeter

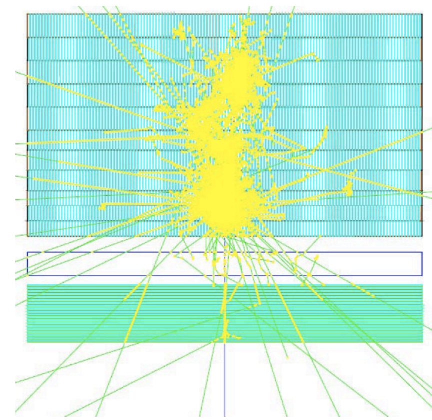
E-Calo Parts	FEC1	FEC2		EMC		BEC2	BEC1
Min. Inner radius R [cm]	3.1	21		48		21	3.1
Min. polar angle θ [°]	0.48	3.2		6.6/168.9		174.2	179.1
Max. pseudorapidity η	5.5	3.6		2.8/-2.3		-3.	-4.8
Outer radius [cm]	20	46		88		46	20
z-length [cm]	40	40		660		40	40
Volume [m^3]	0.3			11.3		0.3	
H-Calo Parts barrel			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	

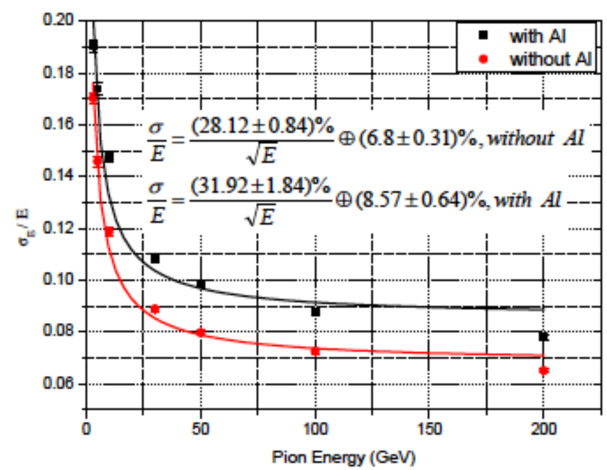
Table 13.6: Summary of calorimeter dimensions.
The electromagnetic barrel calorimeter is currently represented by the barrel part EMC (LAr-Pb module); the setup reaches $X_0 \approx 25$ radiation length) and the movable inserts forward FEC1, FEC2 (Si-W modules ($X_0 \approx 30$) and the backward BEC1, 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

Liquid Argon Electromagnetic Calorimeter

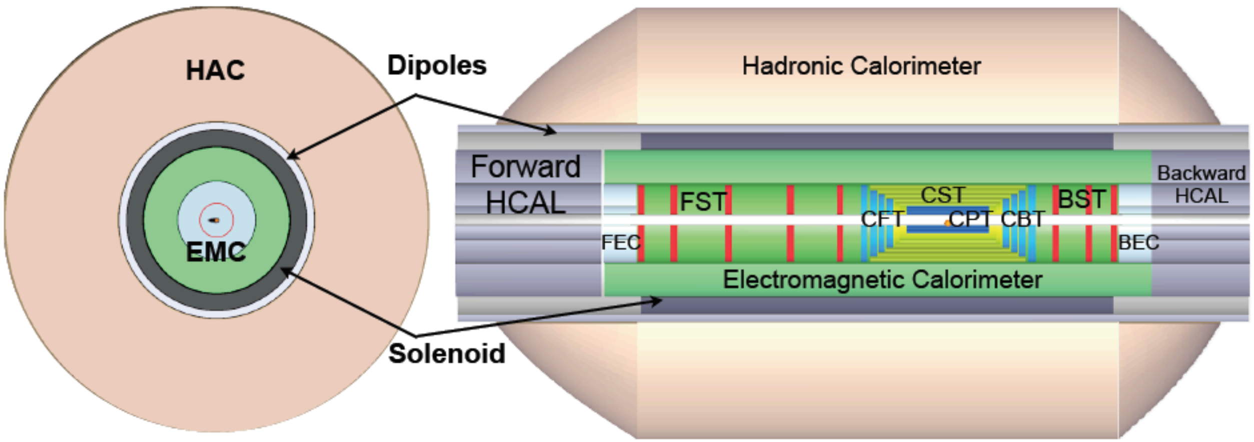


Figure 13.30: x-y and r-z view of the LHeC Barrel EM calorimeter (green).

