Opportunities and challenges for QCD physics in high-energy ep collisions at future facilities

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Speaker's affiliations :

ATLAS

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LHeC

FCC hh ee he

Granada, European Strategy Meeting, May 15th, 2019

Future eh Colliders: EIC *and* LHeC

Most advanced proposals

EIC:

$E_{c.m.s.}$ ~ 0.020- 0.14 TeV

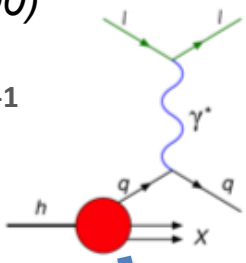
White Paper: arXiv:1212.17010; **#99**

- *Polarised electrons with E_e ~3–20 GeV*
- ***Polarised** (70%) **proton** beams and unpolarised heavy ion beams (A≤200)*
- *High luminosity for **spin physics.***
- **ep peak lumi 10^{33} – 10^{34} cm s^{-2} s^{-1}**

World's first polarised e-p collider and medium energy e-A collider below HERA c.m.s. energy

x_{min} ~ 1 x 10^{-4}

Q^2_{max} ~ 10^3 -10^4 GeV^2



Unravel non-perturbative proton structure with new measurements

LHeC:

$E_{c.m.s.}$ 0.2 - **1.3 TeV**

CDR J. Phys. G 39, 075001 (2012**); #159**

- ***Polarised** electrons with E_e ~30-60 GeV to probe unpolarised LHC proton and ion beams*
- *High luminosity for high Q^2*
- *Lower c.m.s. reached by lowering e and p beam energies to 10 GeV and 1 TeV resp.*
- **ep peak lumi 10^{34} cm s^{-2} s^{-1}**

High-energy frontier e-p and e-A collider running simultaneously with HL-LHC, expanding hugely HERA kinematics ➔ exploring QCD+EW sector (e.g. top, Higgs, BSM…) above HERA c.m.s. energy

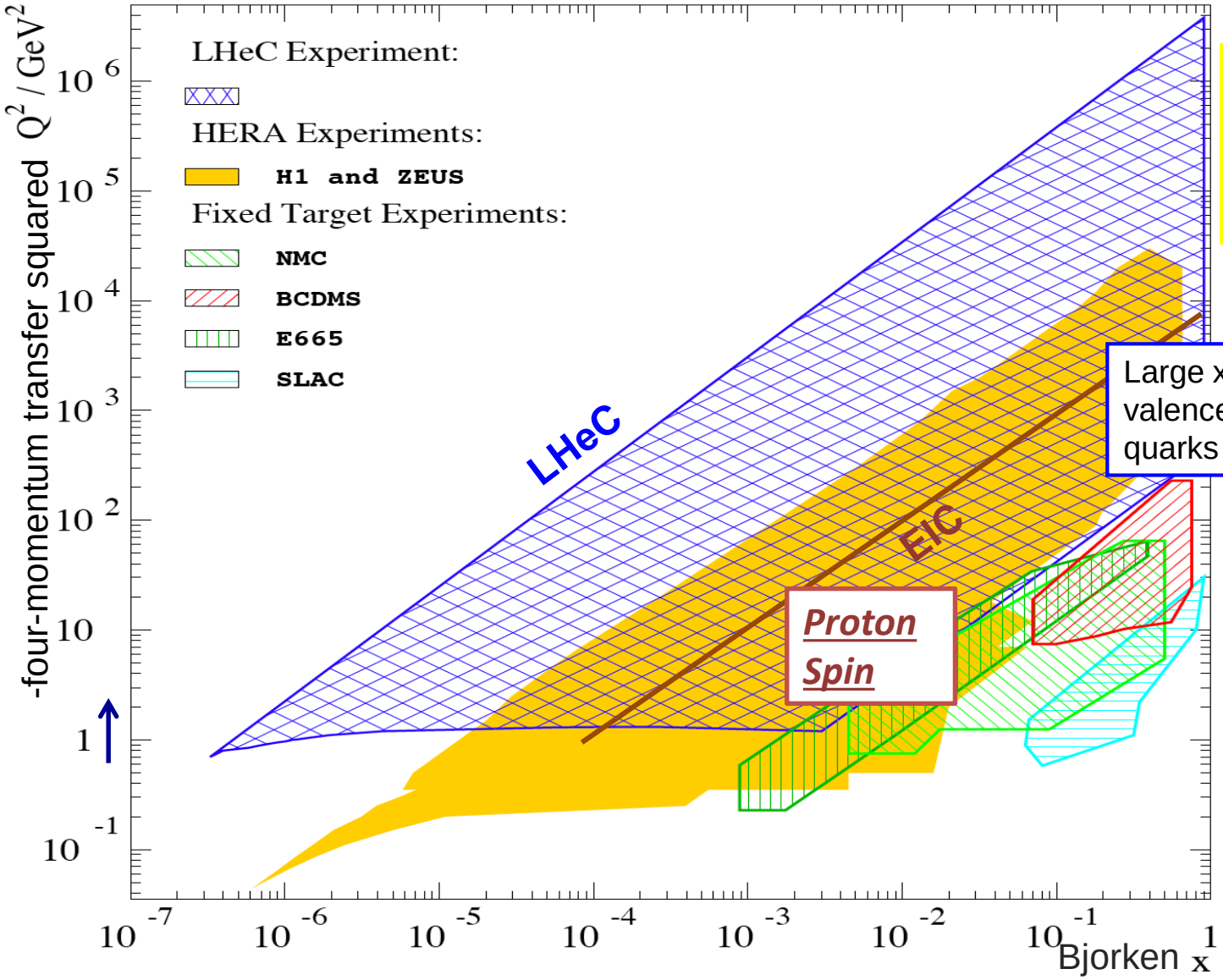
x_{min} ~ 6 x 10^{-7}

Q^2_{max} ~ 10^5 -10^6 GeV^2

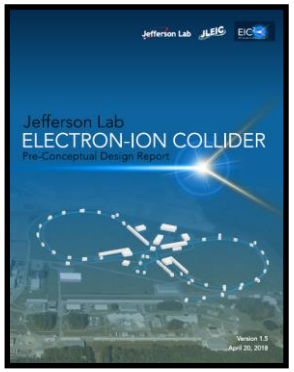
White Paper: arXiv:1212.17010

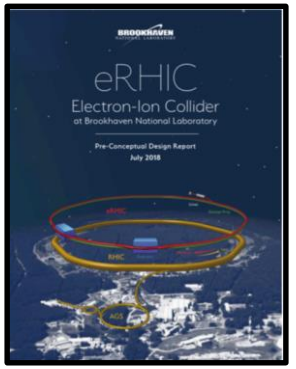
The *Spin* Physics at US-EICs

using polarised e and polarised p beams to unfold spin structure of nucleons



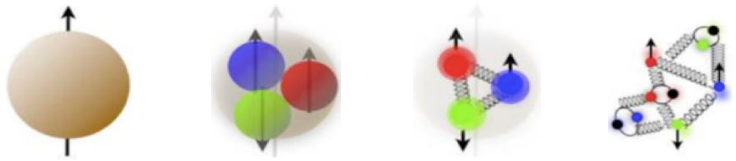
Two realization concepts being developed.
Realization could be as early as 2028-2030.





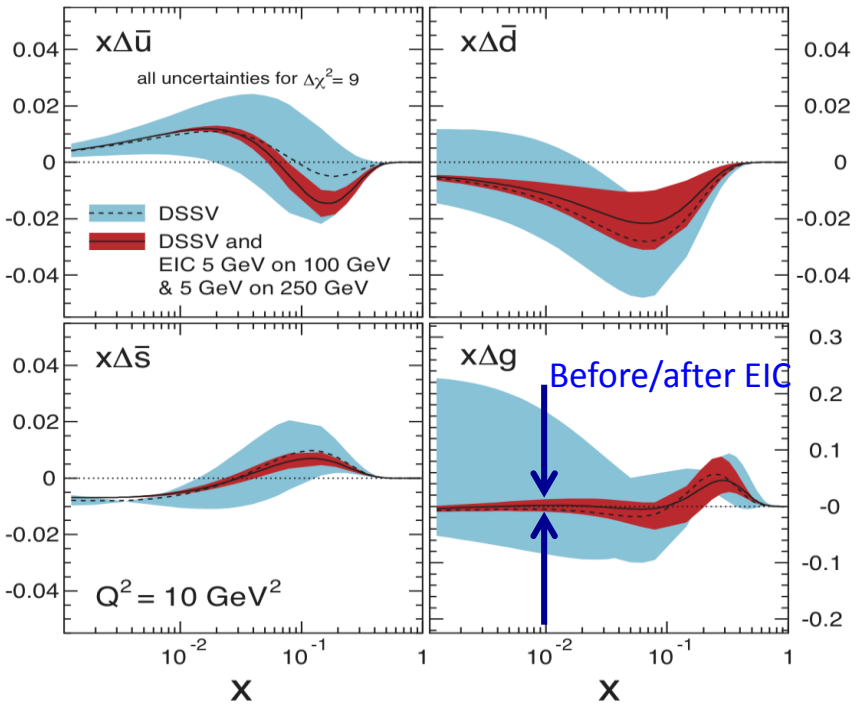
Proton Spin @ EIC

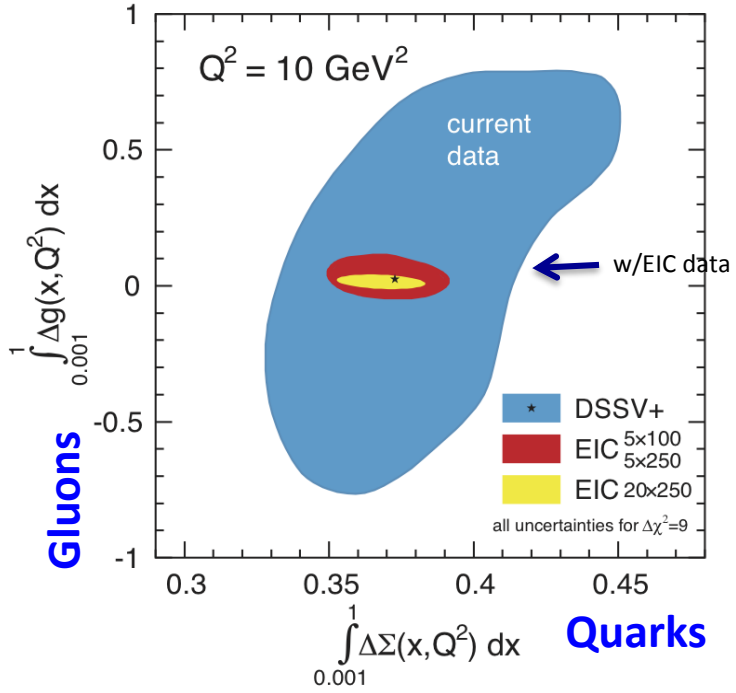
$S(\mu) = \frac{1}{2}$



$\mu \Rightarrow \infty$

Requires longitudinally polarised hadron and electron beams ➔ unique for EIC !





✧ ***Precision measurement of ΔG and ΔΣ via extension to smaller x regime via pQCD scaling violations:*** *challenging measurements since spin asymmetries ➔ 0 for small x*

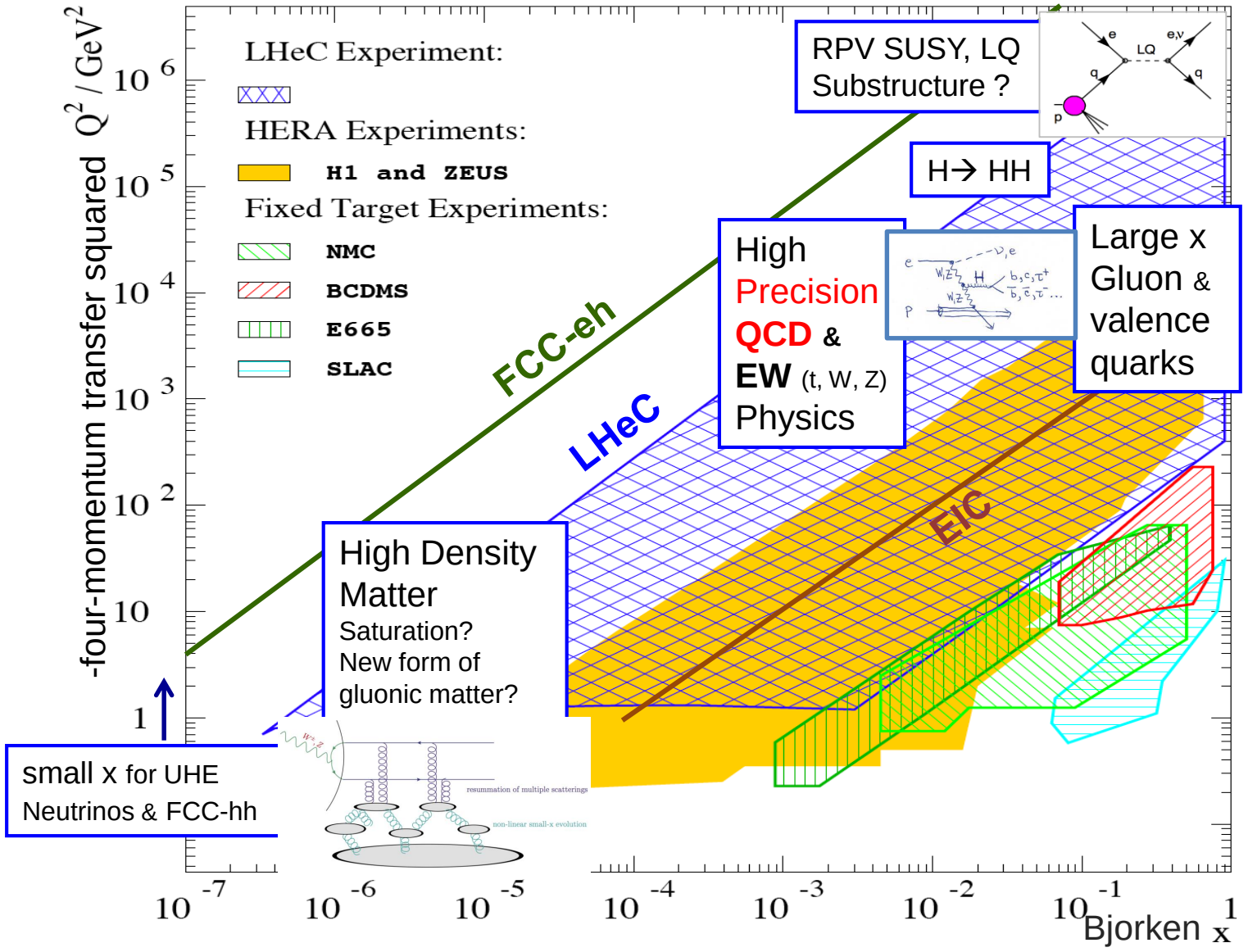
✧ ***Orbital angular momentum L? Explore spin & quantum correlations observables***

➔ ***(Spatial distance from origin) X (Transverse Momentum)***

➔ *needs a wealth of exp. data but link of observables to L remains theoretically challenging*

The ep Physics at the Energy Frontier

and unfold hadron sub-structure for LHC and FCC-hh unambiguously



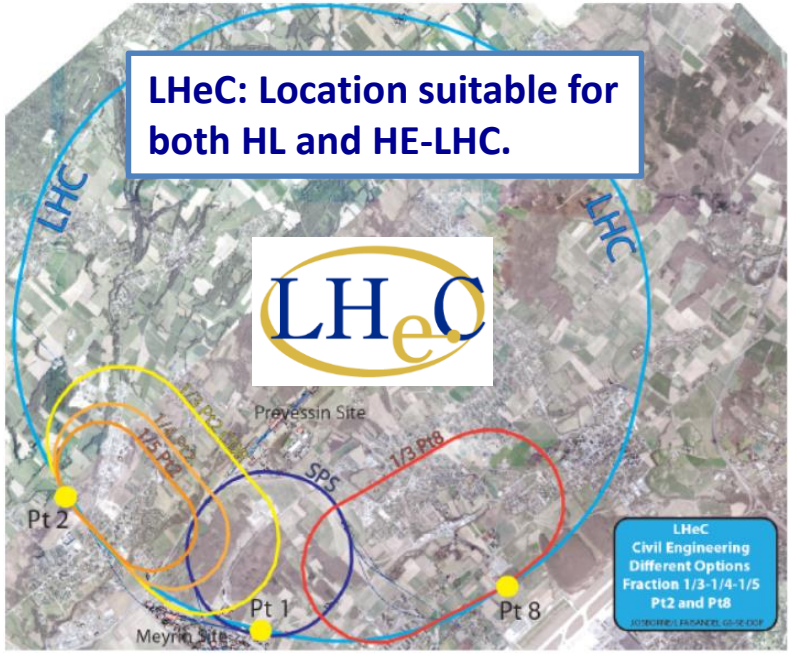
New ep colliders beyond HERA c.m.s.

