POF V.

The vision for MU-FPF

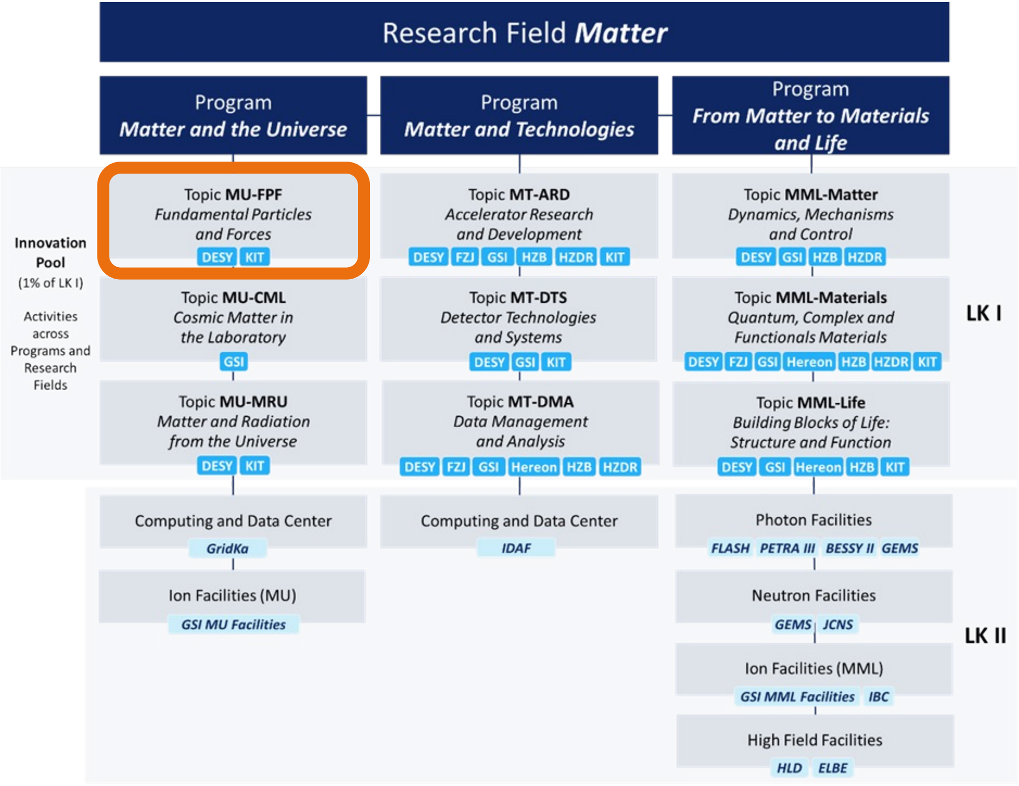
Isabell Melzer-Pellmann, Kai Schmidt-Hoberg
DESY

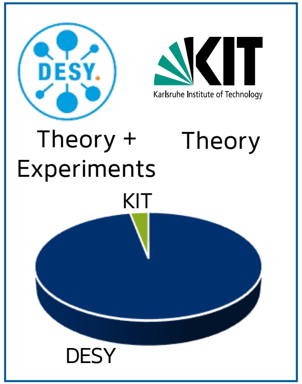
21 July 2025

HELMHOLTZ

Research field Matter

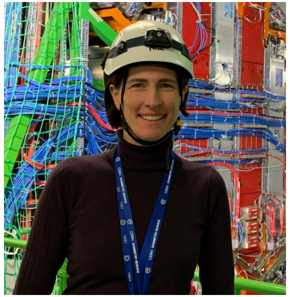
Topic "Fundamental Particles and Forces" aka FPF

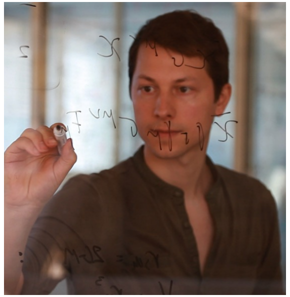




- 2 Helmholtz centers
- 3 locations
- 158 scientists
- 78 Ph.D. students
- 34 MEUR costs / a
- 42 nationalities
  (numbers from 2023)

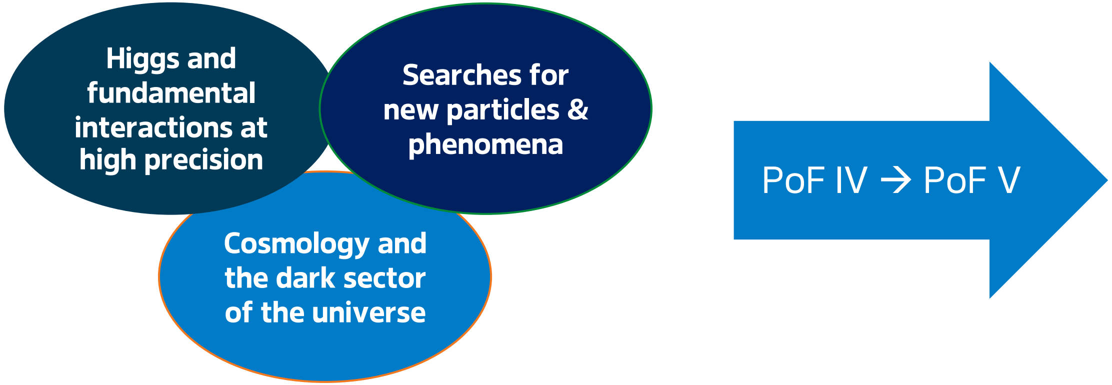
Topic spokespersons:
Isabell Melzer-Pellmann, Kai Schmidt-Hoberg





Changes from PoF IV to PoF V

Foreseen change / adaption of subtopic structure



Fundamental interactions:
Pushing the limits of our understanding of fundamental interactions

The origin of mass:
The origin of mass, the flavour puzzle, and the imbalance between matter and anti-matter

The early universe:
The evolution of the early universe and the nature of the dark sector

Motivation for the change: closer to the science drivers, less thematic overlap between subtopics.

