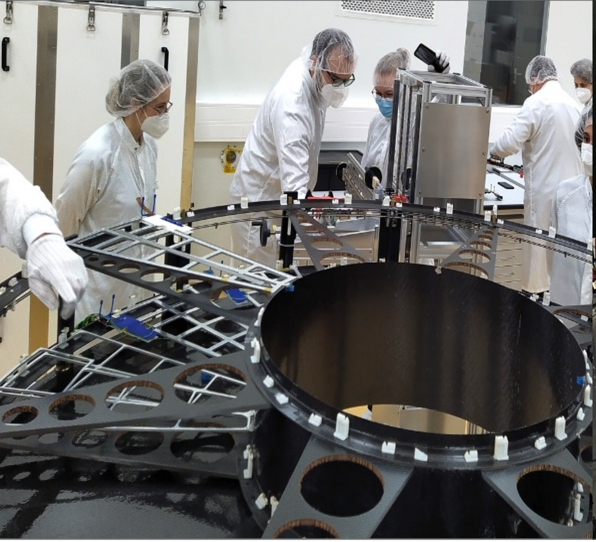
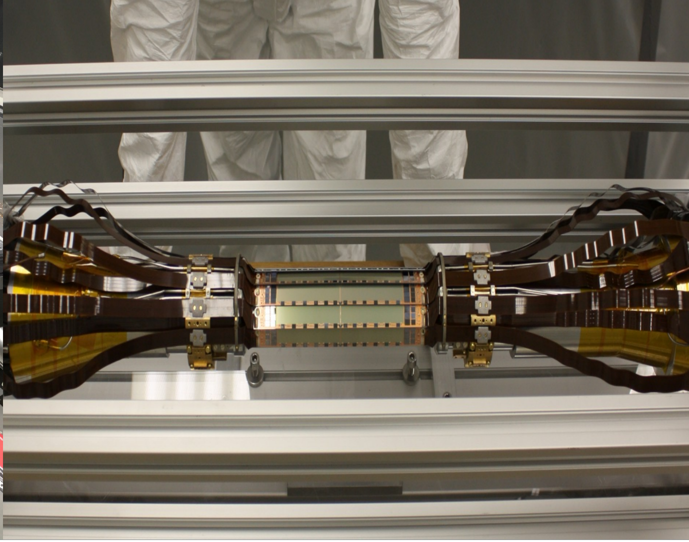




Particle physics at DESY: current projects and future plan

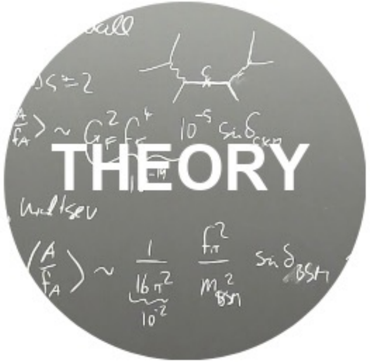
Isabell Melzer-Pellmann

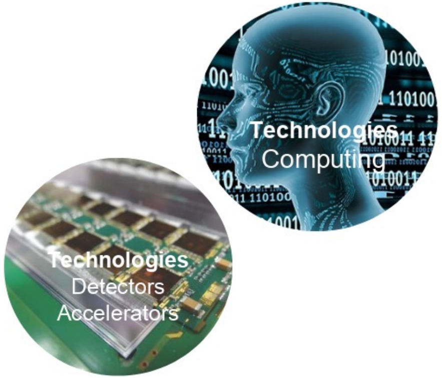
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DESY.

Four pillars of particle physics at DESY

Specific focus areas for the next 10-15 years





Key contributions to global projects at CERN and KEK
- **ATLAS**
- **CMS**
- **Belle II**

Closely work with German universities (natl. hub)

Wolfgang-Pauli-Center:
- World-leading interdisciplinary center for theoretical physics

Theory as “idea factory”

ALPS II: first science run finished

Planned projects > 2029: BabyIAXO, LUXE, MADMAX:

New ideas, e.g. HF GW local experiments (complementing ET)

Strengthen innovation in detectors and computing

Increase 3rd party funding

Strengthen exchange across division and (German) universities

Supporting Infrastructures

… are critical for the success of the scientific programme and for fulfilling the role as national lab: Providing community services, enabling large German contributions, German hub function

Testbeam Facility

FLASH Forward

Computing Center
(incl. National Analysis Facility)

Infrastructure for
on-site experiments

Detector Assembly Facility:
Crucial for HL-LHC upgrades

Wolfgang Pauli Center
(theory)

ATLAS and CMS

Many contributions by the DESY group

Activities in data analysis, alignment and calibration, luminosity, detector development and construction

- Both groups active in **Standard Model measurements**, e.g.:
  - QCD and electroweak precision measurements (e.g. W boson mass, eff. EW mixing angle, α_S)
  - Higgs physics
  - Top physics
  - Measurements in heavy ion collisions, e.g. light-by-light scattering
- Many activities also in **searches for new physics**, e.g. searches for:
  - Heavy neutral leptons
  - Dark Matter
  - Additional vector bosons
  - Additional Higgs bosons
  - Long-lived particles
- Minimal selection of results and upgrade activities on the next slides

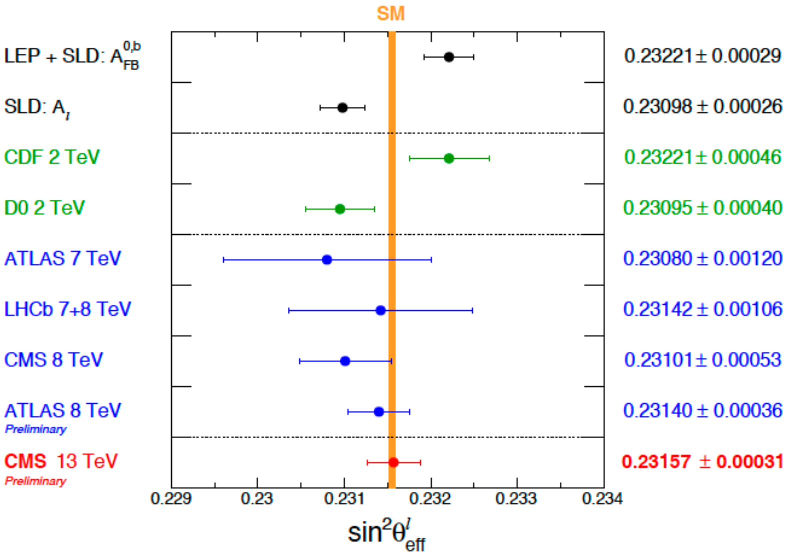
Precision @ CMS: effective electroweak mixing angle

Key parameter in the Standard Model, determined from Z bosons

- **Weak mixing angle:**

$$\sin^2\theta_W = 1 - m_W^2 / m_Z^2$$

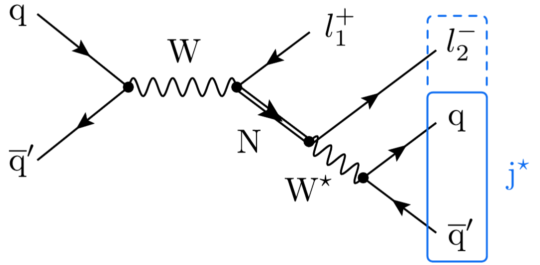
- Presence of axial and vector-axial couplings (and EW mixing angle)
  → non-zero forward-backwards asymmetry A_{FB}, sensitive to effective quantity $\sin^2\theta_{eff}$ (directly related to $\sin^2\theta_W$)
- Extraction possible with high-precision theory model, minimizing the uncertainties on the parton density function
- New CMS result:
  - Most precise hadron collider measurement
  - Excellent agreement with SM prediction



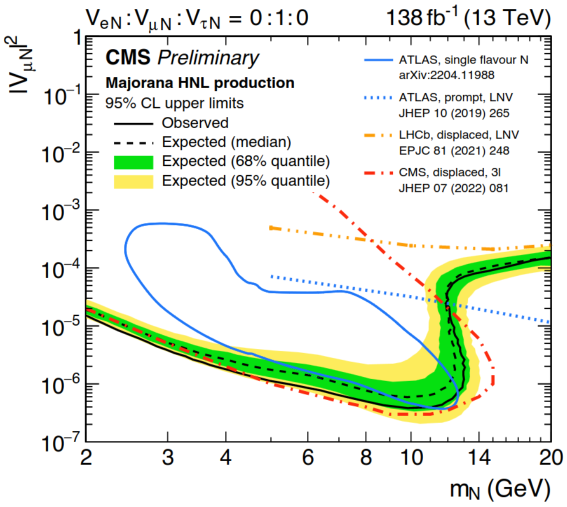
Search for long-lived heavy neutral leptons

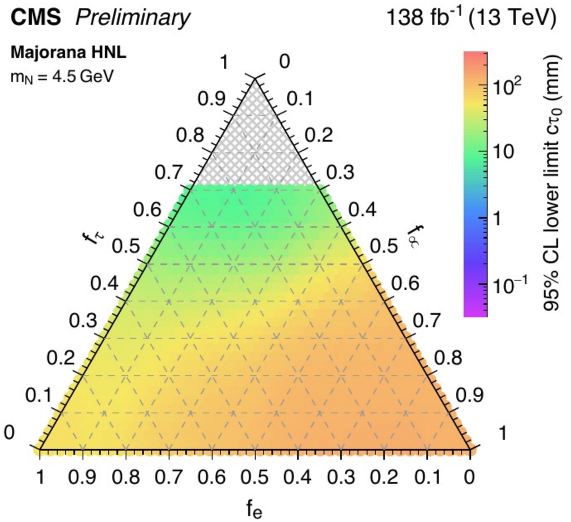
Heavy neutral leptons (HNLs) predicted by see-saw mechanism

- Can explain: neutrino masses/oscillations, dark matter, baryon asymmetry, …
- For small mixing with SM neutrinos → HNL becomes long-lived
- Unique signature: prompt lepton + displaced jet j* (w/ lepton)
  → easy to miss in traditional searches based on standard objects



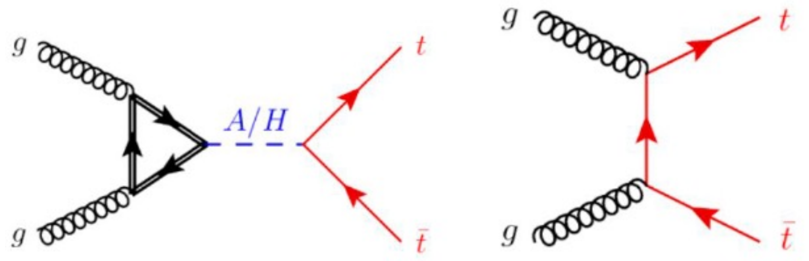
- Background rejected through novel DNN-based displaced jet tagger
- Set limits for arbitrary mixing of HNLs to all 3 lepton generations

