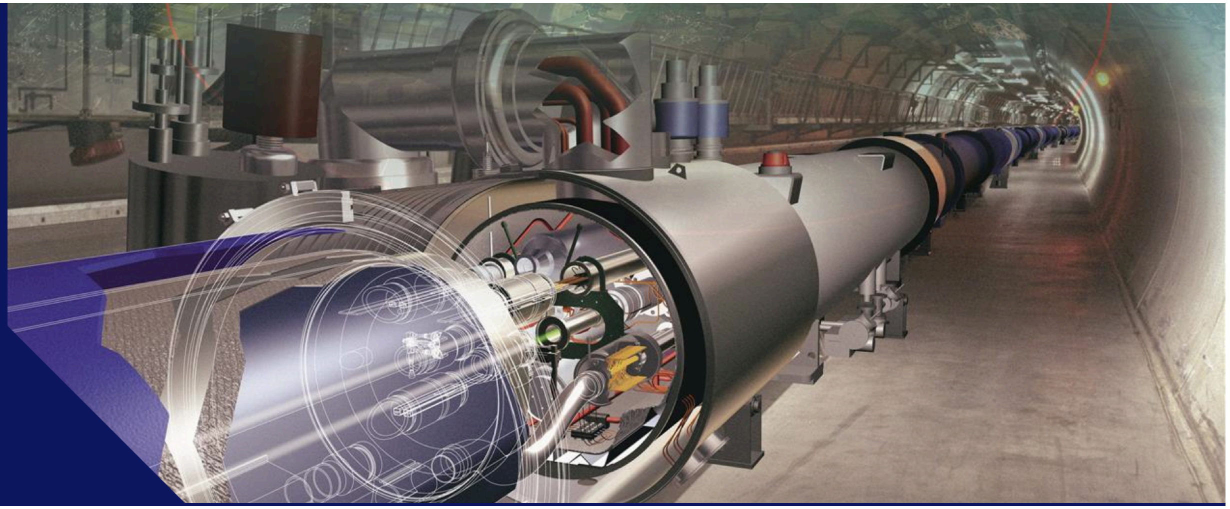
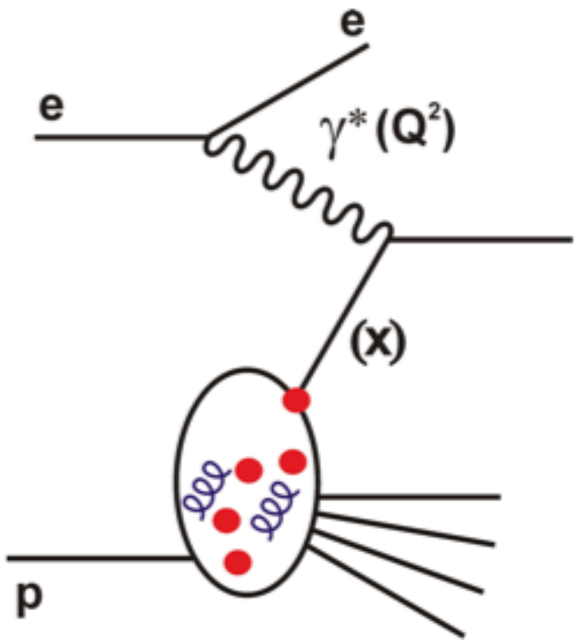
Oxford PP seminar, HT21



Physics at a Future Energy Frontier electron-hadron Collider

Claire Gwenlan, Oxford

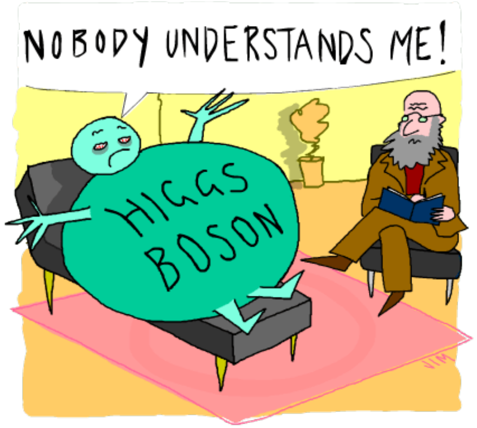
with thanks to the LHeC and FCC-eh study groups



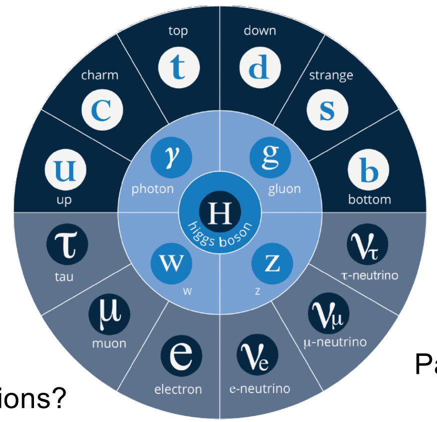
particle physics at the frontier

Higgs

Is it the SM Higgs?
What is its potential?
Is the EW scale stabilised by
new particles,
interactions,
symmetries?
Are there more
Higgs bosons?

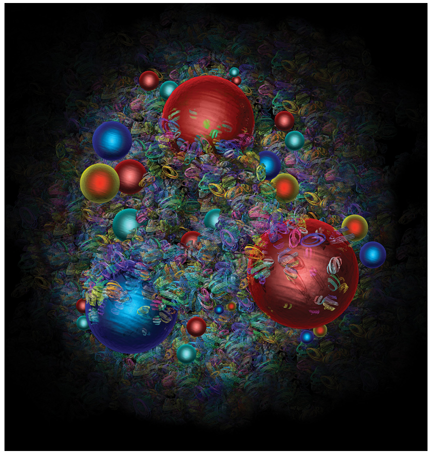


Elementary Particles



3 generations?
Is there deeper substructure?
SUSY, LQs, RH ν's, …?

QCD

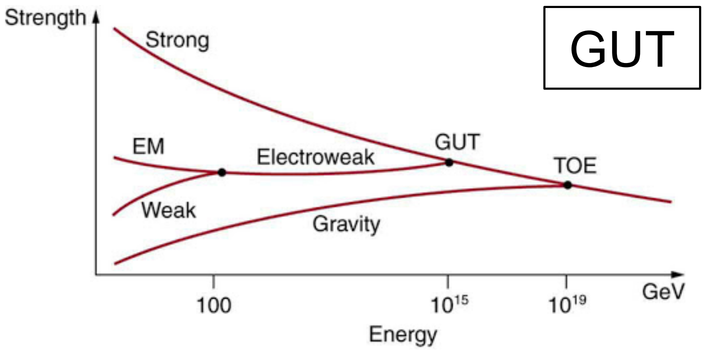


Parton dynamics and structure of proton/nuclei?
How is confinement explained?
Axions, odderons, instantons?

Neutrinos

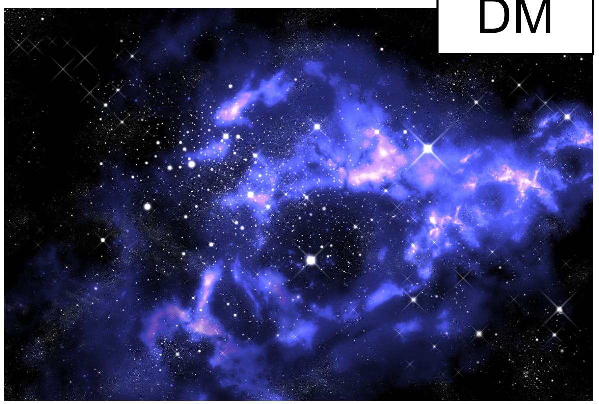
Majorana vs Dirac?
Sterile neutrinos?
CP violation in neutrino sector?

GUT



Is there unification at high scales?
Correct value of α_s? Is the proton stable?
Gravity?

DM



Nature of DM?
Is there of dark sector, and is it accessible to accelerator experiments?

ee, ep, pp: synergy

ee, **ep**, **pp** coexist in history:

also previously

SM building blocks

$p\overset{(-)}{p}$: fixed target, ISR, SppS

lh: SLAC, CDHS, BCDMS, EMC, …

ee: PETRA, PEP, Tristan

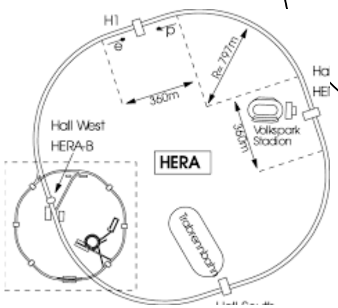
Physics at the Fermiscale

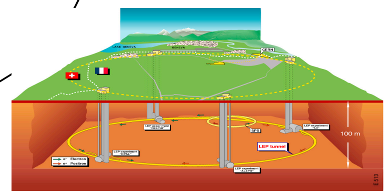
$p\bar{p}$
Tevatron
b, top quarks
MW
No SUSY, BSM

ep
HERA
Gluon dominance, small x
EW unification
pdfs, c, b
No SUSY, BSM

SM triumph

ee
LEP/SLC
MZ, $\sin^2\Theta$
3 neutrino families
HO EW → mt, mH
No SUSY, BSM





Neutrino Physics
Oscillations, PMNS

M Klein

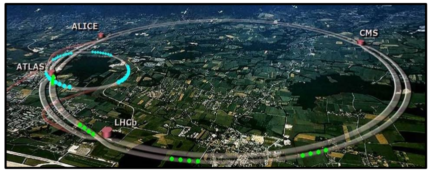
ee, ep, pp: synergy

many questions unresolved – diversity of projects to attack from all sides?

Physics at the TeV scale

and beyond:

FCC (ee, eh, hh)



pp
LHC(b)
Rare Higgs decays, H-HH?
Precision W, Z, top
QCD, Flavor
NO SUSY, BSM – yet

ep
LHeC
Maximise LHC physics:
precision QCD, α_s, EW
Precision Higgs
BSM?
eA

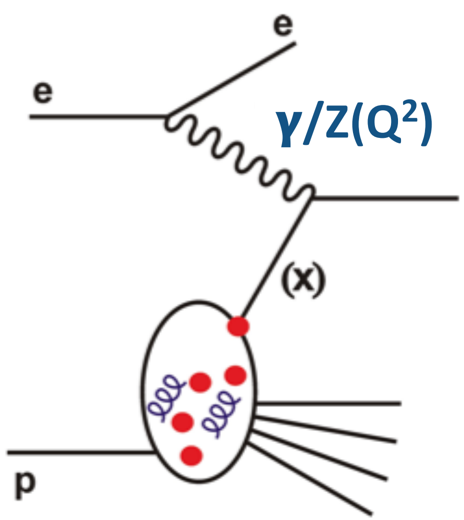
Higgs + New Physics?
High Precision and Searches

ee
ILC, CepC, CLIC
Precision Higgs
Precision EW
α_s
BSM?

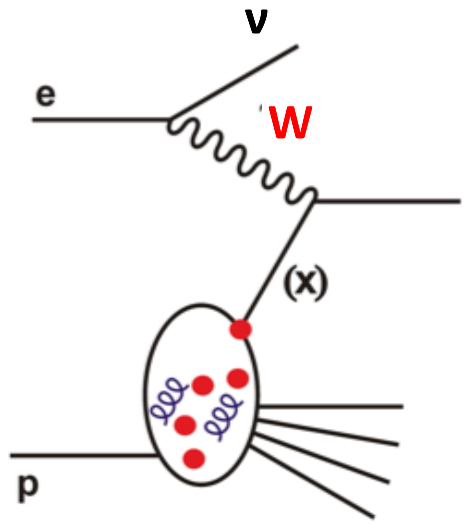
Neutrino Physics
Hierarchy, CP, ... Factory

M Klein

ep Deep Inelastic Scattering



Neutral Current: $ep \rightarrow e'X$



Charged Current: $ep \rightarrow \nu_e X$

Q²: virtuality of exchanged boson

x: proton momentum fraction carried by struck parton

"*The point-like electron "probes" the interior of the proton via the **electroweak force**, while acting as a neutral observer with regard to the **strong force***", R-D Heuer

→ ideal QCD and electroweak laboratory

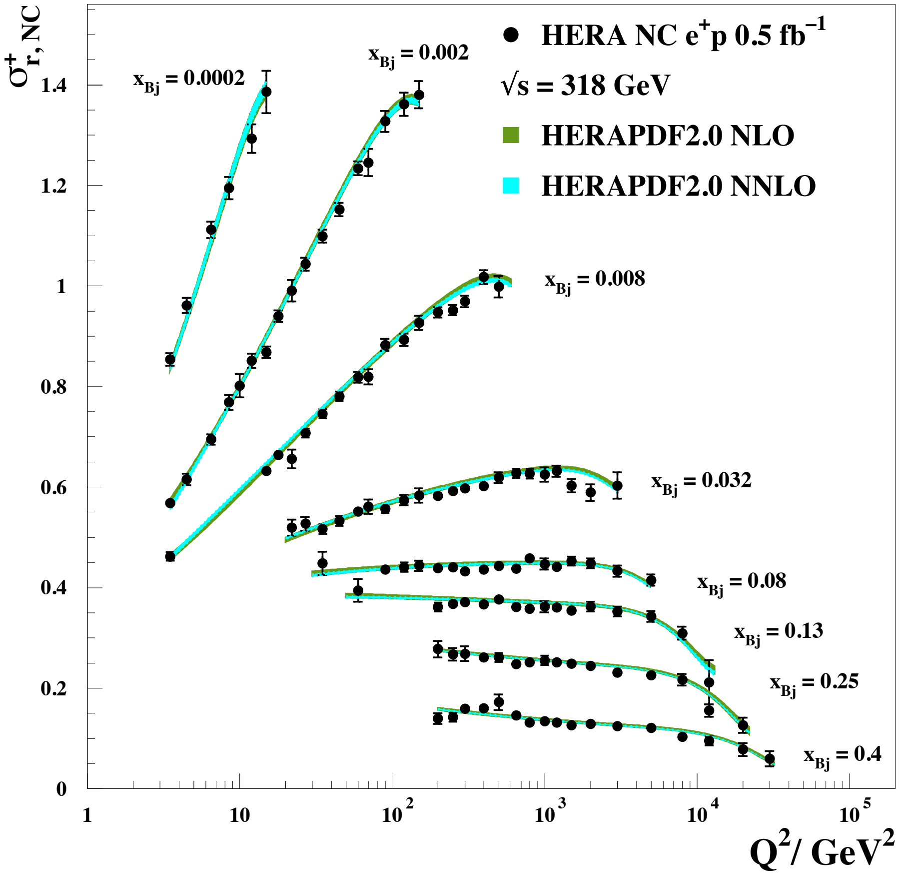
HERA

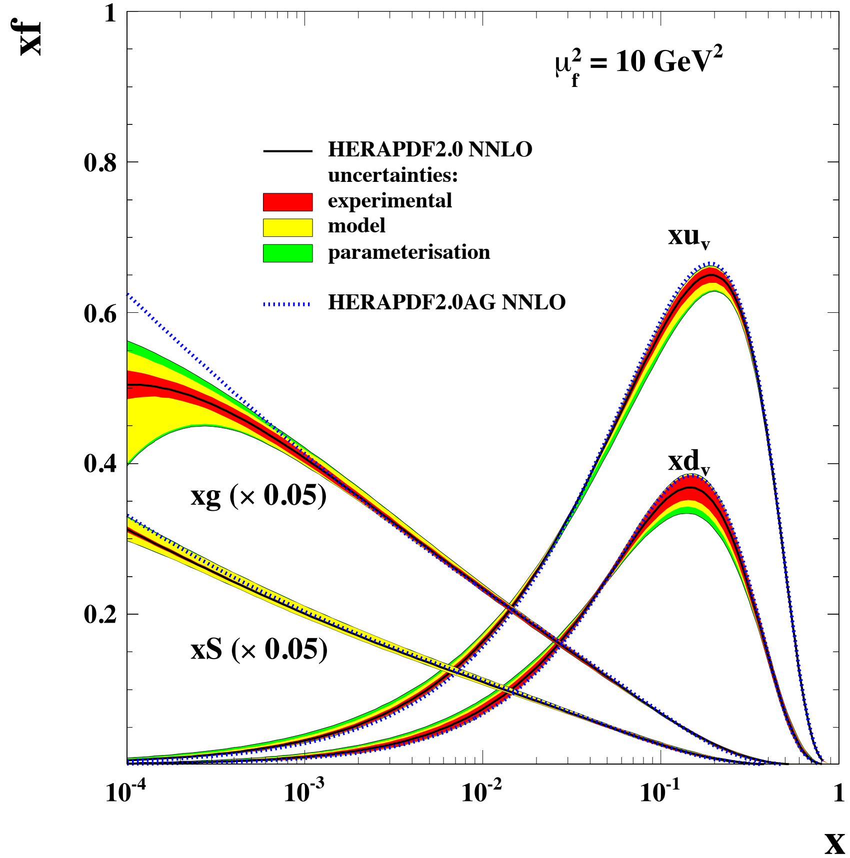
HERA: **1992 – 2007**

DESY, Germany

$\sqrt{s}$ = **320** GeV, L=**1** fb^{-1}

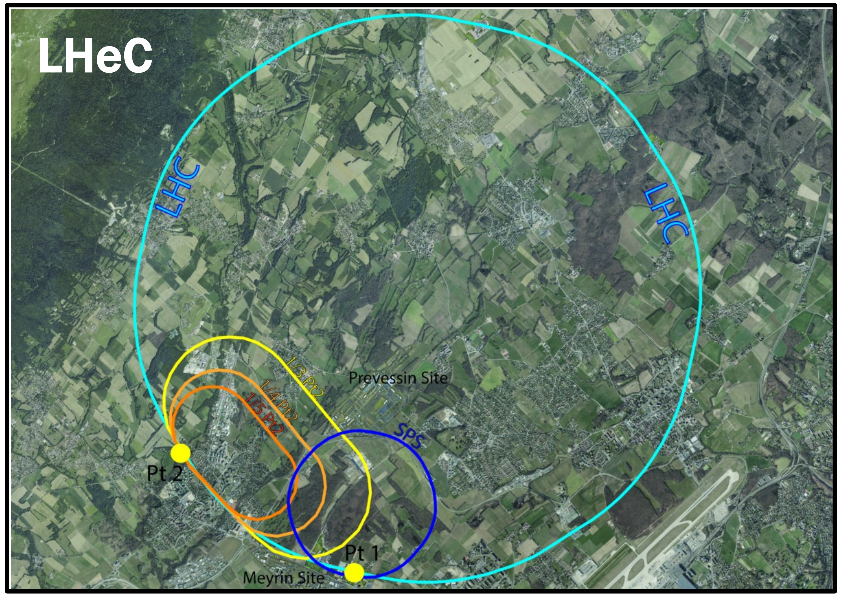
HERA: world's first and to date only **ep** collider





- **HERA** provides most important input to our knowledge of **proton structure**
- **…** and did much more besides! BUT, limited $\mathcal{L}$, $\sqrt{s}$ …

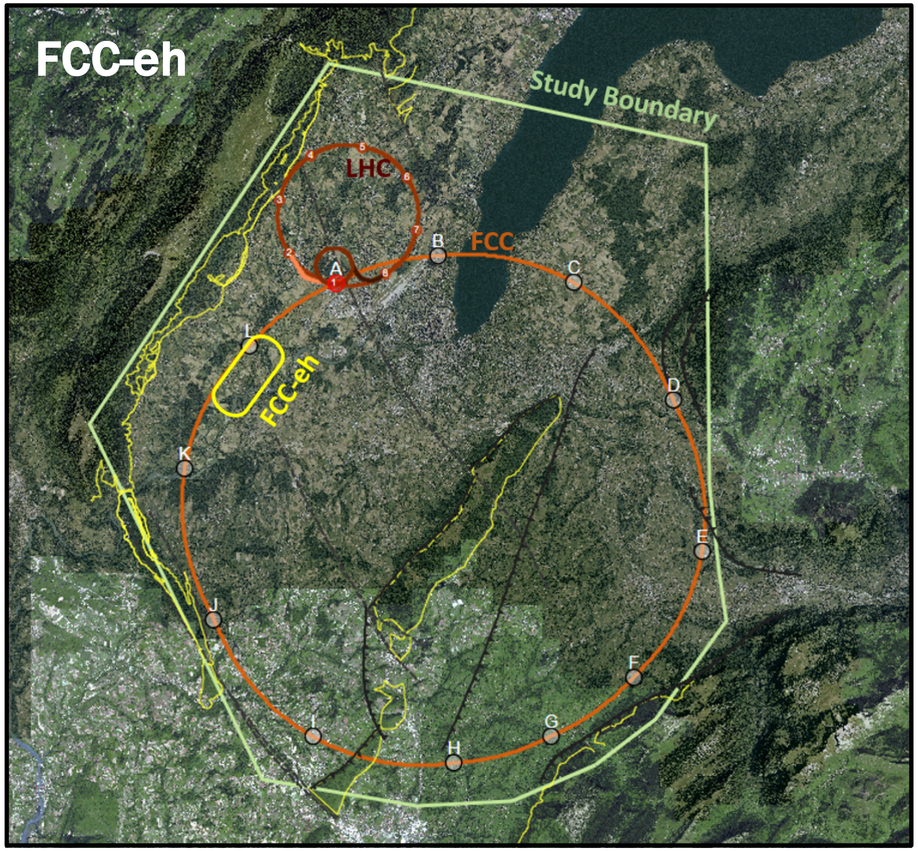
LHeC and FCC-eh



LHeC: arXiV:1206.2913 ; arXiv:2007.14491

- **energy recovery LINAC** (ERL) attached to HL-LHC or FCC
- e beam: ⟶ **50** or **60** GeV
- e polarised: P= **±0.8**
- Lint ⟶ **1 – 2** ab^{-1} **(1000×** HERA!)

Future CERN Colliders: arXiv:1810.13022



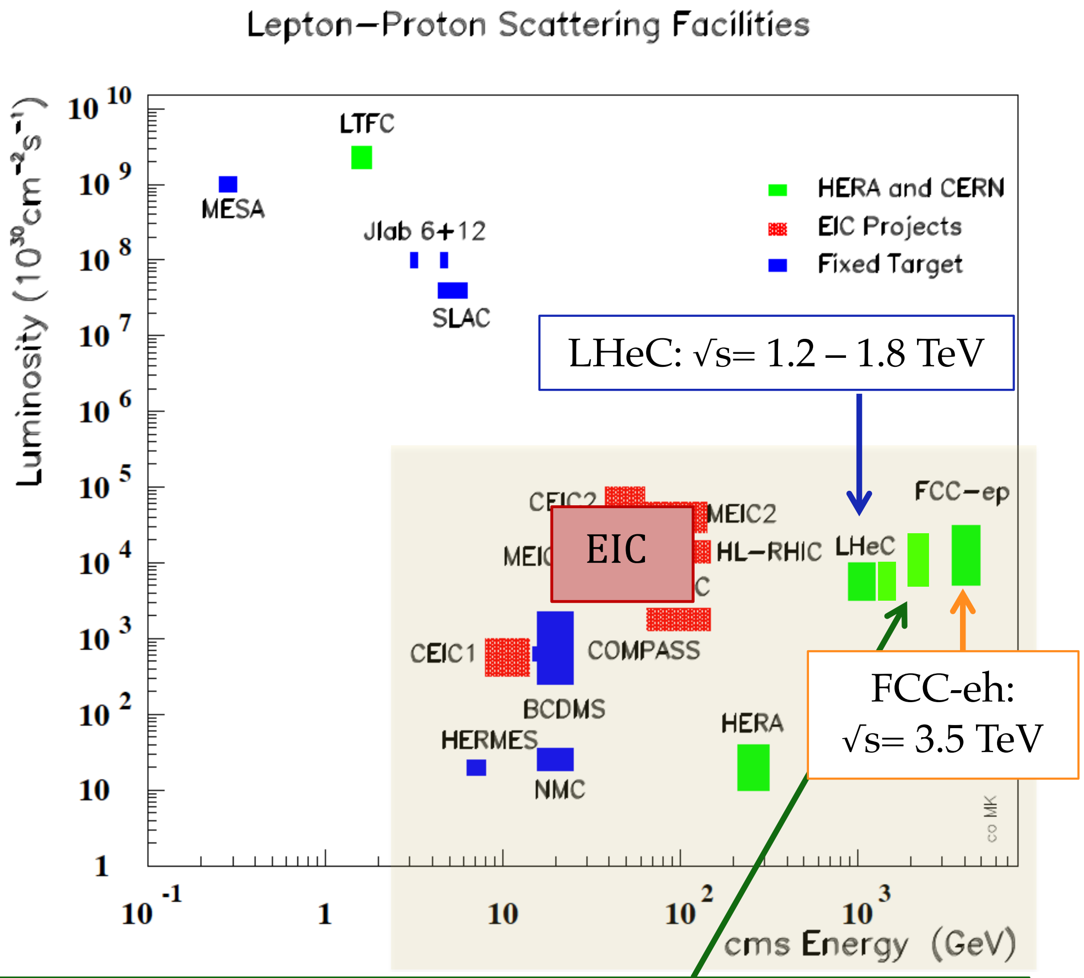
FCC-eh: Eur. Phys. J. C 79, no. 6, 474 (2019)

cost: $\mathcal{O}(1)$ BCHF, **20%** of LHC
CERN-ACC-2018-0061

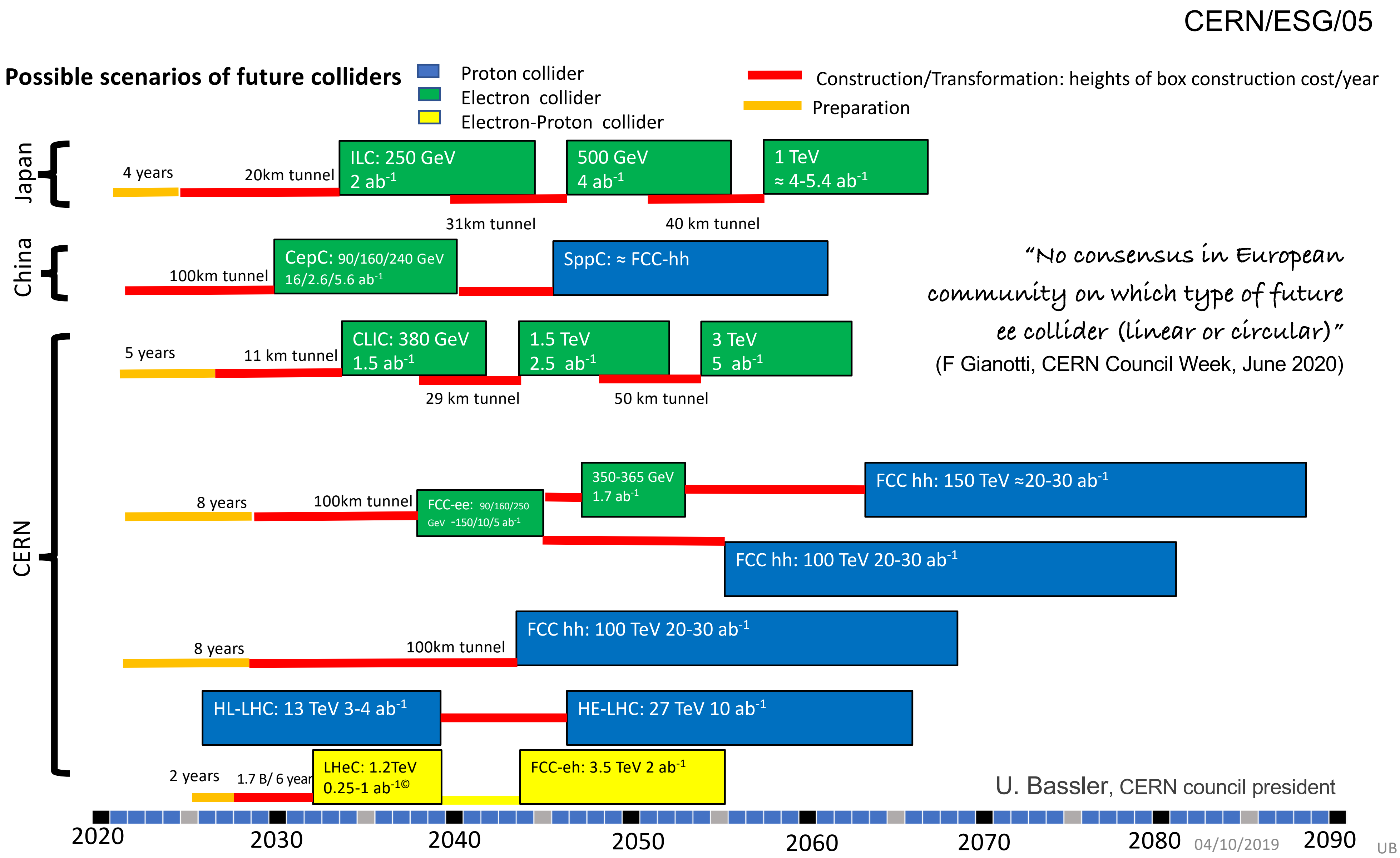
LHeC and FCC-eh

synchronous operation:

- with HL-LHC (**2035+**):
- Ep = **7** TeV, √**s = 1.2 TeV**
- or with HE-LHC:
- Ep = **13.5** TeV, √**s = 1.8 TeV**
- or with LE-FCC:
- Ep = **19** TeV, √**s = 2.1 TeV**
- and/or later with FCC (**2050+**):
- Ep = **50** TeV, √**s = 3.5 TeV**



