From Quarks 1968 to Future DIS at CERN

Bits of History

The Case for the LHeC

Updating the CDR for the European Strategy 2020

Max Klein

UNIVERSITY OF LIVERPOOL

Introduction to the LHeC/FCCeh/PERLE Workshop at Orsay, 27.6.2018

FUNDAMENTAL THEORETICAL QUESTIONS

M. Froissart, Rapporteur

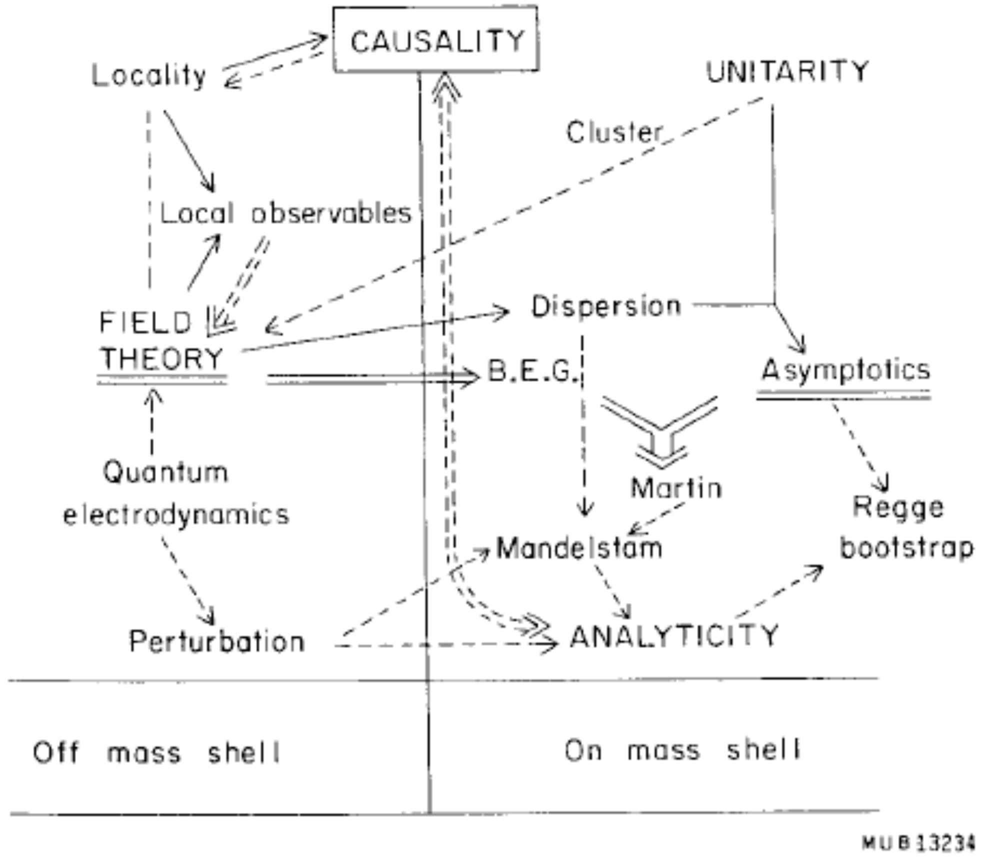
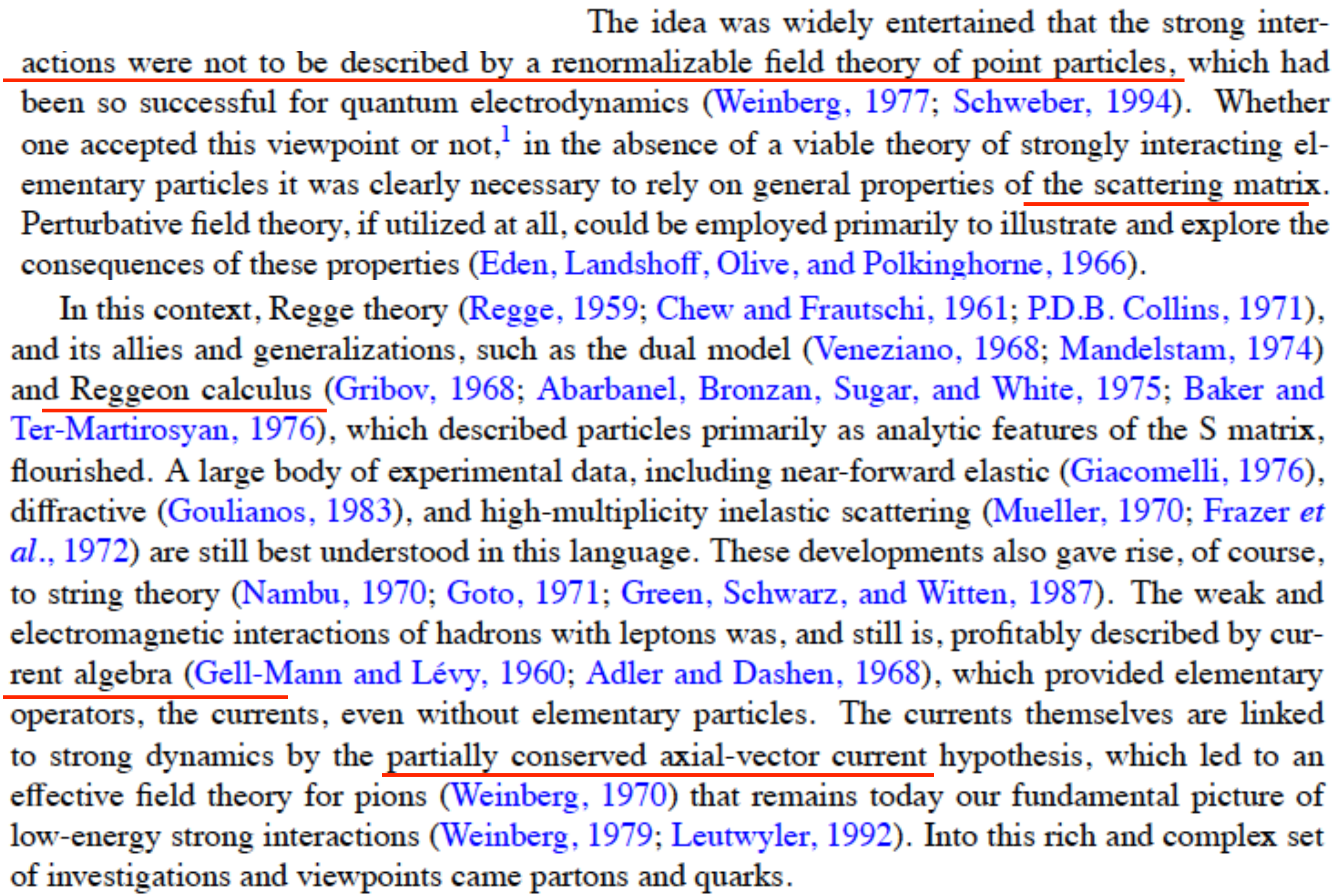


Fig. 1-1. Logical map of "Fundamental" concepts.

Rapporteur Talk at ICHEP 1966



The idea was widely entertained that the strong interactions were not to be described by a renormalizable field theory of point particles, which had been so successful for quantum electrodynamics (Weinberg, 1977; Schweber, 1994). Whether one accepted this viewpoint or not,[1] in the absence of a viable theory of strongly interacting elementary particles it was clearly necessary to rely on general properties of the scattering matrix. Perturbative field theory, if utilized at all, could be employed primarily to illustrate and explore the consequences of these properties (Eden, Landshoff, Olive, and Polkinghorne, 1966).

In this context, Regge theory (Regge, 1959; Chew and Frautschi, 1961; P.D.B. Collins, 1971), and its allies and generalizations, such as the dual model (Veneziano, 1968; Mandelstam, 1974) and Reggeon calculus (Gribov, 1968; Abarbanel, Bronzan, Sugar, and White, 1975; Baker and Ter-Martirosyan, 1976), which described particles primarily as analytic features of the S matrix, flourished. A large body of experimental data, including near-forward elastic (Giacomelli, 1976), diffractive (Goulianos, 1983), and high-multiplicity inelastic scattering (Mueller, 1970; Frazer *et al.*, 1972) are still best understood in this language. These developments also gave rise, of course, to string theory (Nambu, 1970; Goto, 1971; Green, Schwarz, and Witten, 1987). The weak and electromagnetic interactions of hadrons with leptons was, and still is, profitably described by current algebra (Gell-Mann and Lévy, 1960; Adler and Dashen, 1968), which provided elementary operators, the currents, even without elementary particles. The currents themselves are linked to strong dynamics by the partially conserved axial-vector current hypothesis, which led to an effective field theory for pions (Weinberg, 1970) that remains today our fundamental picture of low-energy strong interactions (Weinberg, 1979; Leutwyler, 1992). Into this rich and complex set of investigations and viewpoints came partons and quarks.

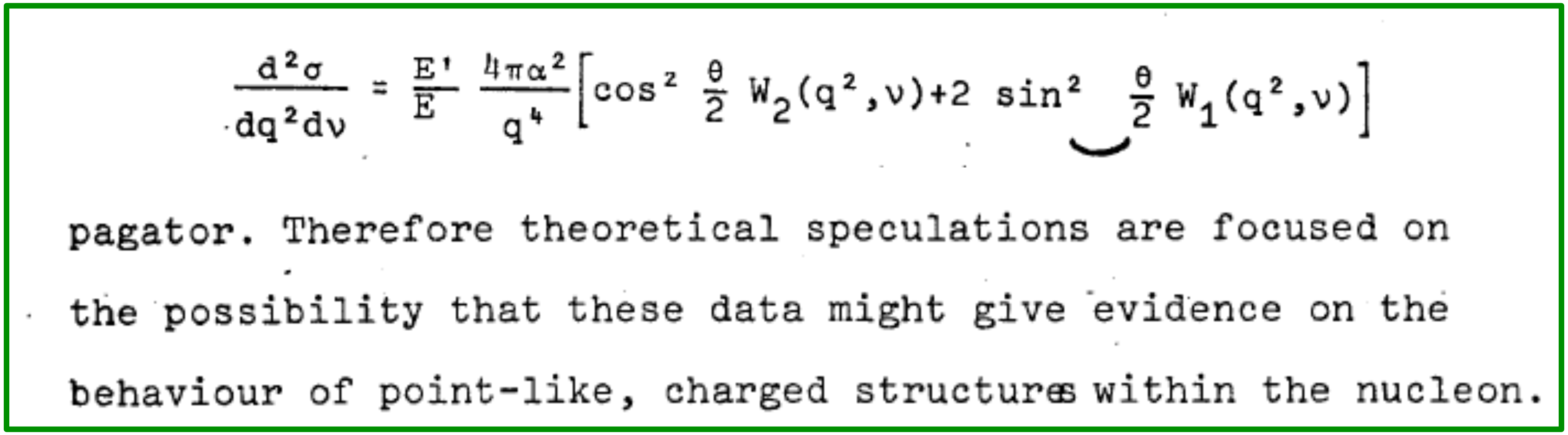
QCD evolved from a Lagrangian with the property of asymptotic freedom to a sophisticated tool for the calculation of high energy processes. R.K. Ellis Nuovo Cimento 39C(2016)355

SLAC-PUB-502
September 1968
(EXP)

ELECTROMAGNETIC INTERACTIONS: LOW q^2 ELECTRODYNAMICS; ELASTIC AND INELASTIC ELECTRON (AND MUON) SCATTERING*

W.K.H. PANOFSKY

Stanford Linear Accelerator Center
Stanford University, Stanford, California

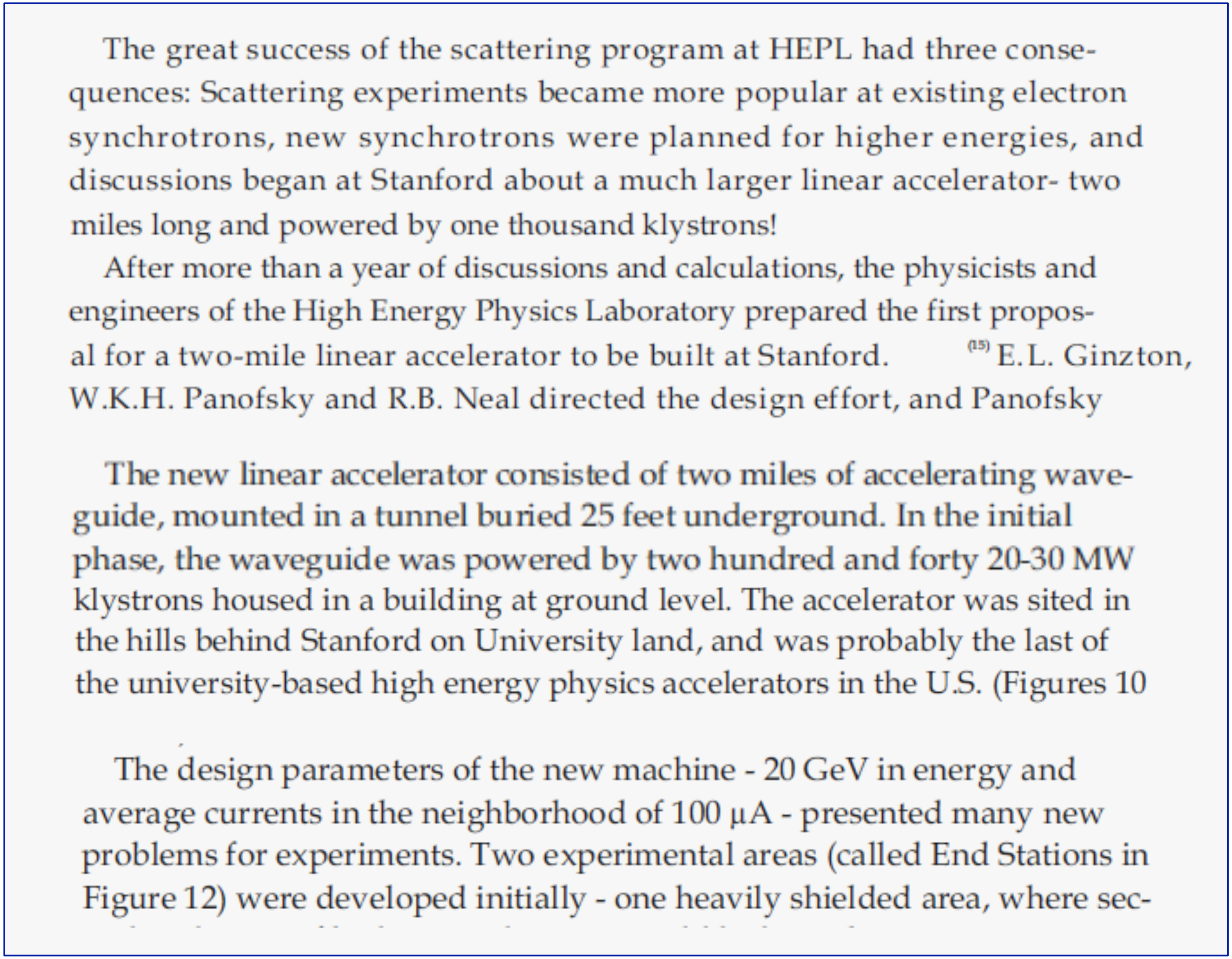


$$\frac{d^2\sigma}{dq^2d\nu} = \frac{E'}{E}\frac{4\pi\alpha^2}{q^4}\left[\cos^2\frac{\theta}{2}W_2(q^2,\nu)+2\sin^2\frac{\theta}{2}W_1(q^2,\nu)\right]$$

pagator. Therefore theoretical speculations are focused on the possibility that these data might give evidence on the behaviour of point-like, charged structures within the nucleon.

(Presented at XIVth International Conference on High Energy Physics, August 28 to September 5, 1968, Vienna.)

2mile Linac



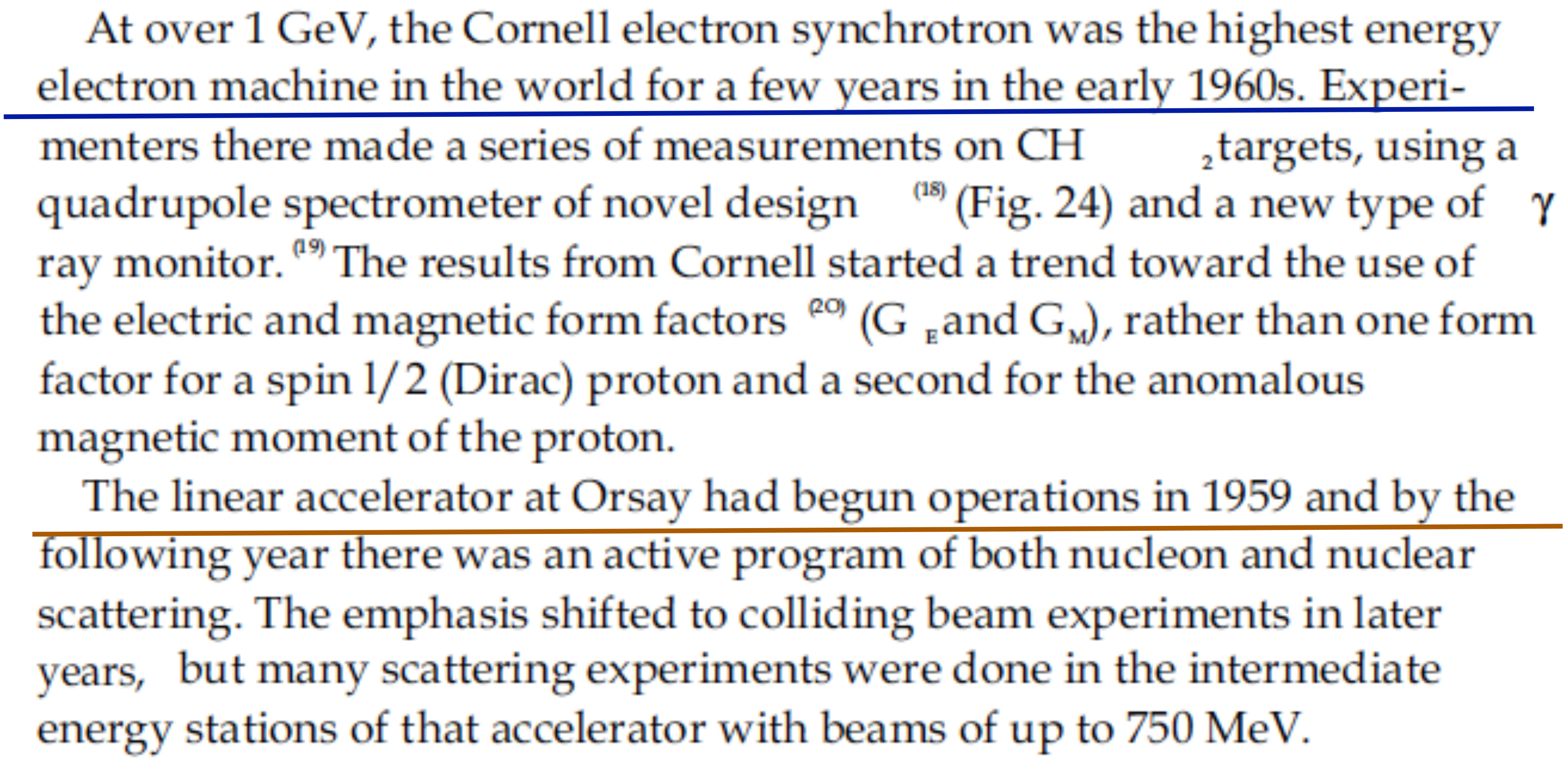
The great success of the scattering program at HEPL had three consequences: Scattering experiments became more popular at existing electron synchrotrons, new synchrotrons were planned for higher energies, and discussions began at Stanford about a much larger linear accelerator- two miles long and powered by one thousand klystrons!

After more than a year of discussions and calculations, the physicists and engineers of the High Energy Physics Laboratory prepared the first proposal for a two-mile linear accelerator to be built at Stanford. (15) E.L. Ginzton, W.K.H. Panofsky and R.B. Neal directed the design effort, and Panofsky

The new linear accelerator consisted of two miles of accelerating waveguide, mounted in a tunnel buried 25 feet underground. In the initial phase, the waveguide was powered by two hundred and forty 20-30 MW klystrons housed in a building at ground level. The accelerator was sited in the hills behind Stanford on University land, and was probably the last of the university-based high energy physics accelerators in the U.S. (Figures 10

The design parameters of the new machine - 20 GeV in energy and average currents in the neighborhood of 100 µA - presented many new problems for experiments. Two experimental areas (called End Stations in Figure 12) were developed initially - one heavily shielded area, where sec-

Cornell and Orsay

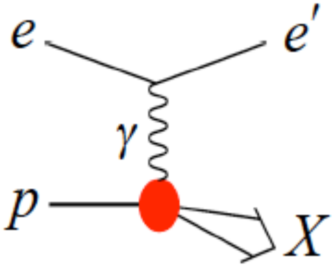


At over 1 GeV, the Cornell electron synchrotron was the highest energy electron machine in the world for a few years in the early 1960s. Experimenters there made a series of measurements on CH_2 targets, using a quadrupole spectrometer of novel design (18) (Fig. 24) and a new type of γ ray monitor. (19) The results from Cornell started a trend toward the use of the electric and magnetic form factors (20) (G_E and G_M), rather than one form factor for a spin 1/2 (Dirac) proton and a second for the anomalous magnetic moment of the proton.

