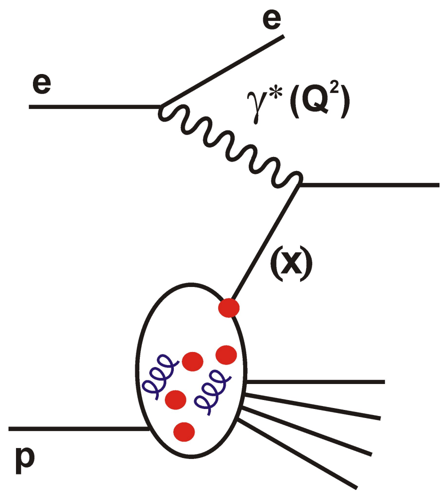
Future High Energy Electron - Hadron Scattering: The LHeC Project



Paul Newman
Birmingham University

Jammu, 8 September 2013

- *Lepton-hadron collider for the 2020s, based on the high lumi LHC*
- *Can we add ep and eA collisions to the existing LHC pp, AA and pA programme?*

Conceptual Design Report (July 2012)

630 pages, summarising 5 year workshop commissioned by CERN, ECFA and NuPECC

~200 participants, 69 institutes

Additional material in subsequent updates:

"A Large Hadron Electron Collider at CERN" [arXiv:1211.4831]

"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]

Journal of Physics G
Nuclear and Particle Physics

[arXiv:1206.2913]

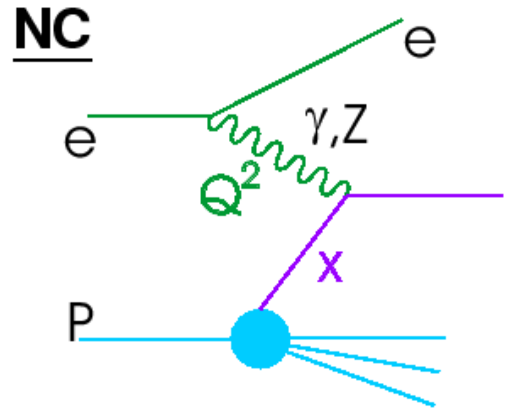
Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN
Report on the Physics and Design Concepts for Machine and Detector
LHeC Study Group

iopscience.org/jphysg

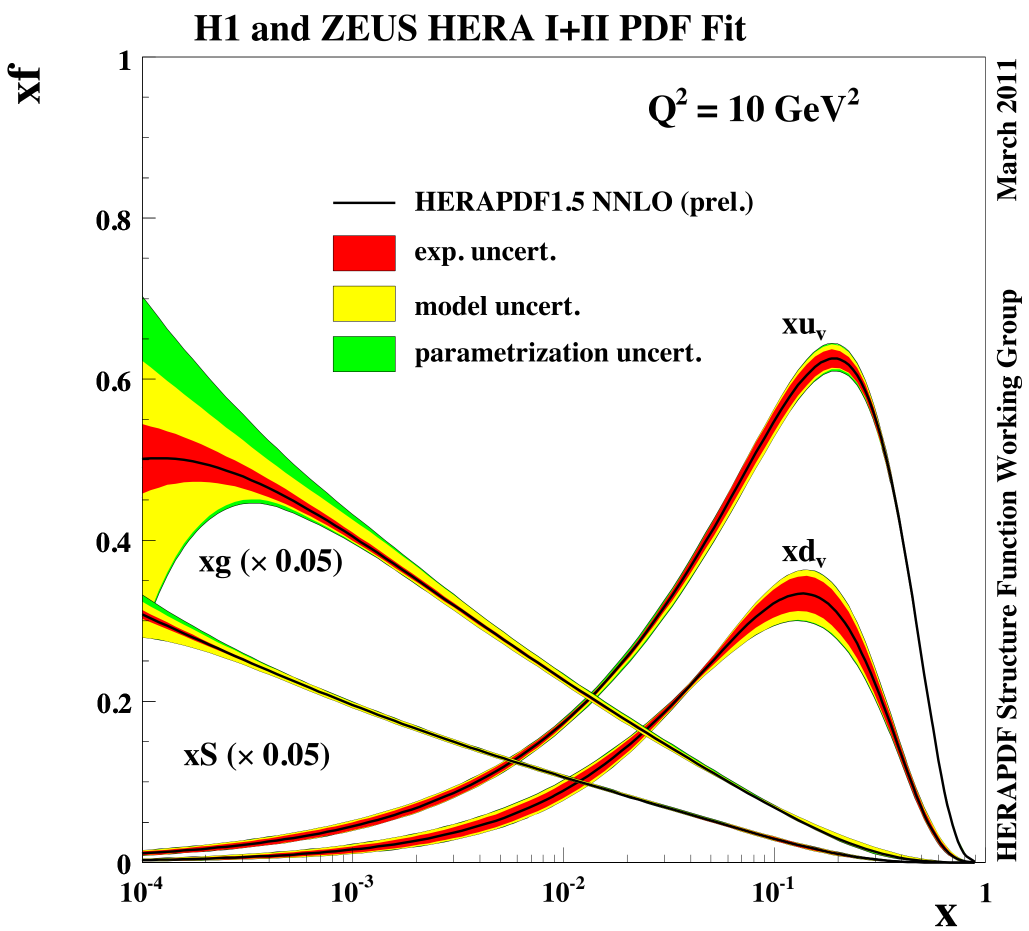
IOP Publishing

DIS and HERA



Q^2: exchanged boson resolving power

x: fractional momentum
of struck quark



HERA Proton parton densities in x range well matched to LHC rapidity plateau … BUT…

- Insufficient lumi for high x

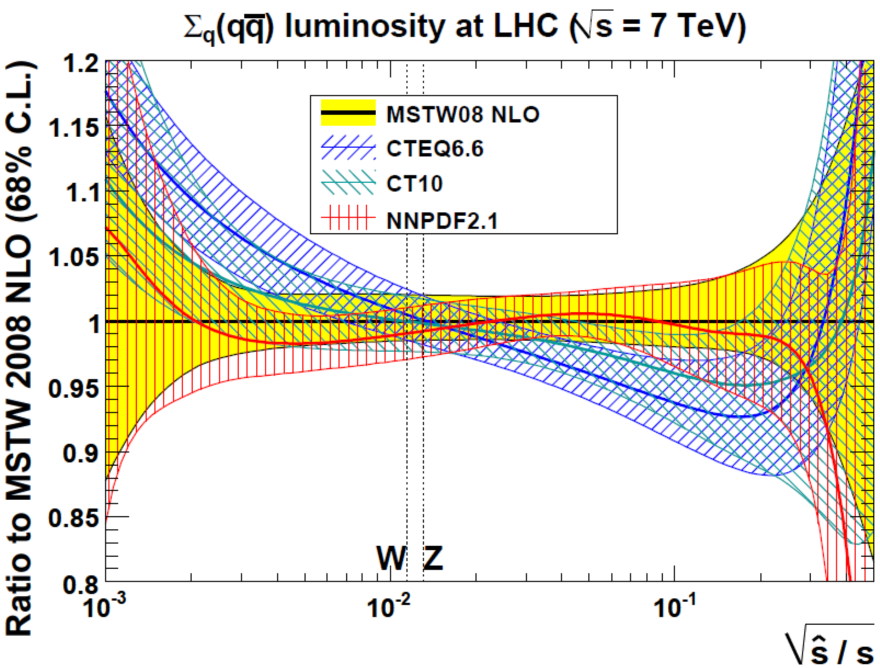
- Lack of Q^2 lever-arm for low x gluon

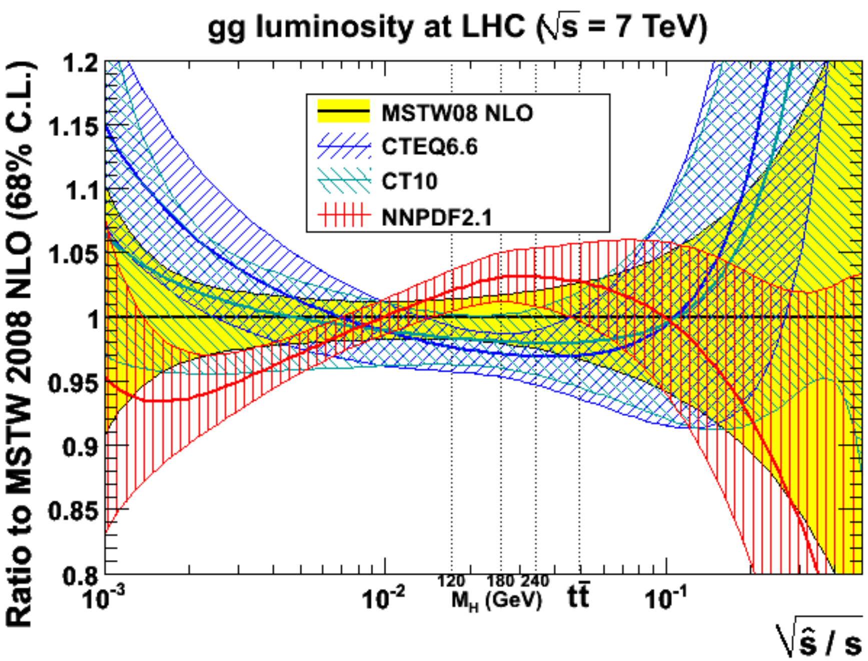
- Assumptions on quark flavour decomposition