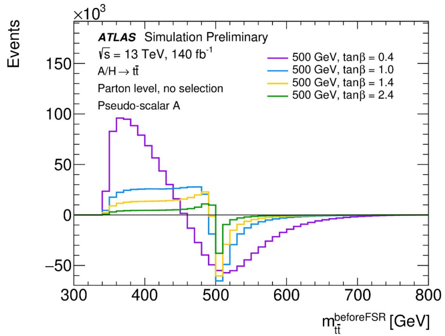




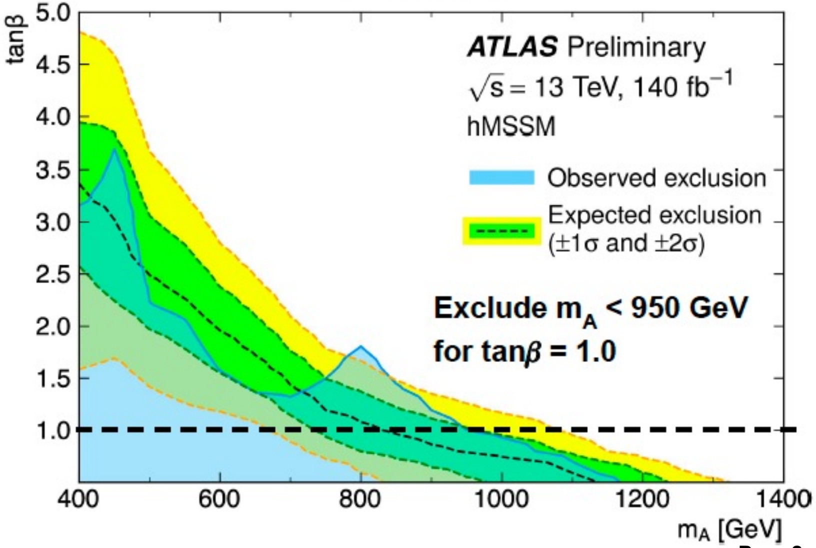
Searches for more Higgs bosons at ATLAS

Higgs decay to top-antitop pairs





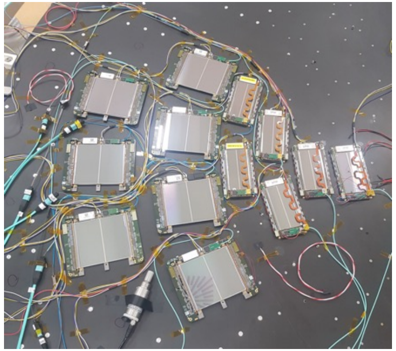
- **Is there only one H-boson?**
- Dominant BR of A/H → ttbar at high mass & low tanβ
- Signal process interferes strongly with irreducible background from SM ttbar events
  → peak-dip structure for signal
  → highly model dependent
- New limit extends beyond 1 TeV at low tanβ
  - Previously only m_A<700 GeV excluded

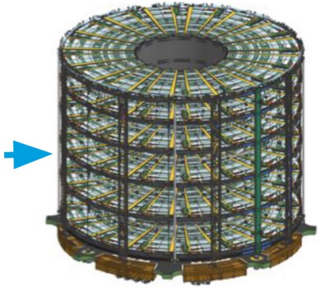


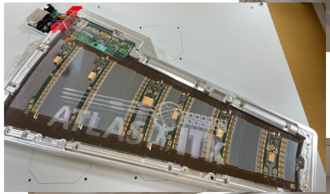
Upgrade activities of ATLAS and CMS for HL-LHC

Heavy use of the Detector Assembly Facility

- Both ATLAS and CMS will build one Silicon Tracker endcap





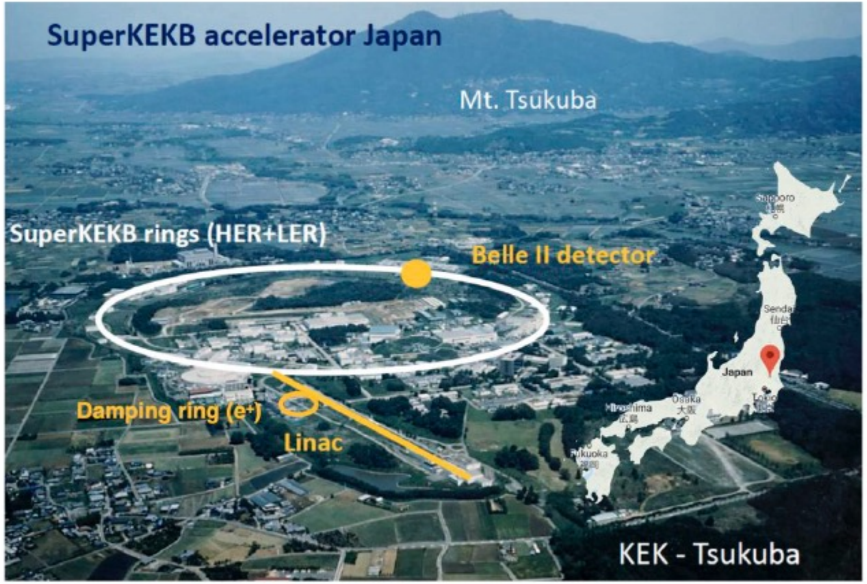


Belle II

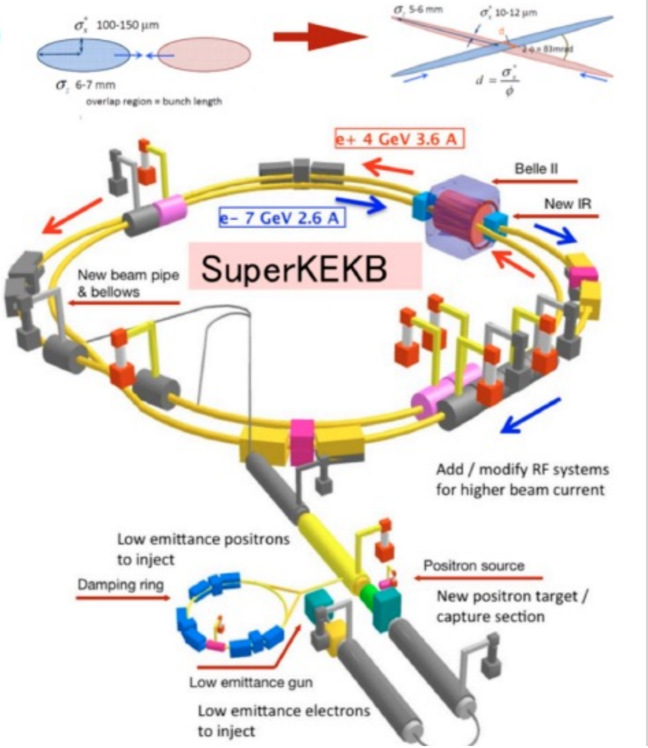
Belle II at SuperKEKB

A flavorful factory

- Asymmetric-energy e^+e^- collider operating at $\Upsilon(4S)$ mass peak
- Also operating at 60 MeV below $\Upsilon(4S)$ and energy scan around $\Upsilon(5S)$



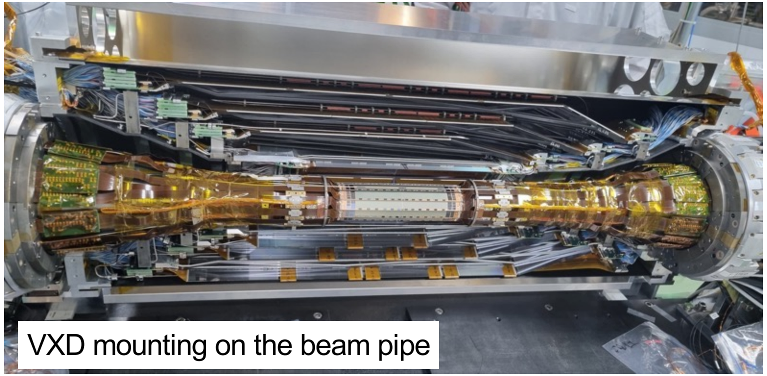
Upgraded detector and accelerator



Belle II Pixel Vertex Detector

Installed and commissioned with strong DESY contribution

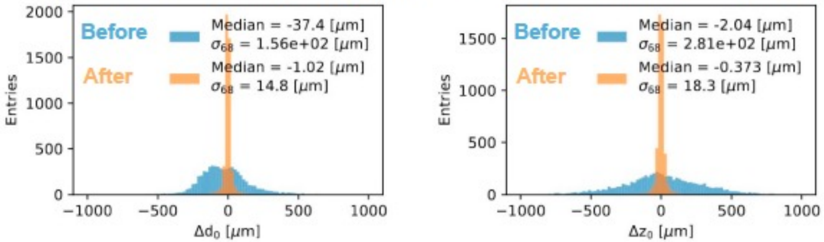
- After many years of preparation, the new two-layer PXD2 was installed in Belle II
- Part of physics data taking since February 2024
- First alignment successfully done with Millipede-II software [1]



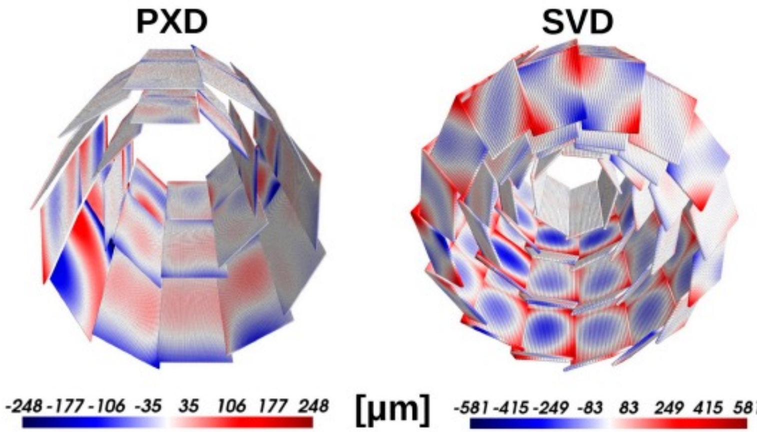
VXD mounting on the beam pipe

[1] Millipede (V. Blobel, C. Kleinwort):
https://www.desy.de/~kleinwrt/MP2/doc/html/index.html

