Approaching QCD with FCC

Before QCD
Chromodynamics
ee pp ep
Tool for Discovery in pp
High Precision Coupling GUTs?
Parton Distributions
High Density QCD
Parton Dynamics in Nuclei

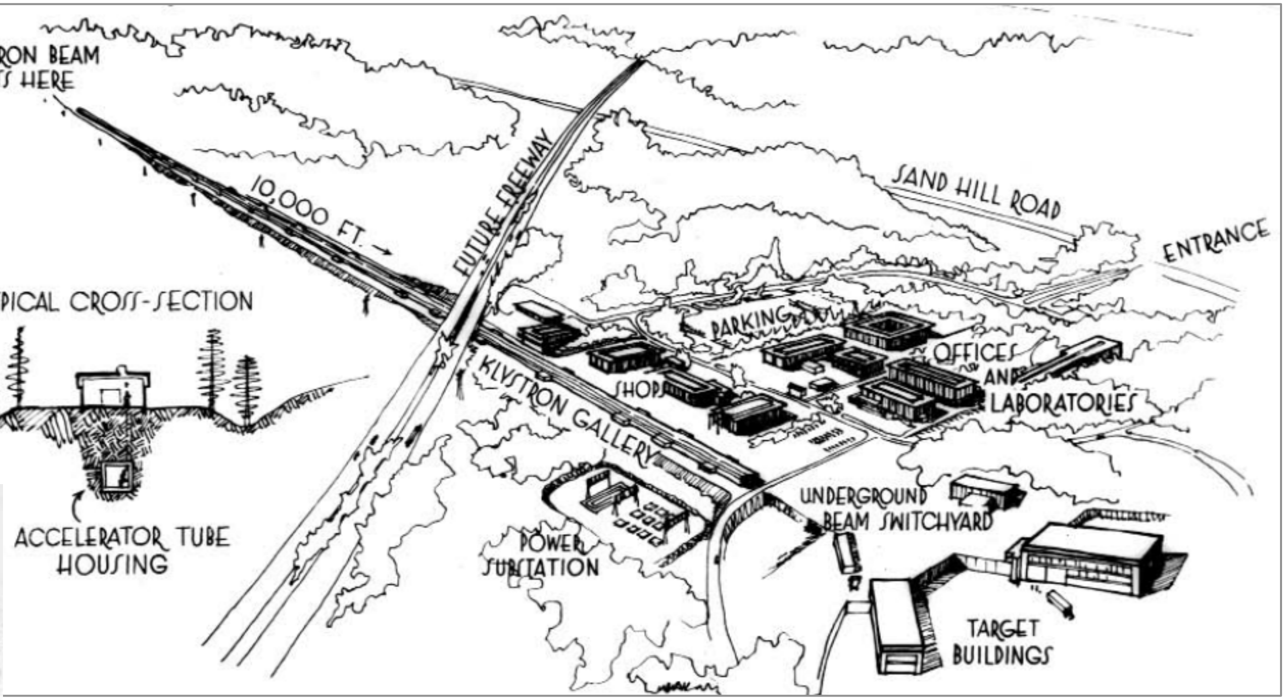
In memory of Willy van Neerven, Wu-Ki Tung, Guido Altarelli, Lev Lipatov and James Stirling

Max Klein
University of Liverpool, H1 and ATLAS

Talk at the FCC Symposium, CERN, 5.3.2019

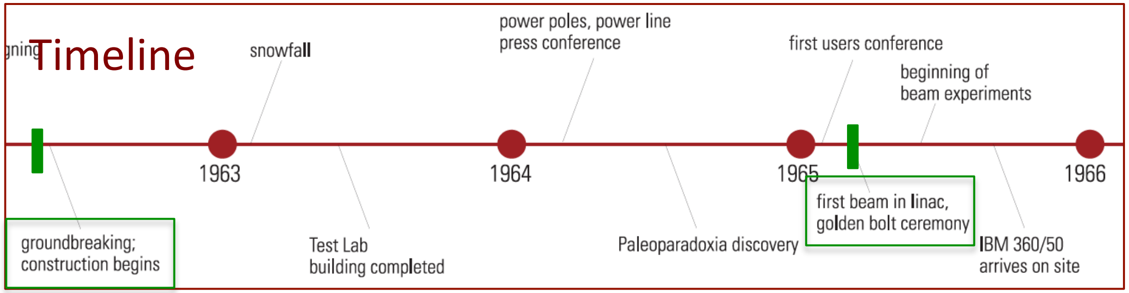
Thanks to Nestor Armesto, Davide D'Enterria, Michelangelo Mangano, Voica Radescu + the eh QCD team.

Two-mile electron linac at SLAC



Pief Panofsky and Burt Richter, 1962

Timeline



groundbreaking; construction begins

snowfall

Test Lab building completed

power poles, power line press conference

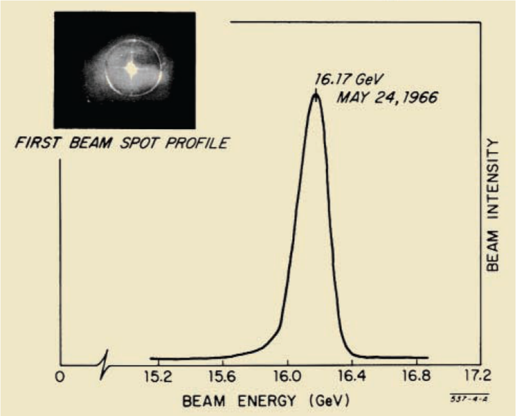
Paleoparadoxia discovery

first users conference

first beam in linac, golden bolt ceremony

beginning of beam experiments

IBM 360/50 arrives on site



Three Messages from the 2m LiNAC

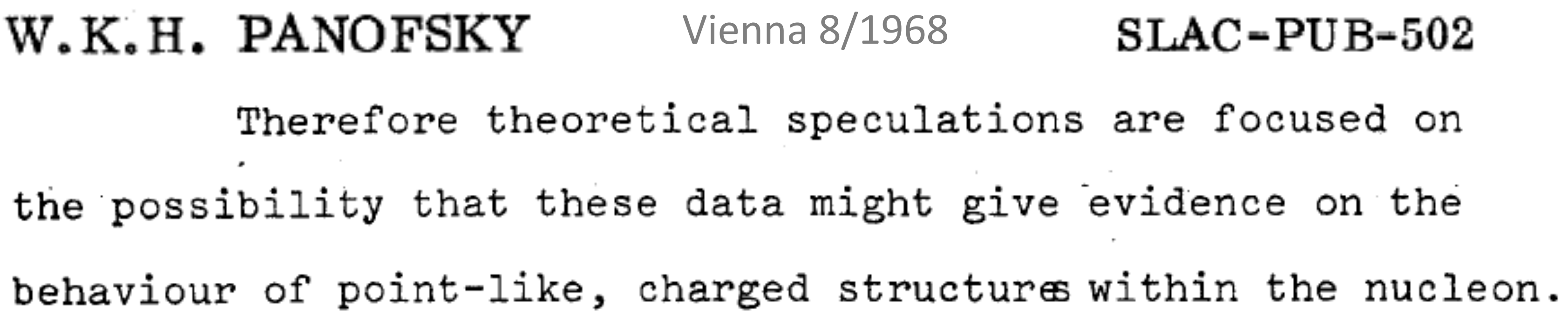
-- **you do NOT need to promise to discover dark matter or know what new to expect when you increase the energy range** (a comment for Sabine H., we yet may have to readjust our perception about nature, its richness and our ability to predict it. ‘we like to see the field to be driven by experiment’ – Burt Richter 2009)

-- **you can build a 2 mile electron linac in 3 years time, if you really want it**
of course we could build LHeC as a bridge project, if only we decided to do so!

-- **electron-proton scattering is the best means to explore the substructure of matter**
a necessary complement to the LHC/FCC and moreover, now a unique Higgs facility

50 years since the discovery of quarks by the SLAC-MIT ep scattering experiment

---



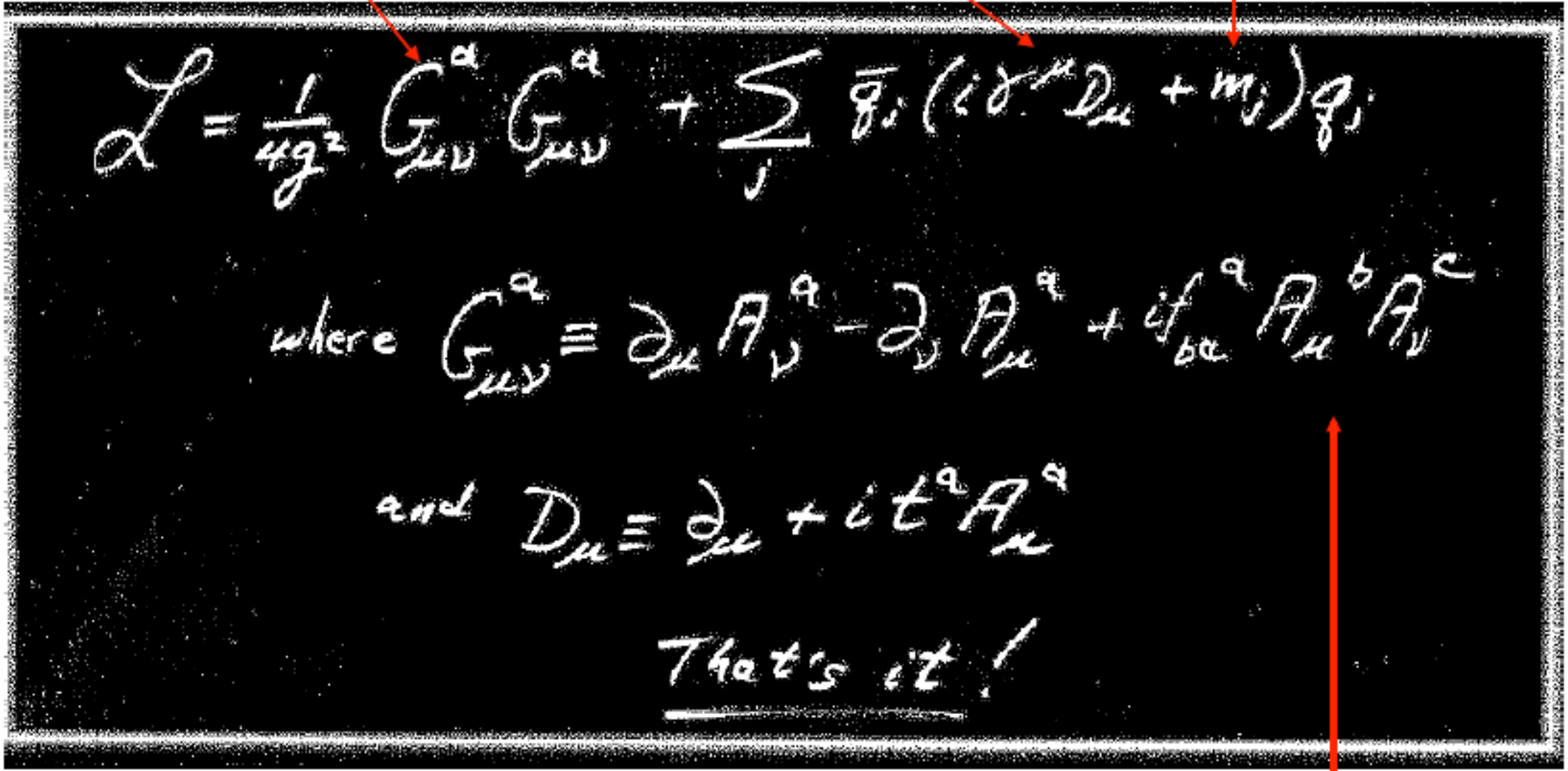
W.K.H. PANOFSKY Vienna 8/1968 SLAC-PUB-502

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.

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

QCD is key for all FCC-ee,eh,hh physics

▶ Though QCD is *not per se* the main driving force behind FCC, QCD is crucial for many FCC measurements (signals & backgrounds):

- High-precision α_s: Affects SM fits/tests, all hadronic cross sections & decays
- N^nLO+N^nLL corrections: Needed for all x-sections with initial/final hadrons
- Heavy-Quark/Quark/Gluon separation, subjet structure, boosted topologies,...: Needed for all precision measurements & BSM searches with jets.
- High-precision (n)PDFs: In h-h collisions, affects all precision W,Z,H (mid-x) measurements, all BSM searches (high-x), & beyond-DGLAP (low-x) studies.
- Semihard QCD: low-x gluon saturation, multiple hard parton interactions,… Note: $Q_0 \sim 10$(!) GeV at 100 TeV.
- Many-body QCD: Partonic collective behaviour in high particle-density systems, Colour reconnection in "central" h+h collisions; impact on fundamental quantities in jetty final-states (m_W, m_{top} extractions,…),
- Non-pQCD: Control of hadronization+diffraction+... is basic at FCC-pp with $\mathcal{O}$(1.000) pileup, backgds,...

QCD is far from being fully developed, it will evolve and may break:

Developments

AdS/CFT
Instantons
Odderons

Non pQCD, Spin
Quark Gluon Plasma

QCD of Higgs boson

N^kLO, Monte Carlos..
Resummation
BFKL evolution

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

Discoveries

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

Breaking of Factorisation [ep-pp]

Free Quarks

Unconfined Color

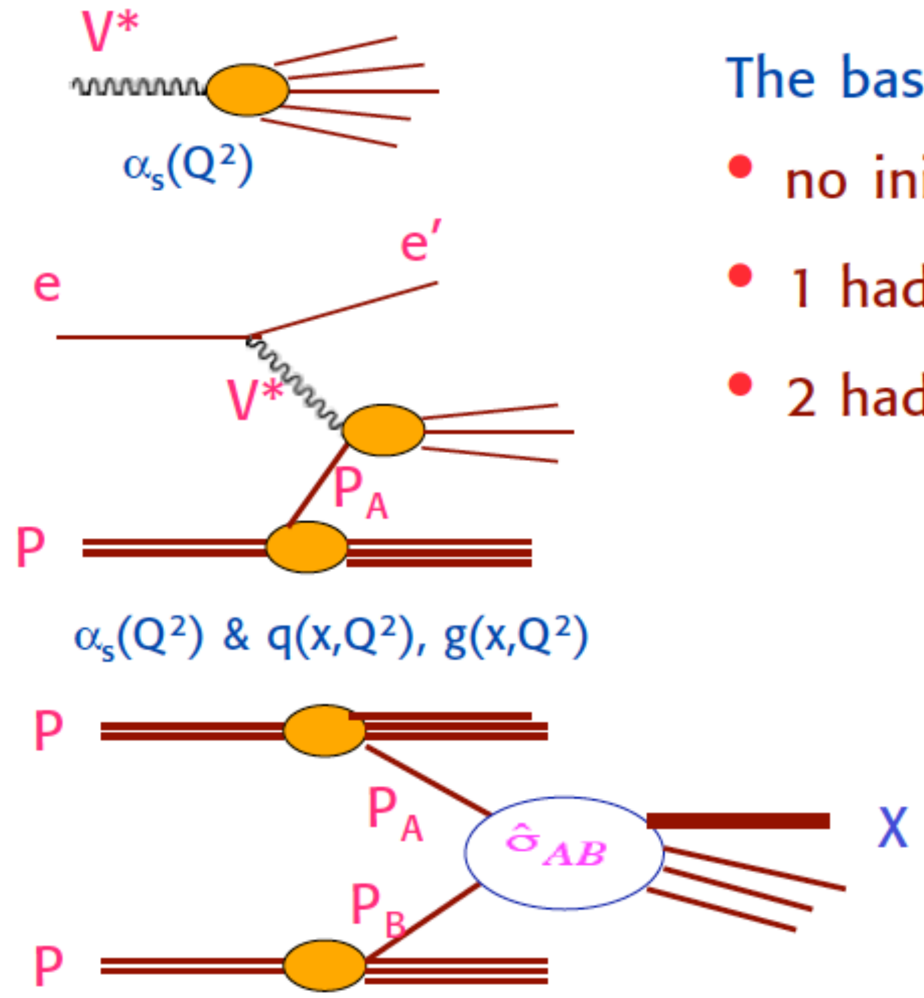
New kind of colored matter

Quark substructure

New symmetry embedding QCD

C. Quigg, arXiv1308.6637

QCD is much more than a tool to find BSM physics, by itself it may lead beyond the SM



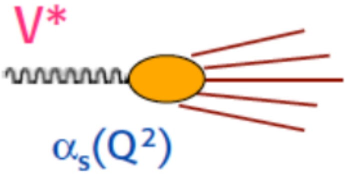
The basic experimental set ups:

- 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

Guido Altarelli DIS2009, Madrid [before the FCCee/eh/hh..]

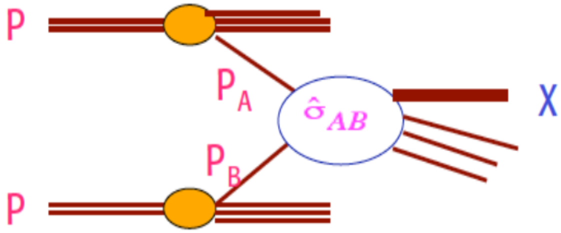
QCD with ee pp ep



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

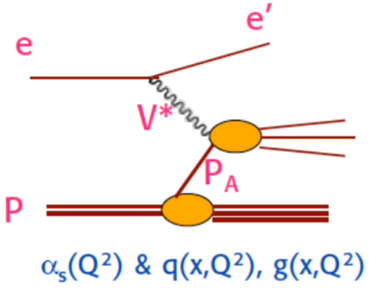
Final state arises completely from short distance interaction of virtual boson with quarks: NO PDFs, but jets, α_s
Njets +0, energy, angles. Unique association of q,g with jets
Observation of 3-jet events at PETRA to discover the gluon

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



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

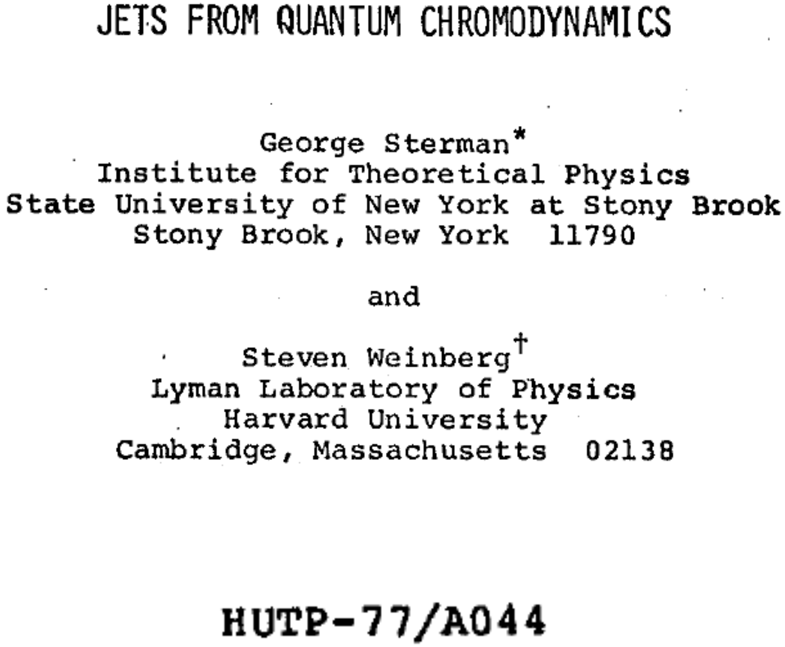
Many initial partons but only two interact.
"rest" is the underlying event of soft i.a.'s
Dynamical coupling of all components. MPIs
N jets at large pT +X, pseudorapidity + azimuth
Ledermann-**Drell-Yan scattering, jets**
Scattering depends on parton distributions
Saved the SM in 1984, Bern. Discovery of gg→ Higgs



$\sqrt{s} = 2\sqrt{E_eE_p}$ = 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
Discovery of partons and the QPM … **DGLAP**

QCD – tool for discovery



JETS FROM QUANTUM CHROMODYNAMICS

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

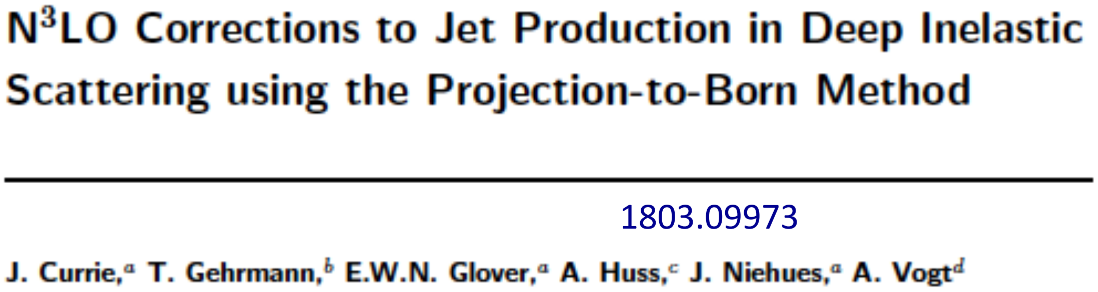
and

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

HUTP-77/A044

pQCD Theory

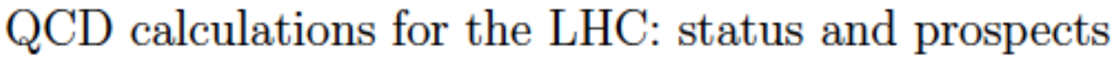
Major, impressive theoretical progress in pQCD calculations to N^{k}LO, e.g.



