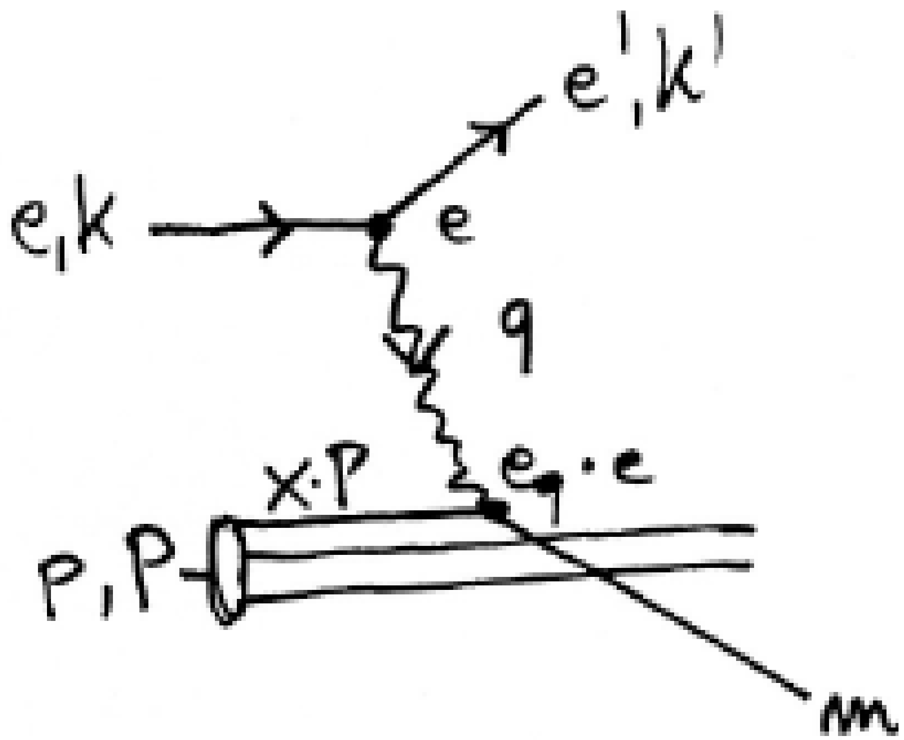
LHeC & Lepton-hadron Colliders



- Deep Inelastic Scattering
- LHeC Design Overview
- PDFs and α_S
- Higgs in ep Collisions
- Next Steps

Eram Rizvi

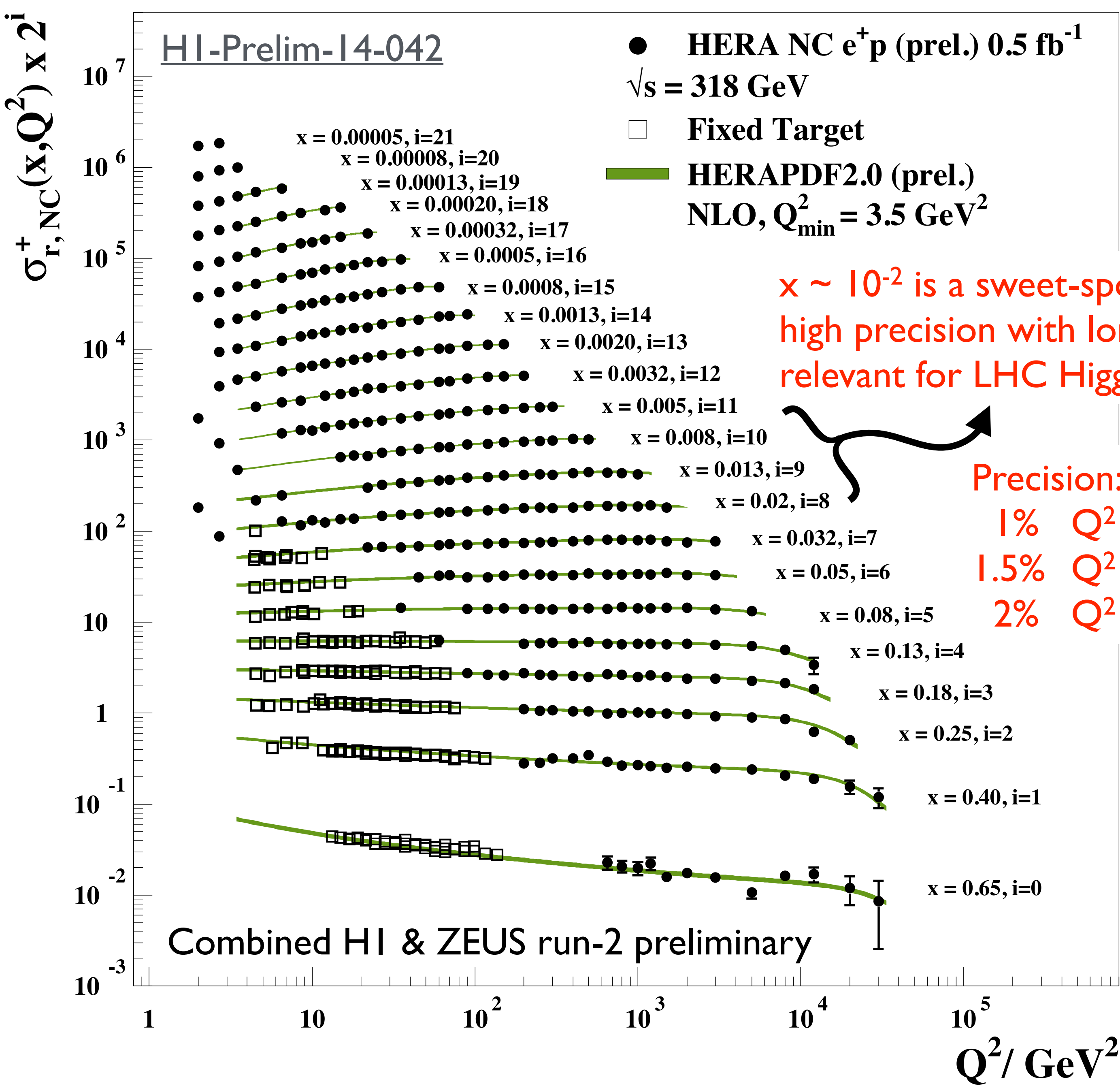
PPAP Community Meeting
Rutherford Lab

21-22nd July 2014

HERA Legacy

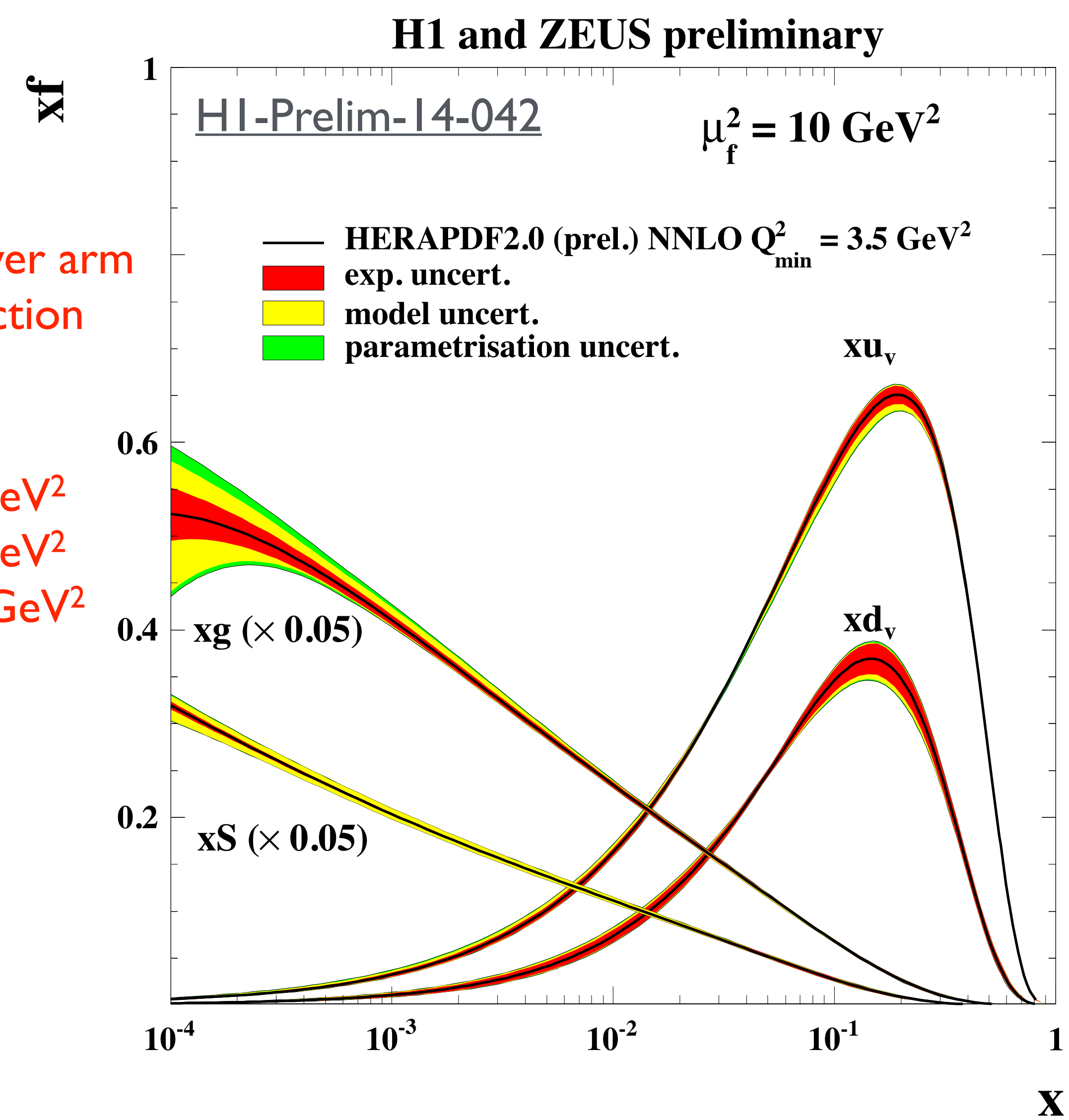
HERA data provided detailed insight into parton dynamics
Established NNLO pQCD
Underpins all LHC measurements
Precise determination of PDFs (specially gluon)
⇒ accurate predictions of LHC Higgs production

H1 & ZEUS collected 0.8 fb^{-1} in e^+ / e^- modes
$\sqrt{s}$ = 0.3 TeV
Flavour separation from NC and CC DIS
Independent of nuclear effects
HERAPDF2.0 uses final combined H1/ZEUS data
Improved precision at high x (incl. gluon)
Achieved with strong UK involvement



$x \sim 10^{-2}$ is a sweet-spot
high precision with long Q^2 lever arm
relevant for LHC Higgs production

Precision:
1% $Q^2 < 100$ GeV^2
1.5% $Q^2 < 500$ GeV^2
2% $Q^2 < 3000$ GeV^2



Deep Inelastic Scattering

US led electron-ion collider projects:
EIC (JLAB) / eRHIC (Brookhaven)
heavy ion programme
Interest from UK community

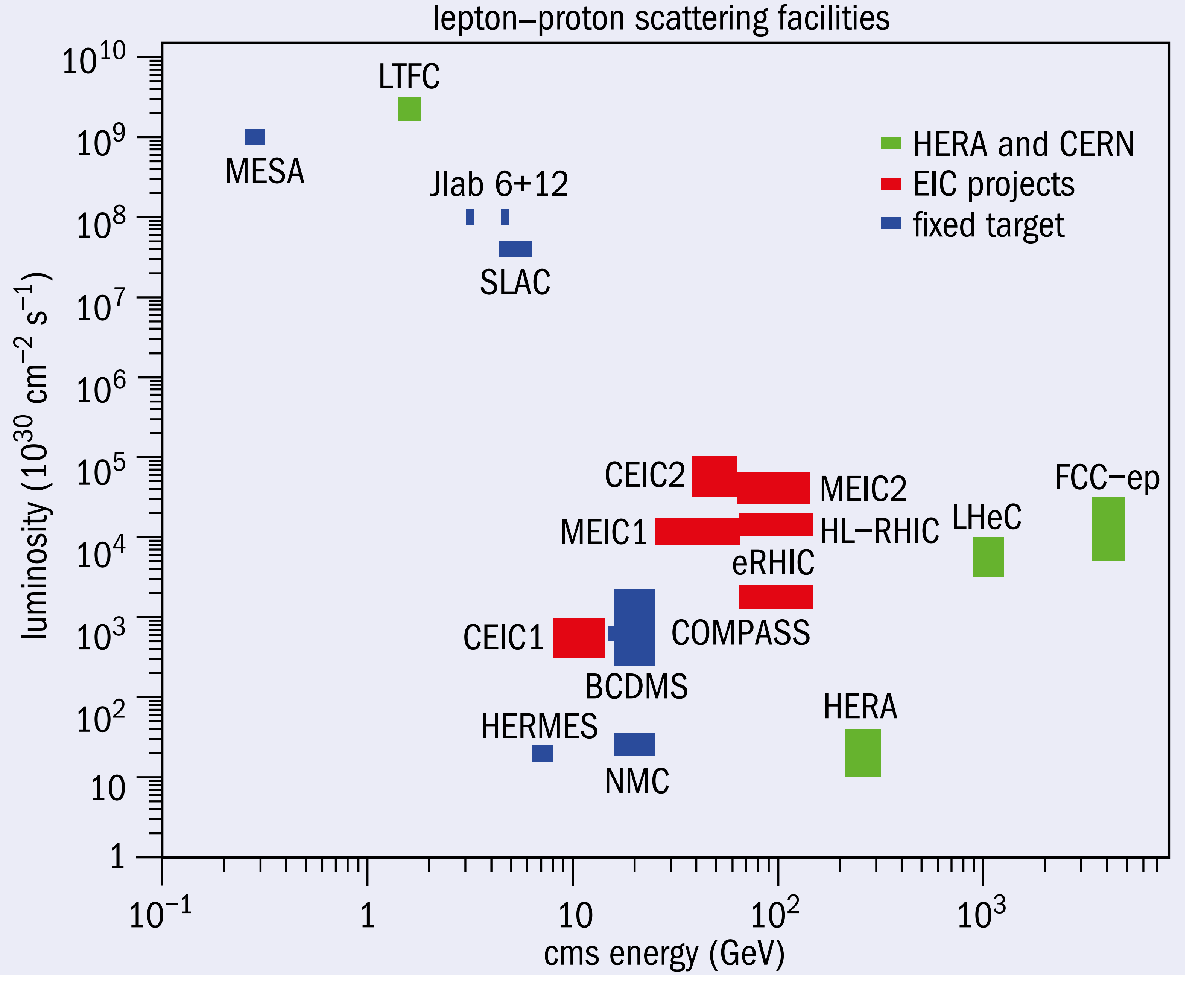
LHeC:
ep collisions with 7 TeV LHC p-beam
synchronous running with LHC pp collisions
… or FCC (hadron-electron machine)

