Alternative Futures for CERN: The Large Hadron-electron Collider

Paul Newman (Birmingham)

Alternatives Meeting
Imperial College, 24 September 2024

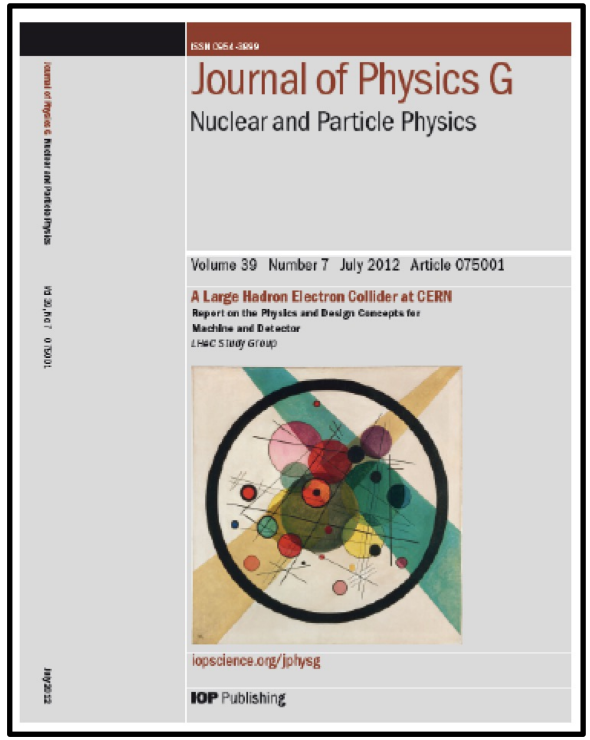
An overview of the project, its context & physics programme

… see also

Oliver:	The LHeC machine
Nick, Loukas, Greg:	Expert consideration of Higgs, EW and flavour/top capabilities

Max Klein

13/5/1951 – 23/8/2024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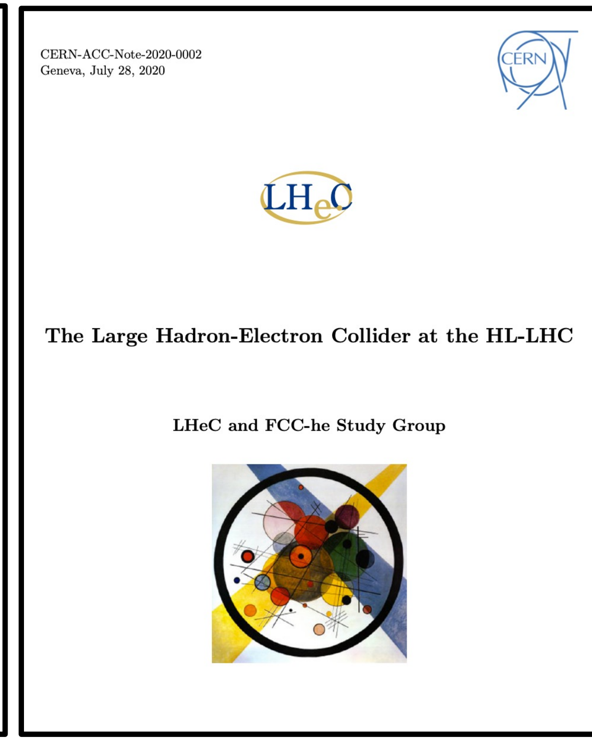
A Large Hadron Electron Collider at CERN
Report on the Physics and Design Concepts for Machine and Detector
LHeC Study Group
iopscience.org/jphysg
IOP Publishing

arXiv:1206.2913


CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

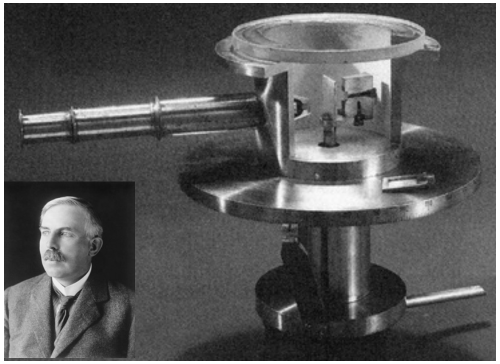
The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

arXiv:2007.14491

2008 2009 2010 2012 2014 2015 2017 2018 2019 2022

Scattering Experiments Exploring Matter

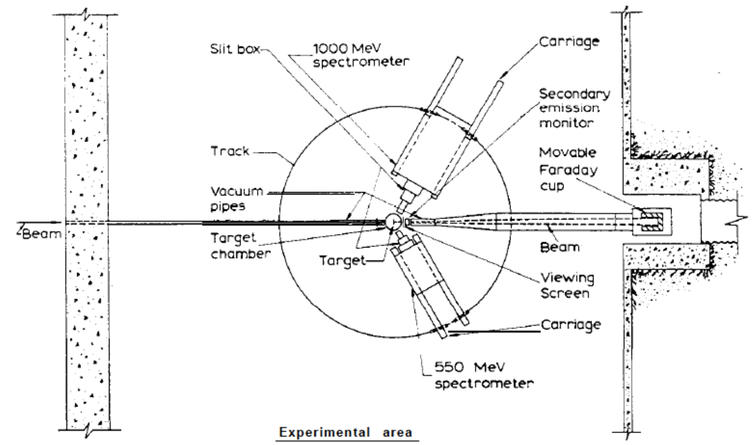


Rutherford, 1926

"It would be of great scientific interest if it were possible to have a supply of electrons … of which the individual energy of motion is greater even than that of the alpha particle."

1950s, Hofstadter, 200 MeV electrons on fixed targets

First observation of finite proton size



1969, SLAC, 20 GeV electrons on fixed targets

Absence of dependence of (suitably expressed) cross section on q^2 (= squared 4 momentum transfer) implies scattering from point-like quarks

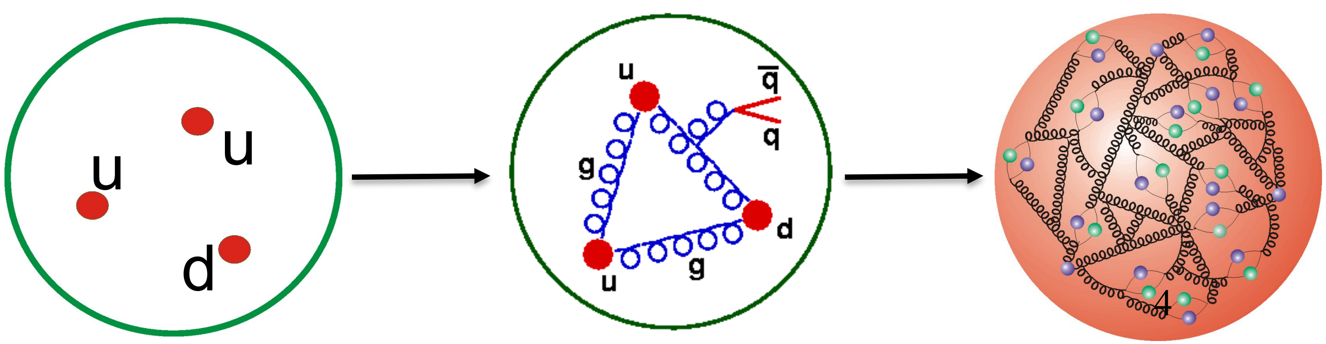
- The only ever collider of electron with proton beams:
  $\sqrt{s_{ep}} \sim 300$ GeV