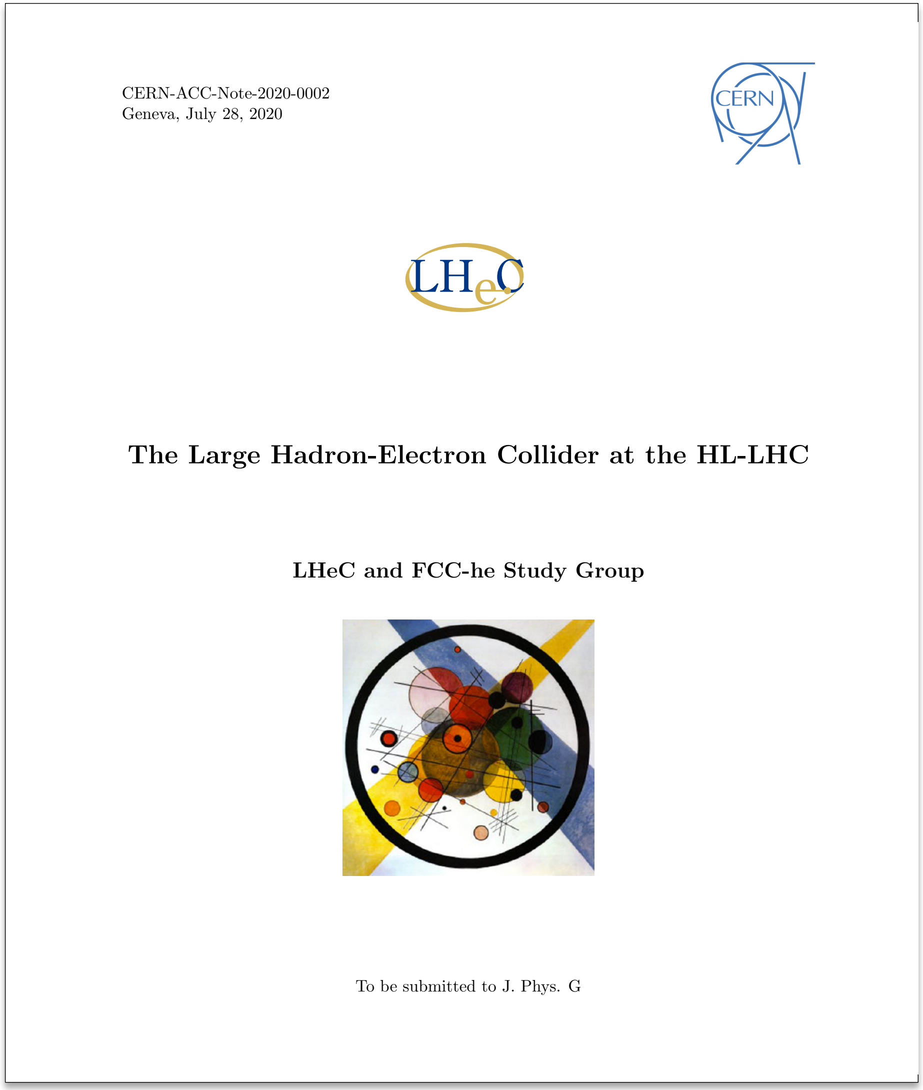
“LE-FCC-eh”: √s= 2.1 TeV
(earlier operation with current magnet technology, Ep=19 TeV)



LHeC: installation during **LS4**;

concurrent operation through LHC **Runs 5/6**; and period of **dedicated running**, arXiv:[1810.13022](1810.13022)

LHeC and FCC CDRs


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

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

To be submitted to J. Phys. G

LHeC white paper: arXiv:**2007.14491**
submitted to J.Phys.G
update to CDR, arXiV:1206.2913 (600 citations)

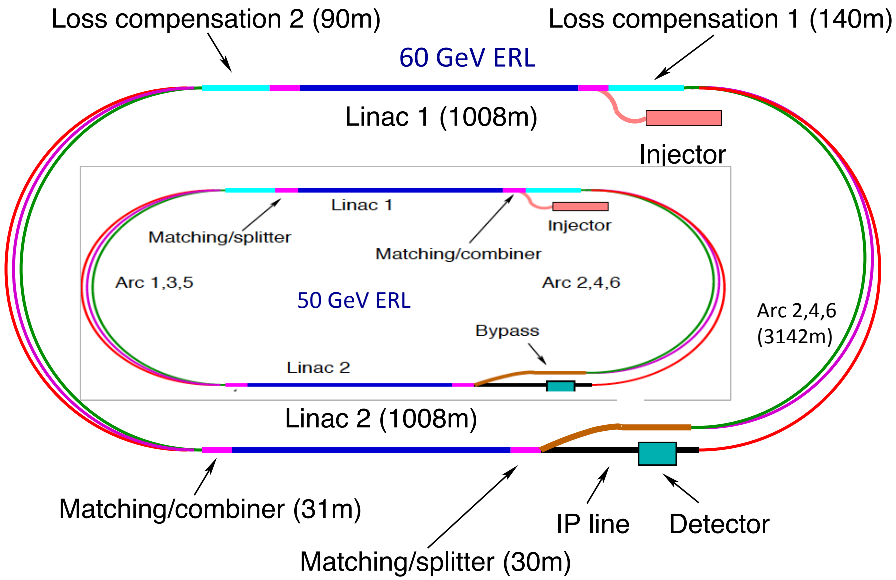
compilation of new and updated studies over the past years,
400 pages, 300 authors, 156 institutions

5 page summary:
ECFA newsletter No. 5, August 2020
https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf

see also, CERN-ACC-Note-2018-0084
submitted to EU strategy update

FCC CDR, vols 1 and 3:
physics, EPJ C79 (2019), 6, 474
FCC with eh integrated, EPJ ST 228 (2019), 4, 755

energy recovery linac (ERL)



3-turn racetrack energy recovery configuration

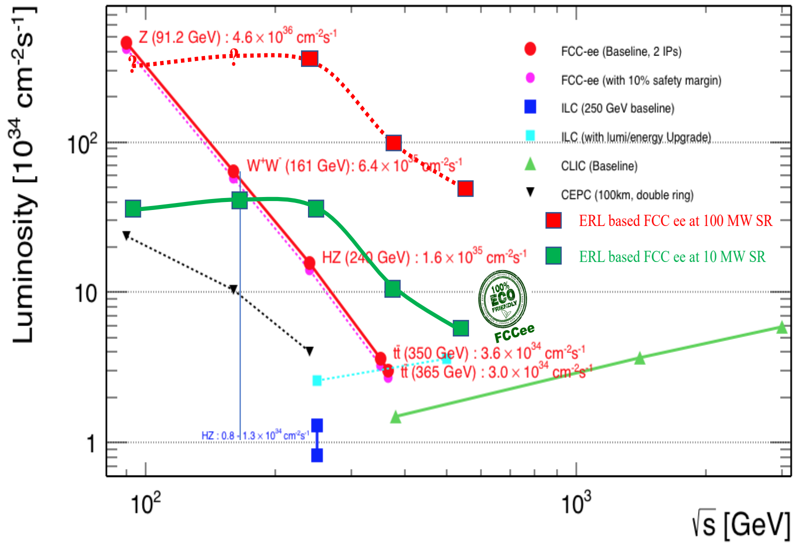
(Ie = **20** mA for **10^{34}** $cm^{-2}s^{-1}$ luminosity, f=**801.58** MHz)

ERL: one of few revolutionary concepts for accelerator design; huge potential, just evolving; recognised as a high-priority future initiative for CERN ([ESPP]())

many technical synergies, EG:

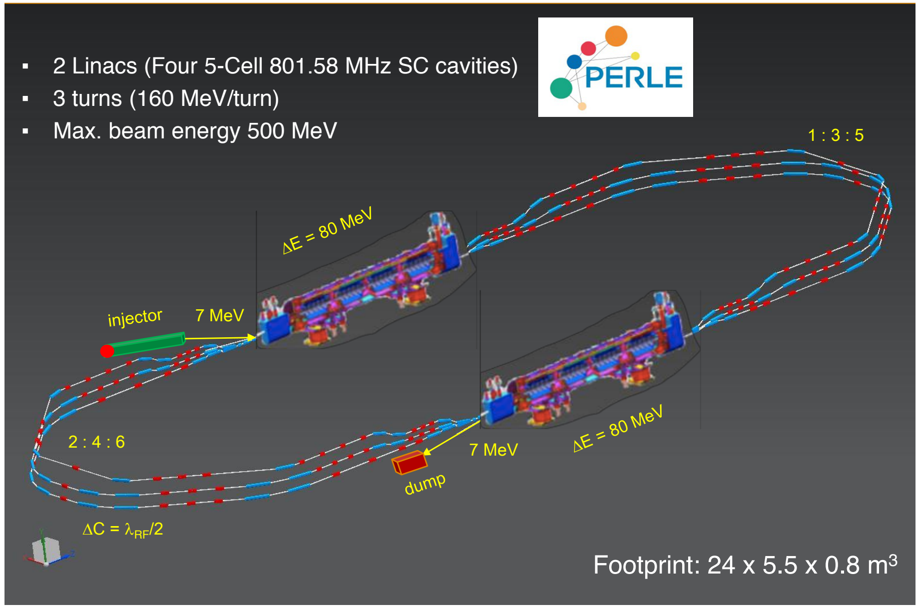
FCC-ee: ERL suggested as alternative approach (arXiv:[1909.04437]())

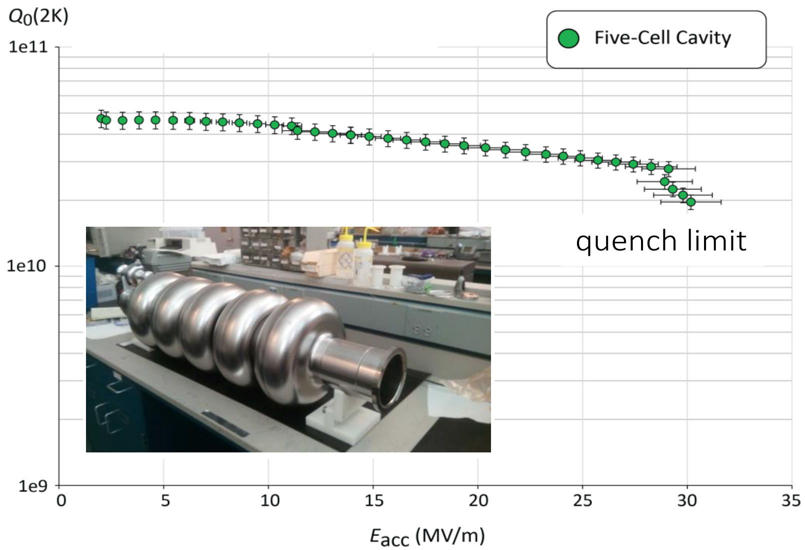
160 – 500 GeV, ERL-based FCC-ee promises higher energy reach and luminosity while consuming much less power (**thick green**)



PERLE powerful **ERL** for **e**xperiments

BINP, CERN, Cornell, Daresbury, JLab, Liverpool, iJCLab +





1st Nb 802 MHz SRF cavity successfully fabricated and tested (Oct 17, JLab)

PERLE: international collaboration built to realise **500** MeV energy facility at Orsay, for development of ERL with LHeC conditions

will also provide $\mathcal{O}$(100 MeV) physics

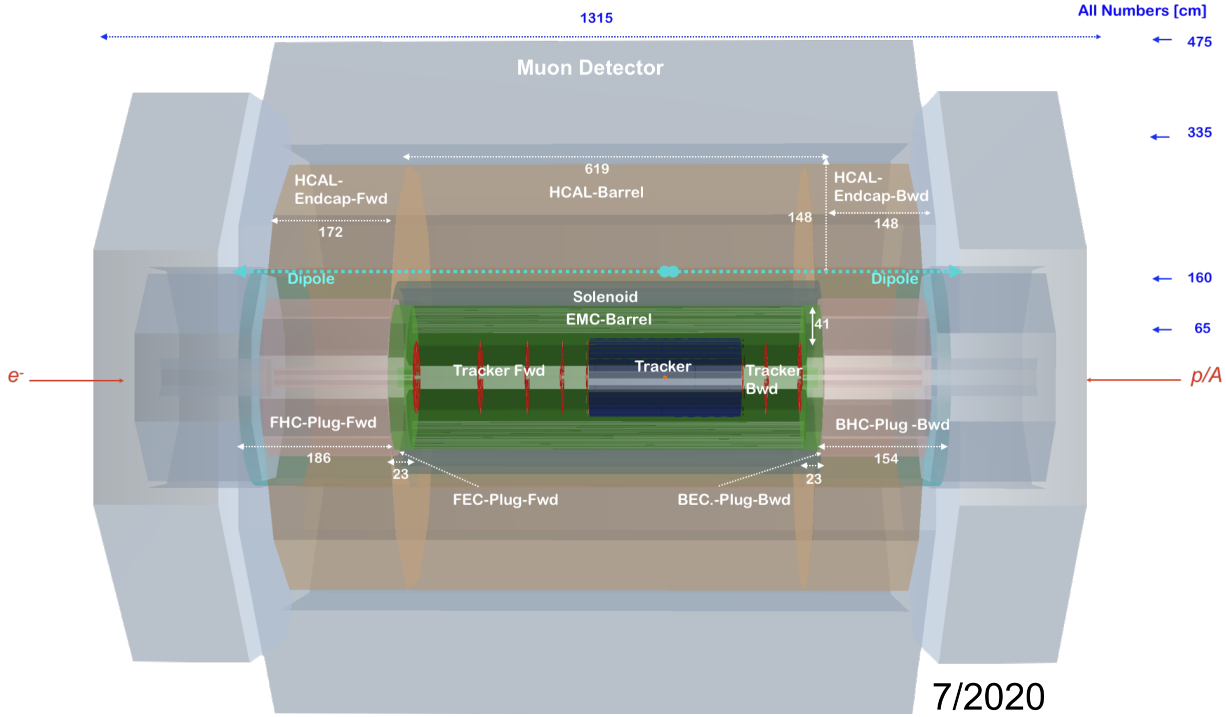
CDR: arXiv:1705.08783
ESPPU: CERN-ACC-2018-0086

PERLE Coll. Meeting, 2020,
https://indico.cern.ch/event/923021/

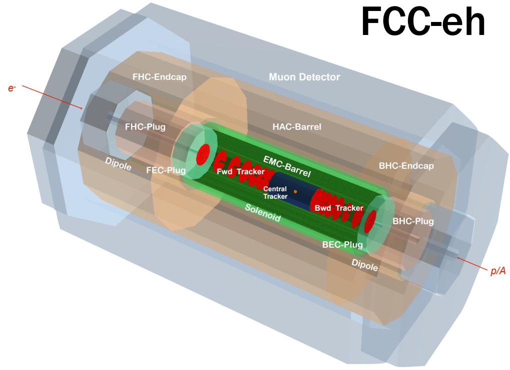
PERLE is progressing (source, injector, magnets, …, radiation safety, … and recognition)

LHeC detector concept

L×D=13 × 9 m² [FCCeh: 19 ×12 m², about CMS size]

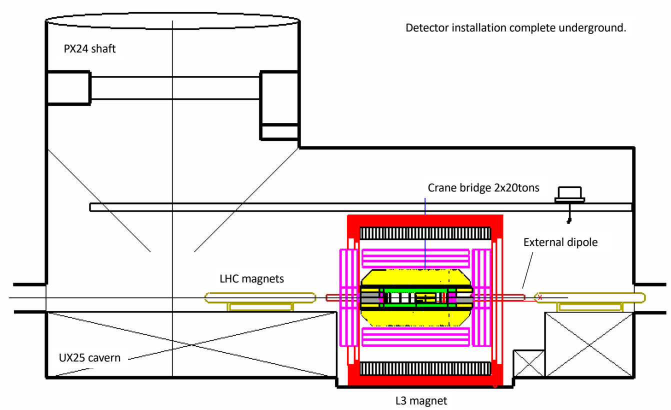


FCC-eh



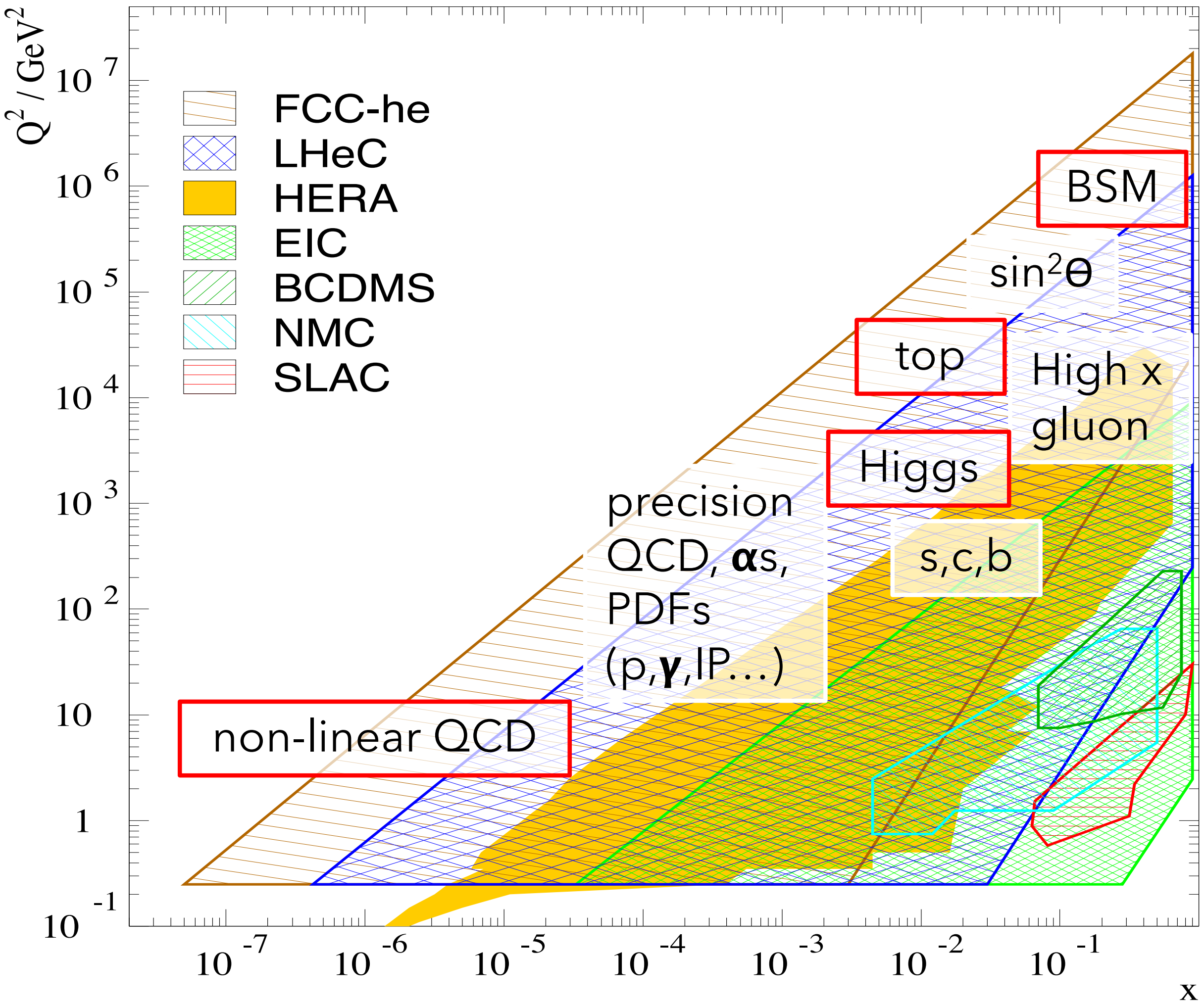
study of installation in IP2 cavern commensurate with 2-year shut down

'no' pile up (max **0.1**); much less radiation wrt pp (**1/1000**); high precision through over-constrained kinematics: e-h; coverage 1 → 179°; modular for rapid installation; tracker radius 40 → 60 cm; B 3.5T



LHeC initial design described in detail in CDR, arXiV:1206.2913; updated in arXiv:2007.14491

physics with energy frontier DIS



world's cleanest high resolution **MICROSCOPE**

EMPOWERMENT of the LHC/FCC physics programme

CREATION of a precision, novel Higgs facility

DISCOVERY of new physics

REVOLUTION of Nuclear Particle Physics

(taken from M Klein)

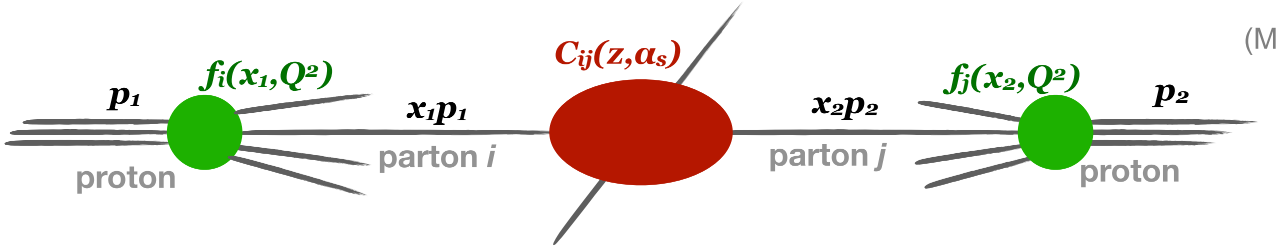
×**15**/**120** extension in Q^2,1/x reach vs **HERA**

parton distribution functions

QCD collinear factorisation:

$$y = Y - \frac{1}{2}\log\frac{x_1}{x_2}$$

$$\frac{d\sigma}{dQ^2\, dY\, dp_t \ldots} \simeq \sum_{i,j=g,q} \int_\tau^1 dx_1 \int_\tau^1 dx_2\, f_i(x_1, Q^2)\, f_j(x_2, Q^2)\, C_{ij}\left(\frac{\tau}{x_1 x_2}, y, p_t, \ldots, \alpha_s\right)$$

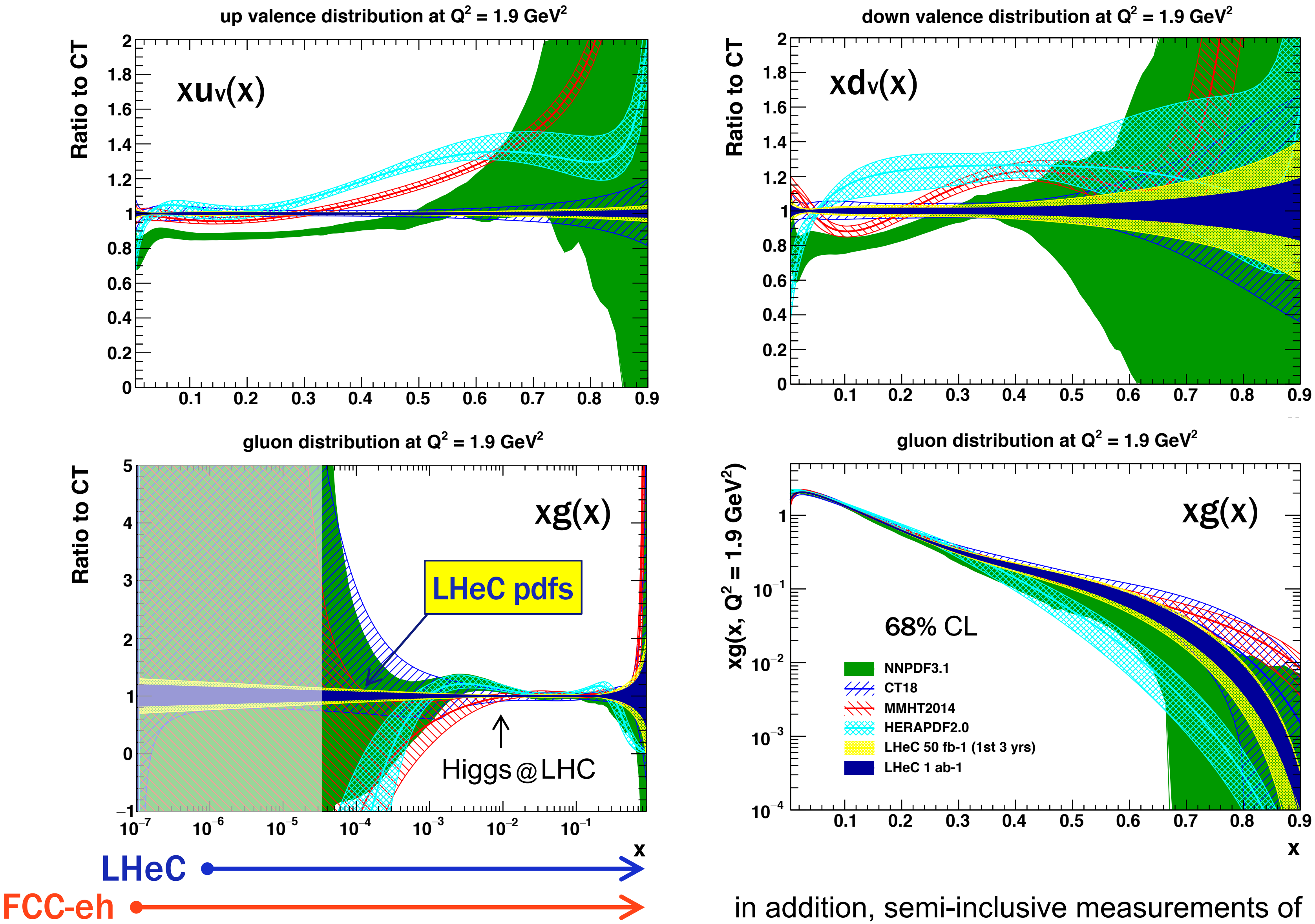


(M Bonvini)

- partonic cross sections $C_{ij}(z, y, p_t, \ldots, \alpha_s)$ (observable-dependent, perturbative)
- parton distribution functions (**pdfs**) $f_i(x, Q^2)$ (universal, non-perturbative)

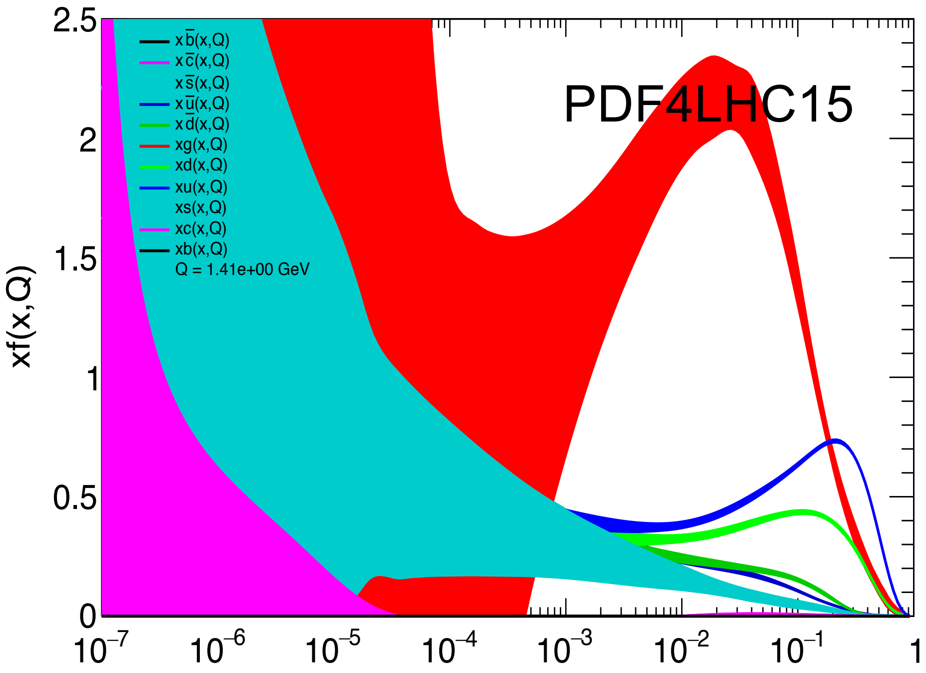
pdf uncertainties currently limit BSM searches, Higgs measurements, and precision measurements of, EG. MW, sin²ϑW (where small discrepancies may indicate BSM physics) at the LHC arXiv:[2007.14491](https://arxiv.org/abs/2007.14491)

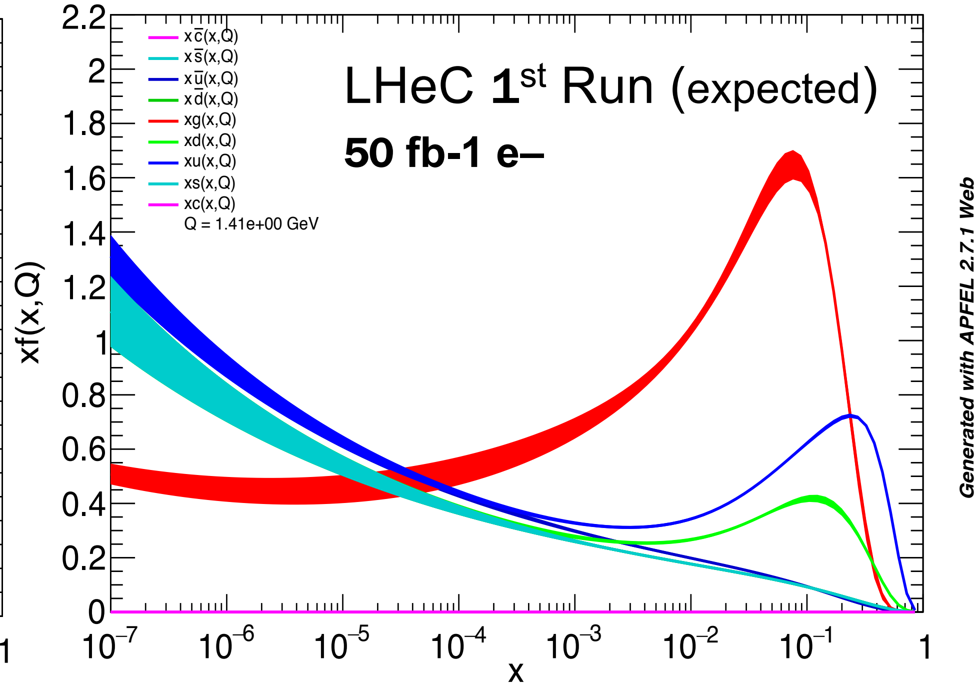
quark and gluon pdfs



in addition, semi-inclusive measurements of s,c,b,t disentangles all flavours; jets for improvement to xg etc.

