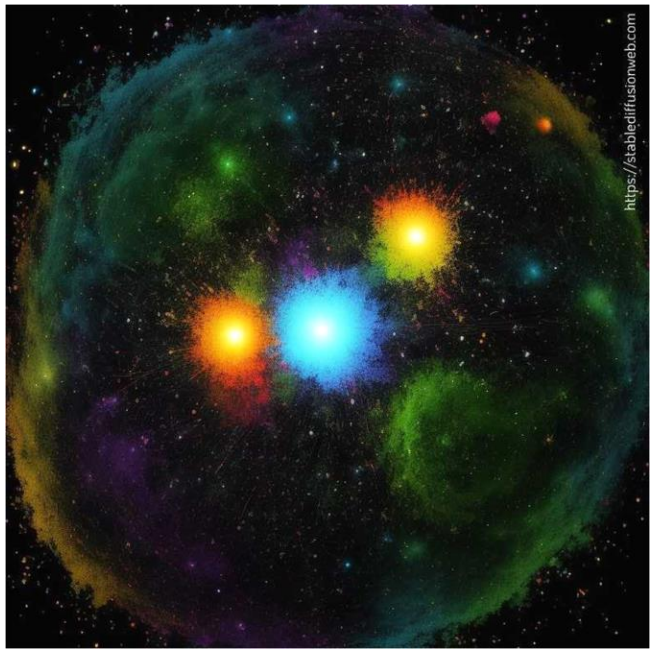
HADRON PHYSICS

Karin Schönning, Uppsala University

THE WORLD OF HADRONS



- Hadron size: ~ 1 fm.
- Hadron lifetime: $<10^{-24}$ s – $>10^{30}$ y.
- Hadron mass: Much larger than the mass of its constituents.
- Hadron decays: Can be complex or rare, or both.

→ *How do hadron properties emerge from the strong interaction?*

Picture adapted from Kosmos 2023 (Yearbook of the Swedish Physical Society)

THEORY APPROACHES

Challenge: *How to describe non-perturbative strong interactions from first principles of Quantum ChromoDynamics (QCD)?*

Solutions:

Lattice QCD

Effective field theories (EFTs)

Functional methods

Dispersion relations

EXPERIMENTAL APPROACHES

Facilities: Dedicated hadron experiments Multi-purpose experiments

Beams: Photons Leptons Hadrons Heavy ions Nuclei

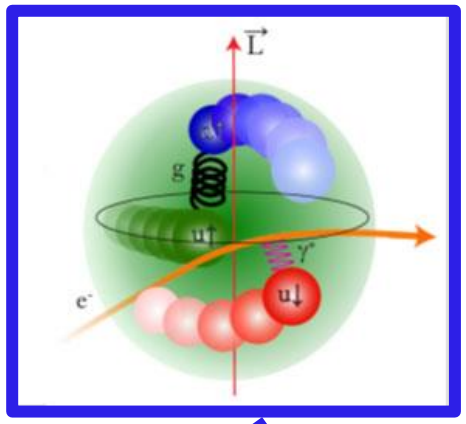
Targets: Gas liquid solid polarized or Colliding beams

Energies: 100 MeV → TeV

Large variety of combinations

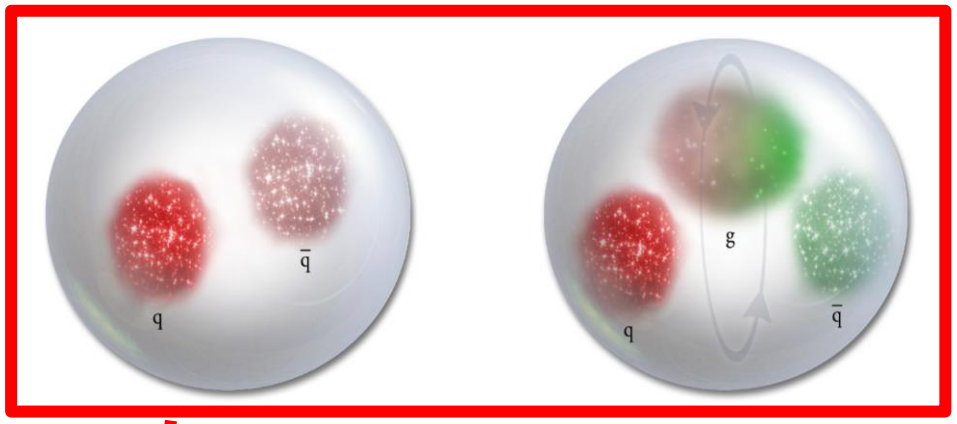
- all are needed to grasp all aspects of the strong interaction!

Structure



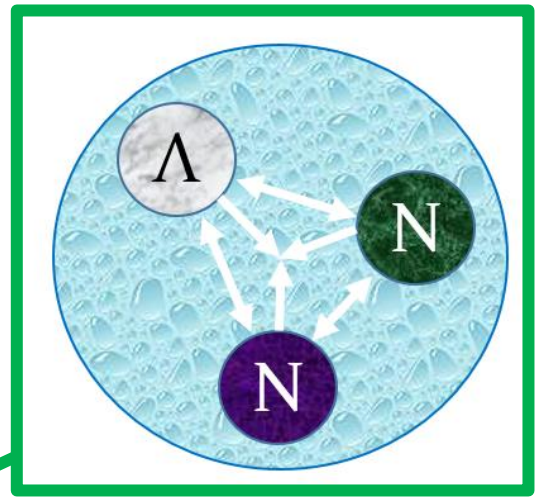
AMBER, BESIII, Belle II, Jlab, MAMI, PANDA