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

1803.09973

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

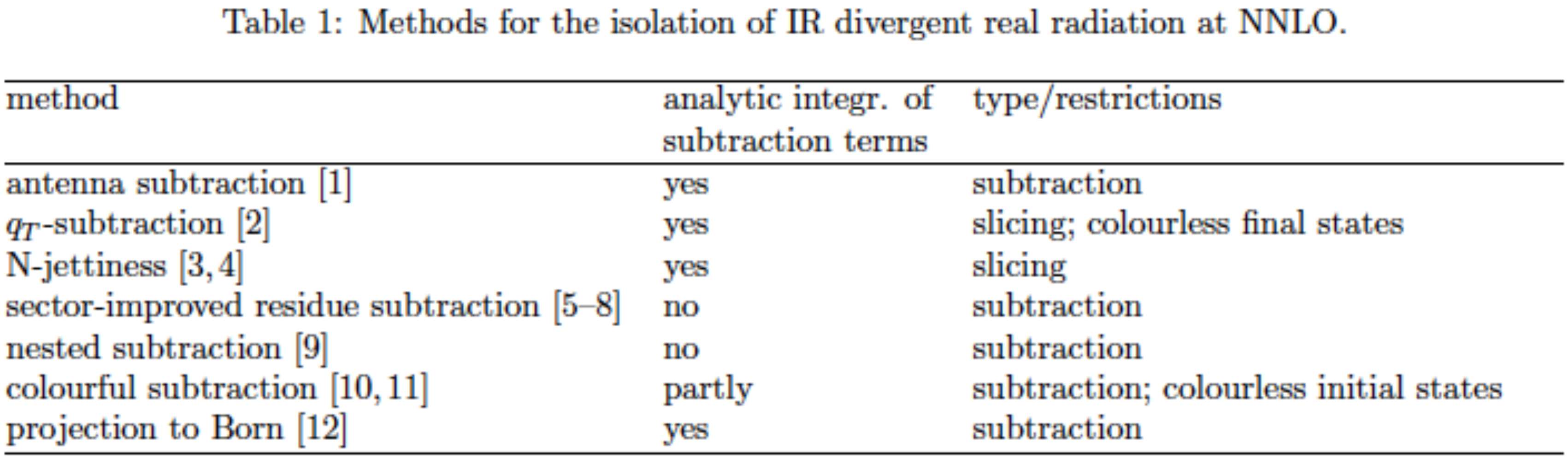


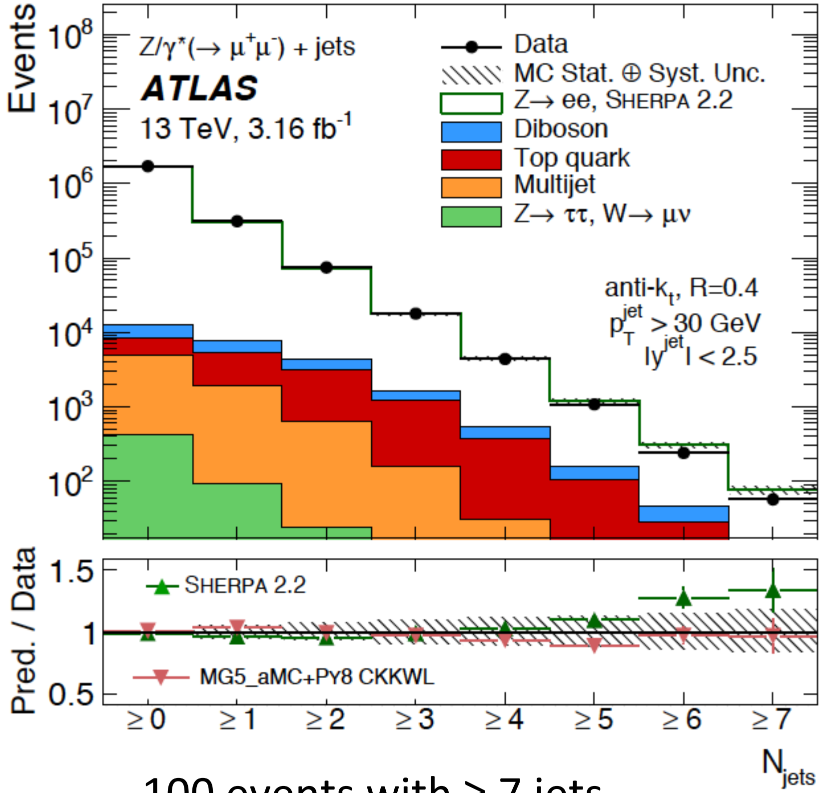
Table 1: Methods for the isolation of IR divergent real radiation at NNLO.

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

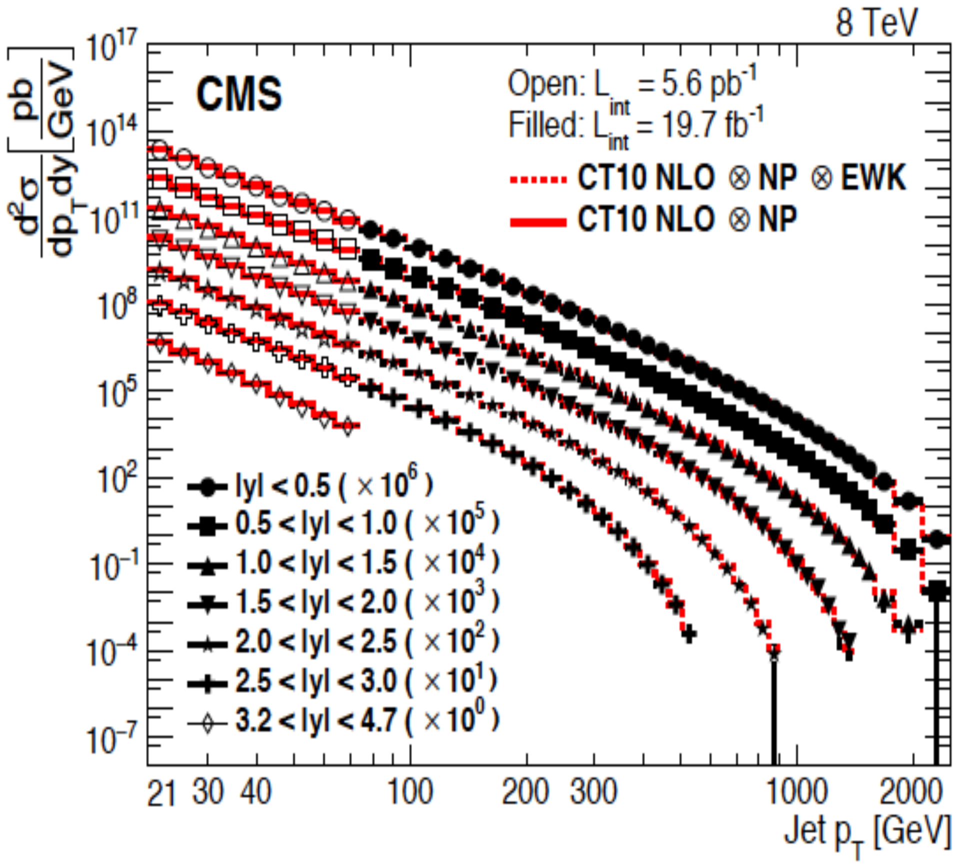
QCD at work at the LHC

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

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



100 events with ≥ 7 jets

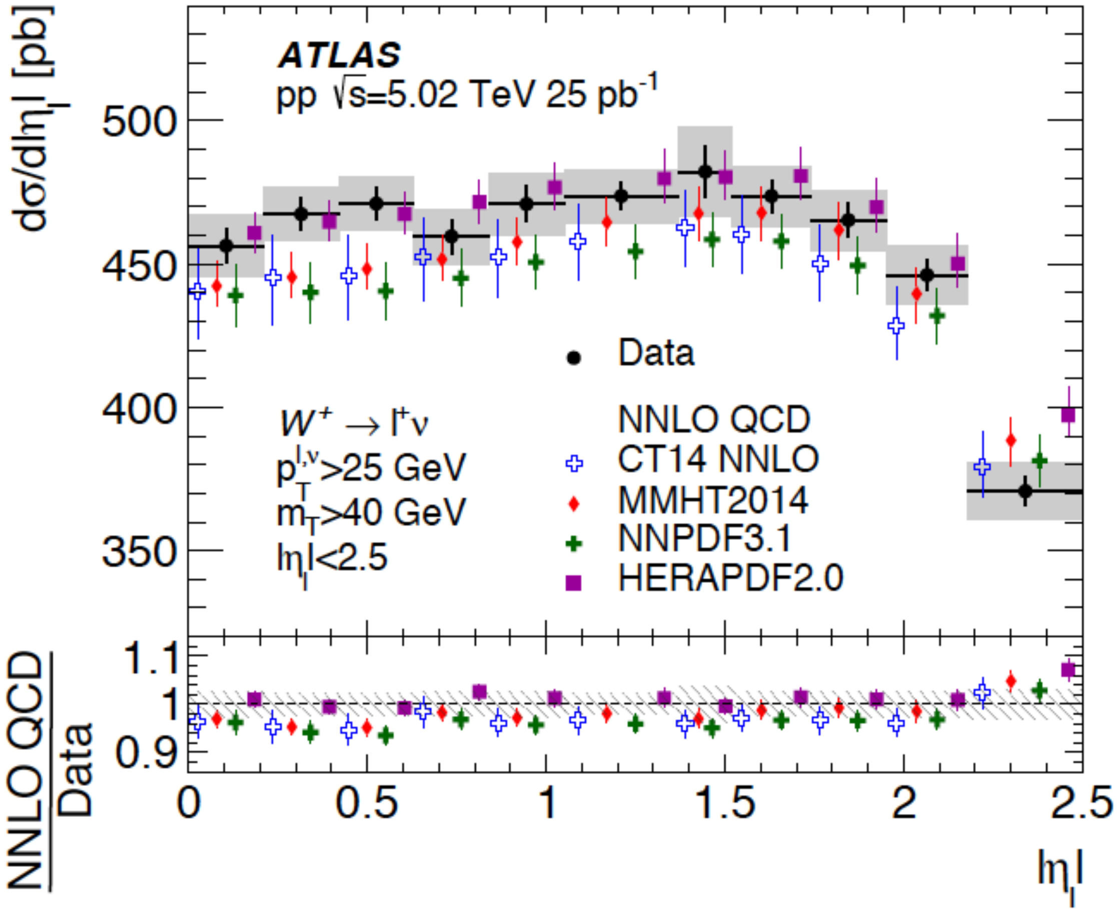


10 orders of magnitude in cross section

Multi-jets

Very high scales (low for FCChh..)

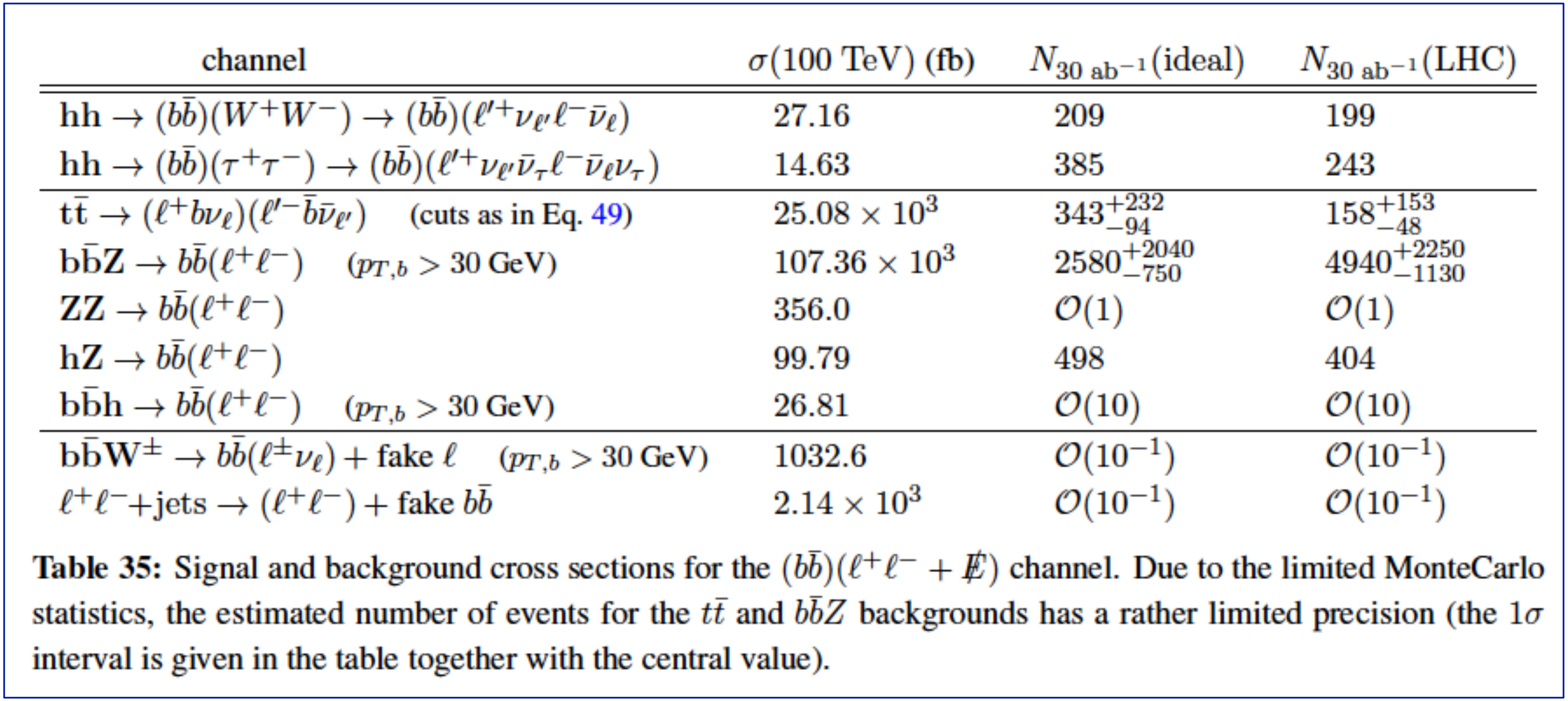
W and Z



ATLAS
5 TeV W,Z data
1810.08424

HERAPDF2.0 is best and very good while CT14 is worst, as opposed to jets

Double-Higgs Production at FCCpp



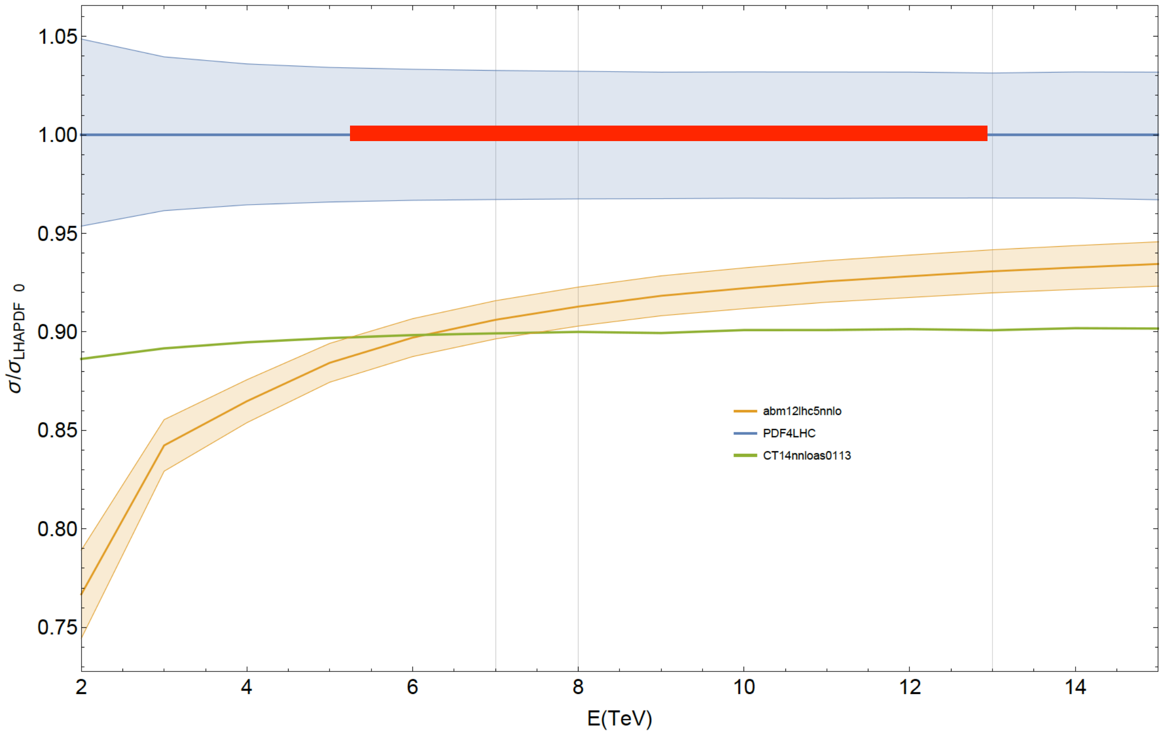
channel	$\sigma(100\ \text{TeV})$ (fb)	$N_{30\ \text{ab}^{-1}}$(ideal)	$N_{30\ \text{ab}^{-1}}$(LHC)
$\text{hh} \to (b\bar{b})(W^+W^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\ell^-\bar{\nu}_\ell)$	27.16	209	199
$\text{hh} \to (b\bar{b})(\tau^+\tau^-) \to (b\bar{b})(\ell'^+\nu_{\ell'}\bar{\nu}_\tau\ell^-\bar{\nu}_\ell\nu_\tau)$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

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.

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

C Anastasiou et al, arXiv:1602.00695

True PDF errors?