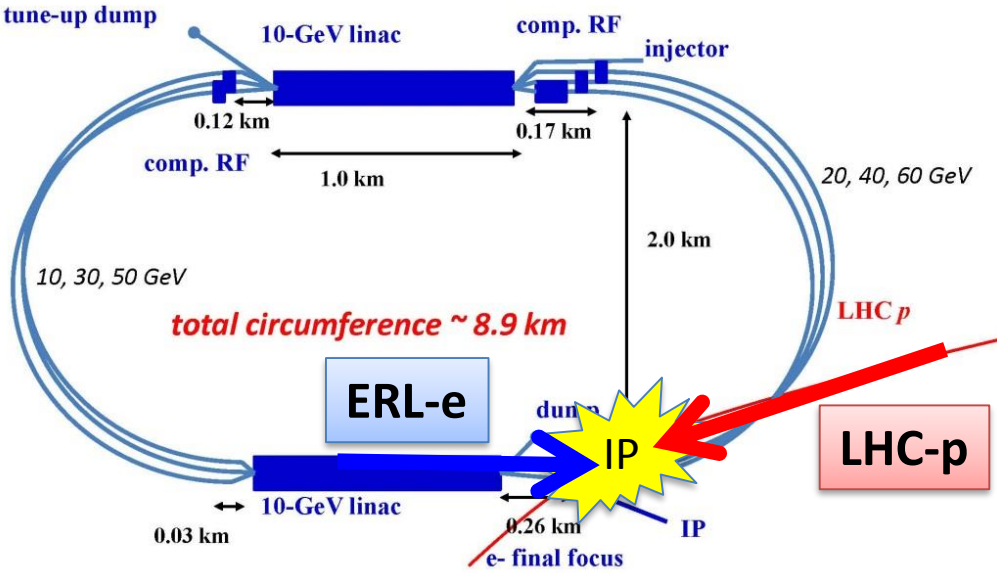
Extensions of both x and Q^2 ranges are crucial for pp experiments and HEP theory developments;

HERA established the validity of pQCD down to $x > 10^{-4}$ (DGLAP) due to a very high lever arm in Q^2:

→ high luminosity colliders with high c.m.s. energy of 1.3 – 3.5 TeV

LHeC electrons for hh : ERL + LHC/FCC





Concurrent eh and LHC operation!
Same ***Twin Collider*** idea holds for HE-LHC and FCC-hh

Nominal: 60 GeV e-ERL external to pp rings
LHC pp@14 TeV & **ep@1.3 TeV : LHeC**
HE-LHC pp@27 TeV & ep@1.8 TeV : HE-LHeC
FCC pp@100 TeV & **ep@3.5 TeV : FCC-eh**

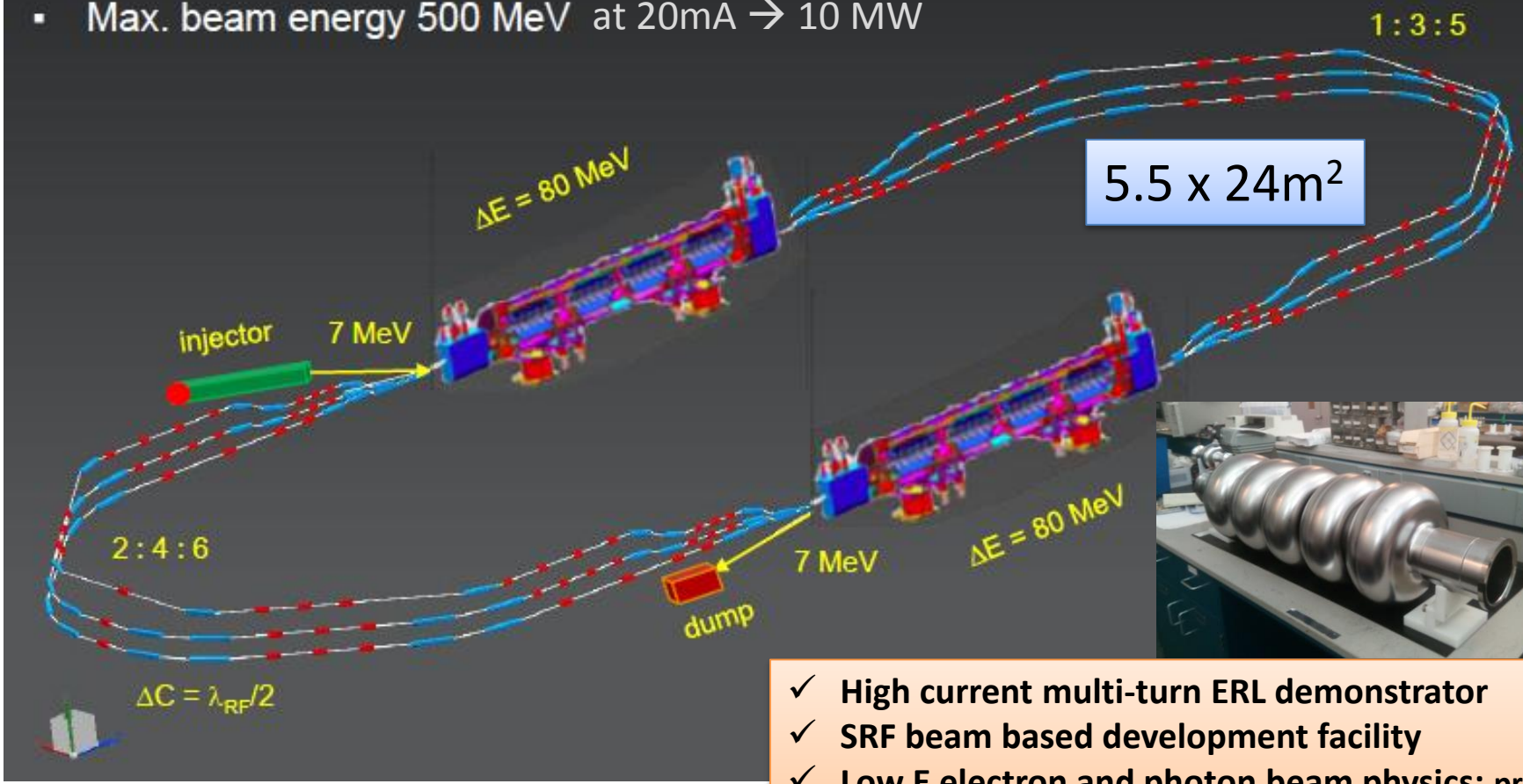
- LHeC realization could be in LS4
- **For full QCD programme: L= 50 fb^{-1} total collected in first 3 years** → 100X HERA luminosity!
- **Operation scenario: F. Bodry et al.** CERN-ACC-2018-0037 [arXiv:1810.13022]

ERL design detailed in **LHeC CDR: arXiv:1206.2913** and updates at LHeC/FCC-eh WS@CERN, 9/17 and Orsay, 6/18 and next WS in October, 24-25, 2019

For ERL: PERLE @ Orsay

CERN, JLAB, Daresbury, Liverpool, Novosibirsk, LAL and IPN, +

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



- ✓ **High current multi-turn ERL demonstrator**
- ✓ **SRF beam based development facility**
- ✓ **Low E electron and photon beam physics: proton radius, sin2theta, photo-nuclear physics**
- ✓ **High intensity: O(100) x ELI**

cf Walid Kaabi, FCC Week 2018, update DIS2019

Five themes for discussion

"DGLAP" proton (sub) structure

Low-x parton dynamics
& gluon saturation?

Beyond the collinear parton model:
opening a new QCD lab & 3D nucleon

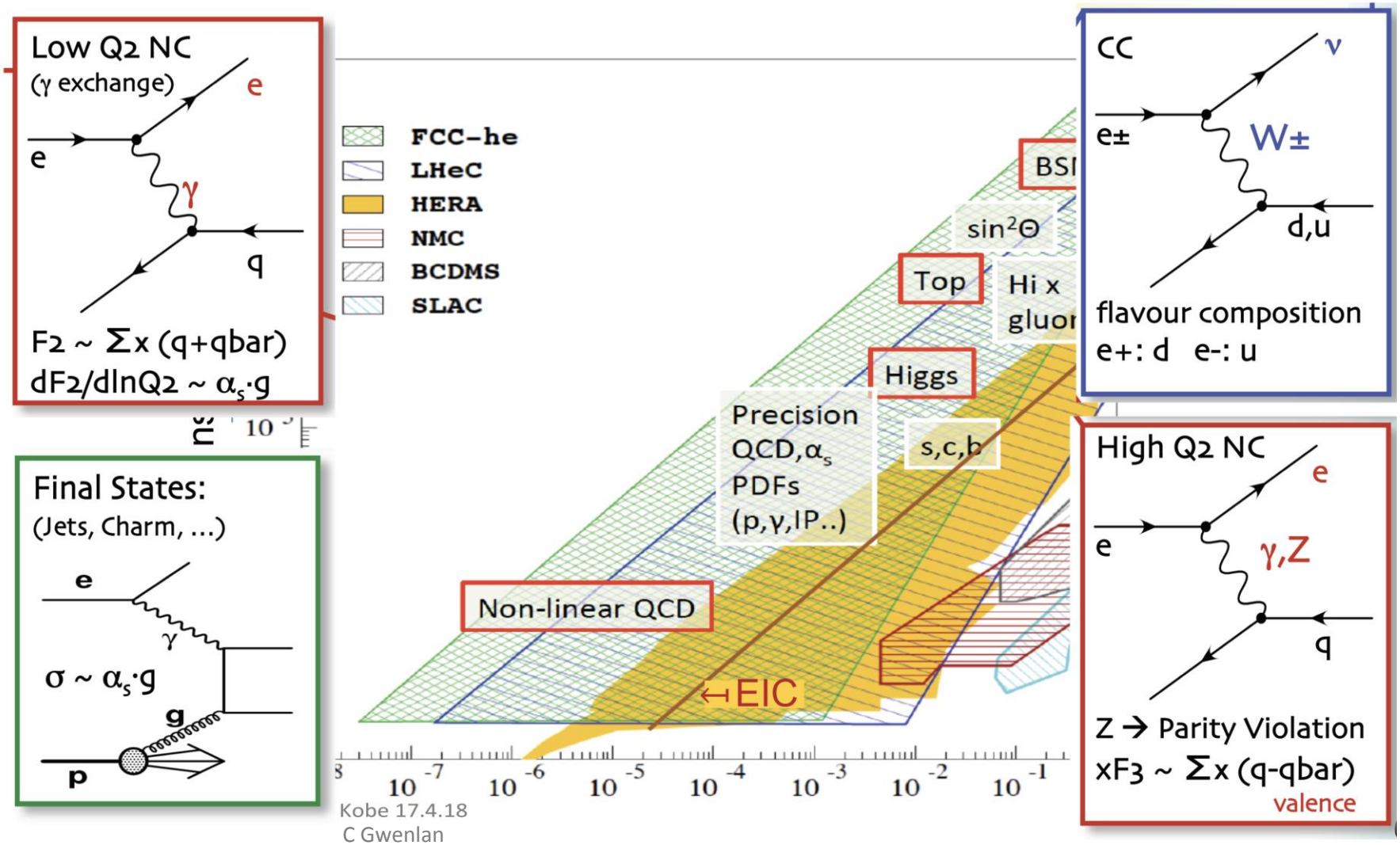
High precision QCD from ep for
pp+ep synergies

