ESPPU Open Symposium Physics Summary I: SM measurements, indirect searches, neutrino physics, flavour physics

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Nikhef ESPPU-NL Strategy Meeting, September 16th 2025

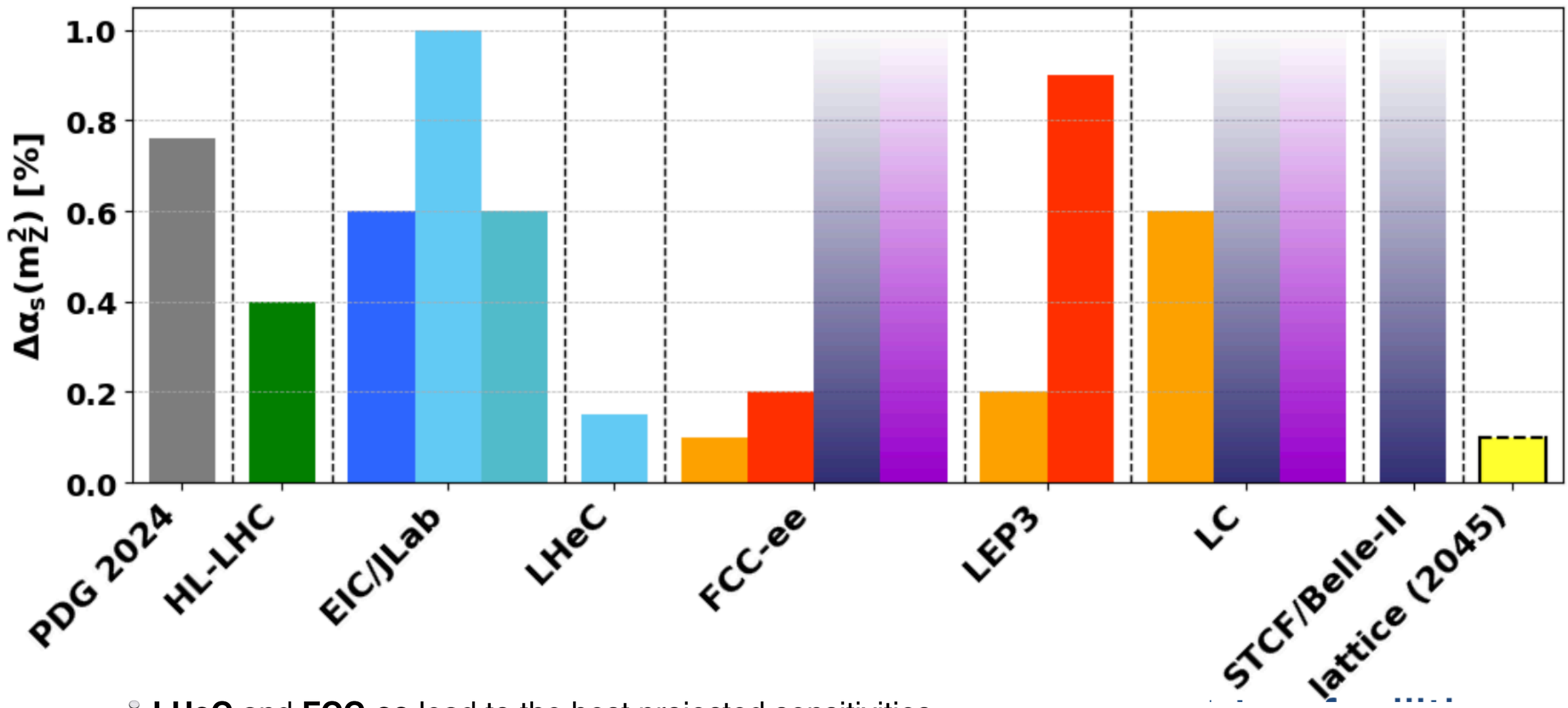
SM Measurements

***Sources**:*

- ``*The Electroweak physics landscape beyond the LHC: Open questions and exploration at future colliders"* (M. Dunford) https://agenda.infn.it/event/44943/contributions/263361/attachments/137560/206780/2025_06_22_Venice.pdf
- ``*Open questions and experimental prospects: precision QCD & internal structure of protons and nuclei"* (C. Diaconu) https://agenda.infn.it/event/44943/contributions/263364/attachments/137571/206899/V14_DIACONU_SI_VENICE2025.pdf
- ` `*Open questions and experimental prospects: hot and dense QCD & QCD connections to hadronic, nuclear and astrophysics"* (A. Dainese), https://agenda.infn.it/event/44943/timetable/#20250625.detailed:~:text=Dainese_ESPP_Jun2025.pdf

Strong coupling

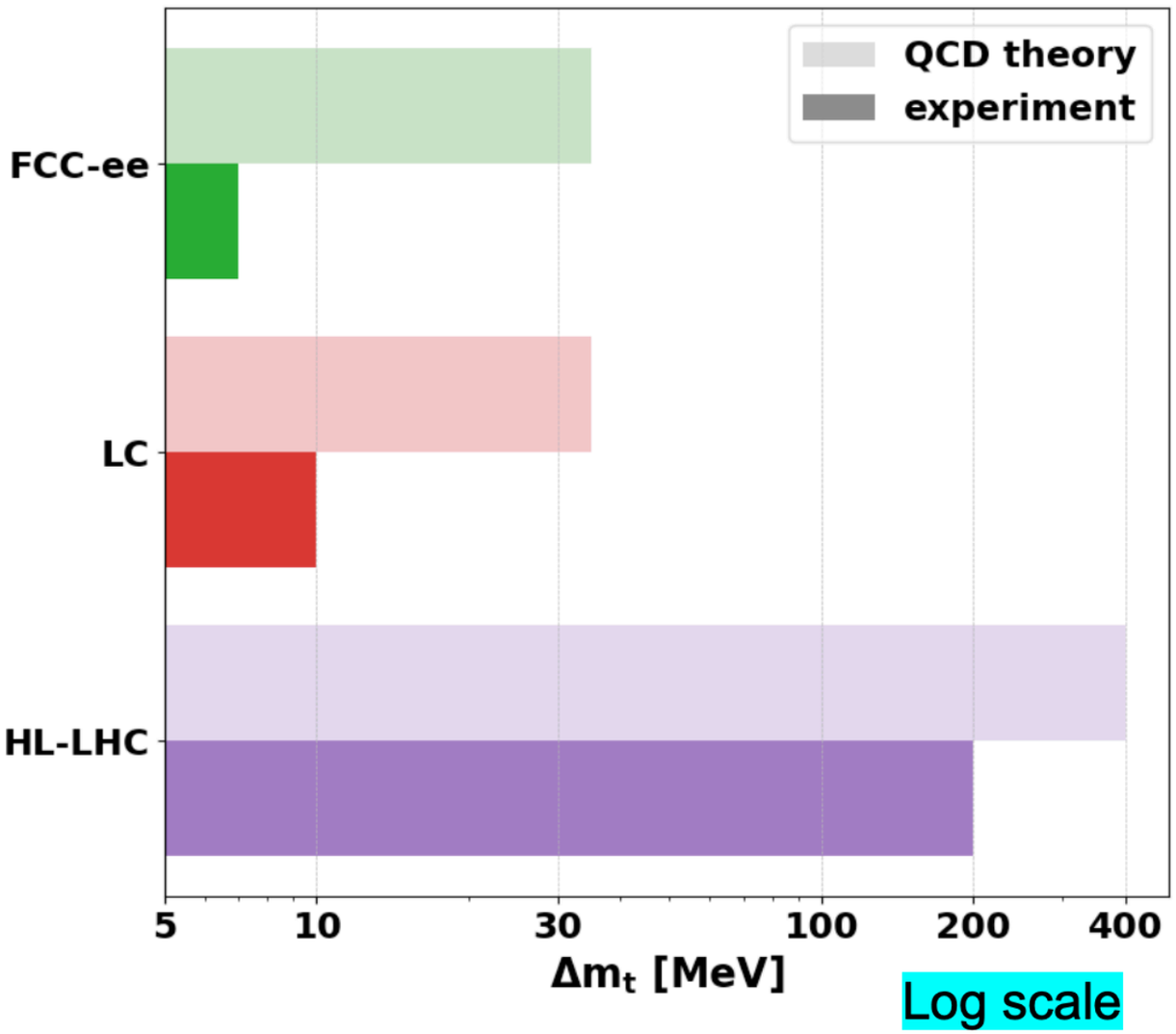
- Fundamental SM parameter, **worst known** of all fundamental interaction couplings



- **LHeC** and **FCC-ee** lead to the best projected sensitivities
- Will we need to measure the strong coupling at all, given progress in **lattice QCD**?

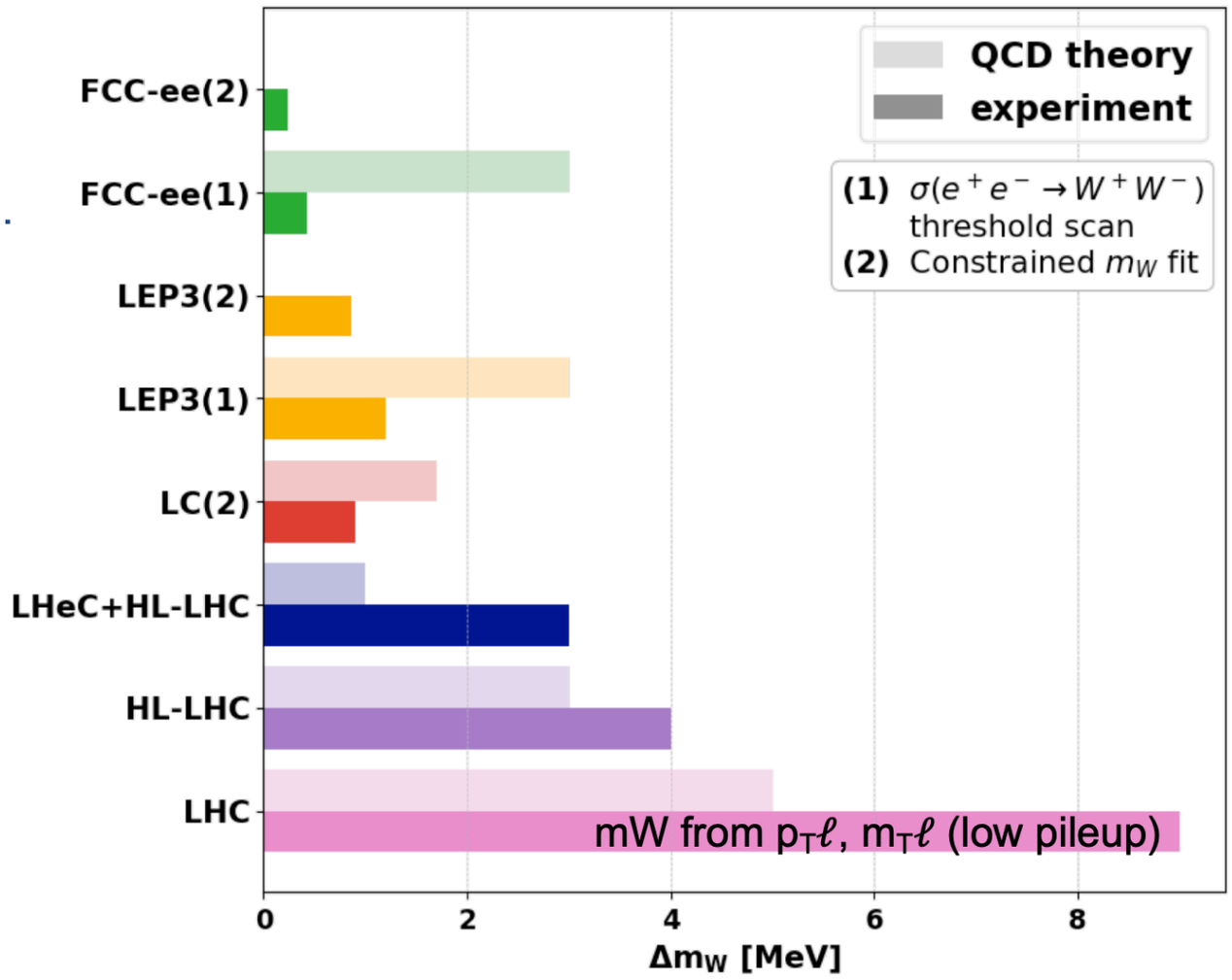
n.b. lattice QCD **assumes the SM**, which may not be true at high energies

