Approaching QCD with FCC

a few observations on

QCD
ee pp ep
Jets
Coupling
PDFs
Low x

In memory of Willy van Neerven, Wu-Ki Tung, Guido Altarelli and Lev Lipatov

Max Klein
University of Liverpool, H1 and ATLAS

Talk at the FCC Week 2018, Amsterdam, 11.4.18

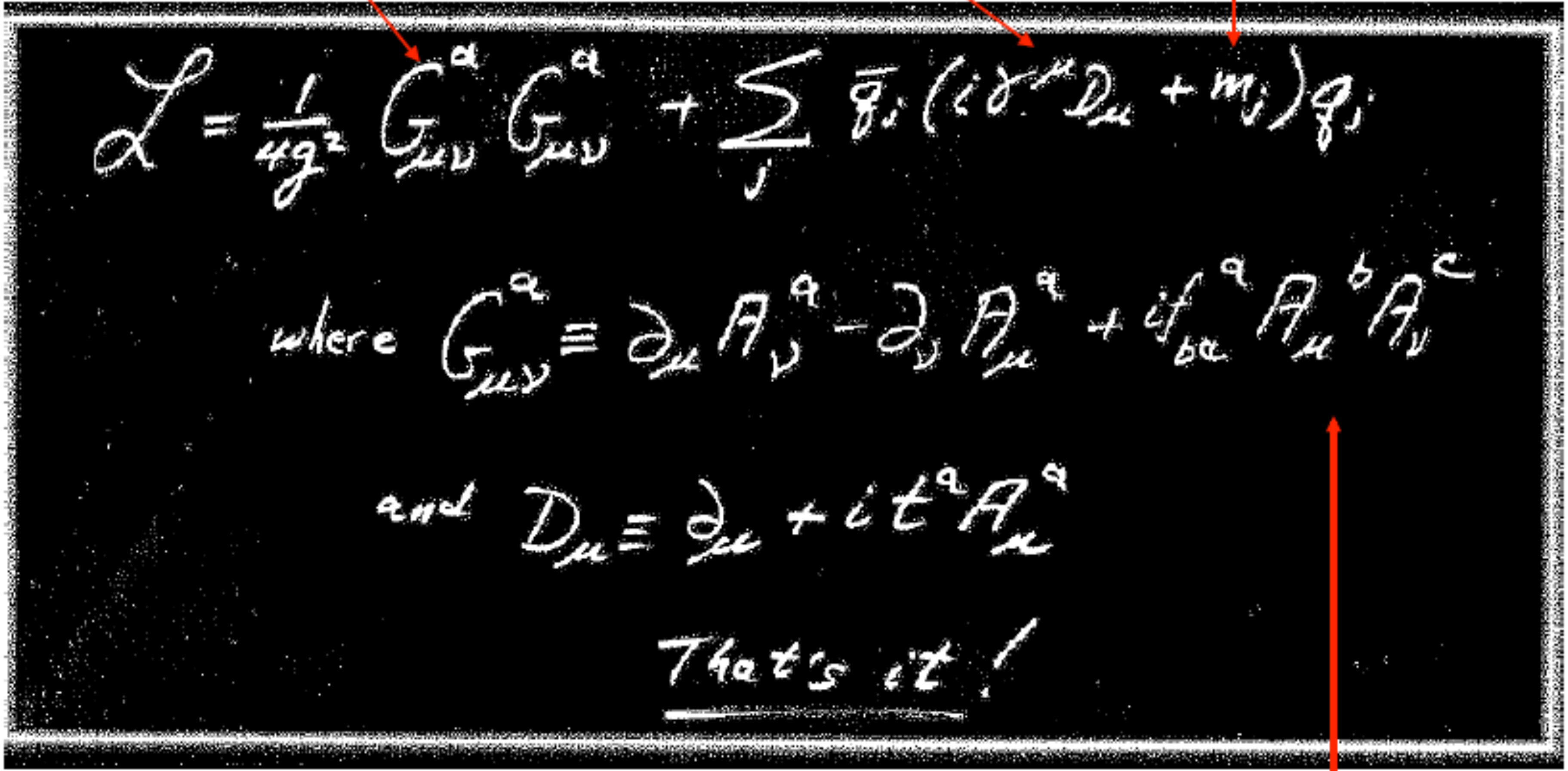
Many thanks to Davide D'Enterria, Alain Blondel, Michelangelo Mangano, Voica Radescu + the eh QCD team.

QCD

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!

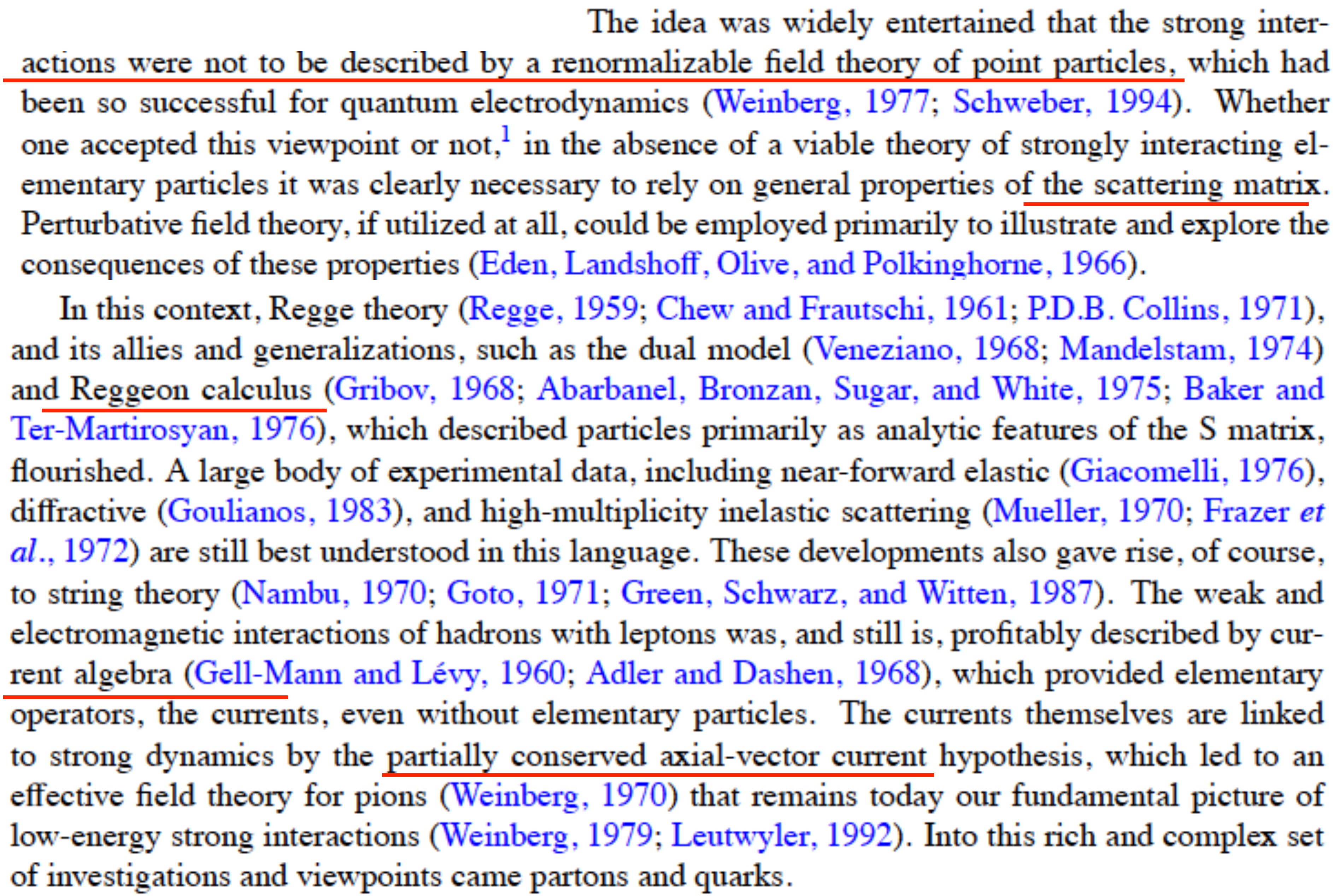
j … quark flavors

a,b,c … 3 colors

μ,ν … space-time

selfinteraction
of gluon field

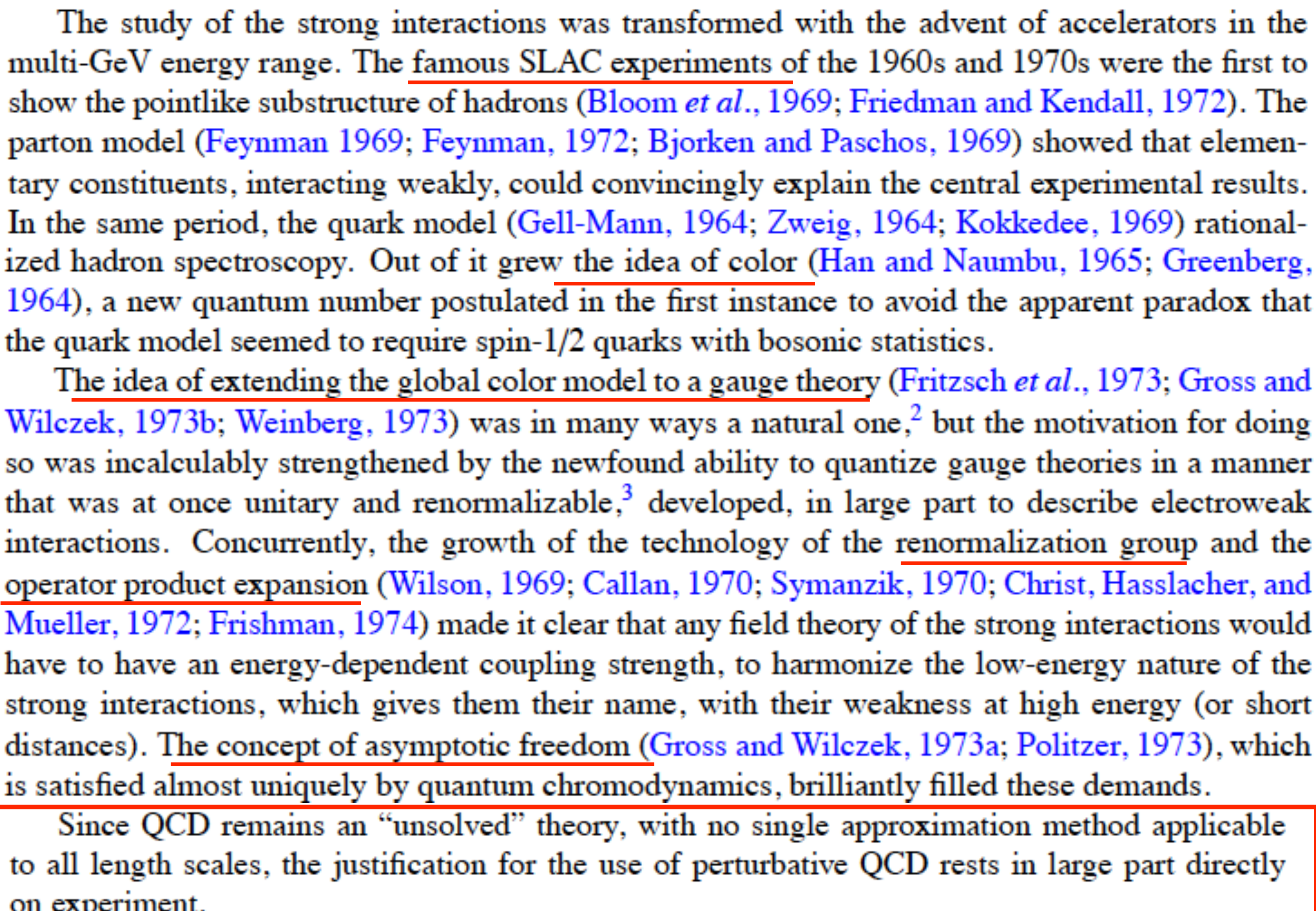
F.Wilczek, Physics Today, August 2000.



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

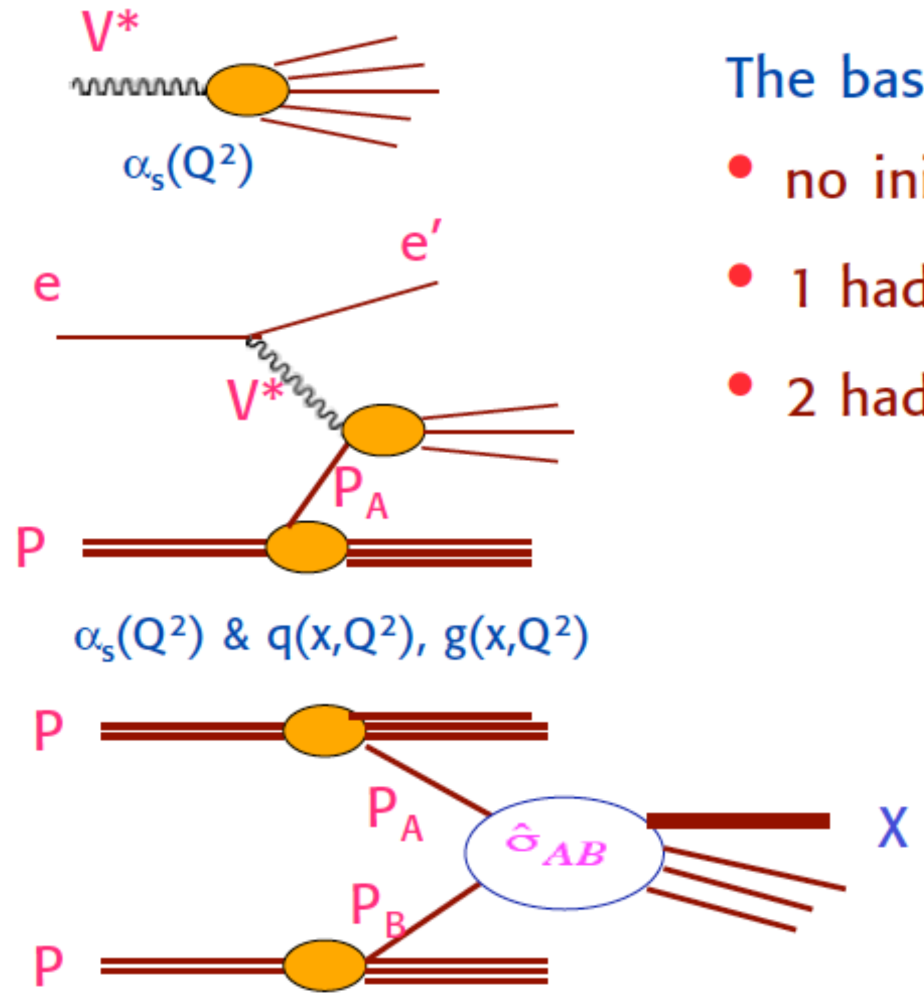


The study of the strong interactions was transformed with the advent of accelerators in the multi-GeV energy range. The famous SLAC experiments of the 1960s and 1970s were the first to show the pointlike substructure of hadrons (Bloom *et al.*, 1969; Friedman and Kendall, 1972). The parton model (Feynman 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

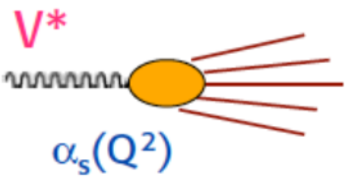


The basic experimental set ups:

- 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

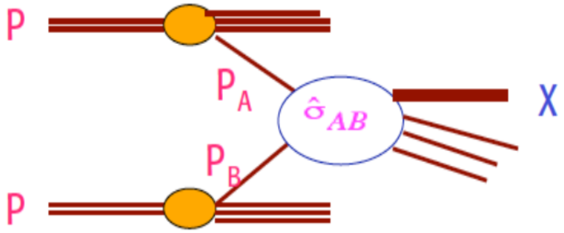
QCD with ee pp ep



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

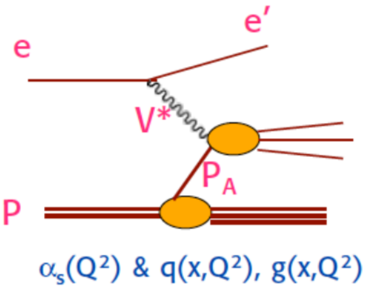
Final state arises completely from short distance interaction
of virtual boson with quarks: NO PDFs, but jets, α_s
Njets +0, energy, angles. Unique association of q,g with jets
Observation of 3-jet events at PETRA to discover the gluon

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)

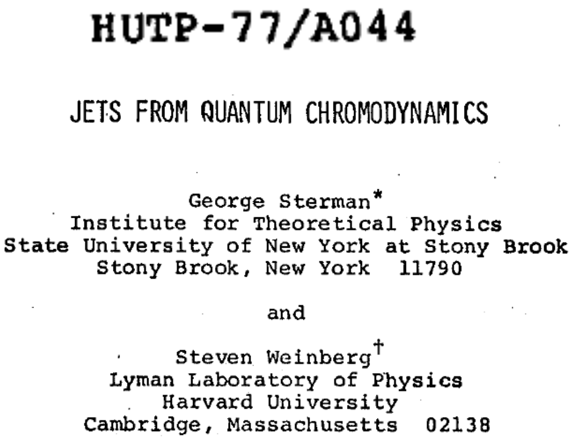


$\sqrt{s} = 2\sqrt{E_e E_p}$ = 1.3, 1.8, 3.5 TeV

“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

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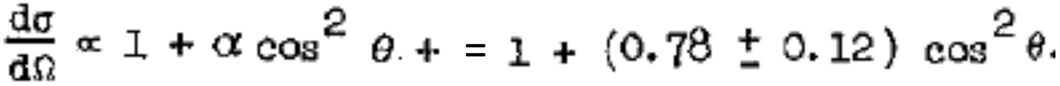
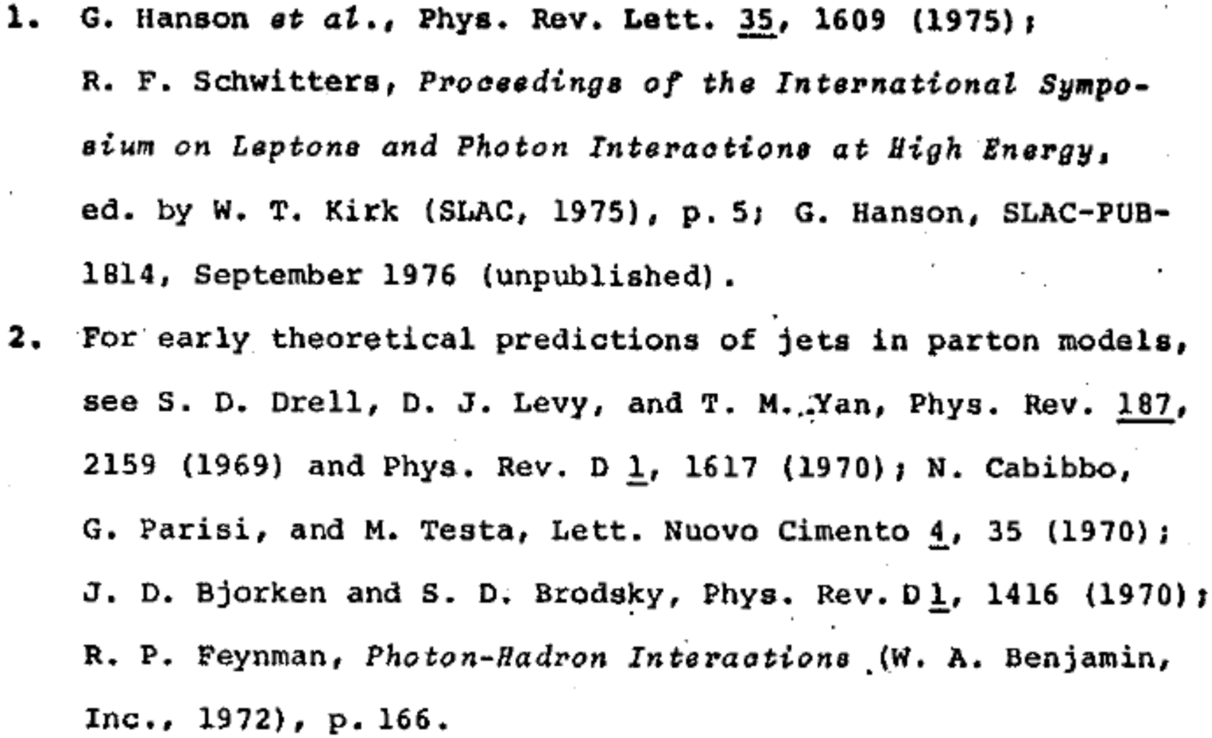


$$\frac{d\sigma}{d\Omega} \propto 1 + \alpha \cos^2 \theta + = 1 + (0.78 \pm 0.12) \cos^2 \theta.$$

