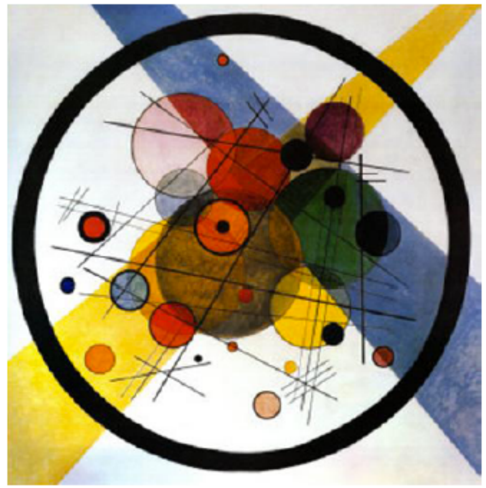
Physics at FCC-eh

A brief introduction for the IAC

For internal use and discussion with the FCC international advisory committee



DRAFT 28.6. 11pm

W Kandinski (1923)
Circles in a cirle
Philadelphia Art Museum
Logo of CDR on LHeC

FCC-eh
E_p =50 TeV

HE LHC
E_p=12.5 TeV

+ ERL electrons
E_e=60 GeV

Max Klein
University of Liverpool

For the electron-hadron study group

For references,
please consult
lhec.web.cern.ch

LHeC CDR
arXiv:1206.2913
J.Phys. G39 (2012) 075001

FCC IAC Review, CERN, 29th of June 2017

Next decades

Rolf Heuer at
Aix Les Bains
1. 10. 2013

Road beyond Standard Model

LHC results vital to guide the way at the energy frontier

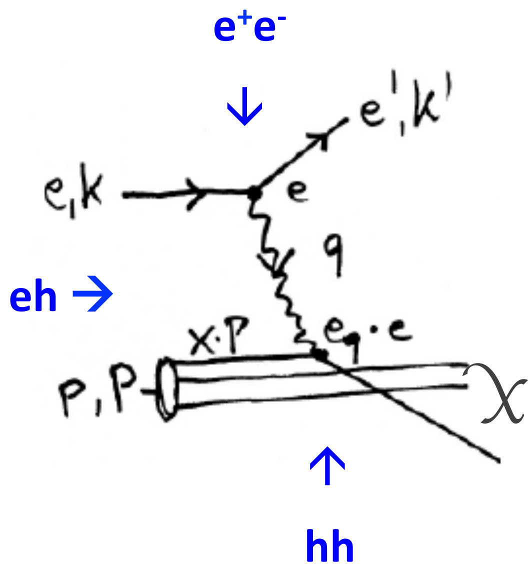
At the energy frontier through synergy of

hadron - hadron colliders (LHC, (V)HE-LHC?)

lepton - hadron colliders (LHeC ??)

lepton - lepton colliders (LC (**ILC** or CLIC) ?)

Deep Inelastic Scattering [eh → e'X]



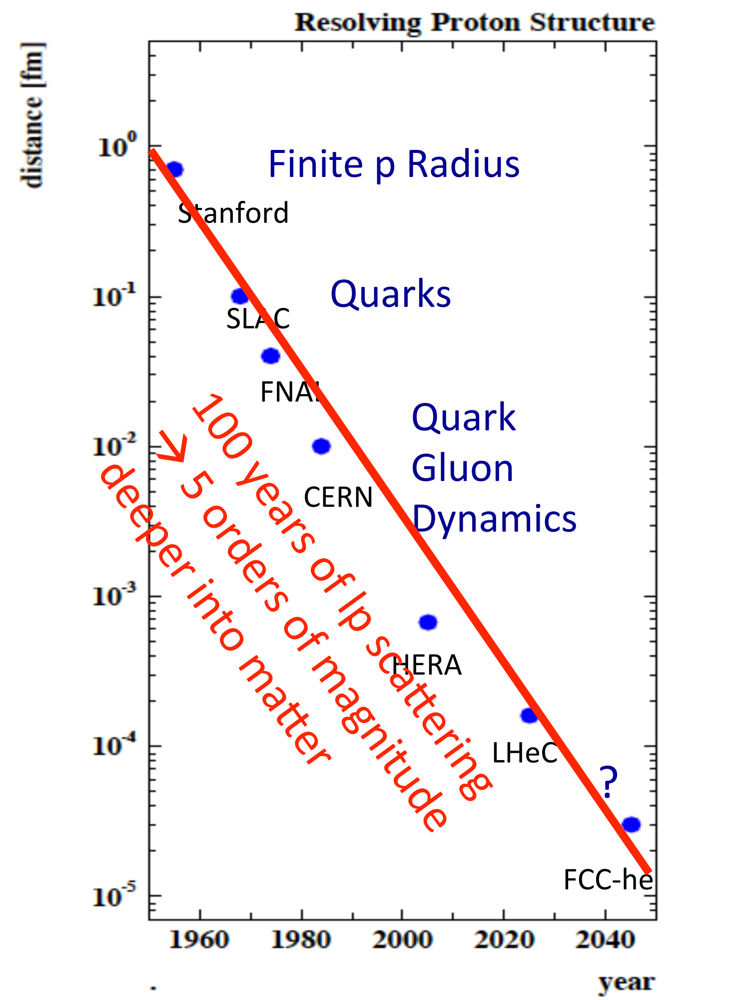
$$x = \frac{Q^2}{sy}$$

$$Q^2 = -(k - k')^2$$

$$y_{lab} = 1 - \frac{E_e'}{E_e}$$

$$s = 4E_eE_p$$

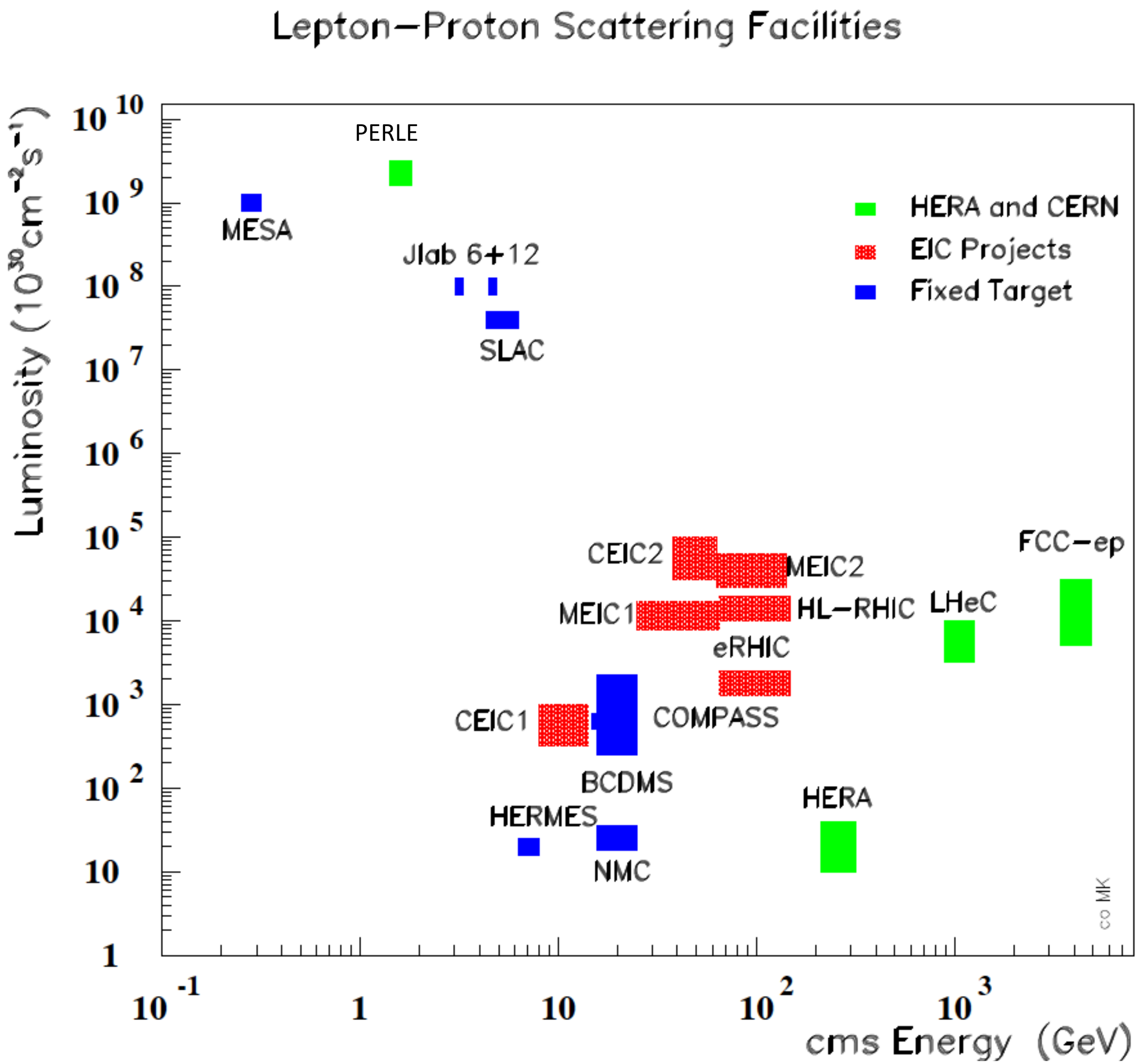
HERA-LHeC-FCC-eh: finest microscopes with resolution varying like $1/\sqrt{Q^2}$



electromagnetic radius

- Parton momentum fixed by electron kinematics
- Incl. NC (γ,Z) and CC ($W^{\pm}$) independent of hadronisation
- Rigorous theory: Operator expansion (lightcone)
- Parton momentum distributions to be measured in DIS
- Collider- HERA: y_h=y_e : Redundant kinematics

Intensity and Energy Frontier of Future DIS

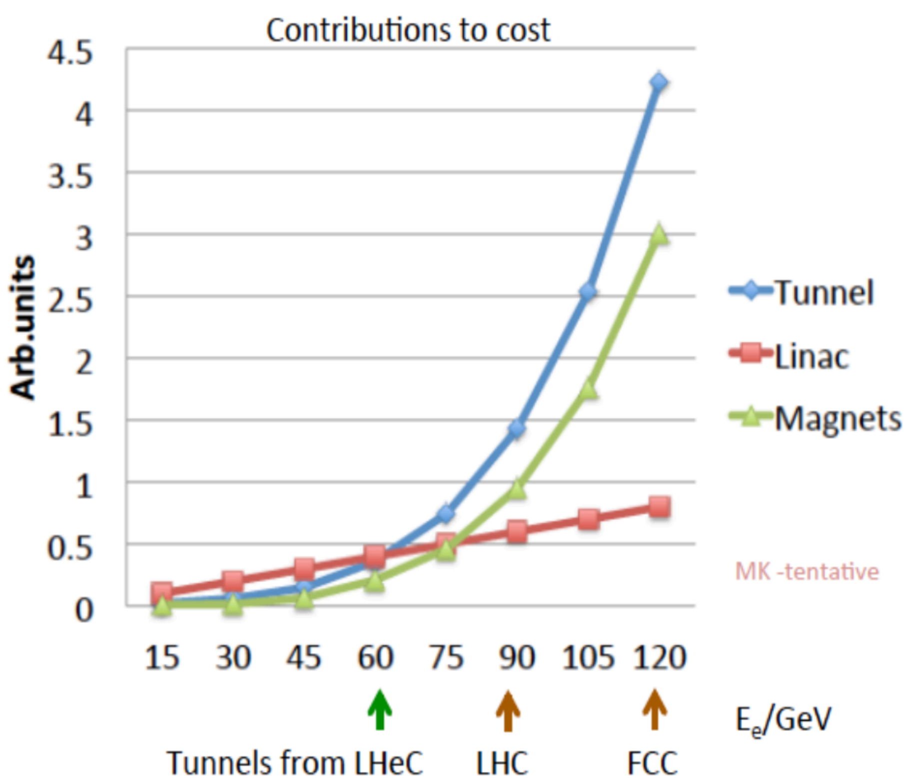


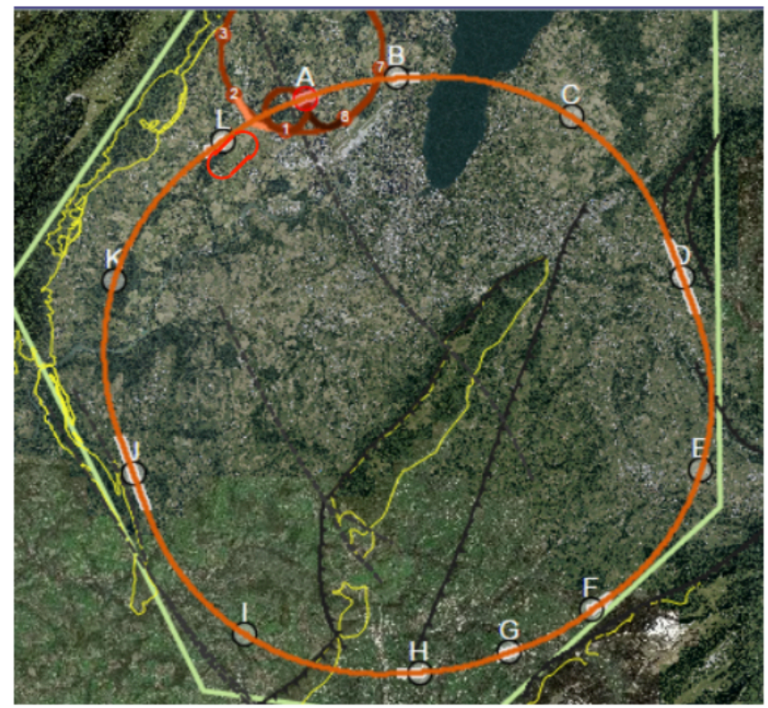
From CERN Courier
MK, H.Schopper
June 2014

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

CERN: LHC+FCC: the only realistic opportunity for energy frontier deep inelastic scattering
Huge step in energy (Q^2,1/x) and 2-3 orders of magnitude higher luminosity than HERA

Cost vs Energy & Physics





Jo Stanyard/J Osborne

A rough extrapolation of a 3-turn ERL shows how the cost rises strongly with the electron beam energy. We therefore, currently stick to 60 GeV which maximizes physics return.

