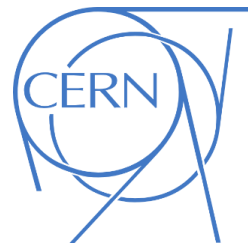


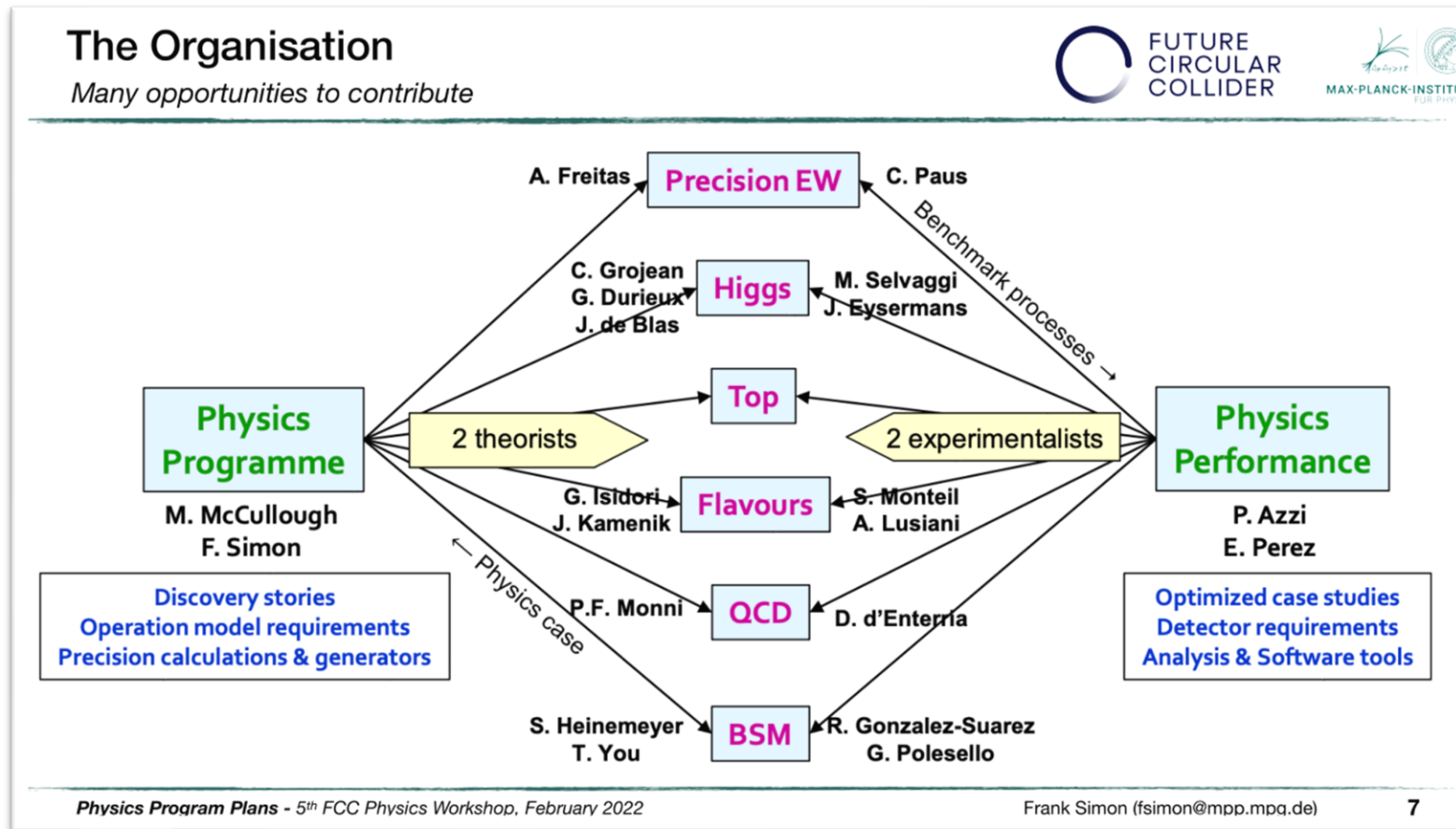
# BSM at FCC

Tevong You



# Introduction

- **FCC feasibility study** under way, to be reviewed/**completed** by end of 2023/**2025**