- Equivalent to **50 TeV** electrons on fixed target

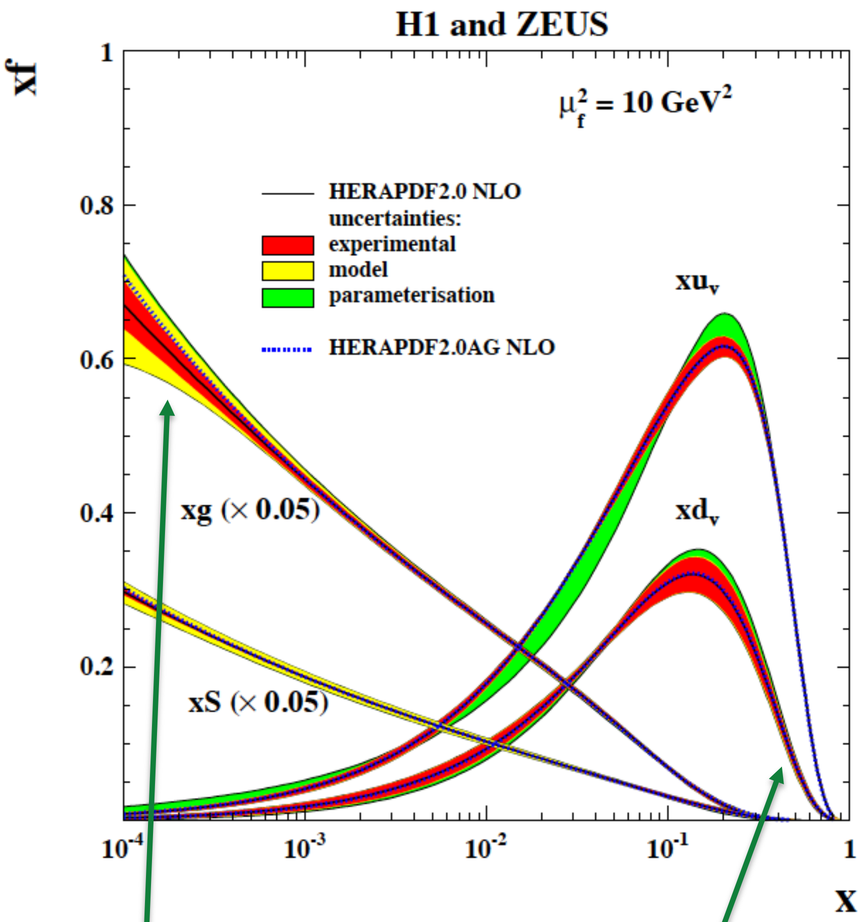
… Resolved dimension
  ~ 10^{-20} m

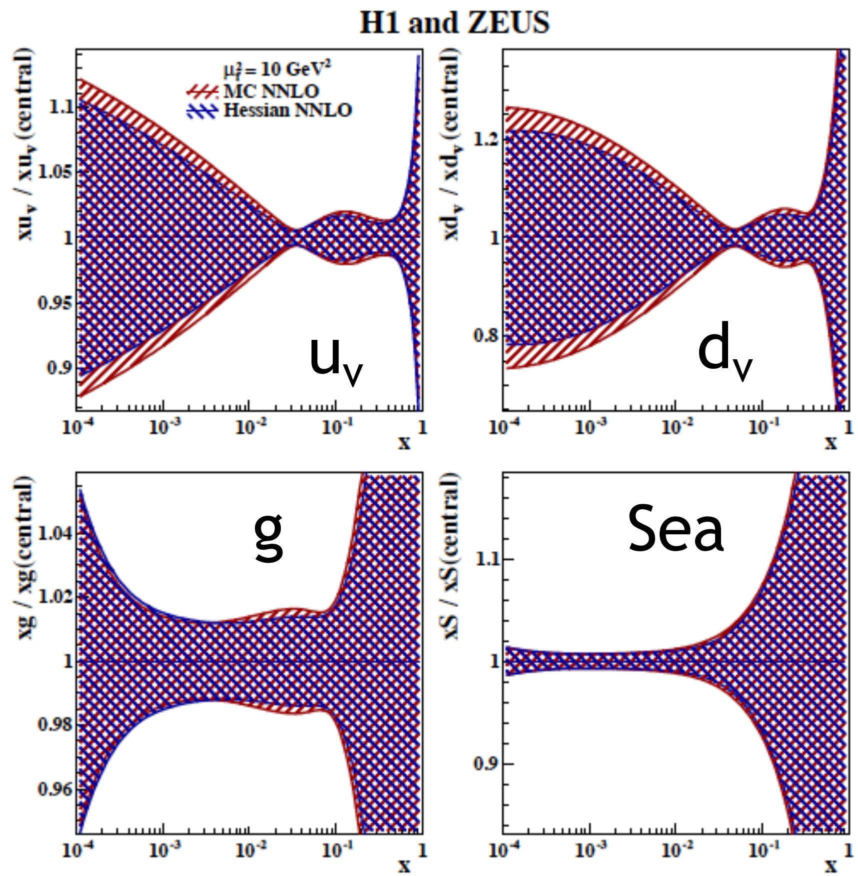
→ Source of much of our knowledge of proton (longitudinal) structure extending to partons of $x<10^{-4}$ mom^{m} fraction

BUT …
→ Only ~0.5 fb^{-1} per experiment
→ No deuterons or nuclei
→ No polarised targets



Proton PDFs from HERA (HERAPDF2.0)





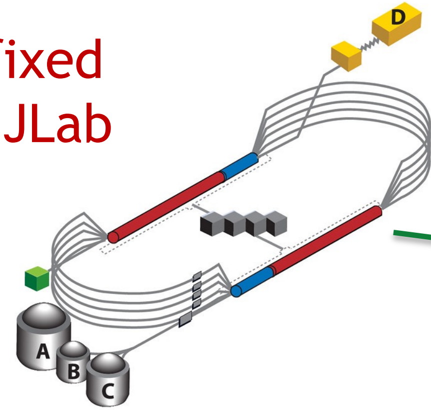
Strong interaction dragons?

Input to energy frontier discovery?

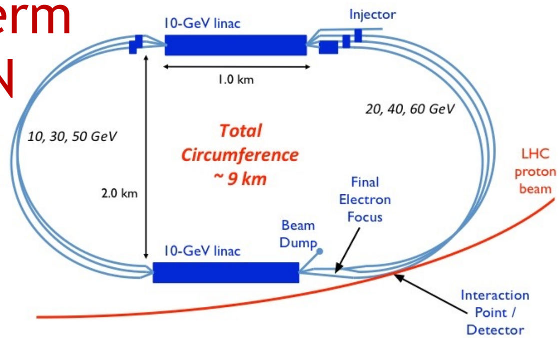
- At x ~ 10^{-2} : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below x=10^{-3} (kinematic limit)
  - above x=10^{-1} (limited lumi)