Spectroscopy



AMBER, BESIII, Belle II, ELSA, Jlab, LHCb, PANDA

Interactions



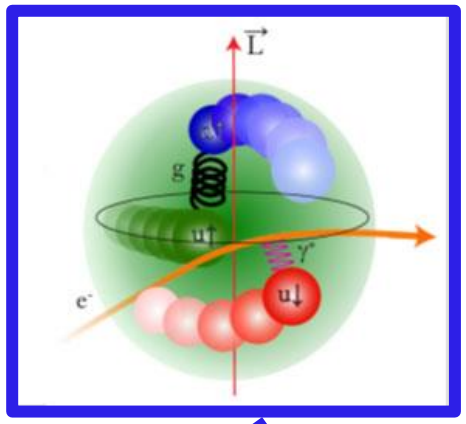
ALICE, Jlab, J-PARC, HADES, PANDA

Hadron Physics

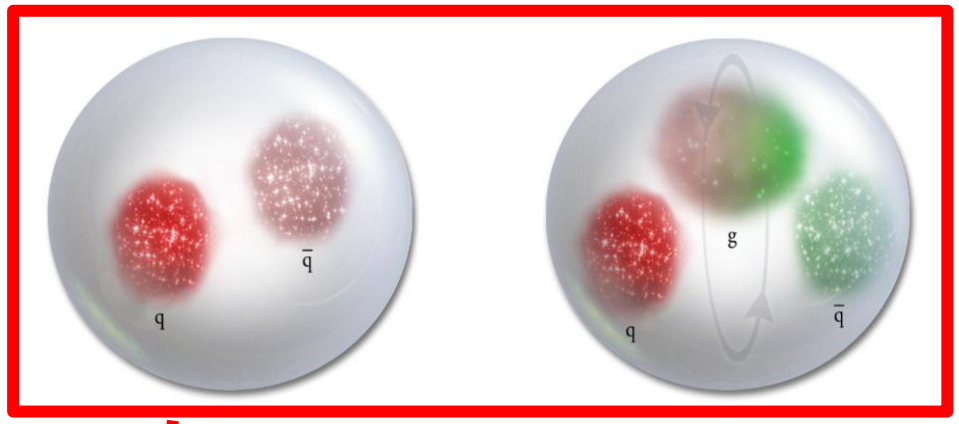
Precision & rare processes

BESIII, Belle II, LHCb, MESA, NNBAR/HIBEAM, PANDA

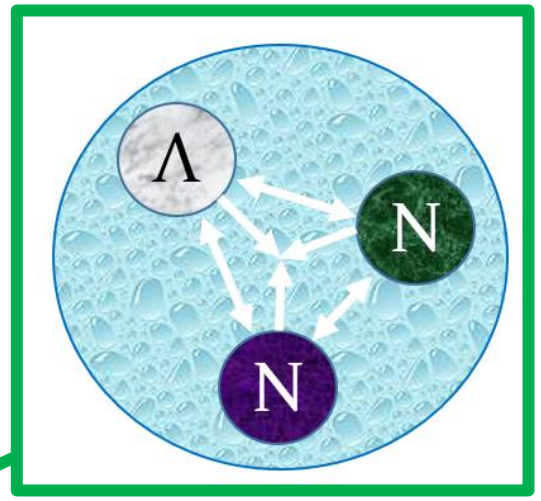
Structure



Spectroscopy



Interactions



BESIII, Belle II, PANDA, theory

HADES, PANDA

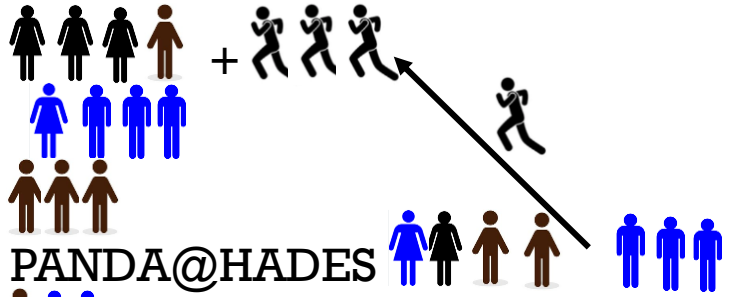
Hadron Physics in Sweden

Precision & rare processes

BESIII, Belle II, LHCb, NNBAR/HIBEAM, PANDA, theory

HADRON PHYSICS IN SWEDEN

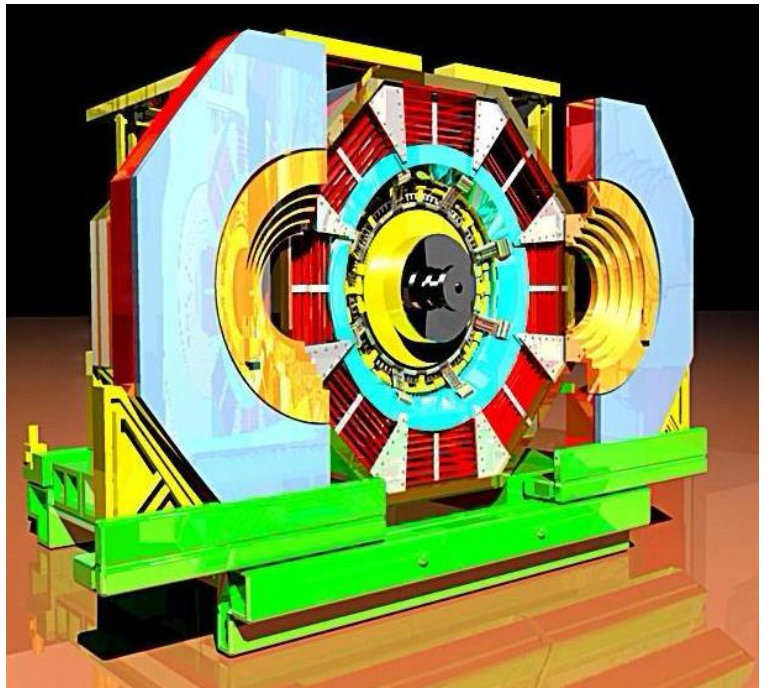
Disclaimer: Heavy-ion physics and HIBEAM/NNBAR will be treated in separate talks.

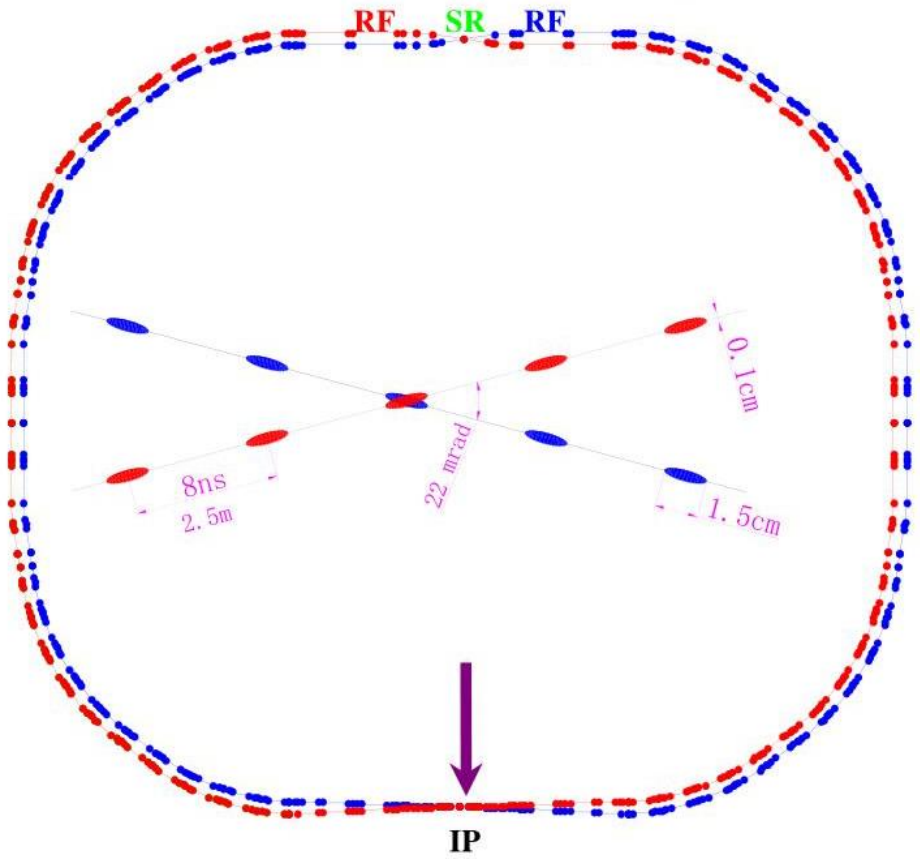
- Lund: Theory
- Stockholm: PANDA, PANDA@HADES
- Uppsala:
  - Belle II + 
  - BESIII
  - LHCb
  - PANDA, PANDA@HADES
  - Theory

