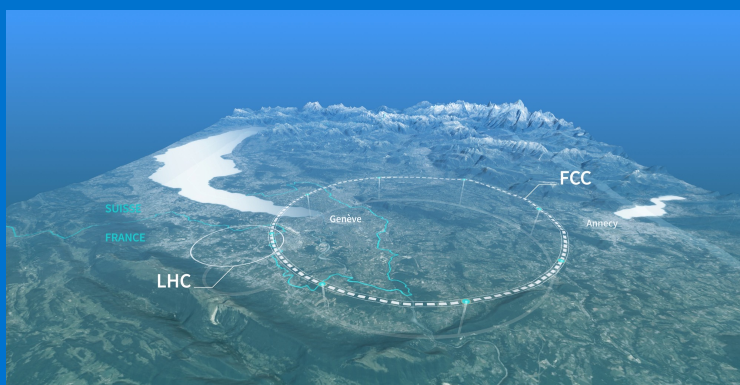
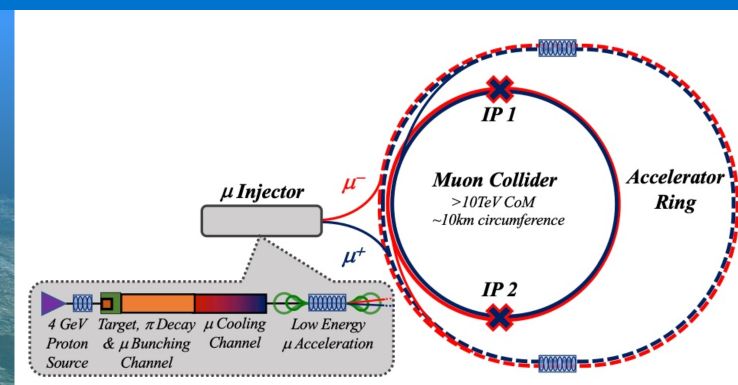
UNIVERSITY OF CAMBRIDGE

Murray Edwards College
University of Cambridge

Future colliders: 10 TeV pCM colliders (pp/ep, $\mu^+\mu^-$)

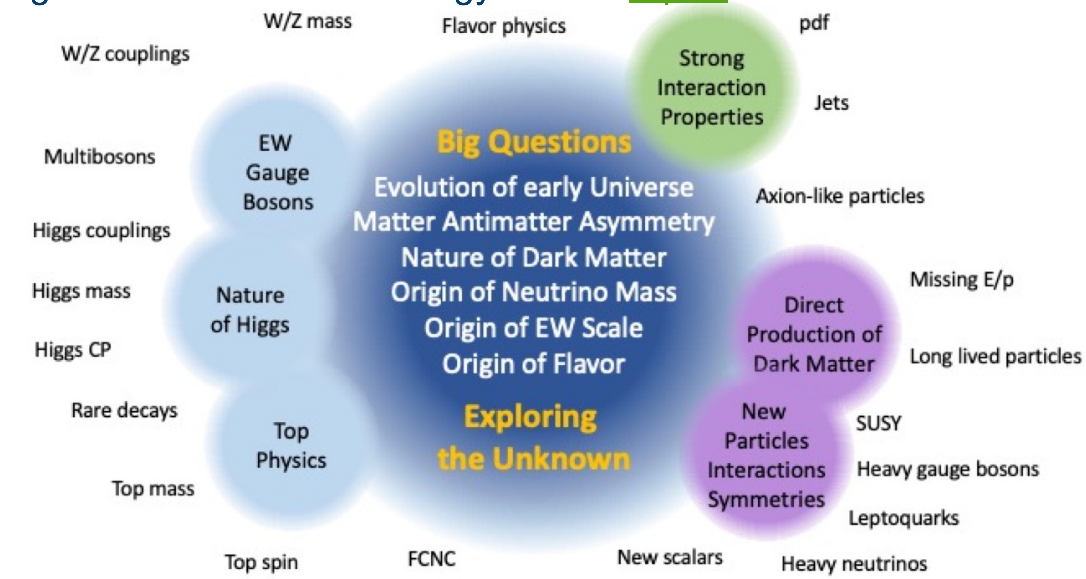




Dr Sarah Williams, University of Cambridge

Introductions: big questions in particle physics

Image credit: snowmass energy frontier report



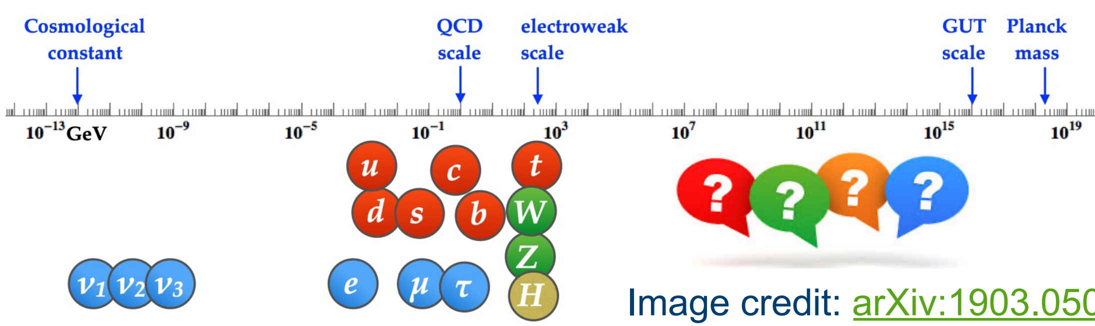


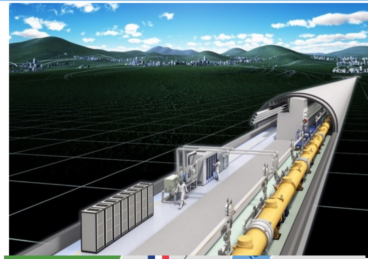
Image credit: arXiv:1903.05063

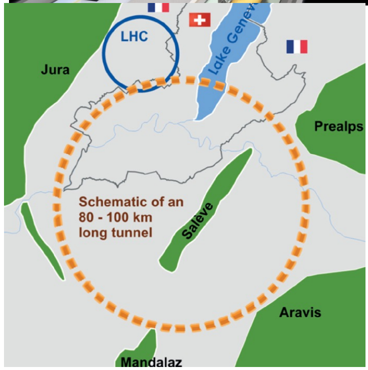
- Outstanding questions about nature/our universe could be solved through uncovering new physics at particle colliders.
- Unlike the Higgs discovery, we no longer have a clear idea of the (energy) scale at which it might appear.
- (Maximally) exploring the unknown is key…

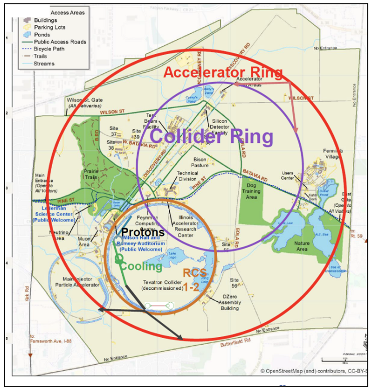
What should come after the HL-LHC?

What should come after the (HL-)LHC?