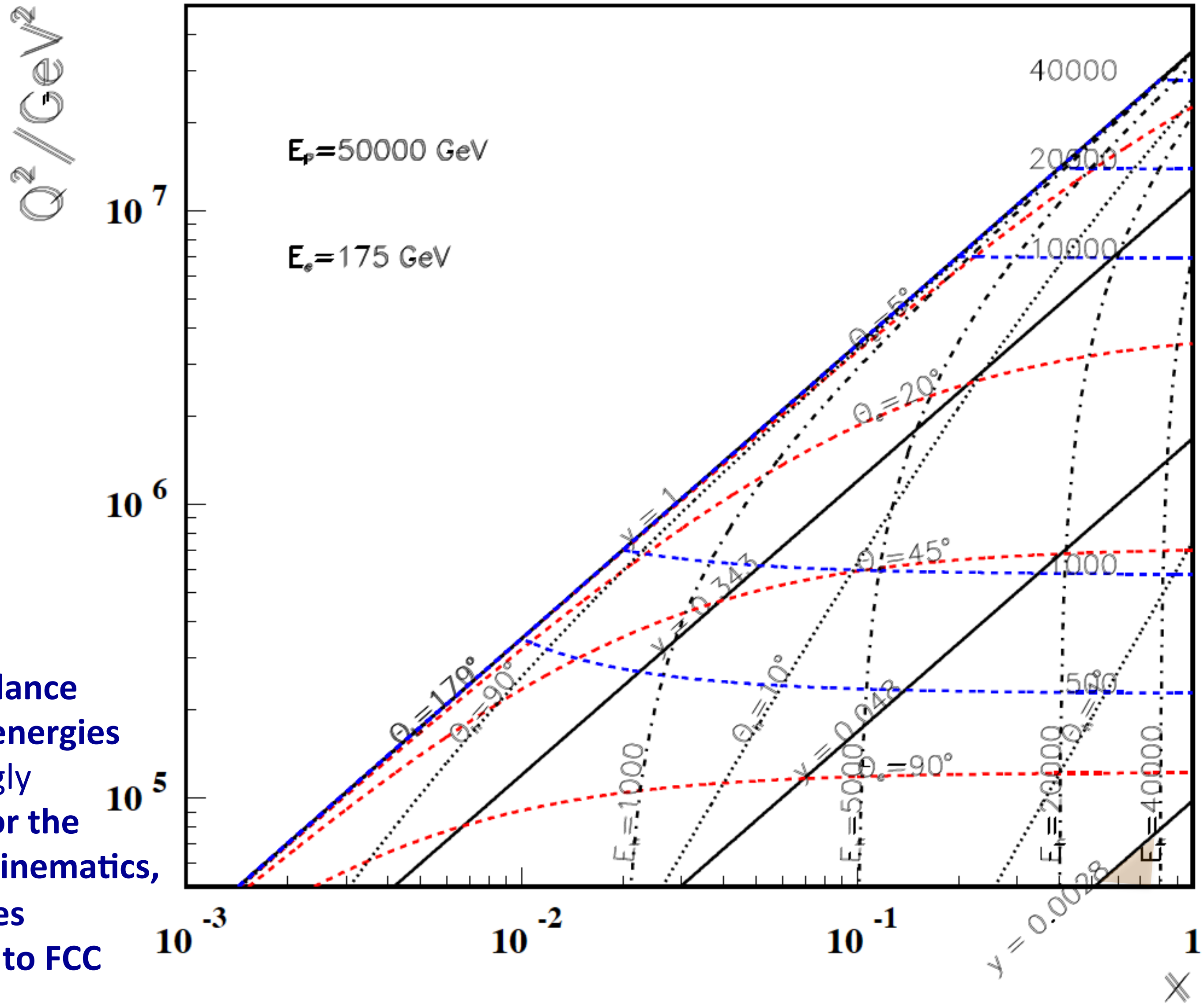
ERL is of modular, multi-use for eh at CERN

CE prefers the 9km circumference ERL to be placed to L, For HE LHC the ERL would be in place (IP2).

Conclusion: we consider the LHeC ERL as baseline for *eh*

High Q^2

Rutherford backscattering
of dozens of TeV e- energy



FCC-he
175 GeV
60 GeV

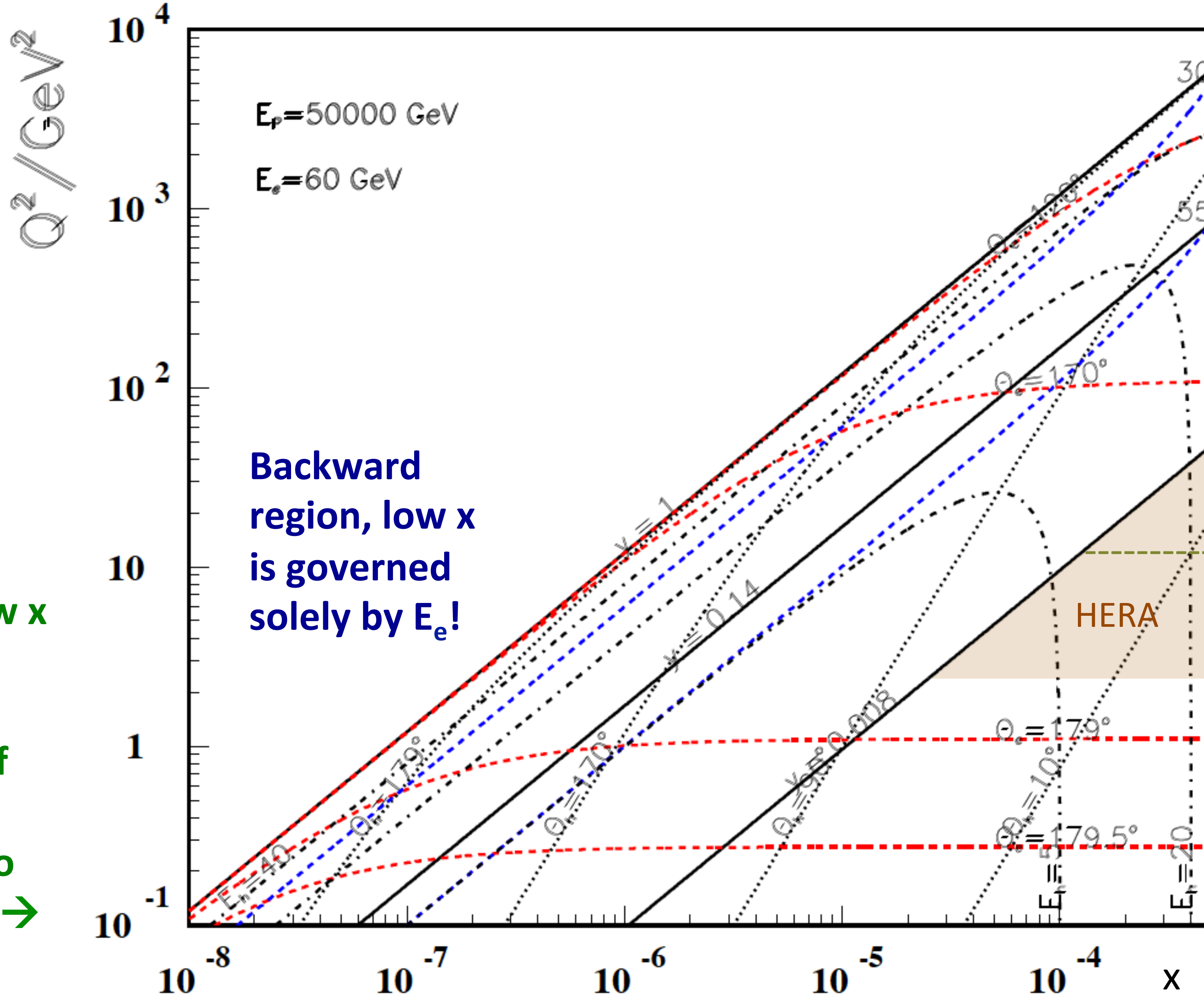
LHeC

← ϑ_h=1°

← HERA

Large imbalance of e and p energies is surprisingly **tolerable for the high Q², x kinematics, LHeC bridges from HERA to FCC**

Low x



FCC-he
60 GeV

LHeC

← 179° @ 180 GeV

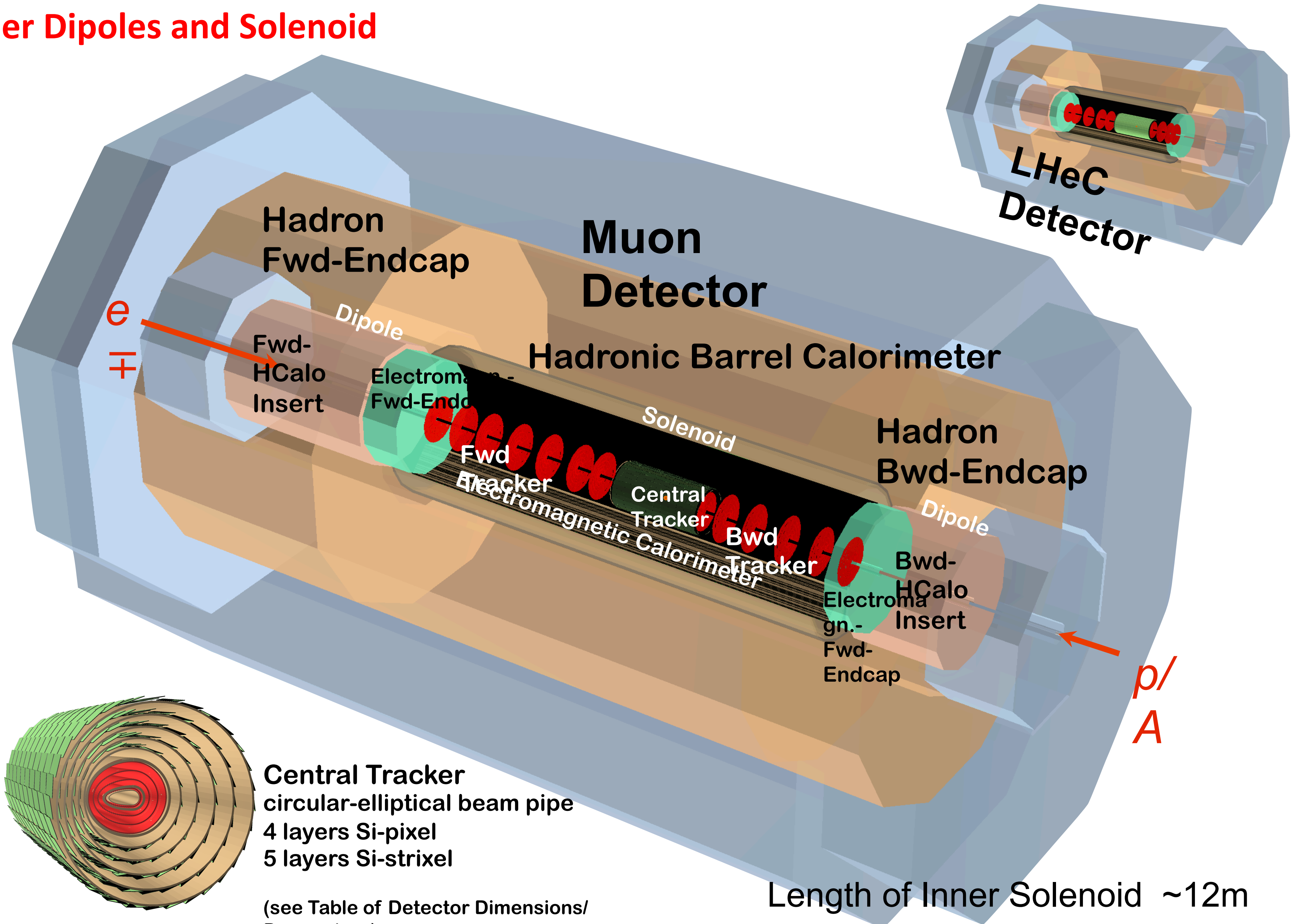
.. very low x requires not the maximum of E_e

