POF V.

The vision for MU-FPF

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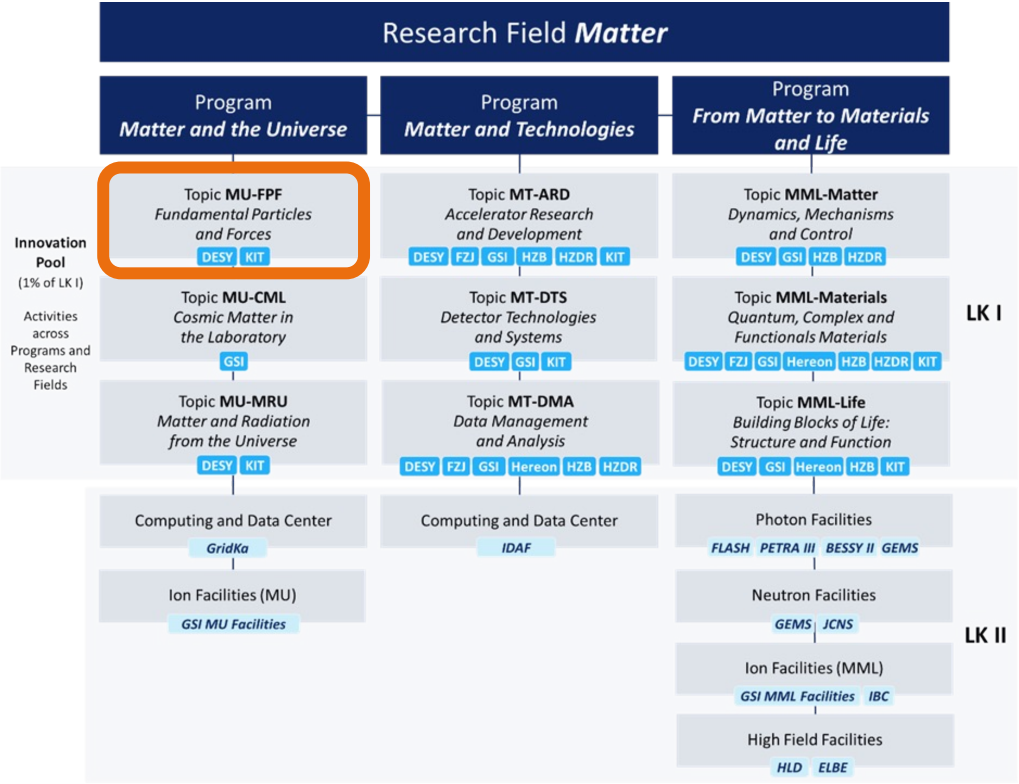
DESY

21 July 2025

HELMHOLTZ

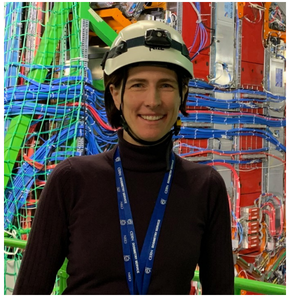
Research field Matter

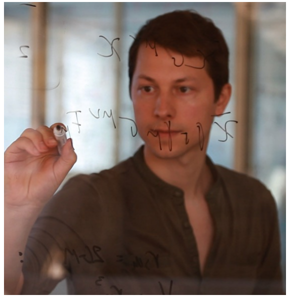
Topic "Fundamental Particles and Forces" aka FPF



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

(numbers from 2023)





Changes from PoF IV to PoF V

Foreseen change of the subtopic structure

- Higgs and fundamental interactions at high precision
- Searches for new particles & phenomena
- Cosmology and the dark sector of the universe

PoF IV → PoF V

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

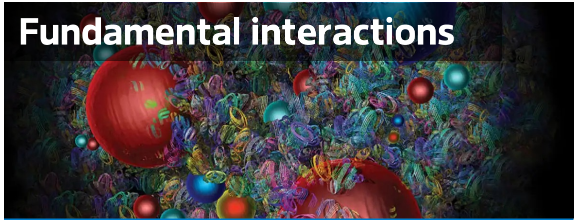
The early universe:
The evolution of the early universe and the nature of the dark sector

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

PoF V subtopic structure and science drivers

Science drivers addressing the big questions of nature: Understanding the quantum universe

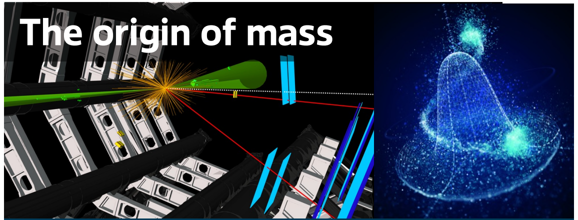
Fundamental interactions



Pushing the limits of our understanding of fundamental interactions

- Electroweak (EW) precision and Higgs physics (HH and Higgs potential)
- Strong-field QED
- QCD (incl. lattice and QC)
- Probing extensions of the SM

The origin of mass



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

- Dynamics of EW symmetry breaking
- Higgs as portal to new particles
- Top and B and Tau physics
- Charge-parity violation
- Lepton flavor universality