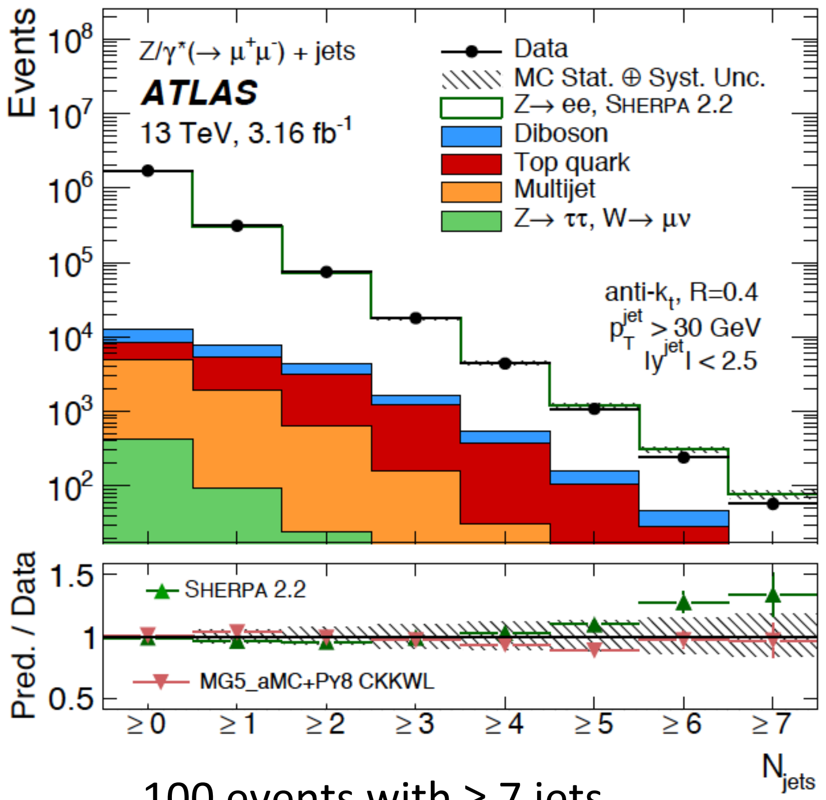
Jets in e^+e^- at > 5 GeV at SPEAR at Stanford



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.

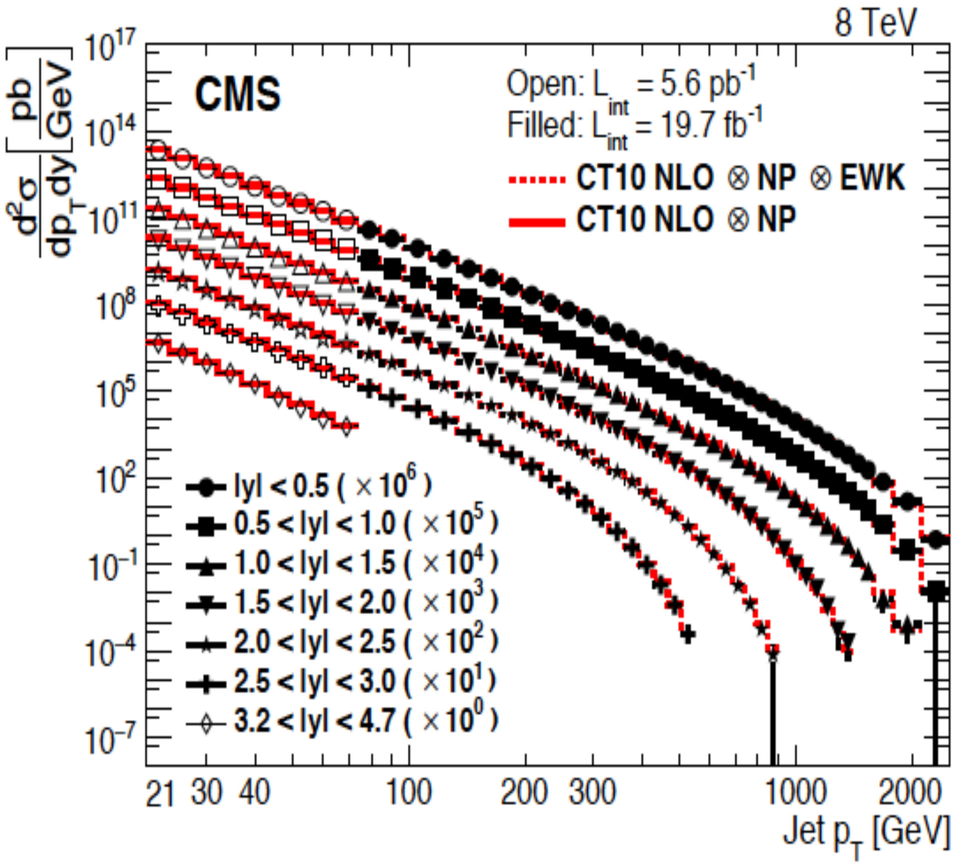
QCD at work at the LHC

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



100 events with ≥ 7 jets

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

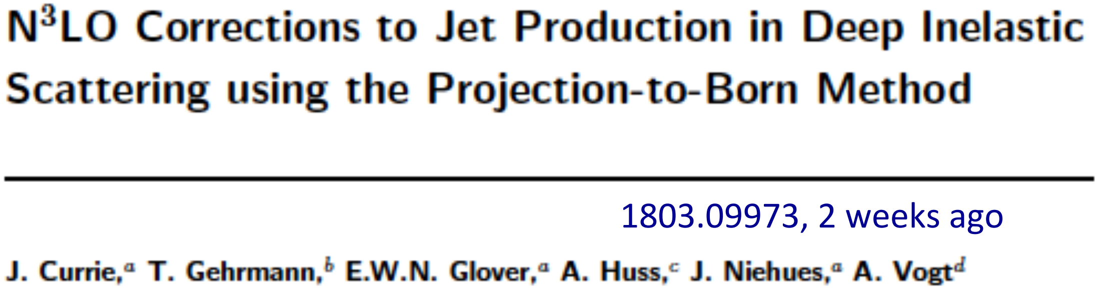


10 orders of magnitude in cross section

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

pQCD Theory

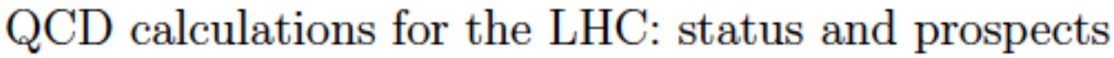
Substantial and remarkable theoretical progress in pQCD calculations to N^{k}LO, e.g.



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

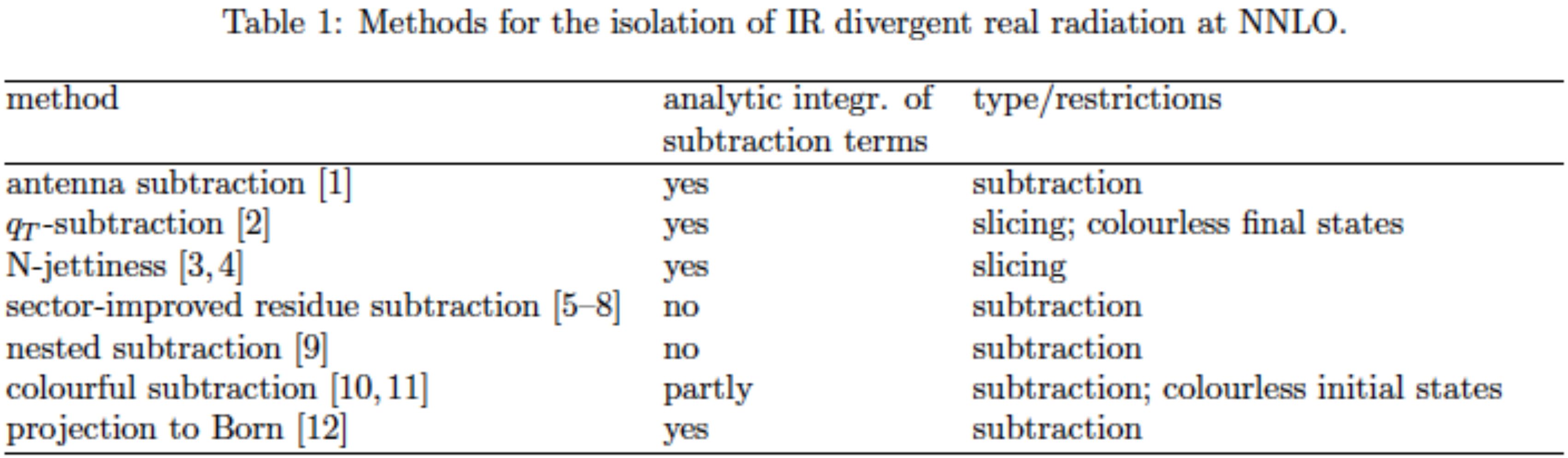


Table 1: Methods for the isolation of IR divergent real radiation at NNLO.

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

QCD & $\gamma\gamma$ physics at FCC-ee

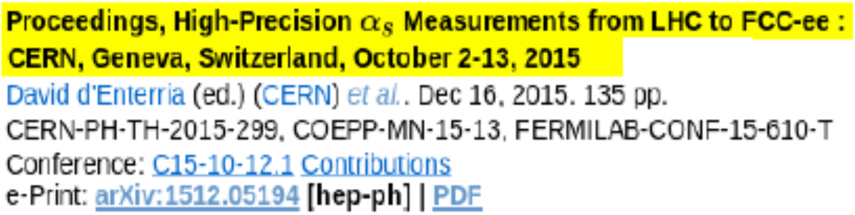
FCC week 2018

Amsterdam, 10th April 2017

David d'Enterria (CERN)

- FCC-ee QCD studies: arXiv:1702.01329, arXiv:1512.05194

Proceedings, Parton Radiation and Fragmentation from LHC to FCC-ee : CERN, Geneva, Switzerland, November 22-23, 2016
David d'Enterria (ed.) (CERN), Peter Z. Skands (ed.) (Monash U.).
Feb 4, 2017. 181 pp. COEPP-MN-17-1
Conference: C16-11-21.1 Contributions
e-Print: arXiv:1702.01329 [hep-ph] | PDF

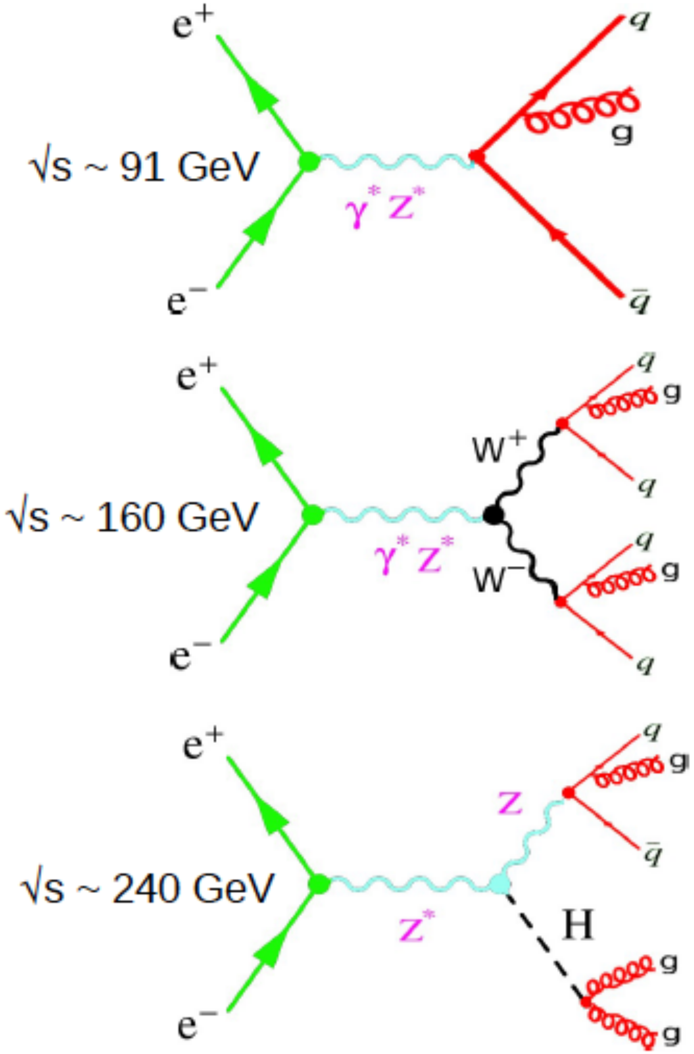


Proceedings, High-Precision α_s Measurements from LHC to FCC-ee : CERN, Geneva, Switzerland, October 2-13, 2015
David d'Enterria (ed.) (CERN) *et al.*. Dec 16, 2015. 135 pp.
CERN-PH-TH-2015-299, COEPP-MN-15-13, FERMILAB-CONF-15-610-T
Conference: C15-10-12.1 Contributions
e-Print: arXiv:1512.05194 [hep-ph] | PDF

- FCC-ee $\gamma\gamma$ studies: arXiv:1712.07023 [PHOTON'17 proceeds.]

QCD and γγ physics in e^+e^- collisions

- e^+e^- collisions provide an extremely clean environment with fully-controlled initial-state to very precisely probe q,g dynamics:



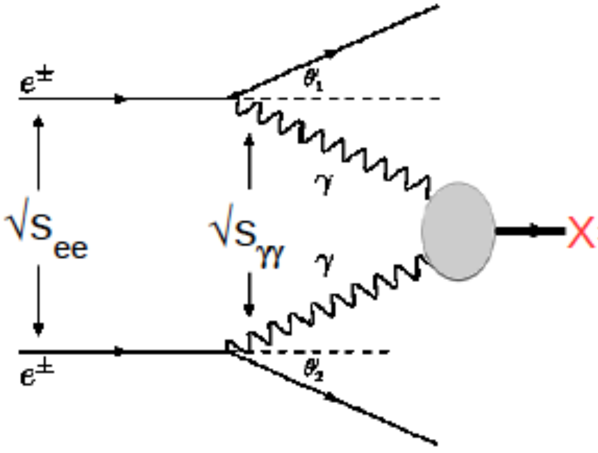
Advantages compared to p-p collisions:

- QED initial-state with known kinematics
- Controlled QCD radiation (only in final-state)
- Well-defined heavy-Q, quark, gluon jets
- Smaller non-pQCD uncertainties:

  no PDFs, no QCD "underlying event",...

  Direct clean parton fragmentation & hadroniz.

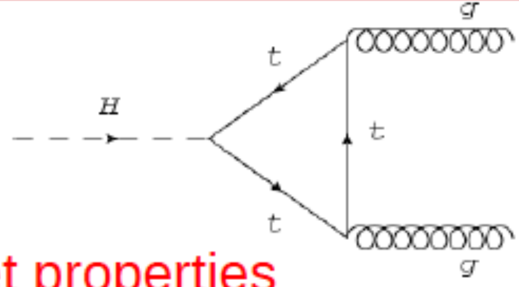
- Plus (B)SM physics in γ γ (EPA) collisions:



X= hadrons, H, WW, ZZ, φ,...

High-precision g-jet studies via $e^+e^- \to H(gg)+X$

- FCC-ee H(gg) is a "pure gluon" factory:
  H → gg (BR~10% accurately know) provides
  O(200.000) extra-clean digluon events:
  - High-precision study of gluon radiation & g-jet properties



Handles to split degeneracies

H→gg vs Z→qq

Rely on good **H→gg vs H→bb** separation;
mandated by Higgs studies requirements anyway?

Z→bbg vs Z→qq(g)

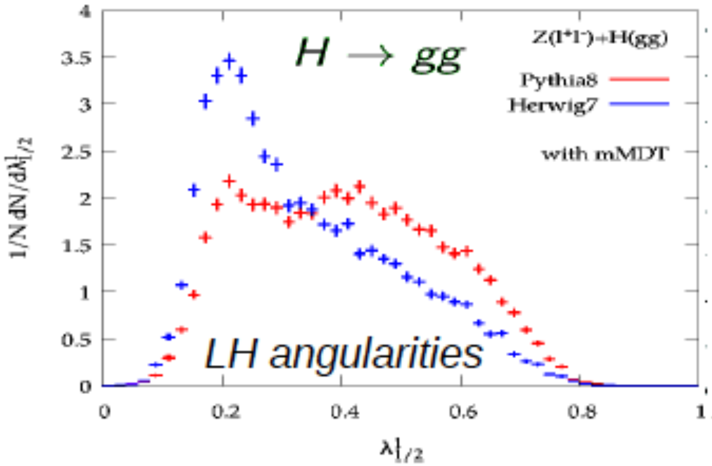
g in one hemisphere recoils against two b-jets in other hemisphere: **b tagging**

Vary jet radius: small-R → calo resolution

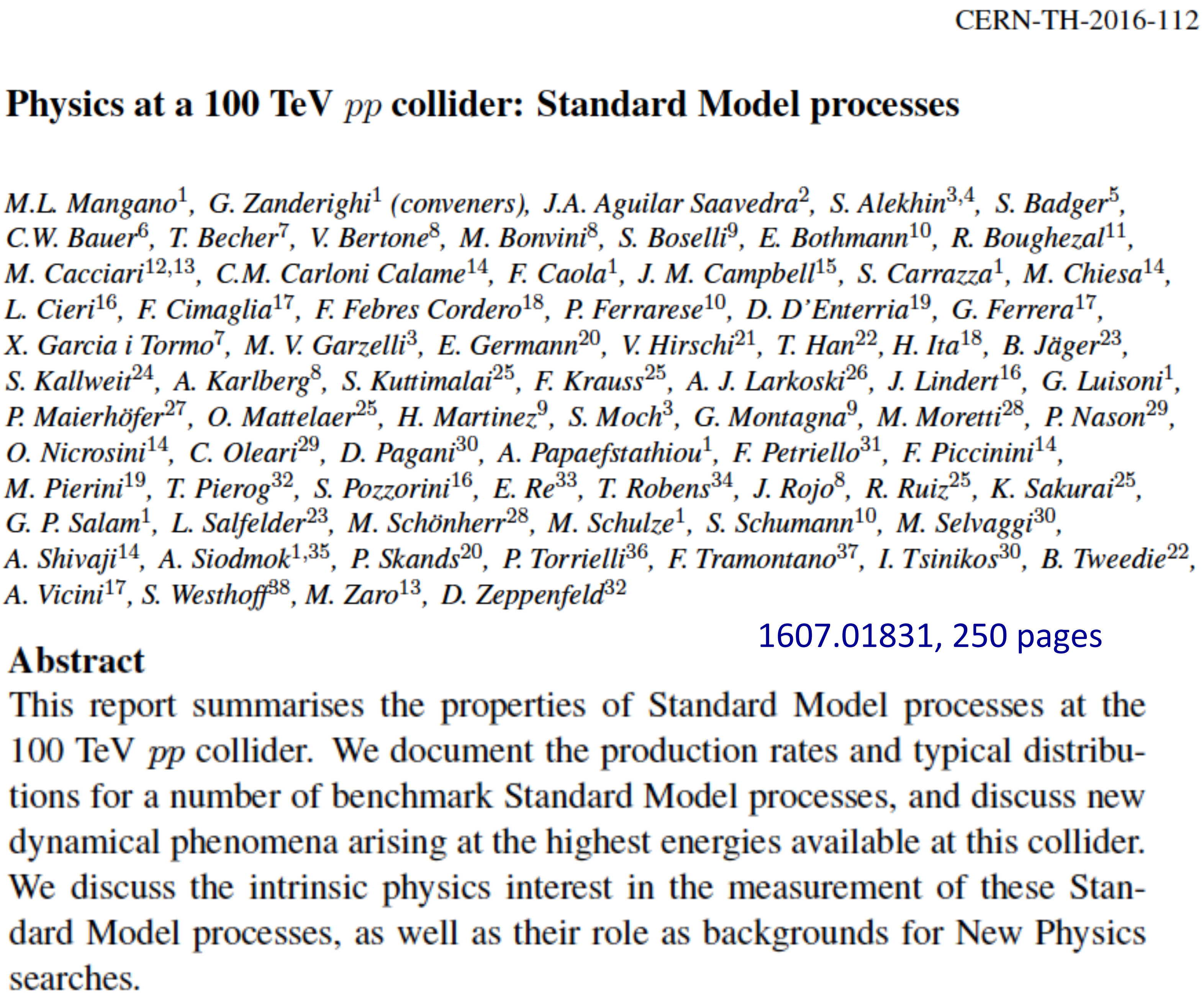
(R ~ 0.1 also useful for jet substructure)

Vary E_{CM} range : below m_Z : radiative events
→ **forward** boosted
(also useful for FFs & general scaling studies);
Scaling is **slow**, logarithmic → large lever arm

G. Soyez, K. Hamacher, G. Rauco, S. Tokar, Y. Sakaki



- Check N^nLO antenna functions
- Improve q/g/Q discrim.tools (BSM)
- Octet neutralization? (zero-charge gluon jet w/ rap-gaps)
- Colour reconnection? Glueballs ?
- Leading η's,baryons in g jets?