- e^+e^- machine?
  - Linear collider?
    - **CLIC** (CERN?)
    - **ILC** (Japan?)
  - Circular collider?
    - **CepC** (China)
    - **FCC-ee/hh** (CERN)
- Hadron collider? → **FCC-ee/hh** (CERN)
- Muon collider? (Fermilab?)
- (more) HL-LHC+ ep (CERN)





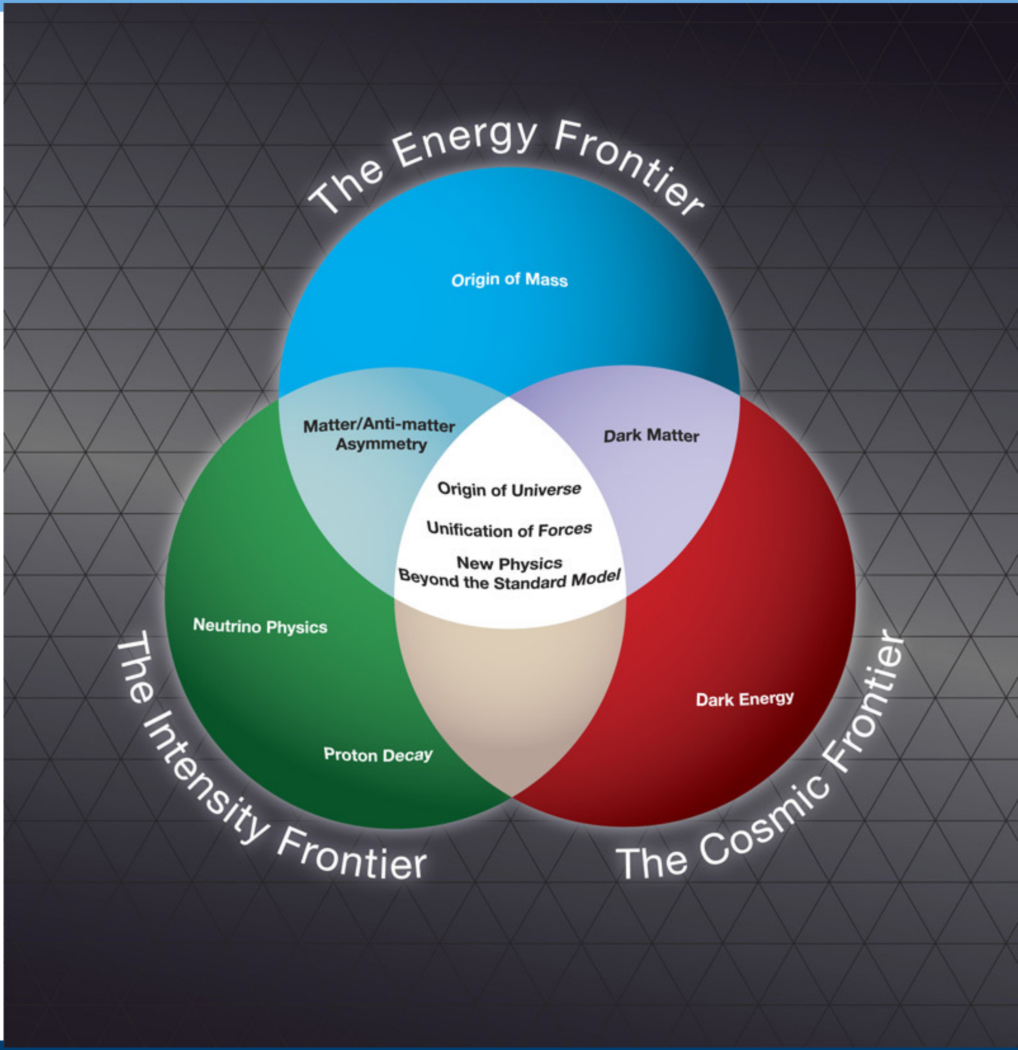


Broad agreement in most recent ESPPU and Snowmass P5 processes for (1) an Intensity-Frontier "Higgs factory" followed by (2) ambitions to push the Energy frontier into the 10 TeV pCM range…

Frontiers in particle physics

- Pushing the intensity and energy frontiers represent two complementary routes for probing new physics.

- This talk will focus on two options for achieving (2):
  - High energy (~100 TeV) pp collisions (i.e. FCC-hh) which could be complemented by intensity frontier ep collisions (FCC-eh).
  - High-energy (~10 TeV) muon collider, which could provide both a “discovery” machine and “Higgs factory”



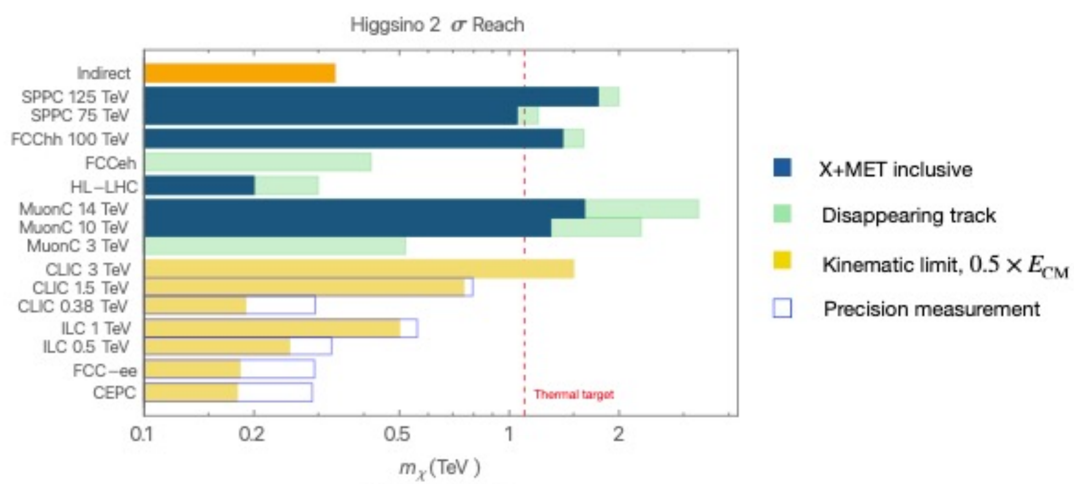
Energy frontier physics drivers

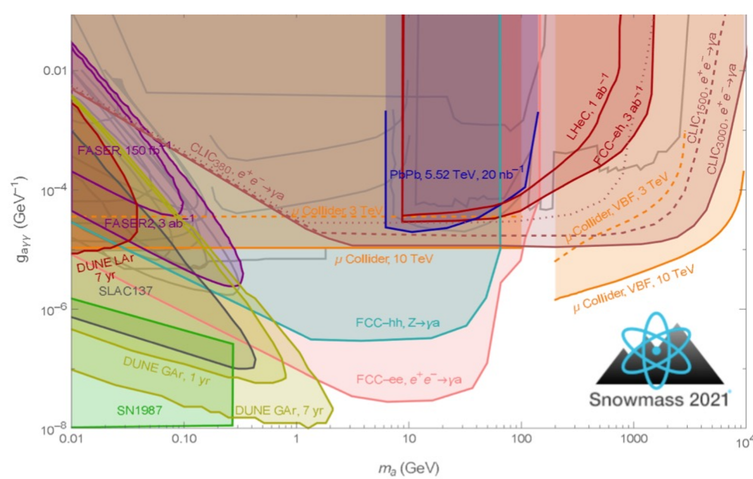
Details on Higgs-factory prospects of muon collider in backup!

More info in the Snowmass energy frontier report: https://arxiv.org/pdf/2211.11084

- Higgs self-coupling (targeting ~ 5%).
- Rare Higgs decays (with high luminosities).
- Unprecedented BSM sensitivity.
- WIMP dark matter coverage.

collider	Indirect-h	hh	combined
HL-LHC [40]	100-200%	50%	50%
ILC_{250}/C^3-250 [31, 33]	49%	–	49%
ILC_{500}/C^3-550 [31, 33]	38%	20%	20%
ILC_{1000}/C^3-1000 [31, 33]	36%	10%	10%
$CLIC_{380}$ [35]	50%	–	50%
$CLIC_{1500}$ [35]	49%	36%	29%
$CLIC_{3000}$ [35]	49%	9%	9%
FCC-ee [36]	33%	–	33%
FCC-ee (4 IPs) [36]	24%	–	24%
FCC-hh [41]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [39]	-	15-30%	15-30%
μ(10 TeV) [39]	-	4%	4%



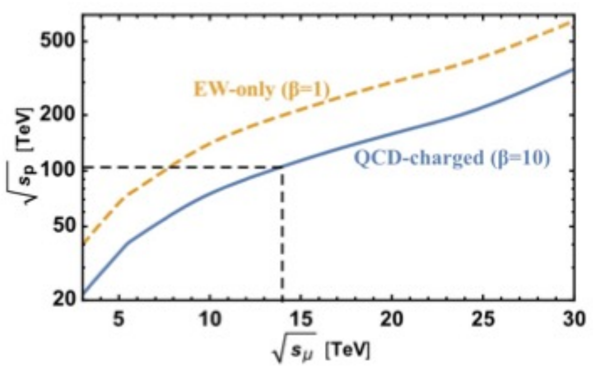


Comparison of colliders

Apologies for potential over-simplifications here!

