The LHeC

Deep Inelastic ep/eA Scattering at the Energy Frontier

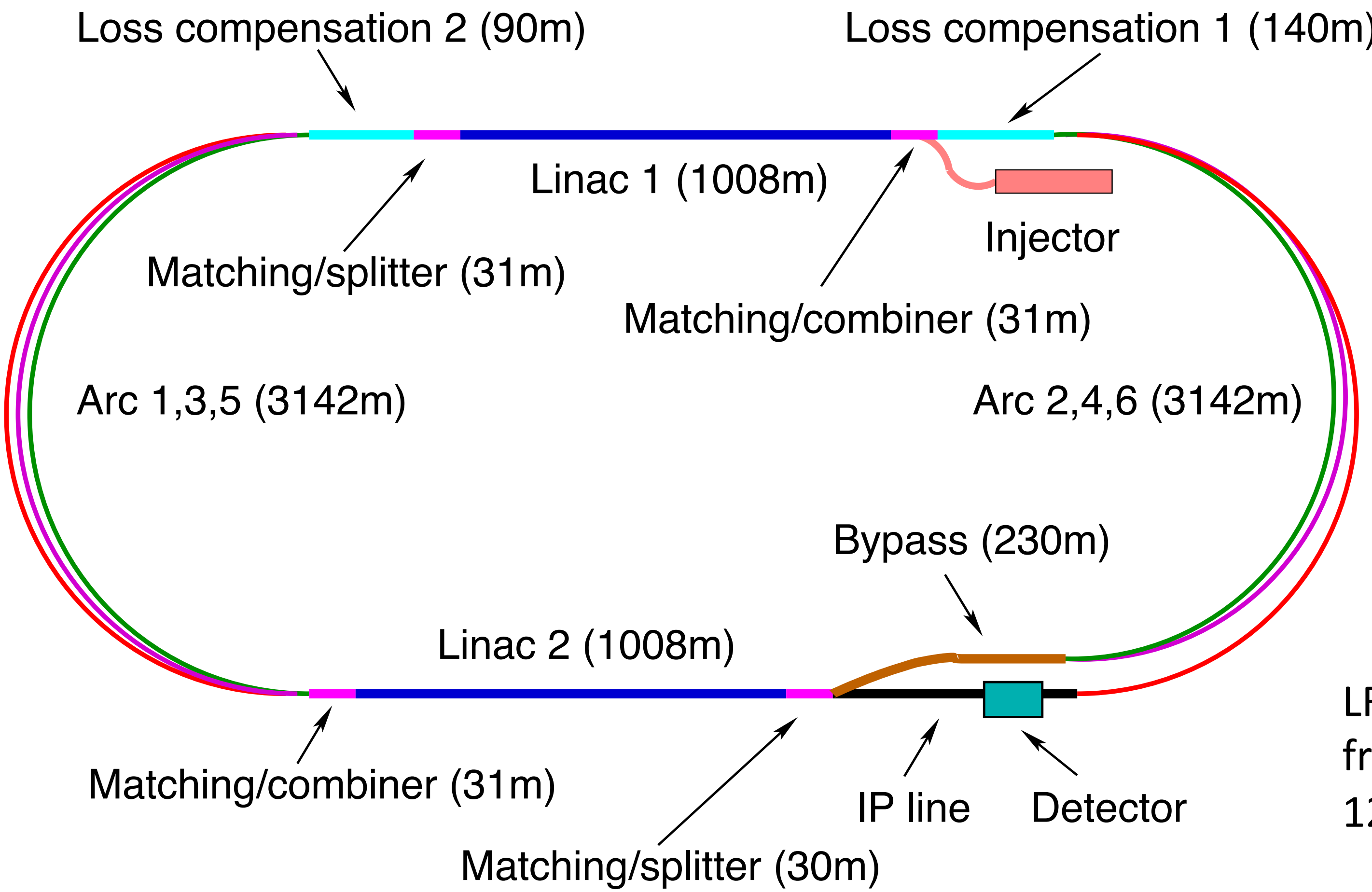
Physics
Accelerator Design
ERL Test Facility Design
FCC-he
Status+Outlook

Max Klein (University of Liverpool and CERN)

lhec.web.cern.ch

ICFA Meeting at Beijing, 29th of October 2014 - for the LHeC Study Group

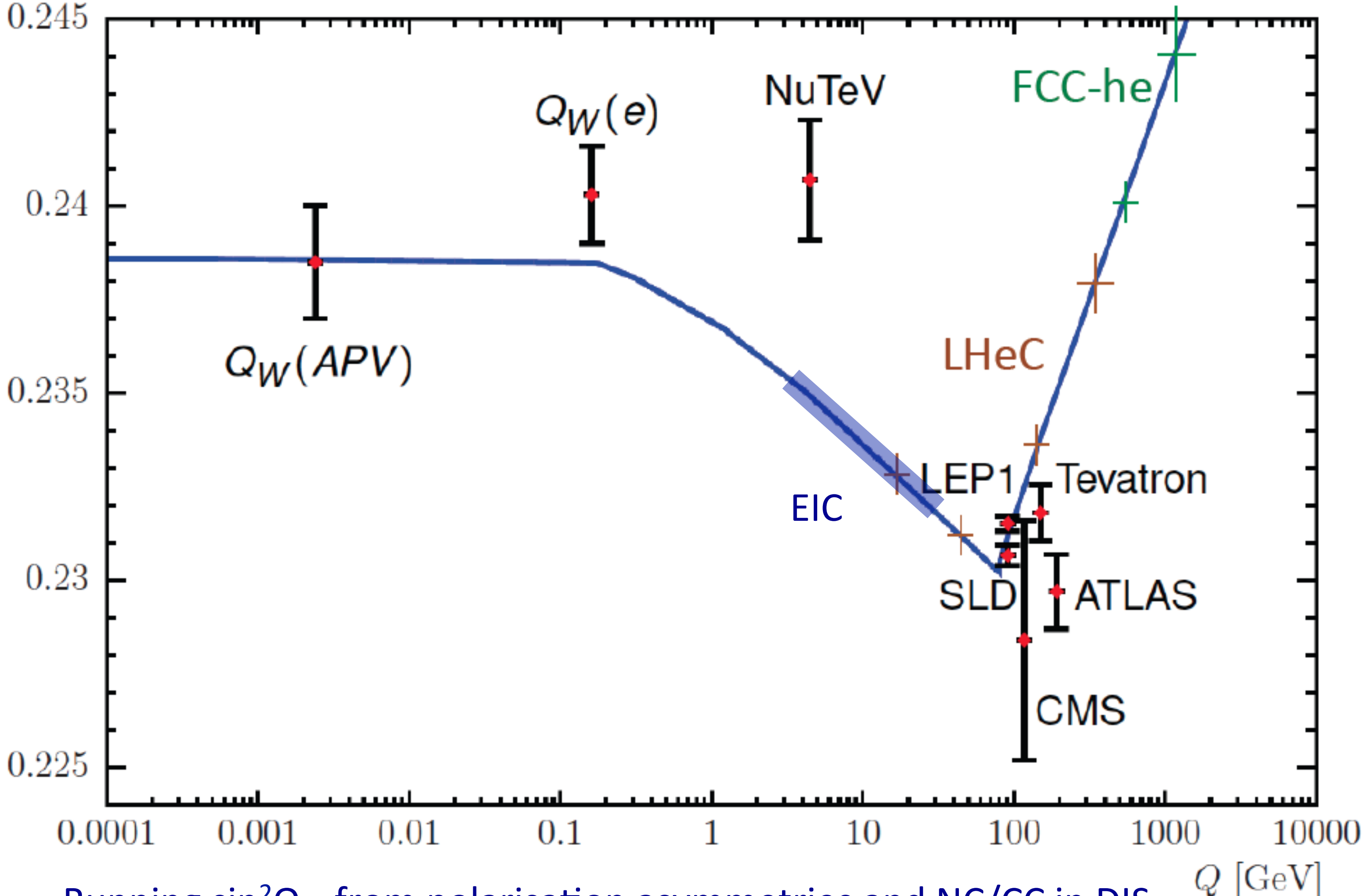
Large Hadron Electron Collider for synchronous ep and pp OP @ LHC



LR option from CDR 1206.2913

60 GeV electron beam energy, L= 10^{33} cm^{-2}s^{-1}, √s=1.3 TeV: Q^2_{max}= 10^6 GeV^2, 10^{-6} < x< 1
Recirculating linac (2 * 1km, 2*60 cavity cryo modules, 3 passes, ERL, < 100MW, 1/3 LHC)

Electroweak ep Physics Beyond the Z



Running $\sin^2\Theta_W$ from polarisation asymmetries and NC/CC in DIS

Low scales from MESA, Jlab and possibly the CERN Testfacility

QCD is the richest part of the Standard Model

Crucial questions+tasks

AdS/CFT
Instantons
Odderons
Non pQCD
QGP
N^kLO
Resummation
Saturation and BFKL
Non-conventional PDFs …

QCD may break .. (Quigg DIS13)

Breaking of Factorisation
Free Quarks
Unconfined Color
New kind of coloured matter
Quark substructure
New symmetry embedding QCD

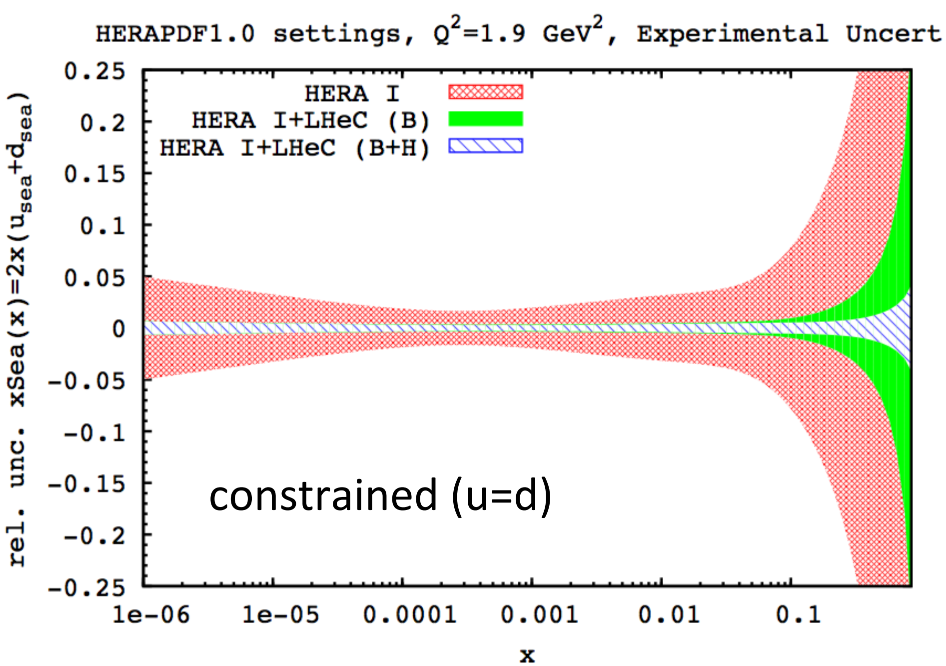
Parton (Quark and Gluon) Distributions

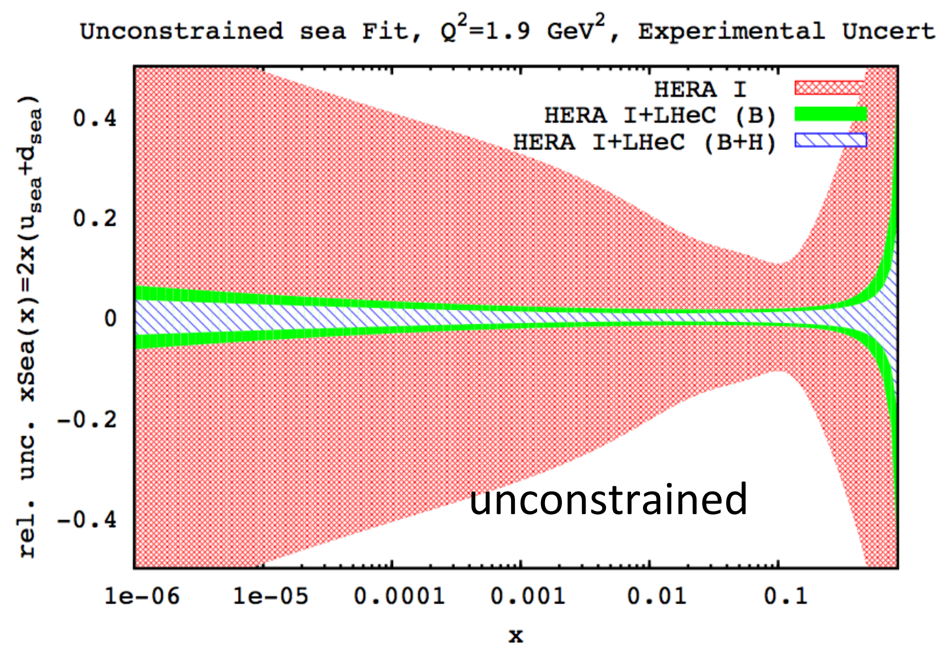
PDF	comment	LHeC
u valence d valence	after 40 years still do no know d/u at high x	CC free of nuclear effects
up sea down sea	not distinguished at HERA	NC and CC
strange	unknown basically (neutrinos, W,Z)	Ws → c : CC at high Q^2
charm	HERA to ~5%, threshold, intrinsic (sea=anti??)	NC
beauty	HERA ~20%. bb→ A ? HQ treatment in QCD	NC
top	takes % of p momentum	CC at LHeC
gluon	low x saturation?, medium x Higgs, high x BSM	df2/dlnQ^2