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

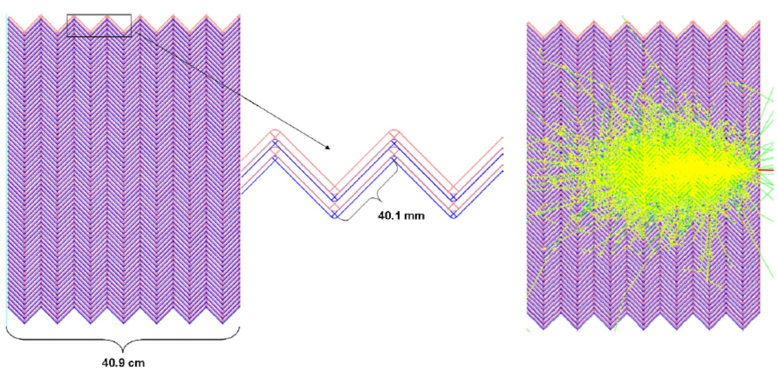


Figure 13.35: View of the parallel geometry accordion calorimeter (left) and simulation of a single electron shower with initial energy of 20 GeV (right).

GEANT4 Simulation

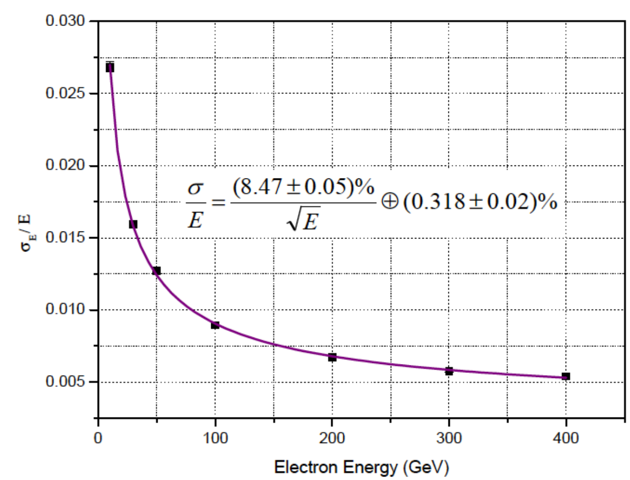
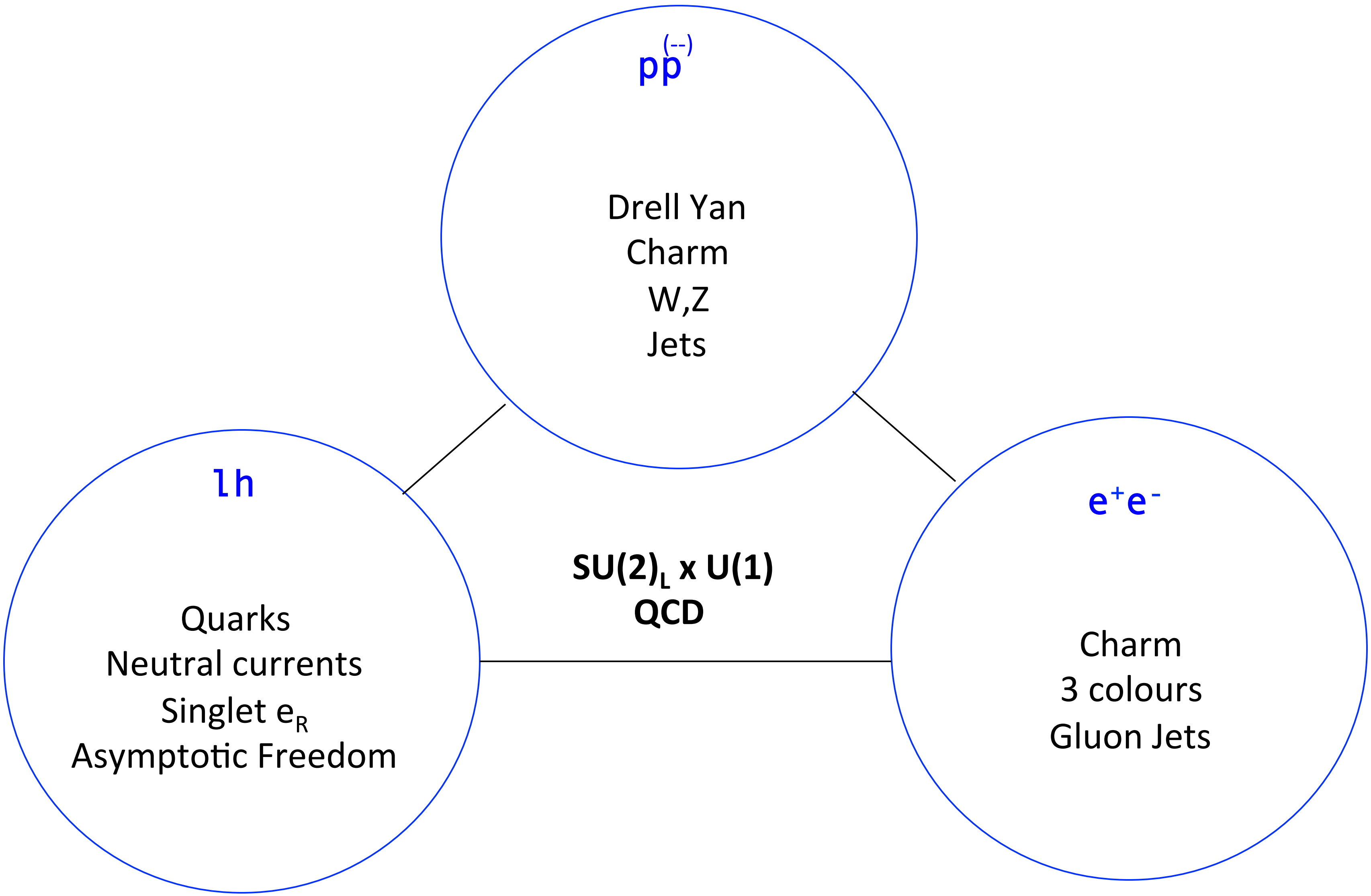


