The Quark-Gluon Structure of the Proton

Introduction
HERA
LHC and the LHeC

Max Klein

UNIVERSITY OF LIVERPOOL

Talk at the DPG Particle Physics, Dresden, March 8th, 2013

On the occasion of the receipt of the Max-Born-Price by the DPG and the IoP

Victor Weisskopf (1908-2002) Maria Goeppert (1906-1972) Max Born (1882-1970)

Quarks

early ep scattering

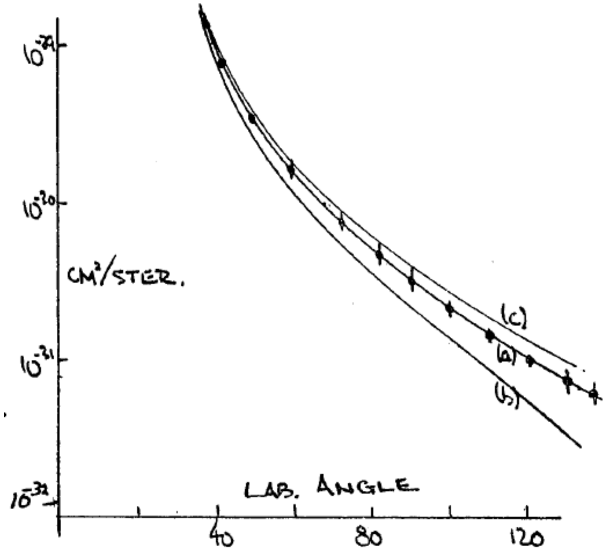
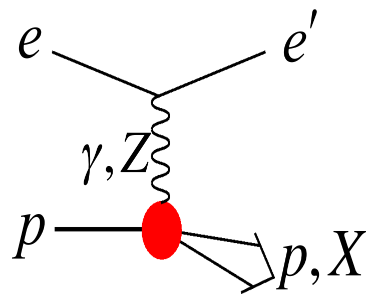
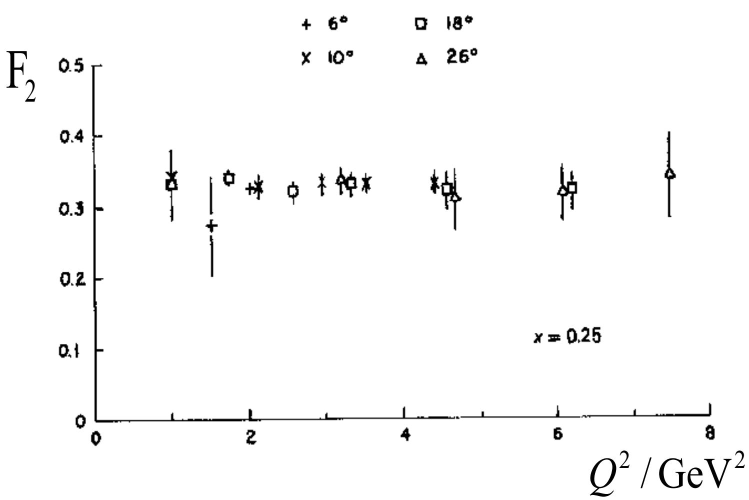


Fig. 2

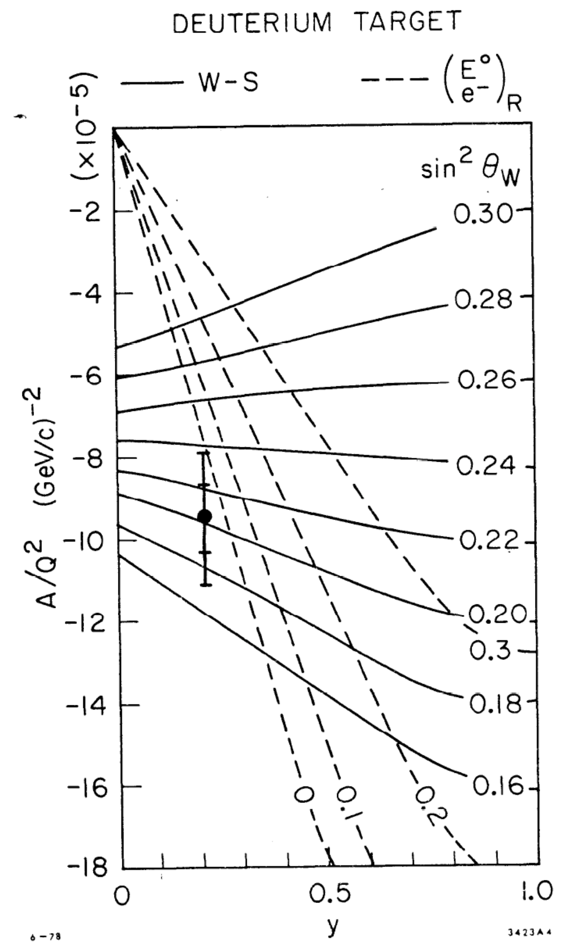
Hofstadter et al, 1955, r_p=0.74±0.20fm





SLAC-MIT 1968 Bj Scaling → Partons

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



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

SLAC-PUB-2148
July 1978

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

$F_2(x,Q^2)$ 1969-1989

Low x?

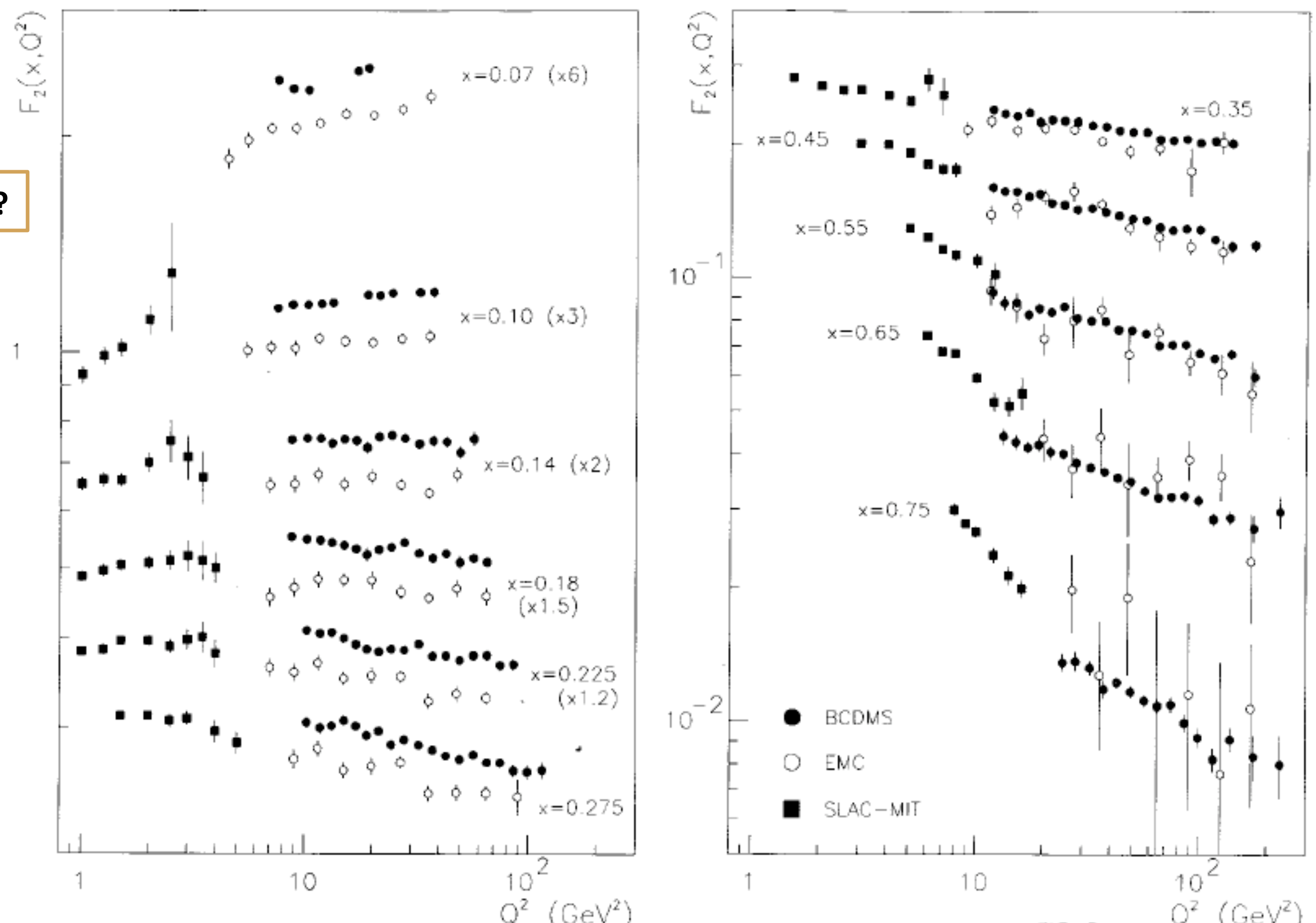


FIG. 3

Q^2=sxy

High x, low y?

$\delta F_2/F_2 \sim 1/(1-x)$

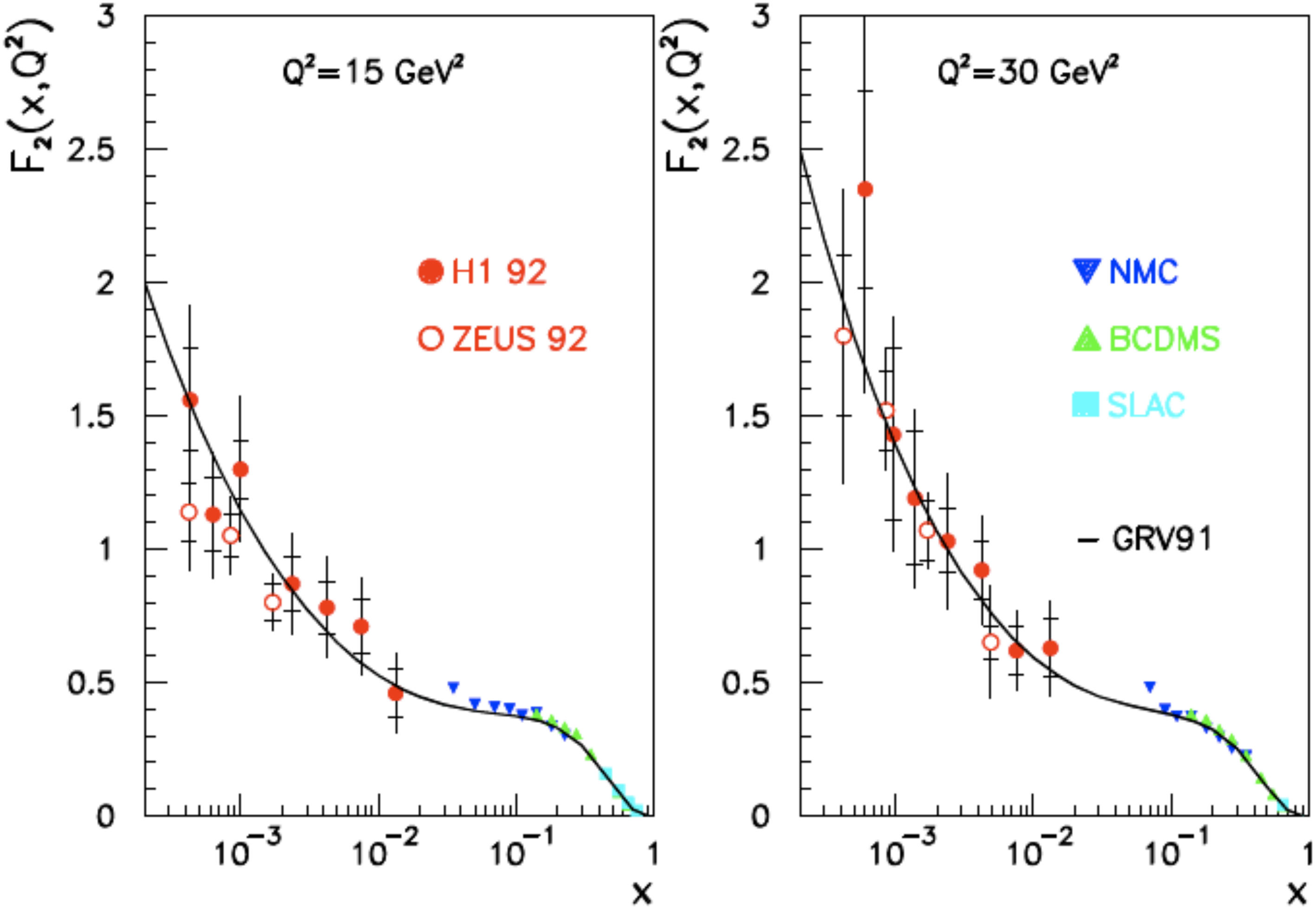
Regge limits

Phys.Lett. B223 (1989) 485

CERN-EP/89-06
January 17th, 1989

lN : SLAC, FNAL, BCDMS, EMC??, NMC, COMPASS..
νN: GGM, BEBC, HPWF, CDHSW, CHARM, NuTEV..

The first F_2 from HERA



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

The first F_2 from H1

systematic errors

		e	m
E_e	2% and ±2% smearing	5-15%	3-6%
ϑ	5 mrad	4-12%	4-8%
y_{JB}	fragmentation [D^-, PS vs HERWIG], 7% energy scale, $(y_{JB}-y_{Gen})/y_{Gen}$, thresholds	–	10-25%
Z_{vtx}	statistics, satellite bunch, comparison of methods I, II		7%
BPC, tracker cut, EBDI/ECRA, cluster-hit			6%
structure fct.	D^-/D^0 (lowest x).		5-10%
radiative corrections	(MC statistics for I) Z_{vtx}, $E-p_z$ in MC	8%	2%
bin centre correction	$(\alpha, E, \vartheta \to x, Q^2)$	5%	2%
		17-29%	18-29%

- statistics: 950 events
- scale error: lumi 7% TOF, trigger → 9%

e = electron method

$Q^2=Q^2_e$, $y=y_e$, $\delta\sigma/\sigma \sim 1/y_e$

m = mixed method

$Q^2=Q^2_e$, $y=y_h$, $\delta\sigma/\sigma \sim 1/(1-y_h)$

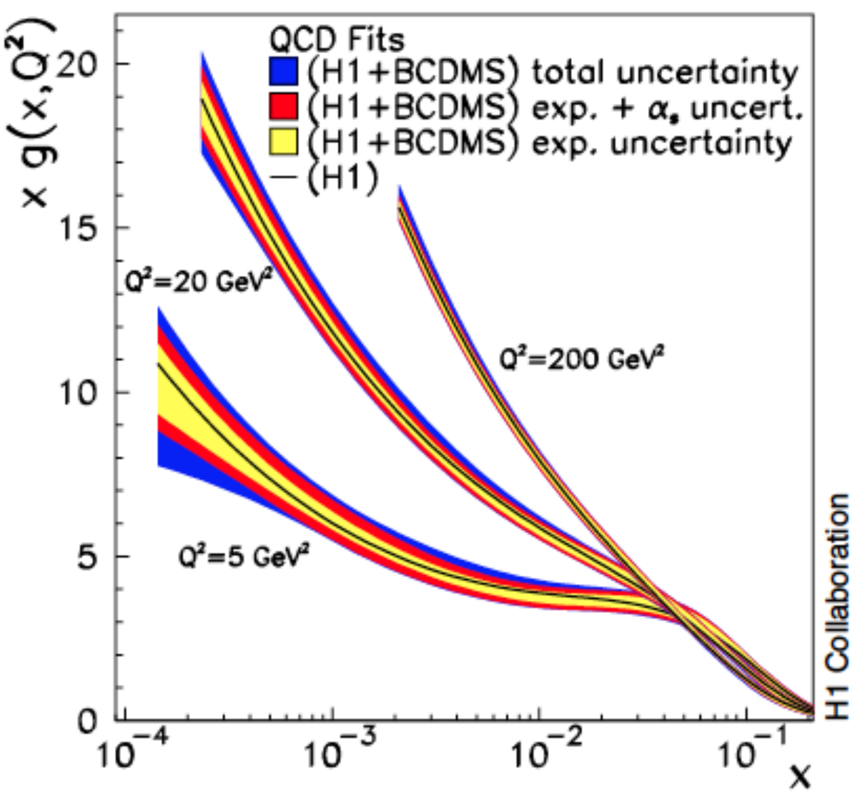
Access to small y (large x) by using electron AND hadron kinematics.

