Flavour physics with new eyes

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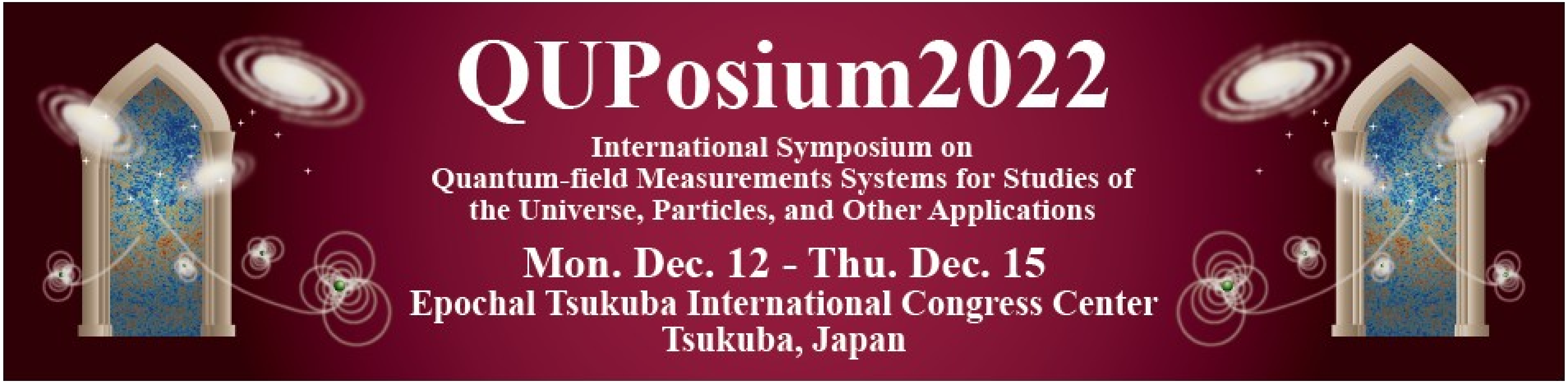
University of Warwick

13 December 2022



What is flavour physics?

WIKIPEDIA
The Free Encyclopedia

Flavour (particle physics)

From Wikipedia, the free encyclopedia

In particle physics, **flavour** or **flavor** is a quantum number of elementary particles. In quantum chromodynamics, flavour is a global symmetry. In the electroweak theory, on the other hand, this symmetry is broken, and flavour-changing processes exist, such as quark decay or neutrino oscillations.

Flavour in particle physics

Flavour quantum numbers:

- Baryon number: B
- Lepton number: L
- Strangeness: S
- Charm: C
- Bottomness: B'
- Topness: T
- Isospin: **I** or I_3
- Weak isospin: **T** or T_3
- Electric charge: Q
- X-charge: X

Combinations:

- Hypercharge: Y
  - $Y = (B + S + C + B' + T)$
  - $Y = 2\,(Q - I_3)$
- Weak hypercharge: Y_W
  - $Y_W = 2\,(Q - T_3)$
  - $X + 2Y_W = 5\,(B - L)$

Flavour mixing

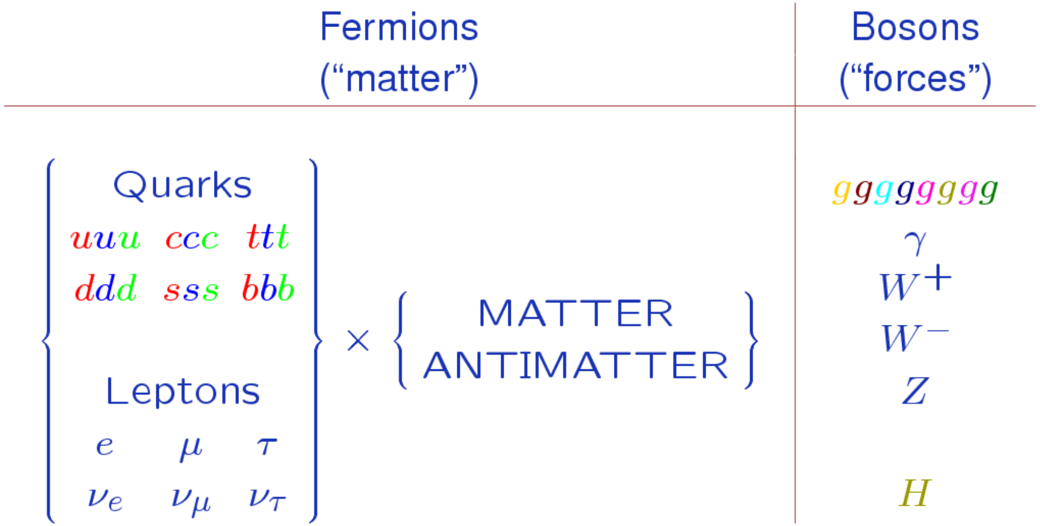
- CKM matrix
- PMNS matrix
- Flavour complementarity

"The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks."

RMP 81 (2009) 1887

Mysteries of flavour physics

- Why so many fermions?
- What explains
  - the mixing patterns?
  - the matter-antimatter asymmetries (CP violation)?
- Are there connections between quarks and leptons?



Will focus in this talk mainly on studies of the b quark …
which means studies of b hadrons (important role of QCD)

The CKM matrix

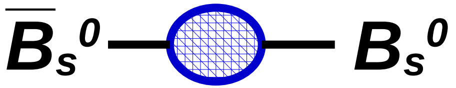
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

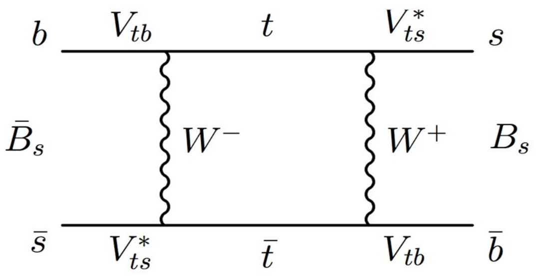
- A 3x3 unitary matrix
  - Encodes relative misalignment of mass and flavour bases that arises in the Standard Model following electroweak symmetry breaking (Higgs mechanism)
- Described by 4 real parameters – allows CP violation (KM: Prog.Theor.Phys. 49 (1973) 652)
- Highly predictive
  - Describes phenomena at energies from nuclear β decay to top quark decays

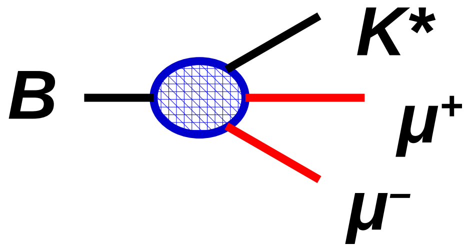
Will focus in this talk mainly on studies of the b quark …
which means studies of b hadrons (important role of QCD)

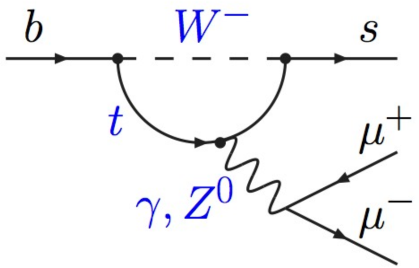
Seeing and inferring

- Weak decays of b hadrons involve virtual mediators
- We only “see” the final state particles
  - but can “infer” information about the mediators
  - advantage: not limited by energy of collisions
  - loop processes particularly interesting due to SM structure
- Formally, use effective field theory









Seeing and inferring

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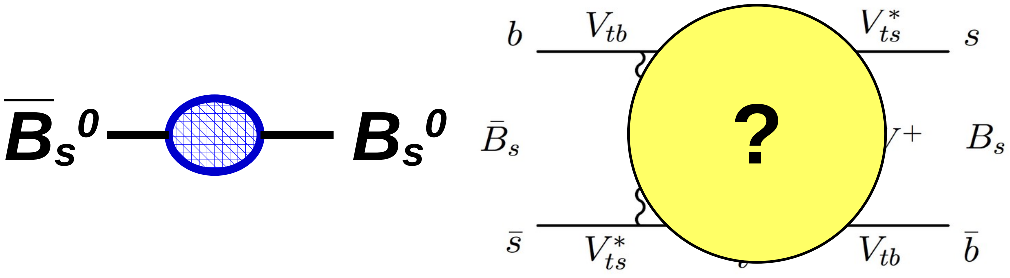
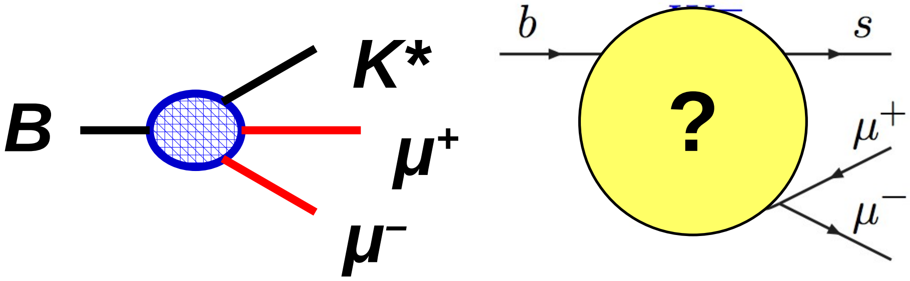
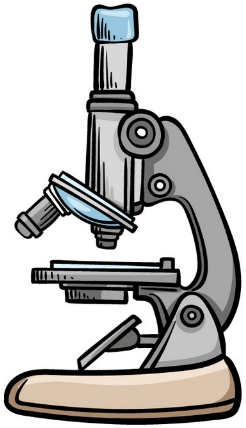
? could be at O(10 TeV)





The flavour ~~micro~~zeptoscope

- Flavour physics provides a wide range of Standard Model tests
  - Genuine potential for discovery of physics beyond
- SM structure is distinctive, and need not be replicated BSM
  - Absence of tree-level flavour-changing neutral currents
  - V-A structure of the charged current
  - Universality of couplings to different leptons
- Quark mixing (CKM matrix) described by only 4 parameters
  - Highly overconstrained → allows powerful consistency tests
- Sensitivity limited by precision
  - For theoretically clean channels, this means data sample size



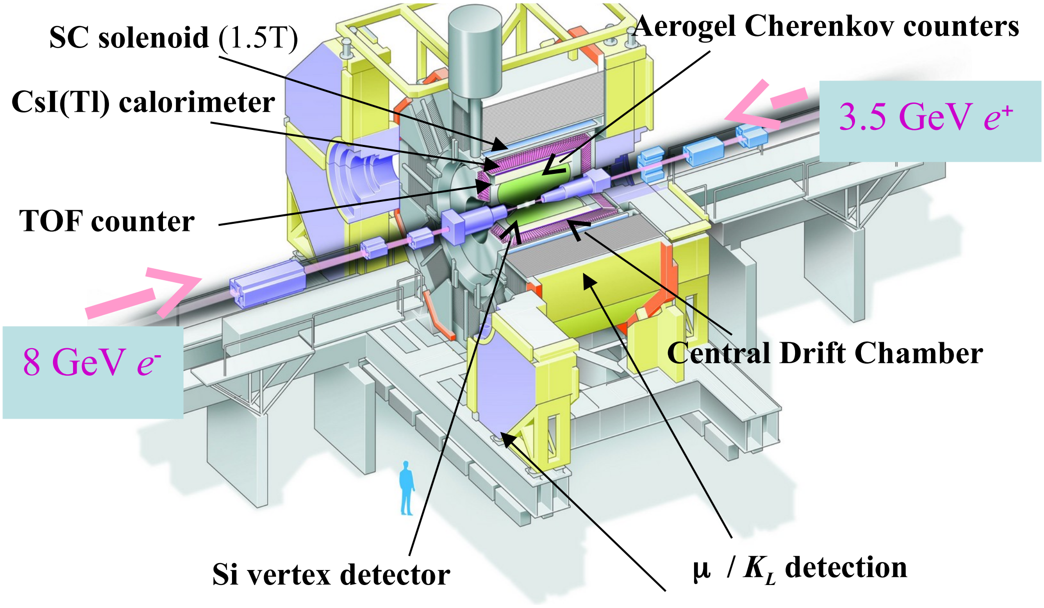
iHeartCraftyThings.com

Experiments

Results to date dominated by experiments at e^+e^- "B factories" (BaBar & Belle; ~2001-2010) and hadron colliders (LHCb; ~2011-20)

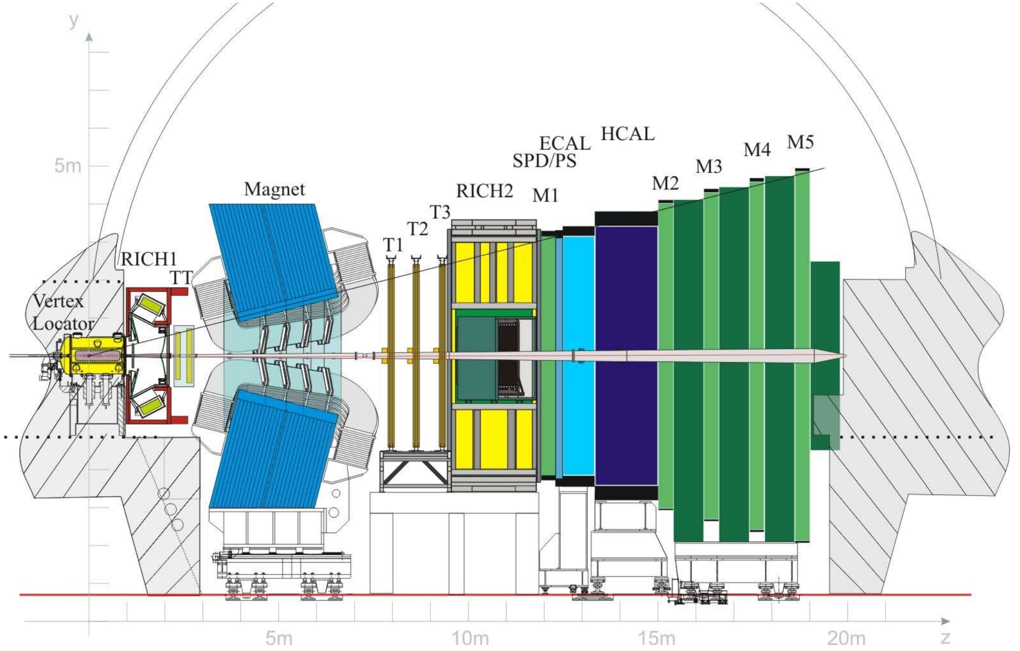
Belle at KEKB

(asymmetric e^+e^- collisions at Υ(4S))