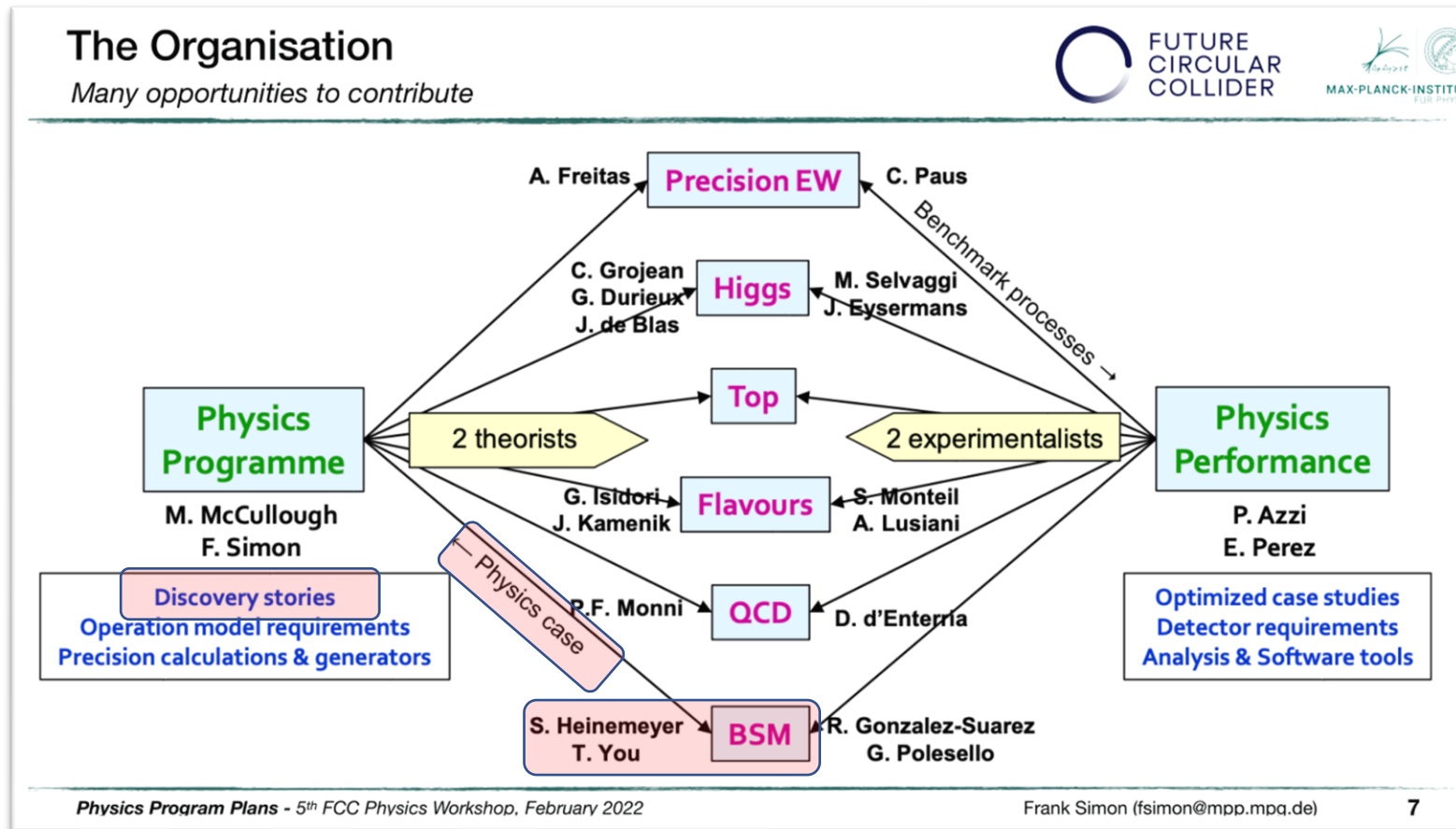


Slide by Frank Simon

- **Soliciting suggestions:** open invitation to get involved in **BSM at FCC** *at any level*

# Introduction

- **FCC feasibility study** under way, to be reviewed/**completed** by end of 2023/**2025**



Slide by Frank Simon

- **Soliciting suggestions:** open invitation to get involved in **BSM at FCC** *at any level*

# “Discovery stories” → “Exploring origins”

- What is the **purpose** of the FCC?