Top quark and W boson masses



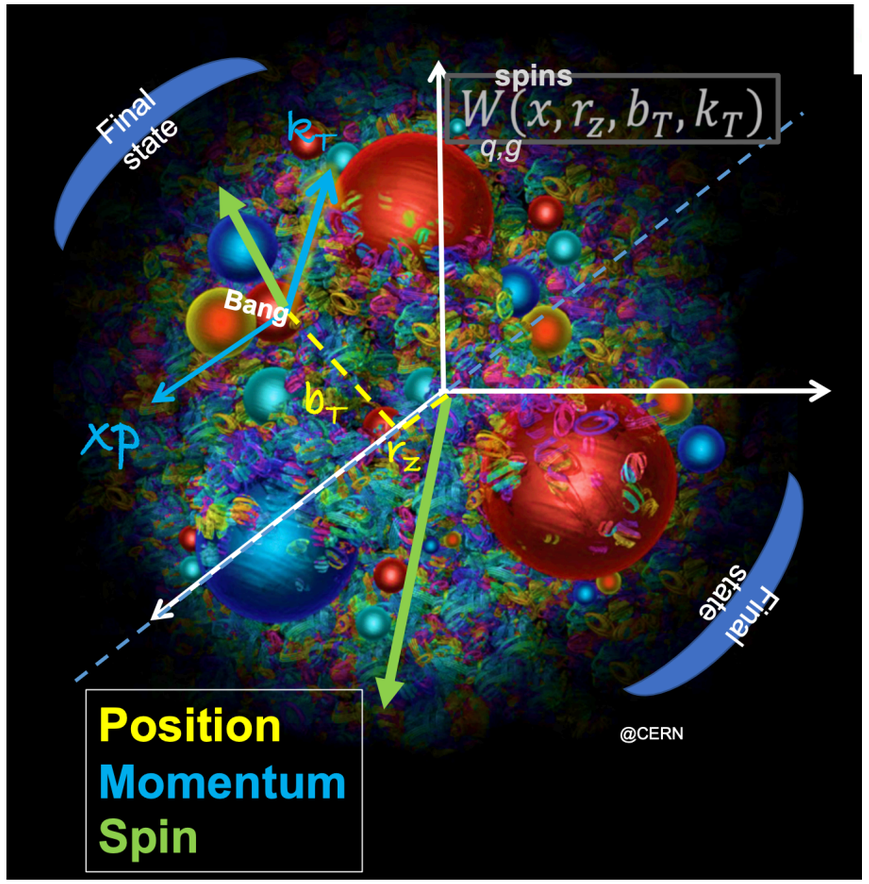
Log scale

- Crucial to study **EW vacuum stability**
- At hadron colliders, sensitivity limited by **non-perturbative physics**
- Lepton colliders require r**un at > 365 GeV**, which would take place at a second stage after Higgs/EW runs

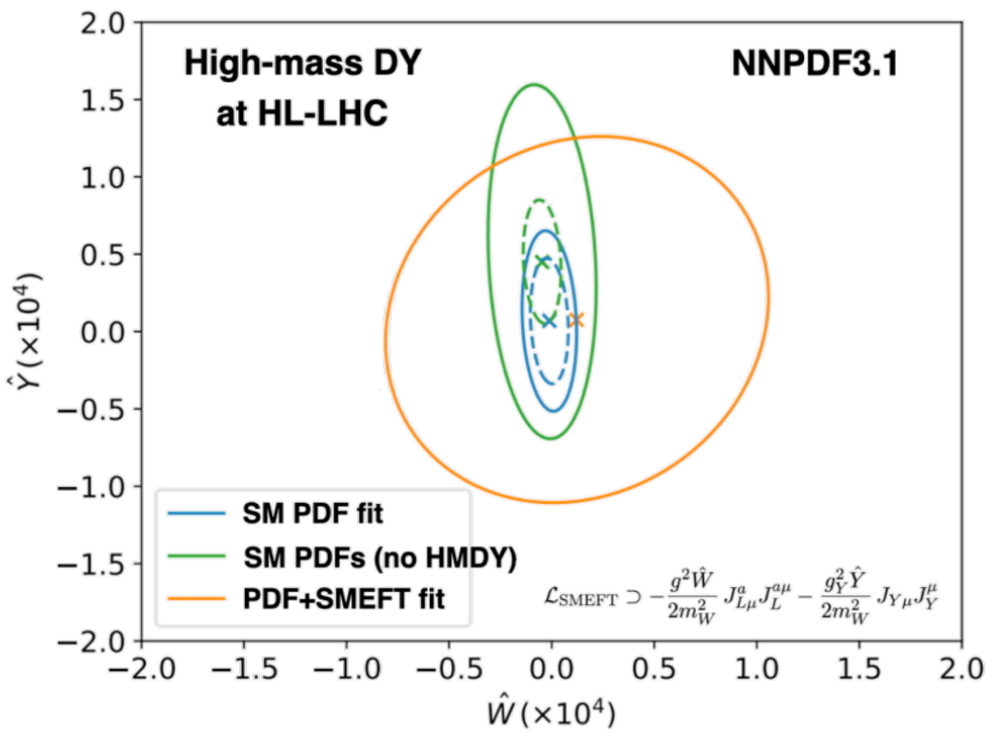


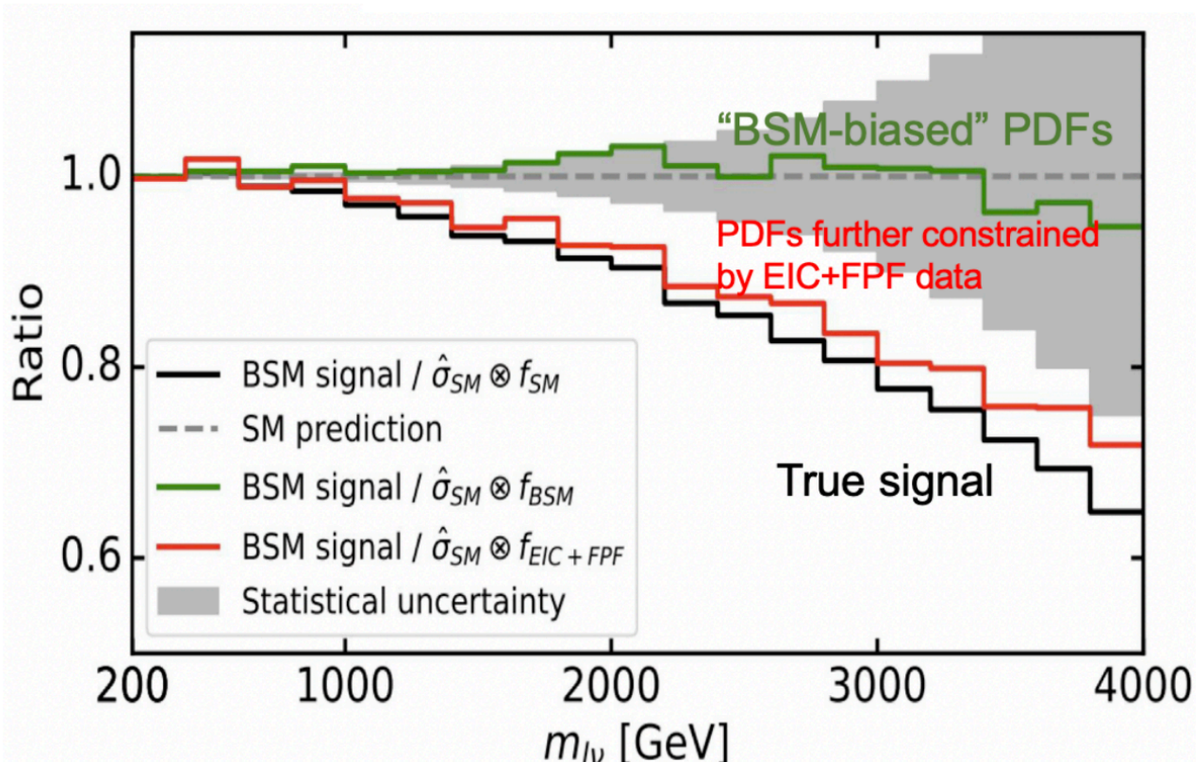
- LHC measurements limited (now) by PDFs
- Ultra-clean measurements at FCC-ee from **161 GeV threshold run**

Proton structure



- Determined by **non-perturbative QCD dynamics**
- Limiting factor for **many measurements at hadron colliders**, both for SM parameters and for **New Physics searches** in SMEFT-like scenarios
- Resolving proton structure interesting on its own to **unravel new phenomena in the strong force**





Proton structure

Quantity or question/ experiment	LHC in fixed target mode D, B, quarkonium, light hadrons	(HL)LHC in collider mode D, B, quarkonium, light hadrons, UPCs, DY	Alice FoCal Photons and jets	SHiP ν flux from charm, NC and CC DIS	EIC NC, CC and jets in DIS, light and heavy flavour ID, exclusive diffraction	FPF ν flux from charm, NC and CC DIS	LHeC NC, CC and jets in DIS, heavy flavour ID, exclusive diffraction	FCC-ee/ LEP3/ CEPC/LC FFs of light and heavy quarks, jets, γγ	MuCol ν flux from muons	FCC-hh D, B, quarkonium, light hadrons, UPCs, DY
PDFs		Most information available	Simultaneous fits of proton and nuclei	Simultaneous fits of proton and nuclei; F_4, F_5	Covered by HERA	Simultaneous fits of proton and nuclei; F_4, F_5			Simultaneous fits of proton and nuclei	Kinematic reach
nPDFs		Most information available	Region overlapping with current pPb							Kinematic reach
TMDs		DY, jets	Little PID			No prospects	Little PID in current project	FFs needed for PDFs, and TMD in jets		DY, jets
GPDs		Currently UPCs	No prospects			Little PID in current project				Currently UPCs
Small-*x* dynamics	Large x needed for small x			Large x needed for small x	Kinematic reach	Kinermatic reach		γγ	Large x needed for small x	

Dark green: Highest precision/breadth; Light green: strong/focussed contributions; White: no contribution.