Black & brown: main activity
Blue: side activity or senior (beyond 69 y) positions

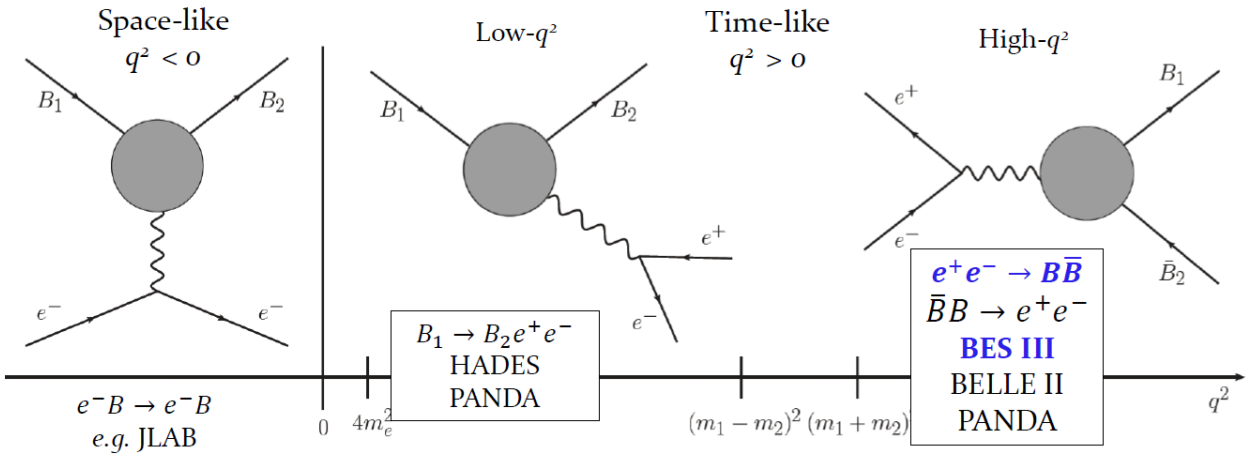
BESIII AT BEPC-II, CHINA

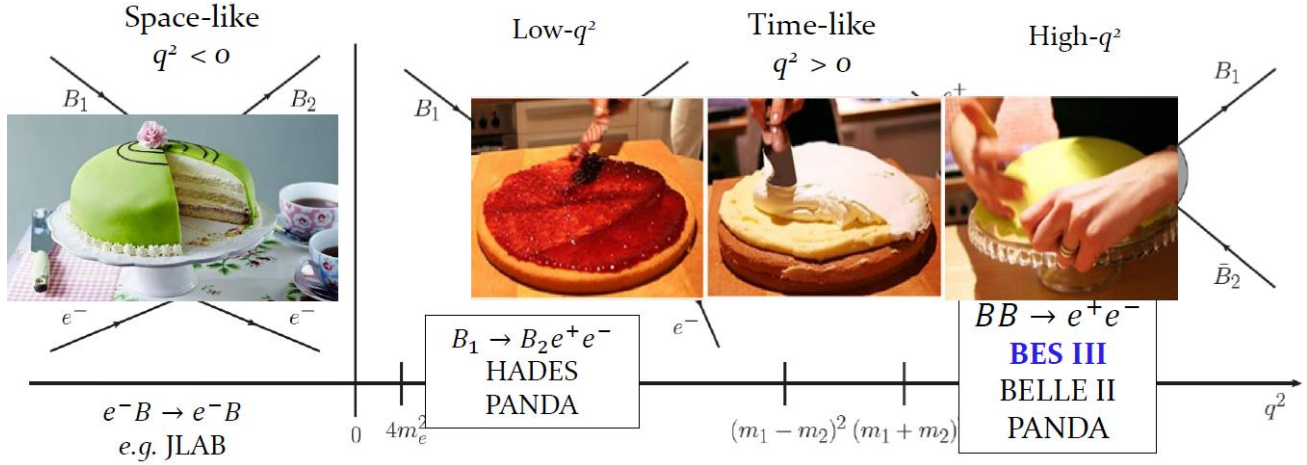
- CMS energies within 2.0 - 4.95 GeV.
- Optimised in the τ-charm region
- Luminosity ~ 10^{33} $cm^{-2}s^{-1}$
- Uppsala members since 2012





RECENT HIGHLIGHTS





BESIII

Article | Open access | Published: 11 October 2024

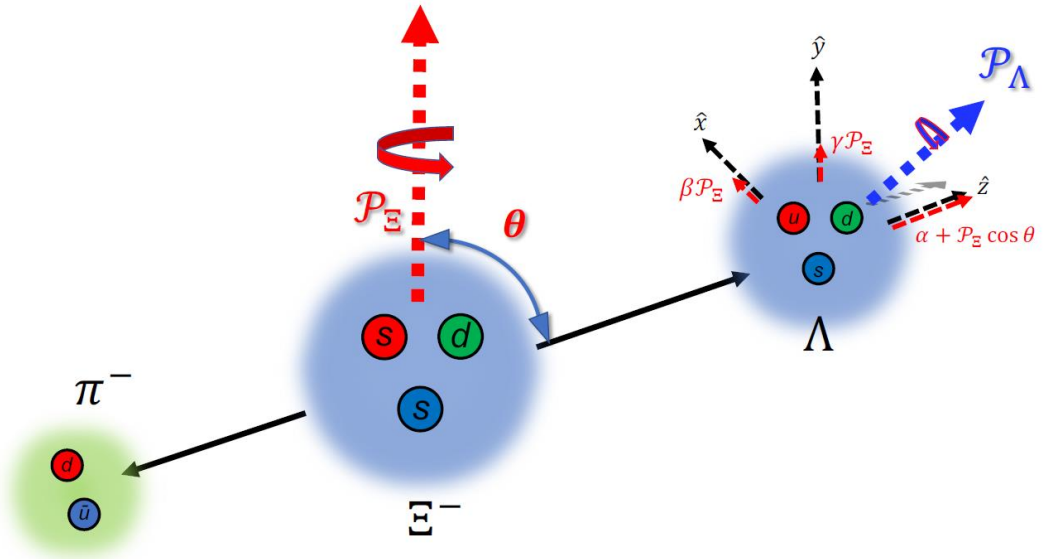
Extracting the femtometer structure of strange baryons using the vacuum polarization effect

The BESIII Collaboration

Nature Communications **15**, Article number: 8812 (2024) | Cite this article

2716 Accesses | **182** Altmetric | Metrics

RECENT HIGHLIGHTS



nature

Article | Open Access | Published: 01 June 2022

Probing CP symmetry and weak phases with entangled double-strange baryons

The BESIII Collaboration

606, 64–69 (2022) | Cite this article

OPEN ACCESS | GO MOBILE » | ACCESS BY UPPSALA UNIVERSITETSBIBLIOTEK

Strong and Weak *CP* Tests in Sequential Decays of Polarized Σ^0 Hyperons

M. Ablikim[1], M. N. Achasov[4,c], P. Adlarson[76], O. Afedulidis[3], X. C. Ai[81], R. Aliberti[35], A. Amoroso[75a,75c], Q. An[72,58,a], Y. Bai[57] *et al.* (BESIII Collaboration)