60 GeV electron beam ⇒ $\sqrt{s}$ = 1.3 TeV
Polarised electron beam ~ 90%

FCC 50 TeV p-beam ⇒ $\sqrt{s}$ = 3.5 TeV

Kinematic range:
$Q^2 \rightarrow 10^6$ GeV^2
$10^{-6} < x < 1$
$\mathcal{L} = 10^{33} - 10^{34}$ cm^{-2}s^{-1}

Factor ~1000 increase in $\mathcal{L}$ compared to HERA
Factor ~20 increase in x,Q^2 range



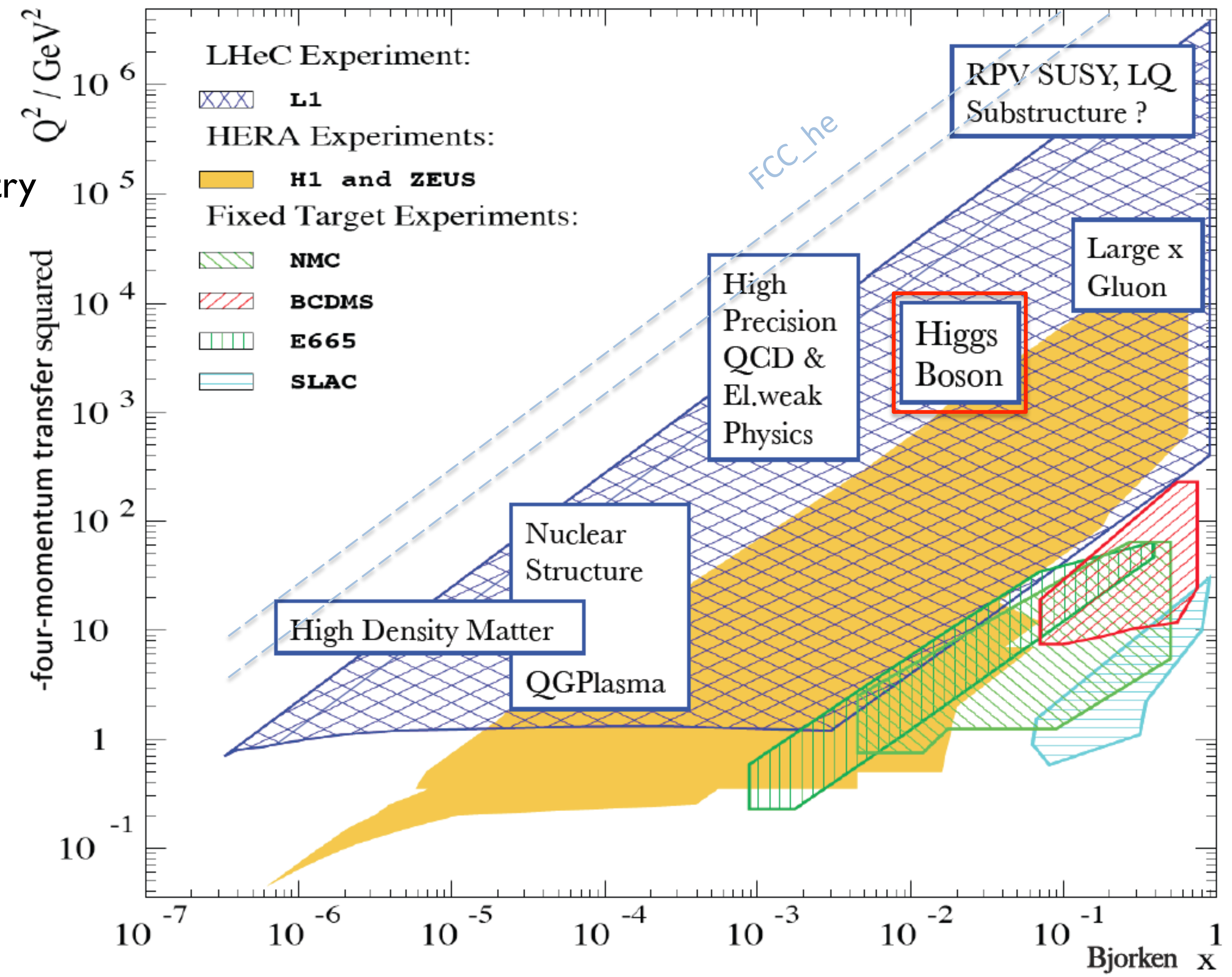
Collect 10 – 100 fb^{-1} per year
Precision ep physics with 1 ab^{-1} in a decade

LHeC Physics

Proton structure
- complete flavour decomposition
  u/d , s , c , b, g
- remove assumptions on p ↔ d symmetry

High precision QCD & EW physics
α_s ~ 0.1% accuracy
High density matter
Gluon saturation
Higgs properties
RP violating SUSY
Leptoquarks
Quark sub-structure
… ??

As well as
e-deuteron
heavy ion scattering
Quark-gluon plasma
$\mathcal{L}$ $=10^{31} - 10^{32}$ for nuclei

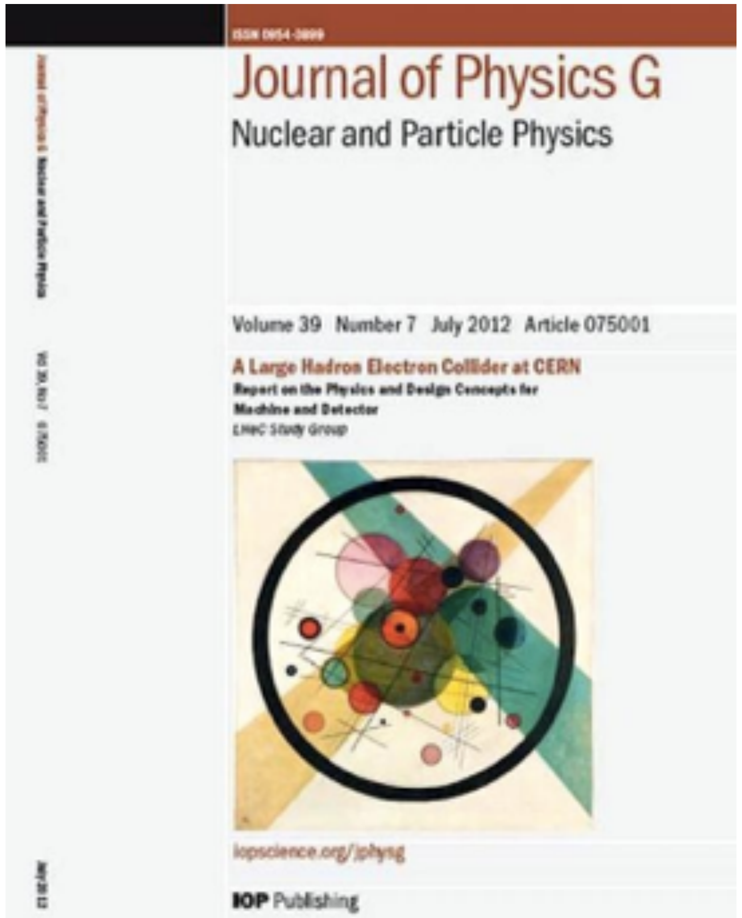


Physics goals complementary to LHC
Precise high x PDFs extend the LHC discovery potential
Higgs properties accessible at LHeC

LHC searches: largest uncertainty from PDFs
ATLAS contact interactions 8 TeV arXiv:1407.2410
ATLAS Z-prime search 8 TeV arXiv:1405.4123
ATLAS quantum gravity search 8 TeV arXiv:1311.2006