Very low x reaches direct range of UHE neutrino physics →

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

FCC-he Detector Layout - Scaled Version of LHeC Detector

Inner Dipoles and Solenoid



Five Major Themes of electron-hadron Physics

Cleanest High Resolution Microscopes

Joint ep and pp Physics

High Precision Higgs Exploration

Discovery Beyond the Standard Model

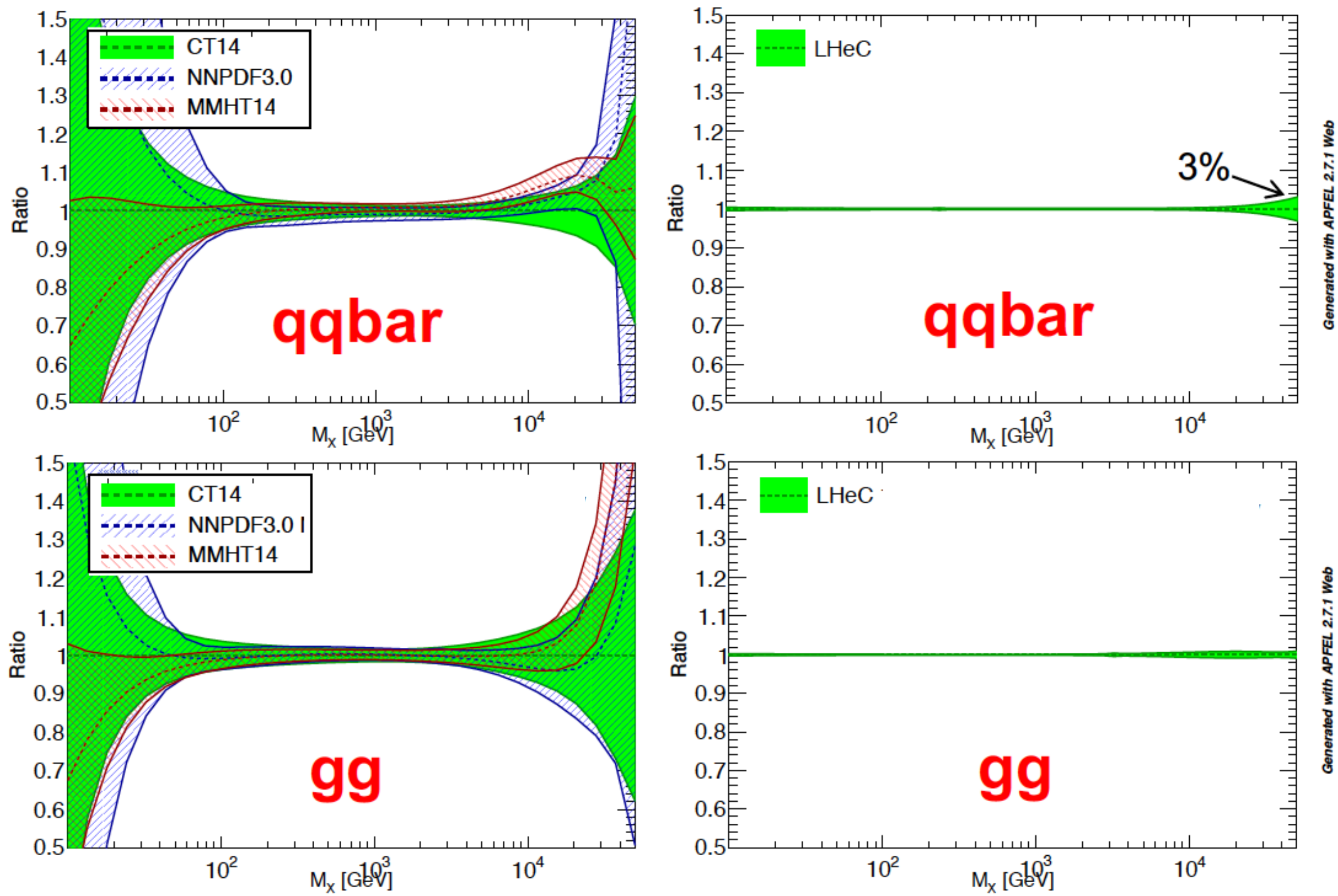
A Unique Nuclear Physics Facility

Unravelling structure of matter

Resolve parton structure of the proton completely: u_v,d_v,s_v?,u,d,s,c,b,t and xg
Unprecedented range, sub% precision, free of parameterisation assumptions,
Resolve p structure, solve non linear and saturation issues, test QCD, N^3LO…

Strong Coupling in inclusive DIS to O(0.1)%

Lattice??
Jets??
ee?
BCDMS??
GUTs?
Higgs in pp
…



Completely new PDF Analysis under way for CDR(s)

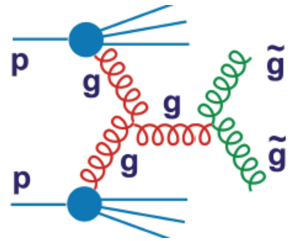
Note that LHC is about to reach its own limits on PDFs. pp is NOT DIS, cf ATLAS W,Z to 0.5%

Empowering pp Discoveries

External, reliable input (PDFs, factorisation..) is crucial for range extension + CI interpretation

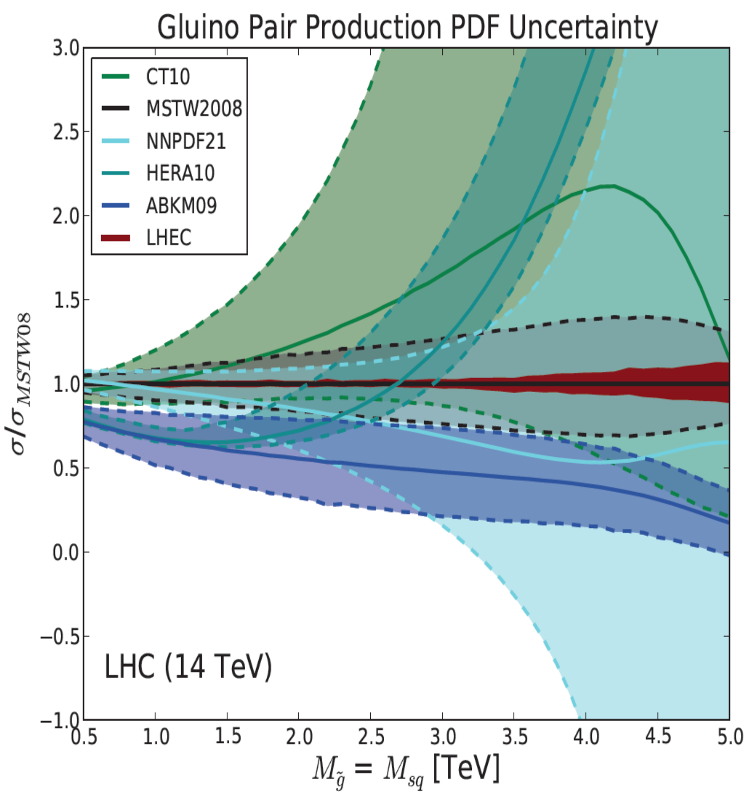
GLUON

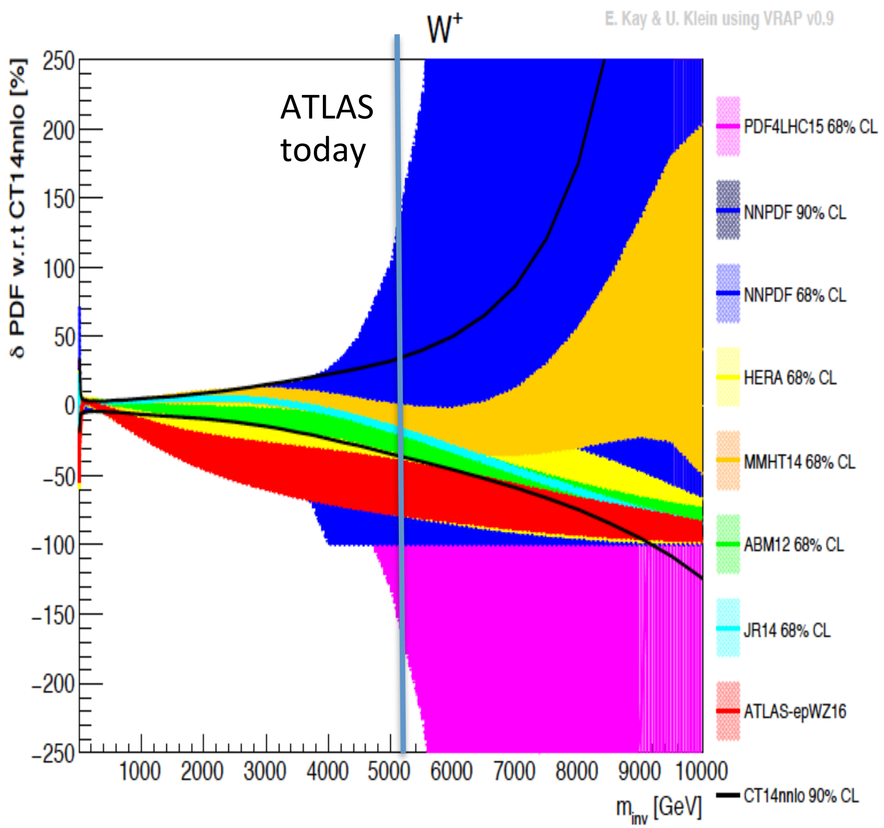
SUSY, RPC, RPV, LQS..



QUARKS

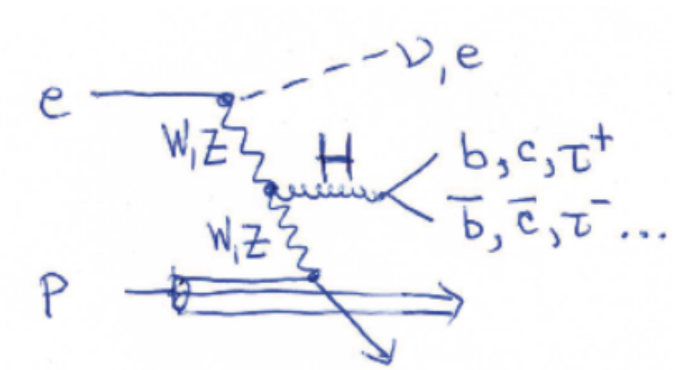
Exotic+ Extra boson searches at high mass





FCC-he: mass range:50/7 larger: eh vital to resolve high mass (x) region: "synergy" for CDR

Higgs Physics with *ep*



High cross section (cc: LHeC 200fb, FCC-eh 1pb)

Electroweak production, uniquely CC vs NC

Access to WW-H-WW and ZZ-H-ZZ

No pileup, clean theory, challenging simulations

SM coupling measurement expectations

κ in %	HL LHC	LHeC HL	LHeC HE	FCC-eh
H → bb	10?	0.5	0.3	0.2
H → cc	50??	4	2.8	1.8

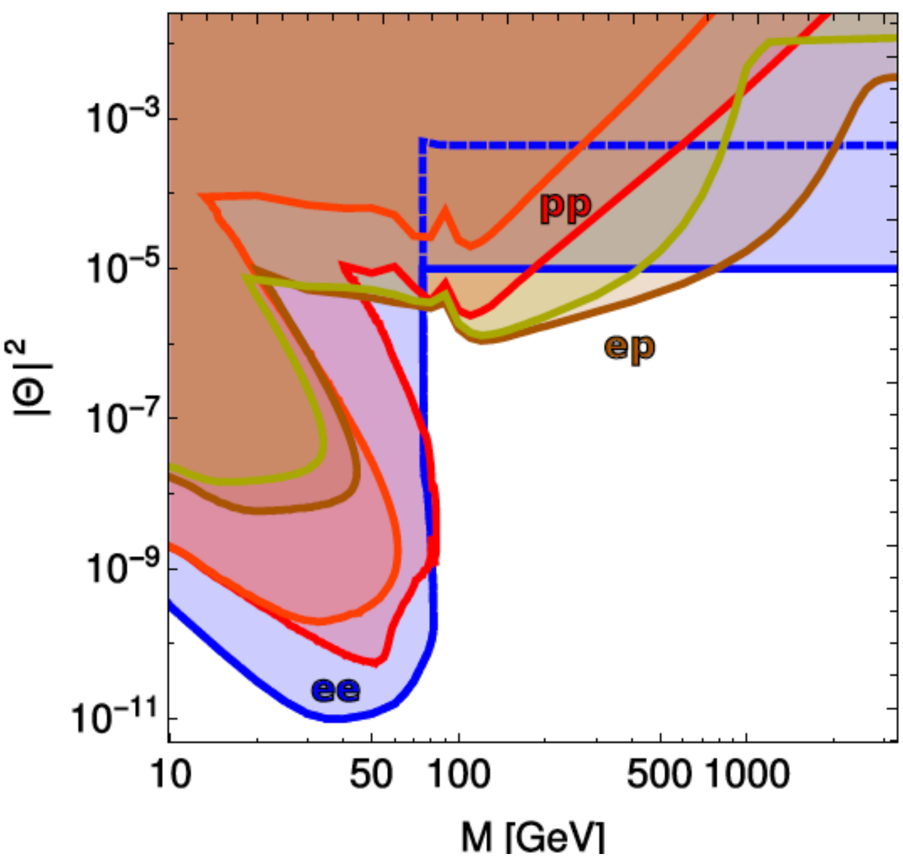
ep when added to pp turns the pp colliders into high precision Higgs facilities. Removes gg-H QCD uncertainties (N^3LO) in pp

Recent Higgs-in-ep studies for CDR: Higgs self coupling from FCC-eh associated top-Higgs production, Higgs into invisible (dark matter), Exotic Higgs physics: H into light scalars, H^{--} and others

for CDR: complete SM (τ,W,g?) and add BSM Higgs studies, integrate with hh/ee

Possible Discoveries Beyond SM with eh

Search for Sterile Neutrinos
(LHC/FCChh FCCee LHeC/FCCeh)



QCD:

(No) saturation of the gluon density

QCD radiation pattern (BFKL?) – hh!