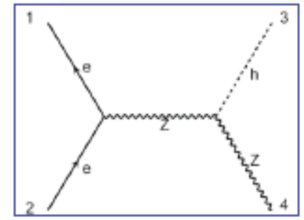
Figure 13.36: LAr accordion calorimeter energy resolution for electrons between 10 and 400 GeV.

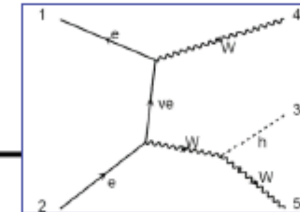
The 10-100 GeV Energy Scale [1968-1986]

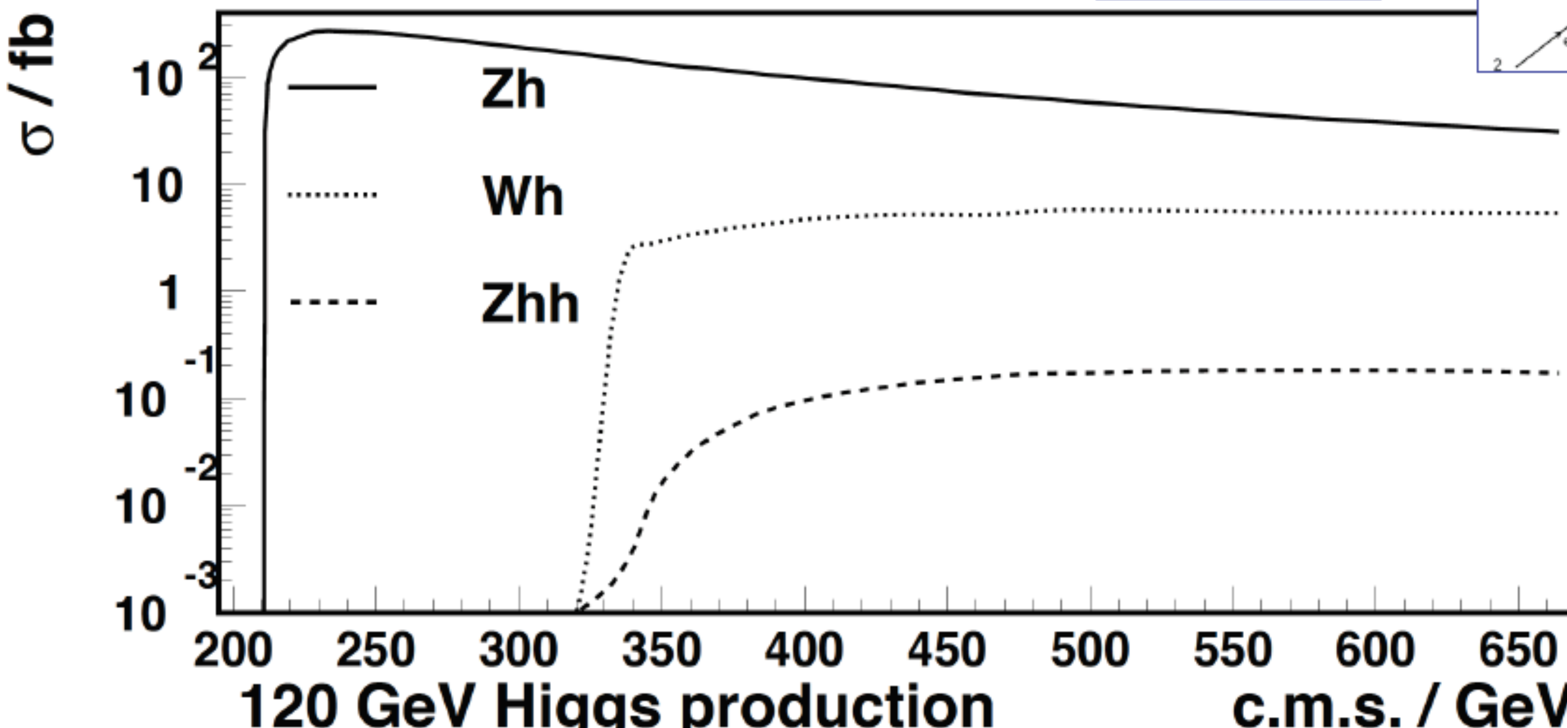


120 GeV Higgs in e+e-

Madgraph5, CTEQ6L1, $M_H^2+P_t^2$, narrow width
Decay into h→ bb and Z→ee : factor 0.025



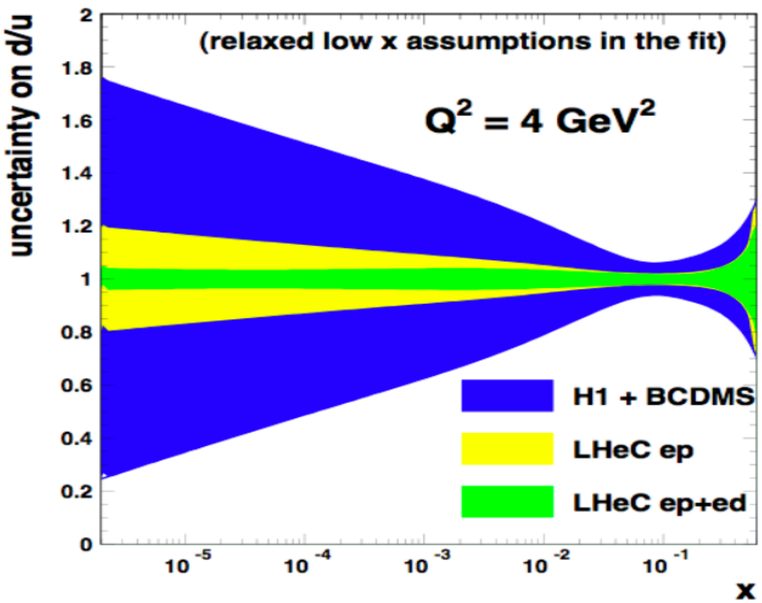