http://cern.ch/lhec

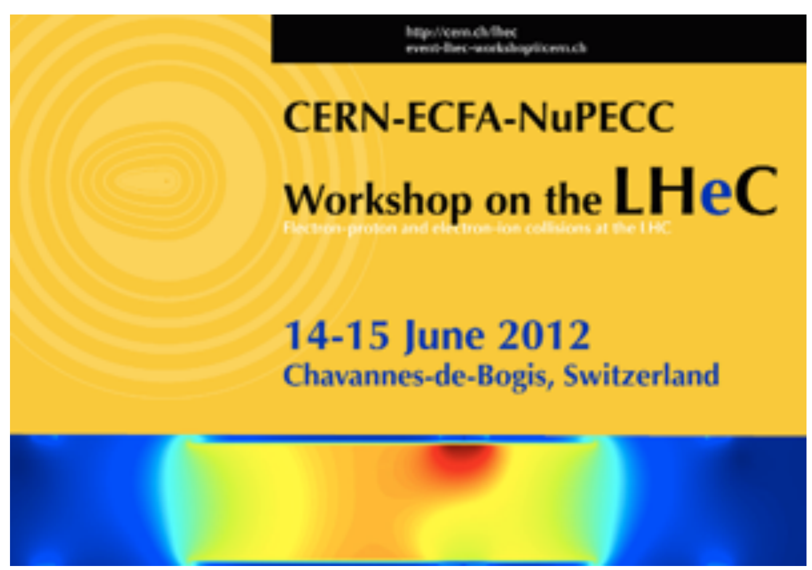
LHeC Study Group

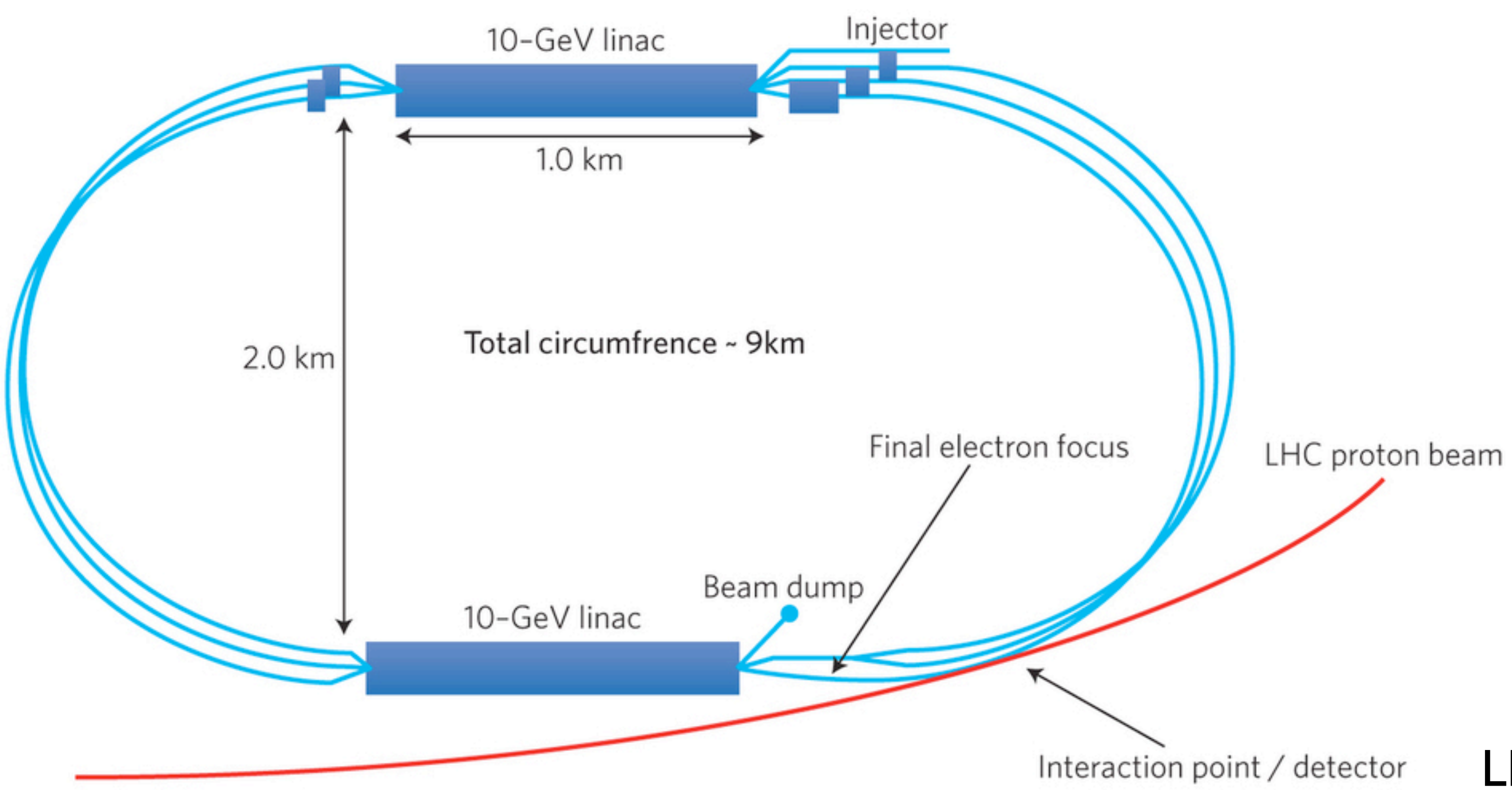


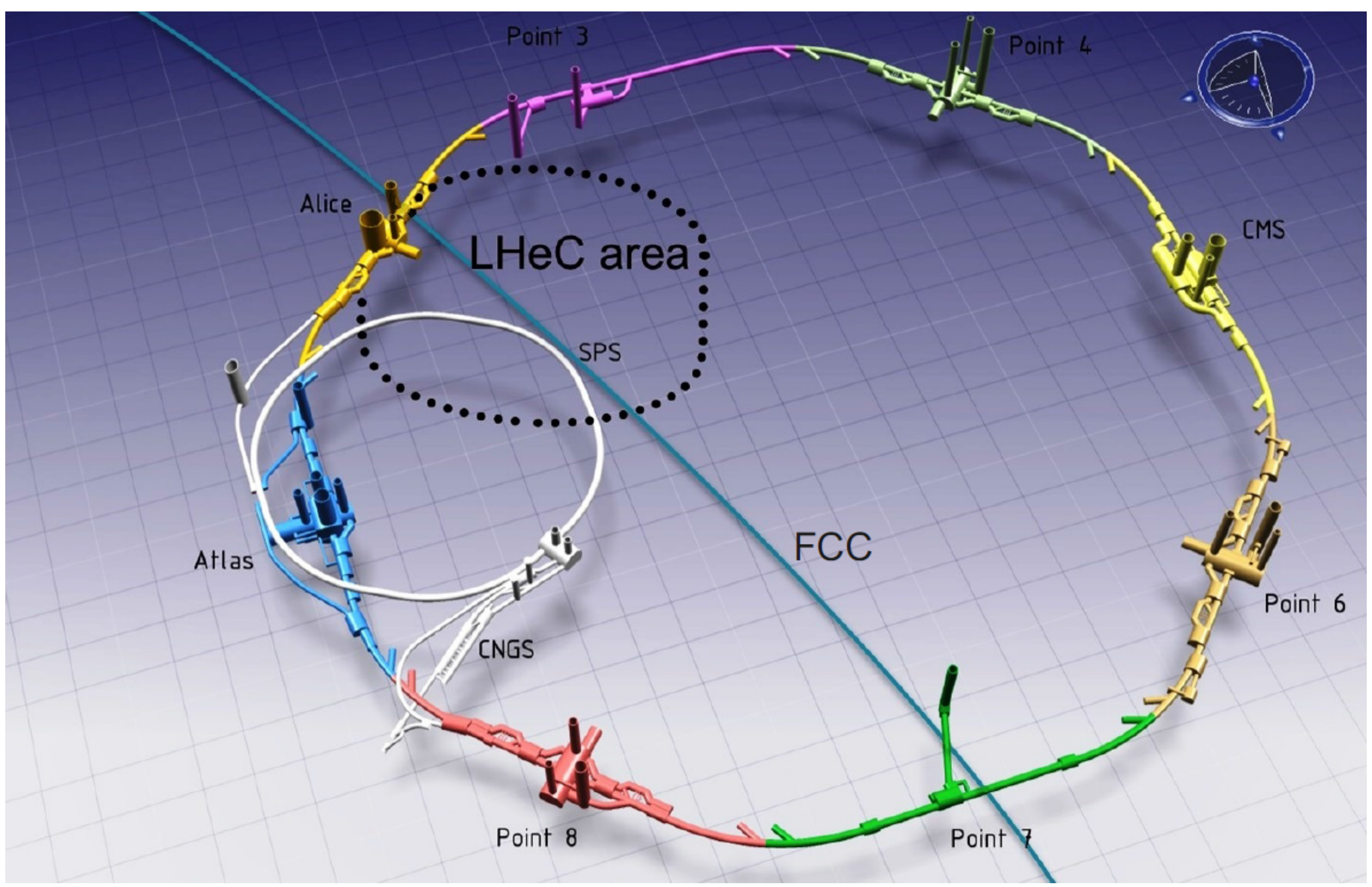
J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], P.Adzic[74], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], B.Allanach[73], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], 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]

arXiv:1206.2913 CDR
arXiv:1211.5102 LHC ↔ LHeC

Several international workshops since 2008
Conceptual Design Report Published mid 2012
Will focus on new developments since then







60 GeV electron beam achieved with
2 x 1 km recirculating energy recovery linac
3 pass arcs with 2 x 60 cavity cryo-modules
accelerating gradient 20 MV/m

Total machine power ~ 80 MW
- cryogenics
- linac power
- synchrotron compensation
- injectors & magnets

Tunnel civil engineering independent of LHC

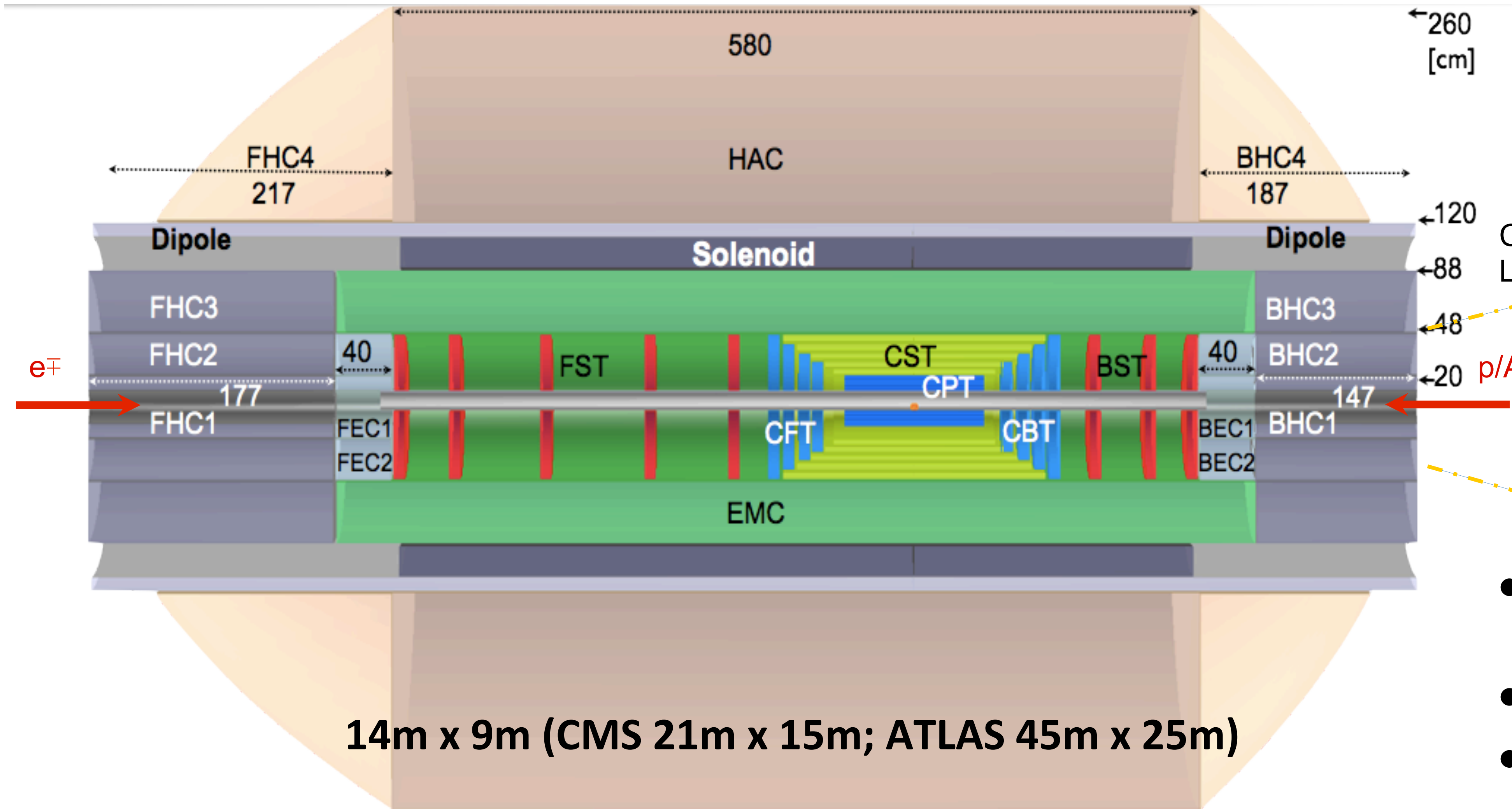
LHeC could operate simultaneously
- with pp collisions in LHC
- with ep collisions in FCC-he

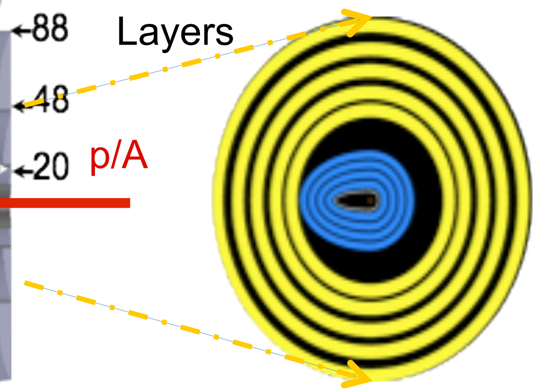
or be injector for FCC-ee machine

$\mathcal{L} = 10^{34}$ cm^{-2}s^{-1} seems feasible compared to CDR:
- more intense electron source
- better p focussing
- smaller p & e emittance
- over-performance of existing LHC

$\mathcal{L}$ for ILC / LHC / LHeC all on a par
Higgs production cross section in ee ≈ ep ~ 200 fb

Detector Design Requirements





- Demanding specification but less stringent than ATLAS/CMS
- Forward tracking is crucial
- Rest on existing technology → no large R&D effort

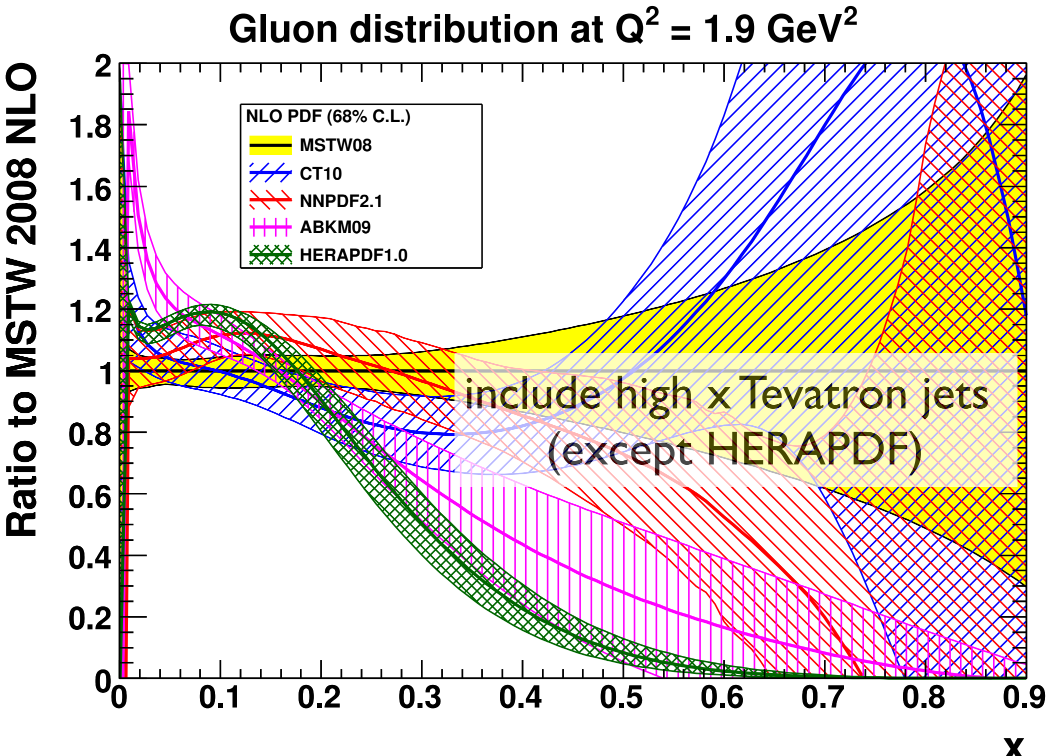
3.5 T solenoid
0.5 T dipole magnets inside IR to bend electron beam to collision
strong synchrotron fan → elliptical beam pipe in IR
Calorimetry similar to ATLAS
LAr EM calo $\sigma/E = 9\% / \sqrt{E} \oplus 0.3\%$
Scintillating tile HAD calo $\sigma/E = 32\% / \sqrt{E} \oplus 9\%$
Muon system - tagging only - momentum from inner tracker