The linear accelerator at Orsay had begun operations in 1959 and by the following year there was an active program of both nucleon and nuclear scattering. The emphasis shifted to colliding beam experiments in later years, but many scattering experiments were done in the intermediate energy stations of that accelerator with beams of up to 750 MeV.

…Further from R Taylor (1929-2018)
Nobel Prize Lecture

Deep Inelastic Scattering ep → eX (1969)

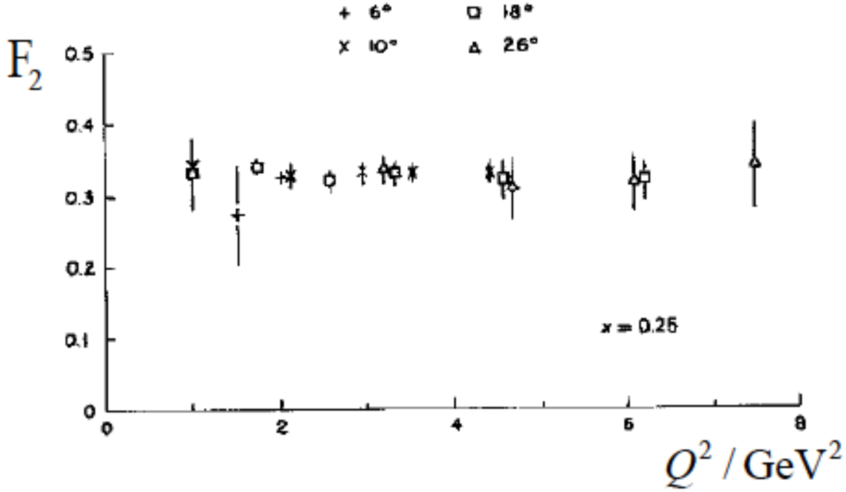


$$\boxed{E_e = 1.5 \ldots 20\,\mathrm{GeV}}$$

$$\theta = 6^\circ \ldots 26^\circ$$

$$Q^2 = 1 \ldots 7\,\mathrm{GeV}^2$$

resolution $\propto \frac{1}{Q} \approx 10^{-16}\,\mathrm{m}$



$$F_2(Q^2, \nu) \rightarrow F_2(x)$$

pointlike scattering centers inside the proton

x = momentum fraction carried by quarks

Friedman, Kendall, Taylor

The Quark Parton Model

$F_2(ep) = x\,[e_u^2\,(u+\text{ubar}) + e_d^2\,(d+\text{dbar})]$

$F_2(ep) = x\,[e_u^2\,(u+\text{ubar}) + e_d^2\,(d+\text{dbar})]$

$q = q_v + q_s$ (Kuti Weisskopf)

If $u_s = \text{ubar} = d_s = \text{dbar}$

$\rightarrow F_2(ep) - F_2(en) = x\,[e_u^2\,u_v - e_d^2\,d_v]$

$e_u = 2/3$, $e_d = -1/3$

till today u_v is better known than d_v

$\rightarrow F_2(eN)/F_2(\nu N) = 1/2\,(e_u^2 + e_d^2)$

SLAC/GGM: 0.29 +- 0.05 (1974)

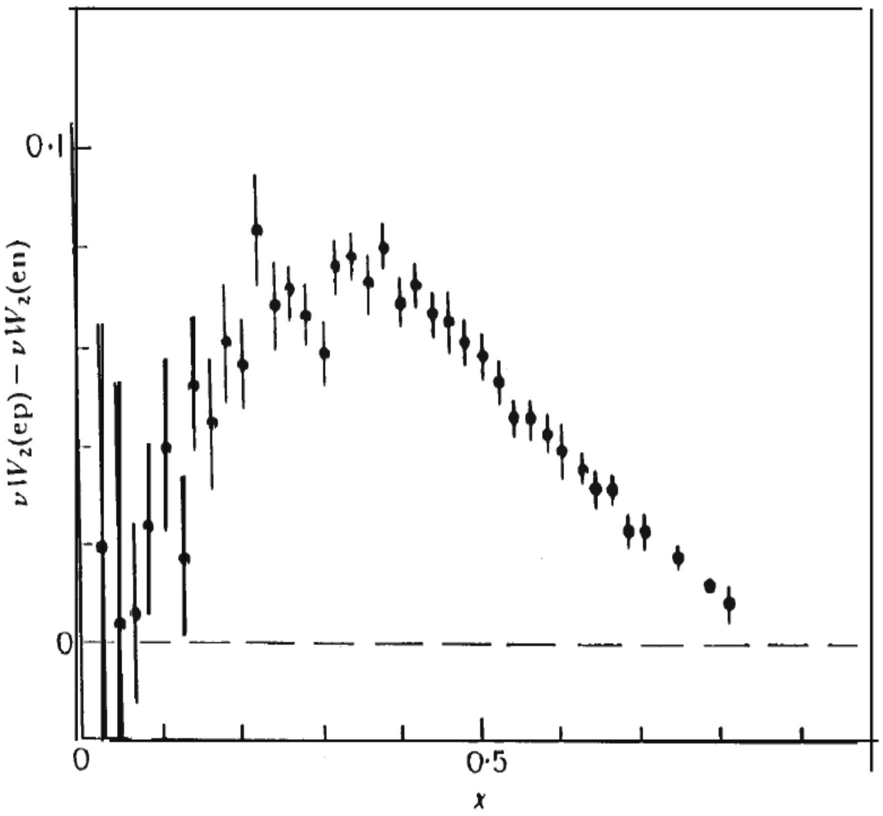
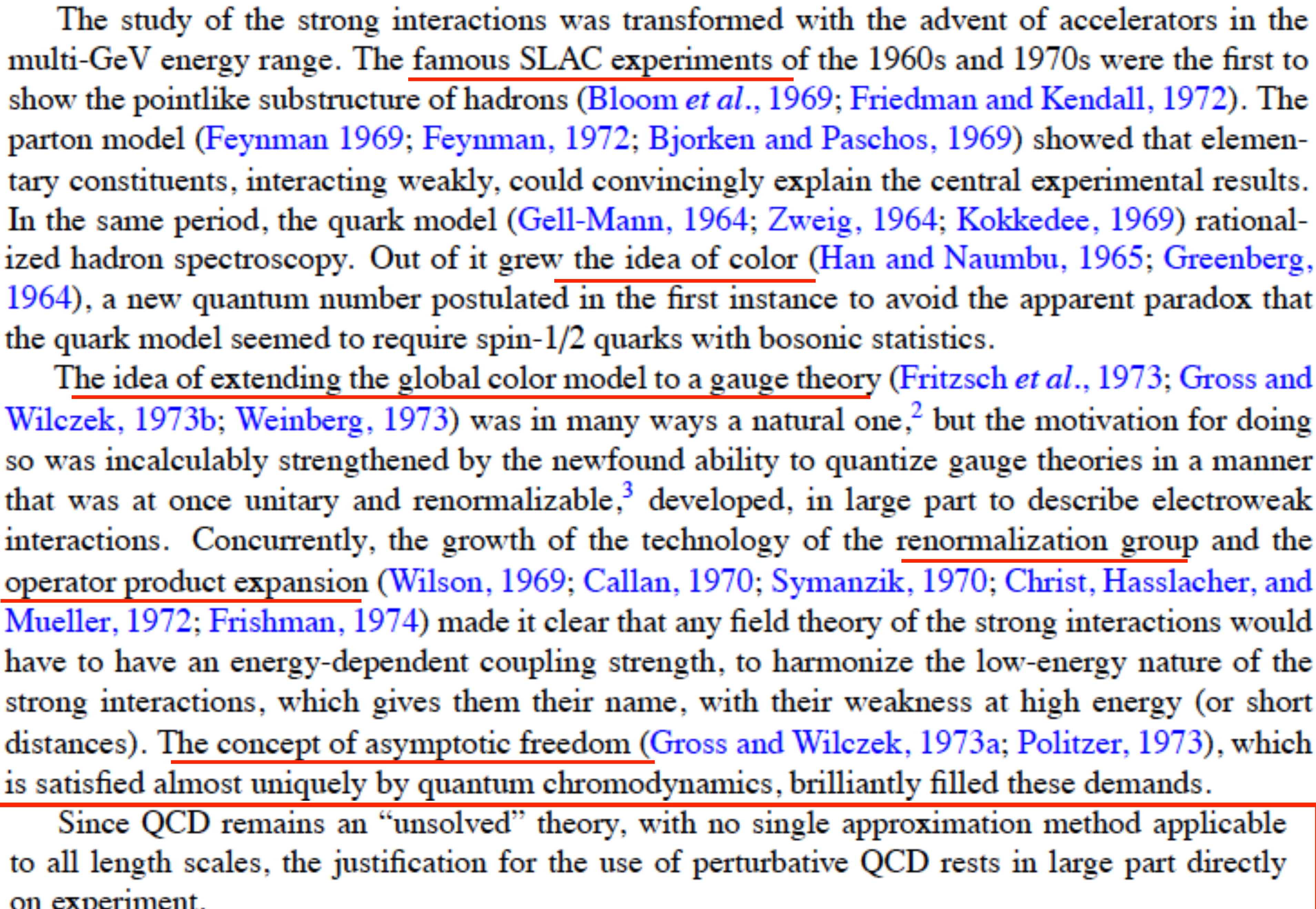


Fig. 8: Values of $\nu W_2^p - \nu W_2^n$ as a function of x.

J Friedman, Nobel prize lecture

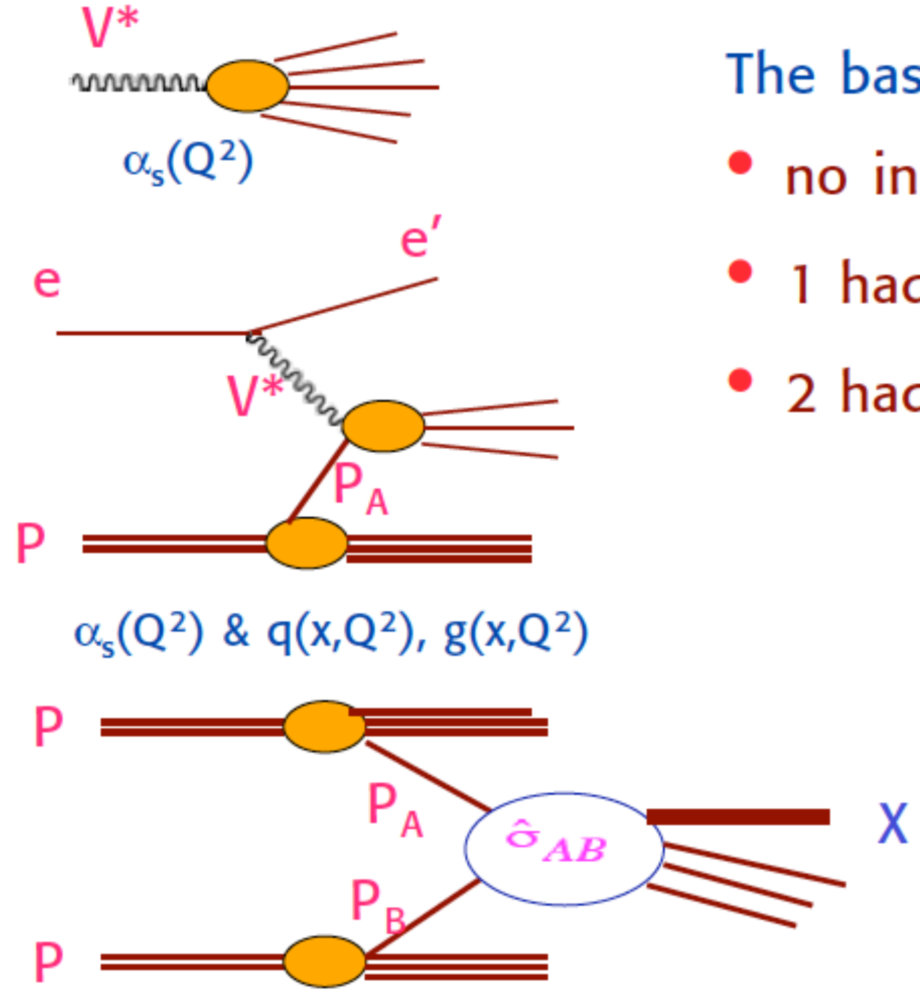


The study of the strong interactions was transformed with the advent of accelerators in the multi-GeV energy range. The famous SLAC experiments of the 1960s and 1970s were the first to show the pointlike substructure of hadrons (Bloom *et al*., 1969; Friedman and Kendall, 1972). The parton model (Feynman 1969; Feynman, 1972; Bjorken and Paschos, 1969) showed that elementary constituents, interacting weakly, could convincingly explain the central experimental results. In the same period, the quark model (Gell-Mann, 1964; Zweig, 1964; Kokkedee, 1969) rationalized hadron spectroscopy. Out of it grew the idea of color (Han and Naumbu, 1965; Greenberg, 1964), a new quantum number postulated in the first instance to avoid the apparent paradox that the quark model seemed to require spin-1/2 quarks with bosonic statistics.

The idea of extending the global color model to a gauge theory (Fritzsch *et al*., 1973; Gross and Wilczek, 1973b; Weinberg, 1973) was in many ways a natural one,[2] but the motivation for doing so was incalculably strengthened by the newfound ability to quantize gauge theories in a manner that was at once unitary and renormalizable,[3] developed, in large part to describe electroweak interactions. Concurrently, the growth of the technology of the renormalization group and the operator product expansion (Wilson, 1969; Callan, 1970; Symanzik, 1970; Christ, Hasslacher, and Mueller, 1972; Frishman, 1974) made it clear that any field theory of the strong interactions would have to have an energy-dependent coupling strength, to harmonize the low-energy nature of the strong interactions, which gives them their name, with their weakness at high energy (or short distances). The concept of asymptotic freedom (Gross and Wilczek, 1973a; Politzer, 1973), which is satisfied almost uniquely by quantum chromodynamics, brilliantly filled these demands.

Since QCD remains an "unsolved" theory, with no single approximation method applicable to all length scales, the justification for the use of perturbative QCD rests in large part directly on experiment.

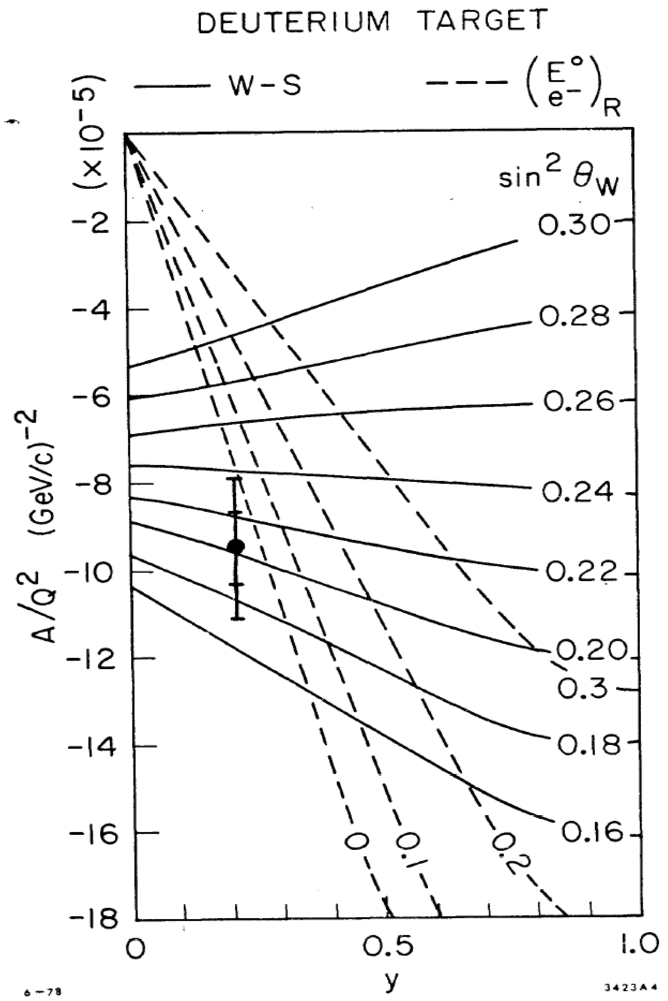
Handbook of perturbative QCD, CTEQ



The basic experimental set ups:

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

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



Polarised eD Scattering

SLAC-PUB-2148
July 1978
(T/E)

$$A/Q^2 = (-9.5 \pm 1.6) \times 10^{-5}\ (\mathrm{GeV}/c)^{-2}$$

20 GeV polarised electrons, P=0.37, Q^2 ~ 2 GeV^2

C.Prescott … W.Jentschke

→ $SU_L(2) \times U(1)$, electron r.h. singlet: GWS eweak theory

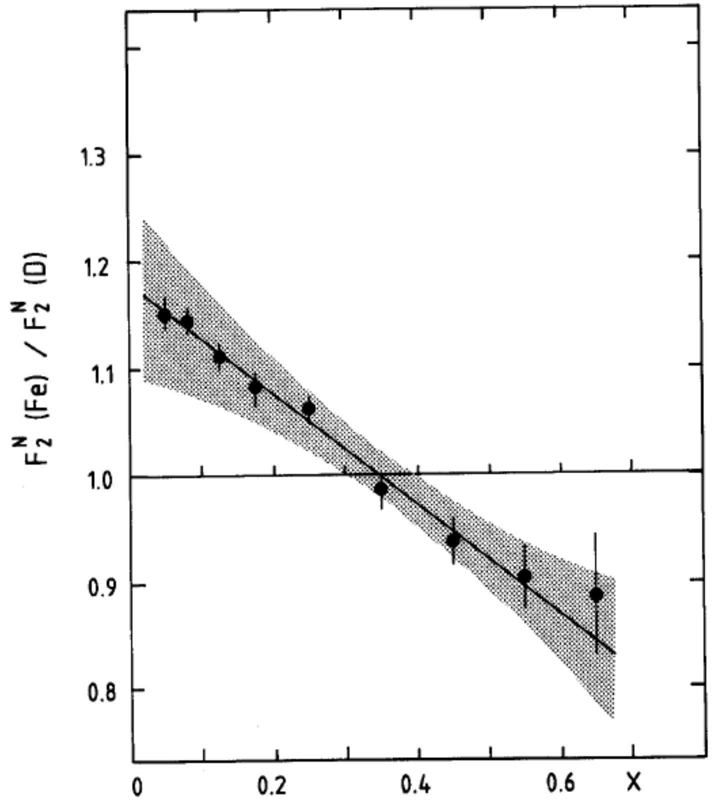
Of crucial importance to this experiment was the development of an intense source of longitudinally polarized electrons. The source consisted of a gallium arsenide crystal mounted in a structure similar to a regular SLAC gun with the GaAs replacing the usual thermionic cathode.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/83-14
January 24th, 1983

THE RATIO OF THE NUCLEON STRUCTURE FUNCTIONS F_2^N FOR IRON AND DEUTERIUM

The European Muon Collaboration

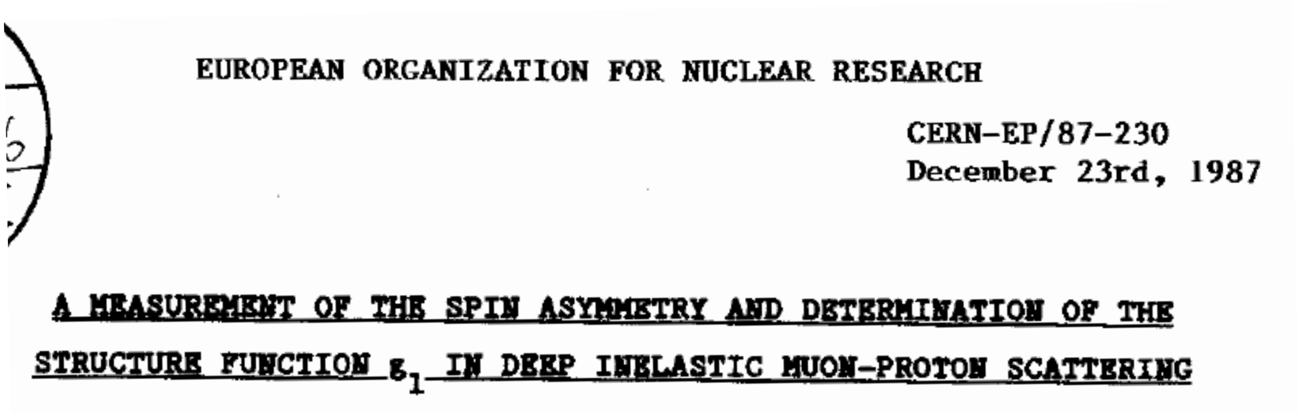


DIS on Nuclei,
Unresolved till today

EIC + LHeC
well complementary

QGP, Deconfinement
Saturation at small x

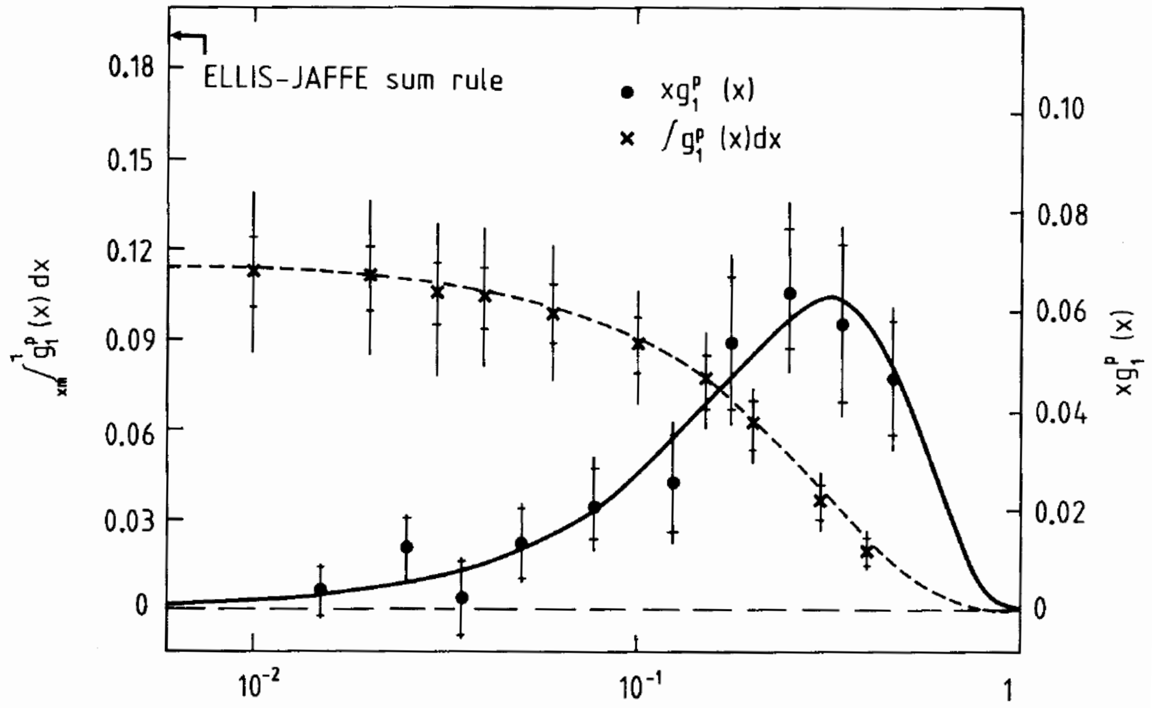
The observed x-dependence of this ratio is in disagreement with existing theoretical predictions.