Resolutions on impact parameters before and after alignment



Sensor position after alignment
(sensor surface deformation in color)



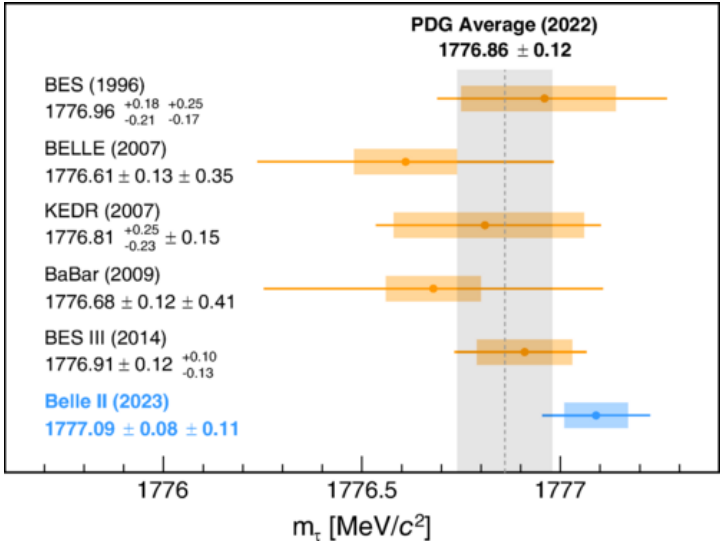
Precision measurement of the τ mass

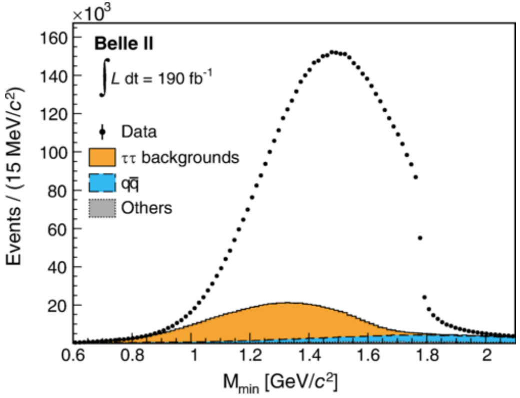
A fundamental Standard Model parameter

- Measure m_τ in the decay $\tau \to 3\pi\nu$ with "pseudo-mass" method:

$$M_{\text{min}} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$

- Neutrino is collinear with (3π) system + beam energy constraint
- Control over systematic uncertainties of high importance
- Accuracy in beam energy $\sqrt{s}$ and momentum p is key to precision
- Result: m_τ = (1777.09 ± 0.08 ± 0.11) MeV/c^2





→ **Precise measurement needed for Lepton Flavor Universality studies and measurement of $\alpha_S(m_\tau)$**

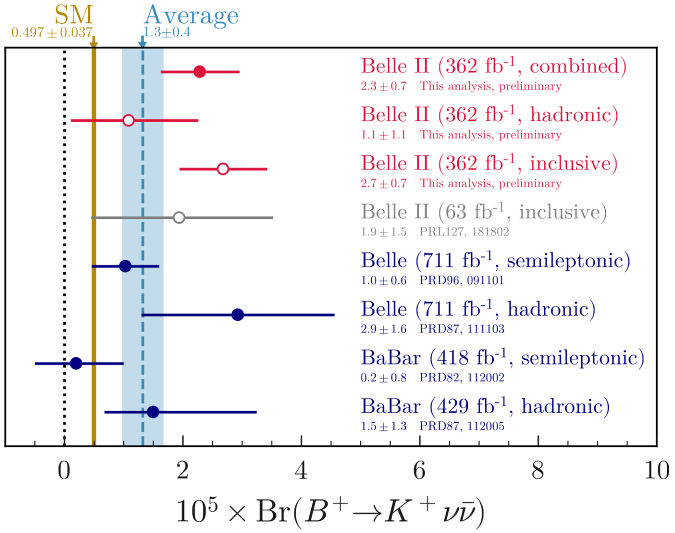
Search for $B^+ \to K^+ \nu\bar{\nu}$

Hint for new physics?

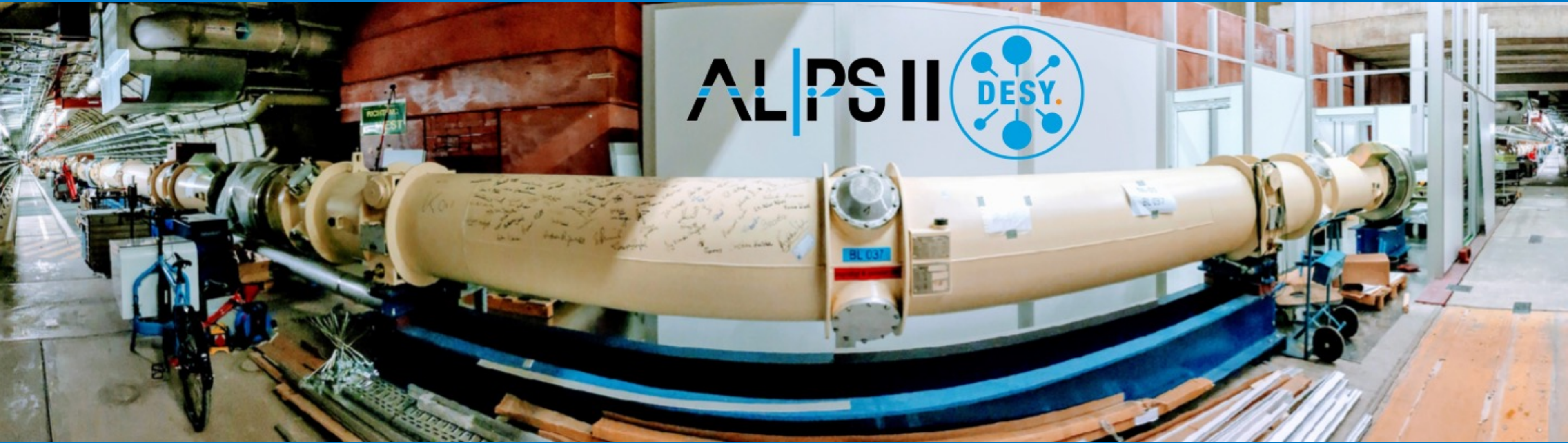
- **Prohibited at tree level in the SM**
  - Branching fraction: $(5.6 \pm 0.4) \times 10^{-6}$ [PRD 107, 119903 (2023)]
  - Precision dominated by theoretical uncertainties from hadronic form factors
- **Can receive significant enhancements from new physics**
  - New invisible particles in the final state, new mediators in the loop
  - Interplay with $B \to K^* \nu\bar{\nu}/K^{(*)}\tau\tau/K^{(*)}\tau\ell$ → probing third generation
  - Some common explanations of R(D(*)), and muon g-2 anomalies
- **Result of combination of two independent analyses**
  - 3.5 significance wrt the background-only hypothesis
  - 2.7 deviation from the SM signal
  - First evidence for the $B^+ \to K^+\nu\nu$ decay
  - Result:

$$\mu = 4.6 \pm 1.0\,(\text{stat}) \pm 0.9\,(\text{syst})$$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = [2.3 \pm 0.5\,(\text{stat})^{+0.5}_{-0.4}\,(\text{syst})] \times 10^{-5}$$

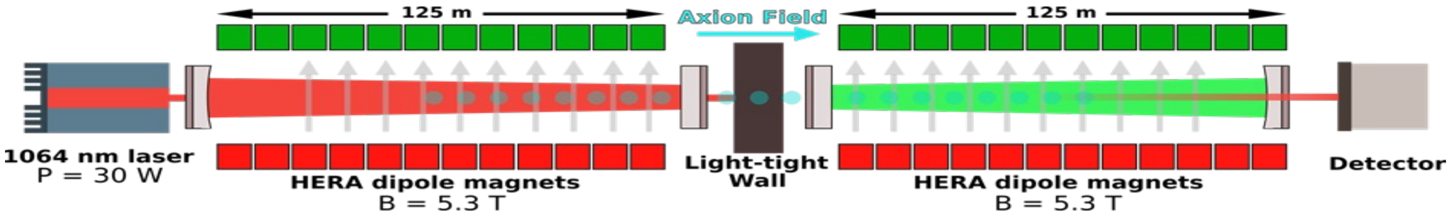


ALPS II



ALPS II

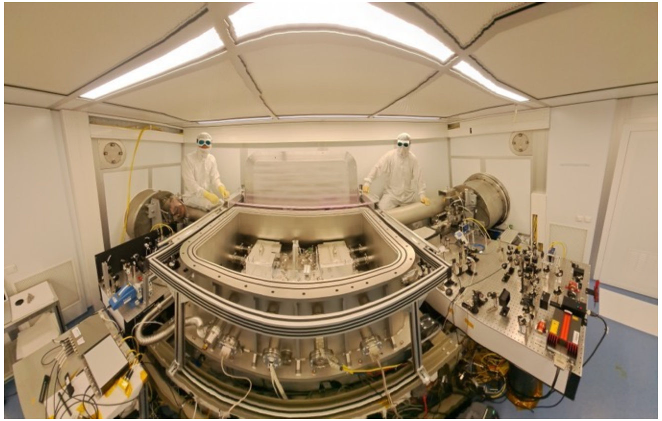
A light shining through wall experiment to find axion-like particles



Central optics breadboard of the ALPS II experiment

Magnet at nominal current on 24 May 2023

The optics hut with the central optics

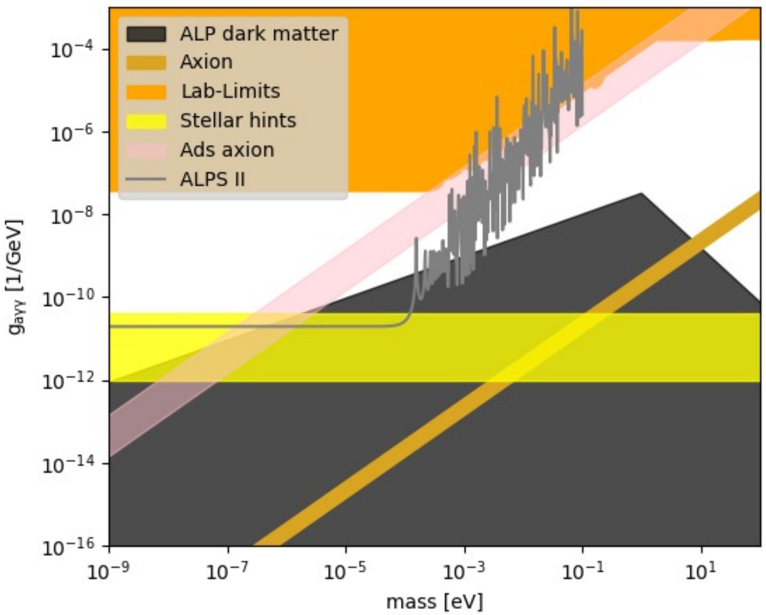


Integrated amount of one million seconds of good data used for first physics publication

