

universität freiburg

Flavour Physics

An experimentalist's perspective

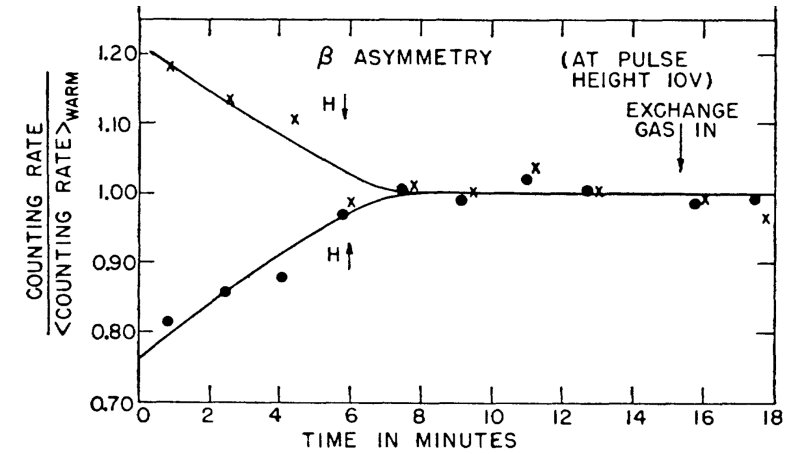
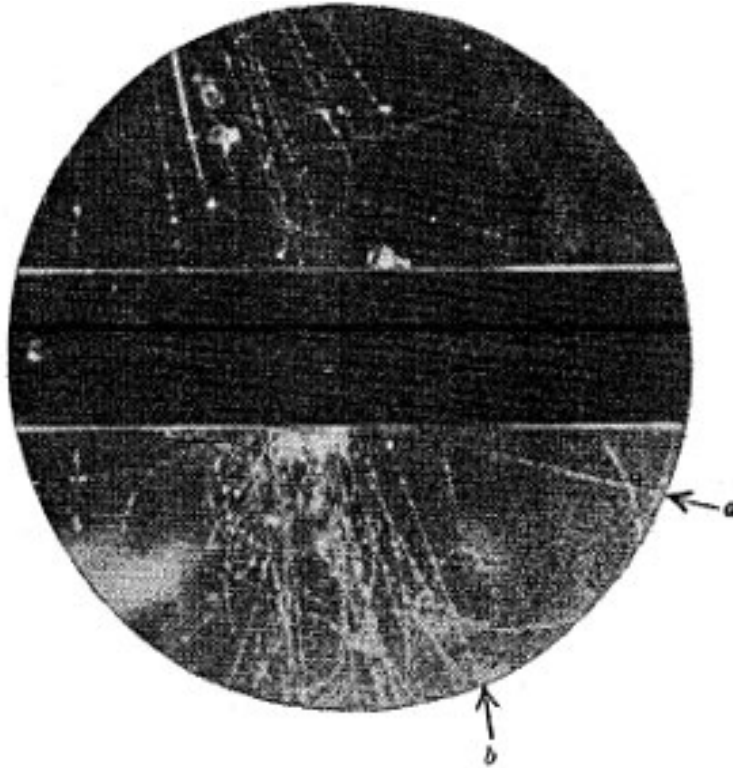
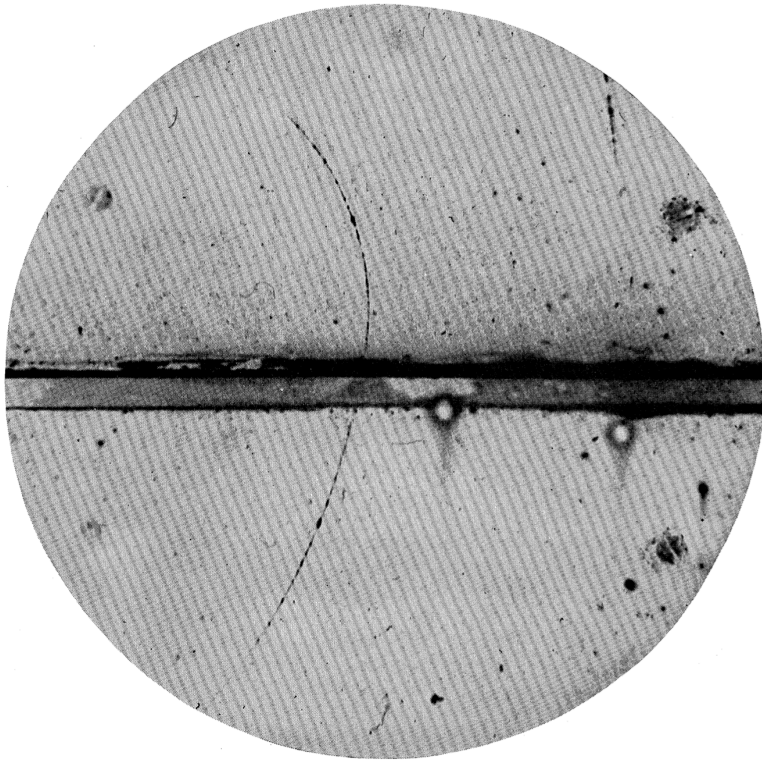
BND School 2026
Prof. Dr. Marco Gersabeck
Rursee, 9 September 2026



Outline

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

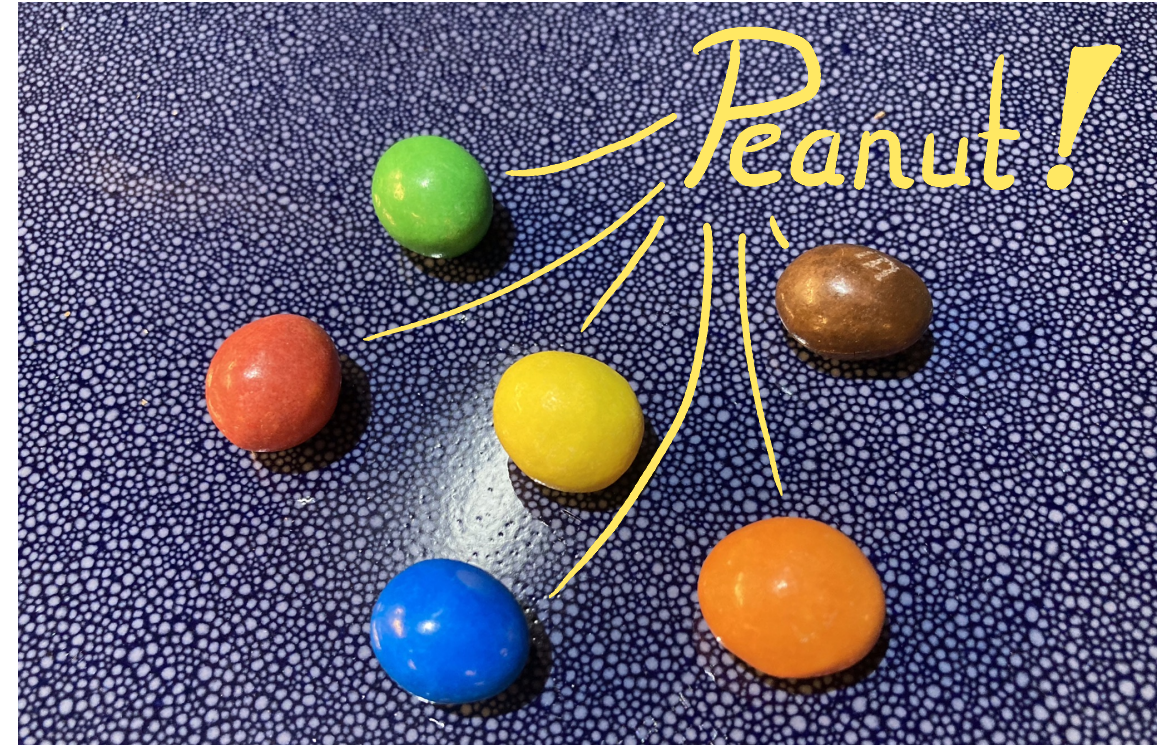
First steps



Flavour physics



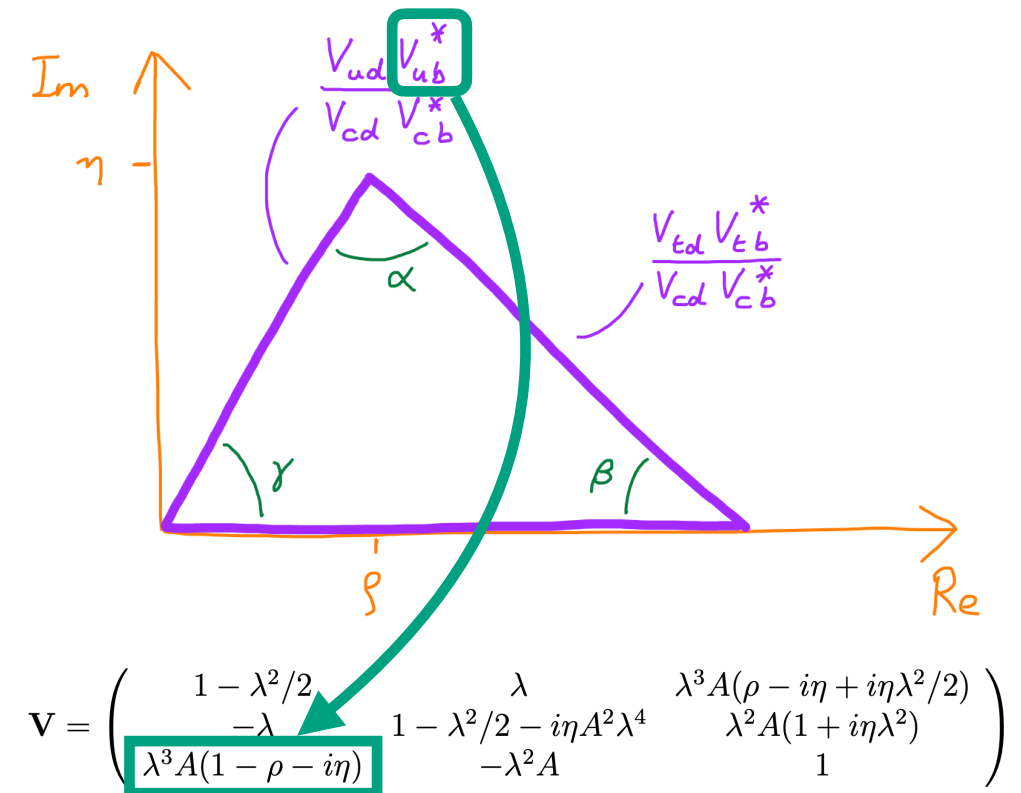
Identifying Beyond the Standard (Cocoa) Model effects
with precision flavour measurements
→ Sensitivity to mass scales beyond reach of direct observation



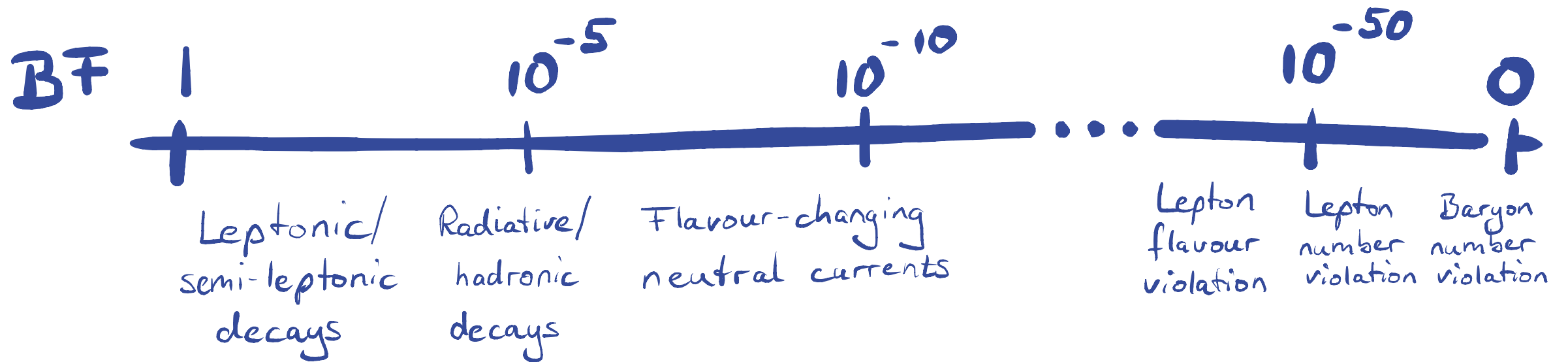
Combining indirect evidence to reveal hidden flavours

(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 $e\nu$, $\mu\nu$, $\tau\nu$
- 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



Precision measurements



Flavour physics

Fast tracking discoveries

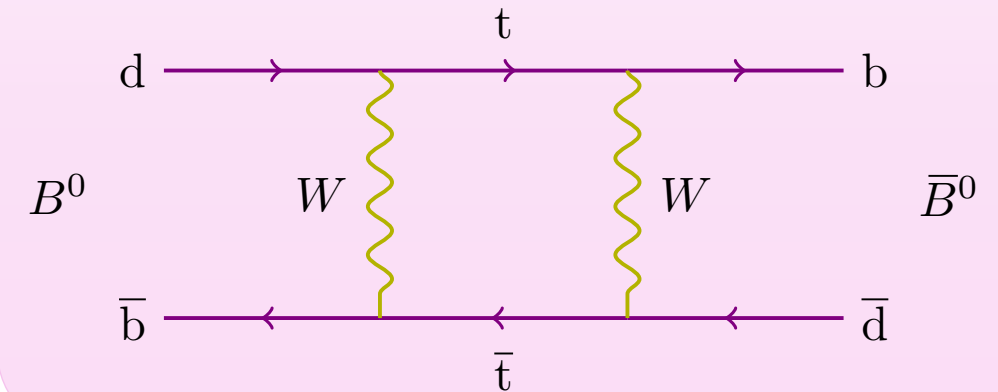
- K^0 - $\bar{K}^0$ mixing and smallness of $K^0 \rightarrow \mu^+ \mu^-$
 - GIM mechanism predicts charm quark in 1970
- Kaon CP violation
 - KM mechanism predicts bottom and top quarks in 1973
 - Charm & bottom quarks discovered: 1974*+1977
- B^0 - $\bar{B}^0$ oscillations discovered in 1987
 - Requires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

Flavour physics

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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

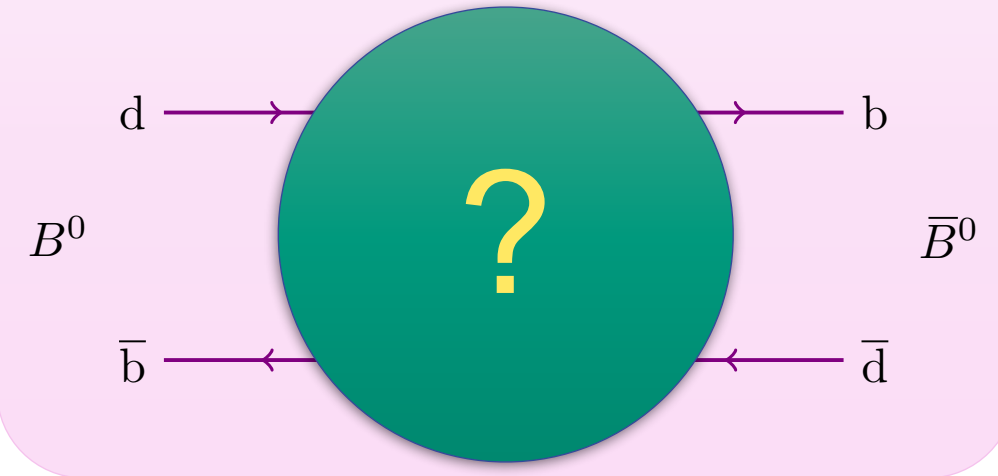


Flavour physics

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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

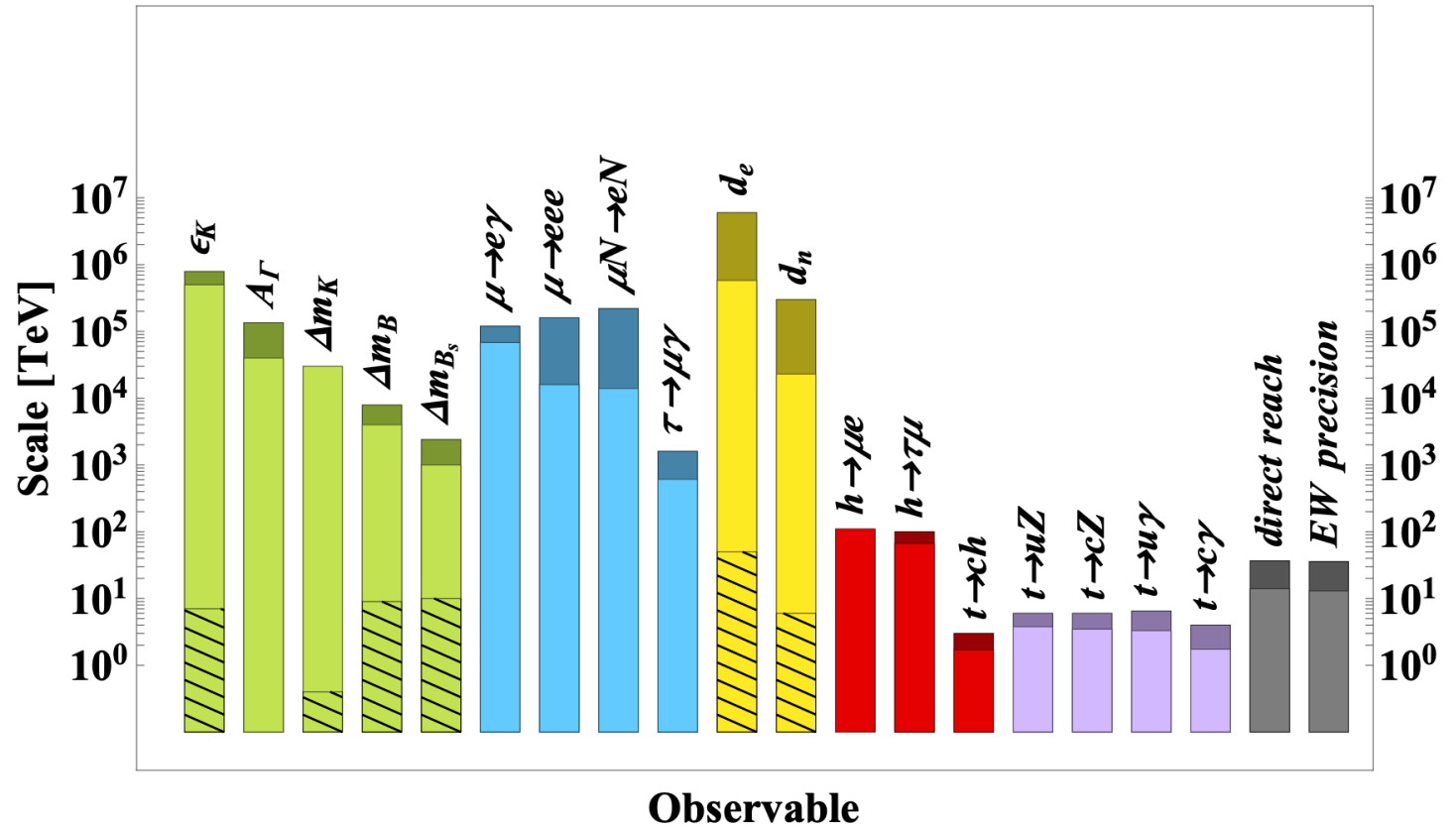


Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct 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 $Y(4S)$: 1.5 nb B^0 from $Y(4S)$: 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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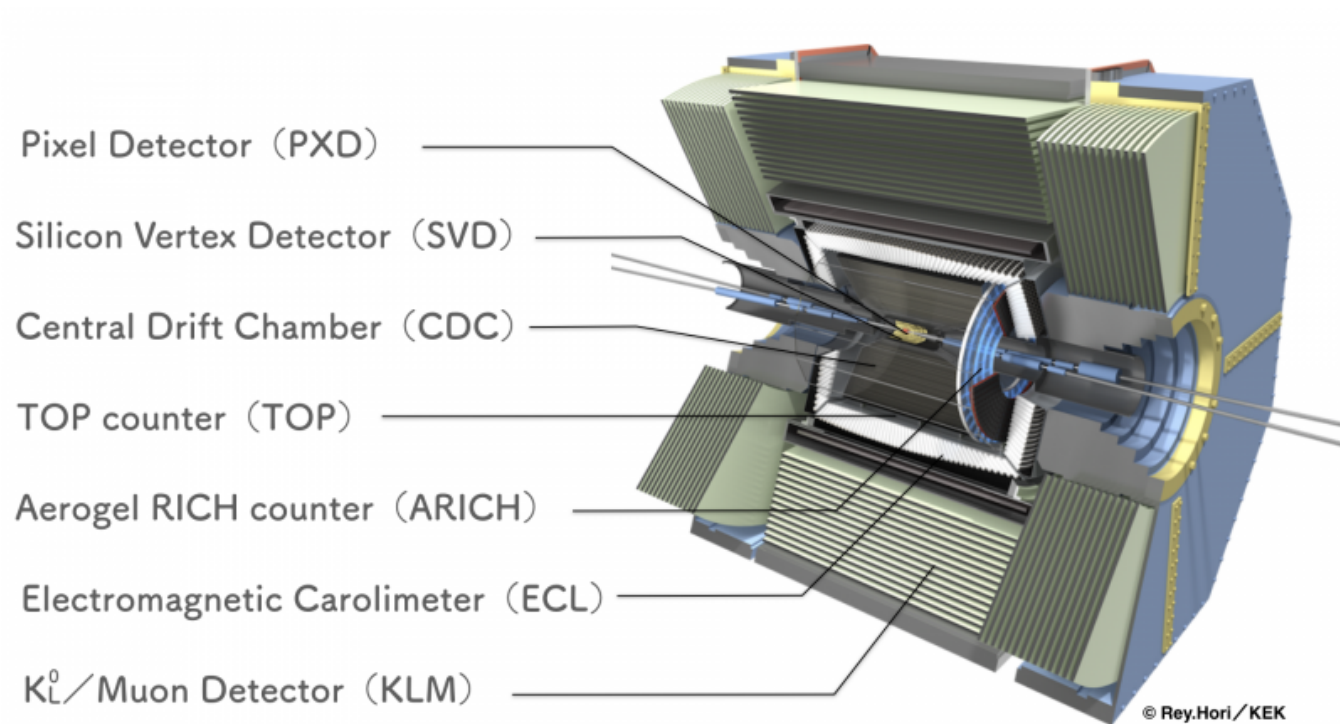
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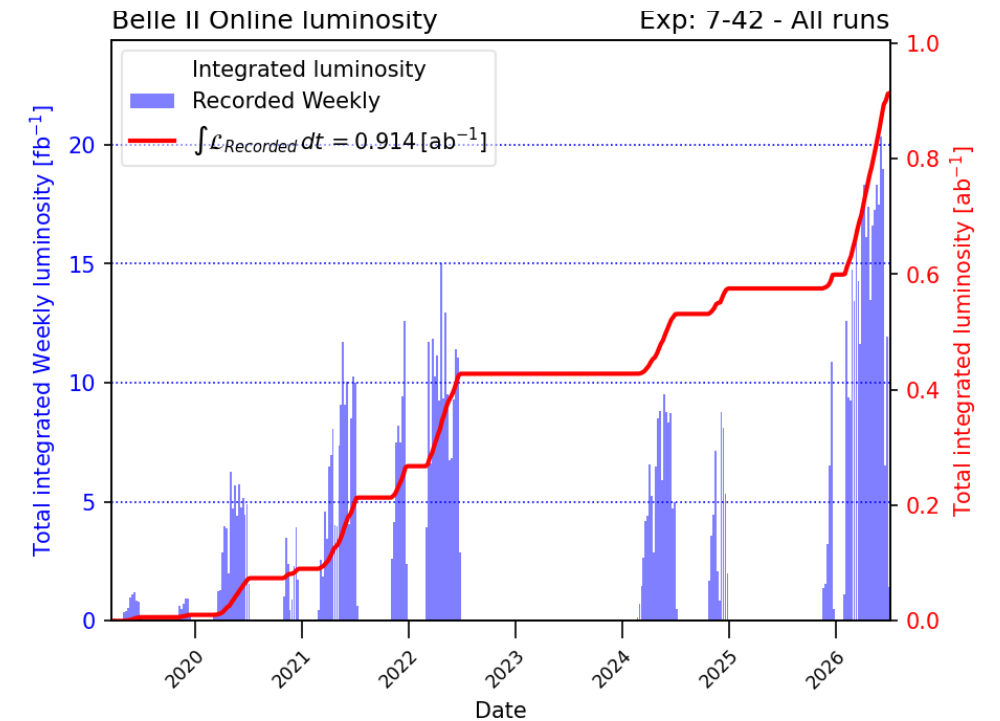
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Comments	Muon production from fixed-target produced pion decay similar	Can produce quantum-correlated meson pairs	Access to all hadron masses

Belle II

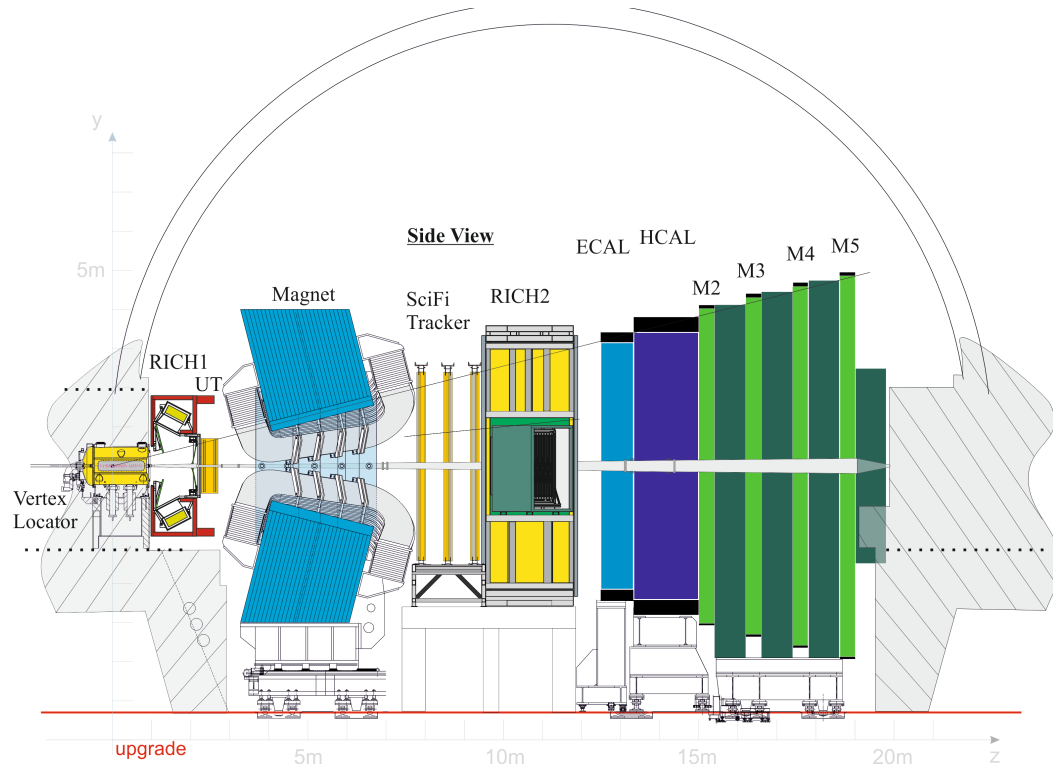


Belle II detector optimised for high-luminosity asymmetric e⁺e⁻ collisions

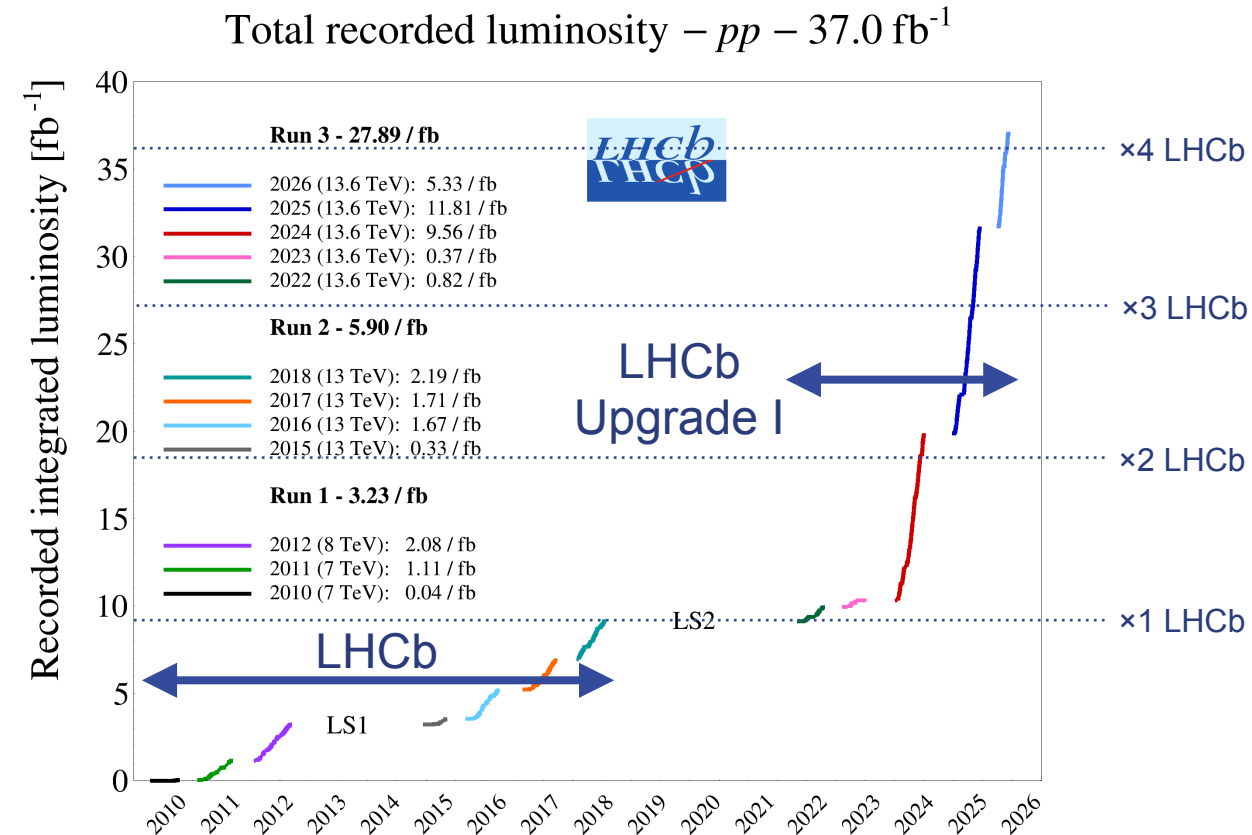


Updated on 2026/07/04 00:00 JST

Instantaneous luminosity improved after intervention
Belle II luminosity now exceeding Belle Y(4S) sample