Changes from PoF IV to PoF V

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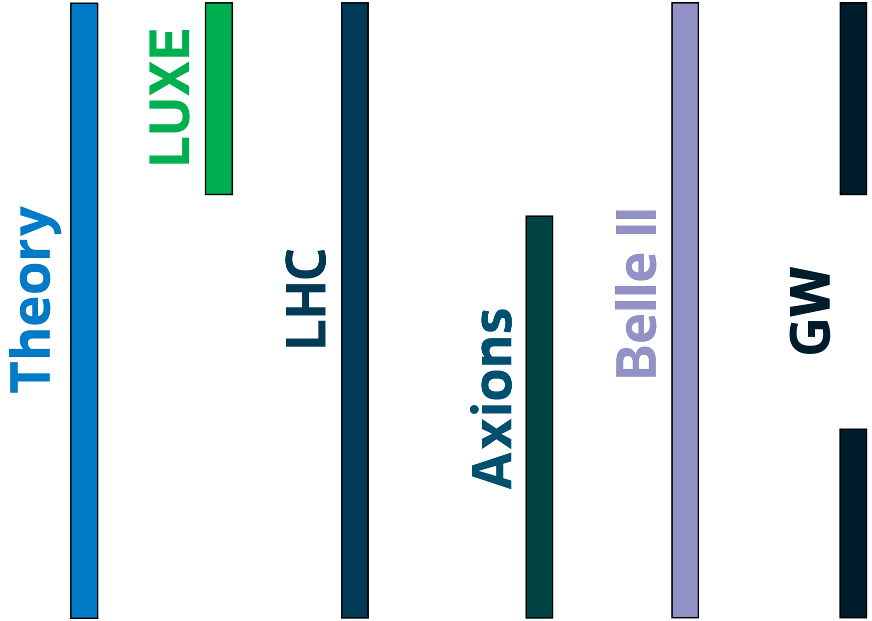

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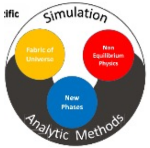
Testbeam Facility (DESY)

Detector Assembly Facility (DAF, DESY)

Computing Centres GridKa and IDAF

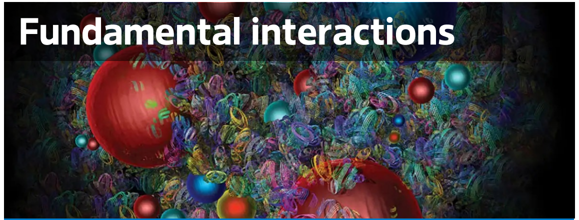
Wolfgang Pauli Centre



PoF V Subtopic Structure and Science Drivers

Our science drivers address the big questions of nature: Understanding the quantum universe

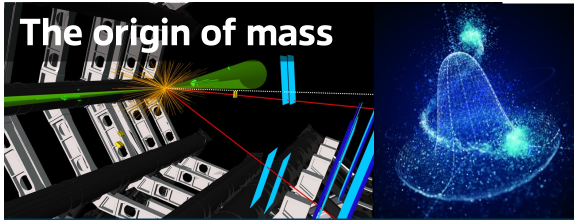
Fundamental interactions



Pushing the limits of our understanding of fundamental interactions

- QCD (incl. lattice and QC)
- Electroweak (EW) precision and Higgs physics (HH and Higgs potential)
- Strong-field QED
- Searches for extensions of the SM (e.g. SUSY, additional gauge or Higgs bosons,…)
- Search for the unknown (aka anomaly detection)

The origin of mass



The origin of mass, the flavour puzzle, and the imbalance between matter and anti-matter

- Dynamics of EW symmetry breaking
- Top and B and Tau physics
- Charge-parity violation
- Lepton flavor universality

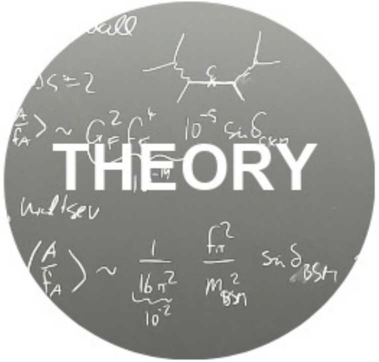
The early universe

The evolution of the early universe and the nature of the dark sector

- Cosmology (inflation, baryogenesis,…)
- Searches for dark matter candidates (incl. collider searches, Axions, ALPs,…)
- Gravitational waves
- EW phase transition

Towards PoF V

Focus areas in MU-FPF (Fundamental Partices and Forces)



Off-site experiments:

Key contributions (data analysis, commissioning and operation) to global projects at CERN and KEK:

- **ATLAS and CMS**
- **Belle II**

Engage in future collider decision and preparation

New detector project?