summary of LHeC pdfs



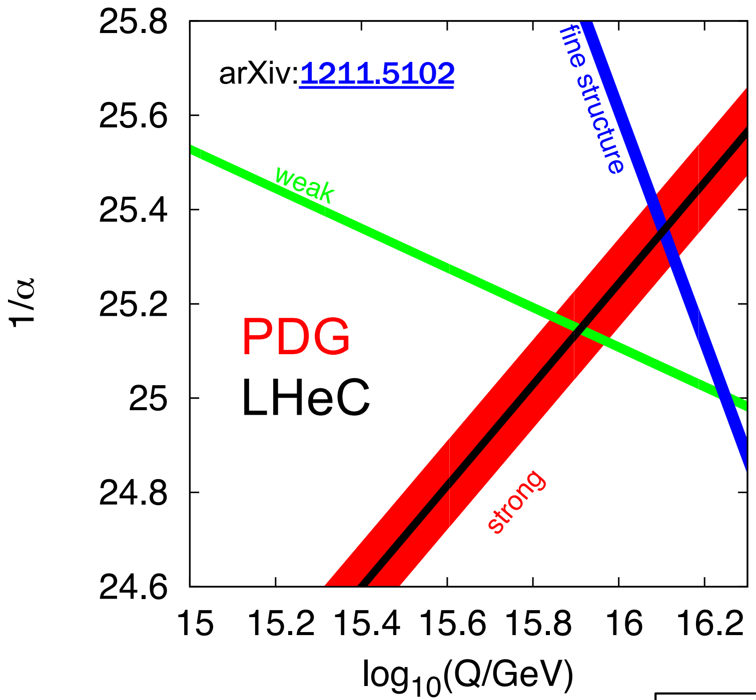


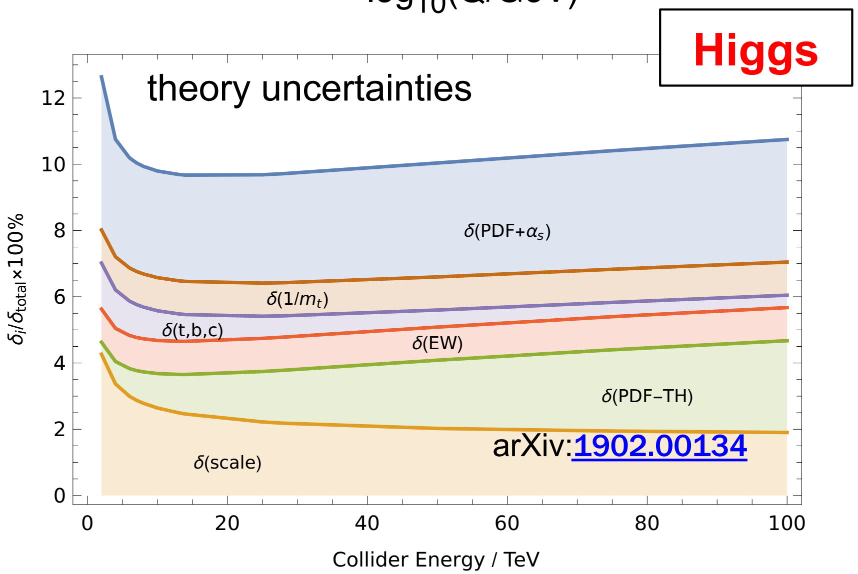
situation today → after 1st LHeC Run (3 yrs)

with further improvements after full running period, plus HQs, DIS jets, …

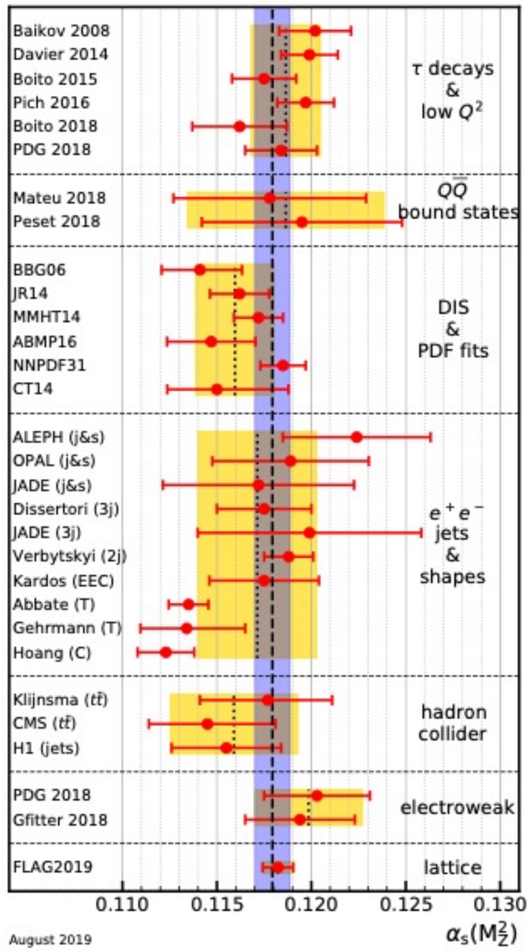
- complete unfolding of parton content in unprecedented kinematic range: **u, d, s, c, b, t, xg**
- **theory:** N³LO, no nuclear corrections, …

strong coupling, αs





PDG20

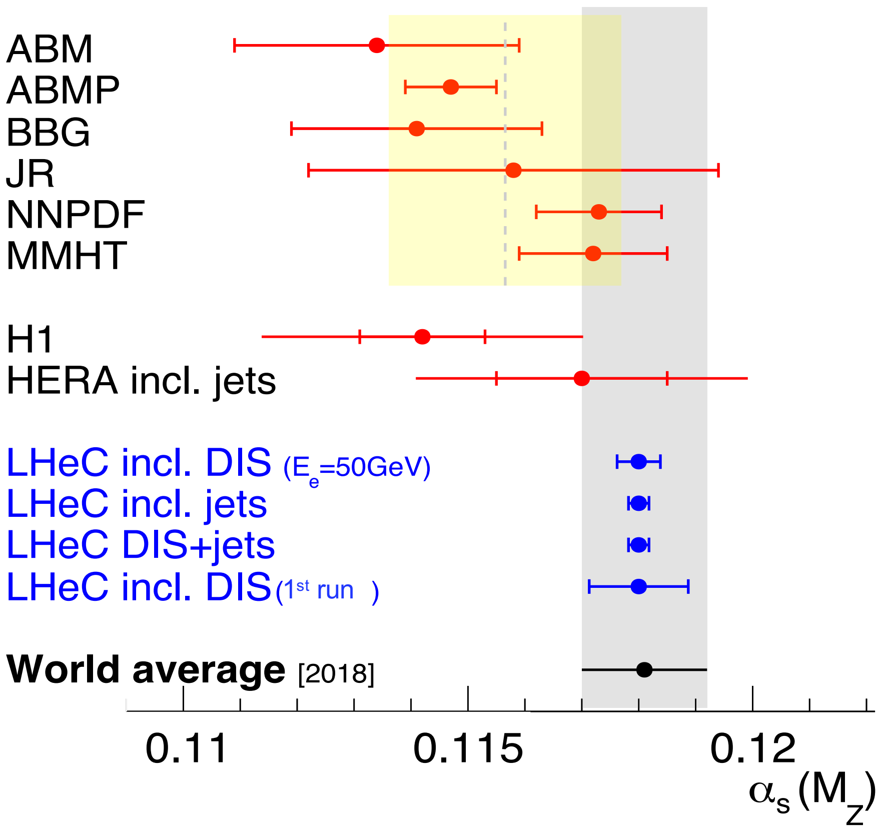


- αs is least known coupling constant
- world av.: $\alpha_s(M_Z^2)$ = 0.1179±0.0010
- current state-of-the-art: δαs/αs = $\mathcal{O}$(1%)

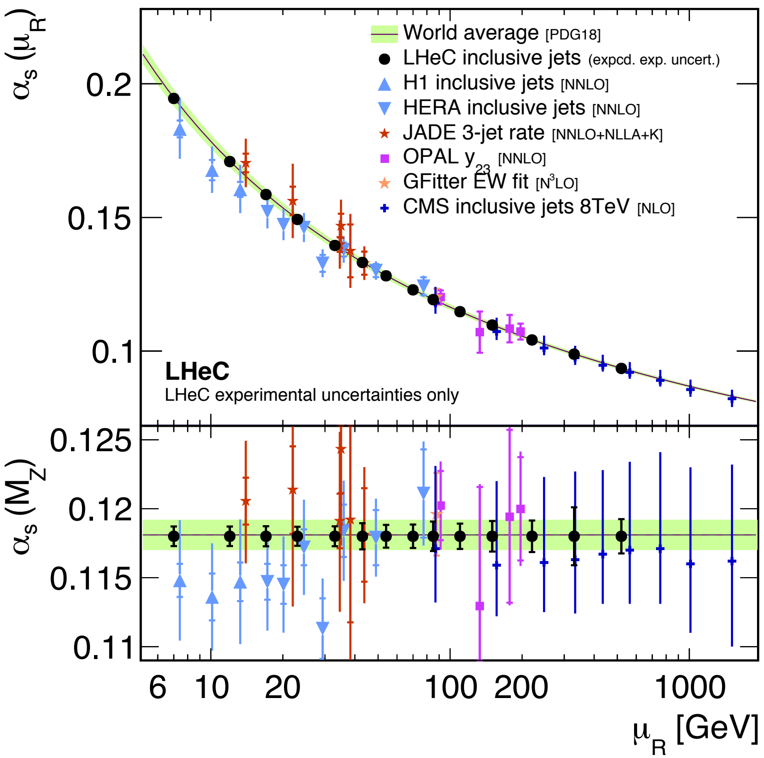
arXiv:[2007.14491](https://arxiv.org/abs/2007.14491)

strong coupling, αs

αs determinations at NNLO QCD:



fit to subsets of ep jet data



LHeC simultaneous **PDF+αs** fit:

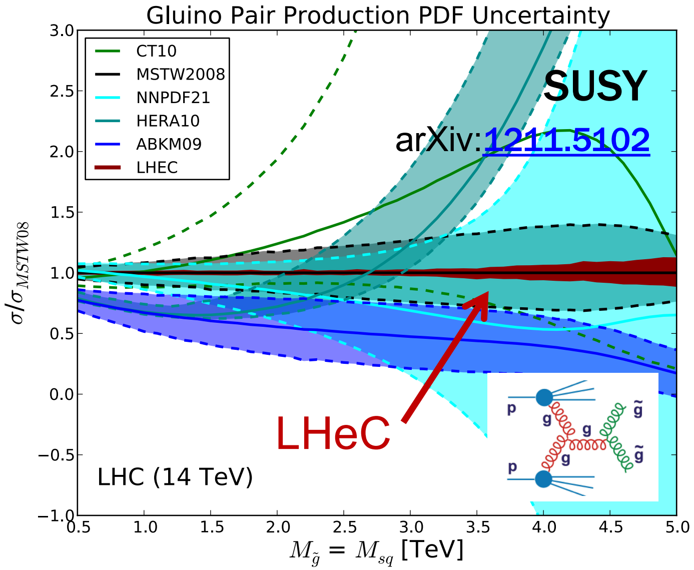
Δαs(MZ) (exp.+pdf) = **±0.00022** (inclusive DIS)

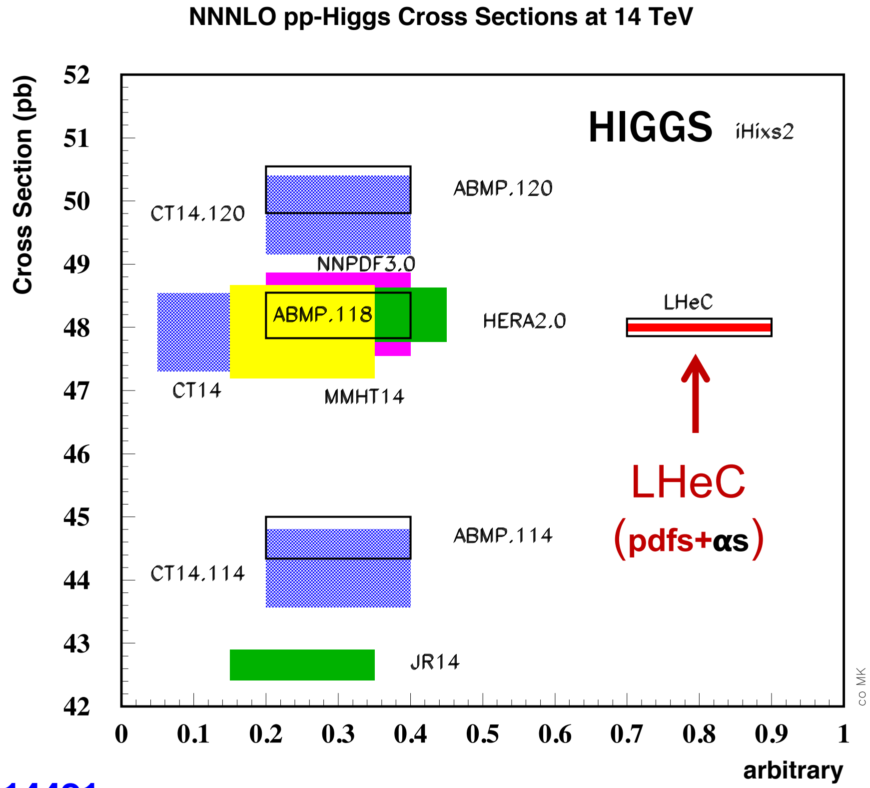
Δαs(MZ) (exp.+pdf) = **±0.00018** (incl. DIS & jets)

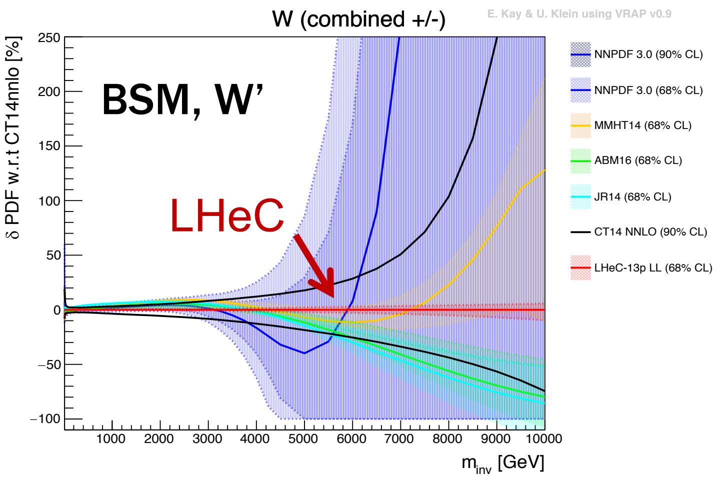
- achievable precision $\mathcal{O}$(0.1%) at same level as αs from FCC-ee
- **QCD theory uncertainties** will be limiting factor

empowering the LHC: Higgs and BSM

external, reliable, precise **pdfs** needed for
range extension and **interpretation**





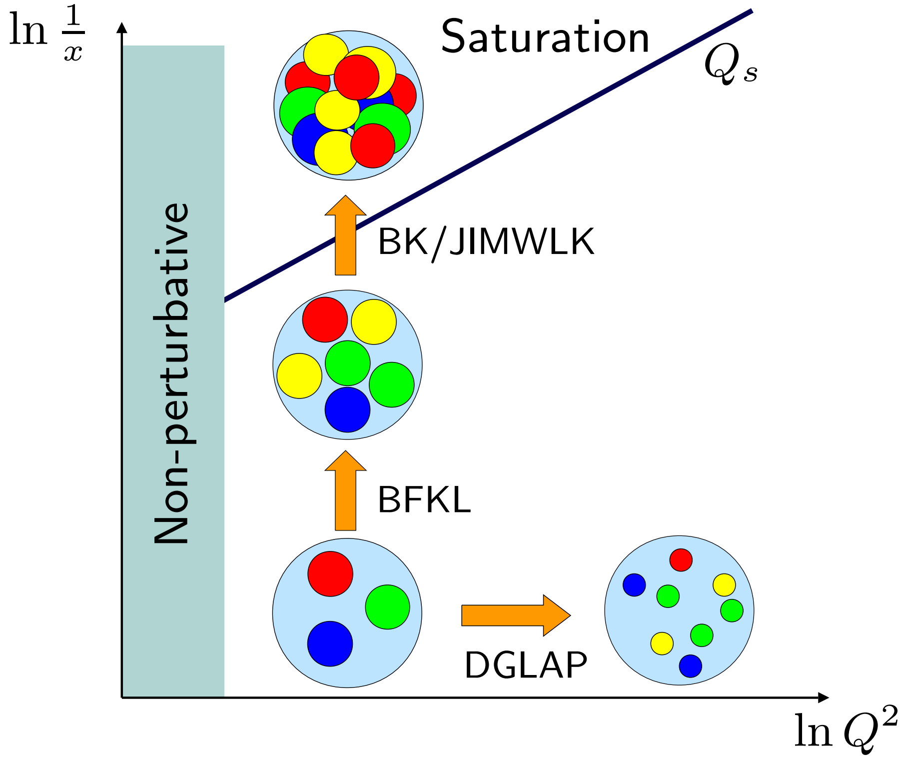


arXiv:2007.14491

CONTACT INTERACTIONS: $\mathcal{L}_{\rm CI} = \frac{g^2}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma_\mu q_i)(\bar{\ell}_i\gamma^\mu\ell_i)$

Model	ATLAS (Ref. [702])	HL-LHC	
	$\mathcal{L} = 36\,\mathrm{fb}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (LHeC)
LL (constr.)	28 TeV	58 TeV	96 TeV
LL (destr.)	21 TeV	49 TeV	77 TeV
RR (constr.)	26 TeV	58 TeV	84 TeV
RR (destr.)	22 TeV	61 TeV	75 TeV
LR (constr.)	26 TeV	49 TeV	81 TeV
LR (destr.)	22 TeV	45 TeV	62 TeV

exploration of small x QCD



- **small x** – various phenomena may occur which go beyond standard DGLAP QCD evolution:
- BFKL, connected to small x resummation of $\log \frac{1}{x}$ terms
- gluon recombination → non-linear evolution, parton saturation

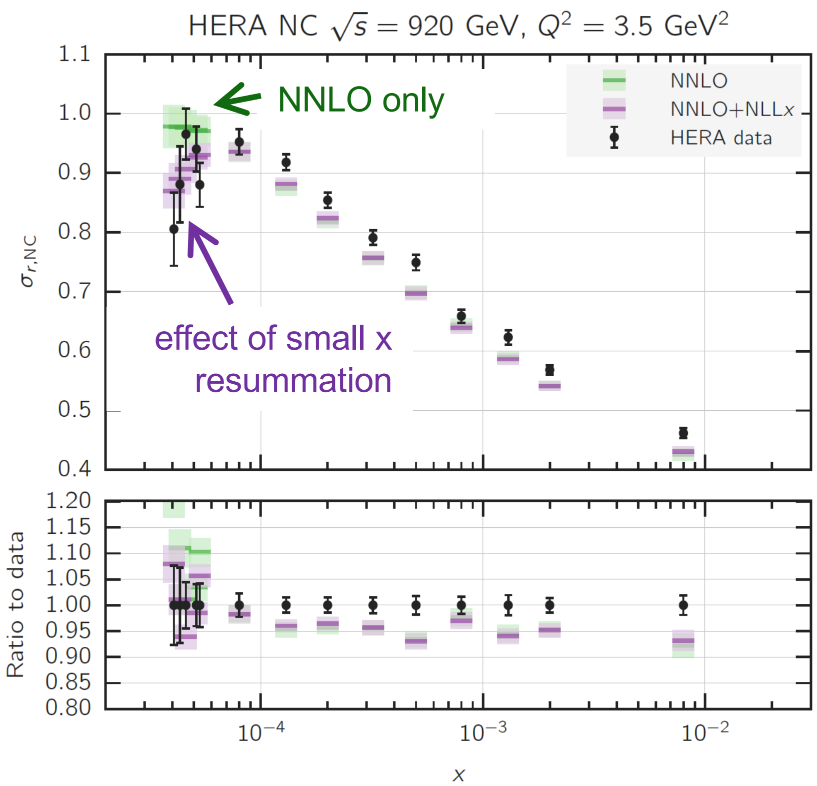
unprecedented opportunity to explore **small x** with **LHeC/FCC-eh**
×15/120 extension in 1/x cf. HERA

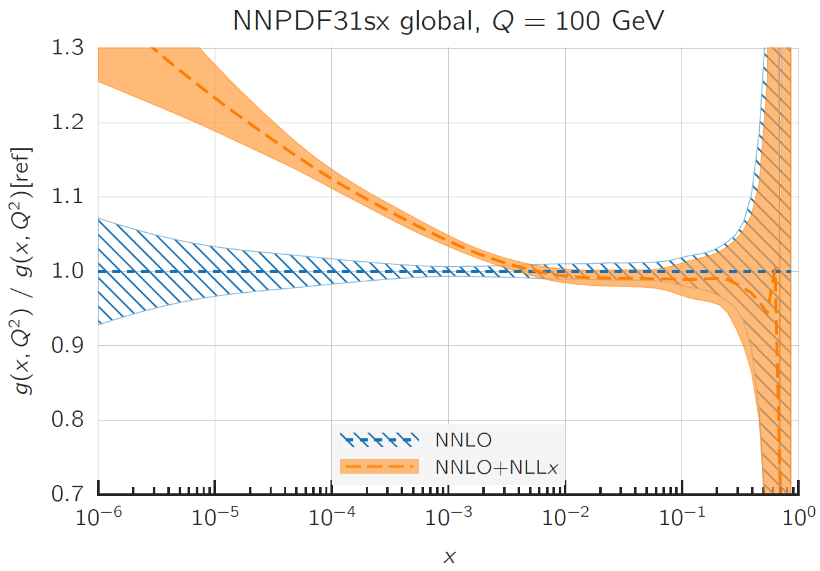
$\tau = \frac{Q^2}{s}$	Higgs	Z, W	low mass DY	$c\bar{c}$
LHC (13 TeV)	10^{-4}	5×10^{-5}	$\sim 10^{-6}$	$\sim 10^{-7}$
FCC-hh (100 TeV)	1.5×10^{-6}	8×10^{-7}	$\sim 10^{-8}$	$\sim 10^{-9}$

(note: typical values $x_1, x_2 \sim \sqrt{\tau}$)

central rapidity ↑

small x at HERA





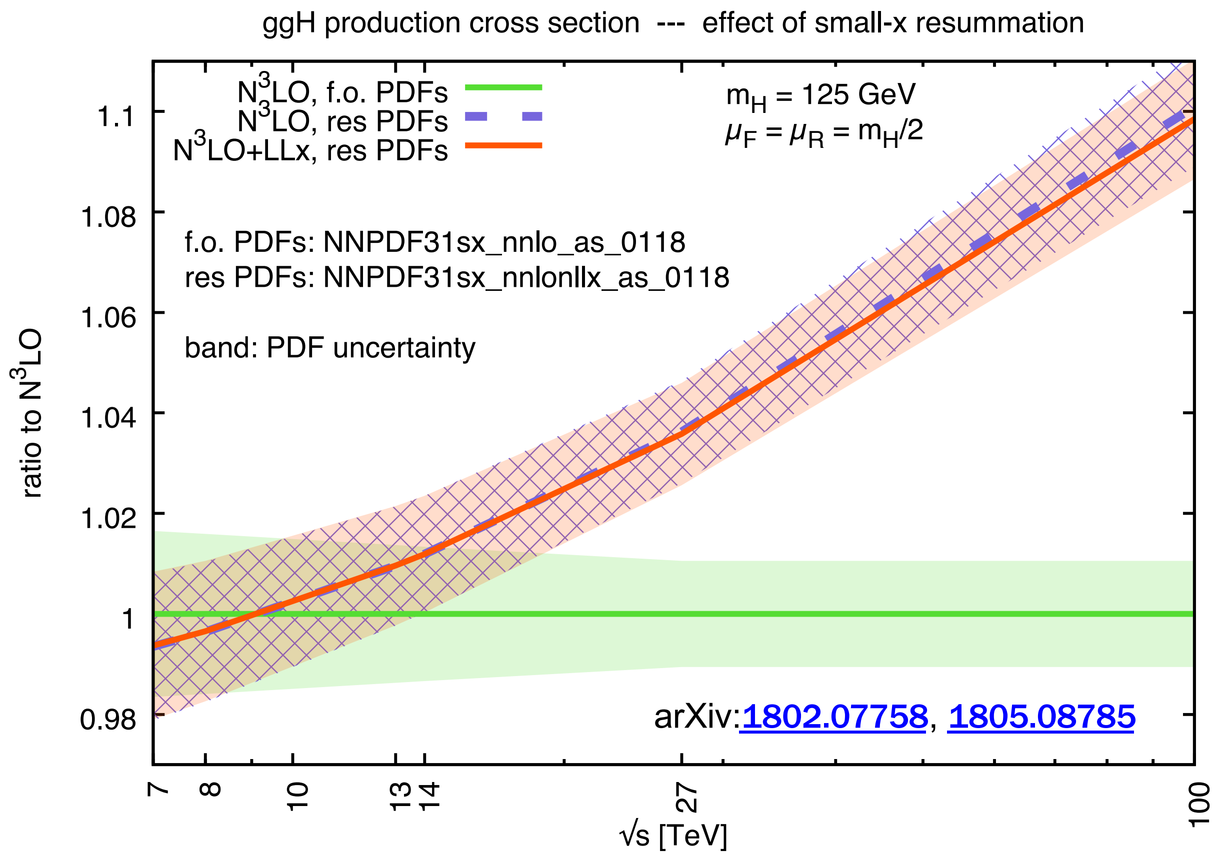
- recent evidence for onset of BFKL dynamics in HERA inclusive data,
- arXiv:1710.05935; 1802.00064

(see also, arXiv:1604.02299)

- mainly affects **gluon pdf** – dramatic effect for **x** $\lesssim$ **10^{-3}**
- impact for LHC and FCC phenomenology

- NB, gluon pdf obtained with small x resummation grows more quickly – **saturation** at some point!

impact on pp phenomenlogy

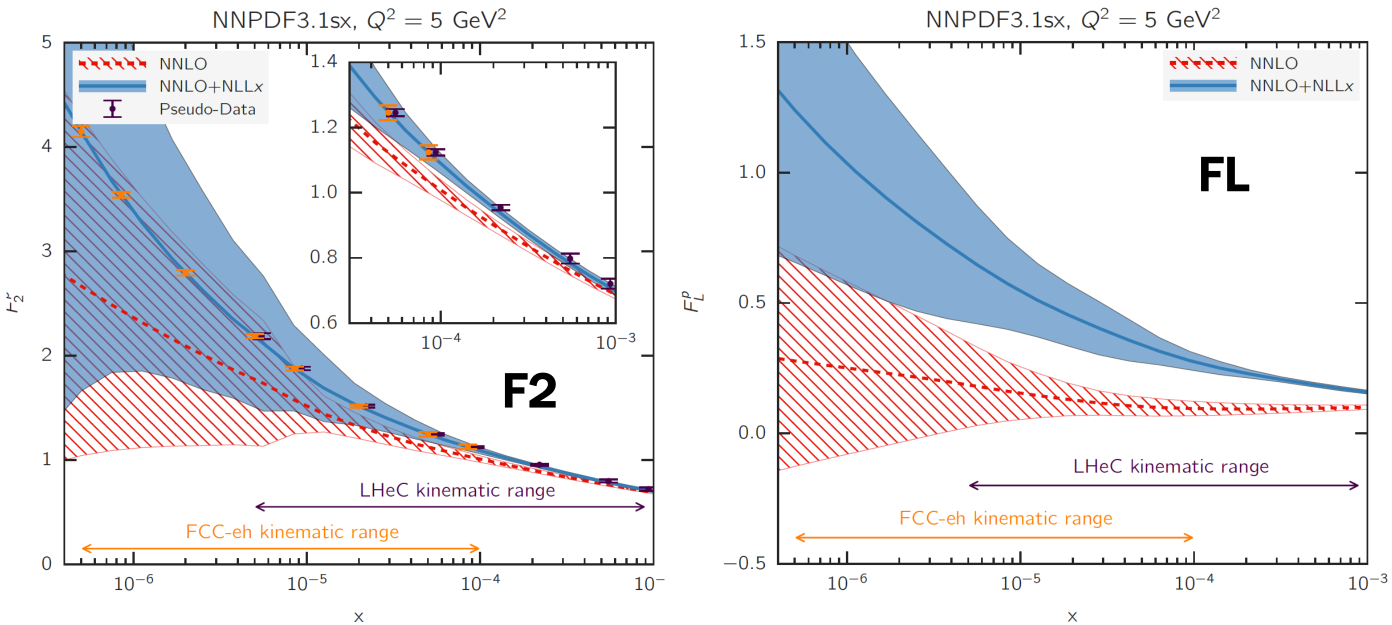


- effect of small x resummation on gg→H cross section for LHC, HE-LHC, FCC
- significant impact, especially at ultra low x values probed at FCC

(see also recent work on forward Higgs production, arXiv:2011.03193; other processes in progress)

arXiv:1710.05935

the role of future ep colliders

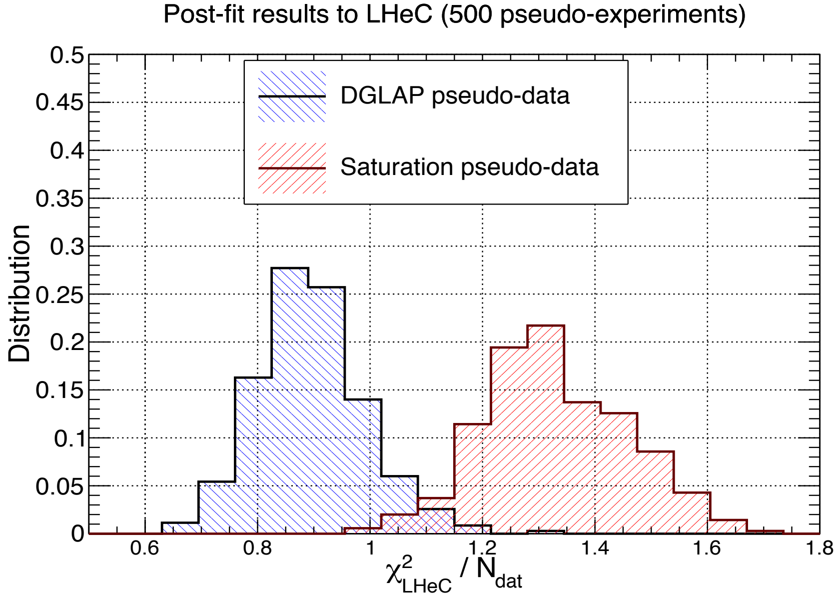


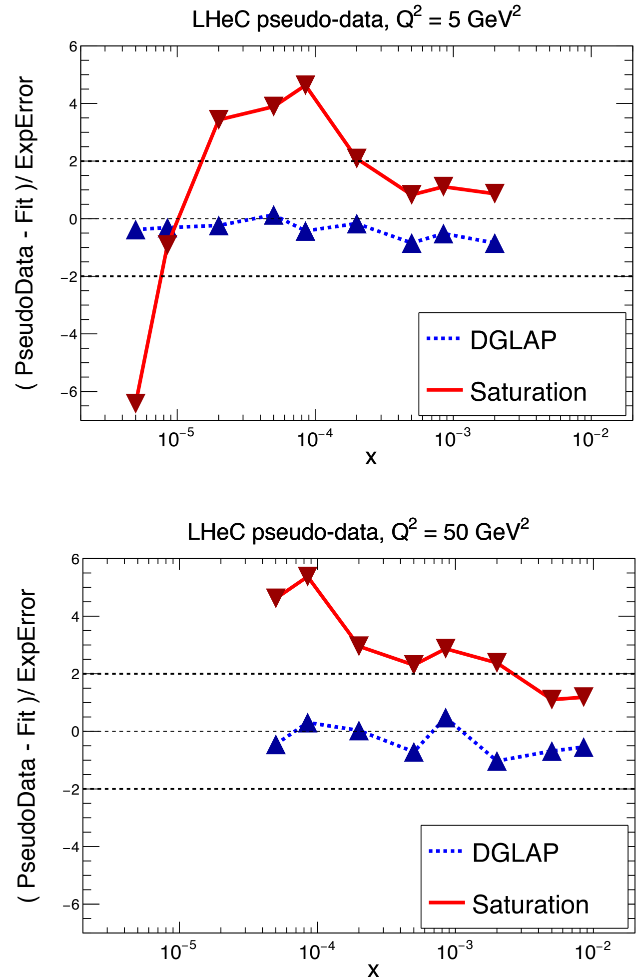
NC cross section: $\sigma_{r,\mathrm{NC}} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$ $\quad y = \frac{Q^2}{x\,s}$