CERN-TH-2016-112

Physics at a 100 TeV *pp* collider: Standard Model processes

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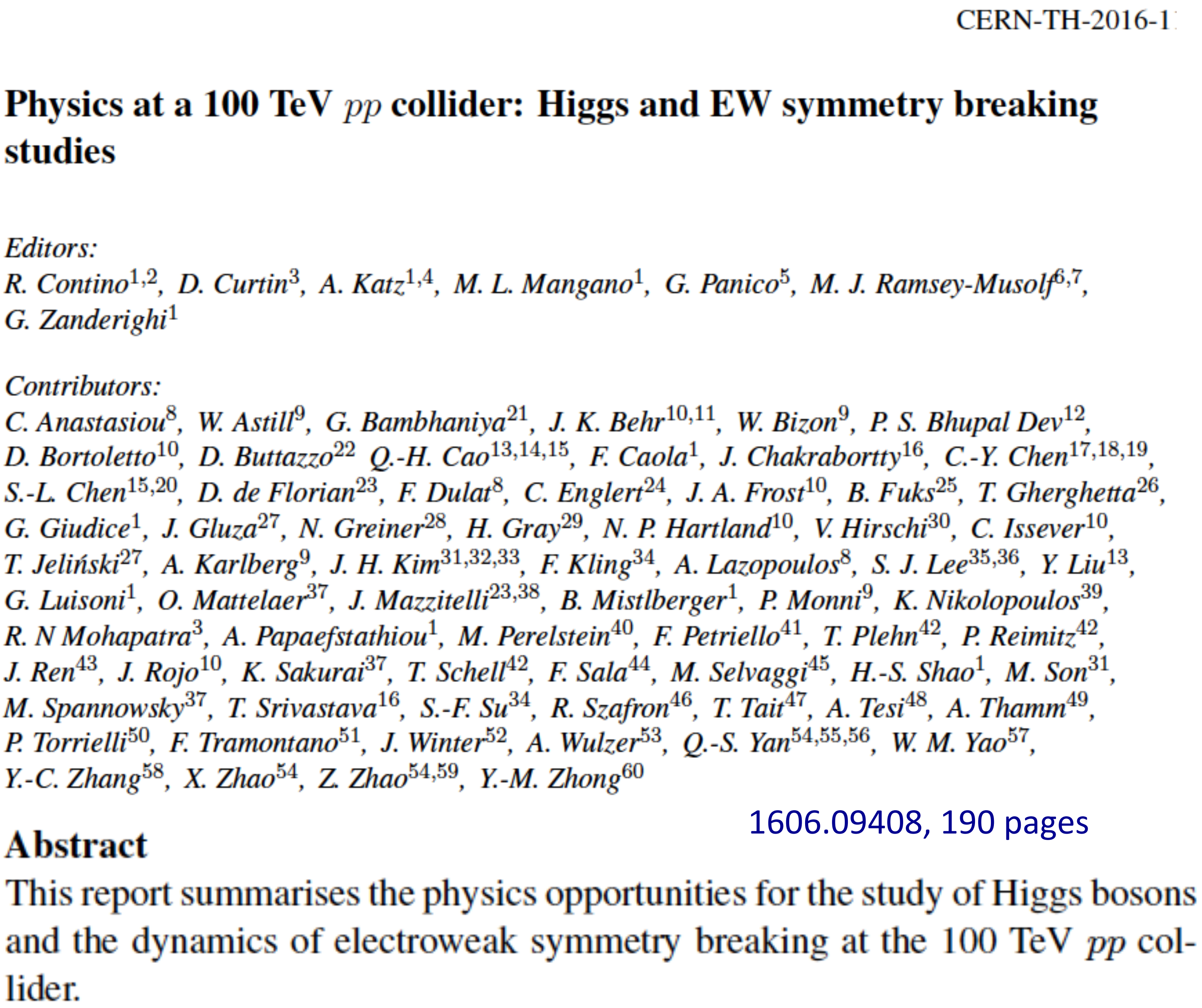
1607.01831, 250 pages

Abstract

This report summarises the properties of Standard Model processes at the 100 TeV *pp* collider. We document the production rates and typical distributions for a number of benchmark Standard Model processes, and discuss new dynamical phenomena arising at the highest energies available at this collider. We discuss the intrinsic physics interest in the measurement of these Standard Model processes, as well as their role as backgrounds for New Physics searches.



CERN-TH-2016-1

Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies

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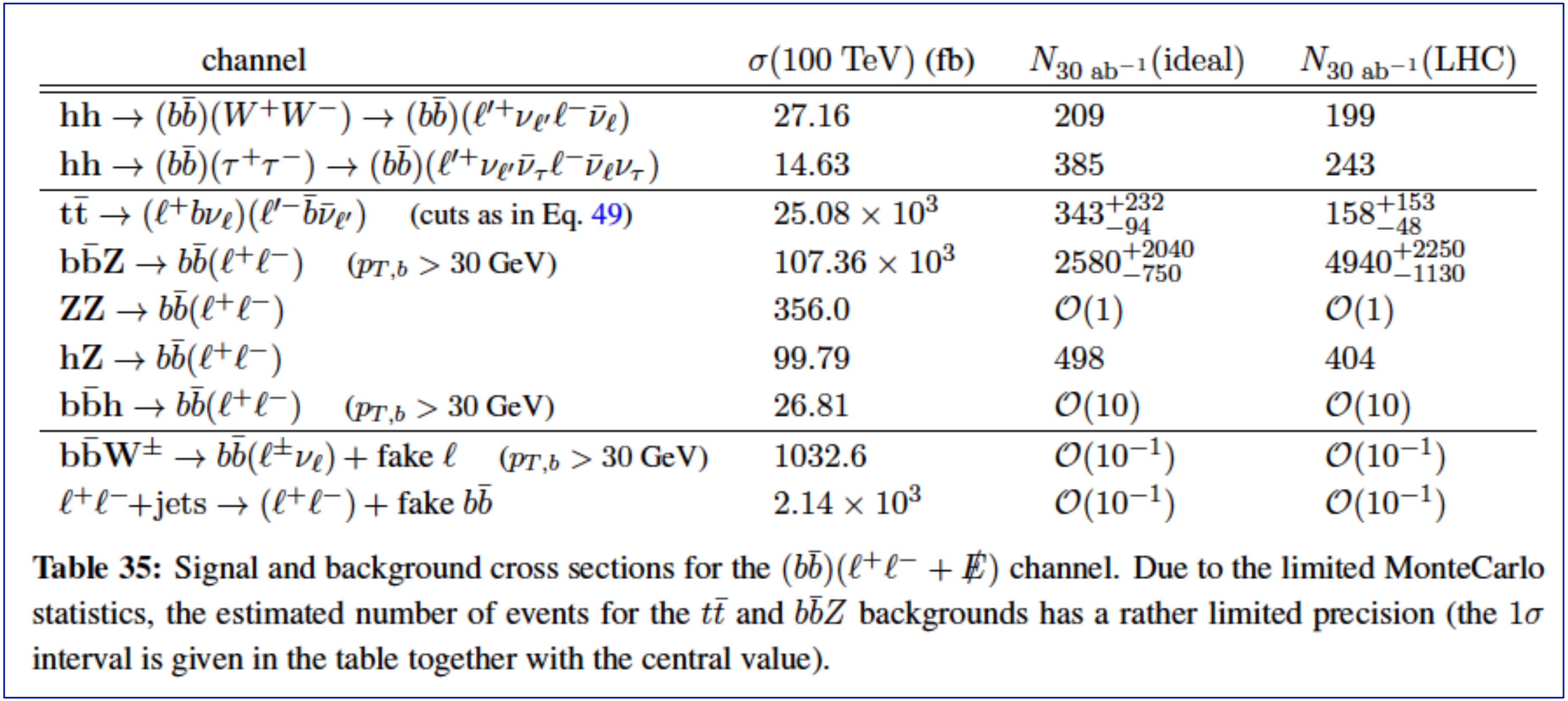
1606.09408, 190 pages

Abstract

This report summarises the physics opportunities for the study of Higgs bosons and the dynamics of electroweak symmetry breaking at the 100 TeV pp collider.

Double-Higgs Production at FCCpp



channel	σ(100 TeV) (fb)	$N_{30\ \mathrm{ab}^{-1}}$(ideal)	$N_{30\ \mathrm{ab}^{-1}}$(LHC)
$\mathbf{hh} \to (b\bar{b})(W^+W^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\ell^-\bar{\nu}_\ell)$	27.16	209	199
$\mathbf{hh} \to (b\bar{b})(\tau^+\tau^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\bar{\nu}_\tau\ell^-\bar{\nu}_\ell\nu_\tau)$	14.63	385	243
$\mathbf{t\bar{t}} \to (\ell^+ b\nu_\ell)(\ell'^- \bar{b}\bar{\nu}_{\ell'})$ (cuts as in Eq. 49)	25.08×10^3	343^{+232}_{-94}	158^{+153}_{-48}
$\mathbf{b\bar{b}Z} \to b\bar{b}(\ell^+\ell^-)$ ($p_{T,b} > 30$ GeV)	107.36×10^3	2580^{+2040}_{-750}	4940^{+2250}_{-1130}
$\mathbf{ZZ} \to b\bar{b}(\ell^+\ell^-)$	356.0	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\mathbf{hZ} \to b\bar{b}(\ell^+\ell^-)$	99.79	498	404
$\mathbf{b\bar{b}h} \to b\bar{b}(\ell^+\ell^-)$ ($p_{T,b} > 30$ GeV)	26.81	$\mathcal{O}(10)$	$\mathcal{O}(10)$
$\mathbf{b\bar{b}W^\pm} \to b\bar{b}(\ell^\pm\nu_\ell)$ + fake ℓ ($p_{T,b} > 30$ GeV)	1032.6	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10^{-1})$
$\ell^+\ell^-$+jets $\to (\ell^+\ell^-)$ + fake $b\bar{b}$	2.14×10^3	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10^{-1})$

Table 35: Signal and background cross sections for the $(b\bar{b})(\ell^+\ell^- + \not{E})$ channel. Due to the limited MonteCarlo statistics, the estimated number of events for the $t\bar{t}$ and $b\bar{b}Z$ backgrounds has a rather limited precision (the 1σ interval is given in the table together with the central value).

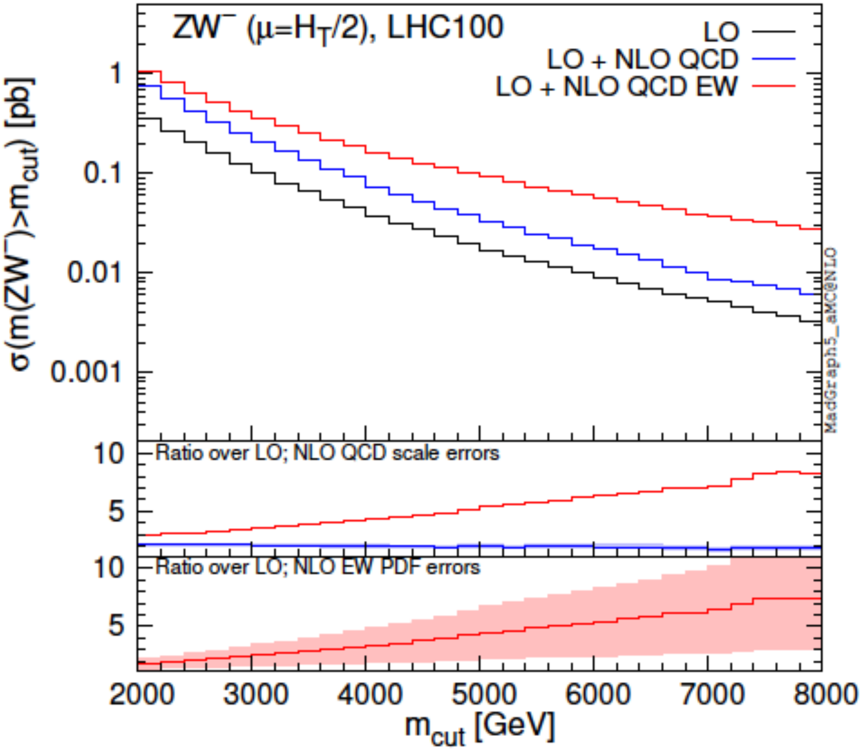
arXiv:1606.09408, p76

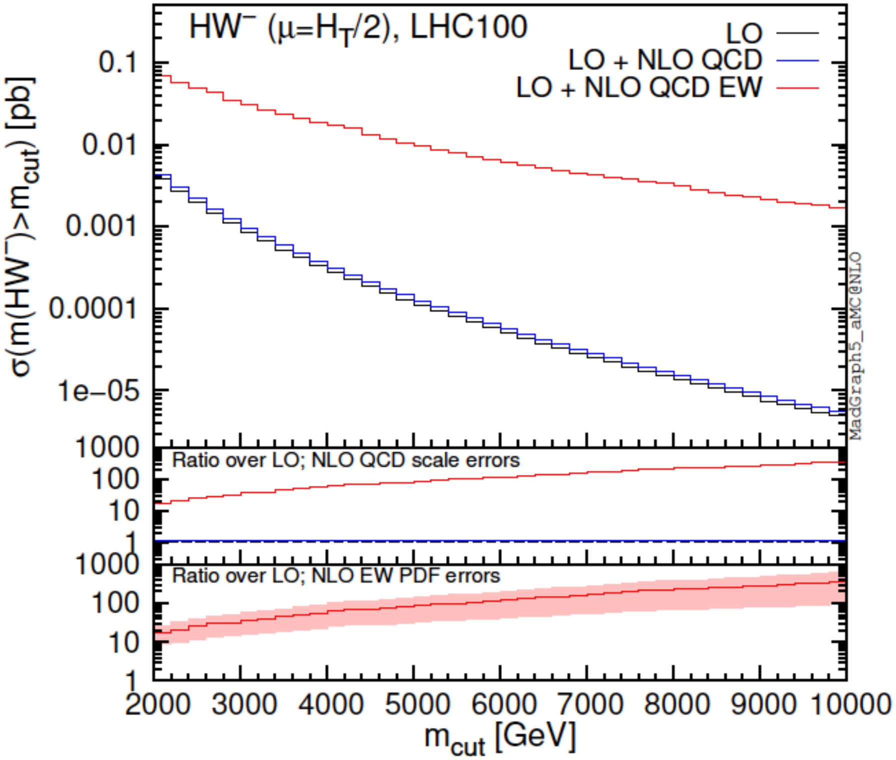
Foregrounds: tt, bbZ and HZ: QCD and electroweak theory in new range crucial to control.
Note: central rapidity for inclusive H production is at x=M/2Ep … low x Bj.

SM and Higgs at FCCpp

pp → Z/H W + X, an example

F. Piccinini in arXiv:1607.01831, FCC-pp





Large higher order corrections, sensitive to photon induced processes, large y,p PDF errors

At FCC (LHC), the QCD of the Higgs boson will become an important area of SM research.

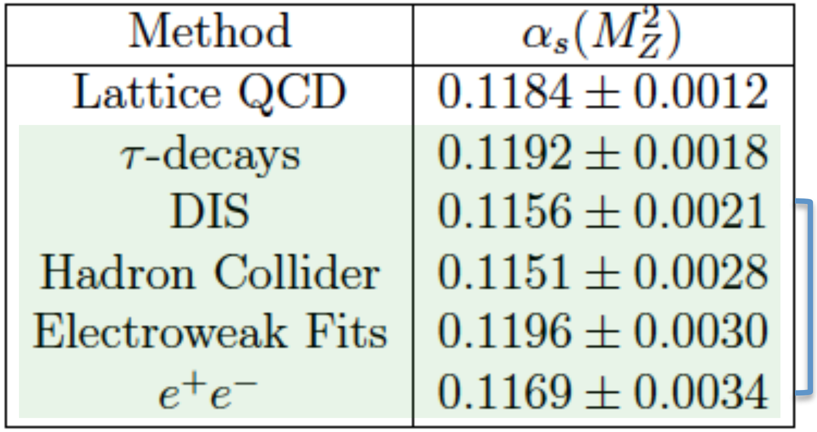
High precision requires precise calculations of combined strong+eweak corrections + PDFs

Strong Coupling Constant

$\beta(\alpha_s) = -(11 - n_s/3 - 2N_f/3)\,\alpha_s^2/2\pi$

$\alpha_s(\mu)$

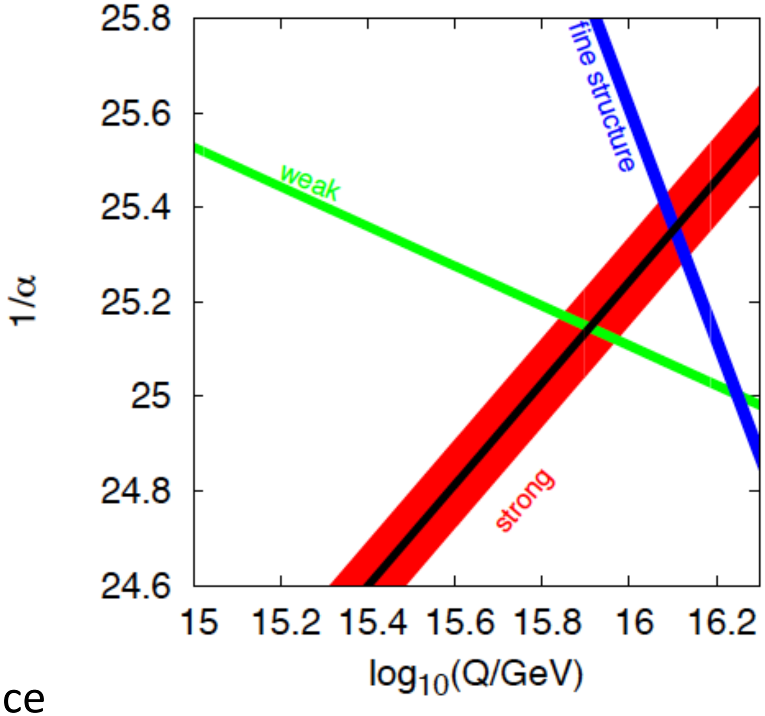
PDG 2016



Method	$\alpha_s(M_Z^2)$
Lattice QCD	0.1184 ± 0.0012
τ-decays	0.1192 ± 0.0018
DIS	0.1156 ± 0.0021
Hadron Collider	0.1151 ± 0.0028
Electroweak Fits	0.1196 ± 0.0030
e^+e^-	0.1169 ± 0.0034

Recent Articles see: G Dissertori 1506.05407
A Deur, S Brodsky, G de Teramond 1604.08082

Grand unification??