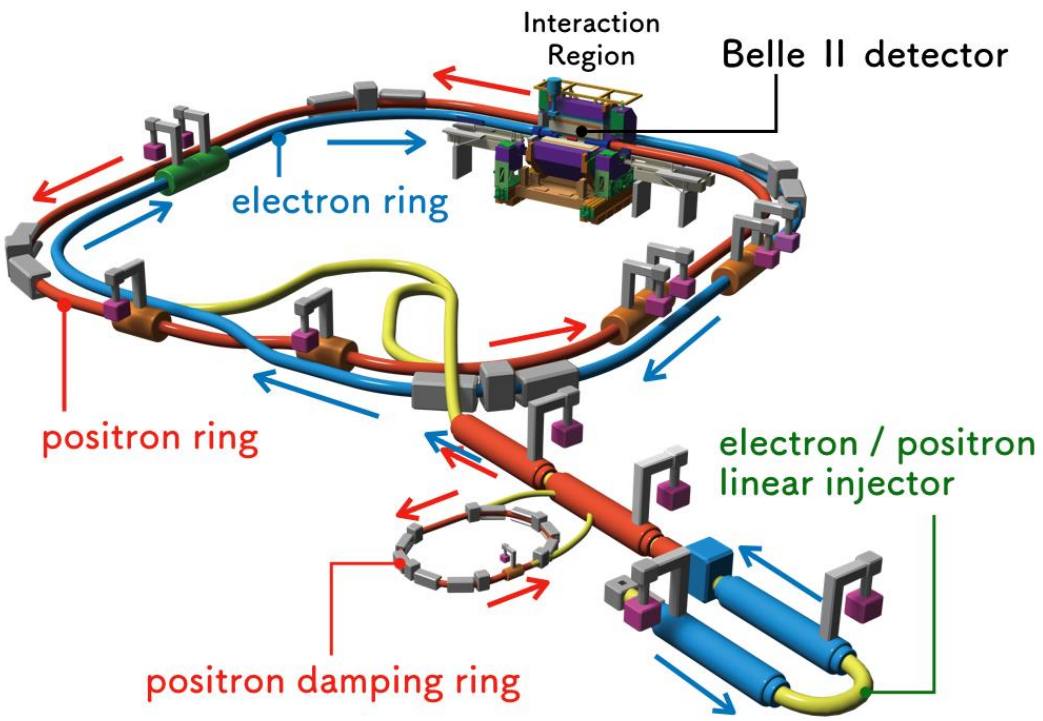
Show more

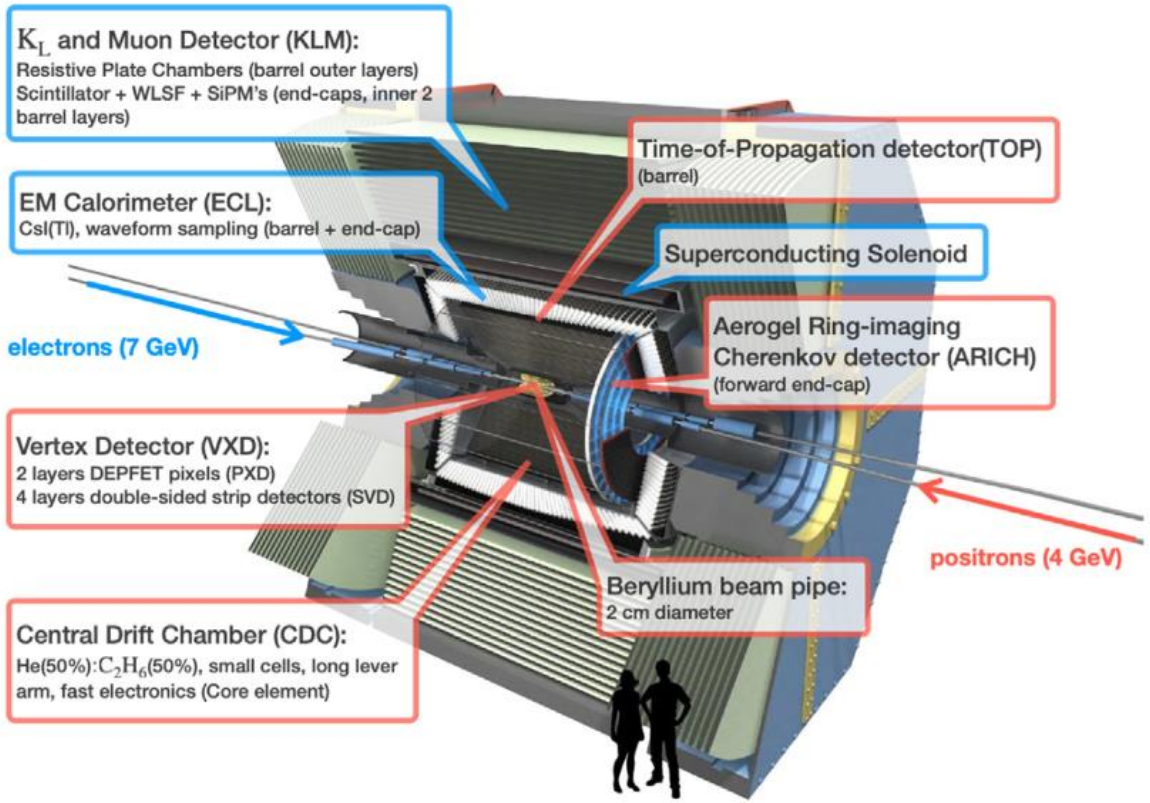
Phys. Rev. Lett. **133**, 101902 – **Published 4 September, 2024**

