universität freiburg

Flavour Physics

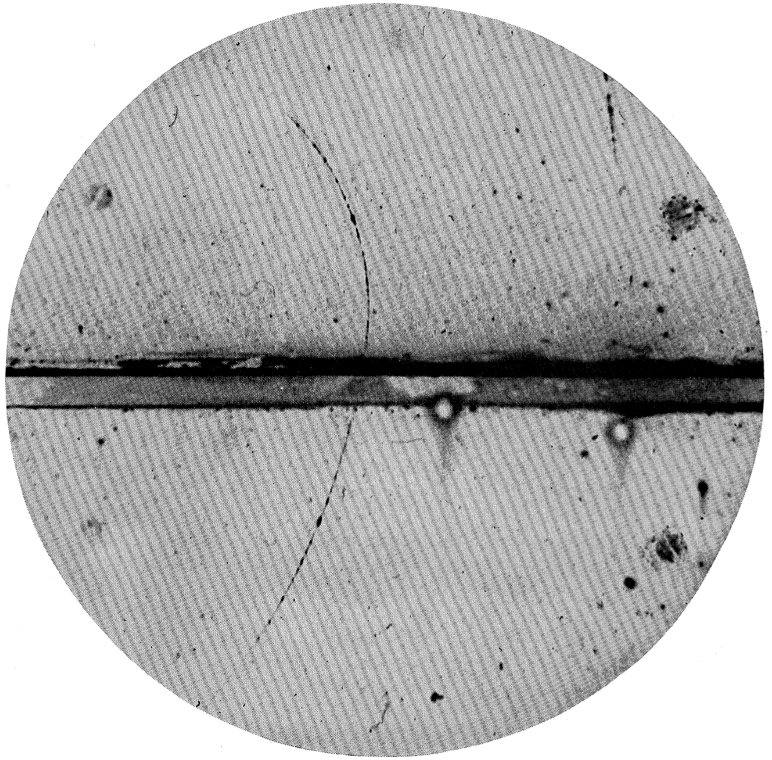
An experimentalist's perspective

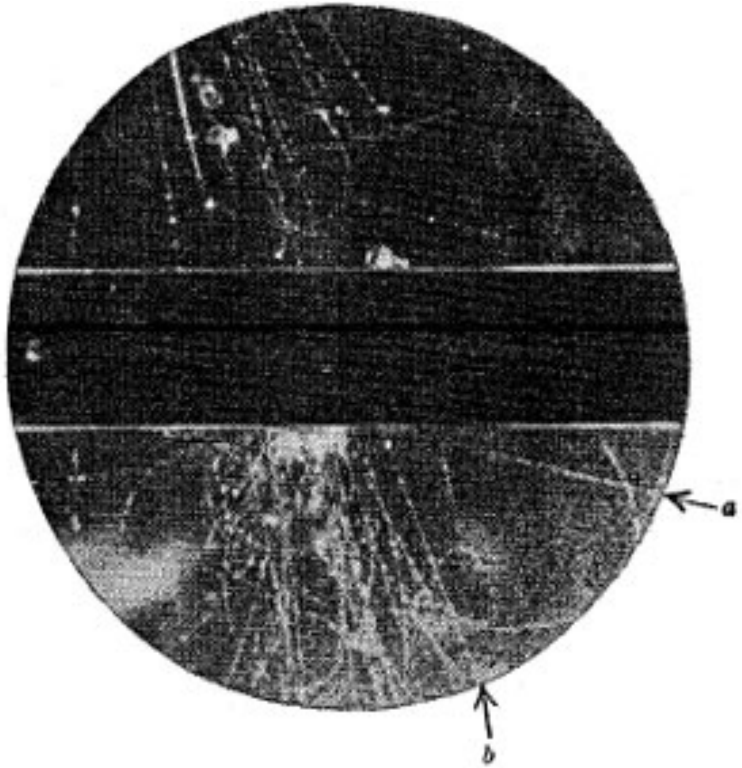
Herbstschule of High-Energy Physics
Prof. Dr. Marco Gersabeck
Bad Honnef, 11.-13. September 2024

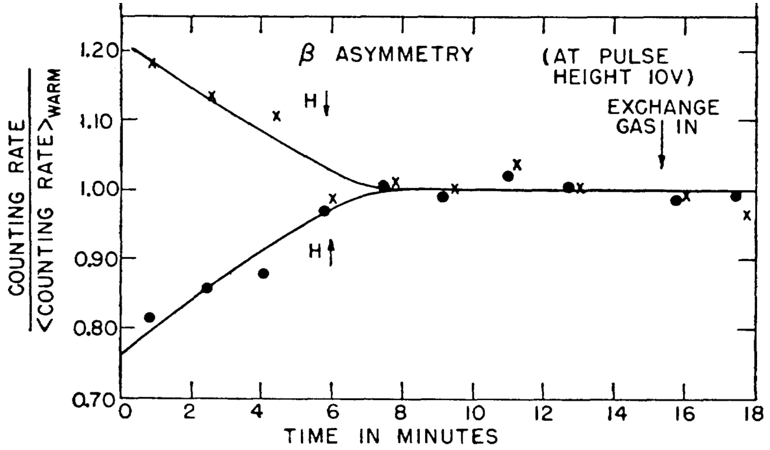
Outline

1. Introduction
2. Detectors and reconstruction
3. Mixing and CP violation
4. Rare processes
5. Future flavour

First steps

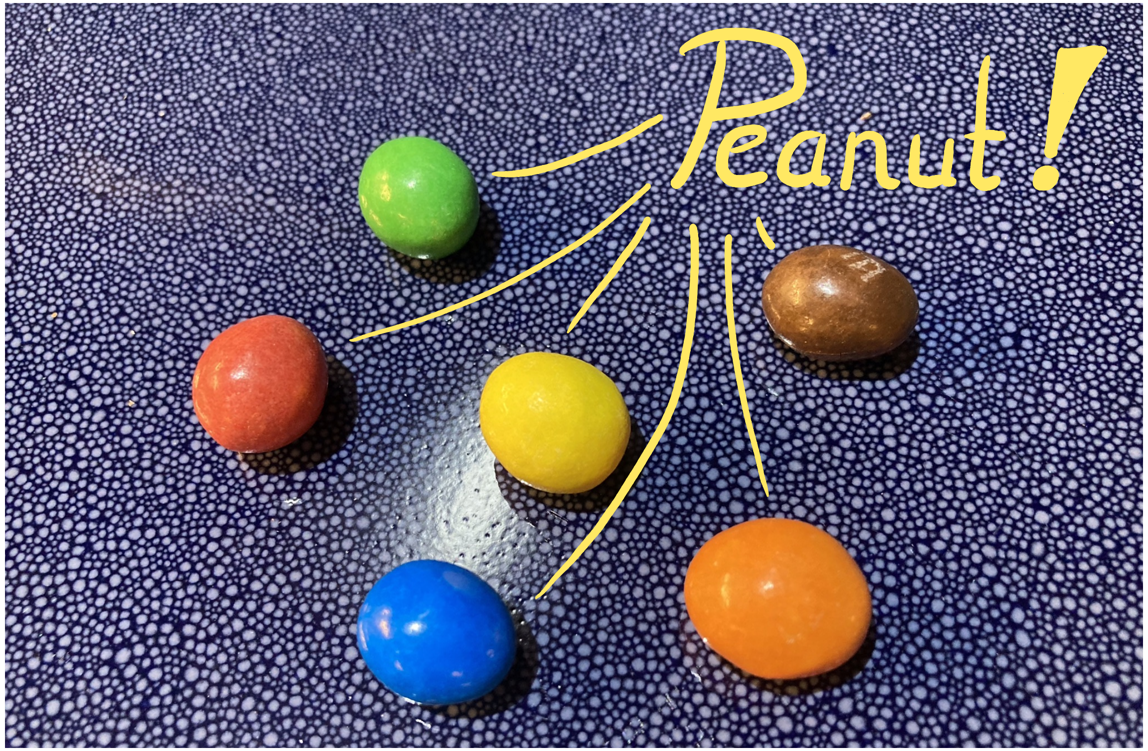



a
b


β ASYMMETRY
(AT PULSE HEIGHT 10V)
EXCHANGE GAS IN
H↓
H↑
COUNTING RATE / <COUNTING RATE>WARM
1.20
1.10
1.00
0.90
0.80
0.70
0 2 4 6 8 10 12 14 16 18
TIME IN MINUTES