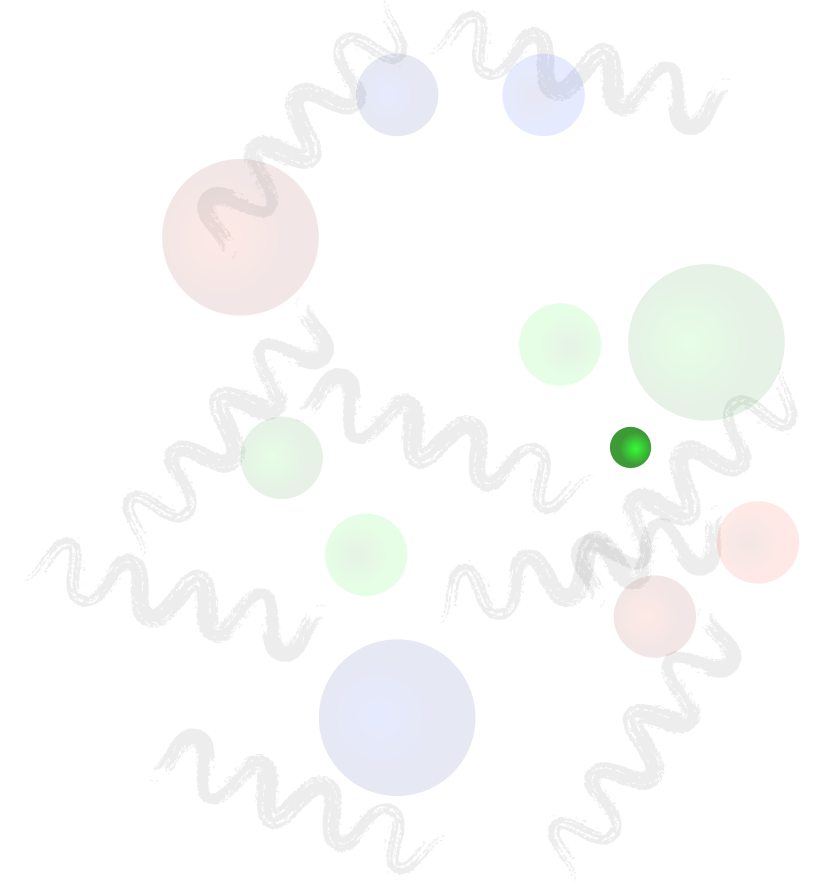
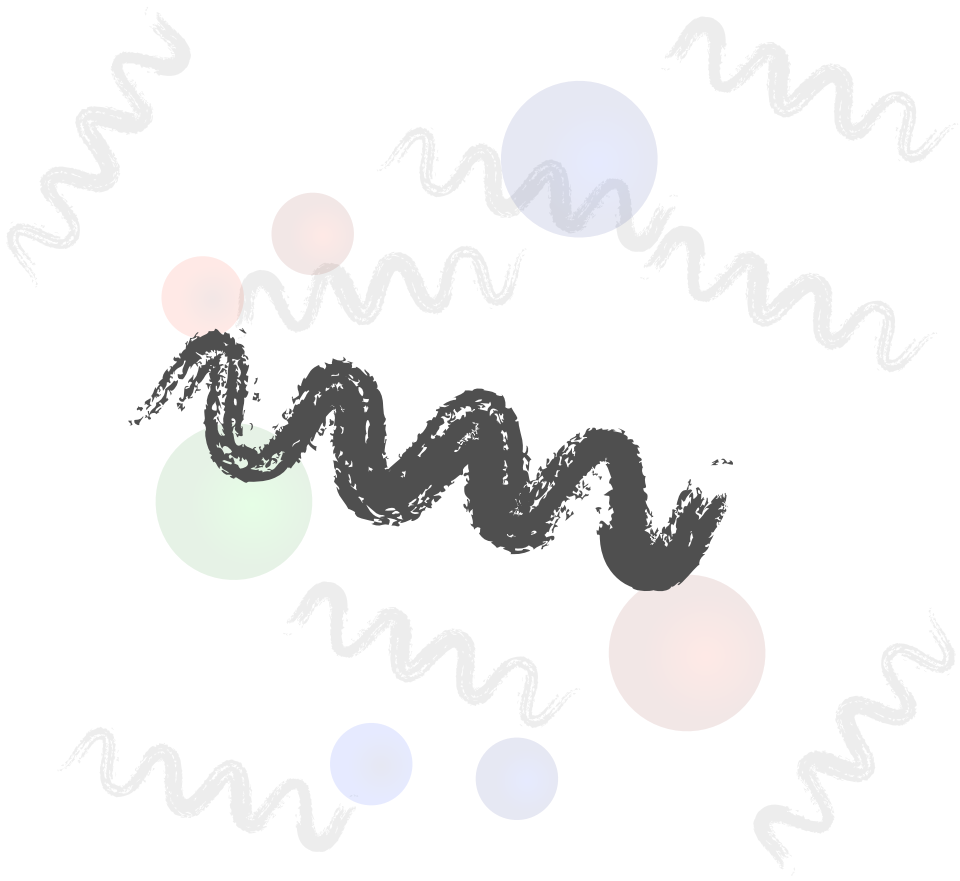


LHCb detector as upgraded during LS2
40 MHz full detector readout into software trigger

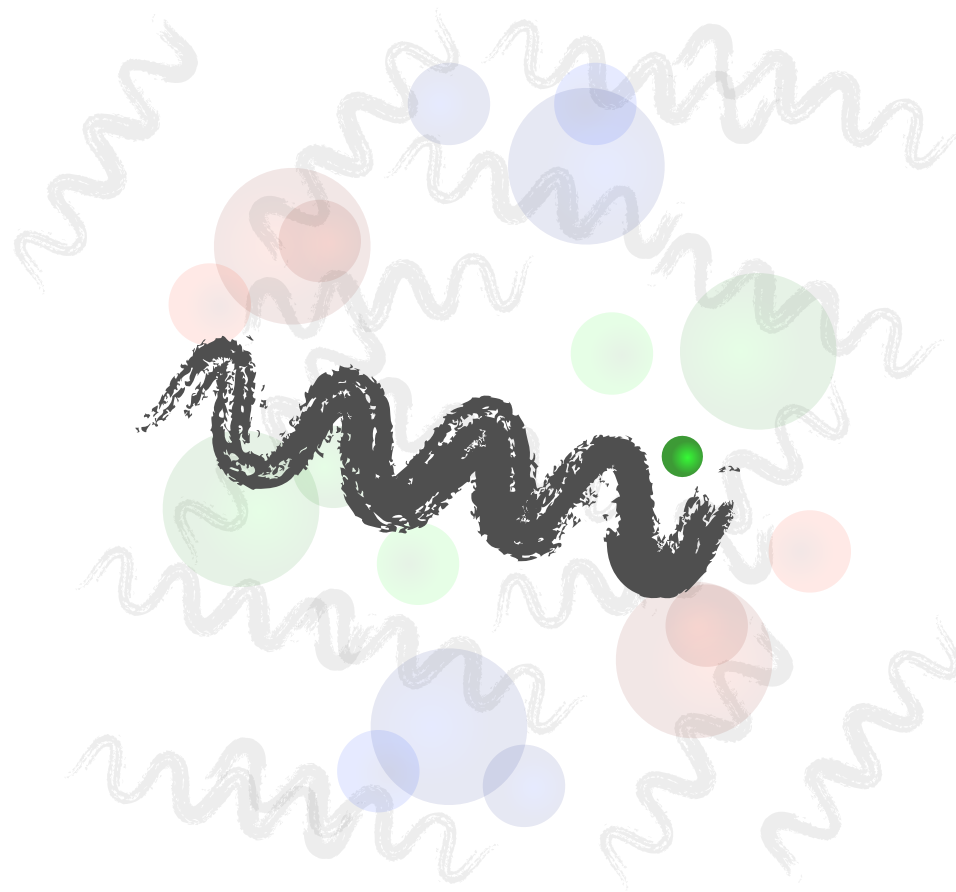


LHCb: up to 2 fb^{-1} / year
LHCb Upgrade I: up to 12 fb^{-1} / year

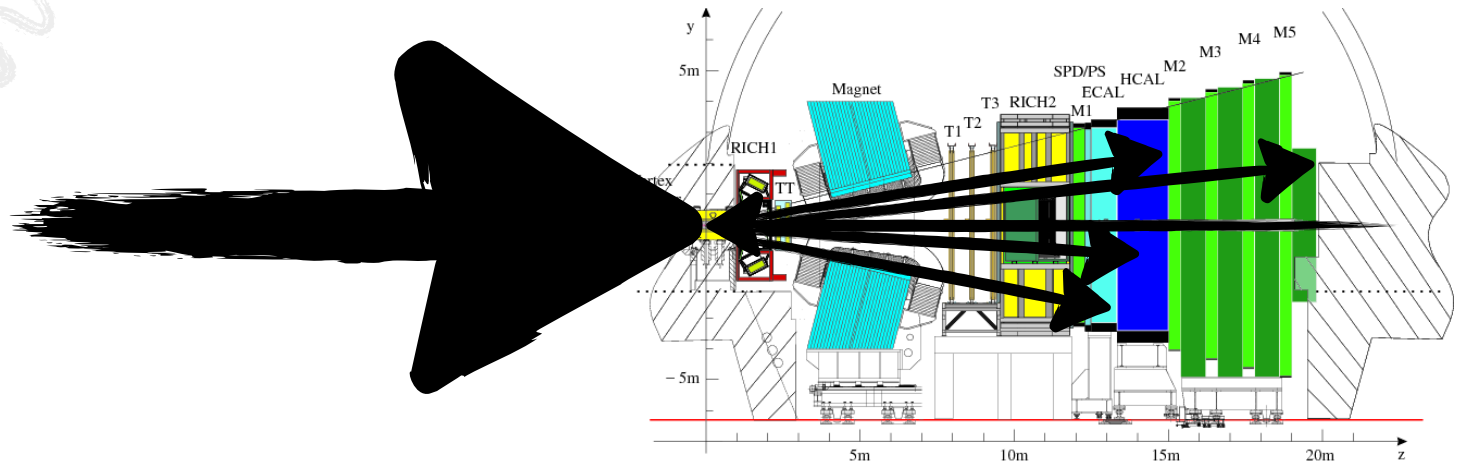
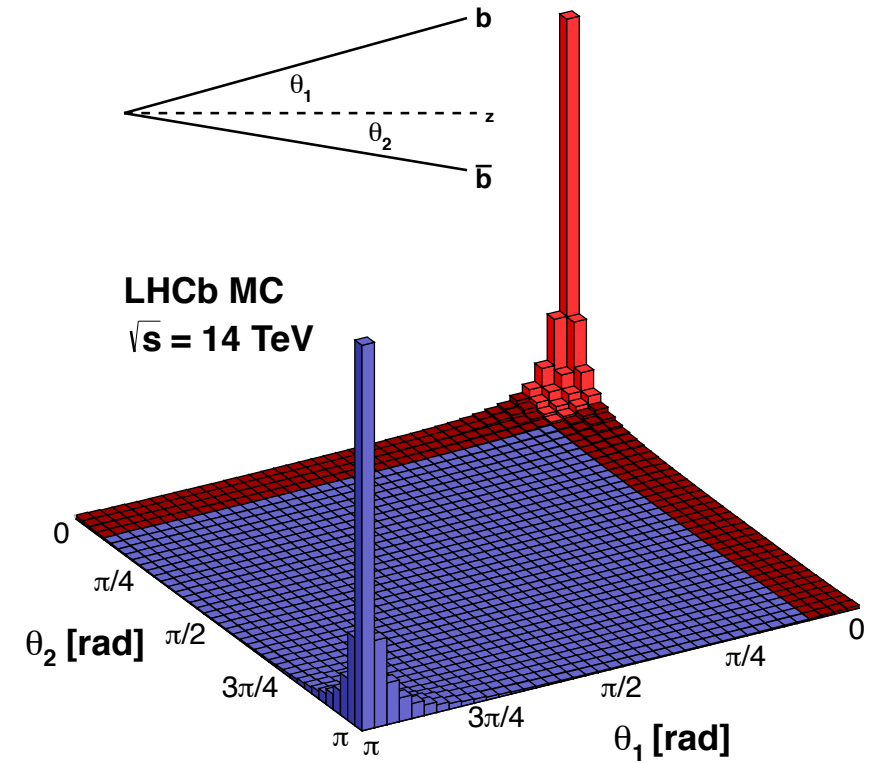
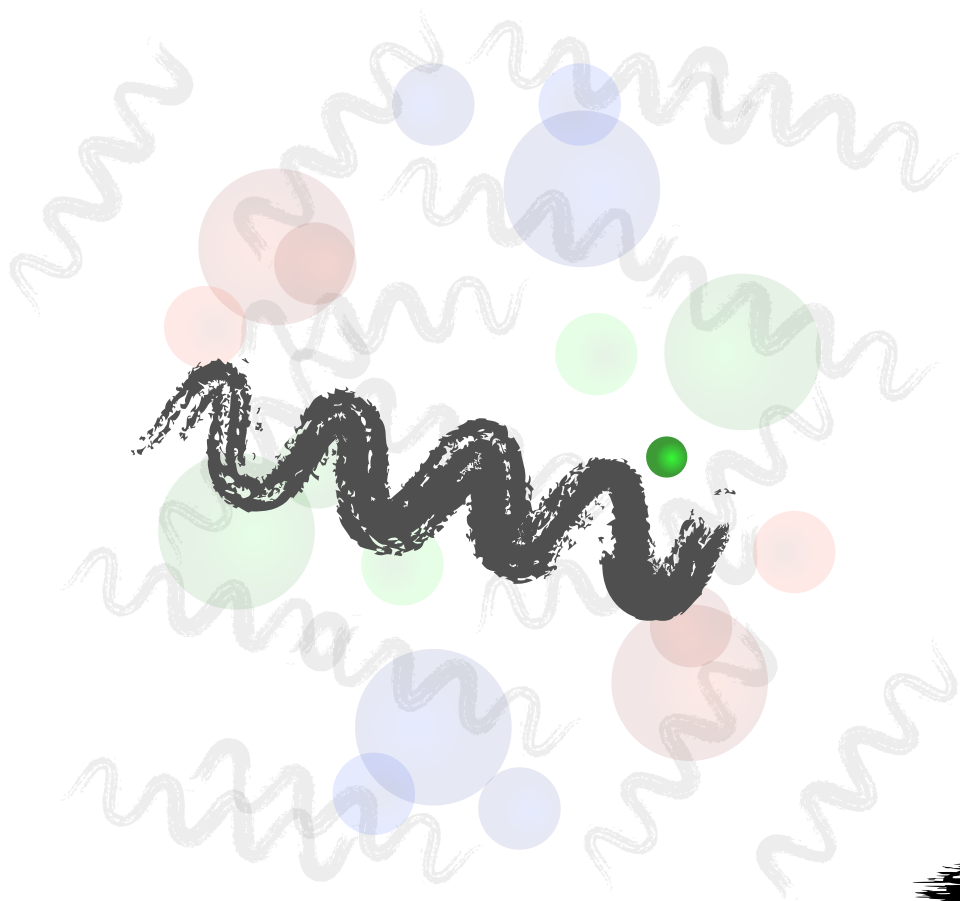
Asymmetric collisions



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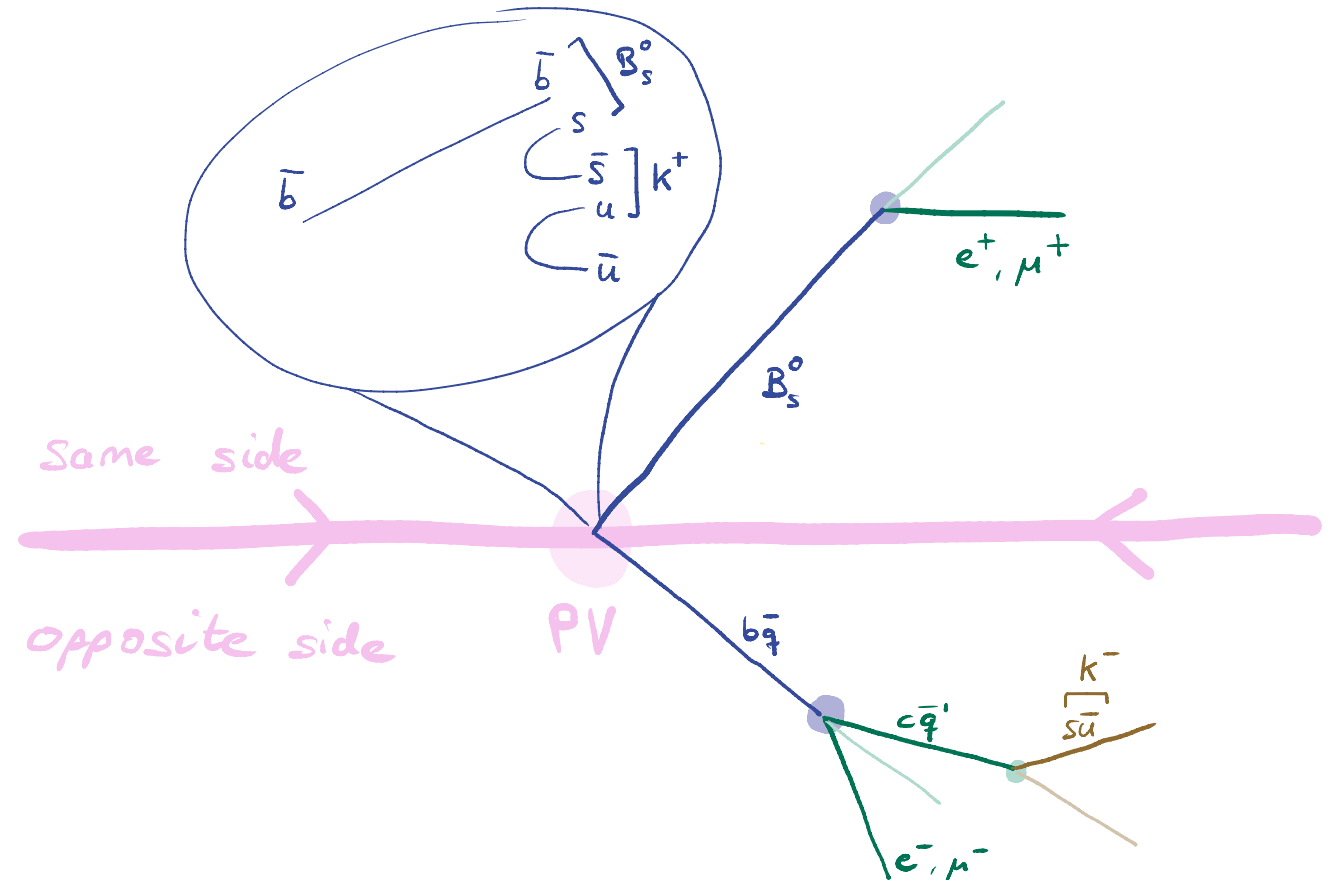
Asymmetric collisions



B flavour tagging

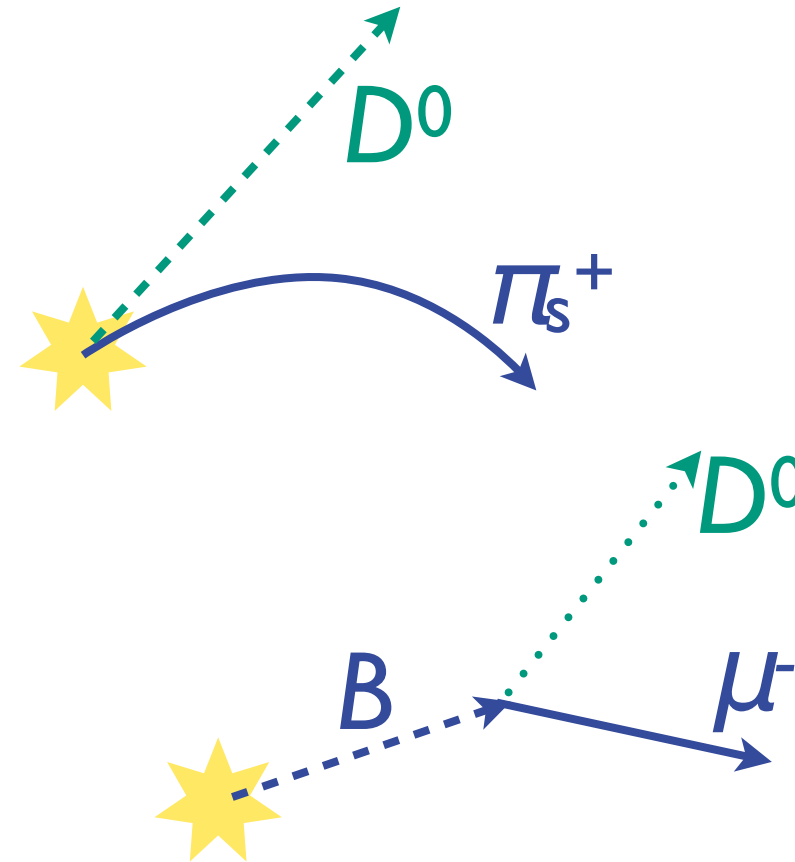
B flavour tagging

- 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

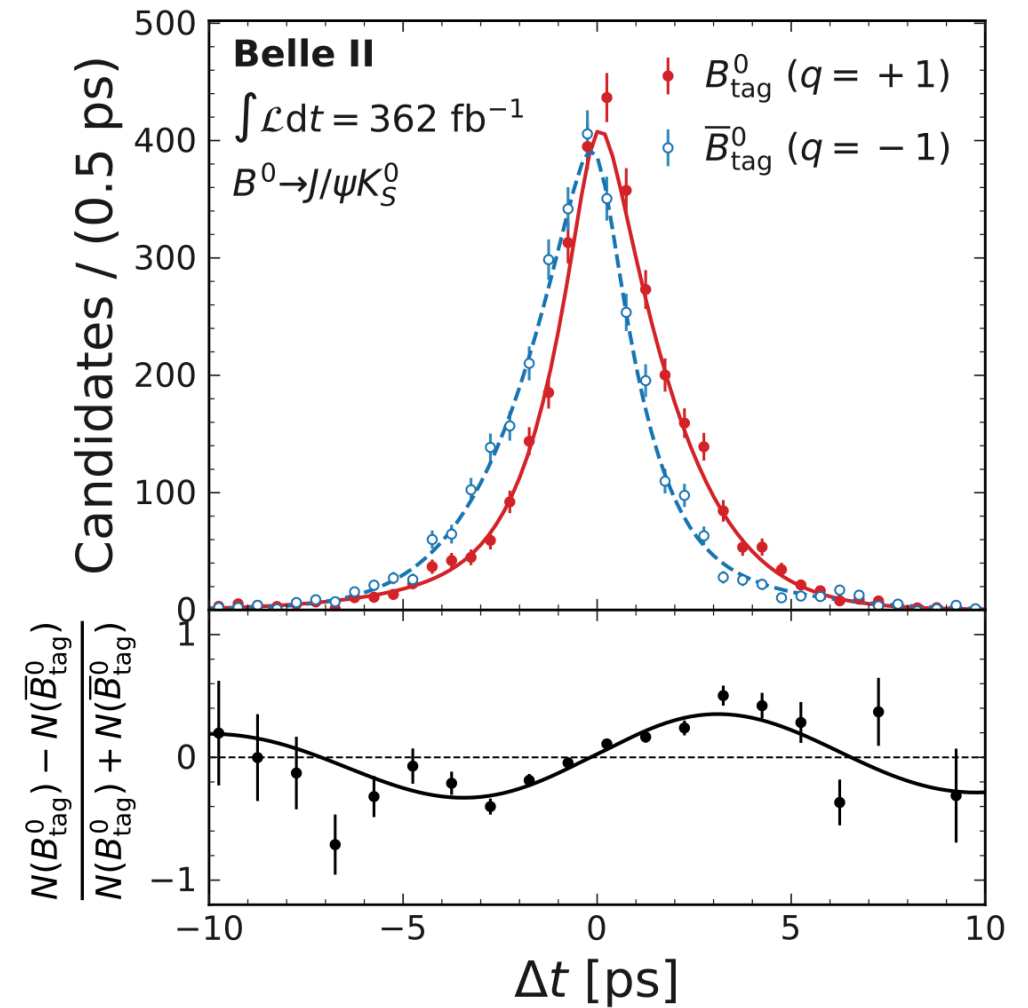
- Can distinguish D^0 from $\bar{D}^0$ in two ways:
- Prompt D^* -tagged
 - Charge of soft pion from strong decay $D^{*+} \rightarrow D^0 \pi_s^+$
 - Larger yields
 - Background from D-from-B
- Charge of muon from semi-leptonic decay $B \rightarrow D^0 \mu^- X$
 - Smaller yields (somewhat)
 - Larger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



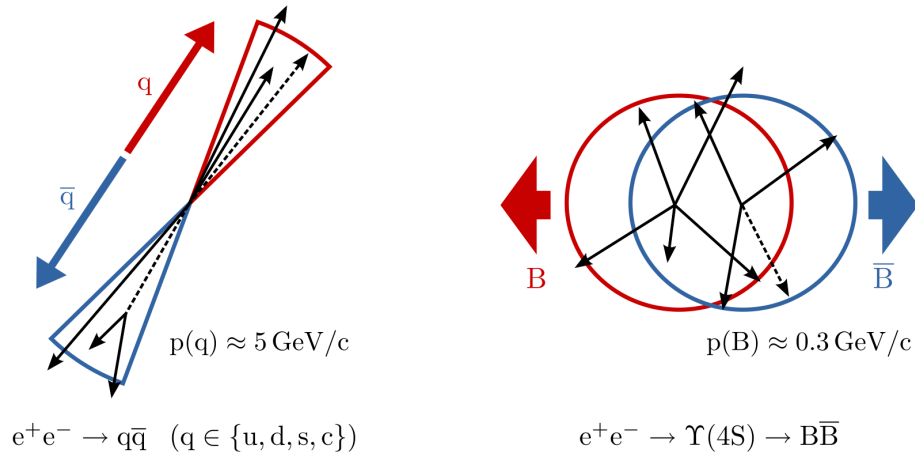
Quantum-correlated states and Decay-time difference

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

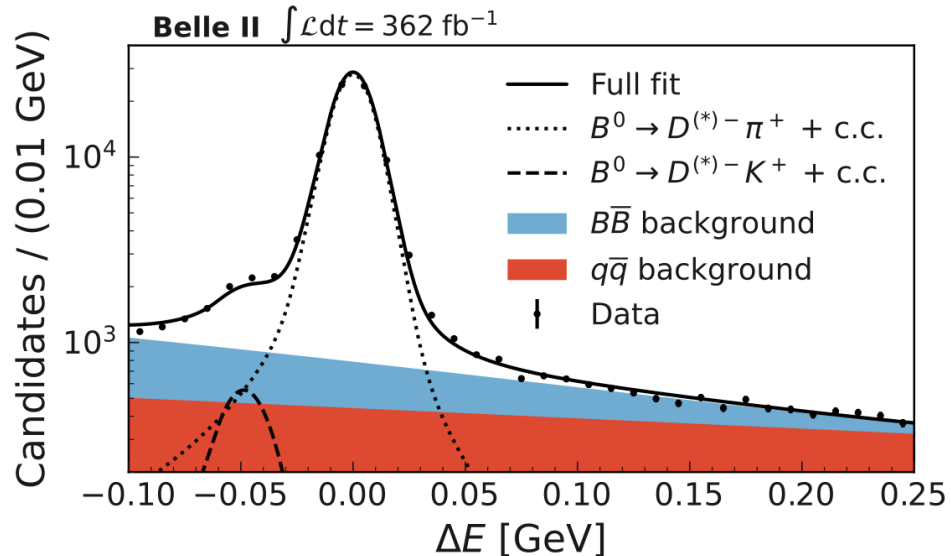
[Belle II, PRD 110 \(2024\) 012001](#)



Credit: [Markus Rörken](#)



[Belle II, PRD 110 \(2024\) 012001](#)

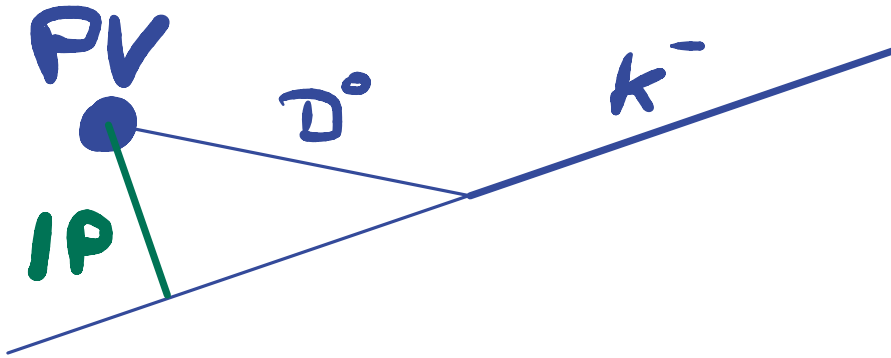


Continuum suppression

- At e^+e^- colliders can exploit precisely known beam energy:
 - E_{beam}^*
- Need to separate resonant events, e.g. $\Upsilon(4S)$, from continuum production
- For fully-reconstructed B decays expect difference of B energy to beam energy to be 0
 - $\Delta E = E_B^* - E_{\text{beam}}^*$
- Beam-constraint mass peaks at B mass for fully reconstructed B momentum

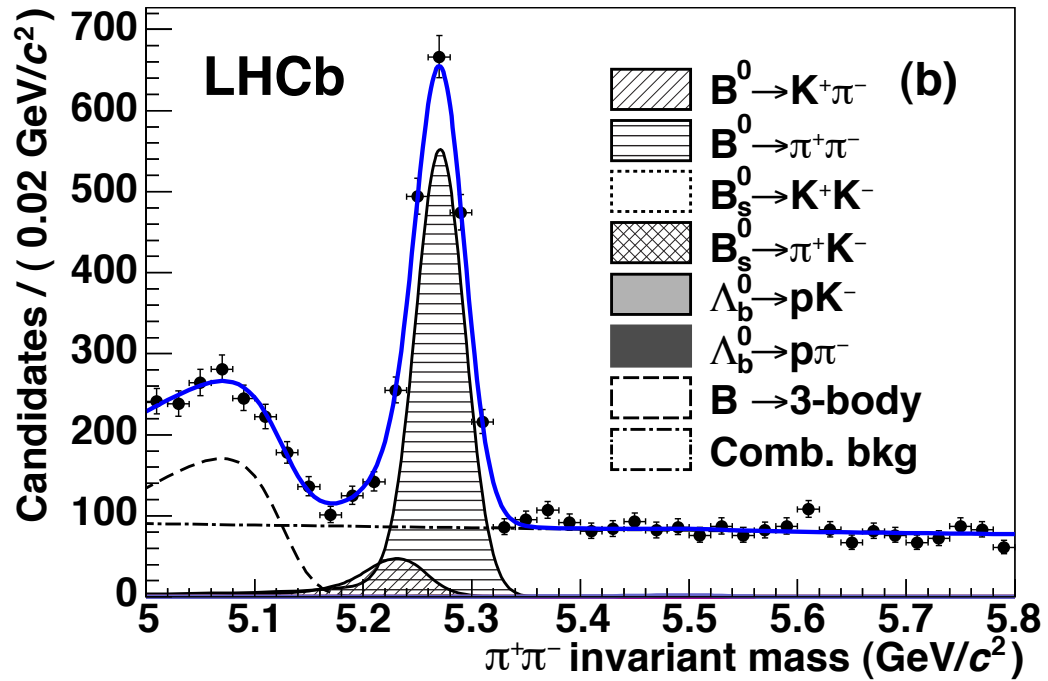
$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^*/c^2 - (p_B^*/c)^2}$$

Impact parameters



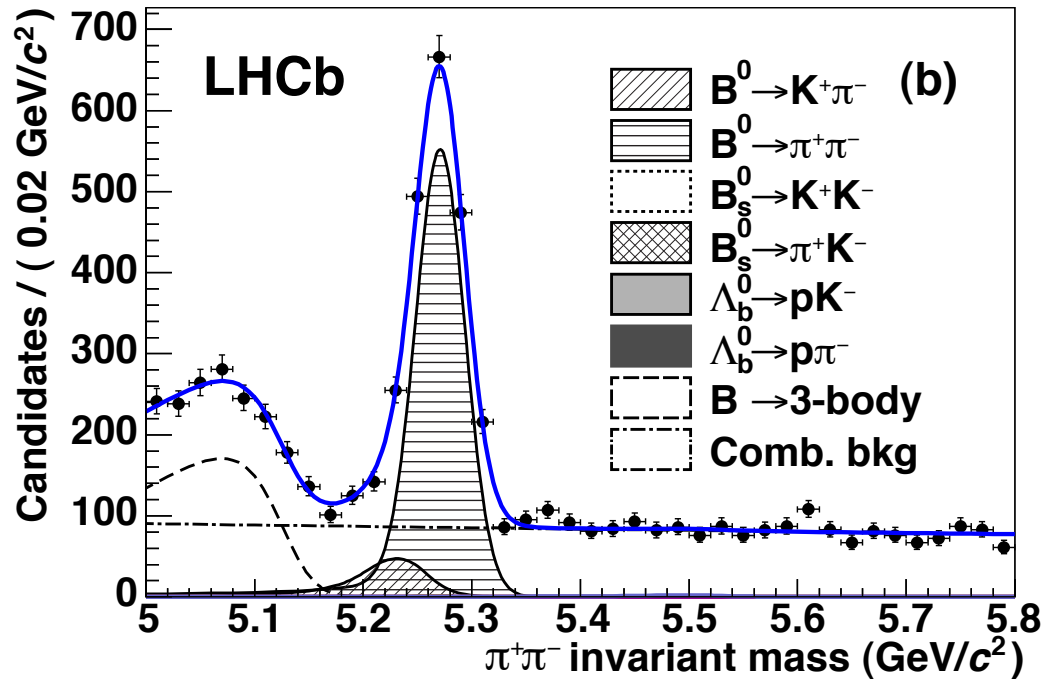
- Impact parameter: shortest distance between straight line (particle trajectory) and point (primary vertex)
- Decay products of particles that fly macroscopic distances have non-zero impact parameters
 - Tell-tale indicator of heavy-flavour decays
 - Per-particle information available without decay 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

Particle identification

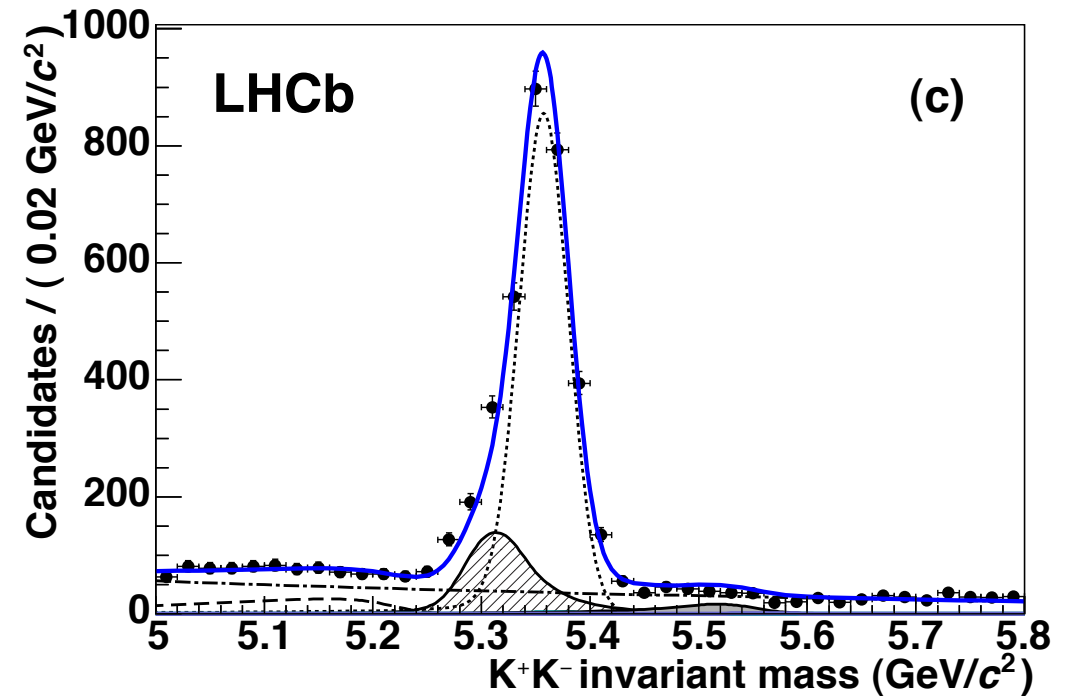


$B \rightarrow hh'$ with PID requirements to identify pions

Particle identification



$B \rightarrow hh'$ with PID requirements to identify pions



$B \rightarrow hh'$ 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

Mixing and CP violation

Time evolution of neutral mesons

CP violation

Constraining the CKM triangle: the angle γ

Neutral mesons states

$$|\psi\rangle = a(t) \begin{pmatrix} |M^0\rangle \\ 0 \end{pmatrix} + b(t) \begin{pmatrix} 0 \\ |\bar{M}^0\rangle \end{pmatrix}$$

- Consider states of neutral mesons
 - These are orthogonal flavour eigenstates

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$$\frac{d}{dt} \langle \psi | \psi \rangle = -\frac{1}{\hbar} \langle \psi | \Gamma | \psi \rangle$$

Show!