FCC-he detector design similar

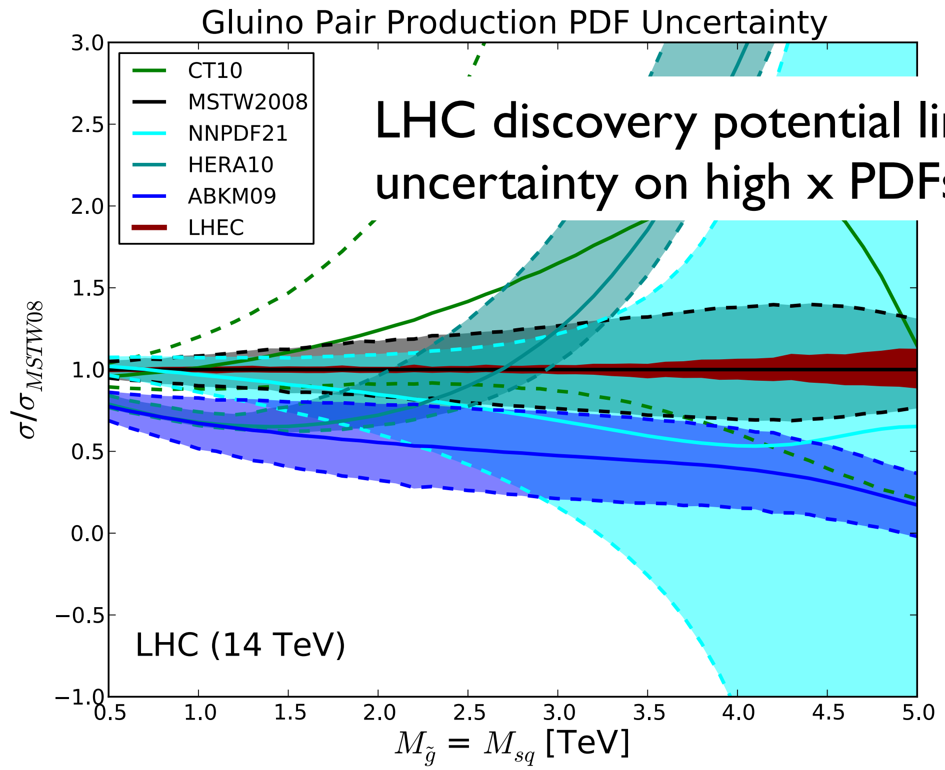
Need 1° acceptance
in forward region for high x & Higgs
in backward region for low x kinematic reco
4 Layer pixel tracker
4 layer central Si tracker + fwd/bwd planes
5/3 wheel forward / backward Si tracker

Provides b-jet tagging to $\eta = 3$
Transverse impact parameter resolution = 10μm

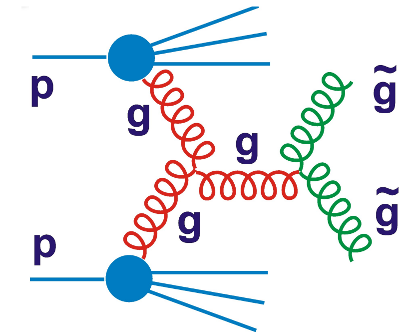
PDFs - gluon



Currently high x gluon unknown for x>0.3



LHC discovery potential limited by uncertainty on high x PDFs

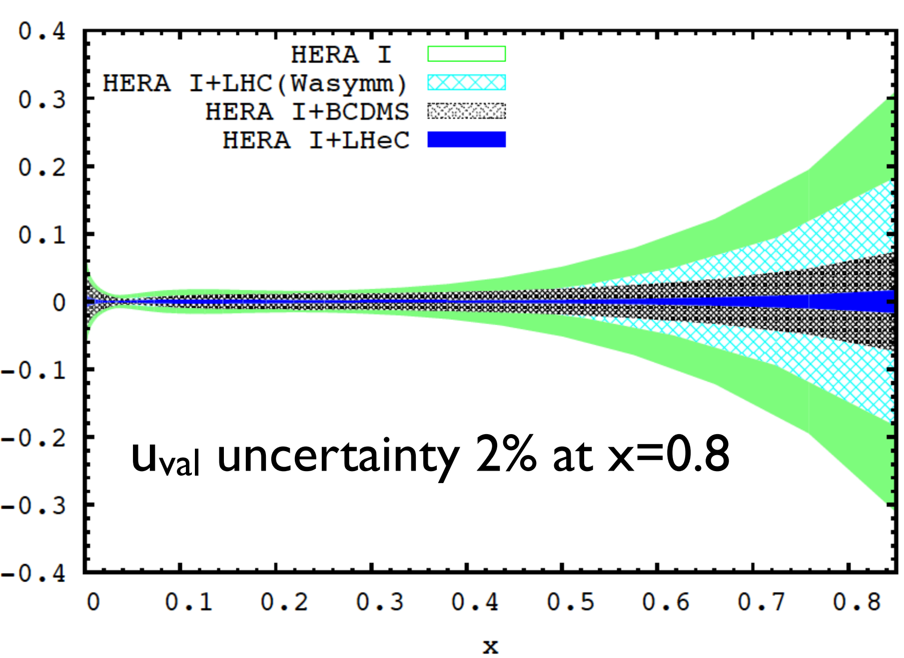


dominant gluino production mode

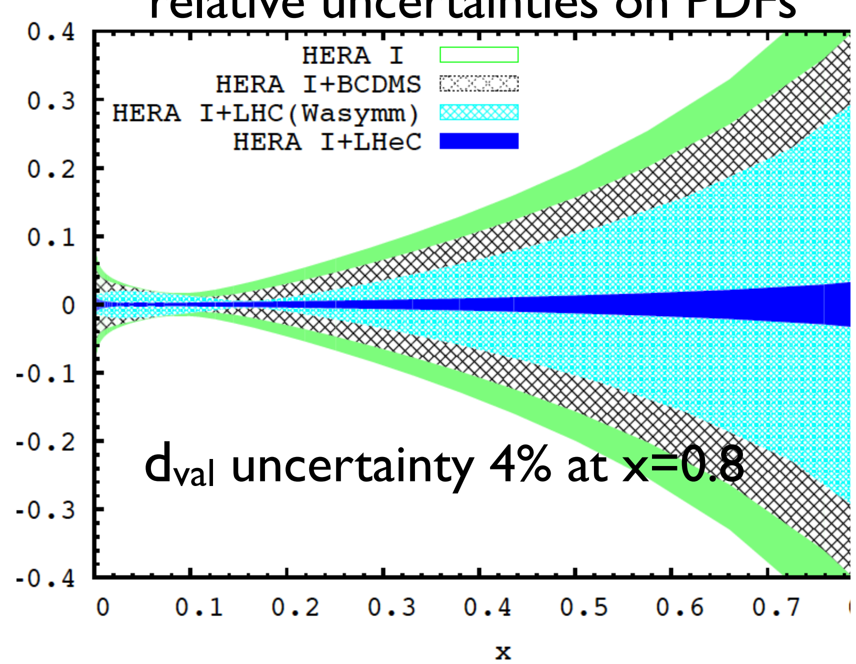
LHeC provides single coherent experiment with which to determine PDFs with well controlled systematics

NLO QCD fit to LHeC + HERA inclusive data incl. experimental systematic uncertainties & correlations

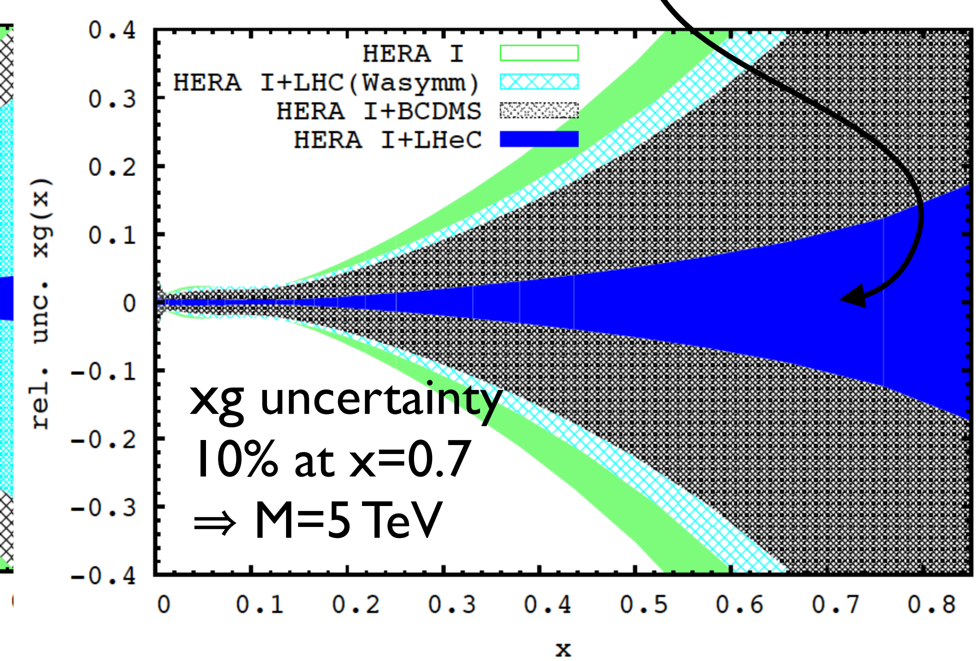
relative uncertainties on PDFs



u_{val} uncertainty 2% at x=0.8



d_{val} uncertainty 4% at x=0.8



xg uncertainty
10% at x=0.7
⇒ M=5 TeV

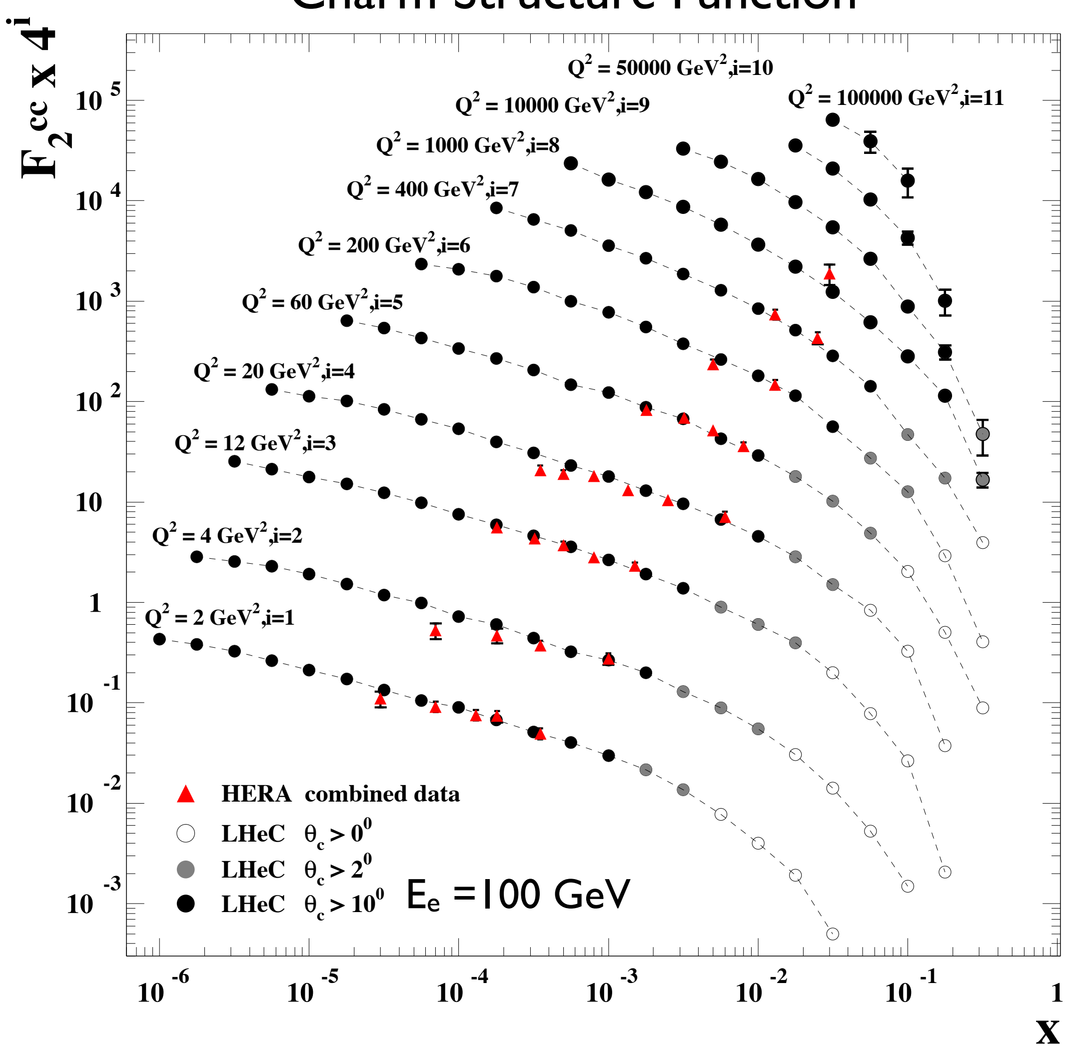
High x u_{val} , d_{val} & gluon PDFs dramatically improved from HERA + LHeC data