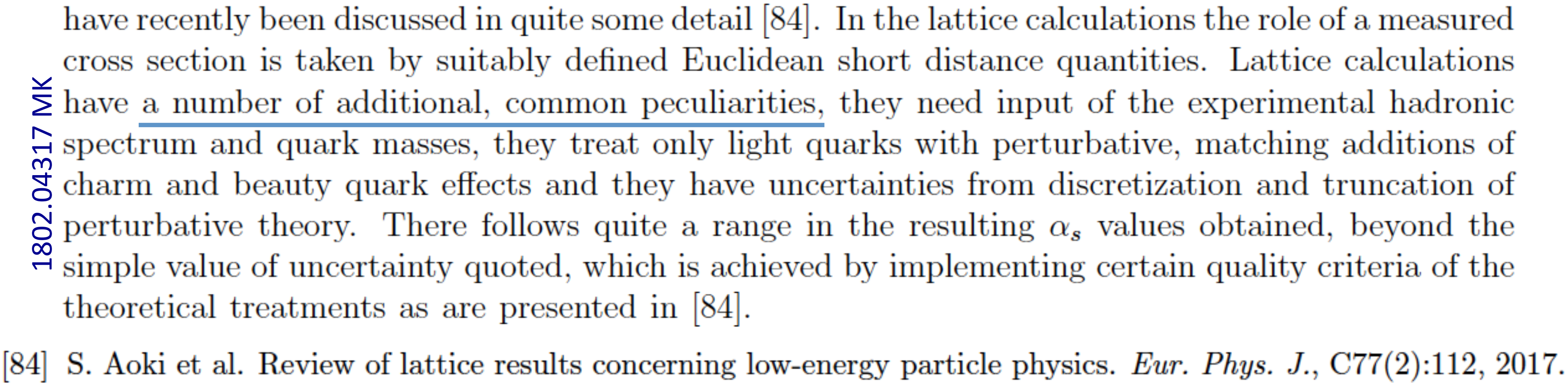


1211.5102 – on the relation of ep+pp

$$\alpha_s(M_Z^2) = 0.1174 \pm 0.0016$$

w/o lattice
1.5% error

1802.04317 MK



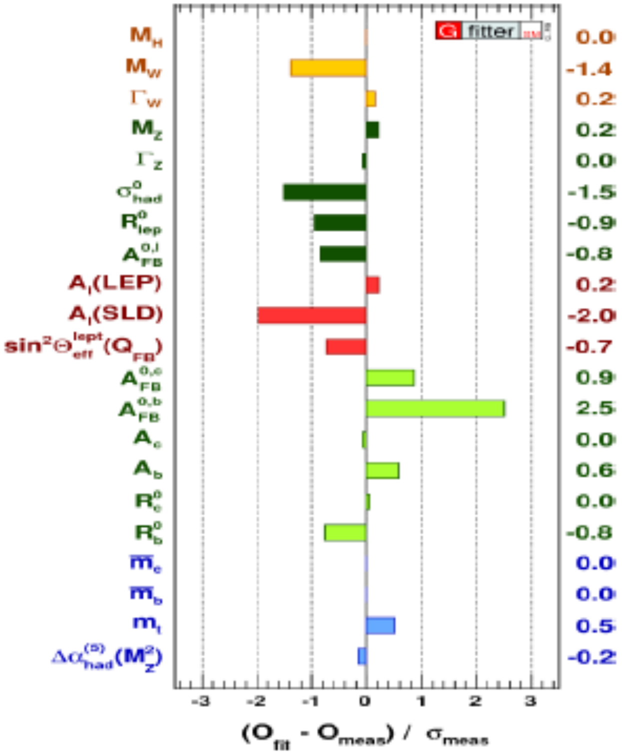
have recently been discussed in quite some detail [84]. In the lattice calculations the role of a measured cross section is taken by suitably defined Euclidean short distance quantities. Lattice calculations have a number of additional, common peculiarities, they need input of the experimental hadronic spectrum and quark masses, they treat only light quarks with perturbative, matching additions of charm and beauty quark effects and they have uncertainties from discretization and truncation of perturbative theory. There follows quite a range in the resulting α_s values obtained, beyond the simple value of uncertainty quoted, which is achieved by implementing certain quality criteria of the theoretical treatments as are presented in [84].

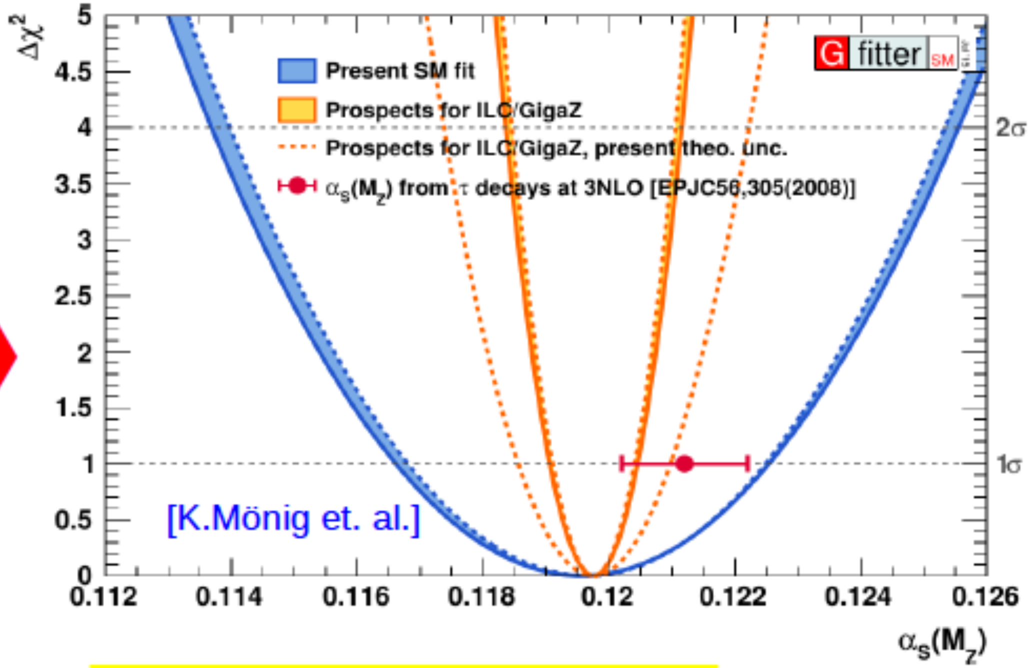
[84] S. Aoki et al. Review of lattice results concerning low-energy particle physics. *Eur. Phys. J.*, C77(2):112, 2017.

α_s via hadronic Z decays

- Computed at N³LO: $R_Z \equiv \frac{\Gamma(Z \to h)}{\Gamma(Z \to l)} = R_Z^{\rm EW} N_C \left(1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5)\right) + \delta_{\rm m} + \delta_{\rm np})$
- LEP: Γ_Z = 2.4952±0.0023 GeV (±0.1%), $R_\ell^0 = \frac{\Gamma_{\rm had}}{\Gamma_\ell}$, $\sigma_{\rm had}^0 = \frac{12\pi}{m_Z} \frac{\Gamma_e \Gamma_{\rm had}}{\Gamma_Z^2}$, $\sigma_\ell^0 = \frac{12\pi}{m_Z} \frac{\Gamma_\ell^2}{\Gamma_Z^2}$

After Higgs discovery, α_s can be directly determined from full fit of SM:



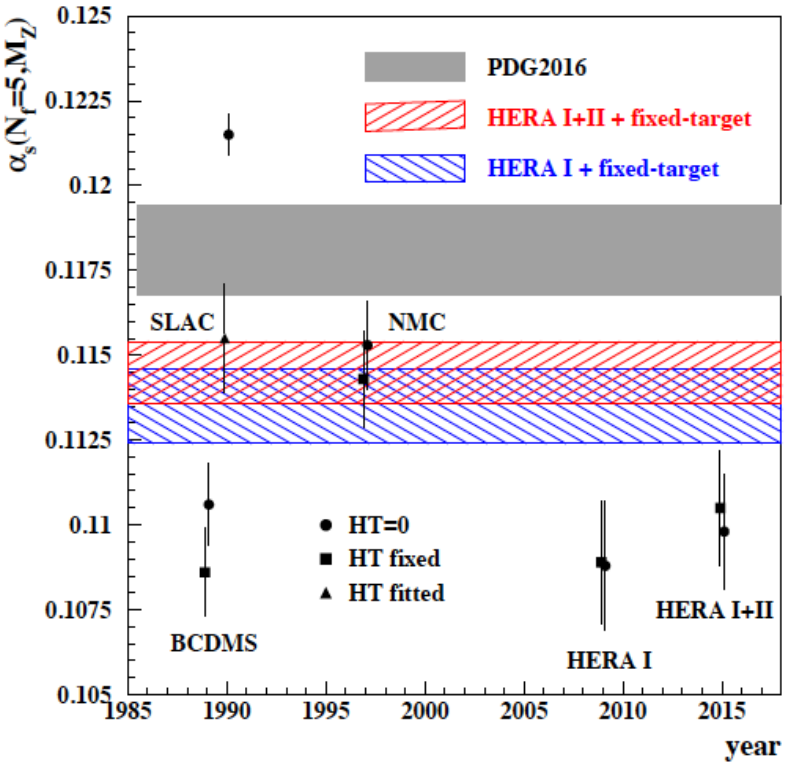


[K.Mönig et. al.]

$\alpha_s(M_Z)$ = 0.1196 ± 0.0030 (±2.5%)

- FCC-ee: – Z stats (×10⁵ LEP) will lead to: **$\delta\alpha_s/\alpha_s < 0.2\%$**
  – TH (parametric) uncertainties: $\sin^2\theta_{\rm eff}$, m_W, $m_{\rm top}$

$\alpha_s(\mu)$ 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?

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

H1 inclusive (1998) NLO

hep-ph/0012053 – highest cited H1 only

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

H1 only jets (2017) NNLO jets!

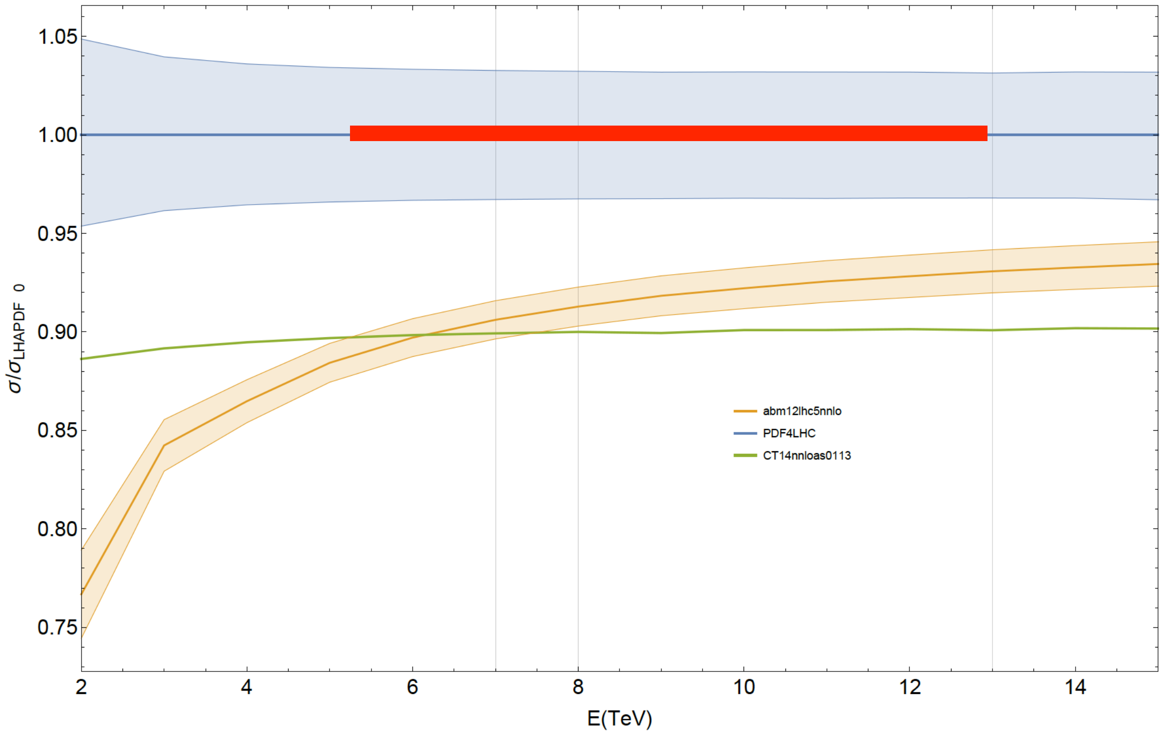
$$\alpha_s = 0.1142 \pm 0.0028\ \ (\mathrm{tot})$$

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

Higgs Cross Section (LHC)



← LHeC
1305.2090

Figure 18: Higgs production cross-section and 68% C.L. PDF+α_s uncertainty from the ABM12 fit and from the CT14 set computed at $\alpha_s = \alpha_s^{ABM}$, normalized by the central value obtained with the PDF4LHC combination.

$$\boxed{\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)}$$

C Anastasiou et al, arXiv:1602.00695

True PDF errors?

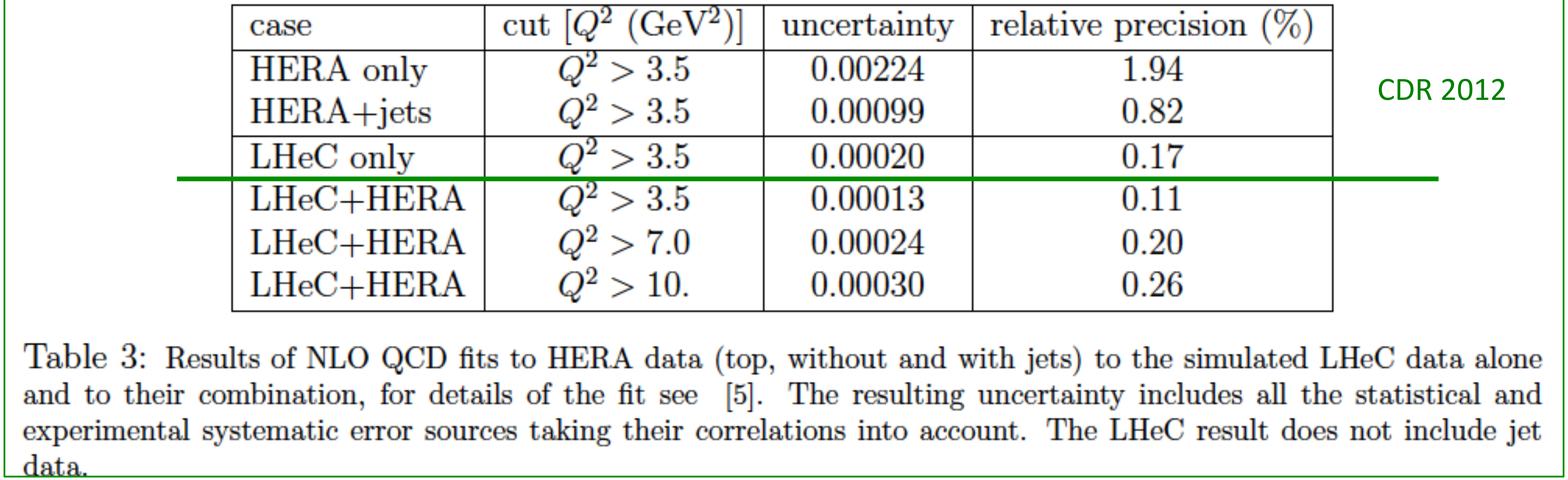
[LHeC/FCCeh at
per-mille level,
mass and xsection]

PDFs to N^{3}LO →
DIS to N^{3}LO
[10 years program]

σ ~ $(\alpha_s\, xg)^2$

High precision pp
Higgs physics requires
high precision
for PDFs and α_s

$\alpha_s(\mu)$ 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.