Flavour physics

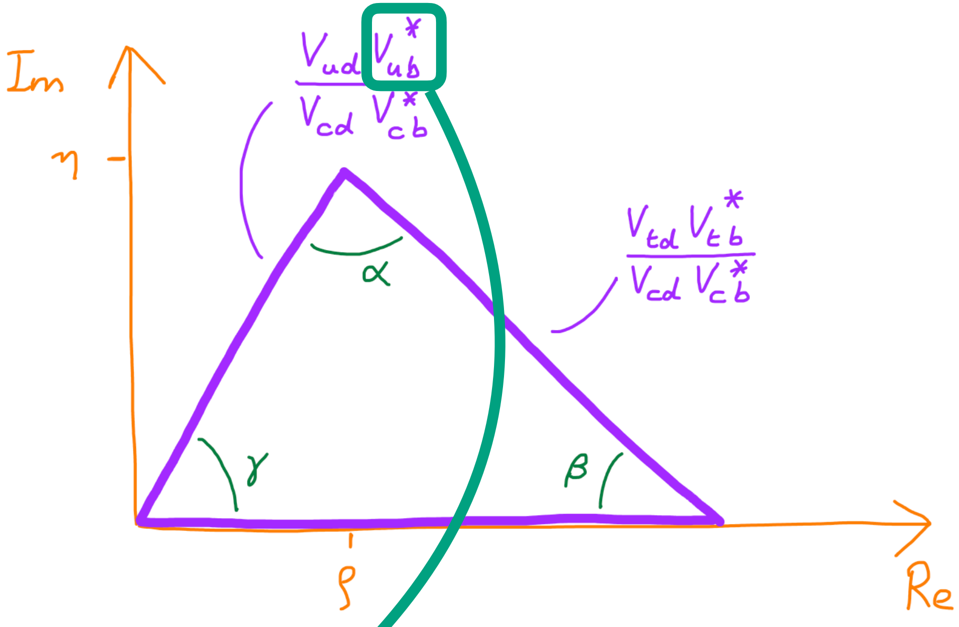
Identifying Beyond the Standard (Cocoa) Model effects
with precision flavour measurements
→ Sensitivity to mass scales beyond reach of direct observation



Combining indirect evidence to reveal hidden flavours

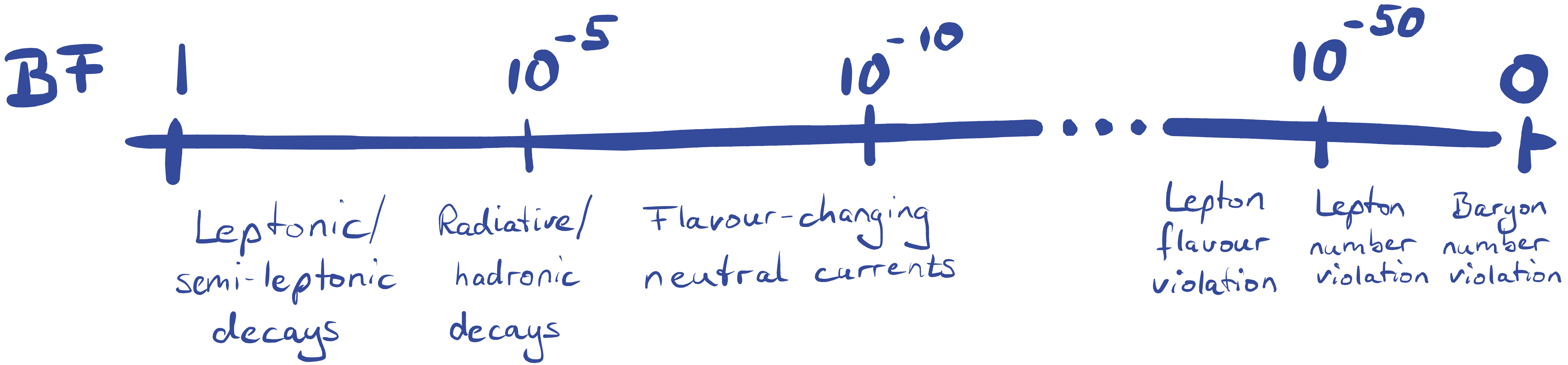
(A)Symmetries

- Ratios or asymmetries are powerful tests due to cancellation of strong interaction effects
- Test SM expectations of a range of symmetries
  - Lepton Universality: W coupling to eν, μν, τν
- Matter-antimatter asymmetry
  - CP violation in decays
  - CP violation in neutral meson-antimeson mixing
  - Interference of the two
- SM CP violation governed by complex phase of CKM matrix



$$\mathbf{V} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta + i\eta\lambda^2/2) \\ -\lambda & 1-\lambda^2/2 - i\eta A^2\lambda^4 & \lambda^2 A(1+i\eta\lambda^2) \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

Precision measurements



Flavour physics
Fast tracking discoveries

- K^0-$\overline{K}^0$ mixing and smallness of $K^0 \to \mu^+\mu^-$
  - GIM mechanism predicts charm quark in 1970
- Kaon CP violation
  - KM mechanism predicts bottom and top quarks in 1973
    - Charm & bottom quarks discovered: 1974*+1977
- B^0-$\overline{B}^0$ oscillations discovered in 1987
  - Requires mtop > 50 GeV to deactivate GIM cancellation
    - Top quark discovered: 1995

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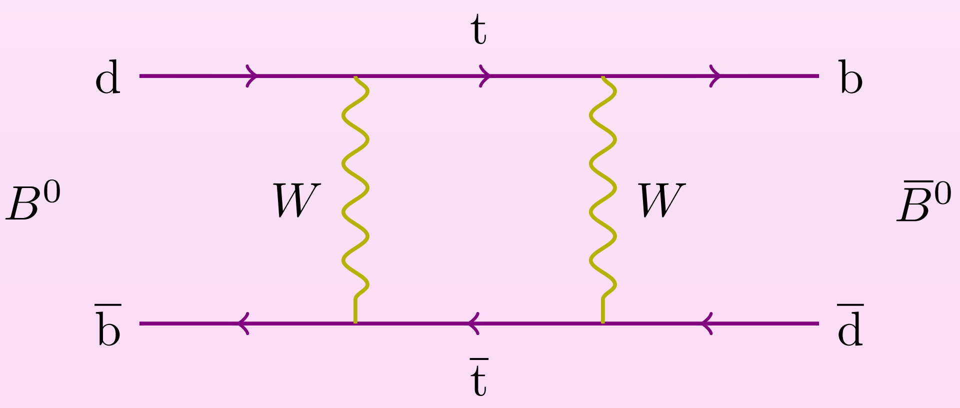
Then: ARGUS, 10^5 $B\bar{B}$ decays, probing 0.1 TeV
Now: LHCb, 10^{12} $B\bar{B}$ decays, probing 100 TeV



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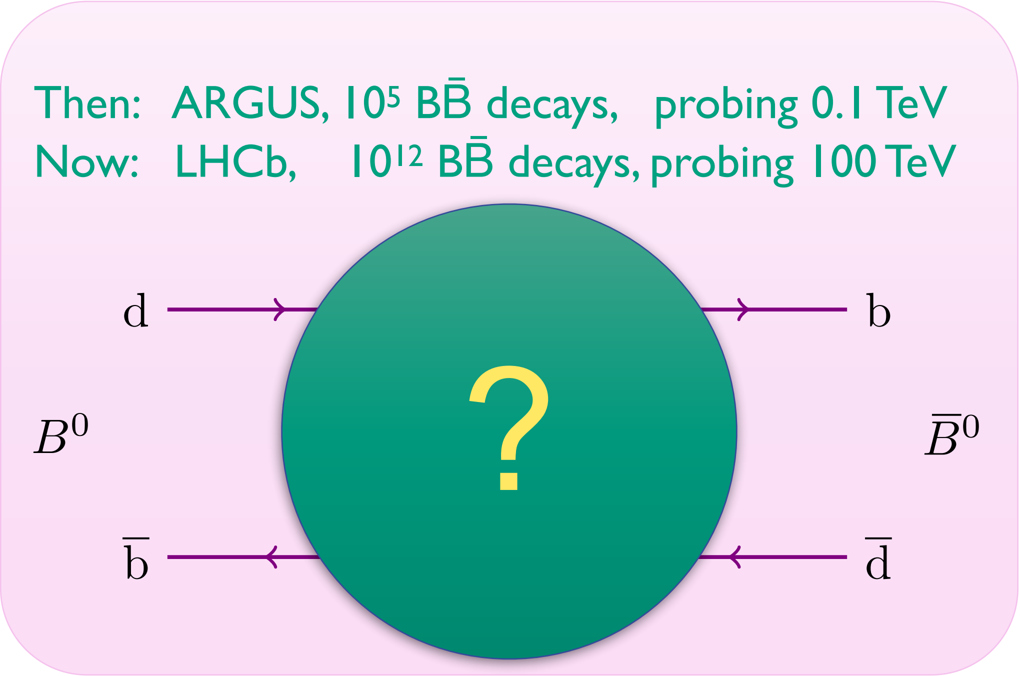