Hadron (pp)

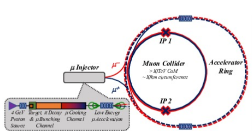
Composite $\sqrt{\hat{s}} \ll \sqrt{s}$
"Messy" collisions



100 TeV pp ≈ 10-15 TeV μμ

(more details in backup)

Muon collider (Fermilab siting) ~ 10 TeV (bigger version to come)



Lepton

Fundamental $\sqrt{\hat{s}} \sim \sqrt{s}$ => Clean(er) collisions

COM energy limited by synchrotron radiation

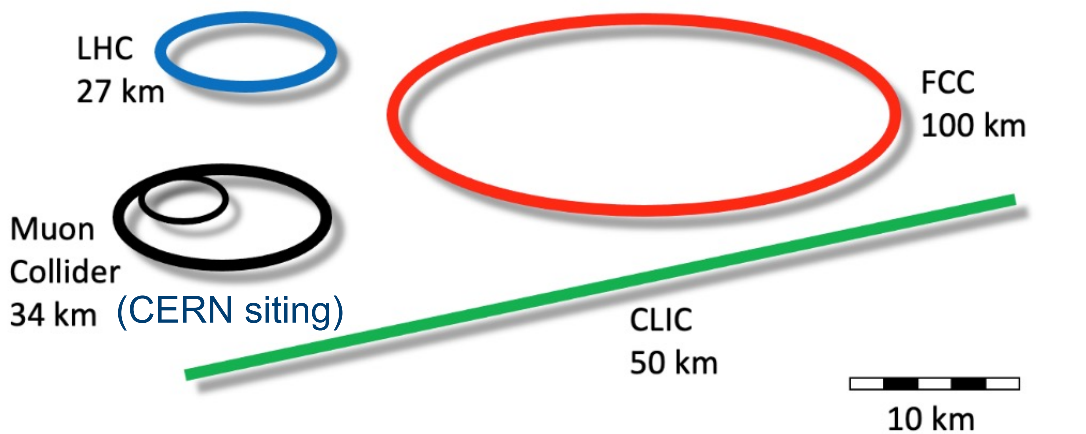
$$P \propto \gamma^4 = \left(\frac{E}{m}\right)^4$$