Hamiltonian eigenstates

$$\mathcal{H}|M_{1,2}\rangle = \lambda_{1,2}|M_{1,2}\rangle$$

- Hamiltonian eigenstates follow time evolution according to eigenvalue equation

$$|M_{1,2}(t)\rangle = e^{-im_{1,2}t - \Gamma_{1,2}t/2}|M_{1,2}(0)\rangle$$

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- Time evolution follows from $M_{1,2}$ equations (later slide)

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- Time evolution follows from $M_{1,2}$ equations (later slide)
- **Exercise:** Evaluate the orthogonality of the Hamiltonian eigenstates and interpret the result: $\langle M_1 | M_2 \rangle$

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Meson lifetimes

$$\langle \psi | \mathcal{H} | \psi \rangle$$

$$\mathcal{H} = H_0 + H_{\text{int}} + \sum_n \frac{H_{\text{int}} |n\rangle \langle n| H_{\text{int}}}{m_0 - E_n}$$

- Effective Hamiltonian is a combination of two Hermitian 2×2 matrices
 - Mass and decay matrices
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 - H_{int} represents weak interaction (think W boson)
- Mass matrix involves principal value calculations and all (also virtual) final states

$$\langle \psi | \mathcal{H} | \psi \rangle \quad \mathcal{H} = H_0 + H_{\text{int}} + \sum_n \frac{H_{\text{int}} | n \rangle \langle n | H_{\text{int}}}{m_0 - E_n}$$

$$M_{11} = m_0 + \langle M^0 | H_{\text{int}} | M^0 \rangle + \sum_n \mathcal{P} \frac{|\langle n | H_{\text{int}} | M^0 \rangle|^2}{m_0 - E_n}$$

$$M_{22} = m_0 + \langle \bar{M}^0 | H_{\text{int}} | \bar{M}^0 \rangle + \sum_n \mathcal{P} \frac{|\langle n | H_{\text{int}} | \bar{M}^0 \rangle|^2}{m_0 - E_n}$$

$$M_{12} = M_{21}^* = \langle M^0 | H_{\text{int}} | \bar{M}^0 \rangle + \sum_n \mathcal{P} \frac{\langle M^0 | H_{\text{int}} | n \rangle \langle n | H_{\text{int}} | \bar{M}^0 \rangle}{m_0 - E_n}$$

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 - Mass and decay matrices
 - Can interpret H_0 as strong interaction
 - H_{int} represents weak interaction (think W boson)
- Mass matrix involves principal value calculations and all (also virtual) final states
- Width matrix is based on sum over accessible final states

$$\langle \psi | \mathcal{H} | \psi \rangle \quad \mathcal{H} = H_0 + H_{\text{int}} + \sum_n \frac{H_{\text{int}} | n \rangle \langle n | H_{\text{int}}}{m_0 - E_n}$$

$$M_{11} = m_0 + \langle M^0 | H_{\text{int}} | M^0 \rangle + \sum_n \mathcal{P} \frac{|\langle n | H_{\text{int}} | M^0 \rangle|^2}{m_0 - E_n}$$

$$M_{22} = m_0 + \langle \bar{M}^0 | H_{\text{int}} | \bar{M}^0 \rangle + \sum_n \mathcal{P} \frac{|\langle n | H_{\text{int}} | \bar{M}^0 \rangle|^2}{m_0 - E_n}$$

$$M_{12} = M_{21}^* = \langle M^0 | H_{\text{int}} | \bar{M}^0 \rangle + \sum_n \mathcal{P} \frac{\langle M^0 | H_{\text{int}} | n \rangle \langle n | H_{\text{int}} | \bar{M}^0 \rangle}{m_0 - E_n}$$

$$\Gamma_{11} = 2\pi \sum_n \delta(m_0 - E_n) |\langle n | H_{\text{int}} | M^0 \rangle|^2$$

$$\Gamma_{22} = 2\pi \sum_n \delta(m_0 - E_n) |\langle n | H_{\text{int}} | \bar{M}^0 \rangle|^2$$

$$\Gamma_{12} = 2\pi \sum_n \delta(m_0 - E_n) \langle M^0 | H_{\text{int}} | n \rangle \langle n | H_{\text{int}} | \bar{M}^0 \rangle$$

Meson lifetimes — II

- Lifetime depends on

$$\Gamma_{11} = 2\pi \sum_n \delta(m_0 - E_n) |\langle n | H_{\text{int}} | M^0 \rangle|^2$$

- Number of available final states
- Available phase space for decay
- Coupling strength for decay
 - Compare CKM elements

- Consider different mesons...

Time evolution

$$|M^0(t)\rangle = \frac{1}{2p} \left[(e^{-im_1 t - \Gamma_1 t/2} + e^{-im_2 t - \Gamma_2 t/2}) p |M^0\rangle + (e^{-im_1 t - \Gamma_1 t/2} - e^{-im_2 t - \Gamma_2 t/2}) q |\bar{M}^0\rangle \right]$$

- Time evolution can be expressed with functions, $f_{\pm}(t)$, which encapsulate time dependence
 - Uses average mass, m , and decay width, Γ
 - Uses dimensionless quantities x and y , which link to the difference in the eigenvalues for $m_{1,2}$ and $\Gamma_{1,2}$

$$|M^0(t)\rangle = f_+(t) |M^0\rangle + \frac{q}{p} f_-(t) |\bar{M}^0\rangle$$

$$|\bar{M}^0(t)\rangle = \frac{p}{q} f_-(t) |M^0\rangle + f_+(t) |\bar{M}^0\rangle$$

$$f_{\pm}(t) = \frac{1}{2} e^{-imt - \Gamma t/2} (e^{(ix+y)\Gamma t/2} \pm e^{-(ix+y)\Gamma t/2})$$



- **Exercise:** derive this
- Various other variants exist in literature

$$m \equiv (m_1 + m_2)/2 \quad \Gamma \equiv (\Gamma_1 + \Gamma_2)/2$$

$$x \equiv \frac{\Delta m}{\Gamma} \quad y \equiv \frac{\Delta \Gamma}{2\Gamma}$$

Meson oscillations

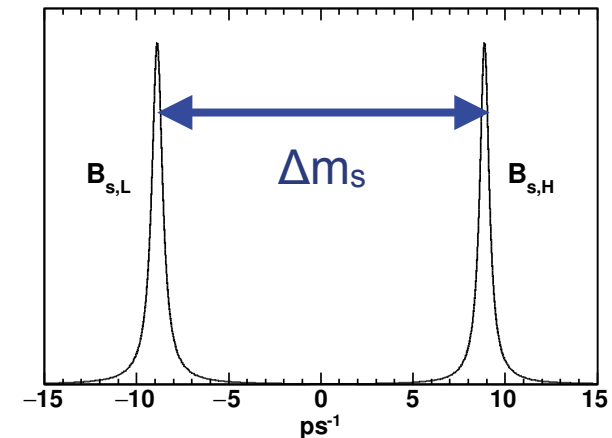
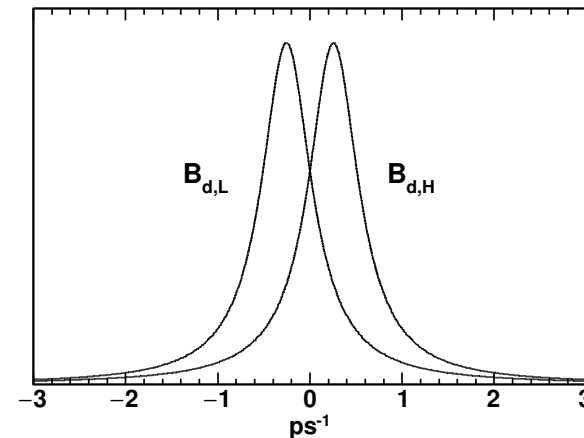
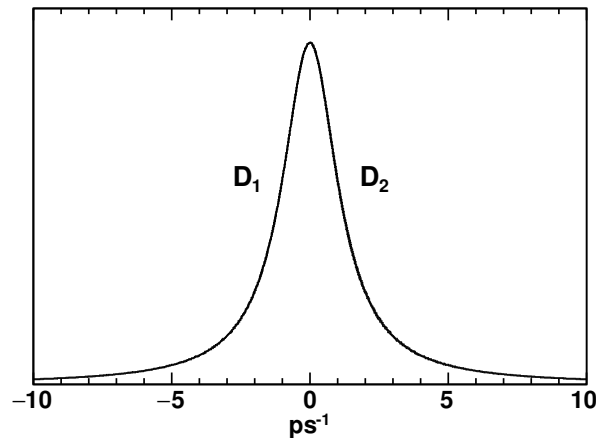
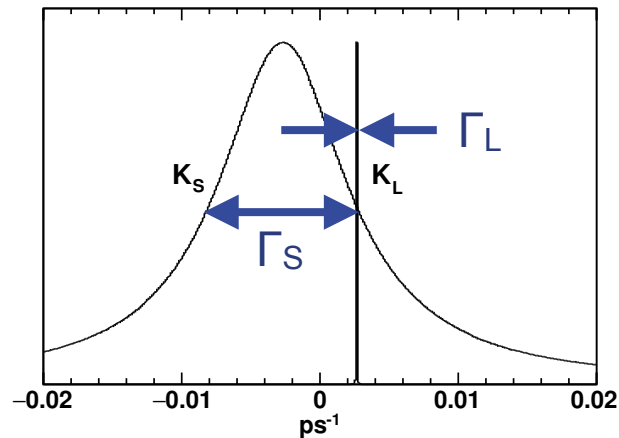
- Observable transition probabilities follow directly from previous equations
- Mass difference, x , related to sinusoidal oscillations
- Width difference alters exponential decay
- Difference in meson-antimeson and antimeson-meson transition solely linked to $|q/p|$

$$\begin{aligned}
 P(M^0 \rightarrow M^0, t) &= P(\bar{M}^0 \rightarrow \bar{M}^0, t) = |f_+(t)|^2 \\
 &= \frac{1}{2} e^{-\Gamma t} [\cosh(y\Gamma t) + \cos(x\Gamma t)] \\
 P(M^0 \rightarrow \bar{M}^0, t) &= \left| \frac{q}{p} \right|^2 |f_-(t)|^2 \\
 &= \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} [\cosh(y\Gamma t) - \cos(x\Gamma t)] \\
 P(\bar{M}^0 \rightarrow M^0, t) &= \left| \frac{p}{q} \right|^2 |f_-(t)|^2 \\
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 \end{aligned}$$

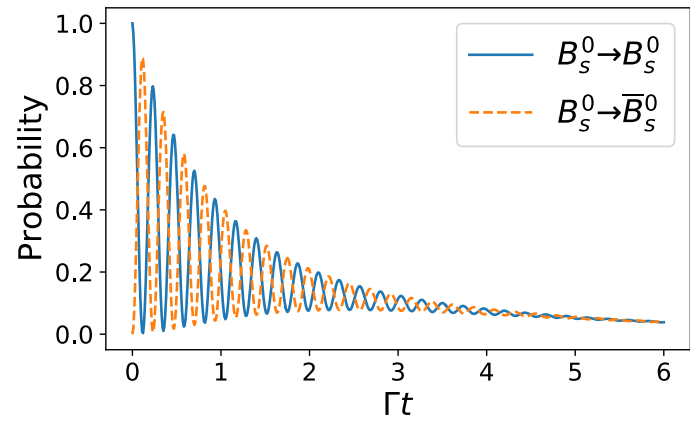
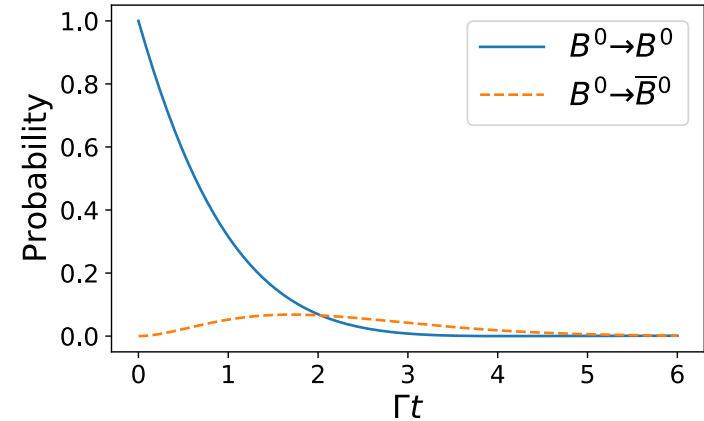
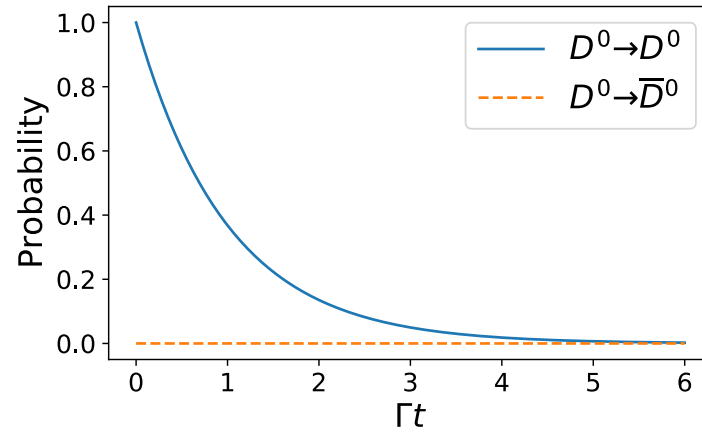
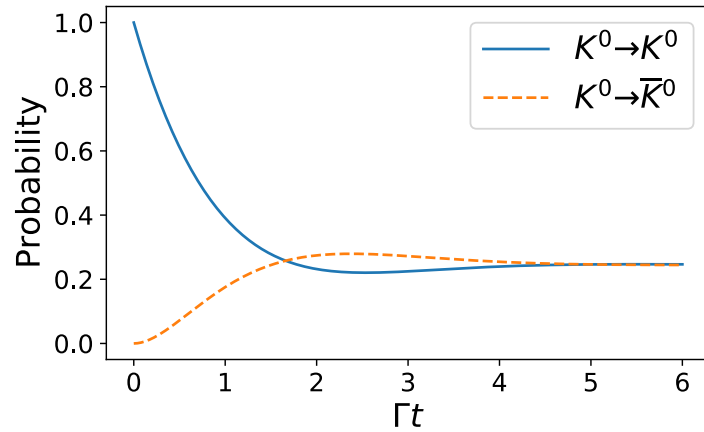
Mixing and mesons

$$P(M^0 \rightarrow \bar{M}^0, t) = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} [\cosh(y\Gamma t) - \cos(x\Gamma t)]$$

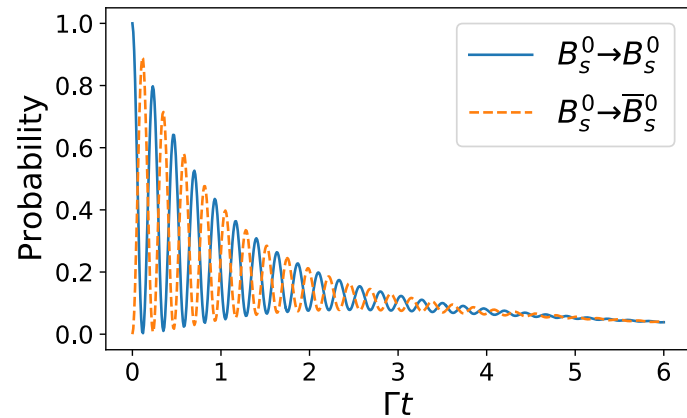
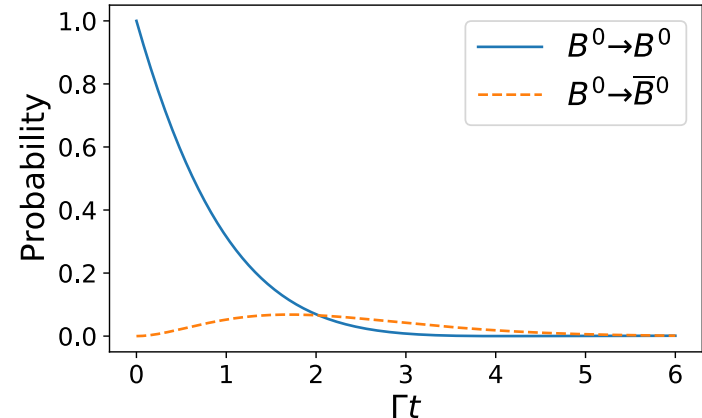
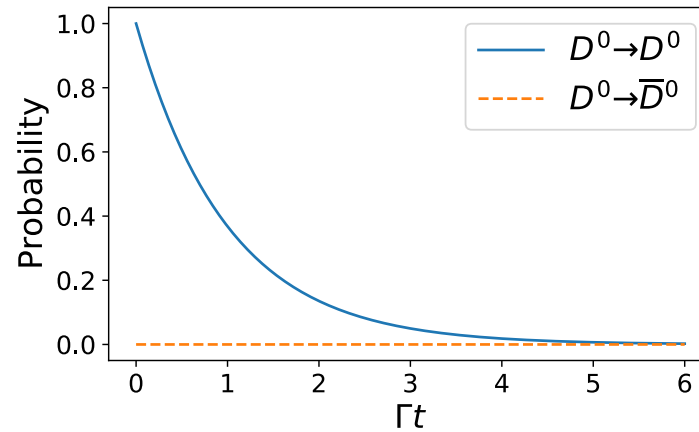
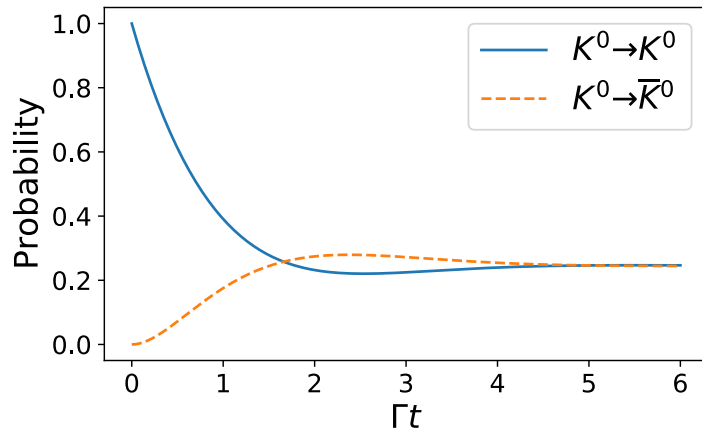
Meson	Mass in GeV	Width in ps^{-1}	Lifetime in ps	x	y
K^0	0.49761(1)	0.005594(2)	89.54(4) 51160(210)	0.946(2)	-0.996(1)
D^0	1.86484(5)	2.438(9)	0.4101(15)	0.0041(4)	0.0065(2)
B^0	5279.66(12)	0.658(2)	1.519(4)	0.769(4)	0.001(5)
B_s^0	5366.92(10)	0.658(2)	1.527(11)	27.01(10)	-0.064(4)



The four neutral mesons oscillating



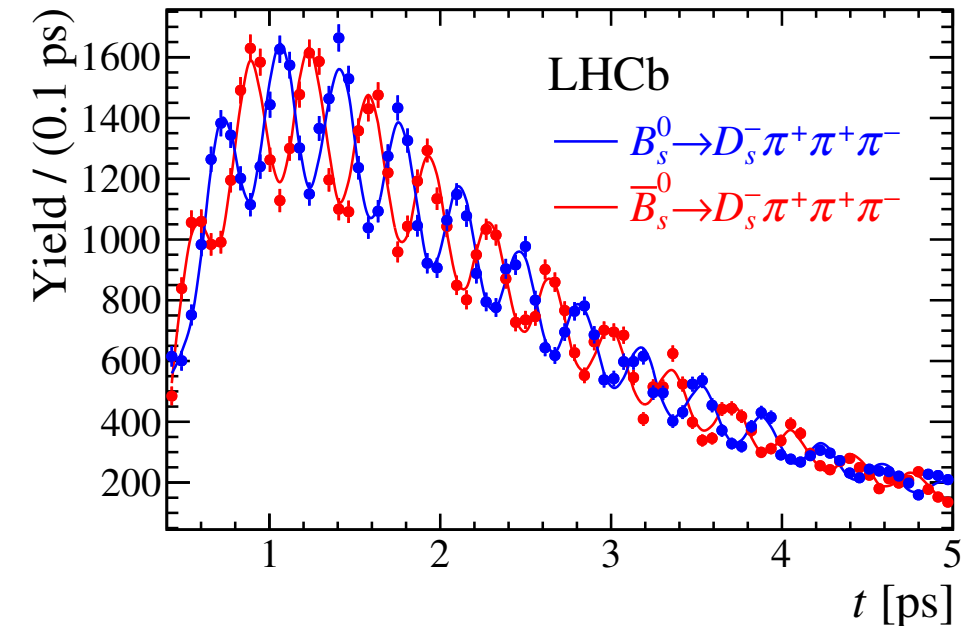
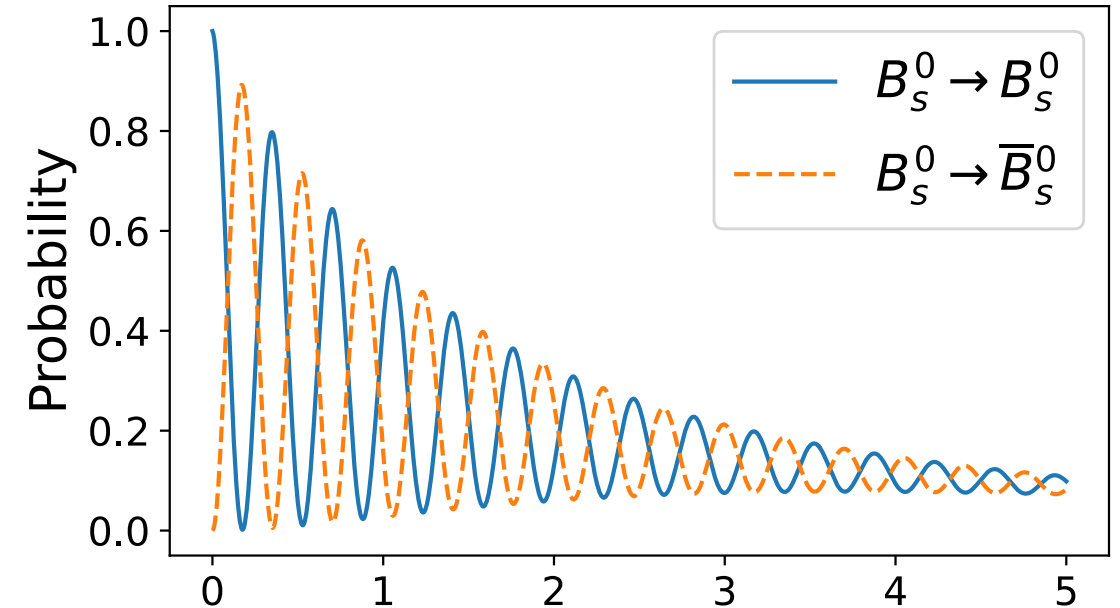
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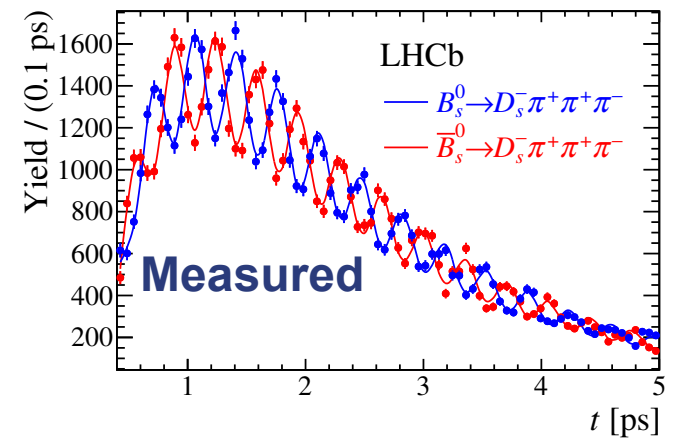
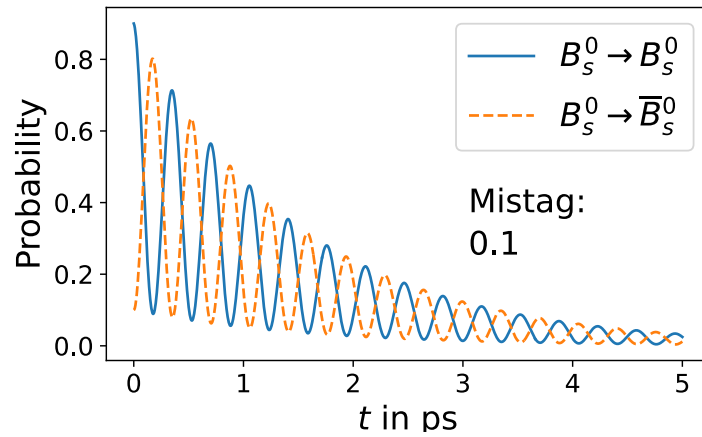
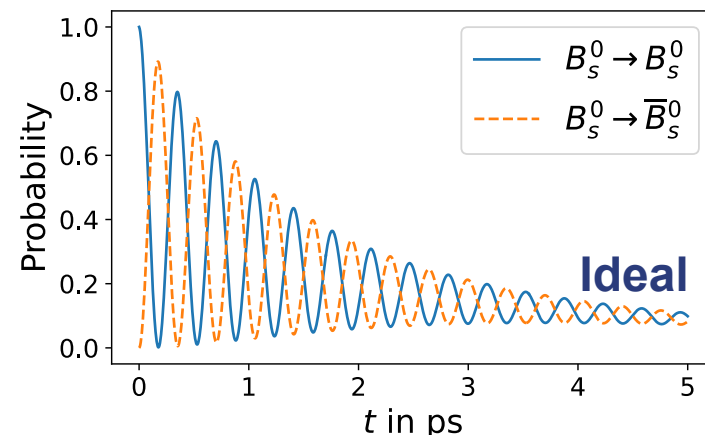
- All mesons shown over 6 average lifetimes (technically avg. widths)
- Kaons split in extremely different lifetimes with long-lived K_L visible as apparently constant state
- D^0 mesons have strongly suppressed oscillations, not visible on this scale
- B^0 and B_s^0 are separated by frequency of oscillation
 - Factor of 35 difference in x

Oscillation measurements

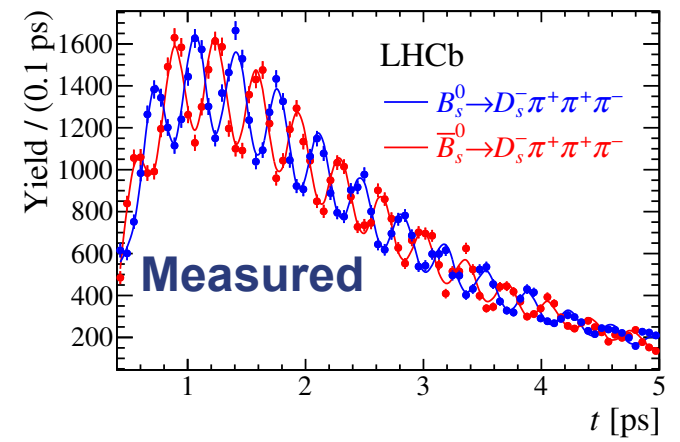
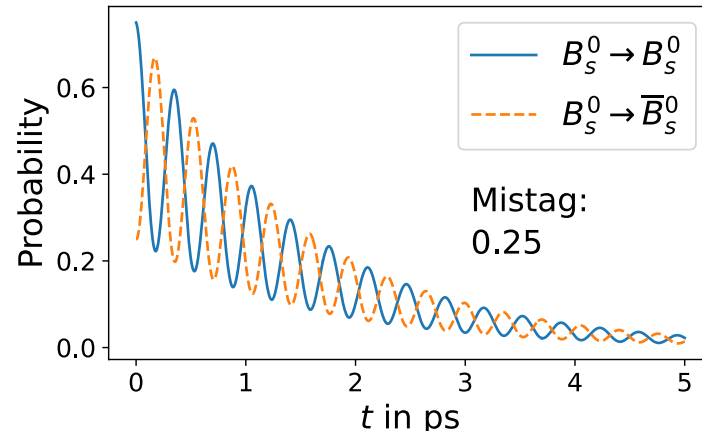
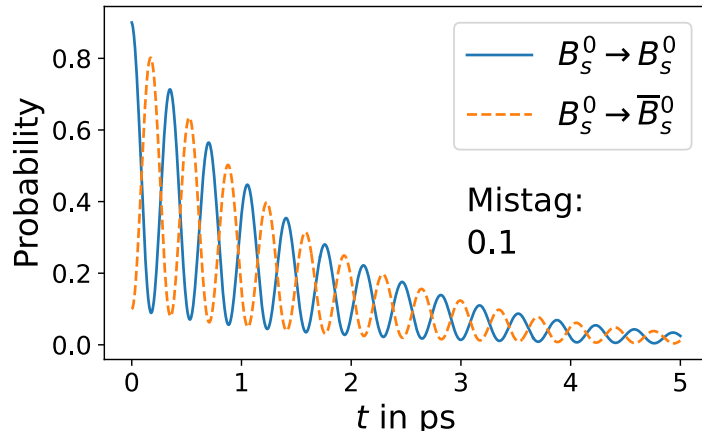
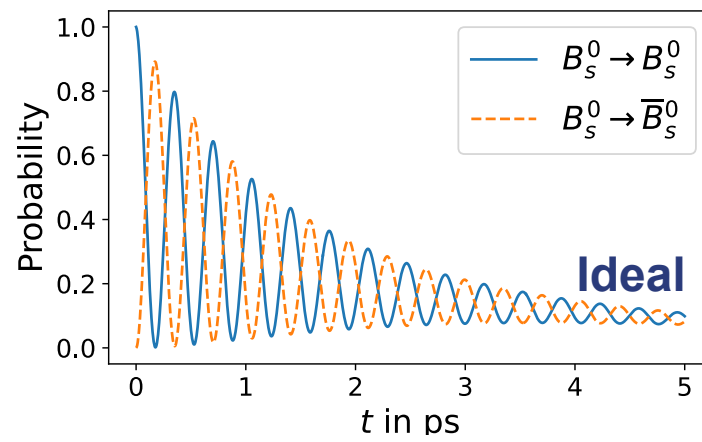
- Oscillation measurements look very different to theoretical curve
- Three significant effects at play...