Theory:

Establish the Wolfgang-Pauli Center as world-leading interdisciplinary center for theoretical physics

Idea factory for future science endeavours

On-site experiments:

- **Planned axion experiments: BabyIAXO, MADMAX**
- **QED at the extreme: LUXE**

New ideas:

- **VMB @ ALPS II**
- **High-frequency GW experiments**

LHC Detector Upgrade Projects

Forschungspolitisches Ziel: milestone to reach in 2031

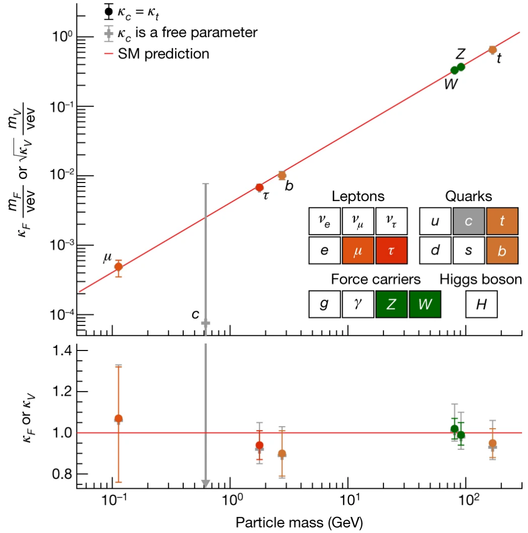
- **New trackers for ATLAS and CMS:**
  - Improved hit resolution for high-pT tracks
  - Extension of tracking into the forward region, e.g. important for VBF production, extension of measurements to the forward region like EW mixing angle
  - Tracking at the trigger level enables precise high-pt jet reconstruction

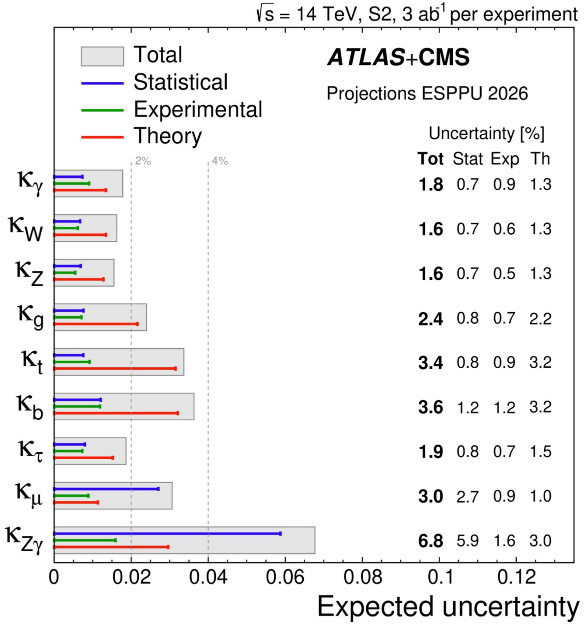
- **HGCAL:**
  - Pileup mitigation in the forward region
  - Granularity, radiation hardness, and extended coverage will be instrumental for jet physics reducing energy resolution and enabling measurements in the forward direction

Fundamental interactions

Investigating the Higgs boson

- **How do particles get their mass – by the SM Higgs mechanism or something else?**
  - → Measure the Higgs boson couplings as precisely as possible, in particular to 2nd generation fermions
  - → Measure top-associated Higgs production (ttH+tH) to access the strongest fermionic Higgs coupling and its properties:
    - → CP odd coupling?
    - → Unexpected (BSM) contributions?

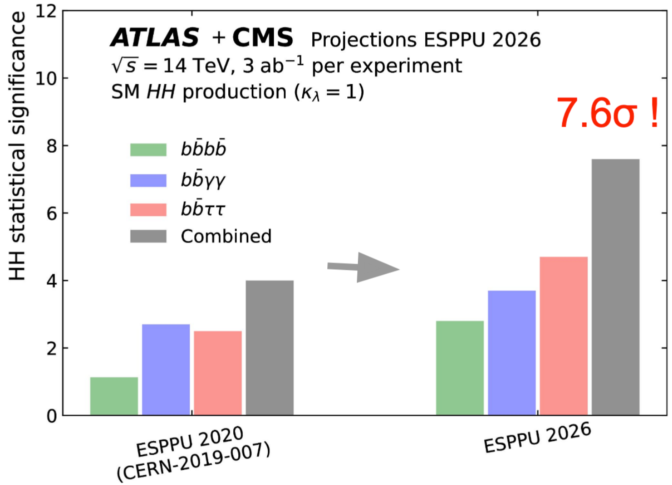




Fundamental interactions

The more the merrier: tackling the di-Higgs production

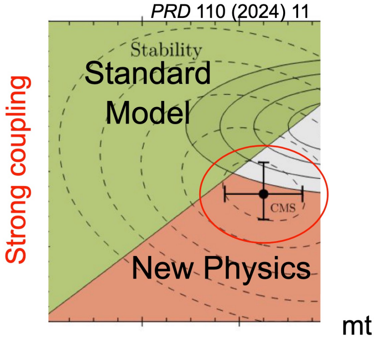
- **How does the Higgs potential look like (exactly)?**
- **What is the mechanism of electroweak symmetry breaking?**
- **Does the Higgs boson couple to itself as we expect?**
  - → HL-LHC allows for the first time to constrain the Higgs self-coupling
  - → Best way to get access to the Higgs potential; 5σ discovery already with 2 ab^{-1}
    - – Room for surprises: new heavy resonances could enhance cross section!
    - – Most sensitive channels are exactly those where DESY profits from expertise on object performance
    - – 5σ discovery already with 2 ab^{-1}
  - → DESY with both ATLAS and CMS groups is in an excellent position to work on combinations
    - – Expect 7.6σ discovery already with 3 ab^{-1}



Fundamental interactions

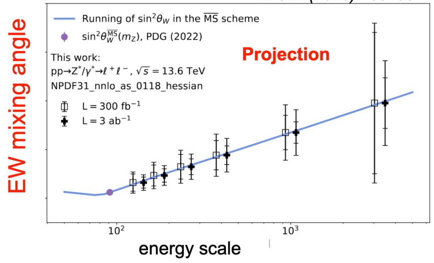
Precision tests of the fundamental forces

- **QuantumChromoDynamics (QCD):**
  - Precision tests, e.g. measurement of the strong coupling parameter α_s at the LHC
  - Lattice calculations



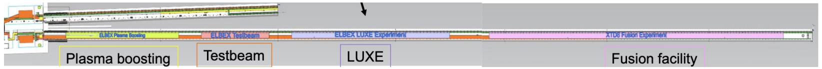
Improve by factor of 2!