LHeC: extended kinematic range: low x, high x, high Q^2 → the ONLY way to unfold all PDFs
ep/eA further determine neutron, photon, pomeron, nuclear densities – HUGE potential

Resolving Partonic Structure free of symmetry assumptions

- Usual assumptions for light quark decomposition at low x may not necessary hold.
- **Relaxing the assumption at low x that u=d , we observe that uncertainties escalate**:





- One can see that for HERA data, if we relax the low x constraint on u and d,the errors are increased tremendously!
- However, when adding the LHeC simulated data, we observe that uncertainties are visibly improved even without this assumption.
- Further important cross check comes from the deuteron measurements, with tagged spectator and controlling shadowing with diffraction…

Constraints on PDFs from LHC – Strange Quark

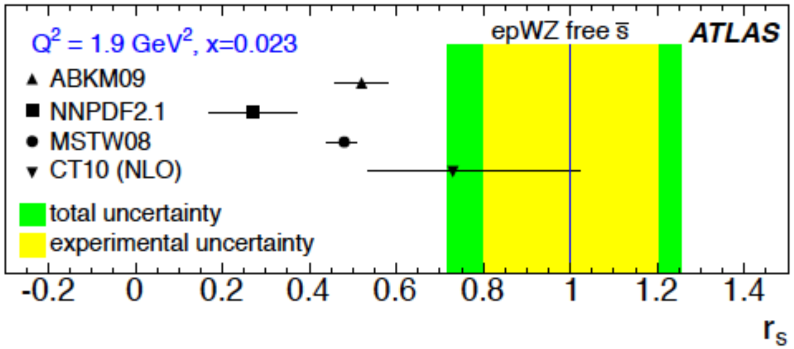


FIG. 2. Predictions for the ratio $r_s = 0.5(s + \bar{s})/\bar{d}$, at $Q^2 = 1.9\,\mathrm{GeV}^2$, $x = 0.023$. Points: global fit results using the PDF uncertainties as quoted; bands: this analysis; inner band, experimental uncertainty; outer band, total uncertainty.

$$r_s = 0.5(s + \bar{s})/\bar{d}$$

$$r_s = 1.00 \pm 0.20_{\mathrm{exp}} \pm 0.07_{\mathrm{mod}}{}^{+0.10}_{-0.15}{}_{\mathrm{par}}{}^{+0.06}_{-0.07}{}_{\alpha_S} \pm 0.08_{\mathrm{th}}.$$

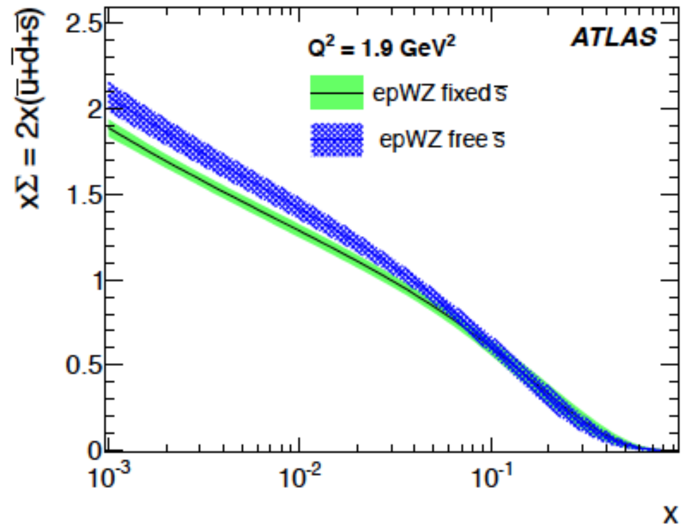
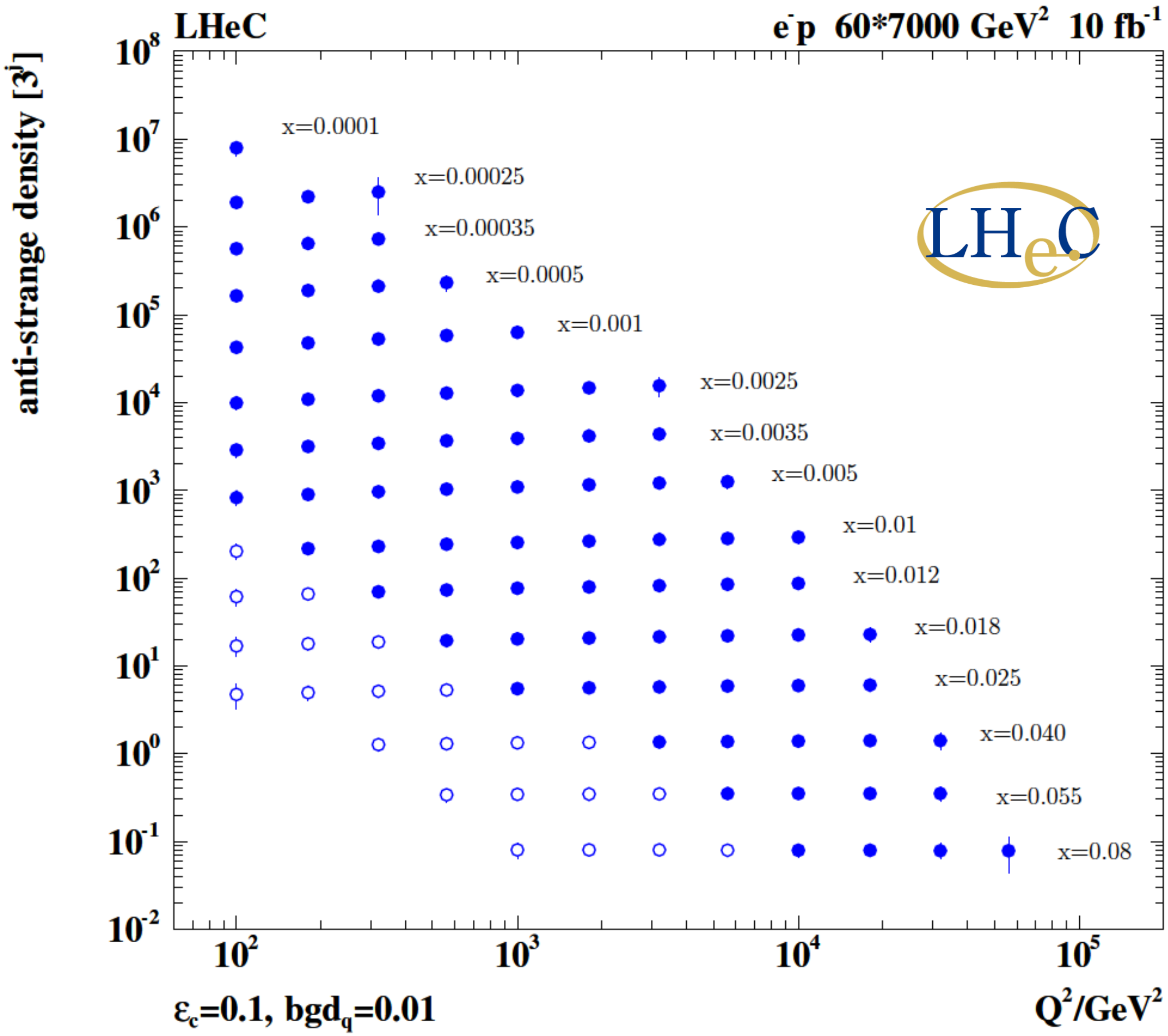


FIG. 3. Distribution of the light sea quarks, $x\Sigma = 2x(\bar{u} + \bar{d} + \bar{s})$, in the NNLO analysis of HERA and ATLAS data with a fixed fraction of strangeness (lower, green curve) and with a fitted fraction of about unity (upper blue curve). The bands represent the experimental uncertainties.

LHC W,Z data (ATLAS, 2010 data, arXiv:1203.4051 suggest **flavour symmetric light sea ?**
Due to 4U+D constraint from HERA an enlarged strange must enhance the light sea

Much disputed in PDF fits relying on neutrino data. Better W,Z data to come. Also Ws-c

Strange Quark Distribution from LHeC



High luminosity

High Q^2

Small beam spot

Modern Silicon

NO pile-up..

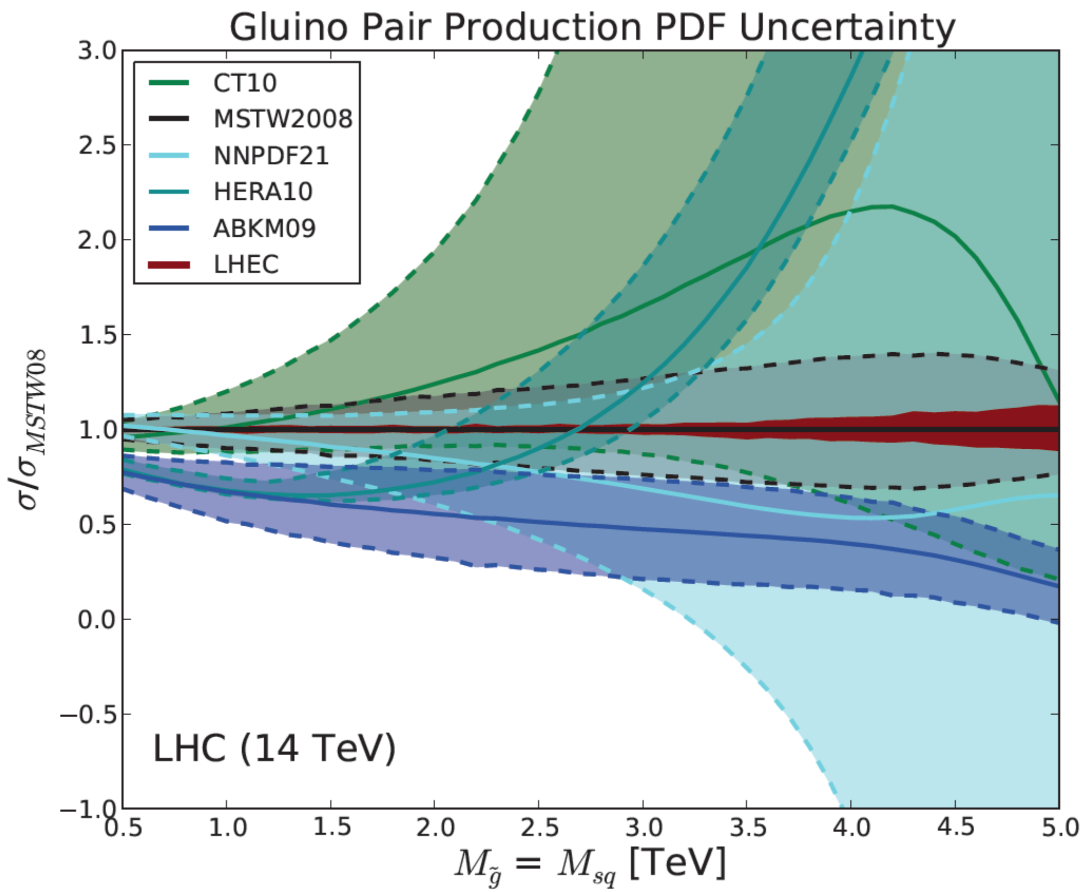
→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

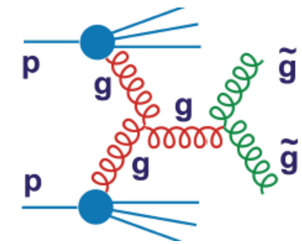
$x = 10^{-4}$ .. 0.05

$Q^2 = 100 – 10^5$ GeV^2

Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter

Gluon-Gluon Luminosity with LHeC



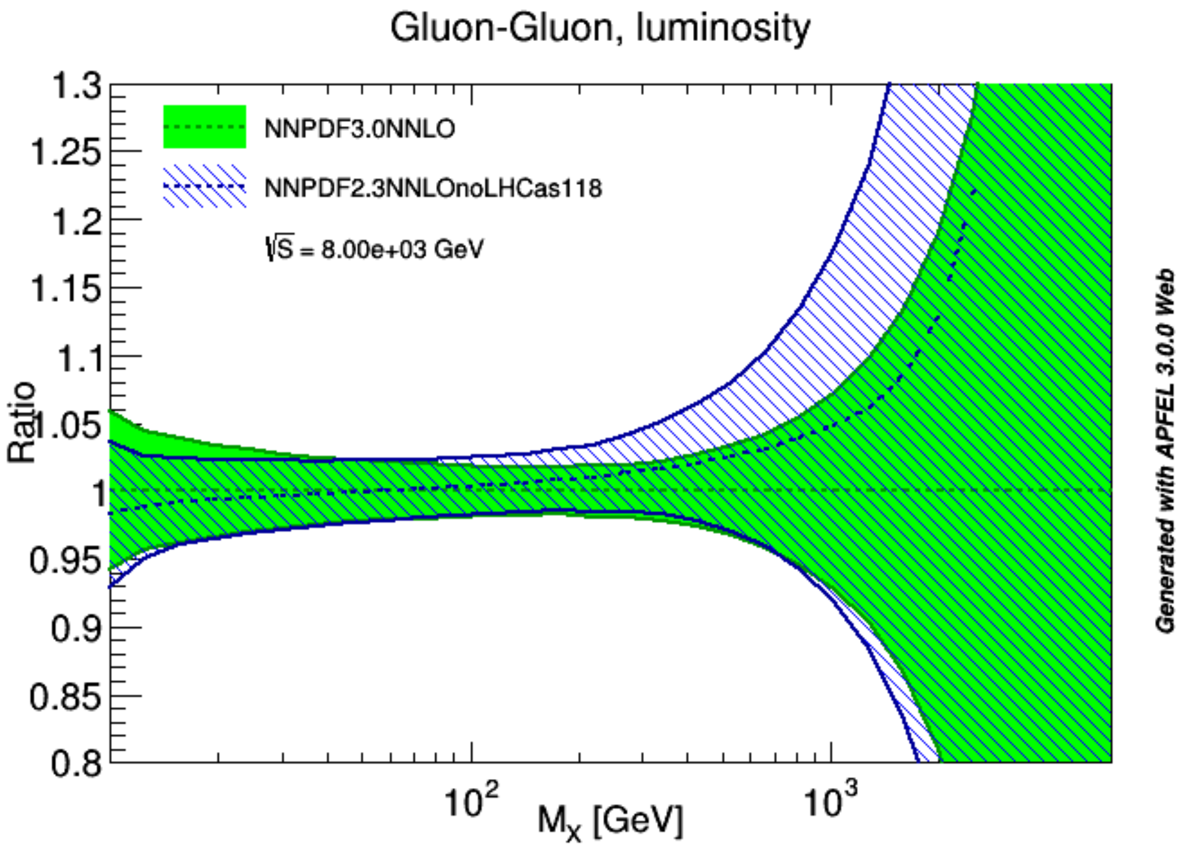


LHeC Note 2012-005
arXiv:1211.5102

LHeC PDFset on LHAPDF
V.Radescu, MK

Full detector simulation (CDR of LHeC) reveals high precision on gluon from LHeC alone.
With the LHC moving to high luminosity we conquer the few TeV mass region and need to know the partons at high x in order to take advantage of the luminosity upgrade.
[M.D'Onofrio yesterday]