$\boldsymbol{e^+e^-}$

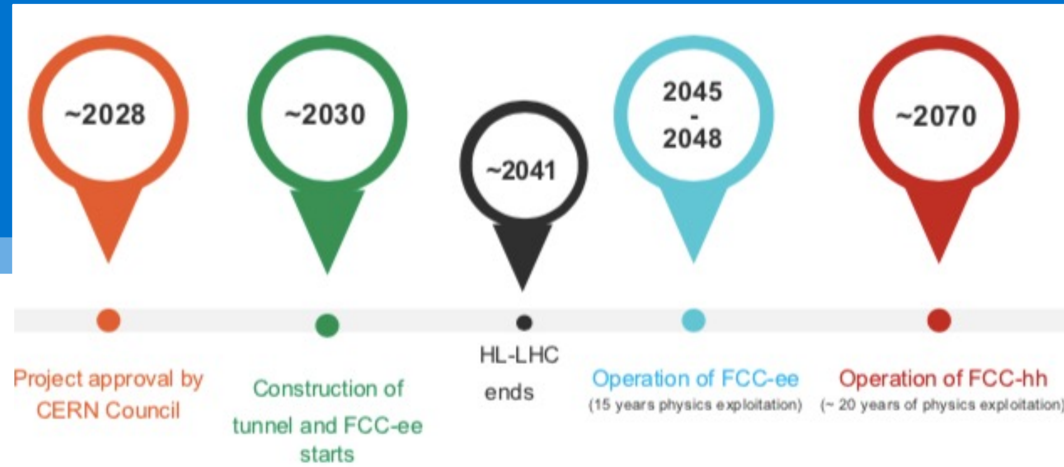
~100 km ring for ~240 GeV

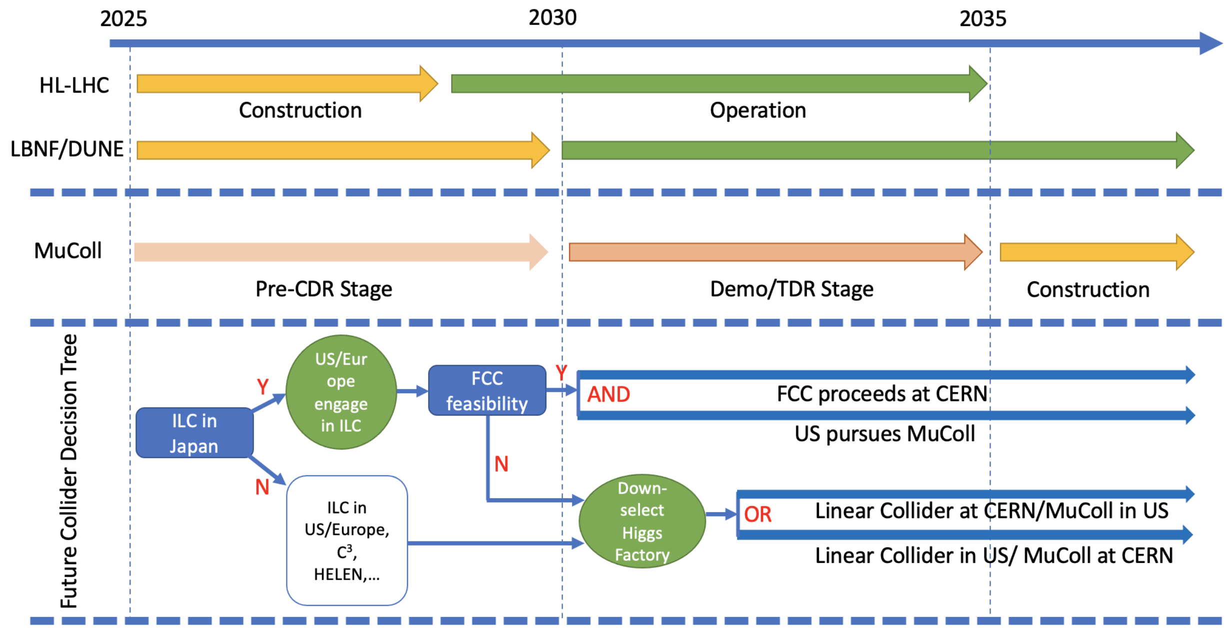
$\boldsymbol{\mu^+\mu^-}$

~10 km ring for ~10 TeV



Timelines = long





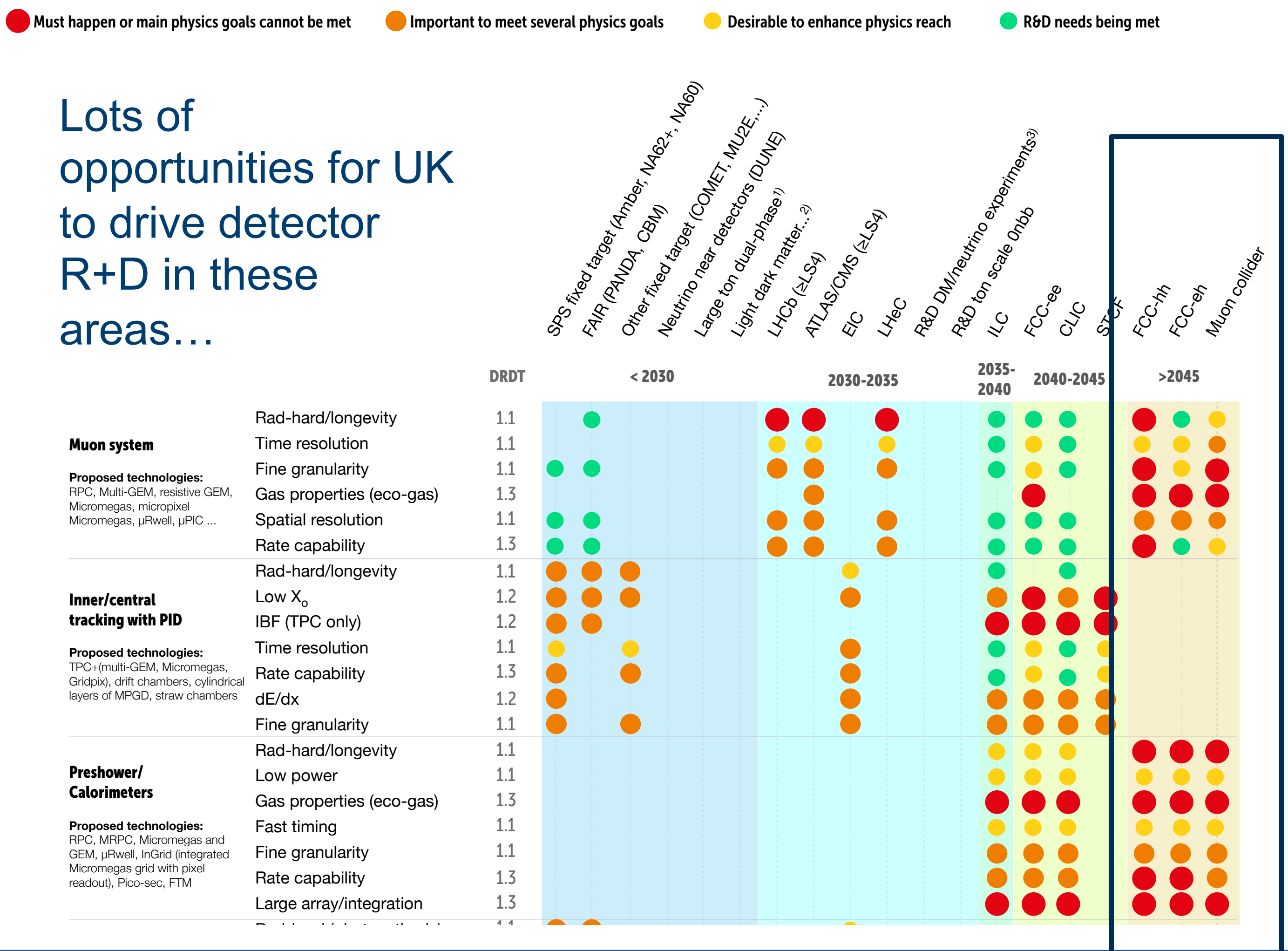
Above= "realistic" schedule for FCC

Left= "optimistic" technology-limited R+D timeline for muon collider from Snowmass.

Important to differentiate technical vs financial risk (and their error bars)

Detector R+D challenges

Taken from the ECFA R+D roadmap

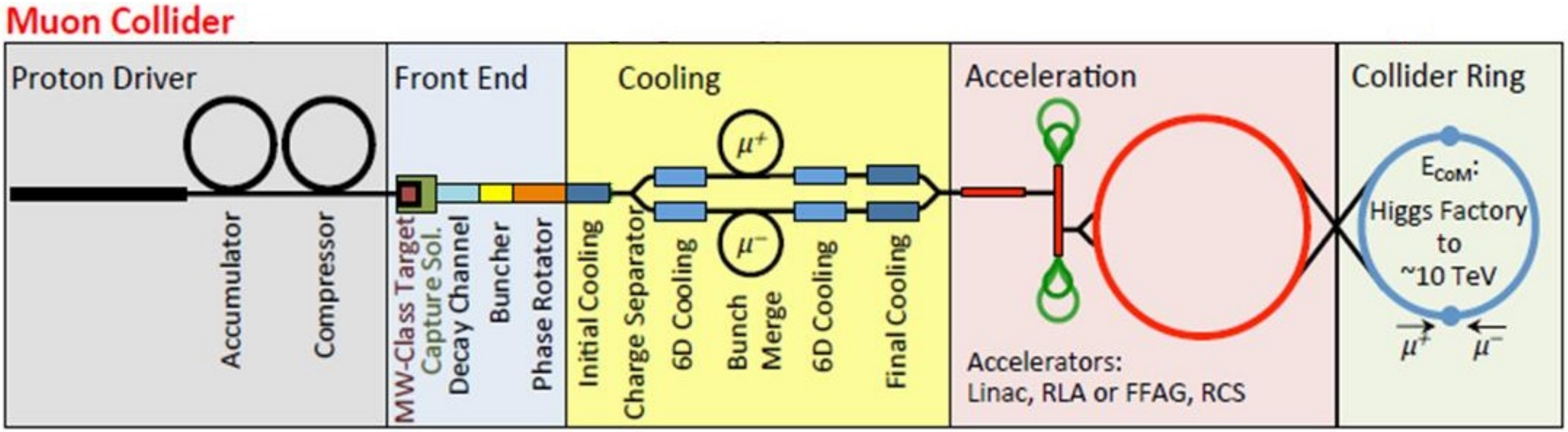


Lots of opportunities for UK to drive detector R+D in these areas…

RED= Essential => We do not have the technology to build detectors to meet the physics needs of 10 TeV pCM EF exploration…

Muon collider challenges => muon decay ($\tau_\mu \sim 2.2\times10^{-6}$s)!

For more information see "Towards a muon collider" https://arxiv.org/abs/2303.08533



- After **production** (as tertiary beam) must be (6D) **cooled** into a single collimated bunch and (rapidly) **accelerated** (need fast ramp-up of magnets) before being **collided.**
- Additional challenges from **beam induced background** (BIB) and significant **neutrino radiation** (careful positioning and simulation studies).

Muon collider challenges: R+D

https://muoncollider.web.cern.ch/

WP	Title
1	Coordination and Communication
2	Physics and Detectors Requirements
3	Proton Complex
4	Muon Production & Cooling
5	High Energy Complex
6	RadioFrequency System
7	Magnet Systems
8	Cooling cell Integration

The next steps towards a muon collider would be a demonstrator of these technologies and further simulation studies on detector challenges and physics potential.

The UK has significant involvement in the growing collaboration (mainly on the accelerator side) and there are interesting synergies with other areas:

- NuSTORM (intense neutrino beam).
- Radiation tolerant and high-field Solenoids.
- High-field dipoles (would also benefit FCC-hh).

STFC RAL	**Deputy Study Leader (Facility) & WP4 (Muon Production) Leader**
Univ. Birmingham	WP2 (Detector & Physics)
Univ. Cambridge	*WP2 (Detector & Physics)*
Univ. Lancaster	WP6 (RF)
Univ. Southampton	WP7 (Magnets)
Univ. Strathclyde	WP6 (RF)
Univ. Sussex	WP2 (Detector & Physics)
Imperial College London	WP4 (Muon Production), WP8 (Cooling integration)
Royal Holloway	WP4 (Muon Production), WP5 (High Energy Complex)
Univ. Huddersfield	WP5 (High Energy Complex)
Univ. Manchester	*WP4 (Muon Production), WP5 (High Energy Complex)*
Univ. Oxford	WP5 (High Energy Complex)
Univ. Warwick	WP4 (Muon Production)
Univ. Durham	WP2 (Detector & Physics)

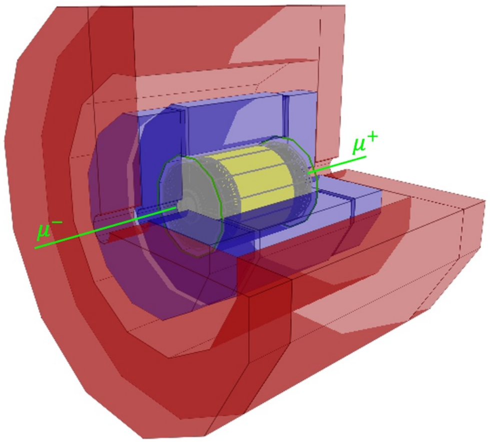
UK muon collider activities

See slides by Karol Krizka here

Following the snowmass/P5 process there's growing momentum in the muon collider community on detector/physics studies as well as accelerator R+D.