- For PDF and QCD (and many electroweak!) measurements, **LHeC is the best future machine**
- Competitive **QCD programs at CERN** with FASER/FPF, LHC Fixed Target, and ALICE/FoCal
- Some uncertainty concerning **EIC prospects** related to funding situation in US

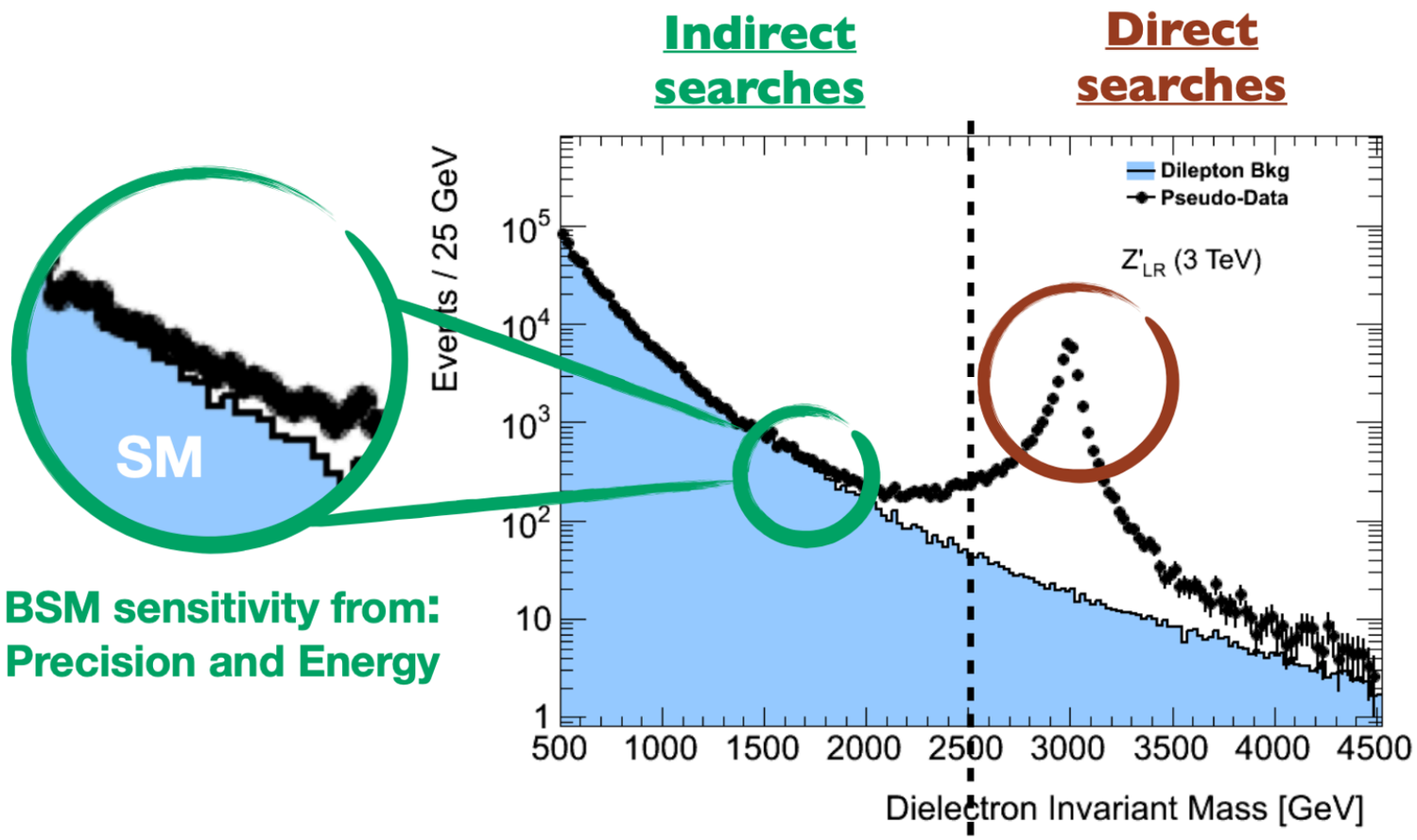
Indirect Searches

***Sources**:*

- ``*Characterisation of the Electroweak sector at future colliders: Comparative assessment"* (J. De Blas), https://agenda.infn.it/event/44943/contributions/263362/attachments/137561/207437/Future_Collider_Comparison.pdf
- ``*Status and open questions in the search for Physics Beyond the Standard Model"* (F. Maltoni), https://agenda.infn.it/event/44943/contributions/263370/attachments/137615/206938/Strategy-Maltoni-BSM-final.pdf

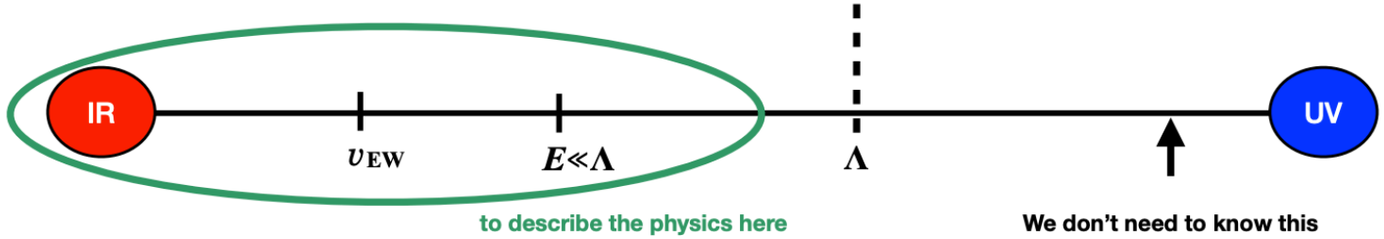
Indirect searches

- Here ``**indirect searches**'' = ``**SMEFT-based**'' analysis
- This includes constraints on UV-complete models (e.g. composite Higgs) arising from precision measurements rather than direct searches: IR and UV physics connected via **EFT matching**
- **SMEFT settings** adopted by PPG not unique, other choices possible (and results may depend on these)

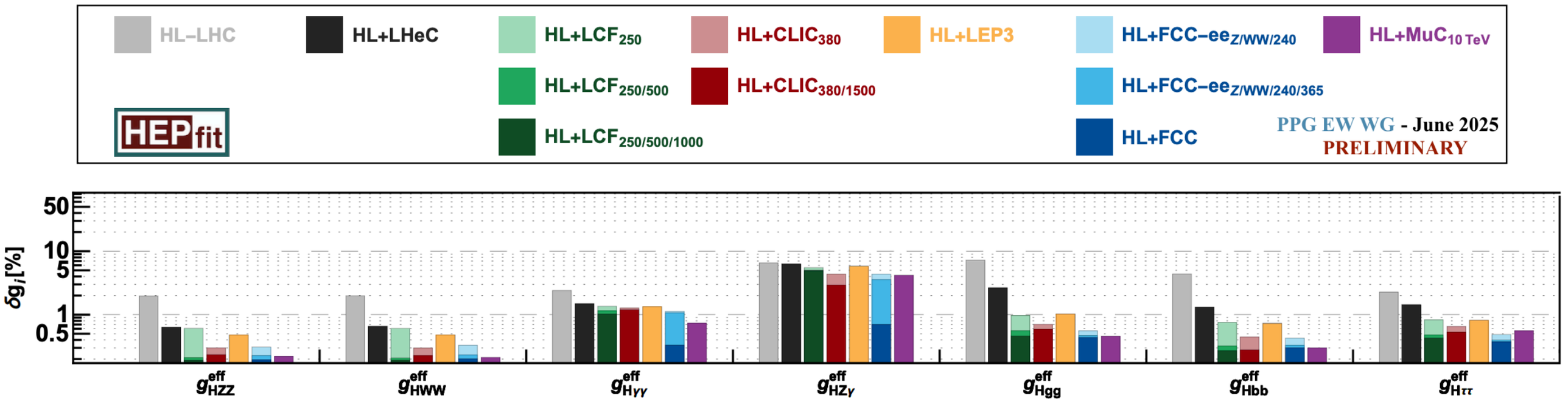


Global SMEFT fit challenging to digest with **O(100) operators**, select highlights

$$\mathcal{L} = \mathcal{L}_{\mathrm{EFT}}(\supset \mathcal{L}_{\mathrm{SM}}) \qquad \mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{NP}} + \mathcal{L}_{\mathrm{NP-SM}}$$



Higgs couplings

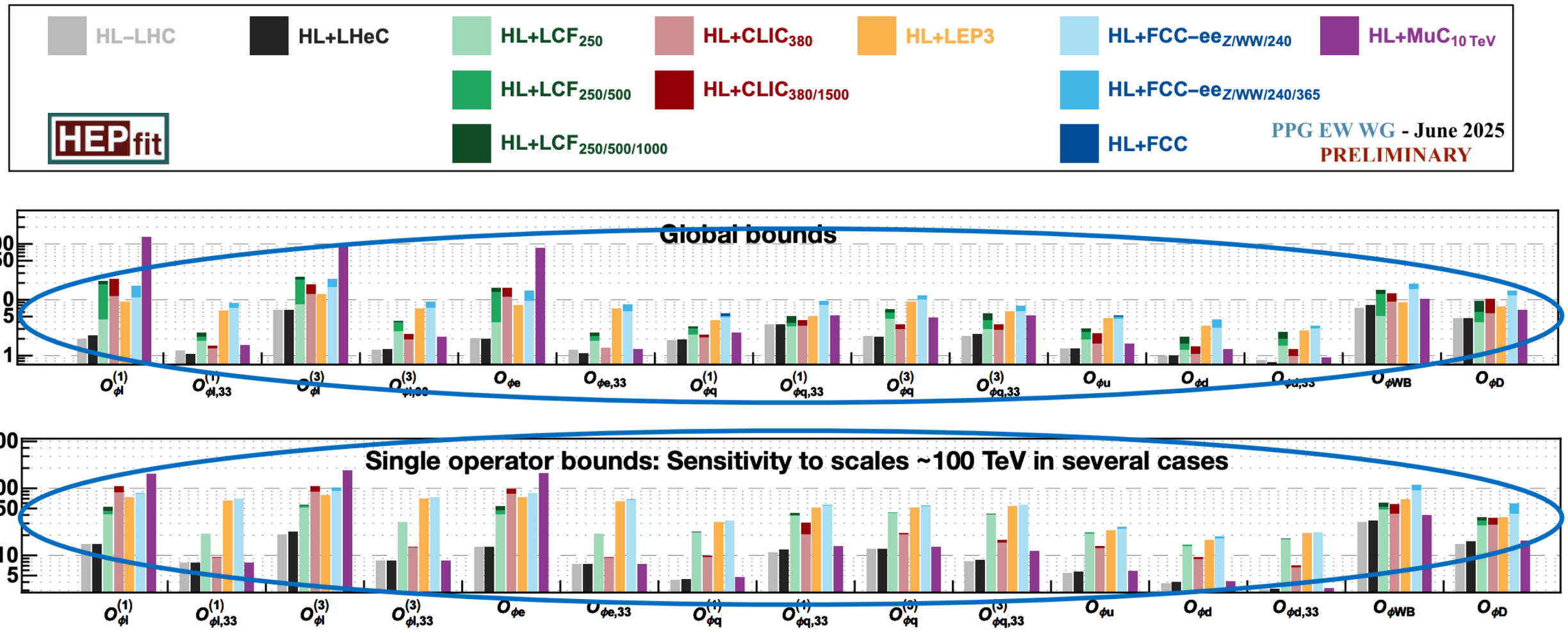


- Effective couplings defined in terms of SMEFT operators
- Close correspondence with direct measurements *e.g.* branching fractions

- The **integrated FCC program** leads to the best global sensitivity
- For LCF, higher energy runs are requires to be competitive for most couplings
- LEP3 is a competitive, affordable Higgs factory
- LHeC improves many of the Higgs couplings (ZZ, WW, bb, tau tau) as compared to HL-LHC

Take into account that each future colliders (scenario) may have **very different timescales**