LHCb at the LHC

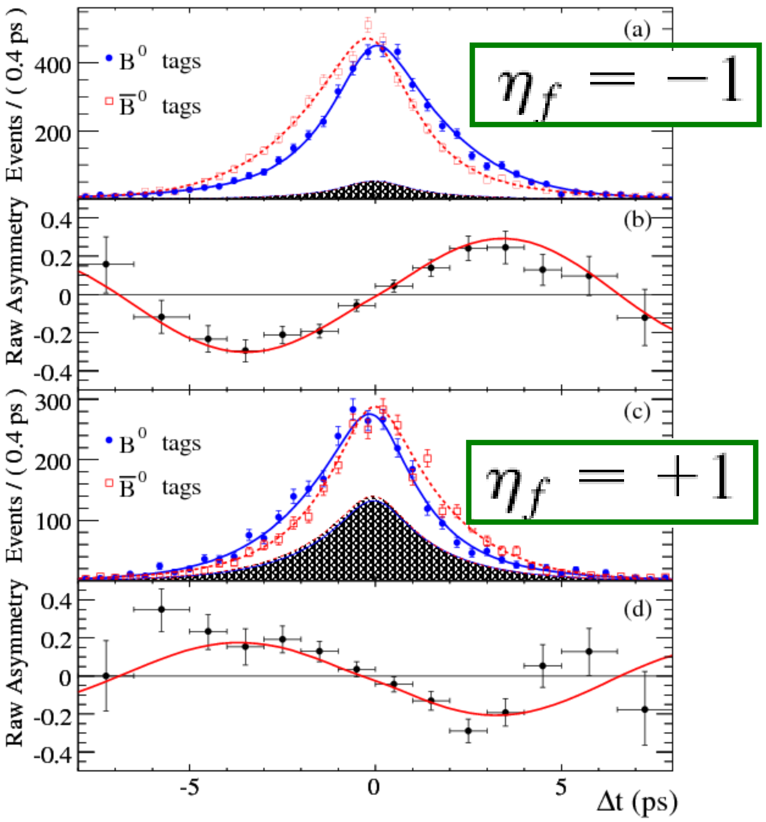
(high energy pp collisions)



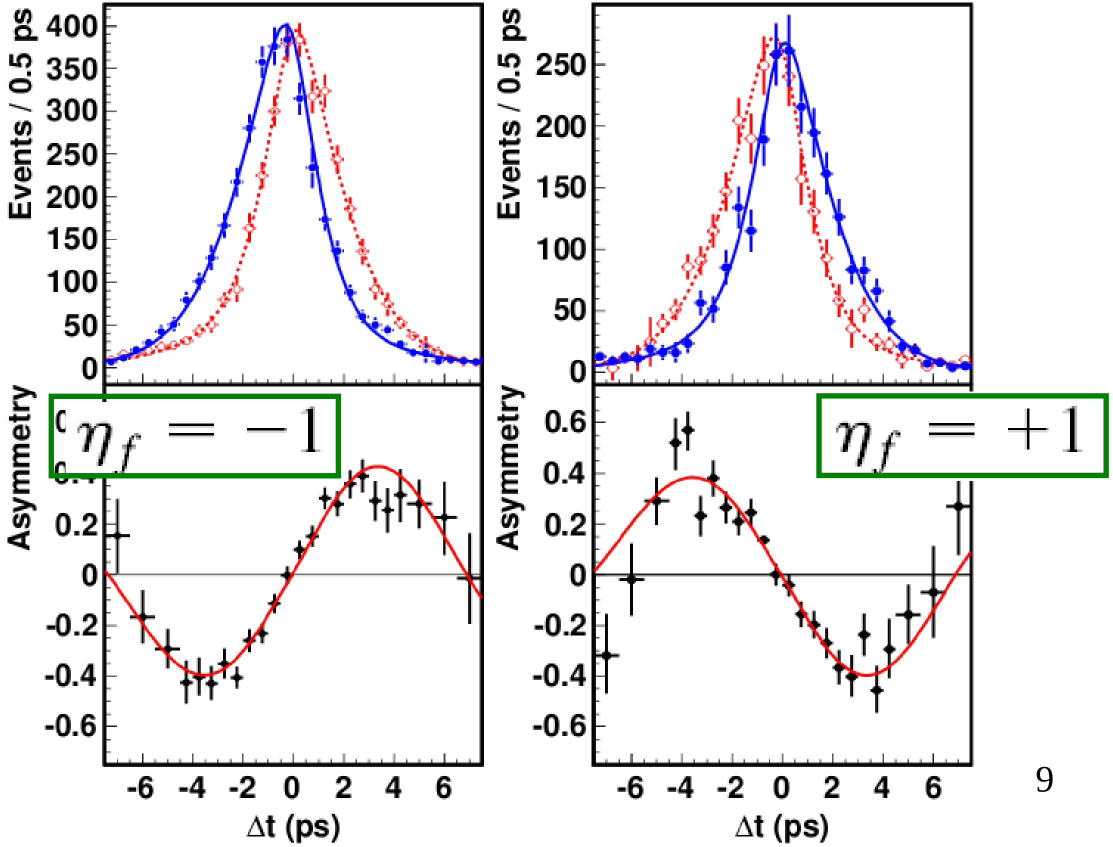
The CKM description of CP violation

Decay-time dependent asymmetry in $B^0 \to J/\psi K^0$

BABAR PRD 79 (2009) 072009



BELLE PRL 108 (2012) 171802



The CKM description of CP violation

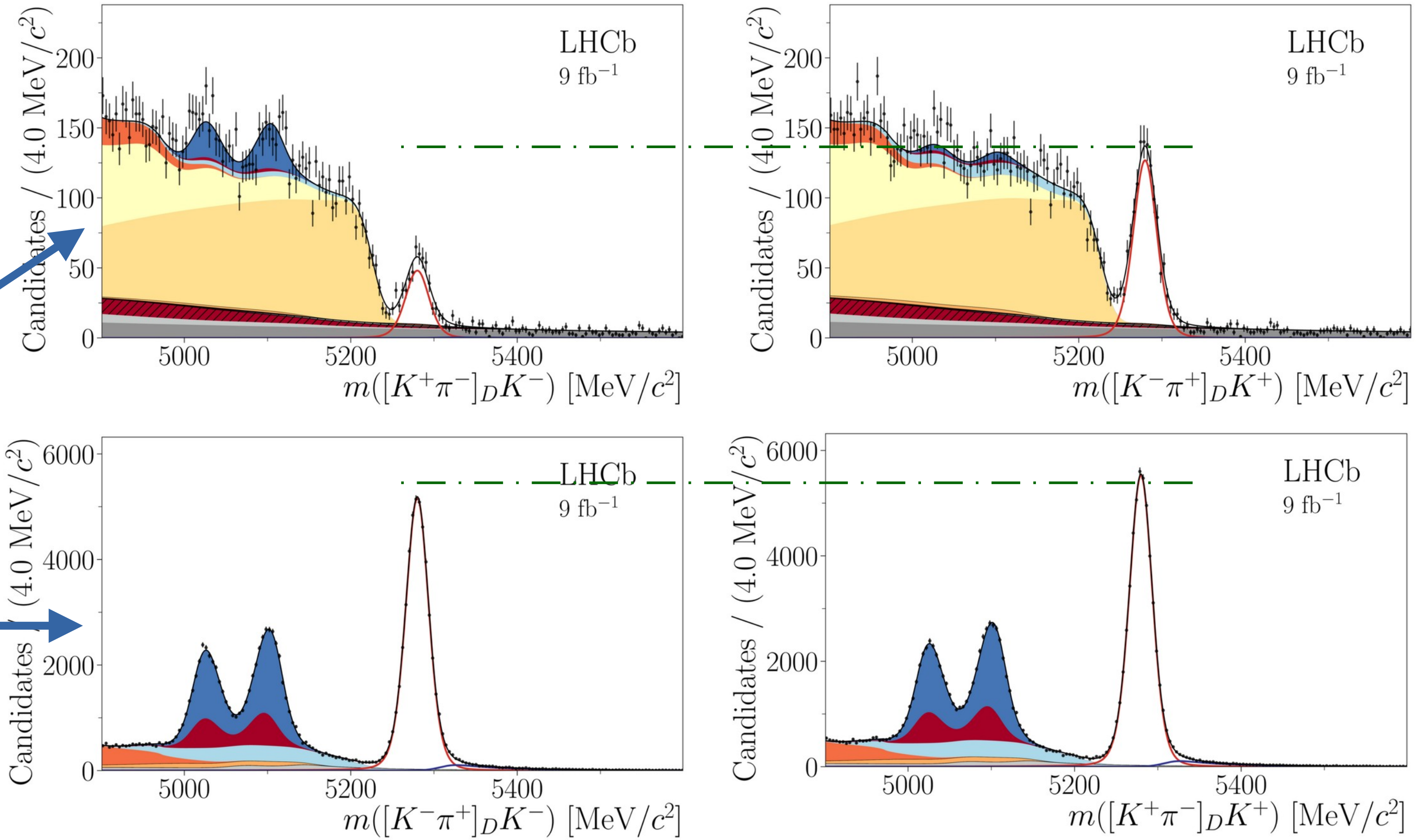
Partial rate asymmetries in $B^{+/-} \to DK^{+/-}$

JHEP 04 (2021) 081

Neutral D meson different admixture of D^0 and $\overline{D}^0$ depending on final state

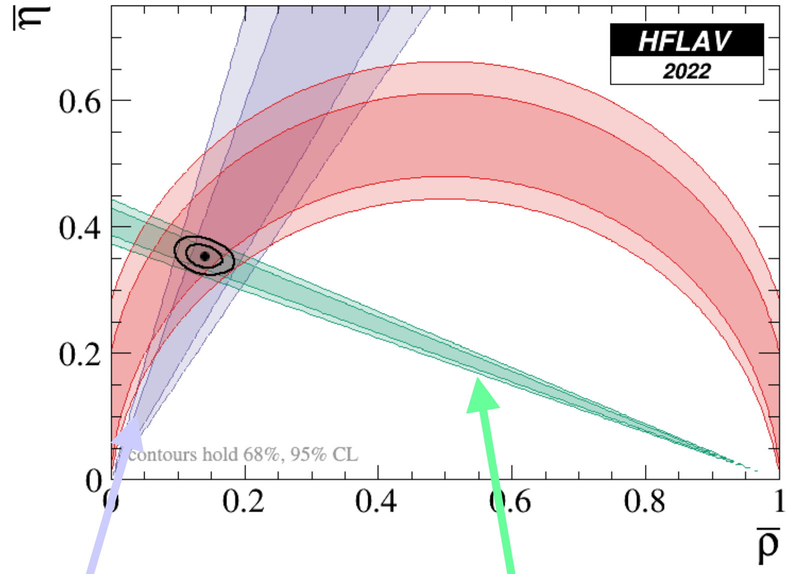
Suppressed mode: enhanced CP violation as two amplitudes of comparable magnitude

Favoured mode: little CP violation (but important to control systematics)

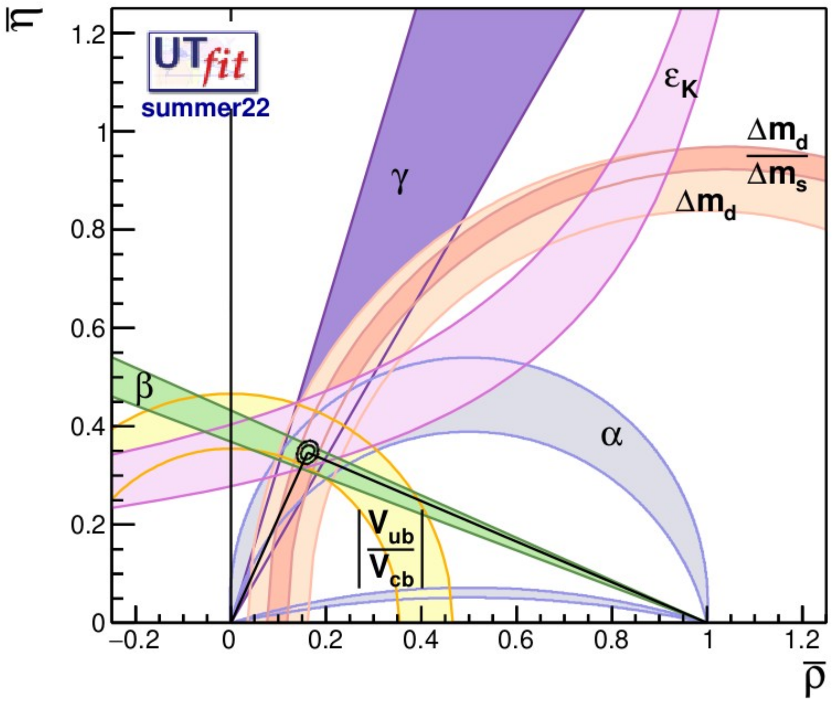


The CKM description of CP violation

arXiv:2206.07501



arXiv:2212.03894



Decay-time dependent asymmetry in $B^0 \rightarrow J/\psi K^0$

Partial rate asymmetries in $B^{+/-} \rightarrow DK^{+/-}$

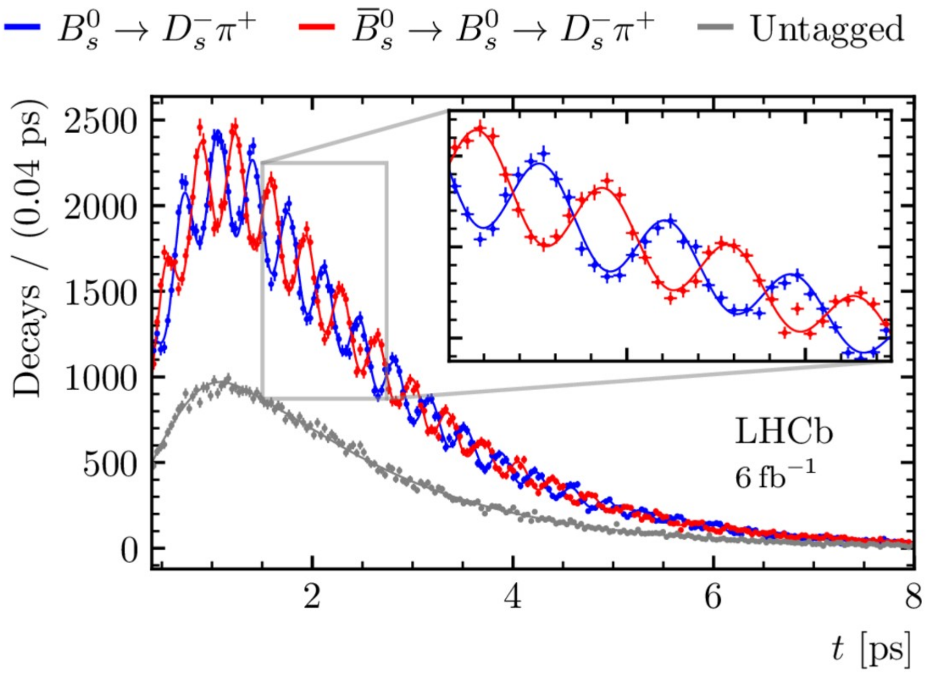
All constraints from different measurements overlap!