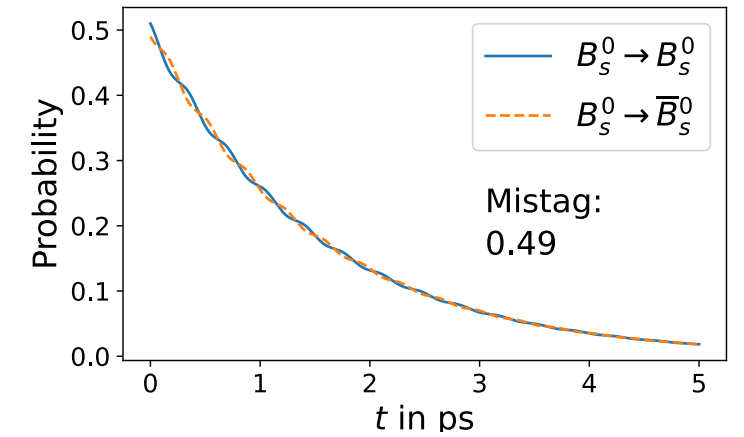
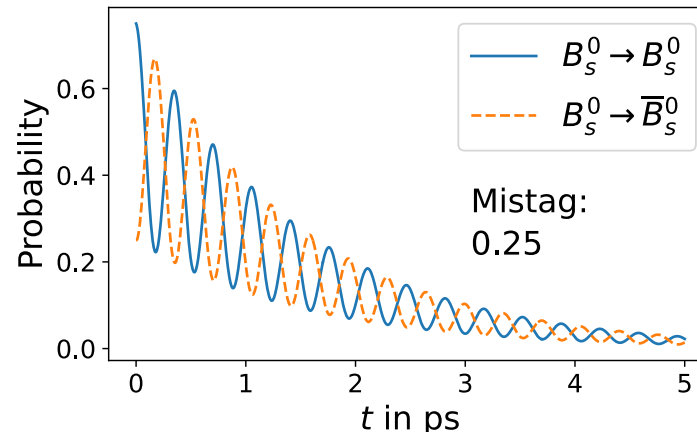
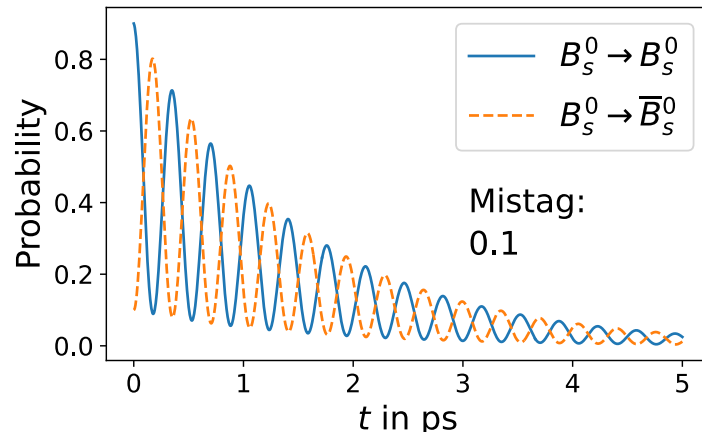
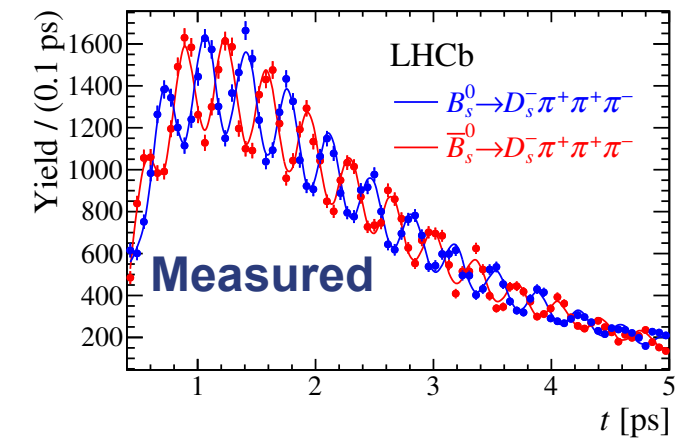
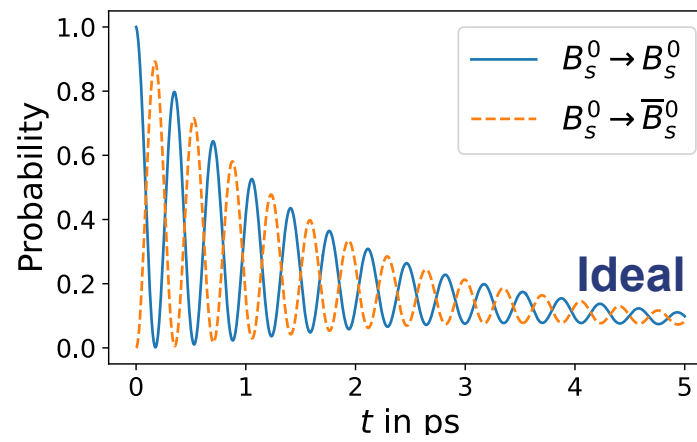
Experimental effects



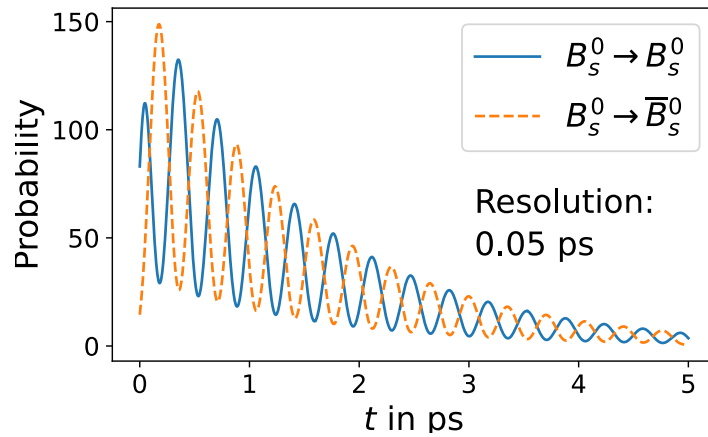
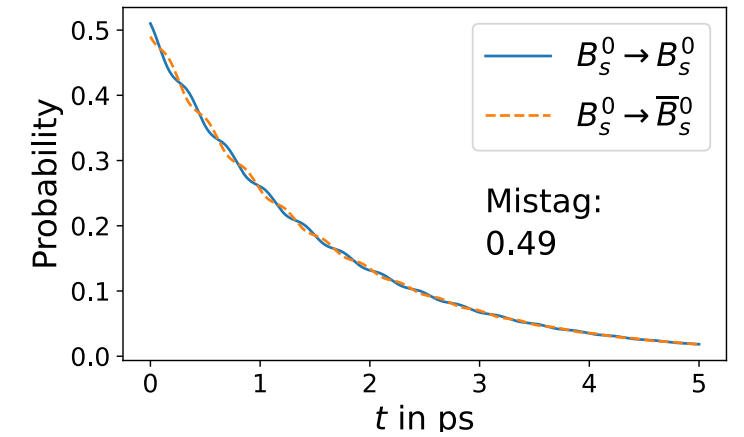
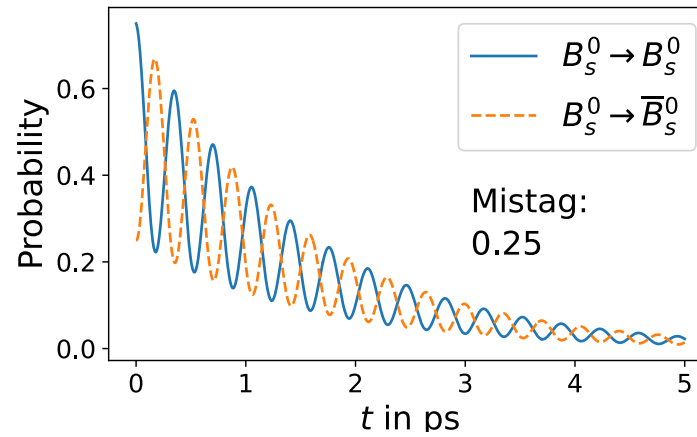
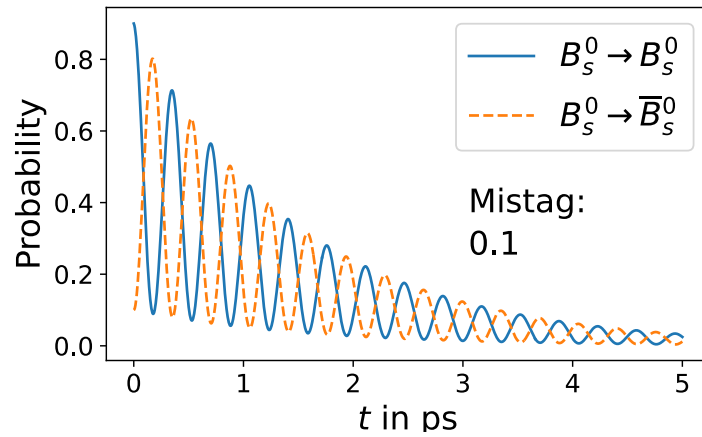
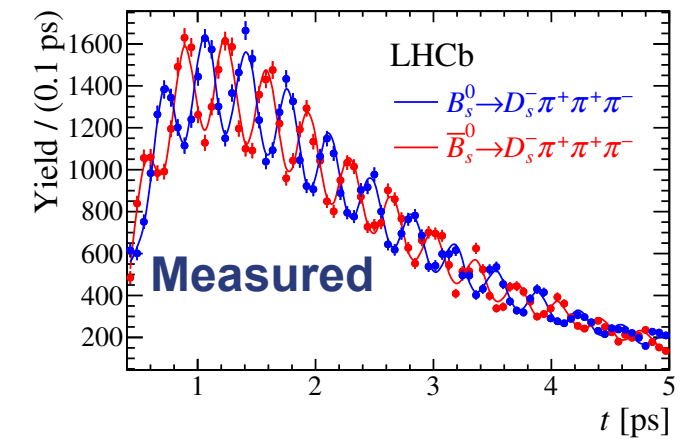
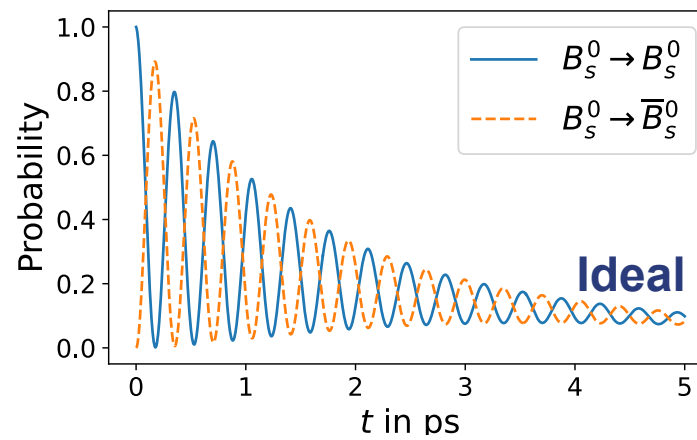
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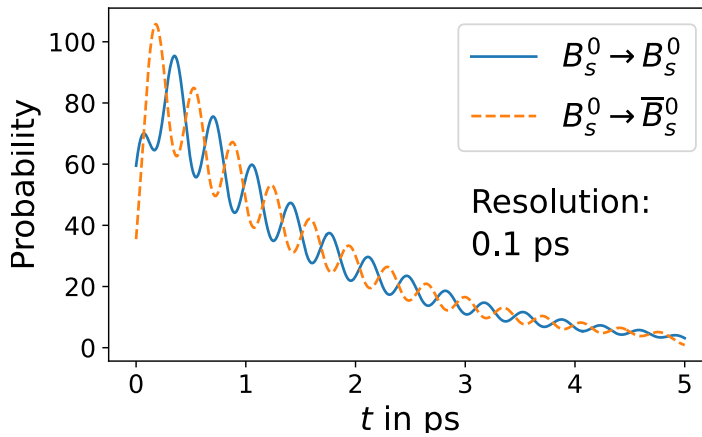
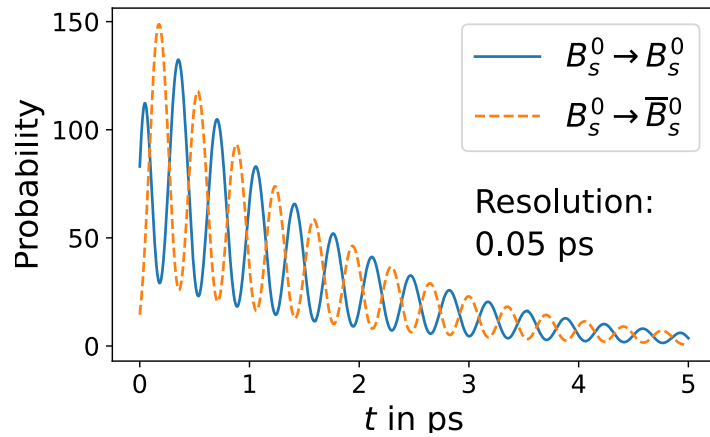
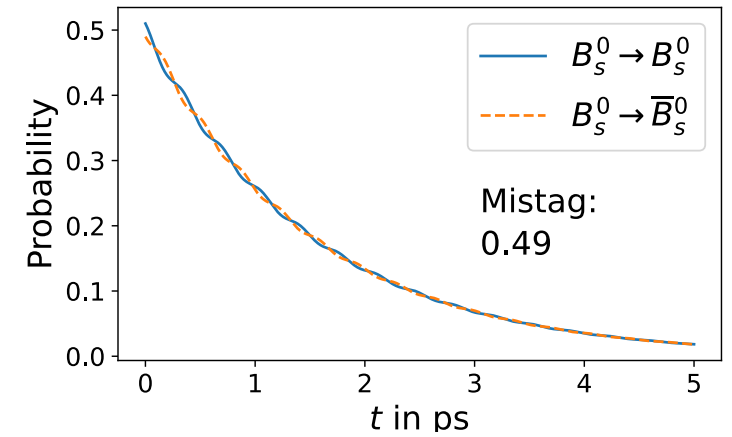
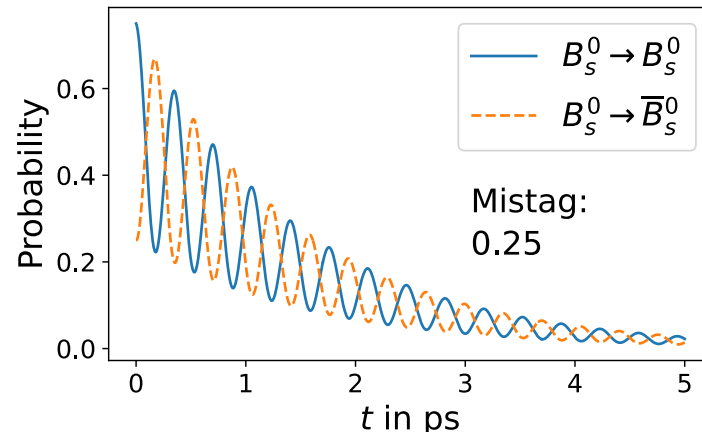
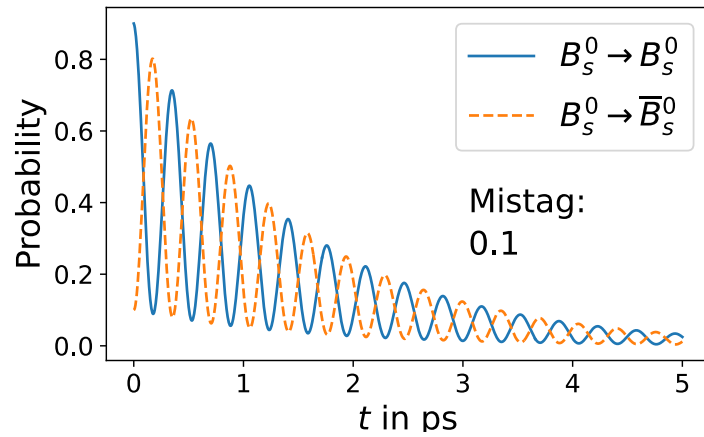
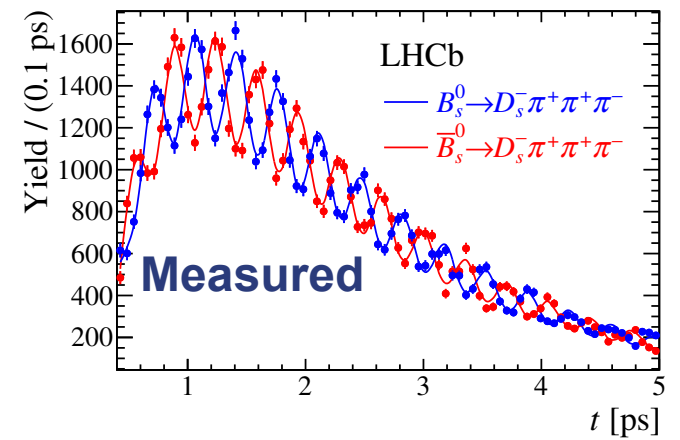
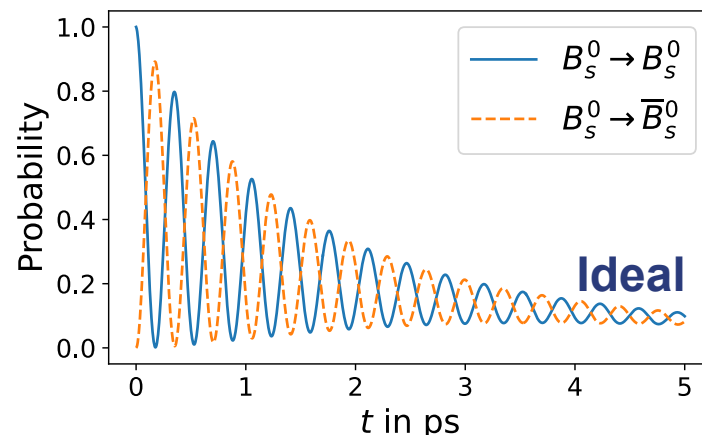
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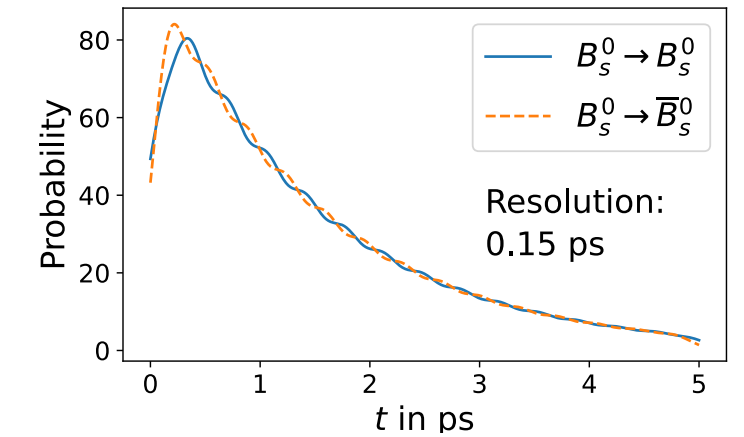
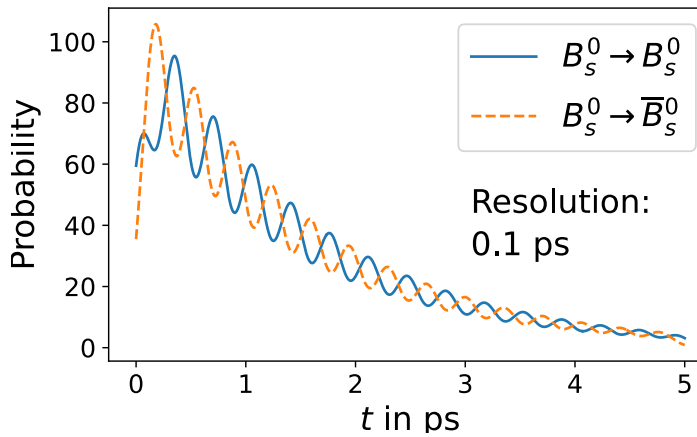
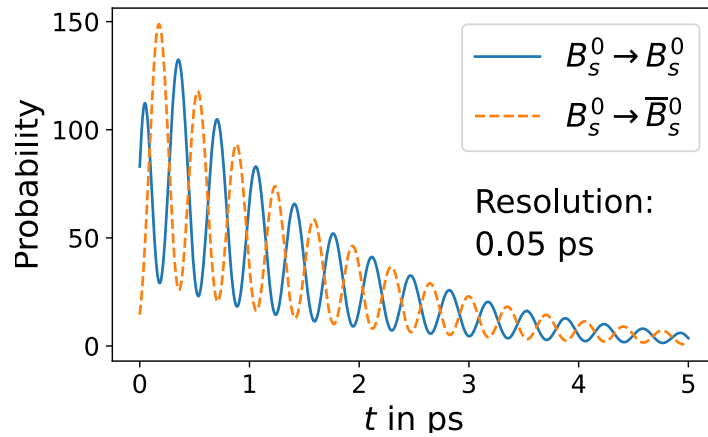
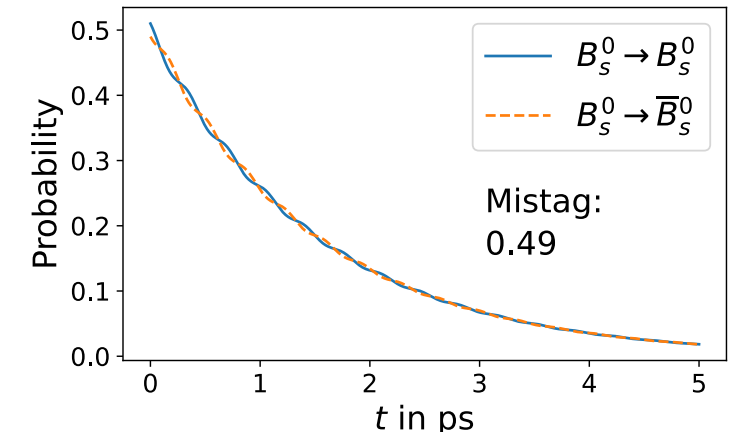
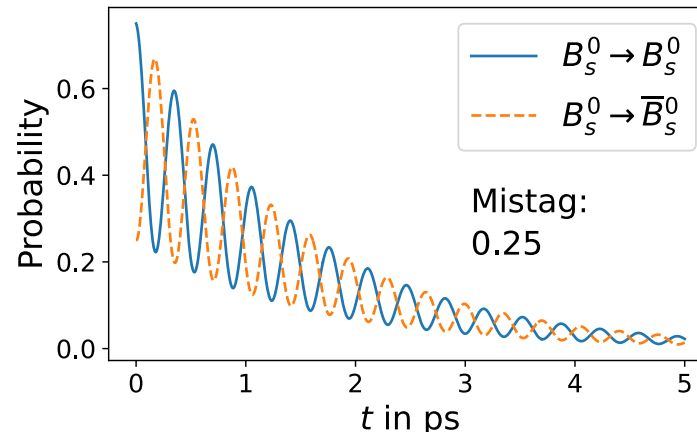
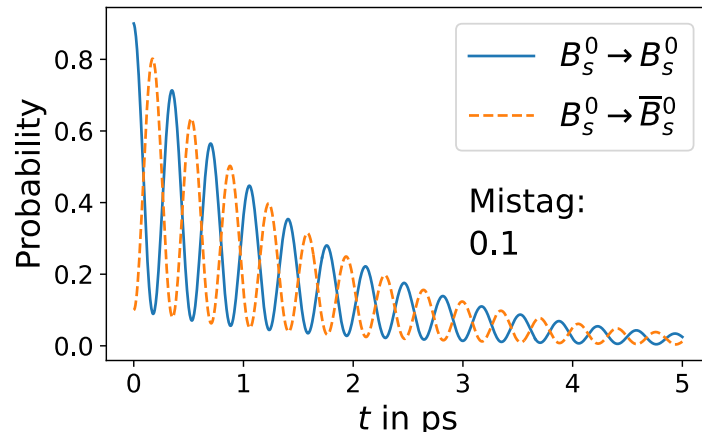
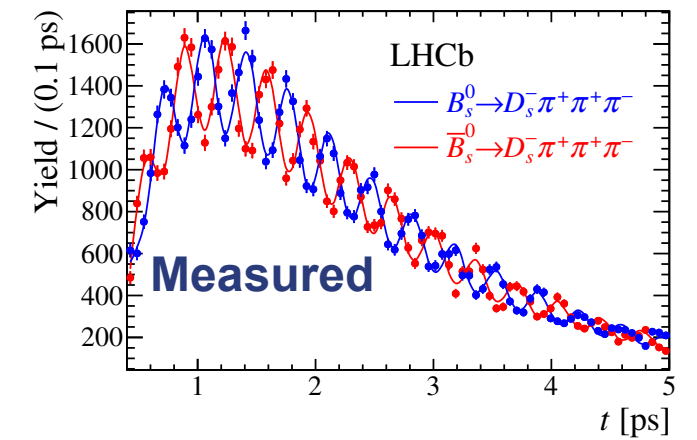
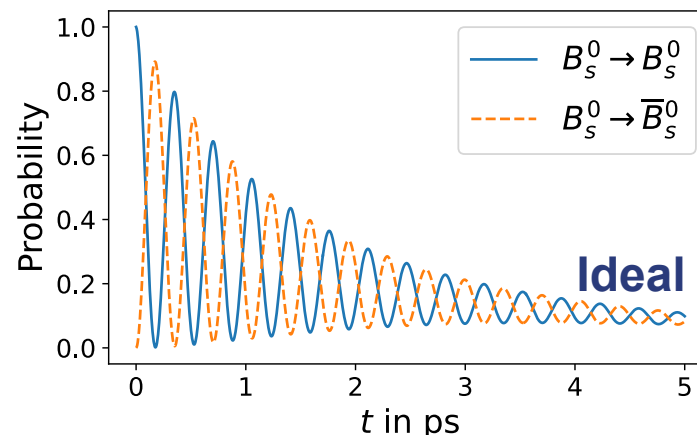
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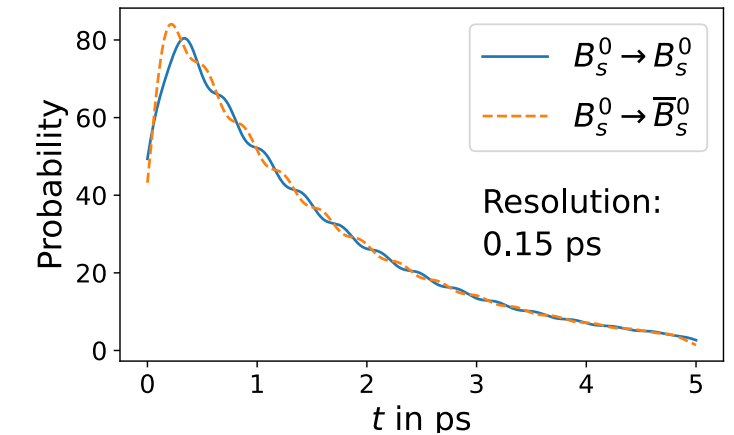
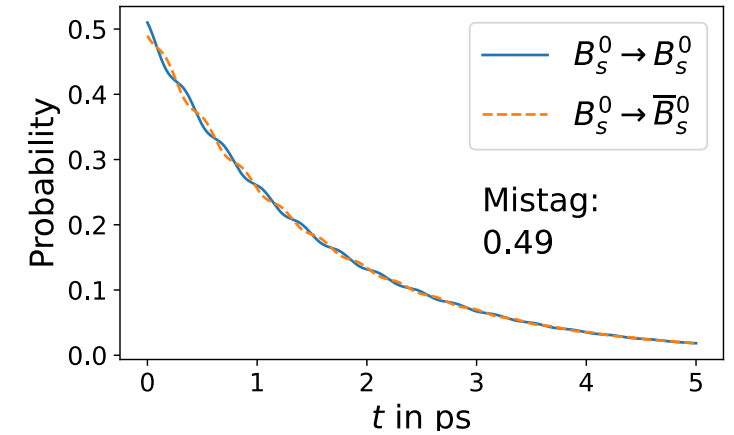
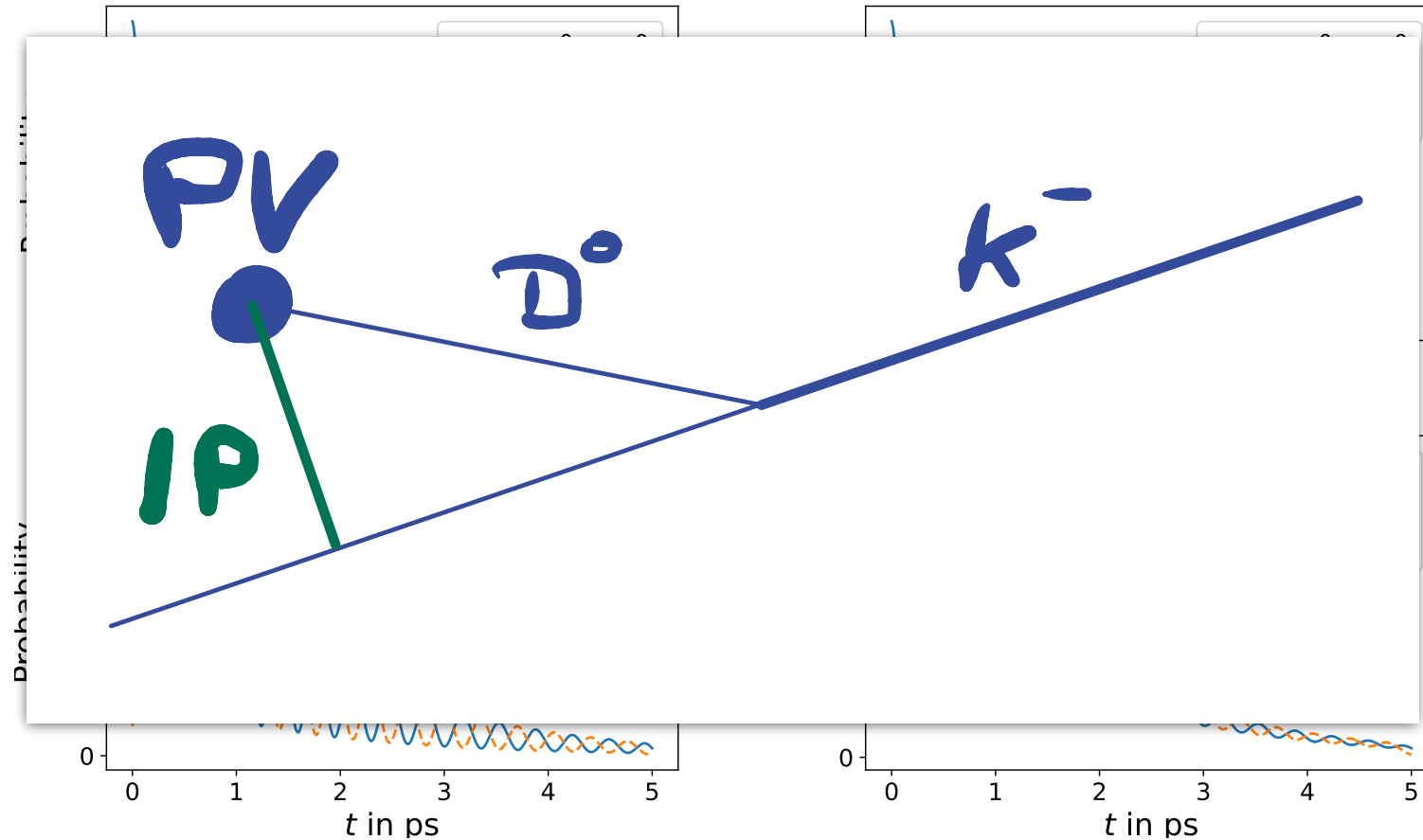
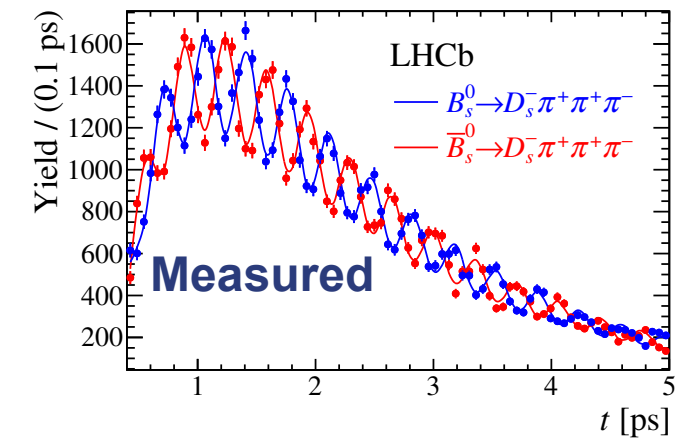
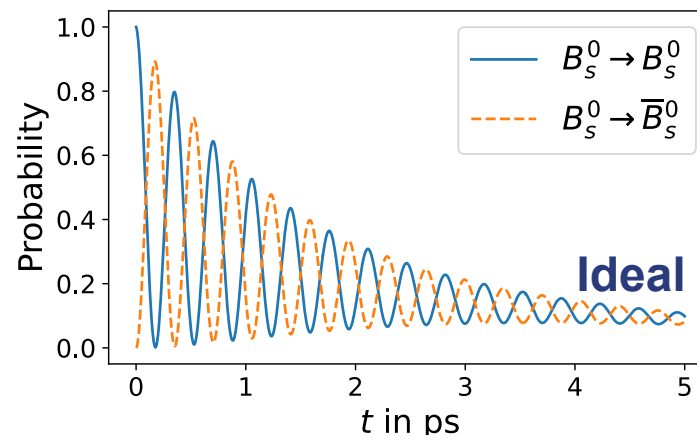
Experimental effects



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CP eigenstates

- CP eigenstates are combinations of flavour eigenstates
 - They overlap with Hamiltonian eigenstates if the magnitudes of q and p are equal.

$$CP|M_{\pm}\rangle = \pm|M_{\pm}\rangle$$

$$|M_{\pm}\rangle = \frac{1}{\sqrt{2}}(|M^0\rangle \pm |\bar{M}^0\rangle)$$

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- **Exercise:** Derive the last equation

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- Time-dependent CP asymmetries are relevant for neutral mesons
 - Separate different types of CP violation

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 - Separate different types of CP violation
- For B mesons can assume $|q/p|=1$
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- For B^0 mesons (as opposed to B_s^0) can assume $y=0$

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$$S \equiv \frac{2\Im(\lambda_f)}{1 + |\lambda_f|^2}, \quad \text{and} \quad C \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2},$$