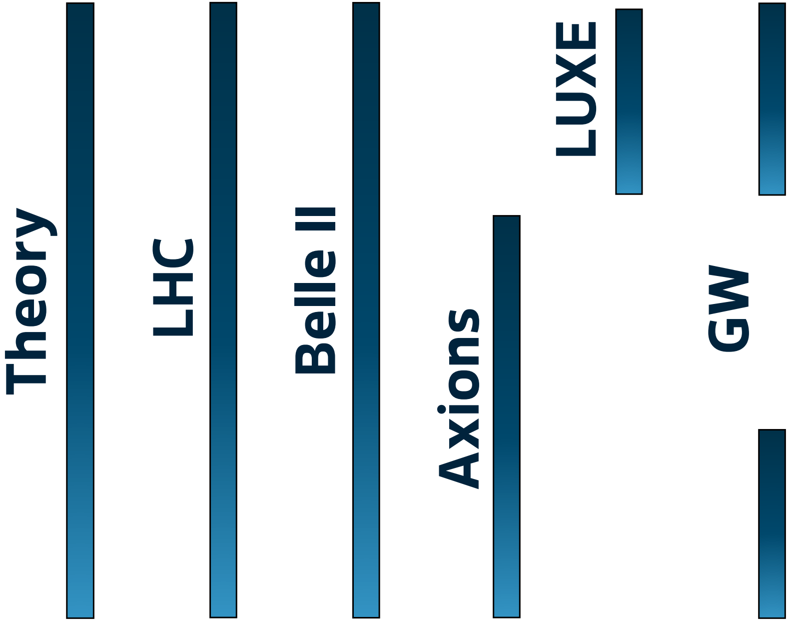
The early universe

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

- Cosmology (inflation, baryogenesis,...)
- Searches for dark matter candidates (WIMPs, axions, ALPs,...)
- Gravitational waves
- EW phase transition

PoF V subtopic structure

Connection to theory and experiments



Fundamental interactions:
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Testbeam Facility

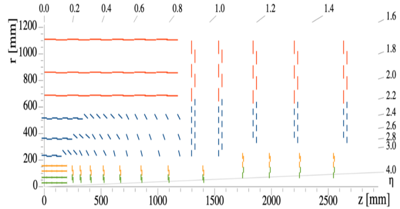
Detector Assembly Facility (DAF)

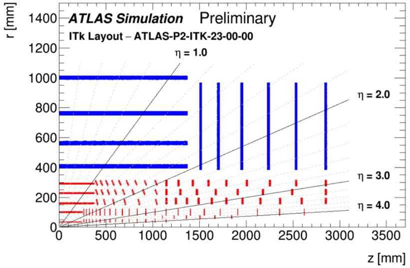
Computing Centres GridKa and IDAF

Connection to MT

LHC Detector Upgrade Projects

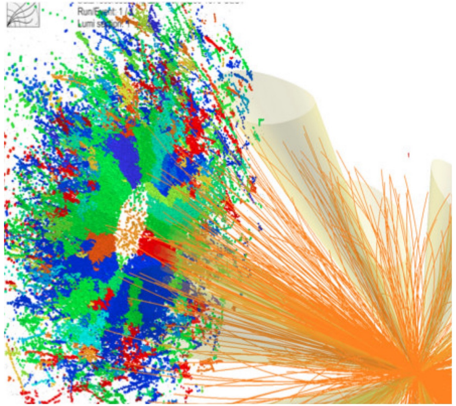
… will continue to be a major effort





- **New trackers for ATLAS and CMS:**
  - Increased granularity → **cope with the dense environment** at HL-LHC
  - Increased radiation tolerance → cope with the **harsh radiation** at HL-LHC
  - Improved hit resolution for high-pT tracks
  - Track trigger (@CMS) → **data reduction at trigger** readout by factor 10-20
  - Extended tracking to the forward region → better access to **VBF measurements**

- **HGCAL:**
  - First particle flow calorimeter at a hadron collider, first **precise 5-D calorimeter** with the timing information
  - Granularity, radiation hardness, and extended coverage: instrumental for jet physics reducing energy resolution and enabling measurements in the forward direction (+ pileup mitigation)
  - Key to **improving high profile physics topics at HL-LHC** → HH, H signatures, VBF, tau signatures, forward flavour-tagging



DESY acts as a hub creating links to other institutes in Germany (and internationally)

LHC Detector Upgrade Projects

… getting it to work!!!

- **Make most of experience of construction at DESY**
  - Commissioning (2027-2029) and early data taking (2029-2030)
  - initial alignment and calibration(2029-2030): profit from existing know-how and test beam experience
  - Initial performance papers (2030-2032) profit from production experience

Perfect opportunity for young people to “touch the detector” and become real experimentalists

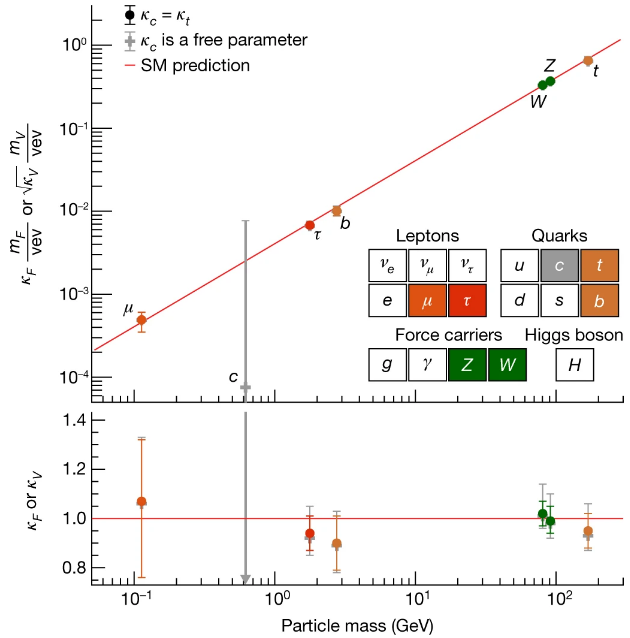
- **Profit of the ML papers being written in our groups**
  - Reconstruction and low-level expertise at DESY (alignment, particle flow, …)
  - Be the first/leading to put this in HL-LHC physics analyses
  - Let’s show that it works in real life!