Surprises and QCD discoveries

Unfolding the Structure of the Proton

on firm theoretical grounds: factorisation proven for DIS

→ NNLO proton structure based on HERA (+fixed target data) for Tevatron and LHC



NC: Neutral Current DIS

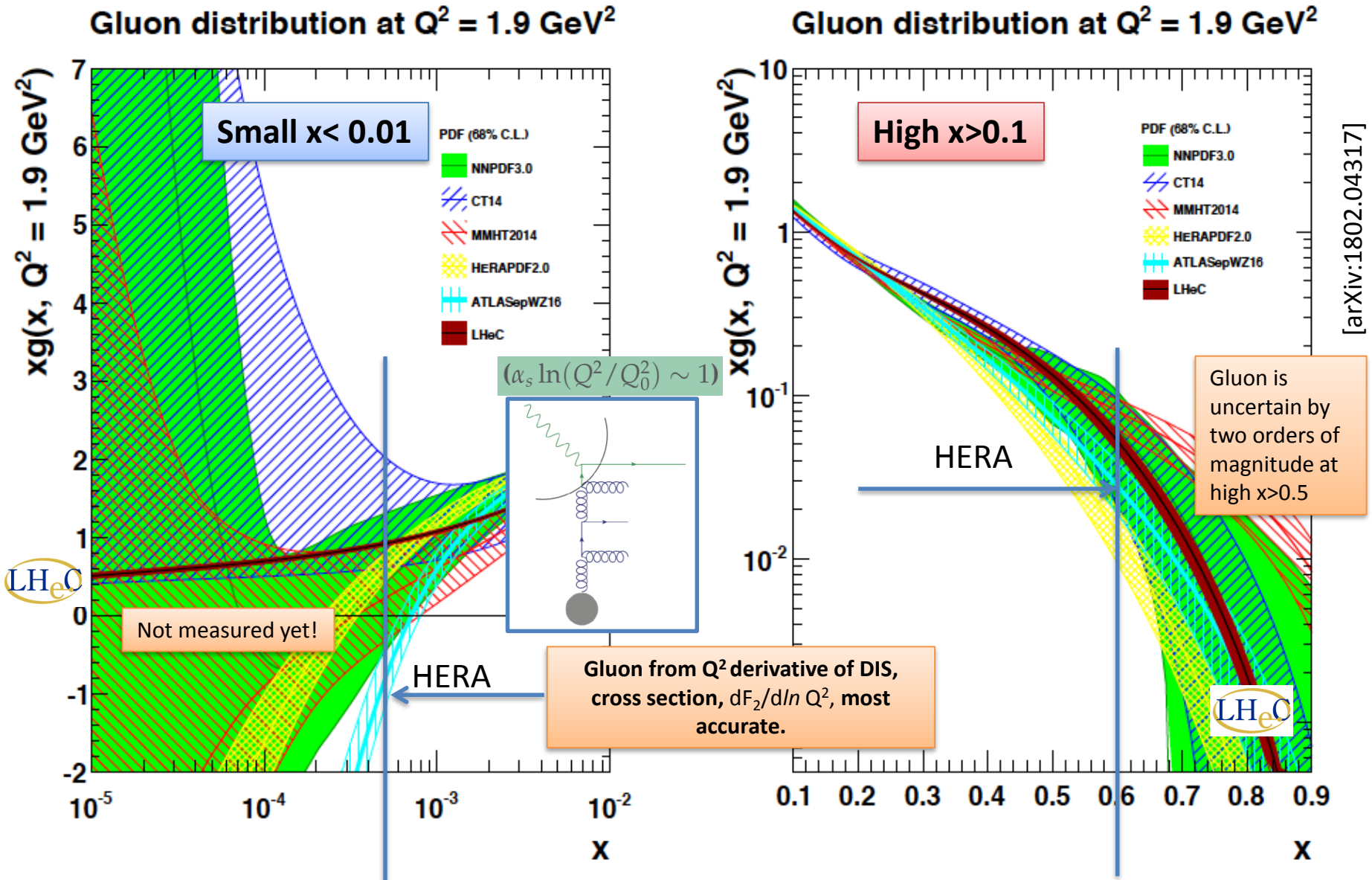
CC: Charged Current DIS

Understanding the Gluon

Hera's ep legacy and limitation

DGLAP approach

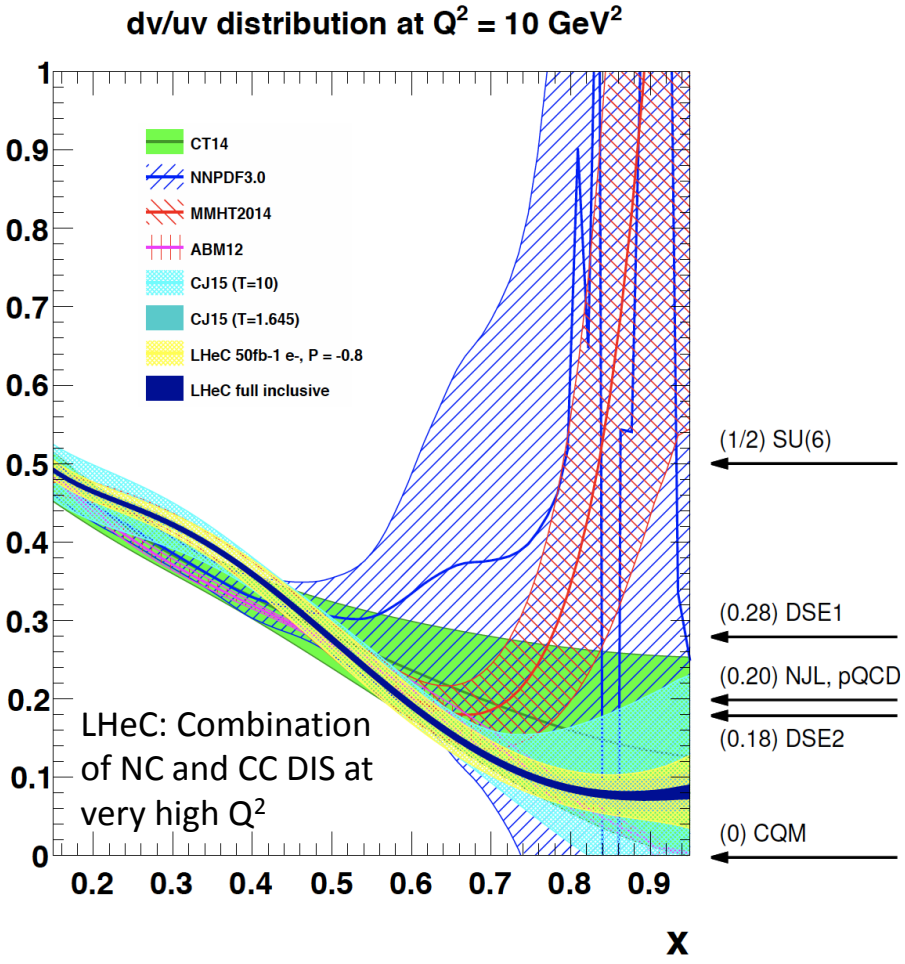
Low and high x parton distributions are intertwined by momentum sum rules!



Plot from C Gwenlan, DIS2019

d/u at large x

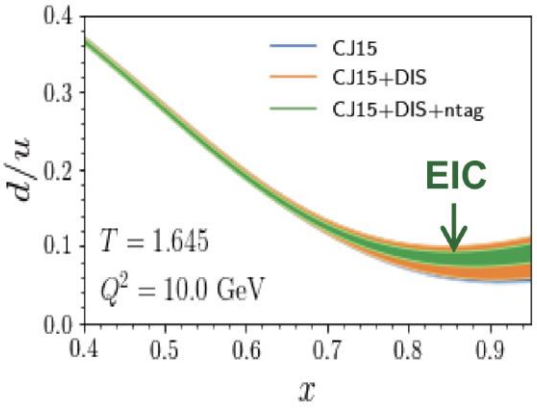
→ subtle measurements since d_v and u_v decrease drastically for x→1



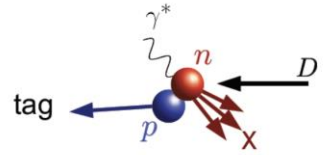
d/u essentially unknown at large x

no predictive power from current pdfs;
conflicting theory pictures;
data inconclusive, large nuclear uncerts.

resolve long-standing mystery of d/u ratio at large x



EIC: NC DIS in ep and eD; tagged spectator proton



→ **Crucial test of pQCD: non-singlet quark distributions do 'not' evolve with Q^2?**

Charm and Beauty

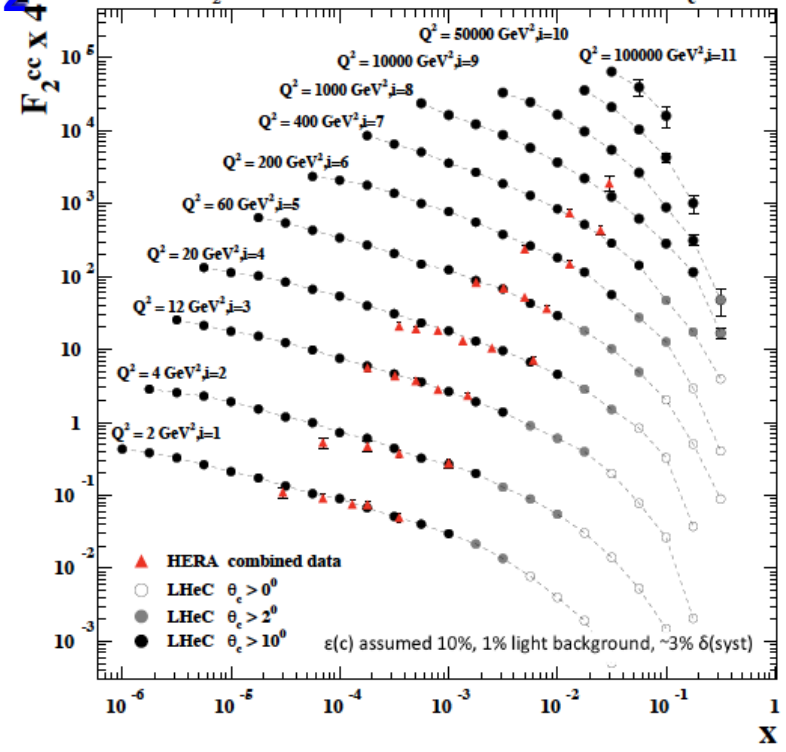
- Significant extension of HERA2.0 + jets : 1-year of LHeC means 10 times luminosity of 15-years-HERA
- N^{3}LO DIS theory framework
- New world of heavy quark PDFs; s, c, b, t → clarification of HFL schemes

Heavy Flavour with LHeC

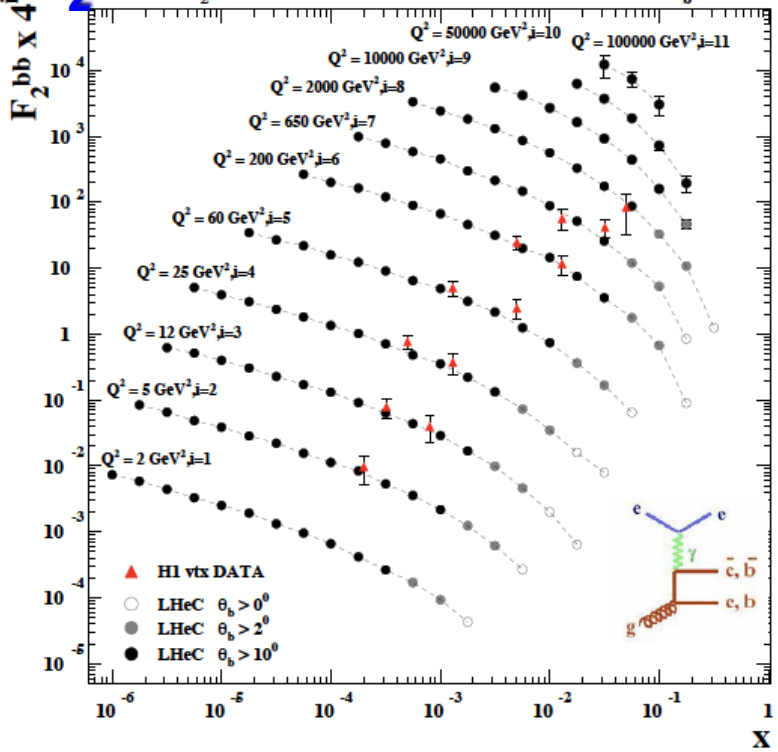
Beam spot (in xy): 7µm
Impact parameter: better than 10µm
Modern Silicon detectors, no pile-up
Higher E, L, Acceptance, ε, than at HERA
→ Huge improvements predicted

LHeC CDR arXiv:1206.2913

F_2^{cc}



F_2^{bb}



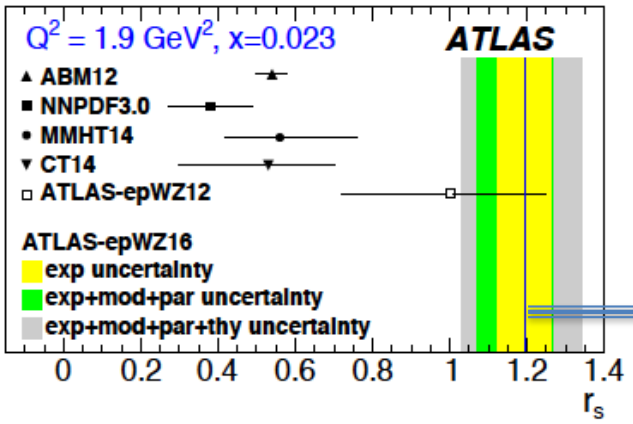
LHeC: enormously extended range and much improved precision c.f. HERA

- **δMc = 50 (HERA)** to **3 MeV**: impacts on αs, regulates ratio of charm to light, crucial for precision t, H
- **δMb** to **10 MeV**; MSSM: Higgs produced dominantly via $b\bar{b} \rightarrow A$

Strange Strange Quark Distributions

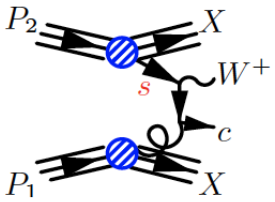
Evidence of enhanced strange-to-light sea density at x~0.01

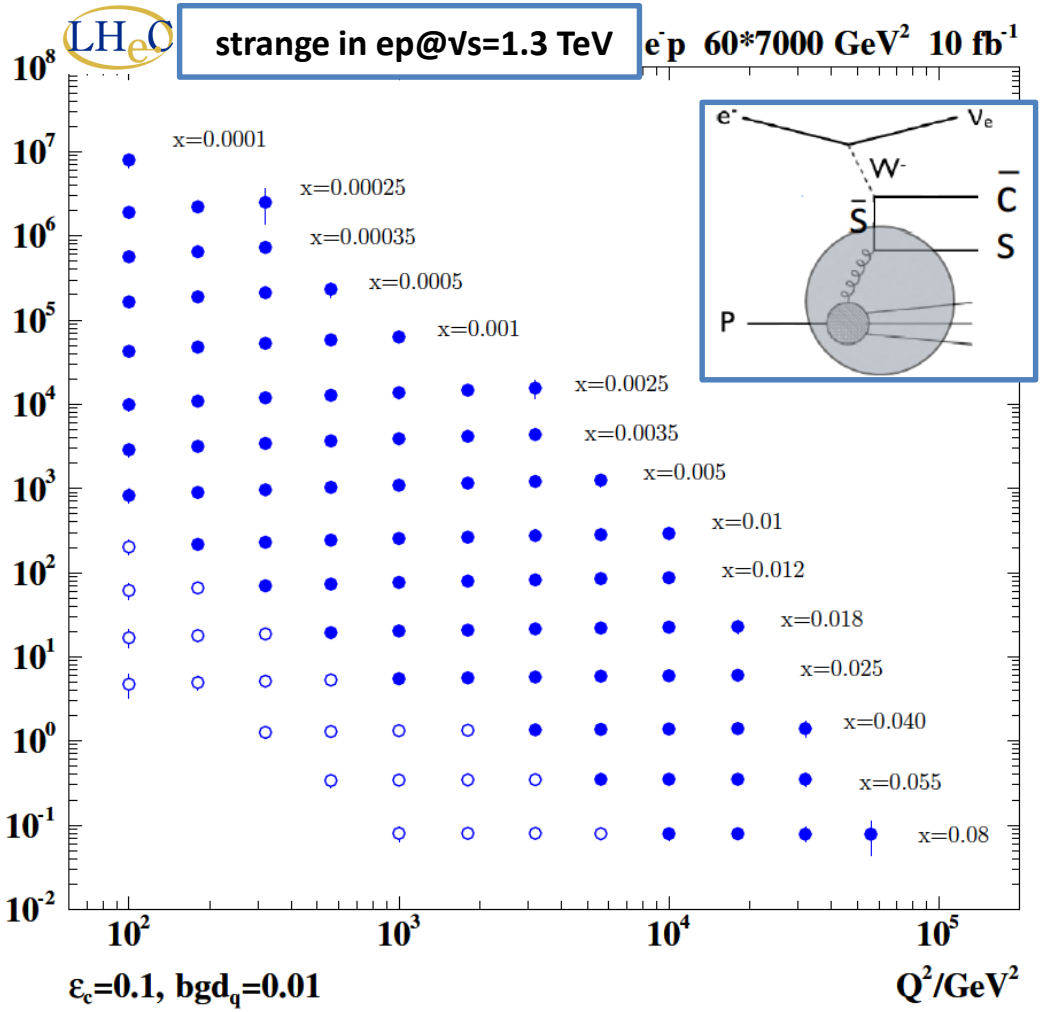
[ATLAS 2016: 1612.0301, PRD]



anti-strange density [$\bar{s}$]

➔ based on high precision inclusive W and Z data and ~ 5 years of analysis and joint HERA+ATLAS QCD fit and ATL-PHYS-PUB-2019-016





LHeC : Precision measurement of strange, also of charm, beauty and top → N^{3}LO
→ Complete unfolding of the flavour structure of the proton for the first time
→ Enables and requires a new kind of PDF fits and clarification of HFL scheme.