DOI: https://doi.org/10.1103/PhysRevLett.133.101902

CP tests
Hadron structure
Hadron interactions

CP tests
Baryon number violation



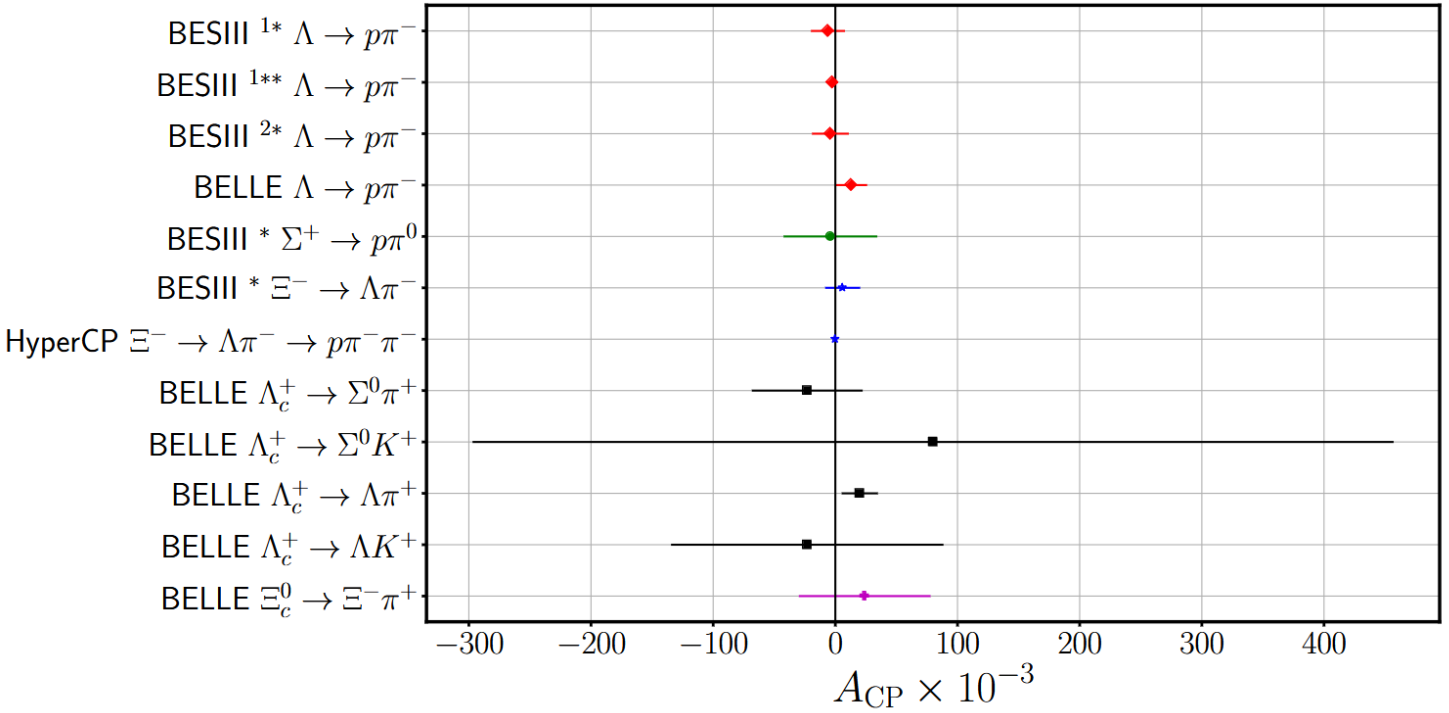


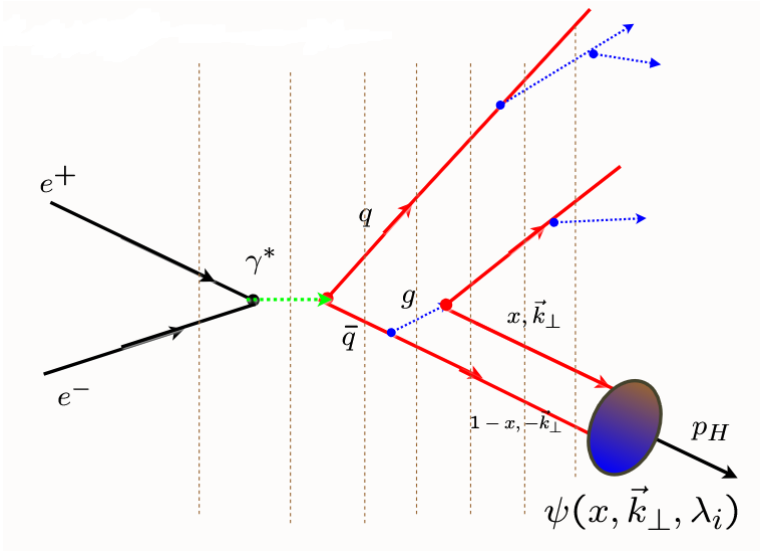
- New generation B factory
- Goal of collecting 50 ab^{-1} of e^+e^- collision data
- Different production mechanisms
  → Υ(NS), $q\bar{q}$ fragmentation, EM processes, lineshapes…
- Near 4π detector coverage
  → searches for ”invisible” states
- Measured charged and neutral particles

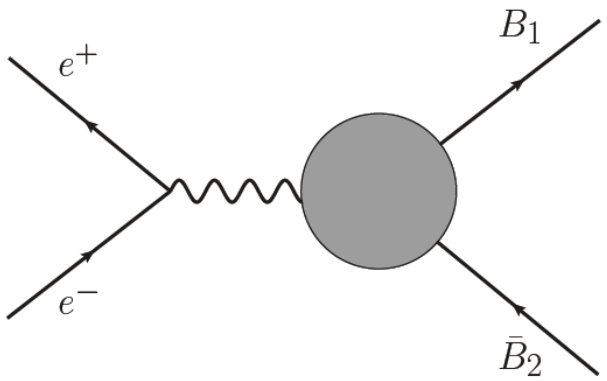
OUR INTERESTS

Hyperon structure

- Fragmentation functions ($e^+e^- \to q\bar{q}$)
- Form factors ($e^+e^- \to Y\bar{Y}$)

