Future High Energy Electron-Hadron scattering: LHeC and FCC-he projects

Anna Staśto
Penn State & INP Krakow

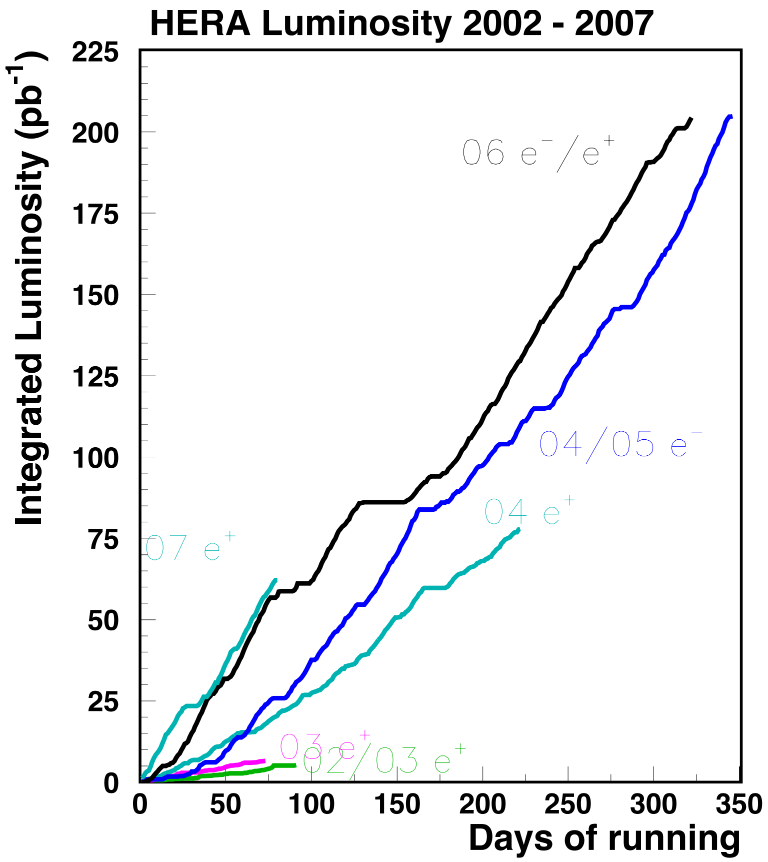
http://lhec.web.cern.ch/

- *Physics prospects*
- *Detector and machine considerations*
- *Outlook*

Aspen Center of Physics, January 31st 2015

Deep inelastic electron-proton collider

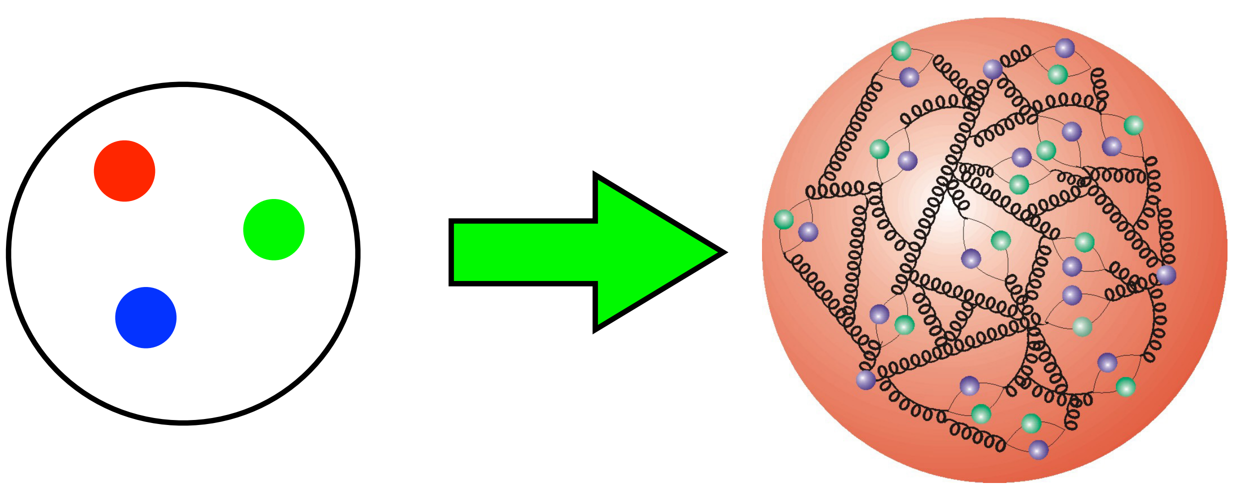
HERA Hamburg 1992-2007

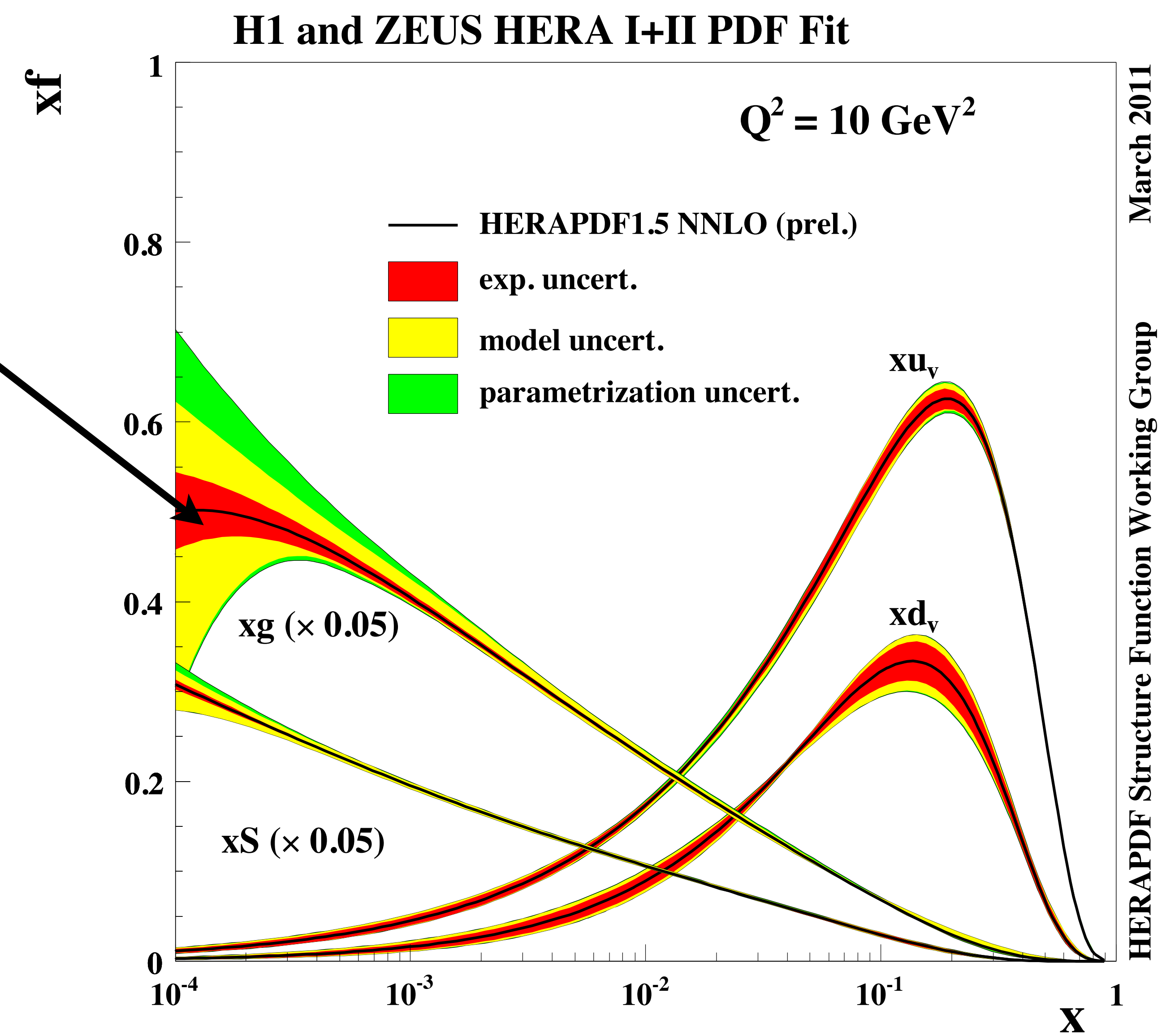


Results from HERA

HERA established detailed proton structure: parton density functions.

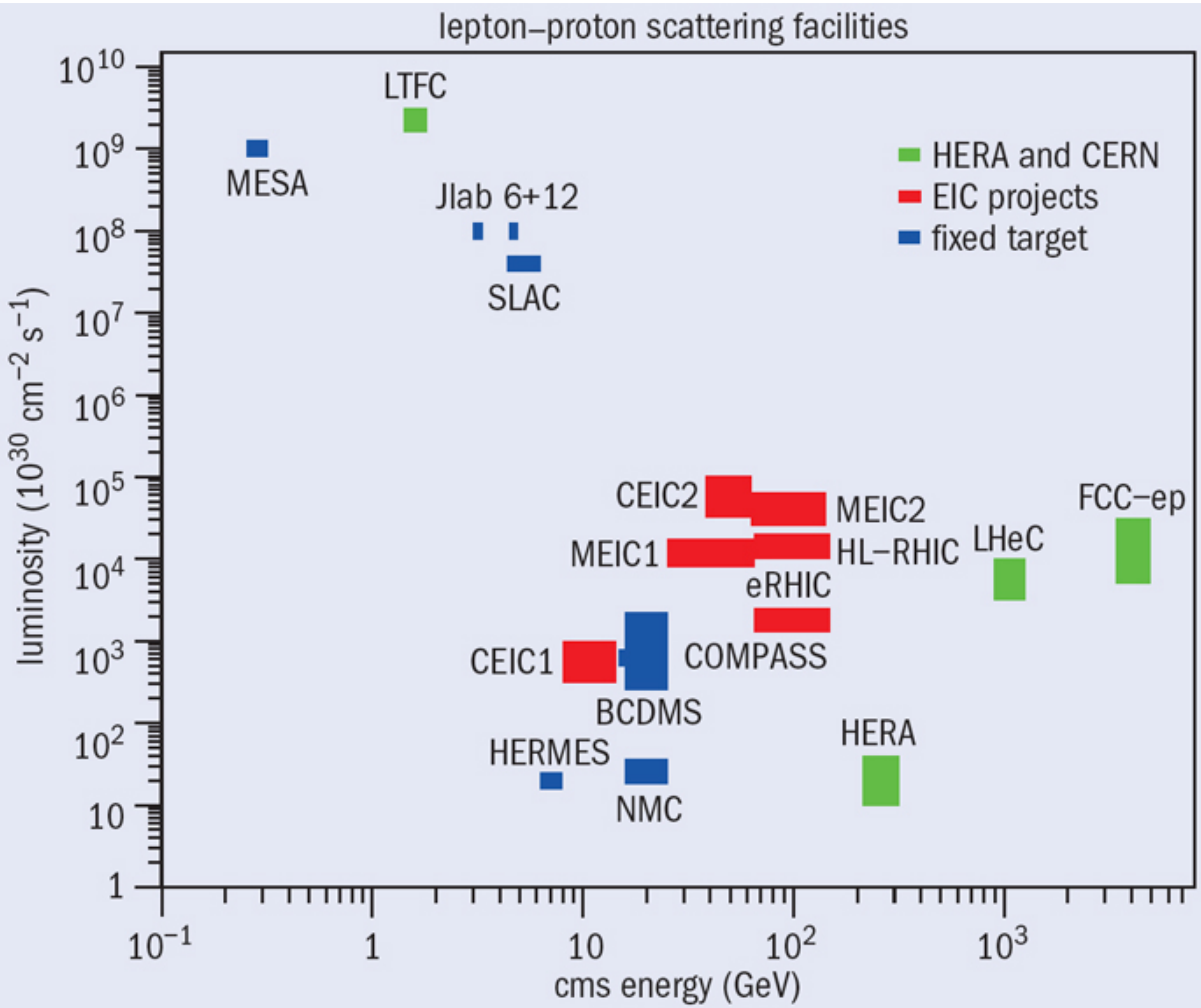
Increasing role of gluons at small x. Proton structure is highly complex due to the QCD radiation (evolution).





Other results: measurement of coupling constant, jets, photon structure, diffractive processes (in about 10% events), charm and bottom structure functions, PDFs essential for interpreting Tevatron and LHC results, limits for new physics (leptoquarks).