PDFs - heavy flavours

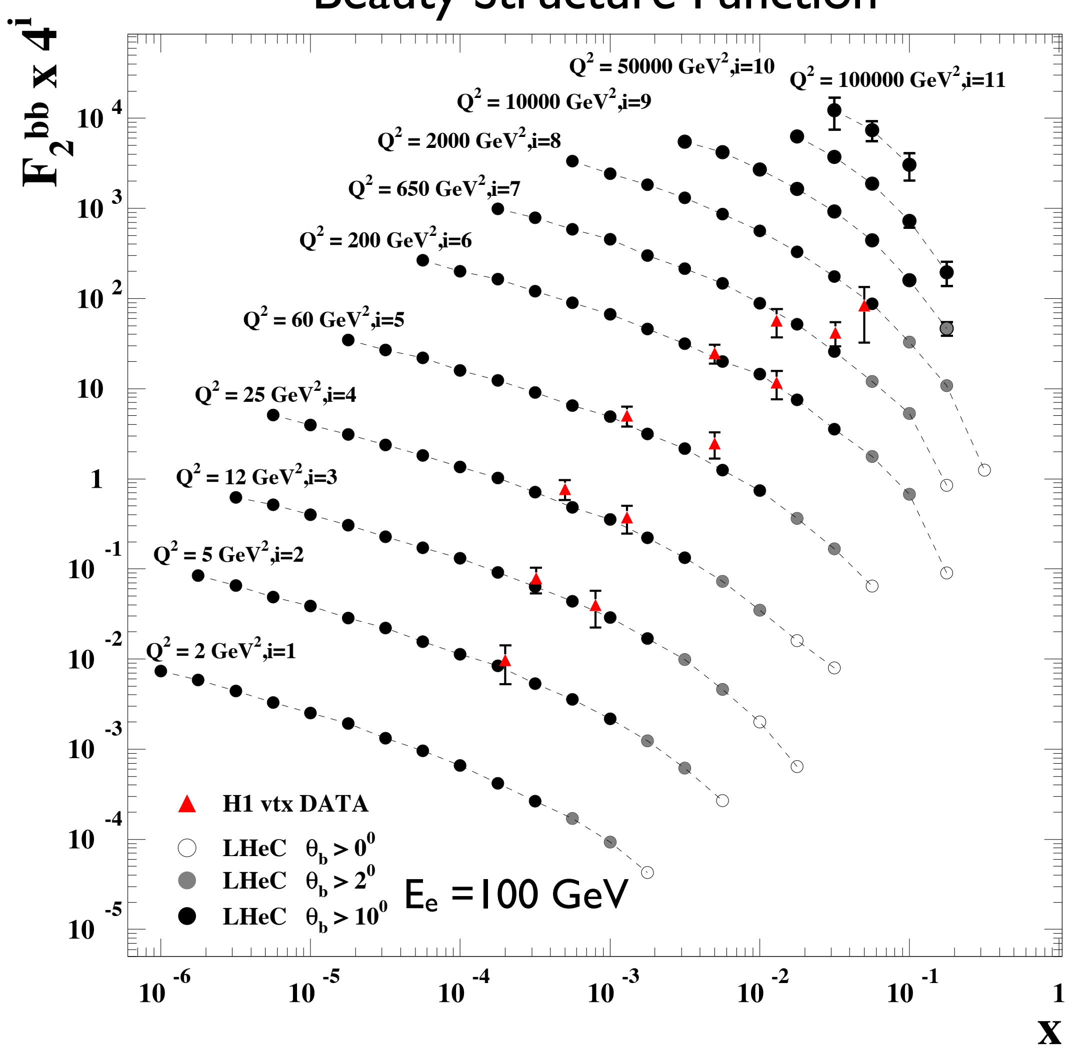
LHeC will provide direct access to charm and beauty PDFs
Simulations here assume E_e = 100 GeV for 10 fb^{-1} data
Tagging efficiency ~10% for charm and 50% for beauty

In addition charged current W+s → c process allows direct measurement of strange

Charm Structure Function



Beauty Structure Function

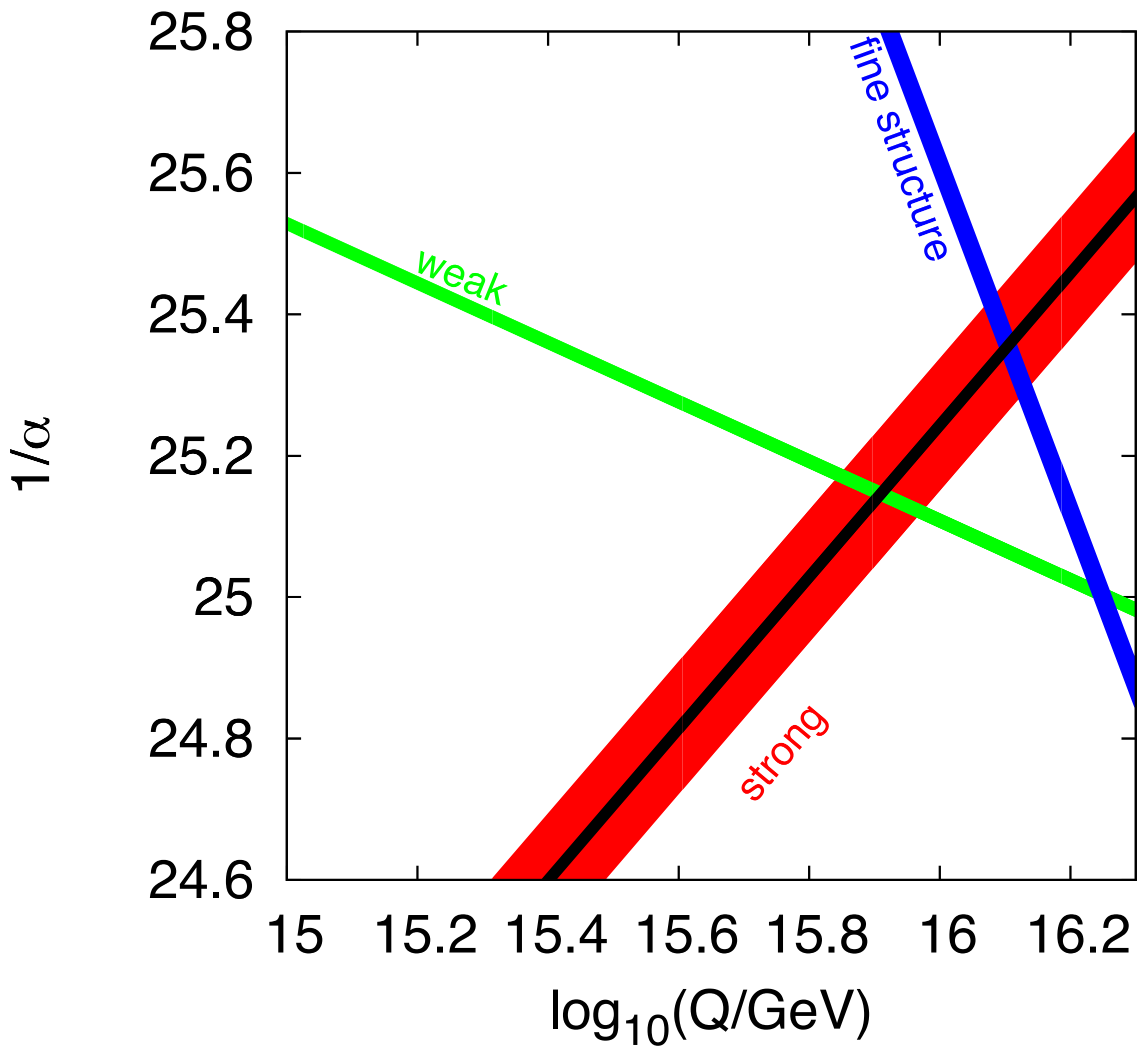


Simple parton level study with statistical uncertainties only (<1%)
Guided by experience from HERA & LHC tagging performance

Important for testing heavy flavour theory

Very large phase space opened up
Region of x>0.1 becomes accessible at highest Q^2
Forward low angle tagging to ~1° essential for high x

Strong Coupling α_S



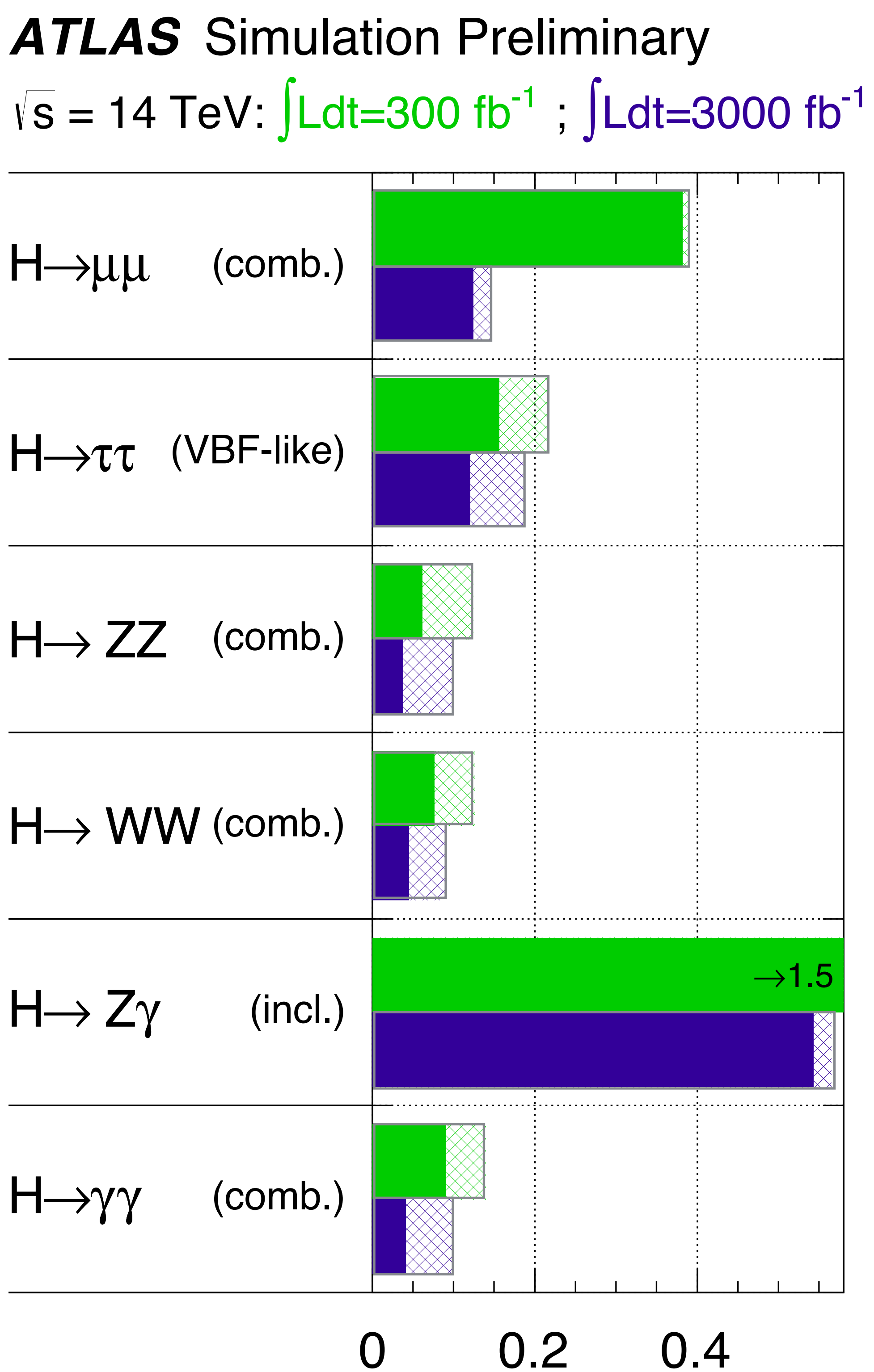
Strong coupling is a fundamental parameter of SM
Current experimental precision ~ 1% (mostly tau & DIS)
- analyses performed at NNLO and N^3LO

LHeC data on inclusive structure functions could reach α_S ±0.2%
Includes projected experimental uncertainties (incl. correlations)
Accuracy is obtained from
- large kinematic range in Q^2 constrains xg via scaling violations
- large range in x: $10^{-6} < x < 0.8$
- accurate low x data constrain high x by momentum sum rule
- accurate high x data reduce α_S / xg correlation
- range further extended using HERA data

DIS jet data could bring further improvement if theory is controlled

Theoretical treatment of heavy quarks will be important

current α_S uncertainty
projected α_S uncertainty from LHeC + HERA inclusive DIS



ATL-PHYS-PUB-2013-014

Projected Higgs production uncertainty with 300 fb^{-1} and 3000 fb^{-1}

Solid bands: projected experimental uncertainties

Shaded bands: include theoretical uncertainties (PDF $\oplus$ α_S $\oplus$ scale)