Sensitivity of PDFs to LHC - Gluon



No LHC
With LHC
NNPDF3.0
(Oct. 2014)
S.Forte et al

Large uncertainties at high mass

- yy induced proc.s
- k factors
- eweak corrections

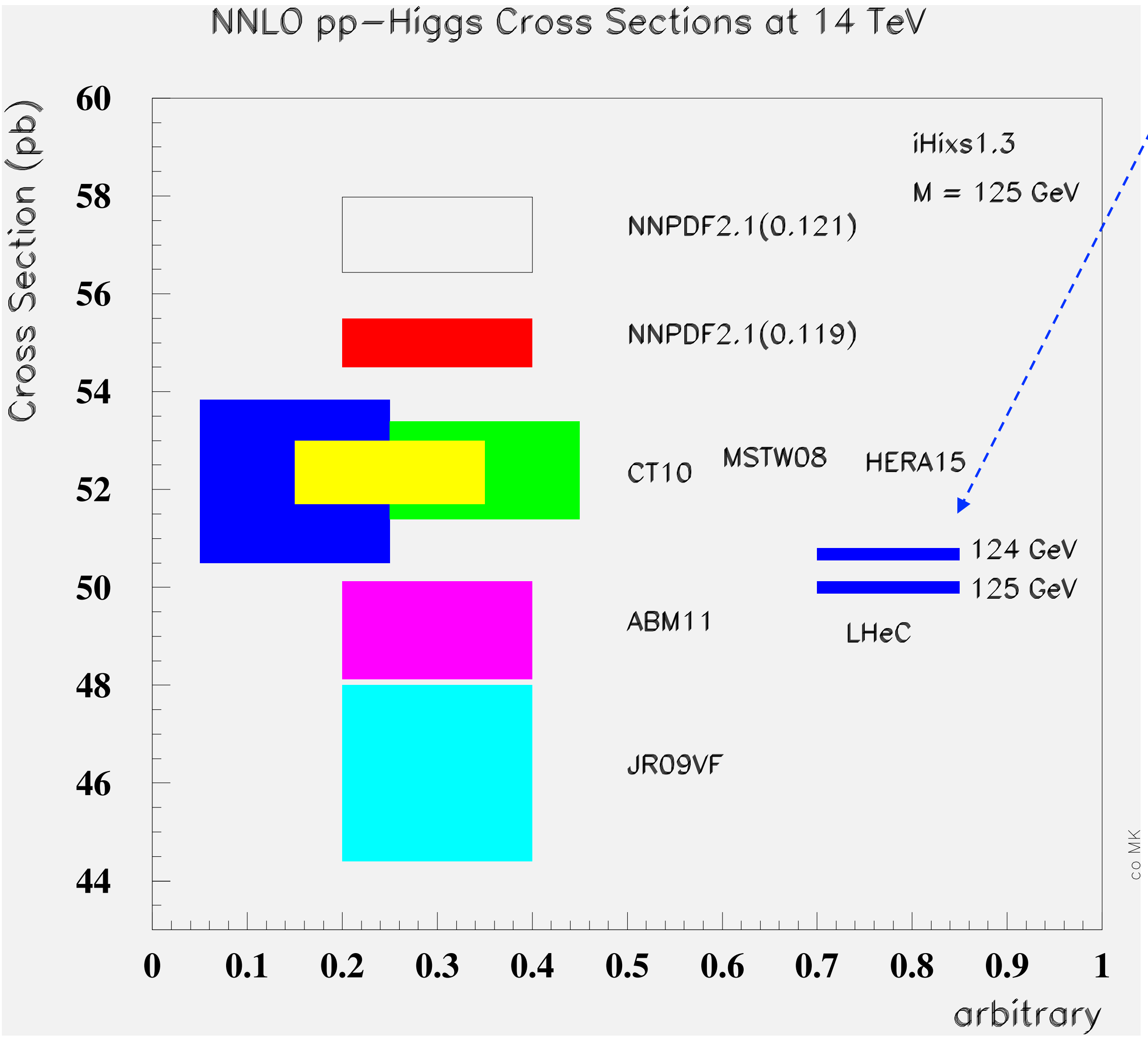
...

U.Klein LesHouches
arXiv:1405.1063

LHC: W+c, P_T(W), top, double differential W,Z data + previous input to NNPDF

New physics appearing as contact interaction would be confused with PDFs
Long range onset effects of new resonances: new physics or PDFs ??
High luminosity, high mass searches requires independent, precise PDFs ep--pp

Precision PDFs for Higgs at the LHC



O.Brüning and M.K. arXiv:1305.2090, MPLA 2013

LHeC:

Exp uncertainty of predicted H cross section is 0.25% (sys+sta), using LHeC only.

Leads to H mass sensitivity.

Strong coupling underlying parameter (0.005 → 10%). LHeC: 0.0002 !

Needs N^{3}LO

HQ treatment important …

Strong Coupling Constant

α_s least known of coupling constants

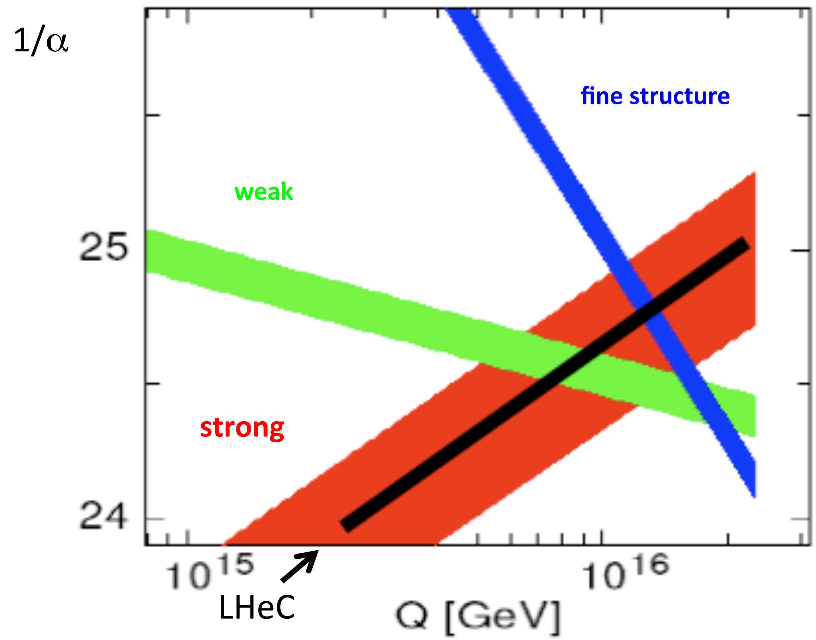
Grand Unification predictions suffer from $\delta\alpha_s$

Is DIS lower than world average (?)

LHeC: per mille - indep. of BCDMS.

Challenge to experiment and to h.o. QCD →
A genuine DIS research programme rather than one outstanding measurement only.

More or as accurate as lattice QCD
(cf Les Houches 2013)

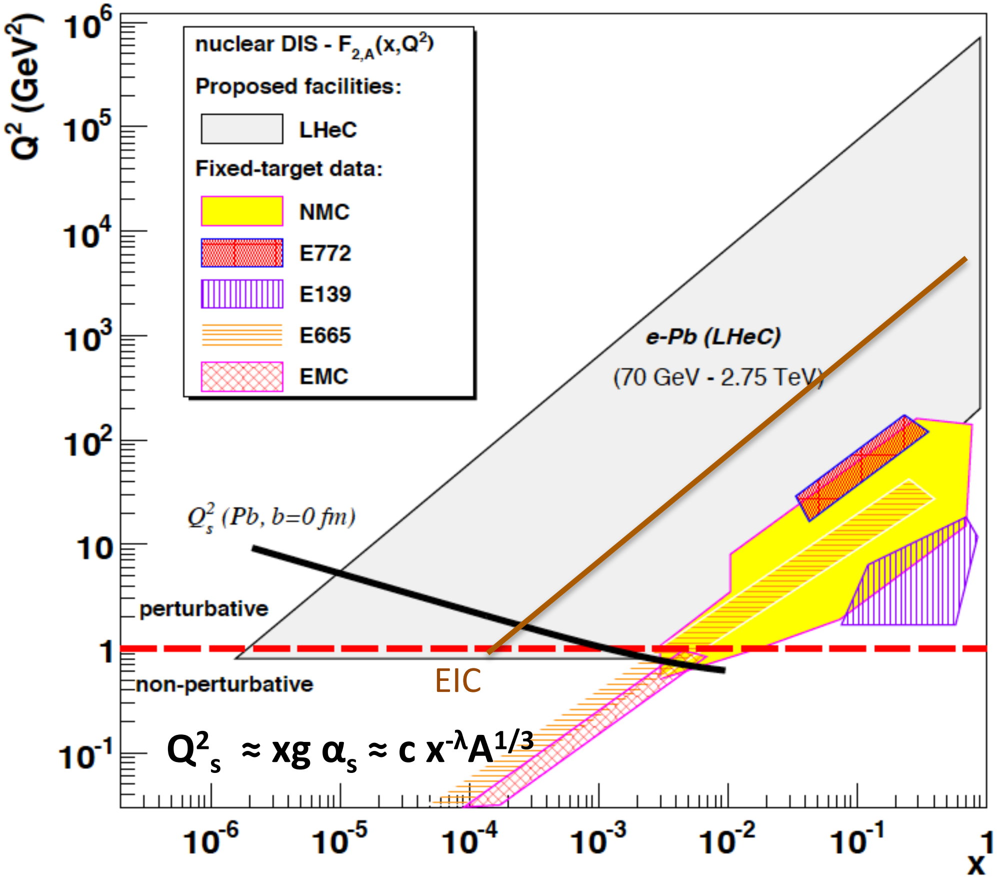


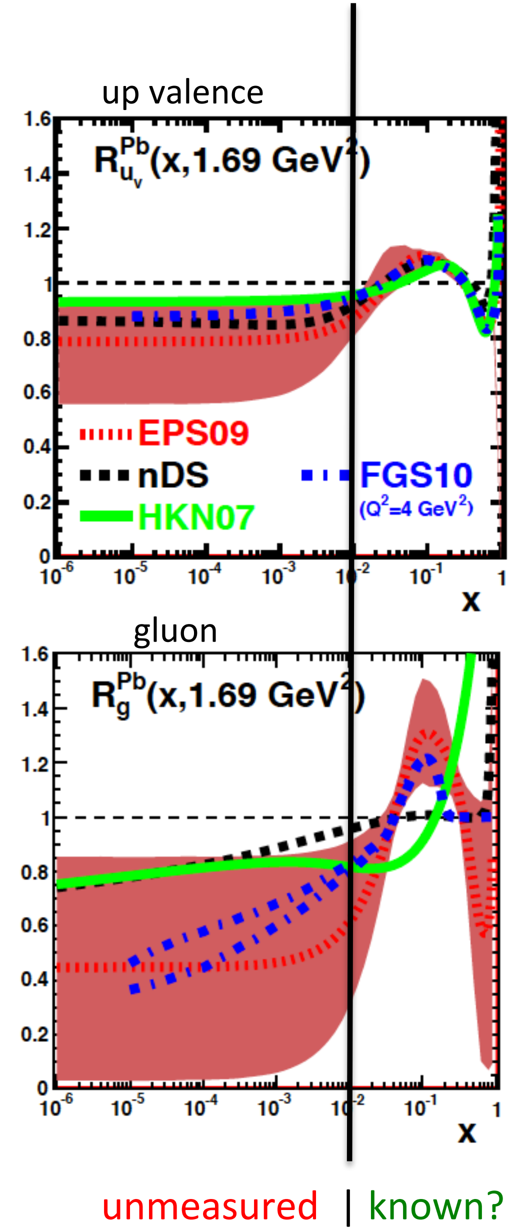
case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 >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

DATA	exp. error on α_s
NC e+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=(1)**
(1) $\gamma_h > 5°$	0.36% :=(2)
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%

