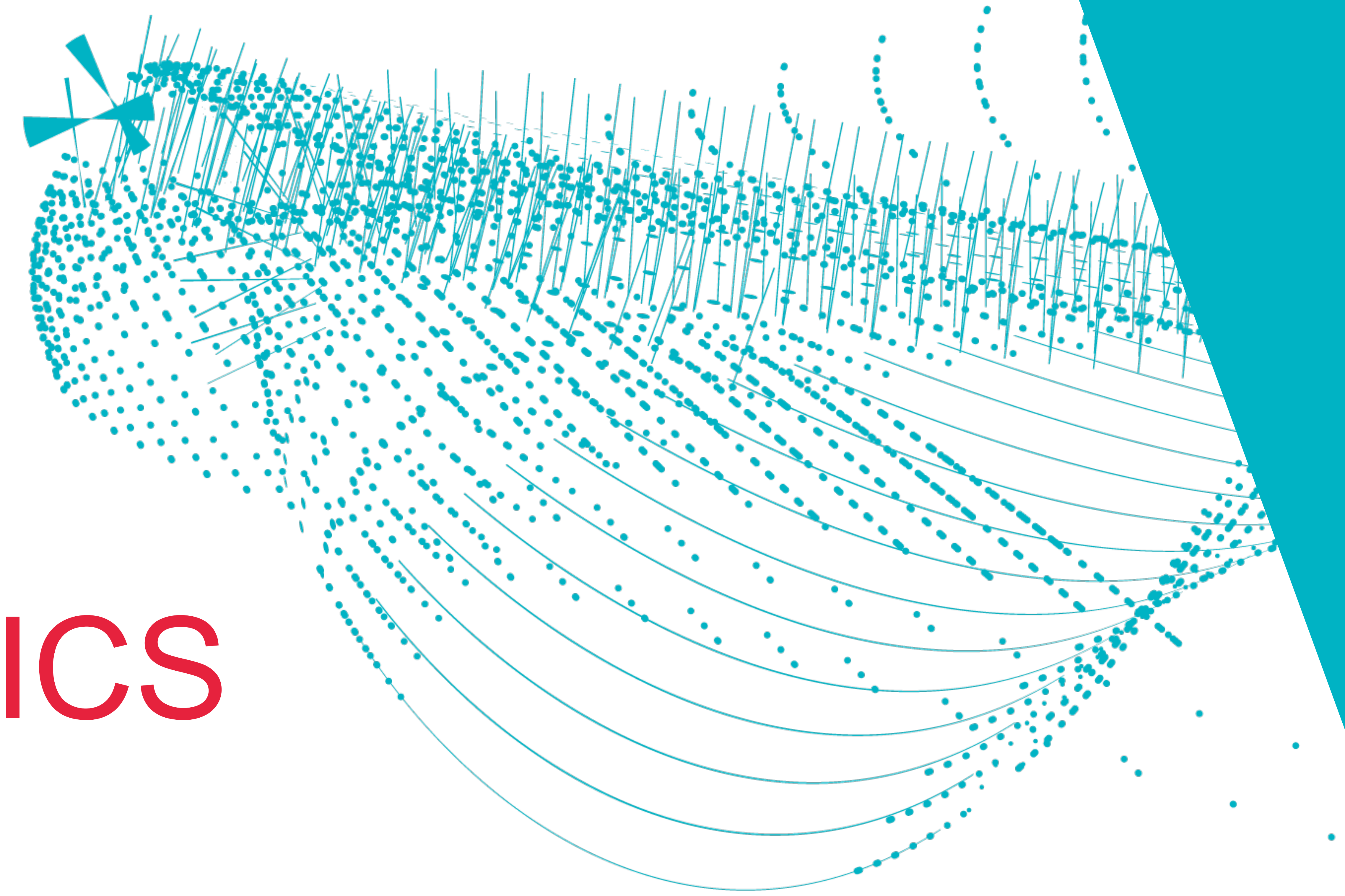
STRATEGY DAY SUMMARY OF PHYSICS SESSION



WOUTER WAALEWIJN & PANOS CHRISTAKOGLOU

SUMMARY OF THE SESSION

Time	Session	Speaker	Location	Slot
	Introduction	*Wouter Waalewijn*	*Nikhef*	10:55 - 11:00
11:00	**Standard Model Effective Field Theory and PDFs**	*Juan Rojo*	*Nikhef*	11:00 - 11:04
	Dark sectors	*Susanne Westhoff*	*Nikhef*	11:04 - 11:08
	(high density) QCD studies	*Marco van Leeuwen*	*Nikhef*	11:08 - 11:12
	Flavour physics	*Ann-Kathrin Perrevoort*	*Nikhef*	11:12 - 11:16
	Higgs physics	*Frank Filthaut*	*Nikhef*	11:16 - 11:20
	BSM searches	*Robin Hayes*	*Nikhef*	11:20 - 11:24
	Connections between gravitational waves and future colliders	*Andreas Freise*	*Nikhef*	11:24 - 11:28
	Discussion on summarizing the physics cases		*Nikhef*	11:30 - 11:50
12:00	**Discussion on prioritizing the physics cases**		*Nikhef*	11:50 - 12:15

Very clear, enthusiastic pitches with concrete messages + respected time allocation (many thanks!!!)

SUMMARY OF FEEDBACK

Principle components of the physics case:

- Higgs precision (especially the self-coupling)
- need a discovery potential beyond the Standard Model
- inclusive flavour program (heavy quarks, light quarks, leptons, neutrino)
- adaptability to new physics cases and new technologies
- sufficient resources to be available for new smaller experiments in addition to the major collider and for developing new enabling technologies
- synergies with astroparticle, GW and nuclear physics are to be part of our particle physics case
- low-x physics is to be considered as uncharted territory

What we learned from the presentations and the pitches:

Some elements of FCC-ee useful for Heavy Ion

Aspect of polarization not addressed

Flavour physics a central topic for future colliders

Synergy between ET and CERN from the technology point of view

All options have there science case

Physics cases, how can precision bring new insights:

Is a valid path towards discoveries

Synergies between sub-topics:

Develop concrete programs with a portfolio of experiments, including techn developments

Group 3
Chair Niels van Bakel secr. Peter Kluit
- Unclear except: Higgs clear case e.g. self coupling Higgs
- No strong physics case: no big lead what is next

Physics case:
a) Higgs coupling and self coupling
b) Keep options open
Diverse program keep money for ot
wait with decisions postpone
Postponing might be dangerous …

Group 7
Hella, David, Gerhard, Patrick, Andreas

Did you learn anything new from the pitches?
- Many science goals can be done with all the colliders -> Higgs physics driving force and the rest is secondary

To what extent do the cases made in the pitches focus on improving precision discovery?
- No single scenario that makes it very clear
- For indirect searches Higgs-sector good place to look for (expect to cou Higgs)
- What is the "failure mode", i.e. what collider would provide the best inp next-future collider?
- How extendable is the project? Do we lock ourselves for the next N-yea

Are there any cases where precision cases present potential for discovery une or complete new phenomena?
- Do direct searches do better than indirect?
- Indirect searches can probe further. Gerhard gives example of J/psi dis
- Use indirect to then tune, can't do this with hh-machine

Most important question not addressed in session:
- Timeline and resources. "We can't wait for 40 years"
- FCC-hh is always assuming FCC-ee, have to be careful that focus on F does not "kill" earlier program

Session 2:
Nice to have vs Must have
- Higgs machine is a must have
- Need to have a tunable program, there is always a price, e.g. Luminosity. Sacrifice stats for a broader program
- Broader Higgs program -> Lin collider better
- 10 years of additional (HL)-LHC data will give marginal additional info for future collider decision

- "4 IPs vs 1 IP", if you make a huge discovery someone else needs to reproduce the results
- Are there too many particle physicists for the physics? Can an experiment with 10000 physicists work? Would need to scale down.
- Do you really need multiple experiments? Astronomy has moved away from that assuming that later experiments/observatories will be able to verify. Can also use completely independent teams to verify. Money for accelerator so much more than experiment, so perhaps "cheap" insurance.

notes from group 10

We think that we need a discovery machine in the immediate future which is better rather than a precision one as
a discovery machine would do directly what a precision machine would do indirectly and we need a discovery in order to secure funding in the future.

we discussed 3 options:
1) a linear collider immediately after HL-LHC because thes linear Collider could be modular and we can extend it when money comes in. It is important that we can reach 500 TeV, 1.5 TeV and 3 TeV. (a flexible machine).
And then for the long term , the muon collider at CERN which would have the advantage of being a discovery but also a precision one.
The drawback of this options is that we lose at CERN the knowledge on pp accelerators
The advantage is also we do not stop HL-LHC, the youngest generation is enthusiastic about it and the physics reach that it has that won't be reached anymore until we have a hh machine or the muon collider.