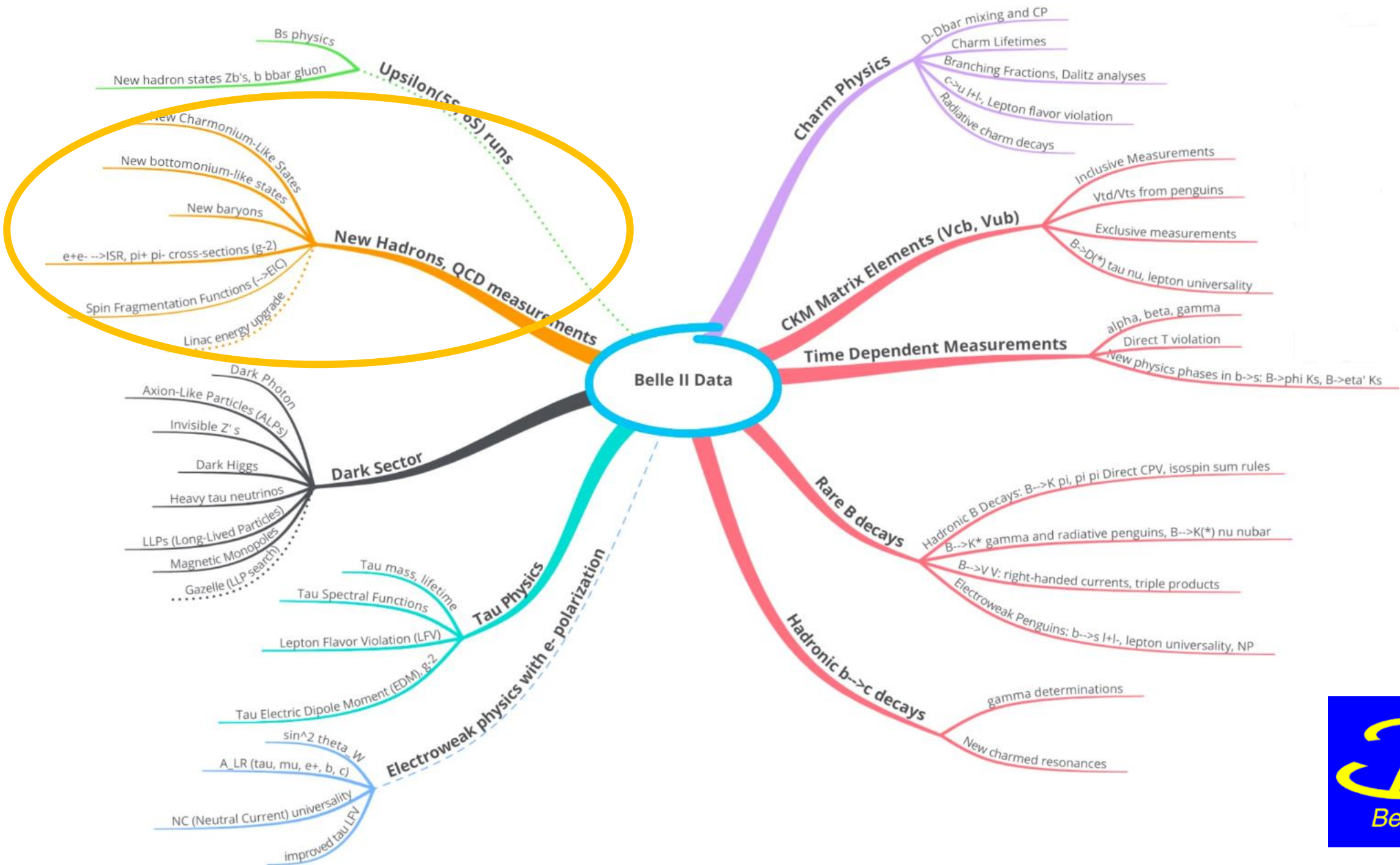


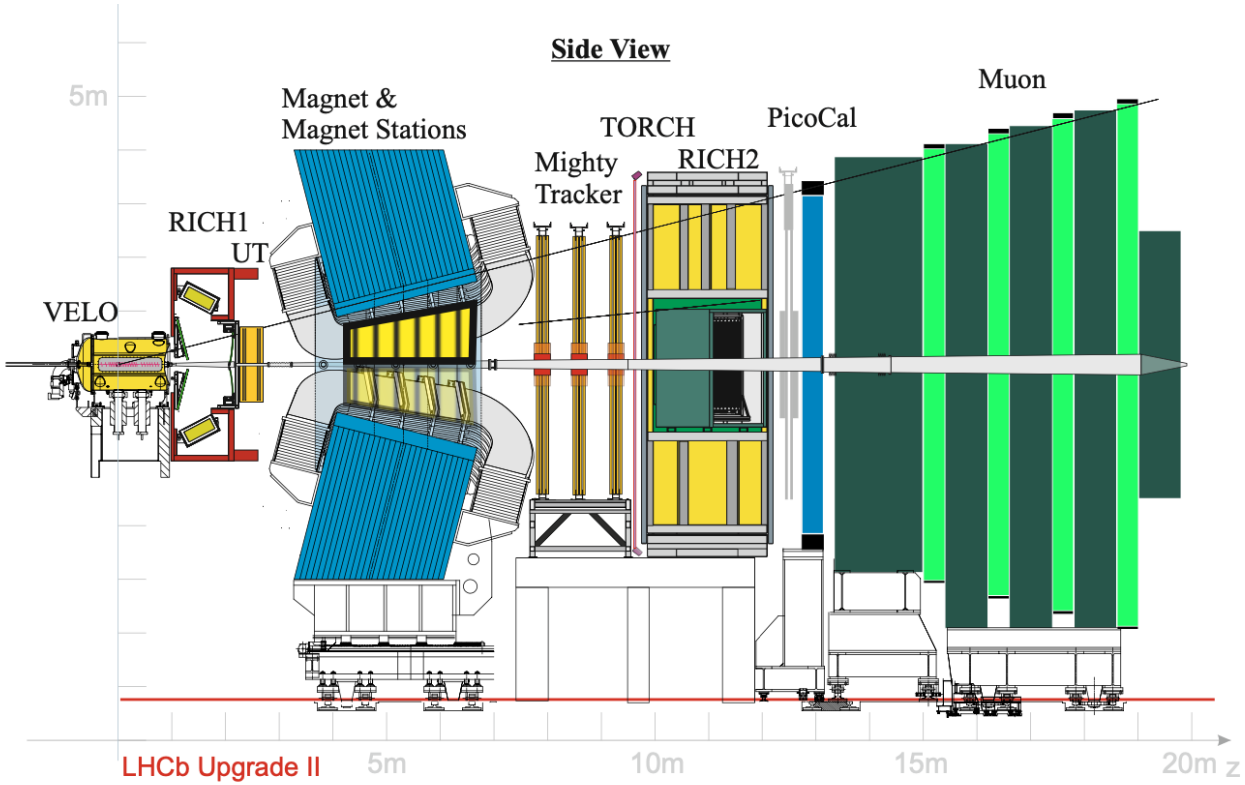




Hyperon decays

- CP tests in charm baryon decays
- Sequential decays including neutrals
- Large data samples allow multi-dimensional analyses