ALPS II: First science results

Hot of the press from data taken until 6 May 2024

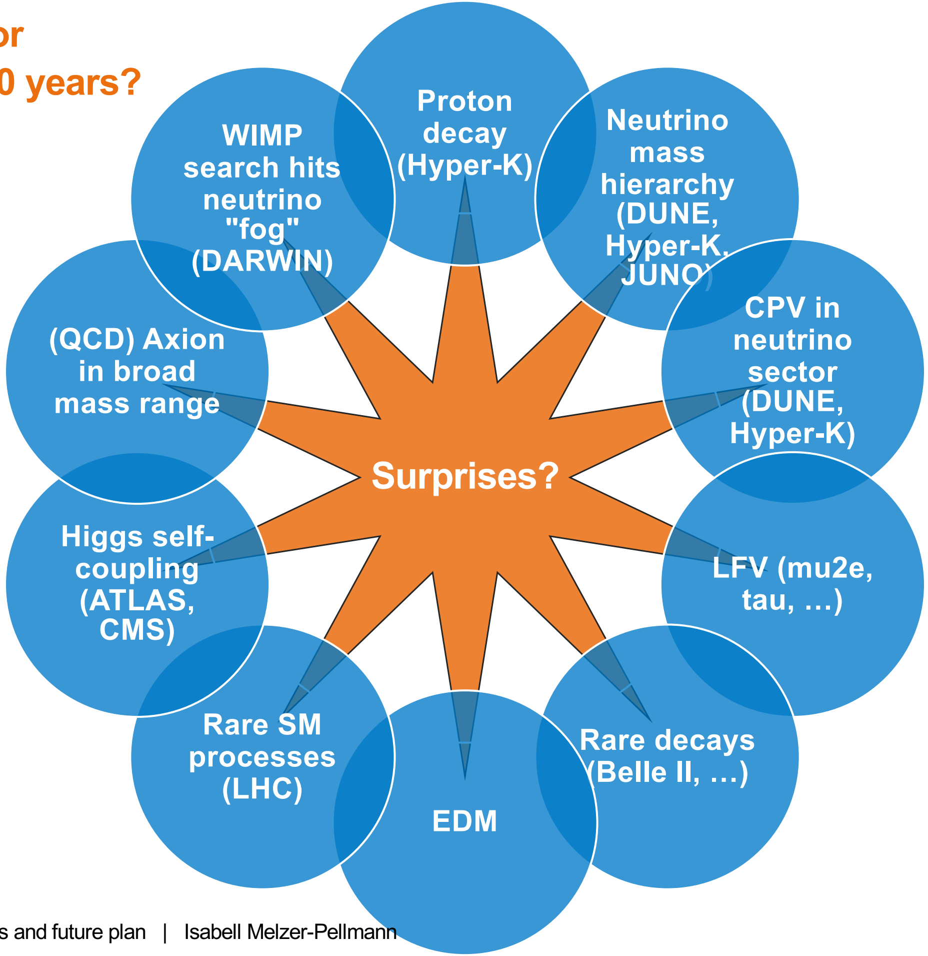
- Initial science runs, primarily aiming at stray-light hunting and verifying the performance of the optical systems, successfully concluded on 6 May 2024
- ALPS II already improved on the axion-photon coupling constant sensitivity by a factor ≥ 30



Future vision

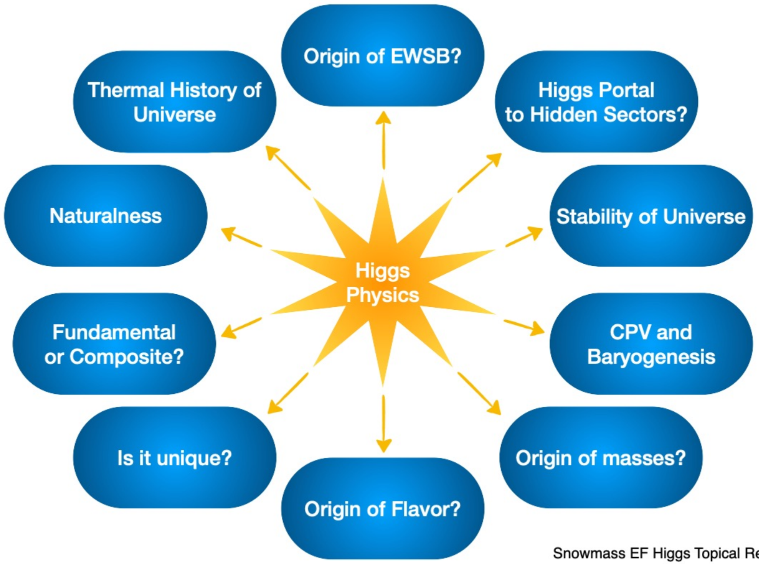
Particle Physics: Quo Vadis?

Where do we expect major progress in the next 10-20 years?

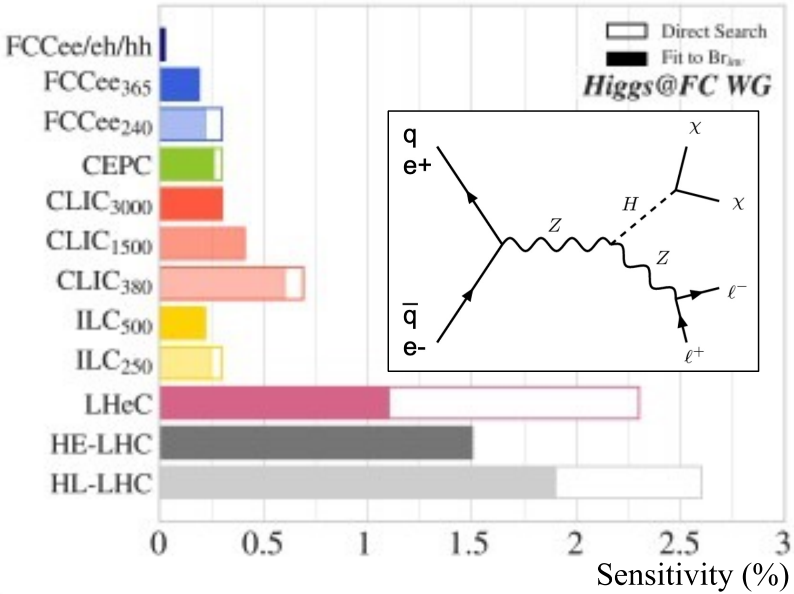


Higgs Precision Measurements

"Higgs is the most important actor … the reason for building the next colliders is to study the Higgs boson to death, full stop" (Nima Arkani-Hamed)



Snowmass EF Higgs Topical Report
S. Dawson, PM, I. Ojalvo, C. Vernieri et al
2209.07510



The Higgs boson is the most bizarre particle ever!

E.g. invisible Higgs: major improvements compared to current sensitivity of ~10%

- HL-LHC : <2.6%
- e+e- colliders: ~0.3%
- FCC-hh: ~0.025% (below SM value)

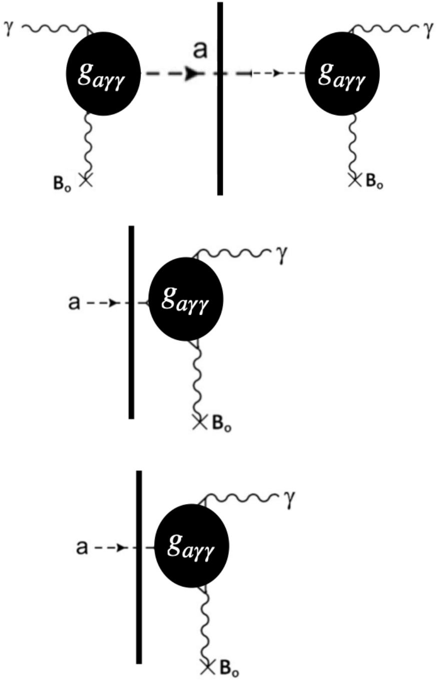
DESY's role as axion laboratory

Complementarity and model dependencies

Source | **Detection**

Lab axions

Solar axions



DESY's role as axion laboratory

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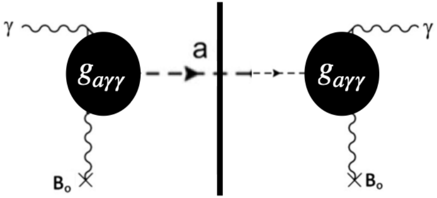
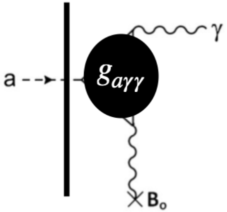
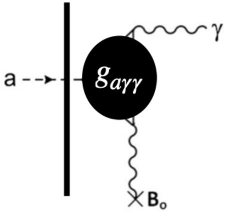
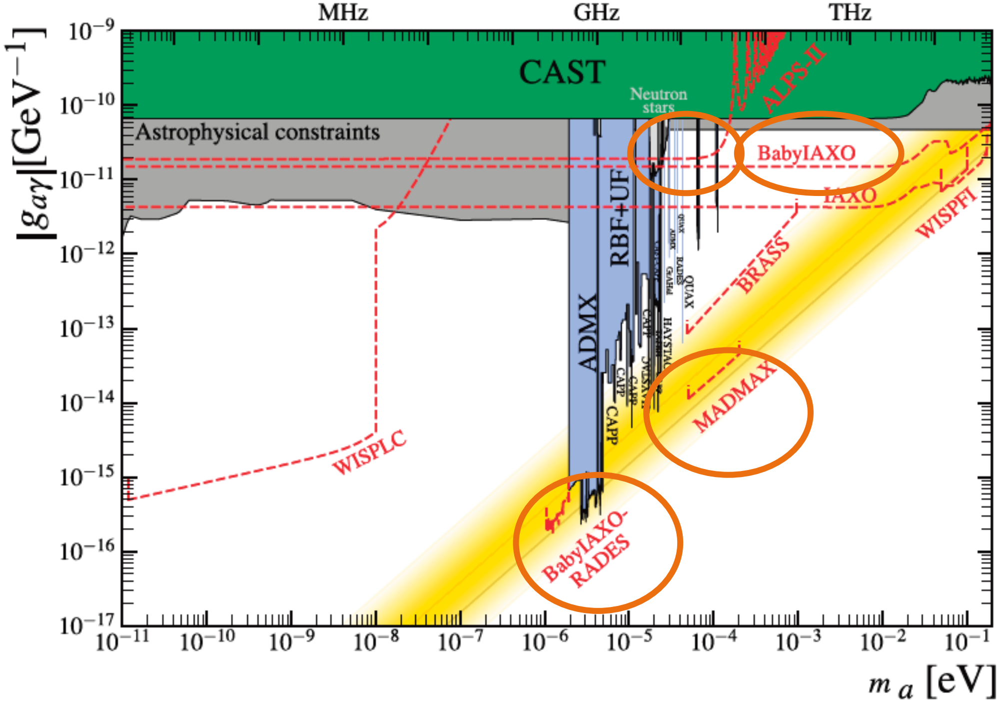