*To explore the fundamental origins of our universe and its laws*

- **Exploring**, not searching
  - “*Exploring the origins of our universe*” is a more accurate **mission statement**, unlike e.g. “*searching for supersymmetry and dark matter*”
  - “*Exploring the origin of the Higgs*” simpler to convey than **naturalness**
- “*Discovery stories*” risks putting the focus on *promising* to **find new physics**
- “*Exploring origins*” puts the focus on **open BSM questions** to be answered
  - Emphasises the FCC as a **general purpose particle observatory** with a *wide-ranging physics programme*, rather than as an expensive search for supersymmetry

# FCC as an origins explorer

- **Origin of matter**
  - EW phase transition, CP violation, baryogenesis, etc.
- **Origin of the Higgs**
  - BSM in post-naturalness era, supersymmetry, compositeness, etc.
- **Origin of flavour**
  - BSM flavour models, B anomalies,  $g-2$ , etc.
- **Origin of dark matter**
  - Including dark sectors more generally
- **Origin of neutrinos**
  - BSM neutrino models, neutrino portal, etc.
- **Origin of the Standard Model**
  - SM is an EFT of an underlying UV theory that it originates from: SMEFT (or HEFT)

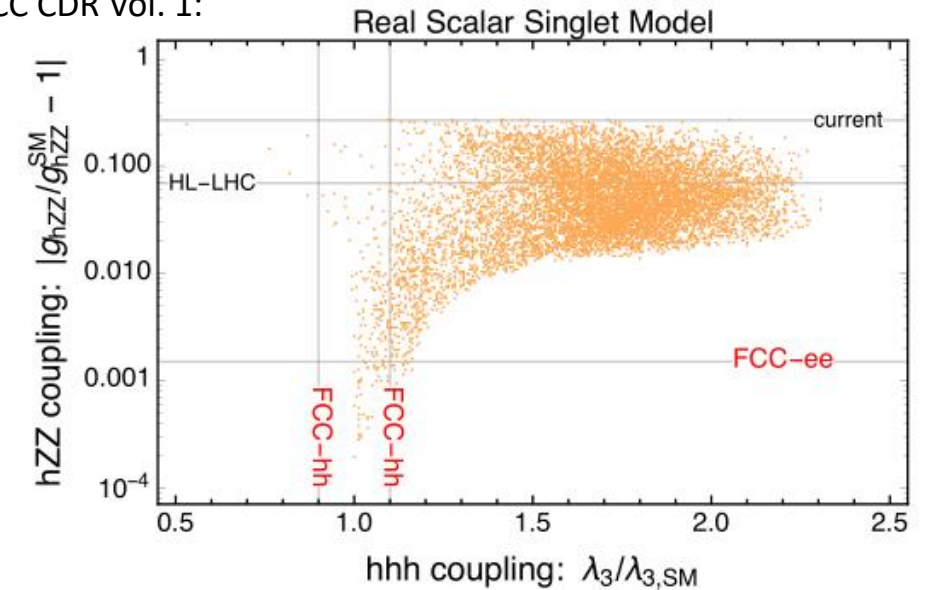
# Origin of ...

- For each category, identify:
  - **Open questions**
  - **BSM models**
  - **Observables**
  - **Connections to other working groups**
  - **Potential names**
    - No commitment at this stage, just identifying those who may be interested
    - Various levels of potential involvement, from discussions to contributing studies

# Origin of matter

- Open question
  - *matter-antimatter asymmetry*
- BSM models:
  - Higgs+singlet first-order **EW phase transition**
  - *New sources of CP violation*  
e.g. 2112.03889 Bonnefoy, Gendy, Grojean, Ruderman
  - **Baryogenesis/Leptogenesis**  
e.g. 2203.05010 Snowmass white paper:
- Observables:
  - Higgs (self-)couplings, exotics, LFV, etc.
- Connection to other working groups:
  - Higgs, precision EW, top, flavour

FCC CDR Vol. 1:



## New physics ingredients

### B/L violation

Dark baryons  
RPV terms  
Sphalerons  
Direct B/L violation

### CP violation

Axions  
CKM phase  
Oscillations  
DM oscillations  
DM chemical potential  
CPV couplings

### Out-of-equilibrium conditions

Freeze-in processes  
Long-lived particles  
QCD phase transition  
EW phase transition  
Particle decays

## Observables

LLP searches    exotic hadron decays    same-sign dilepton asymmetry  
new SU(3)-charged particles    new scalar-Higgs mixing    same-sign tops  
 $0\nu\beta\beta$  decay    missing momentum    induced nucleon decays    Higgs triple coupling  
lepton flavor violation    multijet signals    CPV observables at B factories + LHCb  
gravitational waves    structure formation    X-ray signals     $n - \bar{n}$  oscillations