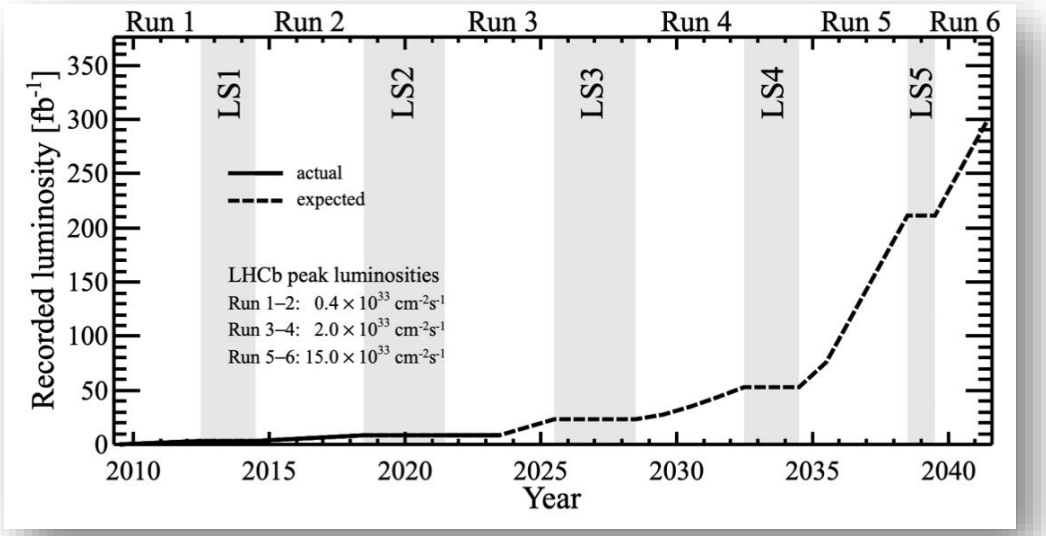

Belle II Data
Upsilon(5S, 6S) runs
Bs physics
New hadron states Zb's, b bbar gluon
New Hadrons, QCD measurements
New Charmonium-Like States
New bottomonium-like states
New baryons
e+e- -->ISR, pi+ pi- cross-sections (g-2)
Spin Fragmentation Functions (-->EIC)
Linac energy upgrade
Dark Sector
Dark Photon
Axion-Like Particles (ALPs)
Invisible Z' s
Dark Higgs
Heavy tau neutrinos
LLPs (Long-Lived Particles)
Magnetic Monopoles
Gazelle (LLP search)
Tau Physics
Tau mass, lifetime
Tau Spectral Functions
Lepton Flavor Violation (LFV)
Tau Electric Dipole Moment (EDM), g-2
Electroweak physics with e- polarization
sin^2 theta_W
A_LR (tau, mu, e+, b, c)
NC (Neutral Current) universality
improved tau LFV
Charm Physics
D-Dbar mixing and CP
Charm Lifetimes
Branching Fractions, Dalitz analyses
c->u l+l-, Lepton flavor violation
Radiative charm decays
CKM Matrix Elements (Vcb, Vub)
Inclusive Measurements
Vtd/Vts from penguins
Exclusive measurements
B->D(*) tau nu, lepton universality
Time Dependent Measurements
alpha, beta, gamma
Direct T violation
New physics phases in b->s: B->phi Ks, B->eta' Ks
Rare B decays
Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
B-->K* gamma and radiative penguins, B-->K(*) nu nubar
B-->V V: right-handed currents, triple products
Electroweak Penguins: b-->s l+l-, lepton universality, NP
Hadronic b-->c decays
gamma determinations
New charmed resonances



Upgrade II (2031-): aim to collect 50 visible interactions per bunch collision

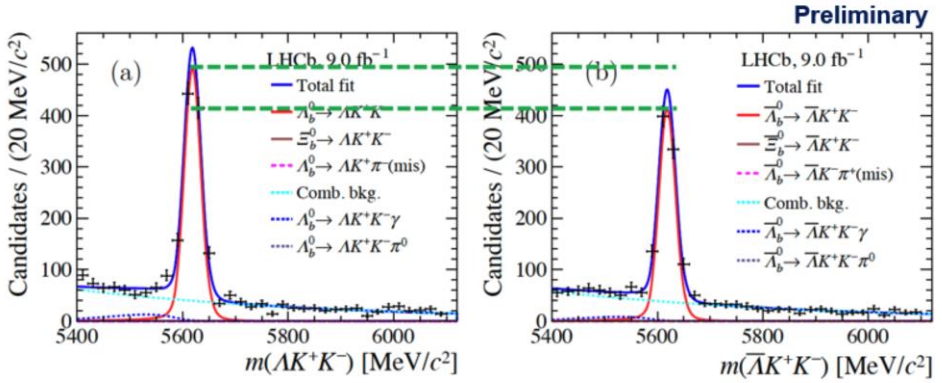
End of Run 6 goal : 300 fb^{-1}

High spatial and timing precision (<50μm, <50ps)



arXiv[hep-ex]:2411.15441

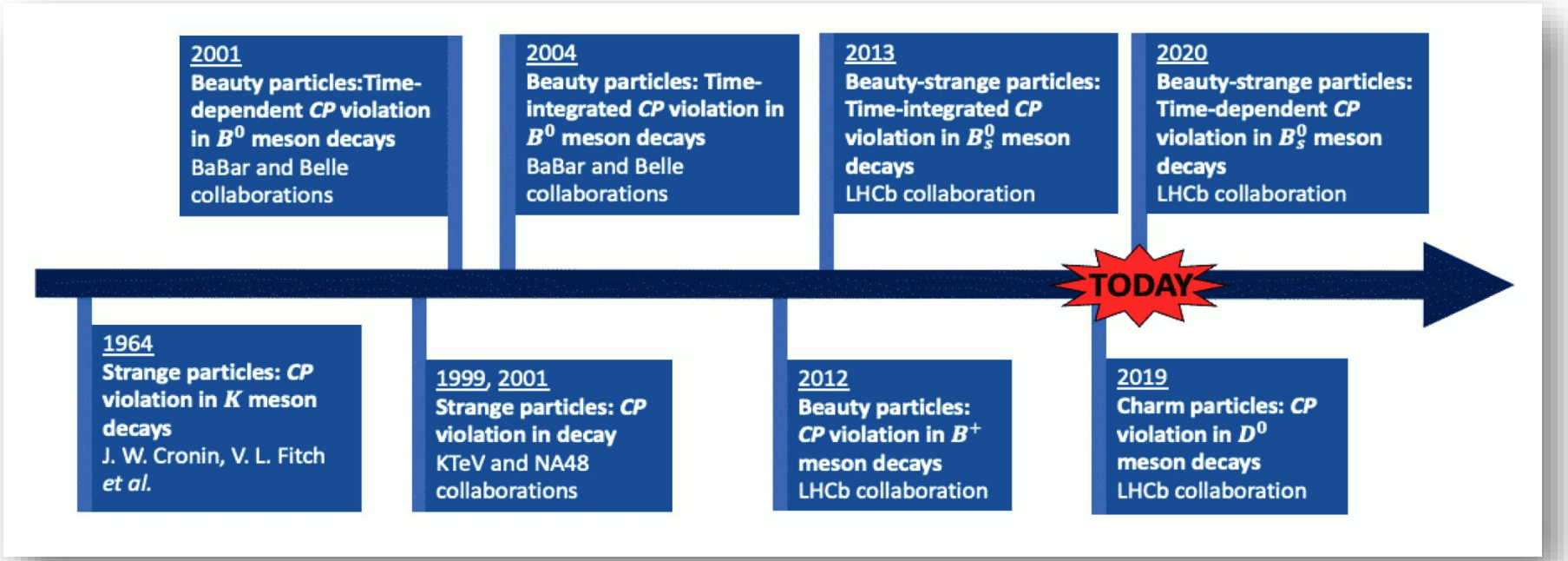
$$\mathcal{A}^{CP}(\Lambda_b^0/\Xi_b^0 \to f) \equiv \frac{\Gamma(\Lambda_b^0/\Xi_b^0 \to f) - \Gamma(\overline{\Lambda}_b^0/\overline{\Xi}_b^0 \to \overline{f})}{\Gamma(\Lambda_b^0/\Xi_b^0 \to f) + \Gamma(\overline{\Lambda}_b^0/\overline{\Xi}_b^0 \to \overline{f})},$$