Two independent QCD analyses using LHeC+HERA/BCDMS

LHeC as an Electron Ion Collider





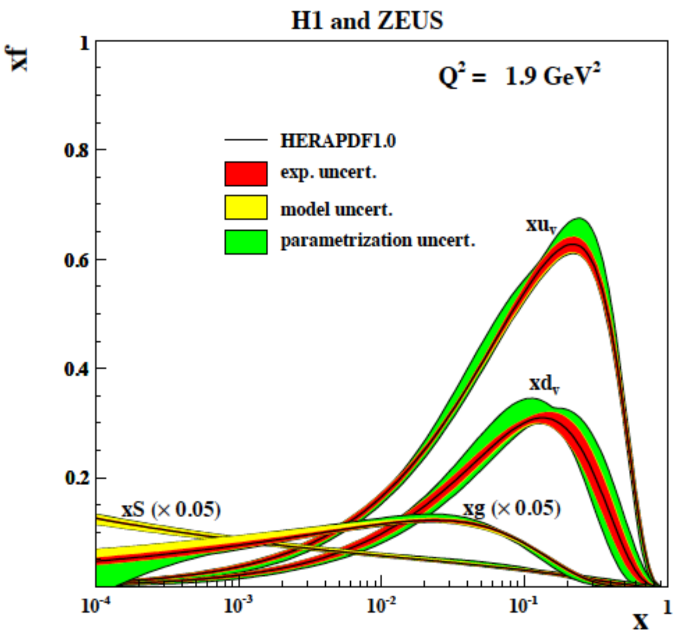
3-4 orders of magnitude extension of lA kinematic range
→ LHeC has huge discovery potential for new HI physics
will put nPDFs on completely new ground - Deuterons

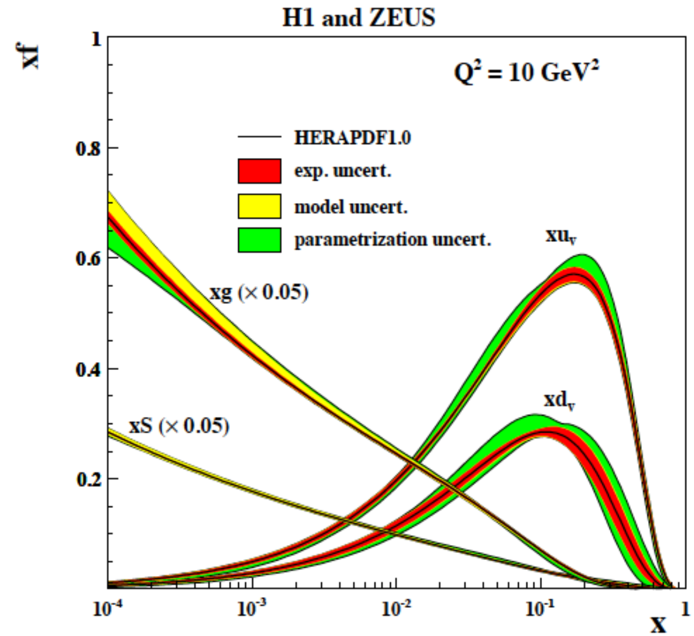
LHeC is part of NuPECCs long range plan since 2010

Saturation

of the gluon density at low x

HERAPDF1.0 arXiv:0911.0884



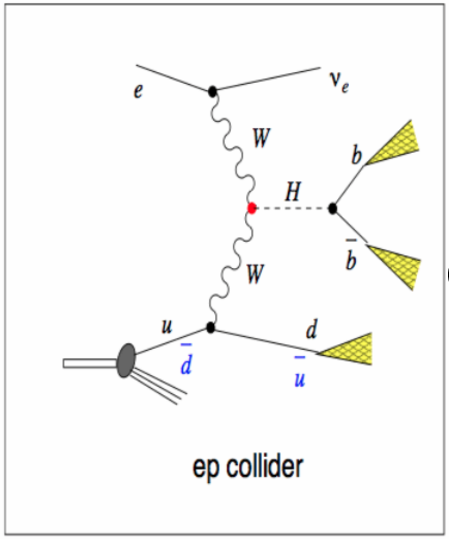


At small x the gluon density is large and it should be damped (saturate) due to non-linear gg interactions, and the (linear) DGLAP equations should be replaced by "BFKL". This is **crucial for QCD, for FCC rates, for UHE neutrino physics and may affect SUSY (Lipatov et al)**

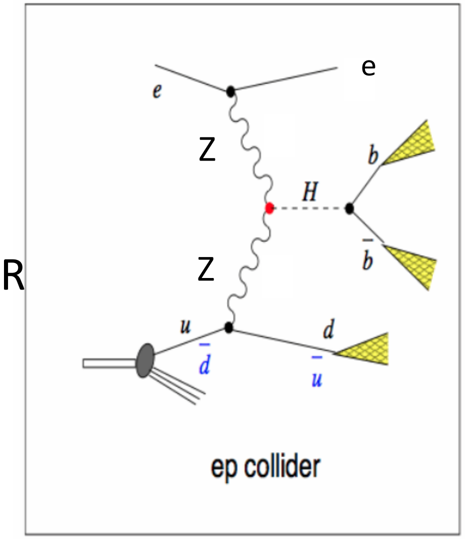
This has NOT been seen at HERA. $xg(x,Q^2)$ is very small at small Q^2 and x and any saturation effect to be established must be observed for $Q^2=O(10)\mathrm{GeV}^2$. It therefore can hardly be seen at EIC's - the ep/A machines with energies much lower than HERA - as $A^{1/3}$ won't help for xg ~0.

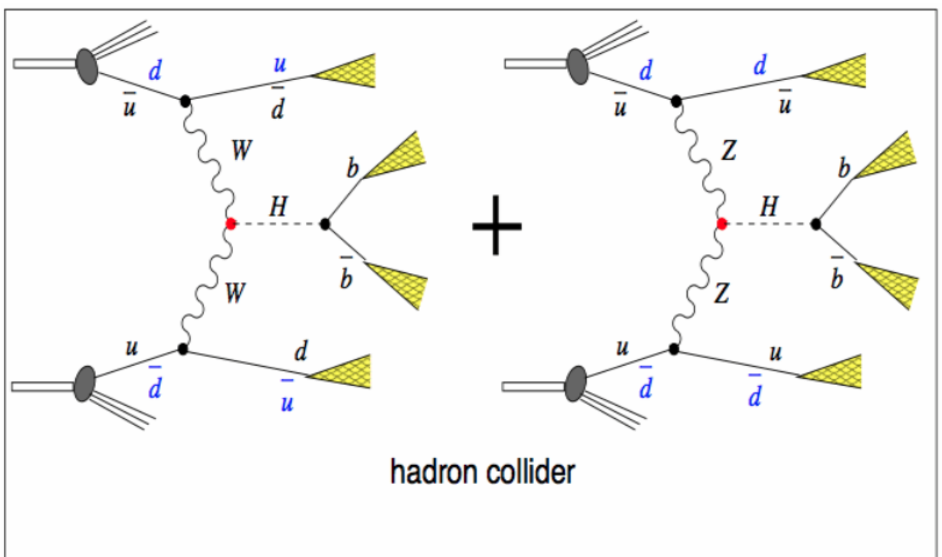
Saturation must be demonstrated in ep and eA to disentangle gg and nuclear effects → LHeC/FCC

VBF Higgs Production at the LH(e)C



OR





Higgs production in ep comes uniquely from either CC or NC

Cross section at LHeC ~200fb (about as at the e^+e^- colliders).

Pile-up in ep at 10^{34} is 0.1, 25ns

Clean(er) bb final state, S/B ~ 1

e-h Cross Calibration → Precision

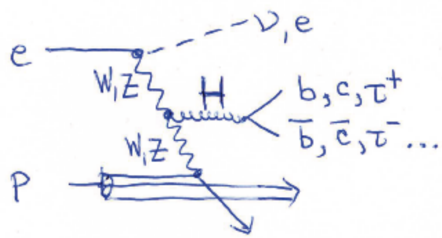
Higgs production in pp comes predominantly from gg→ H

VBFC cross section about 200fb (about as at the LHeC).

Pile-up in pp at 5 10^{34} is 150, 25ns

S/B very small for bb

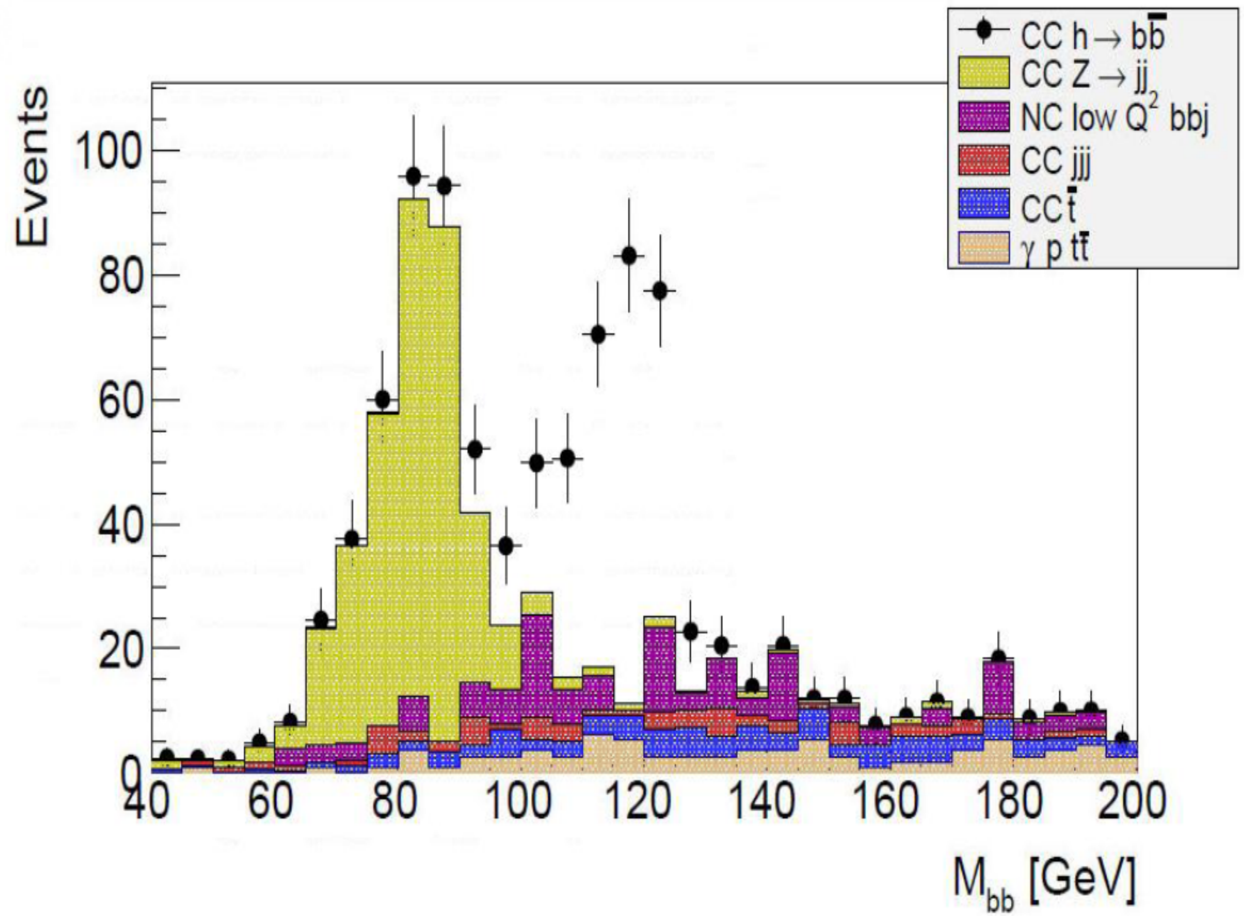
Higgs in ep



Simulation of H→ bb Measurement at the LHeC, 100fb^{-1}

ep→ vH(bb)X
charged currents
σBR~120 fb
μ=0.1
S/B ~1-2
Cut based only

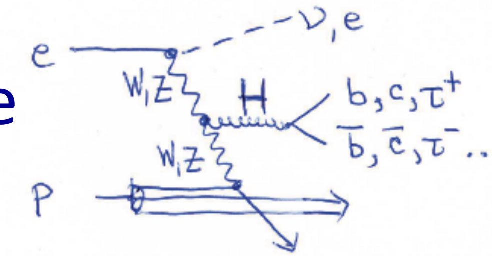
[LHC: VH - BDT's
σ(VH) ~ 130fb 8 TeV
arXiv:1409.6212]



LHeC Higgs Group U.Klein et al.