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

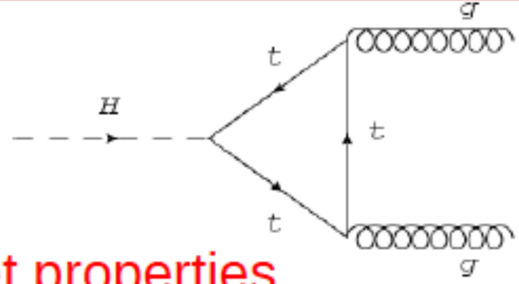
PDFs to N^{3}LO →
DIS to N^{3}LO
[10 years program]

$\sigma \sim (\alpha_s\, xg)^2$

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

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**

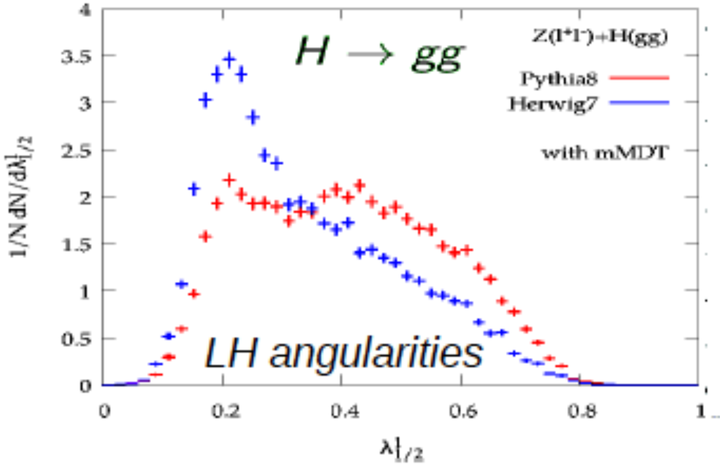
Vary jet radius: small-R → calo resolution

(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

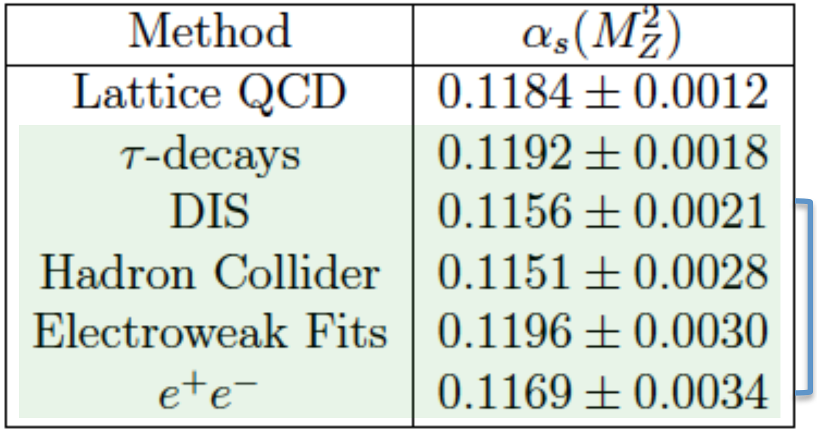


- Check N^nLO antenna functions
- Improve q/g/Q discrim.tools (BSM)
- Octet neutralization? (zero-charge gluon jet w/ rap-gaps)
- Colour reconnection? Glueballs ?
- Leading η's,baryons in g jets?

The strong coupling constant

$\alpha_s(\mu)$

PDG 2016



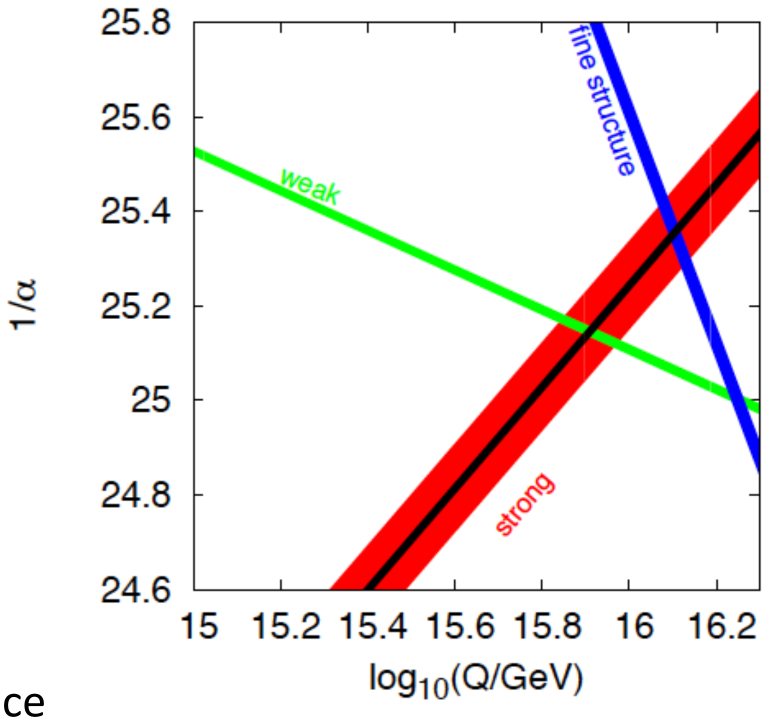
Method	$\alpha_s(M_Z^2)$
Lattice QCD	0.1184 ± 0.0012
τ-decays	0.1192 ± 0.0018
DIS	0.1156 ± 0.0021
Hadron Collider	0.1151 ± 0.0028
Electroweak Fits	0.1196 ± 0.0030
e^+e^-	0.1169 ± 0.0034

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

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

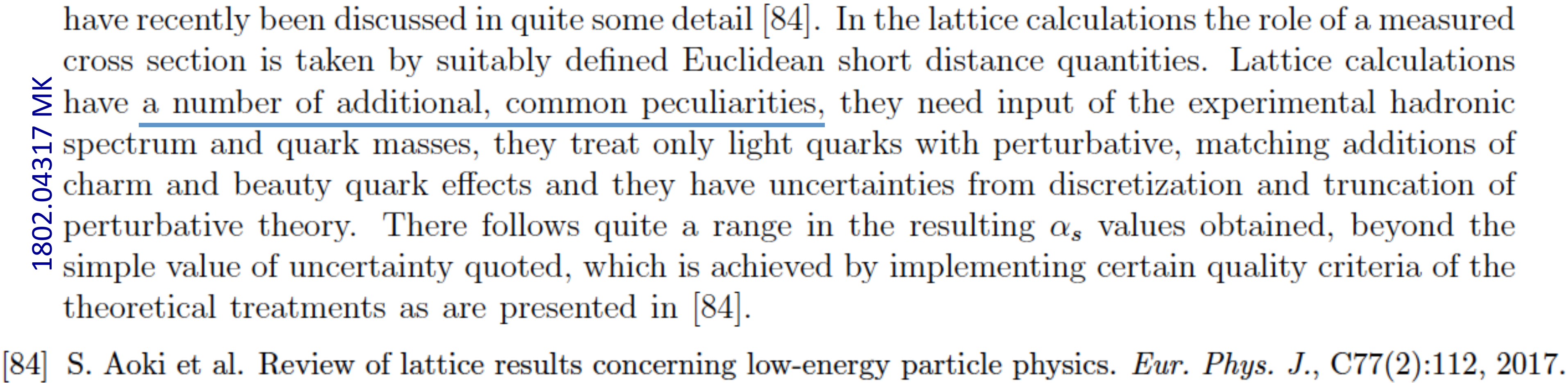
w/o lattice
1.5% error

Grand unification??



1211.5102 – on the relation of ep+pp

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.

Strong Coupling Constant in e^+e^-

From Z pole: dominantly $R_l^0 = \Gamma_{had} / \Gamma_l$

Error on R_l^0 [10^{-5}] **today** [18]: exp 25
thy 6

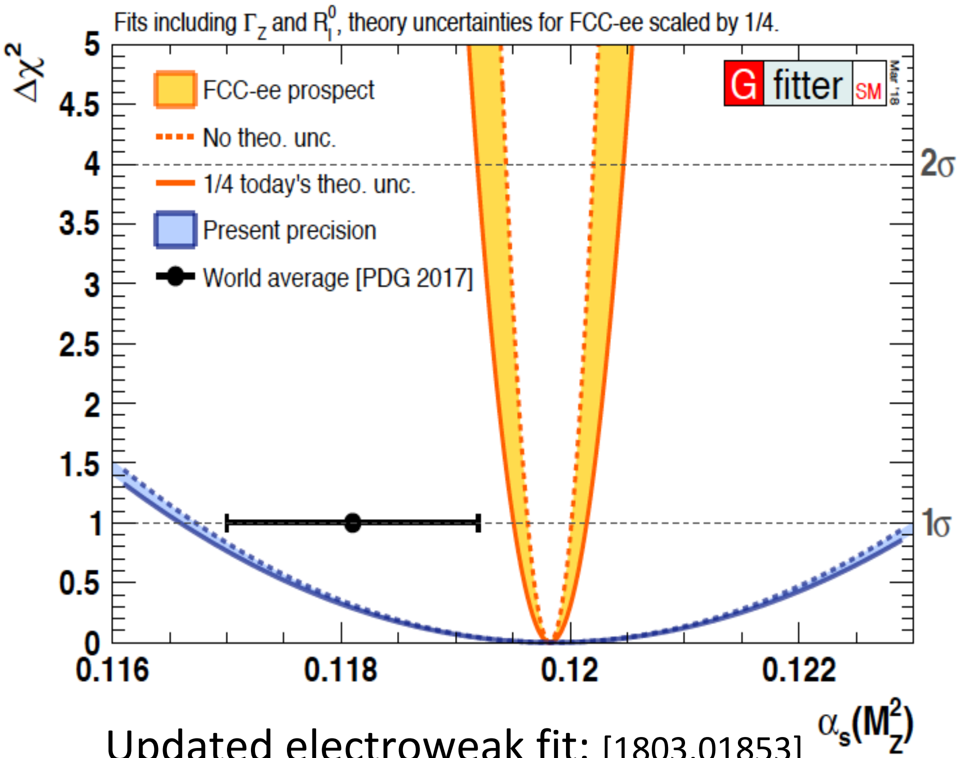
FCCee
exp errors on R: stat: 0.6, syst: 2-10

Gfitter study: R.Kogler et al
assumed exp error on R_l^0 = 1
thy = thy(18)/4 *)

Error on strong coupling FCC-ee

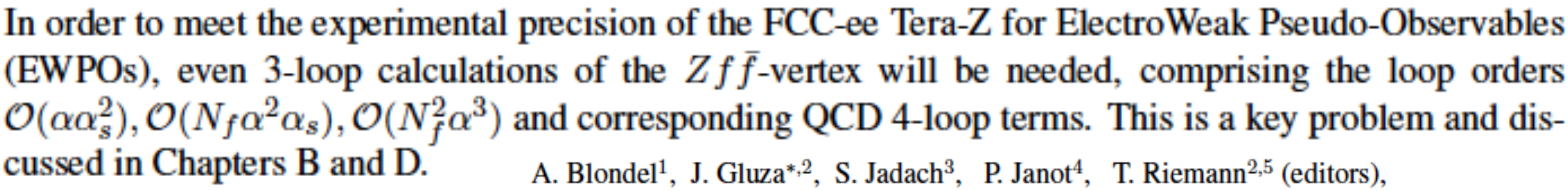
with present thy uncertainty	**± 0.92%**
no theory uncertainty	**0.17%**
¼ of present theory uncertainty	**0.25%**

1809.01830 *) **Theory Workshop on Tera-Z 1/18**



Updated electroweak fit: [1803.01853]

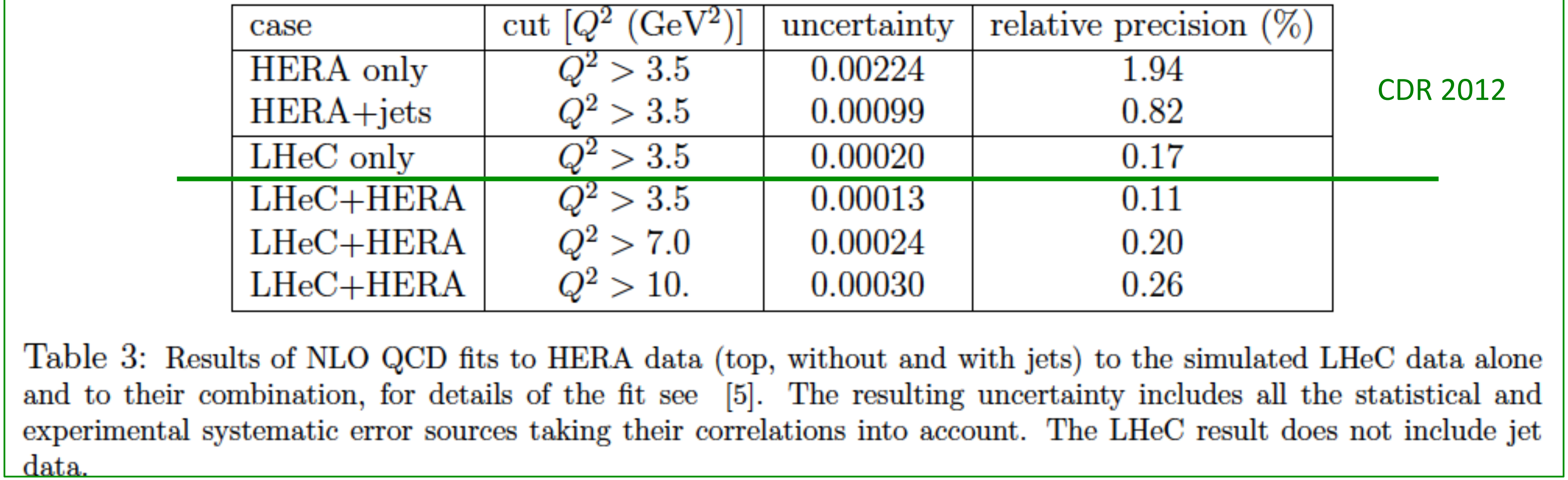
+ Other determinations: WW, event shapes



In order to meet the experimental precision of the FCC-ee Tera-Z for ElectroWeak Pseudo-Observables (EWPOs), even 3-loop calculations of the $Zf\bar{f}$-vertex will be needed, comprising the loop orders $\mathcal{O}(\alpha\alpha_s^2), \mathcal{O}(N_f\alpha^2\alpha_s), \mathcal{O}(N_f^2\alpha^3)$ and corresponding QCD 4-loop terms. This is a key problem and discussed in Chapters B and D.

A. Blondel[1], J. Gluza*[,2], S. Jadach[3], P. Janot[4], T. Riemann[2,5] (editors),

$\alpha_s(\mu)$ 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^3LO 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

Strong Coupling at FCC-hh

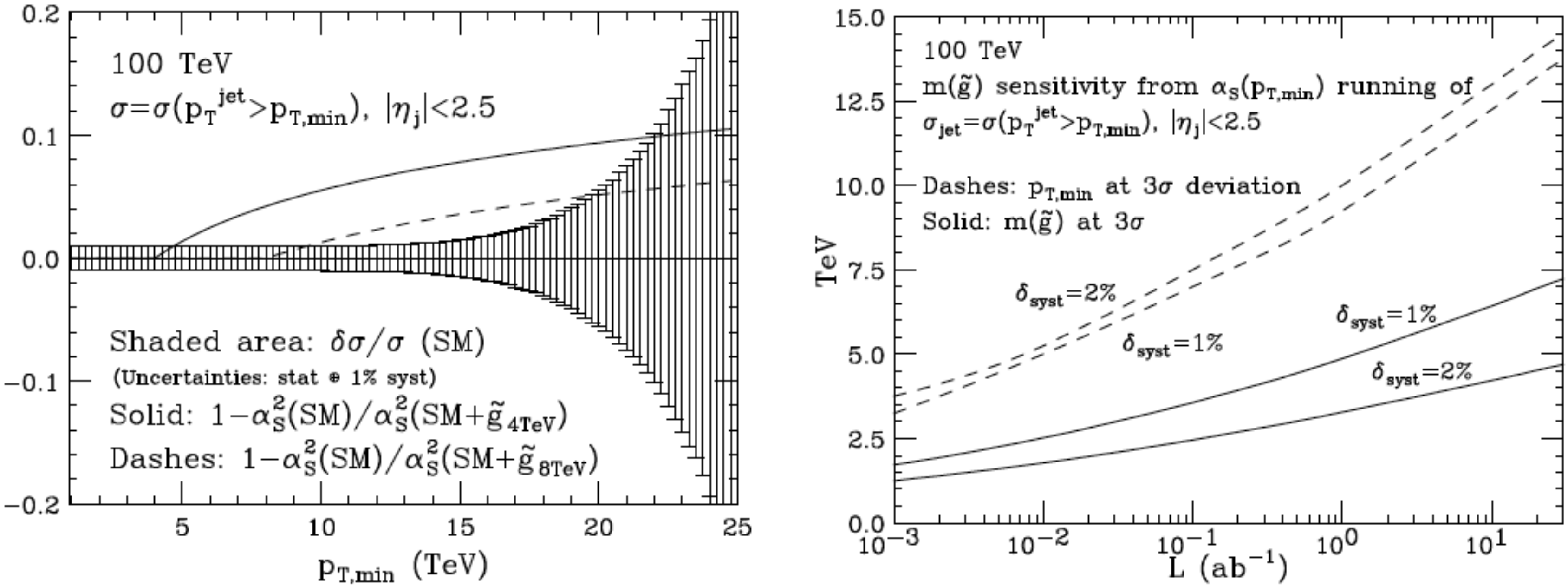
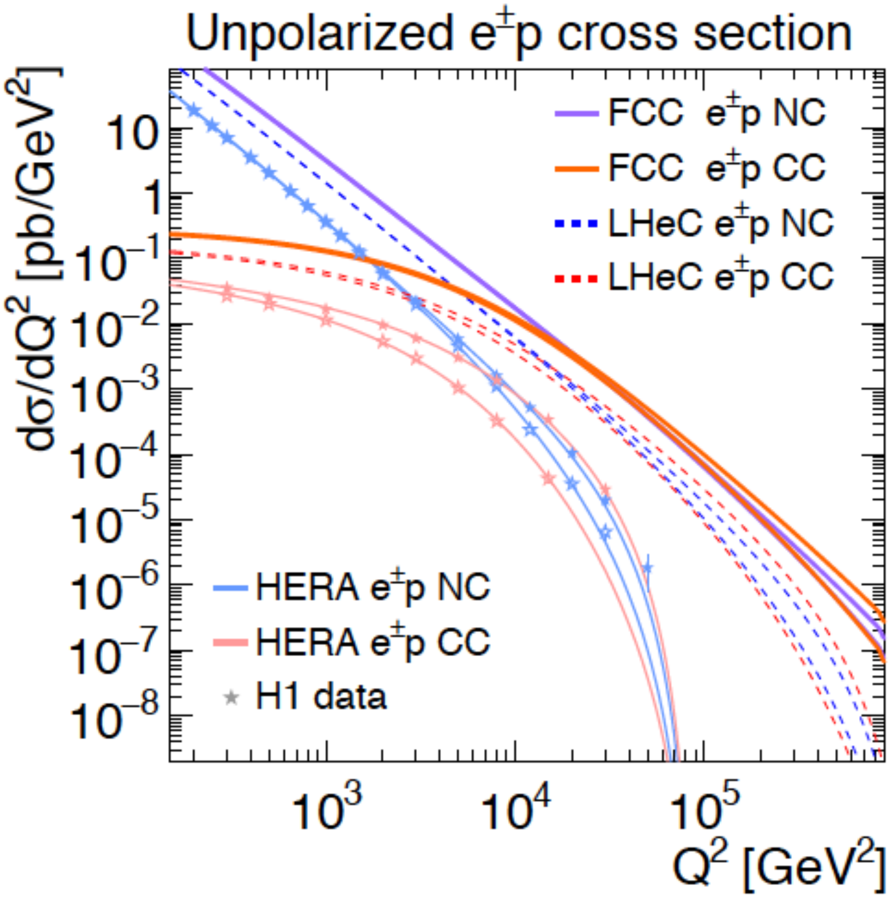
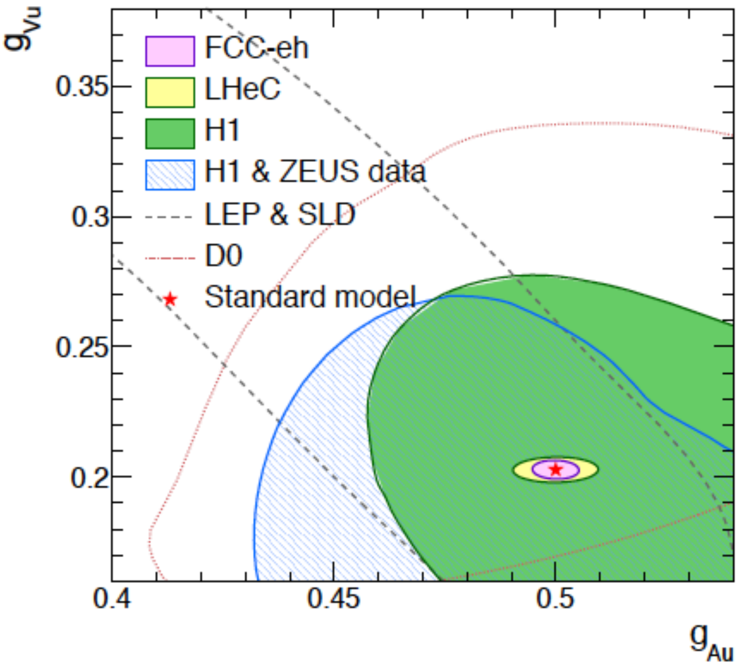


Figure 5.5: Left plot: combined statistical and 1% systematic uncertainties, at 30 ab^{-1}, vs p_T threshold; these are compared to the rate change induced by the presence of 4 or 8 TeV gluinos in the running of α_S. Right plot: the gluino mass that can be probed with a 3σ deviation from the SM jet rate (solid line), and the p_T scale at which the corresponding deviation is detected.