$\Lambda_b^0 \to \Lambda K^+K^-$

$\Delta A_{CP} = 0.083 \pm 0.023 \pm 0.016$

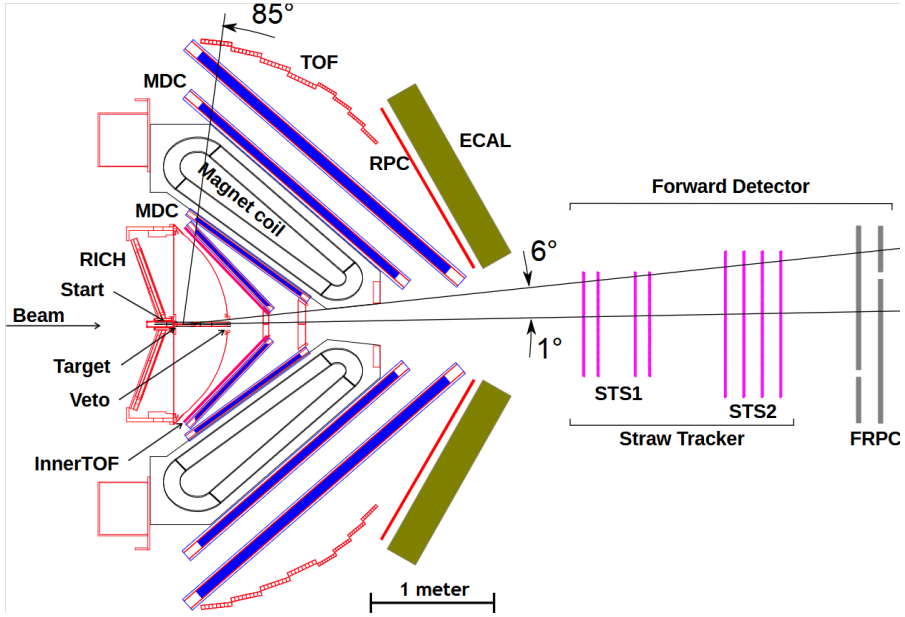
First evidence of CP violation, 3.1σ

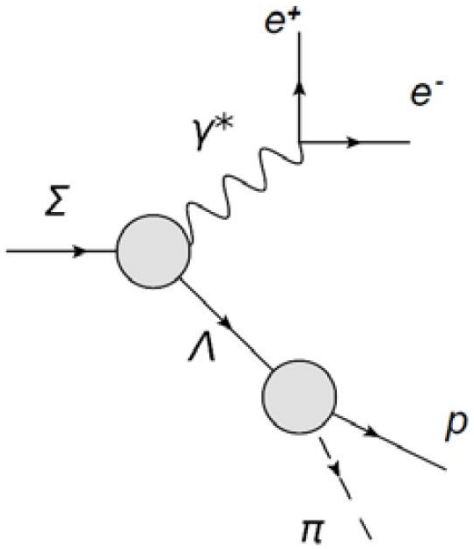


Credit: Patrik Adlarson

WHAT ABOUT PANDA ?

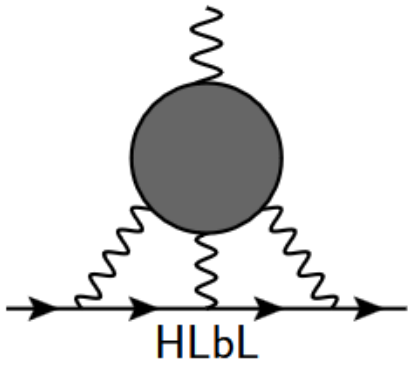
- The stored antiproton beam of PANDA delayed to ~2032 but still in the FAIR agenda and is mentioned as a future flagship in the NuPECC Long Range Plan 2024.
- UU and SU active in the predecessor experiment PANDA@HADES with proton and pion beams.





- Antiproton beams at CERN-AD (lower energies) and J-PARC (lower intensity and resolution) may offer synergies and a chance to keep the antiproton community alive until the launch of PANDA.

HADRON THEORY IN SWEDEN



- Muon *g-2 :* Theory calculations of hadronic light-by-light contribution
  - Connects to experiments at Belle II and BESIII
- Hadron structure:
  - Meson and baryon form factors; connects to experiments at PANDA@HADES, BelleII and BESIII
  - 5D tomography of nucleons and nuclei, photon and gluon form factors; connects to experiments at *e.g.* Jlab and AMBER
- Flavour physics, CP tests in hyperon decays; connects to experiments at Belle II, BESIII and LHCb

QUESTION 4A-C

4a: ”*What other areas of physics should be pursued [at CERN I suppose?], and with what relative priority?*”

4b: ”*What are the most important elements in the response to 4a)?*”

4c: “*To what extent should CERN participate in nuclear physics, astroparticle physics or other areas of science, while keeping in mind and adhering to the CERN Convention?*”

NUPECC RECOMMENDATIONS FOR HADRON PHYSICS

- **Support of existing facilities:** *We recommend the support of the continuation of the successful ongoing hadron physics programs in Europe, and the participation of European groups at global facilities.*

- **Future flagship facilities:** *We recommend the realisation of the antiproton beam facility at FAIR, including the PANDA experiment, and the support of European groups to contribute to the design and construction of ePIC at the EIC.*

- **Theory and computing:** *We recommend the support of theory groups at universities and research centers to prepare the community to benefit from the European investments in supercomputing, and to be ready for quantum computing.*

NuPECC LRP 2024, hadron chapter

SUPPORT OF EXISTING FACILITIES

We recommend the continuing support of the successful hadron physics programs in Europe and the participation of European groups at global facilities. Particularly important hadron physics facilities are

- AMBER at CERN, Switzerland
- ELSA in Bonn, HADES at GSI, and MAMI and MESA in Mainz, Germany
- Jefferson Laboratory in Newport News, USA

Furthermore, we recommend the support of ongoing hadron physics activities at the multi-purpose facilities Belle II, BESIII and the LHC.

NUPECC RECOMMENDATIONS FOR INFRASTRUCTURE

"Nuclear physics opportunities at CERN constitute a world-leading research programme. The construction of ALICE 3 as part of the HL-LHC plans is strongly recommended. Continued support for exploitation and new developments is recommended to maximise the scientific output of ISOLDE, n_TOF, SPS fixed-target programme and AD/ELENA. As the roadmap for the post-LHC future of CERN is developed, a strategy should be prepared to secure future opportunities for continuing world-leading nuclear-physics programmes that are unique to CERN."

NuPECC LRP 2024, infrastructure chapter. NOT exhaustive!

NUPECC RECOMMENDATIONS FOR SYMMETRIES AND FUNDAMENTAL INTERACTIONS

"The AD/ELENA physics programme at CERN should be strongly supported over the long term, including running experiments, planned projects, and potential new proposals."

NuPECC LRP 2024, Symmetries and fundamental interactions chapter. NOT exhaustive!

THANK YOU FOR YOUR ATTENTION!

BACKUP

FUTURE FLAGSHIP FACILITIES

We recommend the expedited realisation of the antiproton experiment PANDA, and the support of European groups to contribute to the electron-ion experiment ePIC. By virtue of their different beam species and energy regimes, PANDA and ePIC will explore complementary physics aspects. In a ten-year perspective, these two next-generation experiments must be made ready to launch.

- ***PANDA**: A recent review concluded that the physics program, including the prospect of unravelling exotic matter, remains unique and compelling. PANDA will strengthen the European position on the global scene and act as a unifying force for the community. Therefore, we recommend support for its construction and for the development of instrumentation, software and analysis tools.*

- ***ePIC**: Here, European researchers will be able to explore unknown features of quarks and gluons inside nucleons and nuclei. We recommend to support the participation of European groups in ePIC, and to reinforce scientific and technological activities which synergize with European projects.*

NuPECC LRP 2024, hadron chapter

THEORY AND COMPUTING

We recommend the support of theory groups at universities and research centres to prepare the community to benefit from the European investment in supercomputing and to be ready for quantum computing.

Theorists play an essential role in interpreting experimental results but also in providing input and predictions for new experiments. To match experimental progress, sophisticated approaches need to be developed. In lattice QCD, the rapid evolution of computational techniques and hardware calls for new algorithms and software. Similarly, quantum computing requires appropriate algorithms and tests on quantum hardware. Support for theoretical groups in terms of positions and career prospects is thus essential for progress in hadron physics.