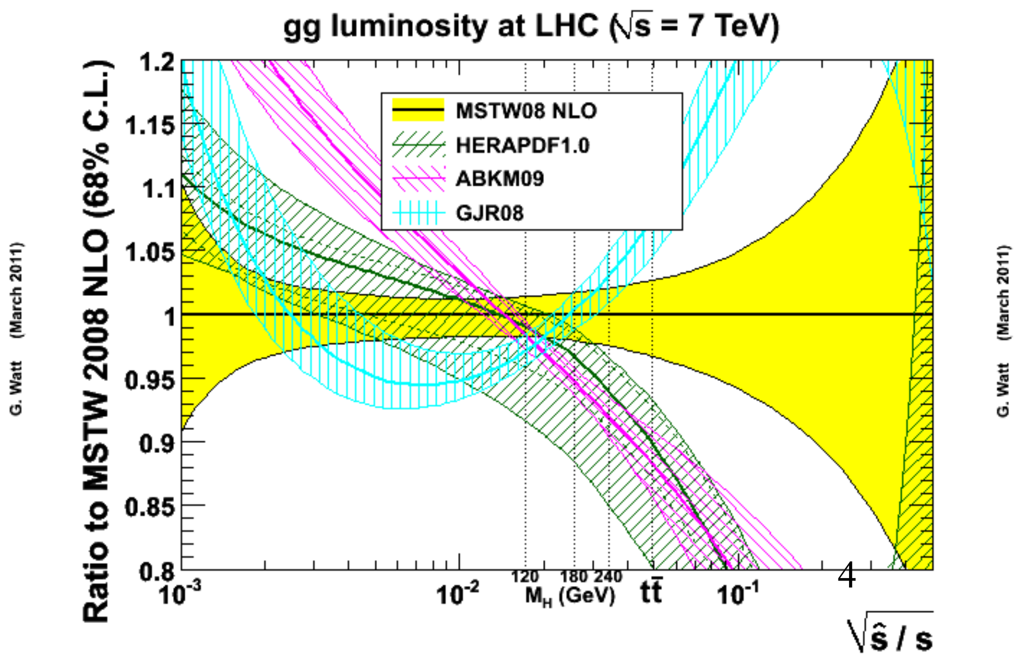
- No deuterons or heavy ions

Current PDFs & LHC

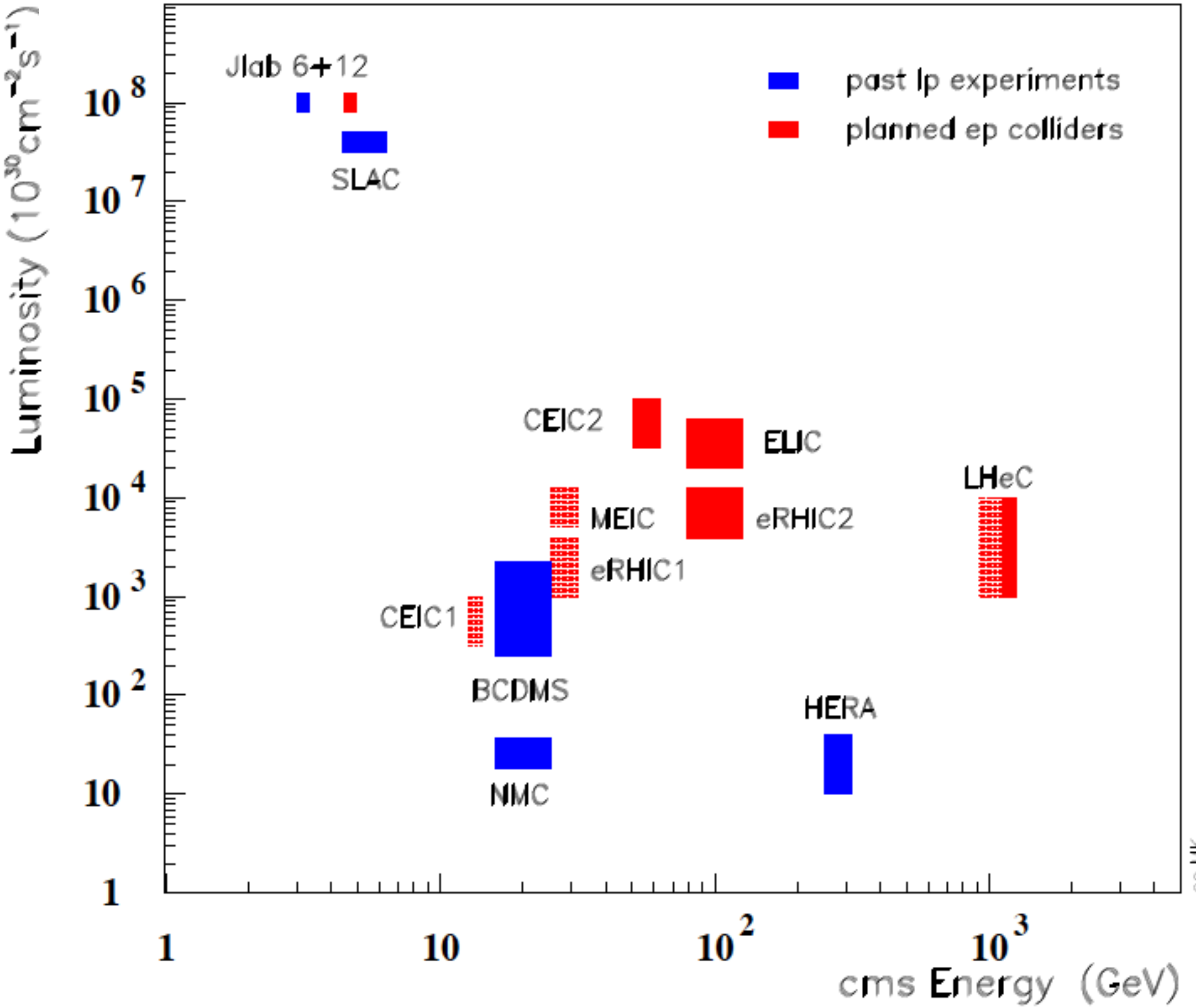
Current uncertainties due to PDFs for particles on LHC rapidity plateau (NLO):
- Most precise for quark initiated processes around EW scale
- Gluon initiated processes less well known
- All uncertainties explode for largest masses







Beyond HERA: LHeC Context



- LHeC is latest & most promising idea to take lepton-hadron physics to the TeV centre of mass scale

- High luminosity: 10^{33} - 10^{34} cm^{-2} s^{-1}

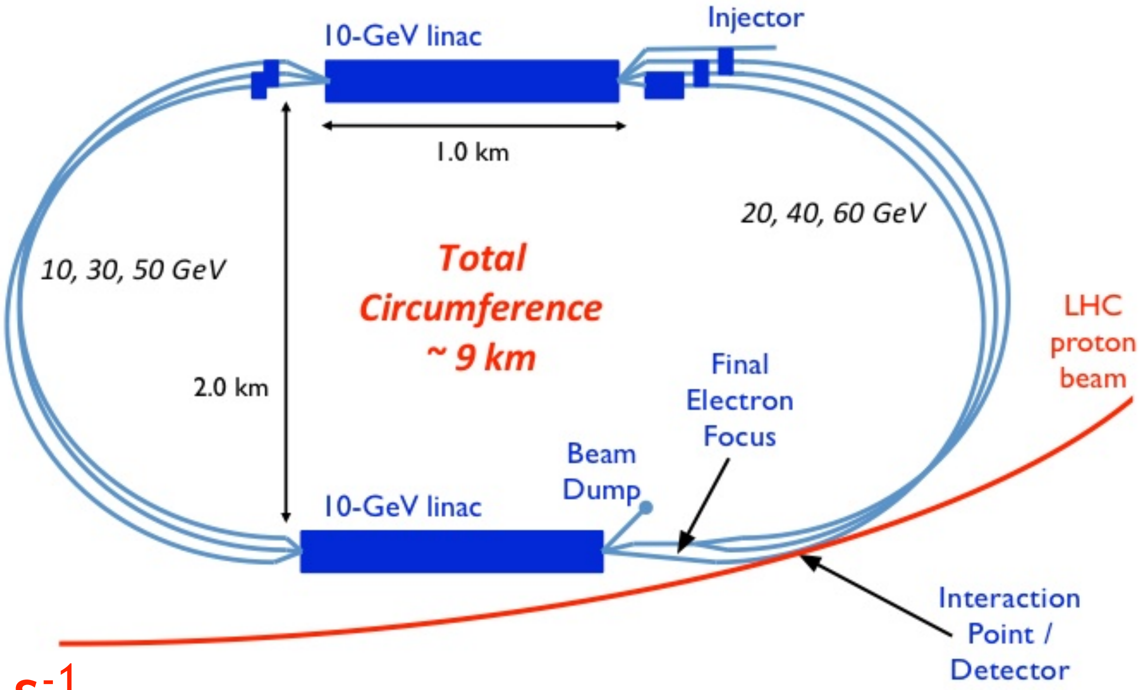
- Runs simultaneous with ATLAS / CMS in post-LS3 HL-LHC period

Baseline# Design (Electron "Linac")

Design constraint: power consumption < 100 MW → E_e = 60 GeV

- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures

[CERN plans energy recovery prototype]



- ep Lumi 10^{33} – 10^{34} cm^{-2} s^{-1}

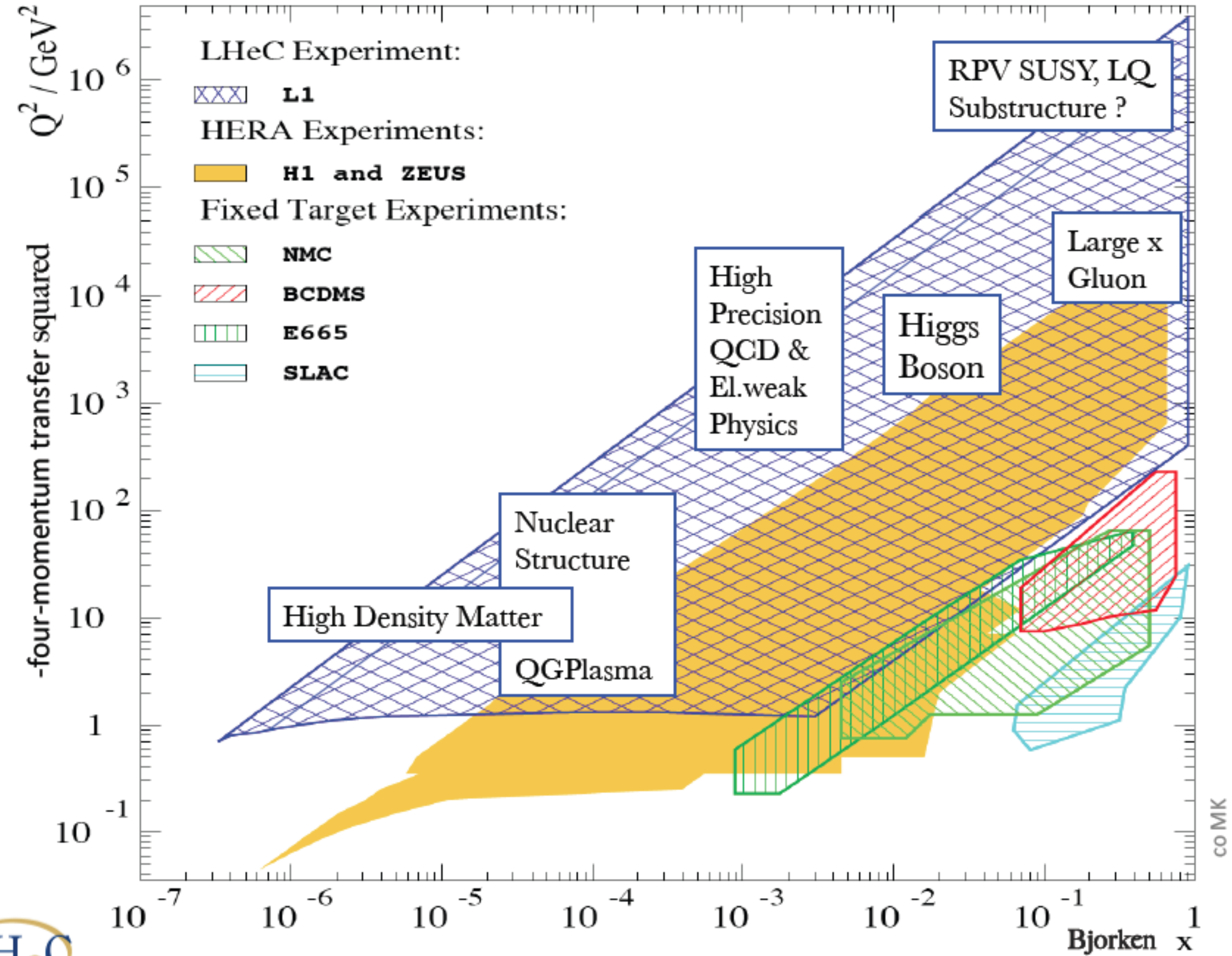
→ 10 - 100 fb^{-1} per year

→ 100 fb^{-1} – 1 ab^{-1} total

- **eD and eA collisions have always been integral to programme**
- **e-nucleon Lumi estimates ~ 10^{31} (10^{32}) cm^{-2} s^{-1} for eD (ePb)**

Alternative designs based on electron ring and on higher energy, lower luminosity, linac also exist