This reconstructs 60% of H in ep with very comfortable S/B ~1 , in CC and NC
→ Enables BSM Higgs (tensor structure of HVV, CP, dark H?) , QCD(H)
→ O(1)% precision on H-bb couplings with small thy uncertainty. H-cc imminent

Higgs Physics in DIS 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

Higgs Parameter List "H-LHeC"

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Function $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma'_{x,y}$ [μrad]	80	40
Beam Current [mA]	1112	25
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^9$
Bunch charge [nC]	35	0.64

HL-LHC proton beam parameters

1000 times HERA Luminosity and 4 times cms Energy

Next Steps

Physics in its Relation to the LHC Programme

Verification of 10^{34} Luminosity in synchronous ep-pp Operation

Further Design of the Interaction Region (SC Magnets, syn.radiation)

Detector Optimisation (Software, IR, Fwd Tracking, Installation Sequence)

Energy-Cost Balance (depends on RUN 2 of the LHC)

Design of ERL Test Facility (multi-pass high current SCRF)

…

lhec.web.cern.ch

Areas of Study Post-CDR *)

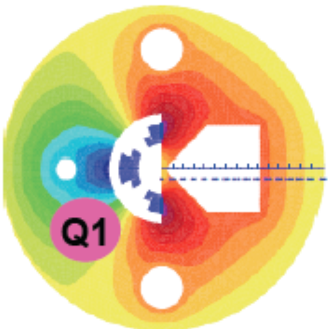
More realistic with dedicated or new tools and evaluation of high luminosity prospect

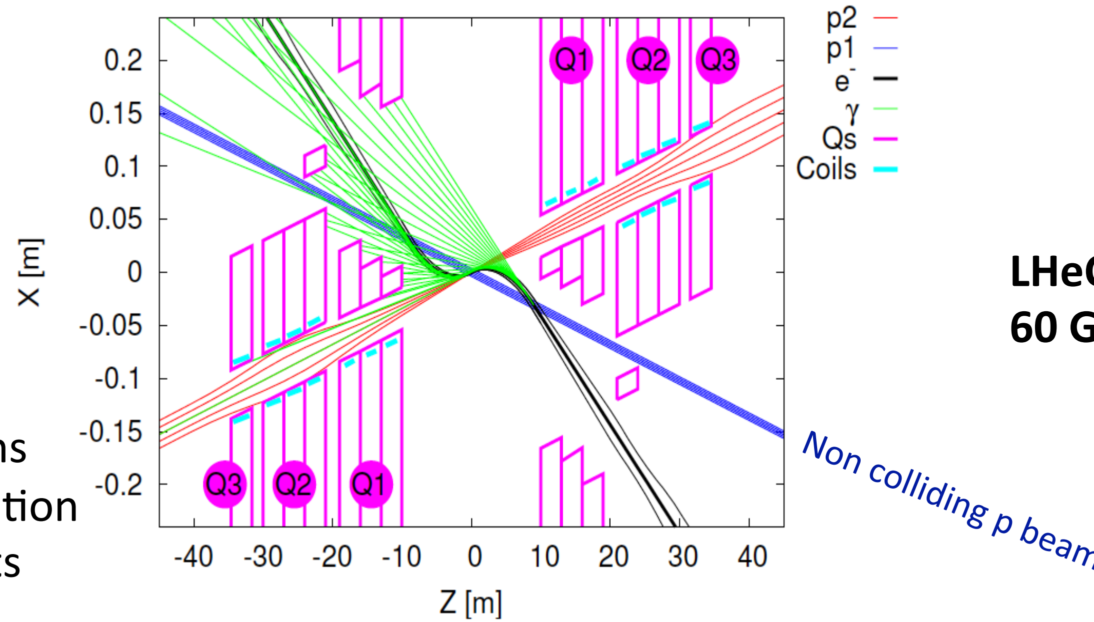
Choice of RF Frequency – 802 MHz
Optimisation of IR Design [L*(e) < L*(p), inner triplet half? quad…]
Integration of p optics into HL-LHC
Integration of e optics into HL-LHC
Beam-beam effects (phase space deformation)
Multi-bunch beam break up
Wakefield effects on multi-bunch instability at IP
Emittance growth
Coherent synchrotron radiation
Fast beam-ion instability (1/3 gap compensated by 1.3 from pinch effect)
Arc optics FODO vs FMC (flexible momentum compaction)
Lattice design
Spreader and combiner
Civil engineering
…

So far no showstopper found for O(10^{34})$cm^{-2}\,s^{-1}$: it requires further serious study and the development of SCRF within a Testfacility

*) Recent presentations by A.Bogacz, O.Bruening, E.Cruz, E.Jensen, D.Schulte, A.Valloni – see Webpage
Work by E.Cruz, M.Korostelev, E.Nissen, J.Osborne, D.Pellegrini, A.Letina, A.Milanese, A.Valloni and others

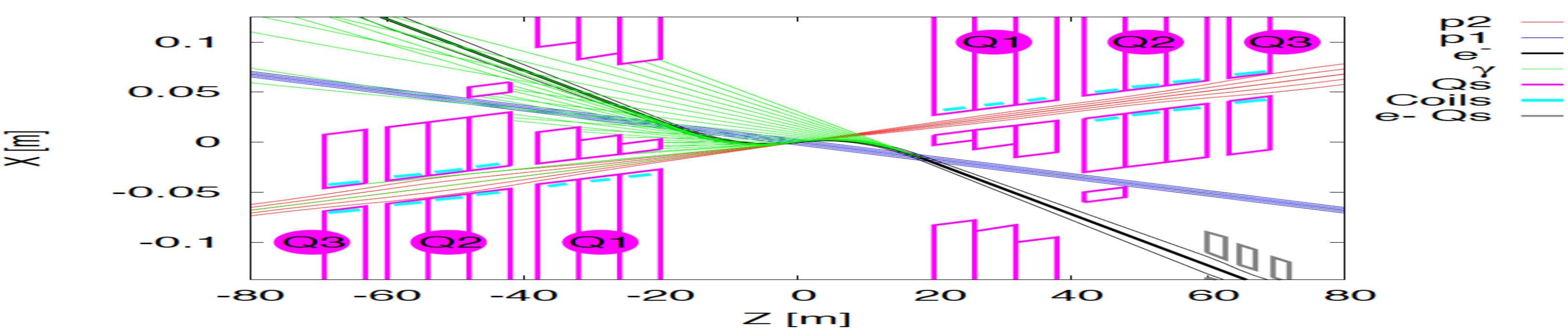
Interaction Regions for ep with Synchronous pp Operation





LHeC (CDR)
60 GeV * 7 TeV

Likely one IR.
Matching e and p beams
Limit synchrotron radiation
Design of inner magnets
Beam-beam effects ….

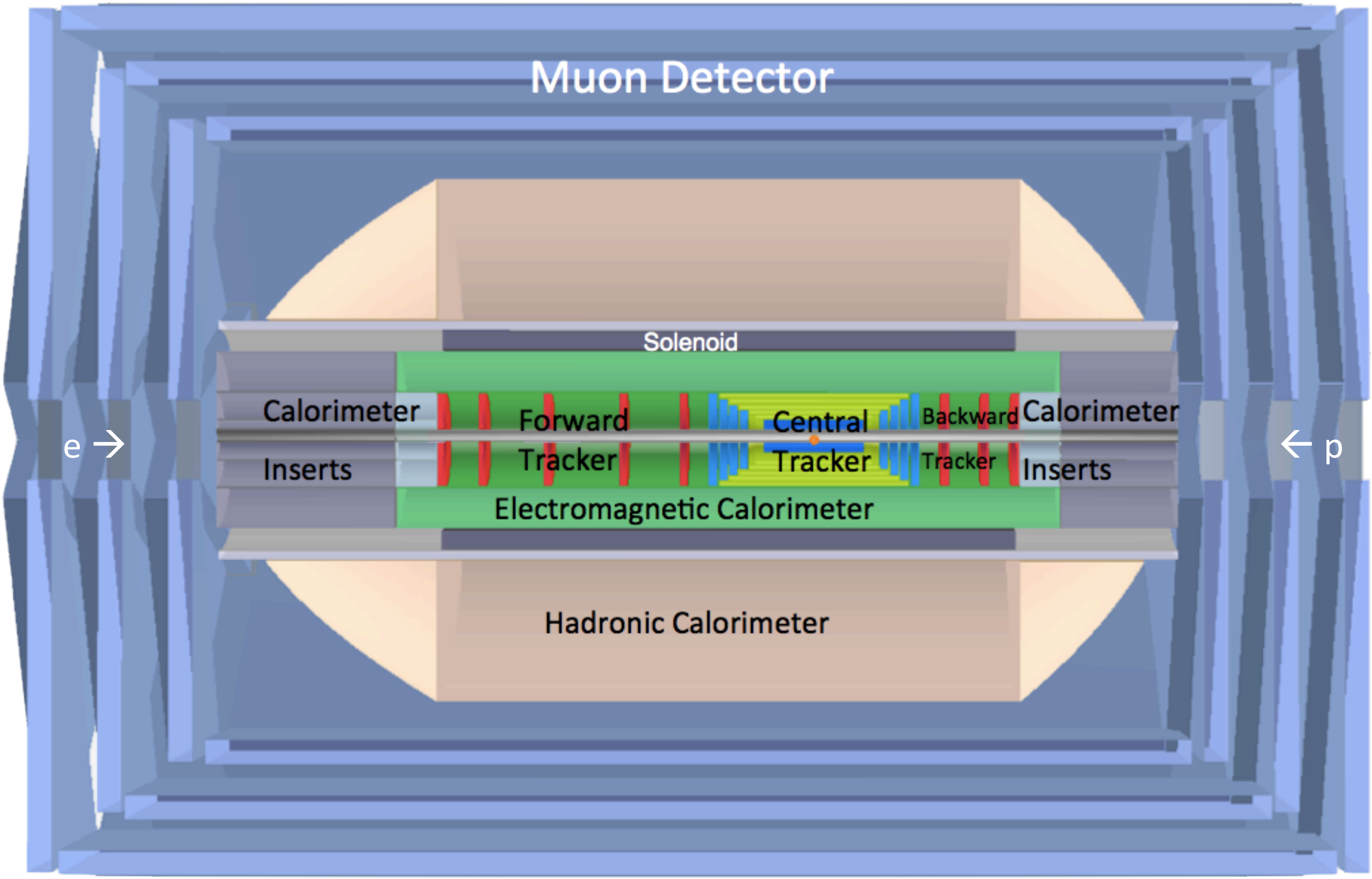


Tentative: ε_p=2µm, β*=20cm → σ_p=3µm ≈σ_e matched! ε_e=5µm ..

FCC-he (ERL)
60 GeV * 50 TeV

Rogelio Tomas, Max Klein, ICHEP14

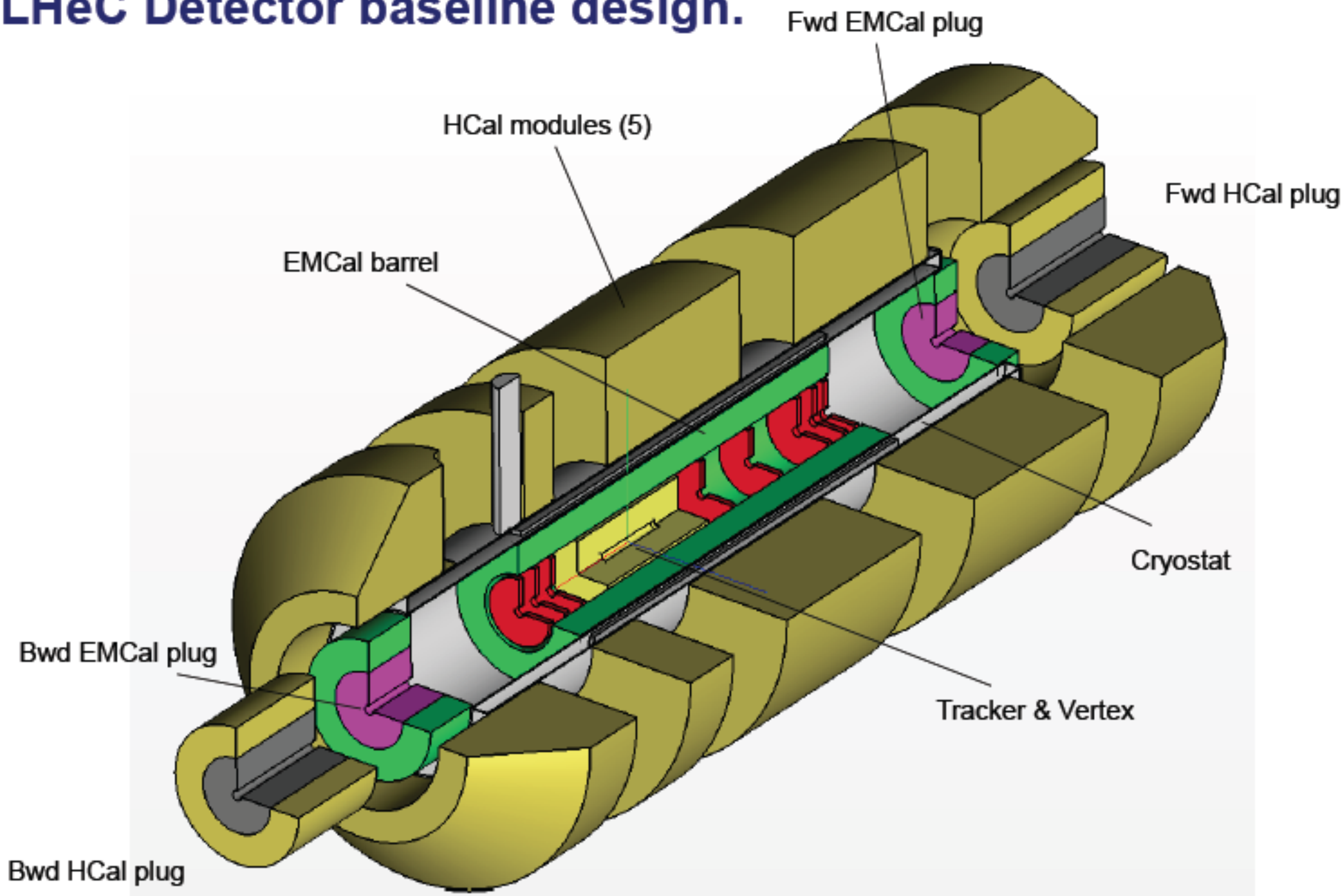
LHeC Detector Overview



Detector option 1 for LR and full acceptance coverage

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)