Lepton-hadron facilities: luminosity vs energy



http://cerncourier.com/cws/article/cern/57304

China
CEIC1 = Electron-Ion Collider

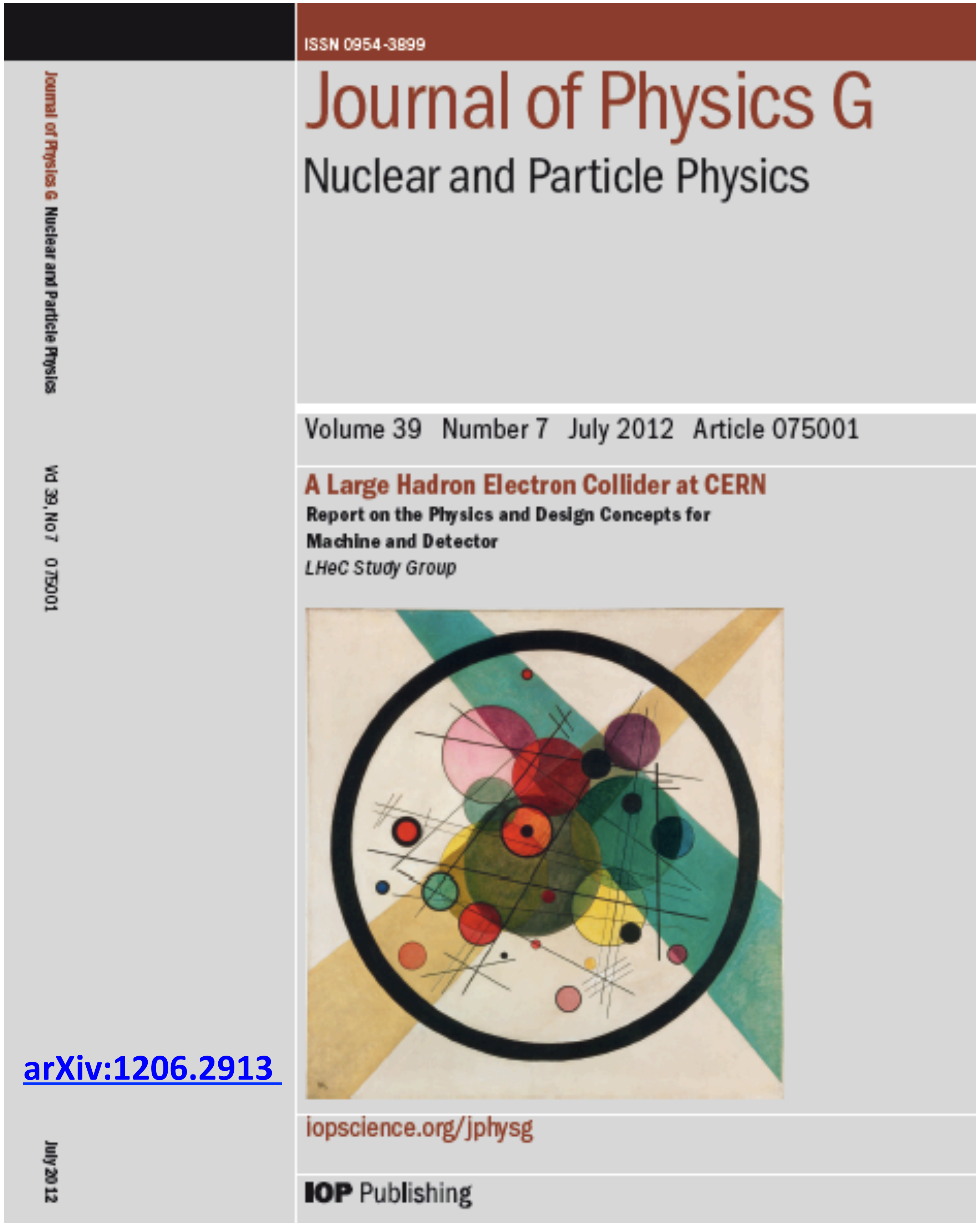
U.S.
MEIC1 = **EIC**@Jlab

eRHIC = **EIC**@BNL

Europe
LHeC = ep/eA collider @ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he
} future extensions

Conceptual Design Report for LHeC



arXiv:1206.2913

LHeC Study Group

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], 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], 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], V.Cetinkaya[01], 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], 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], 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], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], 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], 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], 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], 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], 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], 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], 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[16], 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]

193 authors
631 pages
947 references
5 chapters
14 sections

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IAC Composition June 2014, plus
Oliver Brüning   Max Klein ex officio

The IAC was invited in 12/13 by the DG with the following

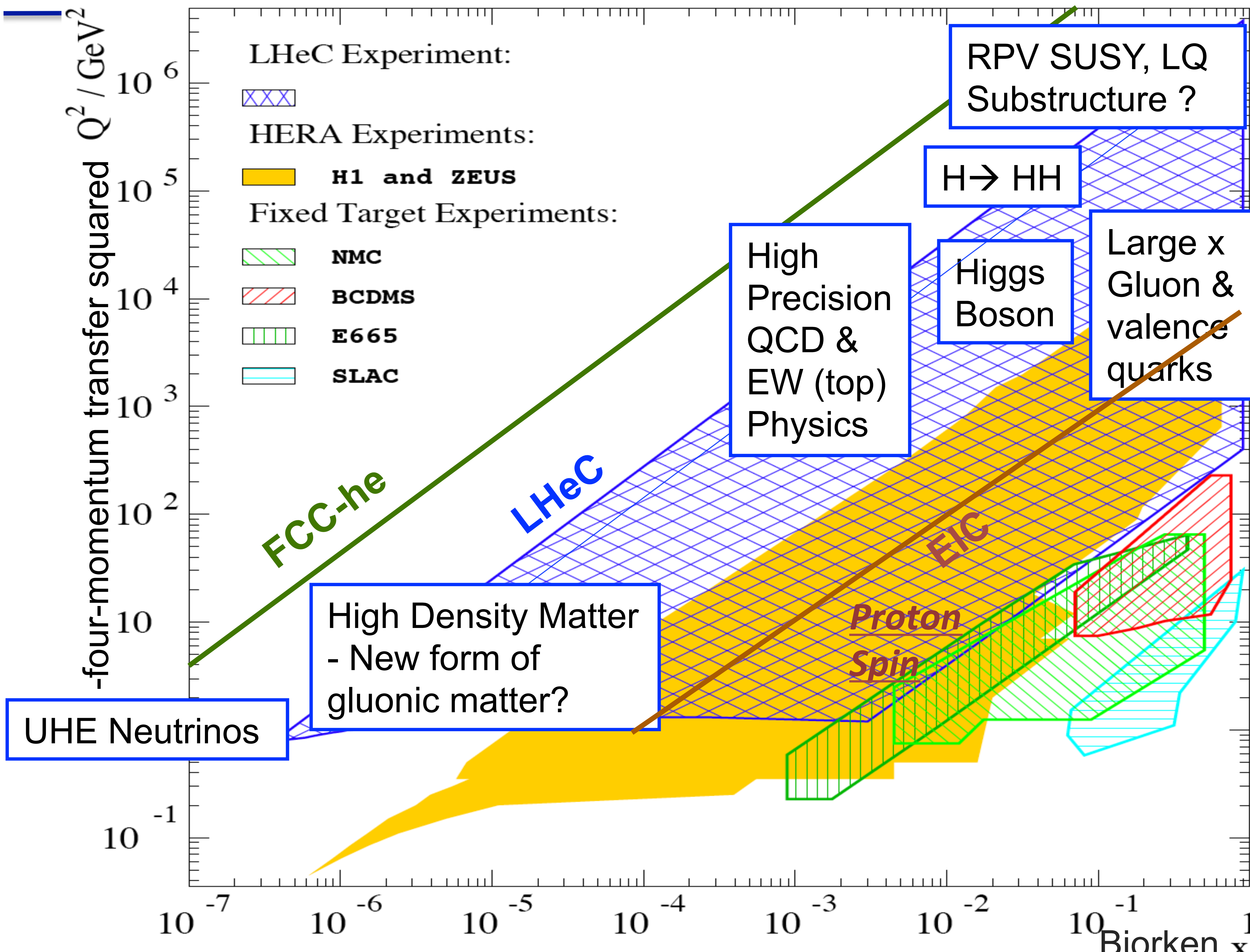
Mandate 2014-2017

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

New domain for ep colliders



HERA established the validity of pQCD (DGLAP) due to a very high lever arm in Q^2.

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

Physics possibilities at LHeC and FCC-he

Beyond Standard Model

Leptoquarks
Contact Interactions
Excited Fermions
Higgs in MSSM
Heavy Leptons
4th generation quarks
Z'
SUSY
???

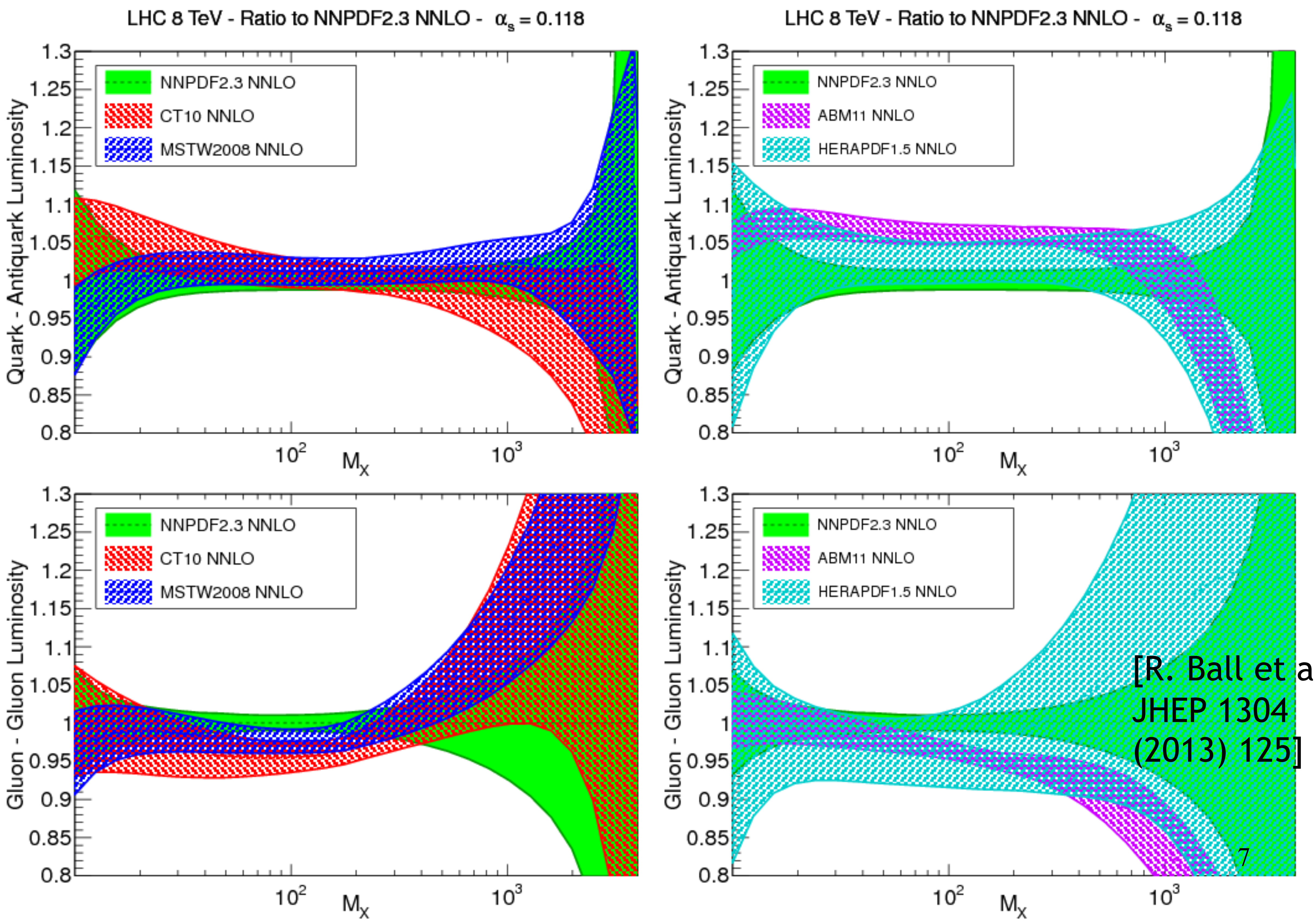
QCD and EW precision physics

Structure functions
Quark distributions from direct measurements
Strong coupling constant to high accuracy
Higgs in SM
Gluon distribution in extended x range to unprecedented accuracy
Single top and anti-top production
Electroweak couplings
Heavy quark fragmentation functions
Heavy flavor production with high accuracy
Jets and QCD in photoproduction
Partonic structure of the photon

Small x and high parton densities

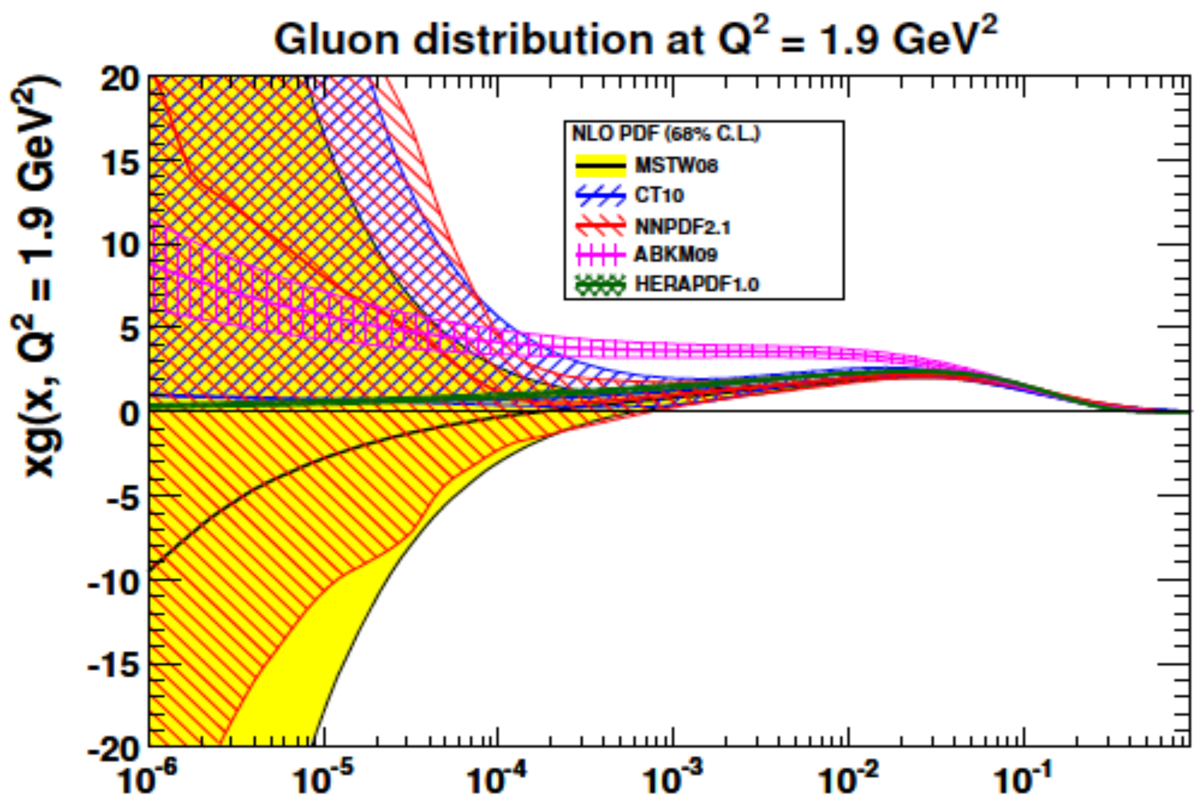
New regime at low x
Saturation
Diffraction
Vector Mesons
Deeply Virtual Compoton Scattering
Forward jets and parton dynamics
DIS on nuclei
Generalized/unintegrated parton distribution functions