Much reduced rad. corrections but uncertainty of hadronic FS

Collider:
Much extended range (52TeV)
redundant kine. reconstruction

The most cited H1 paper

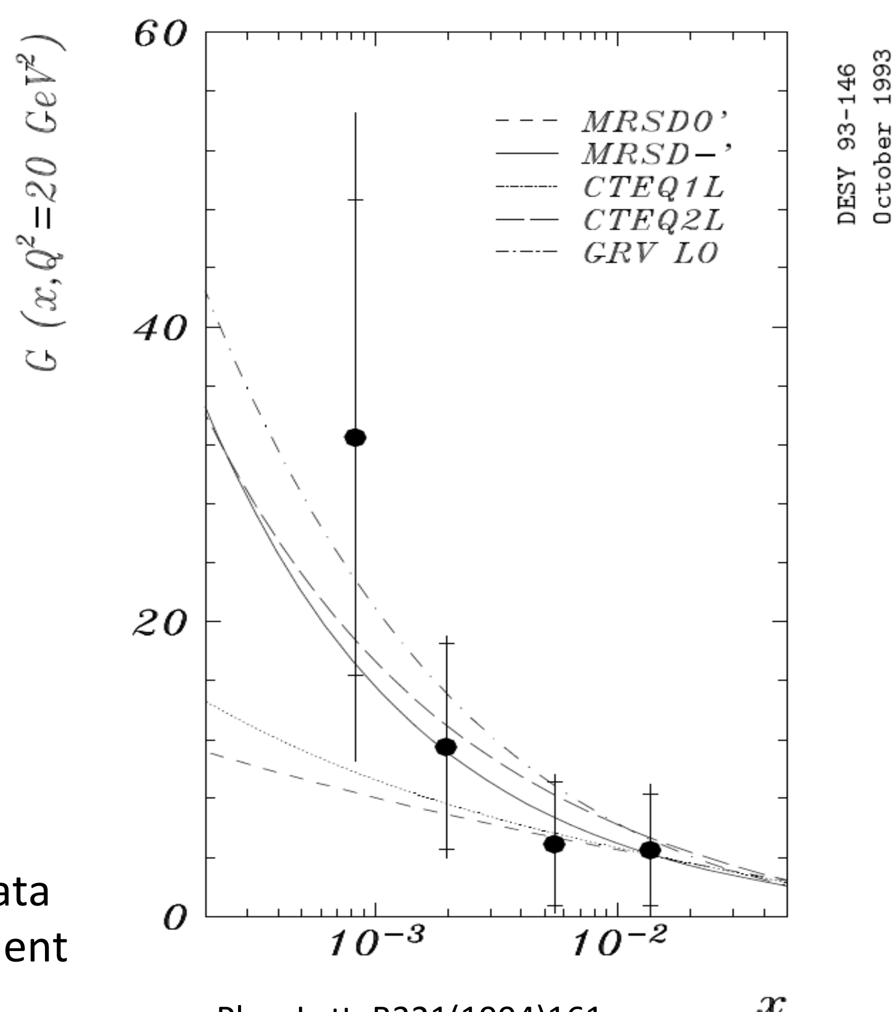
Deep inelastic inclusive ep scattering at low x and a determination of α_s - EPJ C21 (2001)33



Data from 1996/97. This followed the 1994 data paper which was the first accurate measurement of the low Q^2, x DIS cross section of H1

and the first low x gluon

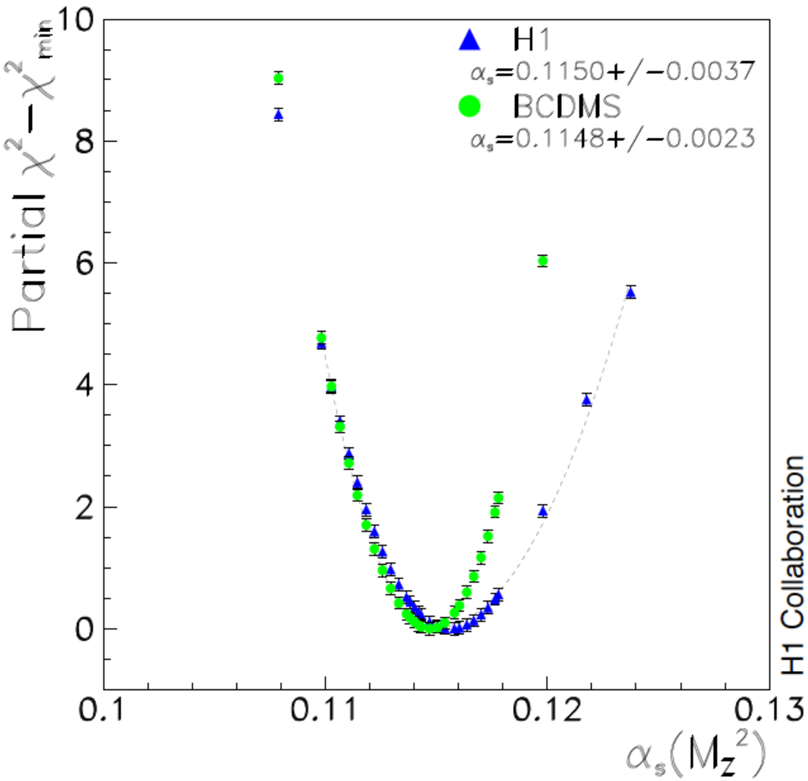
$$\frac{\partial F_2(x,Q^2)}{\partial lnQ^2} \simeq \frac{10\alpha_s(Q^2)}{27\pi} \cdot G(2x,Q^2)$$

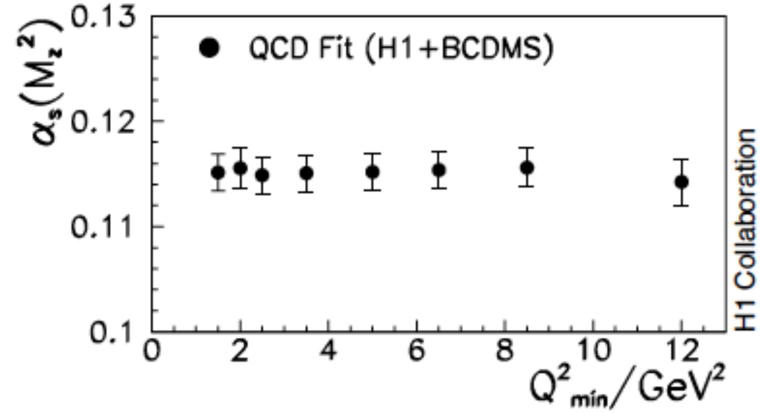


Phys.Lett. B321(1994)161

Measurement of α_s

Deep inelastic inclusive ep scattering at low x and a determination of α_s - EPJ C21 (2001)33





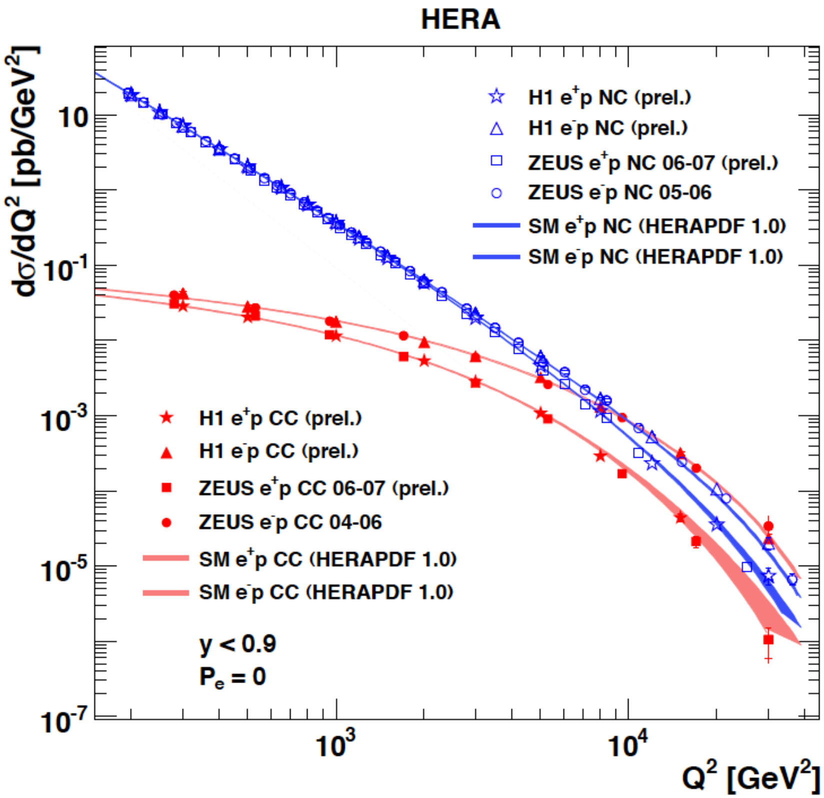
$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017\,(exp)\,^{+\,0.0009}_{-\,0.0005}\,(model)$$

Joint H1+BCDMS – detailed systematic uncertainty study of BCDMS (y > 0.03). Strong but resolvable correlation of the gluon distribution and the strong coupling

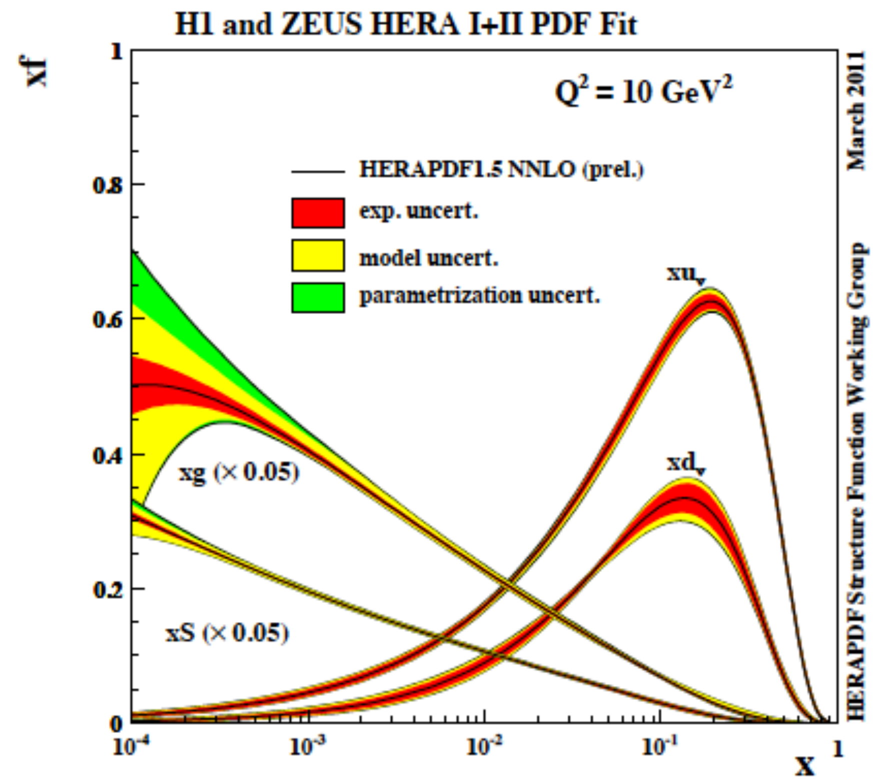
Low x and charm mass dominated model uncertainty – both need substantially improved understanding (LHeC..)!
Large renormalisation scale effect (0.005)

NNLO:
Vermaseren, Moch and Vogt papers 04/05

Results from HERA



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



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

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

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

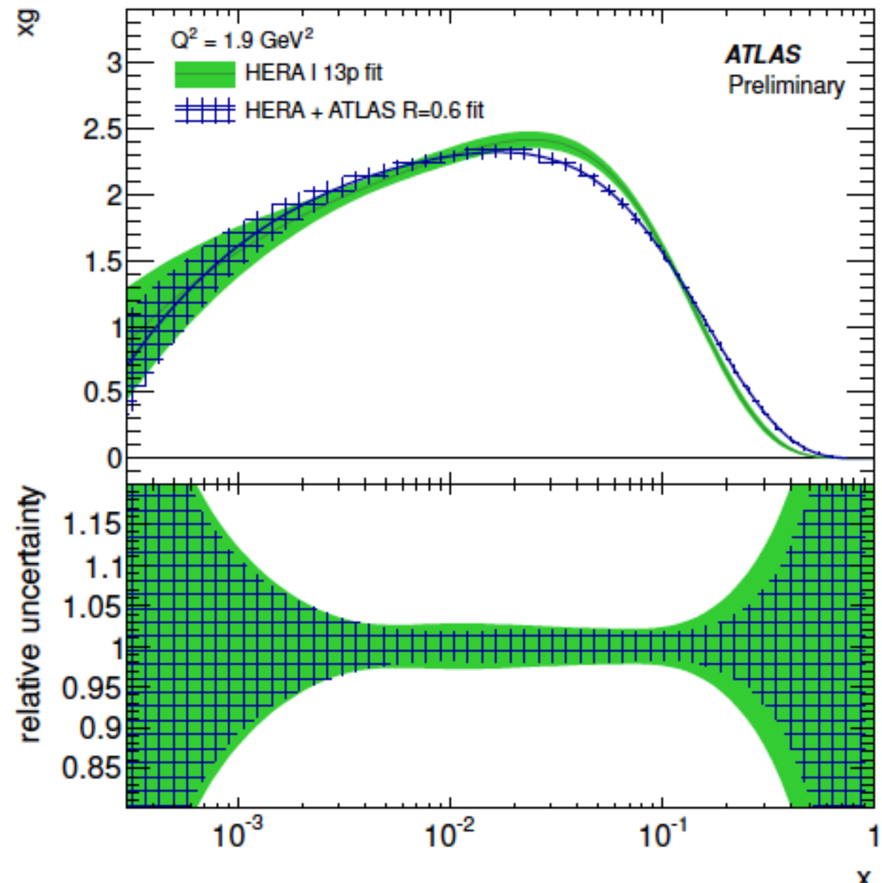
Industry of PDF Determinations

	MSTW08	CTEQ6.6/CT10	NNPDF2.1/2.3	HERAPDF1.0/1.5	ABKM09/ABM11	GJR08/JR09
PDF order	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	NLO, NNLO	NLO, NNLO	NLO, NNLO
HERA DIS	✔ (old)	✔ (old/new)	✔ (new)	✔ (new/newest)	✔ (new)	✔ (new)
Fixed target DIS	✔	✔	✔	-	✔	✔
Fixed target DY	✔	✔	✔	-	✔	✔
Tevatron W, Z	✔	✔	some	-	some	some
Tevatron jets	✔	✔	✔	-	✔	✔
LHC	-	-	-/W,Z+jets	-	-	-
HF Scheme	RTGMVF	SACOT GMVFN	FONLL GMVFN	RT GMVFN	BMSN FFNS	FFNS
Alphas (NLO)	0.120	0.118(f)	0.119	0.1176(f)	0.1179	0.1145
Alphas (NNLO)	0.1171	0.118(f)	0.1174	0.1176(f)	0.1135	0.1124

V.Radescu

The determination of the partonic contents of the proton is a subtle, complex task.
It often involves data which are barely compatible as is tolerated with χ^2 innovations..
Future high precision needs a new, complete PDF data basis and precision h.o. theory.
(cf arXiv:1310.1073,jb)