Current and Future ep Colliders

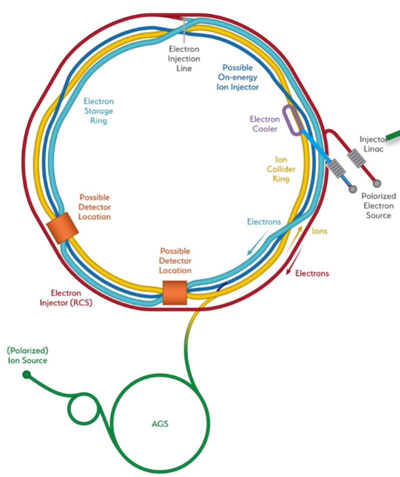
Ongoing fixed target @ JLab

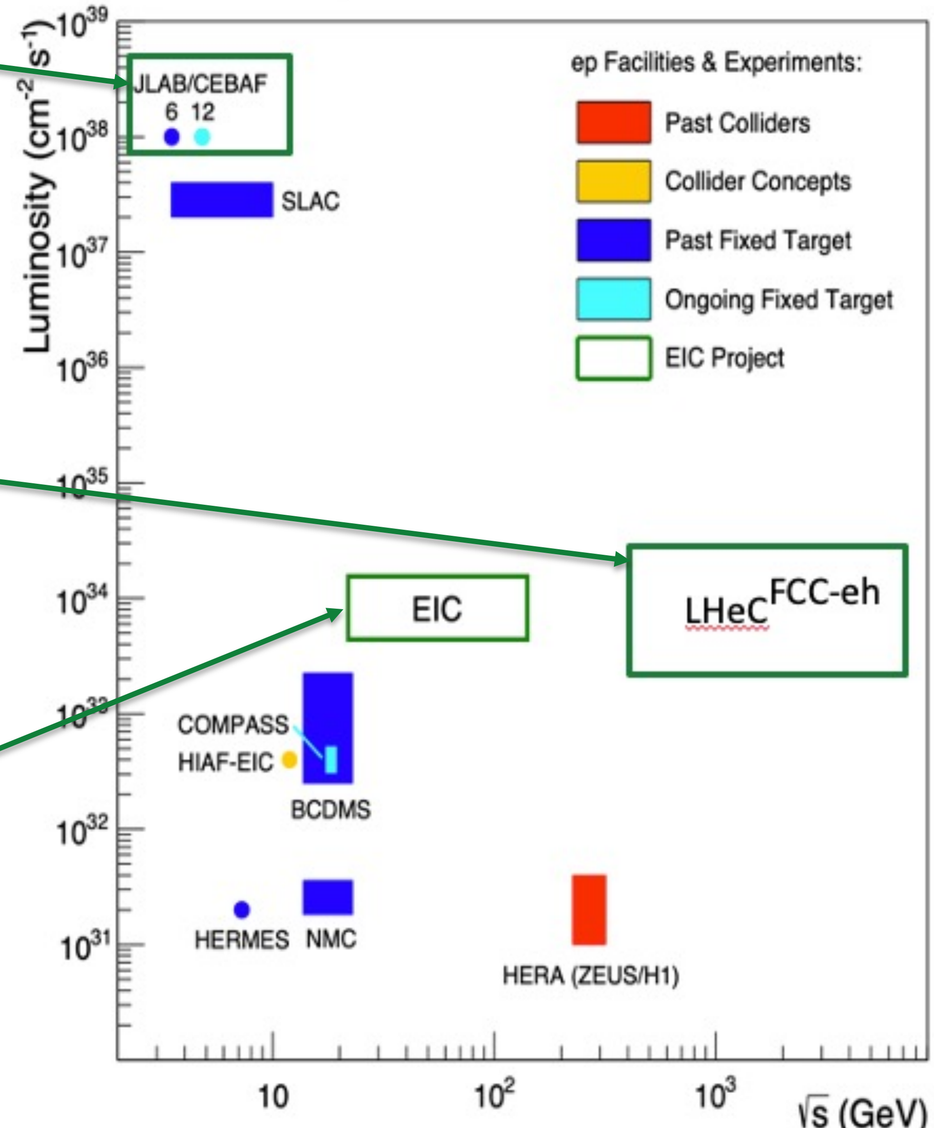


Longer-term @ CERN



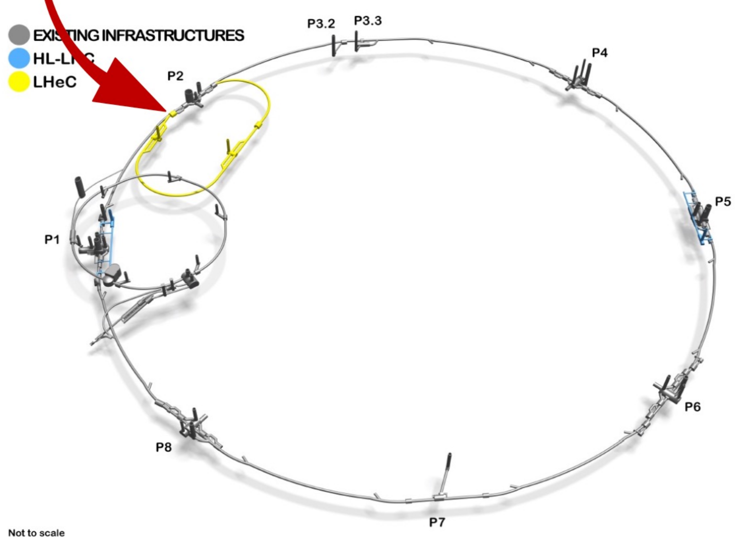
On-target for early 2030s @ BNL



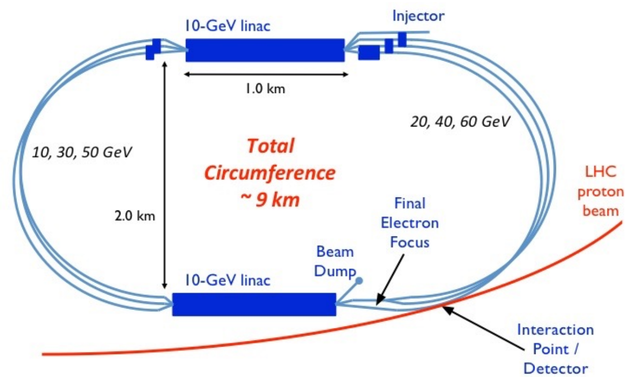


Overview: LHeC and Energy Recovery Linacs

LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)



- Recirculating Energy-Recovery Linac (ERL) colliding with LHC (or FCC) hadrons

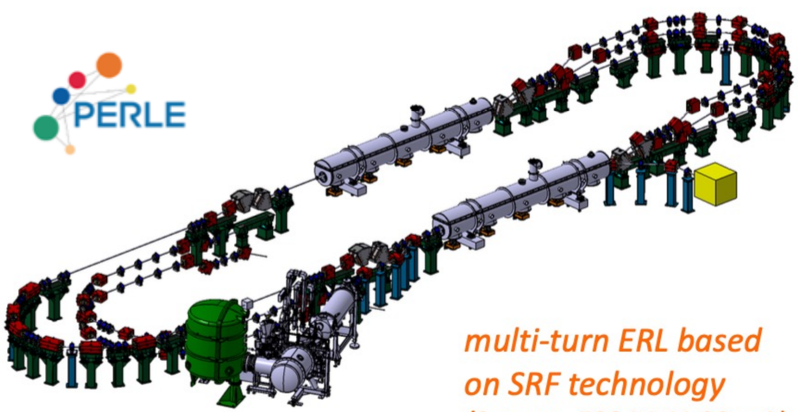


- ‘Sustainable’ acceleration (~100 MW; similar to LHC today)

- Technology development for electron machines or injectors

- ERL Prototype (PERLE @ IJCLab/Orsay) Implementation started. First stage (one turn) by 2028.

PERLE



multi-turn ERL based on SRF technology (3-turns, 500 MeV, 20 mA)

CDR: *J.Phys.G* 45 (2018) 6, 065003

Running Scenarios Considered in CDR

- $e^{\pm}p$ 50 GeV x 7 TeV with lepton polarization +0.8 / 0 / -0.8

Parameter	Unit	Run 5 Period	Run 6 Period	Dedicated
Brightness $N_p/(\gamma\epsilon_p)$	10^{17}m^{-1}	2.2/2.5	2.2/2.5	2.2/2.5
Electron beam current	mA	15	25	50?
Proton β^*	m	0.1	0.7	0.7
Peak luminosity	$10^{34}\,\text{cm}^{-2}\text{s}^{-1}$	0.5	1.2	2.4
Proton beam lifetime	h	16.7	16.7	100
Fill duration	h	11.7	11.7	21
Turnaround time	h	4	4	3
Overall efficiency	%	54	54	60
Physics time / year	days	160	180	185
Annual integrated lumi.	fb^{-1}	20	50	180

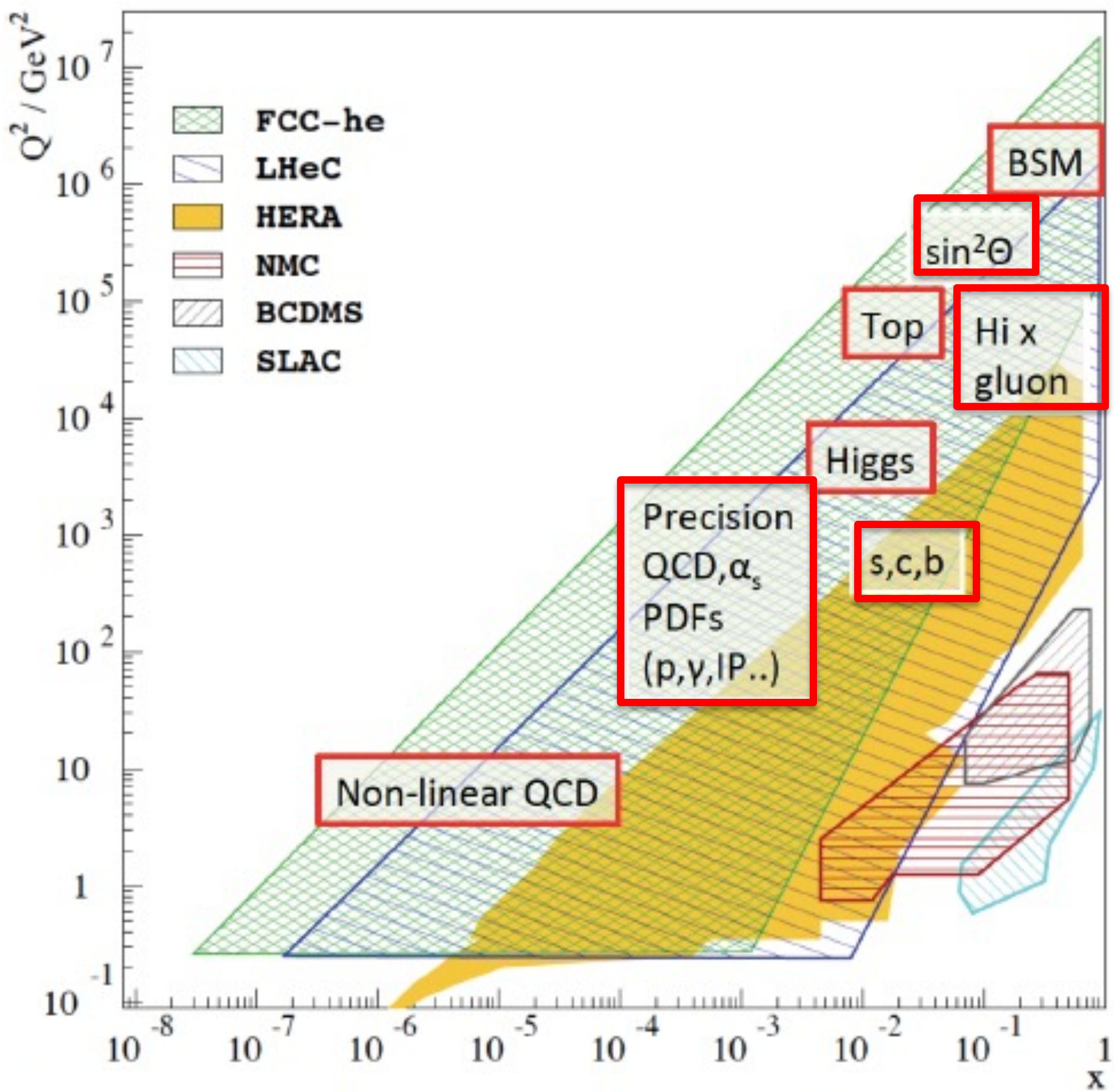
[Pile-up ~0.1]