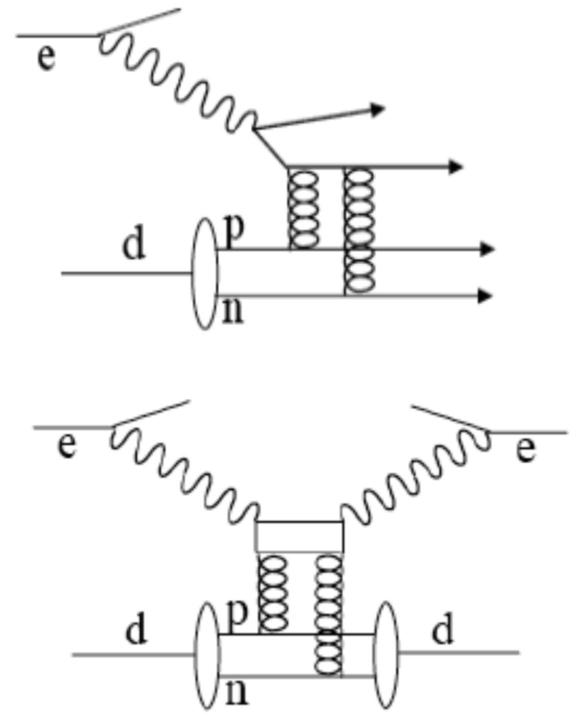


Zh threshold
at 211 GeV
= (120+91) GeV

The ignored Neutron

d/u at low x from deuterons





In eA at the collider, test Gribovs relation between shadowing and diffraction, control nuclear effects at low Bjorken x to high accuracy

Neutron structure unknown in HERA range and below. Crucial to resolve its parton structure and to predict scattering on nucleons rather than proton targets.