PDF constraints from LHC – Jets

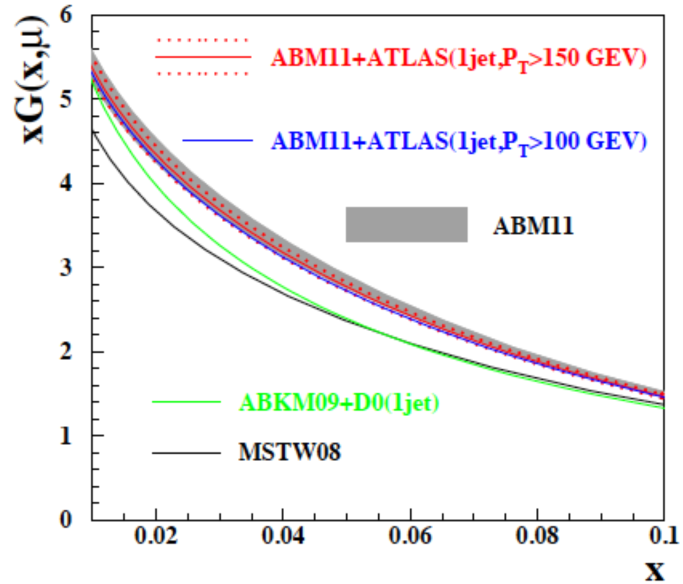


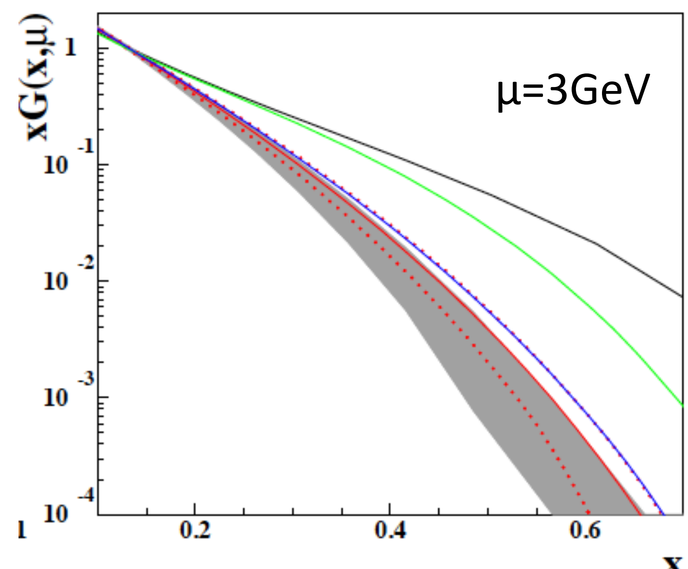
First constraints on gluon distribution from jets: cross sections and ratios 2.7/7 TeV

Will improve, but depends on energy scales, jet definition, non-perturbative effects ..

Similar results from CMS ($W^{\pm}$, DY, top..)

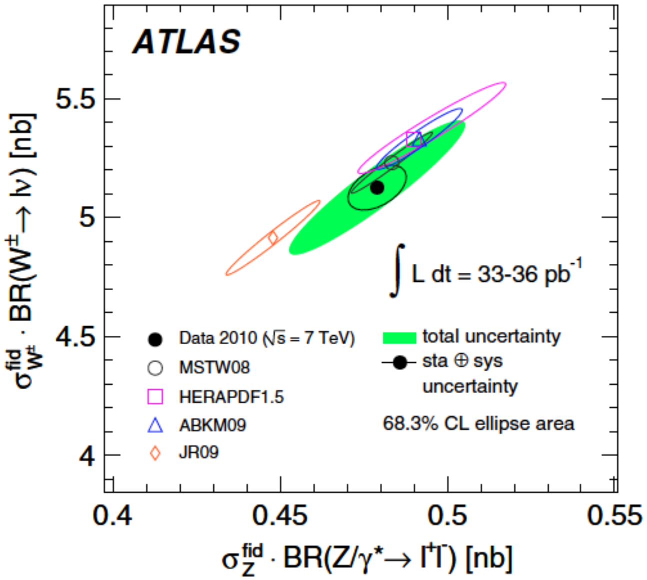
ATLAS-CONF-2012-128





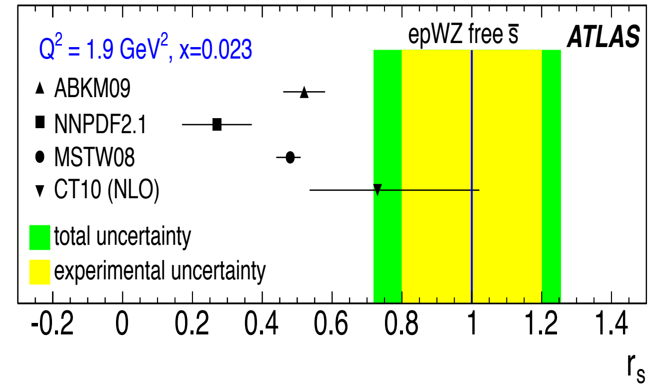
S.Moch 6th Terascale Workshop (Hamburg, 3.12.12)

PDF constraints from LHC - Di-Lepton Production

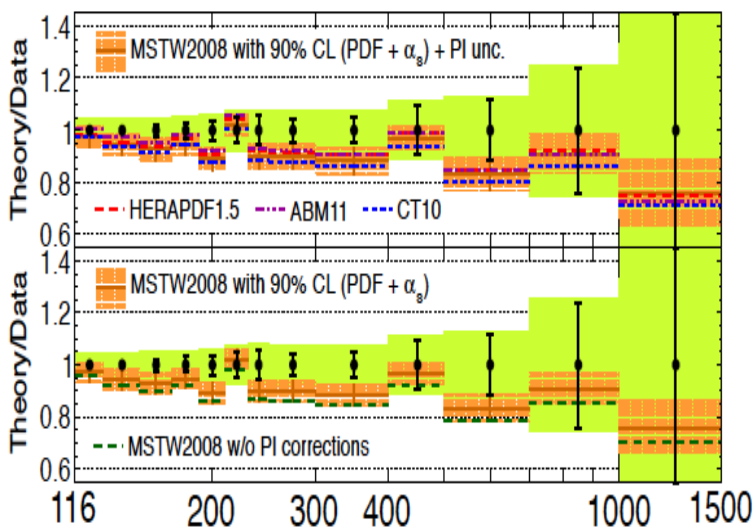


PRD D85 (2012) 072004

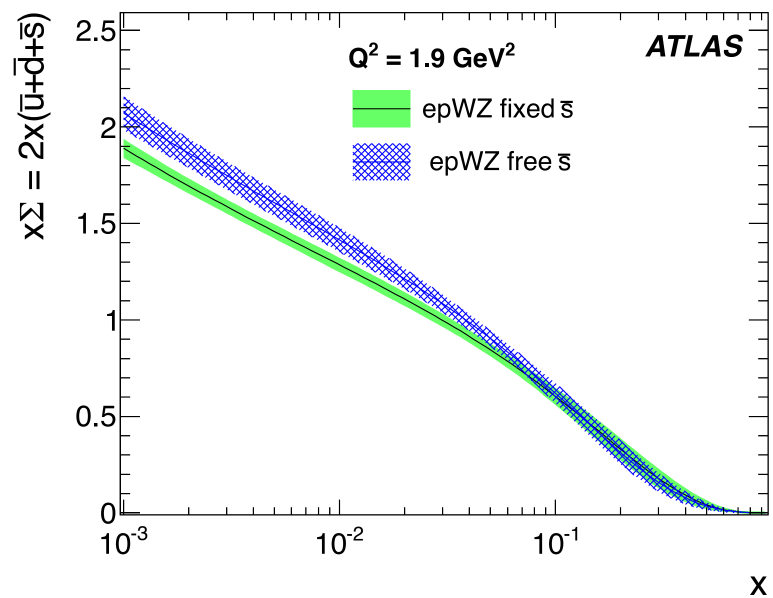
Precision Drell-Yan (W,Z) data constrain PDFs



according to the ATLAS data and HERA+ATLAS QCD analysis: s = d !