Theory error dominates in several channels

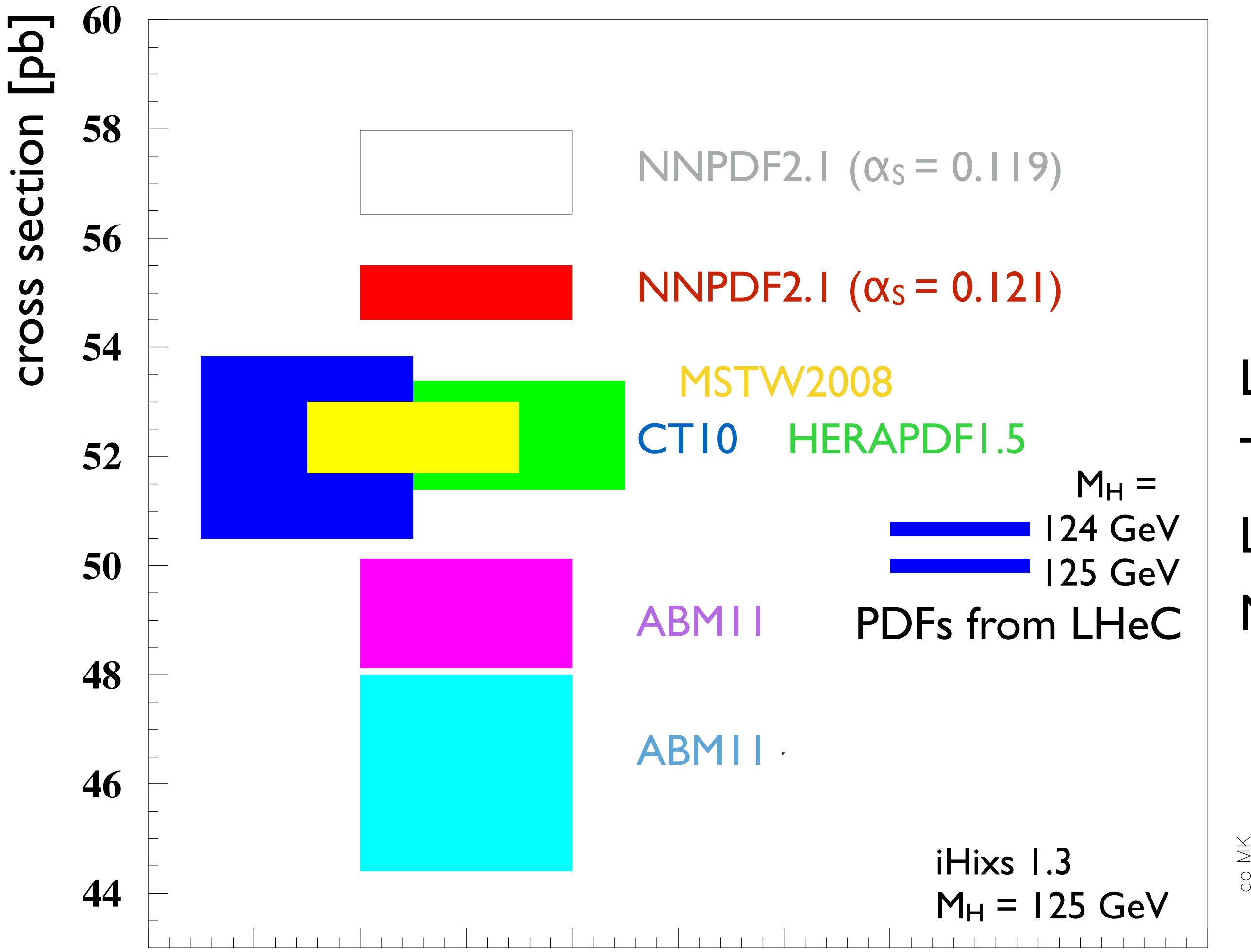
LHeC data will bring large improvements in PDF and α_S precision

N^3LO theory essential to reduce scale uncertainties… in progress now…

Higgs Production in pp

arXiv:1305.2090

NNLO Higgs production cross sections in pp $\sqrt{s}$= 14 TeV



Bands show the PDF eigenvector uncertainty ~2-4%
Additional scale and α_S uncertainty not shown
~10% & ~5% resp.

LHeC could attain precise PDFs with ~0.3% exp. error for σ_{Higgs}

Theoretical uncertainties from α_S and scale variations

Large Q^2 lever arm could yield precision α_S ~ 0.2% uncertainty

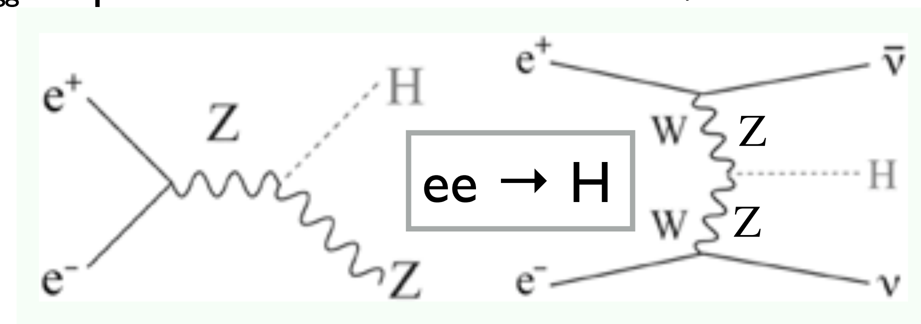
N^3LO required to reduce scale uncertainty

Together these could provide sensitivity to M_{Higgs} through cross-section dependence

Great potential to enhance LHC Higgs programme including sensitivity to exotic Higgs scenarios

Higgs Production in ep

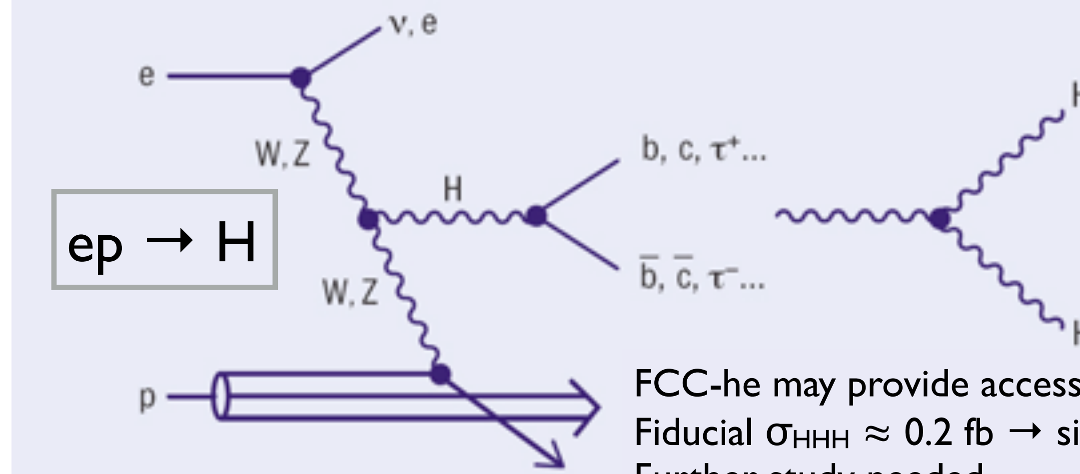
σ_{Higgs} in polarised ee = 250−300 fb at $\sqrt{s}$ = 250−500 GeV



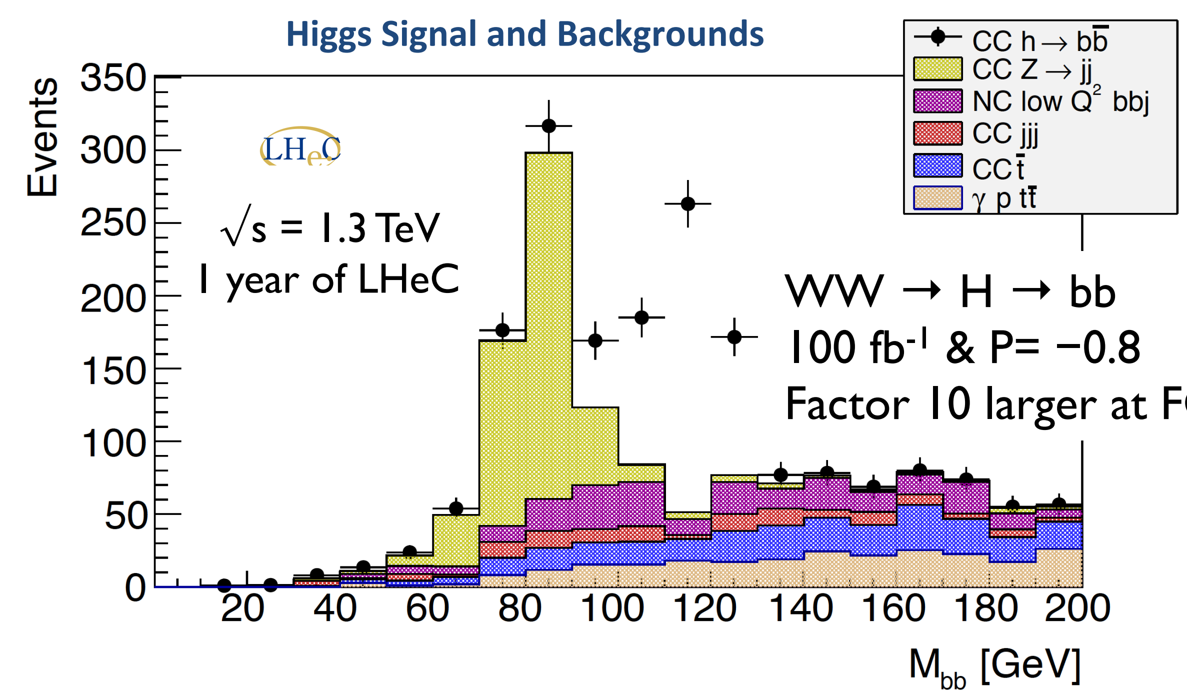
Higgs in e^-p		CC - LHeC ($\sqrt{s}$ = 1.3 TeV)	NC - LHeC ($\sqrt{s}$ = 1.3 TeV)	CC - FHeC ($\sqrt{s}$ = 3.5 TeV)
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$	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

Large Higgs production cross section at LHeC similar to ILC
Enhancement through polarised e⁻ CC channel
Sizeable rates for WW and ZZ and ττ and cc
H→bb studied in CDR

- high signal / background ~ 1-2 [LHC: ~0.01]
- low pile-up ~ 0.1 [LHC: 150 @ 10^{34}]
- ~1% coupling precision with 1 ab^{-1}



FCC-he may provide access to HHH vertex
Fiducial σ_{HHH} ≈ 0.2 fb → similar to ILC
Further study needed



Very clean signal with simple cuts

Prospects look very interesting
Implications for exotic higgs searches
More detailed studies needed…

H → charm / tau decays now under investigation

Next Steps

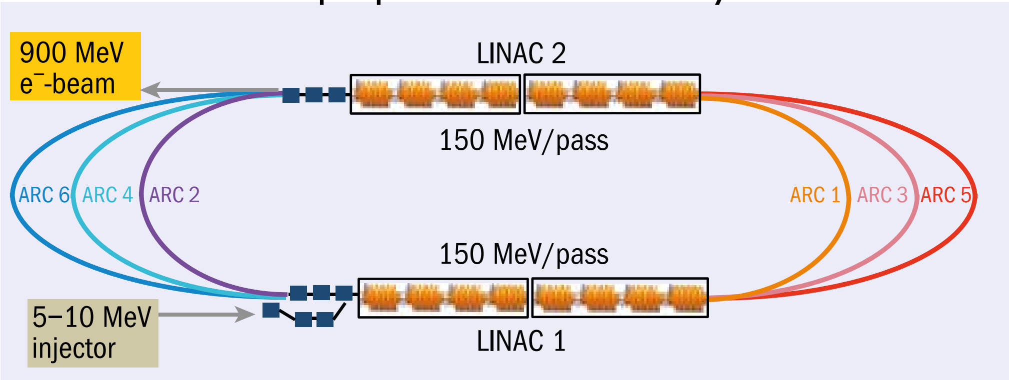
DG invited International Advisory Committee be formed:
Representation from major international labs, experiments & theory community

Mandate 2014-2017:

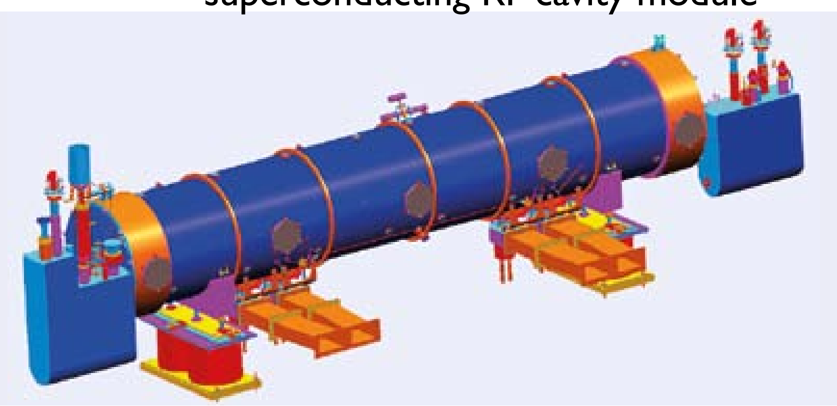
- Advise LHeC Coordination group / CERN directorate on ep / eA developments
- Develop CDR for ERL test facility at CERN
- Assist building international case for ep detector / accelerator development

CERN to help in development towards ep machine using LHC / FCC protons & ions
CERN mid-term plan will fund 2 s/c RF cryo modules 802 MHz (LHeC/FCC/MESA)
ERL test facility proposal being developed in conjunction with JLAB / Mainz / BNL / IHEP & …
- build experience of ERLs at CERN

proposed ERL test facility



superconducting RF cavity module



CERN-LHeC-Note-2012-006 ACC

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Guido Altarelli (Rome)
Sergio Bertolucci (CERN)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
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Hesheng Chen (IHEP Beijing)
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Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (STFC)

Next steps:
near-term - update LHeC physics prospects with more detailed studies
mid-term - performance of an optimised and fully simulated detector