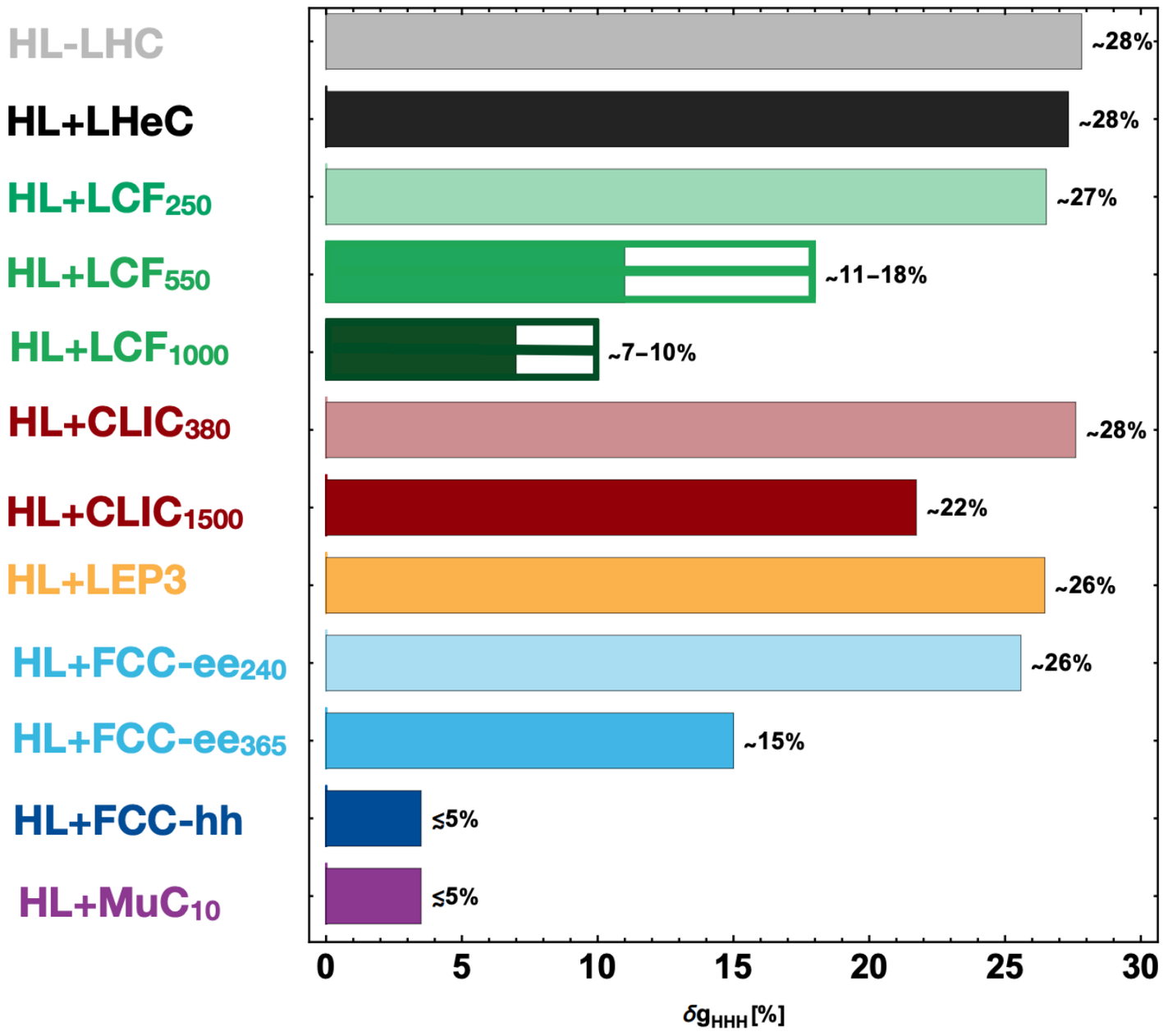
Electroweak interactions

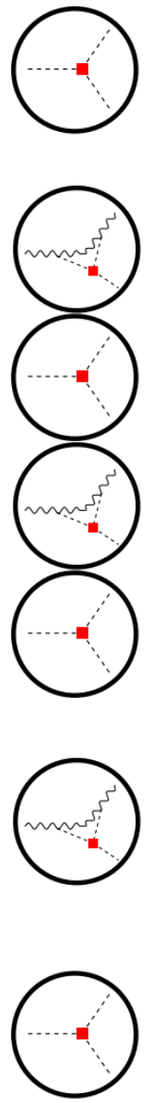


SMEFT fit results for individual and global (multiple operator fits)

- The **integrated FCC program** leads to the best global sensitivity *(no Tera-Z at LCF)*
- MuCol dominates in scenarios where New Physics **couples to the 2nd generation or universally**
- LEP3 not dramatically different than FCC-ee (without the top run)

Higgs self-coupling

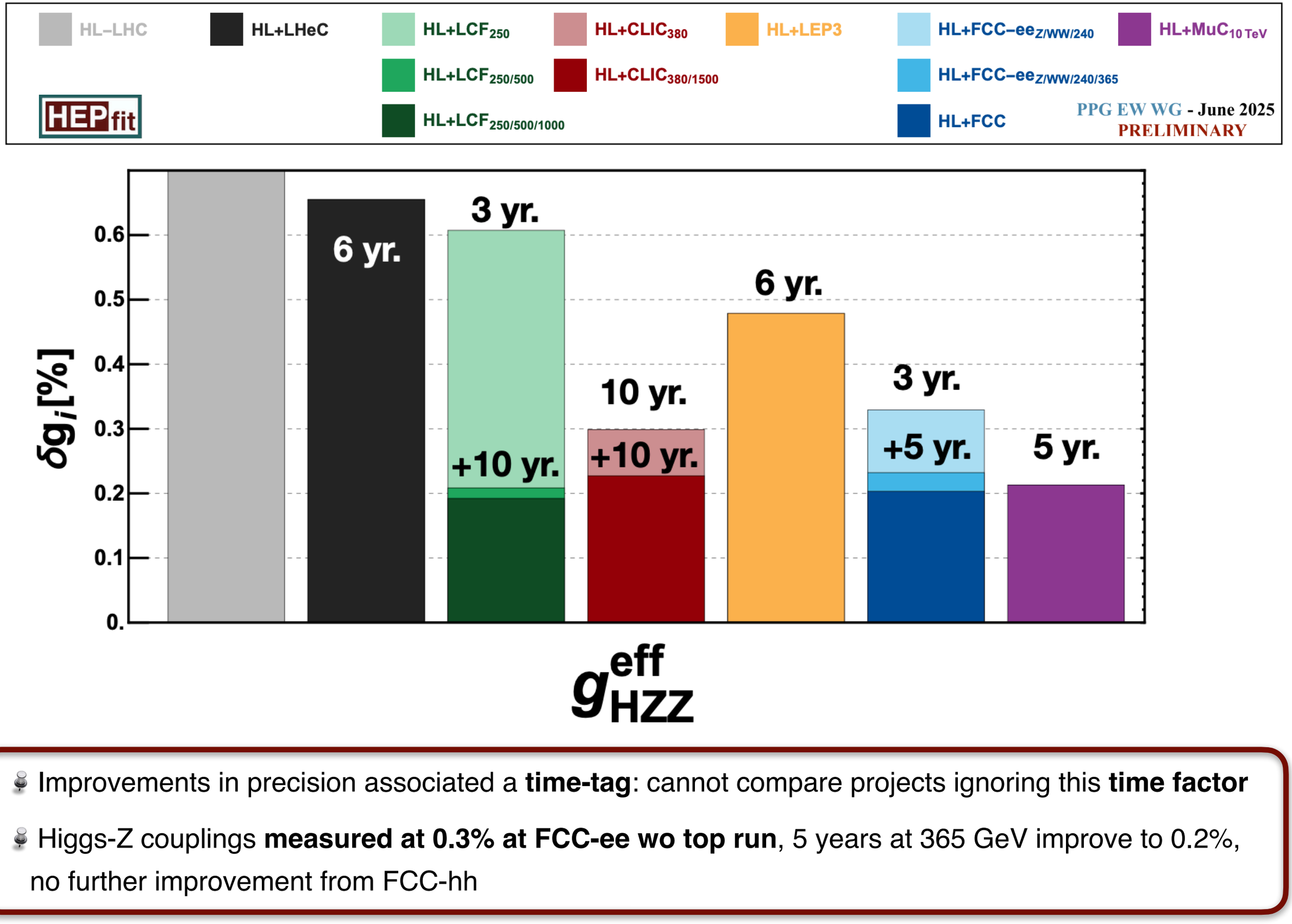




- Flagship analyses at HL-LHC and all future colliders
- **HL-LHC projections** (conservative?) markedly improved as compared to ESPPU19
- Constraints from single Higgs (via loops) depend on SMEFT settings (*e.g.* operator basis)

- Major improvements as compared to legacy HL-LHC only possible at **LCF$_{1000}$**, **FCC-hh & MuCol10**
- Higgs self-coupling unlikely to be a **decisive factor** in next collider recommendations

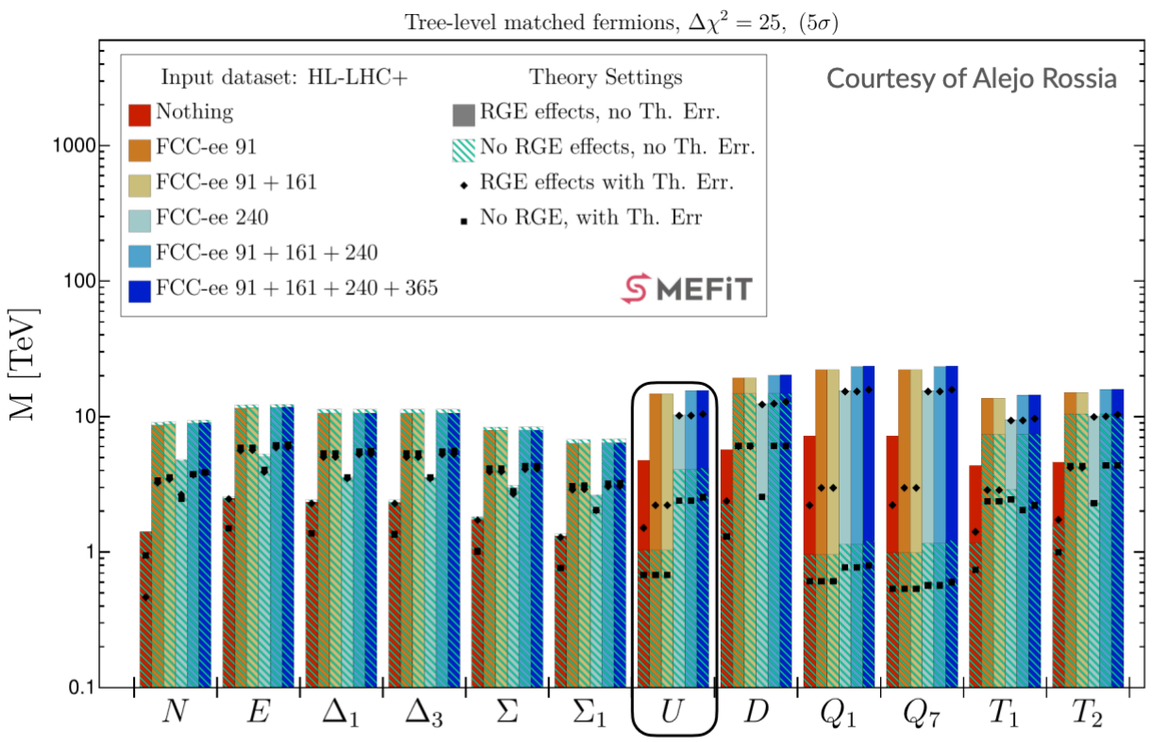
Precision vs Time

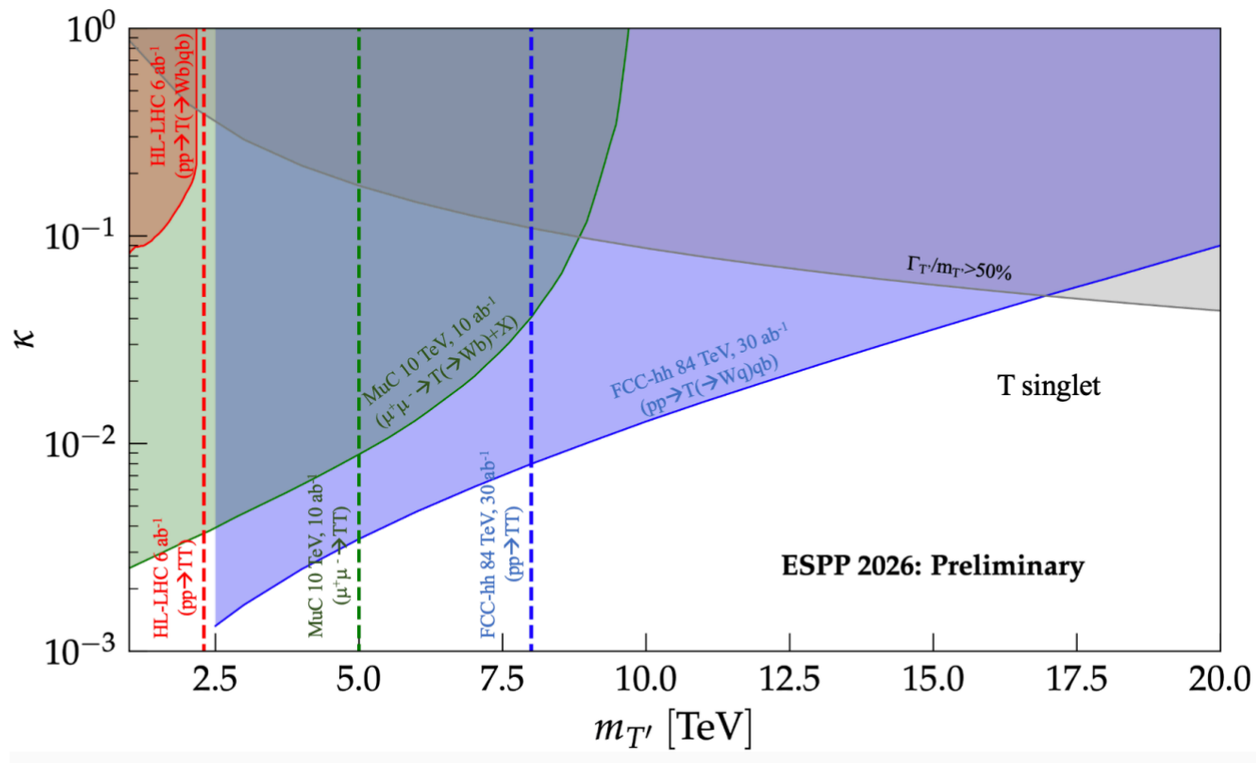


- Improvements in precision associated a **time-tag**: cannot compare projects ignoring this **time factor**
- Higgs-Z couplings **measured at 0.3% at FCC-ee wo top run**, 5 years at 365 GeV improve to 0.2%, no further improvement from FCC-hh