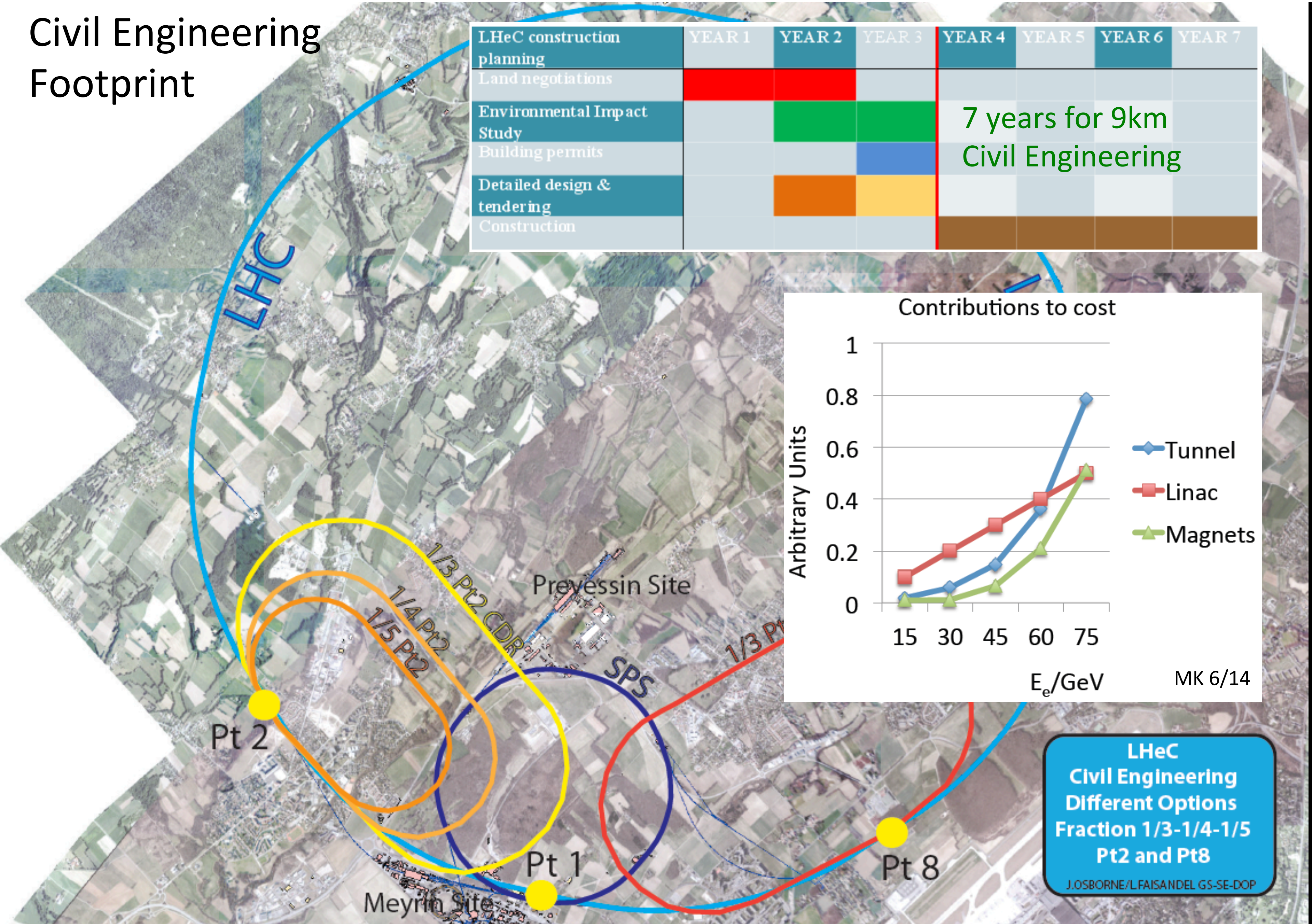
LHeC Detector baseline design.



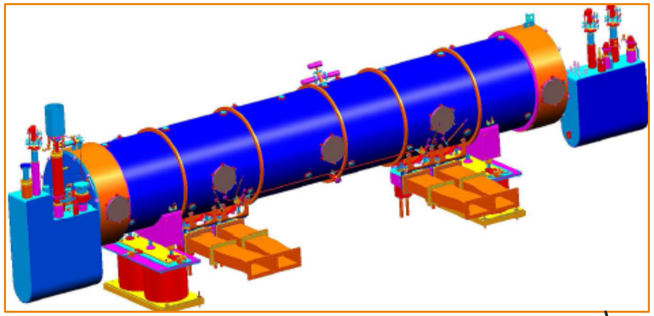
Civil Engineering Footprint

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



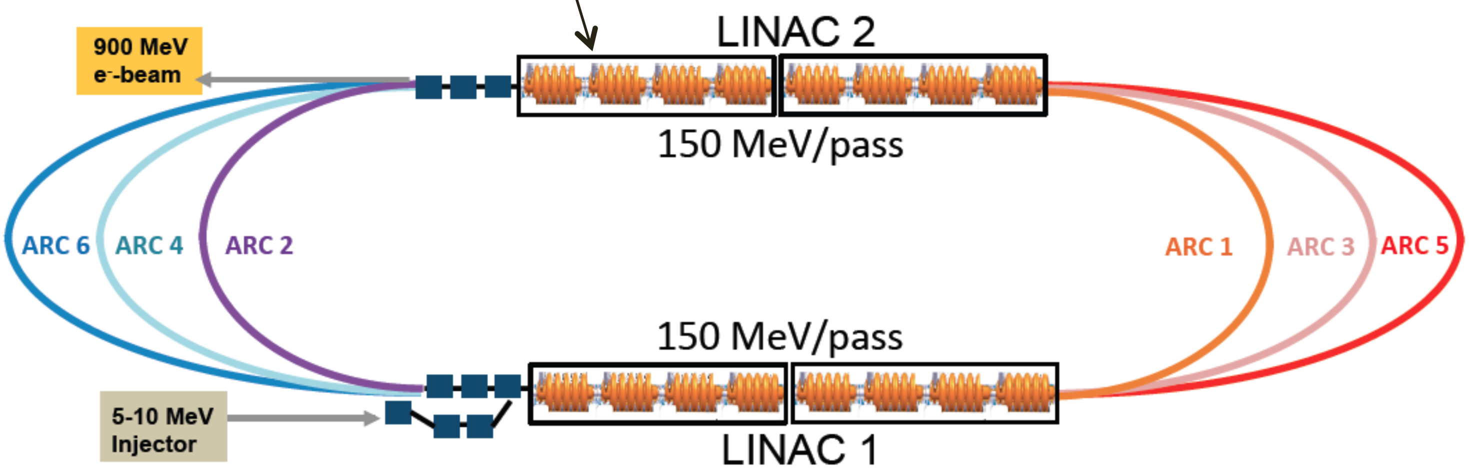
Superconducting RF and ERL Test Facility Design at CERN



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.

Future Circular Collider (FCC) study ; goals: CDR and cost review for the next European Strategy Update (2018)

International collaboration :

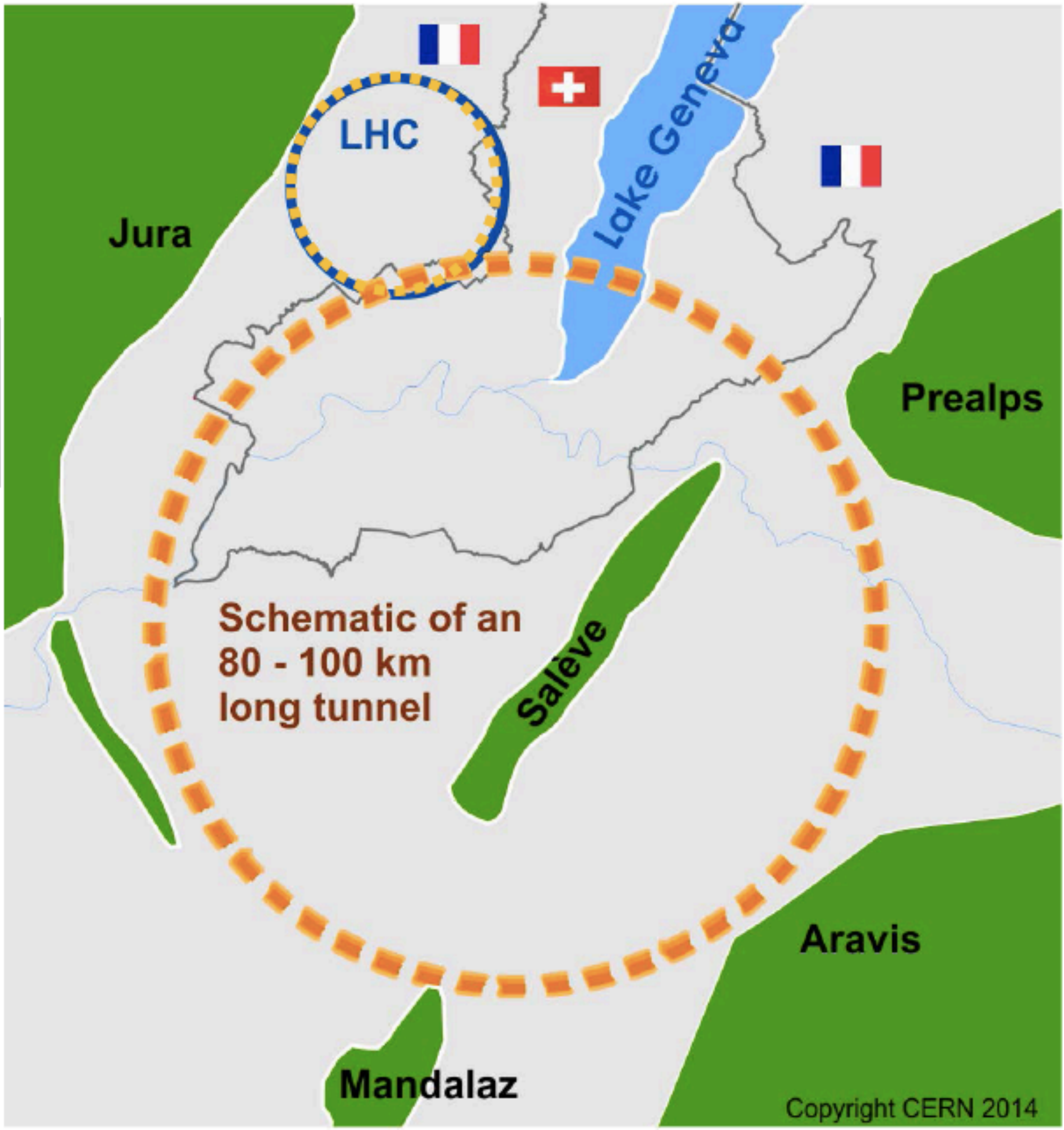
- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV in 100 km

~20 T ⇒ 100 TeV in 80 km

- including ***HE-LHC*** option: 16-20 T in LHC tunnel
- ***e^+e^-* collider (*FCC-ee/TLEP*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **100 km infrastructure** in Geneva area

M. Benedikt



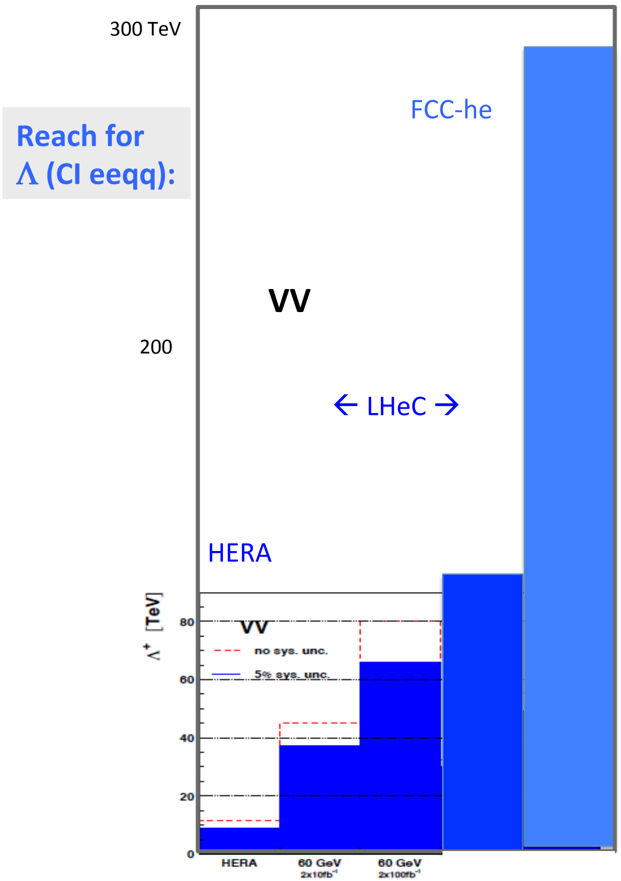
collider parameters	FCC ERL	FCC-ee ring		protons
species	e^- (e^+?)	$e^\pm$	$e^\pm$	p
beam energy [GeV]	60	60	120	50000
bunches / beam	-	10600	1360	10600
bunch intensity [10^{11}]	0.05	0.94	0.46	1.0
beam current [mA]	25.6	480	30	500
rms bunch length [cm]	0.02	0.15	0.12	8
rms emittance [nm]	0.17	1.9 (x)	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