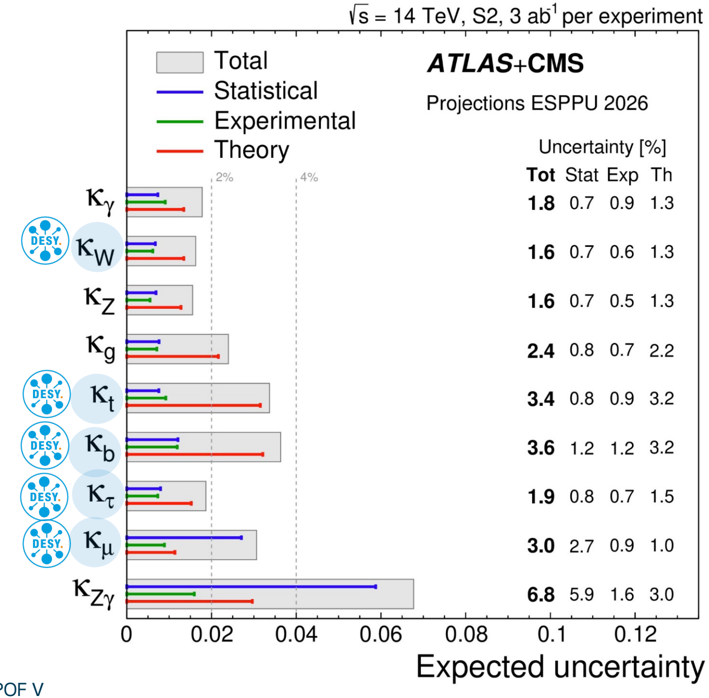
Investigating the detected Higgs boson

How do particles get their mass – by the SM Higgs mechanism or something else?

Measure the Higgs boson couplings as precisely as possible

- → CP odd coupling?
- → Unexpected (BSM) contributions?

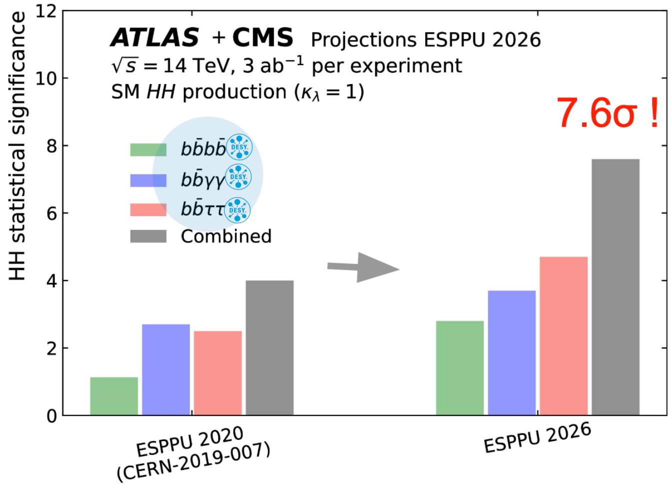




Tackling the di-Higgs production

Possible for the first time during PoF V!!!

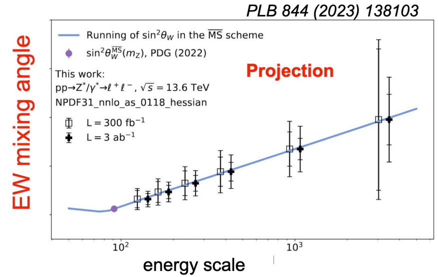
- **Probing the Higgs potential and the mechanism of electroweak symmetry breaking!**
- **Does the Higgs boson couple to itself as we expect?**
  → HL-LHC allows this measurement for the first time!
  – Room for surprises:
    new heavy resonances could enhance cross section!
  – Most sensitive channels are exactly those where DESY profits from expertise on object performance
  → DESY with both ATLAS and CMS groups is in an excellent position to work on combinations
  – **5σ discovery already with 2 ab^{-1}**
    (expected in combination of ATLAS and CMS by the end of PoF V)



Precision tests of the fundamental forces

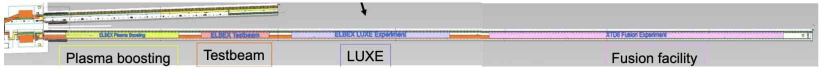
Profiting from new detectors and experiments

- **ElectroWeak (EW) force:**
  - Measurements of the fundamental parameters, e.g. EW mixing angle (exploiting new forward tracking)

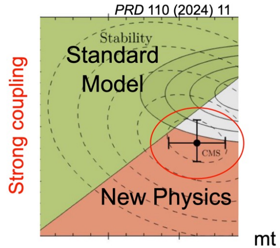


First measurement

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



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

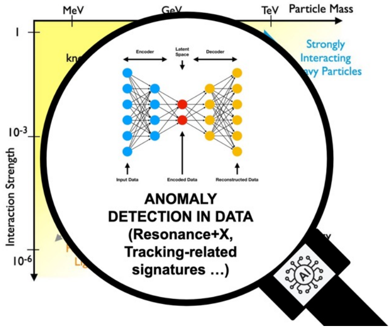


Improve by factor of 2!

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

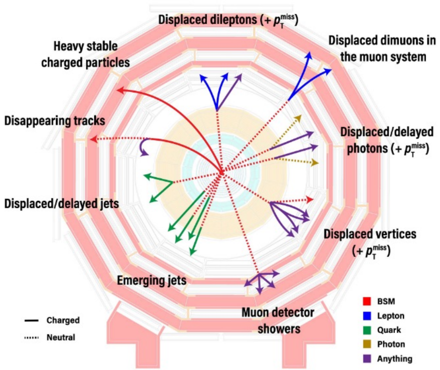
Bring light into open questions

Focus on new opportunities from our detector upgrades and high lumi



- **Probing the Matter-Antimatter asymmetry**
  → Search for CP violation in the Higgs sector
- **Why is the Higgs boson so light?**
  → Search for extensions of the SM, but also for the unknown

New physics with long-lived particles (incl τ leptons, jets, leptons)