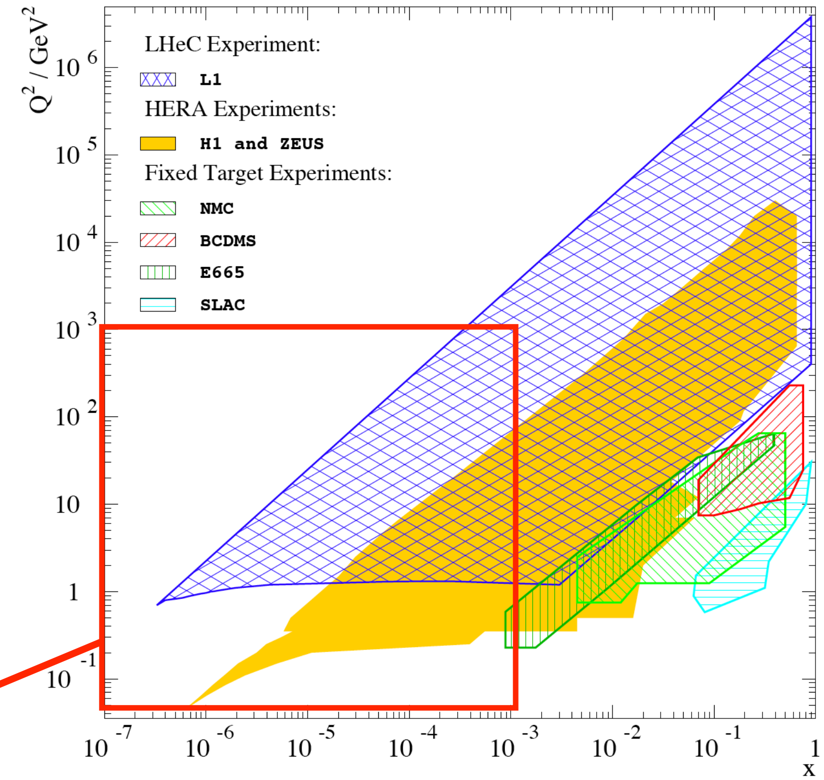
Physics Overview

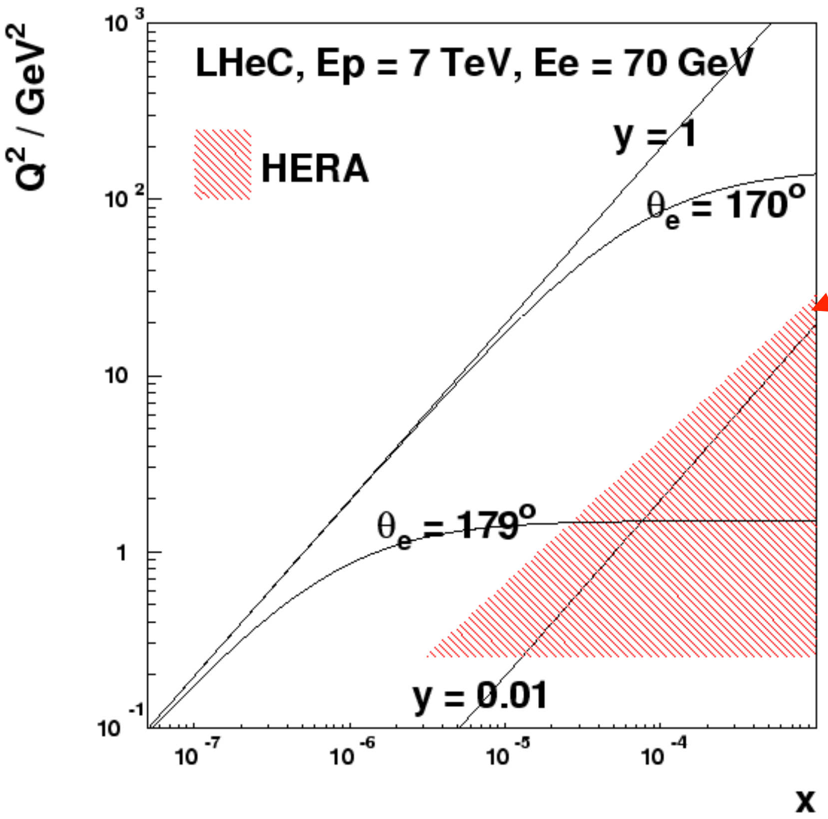


LHeC

LHeC Detector Acceptance Requirements

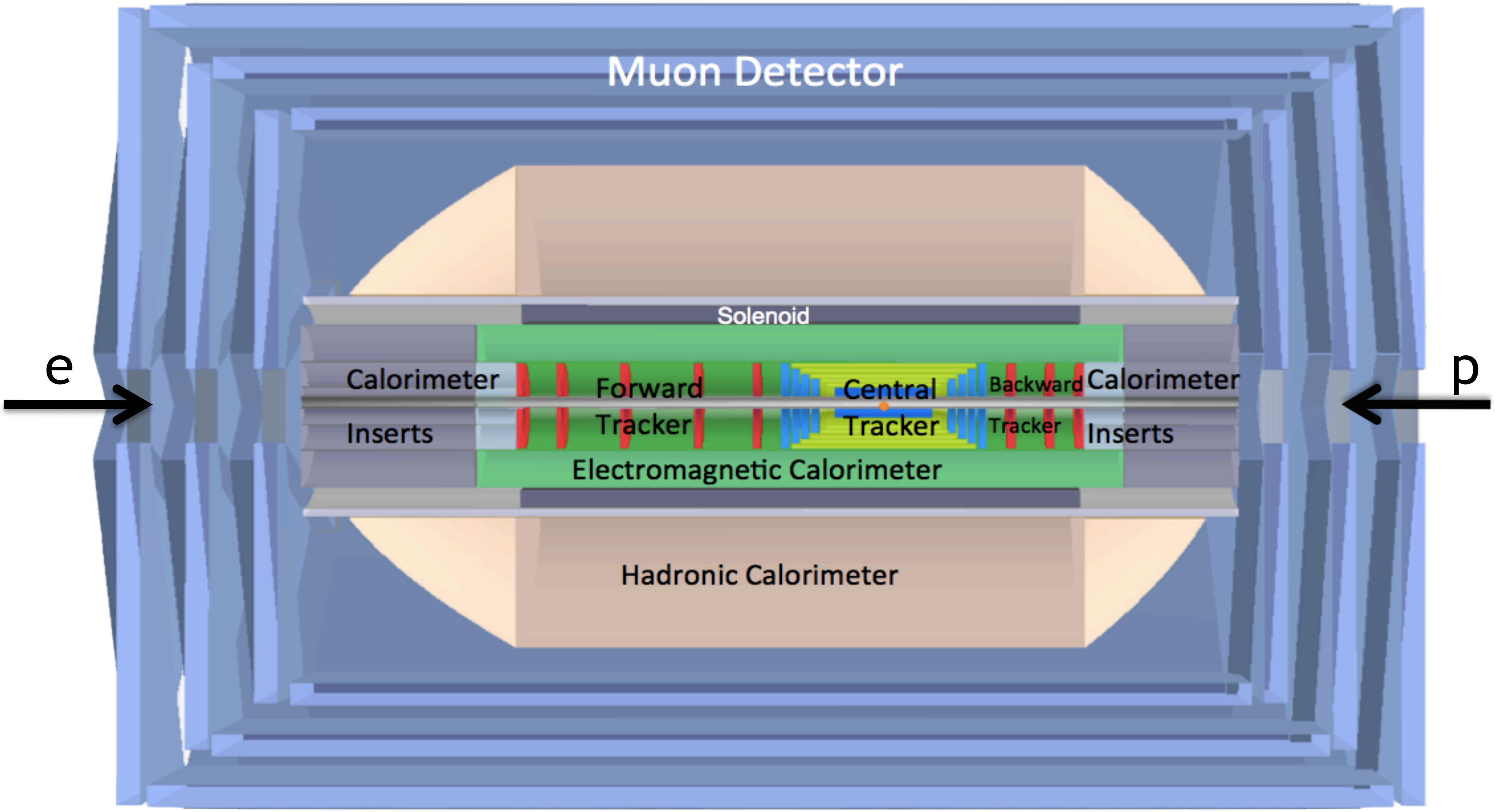
Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} requires scattered electron acceptance to 179°





Similarly, need 1° acceptance in outgoing proton direction to contain hadrons at high x (essential for good kinematic reconstruction)

Detector Overview



- Forward / backward asymmetry reflecting beam energies
- Present size 14m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- **ZDC, proton spectrometer integral to design from outset**

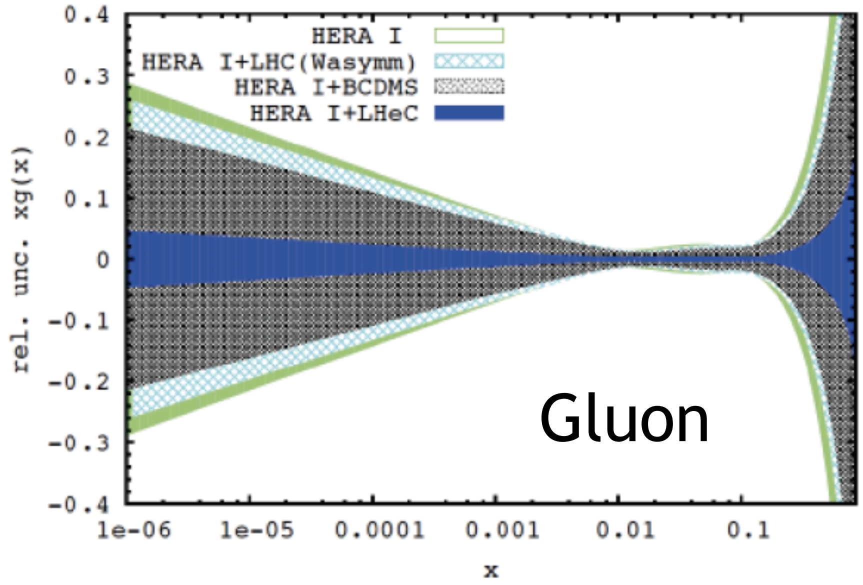
Assumed Systematic Precision

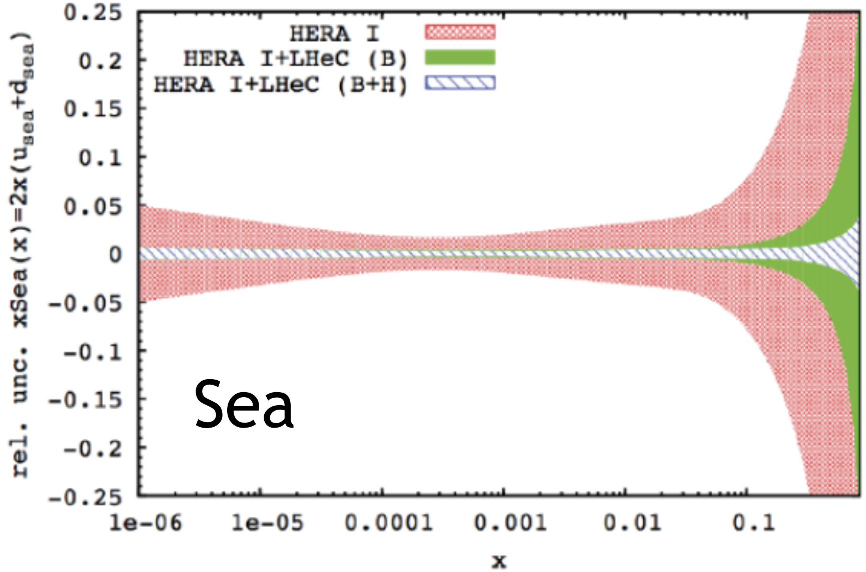
In the absence of a detailed simulation set-up, simulated `pseudo-data' produced with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).

	LHeC	HERA
Lumi [$cm^{-2}s^{-1}$]	10^{33}	$1\text{-}5 \cdot 10^{31}$
Acceptance [°]	1-179	7-177
Tracking to	0.1 mrad	0.2-1 mrad
EM calorimetry to	0.1%	0.2-0.5%
Hadronic calorimetry	0.5%	1-2%
Luminosity	0.5%	1%

PDF Constraints at LHeC

Full simulation of inclusive NC and CC DIS data, including systematics → NLO DGLAP fit using HERA technology…

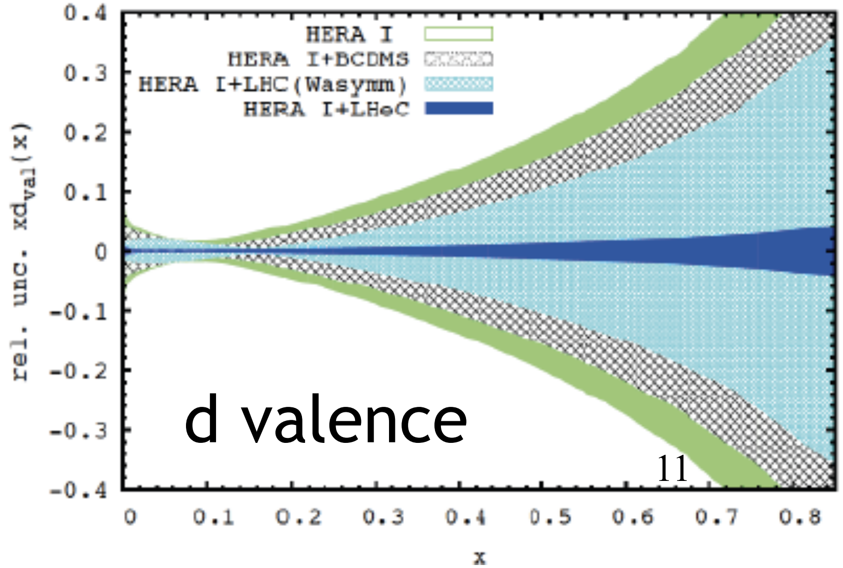




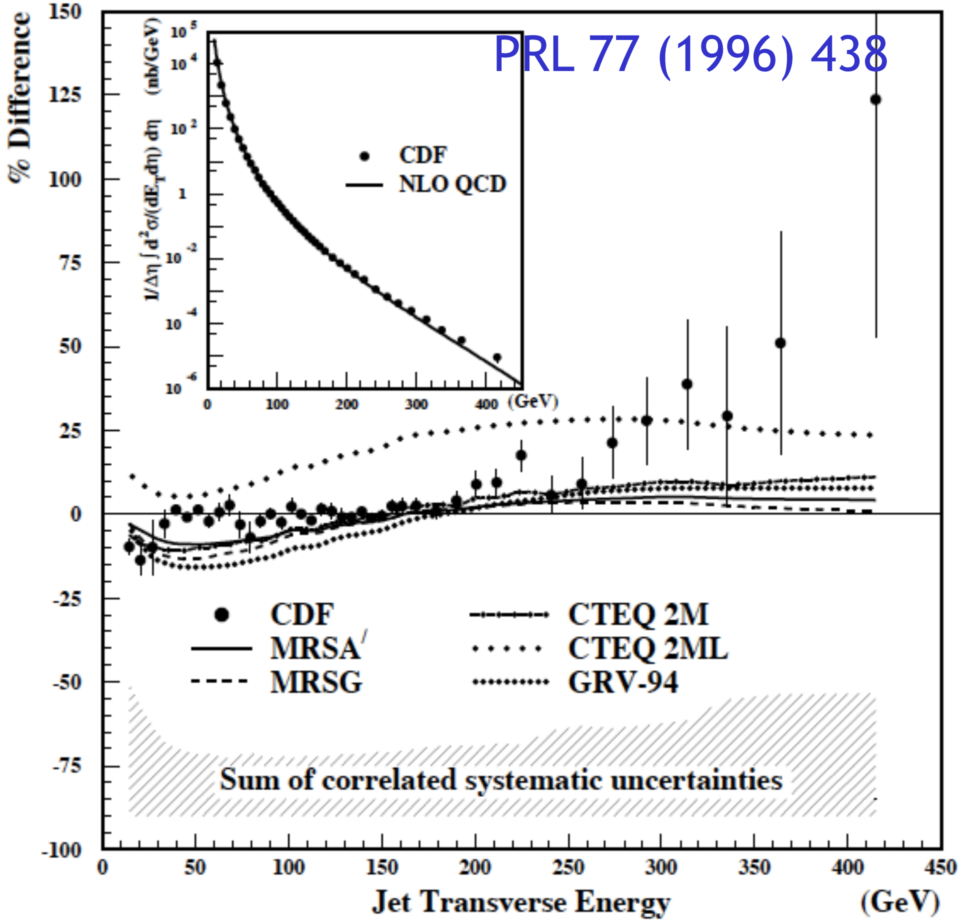
… impact at low x (kinematic range) and high x (luminosity)

… precise light quark vector, axial couplings, weak mixing angle

… full flavour decomposition



Do we need to Care about High x?