Understanding Quark-Gluon Dynamics

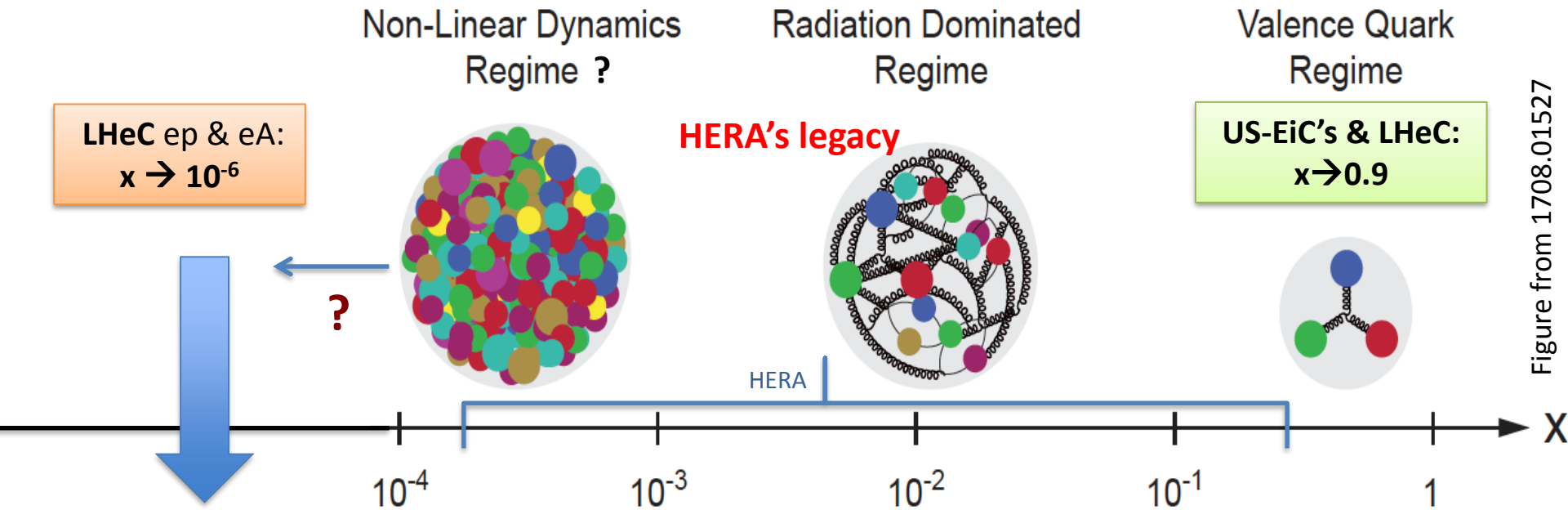


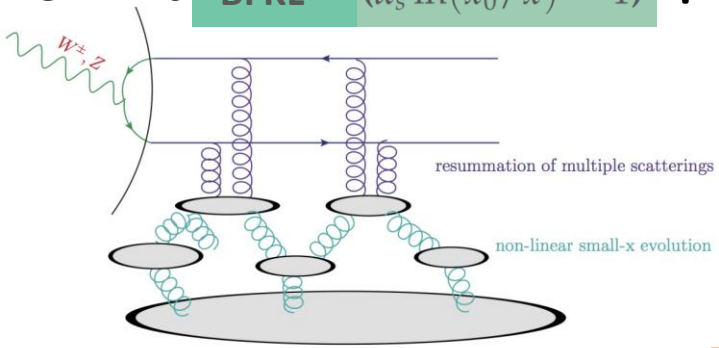
Figure from 1708.01527

Low-x resummation for x→0 : First signs seen at HERA?

High-x resummation for x→ 1

***Measure* change in QCD radiation pattern!?**

DGLAP vs **BFKL** $(\alpha_s \ln(x_0/x) \sim 1)$ **?**



For DY, DIS, Higgs, singular behavior when x→ 1

Eric Laenen, 2010

$$\delta(1-x) \qquad \left[\frac{\ln^i(1-x)}{1-x}\right] \qquad \ln^k(1-x)$$

Resummation:

The art of constructing for some quantity out of a subset of perturbative terms, aided by extra insight, an all-order expression

Or measure gluon saturation?

Needs new, most accurate ep data extending to smallest x, in perturbative region,
to be then confronted with Electron-Ion data at small x <10^{-4}.

Low x Parton Dynamics

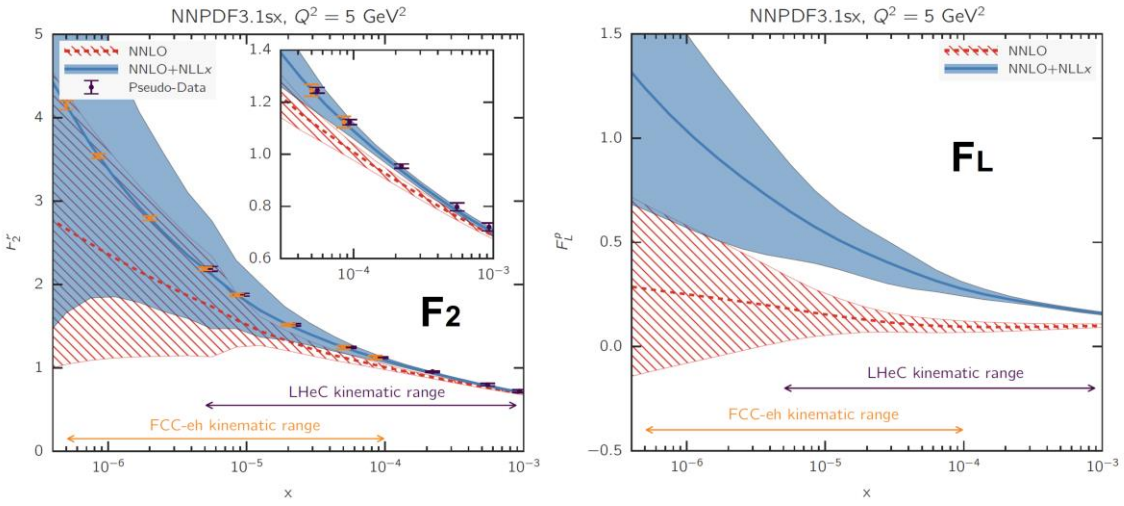
- Low x resummation, BFKL-type QCD radiation or gluon saturation unveiled via precision structure function measurements of F_2 and F_L
- Free broken charge particles? Free colour? The gluon may NOT saturate [decisive test only with F_2 and F_L possible]
- Test of momentum sum rule via precision high and low x data

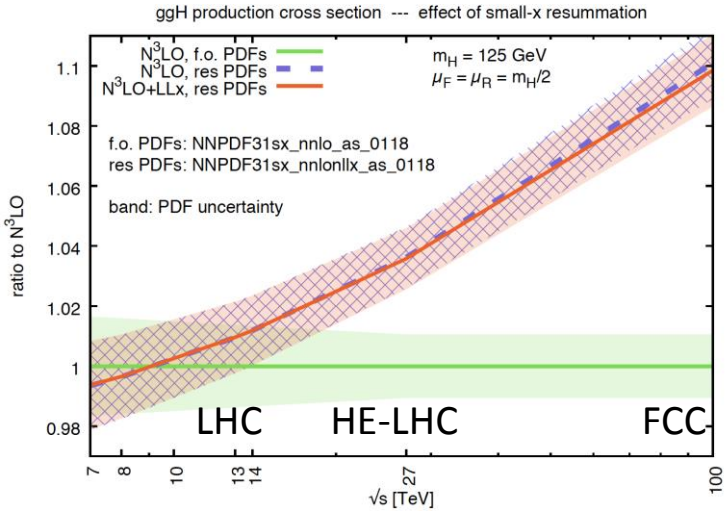
Resummation Effects

gluon at small x

arXiv:1710.05935

gg→ H Cross Sections



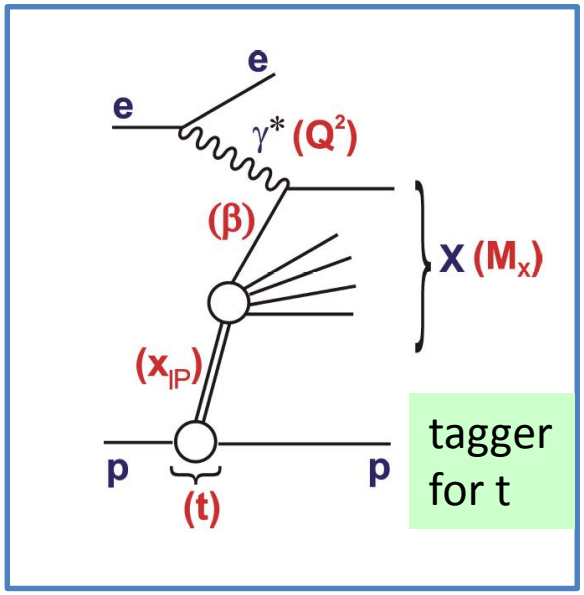


F2 and FL predictions for simulated kinematics of LHeC and FCC-eh

arXiv:1802.07758

Beyond the collinear parton model: opening a new QCD lab

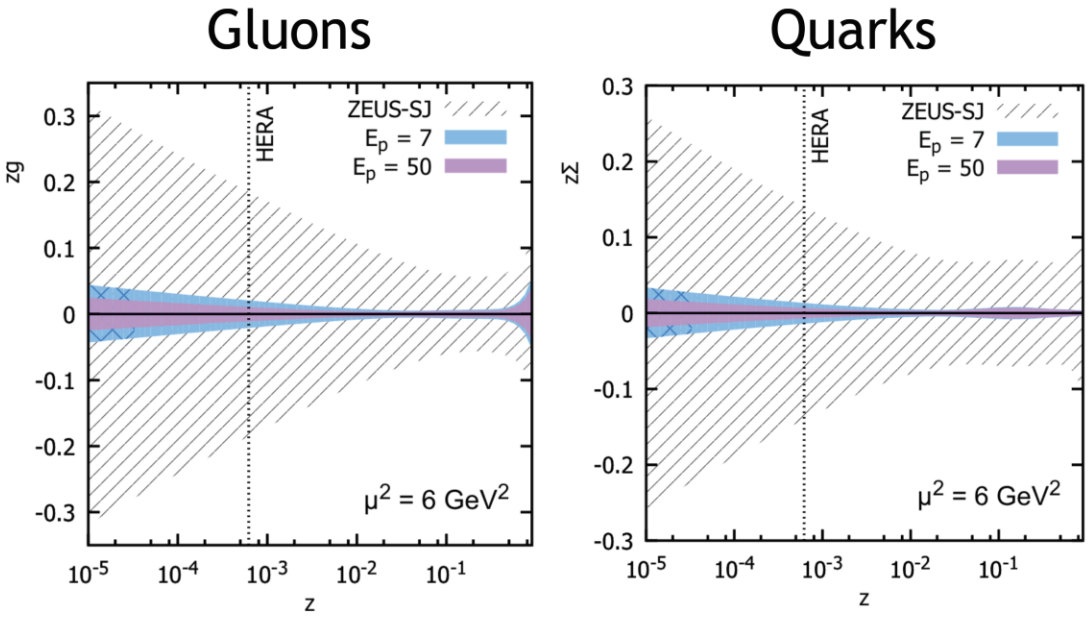
- Diffractive PDFs
- Generalized PDfs, unintegrated PDFs → 3D proton structure, see talk by N Armesto



- Low x_{IP} → cleanly separate diffraction
- Low β → Novel low x effects
- High Q^2 → Lever-arm for gluon,flavour decompositi
- Large M_x → Jets, heavy flavours, W/Z …
- Large E_T → Precision QCD with jets …

Diffractive PDFs

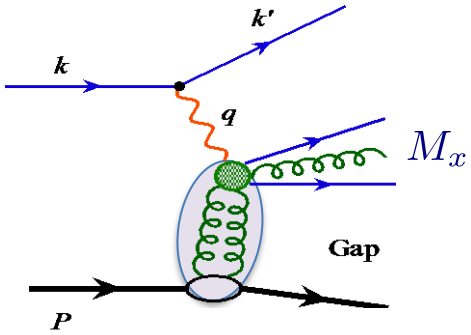
Study by W Slominski & arXiv:1901.09076



Saturation and Diffraction

Experimental challenge : Measurement of t (ZDC?) and detection of FS proton and neutron (incoherent: nucleus breaks up) in ep and eA.

Diffractive cross section: $\sigma_{\rm diff} \propto [g(x,Q^2)]^2$



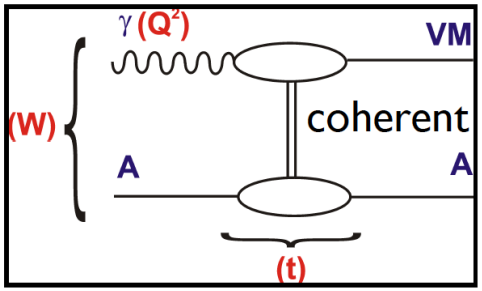
HERA legacy: 10-15% diffractive events in ep; Q^2 dep!

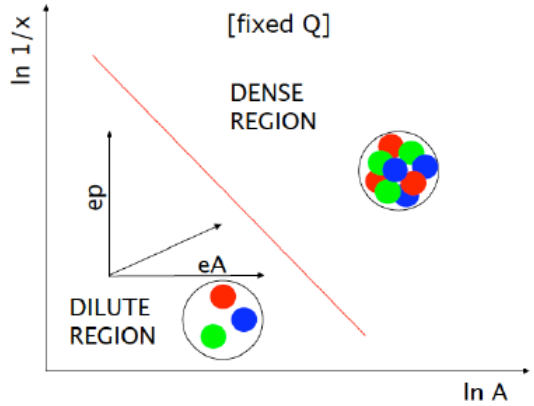
If saturation (CGC) – multiple coherent gluons

→ Diffraction in eA : ~25-30% diffractive contribution

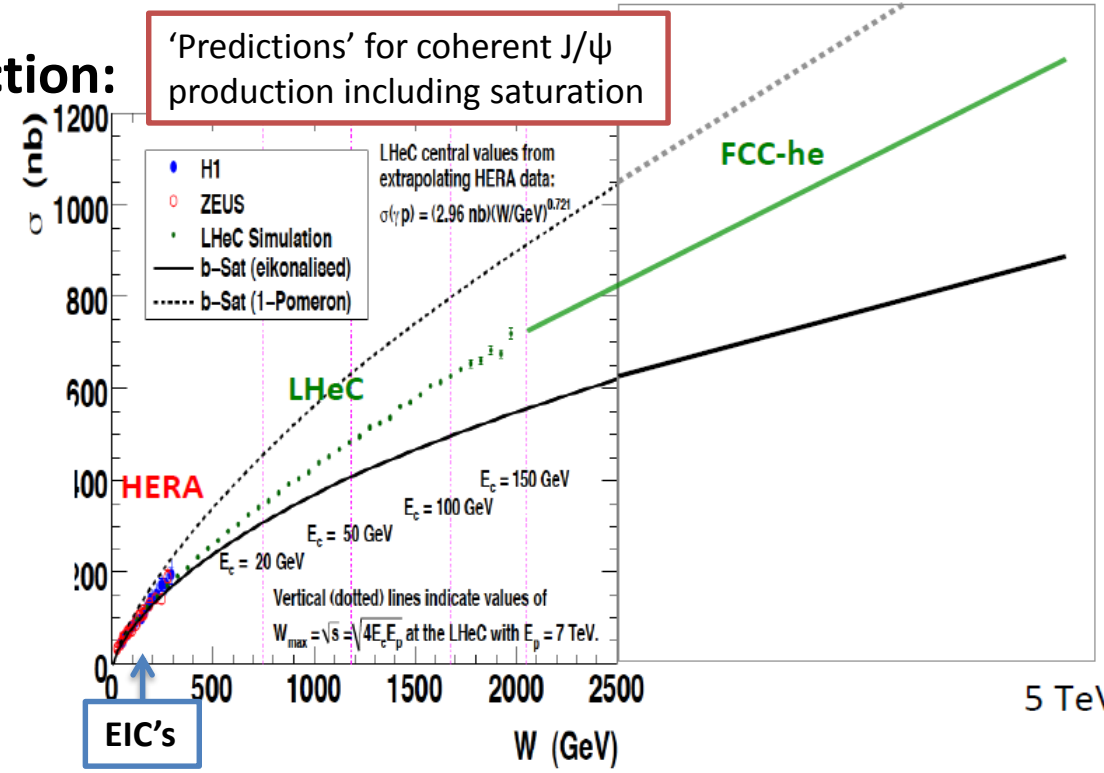
Reminder: Factorization for diffractive processes works in DIS, not in pp, pA, AA

Diffractive vector meson production:





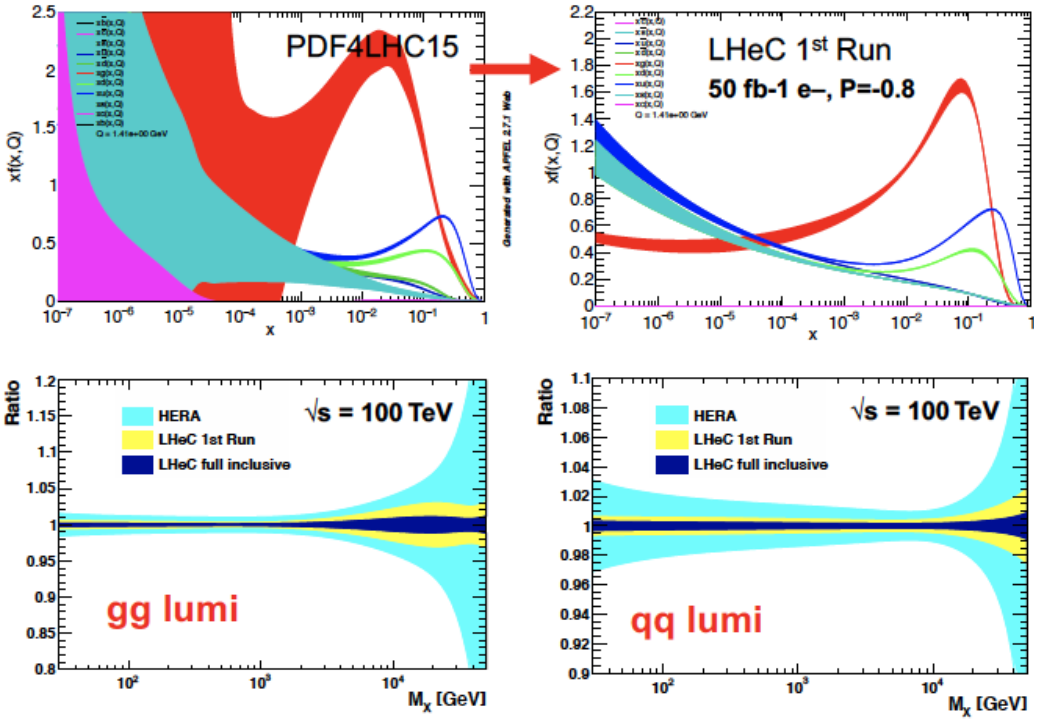
'Predictions' for coherent J/ψ production including saturation



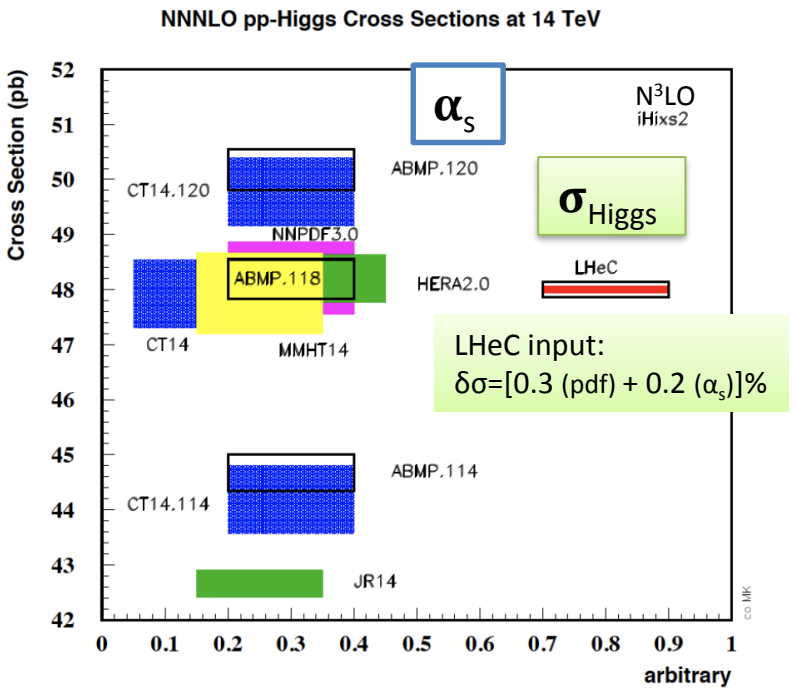
W = √ (ys) extends to ~ 5 TeV at FCC-he

High precision QCD and ep+pp synergies

- N^{3}LO PDFs and precision α_s for σ_{Higgs} in pp (and for AA) – already with first ep run (yellow bands)
- Precision PDFs & α_s for pp discoveries, e.g. W', Z', SUSY, EFT interpretations
- Test of factorization in pp and AA
- Crucial external input for HL-LHC, HE-LHC, FCC-hh, e.g. precision Z predictions for pp luminometer, precision M_W and $\sin^2\theta$ pp+ep measurement



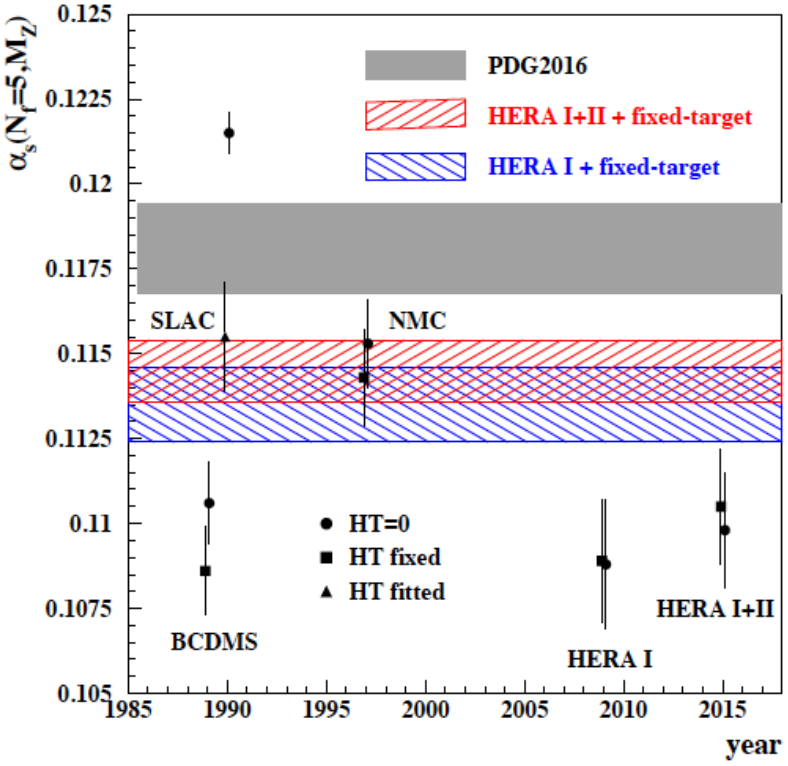
Plot from C Gwenlan, DIS2019



Plot from M Klein, DIS2019

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

Status Now



ABMP 2017 $\alpha_s = 0.1140 \pm 0.0009$

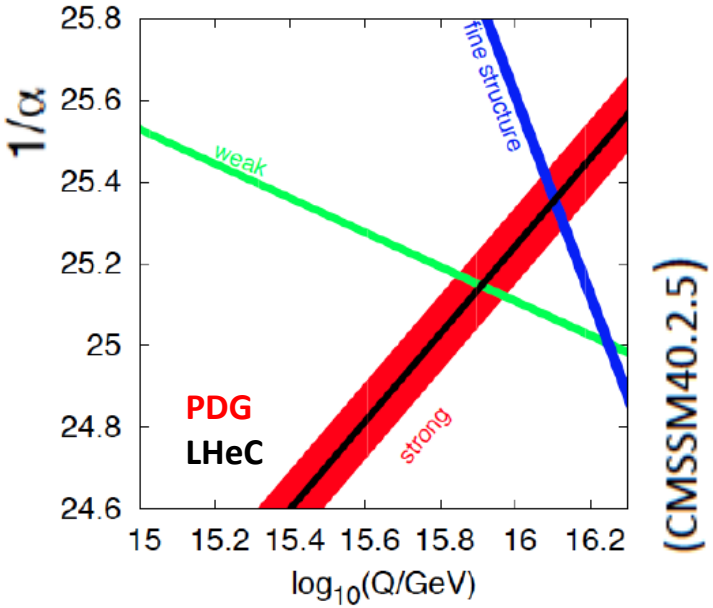
H1 inclusive and jets (2017) NNLO

$\alpha_s = 0.1142 \pm 0.0028$ (tot)

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

Per-mille accuracy at LHeC/FCC-eh

[full simulation]



- Strong coupling known worst of all couplings
- α_s may be LOW and not in agreement with lattice calculations?
- Are interactions unified at GUT scale?

Empower pp Physics with precision ep

Masses of:

Charm HERA 40 MeV : LHeC 3 MeV

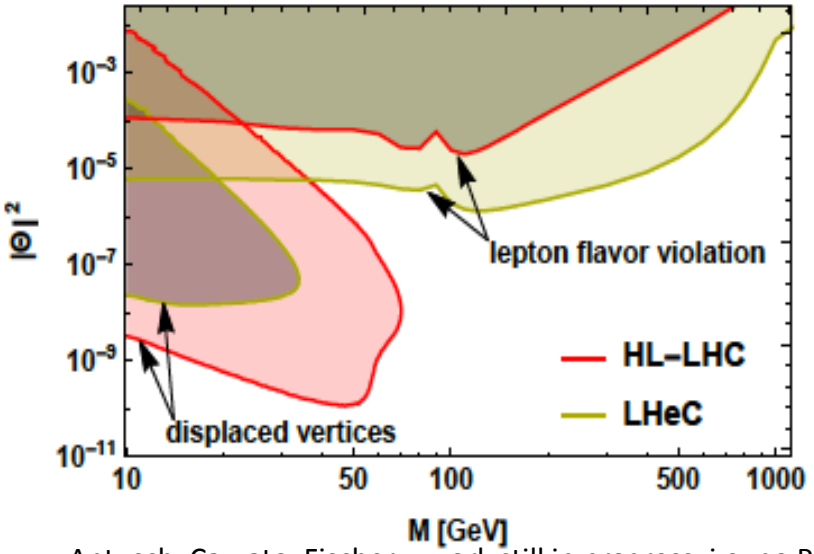
W LHC 19→ 10 MeV: LHeC 15 MeV
and prediction to ±2.8 MeV for pp

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, i.e. no PU for pp

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

CKM, electroweak, α_s …

V_{tb}: to 0.01

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

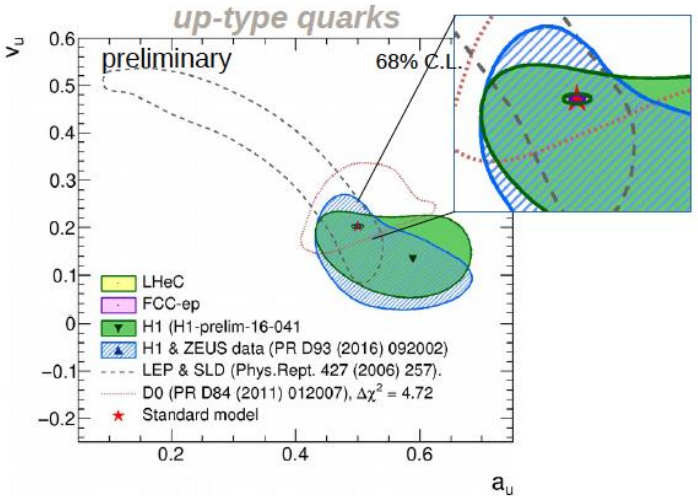
α_s to 0.2% [0.1% with HERA] – GUT?

$\sin^2\theta_W(\mu)$

LHC: better than LEP with LHeC PDFs

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

NC couplings [synergetic with ee, see backup]



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

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

Developments

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

Non pQCD, Spin, Mass
Quark Gluon Plasma

QCD of Higgs boson

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

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

Discoveries

Why no 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

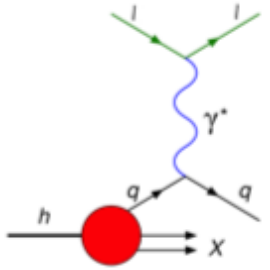
Quark substructure

New symmetry embedding QCD

C. Quigg, arXiv1308.6637

QCD has an exciting future

Summary / Recommendations



Deep Inelastic Lepton-Nucleon Scattering is a fantastic and unique tool to study nucleon structure and unravel QCD with high precision data and on firm theoretical grounds.

The future of DIS experiments is bright with two independent eh colliders at various energy ranges for the development and discovery in the strong interaction physics sector:

- **Medium Energy US-EIC's** with c.m.s < HERA**: *Polarised* nucleon structure→*Spin puzzle*, 3D nucleon structure,** high x proton structure …
- **High Energy CERN-based LHeC's** with c.m.s >>HERA**: Unpolarised nucleon's flavour structure at low and high x, N^{3}LO, α_S, saturation & new dynamics,** 3D nucleon structure**, and** (not discussed here) **Higgs, top, W, Z physics & BSM searches** …

  - ✓ via new kinds of twin colliders using novel *Energy Recovery* acceleration and fully exploiting our highest energy hadron machine(s) *sustainably*

    LHC pp@14 TeV & **ep@1.3 TeV : LHeC**
    HE-LHC pp@27 TeV & ep@1.8 TeV : HE-LHeC
    FCC pp@100 TeV & **ep@3.5 TeV : FCC-eh**
  - ✓ **empowering pp (AA) physics programmes of HL-LHC** *and* for future hh colliders

Energy, luminosity and excellent detectors enable a new level of PRECISION electron-proton colliders for 2030, as also required for pp.

Additional Sources & Thanks

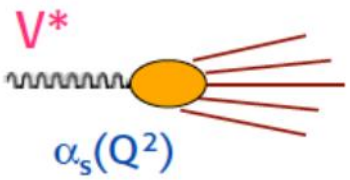
- **The LHeC/FCC-eh study group, http://cern.ch/lhec.**

- "On the Relation of the LHeC and the LHC" [arXiv:1211.5102]
- 2nd FCC Physics Workshop, 15.1.-19.1.2018, CERN,https://indico.cern.ch/event/618254/
- FCC Week 2018, Amsterdam, https://indico.cern.ch/event/656491/
- DIS2018, XXVI Workshop on Deep Inelastic Scattering and Related Subjects, 16.-20.4.2018, Kobe, Japan, https://indico.cern.ch/event/656250/
- Workshop on the LHeC/FCC-he and PERLE at LAL Orsay, 27.-29.6.2018, Orsay, France, https://indico.cern.ch/event/698368/
- FCC Symposium, CERN, March 2019, https://indico.cern.ch/event/789349/timetable/
- DIS2019, Torino, Italy, April 2019, http://dis2019.to.infn.it

Special thanks to my colleagues
in the LHeC/FCC-he study group and the PERLE Collaboration.