New QCD states (instantons)

Higher symmetry embedding QCD

Electroweak:

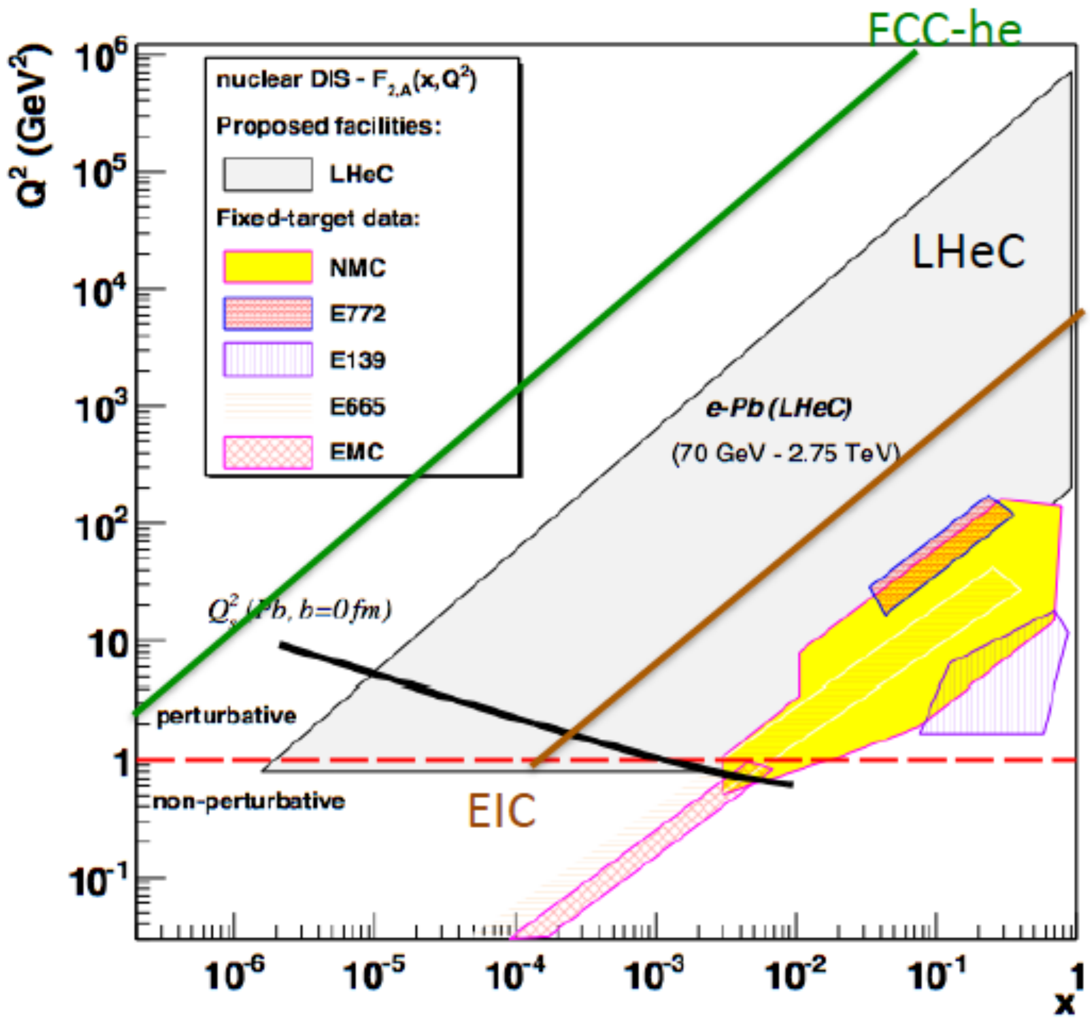
EFTs, CI to 300 TeV, RPV SUSY

Exotic Higgs Decays (Dark Matter..)

Extension of Higgs Sector (H^{++}..)

Sterile Neutrinos …

Electron-Ion Nuclear and Particle Physics



Extension of kinematic range by 4 orders of magnitude:
will change our view on nuclear structure and colour dynamics

Relates to LHC Heavy Ion Physics
- Quark Gluon Plasma
- Collectivity of small nuclei (p)?
- ..

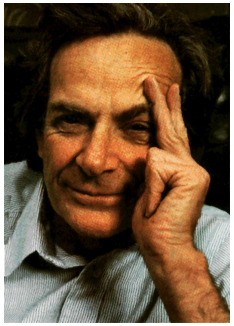
May lead to genuine surprises

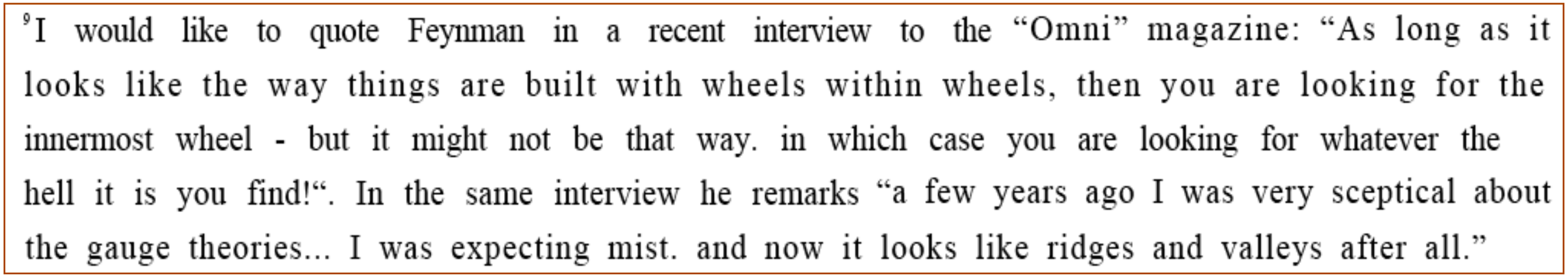
Saturation: non-linear gluon i.a.s
saturation needs very high energy:
Discovery in ep and verification eA

G Milhano on Thursday

For CDR: update in view of LHC (AA,pA) and new simulations, new ansatz to p+N PDFs..

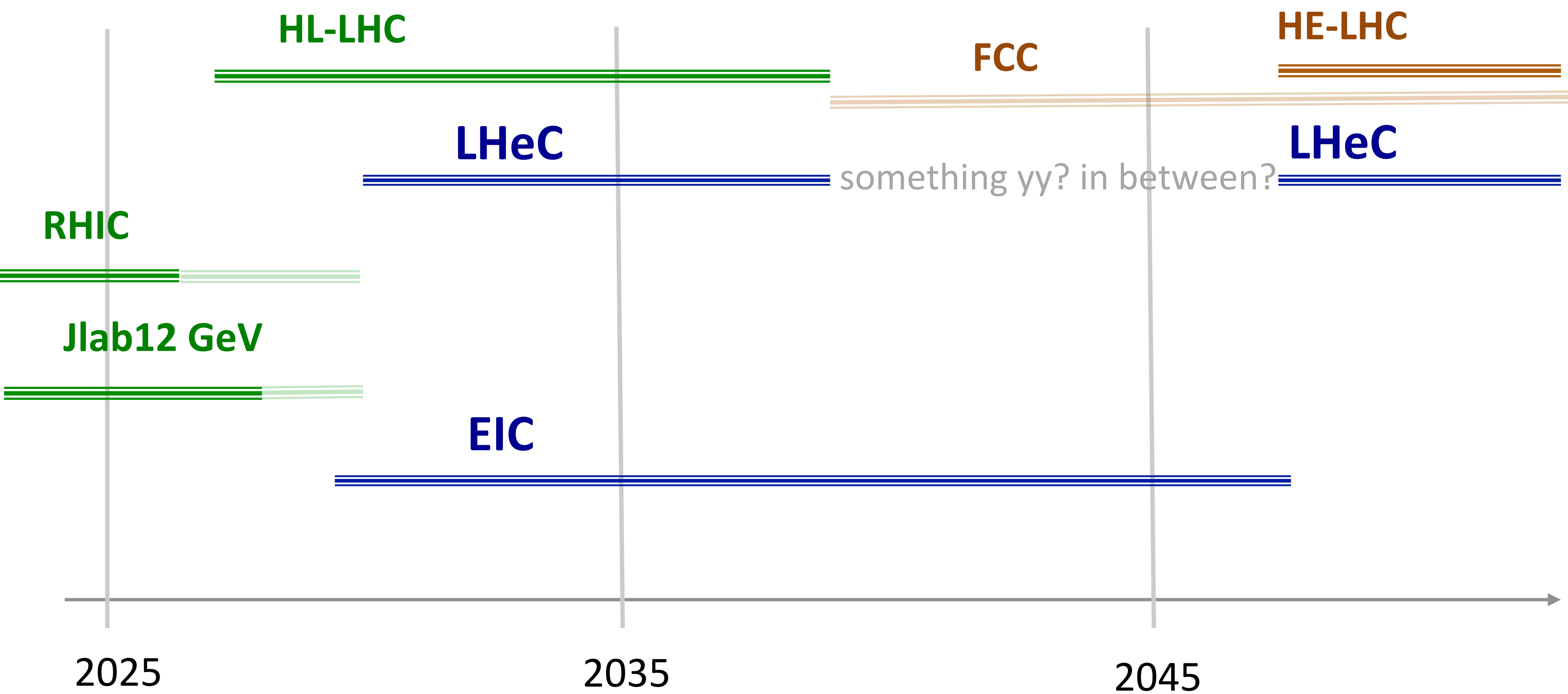
Feynman's Wisdom




[9]I would like to quote Feynman in a recent interview to the "Omni" magazine: "As long as it looks like the way things are built with wheels within wheels, then you are looking for the innermost wheel - but it might not be that way. in which case you are looking for whatever the hell it is you find!". In the same interview he remarks "a few years ago I was very sceptical about the gauge theories... I was expecting mist. and now it looks like ridges and valleys after all."

Cited: Abdus Salam
Nobel Lecture 1979

Projected Timelines for Future ep/eA Colliders



HERA: Proposal 1984, Data 1992-2007, Publications 1993-2018

VHEep: Plasma e − LHC. **Chinese ep/A** projects: Lanzhou (low E) and CEPC/SPPC

Dislaimer: For discussion and illustration at DIS17 only MK+RY, April 7th, 2017, DIS at Birmingham

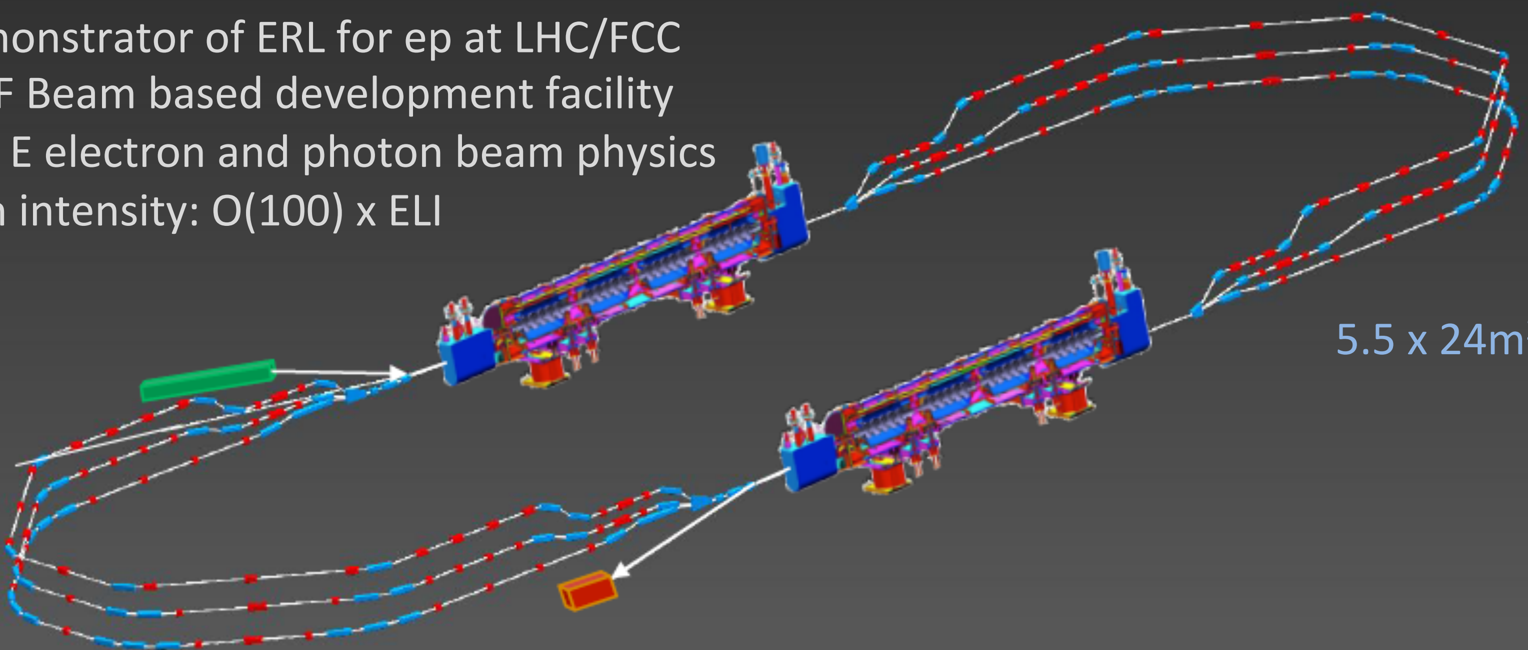
Powerful ERL for Experiments (ep,γp): PERLE at Orsay

title

PERLE at Orsay (LAL/INP) Collaboration: BINP, CERN, Daresbury/Liverpool, Jlab, Orsay +