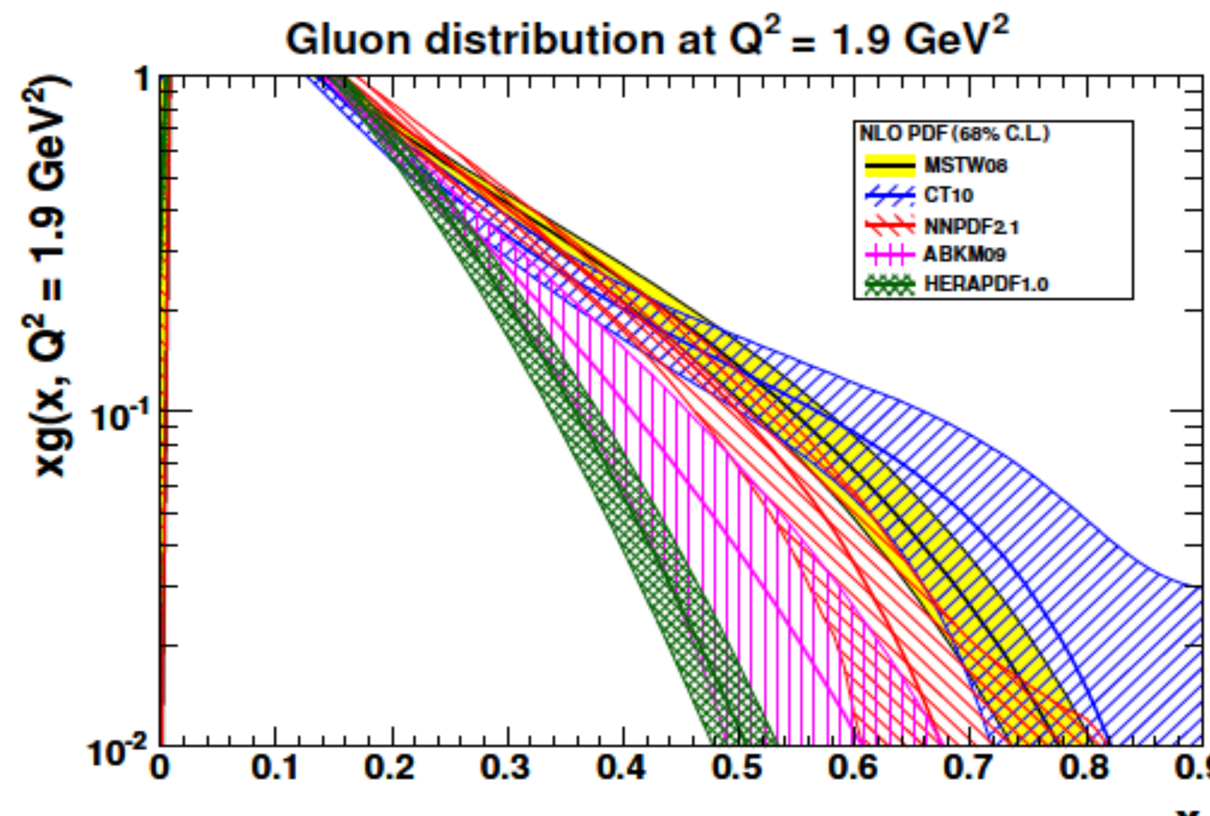
Current PDF Uncertainties at LHC



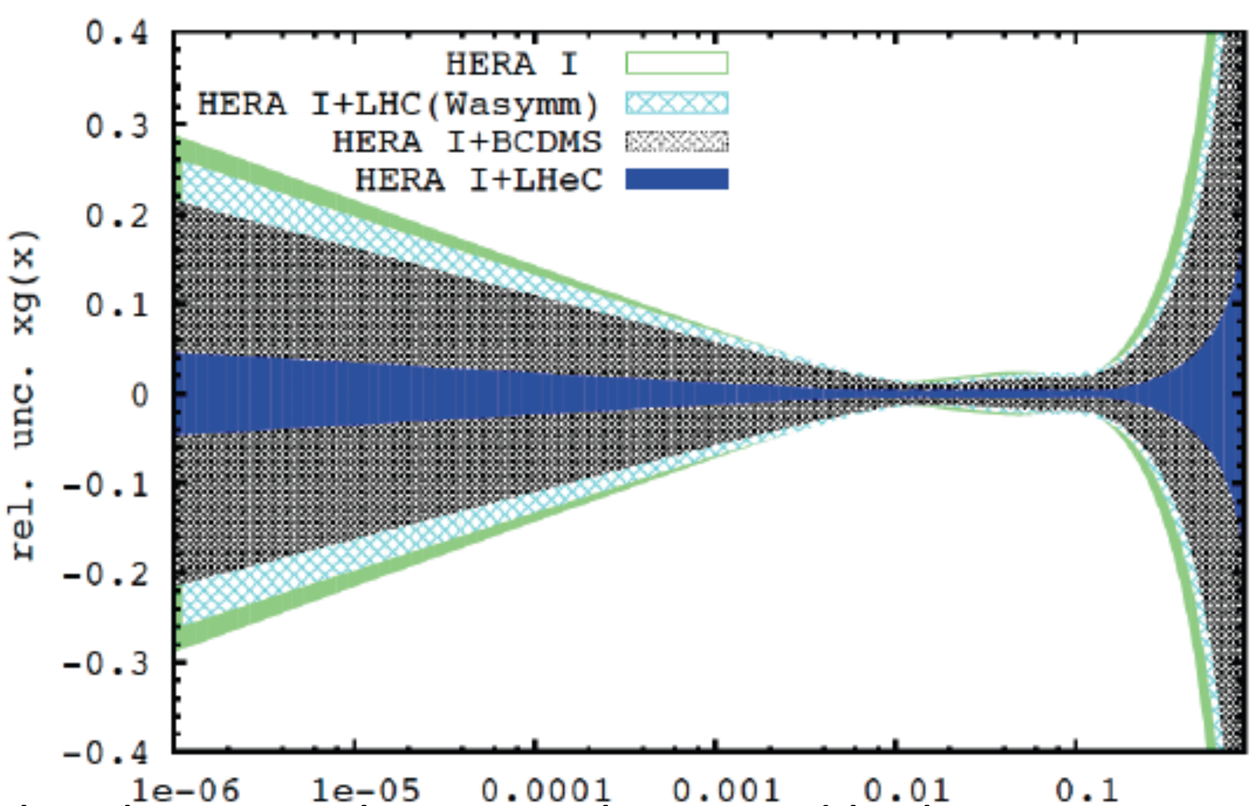
[R. Ball et al., JHEP 1304 (2013) 125]

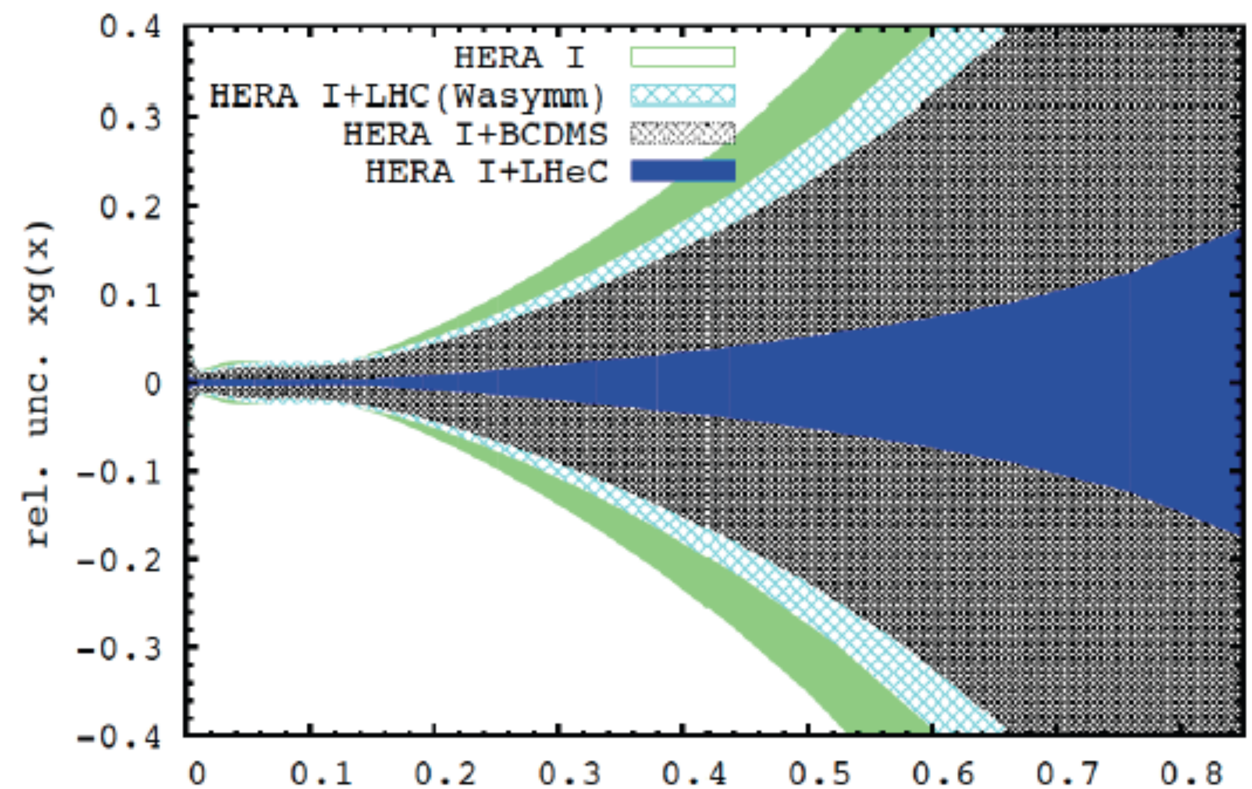
Mapping the Gluon Distribution





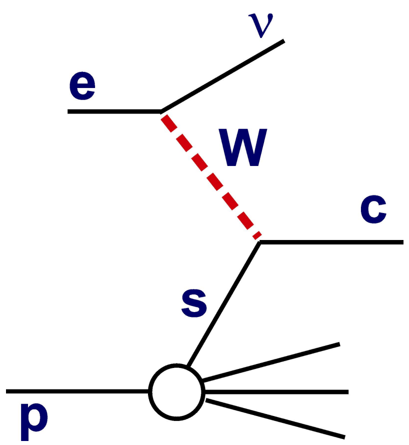
QCD fit analysis (default: NC,CC, LHeC only, following HERAPDF) with full experimental errors