Digression: B^0 and B_s^0 mixing rates

Nature Phys. 18 (2022) 1

To measure mixing rate, need to
- Measure flavour ($B_{(s)}^0$ or $\overline{B}_{(s)}^0$) at production
  - "flavour tagging": exploit properties of other particles produced in the same collision
- Measure flavour at decay
  - use flavour-specific decays like $B_s^0 \to D_s^-\pi^+$ or $D_s^-\mu^+\nu$
- Measure time between production and decay
  - $\Delta z = \beta\gamma c\Delta t$

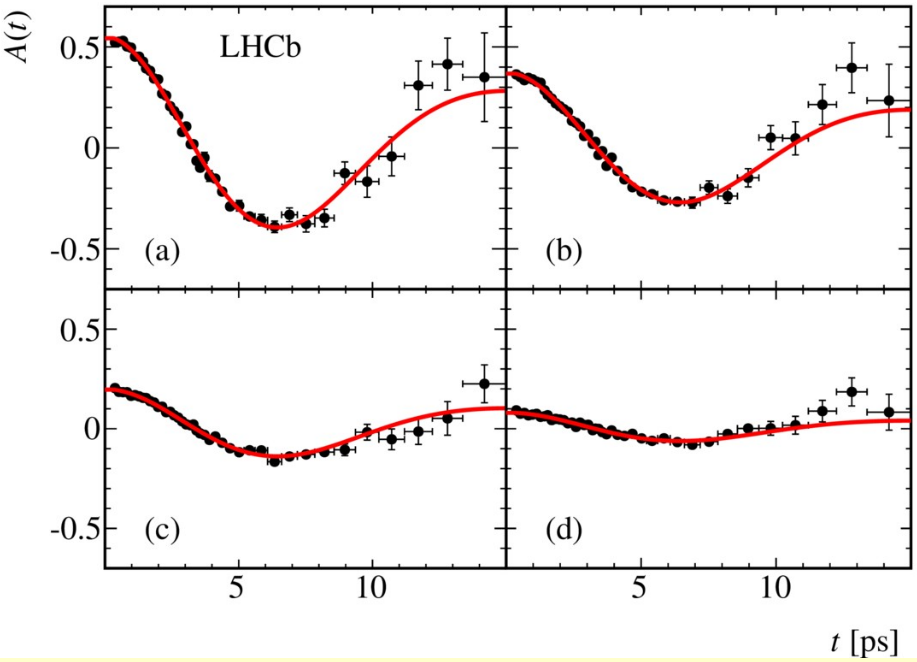
Lorentz boost factors, not CKM angles



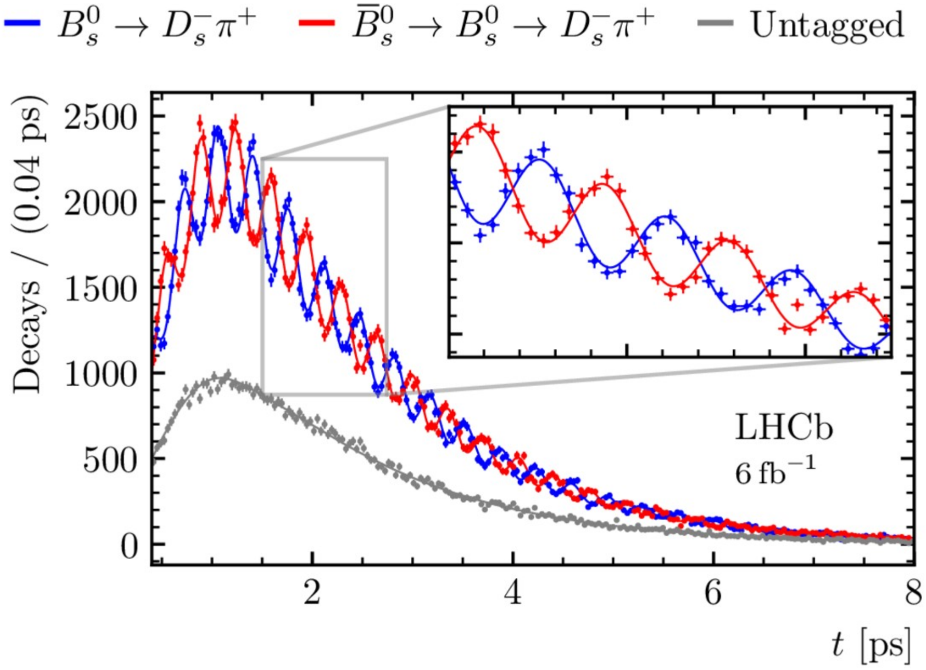
$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ \text{ps}^{-1}$

Digression: B^0 and B_s^0 mixing rates

Eur. Phys. J. C76 (2016) 412



Nature Phys. 18 (2022) 1



$\Delta m_d = 0.5050 \pm 0.0021 \pm 0.0010\ \text{ps}^{-1}$

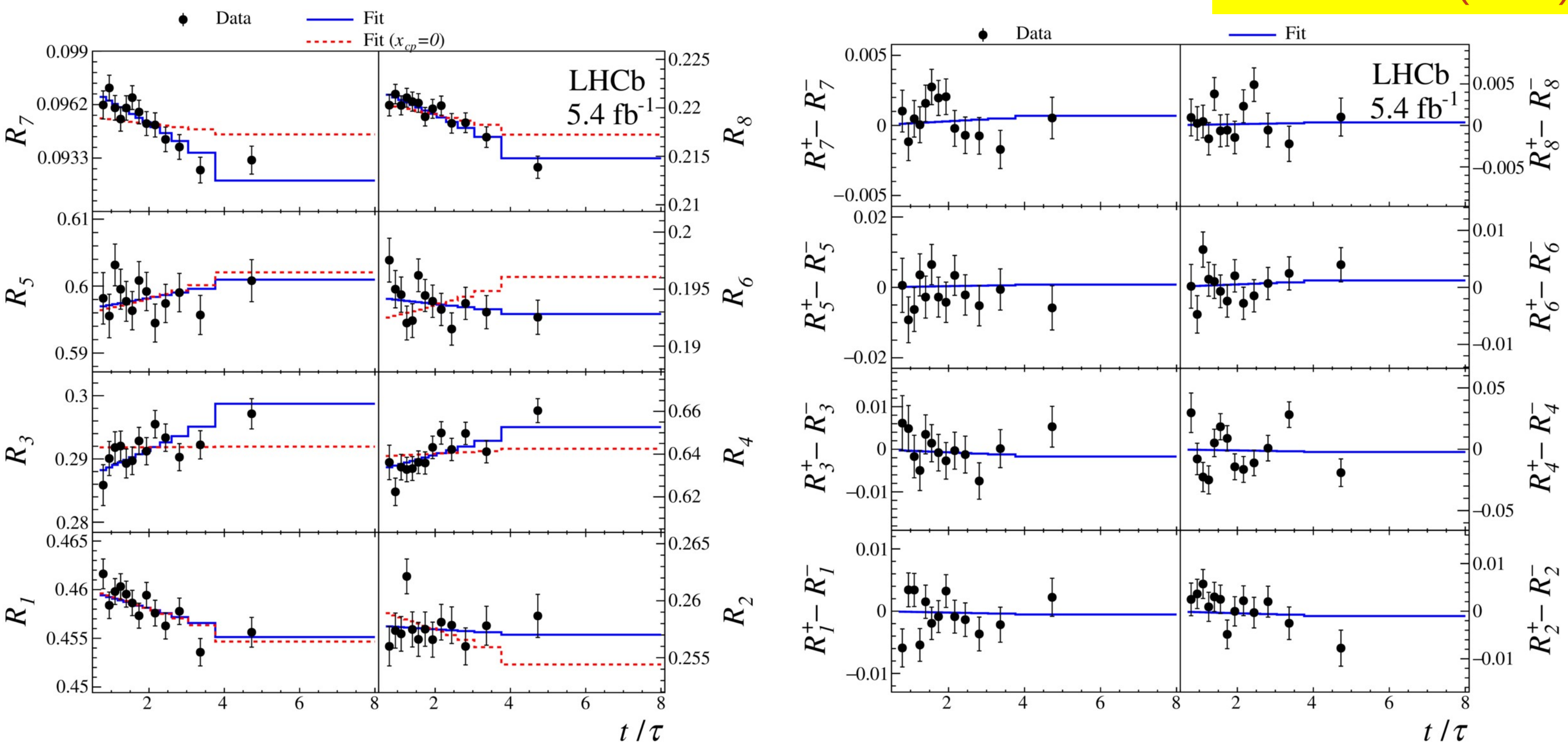
$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ \text{ps}^{-1}$

CP violation in charm oscillations

A null test of the SM

Charm oscillations very slow, so only see $\Delta m_D t$ dependence instead of $\sin(\Delta m_D t)$

PRL 127 (2021) 111801



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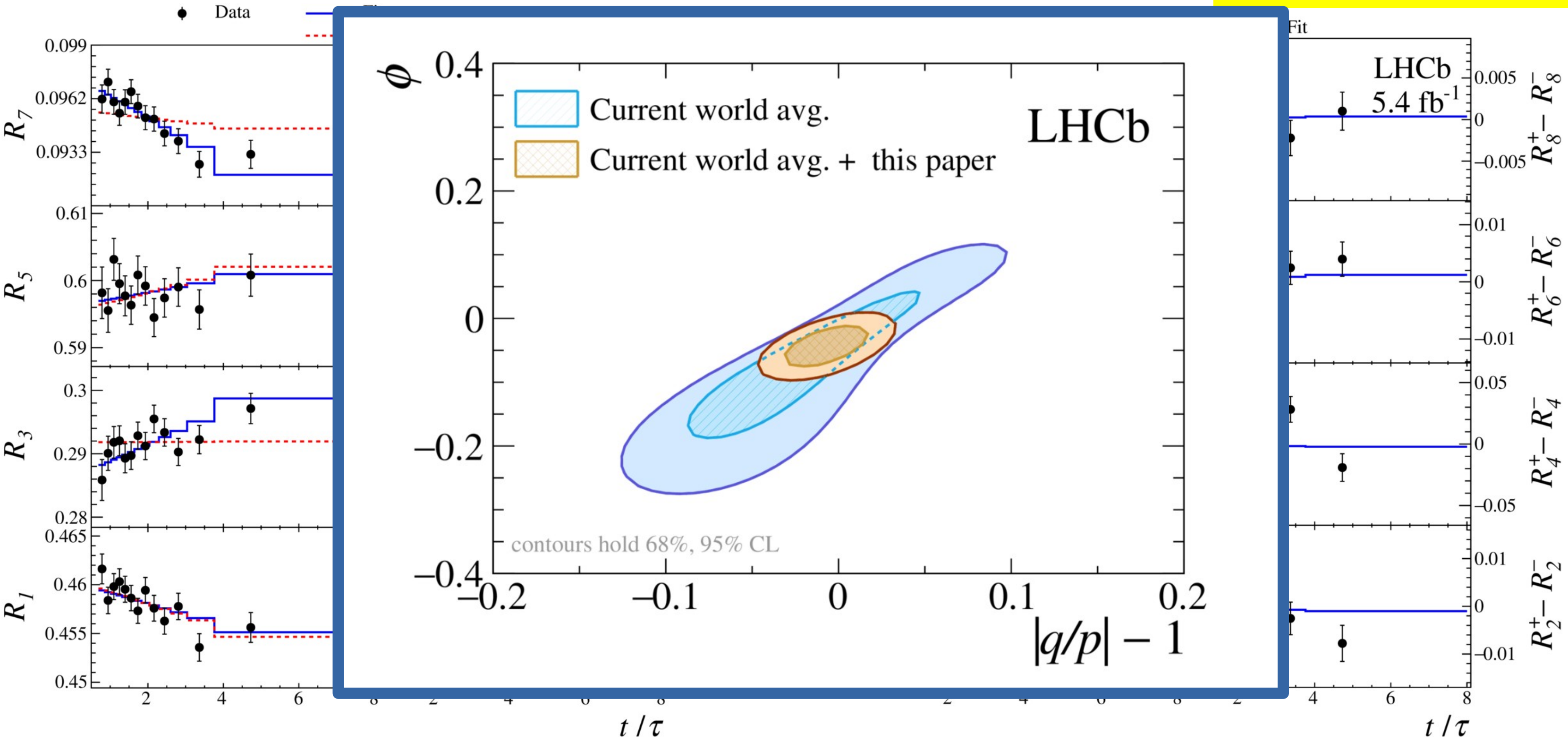
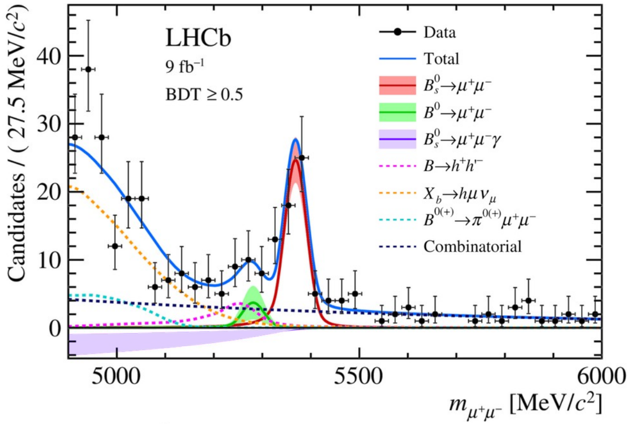
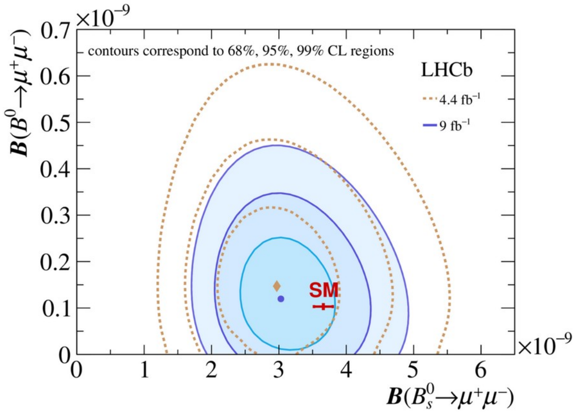