The panel recommends dedicated R&D to explore a suite of promising future projects. One of the most ambitious is a future collider concept: a **10 TeV parton center-of-momentum (pCM) collider** to search for direct evidence and quantum imprints of new physics at unprecedented energies. Turning this concept into a cost-effective, realistic collider design demands that we aggressively develop multiple innovative accelerator and detector technologies. This process will establish whether a proton, electron, or muon accelerator is the optimal path to our goal.

As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design elements while producing exceptionally bright muon and neutrino beams. By taking up this challenge, the US blazes a trail toward a new future by advancing critical R&D that can benefit multiple science drivers and ultimately bring an unparalleled global facility to US soil.



- Aim to grow UK community on the detector R+D side ahead of next EPSSU.
- Next Wednesday (3rd July) there will be a UK workshop on UK contributions to Muon collider detector R+D here at the University of Birmingham https://indico.stfc.ac.uk/event/983/

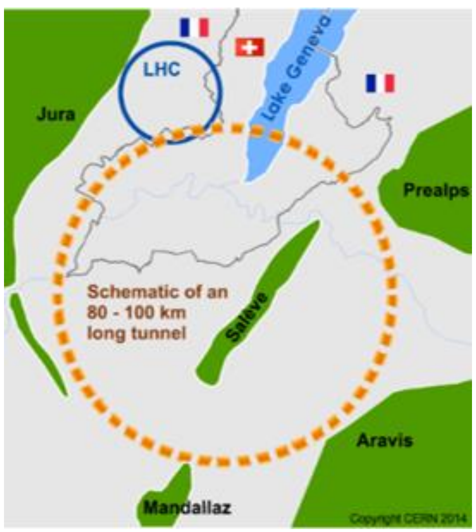
Integrated FCC programme

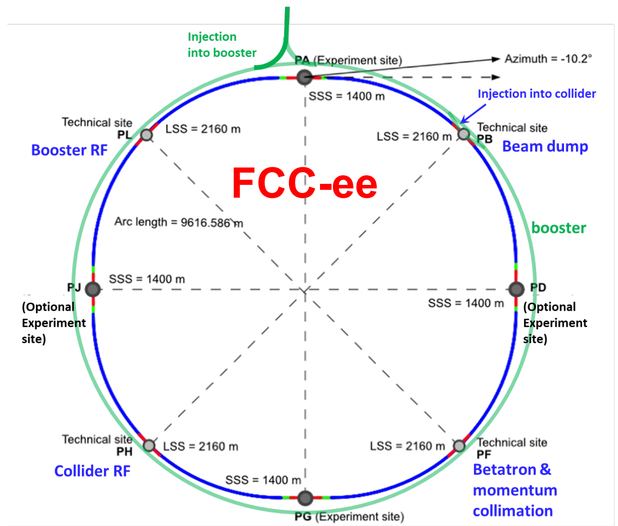
Mid-term review of FCC feasibility study completed this year- aiming to finish in 2025!

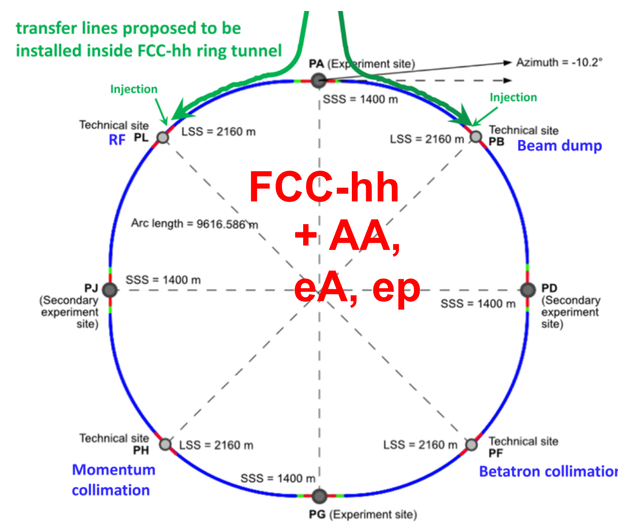
Comprehensive long-term programme maximises physics opportunities at the intensity and energy frontier:

1. FCC-ee (Z, W, H, $t\bar{t}$) as high-luminosity Higgs, EW + top factory.

2. FCC-hh (~ 100 TeV) to maximise reach at the energy frontier, with pp, AA and e-h options (FCC-eh).







2020 - 2040 | 2045 - 2063 | 2070 - 2095

FCC-hh parameters and challenges

Taken from slides by F. Gianotti at FCC week.

Parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	80-116		14	14
dipole field [T]	14 (Nb_3Sn) – 20 (HTS/Hybrid)		8.33	8.33
circumference [km]	90.7		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	1020-4250		7.3	3.6
SR power / length [W/m/ap.]	13-54		0.33	0.17
long. emit. damping time [h]	0.77-0.26		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [µm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	6.1-8.9		0.7	0.36
integrated luminosity [fb^{-1}]	20000		3000	300

If FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:

- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

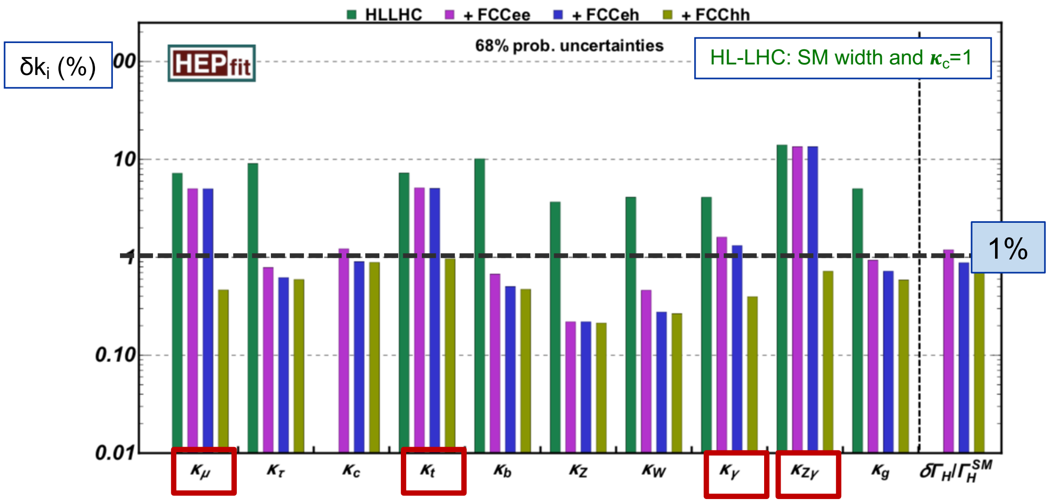
Formidable physics reach, including:

- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ)
- ❑ Final word about WIMP dark matter

6

Synergies in FCC programme- Higgs physics

https://fcc-cdr.web.cern.ch/



- Integrated FCC programme will provide order of magnitude improvement in Higgs couplings.
- e^+e^- colliders can provide a model independent measurement of g_{HZZ} => provides standard candle to normalize other Higgs couplings.

- Can also measure ttZ couplings through $ee \rightarrow t\bar{t}$. This gives a second standard candle used to extract g_{ttH} and g_{HHH} at subsequent hadron machines.
- High-energy pp collisions provide the statistics to access rarer Higgs decays ($H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$) and HH events to give precise ultimate tests of the EWPT (~ 20 million at FCC-hh).

FCC-hh: UK involvement and plans

See slides from Andy Pilkington at the ECFA-UK kick-off

- UK has seen significant activity+interest on the physics/performance side for FCC-hh (see previous dedicated meeting in July '22 and hackathon in May '23.).
- Ongoing studies include:
  - Higgs self-coupling studies (Liverpool, UCL)
  - CPV studies in Higgs interactions (Manchester, Edinburgh, Glasgow, Cambridge).
  - Boosted analysis techniques in ZH, H->bb (UCL).
  - Flavour tagging using GNNs (UCL)
  - Additional scalars in inert 2HDM models (Imperial)

Where possible these efforts will feed into the final FCC feasibility study report!