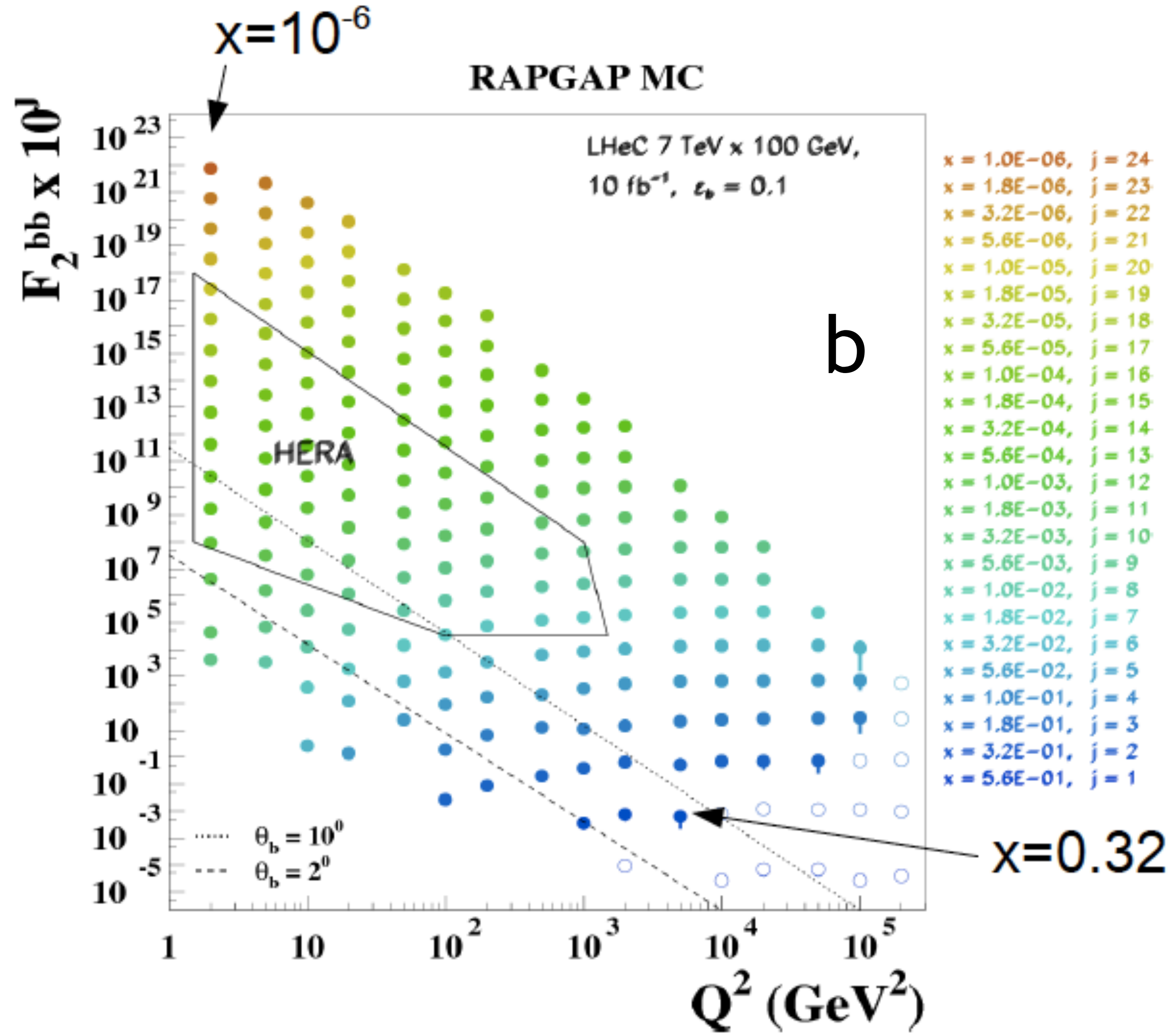


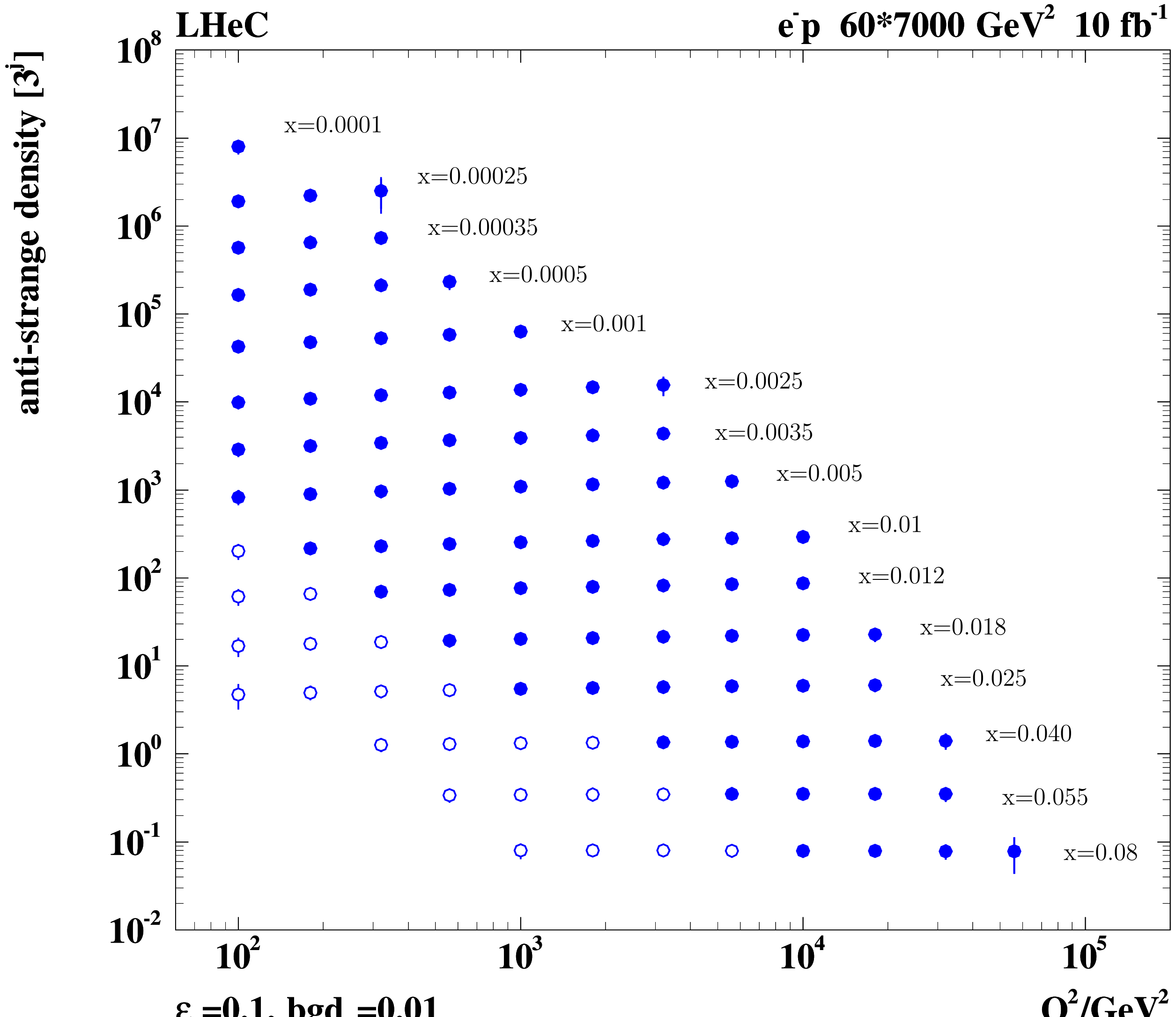
The gluon is unknown at low x and high x – QCD: non-linear evolution, resummation. BSM: hi M – HL-LHC!

Flavor decomposition at the LHeC



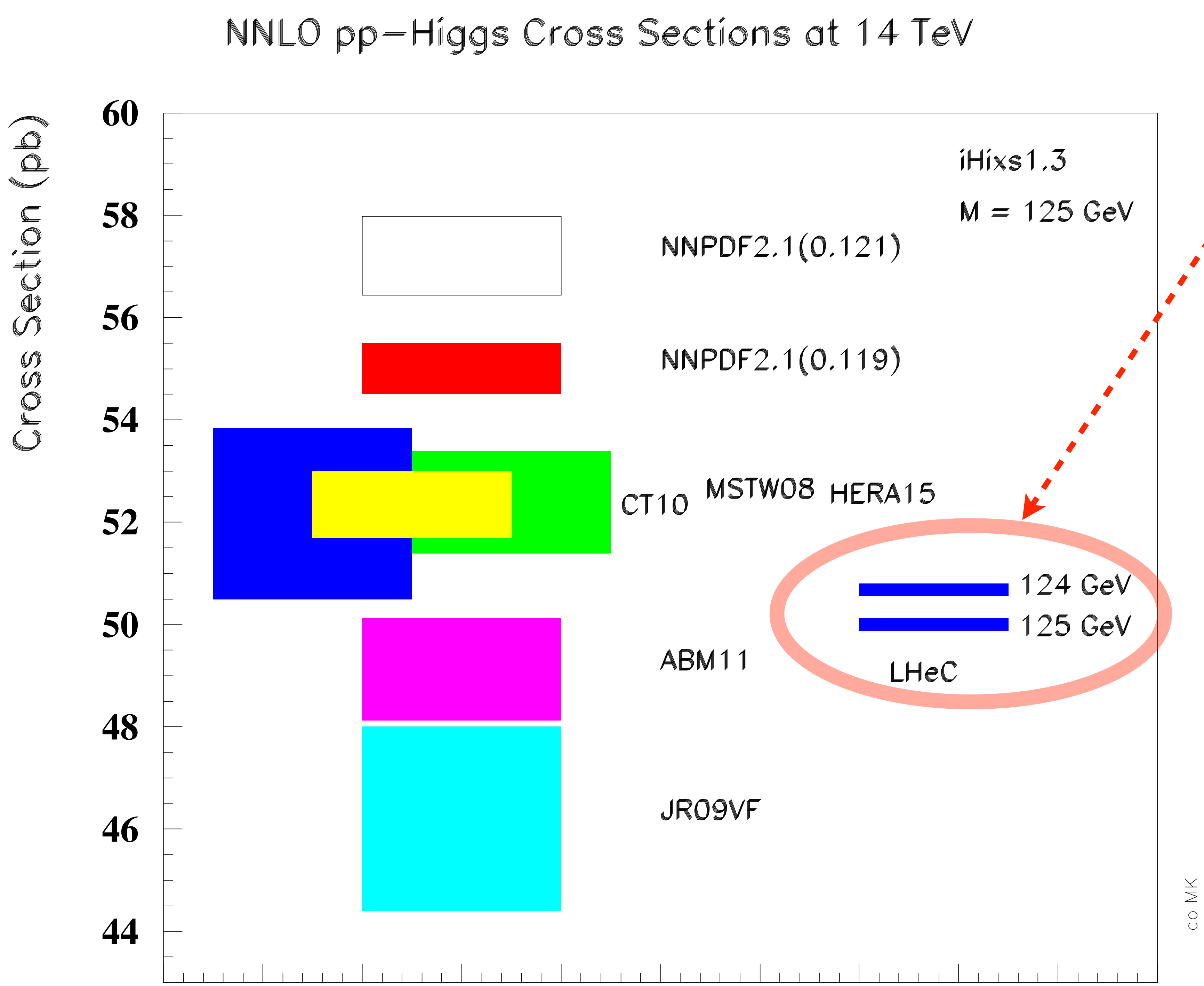
- Beauty as a small x observable
- Precision strange measurement through charm tagging in CC interactions





- High lumi
- High Q
- Charm tagging efficiency 10%
- Closed points acceptance to 10 degrees
- Open points acceptance to 1 degree

Precision PDFs for Higgs in pp



Precision pdfs from LHeC

Uncertainty can be reduced to 0.25%.

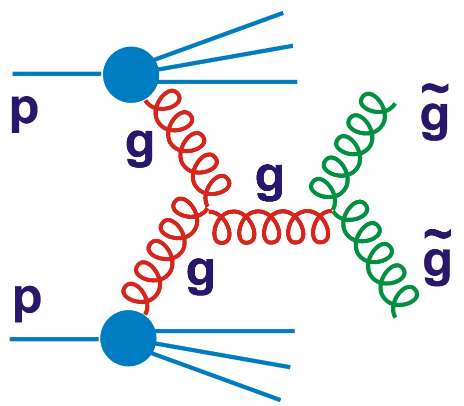
Leads to Higgs mass sensitivity

Similar conclusions can be reached for FCC-hh and FCC-he

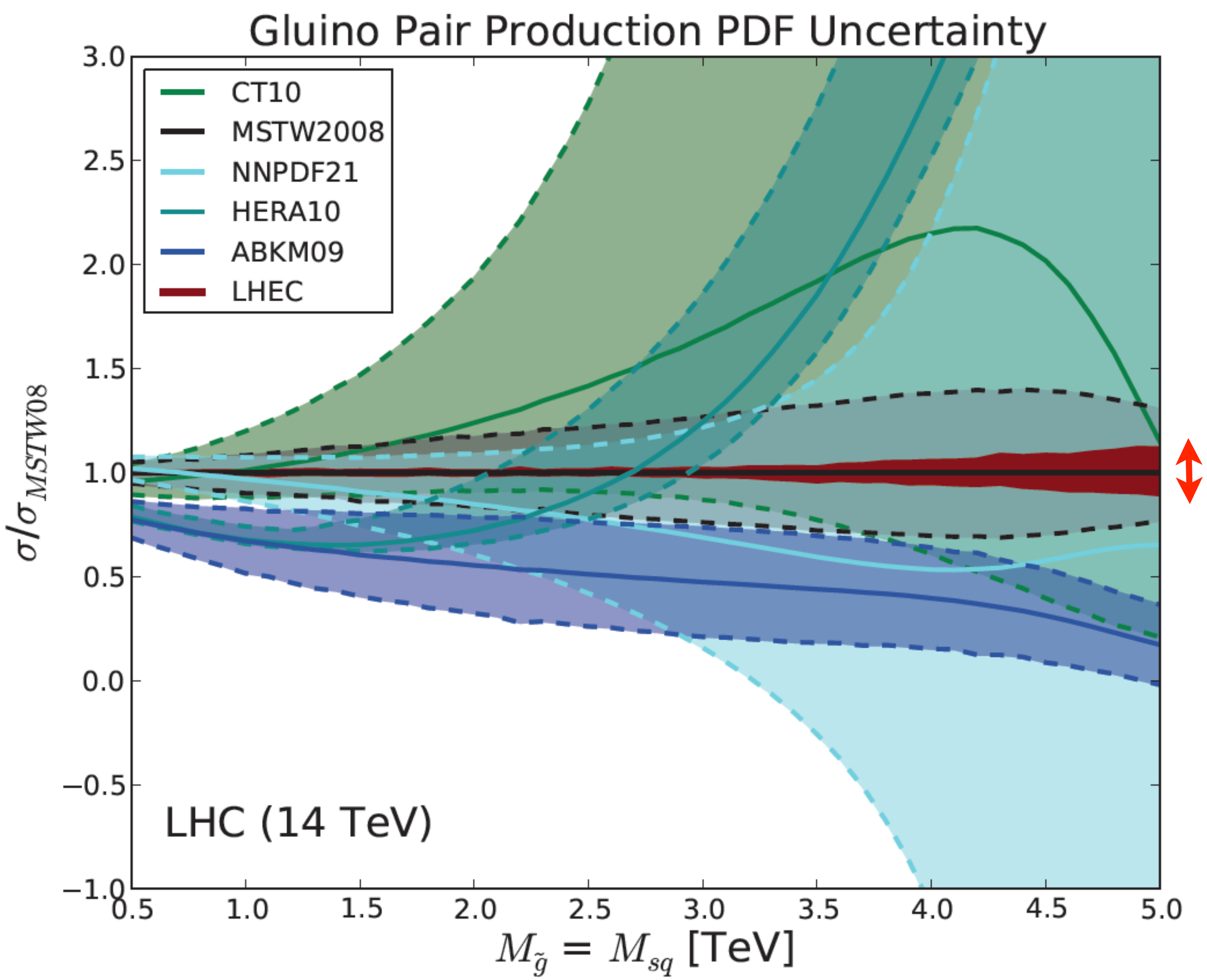
Will need NNNLO calculations

α_S = underlying parameter relevant for uncertainty (0.005 → 10%)
@ LHeC: measure to permille accuracy (0.0002)