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

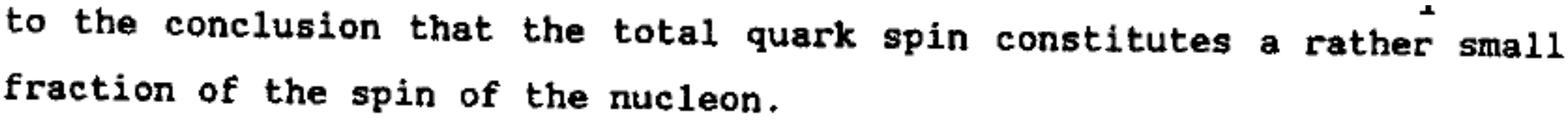
CERN-EP/87-230
December 23rd, 1987

A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION g_1 IN DEEP INELASTIC MUON-PROTON SCATTERING



The 87 discovery of the spin deficit

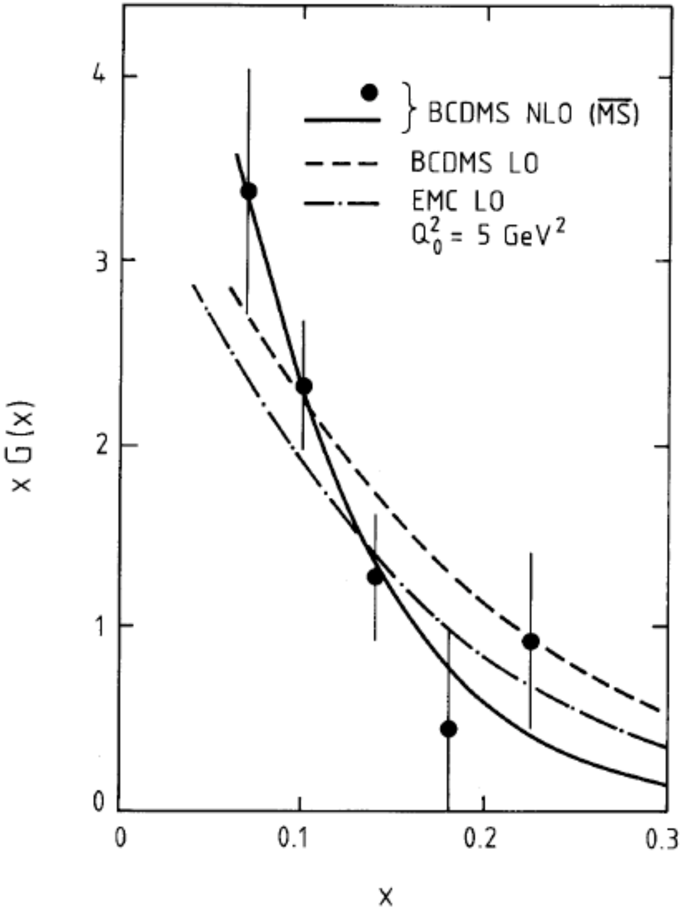
..EMC, HERMES, COMPASS to EIC



to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon.

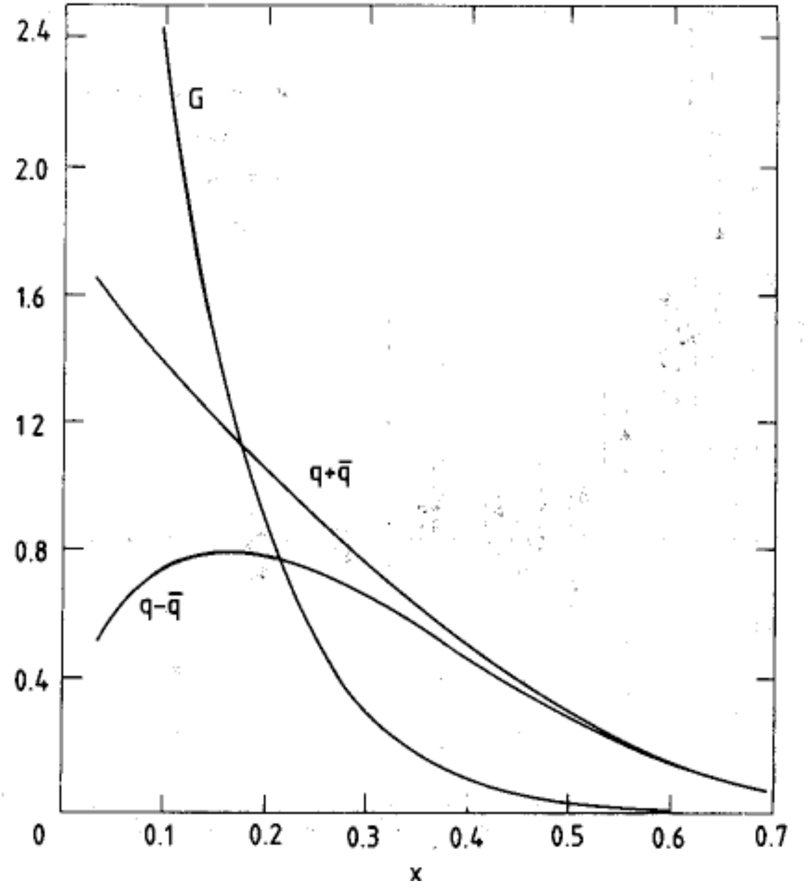
PDFs before HERA - Gluon - $xg(x,Q^2)$

BCDMS



CERN-EP/89-07
January 17th, 1989

CDHS



CERN-EP/89-103
15 August 1989

9 Nov 89: R Taylor at Paris

Low x + Partons - HERA

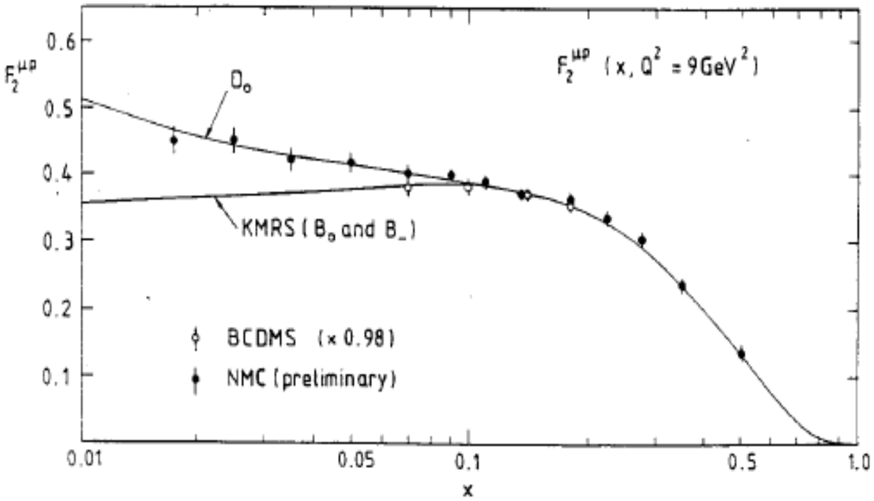


Figure 2: Comparison of NMC and BCDMS data with parton parameterizations

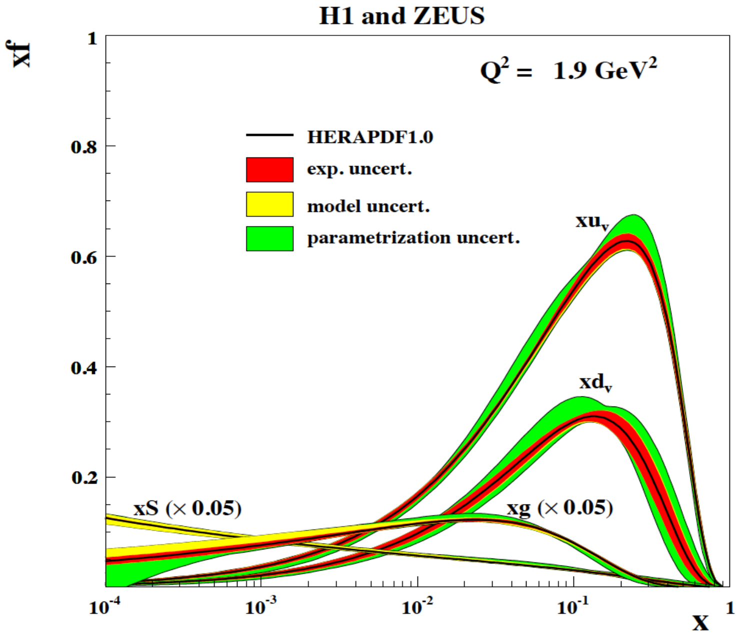
STATUS OF QCD[1]

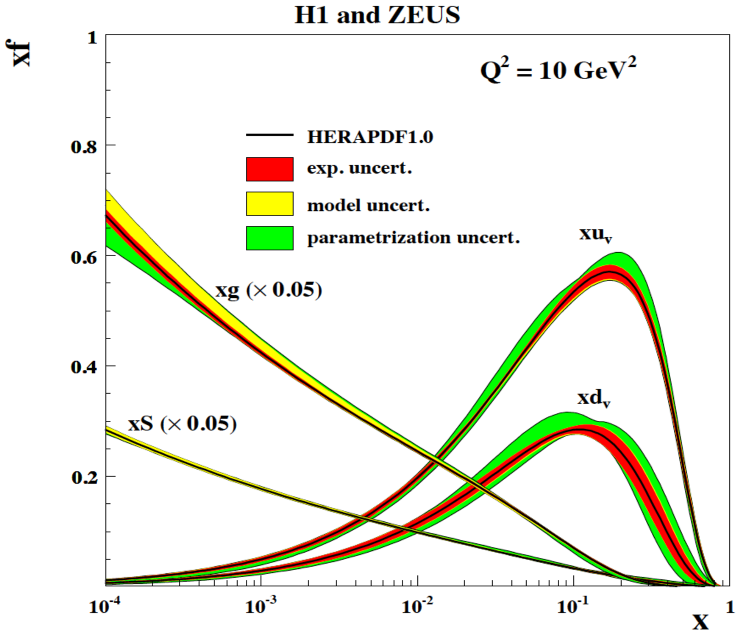
FERMILAB-CONF-93/011-T

January 1993

R.K. Ellis

Low x > 0.01 before HERA





0911.0884

Note: HERA: QCD vacuum dominates p structure at small x. xg vanishes/rises at low/hi Q^2

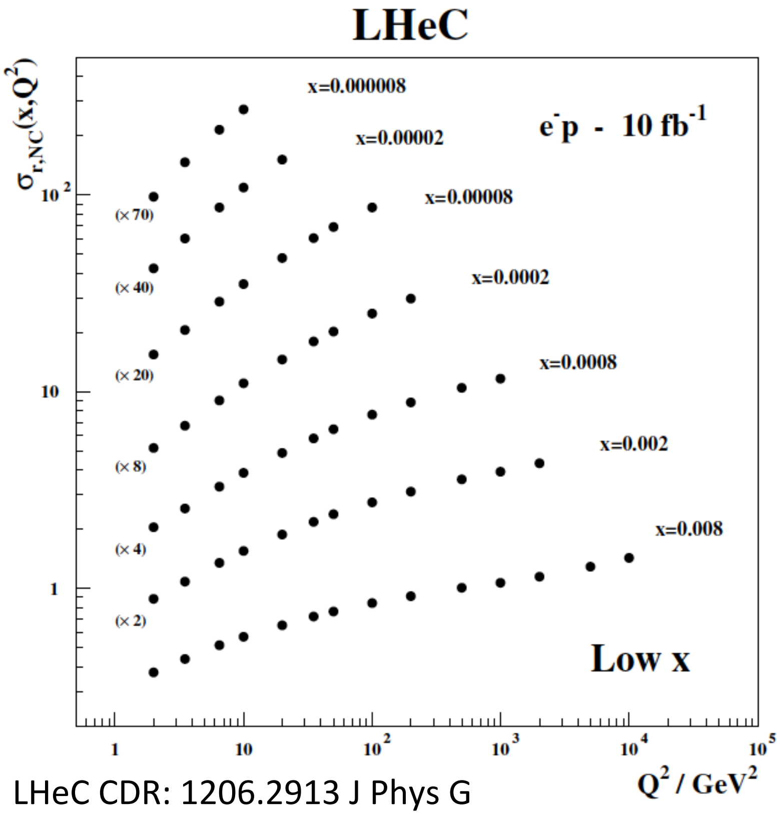
How to determine low x evolution + discover saturation ?

$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 dz\left[F_2(\frac{x}{z})P_{qq}(z) + 2\sum_{i=1}^{N_f} e_i^2 \cdot G(\frac{x}{z})P_{qG}(z)\right]$$

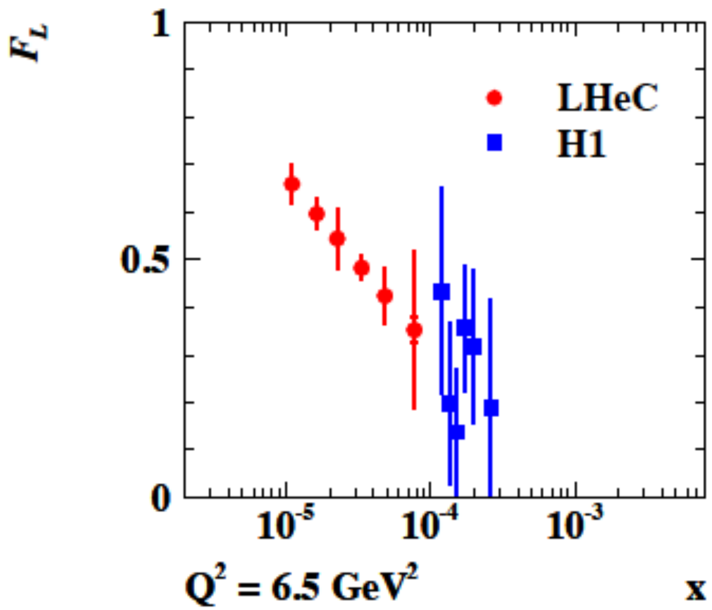
Needs cleanest DIS constraints, proton, not ion, high E: F_2+F_L

$$F_L(x,Q^2) = \frac{\alpha_s}{\pi}x^2\int_x^1\frac{dz}{z^3}\left[\frac{4}{3}F_2(z,Q^2)+2\sum_i^{N_f} e_i^2\cdot G(z,Q^2)\left(1-\frac{x}{z}\right)\right]$$

High precision F_L from variation of E_e independently of LHC/FCC



LHeC CDR: 1206.2913 J Phys G



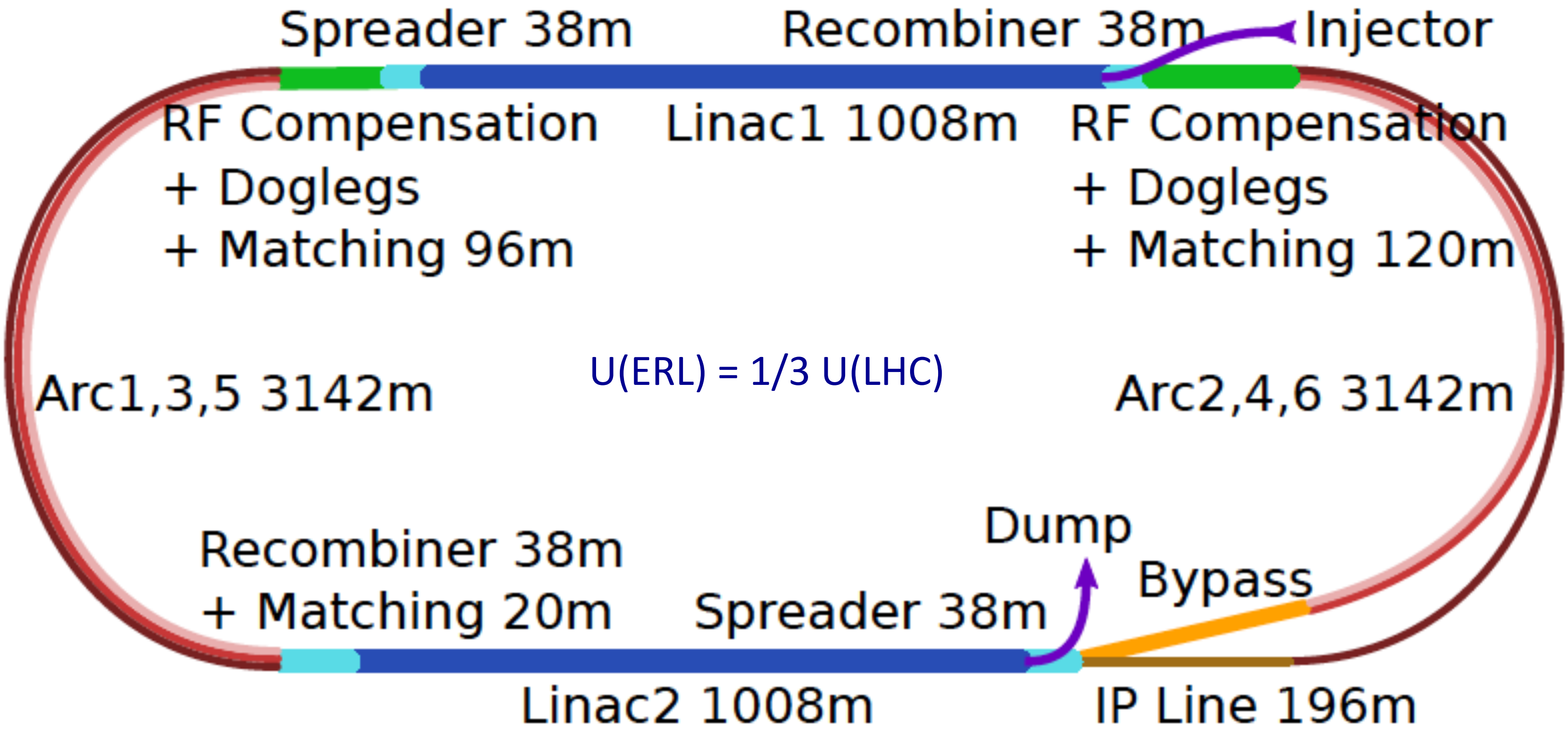
MK: 1802.04317

High precision $F_2(x,Q^2)$ from few days of nominal ep running. Needs large Q^2 and low x ~ 1/s: Impossible at EIC

This constrains DGLAP and rules it out (or not..). cf CDR (LHeC)

The Case for the LHeC

60 GeV Electron ERL added to LHC



Concurrent operation to pp, LHC/FCC become 3 beam facilities. Power limit: 100 MW
10^{34} cm^{-2} s^{-1} luminosity and factor of 15/120 (LHC/FCCeh) extension of Q^2, 1/x reach
1000 times HERA luminosity. It therefore extends up to x~1.
Four orders of magnitude extension in deep inelastic lepton-nucleus (ion) scattering.

Towards a strategy for European Particle Physics

“Two Problems” of HEP

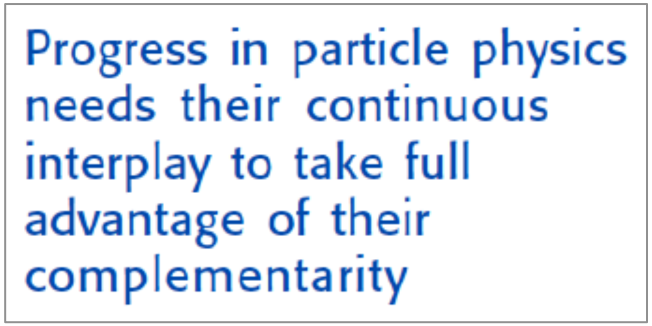
1980: Leon Lederman at ICHEP in Madison:
“Shortage of Money and Overconfidence of Theorists” [SU(5)/SUSY ahead times..]