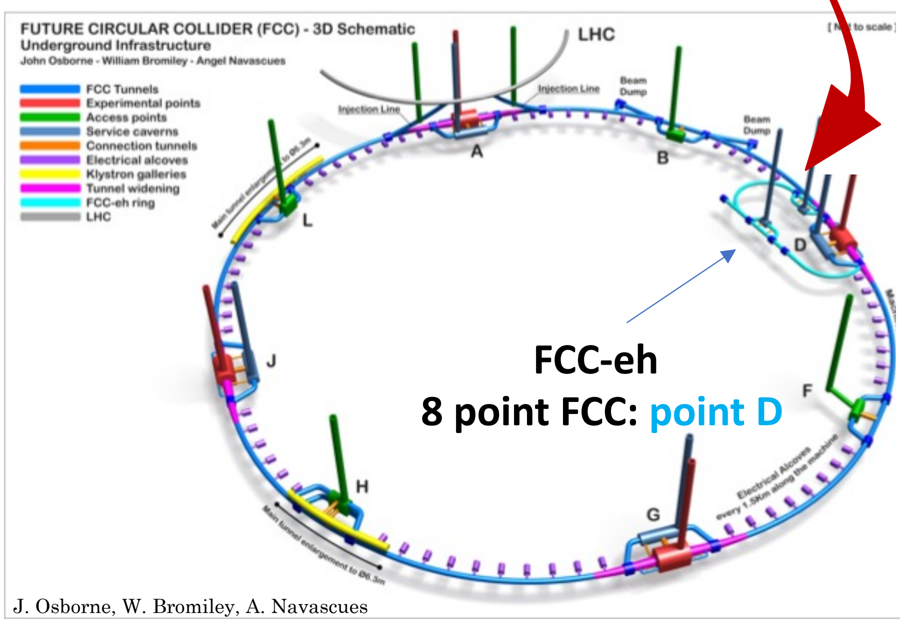
Lots of opportunities to further explore physics potential of FCC-hh in the coming years!

FCC-eh

For a nice review of electron-hadron colliders (including EIC) see https://cds.cern.ch/record/2811194

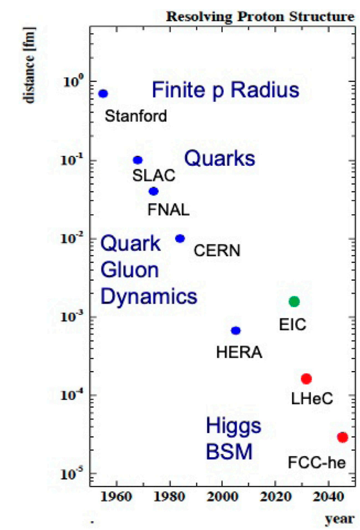
Novel use of Energy Recovery Linac (ERL) technology that will be demonstrated with the PERLE ERL demonstrator (see slides by M. Klein here)

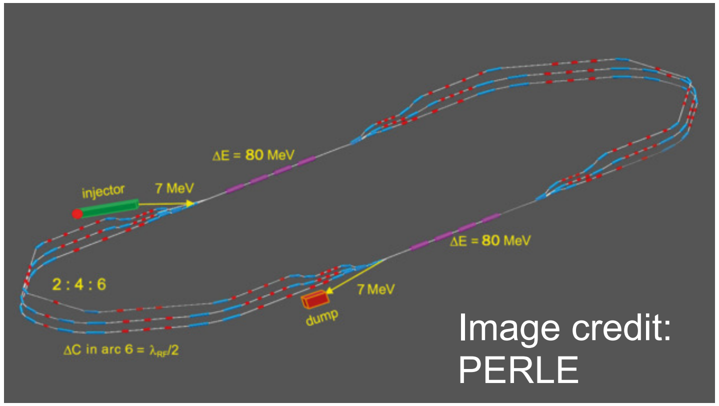
FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh



Taken from slides by J. D"Hondt at FCC week

Use of ERL technologies a key step towards improving sustainability whilst maintaining high luminosities.