Gluino pair production at the LHC



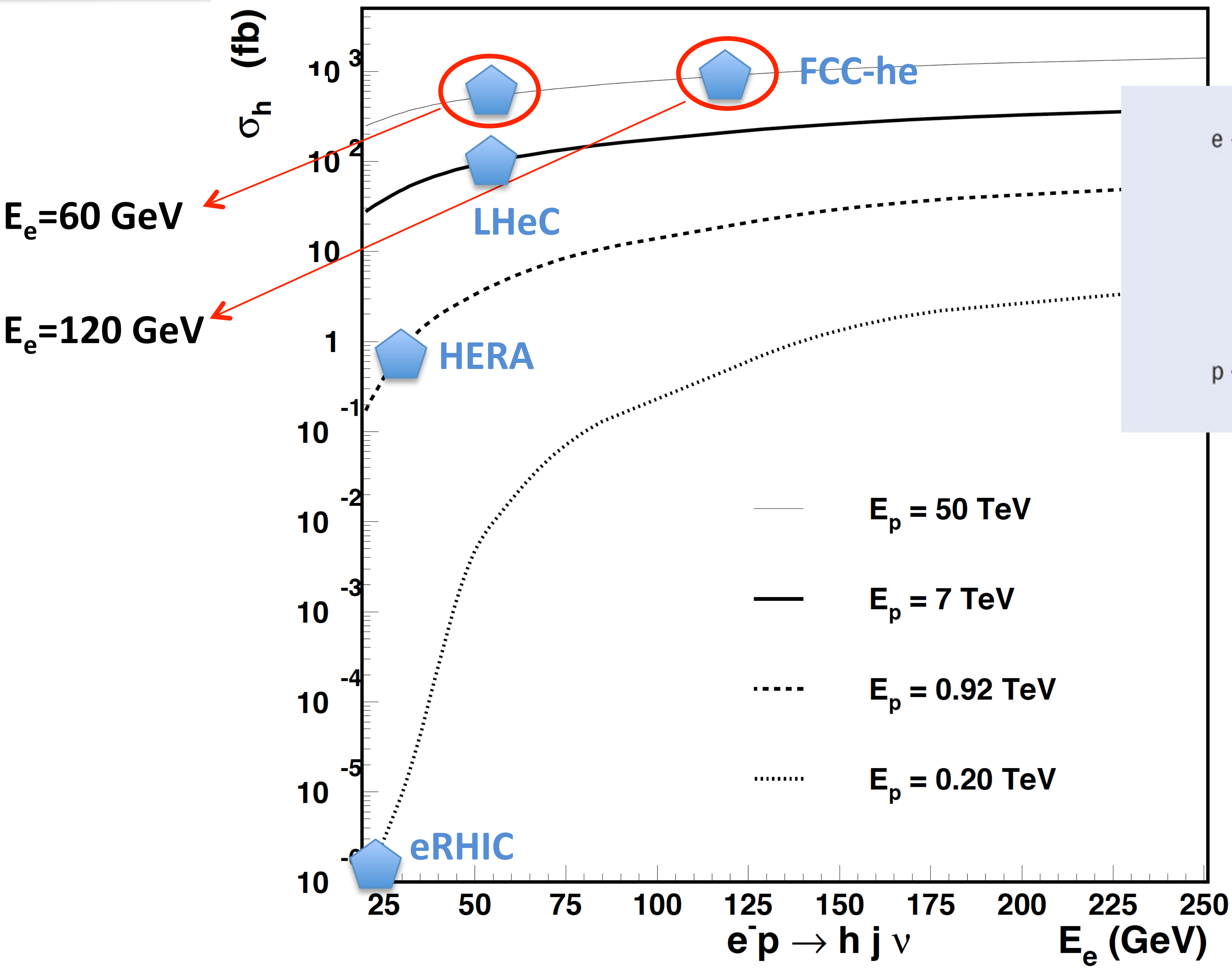
- Signal is the excess at large invariant mass.
- But large gluon pdf uncertainties dominate the total uncertainty for both signal and background.
- Unknown for masses beyond 2TeV.

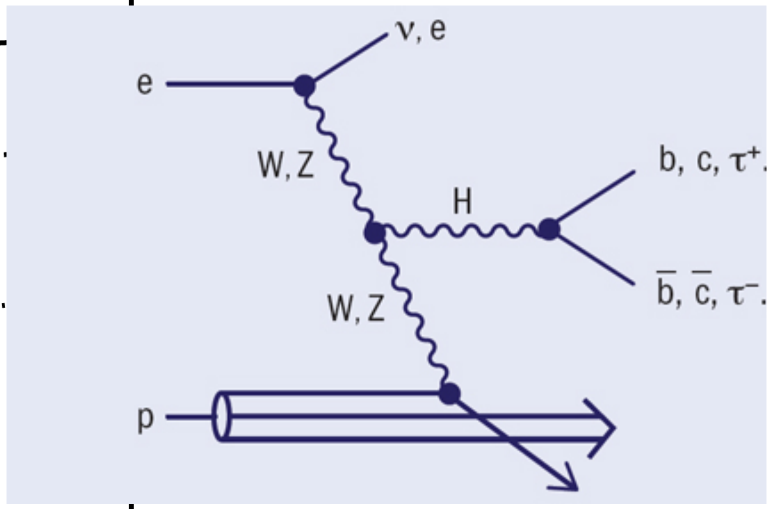


High precision for this process from pdfs constrained by LHeC

Precision PDFs can only be obtained by the measurements in ep machine like LHeC and FCC-he

SM Higgs in ep





LHeC / FCC-he: Sizeable charged current DIS unpolarised **ep cross sections**

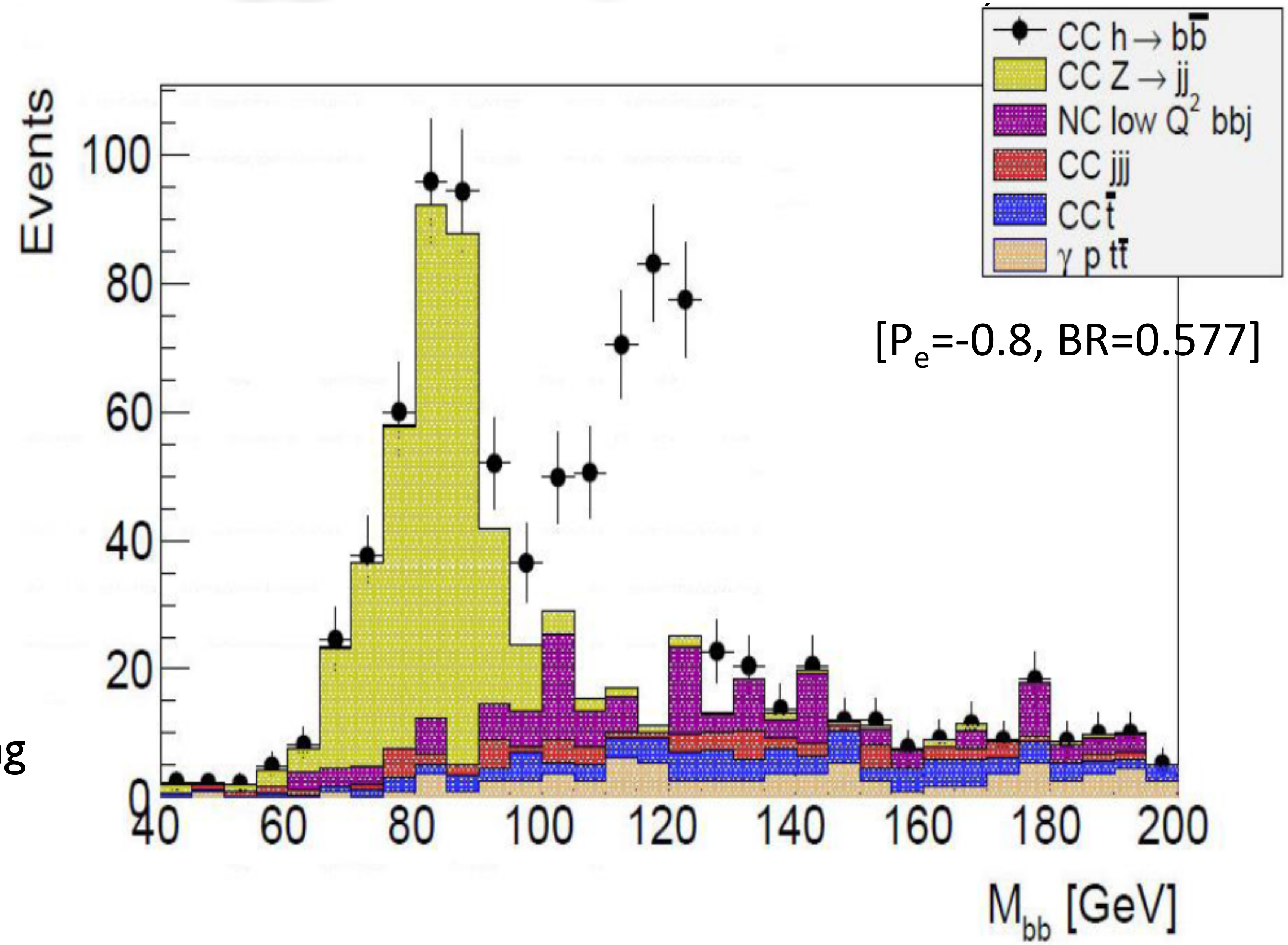
SM Higgs in ep

Study of $H \to b\bar{b}$ at LHeC

$$\mathcal{L} = 100\ \mathrm{fb}^{-1}$$

signal to background ratio is about 1.2

With 10 times more data
1% precision on the $Hb\bar{b}$ coupling

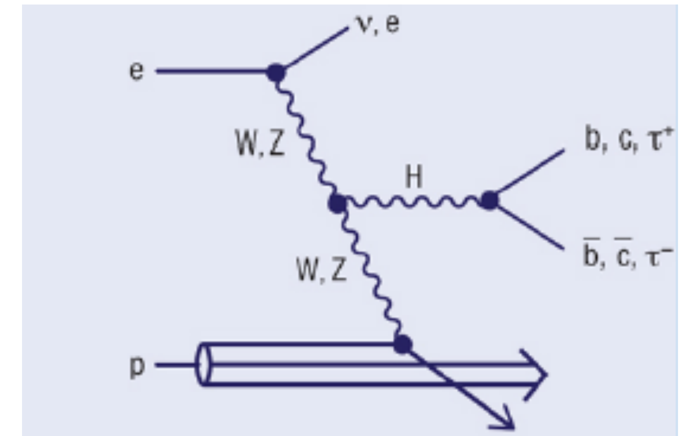


[P_e=-0.8, BR=0.577]

Ongoing studies on the $H \to c\bar{c}$ simulation

Higgs production at the LHeC and FCC-he

Higgs in e^-p	CC - LHeC	NC - LHeC	CC - FHeC
Polarisation	-0.8	-0.8	-0.8
Luminosity [ab^{-1}]	1	1	5
Cross Section [fb]	196	25	850
Decay BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$ 0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$ 0.029	5 700	700	123 000
$H \to \tau^+\tau^-$ 0.063	12 350	1 600	270 000
$H \to \mu\mu$ 0.00022	50	5	1 000
$H \to 4l$ 0.00013	30	3	550
$H \to 2l2\nu$ 0.0106	2 080	250	45 000
$H \to gg$ 0.086	16 850	2 050	365 000
$H \to WW$ 0.215	42 100	5 150	915 000
$H \to ZZ$ 0.0264	5 200	600	110 000
$H \to \gamma\gamma$ 0.00228	450	60	10 000
$H \to Z\gamma$ 0.00154	300	40	6 500

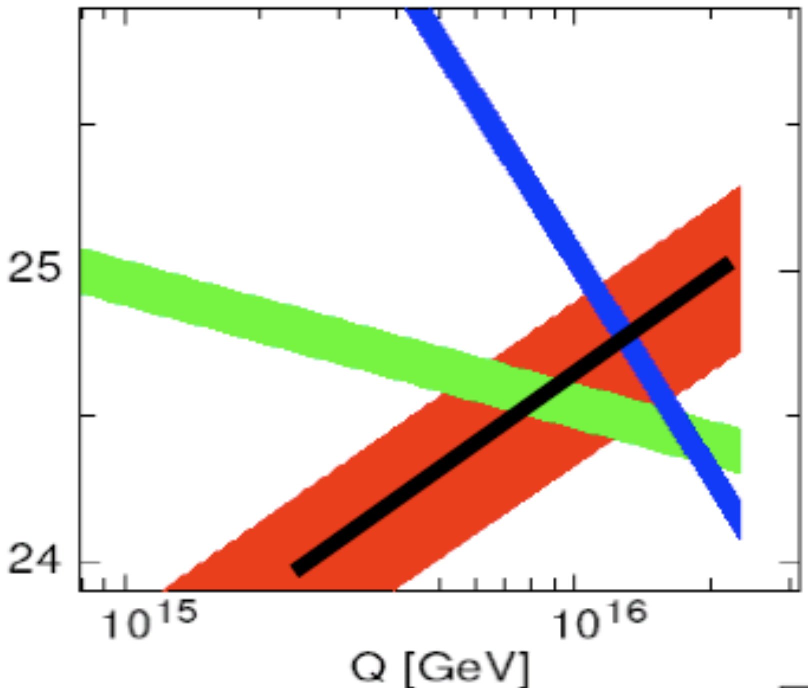


Cross section at FCC-he 1pb ep→ νHX

Luminosity O(10^{34}) is crucial for H → HH [0.5 fb] and rare H decays

Event rates for 1ab^{-1}. Note the LHeC WW-H cross section is as large as the Z*→ ZH cross section at the ILC or FCC- or CEPC, but it is much larger at the FCC-he

Precision measurement of strong coupling constant



Strong coupling is least known of all couplings

Grand unification predictions suffer from uncertainty

DIS tends to be lower than the world average

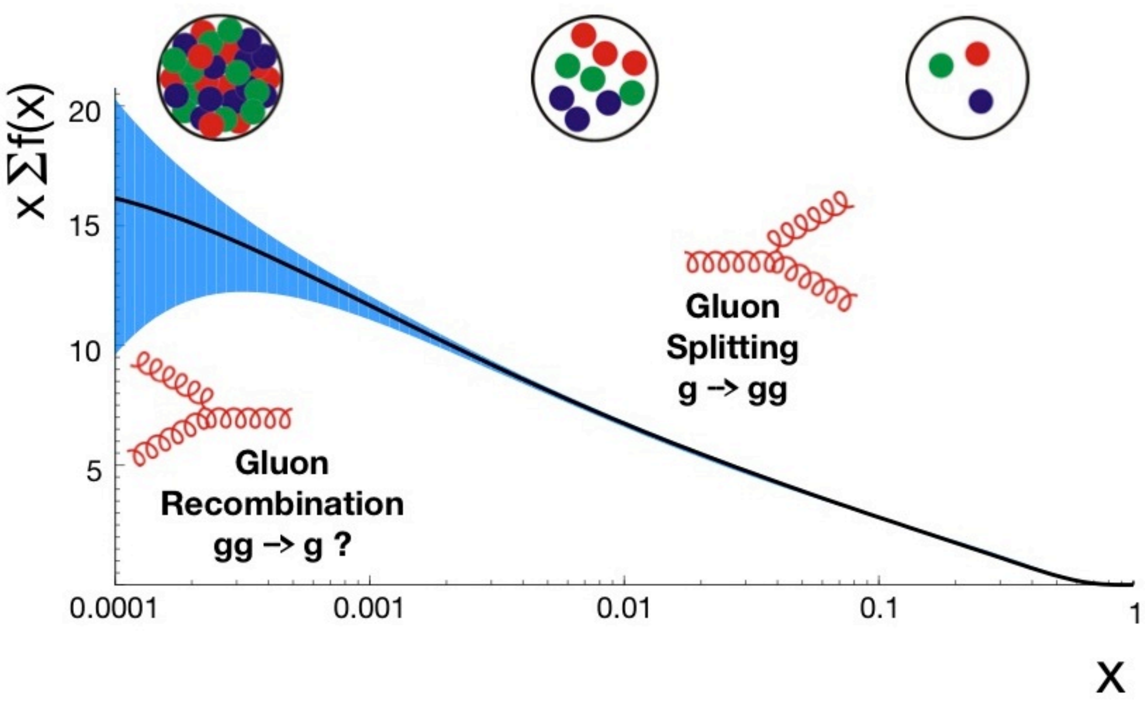
case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 >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

LHeC promises per mille accuracy on alphas!