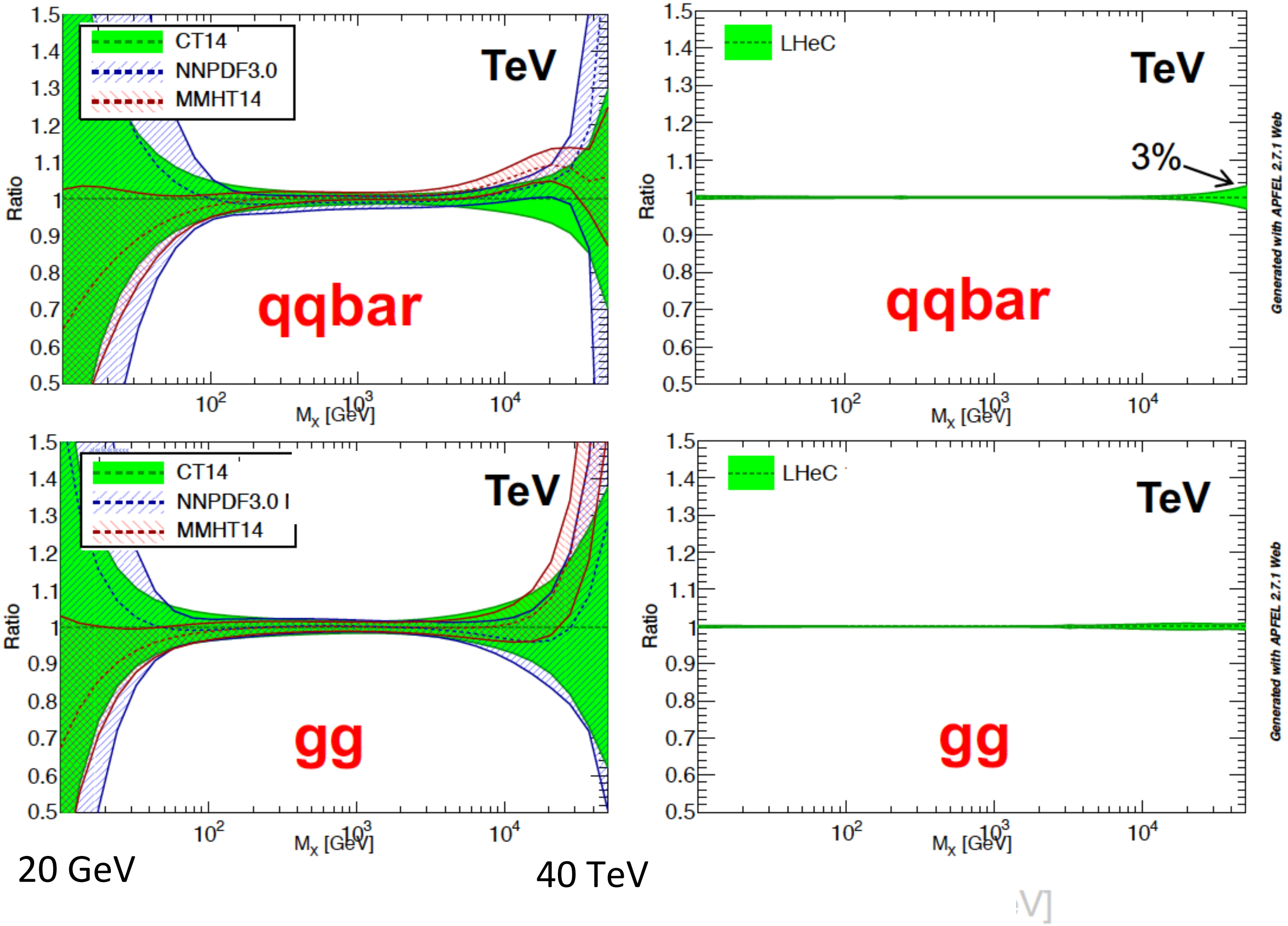
CDR 2012

- 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

Parton Distribution Functions

The LHeC 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^{3}LO…



20 GeV

40 TeV

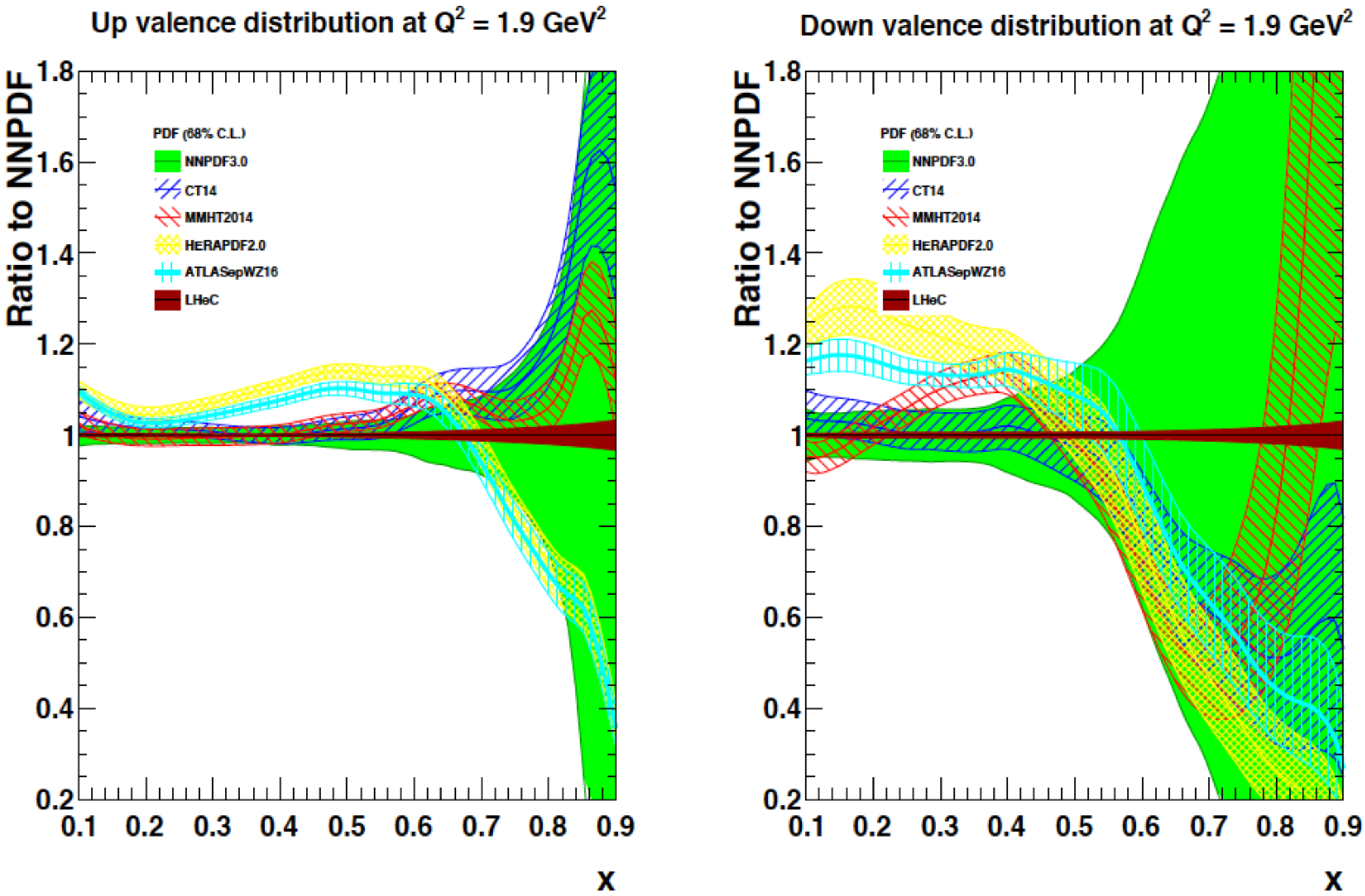


Figure 2: Determination of the valence quark distributions as functions of Bjorken x. Plotted are the ratios to the NNPDF result with uncertainties displayed as are provided by the individual sets, left for the up-valence quark and right the down-valence quark distribution. For the LHeC the total uncertainty is plotted and the central value assumed to agree with NNPDF. As non-singlet quantities, the valence quark distributions are approximately the same with varying Q^2.

C Gwenlan, MK

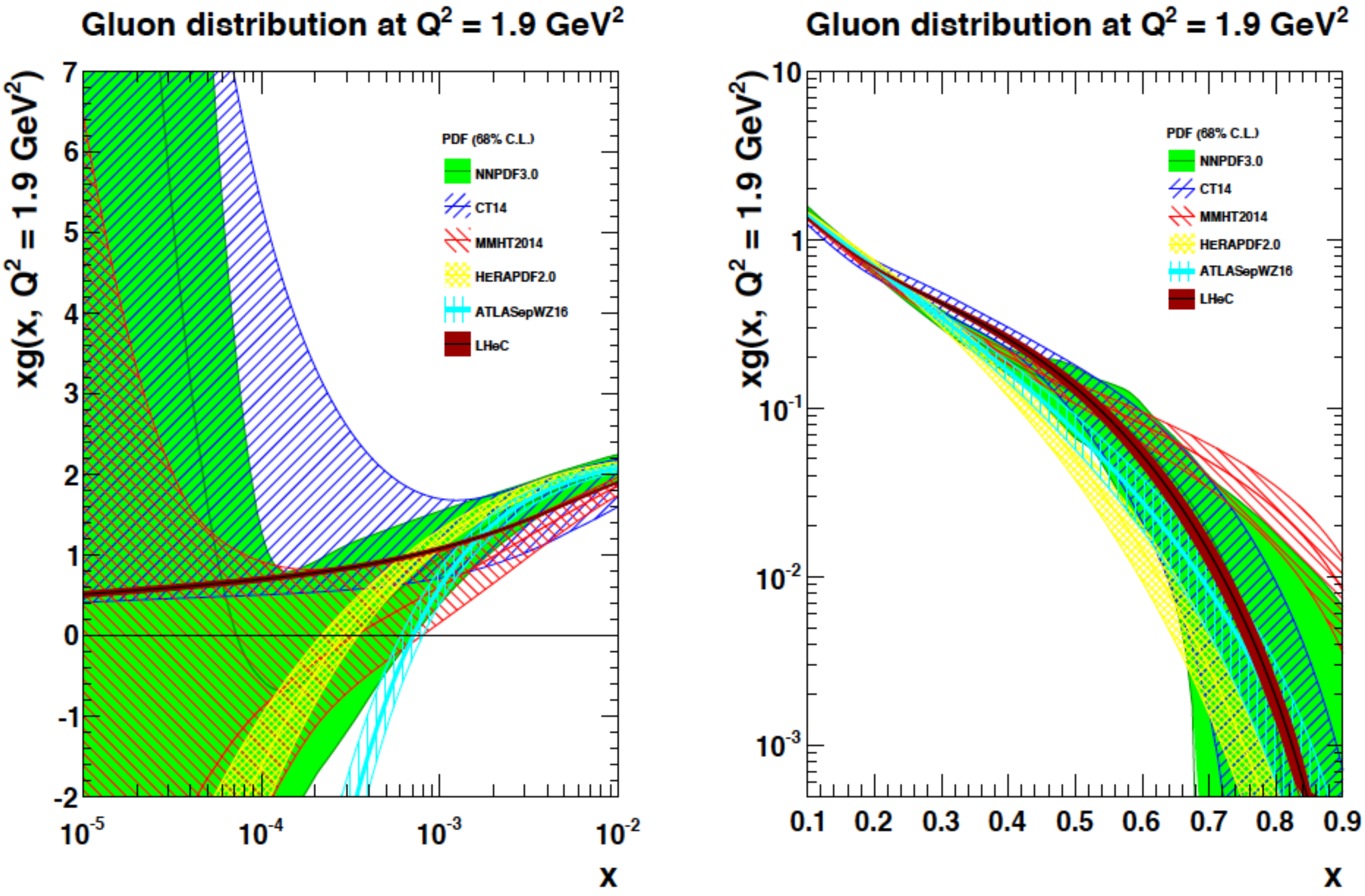
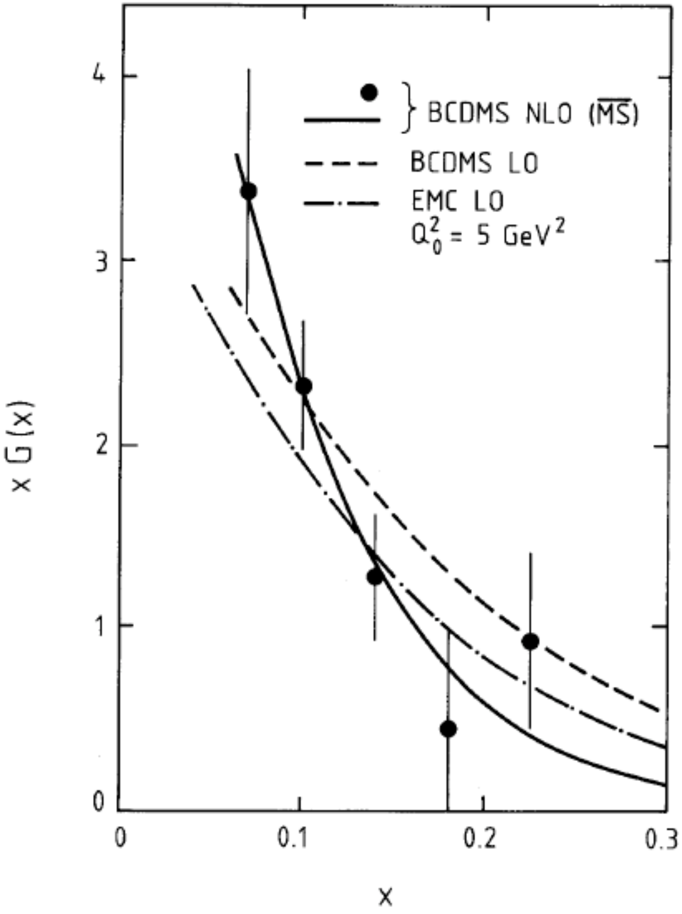


Figure 3: Determination of the gluon momentum distribution in the proton. The expected total experimental uncertainty on xg from the LHeC (dark purple bands) is compared with the most recent global PDF determinations which include the final HERA data, covering for xg a range from $x \simeq 5\ 10^{-4}$ to $x \simeq 0.6$, and much of the LHC data from Run I. Left: xg at small x; Right at large x.

C Gwenlan, MK

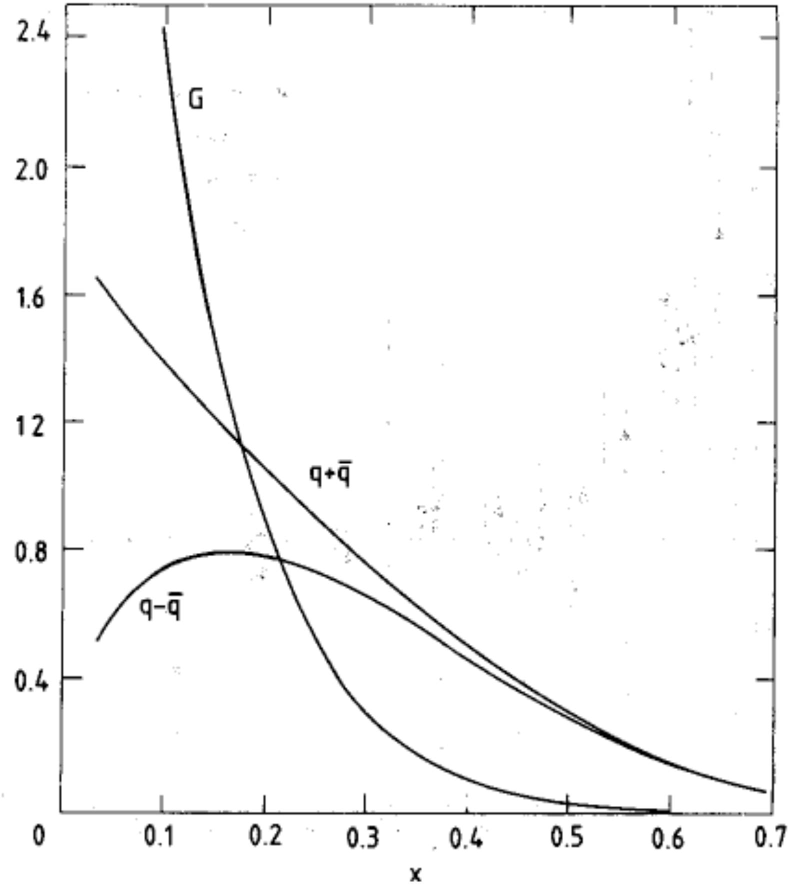
PDFs before HERA - Gluon - $xg(x,Q^2)$

BCDMS



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

CDHS



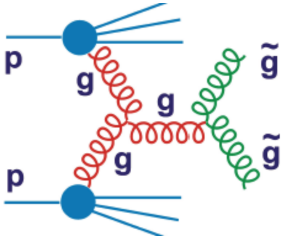
CERN-EP/89-103
15 August 1989

Empowering pp Discoveries

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

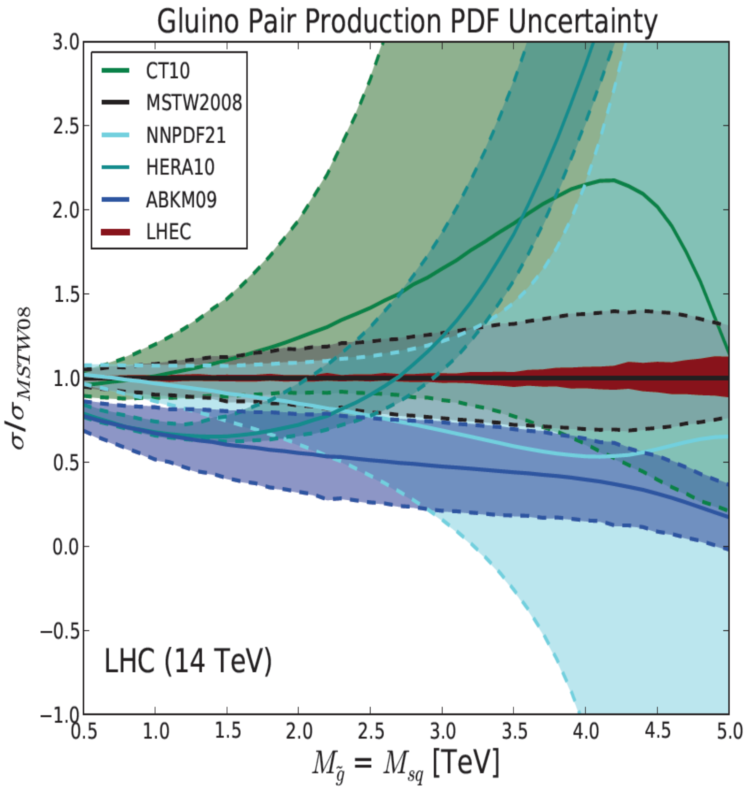
GLUON

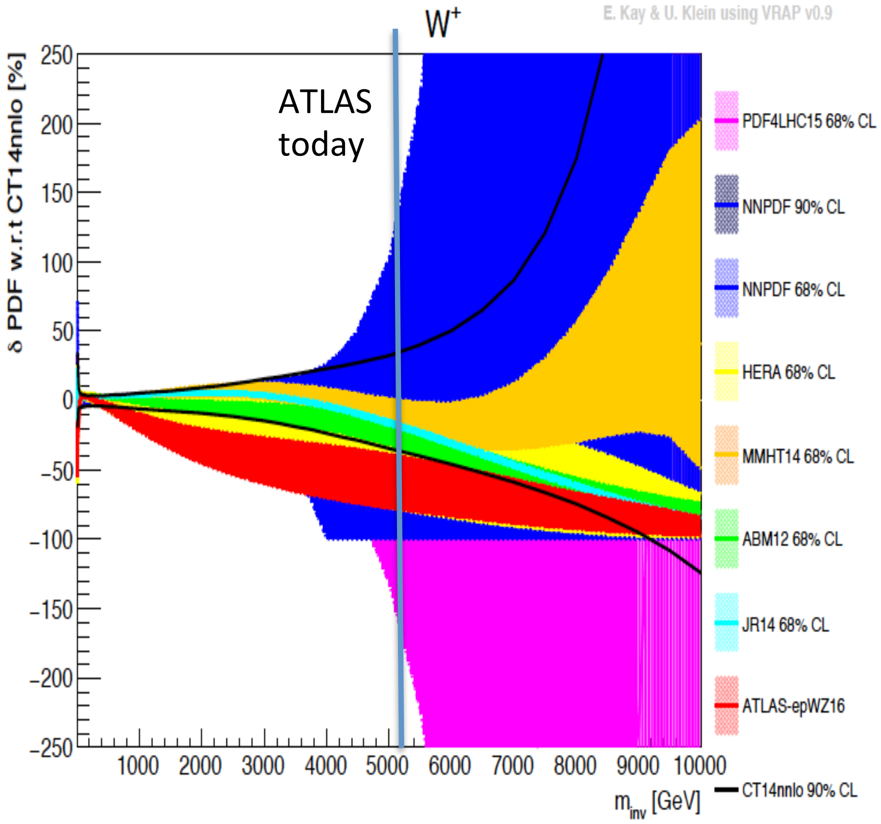
SUSY, RPC, RPV, LQS..



QUARKS

Exotic+ Extra boson searches at high mass





ATLAS
today

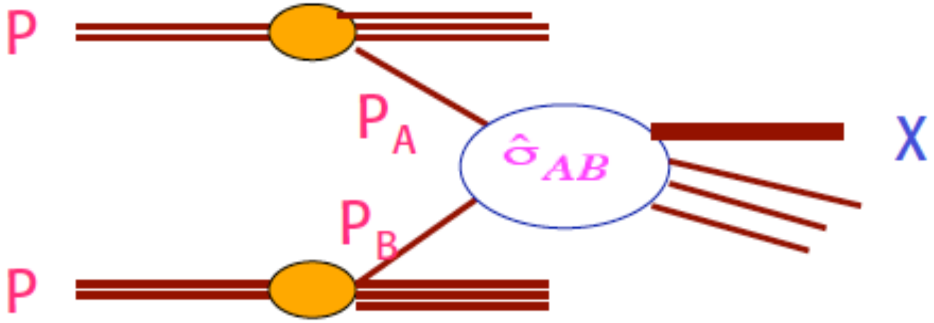
Parton densities extracted from DIS are used to compute hard processes, via the Factorisation Theorem:

x times density of parton A

$$\sigma(s) = \sum_{A,B} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} p_A(x_1, Q^2) p_B(x_2, Q^2) \hat{\sigma}_{AB}(x_1 x_2 s, Q^2)$$

reduced X-section

For example, at hadron colliders



V=γ*,W,Z

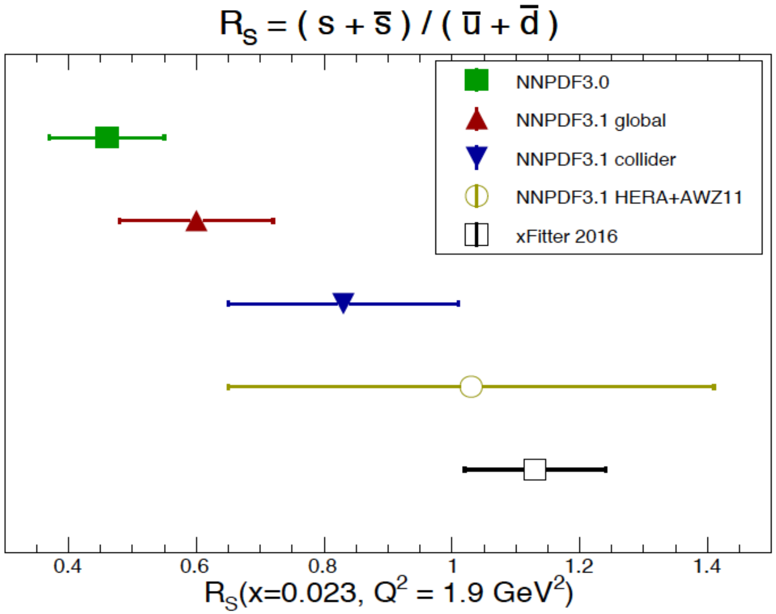
X=V, jets, QQ, H.....