ATLAS-CONF-2012-159

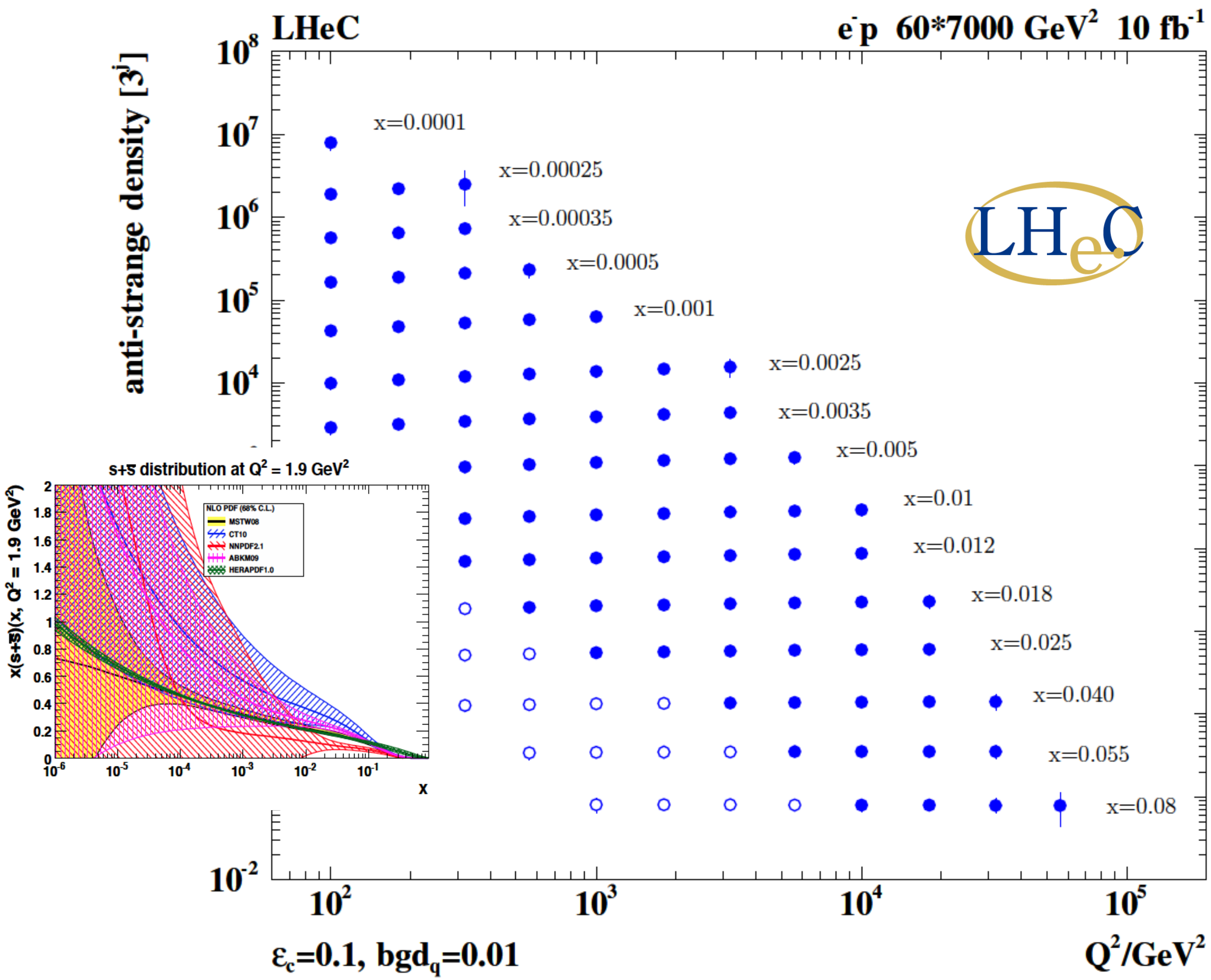


PRL 109(2012)012001

Very high precision required for any constraint on PDFs

Change of strange affects sea - UHE ν

Strange Quark Distribution



High luminosity

High Q^2

Small beam spot

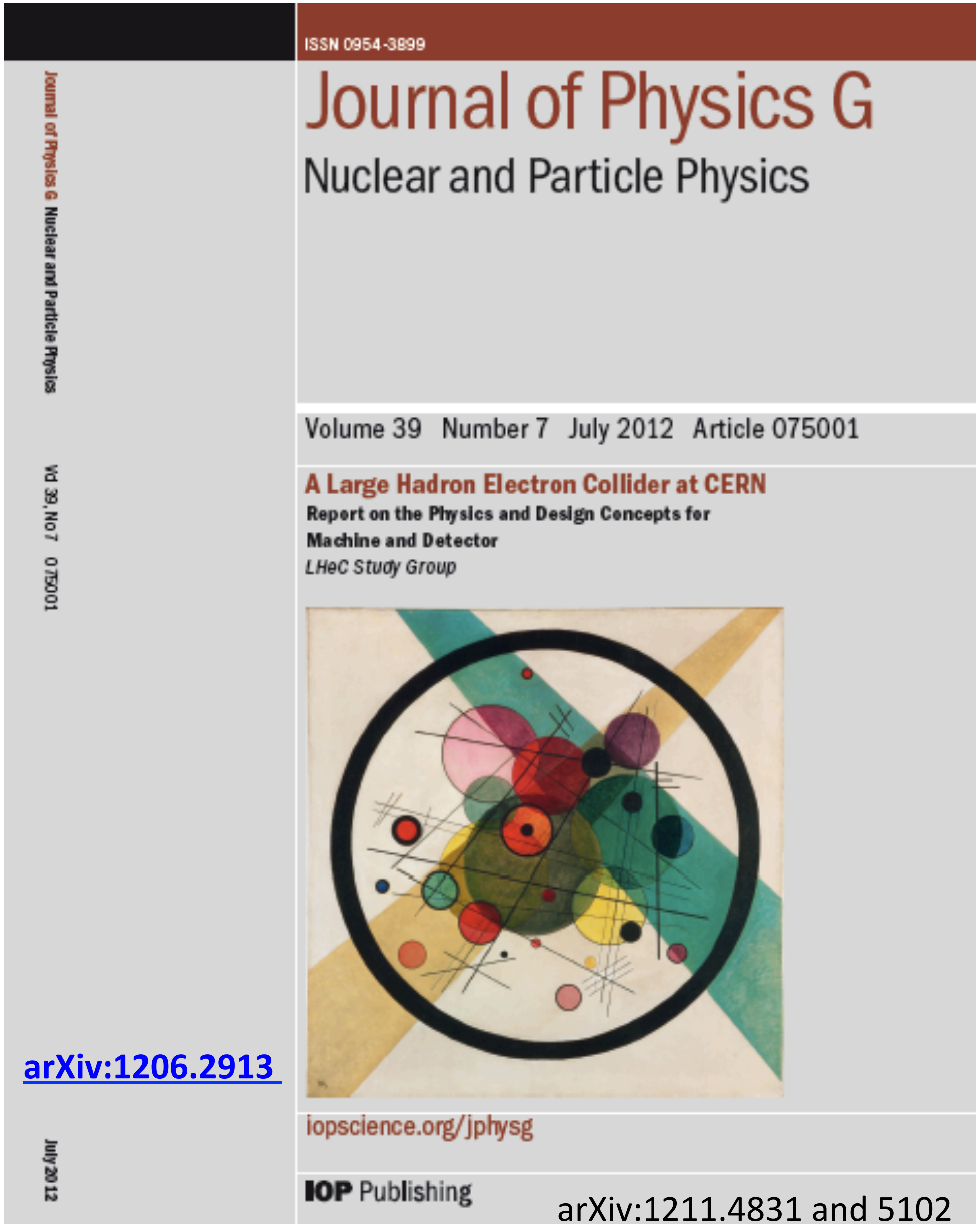
Modern Silicon

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



arXiv:1206.2913

arXiv:1211.4831 and 5102

CERN Referees

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

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

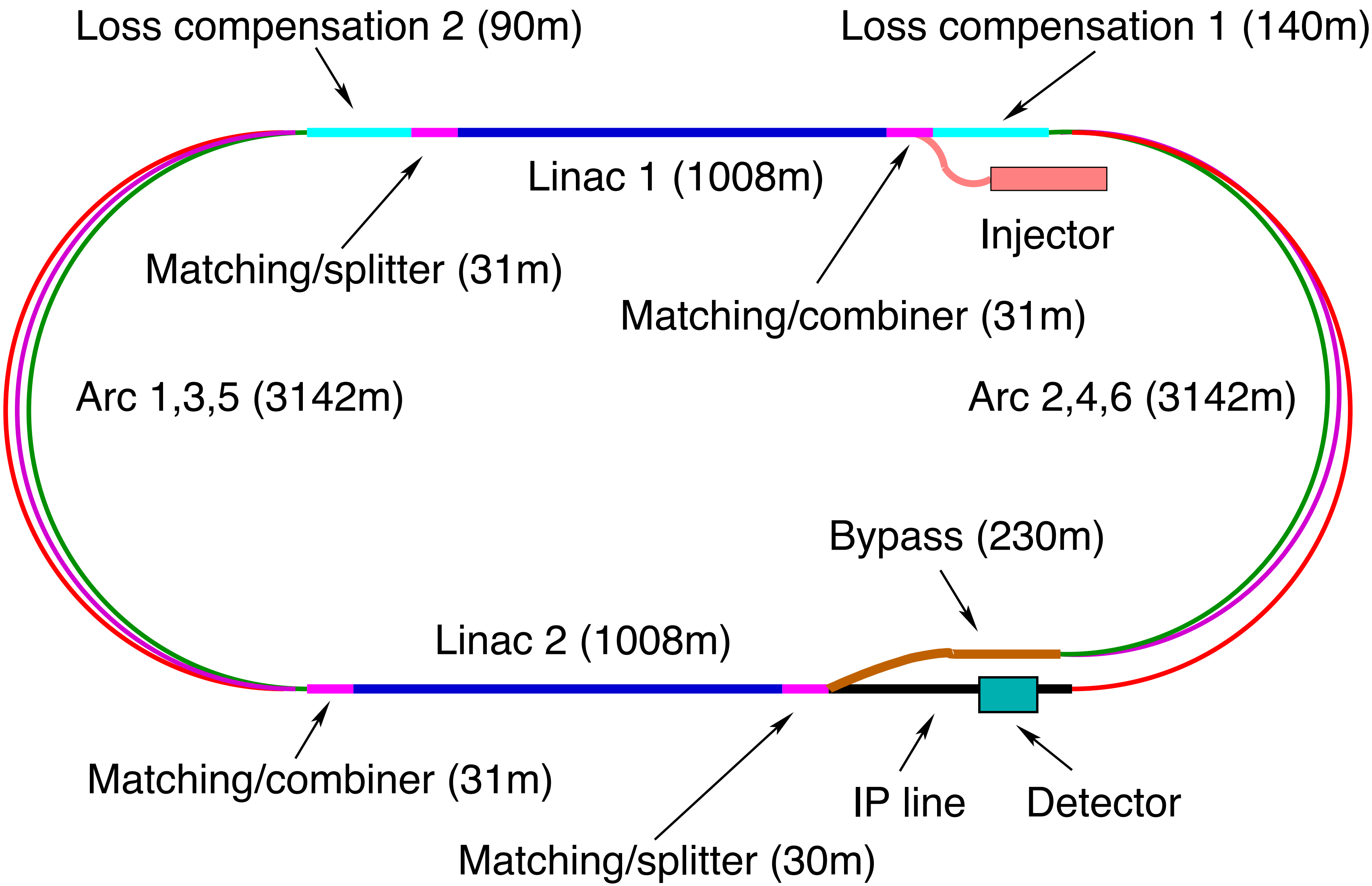
“BFKL evolution and Saturation in DIS”

“Critical gravitational collapse”

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

LHeC

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



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. New dipole magnets. “SAPHIRE” 4 pass 80 GeV option: γγ→ H

Accelerator Design: Participating Institutes

CERN

SLAC NATIONAL ACCELERATOR LABORATORY

NTNU Norwegian University of Science and Technology

ECFA

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

DESY

LAL Physique des accélérateurs

INFN Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Legnaro

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITY OF LIVERPOOL

KEK

BROOKHAVEN NATIONAL LABORATORY

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

Source	Power [MW]
Cryogenics (linac)	21
Linac grid power	24
SR compensation	23
Extra RF cryopower	2
Injector	6
Arc magnets	3
Total	**78**

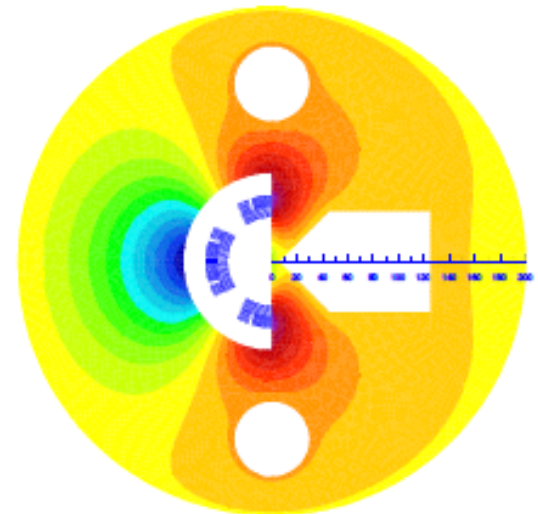
Parameters and Design

257 pages of technical design
in the CDR arXiv:1206:2913, e.g.

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 (e^+ none)	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 (0.3 for e^+)	
CM energy [TeV]	1.3, 0.81	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1 (10), 0.2	

Update of parameter table in view of H - arXiv:1211:5102

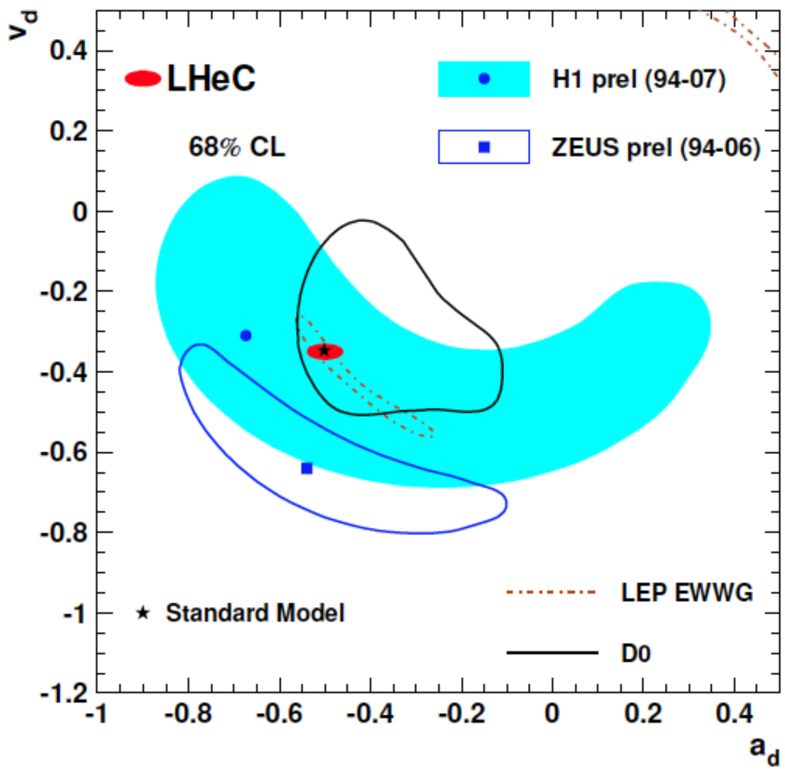
Designed for synchronous ep and pp operation

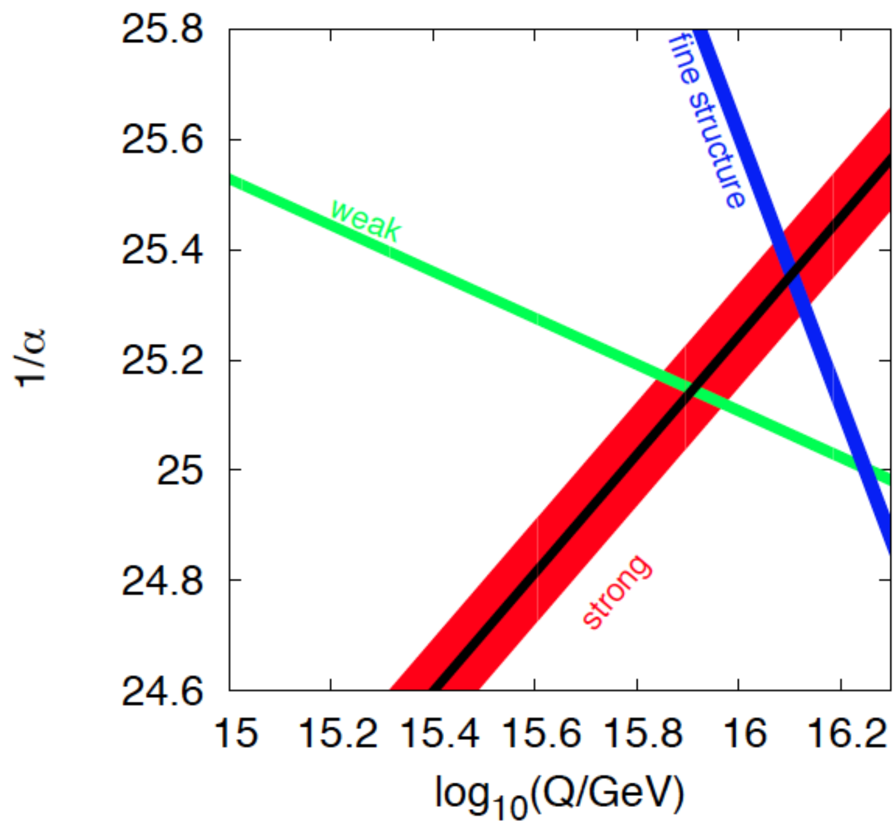


"Q1" SC 3-beam IR magnet

1→3 beam spreader design

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

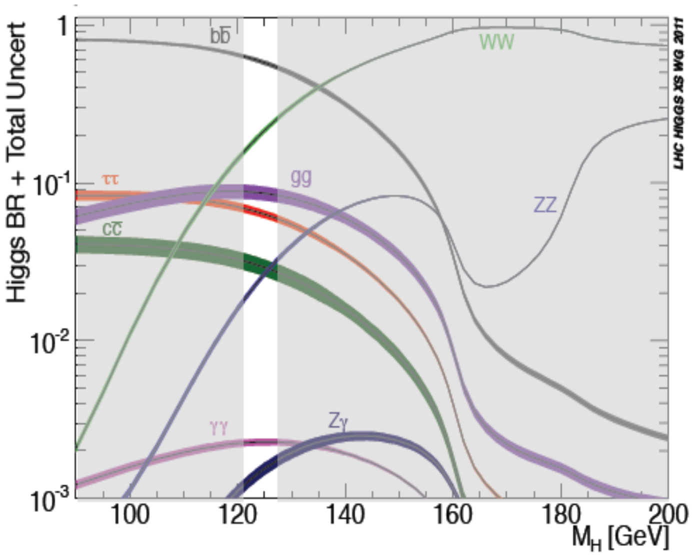
Higgs and LHeC

Precision measurements of couplings **in WW and ZZ production** (CDR: bb study in CC)
Measurement of CP properties ($J^{PC}=0^{++}$ in SM; MSSM has 2 CP-even and 1 CP-odd states)

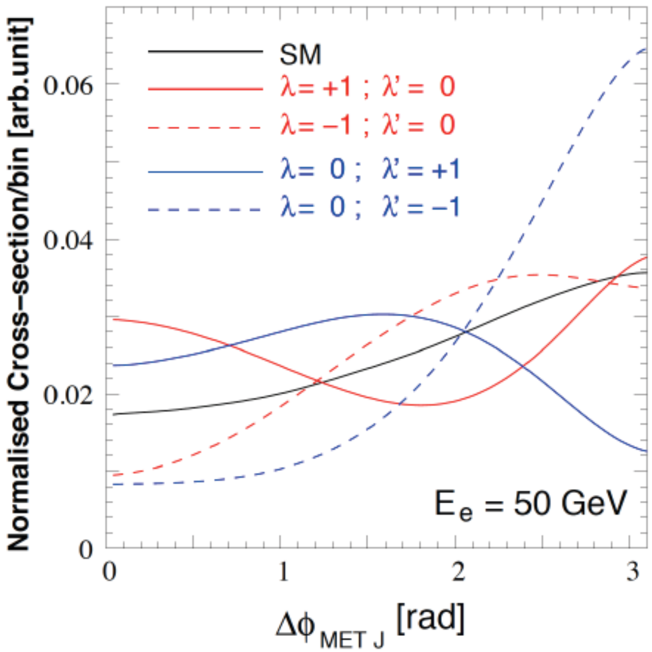
First LHeC Higgs study: WW → H → bb

PGS for detector, cut based analysis, S/B =1, 500 H-bb events for 100fb^{-1}
→ **2-3% H-bb coupling precision**

thy corrections small:
J.Blümlein et al, NP B395(1993)35

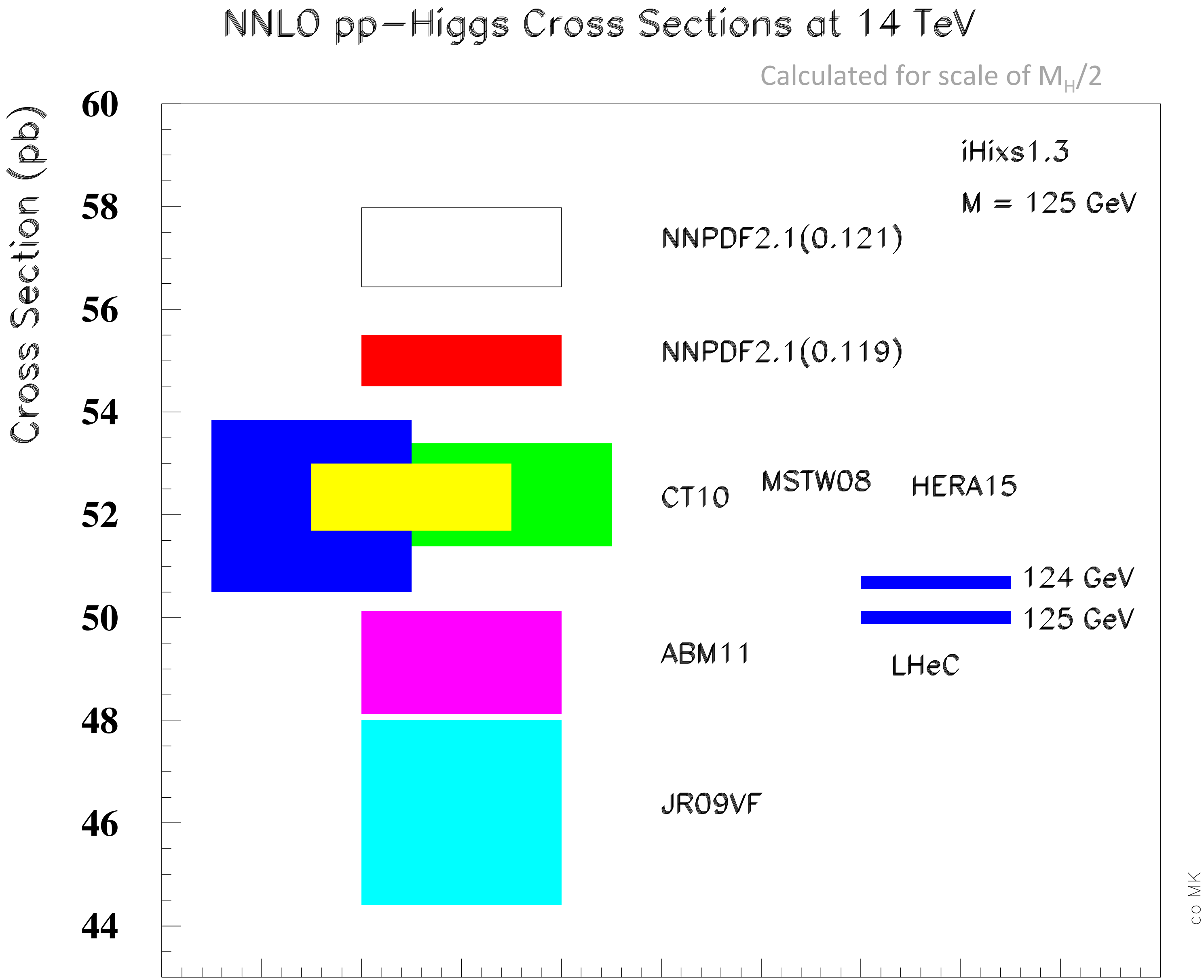


$$\Gamma^{(BSM)}_{\mu\nu}(p,q) = \frac{-g}{M_W}\left[\lambda\,(p.q\,g_{\mu\nu} - p_\nu q_\mu) + i\,\lambda'\,\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$



ICHEP12: J Campbell: ultimate limitation of Higgs measurements from LHC by PDFs/QCD →

With high luminosity the LHeC has a huge potential for precision Higgs physics, which is being further evaluated.