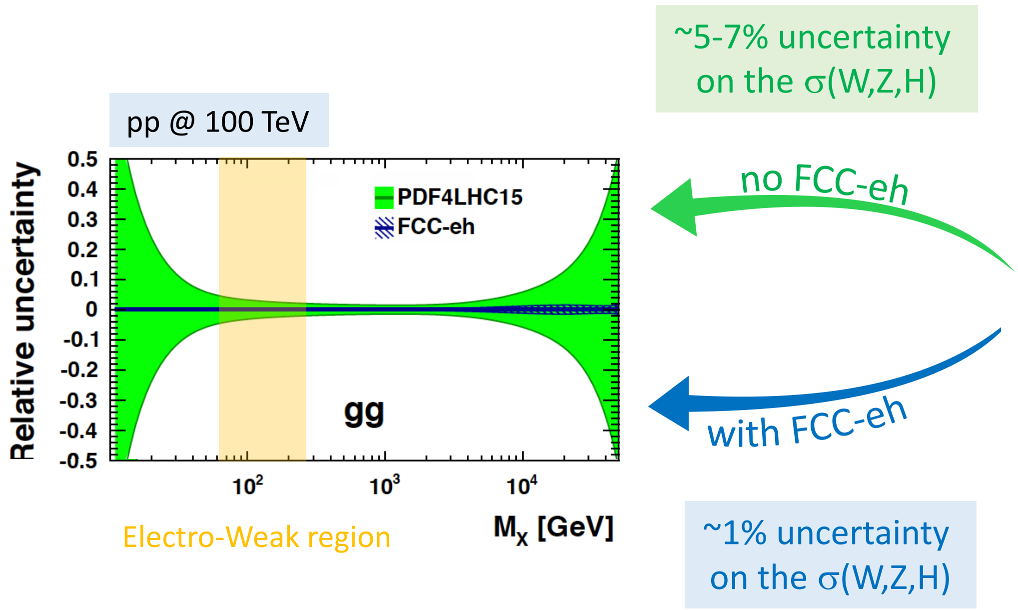


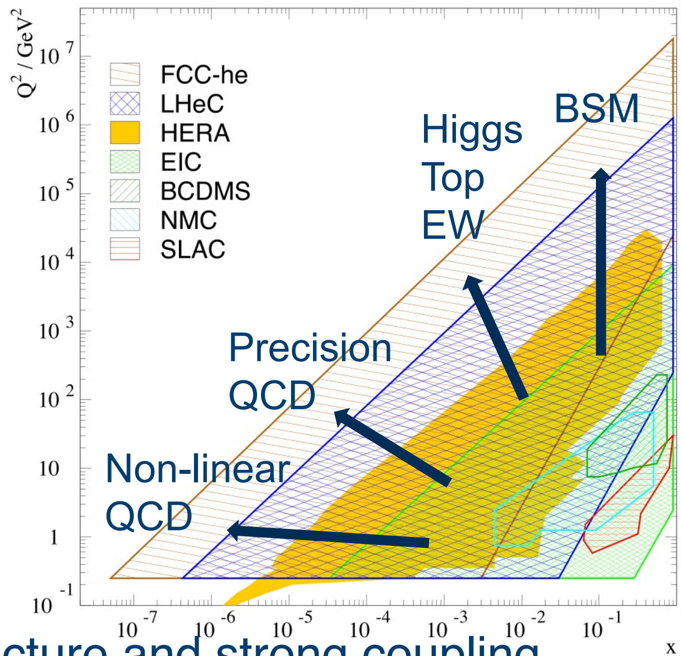


Synergies in FCC between ep and pp

Taken from slides by J. D"Hondt at FCC week

Taken from updated CDR





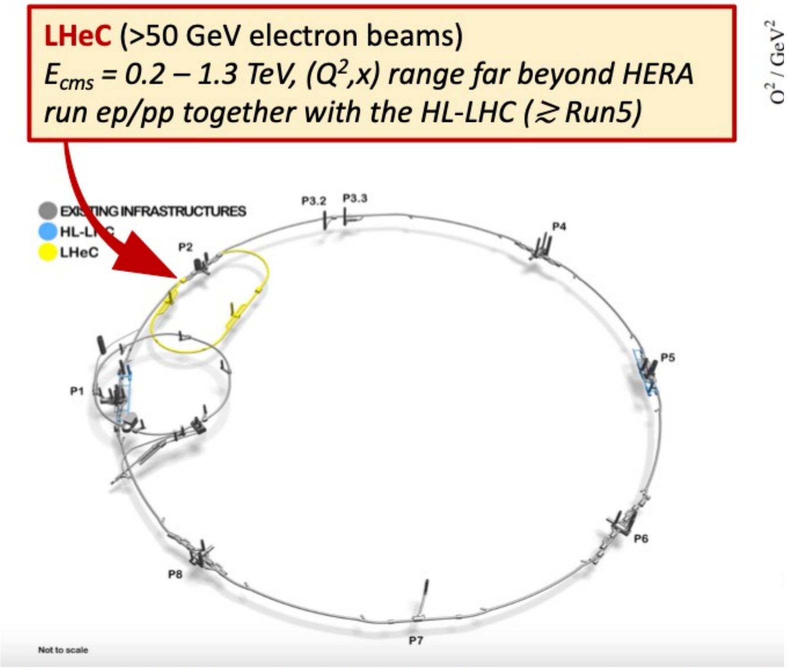
- Empower FCC-hh with precision input on hadron structure and strong coupling (to permille accuracy) during parallel running.
- Complementary measurements of Higgs couplings (CC+NC DIS x-sections, no pile-up, clean)- see slides by U. Klein here
- Plus… complementary BSM prospects (LLPs, LFV, not-too-heavy scalars, GeV-scale bosons)

Ongoing ep efforts: the ep/eA @ CERN study

https://indico.cern.ch/event/1335332/

Mandate renewed in October 2022, with kick-off in October 2023

"CERN continues to support studies for the LHeC and the FCC-eh as potential options for the future and to provide input to the next Update of the European Strategy for Particle Physics. The study is to further develop the scientific potential and possible technical realization of an ep/eA collider and the associated detectors at CERN, with emphasis on FCC."



The UK has significant leadership in this effort- for more detail see slides from Uta Klein at the ECFA-UK kick-off meeting and the backup

Conclusion + outlook

Conclusion

- Have tried to provide a whistlestop tour of the landscape and UK involvement in plans for 10 TeV pCM colliders.

- Please feed into studies/discussions in the 10 TeV pCM strand of the ECFA-UK September workshop (and come along)- contacts are Andy Pilkington (Andrew.Pilkington@cern.ch , Karol Krizka (k.krizka@bham.ac.uk) and myself (sarah.louise.williams@cern.ch)

- Whilst high-energy ep colliders featured in this talk- also very relevant for HL-LHC era with significant UK involvement in the ep/eA @CERN study- there will be a dedicated ep strand for the ECFA-UK workshop- contacts are Uta Klein (uklein@hep.ph.liv.ac.uk) and Matthew Wing (m.wing@ucl.ac.uk).

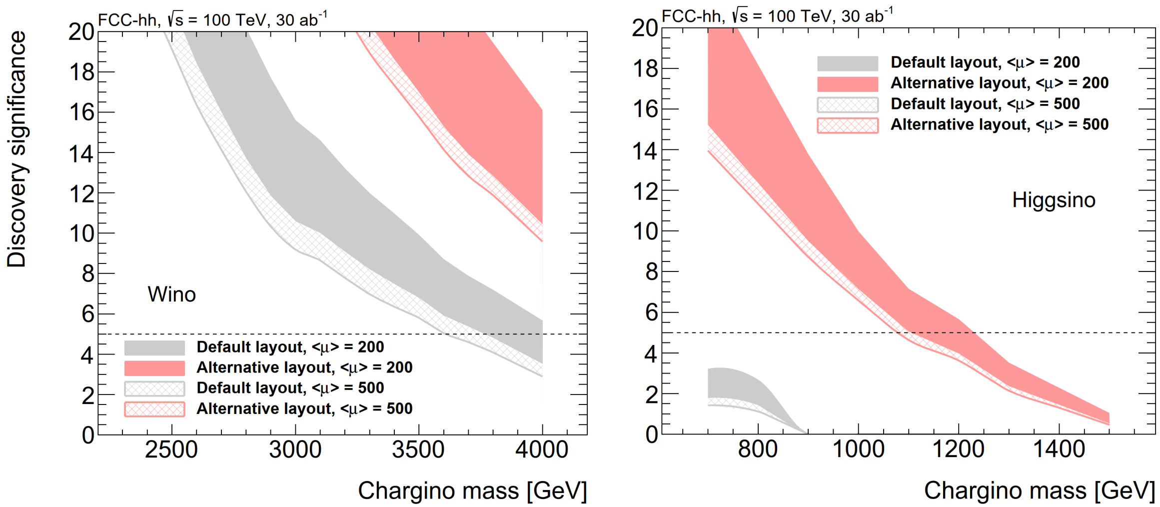
- Happy to take questions/comments.

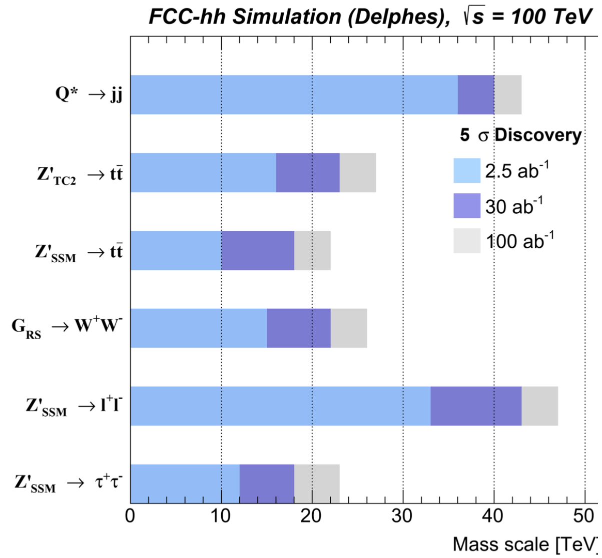
Backup

FCC -hh synergies - BSM searches

More details in FCC TDR and ESU submissions here

FCC-hh sensitivity to direct NP





Cover full mass range for discovery of WIMP dark matter candidates

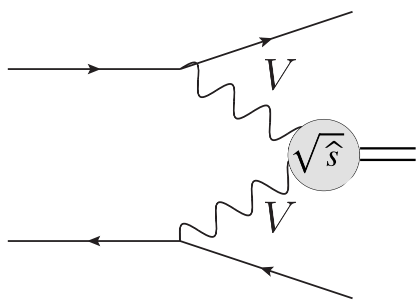
Substantial discovery reach for heavy resonances

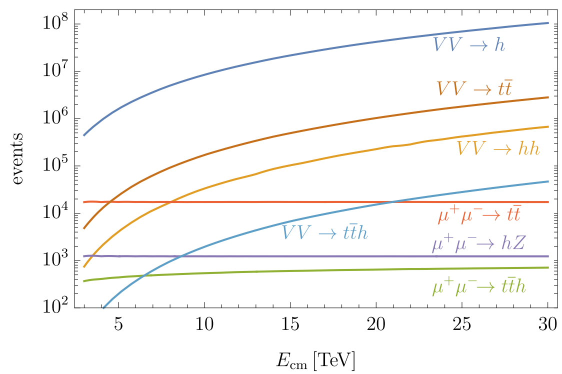
In summary- exciting possibilities to discover/characterize NP that could be indirectly predicted through precision measurements at FCC-ee