Running concurrently with pp at HL-LHC:
… integrated lumi of 20 fb-1 per year at Run 5 → 50 fb^{-1} initial dataset
… integrated lumi of 50 fb-1 per year at Run 6 → few 100 fb^{-1} total @ HL-LHC

Running in standalone ep mode:
… integrated lumi of 180 fb-1 per year → 1 ab^{-1} total target in a few years

- eA 50 GeV x 2.76 TeV at 10 fb-1 per year

LHeC Physics Targets and Detector Implications



Standalone Higgs, Top, EW, BSM programme

→ General purpose particle physics detector
→ Good performance for all high p_T particles
→ Heavy Flavour tagging

Precision proton PDFs, including very low x parton dynamics in ep,eA

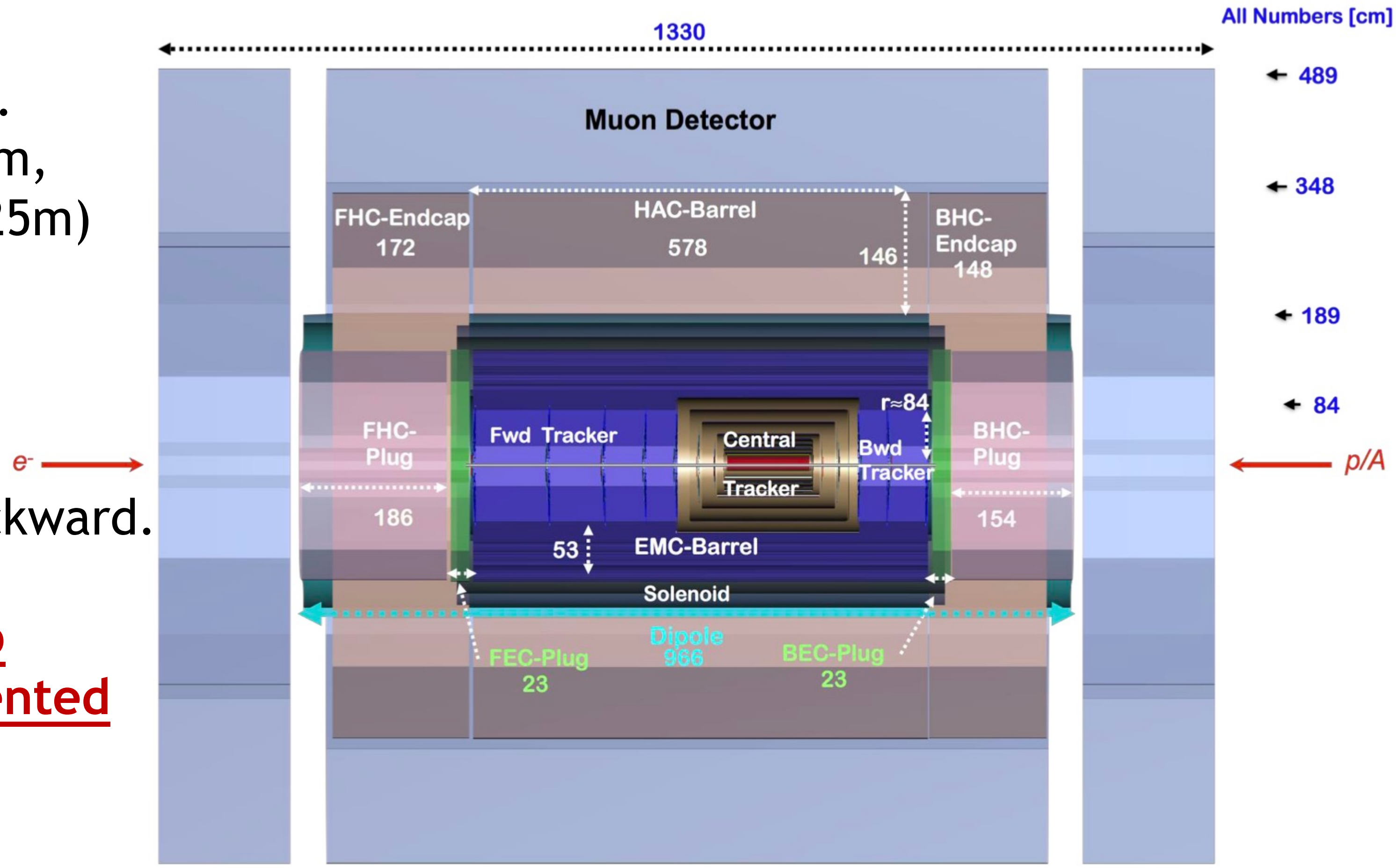
→ Dedicated DIS exp't
→ Hermeticity
→ Hadronic final state resolution for kinematics
→ Flavour tagging / PID
→ Beamline instruments

Detector Overview (as in 2020 CDR Update)

<u>Compact</u>
13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)

<u>Hermetic</u>
- 1° tracking acceptance forward & backward.

<u>Beamline also well instrumented</u>



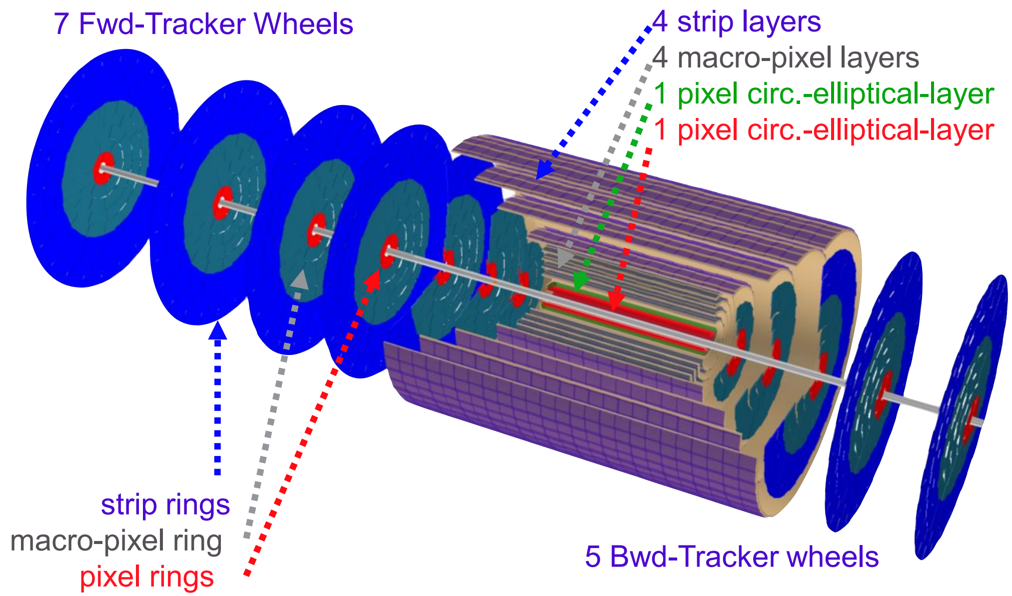
<u>'Could be built now', but many open questions:</u>
- A snapshot in time, borrowing heavily from (HL)-LHC (particularly ATLAS)
- Possibly lacking components for some ep/eA physics (eg. Particle ID)
- Not particularly well integrated or optimized

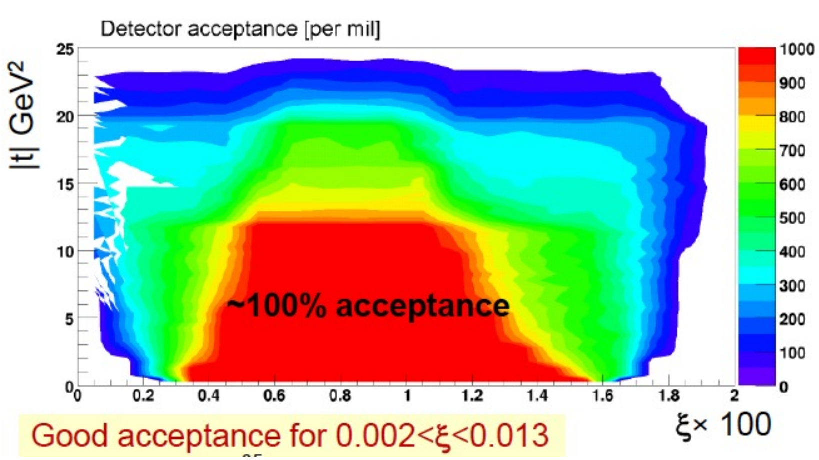
<u>… Synergies with EIC, LHCb, ALICE, future lepton colliders still to be explored</u>