Testing the SM with rare B decays

The highly suppressed $B_{(s)}^0 \rightarrow \mu^+\mu^-$

PRL 128 (2022) 041801





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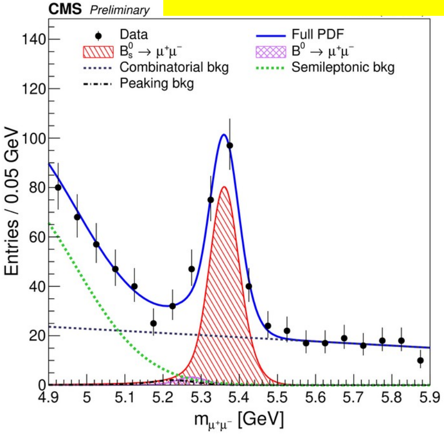
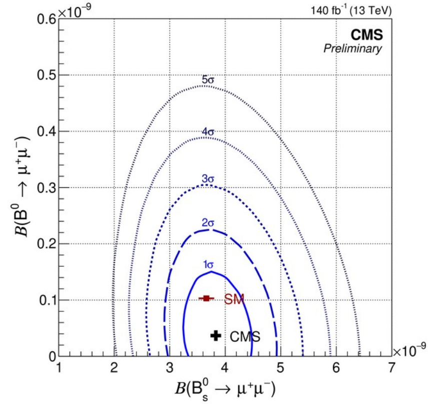
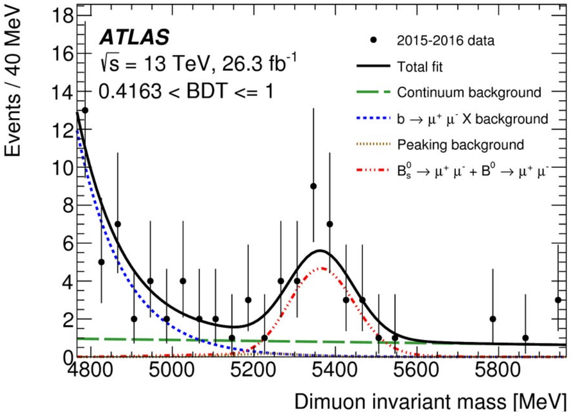
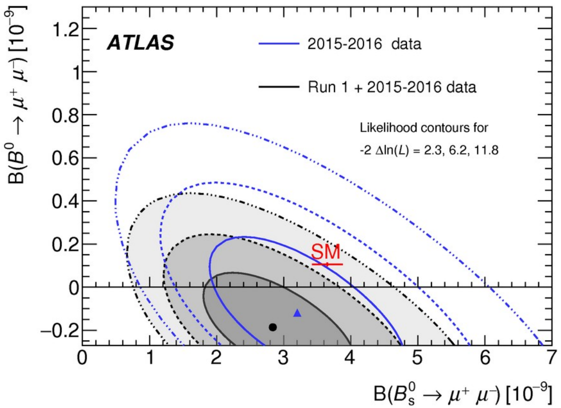




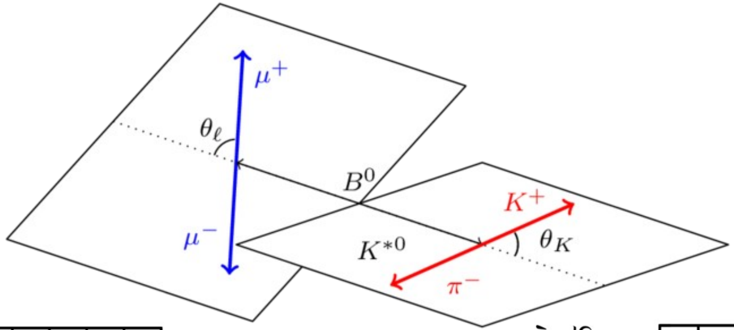
JHEP 04 (2019) 098



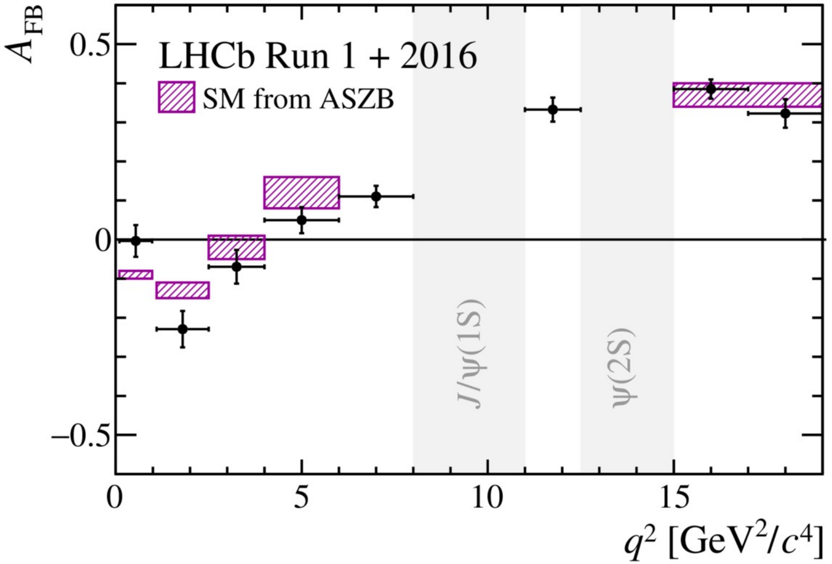


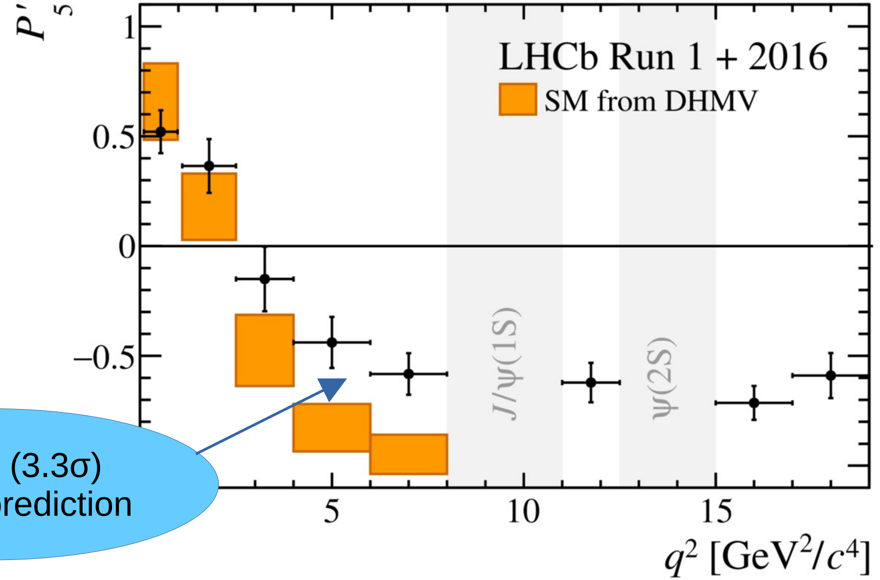
Testing the SM with rare B decays

Angular distributions of $B^0 \to K^{*0}\mu^+\mu^-$



PRL 125 (2020) 011802



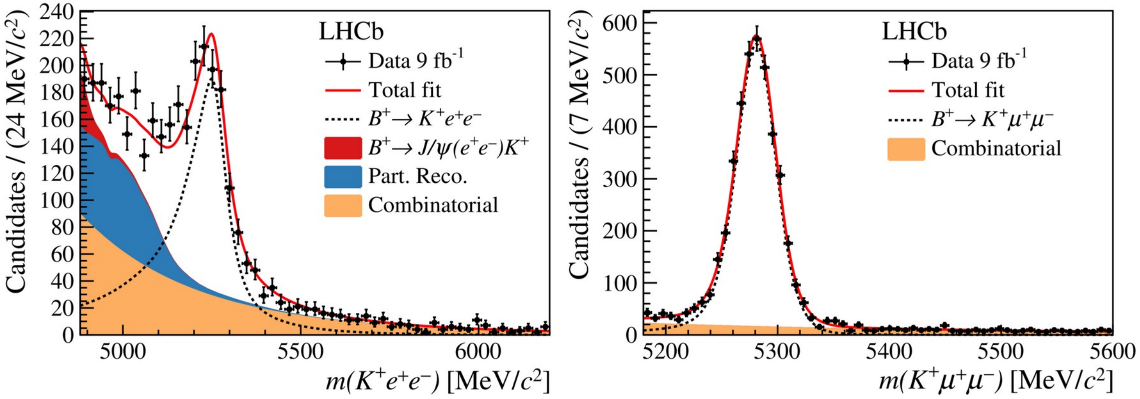


Tension (3.3σ)
with SM prediction

Testing the SM with rare B decays

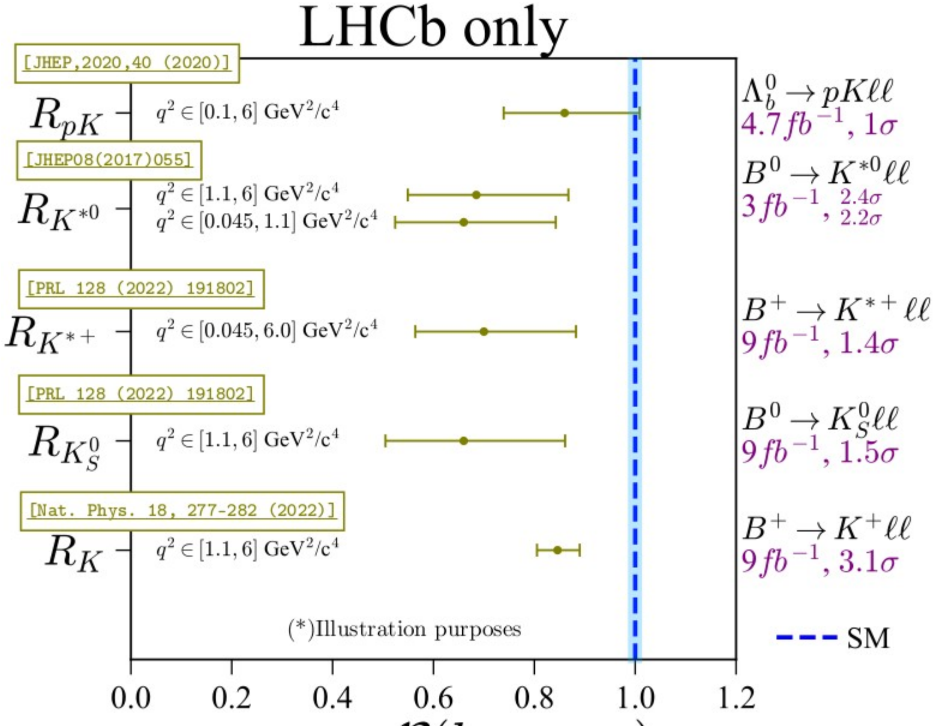
Lepton universality in $B \to K^{(*)} l^+ l^-$ decays

Nature Phys. 18 (2022) 277



$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

Tension (3.1σ) with SM prediction



$$R_X = \frac{\mathcal{B}(b \to s\mu\mu)}{\mathcal{B}(b \to see)}$$

(*) Measurements from Belle not shown (larger statistical uncertainties)

New results coming soon!

“Do not look sad. We shall meet soon again."