- very large sensitivity and discriminatory power to pin down details of **small x QCD dynamics**
- measurement of FL has a significant role to play, arXiv:1802.04317

arXiv:2007.14491

saturation





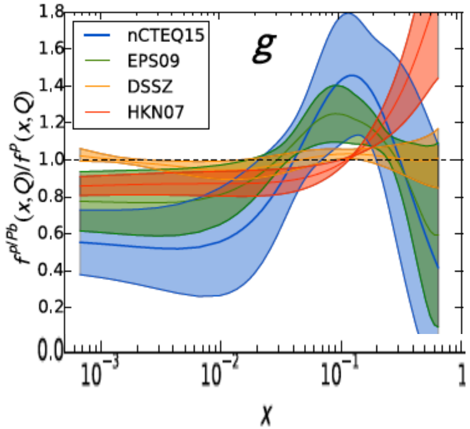
- QCD DGLAP fits **cannot** absorb all effects of saturation
- **possible to identify saturation by distortions in pulls** → DGLAP fits cannot absorb a non-DGLAP Q^2 dependence

nuclear pdfs at LHeC and FCCeh

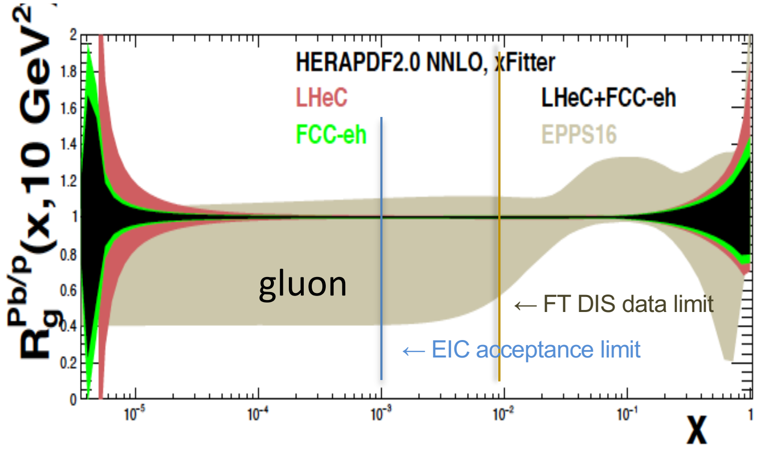
- unique nuclear/HI physics programme
- extension of fixed target range by $\times 10^3 - 10^4$
- parton structure of nuclei, independent of proton pdfs
- QCD of QGP
- saturation
- …

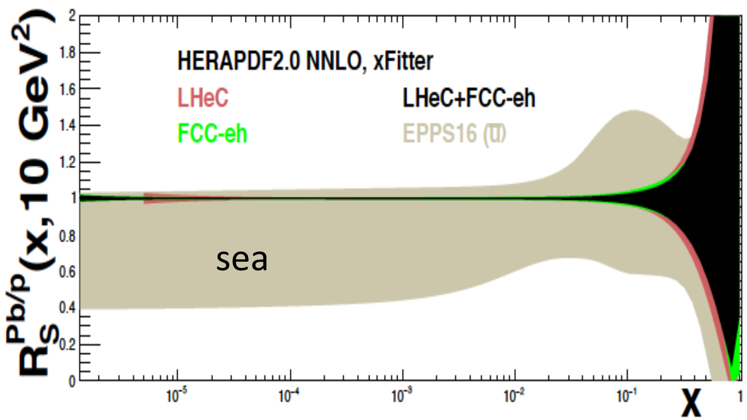
present status on xg Pb/p

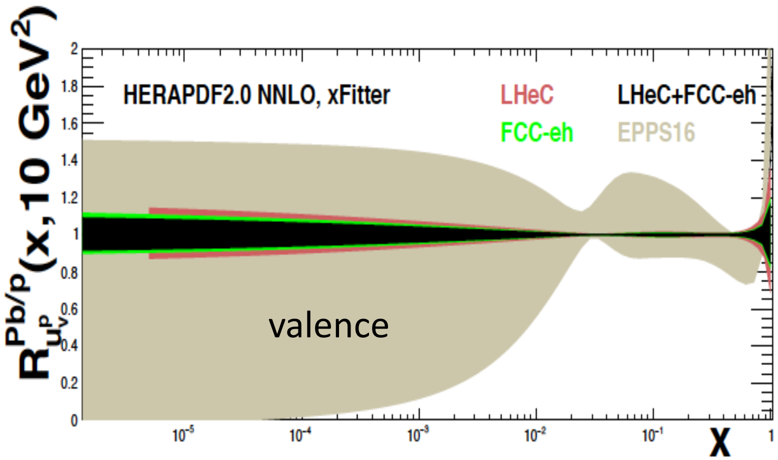
arXiv:1612.05741



arXiv:2007.14491





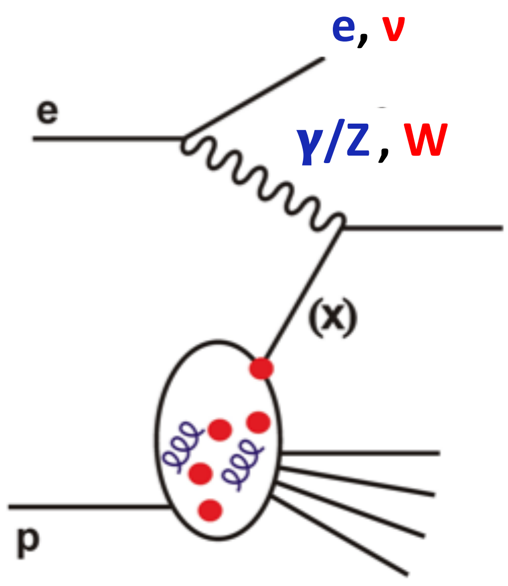


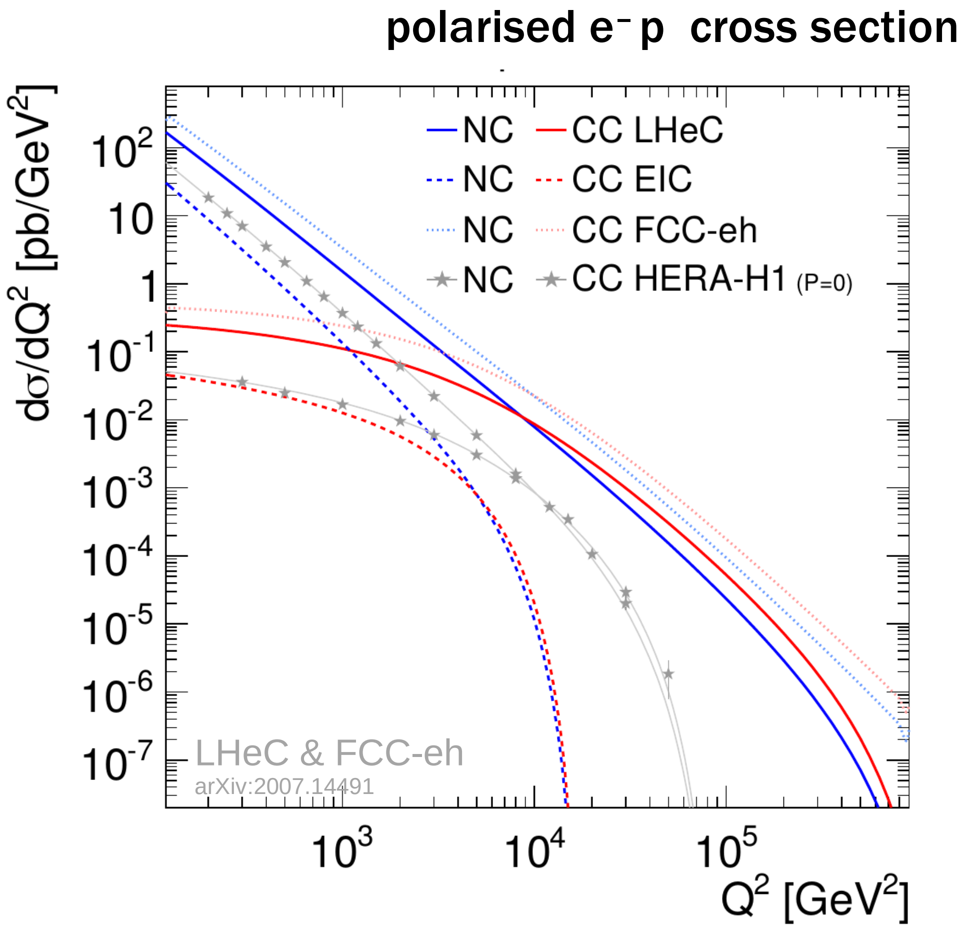
LHeC: $\Delta X^2=1$, EPPS $\Delta X^2=52$

Ri = nuclear modification factor to free nucleon **pdf**

M Klein

precision electroweak physics





NC couplings:

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\,(I_{\mathrm{L},f}^3 - 2Q_f\kappa_{\mathrm{NC},f}\,\sin^2\theta_{\mathrm{W}})$$

$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}}\,I_{\mathrm{L},f}^3$$

on-shell scheme:

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

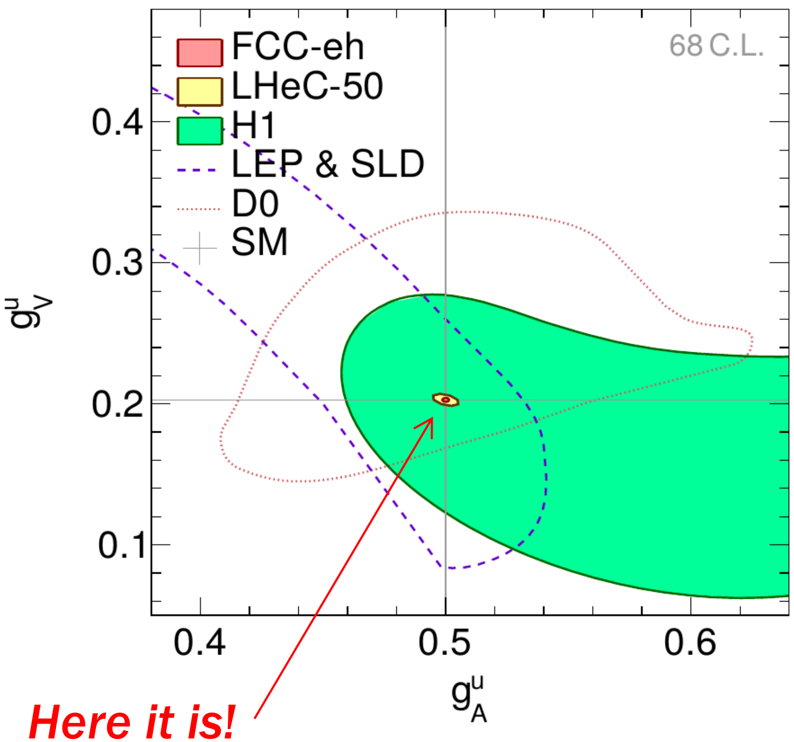
independent SM parameters: **α**, MZ, MW + pdfs

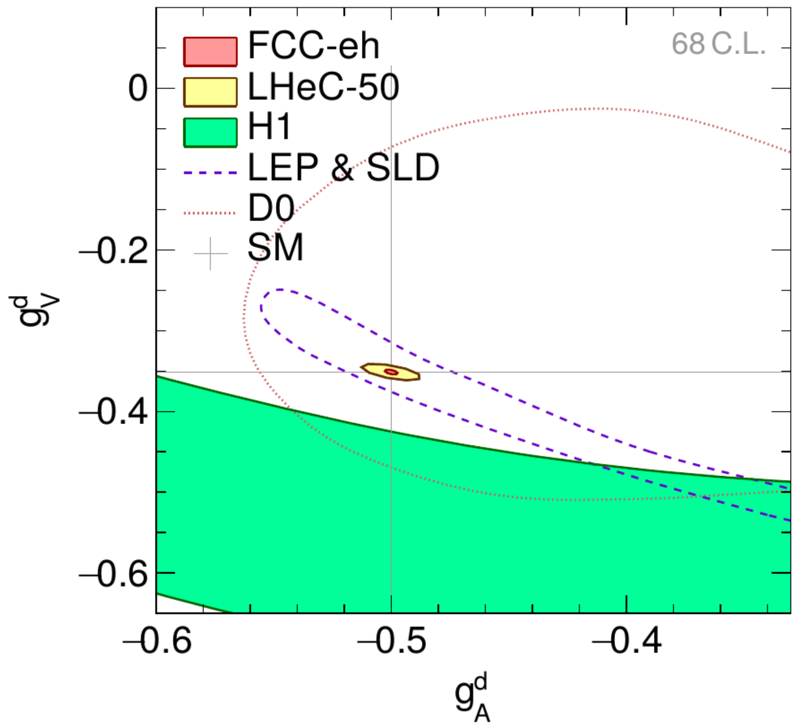
NC light quark couplings

FCC WS Nov 2020

arXiv:2007.11799

4 coupling parameters determined together with **pdfs**





Here it is!

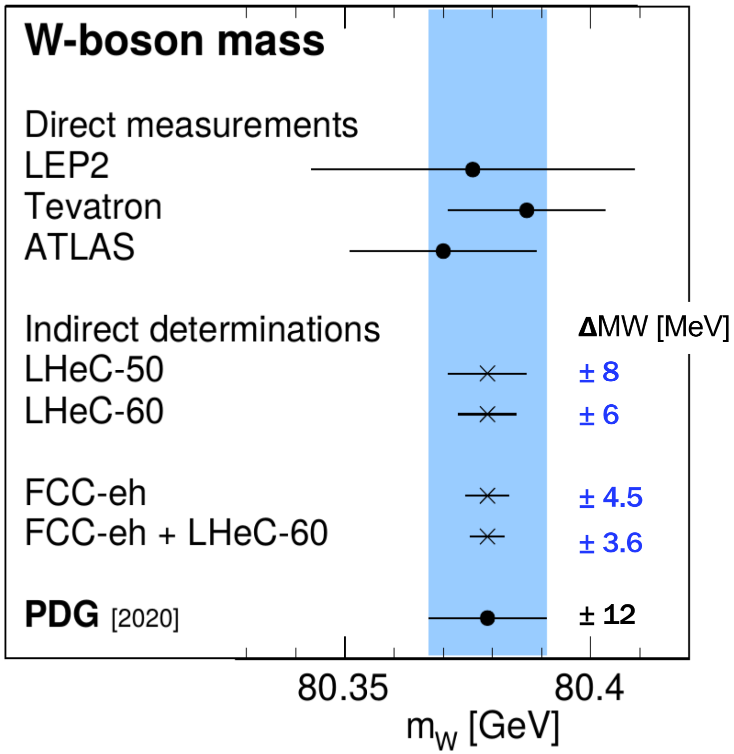
(LHeC improves constraints by more than order of magnitude; FCC-eh to per-mille level)

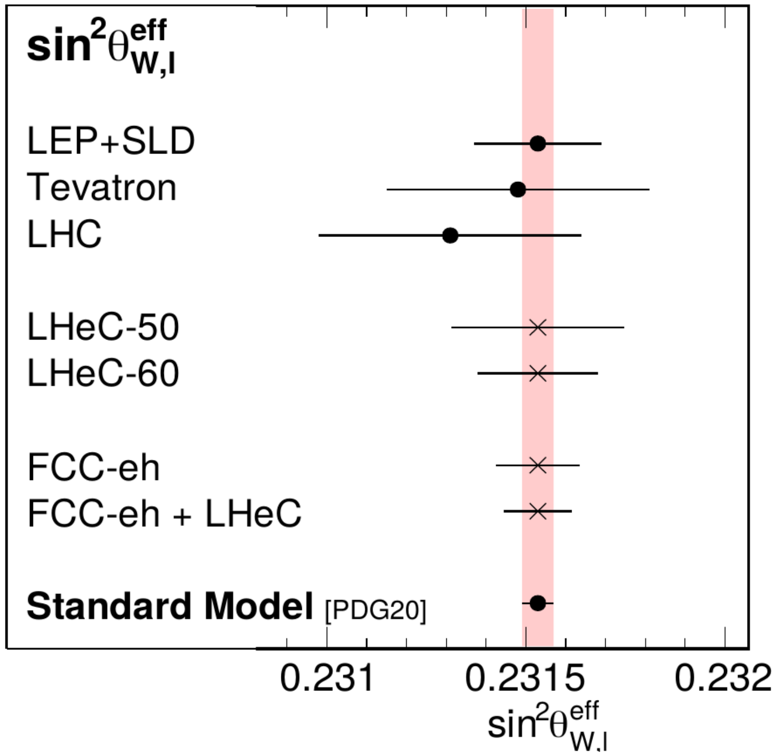
$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\,(I^3_{\mathrm{L},f} - 2Q_f\kappa_{\mathrm{NC},f}\,\sin^2\theta_{\mathrm{W}})$$
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}}\,I^3_{\mathrm{L},f}$$

sensitive to variety of BSM scenarios, EG. Z', leptoquarks, RPV SUSY, …

MW and sin²θW

pdf+EW fits





- MW: most precise determination from a single experiment
- complementary to direct measurements

- $\sin^2\theta W$: potential for most precise measurement from single experiment
- can also test SM-prediction of scale dependence across wide range of scale to $\mathcal{O}(0.1\%)$ precision

arXiv:2007.14491
arXiv:1902.04070

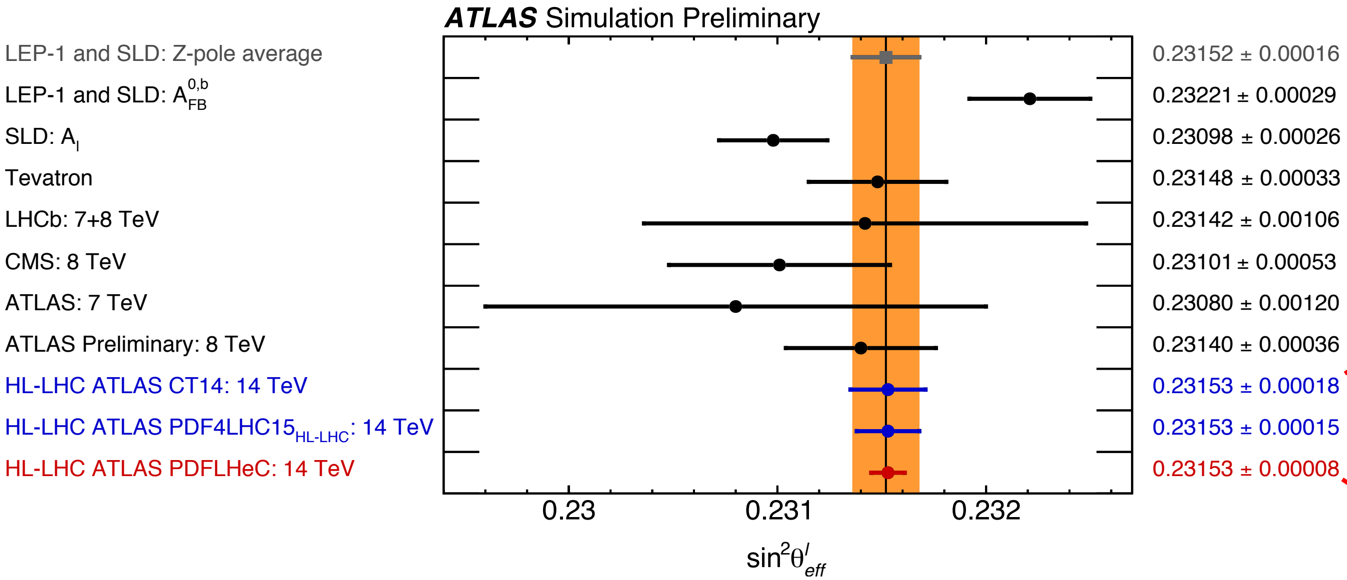
empowering the LHC: EW

MW

Parameter	Unit	ATLAS (Ref. [431])	HL-LHC projection			
		CT10	CT14	HL-LHC	LHeC	LHeC
Centre-of-mass energy, $\sqrt{s}$	TeV	7	14	14	14	14
Int. luminosity, $\mathcal{L}$	fb^{-1}	5	1	1	1	1
Acceptance		$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 4$
Statistical uncert.	MeV	± 7	± 5	± 4.5	± 4.5	± 3.7
PDF uncert.	MeV	± 9	± 12	± 5.8	± 2.2	± 1.6
Other syst. uncert.	MeV	± 13	-	-	-	
Total uncert. Δm_W	MeV	± 19	13	7.3	5.0	4.1

← pdf uncertainty

$\sin^2\theta W$



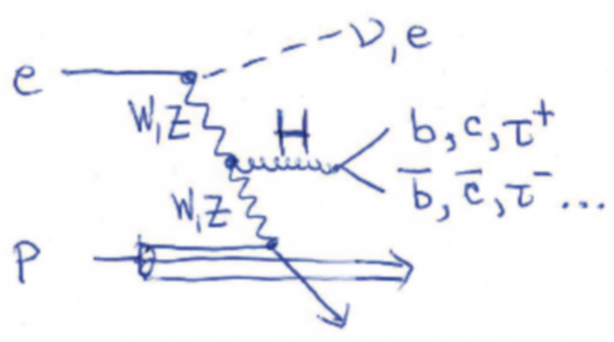
± 0.00009 (exp) ± **0.00016** (pdf)
± 0.00007 (exp) ± **0.00013** (pdf)
± 0.00007 (exp) ± **0.00003** (pdf)

↑ pdf uncertainty

with LHeC pdfs: pdf uncertainty becomes sub-dominant!

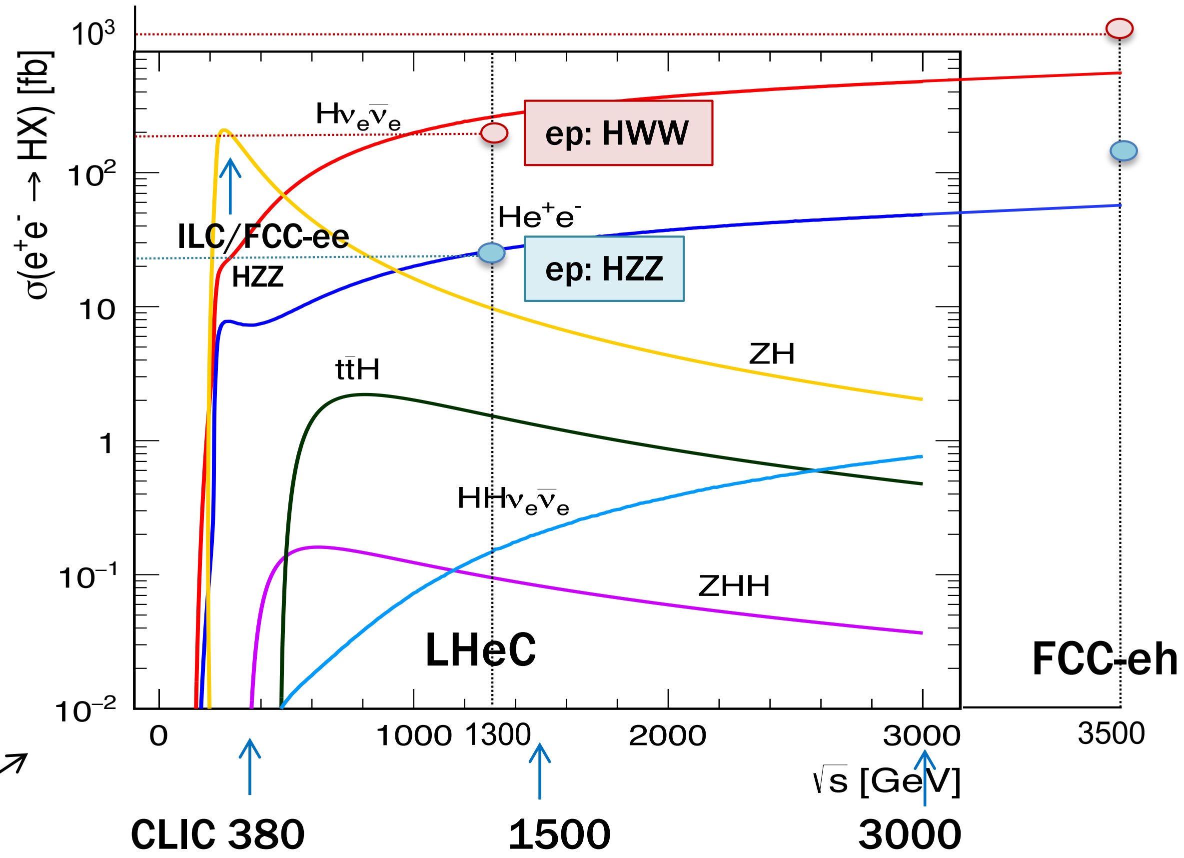
Higgs at ep vs ee

ep:



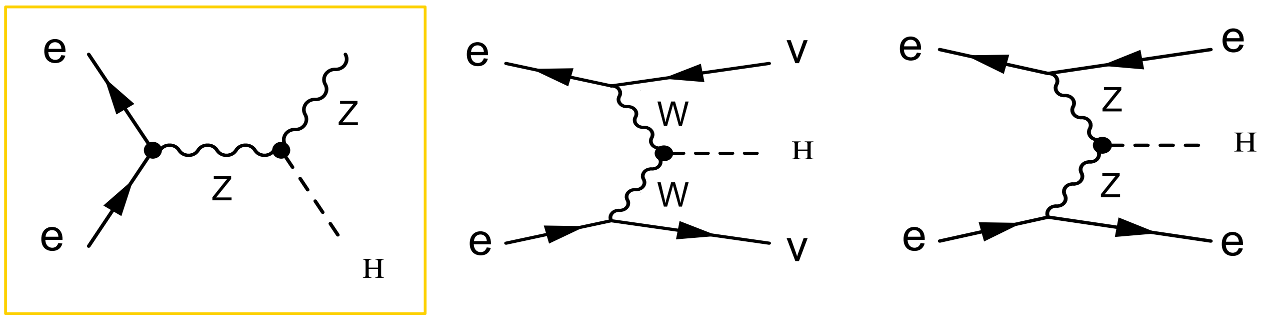
ep: CC – WW fusion

ep: NC – ZZ fusion



versus **ee:**

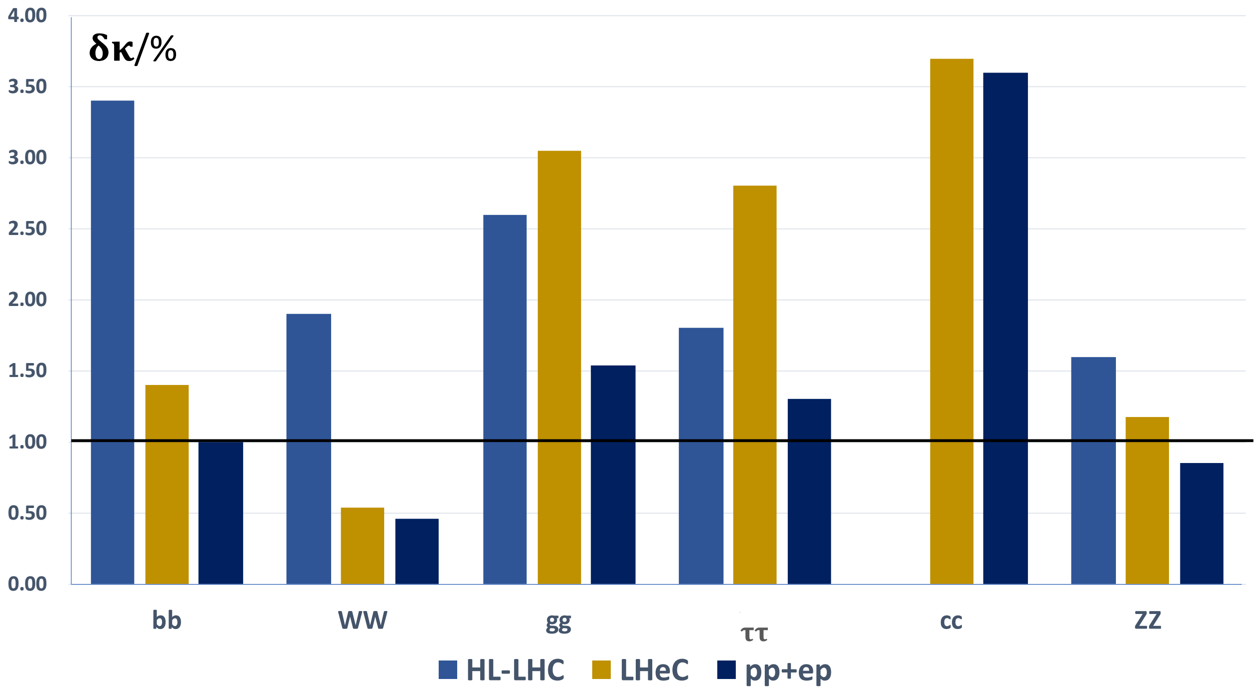
(dominant production mechanisms)