The reach of flavour

- Indirect participation of BSM particles opens door to heavy virtual particles
- Can outperform direct reach by many orders of magnitude
- Requires non-minimally flavour violating new physics
- MFV scenario still offers discovery potential, e.g. in B-meson oscillations

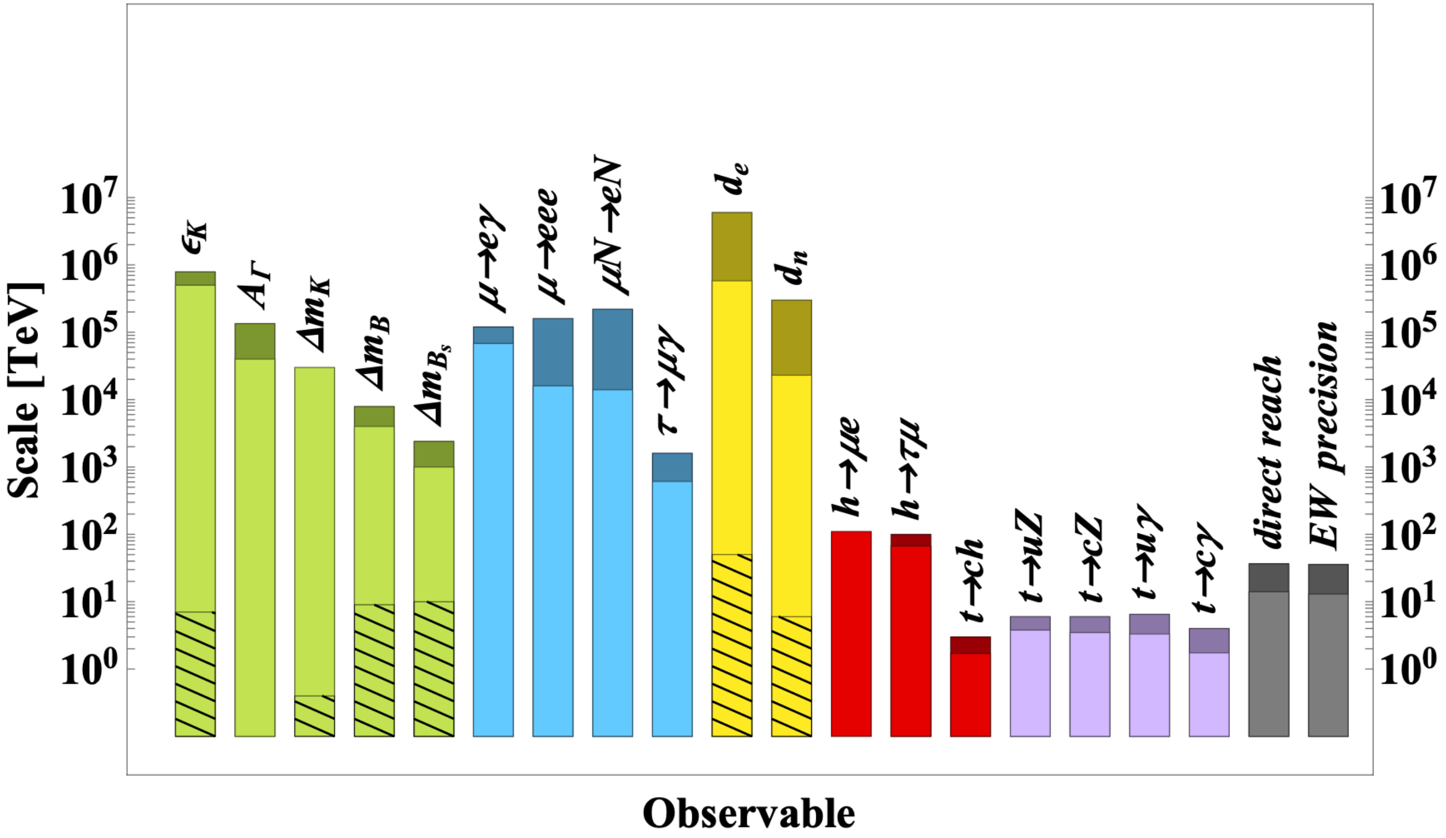

Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS).

Detectors and reconstruction

Production
Experiments
Reconstruction

Experiments

Flavour production

	Fixed target	e^+e^- collider	Hadron collider
Cross-section	NA62: 4×10^{-6} kaon decays in detector per proton on target	D^0 from $\psi(3770)$: 8 nb D^0 from $\Upsilon(4S)$: 1.5 nb B^0 from $\Upsilon(4S)$: 1.1 nb	LHCb acceptance@13 TeV $c\bar{c}$ pairs: 2.4 mb $b\bar{b}$ pairs: 0.14 mb

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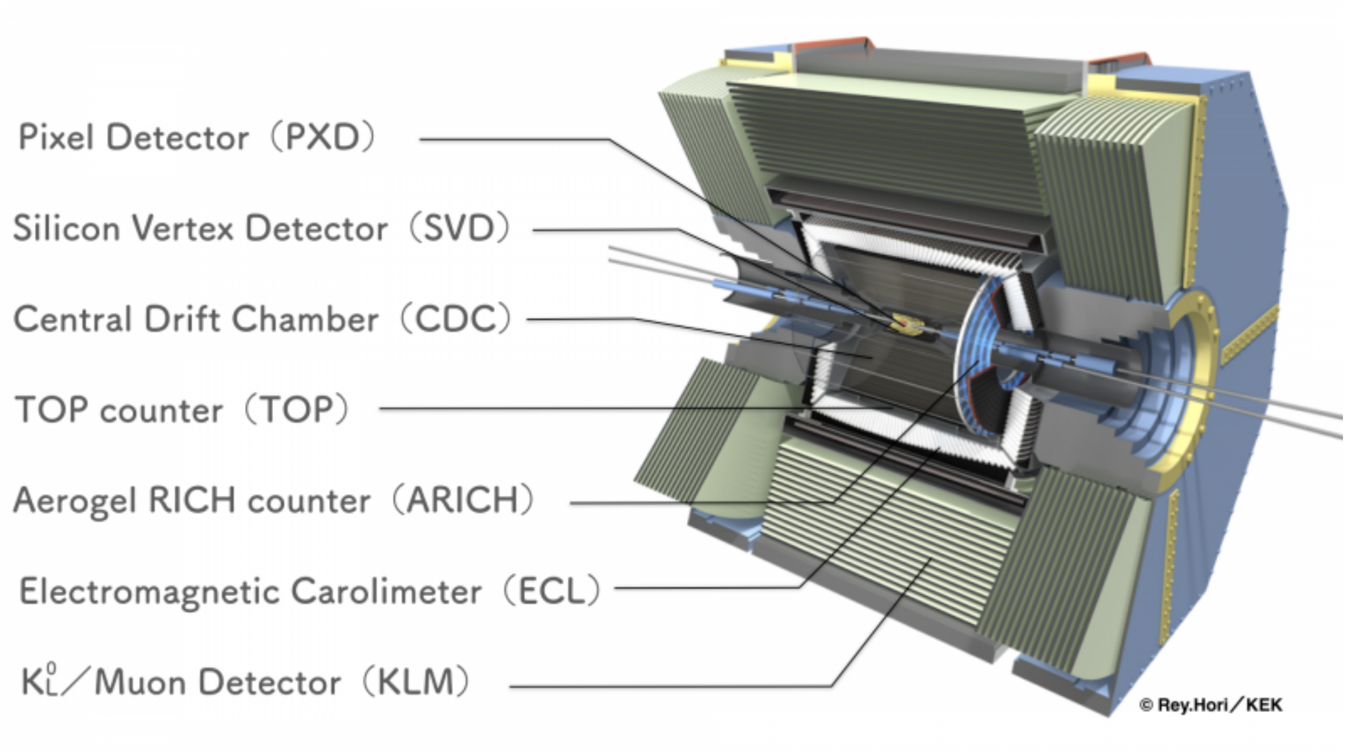
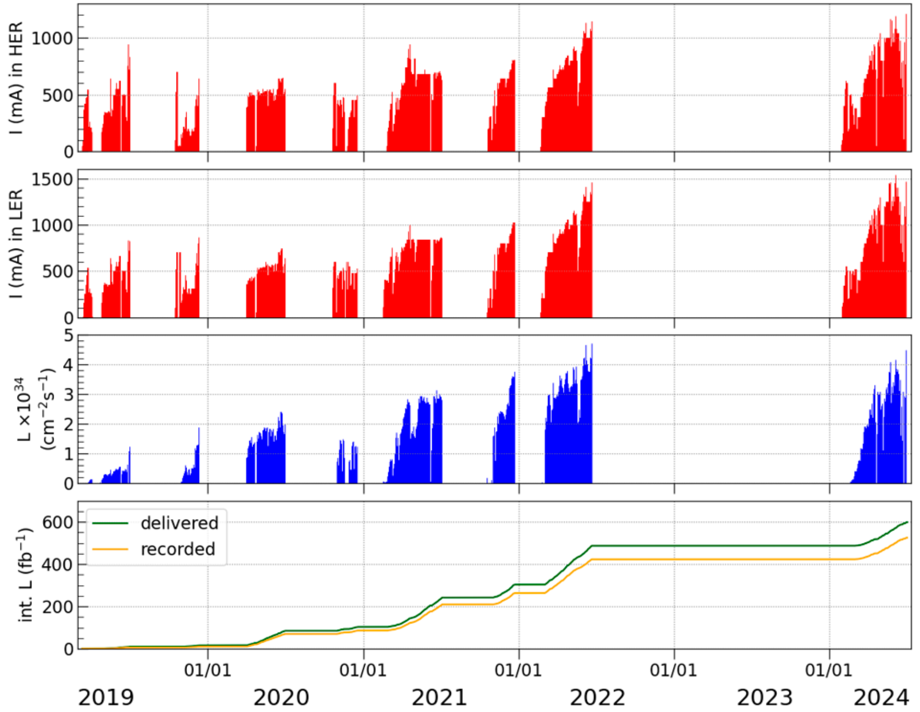
Comments	Muon production from fixed-target produced pion decay similar	Can produce quantum-correlated meson pairs	Access to all hadron masses