Collider unique to en (p tag, diffraction)

From HERA to the LHeC

Deep Inelastic Scattering
QCD and Electroweak Physics
Nuclear Physics
New Physics: ep and pp at the LHC
Higgs with the LHeC
Accelerator and Detector Design
Prospects

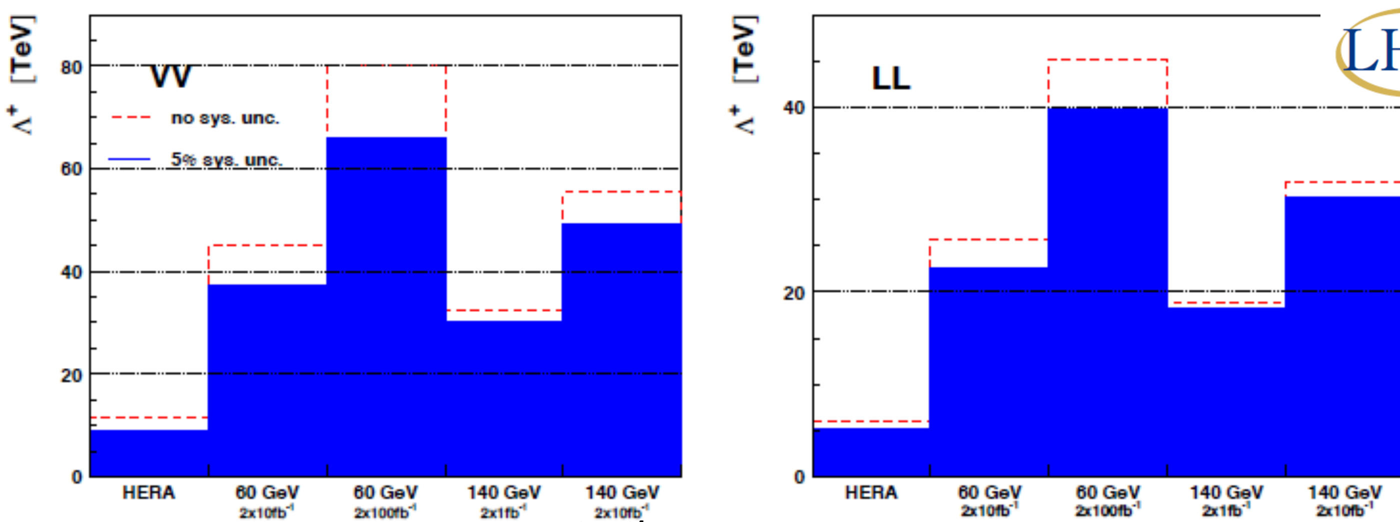
Max Klein
UNIVERSITY OF LIVERPOOL

http://cern.ch/lhec

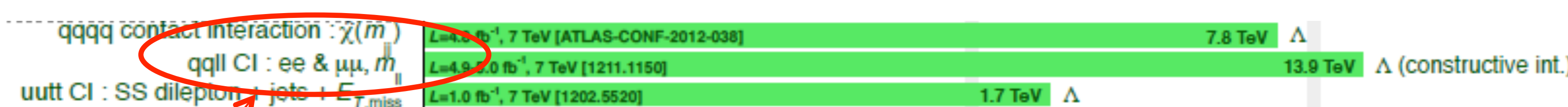
Colloquium at Mainz, Germany, June 25th, 2013

Contact interactions (eeqq)

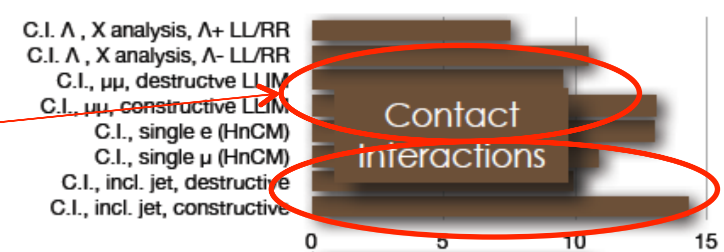
- New currents or heavy bosons may produce indirect effect via new particle exchange interfering with γ/Z fields.
- Reach for Λ (CI eeqq): 25-45 TeV with 10 fb^{-1} of data depending on the model