Detector technologies build on LHC and EIC and inform future lepton colliders

e.g. Silicon tracker design in CDR

- HV-CMOS MAPS with bent / stitched wafers (as ALICE and ePIC) and semi-elliptical inner layers to cope with synchrotron fan → ~20% X_0 / layer up to η~4.5





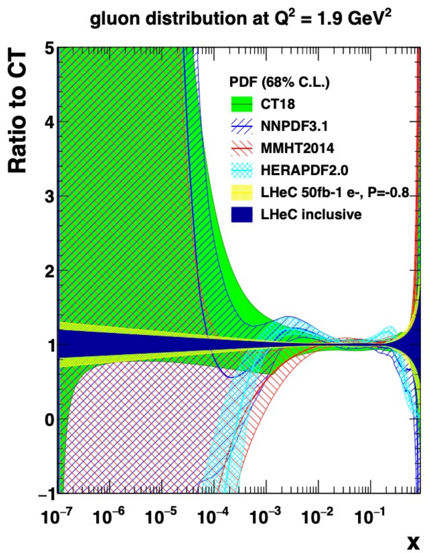
e.g. Forward proton spectrometer in cold region (~420m)?

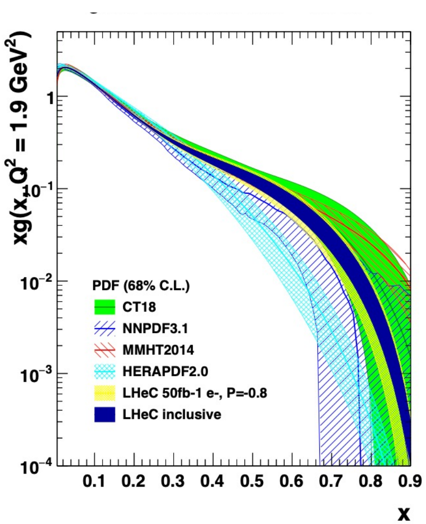
- Reuse of technology proposed for LHC, accessing protons scattered at very low momentum loss

The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC

Revolutionary Proton PDF Precision

e.g. High x
Gluon Density



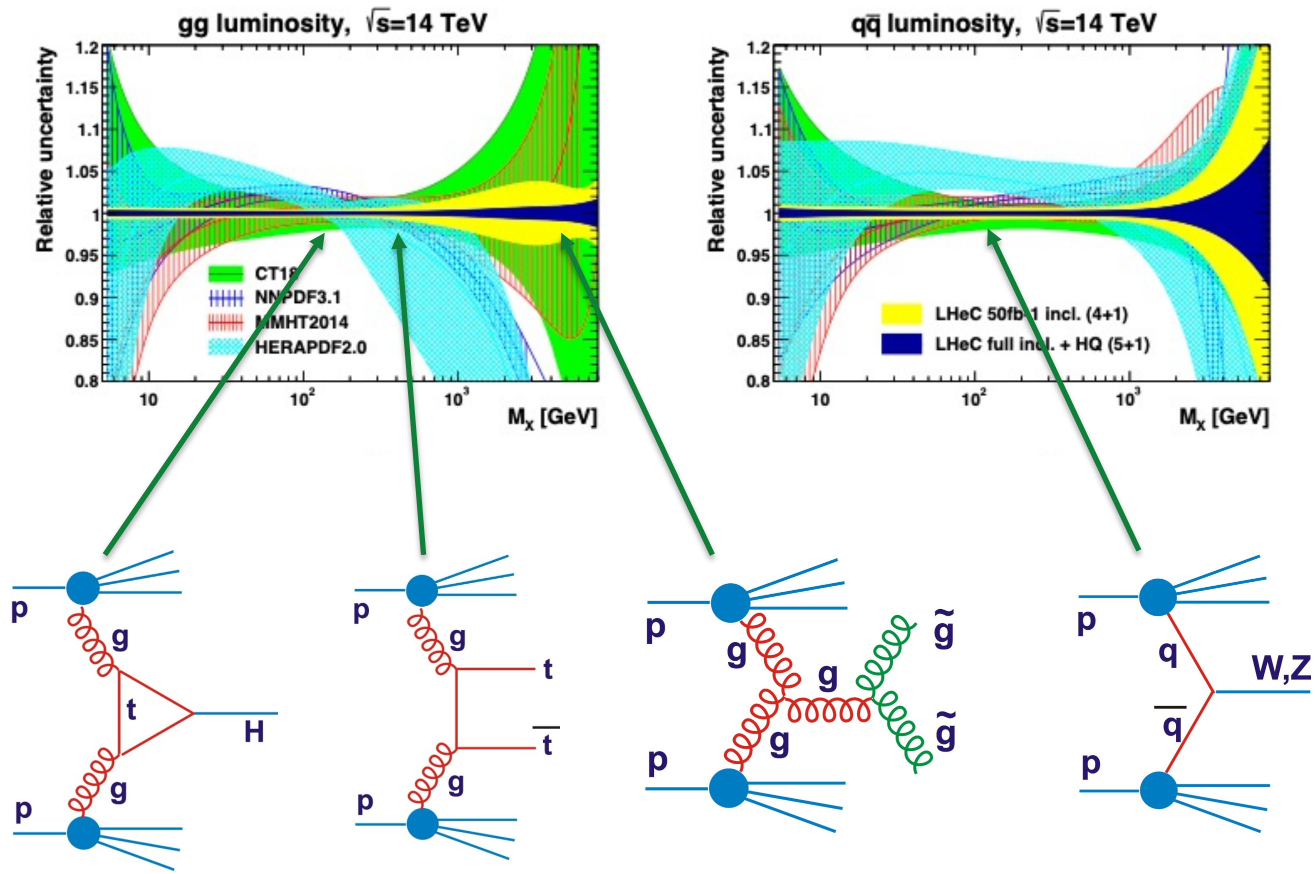


→ Facilitates LHC / FCC-hh precision measurements and BSM searches

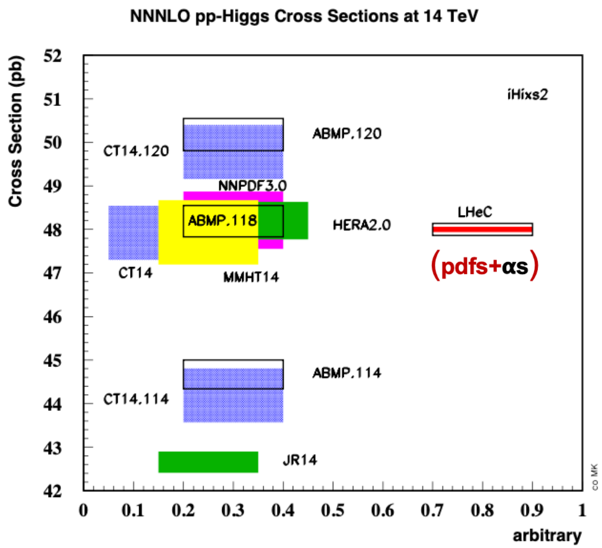
→ Elucidates novel very low x dynamics

→ Simultaneously α_s to 0.2% experimental error

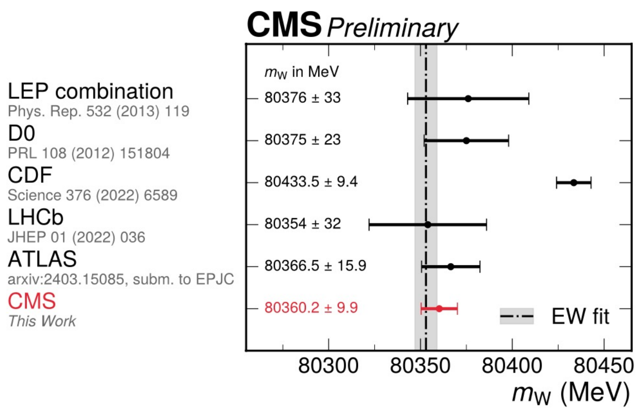
e.g. Parton luminosities for pp at 14 TeV