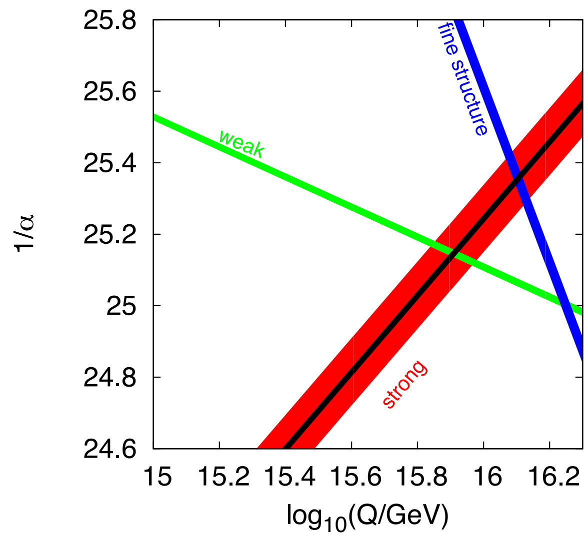


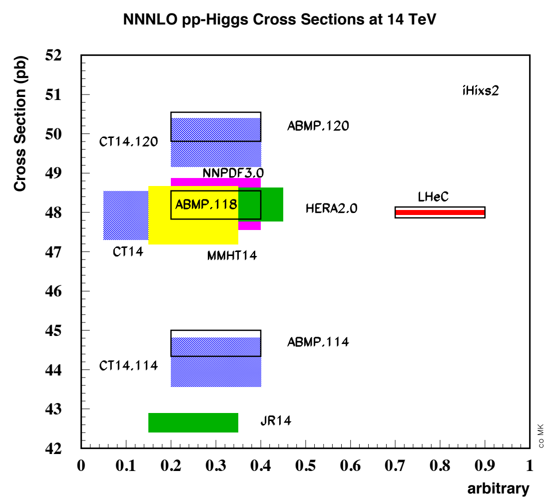
Higgs in ep and pp

SM Higgs couplings from **pp** and **ep**

(κ framework, arXiv:[1307.1347](1307.1347); SM couplings modified by factor $\kappa_i \equiv g_{Hi}/g_{Hi}^{SM}$)







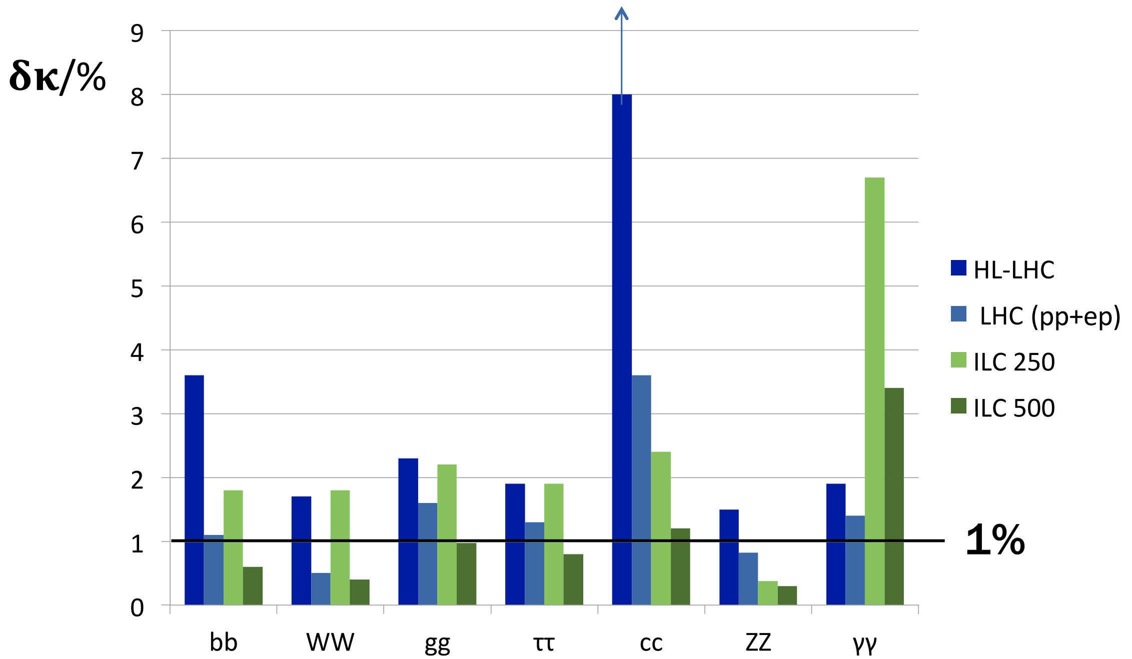
combined **ep+pp** at LHC reaches below **1%** for dominant channels

ep adds charm

analysis in EFT framework in progress

HL-LHC projections: arXiv:[1902.00134](1902.00134)

Higgs in ep, pp and ee



99.9% of Higgs decays

arXiv:2007.14491

	FCC-ee uncertainty (%)	FCC-eh uncertainty (%)
Γ_H	1.3	SM
κ_{bb}	0.61	0.74
$\kappa_{\tau\tau}$	0.74	1.10
κ_{cc}	1.21	1.35
$\kappa_{\mu\mu}$	9.0	–
κ_{ZZ}	0.17	0.43
κ_{WW}	0.43	0.26
κ_{gg}	1.01	1.17
$\kappa_{\gamma\gamma}$	3.9	2.3
κ_{tt}	–	1.7

CERN-ACC-2018-0056

NB, **ee** measures ΓH with Z recoil; **ee** is mainly ZZH, while **ep** mainly WWH; complementary also to **pp**

ECFA newsletter No. 5, August 2020
https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf

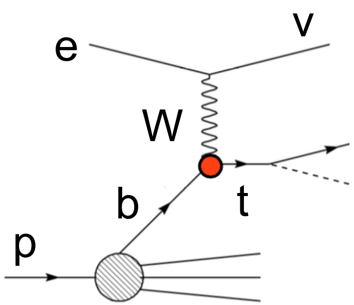
comprehensive review on complementarity of colliders
arXiv:1905.03764

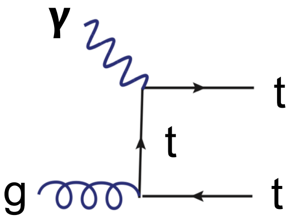
HL-LHC projections: arXiv:1902.00134
(part of CERN YR: CERN-2019-007)

ep as a top quark factory

arXiv:[2007.14491]
[EPJ C79 (2019), 6, 474]

CC DIS



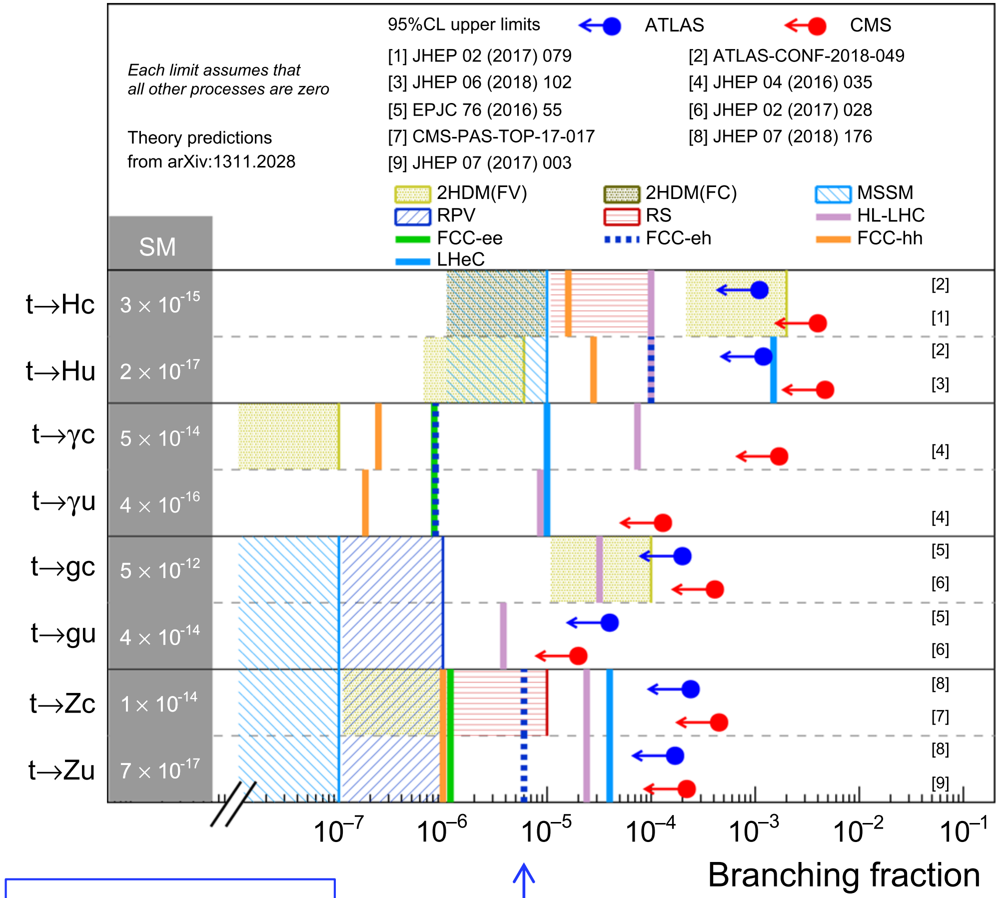


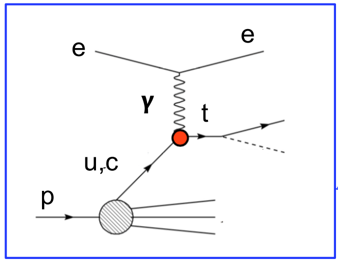
NC (γp) DIS

- just some **EGs,**
- **|Vtb|** : **1%** precision (L=**100** fb^{-1})
- c.f. current best LHC measurement: **4%**
- same analysis: anomalous **Wtq** couplings (**1 – 14%,** depending on coupling)
- **Vts** and **Vtd** also accessible
- **Vts** probes SM prediction directly for **first time**

- **FCNCs:**
- t-quark FCNCs very suppressed in SM
- collider complementarity; test: little-Higgs, SUSY, technicolor, extra spatial dimensions, …

FCNC top quark couplings – summary:





t-quark FCNC in linear ee studied in EG,
arXiv:[1807.02441]

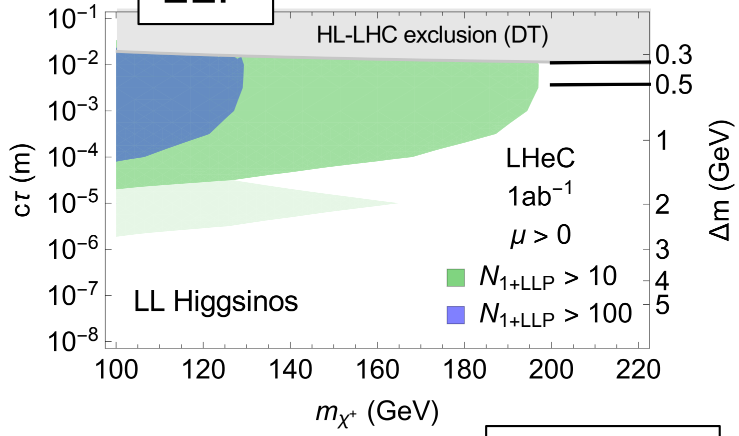
arXiv:2007.14491

BSM

- selected examples:

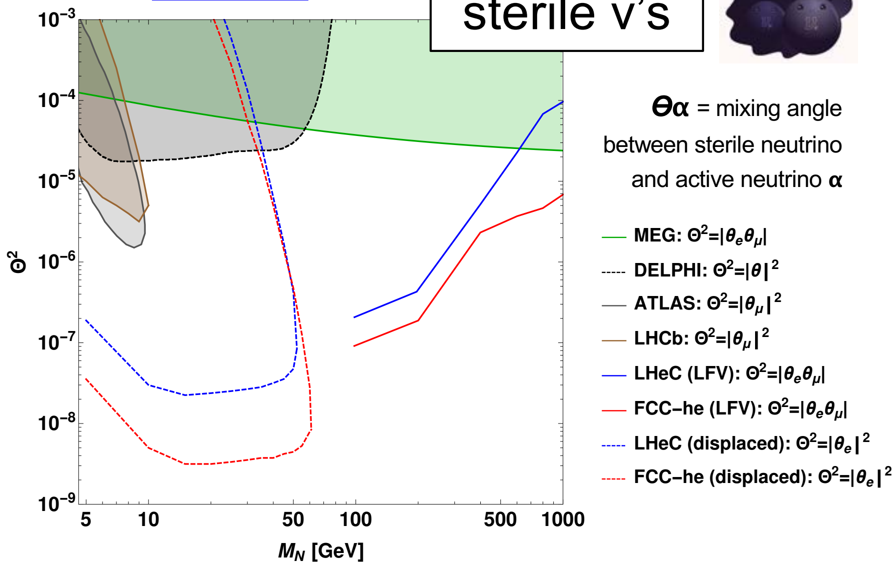
LLP

arXiv:1712.07135



sterile ν's

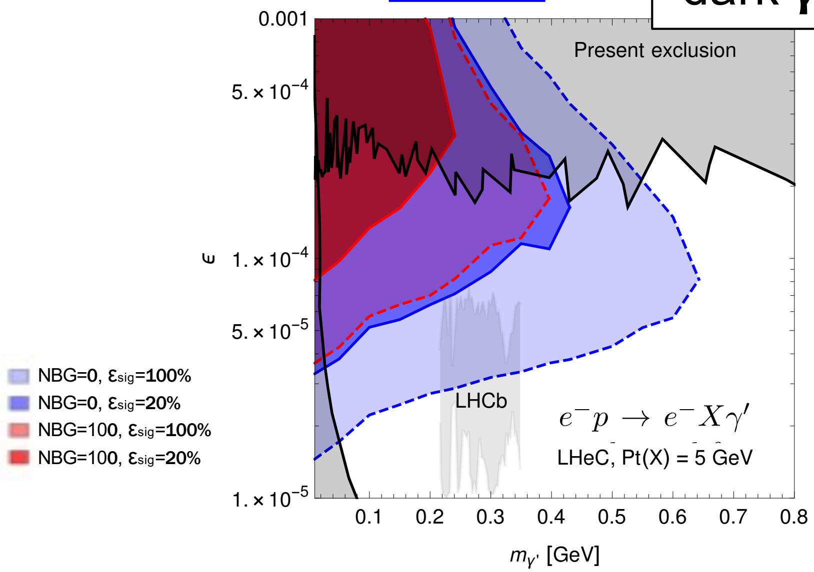
arXiv:1908.02852



Θα = mixing angle between sterile neutrino and active neutrino **α**

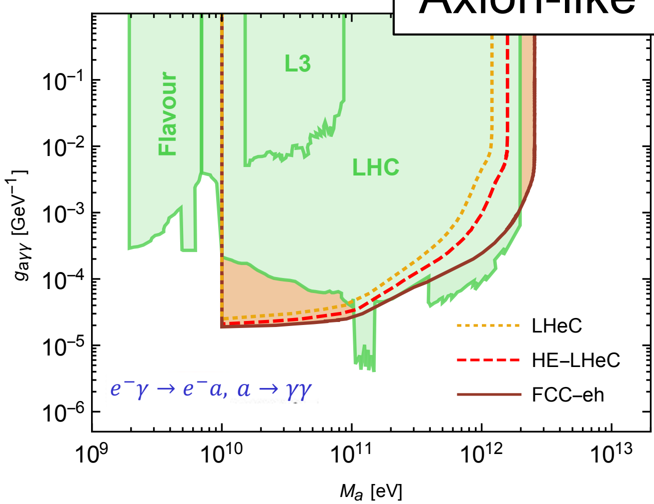
dark γ's

arXiv:1909.02312



Axion-like particles

arXiv:1904.10657



- also:
- LQs
- BSM Higgs
- SUSY (RPV; EWinos in compressed scenarios, prompt and LLP, …)
- …

statement of the IAC

Members of the Committee

Sergio Bertolucci (Bologna)
Nichola Bianchi (INFN, now Singapore)
Frederick Bordy (CERN)
Stan Brodsky (SLAC)
Oliver Brüning (CERN, coordinator)
Hesheng Chen (Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Max Klein (Liverpool, coordinator)
Shin-Ichi Kurokawa (KEK)
Victor Matveev (JINR Dubna)
Aleandro Nisati (Rome I)
Leonid Rivkin (PSI Villigen)
Herwig Schopper (CERN, em.DG, Chair)
Jürgen Schukraft (CERN)
Achille Stocchi (Orsay)
John Womersley (ESS Lund)

In conclusion it may be stated

- The installation and operation of the LHeC has been demonstrated to be commensurate with the currently projected HL-LHC program, while the FCC-eh has been integrated into the FCC vision;
- The feasibility of the project as far as accelerator issues and detectors are concerned has been shown. It can only be realised at CERN and would fully exploit the massive LHC and HL-LHC investments;
- The sensitivity for discoveries of new physics is comparable, and in some cases superior, to the other projects envisaged;
- The addition of an ep/A experiment to the LHC substantially reinforces the physics program of the facility, especially in the areas of QCD, precision Higgs and electroweak as well as heavy ion physics;
- The operation of LHeC and FCC-eh is compatible with simultaneous pp operation; for LHeC the interaction point 2 would be the appropriate choice, which is currently used by ALICE;
- The development of the ERL technology needs to be intensified in Europe, in national laboratories but with the collaboration of CERN;
- A preparatory phase is still necessary to work out some time-sensitive key elements, especially the high power ERL technology (PERLE) and the prototyping of Intersection Region magnets.

Recommendations

i) It is recommended to further develop the ERL based ep/A scattering plans, both at LHC and FCC, as attractive options for the mid and long term programme of CERN, resp. Before a decision on such a project can be taken, further development work is necessary, and should be supported, possibly within existing CERN frameworks (e.g. development of SC cavities and high field IR magnets).

ii) The development of the promising high-power beam-recovery technology ERL should be intensified in Europe. This could be done mainly in national laboratories, in particular with the PERLE project at Orsay. To facilitate such a collaboration, CERN should express its interest and continue to take part.

iii) It is recommended to keep the LHeC option open until further decisions have been taken. An investigation should be started on the compatibility between the LHeC and a new heavy ion experiment in Interaction Point 2, which is currently under discussion.

After the final results of the European Strategy Process will be made known, the IAC considers its task to be completed. A new decision will then have to be taken for how to continue these activities.

Herwig Schopper, Chair of the Committee, Geneva, November 4, 2019

(published in LHeC CDR update, arXiv:2007.14491)

integration of eA and AA detector concepts

- ALICE currently resides in IP2, with a programme extending to LS4, and plans for a new compact HI detector

- novel thought/study first mentioned in ECFA newsletter No. 5, August 2020
  https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf

- could we unify the LHeC (arXiv:2007.14491) and novel Heavy Ion detector ("A3", arXiv:1902.01211) concepts, in order to commonly use IP2?

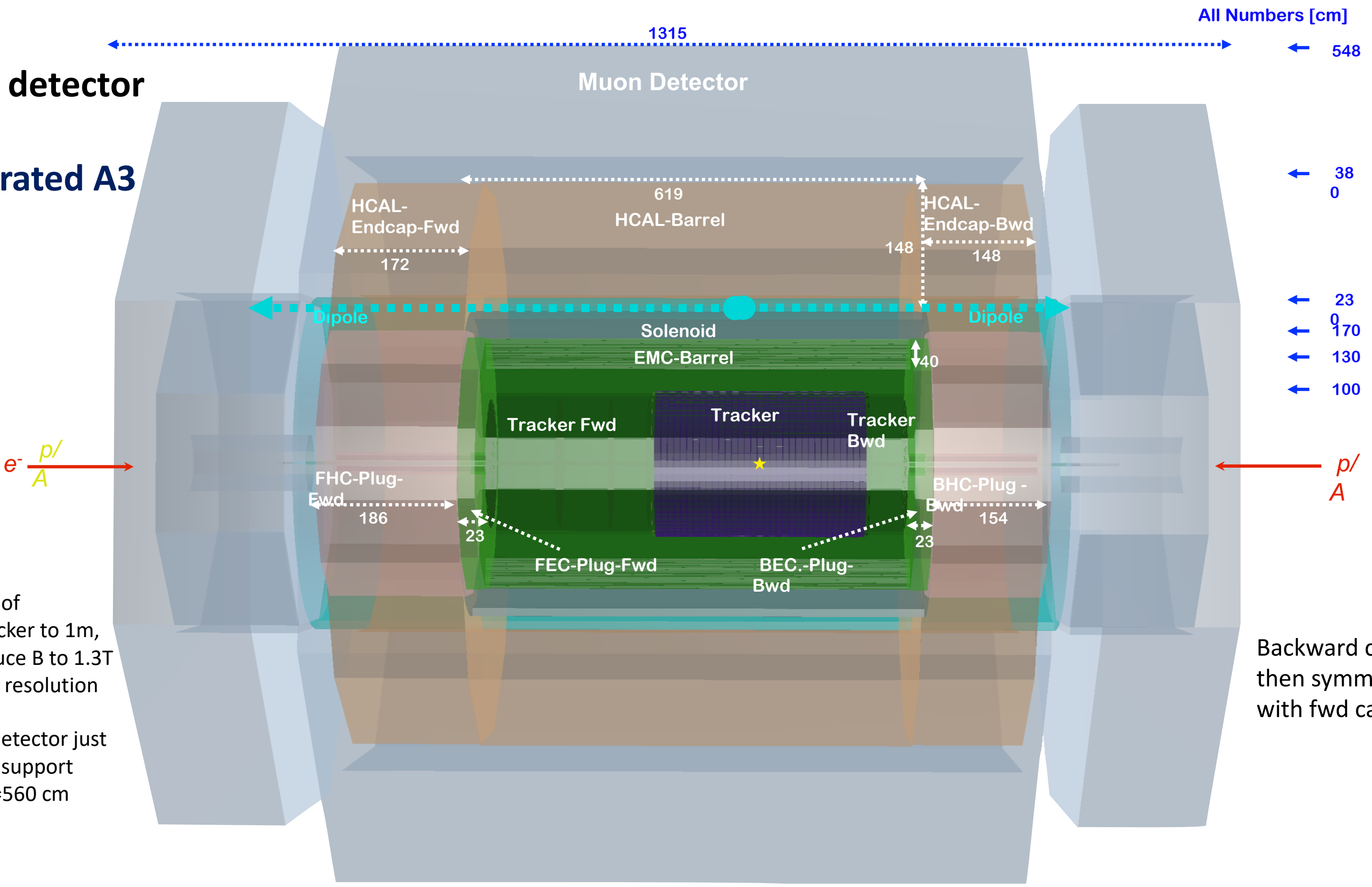
- if so, then two kinds of operation:

1. pp or AA data taking in all 4 IPs of LHC
2. ep data taking in IP2 synchronous with pp in ATLAS, CMS, LHCb

- **enriches physics potential; requires study of joint detector and IR design!**

integration of eA and AA detector concepts

LHeC detector
with
integrated A3



Increase of radii, tracker to 1m, may reduce B to 1.3T for same resolution

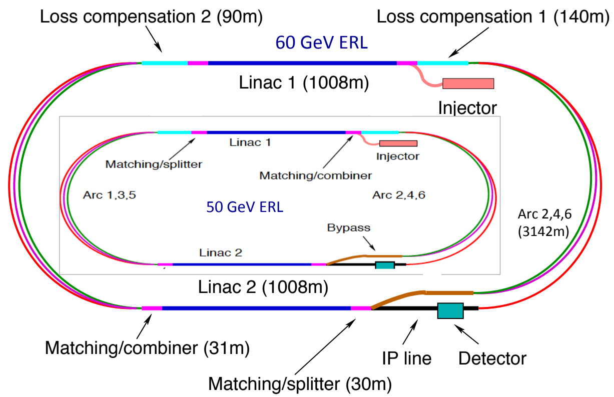
Overall detector just fits in L3 support R_{free}(L3)=560 cm

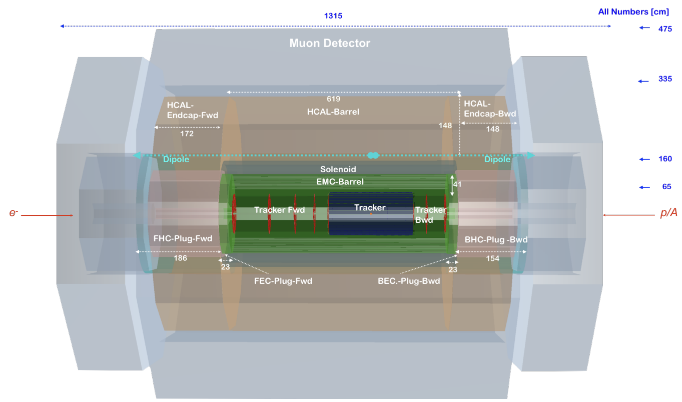
Backward calos then symmetric with fwd calos

work in progress, P. Kostka et al.

summary

- **LHeC affordable**: $\mathcal{O}(1)$ BCHF for another TeV collider
- **sustains the HL-LHC** and exploits $\mathcal{O}(5)$ BCHF investment
- **unique physics**: microscope of substructure; crucial complement to LHC (/FCC), empowering precision measurements and searches; unique Higgs facility; QCD and EW sector discovery; HI physics revolution
- **technology**: accelerator: novel SRF ERL, green power facility; detector: exciting place for new technology (CMOS, …)
- **LHeC merged with A3**: would resolve conflict on IP2 and promise new chapter of HI and accelerator physics (**tentative**)



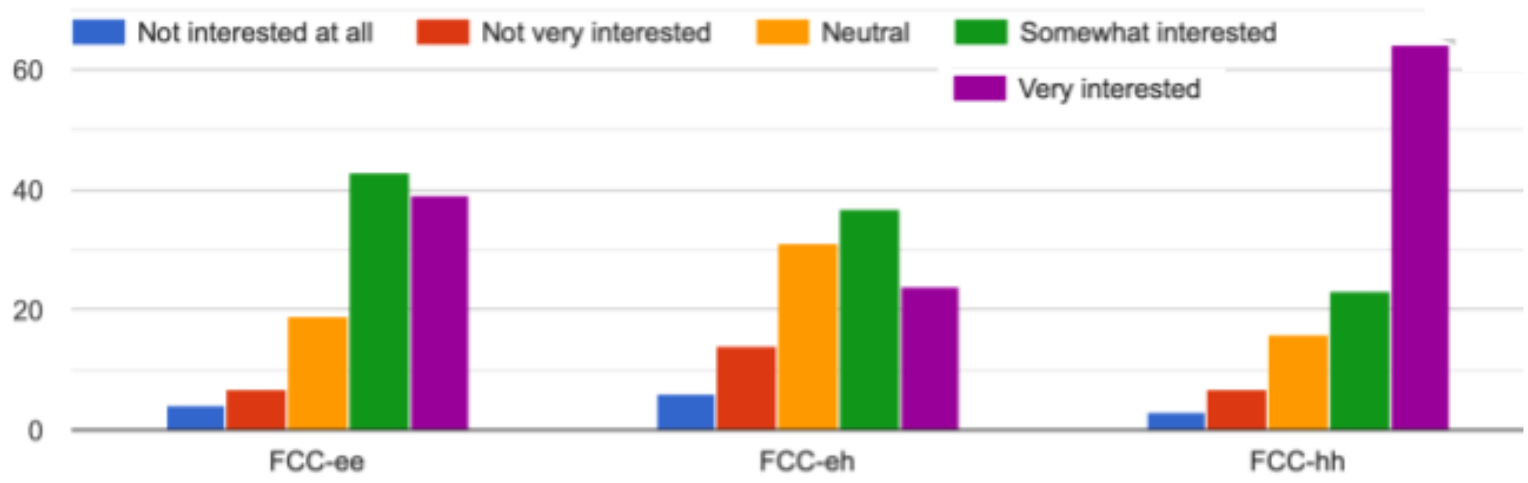


- **next steps**: PERLE facility at Orsay; considerations for a detector proposal to LHCC; ***"LHeC option should be kept open"*** (IAC recommendation to CERN DG), embedded in and subject to CERN's future

extras

ECFA early career researchers debate for ESPPU

If you agree that CERN should build the FCC, which project(s) are you interested in?



CERN/ESG/05

Organisation

International Advisory Committee
Mandate by CERN (2014+17) to define
"..Direction for ep/A both at LHC+FCC"

Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
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
Juergen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (ESS)

We miss Guido Altarelli.