Similar to LHC

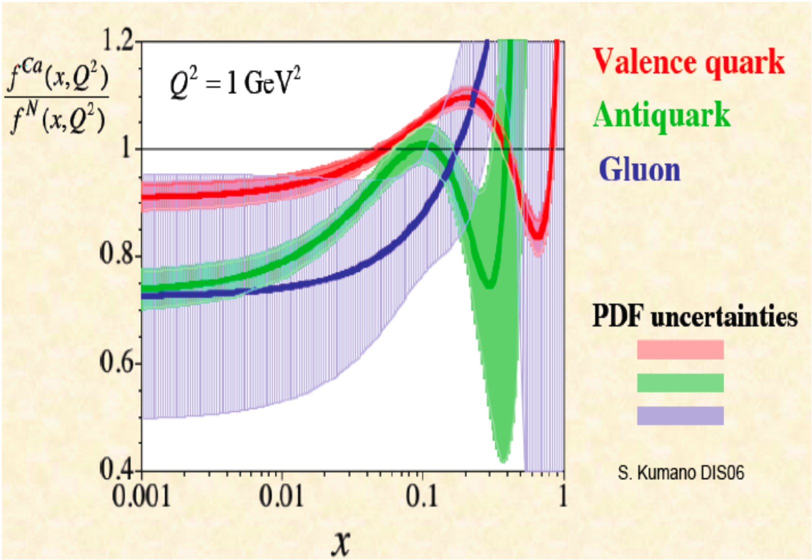


ATLAS and CMS constraints on eeqq CI (expected up to 30-40 TeV at c.o.m. 14 TeV LHC)

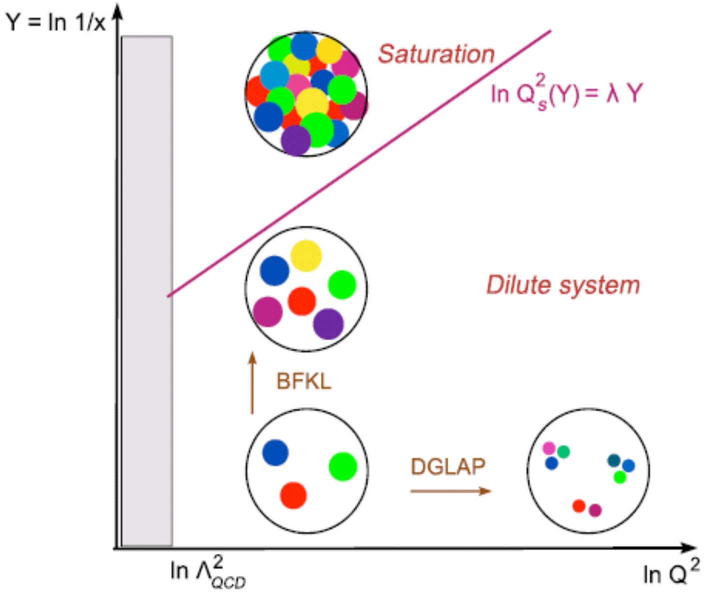


Nuclear Physics with the LHeC

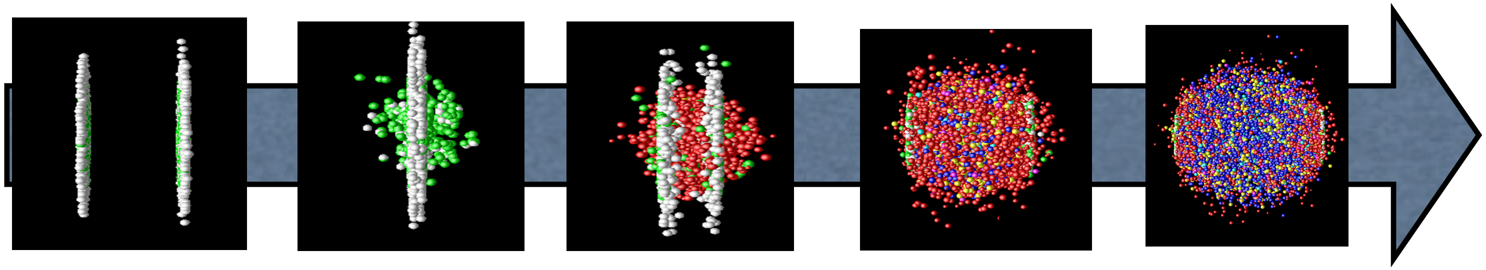
1. Nuclear Parton Distribution Functions



2. Saturation (low x, nonlinear QCD)



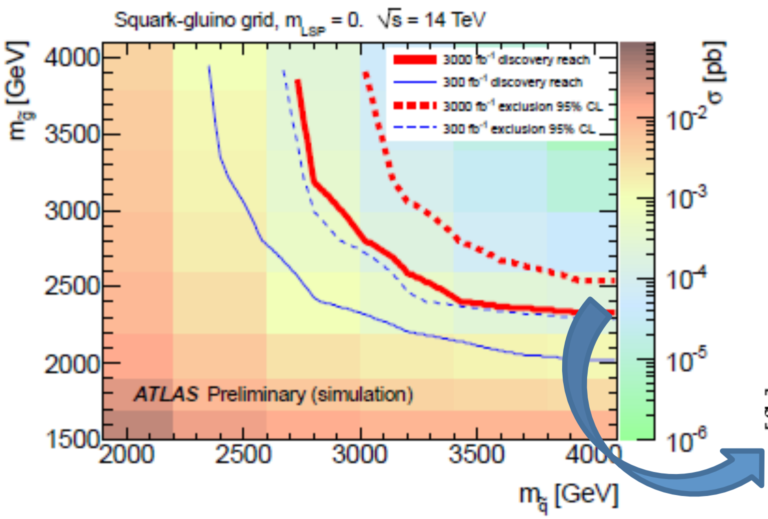
3. Quark Gluon Plasma, its initial and final states