2) having Fcc-hh immediately at 60 GeV in a 90 km tunnel. This is a very concrete possibility that is coming up and
we would be able in 2045 to have magnets that would allow us to run at this energy without too much energy consumption (recent outcome from accelerator department at CERN).
60 TeV would allow us to study already the Higgs sector and di-higgs!

This machine would then be updated to 80 -120 TeV.
If we want still to have a precision machine we could have a ILC but there was no strong reason identified.

we could finish HL-LHC

3) A similar possibility would be to have a hh machine in the present LHC tunnel that could run in 2045 at 28 TeV in 2045
And the have a muon collider afterwards.
This option would allow to finish HL-LHC and keep accelerator knowledge. but the energy consumption here would be high (for he ma

both option 1 2 and 3 allow us to have a discovery machine immediately and to avoid to stop the HL-LHC before run 5 that is very im
which Nikhef is involved heavily and is important also for society as fast timing had large medical applications (cancer imaging).

In general e do not see the case for Fcc-ee per se as we would achieve more with a hardon machine. Fcc-ee will not be so useful for c
would be indirect via ZH and not HH.

Physics cases

CERN has to continue with a big discovery project to insure funding.

-discovering new physics directly is the priority
- HH self couplings and direct detection of di_higgs , not indirect (ZH Fcc-ee)
- dark sector
- QCD and Heavy IONs will come for free in any hadron machine

We also think that CERN should diversify its program and therefore we see as favorable
the collaboration with gravitational waves and neutrino experiments,

Group 11

Discussion on summarizing the physics cases.

** Did you learn anything new from these pitches? What was it?*

** To what extent do the cases made in these pitches focus on improving precision measurements vs. enabling discovery of new particles or interactions?*

- Important to emphasise the discovery potential and not on possible exclusion scenarios.

ew UV complete theory as a key goal.

ework to complement new physics searches, but should not be the key selling point.

we employ to maximize the complementarity or overlap between the topics presented?

Physics: if a new particle is found, what are the imprints on precision observables? Should anomalies in precision observable
blished, what new particles are causing them? Explore their properties (CP violation, etc.); key synergies between the high-energy and
Need very ambitious goals for future collider, not just improve on "exclusion limits"…

ogy driven): precision measurements at FCCee first, then go for FCChh to "discovery" mode…

has advantages in time for precision measurements compared to FCCee, allowing FCChh to be available earlier. This summarises

Strategy Day - Group 12

Topics we find interesting:
– Physics case: only one order of magnitude in a corner of the phase space is not enough to justify a new machine
→ Counterpoint: for heavy neutral leptons, axion-like particles, we can constrain much more than one order of magnitude. Even at the Z pole.
→ Discussion on the usefulness of a new run of the Z pole;
→ For flavour physics: things are not so clear, why we would need a e+e-
→ Anything at the FCC-ee we cannot do in ILC? Polarisation beams can counteract the lumi issue; Interaction points also help with the luminosity;
– Physics case for high energy range is a gamble
– Exploring new territory also interesting for lower energy, even for hidden things we can find directly;
– We don't have a single target in terms of physics case that we aim at;
– Clear that we have a Higgs and there are a number of properties that we have not investigated (not just self coupling but also couplings to second generation etc)
– Should we spend money in a centralised way (CERN) or local institutes;
– Exciting for R&D: should we go into accelerator R&D? If so, we have to go in big; This is not really discussed;
– What precision do we get in the Higgs potential to motivate a new collider;
– also need precision measurement on W and top;

Prioritising the physics cases:
Must-have:
– ZH/Higgs precision (self-coupling, 2nd generation, etc)
– Direct searches → with split opinion on what this actually mean :)

Nice-to-have:
– Accelerator R&D (needed for direct searches in CLIC/muon collider/FCC-hh) – Nice to have at Nikhef, MUST have worldwide
– Polarisation
– Z pole

Our group discussed several things related to fundamental physics potential of future projects.

The clearest case where a future collider can shine is in the Higgs sector which is hard to measure elsewhere. The focus should be on the Higgs: self coupling and other interactions. Any collider should address this.

The BSM case is very important but very hard to quantify. Arguably the gain in energy is not that great considering the many orders of magnitude up to the Plank Scale.
The BSM pitches are therefore not as compelling and things like SMEFT studies are arguably better done in other low-energy experiments. This was also stressed in the flavor pitch.

Must have: measure Higgs sector and maximal BSM chances. Arguably precision can be achieved in a non-collider experiments and where experiments are unique is that COM energy. So we would go for the maximal gain in COM energy.

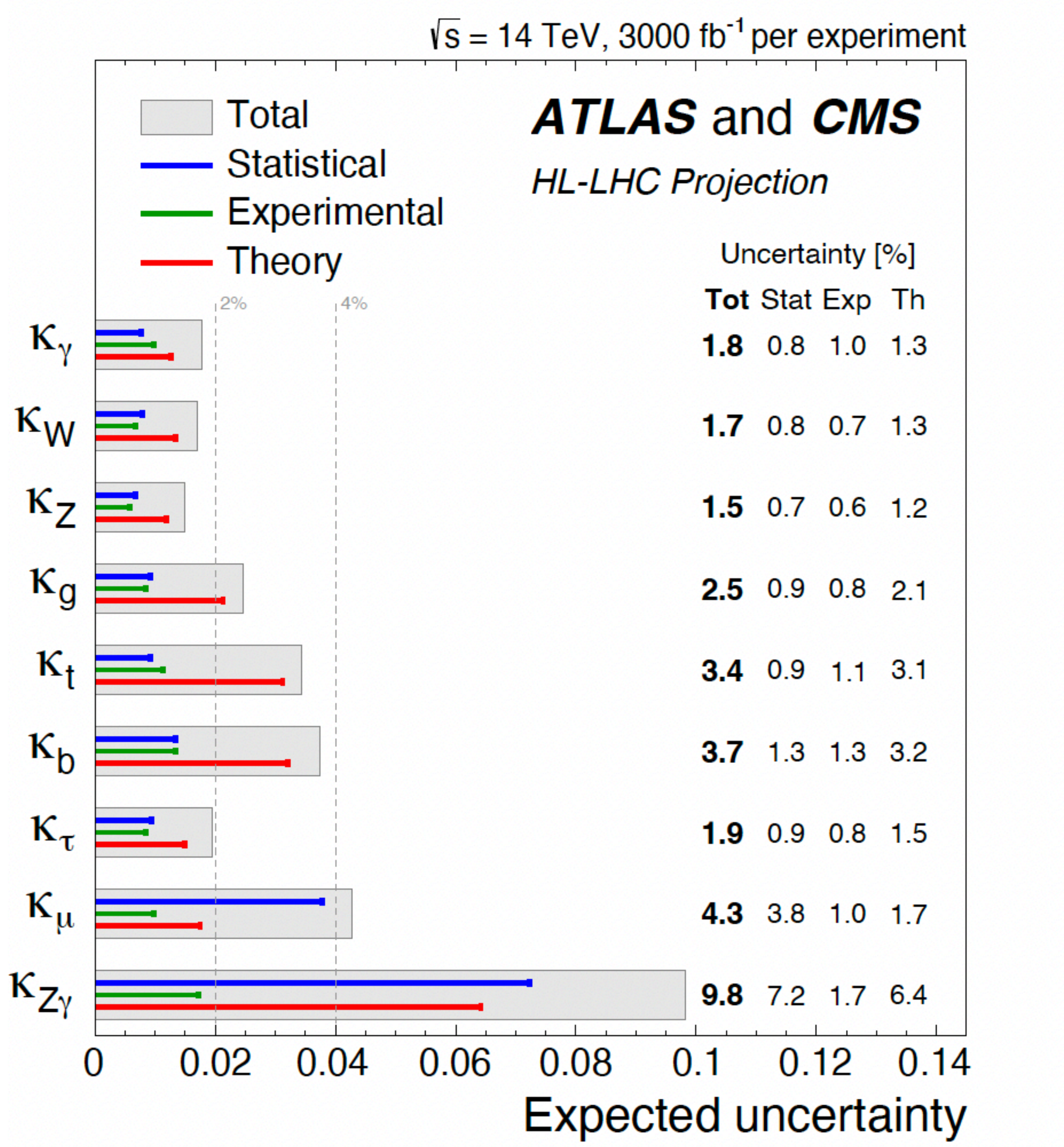
Concerns are that a circular collider will not be able to implement new technology such as wake-field and that by building a giant machine like the FCC (whatever variant) we are putting all our eggs In one basket. More people expressed interest for a smaller linear collider which can still do the Higgs and then, with future technology, afterwards focus on COM. A cheaper experiment also fits better with the current times politically (war, less science funding etc).