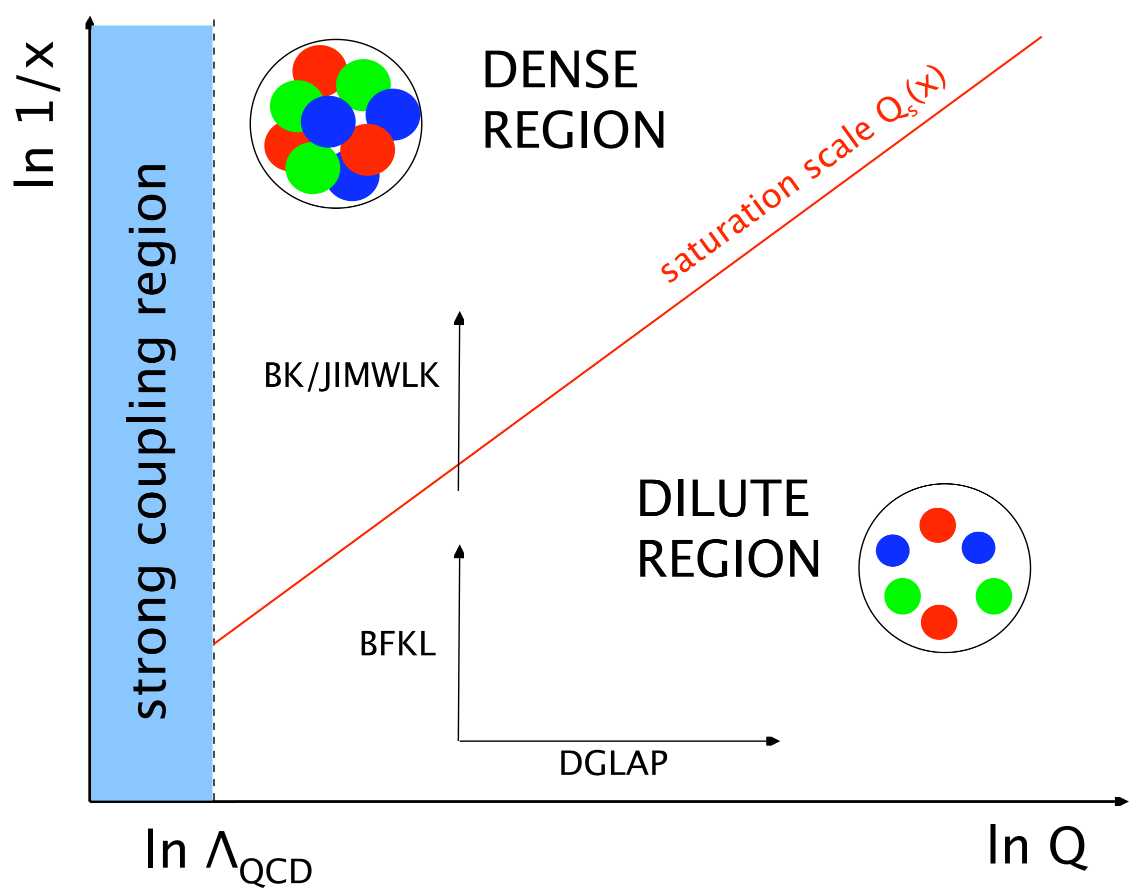
- Previously (HERA, fixed target) limited by uncertainty of low x, which LHeC can cure;
- full exploitation of this requires pQCD at NNNLO;
- LHeC can provide a new level of predicting grand unification

Small x regime

- At small x the linear evolution gives strongly rising gluon density.
- Parton evolution needs to be modified to include potentially very large logs, resummation of log(1/x)
- Further increase in the energy could lead to the importance of the recombination effects.
- Modification of parton evolution by including non-linear or saturation effects in the parton density.



[HERAPDF 1.6 NNLO]

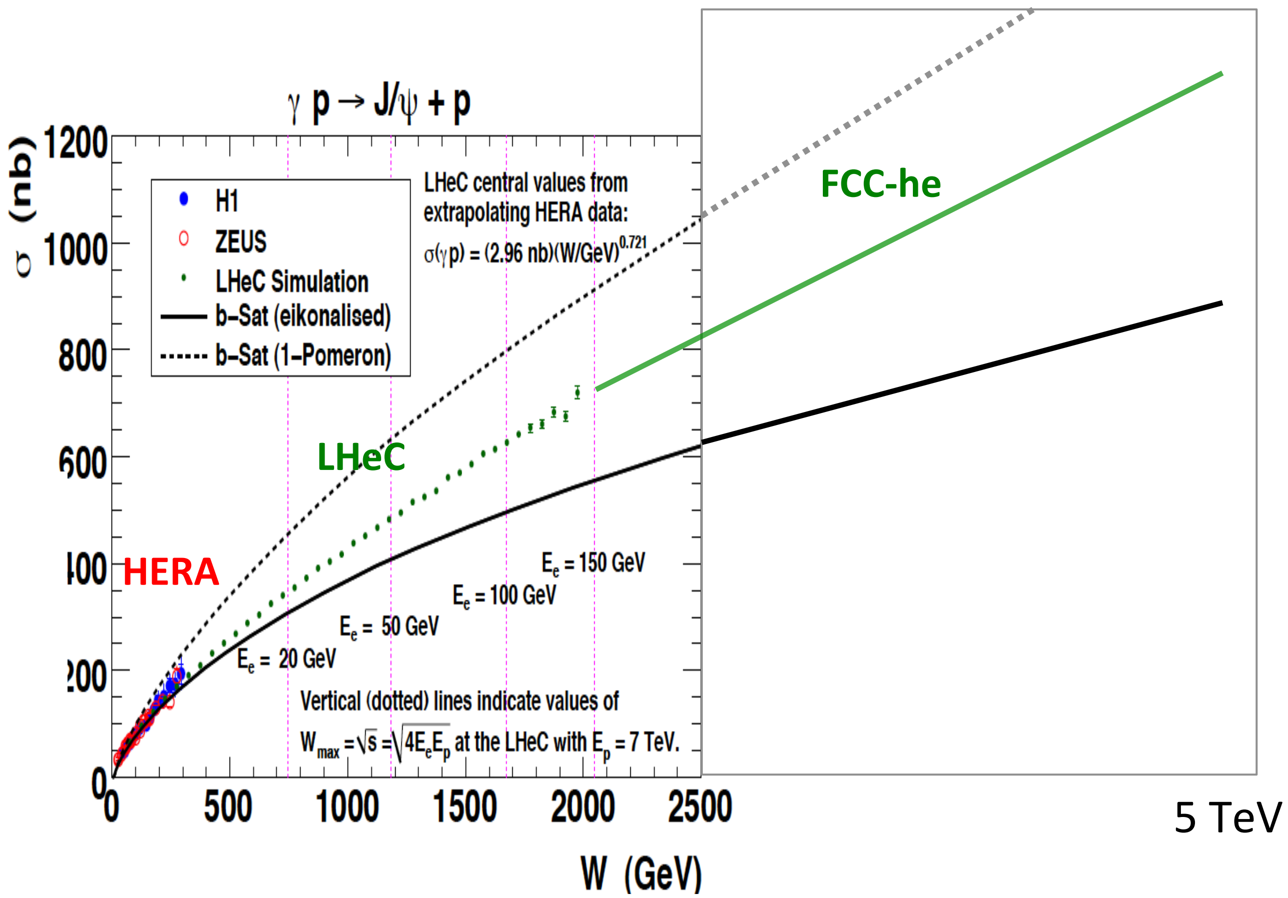


The boundary between the two regimes needs to be determined experimentally.

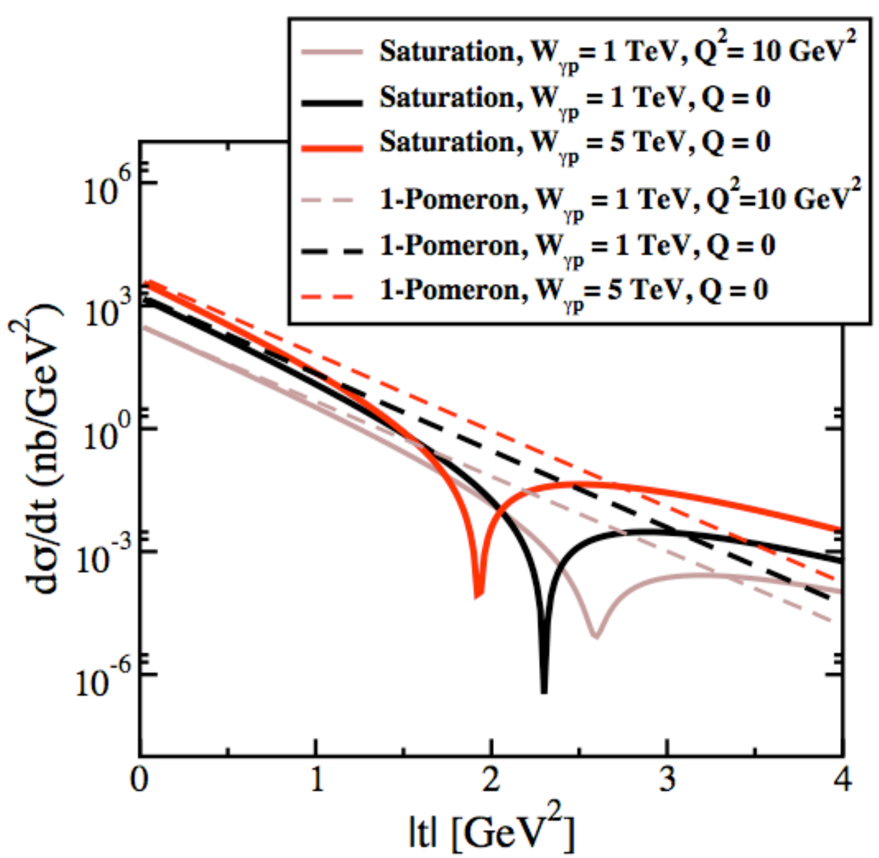
Unique feature of the LHeC & FCC-he: can access the dense regime at fixed, semihard scales Q, while decreasing x.

Small x and vector mesons

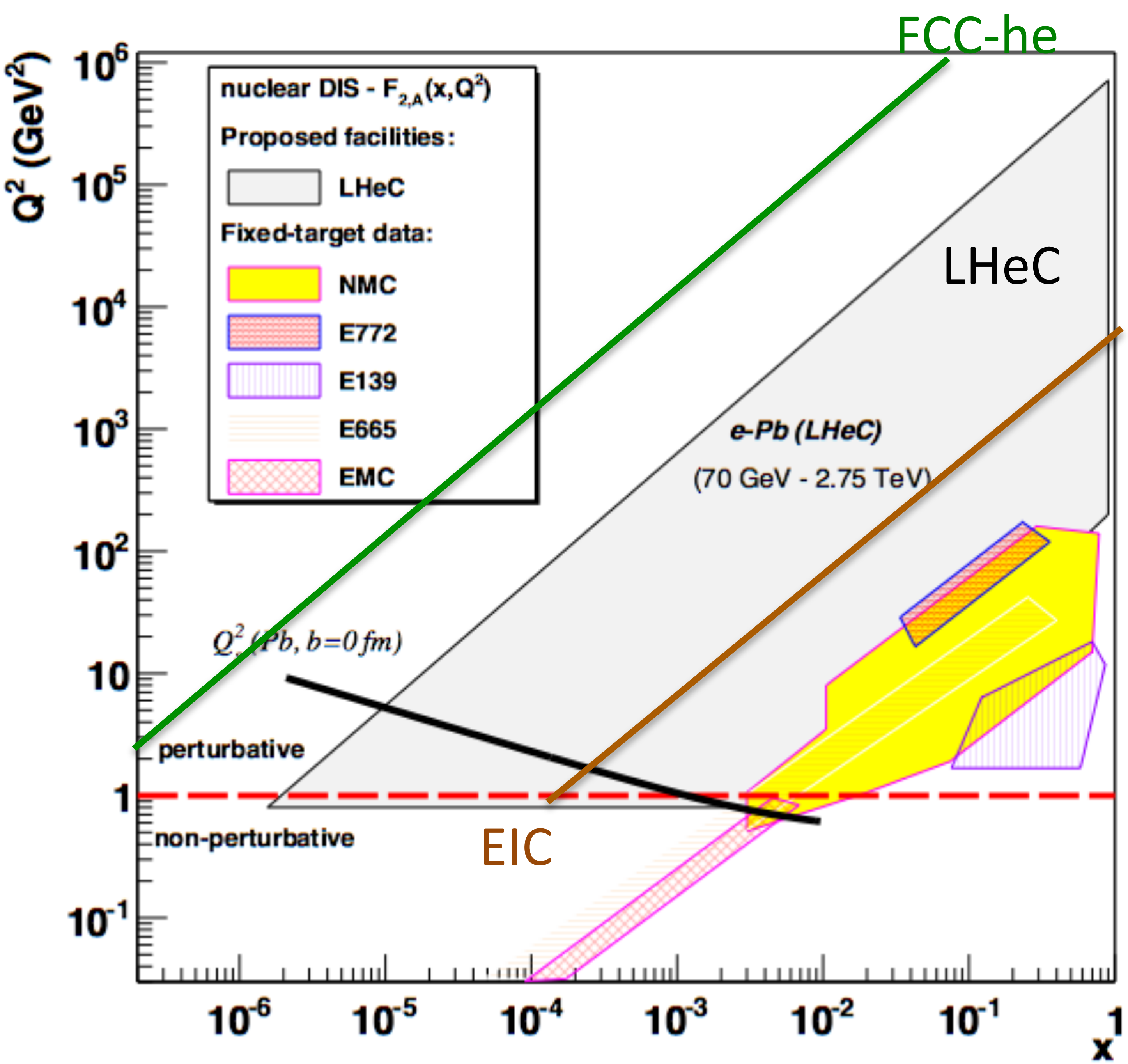
Precision measurement of the elastic diffraction of vector mesons: sensitive to saturation effects. FCC-he extends the kinematic reach up to 4TeV.