Solar axions



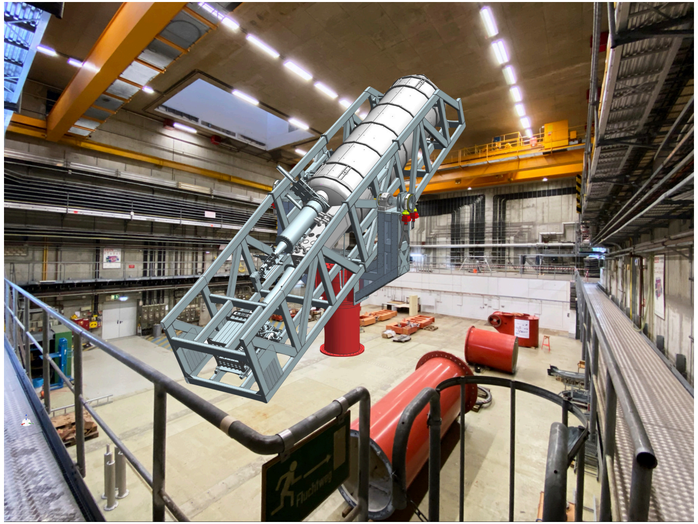


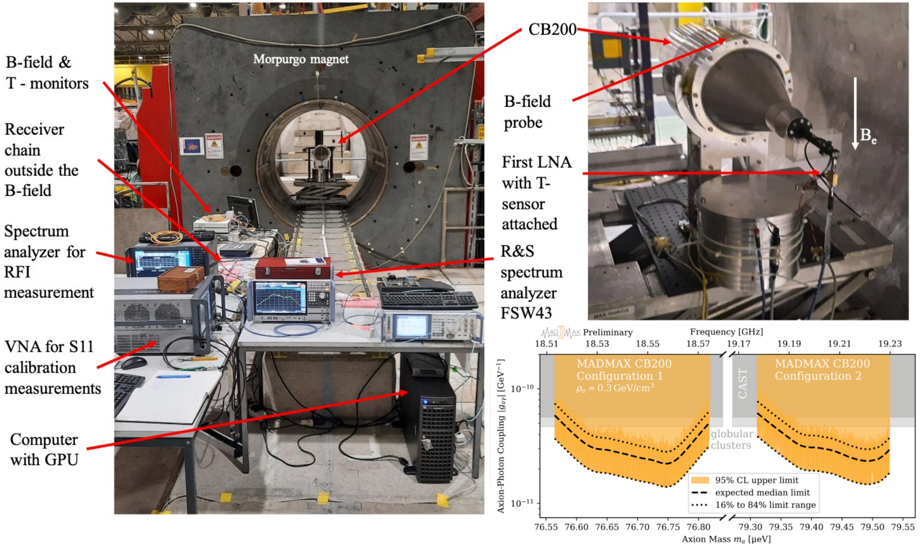


Axion landscape with projections

Future Axion Experiments

Preparing for BabyIAXO and MADMAX, turning DESY into THE axion centre worldwide





BabyIAXO – precursor of IAXO, the International Axion Observatory.

- Helioscope is planned to be installed in the HERA south (ex-ZEUS) hall in the coming years
- Most pressing problem: procurement of SC magnet cable – currently no non-Russian vendor

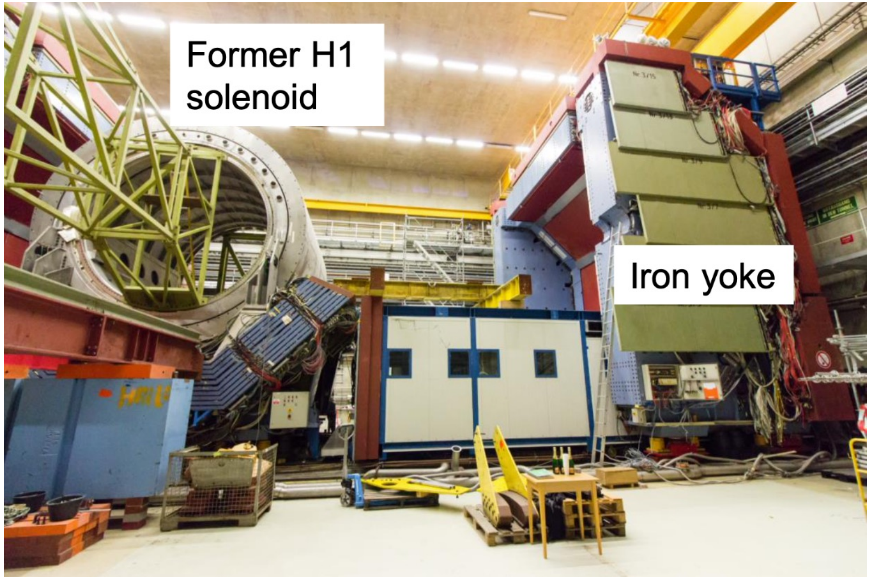
MADMAX – the axion and DM haloscope

- Planned to be installed in the HERA hall north (ex-H1) in the coming years
- Magnet development ongoing, but first physics result published using CERN Morpurgo magnet
- Feasibility studies for use of old H1 iron yoke

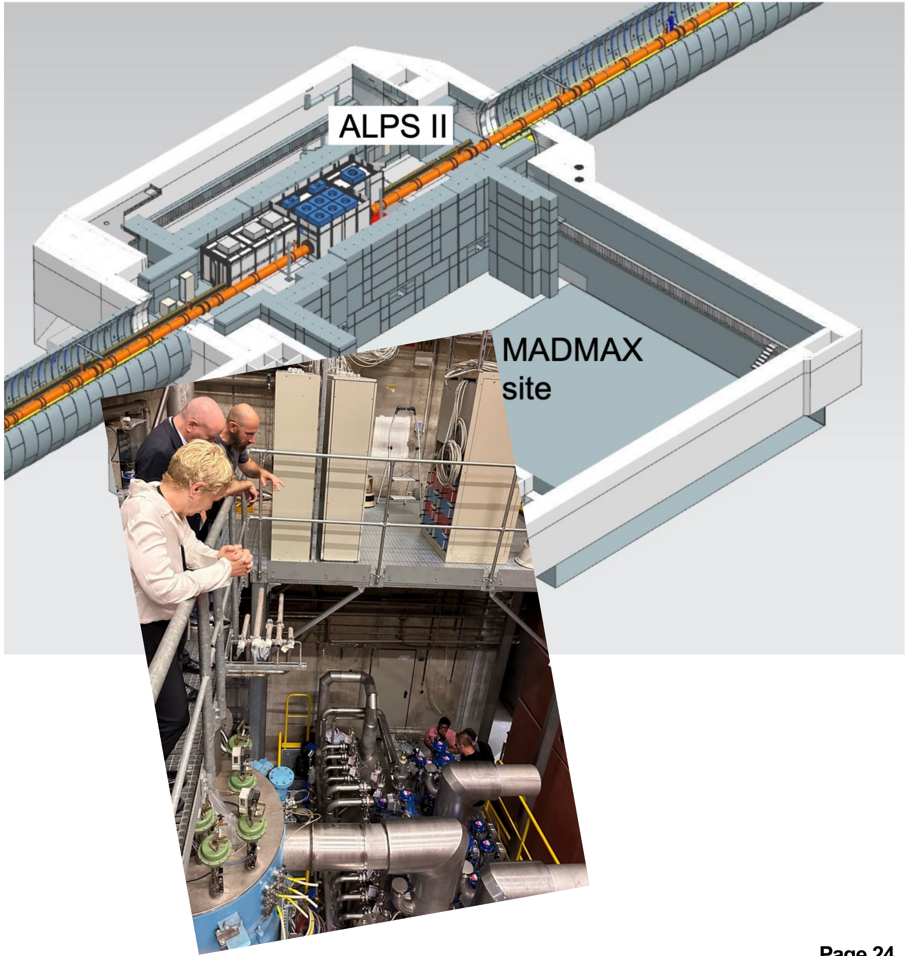
Cryoplatform at DESY

Distribution system of liquid helium (at ~ 4.5 K)

- Located 30 m underground at HERA Hall North
- Supply for up to three experiments (e.g. MADMAX)
- In construction, operation from 2026



Dimensions: height = 16 m, area = 1222 m^2



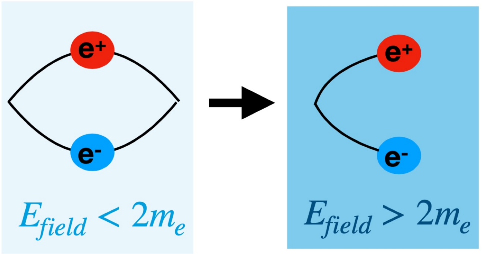
LUXE: Exploring Strong-Field QED

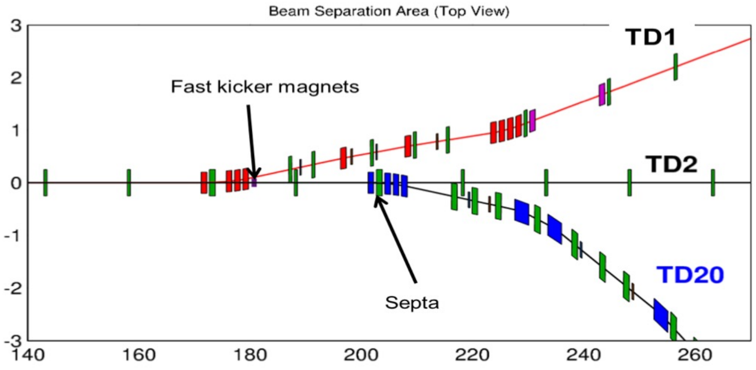
In collaboration with the European XFEL

Critical field phenomenon QED at "Schwinger limit" still unobserved – plan to use XFEL electron beam in collision with strong laser to create critical field:

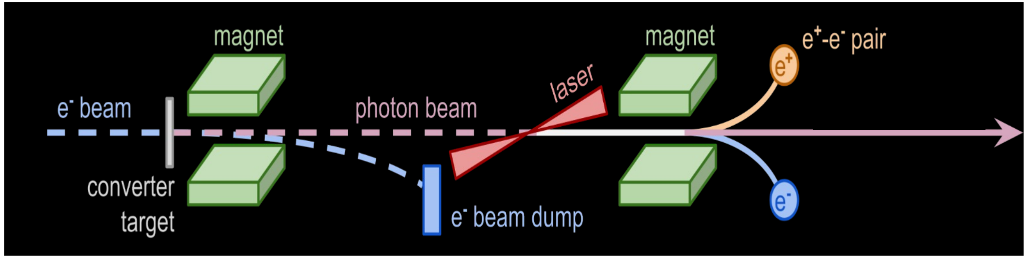
$$E_{\text{crit}} = \frac{mc^2}{e\lambda\!\!\!^{-}_C} = \frac{m^2c^3}{e\hbar}$$

$$= 1.3 \times 10^{16}\ \text{V/cm}$$





Expectation: Observation of Breit-Wheeler pair creation + modified Compton scattering + room for BSM (axions etc.)

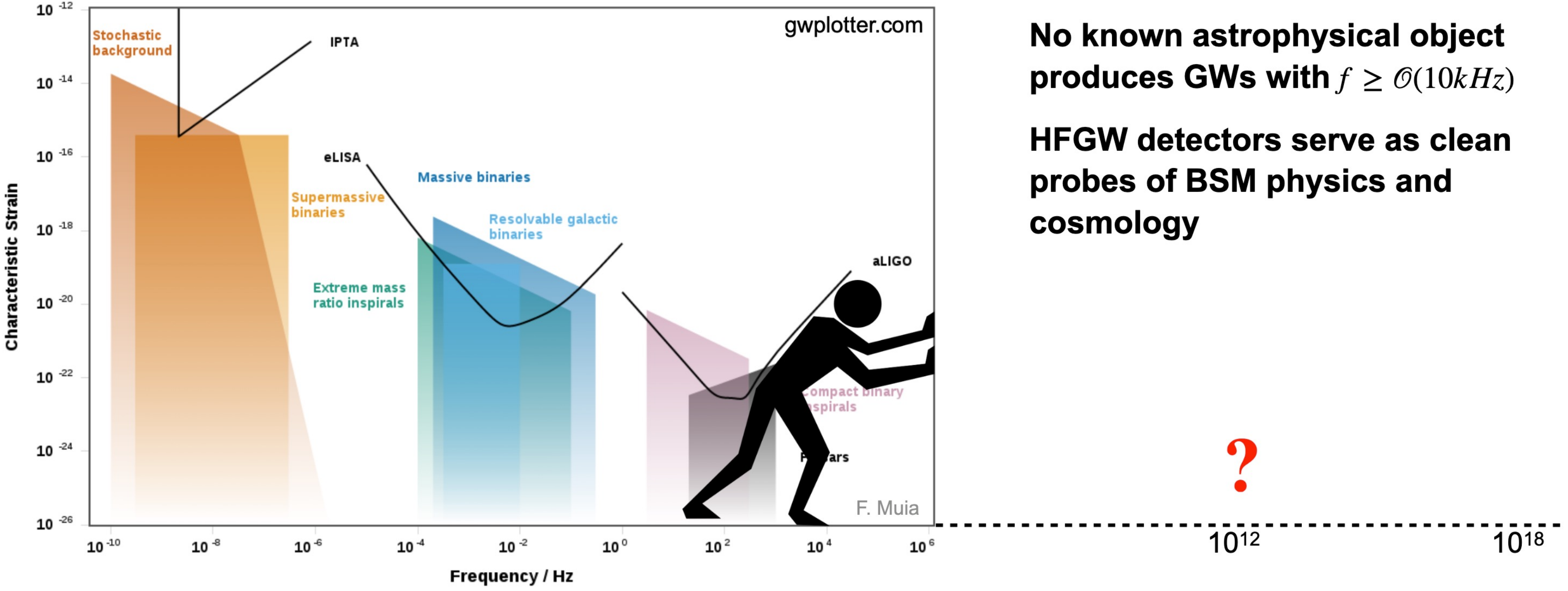


Recent achievements and plans:

- TDR out!
- Plan + funding for tunnel / accelerator modifications (extraction beam line)
- Initial studies with lower-energy laser from Jena planned

High-frequency Gravitational Waves

Focus on high-frequency experiments with particular relevance for cosmology!



No known astrophysical object produces GWs with $f \geq \mathcal{O}(10kHz)$

HFGW detectors serve as clean probes of BSM physics and cosmology

High-frequency Gravitational Waves

Search with cavities

- **GW interaction with cavity walls**
  - Spherical cavities for high Q factor
  - Distance between two cells is used to tune ωG
  - MAGO collaboration published first results in 2005
  - Collaboration moved to Virgo due to funding decisions
- DESY/UHH + FNAL now continue R&D program
- Exploit MAGO cavity at DESY for measurements and matching simulations
- Use Cryoplatform for cooling
- Still a lot or R&D to be done:
  - Low-noise cooling and electronics, suspension system, …
  - Collaboration with DESY accelerator division / UHH experts

- **Estimated sensitivity:**
  - ~6×10^{-21} $Hz^{1/2}$ from 1.8 to 2.2 kHz (near mech. resonance)
  - ~8×10^{-23} $Hz^{1/2}$ projected for the final (larger) cavity design

MAGO cavity at DESY

PIER Seed Grant obtained for the development of the cavity control

The DESY Test Beam Facility

Status and future – also in PETRA IV times

Status today

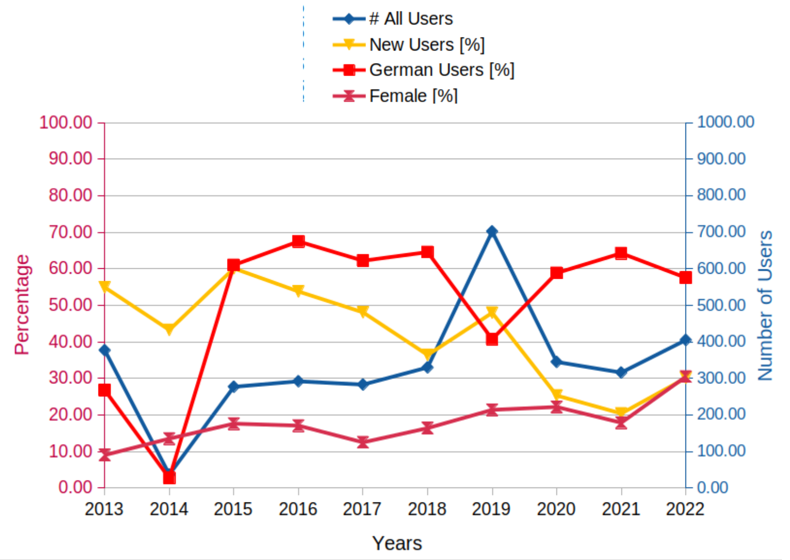
- Operation of 3 beamlines with ~6 GeV at DESY II
- Besides CERN only multi-GeV test beam facility in Europe
- Every year > 400 users

Demand for test beam in 2027 and beyond

- Clear demand for test beam extending over a decade or more
- Driven by HL-LHC, nuclear physics programme and smaller-scale particle and nuclear physics projects

A future test beam facility at DESY IV

- The PETRA IV projects foresees a new injector DESY IV; but current layout does not allow for test beam facility
- To make it usable for a test beam facility, DESY IV requires modest modifications
- If implemented, again leading world-class facility for the next decade or two

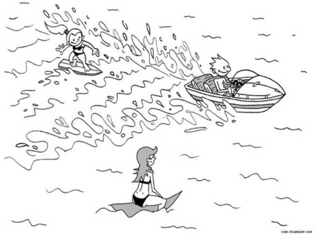


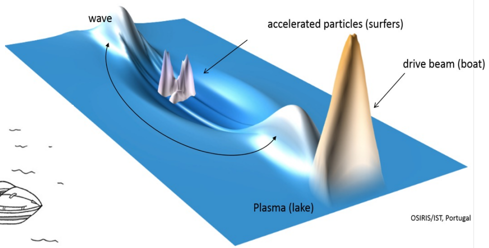
New Acceleration Technologies?