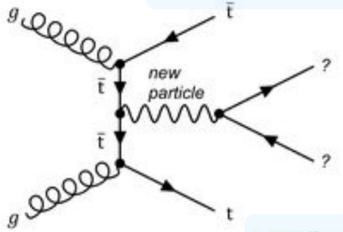


New L1 triggers (HGCAL)

τ-reco (Tracker)

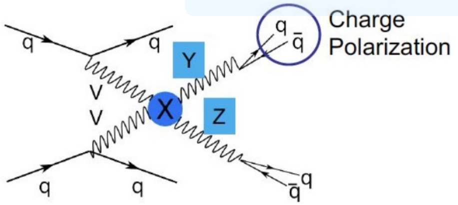
New physics in (multi)top final states
(full range: single top+X through tttt(+X?) signatures)

b-tagging (Tracker)



VBF-produced new physics

Jet-substructure (Tracker)



VBF/forward jets (HGCAL/Tracker)

Machine learning for
- Object identification
- Background prediction
- Event classification

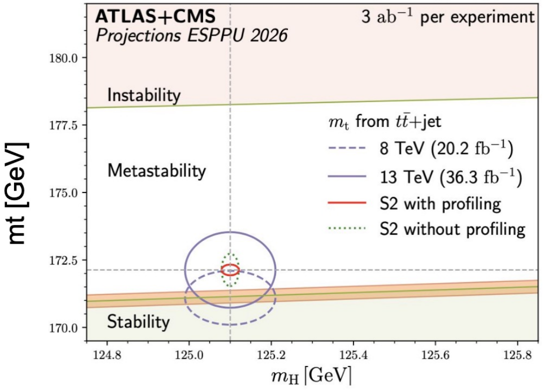
This broad strategy is sensitive to many BSM scenarios and ready for (positive) surprises at HL-LHC

Pattern in fermion masses?

DESY tackles the 3rd generation

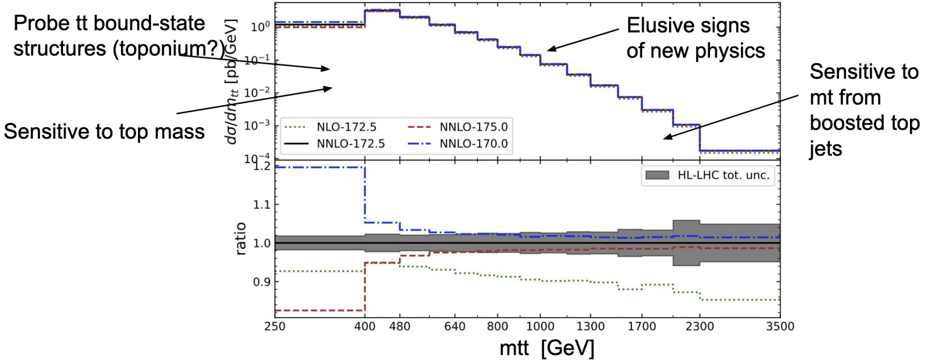
- Understanding the **top quark** and its couplings from the non-relativistic to highly-boosted regime:
  → Ultimate stress test of the SM and window to BSM
- Deliver the most precise **τ mass** measurement at Belle II
- **Is our Universe stable?**
  → Precise measurement of **W and top mass**

arXiv:2504.00672



End HL-LHC mt precision ~ 200 MeV

arXiv:2407.16061

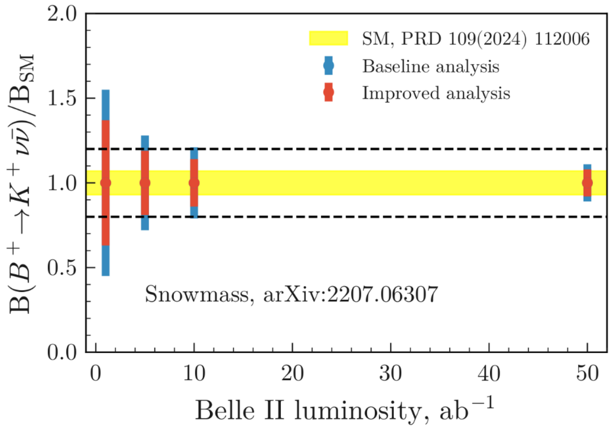


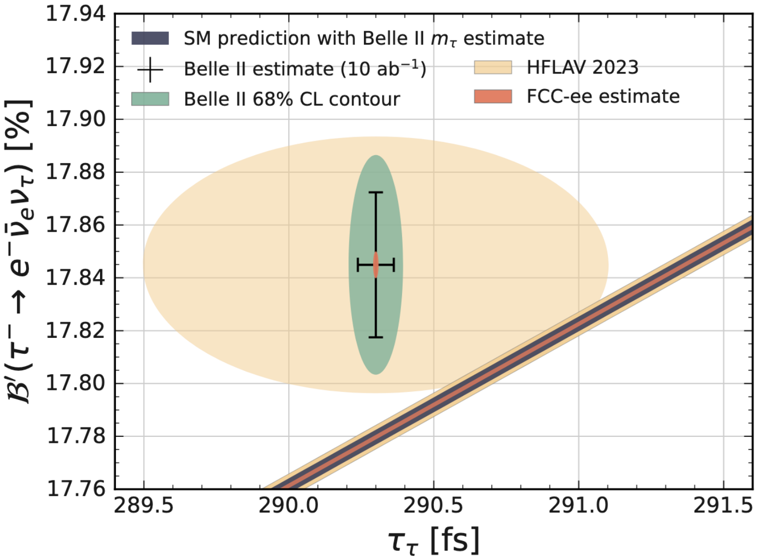
New trackers fundamental

Difference between the 3 generations?

… beyond mass?