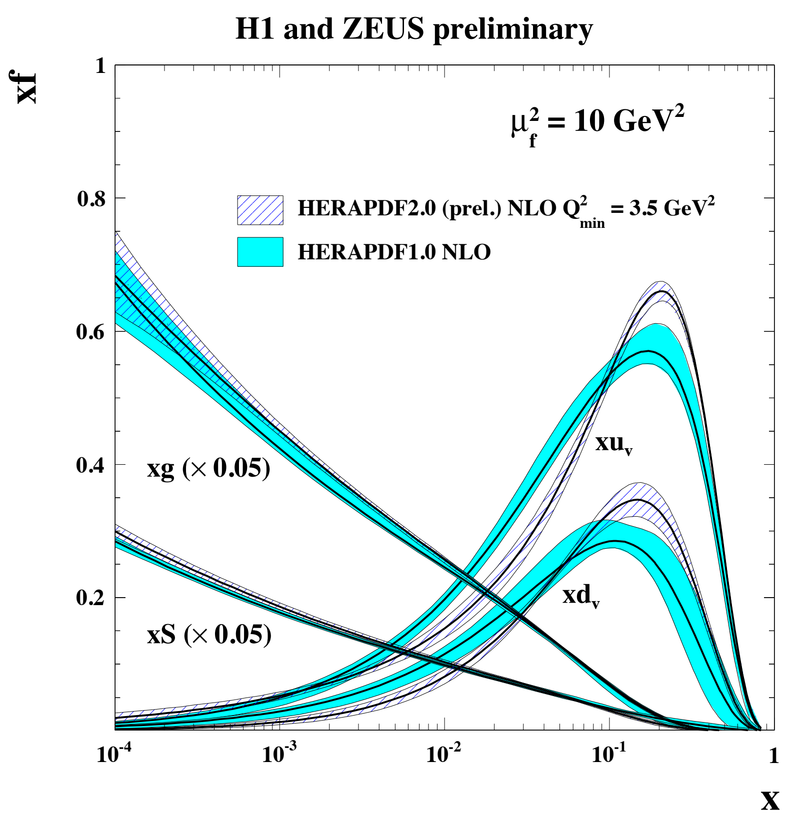
LHeC / FCC-he project puts ep physics at the energy / intensity frontier
Exploits the investment in hadron beams already made
Allows a complete exploration of the TeV scale with pp & ee
Bold project demands further study / consideration & has UK leadership

Backup

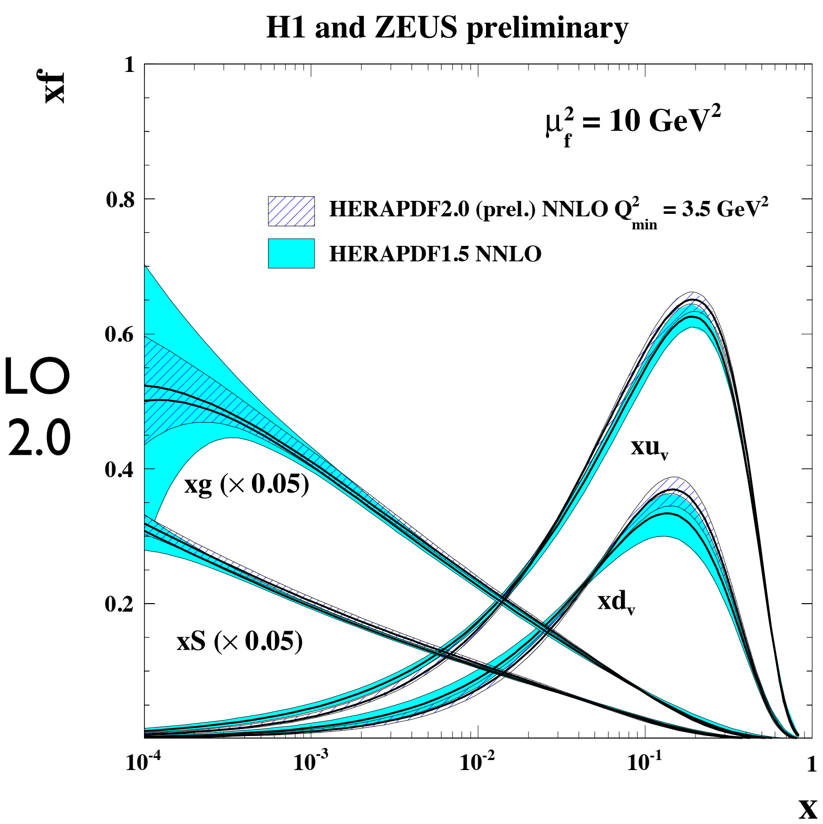
LHeC Machine Parameters

	10^{34}		10^{33}	
10^{34} cm^{-2} s^{-1} Luminosity reach	**PROTONS**	**ELECTRONS**	**PROTONS**	**ELECTRONS**
Beam Energy [GeV]	**7000**	**60**	**7000**	**60**
Luminosity [$10^{33}cm^{-2}s^{-1}$]	**16**	**16**	**1**	**1**
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	**2.5**	**20**	**3.75**	**50**
Beta Funtion $\beta^*_{x,y}$ [m]	**0.05**	**0.10**	**0.1**	**0.12**
rms Beam size $\sigma^*_{x,y}$ [μm]	**4**	**4**	**7**	**7**
rms Beam divergence σ□$^*_{x,y}$ [μrad]	**80**	**40**	**70**	**58**
Beam Current [mA]	**1112**	**25**	**430 (860)**	**6.6**
Bunch Spacing [ns]	**25**	**25**	**25 (50)**	**25 (50)**
Bunch Population	**$2.2*10^{11}$**	**$4*10^{9}$**	**$1.7*10^{11}$**	**($1*10^{9}$) $2*10^{9}$**
Bunch charge [nC]	**35**	**0.64**	**27**	**(0.16) 0.32**