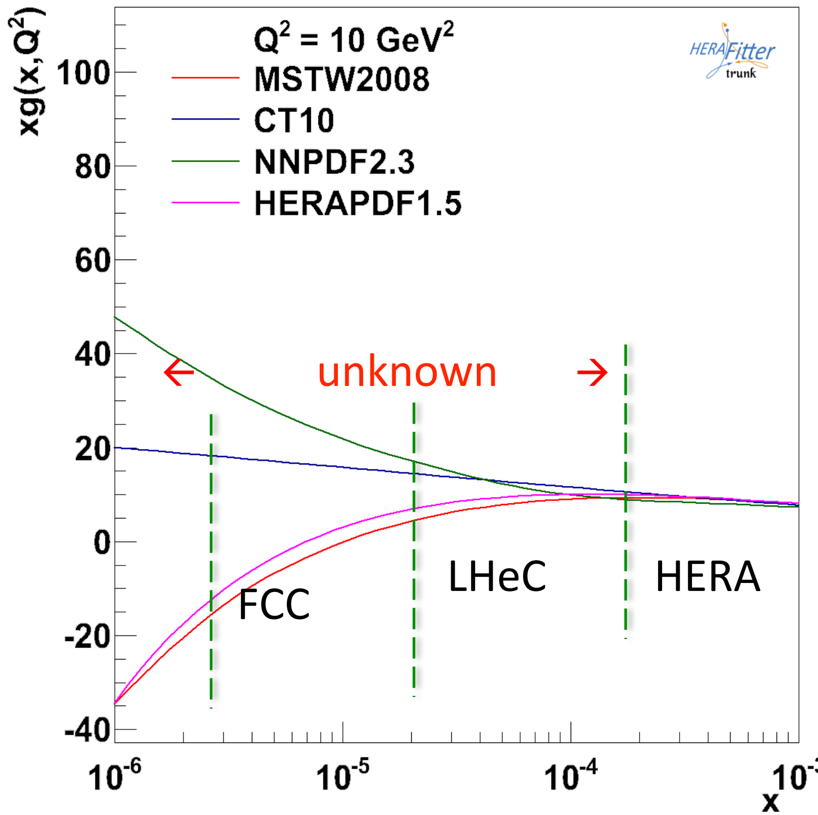
FCC-he Physics

High mass and Q^2 region



LHeC: see CDR 2012

Low x Physics



Huge extension of reach for new physics
Leptoquark reach to √s ≈ 4 TeV

Very low x – close to UHEν region, BFKL?

Higgs selfcoupling (4b final state – under study, cross section 5 times higher than LHeC)

Program being further investigated, Collaboration with hh and ee, Joint Software Group

New LHeC International Advisory Committee

Guido Altarelli (Rome)
Sergio Bertolucci (CERN)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – **Chair**
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (STFC)

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.

Clarification and Tradition

Herwig Schopper at Chavannes 1/14 in the Panel Discussion with the CERN Directorate

My clarifying remark:

Any ep/eA project **cannot be a major CERN flagship project**
Essentially only one experiment,
cannot satisfy > 8000 users

not in competition with main projects (HL-LHC, HE-LHC, CLIC, FCC)
complementary **(in time, resources)**

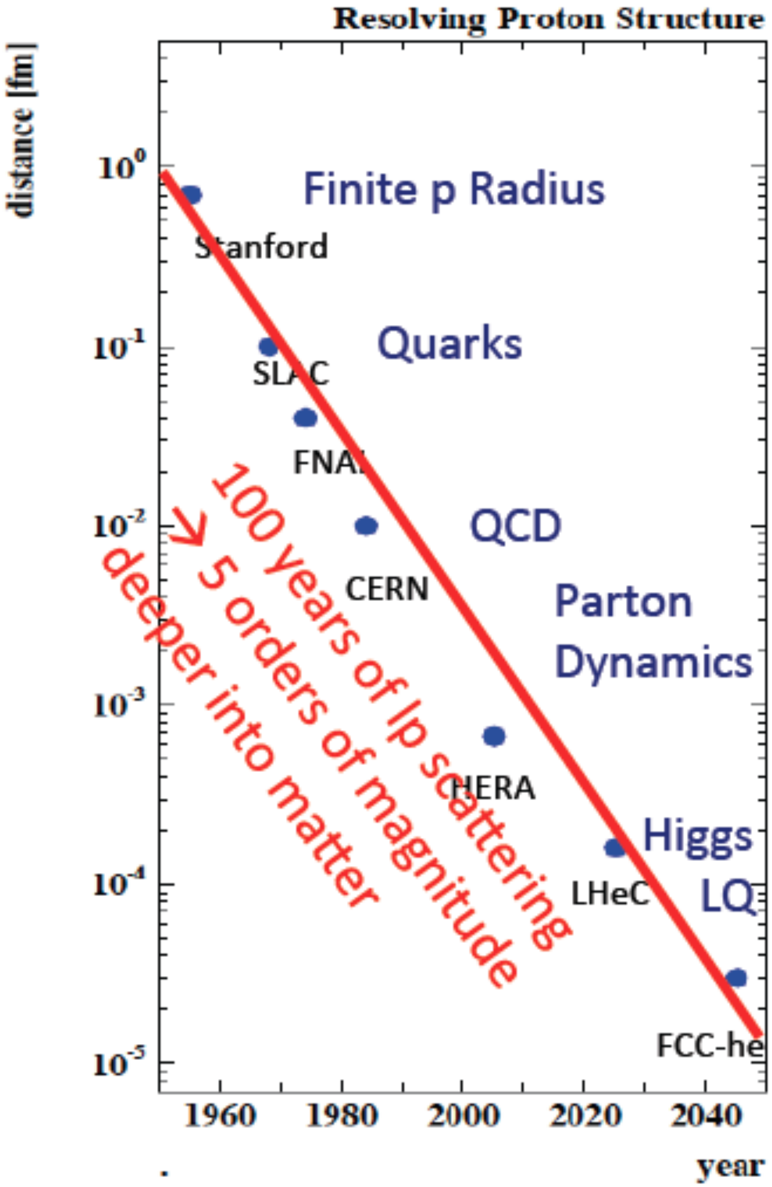
International collaboration will be essential

- **for experiments (detectors, intersections)**
- **accelerator design (parameters, optimisation)**
- **preparing necessary technology (SC rf cavities, possibly ERL test facility)**

As in the tradition of CERN

H.Schopper, M.K. CERN Courier June 2014

Outlook



ep/eA's Big Questions

- Structure of the Visible Matter
- Lepton-Quark Symmetry
- BSM (Higgs+, CI's, RPV SUSY..)
- BSM (Free colour, low x QCD)

ep/eA's Prominent Contributions

- Resolving the Proton PDFs
- Photon,Pomeron, GPDs, Neutron, A
- Higgs in WW and ZZ
- QCD of HI physics (NPDFs)
- Electroweak Physics beyond Z and H
- …

Future of DIS must be maintained:
It is rich, from low to medium and highest energies, and the outcome cannot be fully simulated/predicted. It assists to sustain our field..

http://cern.ch/lhec

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Thanks

to the

LHeC

Study

Group

and

www.lhec.cern.ch

Referees for Design Report

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Nuclei	Nestor Armesto
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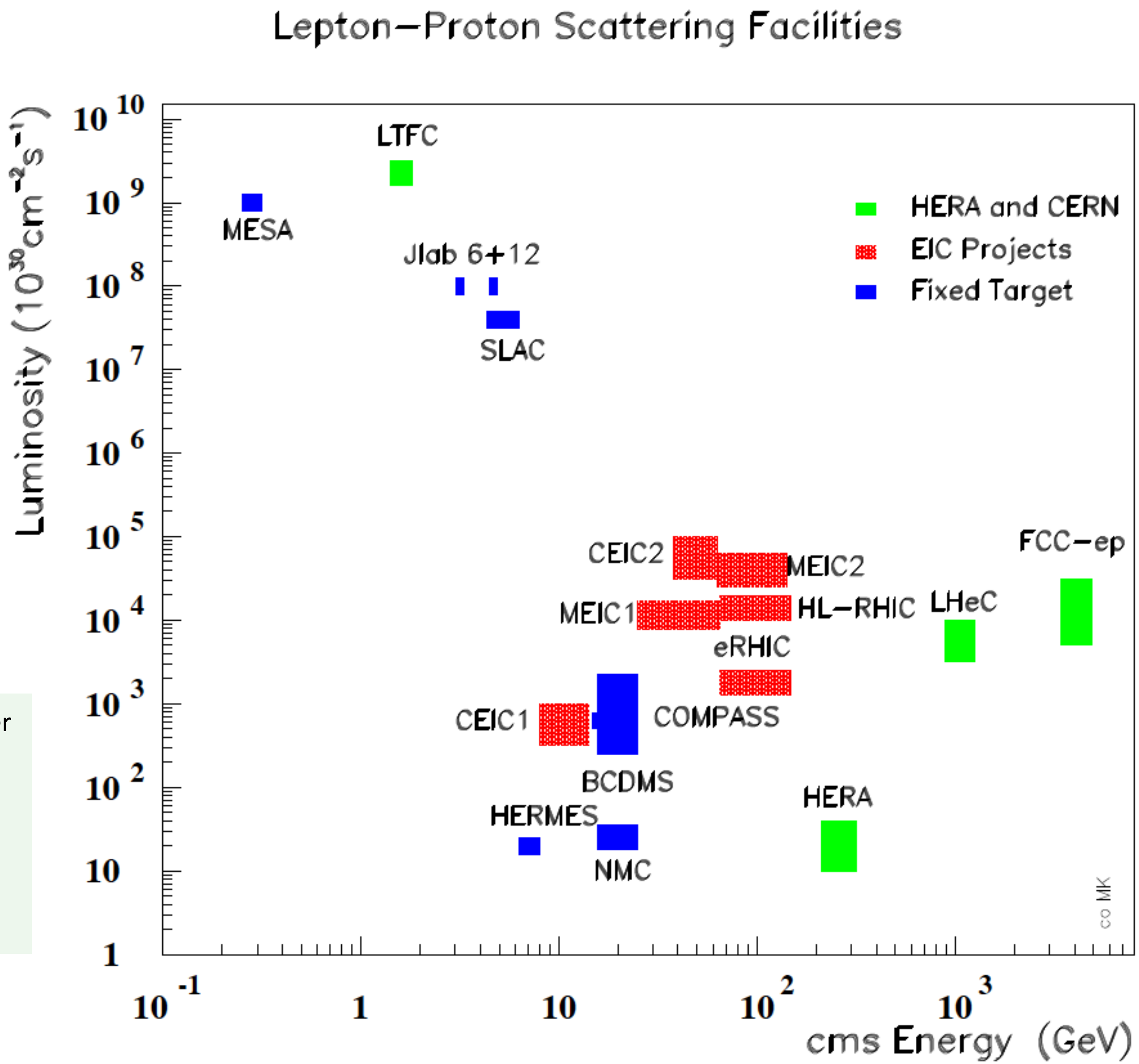
The LHeC design has been a strong community effort