## Scales

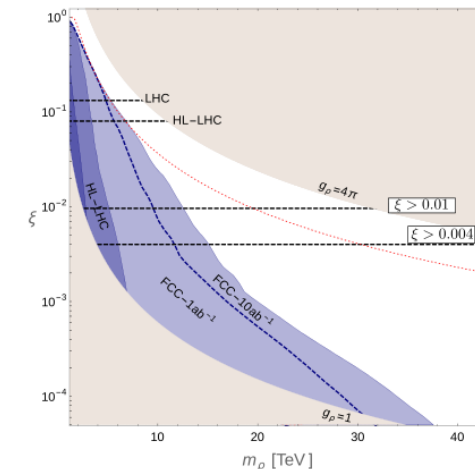
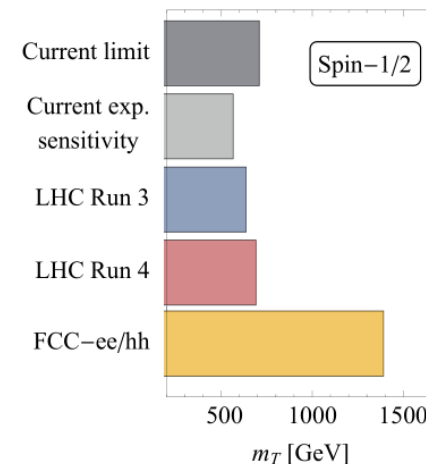
$\mu\text{eV}$     keV    MeV    GeV    TeV

axions    dark matter    neutral meson oscillations  
mesino oscillations    dark baryons    pseudo-Dirac fermions  
WIMPs    New QCD transition  
dark matter     $n - \bar{n}$  oscillations

# Origin of the Higgs

- Open question

- Is the Higgs **composite** or **elementary**?
- Are there **extra spacetime symmetries** or **dimensions**?
- Do these concepts play a role in *addressing the naturalness problem*?
- Is a **new principle** at play in the Higgs sector?



FCC CDR Vol. 1,  
Thamm, Torre, Wulzer, 1502.01701

- BSM models:

- Conventional **symmetry-based** solutions: *e.g. supersymmetry, compositeness/extra-dimensions*
- **Hidden** symmetry-based solutions: *e.g. Twin Higgs* e.g. 2202.01228 Durieux, McCullough, Salvioni
- **Post-natural** BSM
  - i.e. *accept large hierarchy of scales*, whether **accidental** or natural via **cosmological dynamics** or some **UV/IR mechanism**
  - *Split supersymmetry, relaxion, self-organised localisation, vacuum metastability, ...*

e.g. 2105.08617 Giudice, McCullough, TY  
2108.09315 Khoury, Steingasser

- Observables:

- Higgs (self-)couplings, SUSY searches, exotics, VL fermions, BSM triple Higgs couplings ...

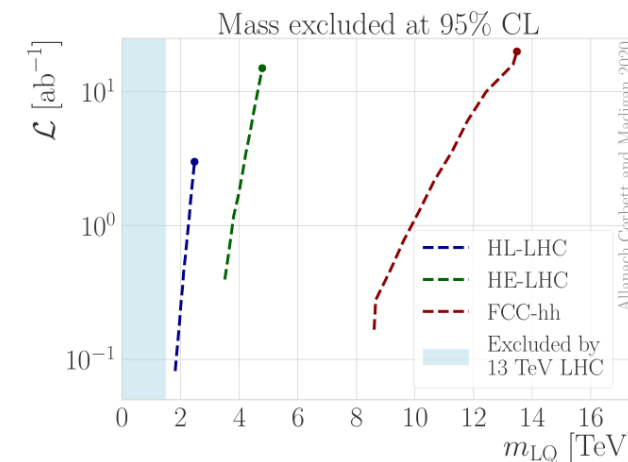
- Connection to other working groups:

- Higgs, precision EW, top, flavour

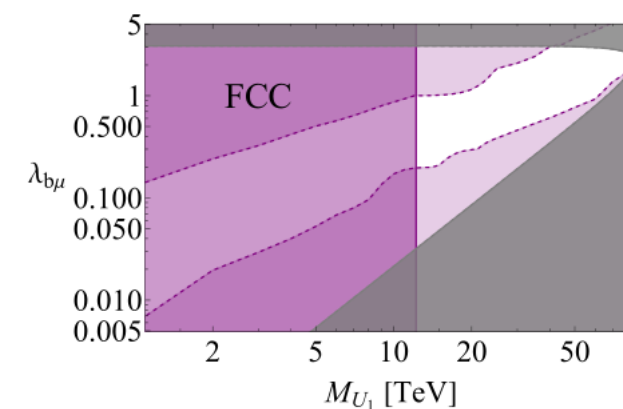


# Origin of flavour

- Open question
  - *Structure of Yukawas and CKM?*
- BSM models:
  - Models addressing **B anomalies** and **muon g-2**
  - *Z', leptoquarks, VL fermions*
- Observables:
  - Higgs (self-)couplings, light yukawas, flavour, top, dileptons, etc.
- Connection to other working groups:
  - Higgs, precision EW, top, flavour, QCD