Belle II

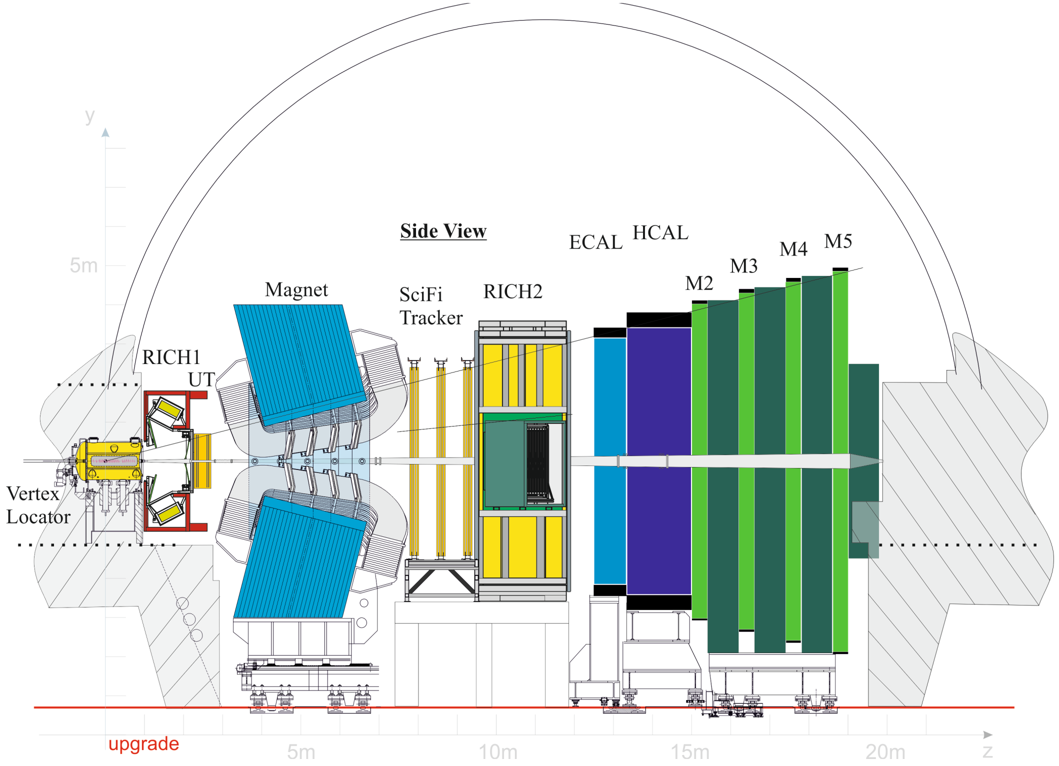


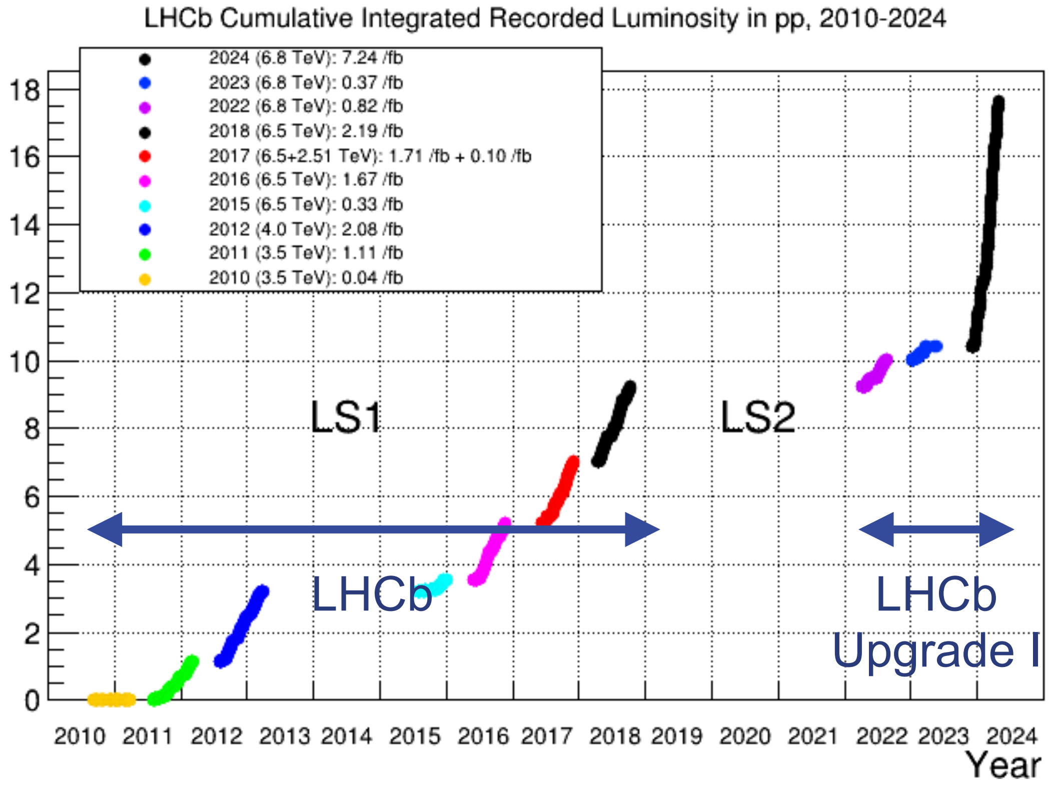


Belle II detector optimised for high-luminosity asymmetric e^+e^- collisions

Data taking continues after recent upgrade completing vertex detector

LHCb