C.S. Lewis,
The Voyage of the Dawn Treader

Testing the SM with rare K decays

The holy grail of kaon physics: $K \to \pi \nu \bar{\nu}$

Highest CKM suppression of the $s \to d$ coupling:

$$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$$

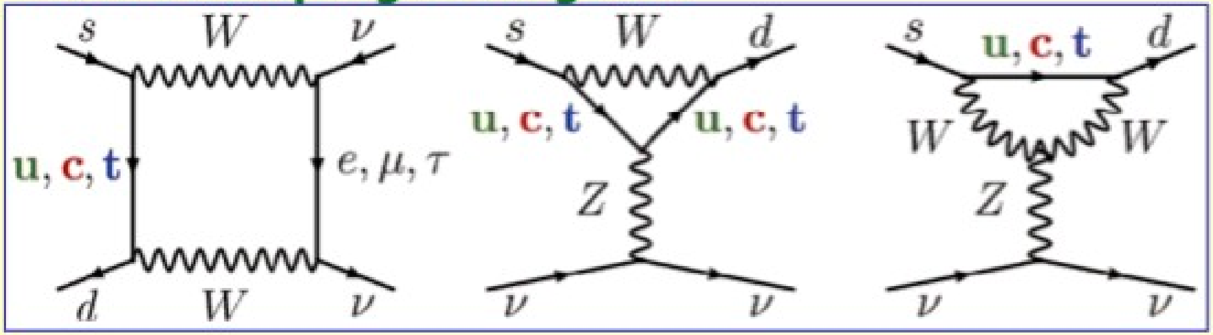
SM branching ratios

(Brod, Gorbahn, Stamou; PRD83 (2011) 034030)

Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu \bar{\nu}(\gamma)$	$7.81 \pm 0.75 \pm 0.29$
$K_L \to \pi^0 \nu \bar{\nu}$	$2.43 \pm 0.39 \pm 0.06$

⇓ CKM parametric (mainly $|V_{ts}|$) ⇓ Intrinsic

SM: box and penguin diagrams

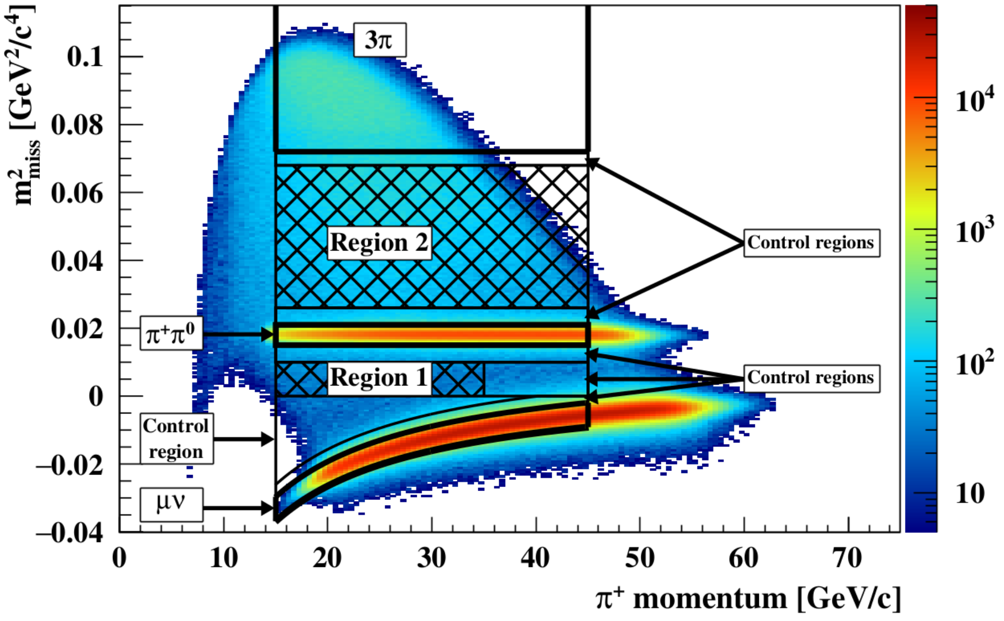


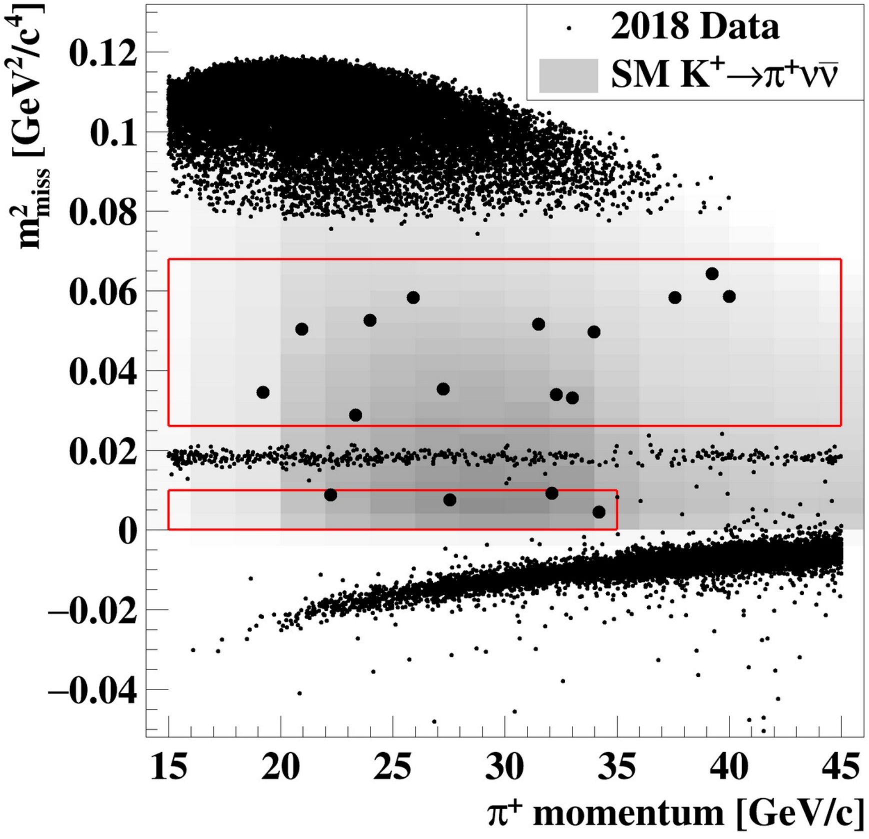
Experiments planning to measure these decays:

- $K^+ \to \pi^+ \nu \bar{\nu}$ (NA62, CERN) & $K^0 \to \pi^0 \nu \bar{\nu}$ (K0T0, J-PARC)

NA62 measurement of $K^+ \to \pi^+ \nu\bar{\nu}$

JHEP 06 (2021) 093





$B(K^+ \to \pi^+\nu\bar{\nu}) = (10.6\,^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$

SM prediction $(8.4 \pm 1.0) \times 10^{-11}$

SuperKEKB and Belle II

SuperKEKB Accelerator

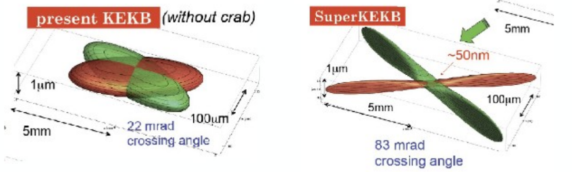
- Low emittance ("nano-beam") scheme employed (originally proposed by P. Raimondi)

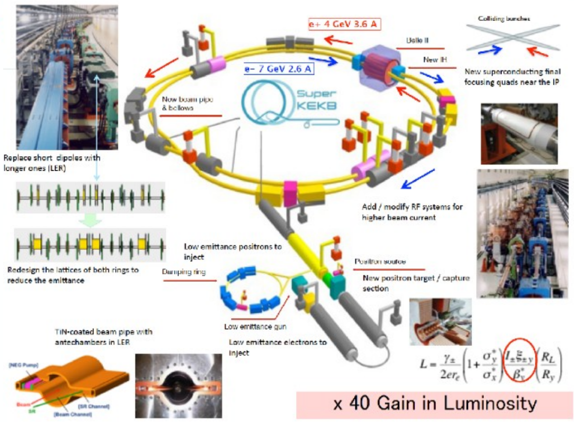
Machine parameters

	SuperKEKB LER/HER	KEKB LER/HER
E(GeV)	4.0/7.0	3.5/8.0
ε_x (nm)	3.2/4.6	18/24
β_y at IP(mm)	0.27/0.30	5.9/5.9
β_x at IP(mm)	32/25	120/120
Half crossing angle(mrad)	41.5	11
I(A)	3.6/2.6	1.6/1.2
Lifetime	~10min	130min/200min
L($cm^{-2}s^{-1}$)	80×10^{34}	2.1×10^{34}

x20 (β_y at IP)

x2 (I)

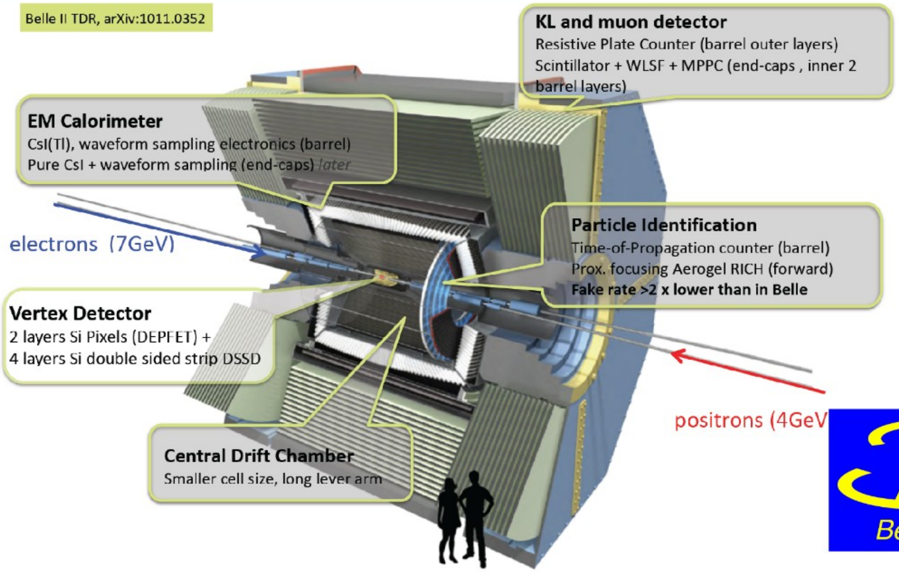




Belle II Detector

- Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)
- Improved performance and hermeticity

Belle II TDR, arXiv:1011.0352

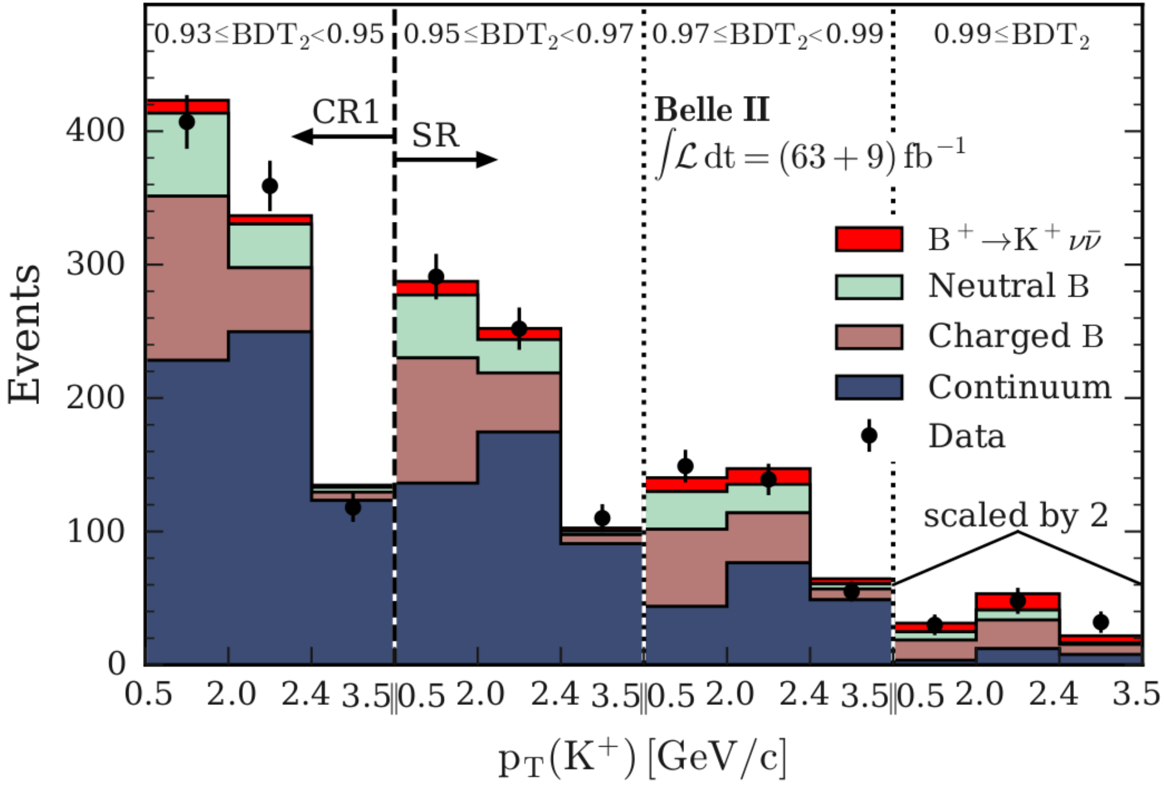


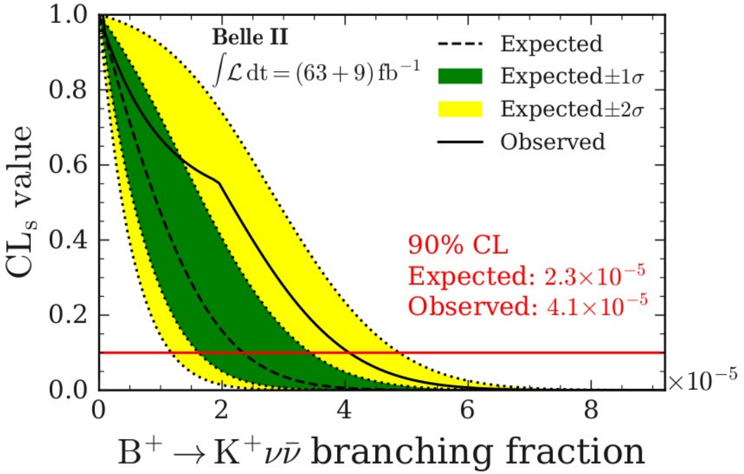
Belle II

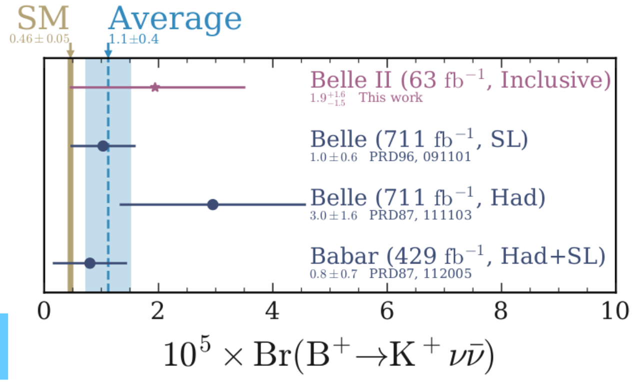
Over 400 fb^{-1} recorded since 2020, will increase ×10 in ~5 years