Today:
Shortage of Money and Missing Confidence of Theory [EFT/ SUSY passed times?]

Reminiscent of the situation as experienced 50 years ago:
before the SM and **discovery of partons in ep at Stanford**

↓

Time for high precision,
high energy,
high luminosity
collider experiments
ee, pp and ep:



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

Guido Altarelli, DIS 2009, Madrid

→

In 2014 CERN decided to set up a new LHeC organisation and an IAC to “assist building the international case of an ep/A collider” at CERN

IAC: Two main tasks:
Update CDR + Testfacility

Organisation*)

International Advisory Committee

Mandate by CERN to define
"..Direction for ep/A both at LHC+FCC"

Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – Chair
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (ESS)

We miss Guido Altarelli.

Coordination Group

Accelerator+Detector+Physics

Gianluigi Arduini
Nestor Armesto
Oliver Brüning – Co-Chair
Andrea Gaddi
Erk Jensen
Walid Kaabi
Max Klein – Co-Chair
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann

5(12) are members of the FCC coordination team

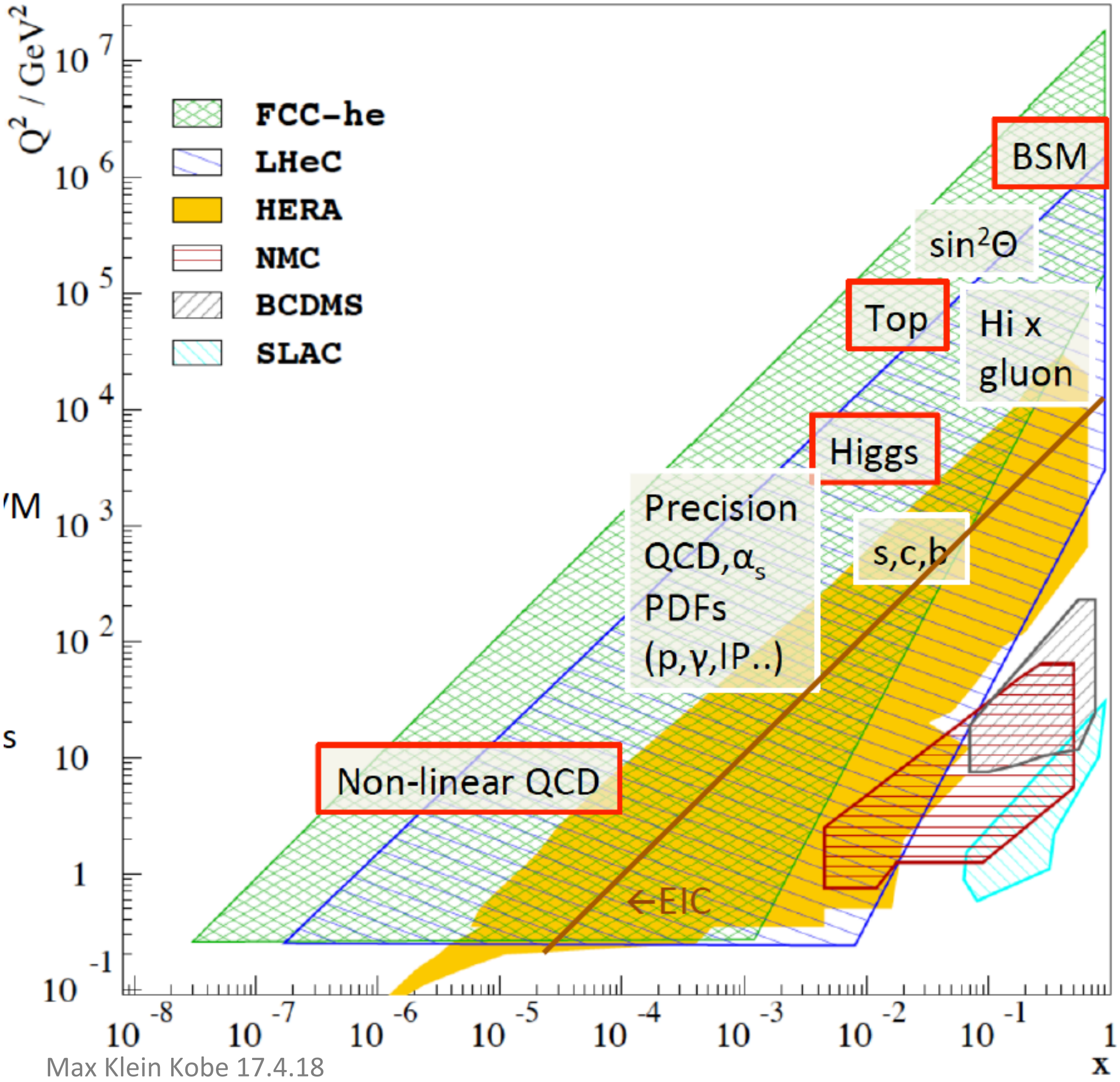
OB+MK: co-coordinate FCCeh

*) April 2018

Working Groups

PDFs, QCD
Fred Olness,
Claire Gwenlan
Higgs
Uta Klein,
Masahiro Kuze
BSM
Georges Azuelos,
Monica D'Onofrio
Oliver Fischer
Top
Olaf Behnke,
Christian
Schwanenberger
eA Physics
Nestor Armesto
Small x
Paul Newman,
Anna Stasto
Detector
Alessandro Polini
Peter Kostka

Physics with Energy Frontier DIS



Raison(s) d'etre of the LHeC

Cleanest High Resolution Microscope: QCD Discovery

Empowering the LHC Search Programme

Transformation of LHC into high precision Higgs facility

Discovery (top, H, heavy ν's..) Beyond the Standard Model

A Unique Nuclear Physics Facility

Huge increase in energy and luminosity enables unique development of particle physics

The Classic DIS Programme with the LHeC: $0 < Q^2 < 10^6$ GeV2, $1 < x < 10^{-6}$

Generalised Parton Distributions [DVCS] – “proton in 3D - tomography”

Unintegrated Parton Distributions [Final State] – DGLAP/BFKL?

Diffractive Parton Distributions [Diffraction] – pomeron, confinement??

Photon Parton Distribution [Photoproduction Dijets,QQ; $F_{2,L}$] - fashionable..

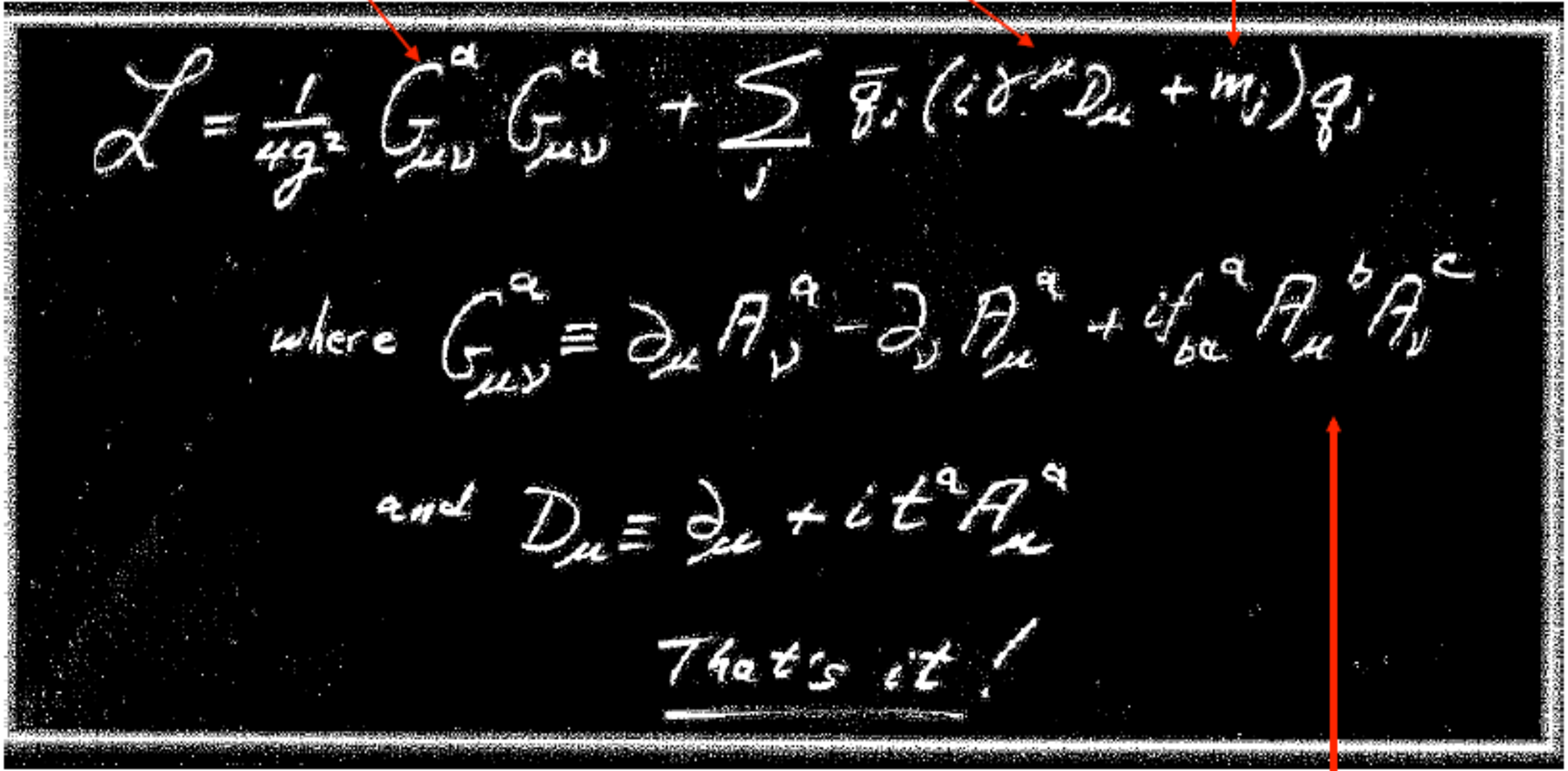
Neutron Parton Distributions [Tagged en (eD) Scattering] – ignored at HERA

see the CDR 1206.2913 + updates

quark mass

gluon

q propagation and q-g interaction



$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j \left(i\gamma^\mu D_\mu + m_j \right) q_j$$

where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$

and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$

That's it!

selfinteraction
of gluon field

j ... quark flavors
a,b,c ... 3 colors
μ,ν ... space-time

F.Wilczek, Physics Today, August 2000.

QCD

That's it?? That may not be it..

Developments

AdS/CFT
Instantons
Odderons
TOTEM ? CERN EP 2017-335

Non pQCD, Spin
Quark Gluon Plasma

QCD of Higgs boson

N^kLO, Monte Carlos..
Resummation
Saturation and BFKL

Photon, Pomeron, n PDFs
Non-conventional partons
(unintegrated, generalised)
Vector Mesons
The 3 D view on hadrons..

Discoveries

CP violation in QCD?
Massless quarks?? Would solve it..
Electric dipole moment of the neutron?
Axions, candidates for Dark Matter

Breaking of Factorisation [ep-pp]

Free Quarks

Unconfined Color

New kind of coloured matter

Quark substructure

New symmetry embedding QCD

C. Quigg, arXiv1308.6637

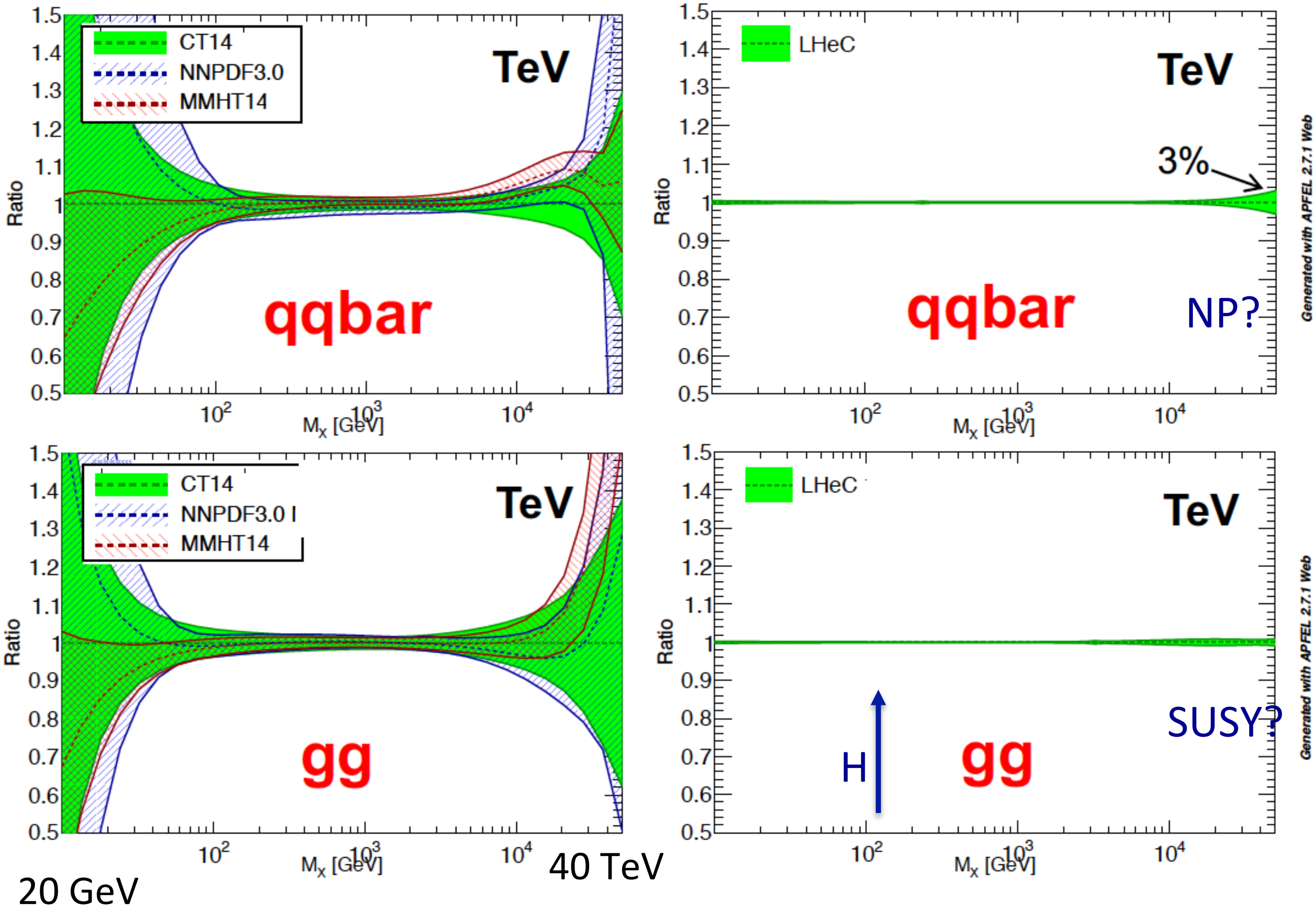
QCD has an exciting future with the FCC

The LHeC collinear proton (and nuclear) PDF Programme

Resolve parton structure of the proton completely: u_v,d_v,s_v?,u,d,s,c,b,t and xg
Unprecedented range, sub% precision, free of parameterisation assumptions,
Resolve p structure, solve non linear and saturation issues, test QCD, N^3LO…

PDFs
are NOT
determined
in pp
but in ep

cf backup



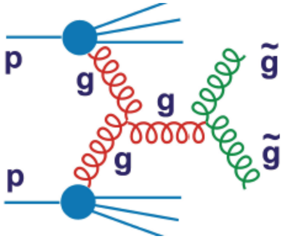
Empowers the LHC H, BSM + SM Physics

Empowering pp Discoveries

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

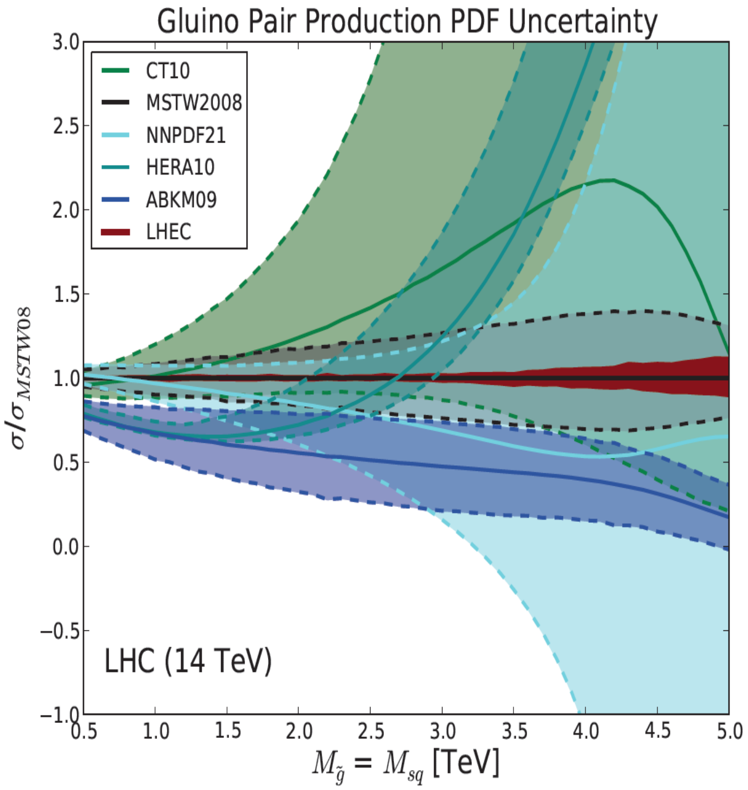
GLUON

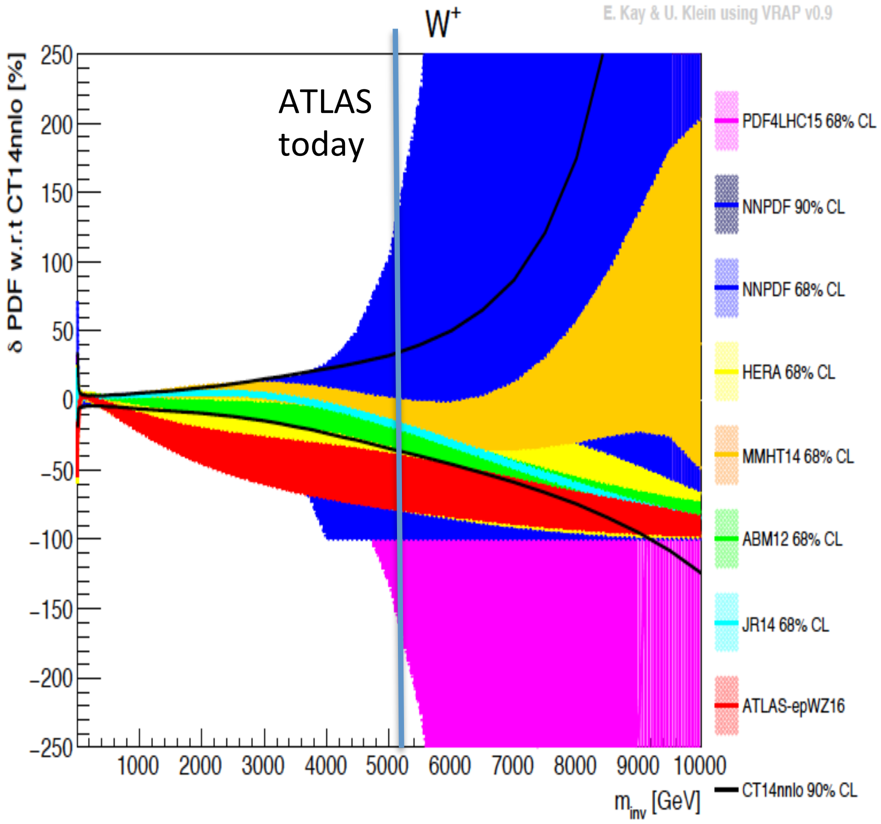
SUSY, RPC, RPV, LQS..