Coordination Group

Accelerator+Detector+Physics

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

5(12) are members of the FCC coordination team

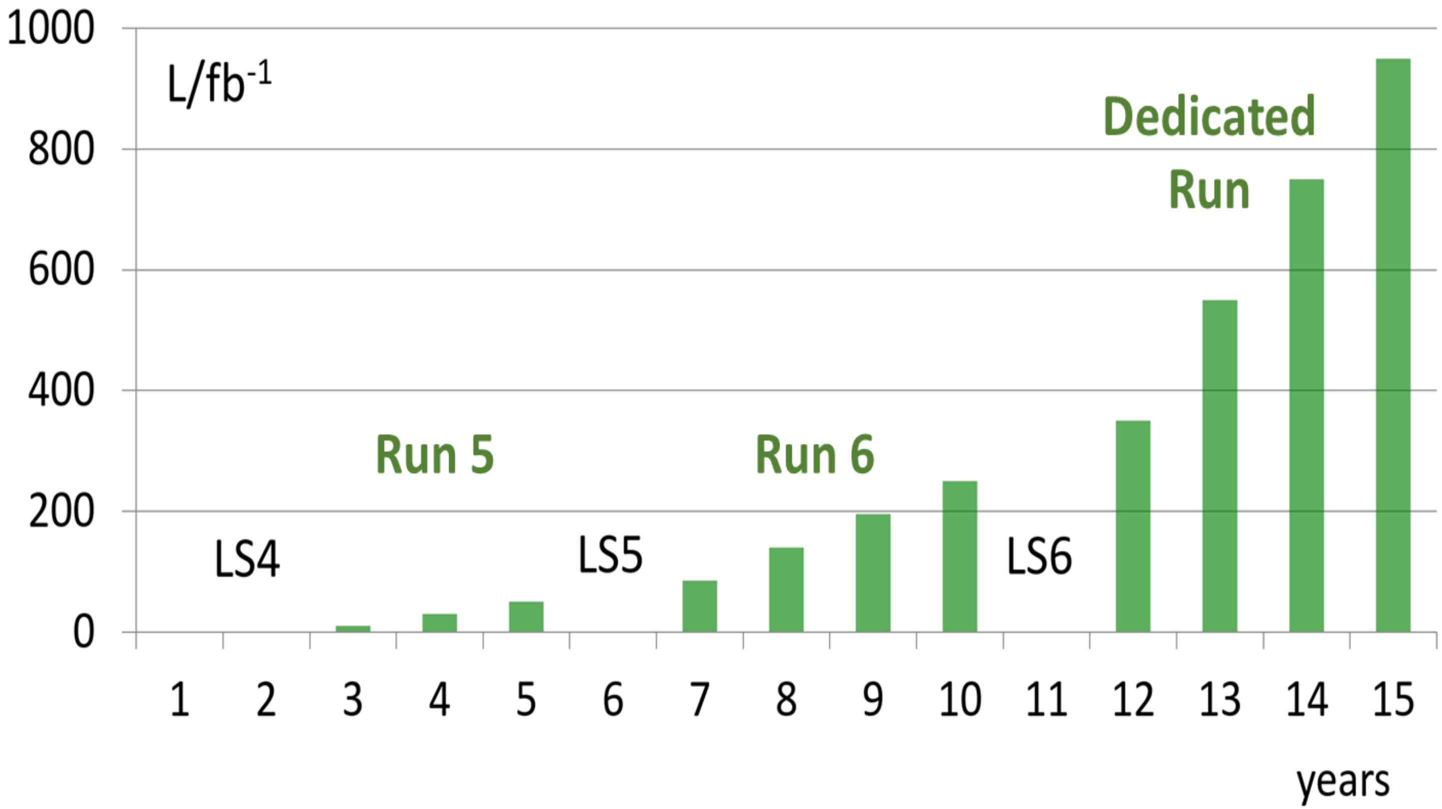
OB+MK: co-coordinate FCCeh

Working Groups

PDFs, QCD
Fred Olness,
Claire Gwenlan
Higgs
Uta Klein,
Masahiro Kuze
BSM
Georges Azuelos,
Monica D'Onofrio
Oliver Fischer
Top
Olaf Behnke,
Christian Schwanenberger
eA Physics
Nestor Armesto
Small x
Paul Newman,
Anna Stasto
Detector
Alessandro Polini
Peter Kostka

LHeC timescale

LHeC projected integrated luminosity:



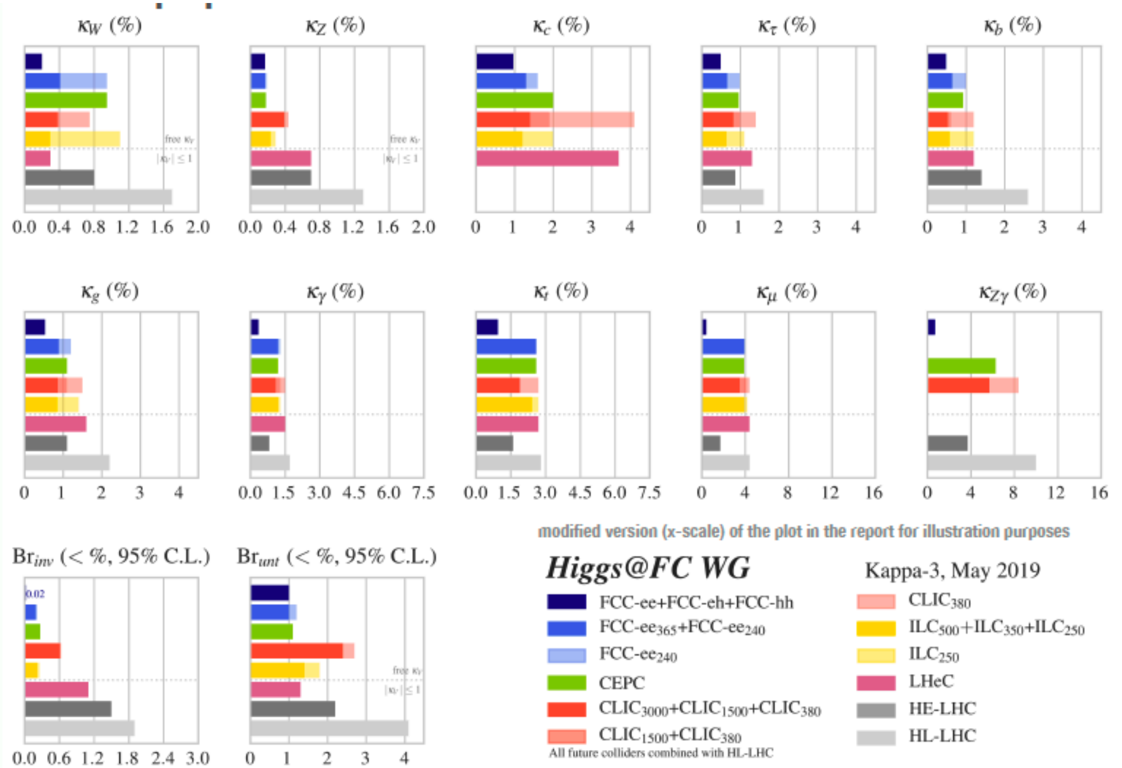
arXiv:[1810.13022](1810.13022)

comparison of colliders

Some observations:

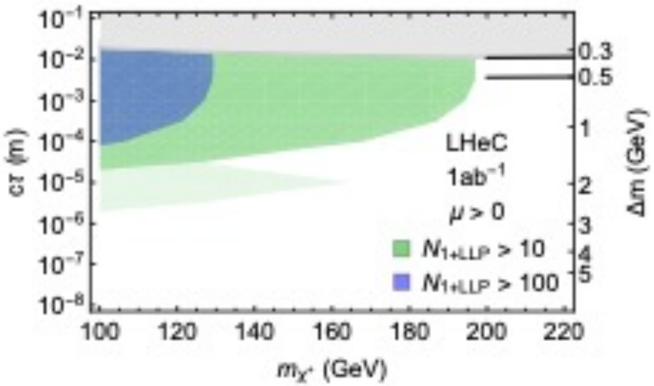
- **HL-LHC** achieves precision of ~1-3% in most cases
  - In some cases model-dependent
- Proposed e^+e^- and ep colliders improve w.r.t. HL-LHC by factors of ~2 to 10
- **Initial stages of e^+e^- colliders** have comparable sensitivities (within factors of 2)
- **ee** colliders constrain $BR \rightarrow untagged$ w/o assumptions
- **Access to κ_c** at ee and eh

arXiv:[1905.03764](https://arxiv.org/abs/1905.03764)

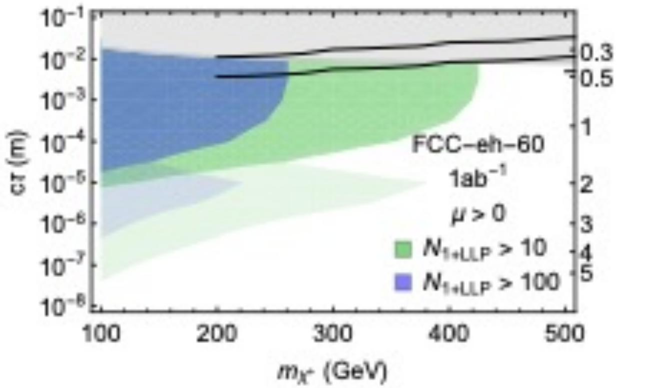


Beate Heinemann, ESU, Granada, 2019

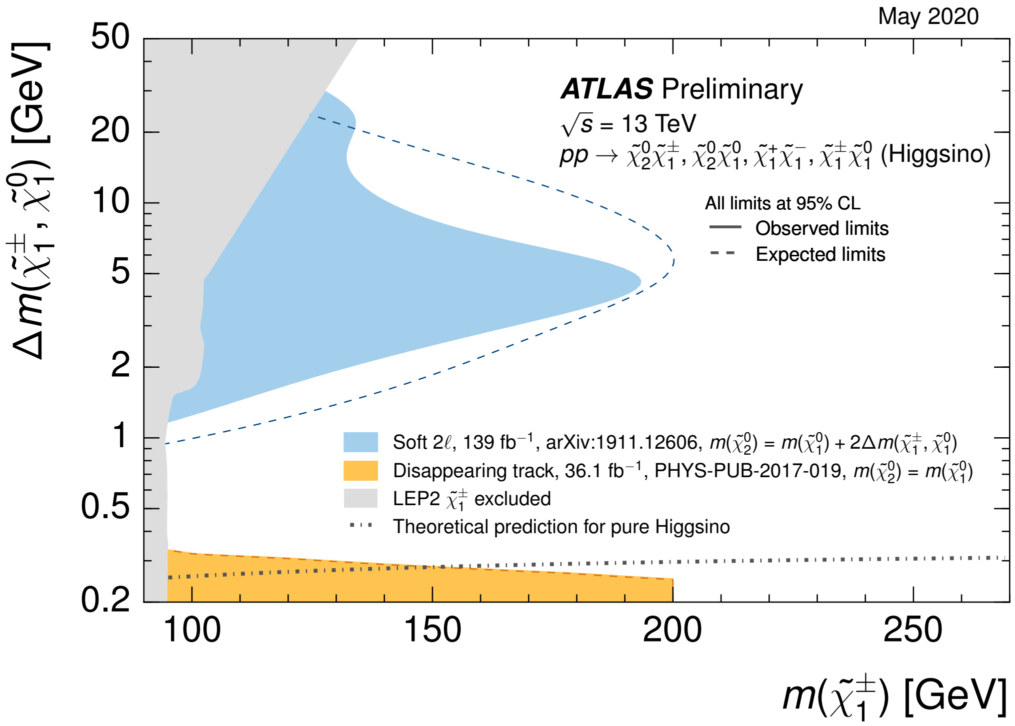
BSM – LLP



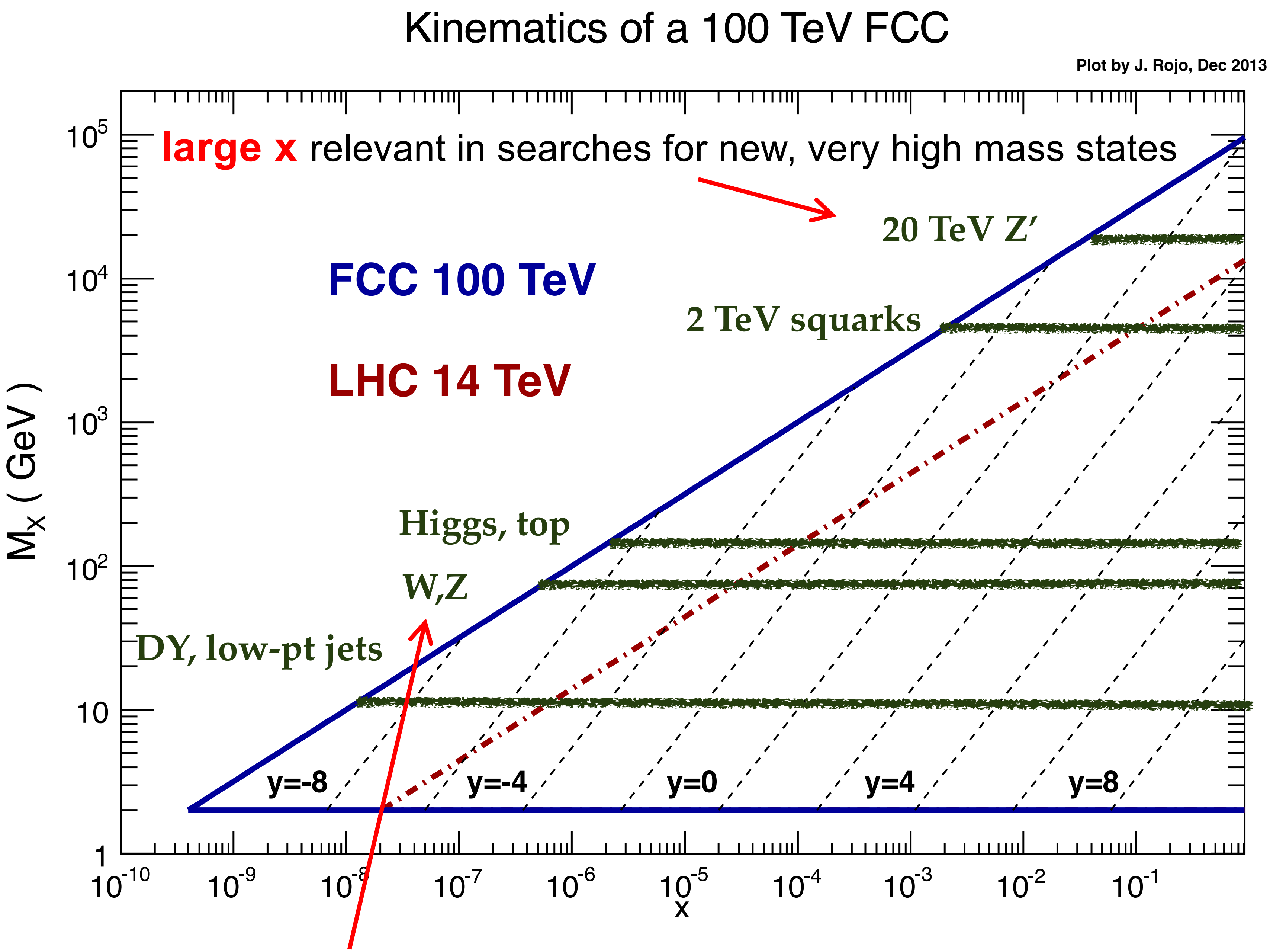
cτ (m)
Δm (GeV)
LHeC
1ab^{-1}
μ > 0
N_{1+LLP} > 10
N_{1+LLP} > 100
m_{χ^+} (GeV)



cτ (m)
FCC-eh-60
1ab^{-1}
μ > 0
N_{1+LLP} > 10
N_{1+LLP} > 100
m_{χ^+} (GeV)

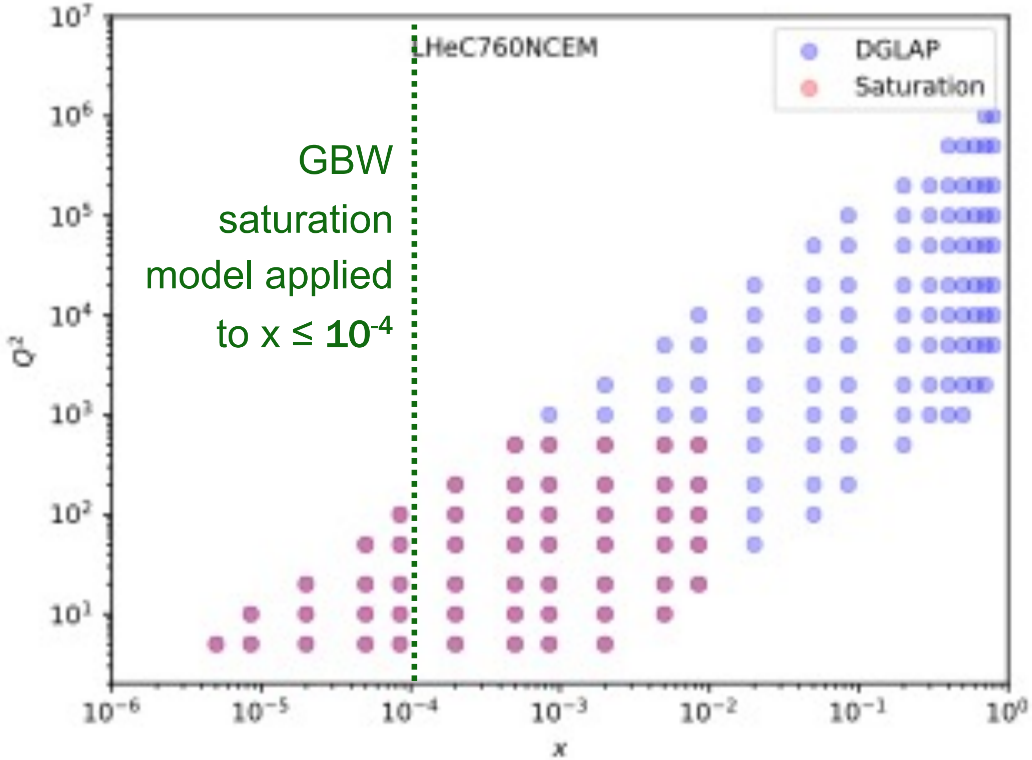


May 2020
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
$pp \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm, \tilde{\chi}_2^0\tilde{\chi}_1^0, \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm\tilde{\chi}_1^0$ (Higgsino)
All limits at 95% CL
Observed limits
Expected limits
Soft 2ℓ, 139 fb^{-1}, arXiv:1911.12606, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0) + 2\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$
Disappearing track, 36.1 fb^{-1}, PHYS-PUB-2017-019, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0)$
LEP2 $\tilde{\chi}_1^\pm$ excluded
Theoretical prediction for pure Higgsino
$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ [GeV]
$m(\tilde{\chi}_1^\pm)$ [GeV]



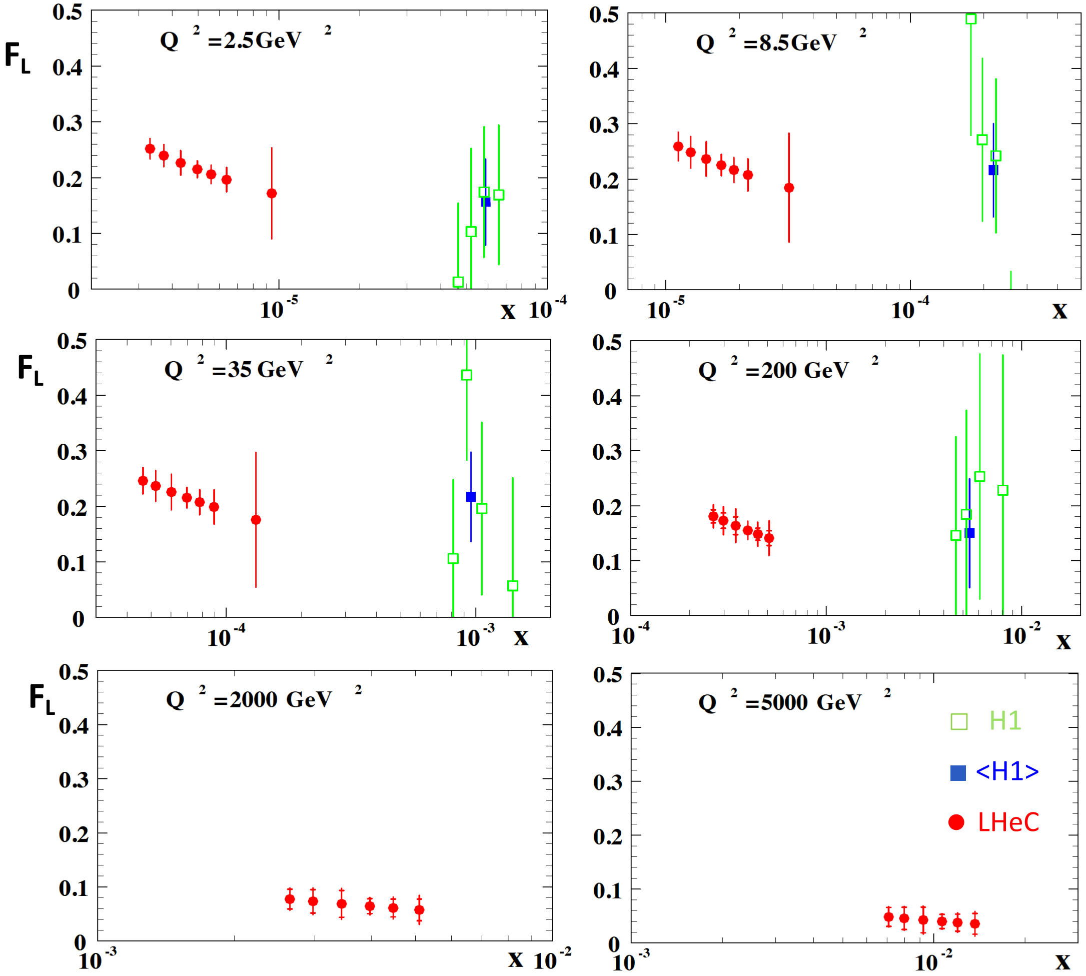
small x becomes relevant even for "common" physics (EG. W, Z, H, t)

saturation



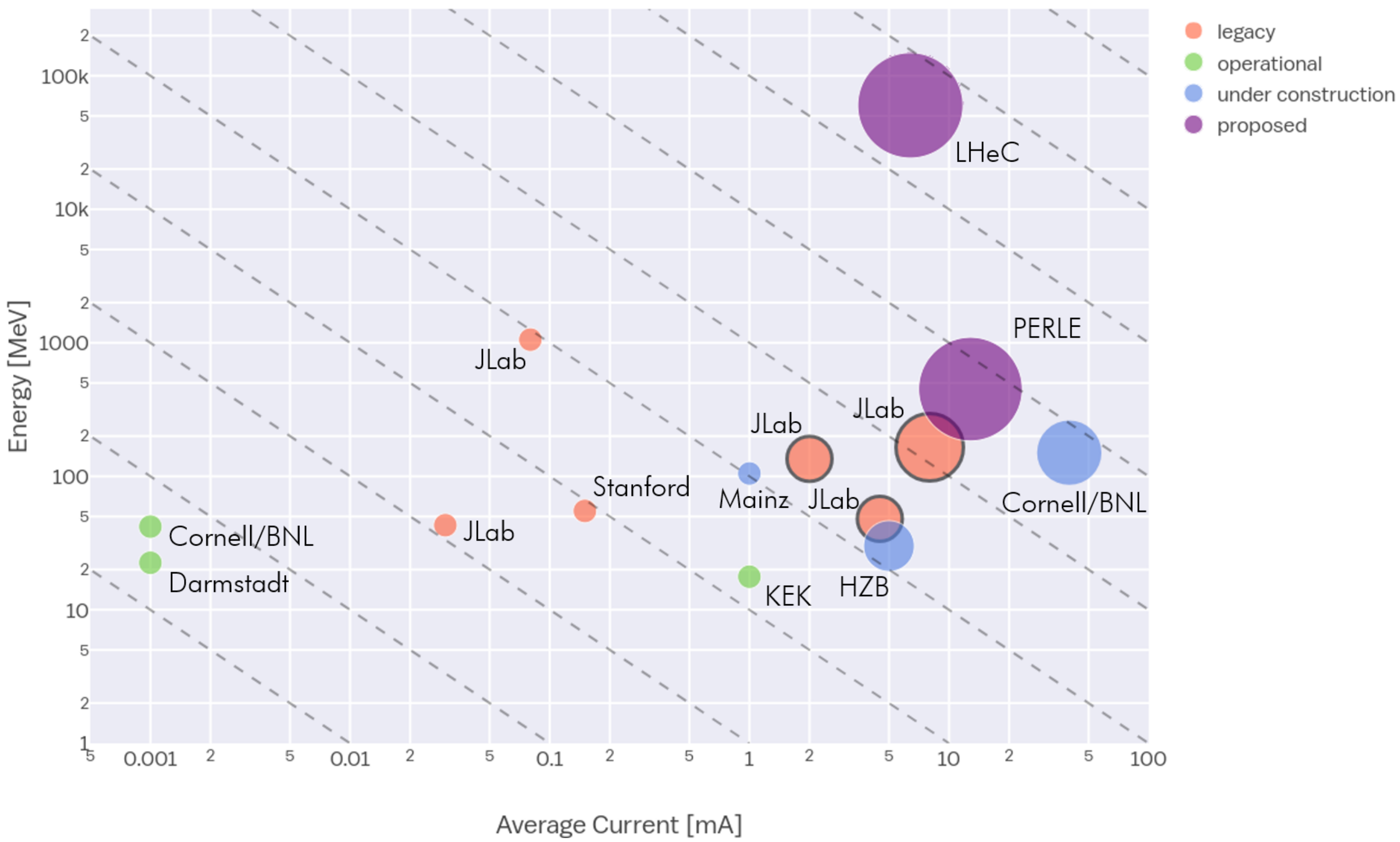
LHeC760NCEM
DGLAP
Saturation
GBW saturation model applied to x ≤ 10^-4
Q^2
x
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0

FL from the LHeC



- **expect significant additional discrimination from dedicated precision measurement of FL** (not yet included in shown studies); incorrect **small x** treatment unlikely to accommodate both F2 **and** FL

ERL landscape



LHeC machine parameters

Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	9	23	8	15

Table 2.3: Summary of luminosity parameter values for the LHeC and FCC-eh. Left: CDR from 2012; Middle: LHeC in three stages, an initial run, possibly during Run 5 of the LHC, the 50 GeV operation during Run 6, both concurrently with the LHC, and a final, dedicated, stand-alone *ep* phase; Right: FCC-eh with a 20 and a 50 TeV proton beam, in synchronous operation.

LHeC coverage

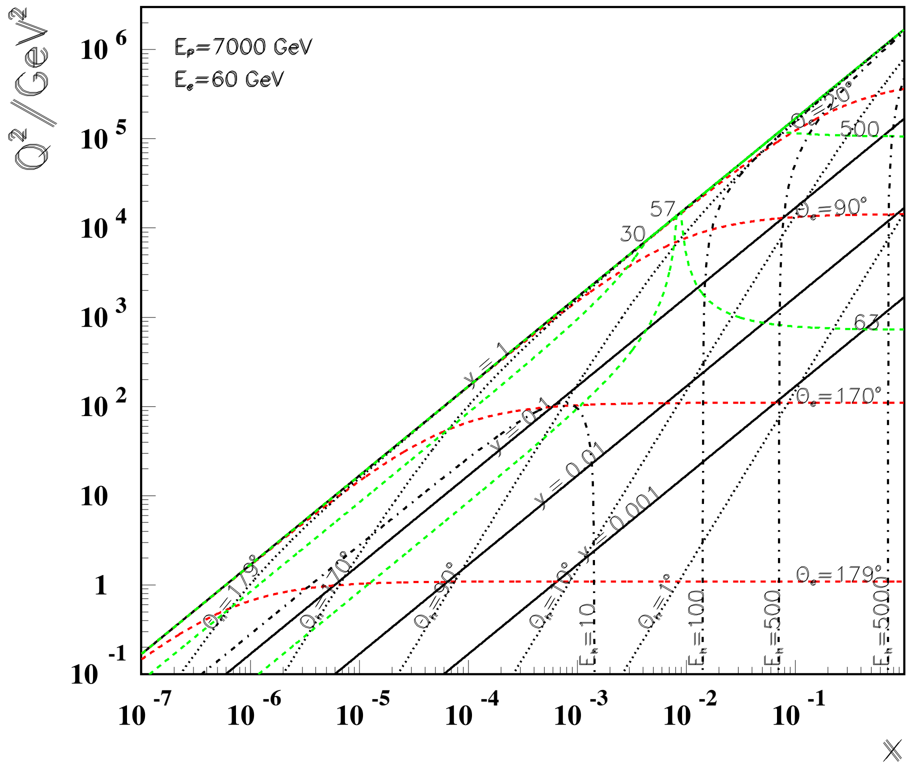
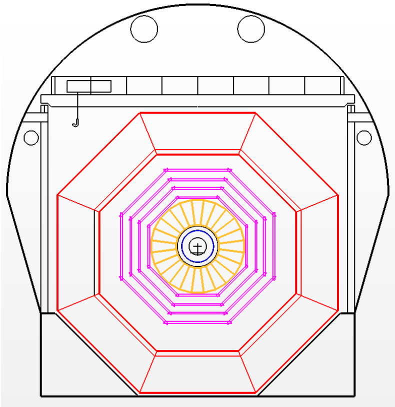
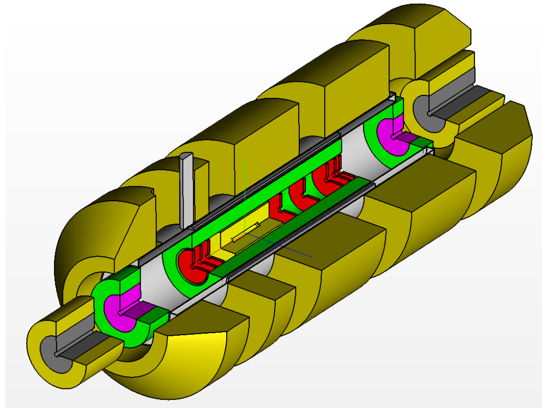


Figure 3.2: Kinematic plane covered with the maximum beam energies at the LHeC. Red dashed: Lines of constant scattered electron polar angle. Note that low Q^2 is measured with electrons scattered into the backward region, highest Q^2 is reached with Rutherford backscattering; Black dotted: lines of constant angle of the hadronic final state; Black solid: Lines of constant inelasticity $y = Q^2/sx$; Green dashed: Lines of constant scattered electron energy E'_e. Most of the central region is covered by what is termed the kinematic peak, where $E'_e \simeq E_e$. The small x region is accessed with small energies E'_e below E_e while the very forward, high Q^2 electrons carry TeV energies; Black dashed-dotted: lines of constant hadronic final state energy E_h. Note that the very forward, large x region sees very high hadronic energy deposits too.