- **ElectroWeak (EW) force:**
  - Further measurements of the electroweak mixing angle (exploiting new forward tracking)
  - Highest energy photon collisions at the LHC



First measurement

- **QuantumElectroDynamics (QED):**
  - What happens at the Schwinger limit?
  - Project for PoF V: **LUXE, profiting from ELBEX extraction at European XFEL**

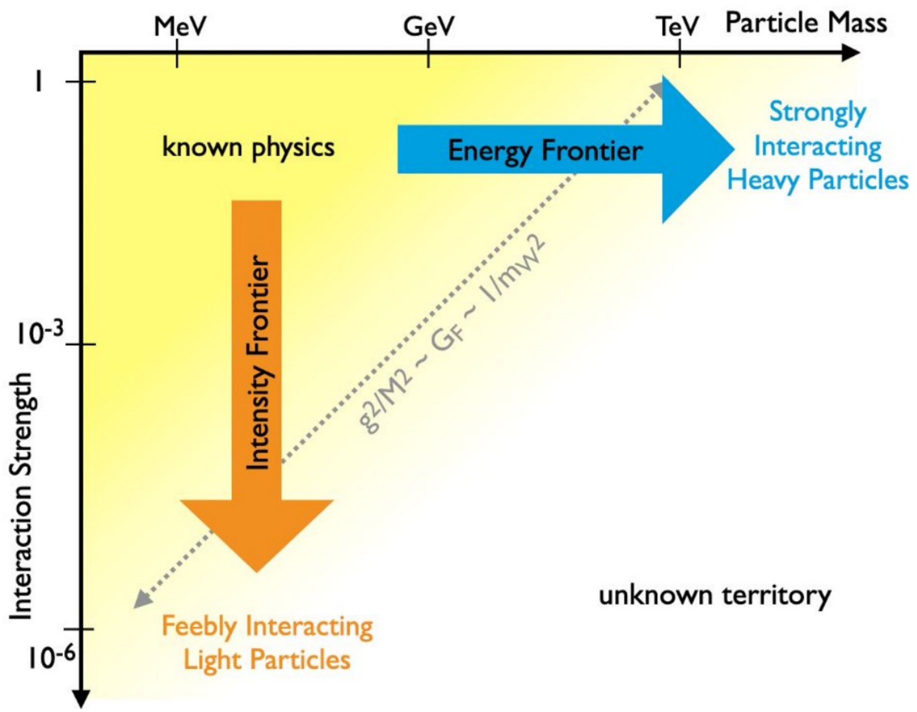


- **Understanding of the content of matter**
  - Measurement of parton distributions
  - Common effort of theory and experiment to treat correlations of SM parameters and PDFs in global SMEFT interpretation

Fundamental interactions

Bring light into open questions

- **What happened to antimatter?**
  → Search for CP violation in the Higgs sector
  → CP violation in $H \rightarrow \tau\tau$ decay: sensitive probe of the model of electroweak baryogenesis
- **Why is the Higgs boson so light?**
  → Search for extensions of the SM, but also for the unknown
  → Focus on signatures that only now first have sensitivity in LHC Run 3 and HL-LHC!
  → Push intensity and energy frontier