- **Test lepton flavor universality** with τ leptons at Belle II
  - Expect significant improvement in **lifetime measurement**
  - Measure $\mathcal{B}(\tau \to \ell \nu_\ell \nu_\tau)$ for the first time and challenge the SM
- Testing our predictions for the three generations by measuring **CKM parameters:** α, β, $|V_{us}|$
- **Measurement of $B^+ \to K^+ \nu\nu$:** interesting since current measurement higher than SM
  - 5 ab^{-1} is sufficient to establish the process (assuming SM)
  - Complement with other channels (B^0 decays, …)





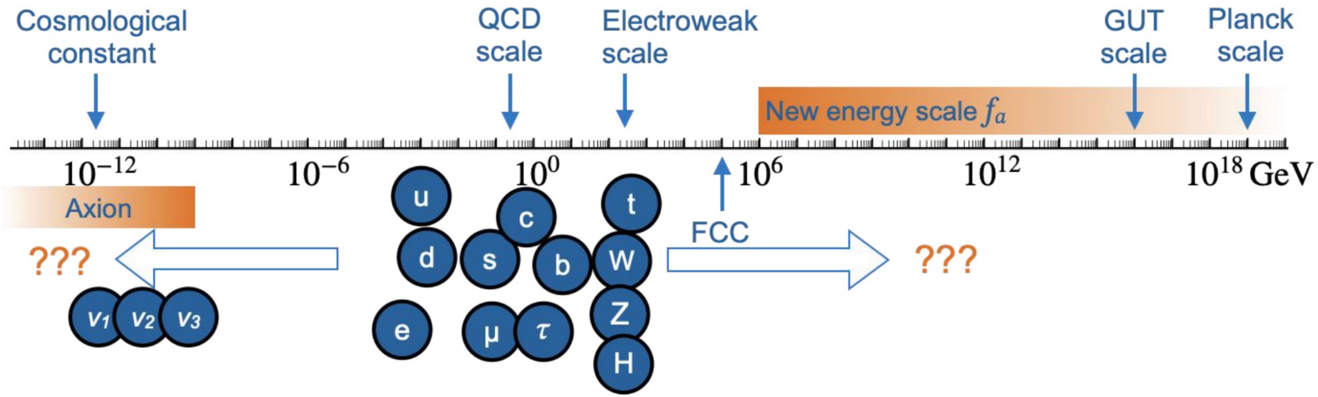
New PXD pivotal for the lifetime measurement

The dark side

… of the early universe

- **What is dark matter?**
  - If produced in the early universe, it could also be produced at colliders!
  - Is the Higgs boson a portal to dark matter?
  - Axions and axion-like particles are viable candidates (and could be produced in the lab or in the sun)

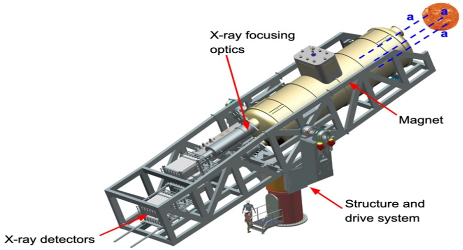
- **What is dark energy?**
  - Ultralight (<10^{-33} eV) axions could be the dynamical dark energy

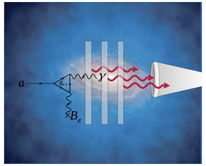


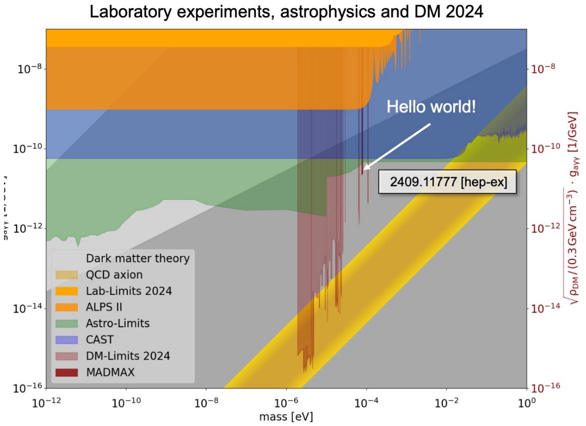
Planned axion searches

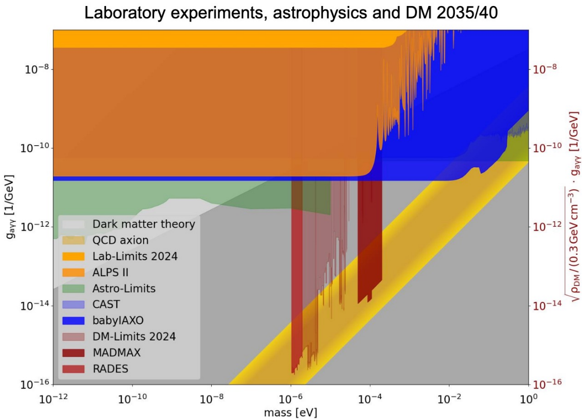
… at DESY as worldwide reknowned Axion Center

- **BabyIAXO**
  - The next generation state-of-the-art helioscope at DESY
  - Sensitivity: ~100x CERN Axion Solar Telescope (CAST)
  - **Goal: BabyIAXO built and taking first data in PoF V**
- **MADMAX**
  - Large resonator from many parallel dielectric disks
  - **Goal 1: MADMAX prototype cryostat up and running**
  - **Goal 2: Final magnet and cryostat to be installed in PoF V**









ALPS II target sensitivity

MADMAX target sensitivity

RADES target sensitivity (using the BabyIAXO magnet)