$B^+ \to K^+\nu\bar{\nu}$ at Belle II

PRL 127 (2021) 181802







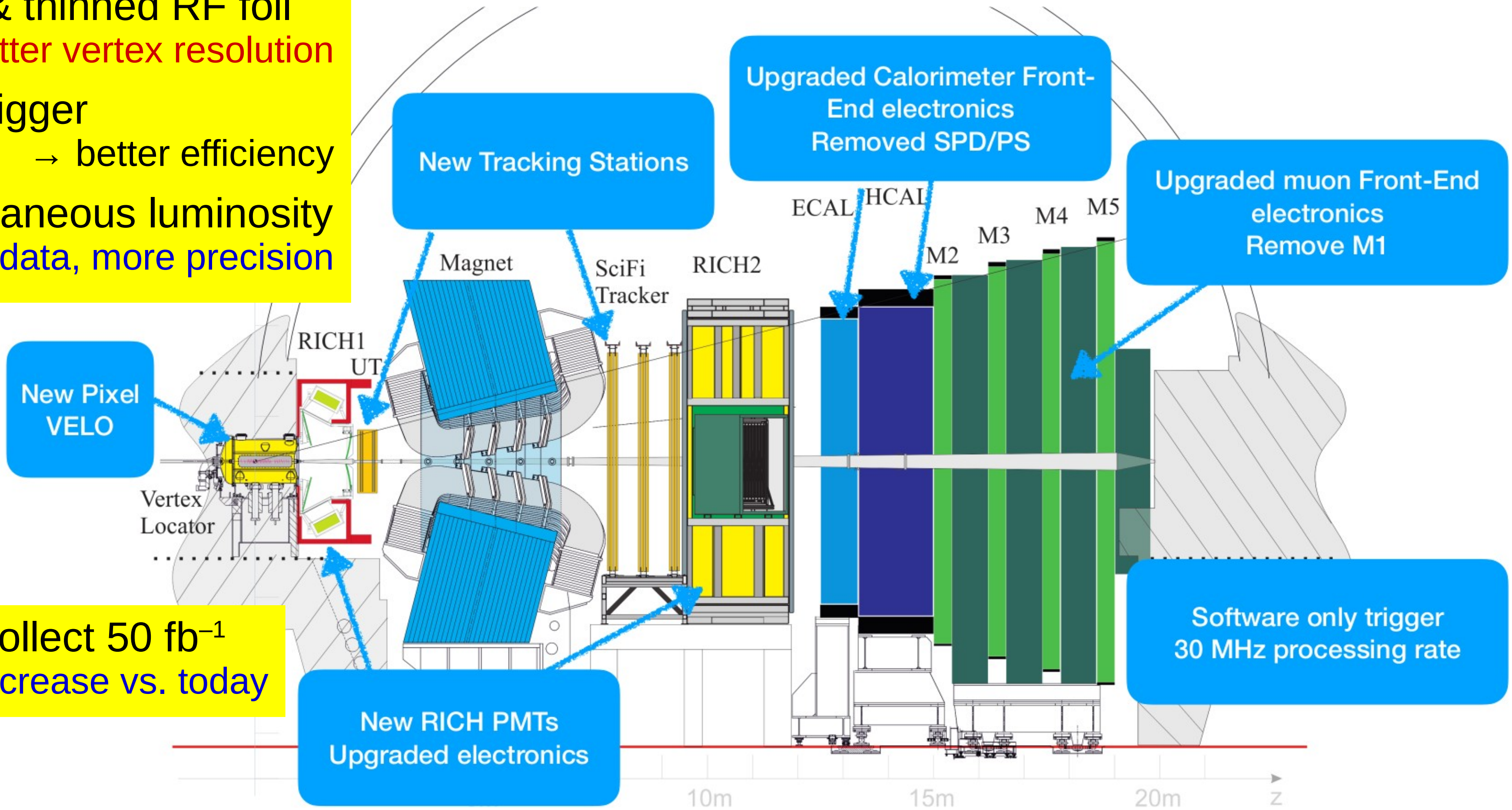
Result with only 63 fb^{-1} competitive with previous world best

LHCb Upgrade I

VELO pixels & thinned RF foil
→ better vertex resolution

All software trigger
→ better efficiency

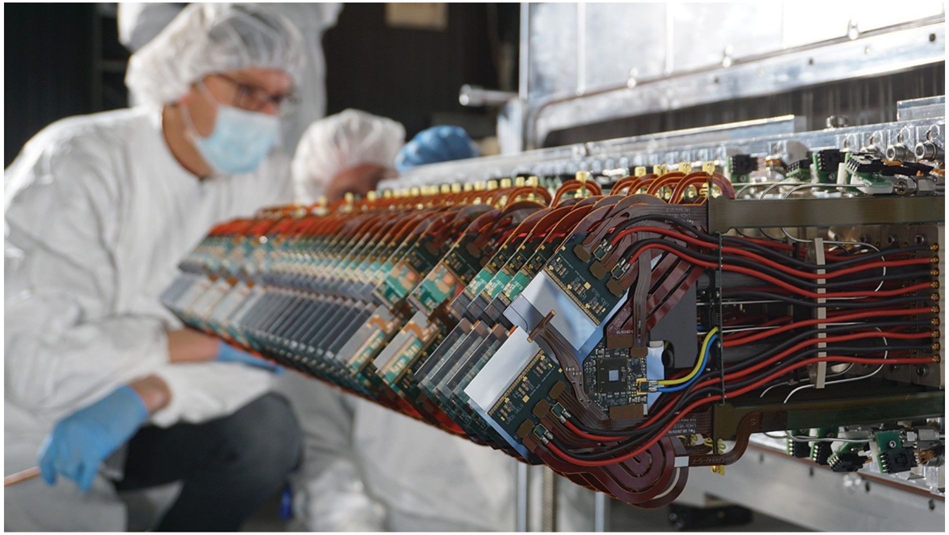
Higher instantaneous luminosity
→ more data, more precision

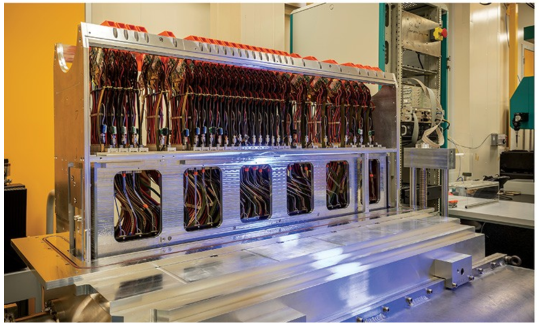


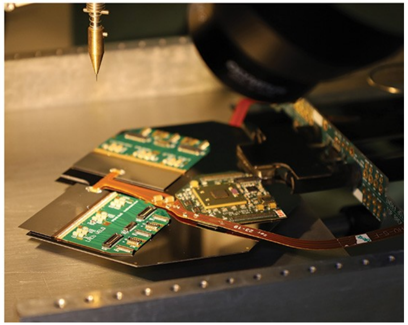
Designed to collect 50 fb^{-1}
→ ×10 data increase vs. today

Pixel VELO

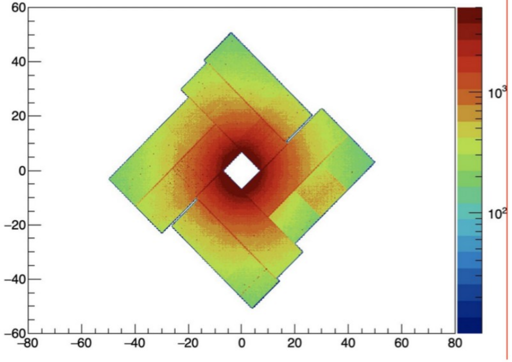
Identification of displaced vertices crucial to identify B decays at hadron colliders

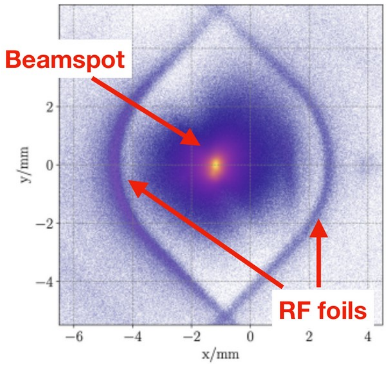


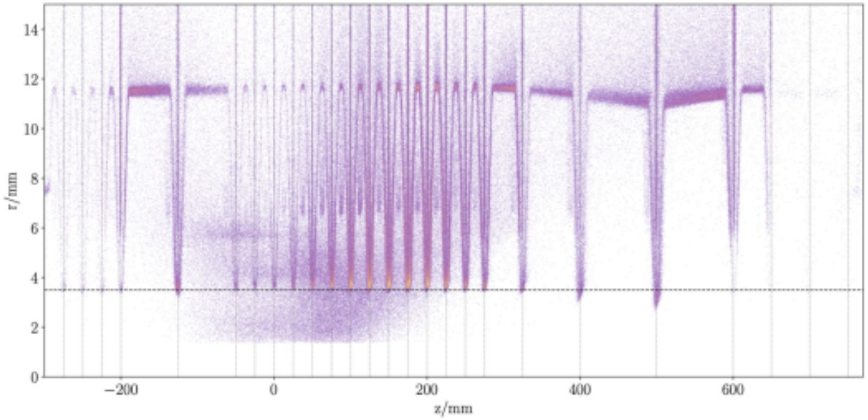




Commissioning ongoing!







Data processing at 30 MHz

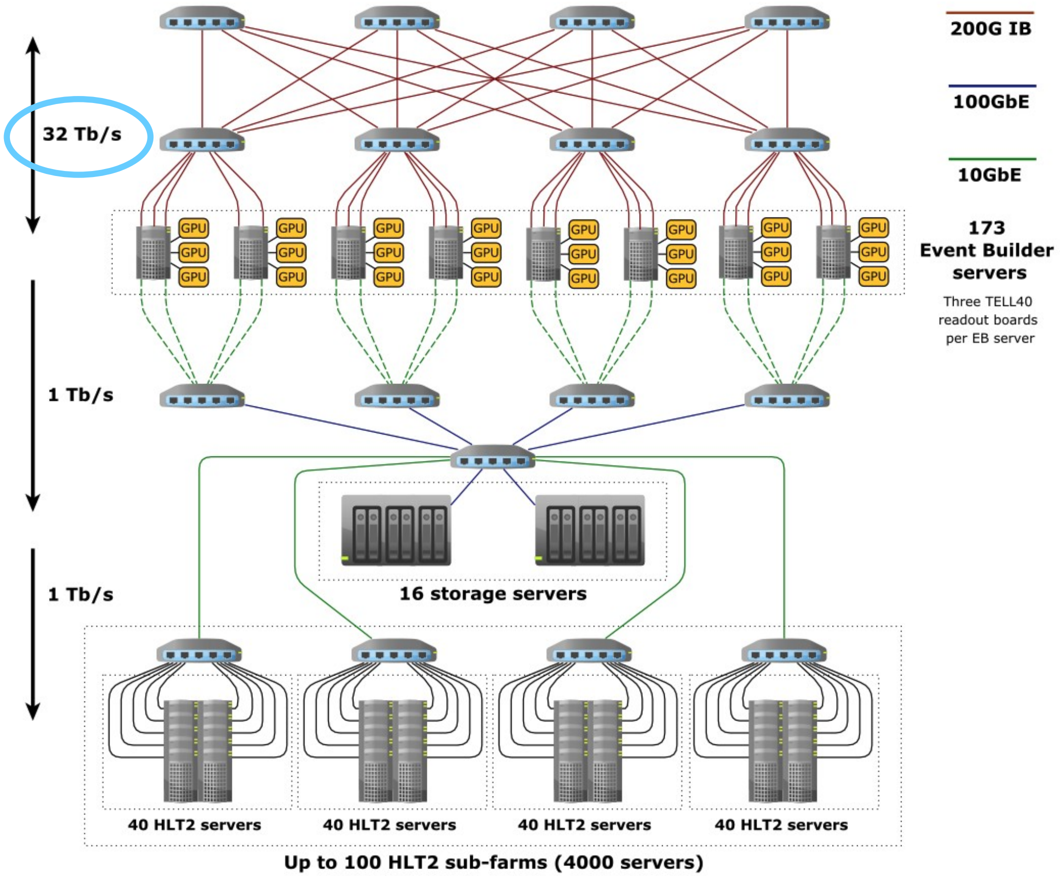
Comput.Softw.Big Sci. 6 (2022) 1

Traditional HEP trigger model:
– select interesting events with loose criteria for later offline analysis