3 turns, 2 Linacs, 400 MeV, 15mA, 802 MHz, Energy Recovery Linac facility

- -Demonstrator of ERL for ep at LHC/FCC
- -SCRF Beam based development facility
- -Low E electron and photon beam physics
- -High intensity: O(100) x ELI



CDR to appear in J Phys G [arXiv:1705. 08783]

See also https://indico.lal.in2p3.fr/event/3428/

A.Bogacz

Concluding Remarks

1. Electron-hadron scattering has **five big themes** (Microscope, Higgs, Joint to pp, BSM, Nuclei)
   → It thus has a unique place in High Energy Physics

2. **ep empowers pp**: searches and high precision (e.g. Higgs in pp+ep – an especially rich mix)
   → ep and pp can operate concurrently: should be seen, studied and understood together

3. QCD needs major new development through novel exp input (ep + pp) and theory
   → **QCD may fail and lead BSM**: non-linear evolution, higher/grand symmetry, breaking of factorisation, valence components of heavy quarks, free colour, instantons, substructure..

4. ions: **eA at CERN is to revolutionise nuclear dynamics** and structure physics
   → chromodynamic understanding of QGP, an EIC requires highest energy to be of highest value

5. Detector: one in LR, two in RR (HE-LHC?) **novel experimental opportunity post HL LHC → crucial!**

6. **PERLE**: in time and scope to learn how to build and operate the ERL at high energy

→ Electron-hadron configuration: genuine, high, added + crucial, **unique value for HEP**
→ The ERL at the HL/HE/FCC **is affordable, i.e. it does NOT affect larger scale decisions** but possibly provides time until those may be taken. The electron energy is a function of available cost (in building and operating the ERL). The ep cms energy is much higher than that of ILC/CepC or FCCee (even CLIC in the FCC-eh case)
→ **ep is an exciting, realistic option for a next energy frontier collider for particle physics**

backup

LHeC/FCC-eh: Organisation*)

International Advisory Committee

"..Direction for ep/A both at LHC+FCC"

- Sergio Bertolucci (Bologna)
- 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 (Lund)

We lost Guido Altarelli.

Coordination Group

Accelerator+Detector+Physics

- Nestor Armesto
- Oliver Brüning – Co-Chair
- Stefano Forte
- Andrea Gaddi
- Erk Jensen
- Max Klein – Co-Chair
- Peter Kostka
- Bruce Mellado
- Paul Newman
- Daniel Schulte
- Frank Zimmermann