Jet cross sections sensitive to $p_{T,min}$ of ~ 20 TeV. Departures in the cross section from 4 or 8 TeV gluinos present in the evolution of the strong coupling at high scales. Study (right) as functions of statistical and systematic error. Precision inferior to eh/ee.

Electroweak + QCD in ep



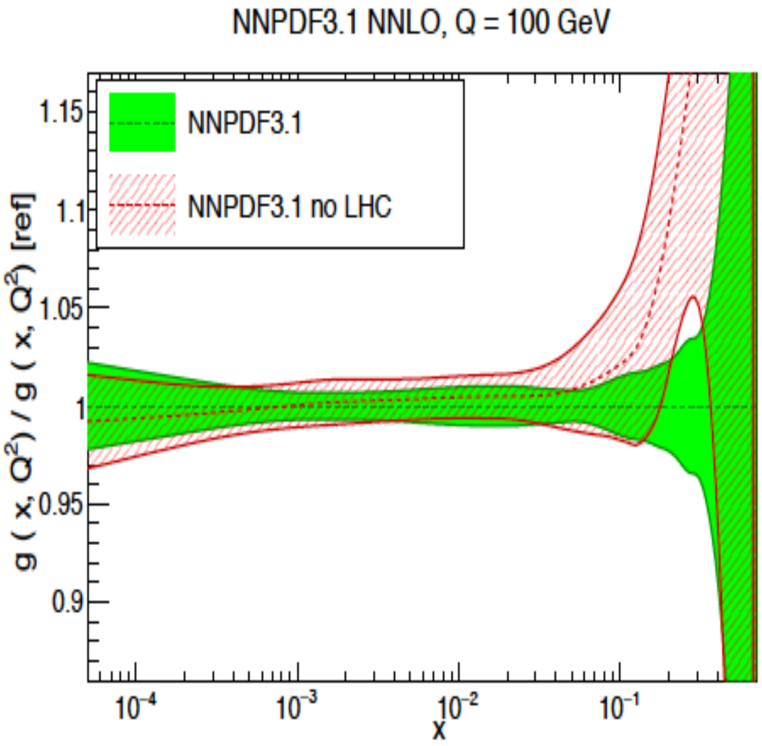


Very high cross sections extending hugely beyond electroweak scale. Large luminosity and high precision in ep enable stringent tests of electroweak physics in spacelike region.

Determination of the weak NC light quark couplings.
Running of $\sin^2\Theta_W$ up to 2 TeV [from 0.1 GeV with PERLE]
10 MeV precision on W,Z mass
CKM as Vtb, Vcs very precise
Not limited by PDFs

Parton Distribution Functions

LHC Folklore: PDFs come from pp



NNPDF3.1 arXiv:1706.00428

LHC data constrain PDFs, BUT do not determine them:

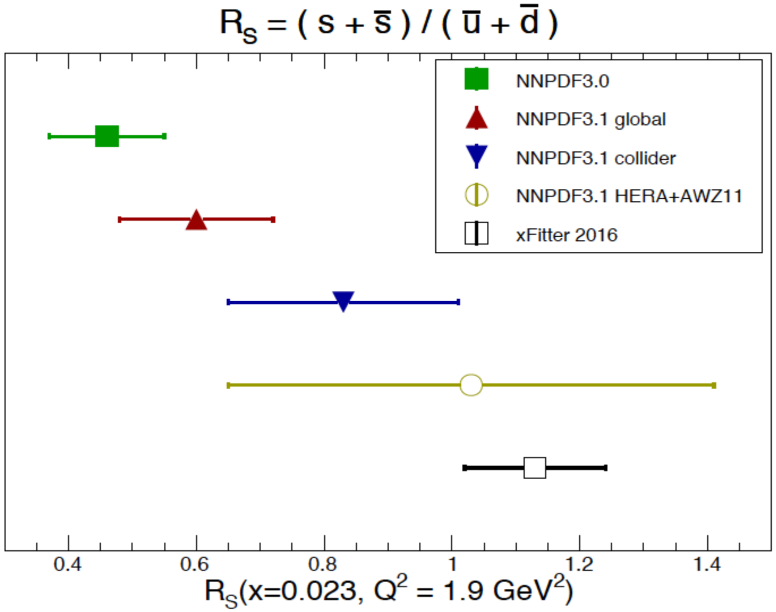
- Needs complete q_i,g unfolding (miss variety) at all x, as there are sumrules
- Needs strong coupling to permille precision, not in pp
- Needs stronger sensitivity (miss Q^2 variation) cannot come from W,Z at $Q^2=10^4$ GeV^2
- Needs clear theory (hadronisation, one scale)
- Needs heavy flavour s,c,b,t 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 ..
- Trouble with jets, direct photons, consistency..

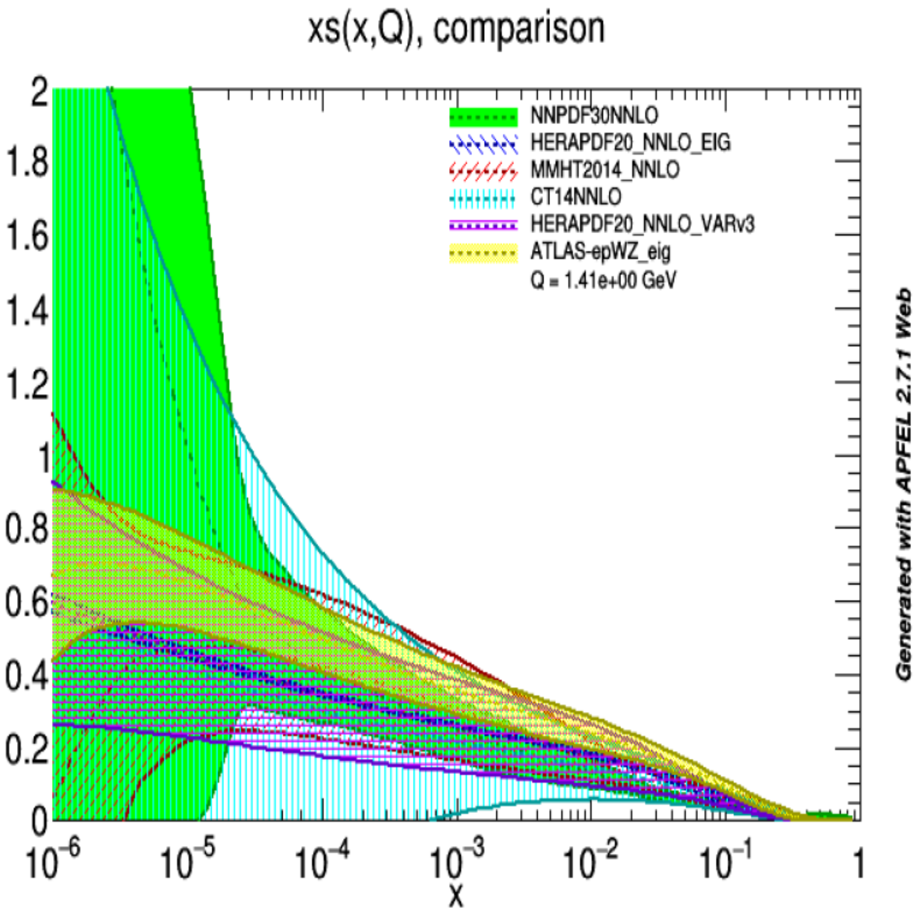
PDFs are not derived from pp scattering. And yet we try, as there is nothing else.., sometimes with interesting results as on the light flavour democracy at x ~ 0.01 (nonsuppressed s/dbar). Can take low pileup runs, mitigate PDF influence .. − but can't do what is sometimes stated.

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

Strange Strange

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



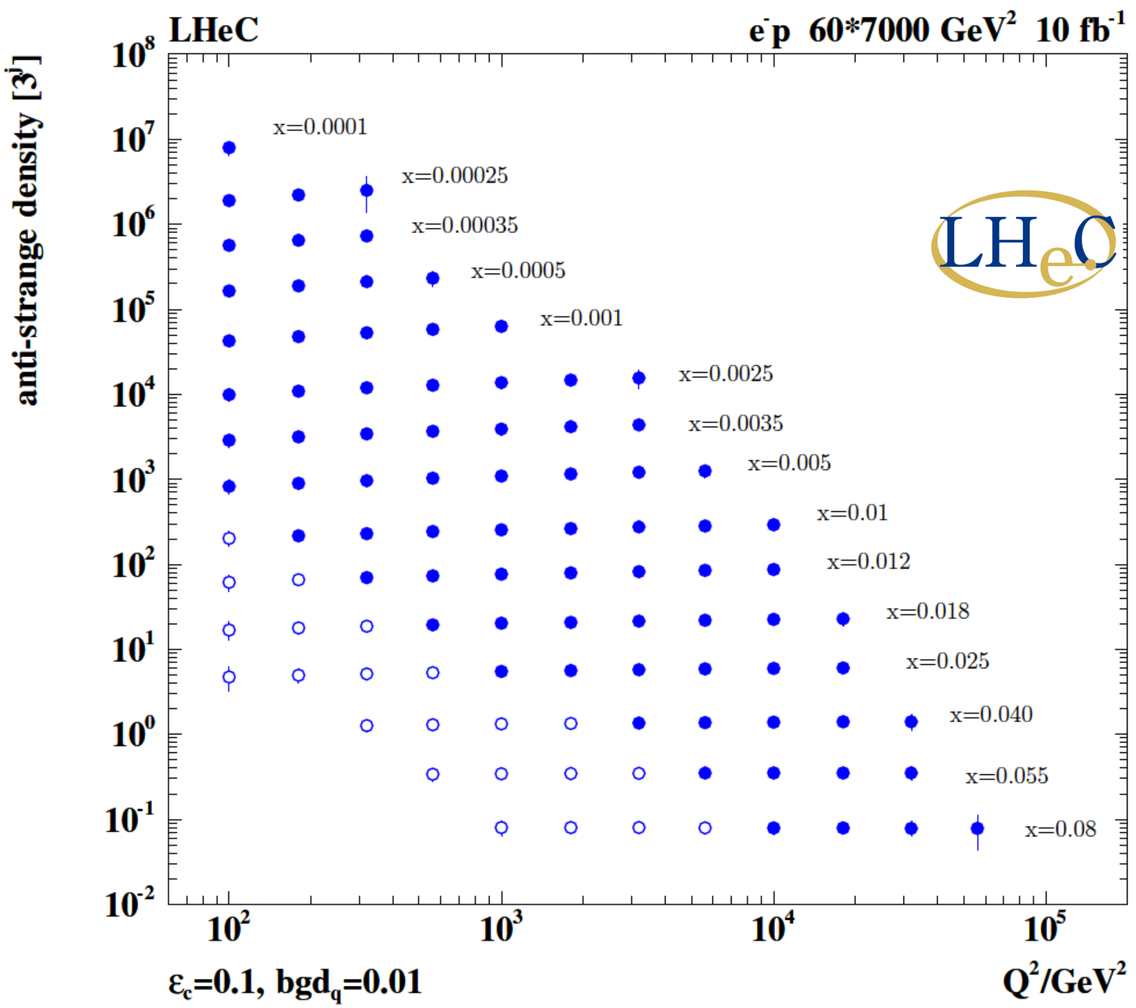


NNPDF3.1 arXiv:1706.00428, note:
“xFITTER16” = ATLAS: 1612.0301
Also look at MMHT and other results

A Cooper-Sarkar, DIS17

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

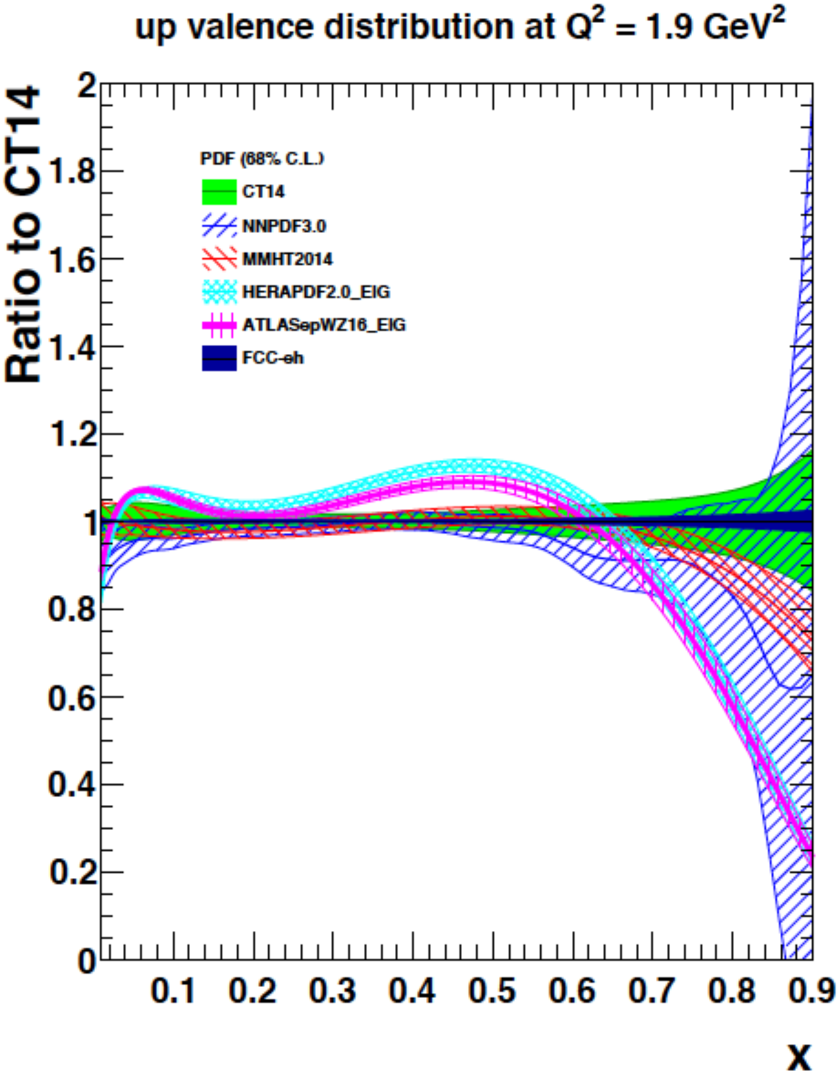
NO pile-up..

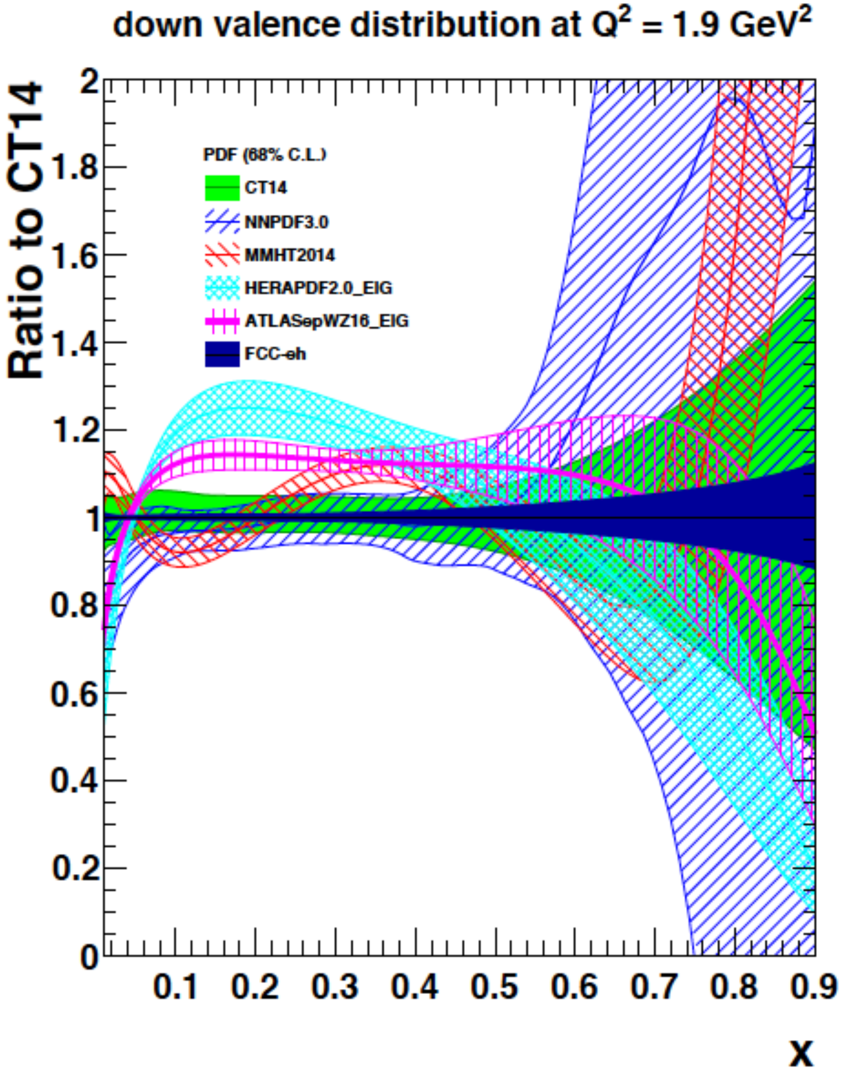
→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