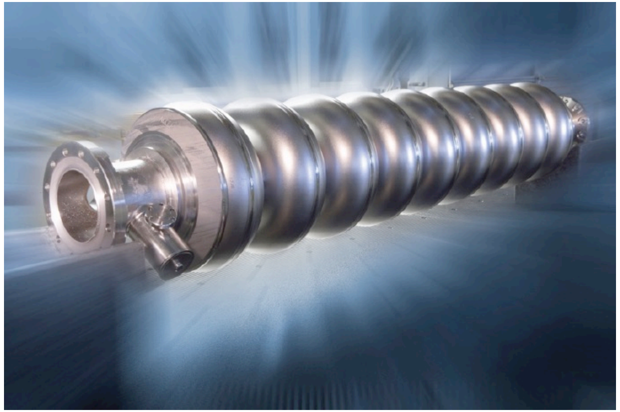
... for more compact accelerators

Exploring new technologies

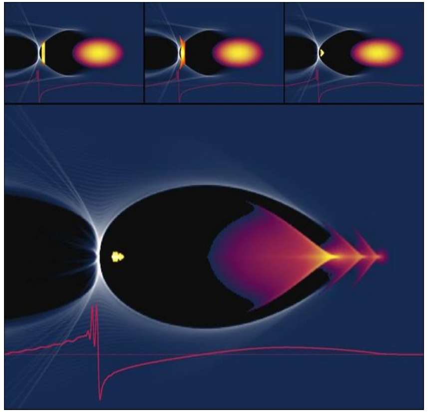
- Conventional accelerators with higher gradients (superconducting ILC technology used in EuropeanXFEL)
- Plasma wakefield acceleration:
  → strong research at DESY
  → first use-case could be the injector for the new synchrotron project PETRA IV



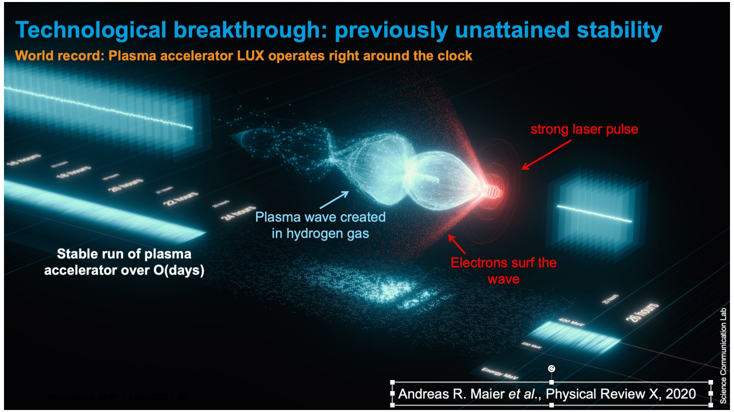




ILC accelerator cavity; 30 MV / m



Plasma wakefield acceleration



Summary

Particle physics at DESY: current and future plan

Finalisation of LHC upgrades

- HL-LHC start delayed to 2029
- Maintain robust engagement at ATLAS and CMS during HL-LHC

Belle II

- Continue engagement to collect 50/ab until 2034

Rich on-site experiment programme at DESY foreseen for the next decade

- ALPS II running, LUXE, BabyIAXO and MADMAX in planning
- R&D on high-frequency GW experiments using local infrastructure

Next major CERN project (Higgs factory):

- Expect decision ~2028 **=>** contribute to R&D and decision

Theory

- Close collaboration and exchange of ideas

BACKUP

The HALFH Concept

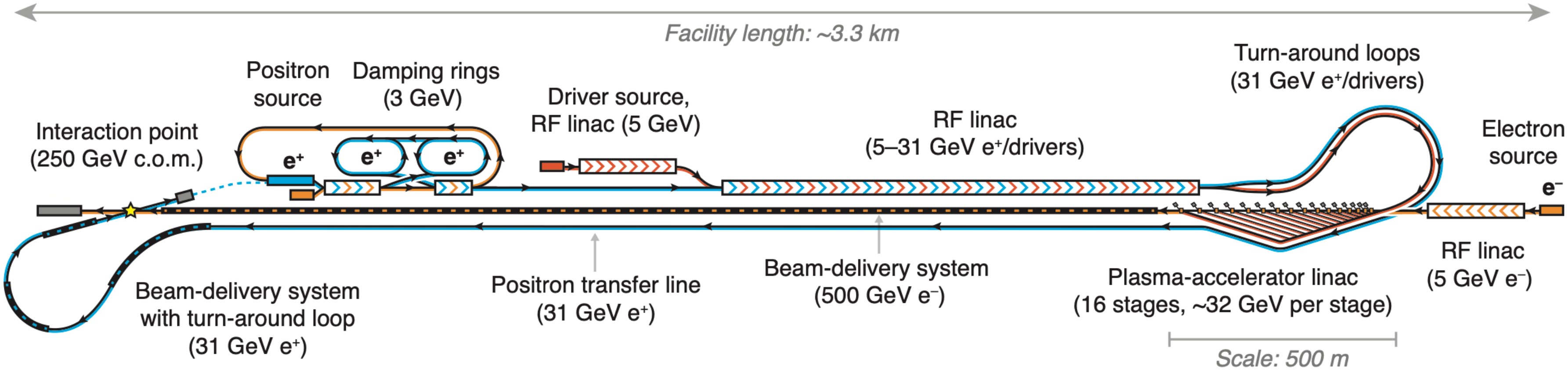
B. Foster et al., arXiv:2303.10150
New J. Phys. 25, 093037 (2023)

The next step in lepton colliders? A Hybrid Asymmetric Linear Higgs Factory

Hybrid concept to reach central European strategy goal of a Higgs factory as highest priority:

- 500 GeV electron beam accelerated by a beam-driven plasma wakefield accelerator
- 31 GeV positron beam accelerated by a conventional accelerator

→ Center-of-mass energy of 250 GeV, but luminosity reach unclear

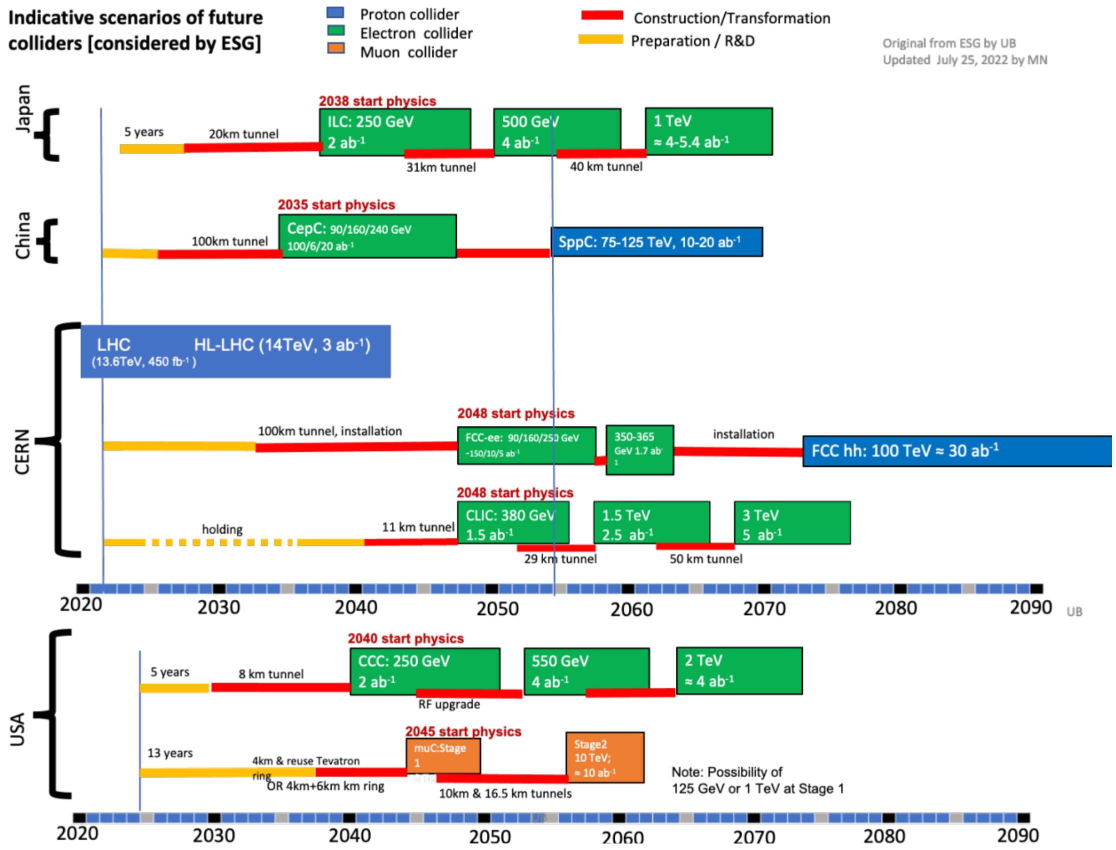


Currently exploring the concept for physics potential and R&D needs
Input for next update of European strategy for particle physics?

Timelines for possible new collider projects

As updated for Snowmass

- **Technologically-driven → start of data-taking in ~late 30ies** (except for **CERN** projects due to coupling to HL-LHC programme **→ late 40ies**
- **ILC and CEPC require political decisions very soon** to maintain timelines shown here
- **If Higgs factory will be built elsewhere, CERN could to for FCChh directly (~60ies)**



Future Colliders: e+e- Colliders and Higgs Factories

EPPSU number one priority

CERN is very focussed on the FCC (90.7 km circular e+e- collider)

- End of ‘23: Midterm review of FCC feasibility study; End of ‘25: Final feasibility study
- Linear collider R&D for ILC and CLIC supported at lower level

China: focussed on CEPC (100 km circular e+e- collider): 5-year plan in 2025

Japan and the ILC

- Critical R&D still supported (ITN for 4 years); funding scenario unclear

New idea from SLAC: Cool Copper Collider (C3): R&D needed

- US P5 strategy process still ongoing!

New idea at DESY: “HALHF” hybrid collider including **plasma-based acceleration**

Energy Recovery Linacs: considered for ep collider, demonstrator facilities starting

→ Need a decision with next EPSSU update

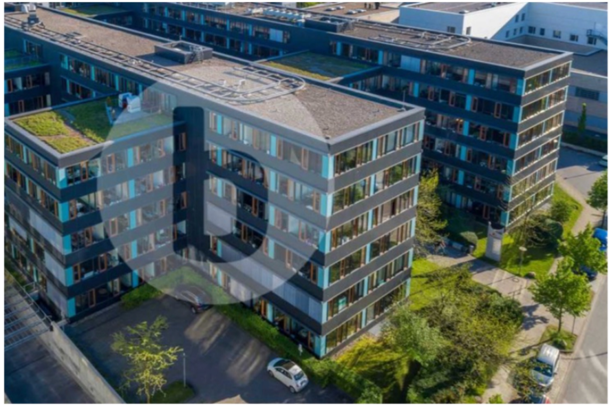
The Wolfgang Pauli Center

Uniting the different theory groups of Universität Hamburg and DESY

- Mission to a **leading center for theoretical physics** that pursues and promotes interdisciplinary research to address the fundamental challenges in our **understanding of matter, materials and the universe**
- Fostering collaboration between **particle physics, astrophysics and cosmology, mathematical physics, condensed matter, quantum optics and chemical physics**
- Strategic partnerships with theory institutes both within Germany and internationally
- 350 theorists (faculty, postdocs, PhD students) from 12 different institutions