More differential measurements can help to map the gluon density in the proton.
Shifts in the dips of t-distribution, as a signal for parton saturation



LHeC and FCC-he as an electron-ion collider



Nuclear structure below x=0.01 is completely unknown.

LHeC and FCC-he will extend the kinematic range by 4-5 orders of magnitude.

Electron-ion collisions are the best precision tools to study partonic structure of cold nuclear matter. Important for initial state for heavy ion collisions.

Pin-down the nuclear effects on the propagation of partons through the nuclear matter.

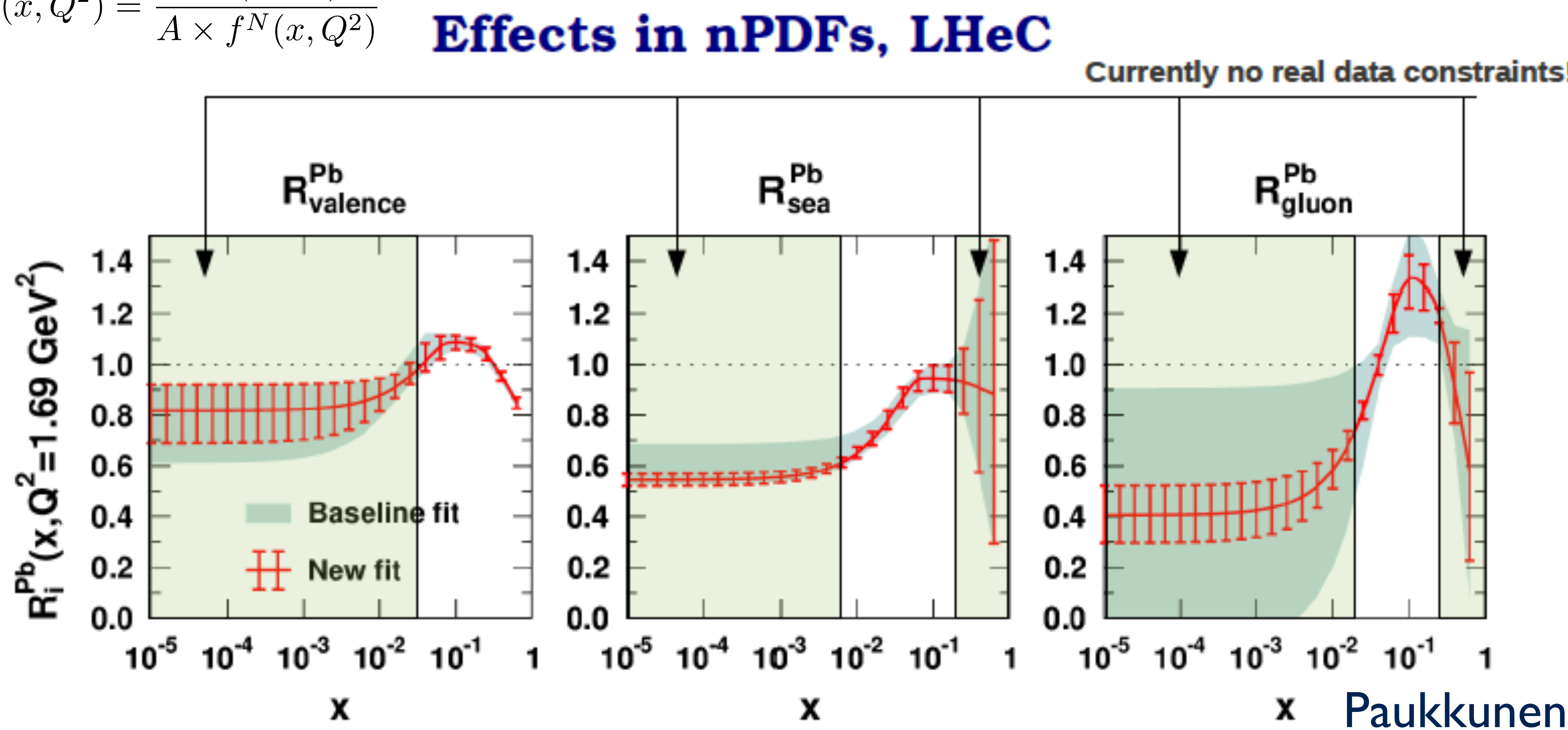
High parton density enhanced by low x and nuclear effects.

Saturation scale $Q^2_{sA} \sim A^{1/3} Q^2_{sp} \sim x^{-\lambda} A^{1/3}$

Constraints on nuclear PDFs

Nuclear ratio:

$$R_f^A(x,Q^2) = \frac{f^A(x,Q^2)}{A \times f^N(x,Q^2)}$$



- Huge reduction of the uncertainties after including LHeC pseudodata, particularly for sea and gluon.
- Adding charged current interaction may help to perform the flavor separation.

Energy Recovery Linac (3 pass)

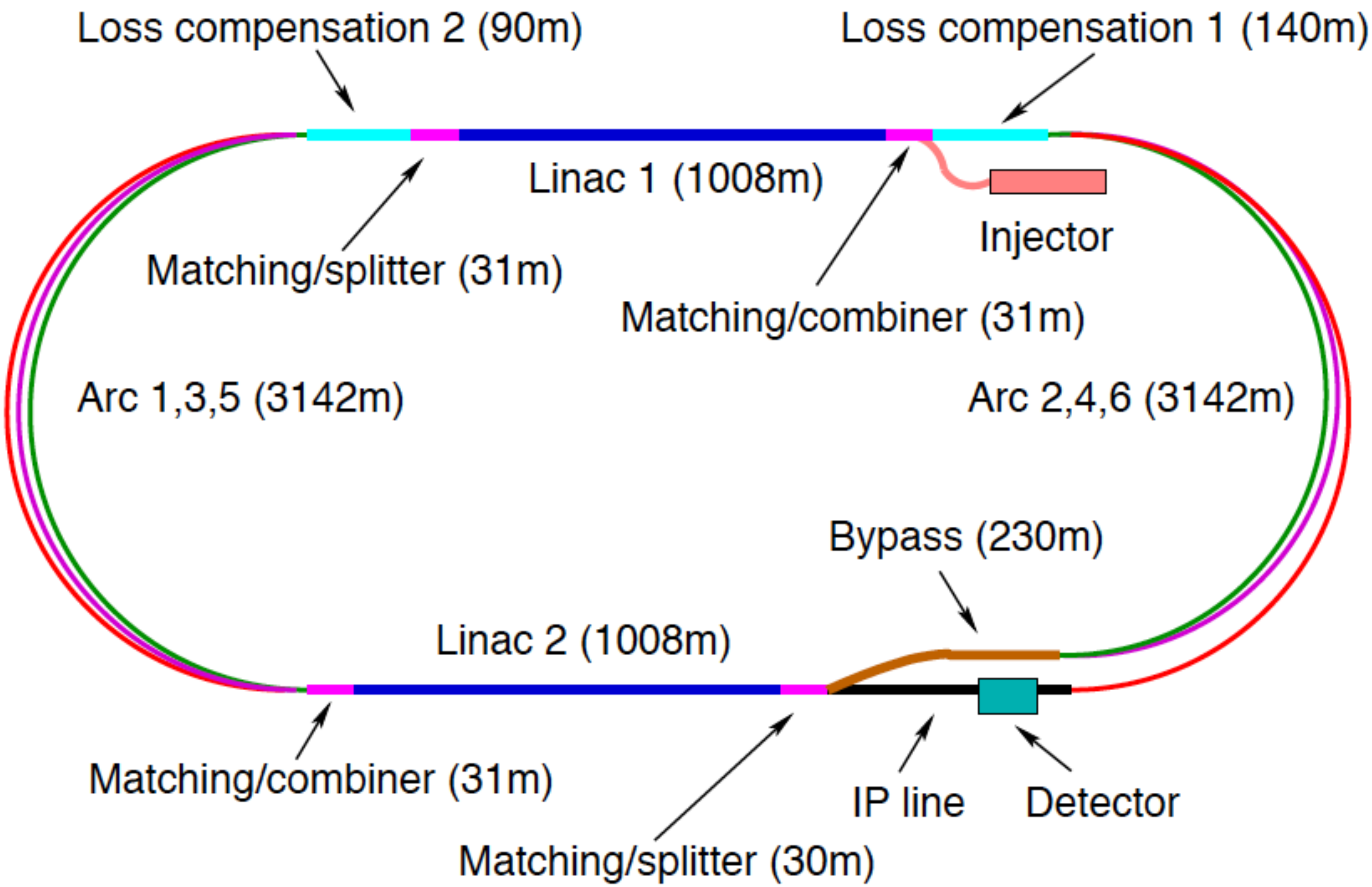


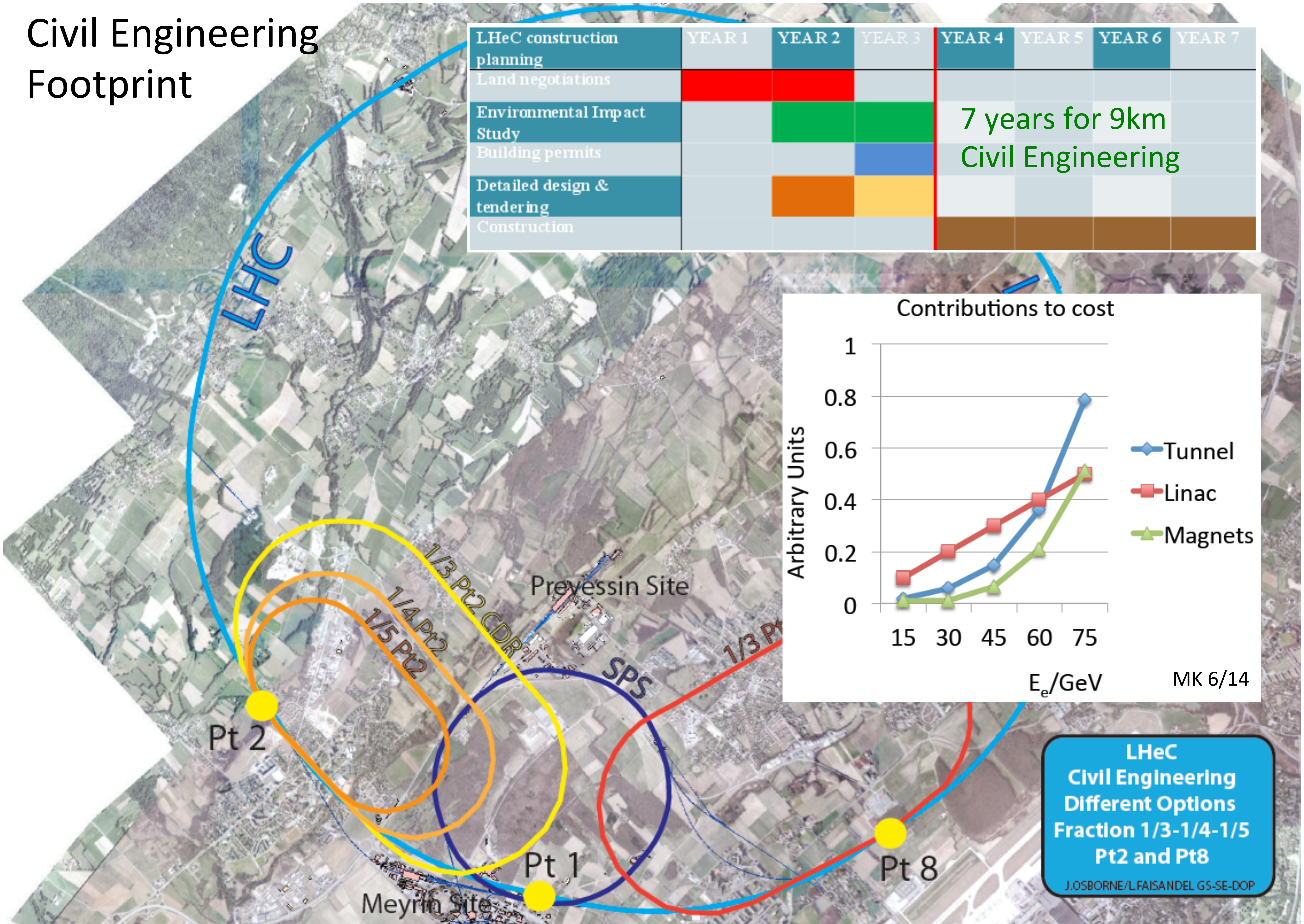
Figure 1: Schematic view on the LHeC racetrack configuration. Each linac accelerates the beam to 10 GeV, which leads to a 60 GeV electron energy at the collision point with three passes through the opposite linear structures of 60 cavity-cryo modules each. The arc radius is about 1 km, mainly determined by the synchrotron radiation loss of the 60 GeV beam which is returned from the IP and decelerated for recovering the beam power. Comprehensive design studies of the lattice, optics, beam (beam) dynamics, dump, IR and return arc magnets, as well as auxiliary systems such as RF, cryogenics or spin rotators are contained in the CDR [1], which as for physics and detector had been reviewed by 24 referees appointed by CERN.