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

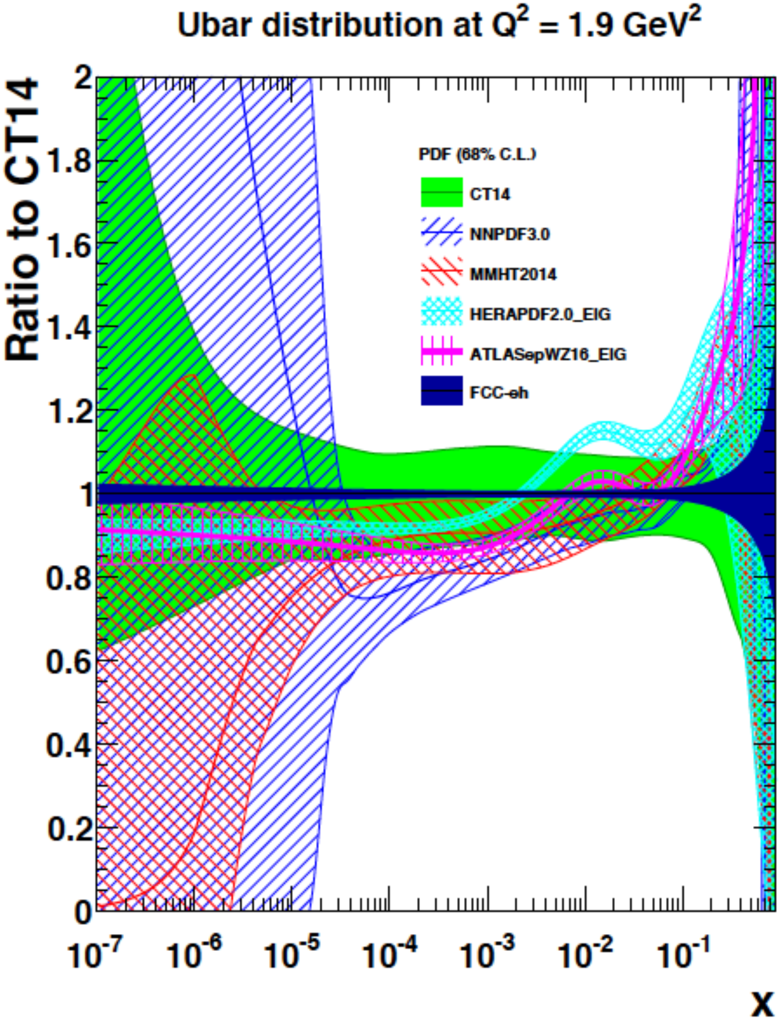
Prospects FCCeh: Valence Quarks

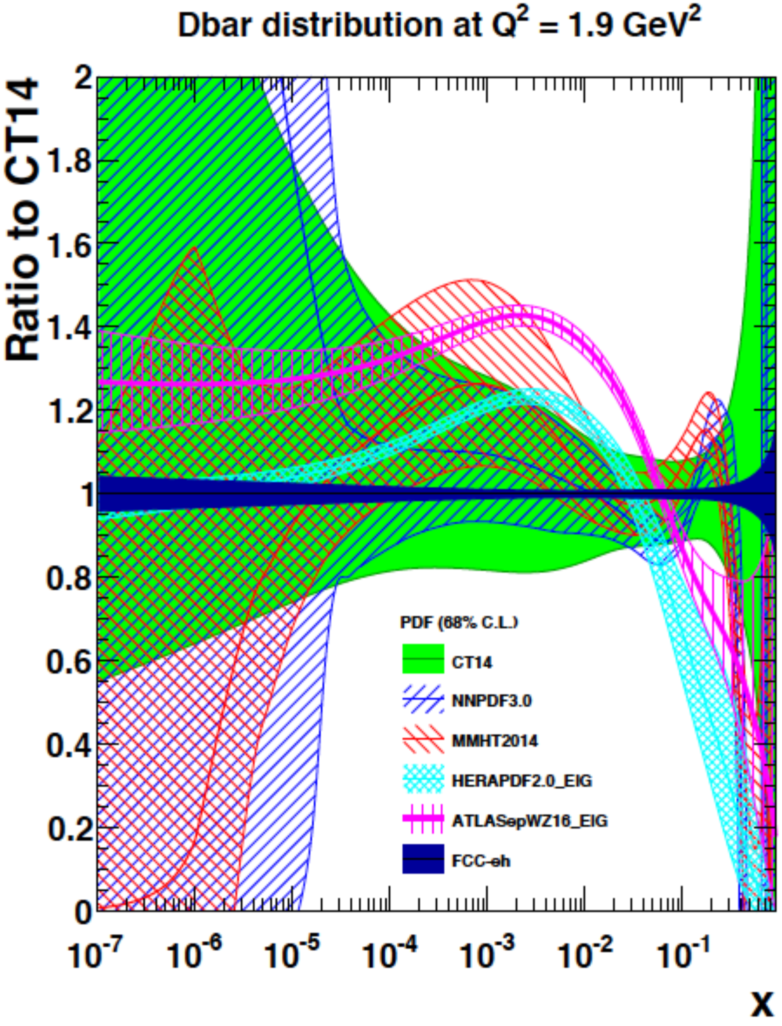




50 years after the discovery of quarks we still do not know the d/u limit for x → 1

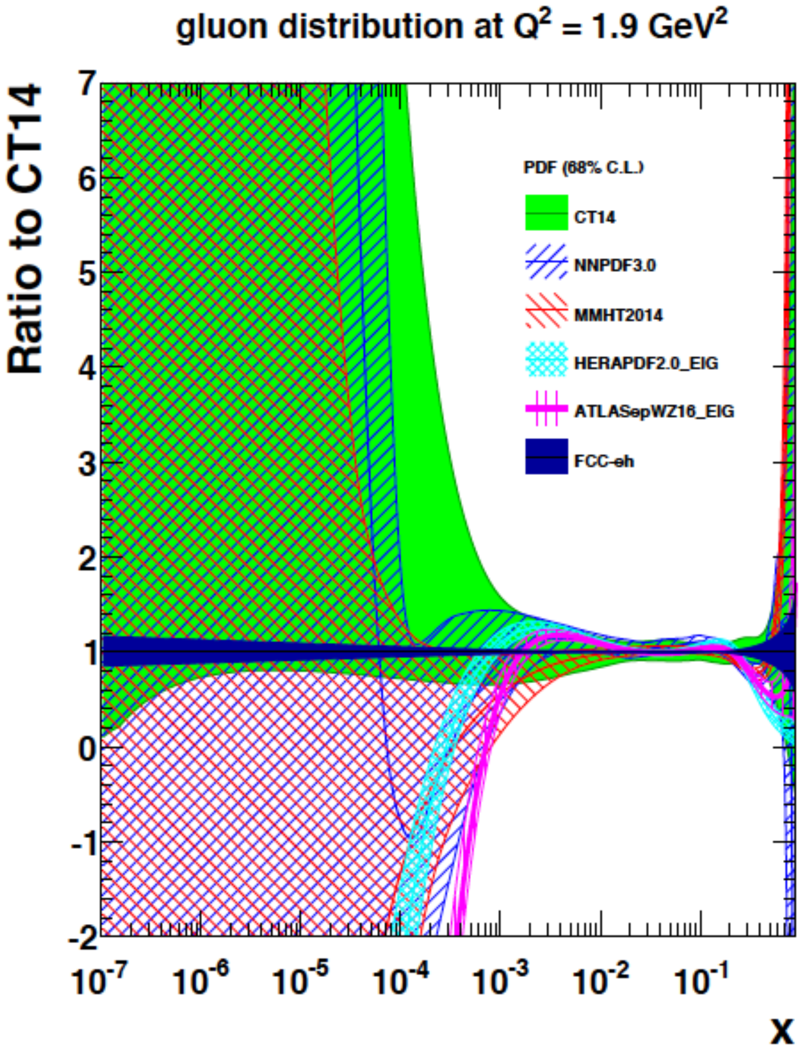
Prospects FCCeh: Sea Quarks



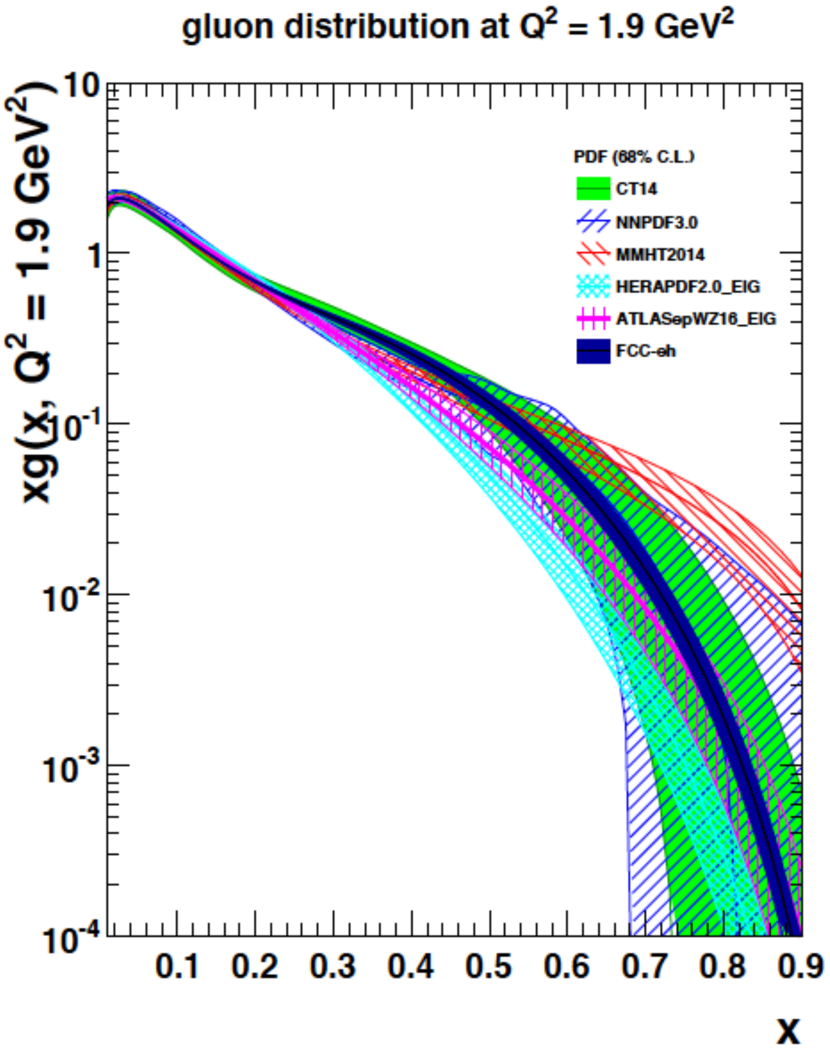


Note this may be obtained from a year of operation (FCCep or LHeC) − study forthcoming

Prospects FCCeh: Gluon Distribution

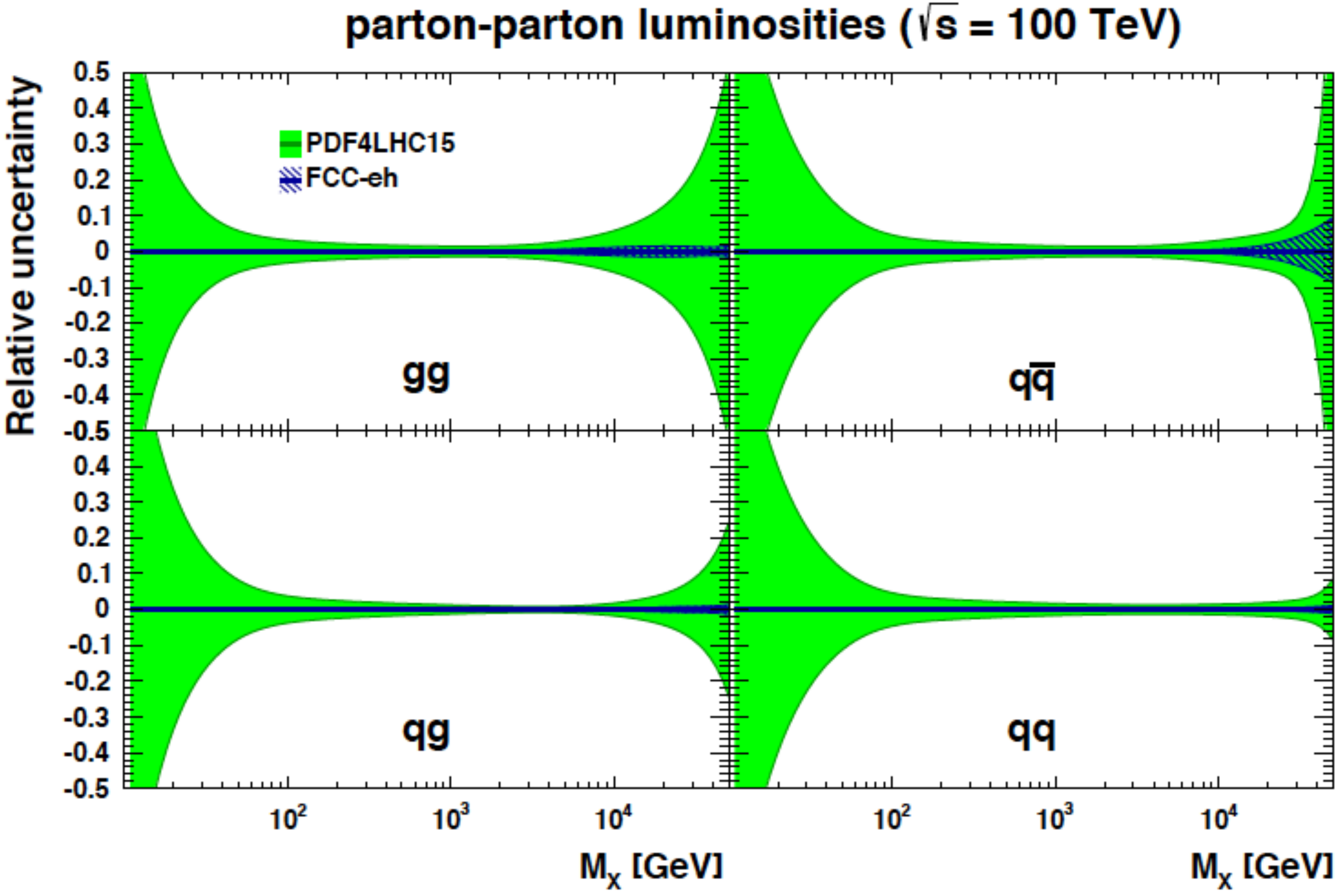


Small x: FCC-ep reaches UHE neutrino range



Large x: inclusive and jets (to come)

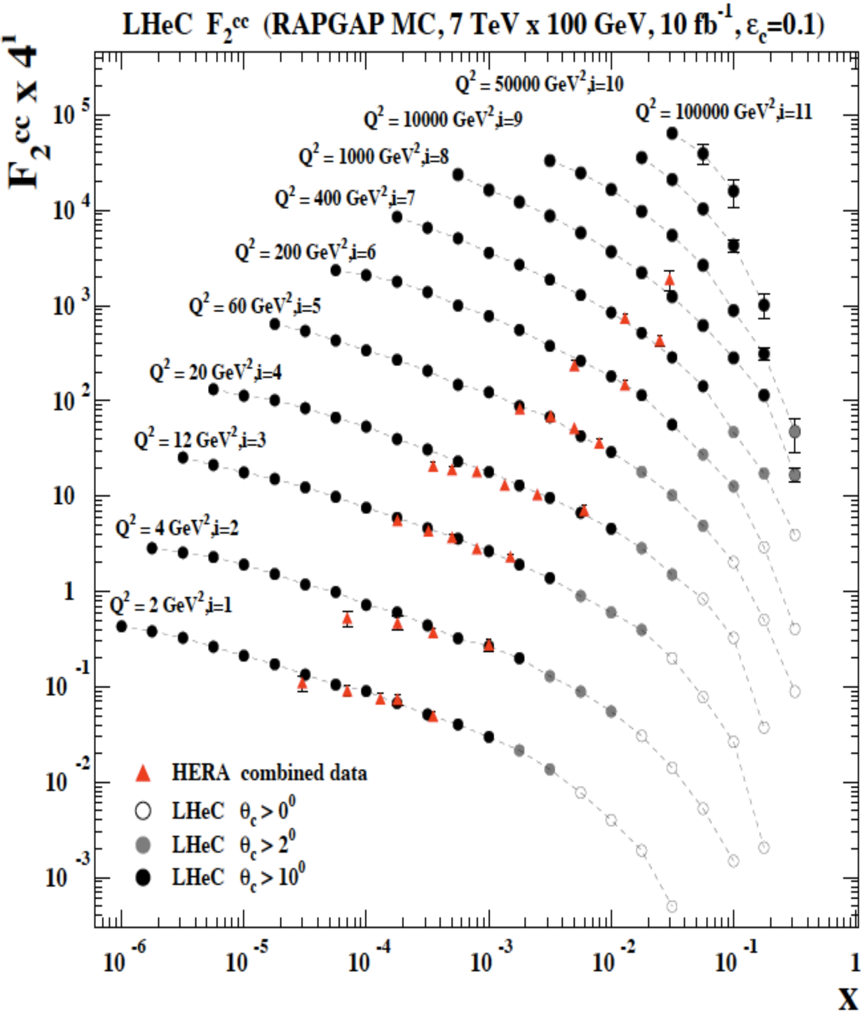
Prospects FCCeh:



Ultimate prediction of pp interactions. external input. Decisive test of factorisation.