Ancient history (HERA, Tevatron)

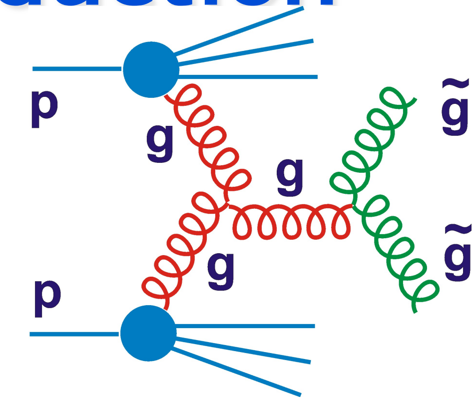
- Apparent excess in large E_T jets at Tevatron turned out to be explained by too low high x gluon density in PDF sets

- Confirmation of (non-resonant) new physics near LHC kinematic limit relies on breakdown of factorisation between ep and pp

Searches near LHC kinematic boundary may ultimately be limited by knowledge of PDFs (especially gluon as x → 1)

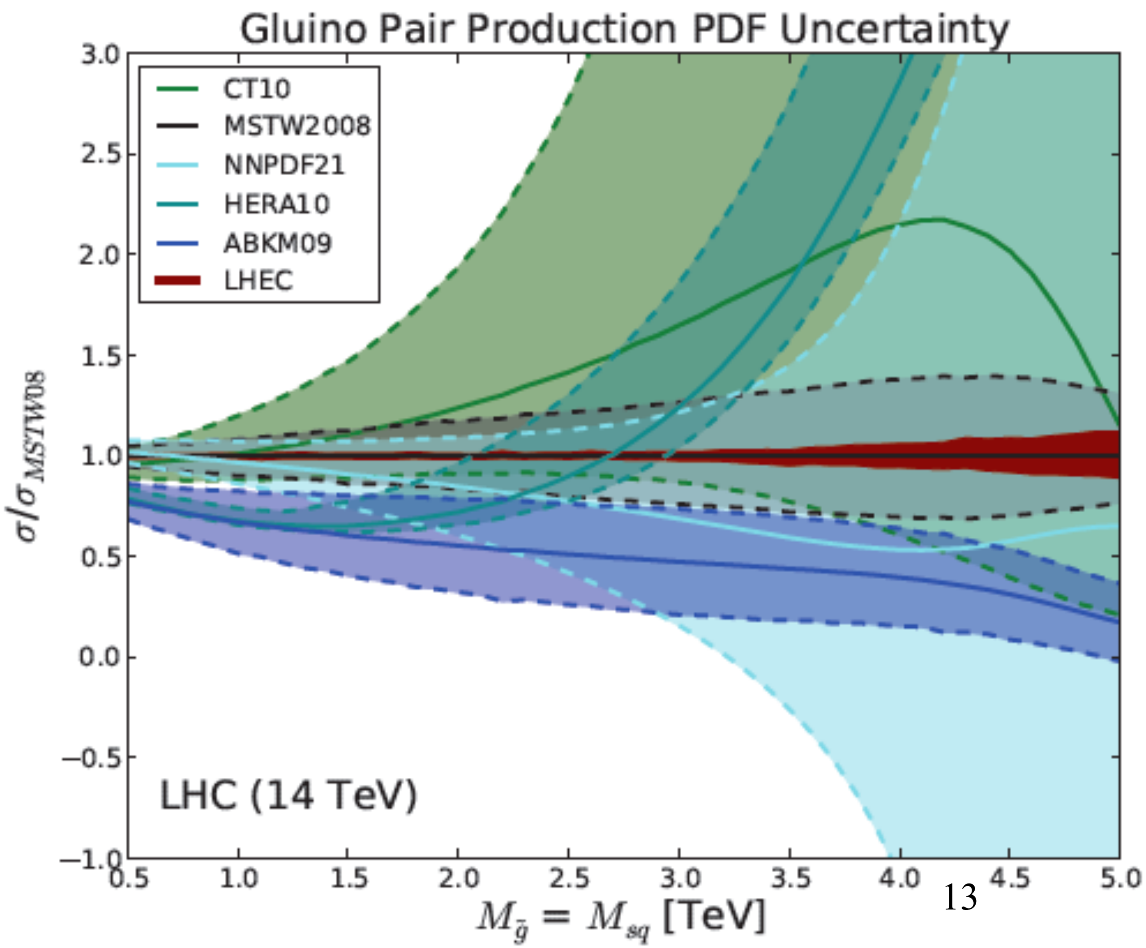
e.g. High Mass 2 Gluino Production

- Signature is excess @ large invariant mass
- Expected SM background (e.g. gg → gg) poorly known for s-hat > 1 TeV.



- Both signal & background uncertainties driven by error on gluon density … Essentially unknown for masses much beyond 2 TeV

- Similar conclusions for other non-resonant LHC signals involving high x partons (e.g. contact interactions signal in Drell-Yan)

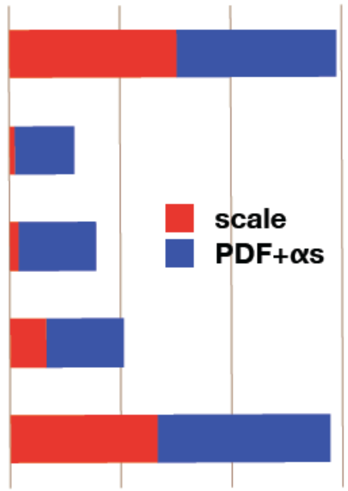


PDF Uncertainties for Higgs Physics

Theory Cross Section Uncertainties

(125 GeV Higgs
J Campbell, ICHEP'12)

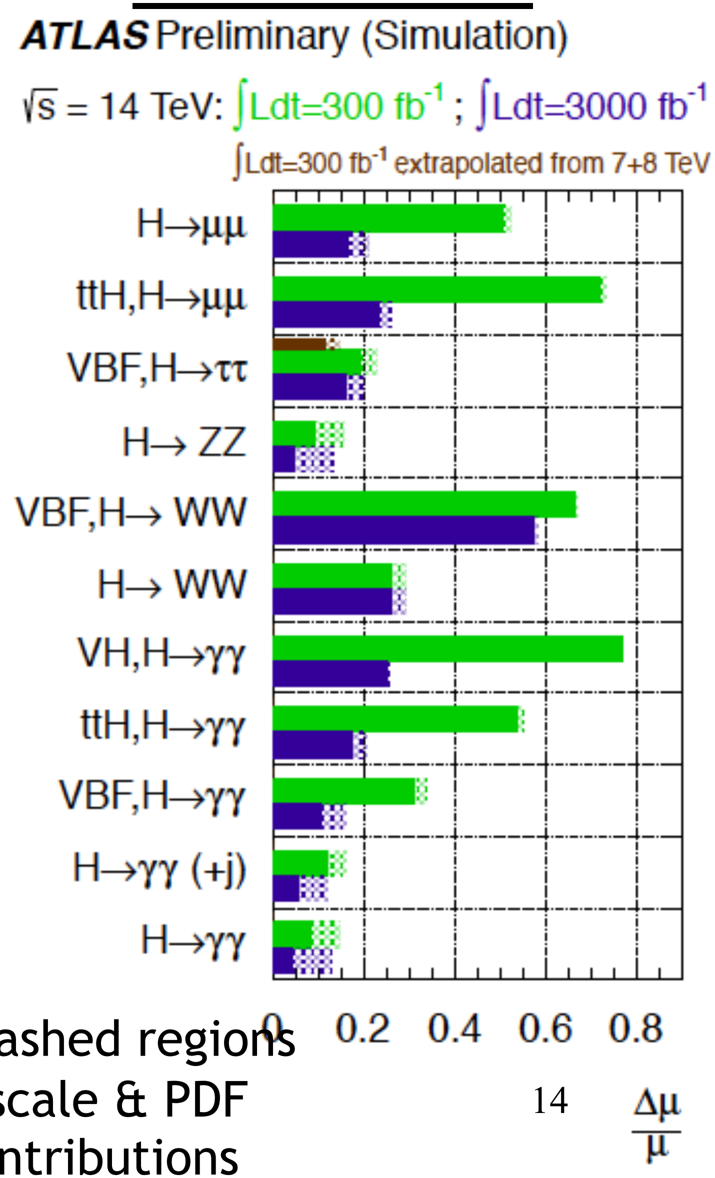
		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



Similarly fermionic modes (bbbar, ccbar)

... tests of Standard Model in Higgs sector may become limited by knowledge of PDFs in HL-LHC era

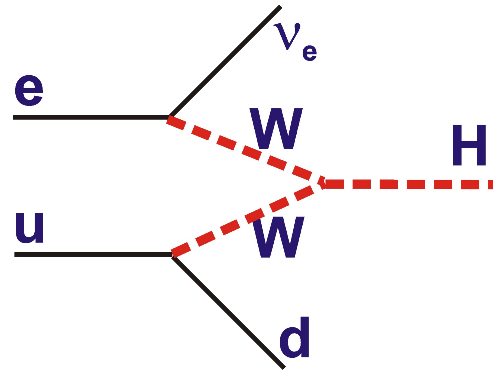
Projected Experimental Uncertainties



[Dashed regions = scale & PDF contributions

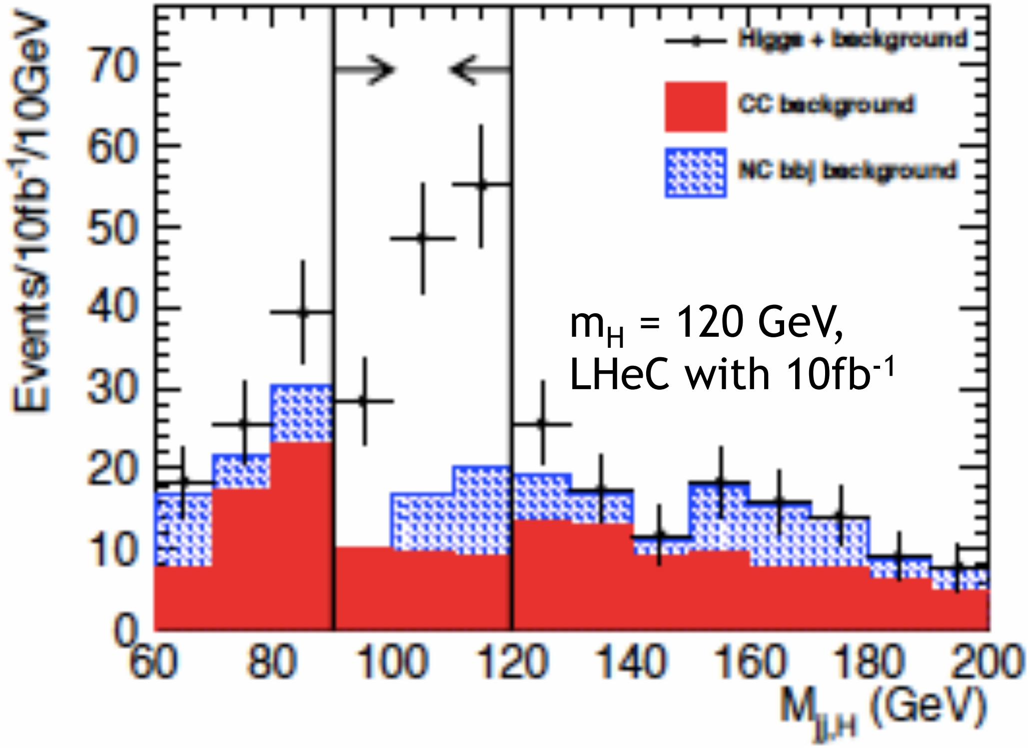
A Direct Higgs Study

Dominant charged current process has similar cross section to linear e+e- collider