Indirect vs direct searches

Extend the SM with vector-like quarks (*a la* composite Higgs models)





- Indirect (SMEFT) searches: discovery of a **20 TeV vector-like quark** possible at FCC-ee
- Direct (resonance) searches: comparable sensitivity **requires FCC-hh**

The separation between **measurements and searches** is ultimately arbitrary: we measure and interpret data, while probing the same underlying physics irrespective of the analysis method

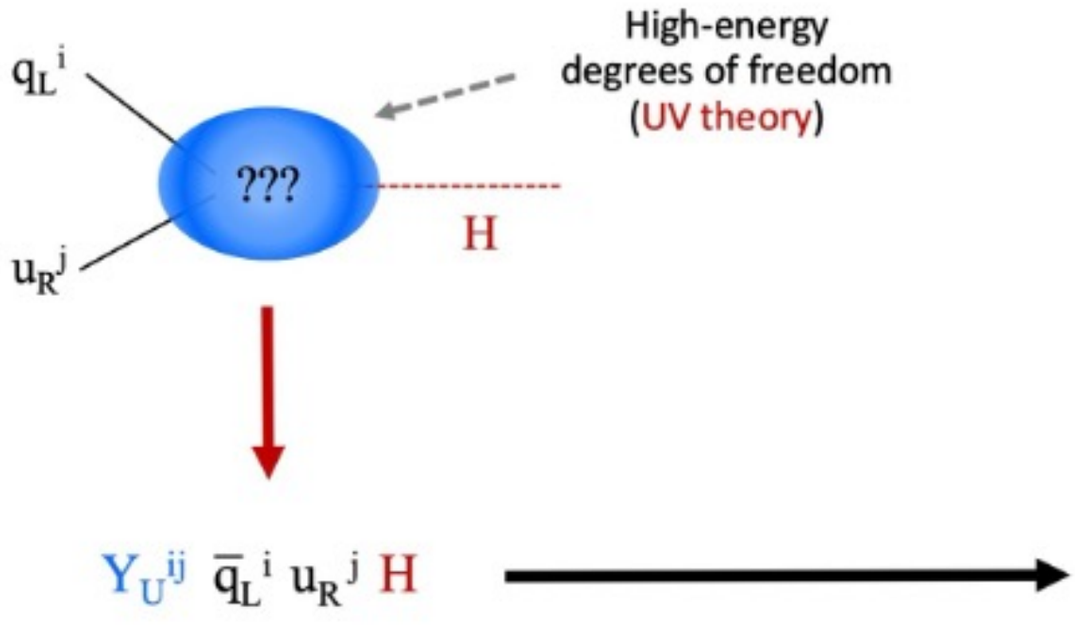
Flavour Physics

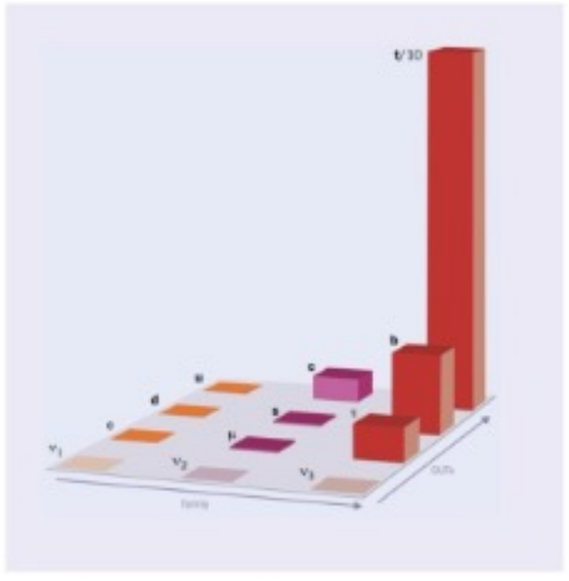
Isidori: https://agenda.infn.it/event/44943/contributions/263367/attachments/137565/206798/Isidori-plenary-slides.pdf
Marie-Helene: :https://agenda.infn.it/event/44943/contributions/263368/attachments/137557/206863/ESPPU206_Venice_MHS.pdf

Flavour matters

Flavour physics: open portal to Beyond the SM physics,
one of the 3 complementary pillars of ESPPU (together with Higgs & EW)

- Inescapable **link between Higgs, BSM, and Flavour** *e.g.* 2000 out of 2499 SMEFT operators probe assumptions on BSM flavour symmetries
- Crucial for the flavour community that **Belle II and LHCb upgrade II reach their planned datasets**: A future collider cannot replace those
- European **kaon physics** programme is terminating. Important to keep options open for smaller facilities and experiments





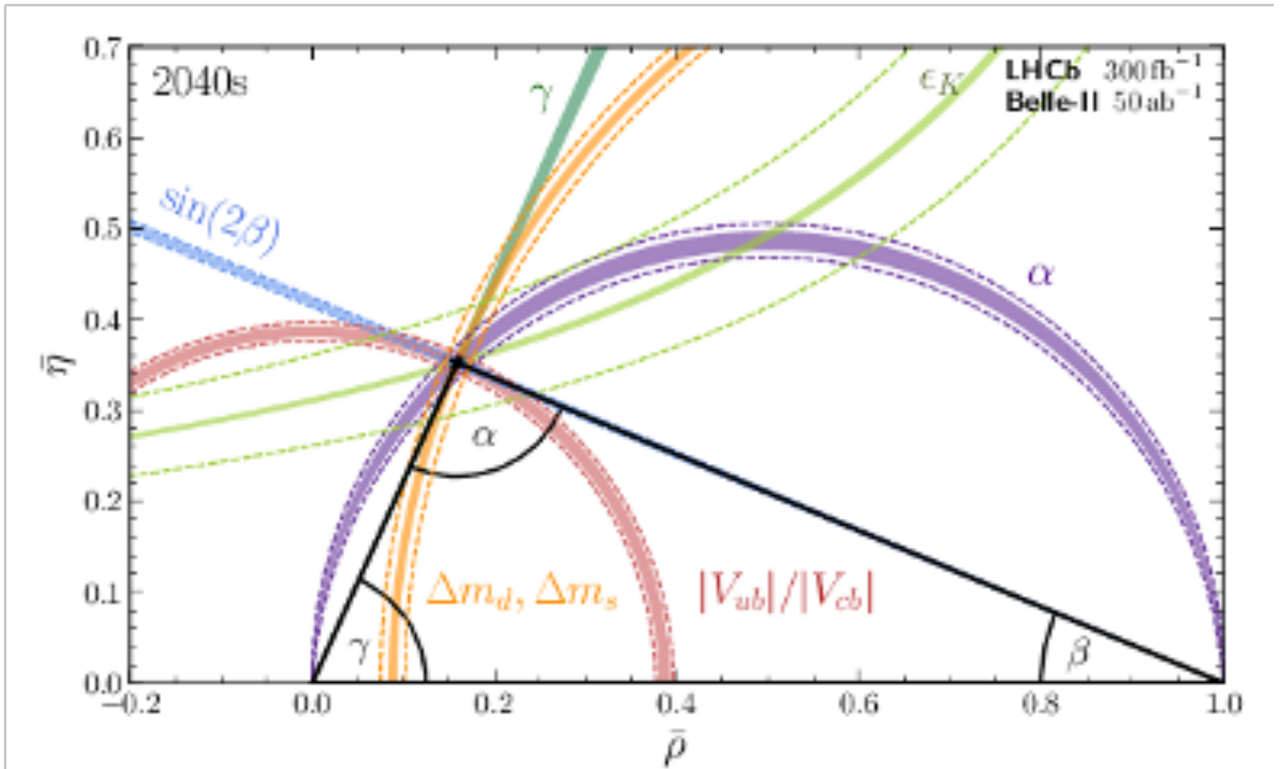
"Message from the UV"
that we need to "decode"

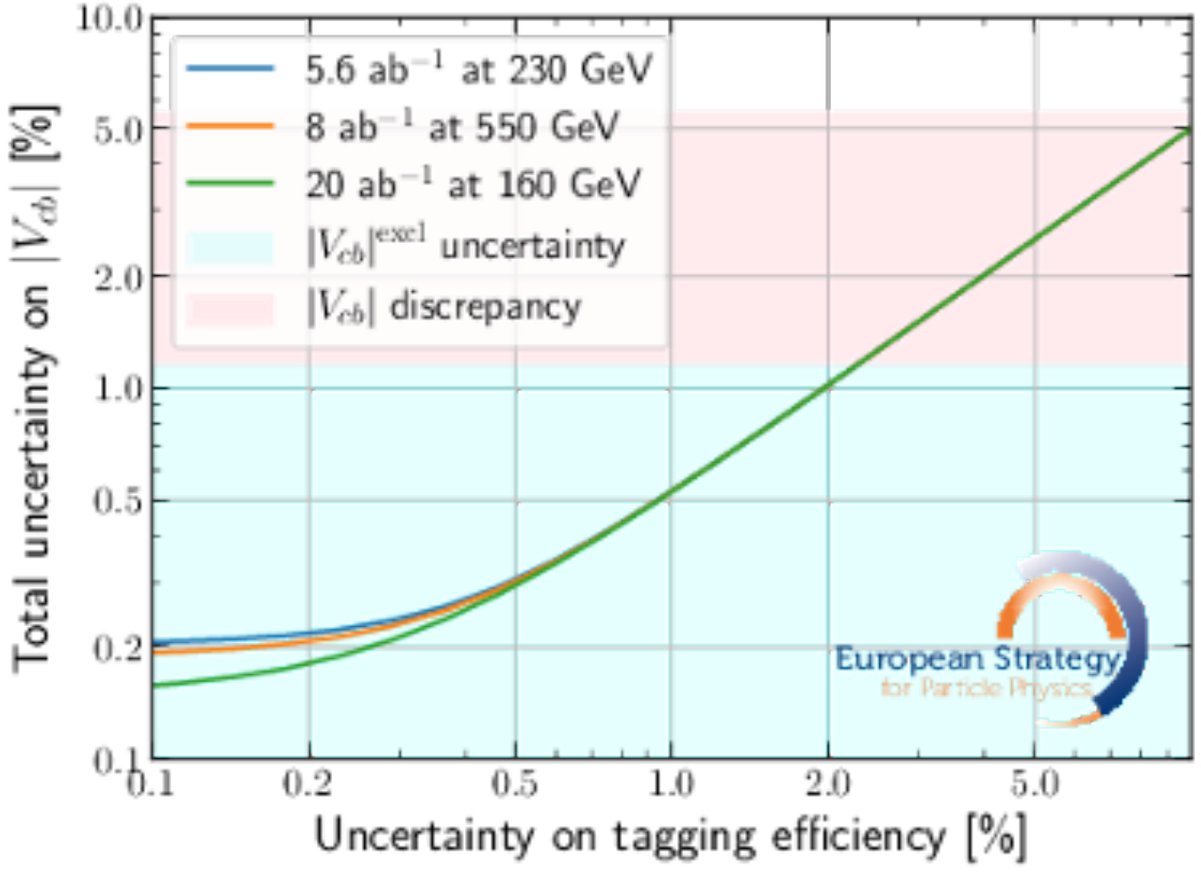
What do we need for flavour

- In 2040 the uncertainties on the CKM unitarity triangle will be dominated by the sides, which we get from **semileptonic B decays**