And More Material

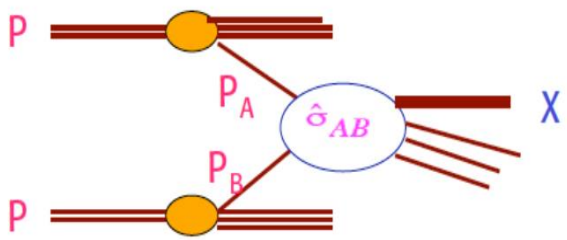
QCD with ee pp ep



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

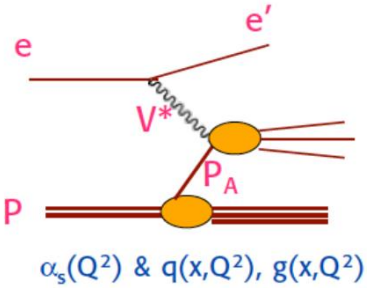
Final state arises completely from short distance interaction of virtual boson with quarks: NO PDFs, but jets, α_s
Njets +0, energy, angles. Unique association of q,g with jets
Observation of 3-jet events at PETRA to discover the gluon

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



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

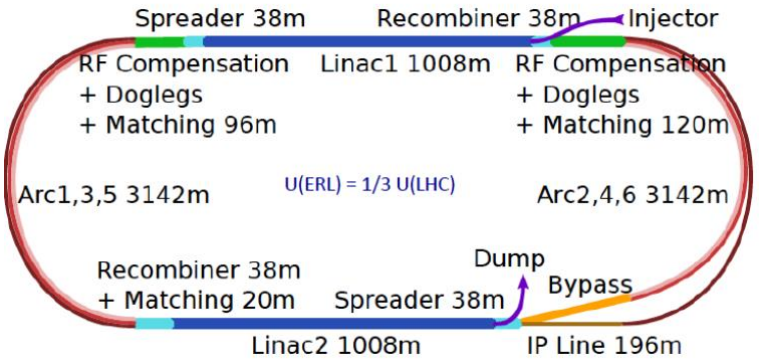
Many initial partons but only two interact.
"rest" is the underlying event of soft i.a.'s
Dynamical coupling of all components. MPIs
N jets at large pT +X, pseudorapidity + azimuth
Ledermann-**Drell-Yan scattering, jets**
Scattering depends on parton distributions
The "Altarelli cocktail" to save the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

Three Reasons of Electrons for LHC/HE-LHC/FCC



Sustainability and Cost

LHC:

- see: SM, Higgs and no BSM
- use: LHC Investment of O(5) BSF
- full exploitation of LHC infrastructure
- run: HL LHC until ~2040

LHeC [1206.2913, update 2/19]

- 1.3 TeV ep/A for O(1)BSF

→ Establish novel ep+pp Twin Collider Facility at CERN:
sustains HL LHC and bridges to CERN's long term future
For installation during LS4 (2030+) and long term use (HE LHC, FCCeh)

Physics

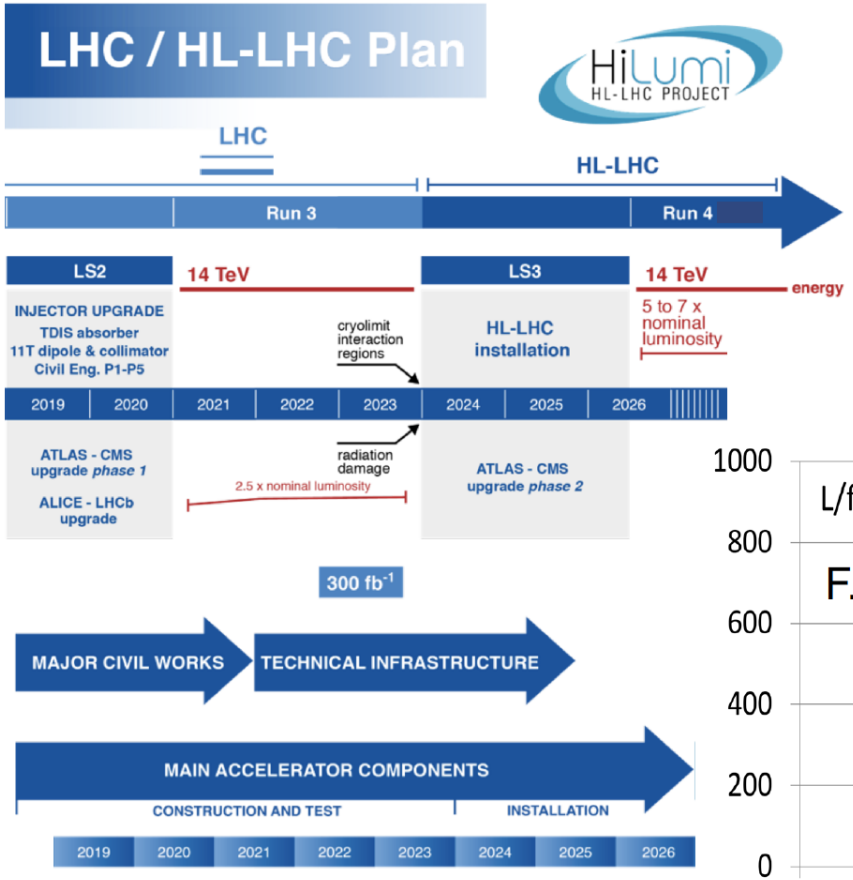
- **Microscope**:
  The "Hubble Telescope" of the Micro-Universe
- **Empowerment** of the LHC Physics Programme
- **Creation** of a precision, novel Higgs facility
- **Discovery** Beyond the Standard Model
- **Revolution** of Nuclear Particle Physics

Technology

Accelerator: Novel SRF ERL, "green" power facility
Detector: Novel high tech (CMOS..) apparatus

→ Keep accelerator and detector base up to date while preparing for colliders that cost O(10)BSF

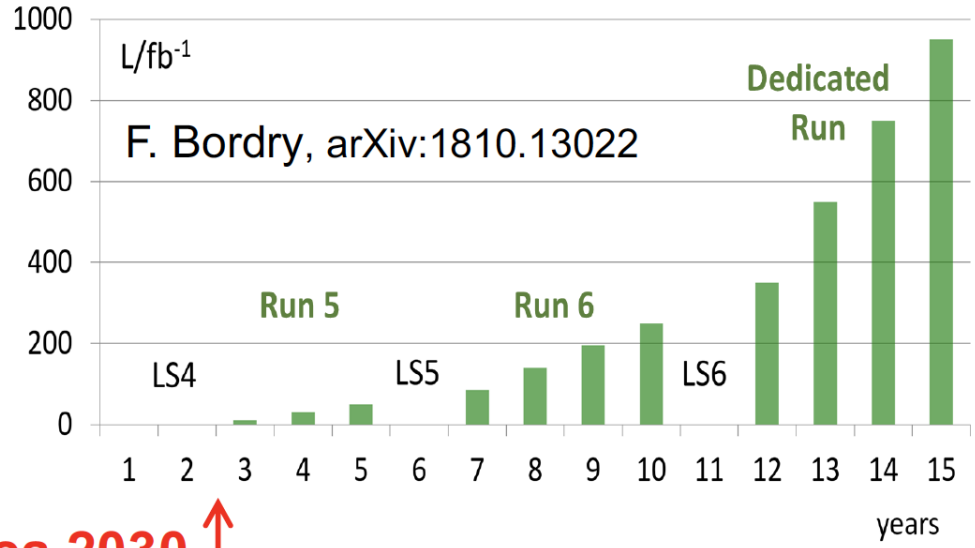
LHeC Timeline at a Glance



today

LHeC 1st run, Lint approx. 50 fb^{-1}
total Lint ⟶ 1 ab^{-1}

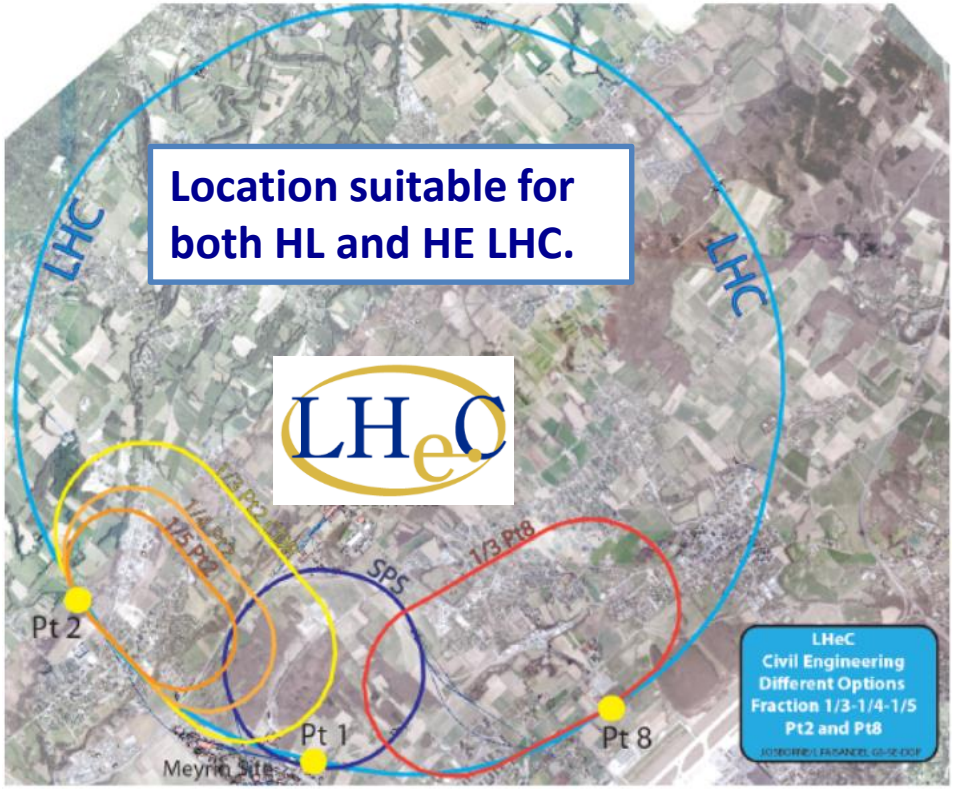
LHeC projected Integrated Luminosity

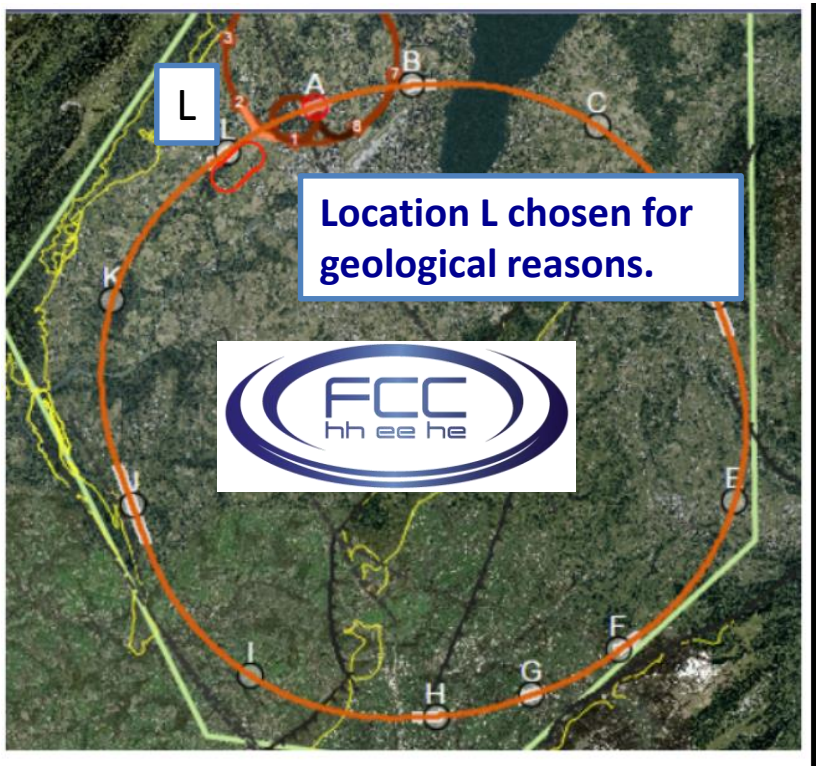


circa 2030

ep: Opportunities and Challenges

ERL-electron beam external to pp rings.





- C(ERL) = 1/n C(LHC): 60 GeV: 1/3 (9km)
→BSM, top, Higgs, Low x all want maximum E_e

C(ERL) = 1/11 C(FCC)
→ New physics may require E_e>60 GeV

Nominal 60 GeV ERL: O(1) BCHF ; 1000 cavities; 3504 dipoles; 1440 quads

Energy – Cost – Physics – Footprint scenarios being worked out further

Peak Luminosity for LHeC, HE-LHeC and FCC-eh

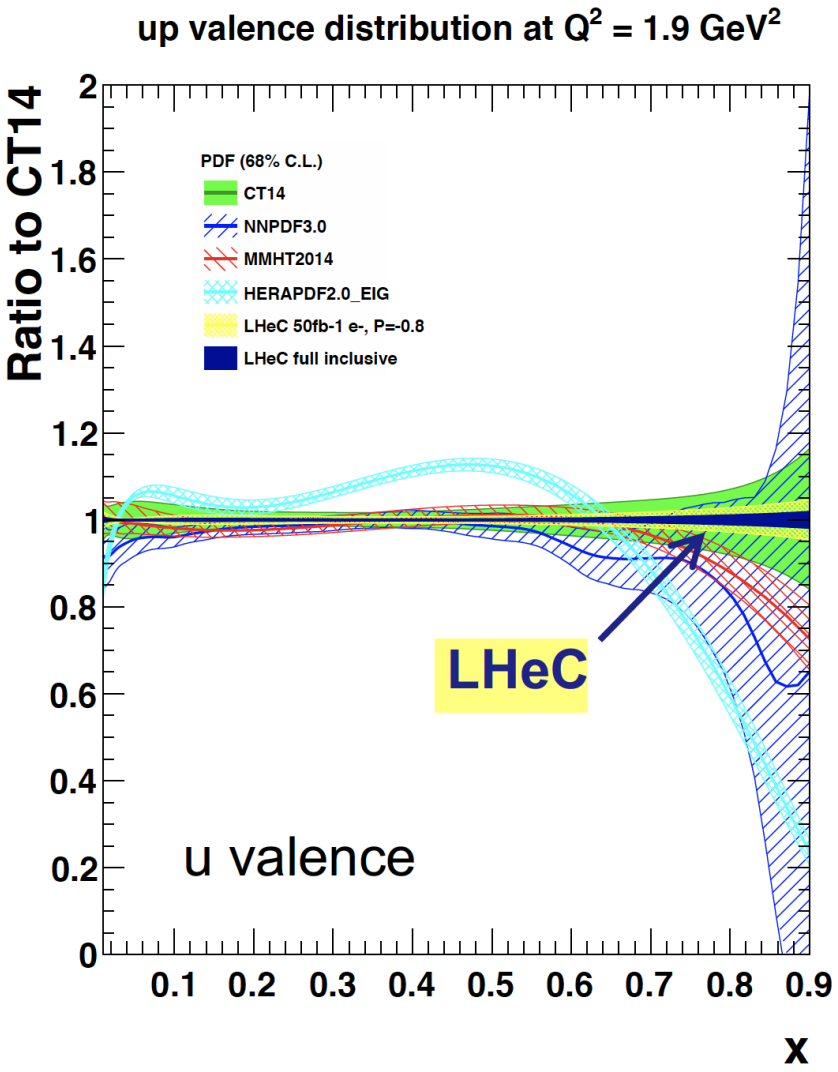
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV] c.m.s.	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

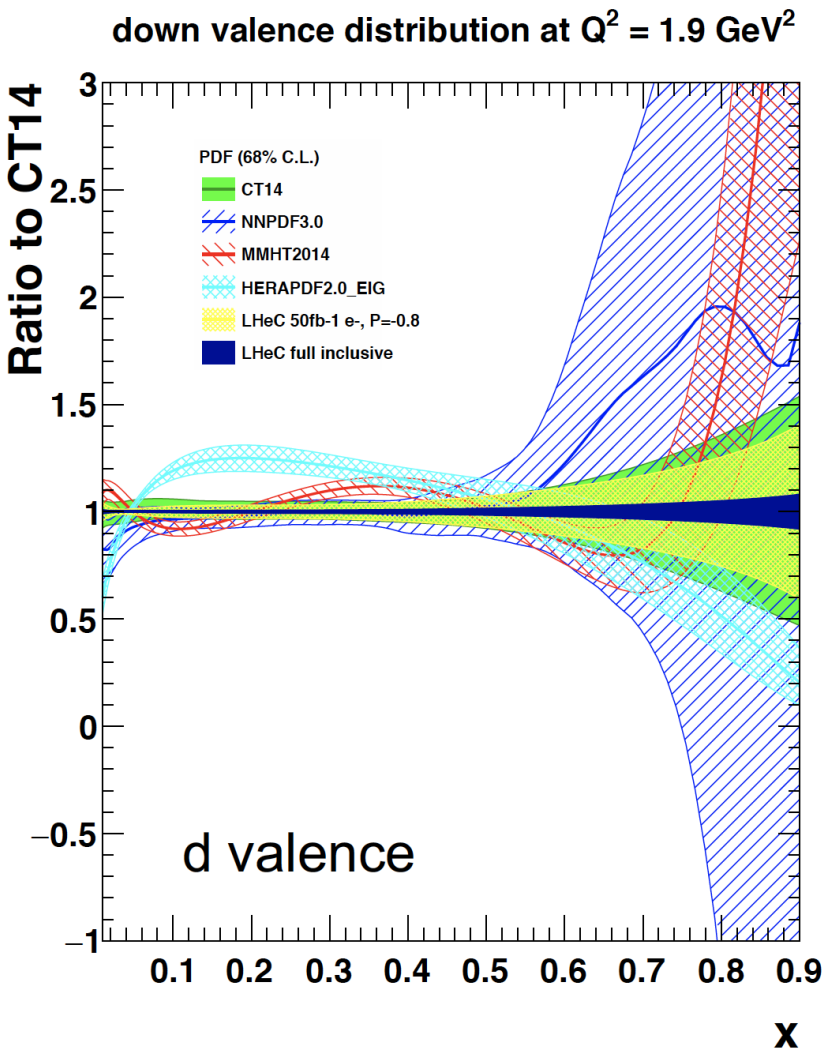
Oliver Brüning[1], John Jowett[1], Max Klein[2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]