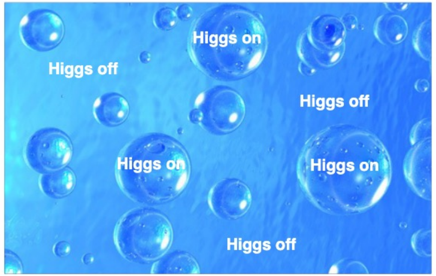
BabyIAXO target sensitivity

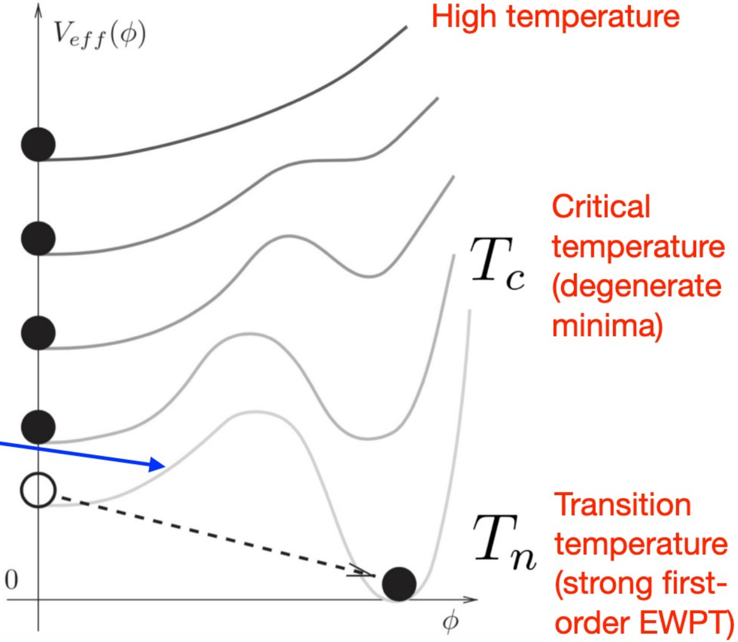
Higgs potential and EW phase transition

… in the early universe

Temperature evolution of the Higgs potential in the early universe:

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



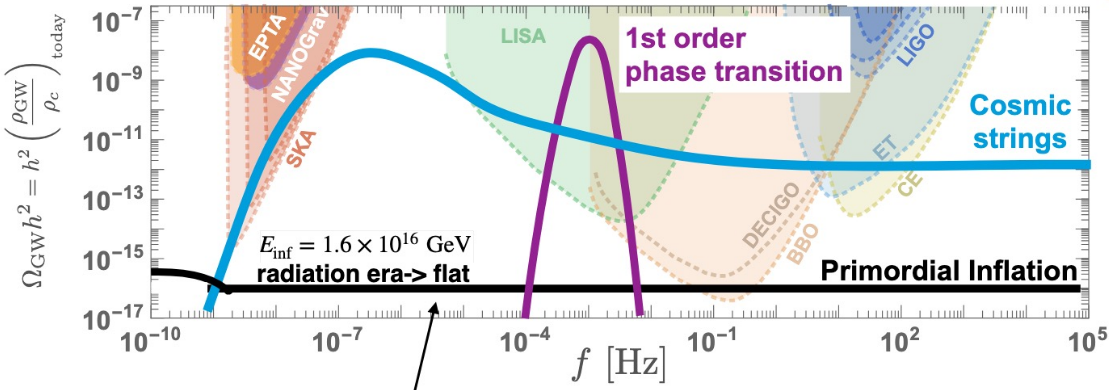


Potential barrier depends on trilinear Higgs coupling(s)

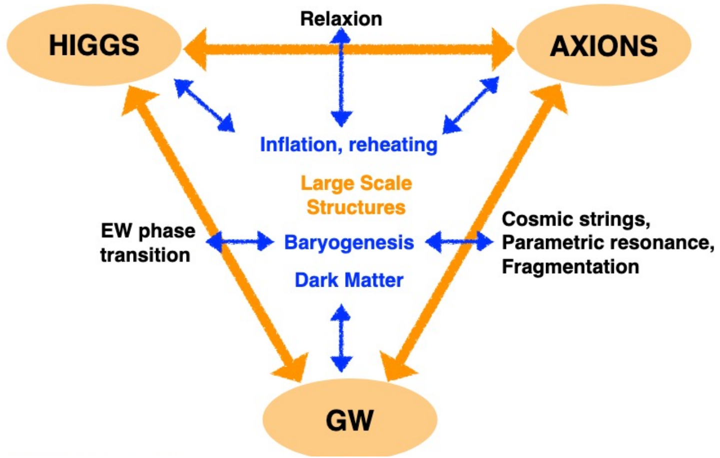
EW baryogenesis: creation of the asymmetry between matter and antimatter in the universe requires strong first-order EWPT

Gravitational waves

… as a probe of the early universe

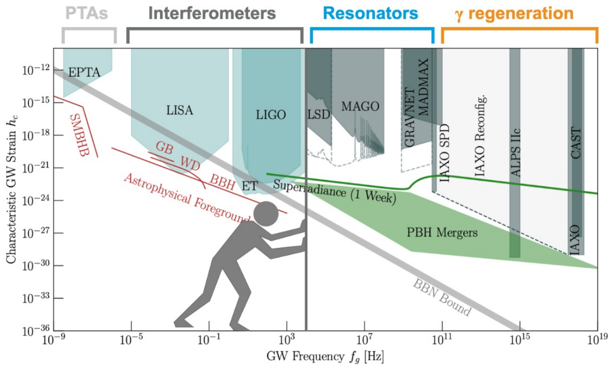


Irreducible GW background from amplification of initial quantum fluctuations of the gravitational field during inflation



Area of opportunity: test 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 sensors, usage of axion infrastructure



New projects

…after finishing the big upgrades

Optimistic scenario: Decision to build FCC-ee by CERN member states still during PoF V

- DESY in prime position:
  - Member of several R&D collaborations
  - Experience in building large scale detectors

Alternative CERN projects will be on the same timescale

Most optimistic timeline for FCC-ee during PoF V:

Earliest Project Approval by CERN Council	2028
Call for CDRs, collaboration forming	2028
Construction of system demonstrators; Physics performance studies for detector optimization	2028-2031
End of HL-LHC upgrade: more detector experts available	2029
4 **Detector CDRs** ready	2031
Production of scalable prototypes	2031-35
4 **Detector TDRs** ready	2035
Detector component production	2036

New projects

…after finishing the big upgrades → Connection to MT

Detector activities: formally part of MT-DTS and MU-FPF:

- **MT-DTS: Detector R&D**
  - Silicon detector R&D: CMOS based Pixel and Strips
  - Silicon photonic transceiver (InnoPool SoPhie)
  - Calorimeter developments
  - Advanced cooling techniques
  - …

- **MU-FPF: Detector construction for experiments**
  - ATLAS and CMS Phase-2 upgrade
  - Belle-II PXD2 (completed)
  - TES for ALPS…
  - In parallel: physics performance and physics-driven detector optimisation for new experiments

Transition from R&D to prototyping and construction involves transition of research programme.