SOME HIGHLIGHTS FROM YOUR FEEDBACK

Highlighted in many of the responses

Completion of the HL-LHC program is essential

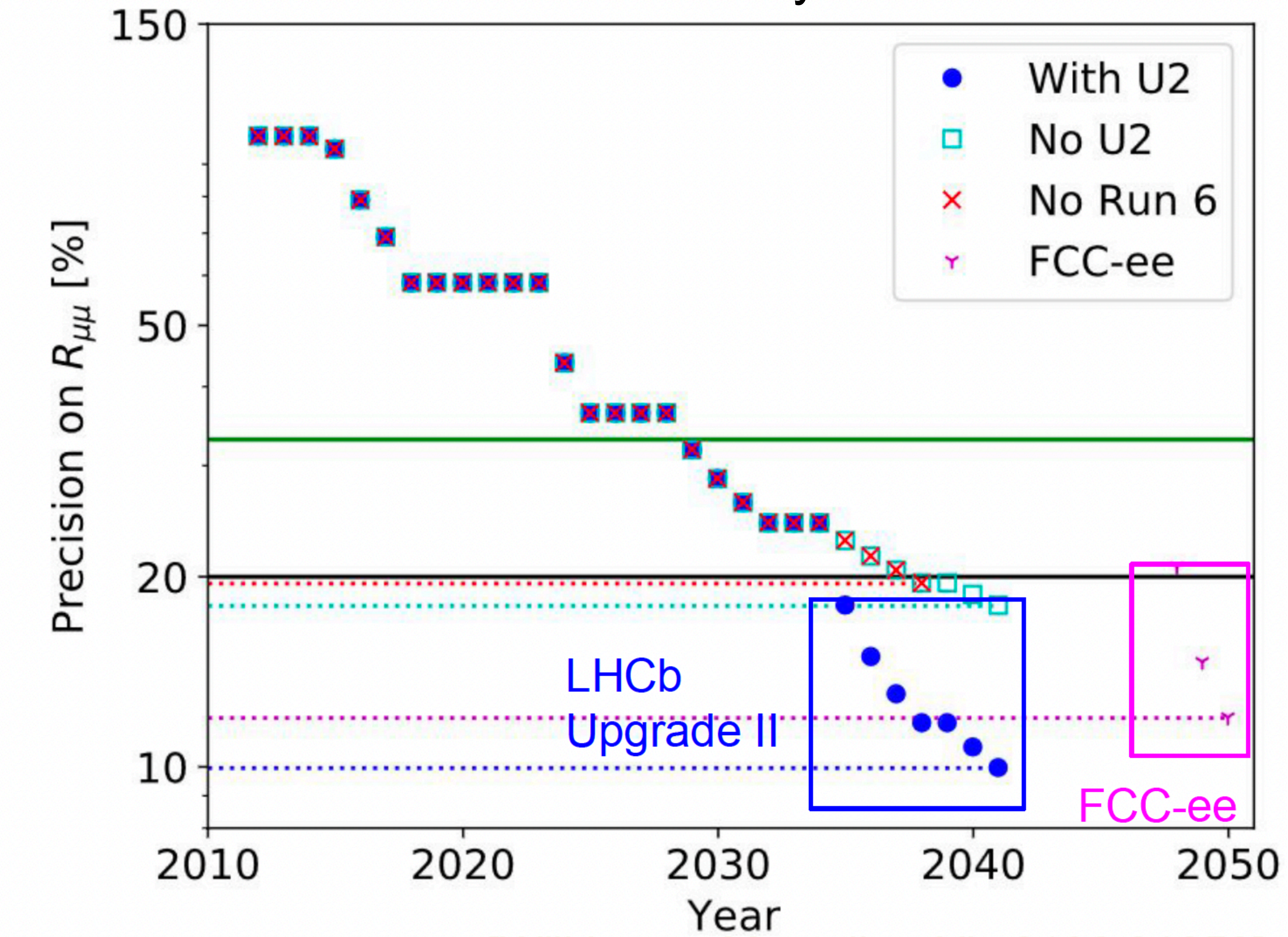
Precision measurements of various coupling constants



Source: 2019 ATLAS+CMS Yellow Report

Frank Filthaut

HL-LHC large impact for flavour physics that can not be matched by future colliders



[Wilkinson, Monteil; arXiv:2106.01259]