Gluon emission from saturated nuclei Glasma? QGP Reconfinement

Impact on discovery/exclusion reach

- PDF uncertainties impact discovery / exclusion reach:
  - Total yields
  - Shape variations on discriminating quantities (in progress)

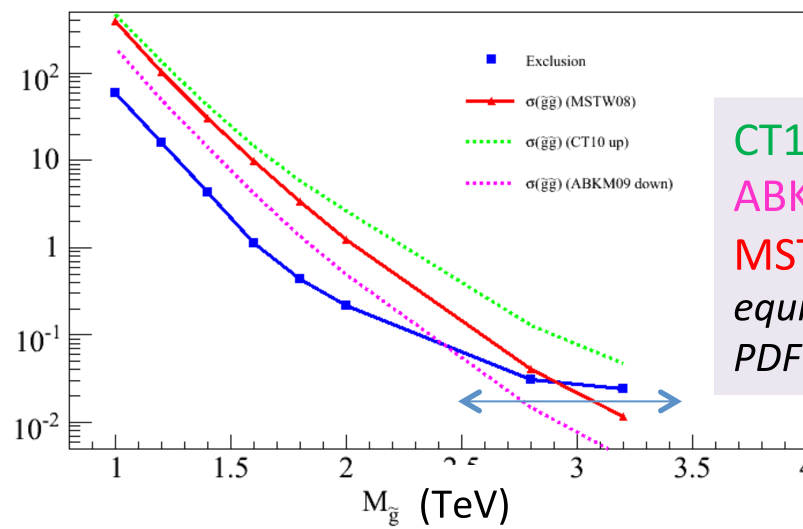


Caution: **very very** preliminary, mostly as illustration

(UL for gl-gl courtesy of G.Redlinger)