Heavy Flavour

Charm: F_2^{cc} and Mass



LHeC CDR arXiv:1206.2913

HERA 0.0005/2.5 .. 0.05/2000 GeV²
LHeC 0.00001/1 .. 0.2/200000 GeV²

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

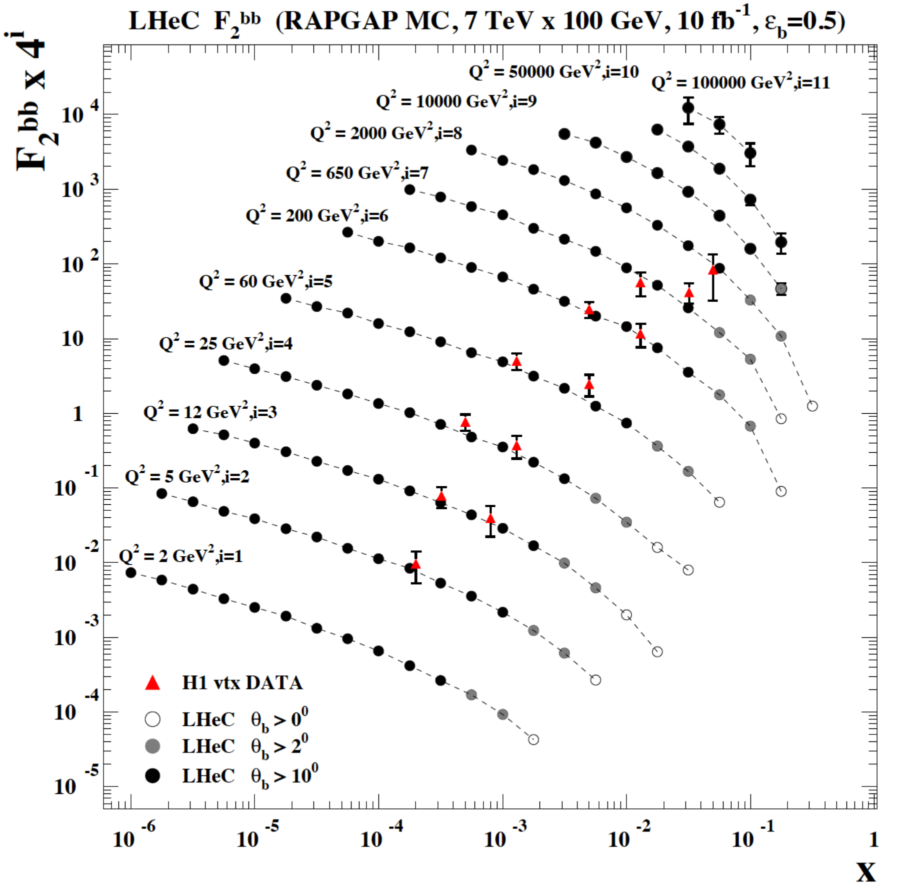
	HERA	LHeC
$m_c(m_c)$/GeV	1.26	?
δ(exp)	0.05	0.003
δ(mod)	0.03	~0.002
δ(par)	0.02	~0.002
$\delta(\alpha_s)$	0.02	0.001

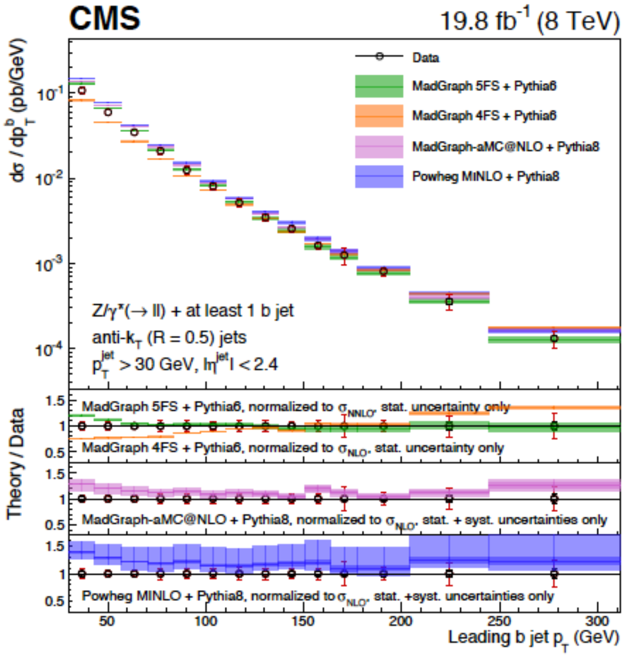
Determination of charm mass to 3 MeV: crucial for M_W in pp or H→ cc in ep

cf also NNPDF3.1 (arXiv:1706.00428) and refs

Bottom: F_2^{bb} and Mass

LHeC CDR arXiv:1206.2913





Bottom density not well known

Scheme dependence affects LHC interpretations

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

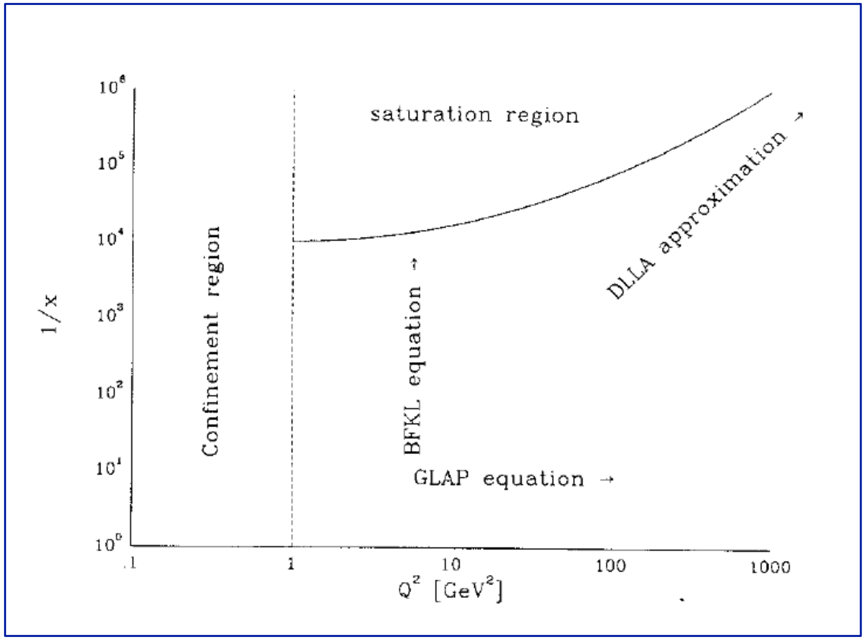
$m_b(m_b)$ with LHeC to 10 MeV

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

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

Physics at Small x

BFKL and Saturation



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

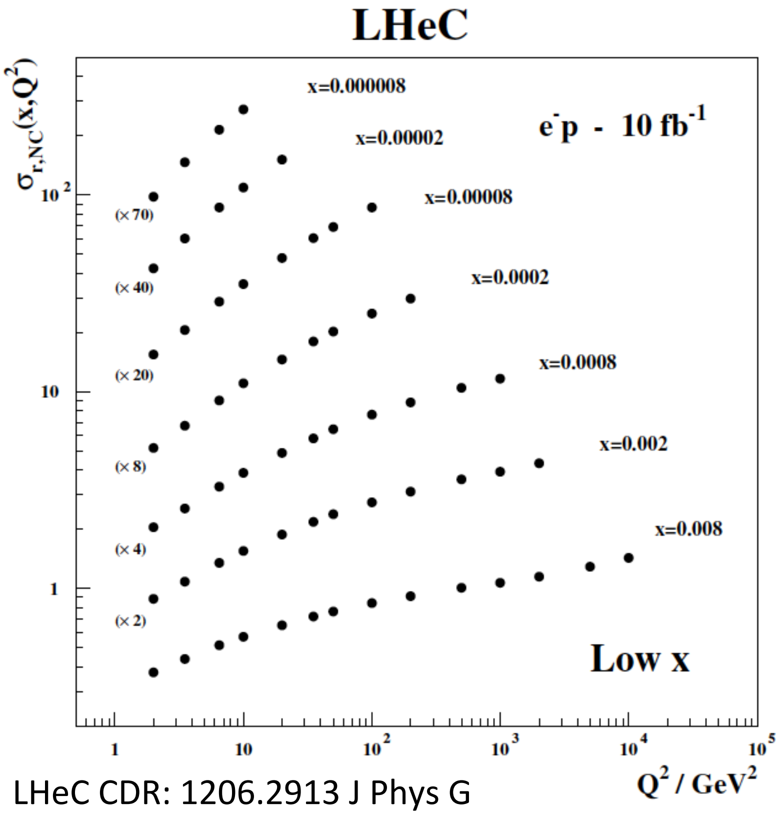
Rise of Gluon (and Quark) densities towards low x discovered at HERA. This may lead to saturation − non-linear interactions and BFKL ln(1/x) effects.
Not discovered at HERA, to much surprise, despite recent 'speculations' ..
Change of parton distributions + evolution → to be clarified for FCC + (HE)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

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

How to determine low x evolution + discover saturation ?

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

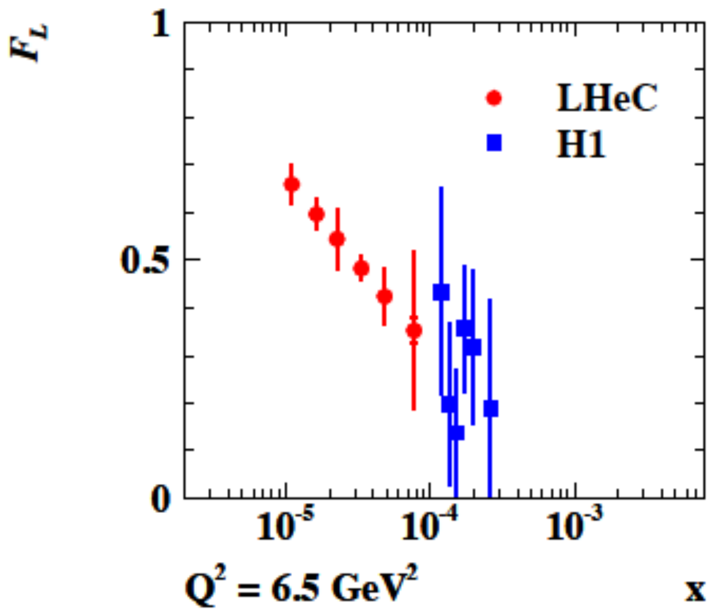
Needs cleanest DIS constraints, proton, not ion, high E: F_2+F_L



LHeC CDR: 1206.2913 J Phys G

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

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



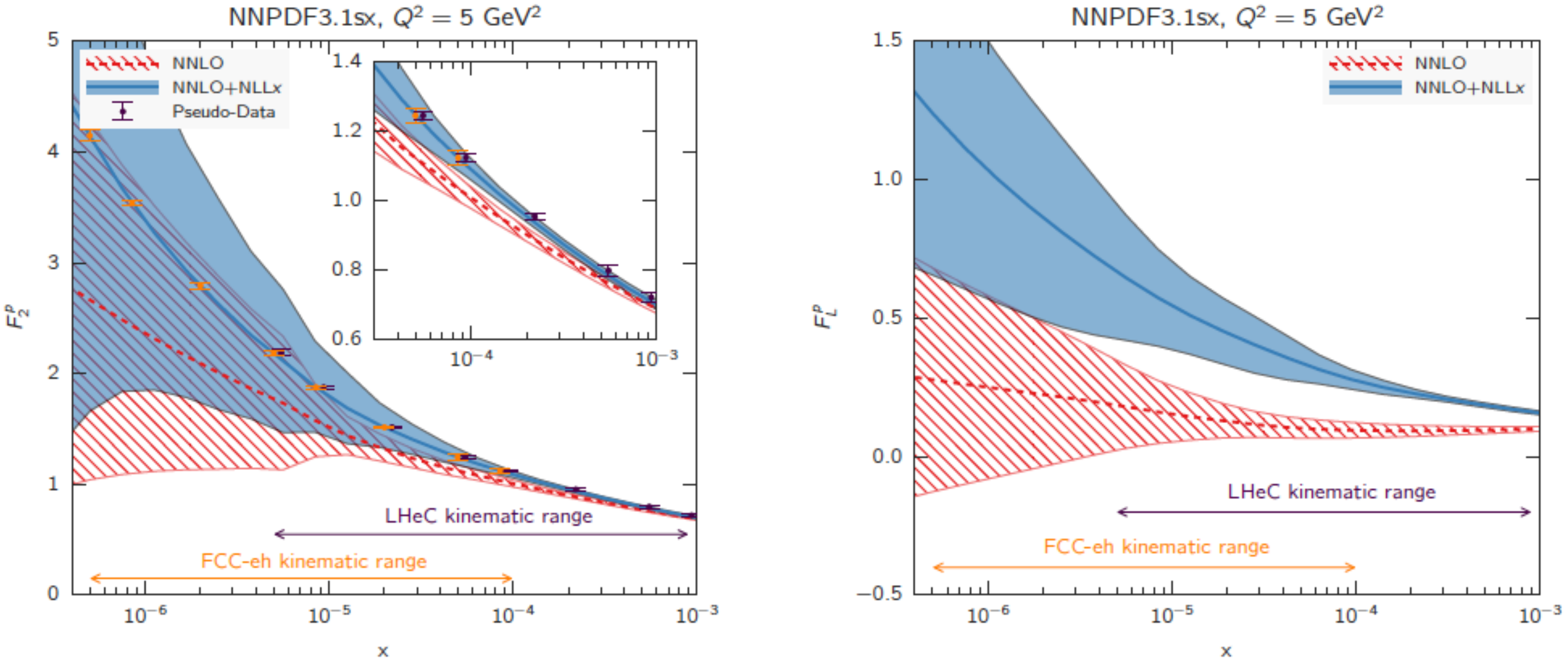
MK: 1802.04317

1802.04317 MK

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

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

BFKL in ep

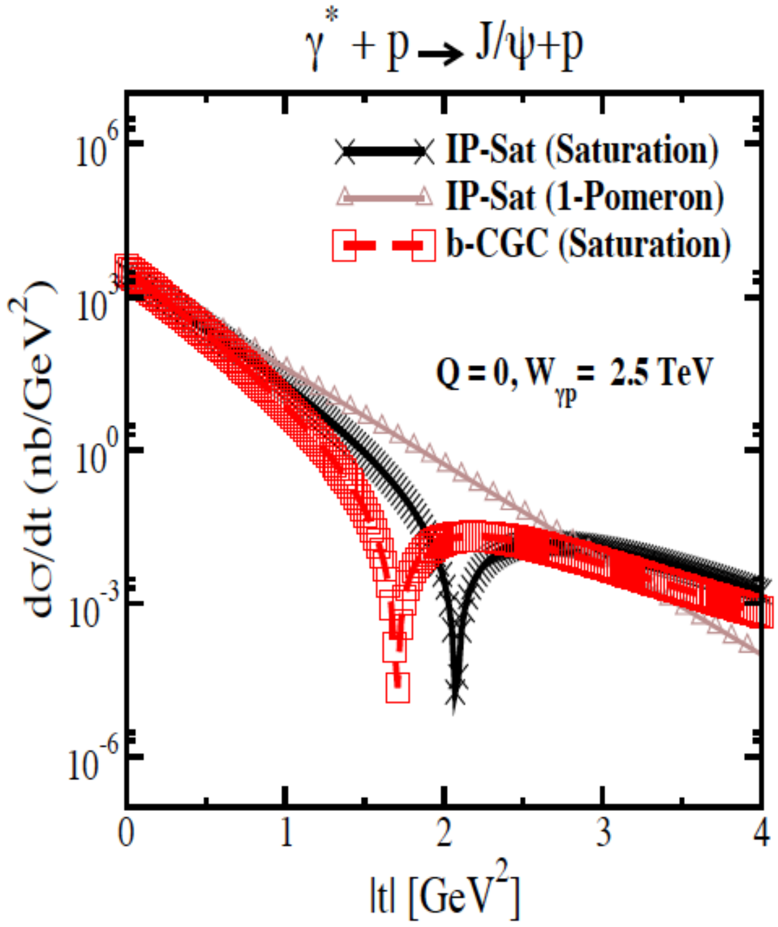


High precision measurements of F_2 and F_L at small x ~ 1/s to discover new parton dynamics

1710.05935 + FCC book

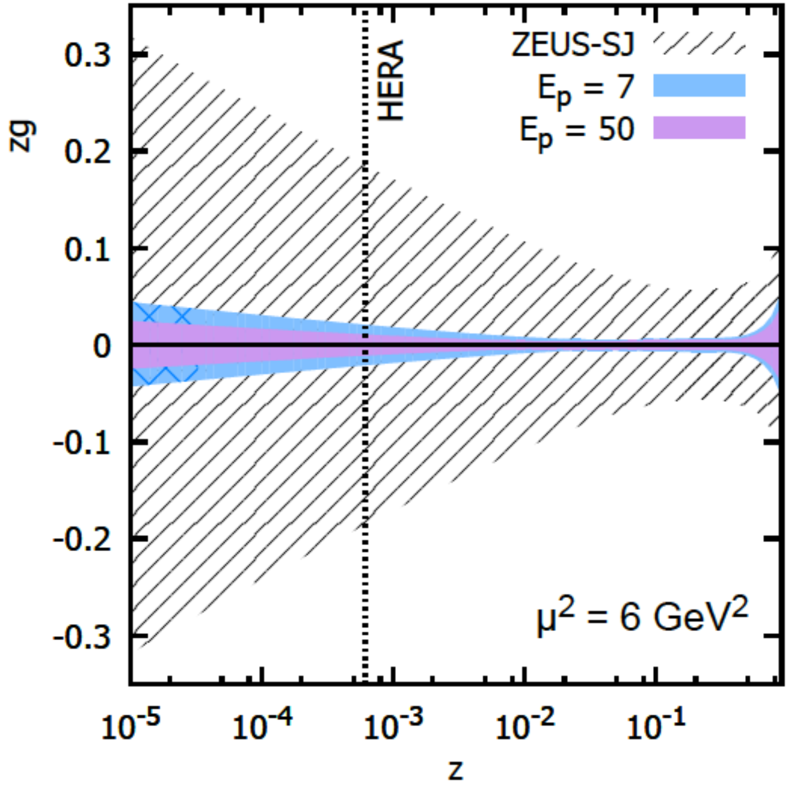
New QCD Physics at Small x in ep

Elastic J/Psi production



t distribution related to Fourier transform of scattering amplitude in impact parameter space

Diffraction

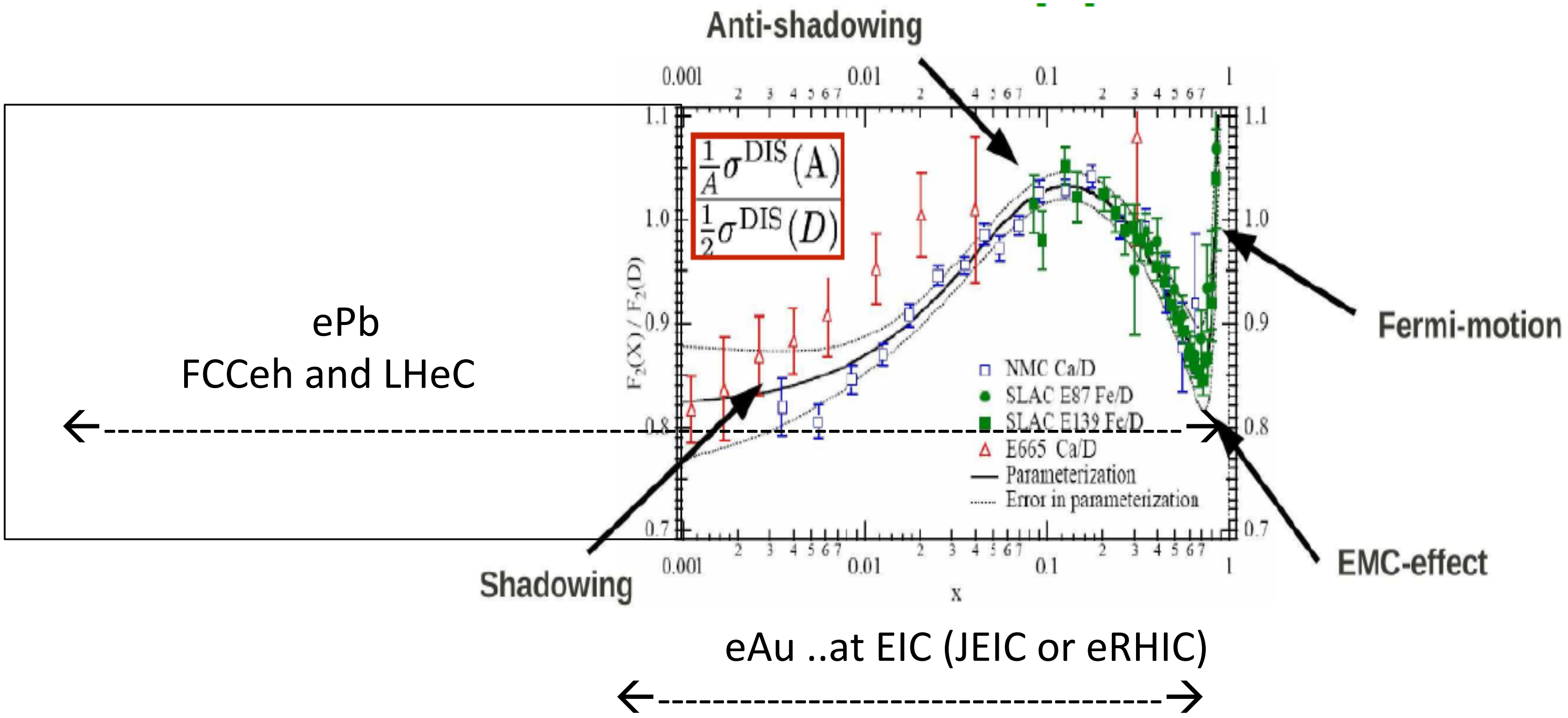


Diffractive gluon density

Electron-Ion Scattering at High Energies

Need high energies to match the QGM scales, to exploit weak interactions and to reach very low Bjorken x. CERN and Europe have a unique EIC scattering programme and should exploit that. Studied as part of the LHeC CDR and for FCCeh.