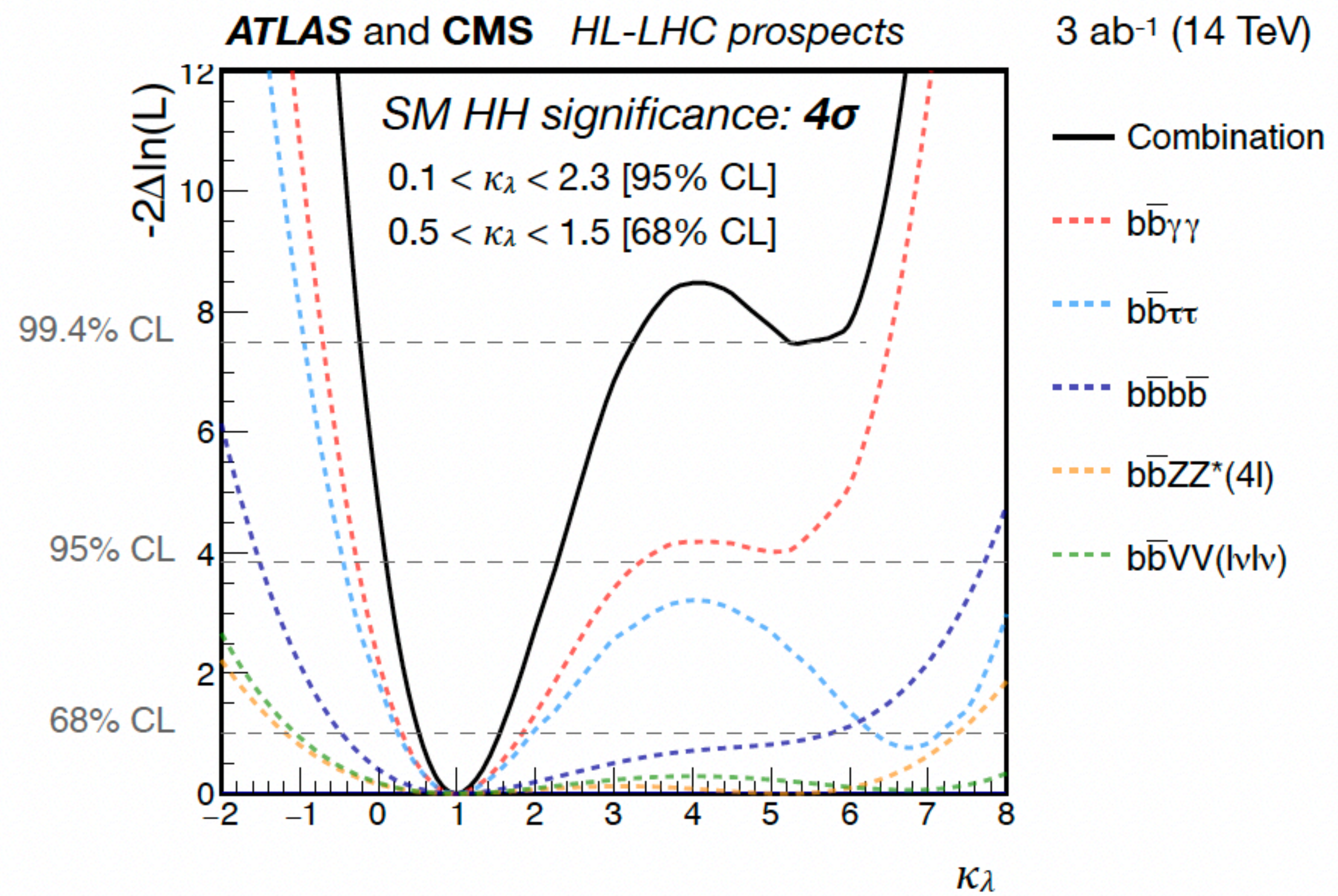
Ann-Kathrin Perrevoort

SOME HIGHLIGHTS FROM YOUR FEEDBACK

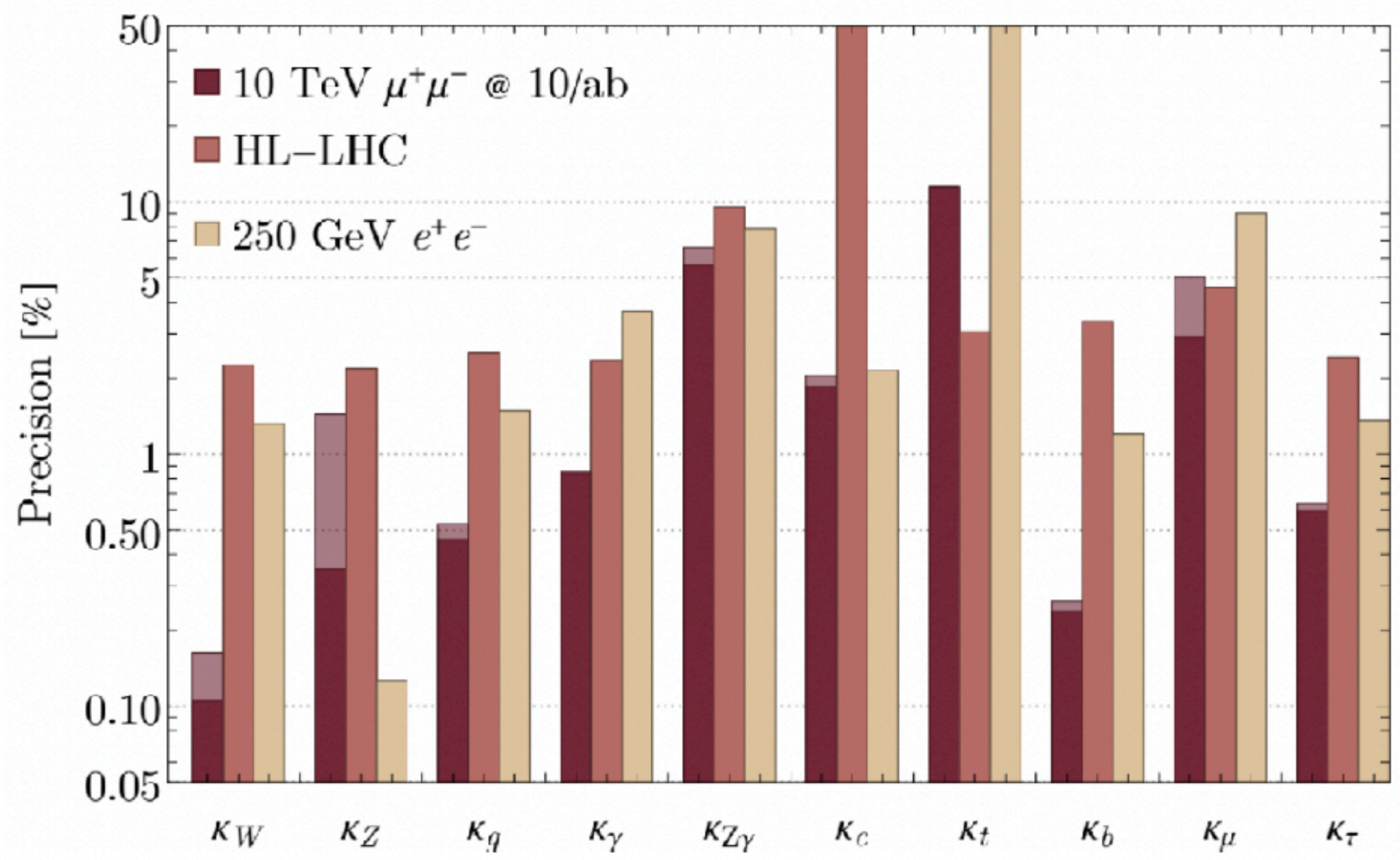
Highlighted in all of the responses

Higgs precision measurements

Various HL-LHC measurements (e.g. Higgs self-coupling) will already provide strong constrains



Source: 2019 ATLAS+CMS Yellow Report



Future colliders will provide improvement beyond HL-LHC
==> access to new physics

SOME HIGHLIGHTS FROM YOUR FEEDBACK

Highlighted in all of the responses

Discovery potential BSM

High-energy $\mu^+\mu^-$ or pp collider

- **Probe direct production of new particles** for masses up to 10s of TeV
  - SUSY, extended Higgs sectors, sterile neutrinos, and more....

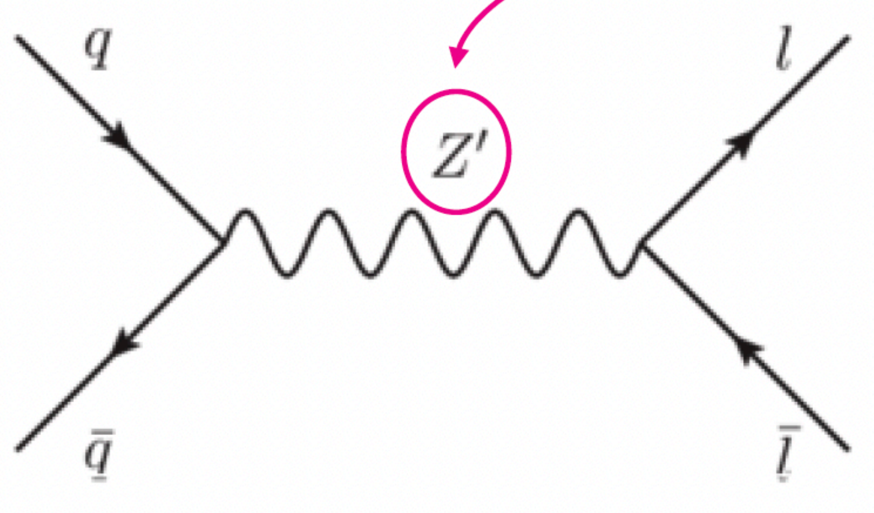
Low-energy e^+e^- Higgs factory

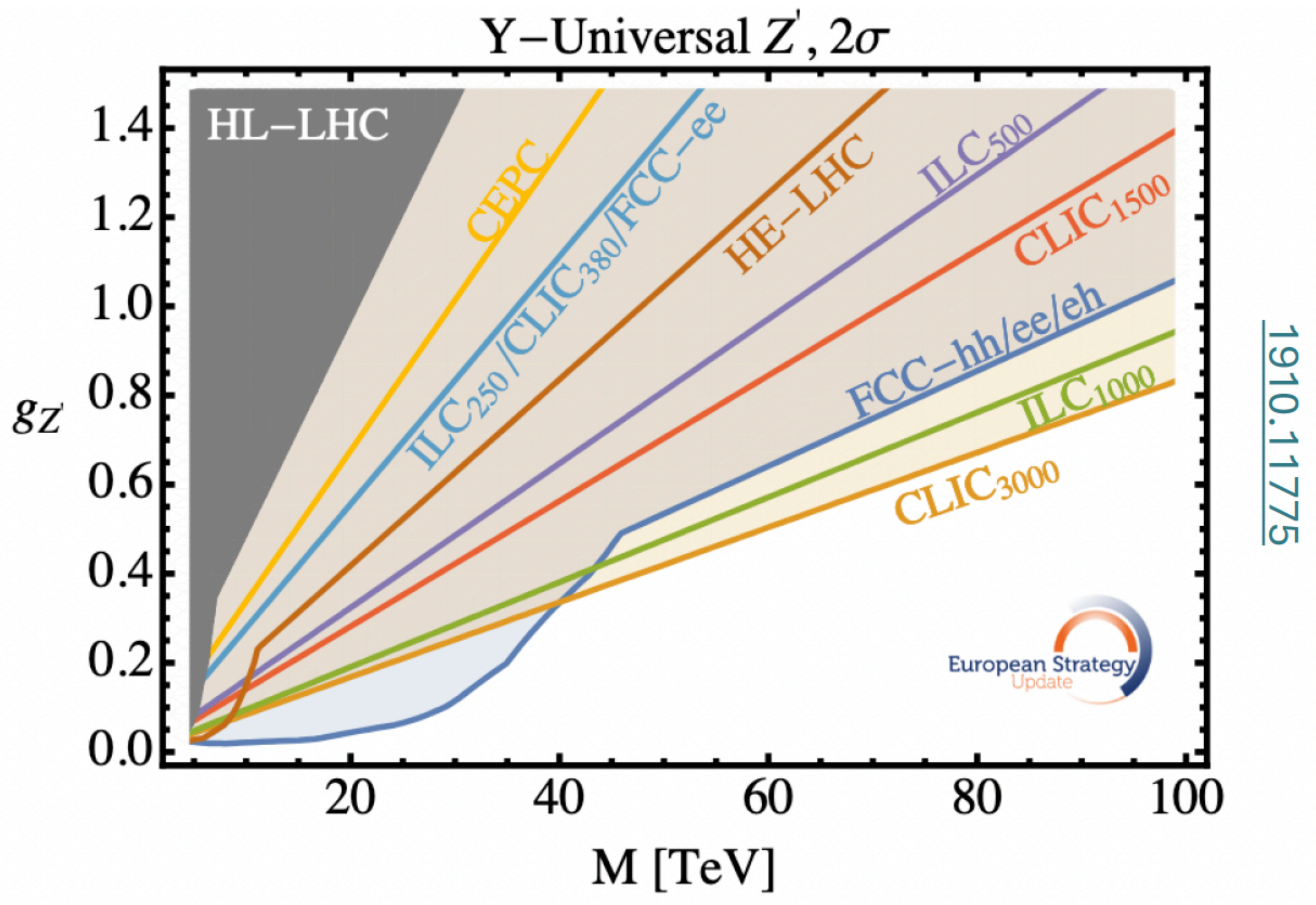
- **Probe direct production of new particles** for sufficiently low masses.
- **Fill in some gaps**:
  - Low-xsec processes with sizeable hadronic BRs
  - Models presenting reconstruction/identification difficulties.
  - Indirect constraints via precision measurements and EFT.