5(11) are members of the FCC coordination team

OB+MK: FCC-eh responsibles
MDO: physics co-convenor

Working Groups

PDFs, QCD
Fred Olness,
Claire Gwenlan

Higgs
Uta Klein,
Masahiro Kuze

BSM
Georges Azuelos,
Monica D'Onofrio

Top
Olaf Behnke,
Christian Schwanenberger

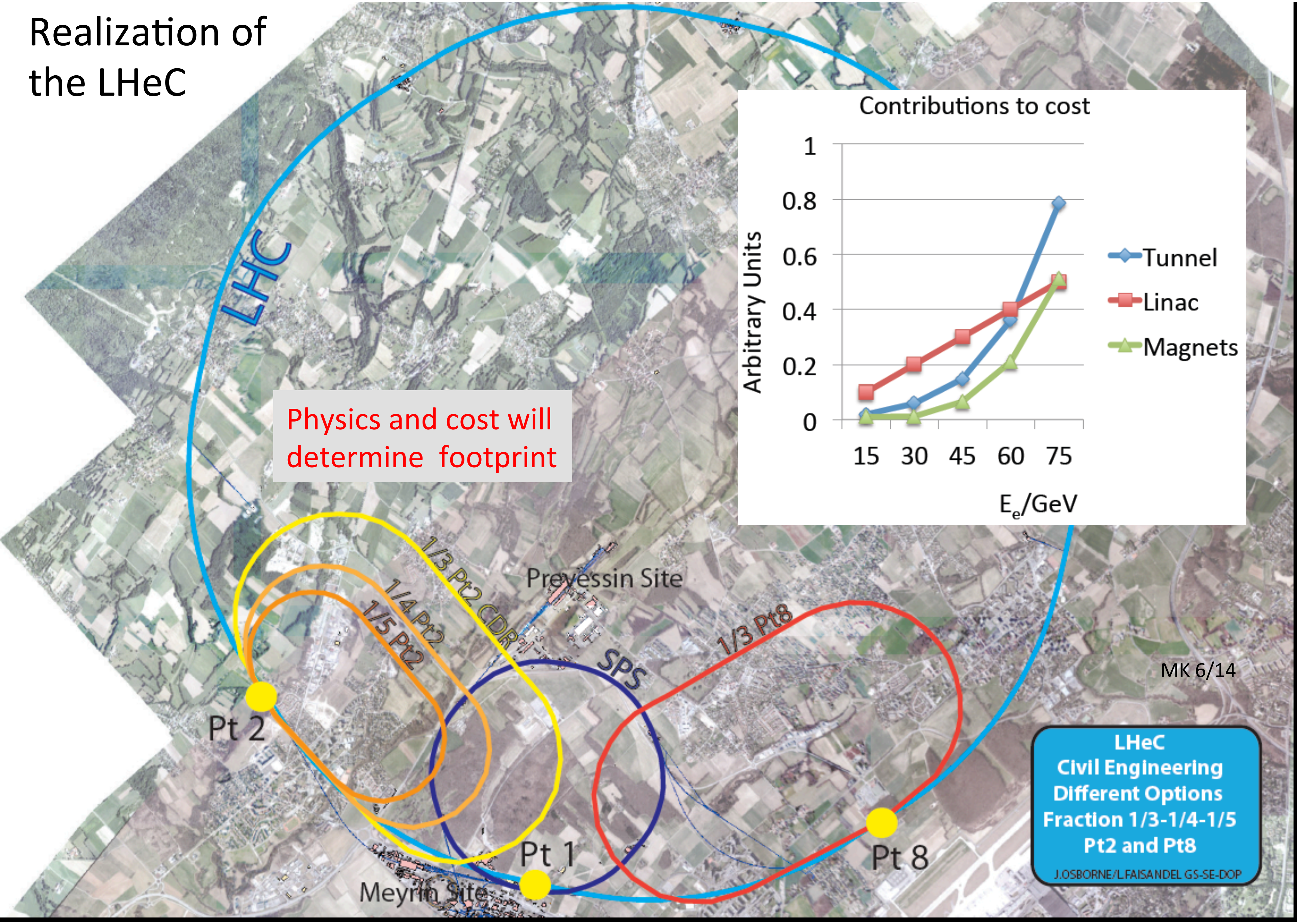
eA Physics
Nestor Armesto

Small x
Paul Newman,
Anna Stasto

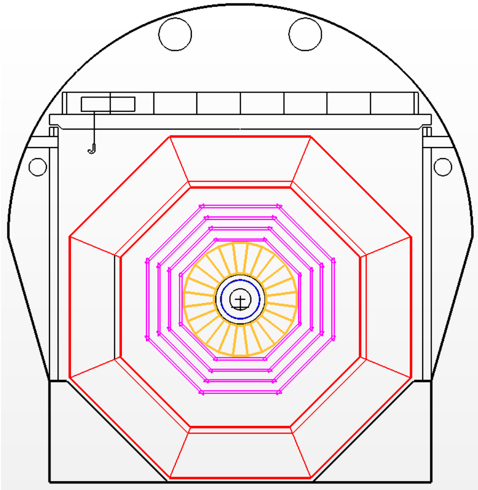
Detector
Alessandro Polini
Peter Kostka

*) June 2017

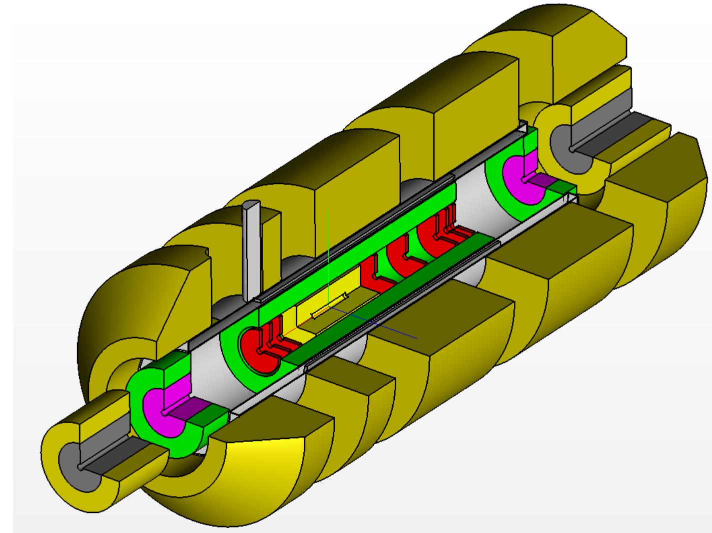
Realization of the LHeC



Installation Study

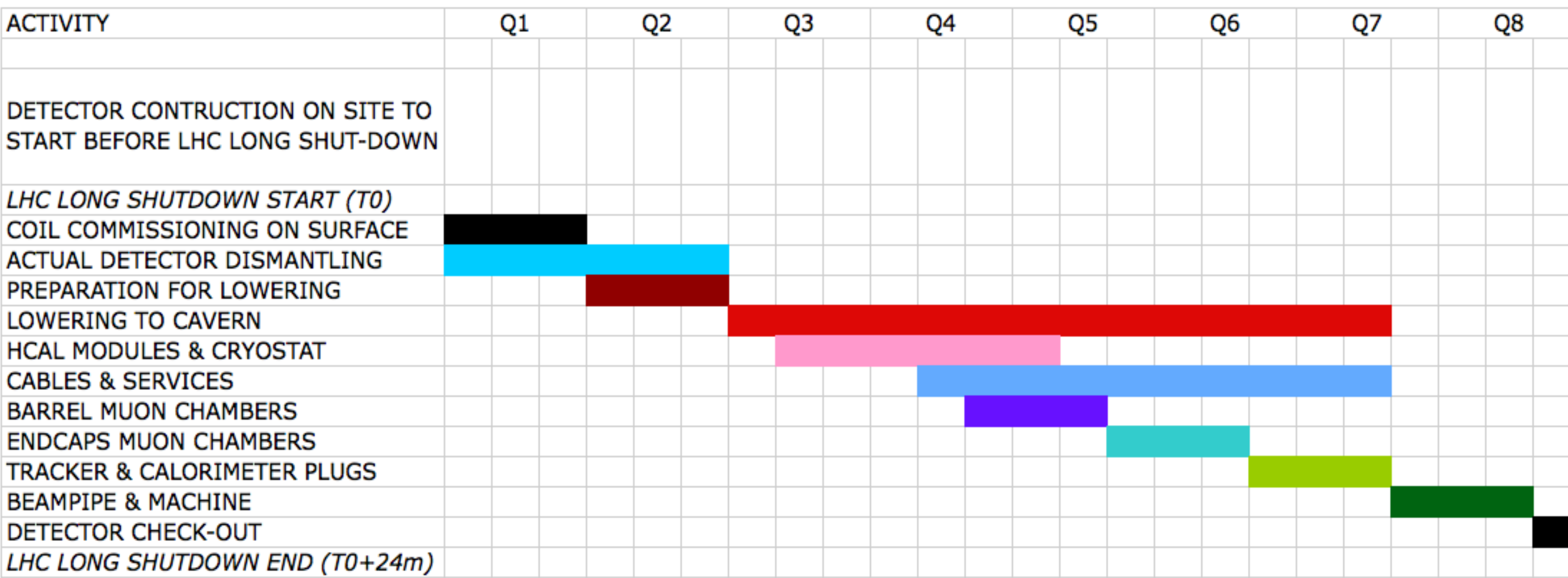


Detector fits in L3 magnet support



Modular structure

LHeC INSTALLATION SCHEDULE



FCC-eh: Tracker, Calorimeters and Steps

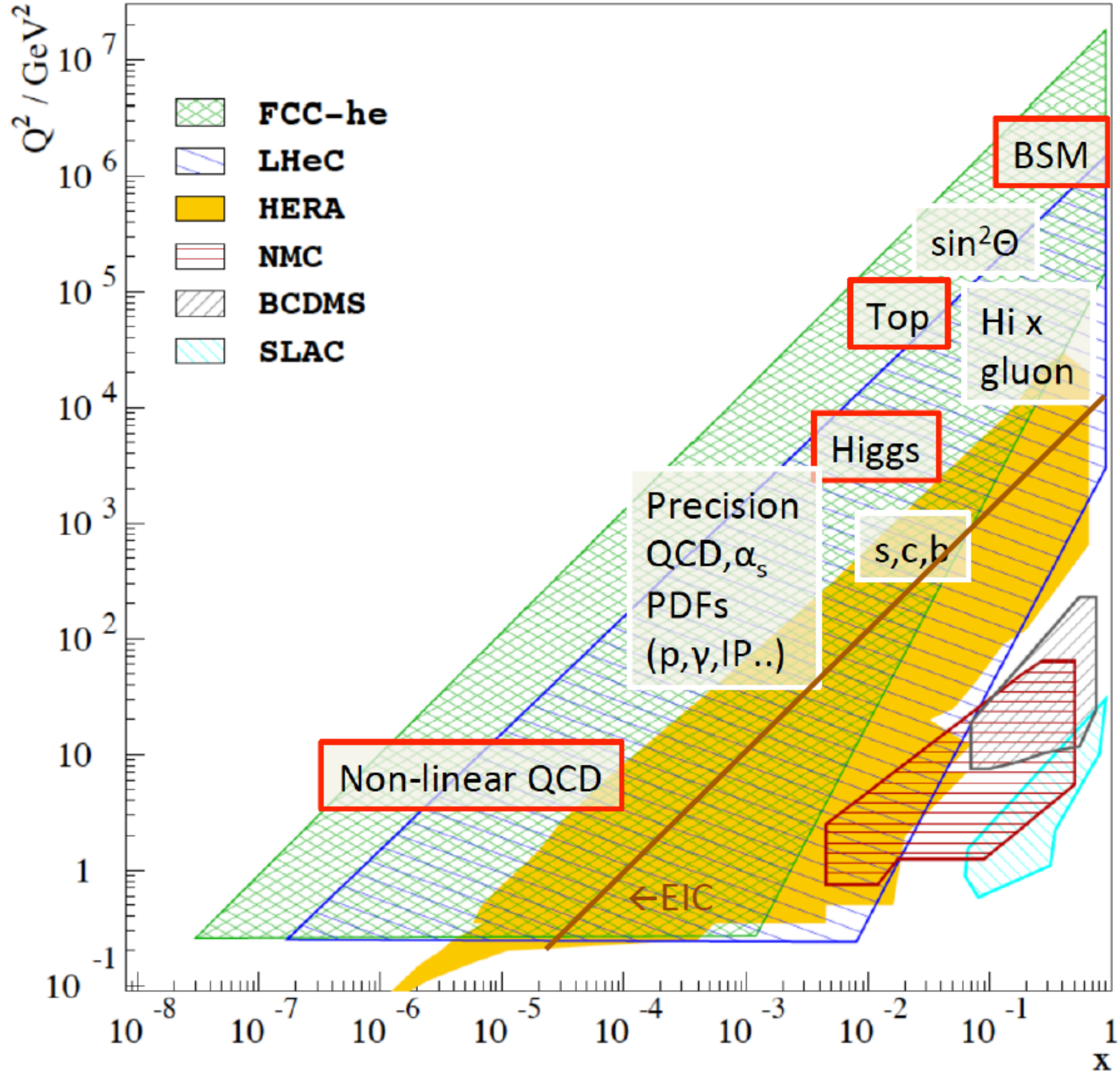
Tracker	FST_{pix}	FST_{strix}	CFT_{pix}	CPT_{pix}	CST_{strix}	CBT_{pix}	BST_{strix}	BST_{pix}
#Wheels	7		2	–	–	2	5	
#Rings/Wheel	2_{inner}	3_{outer}	3/4	–	–	3/4	3_{outer}	2_{inner}
#Layers	–	–	–	4	5	–	–	–
$\theta_{min/max}$ $[^0]$	0.5	3.8	3.6	5.1	24/155	176.4	173.1	179.3
$\eta_{max/min}$	5.4	3.4	3.5	$\pm$3.1	$\pm$1.4	-3.5	-2.8	-5.2
$Si_{pix/strix}$ $[m^2]$	9.7	13.3	2.8	5.4	33.7	2.8	9.7	6.9
Sum-Si $[m^2]$	84.3 double layers taken into account							

Calo	FHC_{SiW}	FEC_{SiW}	$EMC_{SciPb/LAr}$	HAC_{SciFe}	BEC_{SiPb}	BHC_{SiFe}
$\theta_{min/max}$ $[^0]$	0.3	0.4	5.6/173.4	8.6/167	179.4	179.6
$\eta_{max/min}$	6.0	5.6	3.0/-2.7	2.5/-2.2	-5.3	-5.6
Volume $[m^3]$	13.2	3.1	28.8	407	1.98	7.0
Sum-Si $[m^2]$	461					

Input to detector design: HERA, ATLAS/CMS+their upgrades, CALICE, LHeC (CDR and update)

At FCC-eh unlike LHeC we think muon momentum measurement is vital (H-μμ)

Next steps: final choice of CDR technology, IR integration, joint eh-hh consideration, software



Q² / GeV²
FCC-he
LHeC
HERA
NMC
BCDMS
SLAC
BSM
sin²Θ
Top
Hi x gluon
Higgs
Precision QCD,αs PDFs (p,γ,IP..)
s,c,b
Non-linear QCD
←EIC
x

Main eh Tasks for Completion of CDR

4 areas of activity

Accelerator: Update of the eh IR design for LHC/HE-LHC/FCC at 10^{34}

PERLE: Technical design and fabrication+test of an 802 MHz cavity

Detector: Update detector technology choice (collaboration with hh)

Physics: Update wrt LHC results and integration with hh+ee

Contributions to 4 FCC CDR Books (see M Benedikt today)

B1: Physics with the FCC (hh-he-ee)

B2: Summary of FCC-hh with integrated FCC-eh

B3: Details to B2

B6: HE LHC with eh (based on LHeC CDR Update B0)

a total of ~300 FCC pages

Electron-Hadron Scattering at the Energy Frontier –
A Higgs Physics Facility Resolving the Substructure of Matter

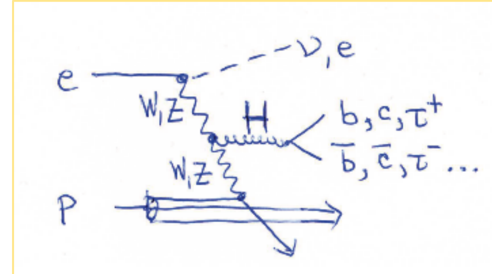
Draft Table of Contents

Update of the LHeC CDR*) and input to EU strategy, reference document for FCC-eh + HE LHC

*) arXiv:1206.2913

29.5.2017

From Higgs facility (LHeC) to Higgs 'factory' (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
1pb ep → νHX

Luminosity
> 10^{34} crucial
for H → HH
0.5 fb
and rare decays

Detector Magnets

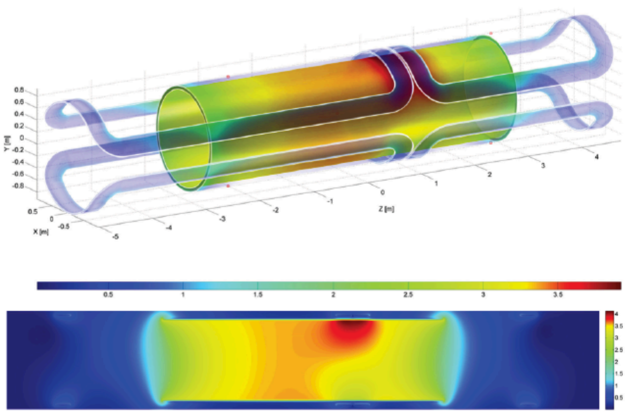


Figure 13.13: Magnetic field of the magnet system of solenoid and the two internal superconducting dipoles at nominal currents (effect of iron ignored). The position of the peak magnetic field of 3.9 T is local due to the adjacent current return heads on top of the solenoid where all magnetic fields add up.

Dipole (for head on LR) and solenoid in common cryostat, perhaps with electromagnetic LAr

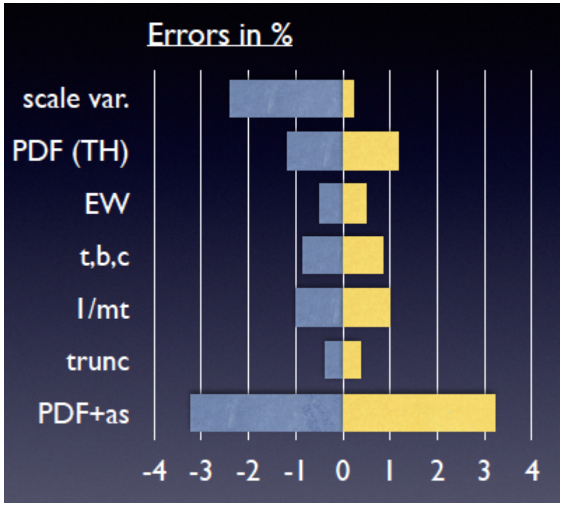
3.5T field at ~1m radius to house a Silicon tracker

Based on ATLAS+CMS experience

Property	Parameter	value	unit
Dimensions	Cryostat inner radius	0.900	m
	Length	10.000	m
	Outer radius	1.140	m
	Coil windings inner radius	0.960	m
	Length	5.700	m
	Thickness	60.0	mm
	Support cylinder thickness	0.030	m
	Conductor section, Al-stabilized NbTi/Cu + insulation	30.0×6.8	mm^2
	Length	10.8	km
	Superconducting cable section, 20 strands	12.4×2.4	mm^2
	Superconducting strand diameter Cu/NbTi ratio = 1.25	1.24	mm
Masses	Conductor windings	5.7	t
	Support cylinder, solenoid section + dipole sections	5.6	t
	Total cold mass	12.8	t
	Cryostat including thermal shield	11.2	t
	Total mass of cryostat, solenoid and small parts	24	t
Electro-magnetics	Central magnetic field	3.50	T
	Peak magnetic field in windings (dipoles off)	3.53	T
	Peak magnetic field in solenoid windings (dipoles on)	3.9	T
	Nominal current	10.0	kA
	Number of turns, 2 layers	1683	
	Self-inductance	1.7	H
	Stored energy	82	MJ
	E/m, energy-to-mass ratio of windings	14.2	kJ/kg
	E/m, energy-to-mass ratio of cold mass	9.2	kJ/kg
	Charging time	1.0	hour
	Current rate	2.8	A/s
	Inductive charging voltage	2.3	V
Margins	Coil operating point, nominal / critical current	0.3	
	Temperature margin at 4.6 K operating temperature	2.0	K
	Cold mass temperature at quench (no extraction)	~ 80	K
Mechanics	Mean hoop stress	~ 55	MPa
	Peak stress	~ 85	MPa
Cryogenics	Thermal load at 4.6 K, coil with 50% margin	~ 110	W
	Radiation shield load width 50% margin	~ 650	W
	Cooling down time / quench recovery time	4 and 1	day
	Use of liquid helium	~ 1.5	g/s

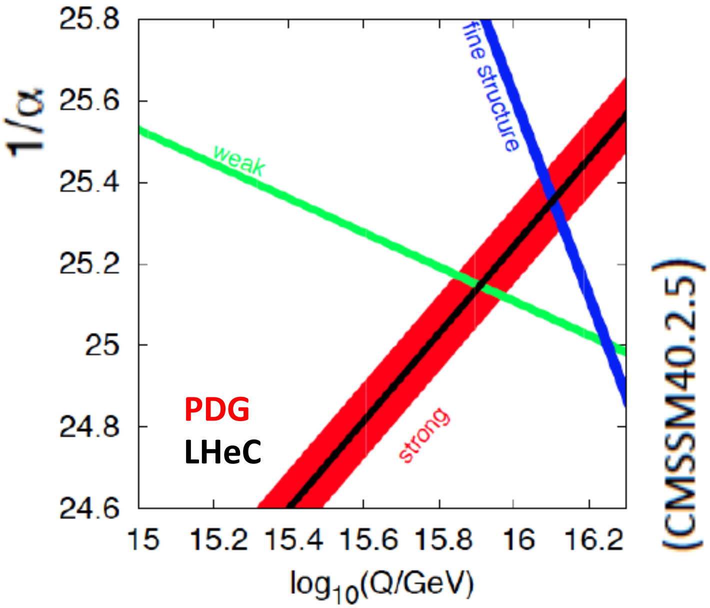
Table 13.1: Main parameters of the baseline LHeC Solenoid providing 3.5 T in a free bore of 1.8 m.

Strong Coupling Constant



Uncertainty on Higgs cross section
Giulia Zanderighi, Vietnam 9/16,
from C.Anastasiou et al, 1602.00695
who also discuss the ABM alpha_s..