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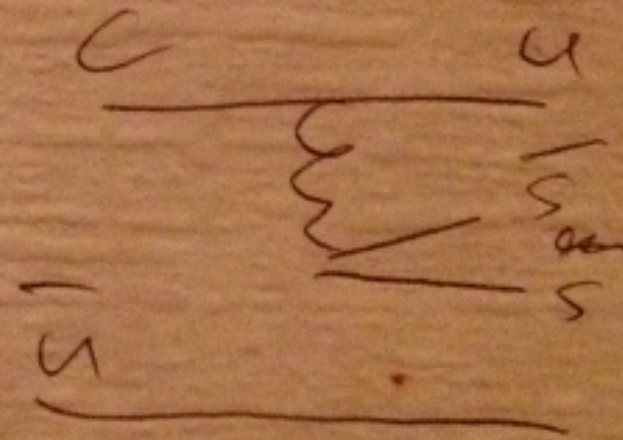
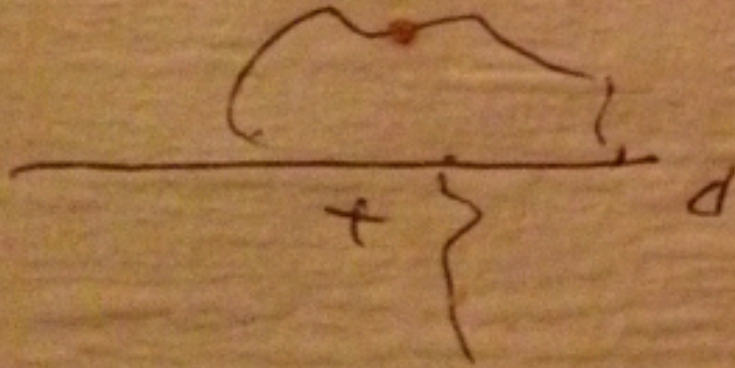
$$S \equiv \frac{2\Im(\lambda_f)}{1 + |\lambda_f|^2}, \quad \text{and} \quad C \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2},$$

- For D^0 mesons use Taylor expansion

$$\Gamma(D^0(t) \rightarrow f, t) = |\mathcal{A}_f|^2 e^{-\Gamma t} \left(1 + [-\Im(\lambda_f)x + \Re(\lambda_f)y]\Gamma t + |\lambda_f|^2 \frac{x^2 + y^2}{2} (\Gamma t)^2 \right)$$



• $b \rightarrow d \bar{s} \bar{s}$



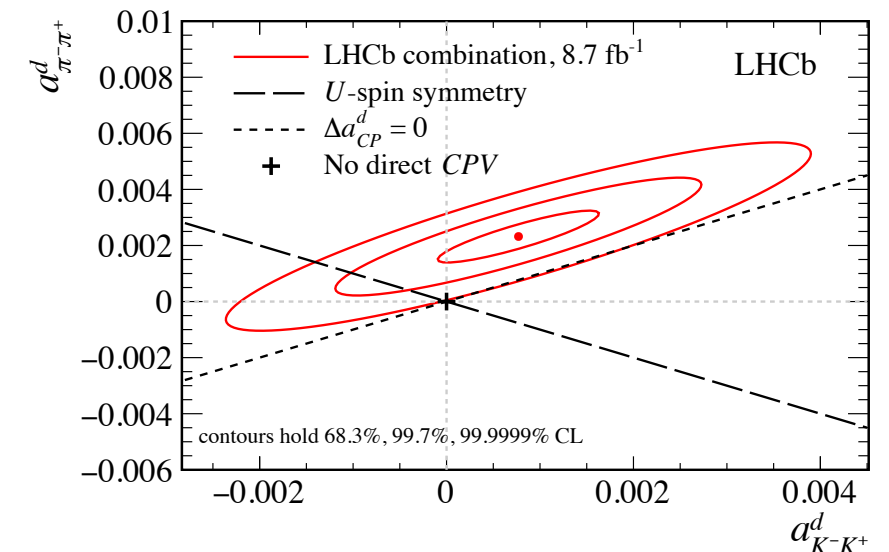
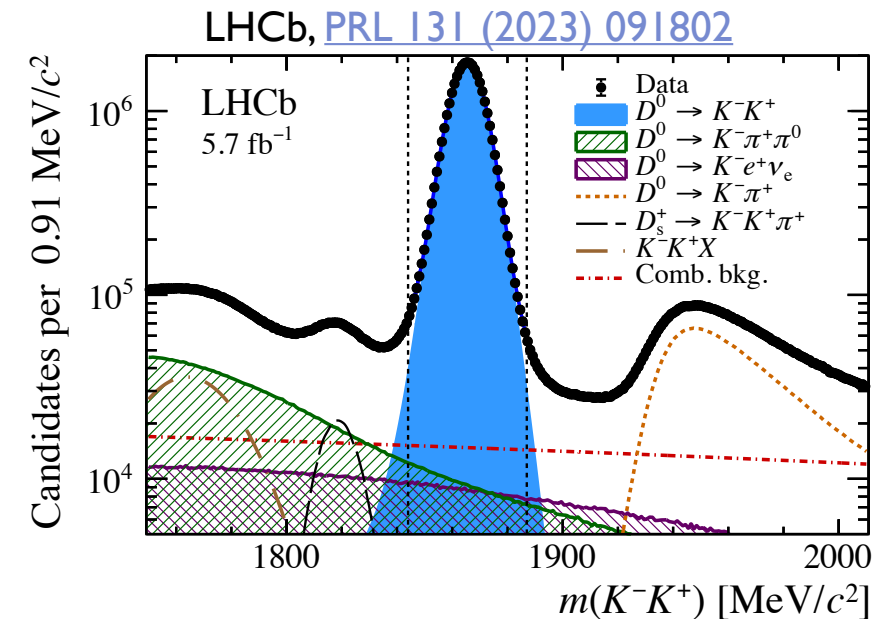
(November 9, 2011, Pizzeria de la Place, Meyrin)

CP violation in decays

- 2019 discovery of CP violation in charm decays:

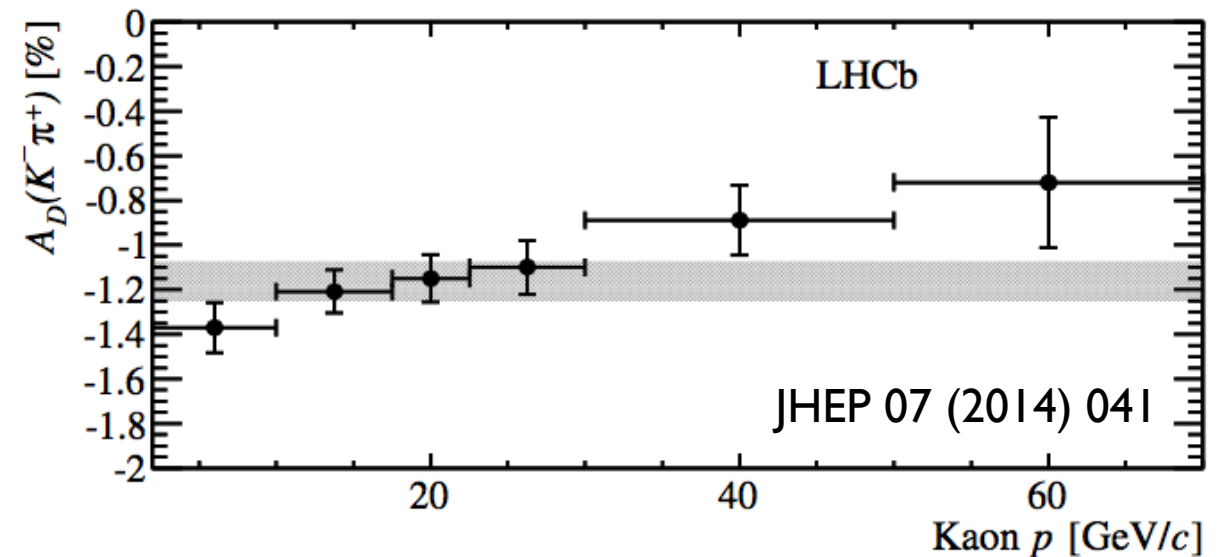
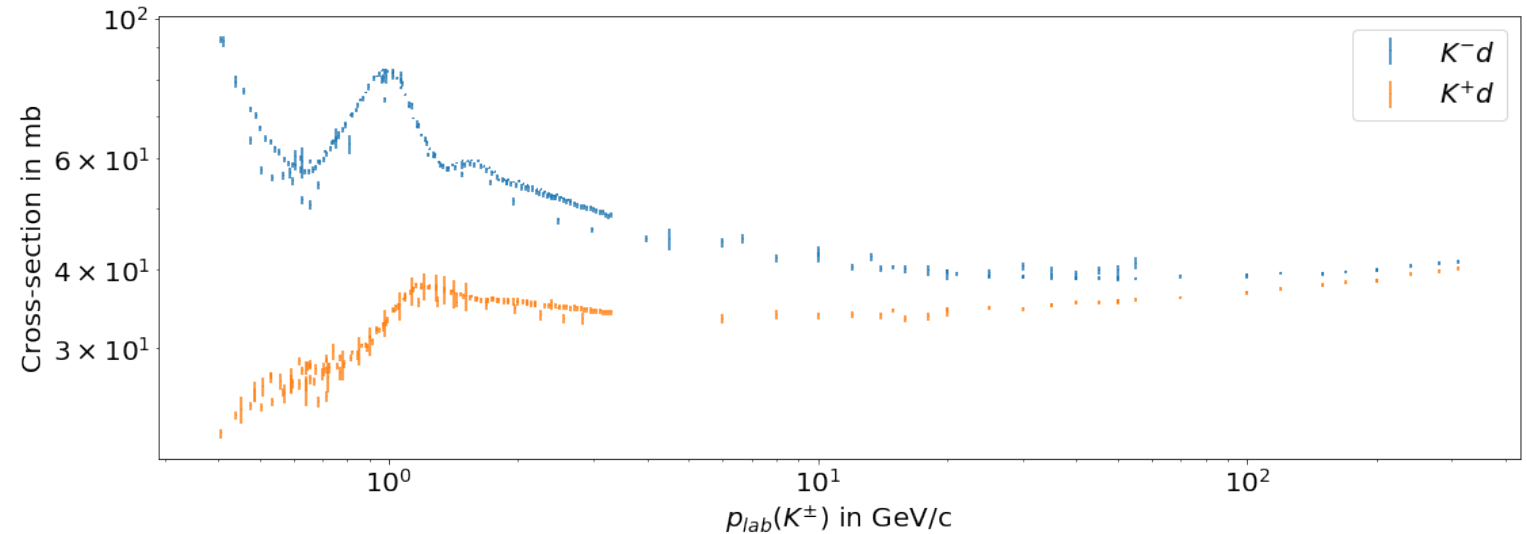
$$\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi) = (-0.182 \pm 0.033)\% \quad \text{LHCb, PRL 122 (2019) 211803}$$

- Prompted investigation of individual decay modes
- Use control channels $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^+ \pi^+ \pi^-$, $D^+ \rightarrow K_S \pi^+$ and $A_{CP}(K_S)$ to constrain production and detection asymmetries
- Result indicates ΔA_{CP} largely driven by $A_{CP}(\pi\pi)$
 - In tension with U-spin symmetry expectation



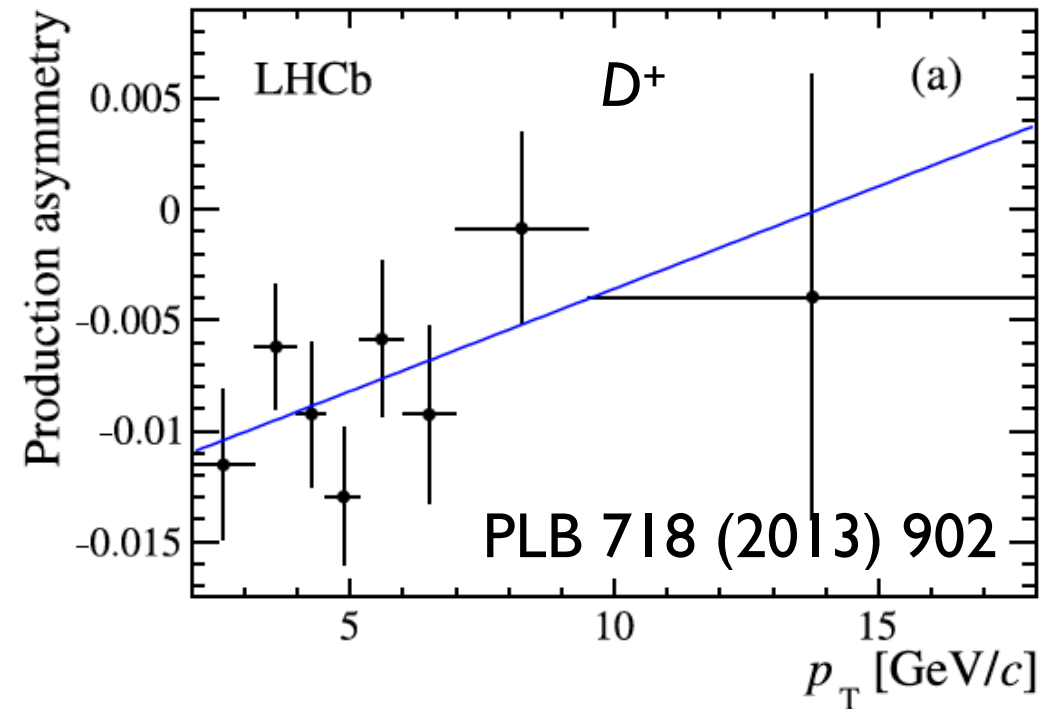
Detection asymmetries

- Two contributions
 - Detector asymmetries
 - Can come from asymmetric construction or different performance, with respect to a magnetic field to lead to a “nuisance” asymmetry
 - May be in part mitigated if field polarity can be reversed
 - Interaction asymmetry
 - Inherent difference of CP-conjugate particle pairs interacting with (hence disappearing in) detector material

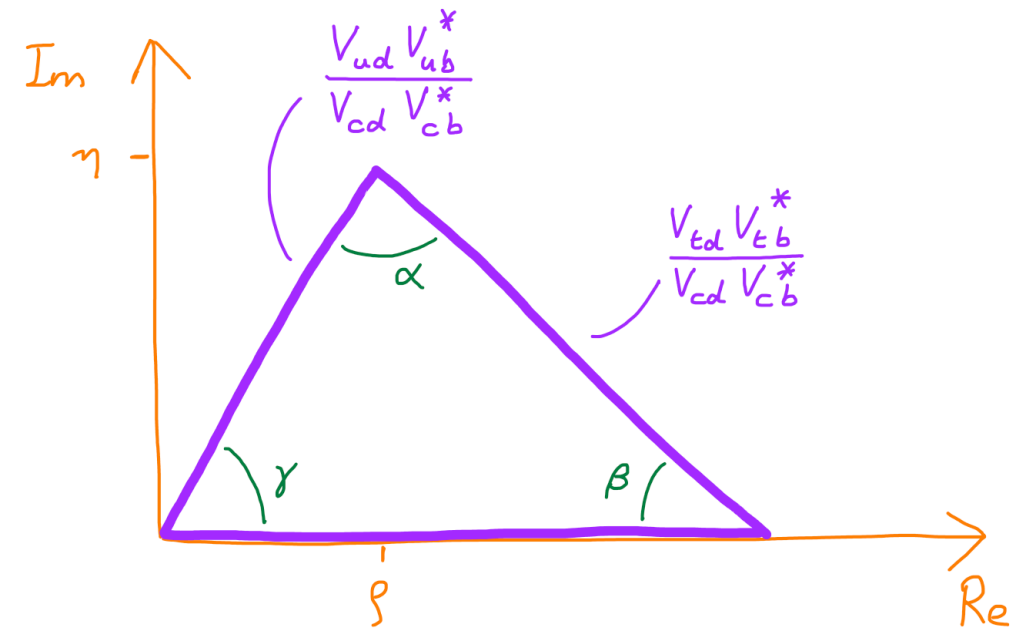


Production asymmetries

- Particular to pp collider
- Valence quarks favour production of matter baryons
 - Hence expect surplus of antimatter mesons
 - More complicated mechanisms are at play too
- Production asymmetry can depend on kinematics
- At symmetric colliders (e^+e^- , $p\bar{p}$)
 - Can have forward-backward asymmetry due to interaction with CP conjugate beam particles



CKM metrology

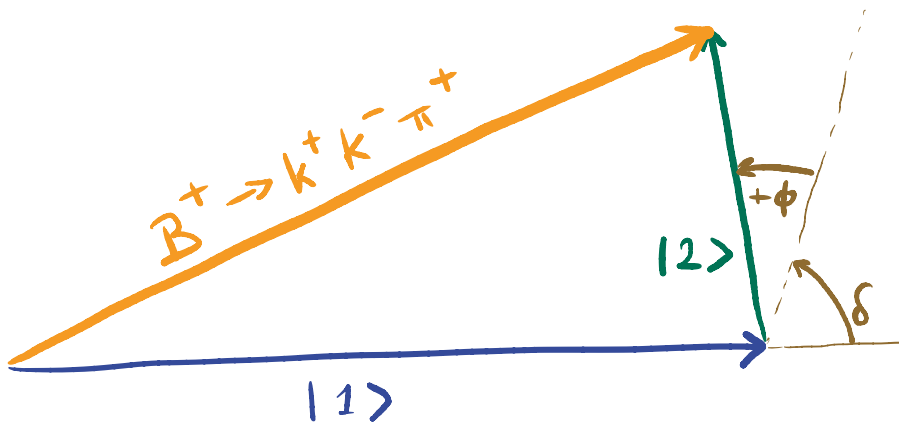
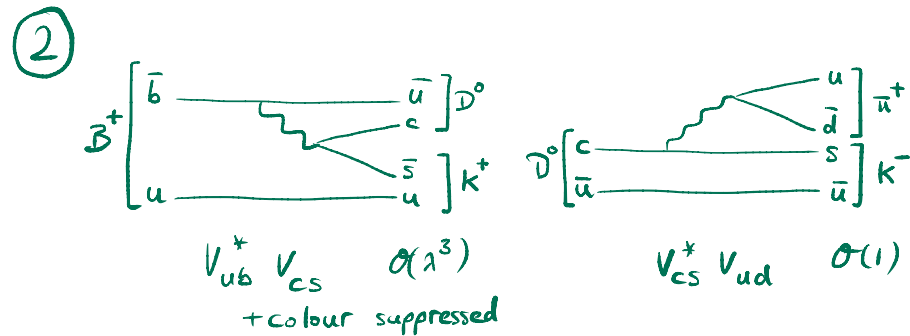
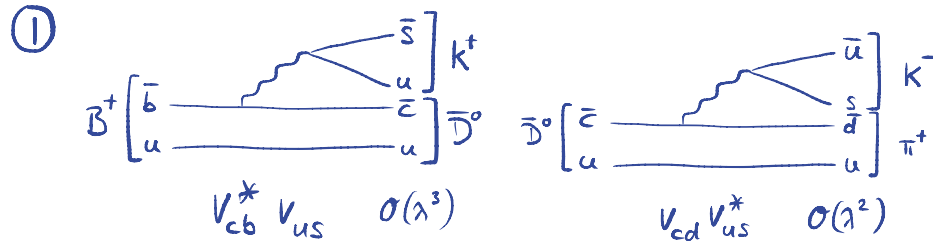


- CKM matrix can be represented by unitarity triangles
 - Off-diagonal elements of unitarity relations depicted in complex plane: $VV^\dagger = \mathbb{1}$
- Complex phases are related to angles in triangle
 - Phases arise largely through smallest elements: V_{ub} and V_{td}
- Sides are determined by magnitude ratios
 - Uncertainties typically driven by uncertainty of smallest elements: V_{ub} and V_{td}

Measuring γ

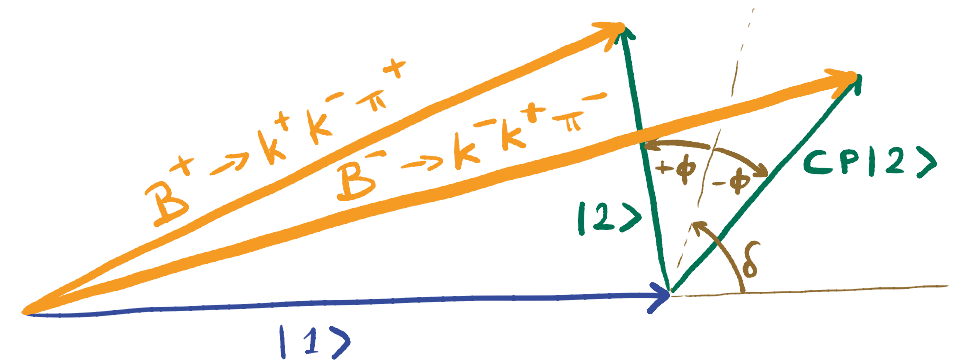
- Many methods to measure γ
 - Here illustrated with Atwood, Dunietz, Soni (ADS)
- All based on analysing two contributing amplitudes
 - 1: $\bar{D}^0$ decay doubly Cabibbo-suppressed
 - 2: B^+ decay colour-suppressed, D^0 decay Cabibbo-favoured
- Similar amplitude magnitudes give sensitivity to phase difference:

$$\begin{aligned}
 \phi &= \arg(V_{cb}^* V_{us} V_{cd} V_{us}^*) - \arg(V_{ub}^* V_{cs} V_{cs}^* V_{ud}) \\
 &= \arg\left(\frac{V_{cb}^* V_{cd}}{V_{ub}^* V_{ud}}\right) \\
 &= \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right) \\
 &= \gamma.
 \end{aligned}$$

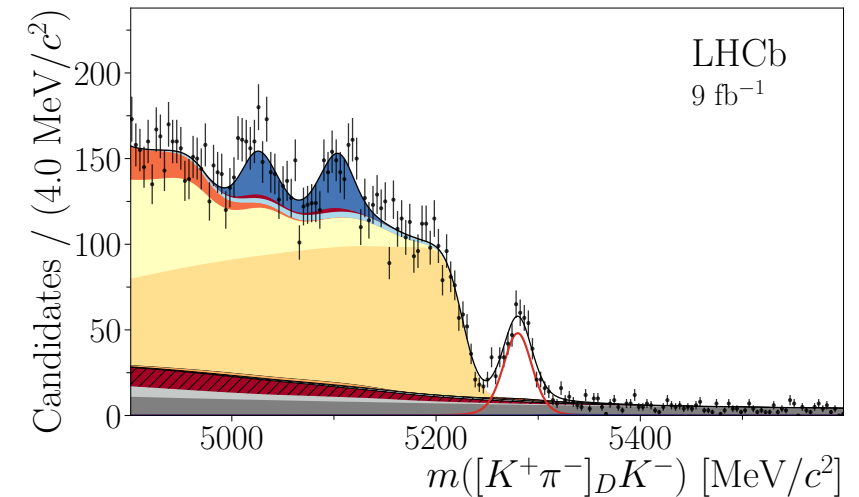
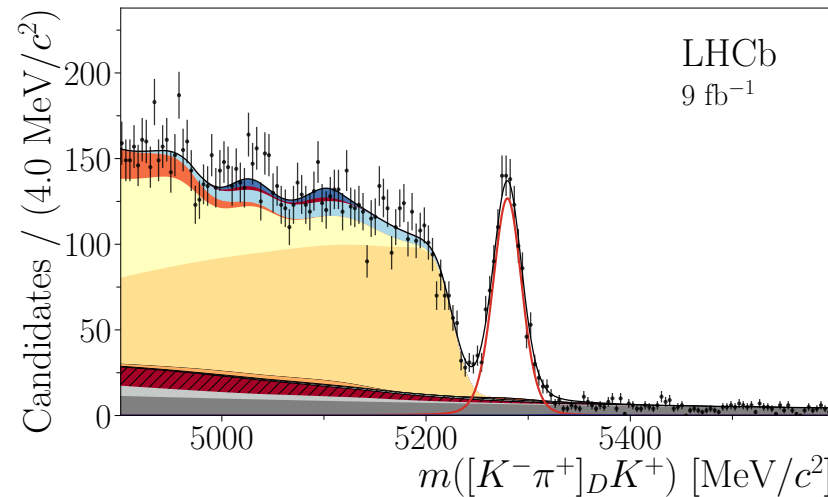


Measuring γ — Part 2

- Measurable rates are combinations of two amplitudes with different strong and weak phases
- Weak phases flip sign under CP conjugation
- CP asymmetries give access to weak phase differences

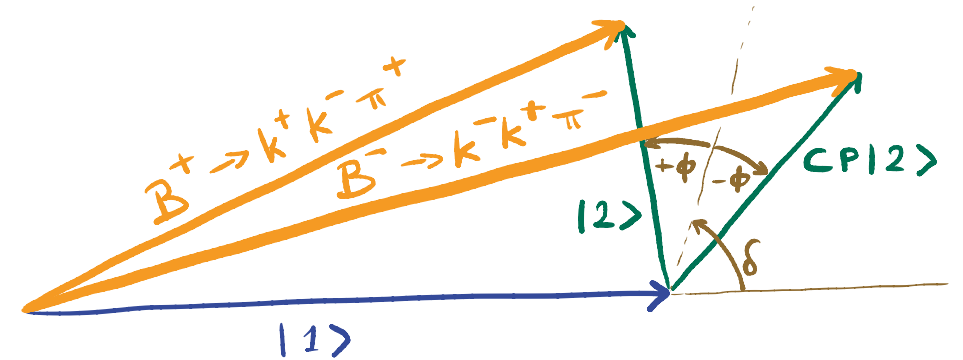


LHCb, JHEP 04 (2021) 081

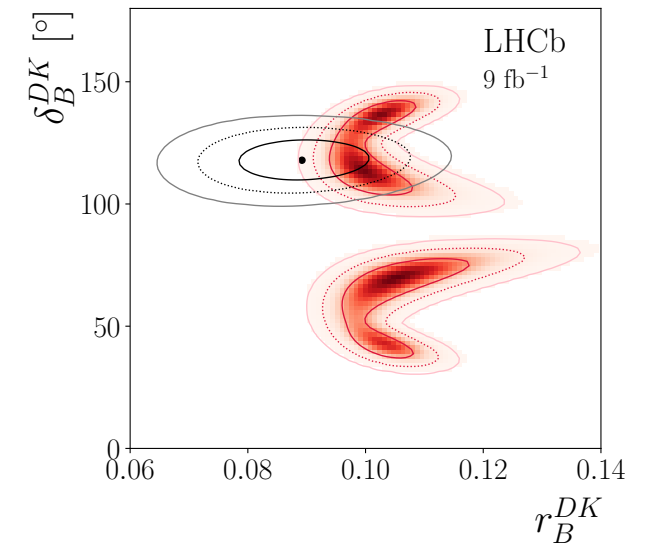
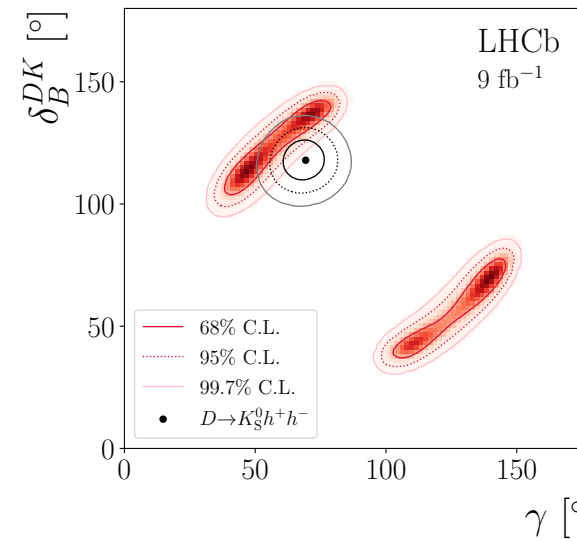


Measuring γ — Part 2

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 - Can lead to ambiguities
 - Exploit external constraints

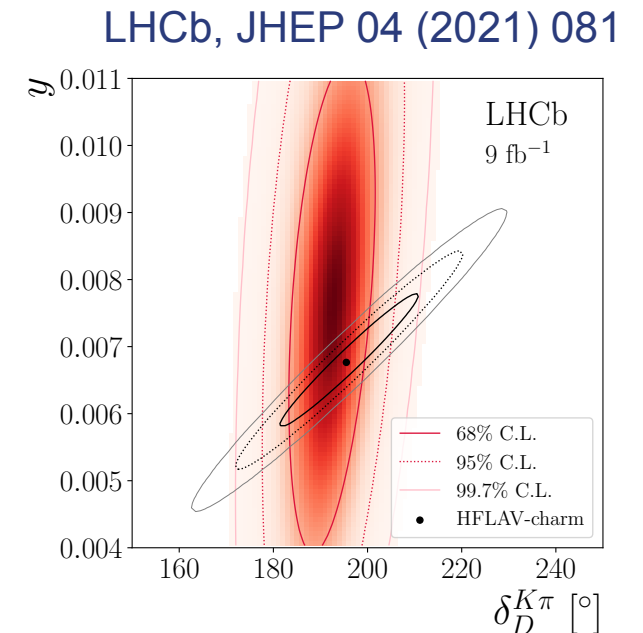
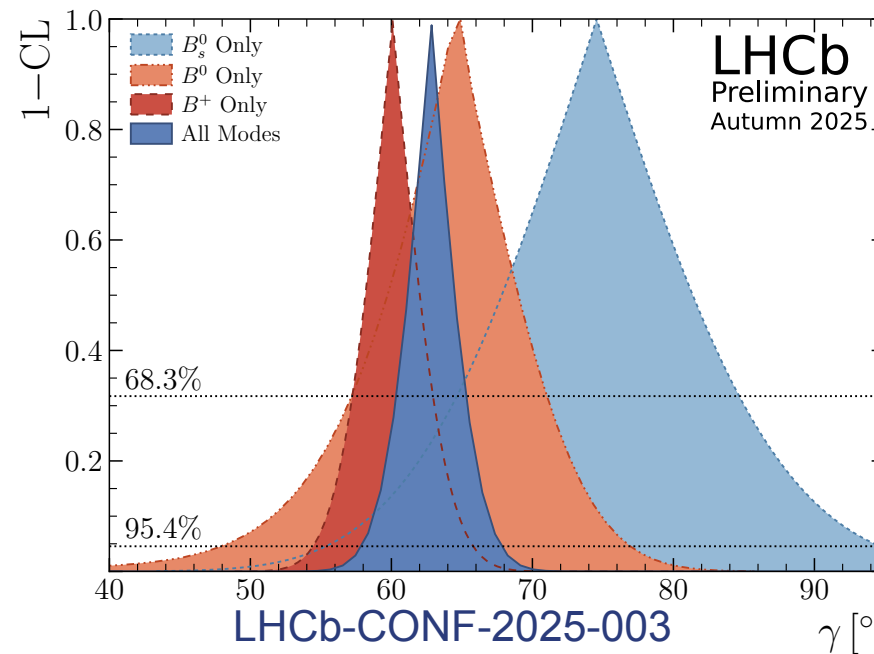
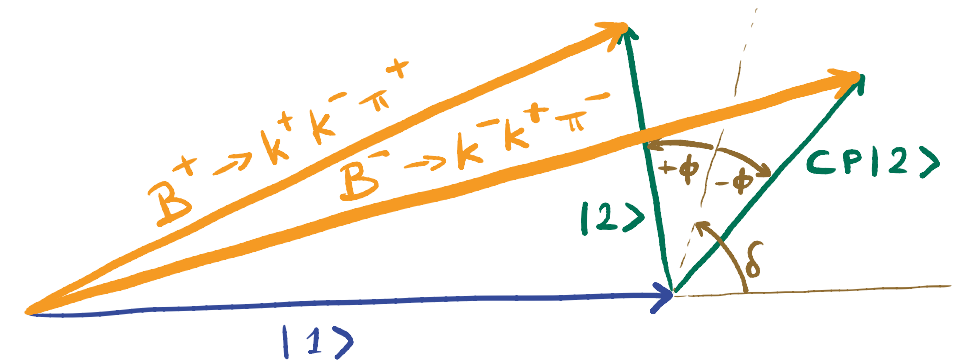


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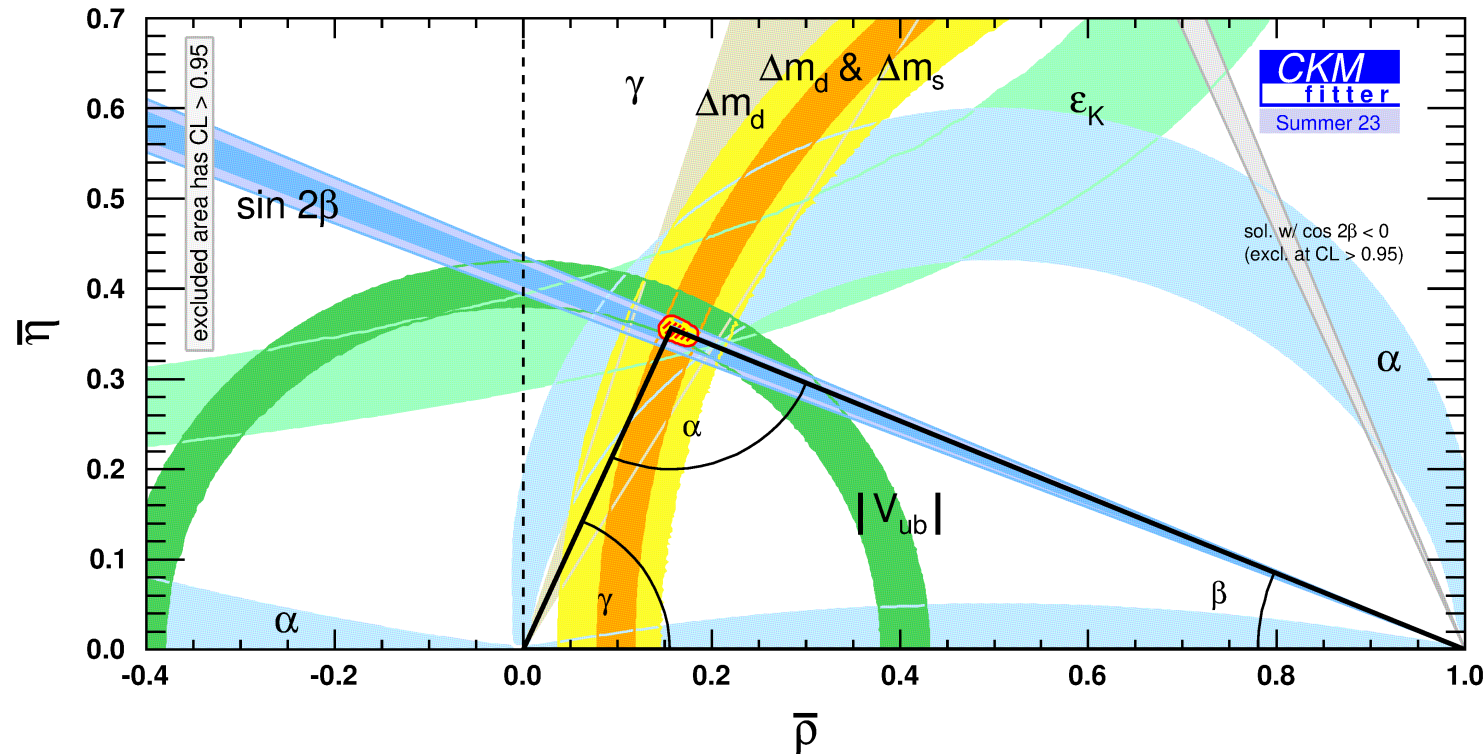