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

Leads to mass sensitivity..

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

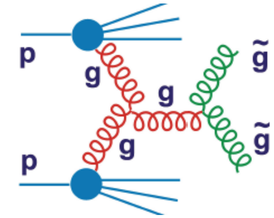
Needs N^3LO

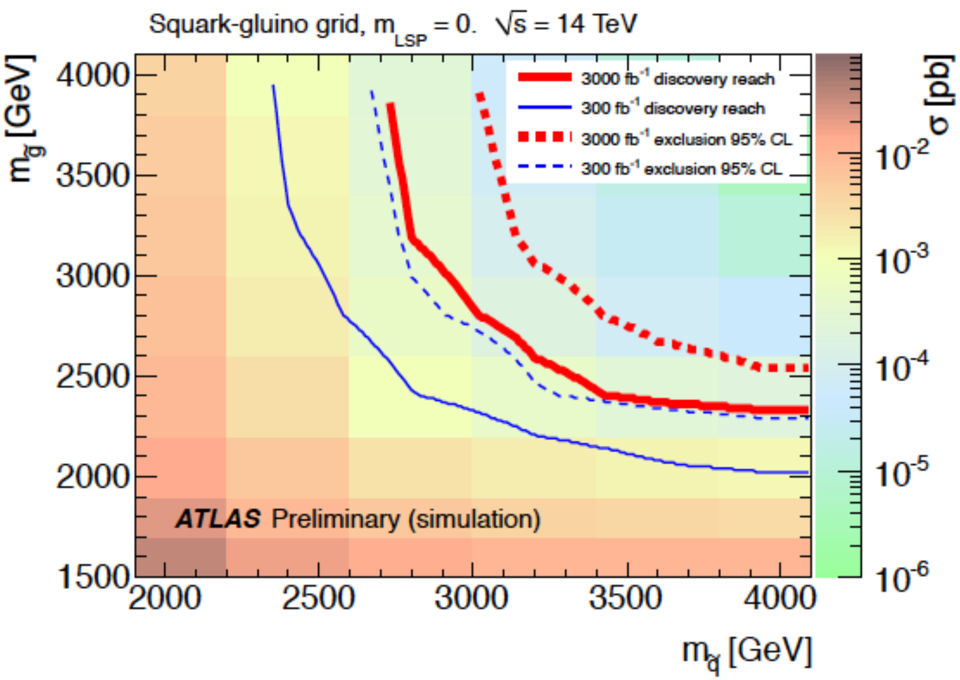
HQ treatment important

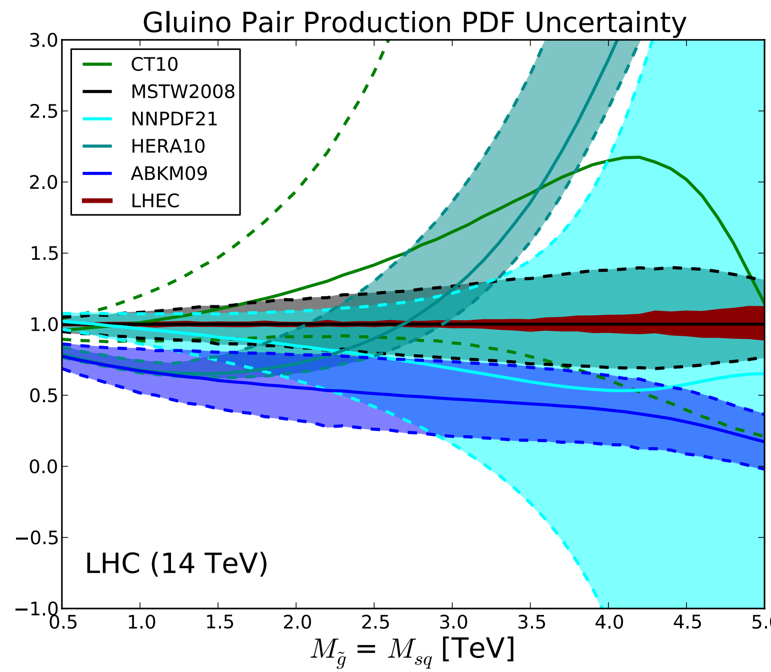
PRECISION σ(H)

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

Searching for High Mass SUSY





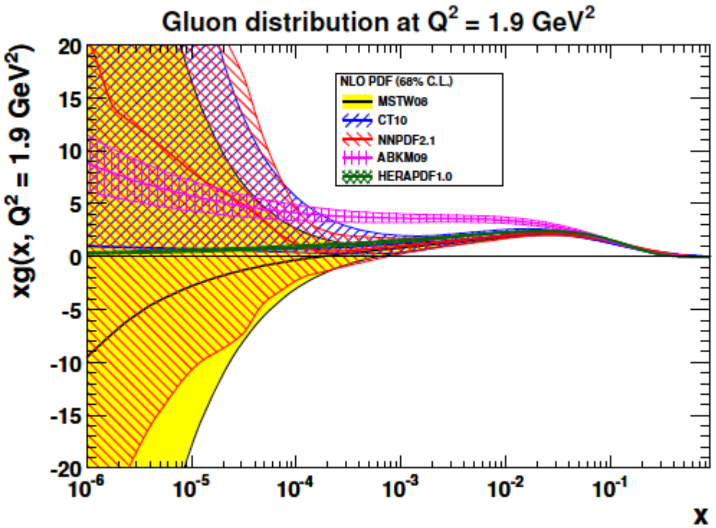


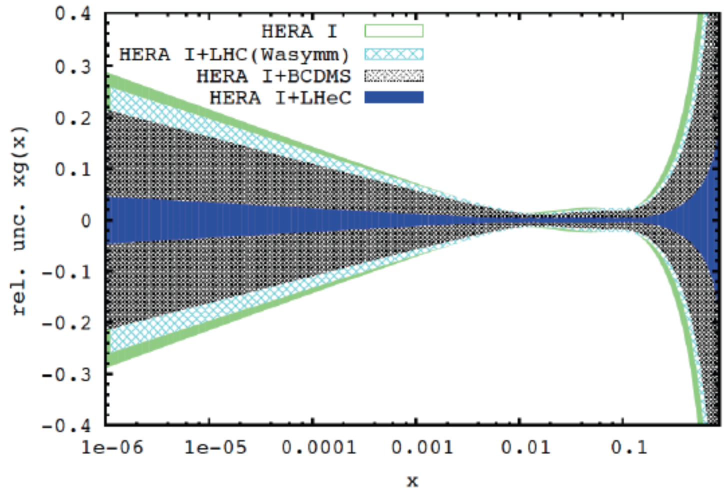
ATLAS October 2012 "Physics at High Luminosity"

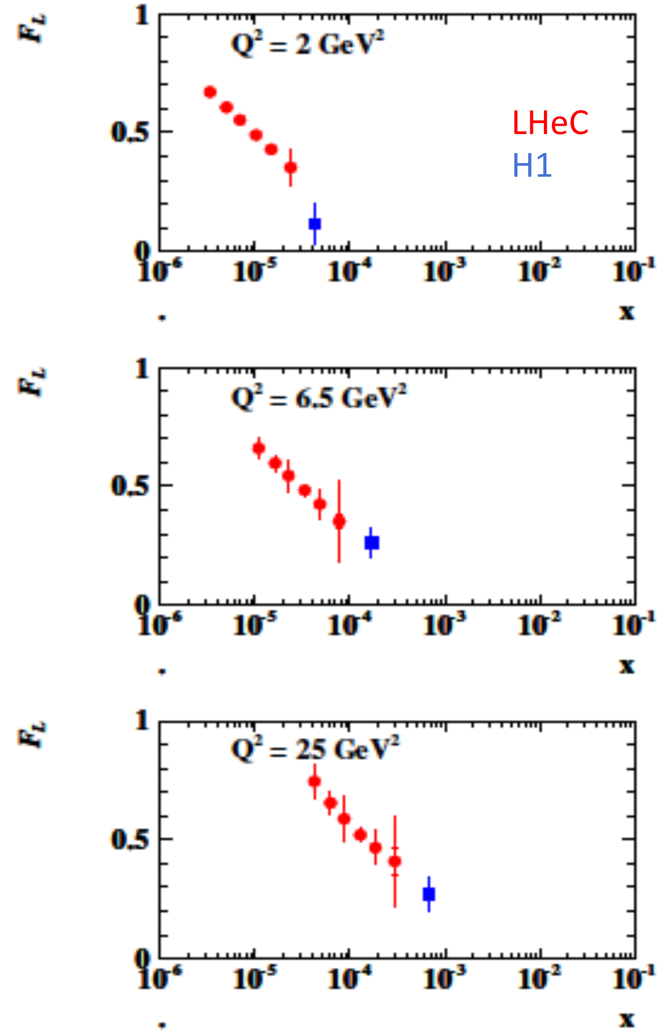
LHeC: arXiv:1211.5102

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

Gluon Saturation at Low x?



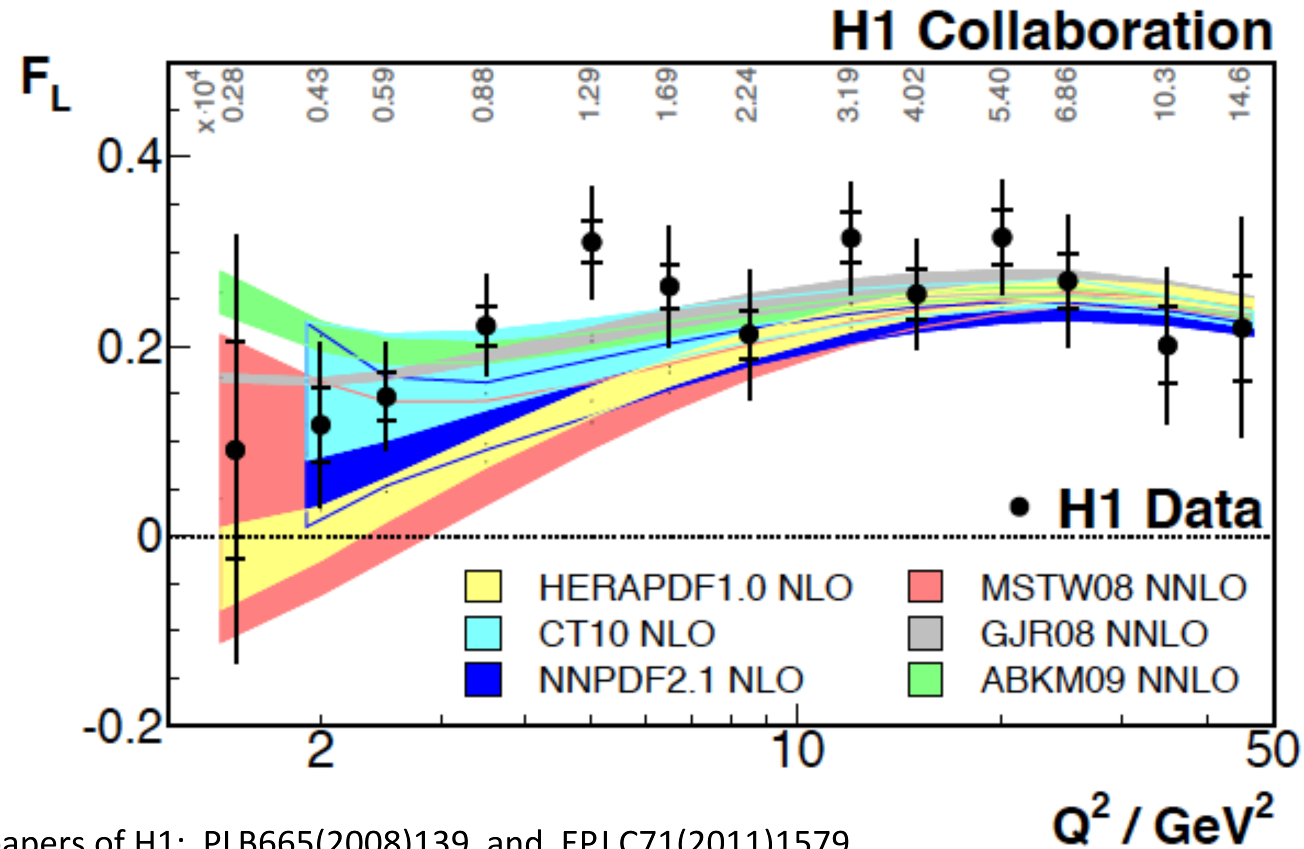




Gluon measurement down to x=10^{-5}, **Saturation or no saturation** (F_2 and precise F_L)
Non-linear evolution equations? Relations to string theory, and **SUSY at ~10 TeV**?