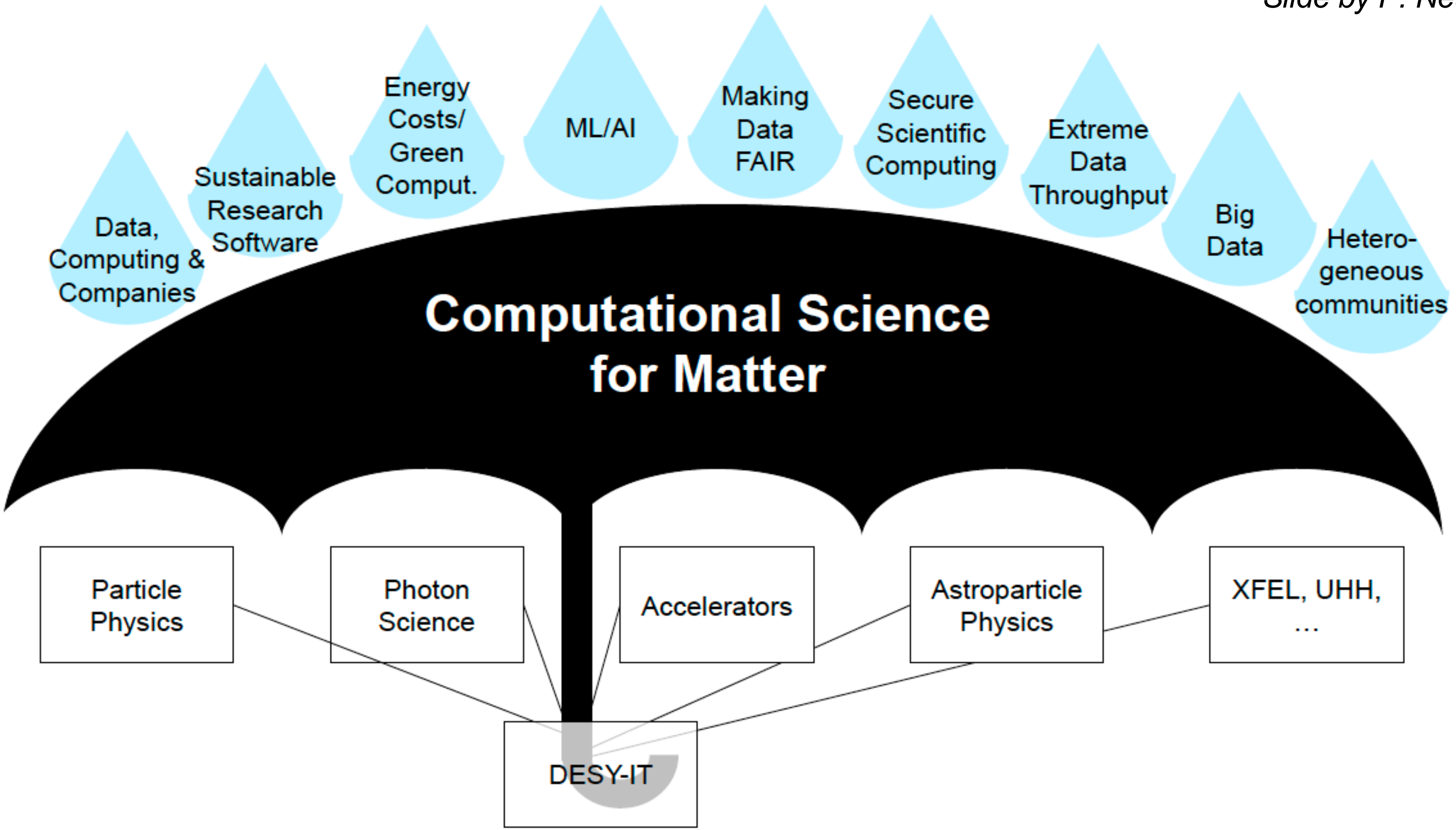
MAX PLANCK INSTITUTE OF QUANTUM OPTICS
MAX PLANCK INSTITUTE FOR GRAVITATIONAL PHYSICS (ALBERT EINSTEIN INSTITUTE)
Max Planck Institute for the Structure and Dynamics of Matter mpsd
GSI
JÜLICH FORSCHUNGSZENTRUM
HI Jena Helmholtz Institute Jena

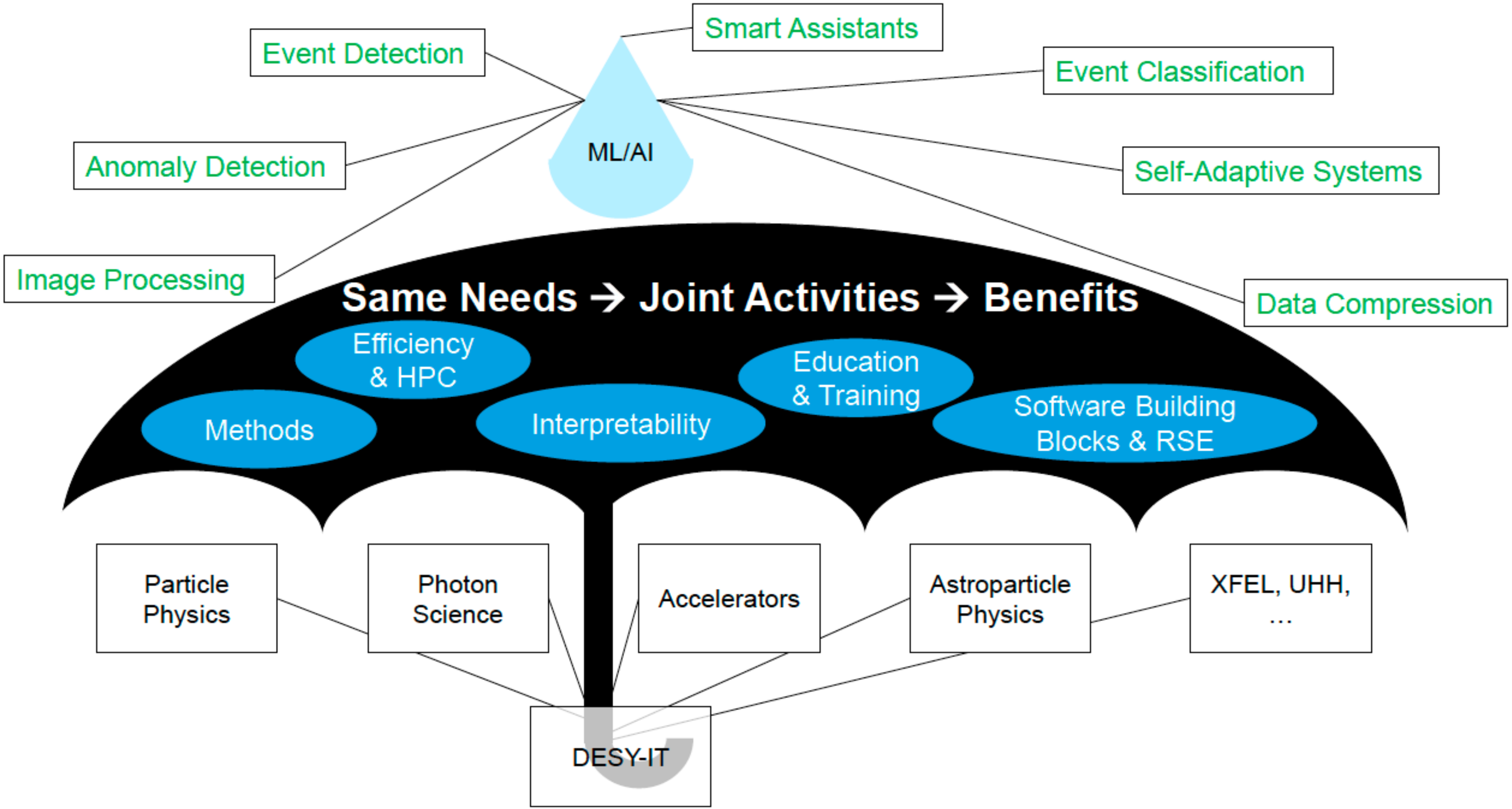
MASSACHUSETTS INSTITUTE OF TECHNOLOGY DEPARTMENT OF PHYSICS CENTER FOR THEORETICAL PHYSICS
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
FLATIRON INSTITUTE
ITAMP INSTITUTE FOR THEORETICAL ATOMIC MOLECULAR AND OPTICAL PHYSICS
מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE



New building for WPC identified, likely to be moving in next year

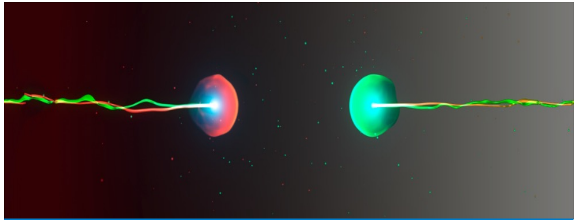
Slide by P. Neumann




Smart Assistants
Event Detection
Event Classification
ML/AI
Anomaly Detection
Self-Adaptive Systems
Image Processing
Data Compression
Same Needs → Joint Activities → Benefits
Efficiency & HPC
Education & Training
Methods
Interpretability
Software Building Blocks & RSE
Particle Physics
Photon Science
Accelerators
Astroparticle Physics
XFEL, UHH, …
DESY-IT

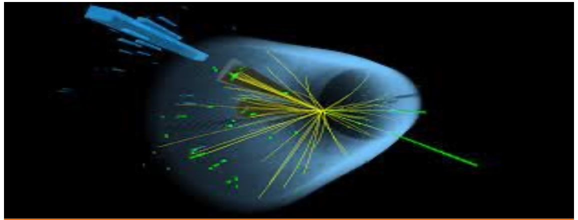
Science Drivers

Addressing the big questions of nature: Understanding the quantum universe



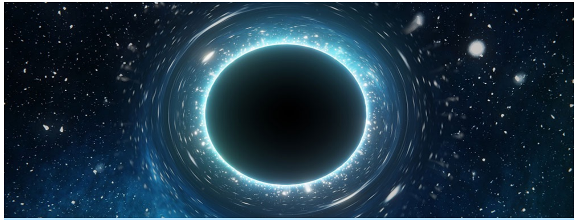
Pushing the limits of our understanding of fundamental interactions

- Strong-field QED
- Strong interactions, QCD
- Lattice QCD
- g-2



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

- Higgs boson
- Top and B physics
- Charge-parity violation
- Lepton flavour universality



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

- Cosmology
- Axions, ALPs
- Gravitational waves
- Dark matter

Fundamental curiosity-driven science

- Development of cutting-edge technologies (detectors, computing, accelerators, lasers, …)
- Very attractive for young high-potentials
- High potential for disruptive technology development important for society, e.g. WWW, imaging technologies, cloud computing, …

Mid- and Long-Term Strategy

Fundamental Particles and Forces