Fundamental interactions

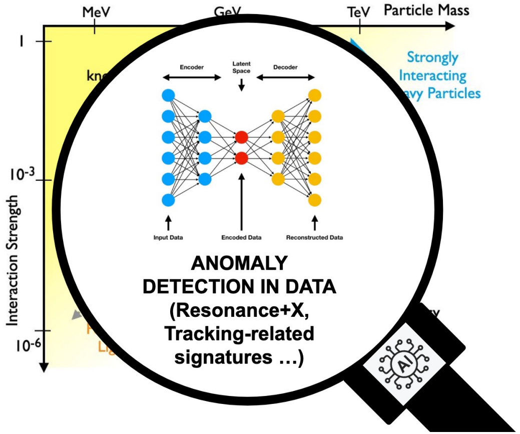
Bring light into open questions

New detectors open new search windows

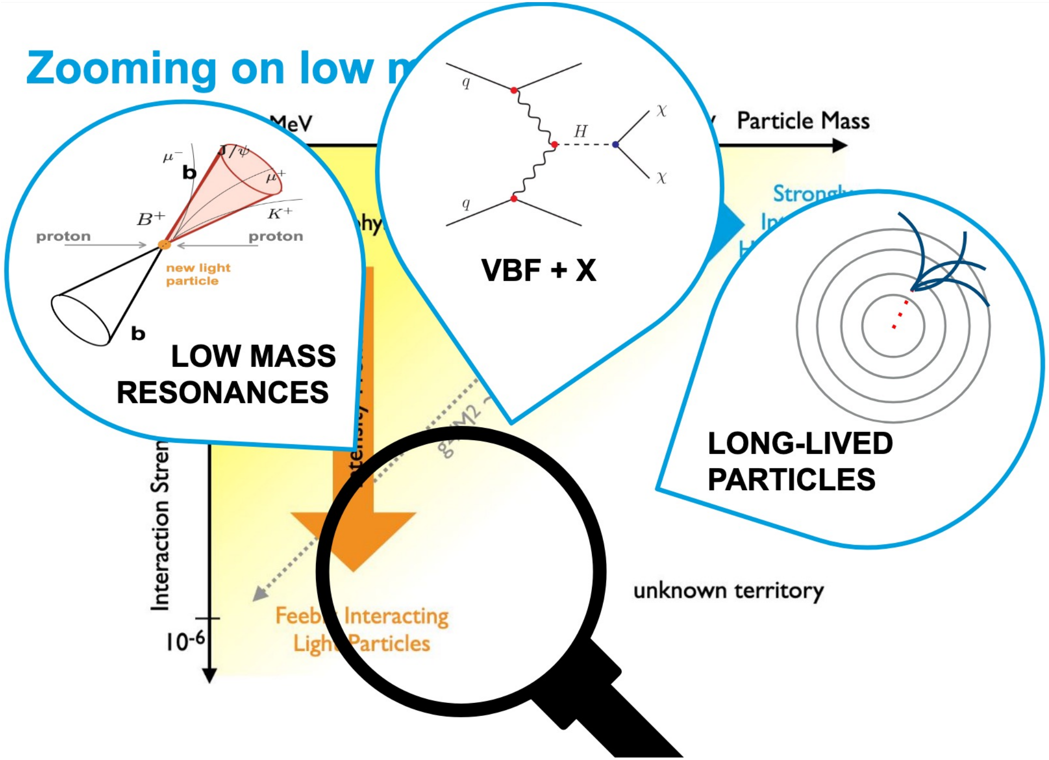
Search in all directions

→ Push intensity and energy frontier

Looking for unknown unknowns



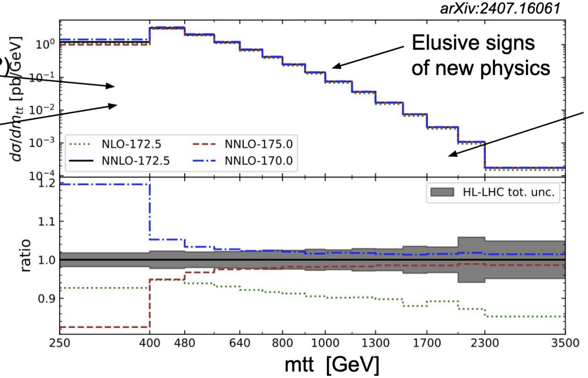
New techniques using Machine Learning



The origin of mass

The top quark

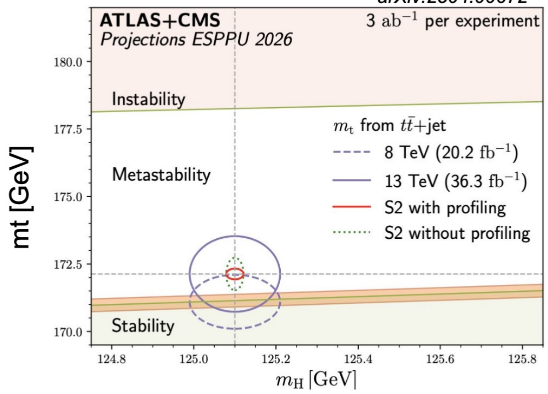
- **Understanding the top quark as a quantum state from non-relativistic to highly-boosted regime:**
  → Ultimate stress test of the SM and window to BSM



- **How does the top quark couple to the bosons?**
  → Measure EW couplings to Z, W, γ via top+vector boson

- **Is our Universe stable?**
  → Precise measurement of W and top mass

New trackers fundamental to identify the top quarks

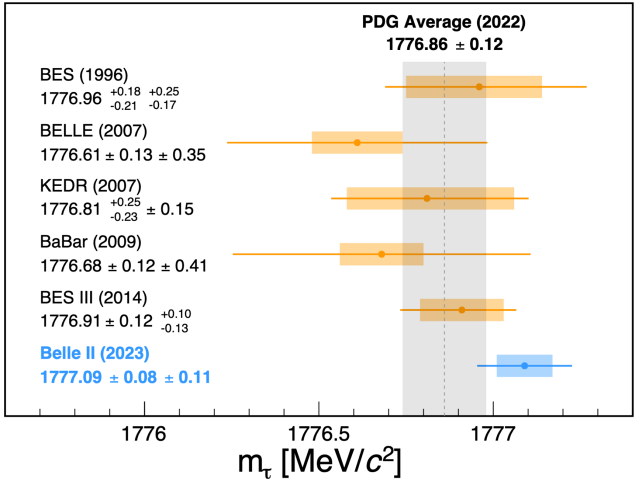


End HL-LHC mt precision ~ 200 MeV

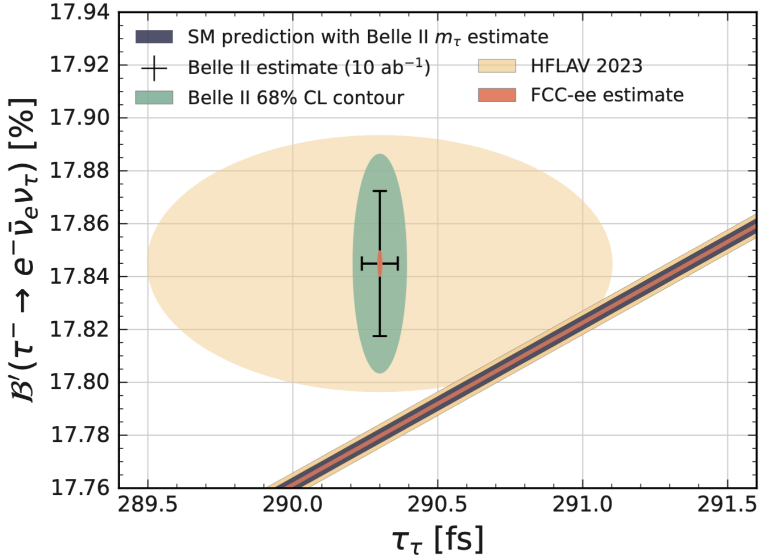
The origin of mass

Is there a difference between the three generations (beyond mass)?