- **α_s least known of coupling constants**
  Grand Unification predictions need smaller $\delta\alpha_s$
- **Is α_s(DIS) lower than world average (?)**
- **LHeC: per mille - independent of BCDMS!**
- **High precision from inclusive data – α_s(jets)??**
- **Challenge lattice QCD**



LHeC simulation, NC+CC inclusive, total exp error

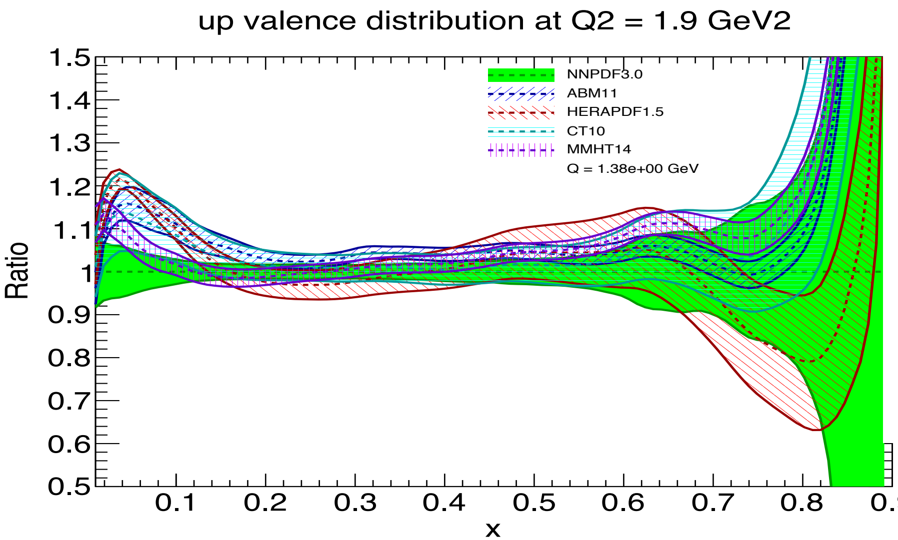
case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 >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

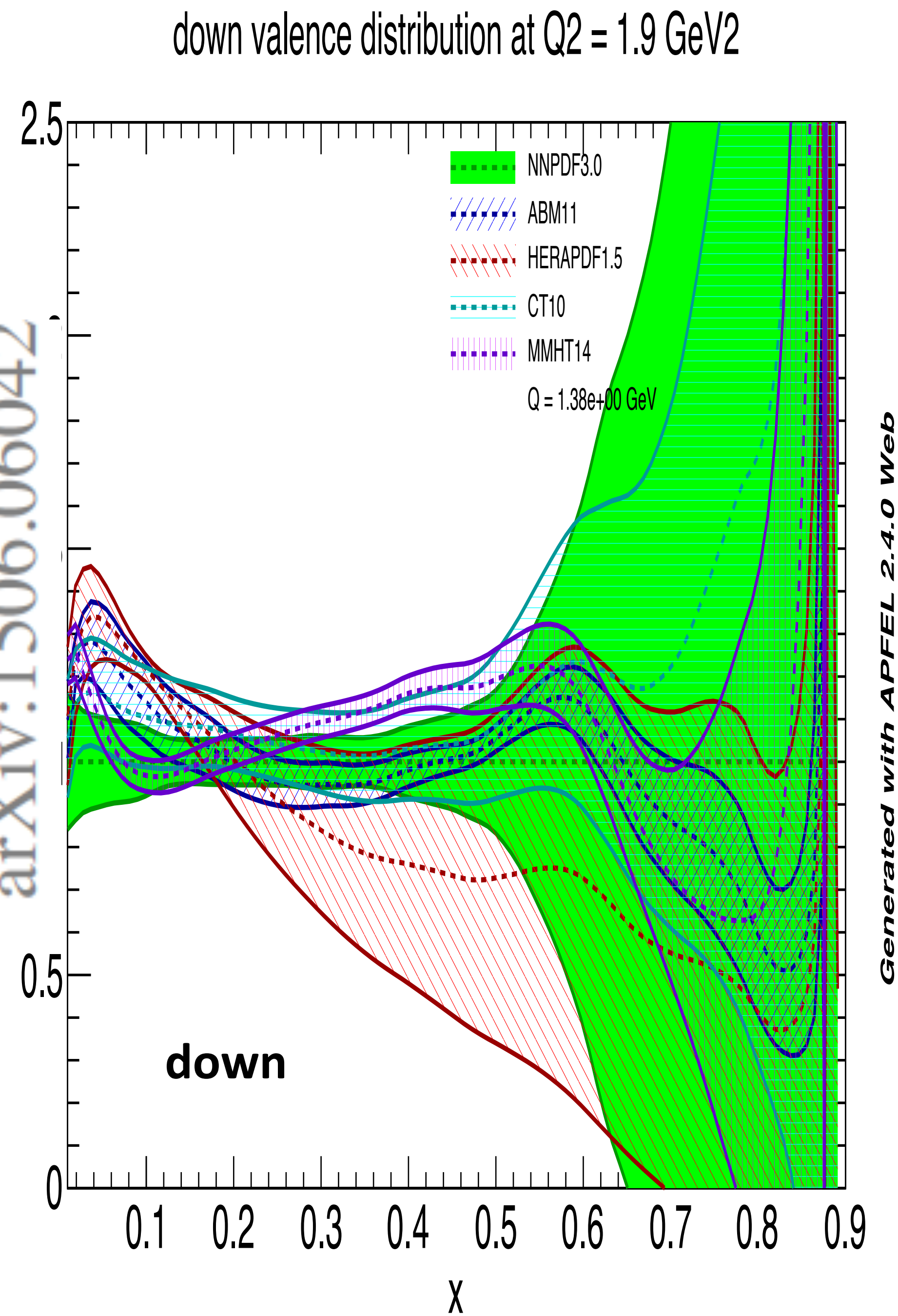
Two independent QCD analyses using LHeC+HERA/BCDMS

Valence quarks

High x crucial for HL LHC searches
Related to DrellYan , W mass etc
d/u → 1 a classic question, still there

up





Valence quarks

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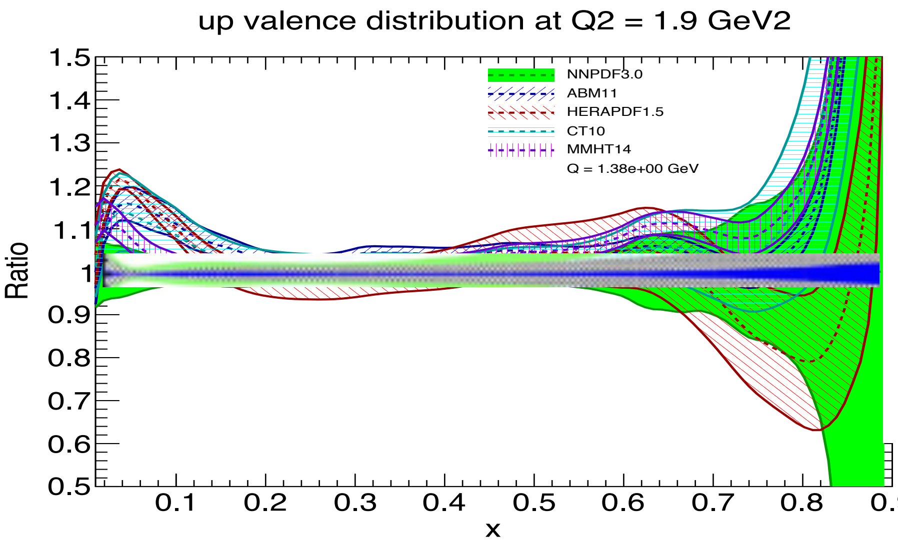
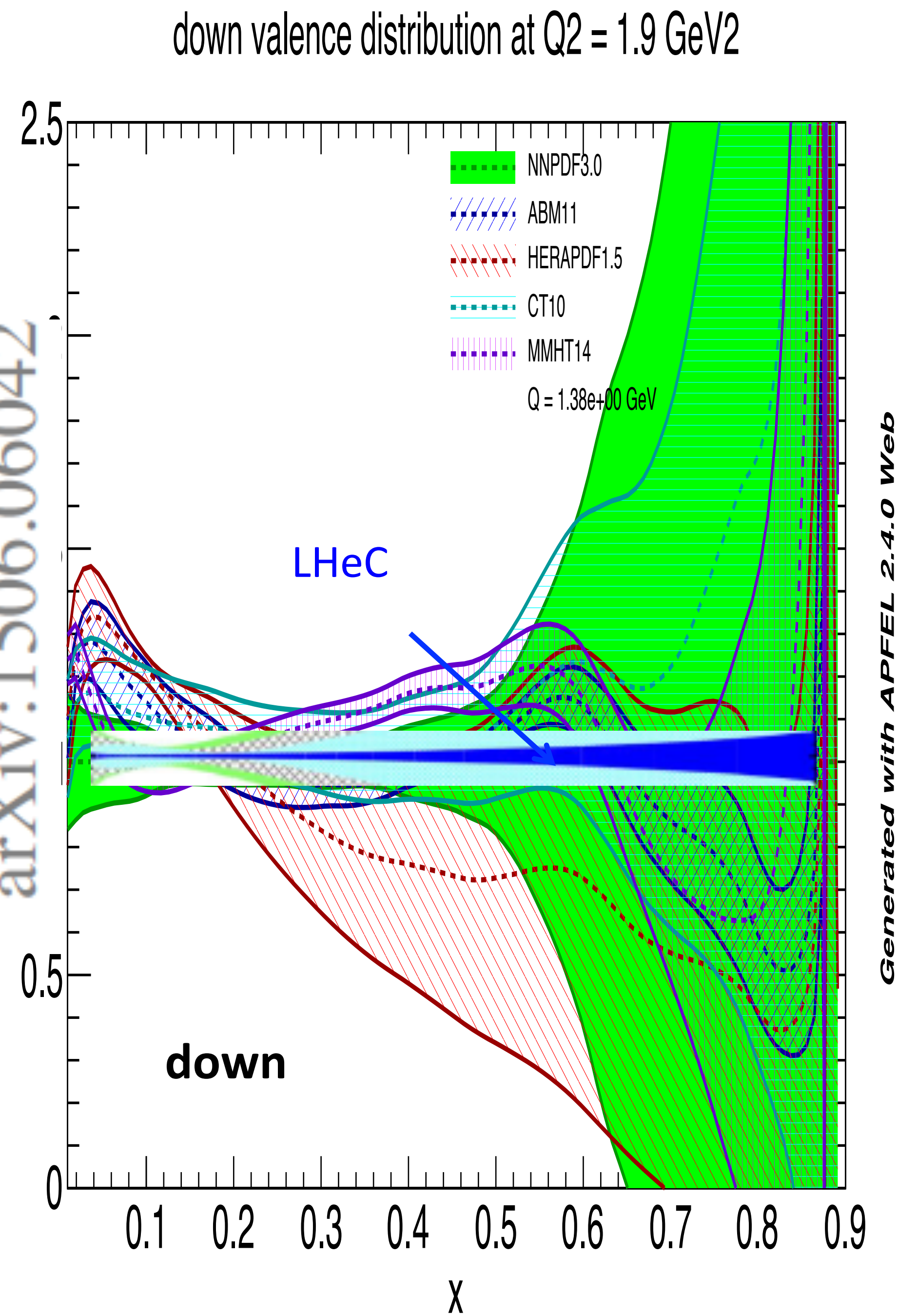
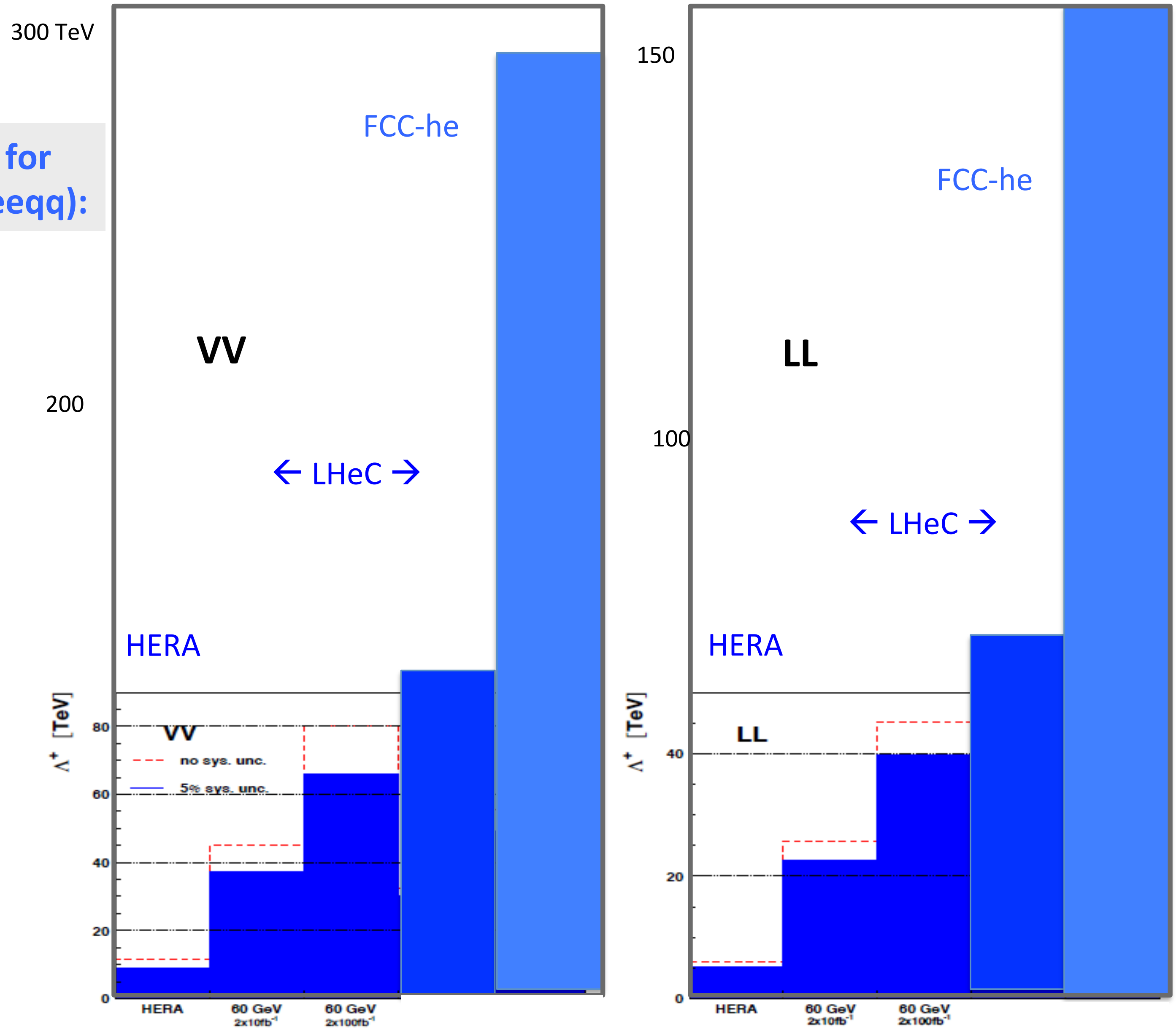