CDR: arXiv:1206.2913


The LHeC design has been a strong community effort
Workshop at Chavannes, I/14

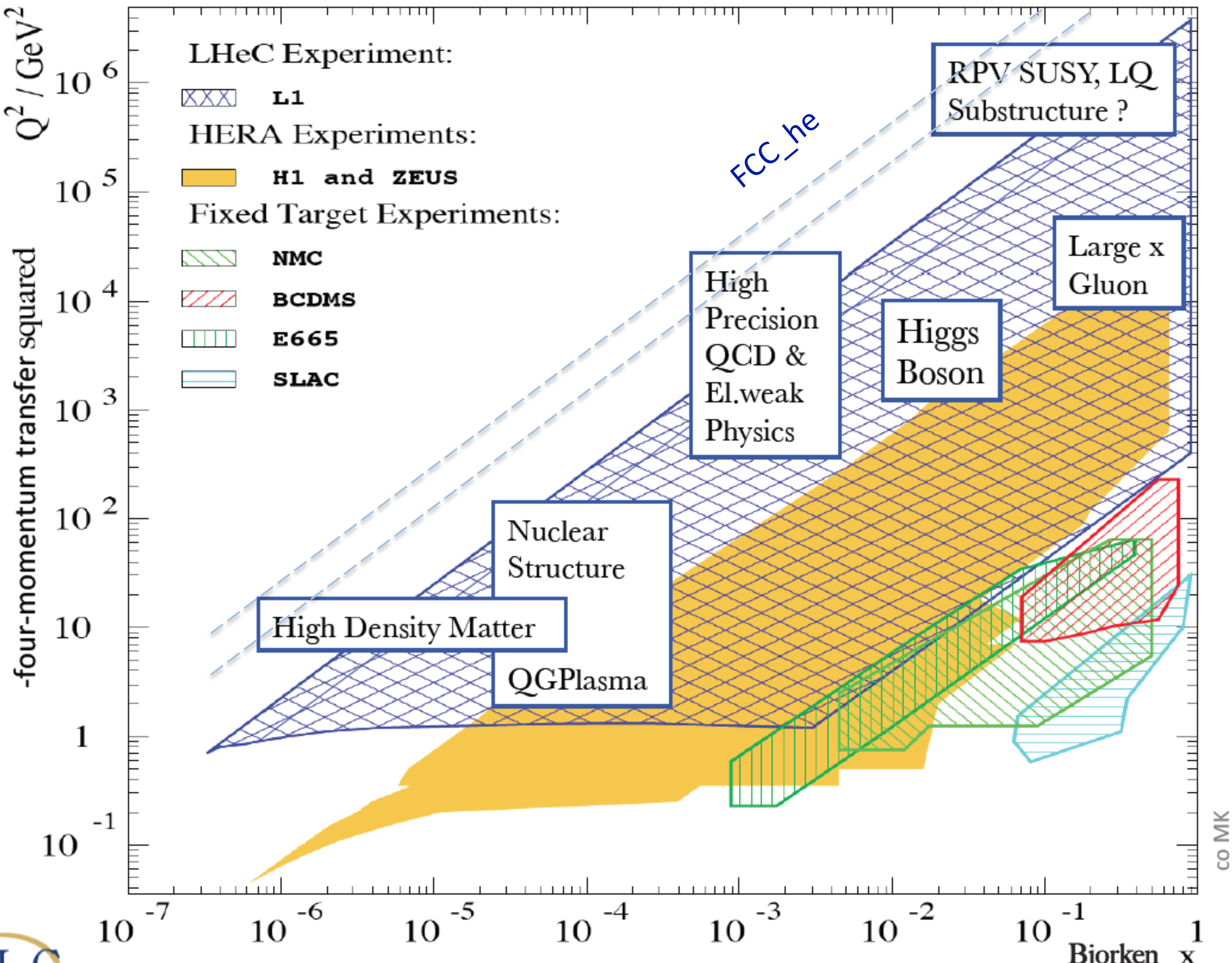


From CERN Courier
MK, H.Schopper
June 2014

With input from
A.Hutton, R.Ent,
F.Maas, T.Rosner

Goals of a CERN ERL-Test Facility

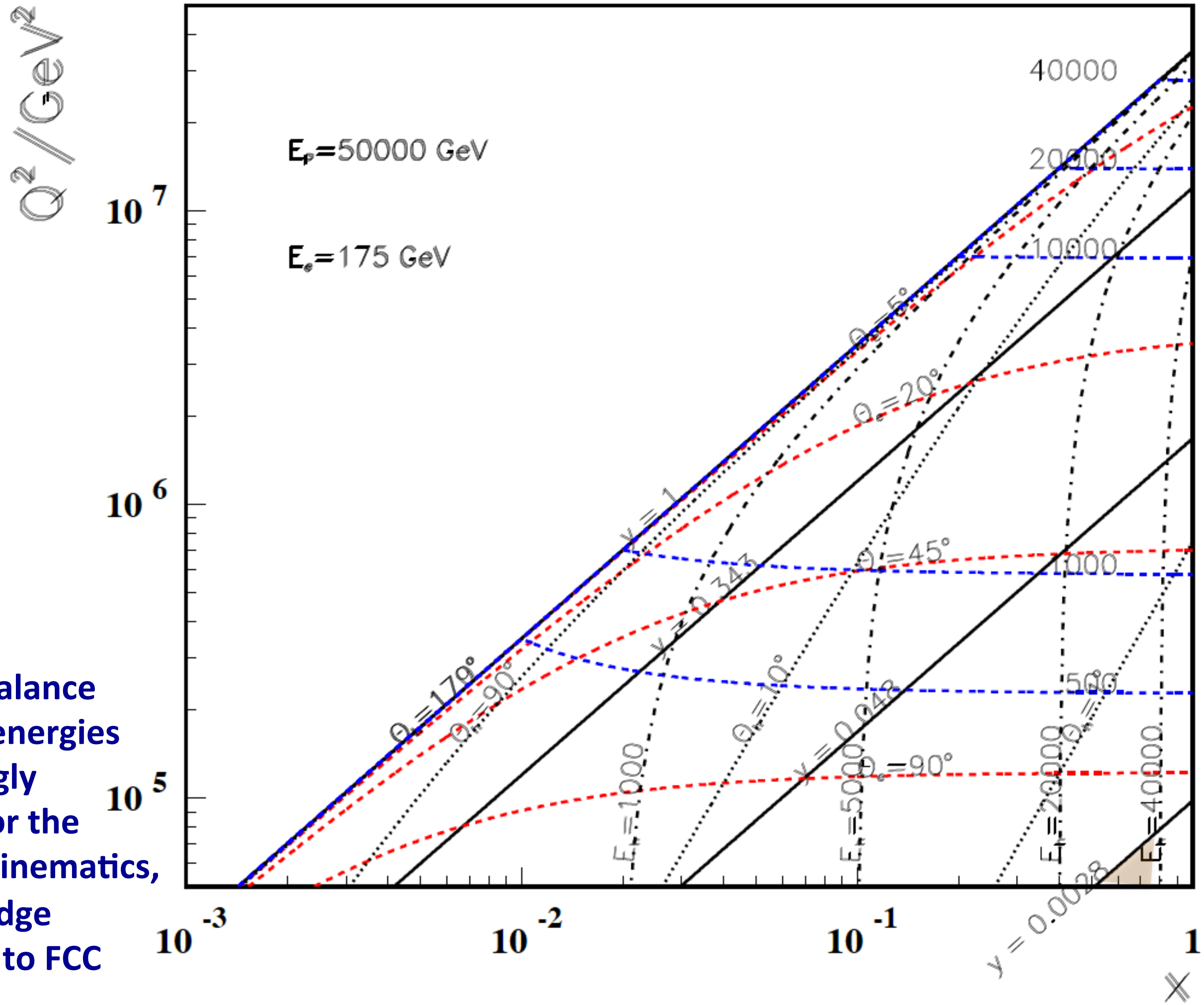
- Main goal: **Study real SRF Cavities with beam** – not interfering with HEP!
  - citing W. Funk ("Jefferson Lab: Lessons Learned from SNS Production", ILC Workshop 2004 http://ilc.kek.jp/ILCWS/):
    - **All problems will not be experienced until the complete subsystem is tested under realistic conditions. Be prepared to test, with full rf power systems and beam, all of the pre-production prototypes.**
- In addition, it would allow to study **beam dynamics & operational aspects** of the advanced concept ERL (recovery of otherwise wasted beam energy)!
- Exploration of the ERL concept with multiple re-circulations and high beam current operation
- Additional goals:
  - Gun and injector studies
  - Test beams for detector R&D,
  - Beam induced quench test of SC magnets
  - … later possibly user facility: $e↑-$ test beams, CW FEL, Compton γ-ray source …
- At the same time, it will be fostering international collaboration (JG|U Mainz and TJNAF collaborations being formalized)



LHeC Experiment:
L1
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
FCC_he
RPV SUSY, LQ
Substructure ?
Large x
Gluon
High
Precision
QCD &
El.weak
Physics
Higgs
Boson
Nuclear
Structure
High Density Matter
QGPlasma
Q^2 / GeV^2
-four-momentum transfer squared
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Bjorken x
co MK

High Q^2

Rutherford backscattering of dozens of TeV e- energy



FCC-he
175 GeV
60 GeV

LHeC

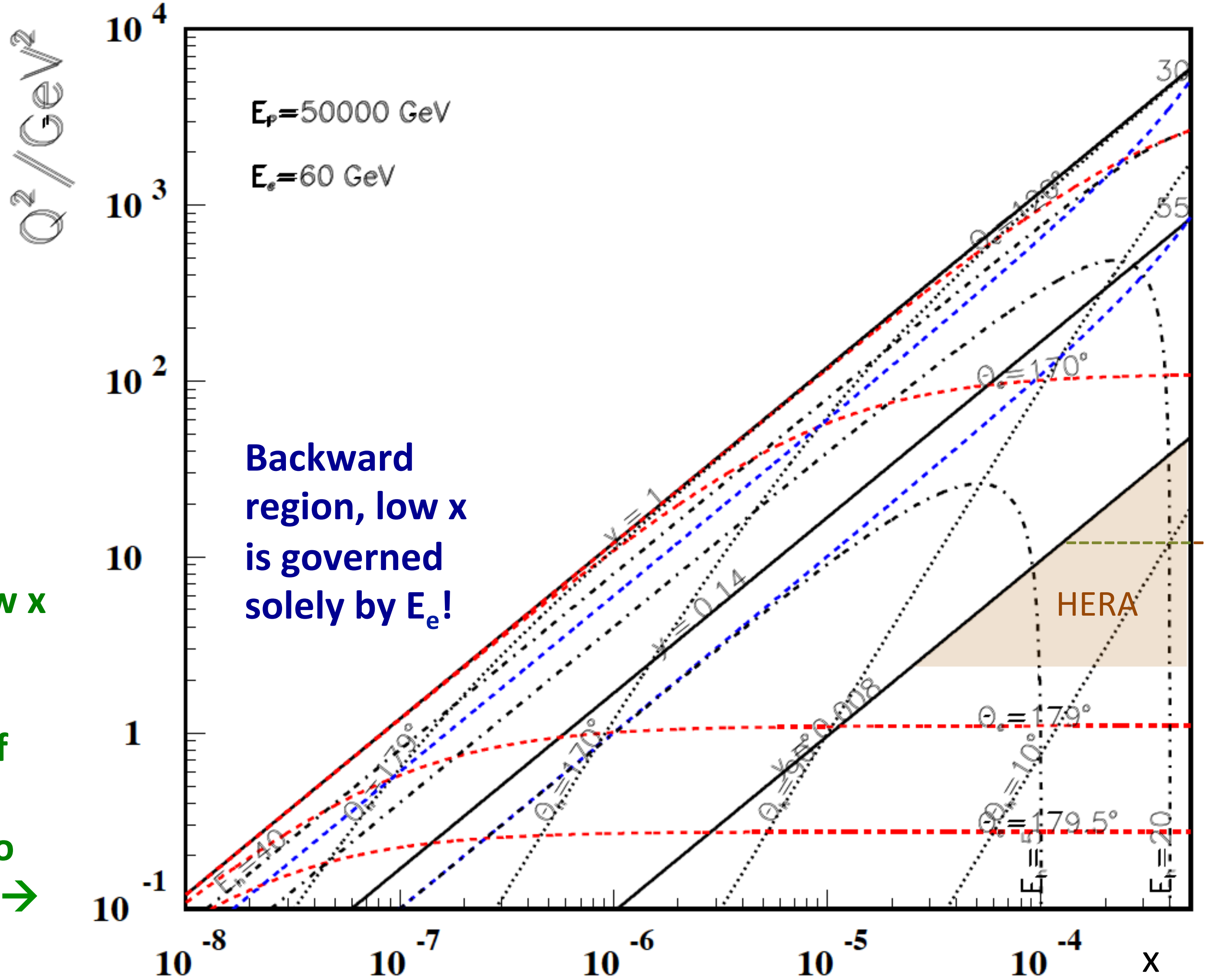
← $\vartheta_h = 1^o$

← HERA

Large imabalance of e and p energies is surprisingly tolerable for the high Q^2, x kinematics, LHeC to bridge from HERA to FCC

Low x

Very low x reaches direct range of UHE neutrino physics →



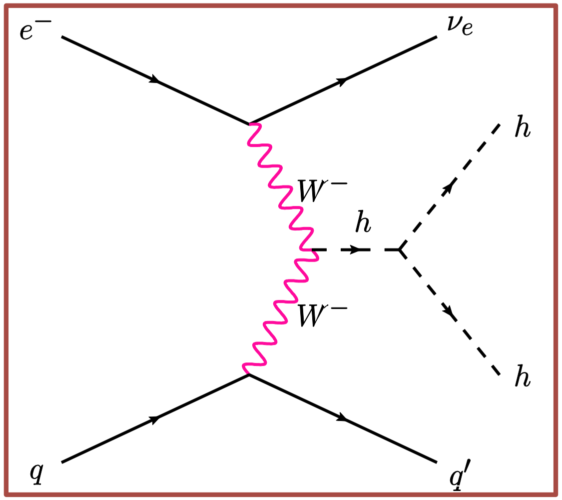
FCC-he
60 GeV

LHeC

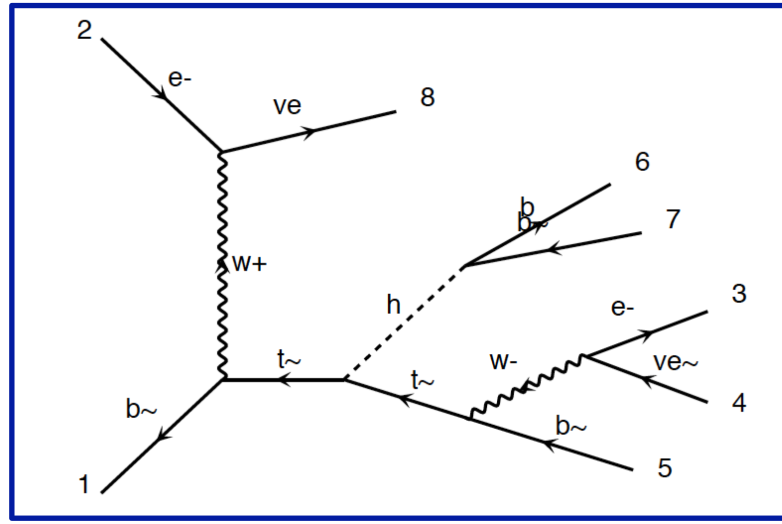
← 179°
@ 180 GeV
.. very low x requires not the maximum of E_e

For x < 10^{-3} no (average) energy deposition exceeding the electron beam energy

HH and tHt in ep



New Tentative Studies



Processes	E_e (GeV)	σ(fb)	σ_{eff}(fb)
$e^- p \rightarrow \nu_e hhj, h \rightarrow b\bar{b}$	60	0.04	0.01
	120	0.10	0.024
	150	0.14	0.034

FCC-he unpolarised
Cross section at 3.5 TeV:

total : 0.7 fb
fiducial : 0.2 fb
using pt(b,j)>20 GeV
ΔR(j.b)>0.4
η(j) <5
η(b) < 3

Polarisation, max lumi, tuning cuts, bb and WW decays may provide O(10%) precision - tentative

Requires time for reliable result (detector, analysis, backgrounds..)

Uta Klein, Masahiro Khuze, Bruce Mellado et al