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

Longitudinal Structure Function



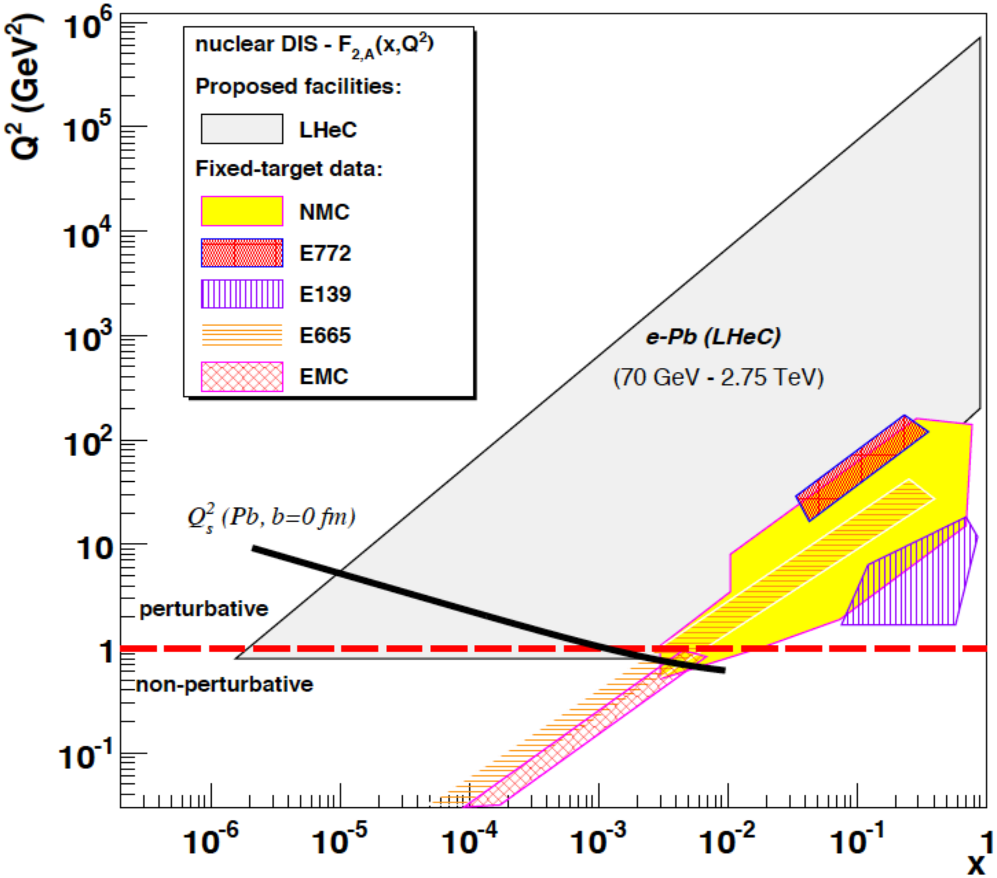
Two F_L papers of H1: PLB665(2008)139 and EPJ C71(2011)1579

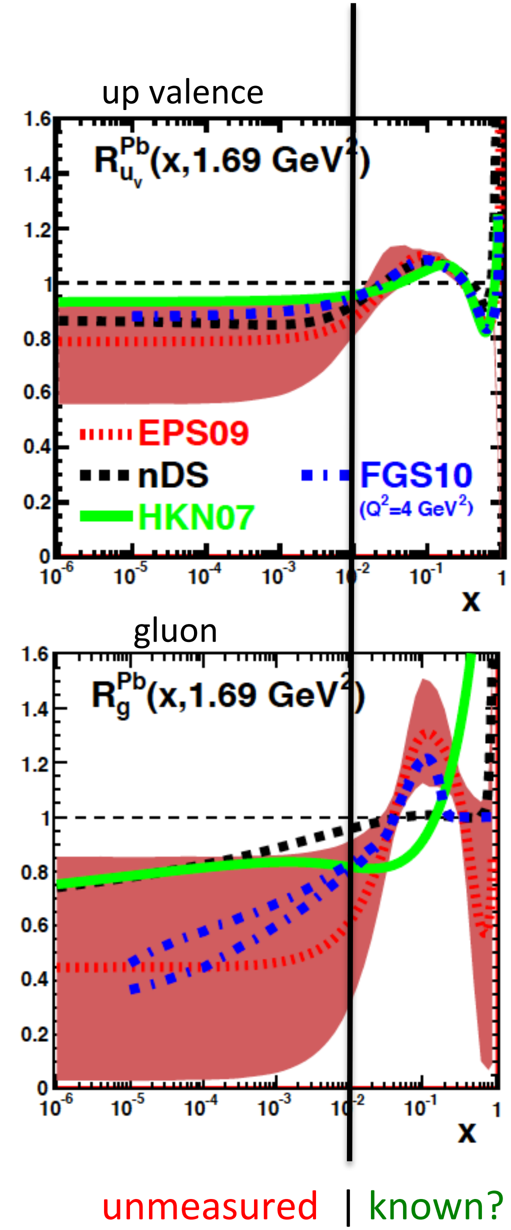
F_L provides independent test of QCD

Data taken in 2007 before termination of HERA.
Low Q^2 accessed with Backward Silicon Tracker (1992-2007), 20 years on F_L …

H.Lippold, A.Meissner, W.Lange, U.Harder, H.Henschel + I. Tsurin et al. Thanks to DESY+H1

LHeC as an electron-ion collider



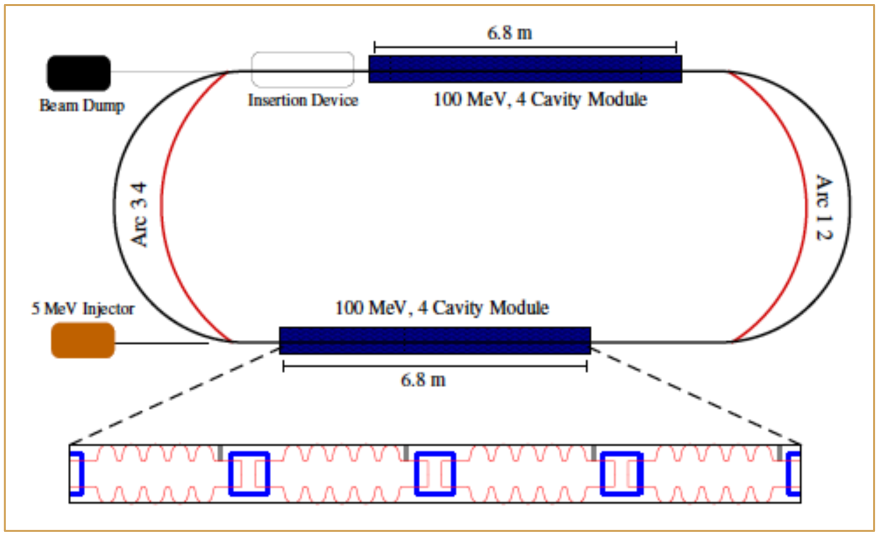


3-4 orders of magnitude extension of lA kinematic range

→ LHeC has huge discovery potential for new HI physics
(bb limit, saturation, deconfinement, hadronisation,QGP..)
will put nPDFs on completely new ground - **Deuterons**

Key developments for the LHeC

LHeC ERL Test Facility at CERN

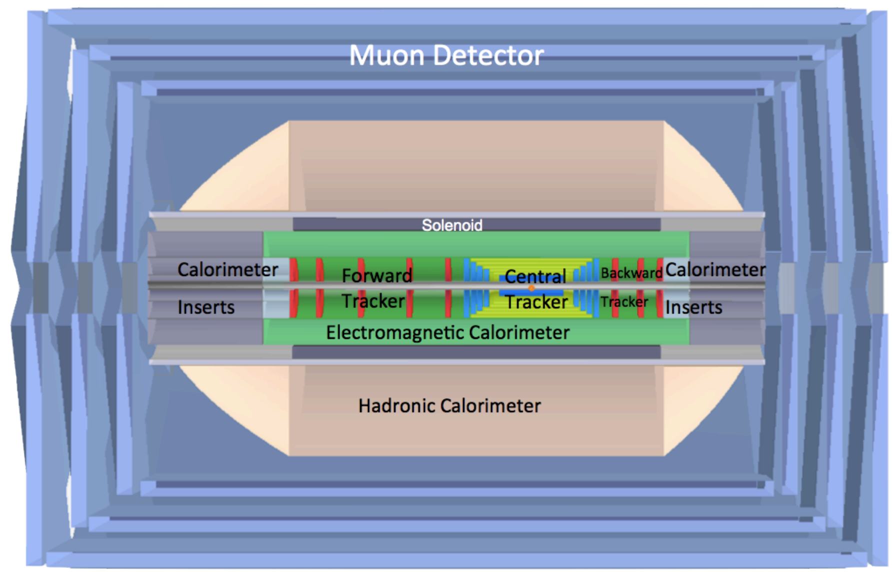


R.Calaga, E.Ciapala, E.Jensen, LHeC-Note-2012-005 ACC

Collaboration with AsTEC, Jlab, Mainz, BNL, Novosibirsk..

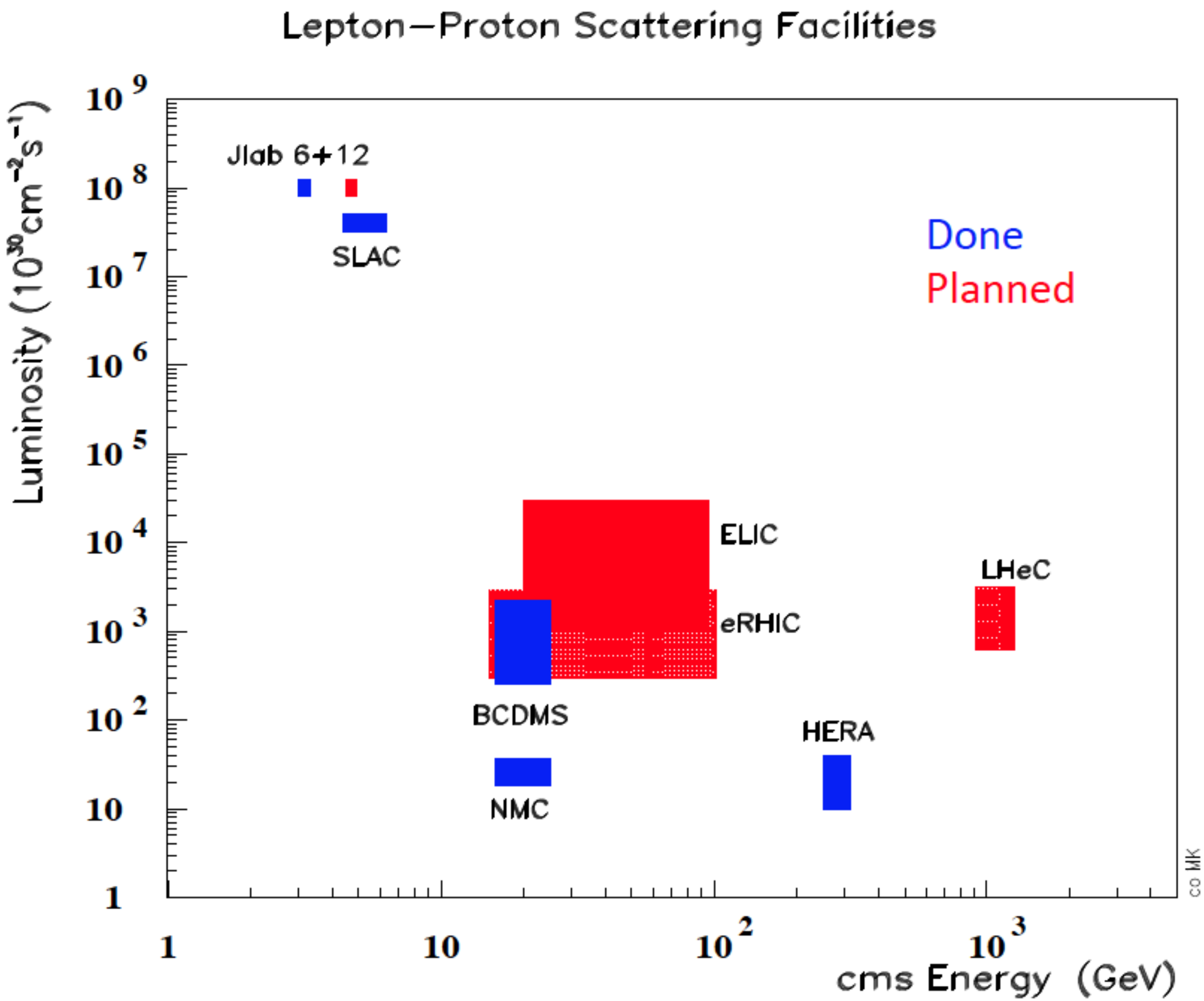
High Q cavity,
Prototype of Q1
Beam Dynamics (ATS, HL-LHC..)
Interaction Region …

Physics studies in view of LHC results (LPCC day on LHeC 18.4.2013).
Higgs and high luminosity, top, …



Further development of ep/eA detector (forward tracking, GEANT5 simulation..)

..Decision on the LHeC realization in a few years, after 2015 (13 TeV pp data)..



The LHeC provides the only, single opportunity to develop DIS as part of HEP for decades, enriching the LHC physics… “it would be a waste not to use it” (G.Altarelli, 2008)

PhD Students

Uta Stoesslein – first F_2 and xg
Sasha Glazov – first precise F_2
Rainer Wallny – alphas
Doris Eckstein – BST momentum
Tomas Lastovicka – self similarity
Ilya Tsurin – BST electronics
Jan Kretzschmar – most precise F_2 ...

Zeuthen H1

Hartmut Baerwolff
Johannes Blümlein
Ulrich Gensch
Helmut Kaufmann
Peter Kostka
Thomas Naumann ..

BCDMS

Dima Bardin
Alberto Benvenuti
Ticiano Camporesi
Igor Golutvin
Francesco Navarria
Jim Pilcher
Tord Riemann
Igor Savin ..

L3: Hans Hofer, Rudolph Leiste
Martin Pohl, Bolek Wieslouch..

COZ
H1 drift chamber built at Zeuthen 1986-91

H1

Alexey Babaev
Vladimir Chekelyan
Jochen Bürger
John Dainton
Franz Eisele
Joel Feltesse
Karsten Gadow
Tim Greenshaw
Carsten Niebuhr
Daniel Pitzl
Emmanuelle Perez
Natasa Raicevic..

ATLAS

Phil Allport
Max Bellomo
Monica D'Onofrio
Fabiola Gianotti
Sasha Glazov
Karl Jakobs
Peter Jenni
Uta Klein
Jan Kretzschmar
Leandro Nisati
Jim Pilcher
The Liverpool ATLAS Group

LHeC

Guido Altarelli
Nestor Armesto
Olaf Behnke
Sergio Bertolucci
Stan Brodsky
Oliver Brüning
Rama Calaga,
John Dainton
Stefano Forte
Rolf Heuer
Uta Klein
Peter Kostka
Paul Laycock
Lev Lipatov
Erk Jensen
John Jowett
Steve Myers
Paul Newman
John Osborne
Emmanuelle Perez
Alessandro Polini
Voica Radescu
Daniel Schulte
Sasha Skrinsky
Anna Stasto
Ferdinand Willeke
Frank Zimmermann ..

Thanks to Zeuthen, Dubna, Zürich, Hamburg, Liverpool and Meyrin, …. to IoP and DPG

Nachbemerkung

In der Enge der von Mauern eingeschlossenen DDR gab es auch den Anspruch, hohe Kultur zu entwickeln, Forschung in vertrauensvoller Zusammenarbeit, ein Ziel, dem die inter- wie auch intranationale Gemeinschaft der Teilchenphysiker stets verpflichtet war. Um sich daran beteiligen zu können, bedurfte es steter Anstrengung, nicht anders als in der freieren Welt, die für zu viele zu lange zu fern war. Gemessen an heutigen Beobachtungen auch in meinem Gastland war meine Ausbildung von hervorragender Qualität. Ich machte das Abitur in einem Kreis von nur 15 Schülern, ausgewählt aus dem ganzen, kleinen Land, an der "Spezialklasse für Mathematik" der Humboldt-Universität zu Berlin, es war das Jahr, da in Stanford in tiefinelastischer Elektron-Proton-Streuung Partonen entdeckt wurden. Unsere Dozenten an der Spezialklasse, wie auch im Physikstudium, das ich in Berlin mit 22 und einem Diplom beendete, gehörten zur Universität und zur Akademie der Wissenschaften, in deren Institut für Hochenergiephysik in Zeuthen ich promovieren durfte, ehe ich am Tag nach meiner Doktorprüfung nach Dubna bei Moskau fuhr, um eine Arbeit zu beginnen, die eben freundlicherweise mit dem Max-Born-Preis bedacht wurde. Ich möchte aus diesem Anlass gern erinnern an meinen Gymnasiallehrer Gerhard Sack, dem ich Stil und Urteil verdanke, sowie an Fritz Bernhard, Kollege von Gustav Hertz in Suchumi, Schirmherr der Mathematikspezialklassen, Leiter des Bereichs "Atomstossprozesse der Festkörperphysik", der mir ungewöhnliche Freiheiten gab und seine hohen Ziele durch Ermutigung und Vertrauen erreichte. Ich möchte ferner erinnern an Klaus-Jochen Biebl, theoretischer Physiker, meinen Doktorvater und damals der Einzige, von dem ich annehmen durfte, dass er wirklich alles verstand, was mir oft fremd war, und auch an den in Dresden gut bekannten Anglisten Hans Joachim Meyer, der mir an der Universität quasi privaten Englischunterricht erteilte. Ihnen und anderen, wie dem Zeuthener Direktor Karl Lanius, voran aber meinen Eltern, Fritz Klein, Historiker, Sohn des Journalisten Fritz Klein sen., der 1935 verstarb, und Anna-Dorothea Klein, Slawistin, Tocher des Pädagogen Heinrich Deiters, meiner eigenen Familie, Freunden und vielen Lehrern habe ich zu verdanken, überhaupt in die Nähe einer Preisauswahl habe kommen zu können. Woran ich hier dankbar erinnern wollte, das sind das wissenschaftliche Ethos und die tiefe Bildung, an denen man sich auch in dem wohl zu Recht untergegangenen Land orientieren konnte, in das ich hineingeboren wurde.