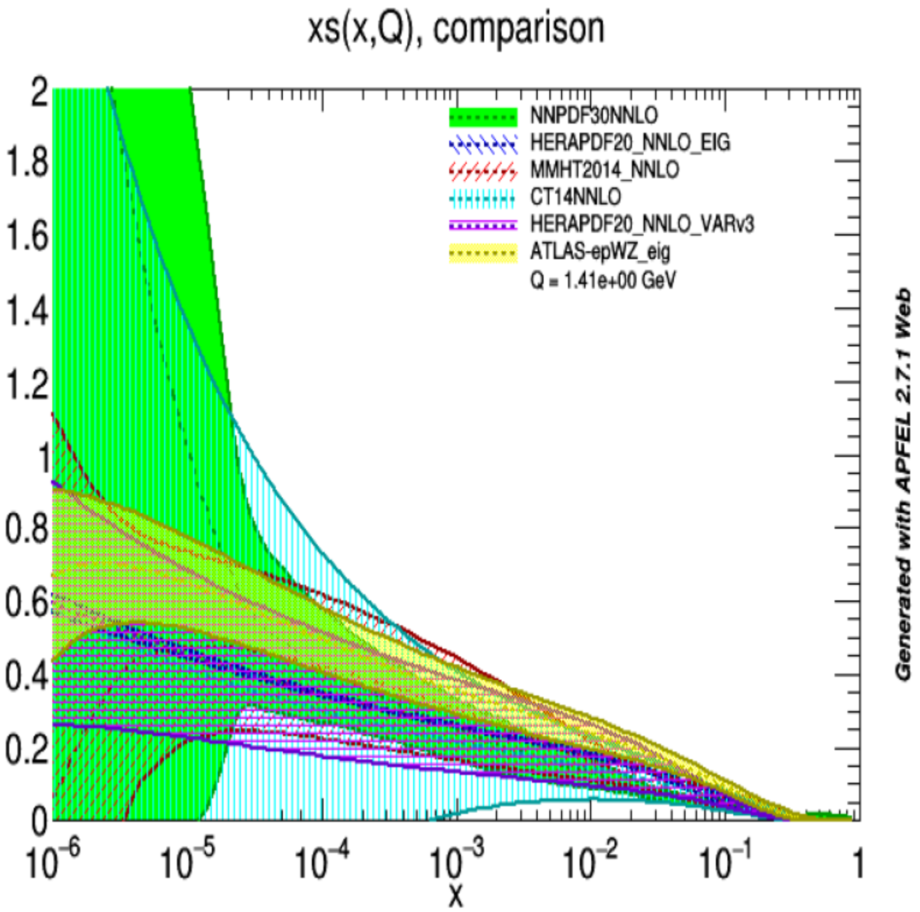
Q=b,c,t

- Very stringent tests of QCD
- Feedback on constraining parton densities

Strange Strange

Strange quark suppression [dimuons in neutrino data] vs light flavour democracy [W,Z LHC]



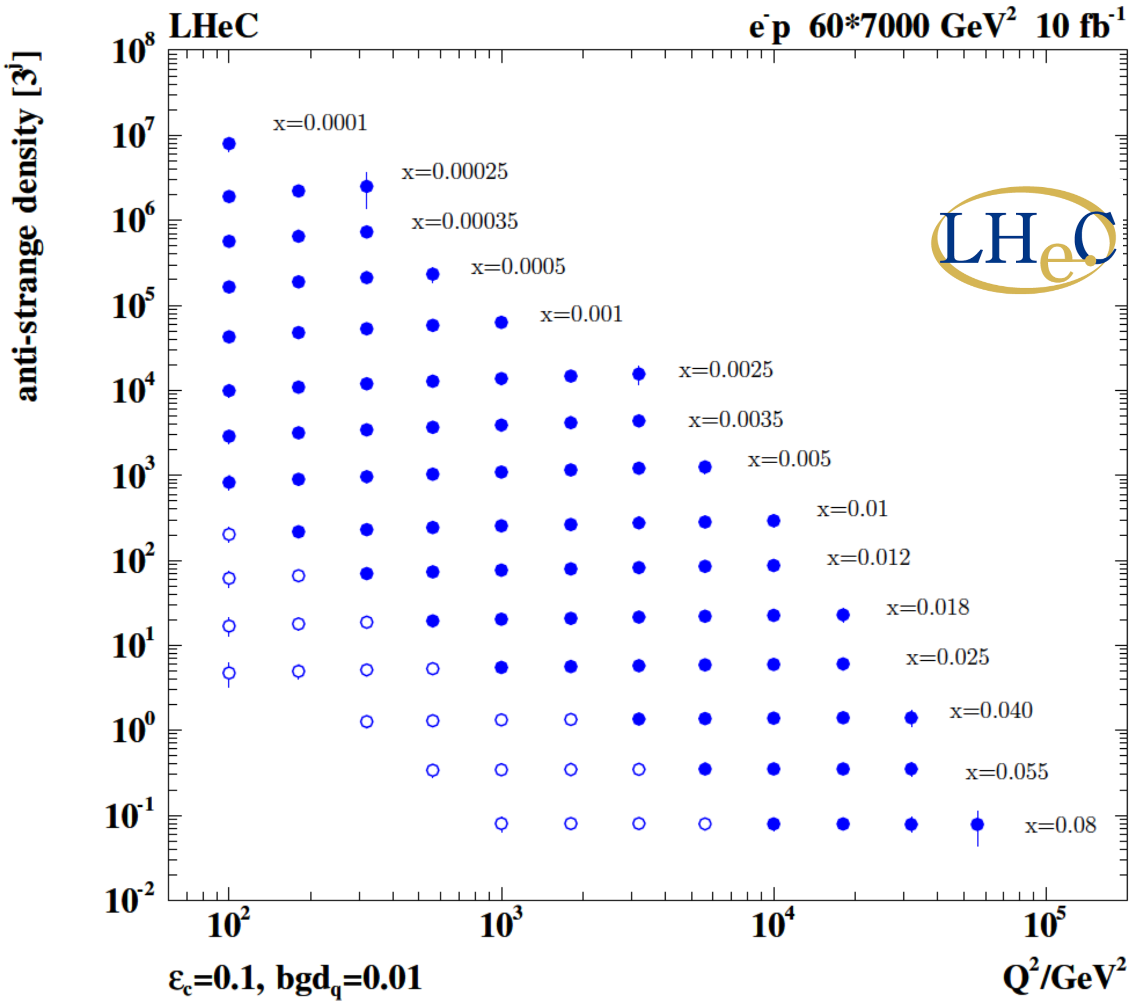


A Cooper-Sarkar, DIS17

NNPDF3.1 arXiv:1706.00428, note:
“xFITTER16” = ATLAS: 1612.0301
Also look at MMHT and other results

The strange quark density, after 50 years of DIS, has remained unknown. Is there a valence s?

Strange Quark Distribution from LHeC



High luminosity

High Q^2

Small beam spot

Modern Silicon

NO pile-up..

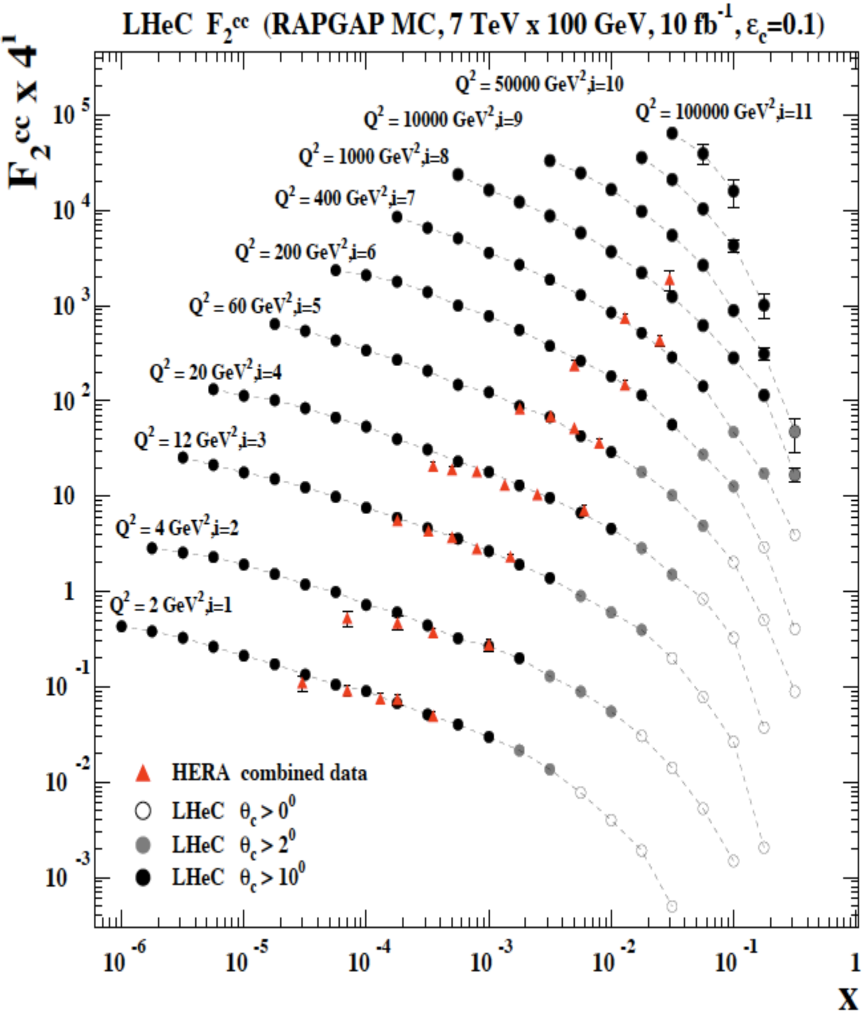
→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

$x = 10^{-4}$ .. 0.1
$Q^2 = 100 – 10^5$ GeV^2

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

Charm: F_2^{cc} and Mass

LHeC CDR arXiv:1206.2913



HERA 0.0005/2.5 .. 0.05/2000 GeV^2
LHeC 0.00001/1 .. 0.2/200000 GeV^2

ε(c) assumed 10%, 1% light background, ~3% δ(syst)

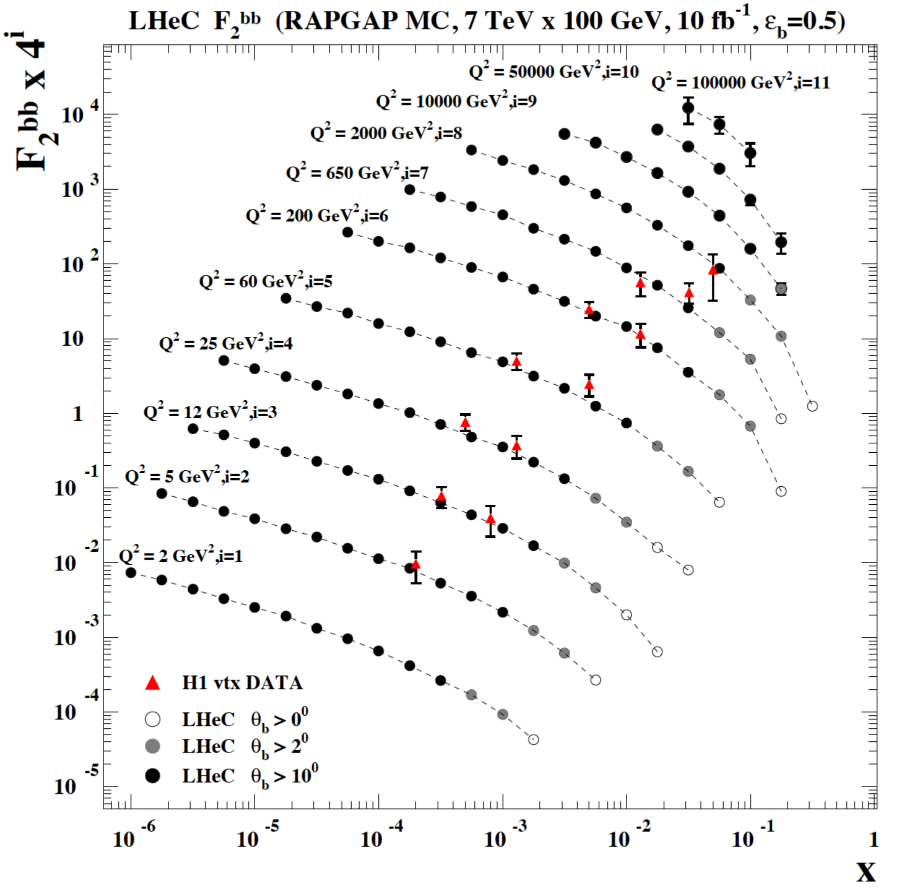
Heavy Flavour with LHeC
Beam spot (in xy): 7µm
Impact parameter: better than 10µm
Modern Silicon detectors, no pile-up
Higher E, L, Acceptance, ε, than at HERA
→ Huge improvements predicted

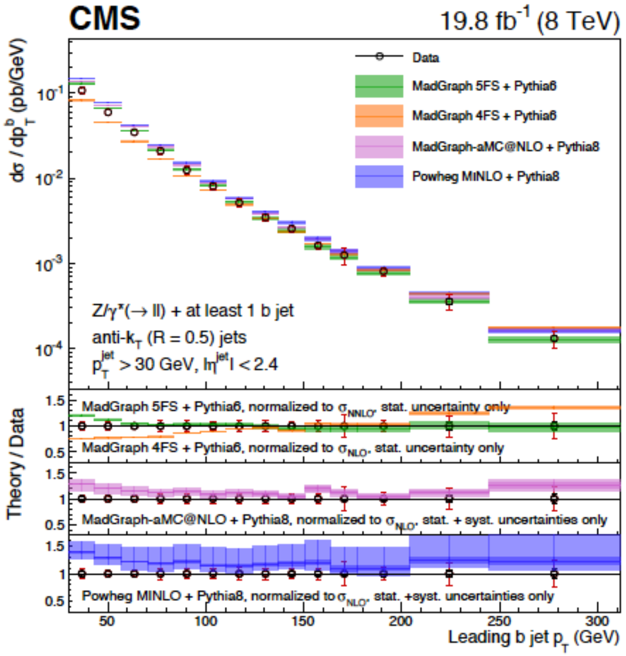
	HERA	LHeC
$m_c(m_c)$/GeV	1.26	?
δ(exp)	0.05	0.003
δ(mod)	0.03	~0.002
δ(par)	0.02	~0.002
$\delta(\alpha_s)$	0.02	0.001

Determination of charm mass to 3 MeV:
crucial for M_W in pp or H→ cc in ep
cf also NNPDF3.1 (arXiv:1706.00428) and refs

Bottom: F_2^{bb} and Mass

LHeC CDR arXiv:1206.2913





Huge improvement vs HERA for the same reasons as for charm
New data H1+ZEUS

Bottom density not well known

Scheme dependence affects LHC interpretations

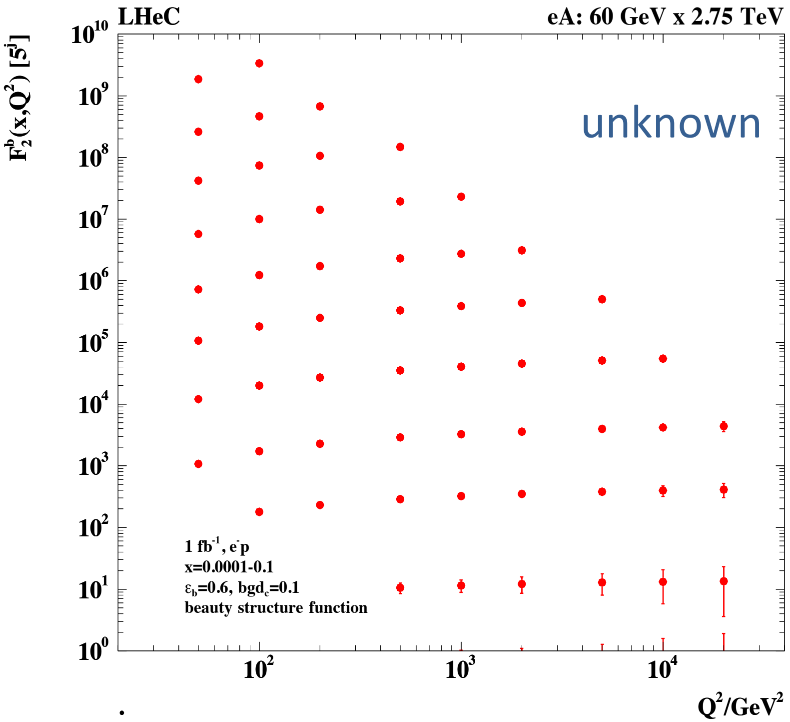
In MSSM: Higgs from bb→ H not gg
(we only miss the MSSM..)

$m_b(m_b)$ with LHeC to 10 MeV

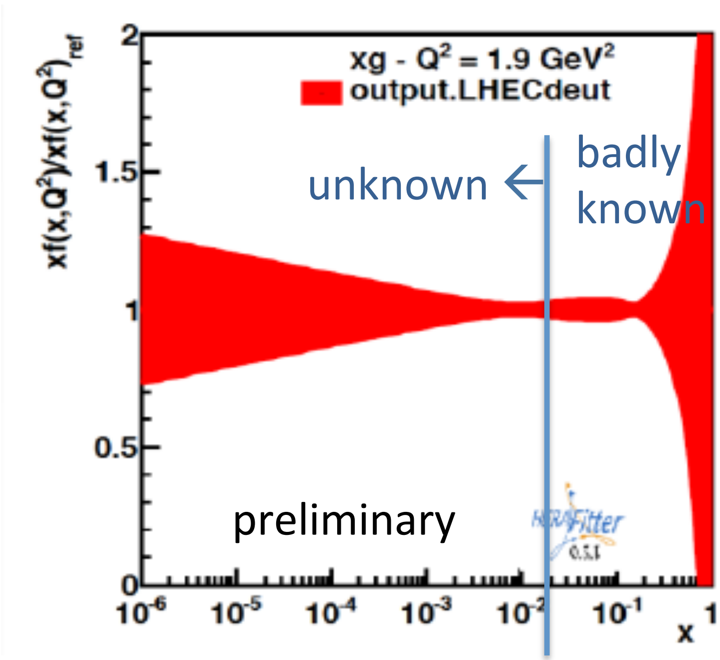
Early theory of HQ: J Collins, R.K Ellis: Nucl Phys B360(91)3
E Laenen, S Riemersma, J Smith, W van Neerven NP B392(93)162

Nuclear QCD through eA at FCCeh/LHeC

Beauty in Lead



δGluon in Lead

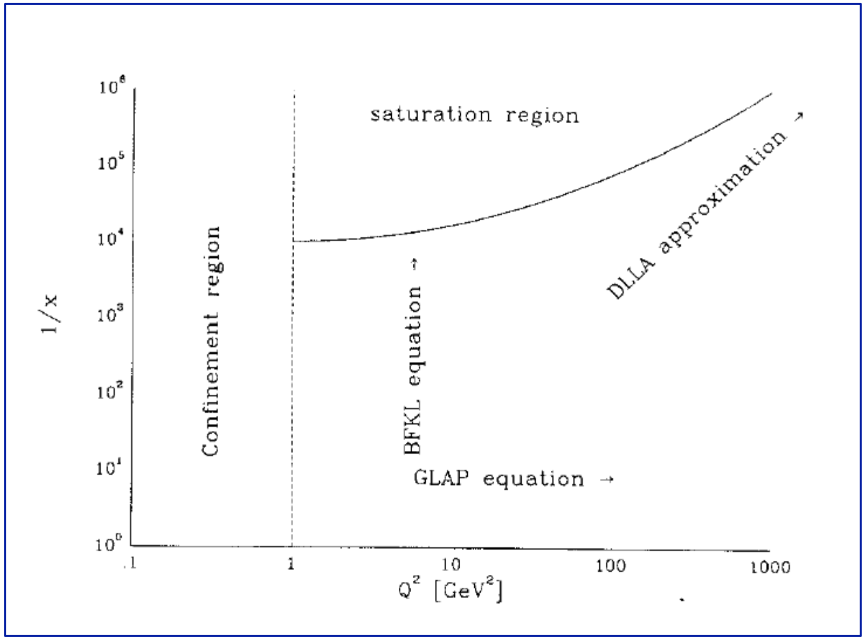


eA: extends kinematic range in Q^2, 1/x by 3-4 orders of magnitude. Lumi 6 10^{32} (J.Jowett)
Measure nPDFs as in ep scattering and determine then the ratio R(x,Q^2)=nPDF/PDF
Shadowing? A1/3 amplification? Saturation? Colour Flow? QGP initial state, collective effects
LHeC has been co-initiated and supported by NuPECC

see: Nestor Armesto FCC week 1/2018, CDR (LHeC) M.K. DOI: 10.1051/epjconf/201611203002