Measuring γ — Part 2

- Measurable rates are combinations of two amplitudes with different strong and weak phases
- Weak phases flip sign under CP conjugation
- CP asymmetries give access to weak phase differences
- Requires input on strong phase difference and amplitude ratios
 - Can lead to ambiguities
 - Exploit external constraints
 - Extract γ with global fit of many decays
 - Latest result
 $\gamma = (62.8 \pm 2.6)^\circ$

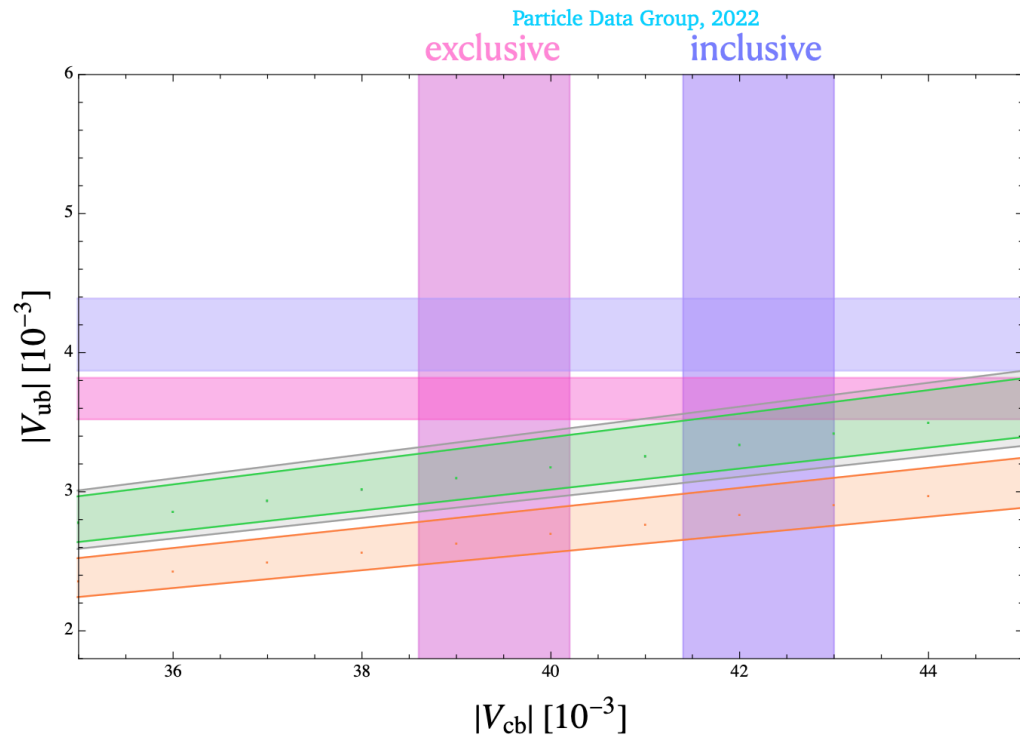


CKM measurements



- Statistical combination of many measurements with theory input
- Apex of triangle in agreement with all inputs
- First determination of angle β was main goal of B-factories BaBar and Belle
 - Nobel Prize 2008
- Angle γ now known to about 1° in large parts due to LHCb input
- Much more precise tests expected especially from Belle II and LHCb in future

Aside: V_{ub} & V_{cb}



From: [Carolina Bolognani, CKM 2023](#)

- Leptonic and semi-leptonic hadron decays used to extract CKM element magnitudes
- Leptonic decays
 - Two-body decays to lepton-neutrino pair:
 - Theoretically clean, but
 - Experimentally difficult to reconstruct and to determine efficiency
- Semi-leptonic decays
 - Decays to Hadron and lepton-neutrino pair:
 - Theoretically challenging due to dependence on decay kinematics with additional challenge for exclusive decays
 - Experimentally easier but still challenging due to neutrino and still more challenging for inclusive decays
- **Bottom line:** lots of theoretical and experimental work ongoing

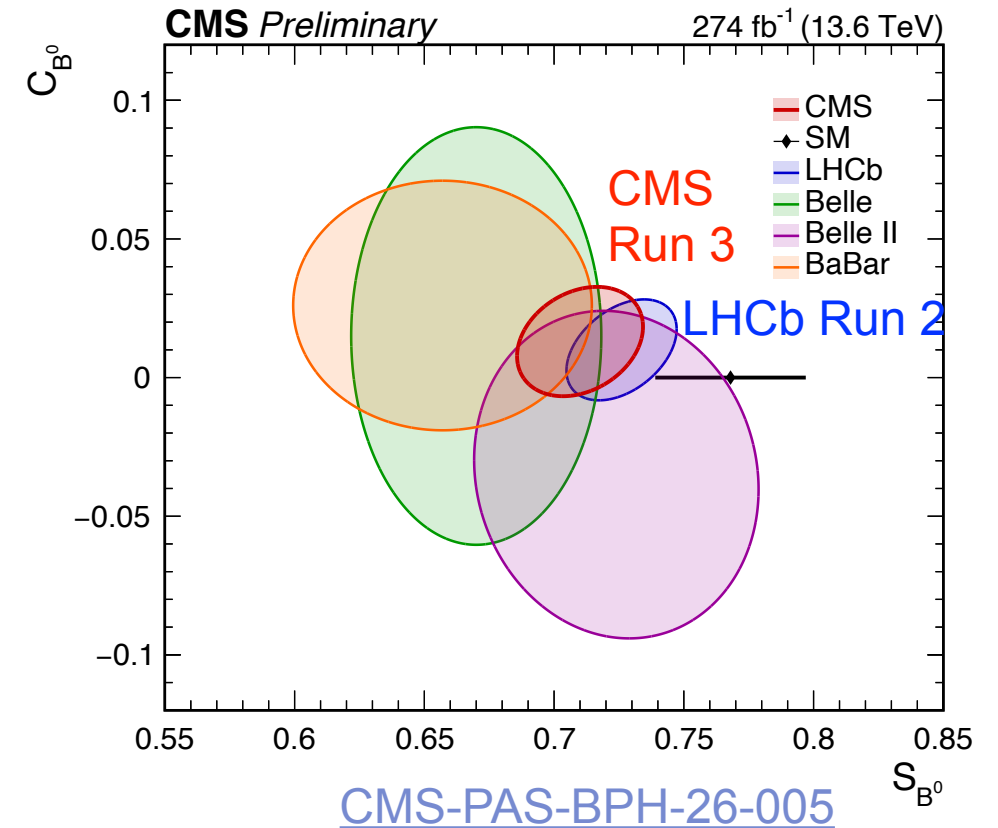
The angle β

- Measured in $B^0 \rightarrow J/\psi K_S$ and related final states

?

- Exercise:

- Determine the angle β in terms of CKM elements
- Convince yourself that this is accessible through the decay $B^0 \rightarrow J/\psi K_S$
 - Hint: Consider B oscillations, the B decay and K oscillations



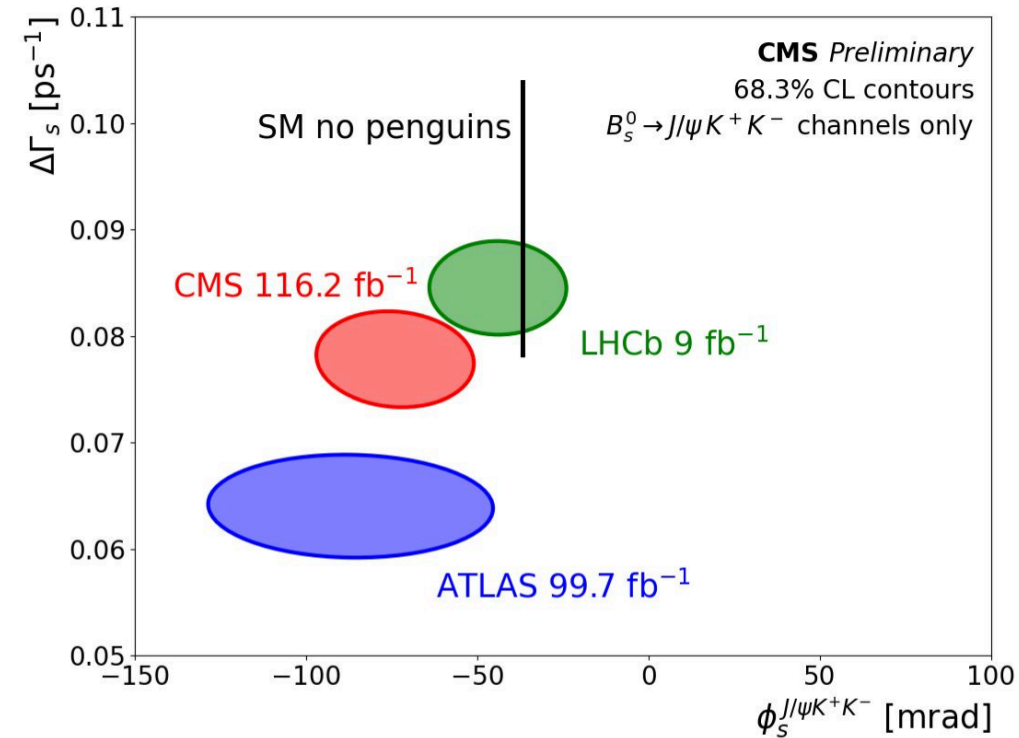
The angle β_s

- Measured in $B^0_s \rightarrow J/\psi \phi$ and related final states
- Let's see how this relates to β_s ...

The angle β_s

- Measured in $B_s^0 \rightarrow J/\psi \phi$ and related final states
- Let's see how this relates to β_s ...
- The angle β_s remains to be measured to be non-zero
 - Latest measurements approaching required sensitivity
 - Some tension between experiments in $\Delta\Gamma_s$ and Γ_s

Comparison with other LHC experiments



From: [Alberto Bragagnolo, Moriond EW 2024](#)
And: [CMS BPH-23-004](#)

Recap

- Neutral mesons oscillate with very different parameters for the different mesons
 - Additional requirement of decay-time resolution
- CP asymmetry requires (at least) two interfering amplitudes with different strong and weak phases
- Time-dependent asymmetry can use different approximations for different mesons

- CP violation observed in kaons, charm and beauty mesons
- Production and detection asymmetries need to be accounted for
- CKM angle γ measured with $B \rightarrow DK$ decays
- CKM element magnitudes measured with (semi-)leptonic decays
- CP violating phase β_s emerging around SM expectation

Rare processes

Rare meson decays

Rare charged lepton decays



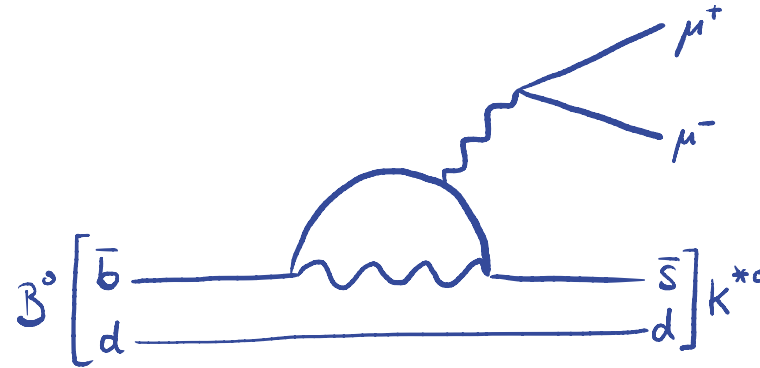
What's rare?

- Allowed but suppressed in SM
 - Typically not considered rare:
 - Colour suppression
 - Cabibbo-suppression
 - Most common rare processes:
 - Flavour-changing neutral currents (FCNC)
- Technically allowed, but suppressed to unmeasurable levels
 - Lepton-flavour violating processes (allowed via neutrino oscillations)
 - Discovery is unambiguous sign of physics beyond the SM
- Forbidden processes
 - Lepton number violation (may have contribution via Majorana neutrinos)
 - Baryon number violation

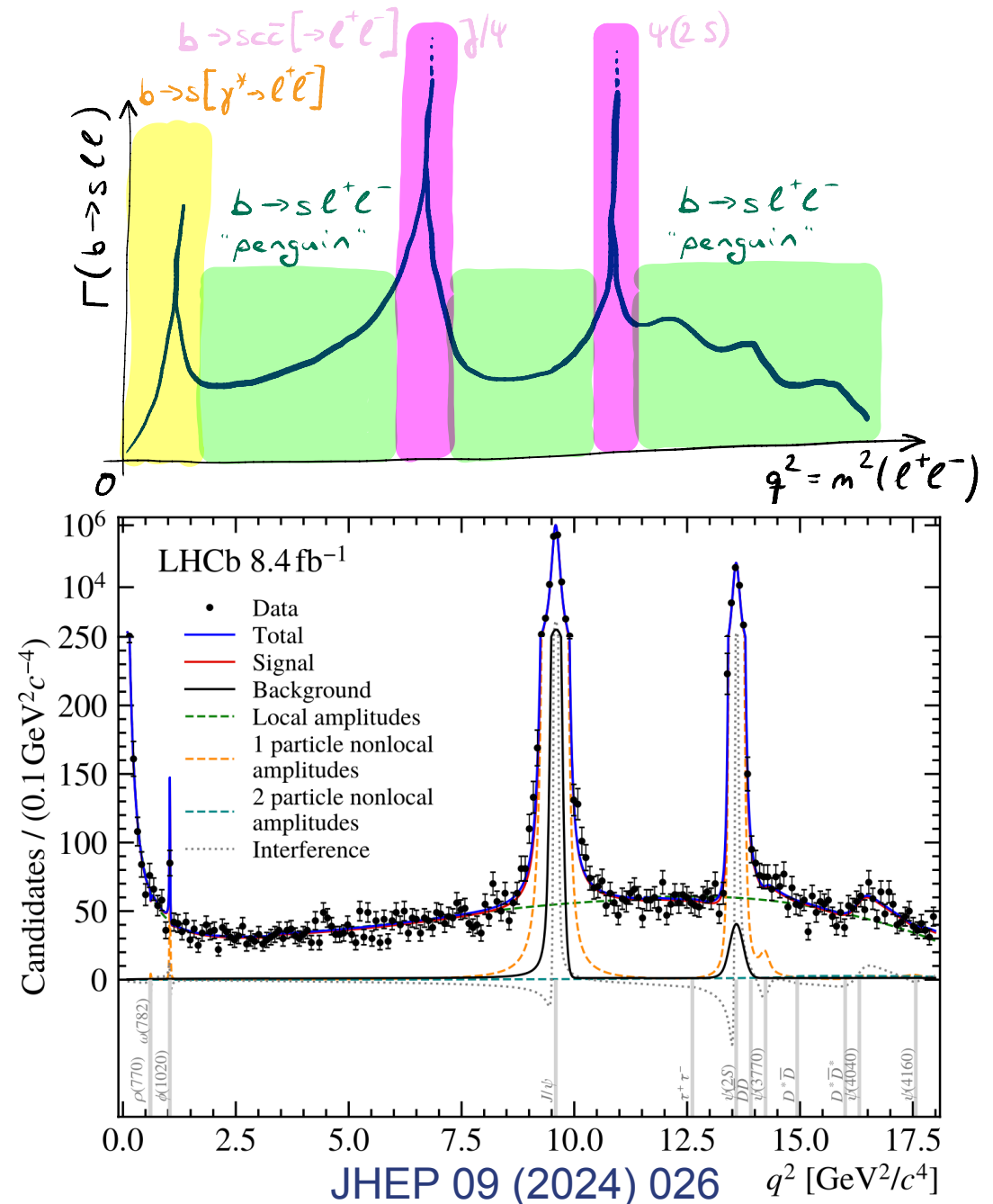


Source: [WikiCommons](#)

$B \rightarrow K^* \mu \mu$



- Flavour-changing neutral current decay
- Not so rare: BF $\sim 10^{-6}$
- Recent LHCb analysis is first comprehensive model-based analysis of the full decay amplitude, including
 - Local amplitudes: direct decay into $\mu^+ \mu^-$ final state
 - 1-particle non-local amplitudes: $\mu^+ \mu^-$ produced through resonances, e.g. ϕ , J/ψ , $\psi(2S)$
 - 2-particle non-local amplitudes: $\mu^+ \mu^-$ produced through rescattering from $D^{(*)} \bar{D}^{(*)}$ or $\tau^+ \tau^-$
 - Interference of the above



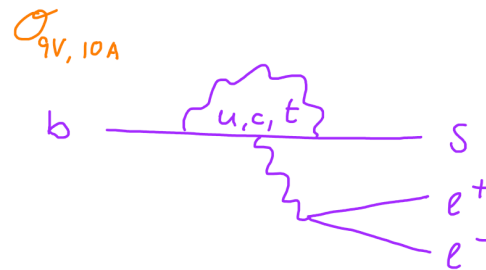
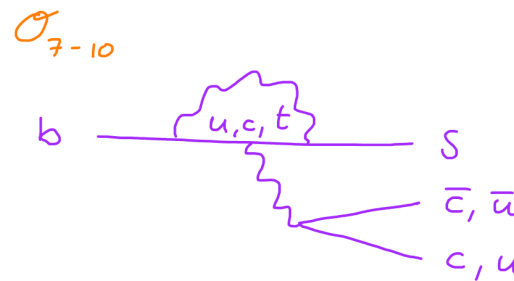
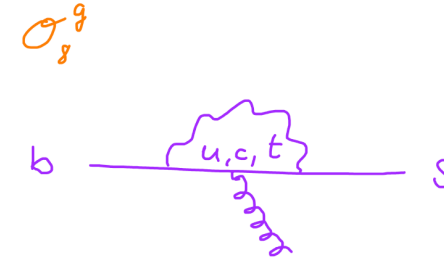
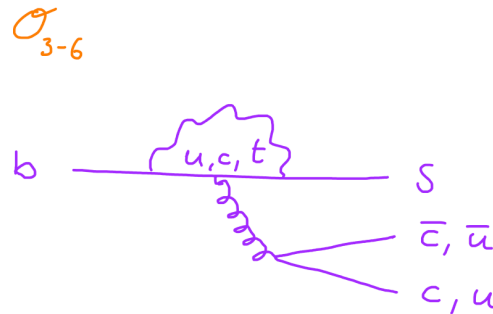
$B \rightarrow K^* \mu \mu$

- Analysis involves decay plane angles defined by di-muon and di-hadron systems
 - Large set of angular observables incl. P'_5
- Use Weak Effective Theory:

$$\mathcal{H}_{\text{WET}} = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i C_i^{(')}(\mu) \mathcal{O}_i^{(')}(\mu)$$
- Operators relate to different types of local interactions
- Wilson Coefficients describe their relative strength

$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L) \bar{\ell} \gamma^\mu \ell,$$

$$\mathcal{O}_{10\ell} = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L) \bar{\ell} \gamma^\mu \gamma_5 \ell$$



$$\frac{d^4 \bar{\Gamma}^{(-)}(B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-)}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi} \sum_i \bar{J}_i^{(-)}(q^2) f_i(\cos \theta_\ell, \cos \theta_K, \phi) G_i$$

$$J_{1s}(q^2) = \frac{2 + \beta_\ell^2}{4} (|\mathcal{A}_\perp^L|^2 + |\mathcal{A}_\parallel^L|^2 + |\mathcal{A}_\perp^R|^2 + |\mathcal{A}_\parallel^R|^2) + \frac{4m_\ell^2}{q^2} \text{Re}(\mathcal{A}_\perp^L \mathcal{A}_\perp^{R*} + \mathcal{A}_\parallel^L \mathcal{A}_\parallel^{R*}), \quad G_i = \int_{m_{K\pi}^2=0.796^2 \text{ GeV}^2/c^4}^{m_{K\pi}^2=0.996^2 \text{ GeV}^2/c^4} g_i(m_{K\pi}^2) dm_{K\pi}^2$$

Breit-Wigner

$$J_{1c}(q^2) = |\mathcal{A}_0^L|^2 + |\mathcal{A}_0^R|^2 + \frac{4m_\ell^2}{q^2} (|\mathcal{A}_t|^2 + 2 \text{Re}(\mathcal{A}_0^L \mathcal{A}_0^{R*})),$$

$$J_{2s}(q^2) = \frac{\beta_\ell^2}{4} (|\mathcal{A}_\perp^L|^2 + |\mathcal{A}_\parallel^L|^2 + |\mathcal{A}_\perp^R|^2 + |\mathcal{A}_\parallel^R|^2),$$

$$J_{2c}(q^2) = -\beta_\ell^2 (|\mathcal{A}_0^L|^2 + |\mathcal{A}_0^R|^2),$$

$$J_3(q^2) = \frac{\beta_\ell^2}{2} (|\mathcal{A}_\perp^L|^2 - |\mathcal{A}_\parallel^L|^2 + |\mathcal{A}_\perp^R|^2 - |\mathcal{A}_\parallel^R|^2),$$

$$J_4(q^2) = -\frac{\beta_\ell^2}{\sqrt{2}} \text{Re}(\mathcal{A}_0^L \mathcal{A}_\parallel^{L*} + \mathcal{A}_0^R \mathcal{A}_\parallel^{R*}),$$

$$J_5(q^2) = \sqrt{2} \beta_\ell \text{Re}(\mathcal{A}_0^L \mathcal{A}_\perp^{L*} - \mathcal{A}_0^R \mathcal{A}_\perp^{R*}),$$

$$J_{6s}(q^2) = -2\beta_\ell \text{Re}(\mathcal{A}_\parallel^L \mathcal{A}_\perp^{L*} - \mathcal{A}_\parallel^R \mathcal{A}_\perp^{R*}),$$

$$J_7(q^2) = -\sqrt{2} \beta_\ell \text{Im}(\mathcal{A}_0^L \mathcal{A}_\parallel^{L*} - \mathcal{A}_0^R \mathcal{A}_\parallel^{R*}),$$

$$J_8(q^2) = \frac{\beta_\ell^2}{\sqrt{2}} \text{Im}(\mathcal{A}_0^L \mathcal{A}_\perp^{L*} + \mathcal{A}_0^R \mathcal{A}_\perp^{R*}),$$

$$J_9(q^2) = -\beta_\ell^2 \text{Im}(\mathcal{A}_\parallel^{L*} \mathcal{A}_\perp^L + \mathcal{A}_\parallel^{R*} \mathcal{A}_\perp^R),$$

$$f_{1s}(\cos \theta_\ell, \cos \theta_K, \phi) = \sin^2 \theta_K,$$

$$f_{1c}(\cos \theta_\ell, \cos \theta_K, \phi) = \cos^2 \theta_K,$$

$$f_{2s}(\cos \theta_\ell, \cos \theta_K, \phi) = \sin^2 \theta_K \cos 2\theta_\ell,$$

$$f_{2c}(\cos \theta_\ell, \cos \theta_K, \phi) = \cos^2 \theta_K \cos 2\theta_\ell,$$

$$f_3(\cos \theta_\ell, \cos \theta_K, \phi) = \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi,$$

$$f_4(\cos \theta_\ell, \cos \theta_K, \phi) = \sin 2\theta_K \sin 2\theta_\ell \cos \phi,$$

$$f_5(\cos \theta_\ell, \cos \theta_K, \phi) = \sin 2\theta_K \sin \theta_\ell \cos \phi,$$

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$$f_8(\cos \theta_\ell, \cos \theta_K, \phi) = \sin 2\theta_K \sin 2\theta_\ell \sin \phi,$$

$$f_9(\cos \theta_\ell, \cos \theta_K, \phi) = \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi.$$

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$$\begin{aligned} J_{1c}^{S'}(q^2) &= \frac{1}{3} \left((|\mathcal{A}_{00}^L|^2 + |\mathcal{A}_{00}^R|^2) + \frac{4m_\ell^2}{q^2} 2 \operatorname{Re}(\mathcal{A}_{00}^L \mathcal{A}_{00}^{R*}) \right), \\ J_{2c}^{S'}(q^2) &= -\frac{1}{3} \beta_\ell^2 (|\mathcal{A}_{00}^L|^2 + |\mathcal{A}_{00}^R|^2), \\ J_{1c}'(q^2) &= \frac{2}{\sqrt{3}} \operatorname{Re} \left(\mathcal{A}_{00}^L \mathcal{A}_0^{L*} + \mathcal{A}_{00}^R \mathcal{A}_0^{R*} + \frac{4m_\ell^2}{q^2} (\mathcal{A}_{00}^L \mathcal{A}_0^{R*} + \mathcal{A}_0^L \mathcal{A}_{00}^{R*}) \right), \\ J_{2c}'(q^2) &= -\frac{2}{\sqrt{3}} \beta_\ell^2 \operatorname{Re} (\mathcal{A}_{00}^L \mathcal{A}_0^{L*} + \mathcal{A}_{00}^R \mathcal{A}_0^{R*}), \\ J_4'(q^2) &= -\sqrt{\frac{2}{3}} \beta_\ell^2 (\operatorname{Re} (\mathcal{A}_{00}^L \mathcal{A}_{\parallel}^{L*}) + \operatorname{Re} (\mathcal{A}_{00}^R \mathcal{A}_{\parallel}^{R*})), \\ J_5'(q^2) &= 2\sqrt{\frac{2}{3}} \beta_\ell^2 (\operatorname{Re} (\mathcal{A}_{00}^L \mathcal{A}_{\perp}^{L*}) + \operatorname{Re} (\mathcal{A}_{00}^R \mathcal{A}_{\perp}^{R*})), \\ J_7'(q^2) &= -2\sqrt{\frac{2}{3}} \beta_\ell^2 (\operatorname{Re} (\mathcal{A}_{00}^L \mathcal{A}_{\parallel}^{L*}) - \operatorname{Re} (\mathcal{A}_{00}^R \mathcal{A}_{\parallel}^{R*})), \\ J_8'(q^2) &= \sqrt{\frac{2}{3}} \beta_\ell^2 (\operatorname{Re} (\mathcal{A}_{00}^L \mathcal{A}_{\perp}^{L*}) - \operatorname{Re} (\mathcal{A}_{00}^R \mathcal{A}_{\perp}^{R*})). \end{aligned}$$

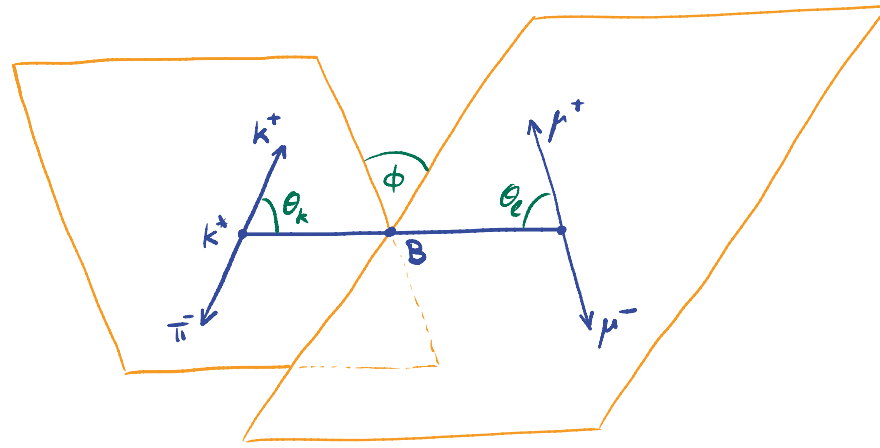
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LASS

$$\begin{aligned} f_{1c}^{S'}(\cos \theta_\ell, \cos \theta_K, \phi) &= 1, \\ f_{2c}^{S'}(\cos \theta_\ell, \cos \theta_K, \phi) &= \cos 2\theta_\ell, \\ f_{1c}'(\cos \theta_\ell, \cos \theta_K, \phi) &= \cos \theta_K, \\ f_{2c}'(\cos \theta_\ell, \cos \theta_K, \phi) &= \cos \theta_K \cos 2\theta_\ell, \\ f_4'(\cos \theta_\ell, \cos \theta_K, \phi) &= \sin \theta_K \sin 2\theta_\ell \cos \phi, \\ f_5'(\cos \theta_\ell, \cos \theta_K, \phi) &= \sin \theta_K \sin \theta_\ell \cos \phi, \\ f_7'(\cos \theta_\ell, \cos \theta_K, \phi) &= \sin \theta_K \sin \theta_\ell \sin \phi, \\ f_8'(\cos \theta_\ell, \cos \theta_K, \phi) &= \sin \theta_K \sin 2\theta_\ell \sin \phi. \end{aligned}$$