Study of H → bbbar in generic simulated LHC detector

	E_e = 150 GeV (10 fb^{-1})	E_e = 60 GeV (100 fb^{-1})
H → bb signal	84.6	248
S/N	1.79	1.05
S/√N	12.3	16.1



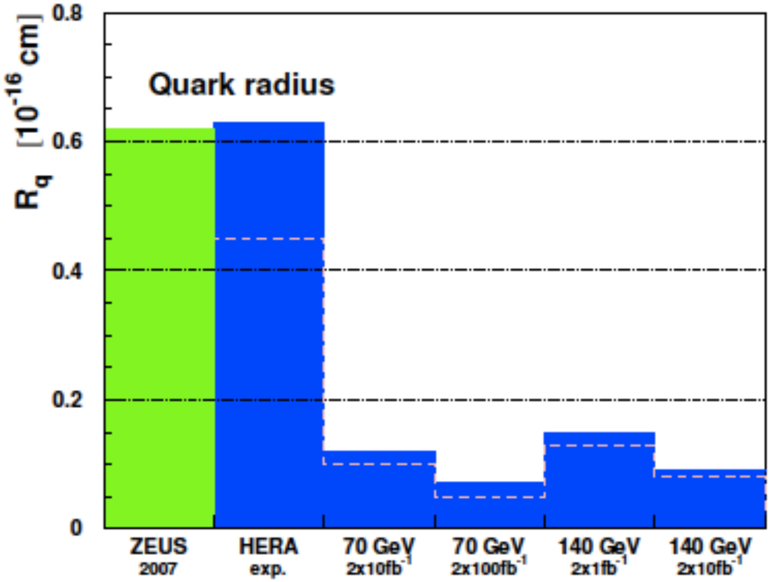
... + 90% lepton polarisation enhances signal by factor 1.9

... + With 10^{34} luminosity, x10 more data

→ ~5000 events @ Ee = 60 GeV … H→bbbar coupling to ~ 1%.

Direct Sensitivity to New Physics

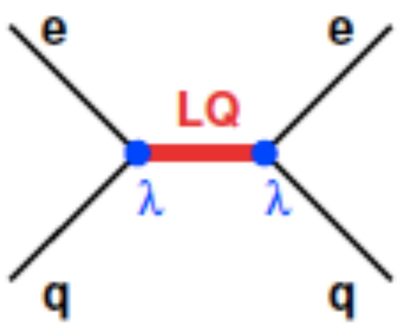
• The (pp) LHC has much better discovery potential than LHeC (unless E_e increases to >~500 GeV and 10^{34} lumi achieved)

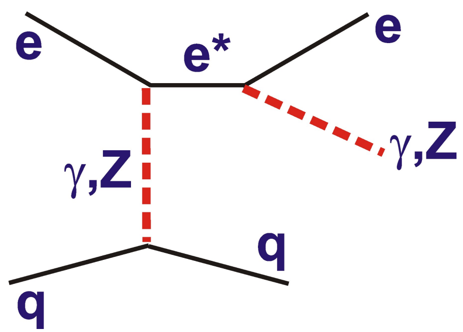


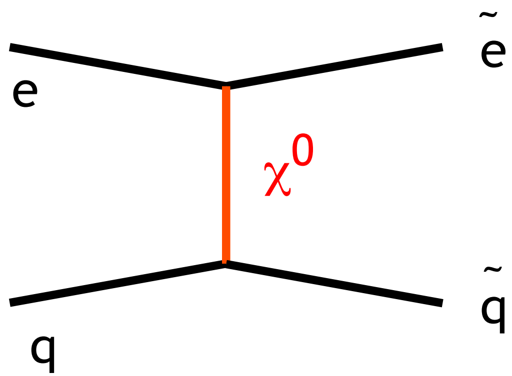
e.g. Expected quark compositeness limits below 10^{-19} m at LHeC

… big improvement on HERA, but already beaten by LHC

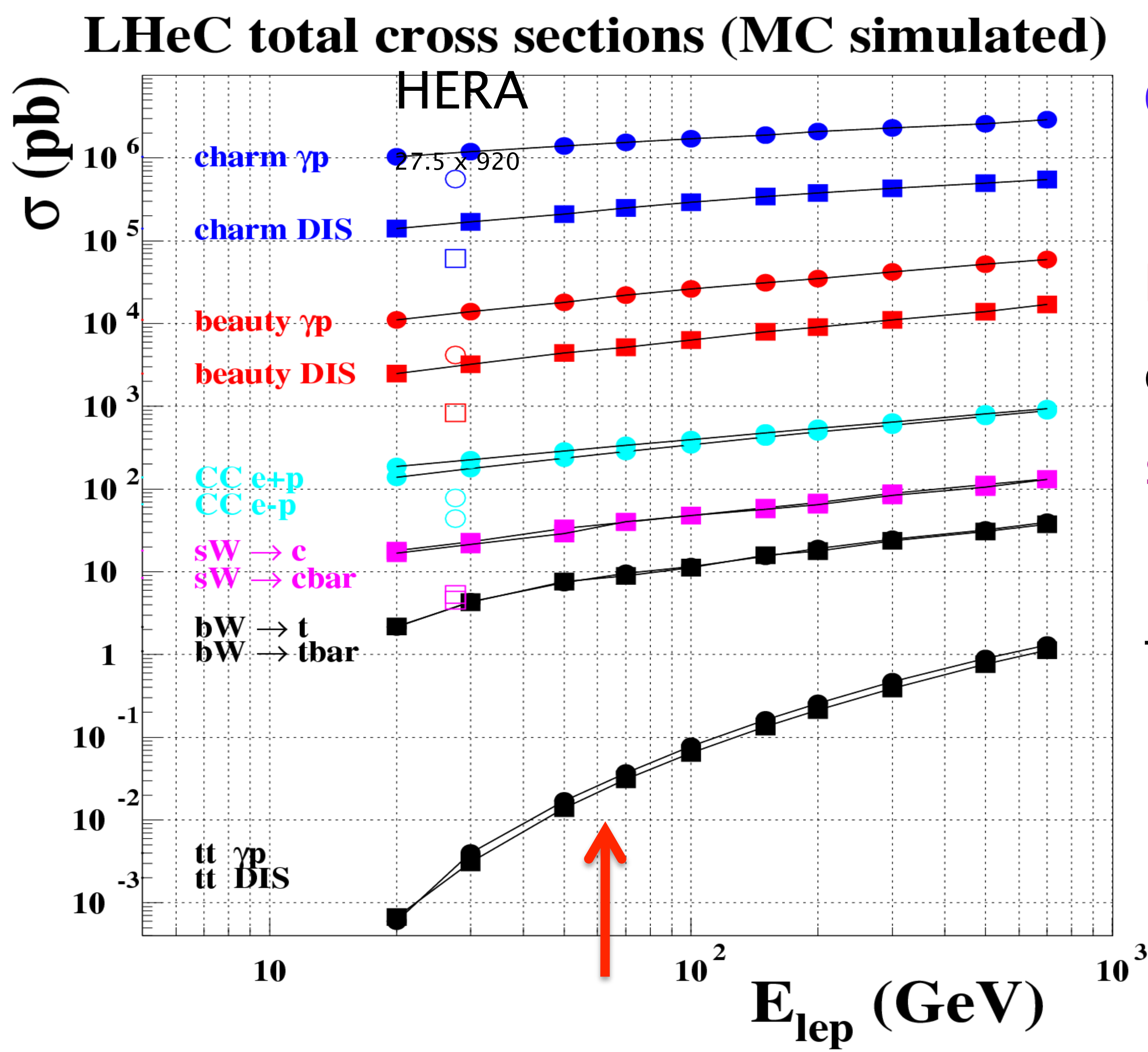
• LHeC *is* competitive with LHC in cases where initial state lepton is an advantage and offers cleaner final states







Cross Sections and Rates for Heavy Flavours



Charm $[10^{10} / 10\ fb^{-1}]$

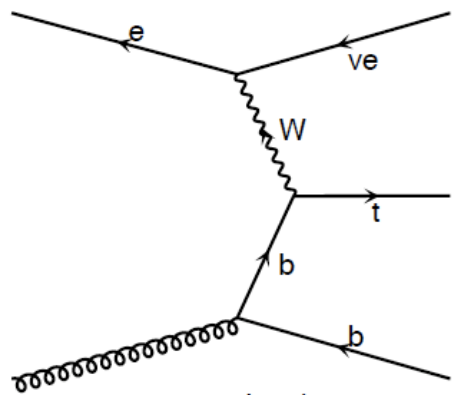
Beauty $[10^{8} / 10\ fb^{-1}]$

cc

sW → c $[4.10^{5} / 10\ fb^{-1}]$

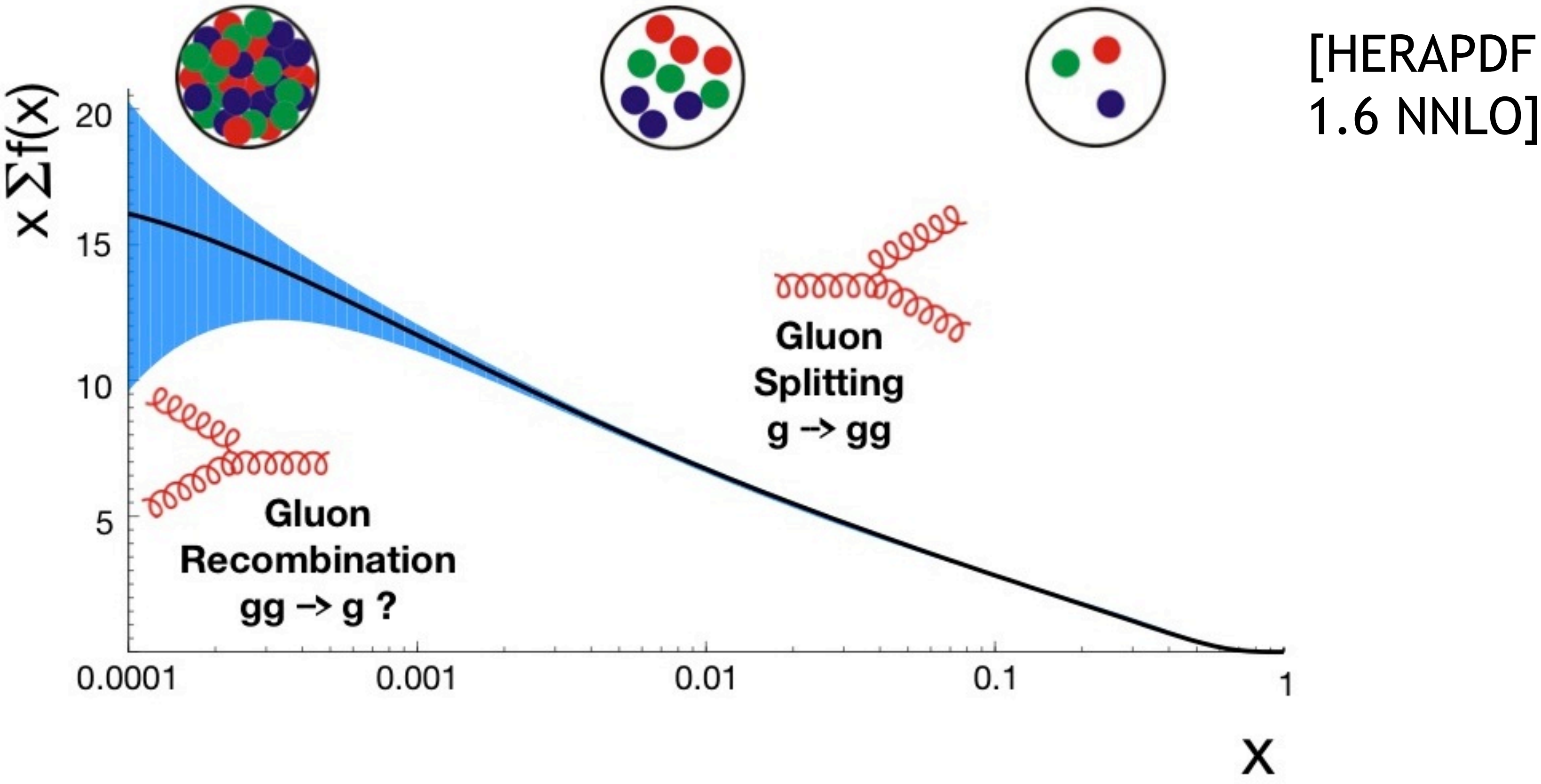
bW → t $[10^{5} / 10\ fb^{-1}]$

ttbar $[10^{3} / 10\ fb^{-1}]$



c.f. luminosity of ~10 fb^{-1} per year …

Low-x Physics and Parton Saturation



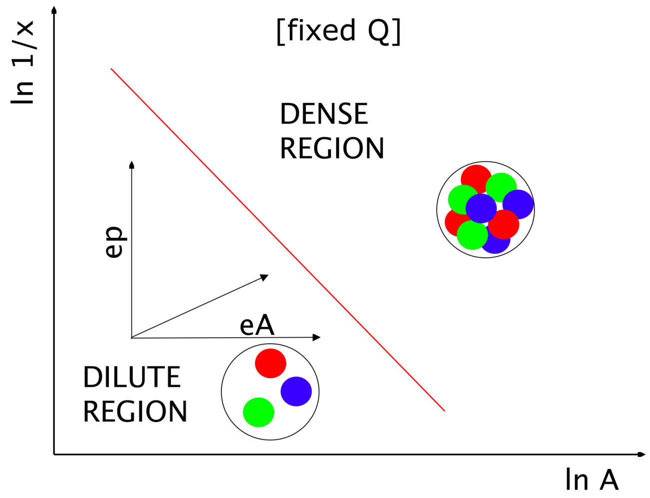
- Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects

… new high density, small coupling parton regime of non-linear parton evolution dynamics (e.g. Colour Glass Condensate)? …

… gluon dynamics → confinement and hadronic mass generation

LHeC Strategy for making the target blacker

LHeC delivers a 2-pronged approach:



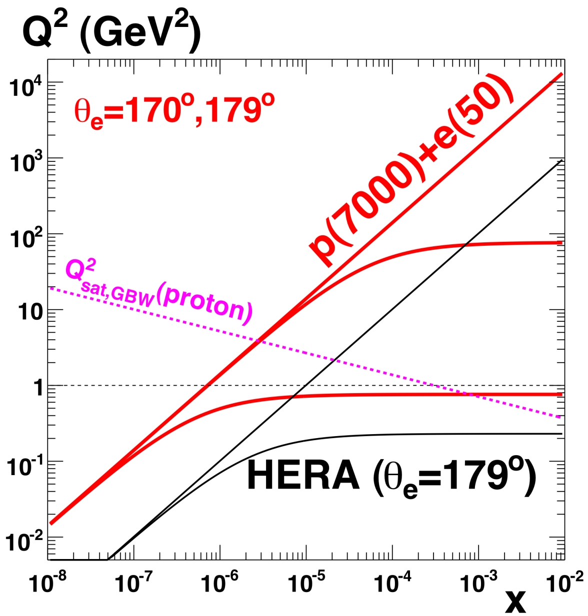
Enhance target `blackness' by:

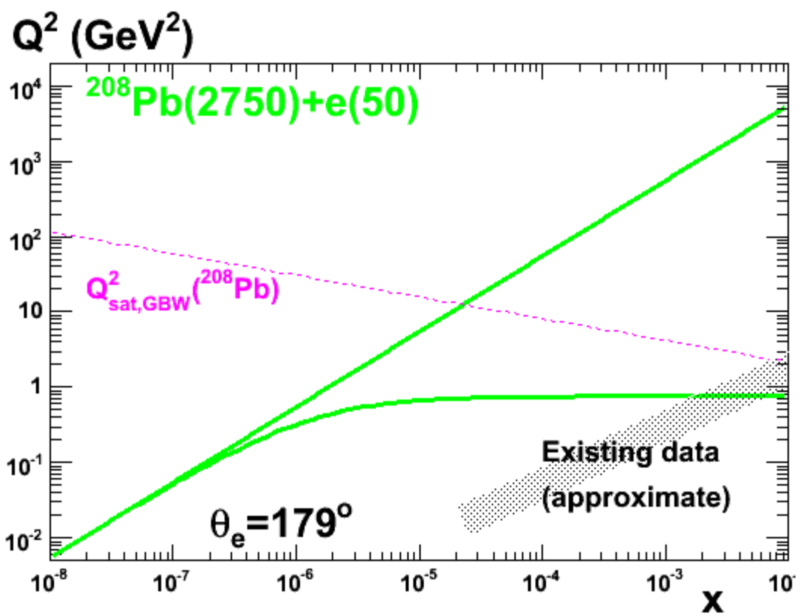
1) Probing lower x at fixed Q^2 in ep

[evolution of a single source]

2) Increasing target matter in eA

[overlapping many sources at fixed kinematics … density ~ $A^{1/3}$ ~ 6 for Pb … worth 2 orders of magnitude in x]



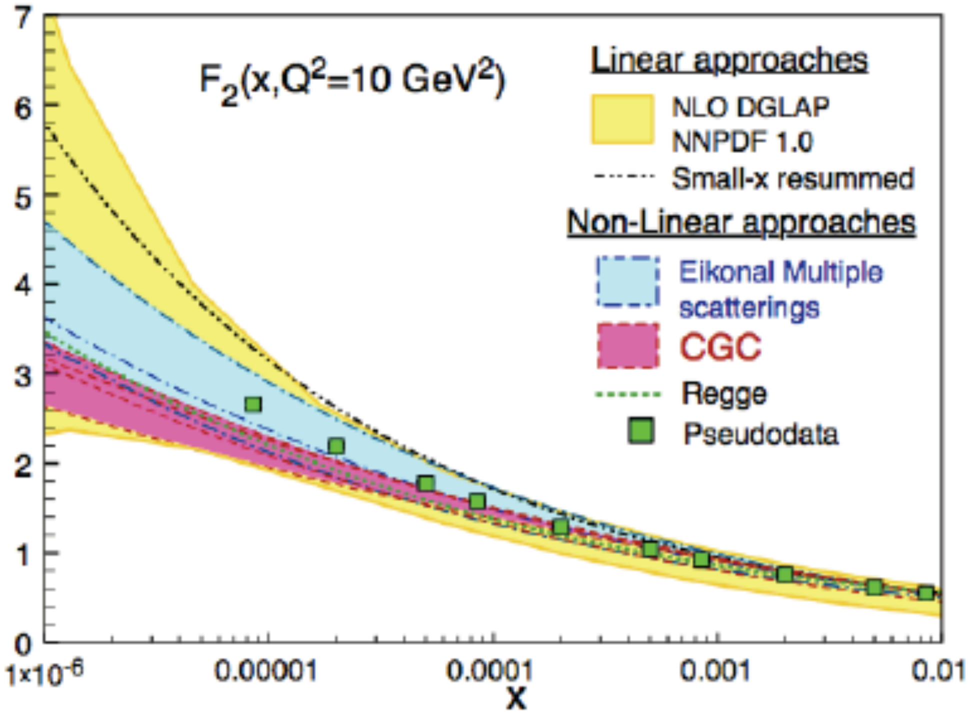


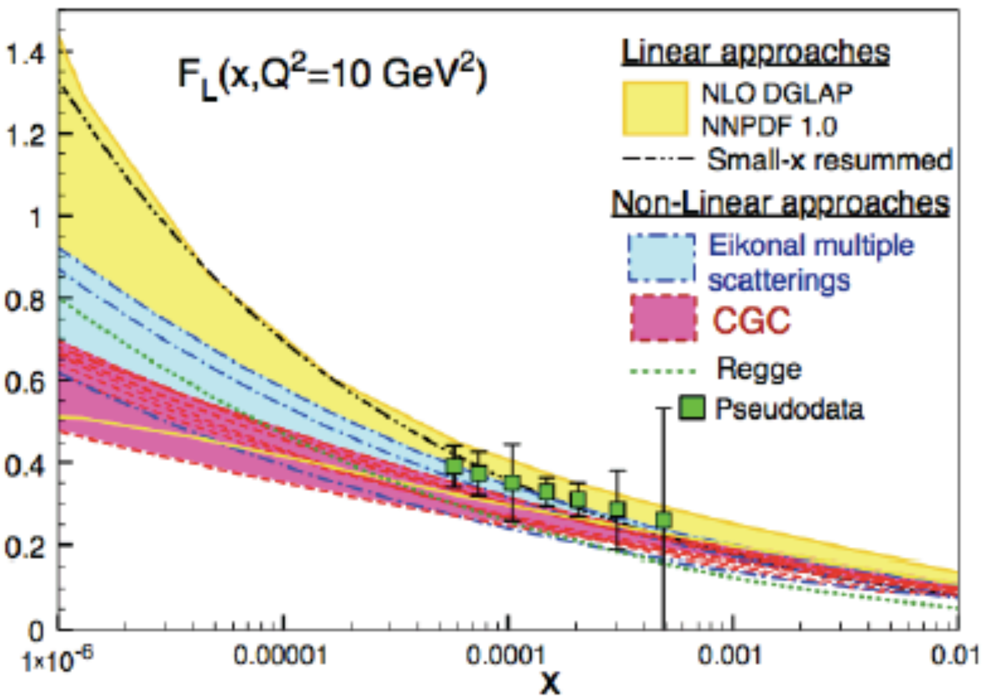
… Reaching saturated region in both ep & eA according to current models

Establishing and Characterising Saturation

With 1 fb^{-1} (1 month at 10^{33} cm^{-2} s^{-1}), F_2 stat. < 0.1%, syst, 1-3%

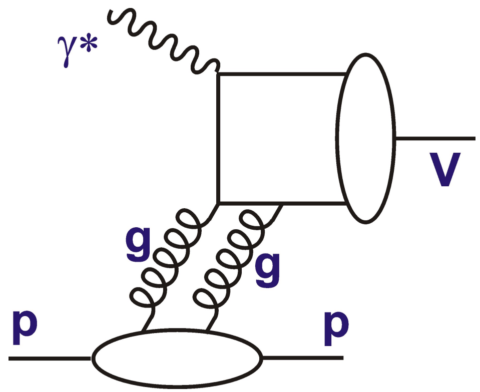
F_L measurement to 8% with 1 year of varying E_e or E_p





- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics
- Unambiguous observation of saturation will be based on tension between different observables e.g. F_2 v F_L in ep or F_2 in ep v eA

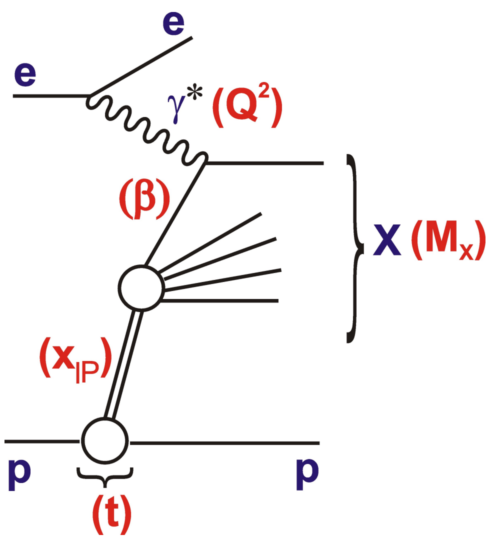
Exclusive / Diffractive Channels and Saturation

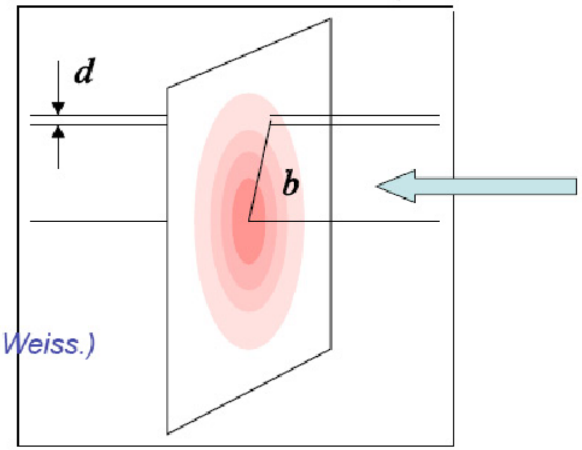


1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon

2) Additional variable t gives access to impact parameter (b) dependent amplitudes

→ Large t (small b) probes densest packed part of proton?