- An e+e- factory opens the possibility to **measure CKM matrix elements directly** in W and top decays

- Key is not statistics but **understanding of the jet mistag**



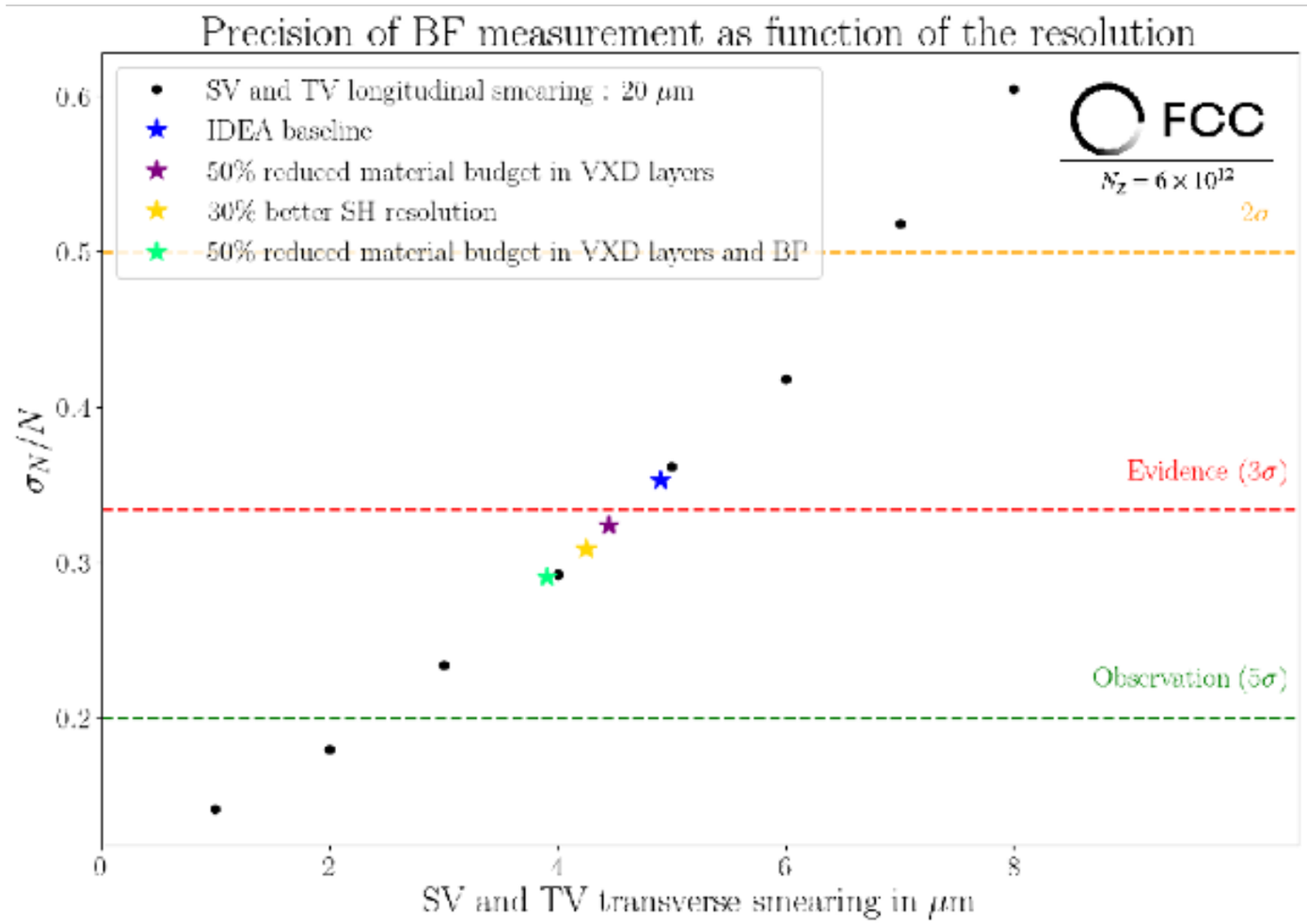


Main flavour channels and projections

- A Tera-Z (@FCC) run could potentially give access to **FCNC decays to the third family**, as $B^0 \to K^*_{\tau^+\tau^-}$, (X → neutrino's, LFV tau decays)

- This requires **exquisite vertex precision** in all four experiments.

- Also dedicated **theory support** (SM predictions) is essential to make progress



Neutrino Physics

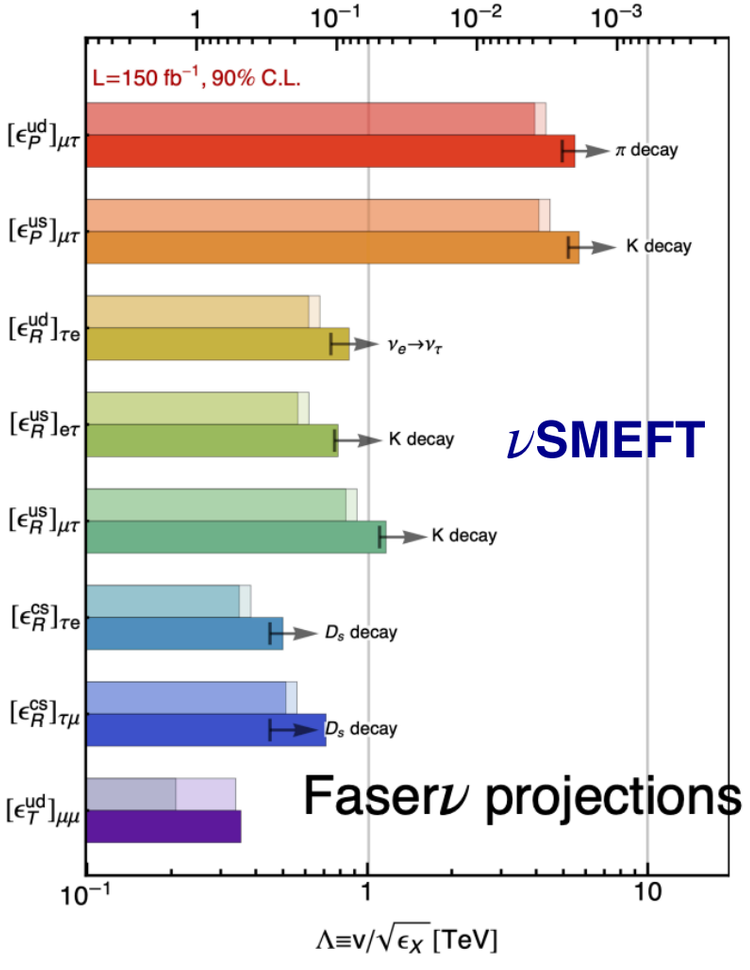
Sources:

- ``*Open questions in neutrino physics and related BSM"* (P. Hernandez), https://agenda.infn.it/event/44943/contributions/263483/attachments/137549/206864/Hernandez_VeneziaIntro.pdf
- ``Measurements of neutrino properties in the SM and beyond" (S. Bolognesi), https://agenda.infn.it/event/44943/contributions/263484/attachments/137558/206868/bolognesi_plenary.pdf
- ``*Cosmic Messengers for particle physics"* (V. Domcke) , https://agenda.infn.it/event/44943/contributions/263485/attachments/137537/206744/Domcke_ESPP_cosmic_messengers_domcke_v5.pdf

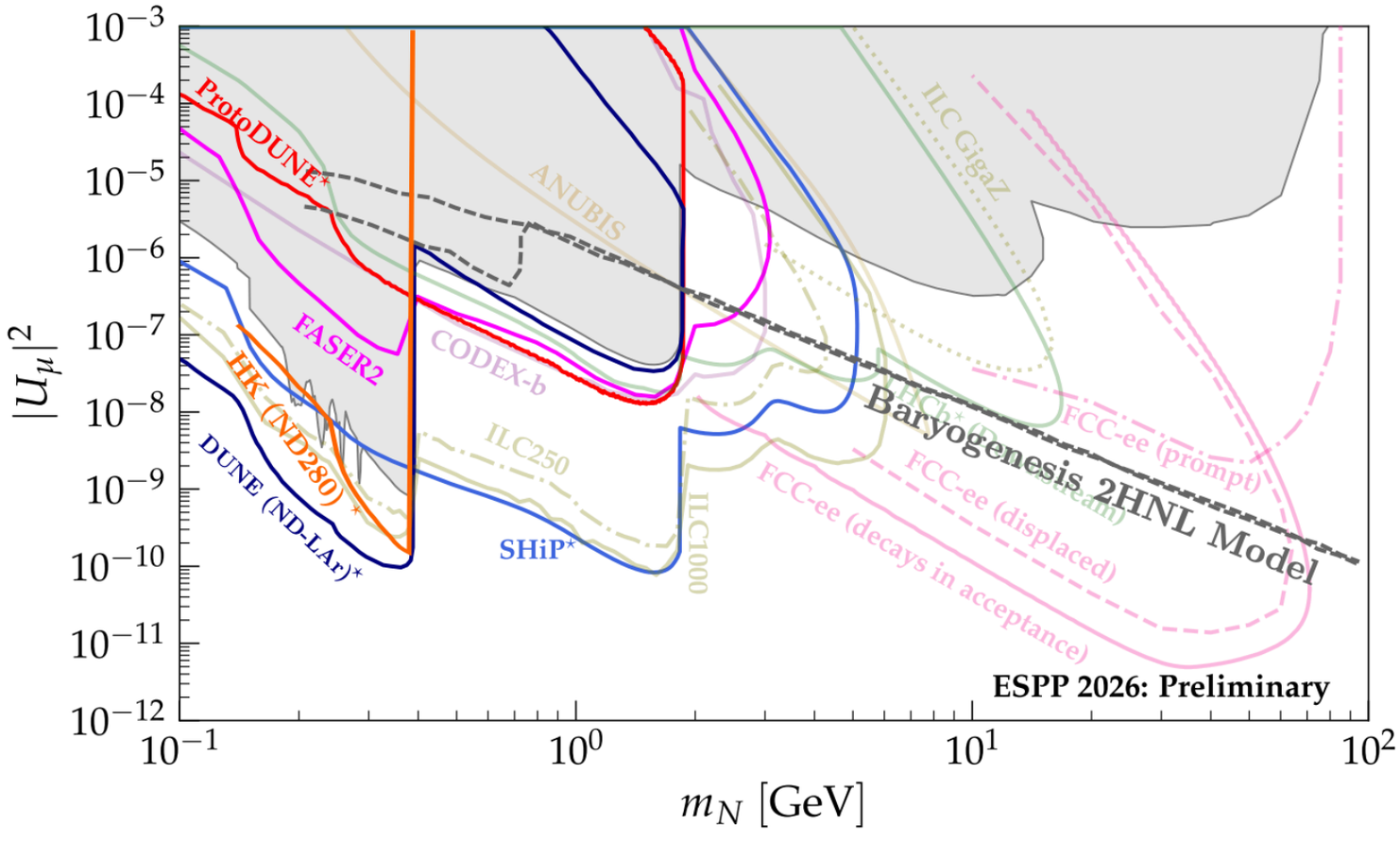
Neutrino physics and the ESPPU

Neutrino experiments address several of the open questions of the SM

- Origin of neutrino masses, mixings, and hierarchy, Dirac vs Majorana
- CP violation in the leptonic sector
- Absolute neutrino mass scale & implications for cosmology
- Non-standard neutrino interactions
- Portals to Dark Sectors, BSM connections through mixing