Goal: QCD of Nuclei, Confinement, Nuclear effects vs non-linear i.a.s, Base of QGP..
Extension of kinematic range by 4 orders of magnitude promises revolutionary changes

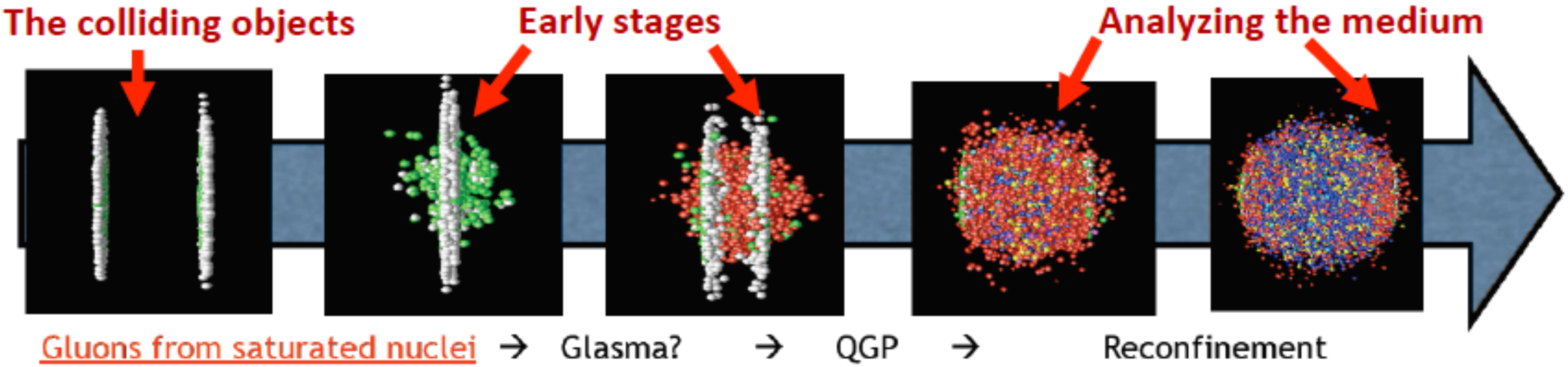


ePb
FCCeh and LHeC

eAu ..at EIC (JEIC or eRHIC)

What we can learn in an ep/eA collider

We do not have a **QUANTITATIVE** understanding of the nuclear behaviour → required for A-A and QGP studies



Dense regime: lack of information about

- small-x partons
- correlations
- transverse structure

Particle production at the very beginning:

- Which factorization?
- How can a system behave as isotropised so fast?

Probing the medium through energetic particles:

- Dynamical mechanisms for opacity
- How to extract accurately medium parameters?

ep and eA:

- nuclear WF & PDFs
- mechanism of particle production
- tomography

ep and eA:

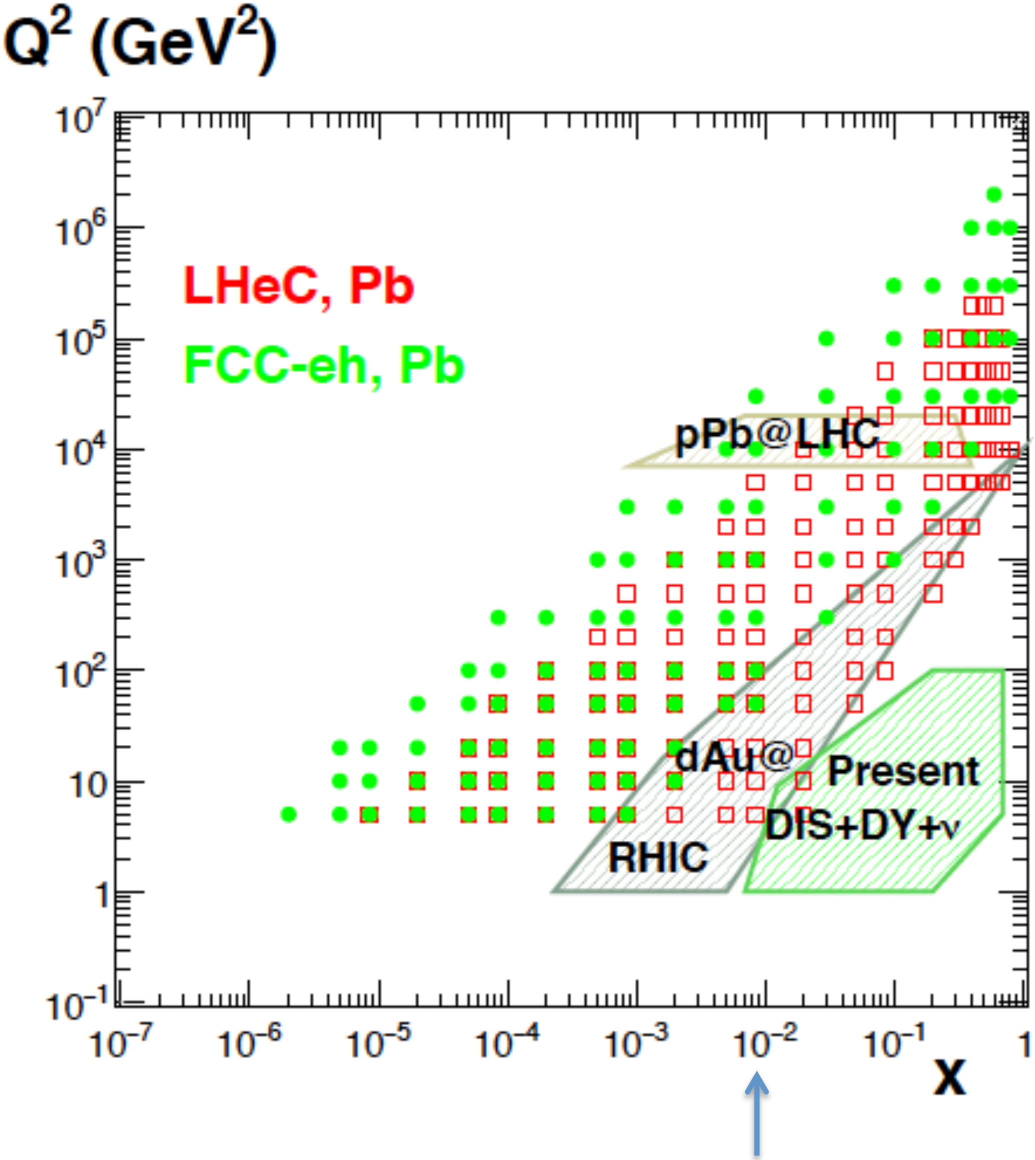
- initial conditions for plasma formation
- how small can a system be and still show collectivity?

ep and eA:

- modification of radiation and hadronization in the nuclear medium
- initial effects on hard probes

N. Armesto DIS2018, Kobe, 17.4.18 and E. Ferreiro, LHeC Workshop 2018, Orsay, 28.6.18

DIS ePb data from LHeC (FCCeh)



x limit of DIS lA data

Huge extension of range. For DIS: 3-4 orders of magnitude

Statistics 10 x HERA ep, about

Very precise: kinematics from scattered lepton and hadronic final state.

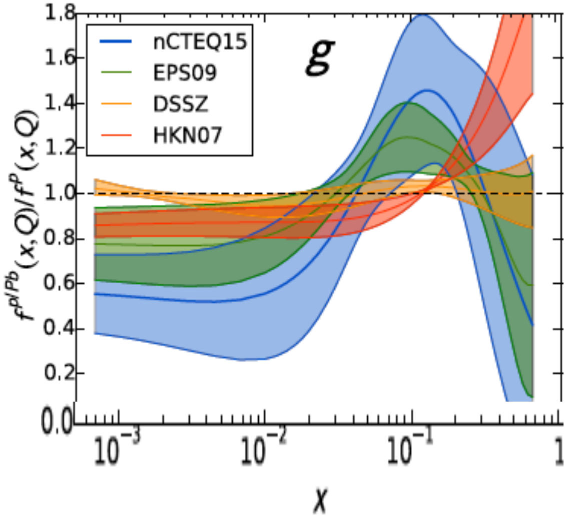
Neutral Current down to x=$10^{-5/6}$
- charm and beauty from ePb

Precise Charged Currents in eA
- **flavour decomposition**
- strange density (Ws → c)

Coherent, precise determination of quark and gluon PDFs for protons and nucleus

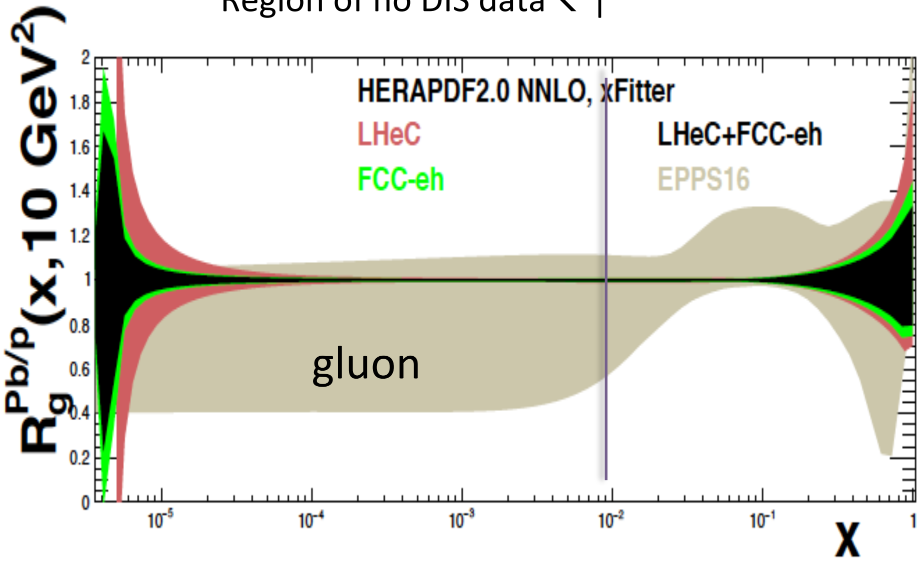
Determination of p and A PDFs at LHeC/FCCeh

present
status →
on xg
Pb/p

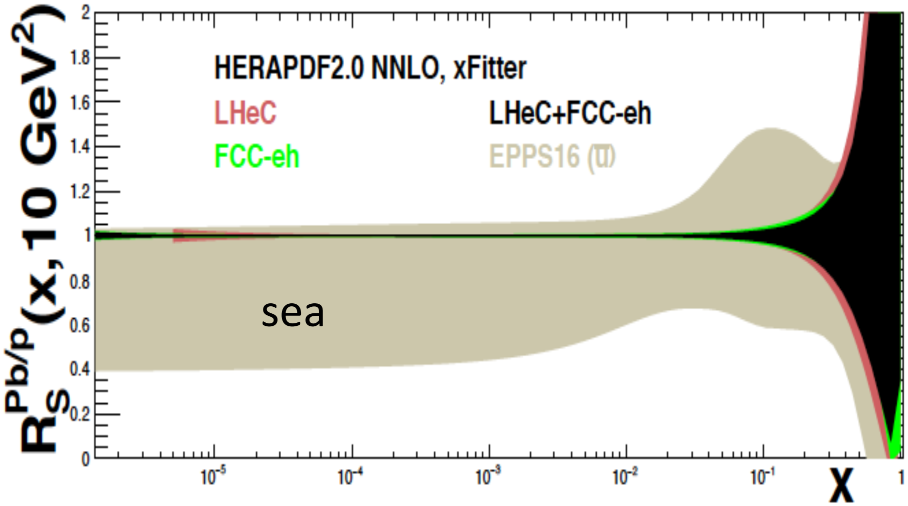


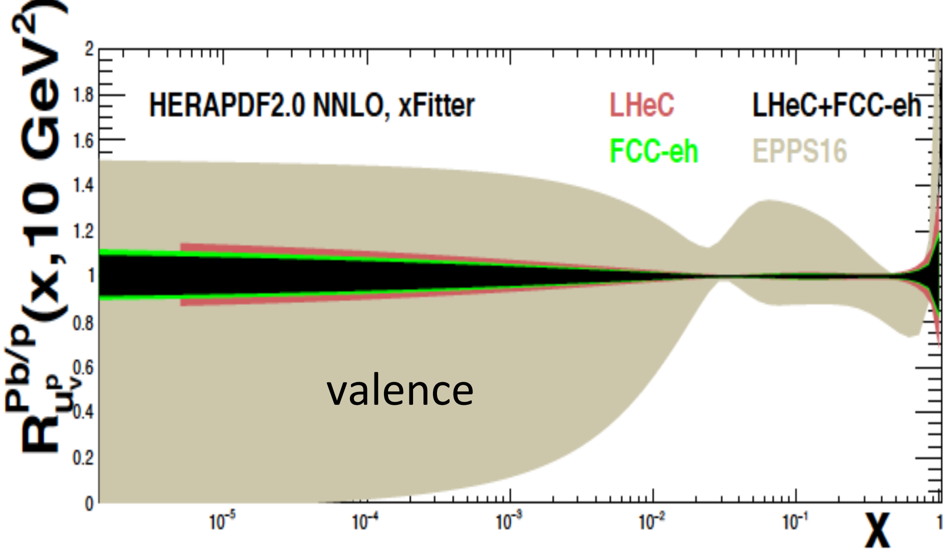
1509.00792

Region of no DIS data ←|



N Armesto, FCC Physics Week 1/2018





LHeC: Full error, $\Delta\chi^2 = 1$. EPPS $\Delta\chi^2 = 52$

Summary

QCD in hh: a tool to understand the observations. Tests at unprecedented scales.
Through LHC QCD got a major boost (theory and phenomenology)

QCD in ee: strong coupling, perturbative parton radiation [jet substructure, fragmentation..]
non-perturbative parton radiation[colour reconnection, hadronisation..]..

QCD in ep: strong coupling to per mille, complete resolution of partonic proton contents
[also n,y,IP and 3D] discovery of non-linear gg interactions, N^3LO prediction of H

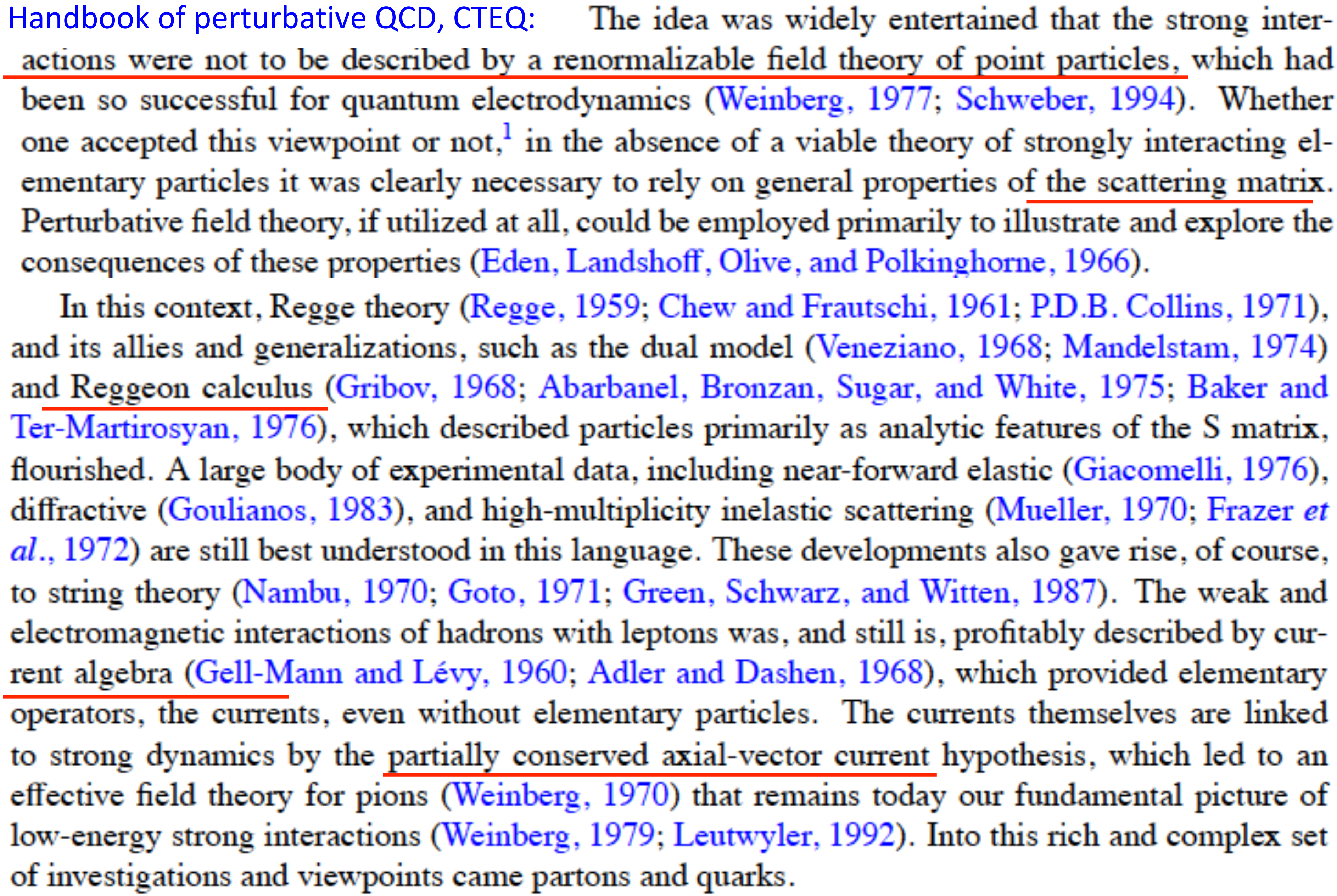
QCD in eA: establish quantitative understanding of parton interactions in nuclei for the
first time. Disentangle nuclear from non-linear effects. The QGP in QCD

QCD in AA: cf Liliana Apolinario later today.