Robin Hayes

Example: (with FCC-hh) Sensitivity for Z' searches up to ~40TeV

Appear in many BSM models, eg. GUT



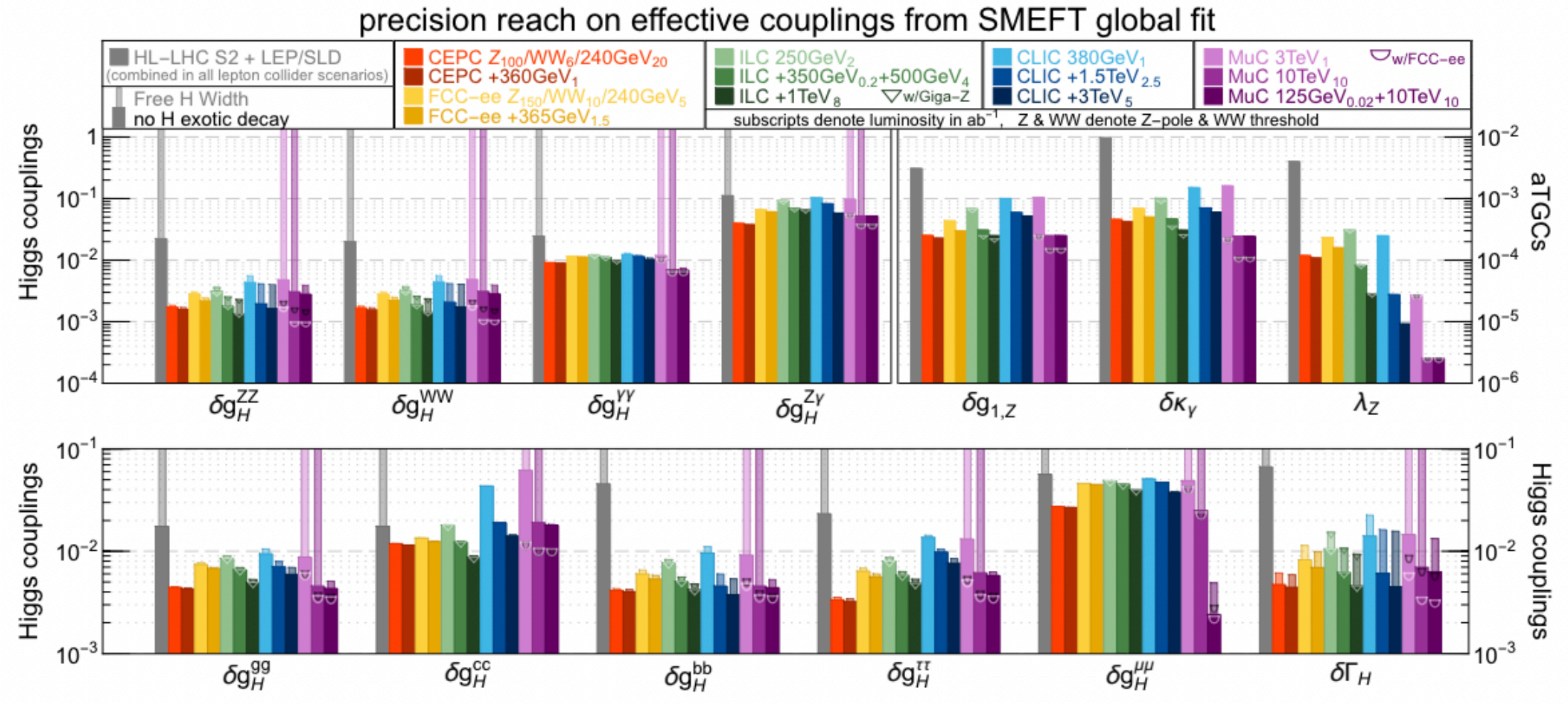


SOME HIGHLIGHTS FROM YOUR FEEDBACK

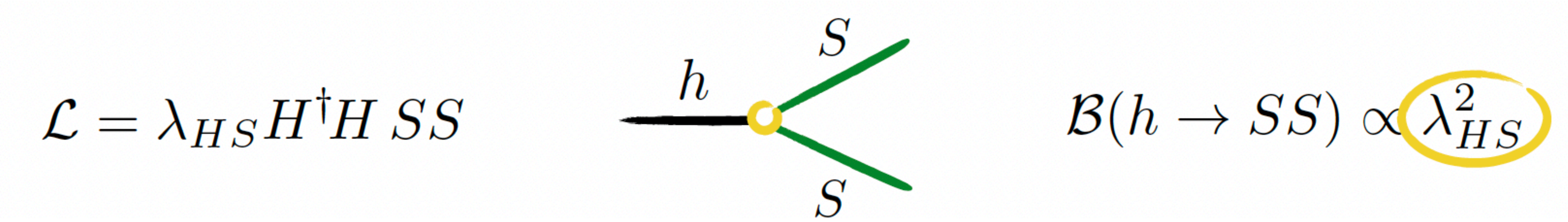
Highlighted in many of the responses

Discovery potential BSM

Precision measurements as a tool to probe new physics at high scales

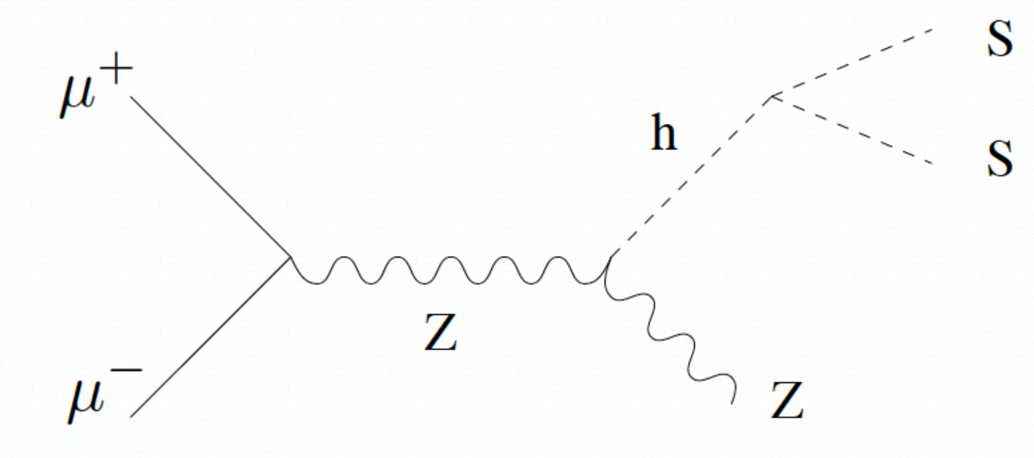


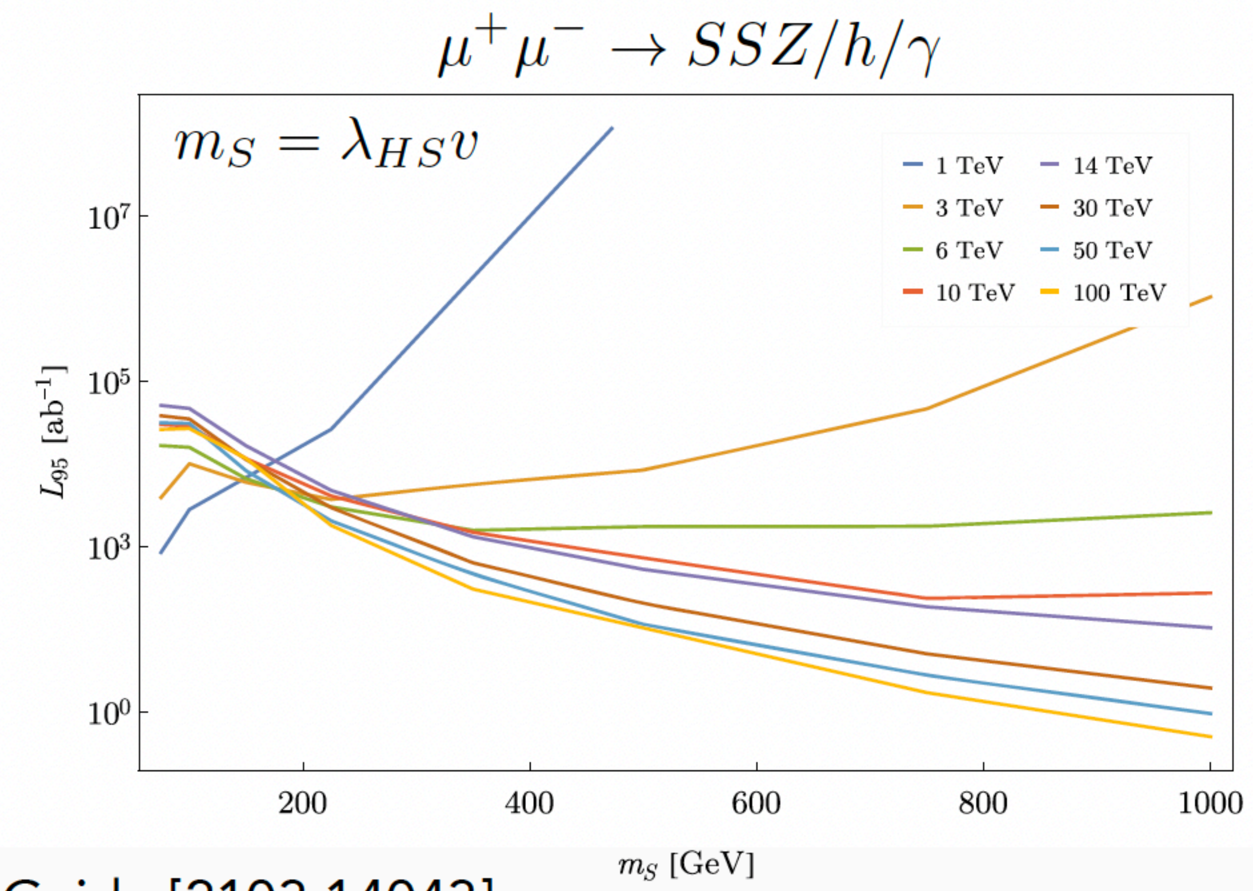