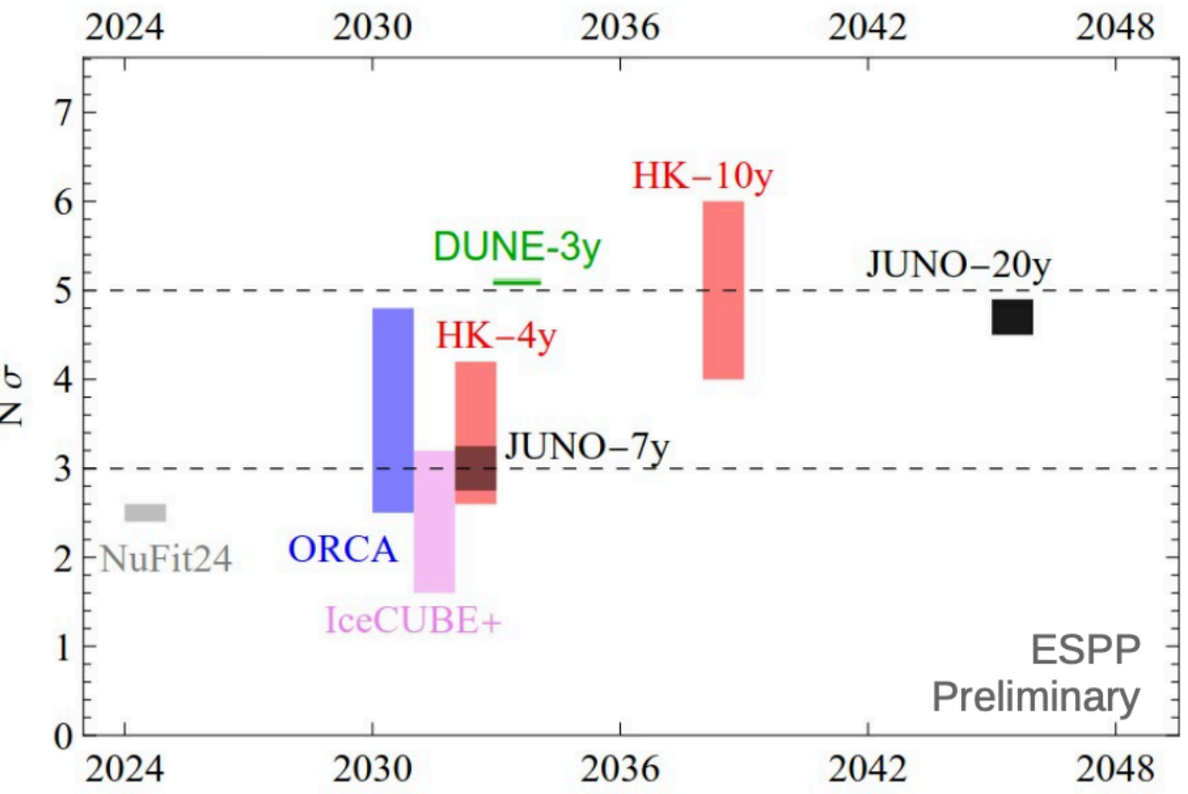


Heavy Neutral Leptons: Collider vs non-Collider searches

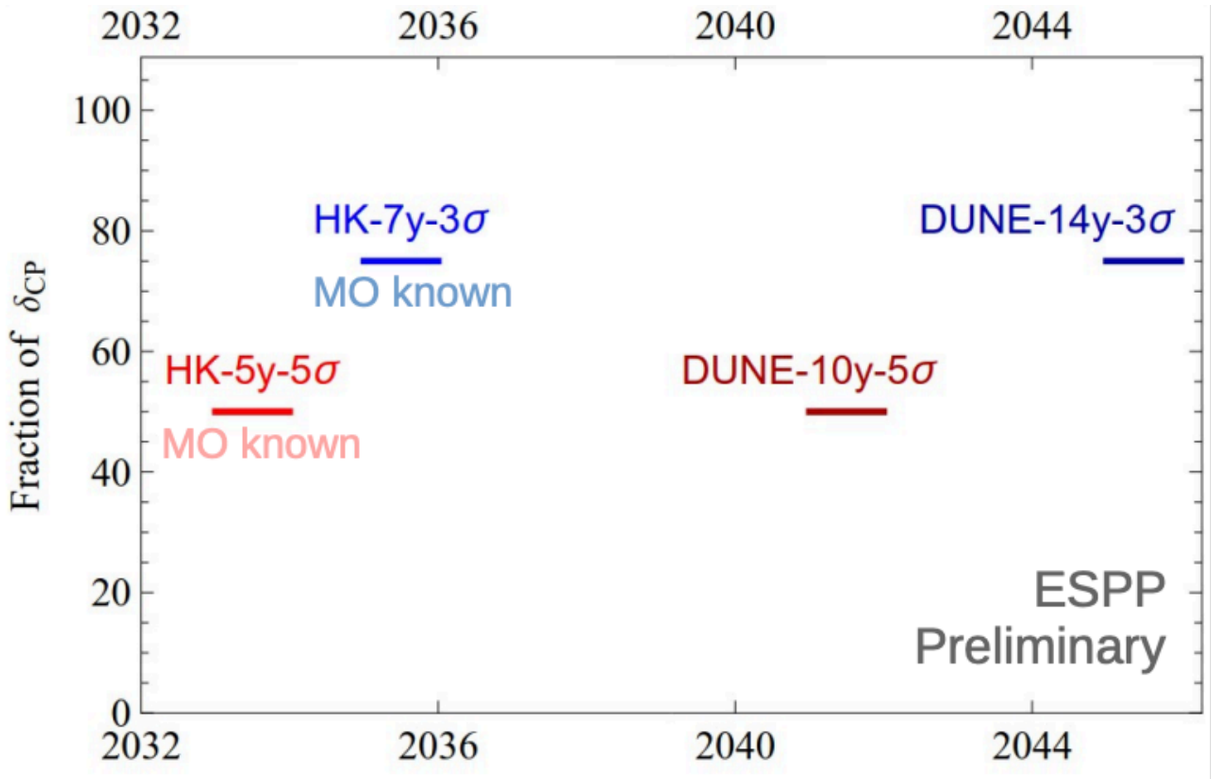


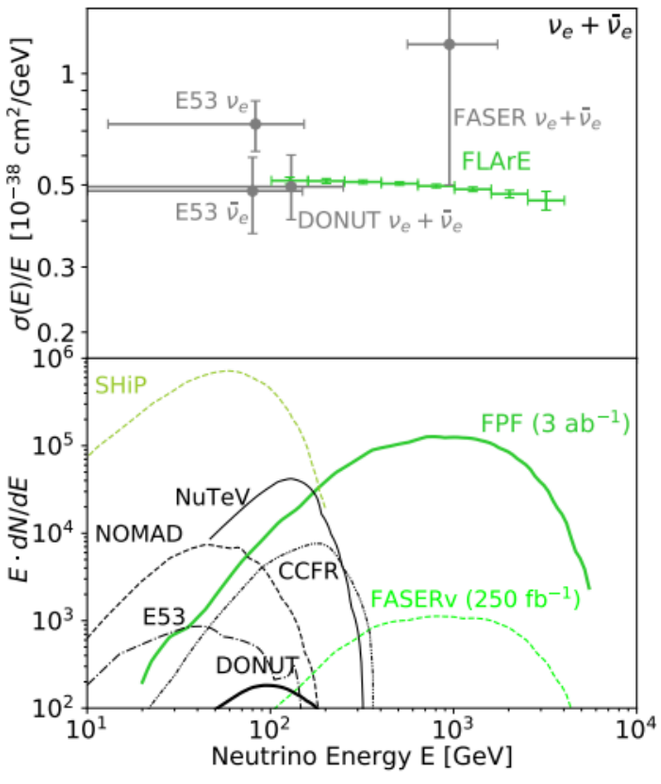
Comparing experiments

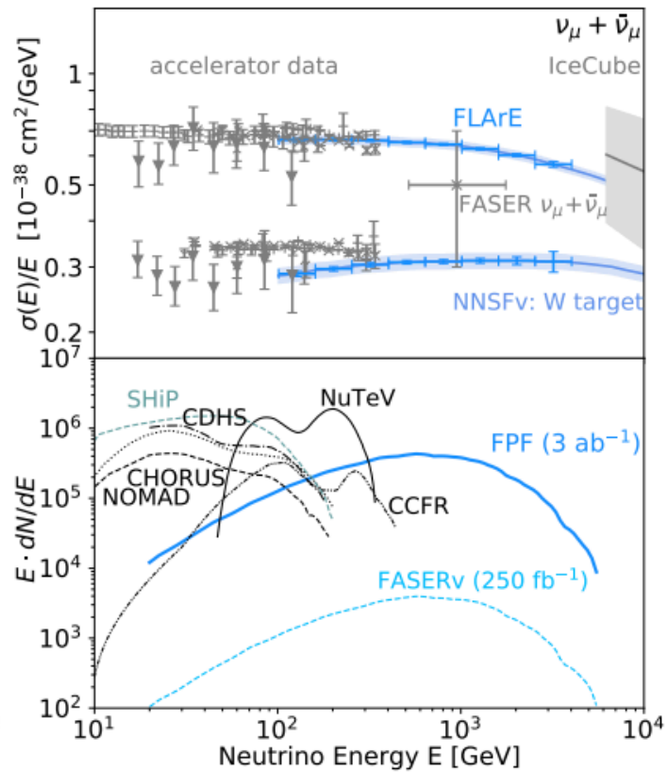
Neutrino mass ordering

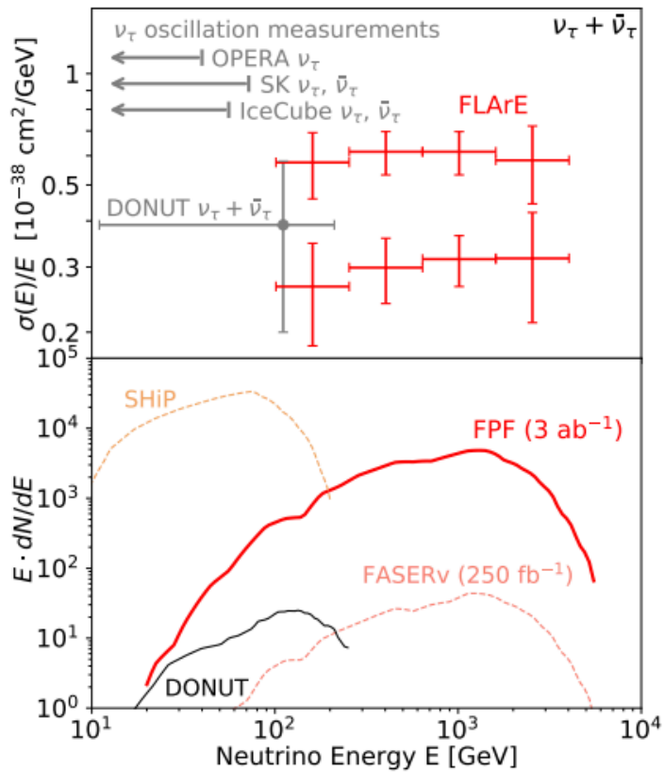


Discovery of CP violation







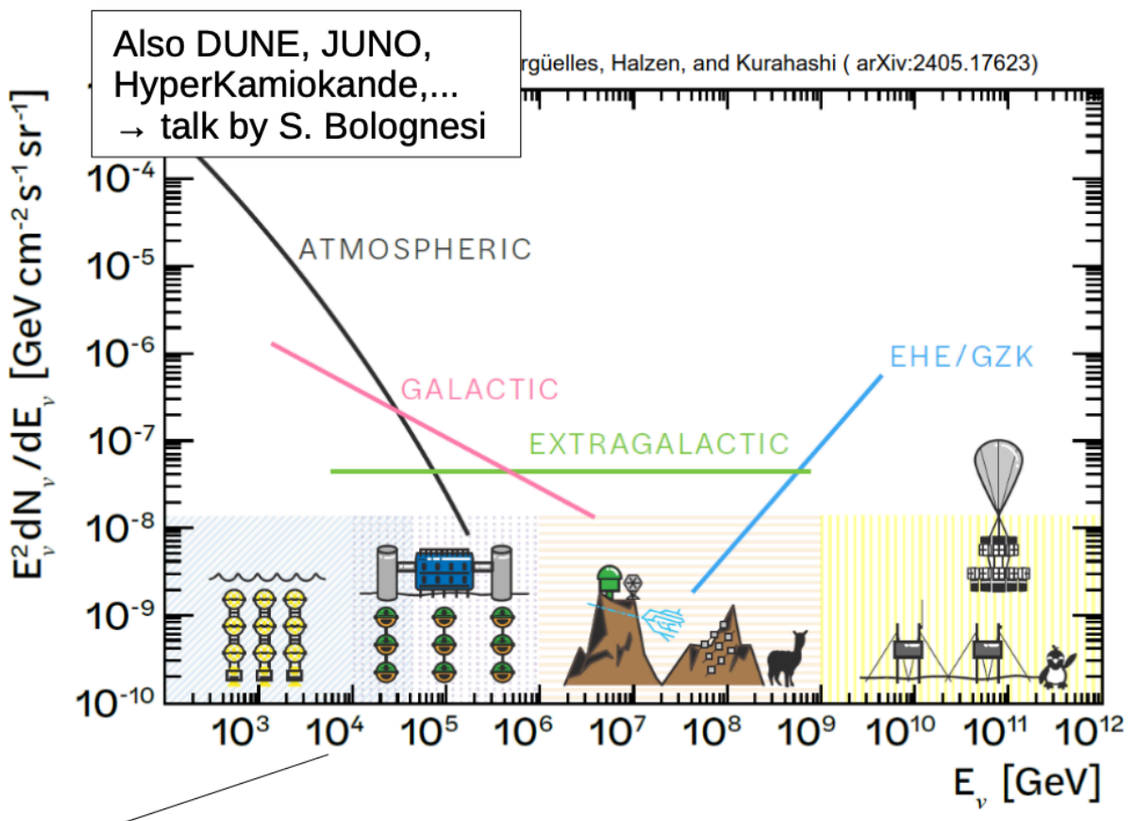


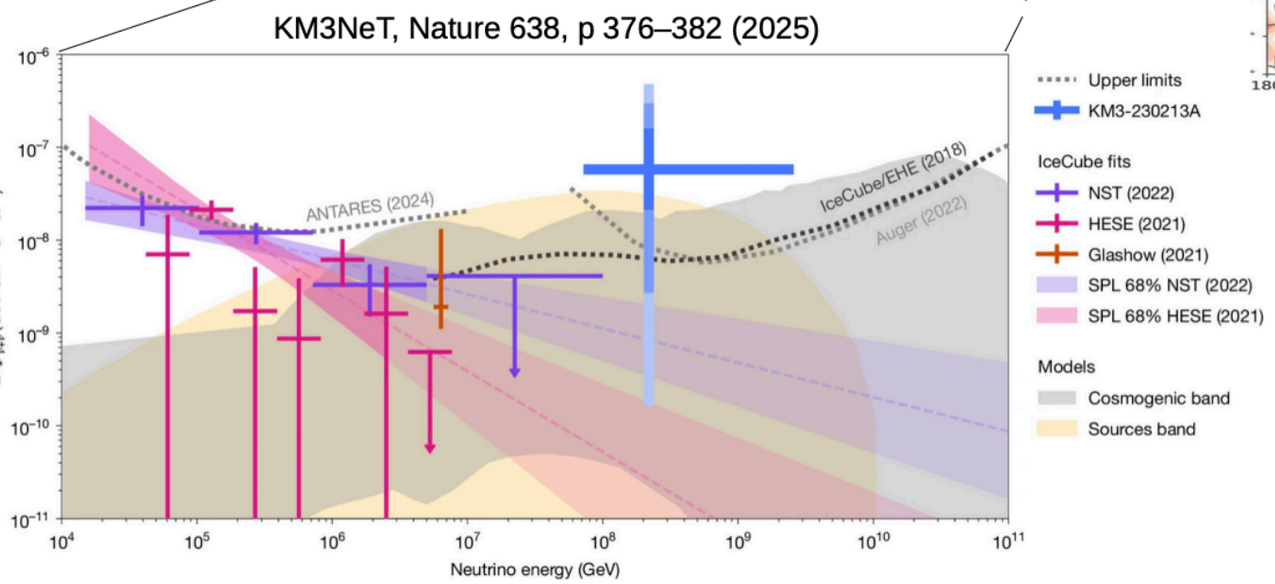
Neutrino fluxes and GeV/TeV cross-sections

Astrophysical messengers

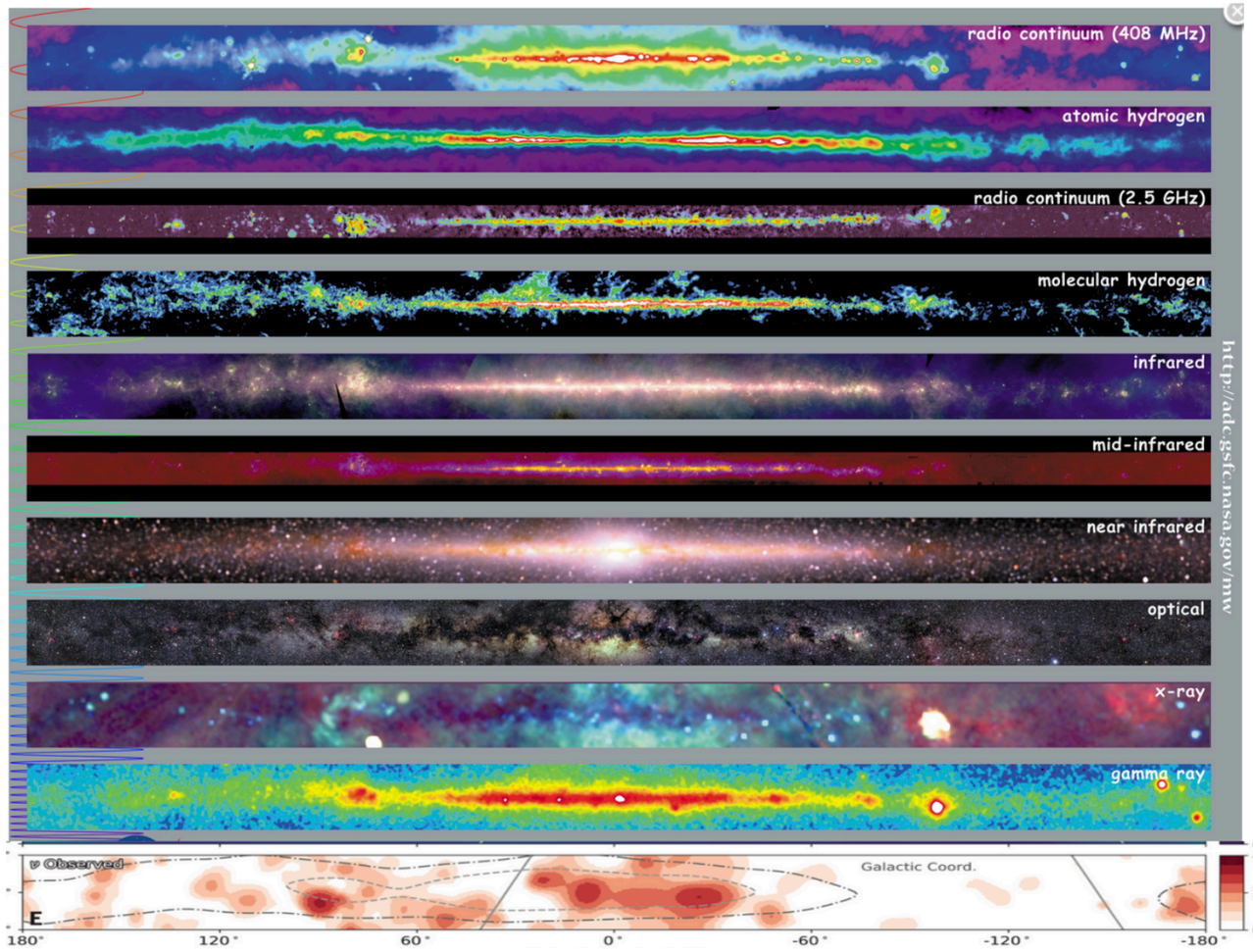
Neutrinos at all energy scales

Also DUNE, JUNO, HyperKamiokande,...
→ talk by S. Bolognesi





Multi messenger Milky Way imaging



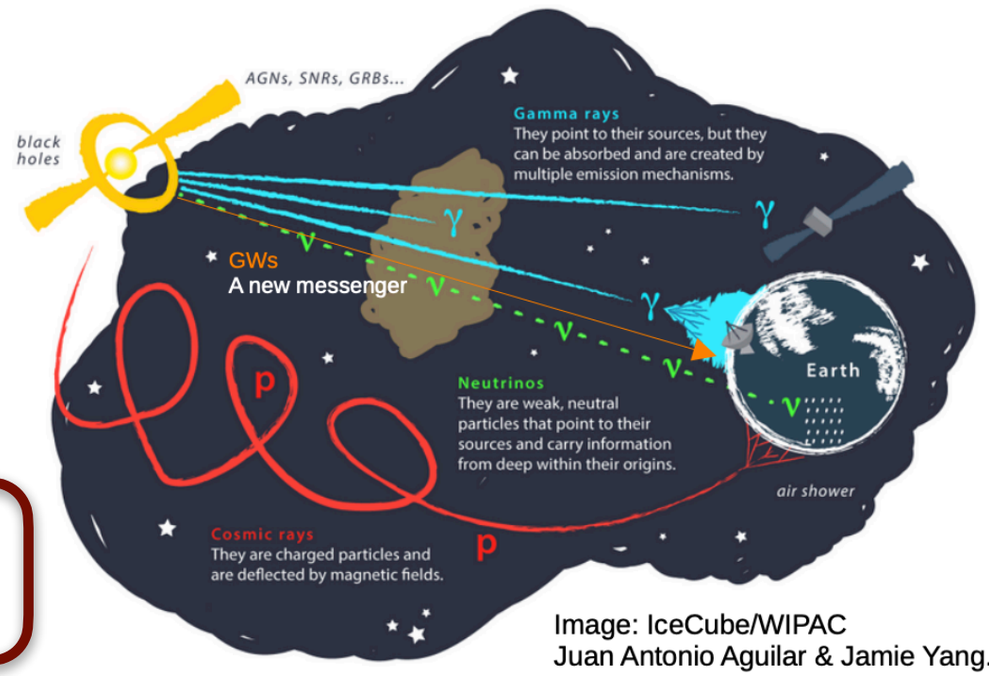


Image: IceCube/WIPAC
Juan Antonio Aguilar & Jamie Yang.

Synergies with colliders: neutrino cross-sections, prompt fluxes, forward hadron production (FASER, SND, FPF)

Gravitational Waves

- Strong-field tests of gravity and cosmology
- Test early universe and TeV-scale particle physics via SGWBs (first order EWPT, topological defects in GUTs,…)
- Nuclear physics from neutron star mergers (QCD phase diagram..)

Current instruments:

- LIGO/Virgo/Kagra network ~ 100 Hz (First detection 2015, currently in run O4b, O5 to start 2028)
- Pulsar timing arrays ~ nHz: EPTA+InPTA, NanoGrav, PPTA, CPTA, Meerkat (First evidence for SGWB)

Future/Proposed instruments:

- Continuous upgrades of PTAs, in particular SKA
- ESA mission LISA, launch 2030s, ~ mHz
- Einstein Telescope (Europe), Cosmic Explorer (US) ~ 100 Hz
- Extending spectral coverage: Astrometry, atom interferometers, R&D for high frequency GW searches,..

Synergies:

- Probe of particle physics at extremely high energies (SGWBs)
- Complementary probe of the weak scale (LISA)
- Vacuum system, civil and technological infrastructures (ET)
- Computing and data analysis, theoretical tools from PP applied to GW waveform computations