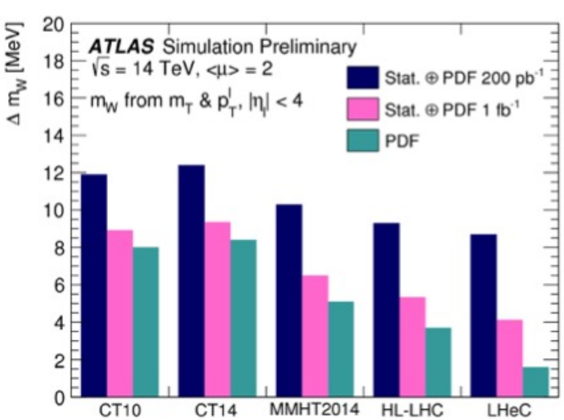
LHeC PDFs Empowering LHC



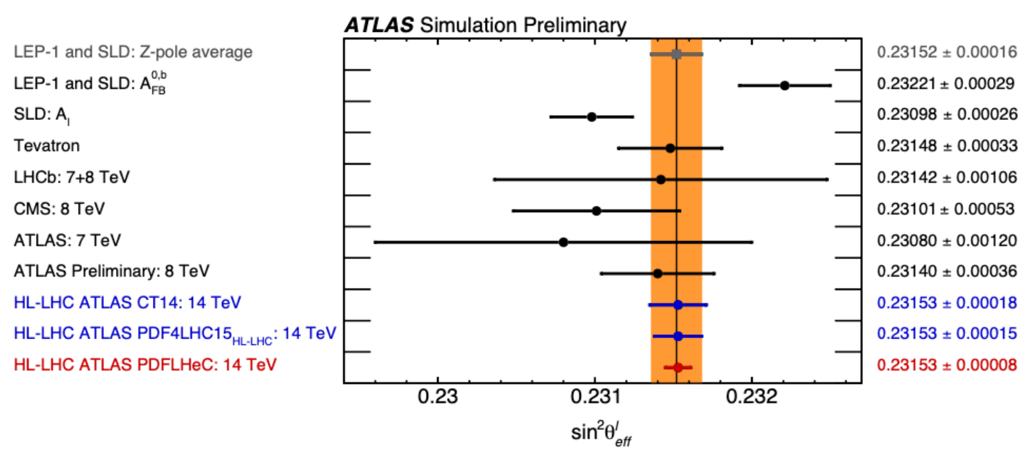
- Theory uncertainty on LHC Higgs production cross section improves dramatically compared with current PDF and α_s knowledge.



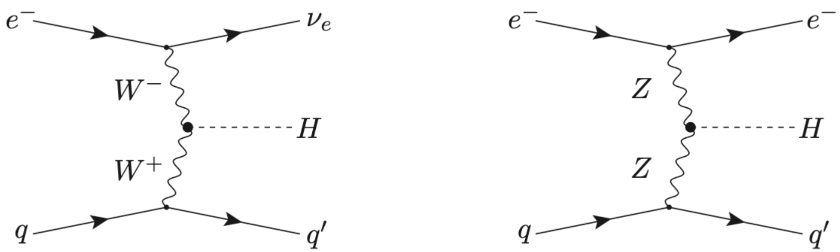
- PDF-related systematics on EW measurements are significant (e.g. LHeC enables $\sin^2\theta$ → 0.03% and reduces δ_{PDF} on M_W → 2 MeV in ATLAS studies)



- Many BSM scenarios ultimately limited by high x PDFs



LHeC (SM) Higgs Programme



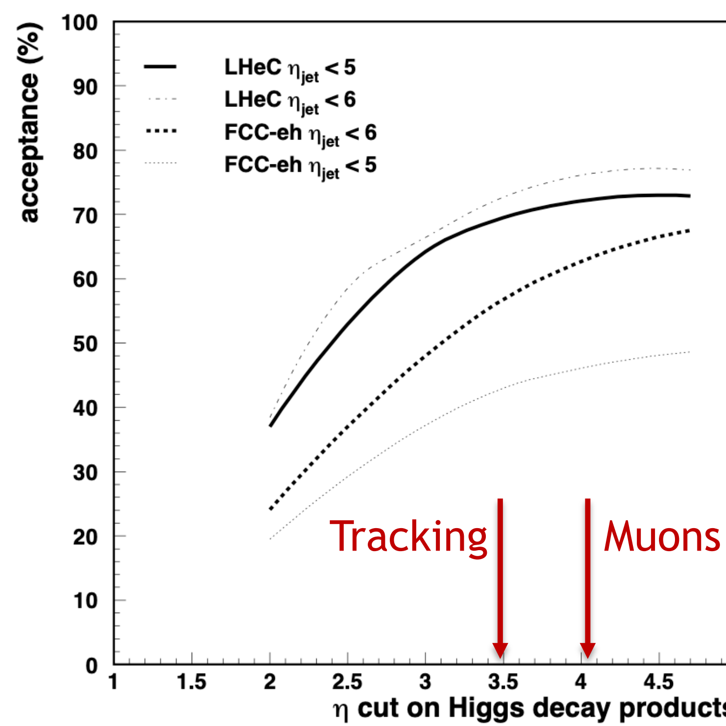
- Dominant production mechanism is charged current (WW)

- Easily distinguished from sub-dominant neutral current (ZZ)

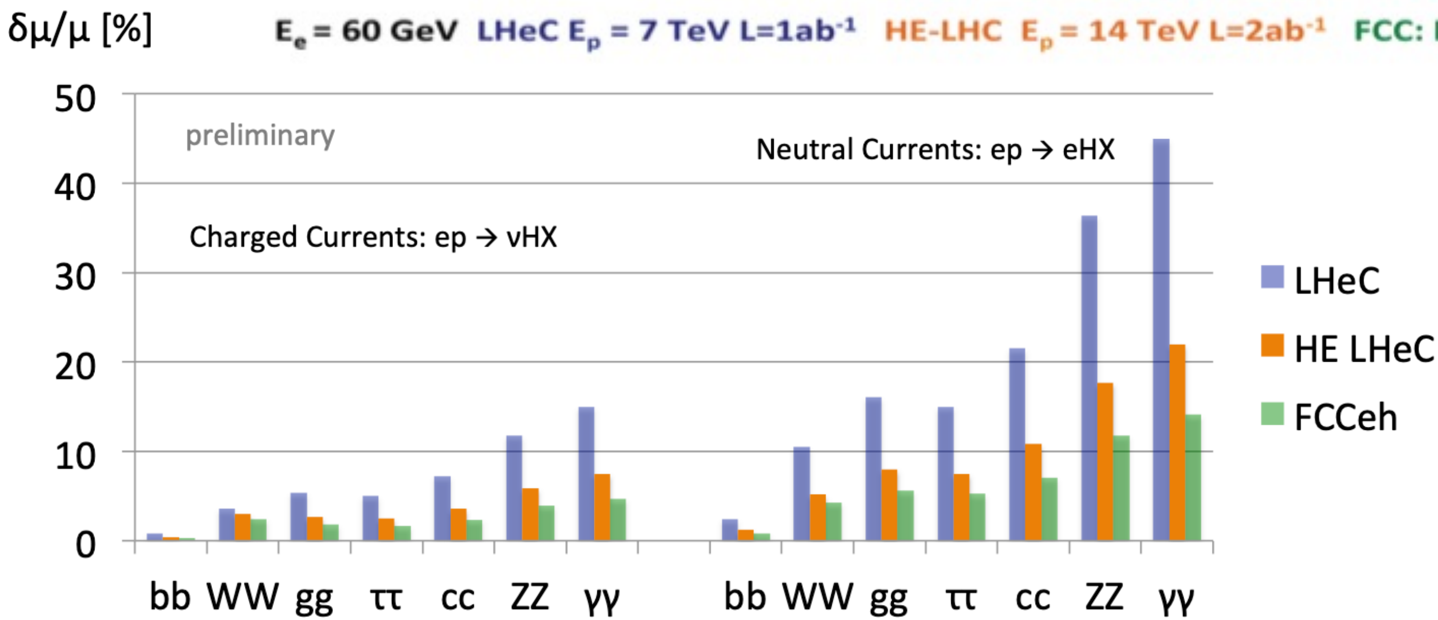
- Full details of simulated analyses of multiple channels in CDR

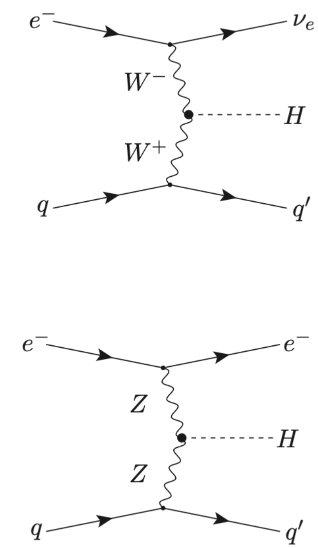
Yields for $1ab^{-1}$ (LHeC), $2ab^{-1}$ (FCC-eh) P=-0.8