QUARKS

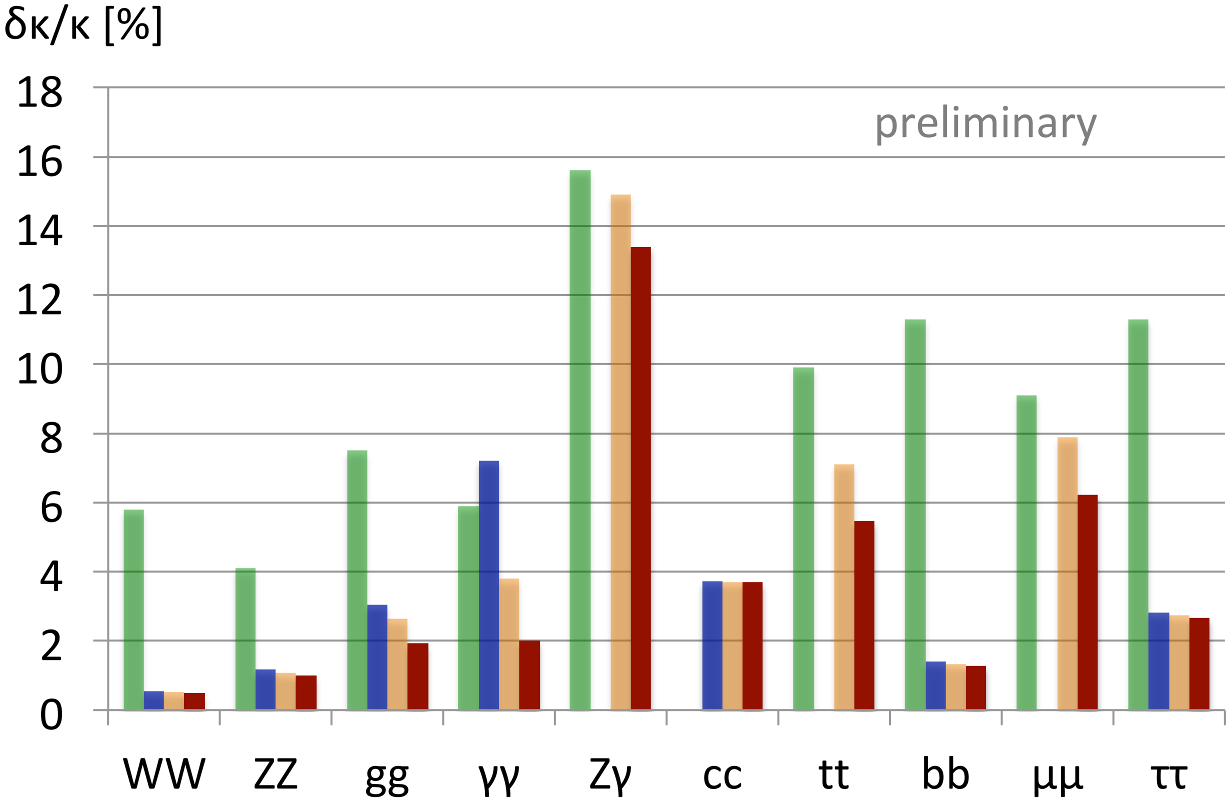
Exotic+ Extra boson searches at high mass

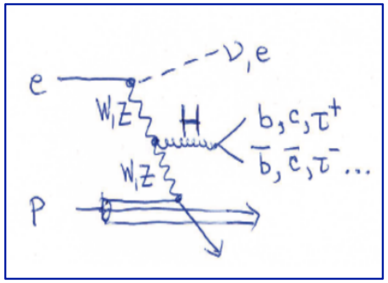




ATLAS today

Determination of SM Higgs Couplings, **HL-LHC** and **LHeC** → **LHC**





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

LHC: ATLAS prospects PUB Note 2014-016

ttH at LHeC to 15%

The addition of ep to pp (LHeC to LHC (HL,HE) and FCC-eh to FCC-pp) **transforms these machines into precision Higgs facilities. Vital complementarity with e^+e^-** (JdB Amsterdam)

Note that the HL LHC prospects are being updated (HL/HE LHC Physics workshop).

New Physics through High Precision

Masses:

Charm HERA 40 MeV LHeC 3 MeV

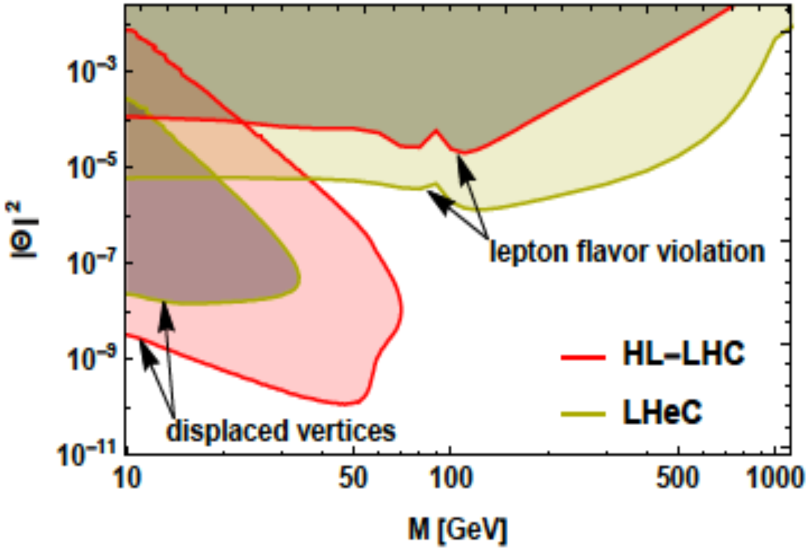
W LHC 19→ 10 MeV LHeC 15 MeV
and prediction to ±2.8 MeV for pp

Top: to be studied

Proton: gluon we are made of…

Higgs: Cross section to 0.3%: Mass dependent. OB, MK 1305.2090

Neutrinos: **Heavy "sterile" Neutrinos**



Antusch, Cazzato, Fischer – work still in progress

Int. J. Mod. Phys., A32(14):1750078, 2017.

CKM, electroweak, alpha_s, …

V_{tb}: to 0.01

V_{cs}: to 0.02 [LHC+LHeC, like ATLAS+HERA]

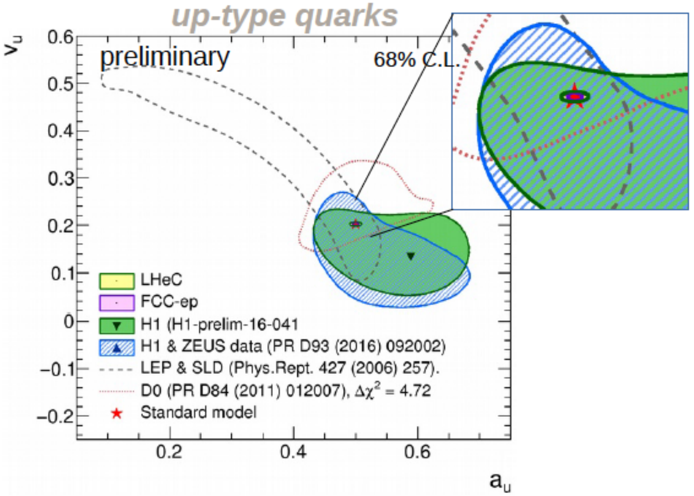
α_s to 0.2% [0.1% with HERA] – GUT?

$\sin^2\theta_W$ (μ)

LHC: better than LEP with LHeC PDFs

LHeC: scale dependence from
0.4 GeV (PERLE) to 1 TeV (LHeC)

NC couplings



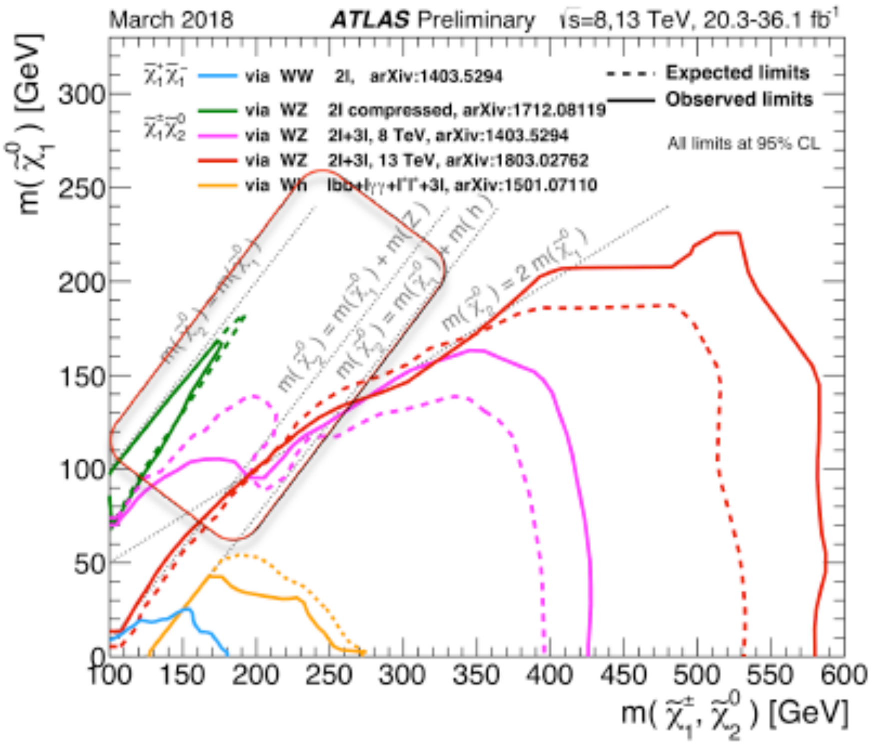
Britzger, MK, Spiessberger, Zhang – work still in progress

Beyond the Standard Model

Higgs into Dark Matter
Higgs into Neutralinos (RPV SUSY)
Higgs into Scalars → 4b

$H^{\pm\pm}$ in Vector Boson Scattering
$H^{\pm}$ in Vector Boson Scattering
H^{+} in 2HDM

Triple Gauge Couplings
Top FCNC
Contact Interactions
Empower LHC Discoveries



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

→ SUSY ewk sector most challenging for pp colliders

cf U Klein + M Donofrio at Amsterdam FCC

D Curtin et al arXiv:1712.07135

> This adds significant motivation for the construction of future $e^- p$ colliders. Together with the invaluable proton PDF data, as well as precision measurements of EW parameters, top quark couplings and Higgs couplings, our results make clear that adding a DIS program to a *pp* collider is necessary to fully exploit its discovery potential for new physics.

References

[1] S. P. Das, J. Hernandez-Sanchez, S. Moretti and A. Rosado, *Prospects for discovering a light charged Higgs boson within the NMSSM at the FCC-eh collider*, 1806.08361.

[2] A. Caliskan and S. O. Kara, *Single production of the excited electrons at the future FCC-based lepton-hadron colliders*, 1806.02037.

[3] H. Hesari, H. Khanpour and M. Mohammadi Najafabadi, *Study of Higgs Effective Couplings at Electron-Proton Colliders*, *Phys. Rev.* **D97** (2018) 095041, [1805.04697].

[4] L. Duarte, G. Zapata and O. A. Sampayo, *Angular and polarization trails from effective interactions of Majorana neutrinos at the LHeC*, *Eur. Phys. J.* **C78** (2018) 352, [1802.07620].

[5] C. Han, R. Li, R.-Q. Pan and K. Wang, *Searching for the light Higgsinos at the CERN LHeC*, 1802.03679.

[6] G. Azuelos, H. Sun and K. Wang, *Search for singly charged Higgs bosons in vector-boson scattering at ep colliders*, *Phys. Rev.* **D97** (2018) 116005, [1712.07505].

[7] D. Curtin, K. Deshpande, O. Fischer and J. Zurita, *New Physics Opportunities for Long-Lived Particles at Electron-Proton Colliders*, 1712.07135.

[8] R. Li, X.-M. Shen, K. Wang, T. Xu, L. Zhang and G. Zhu, *Probing anomalous $WW\gamma$ triple gauge bosons coupling at the LHeC*, *Phys. Rev.* **D97** (2018) 075043, [1711.05607].

[9] K. He, H.-Y. Bi, R.-Y. Zhang, X.-Z. Li and W.-G. Ma, *P-wave excited B_c^{**} meson photoproduction at the LHeC*, *J. Phys.* **G45** (2018) 055005, [1710.11508].

[10] H. Sun, X. Luo, W. Wei and T. Liu, *Searching for the doubly-charged Higgs bosons in the Georgi-Machacek model at the electron-proton colliders*, *Phys. Rev.* **D96** (2017) 095003, [1710.06284].

[11] Y. O. Günaydın, M. Sahin and S. Sultansoy, *Resonance Production of Excited u-quark at the FCC Based $\gamma\ p$ Colliders*, 1707.00056.

[12] A. Caliskan, *Excited neutrino search potential of the FCC-based electron-hadron colliders*, *Adv. High Energy Phys.* **2017** (2017) 4726050, [1706.09797].

[13] L. Han, Y.-J. Zhang and Y.-B. Liu, *Single vector-like T-quark search via the $T \to Wb$ decay channel at the LHeC*, *Phys. Lett.* **B771** (2017) 106–112.

[14] I. Turk Cakir, A. Yilmaz, H. Denizli, A. Senol, H. Karadeniz and O. Cakir, *Probing the Anomalous FCNC Couplings at Large Hadron Electron Collider*, *Adv. High Energy Phys.* **2017** (2017) 1572053, [1705.05419].

[15] Y.-B. Liu, *Search for single production of vector-like top partners at the Large Hadron Electron Collider*, *Nucl. Phys.* **B923** (2017) 312–323, [1704.02059].

[16] Y.-J. Zhang, L. Han and Y.-B. Liu, *Single production of the top partner in the $T \to tZ$ channel at the LHeC*, *Phys. Lett.* **B768** (2017) 241–247.

[17] X. Wang, H. Sun and X. Luo, *Searches for the Anomalous FCNC Top-Higgs Couplings with Polarized Electron Beam at the LHeC*, *Adv. High Energy Phys.* **2017** (2017) 4693213, [1703.02691].

[18] H.-Y. Bi, R.-Y. Zhang, X.-G. Wu, W.-G. Ma, X.-Z. Li and S. Owusu, *Photoproduction of doubly heavy baryon at the LHeC*, *Phys. Rev.* **D95** (2017) 074020, [1702.07181].

[19] B. Coleppa, M. Kumar, S. Kumar and B. Mellado, *Measuring CP nature of top-Higgs couplings at the future Large Hadron electron collider*, *Phys. Lett.* **B770** (2017) 335–341, [1702.03426].

[20] H. Denizli, A. Senol, A. Yilmaz, I. Turk Cakir, H. Karadeniz and O. Cakir, *Top quark FCN couplings at future circular hadron electron colliders*, *Phys. Rev.* **D96** (2017) 015024, [1701.06932].

[21] H.-Y. Bi, R.-Y. Zhang, H.-Y. Han, Y. Jiang and X.-G. Wu, *Photoproduction of the $B_c^{(*)}$ meson at the LHeC*, *Phys. Rev.* **D95** (2017) 034019, [1612.07990].

[22] S. P. Das and M. Nowakowski, *Light neutral CP-even Higgs boson within Next-to-Minimal Supersymmetric Standard model (NMSSM) at the Large Hadron electron Collider (LHeC)*, *Phys. Rev.* **D96** (2017) 055014, [1612.07241].

[23] J. Hernández-Sánchez, O. Flores-Sánchez, C. G. Honorato, S. Moretti and S. Rosado, *Prospect for observing a light charged Higgs through the decay $H^\pm \to cb$ at the LHeC*, *PoS* **CHARGED2016** (2017) 032, [1612.06316].

[24] S. Antusch, E. Cazzato and O. Fischer, *Sterile neutrino searches at future e^-e^+, pp, and e^-p colliders*, *Int. J. Mod. Phys.* **A32** (2017) 1750078, [1612.02728].

[25] S. Liu, Y.-L. Tang, C. Zhang and S.-h. Zhu, *Exotic Higgs Decay $h \to \phi\phi \to 4b$ at the LHeC*, *Eur. Phys. J.* **C77** (2017) 457, [1608.08458].

[26] A. Ozansoy, V. Arı and V. Çetinkaya, *Search for excited spin-3/2 neutrinos at LHeC*, *Adv. High Energy Phys.* **2016** (2016) 1739027, [1607.04437].

[27] G. R. Boroun, B. Rezaei and S. Heidari, *Nuclear longitudinal structure function in eA processes at the LHeC*, *Int. J. Mod. Phys.* **A32** (2017) 1750197, [1606.02864].

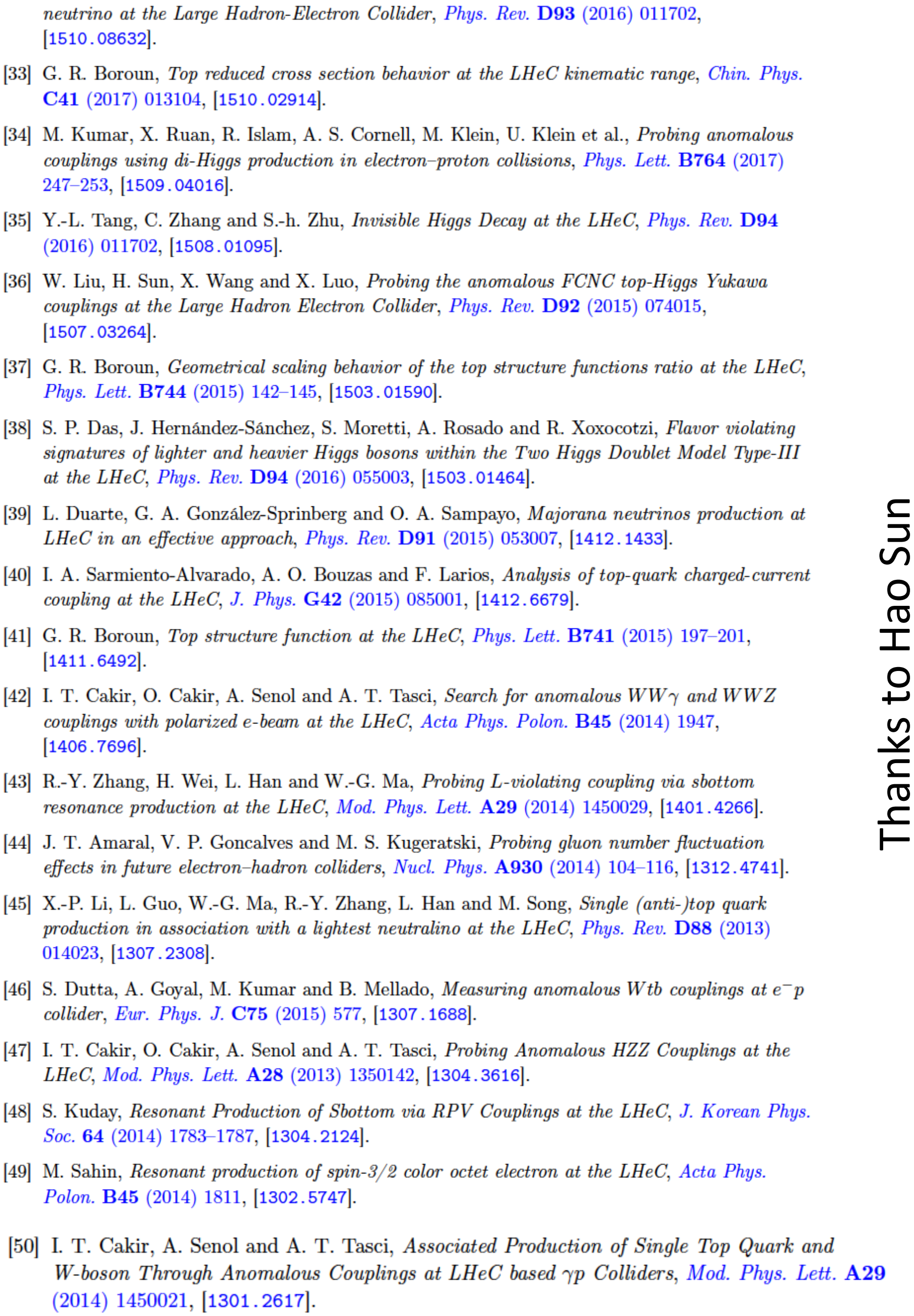
[28] Y. C. Acar, U. Kaya, B. B. Oner and S. Sultansoy, *Color octet electron search potential of FCC based e–p colliders*, *J. Phys.* **G44** (2017) 045005, [1605.08028].

[29] S. Mondal and S. K. Rai, *Probing the Heavy Neutrinos of Inverse Seesaw Model at the LHeC*, *Phys. Rev.* **D94** (2016) 033008, [1605.04508].

[30] M. Lindner, F. S. Queiroz, W. Rodejohann and C. E. Yaguna, *Left-Right Symmetry and Lepton Number Violation at the Large Hadron Electron Collider*, *JHEP* **06** (2016) 140, [1604.08596].

[31] H. Sun and X. Wang, *Exploring the Anomalous Top-Higgs FCNC Couplings at the electron proton colliders*, *Eur. Phys. J.* **C78** (2018) 281, [1602.04670].

[32] S. Mondal and S. K. Rai, *Polarized window for left-right symmetry and a right-handed neutrino at the Large Hadron-Electron Collider*, *Phys. Rev.* **D93** (2016) 011702, [1510.08632].



[33] G. R. Boroun, *Top reduced cross section behavior at the LHeC kinematic range*, *Chin. Phys.* **C41** (2017) 013104, [1510.02914].

[34] M. Kumar, X. Ruan, R. Islam, A. S. Cornell, M. Klein, U. Klein et al., *Probing anomalous couplings using di-Higgs production in electron–proton collisions*, *Phys. Lett.* **B764** (2017) 247–253, [1509.04016].

[35] Y.-L. Tang, C. Zhang and S.-h. Zhu, *Invisible Higgs Decay at the LHeC*, *Phys. Rev.* **D94** (2016) 011702, [1508.01095].

[36] W. Liu, H. Sun, X. Wang and X. Luo, *Probing the anomalous FCNC top-Higgs Yukawa couplings at the Large Hadron Electron Collider*, *Phys. Rev.* **D92** (2015) 074015, [1507.03264].

[37] G. R. Boroun, *Geometrical scaling behavior of the top structure functions ratio at the LHeC*, *Phys. Lett.* **B744** (2015) 142–145, [1503.01590].