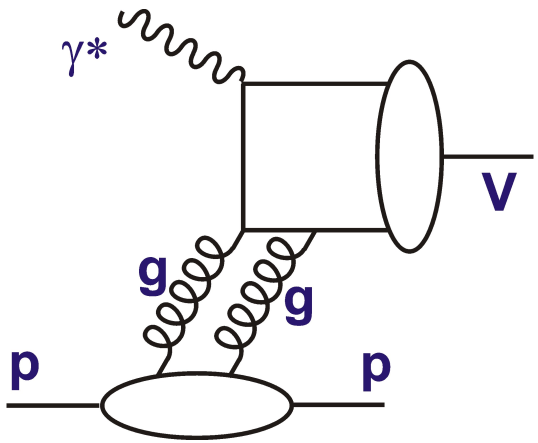


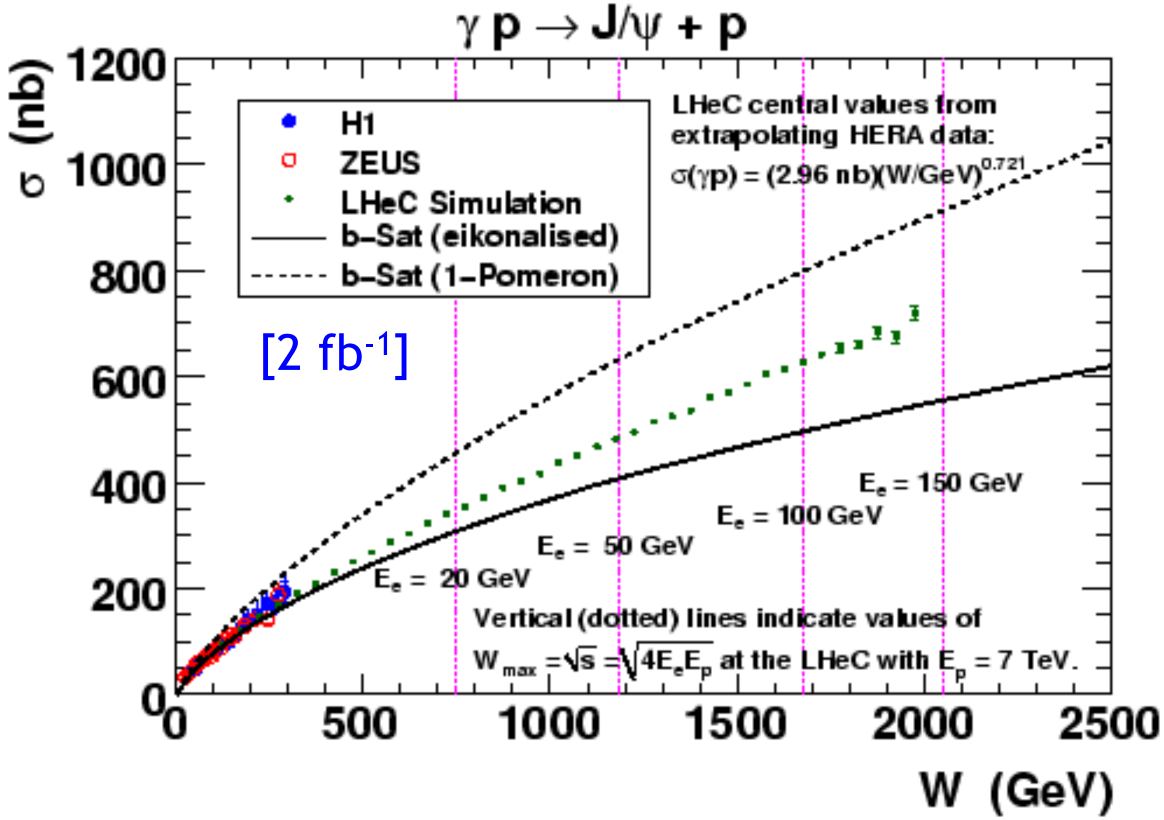
(figure from C. Weiss.)

Central black region growing with decrease of x.

e.g. J/ψ Photoproduction

e.g. "b-Sat" Dipole model
- "eikonalised": with impact-parameter dependent saturation
- "1 Pomeron": non-saturating





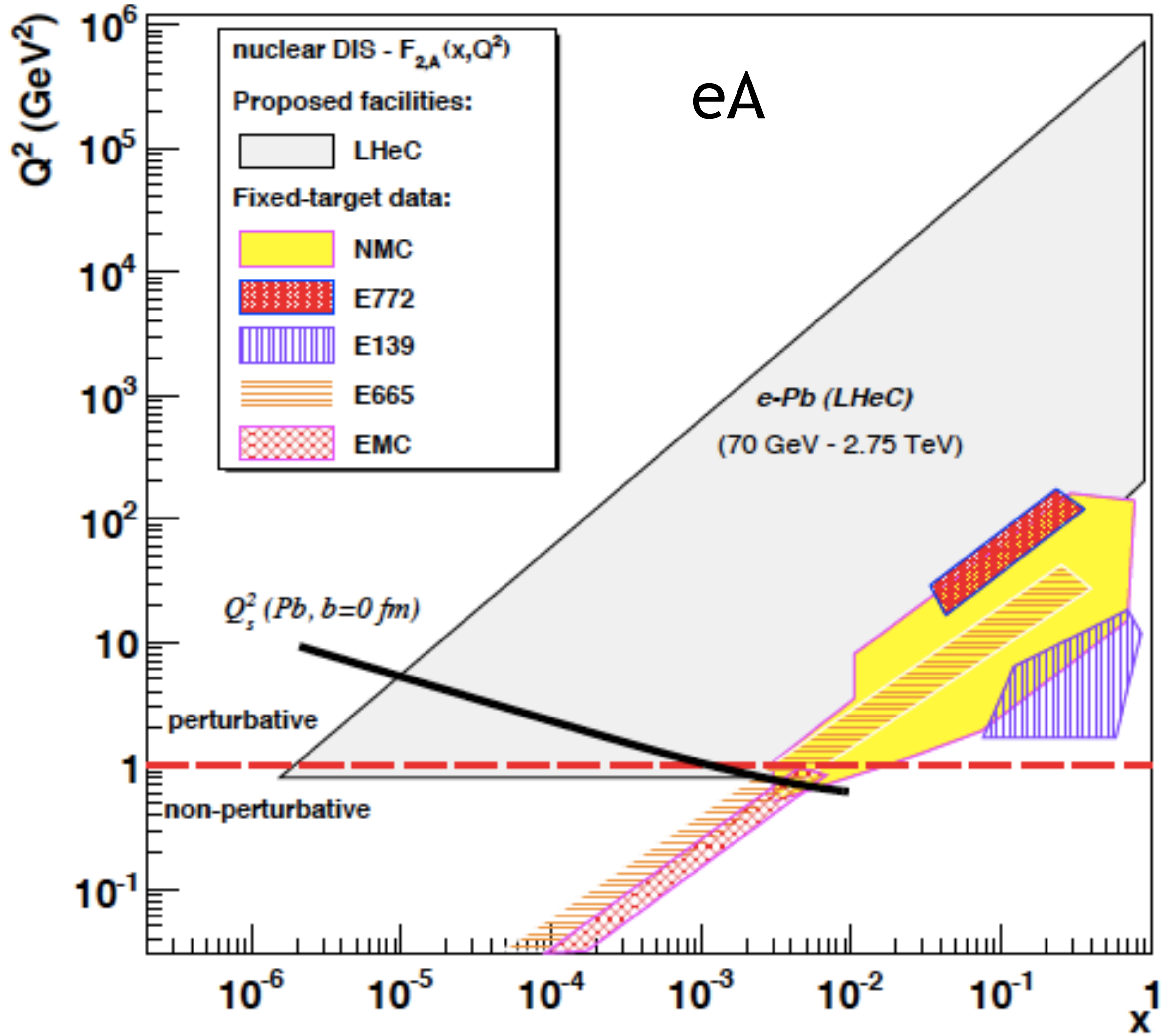
- Significant non-linear effects expected in LHeC kinematic range.

- Data shown are extrapolations of HERA power law fit for E_e = 150 GeV…

  → Sat^n smoking gun?

LHeC as an Electron-ion Collider

Four orders of magnitude increase in kinematic range over previous DIS experiments.

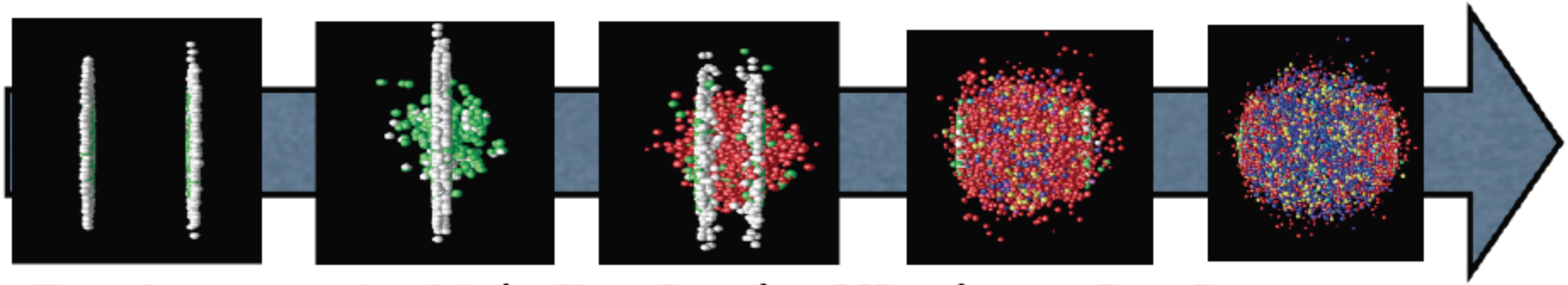


→Revolutionise our view of the partonic structure of nuclear matter.

→ Study interactions of densely packed, but weakly coupled, partons

→Ultra-clean probe of passage of `struck' partons through cold nuclear matter

Relevance to the Heavy Ion Programme



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Nuclear wave function at small x: nuclear structure functions.

- Particle production at the very beginning: which factorisation in eA?

- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

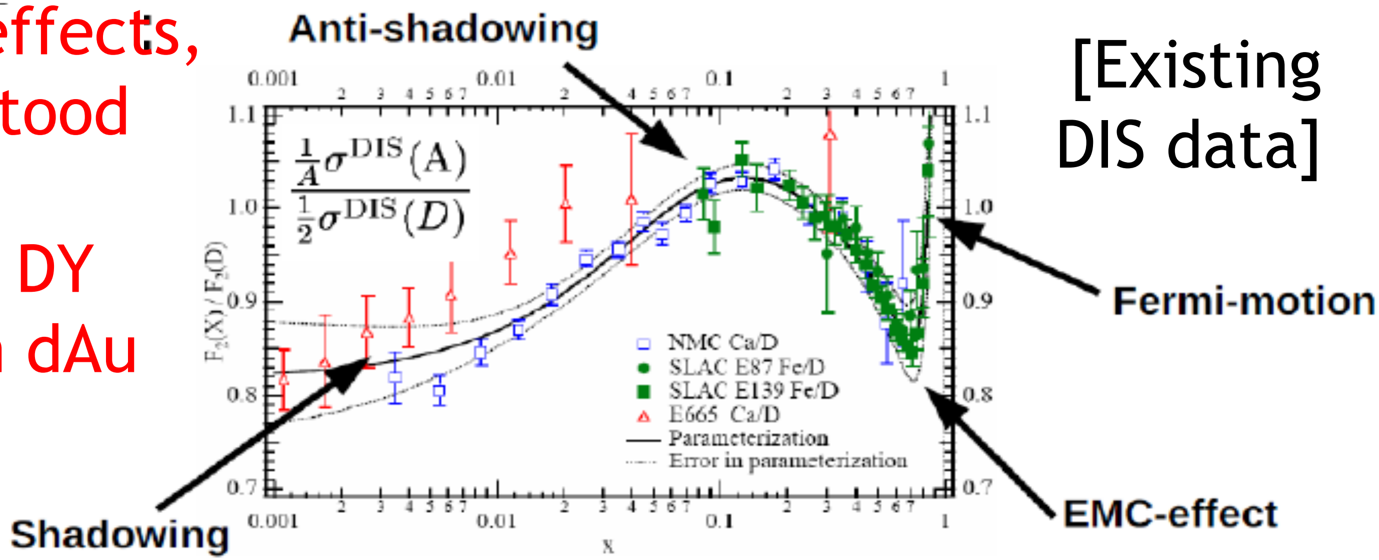
- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

Current Status of Nuclear Parton Densities

- Complex nuclear effects, not yet fully understood

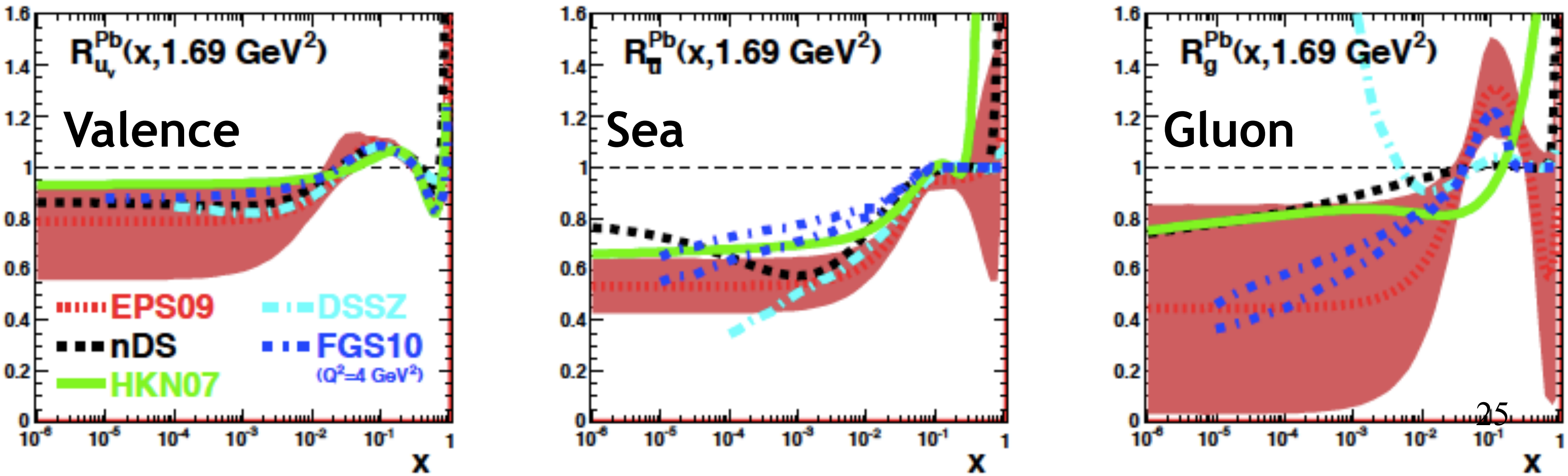
- Quarks from DIS & DY
- Gluon mainly from dAu single π^0 rates