R&D goals in MT-DTS should be aligned with plans in MU-FPF.

Topics of interest in MT

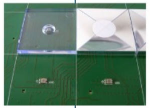
… and connection to DRDs

Silicon detector development is a strong focus of our interest

- Monolithic CMOS
- Novel sensors (ELAD, digital SiPM, …)
- Software tool developments
- Involvement in DRD3 (Silicon)

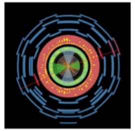
Calorimeter developments

- Highly granular SiPM on tile calorimeter
- Involvement in DRD6 (Calo)



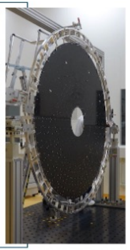
Data transfer

- Silicon photonics
- Advanced interconnects
- Involvement in DRD7 (Electronics)



Integration

- Detector integration center
- R&D on light weight mechanics, local cooling and cooling systems
- Involvement in DRD8 (Integration)



Cryogenic detectors

- Transition Edge Sensors
- Developments for axion/dark matter experiments
- Involvement in DRD5 (Quantum sensors)

Infrastructure

- Detector Assembly Facility
- Test beam

Cross topic goal: Build a demonstrator vertex detector based on CMOS technologies

Investigation of other projects

Recap from last retreat

Consider other projects

- that are scientifically interesting
- that fit our expertise
- that cannot be done by a (small) university group
- where DESY can have an impact
- where the (realistic) timescale fits
- where DESY can act as German hub

Beware: partly obsolete by now

	Physics - Neutrino	Physics - FIPs	Physics - Other	FH Expertise	FH Infrastructure	German Hub	DESY Impact on Project	Cross-Division Synergies	Realistic	Impact on Society	Interesting Tech	Gain for DESY	Timeline
DUNE			PD										
Hyper-K			PD										
ESS-nu			PD										
nuStorm			R&D										
0v2b													
CEvENS													
Short Baseline													
FPF			QCD										
HIKE+SHADOWS+NANU			Flav										
SHIP+SND													
LDMX													
LHCb			Flav										
MATHUSLA/Codex/Anubis													
LUXE NPOD			QED										
Baby-IAXO													
MADMAX													
IAXO													
EDM Storage Ring													

For discussion in the afternoon

Investigation of other projects

Focus on Silicon technology

Consider other projects

- that are scientifically interesting
- that fit our expertise
- that cannot be done by a (small) university group
- where DESY can have an impact
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Experiment	Timescale (start run)	Certain	(MAPS) R&D compatible	System expertise	Si size	DESY involved?	DESY as German hub
P2 Spectrometer @ MESA	In construction	yes	No	?	small	Chip charact.	EC: Prisma++
INSIGHT @ ELSA	2027	yes	No	yes	small	no	EC: Colour meets Flavour
LOHENGRIN @ ELSA	~2030	yes	Maybe Needs also HCAL	yes	10s cm2	no	EC: Colour meets Flavour
LUXE upgrade	Middle 2030ies	no	yes	yes	~200 cm2	On-site	?
Belle-2 tracker upgrade	2034 Decis. 2028	no	Probably not (Obelix)	yes	VTX: 10s cm2 ITT: several m2	yes	yes
KOTO-2 veto	2034	likely	maybe	yes	20*20 cm2	no	No?
KOTO-2 Tracker	2034 or ~8 years later	no	One proposal based on MightyPix	yes	Large, in vacuum	no	No?
LHCb Upgrade 2 MightyTracker	2036	yes	No, will use MightyPix	yes	10s m2	no	yes
newAstrogam	Launch 2041 Decis. 2030	no	No, will use AstroPix	yes	~10 m2	AP project	?

For discussion in the afternoon

We need to plan now for new projects

… to be able to capitalize on our experience!

Decades of experience in leading and supporting physics and detector efforts worldwide

- **Need to maintain and evolve DESY's position as a German hub**
  - In sync with momentum growth in the community
- **Capitalise on DESY strengths:**
  - **In data analysis** and the strong link to **theory**
  - Overall **detector concepts** and optimisation
  - **Software** frameworks and **integration**
  - **Detector technology** competences and **infrastructure**

→ Need to continue in a leading role in PoF V, together with German institutes:
- **→ in growing number of on-site experiments,**
- **→ in current off-site experiments and in future experiments at CERN**
- **→ in possible intermediate projects**

More time for discussion
in the afternoon

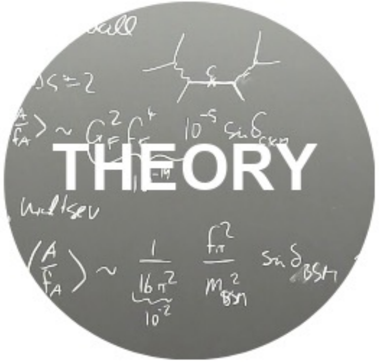
Backup / further info

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?