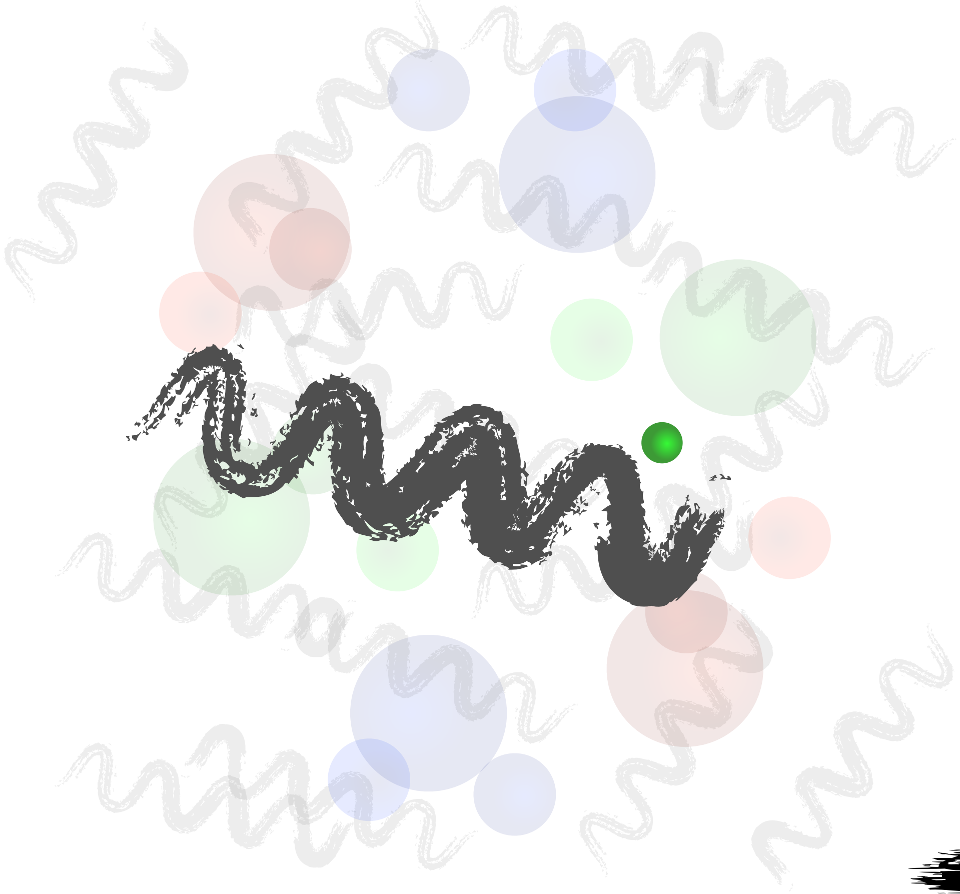


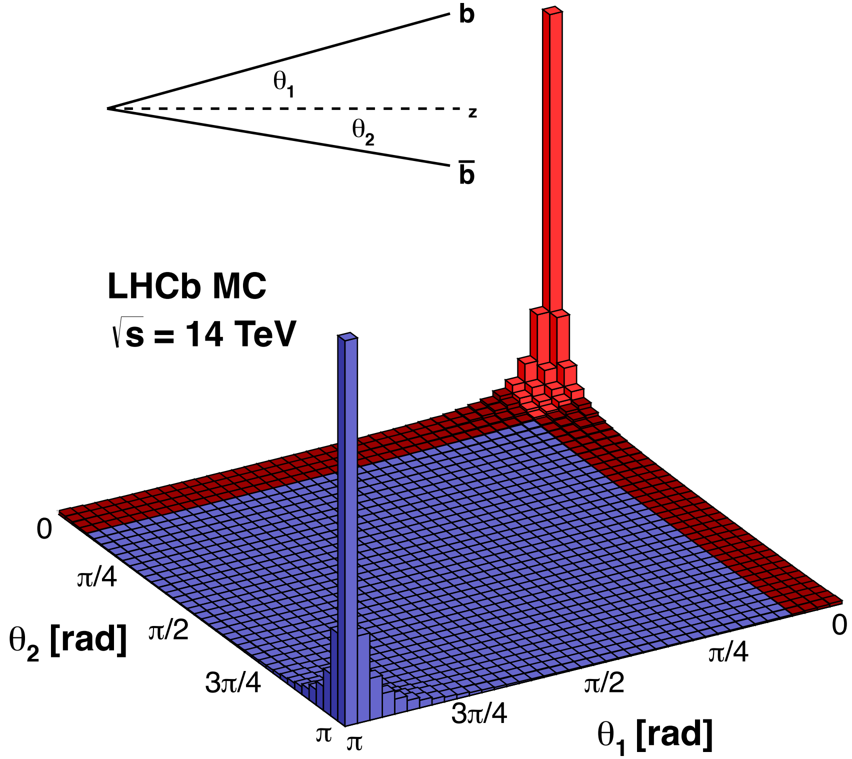
LHCb detector as upgraded during LS2
40 MHz full detector readout into software trigger

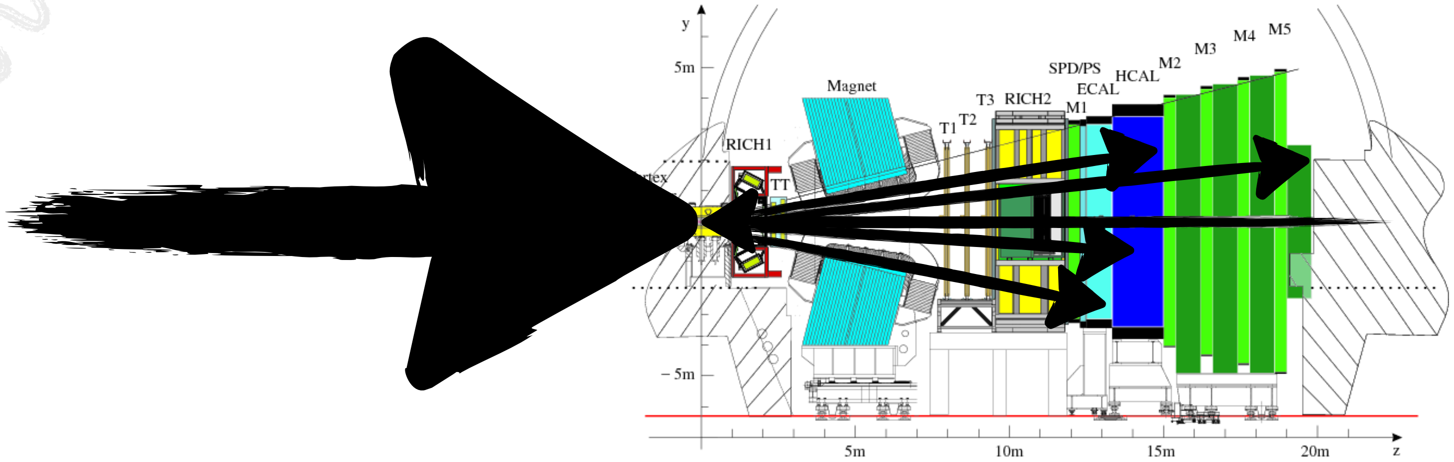
LHCb: up to 2 fb^{-1} / year
LHCb Upgrade I: ~8 fb^{-1} / year