EDMS 17979910 | FCC-ACC-RPT-0012

→ TeV energy frontier: **most powerful Electron-Proton colliders**

Valence Quarks from LHeC

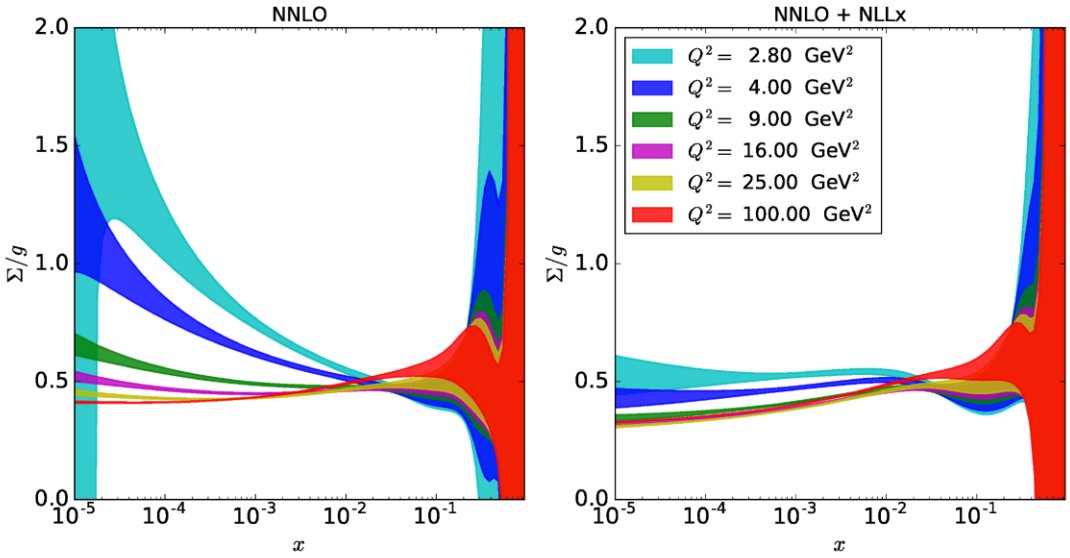




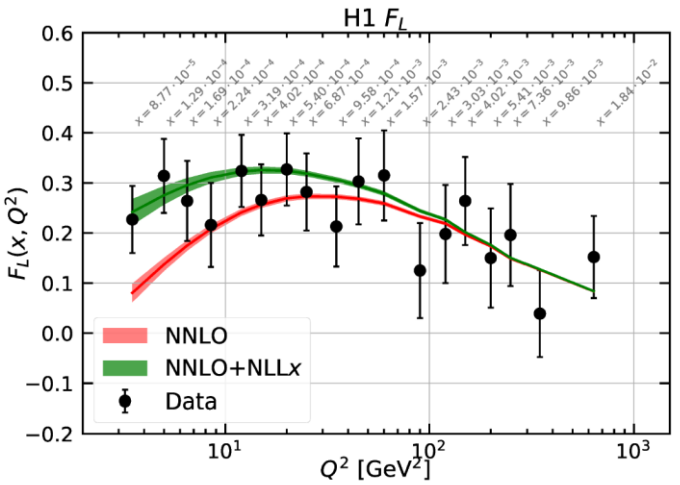
Low-x Resummation@HERA ?

NNLO vs **NNLO**+NLLx

Ratio Σ/g



The structure function F_L



- Quantify the power of the rise of xg and $x\Sigma$ by examining evolution of their ratio.
- Large evolution at NNLO, with the ratio exceeding unity at low scales.
- Ratio is ≤ 0.5 when $\ln 1/x$ resummation is included.

→ more inline with "dynamic" picture of PDFs in which the sea is generated from the gluon perturbativaly like in GRV fits.

Needs new, most accurate ep data extending to smaller x in perturbative region!

$\alpha_s(\mu)$ 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

CDR 2012

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.

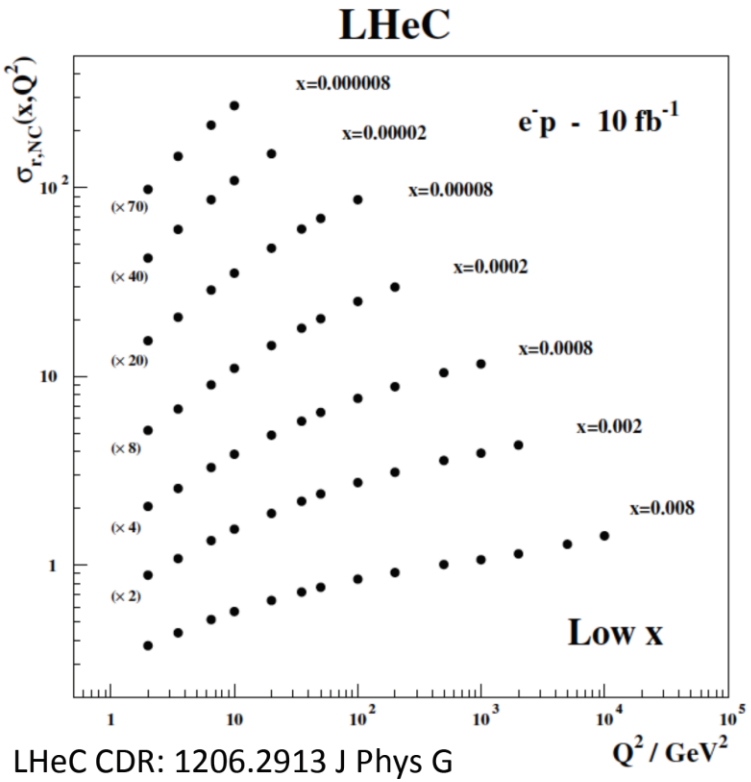
- LHeC/FCCeh lead to 0.1% uncertainty (stat+syst), free of previous DIS deficiencies (HT,nc)
- Joint determination with parton distributions (maybe simplified as H1 published in 2001)
- Needs clarity about low x behaviour as this uses DGLAP.
- Requires to control heavy flavour (theory) at new level (measure 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

and do not forget strong coupling measurements from polarised DIS!

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

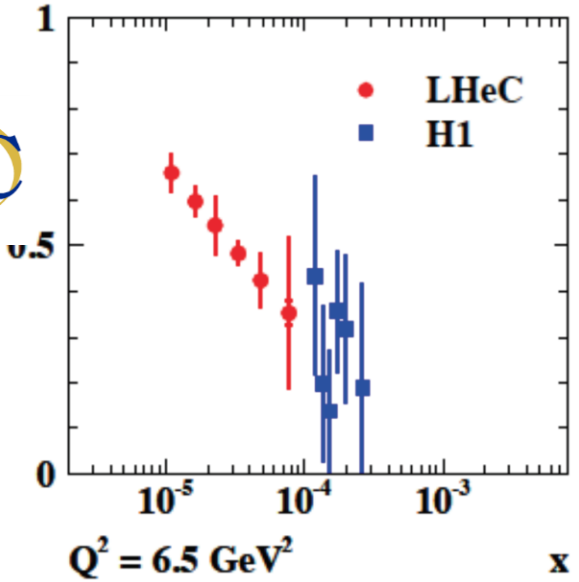


LHeC CDR: 1206.2913 J Phys G

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

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

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



MK: 1802.04317

c.f. LHeC CDR to confirm DGLAP or rule it out

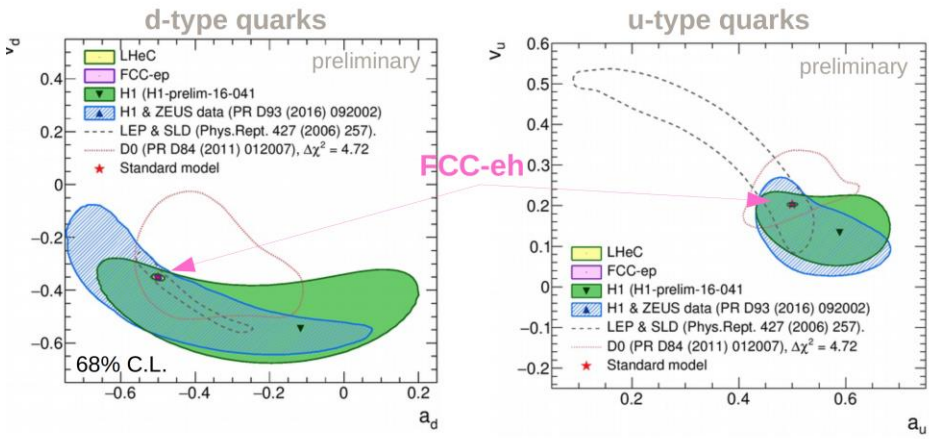
Precision measurements of gluon distribution essential for quantitative studies of onset of **saturation as a high density (small x in ep) and matter ($A^{1/3}$) effect**.

M Klein, FCC Week2018

Electroweak precision observables at FCC eh

- **Electroweak precision measurements at FCC-eh**

Precision measurements of couplings to light quark families

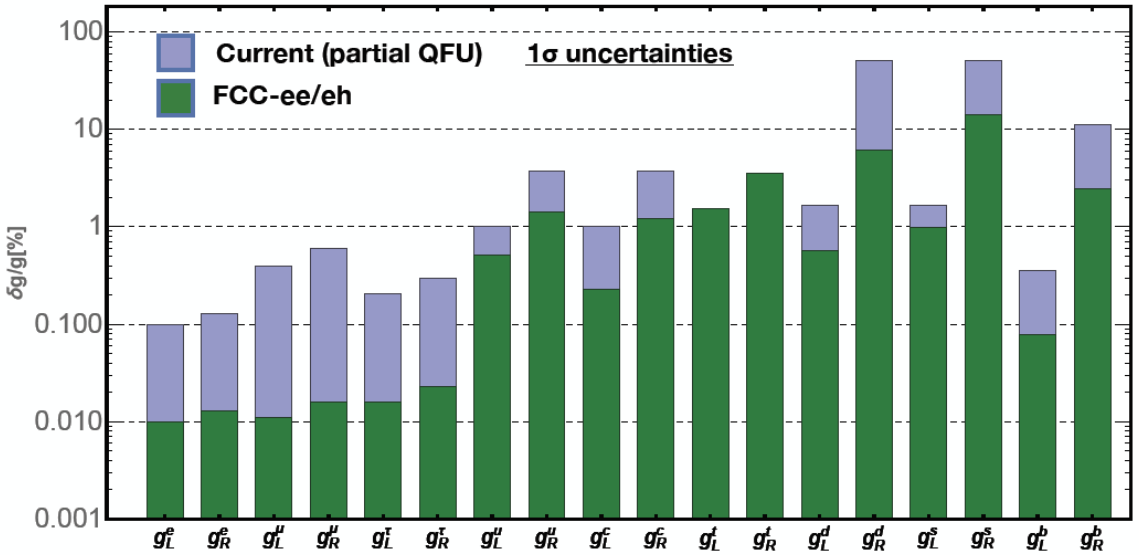


Talk by D Britzger, FCC Physics Week 2018

Observable	Uncertainty	(Relative uncertainty)
g_V^u	0.0022	(1.1%)
g_A^u	0.0031	(0.6%)
g_V^d	0.0049	(1.4%)
g_A^d	0.0049	(0.97%)

- **Global fit to electroweak precision measurements at FCC-ee + FCC-eh**

NEW
ee + ep

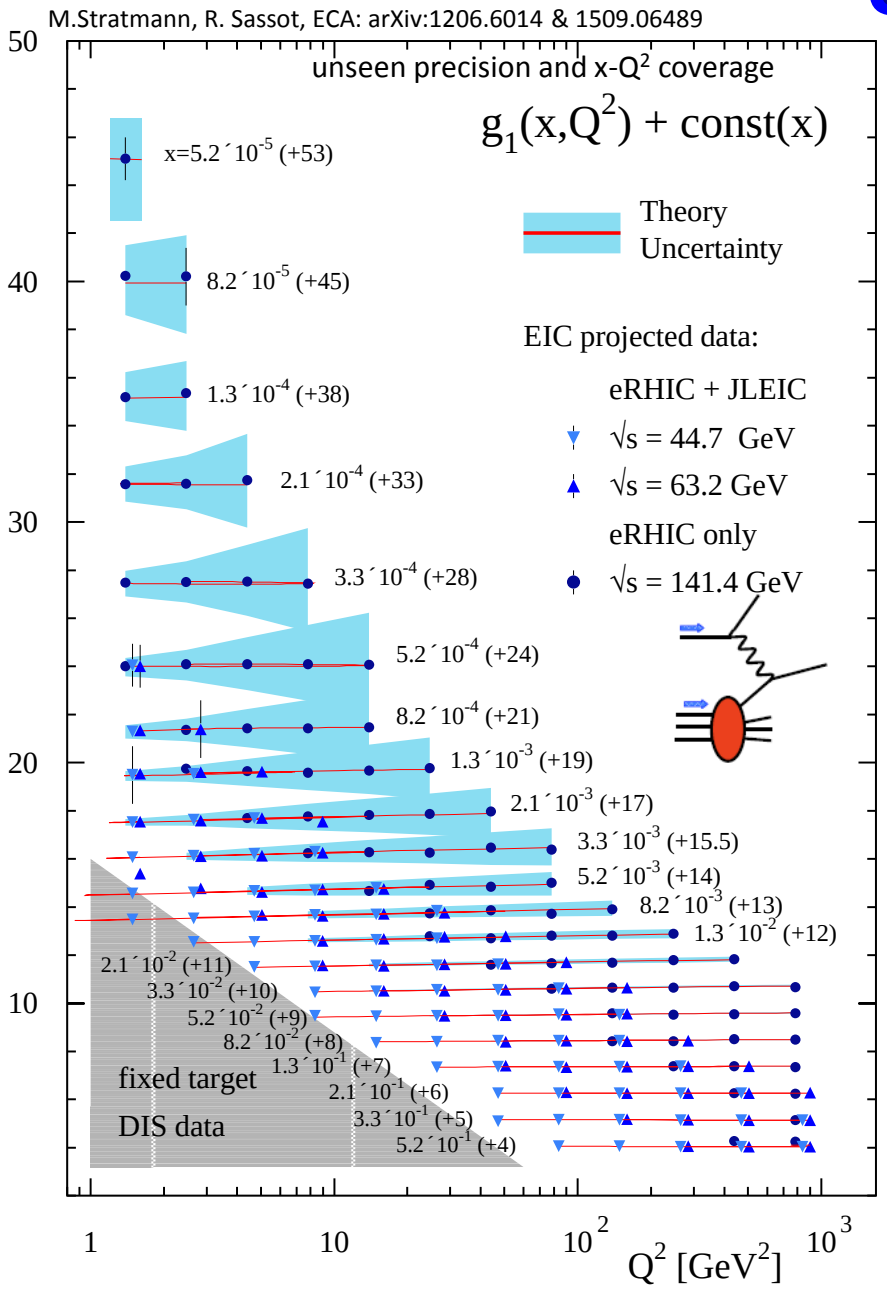


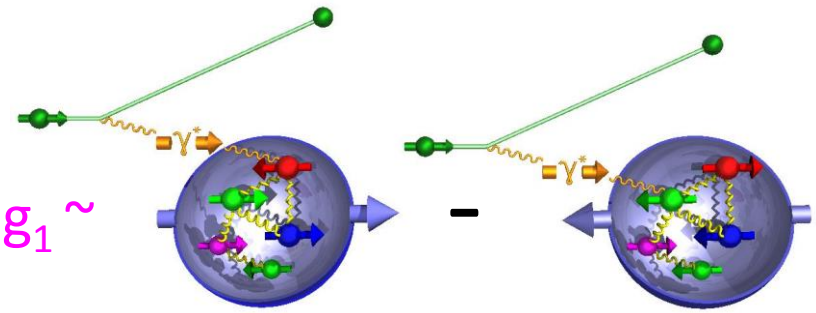
Talk by J deBlas
FCC Week 2018

No Fermion flavour universality assumed

Independent info about all 3 SM fermion families

Spin at US-EIC: ΔΣ & Δg





pQCD scaling violations

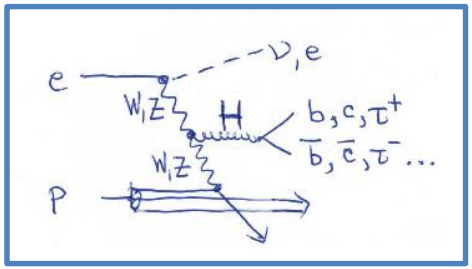
$$\frac{dg_1}{d\log(Q^2)} \sim -\Delta g(x,Q^2)$$