Huge steps from LHC to FCC-hh, from LEP to FCC-ee and from HERA to LHeC/FCCeh. QCD physics at the FCC is a guaranteed and fundamental physics programme which will support and on its own lead to discoveries. QCD remains a most fascinating part of particle physics (related to H, eweak, BSM) and is still far from being 'done'.

backup

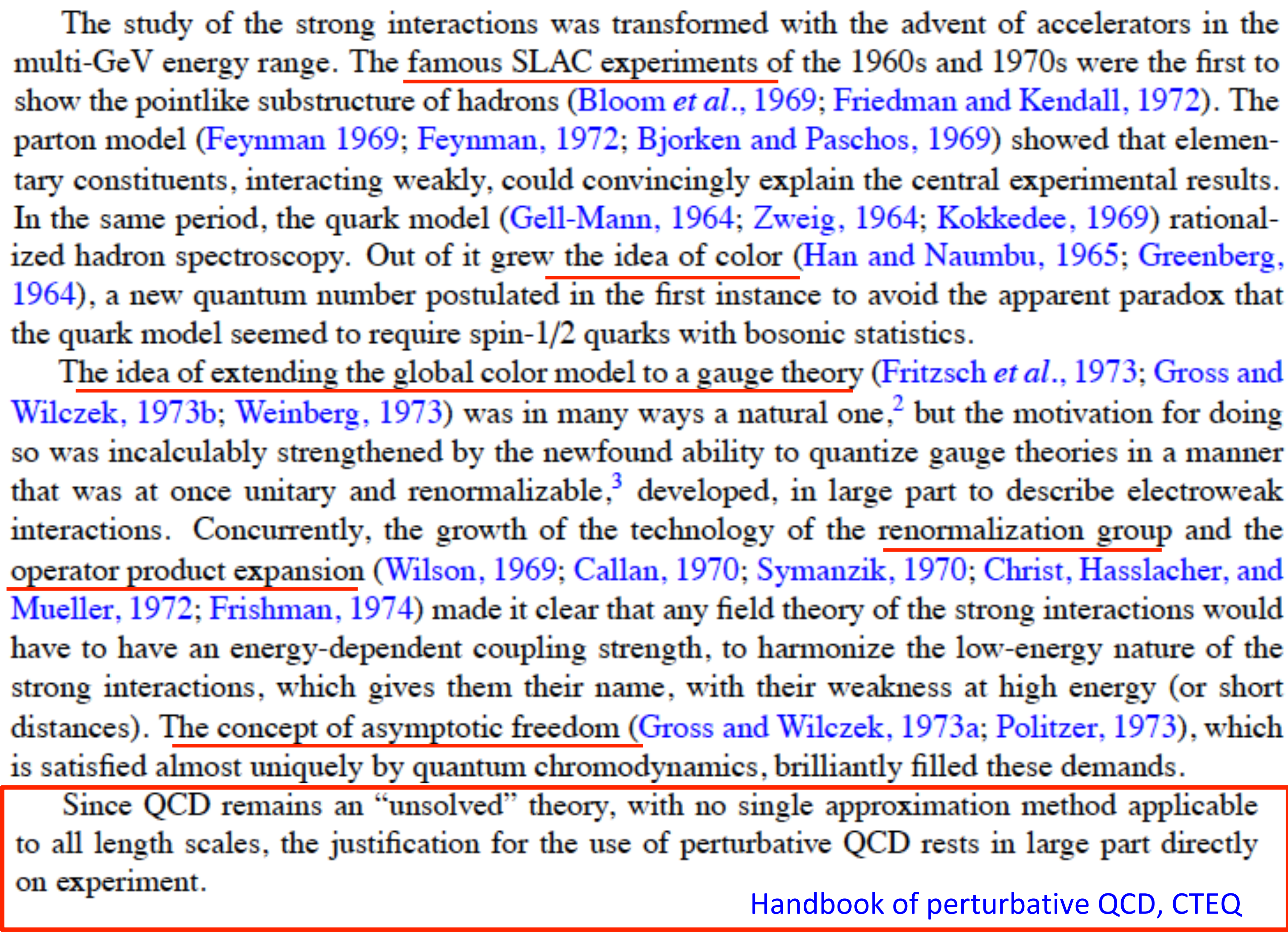
Handbook of perturbative QCD, CTEQ:



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



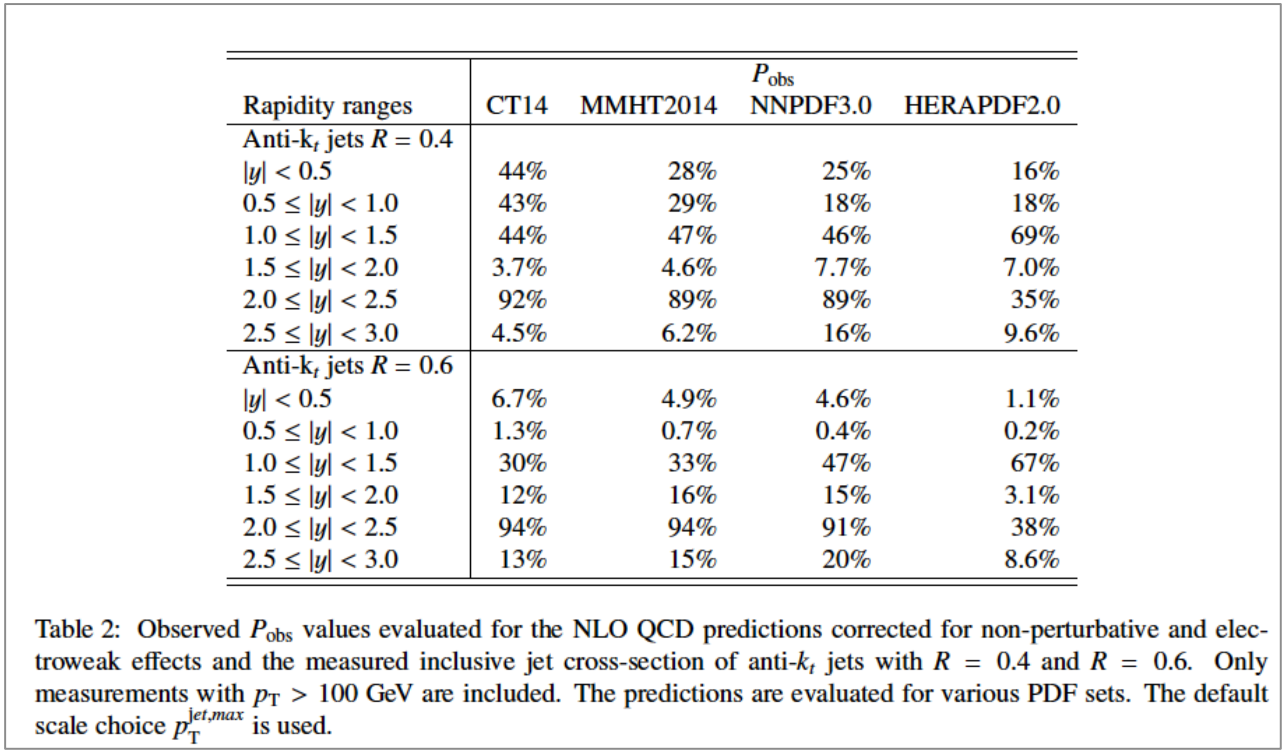
The study of the strong interactions was transformed with the advent of accelerators in the multi-GeV energy range. The famous SLAC experiments of the 1960s and 1970s were the first to show the pointlike substructure of hadrons (Bloom *et al*., 1969; Friedman and Kendall, 1972). The parton model (Feynman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

Jets



Rapidity ranges	P_{obs} CT14	MMHT2014	NNPDF3.0	HERAPDF2.0
Anti-k$_t$ jets $R = 0.4$				
$\|y\| < 0.5$	44%	28%	25%	16%
$0.5 \leq \|y\| < 1.0$	43%	29%	18%	18%
$1.0 \leq \|y\| < 1.5$	44%	47%	46%	69%
$1.5 \leq \|y\| < 2.0$	3.7%	4.6%	7.7%	7.0%
$2.0 \leq \|y\| < 2.5$	92%	89%	89%	35%
$2.5 \leq \|y\| < 3.0$	4.5%	6.2%	16%	9.6%
Anti-k$_t$ jets $R = 0.6$				
$\|y\| < 0.5$	6.7%	4.9%	4.6%	1.1%
$0.5 \leq \|y\| < 1.0$	1.3%	0.7%	0.4%	0.2%
$1.0 \leq \|y\| < 1.5$	30%	33%	47%	67%
$1.5 \leq \|y\| < 2.0$	12%	16%	15%	3.1%
$2.0 \leq \|y\| < 2.5$	94%	94%	91%	38%
$2.5 \leq \|y\| < 3.0$	13%	15%	20%	8.6%

Table 2: Observed P_{obs} values evaluated for the NLO QCD predictions corrected for non-perturbative and electroweak effects and the measured inclusive jet cross-section of anti-k_t jets with $R = 0.4$ and $R = 0.6$. Only measurements with $p_{\mathrm{T}} > 100$ GeV are included. The predictions are evaluated for various PDF sets. The default scale choice $p_{\mathrm{T}}^{\mathrm{jet,max}}$ is used.

NNPDF
1706.00428

Impossible to achieve a good description of all rapidity bins with correlations included…

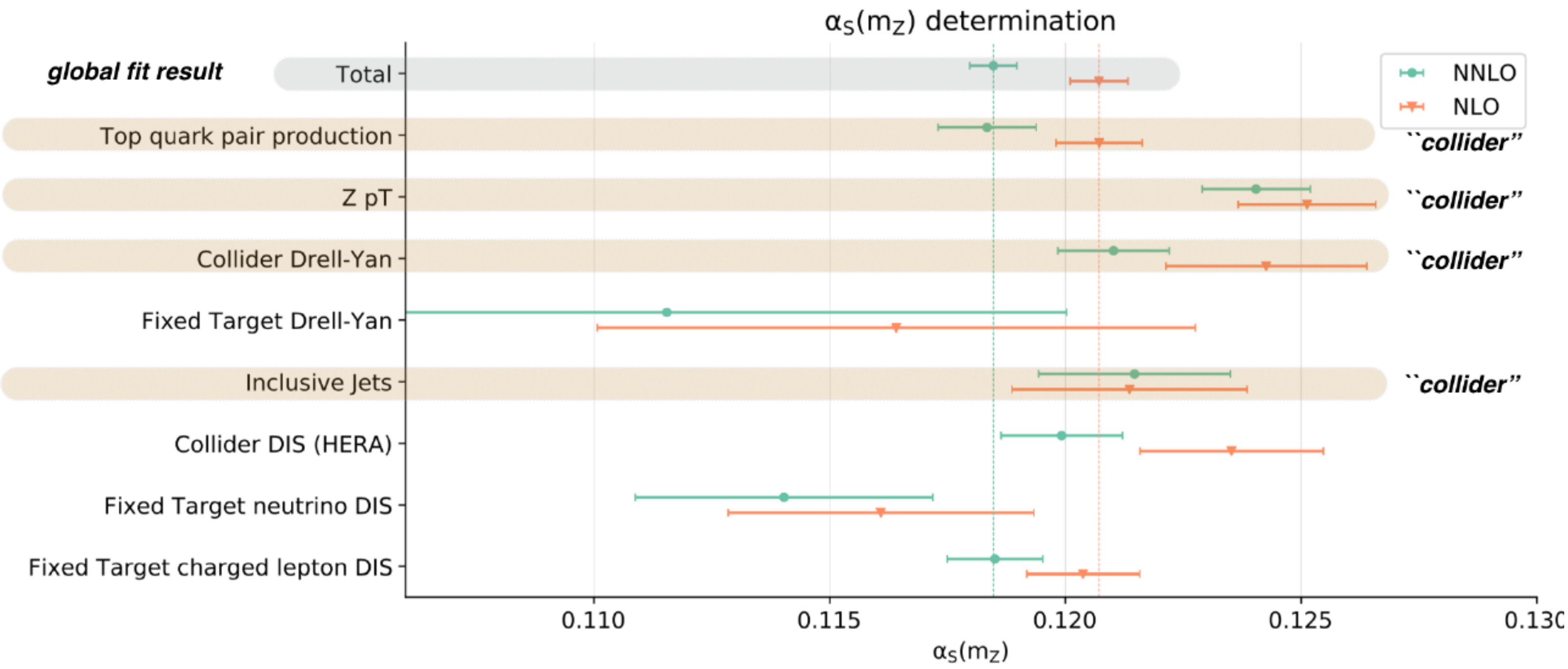
Used only central bin

ATLAS: 1706.03192 8 TeV jet data
“Tensions between the data and the theory predictions are observed”

CT14 best, but not good, and HERAPDF2.0 worst, as opposed to W paper

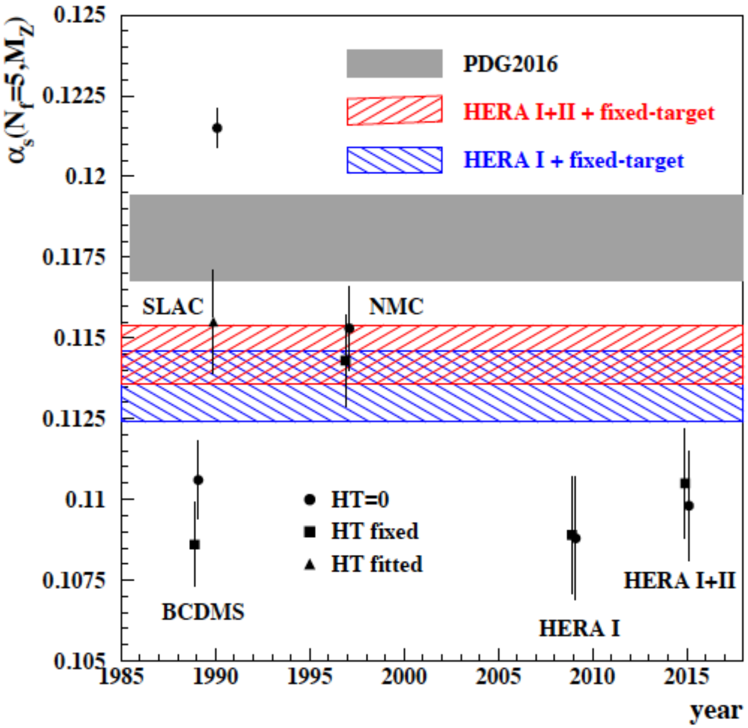
Very extensive studies on data correlations, including also 7 + 13 TeV

Strong Coupling

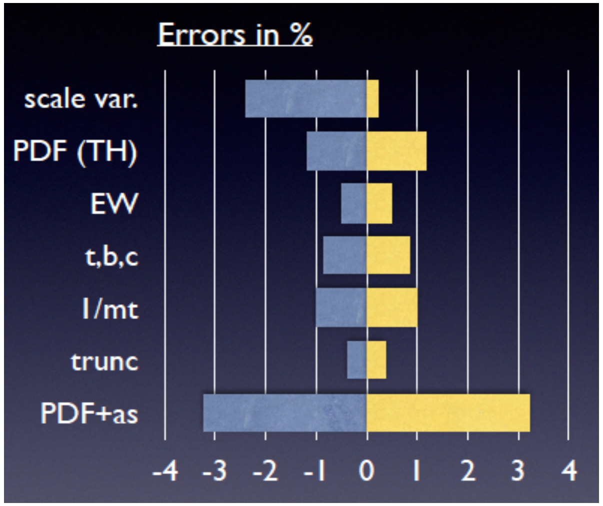


1811.11801

Strong Coupling Constant in ep: DIS



ABM
2017



C.Anastasiou et al, 1602.00695

DIS at N^3LO to match gg→H cross section

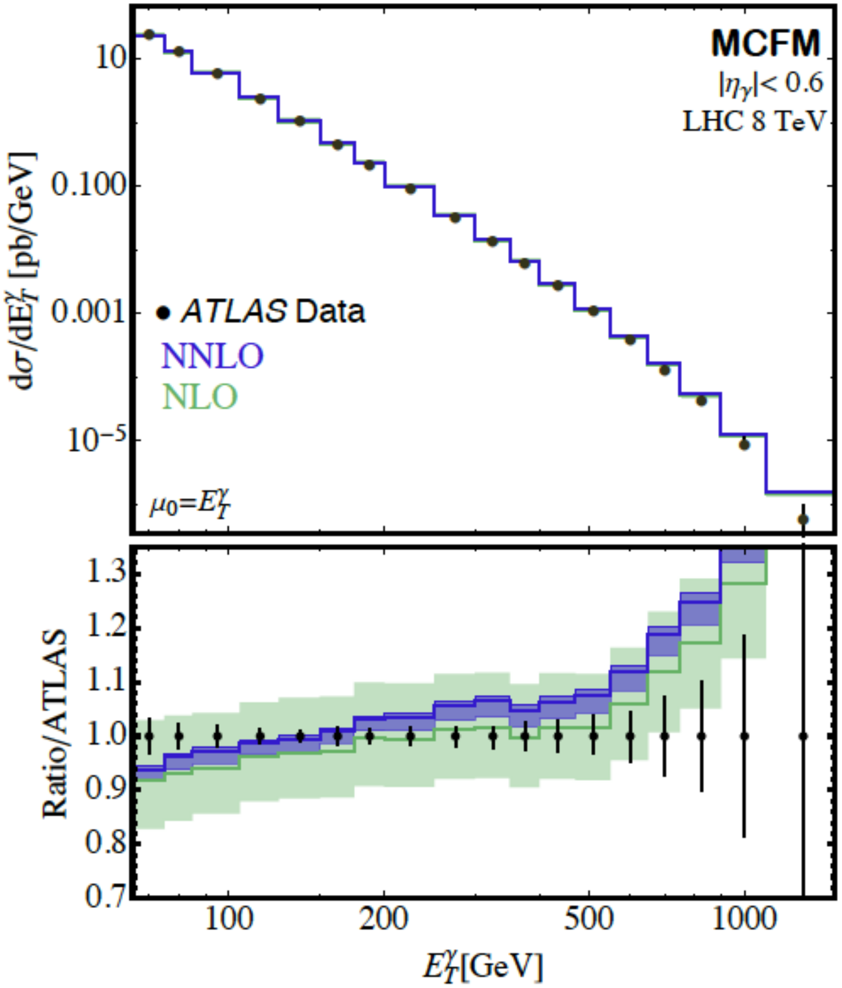
LHeC simulation, NC+CC inclusive, total exp error

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

Two independent QCD analyses using LHeC+HERA/BCDMS

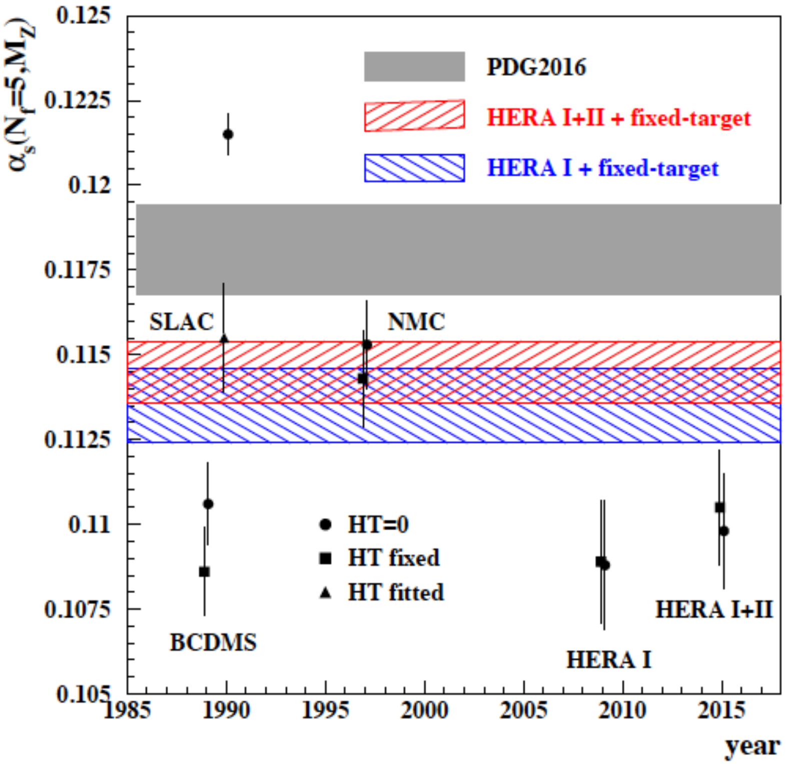
- Is α_s(DIS) lower than world average (?)
- Independent of BCDMS!
- Inclusive vs α_s(jets)??
- Inclusive DIS at LHeC or FCCeh: 0.2% →
- Redundant kinematics. DIS to N^3LO

Direct Photons



1612.04333 direct y at NNLO

$\alpha_s(\mu)$ 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

W and Z