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:

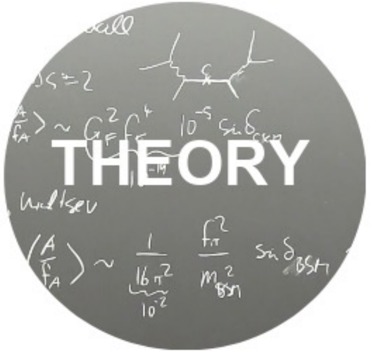
- **Planned axion experiments: BabyIAXO, MADMAX**
- **QED at the extreme: LUXE**

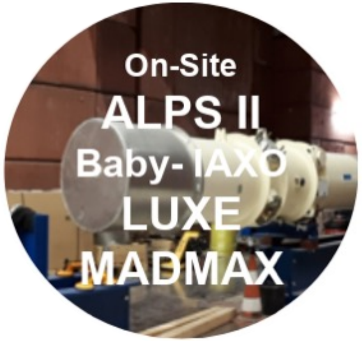
New ideas:

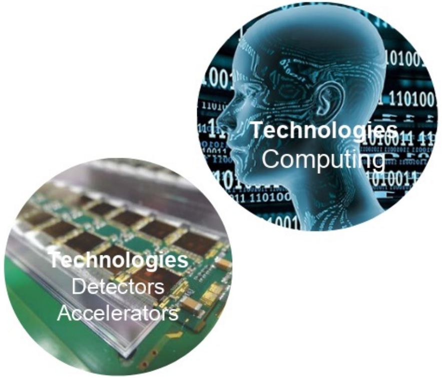
- **VMB @ ALPS II**
- **High-frequency GW experiments**

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!

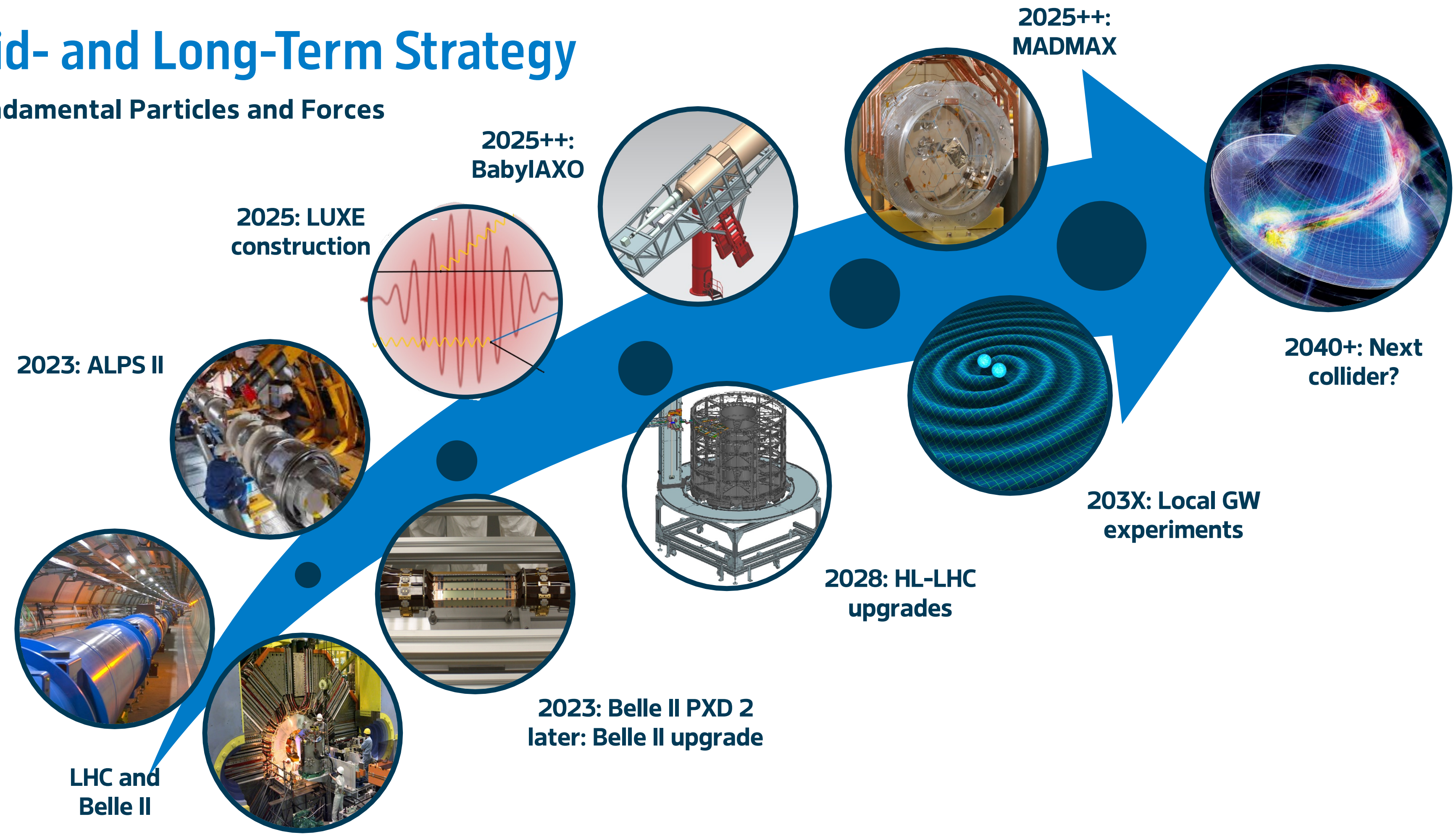
Strengthen innovation in detectors and computing

Increase 3rd party funding

Strengthen exchange across divisions

Mid- and Long-Term Strategy

Fundamental Particles and Forces



The origin of mass

Testing our predictions for the three generations by measuring CKM parameters

- 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

PXD fundamental in controlling resolution function systematics

$B \rightarrow J/\psi K_S^0$ $\qquad$ $B \rightarrow J/\psi K_L^0$