Installation Study

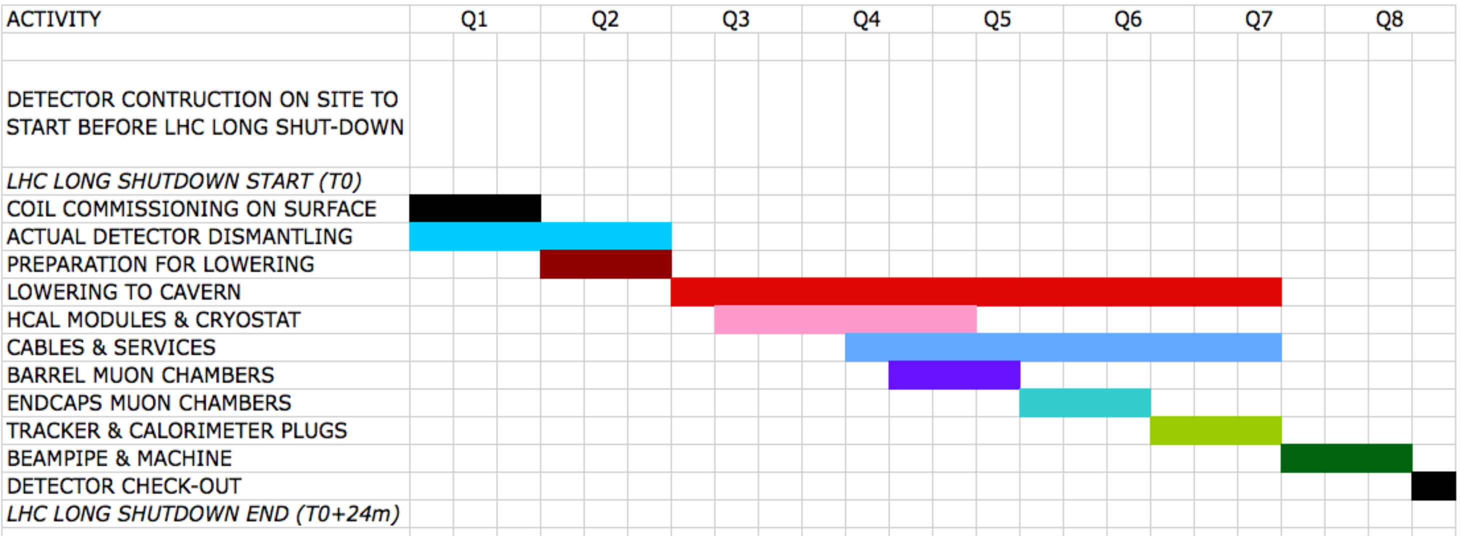


Detector fits in L3 magnet support



Modular structure

LHeC INSTALLATION SCHEDULE



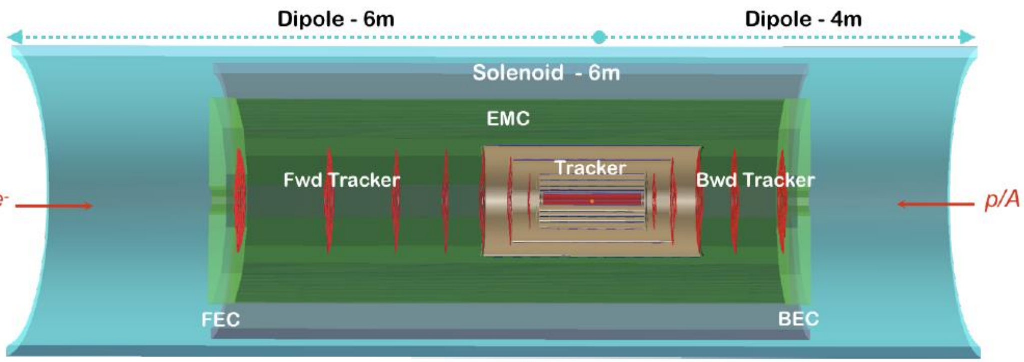
Detector Installation possible within about two-years shutdown: pre-mounting on surface

LHeC should not delay main LHC programme in any significant way.

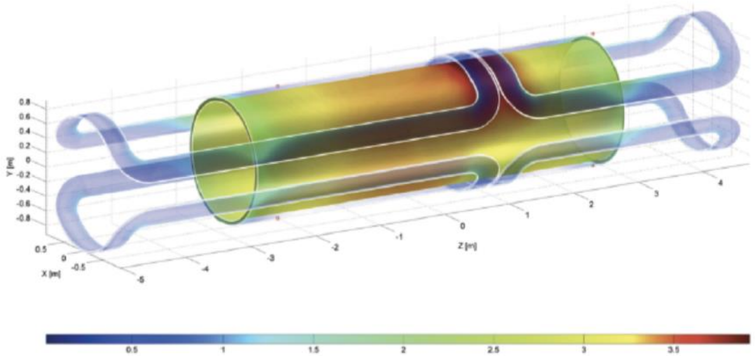
Andrea Gaddi, L Herve et al arXiv:2007.14491

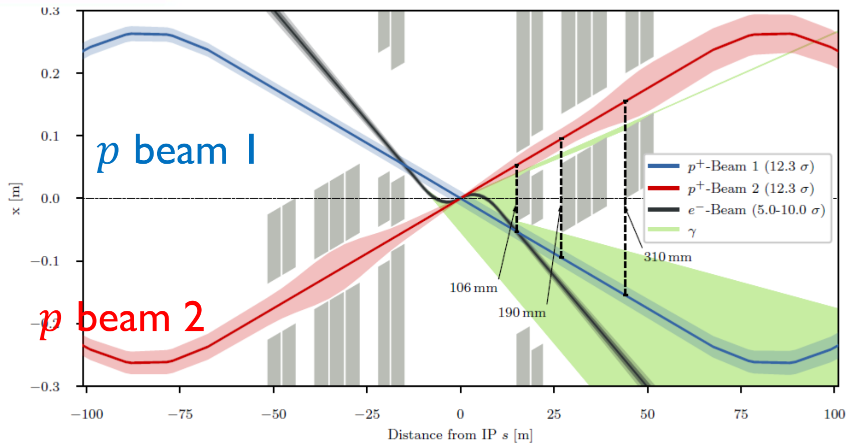
Interaction point and magnet

- Dipole magnet integrated in the detector to bend electron beam
  - Beam-2 p and e brought in head-on collisions
  - Beam-1 with finite angle, unaffected



New re-designed, optimised IR in CDR 2020



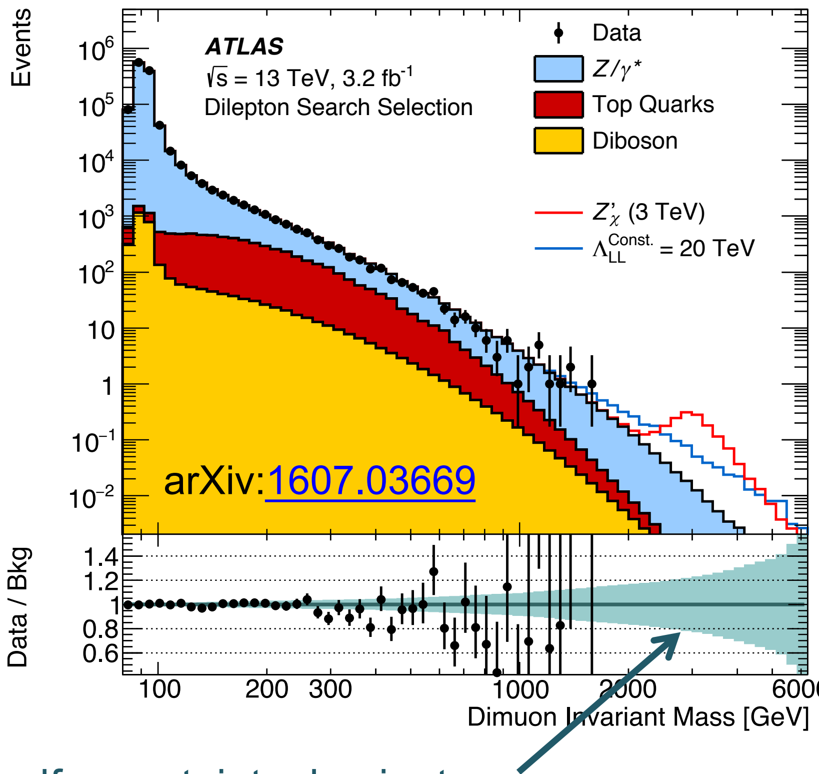


Synchrotron radiation fan (green) 7

Y Yamazaki, ICHEP 20

why pdfs matter

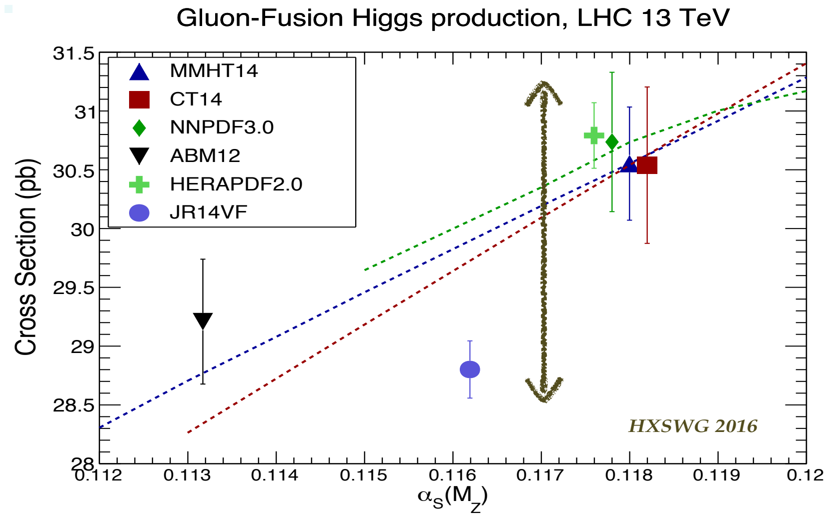
- **BSM searches** and other processes at high scales limited by (lack of) knowledge of **large x gluon** and **quark pdfs** (EG. top, SUSY, LQs, extra heavy bosons, …)
- … plus precision **MW**, **sin²ϑW** (where small discrepancies may indicate BSM physics) and **Higgs**, are also limited by **pdf uncertainties** at medium x, where we know pdfs best!



pdf uncertainty dominates

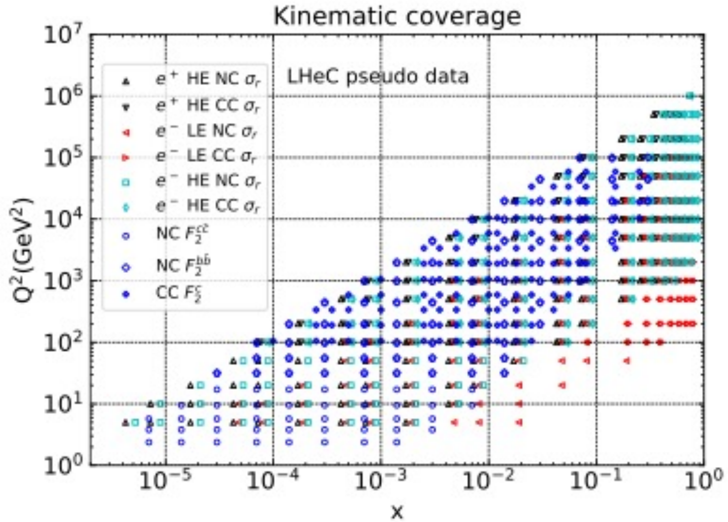
ATLAS Mw, arXiv:1701.07240

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0



LHeC simulated data

Source of uncertainty	Uncertainty
Scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
Scattered electron polar angle	0.1 mrad
Hadronic energy scale $\Delta E_h/E_h$	0.5 %
Radiative corrections	0.3 %
Photoproduction background (for $y > 0.5$)	1 %
Global efficiency error	0.5 %



Parameter	Unit	Data set								
		D1	D2	D3	D4	D5	D6	D7	D8	D9
Proton beam energy	TeV	7	7	7	7	1	7	7	7	7
Lepton charge		−1	−1	−1	−1	−1	+1	+1	−1	−1
Longitudinal lepton polarisation		−0.8	−0.8	0	−0.8	0	0	0	+0.8	+0.8
Integrated luminosity	fb^{-1}	5	50	50	1000	1	1	10	10	50

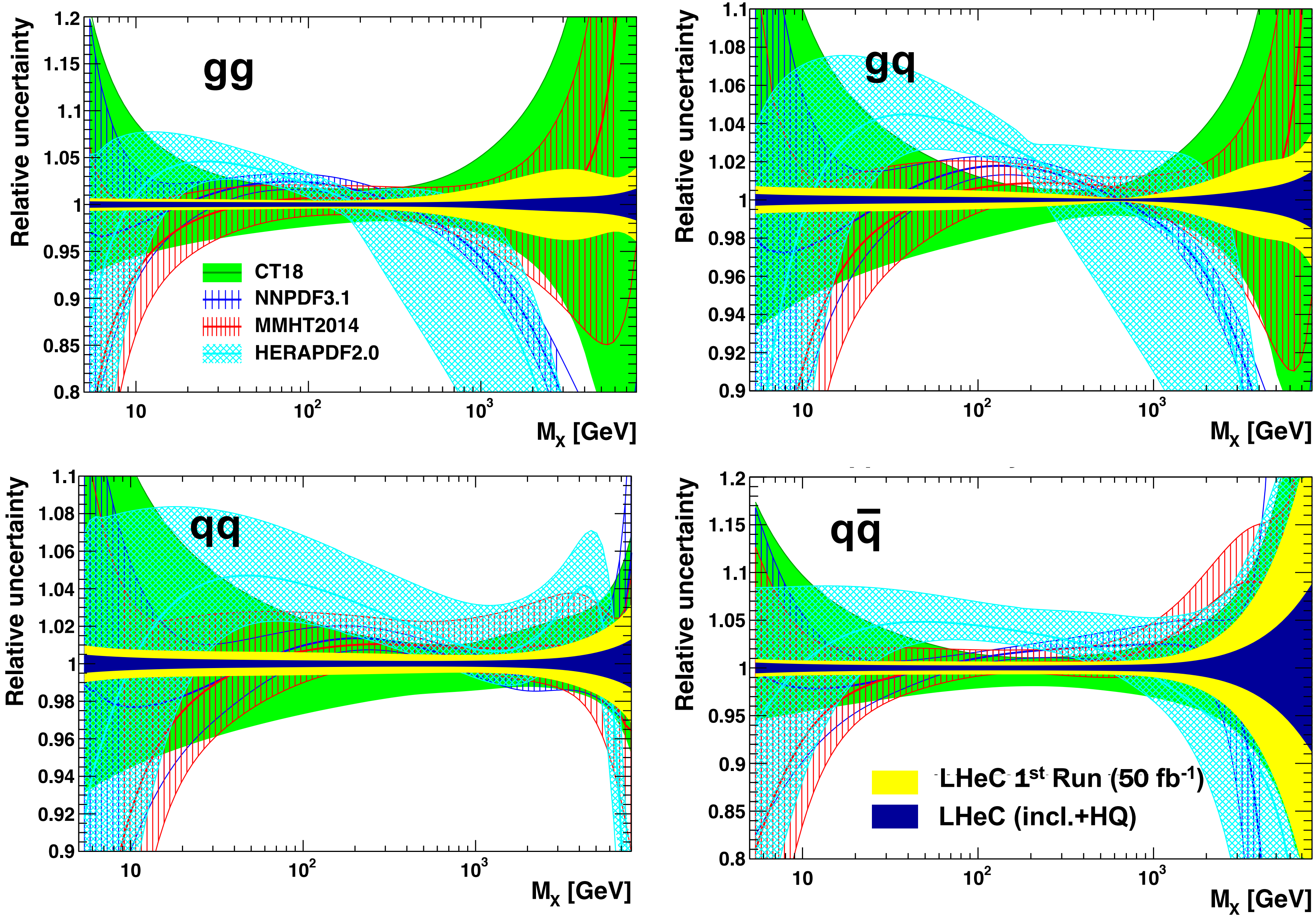
LHeC pdf parameterisation

- QCD fit ansatz based on HERAPDF2.0, with following differences:
- no requirement that ubar=dbar at small x
- no negative gluon term (only for the aesthetics of ratio plots – it has been checked that this does not impact size of projected uncertainties)

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}(1+D_g x) \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v} x^2) \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}} \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}} \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}
\end{aligned}
$$

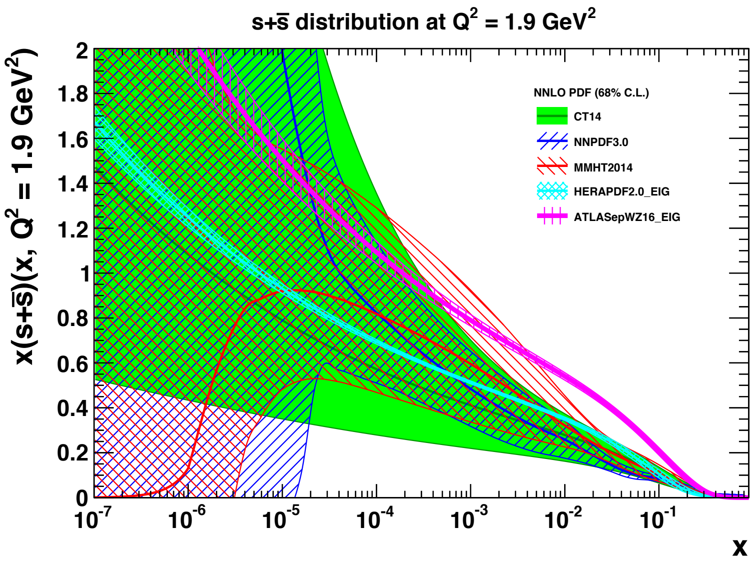
- **4+1** pdf fit (above) has **14 free parameters**
- **5+1** pdf fit for HQ studies parameterises dbar and sbar separately, **17 free parameters**

pdf luminosities @ 14TeV

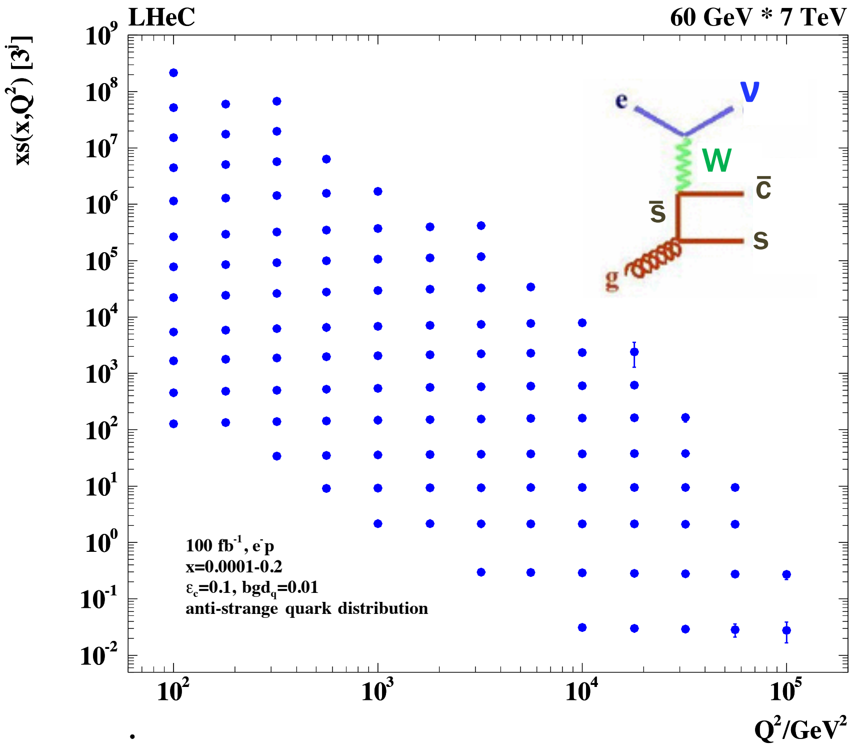


strange, c, b, t

- **strange pdf** poorly known
- suppressed cf. other light quarks? strange valence?

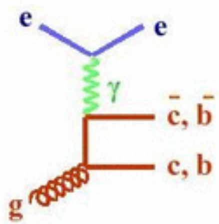


→ **LHeC:** direct sensitivity via charm tagging in Ws→c
(x,Q^2) mapping of strange density for first time



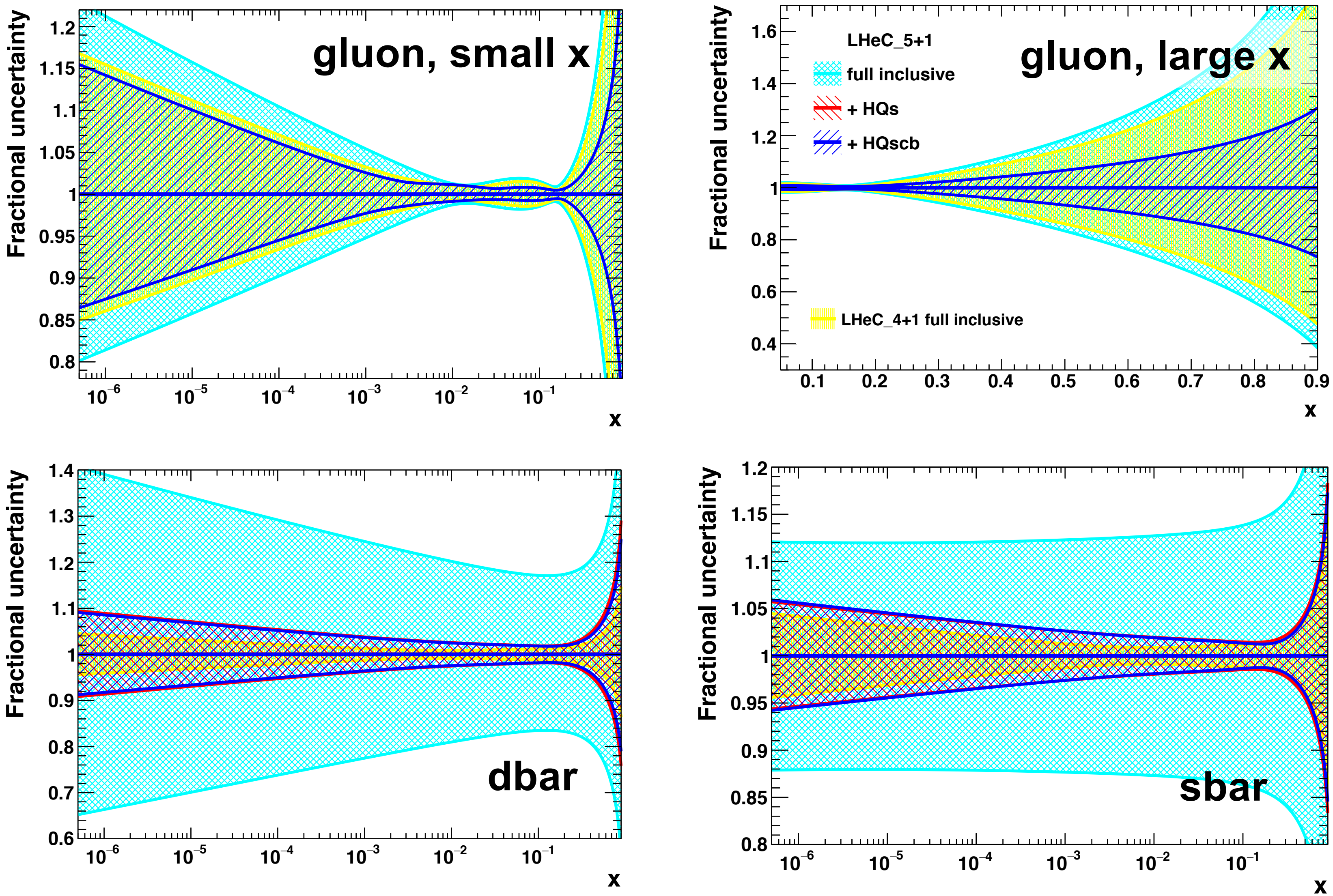
- **c, b:** enormously extended range and much improved precision c.f. HERA

- **δMc = 50 (HERA)** to **3 MeV**: impacts on **α**s, regulates ratio of charm to light, crucial for precision t, H
- **δMb** to **10 MeV**; MSSM: Higgs produced dominantly via b$\bar{b}$ → A



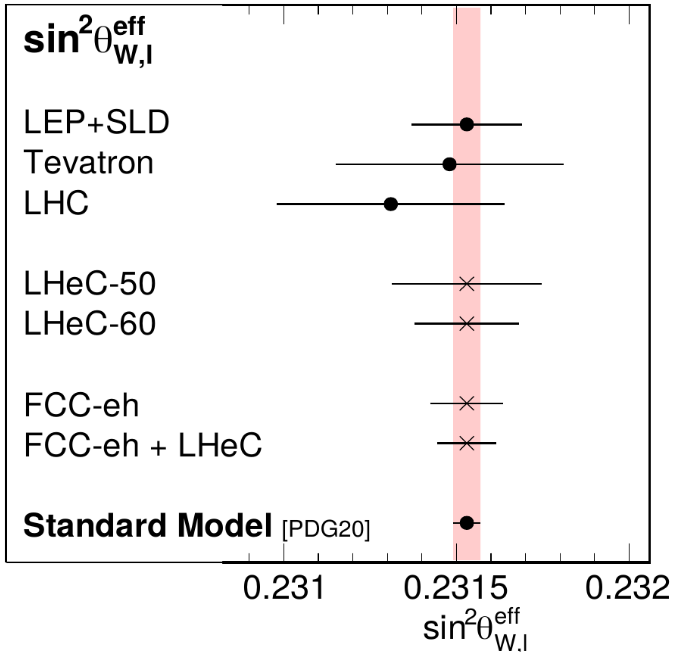
- **t:** at very large Q^2 top quark becomes "light" – opens up new field of research for **t PDFs**

impact of s, c, b

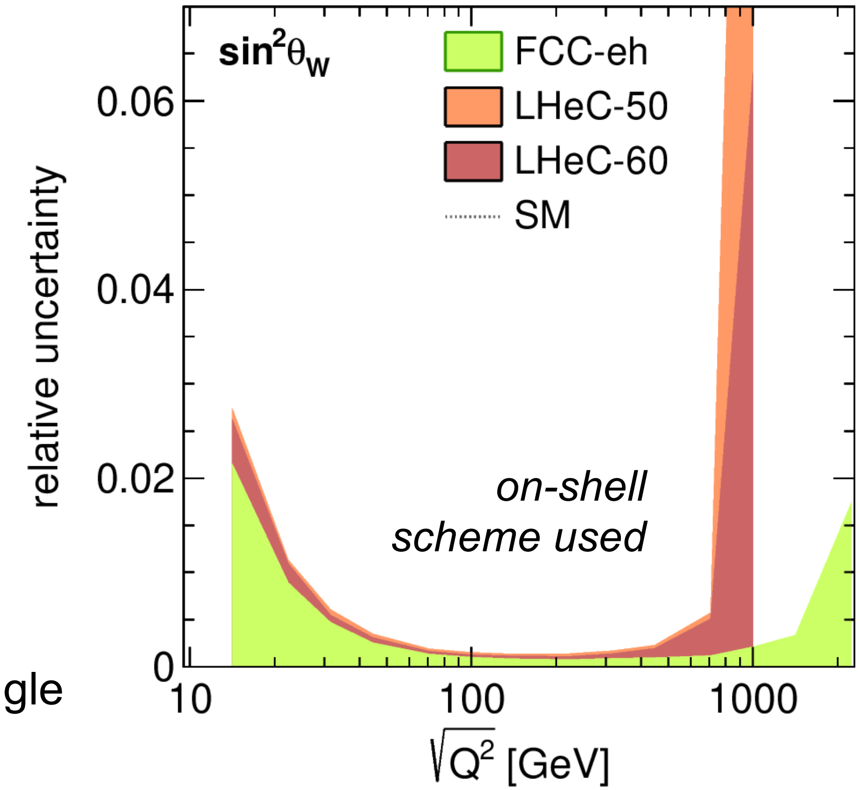


- **4+1** xuv, xdv, xUbar, xDbar + xg **(14)**
- **5+1** xuv, xdv, xUbar, xdbar, xsbar + xg **(17)**

weak mixing angle



scale dependence of weak mixing angle



- potential to become most precise single measurement

$\Delta \sin^2\Theta W^{eff}$ (exp.+pdf)

± 0.00015 (LHeC, Ee = 60 GeV)
± 0.00011 (FCC-eh)
± 0.000086 (FCC-eh + LHeC)

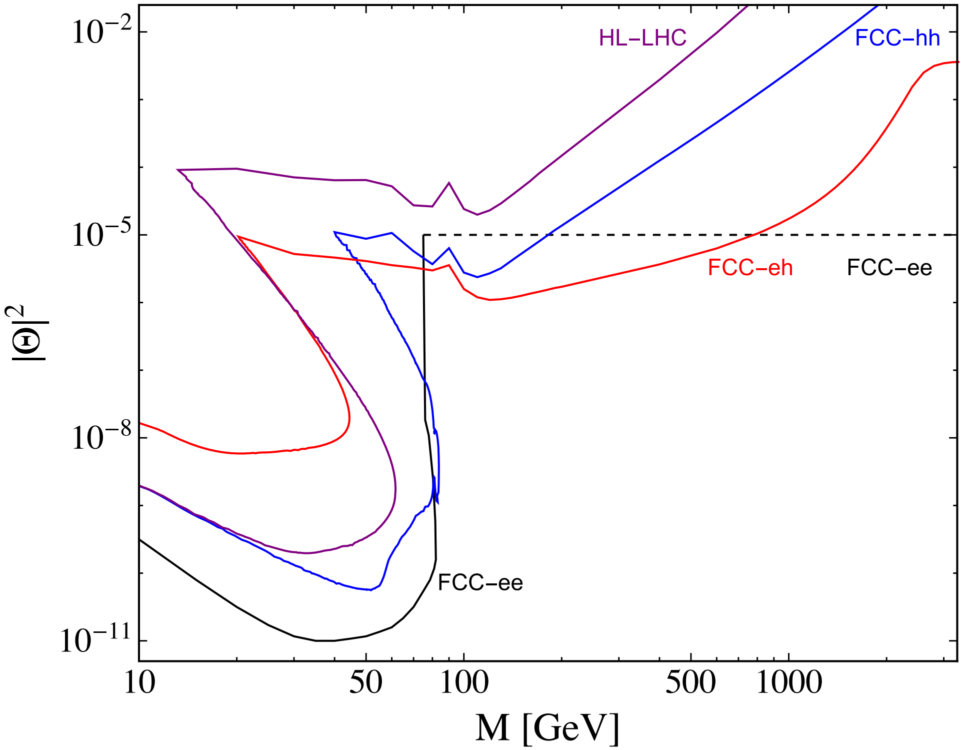
- $\mathcal{O}$(0.1%) precision on $\sin^2\theta W$ over large range in scale (fit subsets of data)
- tests SM-prediction of scale dependence

(NB, theory needed to map $\sin^2\Theta W$ to effective weak mixing angle)