[38] S. P. Das, J. Hernández-Sánchez, S. Moretti, A. Rosado and R. Xoxocotzi, *Flavor violating signatures of lighter and heavier Higgs bosons within the Two Higgs Doublet Model Type-III at the LHeC*, *Phys. Rev.* **D94** (2016) 055003, [1503.01464].

[39] L. Duarte, G. A. González-Sprinberg and O. A. Sampayo, *Majorana neutrinos production at LHeC in an effective approach*, *Phys. Rev.* **D91** (2015) 053007, [1412.1433].

[40] I. A. Sarmiento-Alvarado, A. O. Bouzas and F. Larios, *Analysis of top-quark charged-current coupling at the LHeC*, *J. Phys.* **G42** (2015) 085001, [1412.6679].

[41] G. R. Boroun, *Top structure function at the LHeC*, *Phys. Lett.* **B741** (2015) 197–201, [1411.6492].

[42] I. T. Cakir, O. Cakir, A. Senol and A. T. Tasci, *Search for anomalous $WW\gamma$ and WWZ couplings with polarized e-beam at the LHeC*, *Acta Phys. Polon.* **B45** (2014) 1947, [1406.7696].

[43] R.-Y. Zhang, H. Wei, L. Han and W.-G. Ma, *Probing L-violating coupling via sbottom resonance production at the LHeC*, *Mod. Phys. Lett.* **A29** (2014) 1450029, [1401.4266].

[44] J. T. Amaral, V. P. Goncalves and M. S. Kugeratski, *Probing gluon number fluctuation effects in future electron–hadron colliders*, *Nucl. Phys.* **A930** (2014) 104–116, [1312.4741].

[45] X.-P. Li, L. Guo, W.-G. Ma, R.-Y. Zhang, L. Han and M. Song, *Single (anti-)top quark production in association with a lightest neutralino at the LHeC*, *Phys. Rev.* **D88** (2013) 014023, [1307.2308].

[46] S. Dutta, A. Goyal, M. Kumar and B. Mellado, *Measuring anomalous Wtb couplings at e^-p collider*, *Eur. Phys. J.* **C75** (2015) 577, [1307.1688].

[47] I. T. Cakir, O. Cakir, A. Senol and A. T. Tasci, *Probing Anomalous HZZ Couplings at the LHeC*, *Mod. Phys. Lett.* **A28** (2013) 1350142, [1304.3616].

[48] S. Kuday, *Resonant Production of Sbottom via RPV Couplings at the LHeC*, *J. Korean Phys. Soc.* **64** (2014) 1783–1787, [1304.2124].

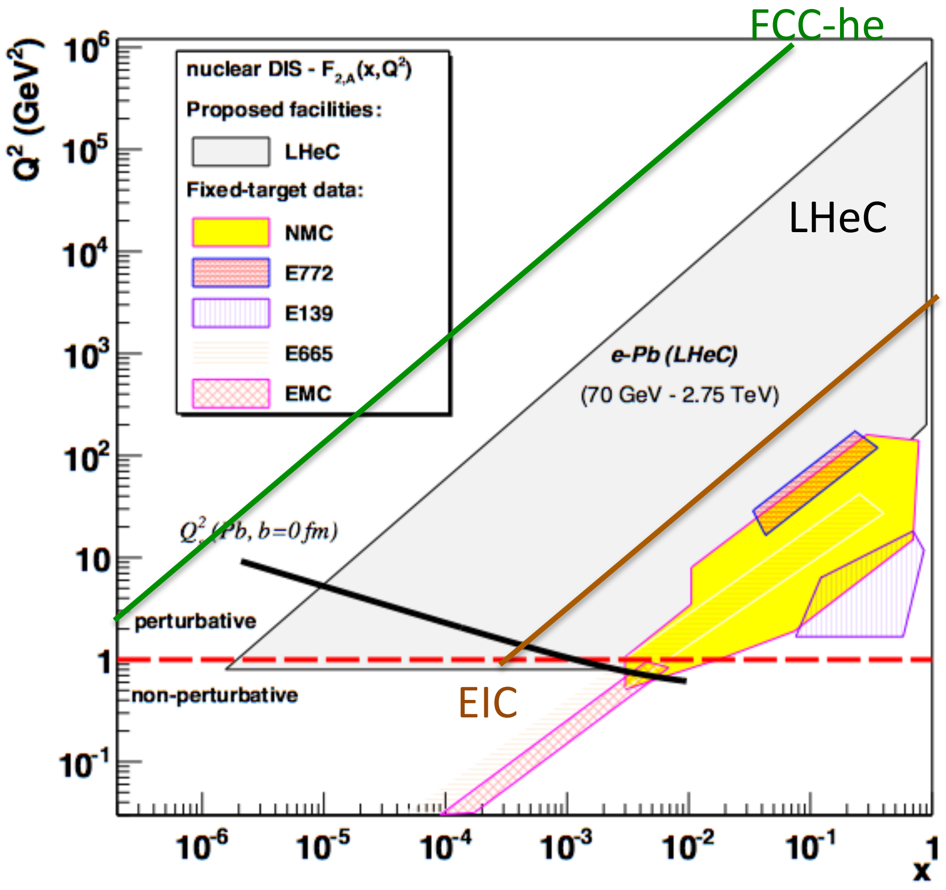
[49] M. Sahin, *Resonant production of spin-3/2 color octet electron at the LHeC*, *Acta Phys. Polon.* **B45** (2014) 1811, [1302.5747].

[50] I. T. Cakir, A. Senol and A. T. Tasci, *Associated Production of Single Top Quark and W-boson Through Anomalous Couplings at LHeC based γp Colliders*, *Mod. Phys. Lett.* **A29** (2014) 1450021, [1301.2617].

Thanks to Hao Sun

50 journal papers on NP with LHeC in recent years

LHeC as Electron Ion Collider



Precision QCD study of parton dynamics in nuclei
Investigation of high density matter and QGP
DGLAP to BFKL – vital for LHC and FCCpp physics

Extension of kinematic range in lA by 4-5 orders of magnitude will change QCD view on nuclear structure and parton dynamics

May lead to genuine surprises…

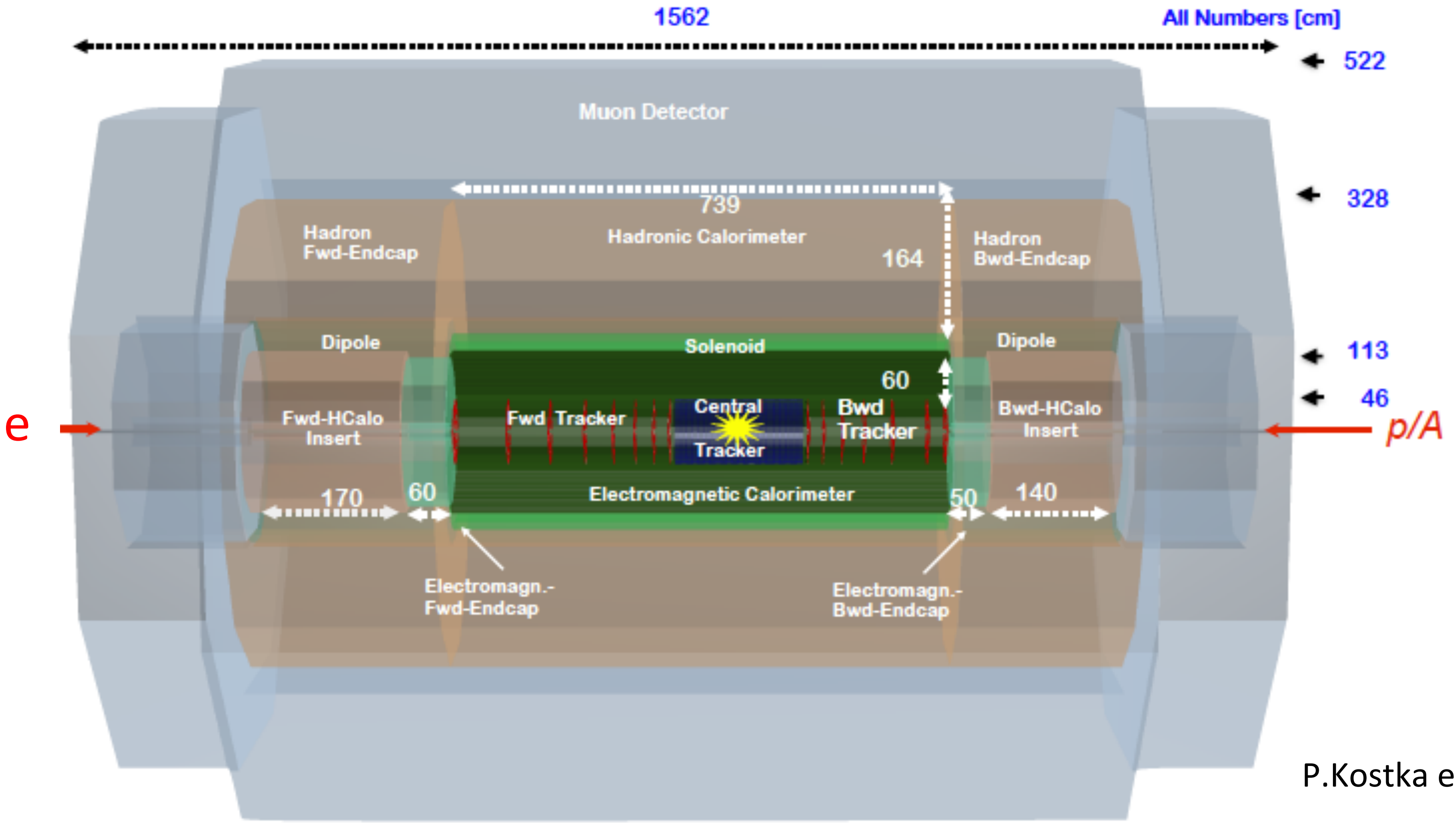
- No saturation of xg (x,Q^2) ?
  [discover saturation in ep THEN analyse eA –separate nonlinear g from nuclear effects]
- Small fraction of diffraction ?
- Broken isospin invariance ?
- Flavour dependent shadowing ?

- Safe: nuclear PDFs like at HERA

→ $R(x,Q^2)$ flavour dependent

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

LHeC Detector for the HL/HE LHC



P.Kostka et al

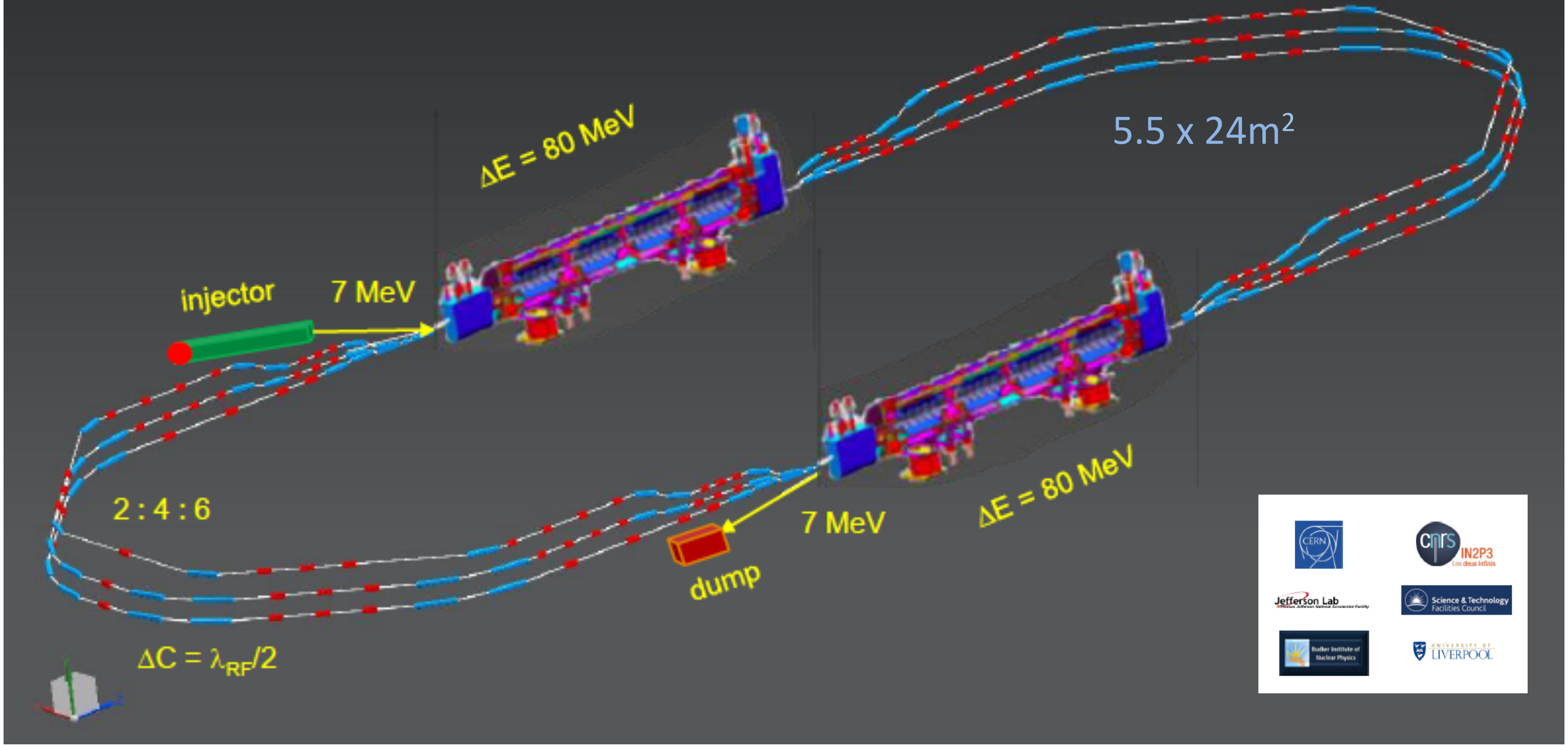
Length x Diameter: LHeC (13.3 x 9 m^2) HE-LHC (15.6 x 10.4) FCCeh (19 x 12)

ATLAS (45 x 25) CMS (21 x 15): [LHeC < CMS, FCC-eh ~ CMS size]

If CERN decides that the HE LHC comes, the LHeC detector should anticipate that

Powerful ERL for Experiments at Orsay

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA → 10 MW

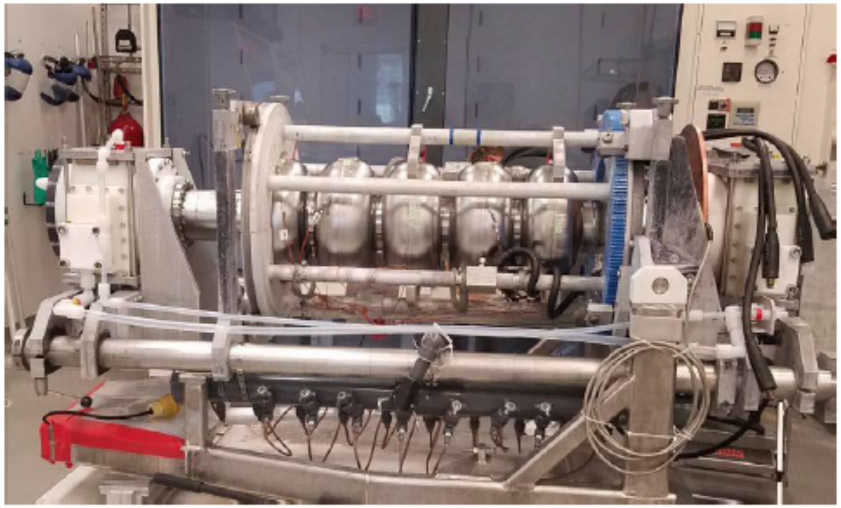


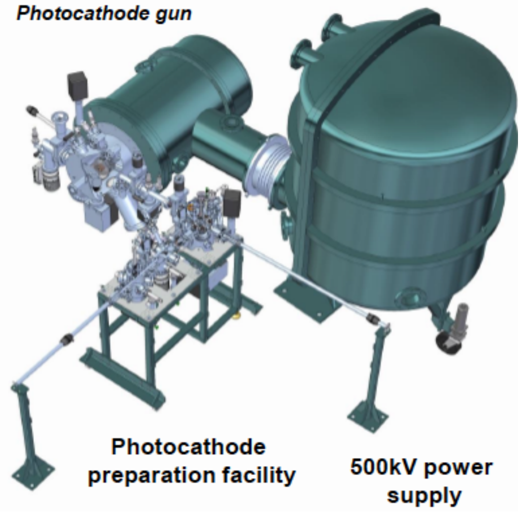
cf Walid Kaabi at Amsterdam FCC

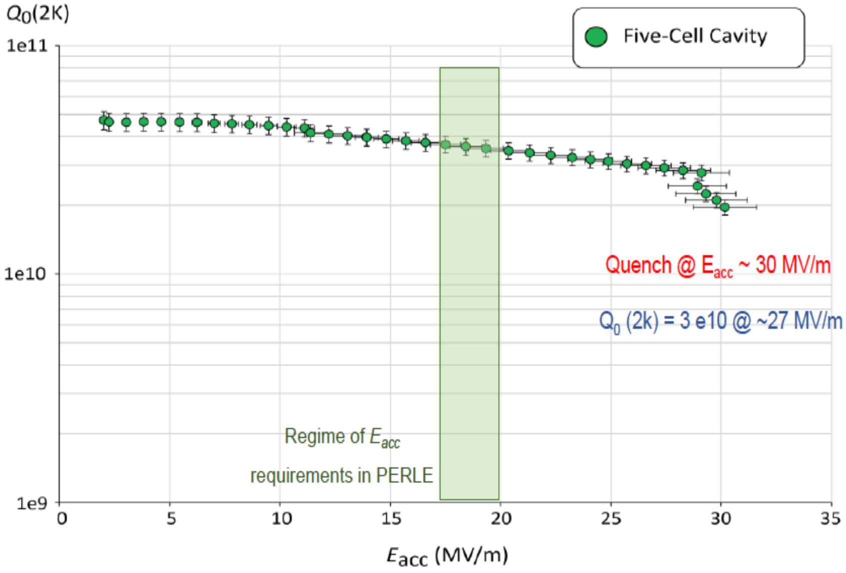
New SCRF, High Intensity (100 x ELI) ERL Development Facility with unique low E Physics

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

First 802 MHz cavity successfully built (Jlab)



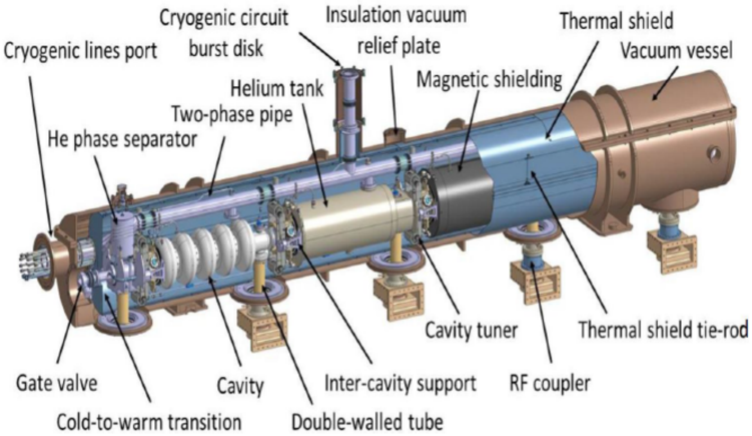




Quench @ E_{acc} ~ 30 MV/m

Q_0 (2k) = 3 e10 @ ~27 MV/m

Regime of E_{acc} requirements in PERLE



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

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

Recent Presentations on LHeC and FCCeh

http://lhec.web.cern.ch

FCC Week Amsterdam 9-13.4.18

Theory
Jo Rudermann, Jorge de Blas
Overviews
Bruce Mellado, Uta Klein

QCD Max Klein
Top Christian Schwanenberger
and Orhan Cakir
Higgs Uta Klein
BSM Monica D'Onofrio
Detector Peter Kostka

Machine Oliver Bruening
Civil Engineering John Osborne
Cavity Frank Marhauser
IR Roman Martin
PERLE Walid Kaabi

DIS Workshop Kobe 16.4.-18.4.

Machine+PERLE Gianluigi Arduini

PDFs Claire Gwenlan
Low x+Diffraction Paul Newman
Nuclear PDFs Nestor Armesto
Higgs Uta Klein
Top Hao Sun
Electroweak Max Klein
New and BSM Jose Zurita

Project Max Klein
Structure of the Proton Uta Klein

FCC David D'Enterria

Towards the European Strategy in Particle Physics

15/15.11. ECFA Symposium at CERN about Future Colliders

December 2018: Submission of a 10 page LHeC (HL/HE LHC) Document
'eh' also part of the separate FCC submission
[Book1 on Physics, Book2 on FCChh +eh, …]

February 2019: Update of the CDR to appear [Main Topic of this Workshop]

May 13, 2019: Symposium in Spain

January 2020: Council + Secretariat Meeting in Bad Honnef (D)

Spring 2020: Update of the 2013 Paper.