- **Test lepton flavor universality with τ leptons at Belle II**
  - Improve systematic uncertainties for τ mass measurement
  - Expect significant improvement in lifetime measurement
  - Measure $\mathcal{B}(\tau \rightarrow \ell \nu_\ell \nu_\tau)$ for the first time and challenge the SM



Most precise m_τ from Belle II, expect further reduction of systematic uncertainties



New PXD pivotal for the lifetime measurement

The origin of mass

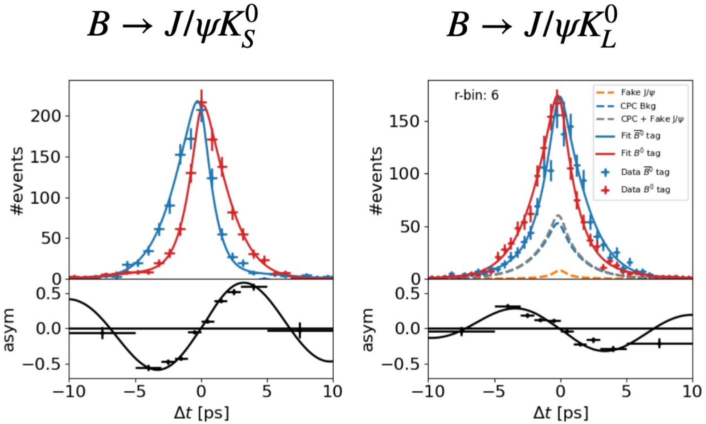
Testing our predictions for the three generations by measuring CKM parameters

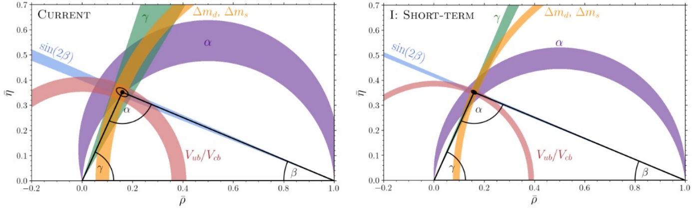
PXD fundamental in controlling resolution function systematics

- β from decay-time-dependent CP analyses of $B \rightarrow J/\psi K^0$ decays
  - With 5 ab-1 of data, statistical precision on beta is expected to be competitive with LHCb with 50/fb of data (both LHCb and Belle II analyses will be systematics-limited)

- α from from analysis of $B \rightarrow \rho\rho$, $B \rightarrow \pi\pi$, $B \rightarrow \rho\pi$ decays
  - Least well known CKM angle so far
  - Belle II will lead the precision

- $|V_{us}|$ exclusive and inclusive from τ decays
  - Value is high when measured in τ decays: Cabibbo angle anomaly
  - As a τ factory, Belle II is uniquely placed to address this issue



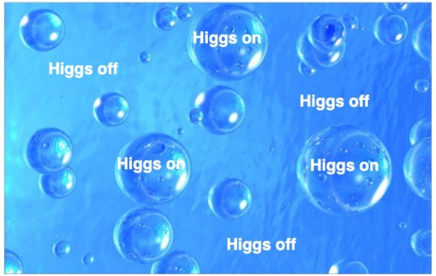


The early universe

Connection of Higgs potential and electroweak phase transition in the early universe

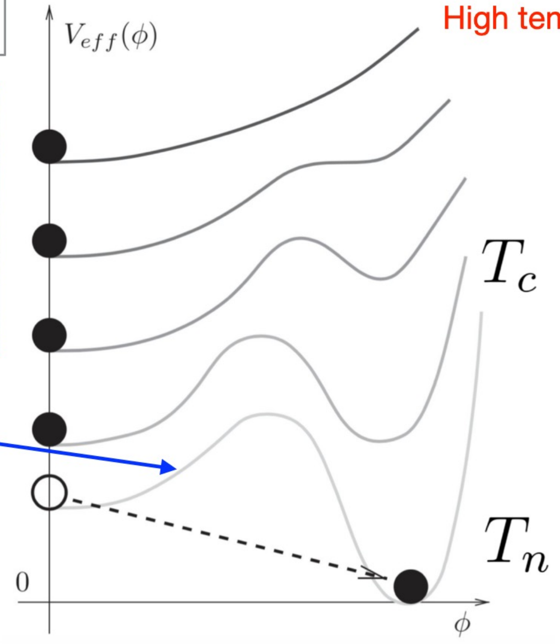
Temperature evolution of the Higgs potential in the early universe:

$$V(\phi, T) = V_0(\phi) + V^{loop}(\phi, T)$$



Potential barrier depends on trilinear Higgs coupling(s)

EW baryogenesis: creation of the asymmetry between matter and antimatter in the universe requires strong first-order EWPT