Allanach, Corbett, Madigan [1911.04455]



Azatov et al [2205.13552]

# Origin of dark matter

- Open question

- What is the **microscopic particle nature** of dark matter?
- Is there an **extended dark sector**?

- BSM models:

- **Higgsino**, **winos**, more general WIMPs
- **Higgs portal**
- **ALPs**

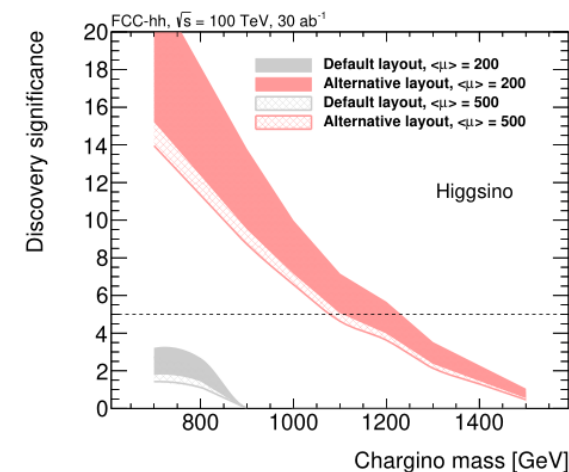
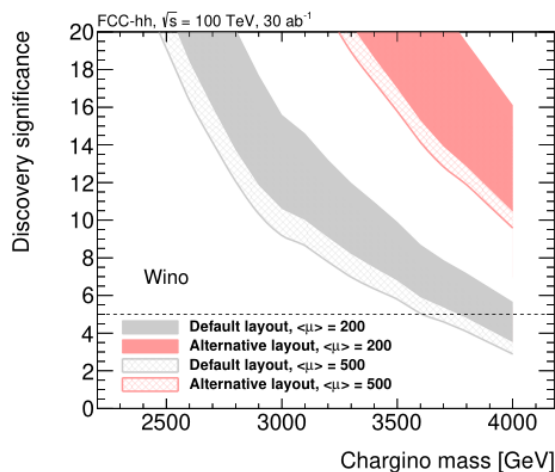
- Observables:

- Higgs (self-)couplings, Higgs invisible decays, MET, LLPs (**SND/FASER@FCC?**), etc.

- Connection to other working groups:

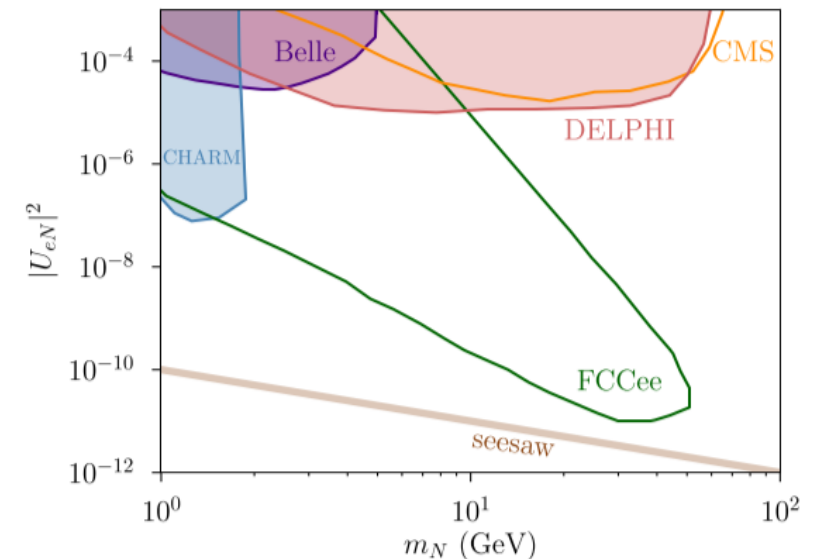
- Higgs, precision EW

FCC CDR Vol. 1:



# Origin of neutrinos

- Open question
  - Is there an **extended neutrino sector**?
- BSM models:
  - *Symmetry-protected pseudo-Dirac neutrinos*, low type-I **see-saw**?
  - Connection to **leptogenesis, Higgs, dark sectors**?
- Observables:
  - Higgs decays, final state leptons, exotics, LLPs, ...
- Connection to other working groups:
  - Higgs, precision EW



# Origin of the SM

- Open question
  - What is the **scale of the underlying theory** that *the SM originates from*?
  - Is the Higgs EFT **linearly** or **non-linearly** realised?