		Number of Events			
		Charged Current		Neutral Current	
Channel	Fraction	LHeC	FCC-eh	LHeC	FCC-eh
$b\bar{b}$	0.581	114 500	1 208 000	14 000	175 000
W^+W^-	0.215	42 300	447 000	5 160	64 000
gg	0.082	16 150	171 000	2000	25 000
$\tau^+\tau^-$	0.063	12 400	131 000	1 500	20 000
$c\bar{c}$	0.029	5700	60 000	700	9 000
ZZ	0.026	5 100	54 000	620	7 900
$\gamma\gamma$	0.0023	450	5 000	55	700
$Z\gamma$	0.0015	300	3 100	35	450
$\mu^+\mu^-$	0.0002	40	410	5	70
σ [pb]		0.197	1.04	0.024	0.15



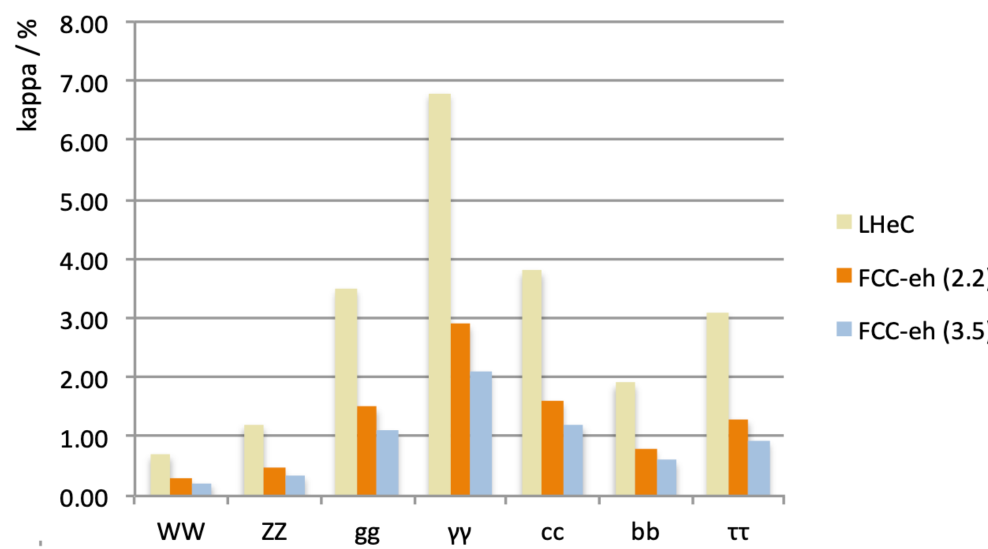
ep Standalone Higgs Sensitivity



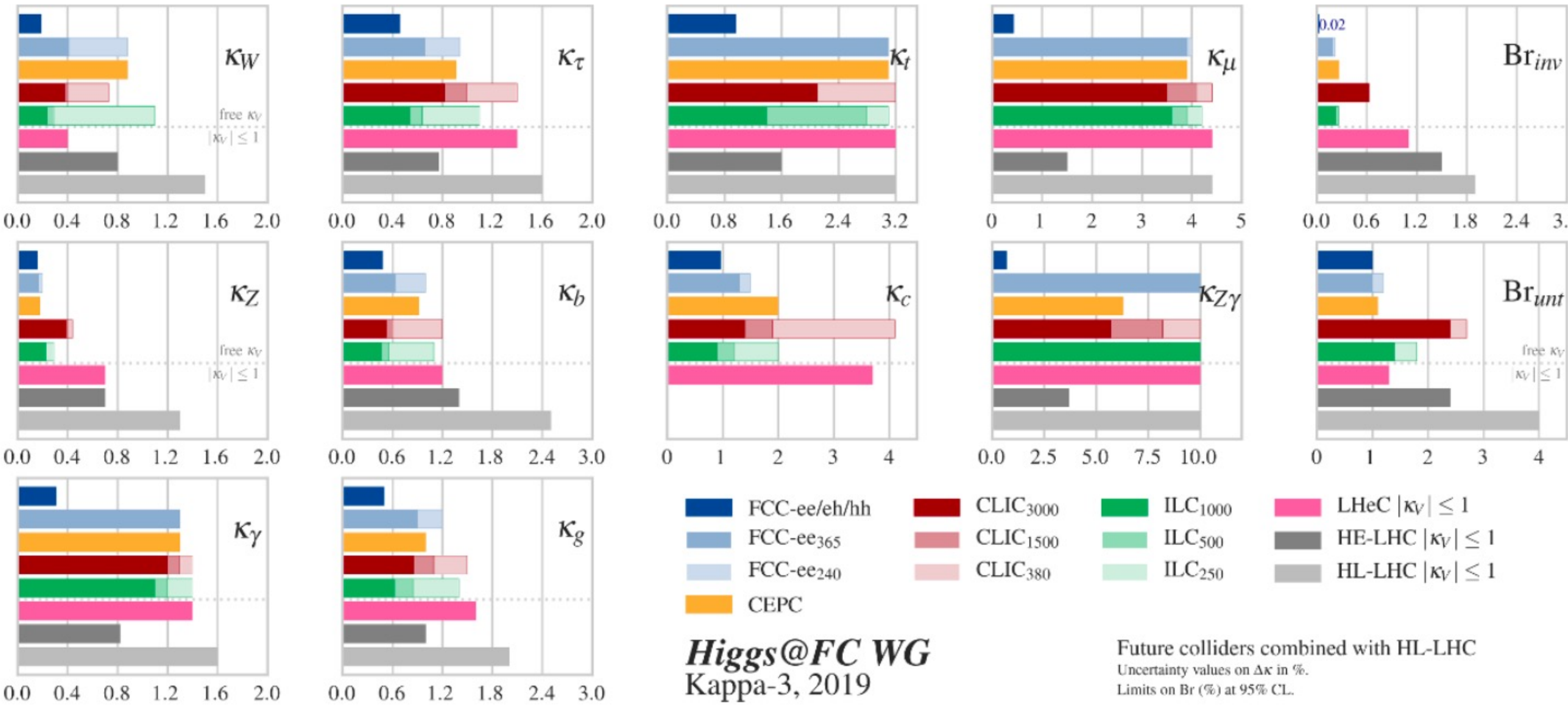


- CC Signal strength uncertainties at 1% level for $H \rightarrow b\bar{b}$, 7% for $H \rightarrow c\bar{c}$ …

- Including initial-state couplings in κ-framework analysis leads to sub-1% WWH coupling precision



Sensitivity in Combination with HL-LHC



- Comparison of proposed future colliders in combination with HL-LHC [JHEP 01 (2020) 139]

- Compared with HL-LHC, κ_b factor 3.5, κ_W factor 4, κ_Z factor 2, κ_c first measurement …

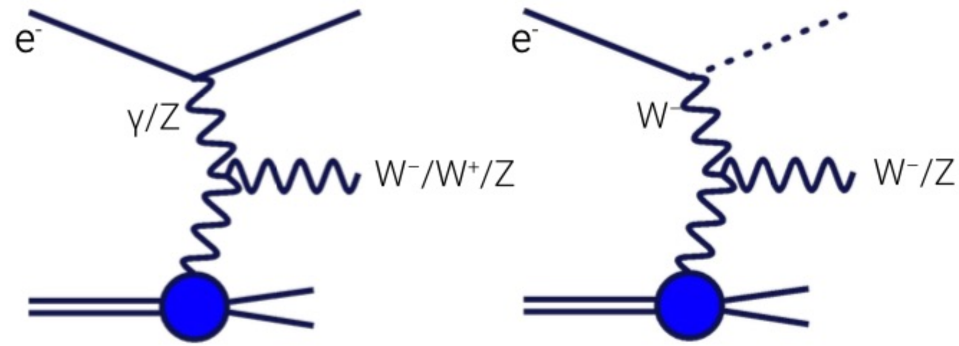
- HL-LHC → LHeC about same as LHC → HL-LHC

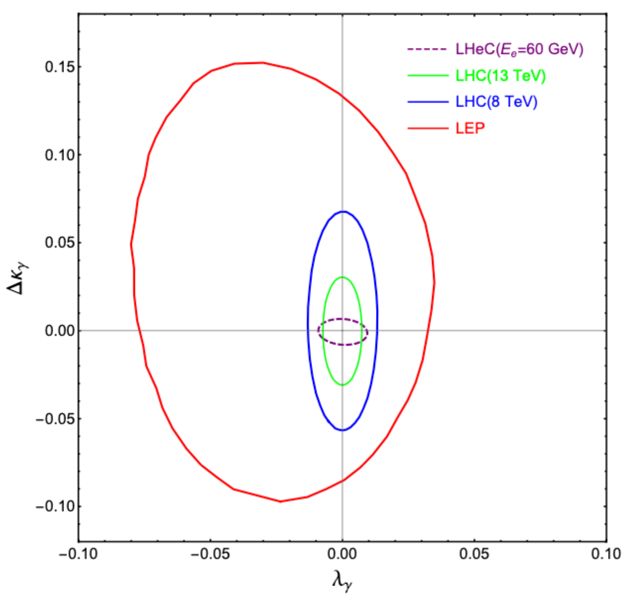
Parameter	Uncertainty		
	HL-LHC	LHeC	HL-LHC+LHeC
κ_W	1.7	0.75	0.50
κ_Z	1.5	1.2	0.82
κ_g	2.3	3.6	1.6
κ_γ	1.9	7.6	1.4
$\kappa_{Z\gamma}$	10	–	10
κ_c	–	4.1	3.6
κ_t	3.3	–	3.1
κ_b	3.6	2.1	1.1
κ_μ	4.6	–	4.4
κ_τ	1.9	3.3	1.3