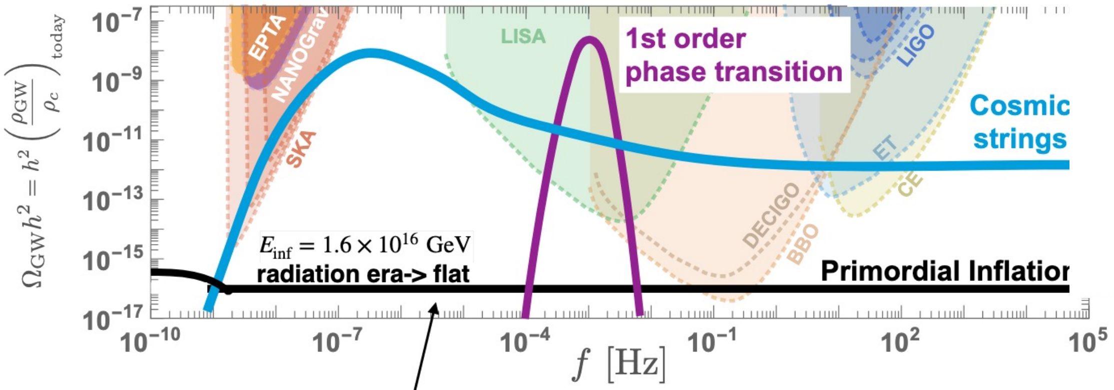
High temperature

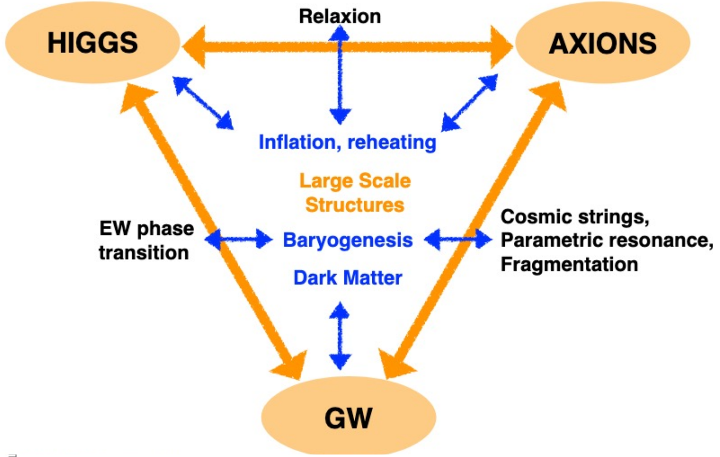
Critical temperature (degenerate minima)

Transition temperature (strong first-order EWPT)

The early universe

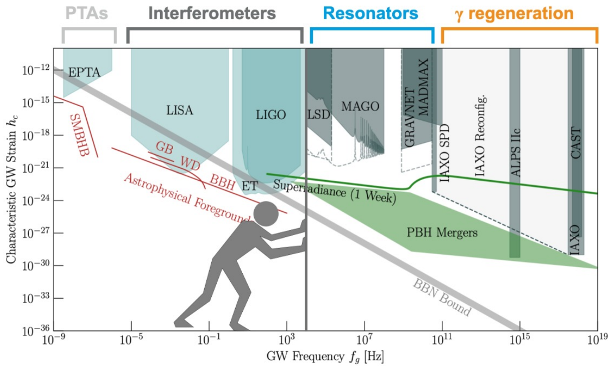
Gravitational waves as a probe of the early universe





Irreducible GW background from amplification of initial quantum fluctuations of the gravitational field during inflation

- **Head also towards high frequencies**
  - No known astrophysical objects over O(kHz): search for new physics
- **Ongoing R&D projects at DESY to establish technologies and assess feasibility**
  - SRF cavities (MAGO), levitated sensor detector, use axion infrastructure

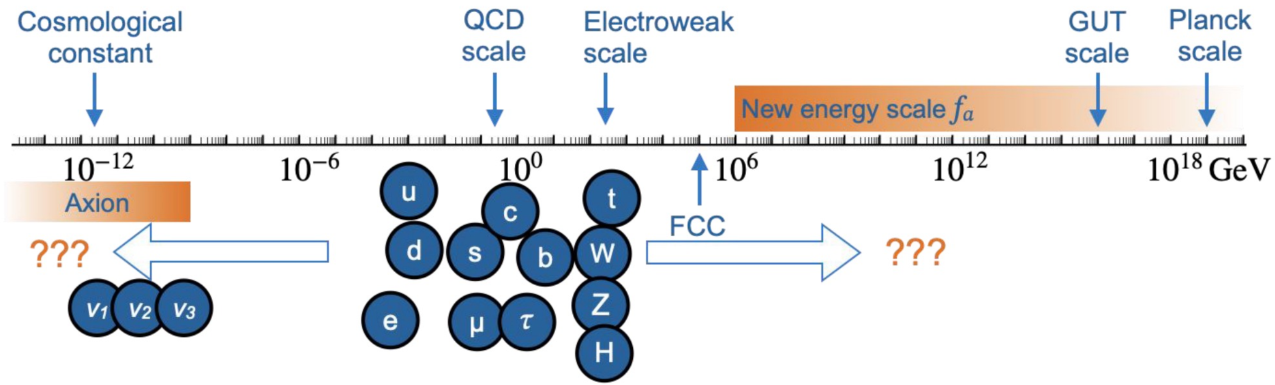


The early universe

… and its dark side

- **What is dark matter?**
  - If produced in the early universe, it could also be produced at colliders with the energy density close to the big bang (WIMP dark matter)
  - Is the Higgs boson a portal to dark matter?
  - Axions and axion-like particles are viable candidates

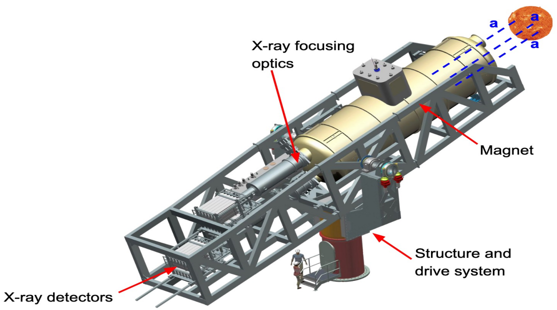
- **What is dark energy?**
  - Ultralight ($<10^{-33}$ eV) axions could be the dynamical dark energy