BSM: sterile neutrinos

FCC CDR, [EPJ C79 (2019), no.6, 474]

complementary prospects for discovery in **ee**, **ep**, **pp**

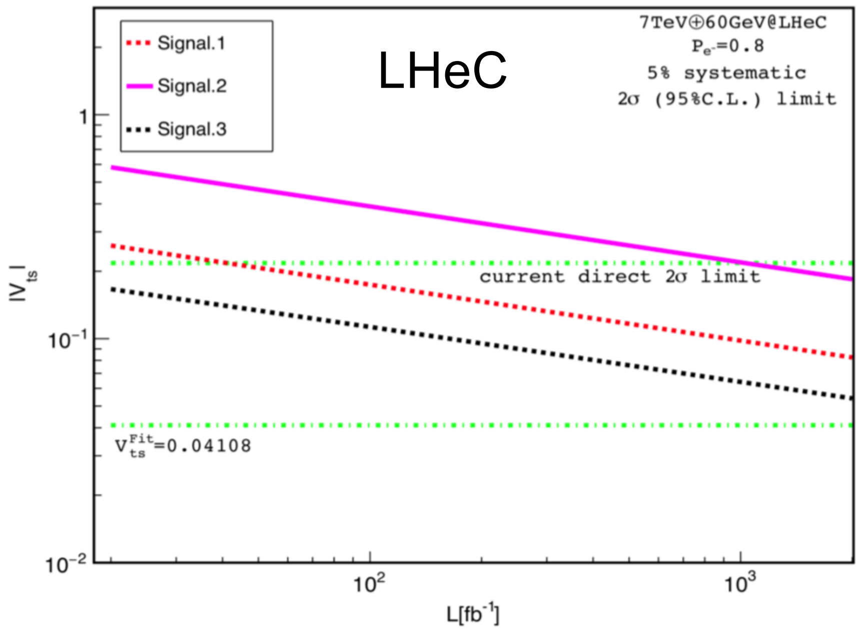


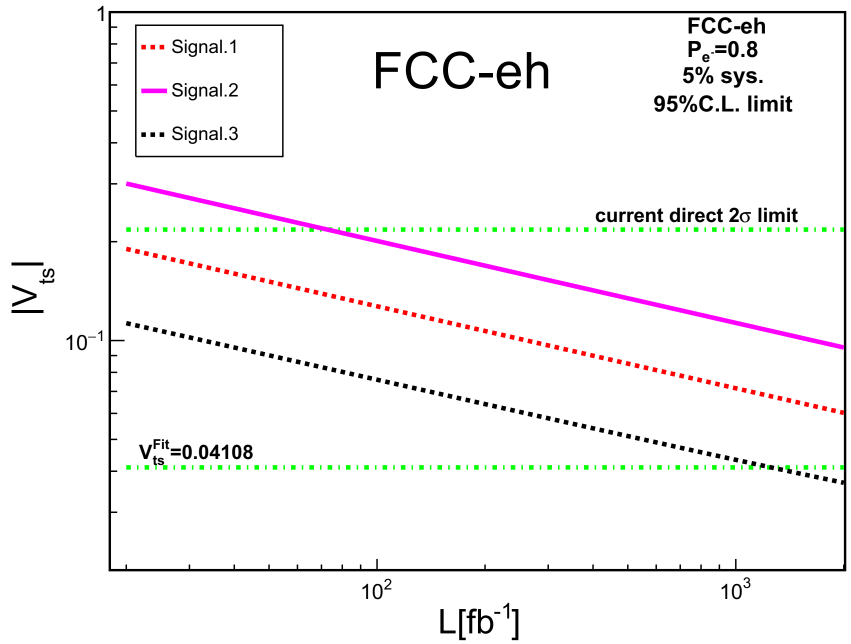
see also arXiv:[1612.02728]

overview of collider searches for heavy sterile neutrinos; promising signatures for **ep** colliders identified

arXiv:2007.14491
EPJ C79 (2019), 6, 474

|Vts| in ep





Signal 1: $pe^- \to \nu_e \bar{t} \to \nu_e W^- \bar{b} \to \nu_e \ell^- \nu_\ell \bar{b}$

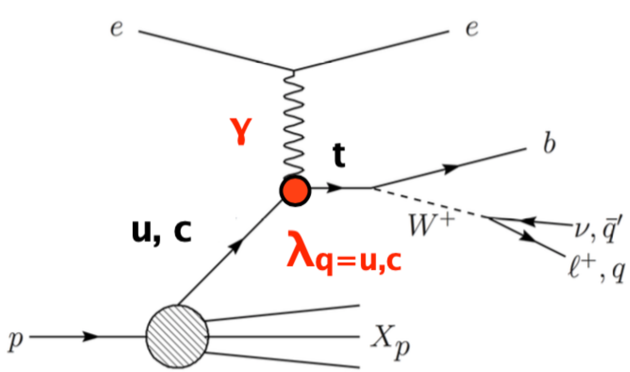
Signal 2: $pe^- \to \nu_e W^- b \to \nu_e \ell^- \nu_\ell b$

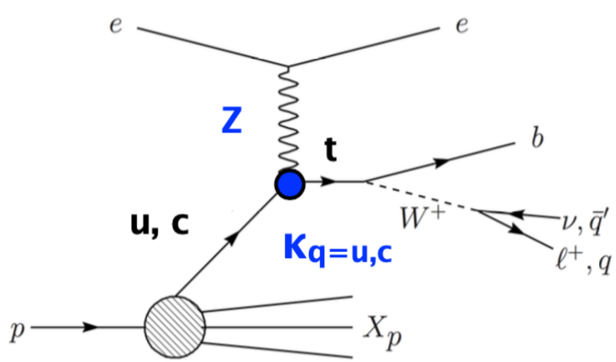
Signal 3: $pe^- \to \nu_e \bar{t} \to \nu_e W^- j \to \nu_e \ell^- \nu_\ell j$

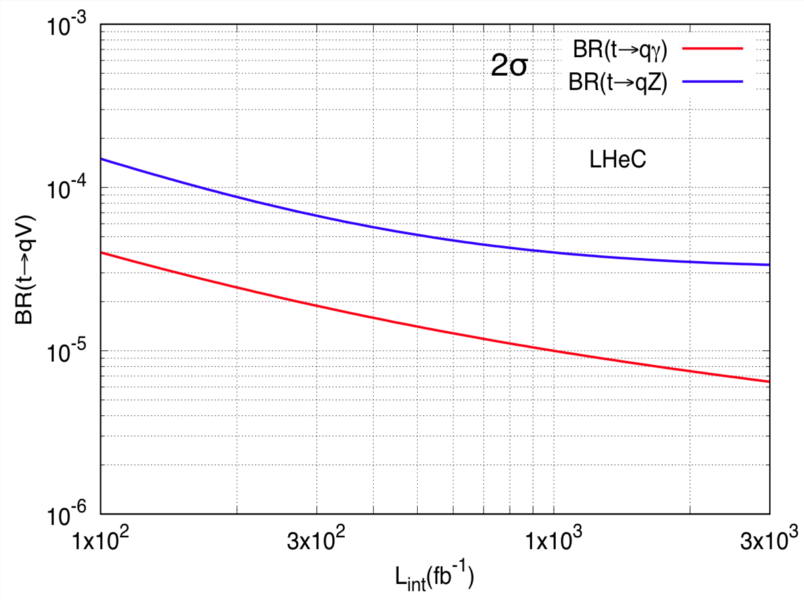
|Vts| will probe SM prediction directly for **first time**

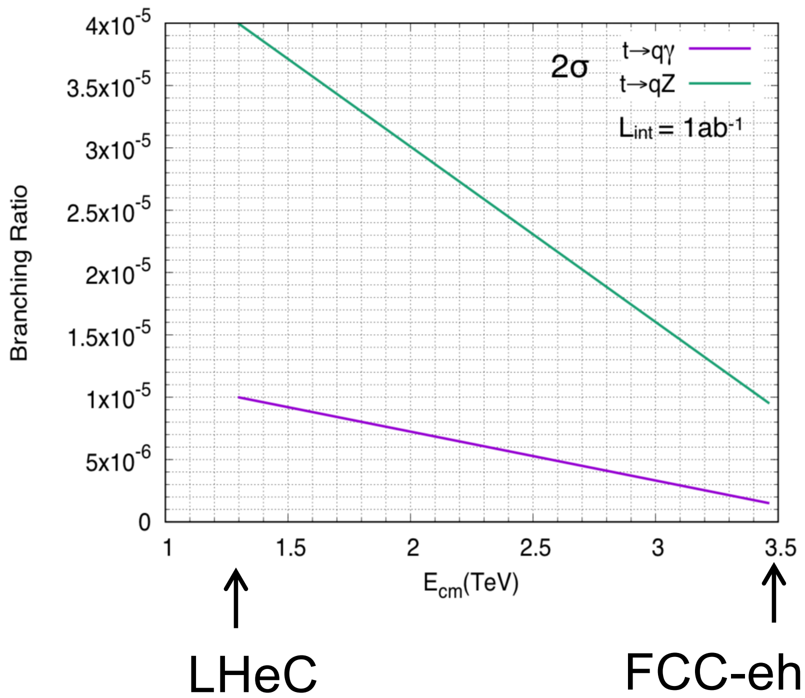
search for anomalous FCNC

arXiv:2007.14491
EPJ C79 (2019), 6, 474



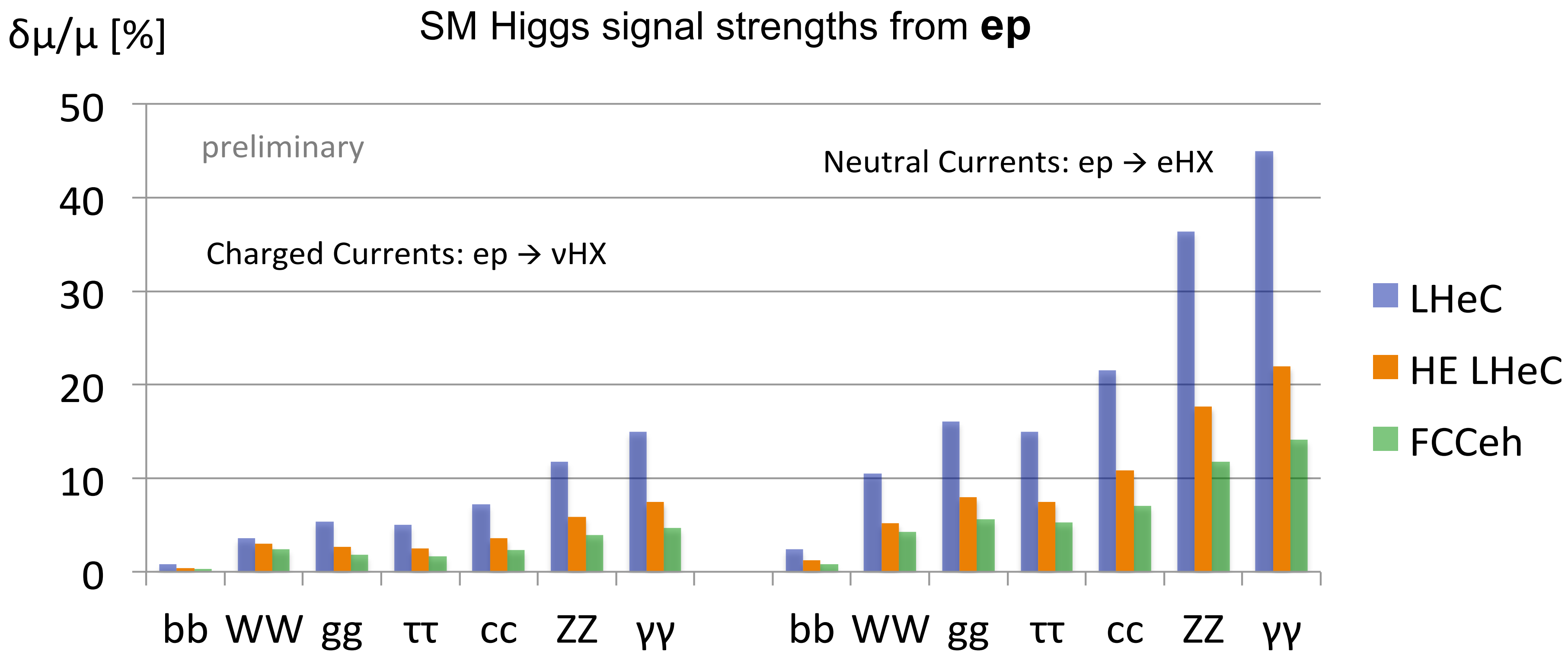






SM Higgs signal strengths

CERN-ACC-2018-0056
arXiv:2007.14491



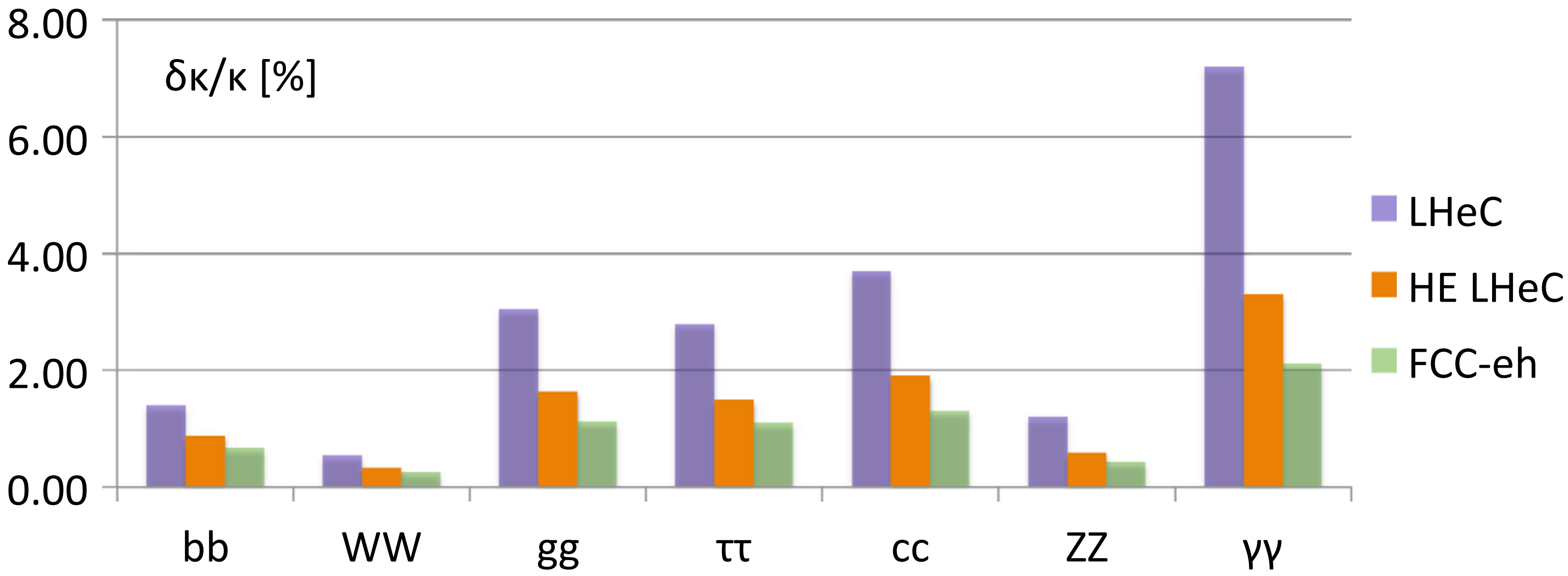
NC and CC DIS together over-constrain Higgs couplings in a combined SM fit

CERN-ACC-2018-0056

Higgs in ep

SM Higgs couplings from **ep**

(κ framework, arXiv:1307.1347; SM couplings modified by factor $\kappa_i \equiv g_{Hi}/g_{Hi}^{SM}$)



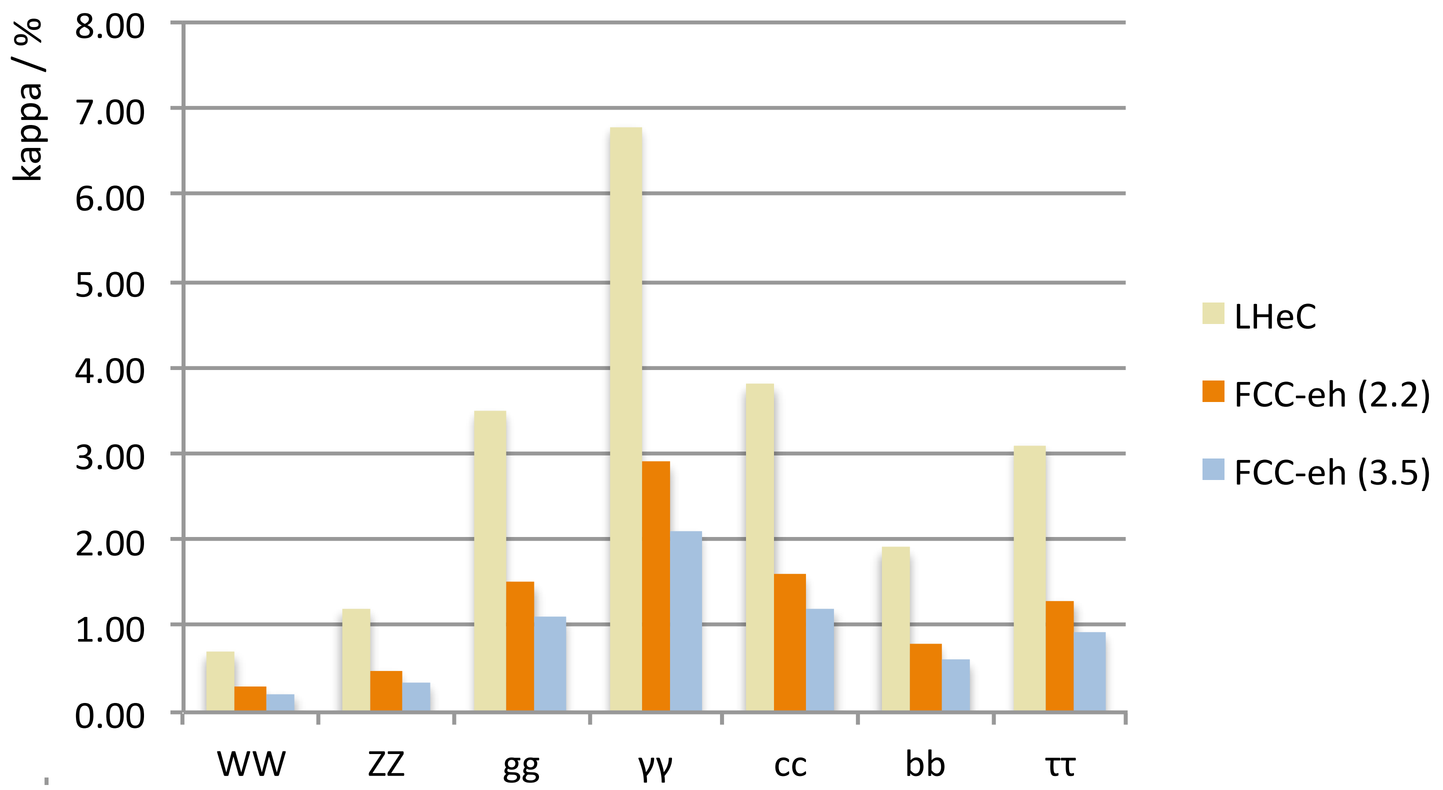
Higgs in ep

CERN-ACC-2018-0056

arXiv:2007.14491

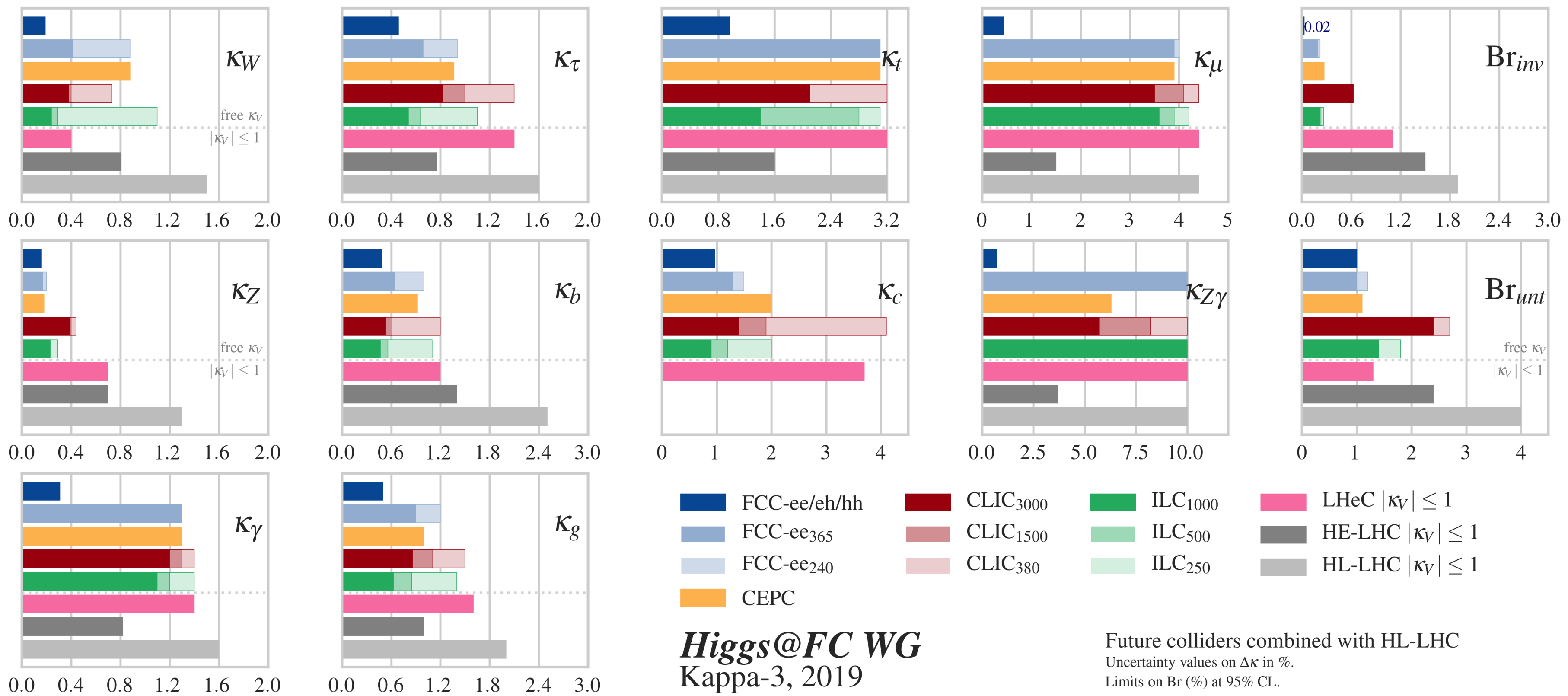
SM Higgs couplings from **ep**

(κ framework, arXiv:1307.1347; SM couplings modified by factor **κi** ≡ g_{Hi}/g_{Hi}^{SM})

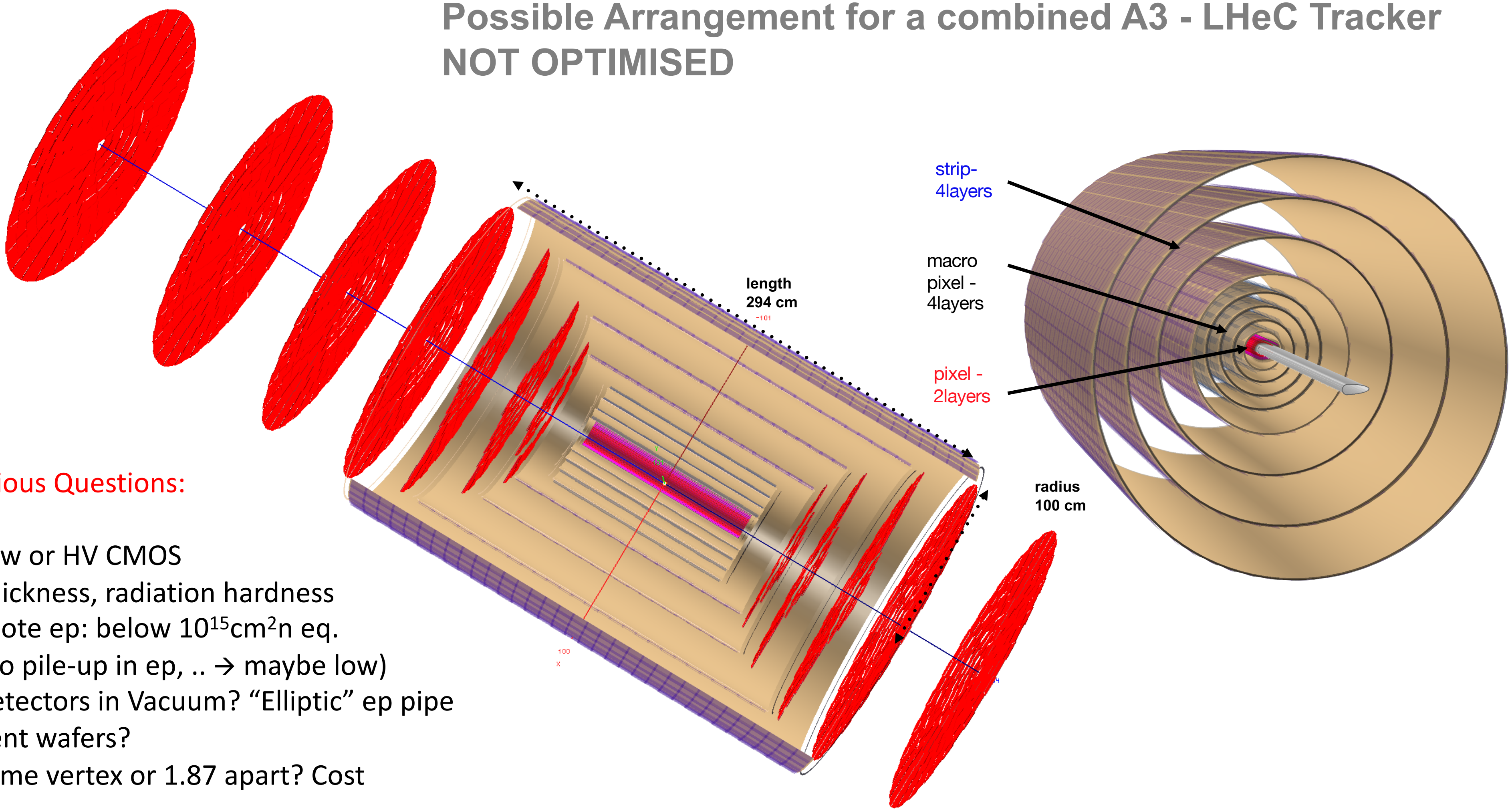


complementarity of colliders

arXiv:1905.03764



Possible Arrangement for a combined A3 - LHeC Tracker
NOT OPTIMISED



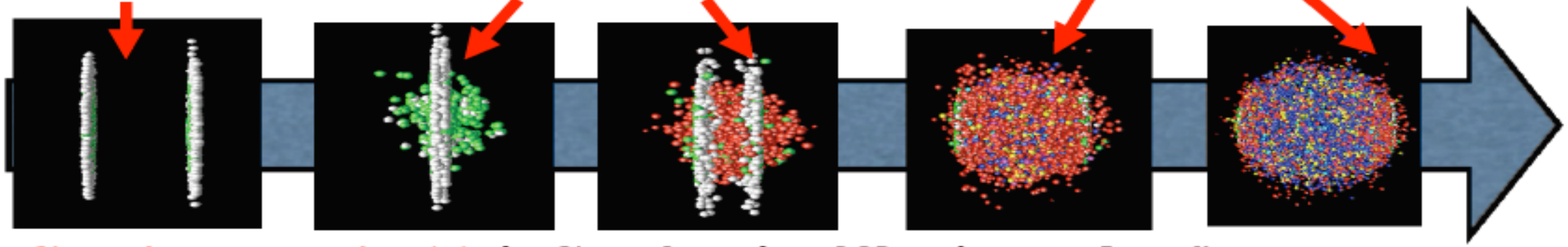
Various Questions:

- Low or HV CMOS
- Thickness, radiation hardness
  (note ep: below $10^{15}cm^2n$ eq.
  no pile-up in ep, .. → maybe low)
- Detectors in Vacuum? "Elliptic" ep pipe
- Bent wafers?
- Same vertex or 1.87 apart? Cost
- ...

What we can learn in an ep/eA collider

We do not have a **QUANTITATIVE** understanding of the nuclear behaviour → required for A-A and QGP studies

The colliding objects **Early stages** **Analyzing the medium**



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

Dense regime: lack of information about	Particle production at the very beginning:	Probing the medium through energetic particles:
• small-x partons • correlations • transverse structure	• Which factorization? • How can a system behave as isotropised so fast?	• Dynamical mechanisms for opacity • How to extract accurately medium parameters?
ep and eA: • nuclear WF & PDFs • mechanism of particle production • tomography	**ep and eA:** • initial conditions for plasma formation • how small can a system be and still show collectivity?	**ep and eA:** • modification of radiation and hadronization in the nuclear medium • initial effects on hard probes

N. Armesto DIS2018, Kobe, 17.4.18 and E. Ferreiro, LHeC Workshop 2018, Orsay, 28.6.18 → 2007.14491

Questions and Tentative Comments on Merger

Initial thoughts and questions and tentative answers

First derived questions:

- Can we generate luminosity at 0 and +1.8m for pp/AA and ep/eA, respectively? yes, time needed sharing
- How does LHeC detector change if we integrate A3 into LHeC extension in radius, B reduced, low V CMOS, ..
- How would A3 detector change? Would it profit from the ep detector environment?
  Muons, calorimetry? Better answered with A3 insight, one would expect this leads to a hard scale program
- How does the physics potential change? eA programme at TeV scales. LHeC is most powerful EIC one can build

Detailed Questions

- Magnetic fields: solenoid: if we go to half our value, and enlarge the radius by 2, we gain factor 2 resolution ok
  Dipole: the dipole (and solenoid) would move further out, any problem? Rather not. Note low material magnets
- Choice of Silicon technology for IT, are we compatible with them? Probably yes. low V CMOS probably ok for LHeC
- Readout and Trigger: speed, data volume, 2 trigger and r/o branches or 1 etc. To be studied
- For c,b tagging the extended ep beam pipe is a nuisance (as it is for ours) --> place Si inside pipe??? challenging
- There are many more..

→ It indeed seems feasible to combine the two detectors and IR concepts (further machine studies ongoing)