Low x Physics

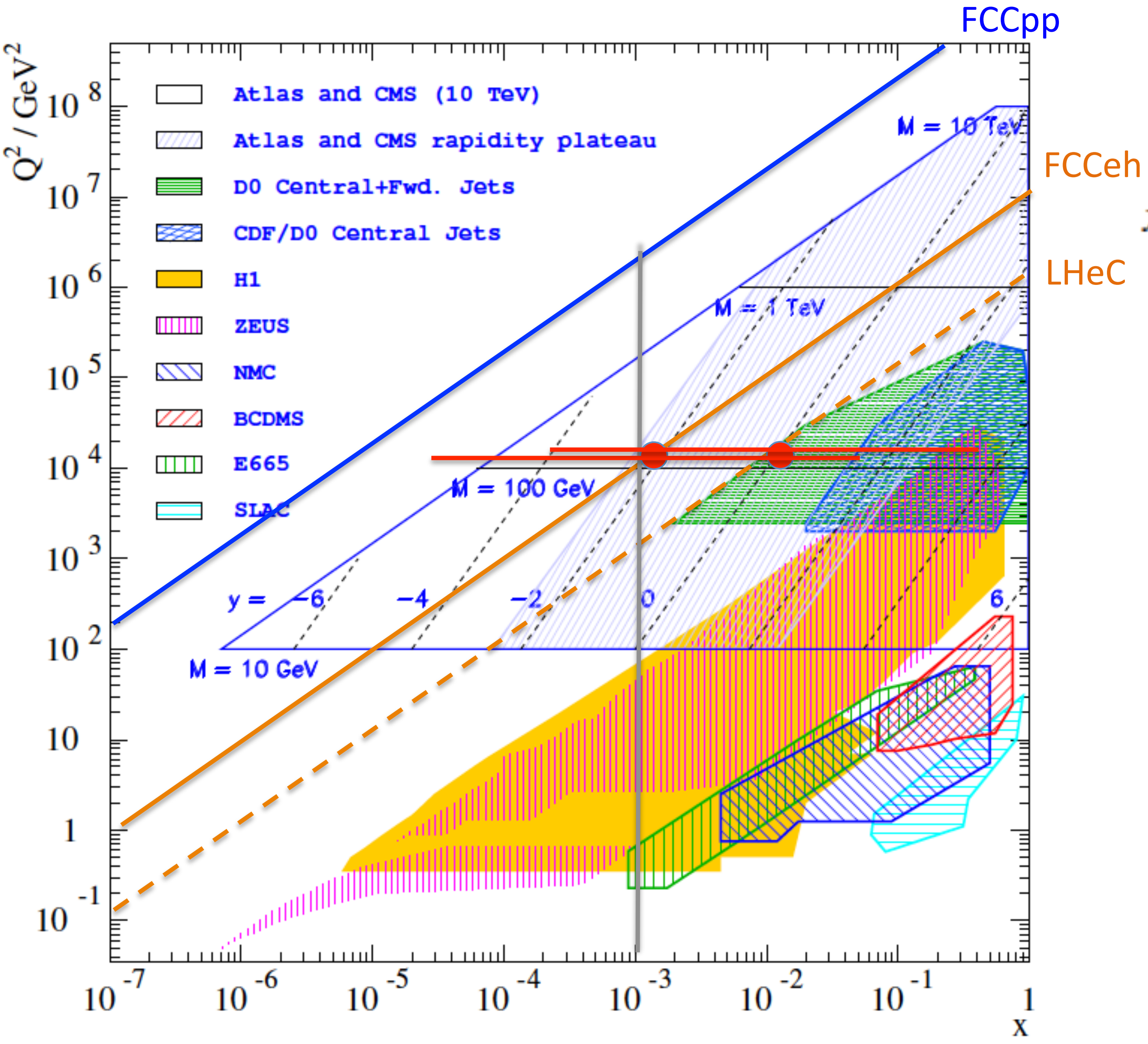
BFKL and Saturation



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



$$x = Me^{\pm y}/\sqrt{s}$$

y=0: $x_0 = M/2E_p$

Higgs at LHC:

$x_0 = 0.0089$

$x_0 = 0.0013$

Higgs physics is and becomes low x physics

Low x Partons

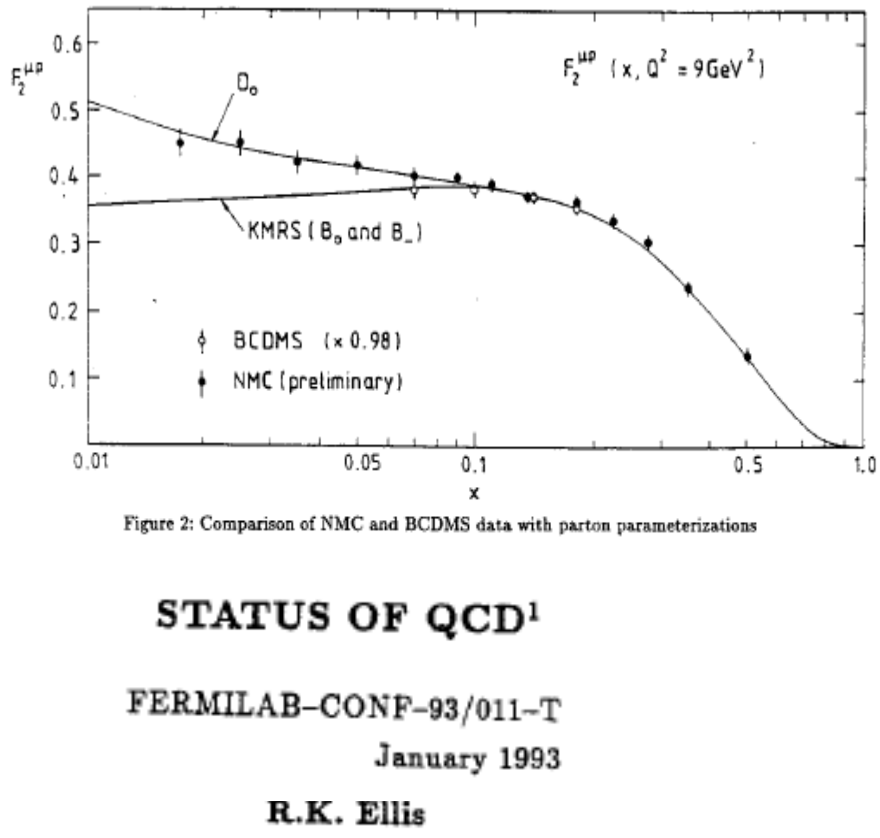


Figure 2: Comparison of NMC and BCDMS data with parton parameterizations

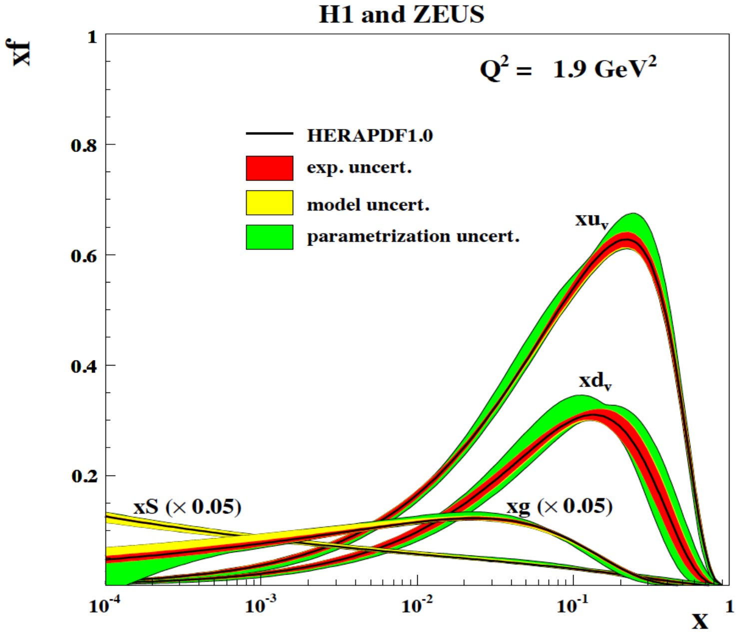
STATUS OF QCD[1]

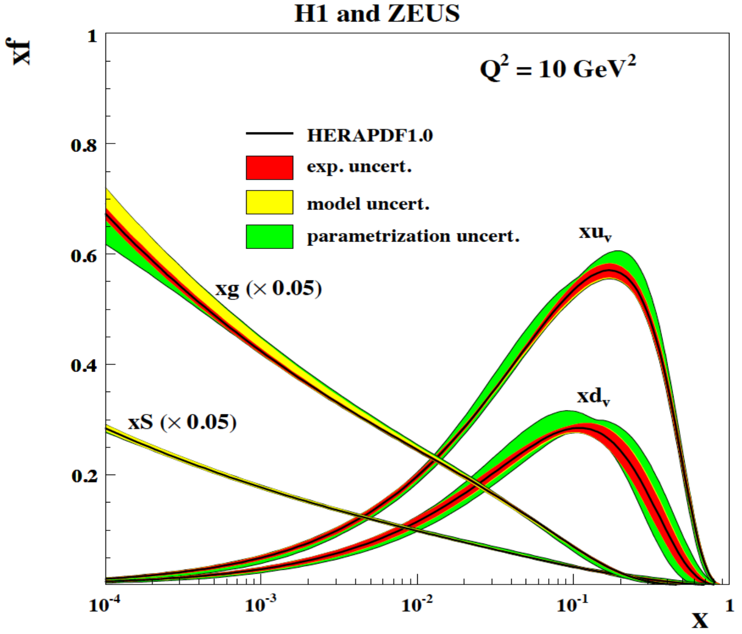
FERMILAB-CONF-93/011-T

January 1993

R.K. Ellis

Low x > 0.01 before HERA





0911.0884

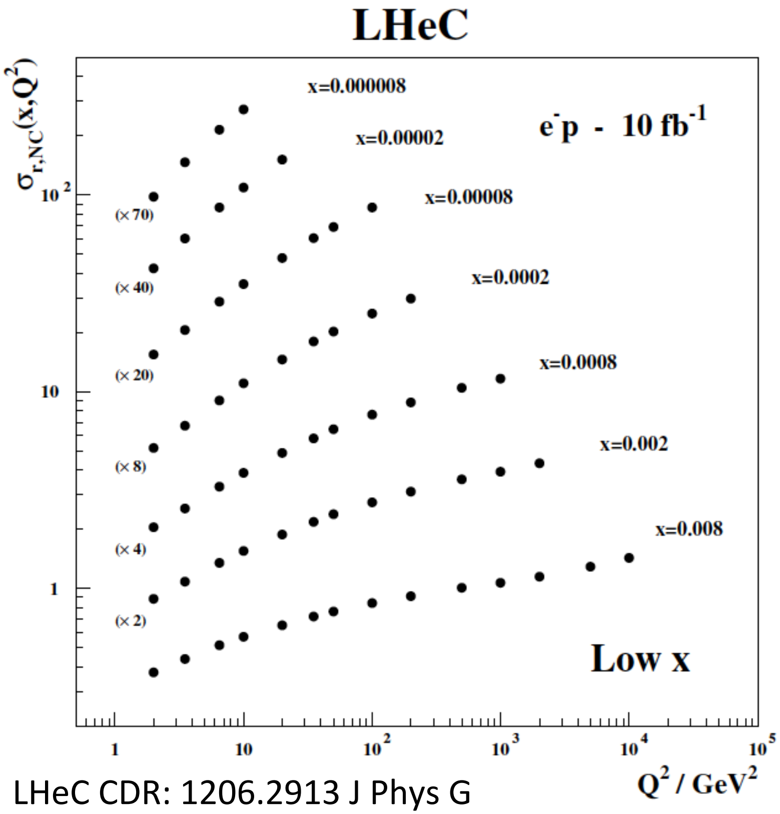
Note: HERA: QCD vacuum dominates p structure at small x. xg vanishes/rises at low/hi Q^2

How to determine low x evolution + discover saturation ?

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

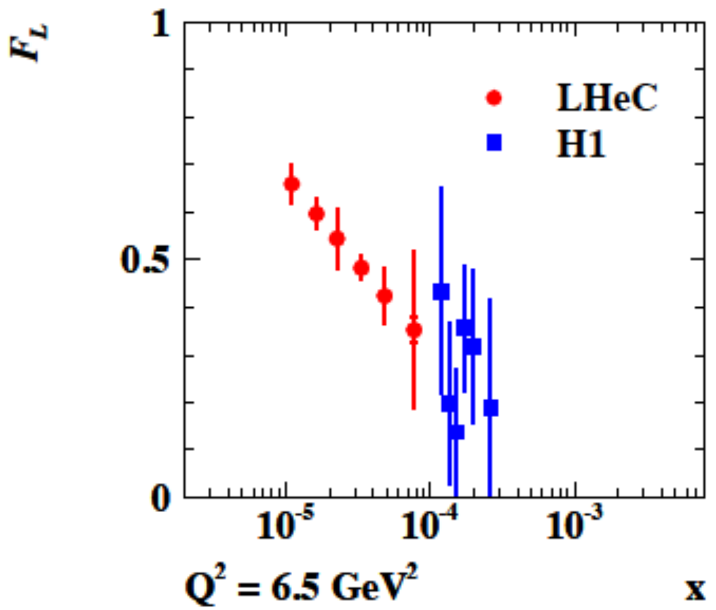
Needs cleanest DIS constraints, proton, not ion, high E: F_2+F_L

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



LHeC CDR: 1206.2913 J Phys G

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



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

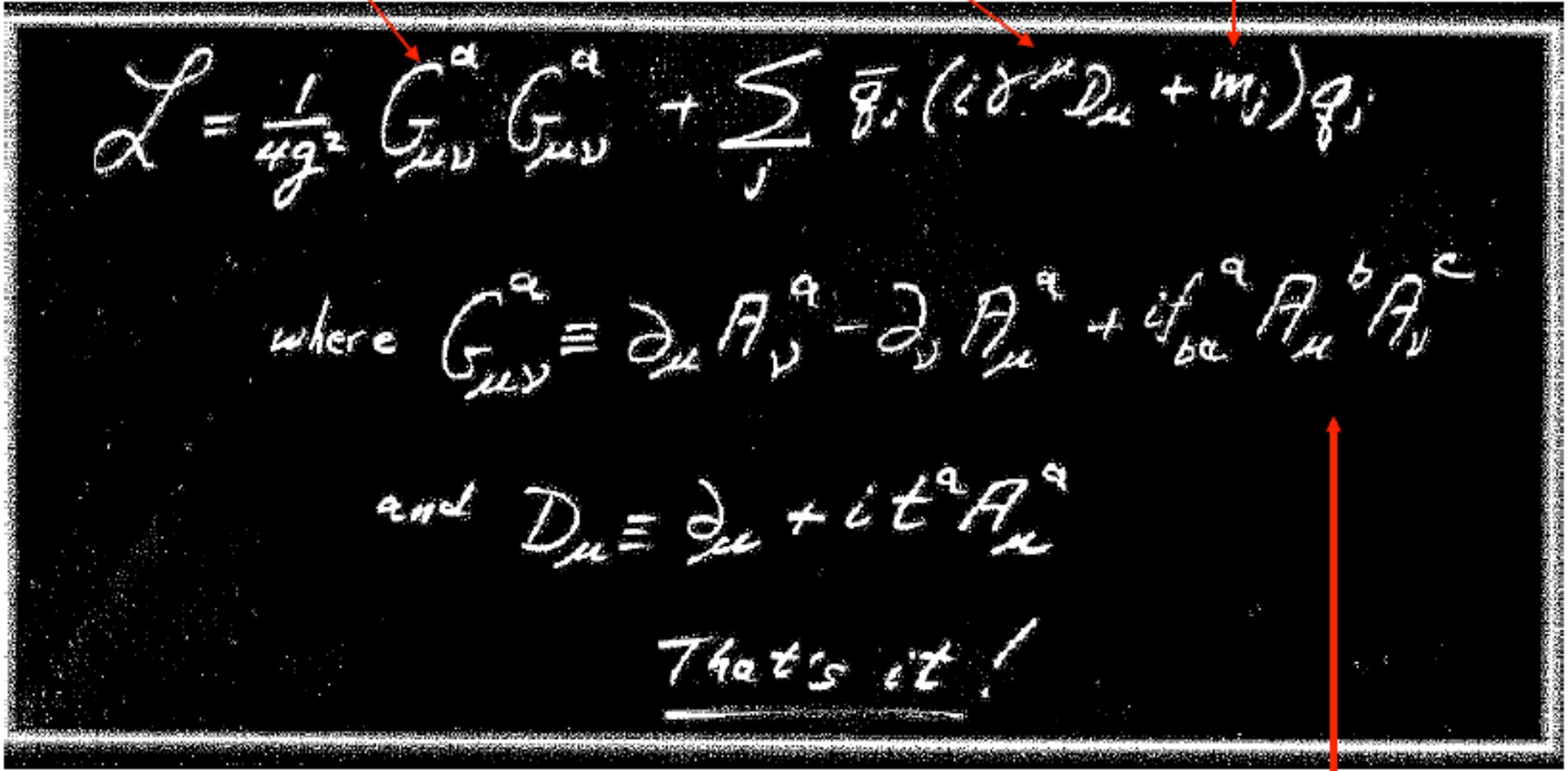
This constrains DGLAP and rules it out (or not..). cf CDR (LHeC)

QCD

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.

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^{k}LO, 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

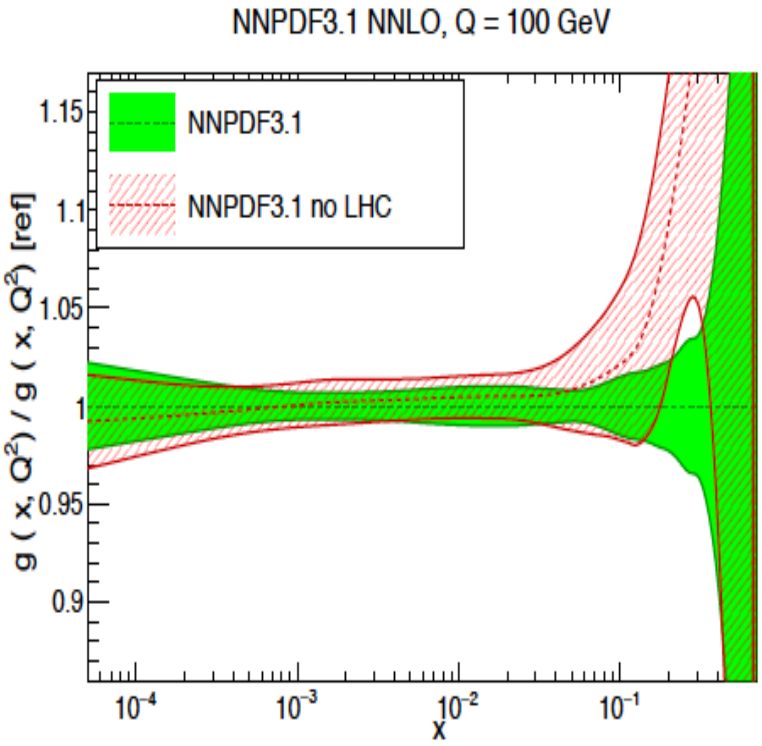
New symmetry embedding QCD

C. Quigg, arXiv1308.6637

QCD has an exciting future with the FCC

backup

LHC Folklore: PDFs come from pp



NNPDF3.1 arXiv:1706.00428

LHC data constrain PDFs, BUT do not determine them:

- Needs complete q_i,g unfolding (miss variety) at all x, as there are sumrules
- Needs strong coupling to permille precision, not in pp
- Needs stronger sensitivity (miss Q^2 variation) cannot come from W,Z at $Q^2=10^4$ GeV^2
- Needs clear theory (hadronisation, one scale)
- Needs heavy flavour s,c,b,t measured and VFNS fixed
- Needs verification of BFKL at low x (only F_2-F_L)
- Needs N^3LO (as for Higgs)
- Needs external input for pp to find QCD subtleties such as factorisation, resummation…to not go wrong
- Needs external precise input for subtle BSM discoveries
- Needs data which yet (W,Z) will hardly be better
- Needs agreement between the PDFs and χ^2+1 ..