Impact on discovery/exclusion contours under various PDF hypothesis in progress

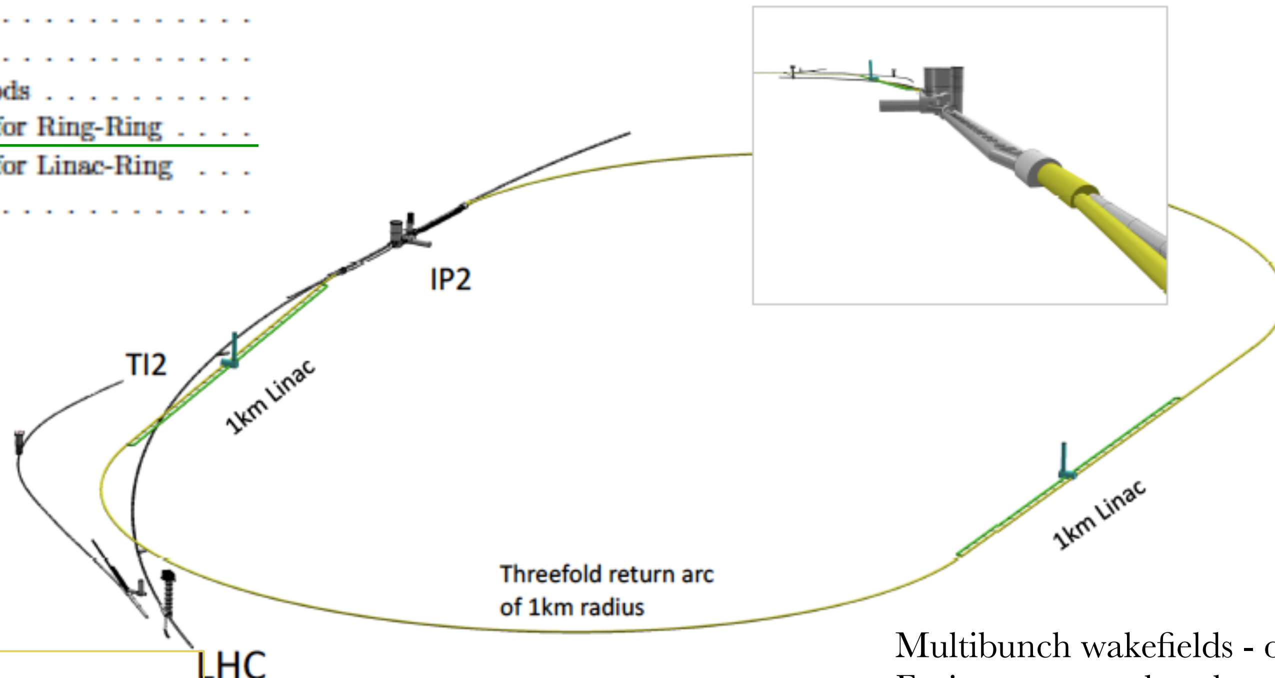
LHC @ 14 TeV 3 ab-1, M(squark) > 4 TeV



CT10 up
ABKM09 down
MSTW08
equivalent to LHeC PDF

Note: impact of PDF uncertainties on SM background also not negligible
However → mitigated by usage of Control Regions and semi data-driven estimate

Linac Characteristics



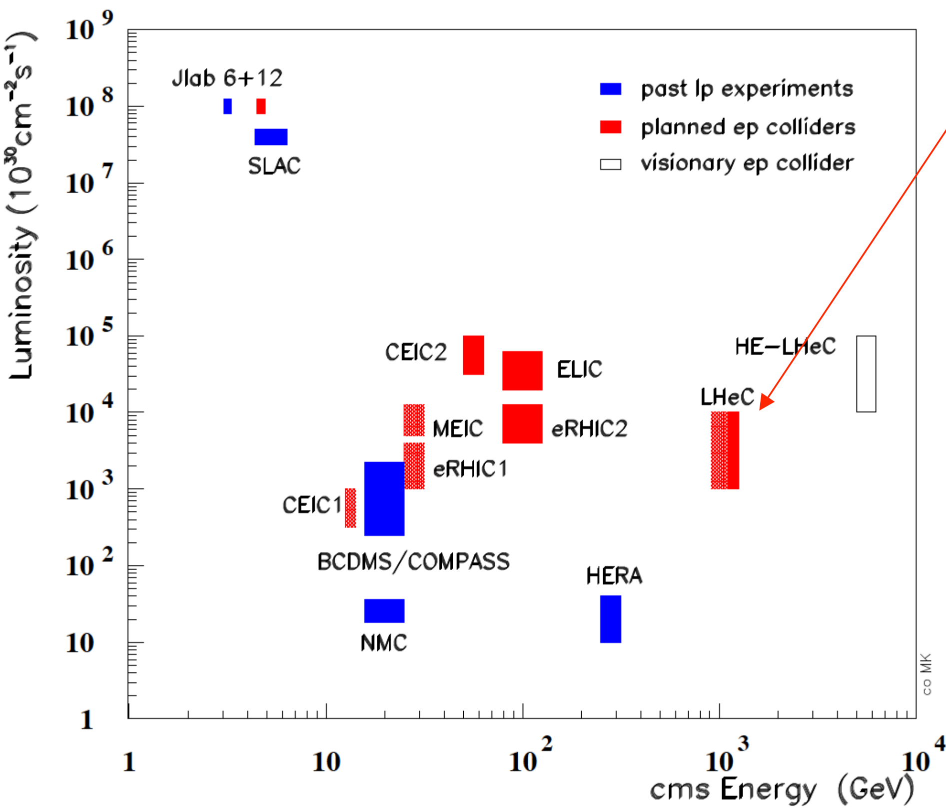
$U_{LHeC}=U_{LHC}/3$: 1.5 x HERA
Tunneling: 150m per week – 60 weeks
Two 1km linacs with 59 cryomodules
of 8 cavities each → 1000 cavities

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.

Large Hadron Electron Collider - LHeC

Information on http://cern.ch/lhec



ep/A synchronous to pp/AA

- LHC is the only place for TeV energy DIS
- ~60 GeV electron beam upgrade to the LHC
- DIS at TeV energies: $Q^2_{max} 10^6$, $x > 10^{-6}$
- **A new Higgs facility** – new detector

Noteable:

- Unprecedent precision (α_s to per mille)
- Complete unfolding of PDFs (1st time)
- Precision electroweak measurements
- Novel precision input for LHC physics
- BSM (RPV SUSY, e*, CI, lq resonances?)
- Quark Gluon Plasma – initial formation

QCD

- Discovery/disproval of saturation at low x
- Less conventional partons (kt, diff., GPDs)
- Nuclear structure in huge kinematic range
- Top with 10pb cross section in DIS, tPDF

Max Klein, Les Houches 12.6.13

The LHeC is a new laboratory for energy frontier particle physics of unique character.

Ref's: CDR arXiv:1205:2913, summary: arXiv:1211.4831, relation to LHC: arXiv:1211:5102