Jaco ter Hoeve



Potential to study large mass scalars

Muon collider:





Muon Smasher's Guide [2103.14043]

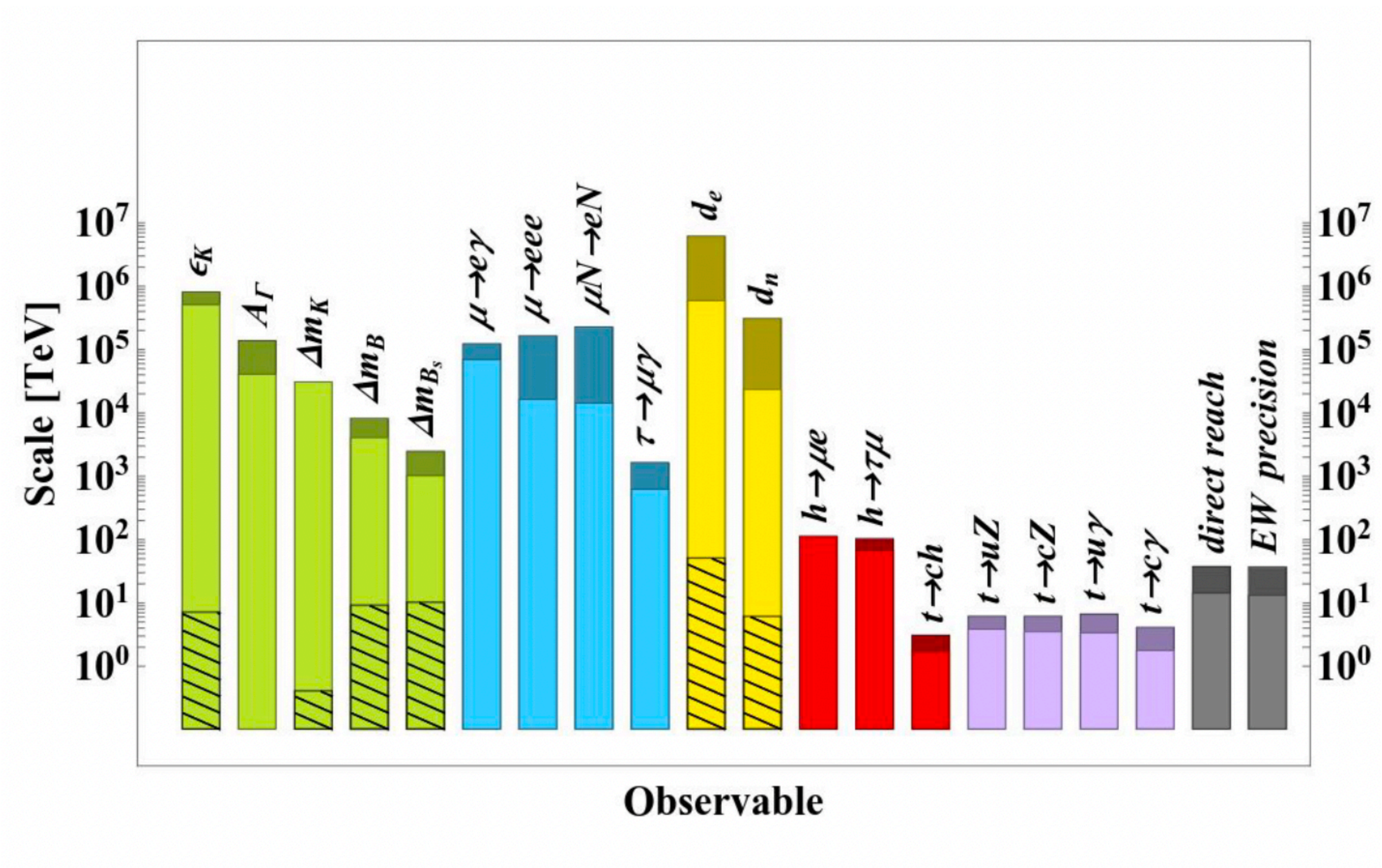
Susanne Westhoff

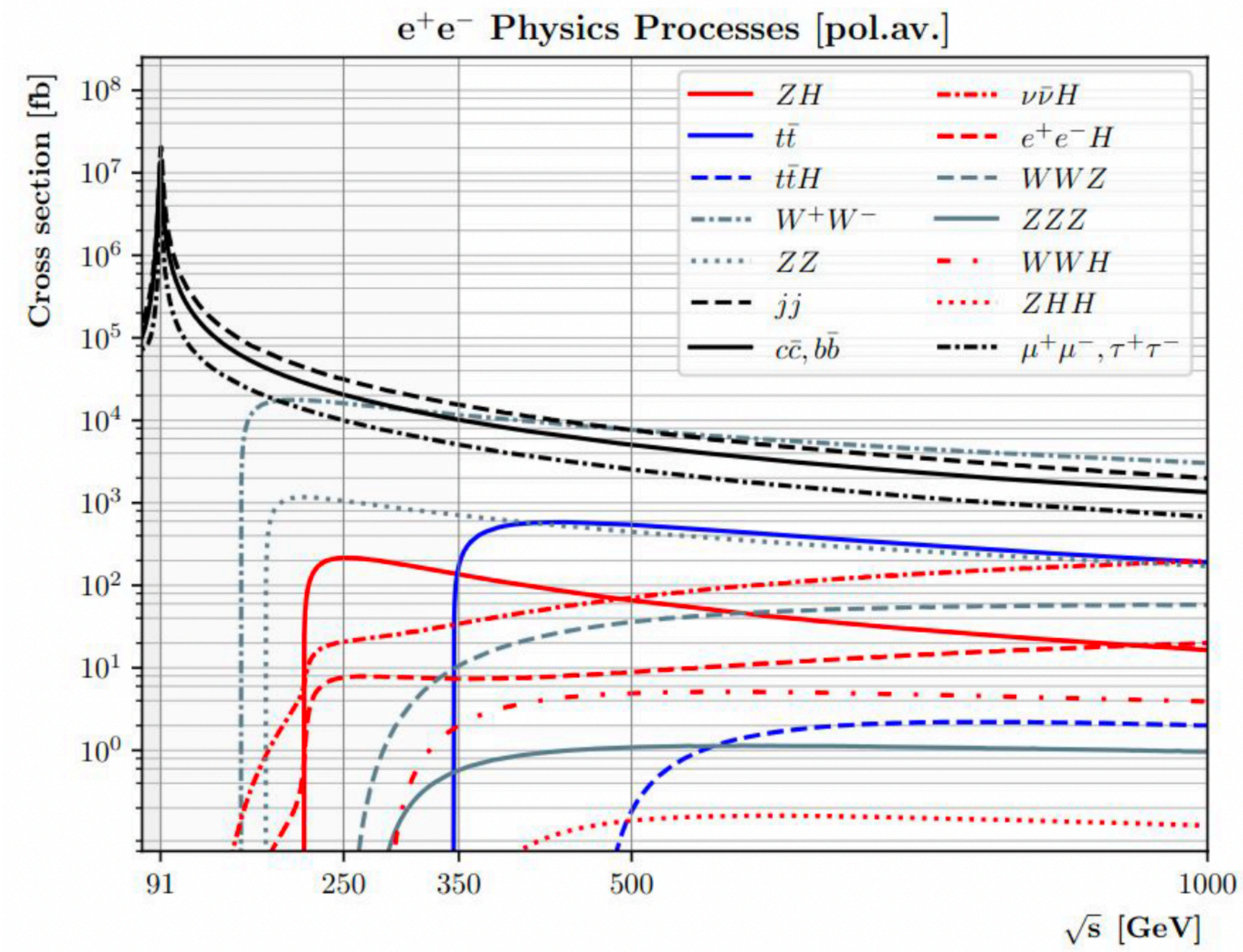
SOME HIGHLIGHTS FROM YOUR FEEDBACK

Highlighted in many of the responses

Flavour program

Detailed studies of flavour sector (lepton, light/heavy, neutrinos) + sensitivity large BSM mass scales and light DM