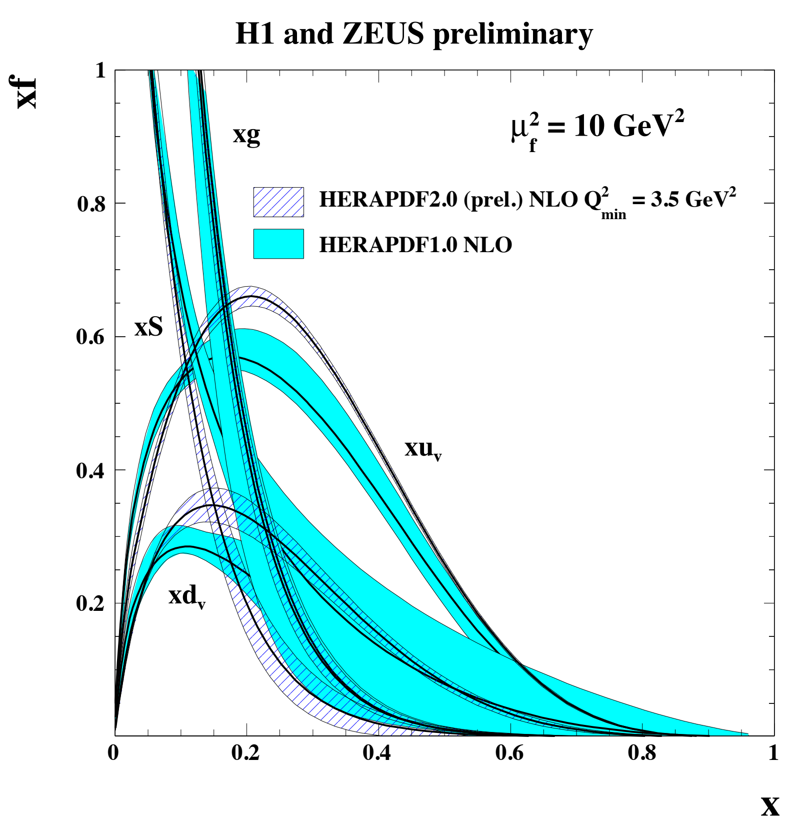
Comparison of HERAPDF 1.5 & 2.0

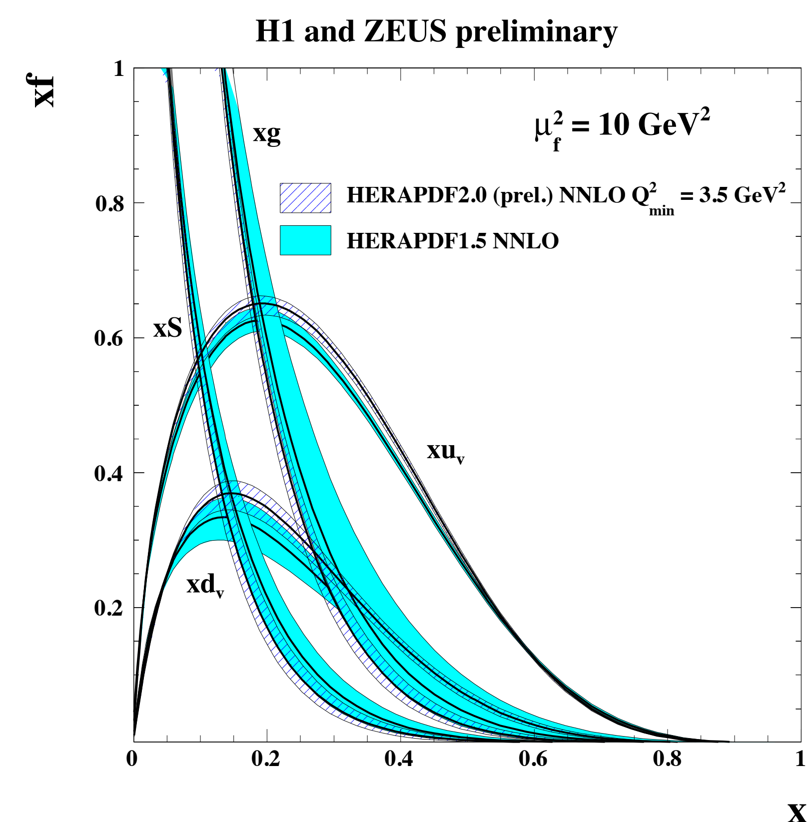


NLO
HERAPDF1.5 vs 2.0

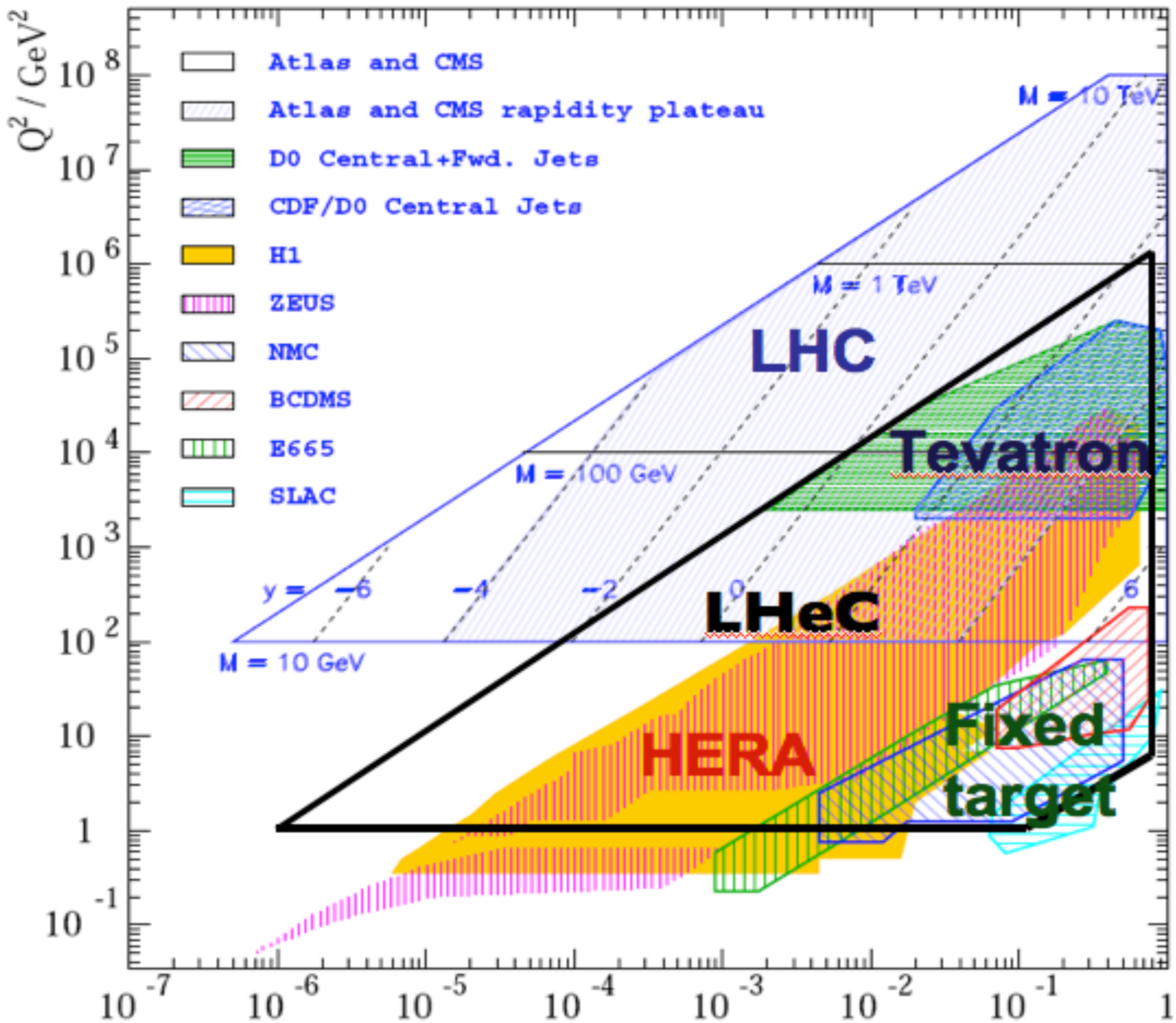


NNLO
HERAPDF1.5 vs 2.0

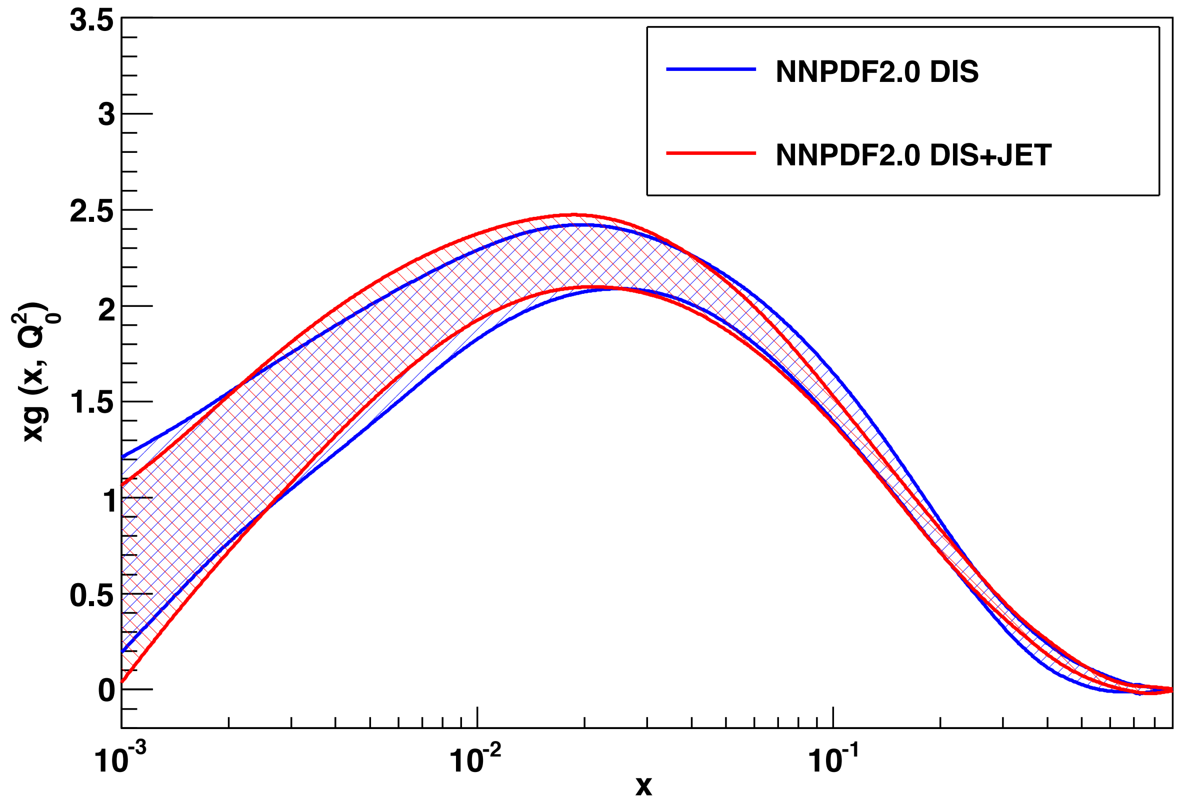


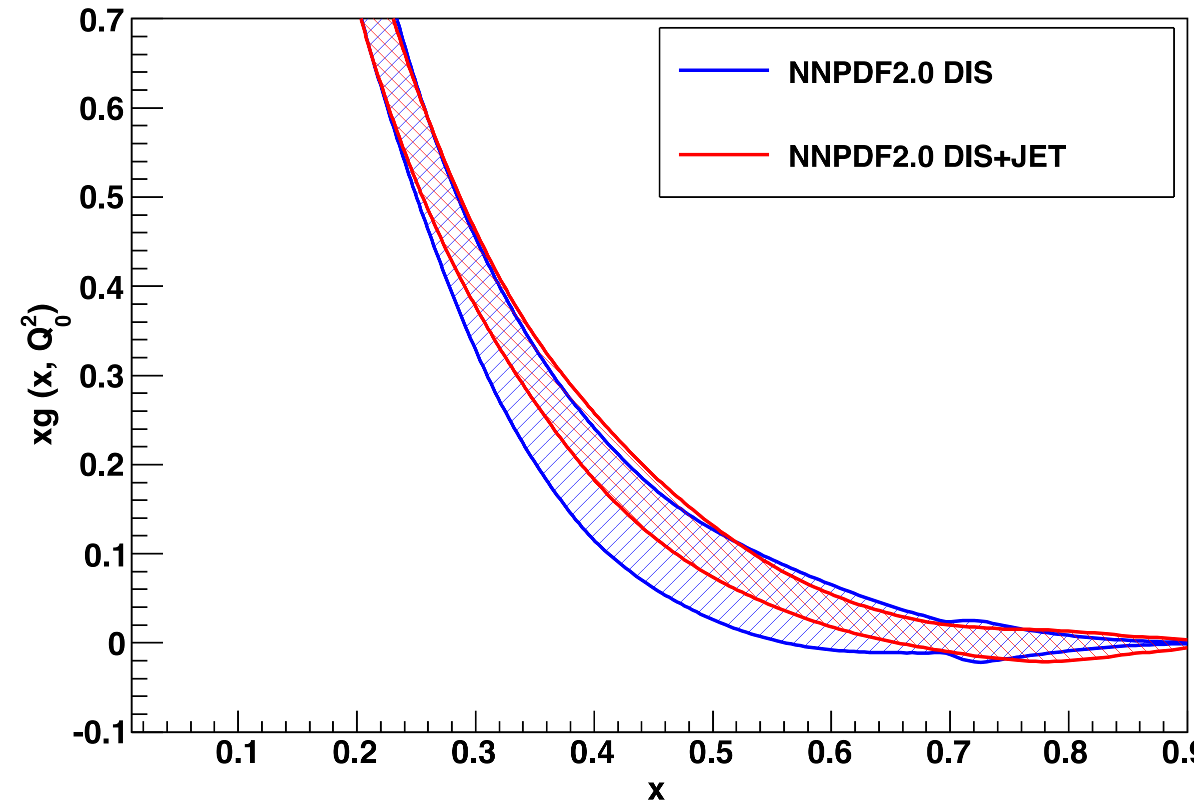


Kinematic Range



Jet Data Constraints





gluon at Q^2 = 2 GeV^2

Tevatron jets consistent with DIS
Test of factorisation:
- compare ep with pp
- gluon contributes at LO but in DIS only in NLO
- pp jets probe higher scales & require pQCD evolution via RGE

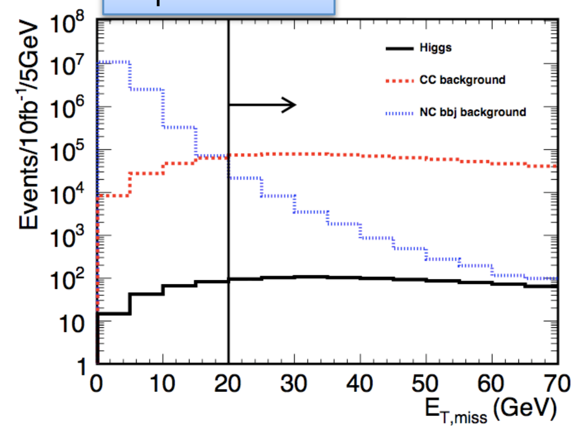
Moderate uncertainty reduction from TeVatron jets
Jet data help constrain α_S

LHeC: $H \to bb$

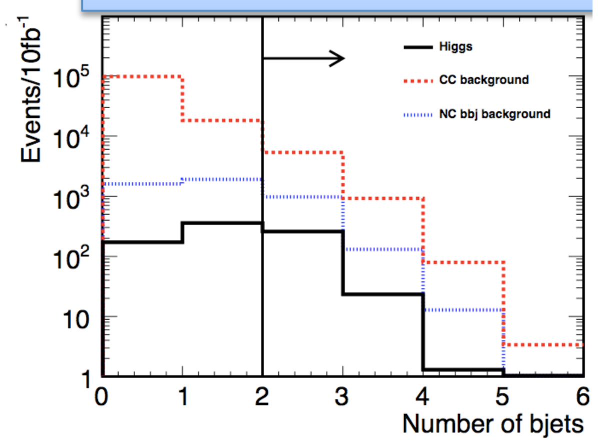
- NC DIS rejection
  - Exclude electron-tagged events
  - $E_{T,miss} > 20$ GeV
  - N_{jet} ($p_T > 20$ GeV) $\geqq 3$
  - $E_{T,total} > 100$ GeV
  - $y_{JB} < 0.9$, $Q^2_{JB} > 400$ GeV^2
- b-tag requirement
  - $N_{b\text{-}jet}$ ($p_T > 20$ GeV) $\geqq 2$
- Higgs invariant mass
  - $90 < M_H < 120$ GeV $\Rightarrow$ 44% of remaining BG is single-top…
- Single top rejection
  - $M_{jjj,top} > 250$ GeV
  - $M_{jj,W} > 130$ GeV

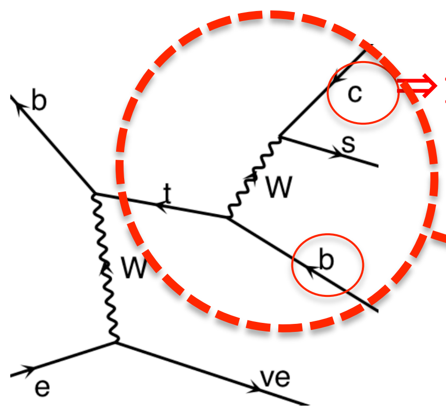
E_T^{miss} cut

$H \to b\bar{b}$
CC BG
NC BG

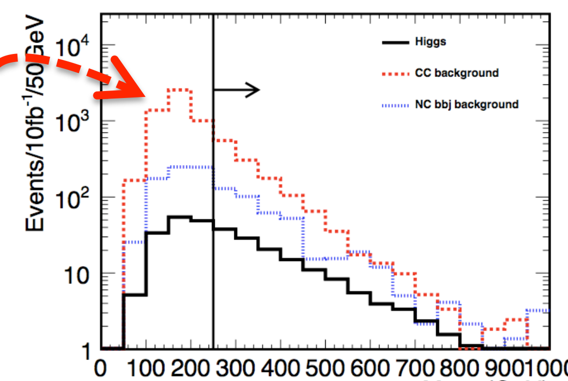


b-tag requirement
Flat efficiency for $|\eta| < 3$ of 60% (c:10%, lq,g:1%)





$\Rightarrow$10% mis-ID

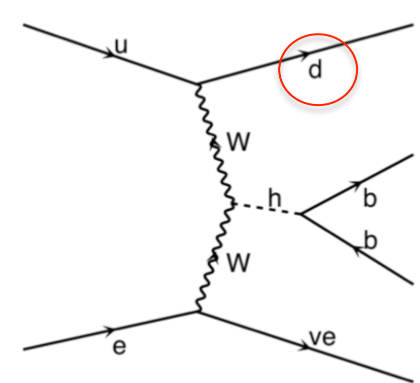


CDR: A Large Hadron Electron Collider at CERN
J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001

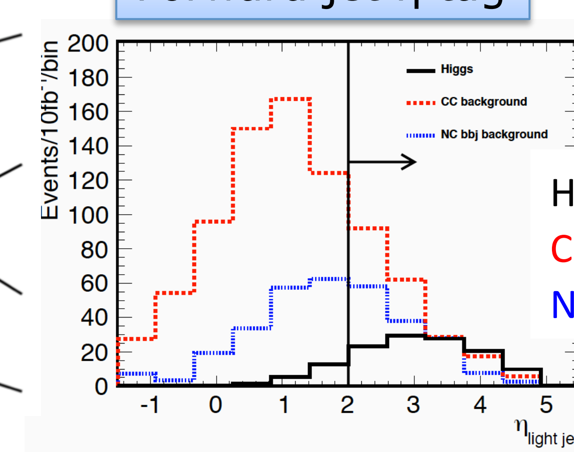
- Forward jet tagging
  - $\eta_{jet} > 2$ (lowest η jet excluding b-tagged jets)

Coordinate:
Fwd: +z-axis along proton beam

$H \to b\bar{b}$ signal



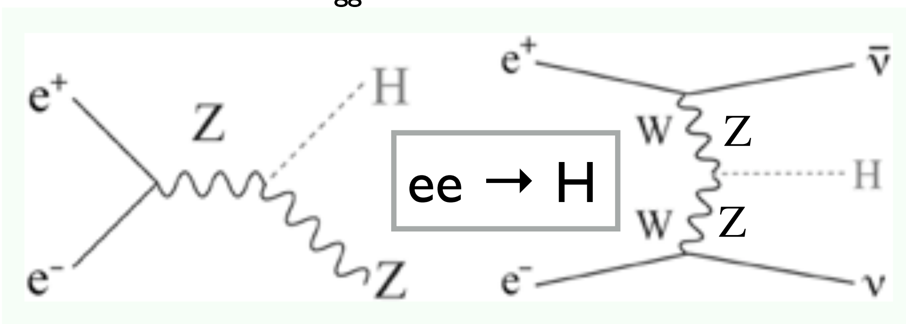
Forward jet η tag



$H \to b\bar{b}$
CC BG
NC BG

- Higgs invariant mass after all selection

σ_{Higgs} in ee ~300 fb



		√s = 1.3 TeV		√s = 3.5 TeV	√s = 250 GeV
Higgs in e^-p		CC - LHeC	NC - LHeC	CC - FHeC	ee
Polarisation		-0.8	-0.8	-0.8	-0.8 / +0.3
Luminosity [ab^{-1}]		1	1	5	1
Cross Section [fb]		196	25	850	300
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	231,000
$H \to c\bar{c}$	0.029	5 700	700	123 000	12,750
$H \to \tau^+\tau^-$	0.063	12 350	1 600	270 000	14,000
$H \to \mu\mu$	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	53,100
$H \to ZZ$	0.0264	5 200	600	110 000	3,000
$H \to \gamma\gamma$	0.00228	450	60	10 000	
$H \to Z\gamma$	0.00154	300	40	6 500	

arXiv:1306.6352

Approximate yields from polarised ee machine at $\mathcal{L} = 10^{34}$ and $\sqrt{s}$ = 250 GeV