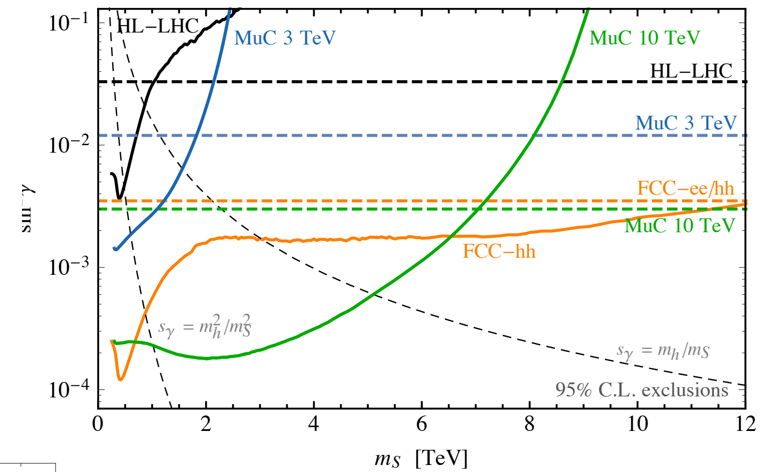
Direct BSM at muon colliders

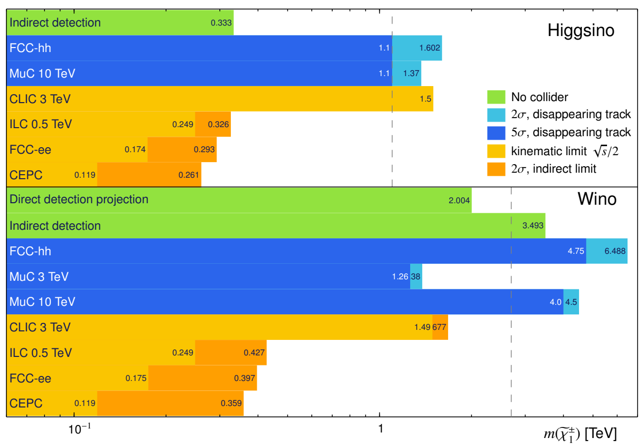
For more information see "Towards a muon collider" https://arxiv.org/abs/2303.08533

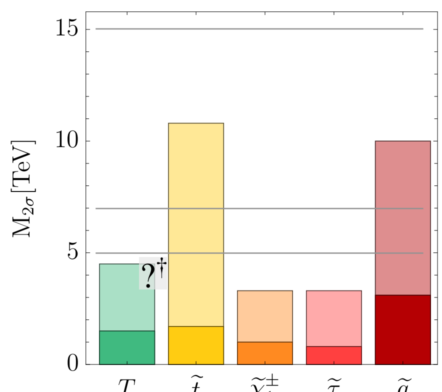
A high-energy muon collider would also be a vector-boson collider=> direct BSM and providing "Higgs factory" (see next slide)











† The low FCC-hh mass reach on Top Partners could be due to a non-optimal analysis

Above: exclusion for scalar singlet mixing with Higgs
Left: comparison of HL-LHC (solid), FCC (shaded) and tentative muon collider reach at 10, 14, 30 TeV (lines)

Higgs precision at EF colliders

Snowmass energy frontier report

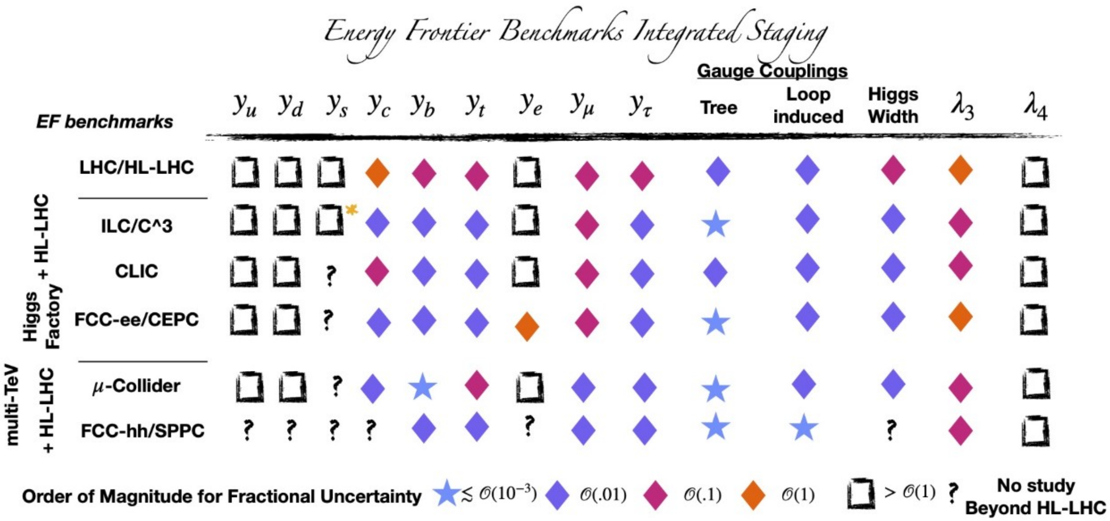
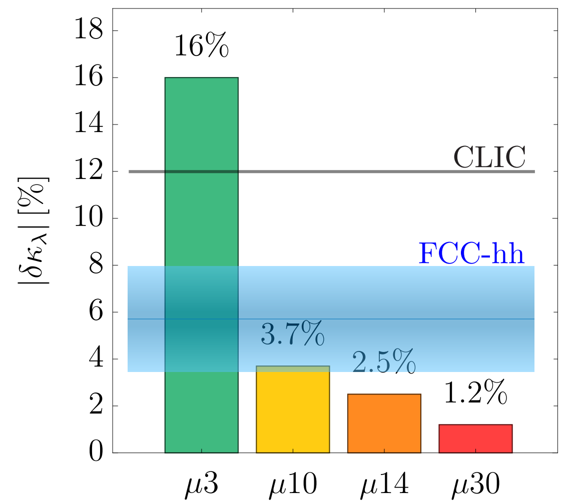


Figure 1-9. *A snapshot of future Higgs precision measurements of SM quantities based on the order of magnitude for the fractional uncertainties with the range defined through the geometric mean. In this figure the ultimate reach of the final stages of all Higgs factories and multi-TeV colliders are shown in combination with the HL-LHC results, as well as the HL-LHC separately. All benchmarks and stages are defined in Section 1.3 of the Energy Frontier Report. The specific precision associated to each coupling can be found in the Higgs-physics Topical Group report [14] and references therein. A * is put on the ILC measurements for the strange-quark Yukawa coupling to single it out as a new measurement proposed during Snowmass 2021, and shown in Fig 1-13. The ? symbol is used in the case where an official study has not yet been performed. It does not connotate that a given collider should be worse than similar ones, but simply that whether it is better or worse based on detector design has not been demonstrated.*



https://arxiv.org/abs/2303.08533

Ongoing ep efforts: the ep/eA @ CERN study

The UK has significant leadership in this effort- for more detail see slides from Uta Klein at the ECFA-UK kick-off meeting.

In consultation with the International Advisory Committee, the Coordination Panel has developed new impact objectives for the ep/eA@CERN study, see also open kick-off meeting.

Coordination Panel members (May 2023): Nestor Armesto, Maarten Boonekamp, Oliver Brüning, Daniel Britzger, **Jorgen D'Hondt (spokesperson),** Monica D'Onofrio, Claire Gwenlan, Uta Klein, Paul Newman, Yannis Papaphilippou, Christian Schwanenberger, Yuji Yamazaki.

International Advisory Committee members (May 2023): Phil Allport, Diego Bettoni, **Frederick Bordry (chair),** Abhay Deshpande, Rohini Godbole, Beate Heinemann, Karl Jakobs, Young-Kee Kim, Max Klein, Eric Laenen, Jean-Philippe Lansberg, Tadeusz Lesiak, Dave Newbold, Vladimir Shiltsev, Johanna Stachel, Achille Stocchi.

New mailing lists have been created for each working group and with just a few clicks you can subscribe to them. Anyone with a CERN account or a light account can register via: *https://e-groups.cern.ch/* (use the search option, and search for "ep-eA-WG" in all e-groups).

WG 1: Proton and nuclear structure from EIC and HERA to LHeC and FCC-eh (conveners: N. Armesto, C. Gwenlan, P. Newman)

WG 2: General-purpose high-energy physics program with precision physics and searches (conveners: M. D'Onofrio, U. Klein, C. Schwanenberger)

WG 3: ep/eA-physics empowering pp/pA/AA-physics (conveners: M. Boonekamp, D. Britzger, C. Schwanenberger)
WG 4: Developing a general-purpose ep/eA detector (conveners: P. Newman, Y. Yamazaki)

WG 5: Developing a sustainable LHeC and FCC-eh collider program (conveners: O. Bruning, Y. Papaphilippou)

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