[ESPPU2020]

Not entirely clear how the flavour program can benefit from a future collider

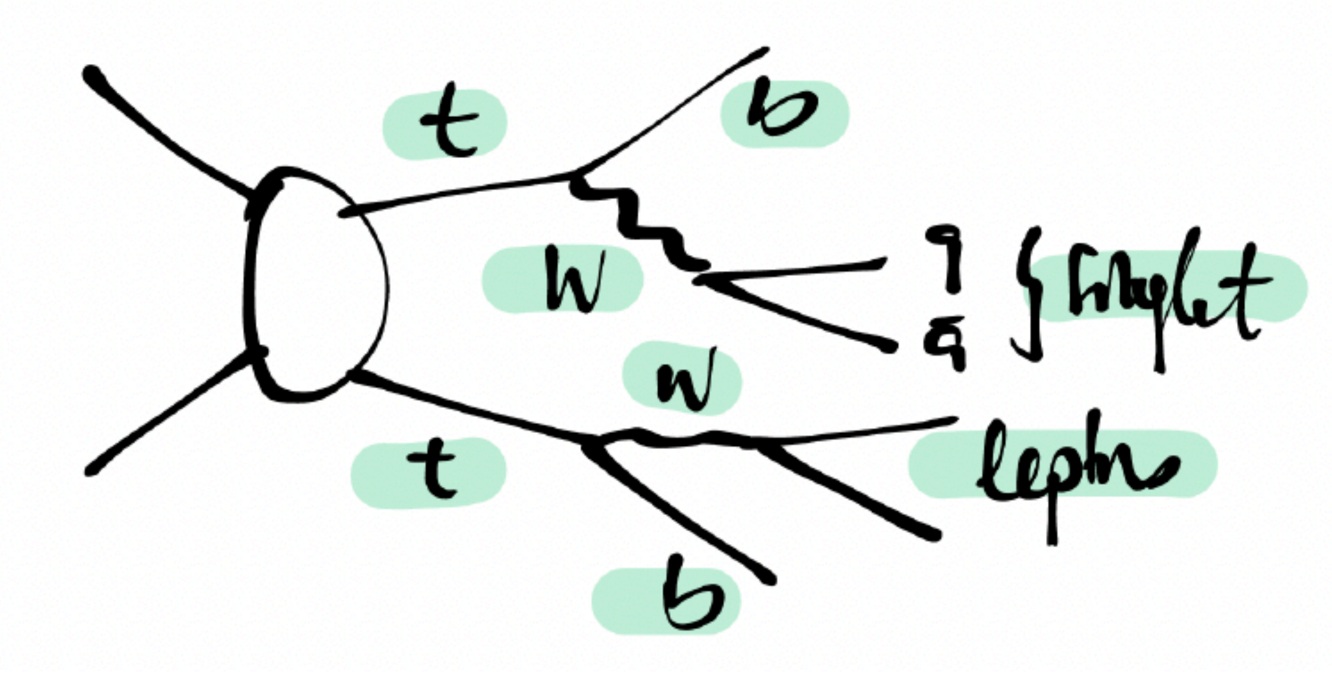
Ann-Kathrin Perrevoort

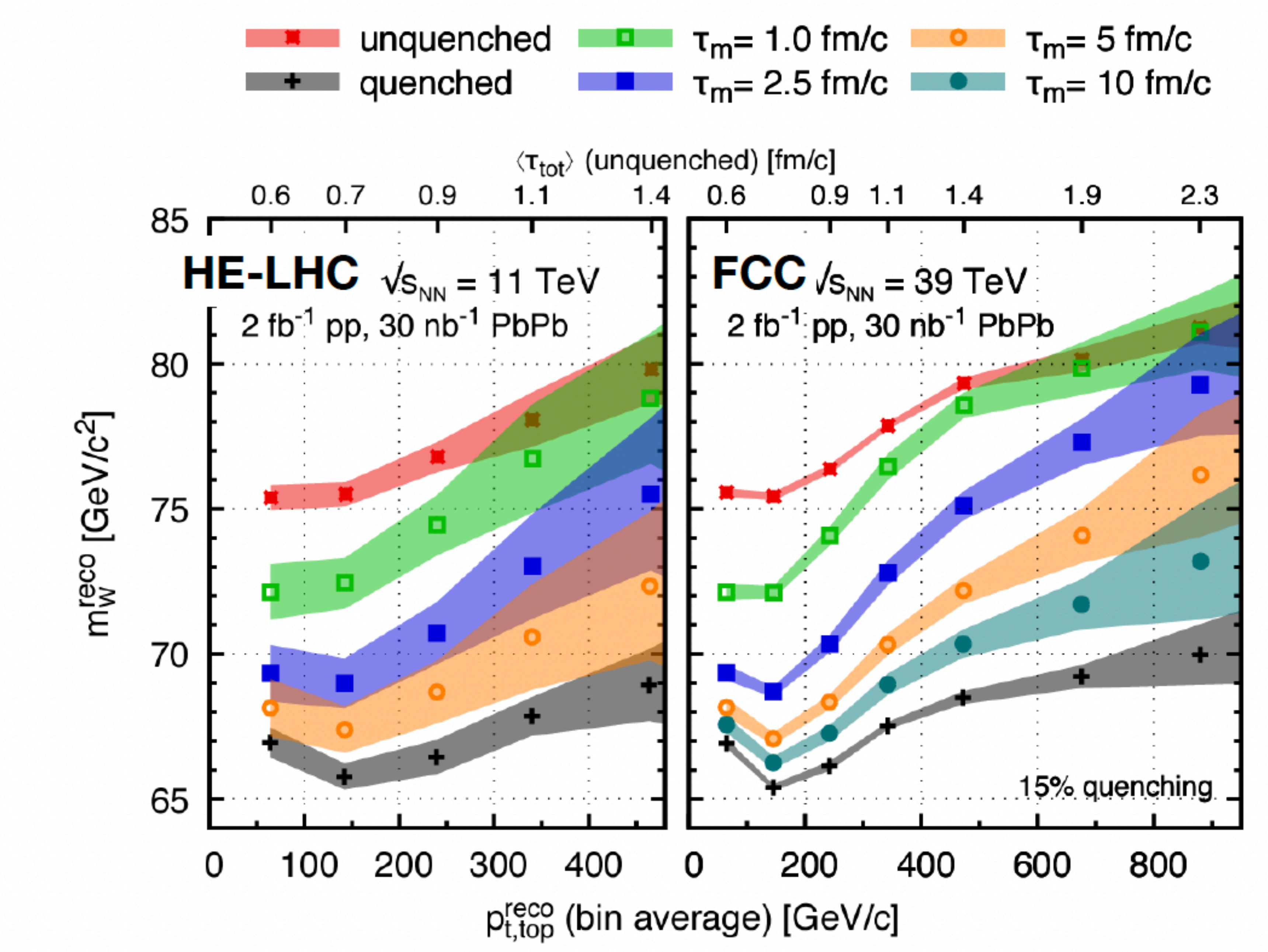
SOME HIGHLIGHTS FROM YOUR FEEDBACK

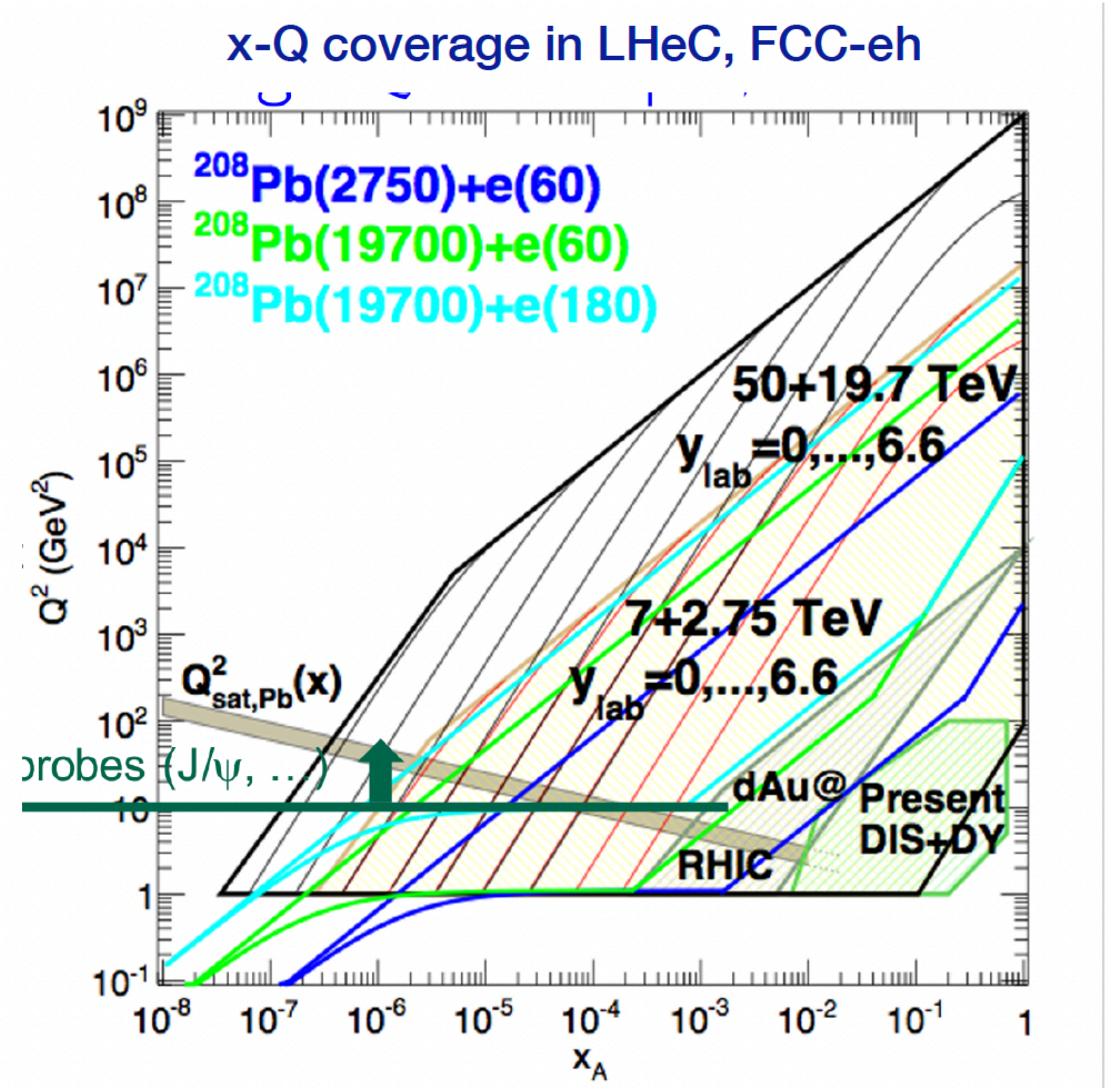
Highlighted in some of the responses

QCD studies + low-x physics

Use boosted tops to study the QGP







Uncharted low-x territory +
ep mode can be used for Higgs studies?

Marco van Leeuwen

SOME HIGHLIGHTS FROM YOUR FEEDBACK

Highlighted in some of the responses

Synergies

GW meet HIC

Article

Constraining neutron-star matter with microscopic and macroscopic collisions

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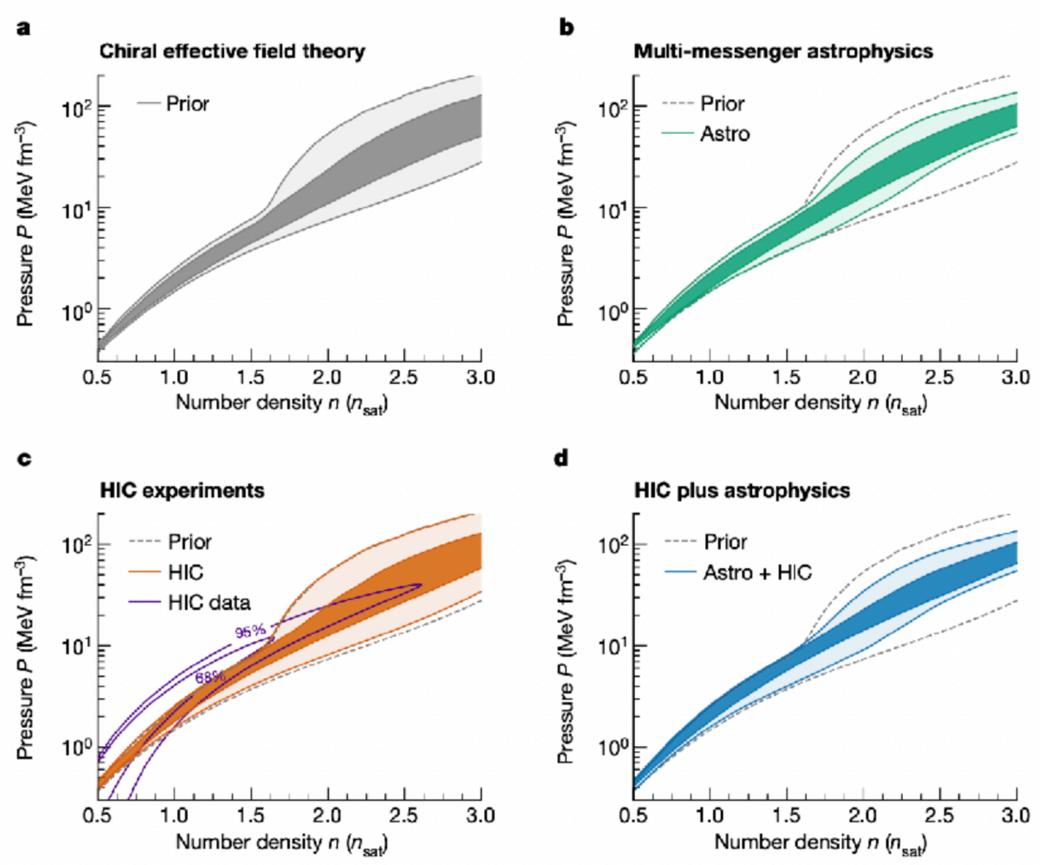
Check for updates

Sabrina Huth[1,2,13✉], Peter T. H. Pang[3,4,13✉], Ingo Tews[5], Tim Dietrich[6,7], Arnaud Le Fèvre[8], Achim Schwenk[1,2,9], Wolfgang Trautmann[8], Kshitij Agarwal[10], Mattia Bulla[11], Michael W. Coughlin[12] & Chris Van Den Broeck[3,4]

Interpreting high-energy, astrophysical phenomena, such as supernova explosions or neutron-star collisions, requires a robust understanding of matter at supranuclear densities. However, our knowledge about dense matter explored in the cores of neutron stars remains limited. Fortunately, dense matter is not probed only in astrophysical observations, but also in terrestrial heavy-ion collision experiments. Here we use Bayesian inference to combine data from astrophysical multi-messenger observations of neutron stars[1–9] and from heavy-ion collisions of gold nuclei at relativistic energies[10,11] with microscopic nuclear theory calculations[12–17] to improve our understanding of dense matter. We