Ring-Ring option as fall back;

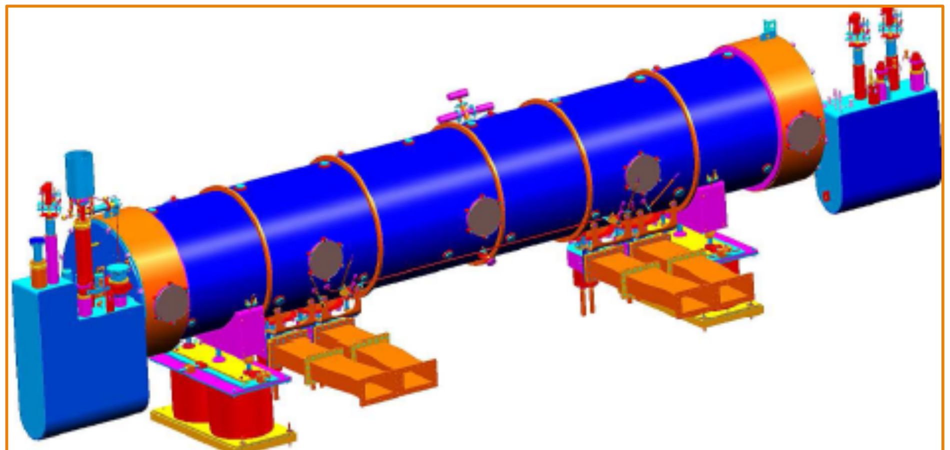
Civil Engineering Footprint

LHeC construction planning	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7
Land negotiations							
Environmental Impact Study							
Building permits							
Detailed design & tendering							
Construction							

7 years for 9km Civil Engineering



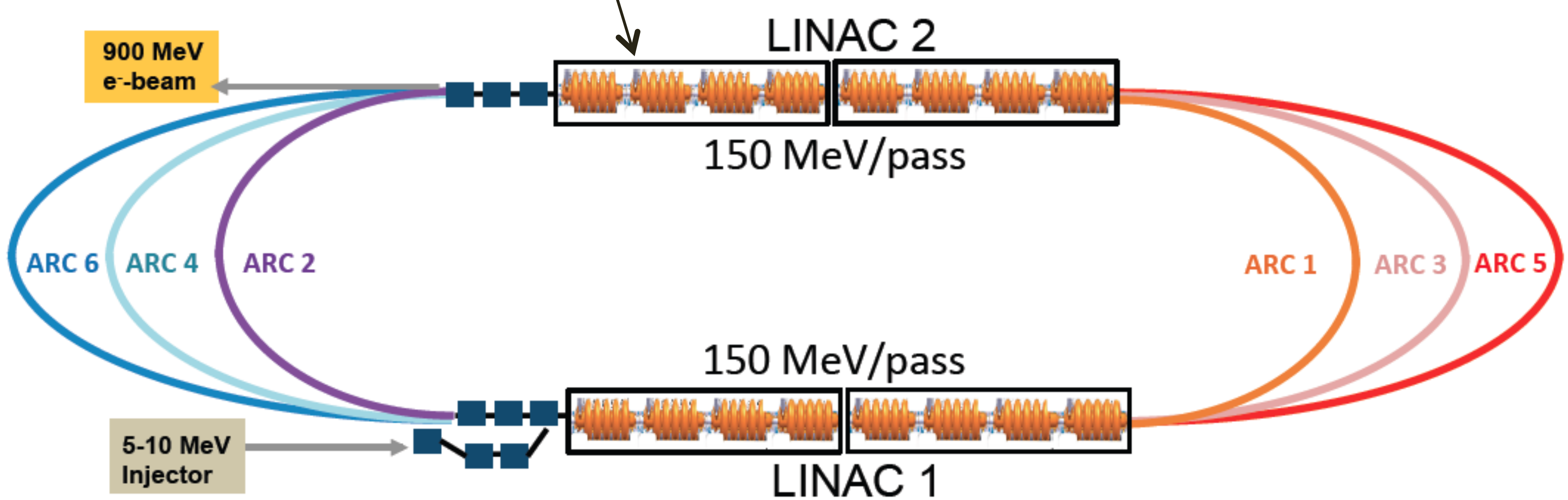
Superconducting RF and ERL Test Facility Design at CERN



R.Calaga, A.Hutton, B. Rimmer, E.Jensen et al.

Frequency 802 MHz
Design and built of 2 Modules (CERN+Jlab+)
Conceptual Design of the LTFC – end of 2015:
SCRF under beam conditions, applications, high quality, high current, multipass, ERL

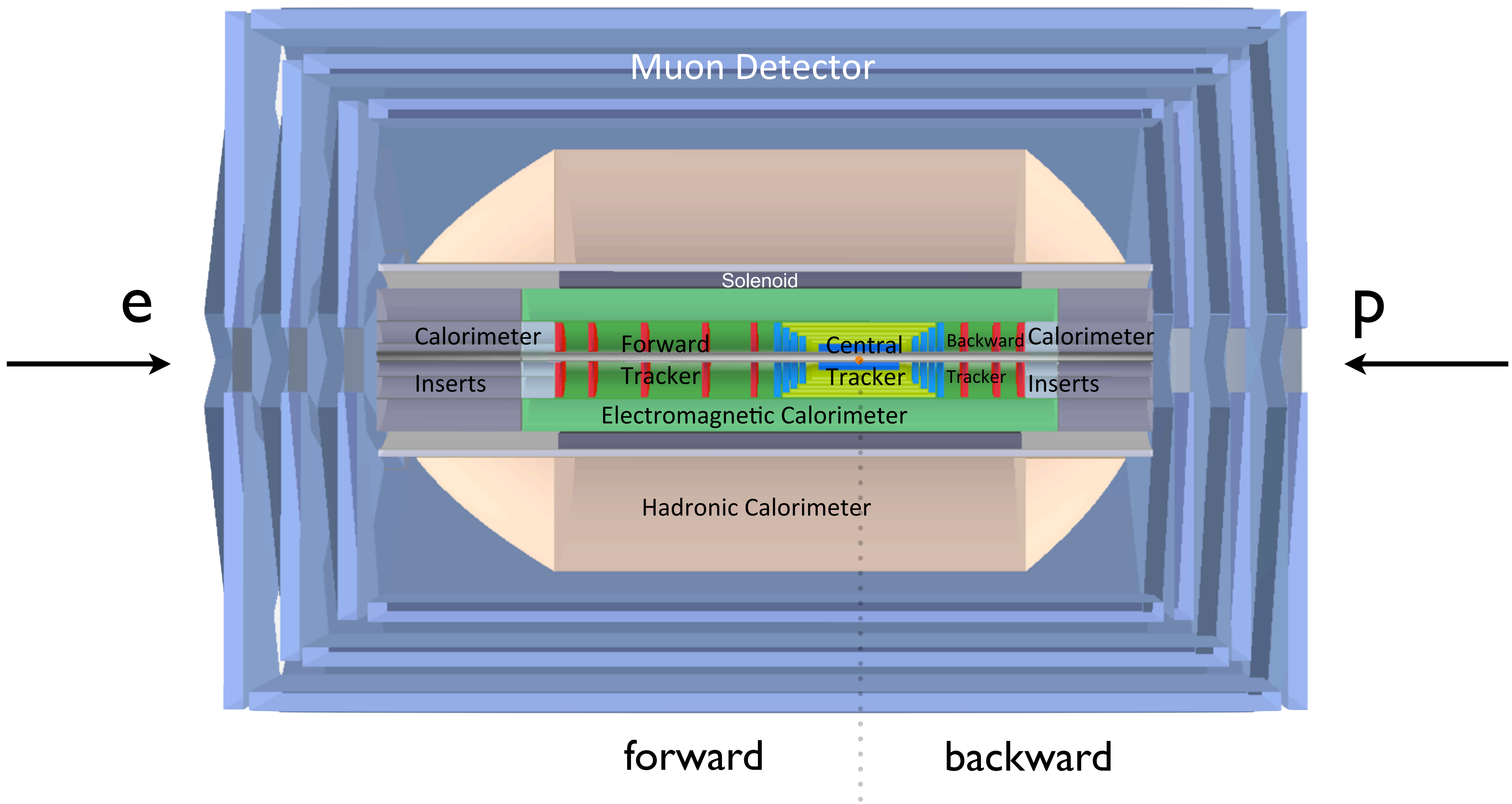
Interest for participation expressed by BINP, BNL, CORNELL, IHEPBj, JLAB ..



Arc optics, Multipass linac optics, Lattice, Magnet specification, … first passes done

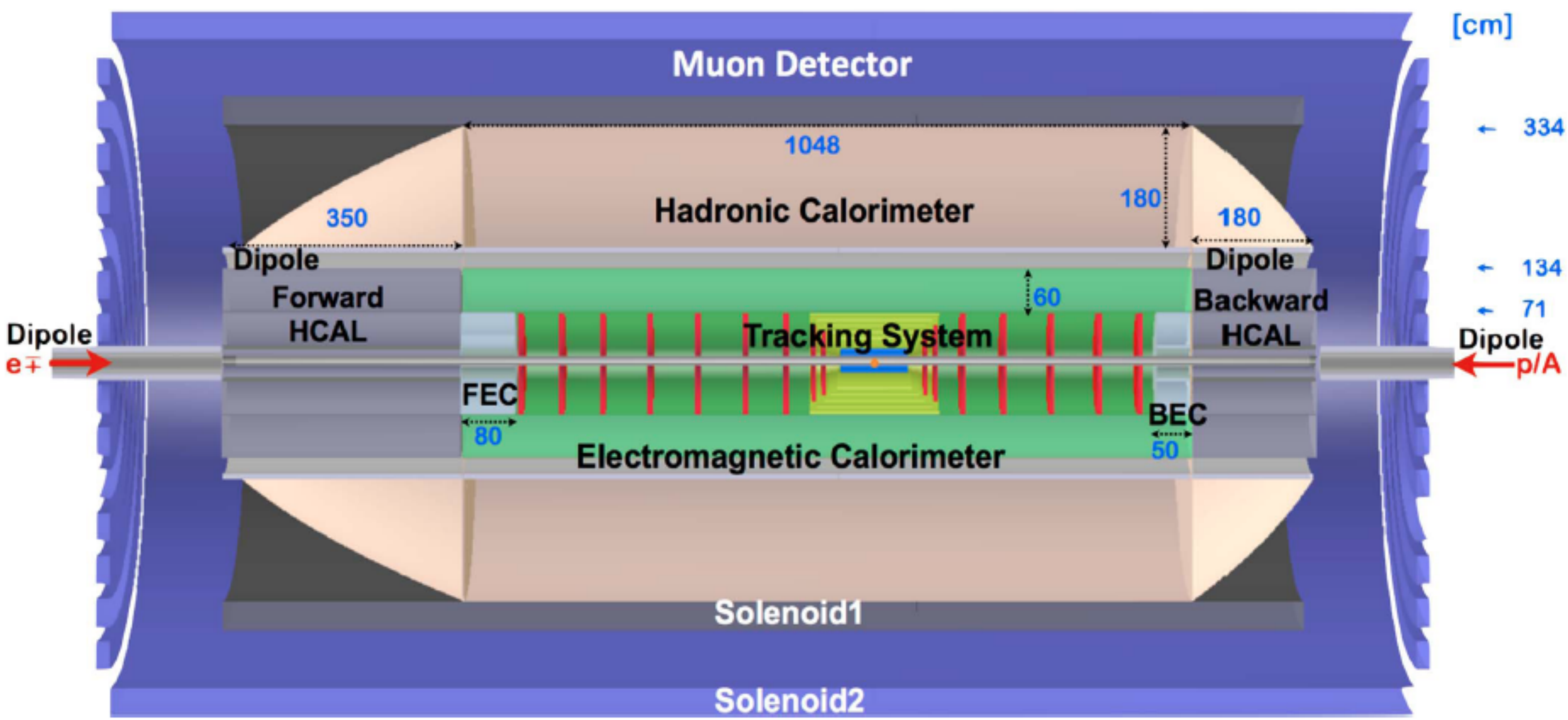
A. Bogazc, A.Valloni, A.Milanese et al.

LHeC detector design



Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =14x9m^2 [CMS 21 x 15m^2, ATLAS 45 x 25 m^2]
Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

First study of detector for FCC-he



Detector for FCC scales by about ln(50/7) ~2 in fwd, and ~1.3 in bwd direction

1000 H → μμ may call for better muon momentum measurement

FCC-he parameters

collider parameters	FCC ERL	FCC-ee ring		protons
species	e^- (e^+?)	$e^\pm$	$e^\pm$	p
beam energy [GeV]	60	60	120	50000
bunches / beam	-	10600	1360	10600
bunch intensity [10^{11}]	0.05	0.94	0.46	1.0
beam current [mA]	25.6	480	30	500
rms bunch length [cm]	0.02	0.15	0.12	8
rms emittance [nm]	0.17	1.9 (x)	0.94 (x)	0.04 [0.02 y]
$\beta_{x,y}$*[mm]	94	8, 4	17, 8.5	400 [200 y]
$\sigma_{x,y}$* [μm]	4.0	4.0, 2.0		equal
beam-b. parameter ξ	(D=2)	**0.13**	**0.13**	0.022 (0.0002)
hourglass reduction	0.92 (H_D=1.35)	**~0.21**	~0.39	
CM energy [TeV]	3.5	3.5	4.9	
luminosity[10^{34}cm^{-2}s^{-1}]	**1.0**	**6.2**	**0.7**	

F.Zimmermann
ICHEP14, June

PRELIMINARY
L is 1000*HERA

Summary and outlook I

- Thorough understanding of the particle physics can only proceed through variety of HEP experiments with different energies and probes. Therefore it is essential to perform and study complementary $\mathrm{e^+e^-/pp/e^\pm p}$ collisions.
- LHeC and FCC-he projects have an unprecedented potential as a high luminosity, high energy DIS machines. Precision DIS measurements: constraining and unfolding PDFs, heavy flavor physics, precision strong coupling , precision electroweak measurements. Higgs properties. Offering a unique window for small x physics and high parton density regime.
- FCC-he project with new energy frontier can address big questions: structure of visible matter, lepton-quark symmetries and BSM physics.
- eA at high energy essential to untangle the complex nuclear structure at low x and constrain the initial conditions for AA at the LHC. Complementary to pp/pA/AA.
- CDR for the LHeC project is complete: arXiv:1206.2913

Summary and outlook II

- New International Advisory Committee and Coordination Group set up by CERN with mandate to further develop LHeC and study prospects at FCC.
- Prospect of higher luminosity at LHeC/FCC-eh $\mathcal{O}(10^{34})\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ calls for reevaluation of the physics possibilities.
- In particular, following Higgs discovery, there is an ongoing effort to study the potential for Higgs precision physics in high luminosity ep machines.
- Physics studies for FCC-he machine, especially the BSM possibilities.
- CDR for the ERL test facility, end of 2015.

More information on both projects can be found:

http://lhec.web.cern.ch/
LHeC CDR, J Phys G39 (2012) 075001
Klein & Schopper, CERN Courier, June 2014
Newman & Stasto, Nature Physics 9 (2013) 448
Bruening & Klein, Mod Phys Lett A28 (2013) 1130011