- BSM models:

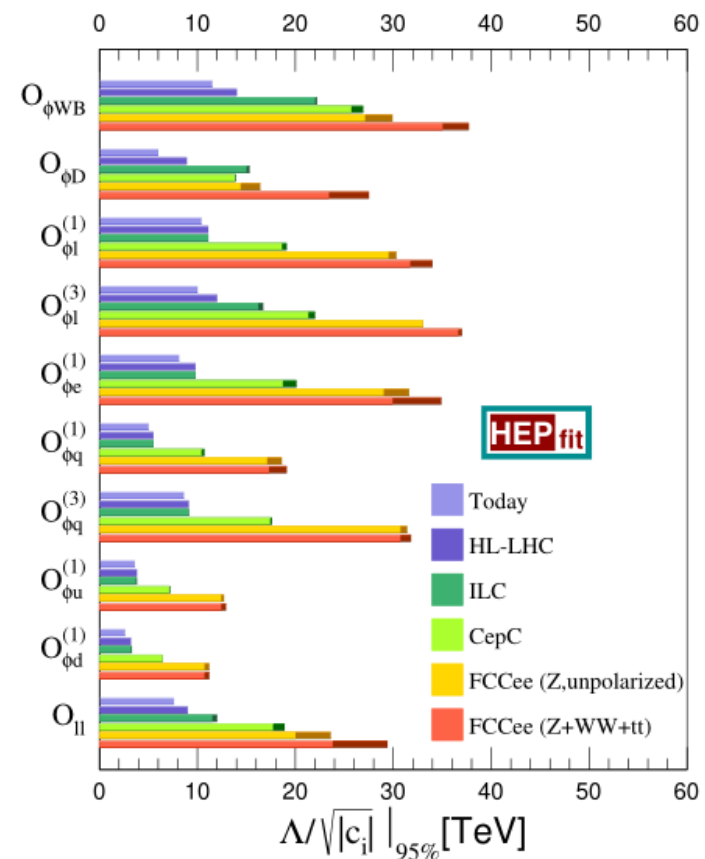
- **SMEFT** and **HEFT** frameworks
- Simplified UV-completion models
- **Loryons** e.g. 2110.02967 Banta, Cohen, Craig, Lu, Sutherland
- **Positivity**, *BSM beyond EFT/QFT?*, ...  
e.g. 2011.03055 Gu, Wang, Zhang

- Observables:

- Higgs (self-)couplings, longitudinally polarized vector bosons, multi-bosons, direct searches, etc. e.g. 1812.09299 Henning, Lombardo, Riemann, Riva

- Connection to other working groups:

- Higgs, precision EW, top, flavour, QCD



1611.05354 de Blas et al

# Conclusion

- 1900: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness.*
- 1920s: A combination of **precision measurements** (Mercury), **aesthetic arguments** (relativity) supported by **null experimental results** (Michelson-Morley), and **theoretical inconsistencies** (Rayleigh-Jeans UV catastrophe) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

# Conclusion

- 2020: Almost all data agree spectacularly with the fundamental framework of the time, *no reason to doubt its universal applicability or completeness.*
- 2050s: A combination of **precision measurements** (B mesons, Hubble), **aesthetic arguments** (naturalness) supported by **null experimental results** (LHC), and **theoretical inconsistencies** (black hole information paradox) lead to an overhaul of the fundamental picture at **smaller scales** and **higher energies** after *pushing the frontiers of technology and theory into new regimes.*

# Conclusion

- **FCC is *vital* to the future of fundamental physics**
  - *No realistic alternative to FCC-ee+hh combined physics x feasibility*
- **Preliminary categorisations**, to be discussed and refined
  - Emphasise *narrative*, not models
- *Novel* **BSM benchmarks?**
- **Observables** to be identified more systematically
- **FCC BSM workshop** at CERN: tentatively September 15-16<sup>th</sup>
  - FCC BSM e-group mailing list:

<https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-BSM>