find that the inclusion of heavy-ion collision data indicates an increase in the pressure in dense matter relative to previous analyses, shifting neutron-star radii towards larger values, consistent with recent observations by the Neutron Star Interior Composition Explorer mission[5–8,18]. Our findings show that constraints from heavy-ion collision experiments show a remarkable consistency with multi-messenger observations and provide complementary information on nuclear matter at intermediate densities. This work combines nuclear theory, nuclear experiment and astrophysical observations, and shows how joint analyses can shed light on the properties of neutron-rich supranuclear matter over the density range probed in neutron stars.



Huth, S., Pang, P.T.H., Tews, I. *et al.* Constraining neutron-star matter with microscopic and macroscopic collisions. *Nature* **606**, 276–280 (2022). https://doi.org/10.1038/s41586-022-04750-w

- The ET project strongly benefits from CERN. Nikhef and CERN can benefit from ET. The ET leadership has a strong CERN background.
- We plan for ET to be visible during the CERN strategy update, and aim at a small change in the status quo. Our exact strategy is still to be decided. Input is very welcome!

Andreas Freise

SOME HIGHLIGHTS FROM YOUR FEEDBACK

Additional remarks:

- adaptability to new physics cases and new technologies
- sufficient resources to be available for new smaller experiments in addition to the major collider and for developing new enabling technologies
- Polarization studies?
- R&D studies for new accelerator directions
- Few other comments not directly connected to physics arguments…

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