- All partons poorly constrained for $x < 10^{-2}$



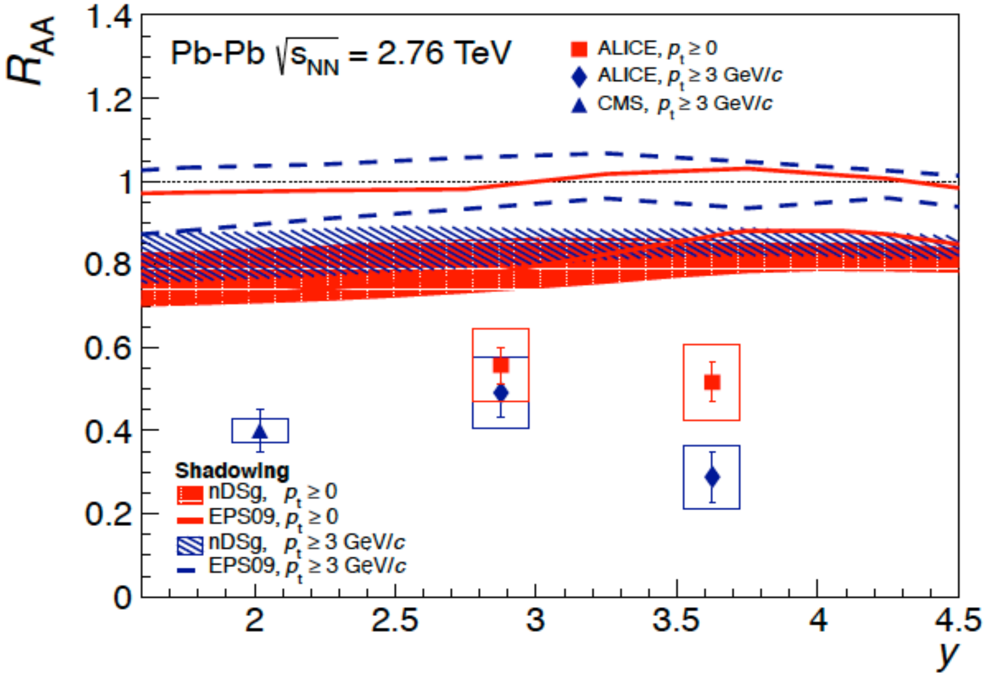
[Existing DIS data]

R_i = Nuclear PDF i / (A * proton PDF i)



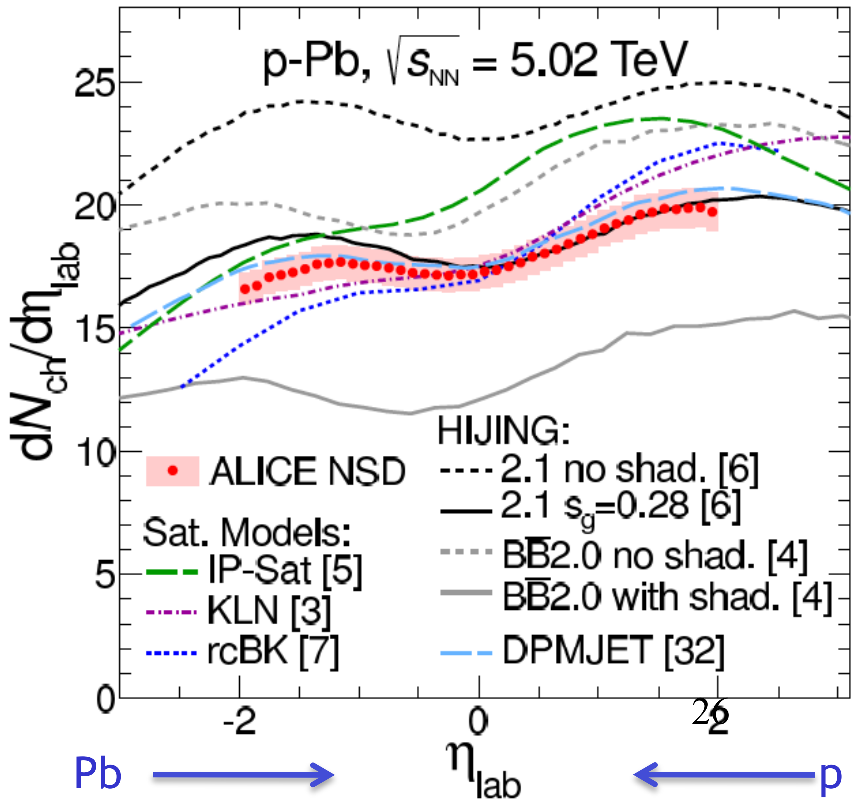
Current Low x Understanding in LHC Ion Data

Inclusive J/Ψ AA data



Uncertainties in low-x nuclear PDFs preclude precision statements on medium produced in AA (e.g. extent of screening of c-cbar potential)

Minimum Bias pA data

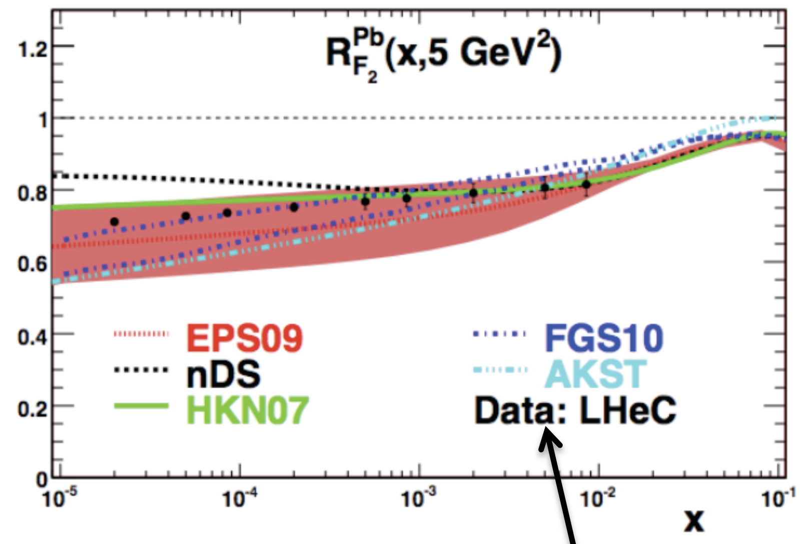


η dependence of pPb charged particle spectra best described by shadowing-only models (saturation models too steep?)

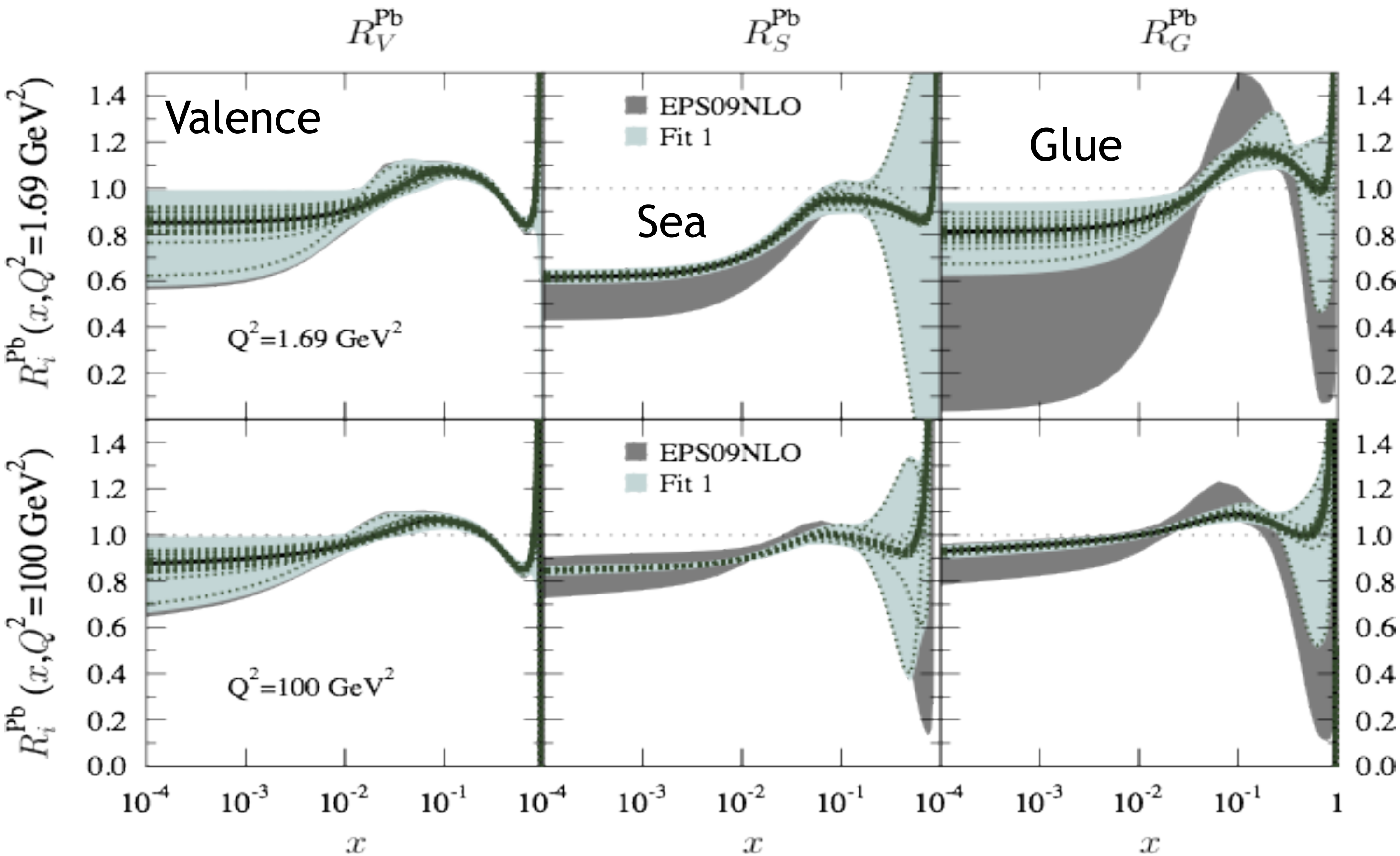
… progress with pPb, but uncertainties still large, detailed situation far from clear

Impact of eA F_2 LHeC data

- Simulated LHeC ePb F_2 measurement has huge impact on uncertainties
- Most striking effect for sea & gluons
- High x gluon uncertainty still large



[Example pseudo-data from single Q^2 Value]



[Effects on EPS09 nPDF fit]

Summary and Outlook

• LHC is new world for p-p physics (even more for heavy ion) physics

• Conceptual Design Report available.

• Timeline?... Optimal impact by running in High Lumi LHC Phase

• Ongoing work …
   - Physics motivation
   - Detector / simulation
   - Superconducting RF, ERL, machine …

More at:

- http://cern.ch/lhec

- CDR [arXiv:1206.2913]

- `Dig Deeper’, Newman & Stasto, Nature Physics 9 (2013) 448

… with thanks to Nestor Armesto, Max Klein, Anna Stasto and many experimentalist, theorist & accelerator scientist colleagues …

LHeC study group …

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], P.Adzic[74], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], B.Allanach[73], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], J.Bracinik[06], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], A.Caldwell[70], V.Cetinkaya[01], V.Chekelian[70], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], P.DiNezza[72], M.D'Onofrio[24], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], A.Glazov[17], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], E.Jensen[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], R.Klees[75], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], M.Kraemer[75], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], J.G.Milhano[76], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], E.Rizvi[71], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], M.Schaefer[75], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], D.South[17], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], P.Thompson[06], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], T.Ullrich[37], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[69], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]