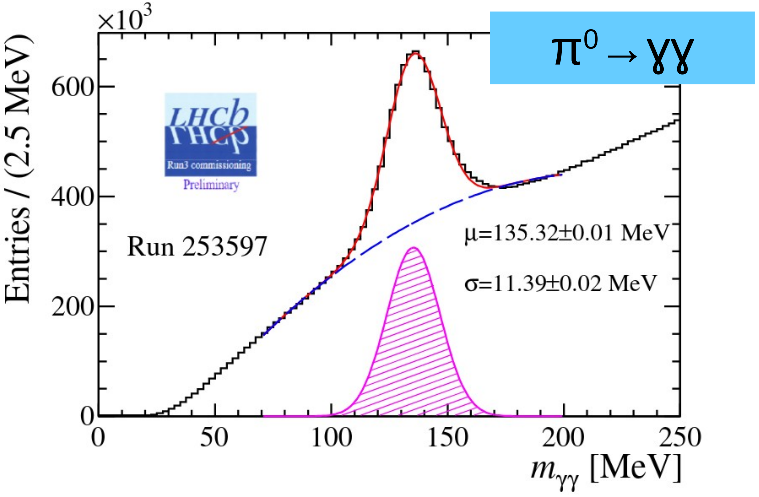
At high luminosity, every pp bunch-crossing contains a potentially interesting event

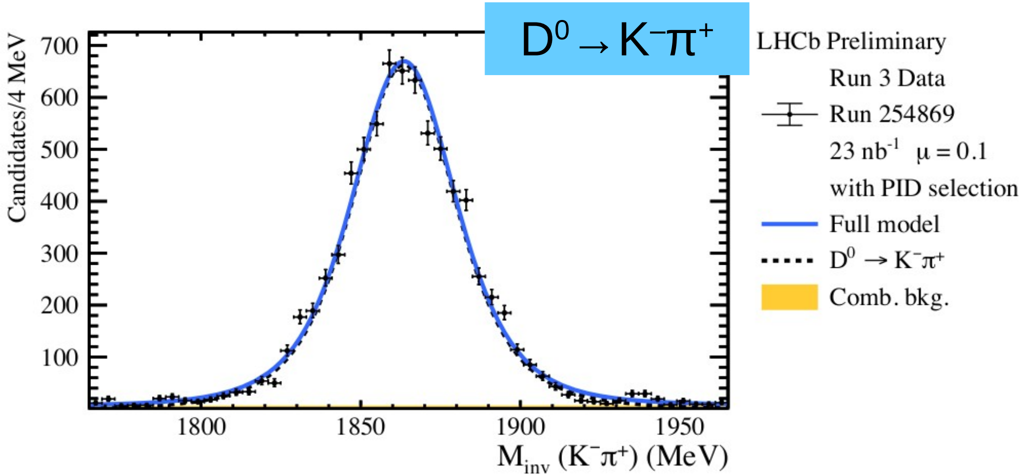
Need a new paradigm
– full software trigger
– first level trigger (HLT1) implemented in GPUs
– offline quality reconstruction: calibration and alignment performed before HLT2
– select relevant information in each event to store for offline analysis

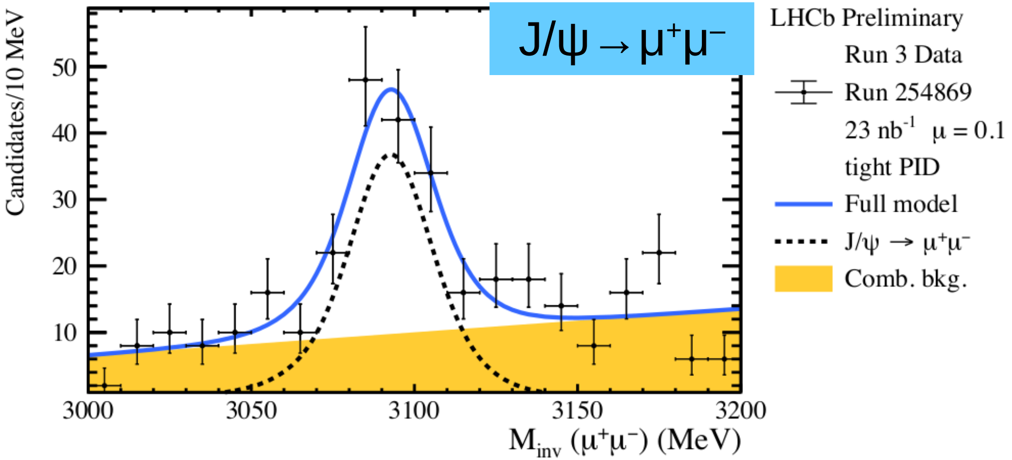
n.b:
data rate from LHCb detector (32 Tb/s)
global internet traffic 2022 (997 Tb/s)



LHCb Upgrade I commissioning







Observations of SM standard candles

Vertexing, tracking, calorimetry and particle identification all working well

Resolution will improve with calibration and alignment

Why stop there?

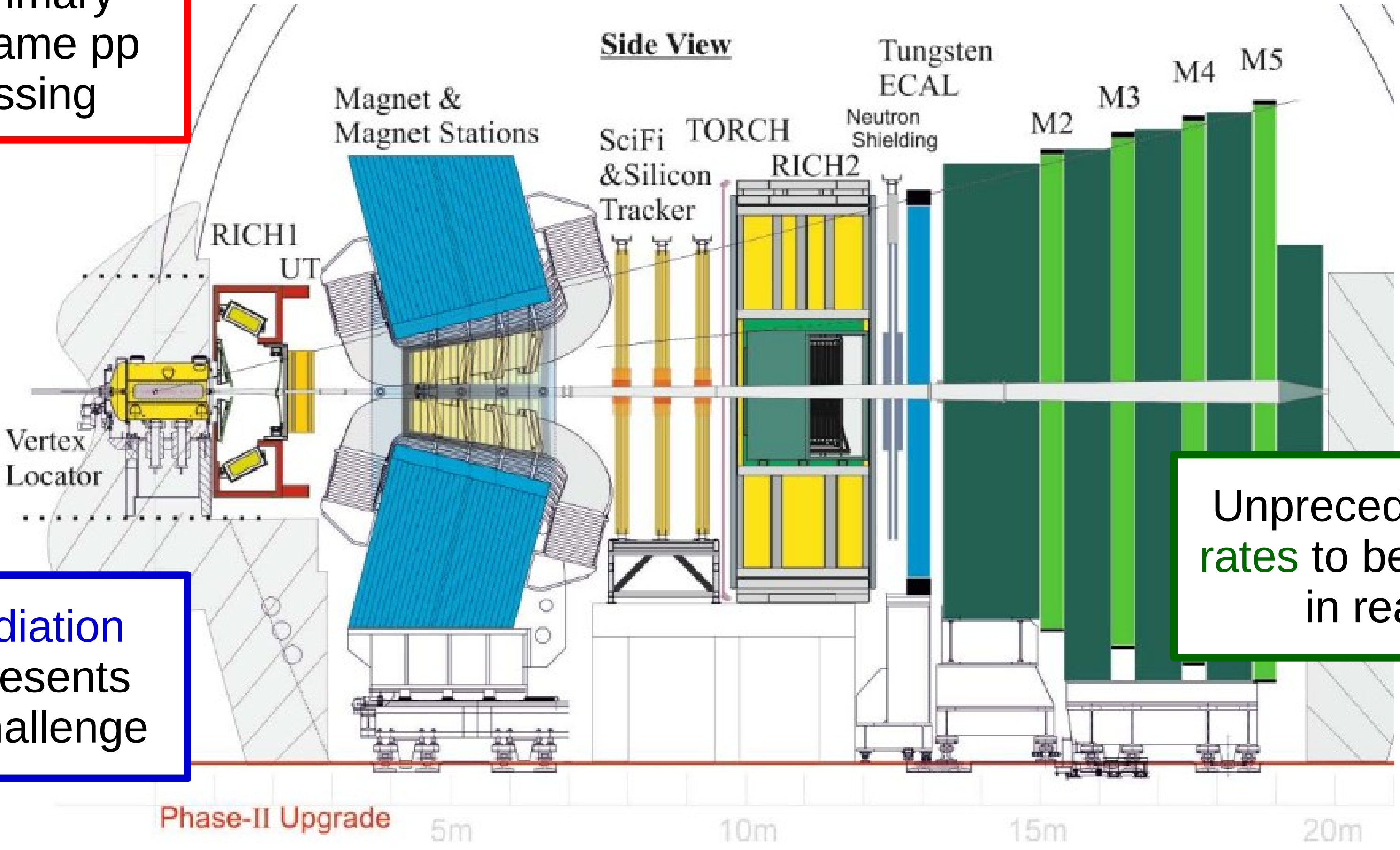
LHCb Upgrade II needed
to fully exploit HL-LHC

LHCb Upgrade I
will get us here

Crucial to use precision timing information to separate primary vertices in same pp bunch crossing

LHCB-TDR-023

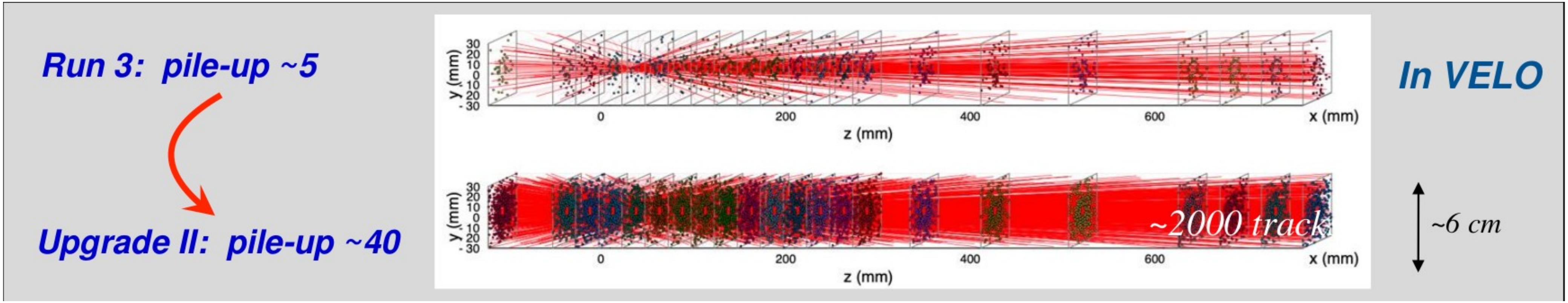
LHCb Upgrade II



Need for radiation hardness presents significant challenge

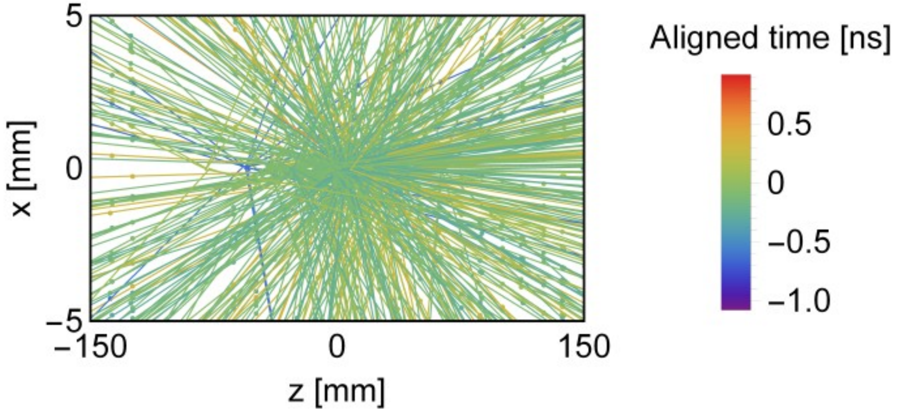
Unprecedented data rates to be processed in real time

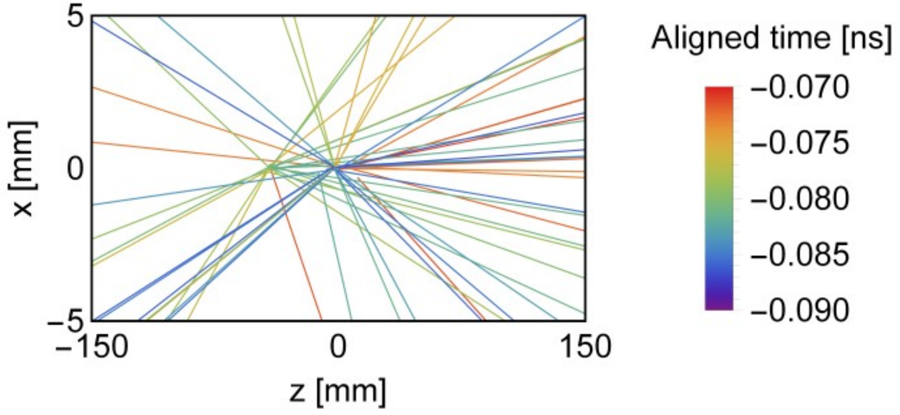
The need for timing



- High LHC luminosity achieved by increasing number of pp interactions per bunch crossing
- Large detector occupancies → many possible fake combinations
- But LHC bunches are long (~50 mm); collisions in each bunch crossing occur over ~0.2 ns
- Detection with ~20 ps resolution per track gives new handle to associate hits correctly