PDFs are not derived from pp scattering. And yet we try, as there is nothing else.., sometimes with interesting results as on the light flavour democracy at x ~ 0.01 (nonsuppressed s/dbar). Can take low pileup runs, mitigate PDF influence .. − but can't do what is sometimes stated.

LHeC/FCCeh vs HERA: Higher Q^2: CC; higher s: small x/g saturation?; high lumi: x→ 1; s, c,b,t.

Final Remark

Testing QCD is in fact more difficult than testing the electroweak sector.

Guido Altarelli, Moriond 1983, Cited by R K Ellis, Nuovo Cim 39C (2016) 355

But: it is worth it, possible beyond all expectation in 1983

How could the simple parton picture (with almost non-interacting partons) possibly hold in QCD (—a strongly interacting quantum gauge field theory)?

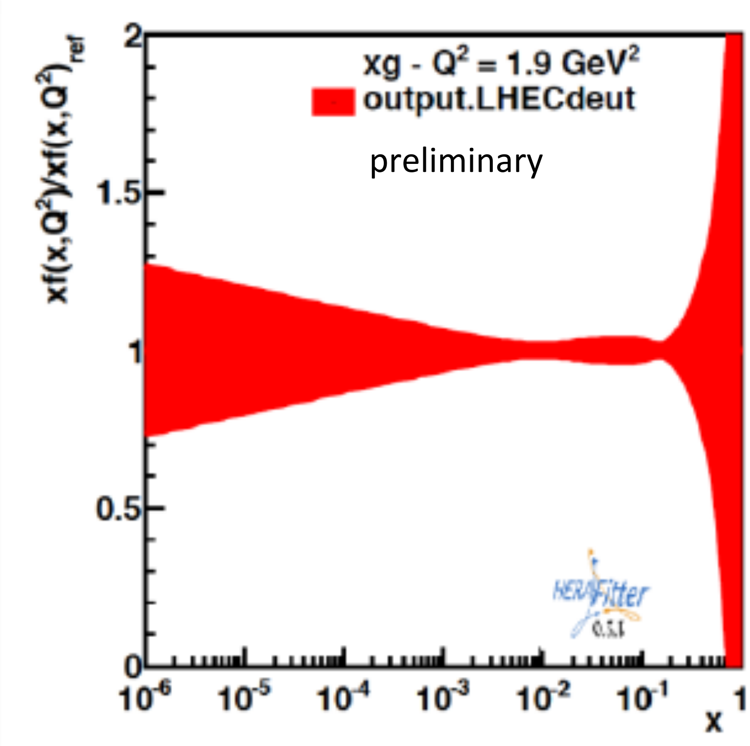
- **Asymptotic Freedom:**
  A strongly interacting theory at long-distances (even confining) can become weakly interacting at short distances (due to scale dependence implied by the RGE).
- **Infra-red Safety:**
  There are classes of "infra-red safe" (IRS) quantities which are independent of long-distance physics, hence are calculable in PQCD.
- **Factorization:**
  There are an even wider class of physical quantities (inclusive cross sections) which can be *factorized* into long distance components (not calculable, but universal) & short-distance components (process-dependent, but infra-red safe, hence calculable).

Wu-Ki Tung CTEQ School 2006

Future Nuclear PDFs with LHeC

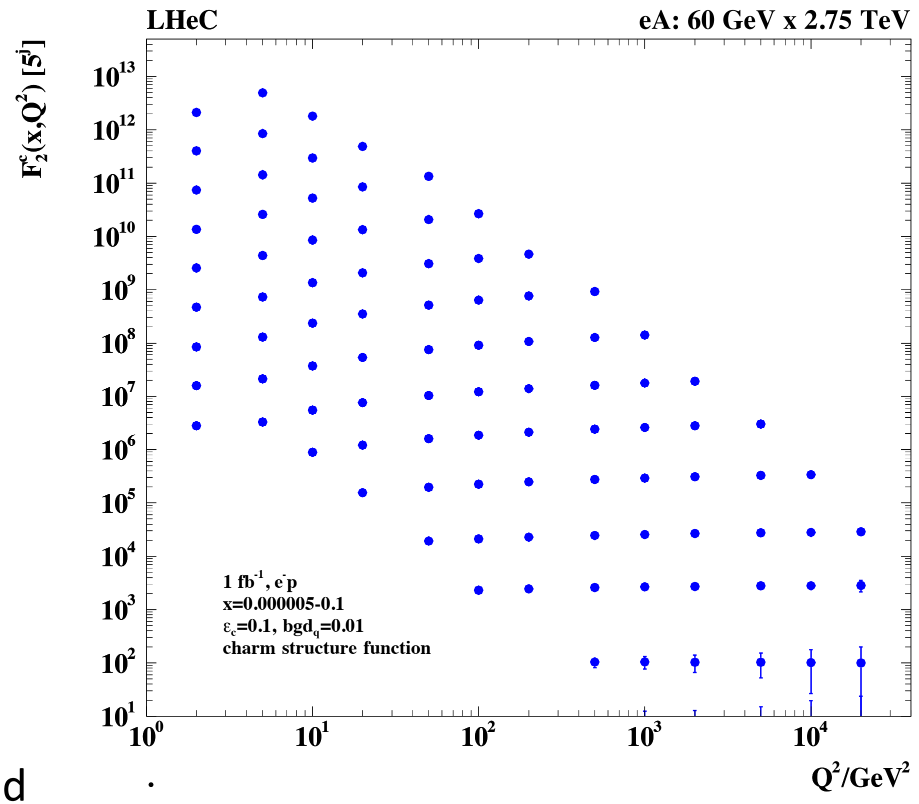
From an eA collider one can determine nuclear PDFs in a novel, the classic way.
Currently: use some proton PDF base and fit a parameterised shadowing term R.
Then: use the NC and CC eA cross sections directly and get R(x,Q^2;p) as p/N PDFs.

Gluon density uncertainty in eA



1fb^{-1} of sole eA isoscalar data fitted

Charm density in nuclei



Impact parameter measurement in eA

FCC-eh PDF program

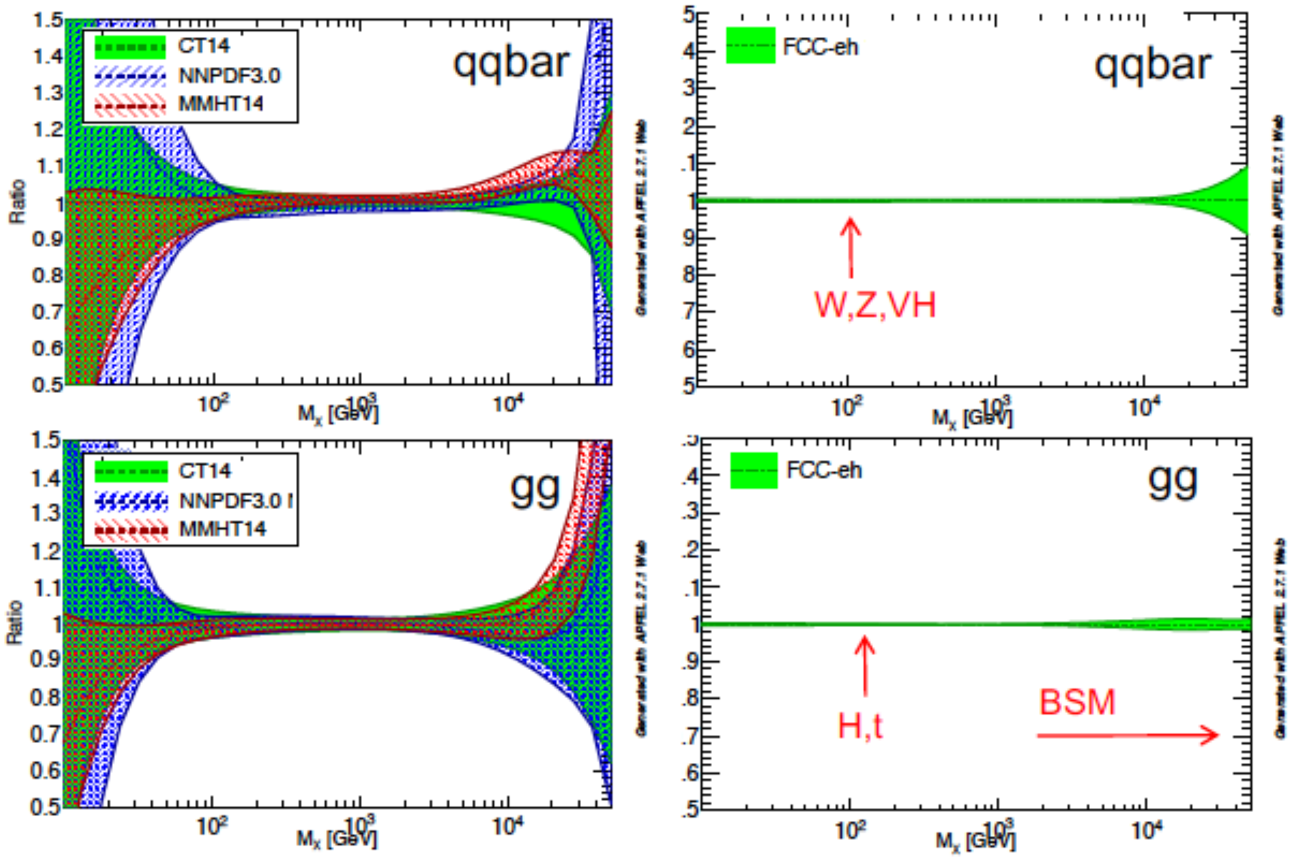
completely resolve parton structure of proton: u_v, d_v, u, d, s, c, b, t and xg

unprecidented kinematic range, sub% precision, free of parameterisation assumptions, N^{3}LO; solve non-linear and saturation issues, test QCD, …

today…

FCC parton luminosities (100 TeV)

… then, with FCC-eh



Claire Gwenlan PDFs at FCCeh – FCC Week 1/2018

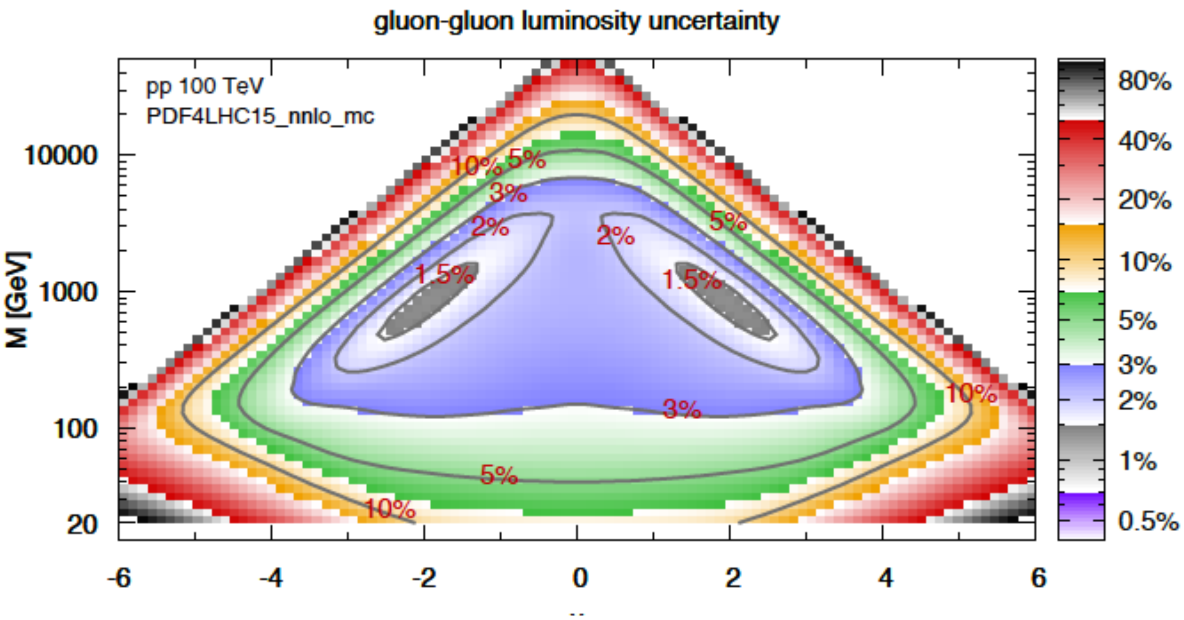
Are applications of PQCD confined to IRS physical observables?

(Most physical observables are not IRS!)

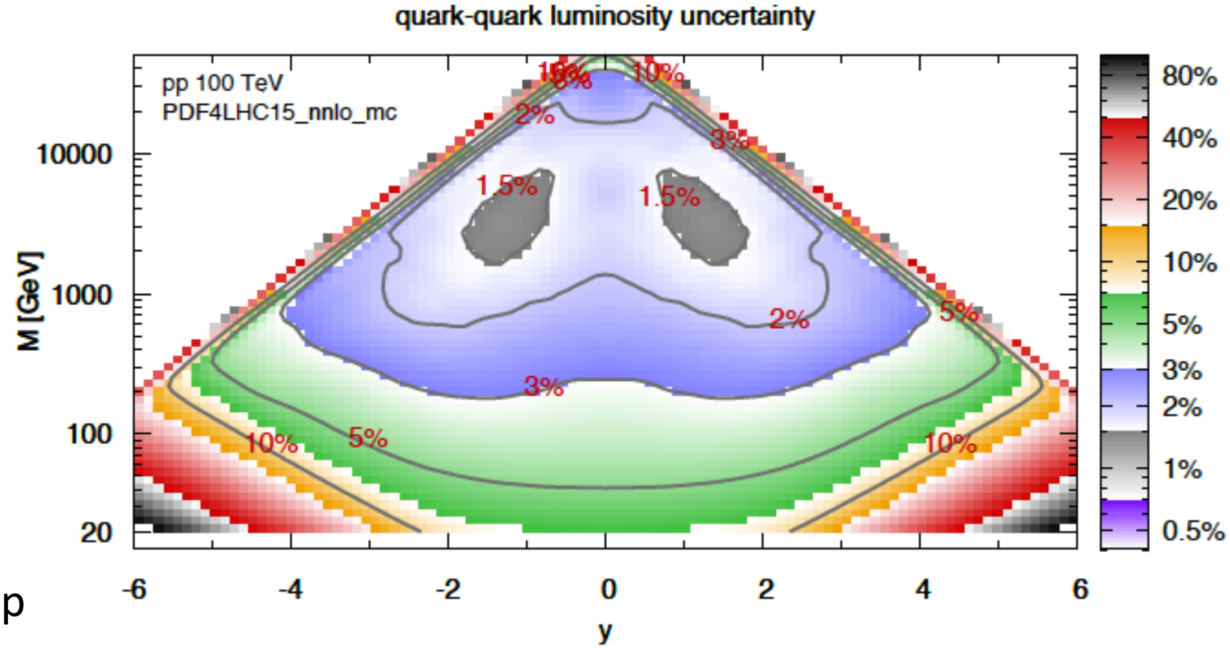
Fortunately not. In fact,

the "QCD Parton Model" for lepton-lepton, lepton-hadron and hadron-hadron scattering cross sections at high energies provides a much more powerful framework for applying PQCD to study a vast range of SM and New Physics processes:

The basic idea behind this class of applications is the factorization of short-distance physics (of leptons, quarks, gluons, new particles) from long-distance physics (of hadrons).



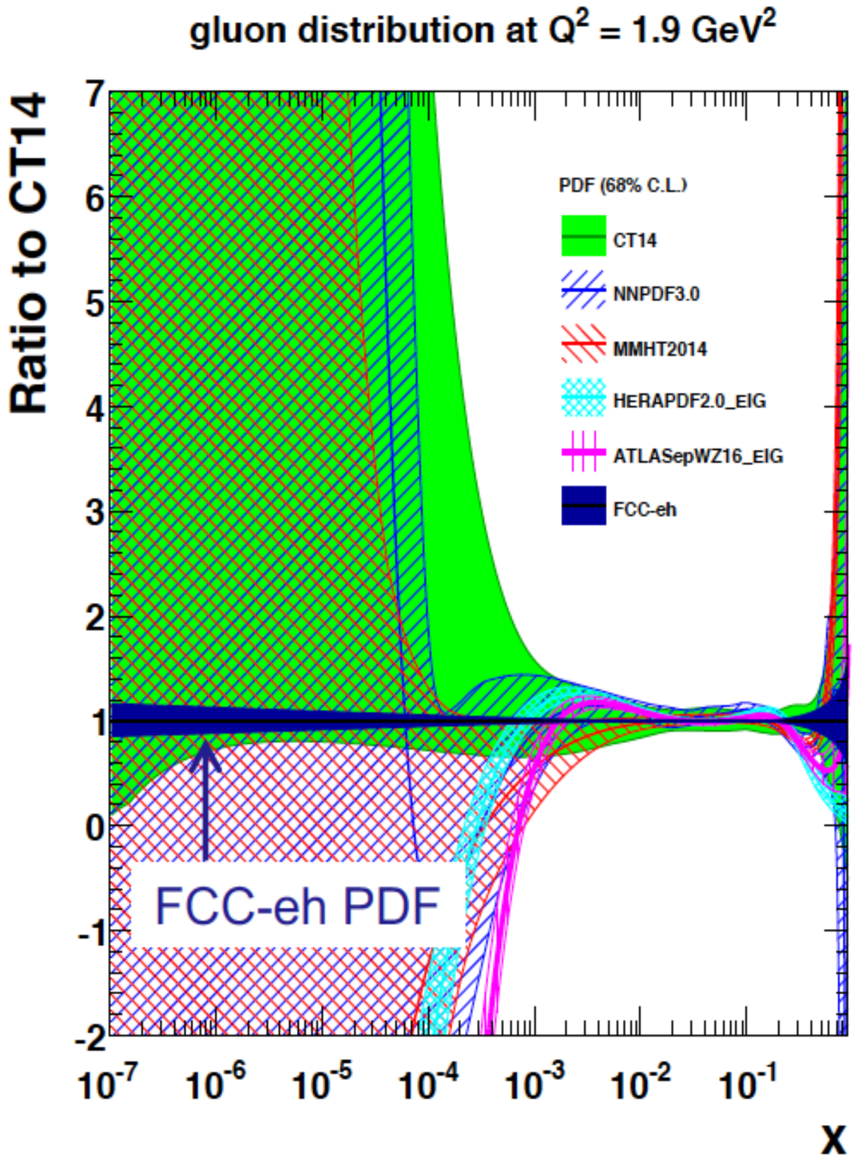
gluon-gluon luminosity uncertainty



quark-quark luminosity uncertainty

arXiv:1607.01831, FCC-pp

gluon at low x



gluon at low x:
recall – no current data much below $x=5\times10^{-5}$ to directly constrain; so even this is an extrapolation for current PDFs at low x

FCC-eh would provide single, precise and unambiguous dataset

(explore low x QCD, DGLAP vs BFKL, non-linear evolution, gluon saturation; implications also for ultra high energy neutrino cross sections)

NNLO singlet splitting functions A completely analytical result

Moch, Vermaseren, Vogt '04