Reach for Λ (CI eeqq):

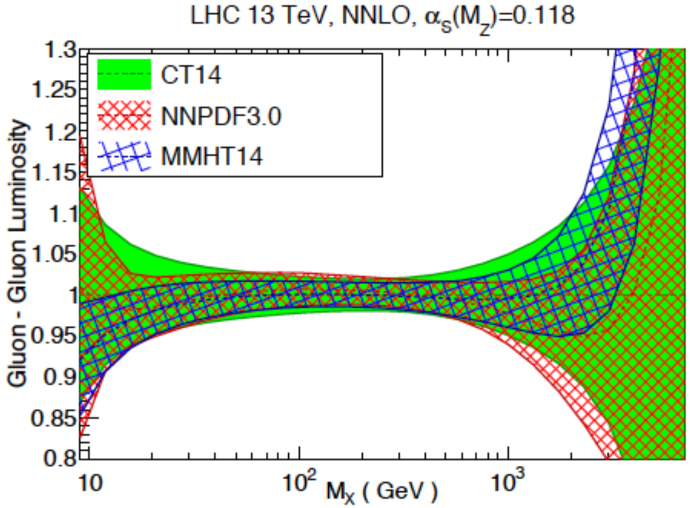


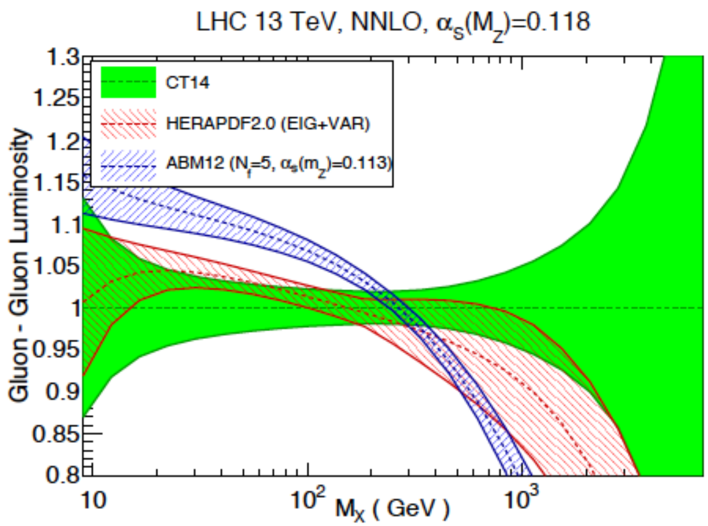
LHeC: see CDR 2012

FCC - rough scaling only – very preliminary

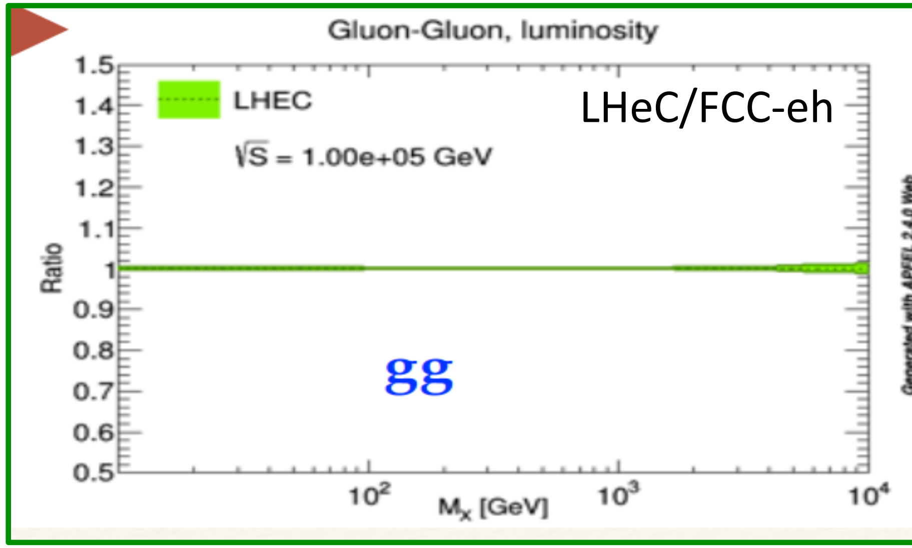
Gluon (gg) Luminosity

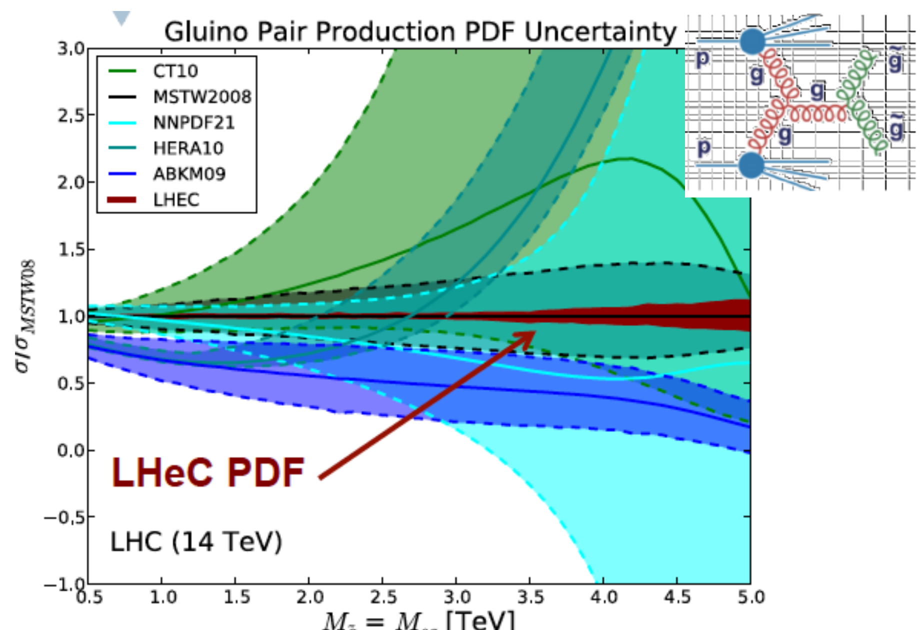
Present status





gg → H dominant process in pp
Crucial for SUSY searches/limits





arXiv:1211.5102

PERLE Intention

D. Angal-Kalinin[3], G. Arduini[1], B. Auchmann[1], J. Bernauer[10], A. Bogacz[4], F. Bordry[1], S. Bousson[9], C. Bracco[1], O. Brüning[1], R. Calaga[1], K. Cassou[2], V. Chetvertkova[1], E. Cormier[6], E. Daly[4], D. Douglas[4], K. Dupraz[2], B. Goddard[1], J. Henry[4], A. Hutton[4], E. Jensen[1], W. Kaabi[2], M. Klein[5], P. Kostka[5], F. Marhauser[4], A. Martens,[2], A. Milanese[1], B. Militsyn[3], Y. Peinaud[2], D. Pellegrini[1], N. Pietralla[8], Y.A. Pupkov[7], R. A. Rimmer[4], K. Schirm[1], D. Schulte[1], S. Smith[3], A. Stocchi[2], A. Valloni[1], C. Welsch[5], G. Willering[1], D. Wollmann[1], F. Zimmermann[1], F. Zomer[2]

Authors of the CDR, but many further colleagues attended the TDR kickoff

The CDR is an expression of interest in: ERL, low energy electron and photon physics, technology development (high quality SCRF), development of the LHeC/FCC-eh etc

It is considered to be a technical facility first but has the potential to become a major user physics and technology development facility then with unique parameters, such as the orders of magnitude increased photon beam intensity wrt ELI now.

Low x

xg for $x < 10^{-4}$ not known, it is not unknown above.

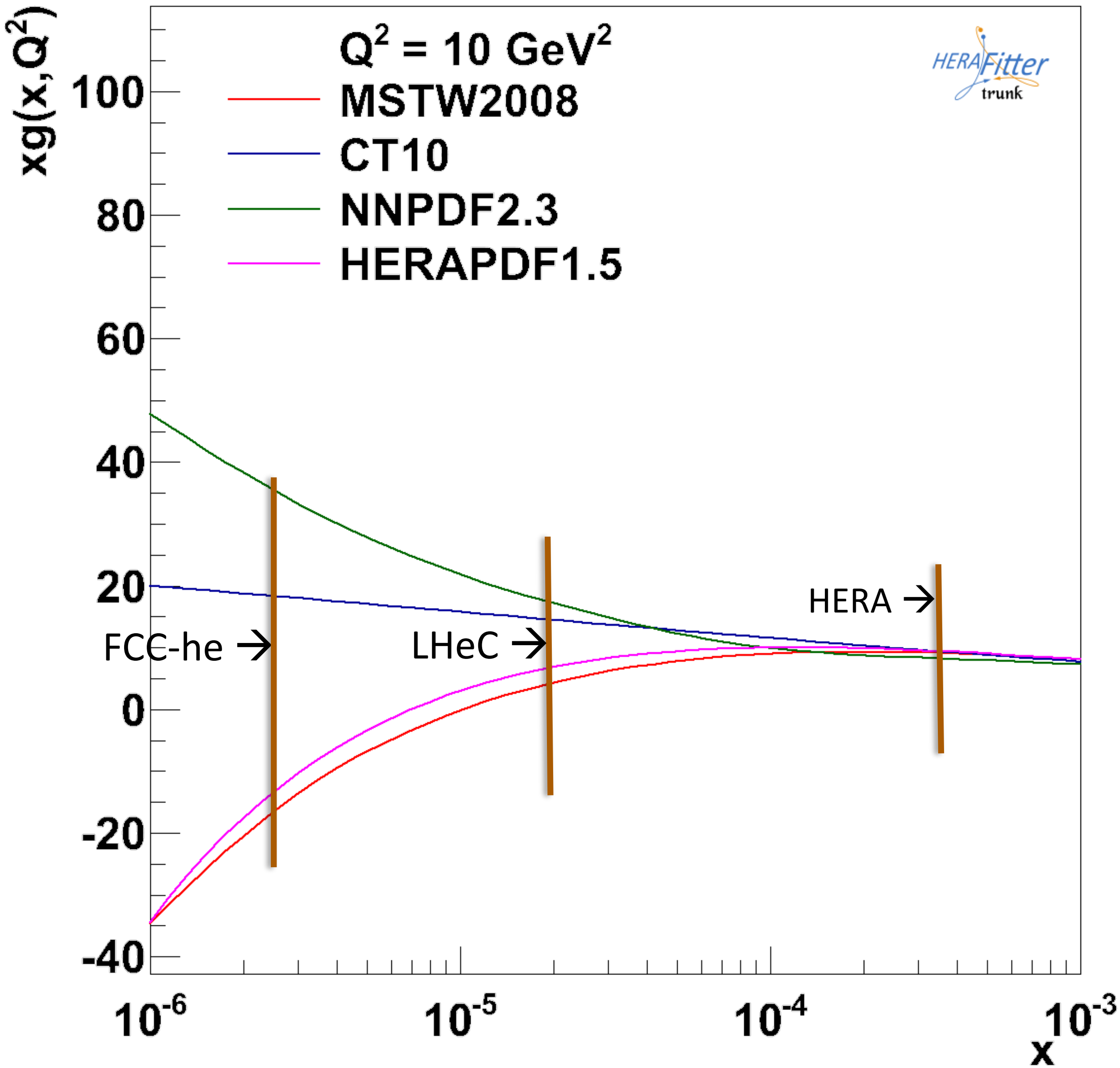
Low x evolution law unlikely linear DGLAP

HERA: where is BFKL?

Needs precision F_2 and F_L in extended x range

Search for Saturation requires xg to be large and α_s to be small → Q^2 ought to be > 10 GeV^2

Affects pp rates because $x=M/\sqrt{s} \exp(\pm y)$



title