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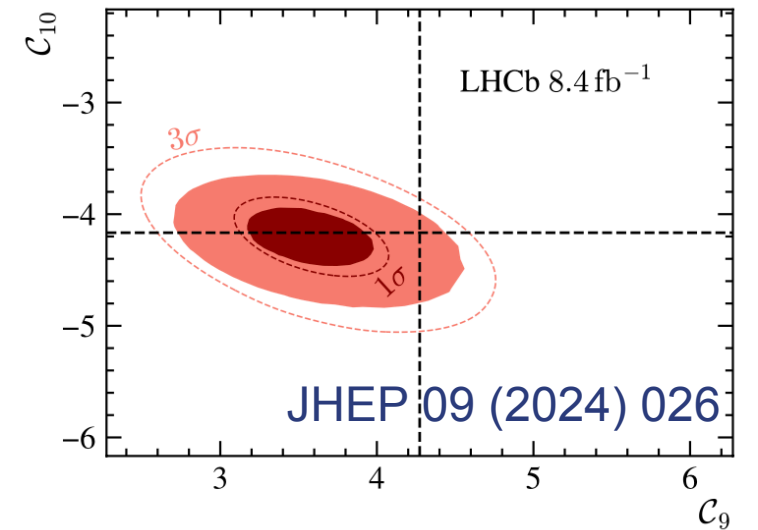
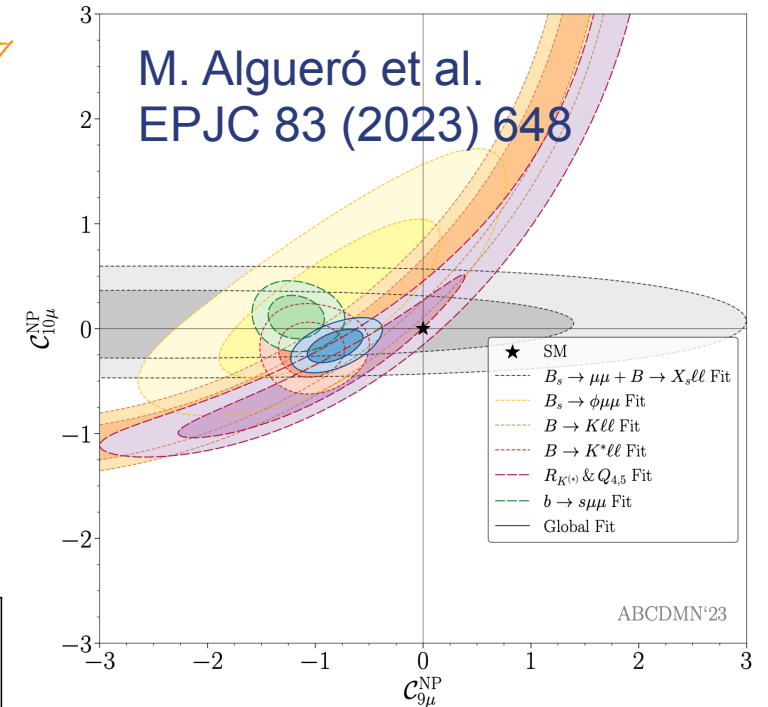
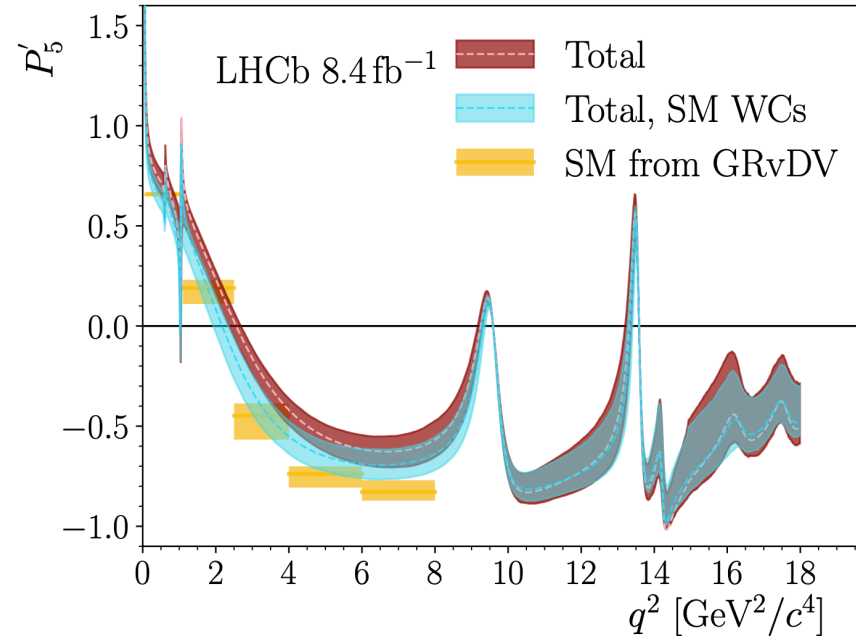
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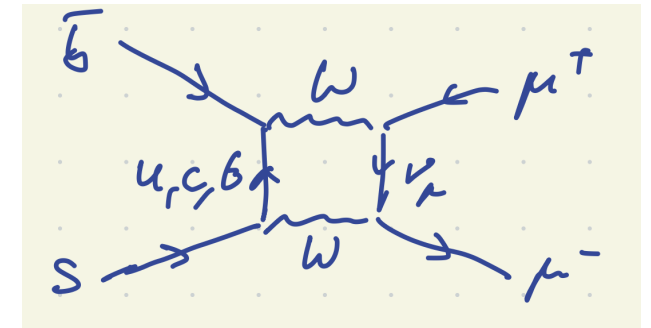
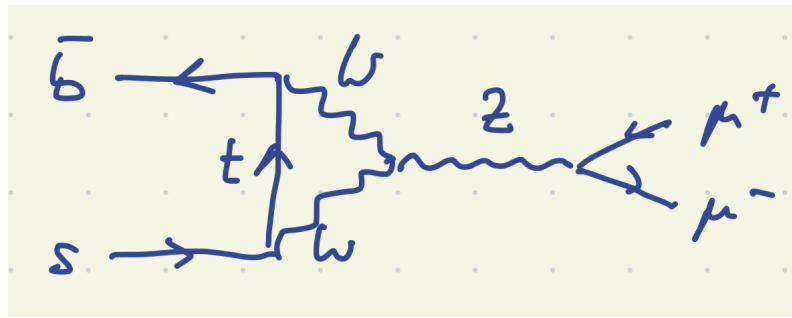
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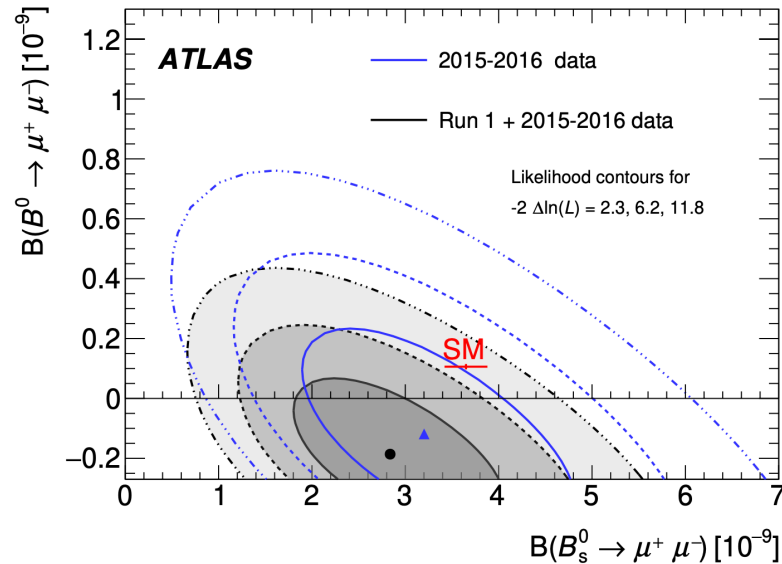


$$B^0_{(s)} \rightarrow \mu^+ \mu^-$$

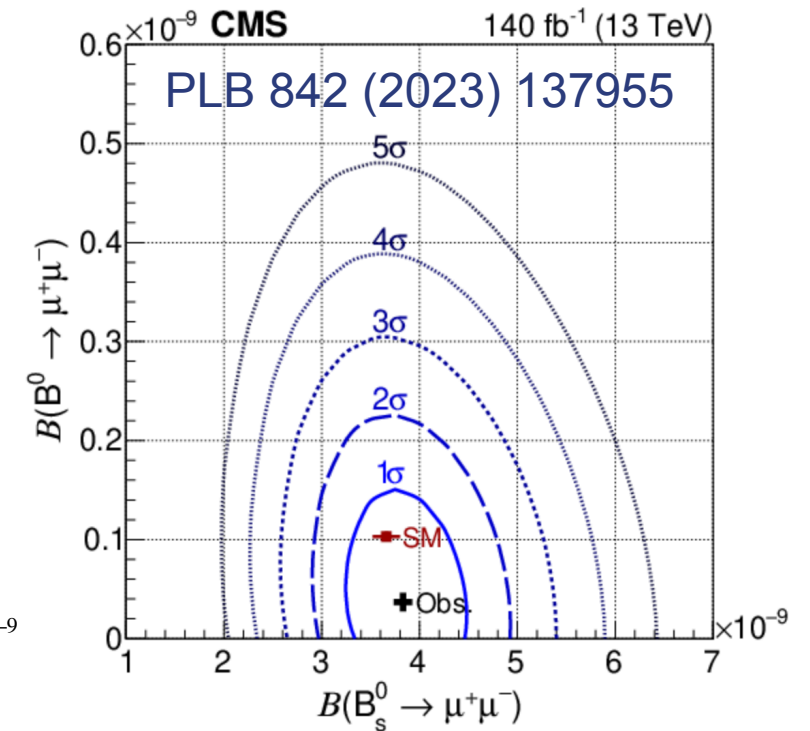
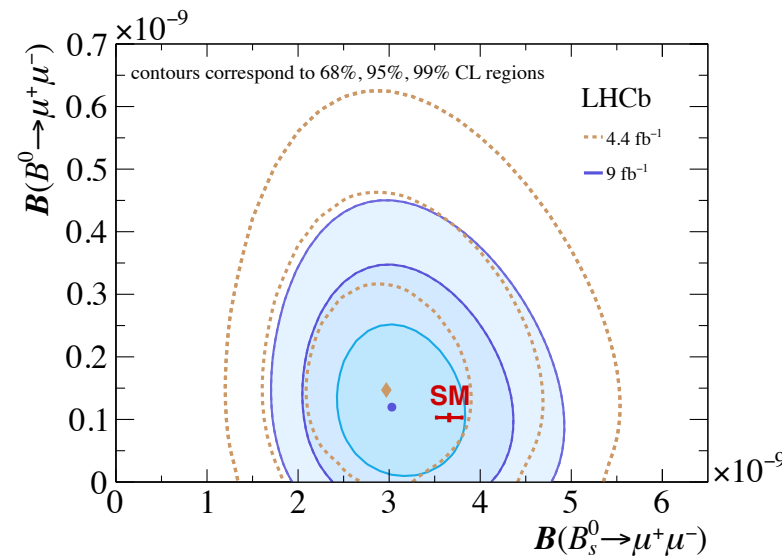


- Very rare decays broadly in agreement with SM, lowish values of B_d decays intriguing
- Effective lifetime measurements of additional interest; will become interesting with more data

JHEP 04 (2019) 098



PRL 128 (2022) 041801



NA62: looking for almost nothing

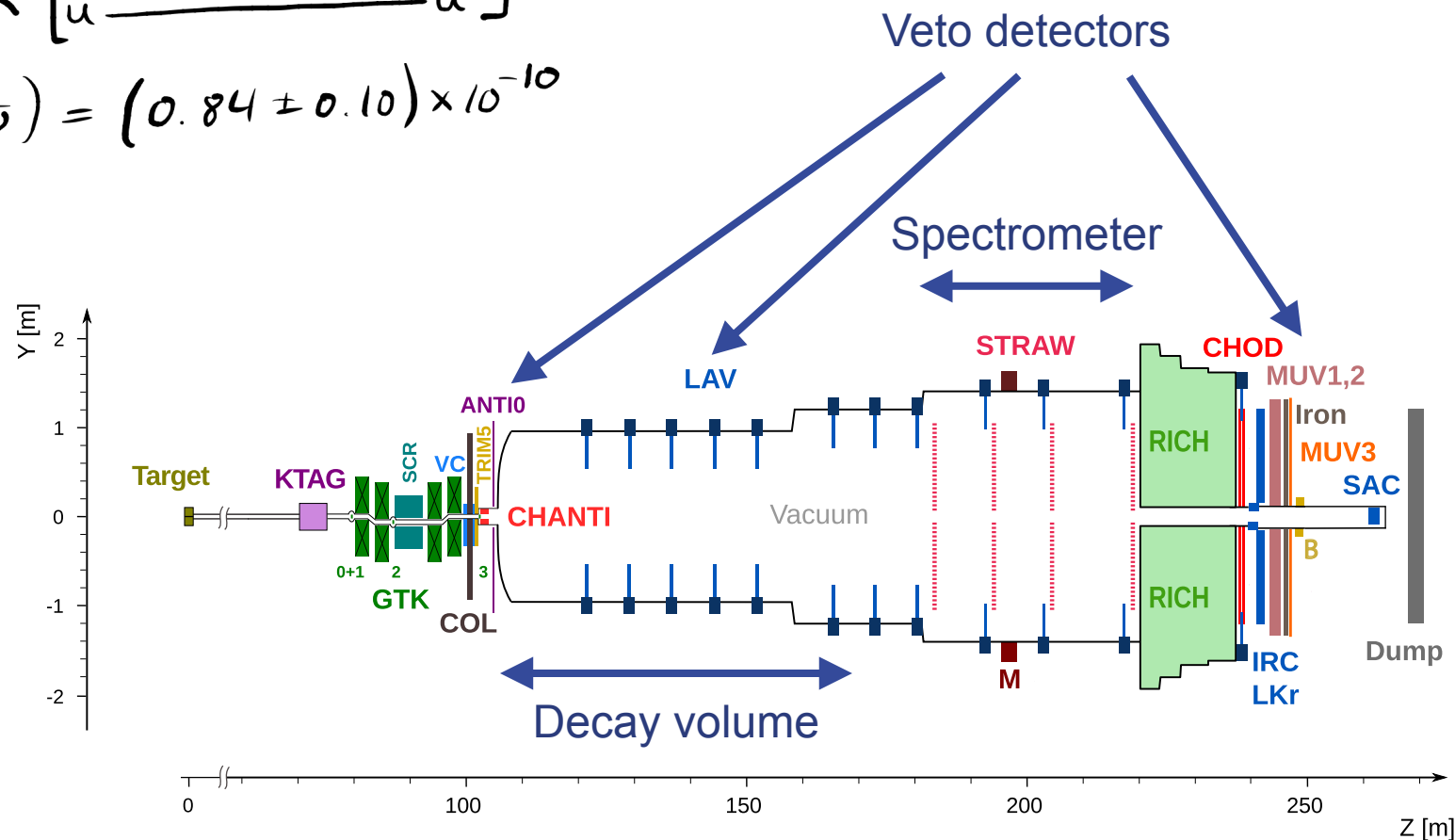
arXiv:2607.16413

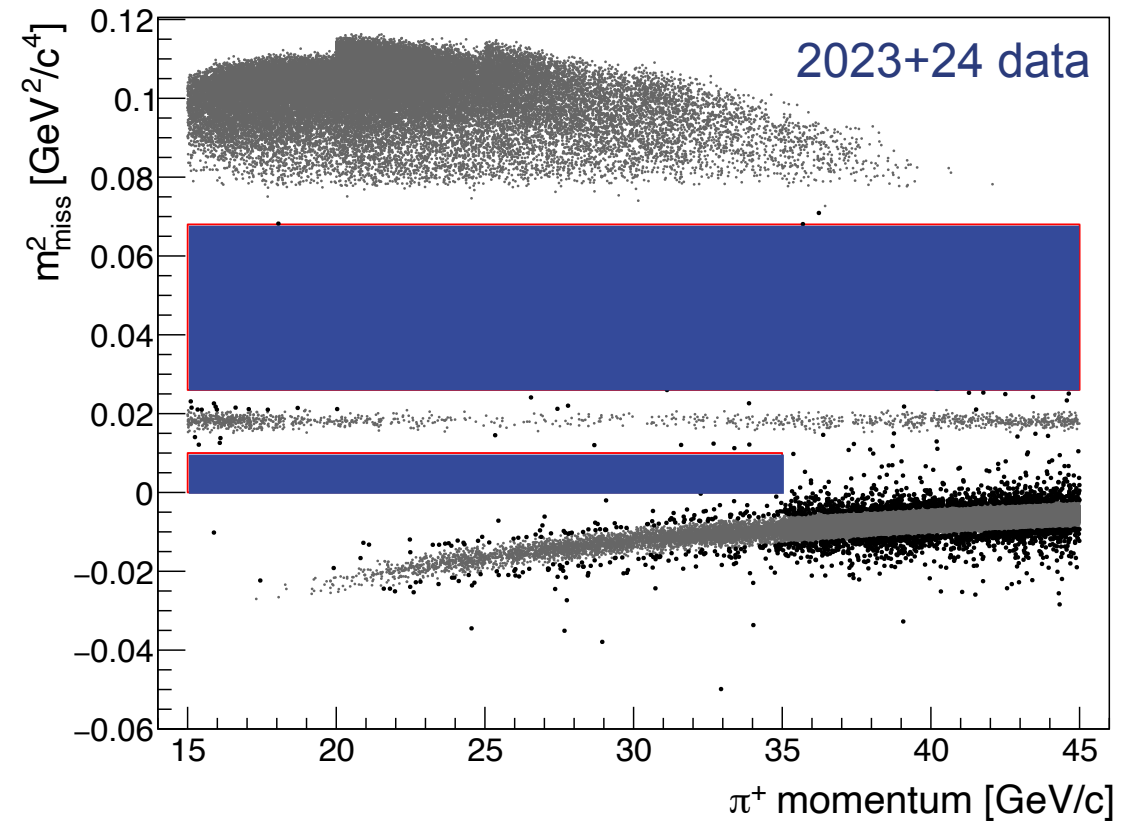
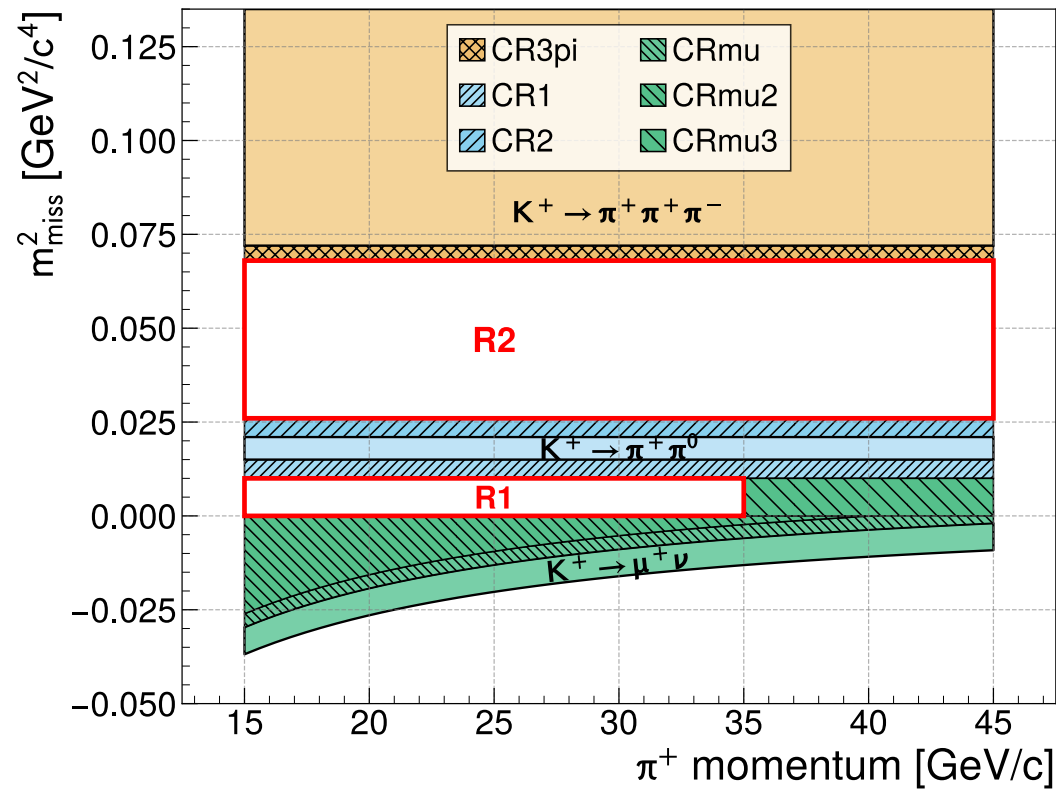
$$K^+ \left[\begin{array}{c} \bar{s} \\ u \end{array} \right] \rightarrow \pi^+ \left[\begin{array}{c} \bar{d} \\ u \end{array} \right] \nu \bar{\nu}$$

$$SM: \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.84 \pm 0.10) \times 10^{-10}$$

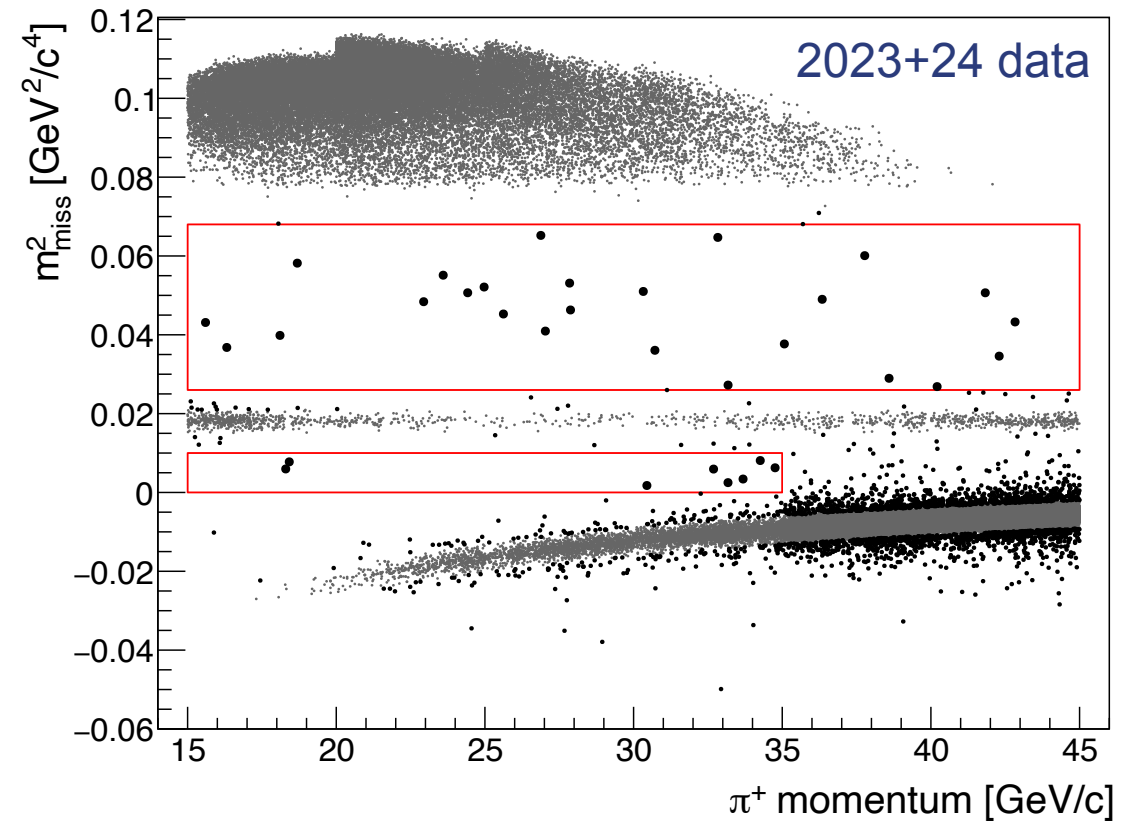
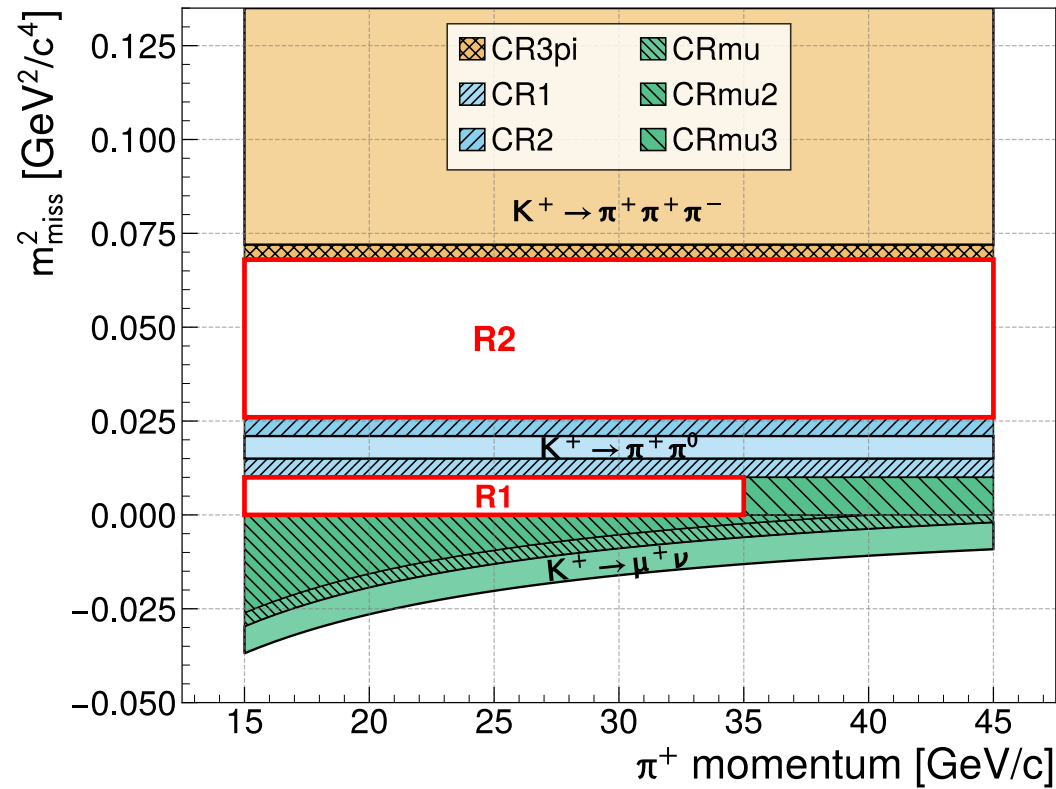
Buras et al., JHEP 11 (2015) 33

- Searching for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- Only one detectable final-state particle
 - Need to measure K^+ momentum
- Requires hermetic veto coverage to suppress background from other decays





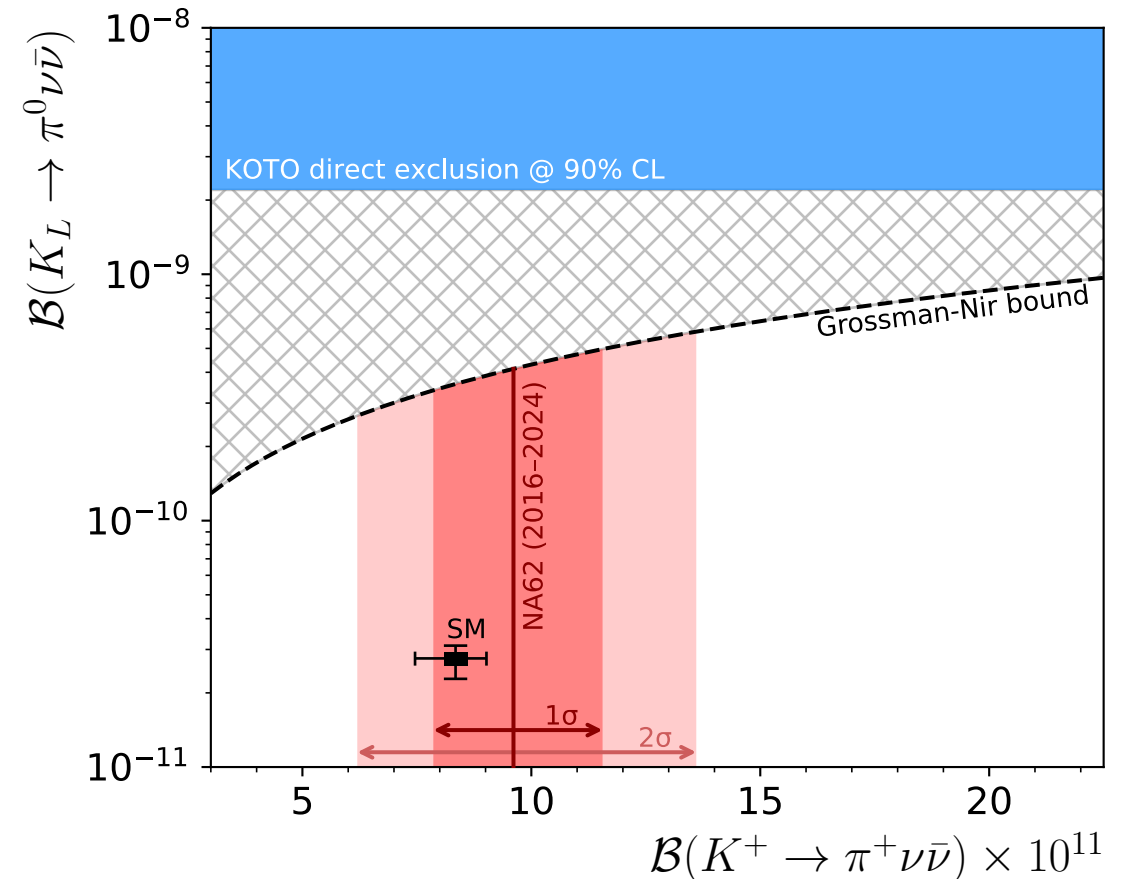
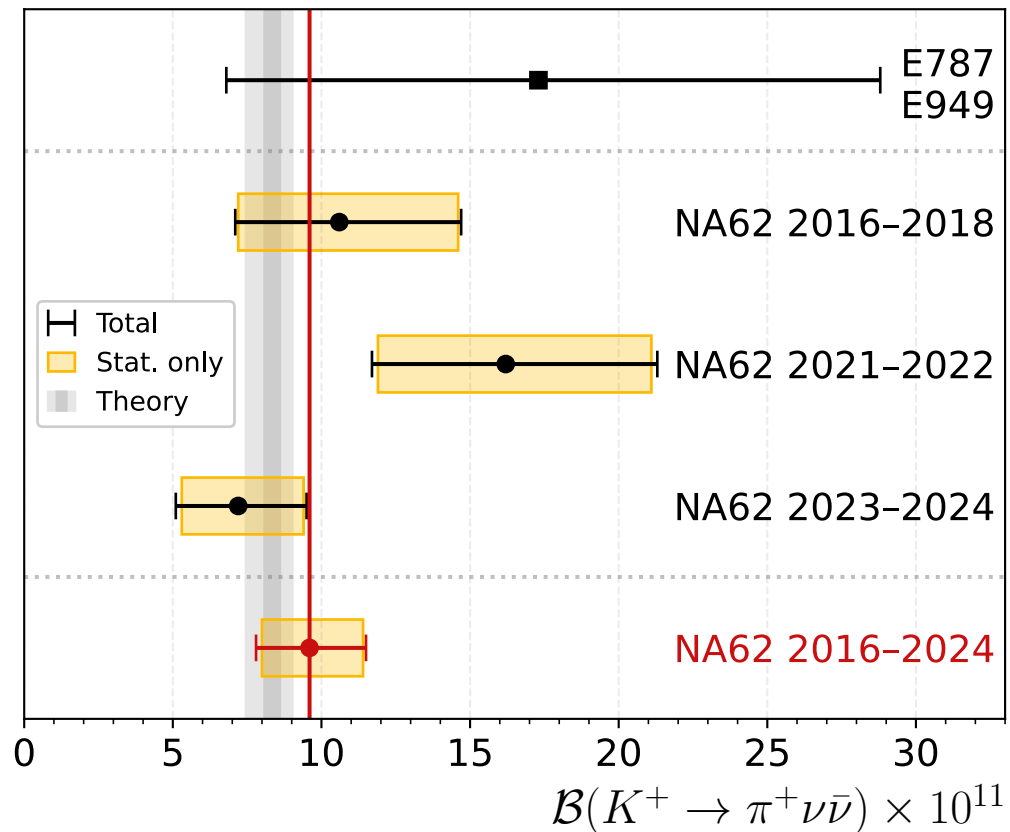
- Signal Region 1+2 (2023+24 only):
 - Expected 12 ± 3 background events
 - Expected 23 ± 1 signal events



- Signal Region 1+2 (2023+24 only):
 - Expected 12 ± 3 background events
 - Expected 23 ± 1 signal events

- Observed: 33 candidates

- 2025+26 results remain to be analysed
- So far excellent agreement with SM with 20% relative precision on branching fraction measurement

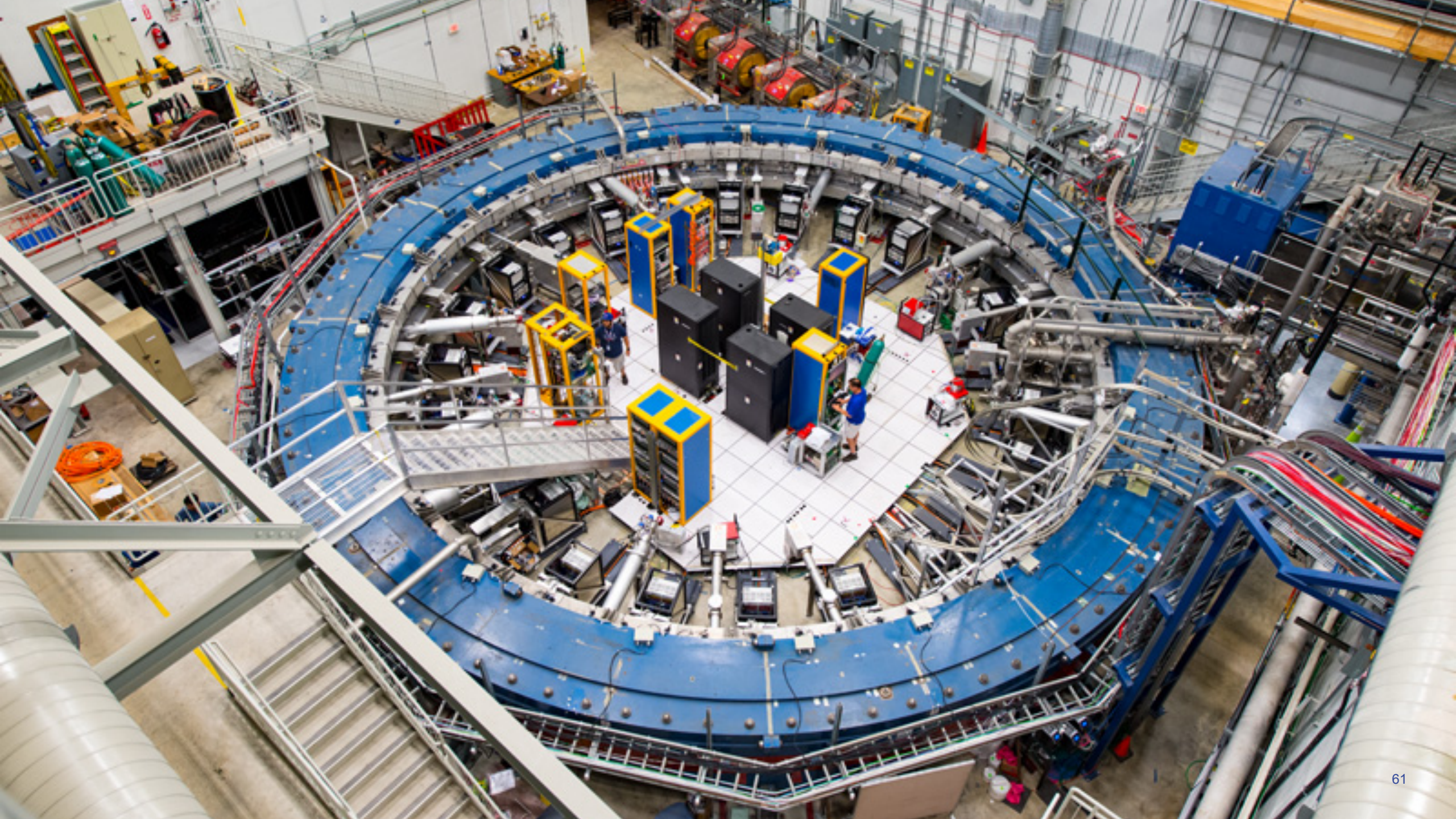




Credit: Fermilab

The muon g-2 storage ring — a story of two experiments





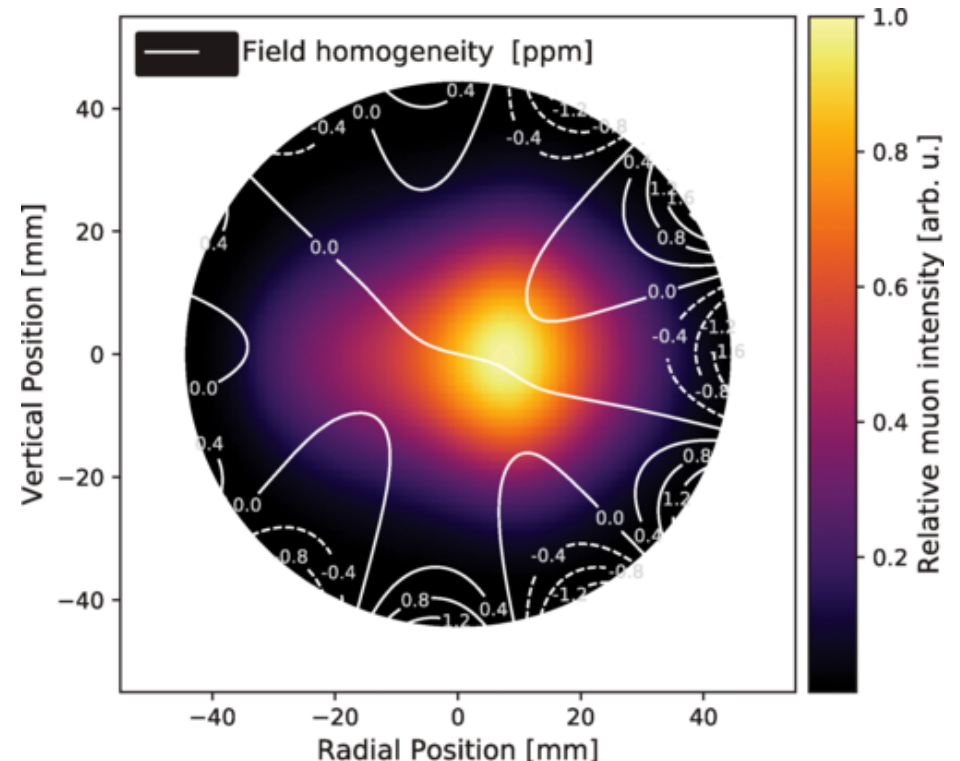
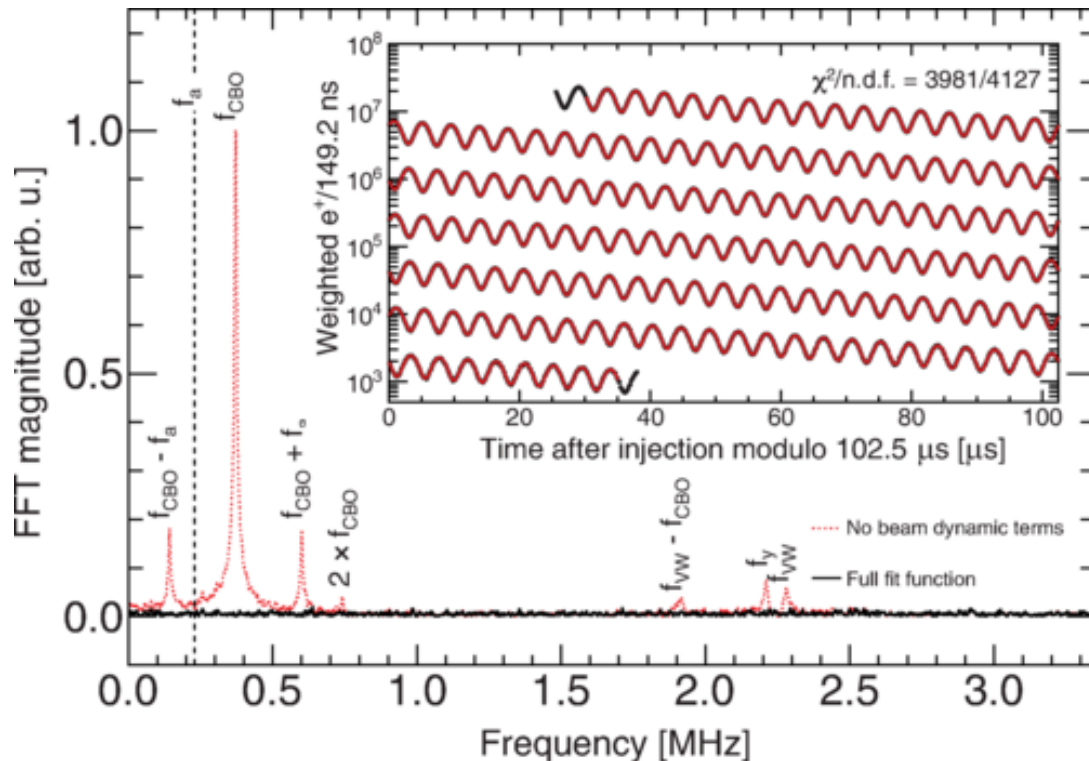
Muon anomalous magnetic moment