Thanks

Candidates for Surprises and Discoveries:

LHeC Physics Programme: **CDR, arXiv:1211.4831 and 5102**

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

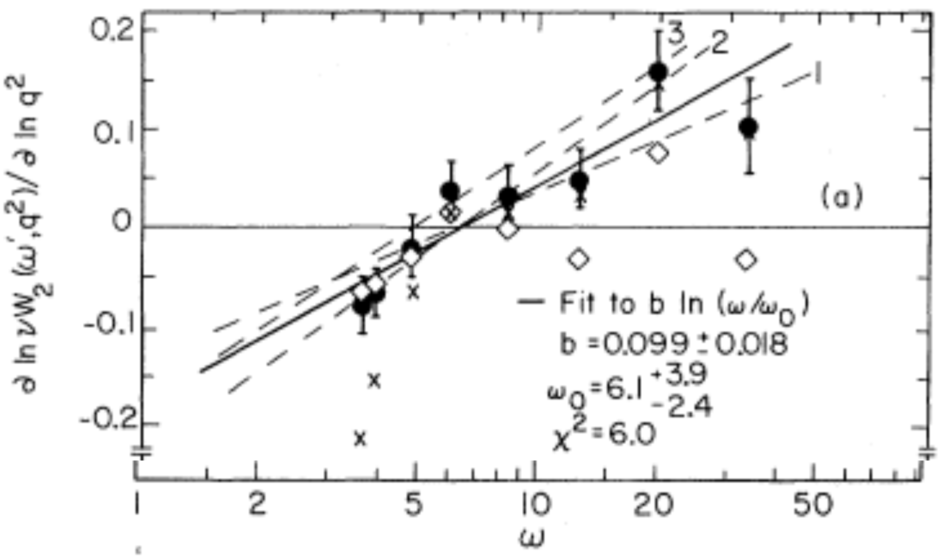
QCD Discoveries	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$
Higgs	WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate
Substructure	electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H?
New and BSM Physics	leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s
Top Quark	top PDF, $xt = x\overline{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c
Precision DIS	$\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure	Proton, Deuteron, Neutron, Ions, Photon
Quark Distributions	valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top
QCD	N^3LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing
Heavy Ions	initial QGP, nPDFs, hadronization inside media, black limit, saturation
Modified Partons	PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

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**

Gluons

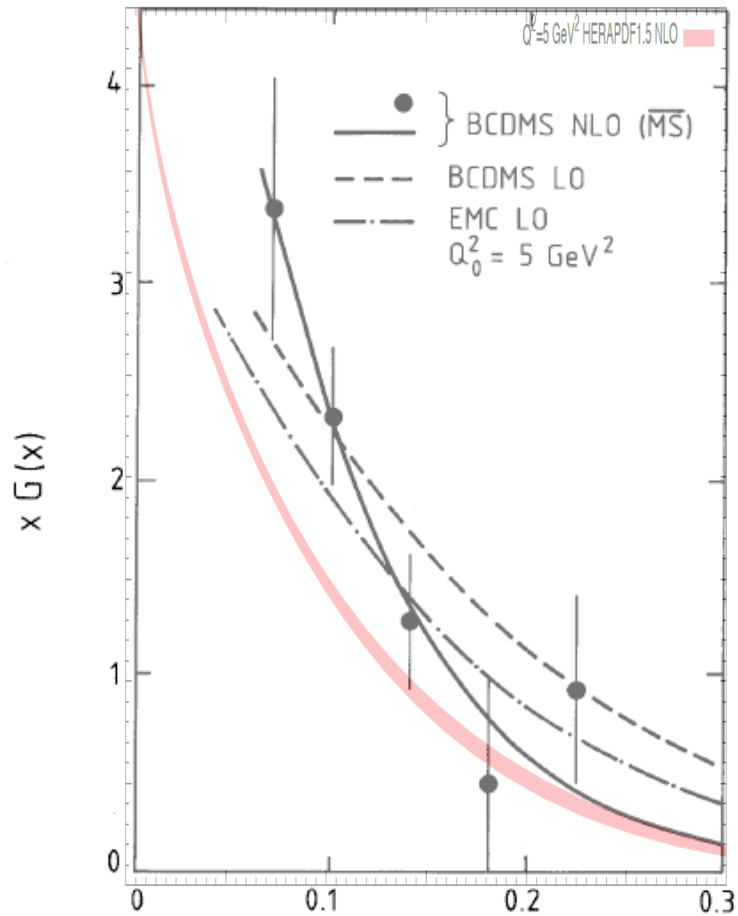
early μN scattering



Scaling violations, FNAL 74, ω=1/x

Thus νW_2 is a decreasing function of q^2 in the range $0.2 < x < 0.3$, it remains fairly constant at $x \simeq 0.2$ and becomes an increasing function of q^2 for $x < 0.2$.

Pattern of scaling violation implied by field theories
Wu-Ki Tung Phys.Rev.D12 (1975) 3613
a friend not forgotten

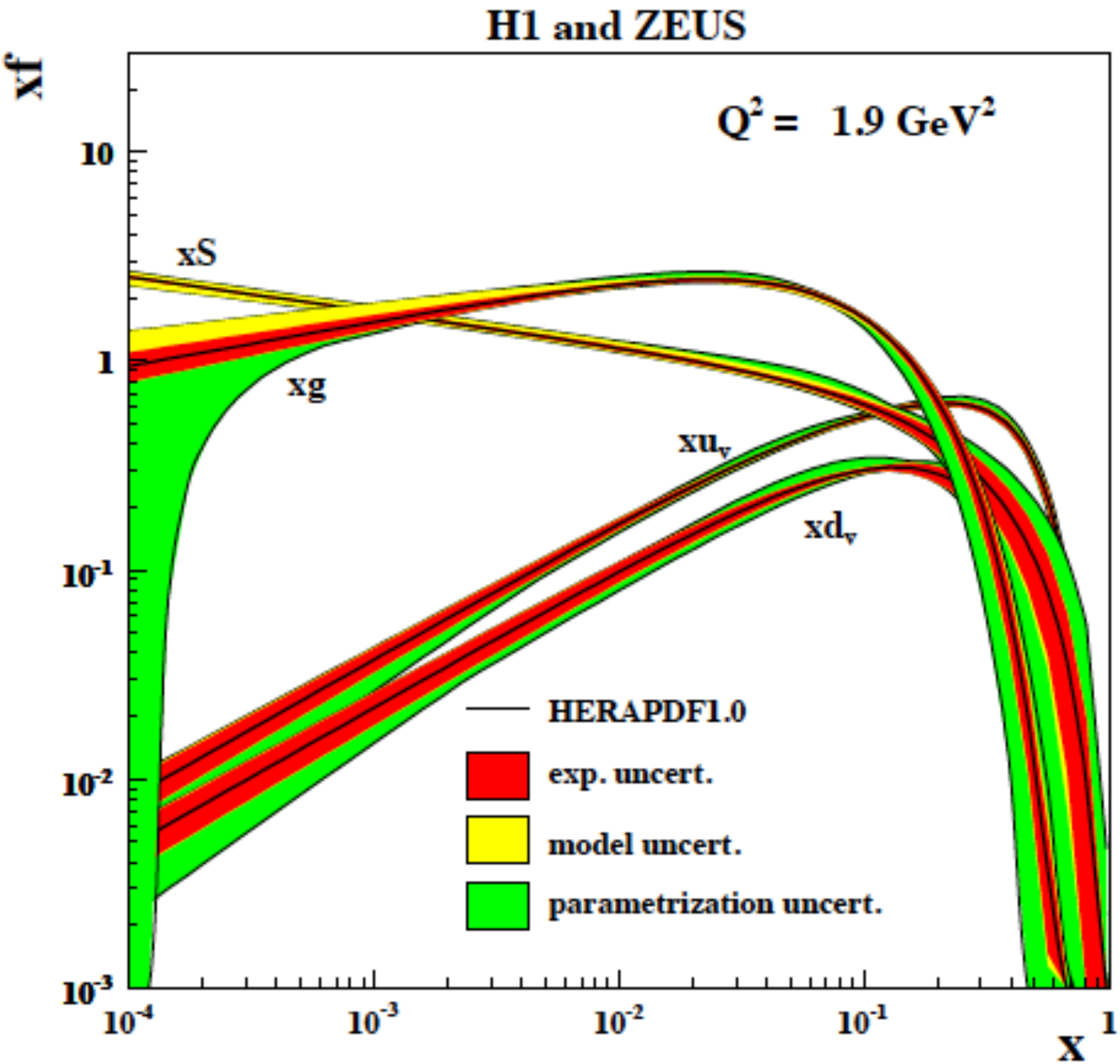


$xG(x,Q_0^2) = 4.5(1-x)^8$ at $Q_0^2 = 5$ GeV²

Phys.Lett. B223 (1989) 490

...DGLAP equations, NLO.

3-jet events at PETRA "the gluon is found" (Abdus Salam at Rochester Conference, Madison 1980)



H1+ZEUS EPJ C64(2009)561

Precision input
EPJ C64(2009)561
and novel data
combination method
lead to

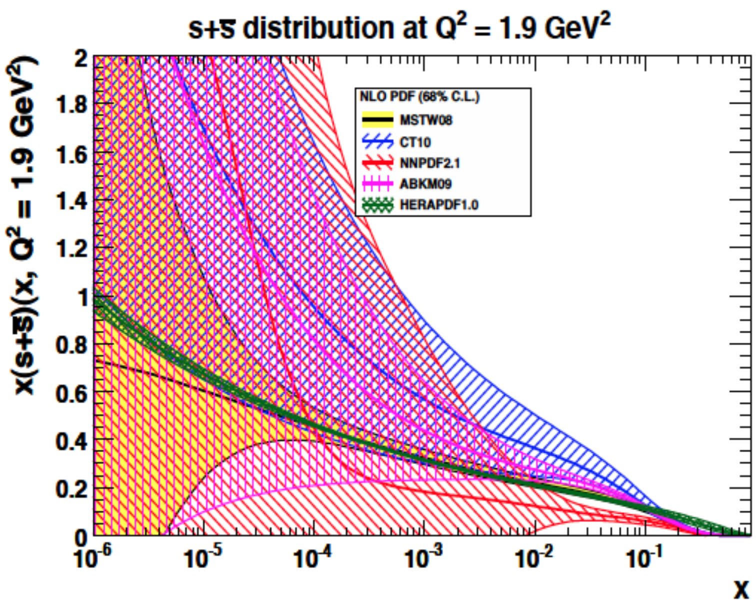
HERAPDF1.0

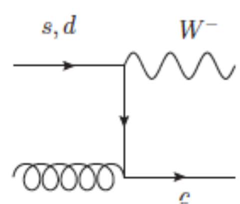
Later added
charm, jets,
NNLO in different
versions.

High x not well
measured at HERA
mainly due to lowish
luminosity. HERA 2
under way

Low x:
no xg information
below x = 2 10^{-4}

Constraints on Strange Quark Distribution - LHC

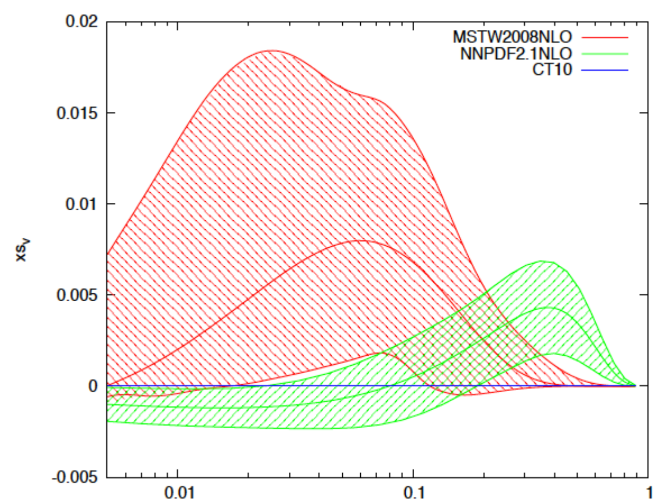




- Large non-perturbative effects to control
- Ratios (W+c/W+j)
- Use charges to access **valence strange**

Scale
$Q^2 = M^2_{W,Z}$

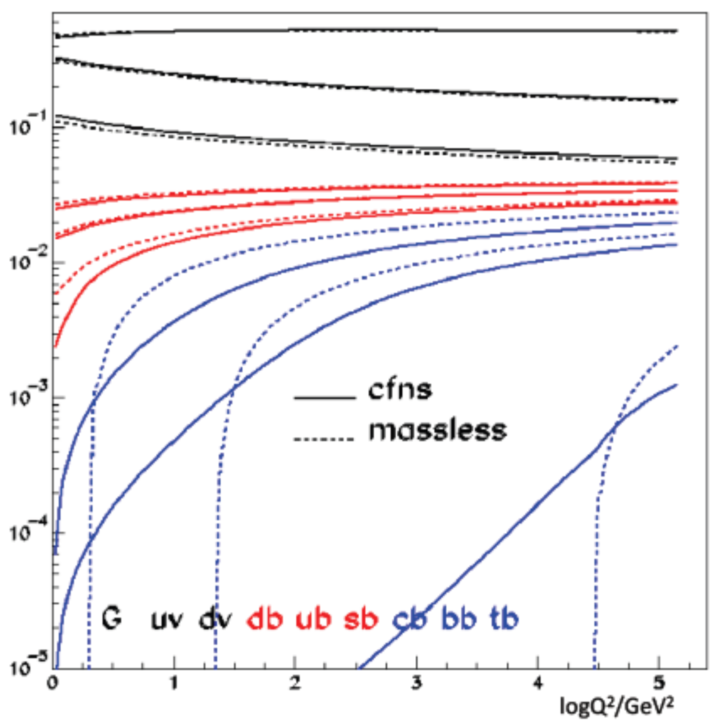
CMS:
PAS-EWK-11-03

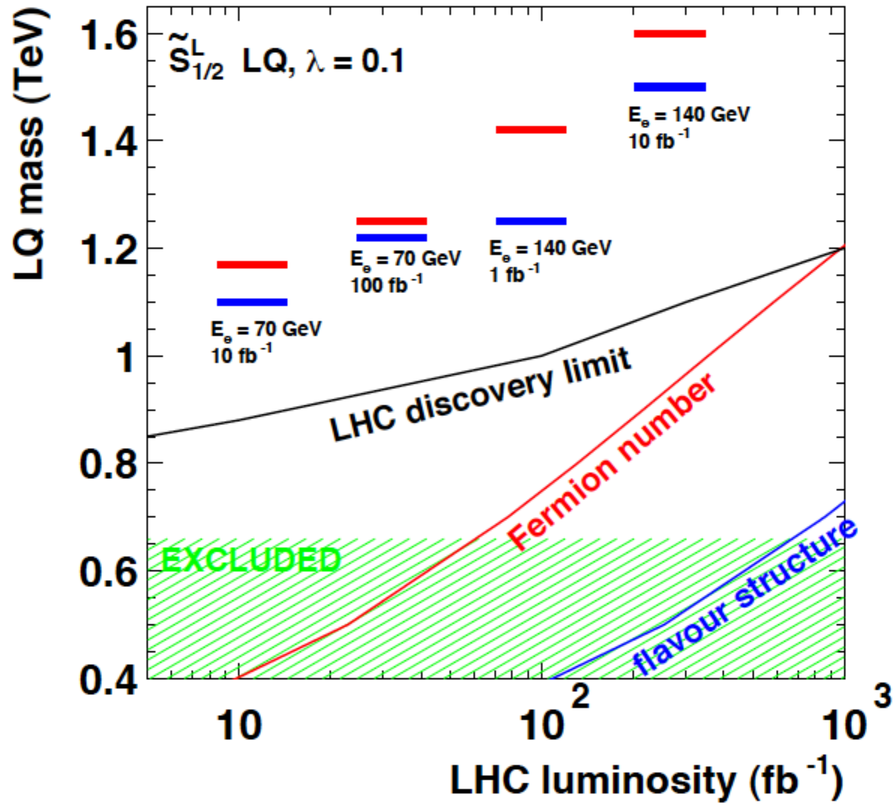


W.Stirling, E.Vryonidou, Phys.Rev.Lett. 109 (2012) 082002

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]