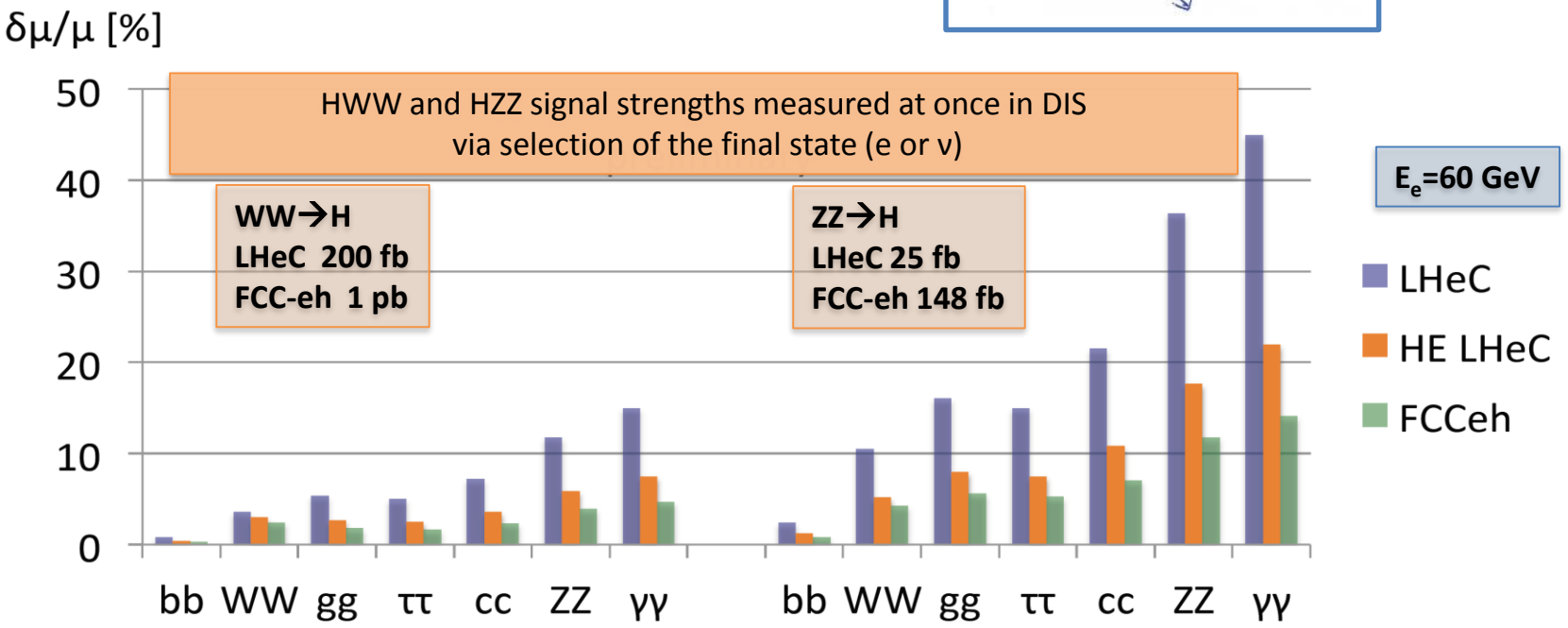
$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx$$

→ **Excellent EIC prospects!**

- **extremely challenging measurement**
- **spin asymmetries very small for x→0**
- **needs excellent control of detector stability, polarisation measurements and measurements of F_2 and F_L**

SM Higgs Signal Strengths in ep





→NC and CC DIS together over-constrain Higgs couplings in a combined SM fit.

Charged Currents: ep → νHX Neutral Currents: ep → eHX

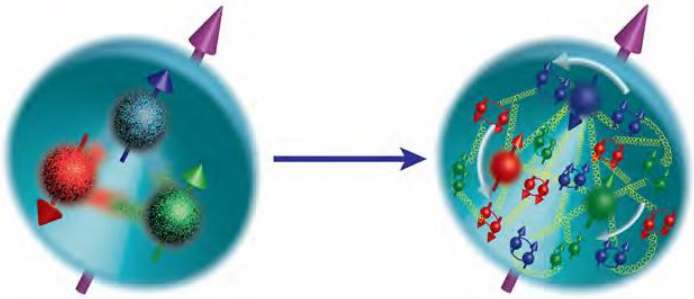
Σ br$_i$=0.99±0.01 precise reconstruction of full width from 7 most frequent decays (2% at LHeC, and 1% at LHeC+LHC). Charged currents only

E_e = 60 GeV **LHeC E_p = 7 TeV L=1ab^{-1}** **HE-LHC E_p = 14 TeV L=2ab^{-1}** **FCC: E_p = 50 TeV L=2ab^{-1}**

3-dimensional exploration of nucleon has ~~just~~ started:
collect as much data as possible on TMDs and GPDs
and try to reconstruct the complete phase-space distribution

M Anselmino, 2010

ideal machine:
high luminosity
x-range including the valence region
Q^2 high enough to neglect higher-twist corrections
P_T high enough to see transition from TMDs to pQCD
precise P_T-Q^2 bins
measure jet asymmetries....



plenty of challenging theoretical issues....

Status of Ji Sum Rule
C Hyde, DIS2018

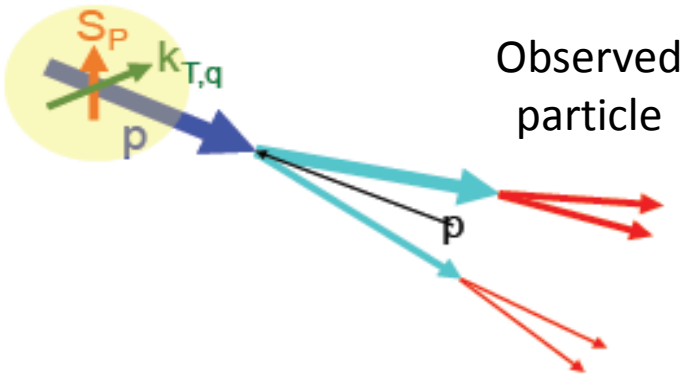
- $H_f(x,0,t)$ essentially known from fits to $F_{1f}(-t) \otimes q_f(x)$
  - Measure $H_f(x,x,t)$ → Determines DD Profile function
  - JLab 12 → higher x, Q^2 range
- $E_f(x,0,t)$ constrained from $F_{2f}(-t)$ and *assumption* $e_f(x)$ does not change sign.
  - Test this assumption
    - x≈0.1 COMPASS 2020
    - x≈0.4 Jlab12
    - Lattice QCD
- My prediction: In 10 years, we will be confident in value of $J_{u,d}$

Explore Spin & Quantum Correlations

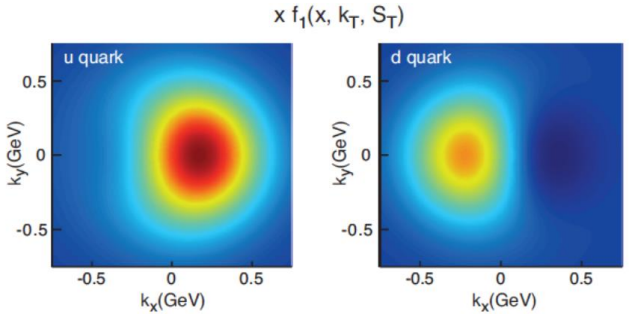
EIC: transversely polarised hadron beam

Quantum correlation between hadron spin and parton motion:

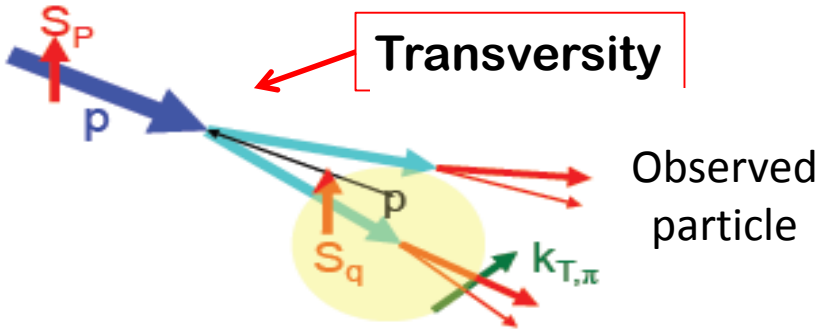
Sivers effect – Sivers function



Hadron spin influences density of unpol. partons in transverse-momentum plane



Quantum correlation between parton spin and hadronization:



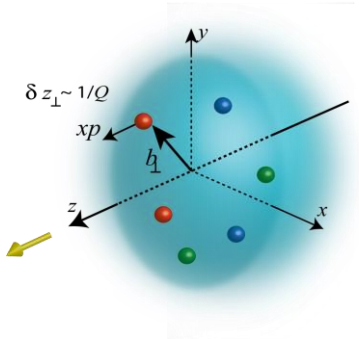
Collins effect – Collins function

Parton's transverse spin influence its hadronization

JLab12 GeV upgrade and COMPASS for valence, EIC covers sea-quarks and gluon!

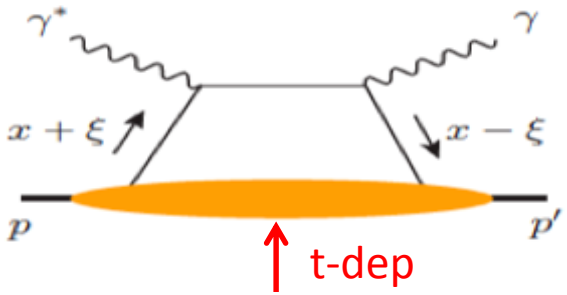
➔ connection of observables to L remains a theoretical challenge

Spatial Imaging of Partons &



Ji Sum Rule $\lim_{t\to 0} \int x dx [H_f(x,\xi,t)+E_f(x,\xi,t)] = 2\,J_f$

Exclusive processes - DVCS:



$$\frac{d\sigma}{dx_B dQ^2 dt}$$

$t = (p' - p)^2$

$\xi = (P' - P)\cdot n/2$

GPDs

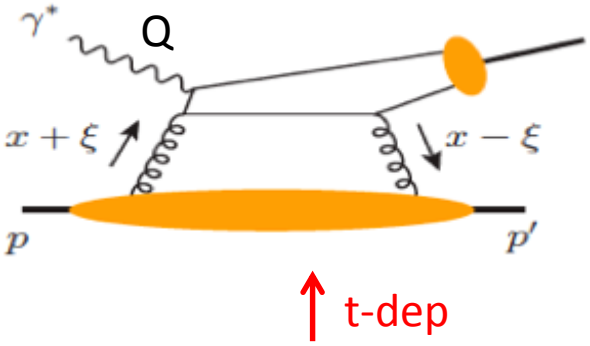
$H_q(x,\xi,t,Q), E_q(x,\xi,t,Q), \ldots$

F.T. of t-dep

Spatial distributions of valence quarks and sea-quarks at large and medium x values

Exclusive vector meson production:

$$\frac{d\sigma}{dx_B dQ^2 dt}$$

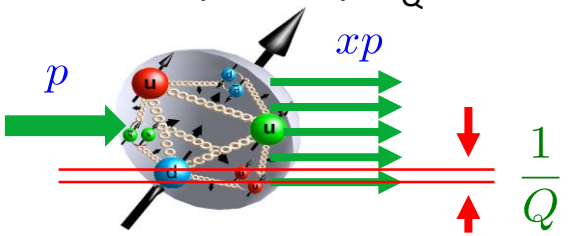


J/Ψ, Φ, …

✧ Fourier transform of the t-dependence

Spatial imaging of glue density

✧ Resolution ~ 1/Q or $1/M_Q$



→ Collect as *much flavour-separated* data as possible on TMDs and GPDs

→ **Huge experimental task!**

The EIC Physics Pillars

- Transverse Momentum Distribution and Spatial Imaging

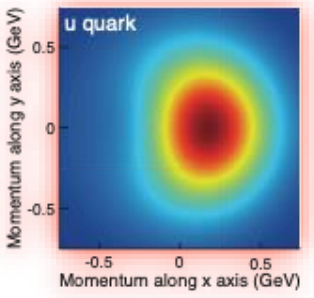
arXiv:1212.1701

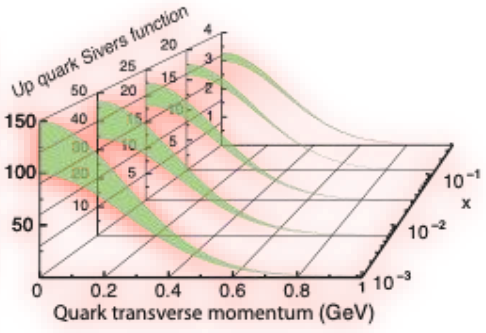
$f(x, k_T)$ 1+2D — Transverse Momentum Distribution (TMD)

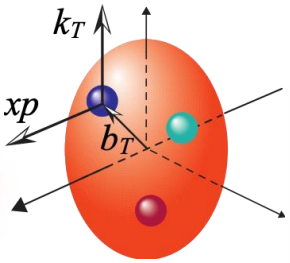
$\int d^2 b_T$ $W(x, b_T, k_T)$ $\int d^2 k_T$ — Wigner Distribution

$f(x, b_T)$ 1+2D — Impact Parameter Distribution

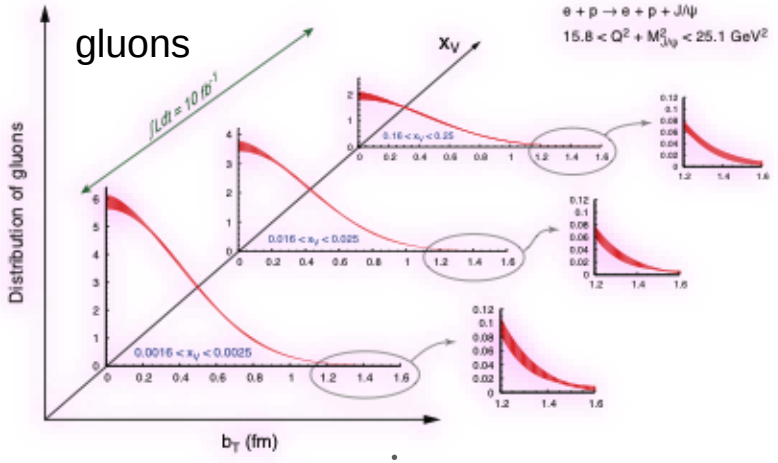
quarks







gluons



- Spin-dependent 1+2D momentum space (transverse) images from semi-inclusive scattering
- Spin-dependent 1+2D impact parameter (transverse) images from exclusive scattering

Fourier transf.
$b_T \leftrightarrow \Delta$: $t = -\Delta^2$

$H(x, 0, t)$

$\xi = 0$

$H(x, \xi, t)$

Generalized Parton Distribution (GPD)

European Strategy for Particle Physics
Granada, Spain, May 13-16, 2019
EICUG Steering Committee