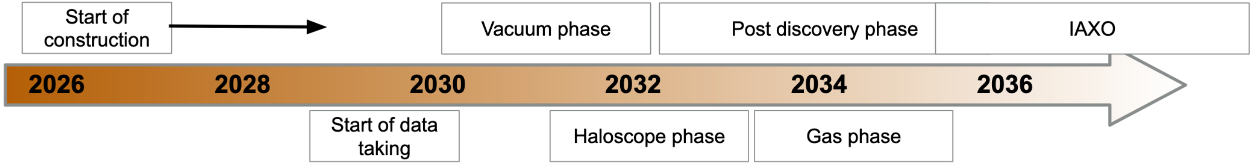


The early universe

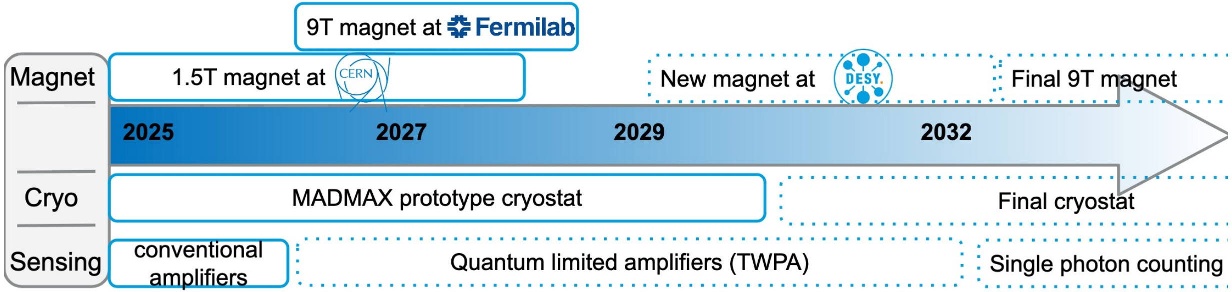
Planned axions searches at DESY

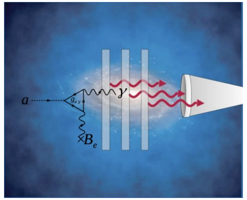
- **BabyIAXO**
  - The next generation state-of-the-art helioscope at DESY
  - Sensitivity: ~100x CERN Axion Solar Telescope (CAST)





- **MADMAX**
  - Large resonator from many parallel dielectric disks





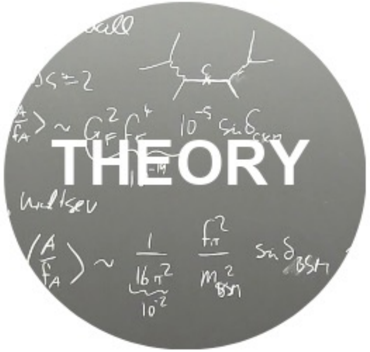
Backup / further info

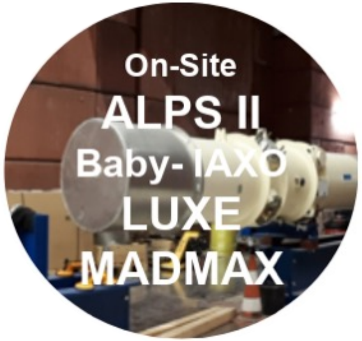
Questions to be answered in the report

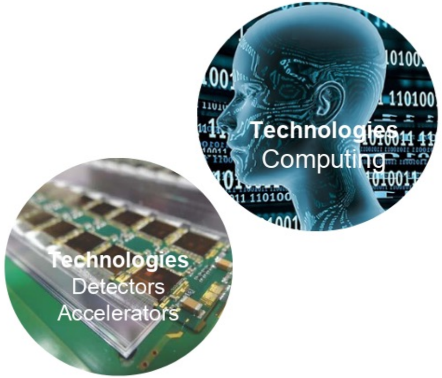
- **Brief description of challenges, scientific goals and strategic relevance, also in relation with research policy objectives and in the context of international developments.**
- **Key questions:**
  - How would you rate the objectives of the topic with regard to **scientific relevance and leadership**?
  - Which pressing societal or **scientific challenges** does it address?
  - How would you rate the topic's potential **impact** with regard to the research field, its technologies and its societal context?
  - How would you evaluate its **alignment with the research policy objectives** of the research field (and with the strategy of the program)?
  - Do you envision **further objectives** that the topic should consider addressing?

Particle Physics at DESY: the Next 10-15 Years

Specific focus areas







Key contributions to global projects at CERN and KEK
- HL-LHC preparation and running in 2029 onwards
- Belle II: expect ~50/ab by 2034

Engage in planning and preparation for future projects (EPPSU decision by 2028)

Maintain broad and world-leading portfolio.

Establish WPC as world-leading interdisciplinary center for theoretical physics

Theory as "Idea factory"

ALPS II: first science run started running in May 2023.
BabyIAXO, LUXE: Solve challenges & find financial resources for PoF V
MADMAX: proof concept in prototyping phase & find financial resources
New ideas, e.g. HF GW local experiments (complementing ET)

~50% of topic resources go into technical work!

Strengthen innovation in detectors and computing

Increase 3rd party funding

Strengthen exchange across divisions

Mid- and Long-Term Strategy

Fundamental Particles and Forces