Large Hadron Electron Collider on one page

E_e = 10-60 GeV, E_p =1-7 TeV: $\sqrt{s}$ = 200 − 1300 GeV. **Kinematics**: $0 < Q^2 < s$, $1 > x \geq 10^{-6}$ (DIS)
Electron Polarisation P=±80%. Positrons: significantly lower intensity, unpolarised
Luminosity: O(10^{34}) $cm^{-2} s^{-1}$. integrated O(1) ab^{-1} for HL LHC and 2 ab^{-1} for HE LHC/FCCeh
e-ions 6 10^{32} $cm^{-2} s^{-1}$ O(10)fb^{-1} in ePb . O(1)fb^{-1} for ep F_L measurements

Physics: QCD: develop+break? The worlds best microscope. BSM (H, top, ν, SUSY..)
Transformations: Searches at LHC, LHC as Higgs Precision Facility, QCD of Nuclear Dynamics
The LHeC has a deep, unique QCD, H and BSM precision and discovery physics programme.

1802.04317

Time: Determined by the Large Hadron Collider (HL LHC needs till ~2040 for 3 ab^{-1})
LHeC: Detector Installation in 2 years, earliest in LS4 (2030/31).
HE LHC: re-use ERL. In between HL-HE, 10 years time of ERL Physics (laser, γγ..)
Very long term: FCC-eh

http://lhec.web.cern.ch

Challenges: Demonstration of ERL Technology (high electron current, multi-turn)
Design 3-beam IR for concurrent ep+pp operation, New Detector with Taggers - in 10 years.

The LHeC is a great opportunity to sustain deep inelastic physics within future HEP.
The cost of an ep Higgs event is O(1/10) of that at any of the 4 e^+e^- machines under consideration
It can be done: the Linac is shorter than 2 miles and the time we have longer than HERA had.

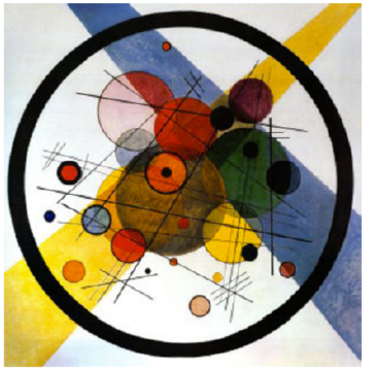
CERN and world HEP: Vital to make the High Luminosity LHC programme a success.

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

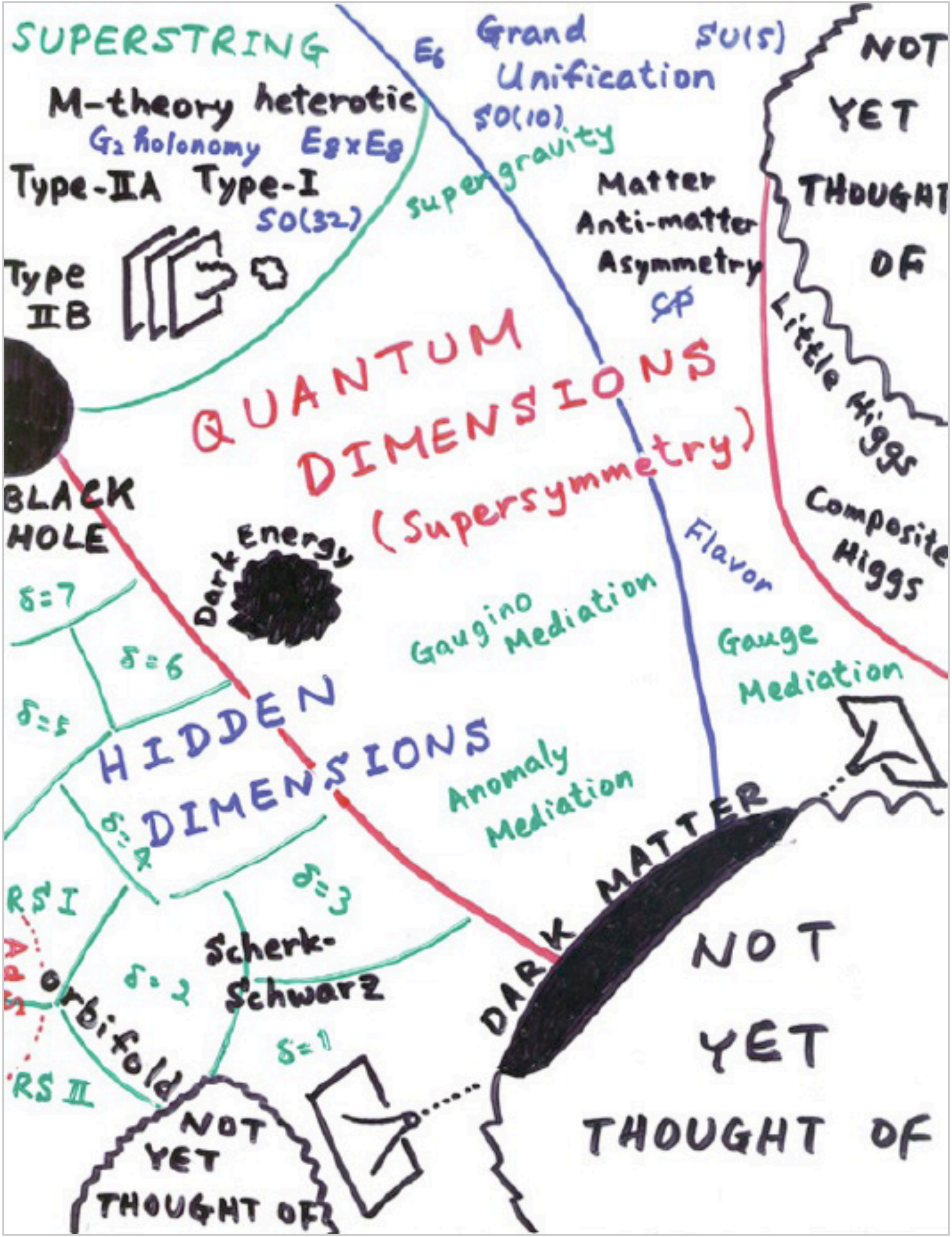
A Higgs Facility Resolving the Substructure of Matter

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

LHeC Collaboration

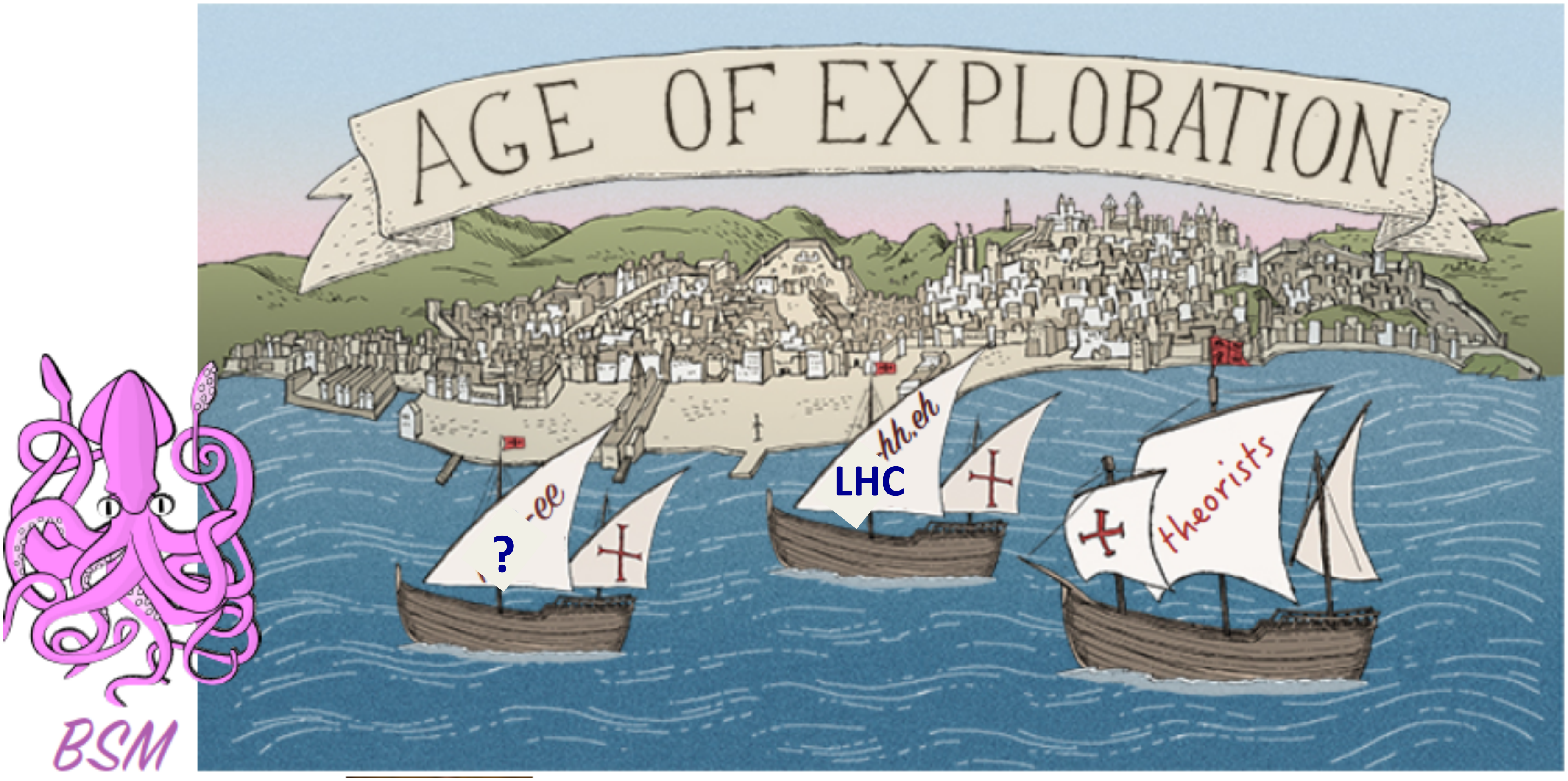


Submitted to J.Phys. G



The SM looks complete, some people believe in the new dark aether, need precision+diversity

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



Jo Ruderman, modified

A currently best bet is HL/HE LHC, ep with both, and CepC: a realistic program for exploring the SM deeper and leading beyond, for the next 40 years ahead.

It needs

Electrons for the LHC

LHeC/FCCeh and PERLE Workshop

June 27-29, 2018
LAL-Orsay, France

Organising Committee:
Nestor Armesto (USC)
Oliver Brüning (CERN)
Walid Kaabi (LAL)
Uta Klein (Liverpool)
Zhiqing Zhang (LAL)

Advisory Committee:
Sergio Bertolucci (Bologna)
Nicola Bianchi (INFN)
Frédérick Bordry (CERN)
Oliver Brüning (CERN)
Stanley Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Max Klein (U Liverpool)
Shin-ichi Kurokawa (Tsukuba)
Victor Matveev (JINR Dubna)
Aleandro Nisati (Rome)
Leonid Rivkin (PSI Villigen)
Herwig Schopper (CERN) - Chair
Jürgen Schuhkraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (ESS Lund)

Coordination Group:
Nestor Armesto (Santiago de Compostela)
Gianluigi Arduini (CERN)
Oliver Brüning (CERN)
Andrea Gaddi (CERN)
Erk Jensen (CERN)
Walid Kaabi (LAL Orsay)
Max Klein (Liverpool)
Peter Kostka (Liverpool)
Bruce Mellado (Wits)
Paul Newman (Birmingham)
Daniel Schulte (CERN)
Frank Zimmermann (CERN)

Physics Convenors:
Nestor Armesto (Santiago de Compostela)
Georges Azuelos (Montreal)
Olaf Behnke (DESY)
Monica D'Onofrio (Liverpool)
Oliver Fischer (Karlsruhe)
Claire Gwenlan (Oxford)
Uta Klein (Liverpool)
Peter Kostka (Liverpool)
Masahiro Kuze (Tokyo)
Paul Newman (Birmingham)
Alessandro Polini (Bologna)
Fred Olness (Dallas)
Christian Schwanenberger (DESY)
Anna Stasto (Pennsylvania)

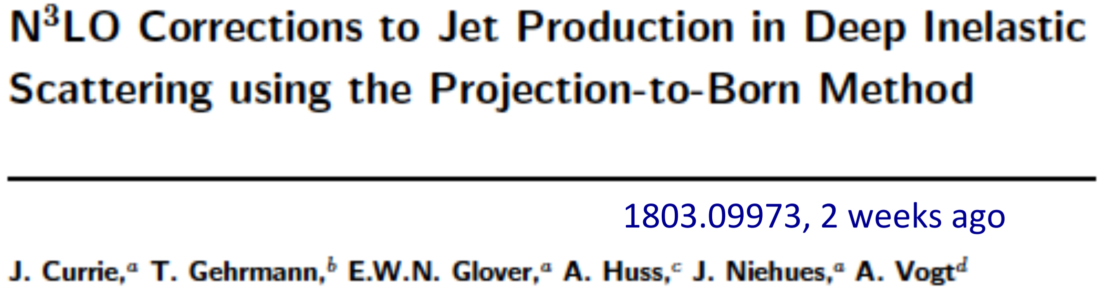
https://indico.cern.ch/event/698368/

Welcome
on behalf of the
Coordination
Group.

backup

pQCD Theory

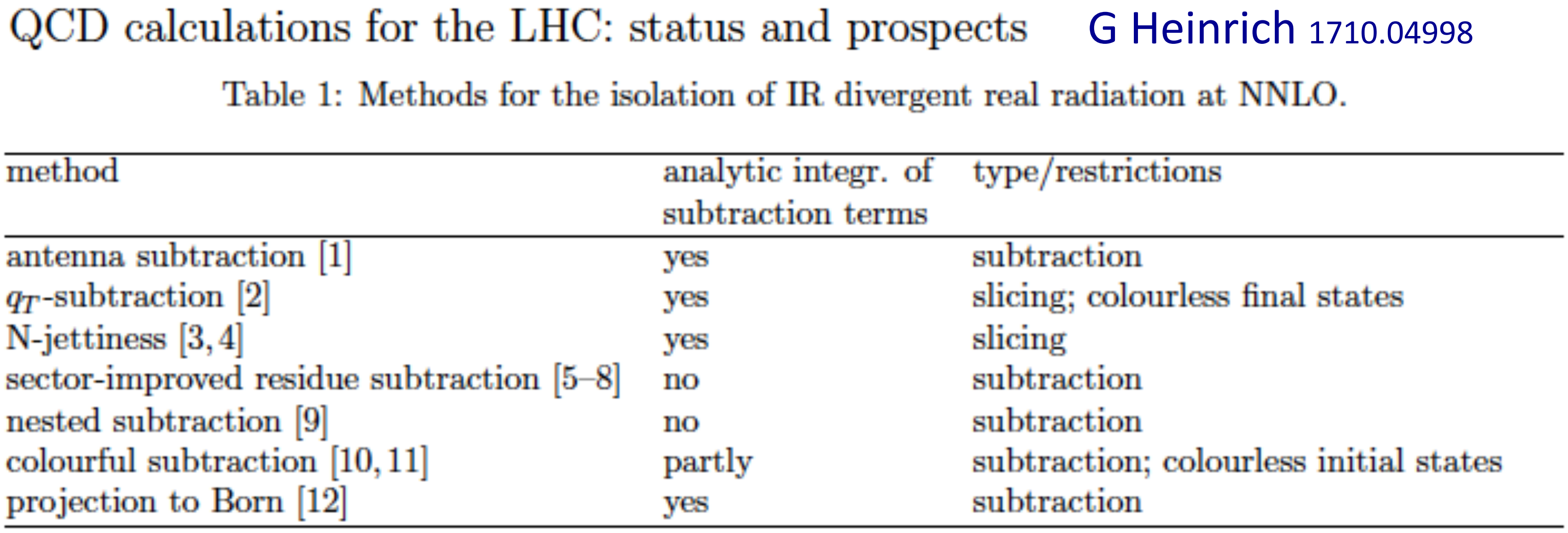
Substantial and remarkable theoretical progress in pQCD calculations to N^{k}LO, e.g.



N^{3}LO Corrections to Jet Production in Deep Inelastic Scattering using the Projection-to-Born Method

1803.09973, 2 weeks ago

J. Currie,[a] T. Gehrmann,[b] E.W.N. Glover,[a] A. Huss,[c] J. Niehues,[a] A. Vogt[d]

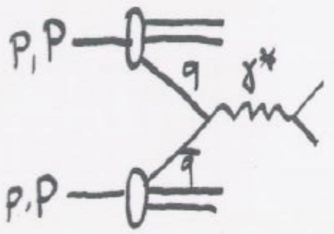


QCD calculations for the LHC: status and prospects

G Heinrich 1710.04998

Table 1: Methods for the isolation of IR divergent real radiation at NNLO.

method	analytic integr. of subtraction terms	type/restrictions
antenna subtraction [1]	yes	subtraction
q_T-subtraction [2]	yes	slicing; colourless final states
N-jettiness [3, 4]	yes	slicing
sector-improved residue subtraction [5–8]	no	subtraction
nested subtraction [9]	no	subtraction
colourful subtraction [10, 11]	partly	subtraction; colourless initial states
projection to Born [12]	yes	subtraction



Drell-Yan 1970

$$\sqrt{s} = 2P = 14 \text{ TeV @ LHC}$$

$$Q^2 = M^2 = s\, x_q x_{\bar q}$$

$$\frac{d\sigma}{dQ^2} = \sum_q \int dx_q \int dx_{\bar q} \; q(x_q) \cdot \frac{d\tilde\sigma_{q\bar q}}{dQ^2} \, \bar q(x_{\bar q})$$

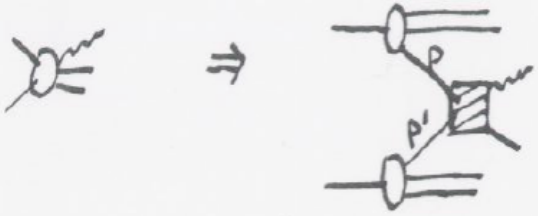
$$\frac{d\tilde\sigma}{dQ^2} = \frac{4\pi\alpha^2}{3N_c Q^2 s} \cdot e_q^2 \, \delta\left(\frac{Q^2}{s} - x_q x_{\bar q}\right)$$

rapidity variable of γ* : $x = \frac{M}{\sqrt{s}} e^{\pm y}$

for vector boson or Higgs production

M^2 and $\frac{M}{\sqrt{s}} e^{\pm y}$ are equivalent to Q^2, x in DIS

factorisation in pp scattering



--> $\sigma = \sum_{p,p'} f_p(\mu^2) \otimes f_{p'}(\mu^2) \otimes \tilde\sigma_{pp'}(\mu)$

↑

W, Z production

jets

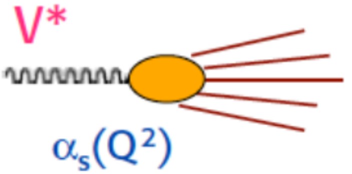
direct photons

need to know the parton distribution functions (pdf's):

from DIS : HERA

measure σ, pdf's, calculate $\tilde\sigma \underset{?}{\Rightarrow} \mathcal{L}_{pp}$

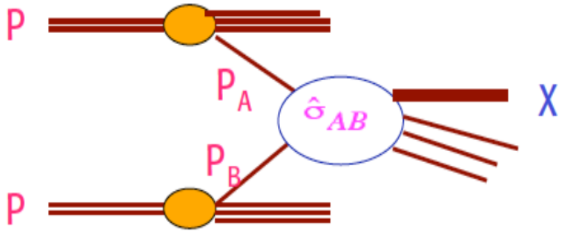
QCD with ee pp ep



$\sqrt{s}=2E_e \approx [G_F\sqrt{2}]^{-1/2} = 246$ GeV

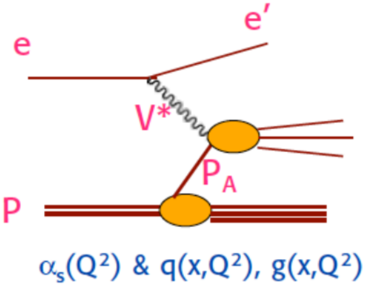
Final state arises completely from short distance interaction
of virtual boson with quarks: NO PDFs, but jets, α_s
Njets +0, energy, angles. Unique association of q,g with jets
Observation of 3-jet events at PETRA to discover the gluon

S Ellis and D Soper, hep-ph/9306280
Successive combination jet algorithm for hadron collisions



$\sqrt{s} = 2E_p = 14, 27, 100$ TeV

Many initial partons but only two interact.
“rest” is the underlying event of soft i.a.’s
Dynamical coupling of all components. MPIs
N jets at large pT +X, pseudorapidity + azimuth
Ledermann-Drell-Yan scattering, jets
Scattering depends on parton distributions
The “Altarelli cocktail” to save the SM (1984, Bern)

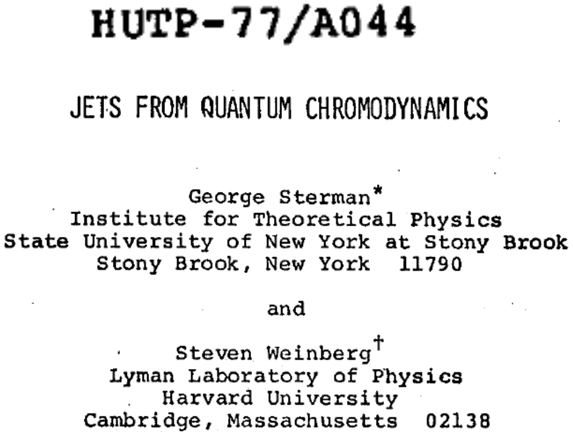


$\sqrt{s} = 2\sqrt{E_e E_p} = 1.3, 1.8, 3.5$ TeV

“Route royale” to the structure and dynamics
of parton interactions inside the proton (nucleon)
Universal partons evolving with resolution scale
x BJ fixed through electron kinematics. PDFs + α_s
Redundant e and h final state reconstruction.
Discovery of partons and the QPM … DGLAP

ep - “option” which ought to be a real part. *Seguil tuo corso, e lascia dir el genti (Dante, KM)*