Electroweak Gauge Bosons

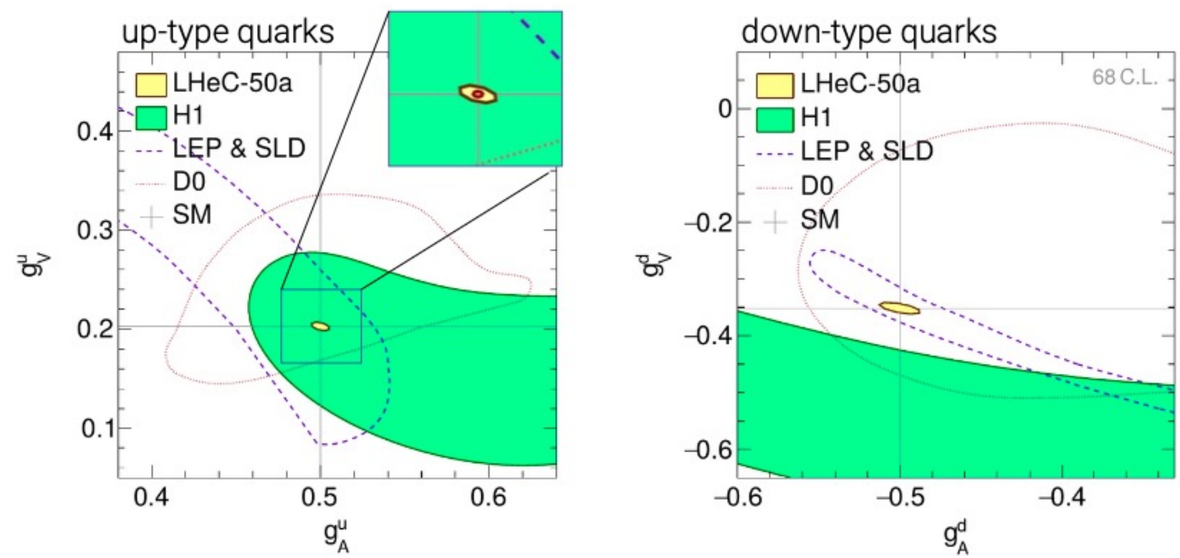
LHeC: $\sigma(H)\sim$ 0.2pb
$\sigma(W)\sim$ 3pb
$\sigma(Z)\sim$ 2pb
$\sigma(t)\sim$ 1pb

… W, Z and (single) top samples ~10^6 events each

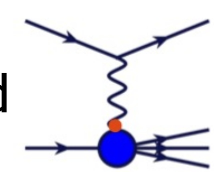




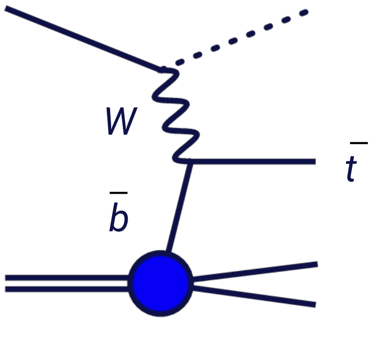
Sensitivity to anomalous TGCs

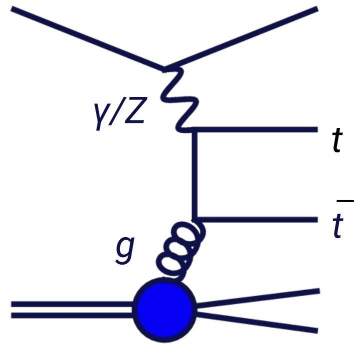


Vector and Axial couplings of Z to light quarks tightly constrained from t-channel Z exchange



Example Top Physics at LHeC

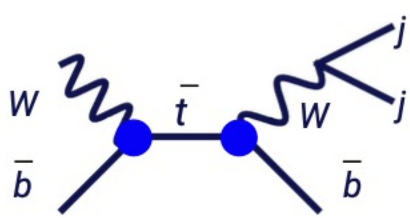




LHeC σ~ 1.9pb
FCC-eh σ~15.3pb

LHeC σ ~ 0.05pb
FCC-eh σ ~ 1.14pb

[~10^6 single top events]

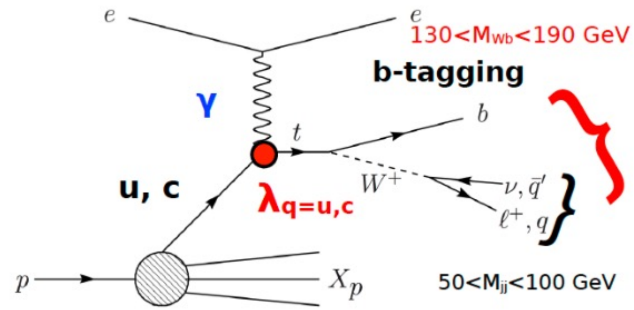


CKM

Cut-based simulation in hadronic channel

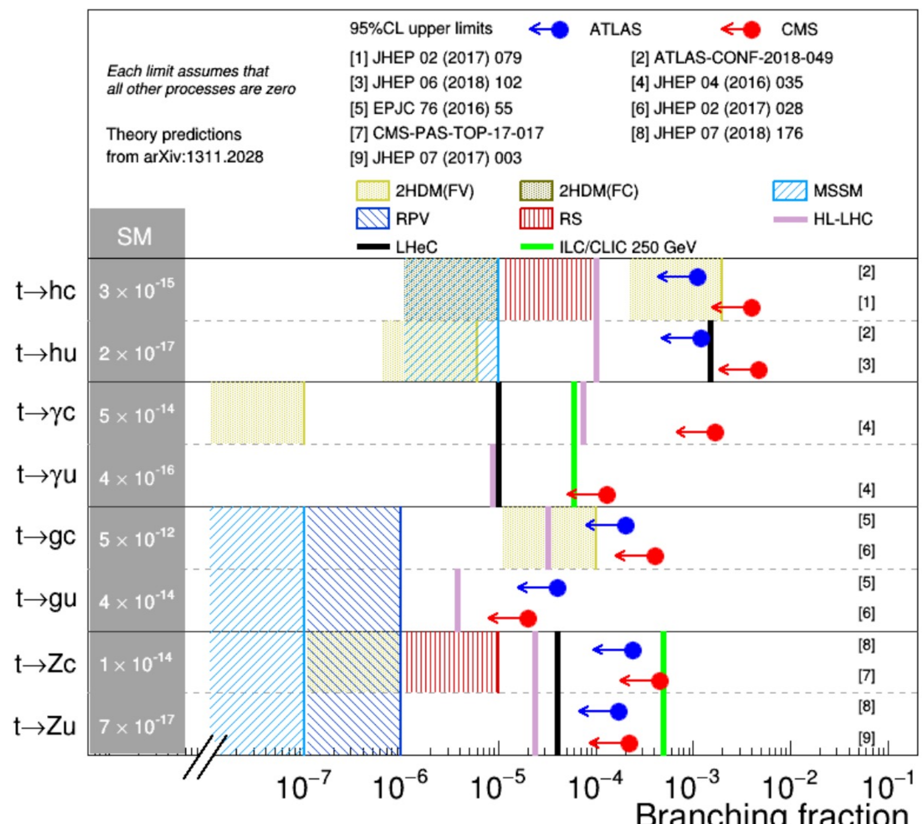
→ 1% V_{tb} precision (now ~5%)

→ Improved V_{ts}, V_{tb} constraints



FCNC

Comparable sensitivity to HL-LHC in tγc, tγu coupling sensitivities



Summary: a 2040s Bridging Opportunity?

- LHeC is not the next major new collider for CERN

- LHeC could be an impactful final upgrade to LHC …

  - potentially ‘affordable’ on required timescale
  - technically realisable for late 2030s
    (ERL technology = critical path)
  - extending energy frontier sensitivity within a
    few years of running
  - complementing and enabling HL-LHC programme
  - ensuring continuity of collisions and scalar sector
    exploration in the 2040s
  - exploring SRF, ERL options & detector technologies

… as a testing ground (injector?) for a future major facility

“Circles in a circle”, Wassily Kandinsky (1923), Philadelphia Museum of Art