Asymmetric collisions

Asymmetric collisions



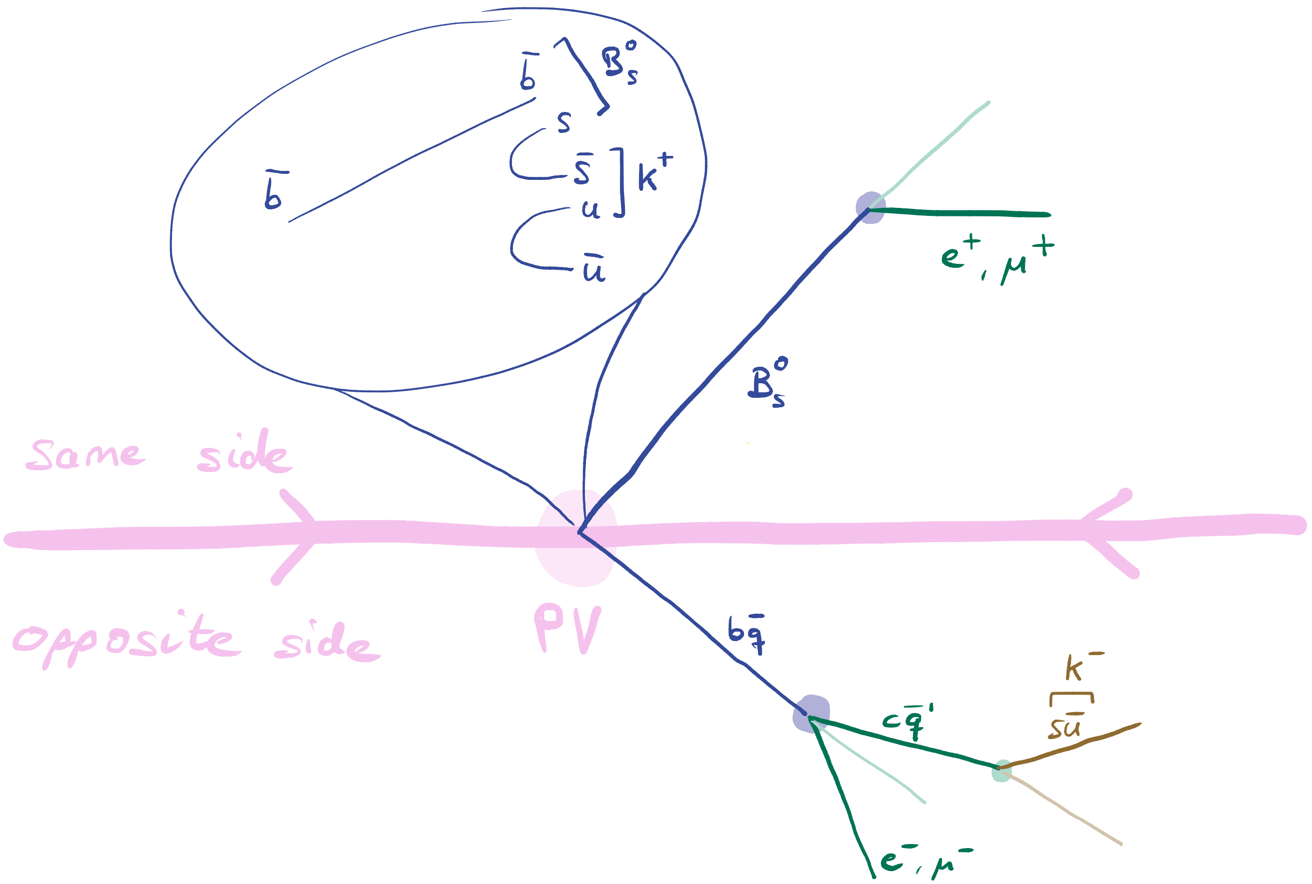




B flavour tagging

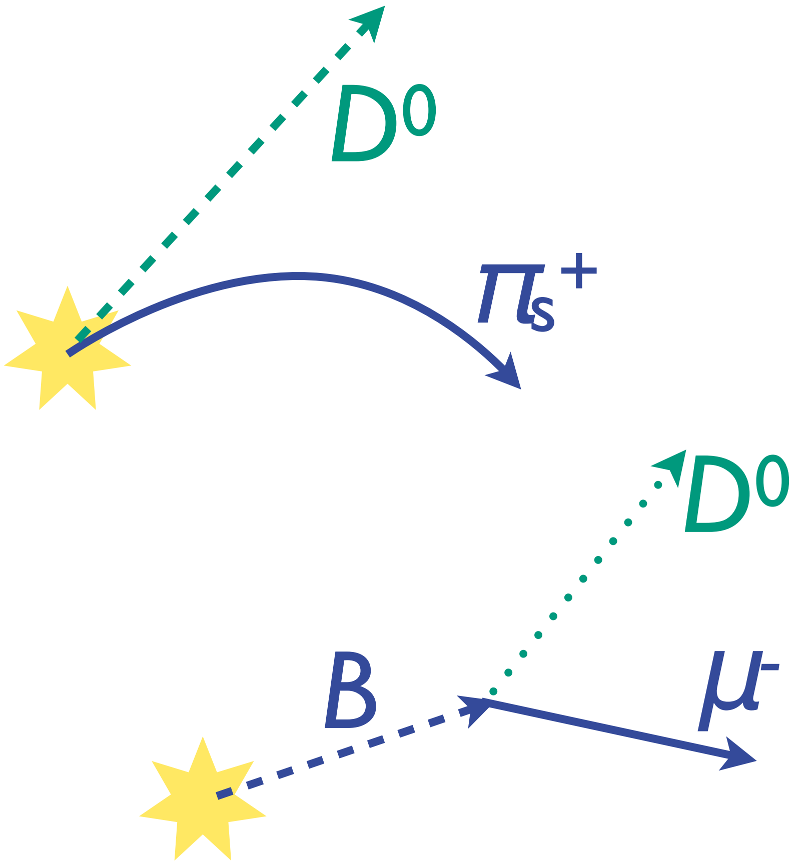
- Apart from proton valence quarks, all quarks are produced as $q\bar{q}$ pairs

- Same side tagging
  - Exploit $q\bar{q}$ connections of light quarks associated to b-quark under study
- Opposite side tagging
  - Exploit decay chain of other quark produced in $b\bar{b}$ pair



Charm flavour tagging

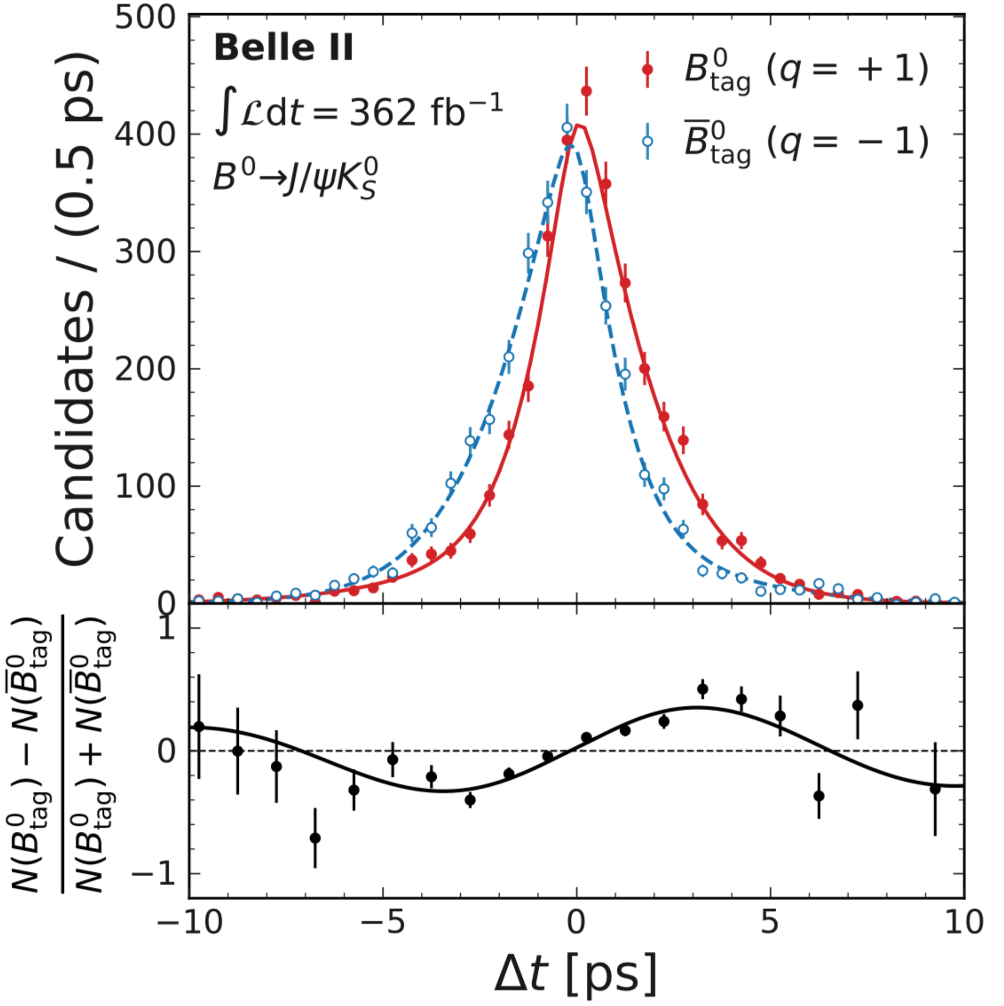
- Can distinguish D^0 from $\overline{D}^0$ in two ways:
- Prompt D*-tagged
  - Charge of soft pion from strong decay $D^{*+} \rightarrow D^0 \pi_s^+$
  - Larger yields
  - Background from D-from-B
- Charge of muon from semi-leptonic decay $B \rightarrow D^0 \mu^- X$
  - Smaller yields (somewhat)
  - Larger level of combinatorial background
  - Independent systematic uncertainties
- Double-tagged
  - The best of both worlds
  - Smallest samples