Jets



HUTP-77/A044

JETS FROM QUANTUM CHROMODYNAMICS

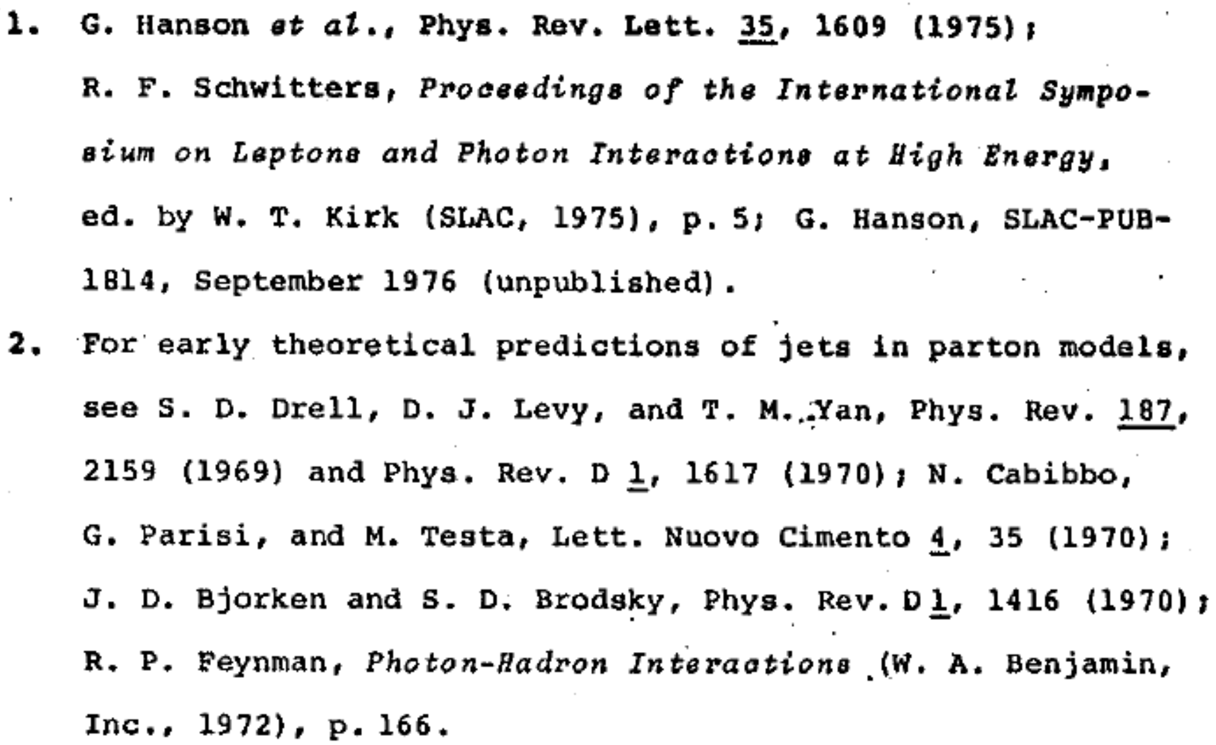
George Sterman*
Institute for Theoretical Physics
State University of New York at Stony Brook
Stony Brook, New York 11790

and

Steven Weinberg†
Lyman Laboratory of Physics
Harvard University
Cambridge, Massachusetts 02138

$$\frac{d\sigma}{d\Omega} \propto 1 + \alpha \cos^2 \theta + = 1 + (0.78 \pm 0.12) \cos^2 \theta.$$

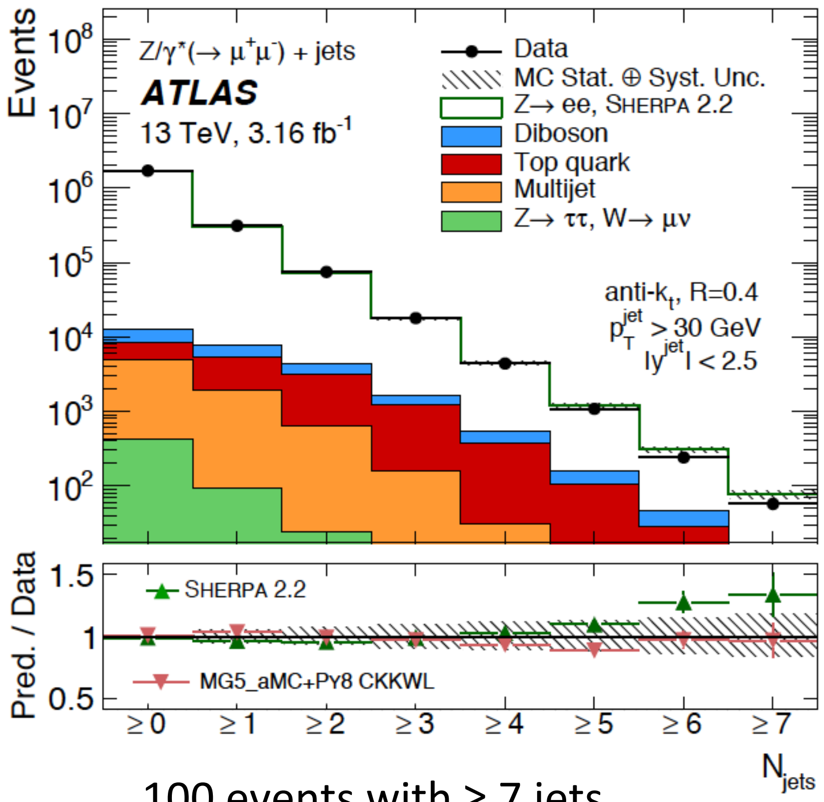
Jets in e^+e^- at > 5 GeV at SPEAR at Stanford



1. G. Hanson *et al.*, Phys. Rev. Lett. 35, 1609 (1975); R. F. Schwitters, *Proceedings of the International Symposium on Leptons and Photon Interactions at High Energy*, ed. by W. T. Kirk (SLAC, 1975), p. 5; G. Hanson, SLAC-PUB-1814, September 1976 (unpublished).
2. For early theoretical predictions of jets in parton models, see S. D. Drell, D. J. Levy, and T. M. Yan, Phys. Rev. 187, 2159 (1969) and Phys. Rev. D 1, 1617 (1970); N. Cabibbo, G. Parisi, and M. Testa, Lett. Nuovo Cimento 4, 35 (1970); J. D. Bjorken and S. D. Brodsky, Phys. Rev. D 1, 1416 (1970); R. P. Feynman, *Photon-Hadron Interactions* (W. A. Benjamin, Inc., 1972), p. 166.

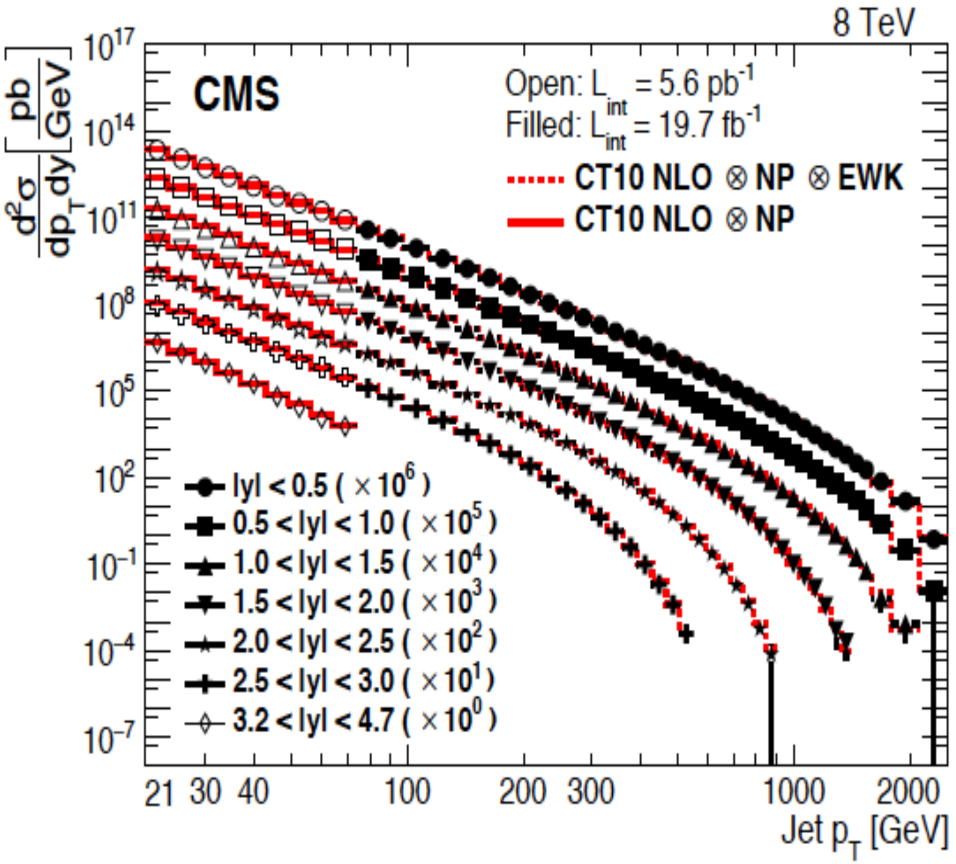
QCD at work at the LHC

1702.05725 Z + n jets ATLAS 3fb^{-1} 13 TeV



100 events with ≥ 7 jets

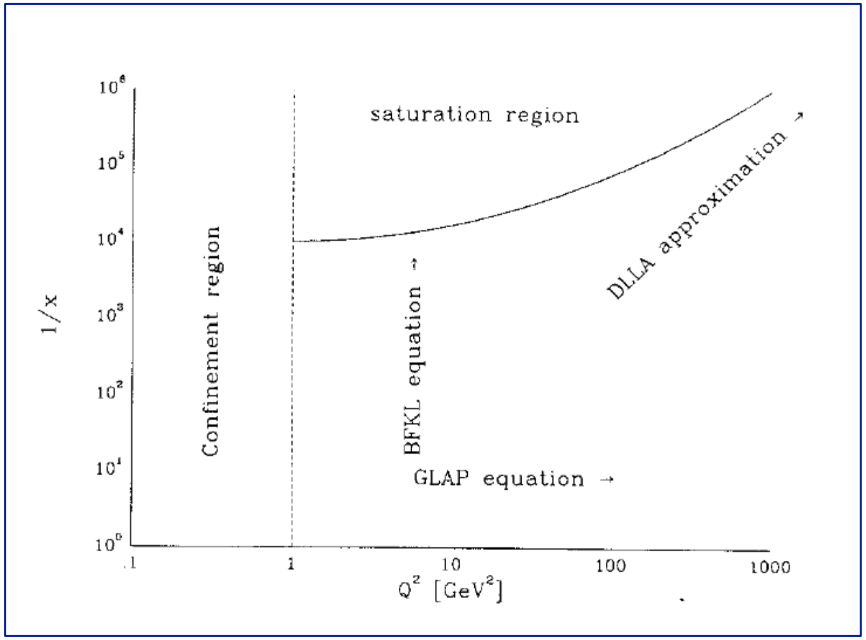
1609.05331 inclusive jets, 26fb^{-1} 8 TeV



10 orders of magnitude in cross section

LHC is the trick to attract a few 1000 physicists to work on QCD: T Sjoestrand, 2007, after we saw ATLAS

BFKL and Saturation

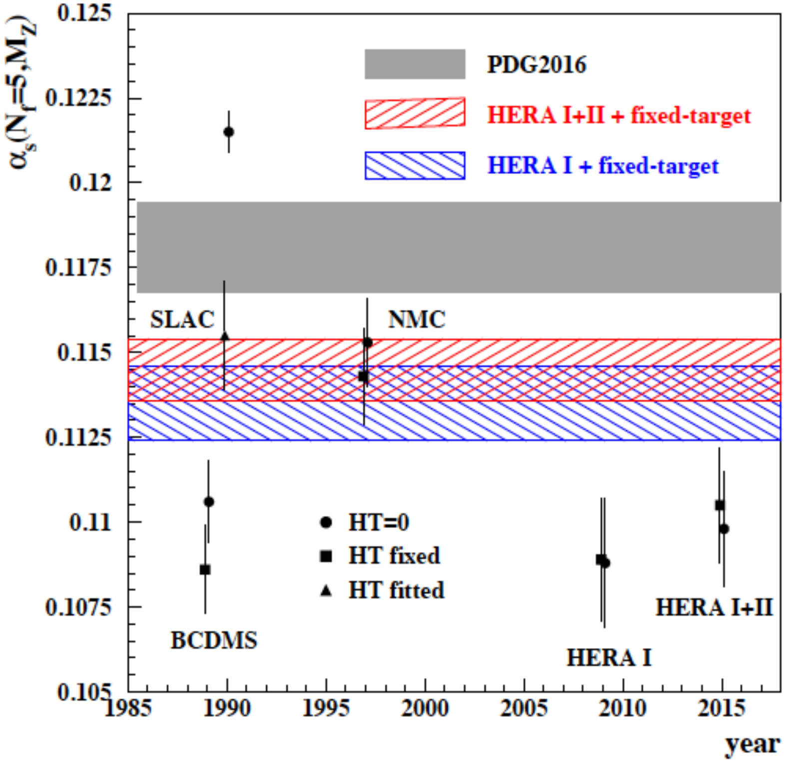


Gribov, Levin, Ryskin. *Semihard Processes in QCD* Phys Rept 100 (1983) 1-150

Rise of Gluon (and Quark) densities towards low x discovered at HERA. This may lead to saturation − non-linear interactions and BFKL ln(1/x) effects.
Not discovered at HERA, to much surprise, despite recent 'speculations' ..
Change of parton distributions + evolution → to be clarified for FCC + (HE) LHC

BFKL papers: *The Pomeranchuk Singularity in QCD/Gauge Theories* 1978/1977

$\alpha_s(\mu)$ in Deep Inelastic Scattering



ABMP 2017 $\alpha_s = 0.1140 \pm 0.0009$

DIS: Fixed target: higher twist corrections $1/Q^2$, nuclear corrections, small lever arm, gluon?

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

H1 inclusive (1998) NLO

hep-ph/0012053 – highest cited H1 only

$$\alpha_s(M_Z^2) = 0.1157 \pm 0.0020\,(exp) \pm 0.0029\,(thy)$$

H1 only jets (2017) NNLO jets!

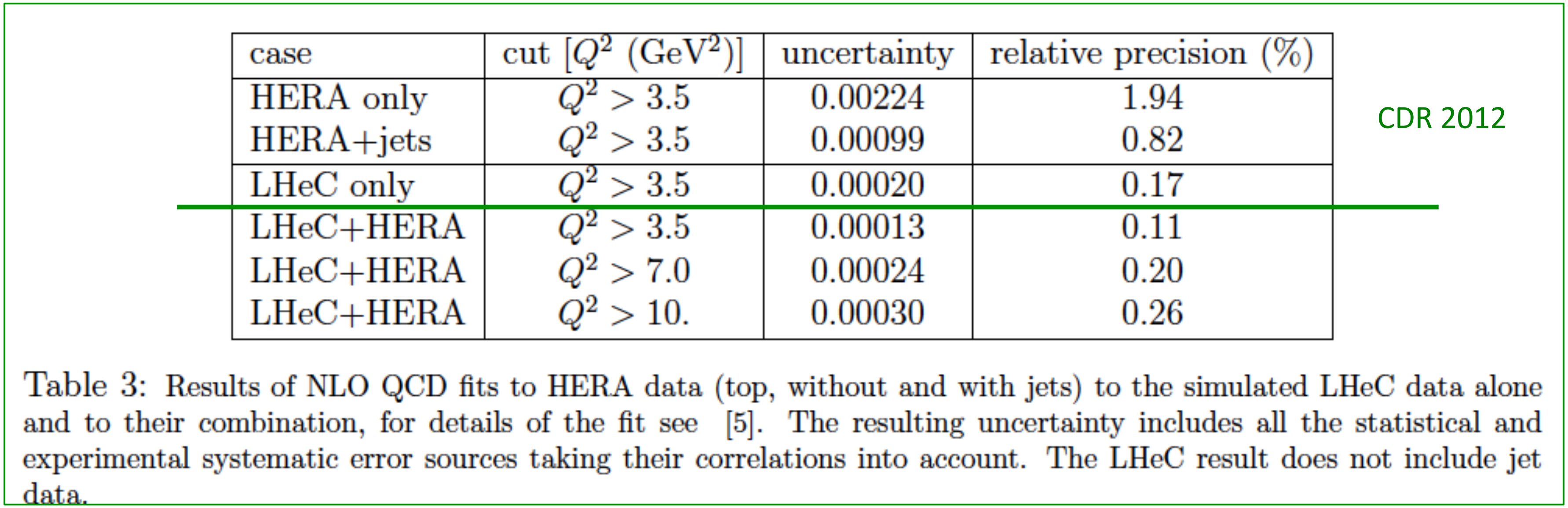
$$\alpha_s = 0.1142 \pm 0.0028\ (\mathrm{tot})$$

H1 inclusive and jets (2017) NNLO

→ It is well possible that α_s is smaller than hitherto assumed. Current practice to exclude ABM is questionable. Like in the lattice case, one constructs, for perhaps respectable reasons, a norm, which gives the impression of higher accuracy than a critical evaluation would lead to.

Current strong coupling precision at best 1-2%: FCC ee and eh want 1-2 per mille

$\alpha_s(\mu)$ at LHeC/FCCeh



case	cut [Q^2 (GeV^2)]	uncertainty	relative precision (%)
HERA only	$Q^2 > 3.5$	0.00224	1.94
HERA+jets	$Q^2 > 3.5$	0.00099	0.82
LHeC only	$Q^2 > 3.5$	0.00020	0.17
LHeC+HERA	$Q^2 > 3.5$	0.00013	0.11
LHeC+HERA	$Q^2 > 7.0$	0.00024	0.20
LHeC+HERA	$Q^2 > 10.$	0.00030	0.26

Table 3: Results of NLO QCD fits to HERA data (top, without and with jets) to the simulated LHeC data alone and to their combination, for details of the fit see [5]. The resulting uncertainty includes all the statistical and experimental systematic error sources taking their correlations into account. The LHeC result does not include jet data.

CDR 2012

- LHeC/FCCeh lead to 0.1% uncertainty (stat+syst), free of previous DIS deficiencies (HT,nc)
- Joint determination with parton distributions (maybe simplified as H1 published in 2001)
- Needs clarity about low x behaviour as this uses DGLAP.
- Requires to control heavy flavour (theory) at new level (measure s, c, b, t also)
- Very high precision of NC (y and Z) and CC and extension to x near 1 will drastically reduce the PDF parameterisation uncertainties
- Scale uncertainties require that N^{3}LO formalism be applied (the bizarre 1/2 .. 2 rule.??)
- The attempt to measure the strong coupling in DIS to permille accuracy requires nothing less than a renaissance of experimental and theoretical DIS (ep) physics

The Case for the LHeC

From the CDR 2012 to the time ahead 2018+

ISSN 0954-3899

Journal of Physics G

Nuclear and Particle Physics

arXiv:1206.2913

Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

IOP Publishing

Particle Physics

Physics Case

Preparations

Max Klein

UNIVERSITY OF LIVERPOOL

Electrons for the LHC

LHeC/FCCeh and PERLE Workshop

June 27-29, 2018

LAL-Orsay, France

Organising Committee:

Nestor Armesto (USC)
Oliver Brüning (CERN)
Walid Kaabi (LAL)
Uta Klein (Liverpool)
Zhiqing Zhang (LAL)

Advisory Committee:

Sergio Bertolucci (Bologna)
Nicola Bianchi (INFN)
Frédérick Bordry (CERN)
Oliver Brüning (CERN)
Stanley Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Max Klein (U Liverpool)
Shin-ichi Kurokawa (Tsukuba)
Victor Matveev (JINR Dubna)
Aleandro Nisati (Rome)
Leonid Rivkin (PSI Villigen)
Herwig Schopper (CERN) - Chair
Jürgen Schuhkraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (ESS Lund)

Coordination Group:

Nestor Armesto (Santiago de Compostela)
Gianluigi Arduini (CERN)
Oliver Brüning (CERN)
Andrea Gaddi (CERN)
Erk Jensen (CERN)
Walid Kaabi (LAL Orsay)
Max Klein (Liverpool)
Peter Kostka (Liverpool)
Bruce Mellado (Wits)
Paul Newman (Birmingham)
Daniel Schulte (CERN)
Frank Zimmermann (CERN)

Physics Convenors:

Nestor Armesto (Santiago de Compostela)
Georges Azuelos (Montreal)
Olaf Behnke (DESY)
Monica D'Onofrio (Liverpool)
Oliver Fischer (Karlsruhe)
Claire Gwenlan (Oxford)
Uta Klein (Liverpool)
Peter Kostka (Liverpool)
Masahiro Kuze (Tokyo)
Paul Newman (Birmingham)
Alessandro Polini (Bologna)
Fred Olness (Dallas)
Christian Schwanenberger (DESY)
Anna Stasto (Pennsylvania)

https://indico.cern.ch/event/698368/

Contribution to a Panel on Future DIS, 17.4.2018, Kobe, for the LHeC/FCCeh Study Group

http://lhec.web.cern.ch