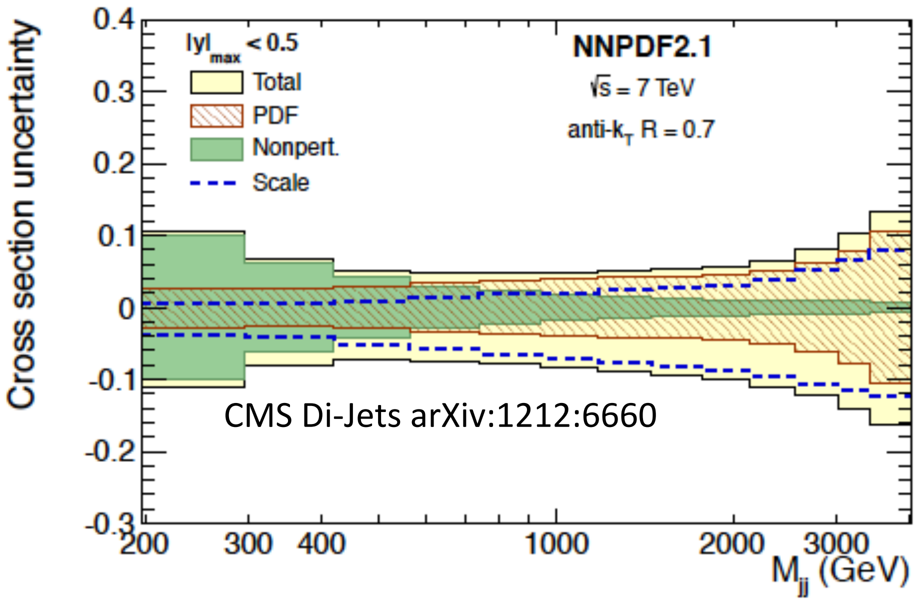




Leptoquarks (-gluons) are predicted in RPV SUSY, E6, extended technicolour theories or Pati-Salam.

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

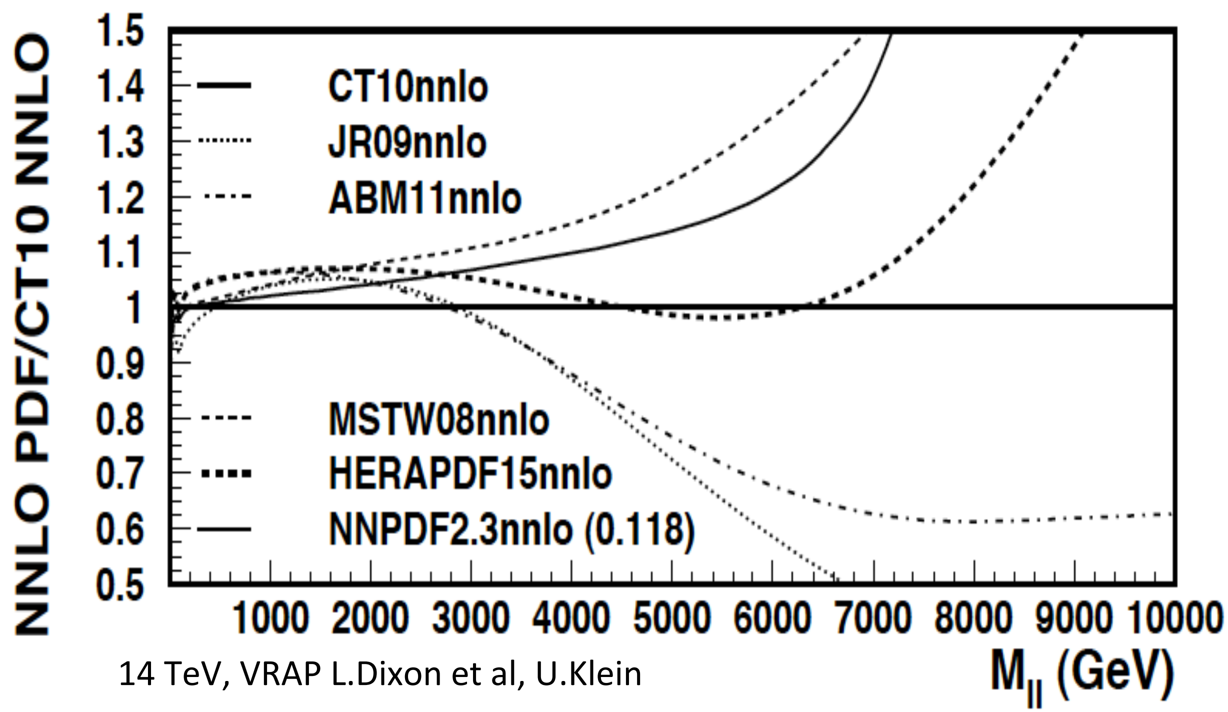
High Mass Drell Yan



CMS Di-Jets arXiv:1212:6660

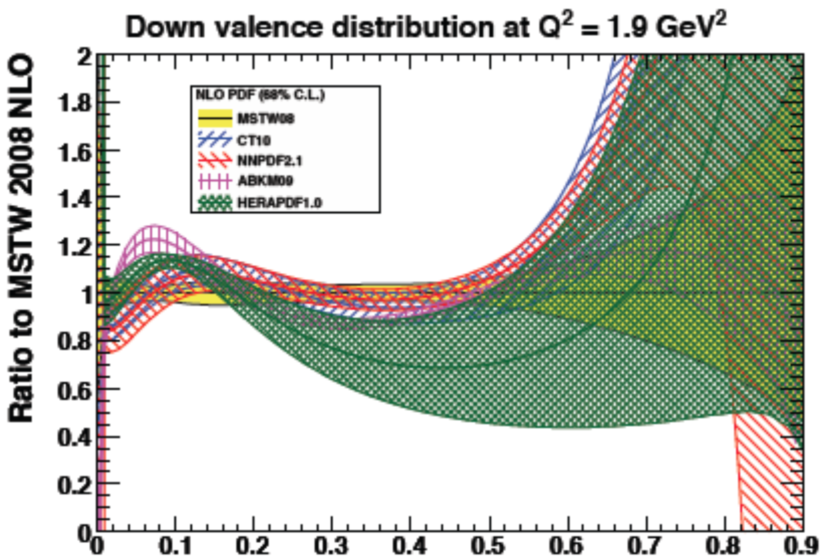
Towards high mass the PDF uncertainties rise, strongly towards the edge (√s) x → 1…

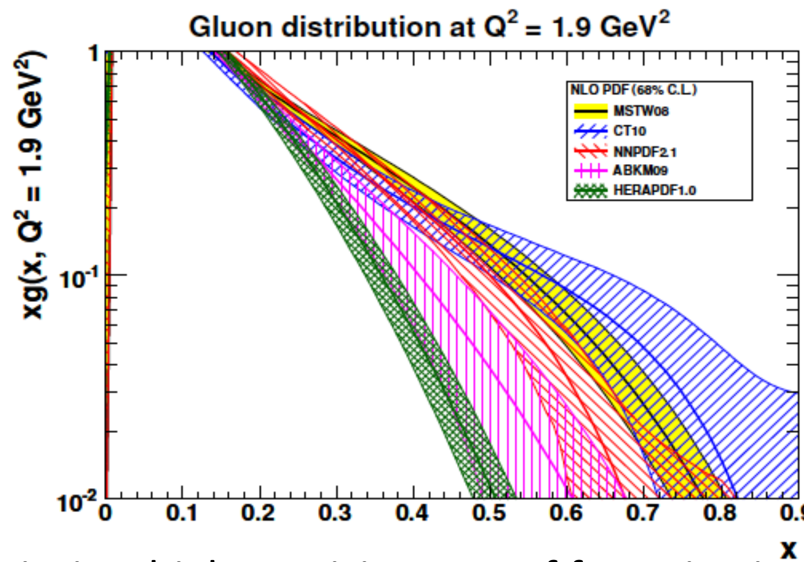
For HL-LHC:
Need to study limits and interferences (ED?) in context with energy calibrations, and thy uncertainties, + PDFs vs BSM expectations



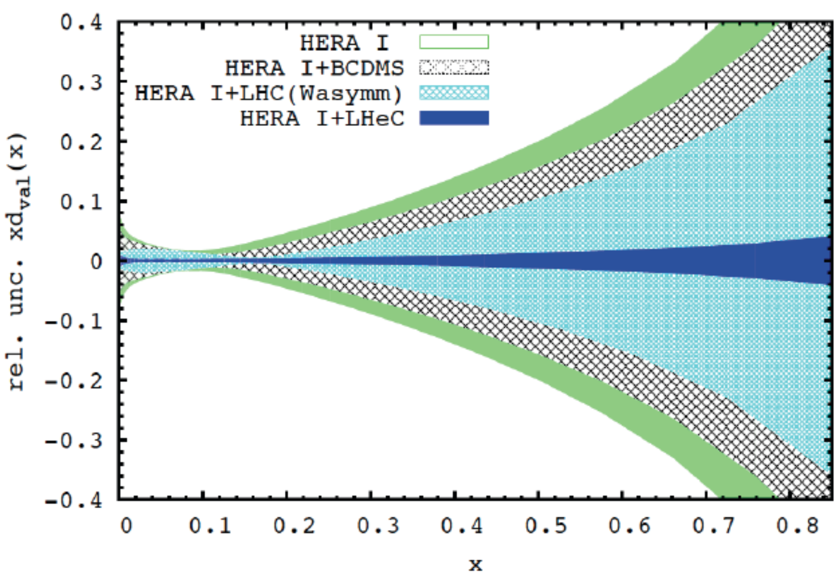
14 TeV, VRAP L.Dixon et al, U.Klein

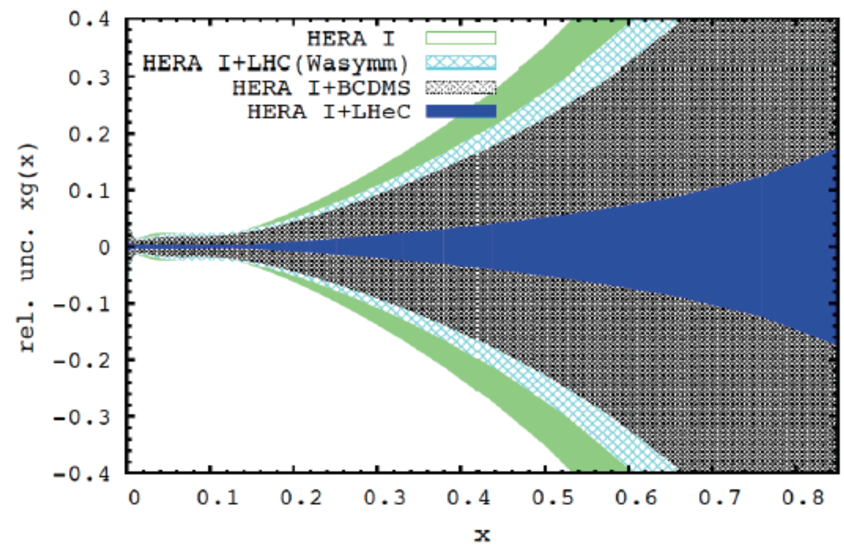
PDFs at Large x





No higher twist corrections, free of nuclear uncertainties, high precision test of factorisation





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

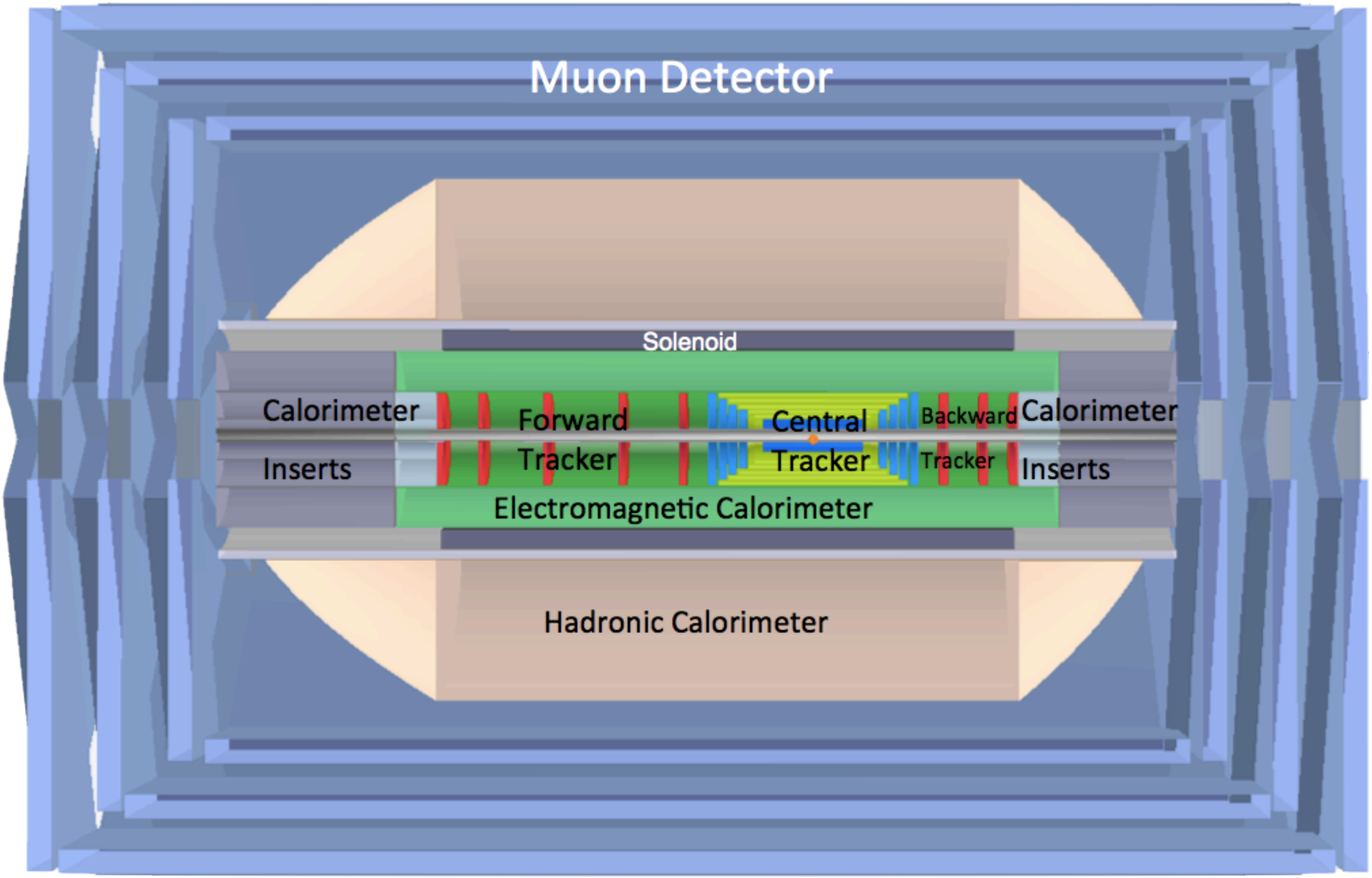
$y \cong 0.005$ .. 0.9
inelasticity

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 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
…

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.

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 =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)