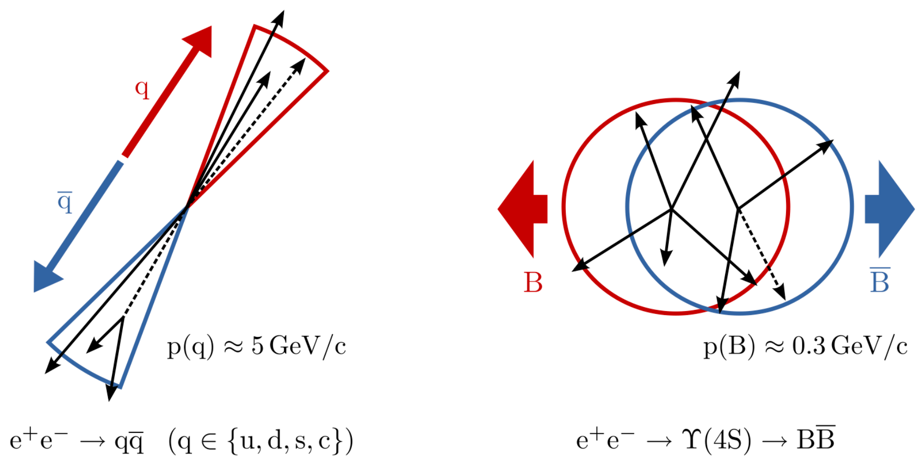
Quantum-correlated states and Decay-time difference

Belle II, PRD 110 (2024) 012001

- Neutral meson-antimeson pairs can be produced in quantum-correlated decays
  - $\phi \to K^0\overline{K}^0$, $\psi(3770) \to D^0\overline{D}^0$, $\Upsilon(4S) \to B^0\overline{B}^0$, $\Upsilon(5S) \to B_s^0\overline{B}_s^0$
  - Decay of one meson in one flavour state determines the other meson to be in the opposite flavour state <u>at that moment in time</u>
  - Measure time evolution of the other meson with respect to that moment
    - $\Delta t = t_1 - t_2$
    - Δt can take negative values



Credit: Markus Röhrken



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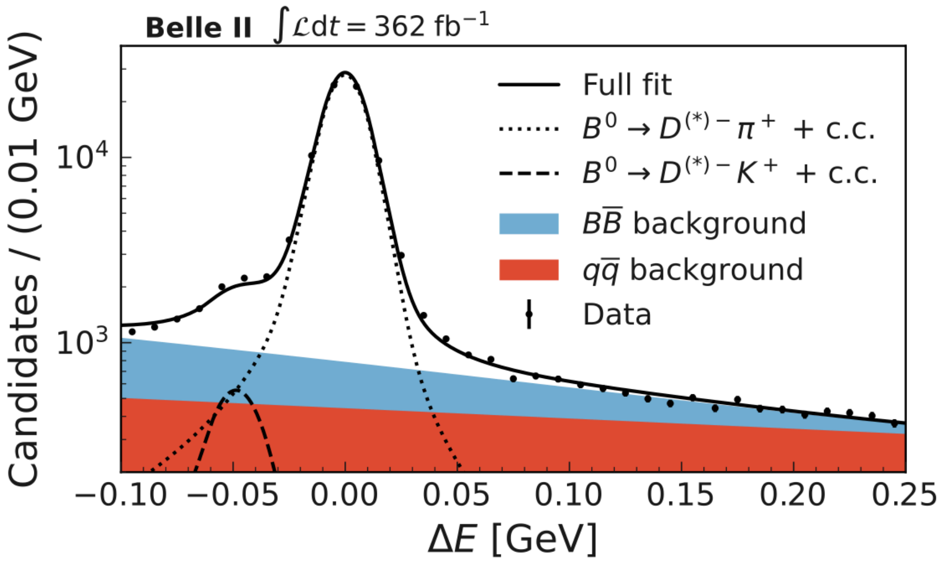
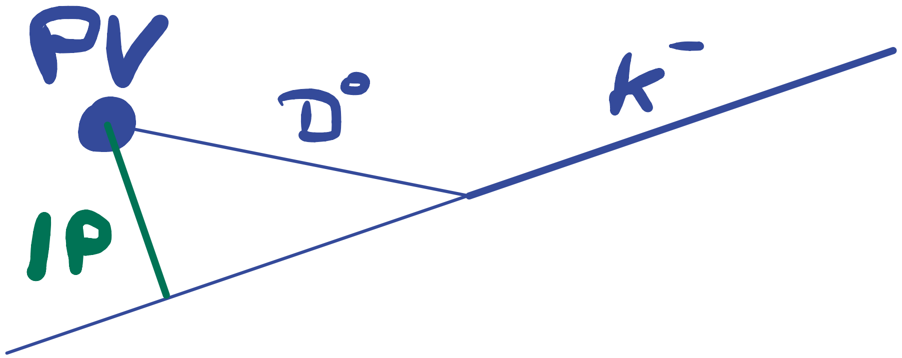


Continuum suppression

- At e+e− colliders can exploit precisely known beam energy:
  - E^{*}_{beam}
- Need to separate resonant events, e.g. Y(4S), from continuum production
- For fully-reconstructed B decays expect difference of B energy to beam energy to be 0
  - $\Delta E = E^{*}_{B} - E^{*}_{\mathrm{beam}}$
- Beam-constraint mass peaks at B mass for fully reconstructed B momentum
  - $M_{\mathrm{bc}} = \sqrt{[E^{*}_{\mathrm{beam}}/c^2 - (p^{*}_{B}/c)^2]}$

Impact parameters



- Impact parameter: shortest distance between straight line (particle trajectory) and point (primary vertex)
- Decay products of particles that fly macroscopic distances have non-zero impact parameters
  - Tell-tale indicator of heavy-flavour decays
  - Per-particle information available without decay reconstruction
- Impact parameters of decaying particles are indicate whether or not they come from preceding heavy flavour decay
  - Most relevant in charm physics
- Need to correct for decay-time bias

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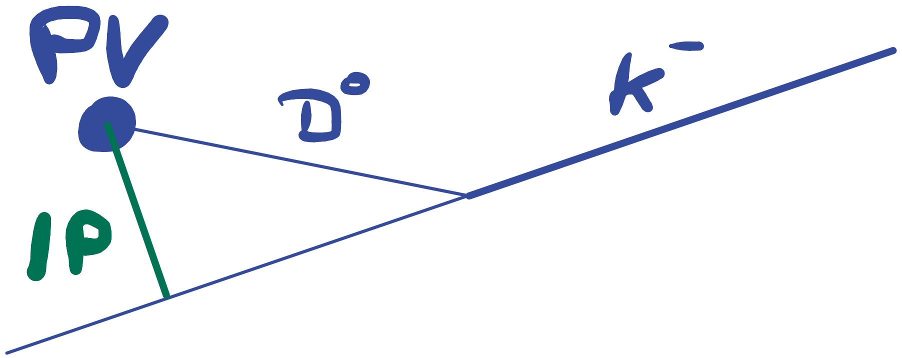