The need for timing





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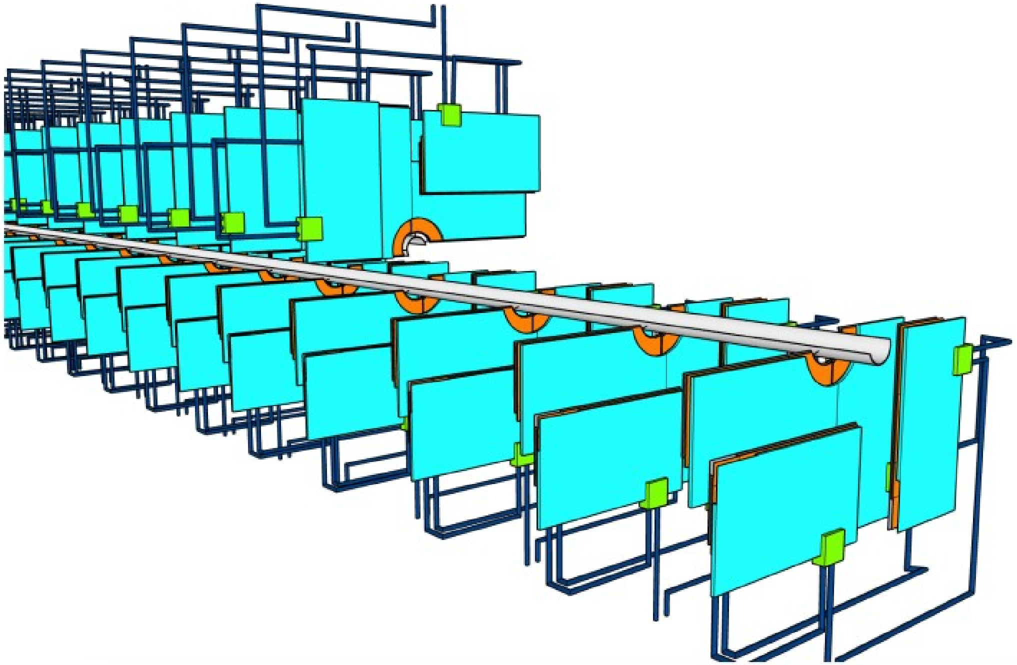
Vertex detector (VELO)

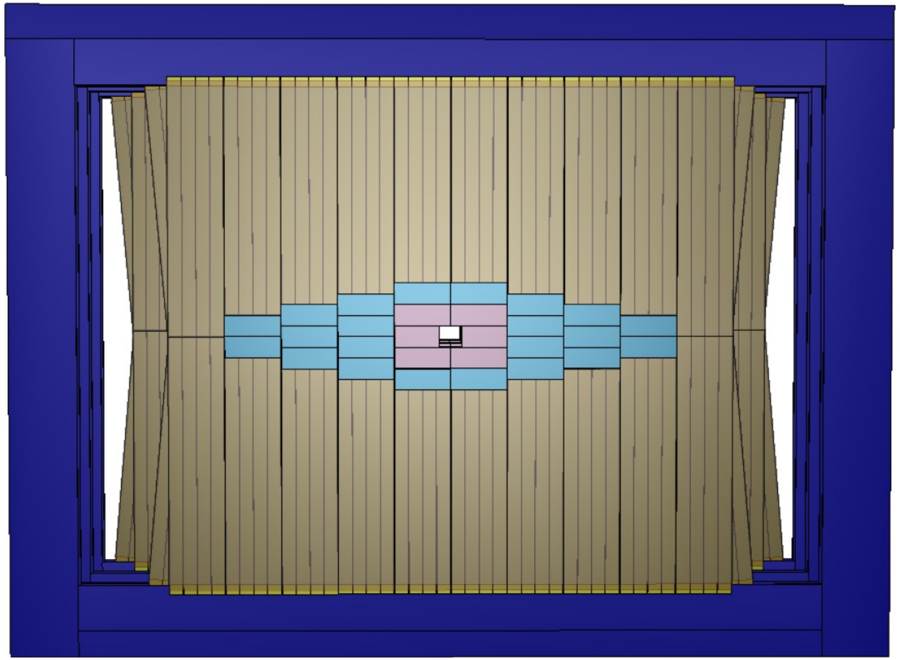
- Candidate sensors
  - thin planar, LGAD, 3D
- Candidate ASICs (28 nm technology)
  - VeloPix2, Timespot
- Mechanical design challenges
  - cooling, module replacement, minimisation of material (RF foil), vacuum compatibility
- Fast tracking, tagging also important for kaon experiments (NA62/HIKE)
  - maybe also for neutrino experiments?

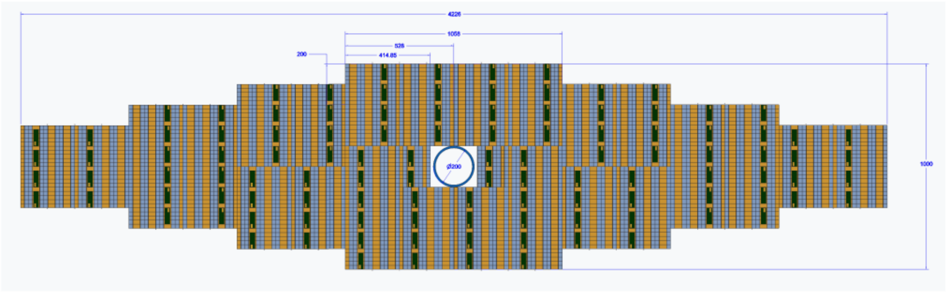
    (see EPJ C82 (2022) 465)



MAPS tracker

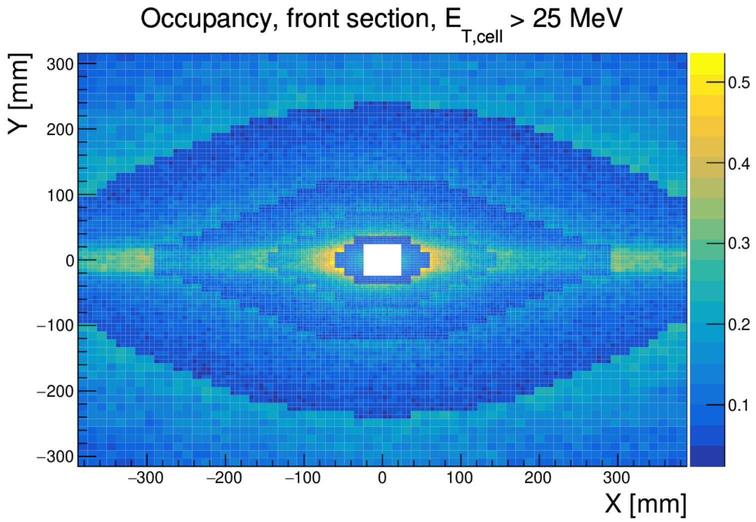
- Central region of SciFi tracking stations to be replaced with silicon detectors
- Use MAPS technology, also for Upstream Tracker (UT)
  - Can meet radiation requirement (3×10^{15} n_{eq}/cm^2 at UT)
  - First large scale tracking detector with this technology
  - Building on experience from STAR, ALICE, ATLAS and mu3e

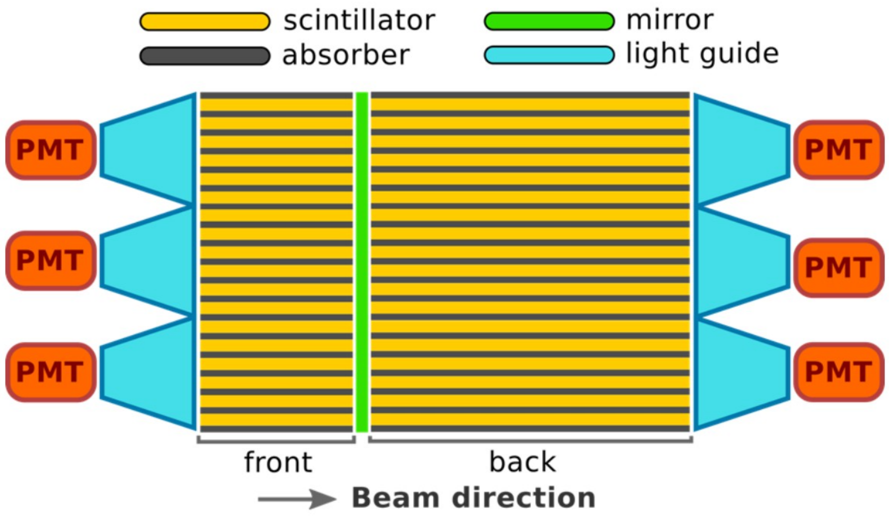




Electromagnetic calorimeter

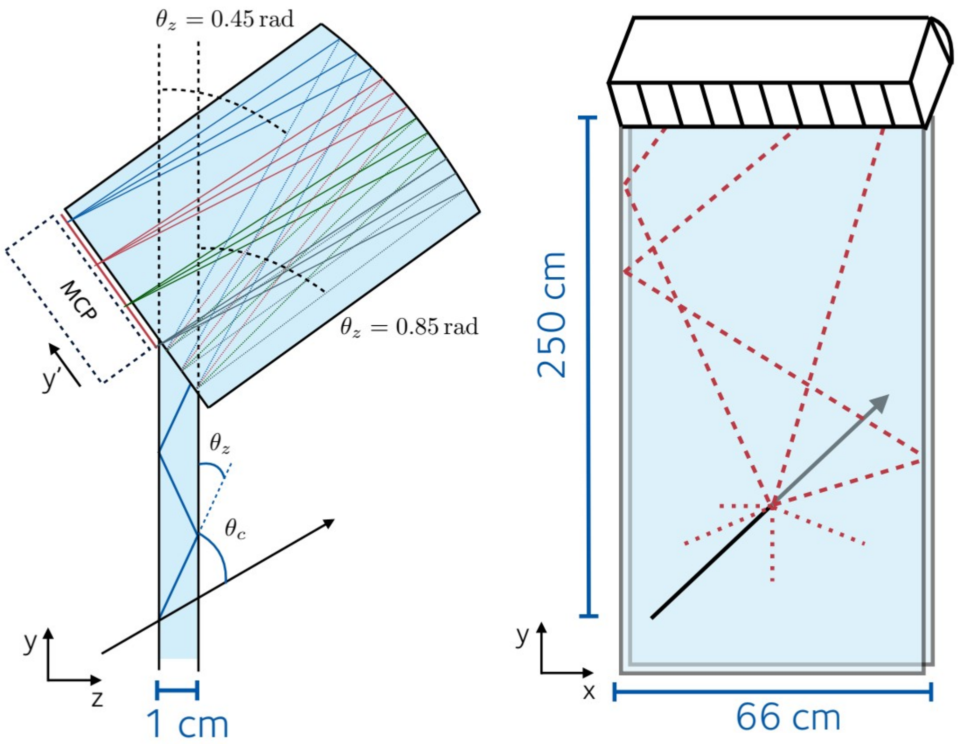
- LHCb ECAL not replaced (except electronics) in Upgrade I
  - in Run 3 will operate at 25× its design luminosity!
- Proposal for crystal fibres (SpaCal) in central region + Shashlik (outer region)
  - timing information (σ_t ~ 20 ps) used to help suppress background





TORCH detector

- Highly-polished quartz plate used as Cherenkov radiator: 1 cm thick (~10% X_0)
- Photons transported by internal reflection + focusing optics to photon detectors. Arrival time and position of photons measured precisely
- Measured Cherenkov angle is used to correct for dispersion in the quartz: TOF+RICH → TORCH
- At ~10m downstream of collision point, require per track resolution of 15 ps for 3σ K/π separation → per photon resolution of 70 ps.
- "Start time" t_0 can be determined from timing of other tracks from primary vertex
  - Associate tracks to correct vertices
  - Reject "ghost" tracks

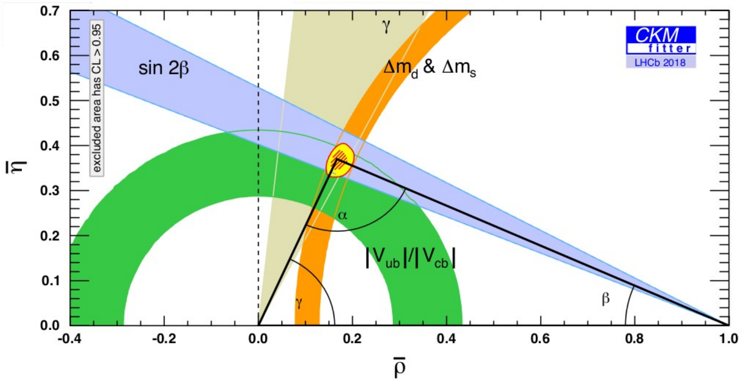


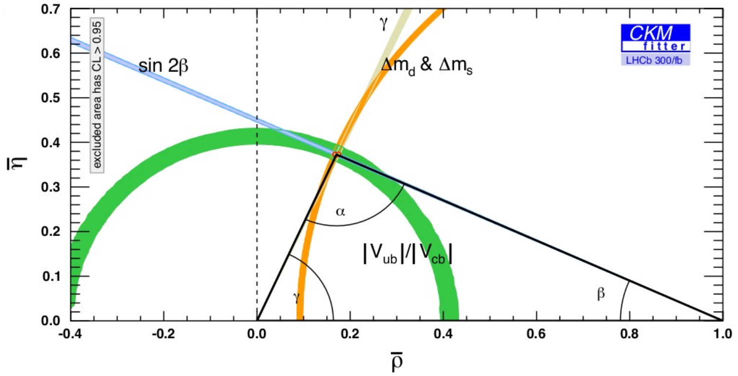
Performance demonstrated in test beam with half-size module: NIM A961 (2020) 163671

LHCb Upgrade II physics impact

LHCB-TDR-023

Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests				
γ ($B \to DK$, *etc.*)	4° [9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad [8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6% [29, 30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4} [34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4} [35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm				
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5} [5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5} [38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5} [37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69% [40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—	—	—	0.2
$A_{\text{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
A_{T}^{Im} ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$ [51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32 [51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [53]	0.148	0.097	0.038
Lepton Universality Tests				
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044 [12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12 [61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026 [62, 64]	0.007	0.005	0.002





Summary

- Flavour physics provides a powerful zeptoscope to probe the smallest scales
  - complementary to Higgs physics and high energy probes
- Enormous progress through B factory and LHC era
  - some tensions with SM predictions to be understood
- Exciting prospects for 2020s with Belle II and LHCb Upgrade I
- Developing technology for the new eyes of LHCb Upgrade II
  - Many opportunities, new collaborators welcome