- $a_\mu = (g_\mu - 2) / 2$
- SM extremely well known, need $\ll$ ppm precision
- Measurement with storage ring of polarised muons, measure electrons from muon decays
- Need superb control of magnetic field and of several other oscillation frequencies

$$N(t) = N e^{-\frac{t}{\gamma \tau_\mu}} [1 - A \cos(\omega_a t + \phi)]$$

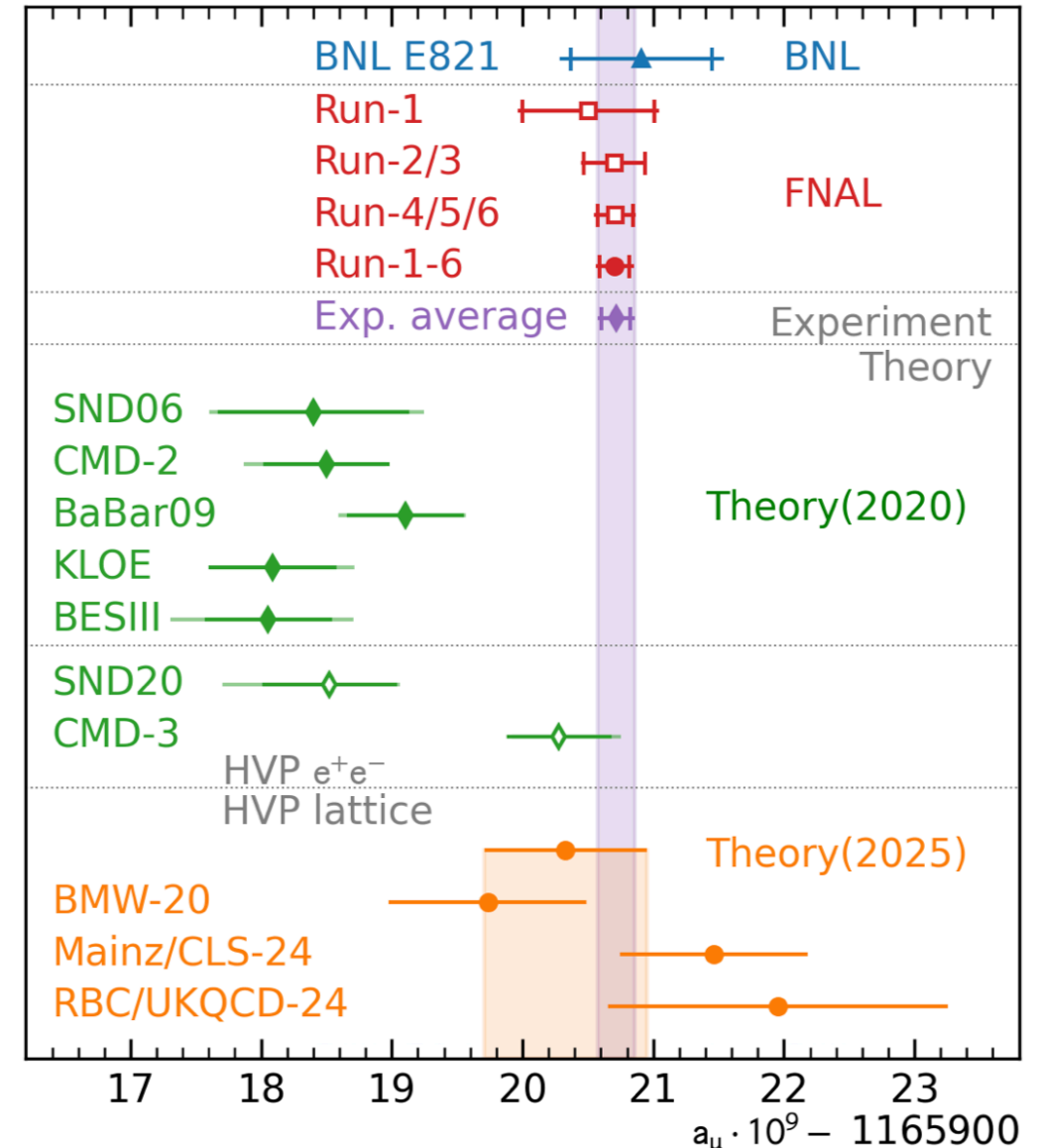
$$\omega_a = -\frac{q}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma - 1} \right) \frac{\vec{B} \times \vec{E}}{c} \right]$$

$= 0 \text{ for } \gamma = 29.1$



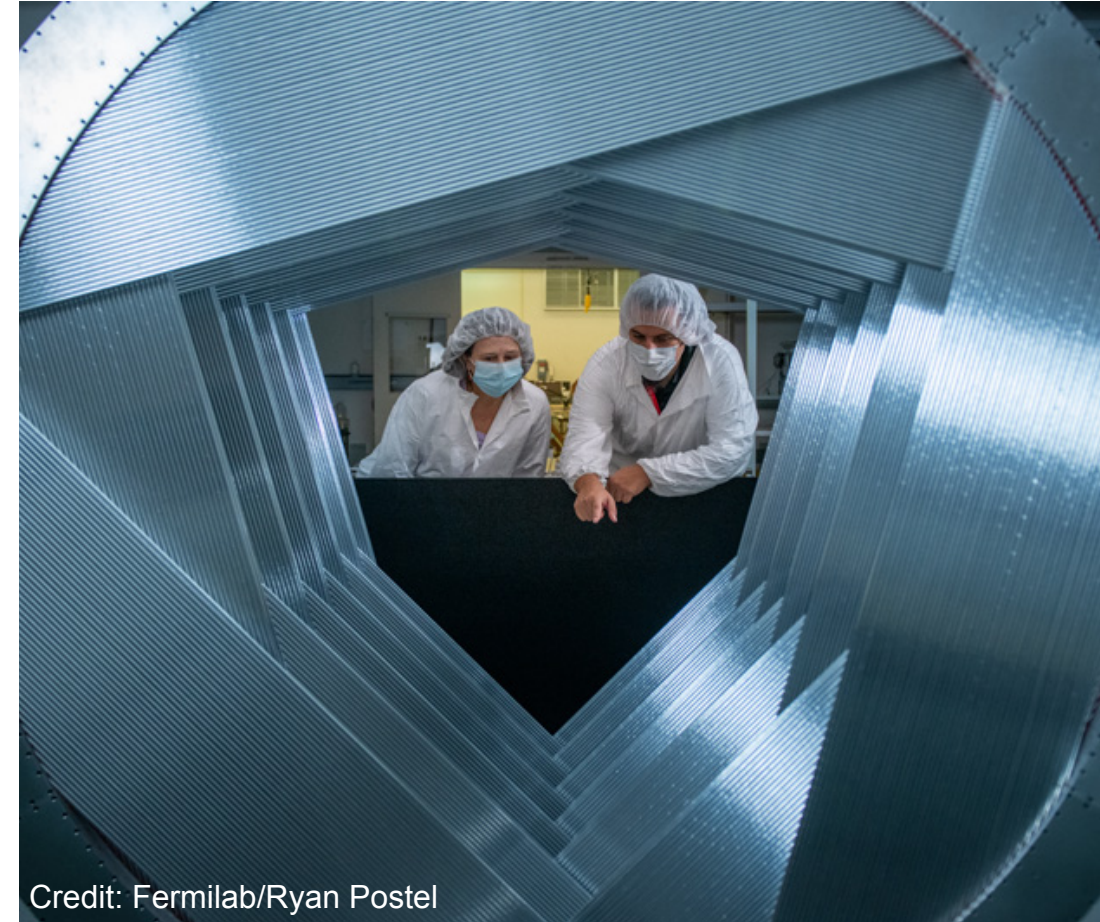
Muon anomalous magnetic moment — Results

- Full FNAL experiment data analysed
- Theoretical situation underwent significant shift
 - Largest uncertainty from hadronic vacuum polarisation contribution
 - Dispersive approach (incl. White paper) uses experimental inputs
 - Tensions between KLOE, BaBar and CMD-3
- Newer lattice results of competitive precision
 - In agreement with BNL & FNAL measurements



Other muon experiments

- J-PARC preparing g-2 measurement with μ^+ beam
 - Data taking planned from 2029/30
- MUonE experiment: precise measurement of hadronic leading order corrections to a_μ with elastic μ -e scattering
 - Test run in 2025, main data taking after LS3 (~2030)
- Several other past and ongoing experiments contributing relevant results
- Charged lepton flavour violation
 - $\mu \rightarrow e \gamma$: MEGII experiment data taking ongoing
 - $\mu \rightarrow e e e$: Mu3e experiment in assembly, commissioning began 2025
 - $\mu N \rightarrow e N$: COMET/Mu2e in construction, data over next 10 years
 - Complementary sensitivity to BSM physics



Credit: Fermilab/Ryan Postel

Recap

- Rare hadron decays
 - Many rare decay measurements transitioning to precision measurements that explore multi-dimensional observables
 - Some tensions persist in $b \rightarrow sll$ transitions (many more variants under study than the two shown here)
 - NA62 established extremely rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- Charged lepton physics under very active study
 - Muon anomalous magnetic moment experiment confirming BNL results
 - Theory picture now in agreement with experiment; experimental follow-up studies under way
 - Charged lepton flavour violation under study with complementary set of experiments

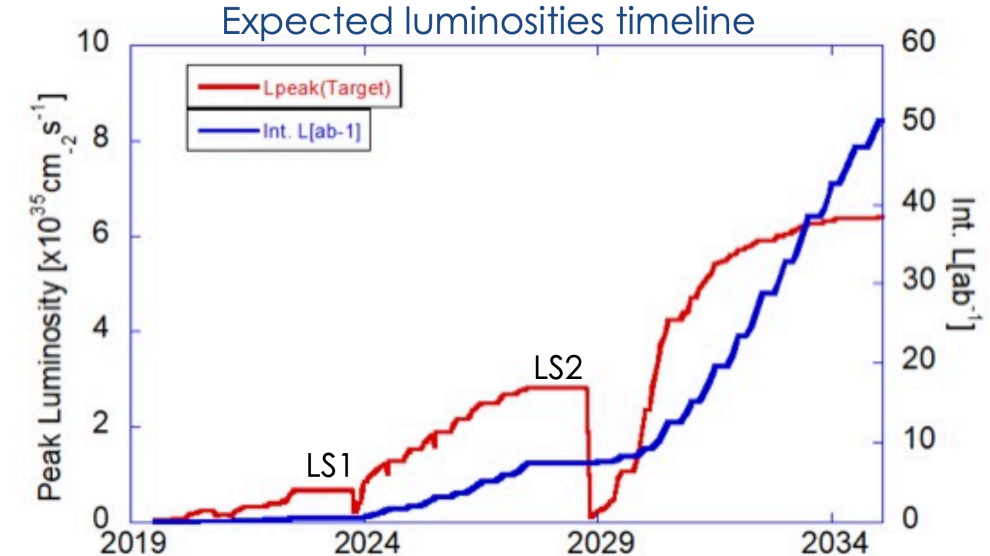
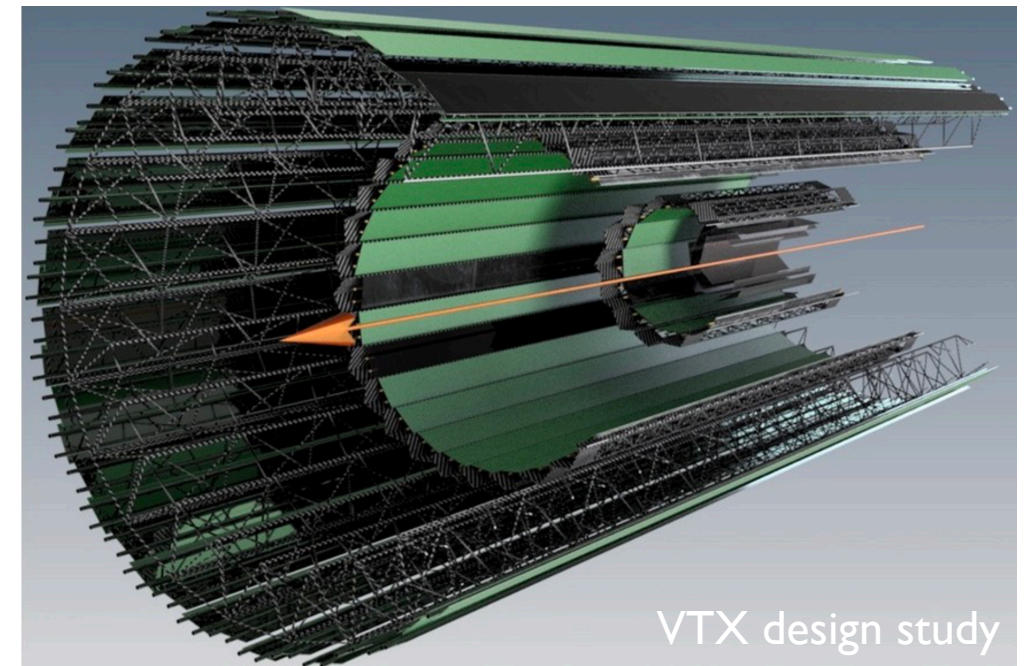
Future flavour

Current and future experiments

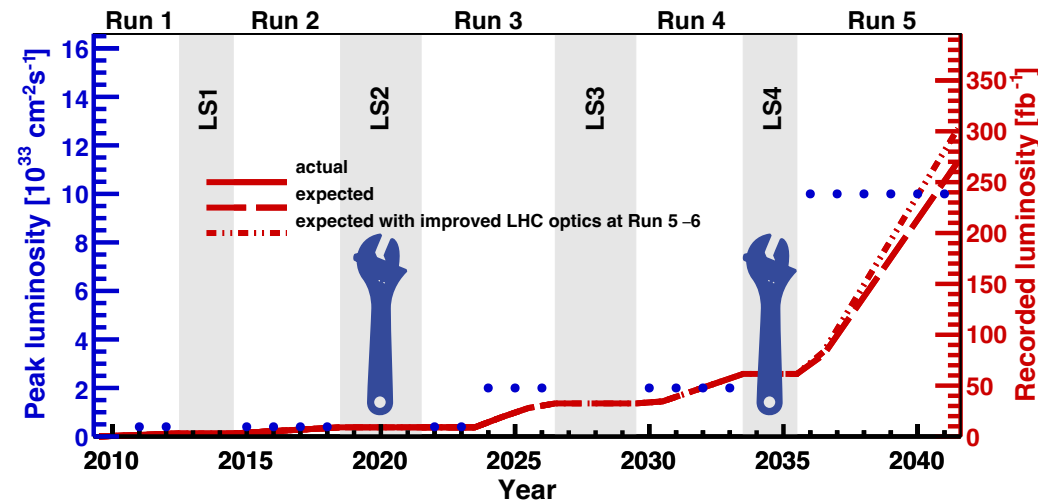


Belle II

- Data taking post LS1
 - Surpassed Belle dataset
 - Operating with improved performance
- LS2 anticipated before end of the decade
- New interaction region to achieve
$$\mathcal{L}_{\text{peak}} = 6.5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$$
- New vertex detector likely required, other detector upgrades being evaluated
- Studies started for future upgrades

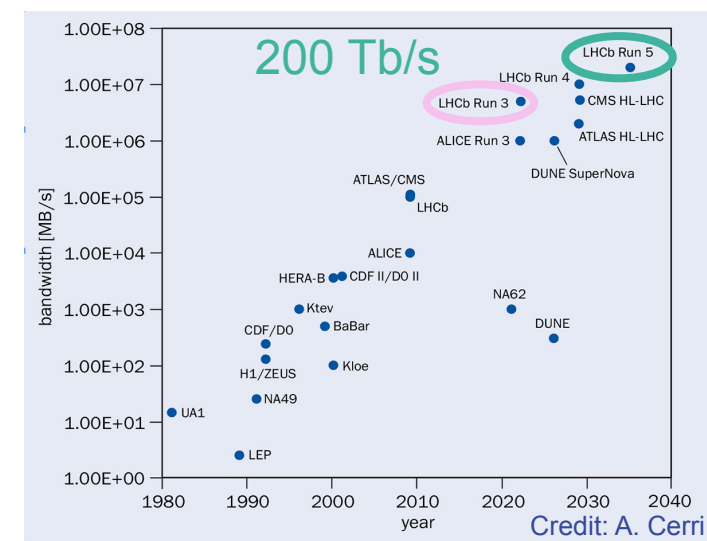


LHCb Upgrade II

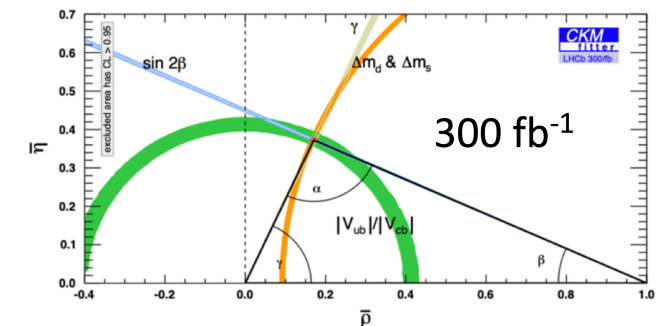
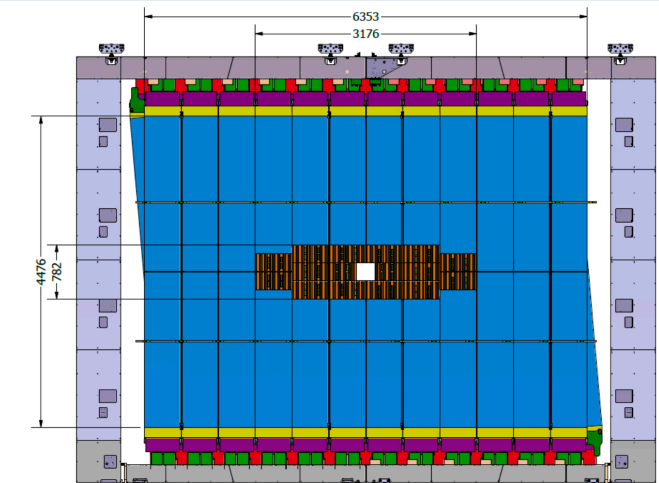


Original Upgrade I Upgrade II

- LHCb Upgrade I introduced full 40 MHz readout and more granular detector to operate at greater instantaneous luminosity with improved performance
- LHCb Upgrade II planned to introduce a further step change in instantaneous luminosity
 - Requires even better granularity paired with time resolution to resolve collisions within one bunch crossing
 - Scoping document approved by LHCC and funding agencies
 - TDRs in preparation for 2027 and installation in LS4 (2033/34)
 - Challenging detector and data processing requirements
 - Increase total luminosity to 300 fb^{-1}

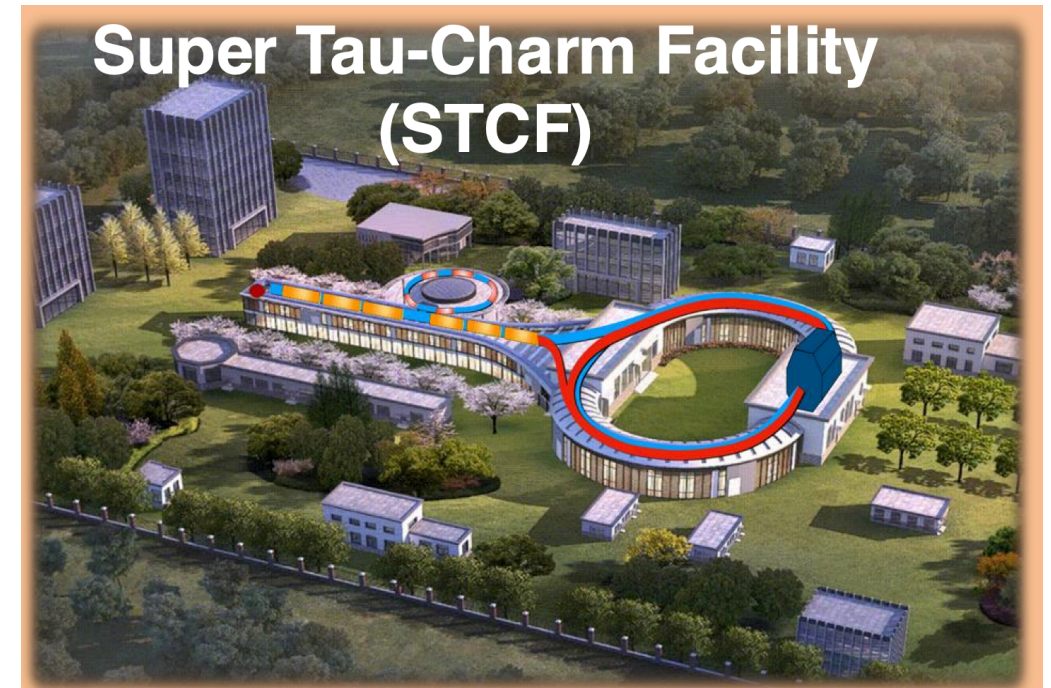


Credit: A. Cerri



Other flavour initiatives

- NA62 finished taking data at CERN but future HIKE programme not pursued by CERN
- KOTO taking data and plans for KOTO II
- ATLAS and CMS will continue to contribute including at HL-LHC
- EDM experiments not mentioned at all here but only for lack of time
- BESIII experiment taking data at higher centre-of-mass energies including accelerator upgrade
- Super Tau-charm factory plans at Hefei

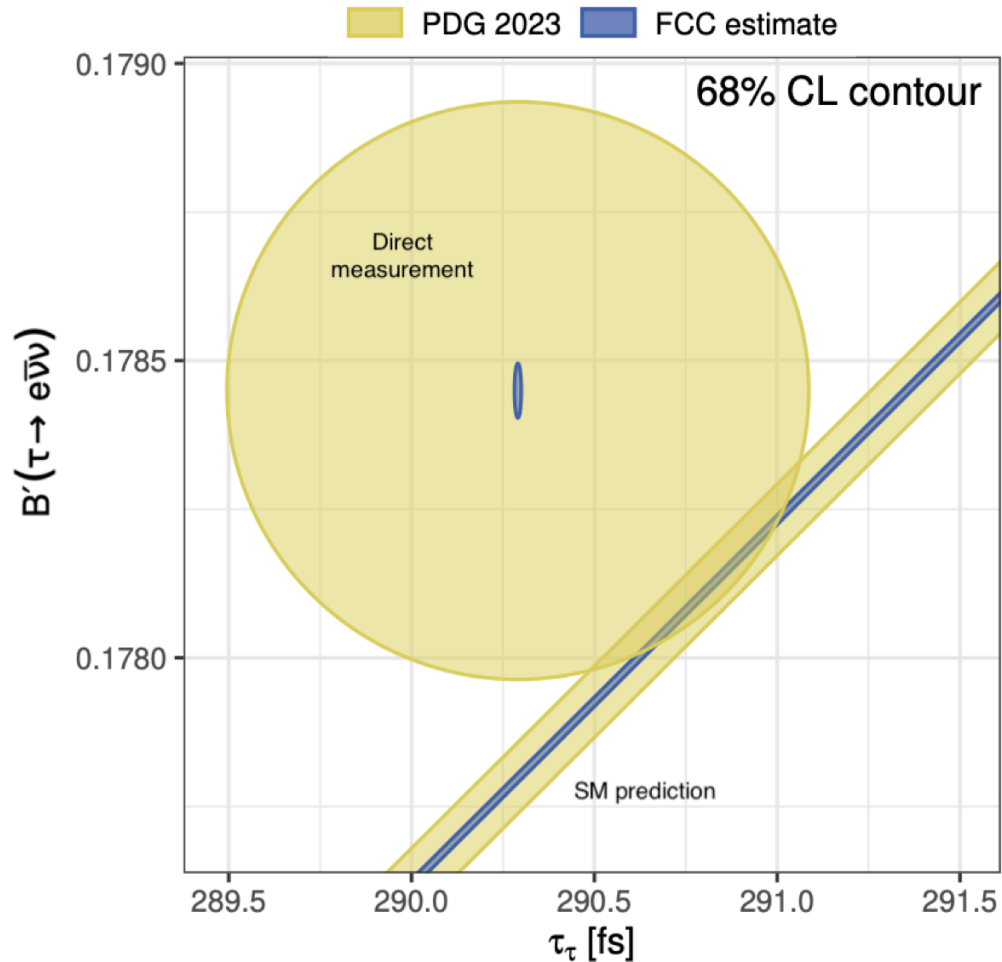


Flavour at FCC-ee

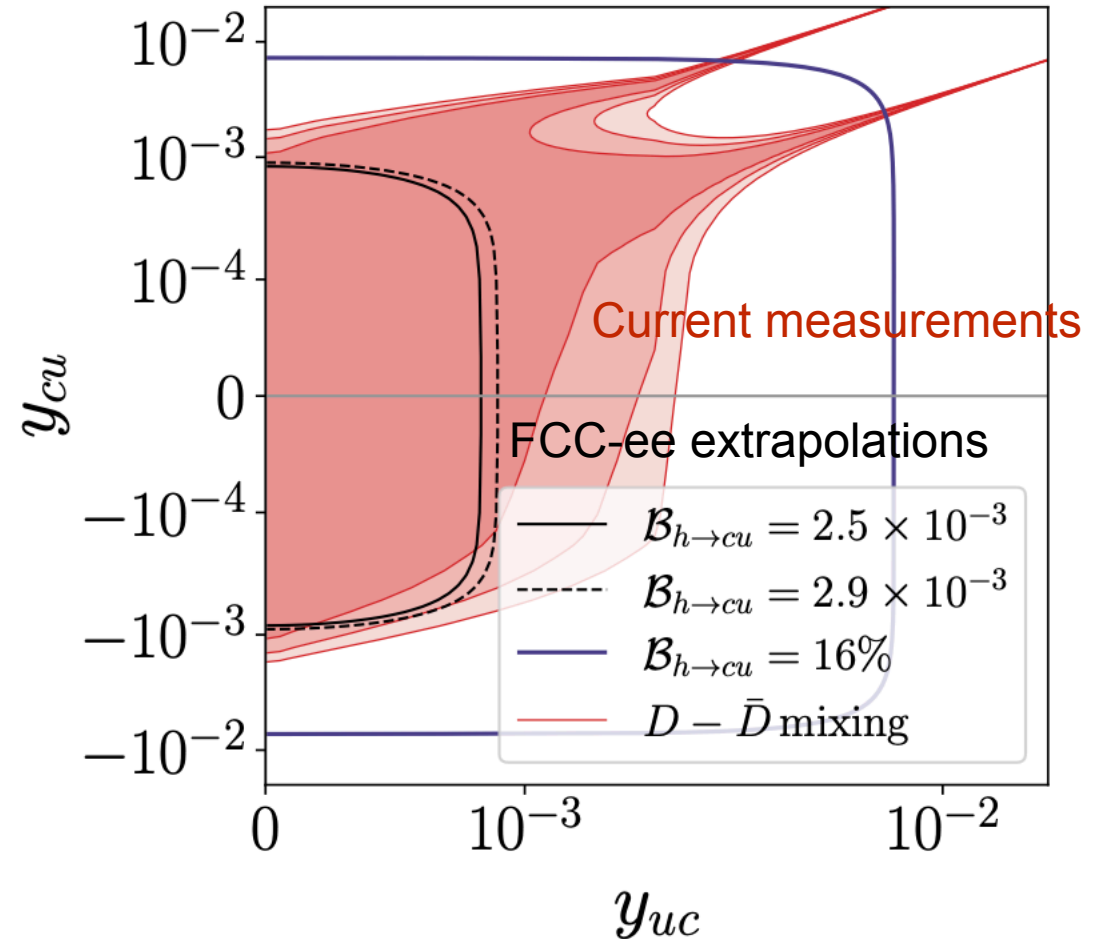
- Future e^+e^- colliders have promising flavour potential when operated at Z-boson centre-of-mass energy
 - Aim to collect up to 6×10^{12} Z decays over 5 years of running
- Z decays to quarks:
 - All hadrons accessible
 - No suppression of b compared to c as in pp collisions
 - About ten times more $b\bar{b}$ and $c\bar{c}$ pairs produced compared to Belle II
- Z decays to charged leptons:
 - Well controlled production especially of tau leptons
- Benefits
 - Kinematic constraints benefits semileptonic decays, especially to taus, and neutrals
 - Boost from Z decays further benefits reconstruction efficiency of invisibles compared to Belle II
- Limitations
 - Sample sizes of fully reconstructed b and c decays cannot compete with LHCb Upgrade II

Flavour at FCC-ee

A. Lusiani, Tau Physics Prospects at FCC-ee



J. Kamenik et al., PRD 109 (2024) L011301



Conclusions

- Flavour physics is conducted by a broad range of specialised experiments, built on a long history of important discoveries
 - With some important contributions from non-specialists
- Flavour tagging, hadron identification and vertex resolution are crucial design requirements
- CP violation now established in all neutral meson systems
- CKM tested to great accuracy (γ nearing 1°) with no obvious discrepancies
 - Some tensions in CKM element magnitudes
- Rare decays being studied in great detail with some tensions in $b \rightarrow sll$ processes
- Muon g-2 tested to fantastic precision with theoretical questions
- Several exciting prospects for charged lepton flavour violation in coming decade
- Major upgrade planned with LHCb Upgrade II with other experiments specialising in kaons (KOTO II), charm (STCF) and beauty (Belle II++) being considered for coming decade and further opportunities at FCC-ee
- Lots of potential for exciting flavour discoveries