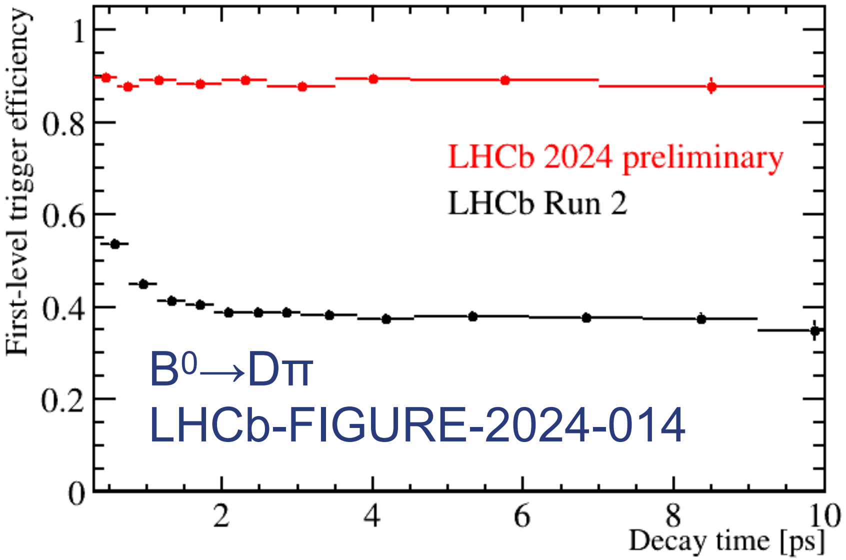

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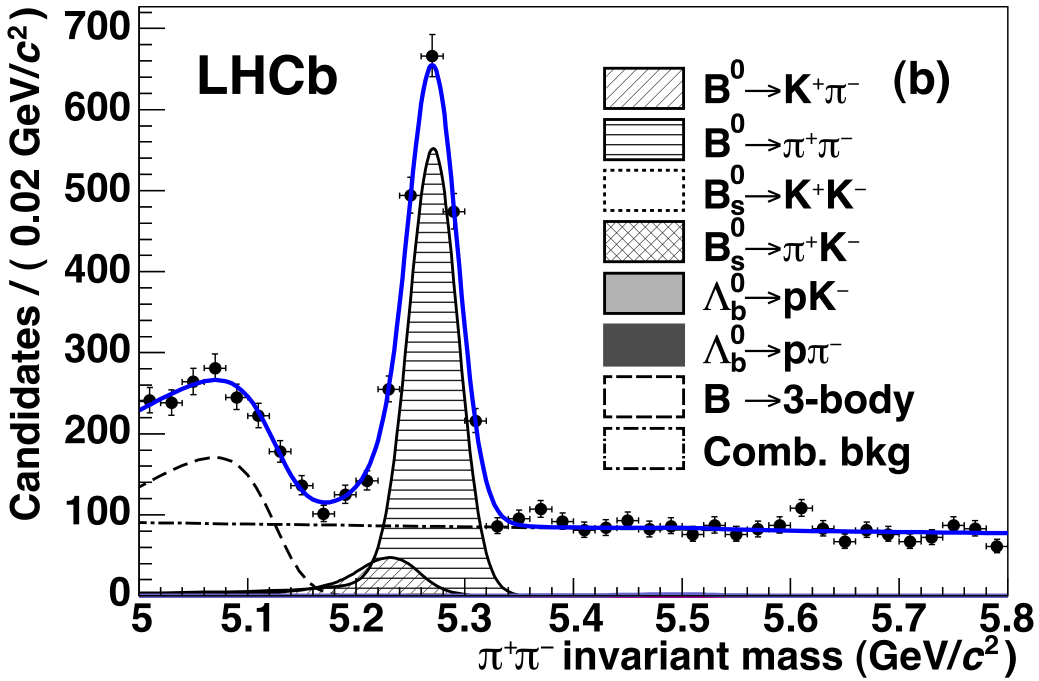

B→hh’ with PID requirements to identify pions

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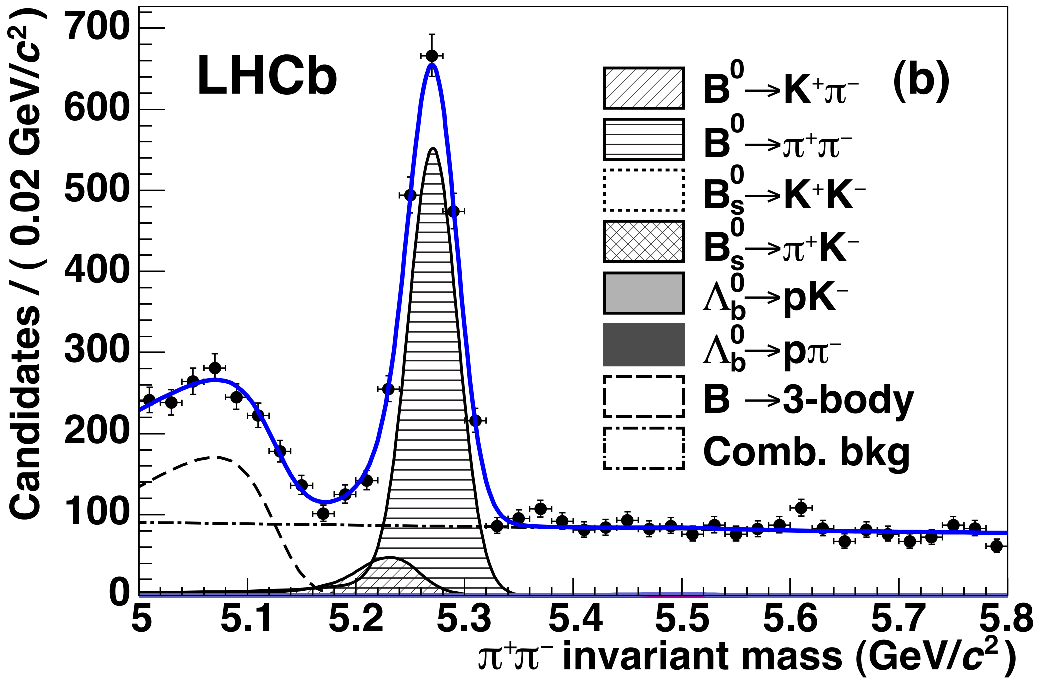

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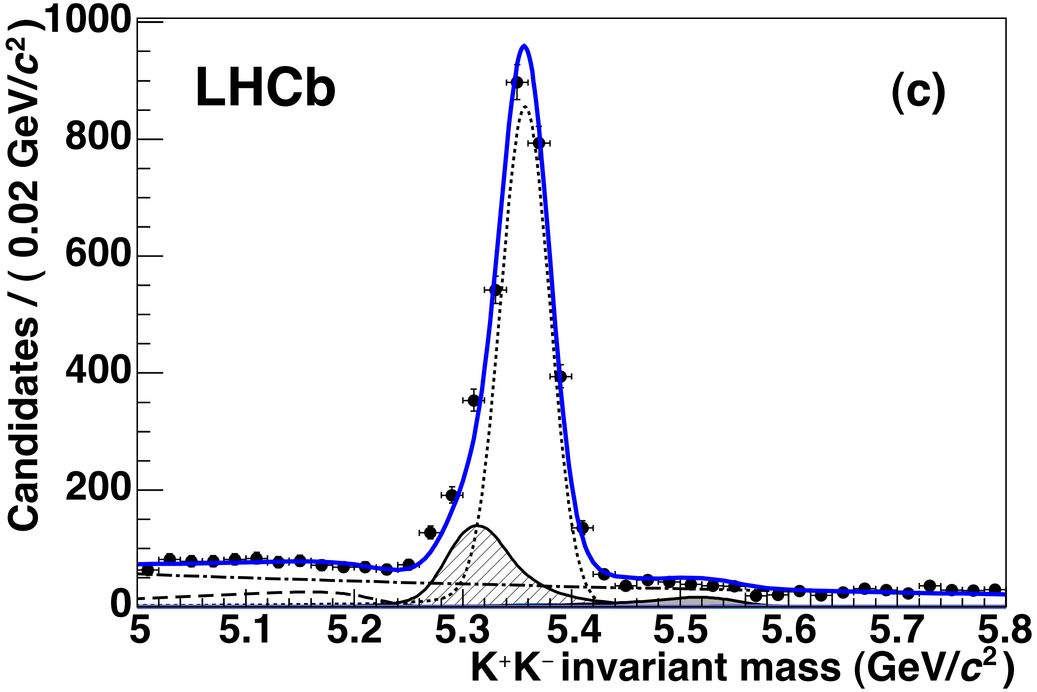

B→hh' with PID requirements to identify kaons

Recap

- Current multi-purpose heavy flavour experiments are BESIII (IHEP), Belle II (KEK) and LHCb (CERN)
- e^+e^- colliders have lower production rates, but can exploit more knowledge about production process
  - Resonant/quantum-correlated production possible
- pp colliders have access to all hadrons with large cross-sections, but more complex event topologies
- Flavour tagging and particle identification crucial for flavour physics